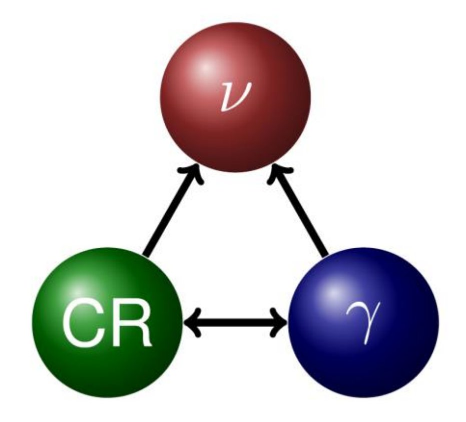
Particle Physics
Beyond Laboratory Energies



Francis Halzen
Wisconsin IceCube Particle Astrophysics Center

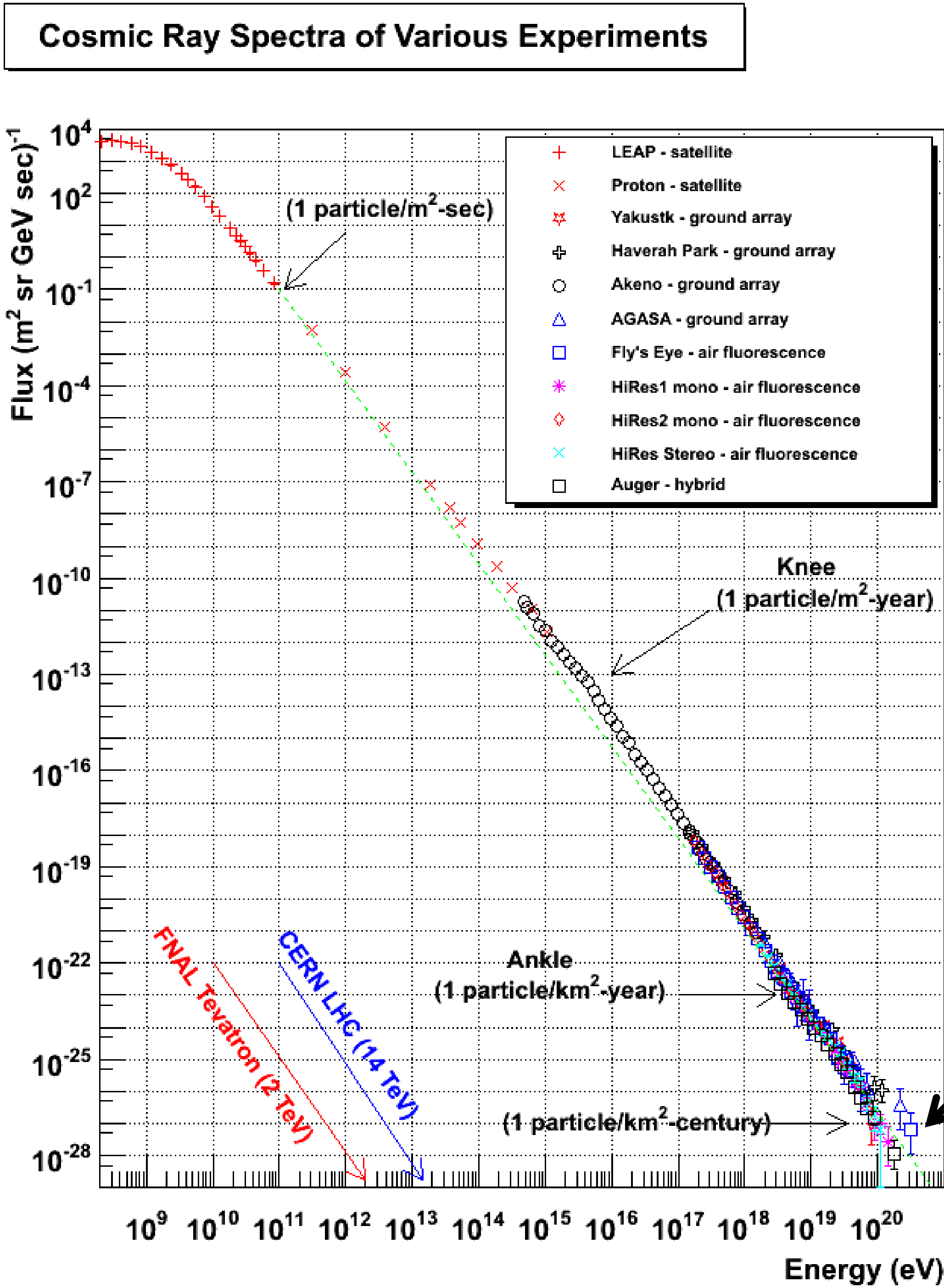
- Nature’s accelerators have delivered the highest energy protons, photons and neutrinos
- closing in on the cosmic ray accelerators?
- New tests of three-flavor neutrino framework
- Probing new physics: sterile neutrinos, Lorentz invariance, quantum structure of space-time…

“The only thing that requires more optimism than doing particle astrophysics is to try to summarize it in 30 minutes”

J.J. Gomez-Cadenas

Nature's accelerators?

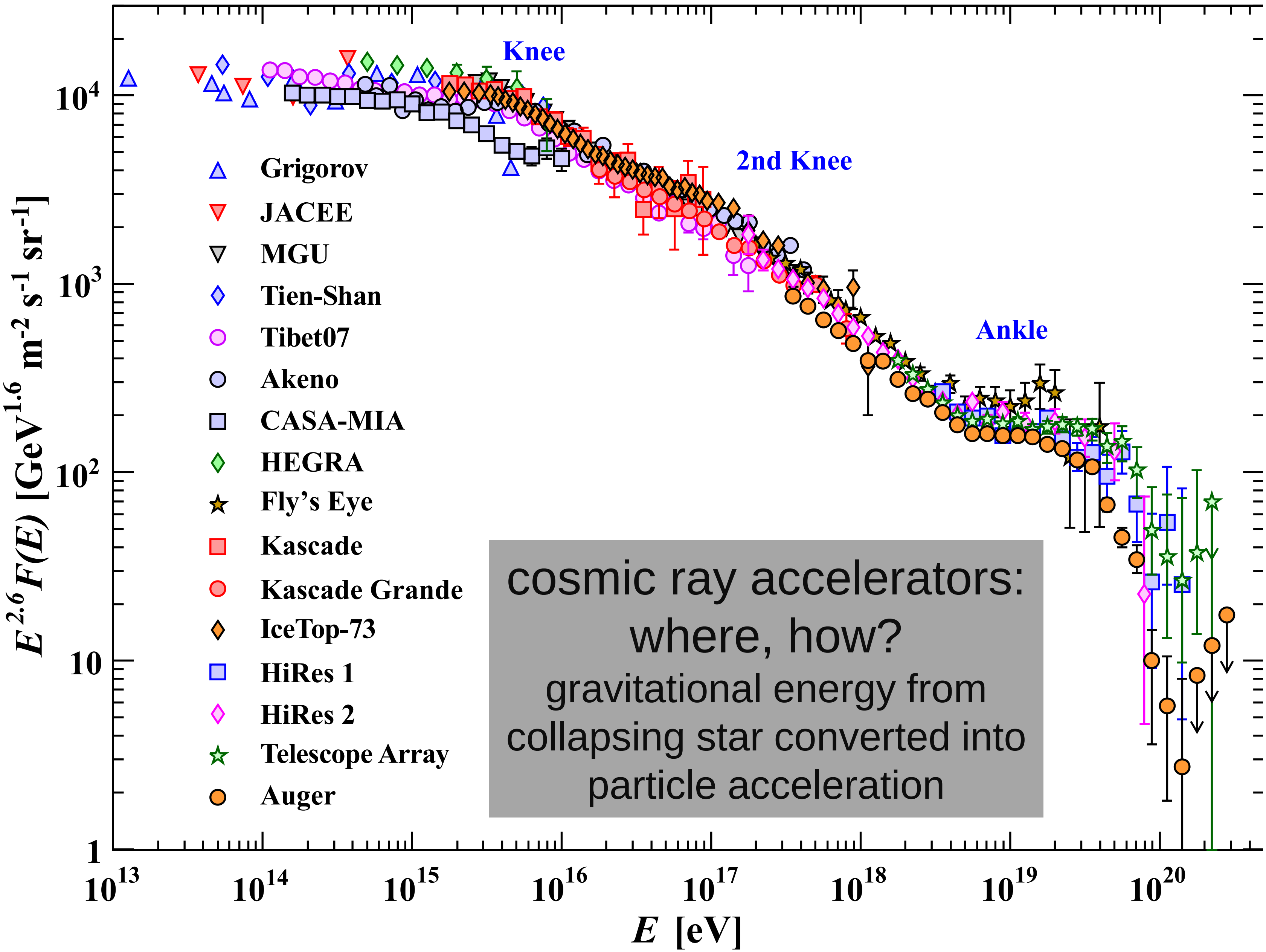
- protons 10^8 TeV
  photons 10^2 TeV
  neutrinos 10^4 TeV



cosmic ray accelerators:
where, how?

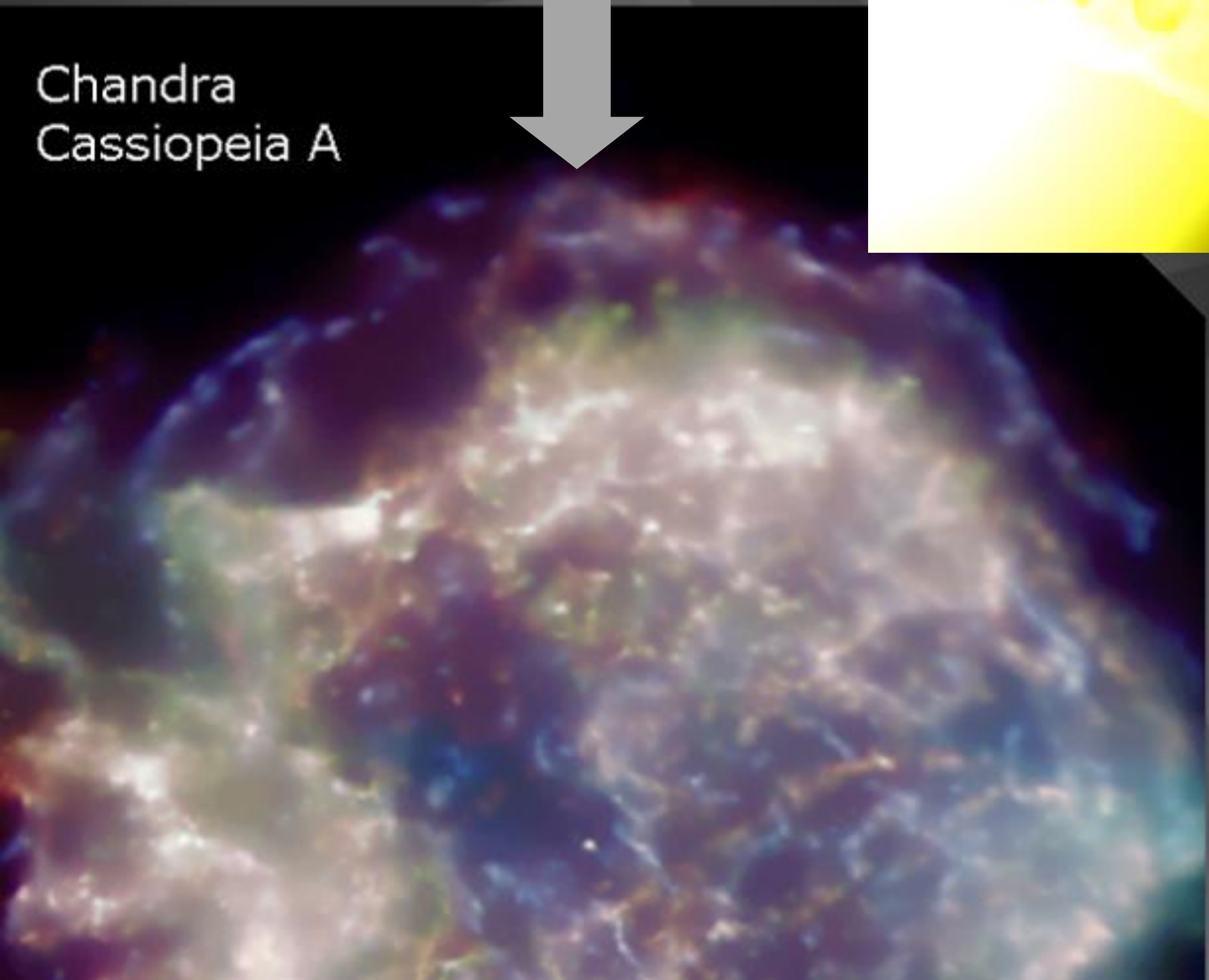
gravitational energy from collapsing star converted into particle acceleration

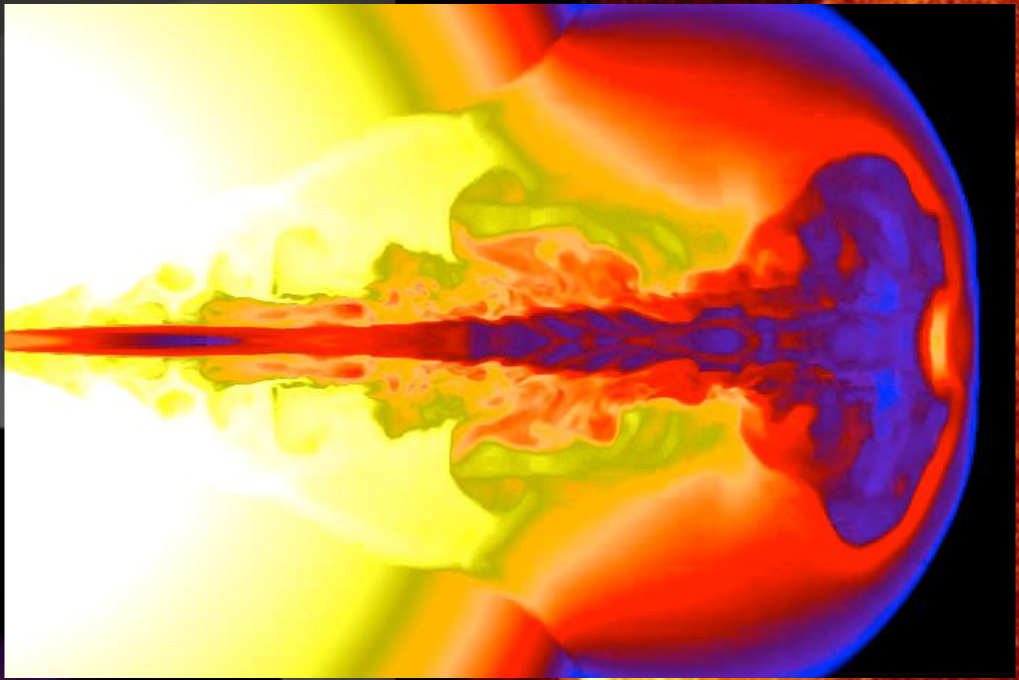
LHC filling the orbit of Mercury



Knee
2nd Knee
Ankle
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
cosmic ray accelerators:
where, how?
gravitational energy from
collapsing star converted into
particle acceleration
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]

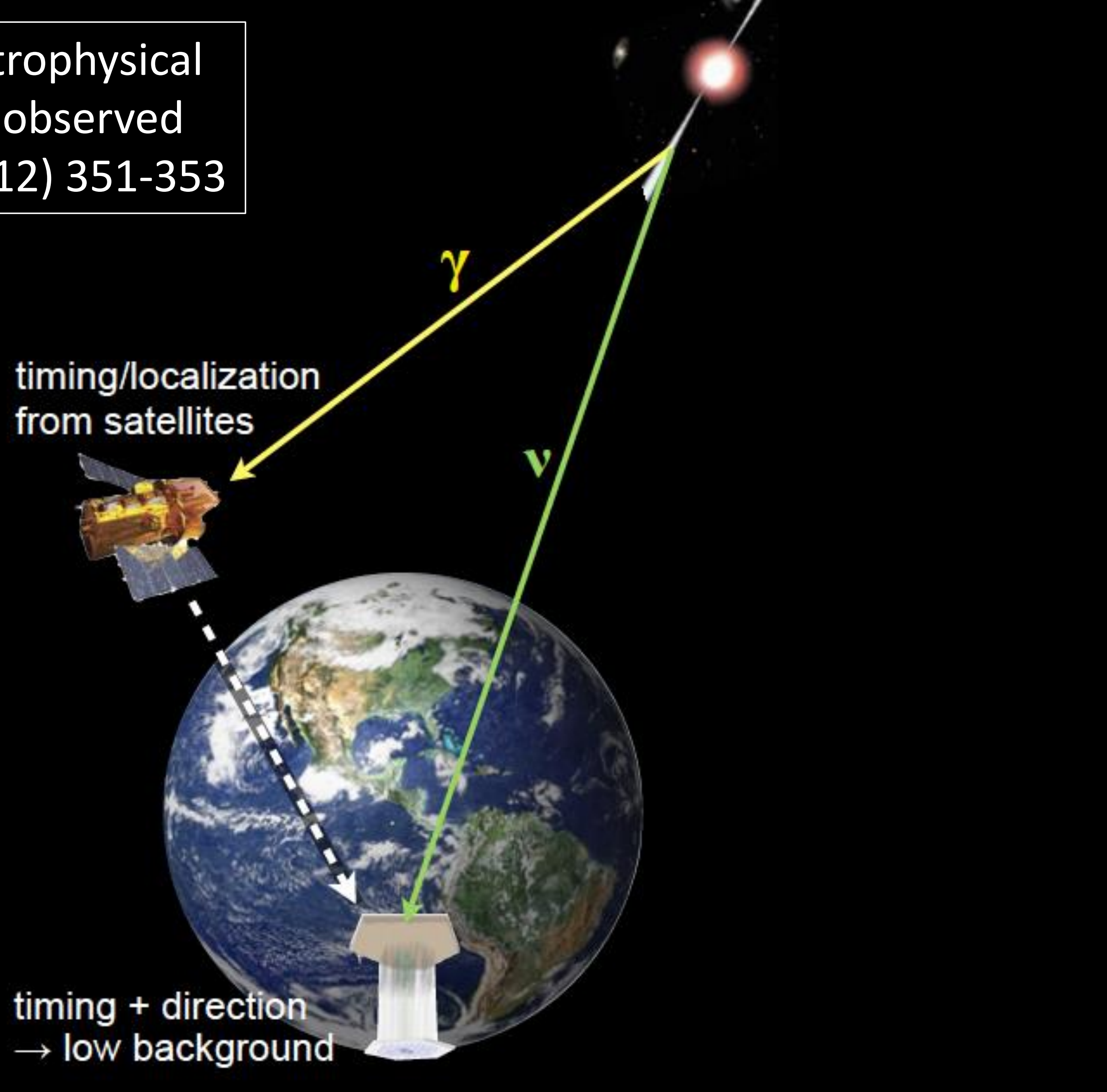
supernova
remnants

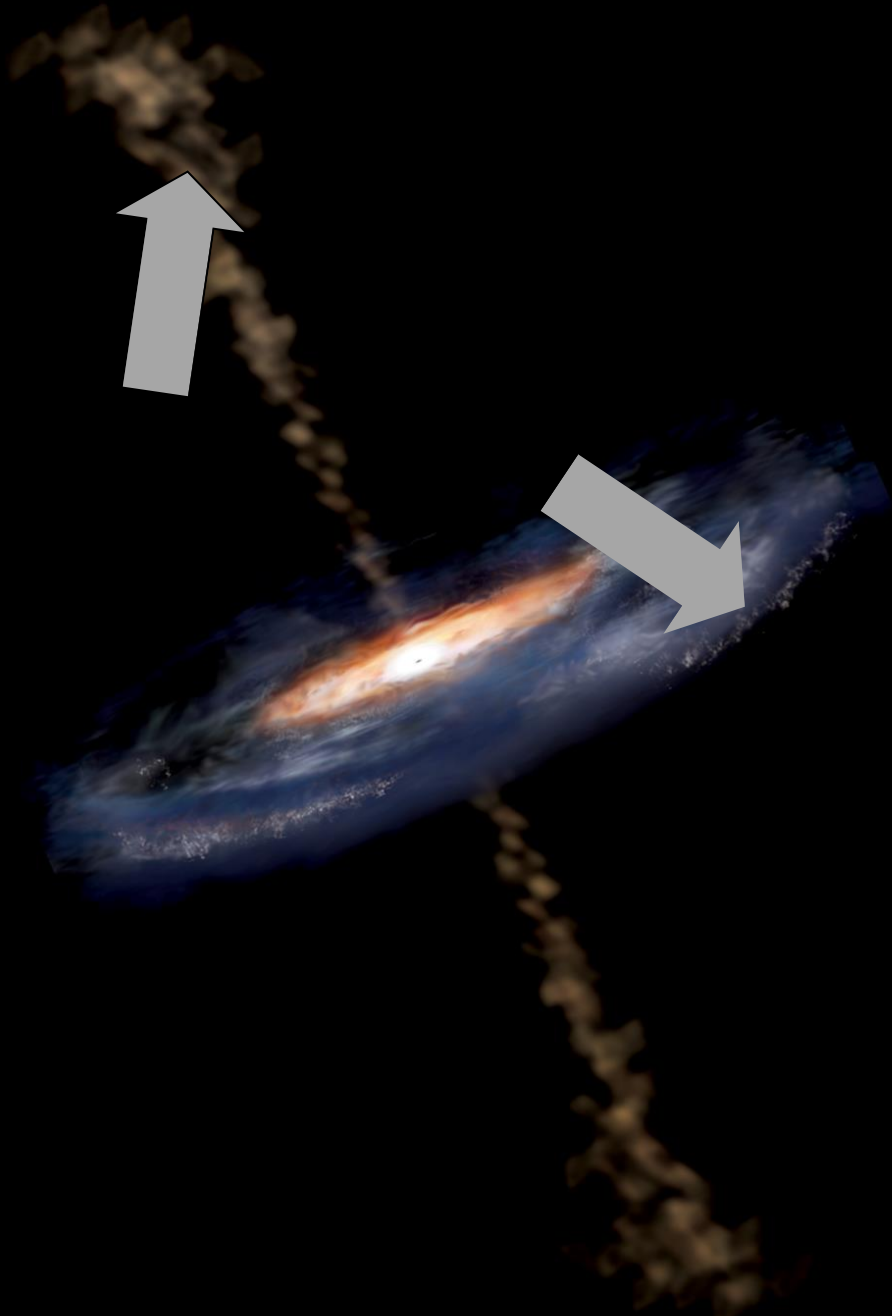




gamma
ray
bursts

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

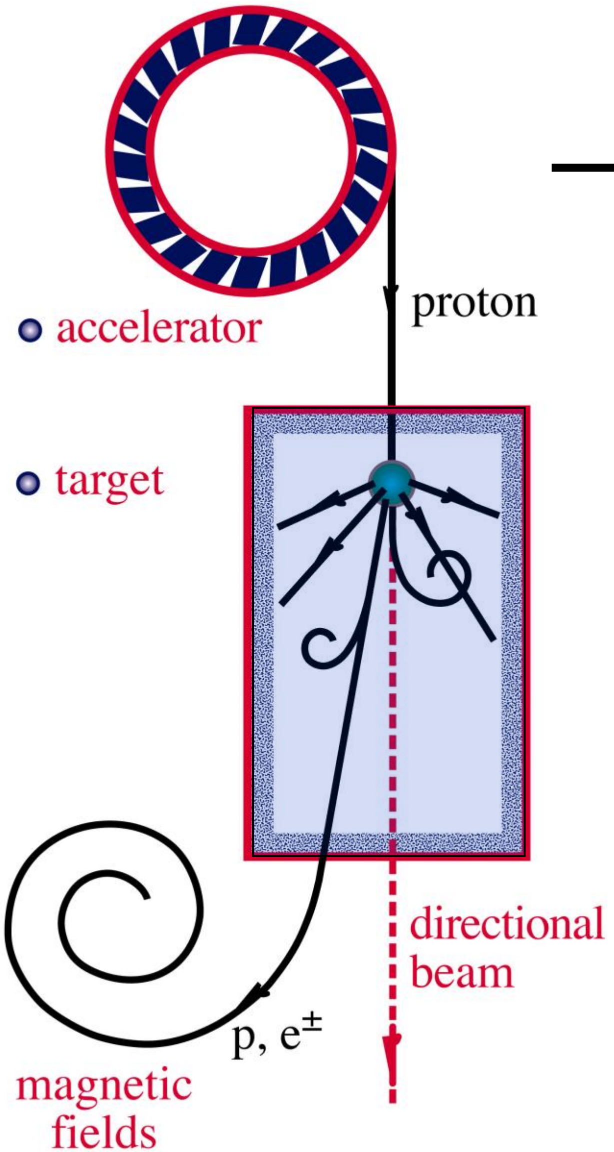




active galaxy

particle flows near supermassive black hole

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

$\rightarrow p + \pi^0$

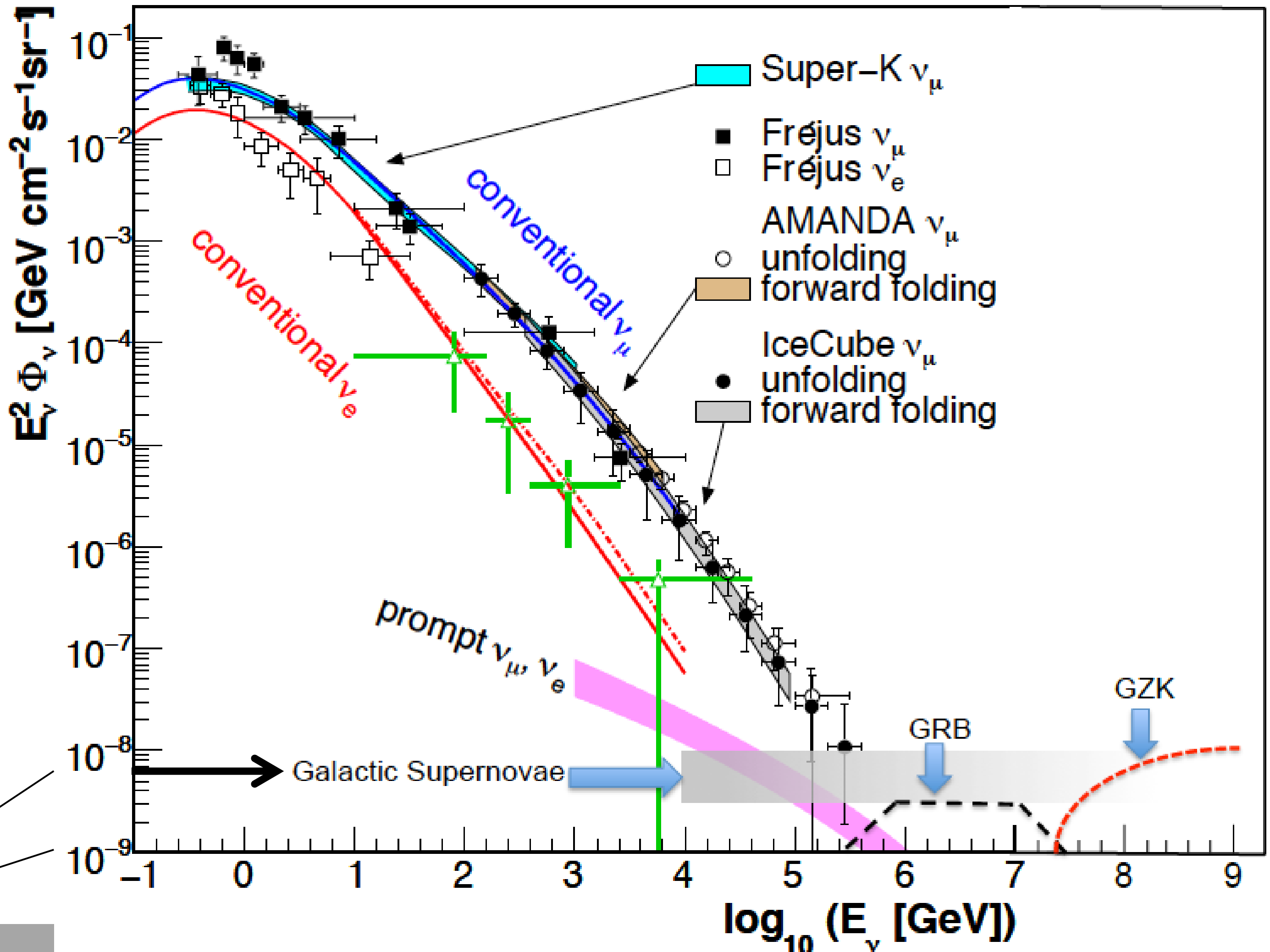
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient 1 km^3 detector

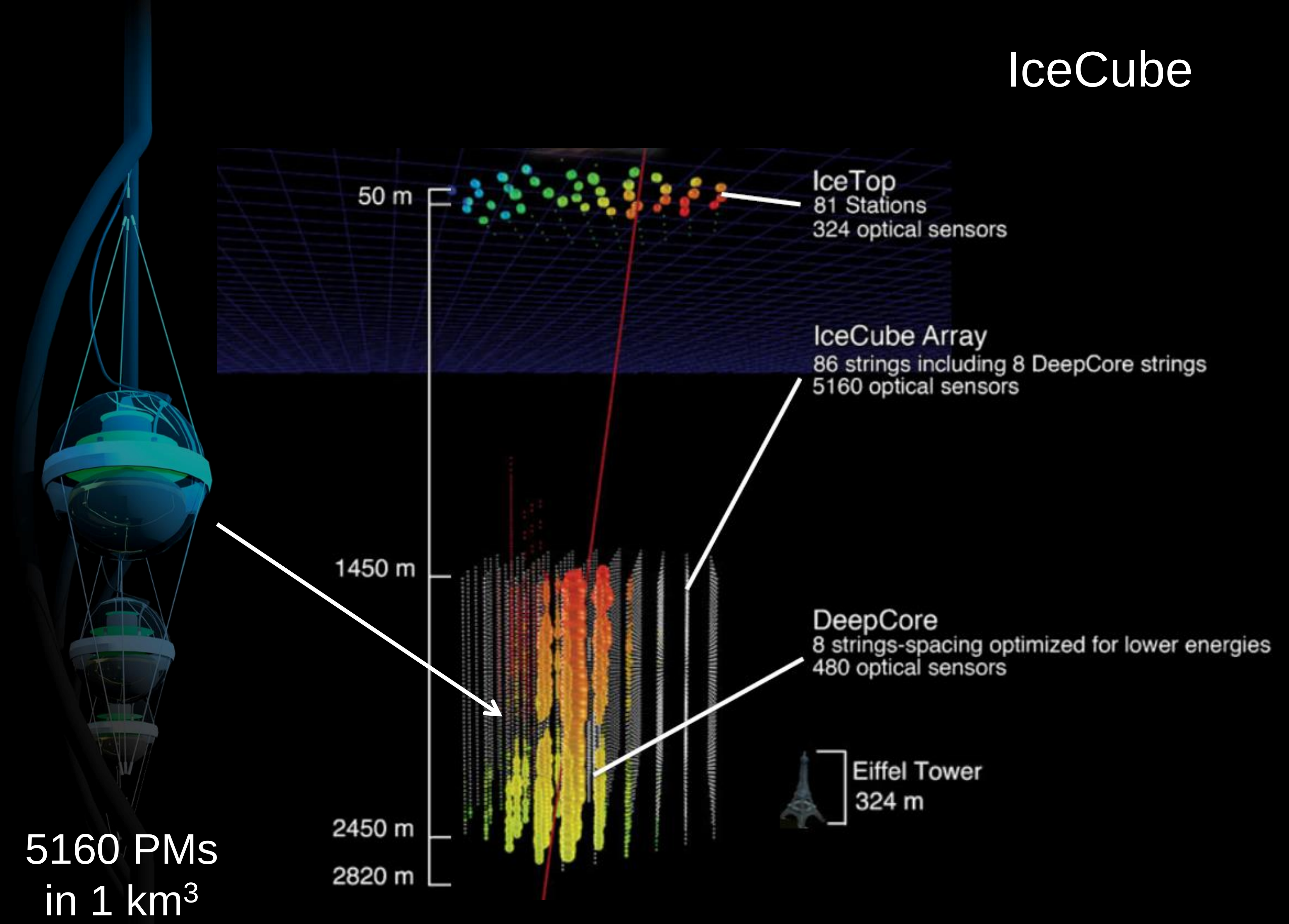


atmospheric

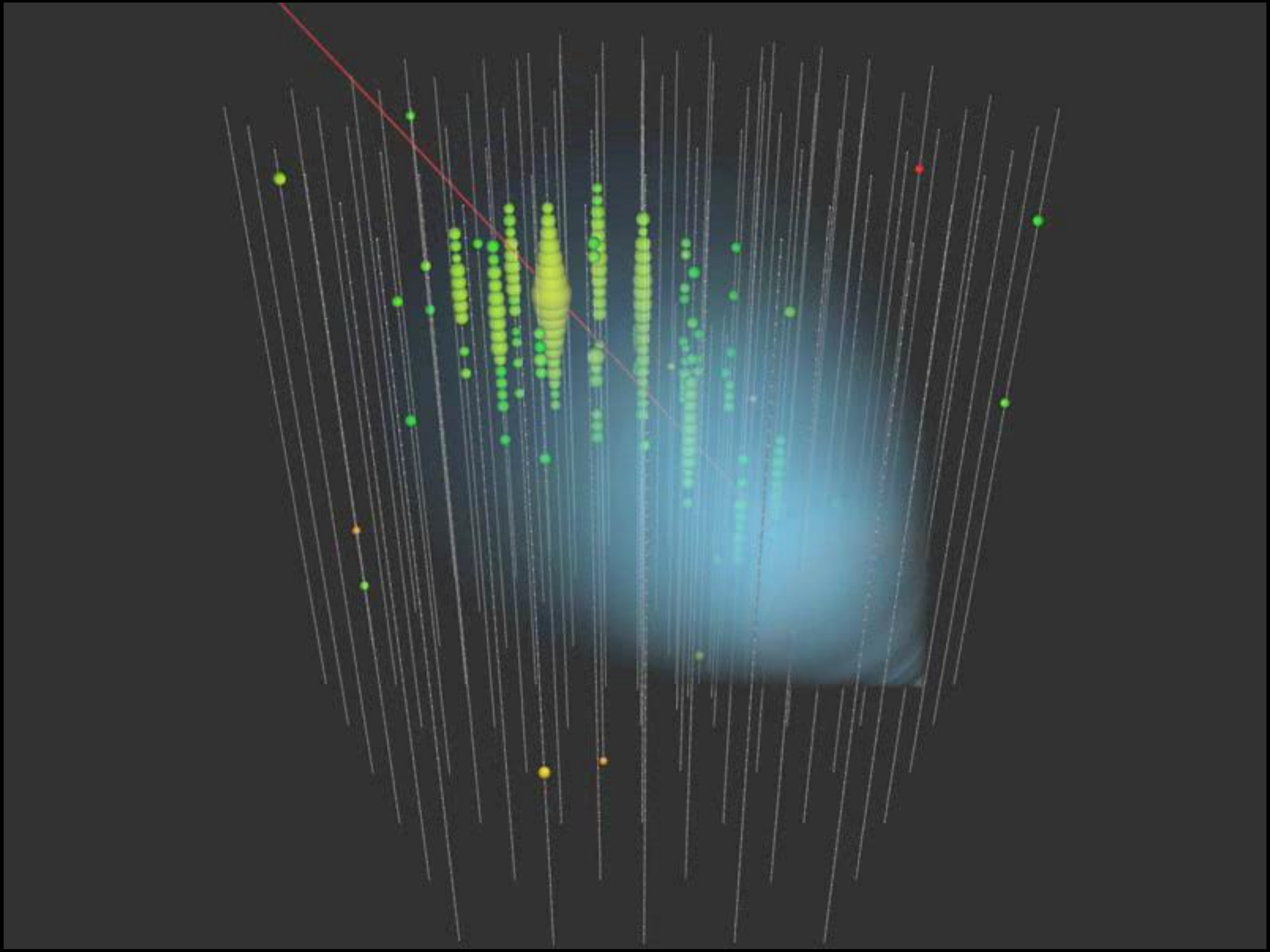
cosmic

100 TeV

IceCube

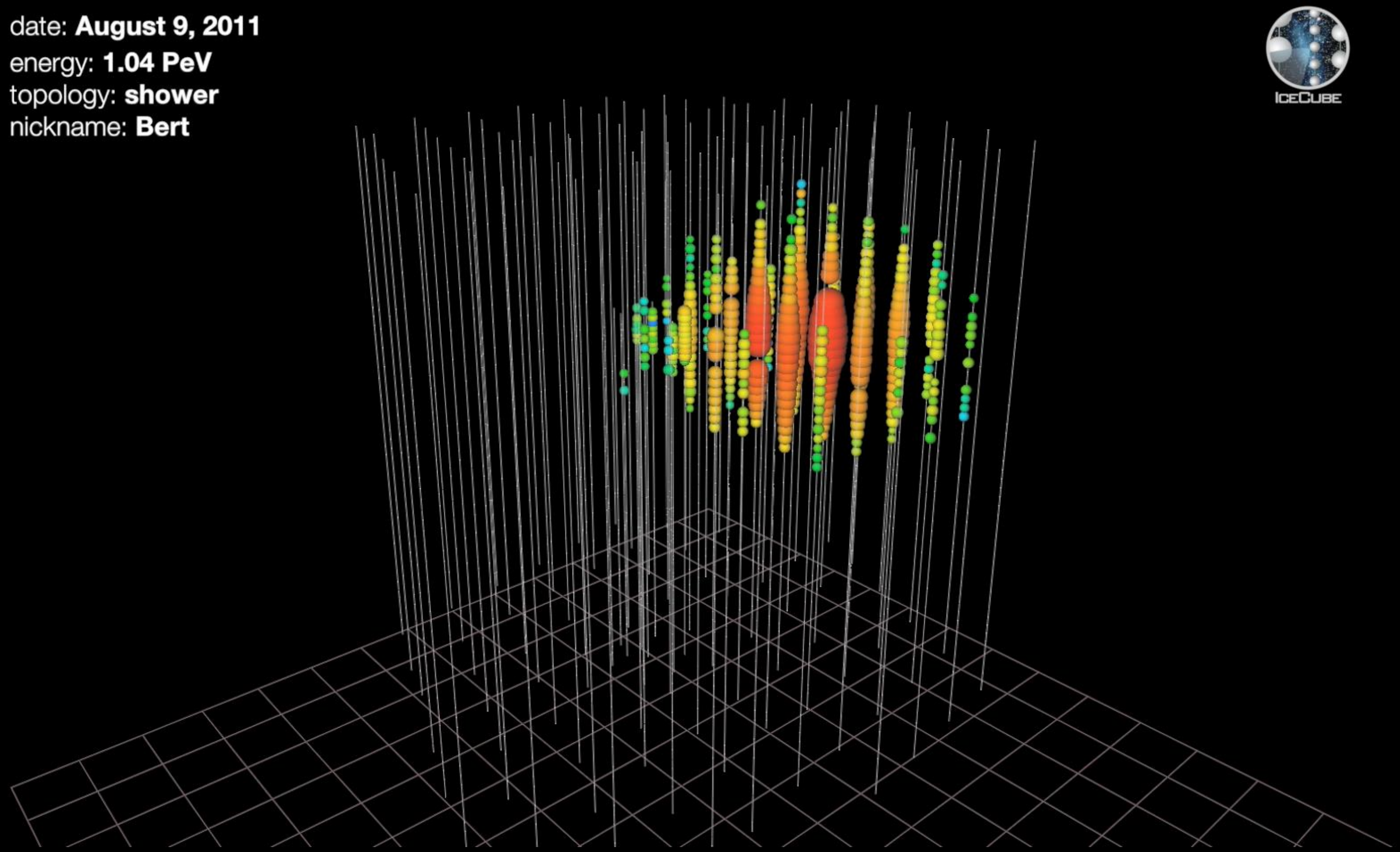


5160 PMs
in 1 km^3

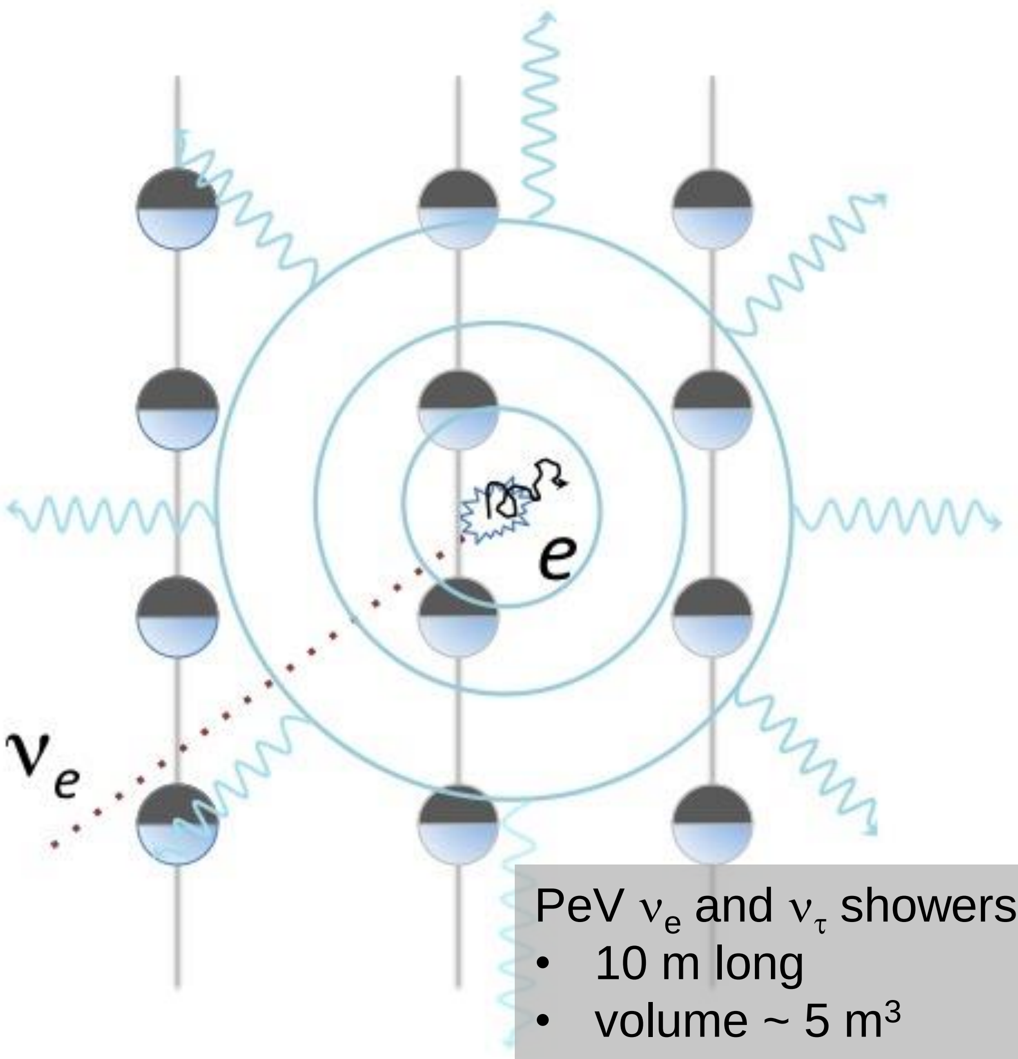


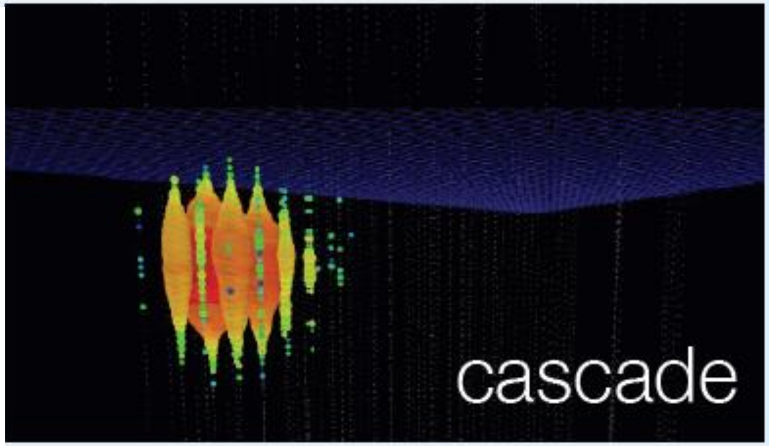
muon track: color is time; number of photons is energy

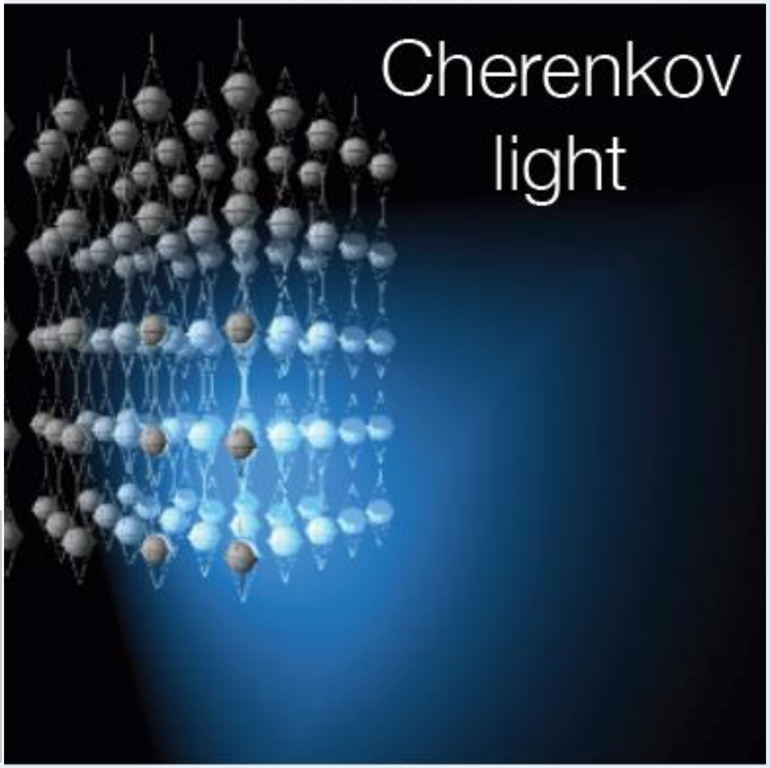
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

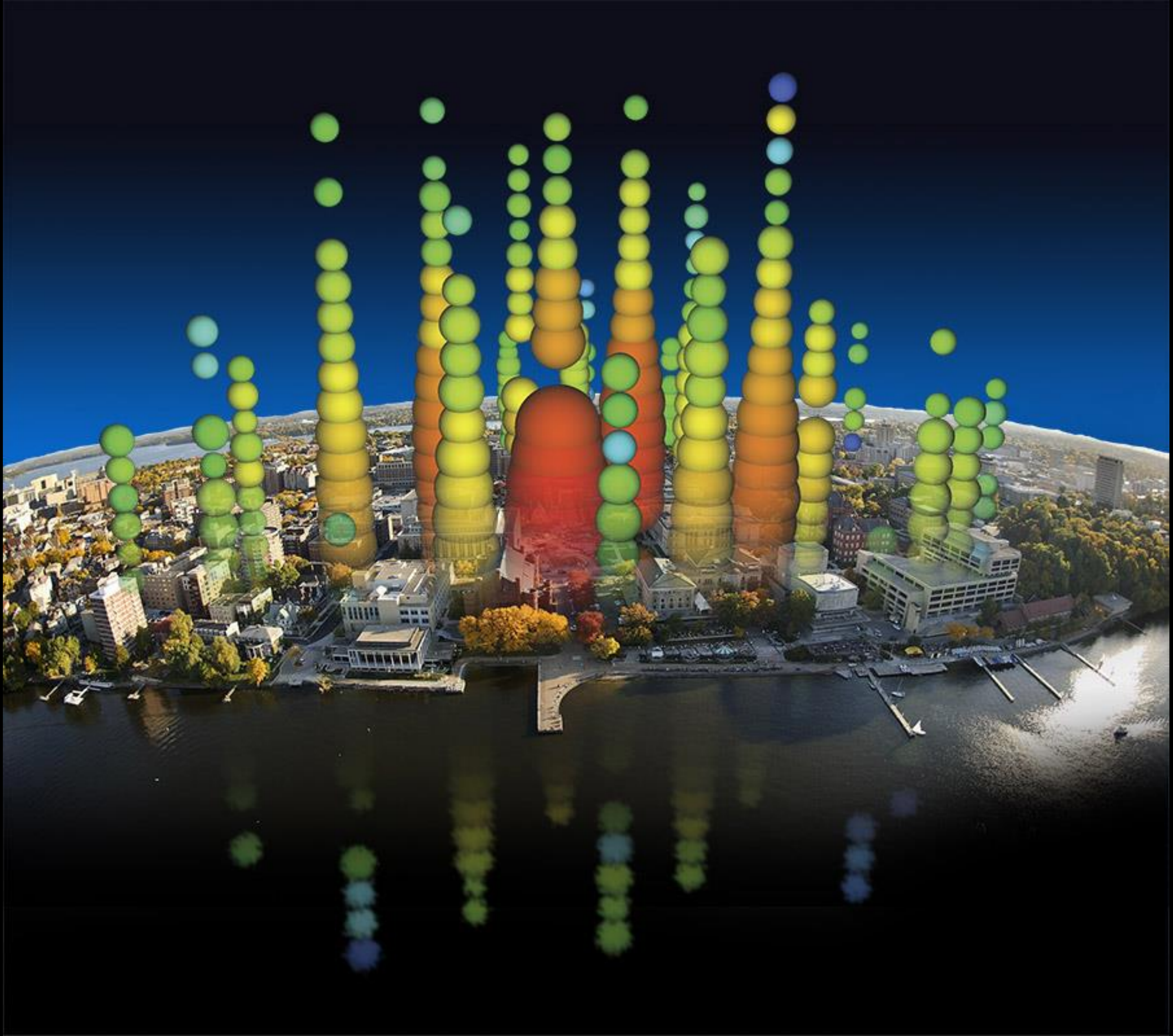






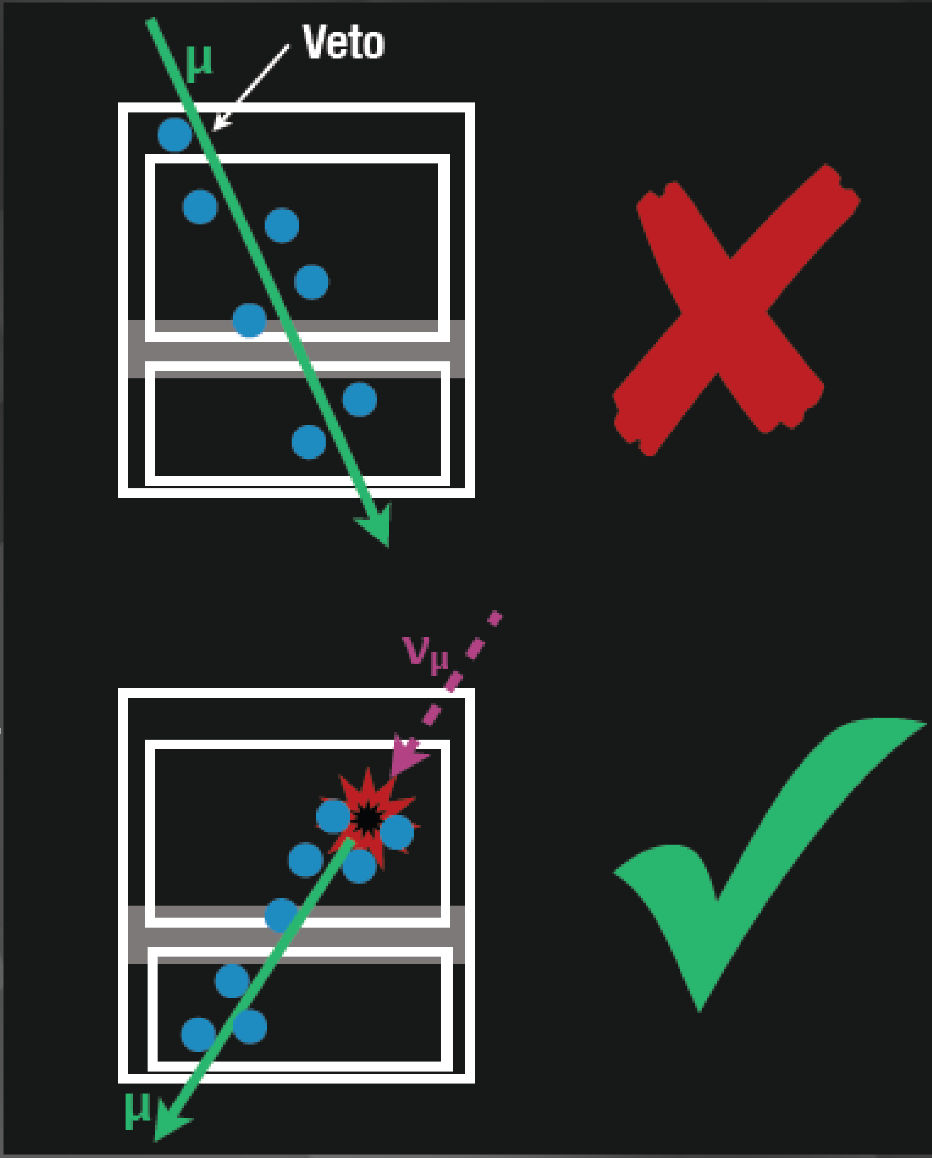
PeV ν_e and ν_τ showers:

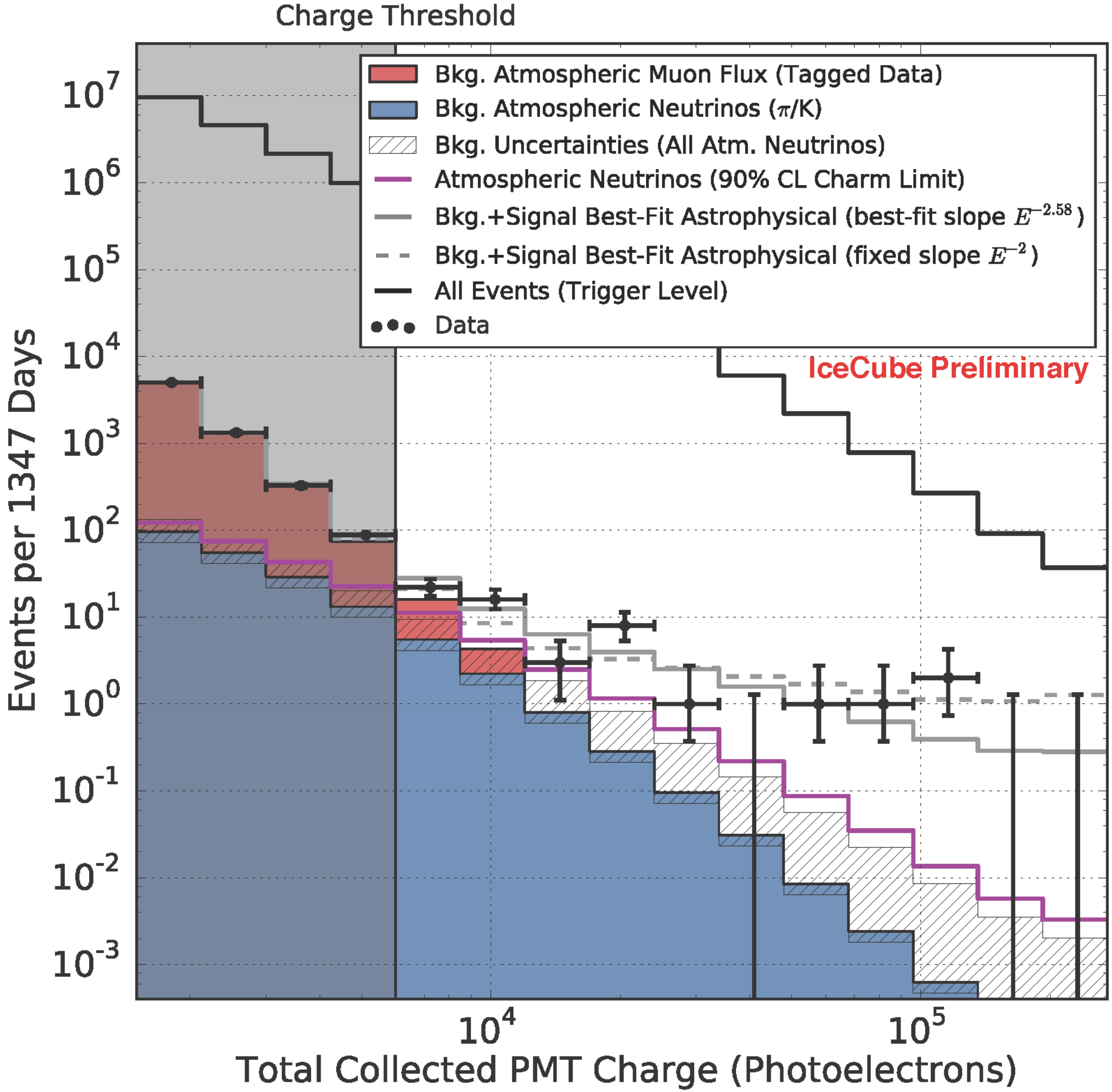
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



High Energy Starting Events

- ✓ 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

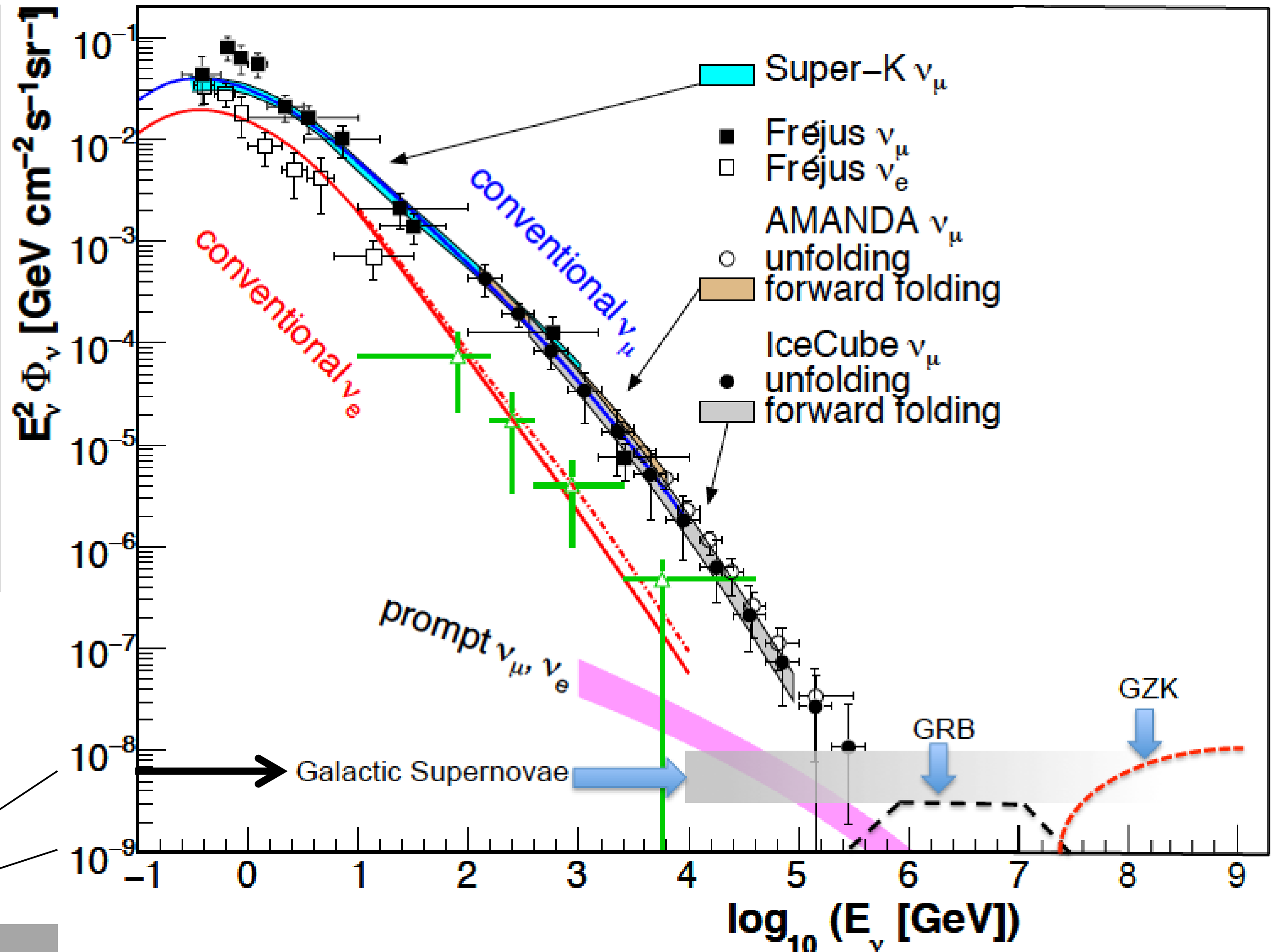




Charge Threshold
Bkg. Atmospheric Muon Flux (Tagged Data)
Bkg. Atmospheric Neutrinos (π/K)
Bkg. Uncertainties (All Atm. Neutrinos)
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
All Events (Trigger Level)
Data
IceCube Preliminary
Events per 1347 Days
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{4}
10^{5}
Total Collected PMT Charge (Photoelectrons)

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears



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

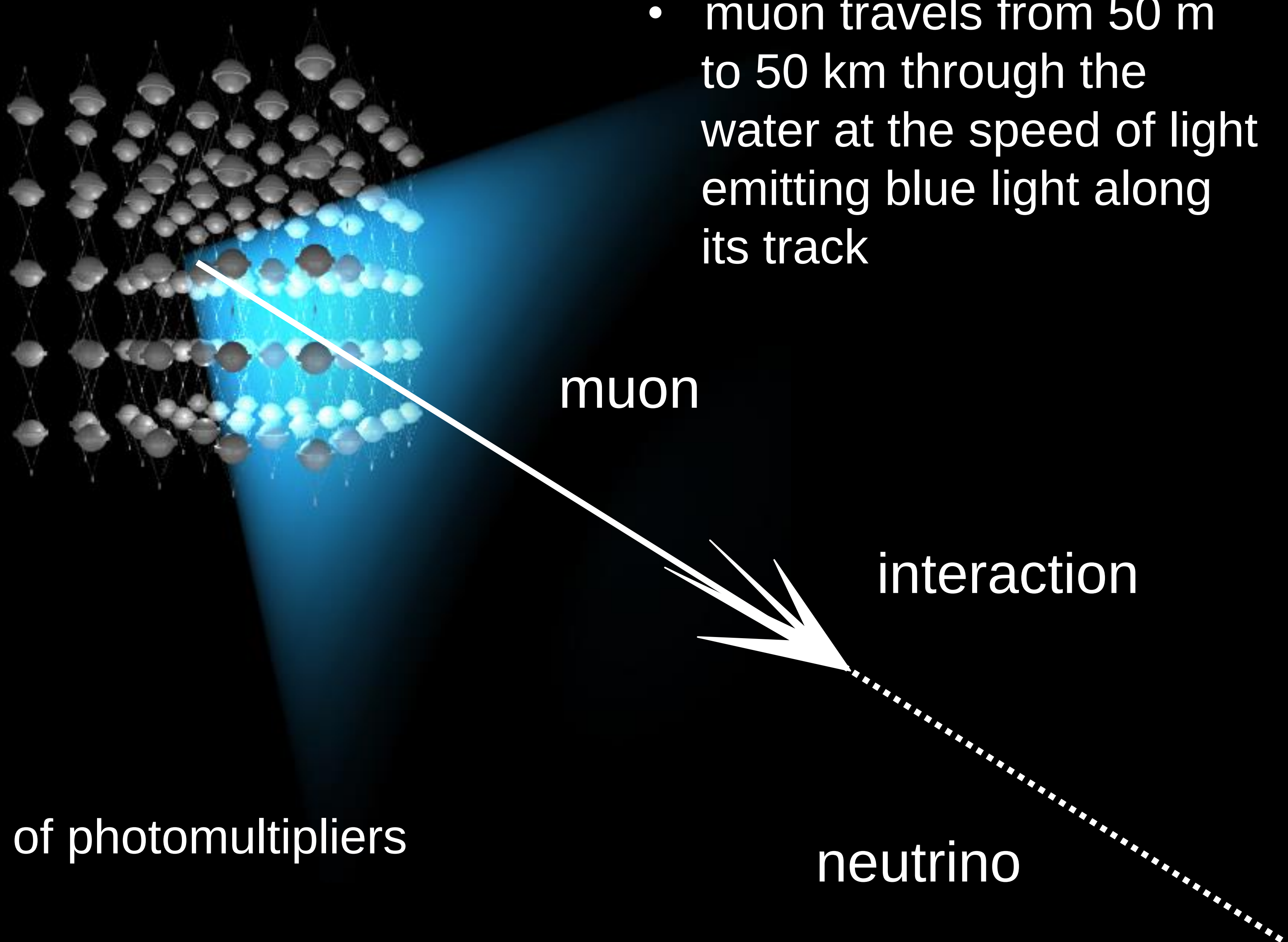
10—100 events per year for fully efficient 1 km³ detector

atmospheric

cosmic

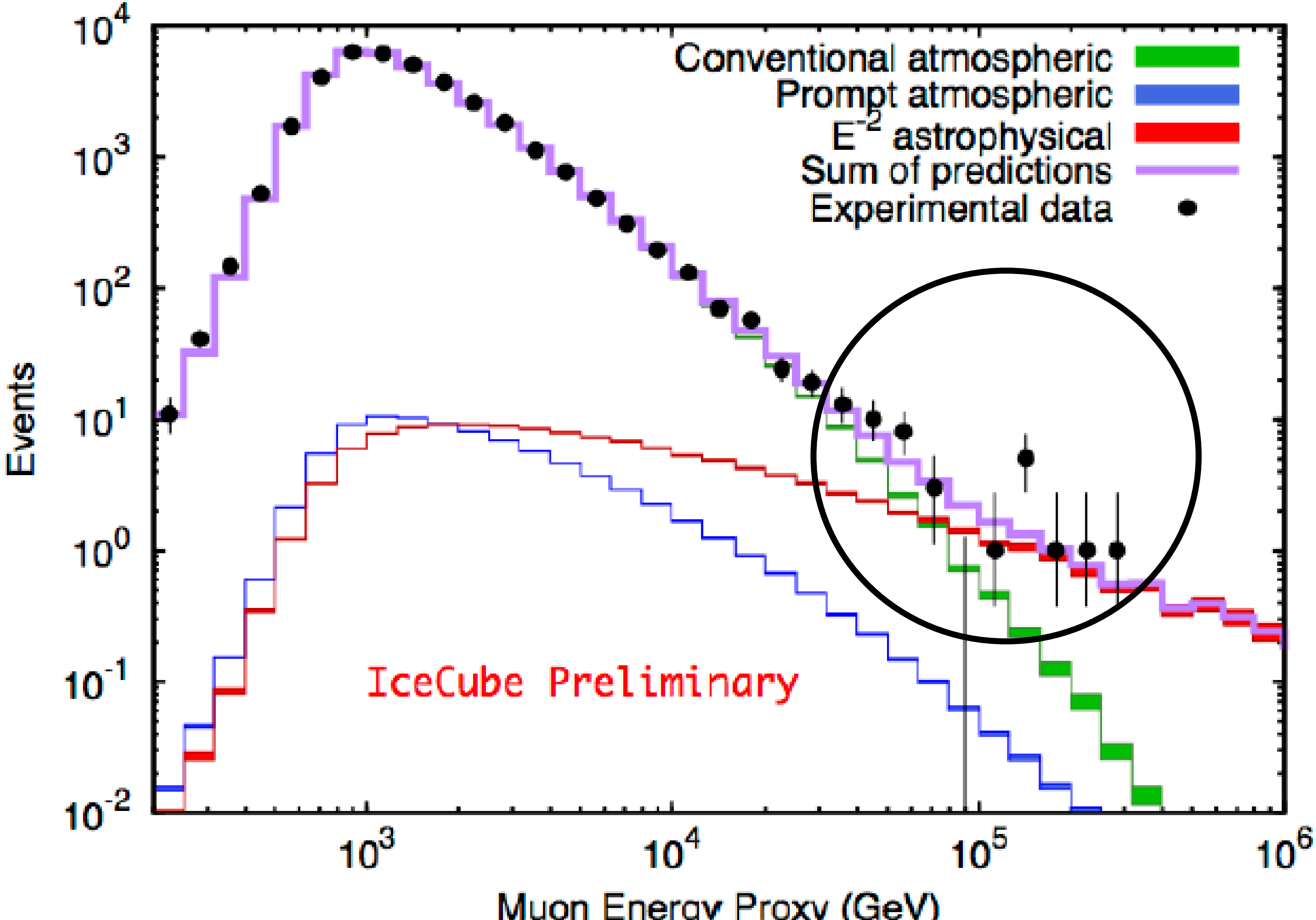
100 TeV

- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

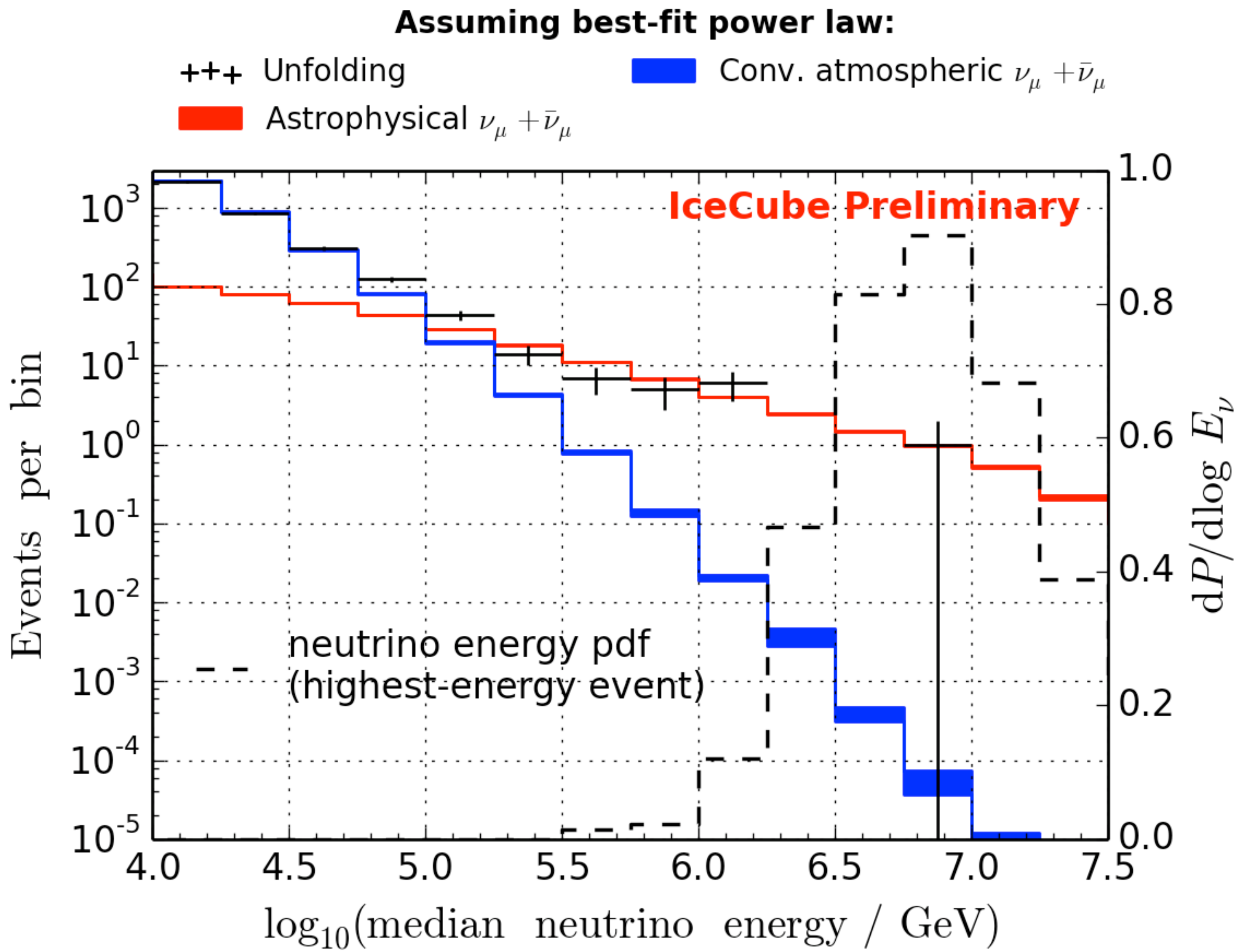


- lattice of photomultipliers

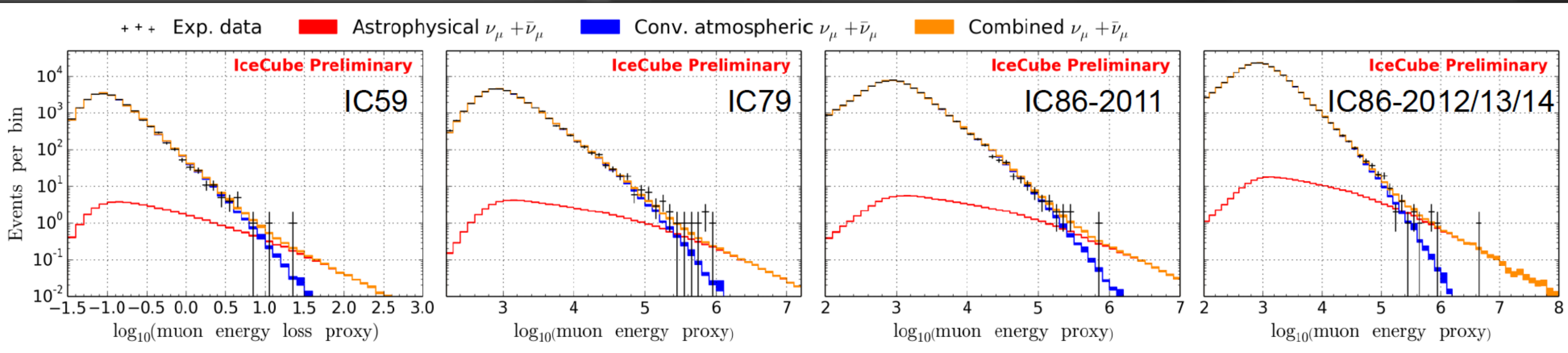
cosmic neutrinos in 2 years of data at 3.7 sigma

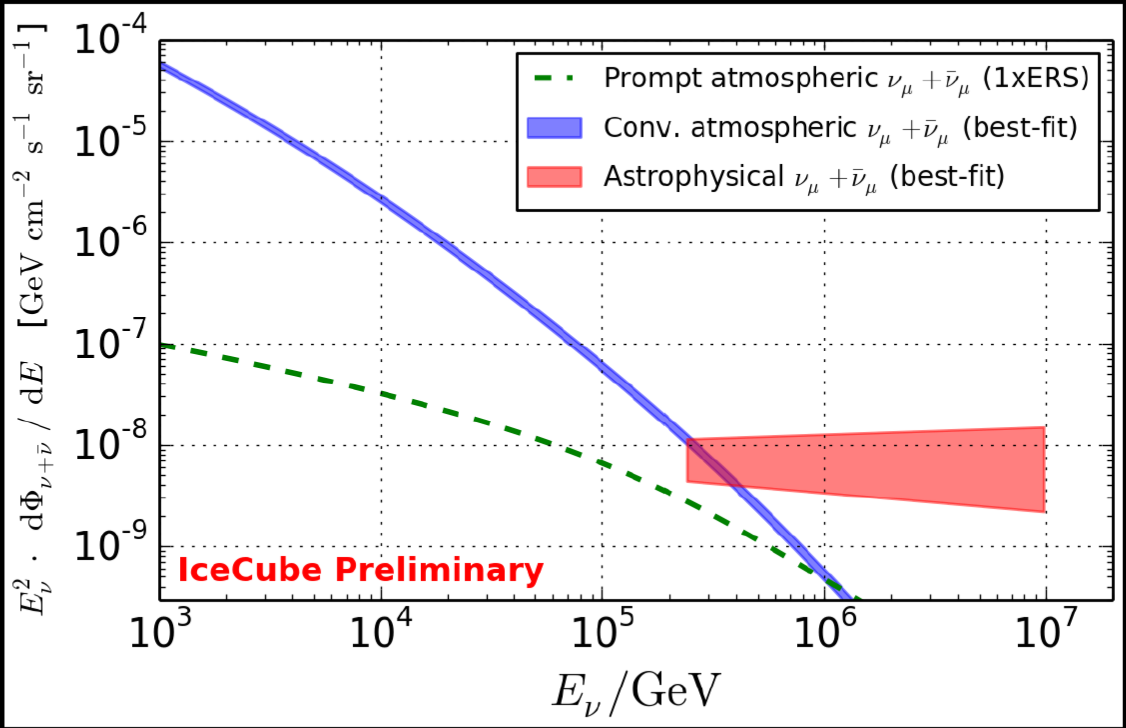


muon neutrinos through the Earth → 6 sigma



for 5.5 years of data: 3.7→ 6.0 sigma and E^{-2} above 200 TeV !





- Best-fit astrophysical normalization:

$$(0.78^{+0.29}_{-0.25}) \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- Best-fit spectral index:

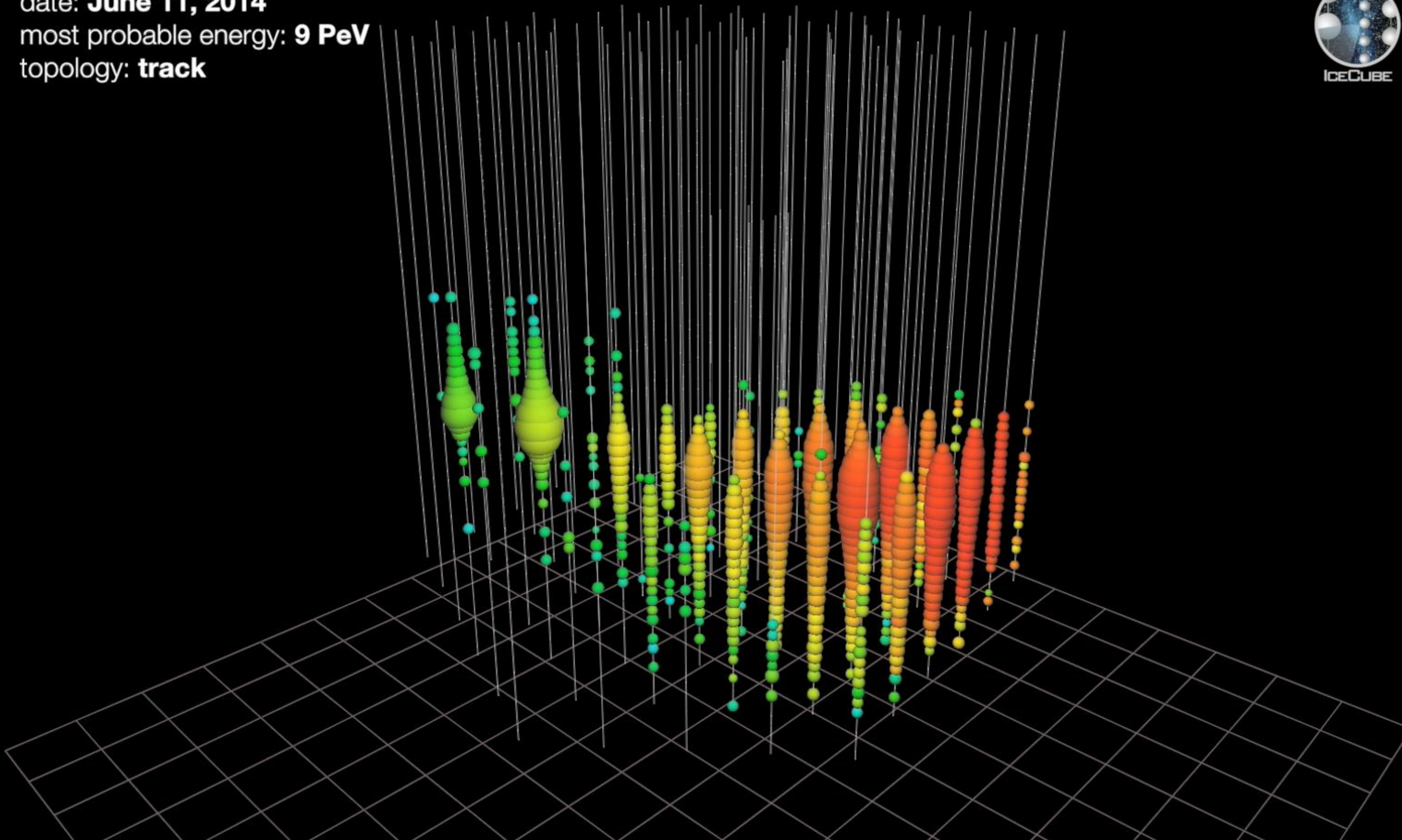
$$\gamma_{astro} = 2.06 \pm 0.13$$

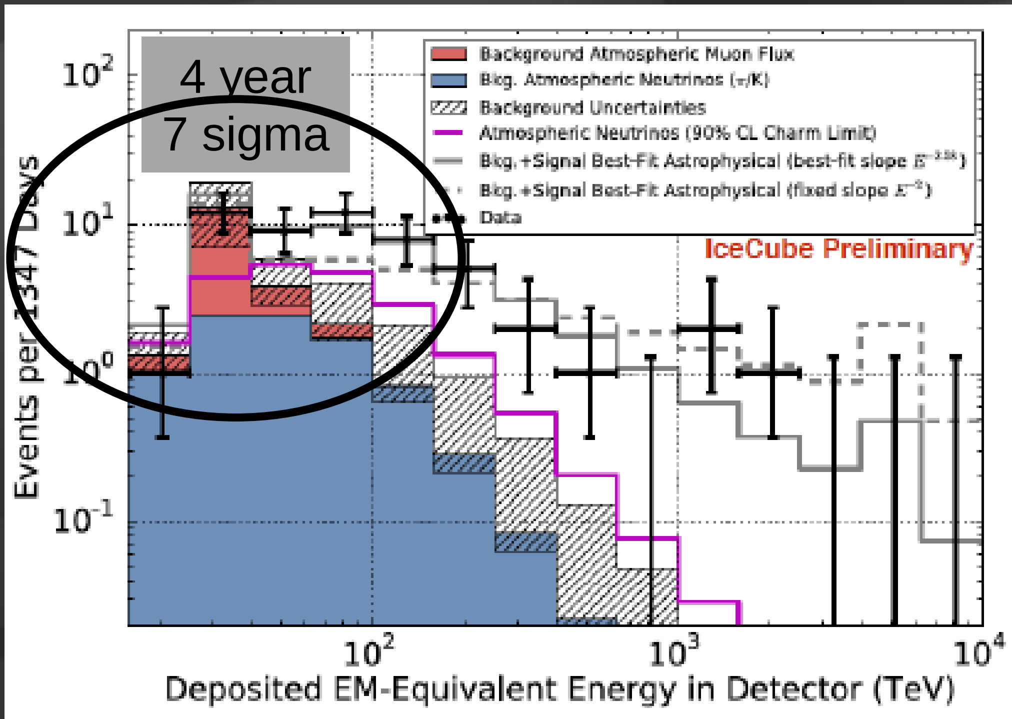
- Energy ranges:

240 TeV – 10 PeV

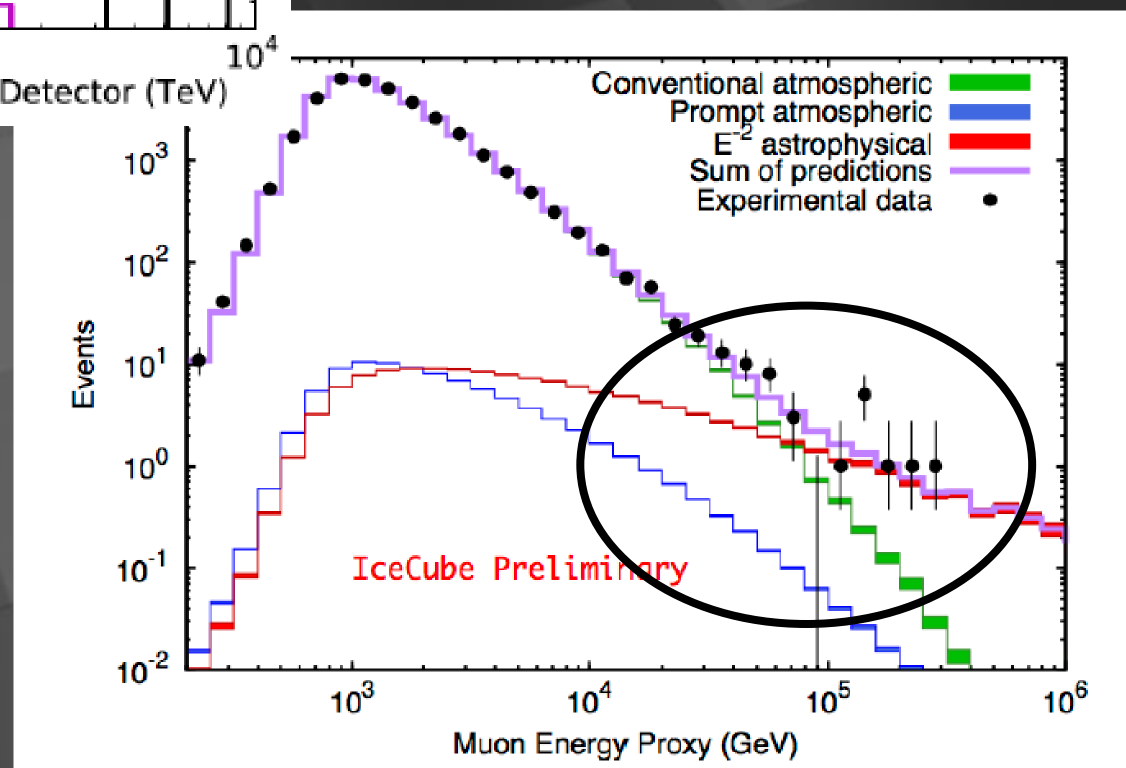
- Atmospheric-only hypothesis excluded by 6.0σ

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



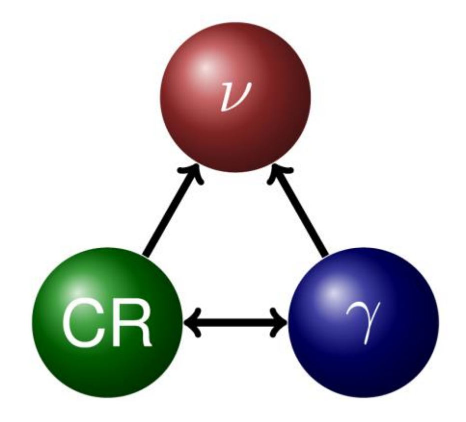


confirmation!
flux of muon neutrinos
through the Earth



neutrinos of all flavors
interacting inside
IceCube

Particle Physics Beyond Laboratory Energies



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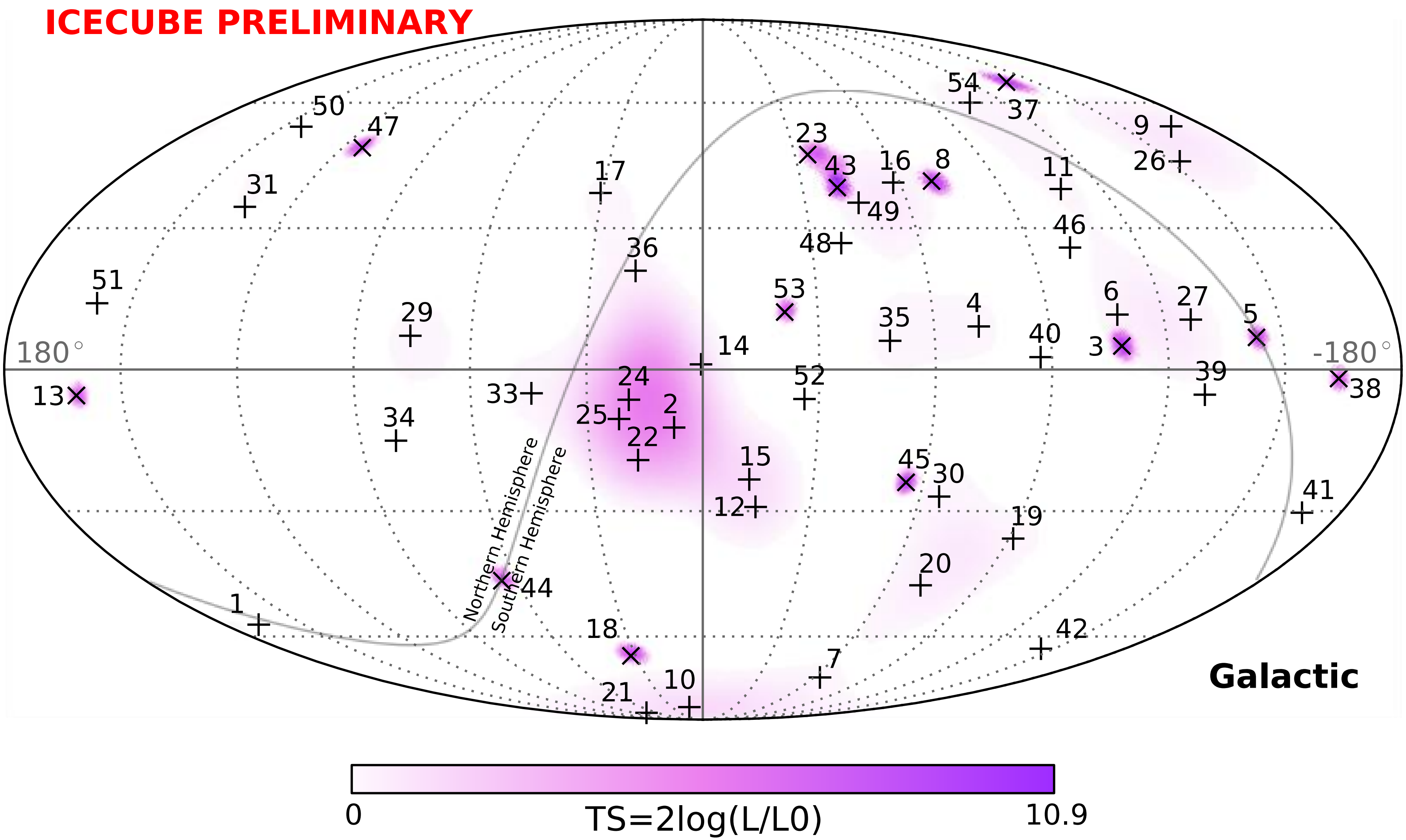
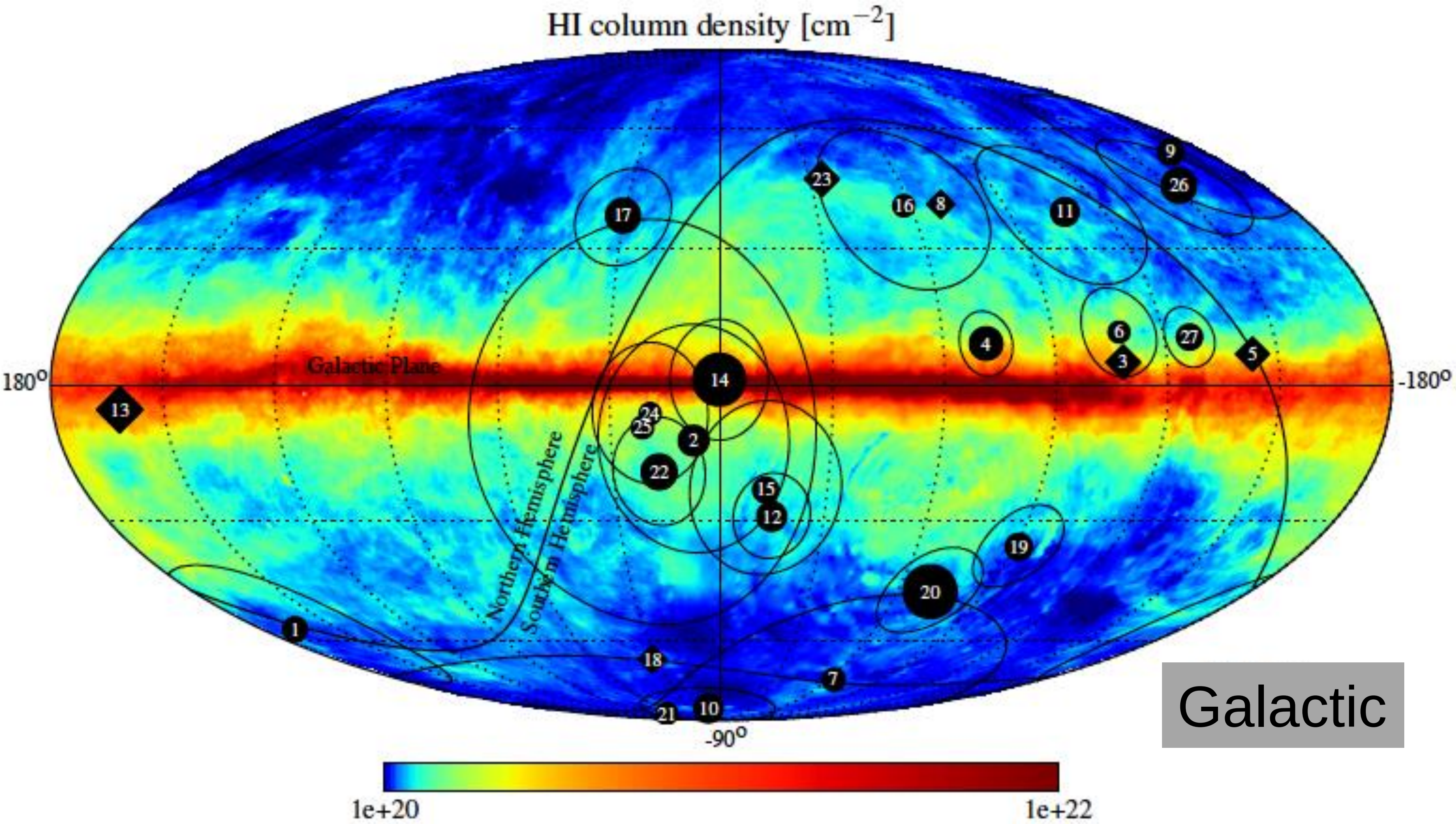
4 year HESE



where do they come from?

correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg

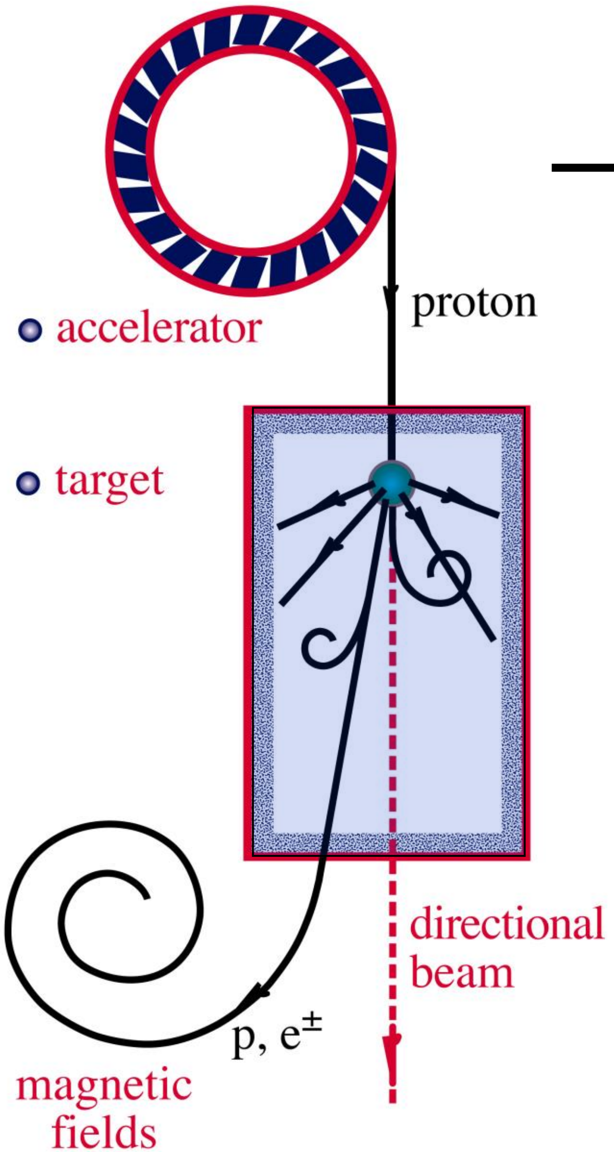


- we observe a diffuse flux of neutrinos from extragalactic sources

- a subdominant Galactic component cannot be excluded

- where are the PeV gamma rays that accompany PeV neutrinos?

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

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

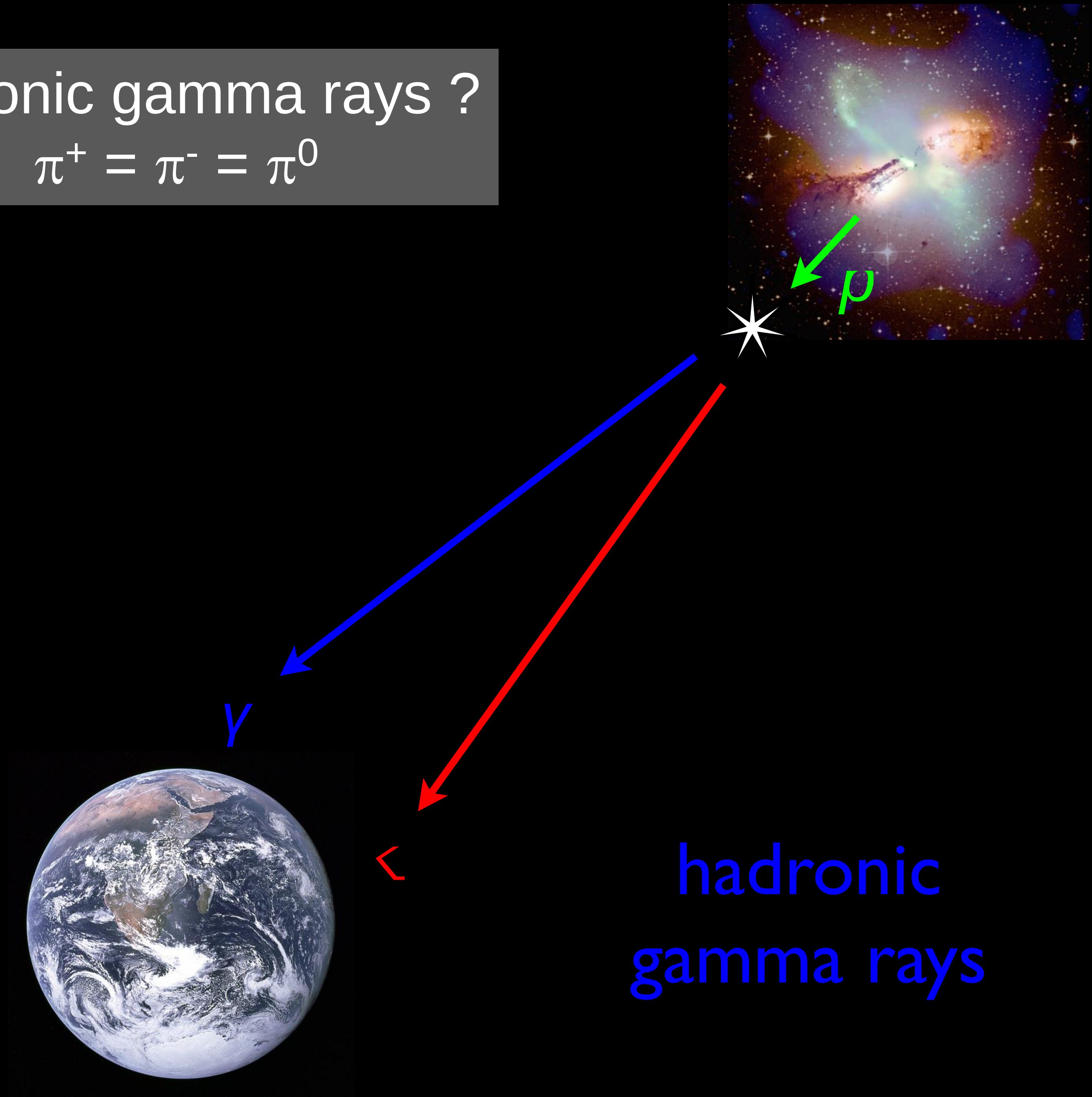
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

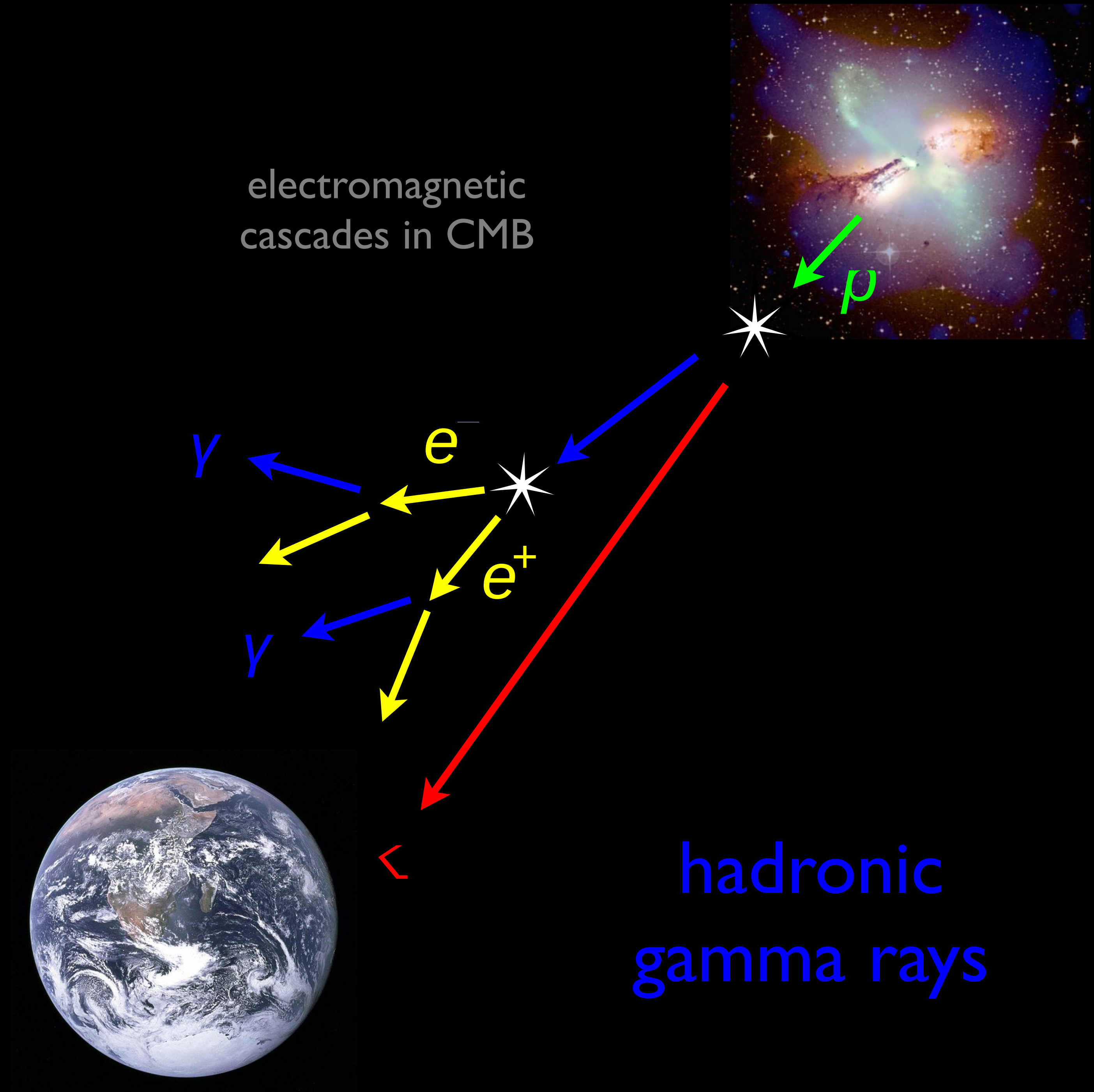
~ cosmic ray + gamma

hadronic gamma rays ?

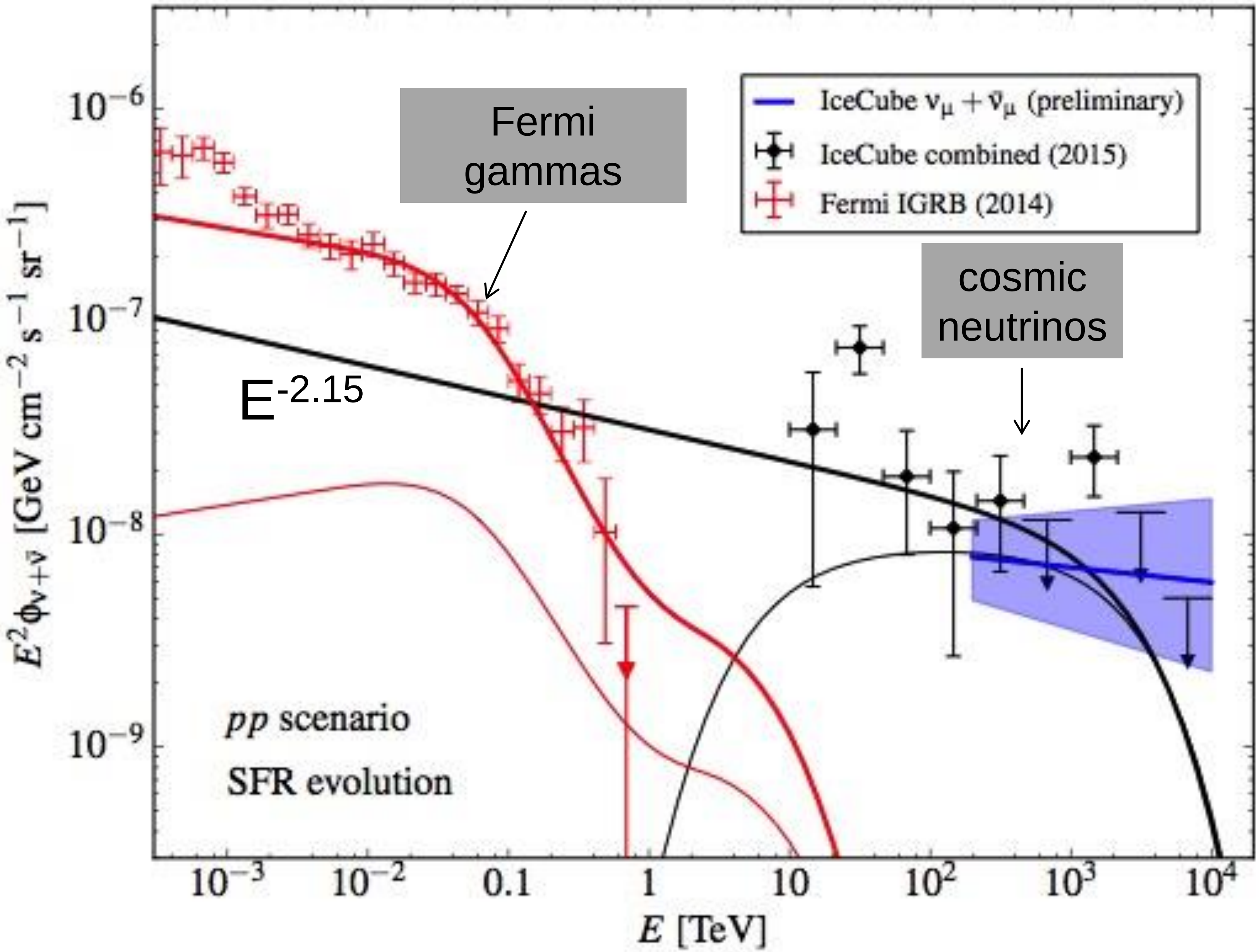
$\pi^+ = \pi^- = \pi^0$



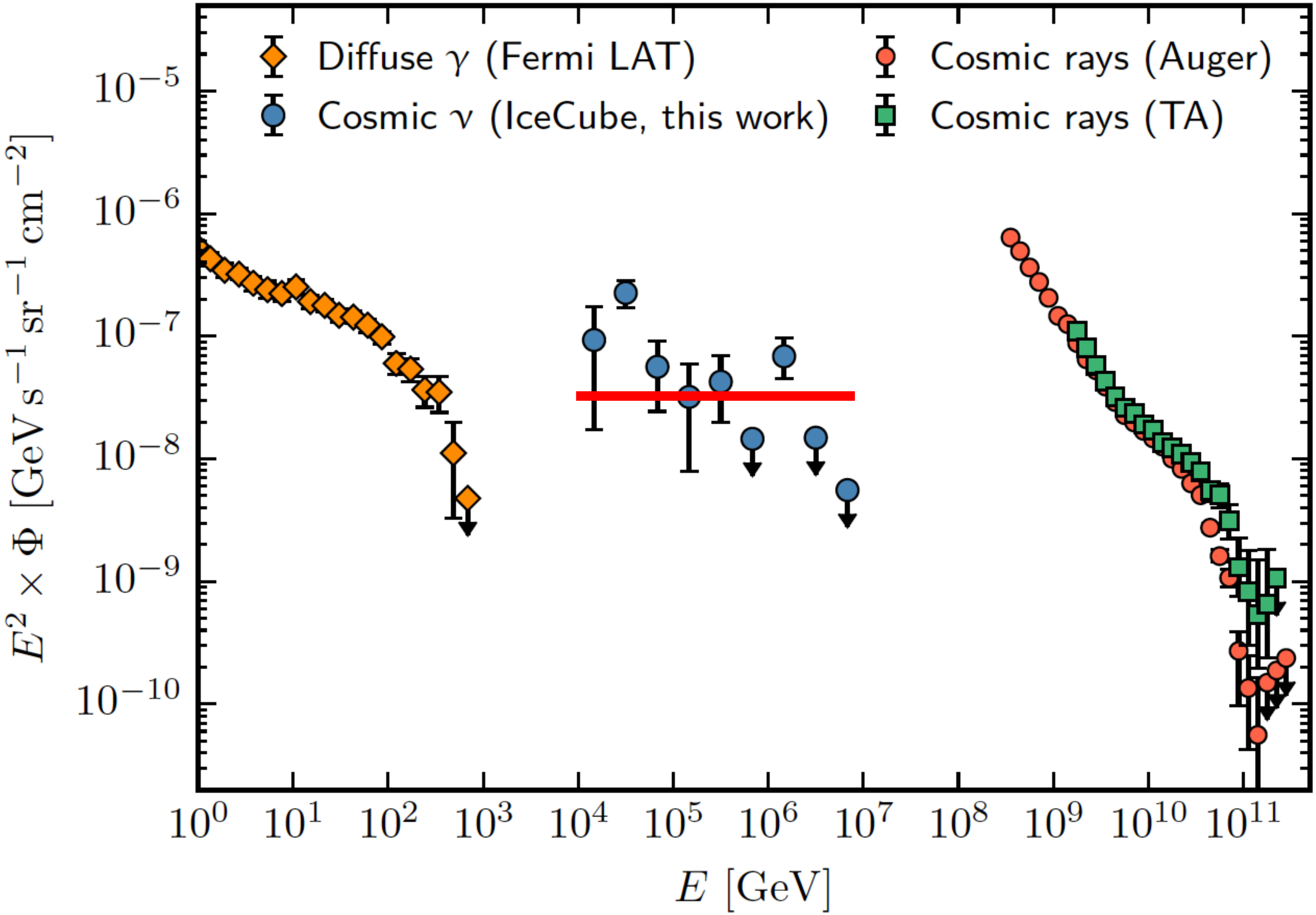
hadronic
gamma rays


electromagnetic
cascades in CMB
p
e⁻
γ
e⁺
γ
ν
hadronic
gamma rays

$p^+ = p^- = p^0$



Fermi gammas
cosmic neutrinos
E-2.15
IceCube ν_μ + ν̄_μ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
pp scenario
SFR evolution
E [TeV]
10−6
10−7
10−8
10−9
10−3
10−2
0.1
1
10
10^2
10^3
10^4

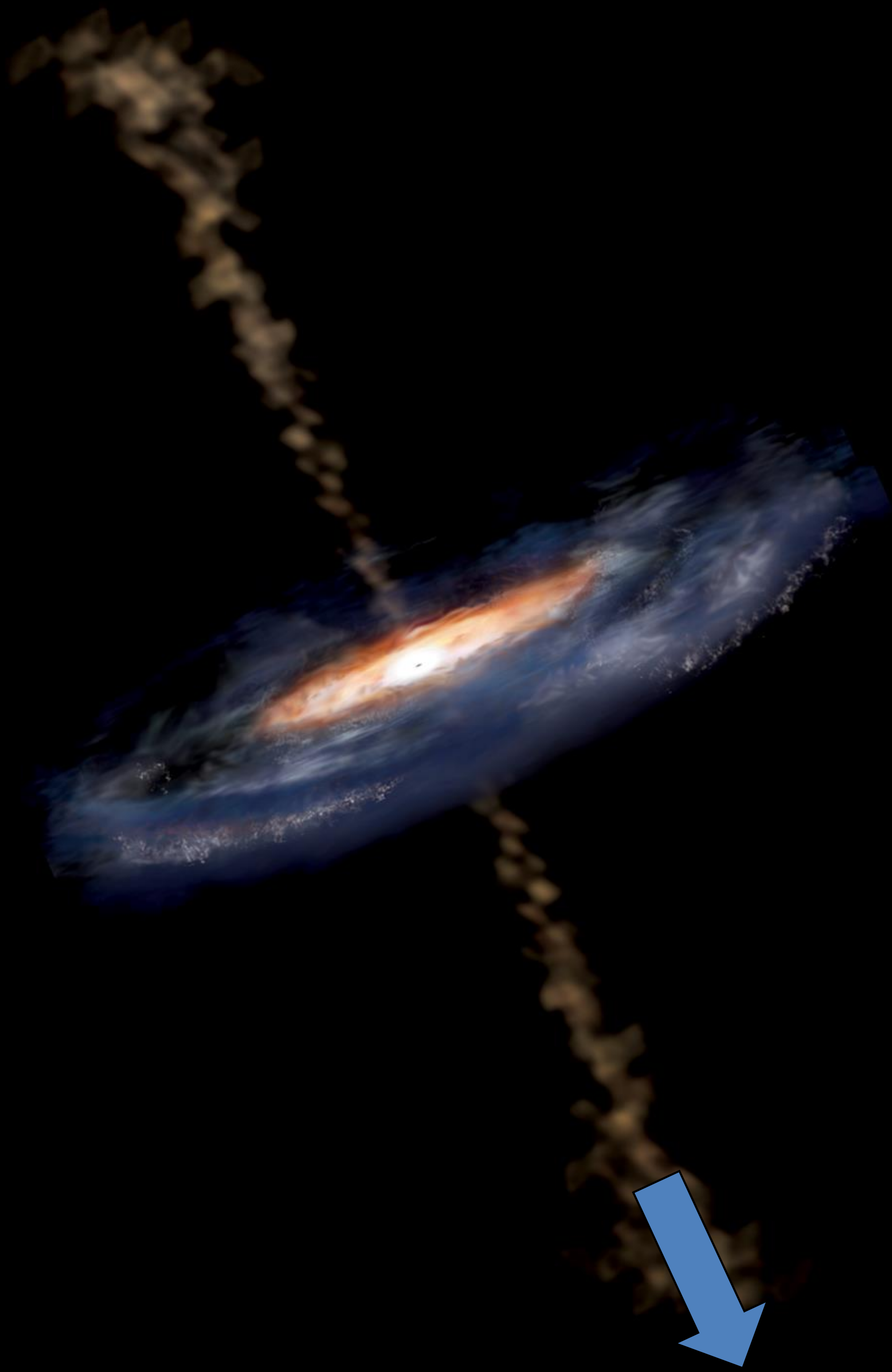


energy in the Universe in gamma rays, neutrinos and cosmic rays

- 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?

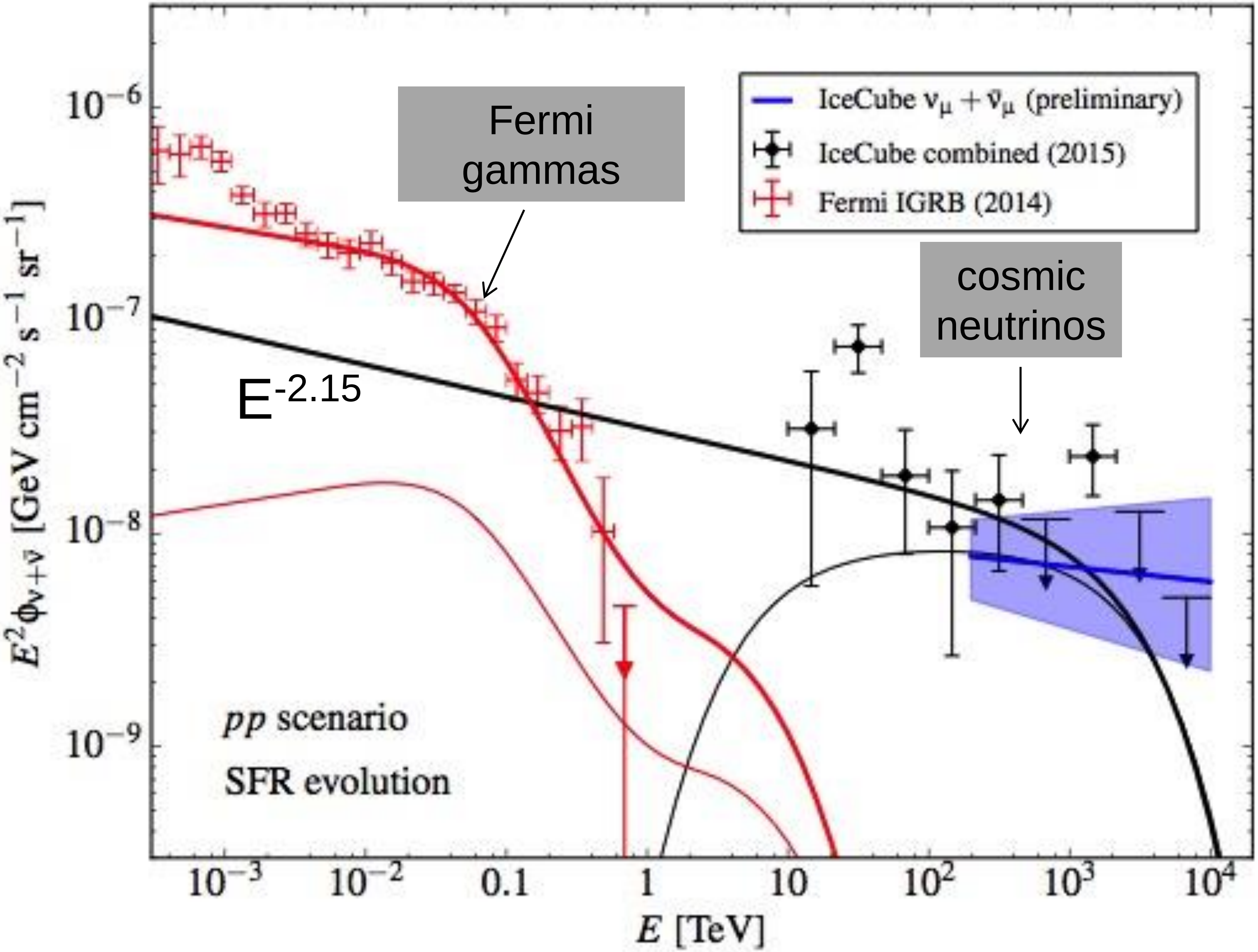


blazars

particle flows near
supermassive
black hole

- there is more

$p^+ = p^- = p^0$


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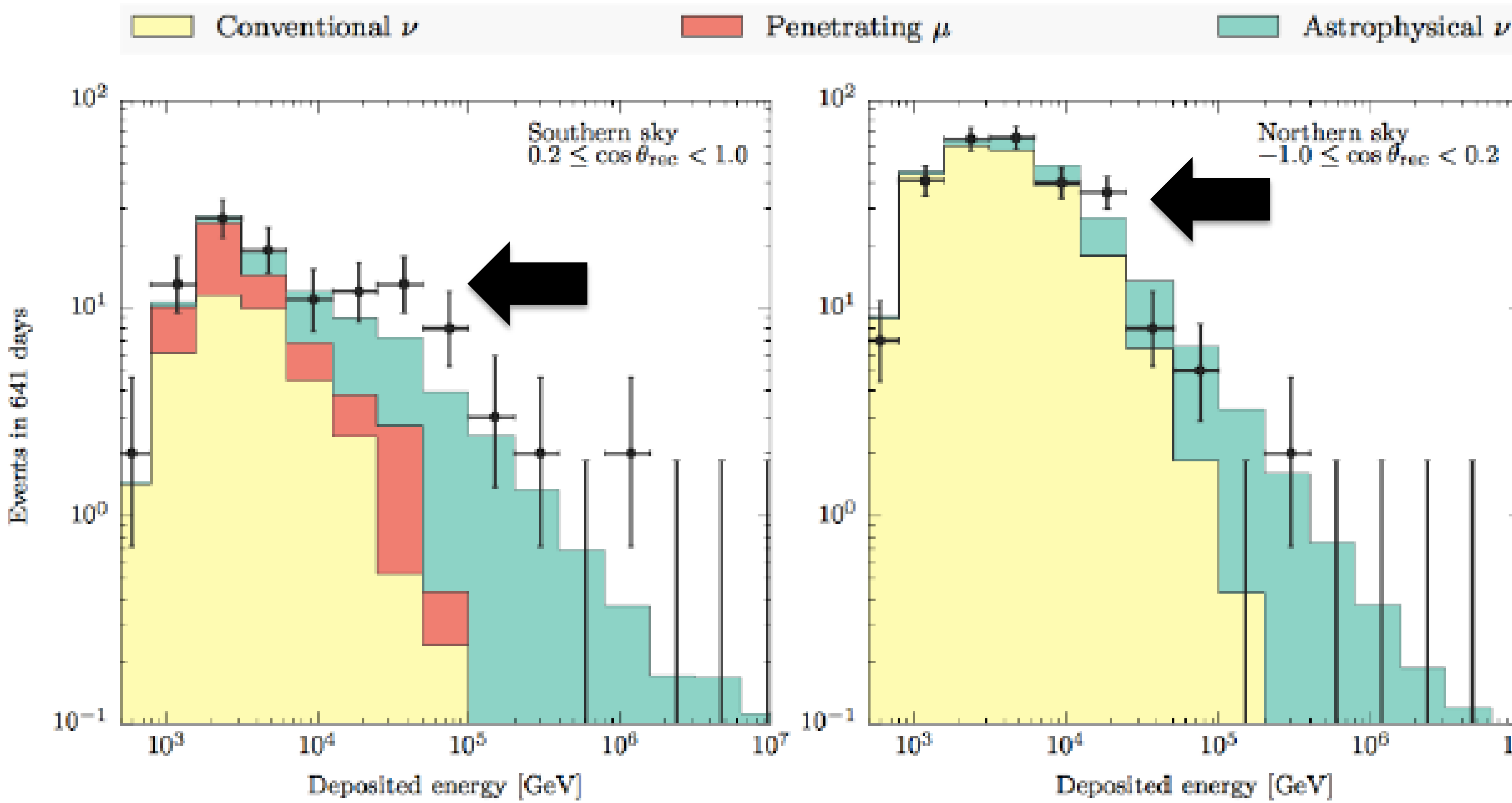
pp scenario
SFR evolution
E²Φν+ν̄ [GeV cm⁻² s⁻¹ sr⁻¹]
E [TeV]
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻³
10⁻²
0.1
1
10
10²
10³
10⁴

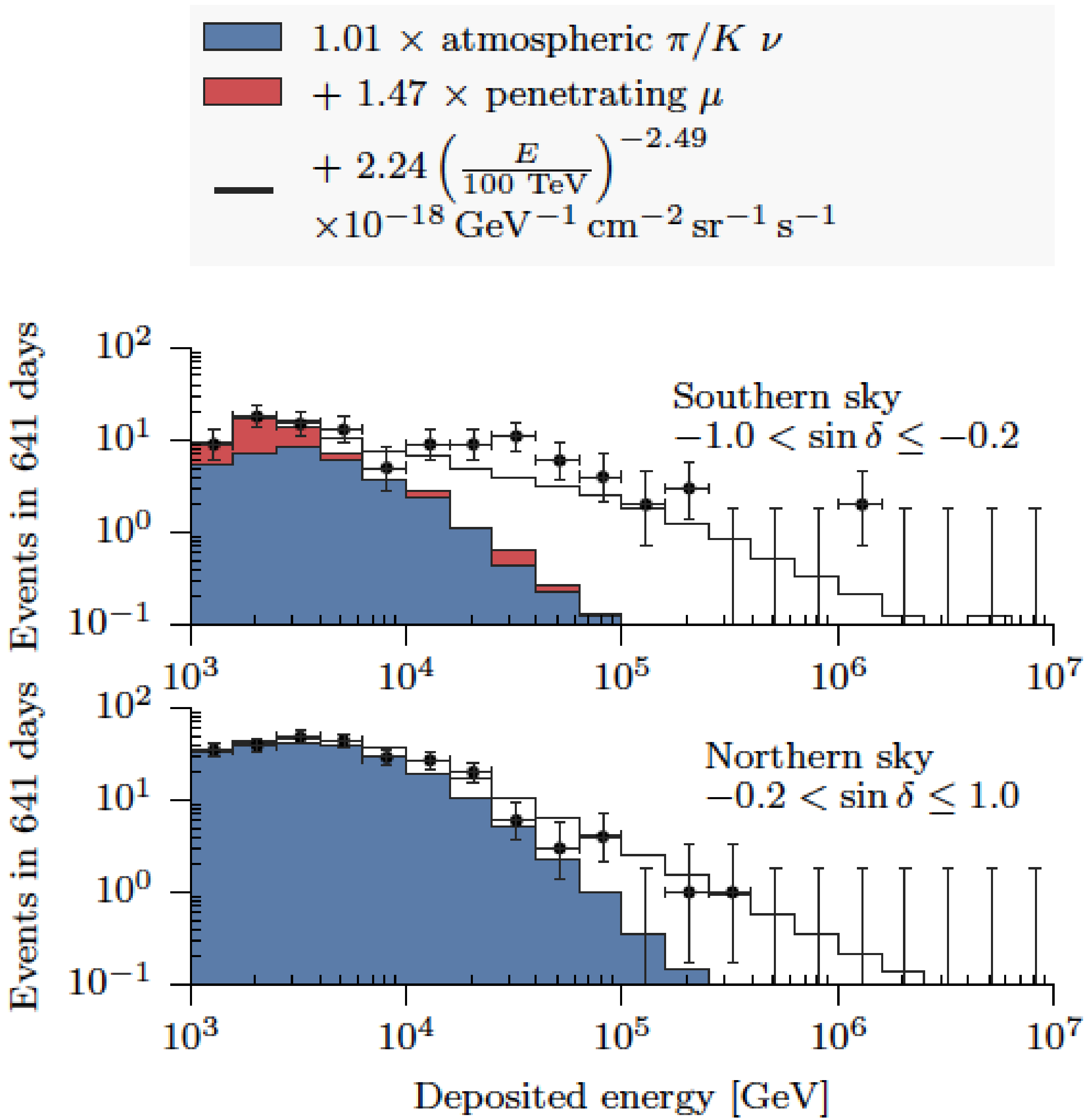
towards lower energies: a second component?



warning:

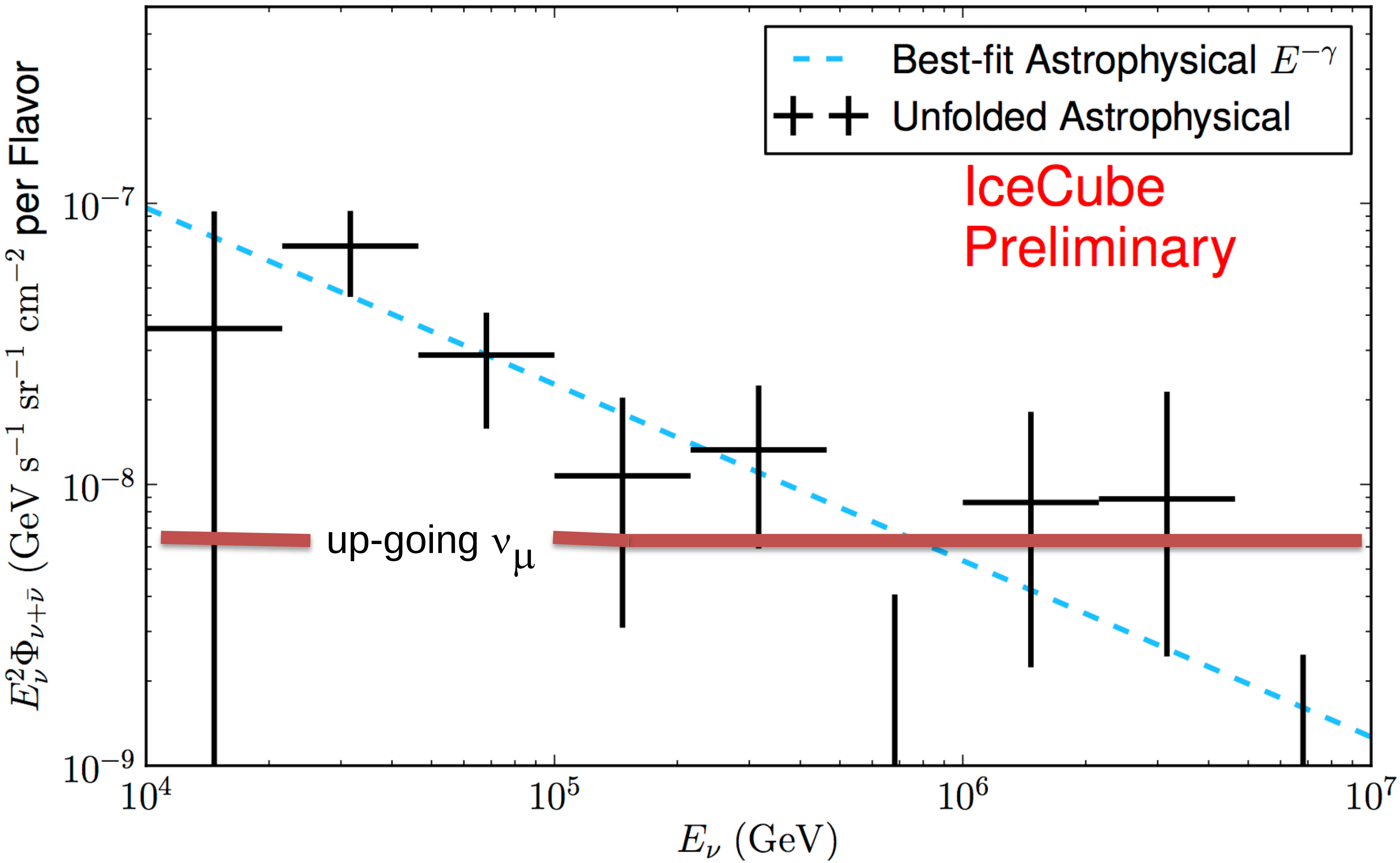
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

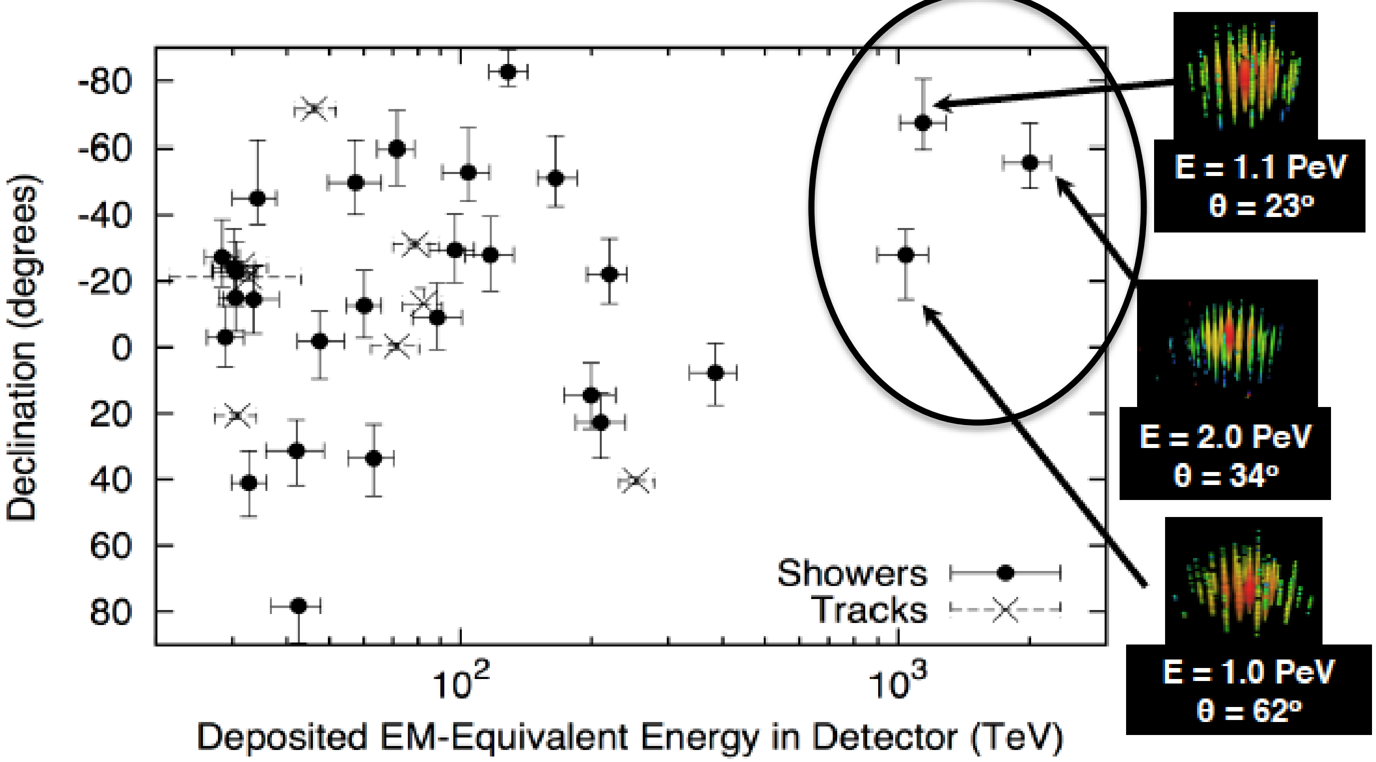


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
+ 2.24 (E / 100 TeV)^−2.49 ×10^−18 GeV^−1 cm^−2 sr^−1 s^−1
Southern sky
−1.0 < sin δ ≤ −0.2
Northern sky
−0.2 < sin δ ≤ 1.0
Events in 641 days
Deposited energy [GeV]

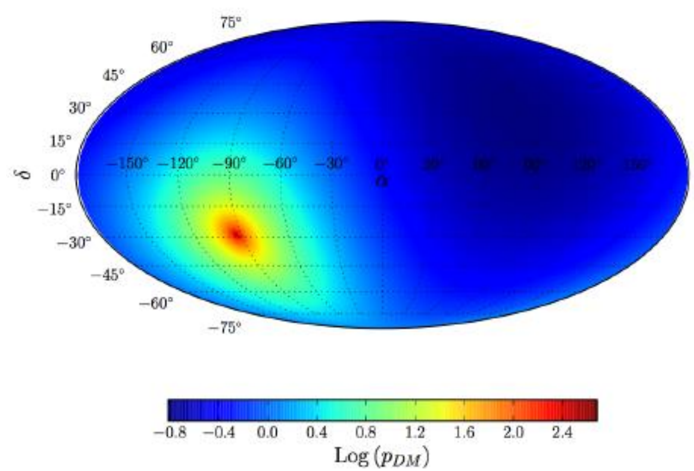
yet lower energies….

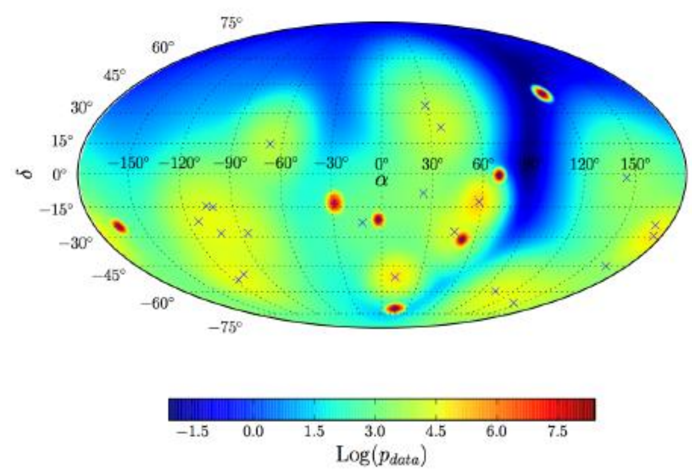


expect surprises: produced by Galactic dark matter halo?



decay of PeV-mass dark matter particle





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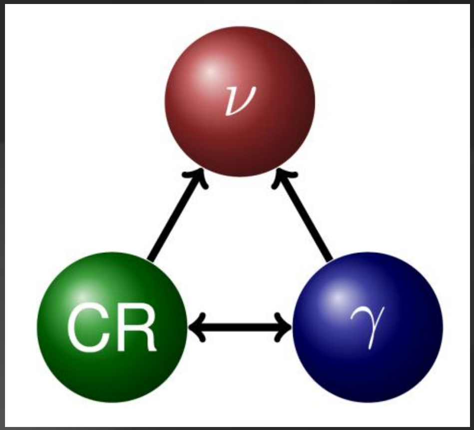

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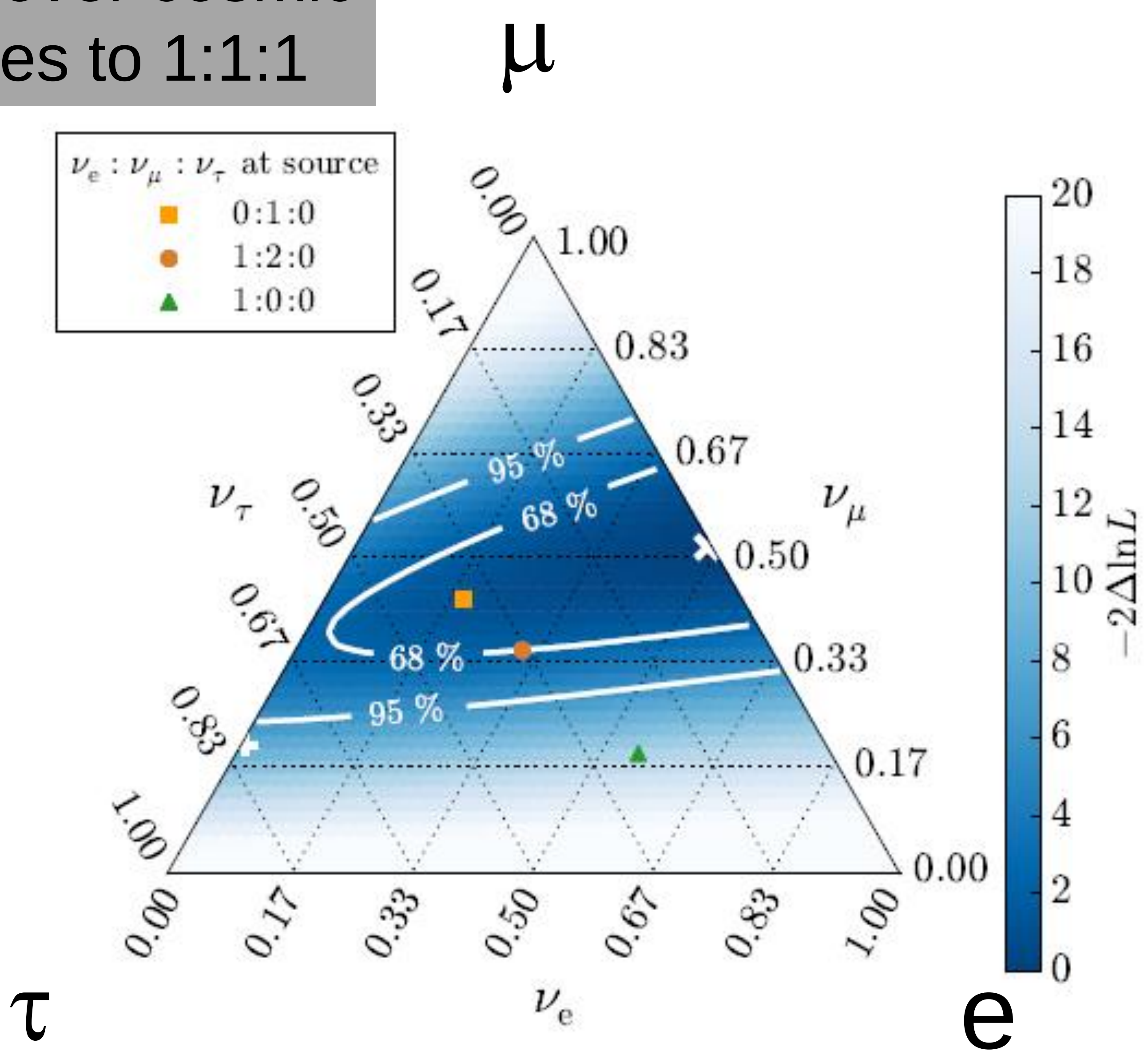
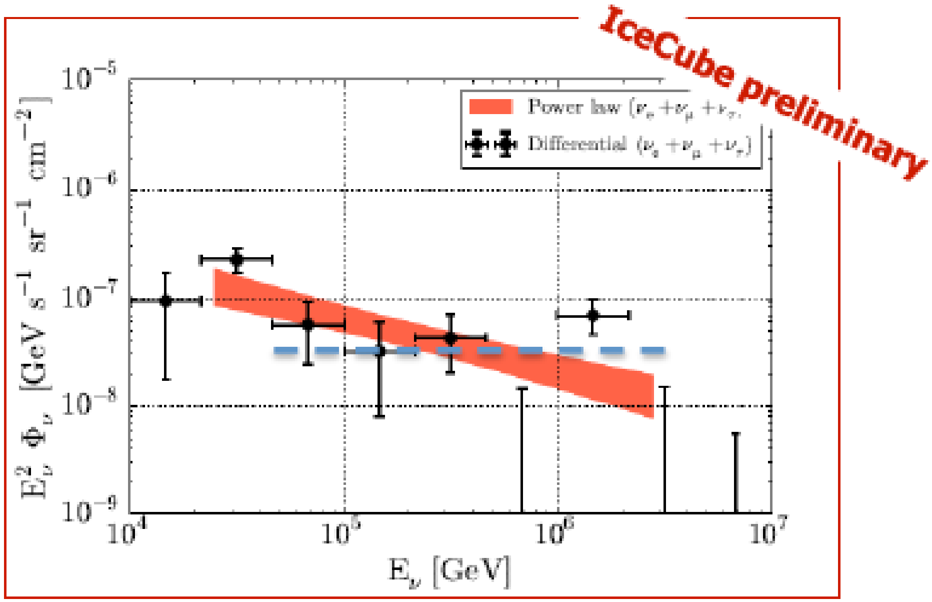
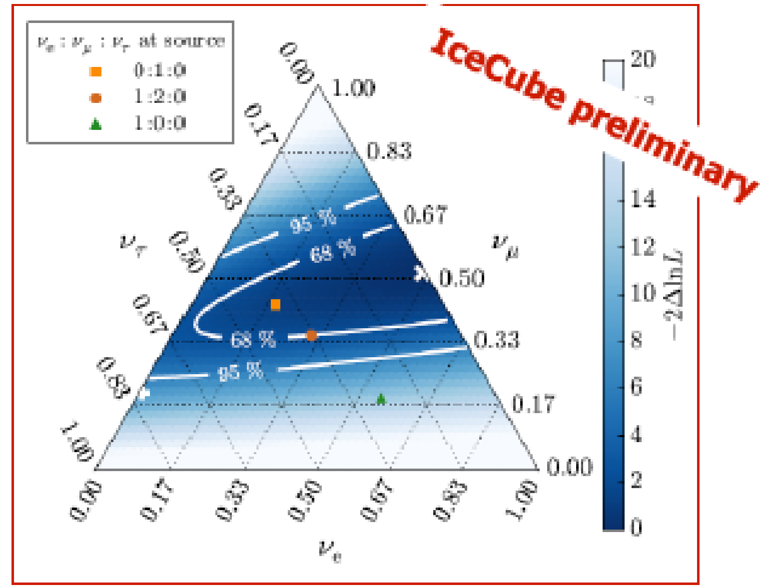
oscillate over cosmic distances to 1:1:1



- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events





assuming isotropic astrophysical flux and ν_e:ν_μ:ν_τ = 1:1:1 at Earth →

unbroken power-law between	25 TeV and 2.8 PeV
spectral index	– 2.5 ± 0.09 (-2 disfavored at 3.8 σ)
flux at 100 TeV	(6.7 ± 1.2)x10^{-18} (GeV · cm^2 · s · sr)$^{-1}$

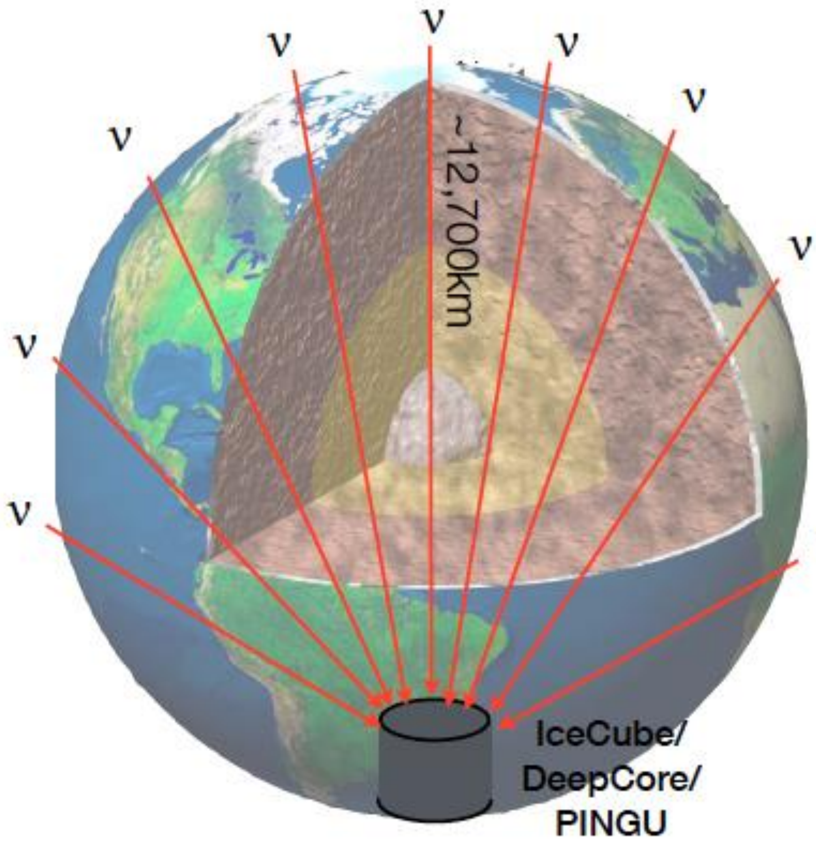
the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

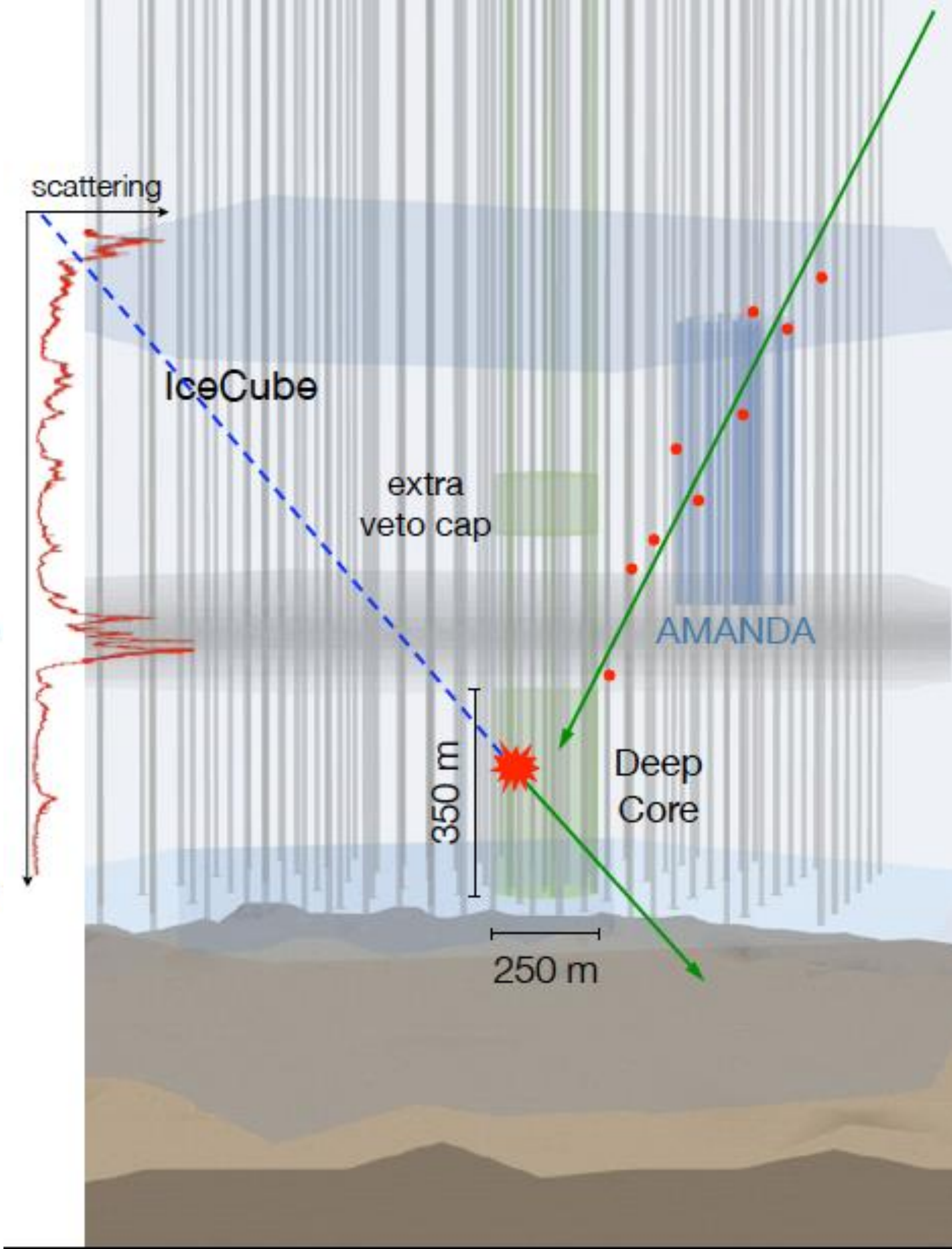
Glashow resonance dictates $\nu_e - \nu_\tau$ mixture events per year:

Φ_{ν_e}	interaction	pp source		
$[\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}]$	type	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

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

one half million atmospheric neutrinos…

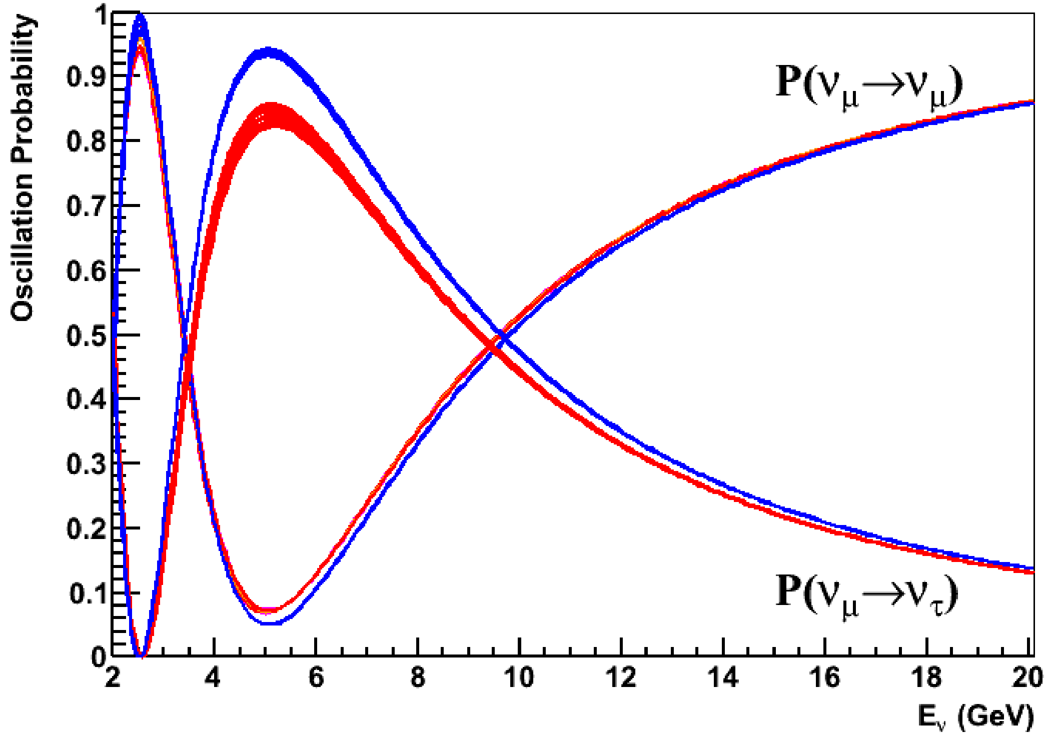


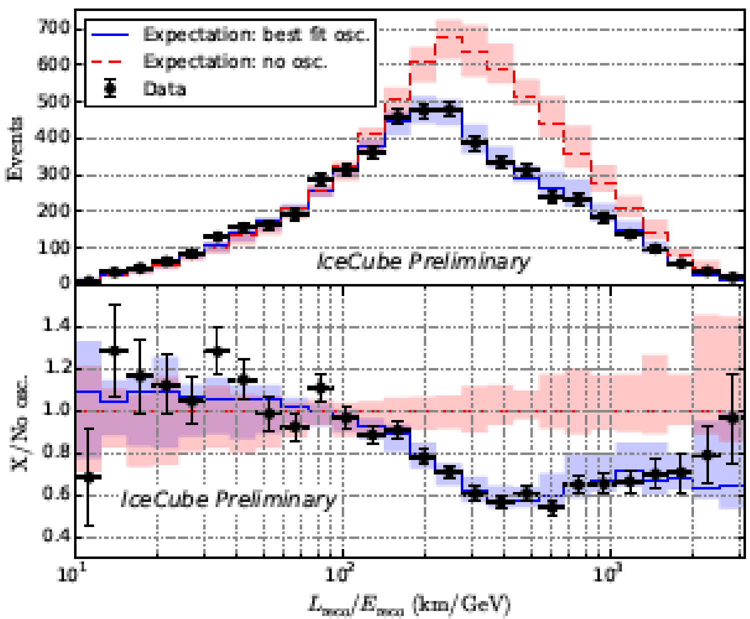


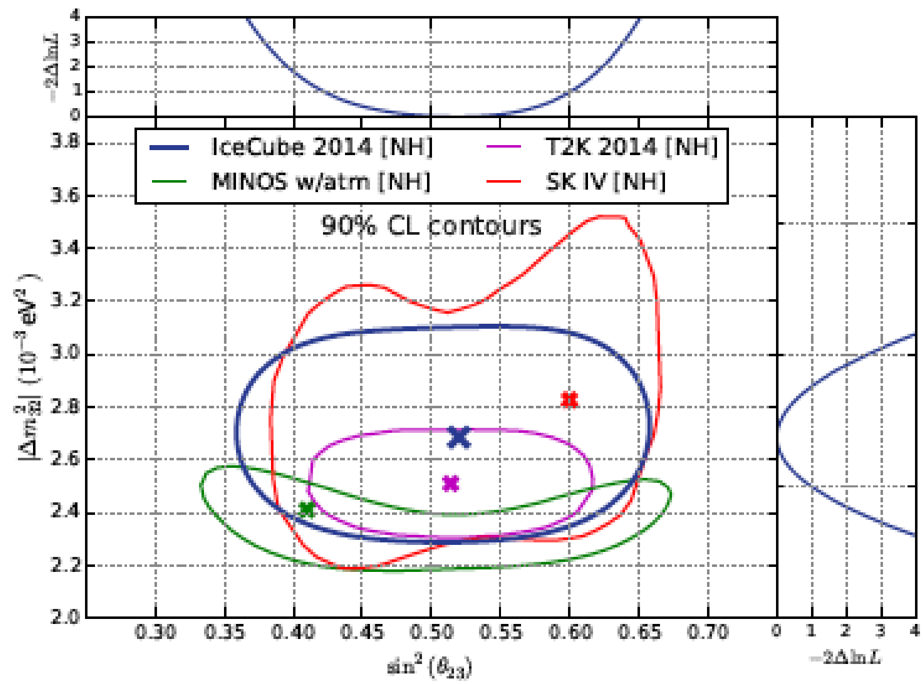
IceCube

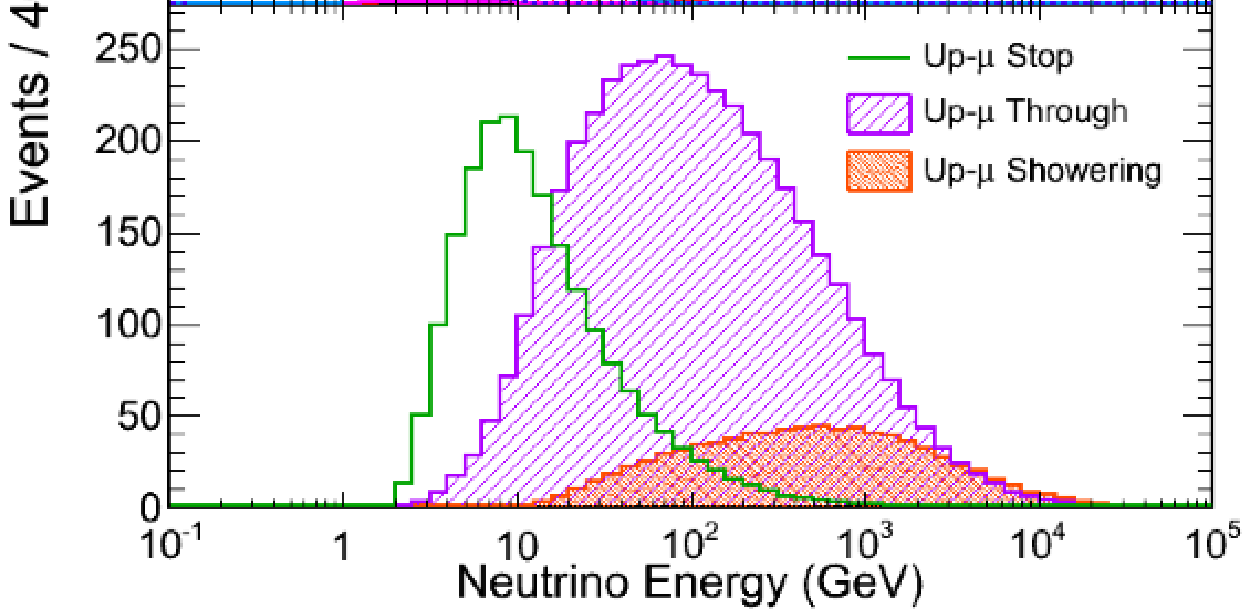
DeepCore

PINGU









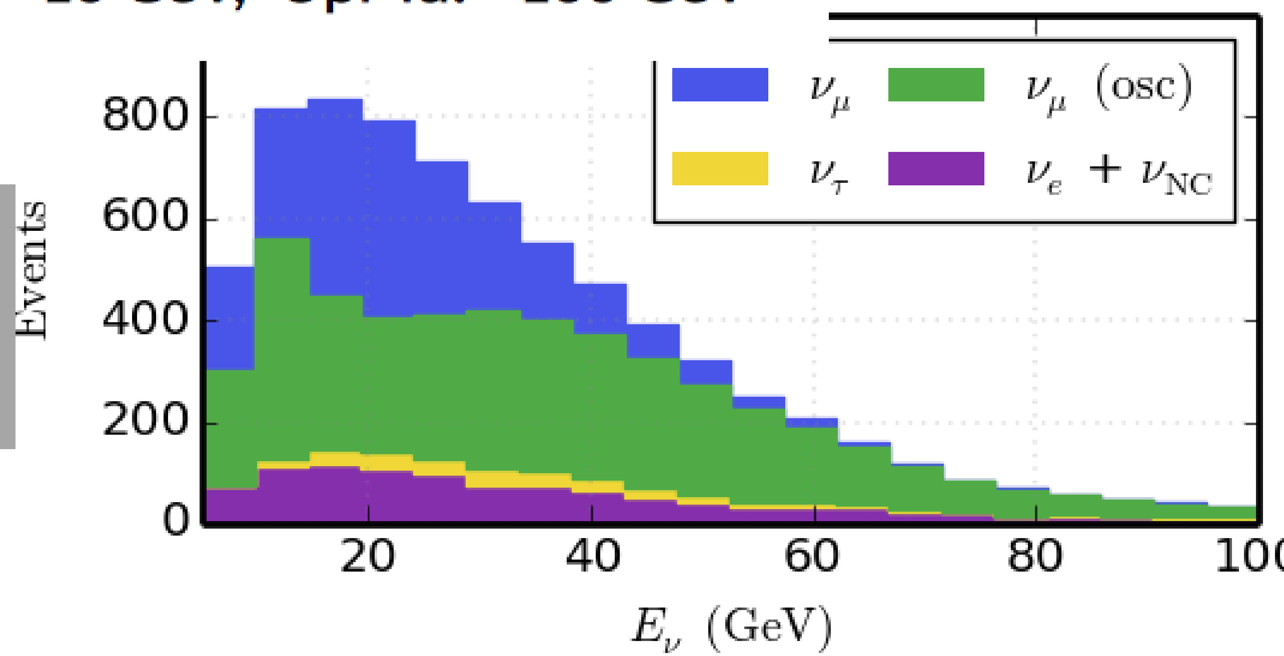
SuperK

~ 1 GeV

- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

IceCube

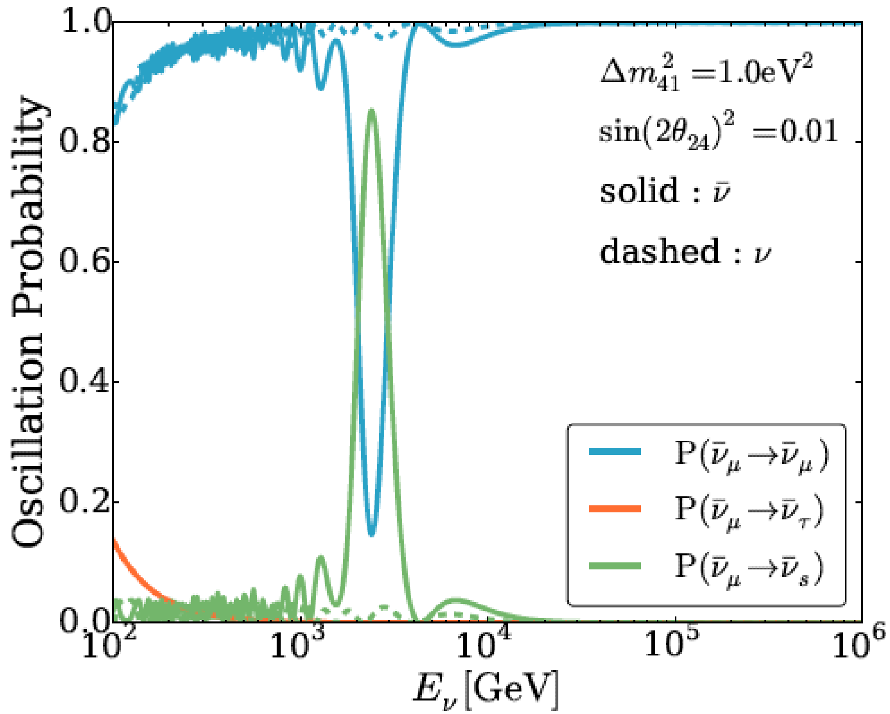
6 GeV < E_{reco} < 56 GeV



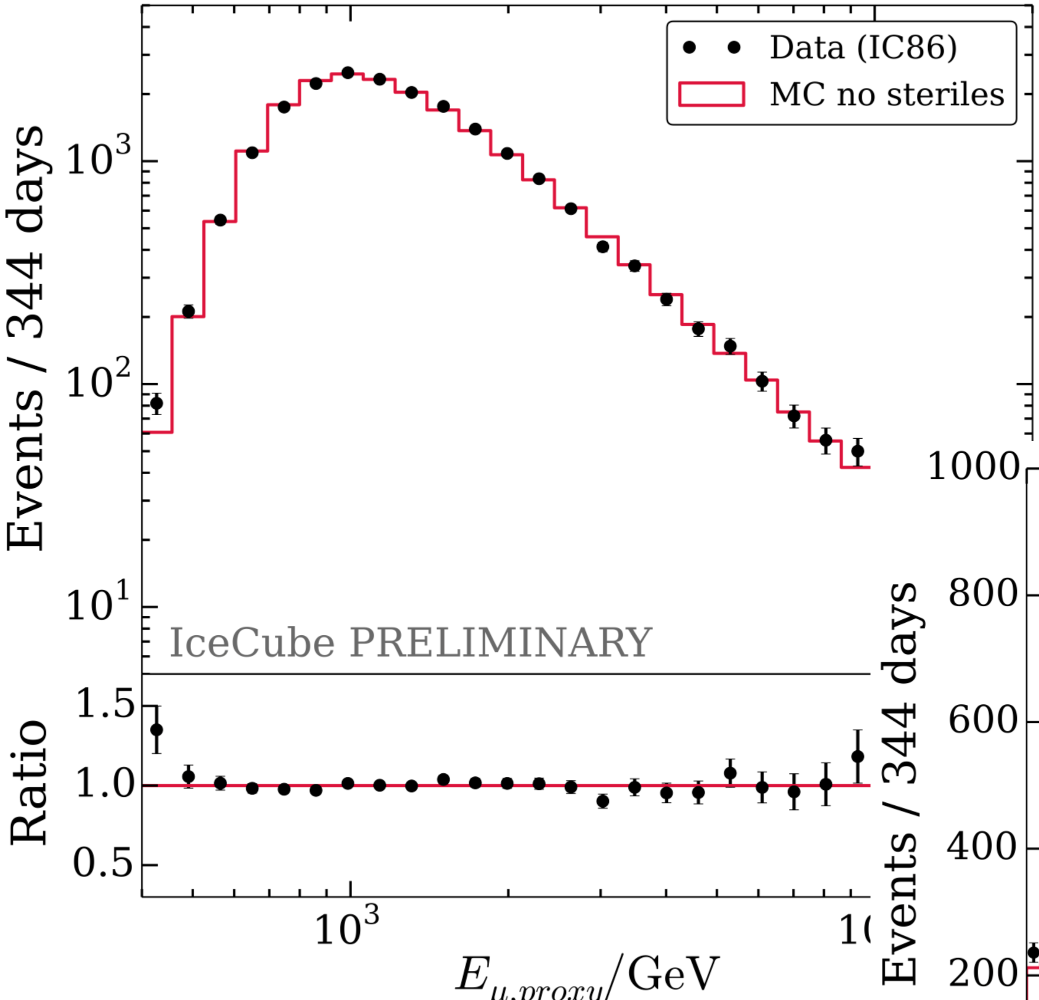
electron neutrino oscillates into sterile → modifies matter effect of the atmospheric neutrino beam observed through the Earth

happens when

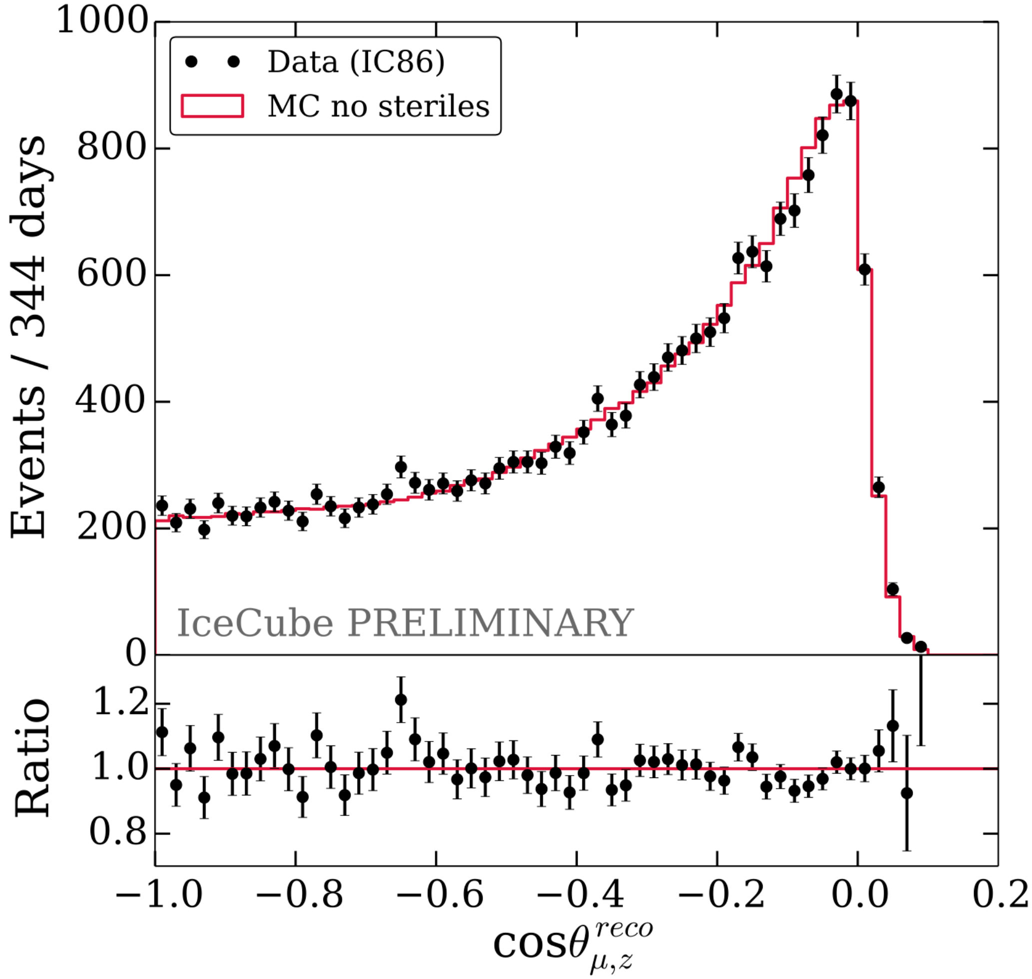
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$

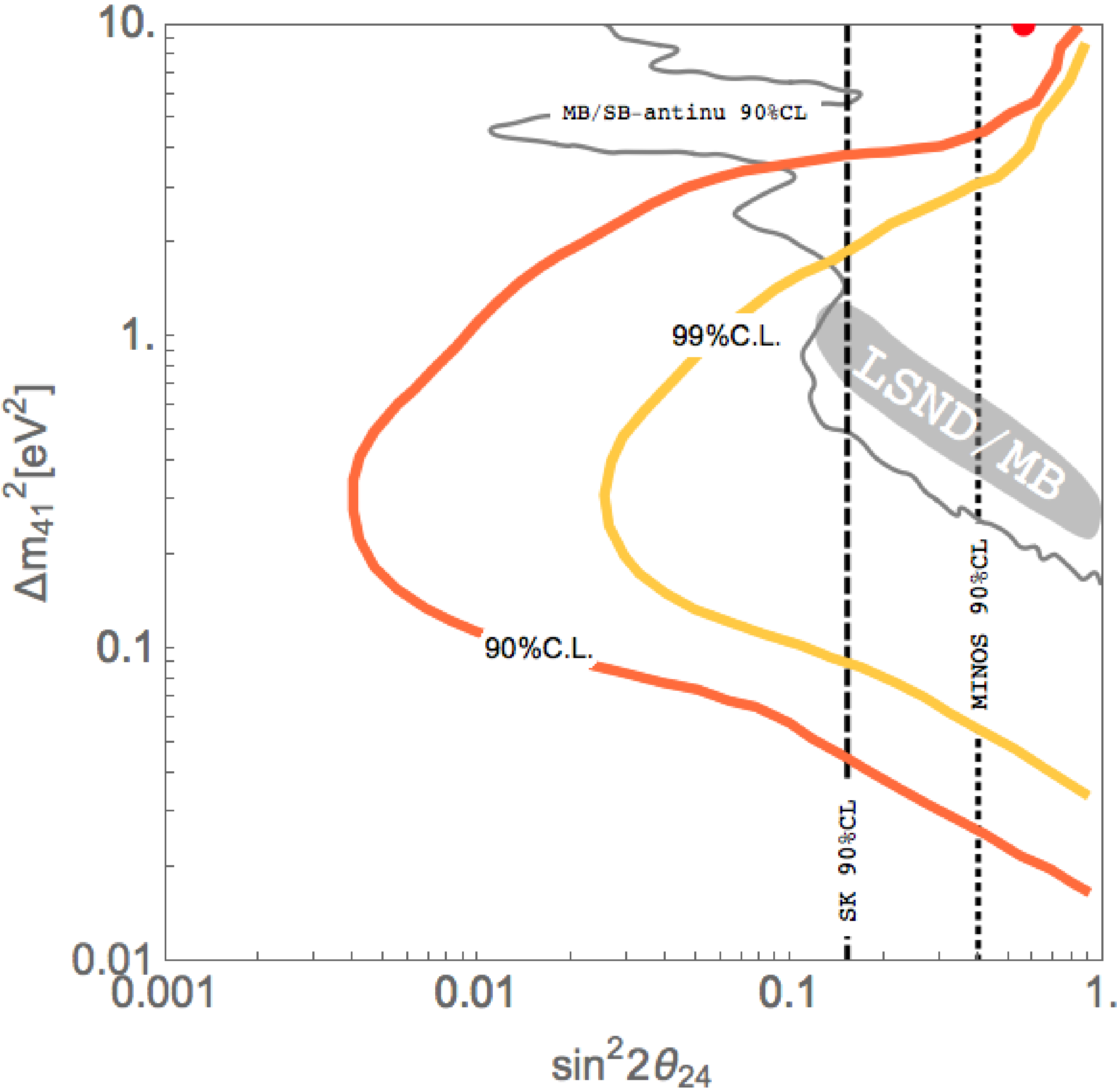


eV sterile neutrino → Earth MSW resonance for 3 TeV neutrino



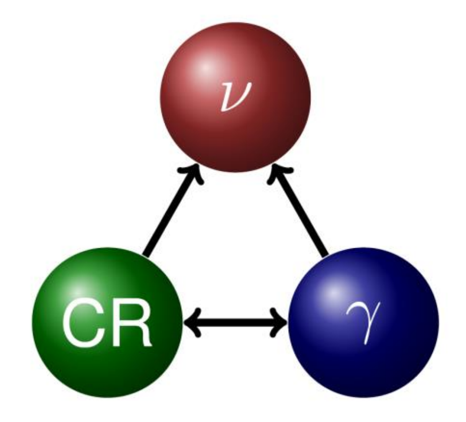
no telltale structure in the zenith angle distribution





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

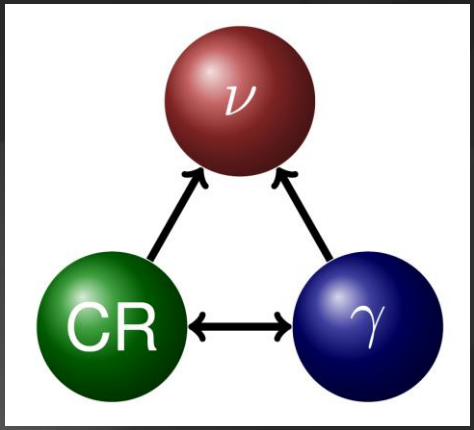
Particle Physics
Beyond Laboratory Energies



Francis Halzen
Wisconsin IceCube Particle Astrophysics Center

- Nature's accelerators have delivered the highest energy protons, photons and neutrinos
- closing in on the cosmic ray accelerators?
- New tests of three-flavor neutrino framework
- Probing new physics: sterile neutrinos, Lorentz invariance, quantum structure of space-time…

conclusions
progress through instrumentation



- larger (TA) and improved (Auger) air shower arrays
- CTA giant ground based photon array
- more (KM3NeT, GVD, ORCA) and next generation (IceCube-Gen2, PINGU) neutrino detectors
- gravitational waves!

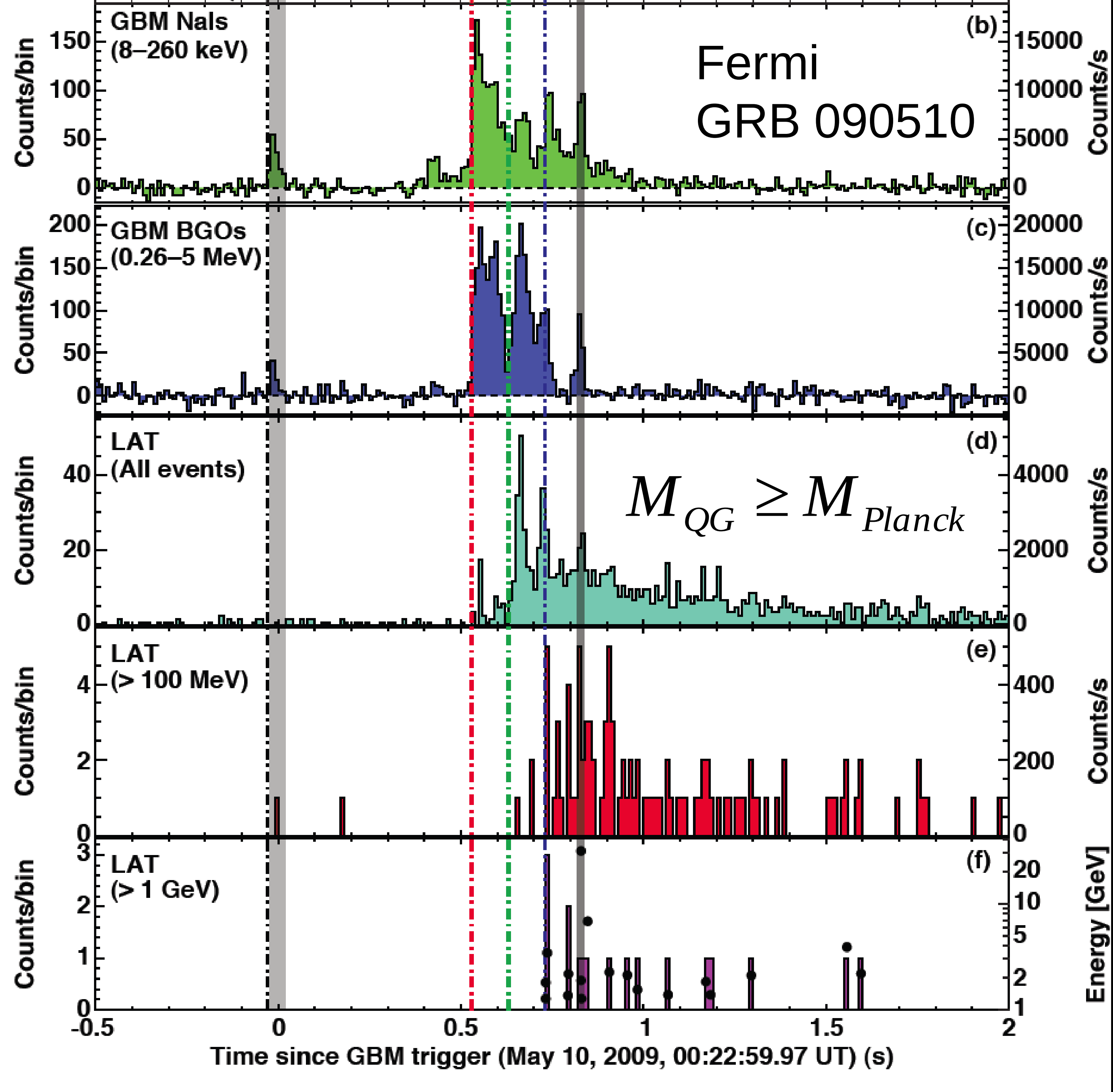
quantized space: matter where the geometry is activated

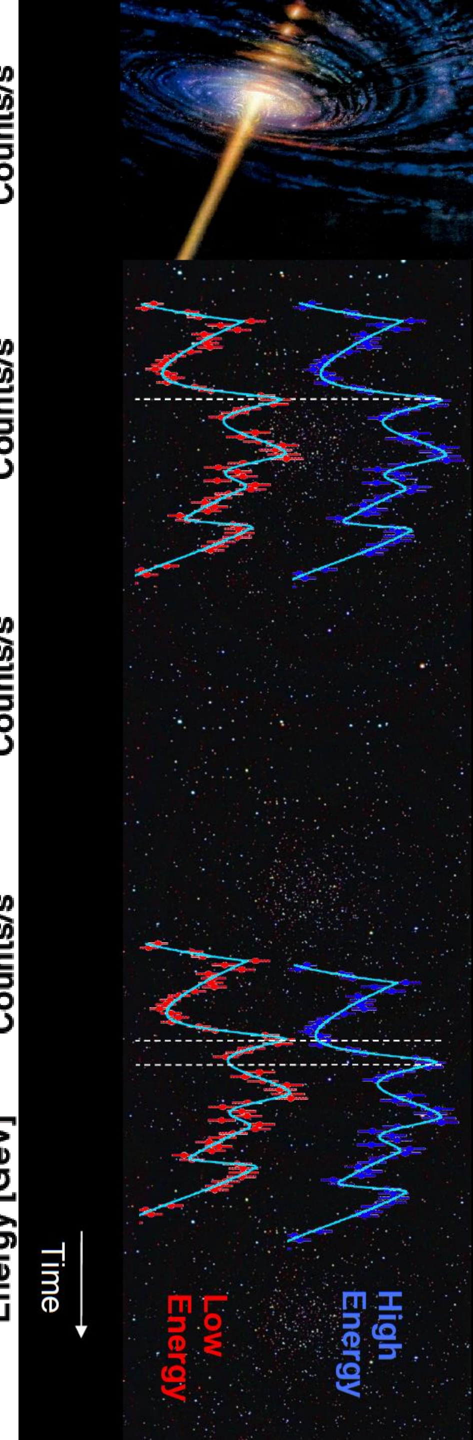
Lorentz violation from Planck scale

- speed of photons and neutrinos depends on their energy, like photons in a crystal
- Planck scale vacuum fluctuations probed by high energy particles

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{QG}}\right)^n \pm \ldots$$

- modification to dispersion relation leads to an energy dependent speed of light: Lorentz invariance violation


Fermi
GRB 090510
$M_{QG} \geq M_{Planck}$
GBM NaIs
(8–260 keV)
(b)
GBM BGOs
(0.26–5 MeV)
(c)
LAT
(All events)
(d)
LAT
(> 100 MeV)
(e)
LAT
(> 1 GeV)
(f)
Counts/bin
Counts/s
Energy [GeV]
Time since GBM trigger (May 10, 2009, 00:22:59.97 UT) (s)


Time
Low Energy
High Energy

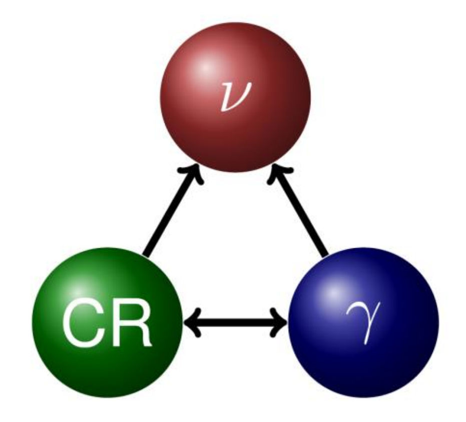
- the existence of PeV neutrino events yields dramatic limits on any possible Lorentz invariance violation: superluminal particles lose their energy to Cherenkov radiation, even in vacuum

$$\nu \rightarrow \nu\, e^{+} e^{-}$$

- sensitivity δ increases dramatically with distance d and observed energy E

$$\delta = \frac{v_{\nu}^{2} - c^{2}}{c^{2}} = a\, d^{-\frac{1}{3}}\, E^{-\frac{5}{3}}$$

conclusions
progress through instrumentation



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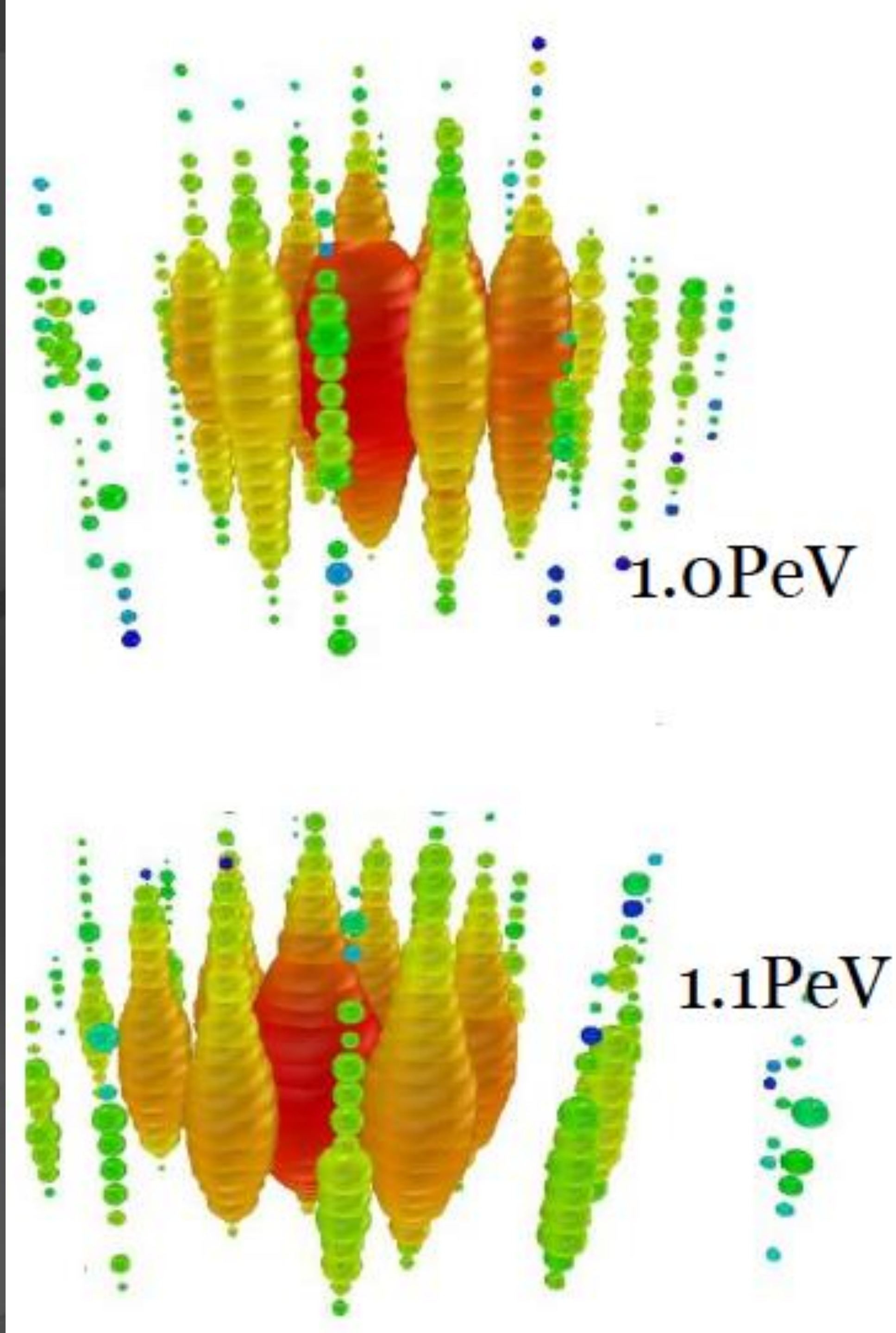

• energy

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

limits on δ (relative velocity between flavors only)

test of:
equivalence principle, quantum gravity and Lorentz invariance

spacetime is smooth at energies near and slightly above the Planck mass.

“general relativity will not last tao hundred years”
M. Turner