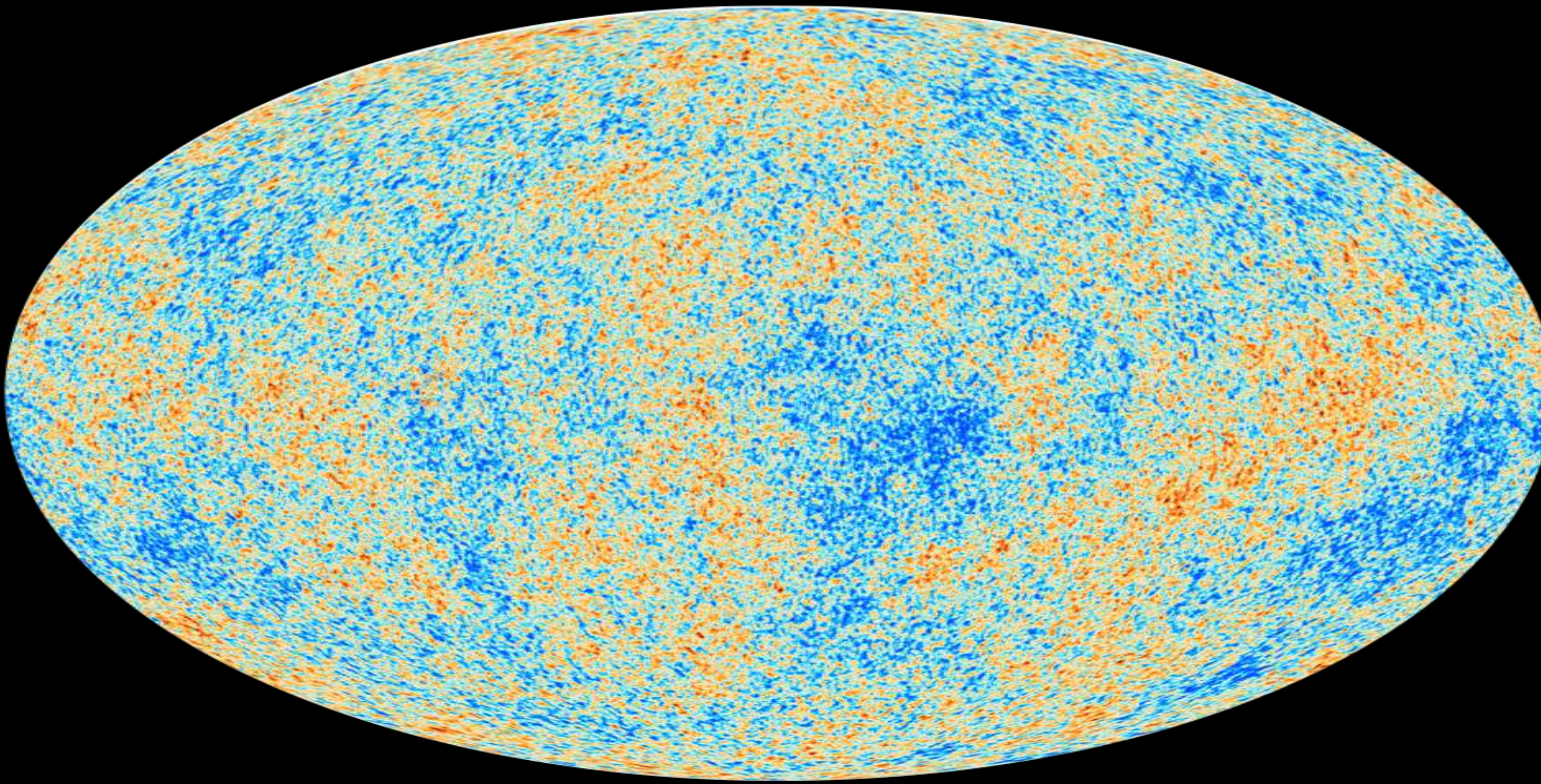
http://www.trisep.ca/program/trisep_halzen_061918.pdf

High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

icecube.wisc.edu

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang

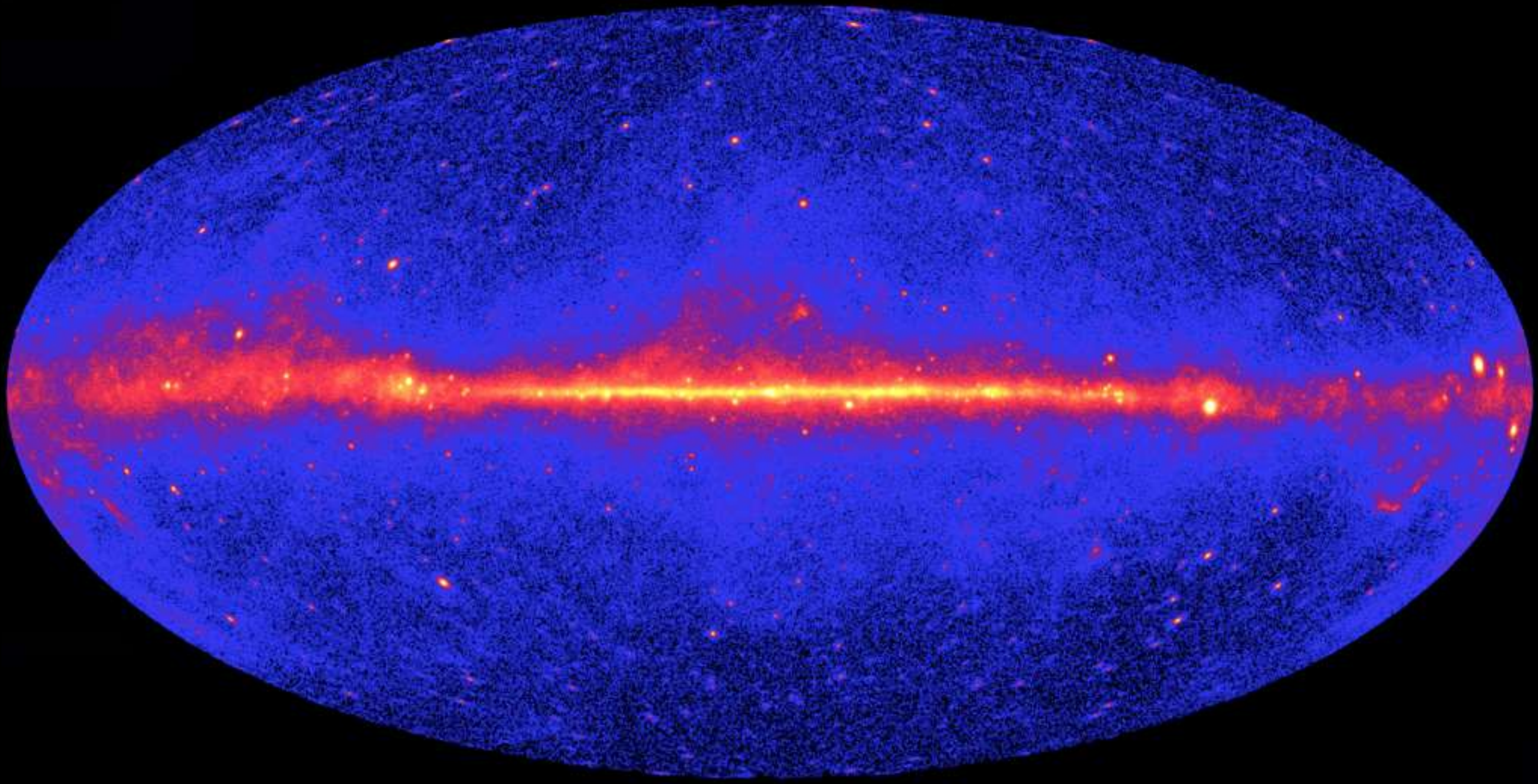


wavelength = 10^{-3} m $\Leftrightarrow$ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky

wavelength = 10^{-6} m ⟺ energy = 1 eV

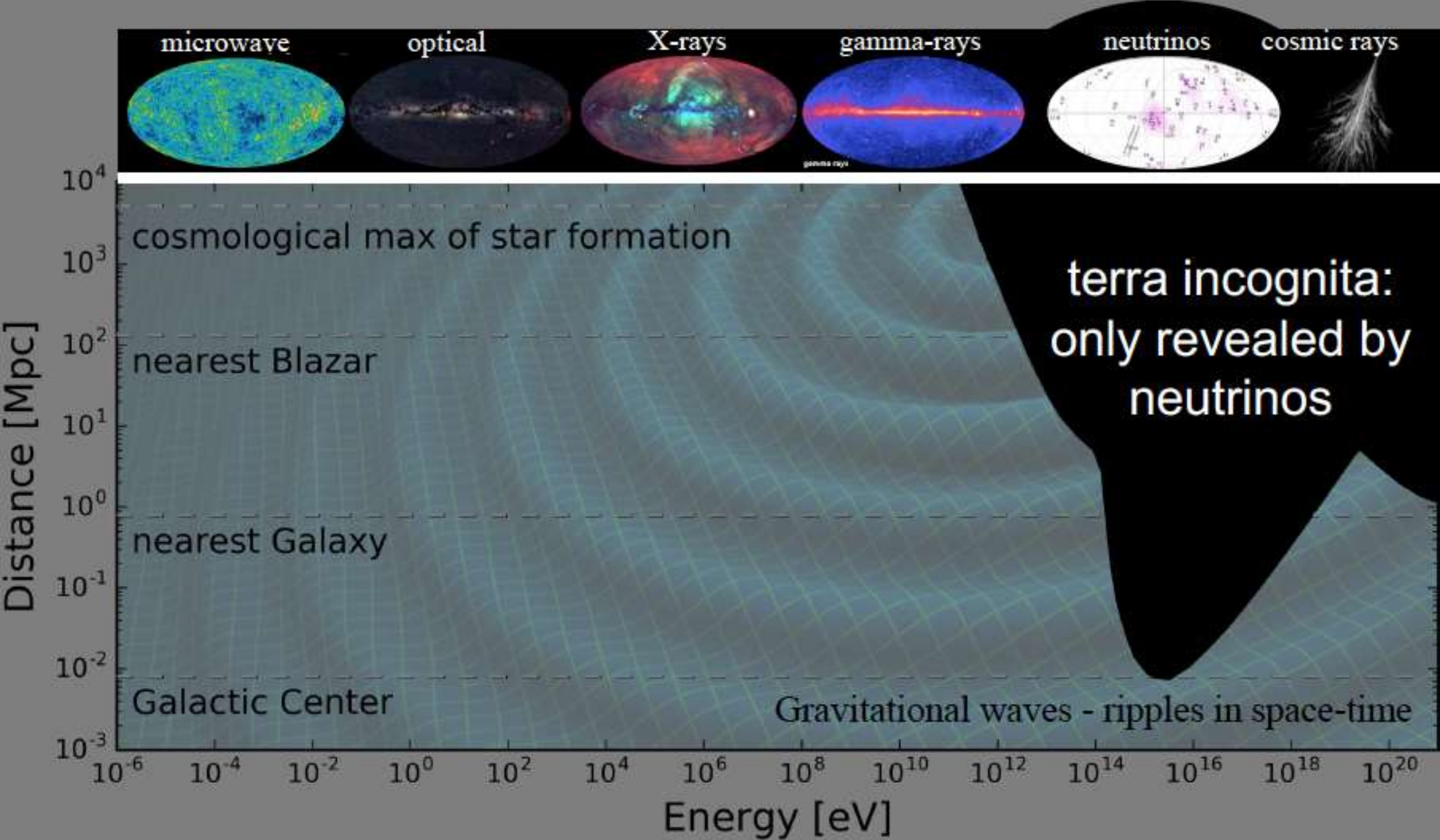
Cosmic Horizons – Gamma Radiation



wavelength = 10^{-15} m ⟺ energy = 1 GeV

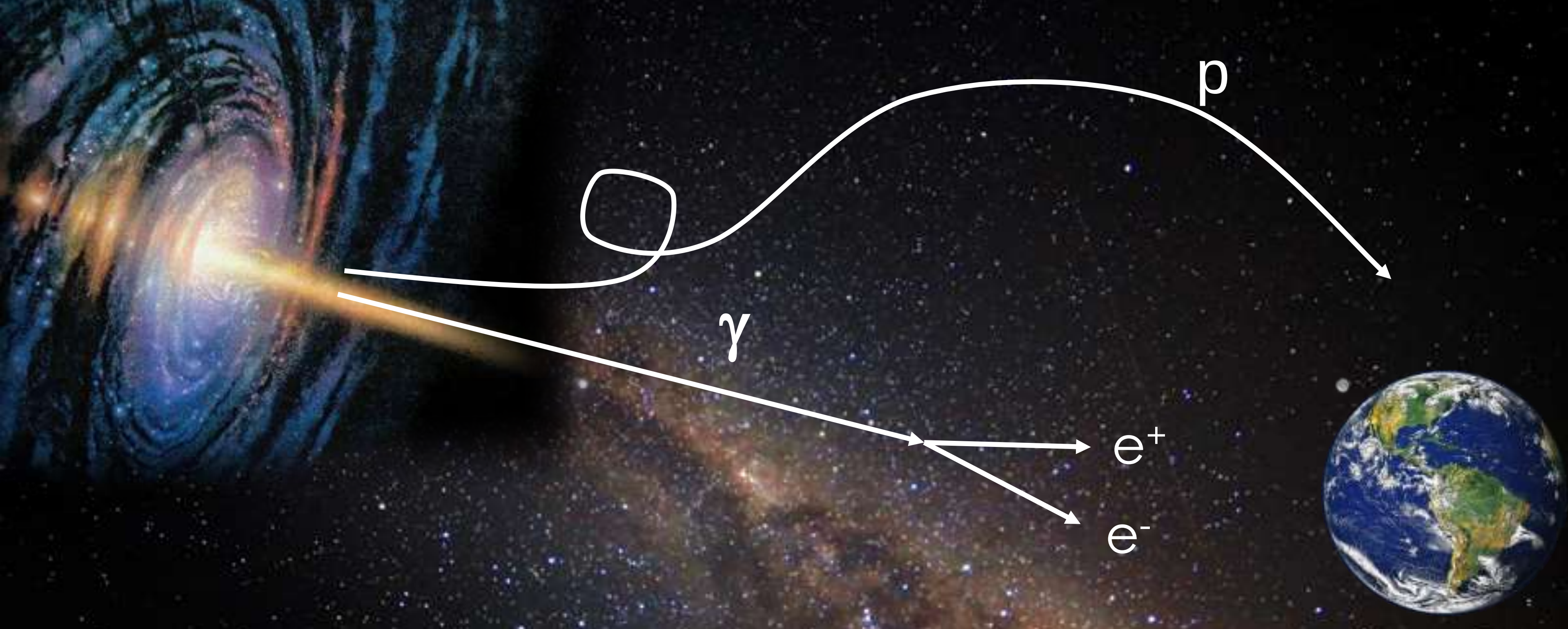
Cosmic Horizons – Gamma Radiation

wavelength = 10^{-21} m ⟺ energy = 10^{3} TeV



- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

The opaque Universe

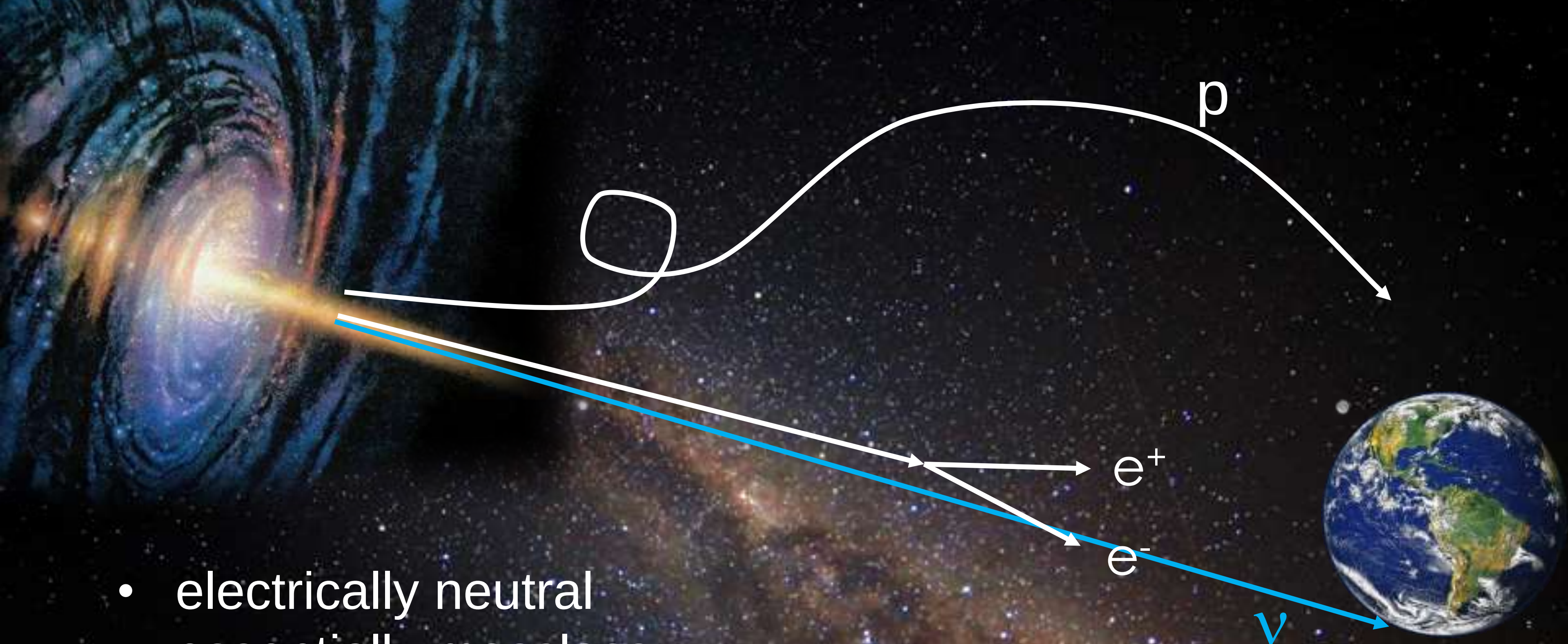


$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons ($411/cm^3$) before reaching our telescopes

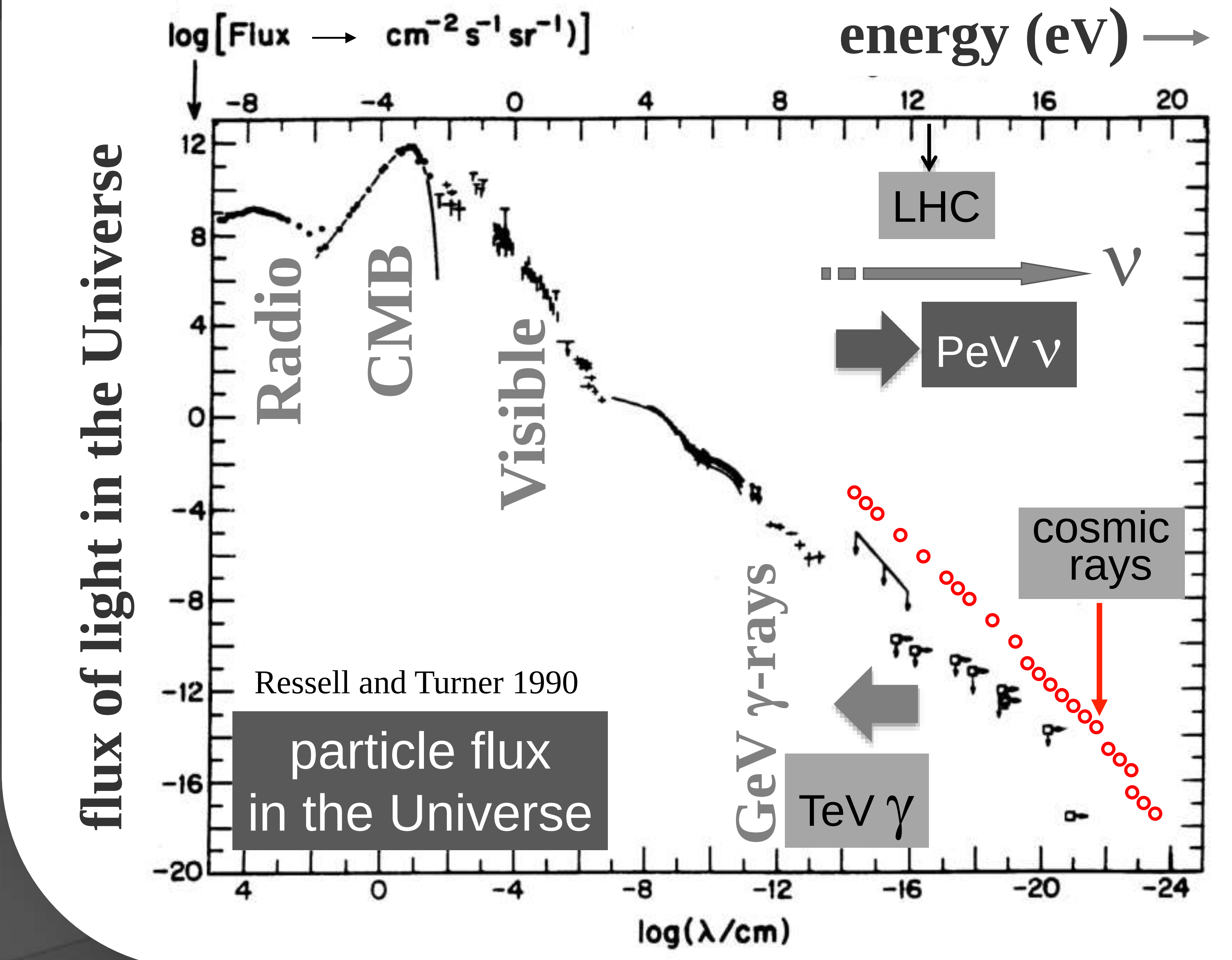
enter: neutrinos

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?



energy (eV)
log[Flux → cm−2 s−1 sr−1)]
-8
-4
0
4
8
12
16
20
flux of light in the Universe
Radio
CMB
Visible
GeV γ-rays
LHC
ν
PeV ν
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux
in the Universe
12
8
4
0
−4
−8
−12
−16
−20
4
0
−4
−8
−12
−16
−20
−24
log(λ/cm)

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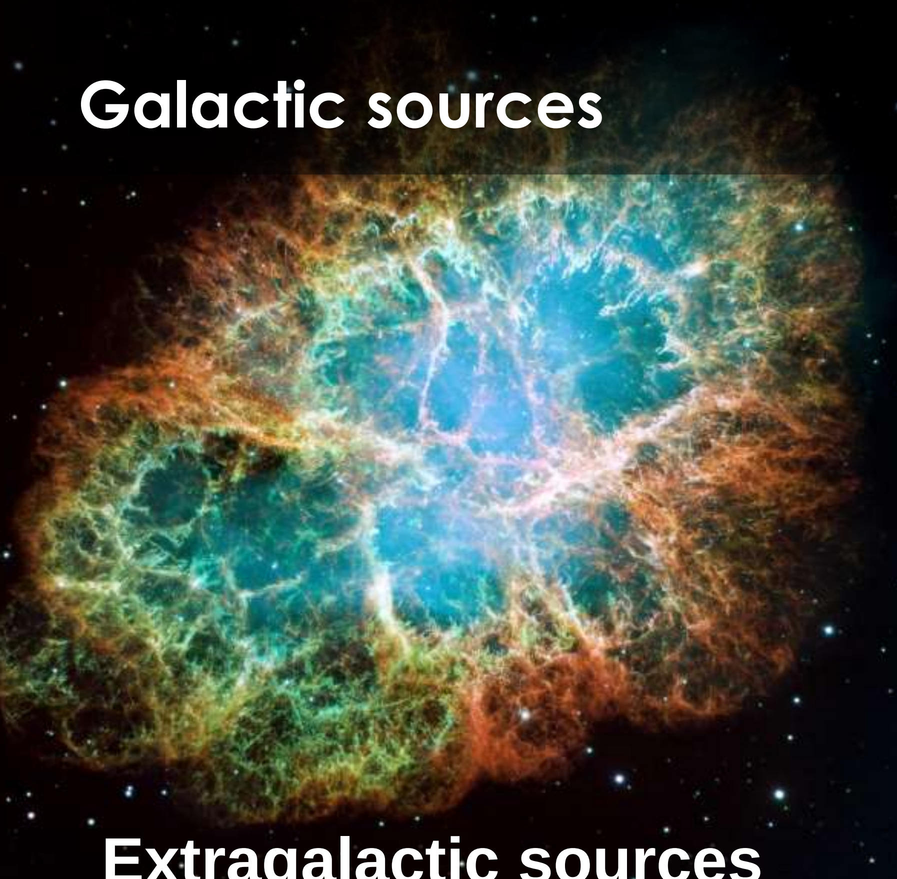
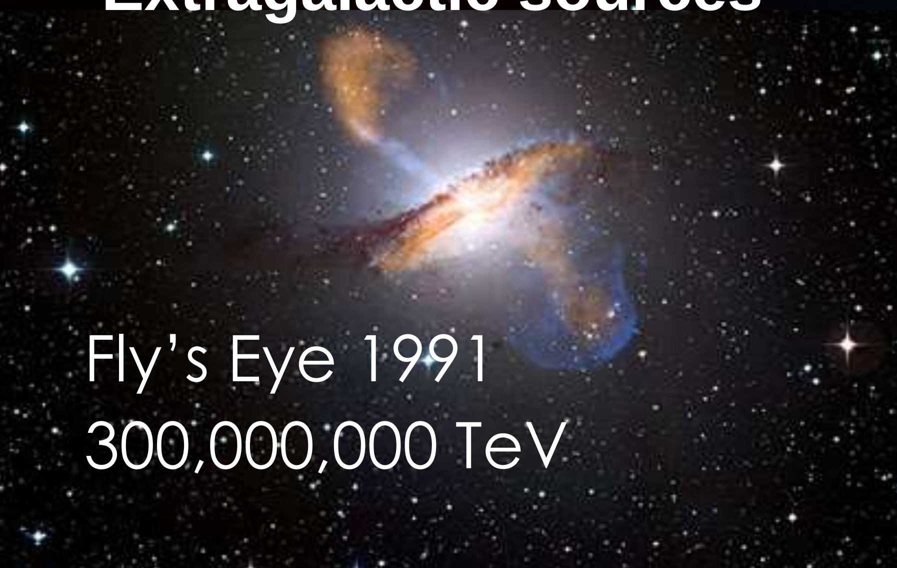
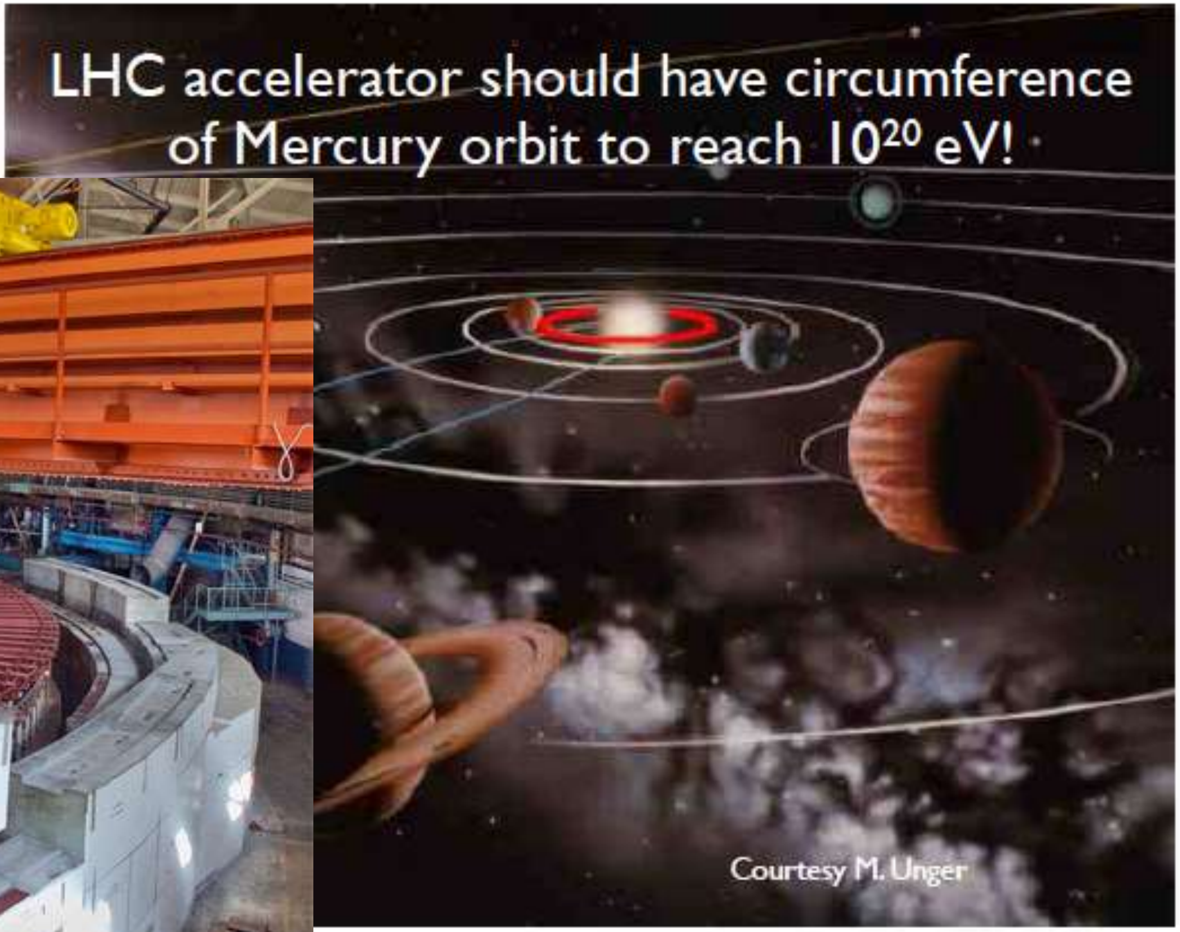

Galactic sources


Extragalactic sources
Fly’s Eye 1991
300,000,000 TeV

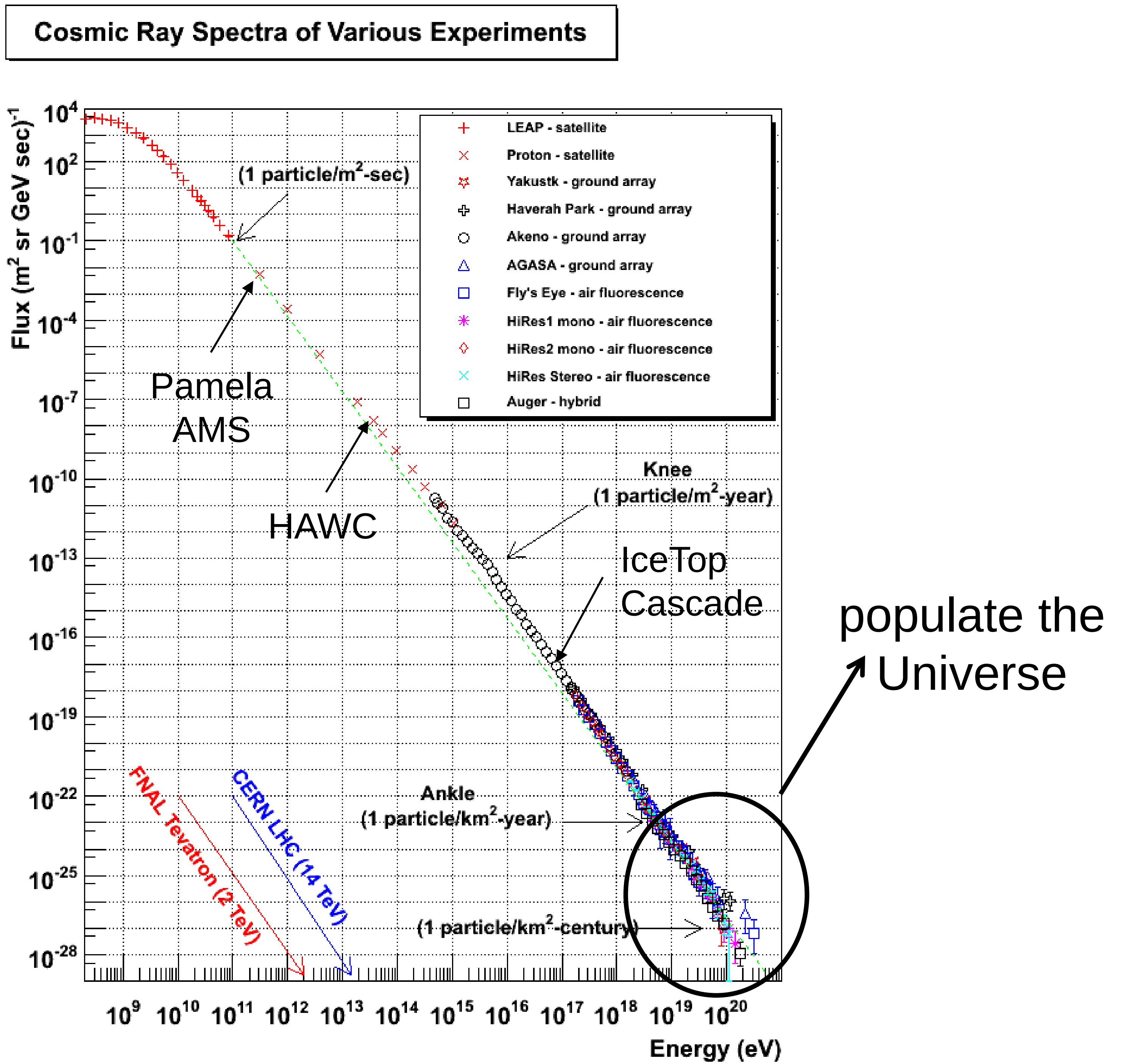

Victor Hess
discovers
cosmic rays
1912

accomodating energy and luminosity are challenging



Fly’s Eye 1991

3,000,000,000 TeV

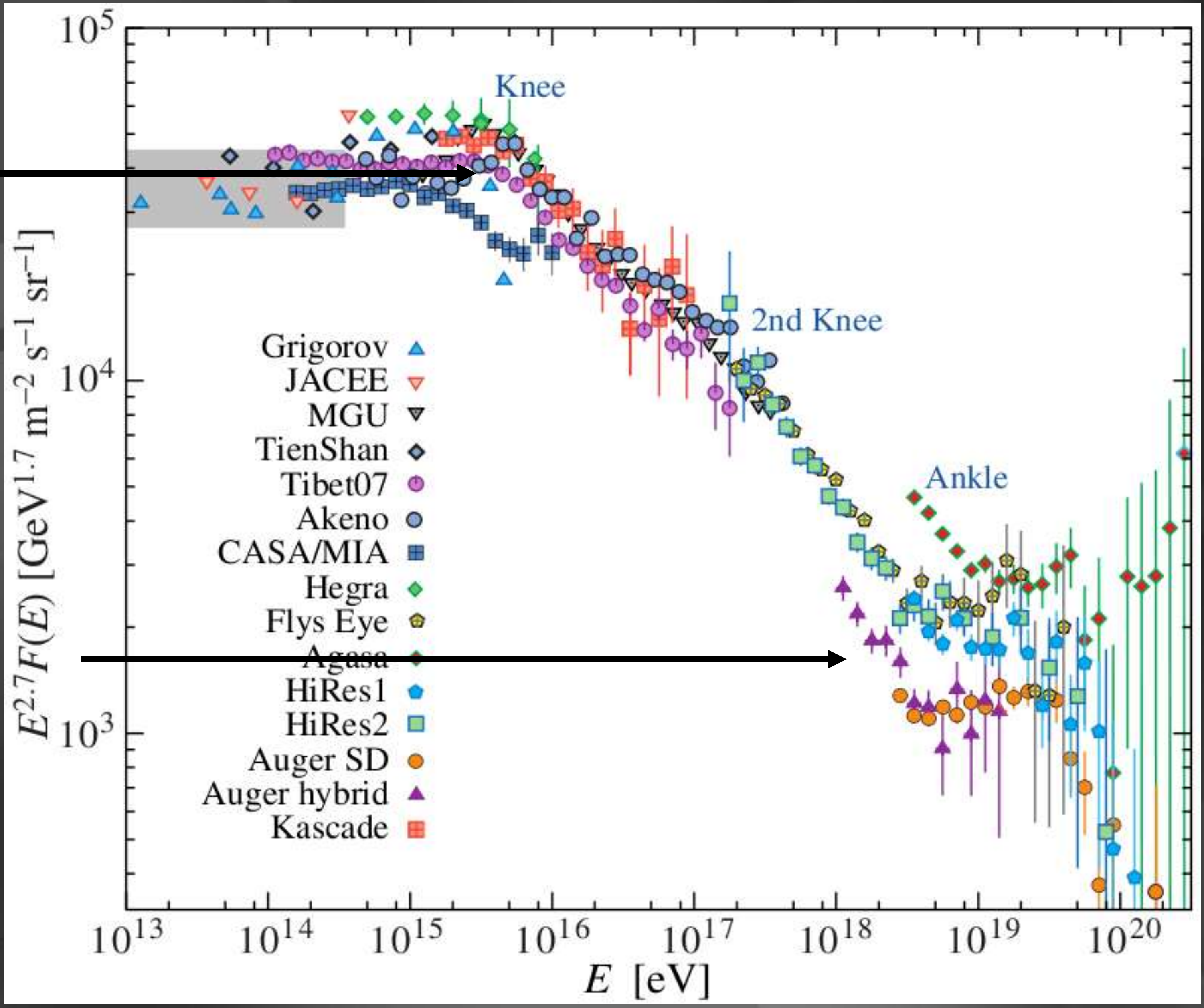


Cosmic Ray Spectra of Various Experiments
Flux (m² sr GeV sec)⁻¹
Energy (eV)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
(1 particle/m²-sec)
Pamela
AMS
HAWC
Knee
(1 particle/m²-year)
IceTop
Cascade
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
populate the
Universe

… often wrong, but never in doubt …

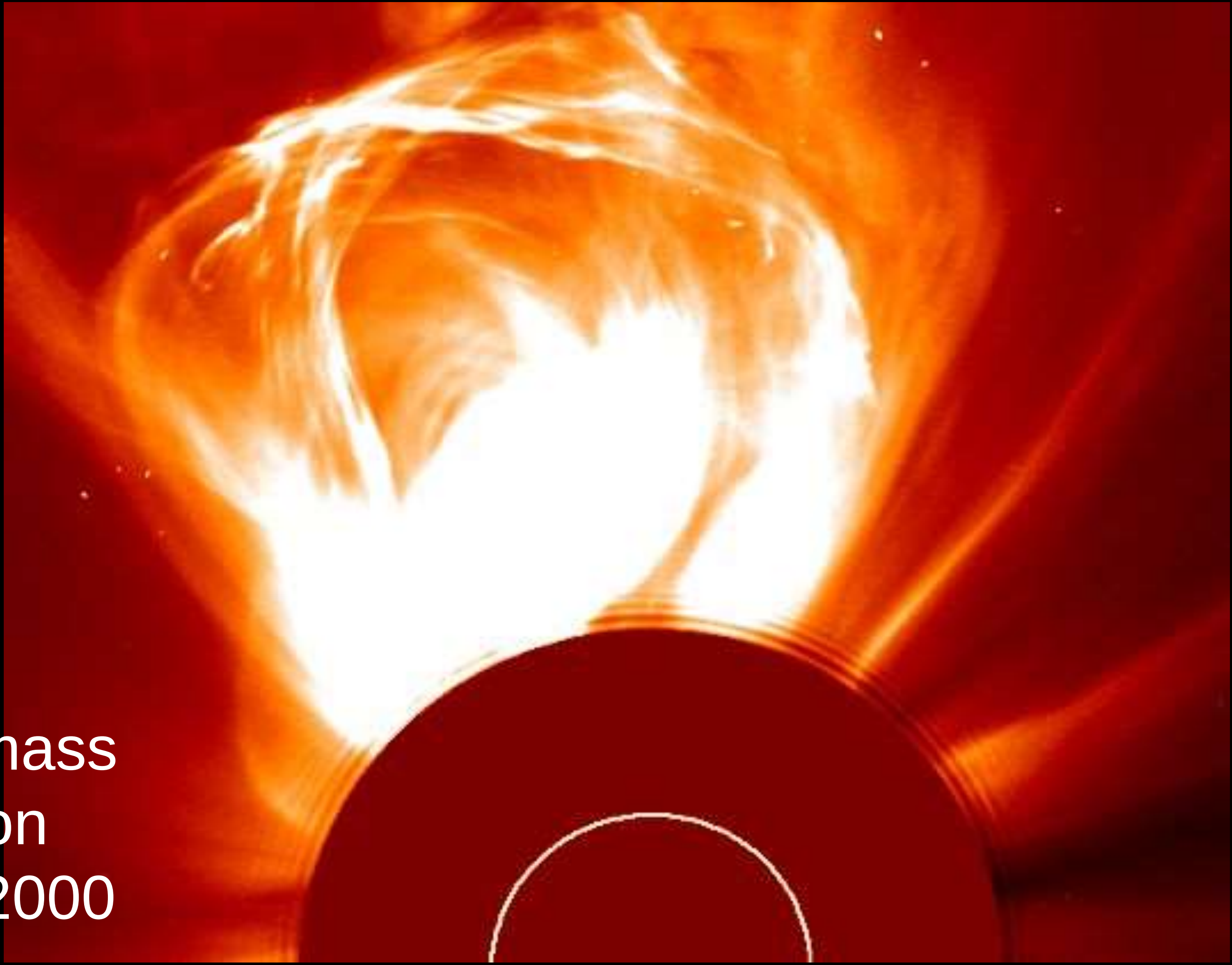
Galactic: supernova remnants?

extragalactic: gamma ray bursts?



the sun constructs an accelerator

the sun constructs an accelerator



coronal mass ejection
09 Mar 2000

- accelerator must contain the particles

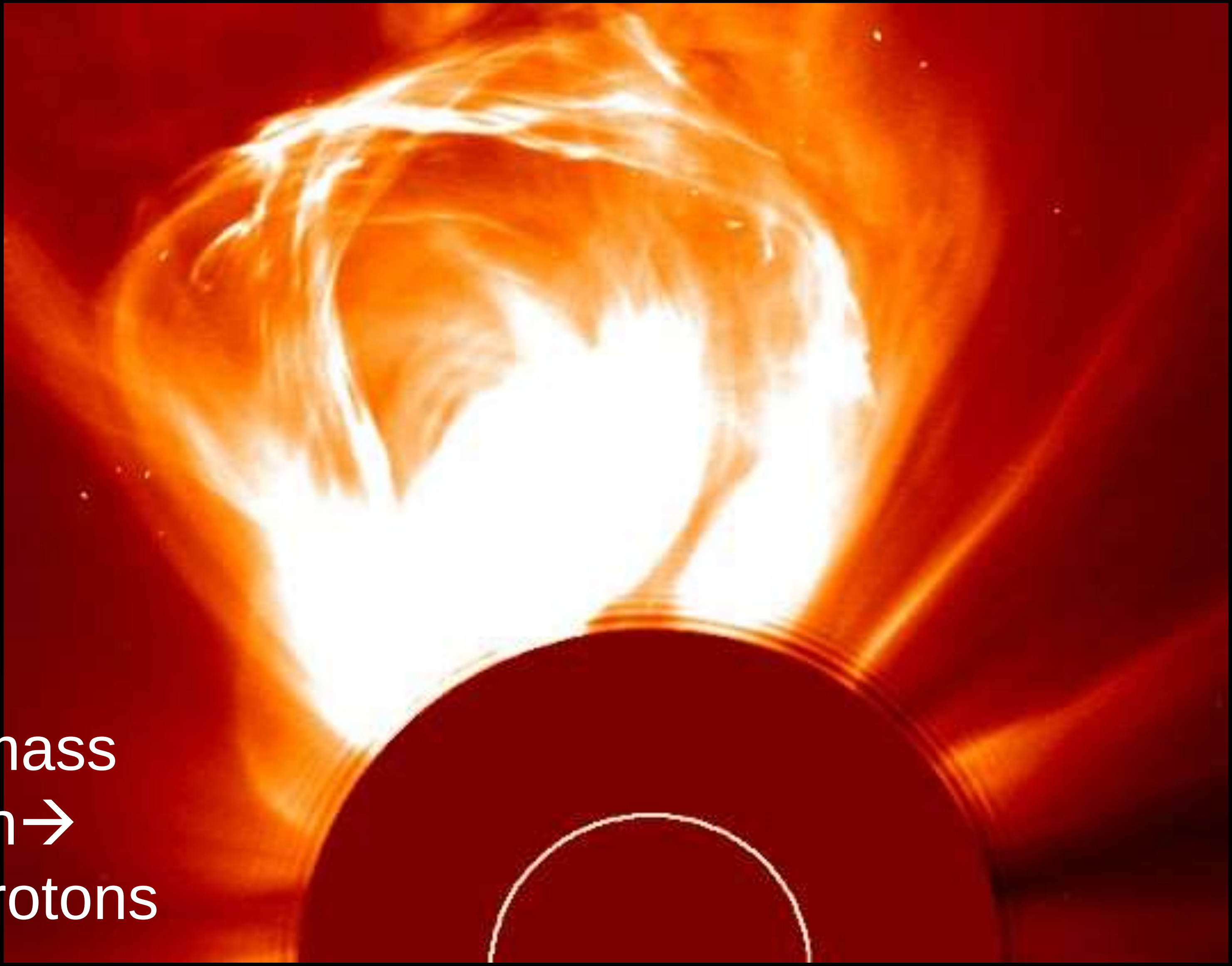
$$R_{gyro} \left(= \frac{E}{\mathrm{v} q B}\right) \leq R$$

$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

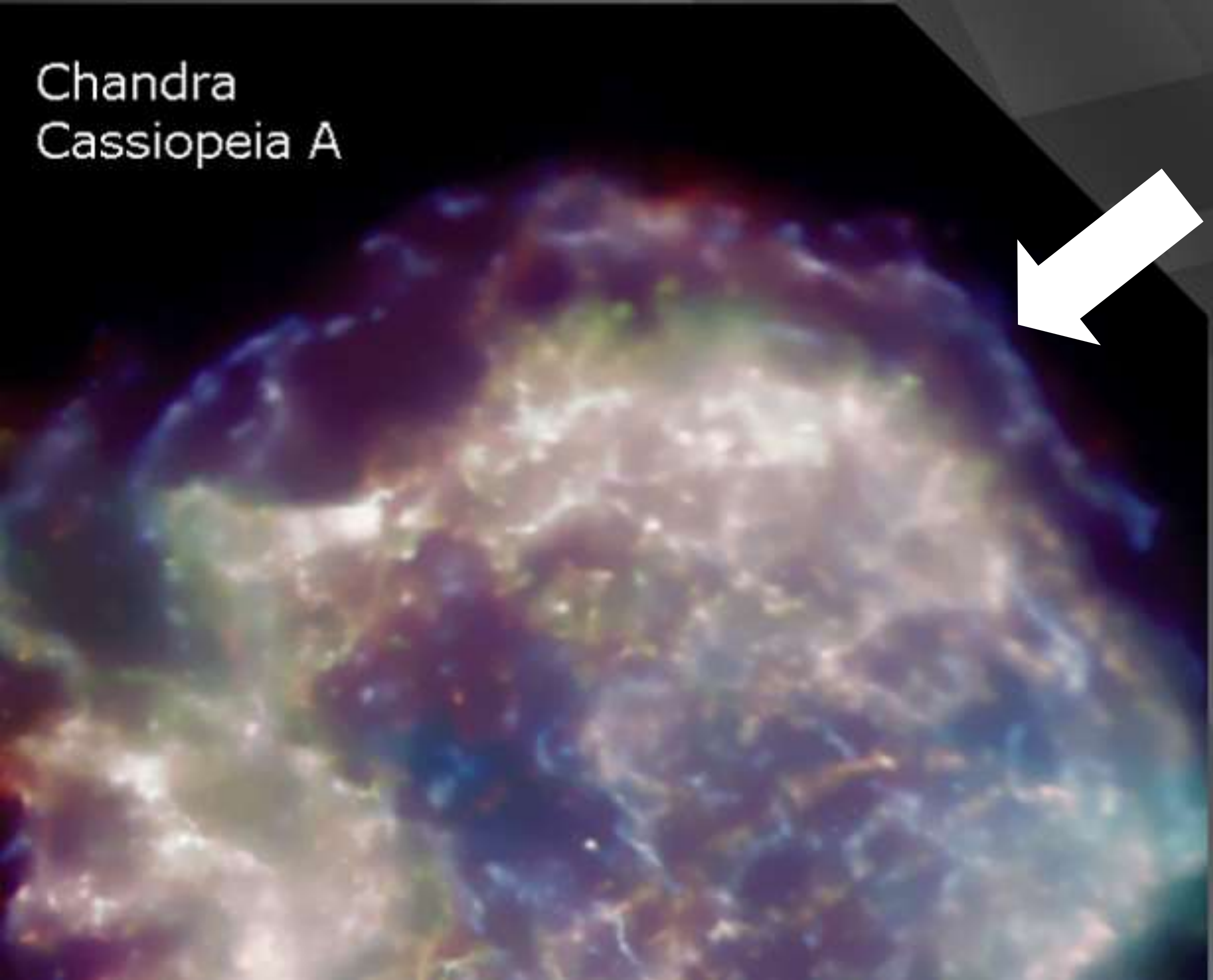
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

the sun constructs an accelerator



coronal mass
ejection→
10 GeV protons

fraction of the graviatational energy released is transformed into the acceleration of particles

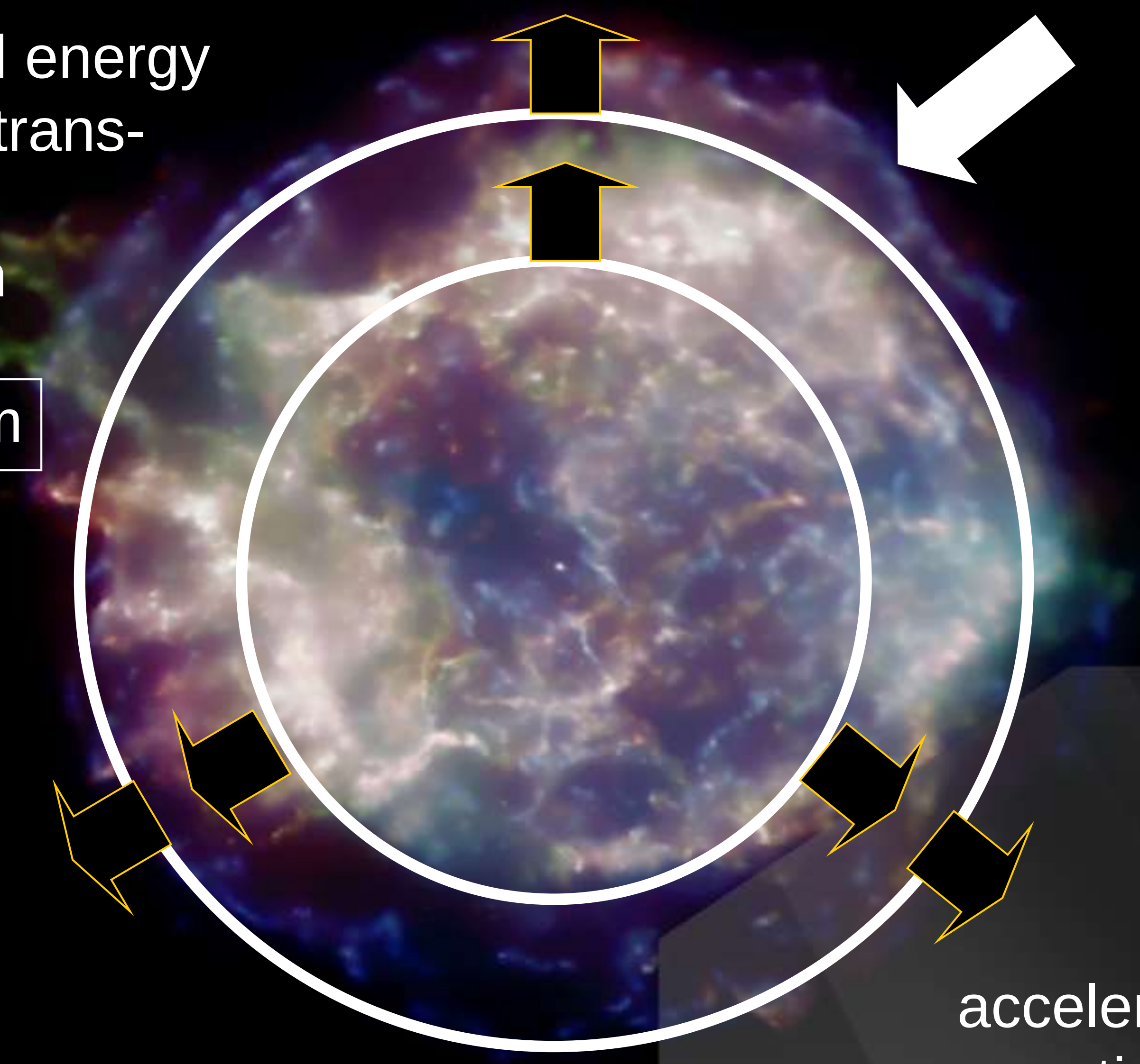


cassiopeia A supernova remnant in X-rays

gravitational energy released is transformed into acceleration

→

E^{-2} spectrum

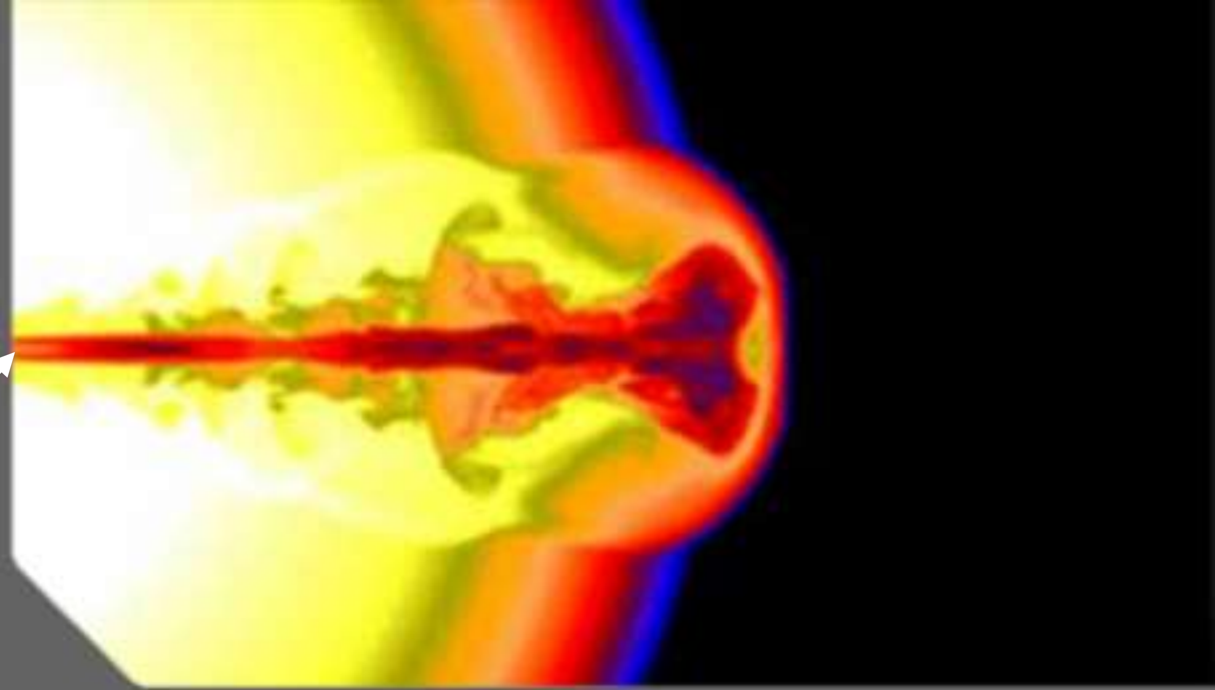


acceleration when particles cross high B-fields and if the star collapses to a black hole …

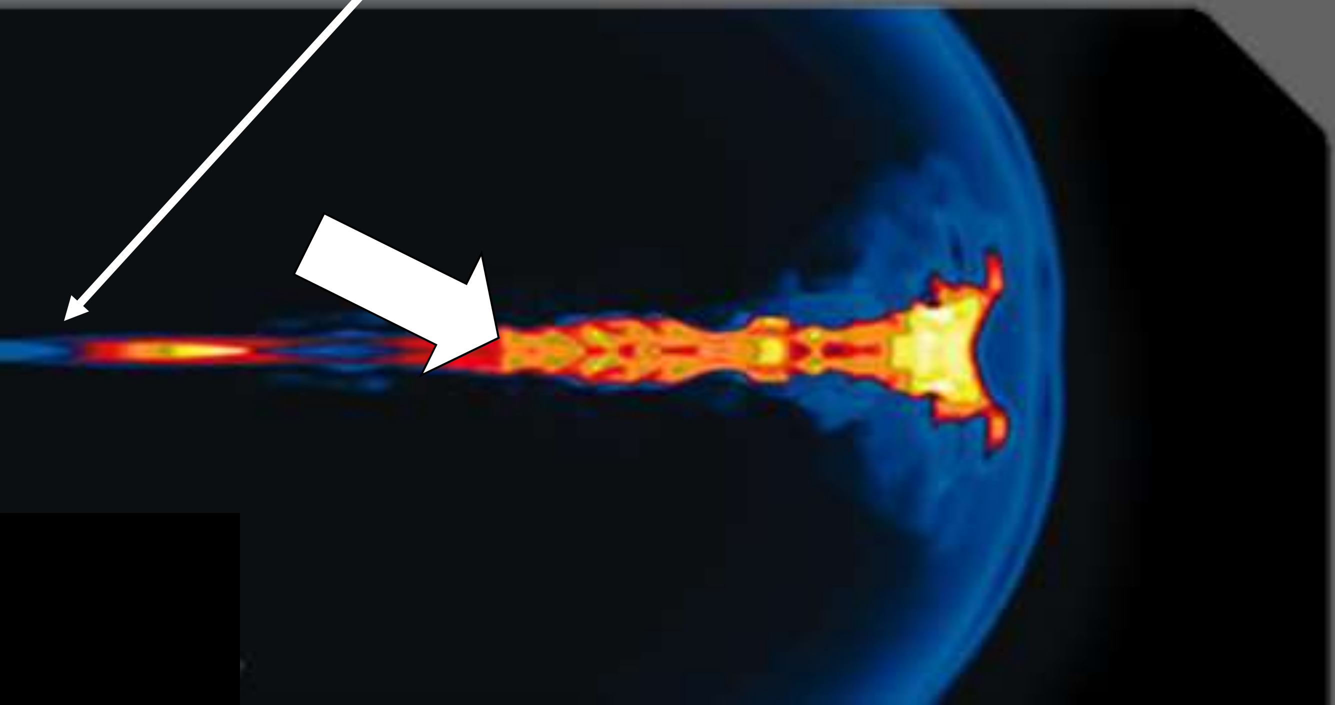
→ happens in seconds not thousands of years
→ beamed not spherical
→ simulation not image

collapse of massive star produces a

gamma ray burst



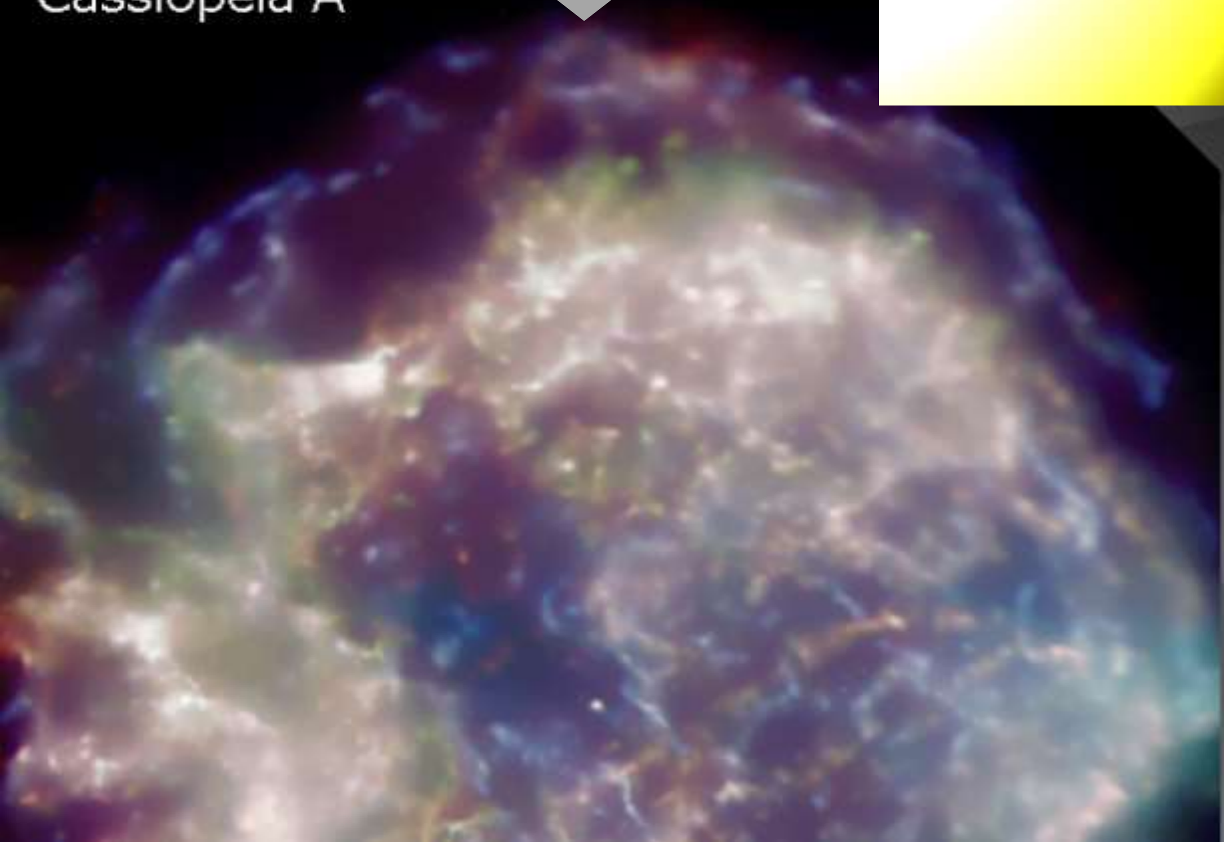
spinning black hole

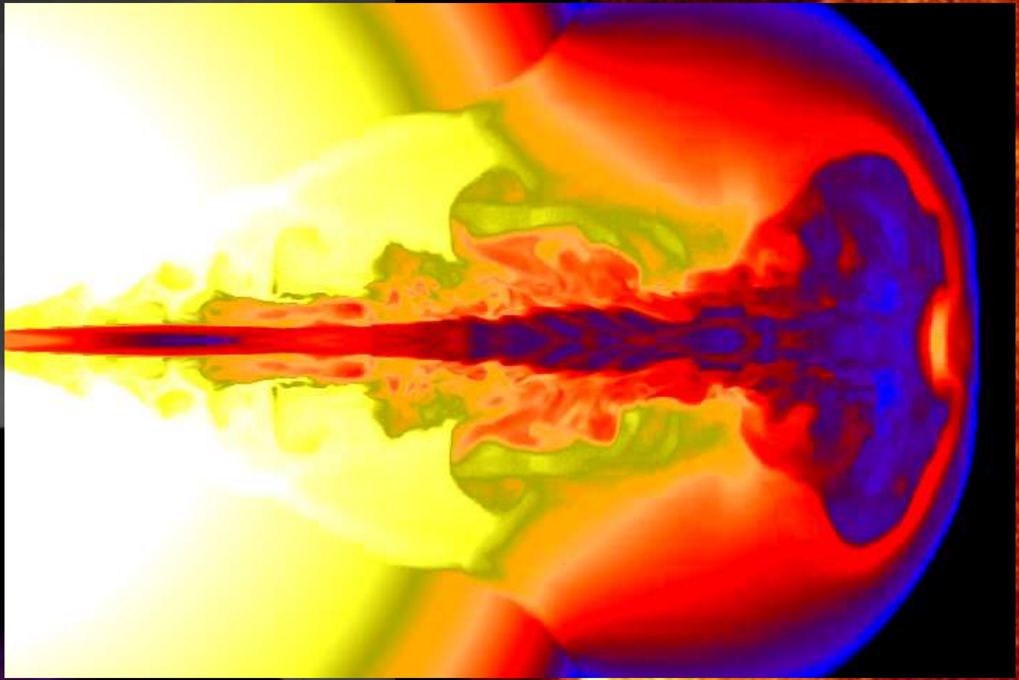


shocks produced in the outflow of the spinning black hole: electrons (and protons ?)

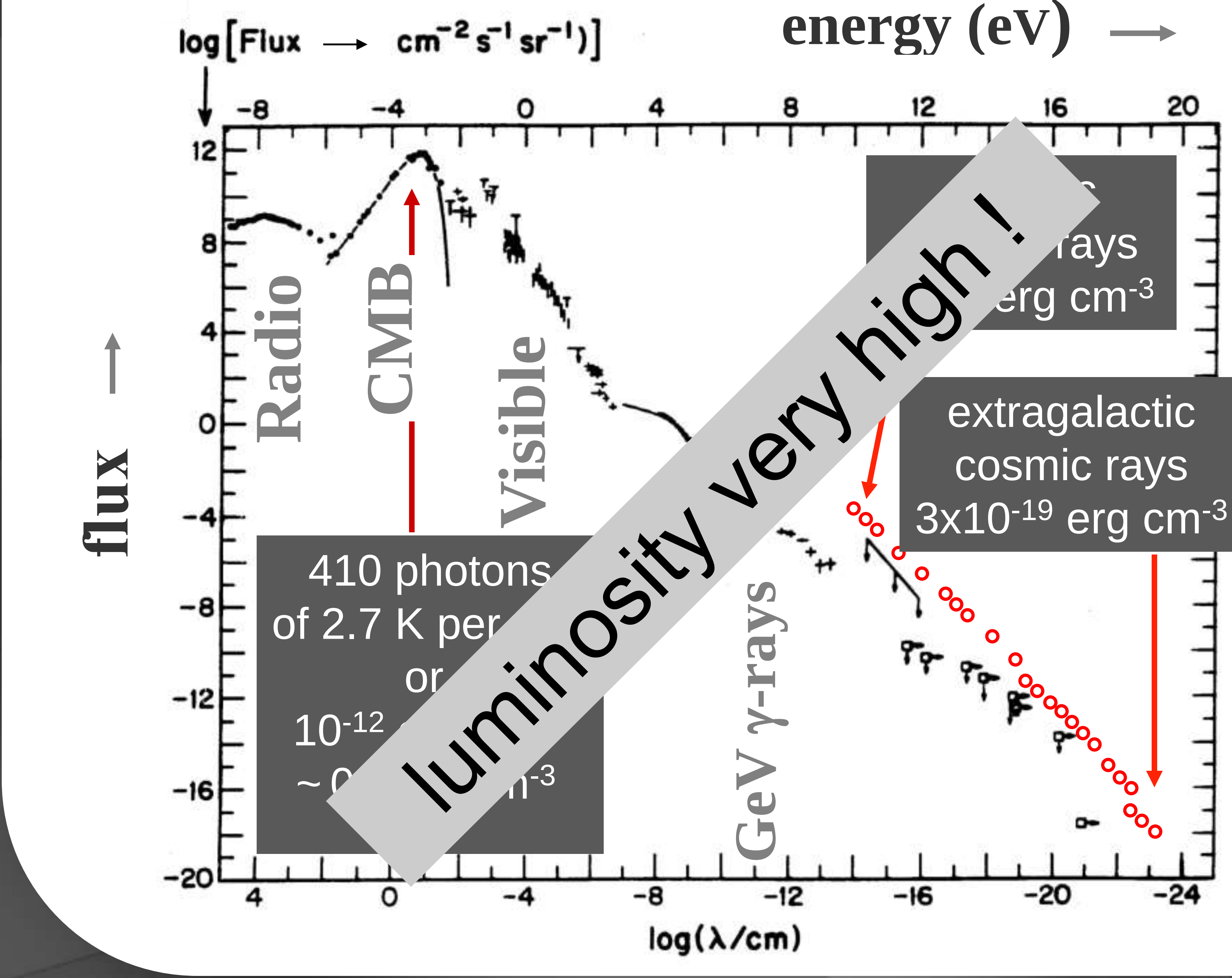
supernova remnants

Chandra
Cassiopeia A



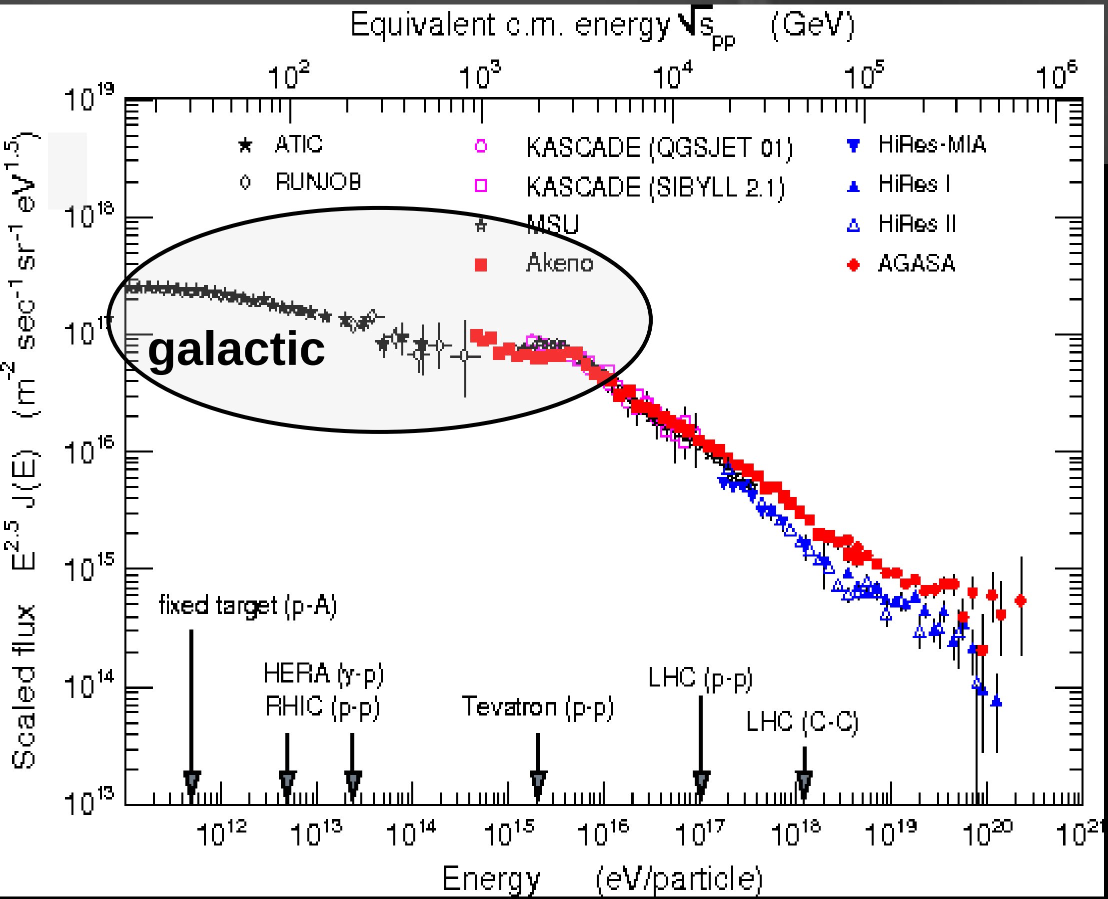


gamma ray bursts



energy (eV)
log[Flux → cm⁻²s⁻¹sr⁻¹)]
flux
Radio
CMB
Visible
GeV γ-rays
410 photons
of 2.7 K per
or
~
rays
erg cm-3
extragalactic
cosmic rays
3x10-19 erg cm-3
luminosity very high !
log(λ/cm)

Cosmic Rays & SNRs



observed energy density of galactic CR:

$\sim 10^{-12}$ erg/cm^3

supernova remnants: 10^{50} ergs every 30 years

$\sim 10^{-12}$ erg/cm^3

for steady state of CR with lifetime 10^6 years

SNRs provide the environment and energy to explain the galactic cosmic rays!

flux of extragalactic cosmic rays

ankle → one 10^{19} eV particle per km squared per year per sr

$$E^2 \frac{dN}{dE} = \frac{10^{19} eV}{(10^{10} cm^2)(3 \times 10^7 \sec)\ sr}$$

cosmic accelerator E^{-2}

$$= 3 \times 10^{-11}\ TeV\ cm^{-2} \sec^{-1} sr^{-1}$$

total flux = velocity x density

$$4\pi \int dE\left(E\frac{dN}{dE}\right) = c\,\rho_E$$

$$\rho_E = \frac{4\pi}{c}\int \frac{3\times 10^{-11}}{E}\,dE\,\frac{TeV}{cm^3}$$

$$= \cdots \log\frac{E_{\max}}{E_{\min}} \cong 10^{-19}\,\frac{TeV}{cm^3}$$

$1\,TeV \cong 1.6\,erg$

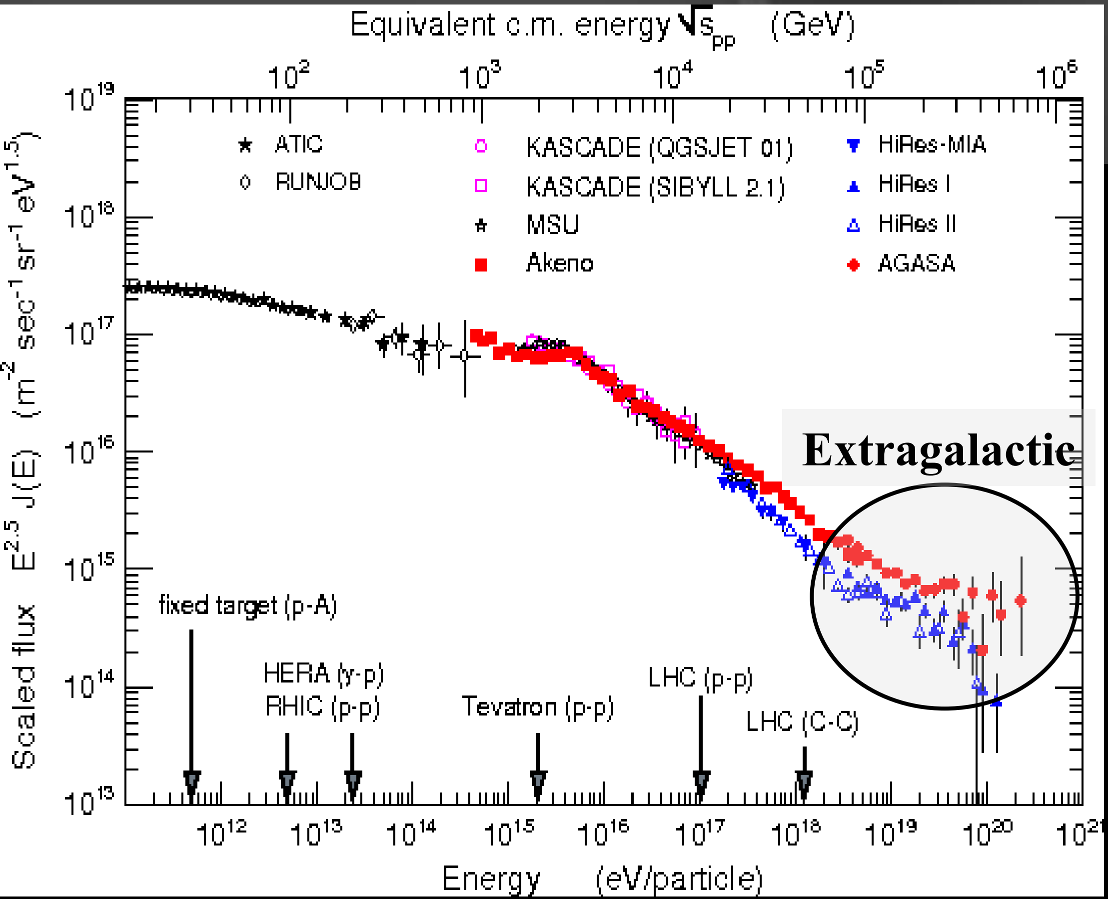
300 GRB per Gigaparsec^3 per year for 10^{10} years (Hubble time)

$$2 \times 10^{51} erg \times \frac{300}{Gpc^3\ yr} \times 10^{10} yr = 3 \times 10^{-19} \frac{erg}{cm^3}$$

- correct cosmology: same answer
- Fermi: photon (electron) energy less than this ?
- challenged by IceCube limits

$$1 Gpc^3 = 2.9 \times 10^{82} cm^3 \quad Hubble\, time = 10^{10}\ years$$

Cosmic Rays & GRBs



observed energy density of extragalactic CR:

$\sim 10^{-19}$ erg / cm^3

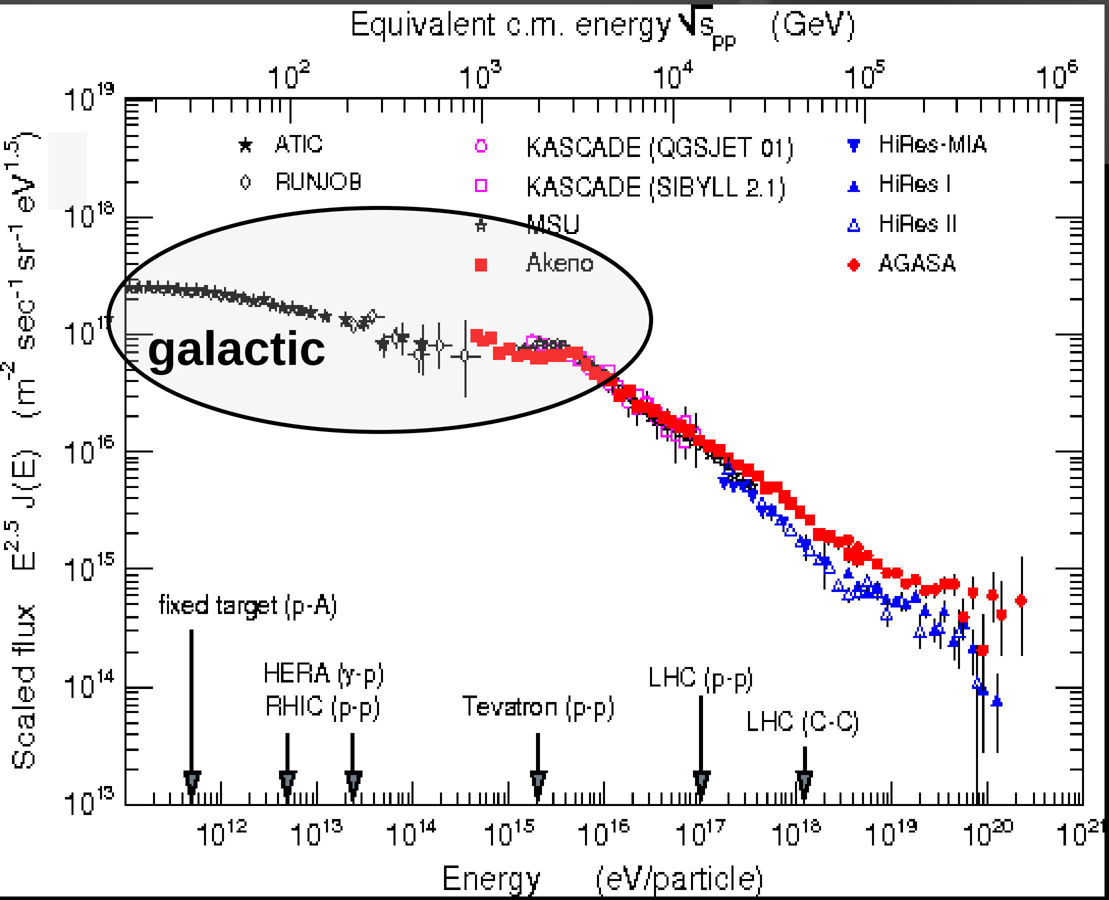
Gamma-Ray Bursts:

2×10^{51} ergs x 300/Gpc^3 x 10^{10} yr

$\sim 10^{-19}$ erg / cm^3

GRBs provide environment and energy to explain the extragalactic cosmic rays!

Cosmic Rays & SNRs



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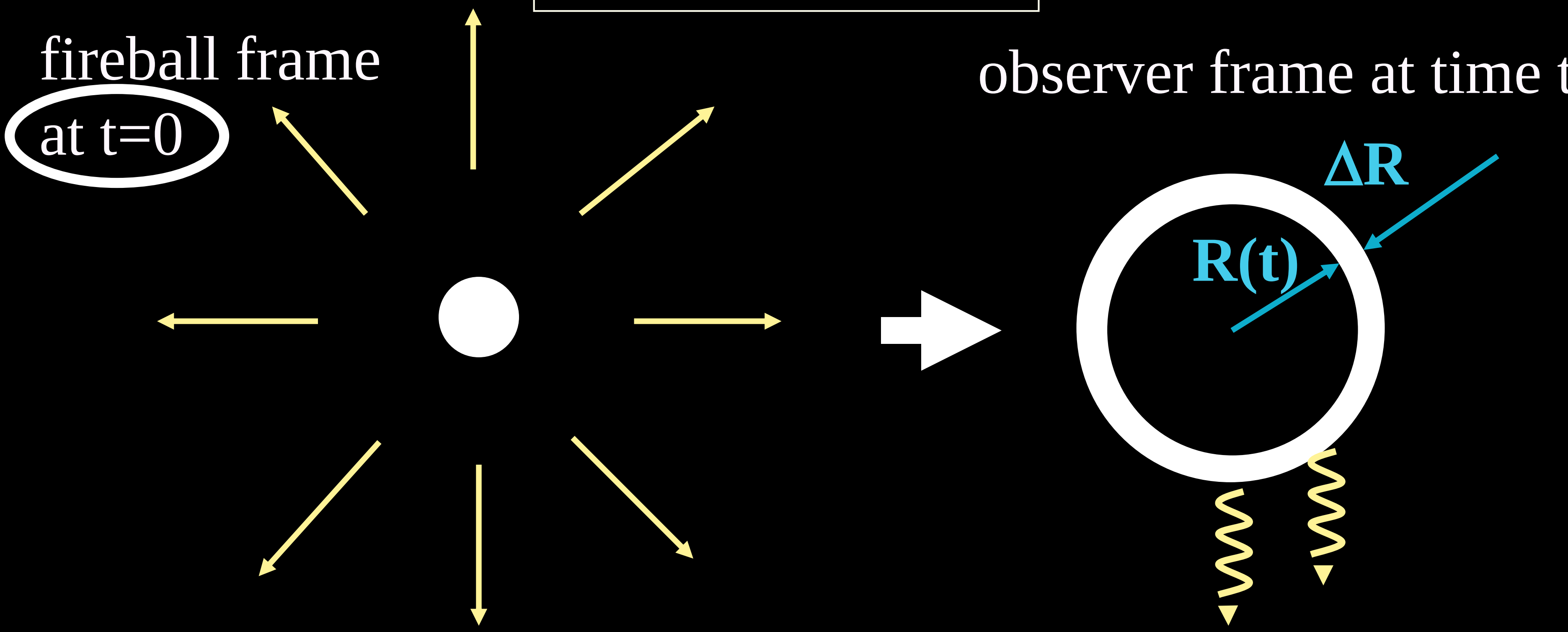
10^{50} ergs every 30 years

~10^{-12} erg/cm^3

for steady state of CR with lifetime 10^6 years

SNRs provide the environment and energy to explain the galactic cosmic rays!

GRB fireball



- 1 MeV
- 10 msec

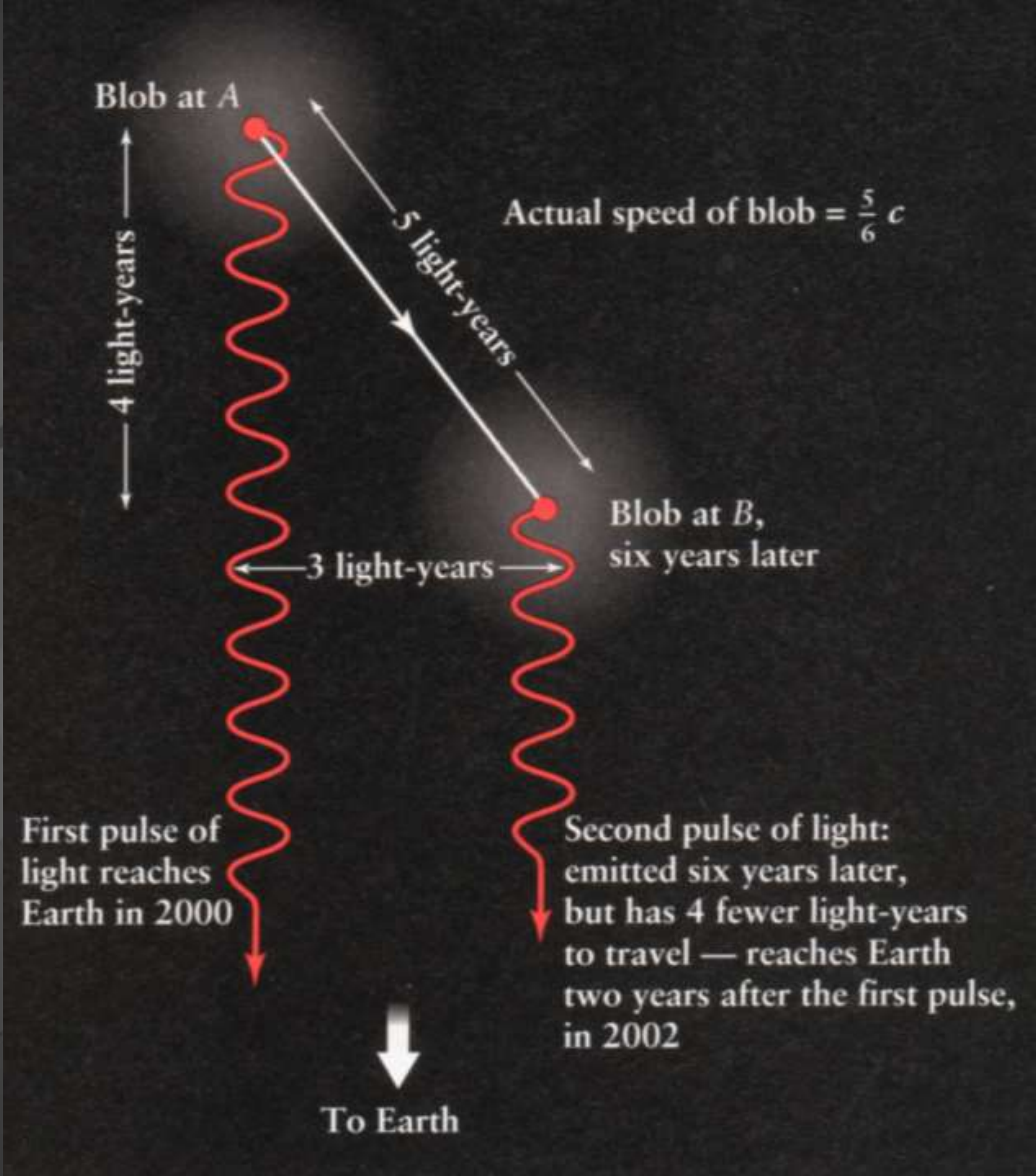
$\Delta R = c\,\Delta t = R_0$ at $t = 0$

$\gamma \sim 10^2 - 10^3$

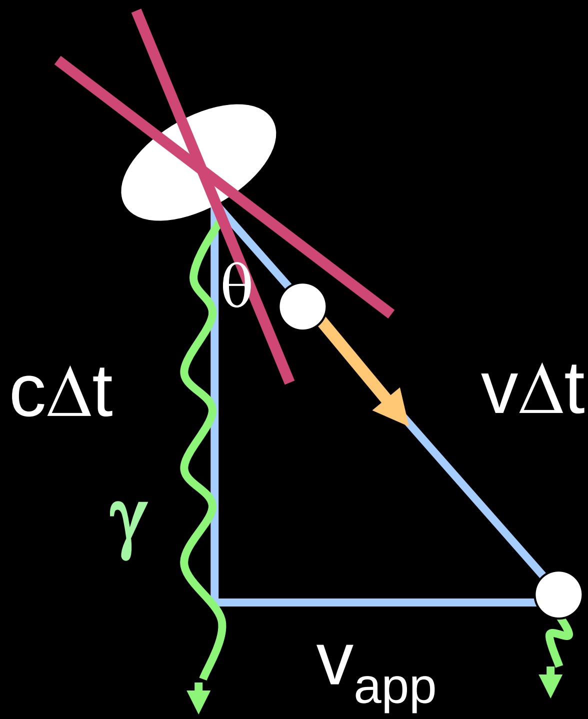
$E = \gamma E'$

$R = \gamma^{-2} R'$

superluminal motion



superluminal motion: boosted accelerators



$\beta = v/c \qquad \gamma = (1-\beta^2)^{-1/2}$

$D^{-1} = (1+z)\,(1 - \beta\cos\theta)\,\gamma$

$$E_{obs} = \gamma E'$$
$$\Delta t_{obs} = \gamma^{-1}\Delta t'$$

$$v_{app} = \frac{v\Delta t \sin\vartheta}{\frac{c\Delta t}{c} - \frac{v\Delta t\cos\vartheta}{c}}$$

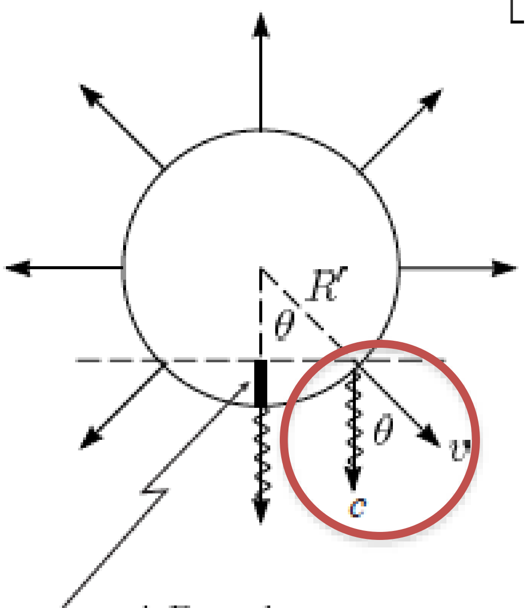
strongest effect :

$$\frac{dv_{app}}{d\vartheta} = 0 \text{ or } \cos\vartheta = \frac{v}{c} = \beta$$

$$\text{or } D = \gamma$$

$$R_0' \simeq 100 \text{ km} \qquad \cos\theta = \frac{v}{c}$$

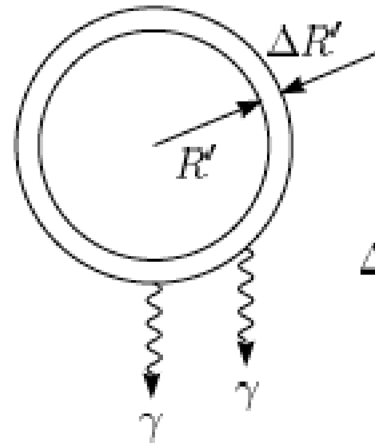
$$\gamma = \left[1 - \frac{v^2}{c^2}\right]^{-1/2} \simeq 10^2\text{–}10^3$$



$$\Delta t = \frac{\Delta R}{c} = \frac{1}{c}(R - R\cos\theta)$$

$$= \frac{R}{c}\left(1 - \frac{v}{c}\right) \simeq \frac{R}{2c}\left(1 - \frac{v^2}{c^2}\right)$$

$$\simeq \gamma^2 \frac{R'}{2c}$$



$$\Delta t = 1 \text{ msec}$$

$$\Delta R' = \gamma c \Delta t$$

$$R' = \gamma^2 c \Delta t$$

$$\gamma = 10^2\text{–}10^3$$

photon density in the fireball

$$n_\gamma = \frac{U'_\gamma}{E'_\gamma} = \frac{\dfrac{L_\gamma \Delta t/\gamma}{4\pi R'^2 \Delta R'}}{\dfrac{E_\gamma}{\gamma}}$$

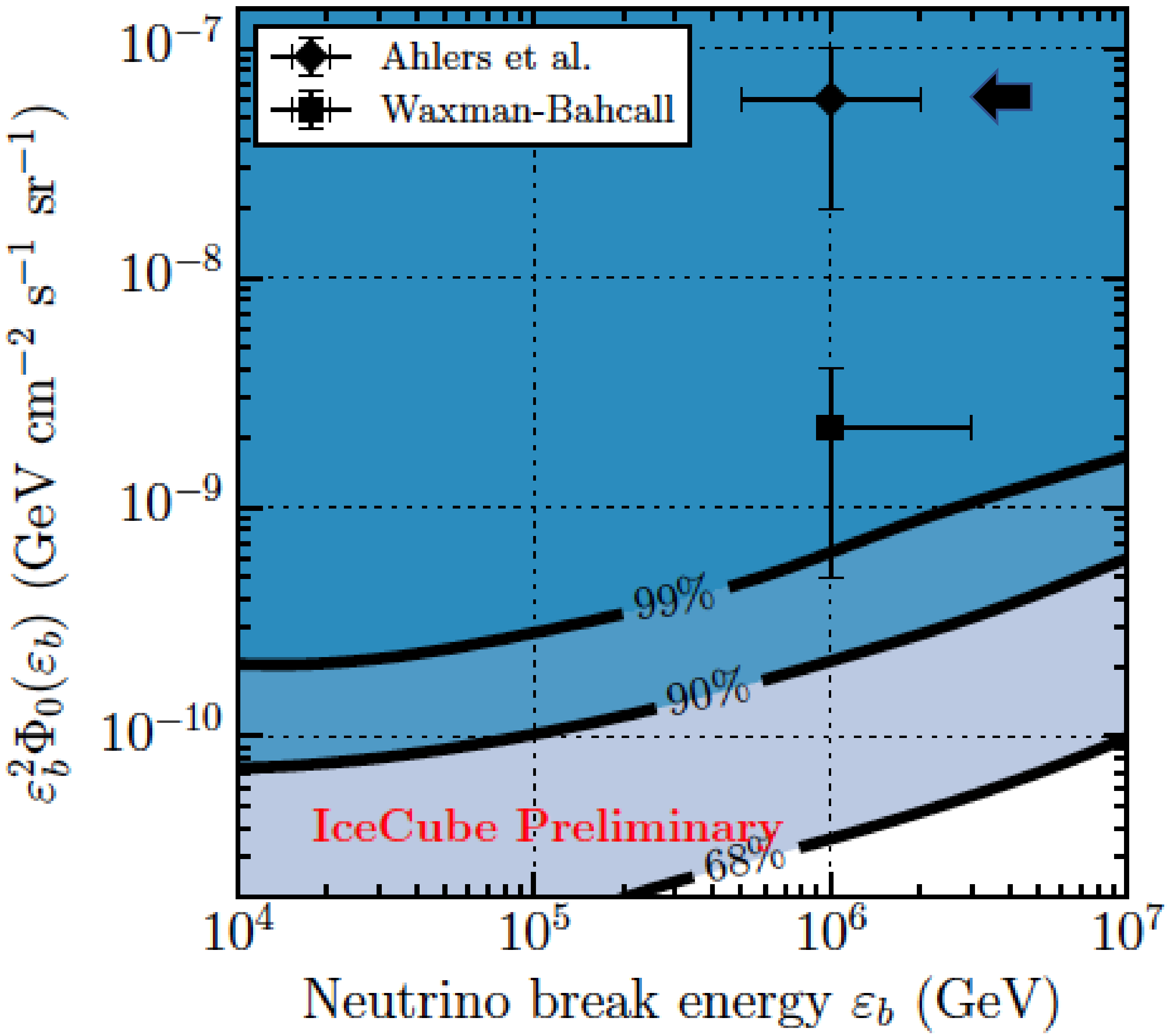
$R' = \gamma^2 c\Delta t$

$\Delta R' = \gamma c \Delta t$

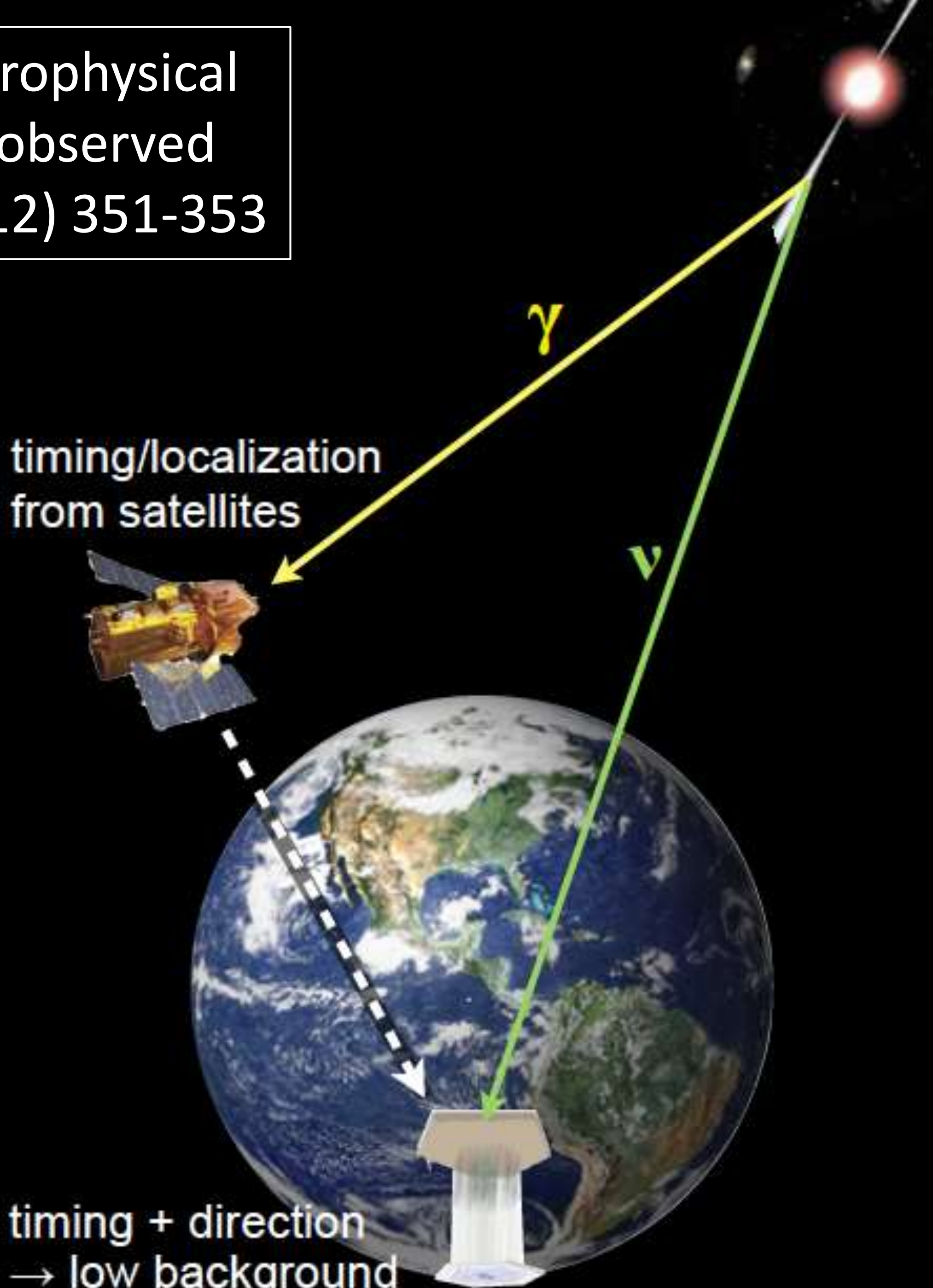
note: for $\gamma = 1$ (no fireball) the optical depth of photons in the fireball is →

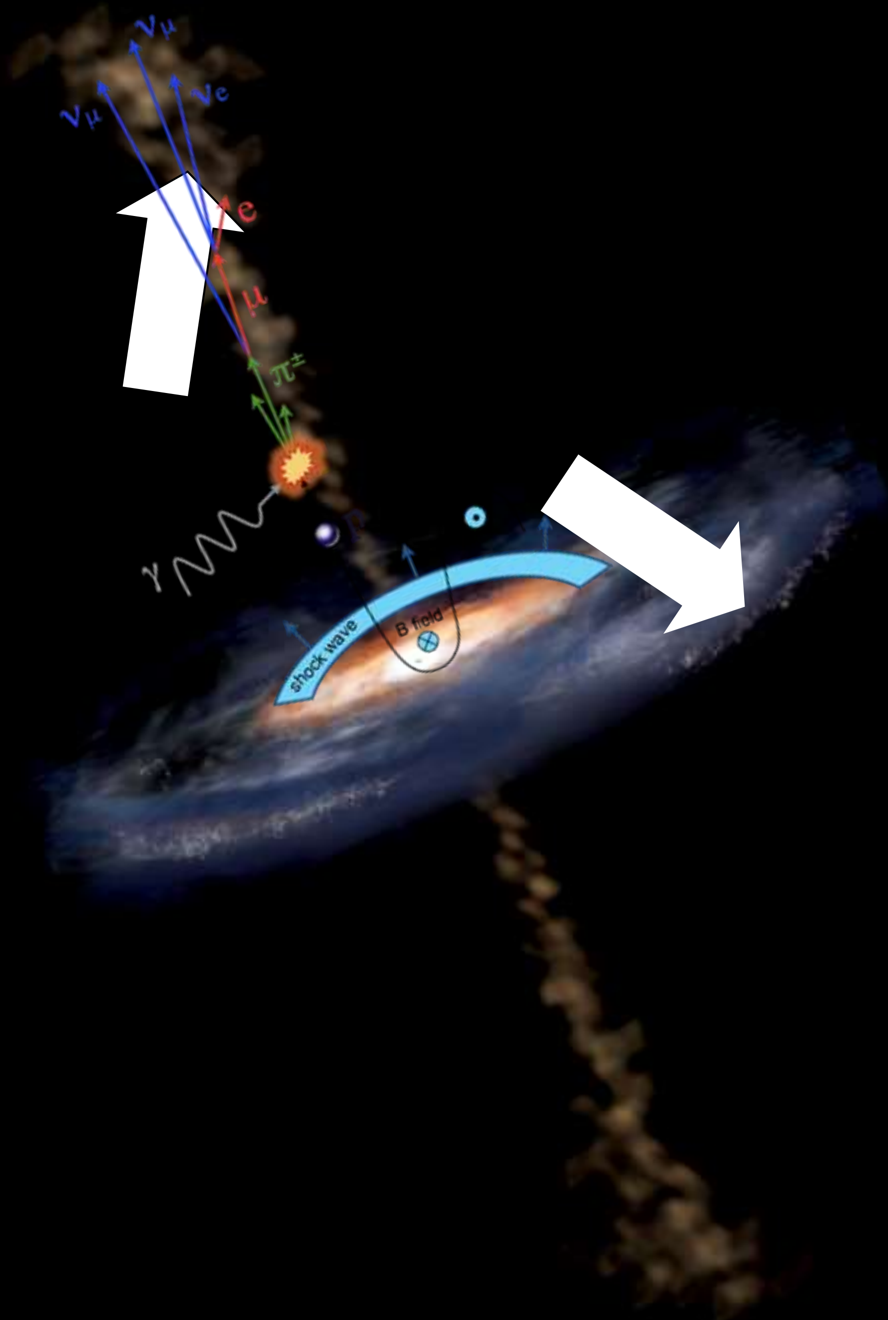
$$\tau_{opt} = \frac{R_0}{\lambda_{Th}} = R_0 n_\gamma \sigma_{Th} \sim 10^{15} \text{ for } 10^{52} \text{ erg in } R_0 \sim 10 \text{ km}$$

cosmic rays produced by the decay of accelerated neutrons



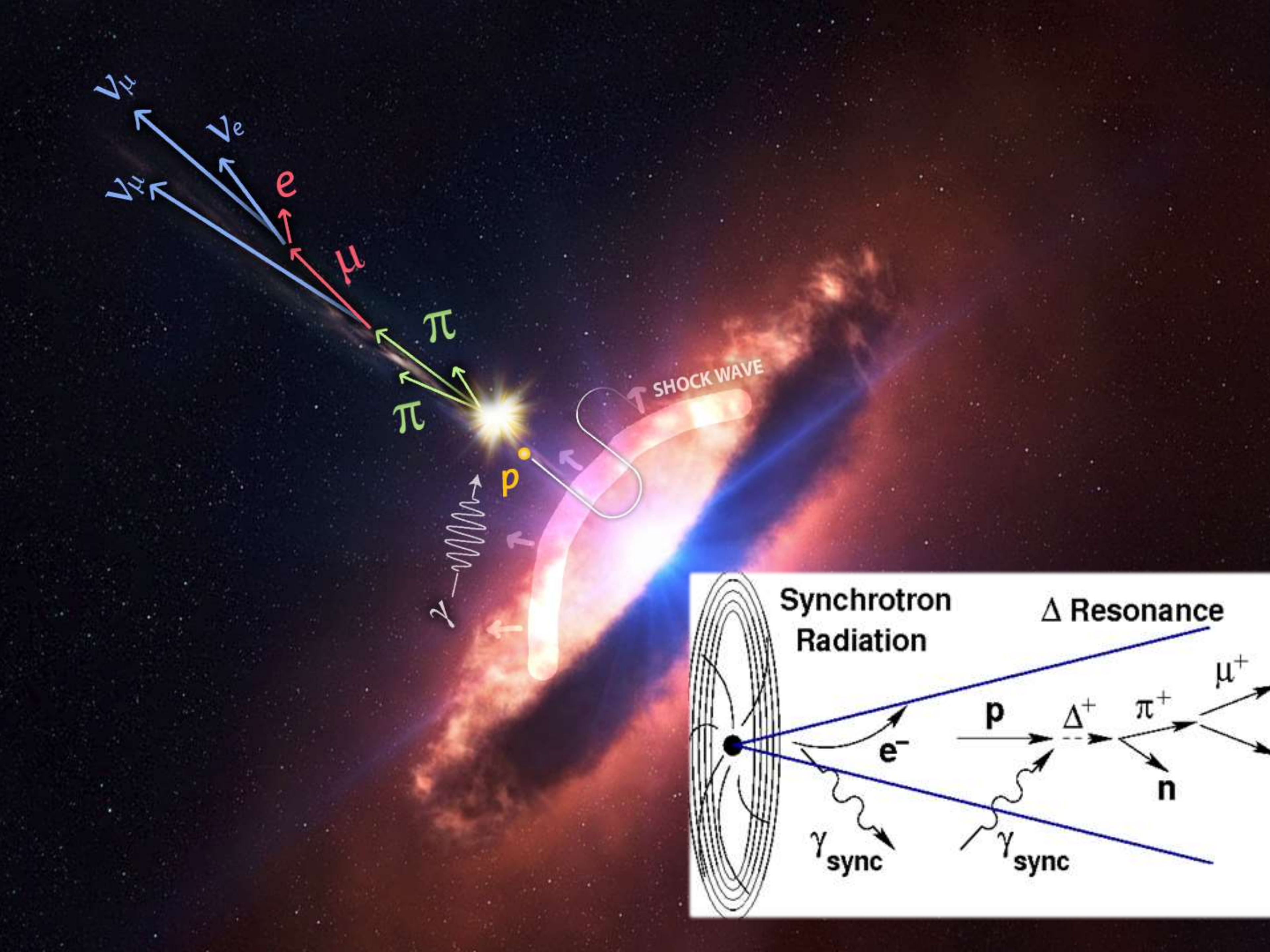
flux < 1% of astrophysical
neutrino flux observed
Nature 484 (2012) 351-353



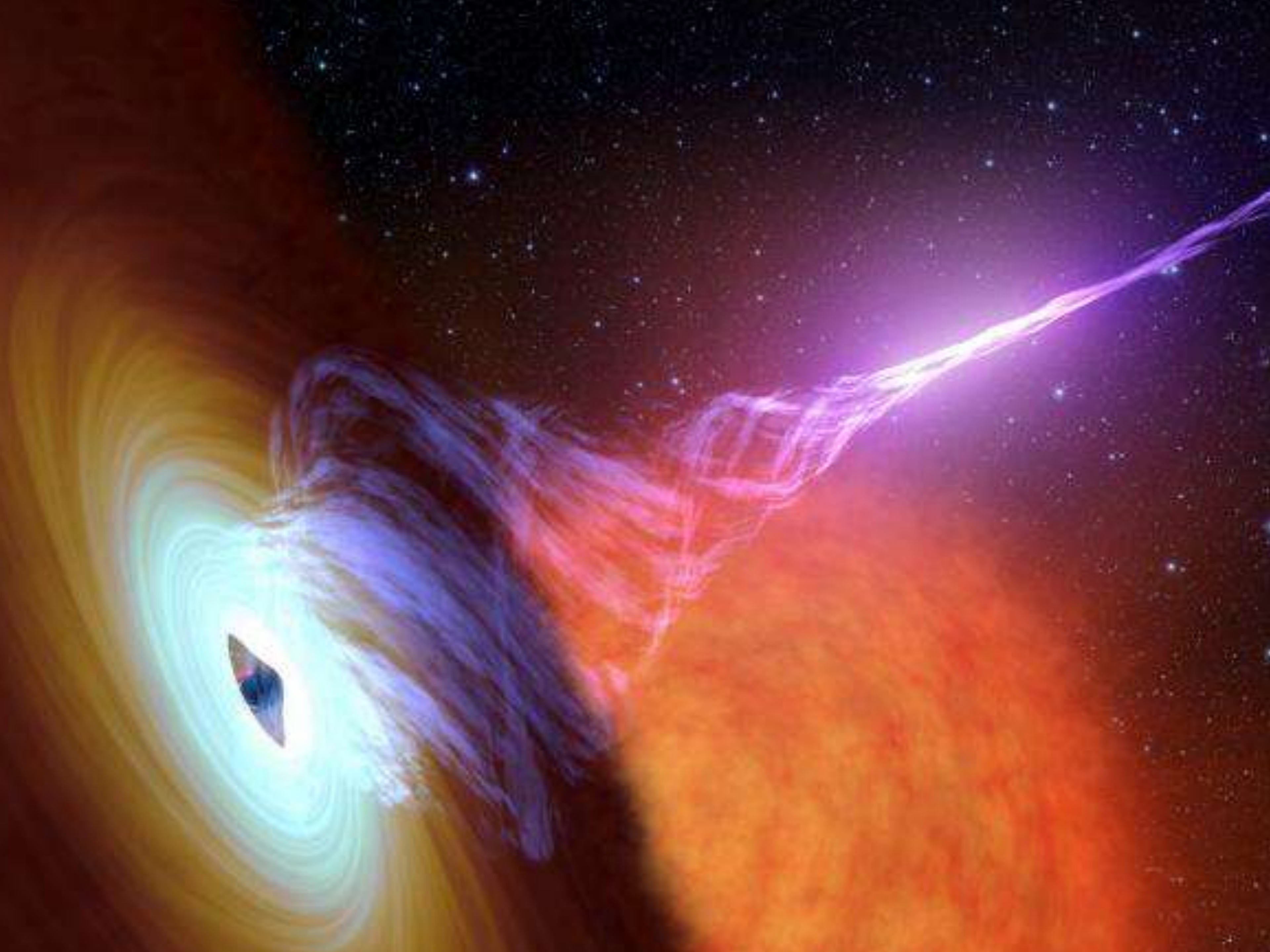


active galaxy

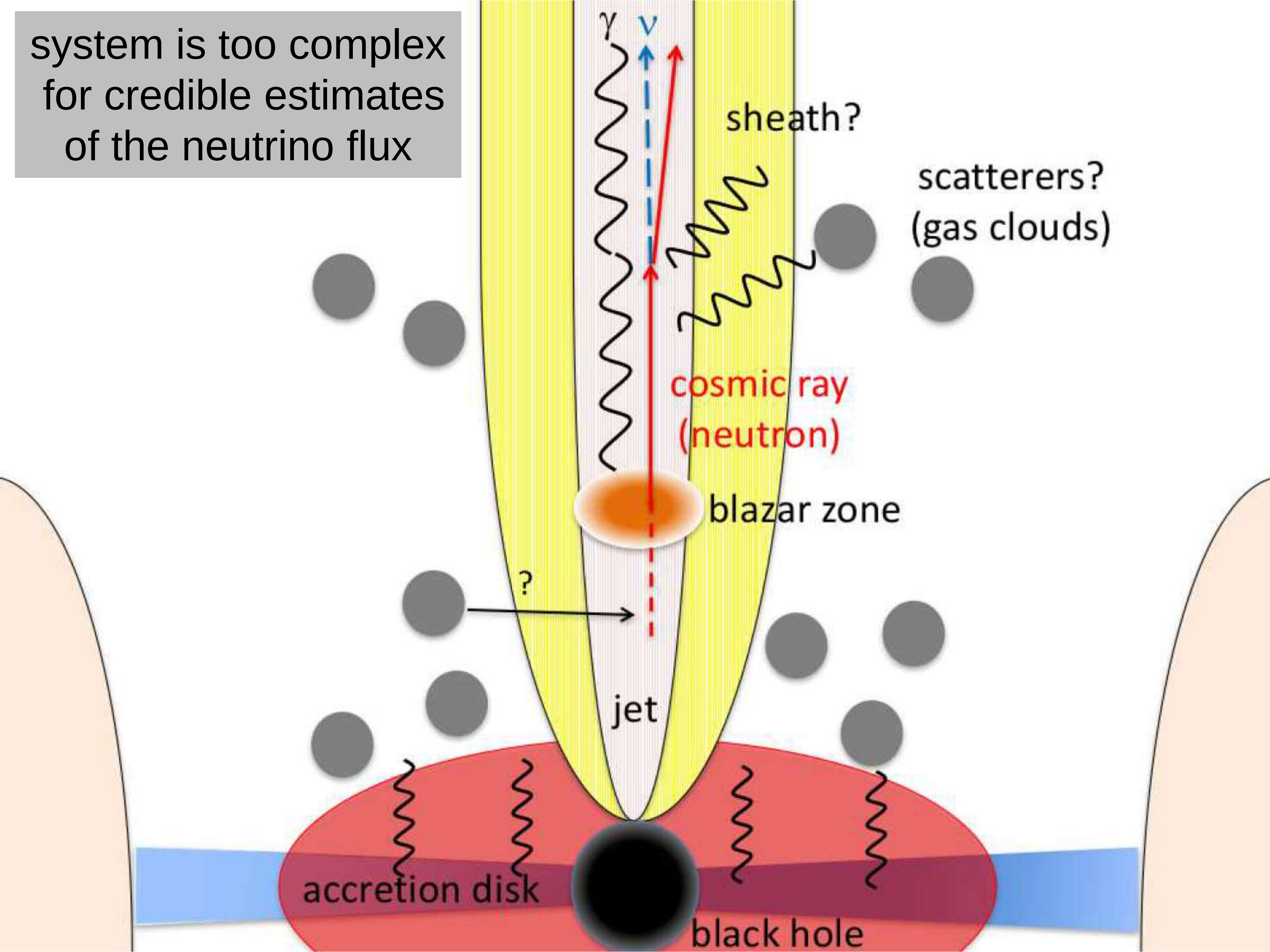
particle flows near supermassive black hole



ν_μ
ν_e
ν_μ
e
μ
π
π
p
γ
SHOCK WAVE
Synchrotron
Radiation
Δ Resonance
e^-
p
Δ^+
π^+
μ^+
n
γ_{sync}
γ_{sync}



system is too complex
for credible estimates
of the neutrino flux



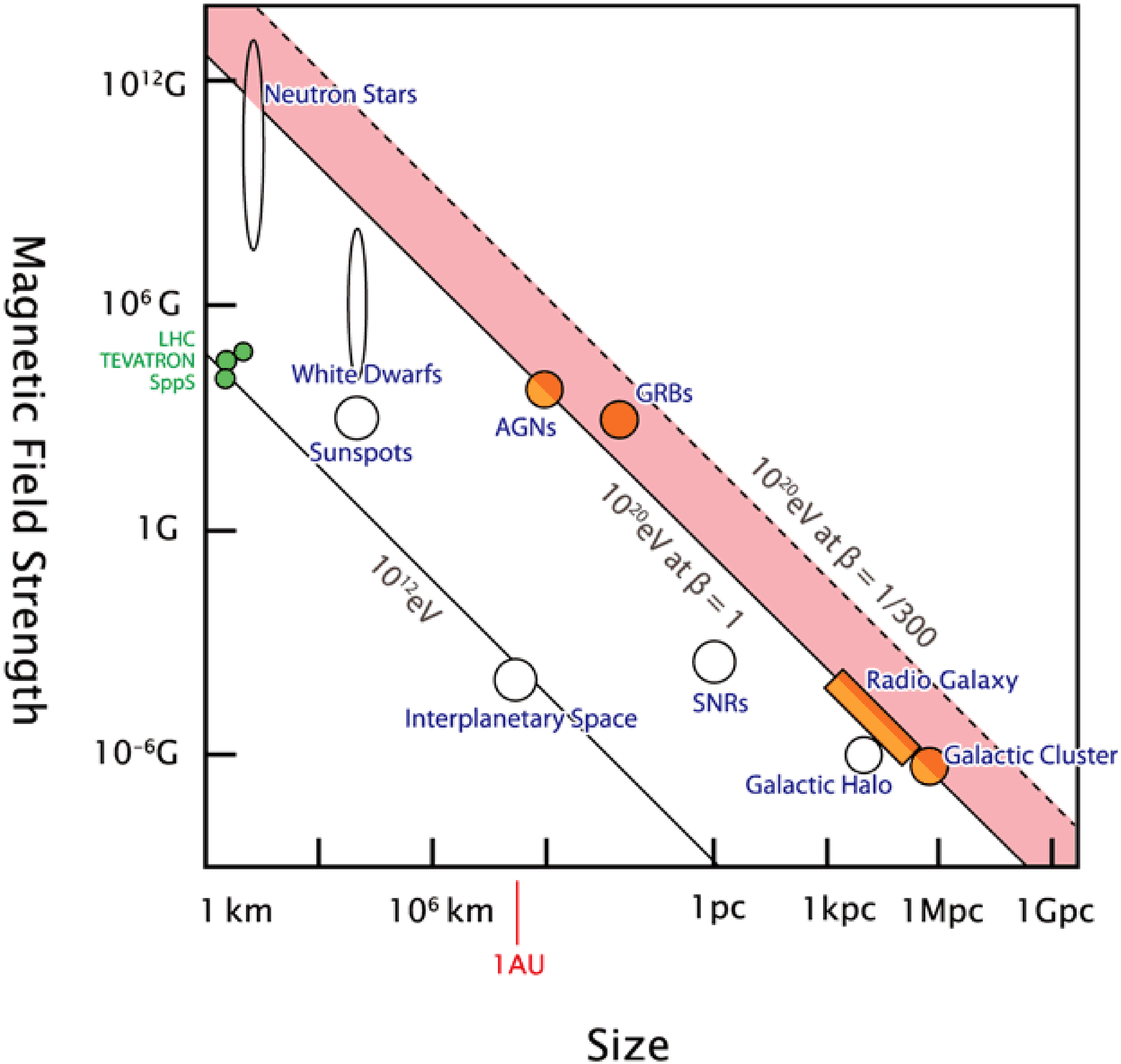
- accelerator must contain the particles

$$R_{gyro} \left(= \frac{E}{\mathrm{v} q B}\right) \leq R$$

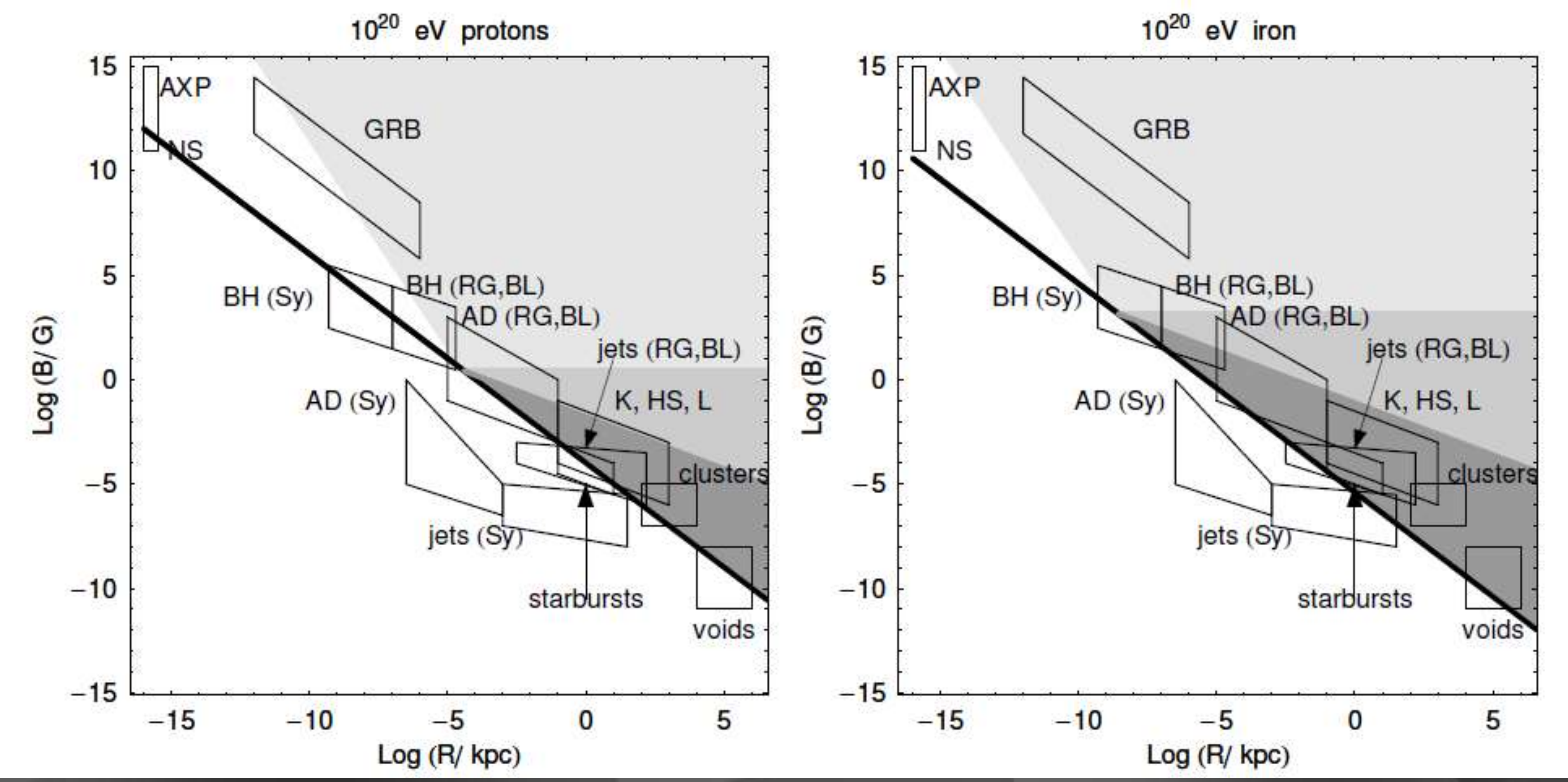
$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well



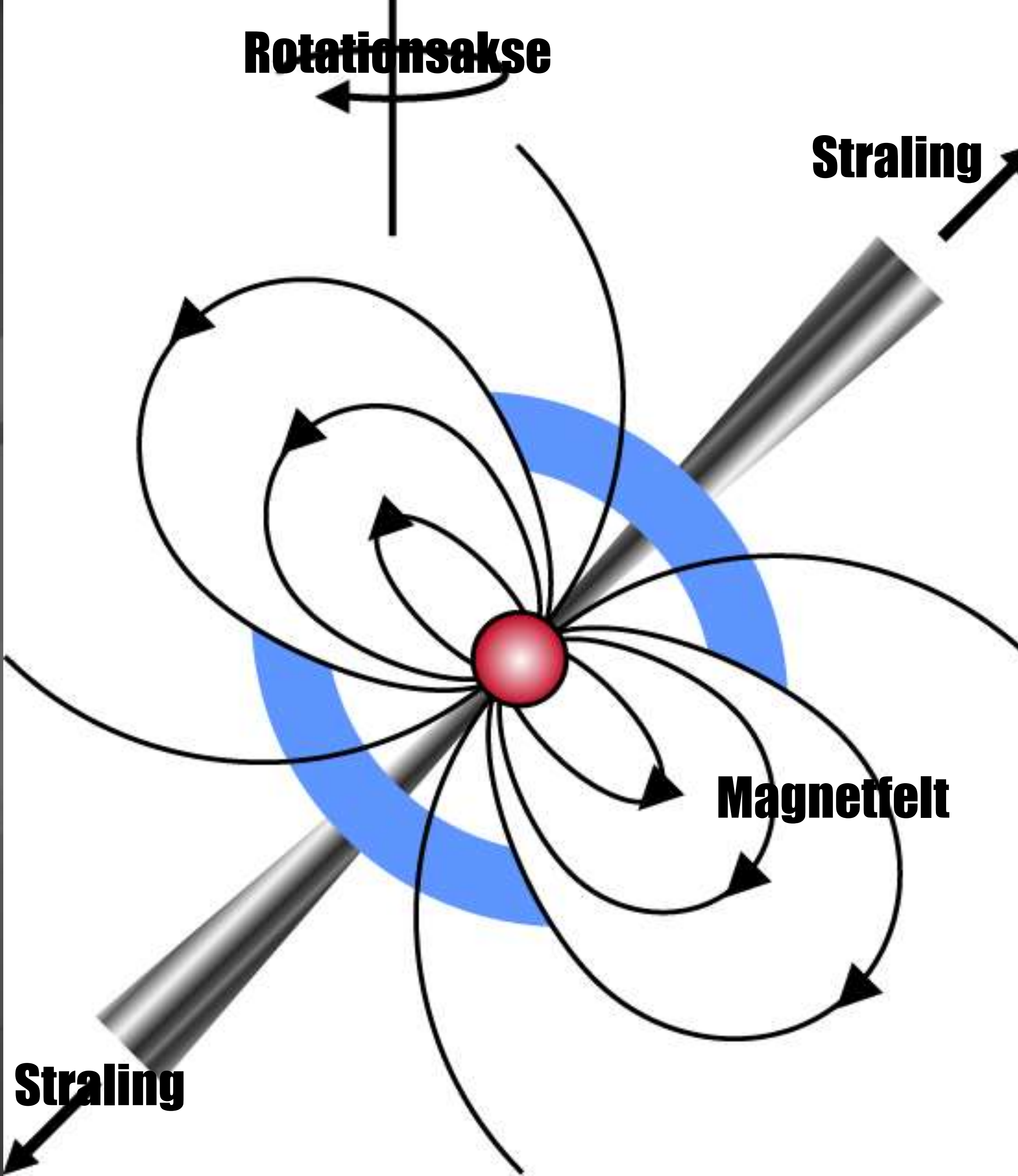
Magnetic Field Strength
10¹²G
10⁶ G
1G
10⁻⁶G
LHC
TEVATRON
SppS
Neutron Stars
White Dwarfs
Sunspots
AGNs
GRBs
10²⁰eV at β = 1/300
10²⁰eV at β = 1
10¹²eV
Interplanetary Space
SNRs
Radio Galaxy
Galactic Cluster
Galactic Halo
1 km
10⁶ km
1 AU
1pc
1kpc
1Mpc
1Gpc
Size



10^{20} eV protons
10^{20} eV iron
AXP
NS
GRB
BH (Sy)
BH (RG,BL)
AD (RG,BL)
jets (RG,BL)
AD (Sy)
K, HS, L
clusters
jets (Sy)
starbursts
voids
Log (B/ G)
Log (R/ kpc)

an example
pulsars

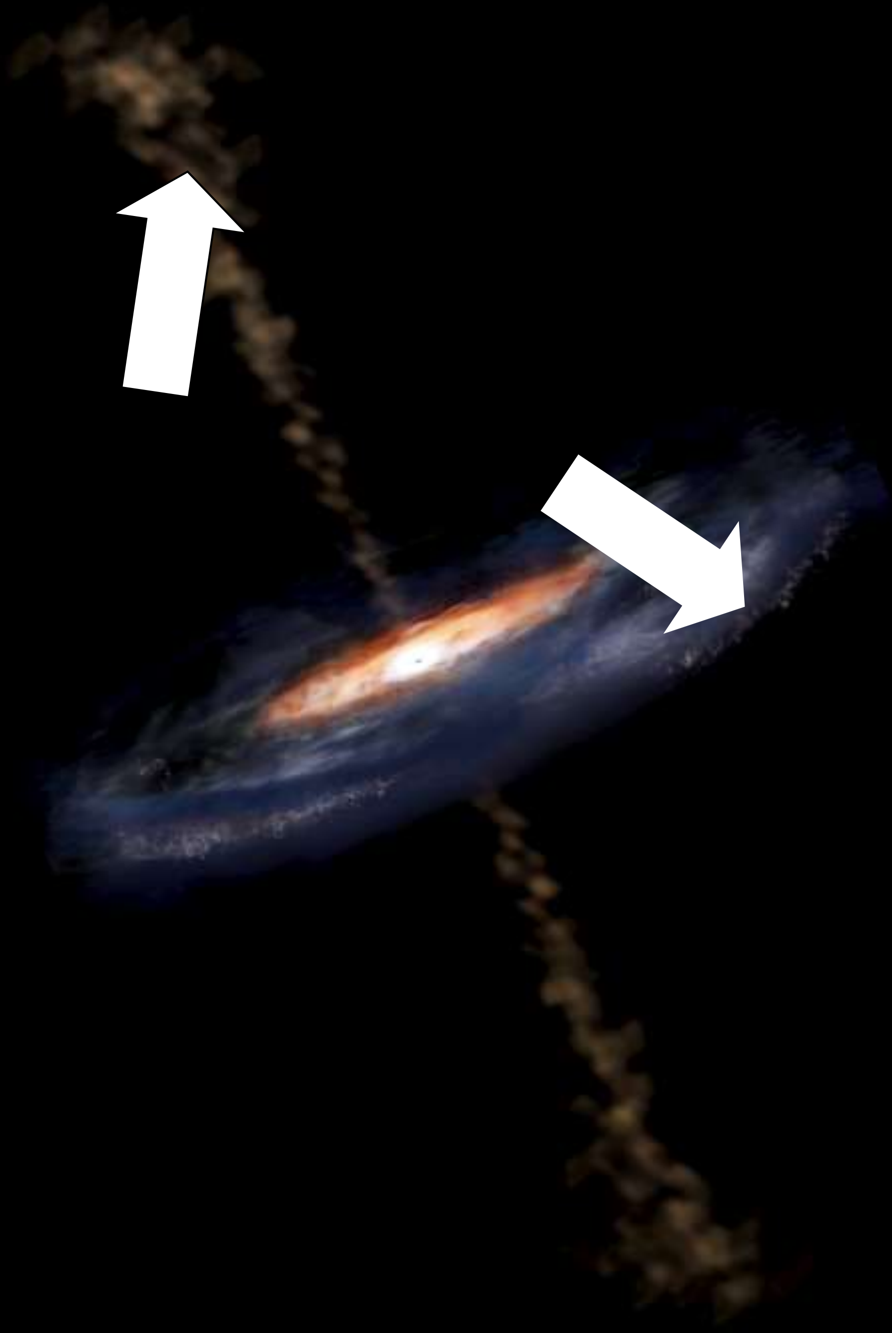
$$v \to \frac{2\pi R}{T}$$



$$E(eV) = B(Tesla)\ R(m)\ \frac{2\pi R}{T}$$

	ms-pulsar	**Fermilab**
R	10 km	km
B	10^8 Tesla	Tesla
T^{-1}	10^3	10^5 (#rev/s)
E	10^7 TeV	10^{12} eV
		= 1 TeV !

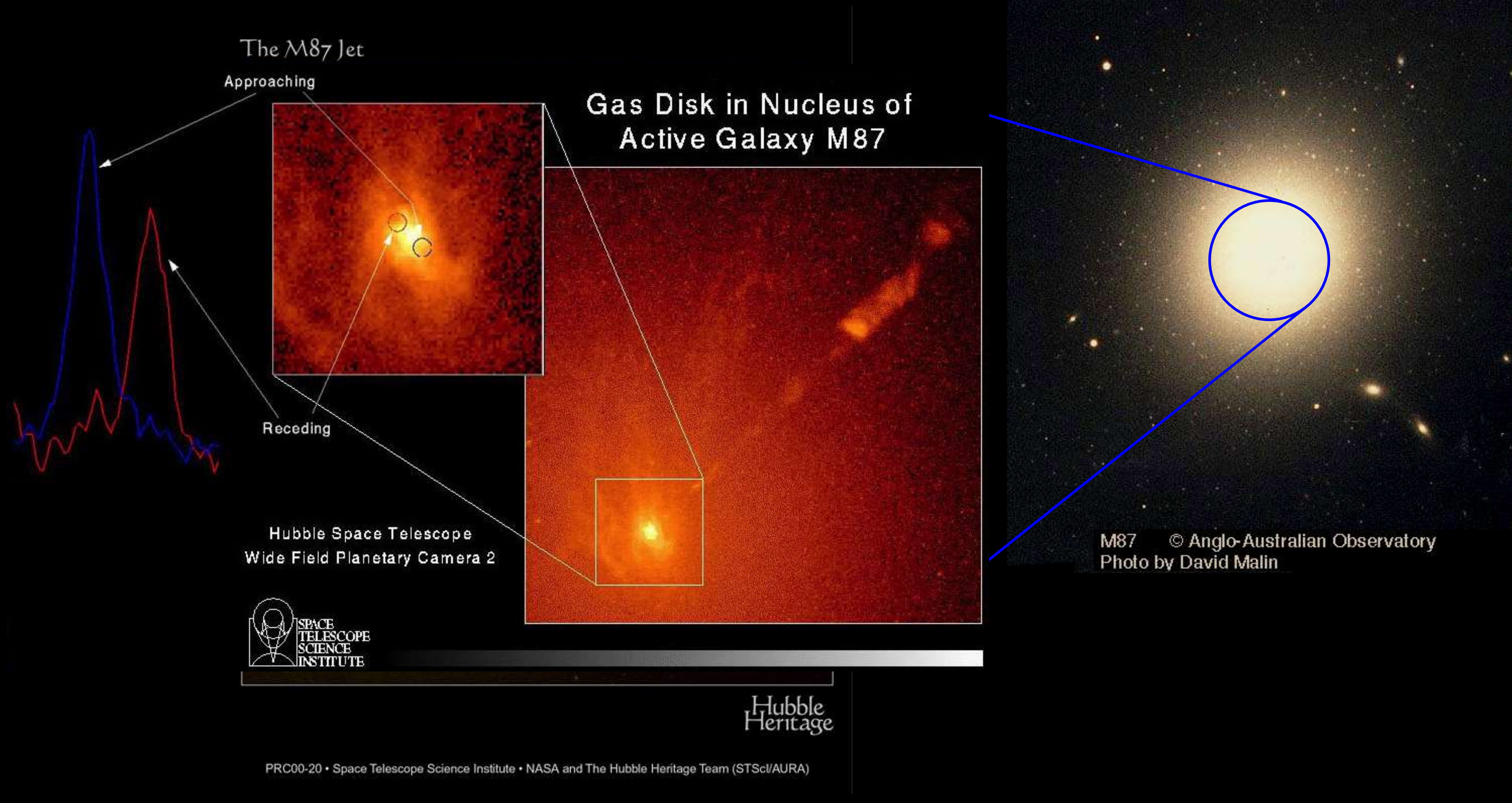
still a very open problem…



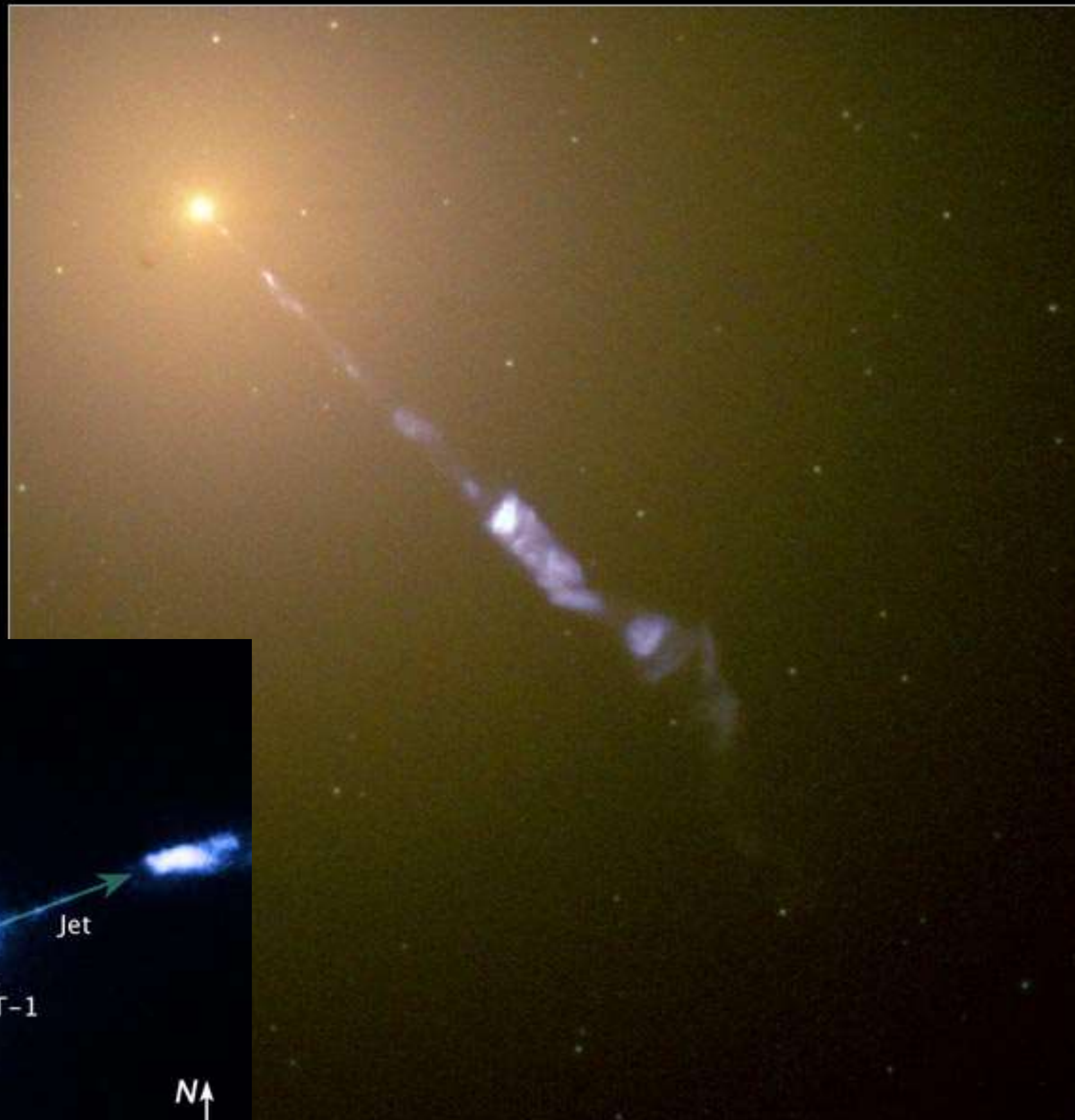
active galaxy

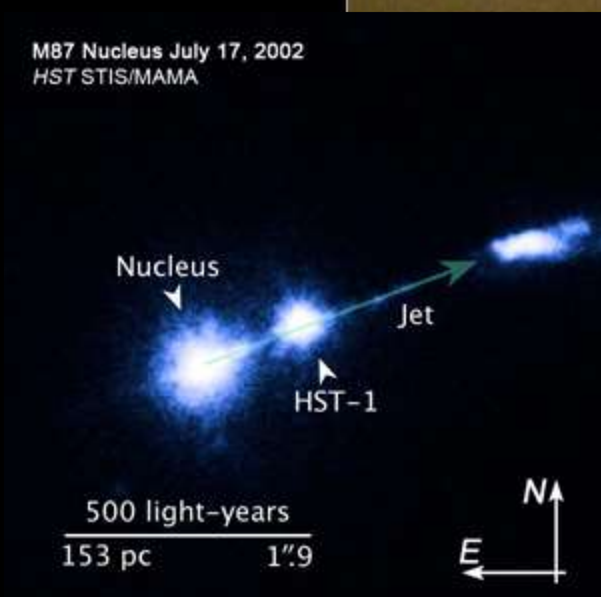
particle flows near supermassive black hole

active galaxy M87



The M87 Jet





Hubble Heritage

High Energy Neutrino Astrophysics
francis halzen

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- cosmic neutrinos: two independent observations
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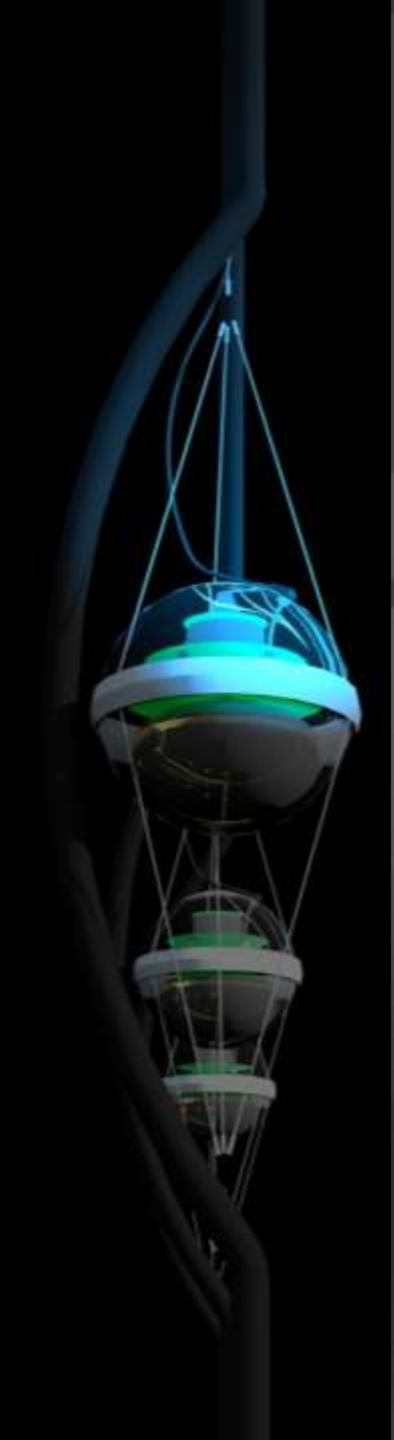


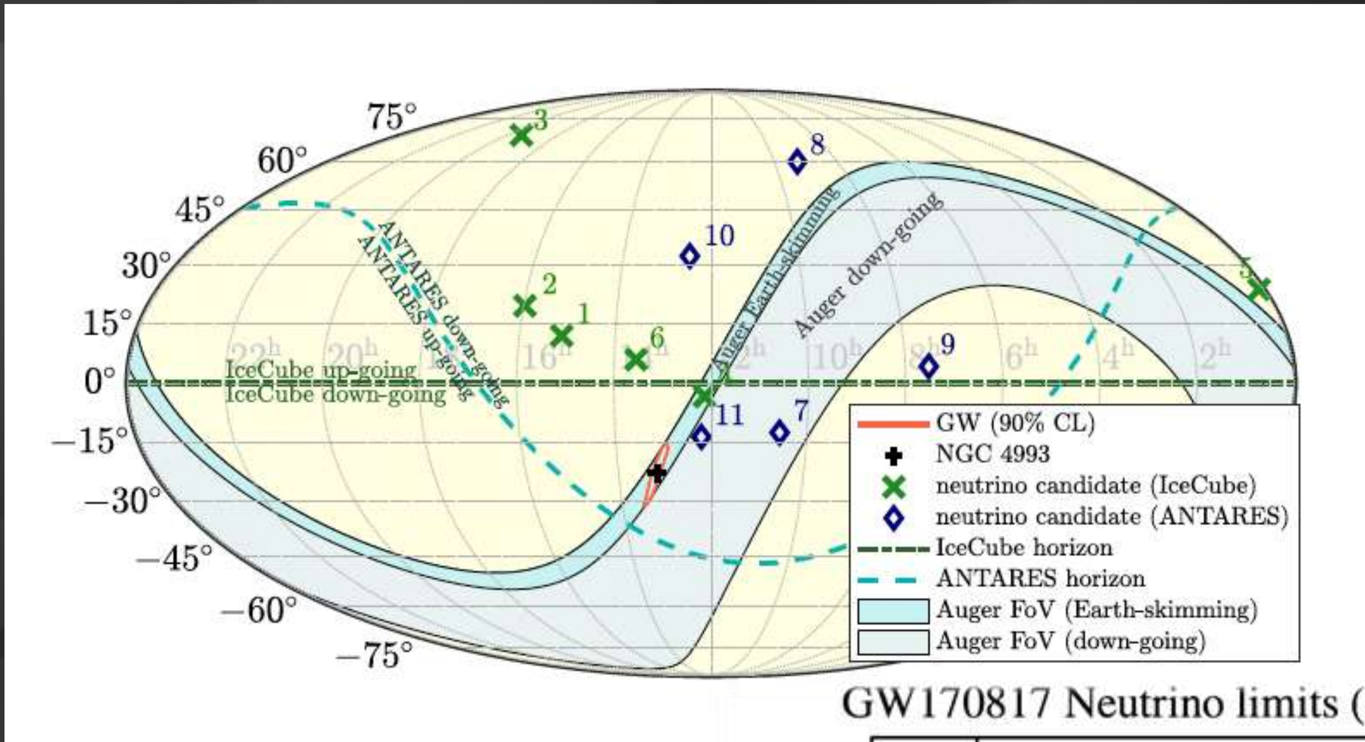
Multimessenger Astronomy

- February 23, 1987
- August 17, 2017
- September 22, 2017
- ….

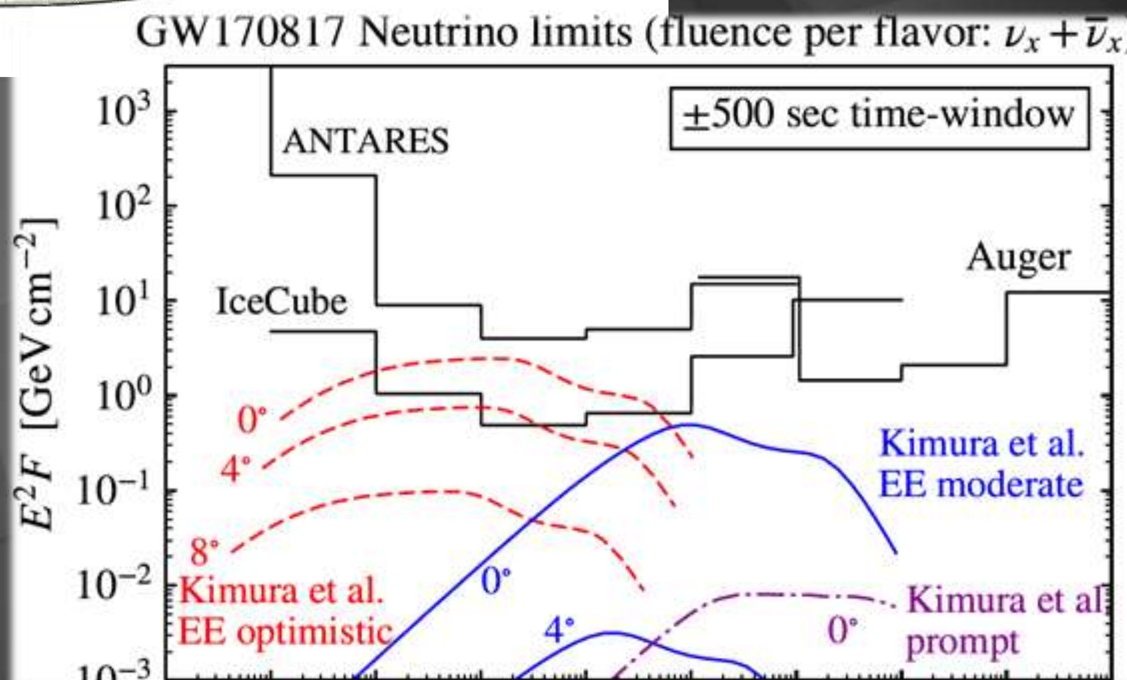
neutron star-neutron star merger

LIGO-VIRGO

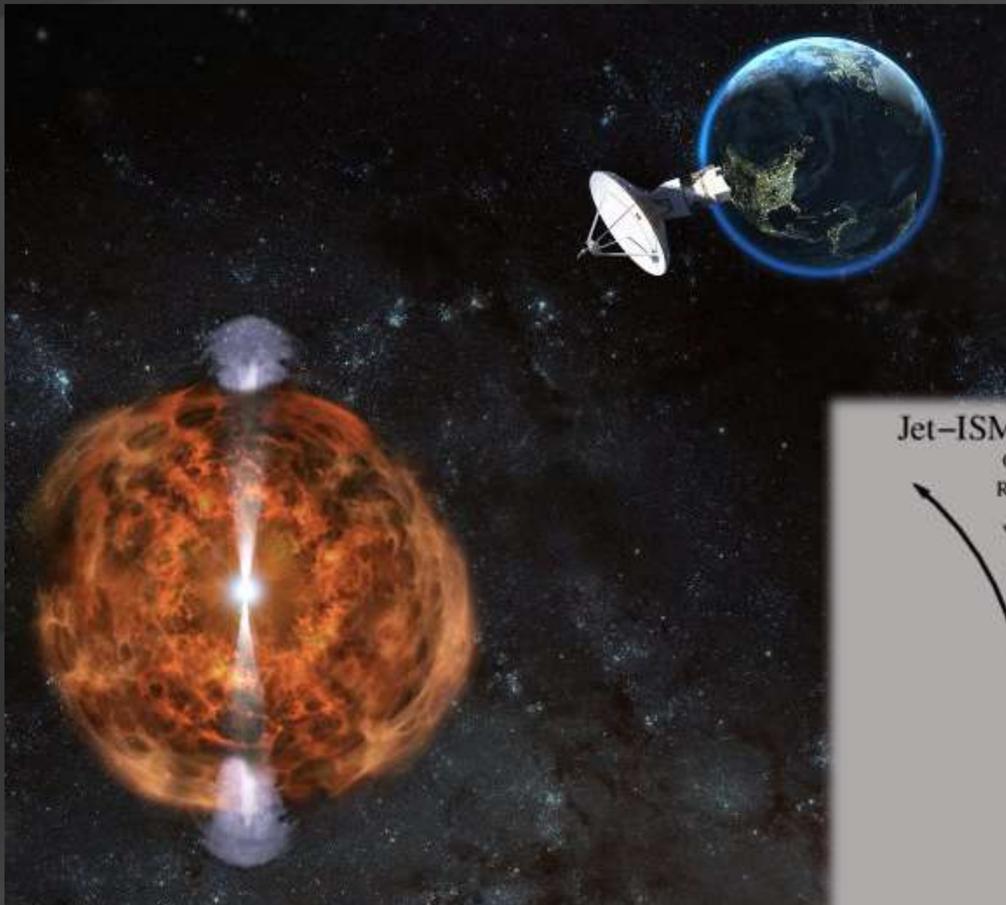
buildup of magnetic fields near merger launches jet



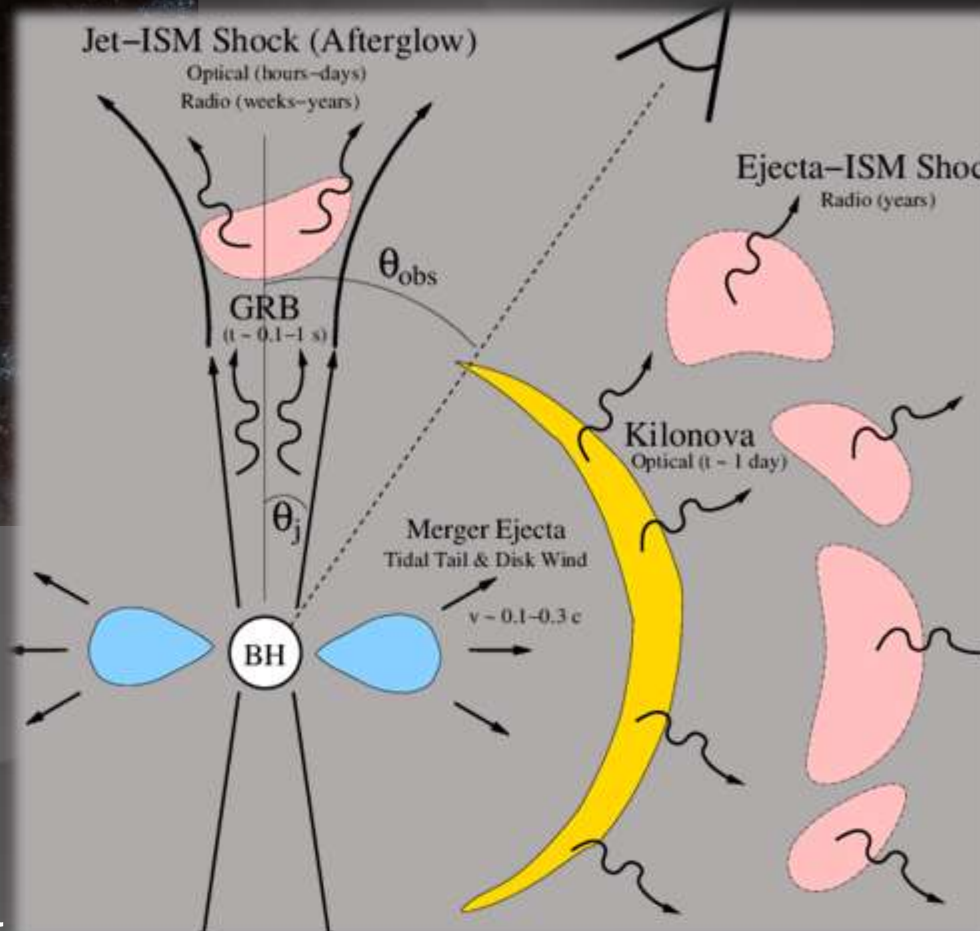
75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
22h
20h
16h
10h
8h
6h
4h
2h
IceCube up-going
IceCube down-going
ANTARES down-going
ANTARES up-going
Auger Earth-skimming
Auger down-going
GW (90% CL)
NGC 4993
neutrino candidate (IceCube)
neutrino candidate (ANTARES)
IceCube horizon
ANTARES horizon
Auger FoV (Earth-skimming)
Auger FoV (down-going)



GW170817 Neutrino limits (fluence per flavor: $\nu_x + \overline{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
E^2F [GeV cm^{-2}]
Kimura et al. EE moderate
Kimura et al. EE optimistic
Kimura et al. prompt



very weak short GRB
seen by Fermi
(off axis?)



MeV neutrino emission:

- ~ 0.01 M_{sun} material ejected
- similar to a supernova

high energy neutrinos from internal shocks inside the ejecta

TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

Number of detected neutrinos from single event at 40 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	6.6	0.55	29
B	0.36	0.023	1.5

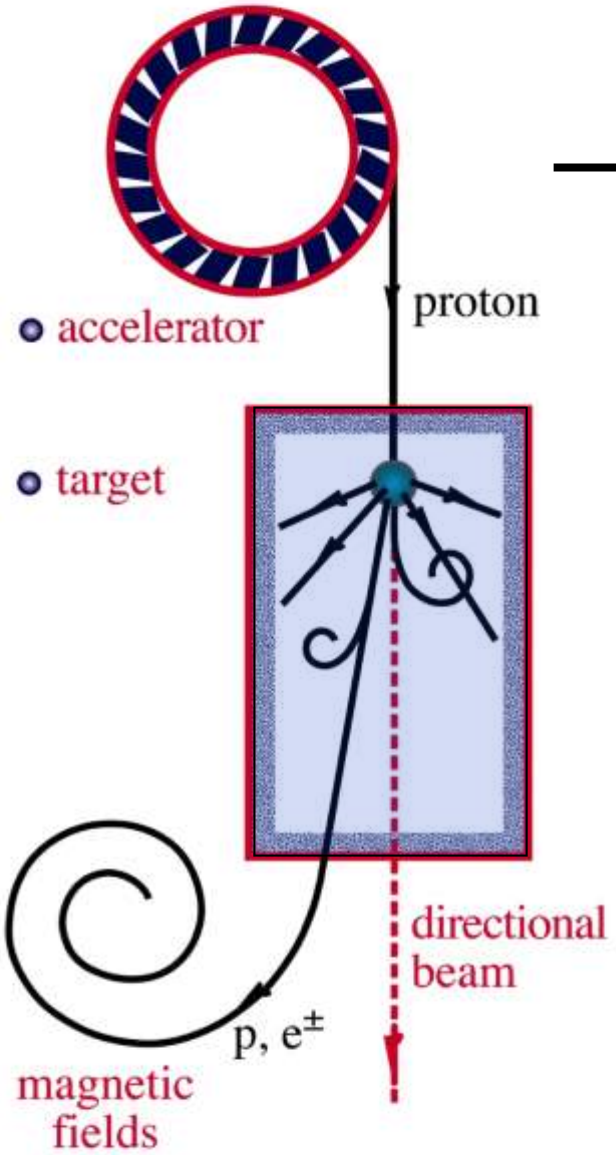
Number of detected neutrinos from single event at 300 Mpc			
model	IceCube-North	IceCube-South	Gen2-North
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]		
model	IceCube	Gen2
A	1.1	2.6
B	0.076	0.28

Kimura et al.

cosmic rays, gamma rays and neutrinos (and gravitational waves)

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

$$p + \gamma \rightarrow n + \pi^+$$

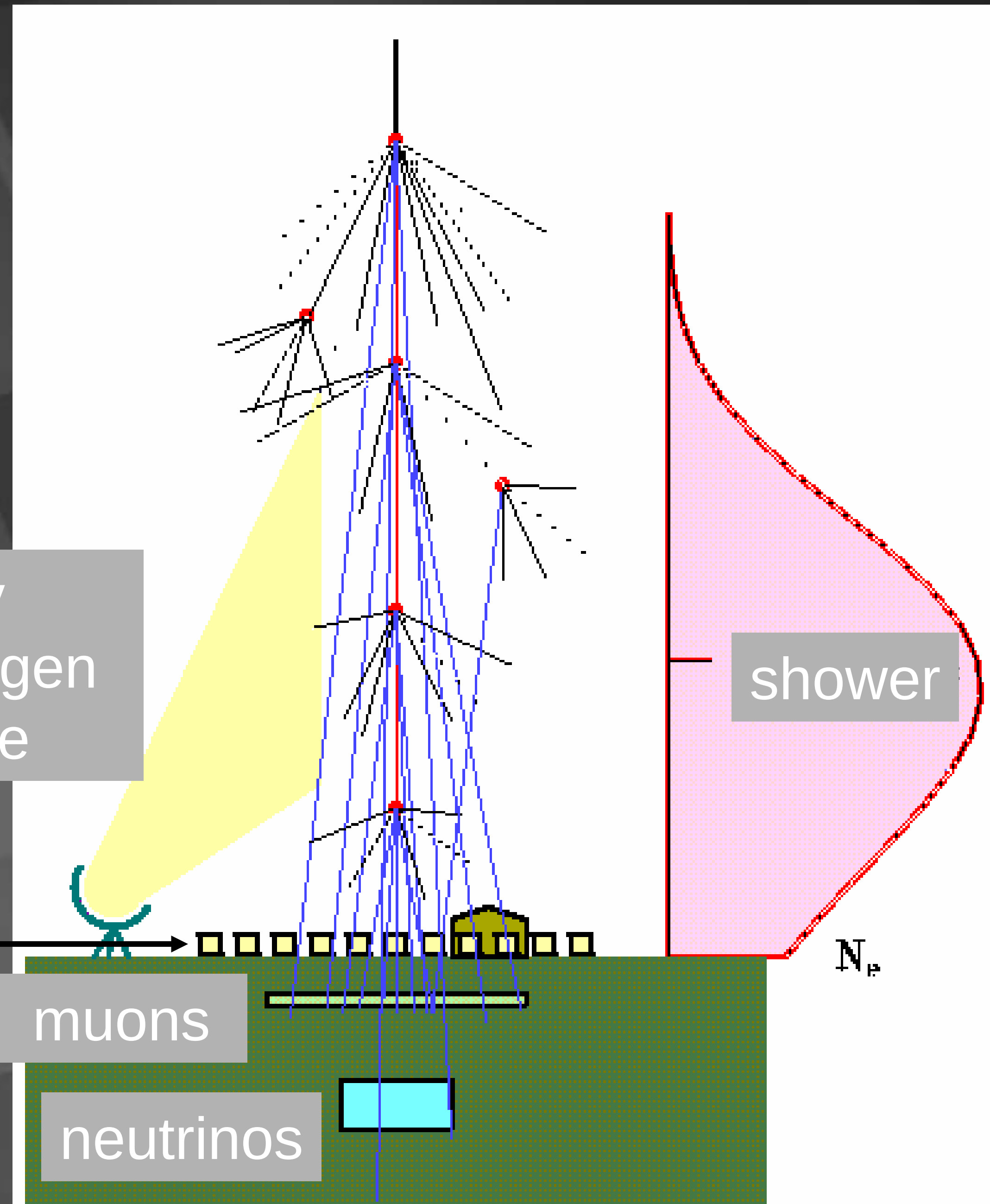
~ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

~ cosmic ray + gamma

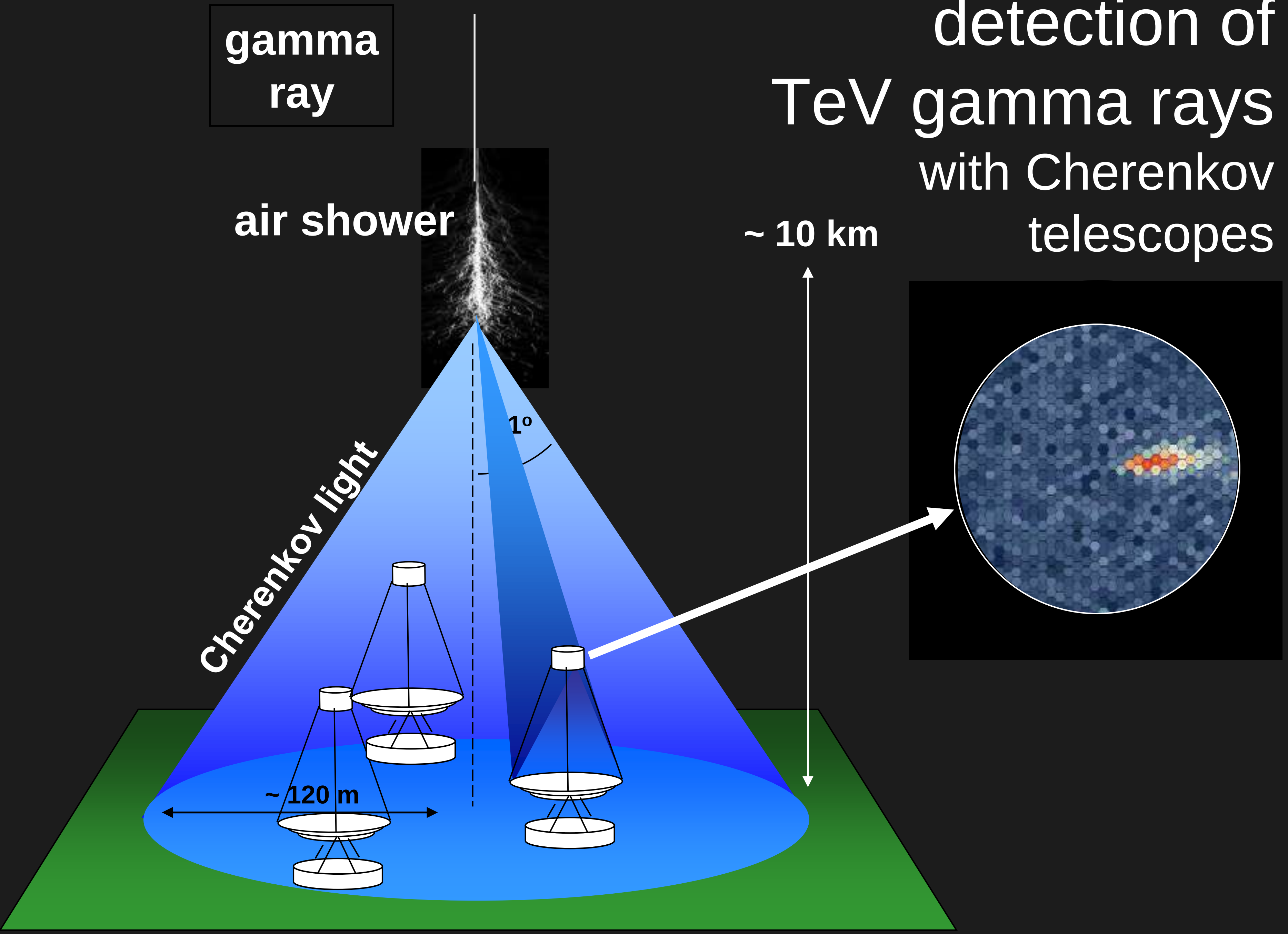
the atmosphere as a particle detector:

- 10 interaction
- 25 radiation lengths



TeV gamma ray astronomy

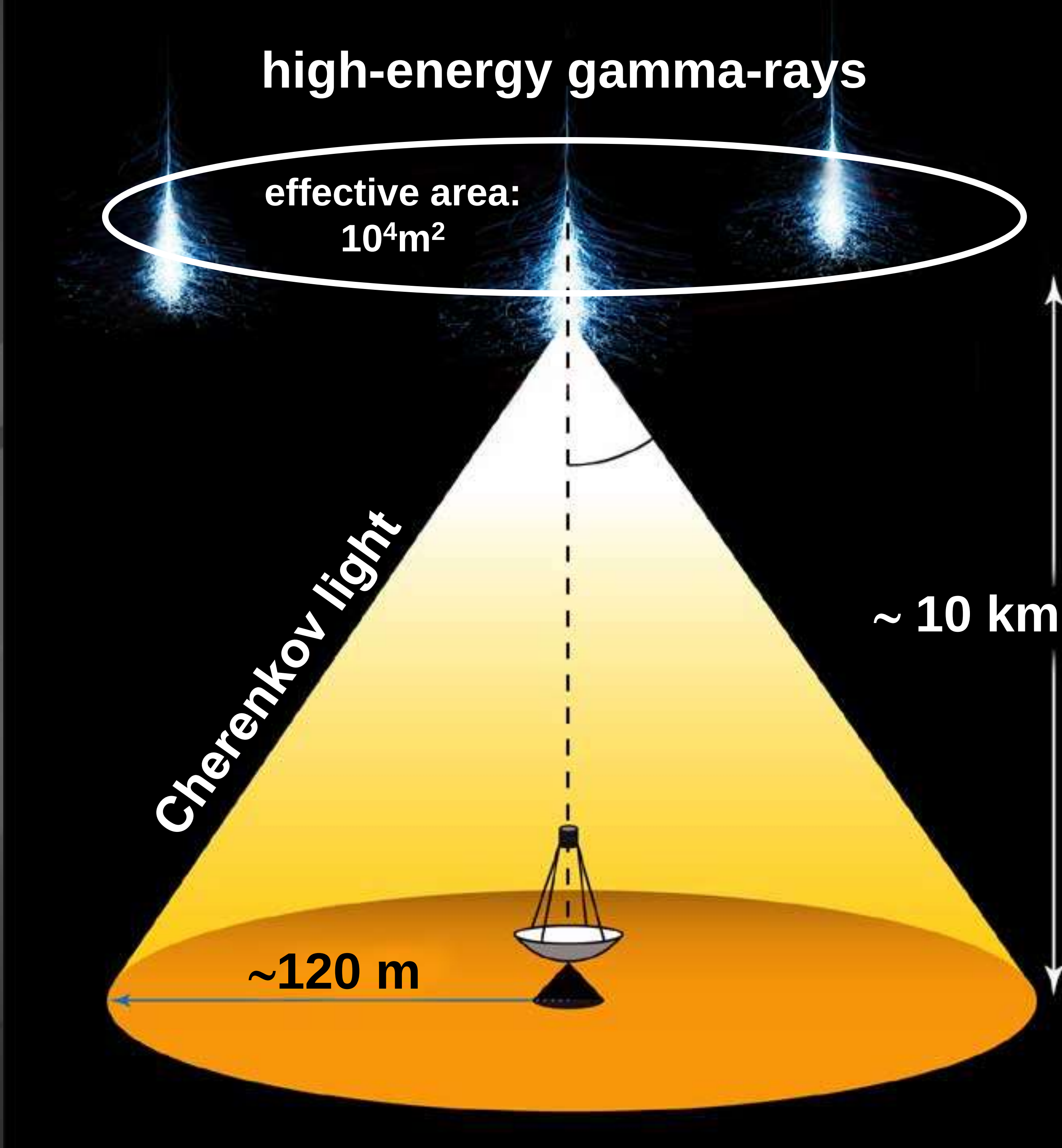
detection of TeV gamma rays with Cherenkov telescopes



•a cosmic photon initiates an electromagnetic shower high in the atmosphere

•the shower particles emit Cherenkov radiation

•this radiation is captured by mirrors read out by a cluster of photomultipliers



MAGIC atmposheric Cherenkov telescope


VERITAS


H.E.S.S.

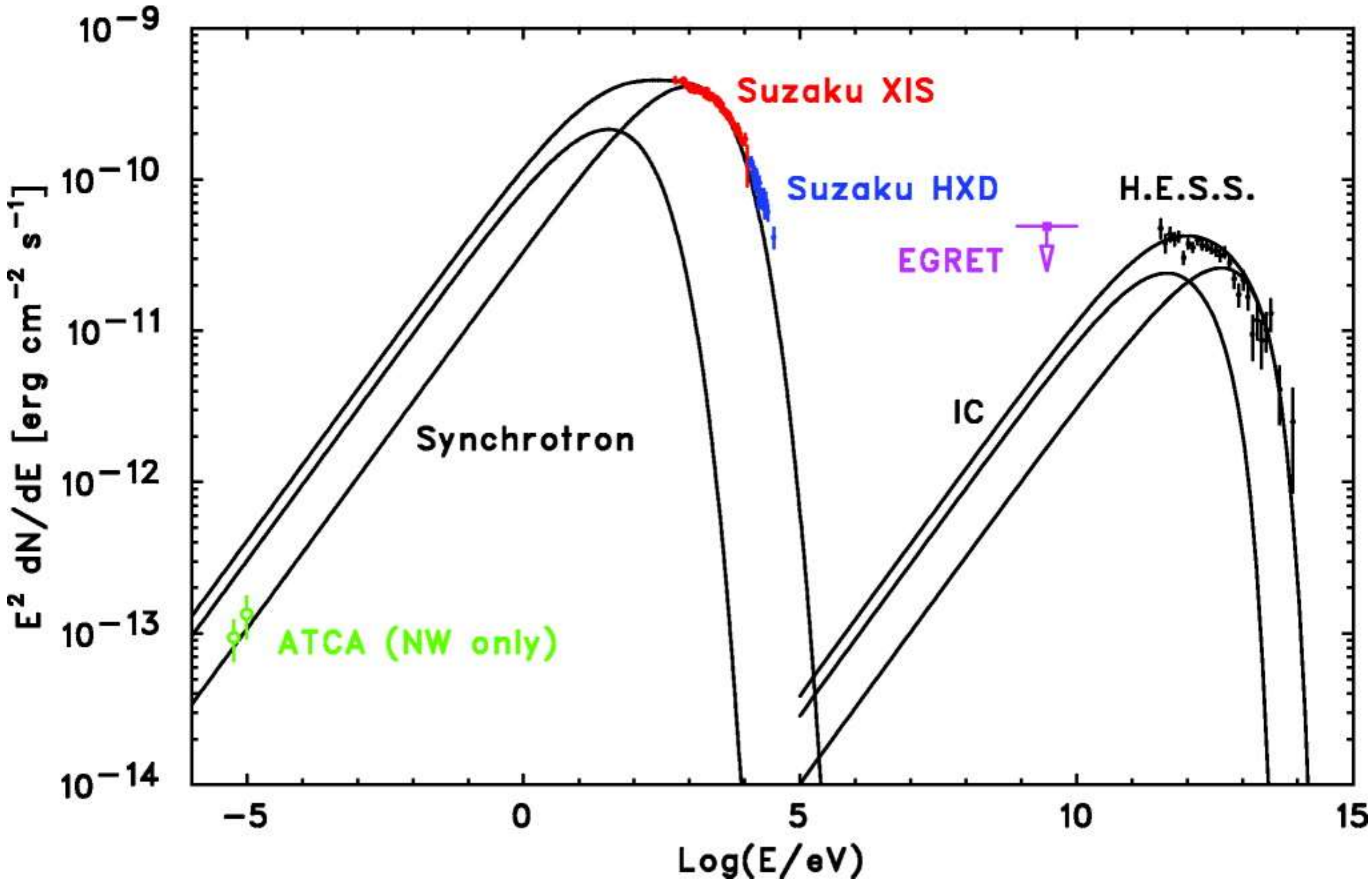
TeV γ survey instruments ~ 2-3 π

gamma rays are
muon-poor air showers

Tibet array and ARGO

Milagro

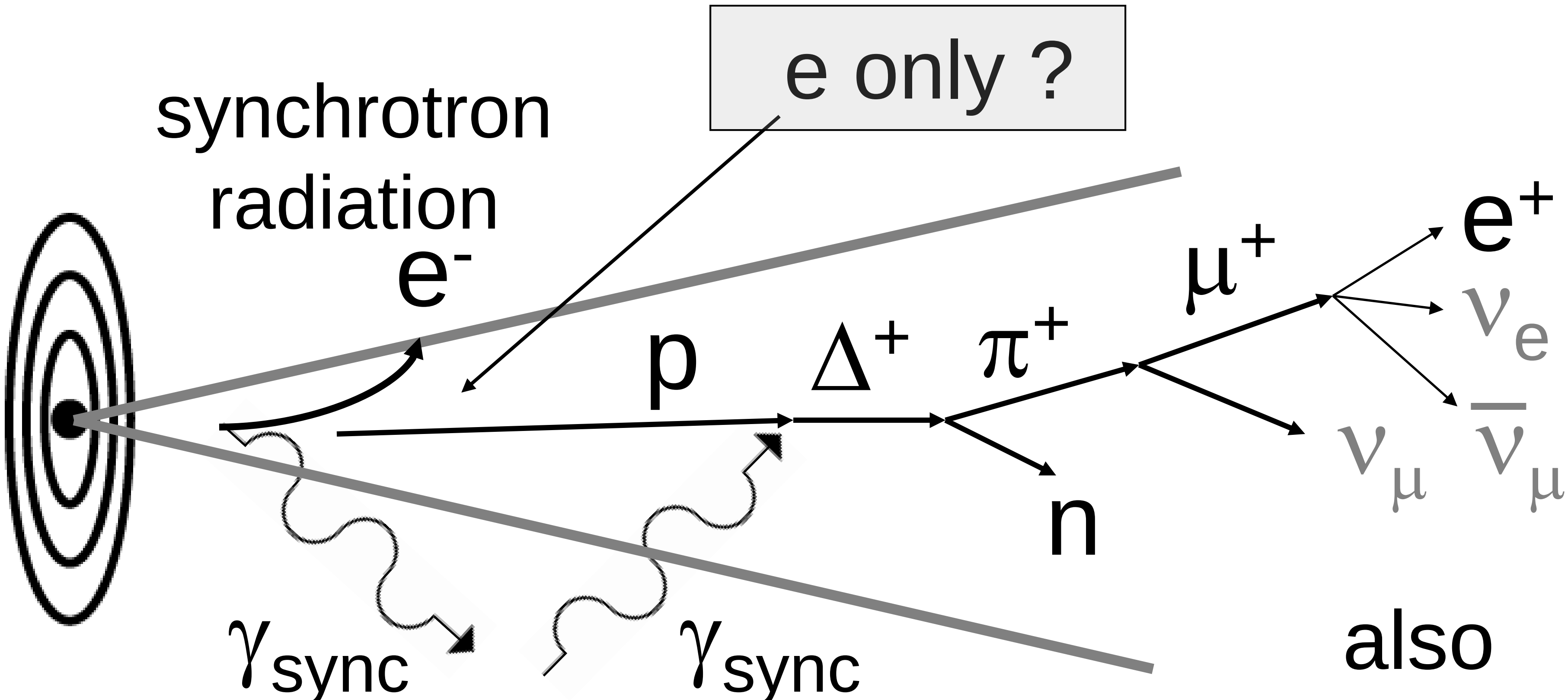
HAWC



a generic gamma ray source:
synchrotron and inverse Compton

PKS 2155-304

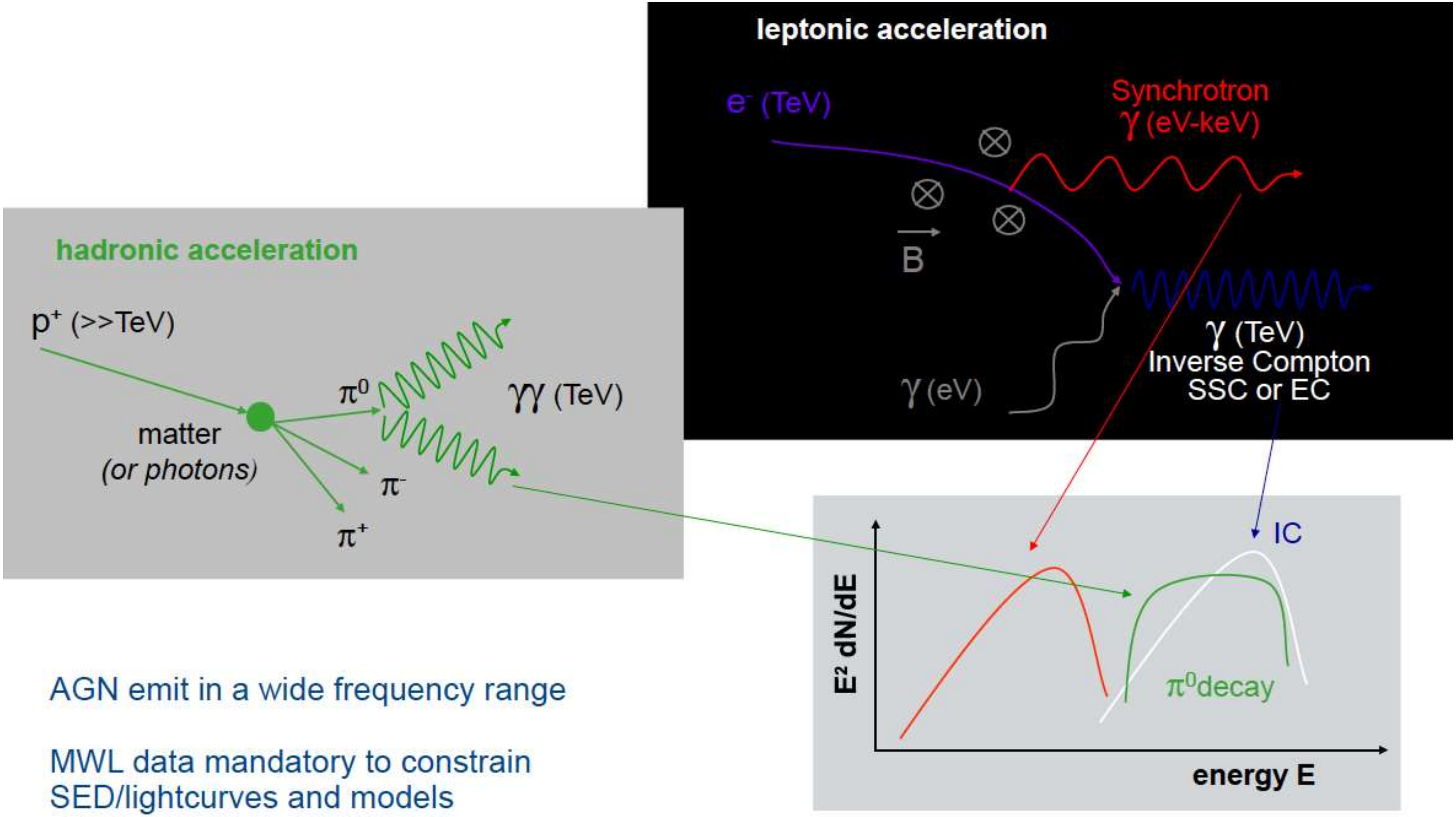
heavenly neutrino beam dump:
photons: synchrotron versus $\pi^0 \rightarrow \gamma\gamma$



also
$\Delta \rightarrow p\pi^0$
$\pi^0 \rightarrow \gamma\gamma$

cosmic rays exist !

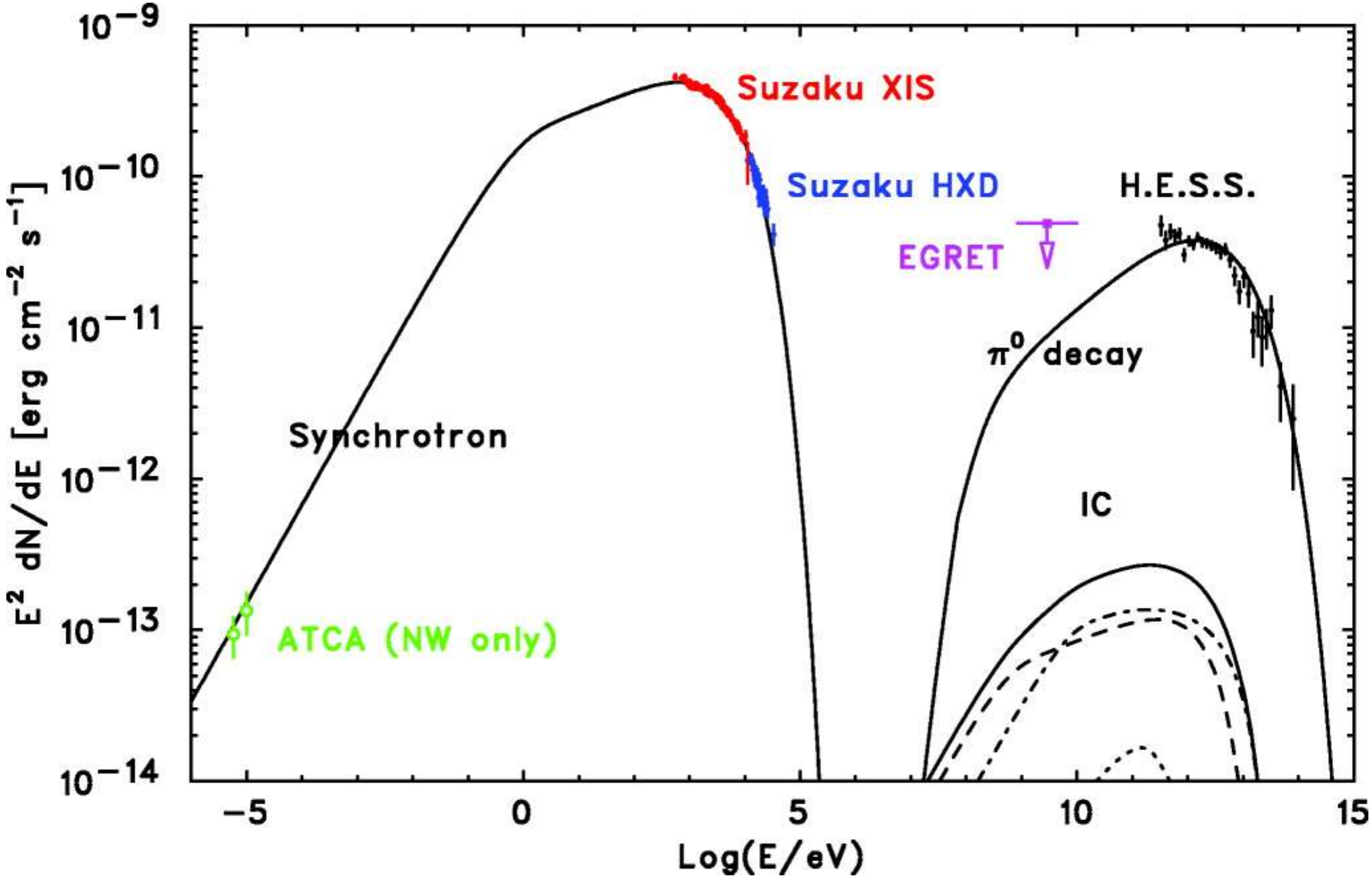
electromagnetic versus hadronic



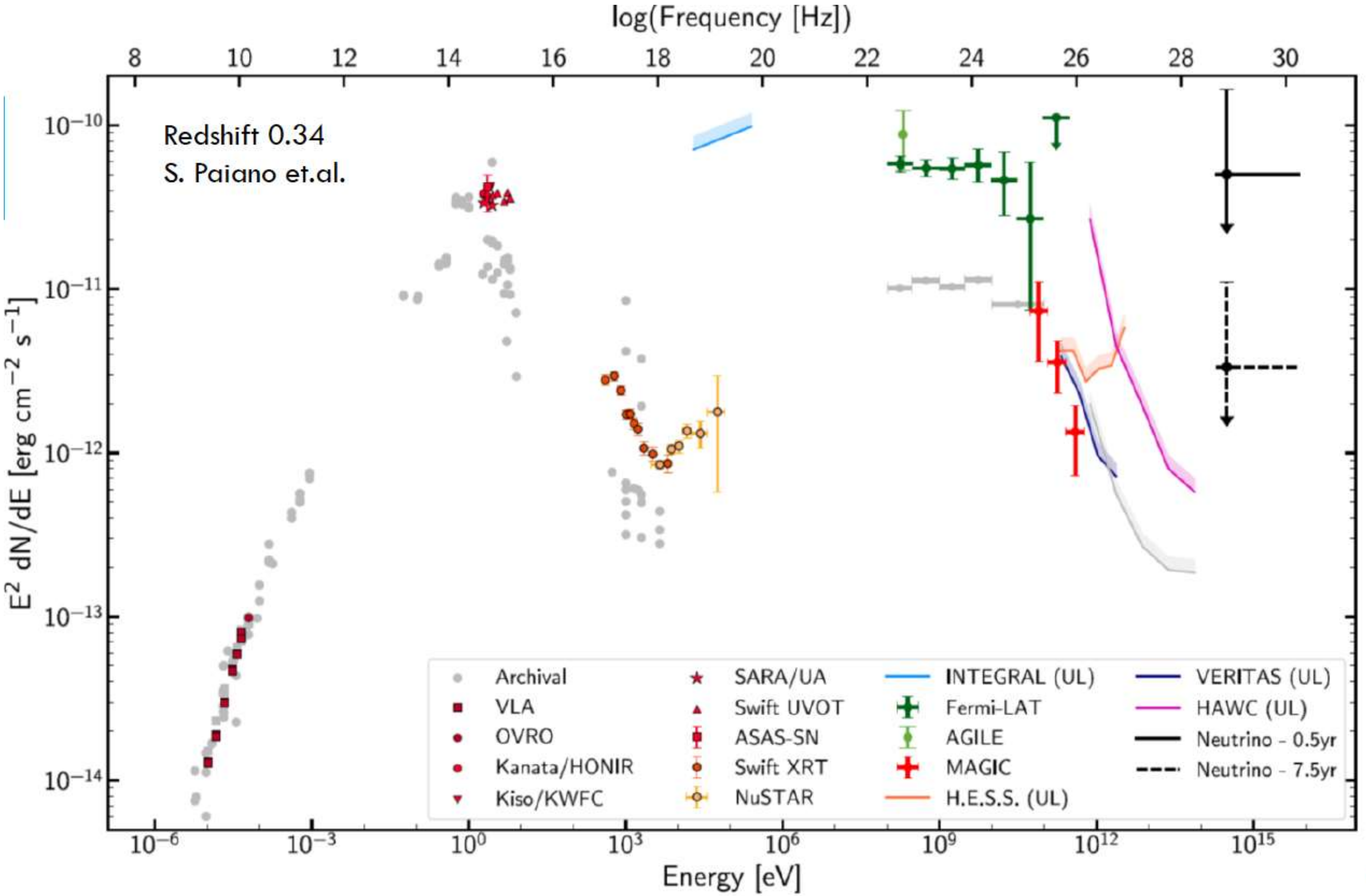
AGN emit in a wide frequency range

MWL data mandatory to constrain SED/lightcurves and models

(adapted from De Lotto, 2009)

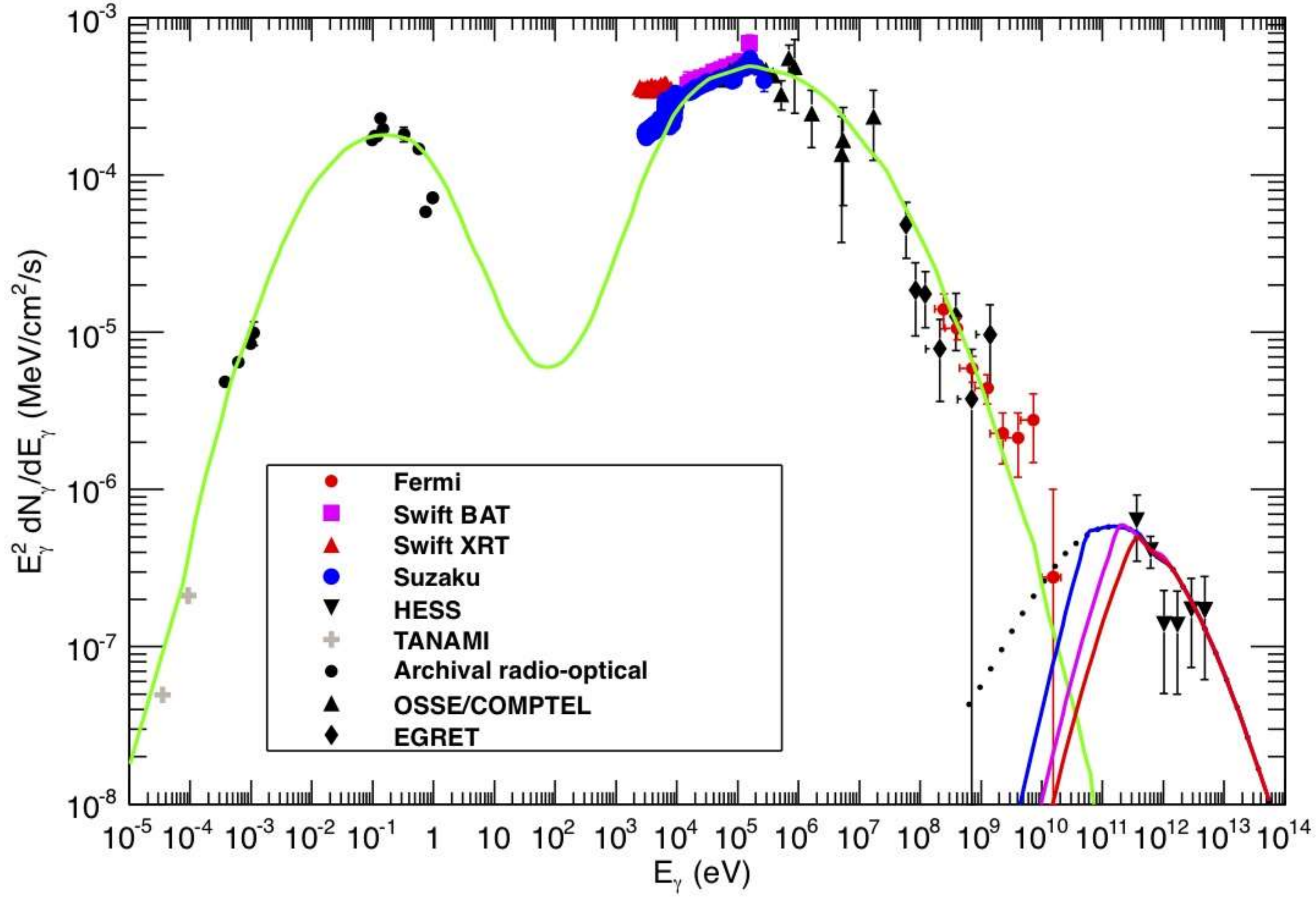


Suzaku XIS
Suzaku HXD
H.E.S.S.
EGRET
π⁰ decay
Synchrotron
IC
ATCA (NW only)
E² dN/dE [erg cm⁻² s⁻¹]
Log(E/eV)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
−5
0
5
10
15



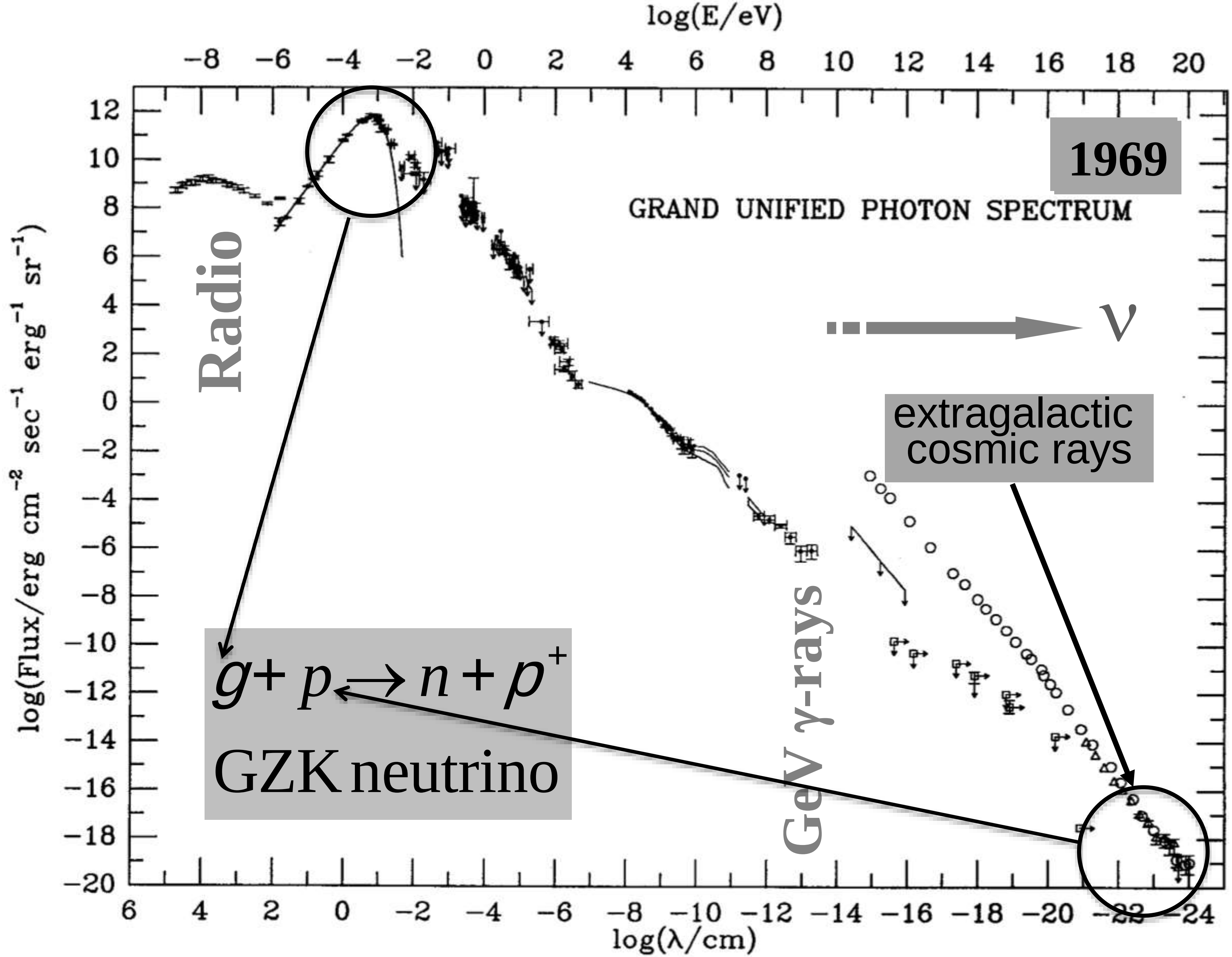
we know this one is hadronic

Centaurus A



$E_\gamma^2\, dN_\gamma/dE_\gamma$ (MeV/cm^2/s)
E_γ (eV)
Fermi
Swift BAT
Swift XRT
Suzaku
HESS
TANAMI
Archival radio-optical
OSSE/COMPTEL
EGRET

cosmic rays



log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic cosmic rays
$g + p \longrightarrow n + p^{+}$
GZK neutrino
GeV γ-rays
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)

cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+}$$

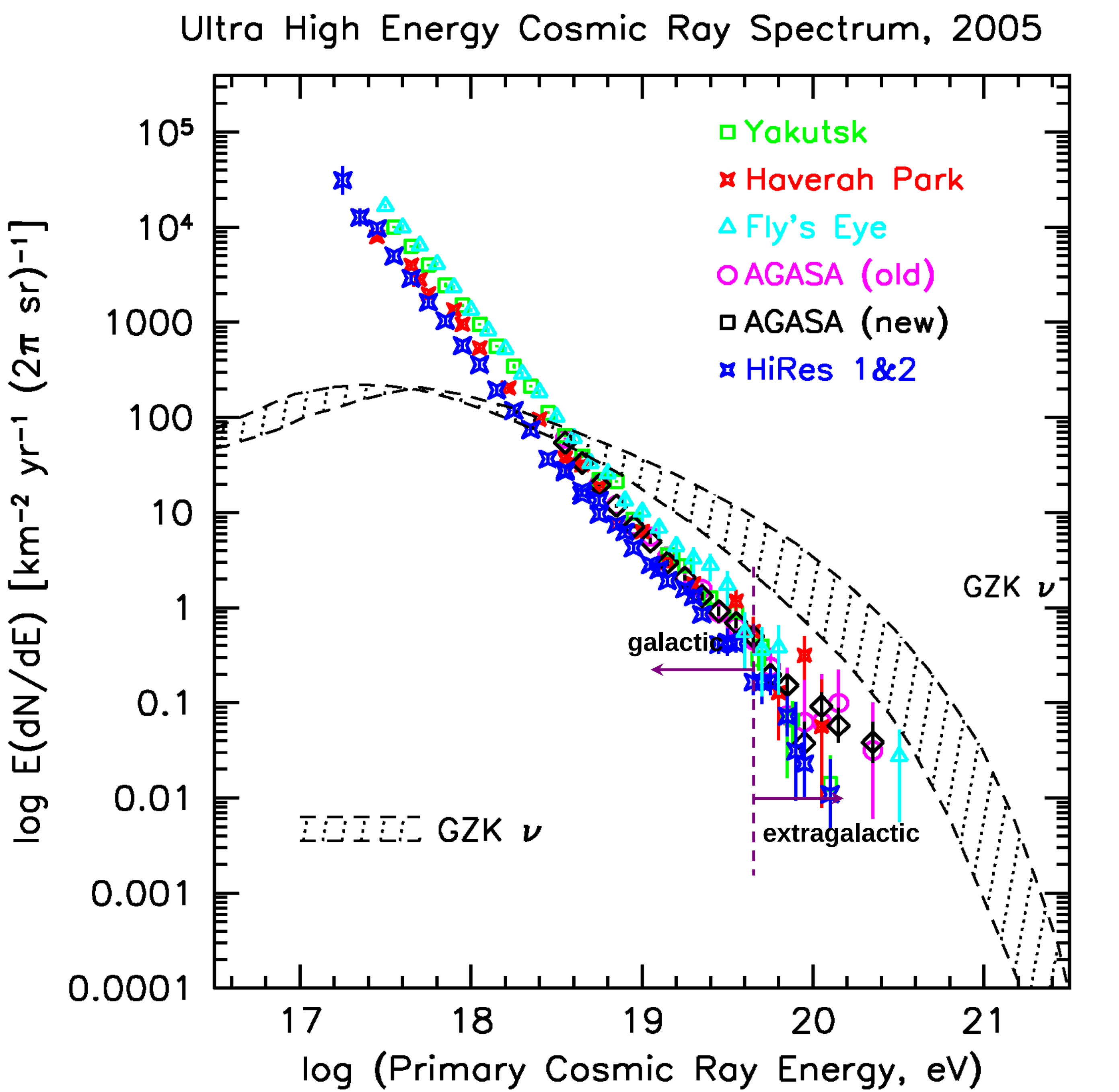
$400\ cm^{-3}$

$10^{-28}\ cm^{2}$

$$l_{\mathrm{int}} = \{n_{cmb} s_{g+p}\}^{-1} \sim 10\,Mpc$$

$$E_p \text{ ³ } 5 \text{´ } 10^{7}\,TeV$$

neutrinos from GZK interactions



cosmic rays interact with the microwave background

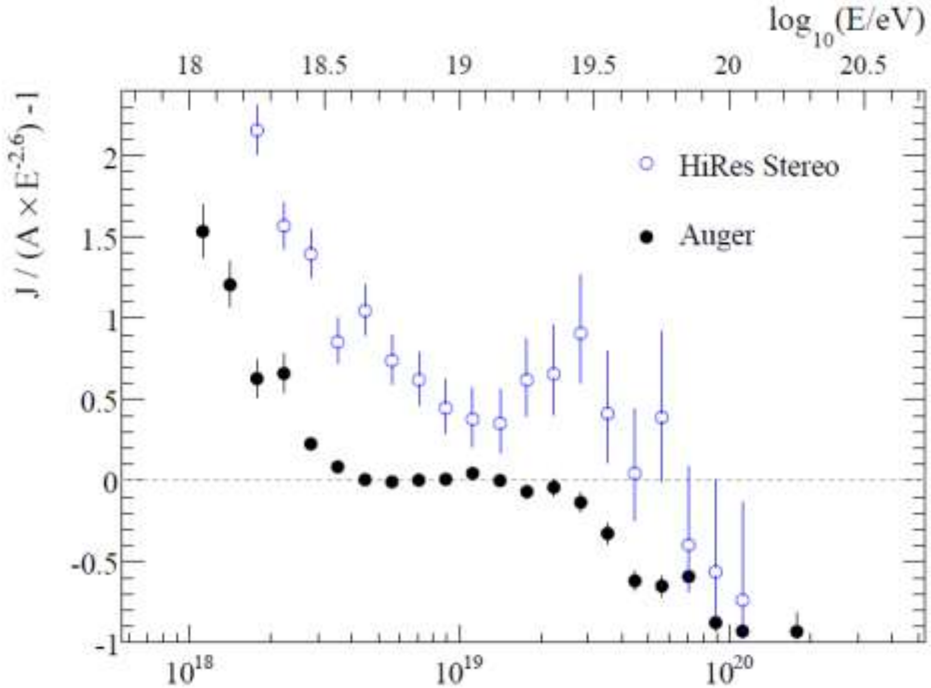
$$p+\gamma \rightarrow n+\pi^{+} \ and \ p+\pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

$$p \rightarrow m + u_m \rightarrow \{e + \overline{u_m} + u_e\} + u_m$$

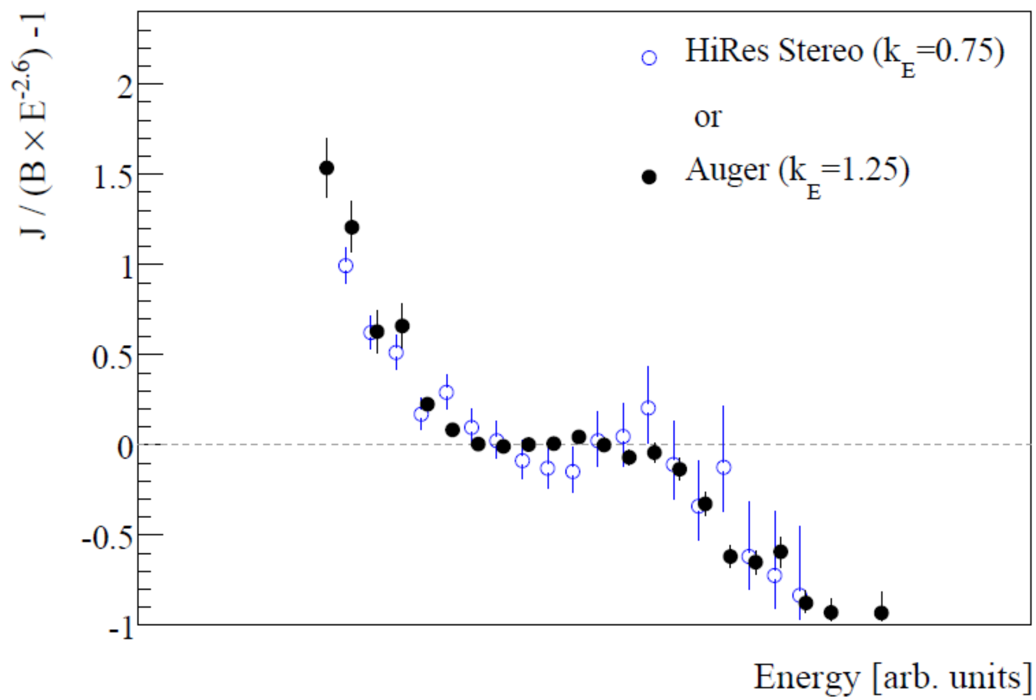
1 event per cubic kilometer per year

...but it points at its source!

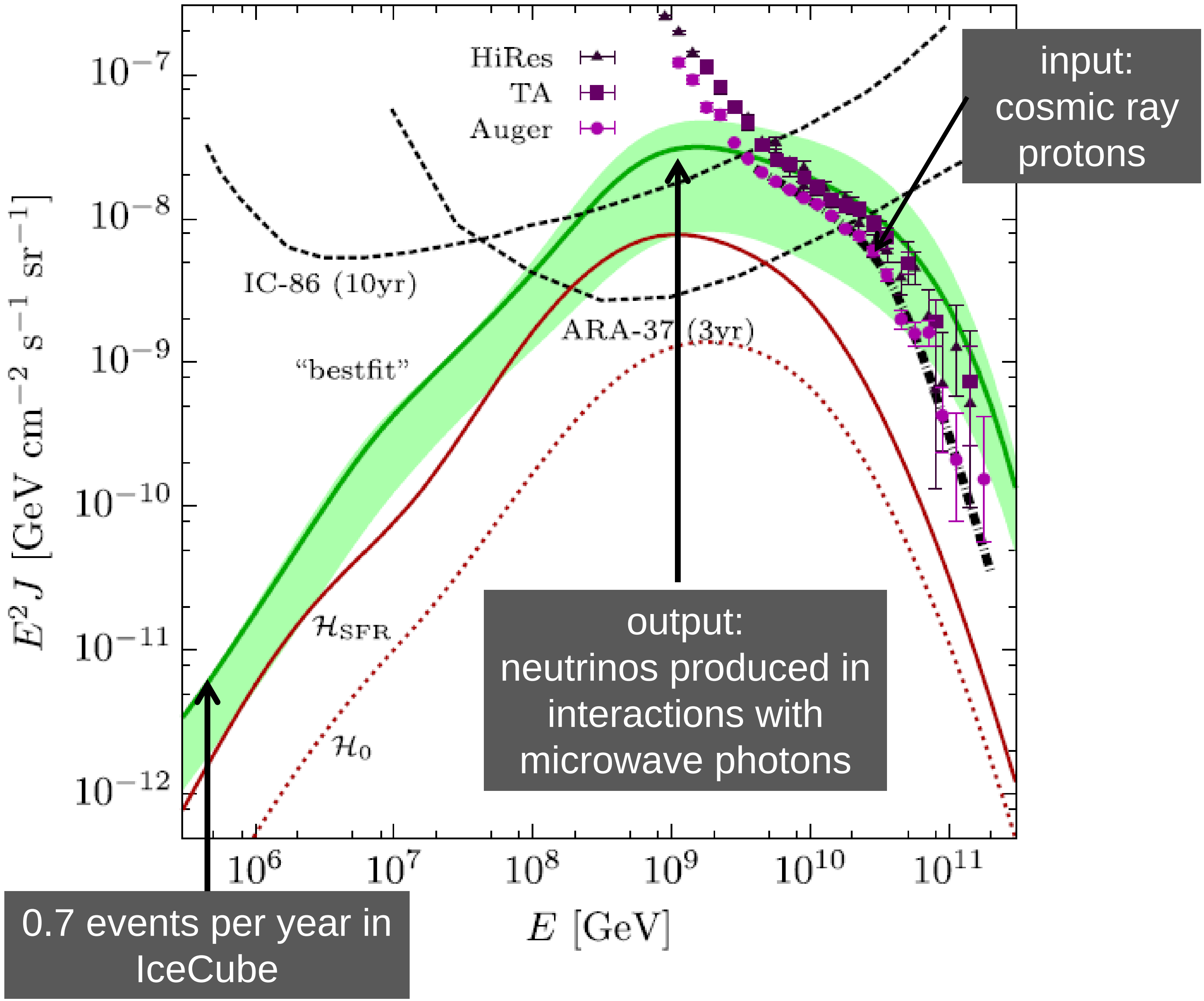


consistent with HiRes and confirmed by Auger and the Telescope Array

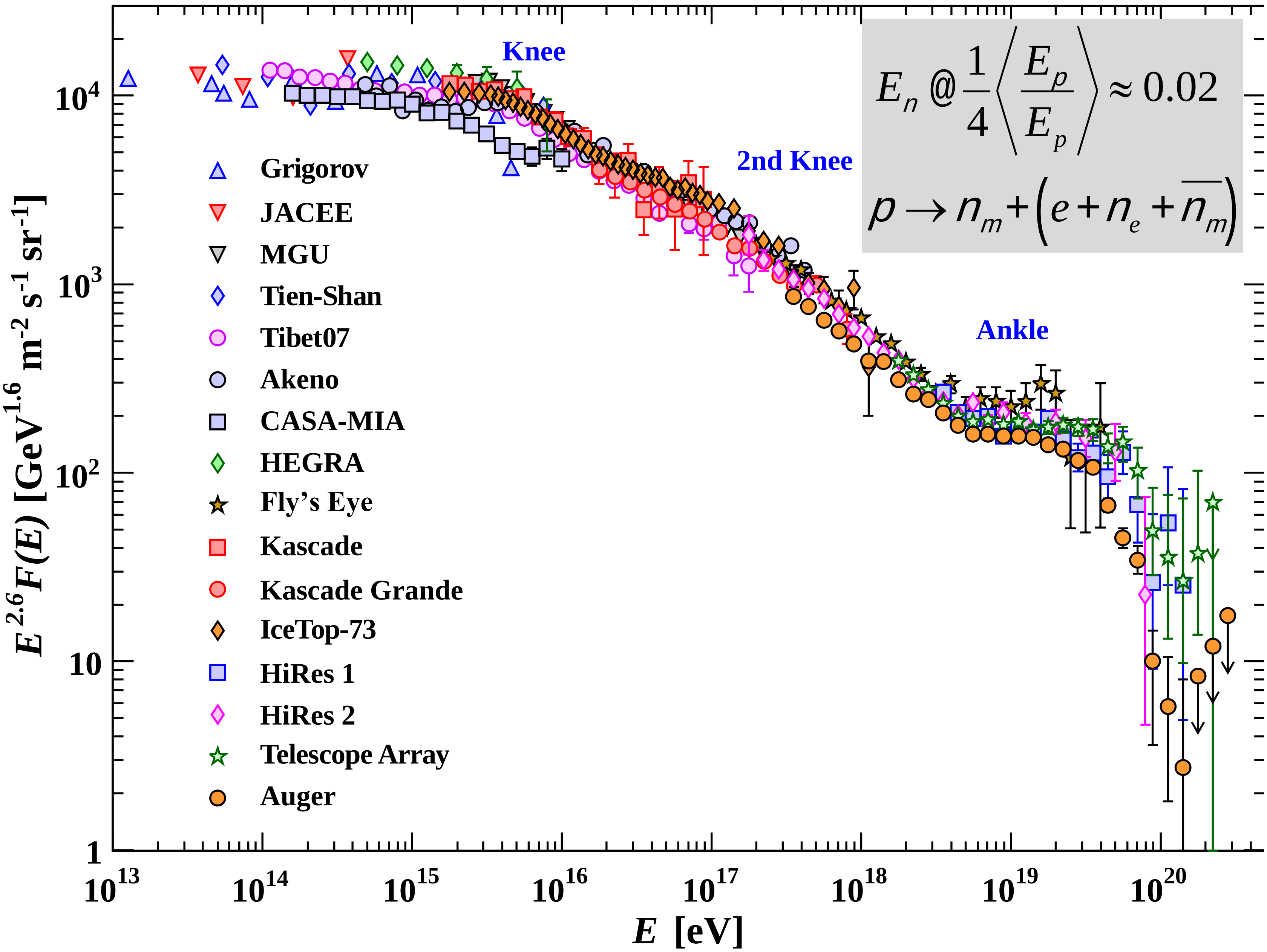
(Auger PRL **101** (2008) 61101, PLB (2010); HiRes APP **32** (2009) 53)



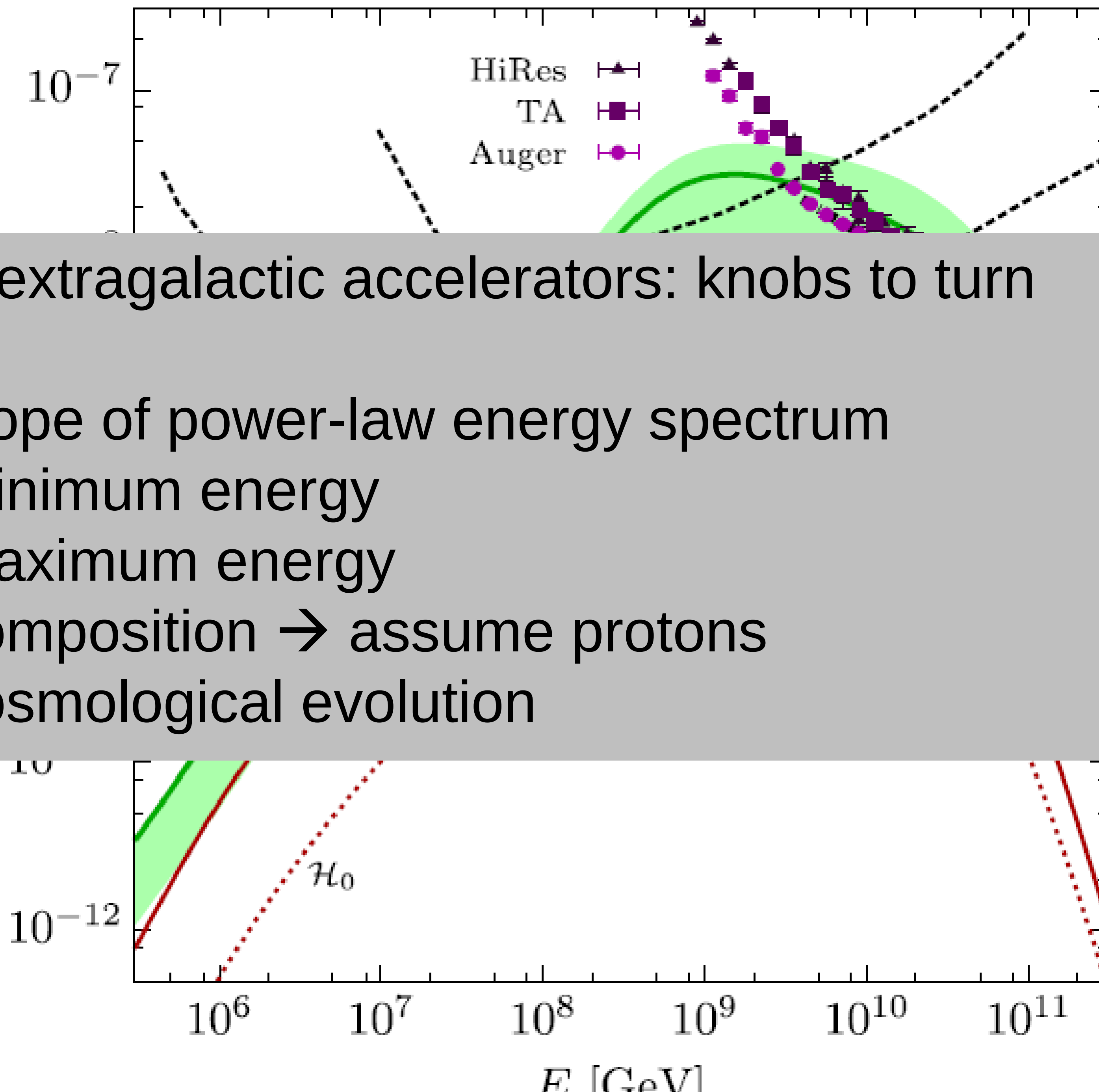
GZK absorption feature appears at the expected energy



input:
cosmic ray protons
output:
neutrinos produced in interactions with microwave photons
0.7 events per year in IceCube
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^6
10^7
10^8
10^9
10^{10}
10^{11}

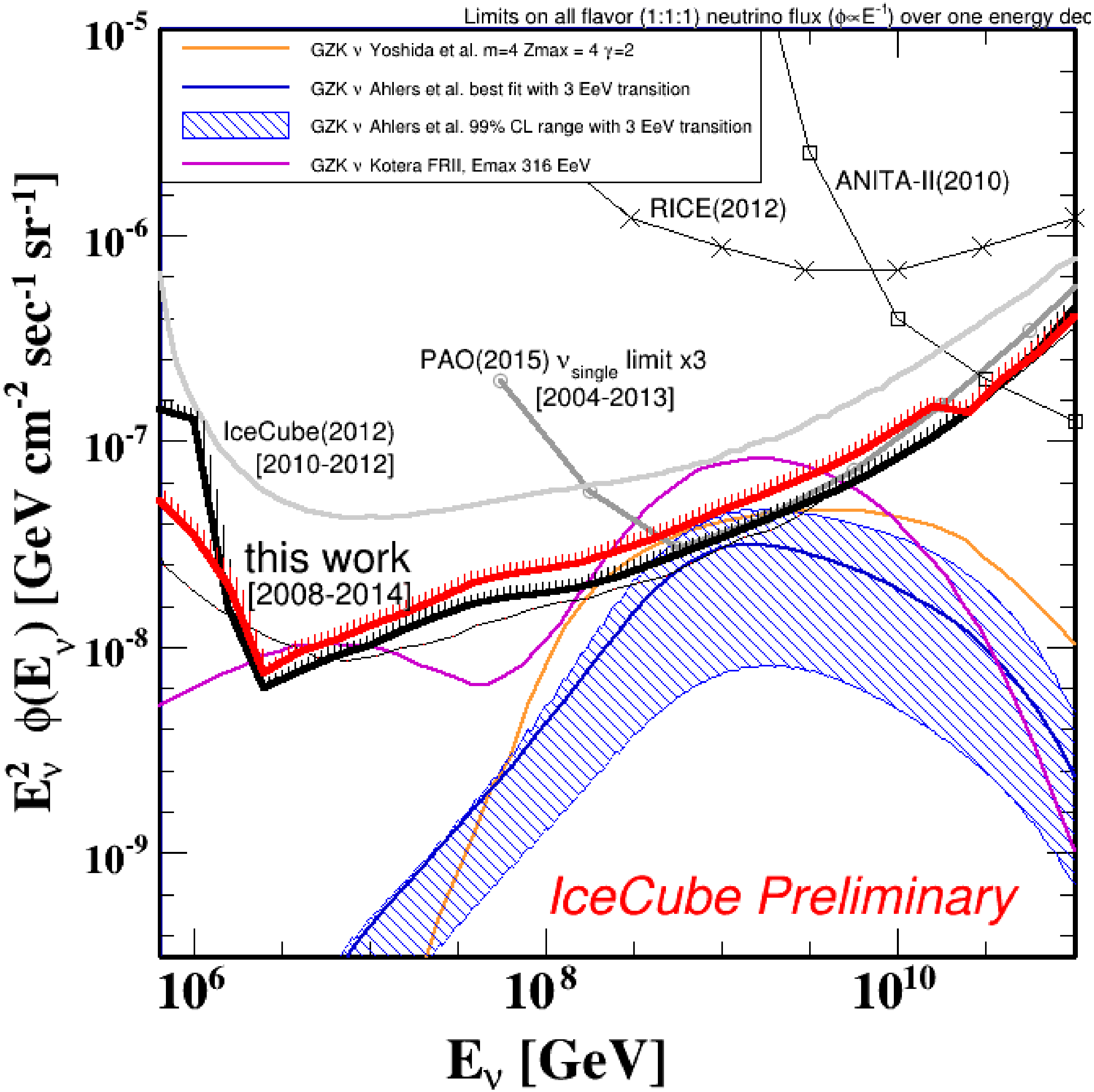


Knee
2nd Knee
Ankle
$E_n @ \frac{1}{4}\left\langle \frac{E_p}{E_p} \right\rangle \approx 0.02$
$p \rightarrow n_m + \left(e + n_e + \overline{n_m}\right)$
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

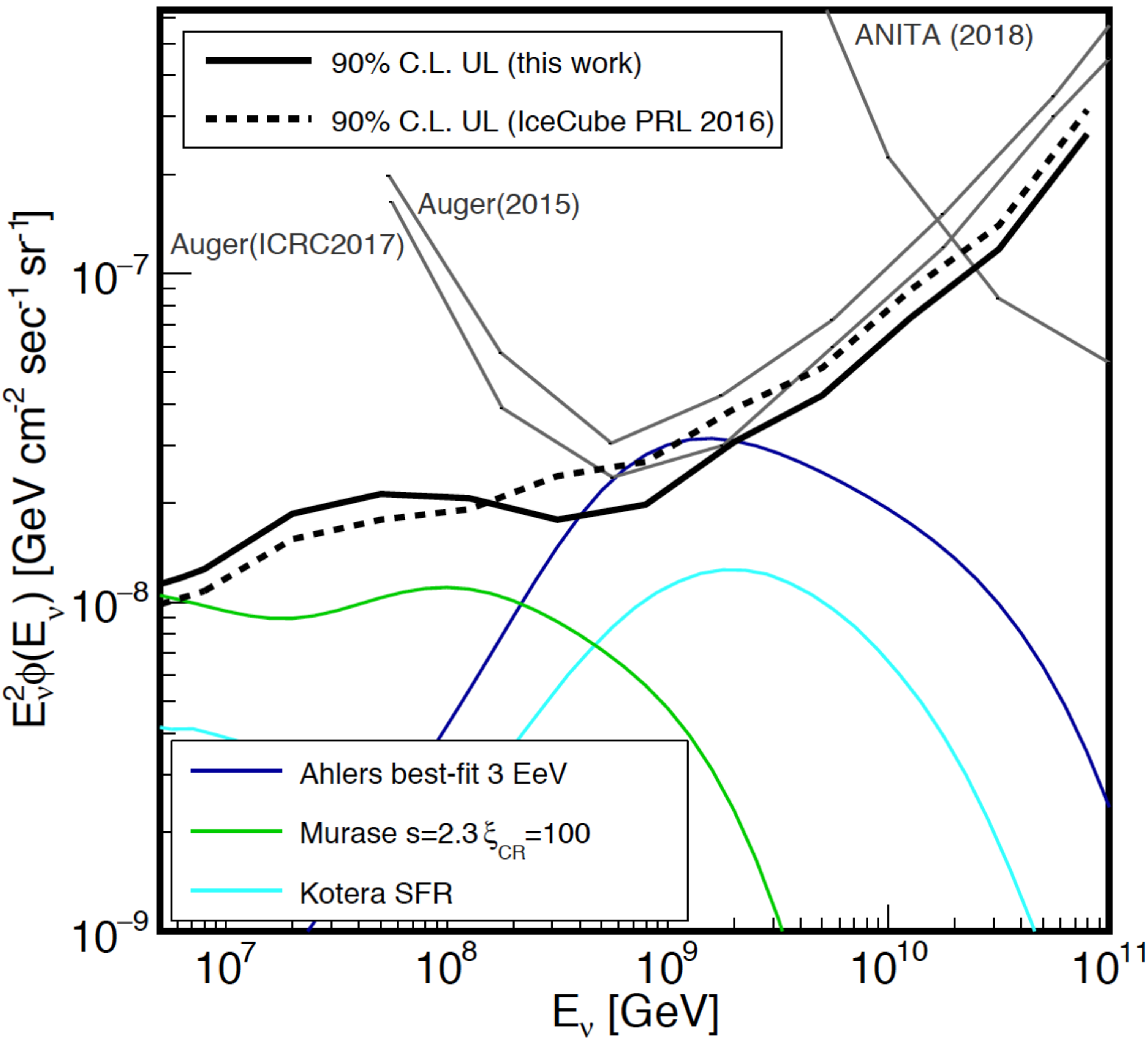


the extragalactic accelerators: knobs to turn

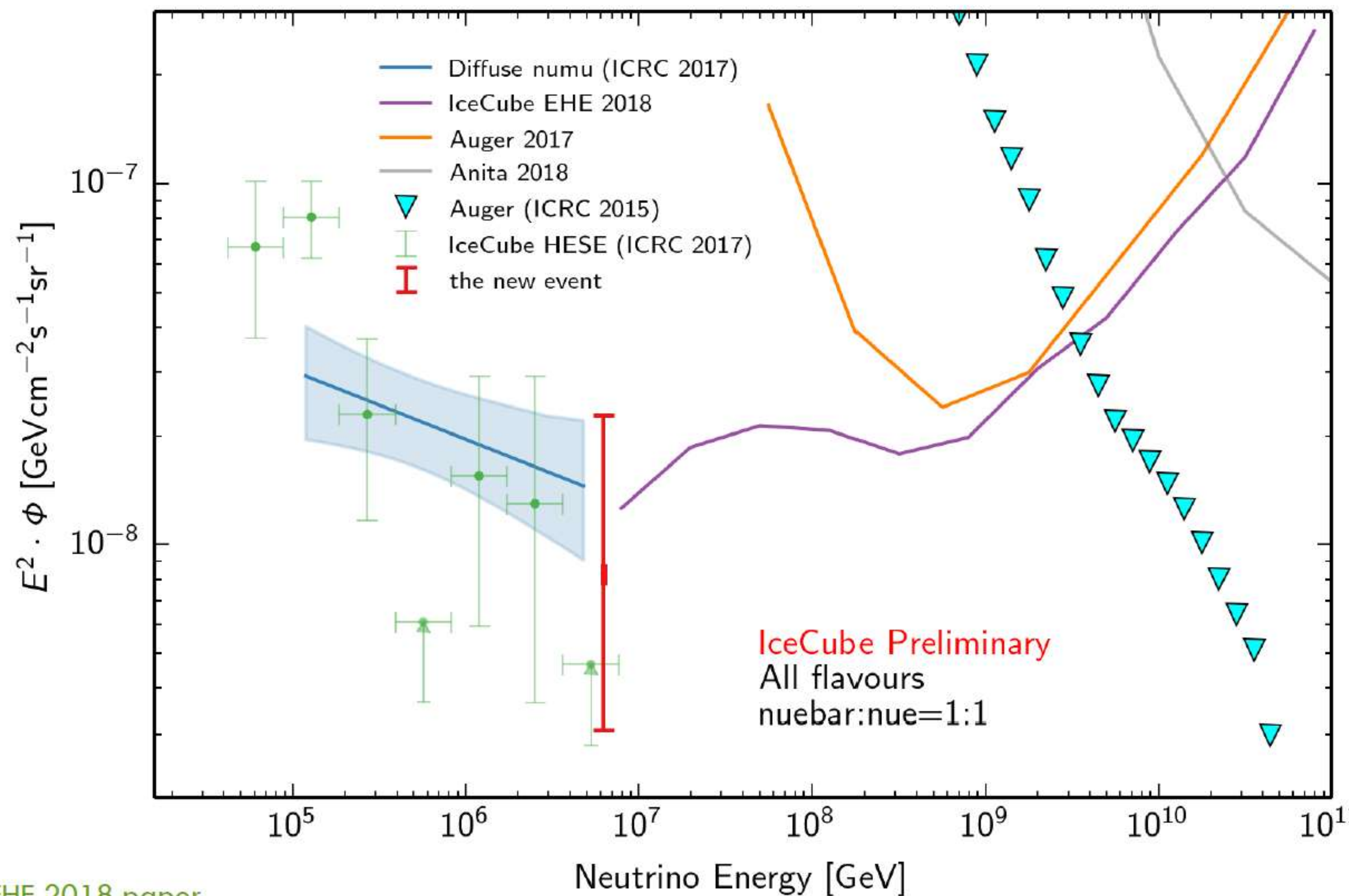
- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution



Limits on all flavor (1:1:1) neutrino flux (φ∝E^-1) over one energy dec
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν_single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
10^-5
10^-6
10^-7
10^-8
10^-9
10^6
10^8
10^10
$E_\nu^2\ \phi(E_\nu)$ [GeV cm^-2 sec^-1 sr^-1]
E_ν [GeV]



90% C.L. UL (this work)
90% C.L. UL (IceCube PRL 2016)
ANITA (2018)
Auger(2015)
Auger(ICRC2017)
Ahlers best-fit 3 EeV
Murase s=2.3 ξ_CR=100
Kotera SFR
10^-7
10^-8
10^-9
10^7
10^8
10^9
10^10
10^11
E_ν [GeV]
E_ν^2 φ(E_ν) [GeV cm^-2 sec^-1 sr^-1]



Link to EHE 2018 paper

IceCube: 0.7events per year (0.32 shower and 0.38 muon)

GEN2: 0.32 x 8 + 0.38 x 4 = 4.1 (p-only out in < 5 years

Ahlers *et al.* [22] best fit, 1 EeV	$2.8^{+0.4}_{-0.4}$	$9.5^{+6.5}_{-1.6}\%$	1.17
Ahlers *et al.* [22] best fit, 3 EeV	$4.4^{+0.6}_{-0.7}$	$2.2^{+1.3}_{-0.9}\%$	0.66
Ahlers *et al.* [22] best fit, 10 EeV	$5.3^{+0.8}_{-0.8}$	$0.7^{+1.6}_{-0.2}\%$	0.48

TABLE I. Cosmogenic neutrino model tests: Expected number of events in 2426 days of effective livetime, p-values from model hypothesis test, and 90%-CL model-dependent limits in terms of the model rejection factor (MRF) [52], defined as the ratio between the flux upper limit and the predicted flux.

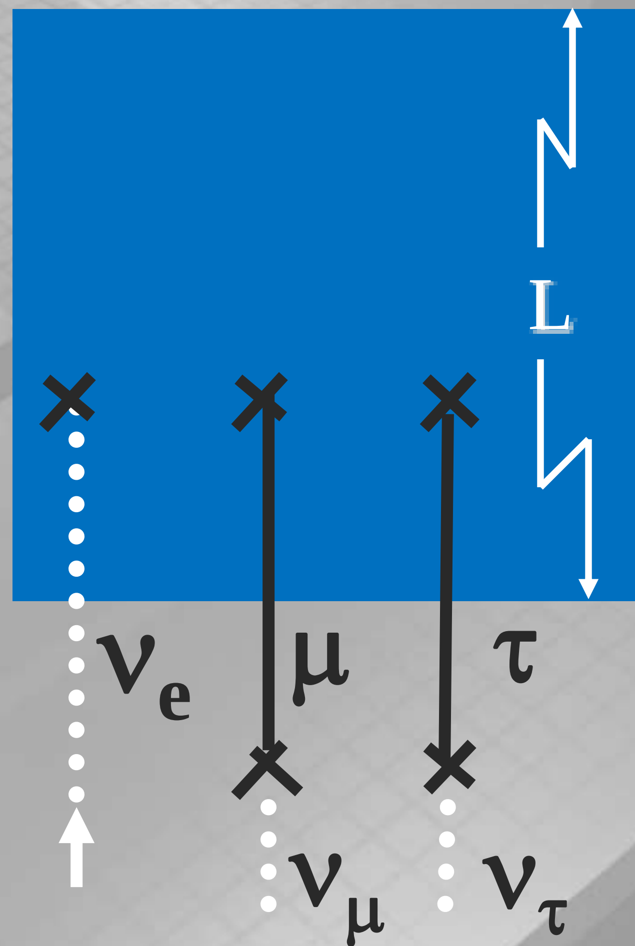
neutrinos

(on the back of the envelope)

how large a telescope: neutrino detection probability?

neutrino survives

$$e^{-\frac{L}{\lambda_\nu}}$$



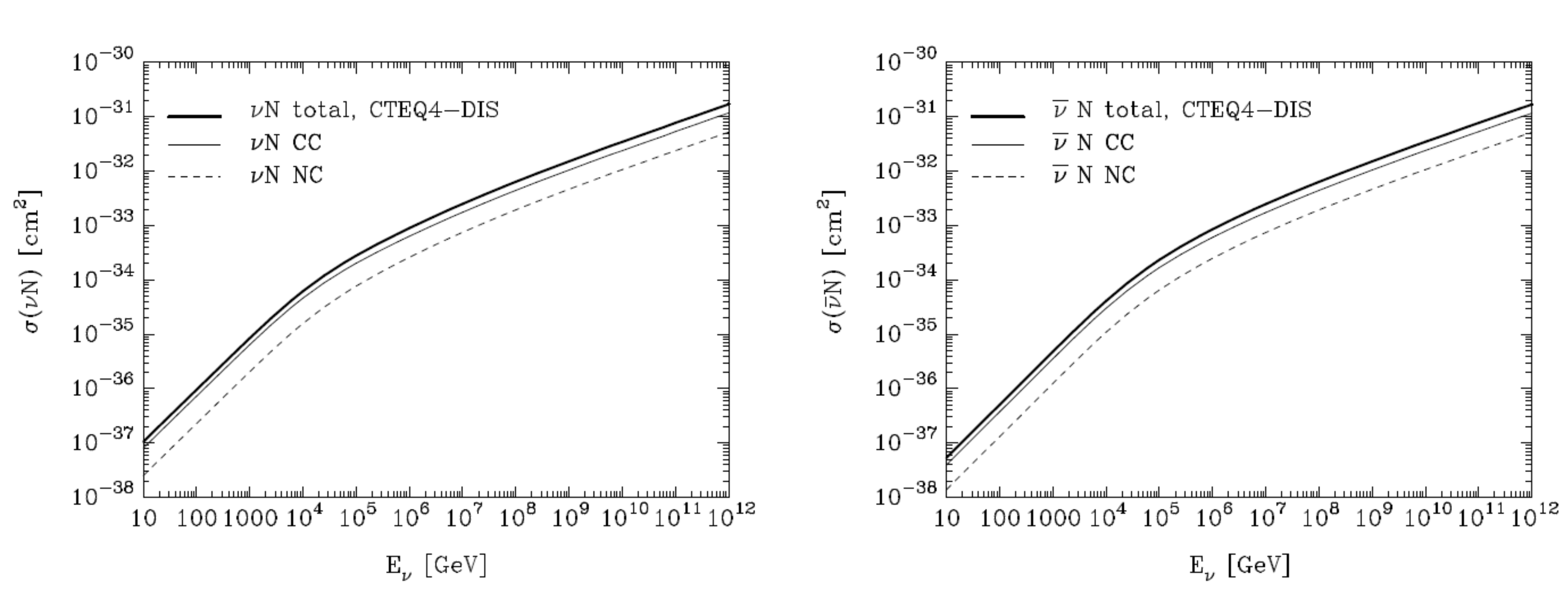
neutrino detected

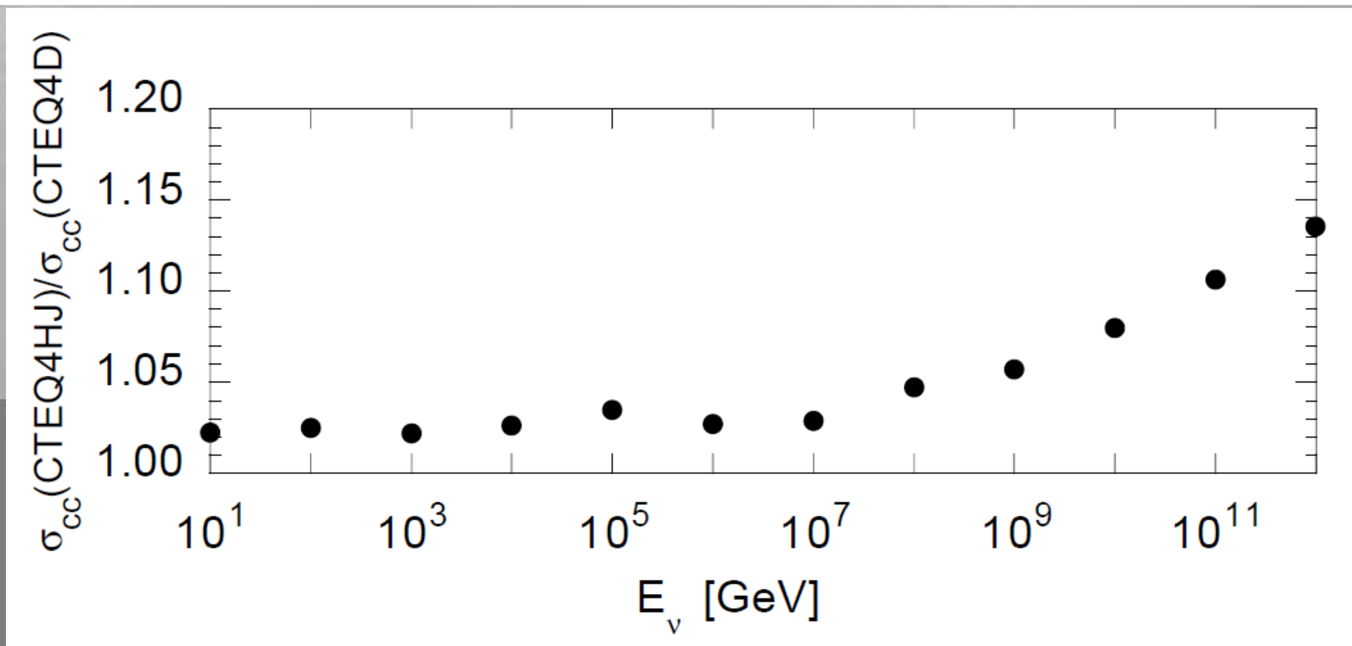
$$1-e^{-\frac{L}{\lambda_\nu}} \cong \frac{L}{\lambda_\nu}$$

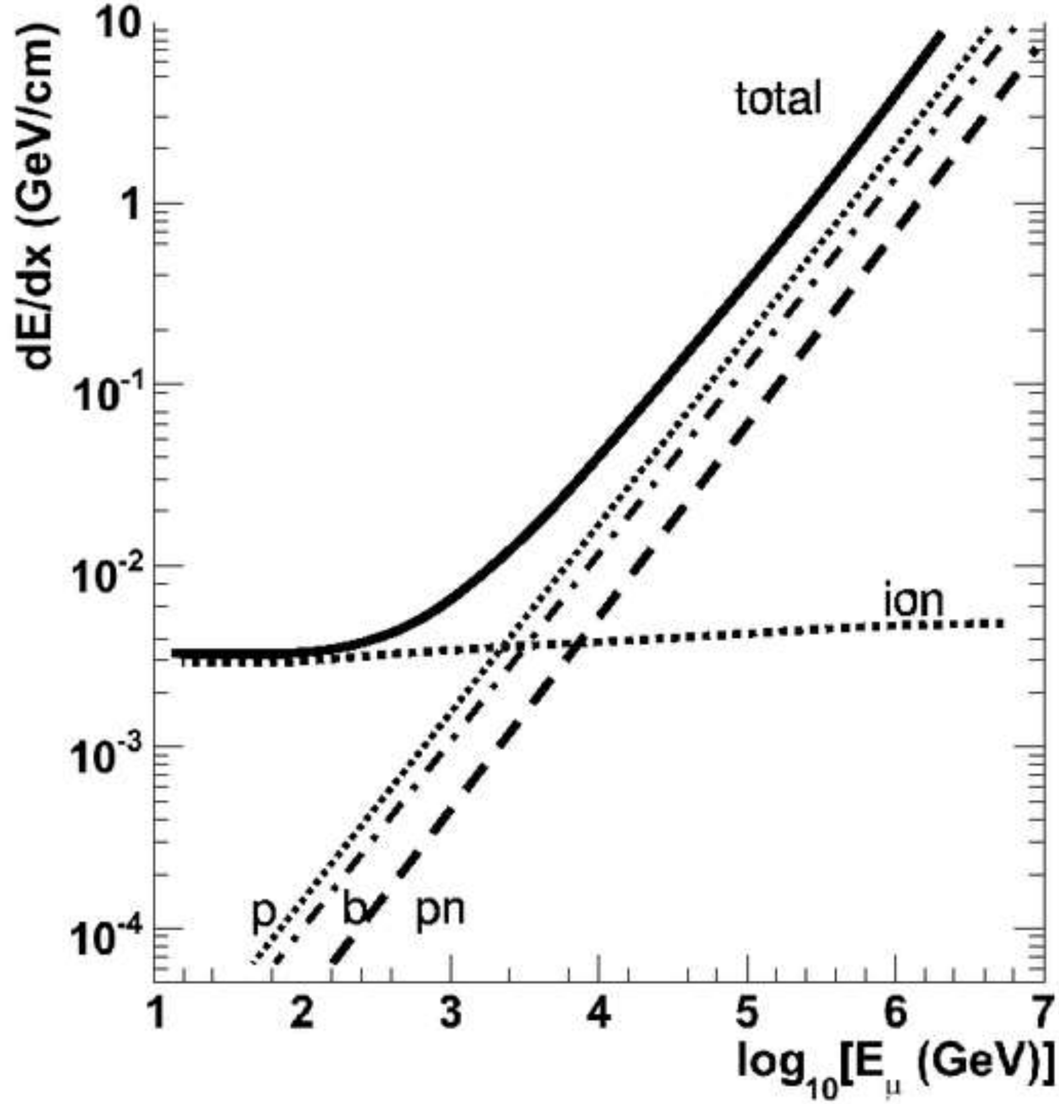
for n_m $L \rightarrow R_m\left[E_m = (1 - y)E_n\right]$

for n_t $L \rightarrow (E_t / m_t)\, c t_t$

$$P_{\mathrm{det}} = n\sigma_\nu L$$

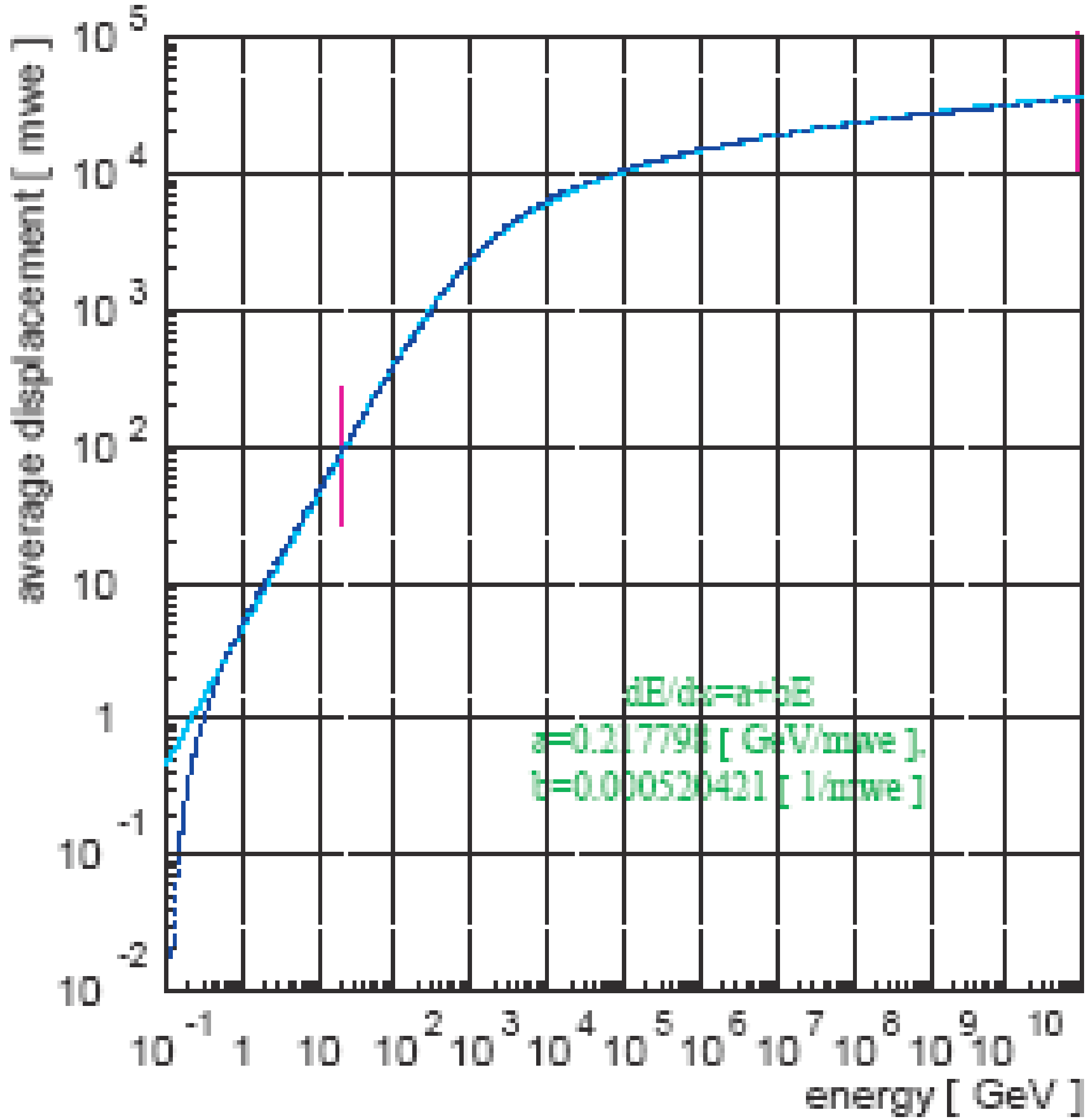

νN total, CTEQ4−DIS
νN CC
νN NC
σ(νN) [cm²]
E_ν [GeV]
ν̄ N total, CTEQ4−DIS
ν̄ N CC
ν̄ N NC
σ(ν̄N) [cm²]
E_ν [GeV]


σ_cc(CTEQ4HJ)/σ_cc(CTEQ4D)
E_ν [GeV]

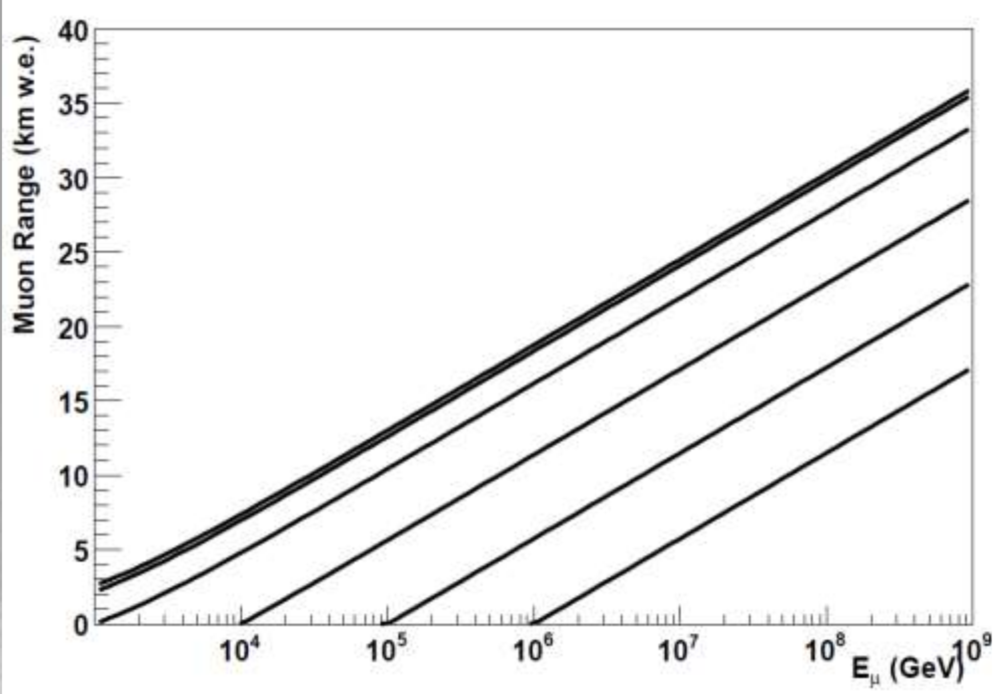


dE/dx (GeV/cm)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
total
ion
p
b
pn
1
2
3
4
5
6
7
$\log_{10}[E_\mu$ (GeV)]

muon range

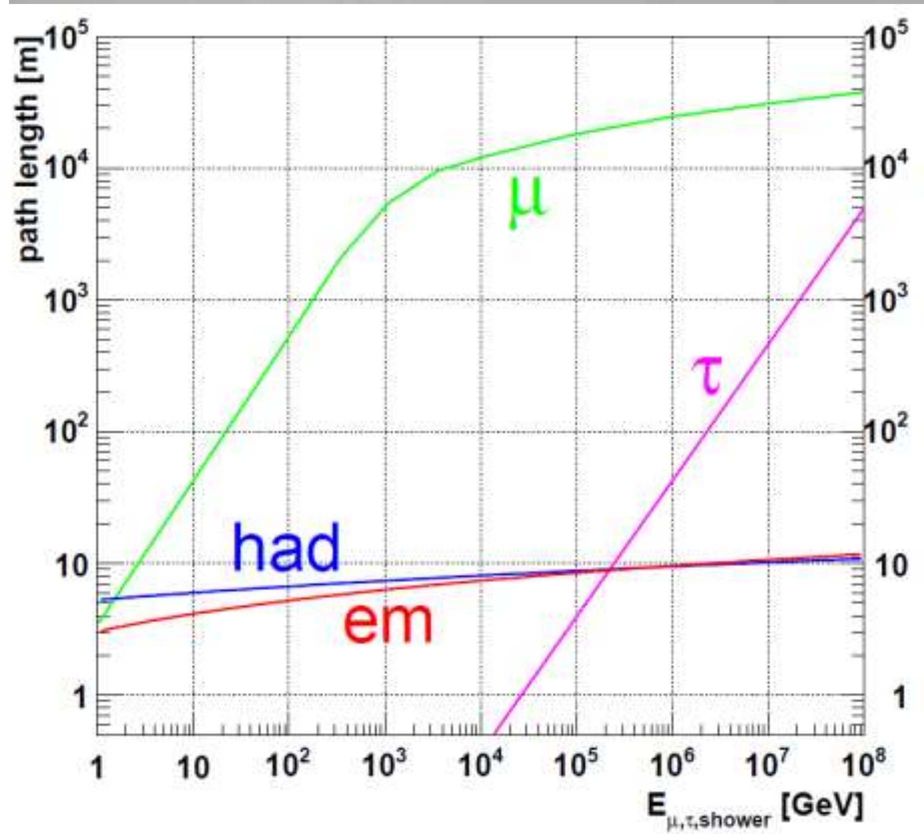


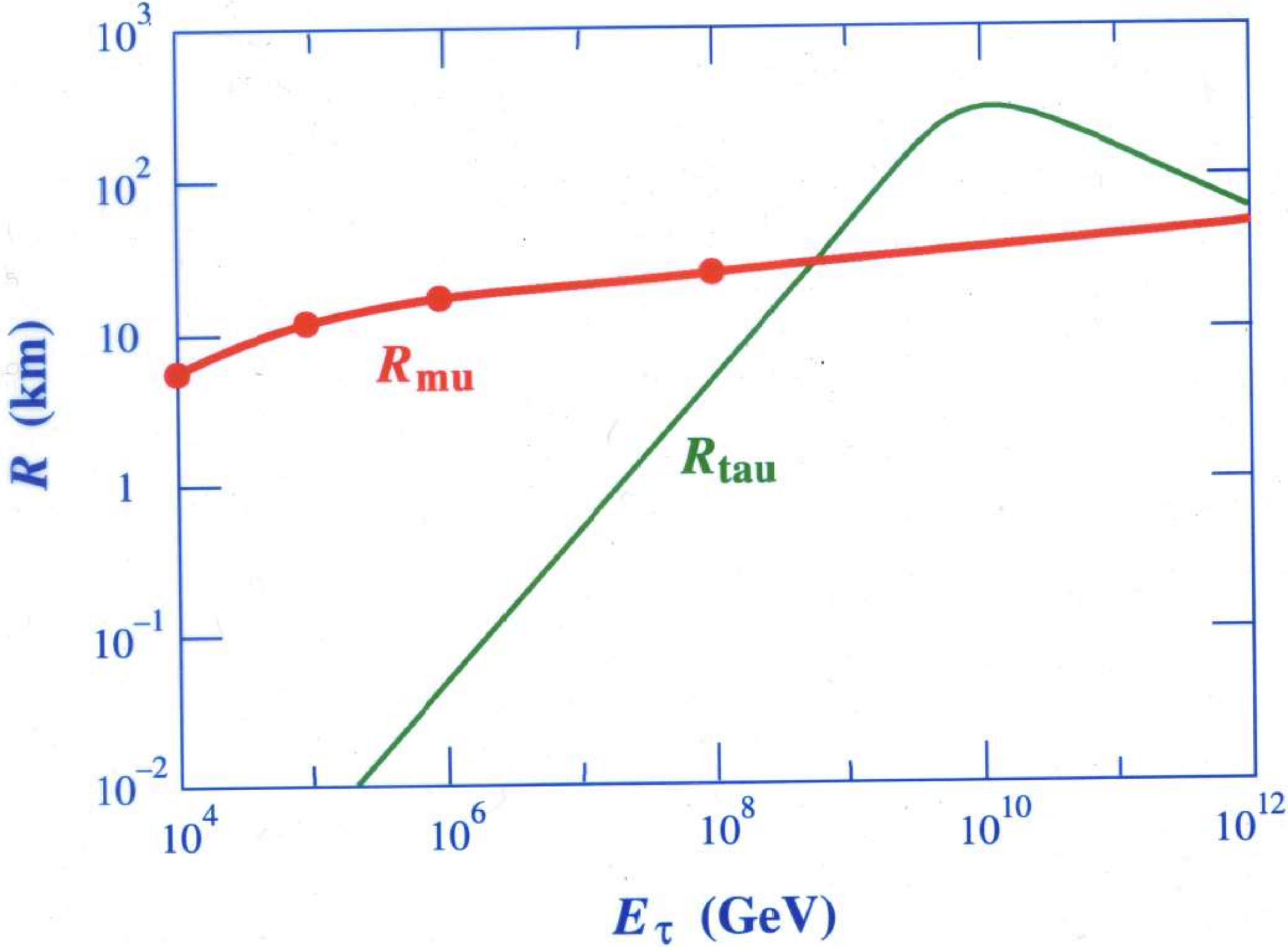
average displacement [mwe]
energy [GeV]
dE/dx=a+bE
a=0.217798 [GeV/mwe],
b=0.000520421 [1/mwe]



← muon range versus energy
for
detector threshold 1-10^6 GeV

pathlength versus energy →





10^3
10^2
10
1
10^{-1}
10^{-2}
R (km)
R_{mu}
R_{tau}
10^4
10^6
10^8
10^{10}
10^{12}
E_τ (GeV)

neutrino and muon area

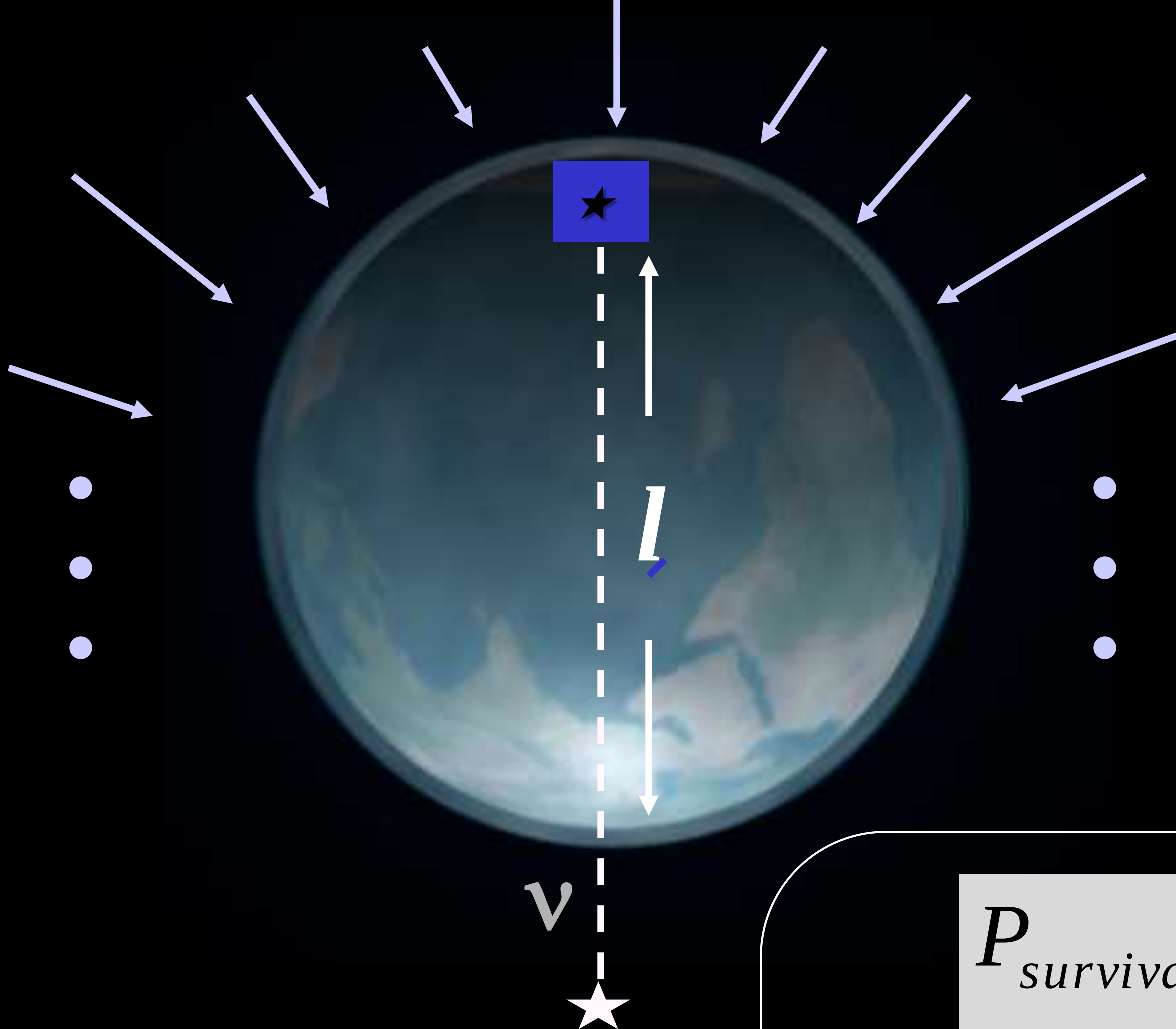
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_\nu = P_{\nu\to\mu}\, A_\mu$$

the earth as
a cosmic ray
muon filter



a neutrino of 70 TeV
has an interaction length
equal to the diameter of
the earth

$$P_{survival} = \exp - \left(l / \lambda_\nu \right)$$

$$\lambda_\nu^{-1} = n \sigma_\nu \left(E_\nu \right)$$

$$n = \rho \, N_A$$

neutrino and muon area

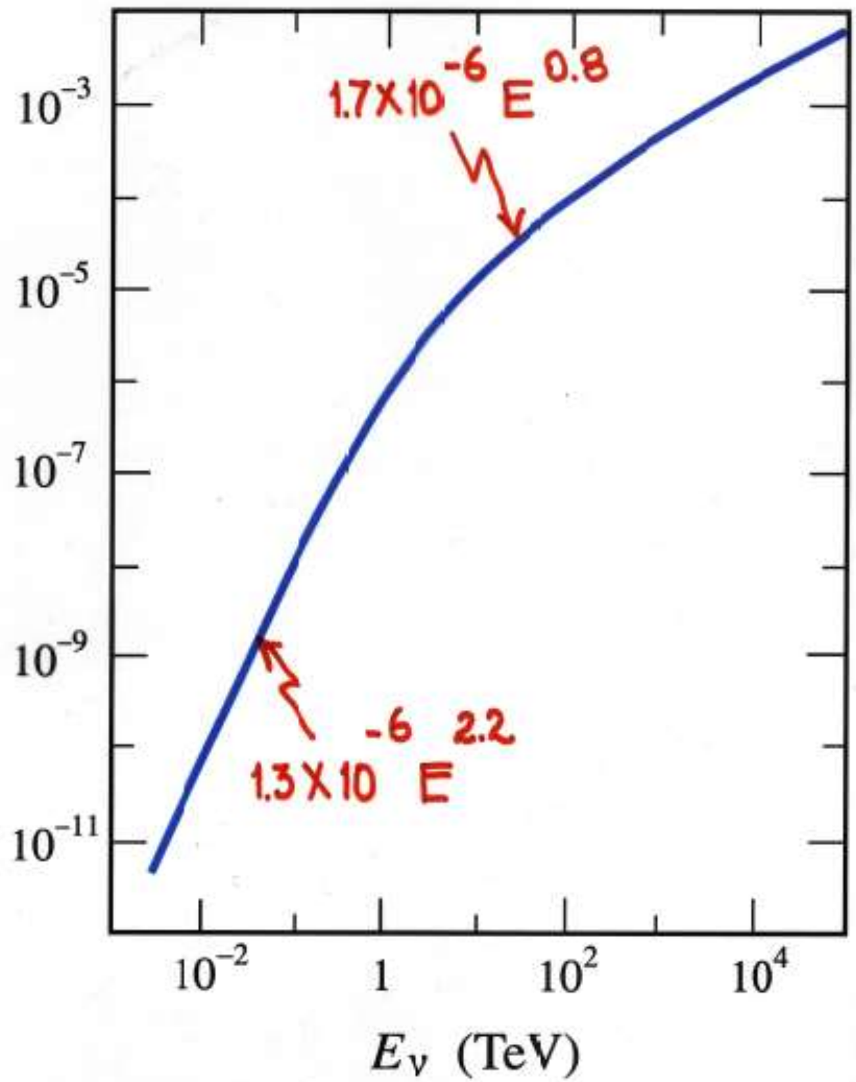
$$events = A_\nu \times \Phi_\nu$$

$$= A_\mu \times P_{\nu\to\mu} \times \Phi_\nu$$

$$P_{\nu\to\mu} = \lambda_\mu / \lambda_\nu = R_\mu n \sigma_\nu \cong 10^{-6} E_{TeV}$$

$$A_n \to A_n = P_{n\to m} P_{survival} \, A_m$$

- $P_{\nu \to \mu} = \text{density} \cdot \sigma_\nu(E) \cdot R_\mu(E)$



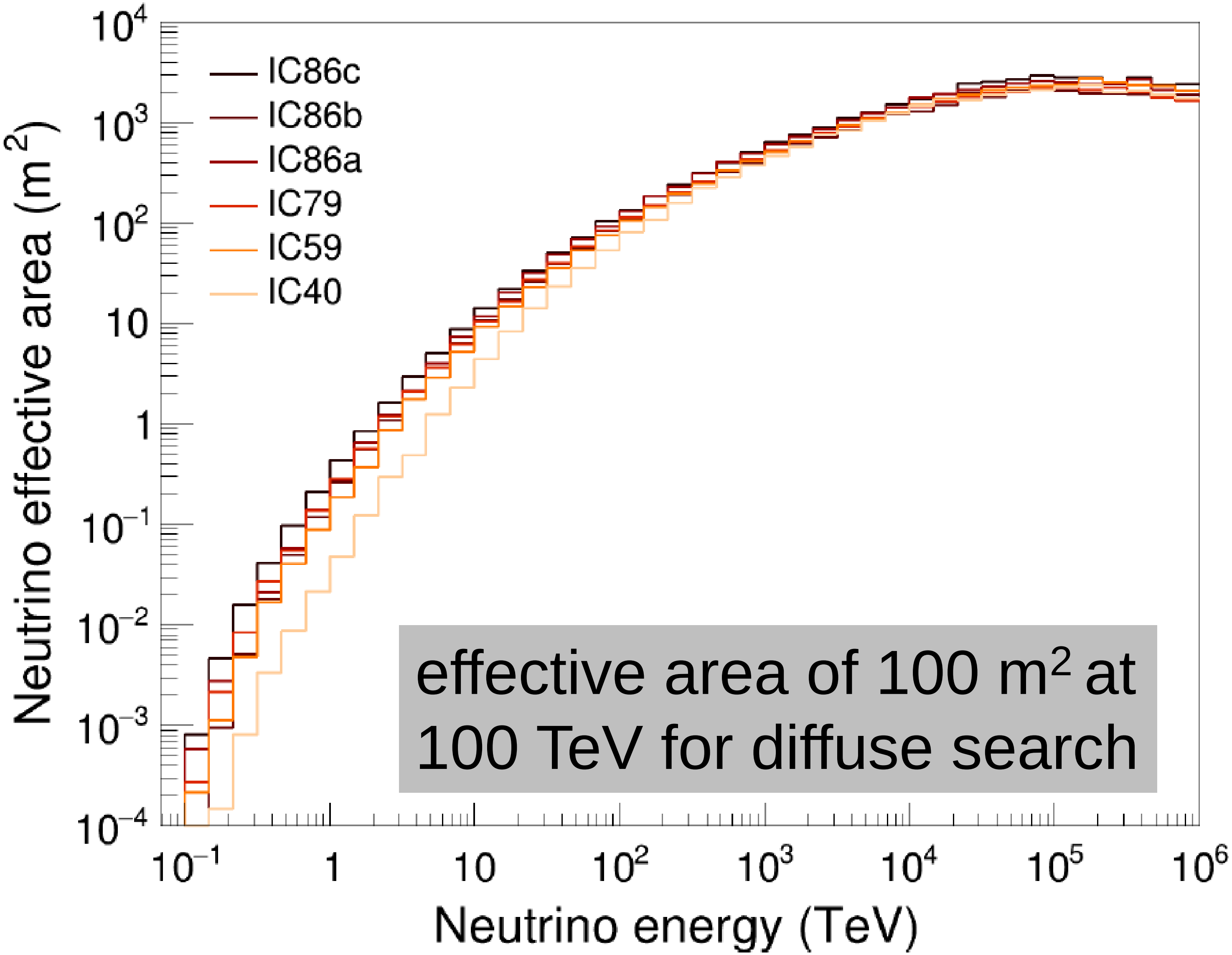
- $N_{events} = \text{AREA} \int \frac{dN_\mu}{dE} P_{\nu \to \mu} \, dE$

effective telescope area at 100 TeV

$$area \times P_{\mu\to\nu} (= \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu \sigma_\nu \cong 10^{-6}\ E_{TeV})$$

- AMANDA ~ ANTARES ~ 1 m^2
- IceCube 22 strings 30 m^2
- IceCube 80 strings 100 m^2

effective area of the time-dependent point source search (in the direction of the TXS source)



effective area of 100 m^2 at 100 TeV for diffuse search

generic theoretical framework

Generic Framework: Hadronic pion production *pp->π^0/±*

rate per energy per time

$$q_{\pi^\pm} = \frac{dN_\pi}{dE_\pi dt} = \int dE_p \int_0^\tau d\tau' \frac{dN_p}{dE_p} e^{-\tau'} \frac{dN_\pi}{dE_\pi}(E_\pi)$$

$$= (1 - exp(-\tau)) \int dE_p \frac{dN_p}{dE_p} n_\pi \delta(E_\pi - < E_\pi >)$$

$$= nl\sigma n_\pi \frac{1}{f_\pi} \frac{dN_p}{dE_p} (\frac{E_\pi}{f_\pi})$$

In most astrophysical situations the optical depth is small $1 - exp(-\tau) \to \tau$

energy fraction $f_\pi = \frac{< E_\pi >}{E_p}$

$$q_{\nu_i}(E_{\nu_i}) = q_\pi(4E_{\nu_i}) dE_\pi / dE_{\nu_i} = 4q_\pi(4E_{\nu_i})$$

Assume the total energy of pions is distributed equally among 4 decay leptons

$$q_{\nu_i}(E_{\nu_i}) = 4nl\sigma n_\pi \frac{1}{f_\pi} \frac{dN_p}{dE_p} (\frac{4E_{\nu_i}}{f_\pi})$$

Diffuse flux for nearby sources at Earth

$$\Phi = \frac{1}{4\pi}\int d^3r\rho(r)\frac{q_\nu(E_\nu)}{4\pi r^2}$$

Point source flux

ρ is the source population density

Integrating over the Universe

$$dr \rightarrow cdt \rightarrow cdz(dt/dz) = cdz\frac{1}{H(z)}$$

$$\Phi = \frac{c}{4\pi}\int \frac{dz}{H(z)}\rho(z)q_\nu((1+z)E_\nu)$$

Number of Neutrinos from a source at zenith angle θ_z at the detector

$$N = t\int_{E_\nu^{th}} dE_\nu \frac{dN_\nu(E_\nu)}{dE_\nu} \times A_\nu^{eff}(E_\nu, \theta_z)$$

Correlate Gamma-ray Flux to Neutrino Flux

Relation between gamma-ray and Neutrino flux

$$E_\gamma J_\gamma(E_\gamma) \simeq e^{-\frac{d}{\lambda_{\gamma\gamma}}} \frac{2}{K} \frac{1}{3} \sum_{\nu_\alpha} E_\nu J_{\nu_\alpha}(E_\nu)$$

$$E_\gamma \simeq 2E_\nu$$

- K is the ratio of charged to neutral pions
- J is the differential flux
- d is the distance to the source
- $\lambda_{\gamma\gamma}$ is the interaction length accounting for the absorption of TeV-PeV gamma-rays in radiation backgrounds.

$p\gamma$ interaction → $K \simeq 1$

pp interaction → $K \simeq 2$

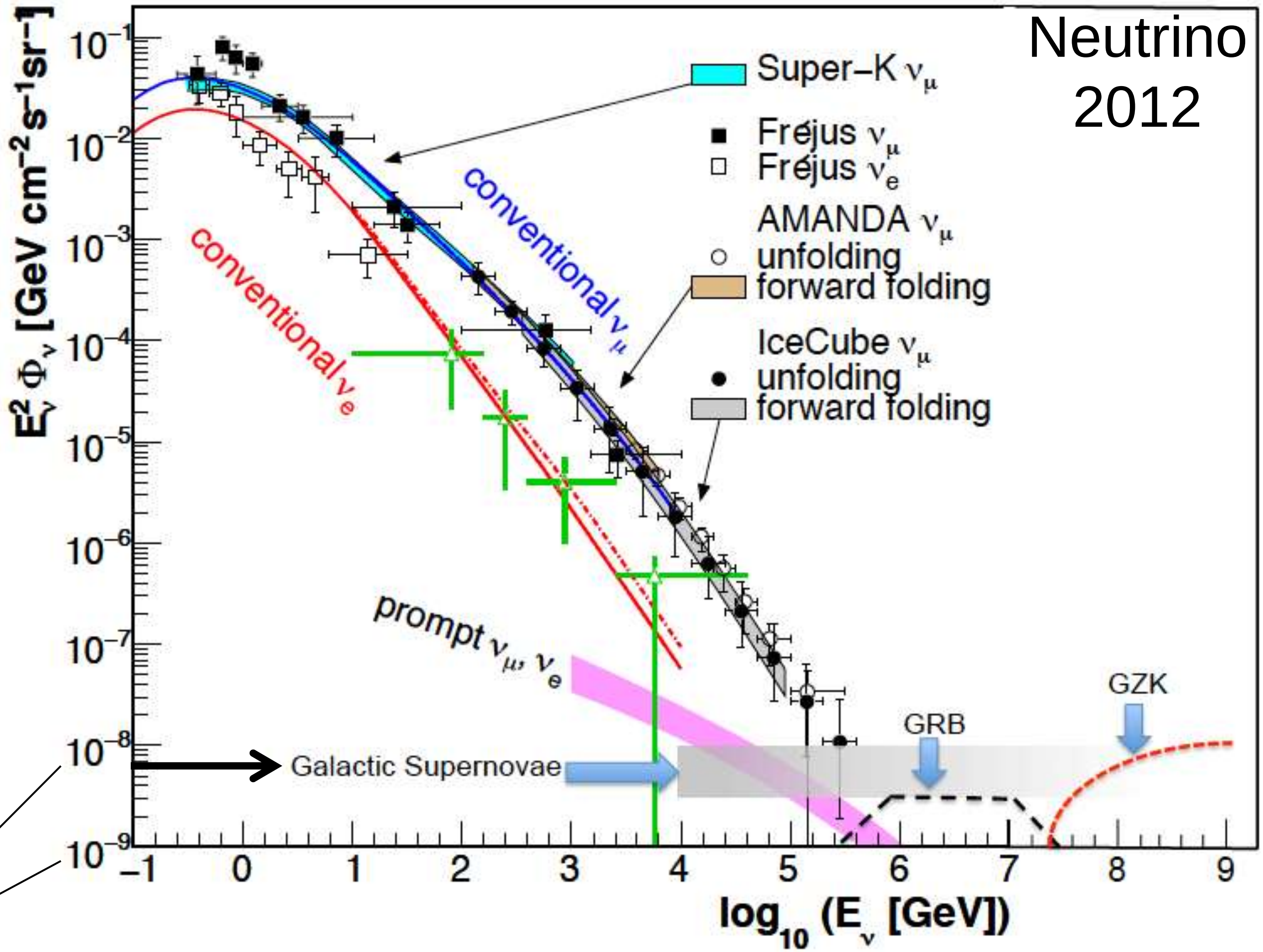
thought to be the main hadronic process for Galactic sources detected by gamma-ray observations.

Sources are optically thin, which is true for many Galactic CR sources. Thus the exponential term can be neglected.

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

$$dN/dE \sim E^{-2}$$



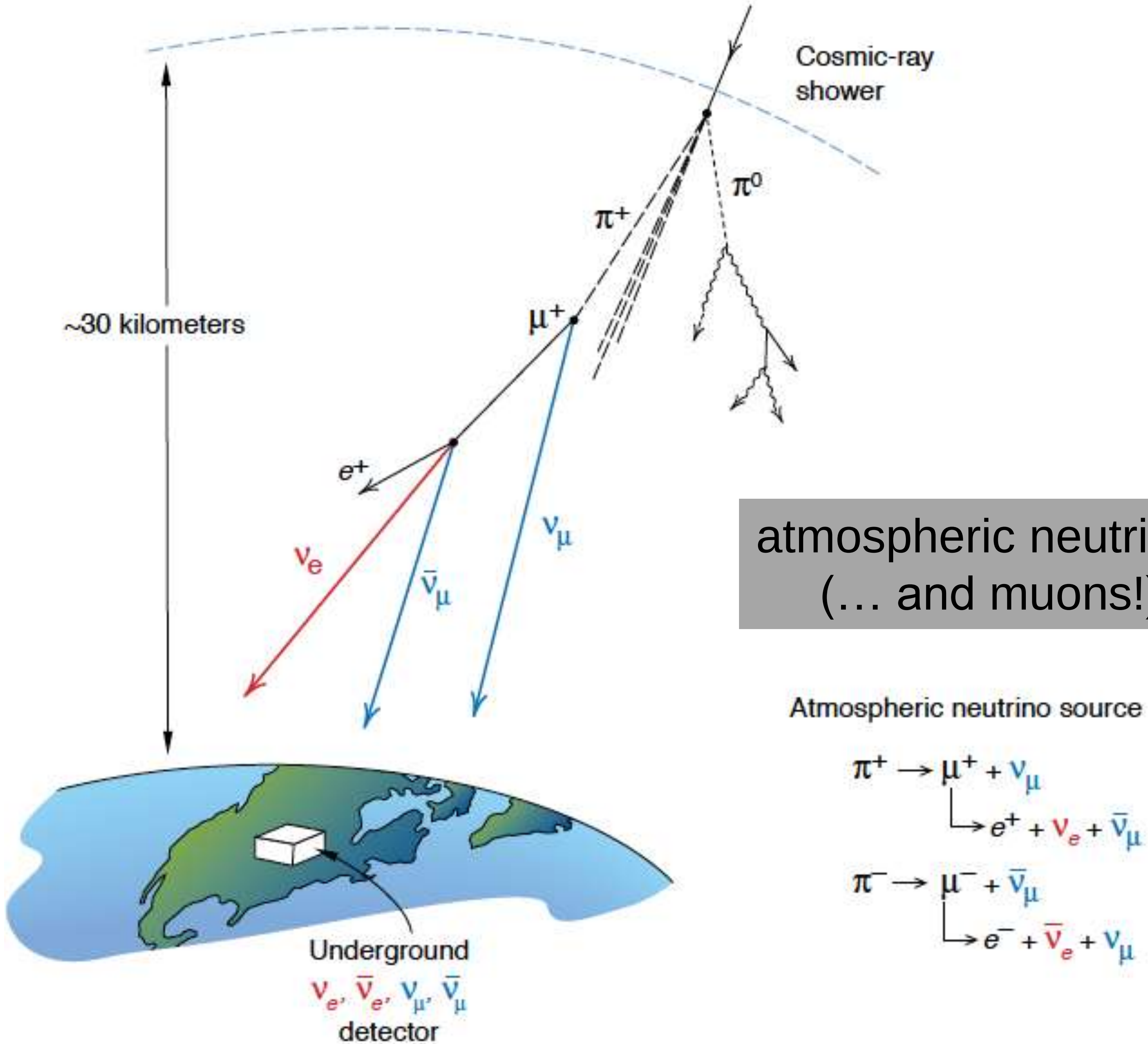
10—100 events per year for fully efficient detector

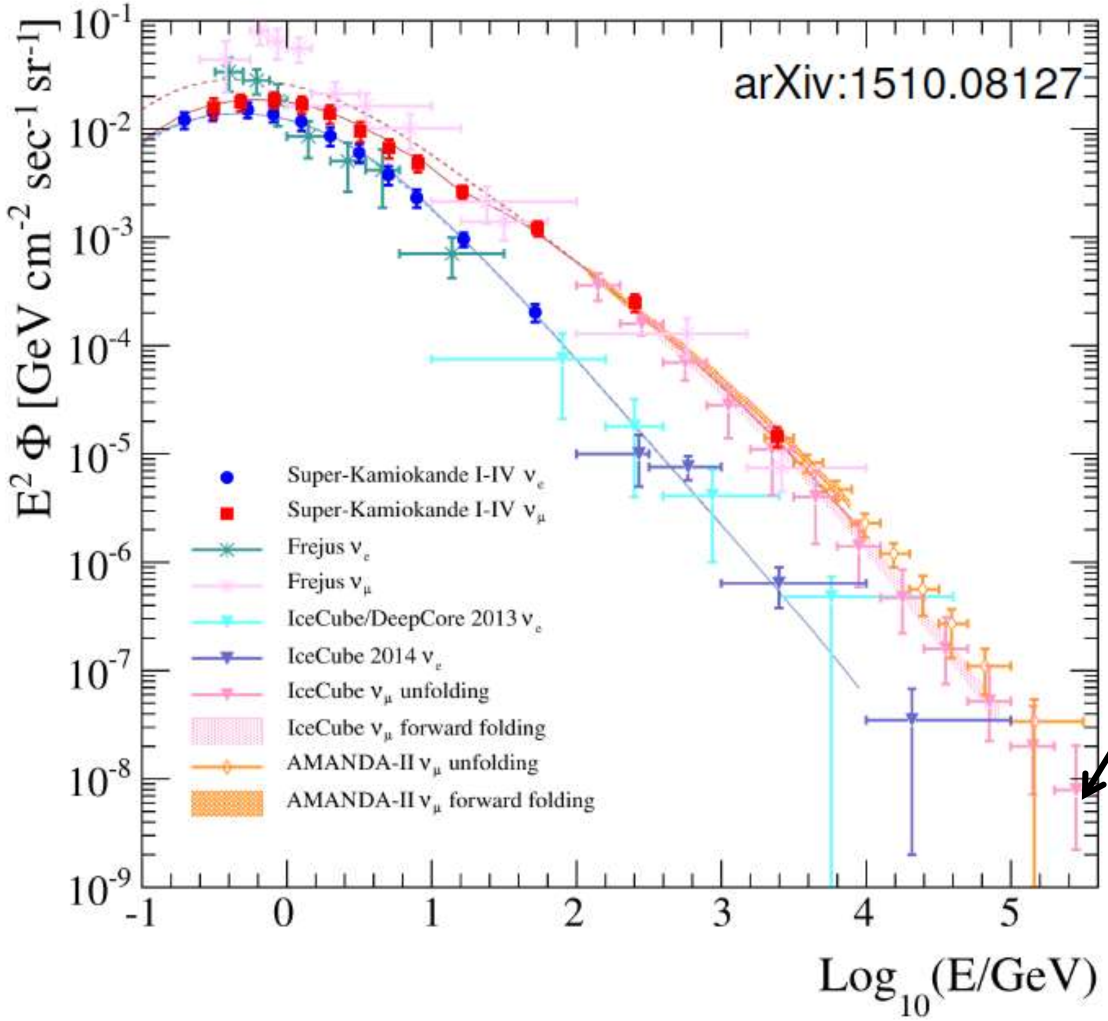
atmospheric

cosmic

100 TeV

atmospheric neutrinos (… and muons!)





< 1 atmospheric neutrino event per cubic kilometer per year

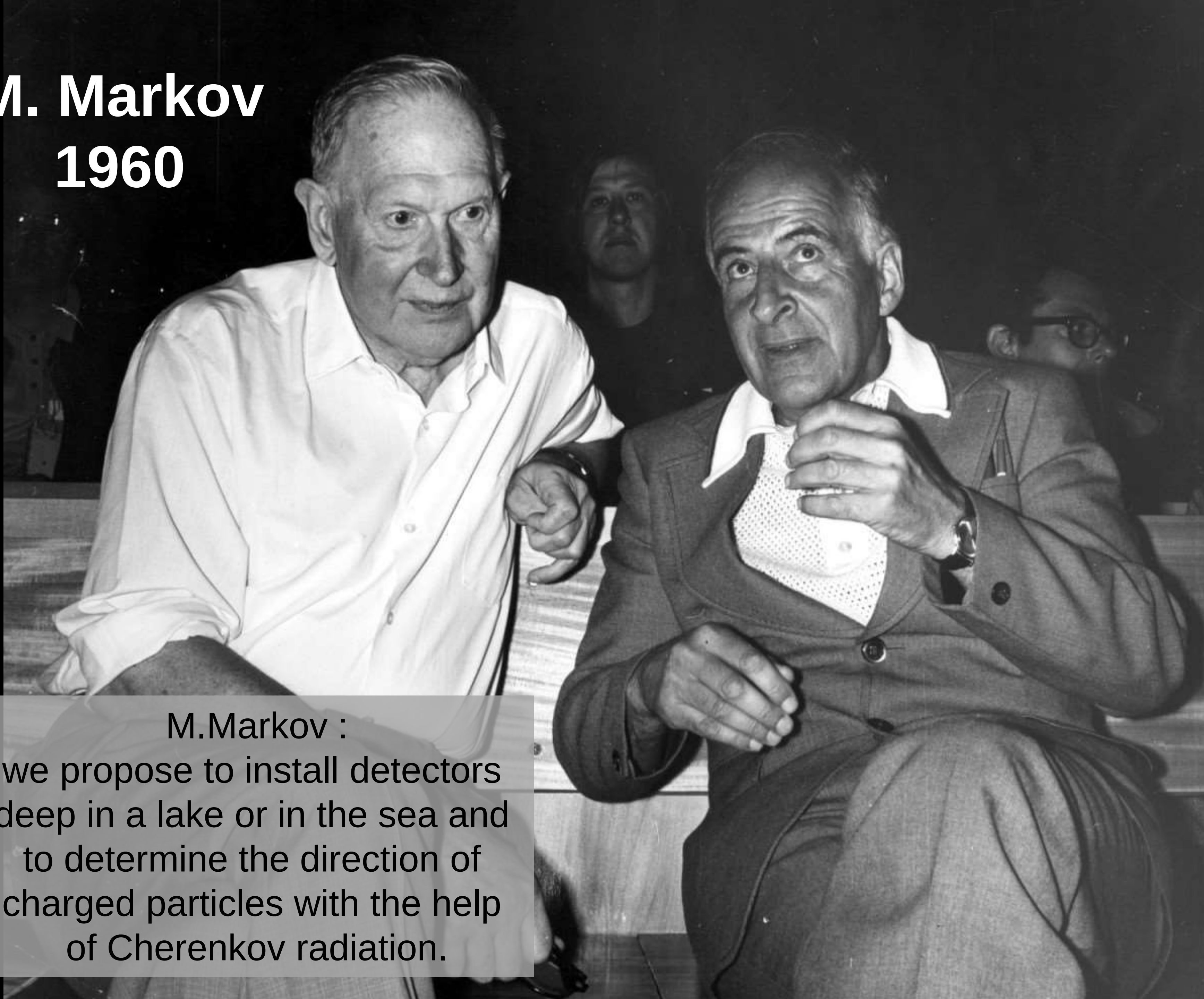
atmospheric neutrino spectrum (energy measurement) well understood

High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

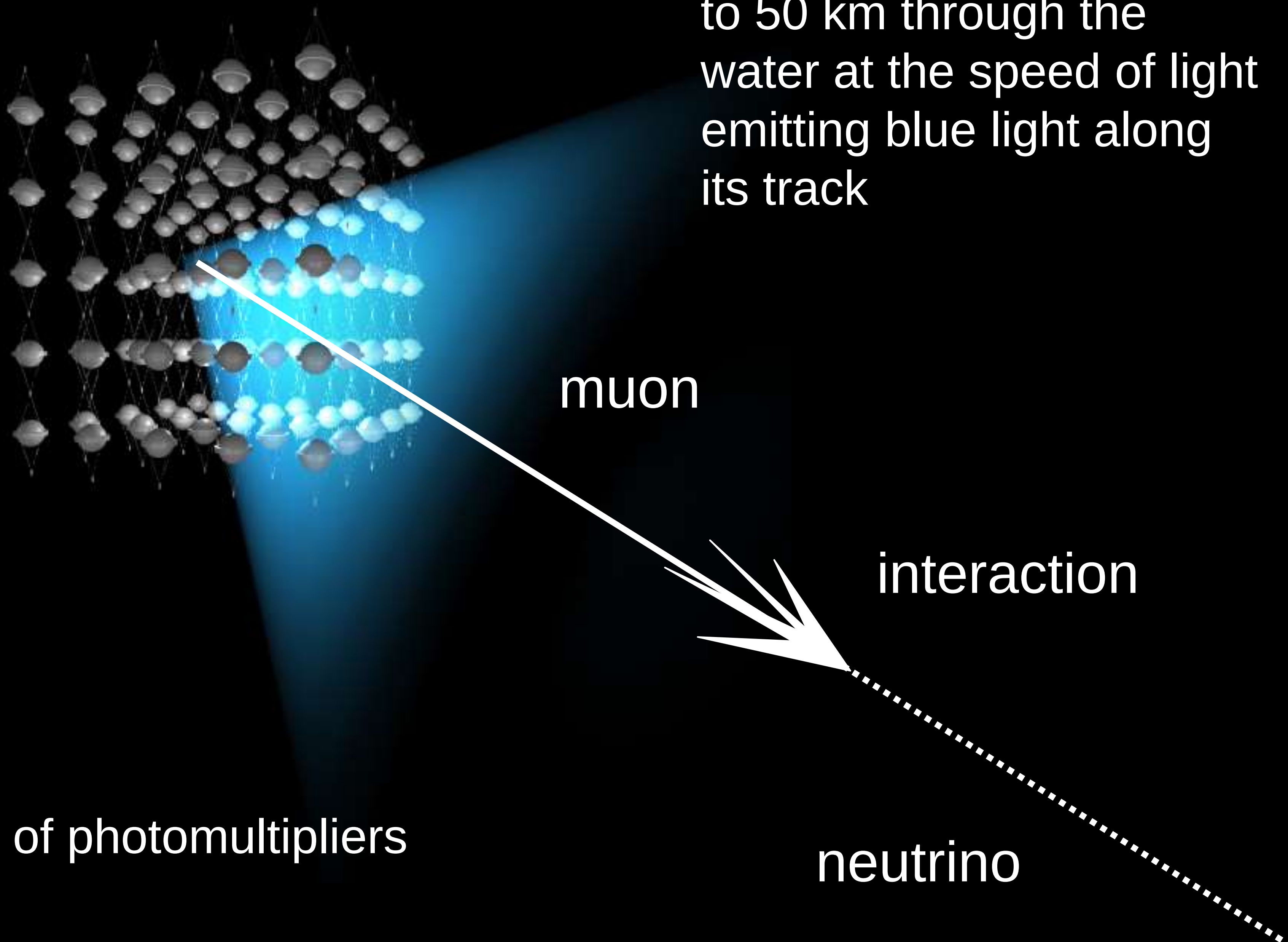
icecube.wisc.edu

M. Markov
1960



M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

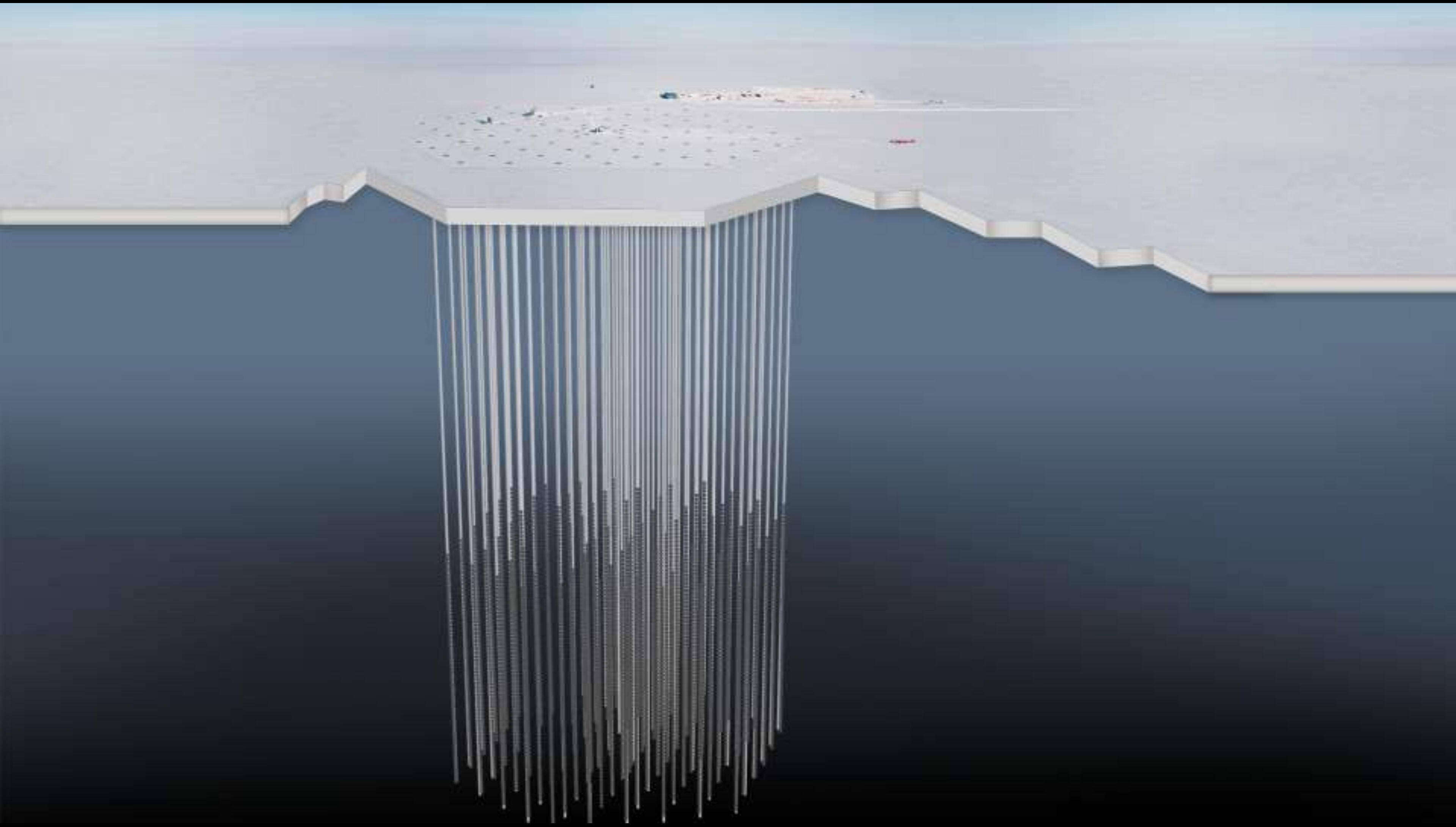
- speed of light in water < c
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



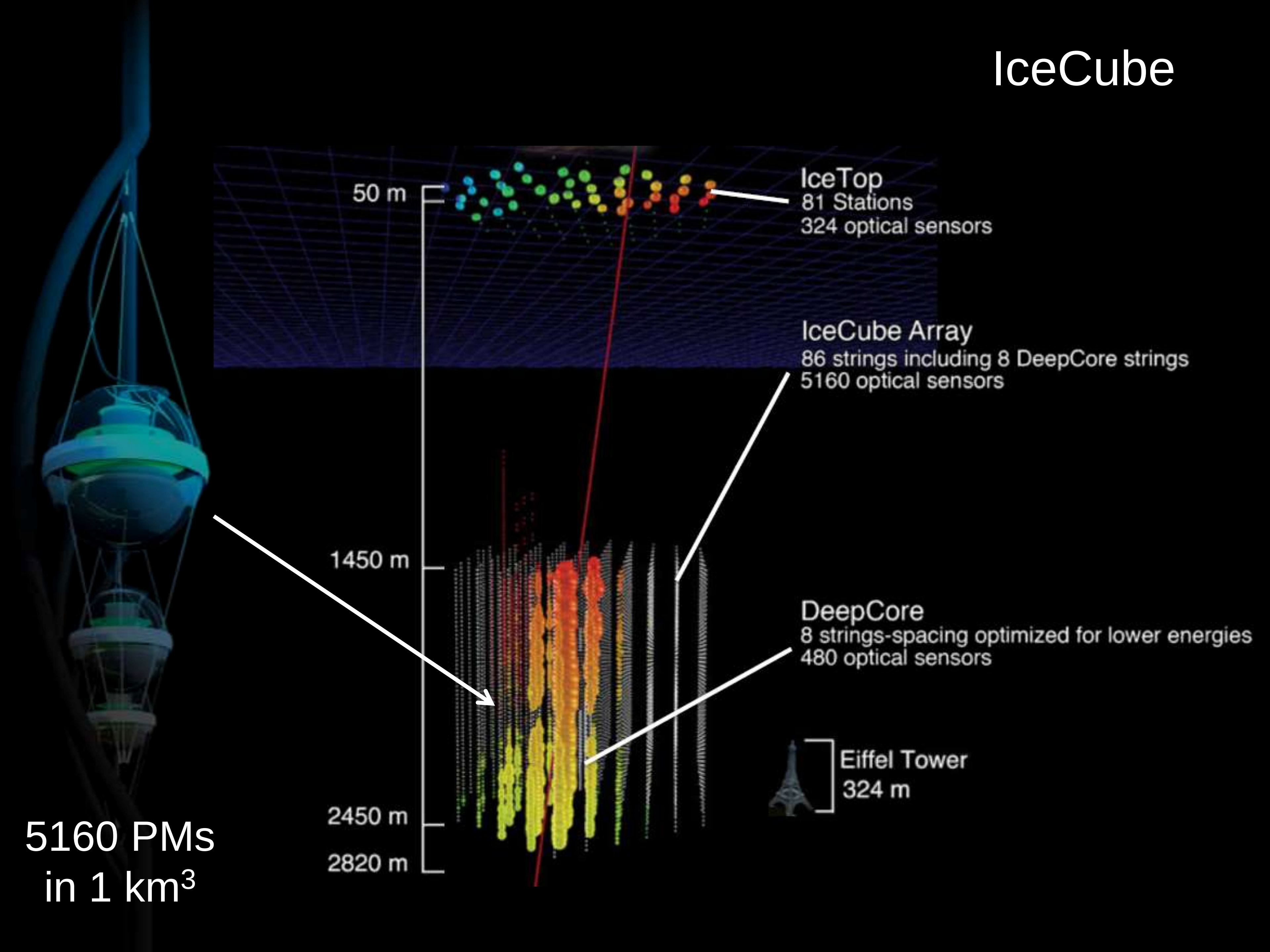
- lattice of photomultipliers


ultra-transparent ice below 1.5 km

instrument 1 cubic kilometer of natural ice below 1.45 km

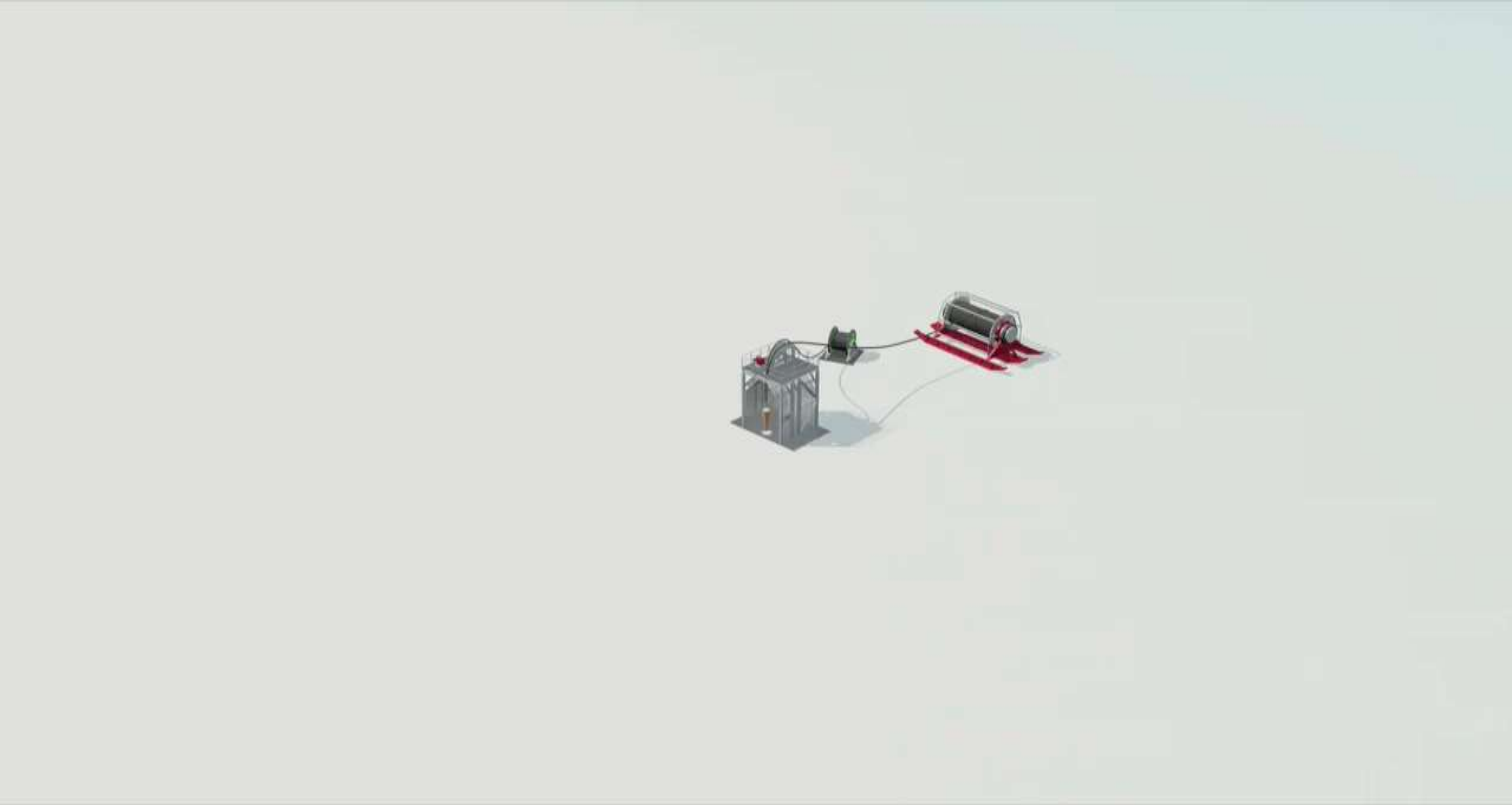


IceCube



5160 PMs
in 1 km^3

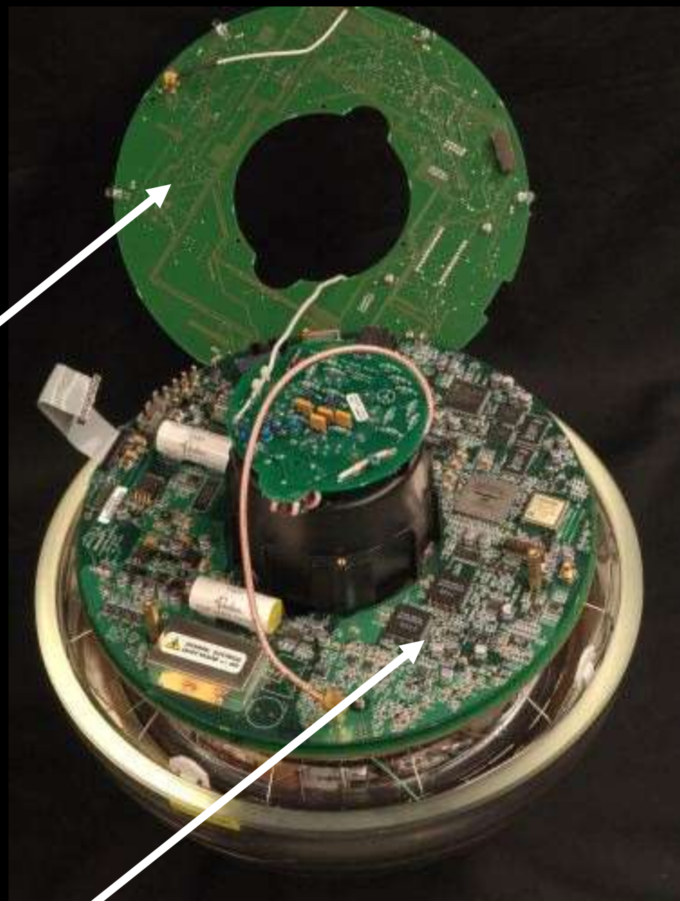
photomultiplier
tube -10 inch

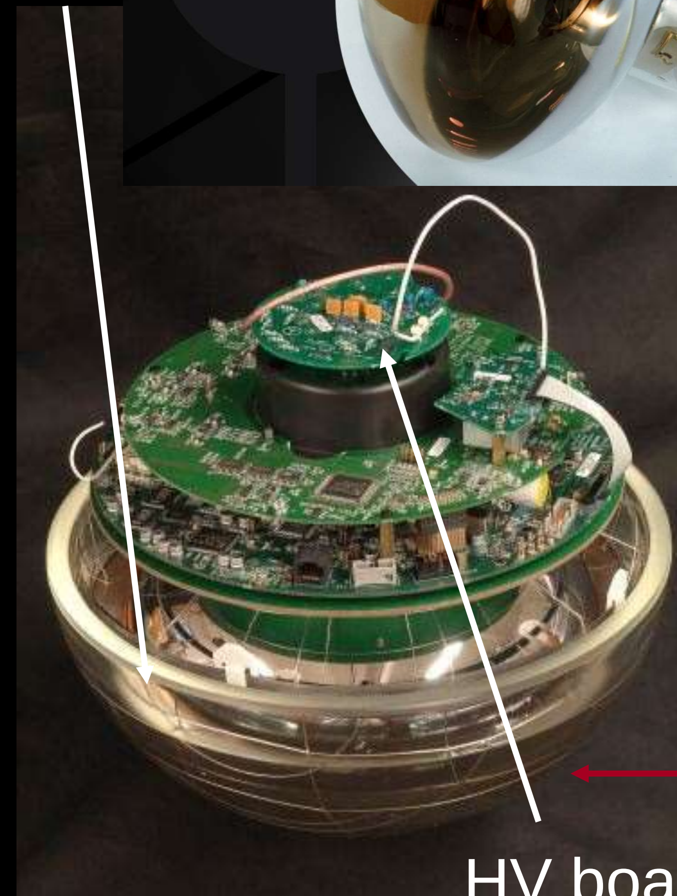


architecture of independent DOMs

10 inch pmt

LED
flasher
board

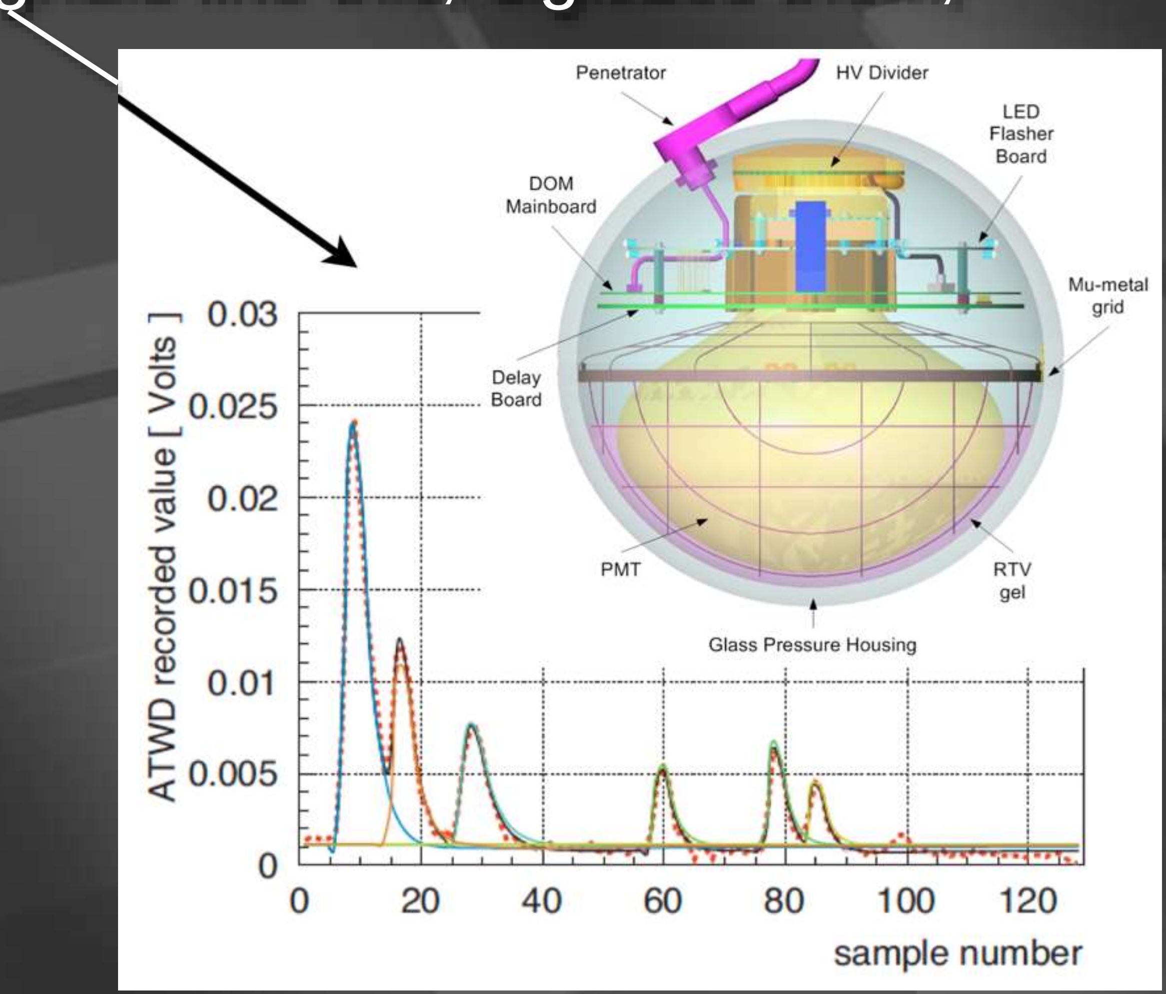




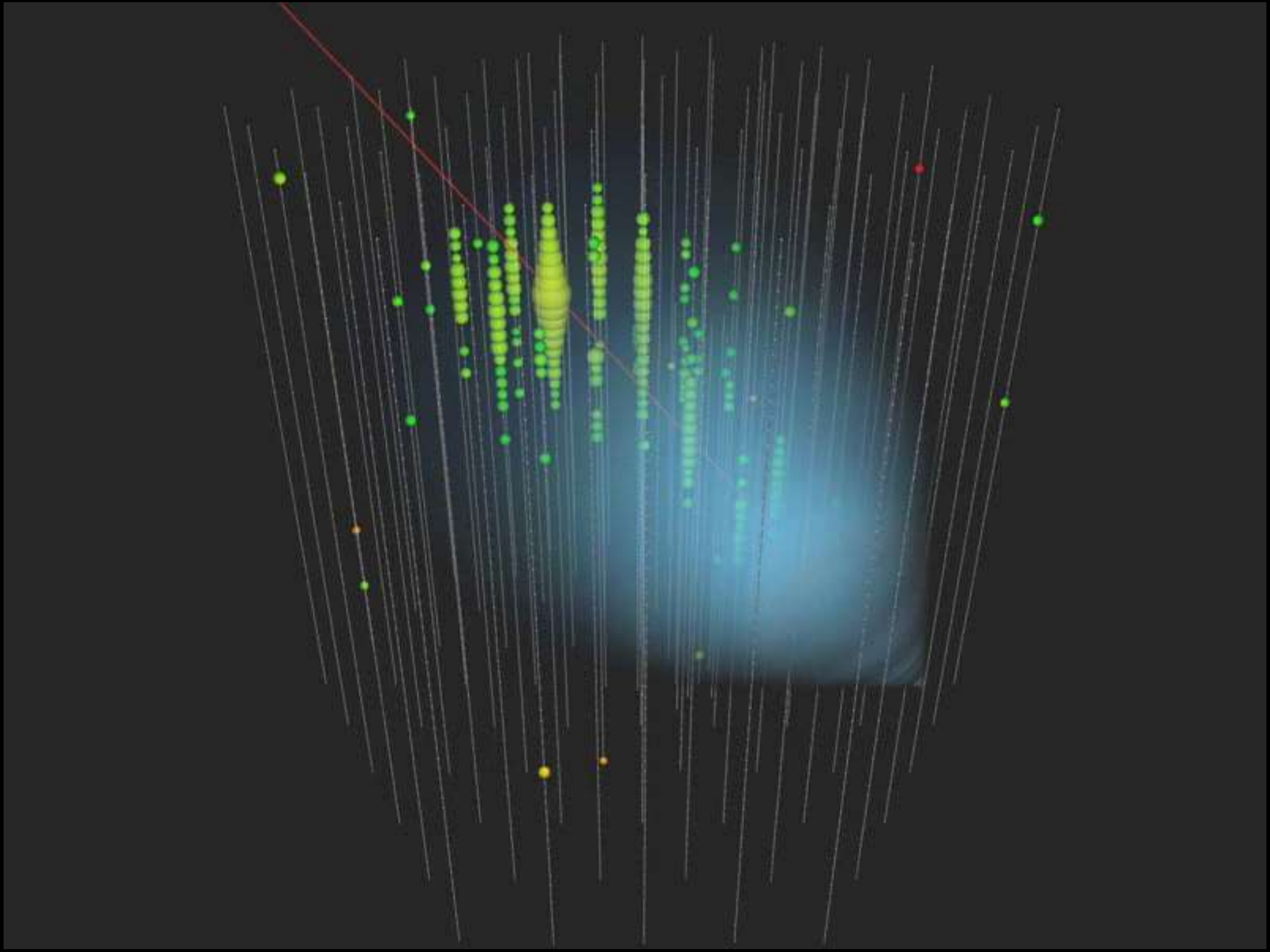
HV board

main
board

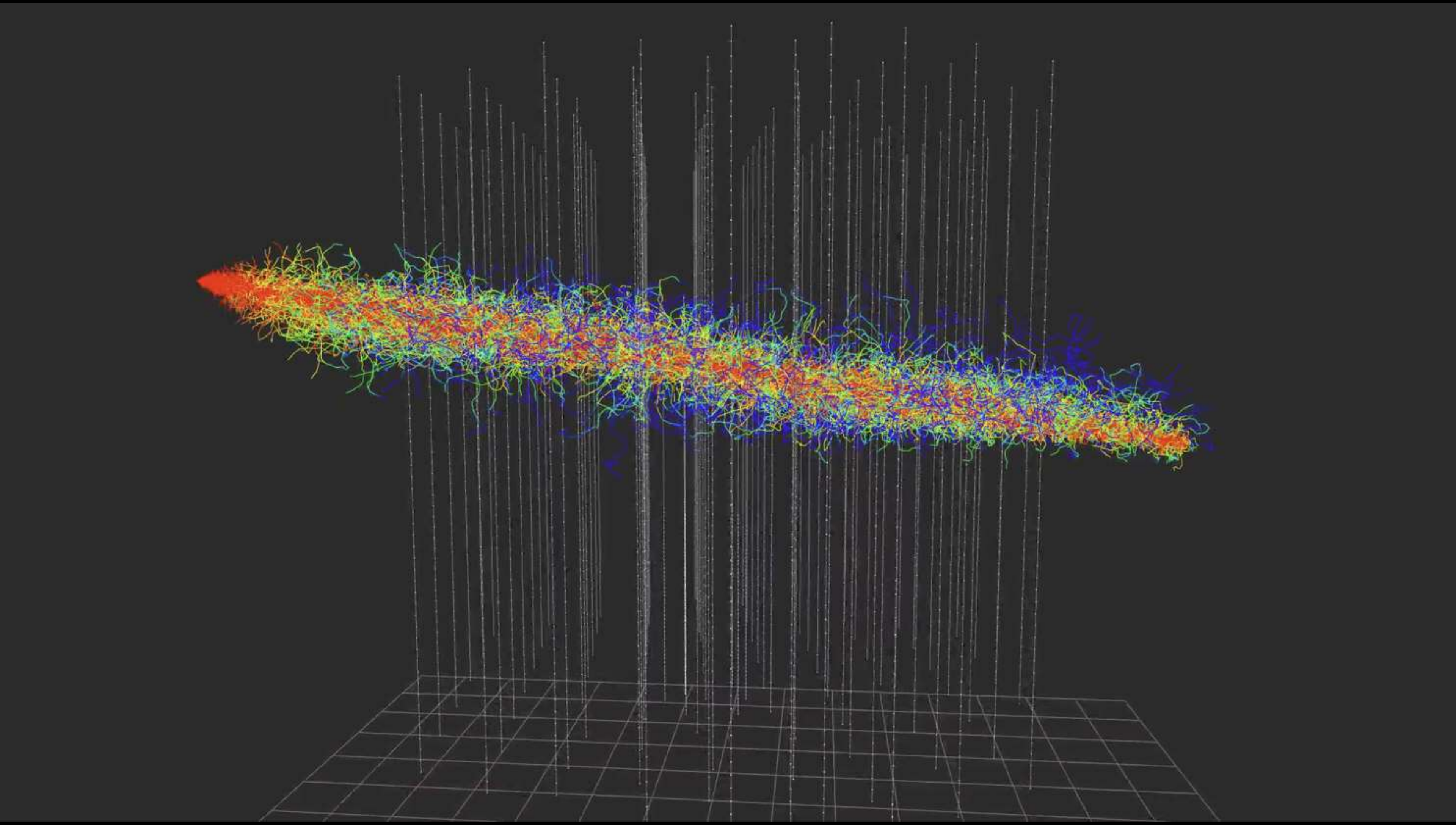
… each Digital Optical Module independently collects light signals like this, digitizes them,

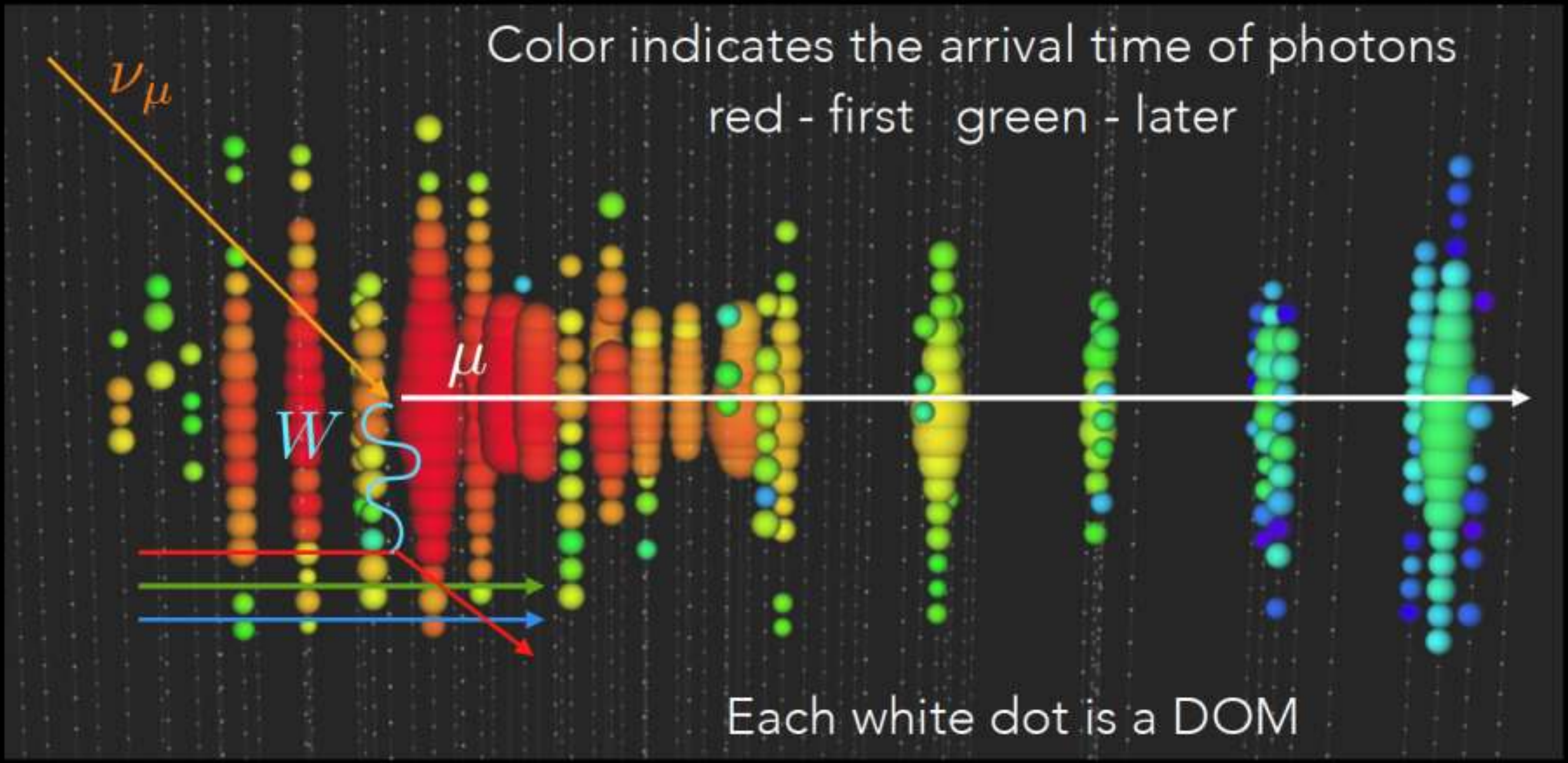


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…



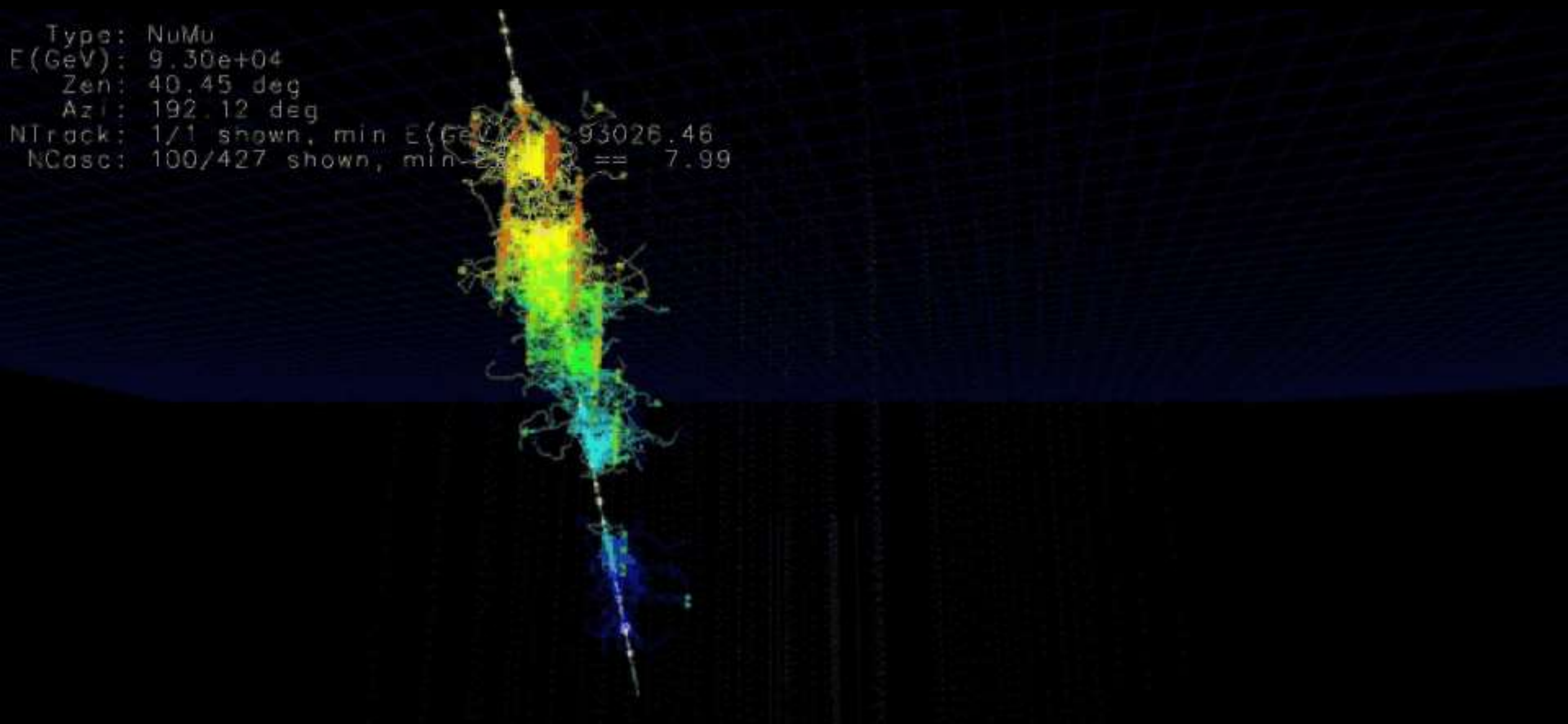
muon track: color is time; number of photons is energy neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



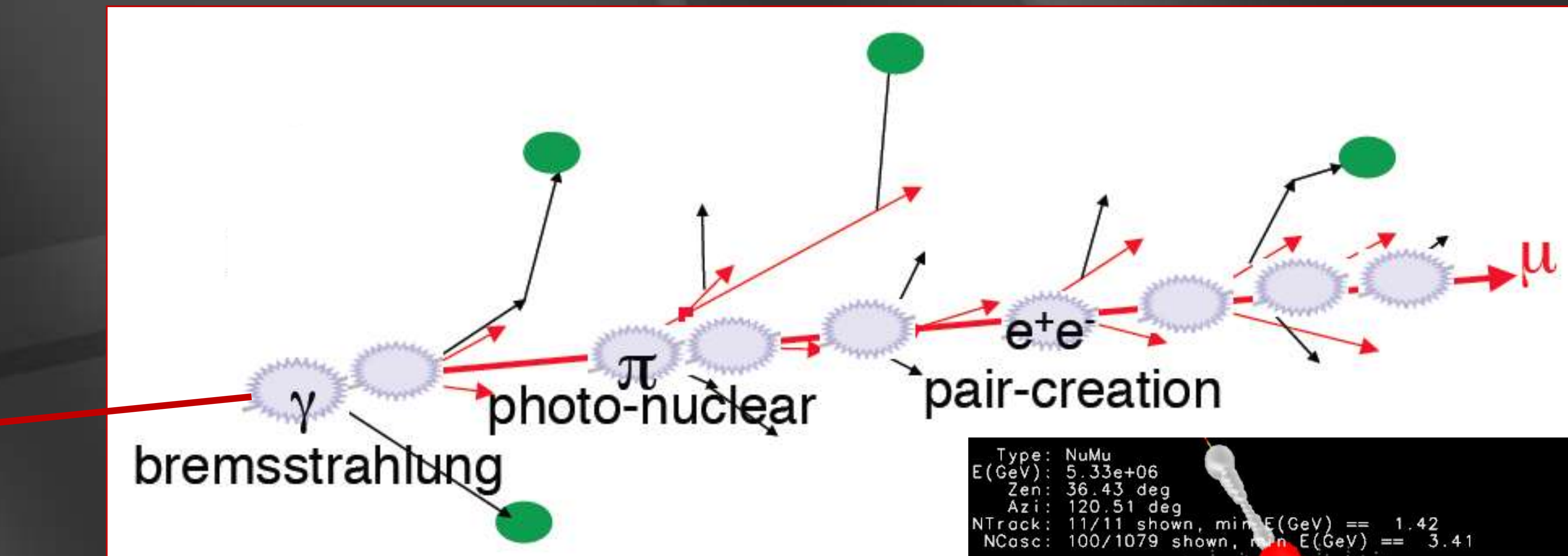


Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

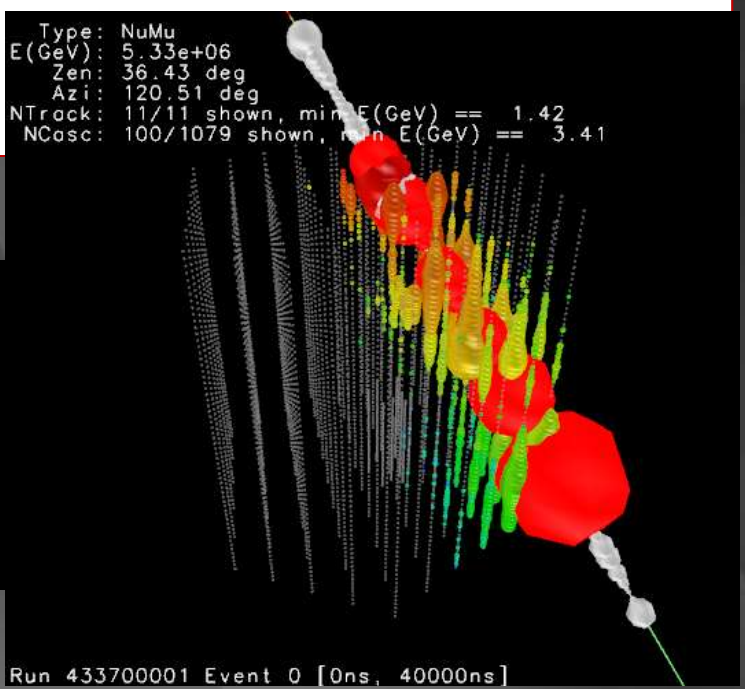
93 TeV muon: light ~ energy

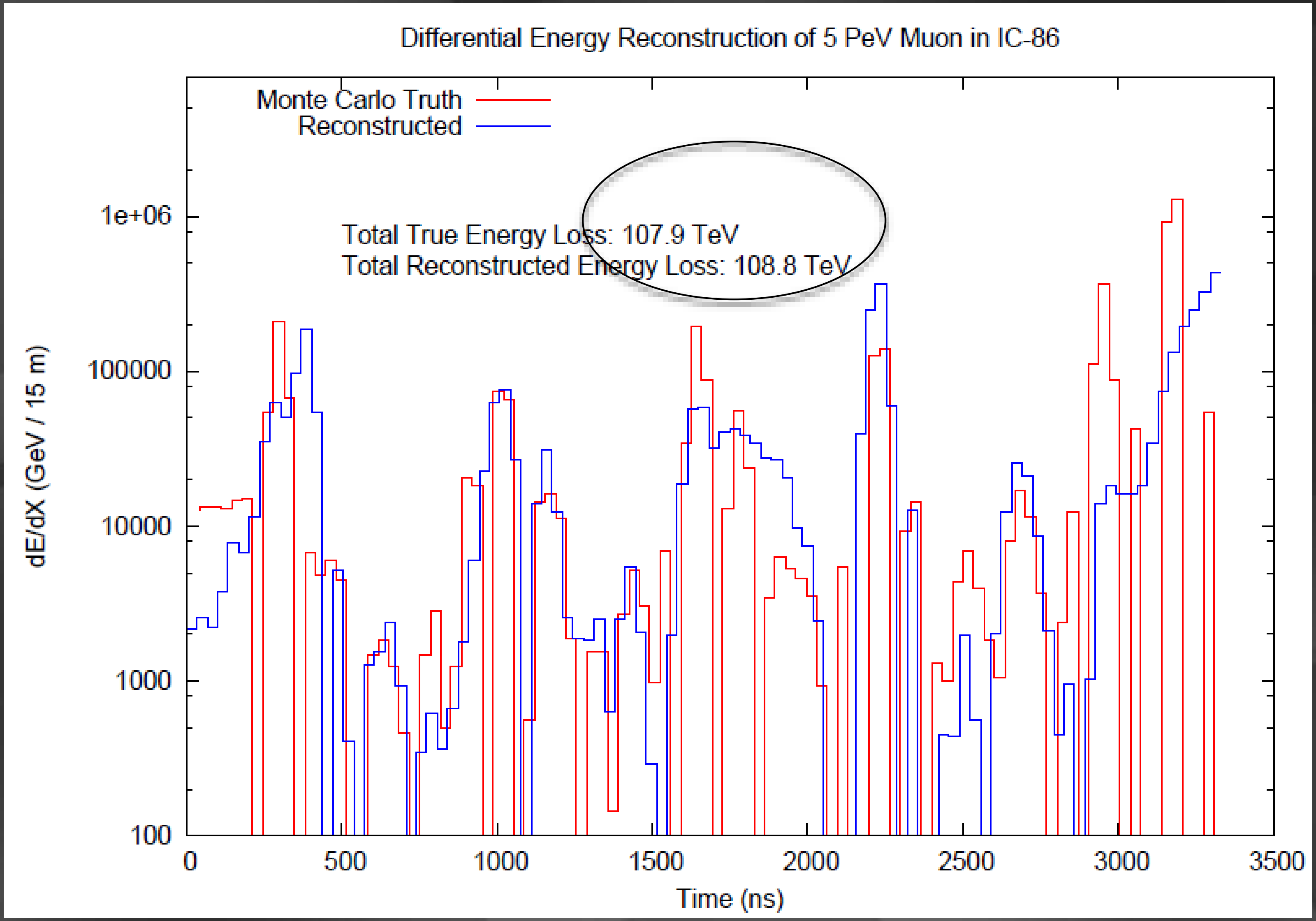


energy measurement (> 1 TeV)



convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

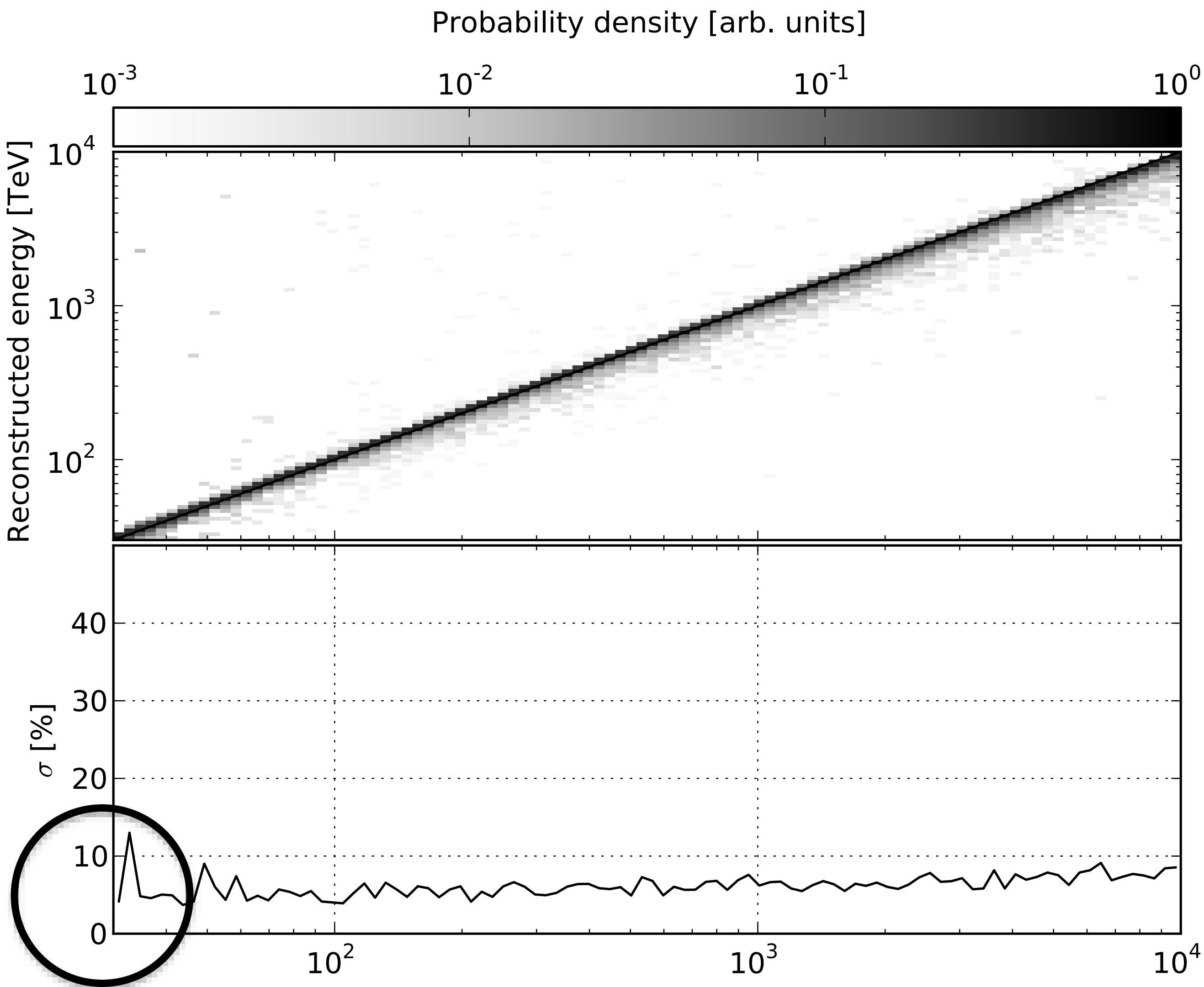


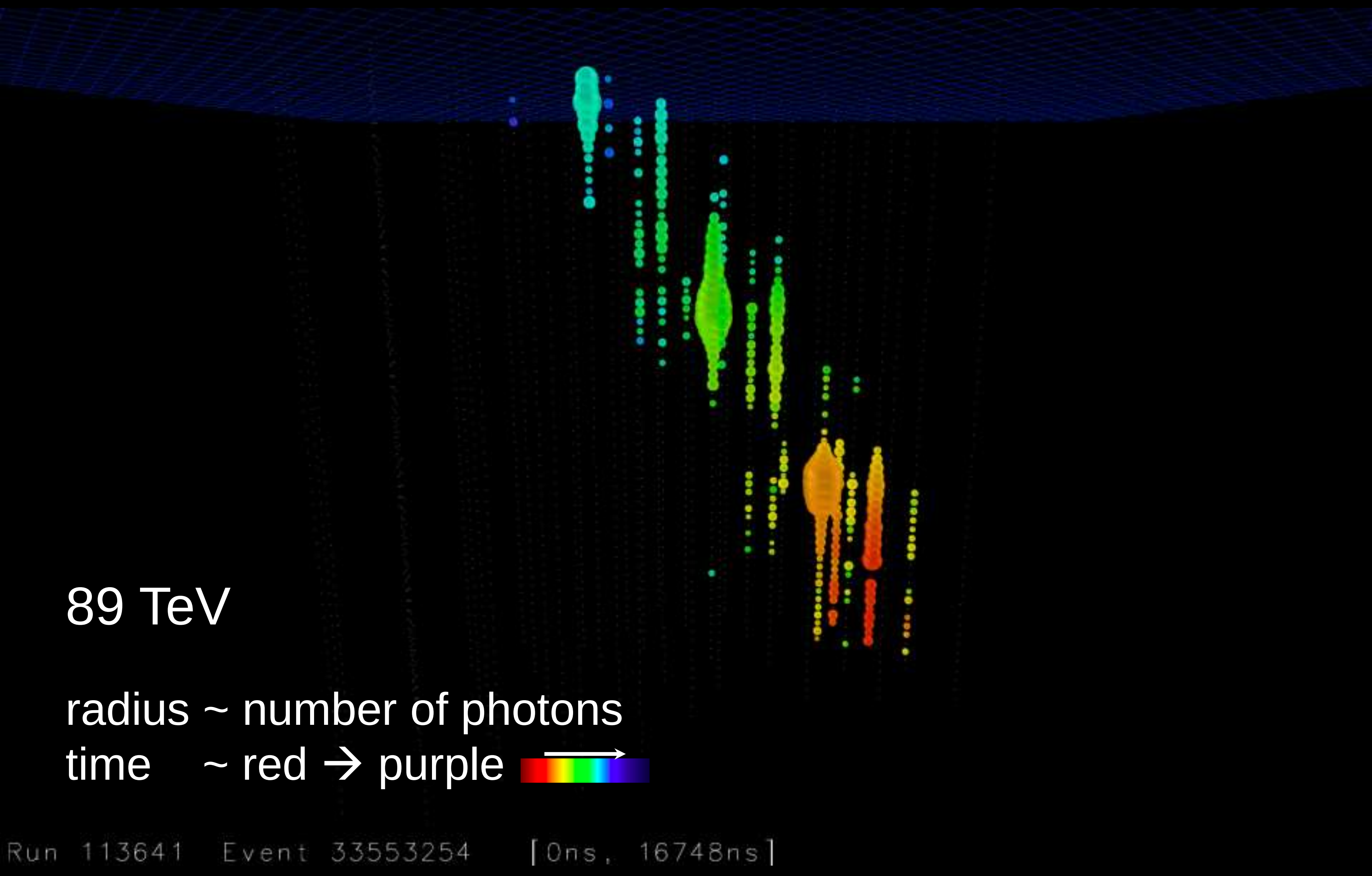


1.1 km

limited angular and energy resolution: computing → ice properties

energy reconstruction of electromagnetic showers

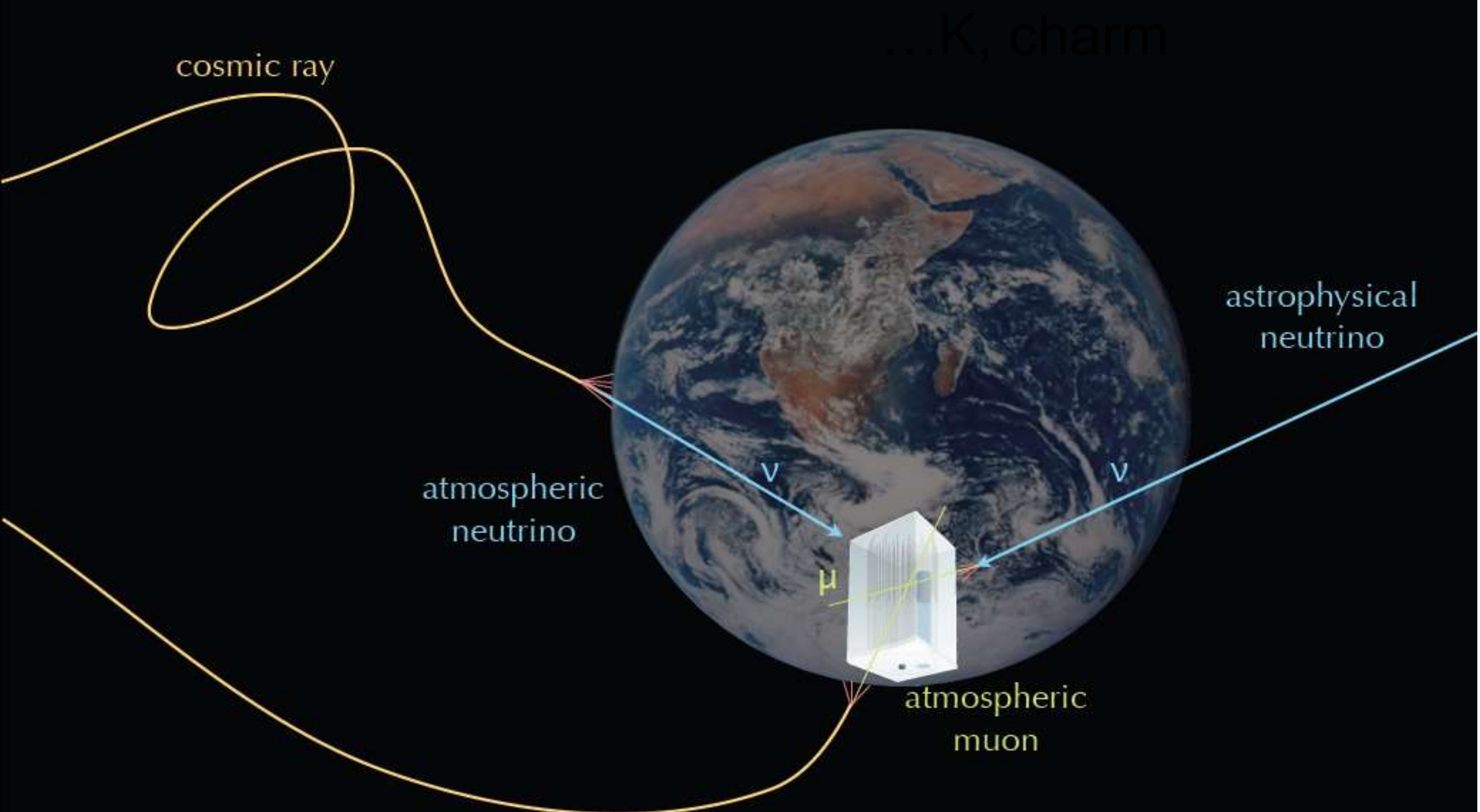


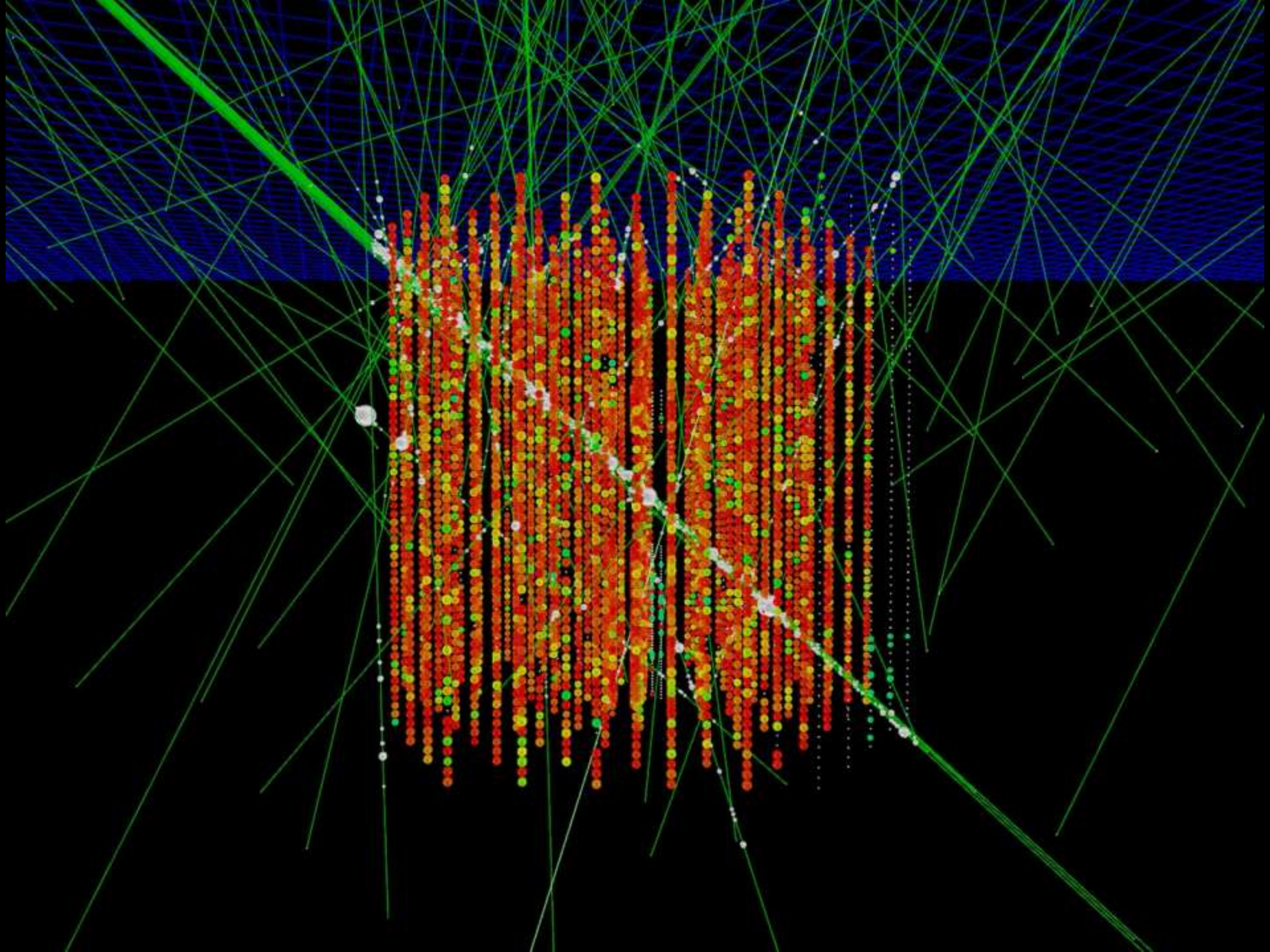


89 TeV

radius ~ number of photons
time ~ red → purple

Signals and Backgrounds





… you looked at 10msec of data !

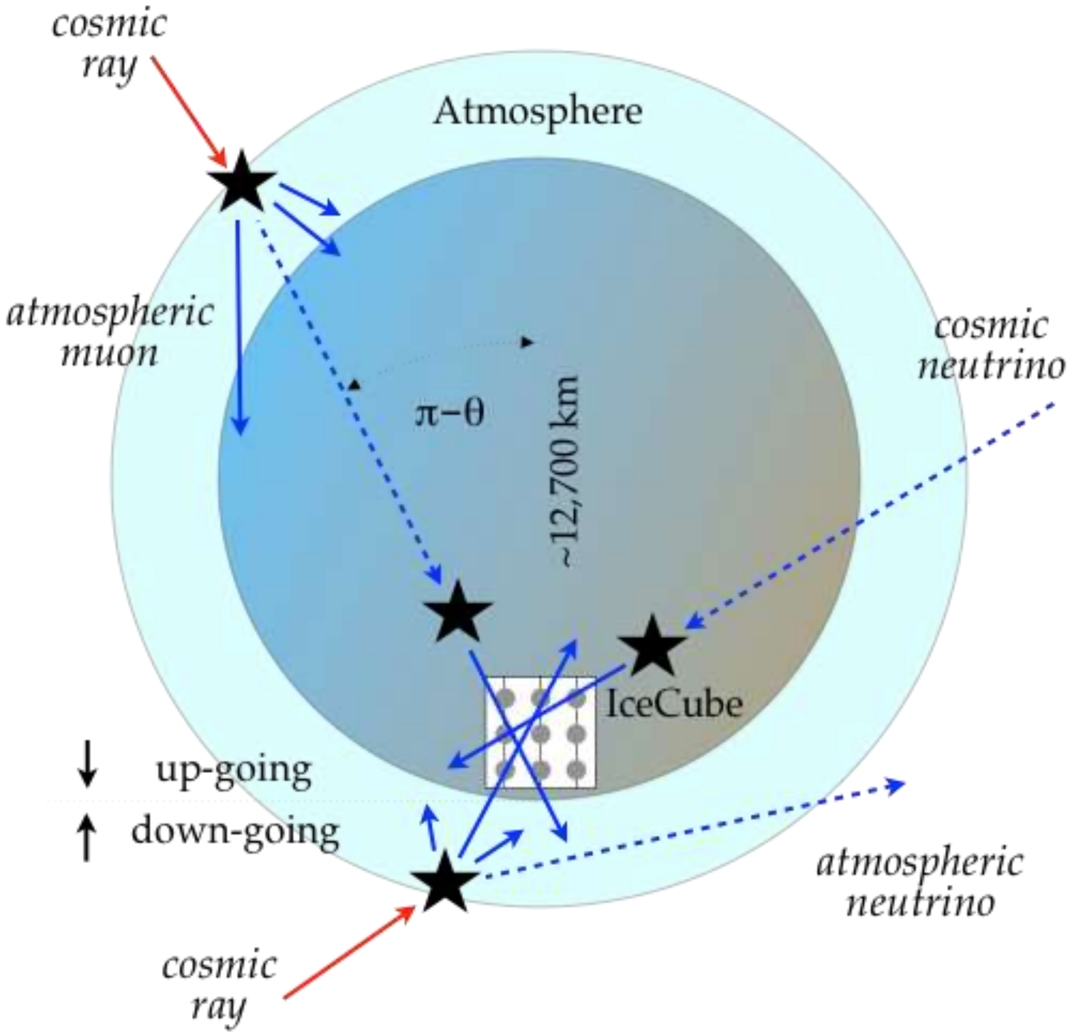
muons detected per year:

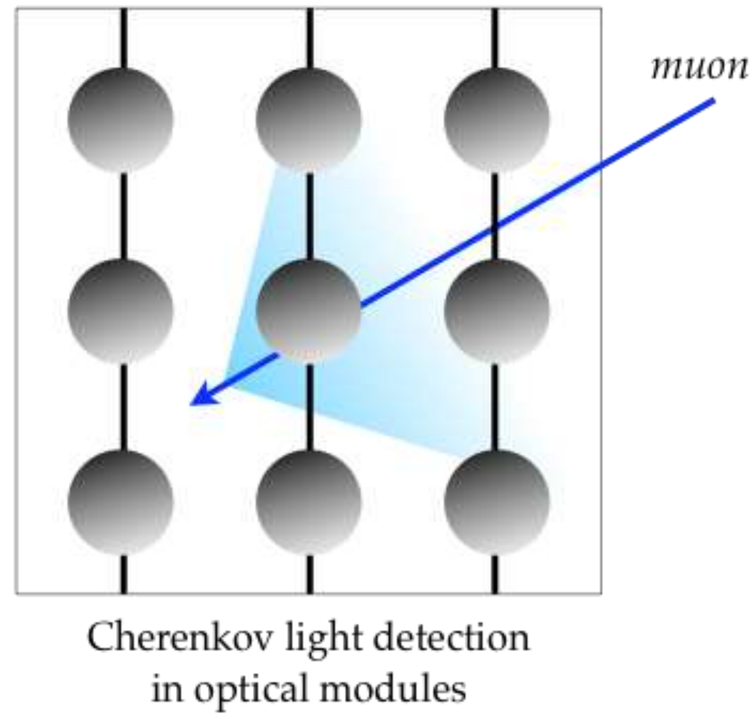
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 10

* 3000 per second

** 1 every 6 minutes

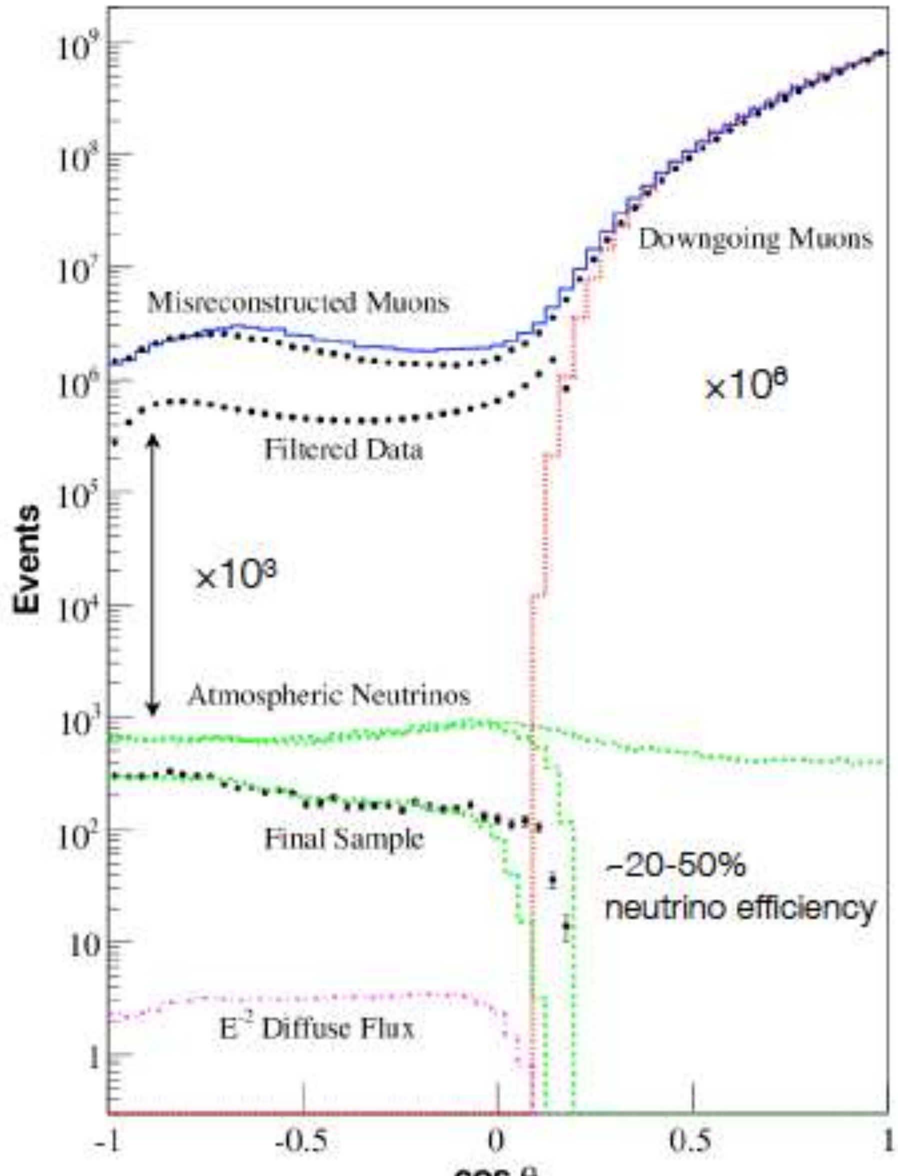
- rejecting atmospheric muons

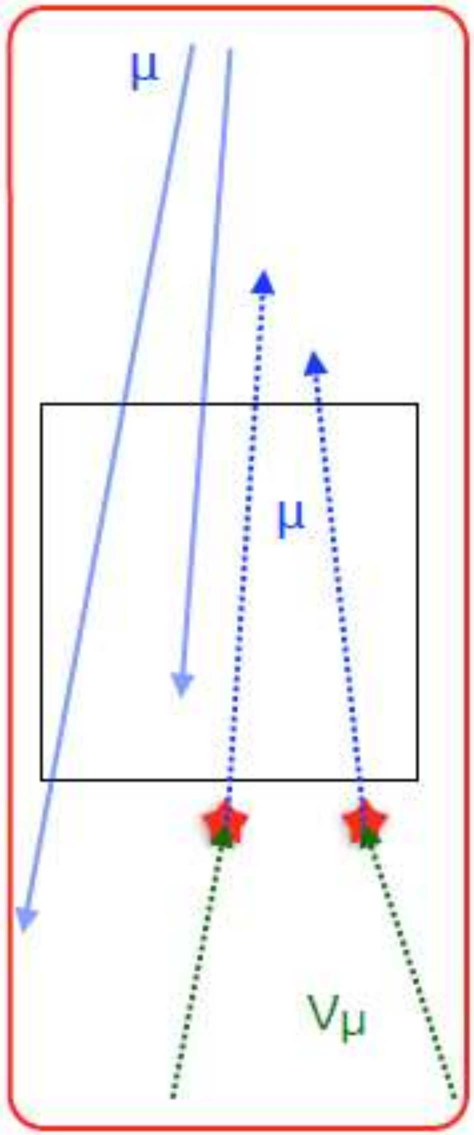




- rejecting atmospheric neutrinos

through-going
(tracks)

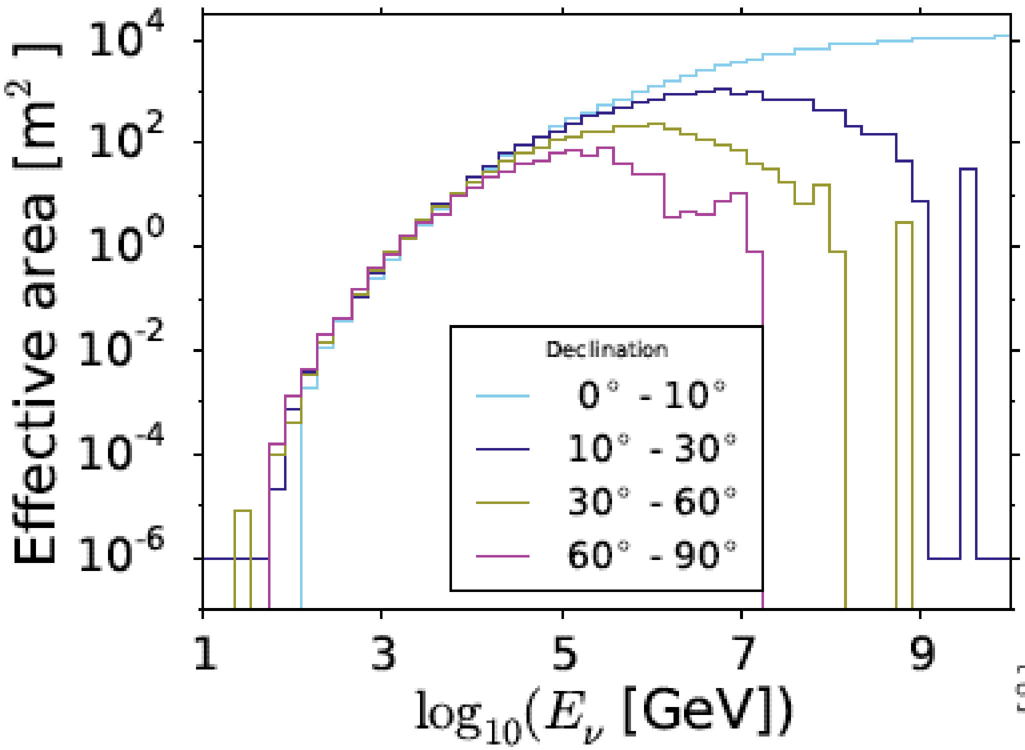




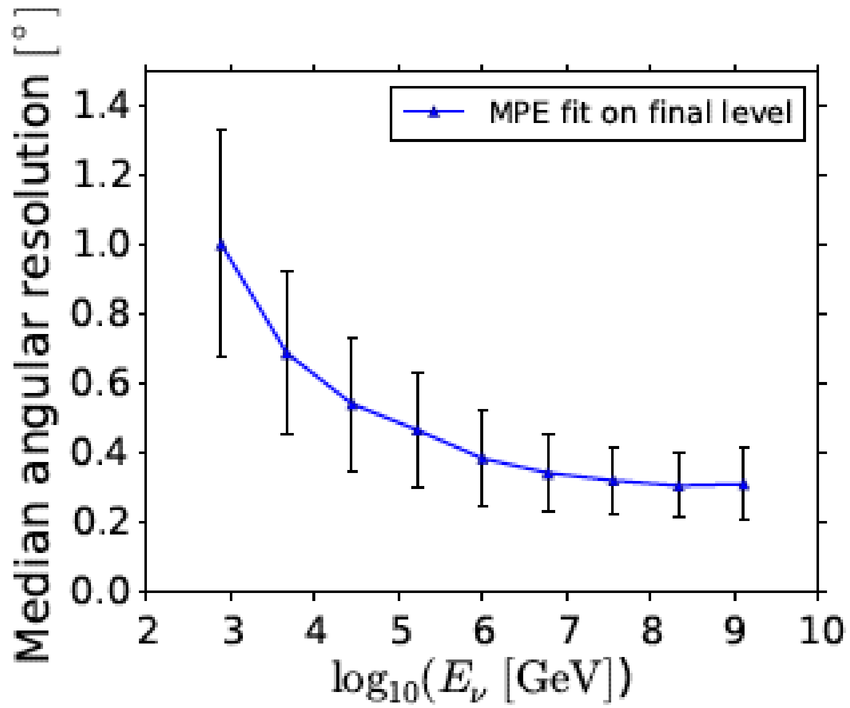
selection cuts for on-line numu extraction

Cut Level	Selection criterion	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	$\cos\theta_{MPE} \leq 0$	1010.5	1523.81	7.166	6.23
1	SLogL(3.5) ≤ 8	282.49	504.44	5.826	5.62
2	$N_{Dir} \geq 9$	8.839	22.01	3.076	4.06
3	$((\cos\theta_{MPE} > -0.2)$ AND $(L_{Dir} \geq 300$ m$)$ OR $(\cos\theta_{MPE} \leq -0.2)$ AND $(L_{Dir} \geq 200$ m$))$	1.124	4.30	2.313	3.69
4	$\Delta_{Split/MPE} < 0.5$	0.100	2.15	1.899	3.26
5	$((\cos\theta_{MPE} \leq -0.07)$ OR $((\cos\theta_{MPE} > -0.07)$ AND $(\Delta_{SPE/Bayesian} \geq 35)))$	0.080	2.08	1.880	3.25
6	$((\cos\theta_{MPE} \leq -0.04)$ OR $((\cos\theta_{MPE} > -0.04)$ AND $(\Delta_{SPE/Bayesian} \geq 40)))$	0.075	2.06	1.875	3.24

Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction by Honda [71], but atmospheric-muon rate is calculated from CORSIKA simulations. The event rate for IceCube data stream corresponds to the total livetime of 332.36 days. The astrophysical neutrino flux is estimated assuming $dN/dE = 1 \cdot 10^{-8}$ GeVcm^{-2}s$^{-1}(\frac{E}{\text{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)



Effective area [m^2]
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Declination
0° - 10°
10° - 30°
30° - 60°
60° - 90°
1
3
5
7
9
$\log_{10}(E_\nu$ [GeV])



Median angular resolution [°]
MPE fit on final level
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])

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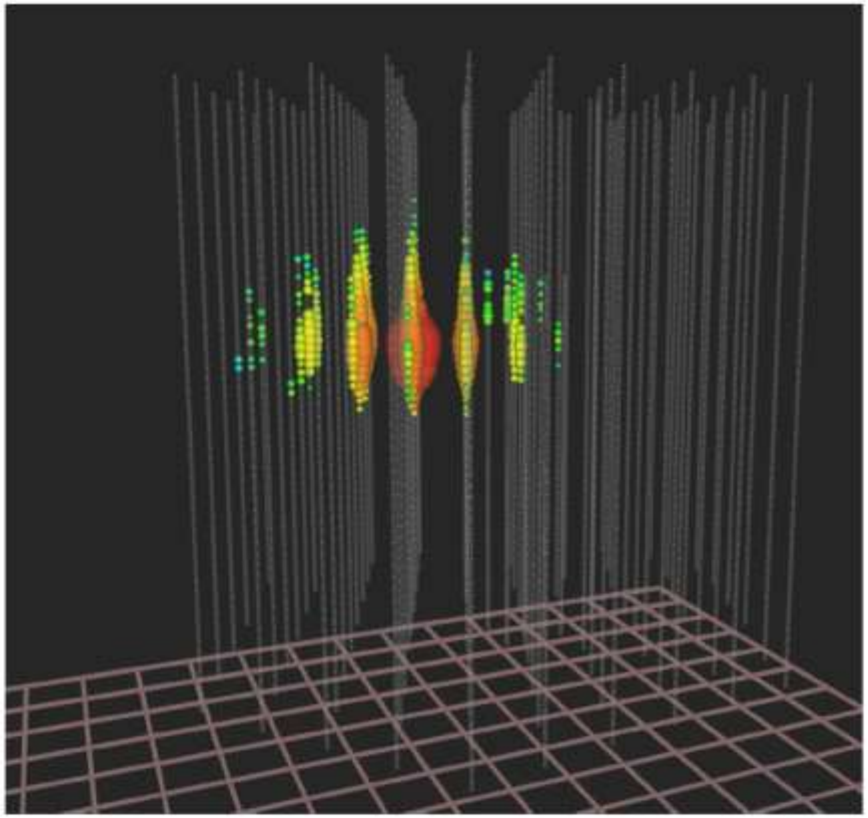
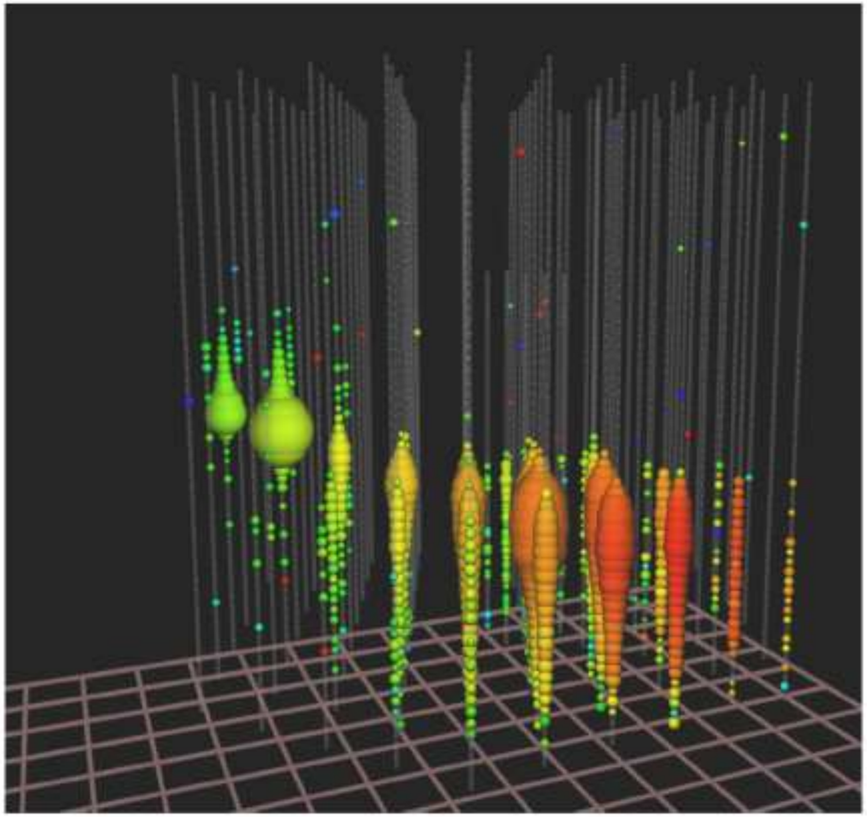
icecube.wisc.edu

isolated neutrinos interacting *inside* the detector (HESE)

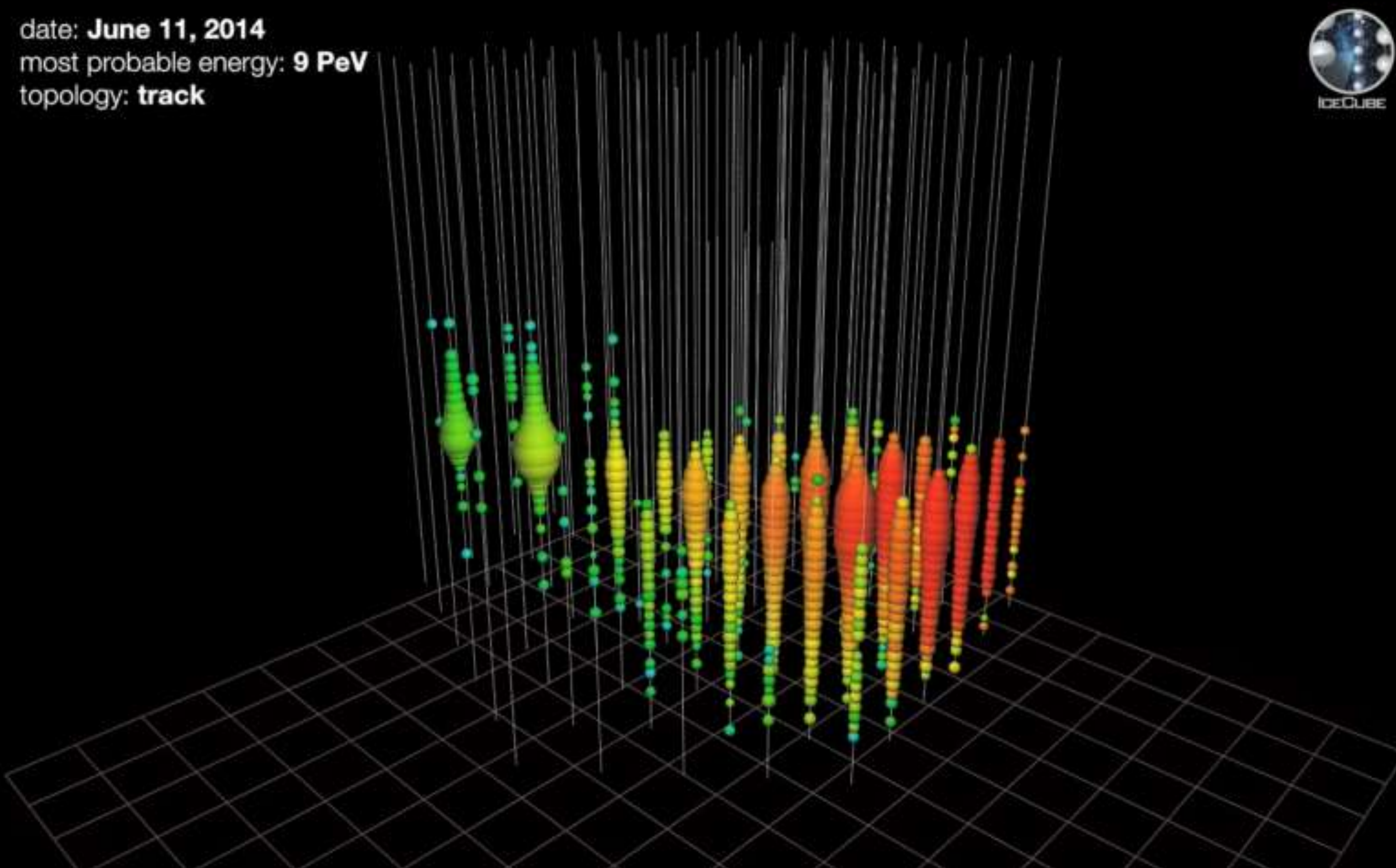
up-going muon tracks (UPMU)

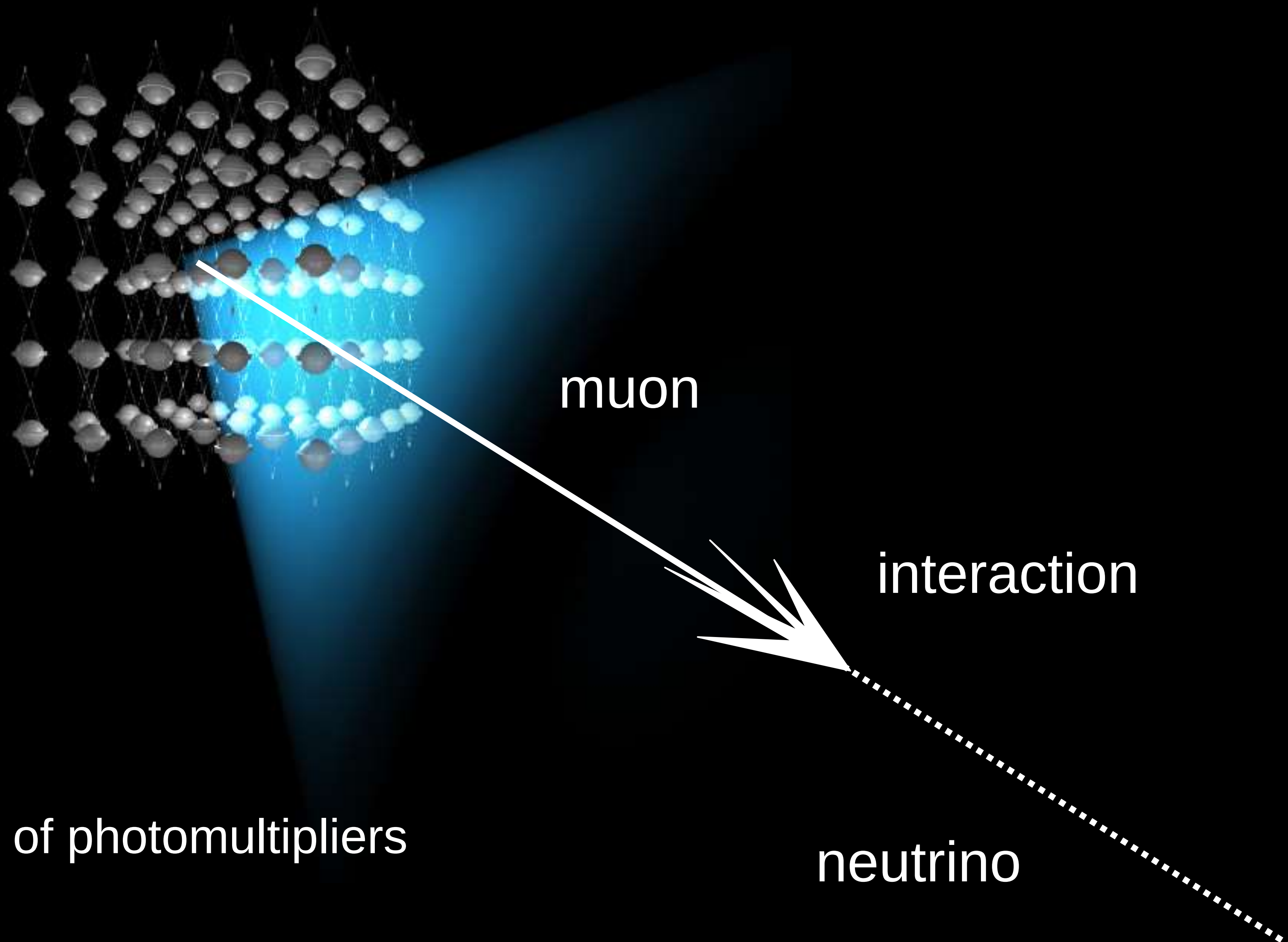




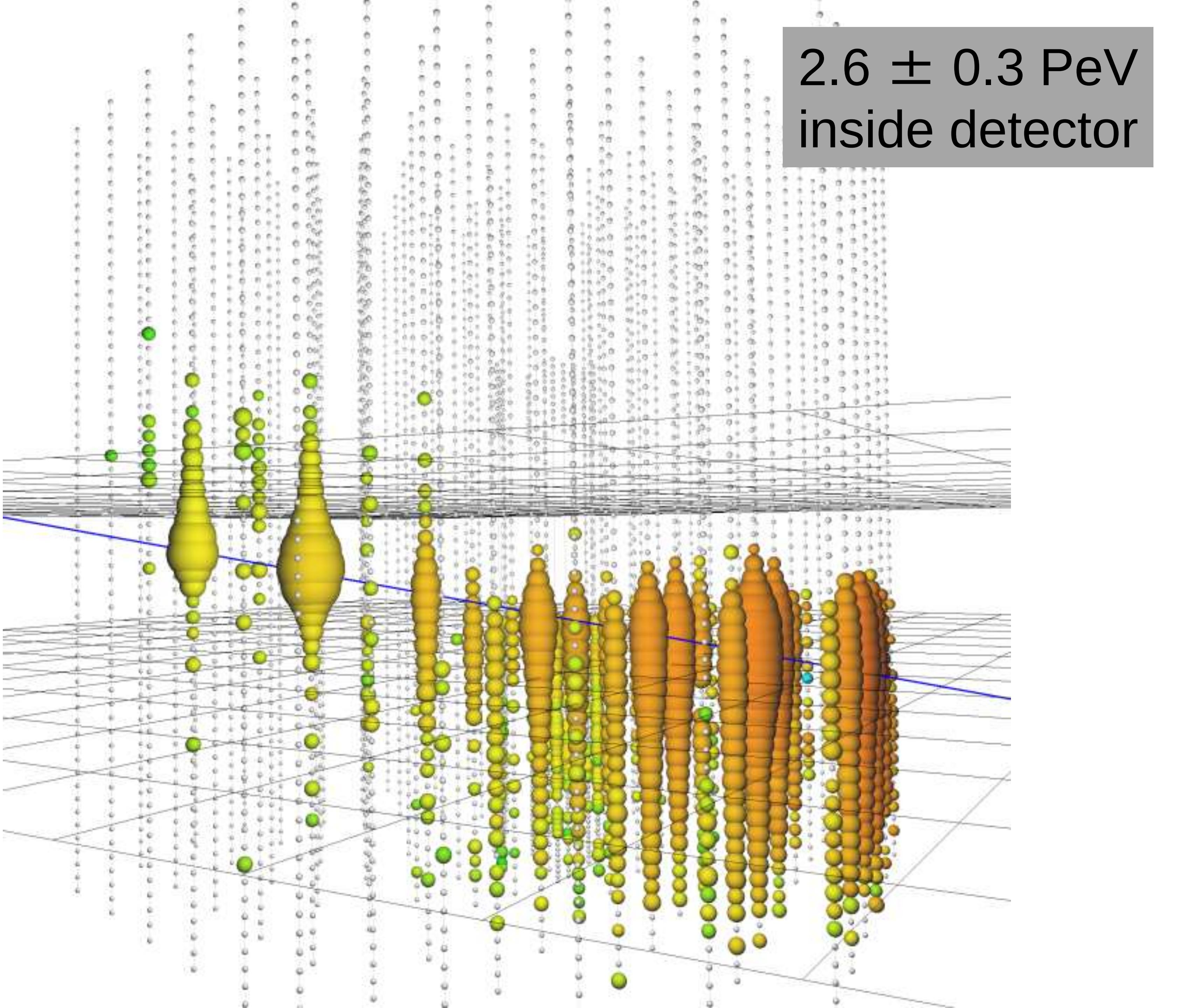
total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5º)


date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube

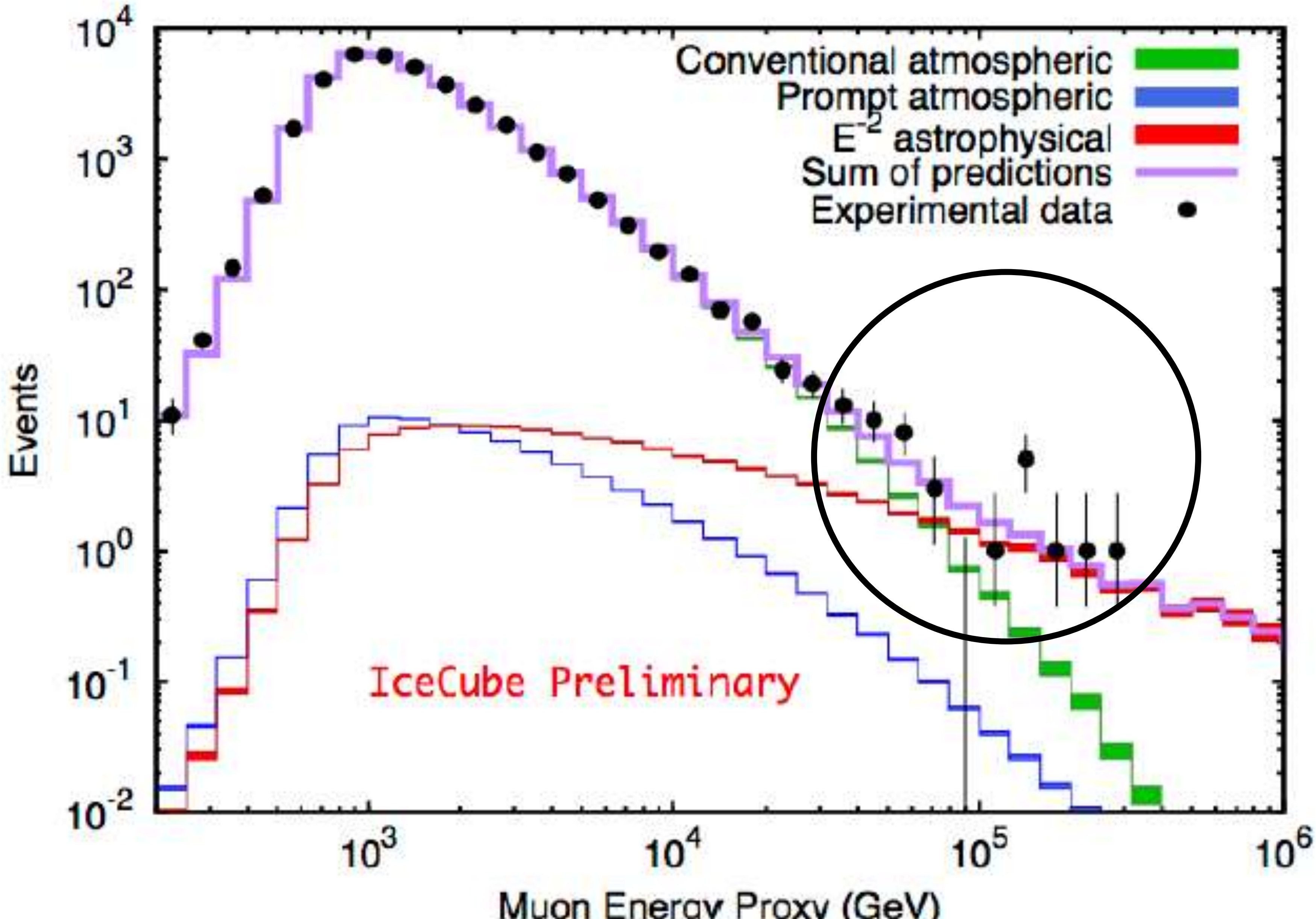


- lattice of photomultipliers



2.6 ± 0.3 PeV
inside detector

cosmic neutrinos in 2 years of data at 3.7 sigma

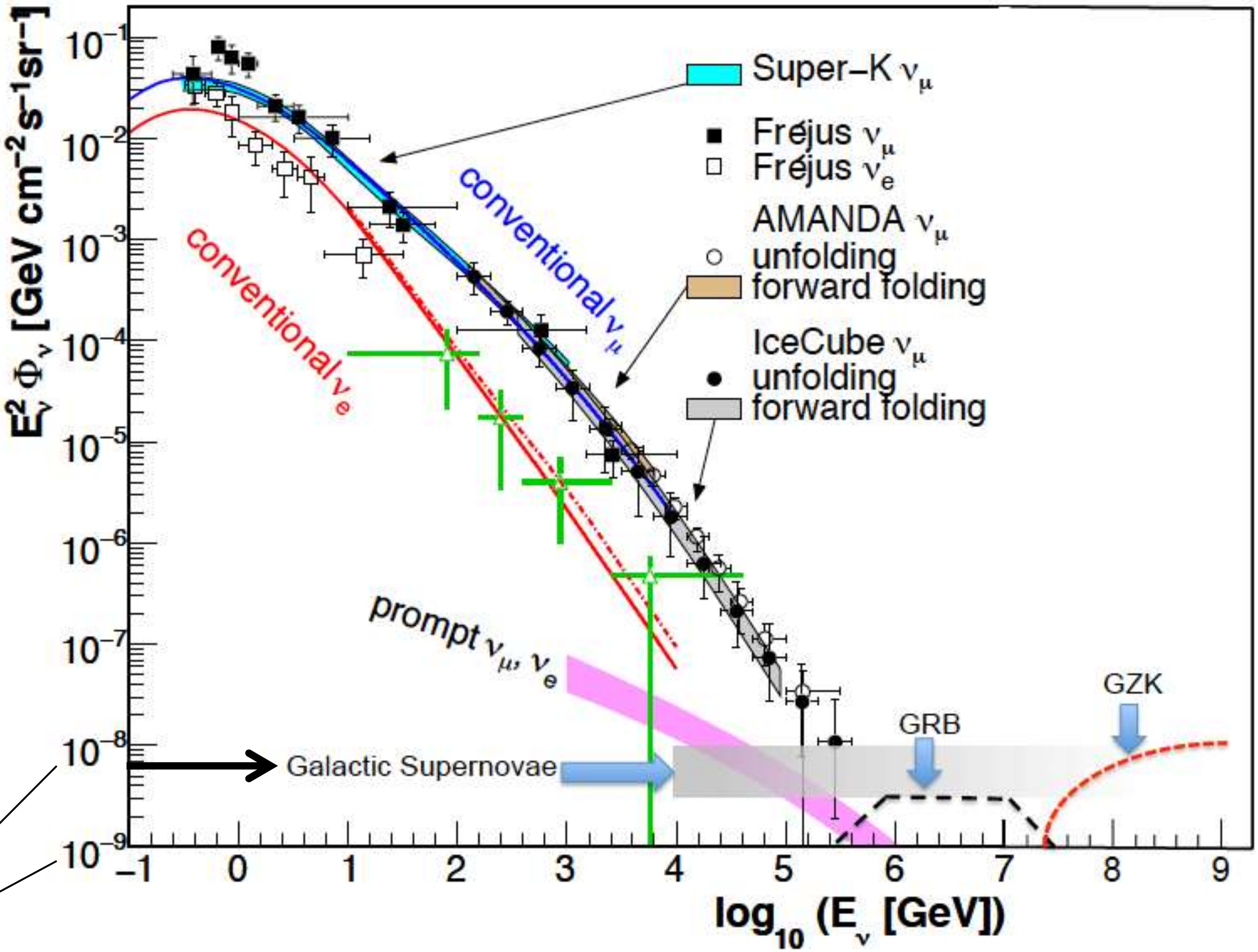


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$dN/dE \sim E^{-2}$

10—100 events per year for fully efficient detector

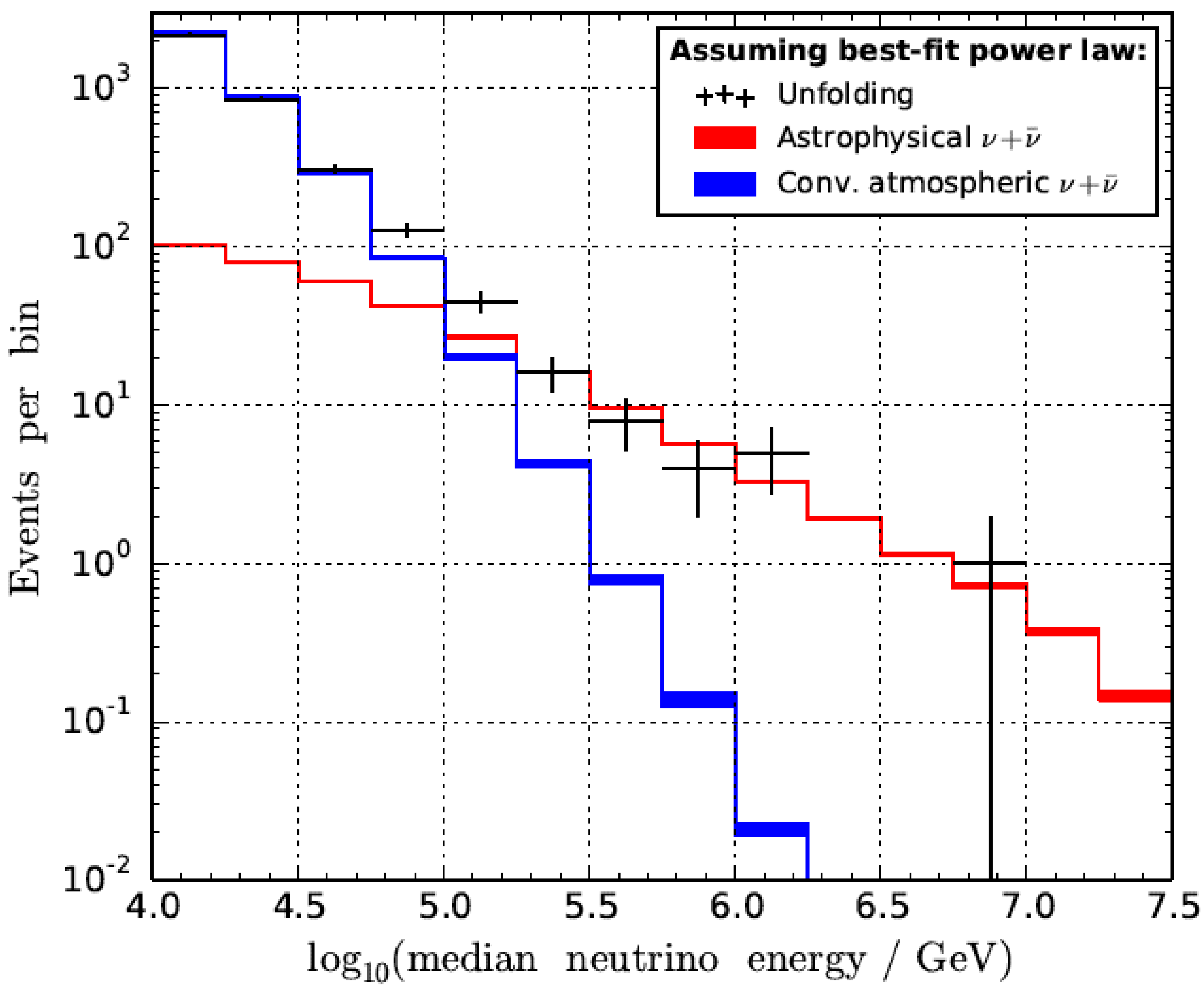


atmospheric

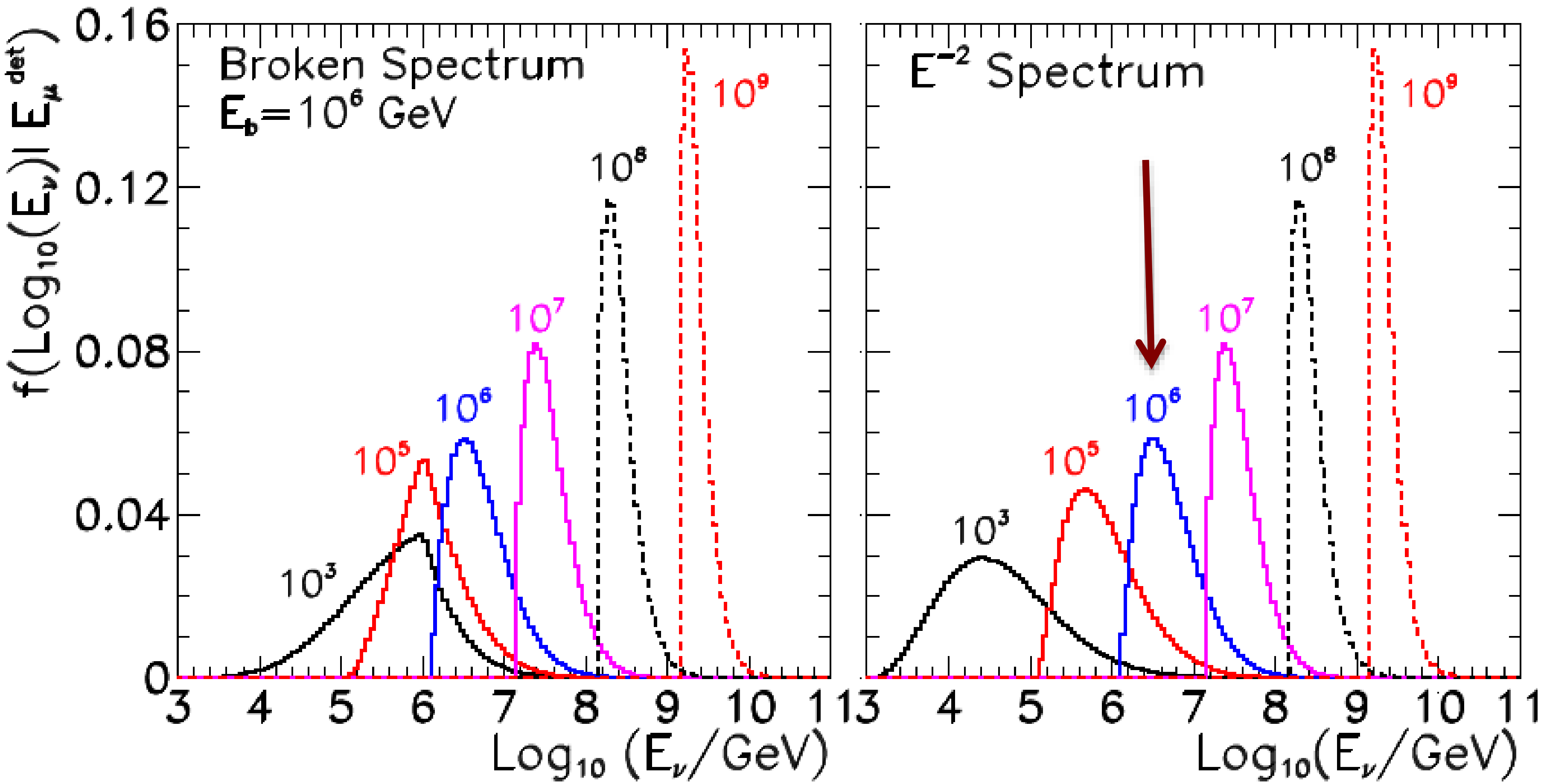
cosmic

100 TeV

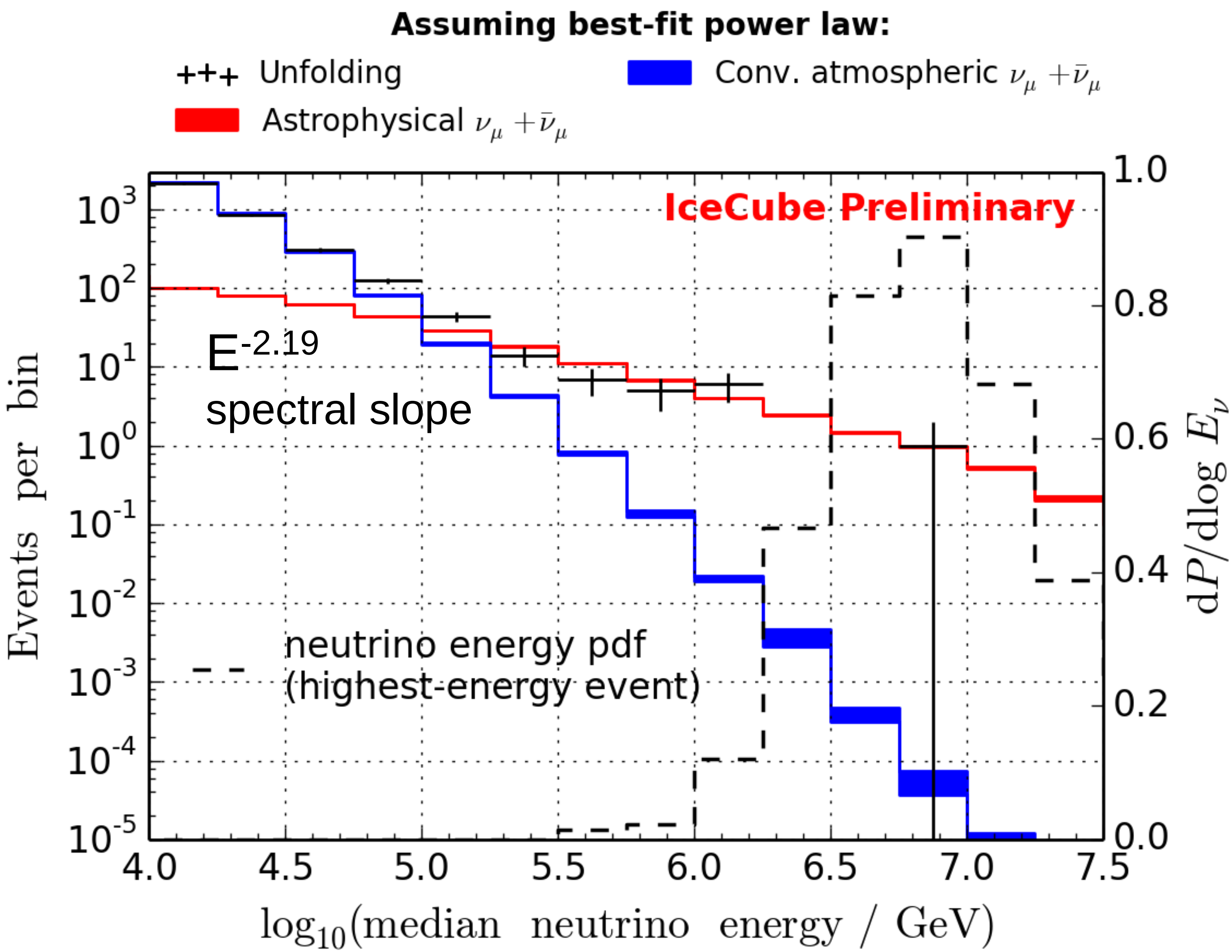
muon neutrinos through the Earth → 5.6 sigma

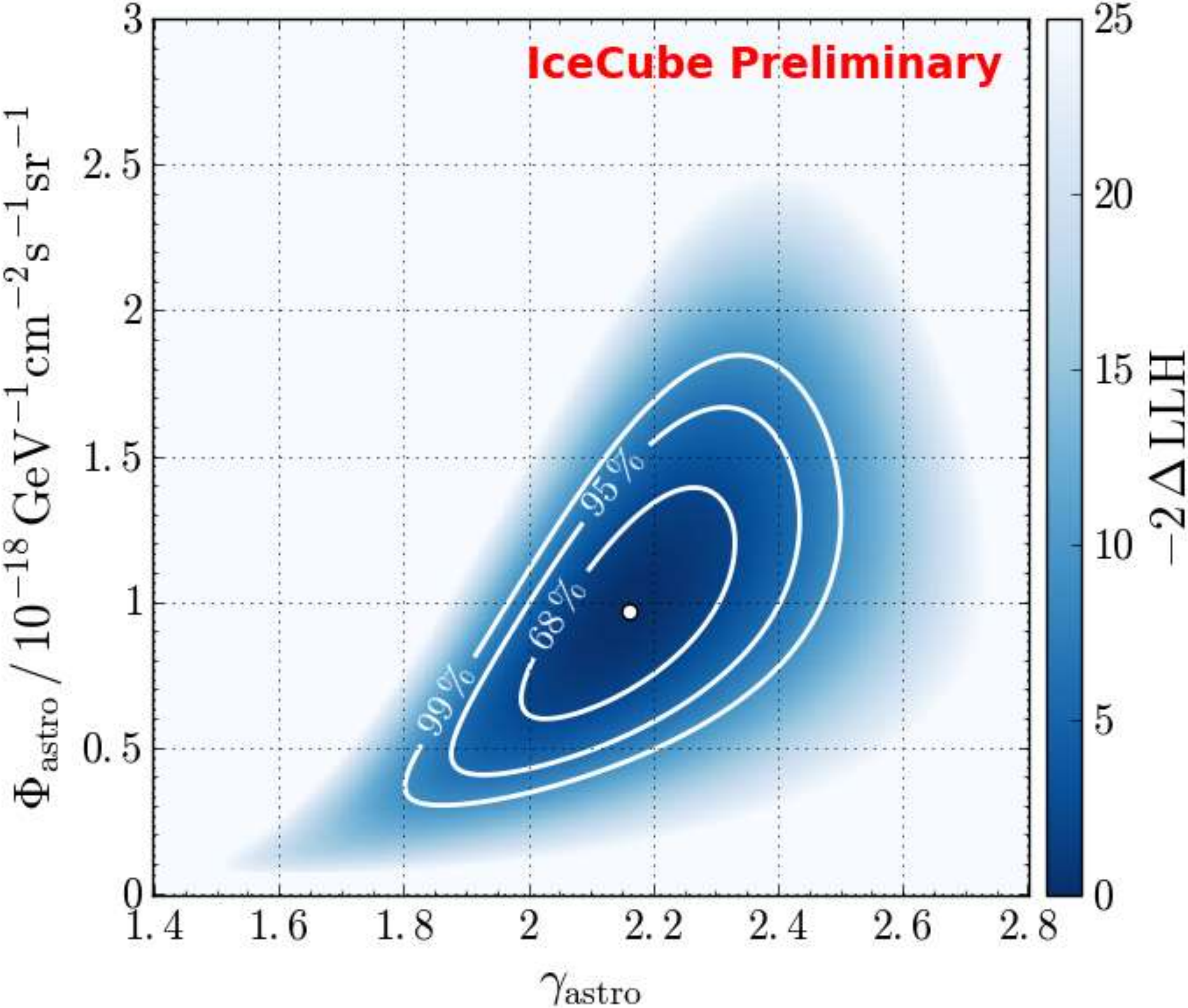


distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube

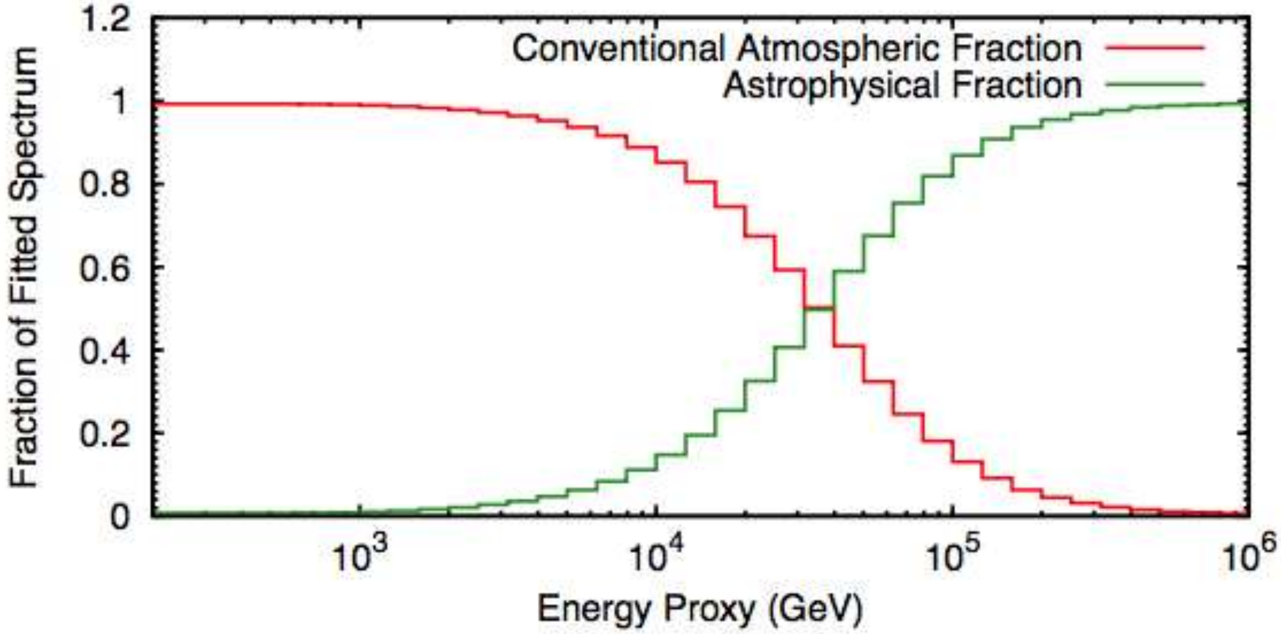


~ 550 cosmic neutrinos in a background of ~340,000 atmospheric
atmospheric background: less than one event/deg^2/year

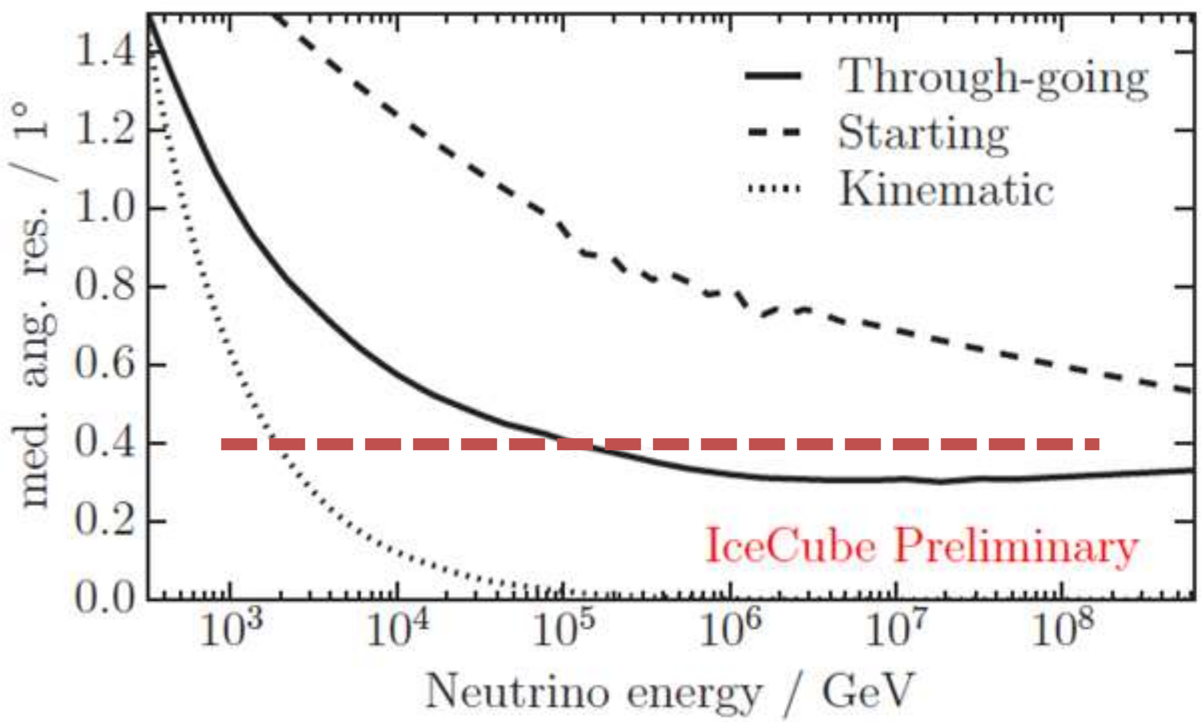



IceCube Preliminary
99%
95%
68%
Φ_{astro} / 10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}
γ_{astro}
$-2\,\Delta\,\mathrm{LLH}$
0
0.5
1
1.5
2
2.5
3
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
5
10
15
20
25

Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5

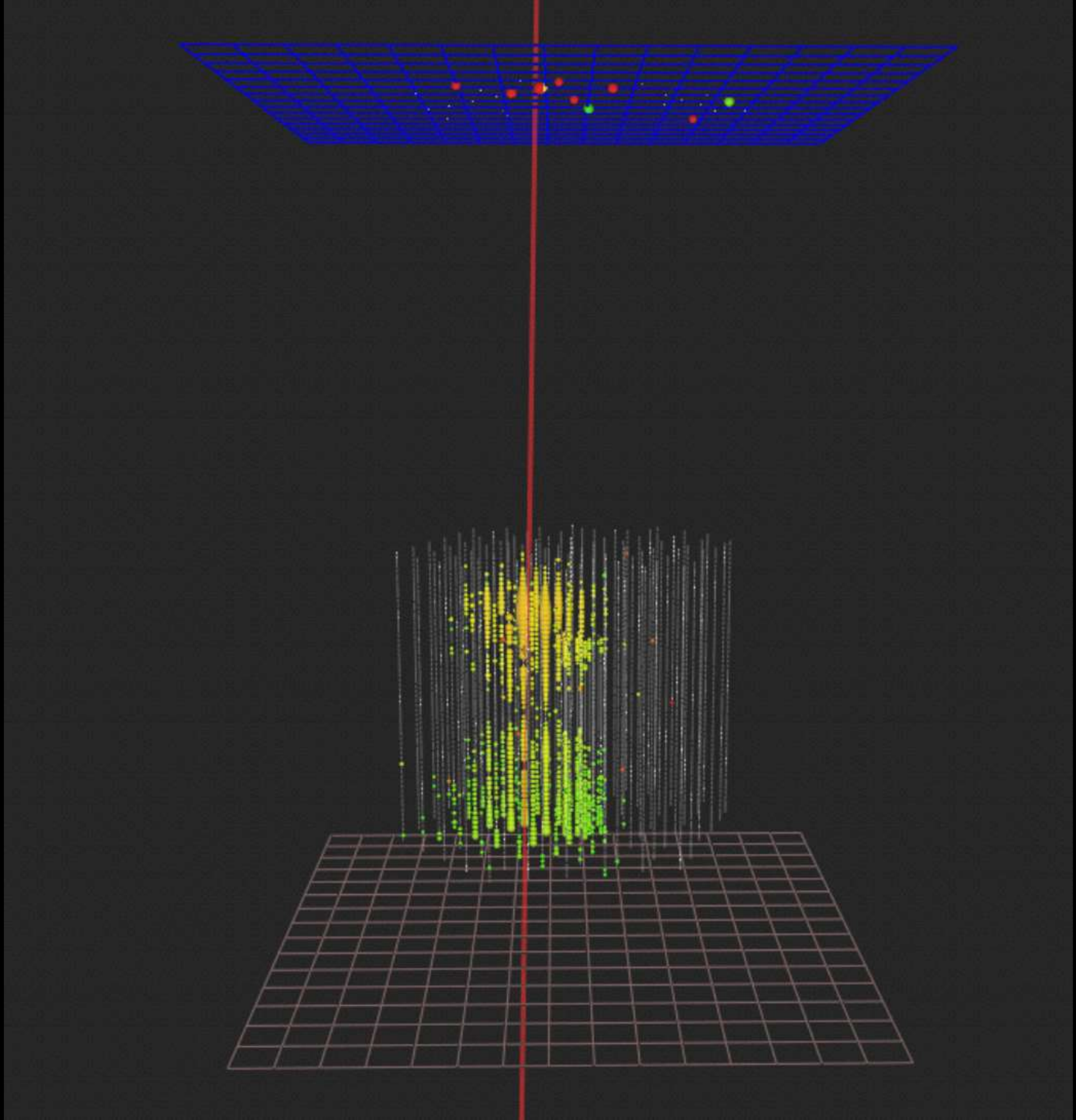


astronomy here: through-going muons with resolution $0.2\sim0.4^0$



430 TeV inside detector
PeV ν_μ
no air shower

all cosmic neutrinos are isolated by self-veto



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cosmic rays interact with the microwave background

$$p+\gamma \rightarrow n+\pi^{+} \ and \ p+\pi^{0}$$

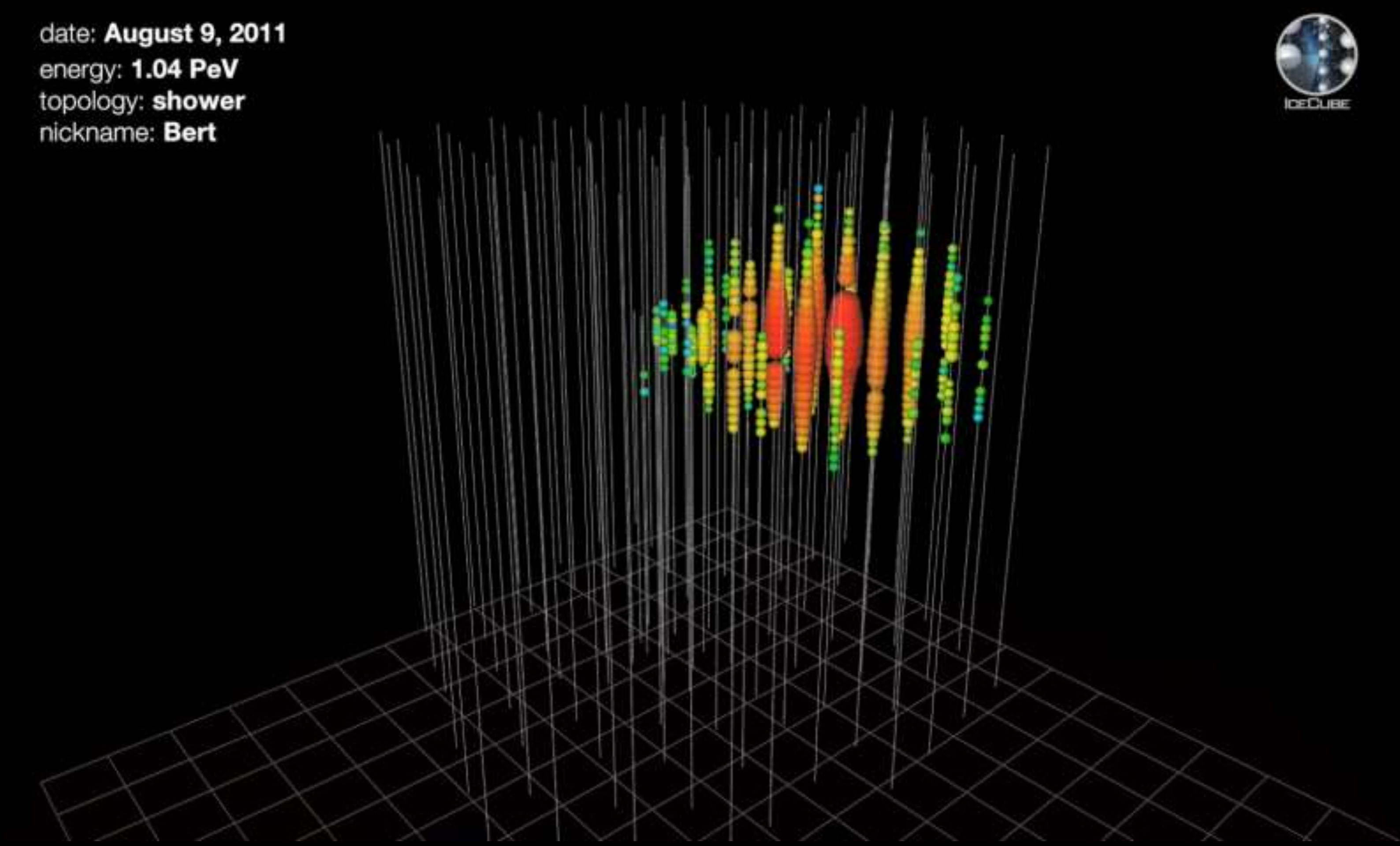
cosmic rays disappear, neutrinos with EeV (10⁶ TeV) energy appear

$$p \rightarrow m + u_{m} \rightarrow \{e + \overline{u_{m}} + u_{e}\} + u_{m}$$

1 event per cubic kilometer per year

...but it points at its source!

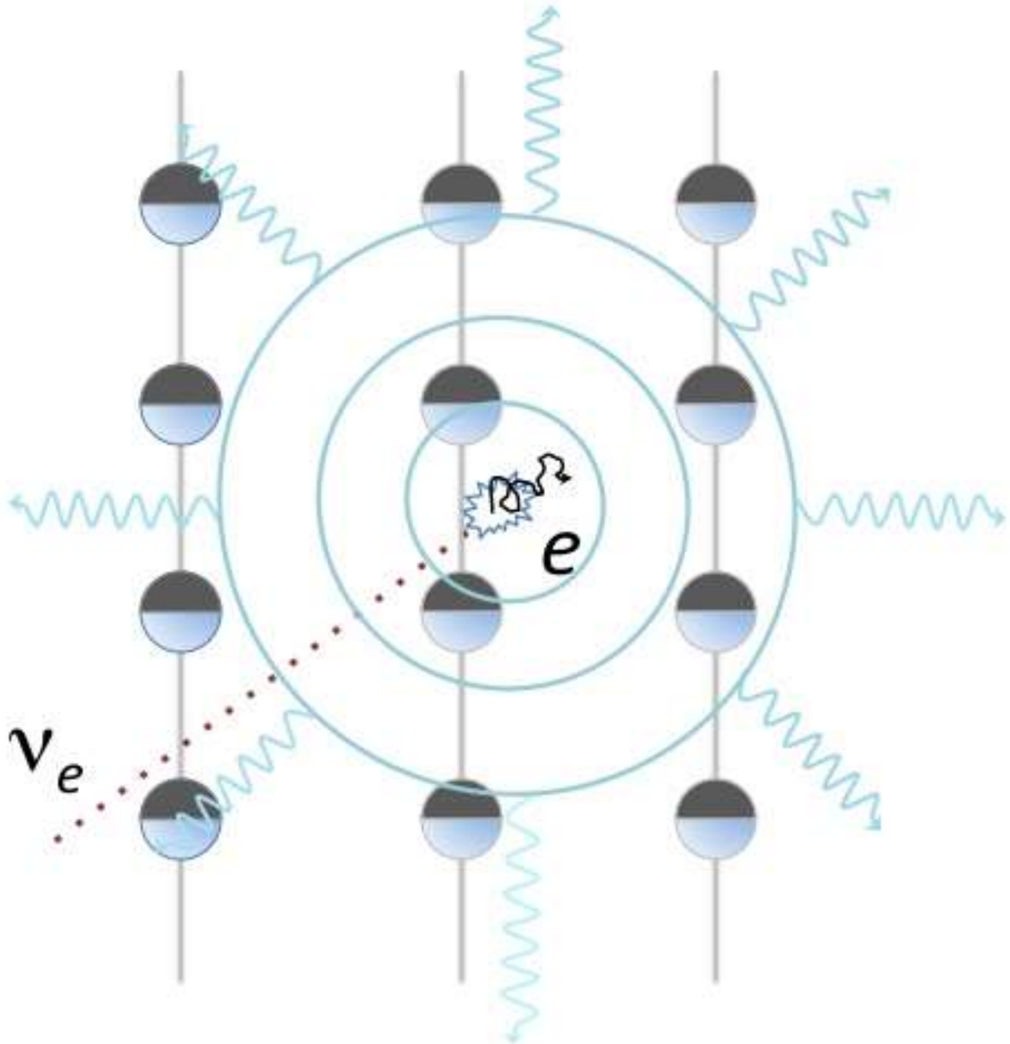
GZK neutrino search: two neutrinos with > 1,000 TeV

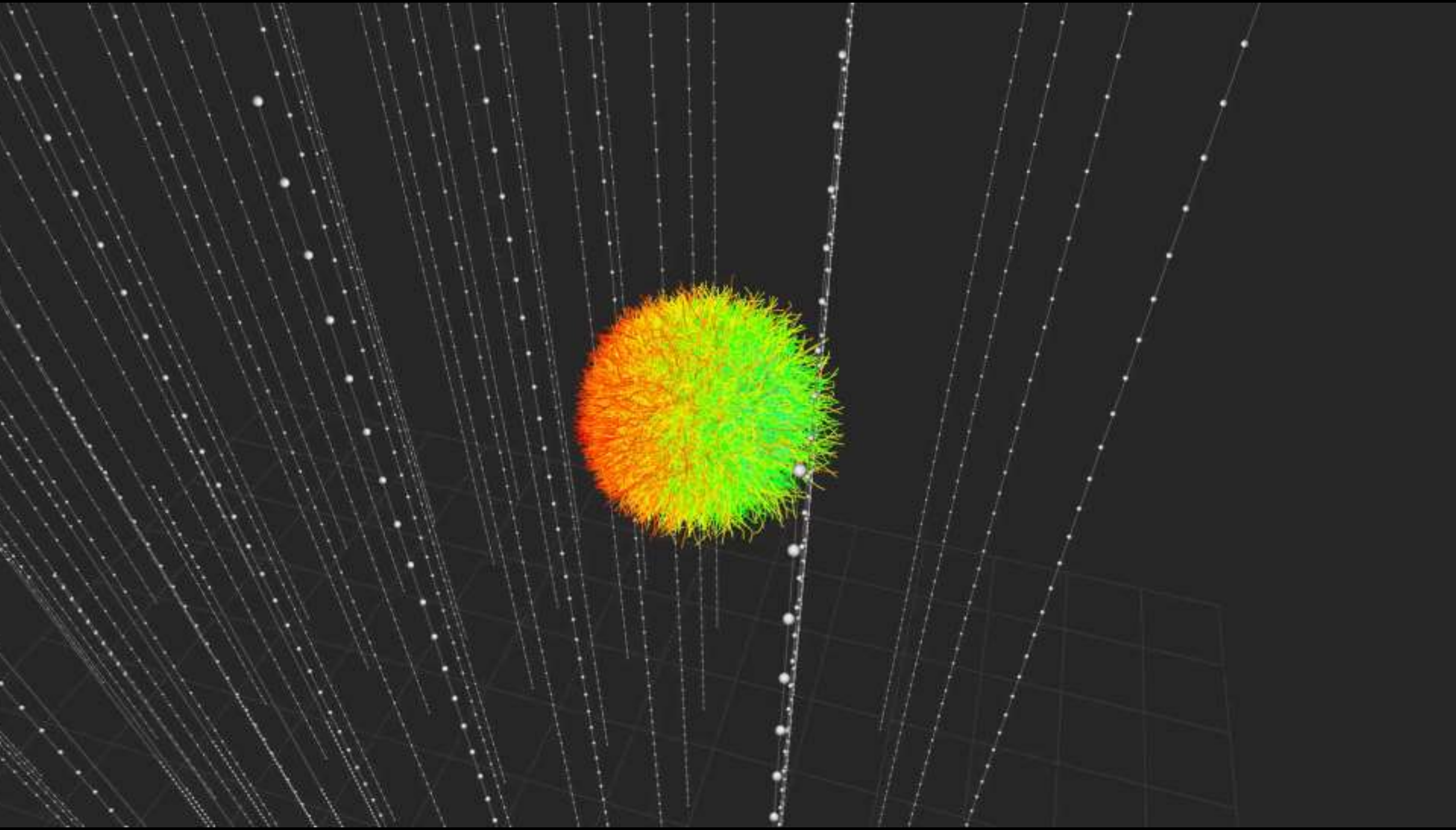


electron showers versus muon tracks

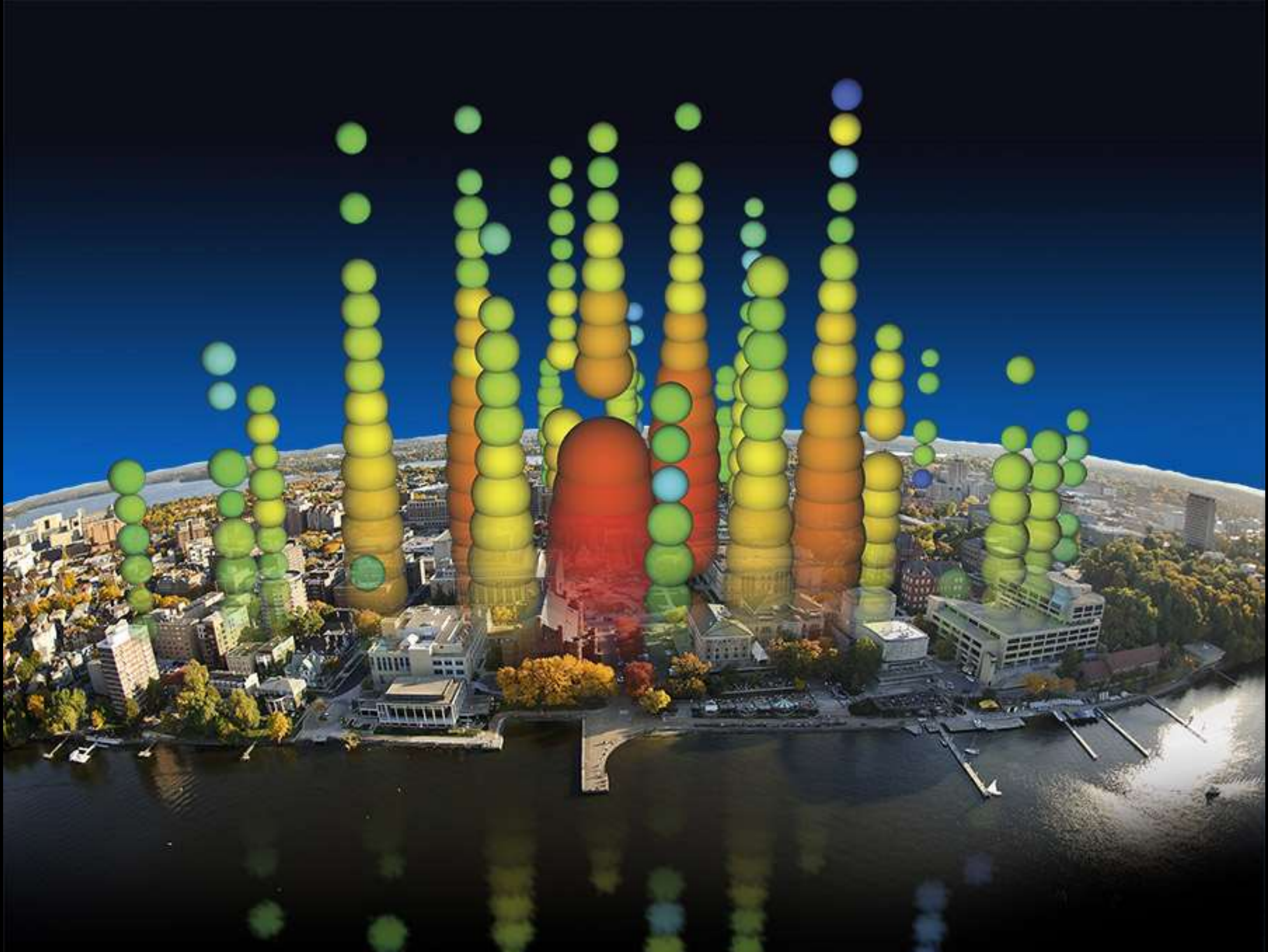
PeV ν_e and ν_τ showers:

- 10 m long
- volume ~ 5 m^3
- isotropic after 25~50 m

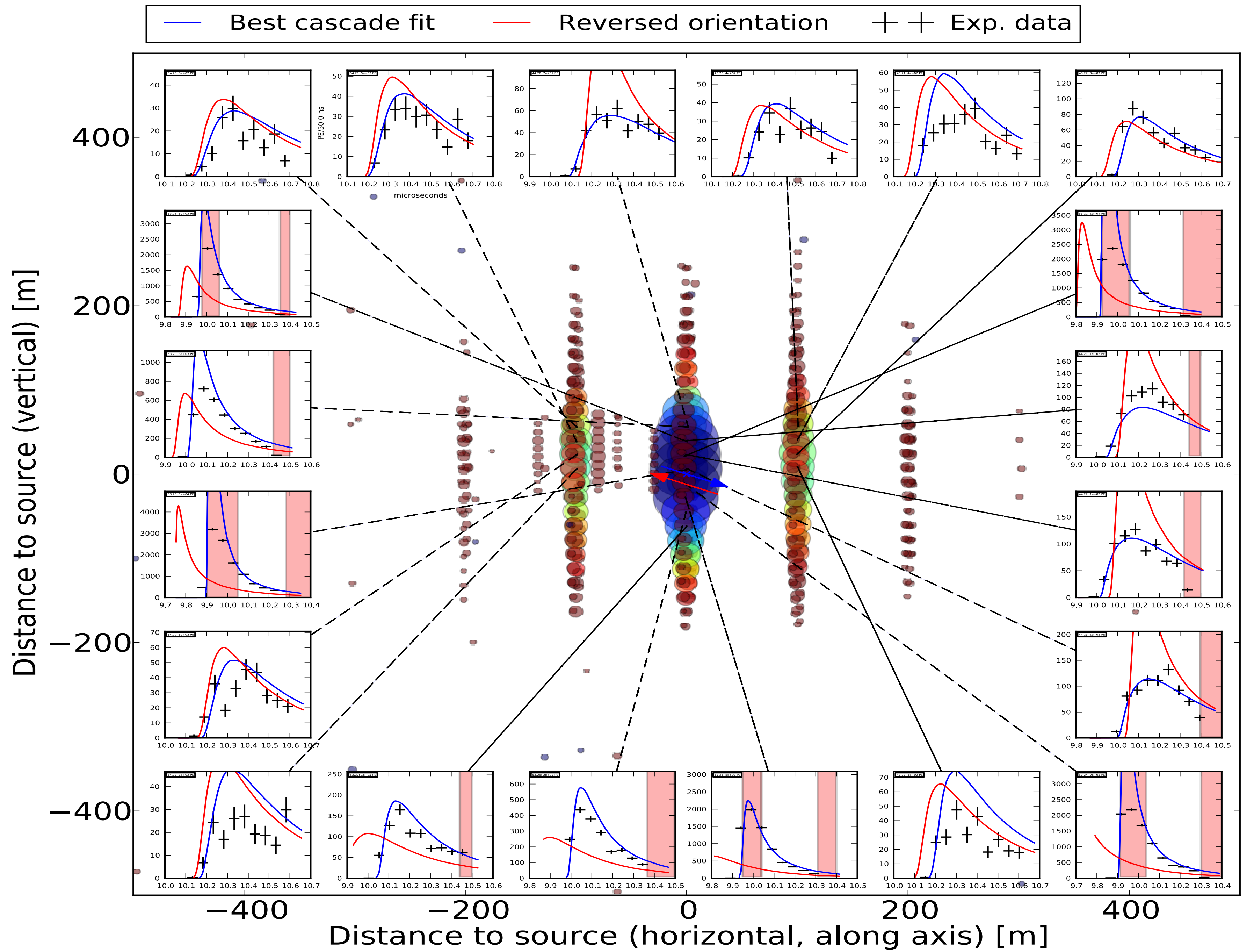




size = energy & color = time = direction

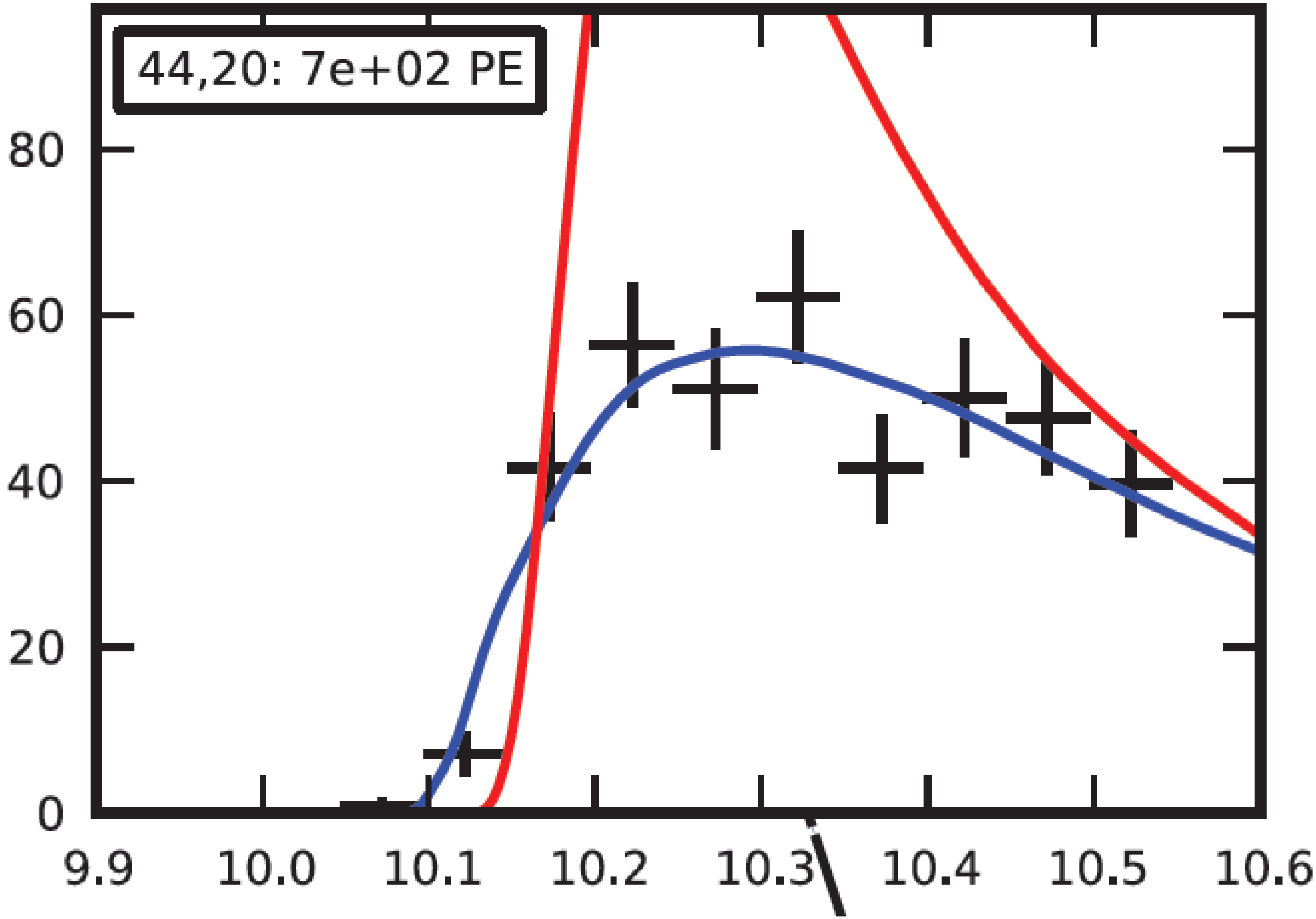


- > 300 sensors
- > 100,000 pe reconstructed to 2 nsec

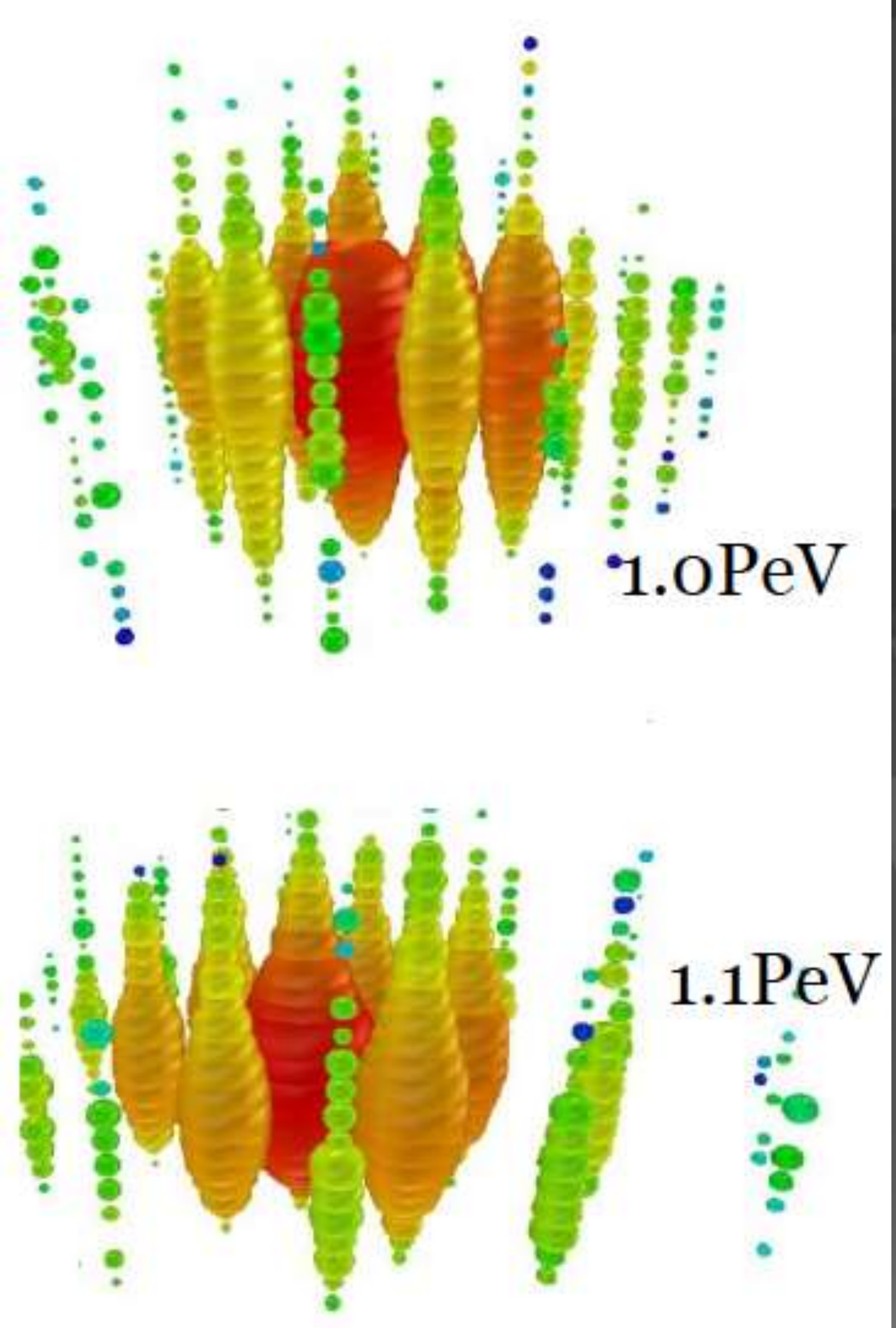


Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
microseconds
PE/50.0 ns

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction



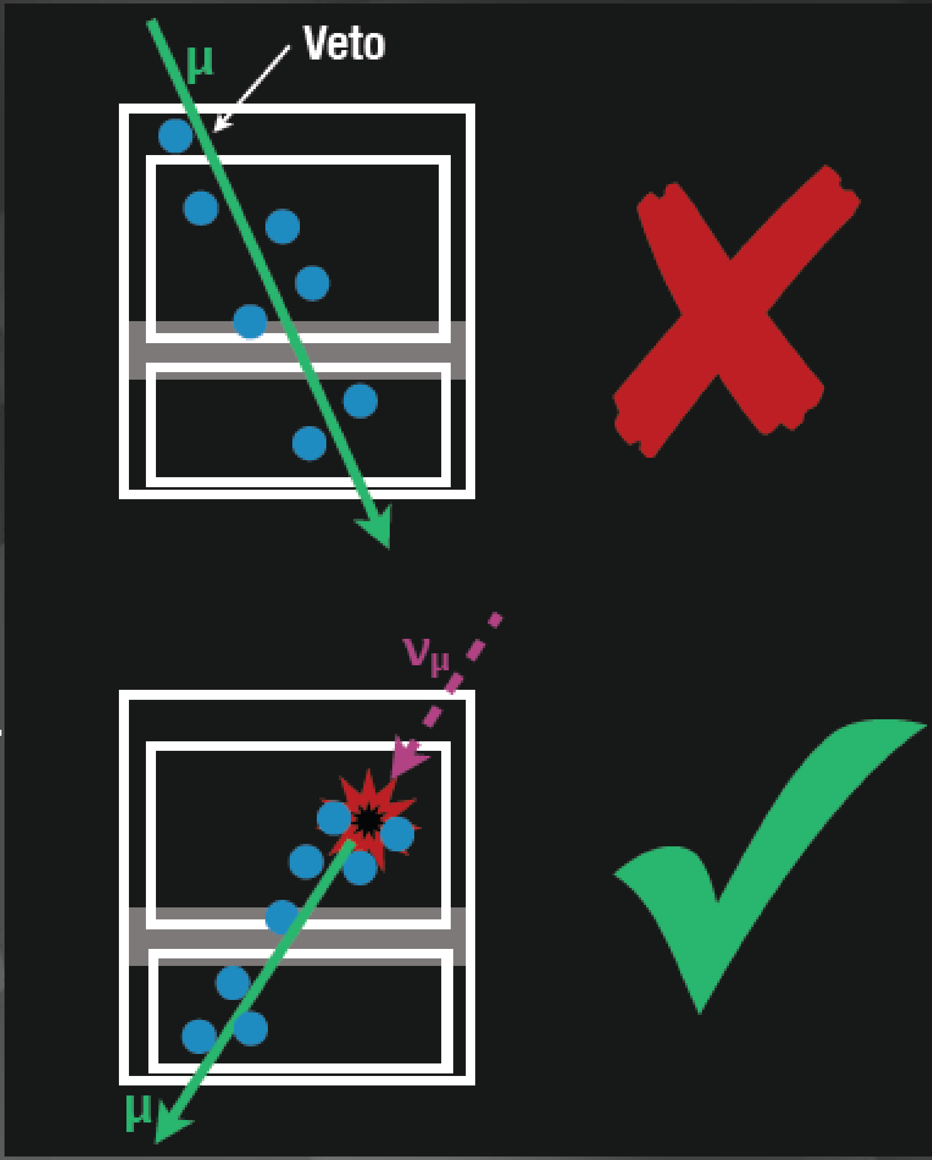
• energy

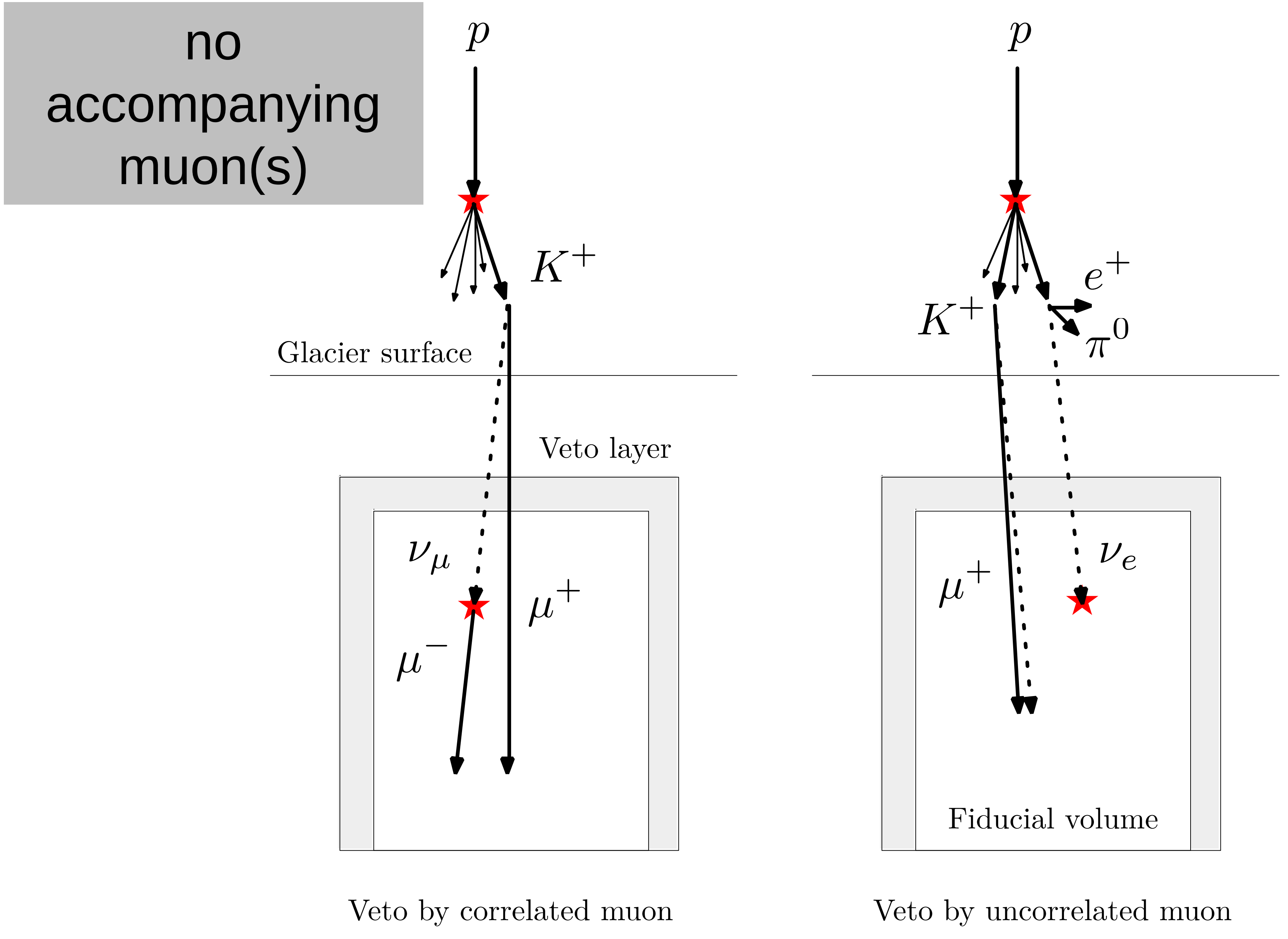
1,041 TeV
1,141 TeV
(15% resolution)

• not atmospheric: probability of no accompanying muon is 10^{-3} per event

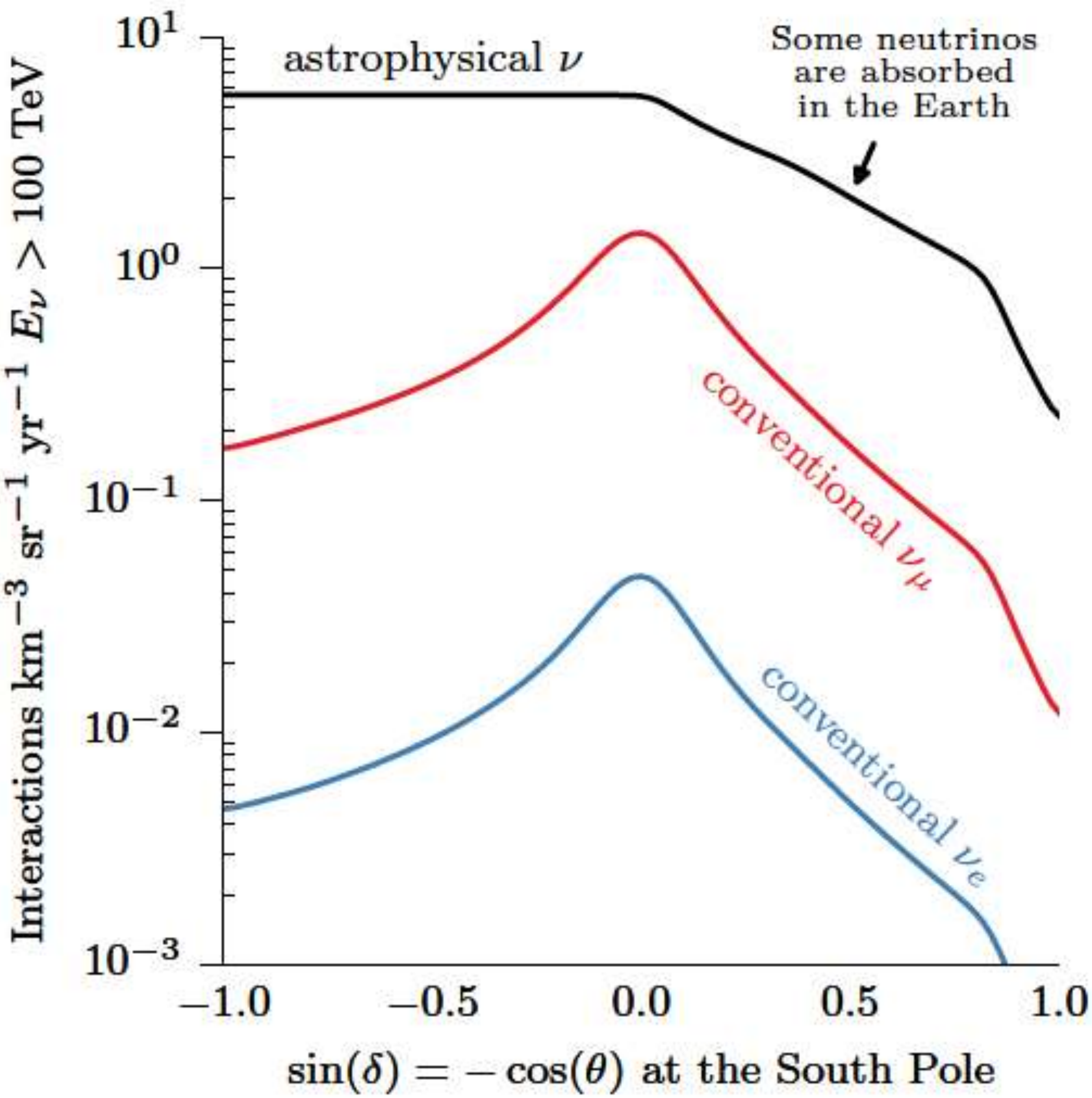
→ flux at present level of diffuse limit

- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry

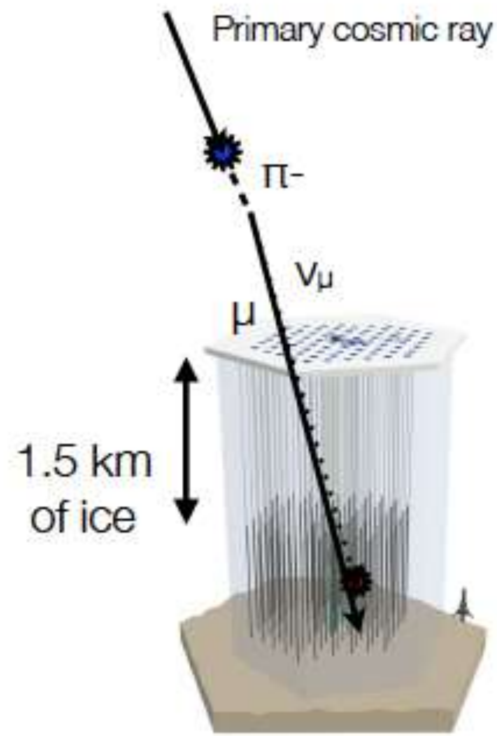



no accompanying muon(s)
p
K+
Glacier surface
Veto layer
νμ
μ+
μ−
Veto by correlated muon
p
e+
K+
π0
νe
μ+
Fiducial volume
Veto by uncorrelated muon

Atmospheric neutrino self-veto



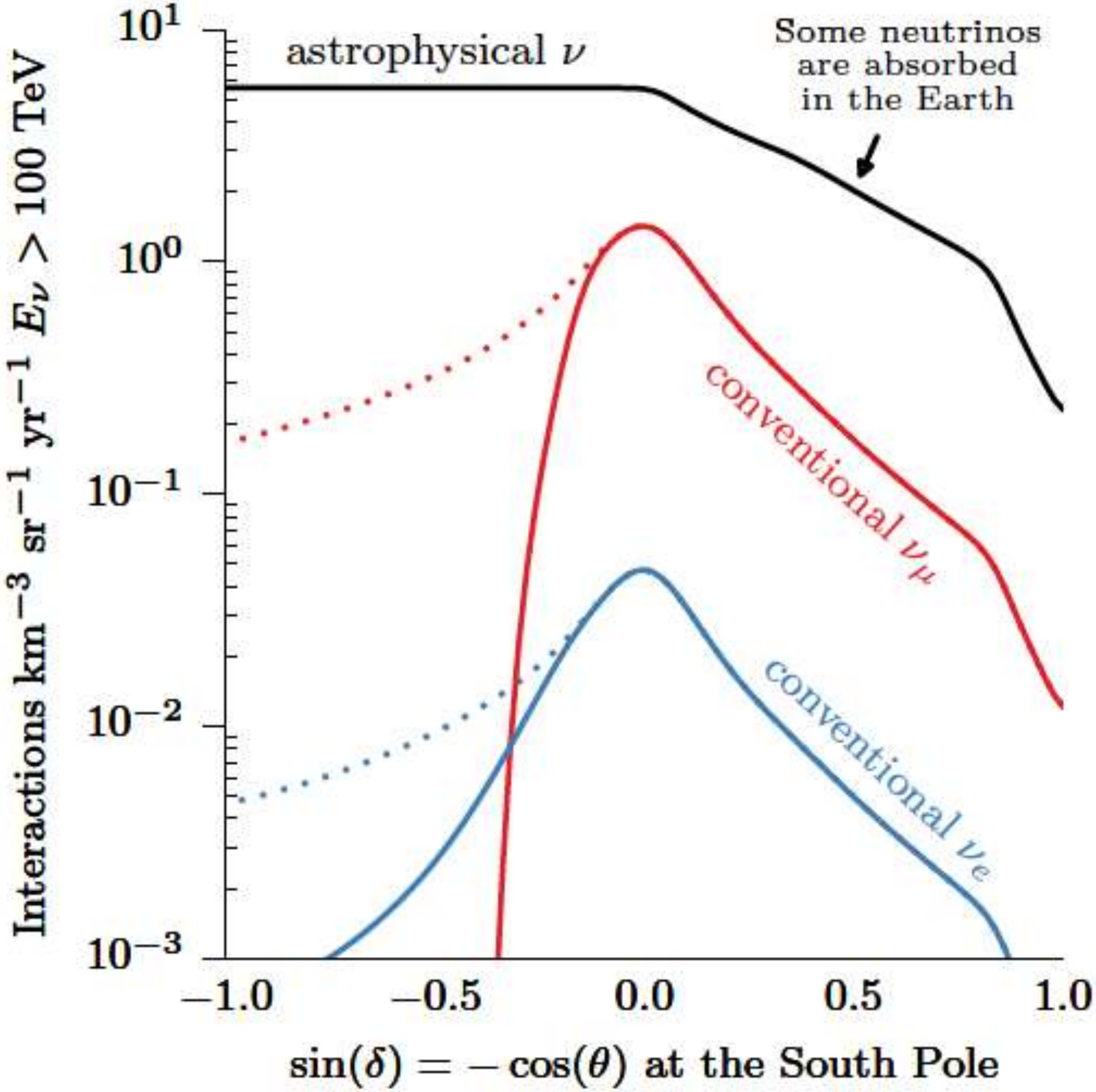
An active muon veto removes down-going atmospheric neutrinos.



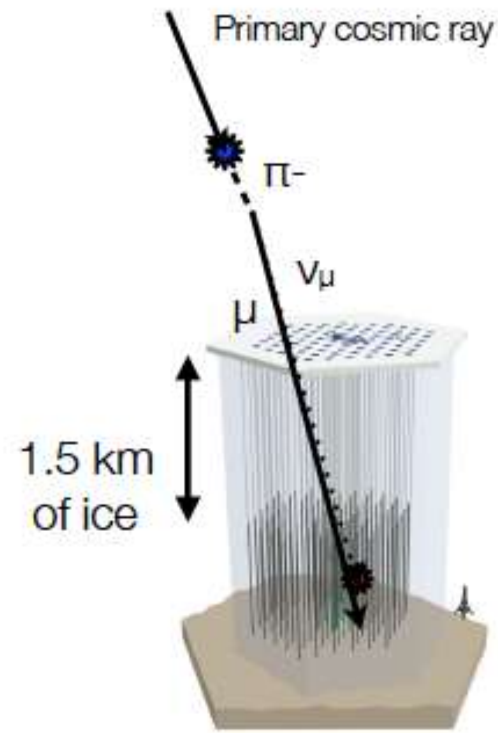
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



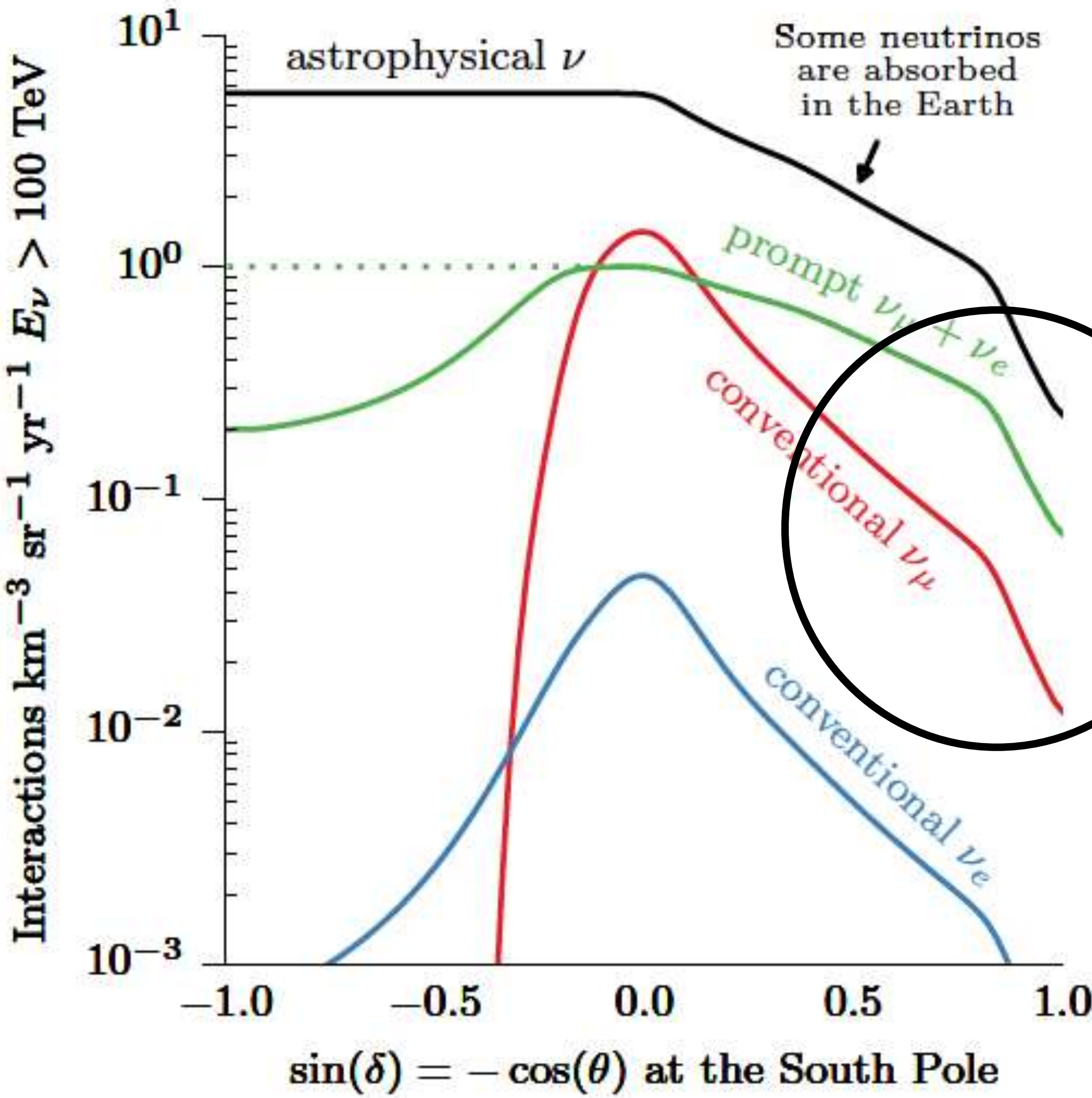
An active muon veto removes down-going atmospheric neutrinos.



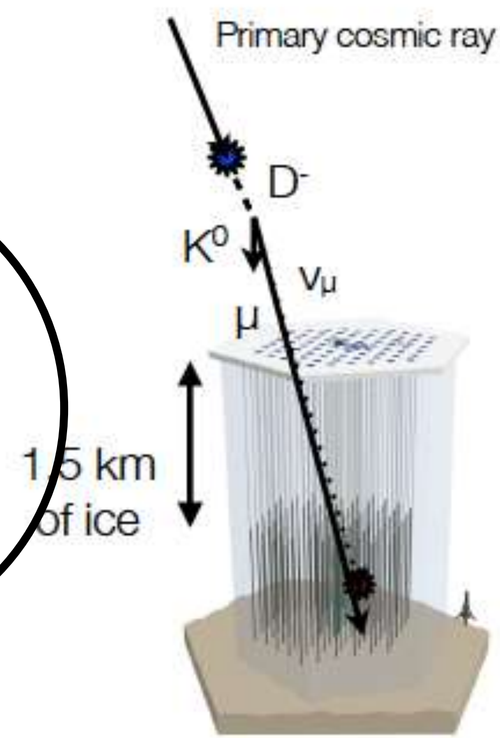
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Atmospheric neutrino self-veto



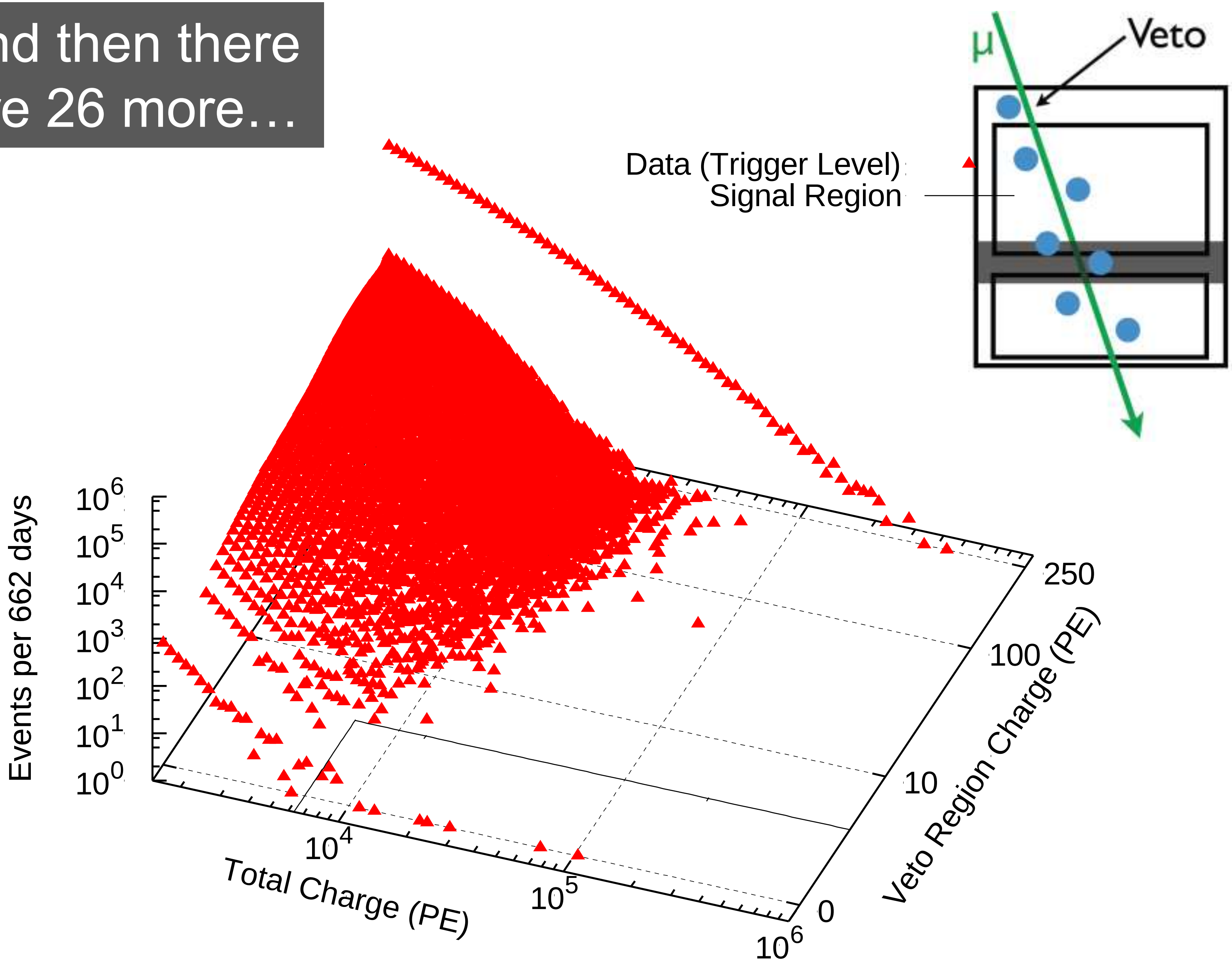
Prompt atmospheric neutrinos are vetoed, too.



Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

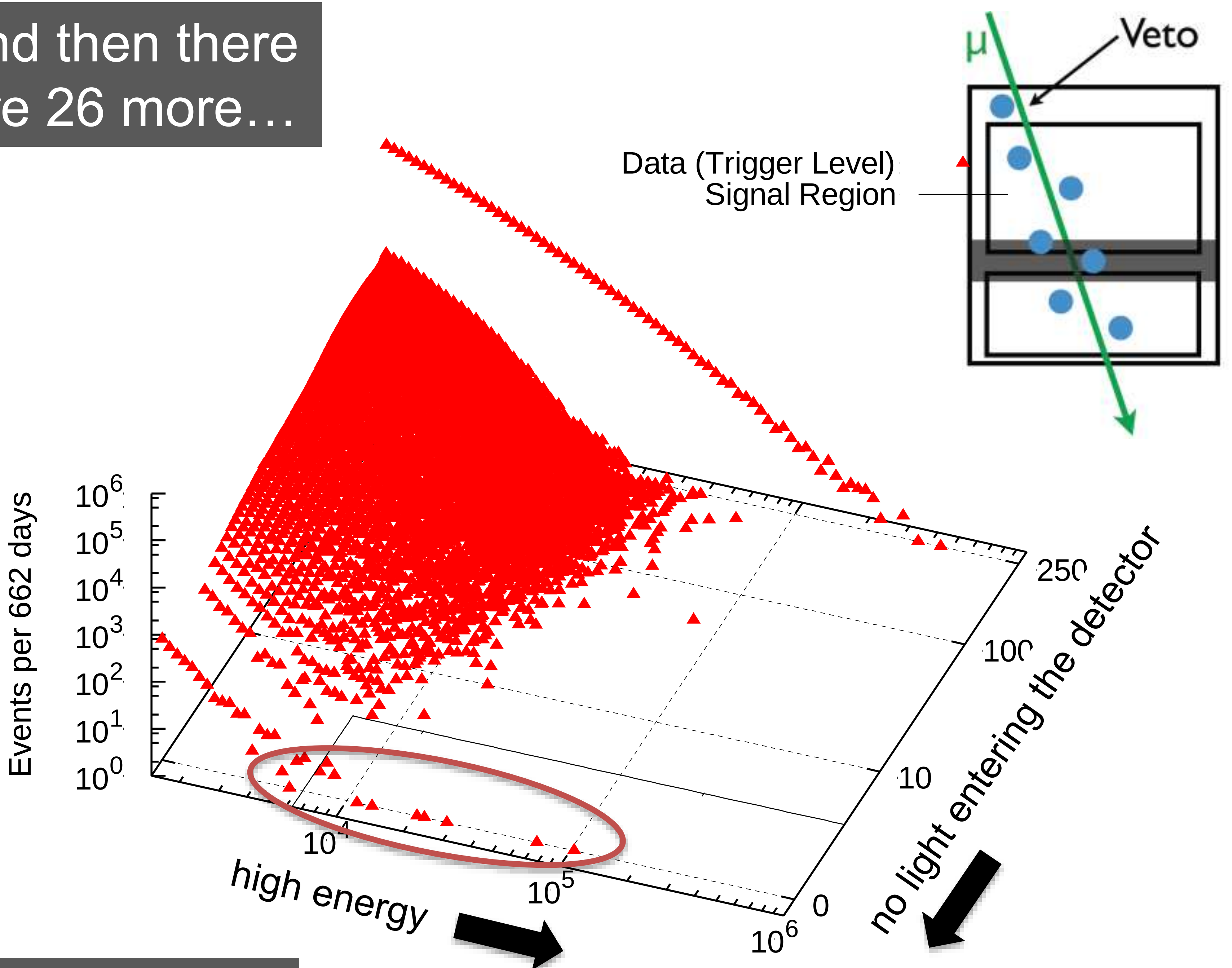
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

…and then there were 26 more…



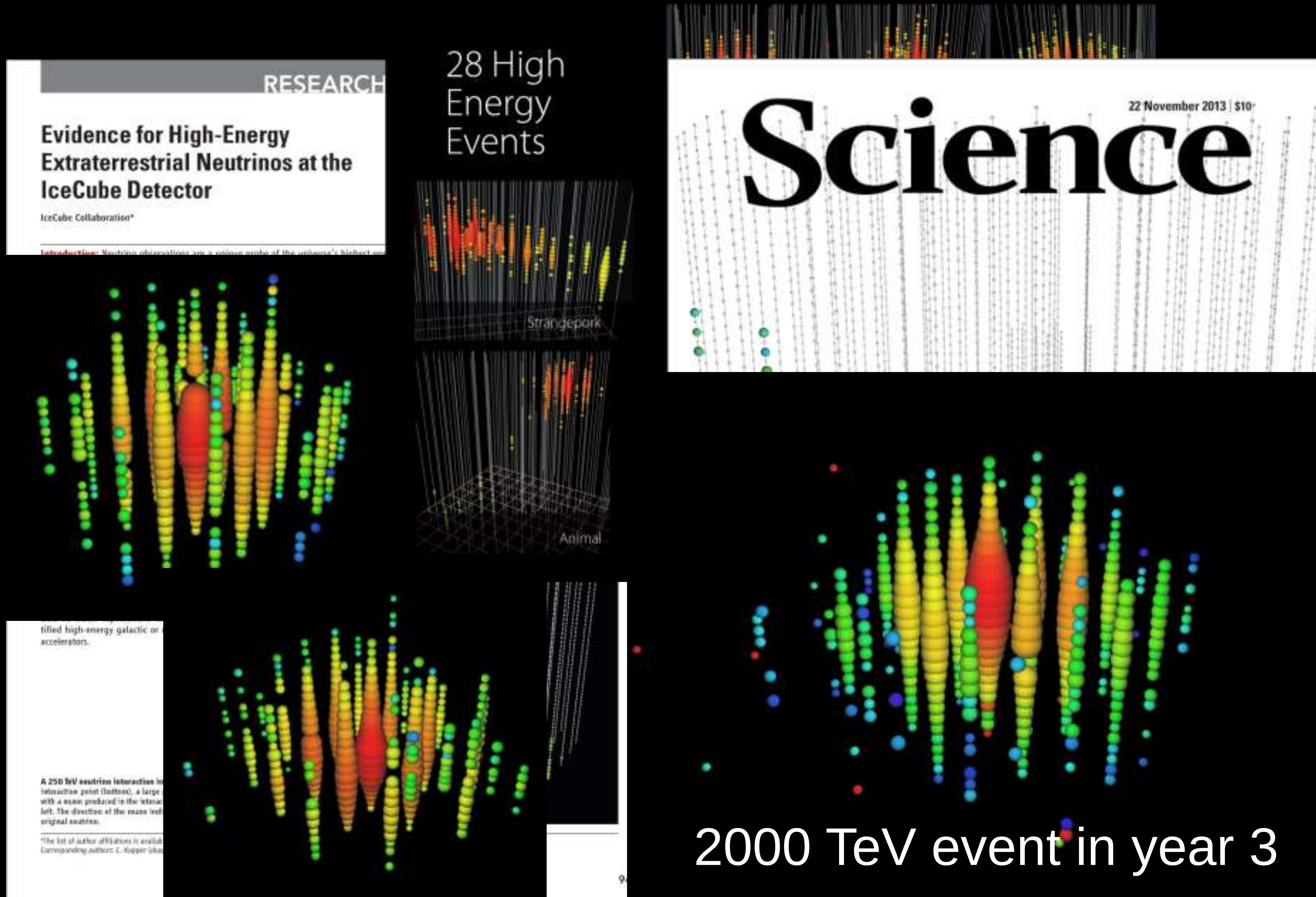
data: 86 strings one year

…and then there were 26 more…



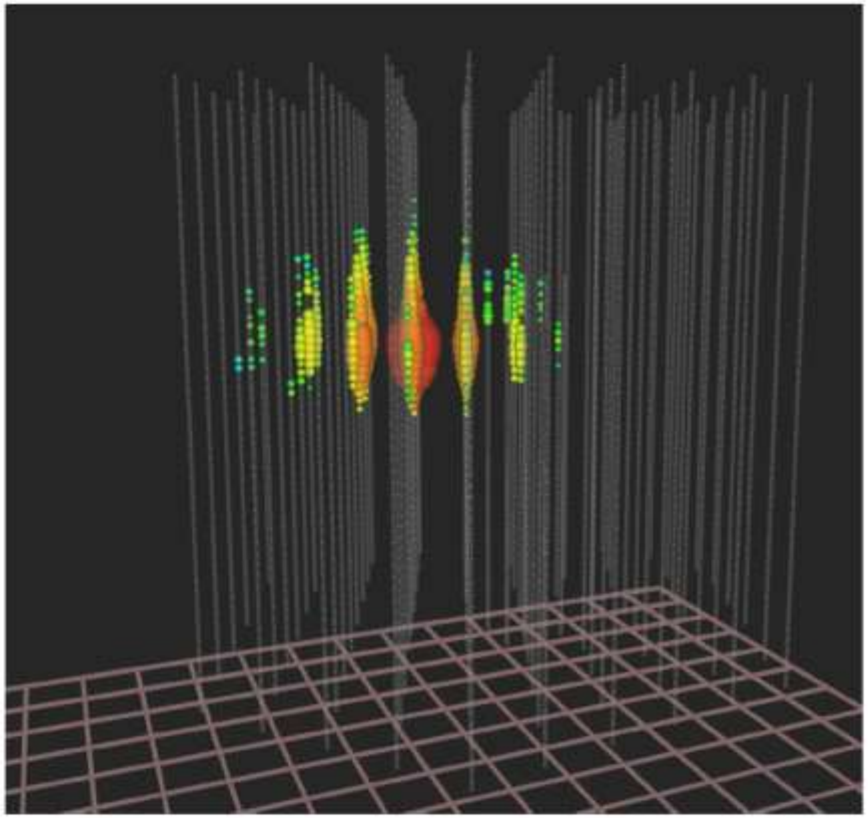
data: 86 strings one year

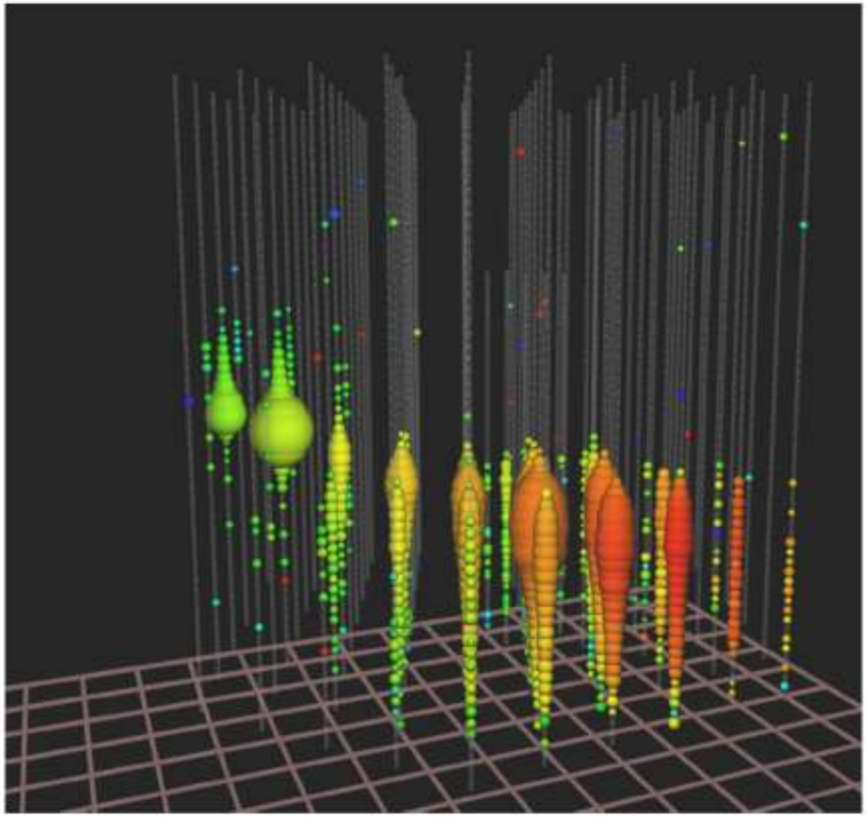
2 old + 26 new events



2000 TeV event in year 3

are the two observations consistent?

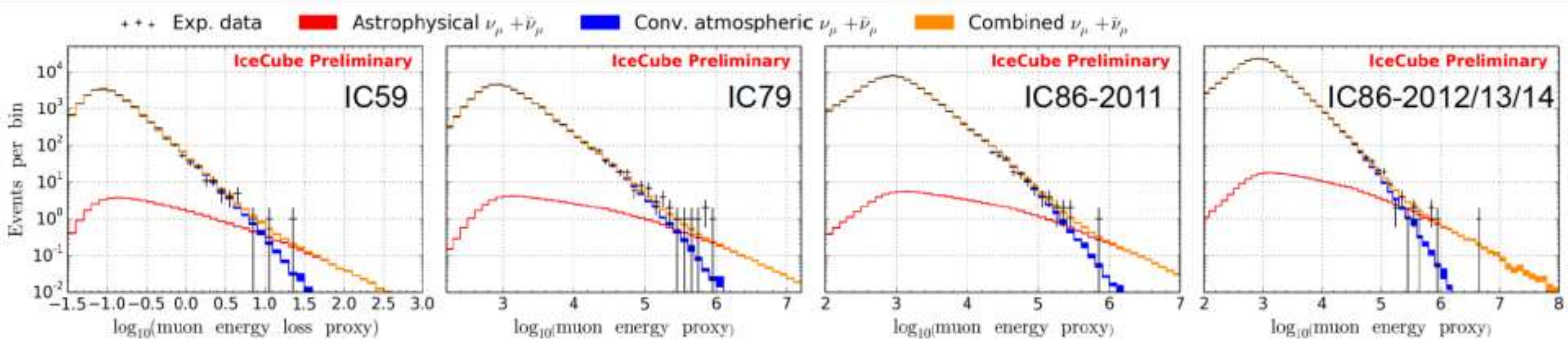




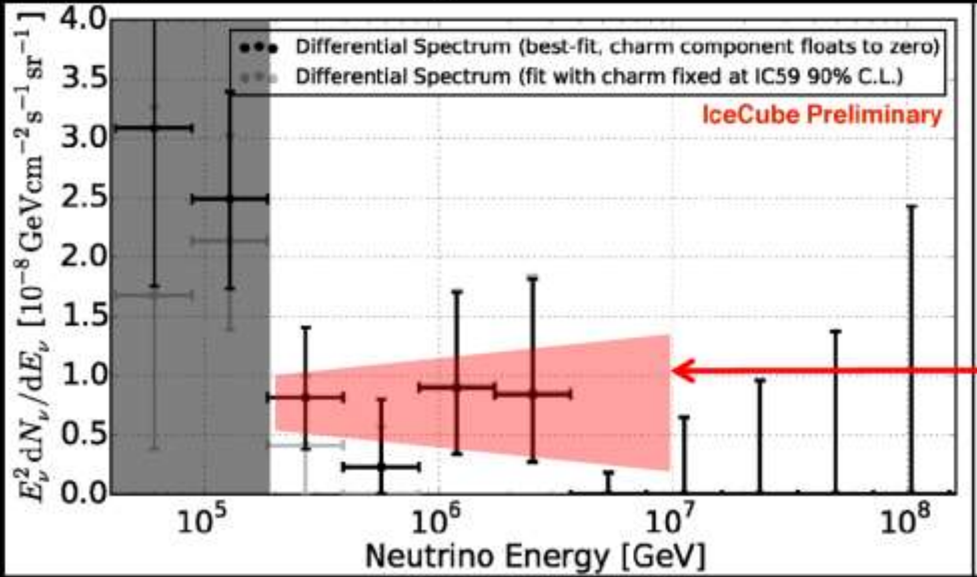
total energy measurement
all flavors, all sky

astronomy: angular resolution
superior (<0.4º)

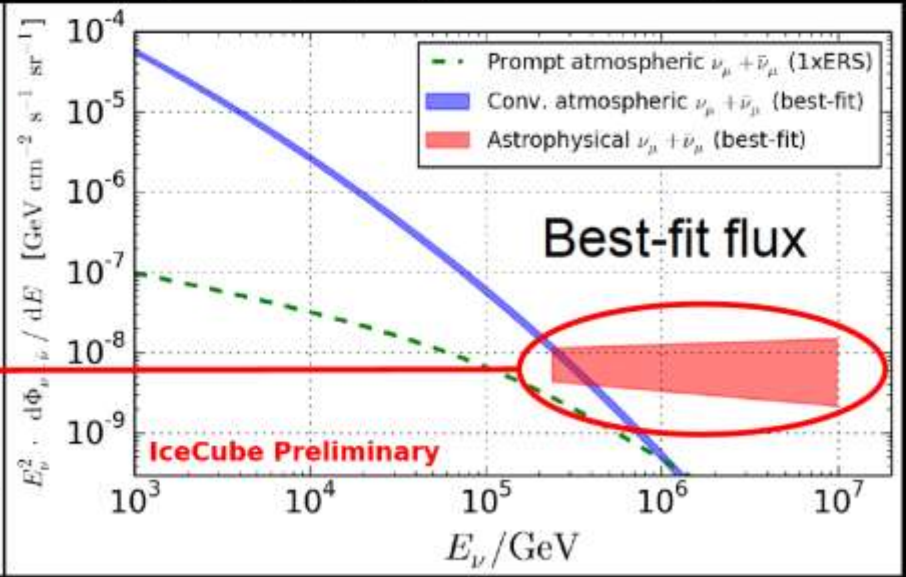
after 6 years: 3.7→ 6.0 sigma

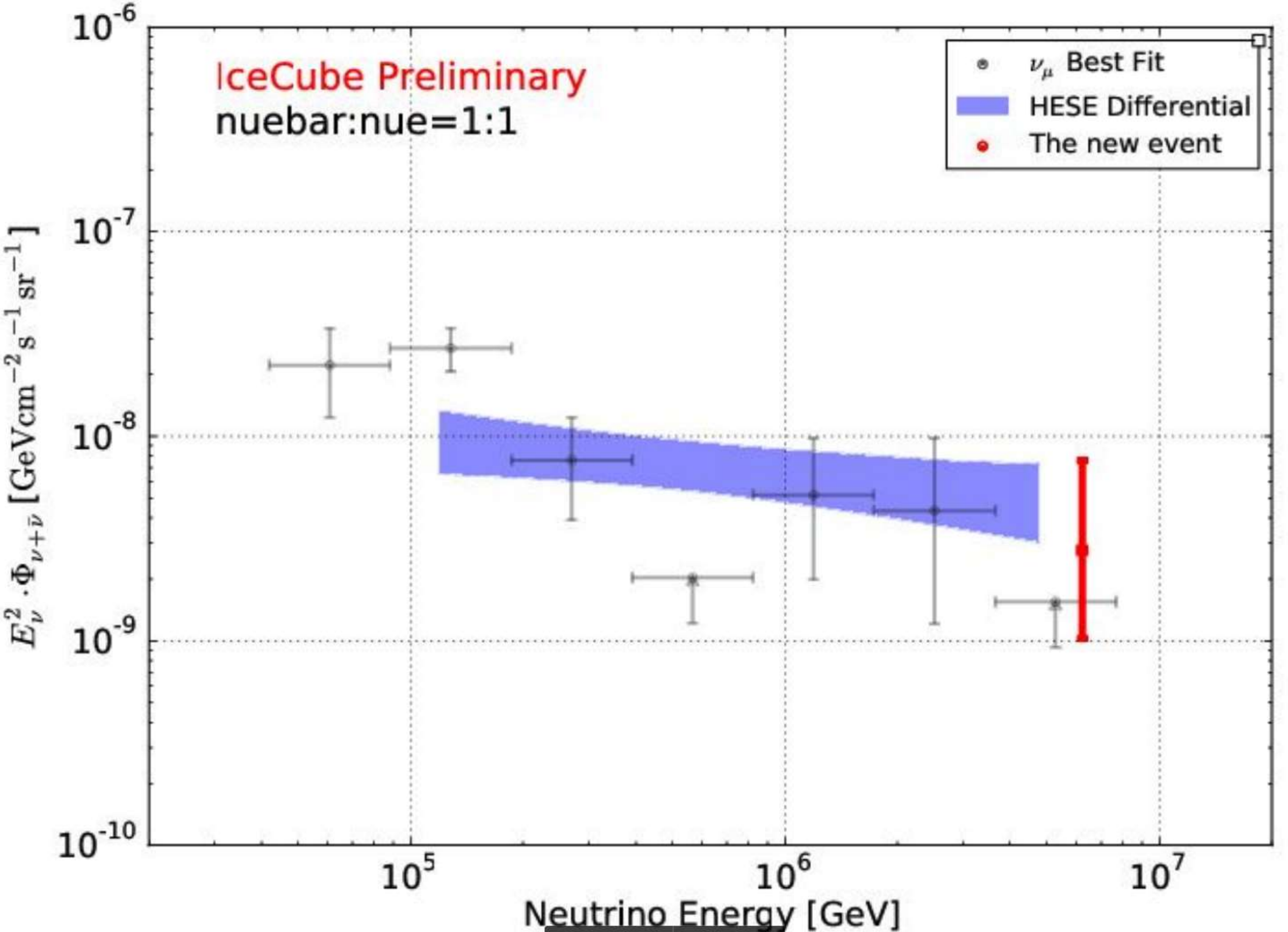


HESE 4 year unfolding
(→ dominated by shower-like events)



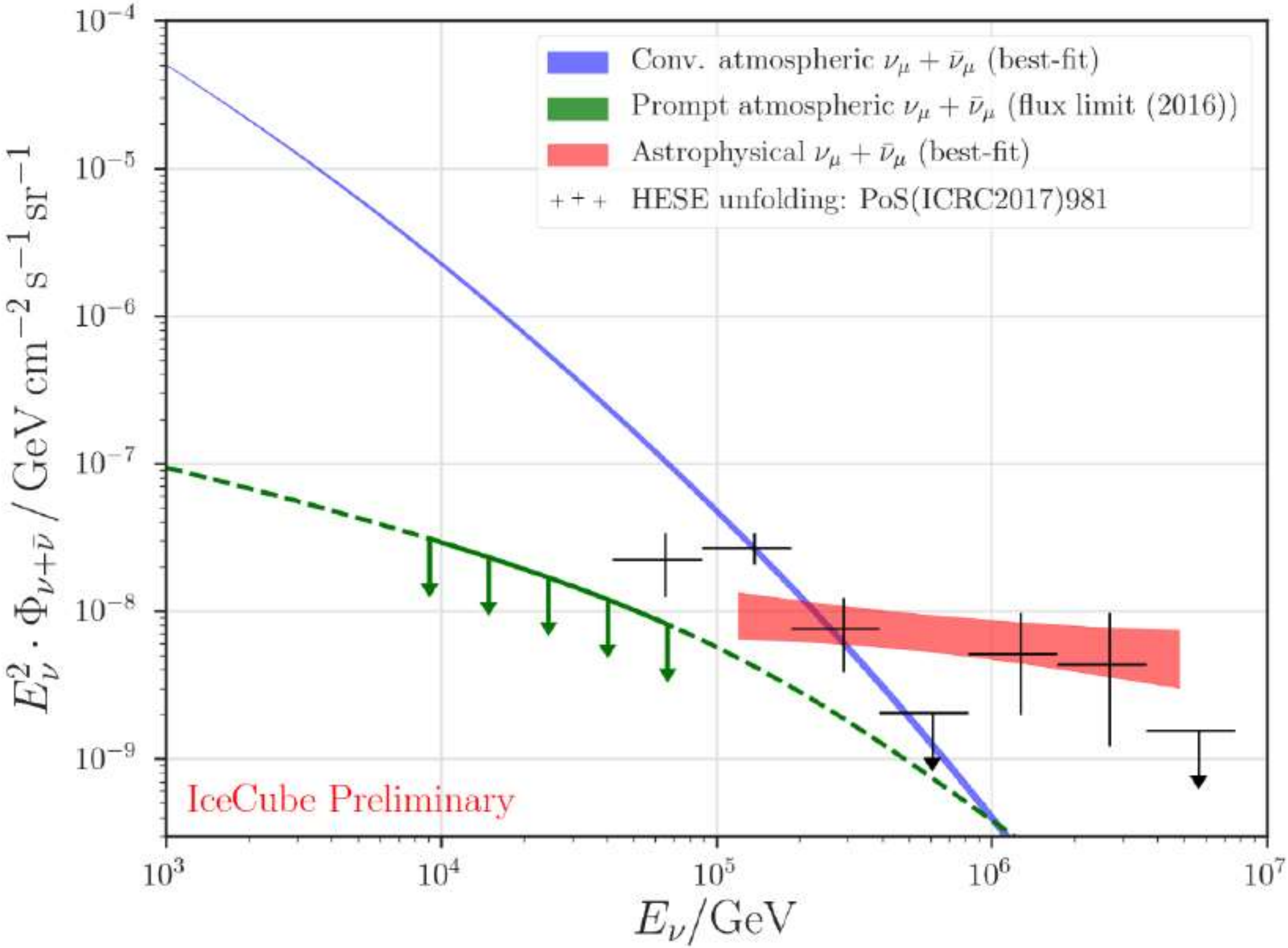
6 year up-going numu analysis





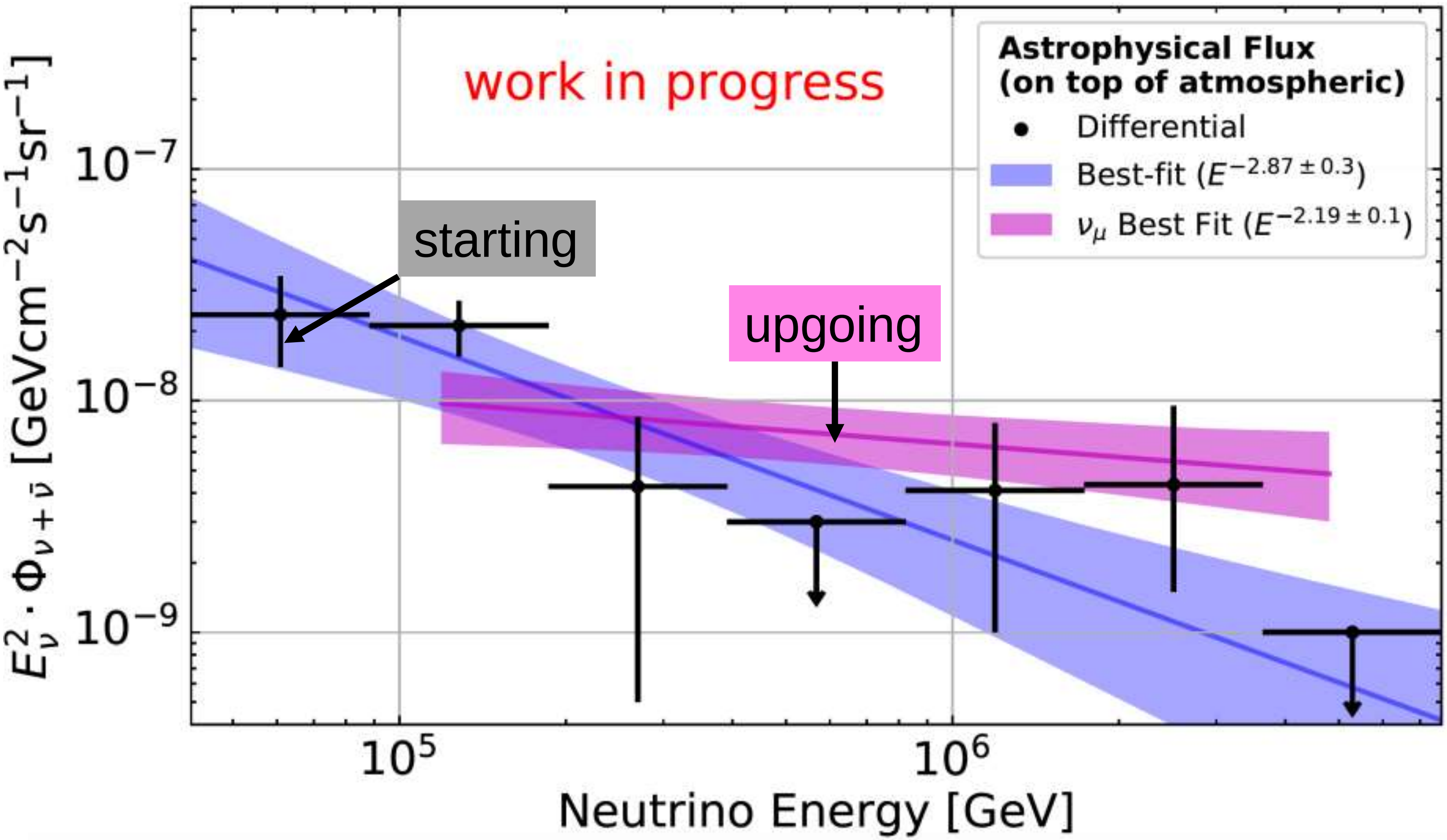
IceCube Preliminary
nuebar:nue=1:1
ν_μ Best Fit
HESE Differential
The new event
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{5}
10^{6}
10^{7}
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [$\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$]
Neutrino Energy [GeV]

Page 3 / 8



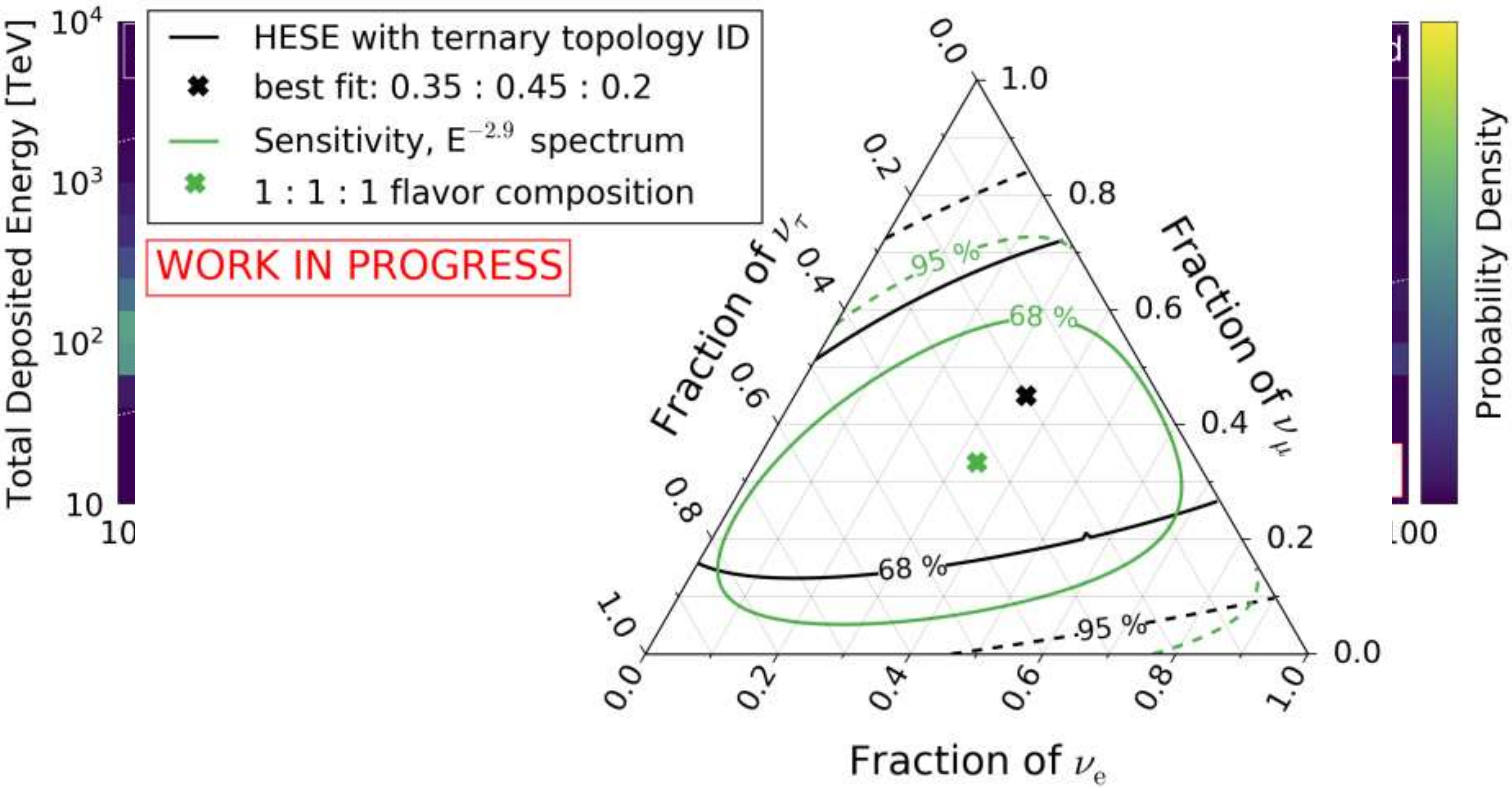
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ / GeV cm^{-2} s^{-1} sr^{-1}
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
Prompt atmospheric $\nu_\mu + \bar{\nu}_\mu$ (flux limit (2016))
Astrophysical $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
HESE unfolding: PoS(ICRC2017)981
IceCube Preliminary
10^3
10^4
10^5
10^6
10^7
E_ν/GeV

high-energy starting events – 7.5 yr

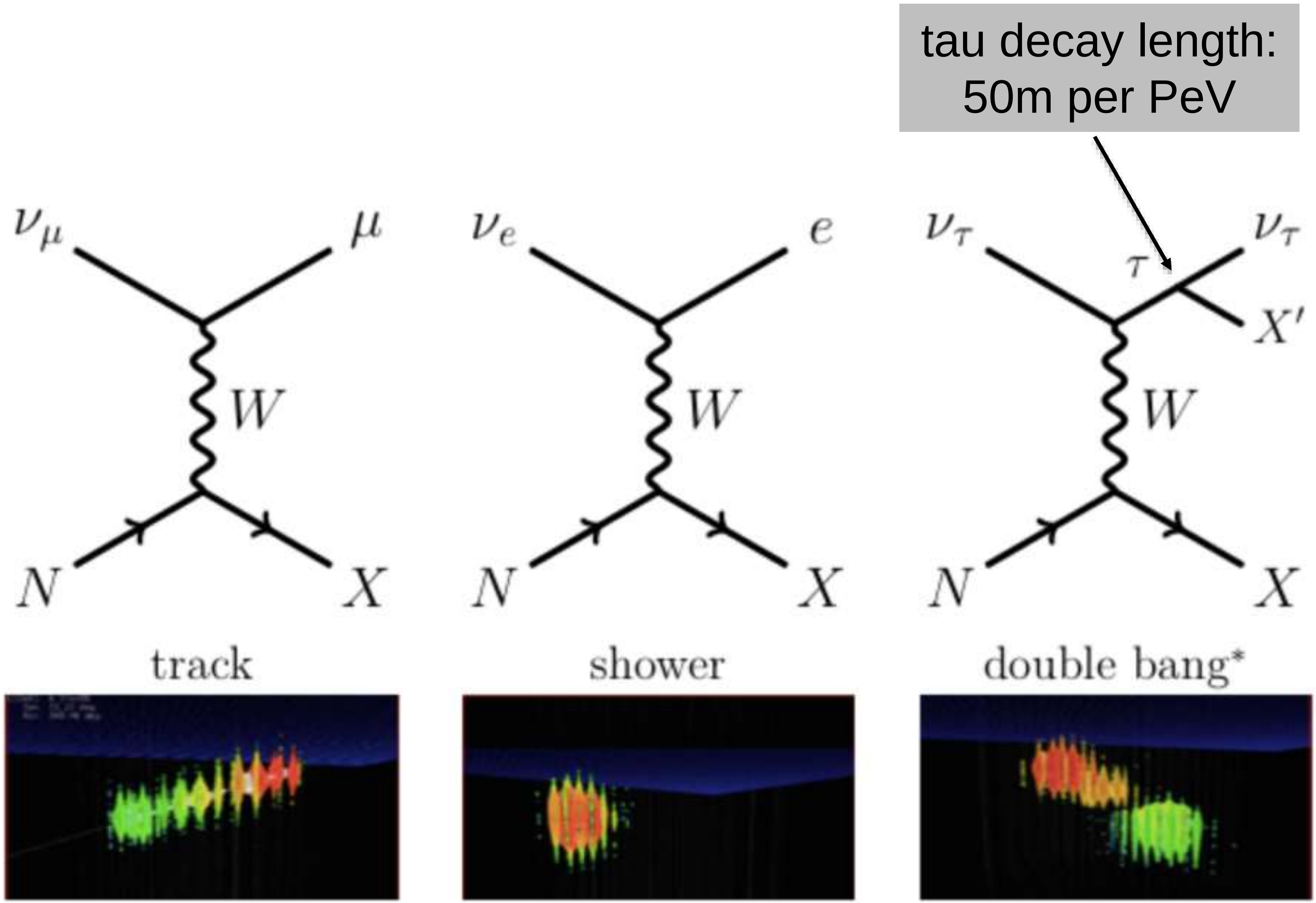


- two methods are consistent
- excess cosmic flux < 100 TeV?

high-energy starting events – 7.5 yr

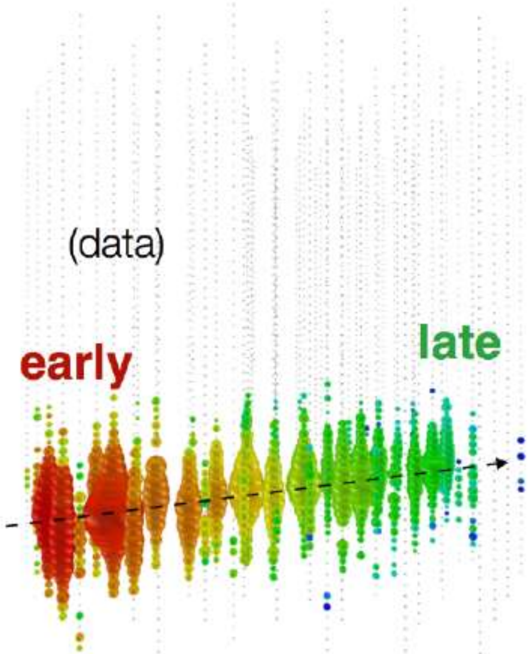


oscillations of PeV neutrinos over cosmic distances to 1:1:1


tau decay length:
50m per PeV
ν_μ
μ
W
N
X
track
ν_e
e
W
N
X
shower
ν_τ
τ
ν_τ
X'
W
N
X
double bang*

event topologies

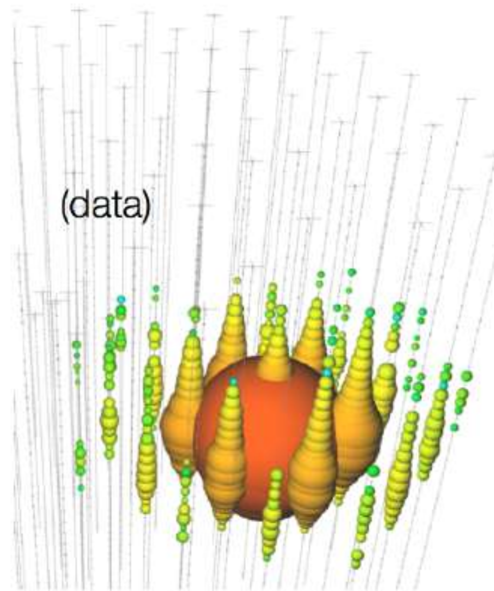
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

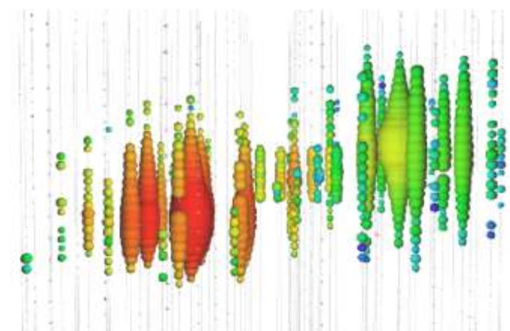


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

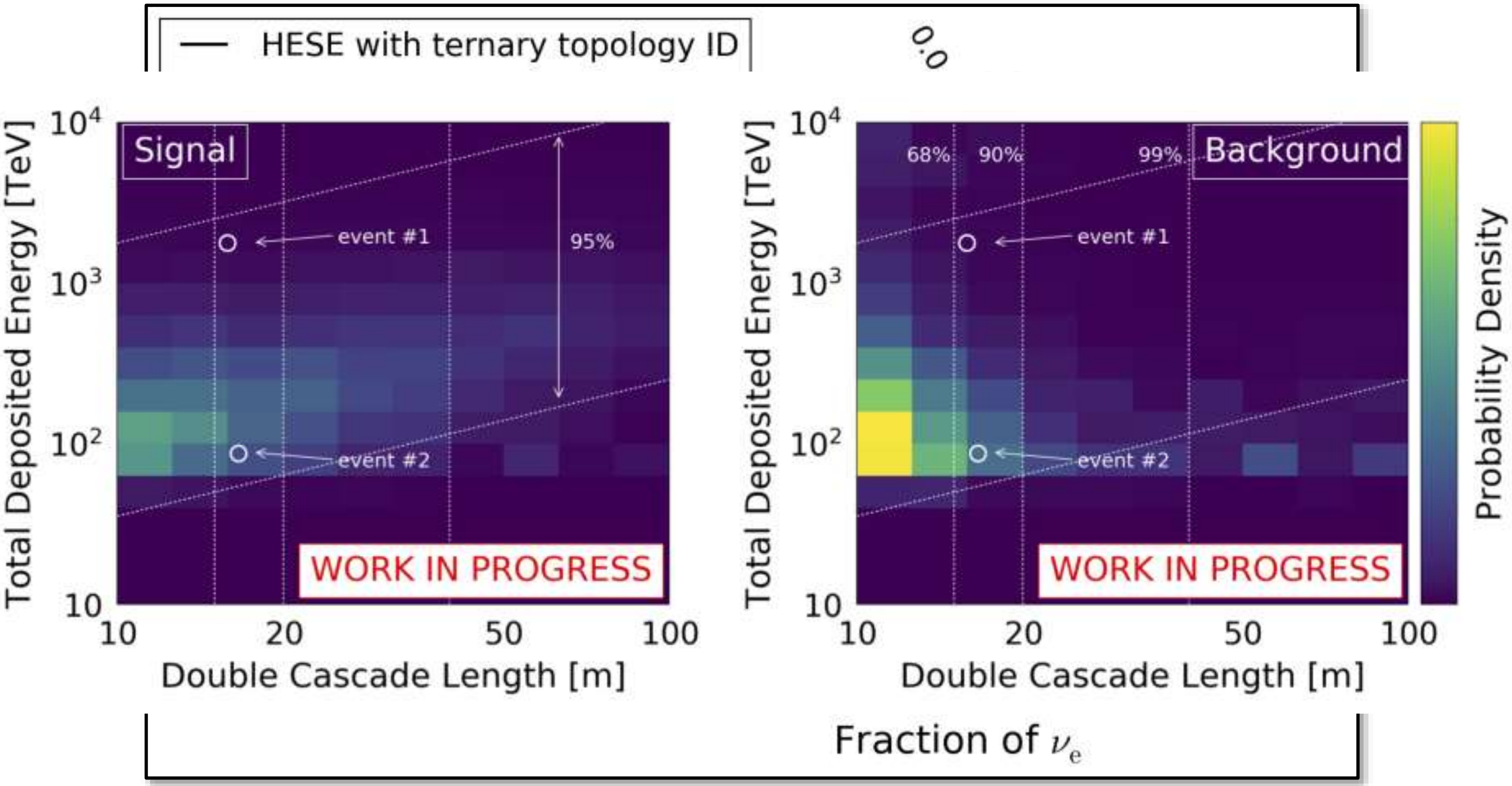
(simulation)



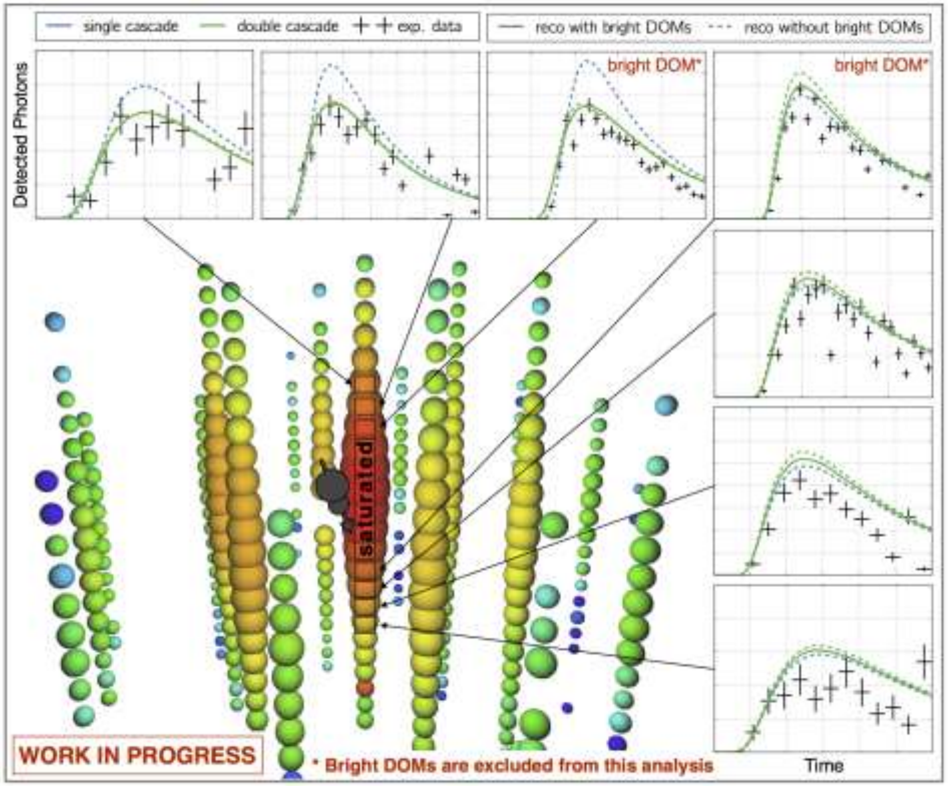
Double cascade

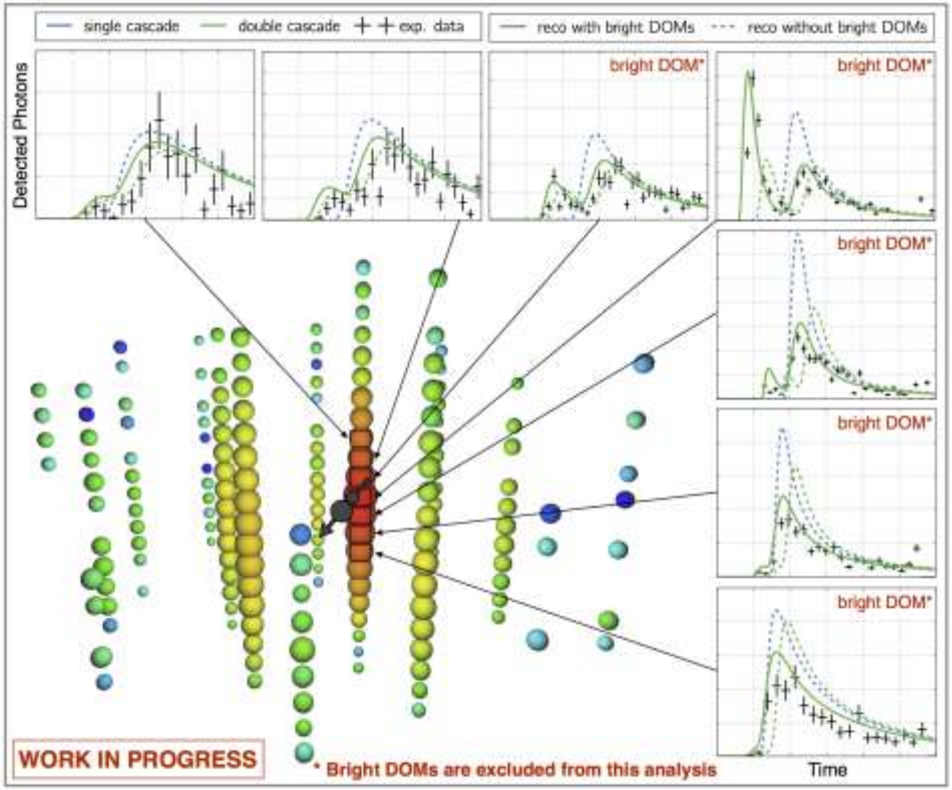
(resolvable above ~100 TeV deposited energy)

high-energy starting events – 7.5 yr



high-energy starting events (starting) – 7.5 yr

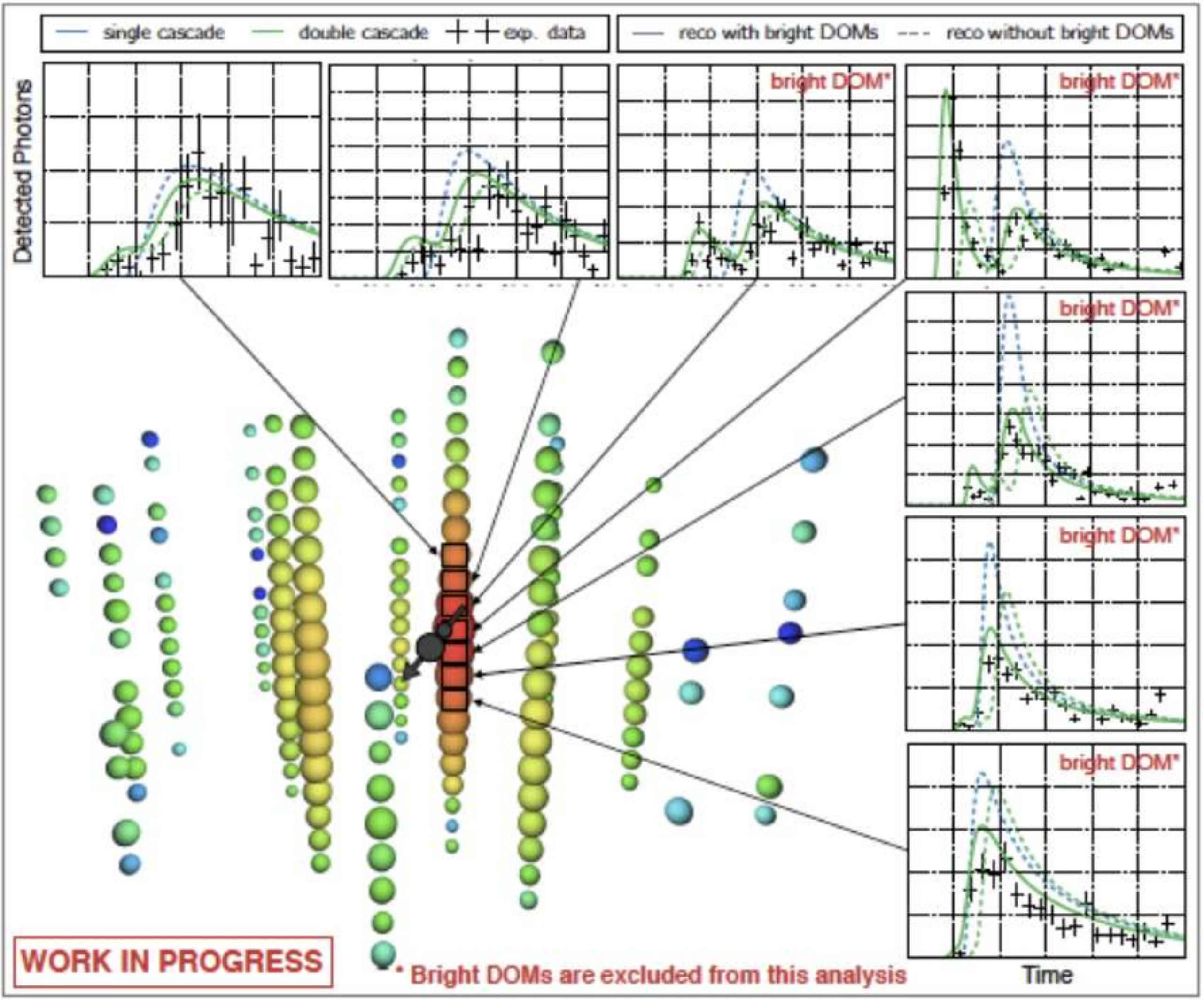


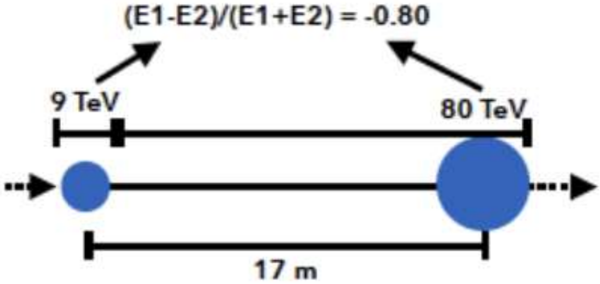


Double cascade Event #1

Double cascade Event #2

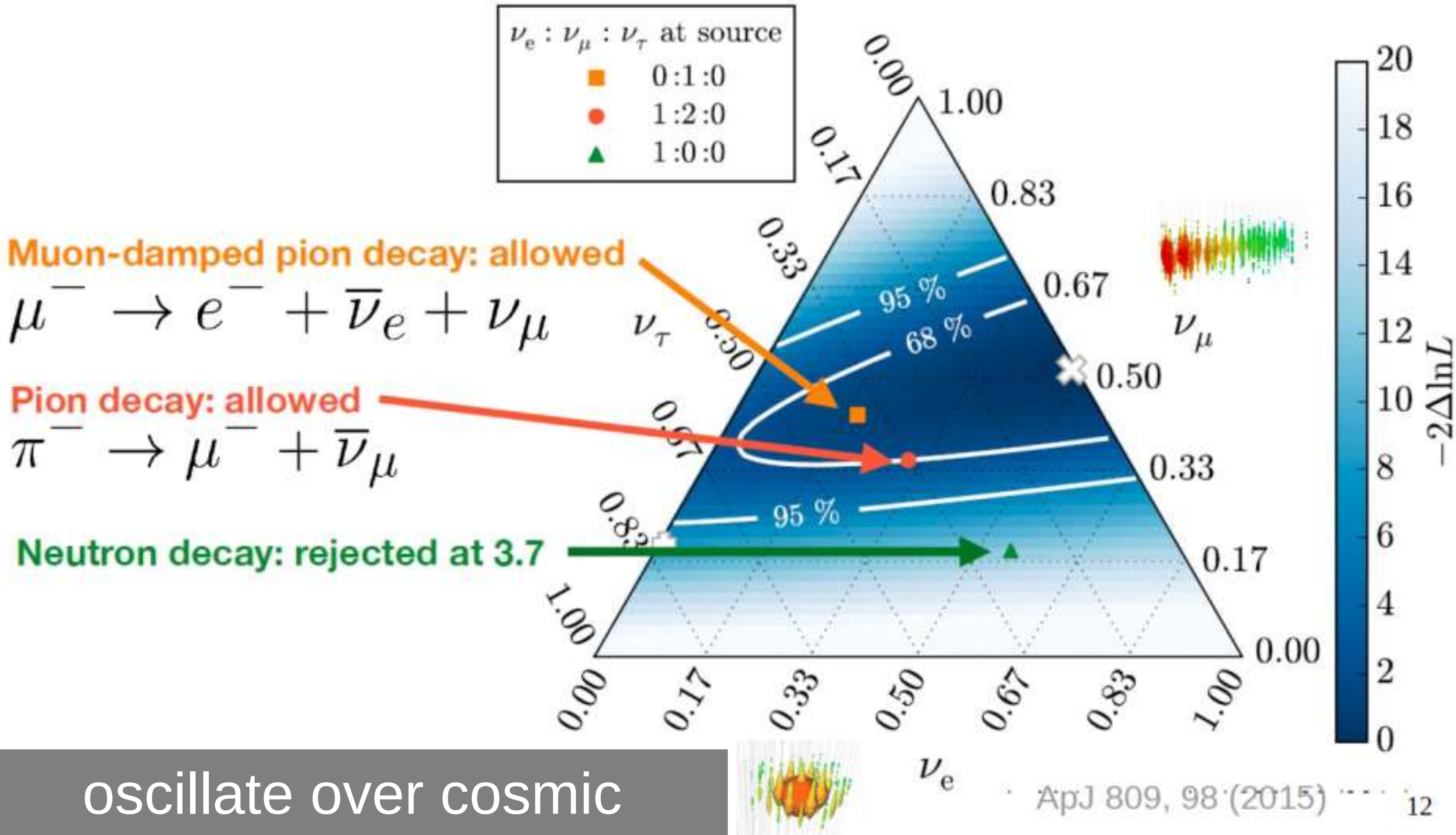
“Bright” DOMs not used in reconstruction
Direction and two reconstructed cascades shown in dark gray





- Observed 2014
- Observed light arrival pattern clearly favors double cascade hypothesis

- Different event signatures allow flavor separation → primarily μ vs. e, τ



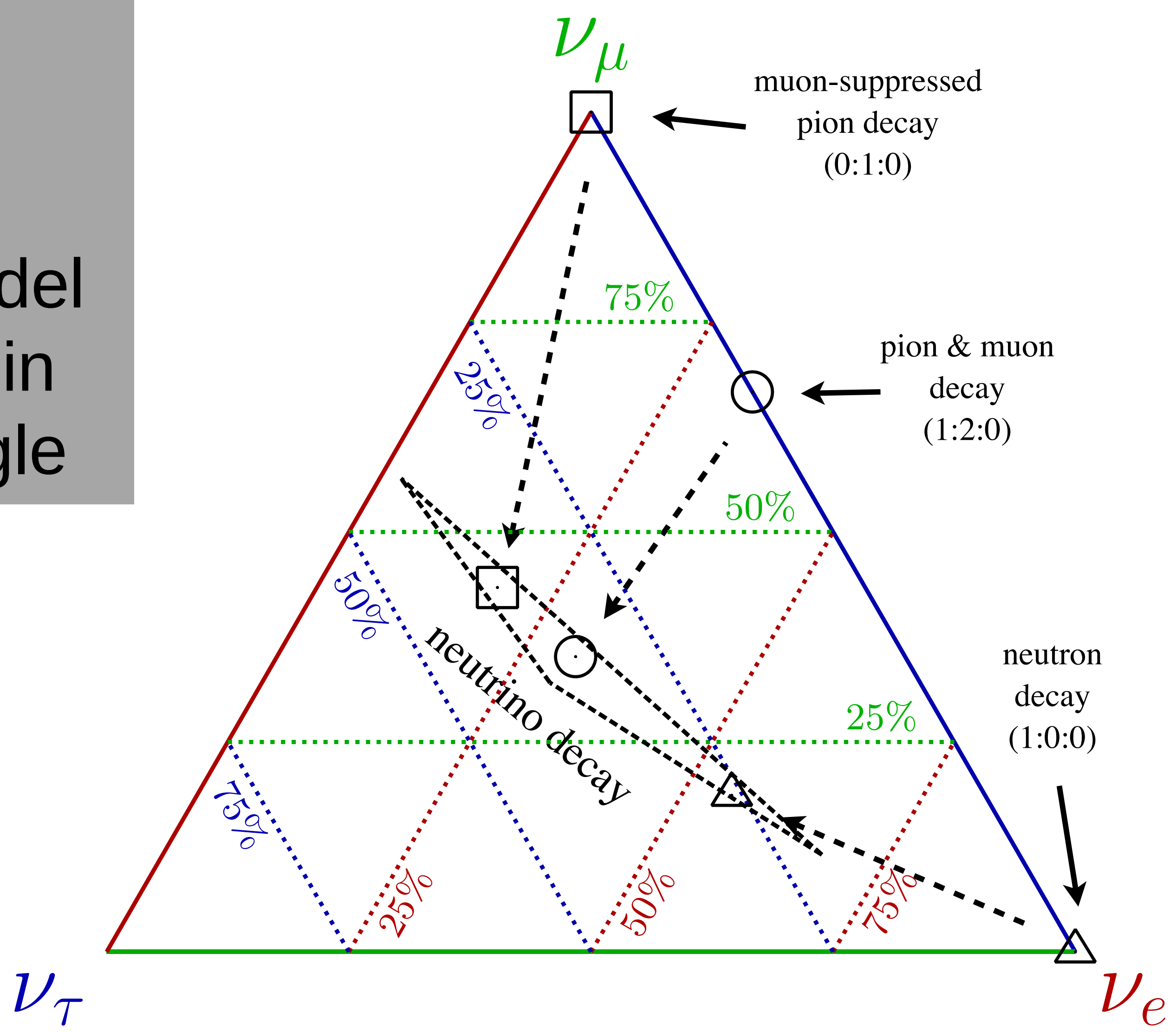
oscillate over cosmic distances to 1:1:1

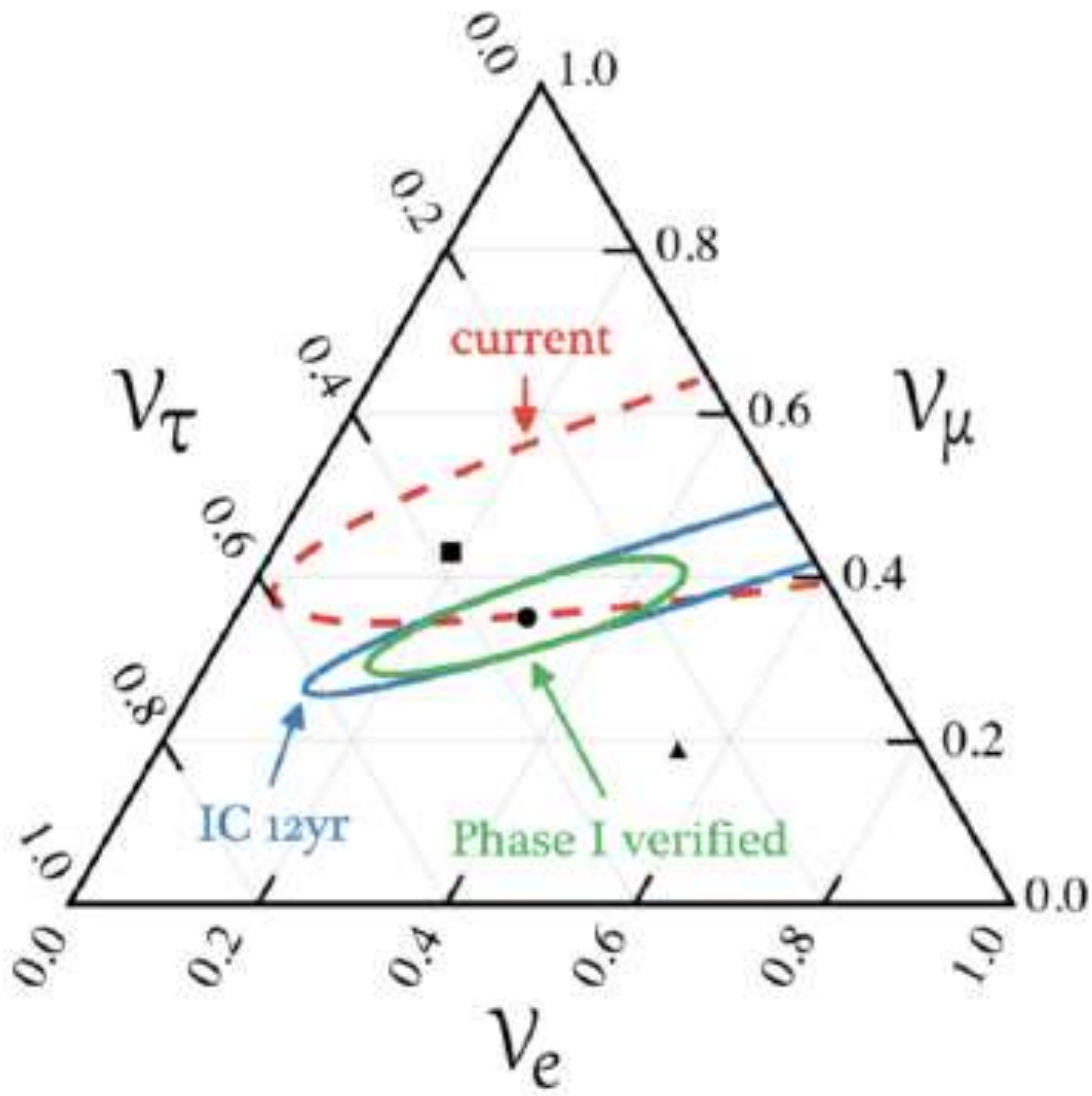
ApJ 809, 98 (2015)

new physics ?

if not…

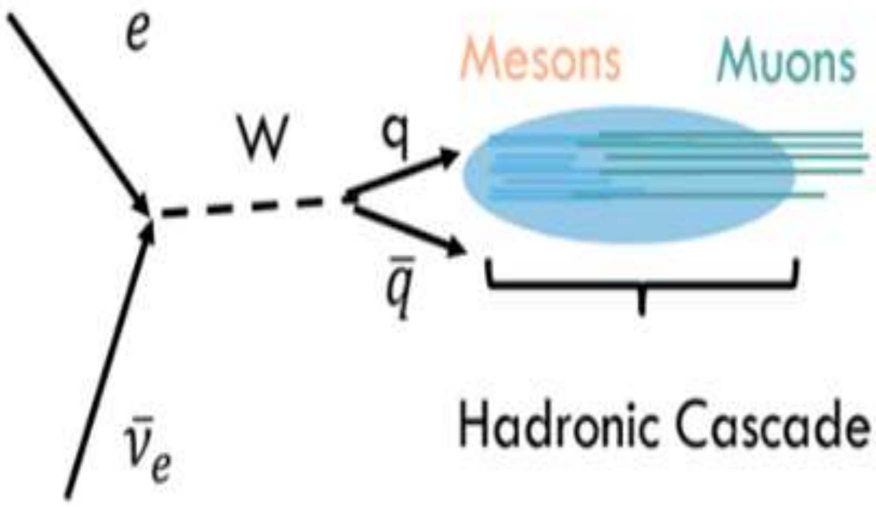
every model ends up in the triangle

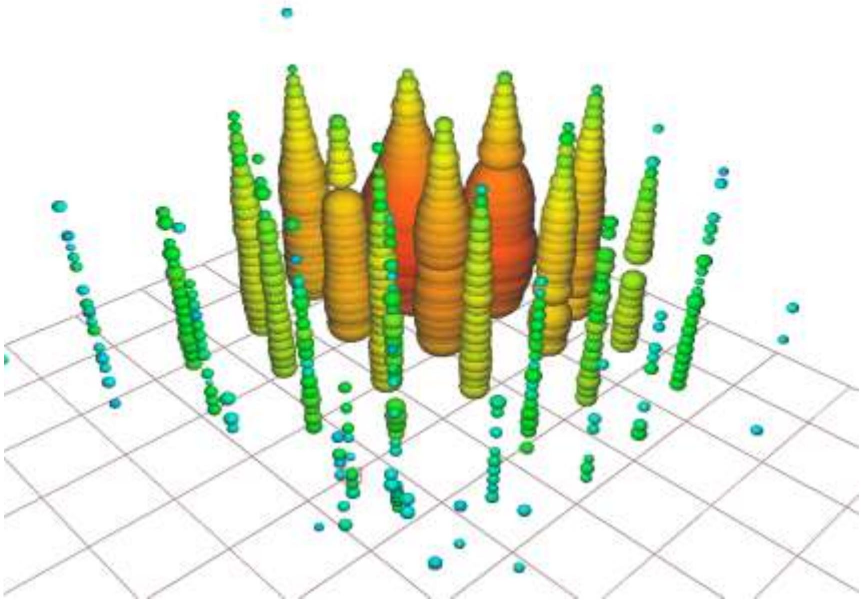


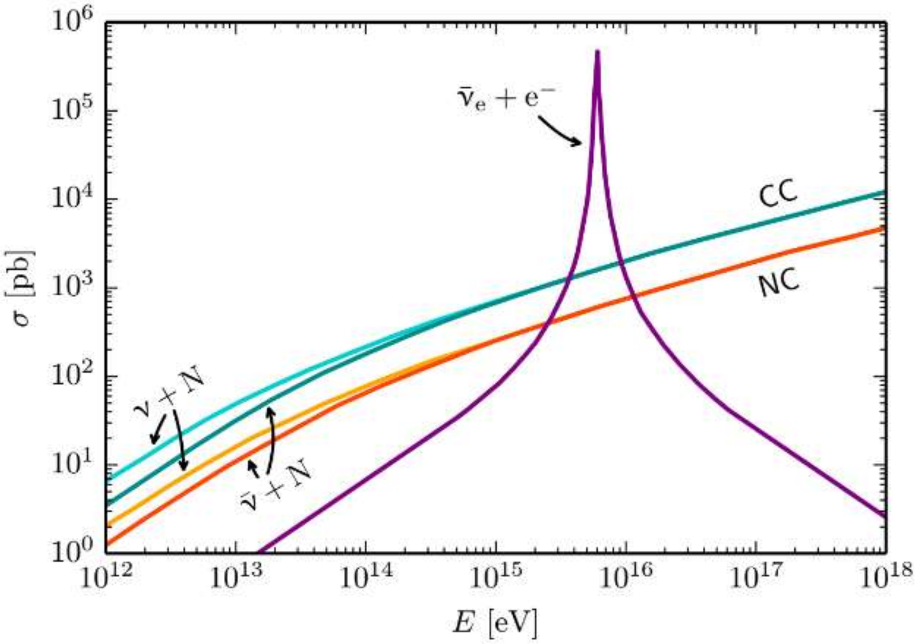


current
IC 12yr
Phase I verified
ν_τ
ν_μ
ν_e
0.0
0.2
0.4
0.6
0.8
1.0

Glashow resonance: anti-ν_e + atomic electron → real W







- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

- → resonance: E_ν = 6.3 PeV

work on-going

the first Glashow resonance event:

anti-ν_e + atomic electron → real W at 6.3 PeV

Resonant Scattering of Antineutrinos

SHELDON L. GLASHOW*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e\rightarrow\bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim2\times10^{12}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

THE interaction responsible for muon decay also permits an inelastic scattering of antineutrinos

coupling strengths of the Z meson to muon and electron currents chosen equal (in accordance with universality)

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power of the coupling constant of Z mesons to leptons, the average cross section near the resonance,

$$\frac{1}{2\Delta}\int_{E_0-\Delta}^{E_0+\Delta}\sigma(E)dE\cong\frac{\pi}{4}\left(\frac{E_0}{\Delta}\right)\left(\frac{E_0}{\Gamma}\right)\sigma_0,$$

depends only upon its square. If the Z-meson mass is not much greater than that of the nucleon, this enhanced cross section is not necessarily beyond experimental reach. We shall consider only values of the Z-meson mass such that $m_K\leqslant m_Z\leqslant m_N$, since smaller values of m_Z would prohibit the use of the Z meson to mediate K-meson decays.

The principal decay modes of the Z meson are expected to be $Z^-\rightarrow e+\bar{\nu}$ and $Z^-\rightarrow\mu^-+\bar{\nu}$. With

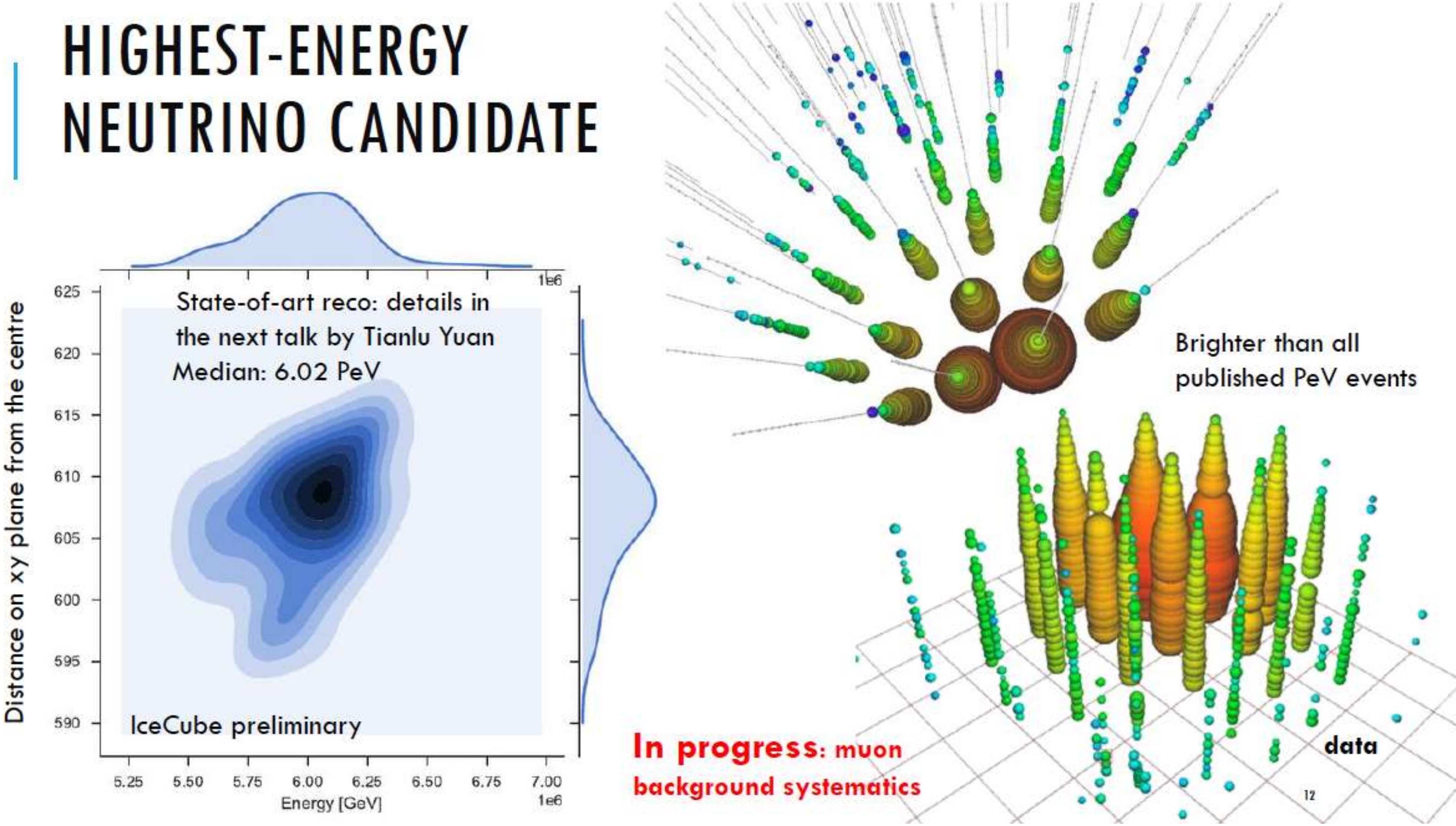
at 9×10^{11} ev the antineutrino flux is 10^{-11} cm^{-2} sec^{-1} Bev^{-1}, and at 2.3×10^{11} ev it is 10^{-9} cm^{-2} sec^{-1} Bev^{-1}. Exposed to these antineutrino fluxes, each target electron will act as a source of 4×10^{-40} muon per second if $m_Z=m_N$, or 10^{-38} muon per second at the lower value of $m_Z=m_K$.

With a muon-sensitive area of one square meter, placed underground, the experimenter might anticipate a counting rate of two per day (at $m_Z=m_K$) or of 0.1 per day (at $m_Z=m_N$) independently of the depth at which the experiment is performed. The counting rate should be relatively insensitive to the orientation of the experimental apparatus with respect to the vertical, since the muons should be produced isotropically in the

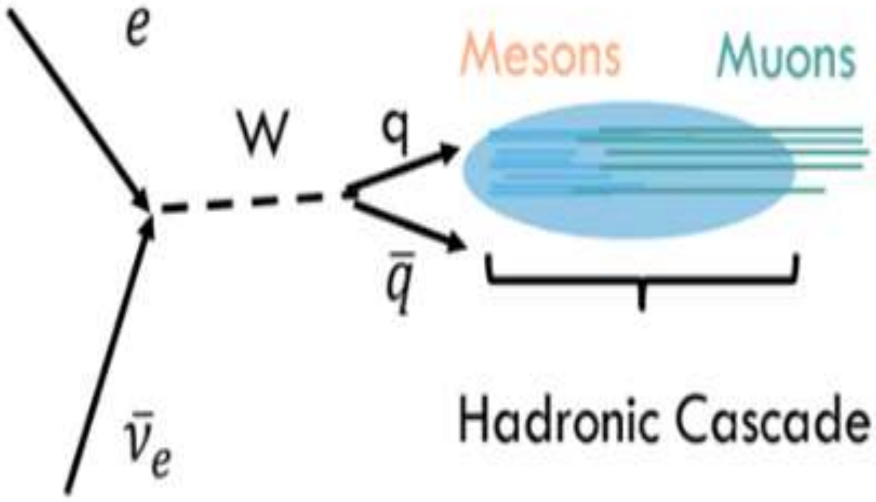
* National Science Foundation Post-Doctoral Fellow.

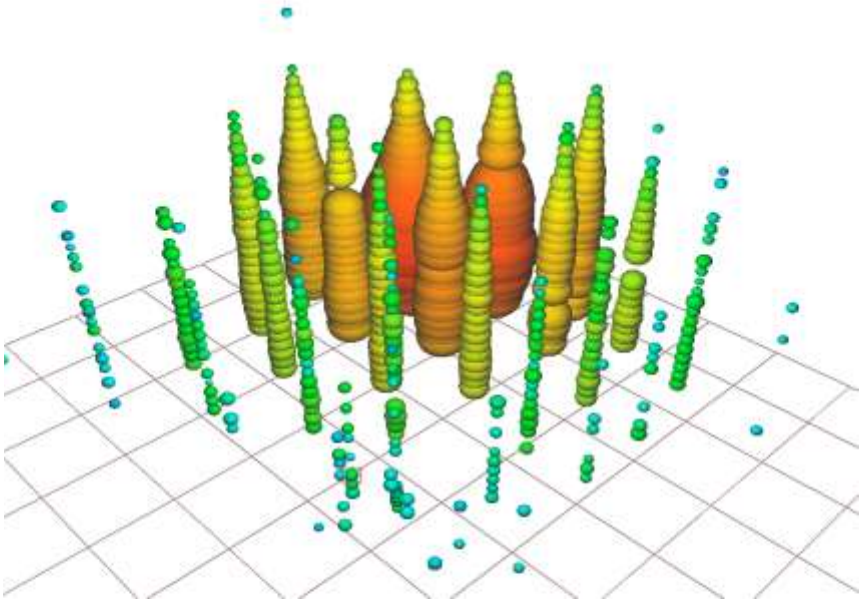
[1] A. Subramanian and S. D. Verma, Nuovo cimento 8, 572 (1959).

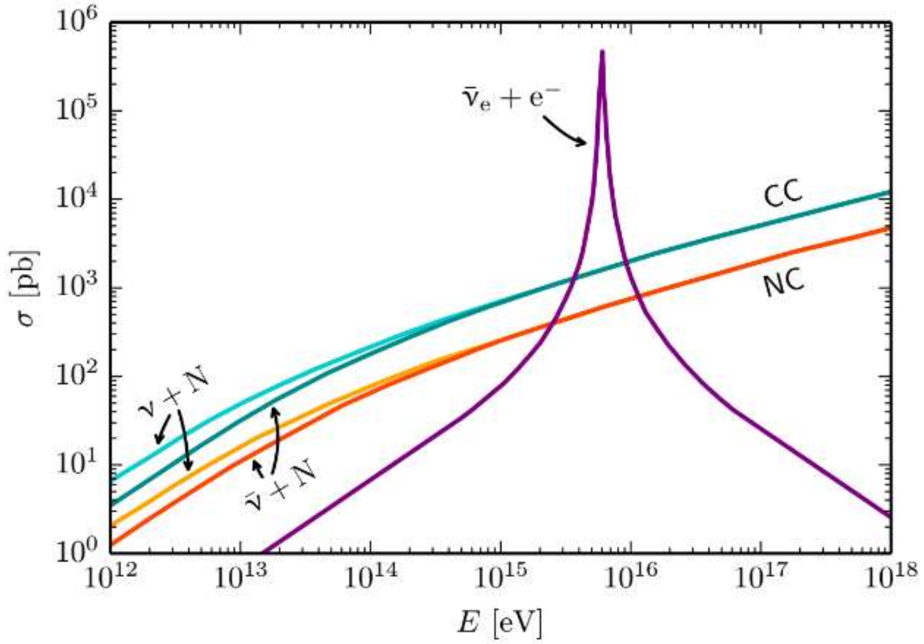
Partially contained event with energy ~ 6 PeV



Glashow resonance: anti-ν_e + atomic electron → real W







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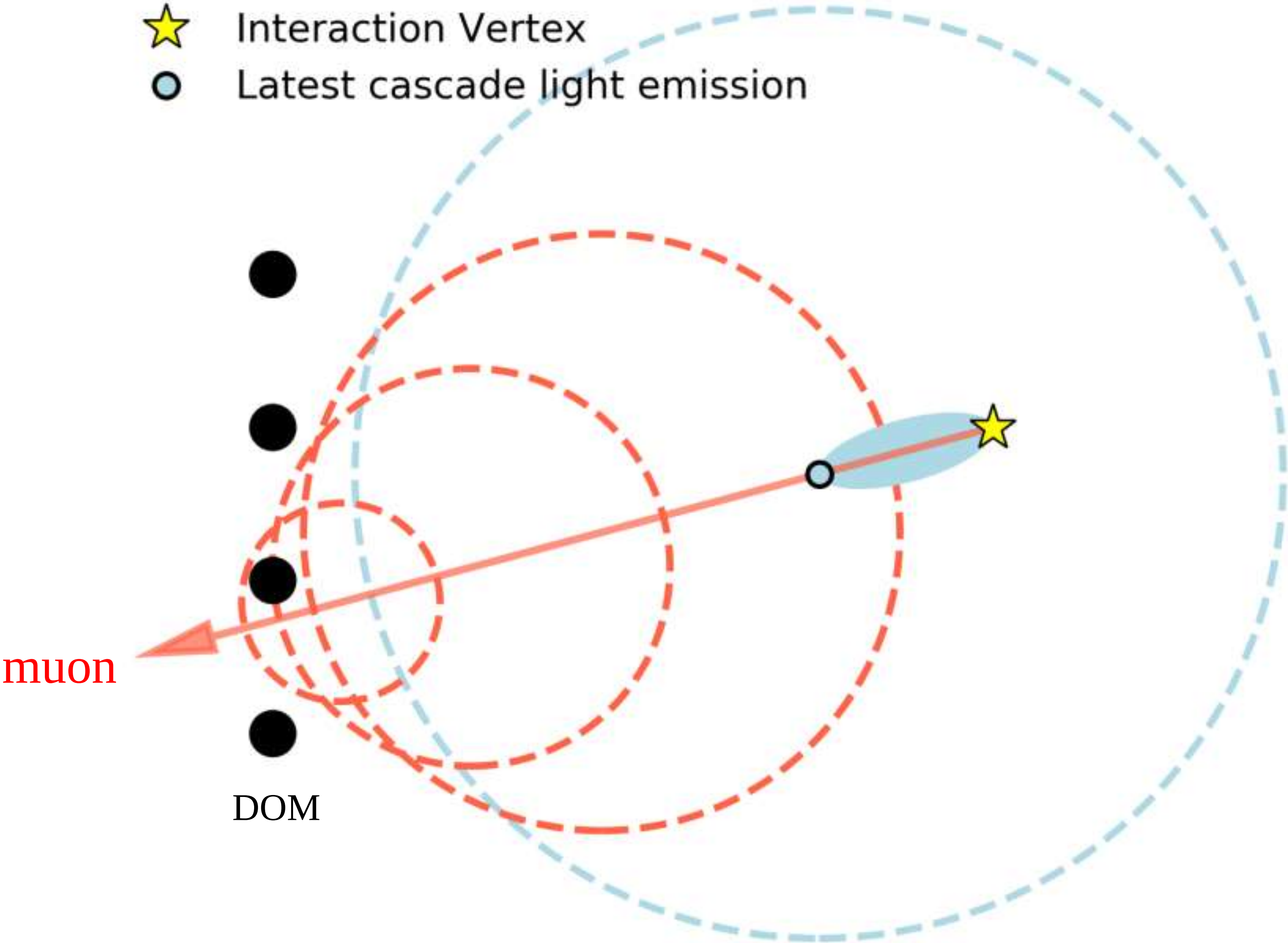
work on-going

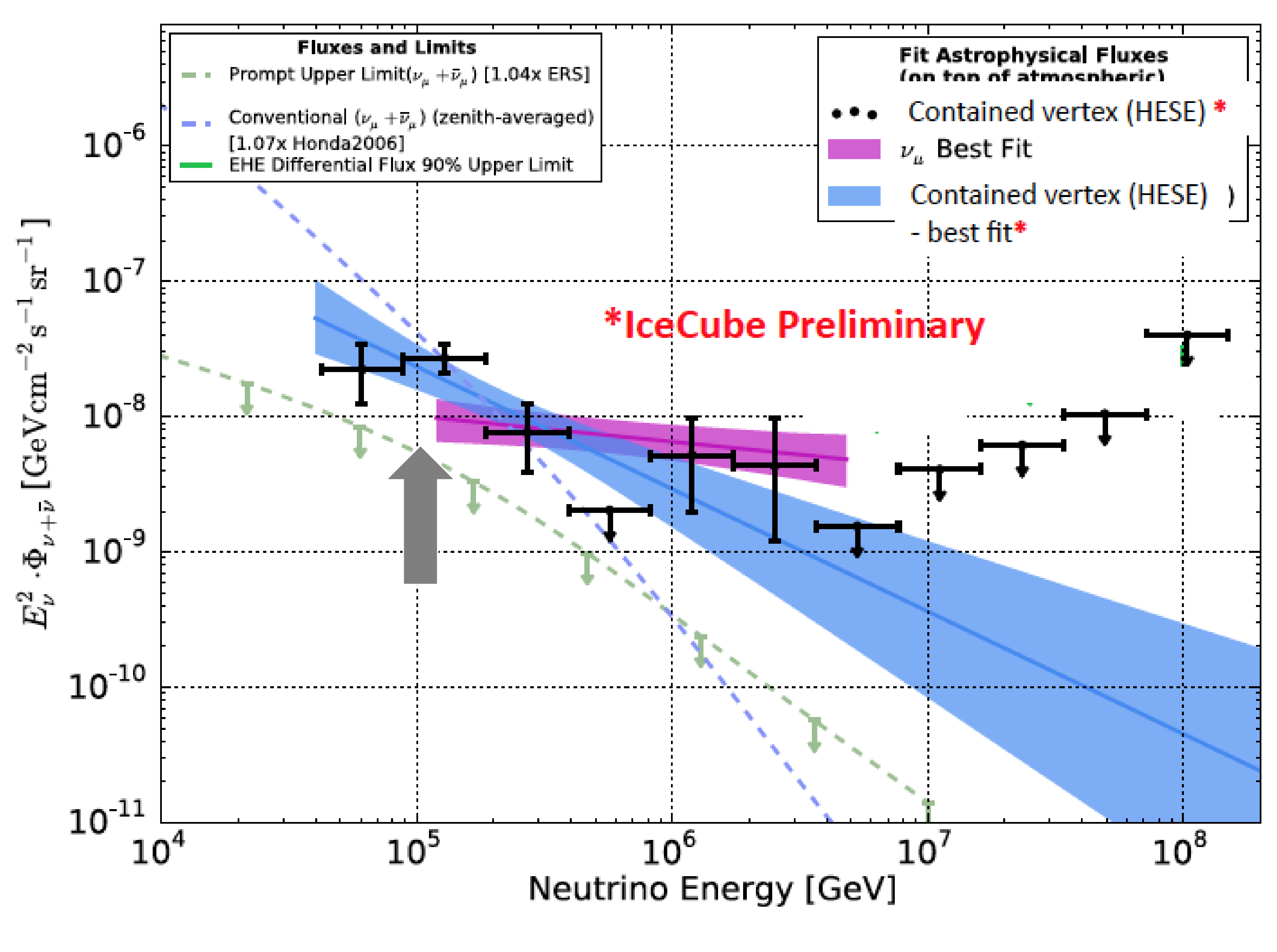

Interaction Vertex
Latest cascade light emission
muon
DOM

Glashow resonance dictates ν_e– ν_τ mixture events per year:

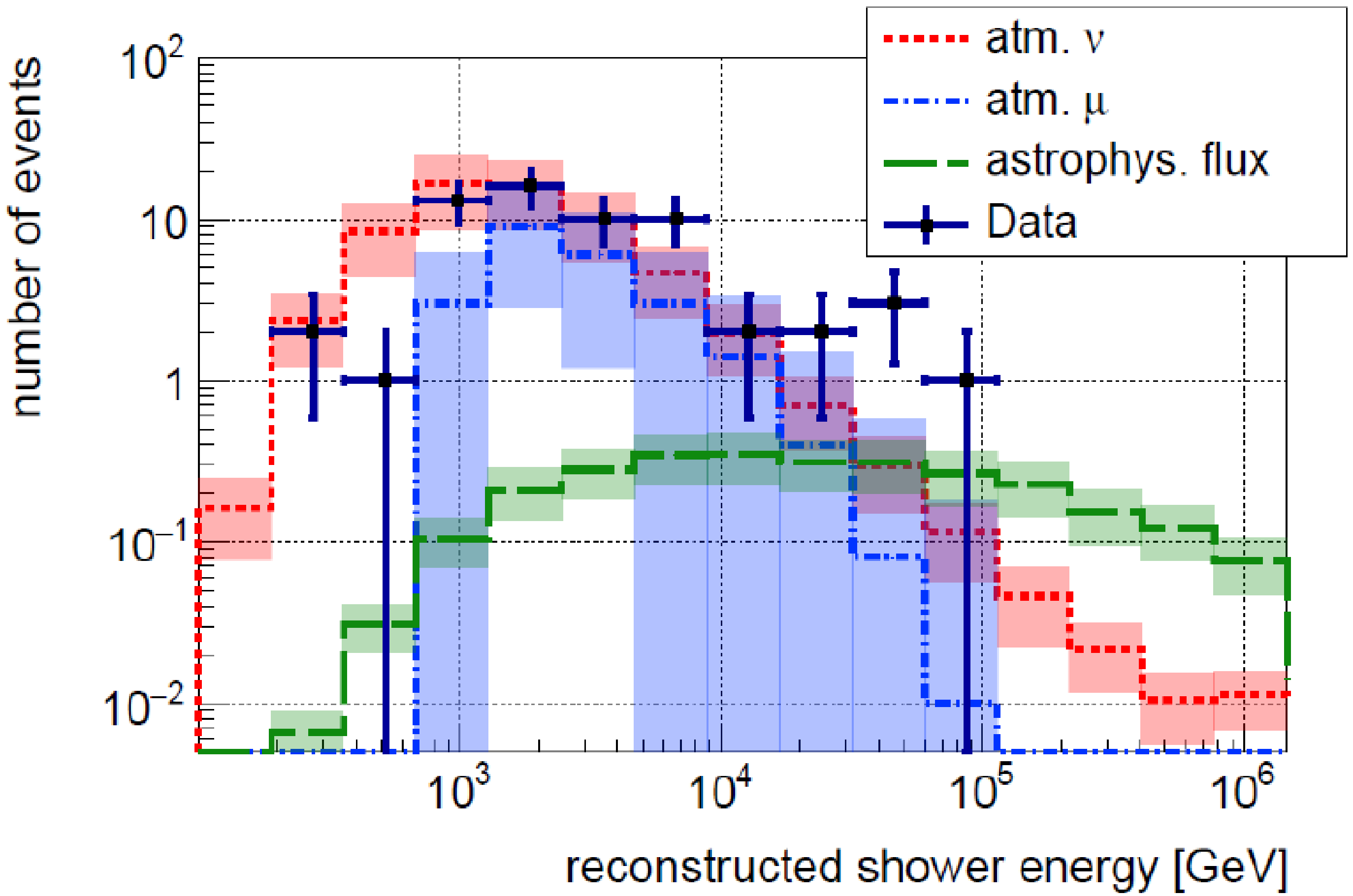
Φ_{ν_e} $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$	interaction type	pp source IC-86	240m	360m
$1.0 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.0}$	GR	0.88	7.2	16
	DIS	0.09	0.8	1.6
$1.5 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.3}$	GR	0.38	3.1	6.8
	DIS	0.04	0.3	0.7
$2.4 \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.7}$	GR	0.12	0.9	2.1
	DIS	0.01	0.1	0.2

$$\overline{n}_e + e^- \rightarrow W$$

- cosmic neutrinos below 100 TeV ?

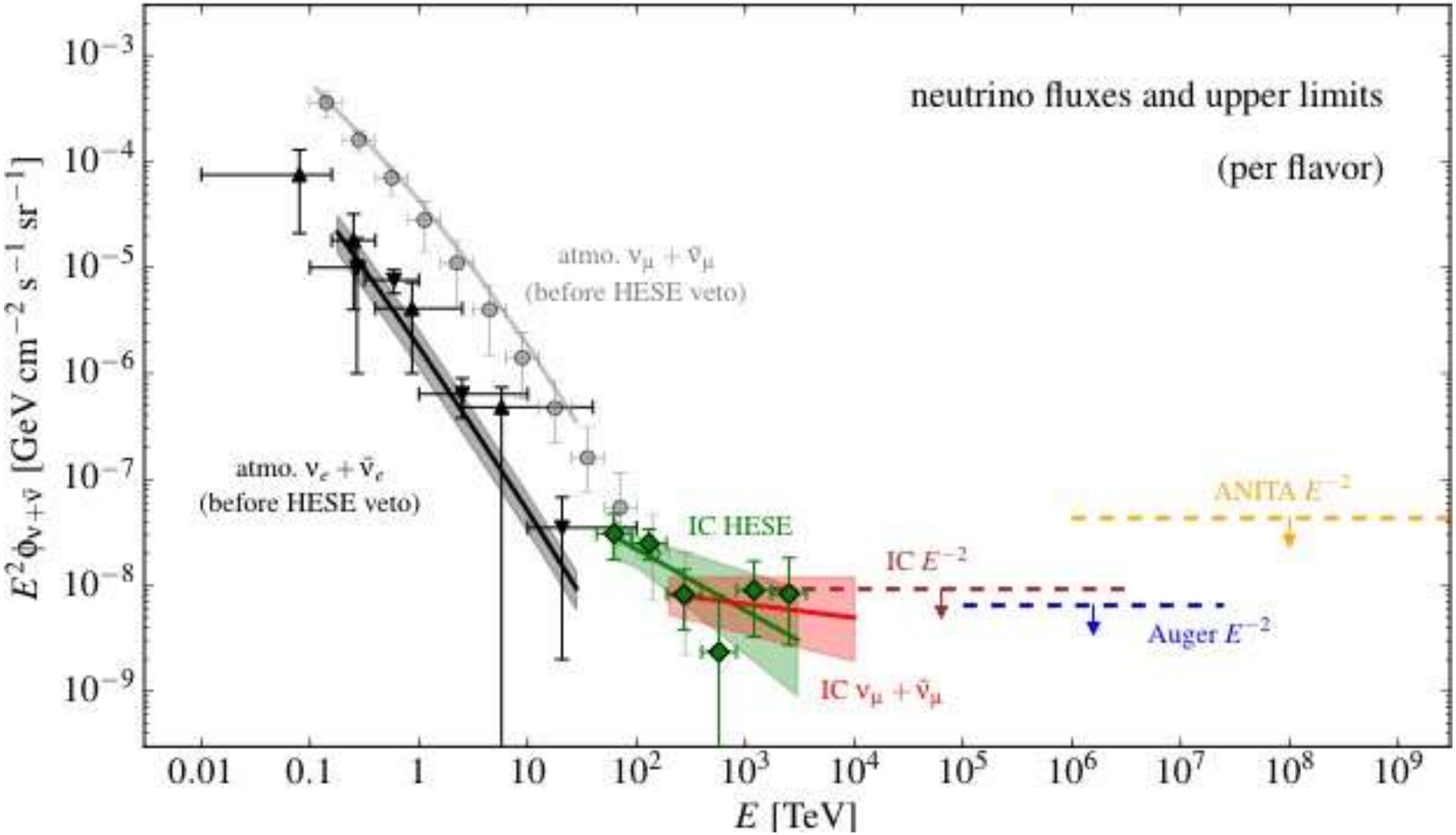

Fluxes and Limits
Prompt Upper Limit($\nu_\mu + \bar{\nu}_\mu$) [1.04x ERS]
Conventional ($\nu_\mu + \bar{\nu}_\mu$) (zenith-averaged)
[1.07x Honda2006]
EHE Differential Flux 90% Upper Limit
Fit Astrophysical Fluxes
Contained vertex (HESE) *
ν_μ Best Fit
Contained vertex (HESE)
- best fit*
*IceCube Preliminary
$E_\nu^2 \cdot \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^4
10^5
10^6
10^7
10^8
Neutrino Energy [GeV]

ANTARES

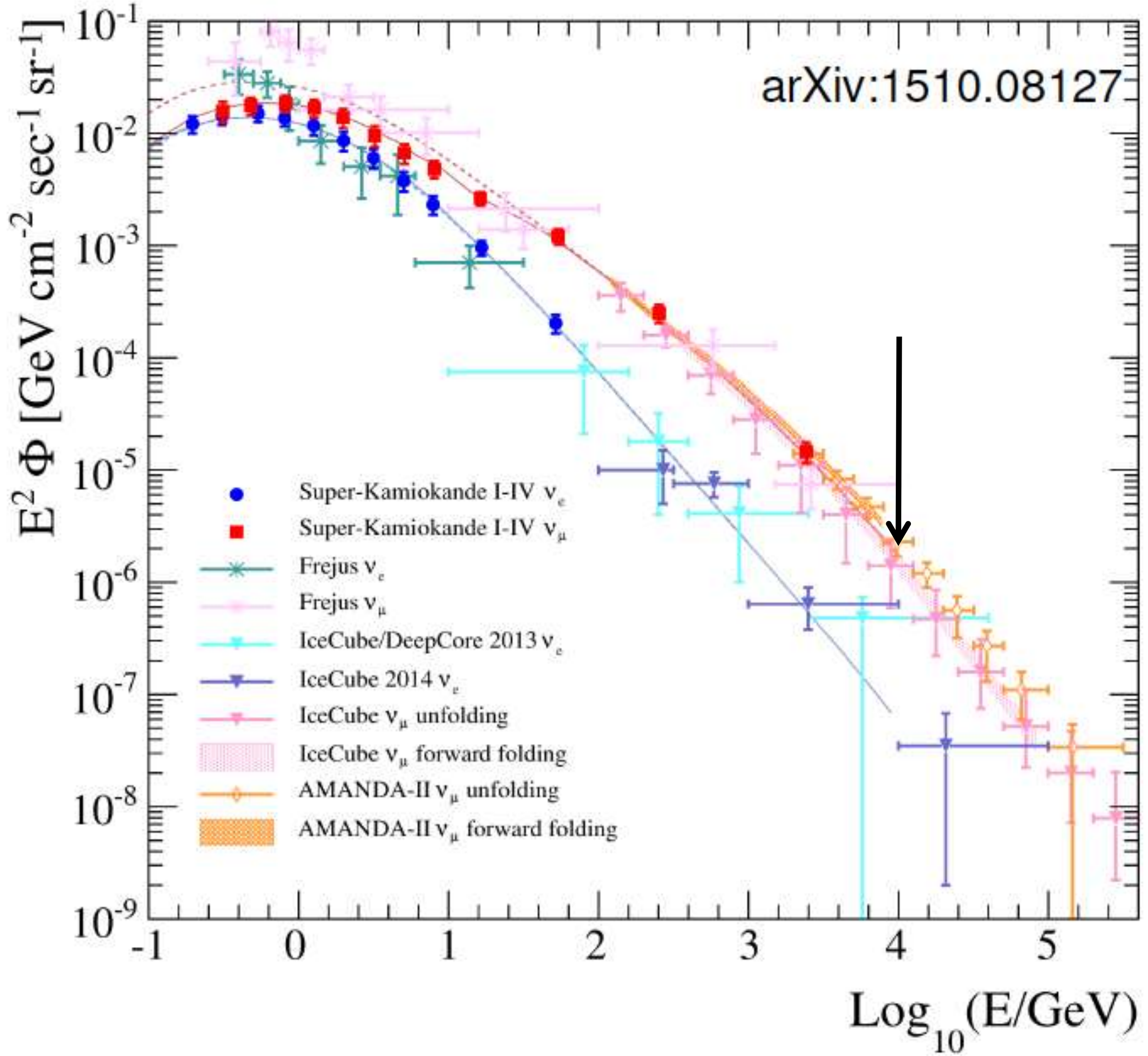


number of events
10^2
10
1
10^{-1}
10^{-2}
10^3
10^4
10^5
10^6
reconstructed shower energy [GeV]
atm. ν
atm. μ
astrophys. flux
Data

not background: prompt decay of charm particles produced in the atmosphere



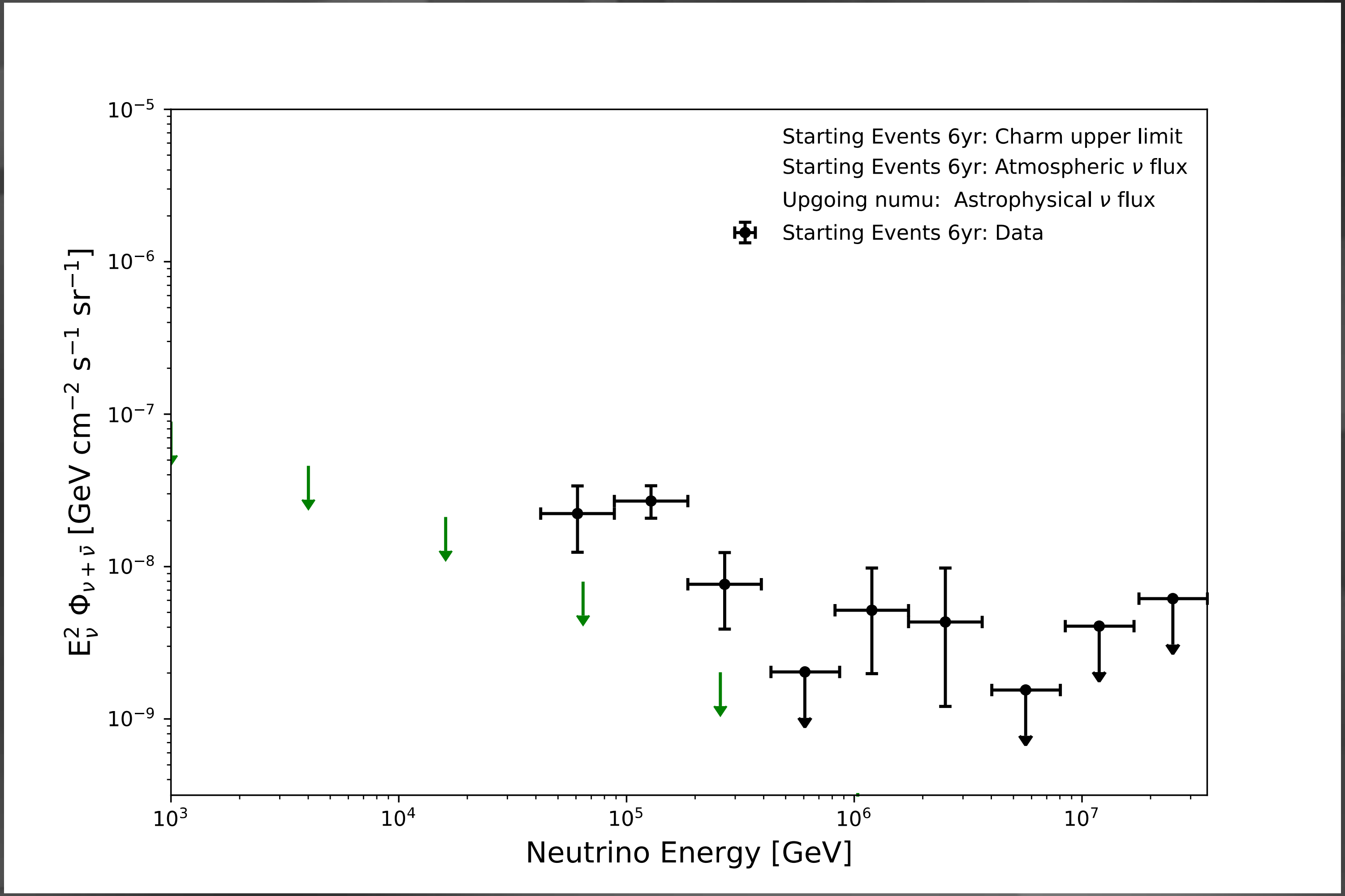
- tracks cosmic ray flux in energy, isotropic in zenith, normalization unknown: does not fit the data
- neutrino events are isolated
- incompatible with observes atmospheric *electron* neutrino spectrum



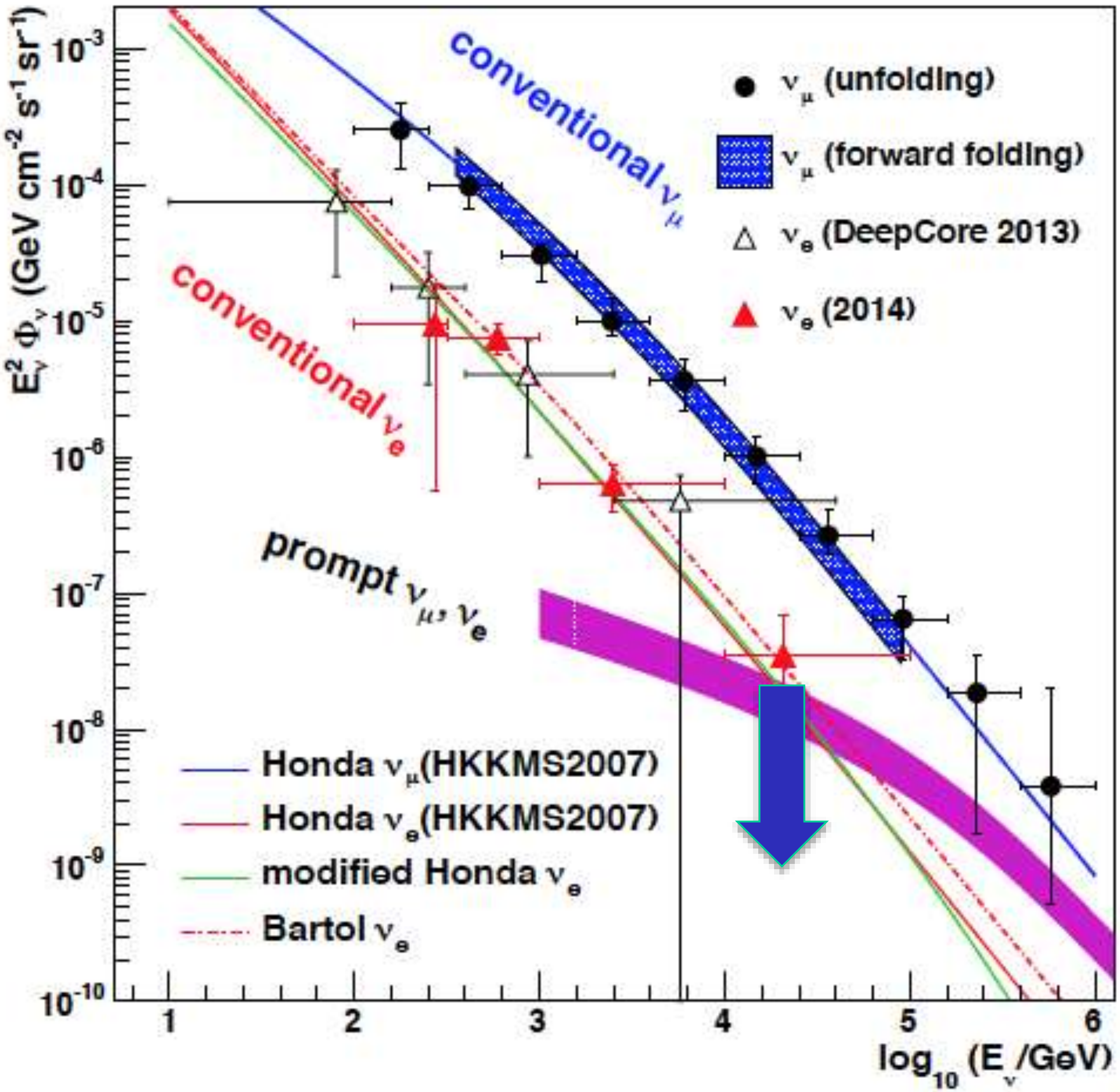
atmospheric neutrino spectrum (energy measurement) well understood at 10 TeV in terms of conventional neutrinos; charm contribution is small

not background: prompt decay of charm particles produced in the atmosphere

- tracks cosmic ray flux in energy, isotropic in zenith (normalization unknown): does not fit the data
- neutrino events are isolated
- constrained by atmospheric *electron* neutrino spectrum

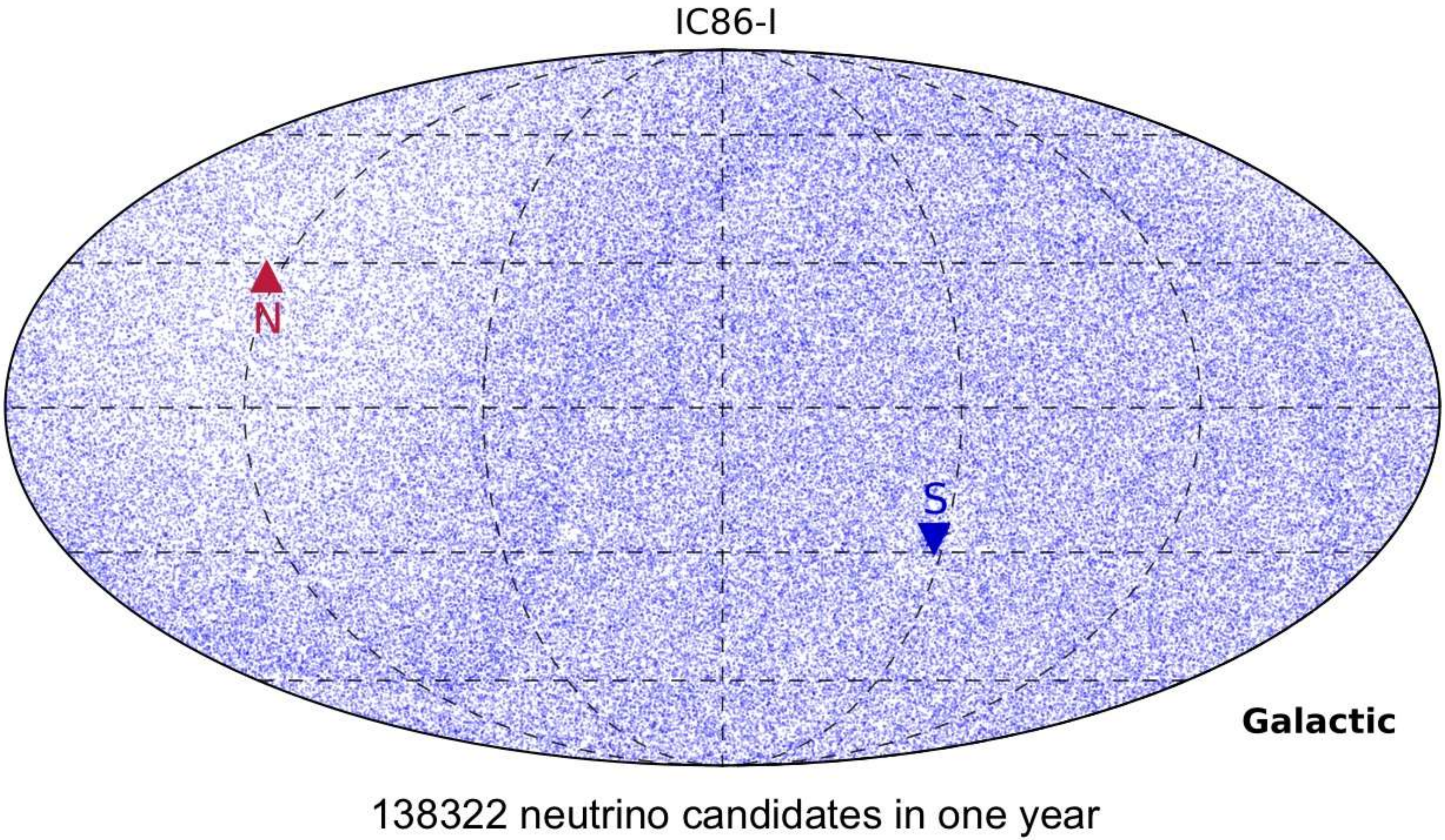


charm limited by atmospheric electrons



High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

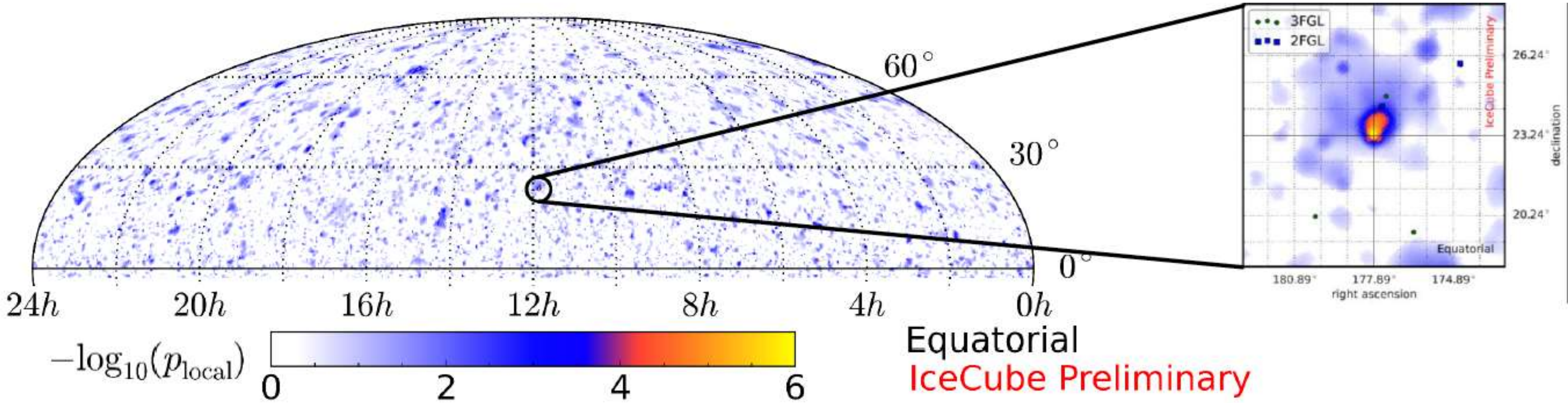


120 cosmic neutrinos

~12 separated from atmospheric background with E>60 TeV

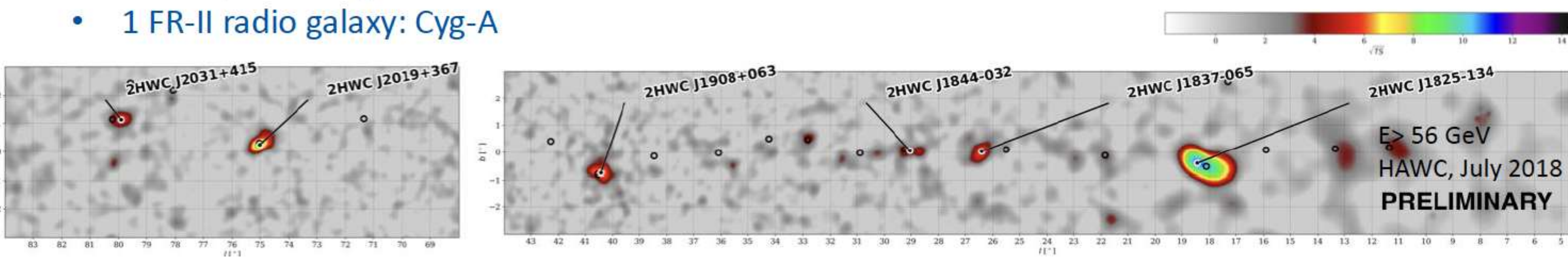
structure in the map results from neutrino absorption by the Earth

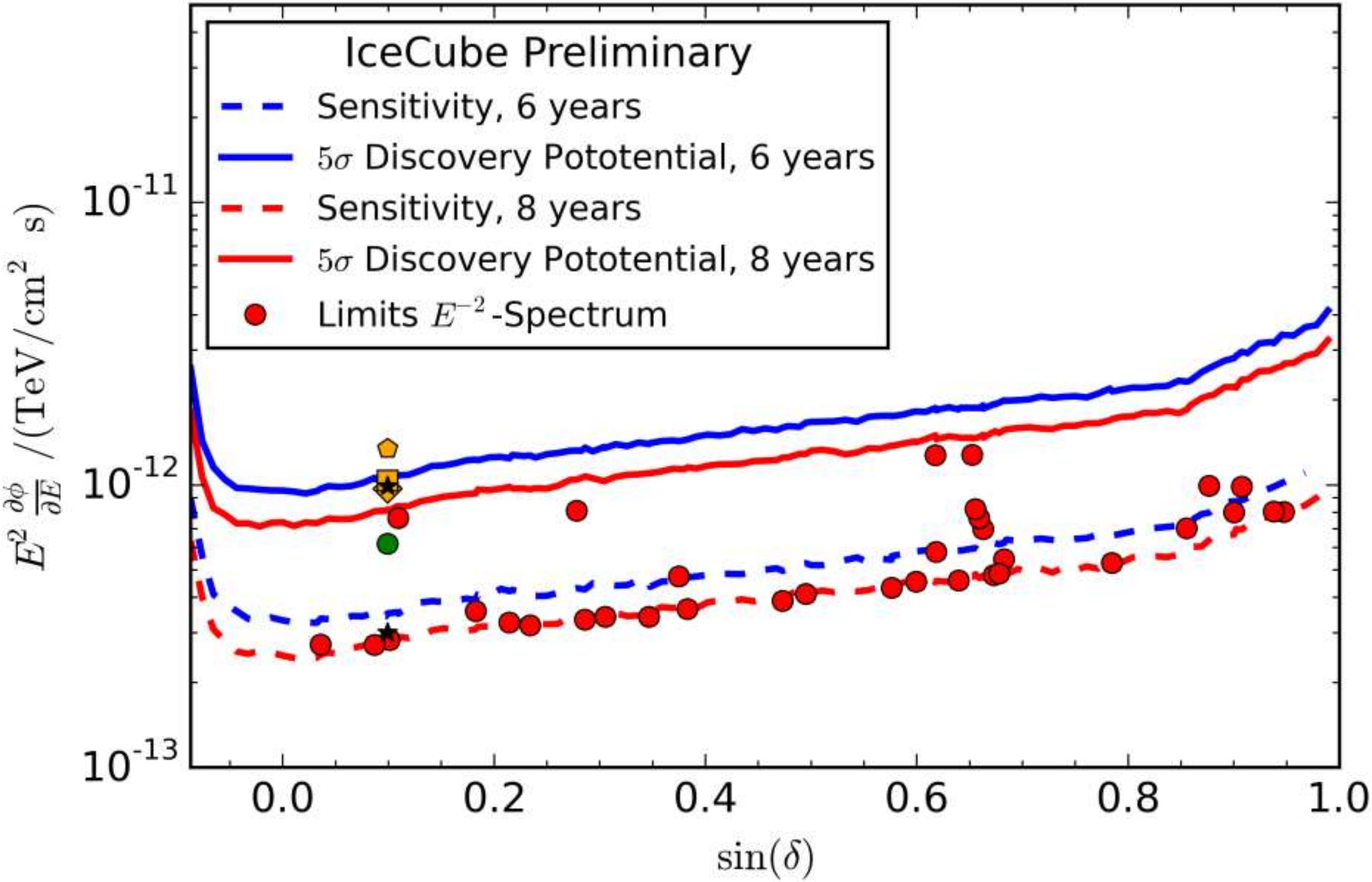
search for point sources with E^{-2} spectrum



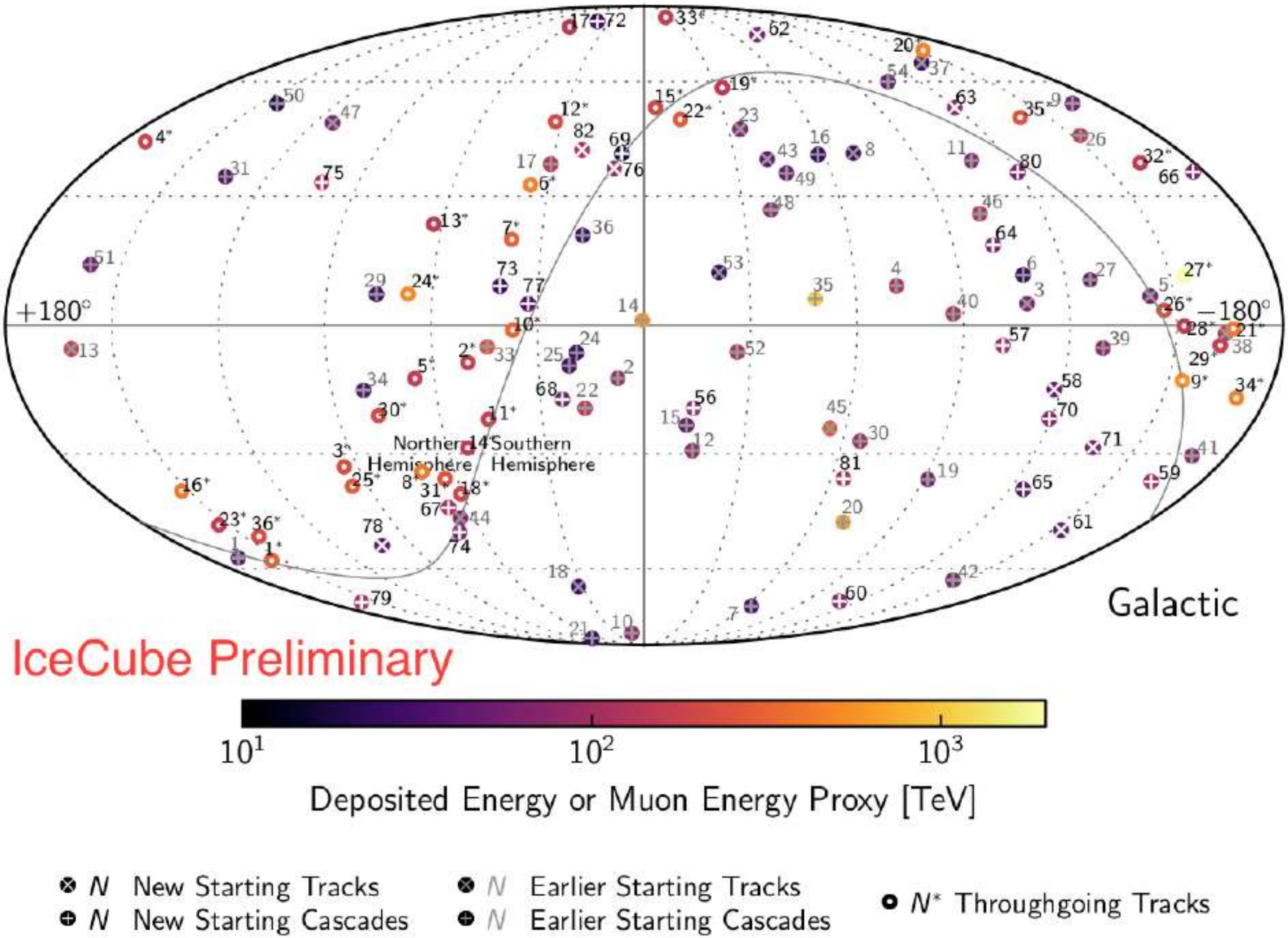
- Time integrated unbinned point source hot spot search
- ~500k events from 8 years (NH) of data, energy-weighted to distinguish atmospheric (isotropic) and astrophysical neutrinos
- IceCube & ANTARES a-priori source catalog with 34 source on NH based on γ-observations 4 sources in catalog have local p-value ~1%
  - 1 galactic: MGRO J1908
  - 2 FSRQ: 4C38.41, 3C454.3
  - 1 FR-II radio galaxy: Cyg-A

→ **Compatible with background**





IceCube Preliminary
Sensitivity, 6 years
5σ Discovery Pototential, 6 years
Sensitivity, 8 years
5σ Discovery Pototential, 8 years
Limits E^{-2}-Spectrum
$E^2 \frac{\partial\phi}{\partial E}$ /(TeV/cm^2 s)
10^{-11}
10^{-12}
10^{-13}
0.0
0.2
0.4
0.6
0.8
1.0
$\sin(\delta)$

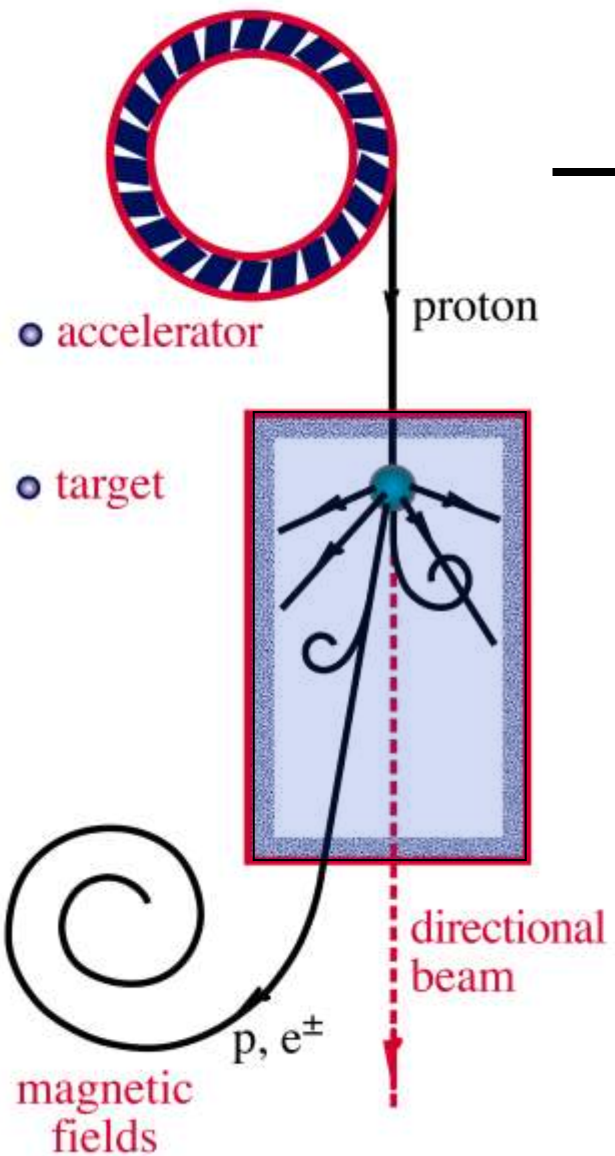

+180°
−180°
Northern Hemisphere
Southern Hemisphere
Galactic
IceCube Preliminary
10^1
10^2
10^3
Deposited Energy or Muon Energy Proxy [TeV]
N New Starting Tracks
N New Starting Cascades
N Earlier Starting Tracks
N Earlier Starting Cascades
N* Throughgoing Tracks

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- [decay of halo dark matter particles?]

High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- **Fermi photons and IceCube neutrinos**
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation
and dust

$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

$\rightarrow p + \pi^{0}$

~ cosmic ray + gamma

neutral pions

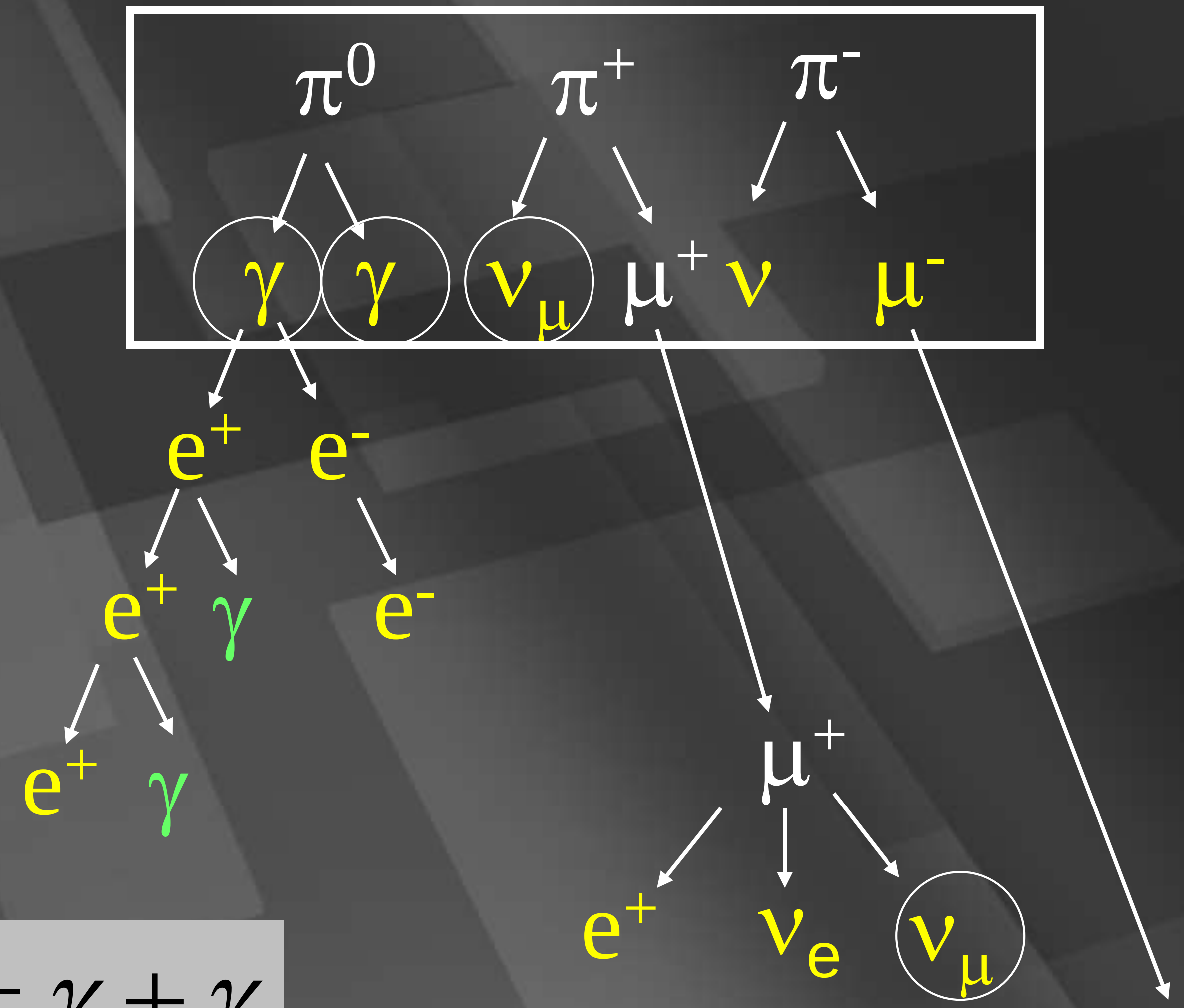
are observed as

gamma rays

charged pions

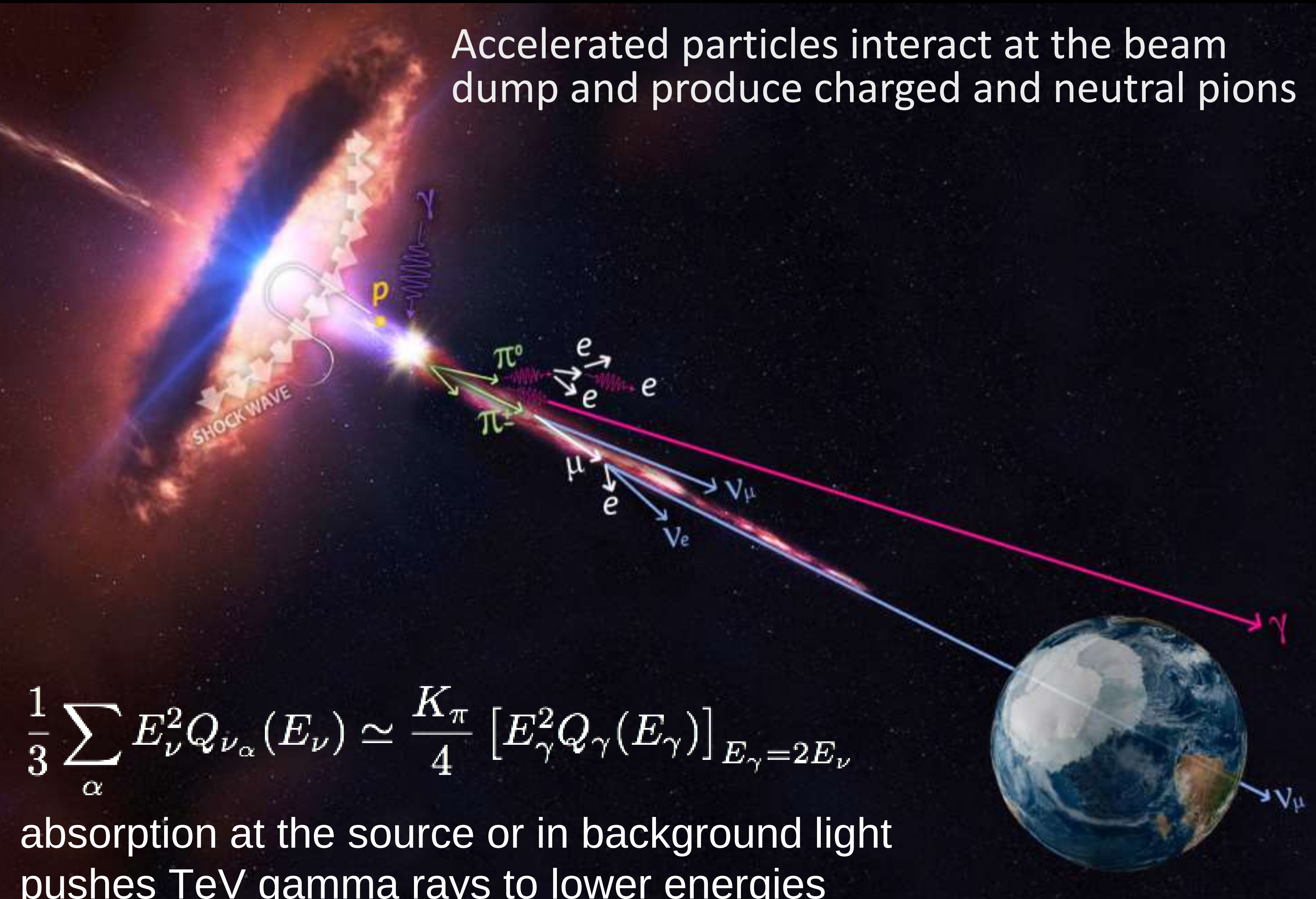
are observed as

neutrinos



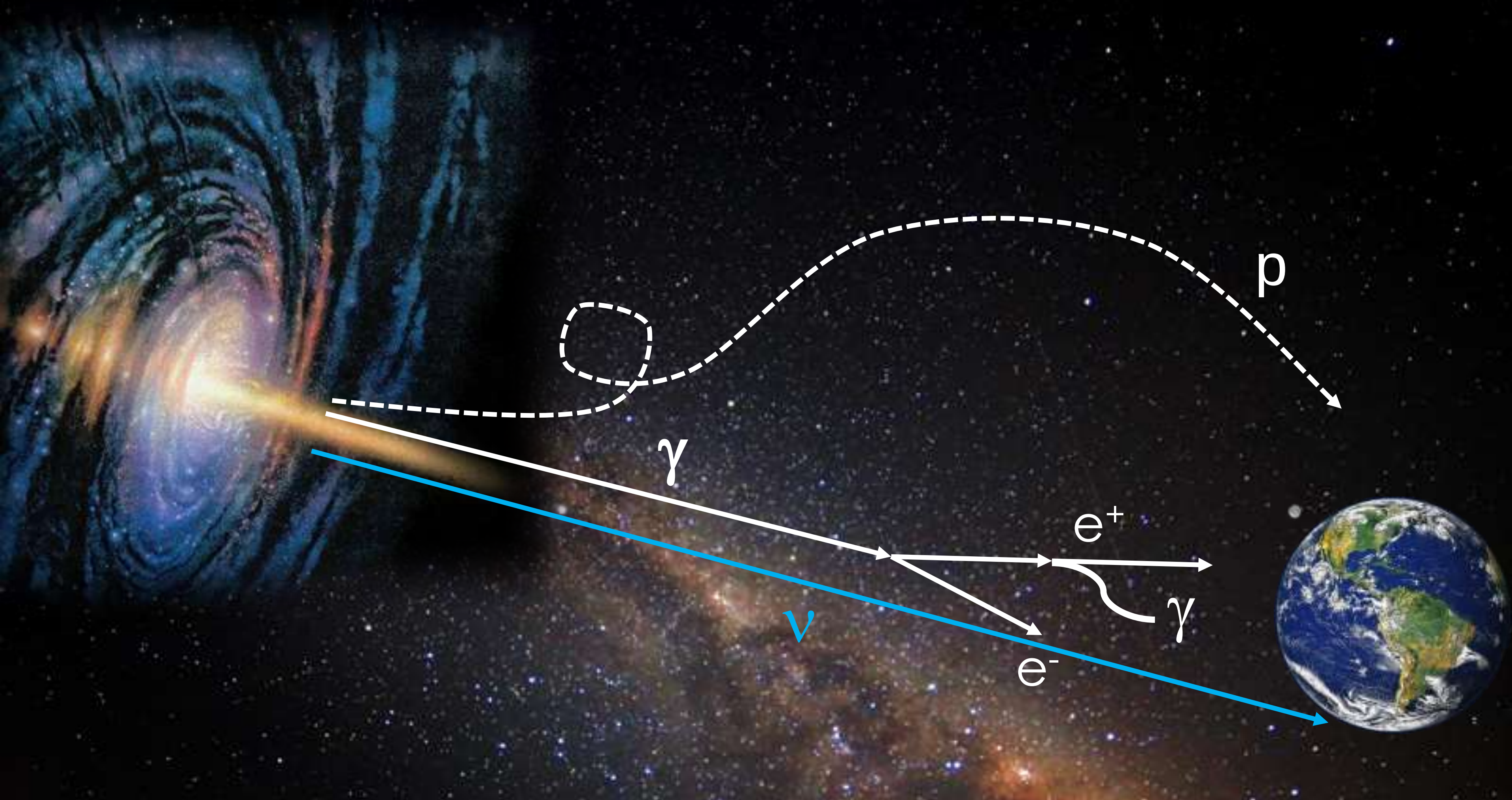
$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

Accelerated particles interact at the beam dump and produce charged and neutral pions

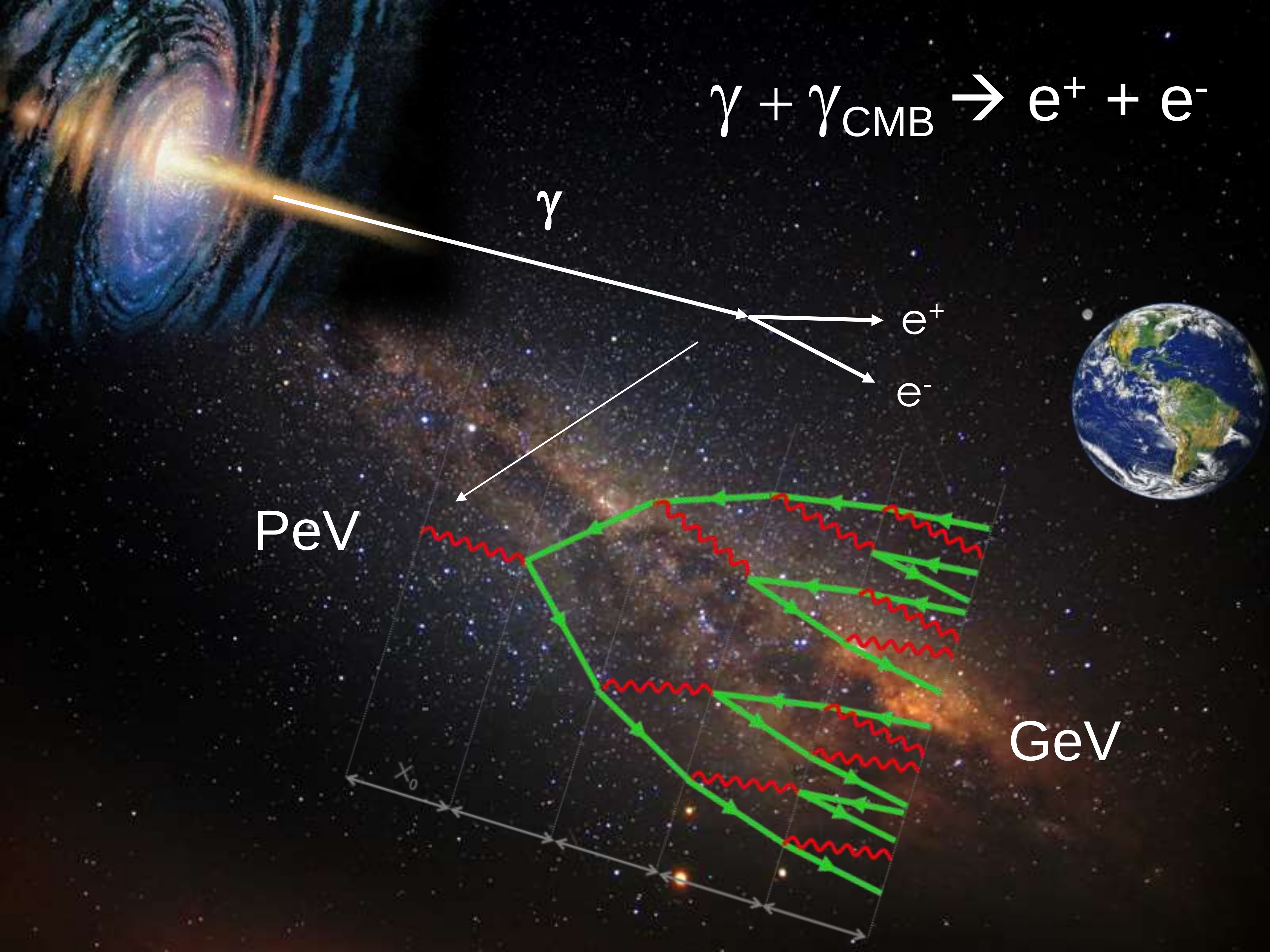


$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma=2E_\nu}$$

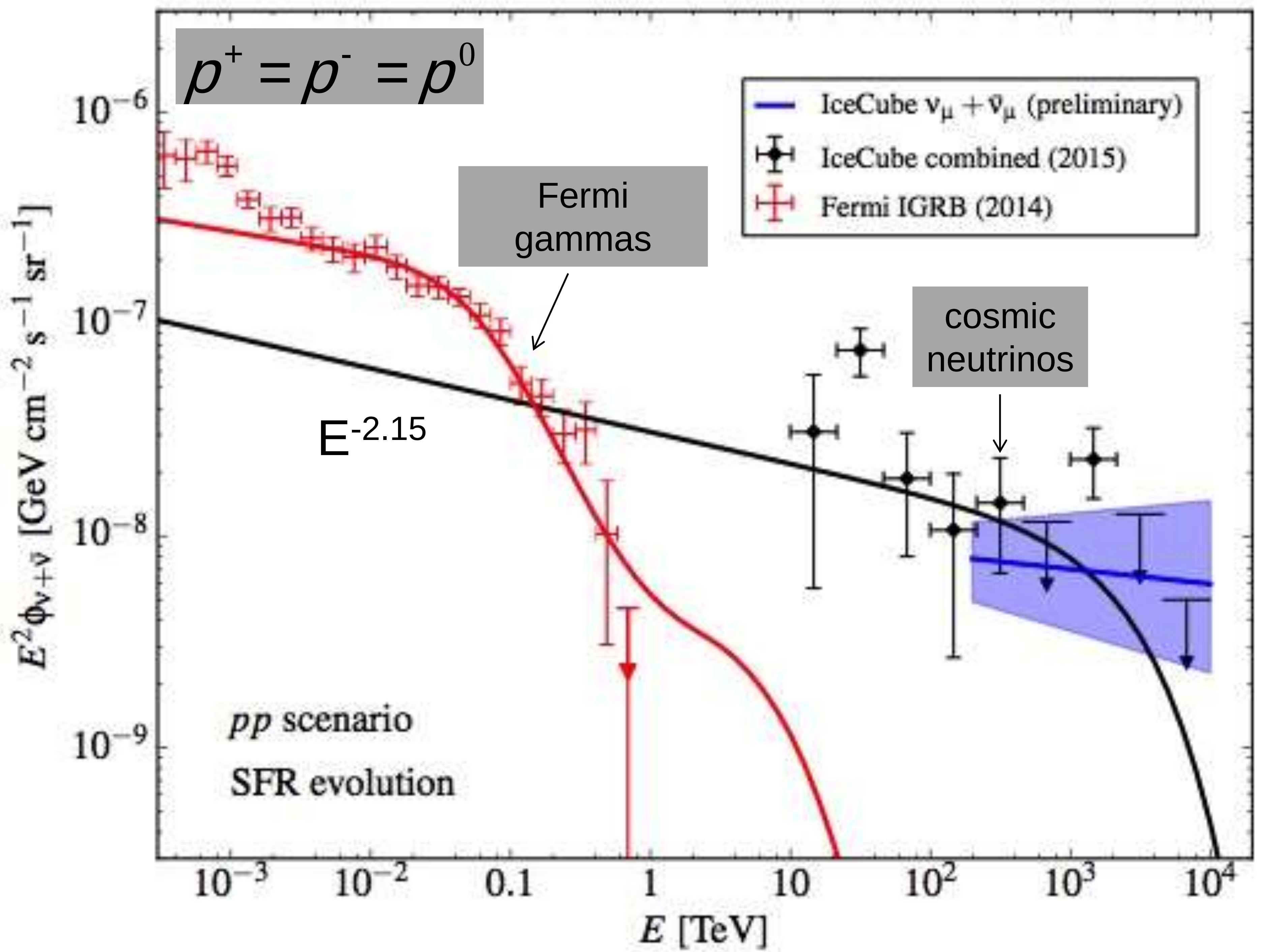
absorption at the source or in background light pushes TeV gamma rays to lower energies



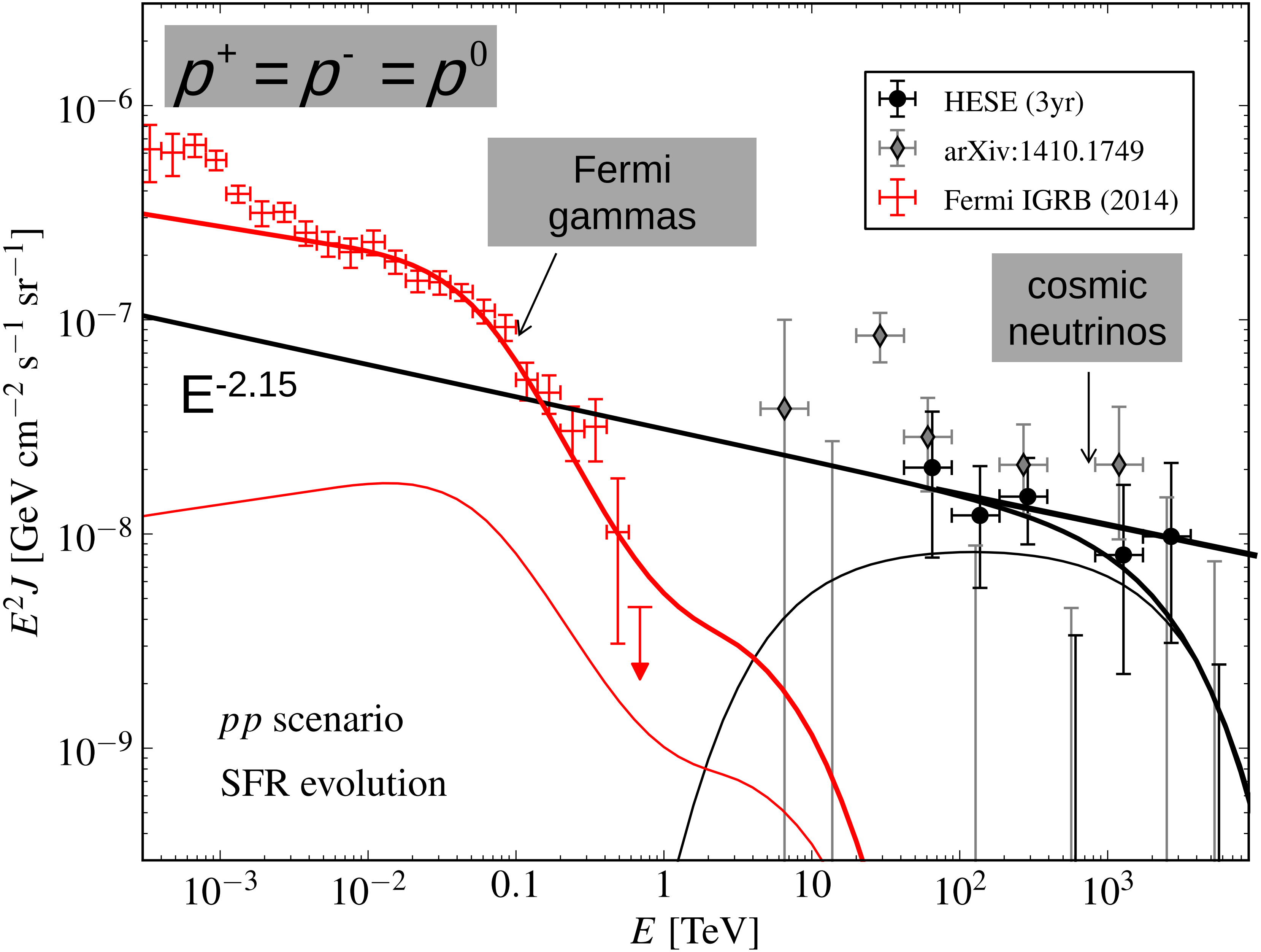
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth



$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
γ
e^+
e^-
PeV
GeV
X_0

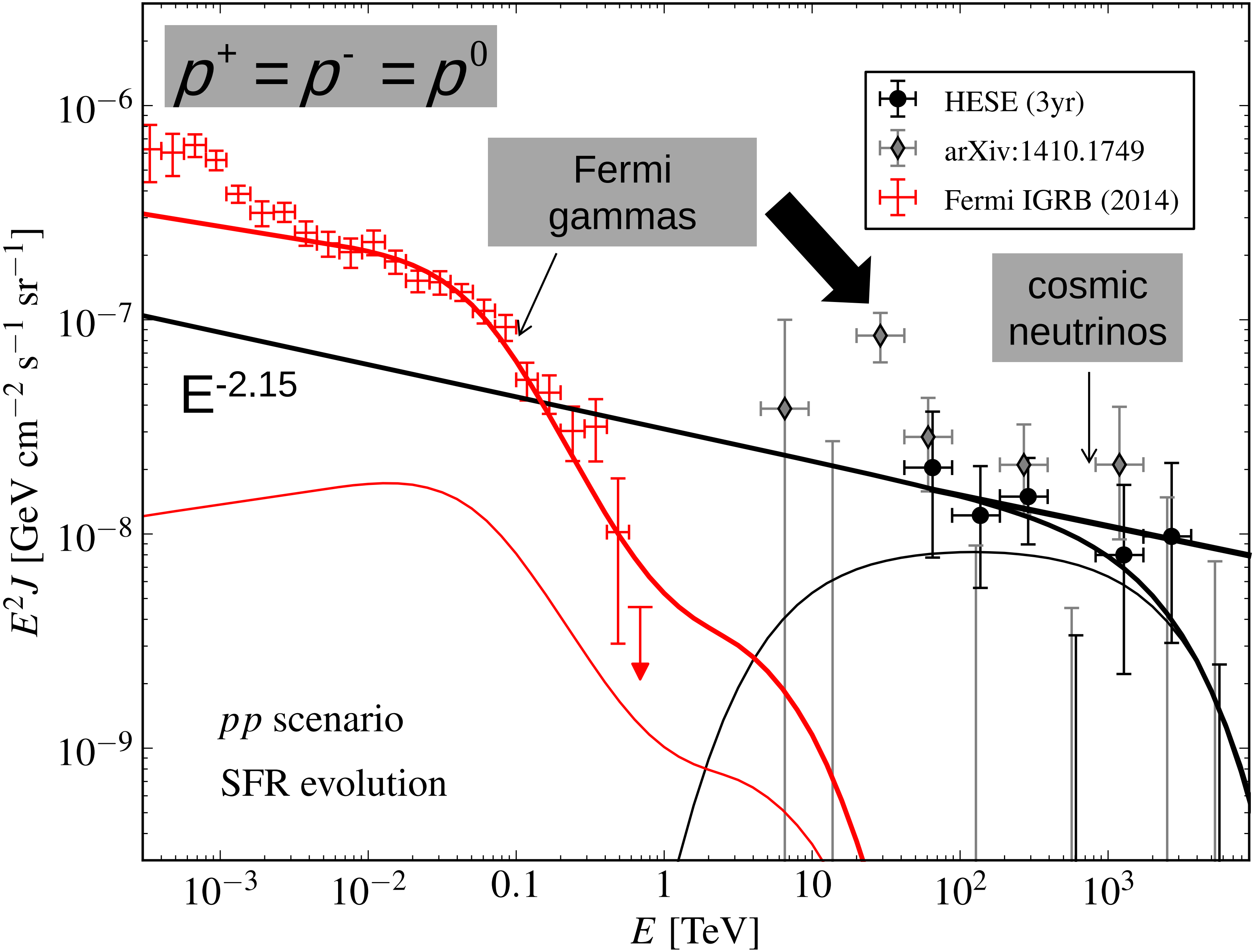


p+ = p- = p0
IceCube νμ + ν̄μ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
E-2.15
pp scenario
SFR evolution
E2Φν+ν̄ [GeV cm−2 s−1 sr−1]
E [TeV]
10−6
10−7
10−8
10−9
10−3
10−2
0.1
1
10
102
103
104

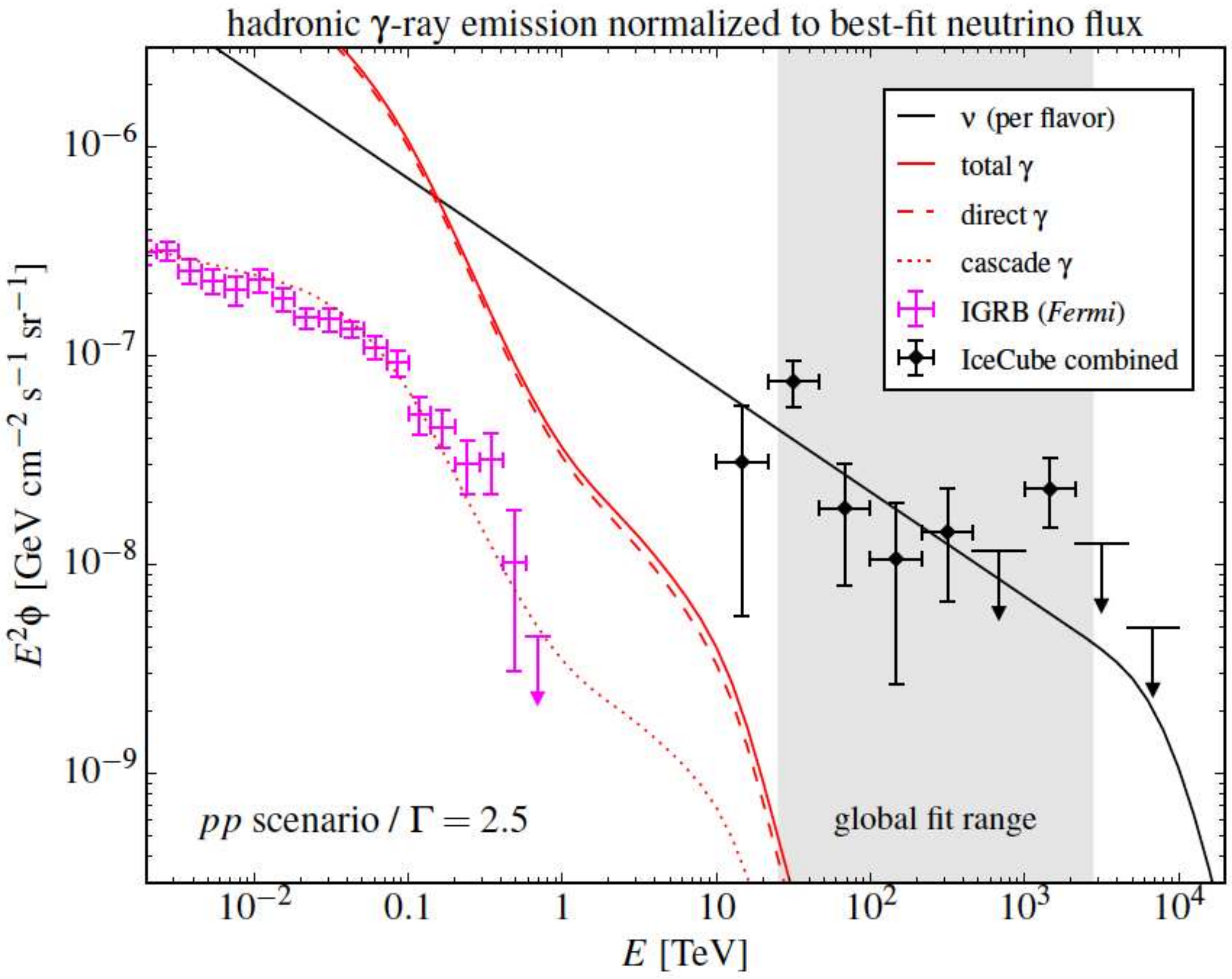


$p^+ = p^- = p^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays



$p^+ = p^- = p^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3



dark sources: a “problem” ?
gamma rays cascade in the source to < GeV energy

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays

equal energy in cosmic rays and neutrinos

$$\rho_{\nu+\bar{\nu}}(E) = \frac{E}{E_p}\left[\xi_z t_H\right]\left[\dot{\rho}_p\right]$$

$$\rho_{\nu+\bar{\nu}}(E) = 4\pi E^2 \frac{dN_\nu}{dE}$$

$$\dot{\rho}_p(E_p) = E_p^2 \frac{d\dot{N}_p}{dE_p} \approx 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

$$\xi_z t_H = \text{evolution of sources} \times \text{Hubble time}$$

$$\Rightarrow E^2 \frac{dN_\nu}{dE} \approx 10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

equal energy in cosmic rays and neutrinos

actually...

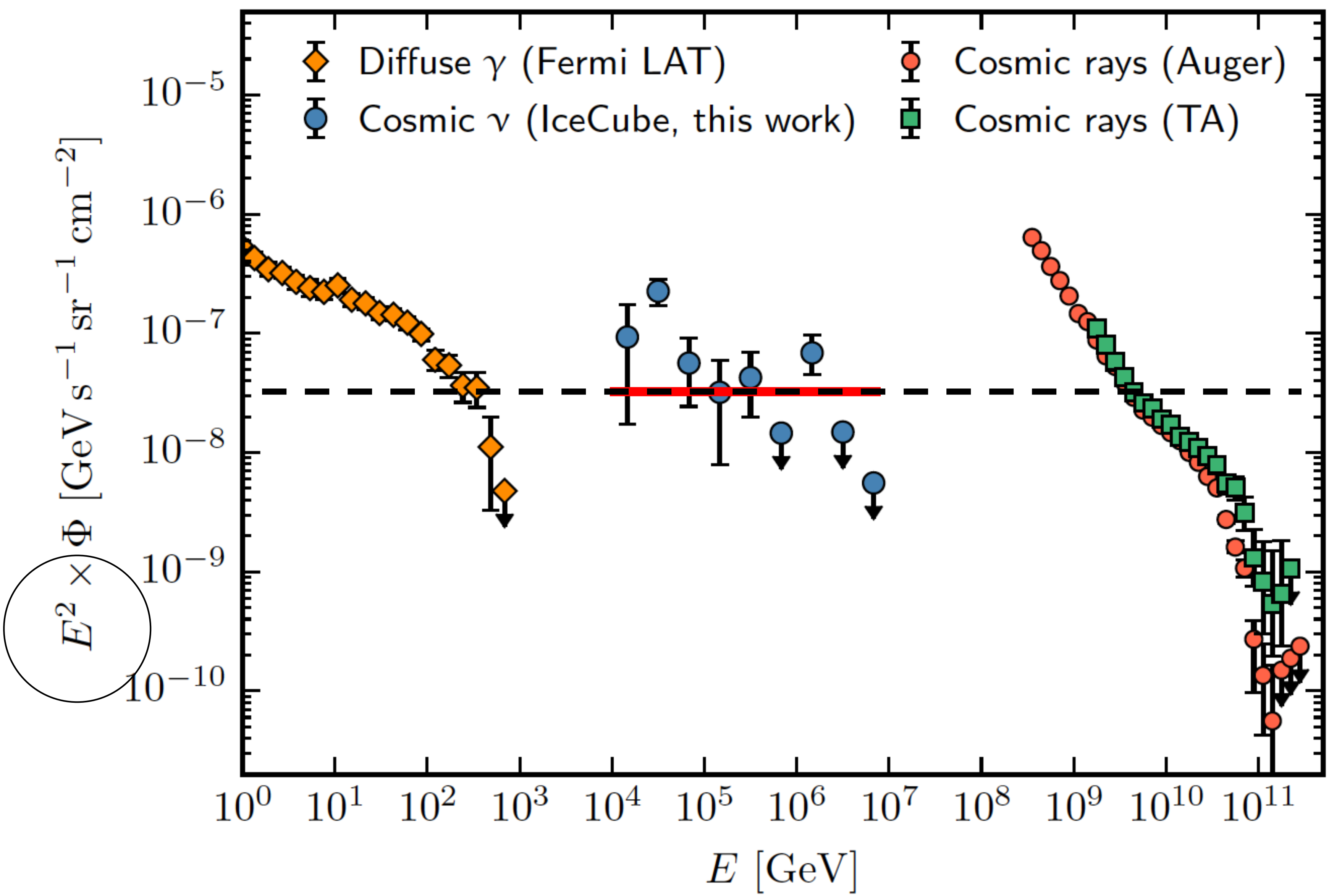
$$\rho_{\nu+\bar{\nu}}(E) = f_\pi \frac{E}{E_p}\left[\xi_z t_H\right]\left[c\dot{\rho}_{cr}\right]$$

- $f_\pi \leq 1$ transparent (to photons) source; equality is the WB bound
- $f_\pi \geq 1$ obscured source
- observed flux is well below the WB bound (at $20 \sim 100$ PeV); have to observe PeV photons

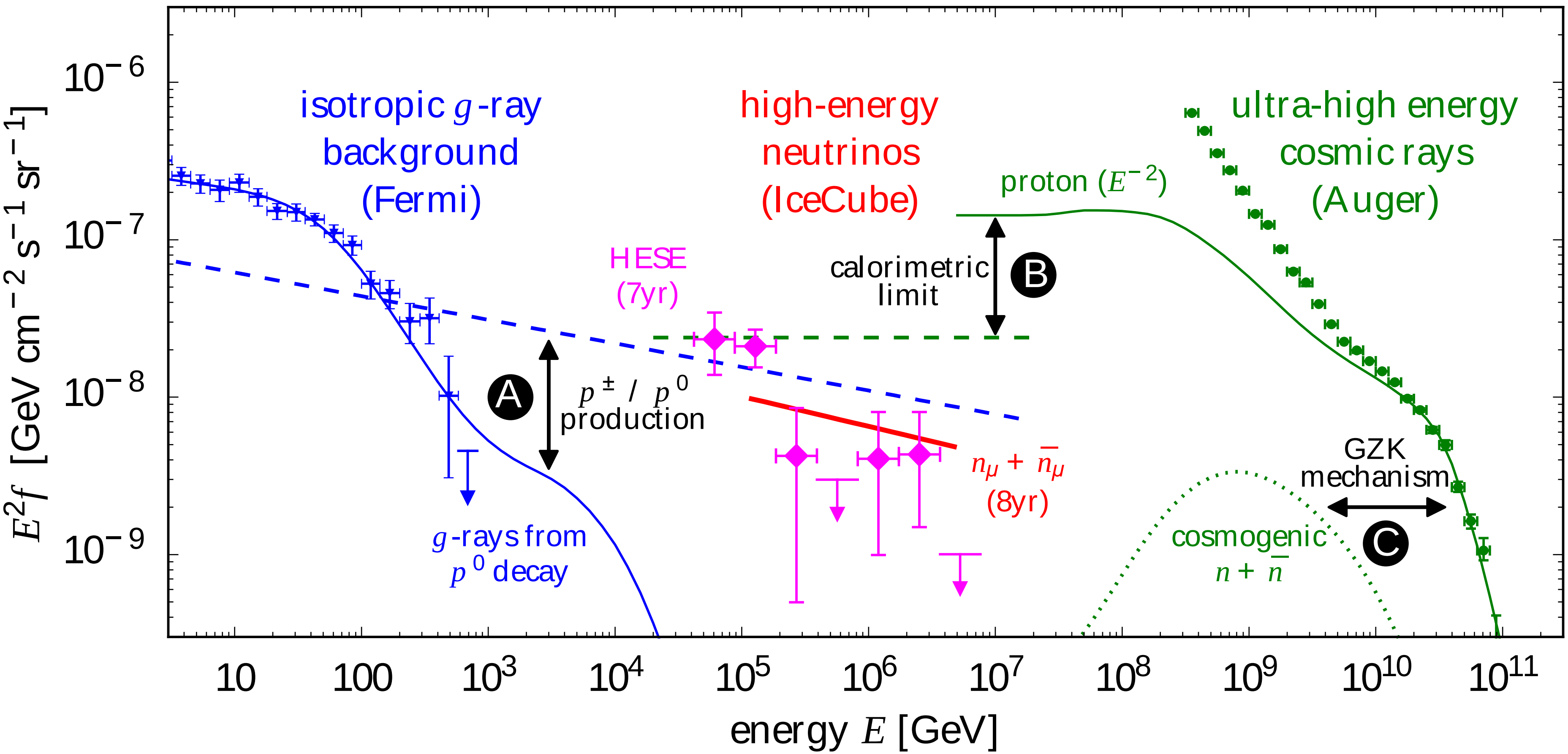
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)

- at some level common Fermi-IceCube sources?



energy in the Universe in gamma rays, neutrinos and cosmic rays

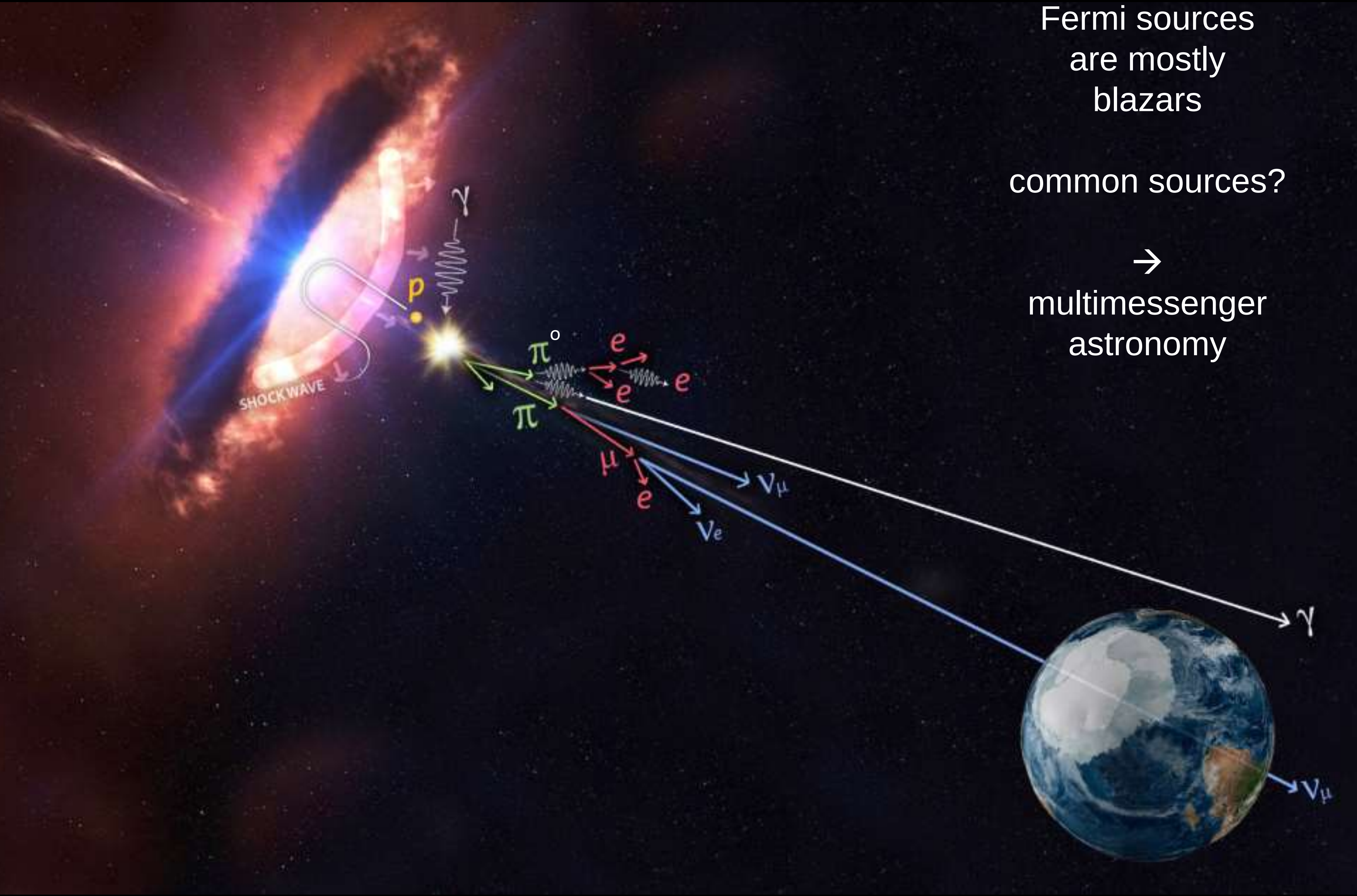


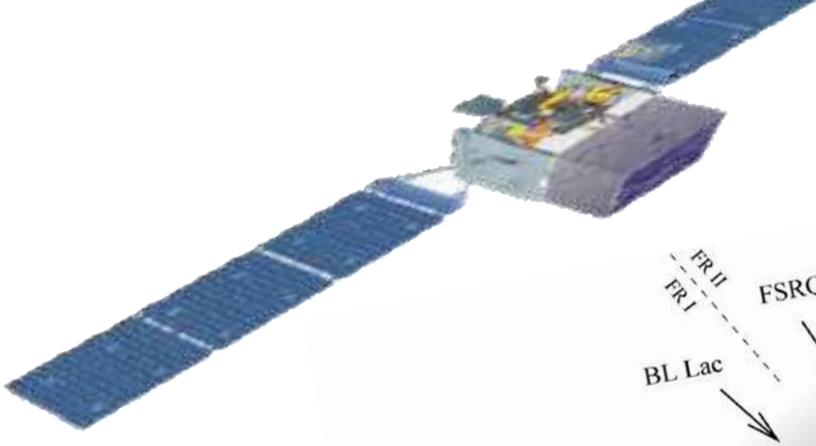
similar energy density in the Universe in extragalactic cosmic rays

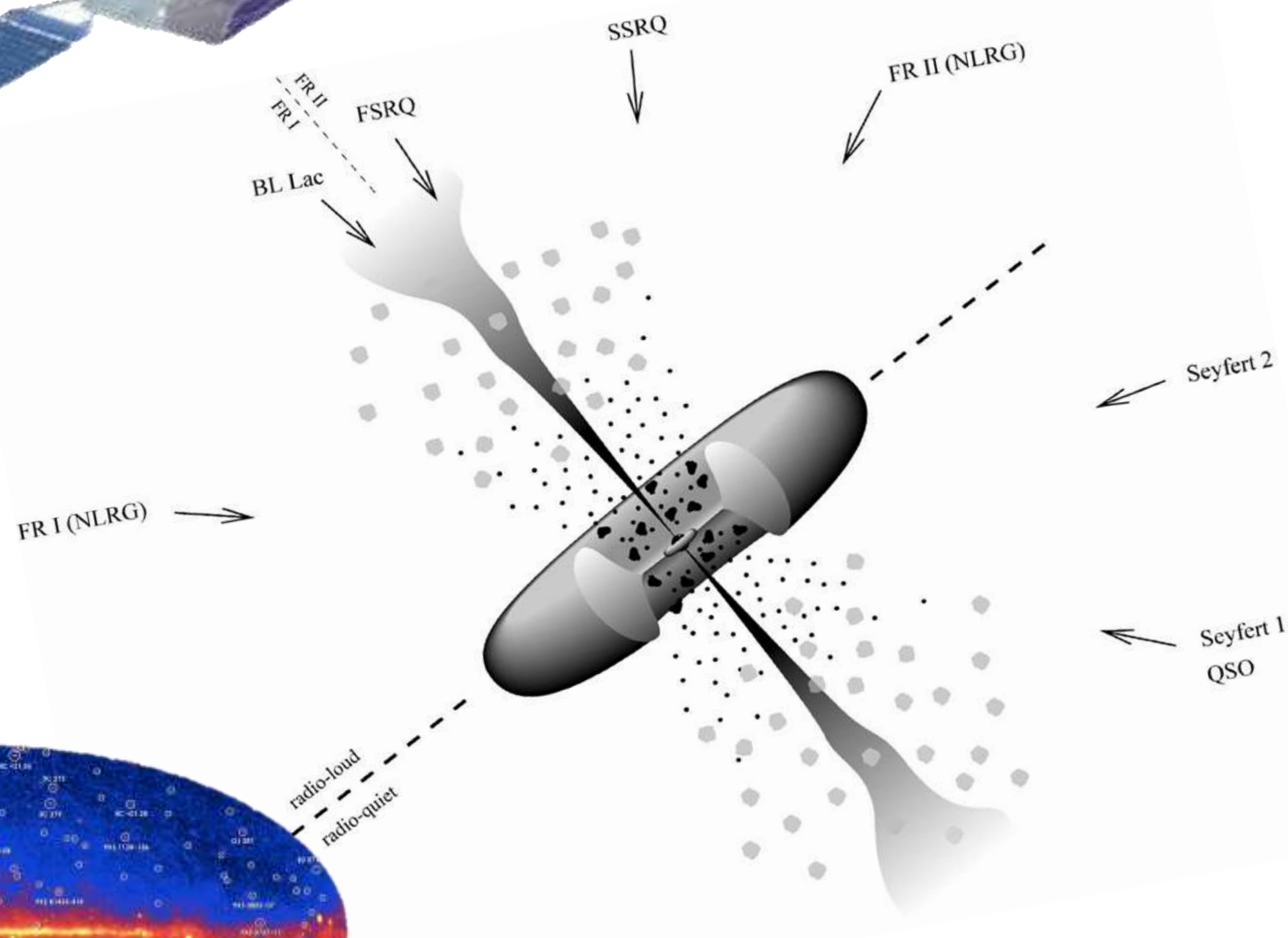
Fermi sources
are mostly
blazars

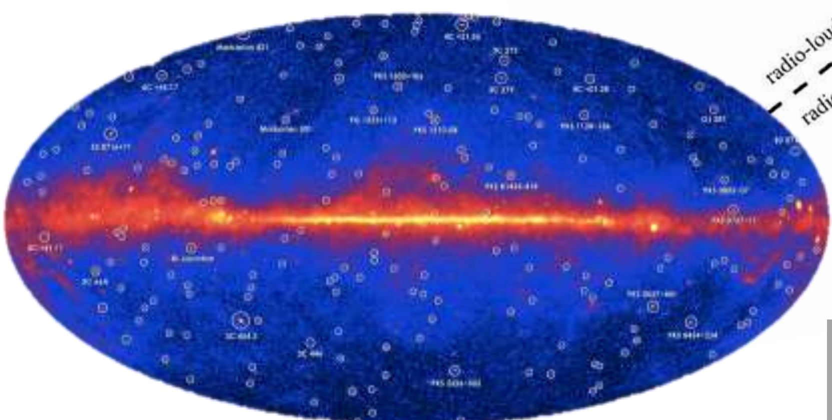
common sources?

→
multimessenger
astronomy









Fermi sky: mostly bazars

High Energy Neutrino Astrophysics
francis halzen

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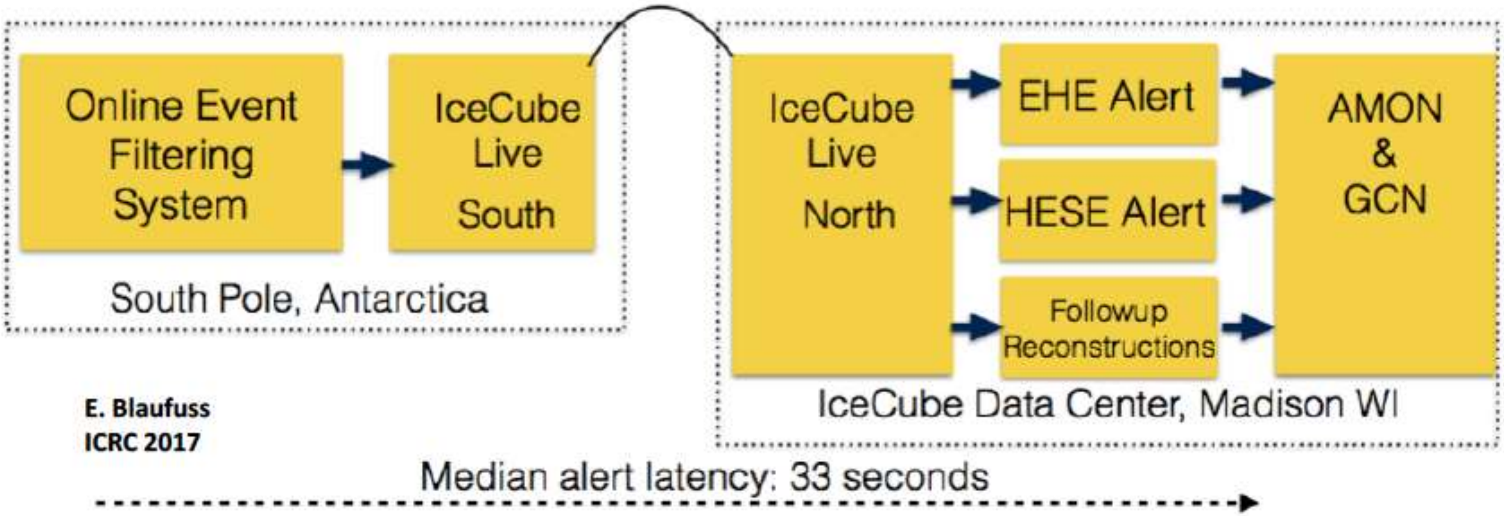
icecube.wisc.edu

Realtime alerts from IceCube

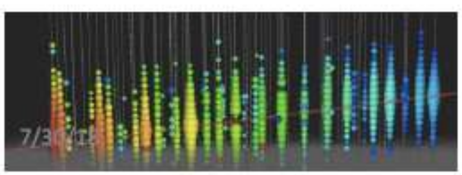


E. Blaufuss
ICRC 2017

Upcoming improvements:

- **New starting event selections**
- **Cascades**
- **Higher astrophysical purity**
- **Improved event information in alerts**

13 alerts sent since 2016
First alert sent within 1 minute
Detailed follow-ups after a few hours



	Starting Tracks	Throughgoing tracks
Energy	> 60 TeV	> 500 TeV
Alerts per year	4.8	4 - 5
Signal events per year	1.1	2.5 - 4

IceCube Coll.: Astropart. Phys., 92, 30 (2017)

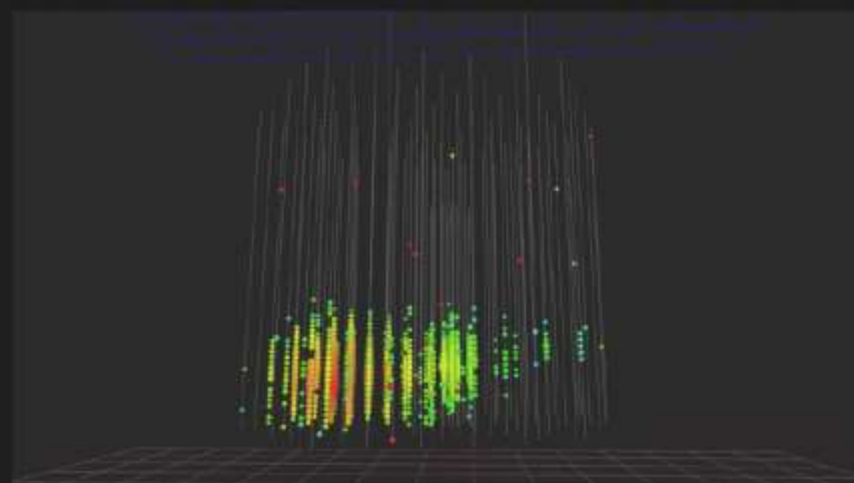
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                 240.7644d {+16h 03m 03s} (current),
                 239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                  +9.2972d {+09d 17' 50"} (current),
                  +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them**.

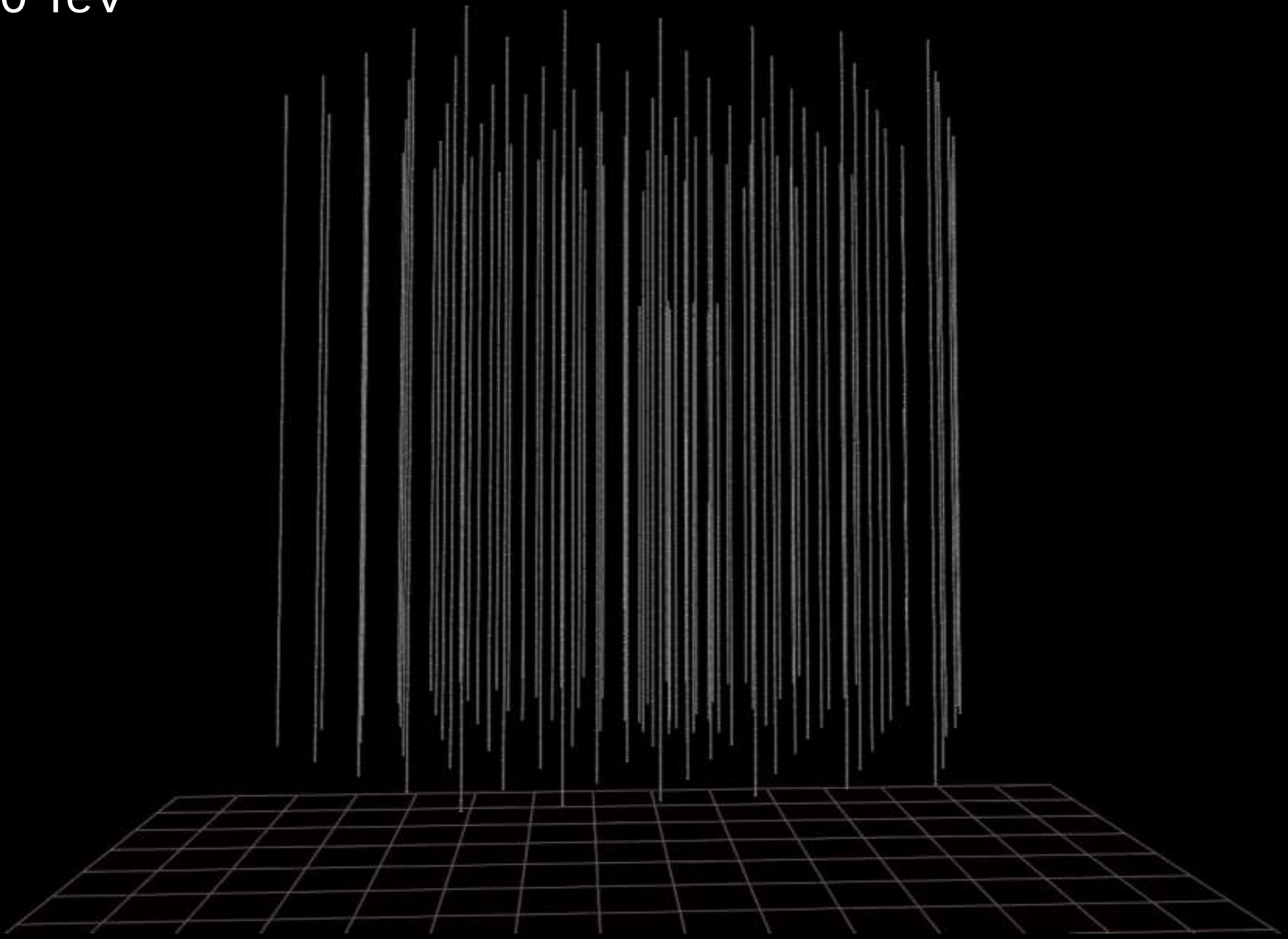


IceCube Trigger

43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

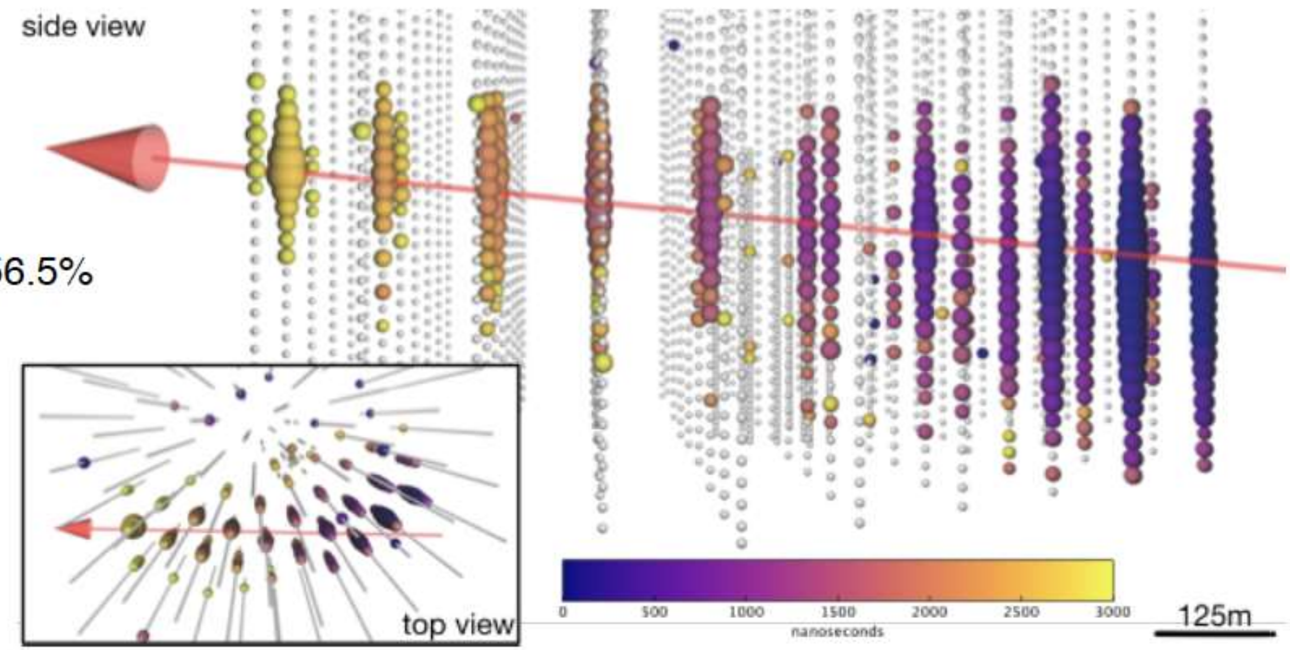
290 TeV



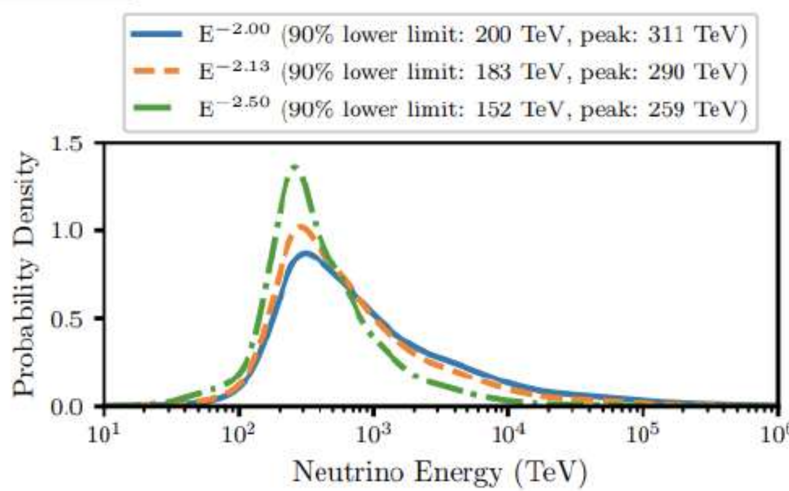
IC-170922A

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)

Signalness: 56.5%



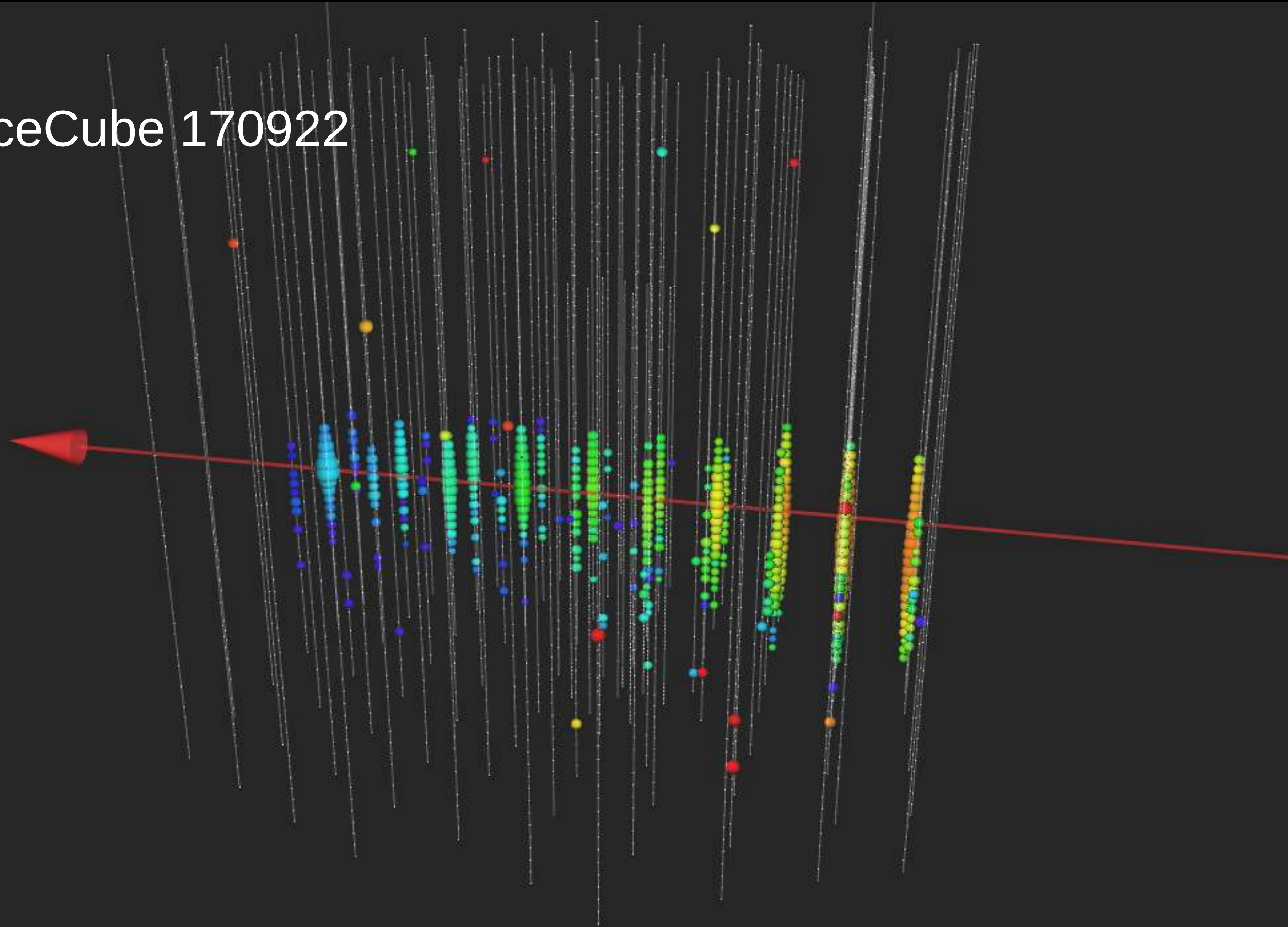
Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).



IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

IceCube 170922



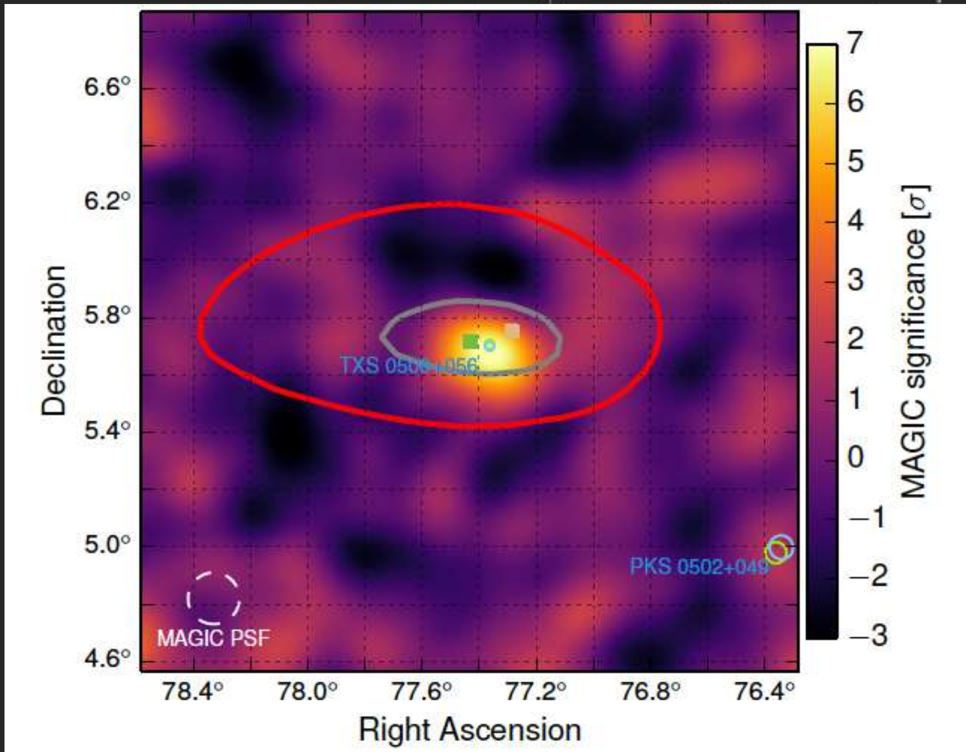
multiwavelength campaign launched by IC 170922

IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

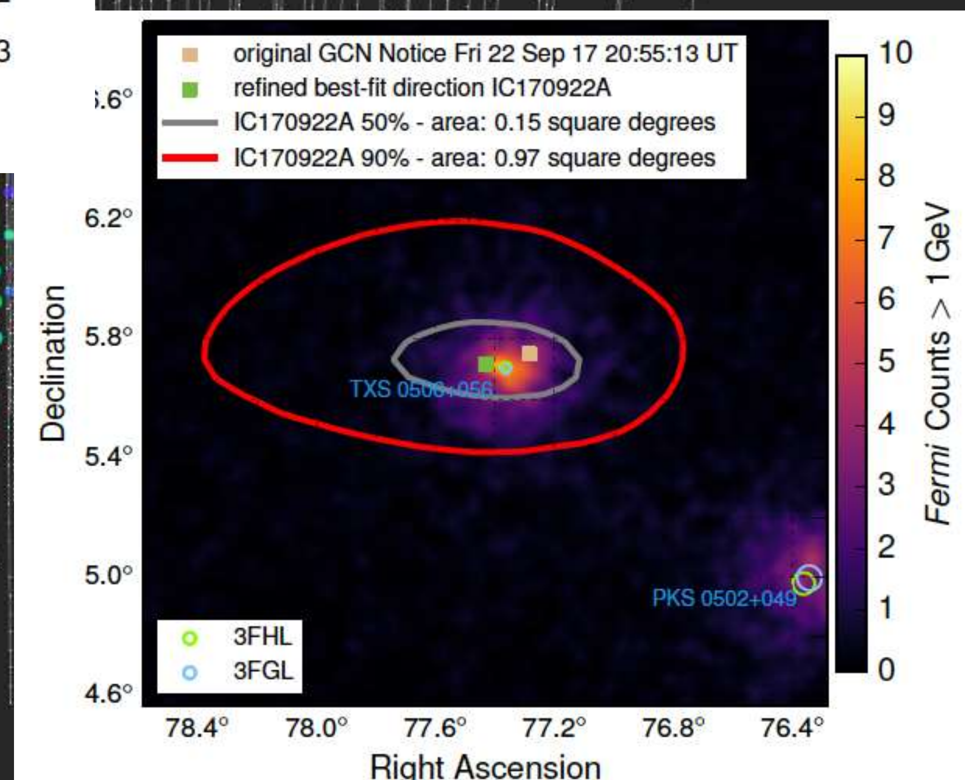
- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43^o Dec 5.72^o
- Fermi-LAT: flaring blazar within 0.1^o (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data

IceCube 170922

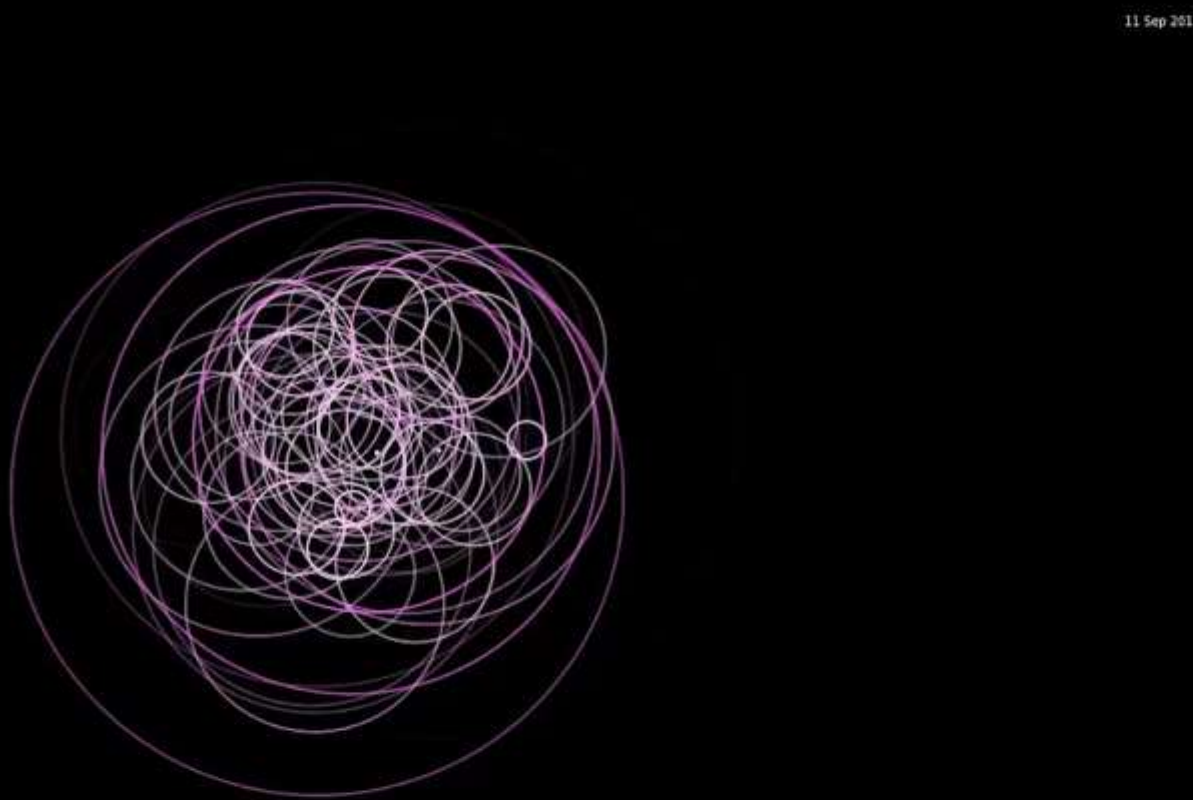
Fermi detects a flaring blazar within 0.06°



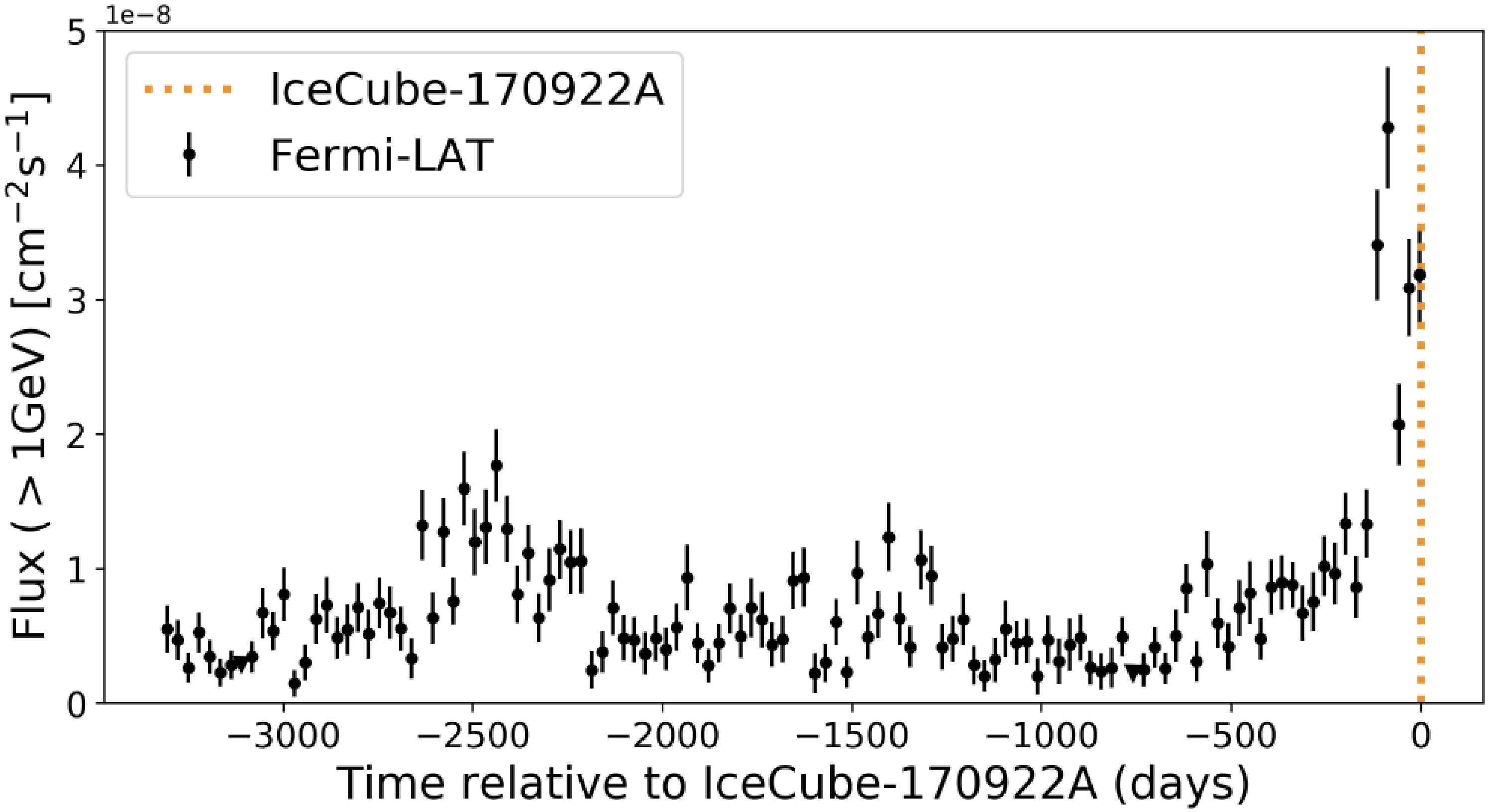
MAGIC detects emission of > 100 GeV gammas



build-up over several months followed by rapid daily variability



Fermi-LAT finds Flaring Blazar

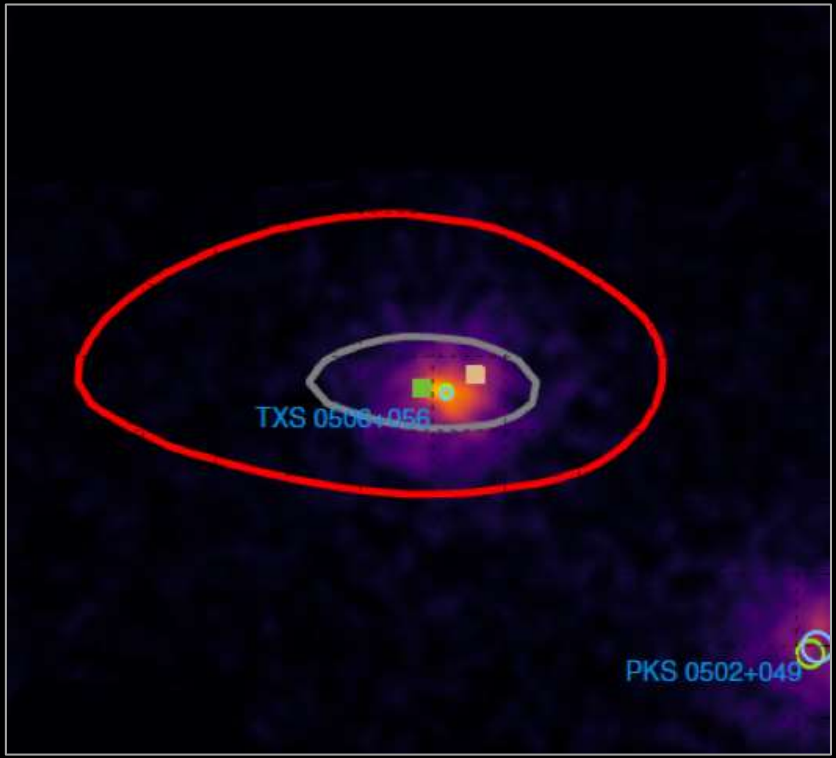


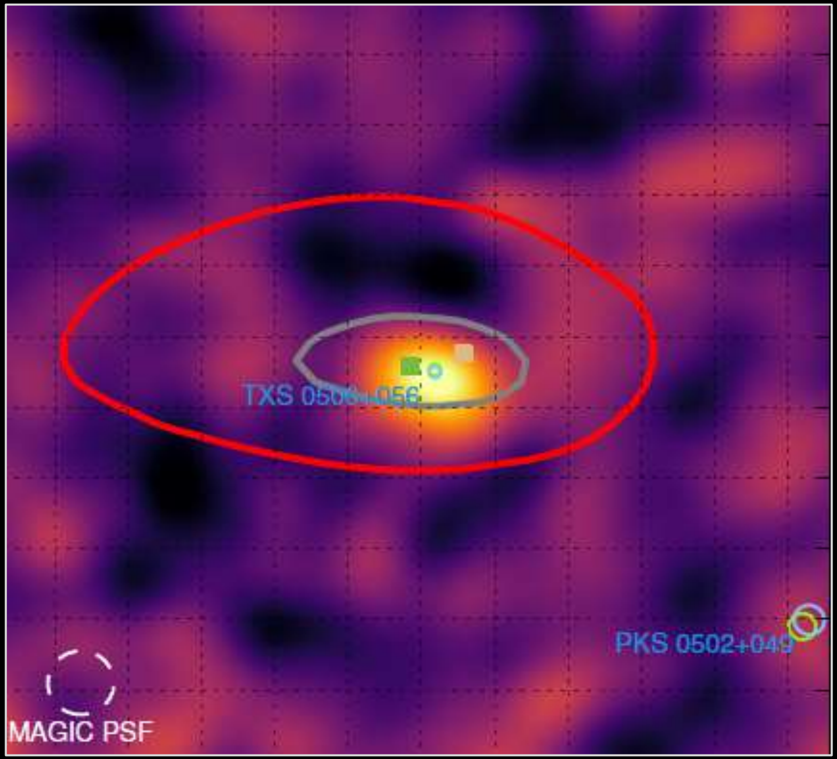
Pre-trials p-value: 4.1σ

10 public alerts and 41 archival events
→Post-trials p-value: 3.0σ

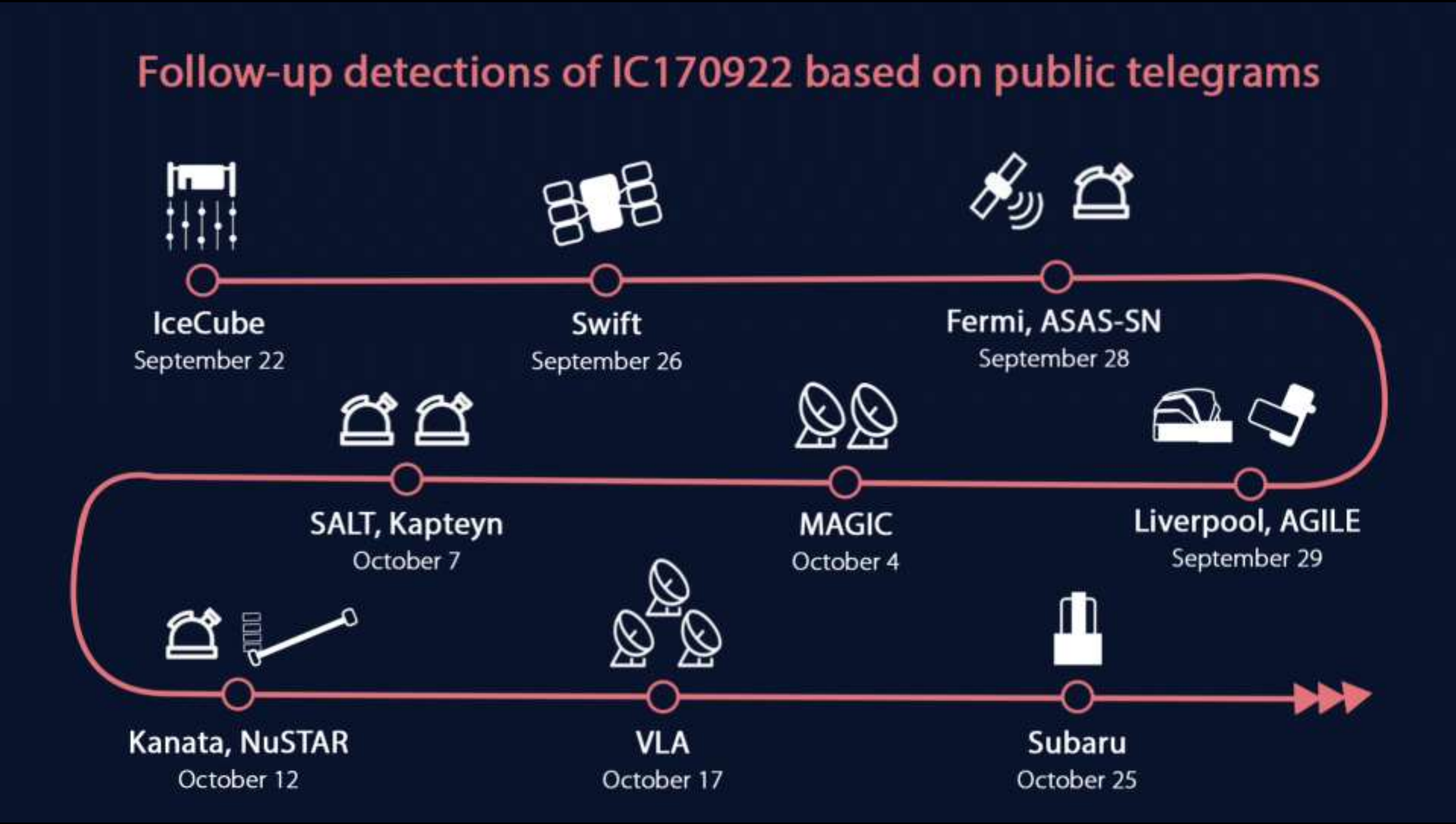
Neutrino points within 0.06º of a known Fermi blazar

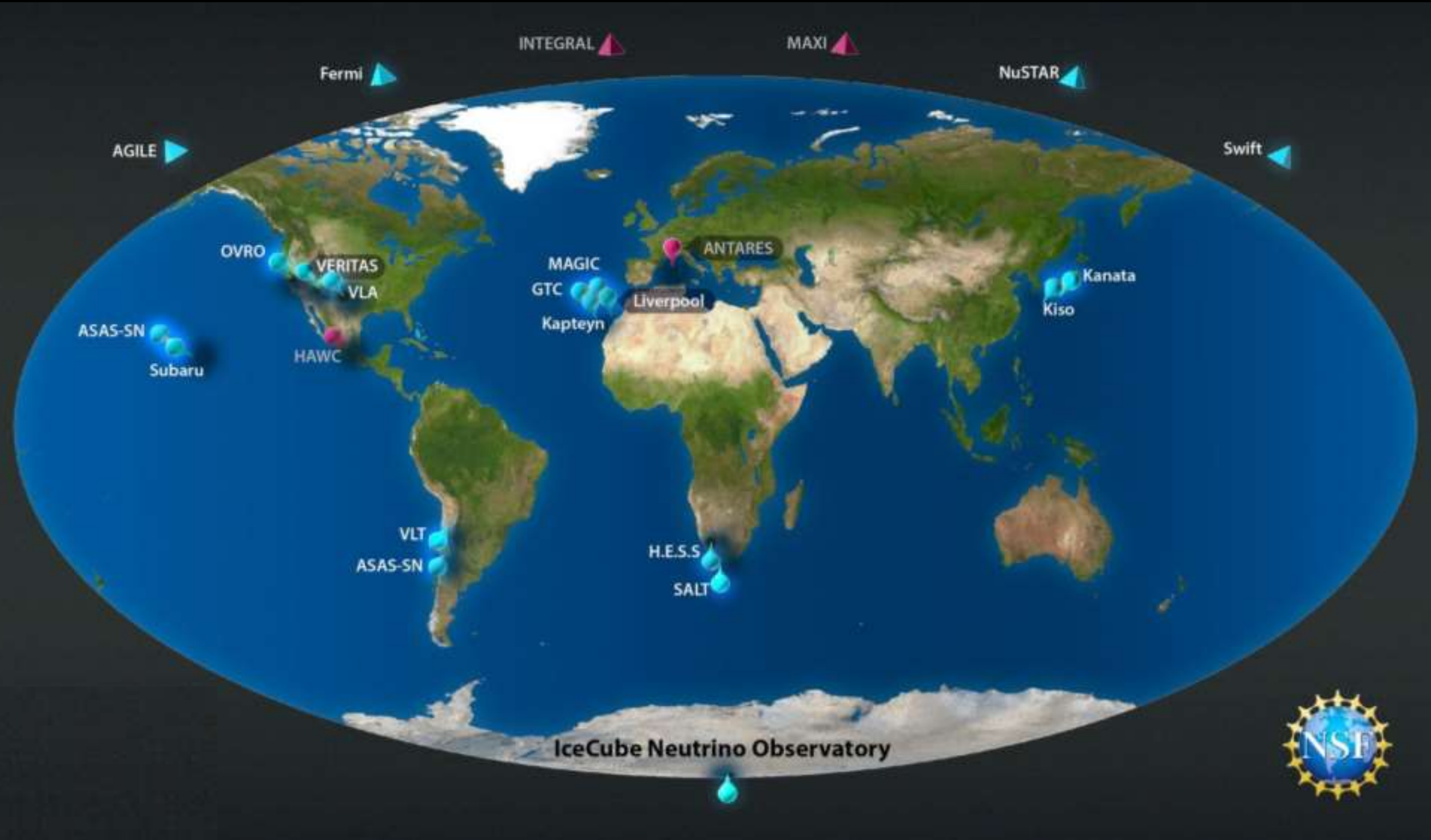
MAGIC detects emission of >100 GeV gammas





MAGIC atmposheric Cherenkov telescope


Follow-up detections of IC170922 based on public telegrams
IceCube
September 22
Swift
September 26
Fermi, ASAS-SN
September 28
Liverpool, AGILE
September 29
MAGIC
October 4
SALT, Kapteyn
October 7
Kanata, NuSTAR
October 12
VLA
October 17
Subaru
October 25


INTEGRAL
MAXI
Fermi
NuSTAR
AGILE
Swift
OVRO
VERITAS
VLA
ANTARES
MAGIC
GTC
Liverpool
Kapteyn
Kanata
Kiso
ASAS-SN
Subaru
HAWC
VLT
ASAS-SN
H.E.S.S
SALT
IceCube Neutrino Observatory

multiwavelength campaign launched by IC 170922

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Draft version February 7, 2018
Typeset using LaTeX preprint2 style in AASTeX61

THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

Simona Paiano,[1,2] Renato Falomo,[1] Aldo Treves,[3,4] and Riccardo Scarpa[5,6]

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(Received February, 2018; Revised February 7, 2018; Accepted 2018)

Submitted to ApJL

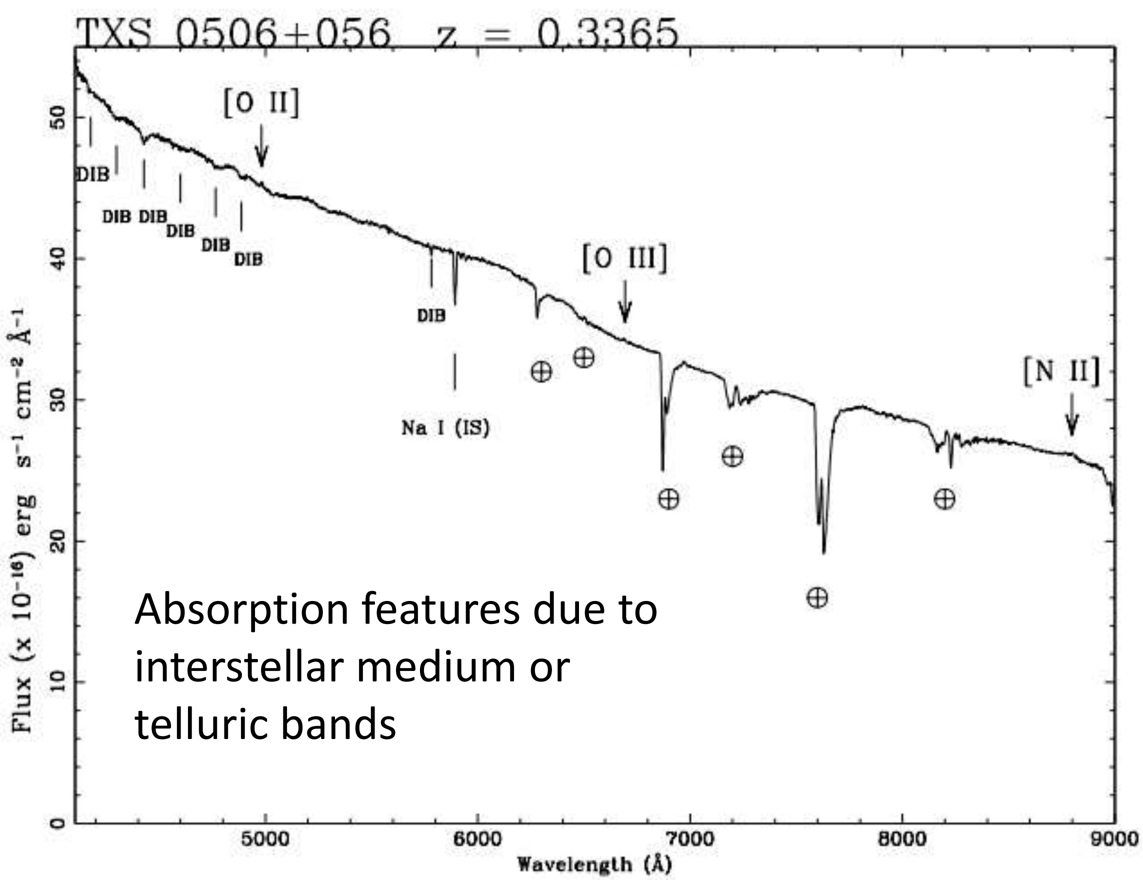
ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW $\sim$ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift z = 0.3365$\pm$0.0010.

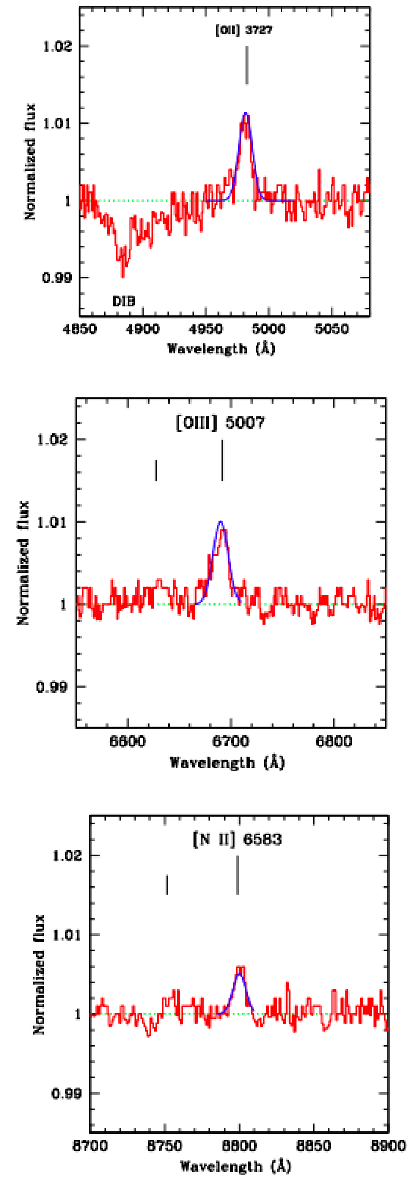
Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies –neutrinos

redshift measurement

z = 0.3365±0.0010



Absorption features due to interstellar medium or telluric bands

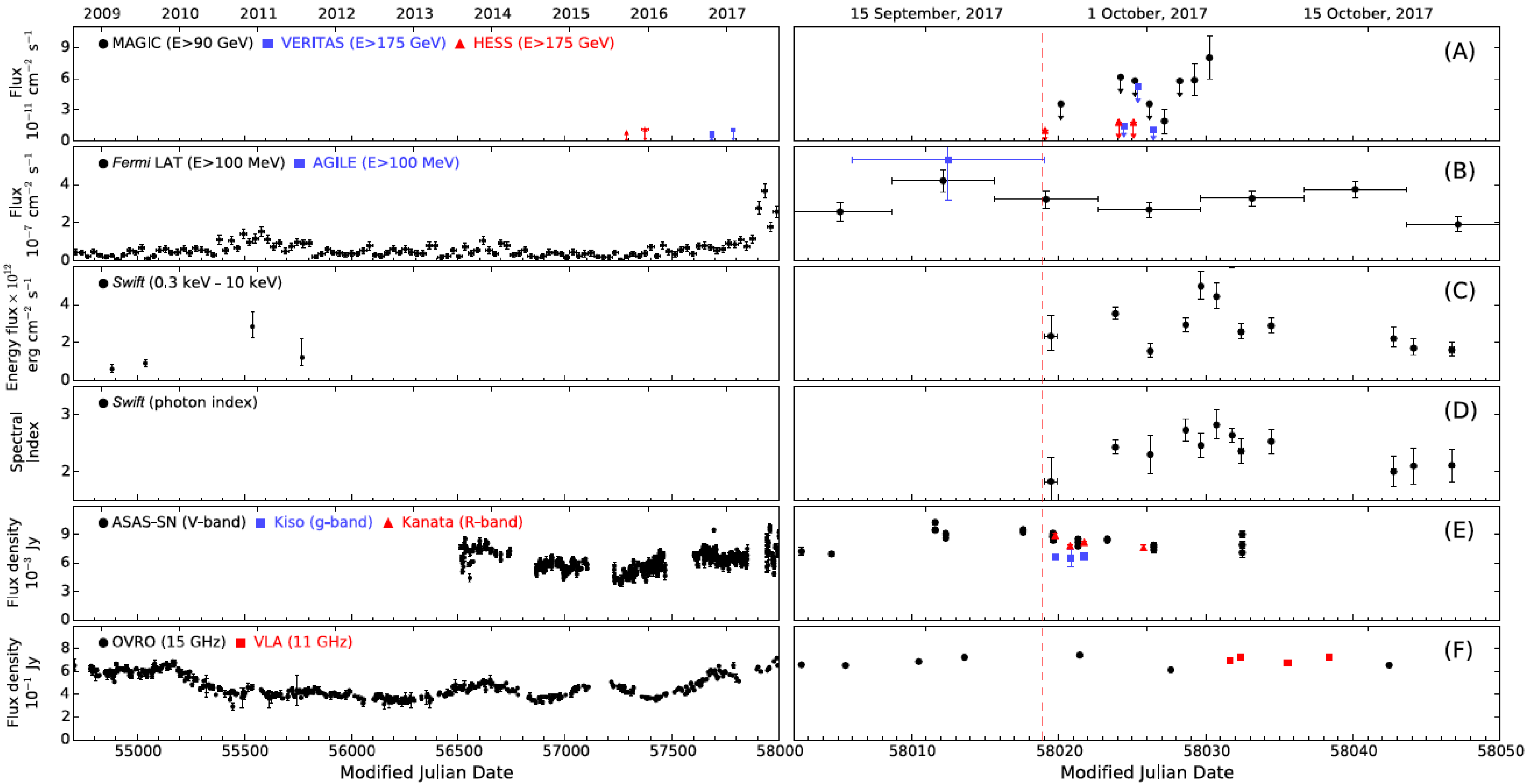


S. Paiano et al. arXiv:1802.01939

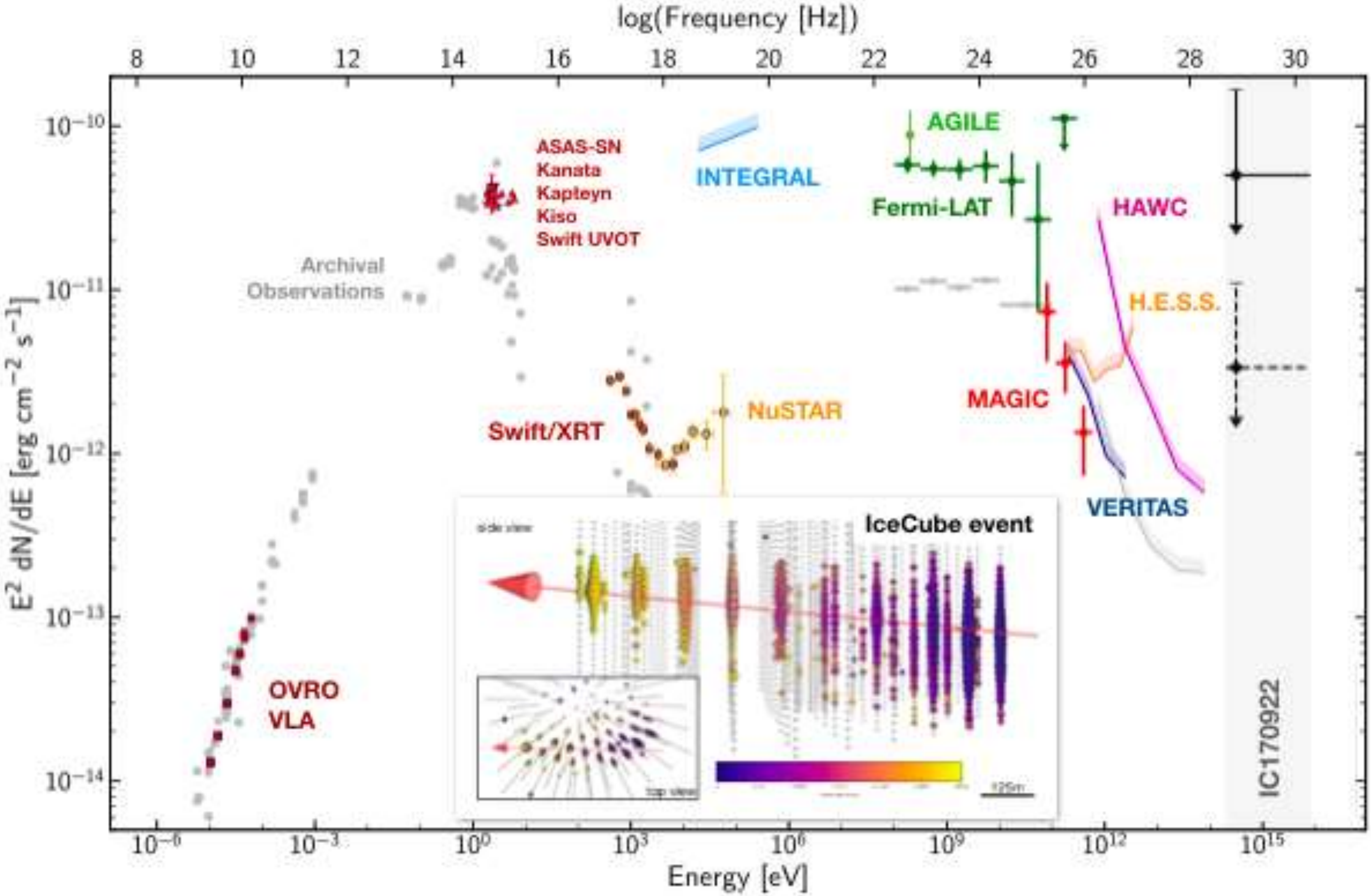
The Source: TXS 0506+056

- Redshift 0.3365±0.0010 (S. Paiano et al. 2018)
- Among 50 brightest blazars in 3LAC

- Outshines nearby blazars like Mrk421, Mrk 501, and 1ES 1959+650 by more than an order of magnitude

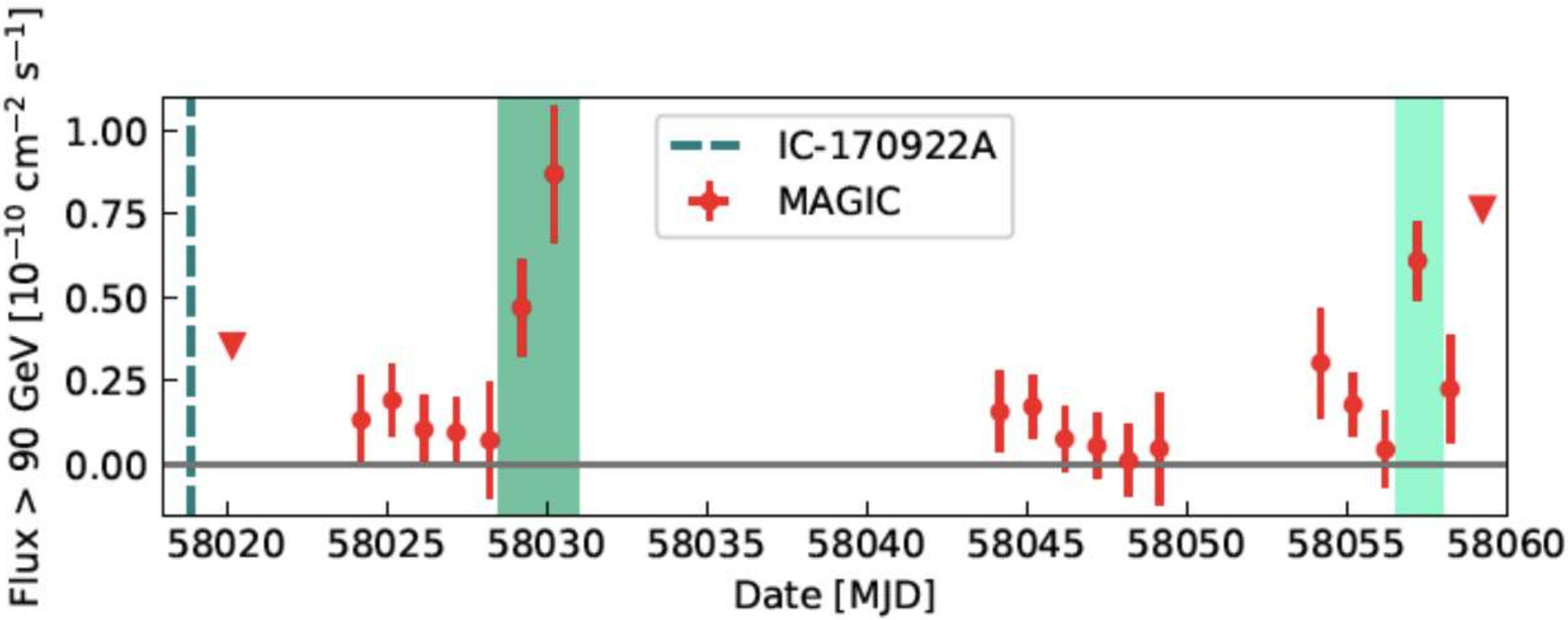


2009 2010 2011 2012 2013 2014 2015 2016 2017
15 September, 2017
1 October, 2017
15 October, 2017
MAGIC (E>90 GeV)
VERITAS (E>175 GeV)
HESS (E>175 GeV)
(A)
Flux 10^{-11} cm^{-2} s^{-1}
Fermi LAT (E>100 MeV)
AGILE (E>100 MeV)
(B)
Flux 10^{-7} cm^{-2} s^{-1}
Swift (0.3 keV – 10 keV)
(C)
Energy flux × 10^{12} erg cm^{-2} s^{-1}
Swift (photon index)
(D)
Spectral Index
ASAS-SN (V-band)
Kiso (g-band)
Kanata (R-band)
(E)
Flux density 10^{-3} Jy
OVRO (15 GHz)
VLA (11 GHz)
(F)
Flux density 10^{-1} Jy
Modified Julian Date
Modified Julian Date

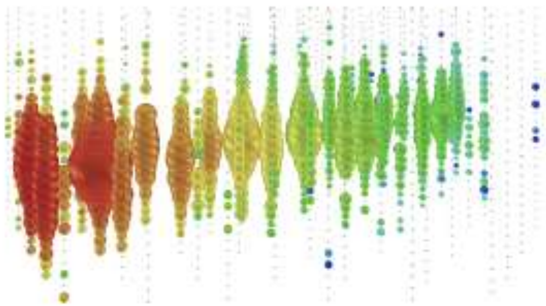


log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
Energy [eV]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
ASAS-SN
Kanata
Kapteyn
Kiso
Swift UVOT
Archival
Observations
INTEGRAL
AGILE
Fermi-LAT
HAWC
H.E.S.S.
MAGIC
NuSTAR
Swift/XRT
VERITAS
OVRO
VLA
IceCube event
IC170922

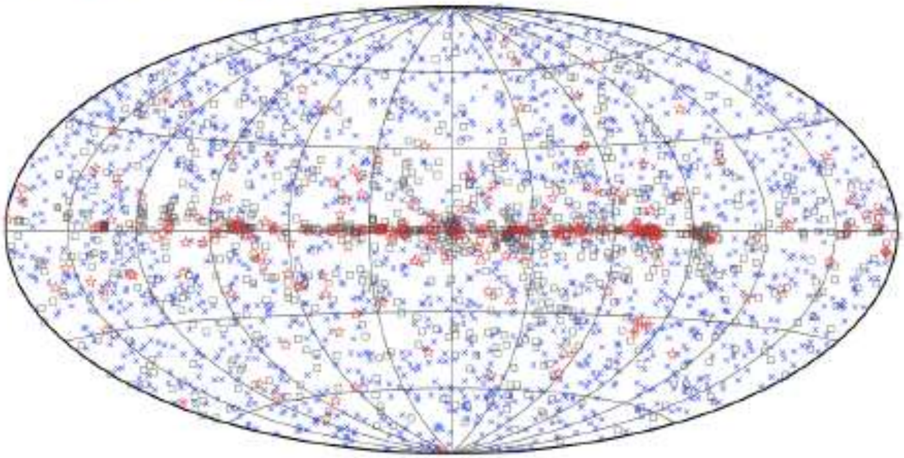
MAGIC finds variability on a 1-day scale
→ compact emission region



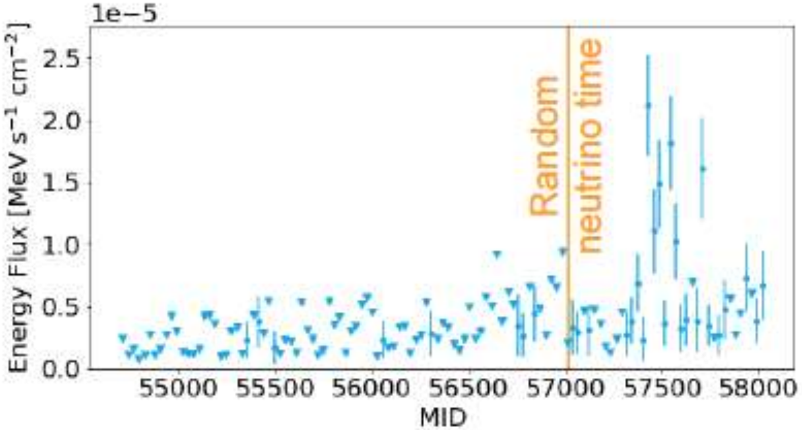
How Likely is it a Chance Probability?



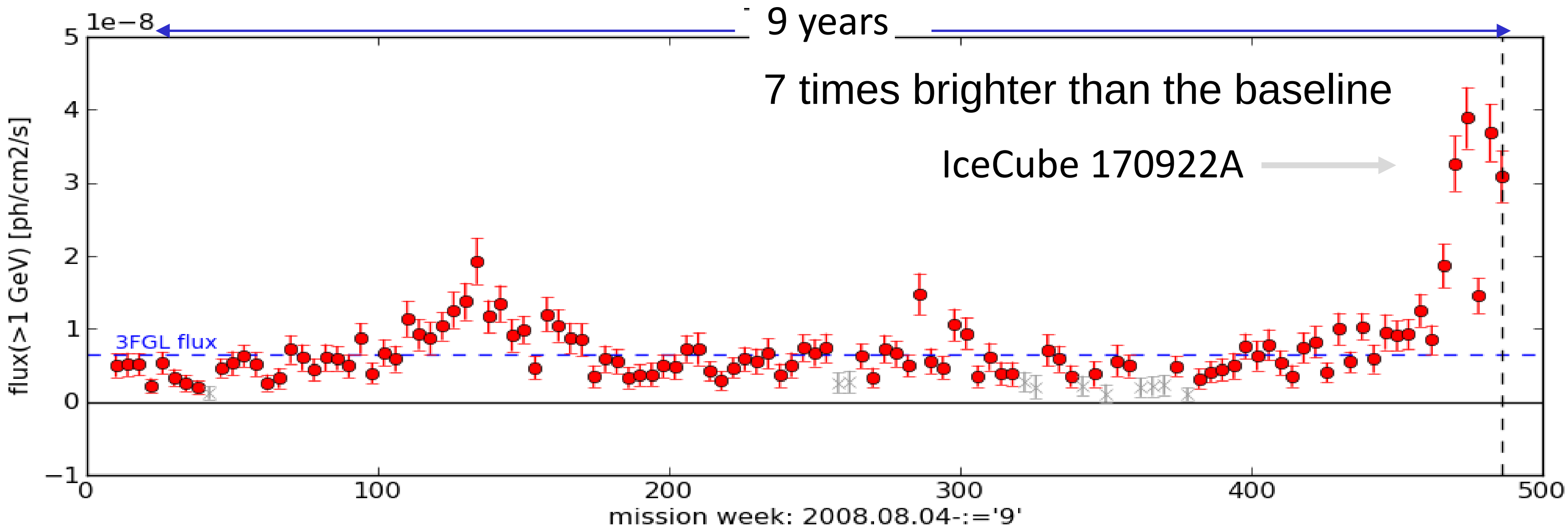
Step I: Draw a random neutrino from a representative sample of high-energy muon-track events



Step II: Are there any extra-galactic Fermi source close in space to the neutrinos?



Step III: What is the gamma-ray energy flux in the time bin when the neutrino arrives?



- $L = \prod_i^N \left(\frac{n_s}{N} P_S + \frac{n_b}{N} P_B \right) \rightarrow TS(N = 1) \propto \log \frac{P_S}{P_B}$

- $P_S = \ P_{spatial}(\vec{x}) \cdot \mathrm{W}_{\mathrm{energy}}(\mathrm{E}_{\mathrm{reco}}, \sin\theta) \cdot W_{temporal}(t)$

① <u>flux variability</u>

$$W_{temp ral} \propto \frac{I_\gamma(t)}{< I_\gamma(t) >}$$

② <u>energy flux</u>

$$W_{temp ral} \propto \int_{1GeV}^{100GeV} E_\gamma \frac{dI_\gamma(t)}{dE_\gamma} dE_\gamma$$

no correlation vs correlation $\rightarrow$ 4.1σ $\rightarrow$

corrections for all 10 alerts issued previously and the 41 archival events

Neutrino emission correlates with

1. gamma-ray energy flux in the range 1-100 GeV

$$w_s(t) = \phi_E(t) = \int_{1\ \mathrm{GeV}}^{100\ \mathrm{GeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

2. relative gamma-ray flux variations in the range 1-100 GeV

$$w_s(t) = \phi_\gamma(t) / \langle \phi_\gamma \rangle$$

3. very high-energy gamma-ray energy flux in the range 100GeV-1TeV (extrapolated from Fermi energy range)

$$w_s(t) = \phi_E(t) = \int_{100\ \mathrm{GeV}}^{1\ \mathrm{TeV}} E_\gamma \frac{d\phi_\gamma(t)}{dE_\gamma} dE\gamma$$

multiwavelength campaign launched by IC 170922

IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43º Dec 5.72º

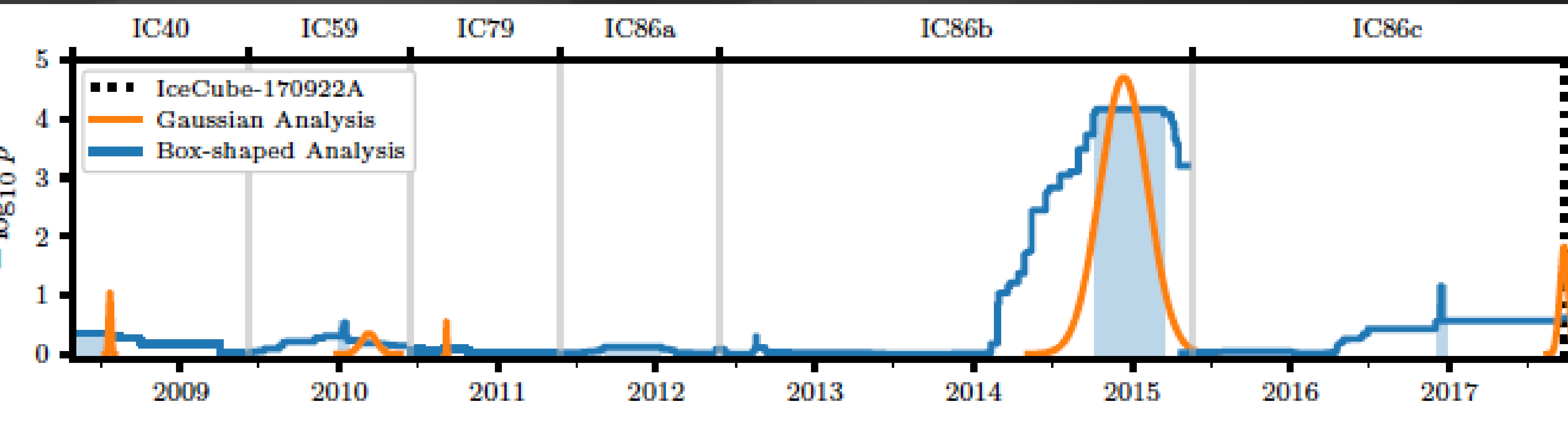
- Fermi-LAT: flaring blazar within 0.1º (7x steady flux)

- MAGIC: TeV source in follow-up observations

- follow-up by 12 more telescopes

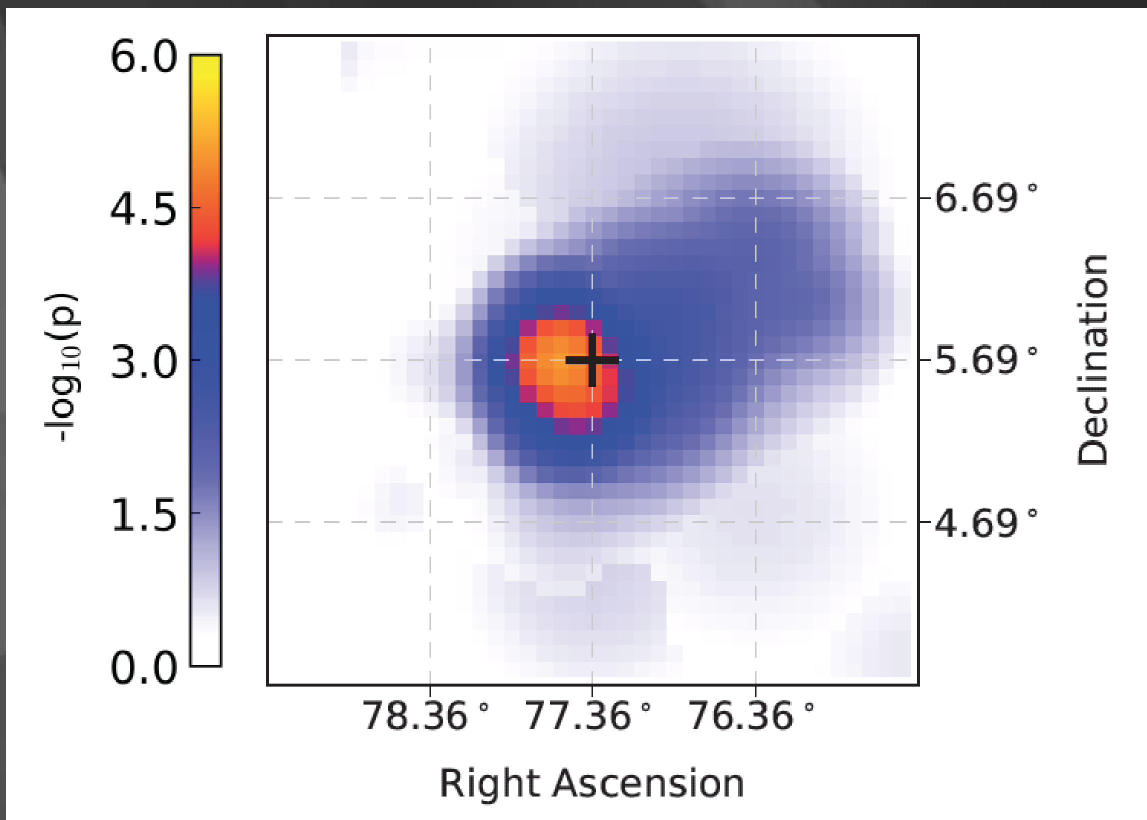
- → IceCube archival data (without look-elsewhere effect)

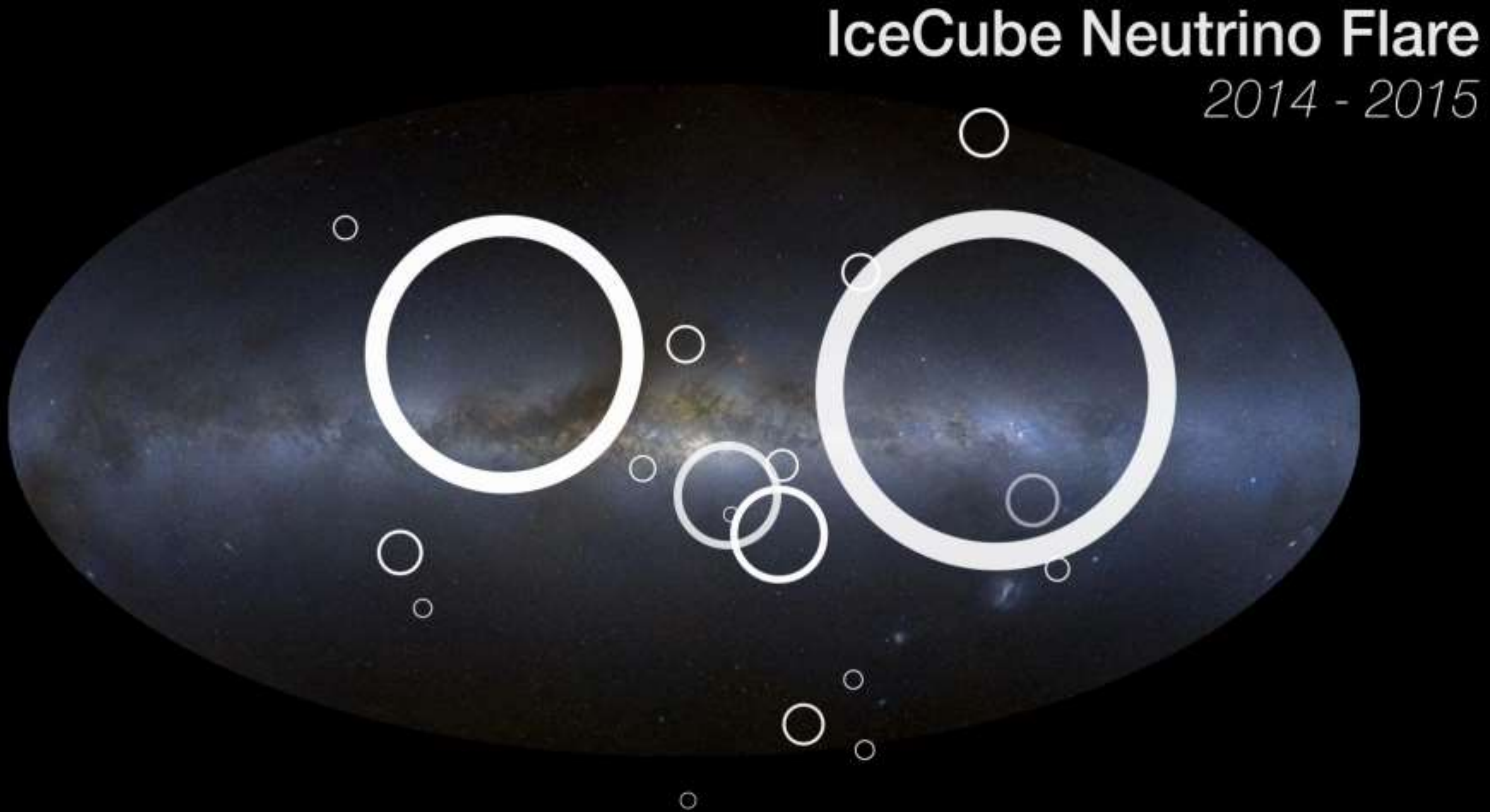
- → Fermi-LAT archival data



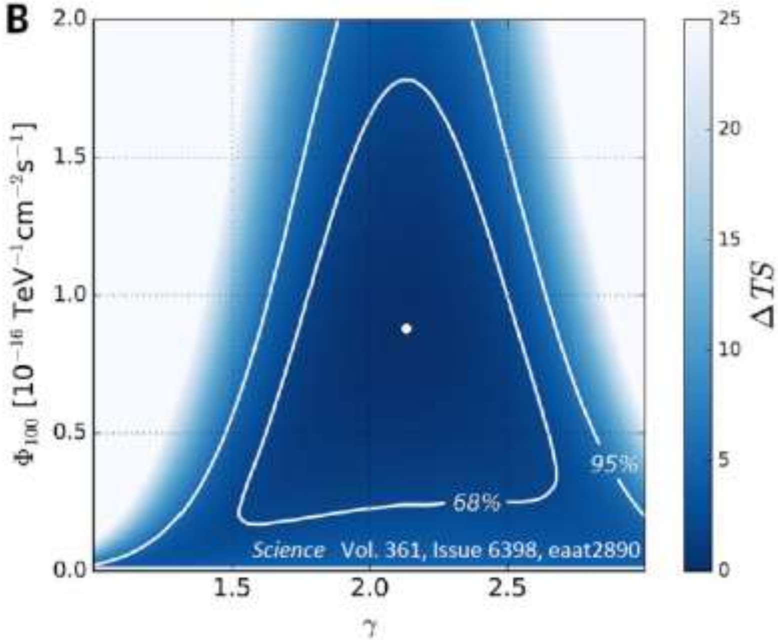
search in archival IceCube data:

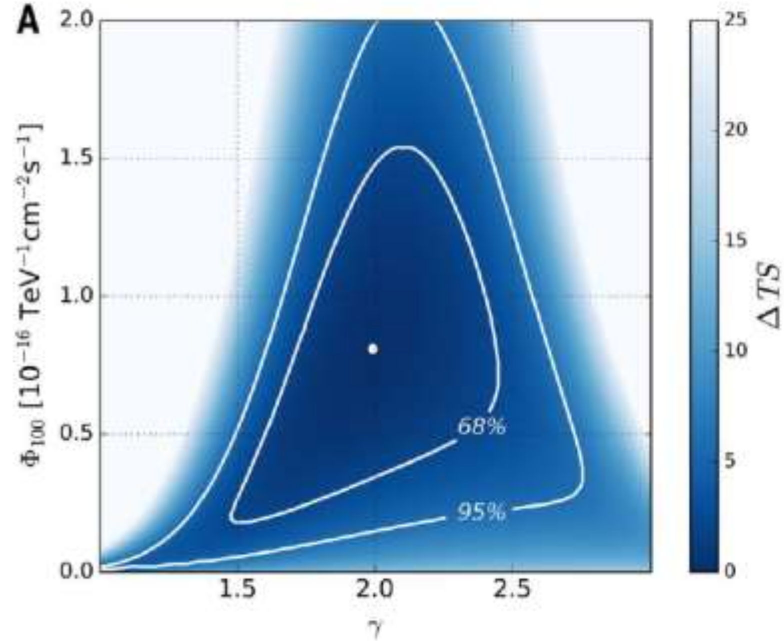
- ~100 day flare in December 2014
- accompanied by hardest Fermi spectrum in 10 yrs ($E^{-1.7}$)





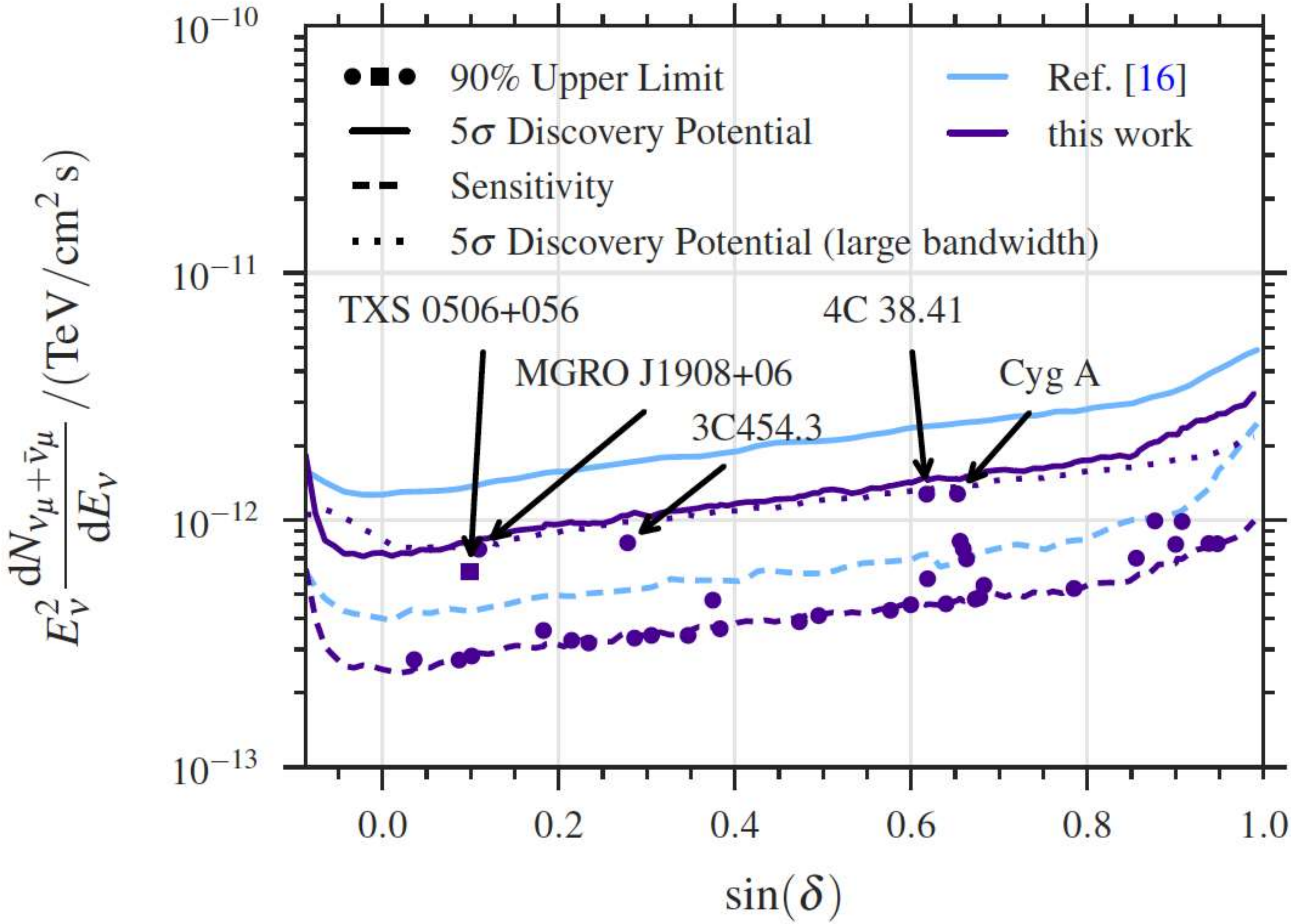
19 events on a background < 6 in 150 days





	7 years (2008-2015)	**9.5 years (2008-2017)**
Normalization @ 100 TeV [TeV^{-1}cm^{-2}s^{-1}]	$\mathbf{(0.9^{+0.6}_{-0.5}) \cdot 10^{-16}}$	$(0.8^{+0.5}_{-0.4}) \cdot 10^{-16}$
Spectral index	$\mathbf{2.1 \pm 0.3}$	2.0 ± 0.3
p-value	**1.6% (2.1σ)**	0.002% (4.1σ)

- Search at exact TXS position
  → Single trial
- 9.5 years includes alert event
  → a posteriory
- 7 year result independent data



90% Upper Limit
5σ Discovery Potential
Sensitivity
5σ Discovery Potential (large bandwidth)
Ref. [16]
this work
TXS 0506+056
MGRO J1908+06
3C454.3
4C 38.41
Cyg A
$E_\nu^2 \frac{dN_{\nu_\mu+\bar{\nu}_\mu}}{dE_\nu}$ / (TeV/cm² s)
sin(δ)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.0
0.2
0.4
0.6
0.8
1.0

we identified a source of high energy cosmic rays:

the active galaxy (blazar) TXS 0506+056 at a redshift of 0.33

extensive multiwavelength campaign will allow us to study the first cosmic accelerator

AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

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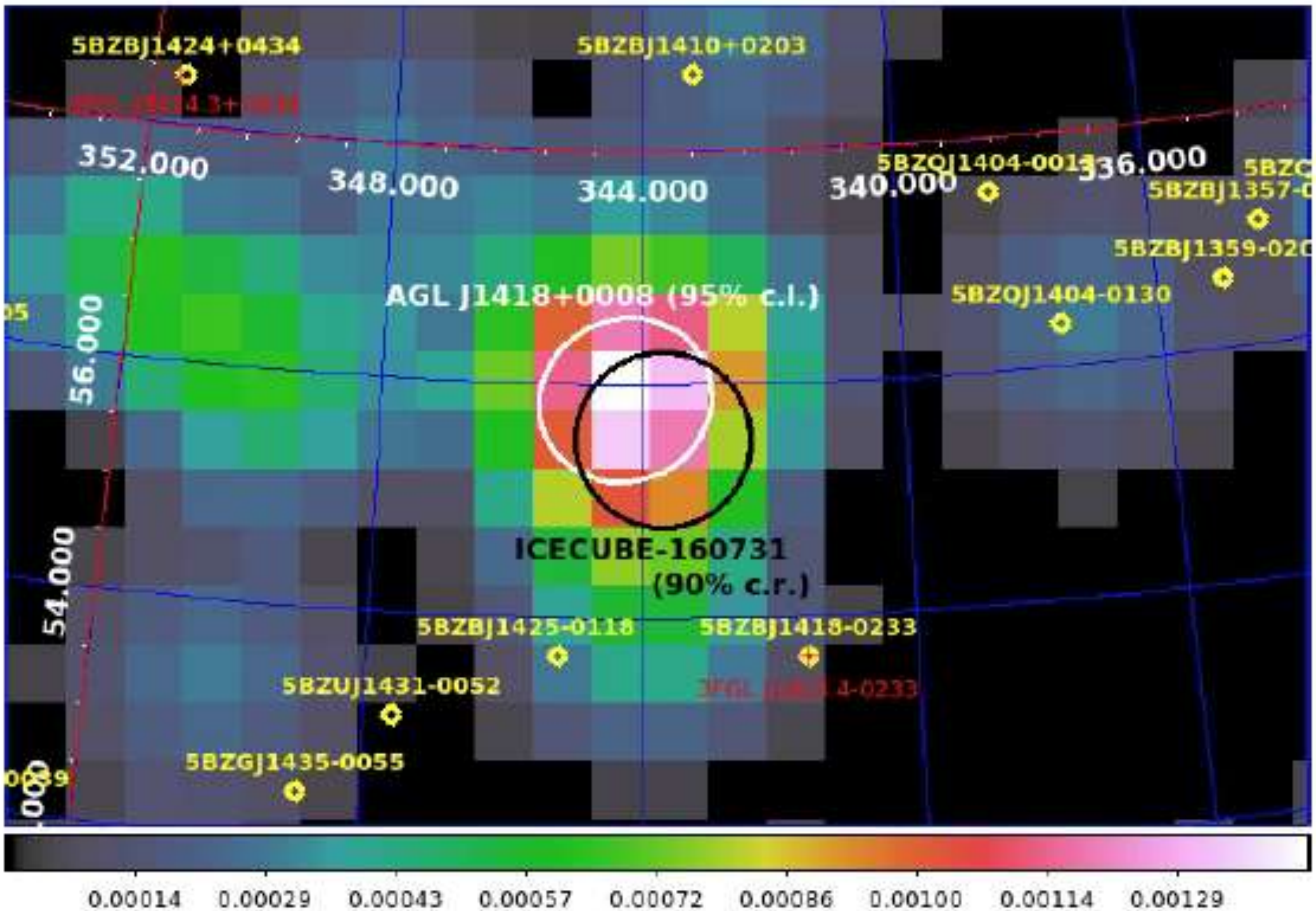
L. A. Antonelli,[1,2] P. Caraveo,[8] P. W. Cattaneo,[9] S. Colafrancesco,[10,2] F. Longo,[11] S. Mereghetti,[8]
A. Morselli,[12] L. Pacciani,[4] G. Piano,[4] A. Pellizzoni,[13] M. Pilia,[13] A. Rappoldi,[9] A. Trois,[13] and S. Vercellone[14]



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fabrizio.lucarelli@asdc.asi.it

The Highest Energy Emission Detected by EGRET from Blazars

Brenda L. Dingus[1] & David L. Bertsch [2]

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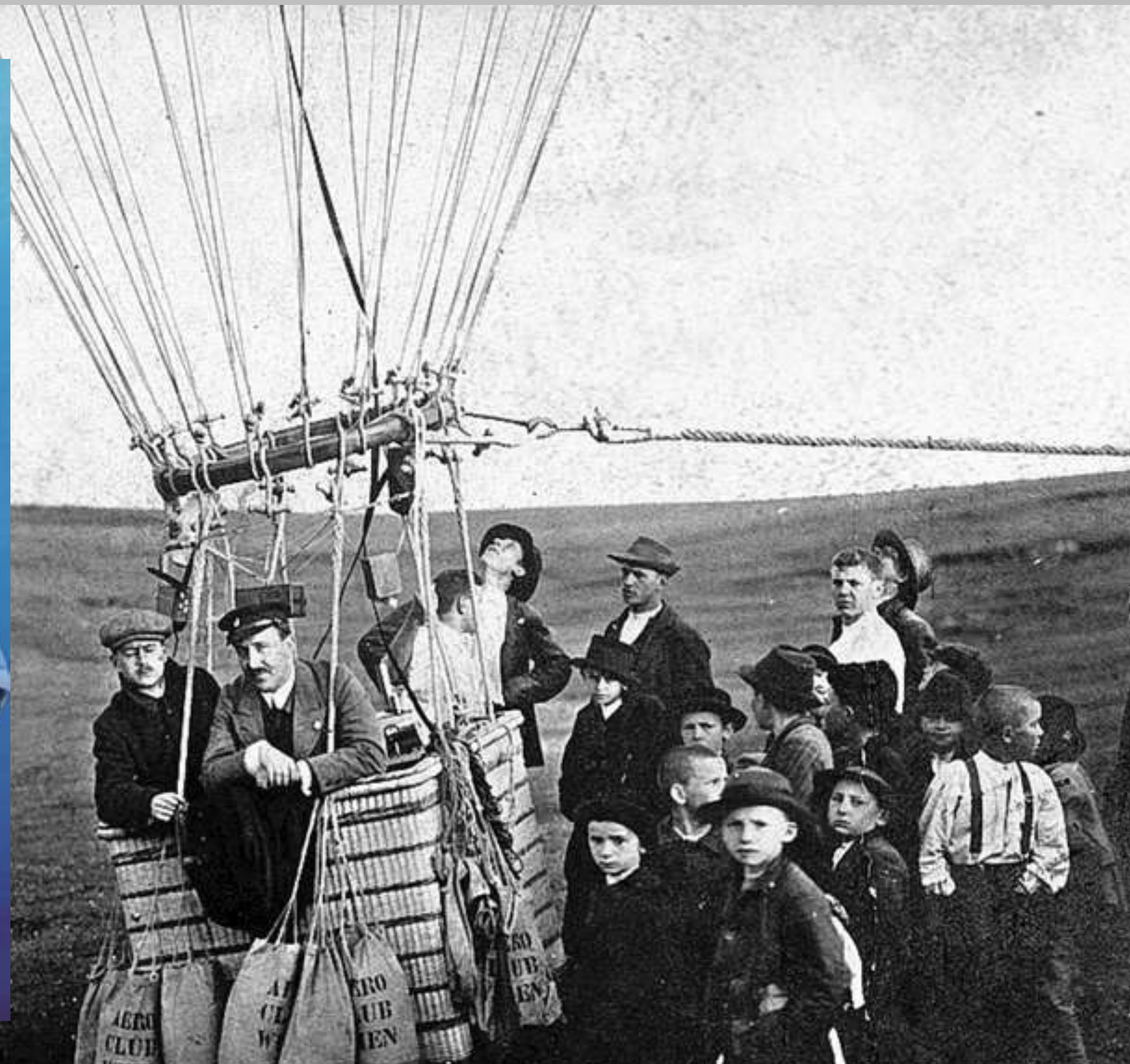
(2)NASA Goddard Space Flight Center, Greeenbelt, MD 20771

Abstract. Published EGRET spectra from blazers extend only to 10 GeV, yet EGRET has detected approximately 2000 γ-rays above 10 GeV of which about half are at high Galactic latitude. We report a search of these high-energy γ-rays for associations with the EGRET and TeV detected blazers. Because the point spread function of EGRET improves with energy, only ~2 γ-rays are expected to be positionally coincident with the 80 blazars searched, yet 23 γ-rays were observed. This collection of > 10 GeV sources should be of particular interest due to the improved sensitivity and lower energy thresholds of ground-based TeV observatories. One of the blazers, RGB0509+056, has the highest energy γ-rays detected by EGRET from any blazar with 2 > 40 GeV, and is a BL Lac type blazar with unknown redshift.

Victor Hess 1912

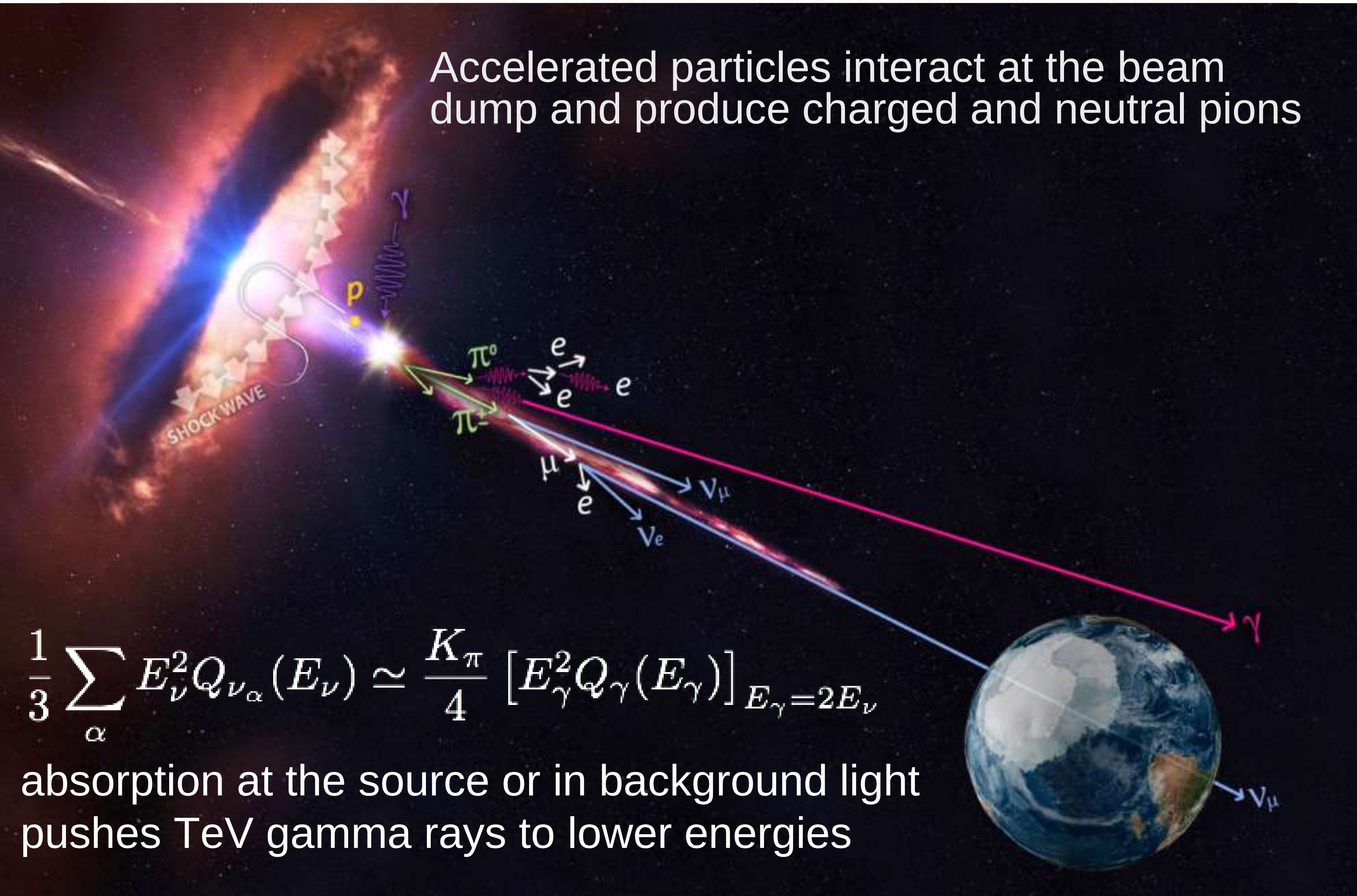


Observation of TXS 0506+056 in Neutrinos

- Two independent analyses found neutrino emission of TXS 0506+056.
- The 9.5 year averaged flux of neutrinos from TXS 0506+056 is dominated by the 2014 burst.
- Gamma ray enhancement coincident with IC 170922A.
- No enhanced gamma ray activity for the neutrino burst in 2014. May be hardening of the spectrum [Padovani+, 2018, Garrappa+, TeVPA2018]

! Challenge: Where are the gamma rays? Why is not there enhanced gamma ray activity?

The neutrino-gamma ray connection



Accelerated particles interact at the beam dump and produce charged and neutral pions

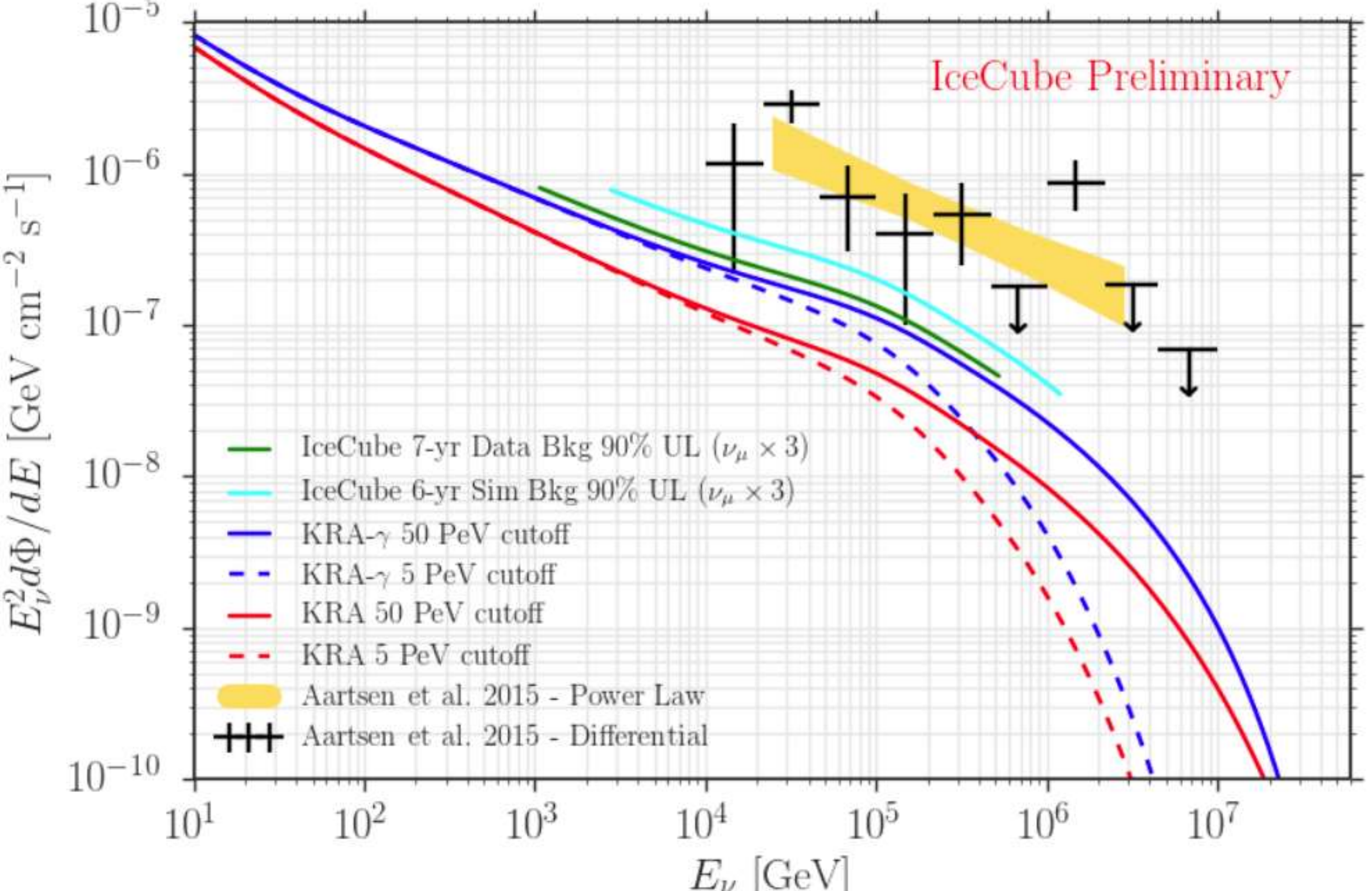
$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4}\left[E_\gamma^2 Q_\gamma(E_\gamma)\right]_{E_\gamma=2E_\nu}$$

absorption at the source or in background light pushes TeV gamma rays to lower energies

High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

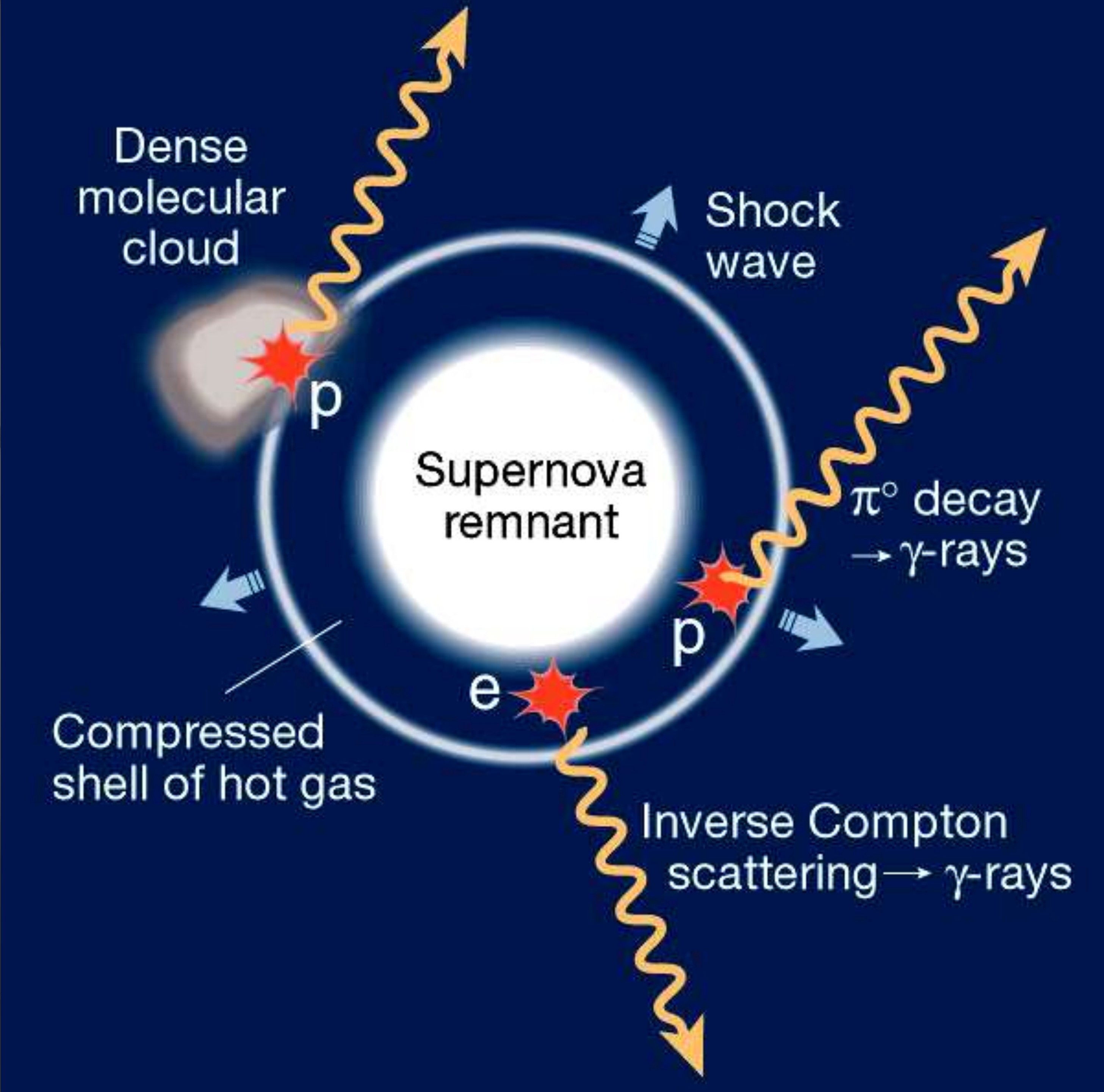
- Galactic sources?



IceCube Preliminary
$E_\nu^2 d\Phi/dE$ [GeV cm^{-2} s^{-1}]
E_ν [GeV]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^1
10^2
10^3
10^4
10^5
10^6
10^7
IceCube 7-yr Data Bkg 90% UL ($\nu_\mu \times 3$)
IceCube 6-yr Sim Bkg 90% UL ($\nu_\mu \times 3$)
KRA-γ 50 PeV cutoff
KRA-γ 5 PeV cutoff
KRA 50 PeV cutoff
KRA 5 PeV cutoff
Aartsen et al. 2015 - Power Law
Aartsen et al. 2015 - Differential

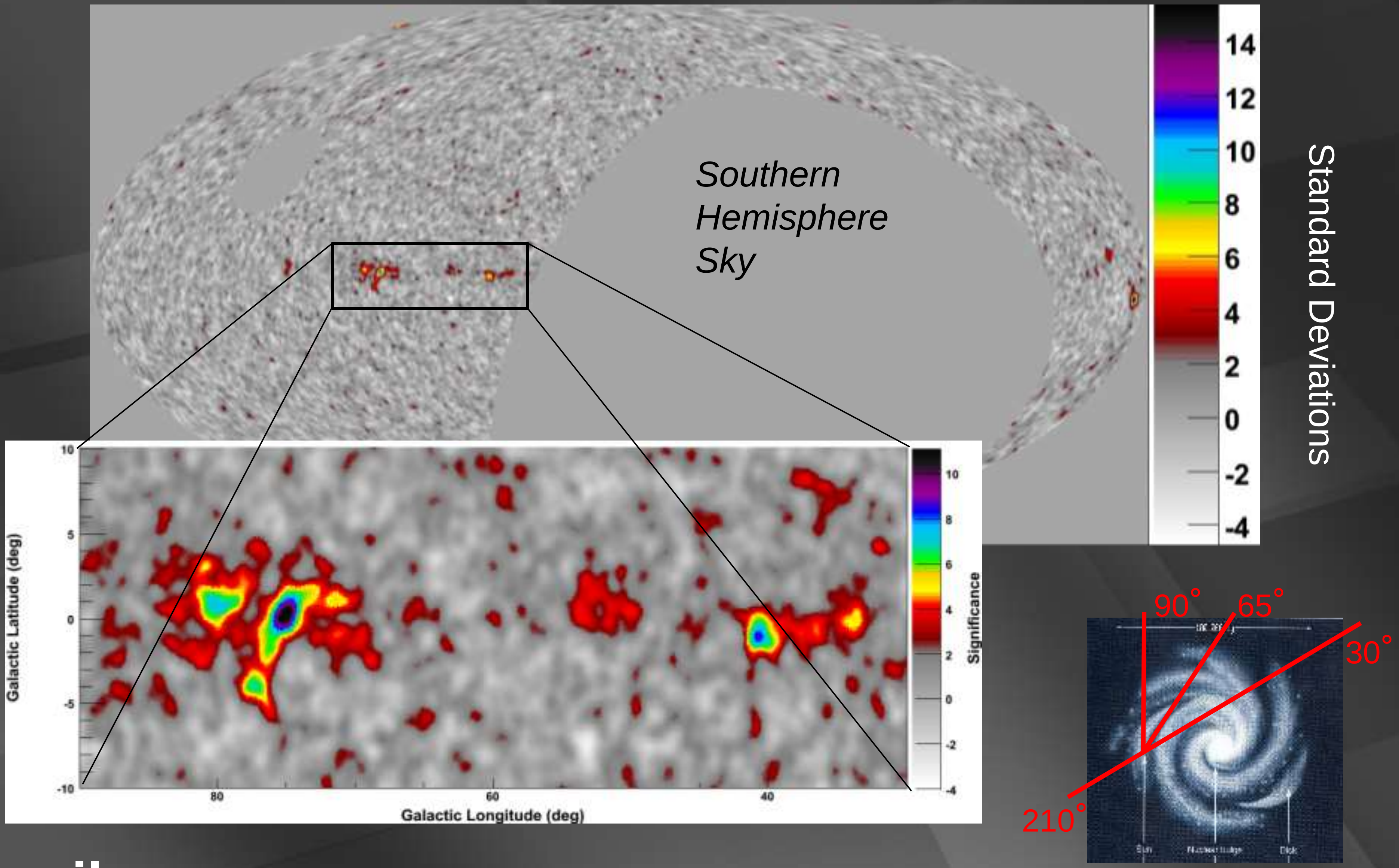
neutrinos from supernova remnants :

molecular clouds as beam dumps → pion production



galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions



milagro

emissivity (units: (note!) per unit volume per GeV per second) in photons produced by a number density of cosmic rays N_p interacting with a target density n_{gas} per cm^3

production rate

total cross section

$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$

$$\mathrm{f}_{p^0} \left(\equiv K_p \right) = < \frac{E_p}{E_p} > \text{ and } \mathrm{q}_g \left(E_g \right) = 2 q_p \left(\frac{E_p}{2} \right)$$

$$\int_{1\,\mathrm{TeV}} dE_\gamma E_\gamma \frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi d^2} L_\gamma$$

$$L_\gamma = V\, Q_\gamma = \frac{W}{\rho_{cr}} Q_\gamma$$

volume of the remnant

energy in >TeV photons produced by cosmic rays per cm^3 per sec

10^{-12} erg/cm^3

γ, ν flux of galactic cosmic rays

a SNR at d = 1 kpc transferring W = 10^{50} erg to cosmic rays interacting with interstellar gas (or molecular clouds) with density n > 1 cm^{-3} produces a gamma-ray flux of

$$E\frac{dN_g}{dE}(>1\,TeV) =$$

$$3\;\; 10^{-11} cm^{-2} s^{-1} \frac{W}{10^{50}\,erg} \frac{n}{1cm^3} \left(\frac{d}{1kpc}\right)^{-2}$$

should be observed by present
TeV gamma-ray telescopes

Milagro sources ?
RX J1713.7-3946??

neutral pions

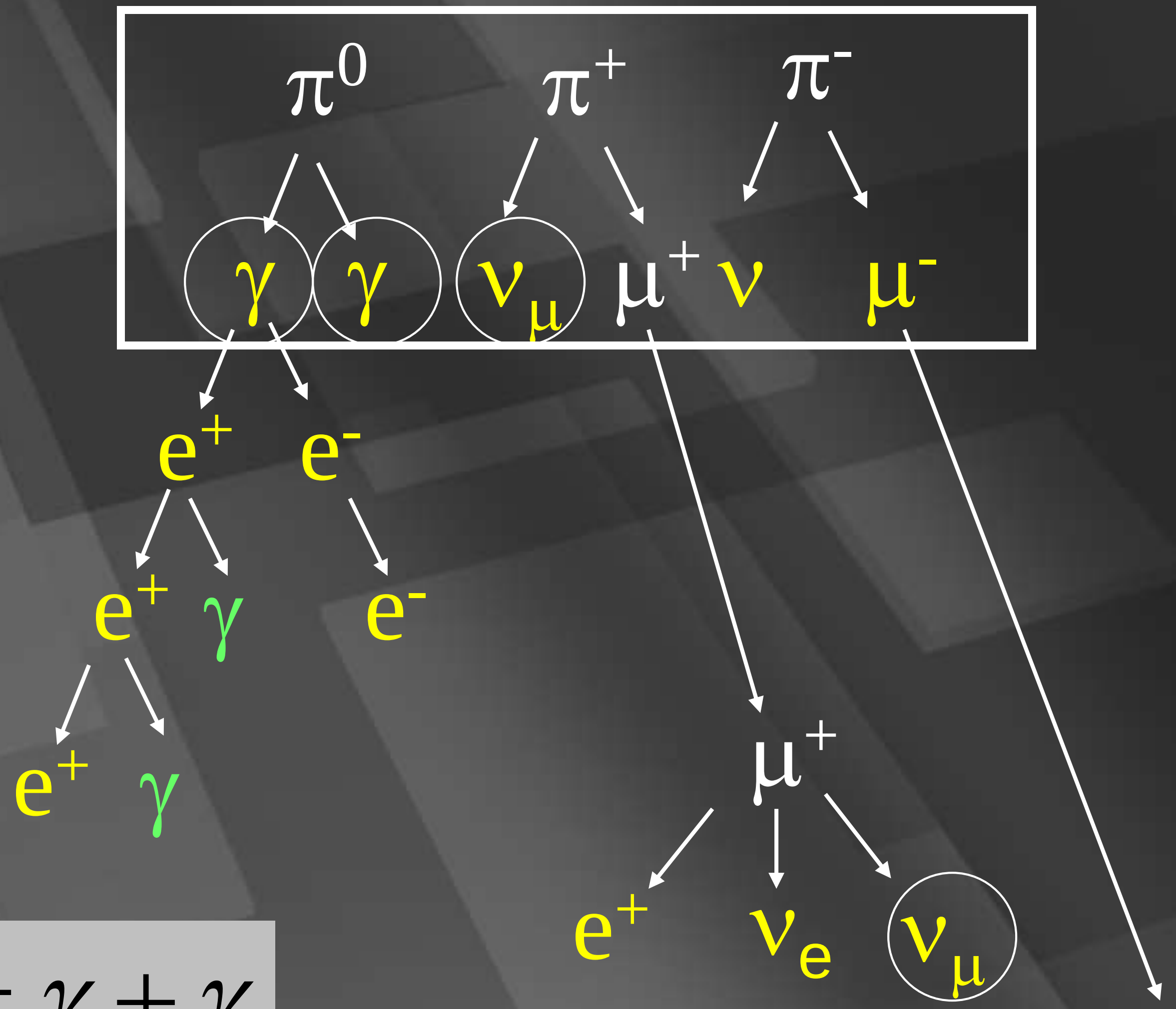
are observed as

gamma rays

charged pions

are observed as

neutrinos



$$\nu_\mu + \bar{\nu}_\mu = \gamma + \gamma$$

ν flux accompanying TeV gammas

$$\frac{dN_n}{dE} @ \frac{1}{2}\frac{dN_g}{dE}$$

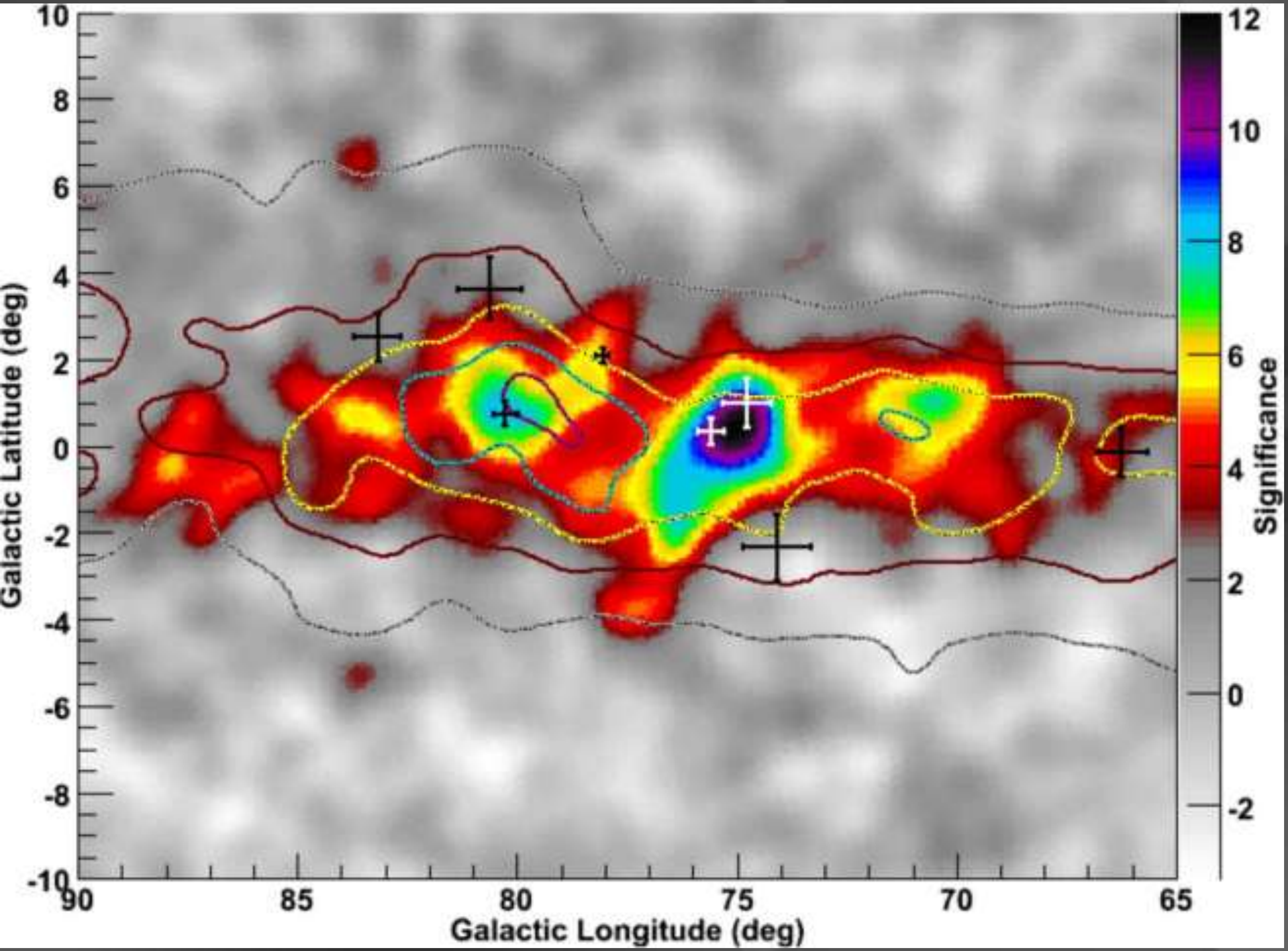
$$\text{number of events} = \text{Area Time} \int dE \, \frac{dN_n}{dE} P_{n \to m}$$

$$= 1.5 \ln\left(\frac{E_{\max}}{E_{\min}}\right) \text{ events per km}^2 \text{ per year per source!}$$

reject background

$$\to E \geq 40\, TeV$$

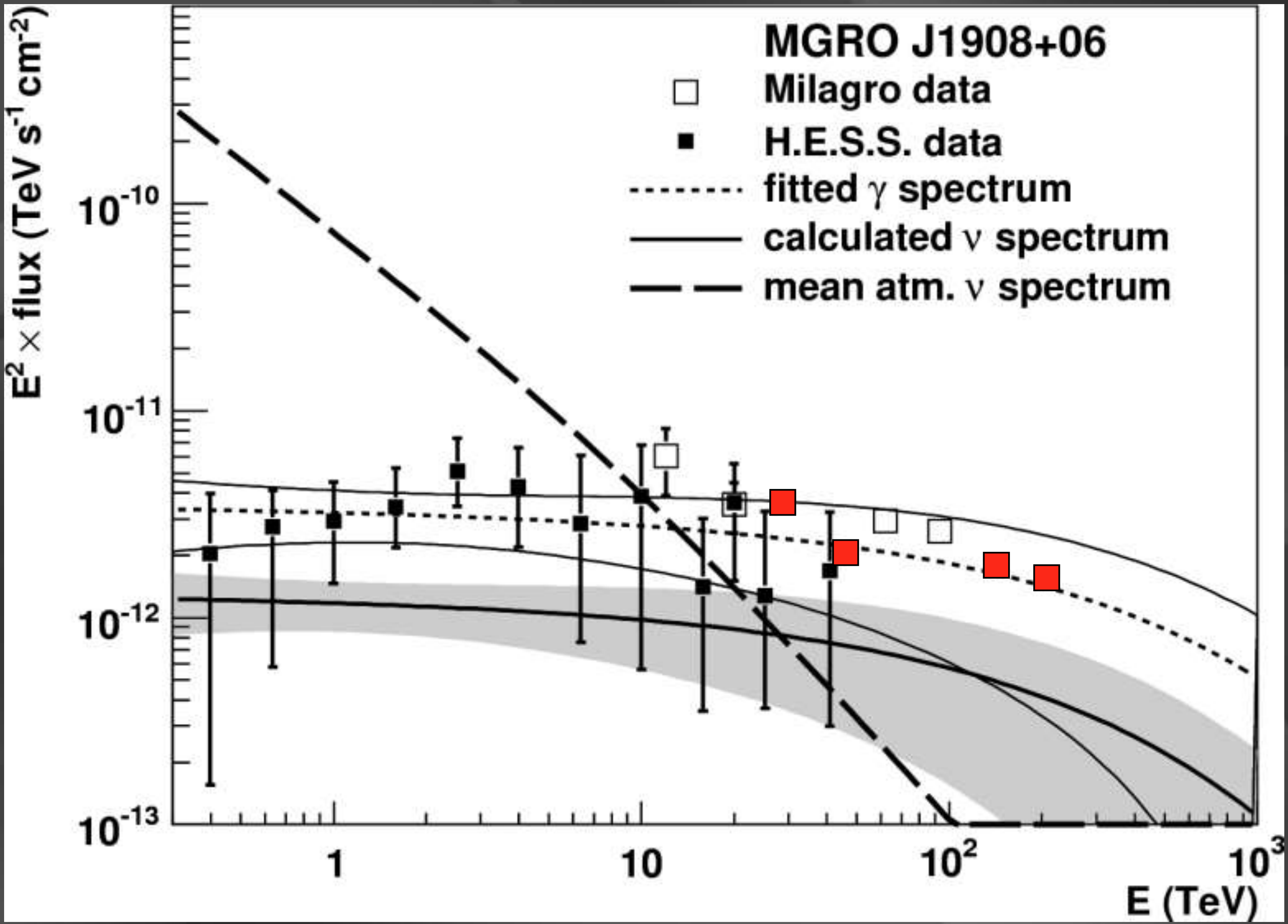
Cygnus region at ~ 1kpc : Milagro



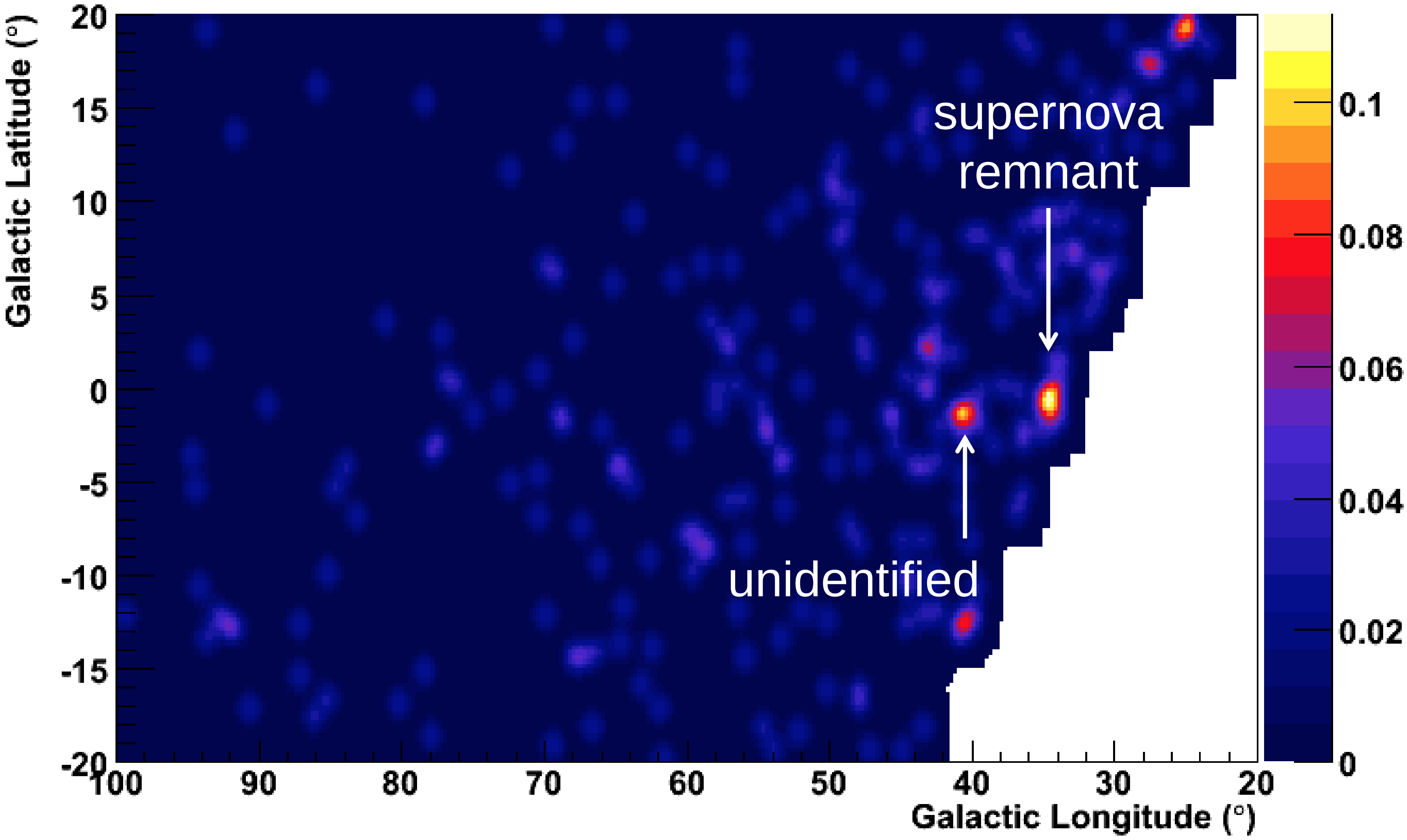
translation of TeV gamma rays into TeV neutrinos yields:

3 ± 1 ν per year in IceCube per source

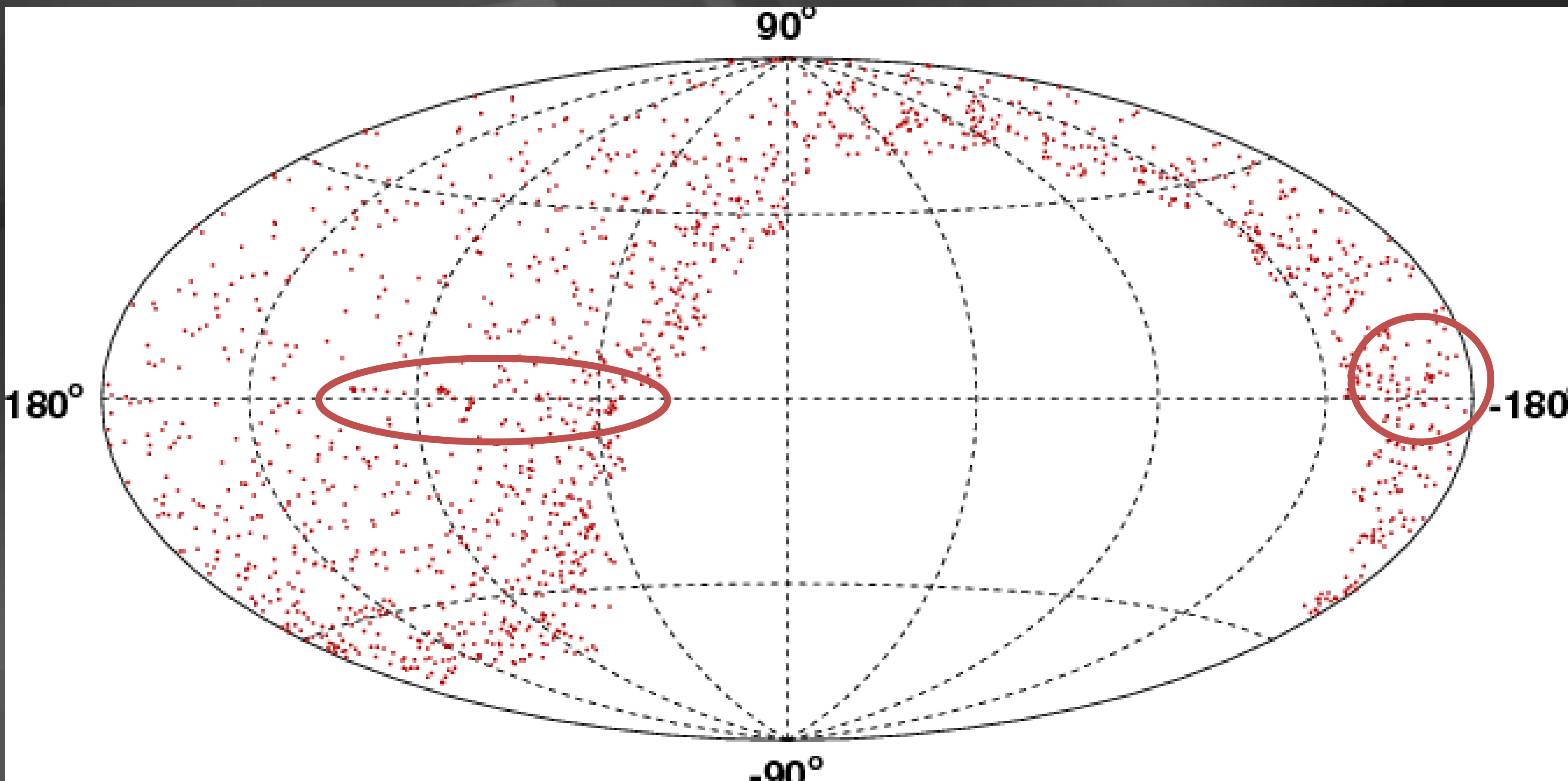
MGRO J1908+06: the first Pevatron? (2007!)



2007 simulated sky map of IceCube in Galactic coordinates after five years of operation of the completed detector. Two Milagro sources are visible with four events for MGRO J1852+01 and three events for MGRO J1908+06 with energy in excess of 40 TeV.



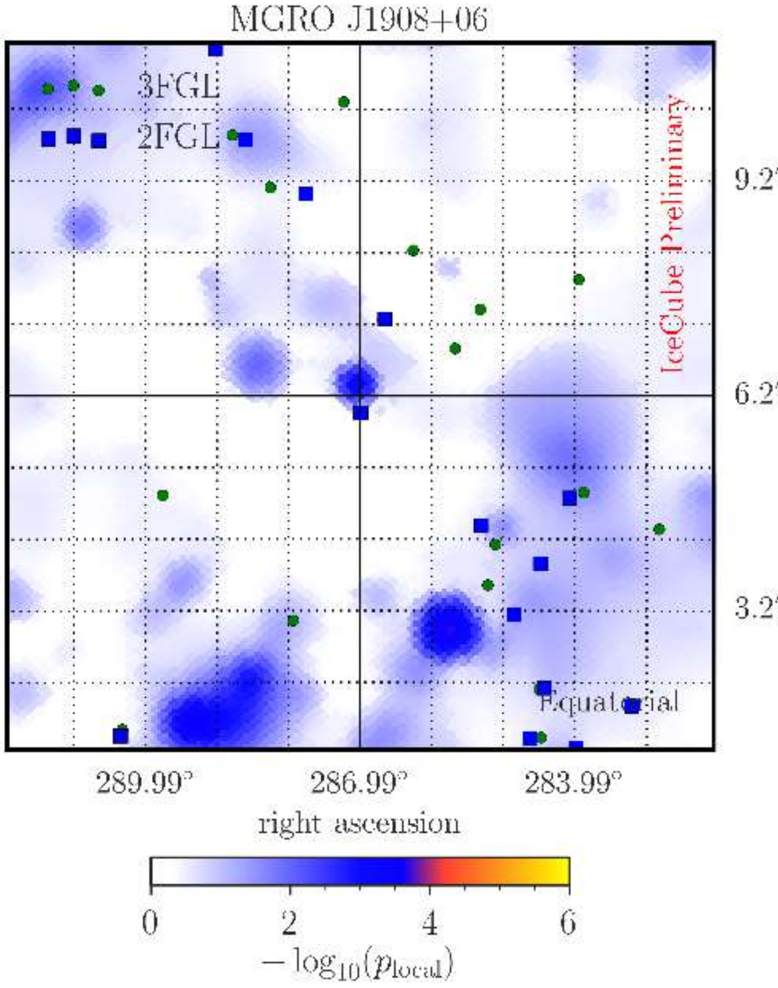
5σ in 5 years of IceCube …
IceCube image of our Galaxy > 10 TeV



- most significant source in pre-defined list (p-value 0.003 pretrial)
- joined HAWC-IceCube analysis in progress using photon templates

Table 1: Results of the pre-defined source list.

Source	Type	α [deg]	δ [deg]	p-Value	TS	n_s	Φ_0 [TeV cm^{-2} s^{-1}]
PKS 0235+164	BL Lac	39.66	16.62	0.7355	-0.400	0.00	$2.04 \cdot 10^{-13}$
1ES 0229+200	BL Lac	38.20	20.29	0.4762	-0.059	0.00	$4.47 \cdot 10^{-13}$
W Comae	BL Lac	185.38	28.23	0.4420	-0.055	0.00	$5.37 \cdot 10^{-13}$
Mrk 421	BL Lac	166.11	38.21	0.2433	0.029	0.48	$8.68 \cdot 10^{-13}$
Mrk 501	BL Lac	253.47	39.76	0.6847	-0.172	0.00	$3.51 \cdot 10^{-13}$
BL Lac	BL Lac	330.68	42.28	0.5104	-0.028	0.00	$5.58 \cdot 10^{-13}$
H 1426+428	BL Lac	217.14	42.67	0.7890	-0.243	0.00	$1.96 \cdot 10^{-13}$
3C66A	BL Lac	35.67	43.04	0.3306	-0.001	0.00	$7.50 \cdot 10^{-13}$
1ES 2344+514	BL Lac	356.77	51.70	0.9264	-0.808	0.00	$1.58 \cdot 10^{-13}$
1ES 1959+650	BL Lac	300.00	65.15	0.2069	0.124	1.69	$1.17 \cdot 10^{-12}$
S5 0716+71	BL Lac	110.47	71.34	0.7230	-0.380	0.00	$3.84 \cdot 10^{-13}$
3C 273	FSRQ	187.28	2.05	0.3807	-0.014	0.00	$4.42 \cdot 10^{-13}$
PKS 1502+106	FSRQ	226.10	10.52	0.2322	-0.000	0.00	$5.98 \cdot 10^{-13}$
PKS 0528+134	FSRQ	82.73	13.53	0.2870	-0.002	0.00	$5.74 \cdot 10^{-13}$
3C454.3	FSRQ	343.50	16.1[illegible]	0.0072	[illegible].503	5.98	$1.26 \cdot 10^{-12}$
4C 38.41	FSRQ	248.81	38.[illegible]3	0.0055	5.[illegible]86	6.62	$1.72 \cdot 10^{-12}$
MGRO J1908+06	NI	286.99	6.2[illegible]	0.0032	6.[illegible]84	3.28	$1.13 \cdot 10^{-12}$
Geminga	PWN	98.48	17.7[illegible]	0.9754	-[illegible].424	0.00	$1.16 \cdot 10^{-13}$
Crab Nebula	PWN	83.63	22.01	0.1188	[illegible].709	4.32	$8.65 \cdot 10^{-13}$
MGRO J2019+37	PWN	305.22	36.83	[illegible]	-3.191	0.00	$1.39 \cdot 10^{-13}$
Cyg OB2	SFR	308.09	41.23	0.3174	-0.002	0.00	$7.53 \cdot 10^{-13}$
IC443	SNR	94.18	22.53	0.8153	-0.457	0.00	$1.22 \cdot 10^{-13}$
Cas A	SNR	350.85	58.81	0.2069	0.033	0.88	$1.05 \cdot 10^{-12}$
TYCHO	SNR	6.36	64.18	0.4471	-0.019	0.00	$8.14 \cdot 10^{-13}$
M87	SRG	187.71	12.39	0.6711	-0.256	0.00	$2.85 \cdot 10^{-13}$
3C 123.0	SRG	69.27	29.67	0.9055	-0.747	0.00	$1.30 \cdot 10^{-13}$
Cyg A	SRG	299.87	40.73	0.0049	6.335	4.30	$1.78 \cdot 10^{-12}$
NGC 1275	SRG	49.95	41.51	0.2582	0.007	0.25	$8.31 \cdot 10^{-13}$
M82	SRG	148.97	69.68	0.8887	-0.888	0.00	$1.83 \cdot 10^{-13}$
SS433	XB/mqso	287.96	4.98	0.8738	-1.085	0.00	$1.01 \cdot 10^{-13}$
HESS J0632+057	XB/mqso	98.24	5.81	0.8359	-0.917	0.00	$1.01 \cdot 10^{-13}$
Cyg X-1	XB/mqso	299.59	35.20	0.5422	-0.106	0.00	$4.93 \cdot 10^{-13}$
Cyg X-3	XB/mqso	308.11	40.96	0.3230	-0.003	0.00	$7.28 \cdot 10^{-13}$
LSI 303	XB/mqso	40.13	61.23	0.2843	0.001	0.17	$1.01 \cdot 10^{-12}$



Detector Complementarity

Wide-field / Continuous Operation

VHE Sensitivity

Fermi, AGILE, EGRET

HAWC, ARGO, Milagro

VERITAS, HESS, MAGIC

Space-Based

- All sky coverage
- GeV range (area->flux limited)

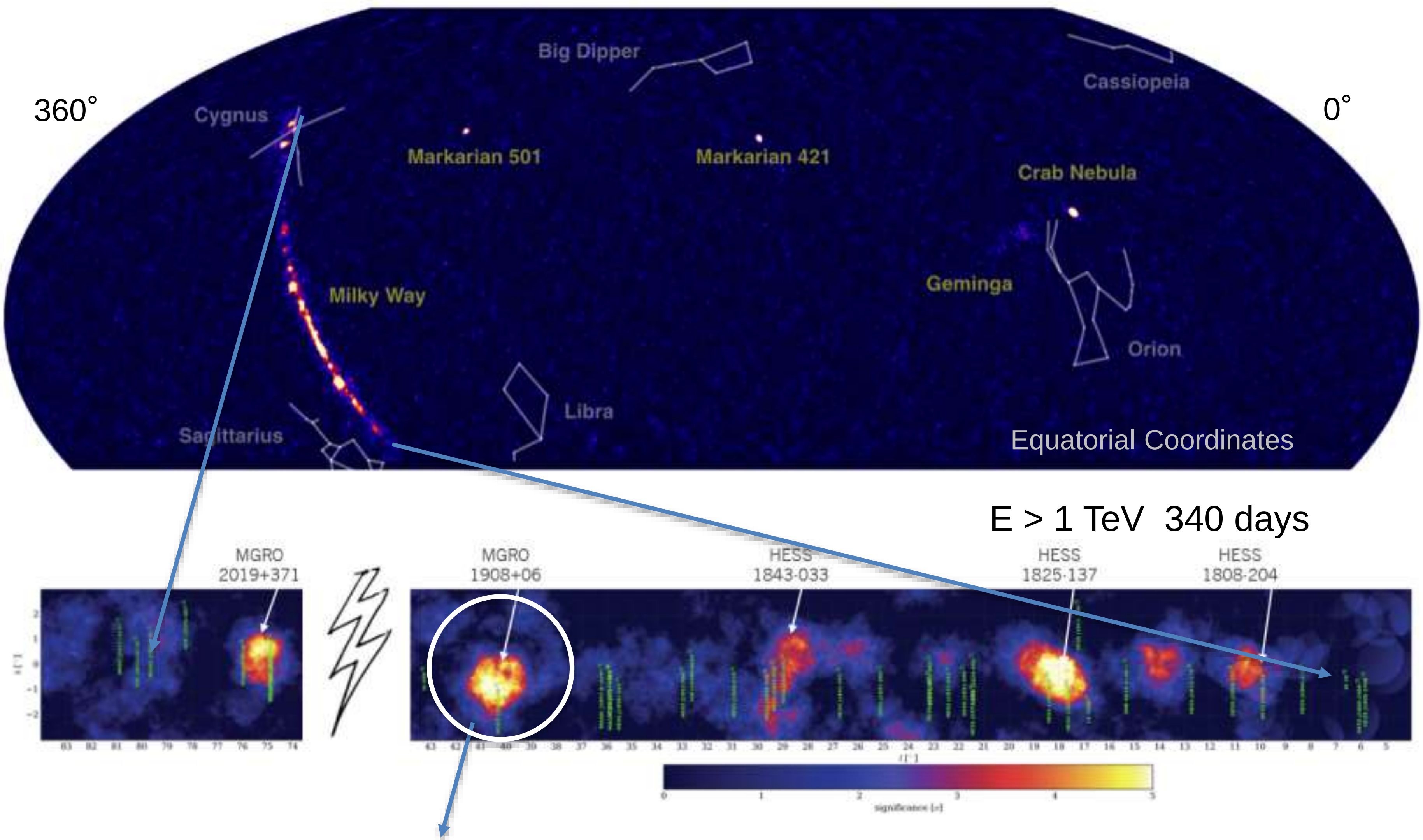
Ground Arrays

- 95% duty cycle, ~2 sr f.o.v.
- Daily coverage of $2/3$ sky
- Unbiased surveys
- Highest energies, E > 100 GeV

IACTs

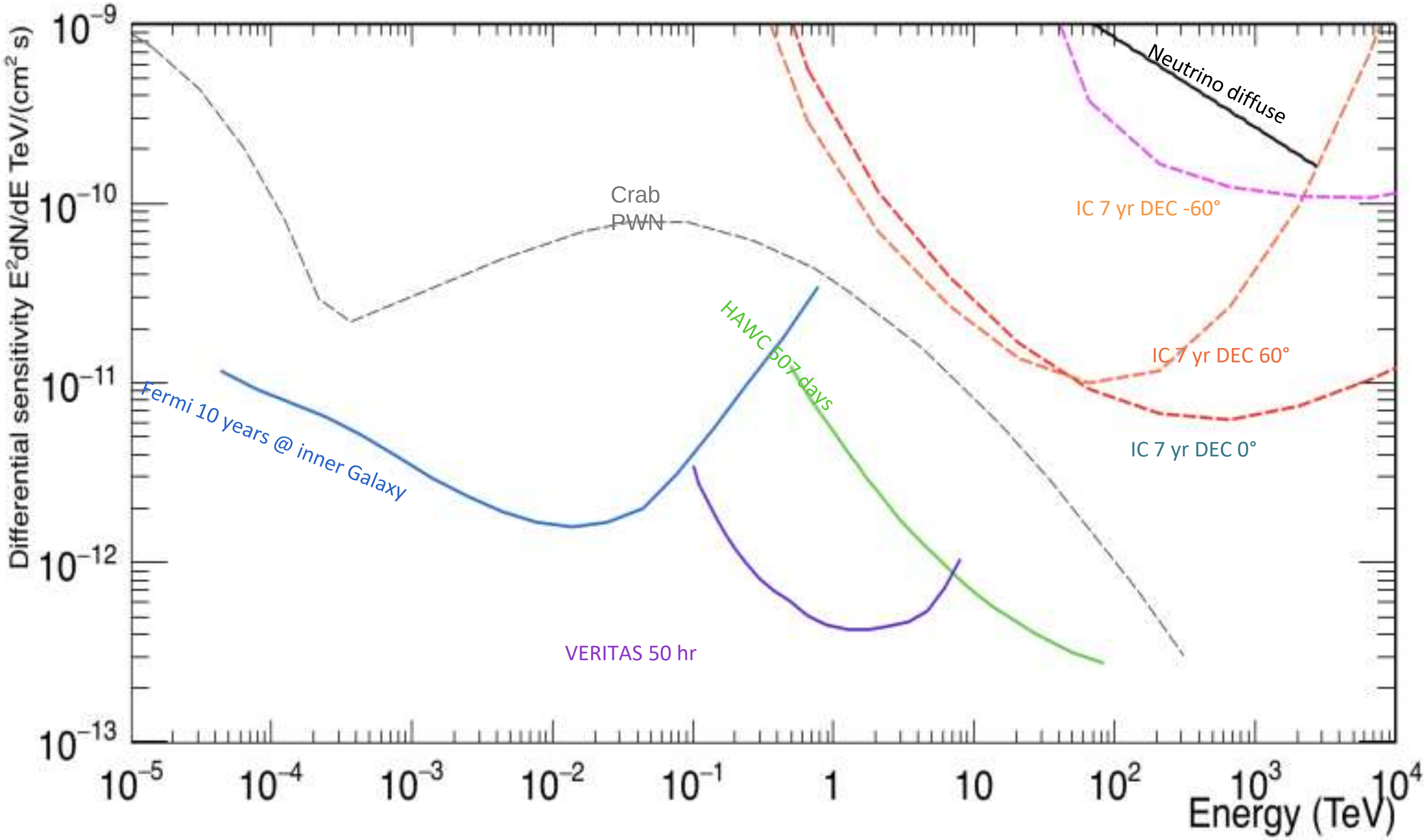
- Excellent pointing
- Highest energies
- Surveys limited

HAWC View of Gamma Ray Sky



MGRO J1908+06

HAWC sky above 55 TeV



Comparisons with HAWC

- HAWC is better at detecting very large emission regio Detected sources are largely SNR/PWNs (2 blazars)
  HAWC is also a survey instrument, so they are accumulating exposure in ~40% of all sky they are surveying.
  This is especially important for E> a few TeV energy range.
- VERITAS is better at detecting gamma-rays with E<a few TeV with moderate exposure w/ source size < 1 degree. Detected various sources (40 extragalactic sources, 33 galactic sources)
  Much better instantaneous sensitivity for E< a few tens of TeV with moderate exposure.
  Better angular resolution, energy resolution.

High Energy Neutrino Astrophysics
francis halzen

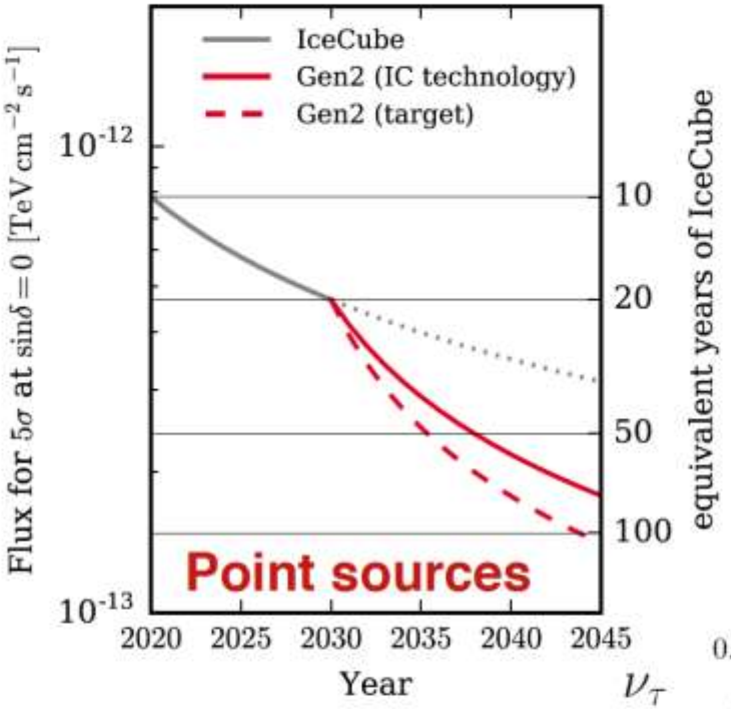
- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

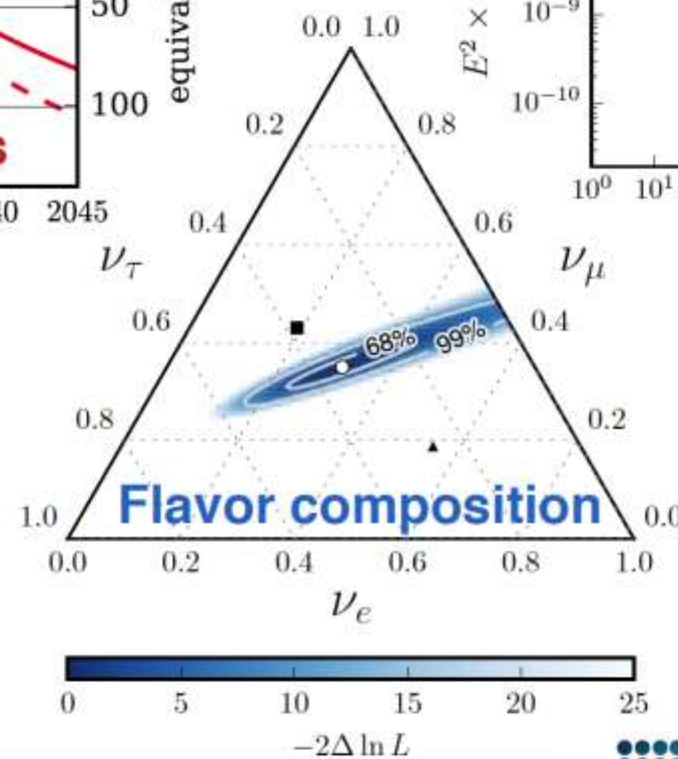
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of ~ 0.1 degree will see multiple neutrinos from single sources and identify the sources

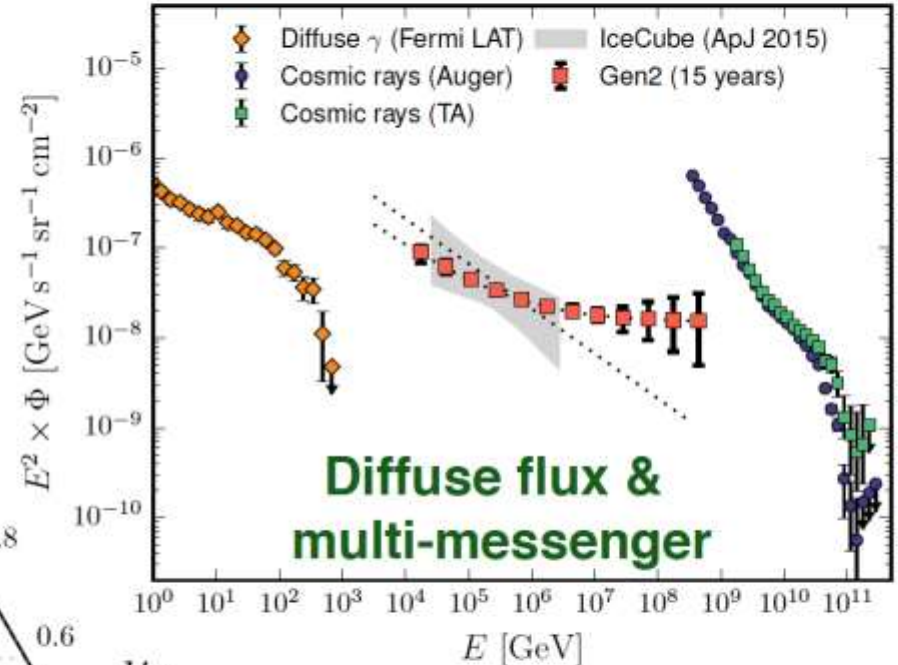
- need 1,000 events versus 100 now in a few years

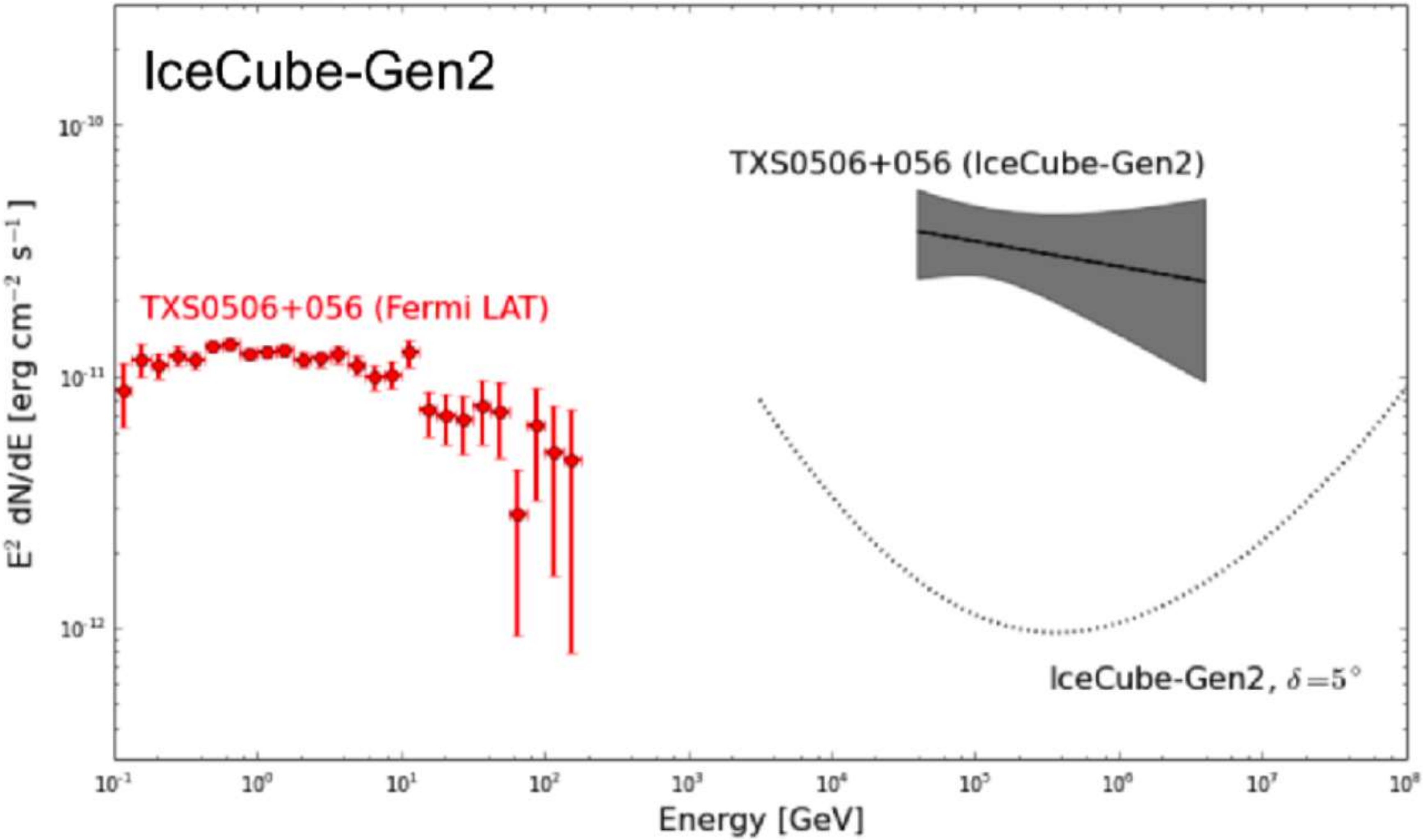
- discovery instrument → astronomical telescope

IceCube-Gen2: Science Case



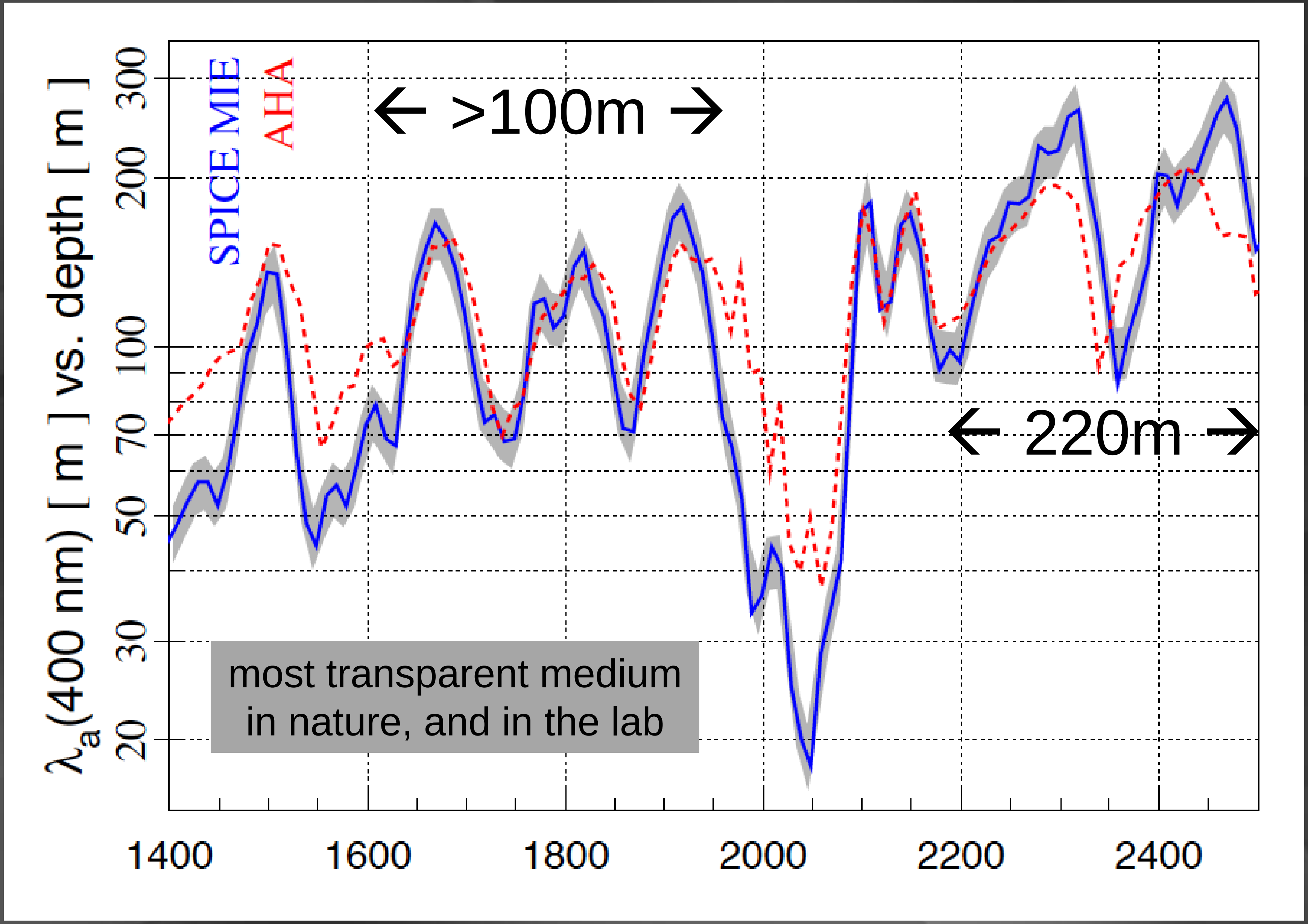




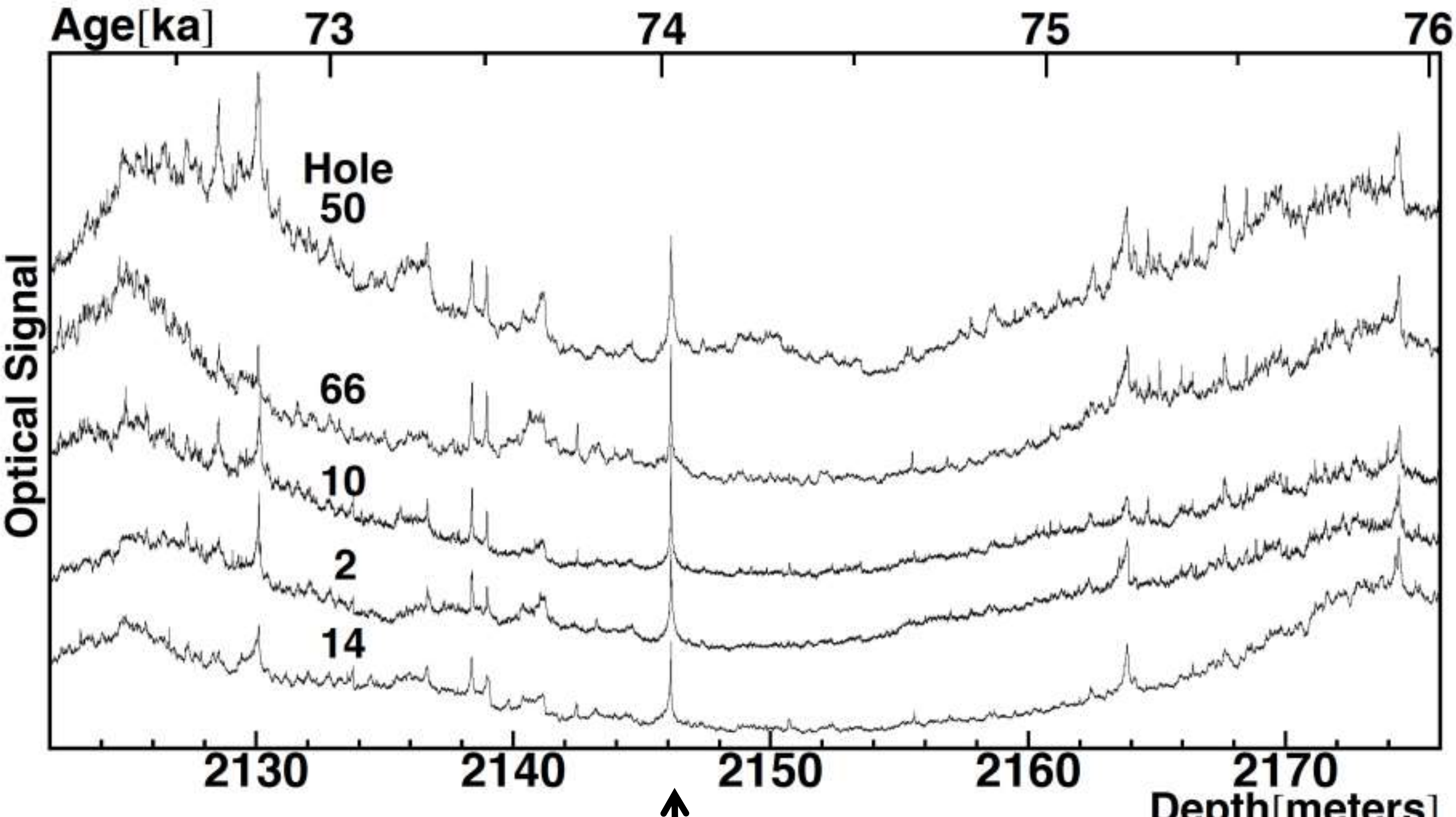


Order of magnitude increase of # TXS0506+056-like flares observable with Gen2

absorption length of Cherenkov light



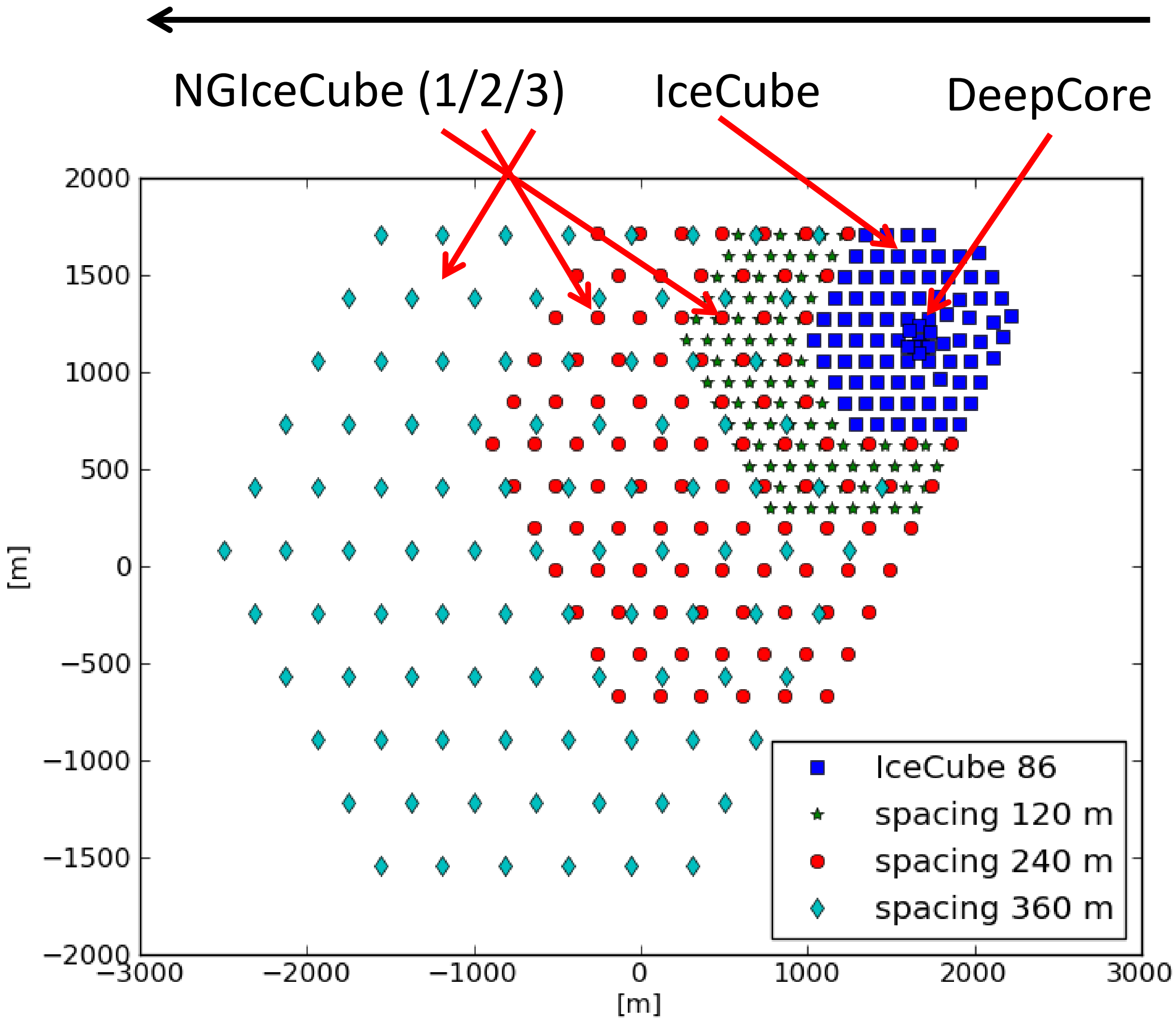
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

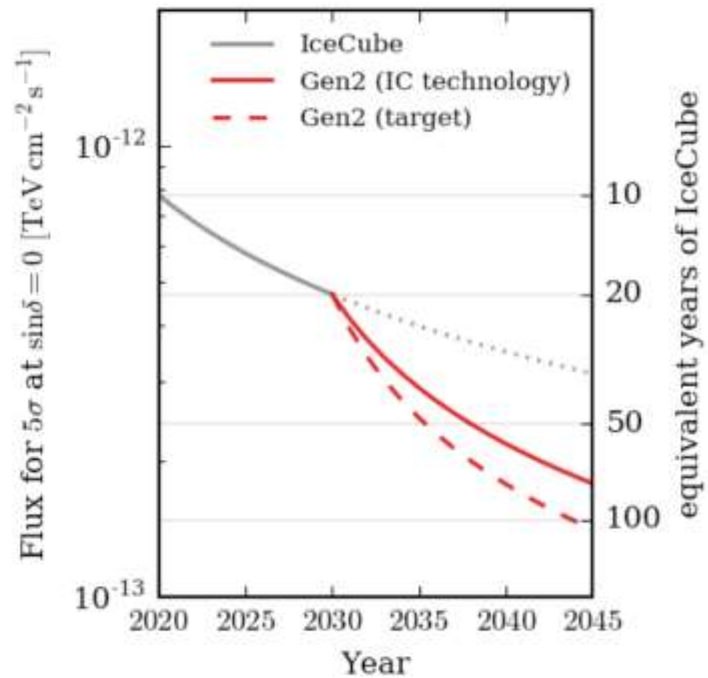
Baseline Gen2 DOM

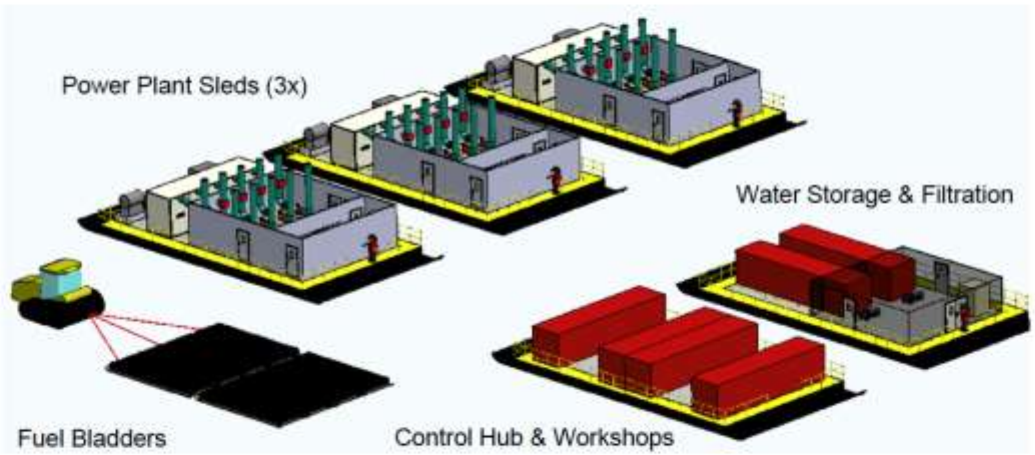
- updated electronics

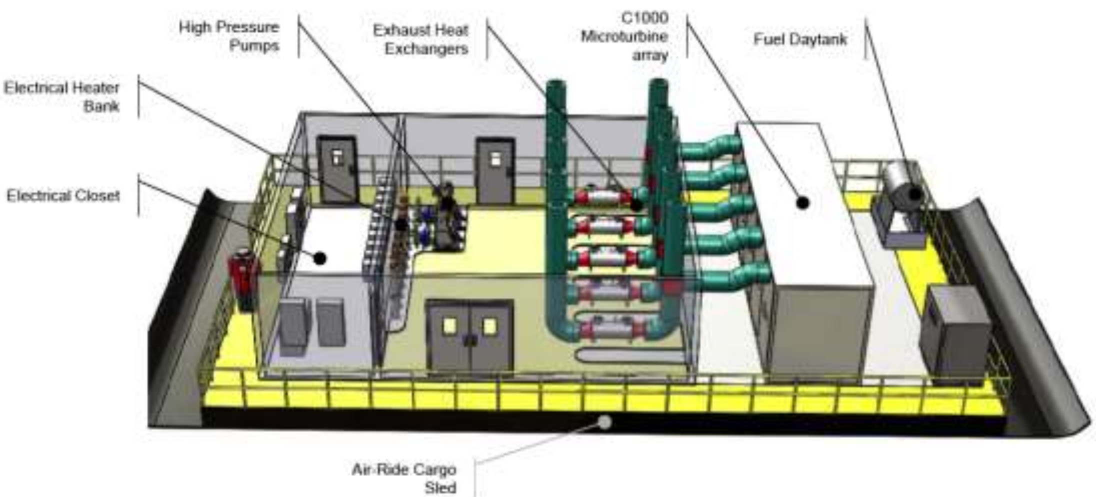
New technologies

- more PMTs
- wavelength shifters
- narrow profile
- better glass, gel

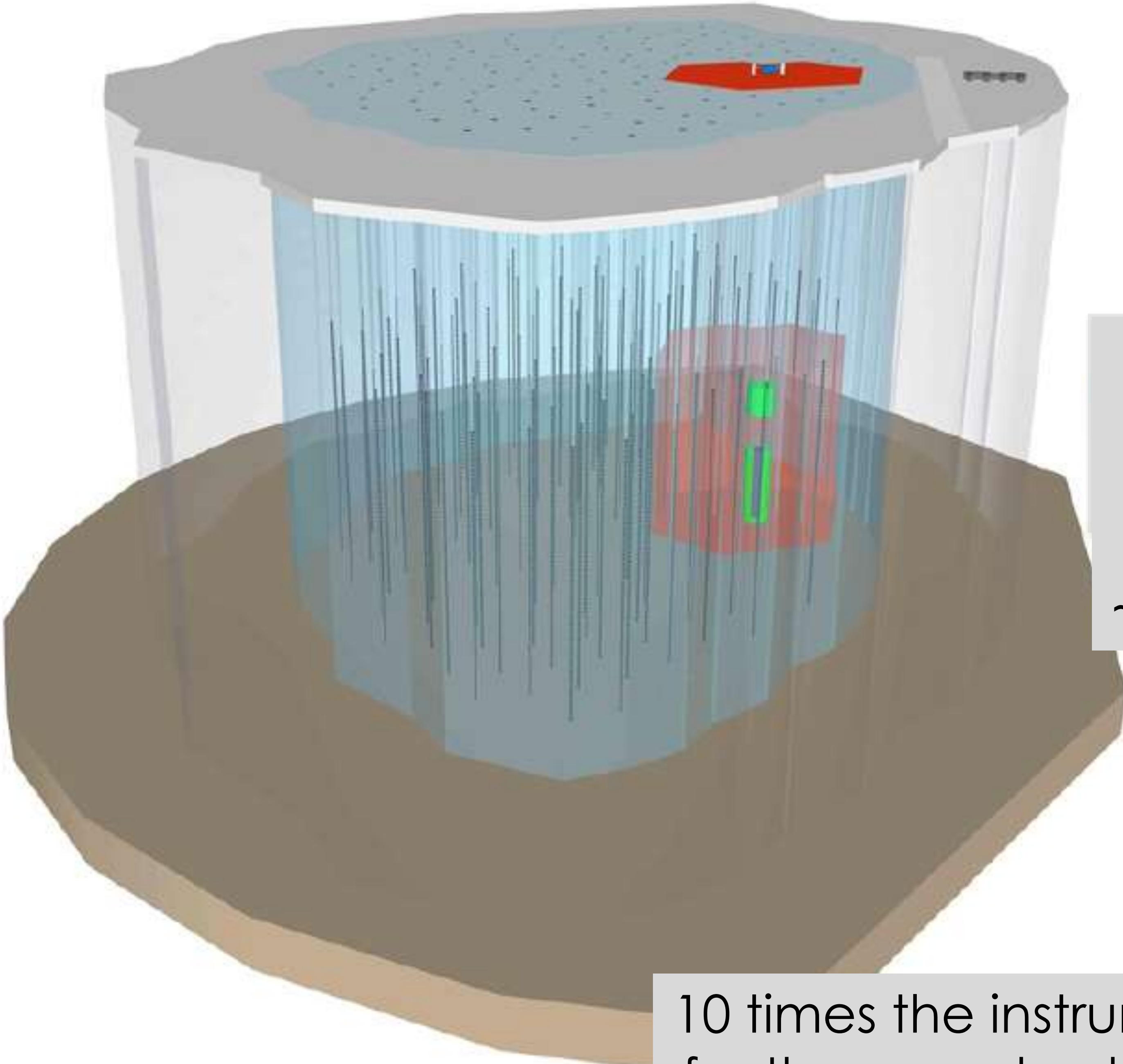
Point source sensitivity







- Next-generation Enhanced Hot Water Drill
  - reduced footprint
  - smaller crew
- Transport equipment and fuel using South Pole Traverse
  - fewer flights needed
- May also reduce hole diameter
  - reduced fuel usage

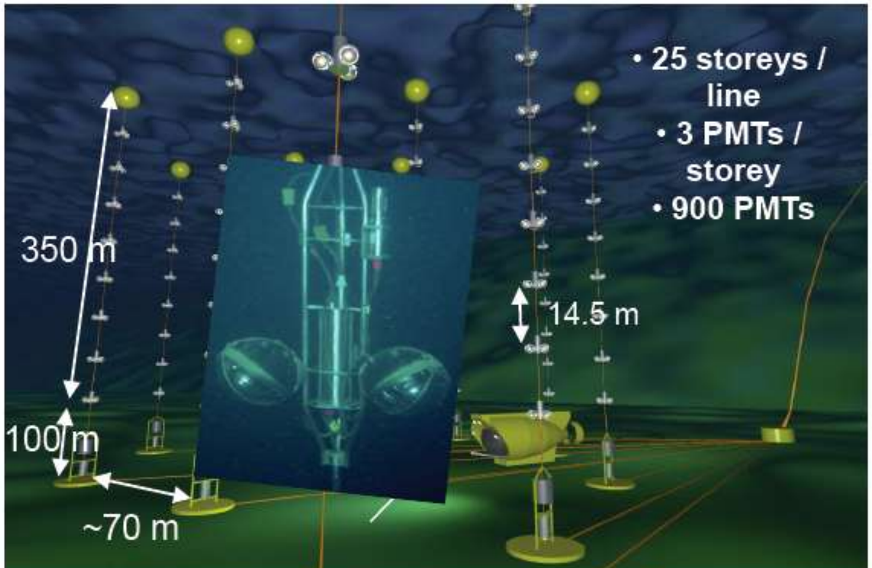


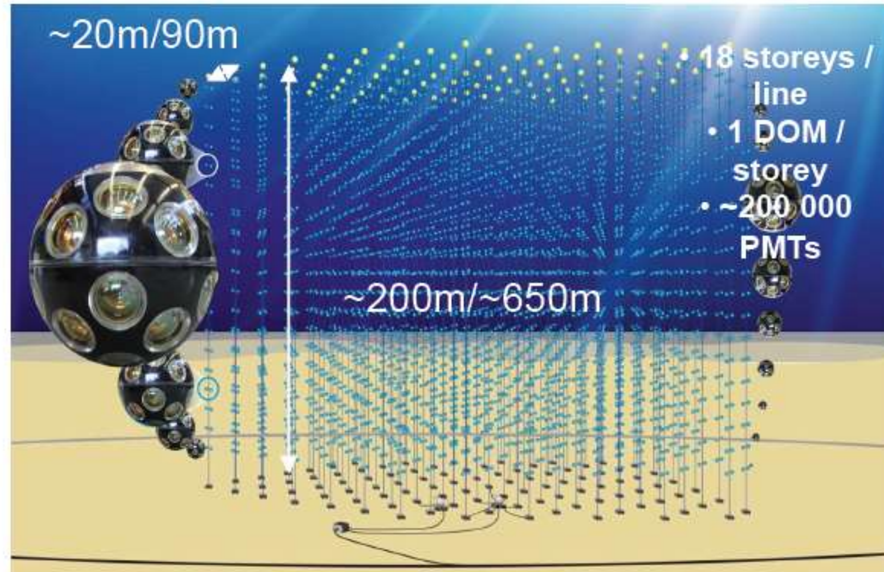
120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume
for the same budget as IceCube

Mediterranean Detectors

ANTARES Complete since 2008 | **KM3NeT Under Construction**

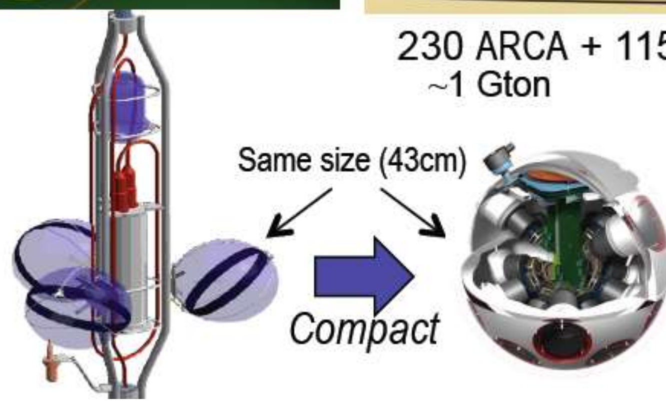




~10 Mton

12 lines
First Generation
First line since 10 years

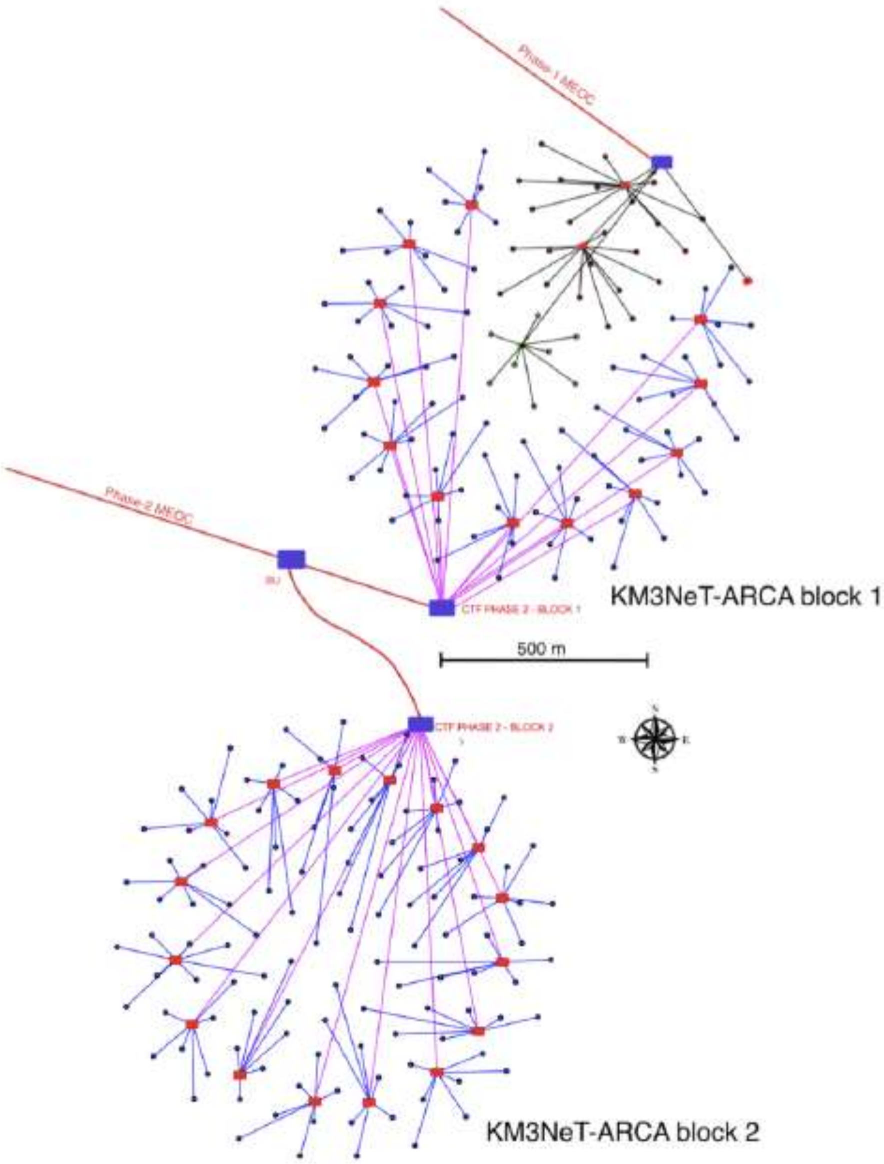
230 ARCA + 115 ORCA lines New Generation
~1 Gton ~6 Mton



• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

A. Kouchner, Neutrino 2016

High energies ARCA



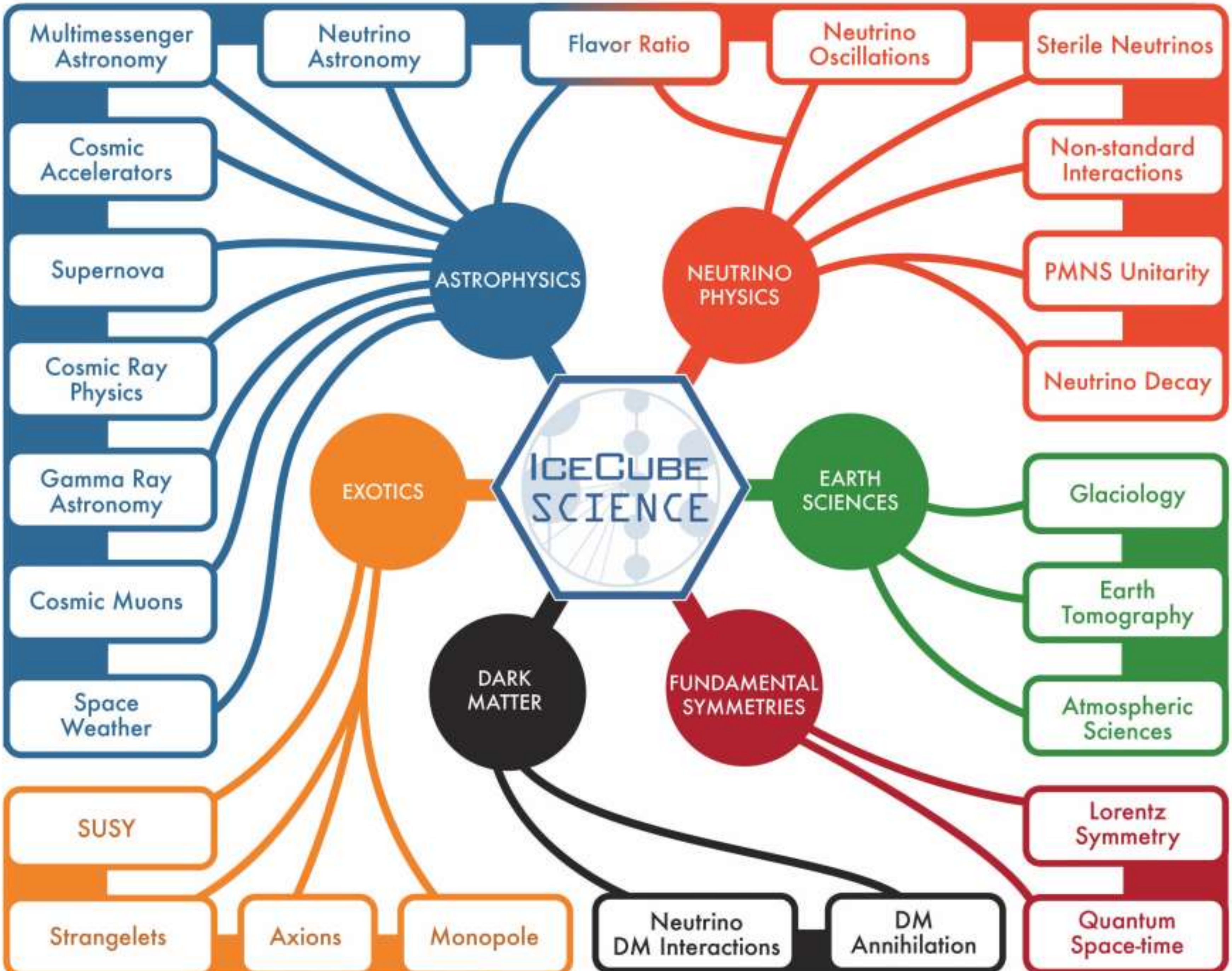
KM3NeT LoI http://arxiv.org/pdf/1601.07459v2.pdf

High Energy Neutrino Astrophysics
francis halzen

- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

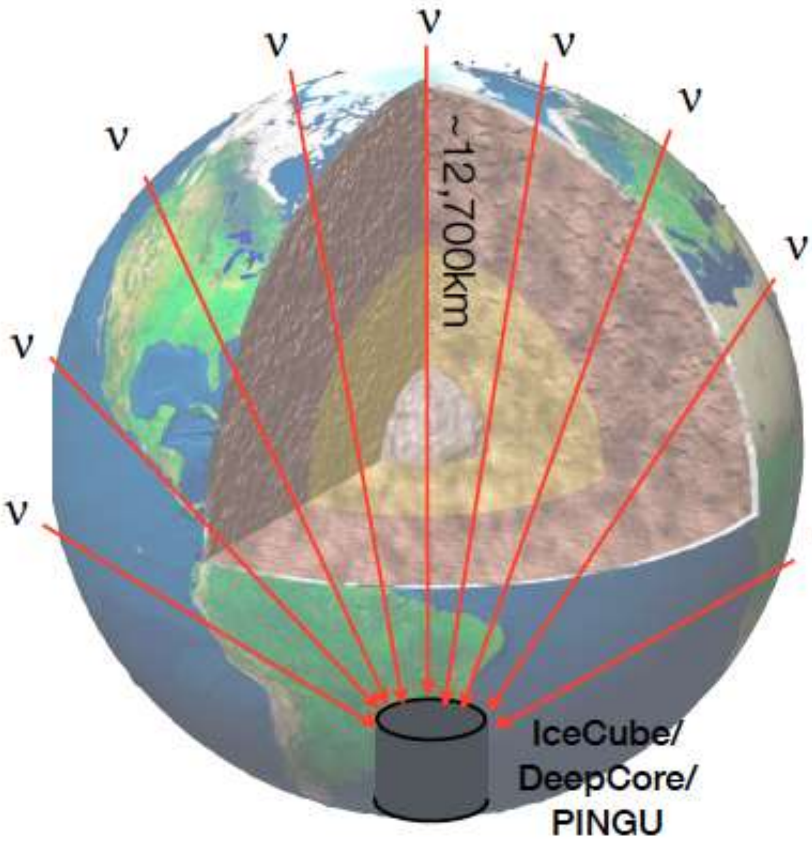
did not talk about:

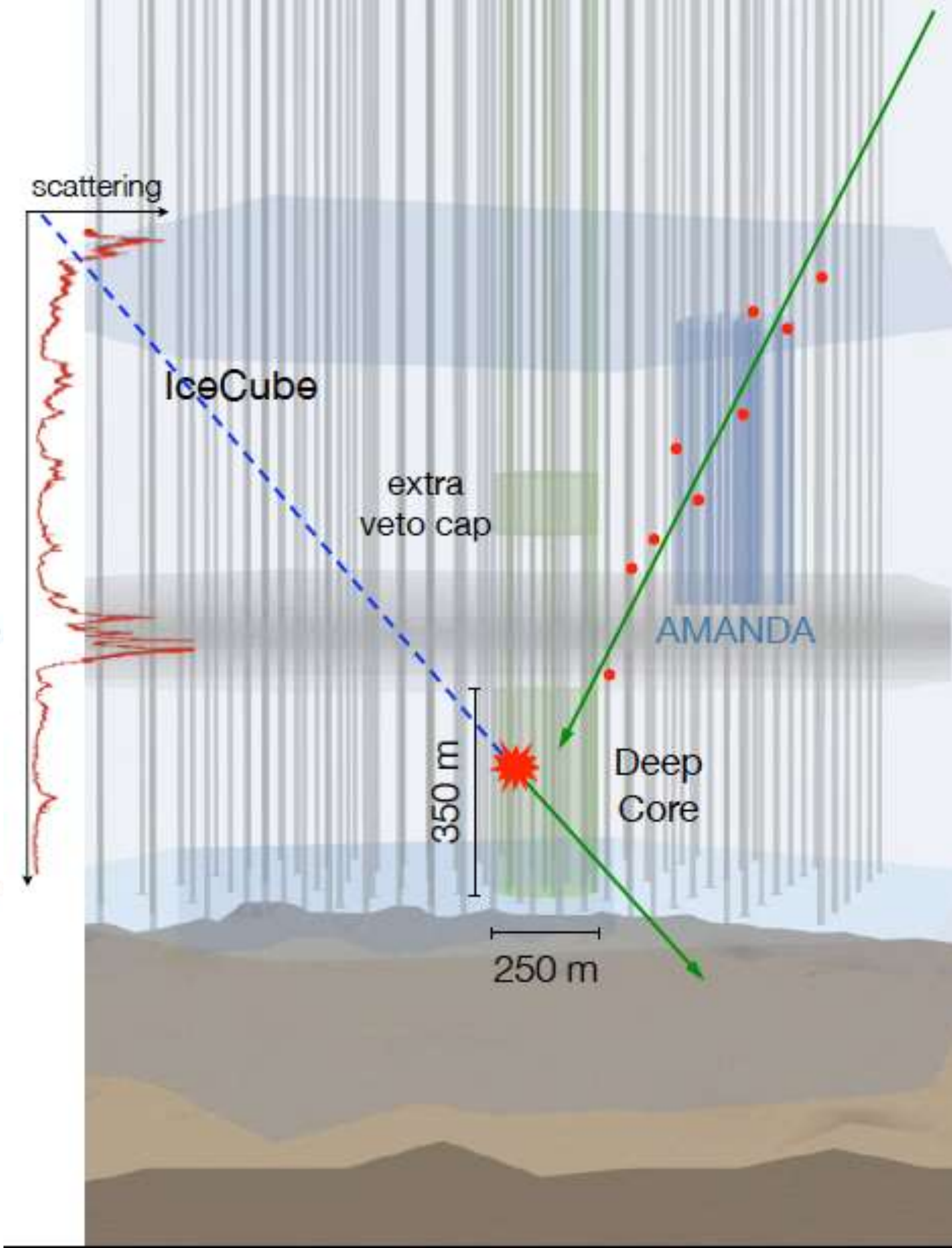
- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- cosmic ray physics, muon maps,…
- PINGU/ORCA
- ….



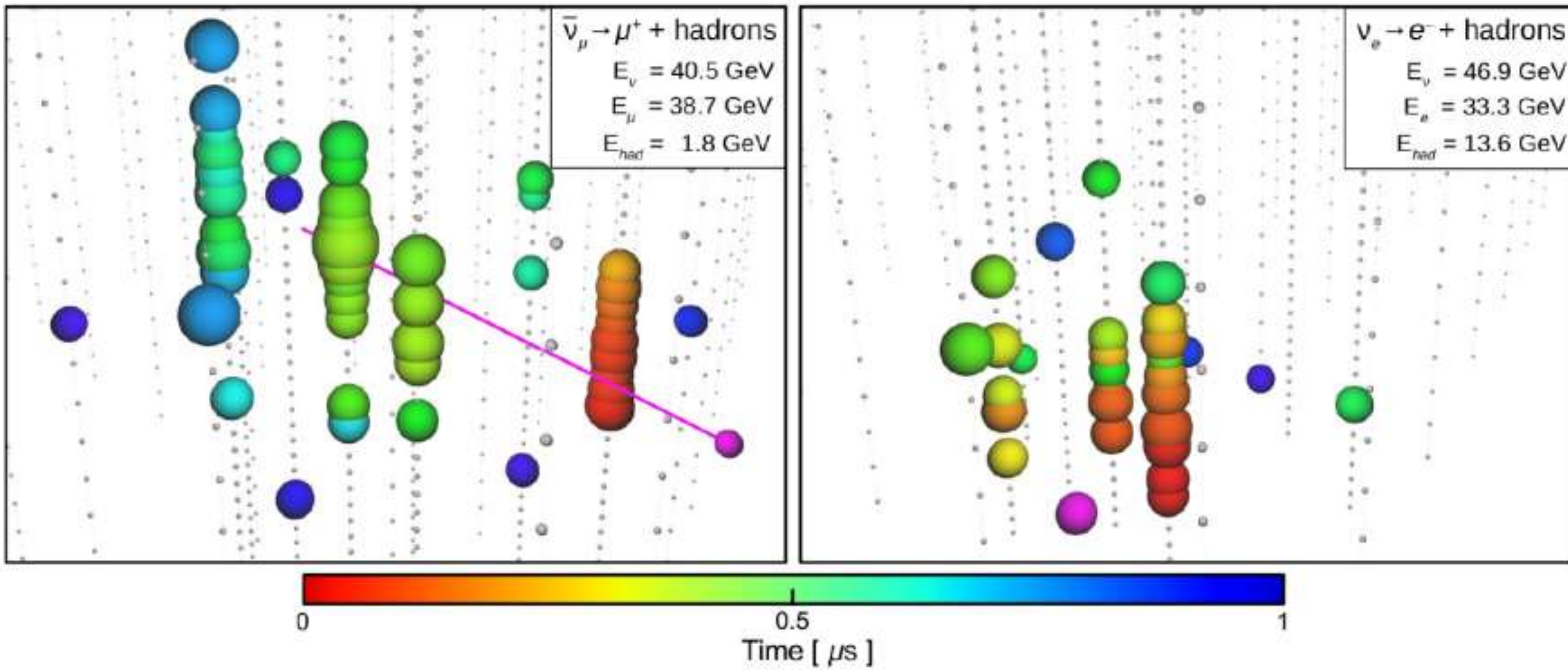
Multimessenger Astronomy
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Cosmic Accelerators
Non-standard Interactions
Supernova
ASTROPHYSICS
NEUTRINO PHYSICS
PMNS Unitarity
Cosmic Ray Physics
Neutrino Decay
Gamma Ray Astronomy
EXOTICS
ICECUBE SCIENCE
EARTH SCIENCES
Glaciology
Cosmic Muons
Earth Tomography
DARK MATTER
FUNDAMENTAL SYMMETRIES
Space Weather
Atmospheric Sciences
SUSY
Lorentz Symmetry
Strangelets
Axions
Monopole
Neutrino DM Interactions
DM Annihilation
Quantum Space-time

one half million atmospheric neutrinos…

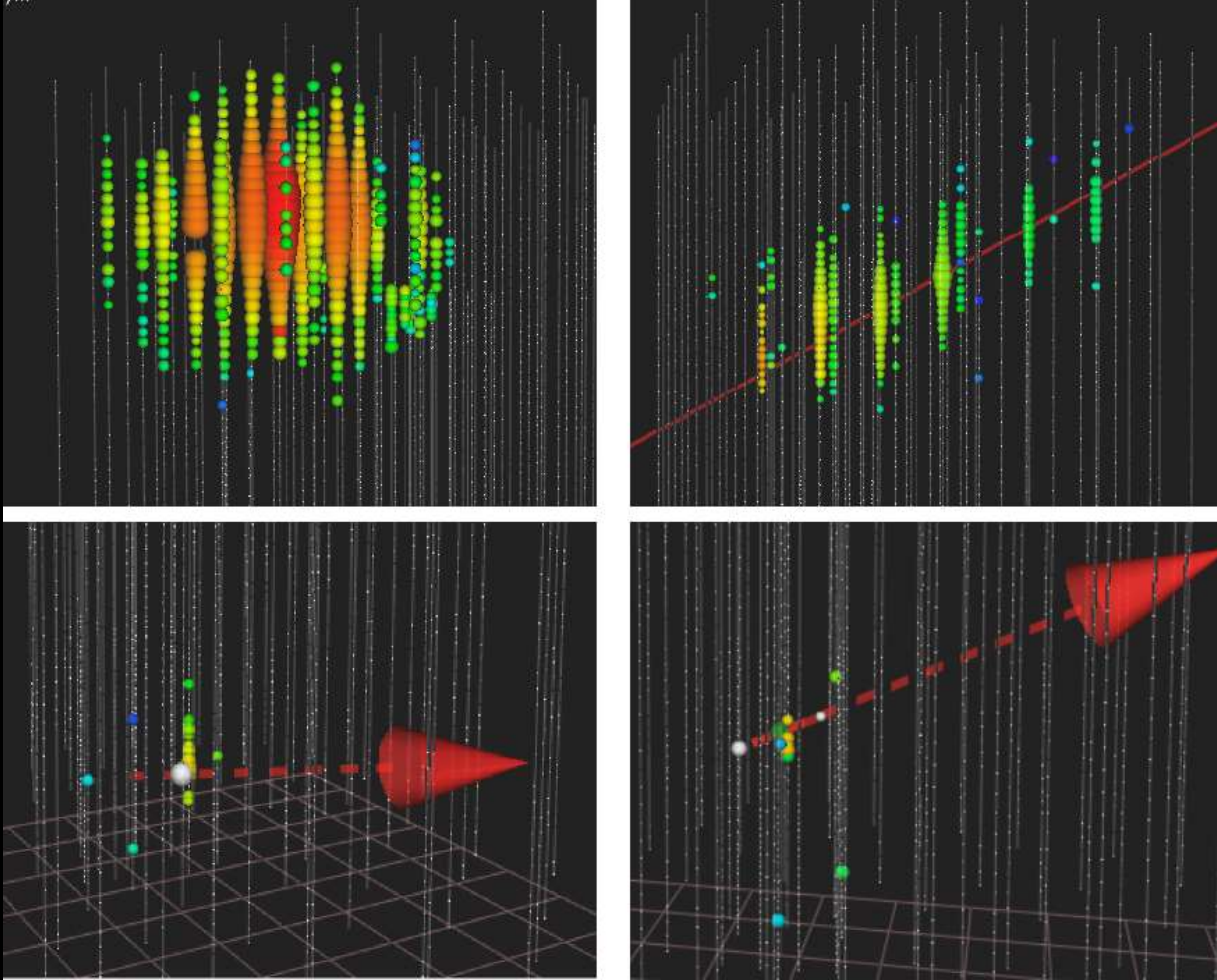


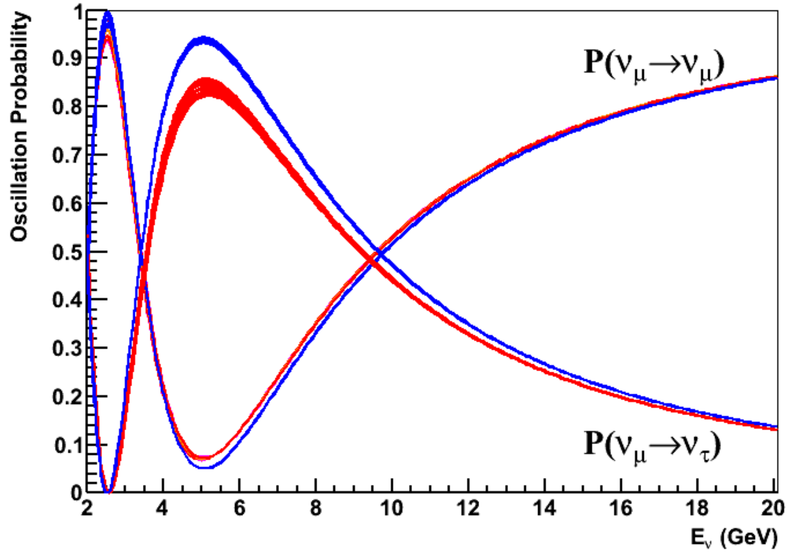


Events in DeepCore

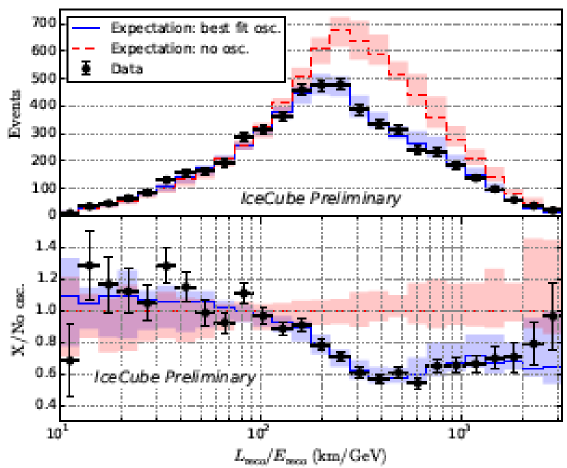


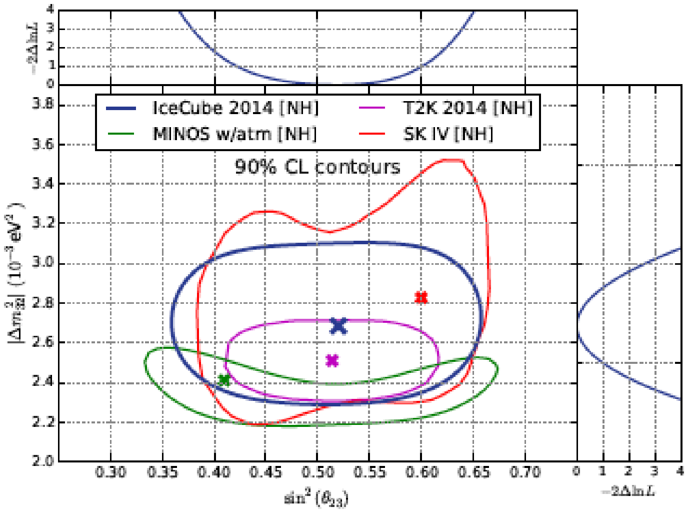
> Events below 50 GeV:





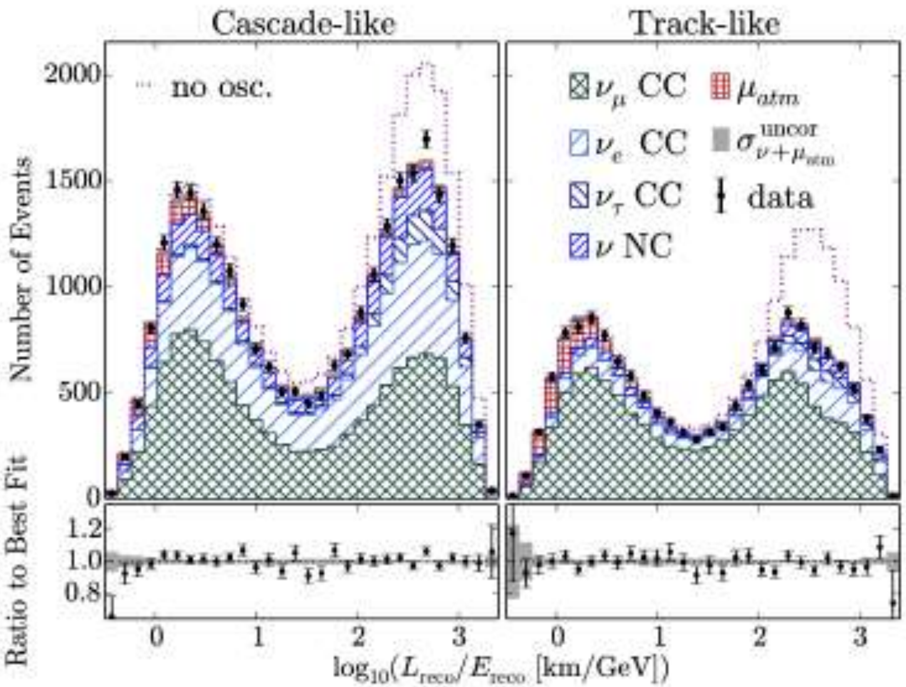
oscillations at 20 GeV



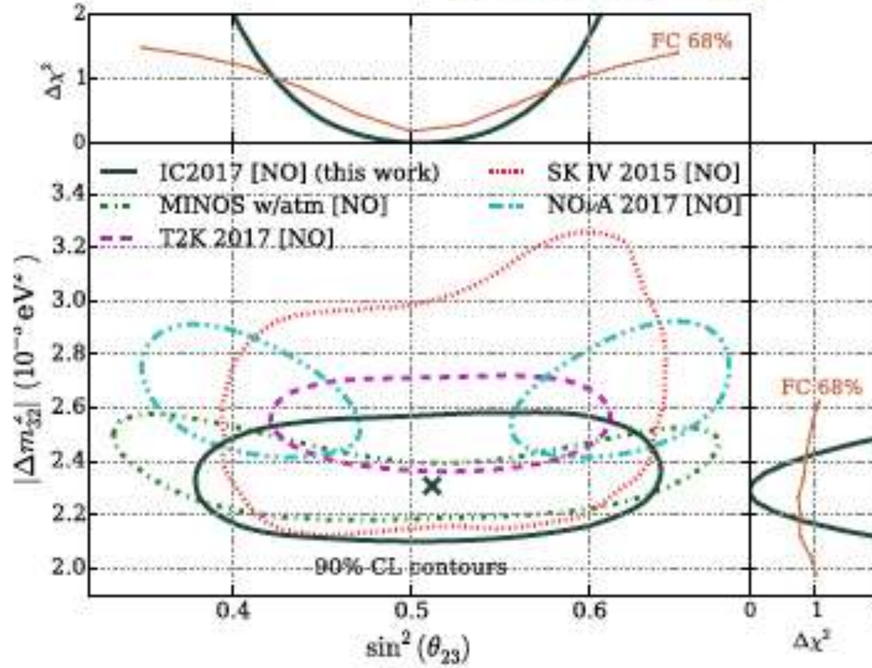


DeepCore: mapping the first oscillation dip at 10 x higher energy
→ new physics?

Neutrino Oscillation



IceCube, PRL 2018



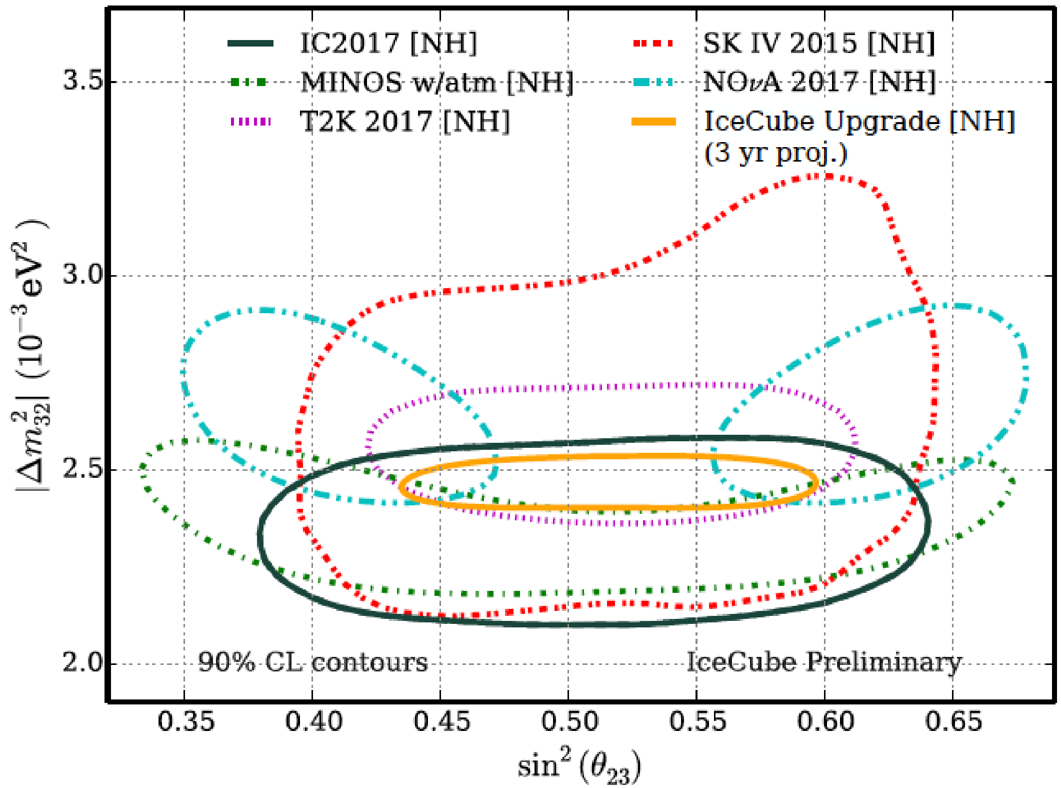
- 3 years of IceCube Deep Core data
- measurements of muon neutrino disappearance, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

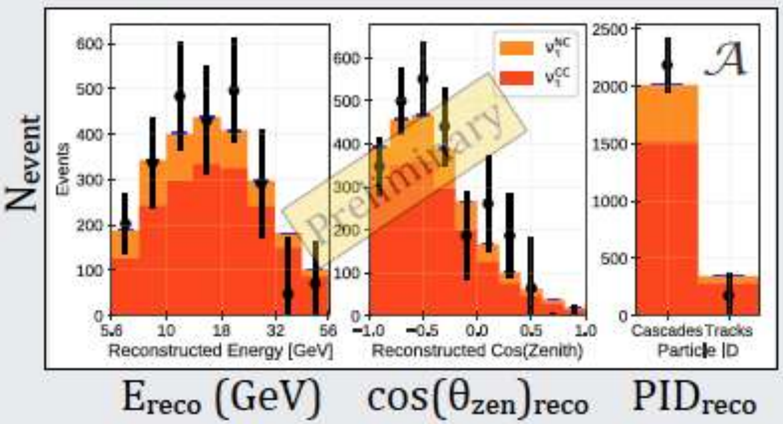
Atmospheric Oscillation Parameters

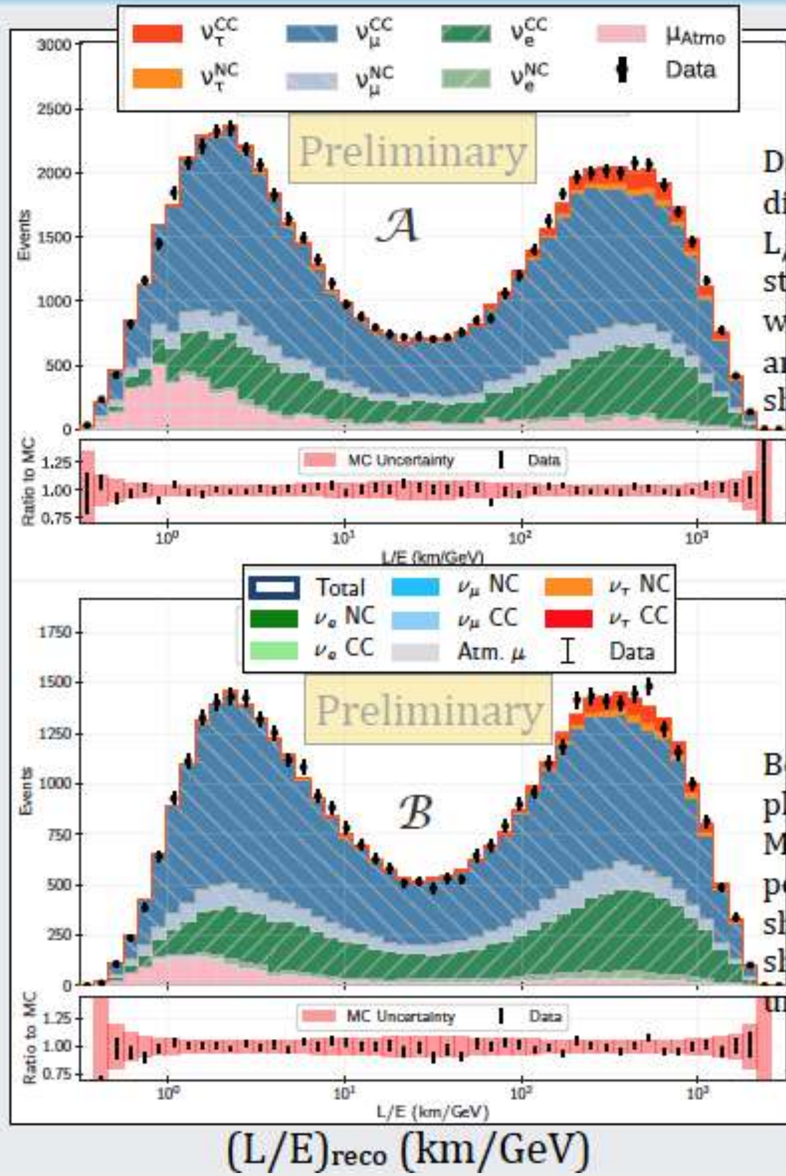
- Currently unclear whether $\sin^2\theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)

Data distributions with best-fit ν_e+ν_μ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.



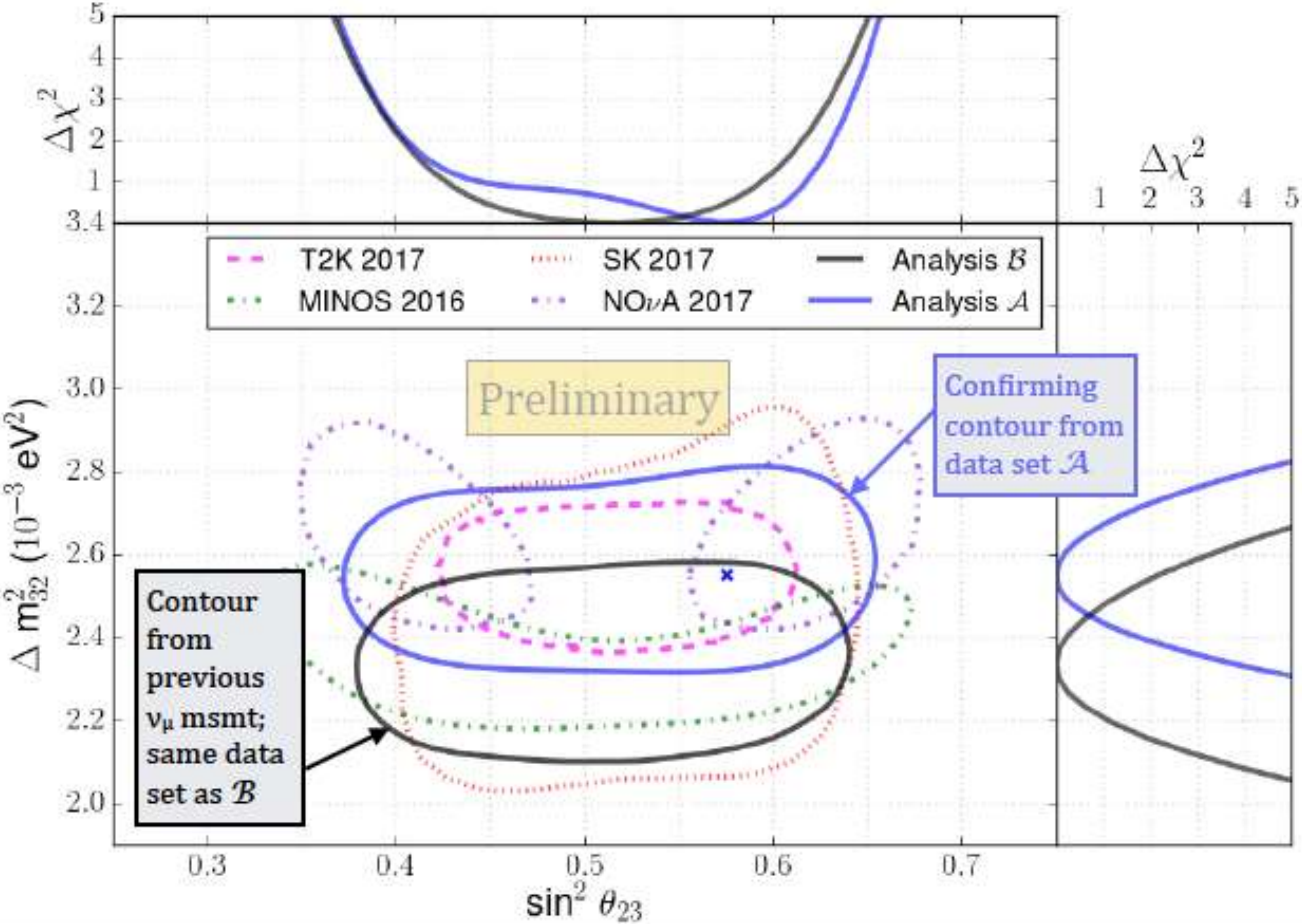


Data distributions vs. L/E (points with stat. error bars), with best-fit ν and μ bkgds. shown (hists.).

Bottom of each plot shows data/MC at best fit point, with shaded region showing stat. unc. of best fit.

- two independent analyses
- one for quality of events
- one for statistics
- both blind

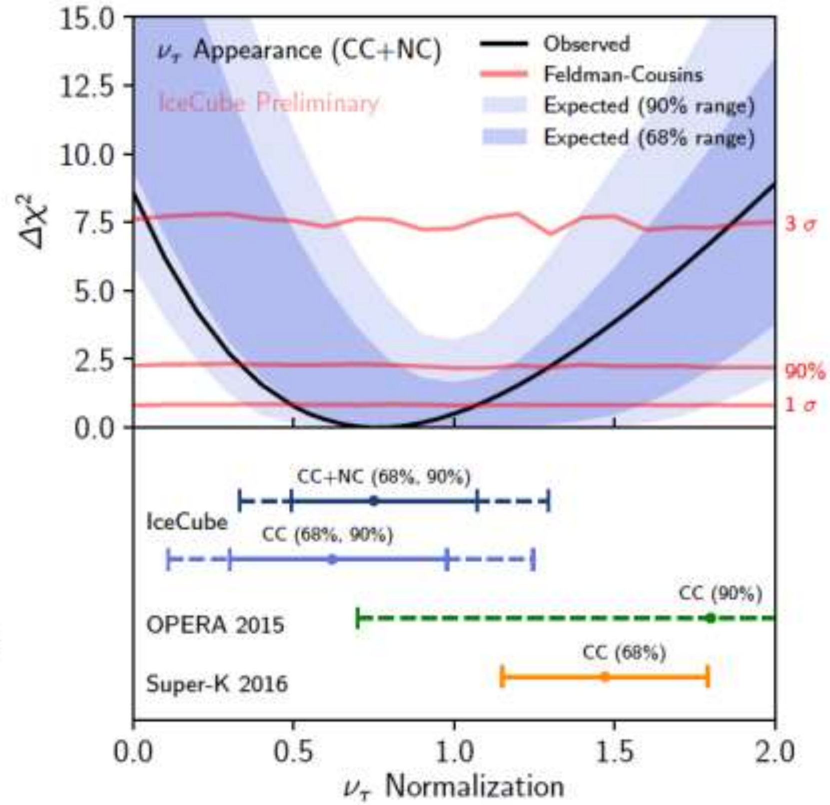
		Analysis A GRECO "High statistics sample"	Analysis B DRAGON "High purity sample"
Simulation	Neutrino Simulation	1. Neutrino interactions / lepton generation: GENIE 2. Lepton propagation / photon generation: PROPOSAL & GEANT4 3. Photon propagation: CLSim (GPU-based software) 4. Noise addition 5. PMT response & readout elections	
	Muon Background Simulation	CORSIKA + MuonGun · Uses H4a Cosmic Ray flux model to directly predict muon background. Run through standard simulation chain.	CORSIKA + Data-Driven · Any muon that would have made it to final level had it not been for a hit in the corridor region is considered a background muon
Selection	Goal	High signal acceptance "High statistics sample"	High signal purity "High purity sample"
	Trigger	At least 3 pairs of locally coincident DeepCore DOMs detect hits in a 2.5 microsecond time window	
	Level 2 "Filter"	Veto events with hits in "veto region" consistent with a muon travelling from there to interaction vertex at $v=c$	
	Level 3	Eliminates events with more than 7 hits in veto region, too many noise hits, too many hits in outer region of DeepCore (i.e. not fully contained),	
	Other low-level cuts	Removes events with too many non-isolated hits in veto region and/or too few non-isolated hits in DeepCore fiducial volume	Fast reconstruction to insure enough DOMs to be consistent with either track or shower signature
	Level 4	BDT to remove atmospheric muons (6 variables) · Charge measured by PMTs (3 vars.) · Simple vertex estimator · Event speed simulator · Calculation of event shape	Straight Cuts · Number of photoelectrons deposited in largest cluster of hits · Event vertex in fiducial volume (contained) · No more than 5 p.e. in veto region total · No more than 2 p.e. in veto region consistent with speed-of-light travel from hit to vertex · Minimum number of non-isolated hits · Space-time interval between 1st and 4th hits consistent with $v \leq c$.
	Level 5	Another BDT to remove atmospheric muons (6 variables) · Time to accumulate charge · Vertex estimator · Center-of-gravity information (2 var.) · Causal hit identifier · Zenith angle estimation	BDT (11 variables) · Charge, time, and location of hit DOMs (multiple variables) · Reconstructed zenith angle & event speed using fast construction
	Level 6	Straight cuts · Inconsistent with intrinsic PMT noise · Spatially compact · Require likelihood-based vertex estimator to be well contained in DeepCore fiducial volume · Reject events with hits along "corridors" in surrounding IceCube volume	Straight cuts · Events with reconstructed paths through corridor region · Starting & stopping position in or near DeepCore (contain)
	Level 7	Reconstruction (better & more accurate than fast reconstruction information above) & reconstructed energy must be 5.6-56 GeV	Reconstruction & no cuts on L7 ?



$\Delta\chi^2$
$\Delta\chi^2$
T2K 2017
SK 2017
Analysis $\mathcal{B}$
MINOS 2016
NOνA 2017
Analysis $\mathcal{A}$
Preliminary
Confirming contour from data set $\mathcal{A}$
Contour from previous ν_μ msmt; same data set as $\mathcal{B}$
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
  - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve ±7% in 3 years
  - ~10% precision needed for real tests of unitarity of PMNS mixing matrix



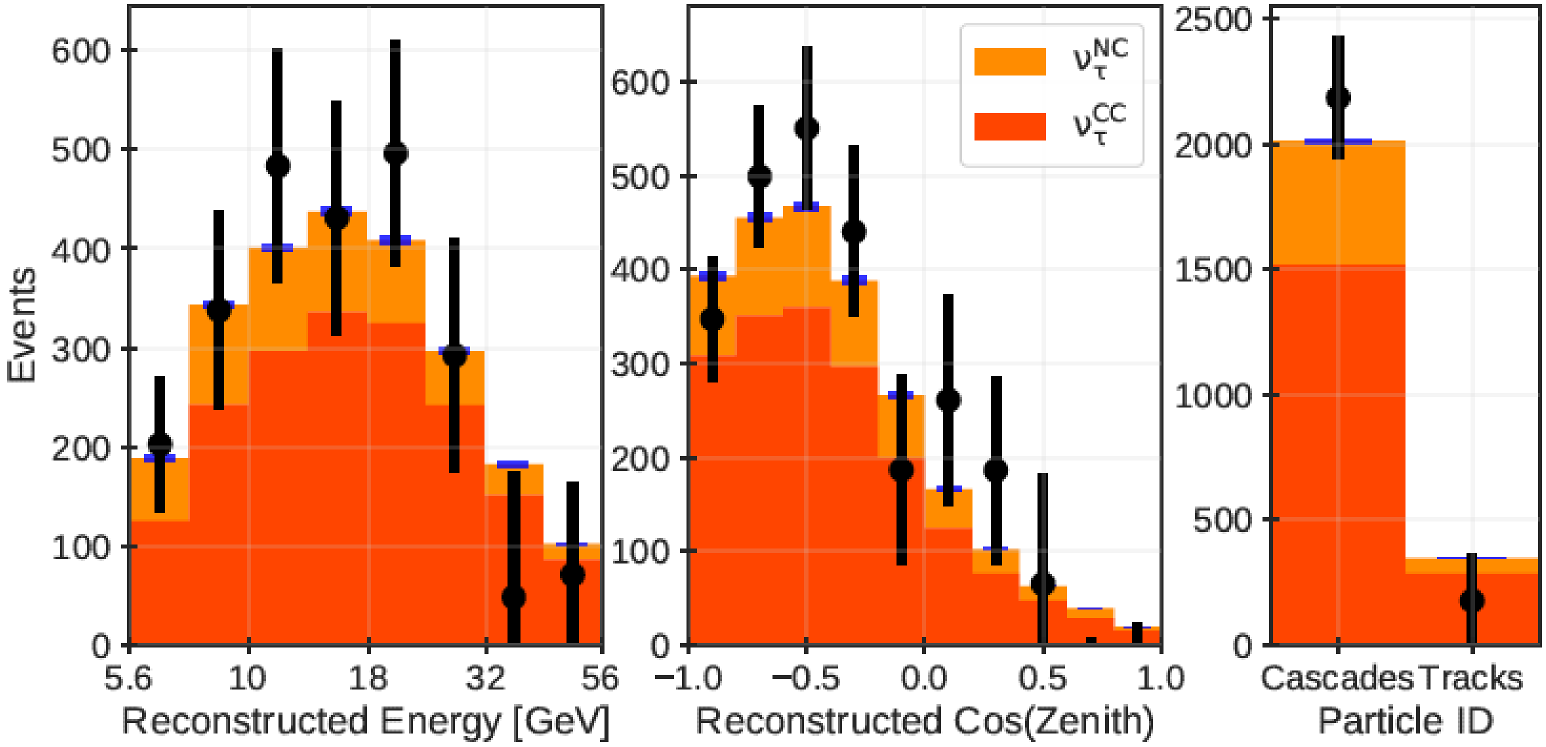
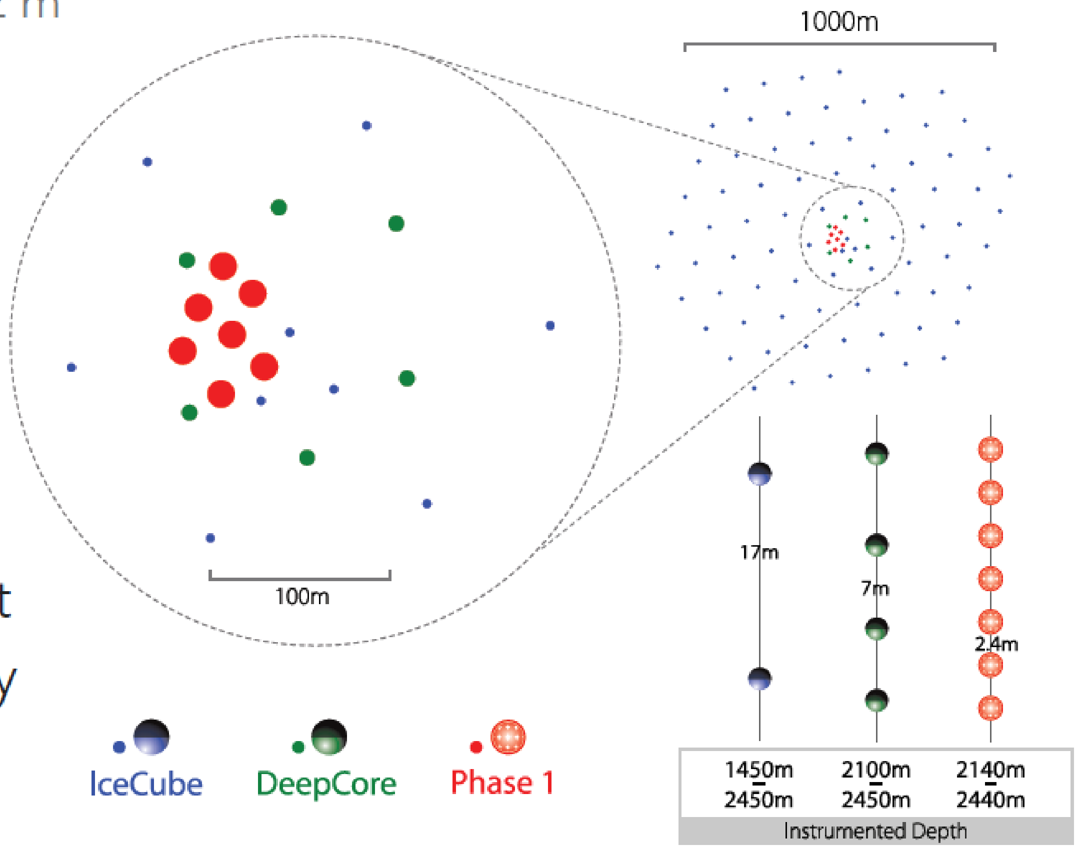
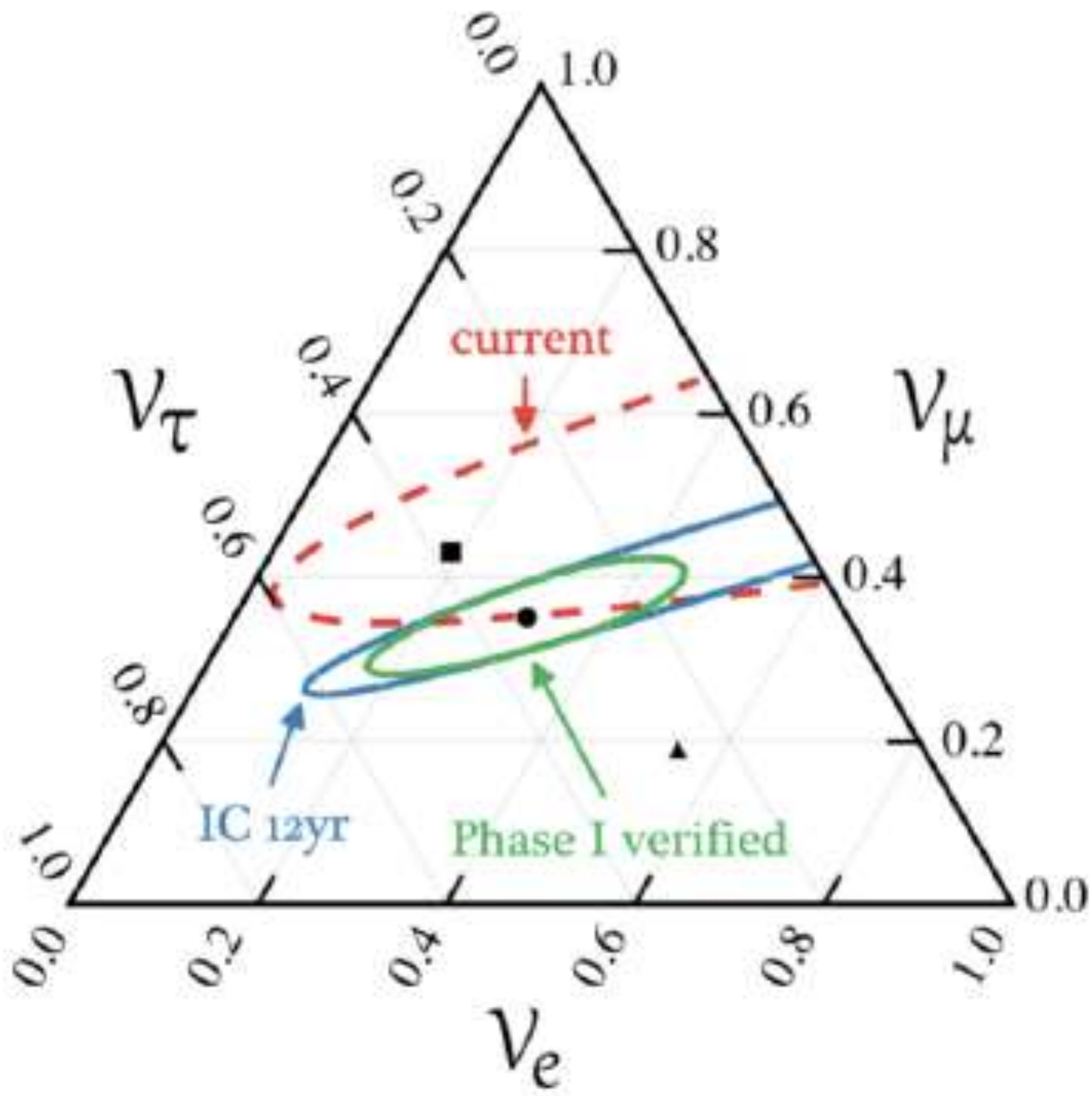


FIG. 14. Distributions of the data with best-fit neutrino and muon backgrounds subtracted, overlaid with the best fit ν_τ hypothesis projected onto the reconstructed energy axis (left), the cosine of the reconstructed zenith angle (middle) and PID categories (right), for Analysis $\mathcal{A}$. Error bars are statistical only.

Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy



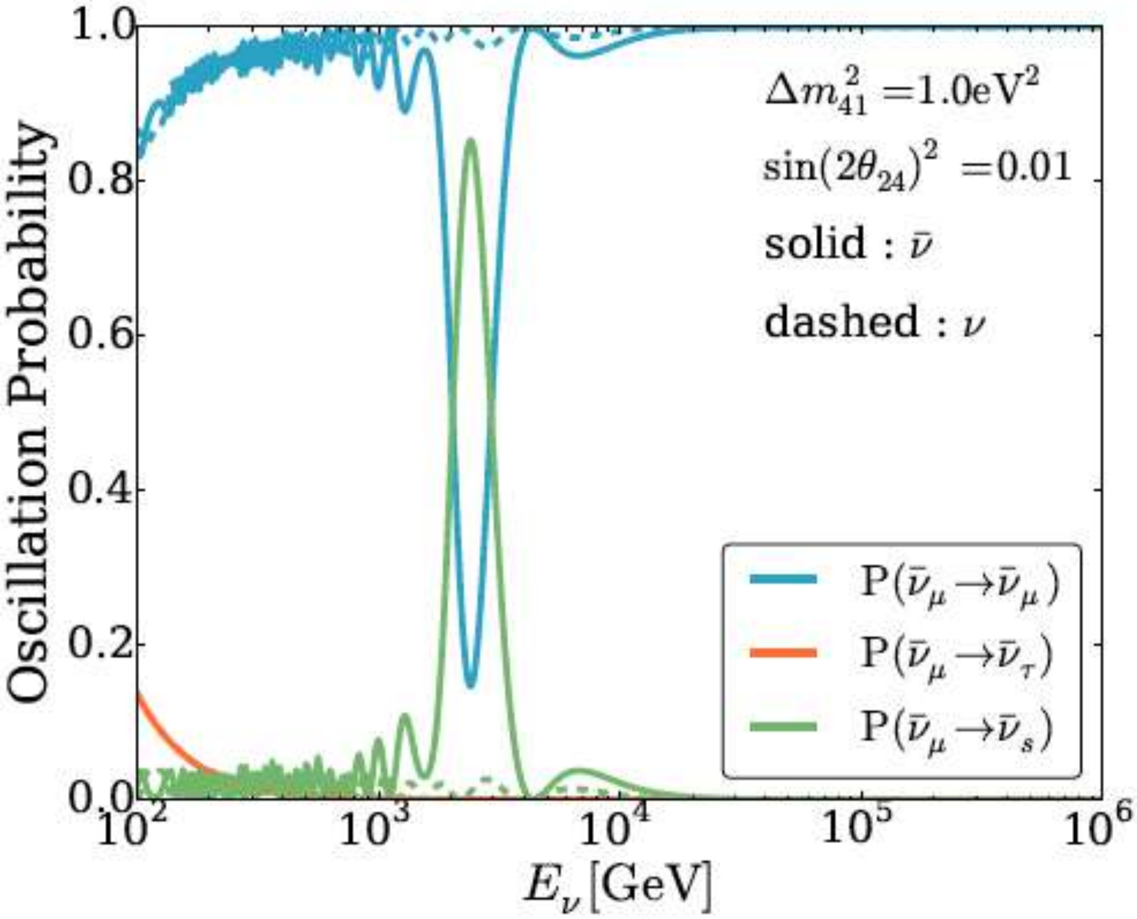


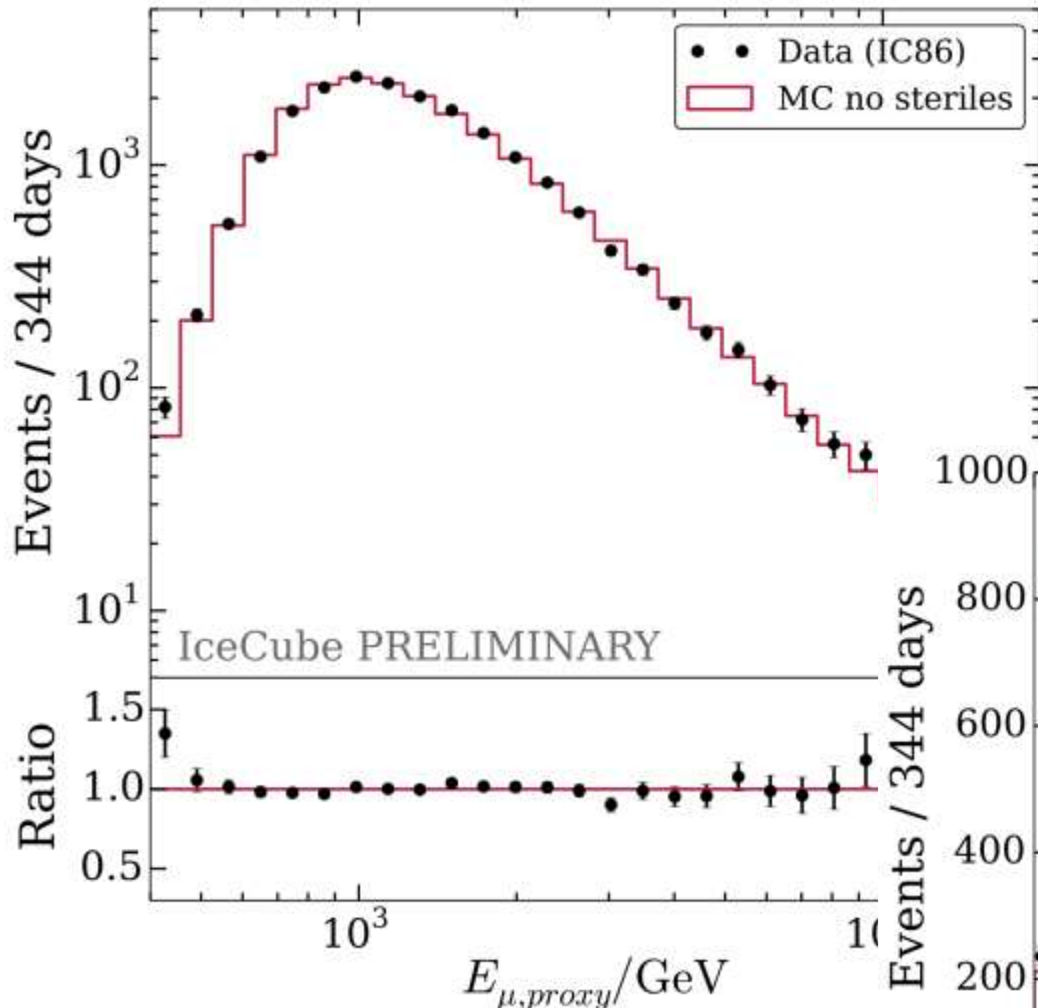
current
IC 12yr
Phase I verified
ν_τ
ν_μ
ν_e
0.0
0.2
0.4
0.6
0.8
1.0

eV sterile neutrino → Earth MSW resonance for TeV neutrinos

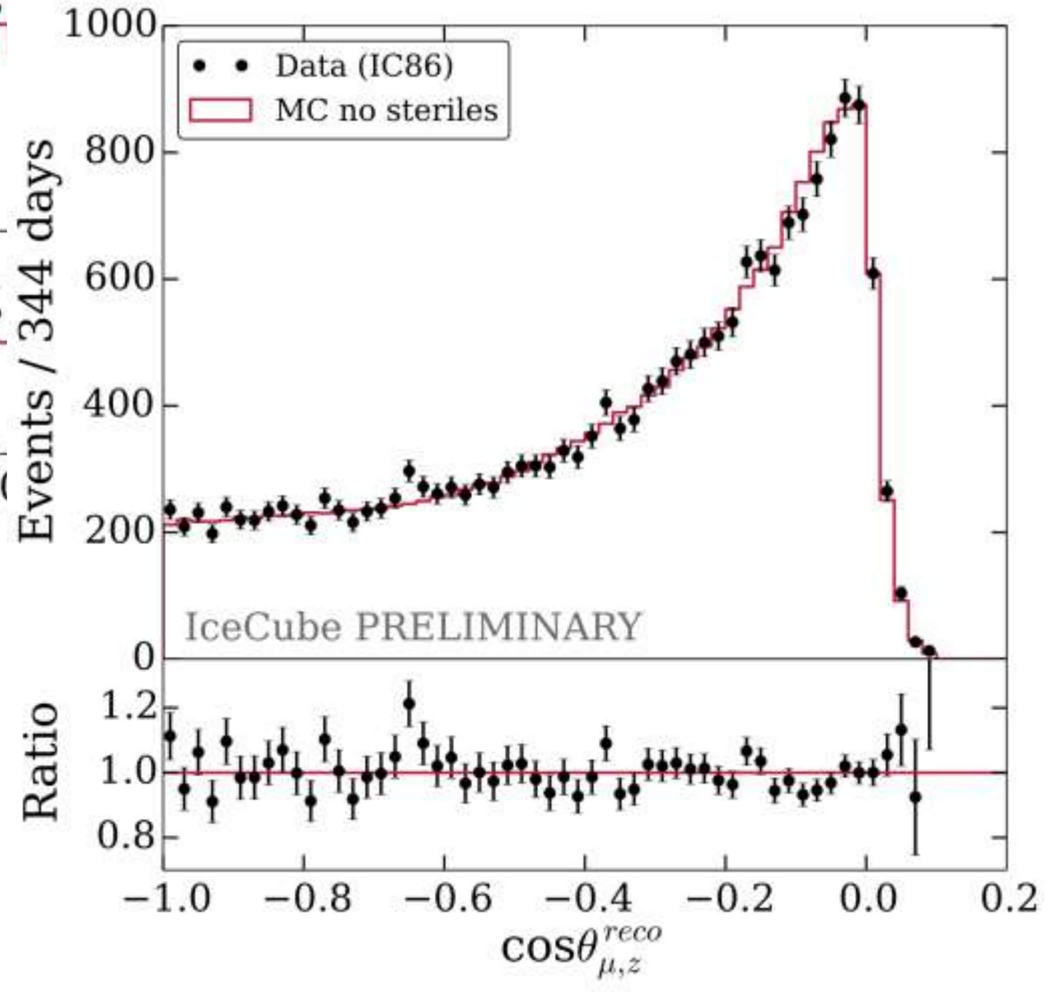
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

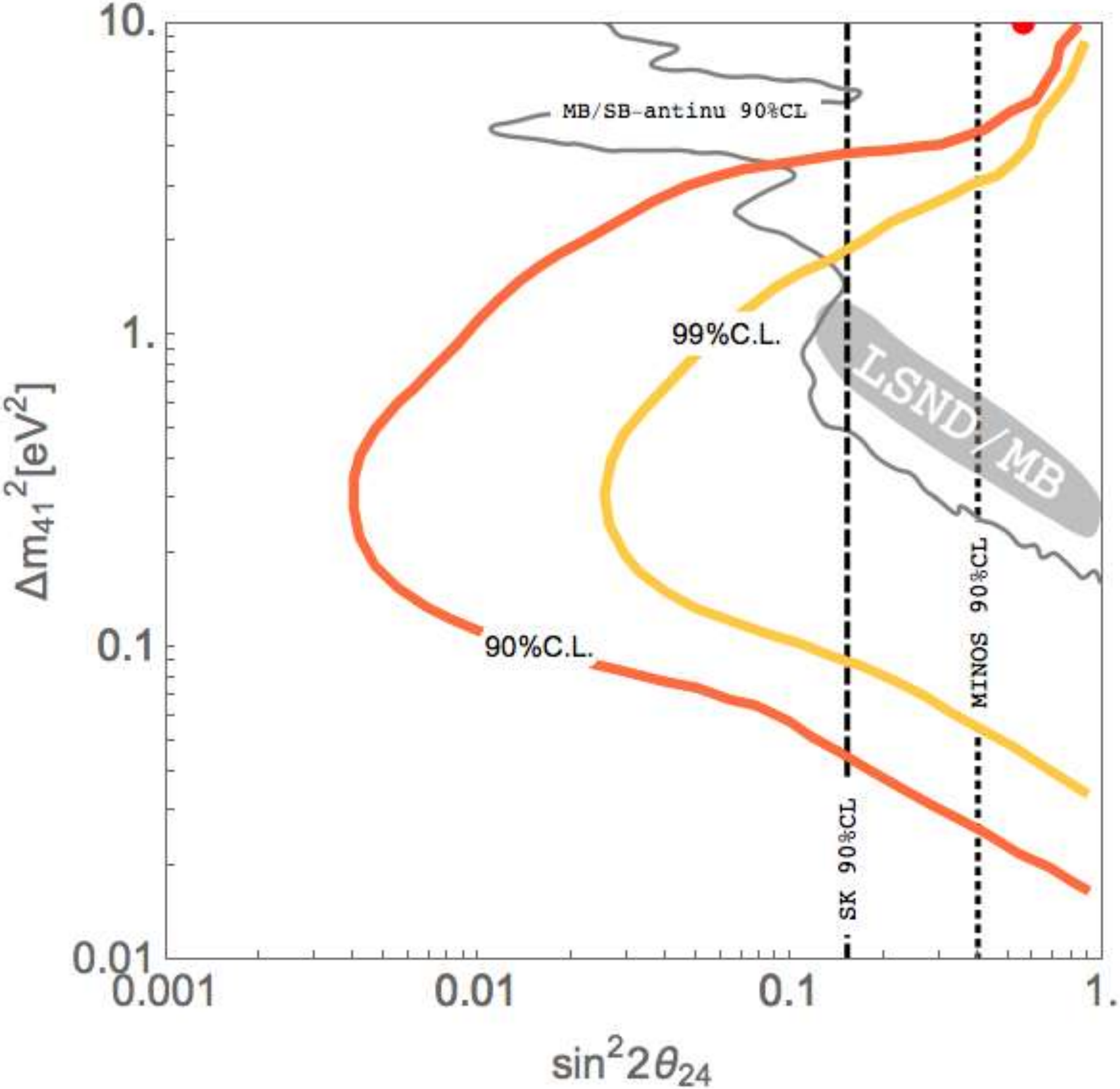
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$





no telltale structure in the zenith angle distribution





10.
1.
0.1
0.01
0.001
0.01
0.1
1.
$\Delta m_{41}{}^2[eV^2]$
$\sin^2 2\theta_{24}$
MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL

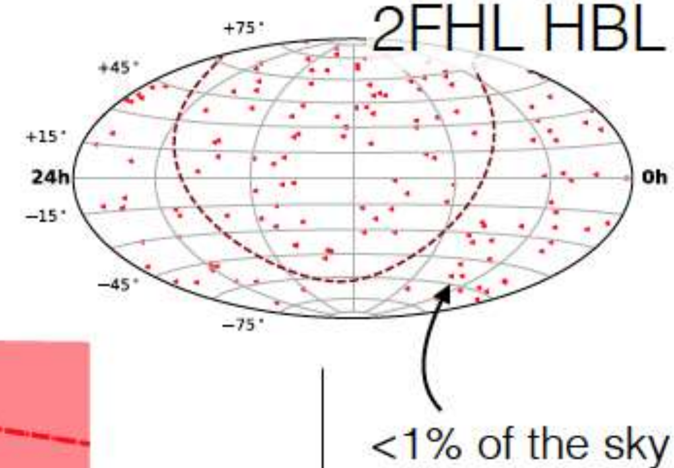
High Energy Neutrino Astrophysics
francis halzen

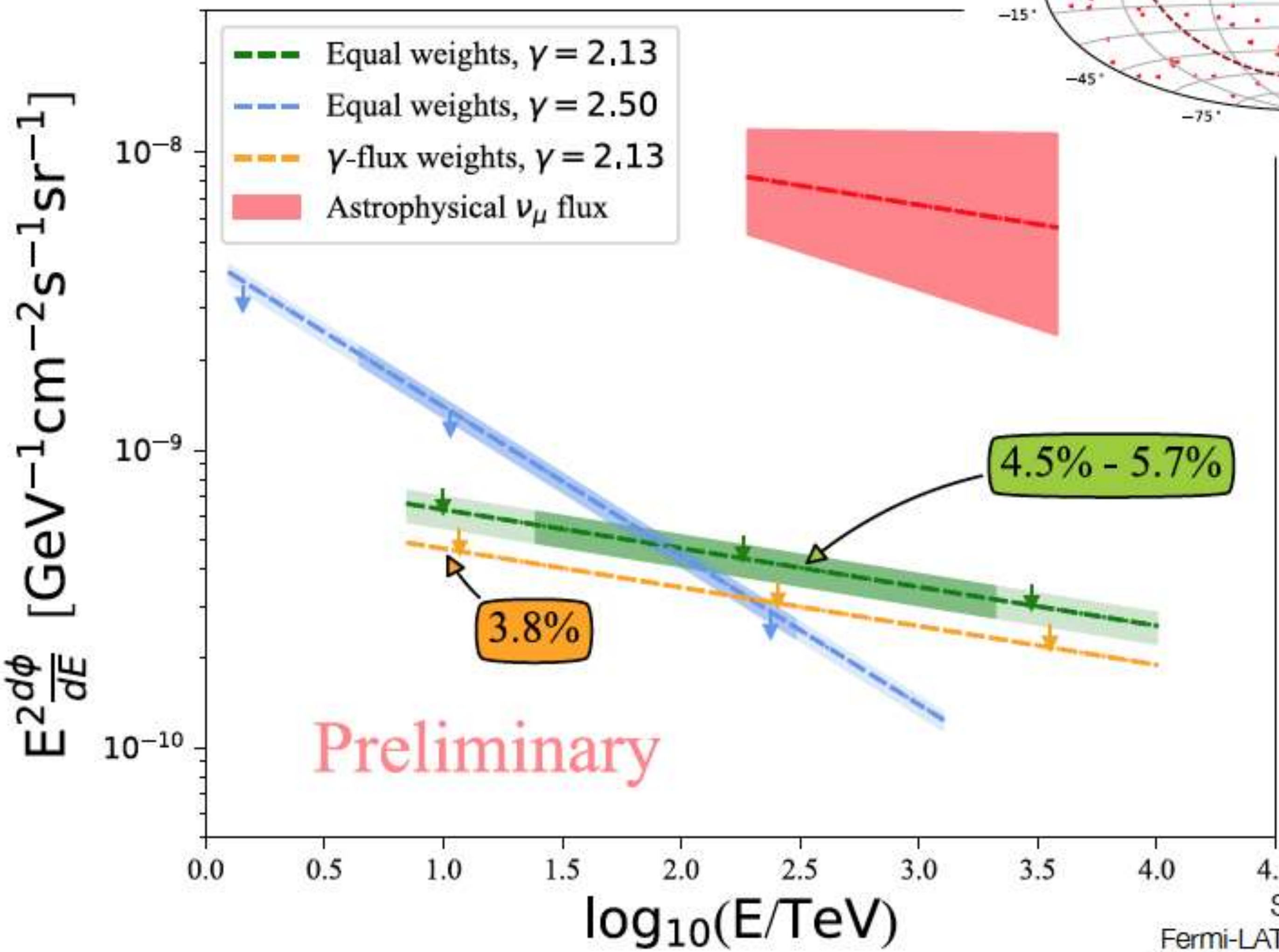
- Cosmic accelerators
- Multimessenger astronomy
- IceCube
- cosmic neutrinos: two independent observations
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- Galactic sources
- IceCube as a facility
- what next?
- theoretical musings (mostly on blazars)

icecube.wisc.edu

Population studies: blazar catalog search

Blazars account for:
85% of extragalactic γ background
< 6-27% of the IceCube neutrino flux





See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

Olbers paradox

$$\phi_{\rm diff} = \int d^3r \frac{L_\nu}{4\pi r^2} \cdot \rho$$

diffuse flux is measured

nearest source

$$\frac{4}{3}\pi d_{ns}^3 \cdot \rho = 1$$

and

$$d_{\rm ns} \sim \rho^{-1/3}$$

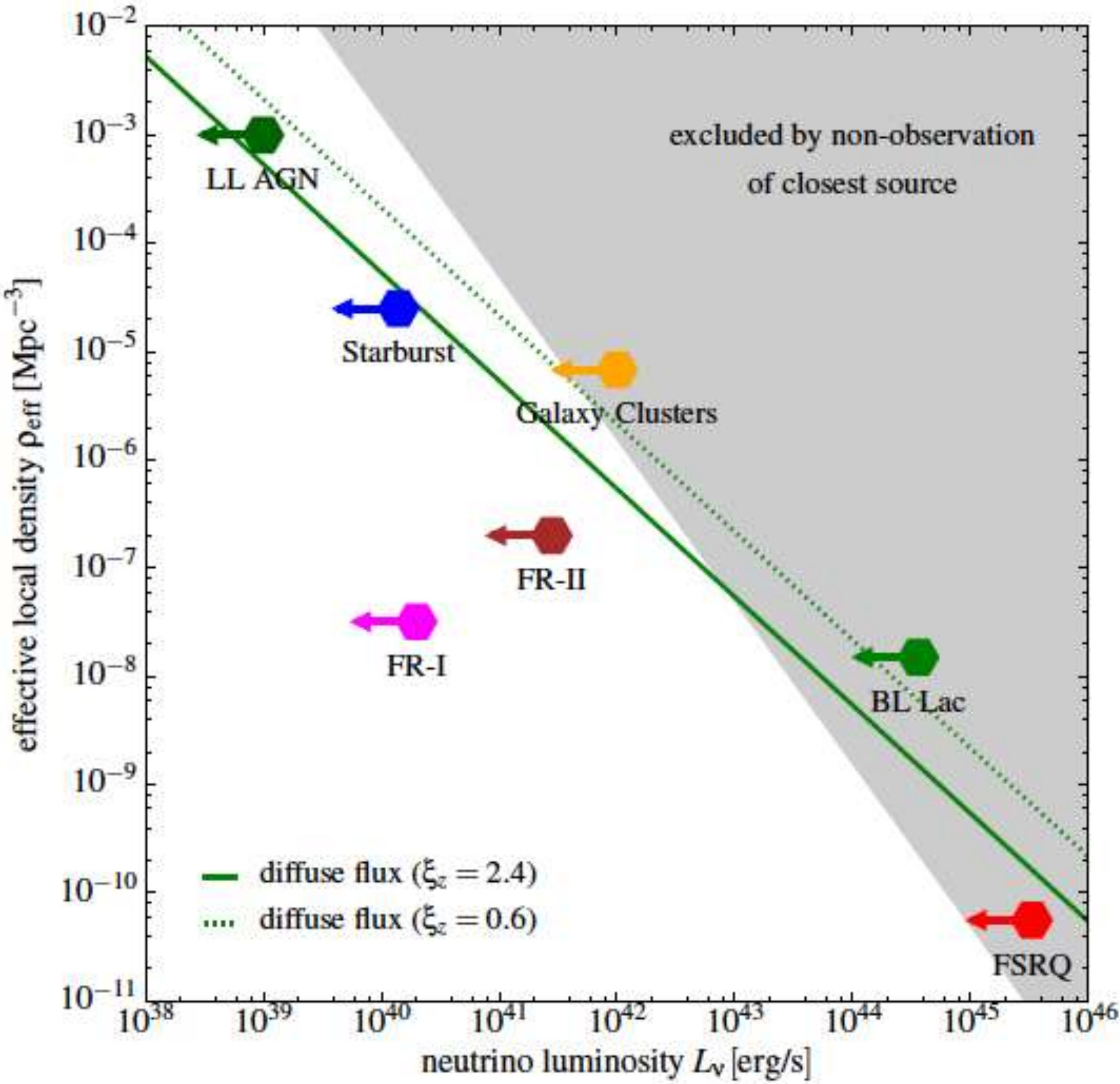
$$\phi_{\rm ns} = \frac{L_\nu}{4\pi d_{\rm ns}^2} \sim (L_\nu \cdot \rho) d_{\rm ns} \sim \phi_{\rm diff} \cdot \rho^{-1/3}$$

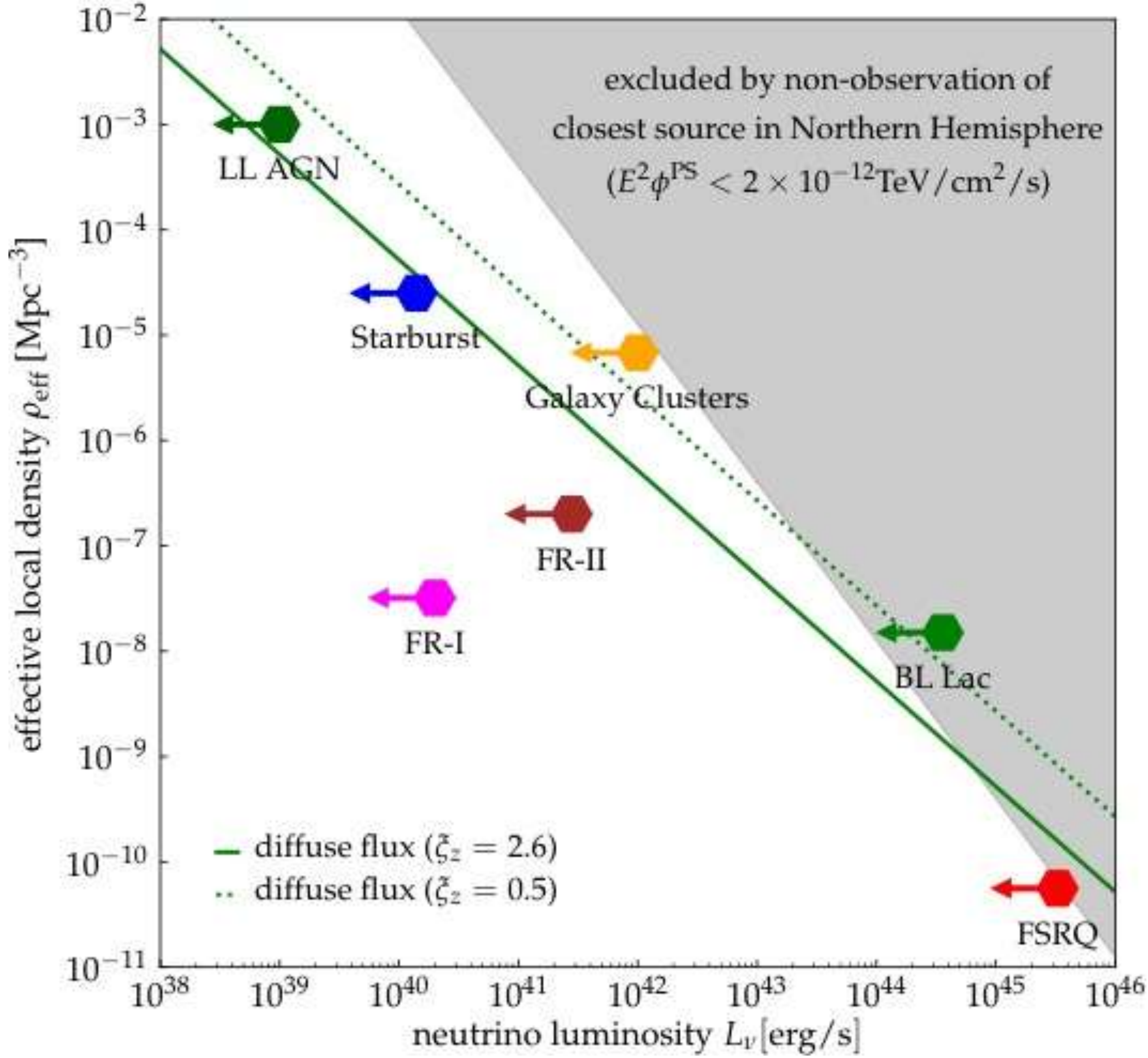
flux nearest source = (diffuse flux observed)(density of sources)$^{-1/3}$

Olbers paradox

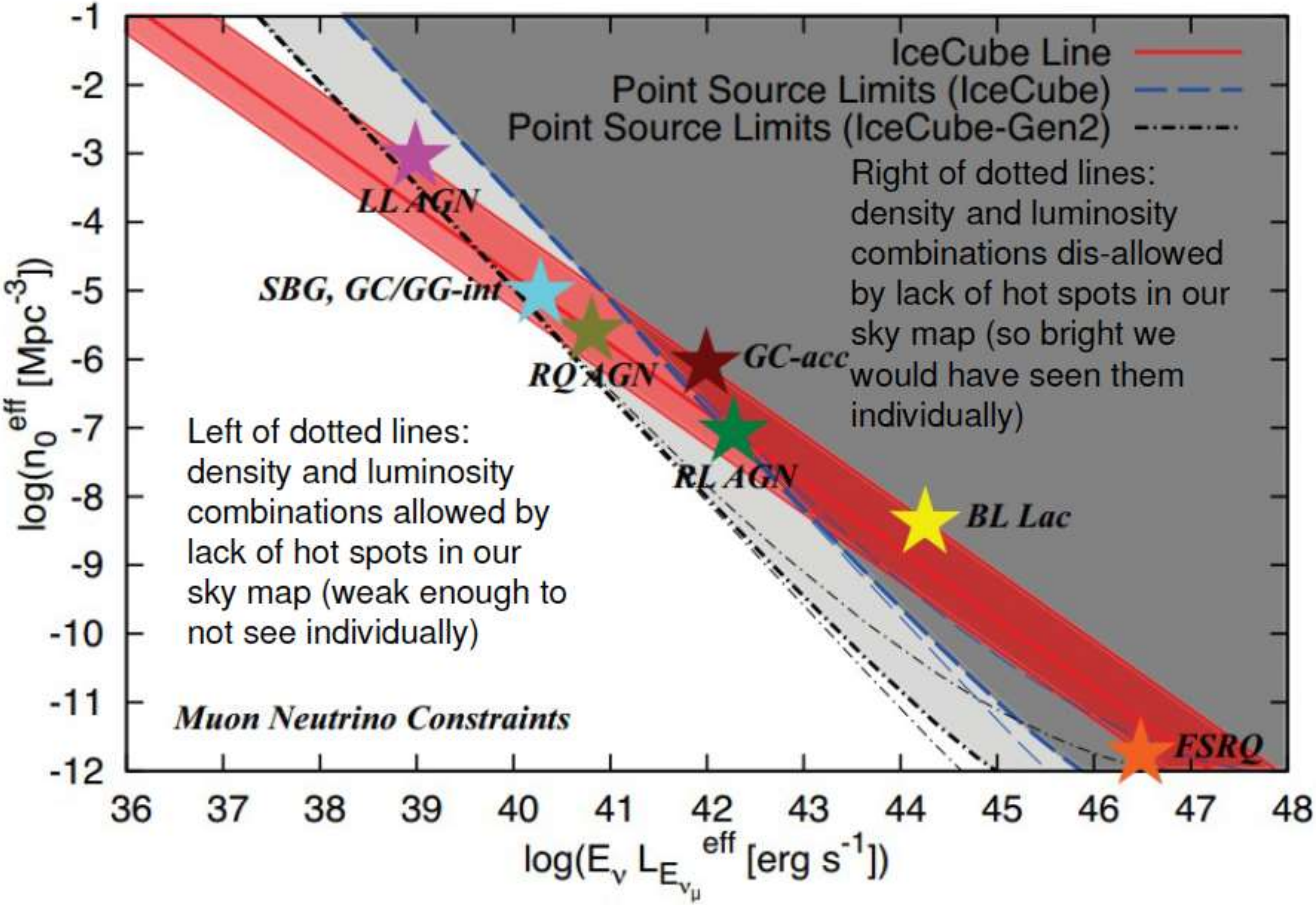
density 10^{-7} Mpc^{-3} soon !

blazars, FSRQ…





excluded by non-observation of
closest source in Northern Hemisphere
($E^2\phi^{PS} < 2 \times 10^{-12}$TeV/cm^2/s)
LL AGN
Starburst
Galaxy Clusters
FR-II
FR-I
BL Lac
FSRQ
diffuse flux ($\xi_z = 2.6$)
diffuse flux ($\xi_z = 0.5$)
effective local density $\rho_{\rm eff}$ [Mpc^{-3}]
neutrino luminosity L_ν [erg/s]


IceCube Line
Point Source Limits (IceCube)
Point Source Limits (IceCube-Gen2)
Right of dotted lines: density and luminosity combinations dis-allowed by lack of hot spots in our sky map (so bright we would have seen them individually)
Left of dotted lines: density and luminosity combinations allowed by lack of hot spots in our sky map (weak enough to not see individually)
LL AGN
SBG, GC/GG-int
RQ AGN
GC-acc
RL AGN
BL Lac
FSRQ
Muon Neutrino Constraints
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
36
37
38
39
40
41
42
43
44
45
46
47
48
$\log(n_0^{eff}$ [Mpc^{-3}])
$\log(E_\nu L_{E_{\nu_\mu}}^{eff}$ [erg s^{-1}])

Neutrino Flux

Neutrino flux from episodic emission from a fraction of a source class

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{c}{4\pi}\frac{\xi_z}{H_0} L_\nu \rho \mathcal{F} \frac{\Delta t}{T}$$

Adopting for the observation of 2014 neutrino burst for TXS:

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{\mathcal{F}}{4\pi}\left(\frac{R_H}{3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2\times 10^{47}\,\mathrm{erg/s}}\right)\left(\frac{\rho}{1.5\times 10^{-8}\,\mathrm{Mpc}^{-3}}\right)\left(\frac{\Delta t}{110\,\mathrm{d}}\frac{10\,\mathrm{yr}}{T}\right)$$

$$= 3\times 10^{-11}\,\mathrm{TeV cm^{-2} s^{-1} sr^{-1}}$$

$$\longrightarrow \mathcal{F} \sim 5\%$$

A special class of blazars that undergo ~ 110-day duration flares like TXS 0506+056 once every 10 years accommodates the observed diffuse flux of high-energy cosmic neutrinos.

[Halzen, AK, Weisgarber, In prep.]

Relating to the Cosmic Rays

The equal energetics of cosmic rays and neutrinos dictates

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{8\pi}\left(1-e^{-f_\pi}\right)\frac{\xi_z}{H_0}\frac{dE}{dt}$$

The CRs energy injection rate $\frac{dE}{dt} \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$

Finding the pion production efficiency of the neutrino source $\longrightarrow$ $f_\pi \gtrsim 0.4$

high opacity for p-gamma interaction. Expected for an efficient neutrino emitter!

Gamma ray opacity is connected to pion efficiency

$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}} f_\pi \longrightarrow \tau_{\gamma\gamma} \simeq 100$$

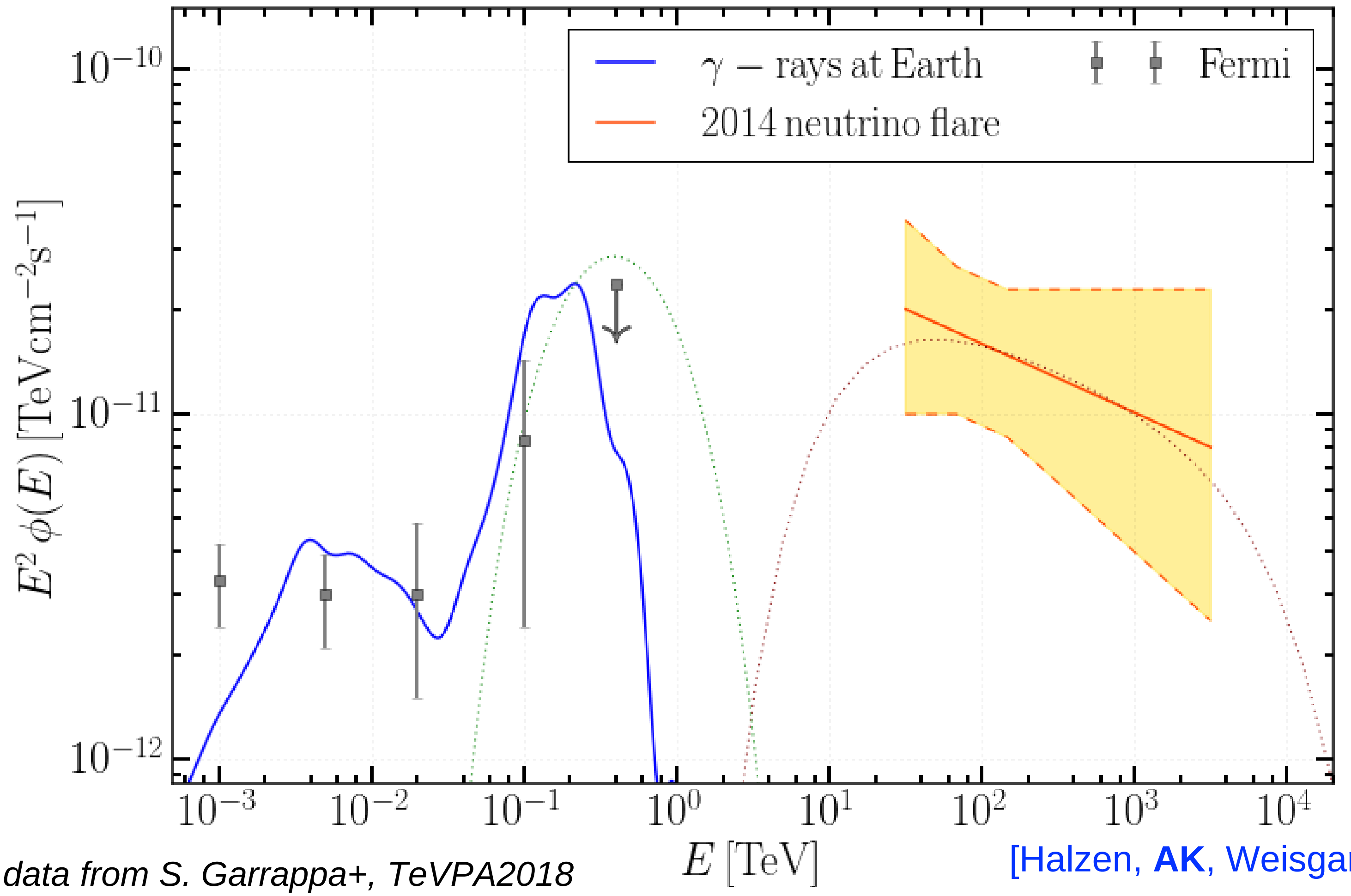
HE gamma rays will be absorbed at the source!

Is this compatible with the gamma ray observations?

[Halzen, AK, Weisgarber, In prep.]

The Multimessenger Picture

Neutrino flux → (energetics) → Gamma ray flux outside the source shifted to lower energies → (EBL Absorption) → Observed flux @ Fermi



**Fermi data from S. Garrappa+, TeVPA2018*

[Halzen, **AK**, Weisgarber, In prep.]

Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos are essential for understanding the non-thermal universe.
- identified the first high-energy cosmic ray accelerator
- from discovery to astronomy: more events, more telescopes
  IceCube-Gen2, KM3NeT and GVD (Baikal)
- 10 years of IceCube data -pass 2 (detector geometry for individual DOMs, use more photons in reconstruction, better optics of ice)

THE ICECUBE COLLABORATION

STRALIA 1

NGDOM 1

UNITED STATES 25

ICECUBE