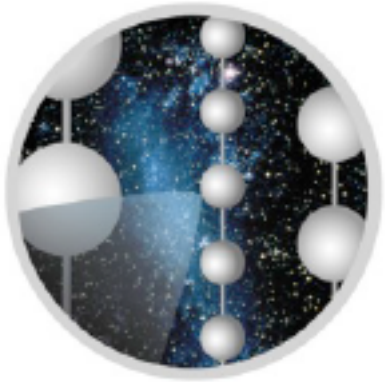
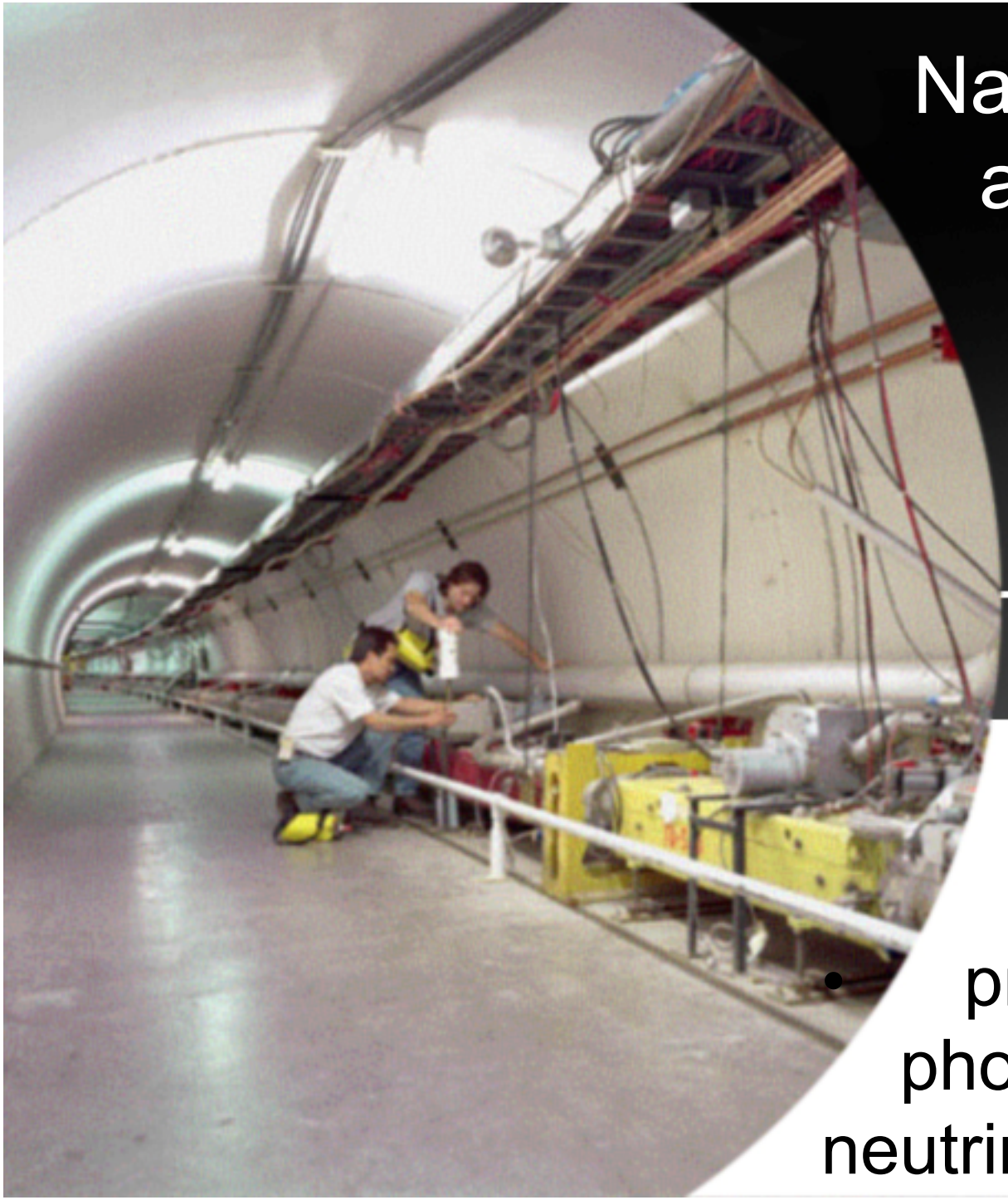


IceCube

francis halzen

- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

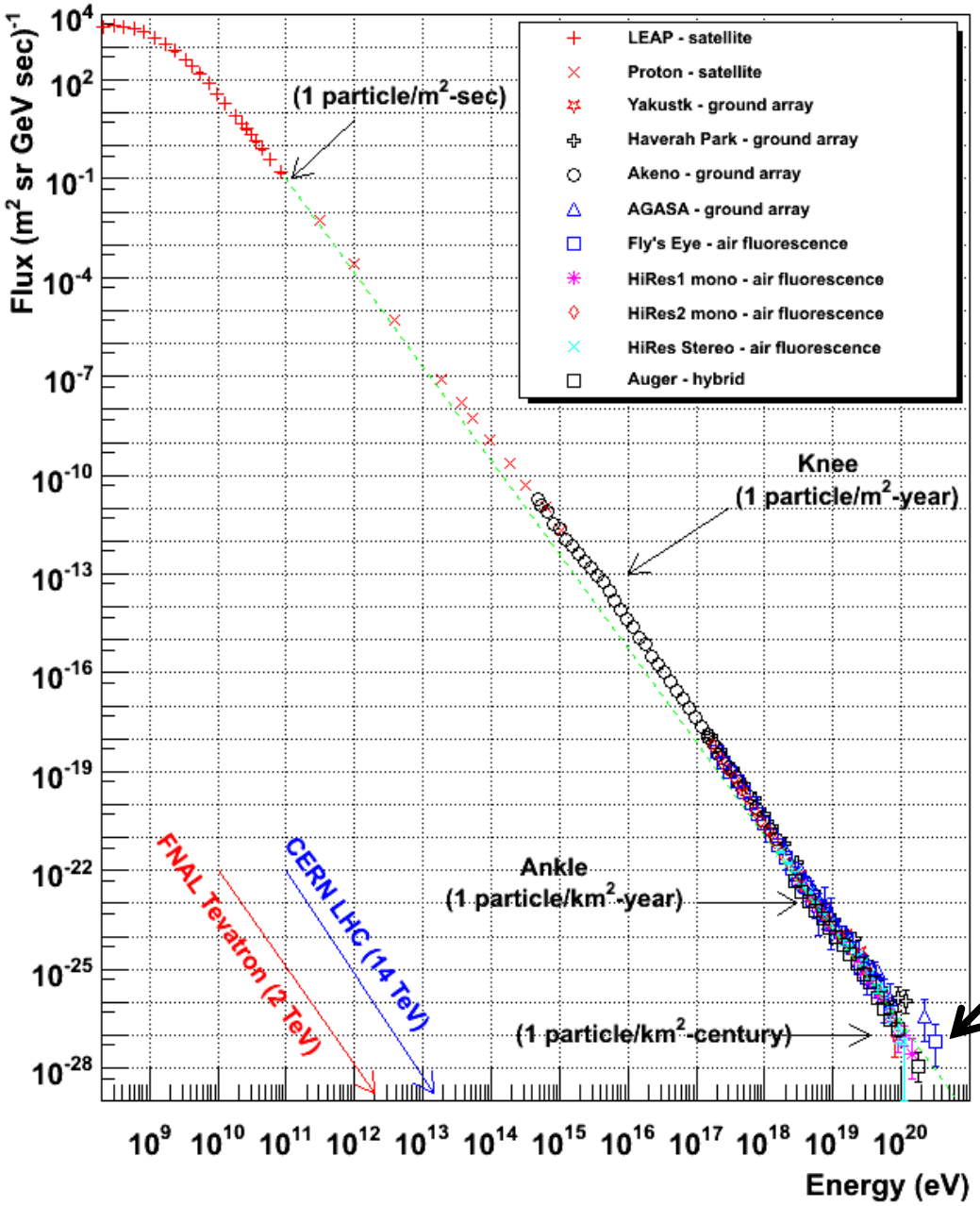
IceCube.wisc.edu



Nature's accelerators?

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

Cosmic Ray Spectra of Various Experiments



cosmic ray accelerators:
where, how?

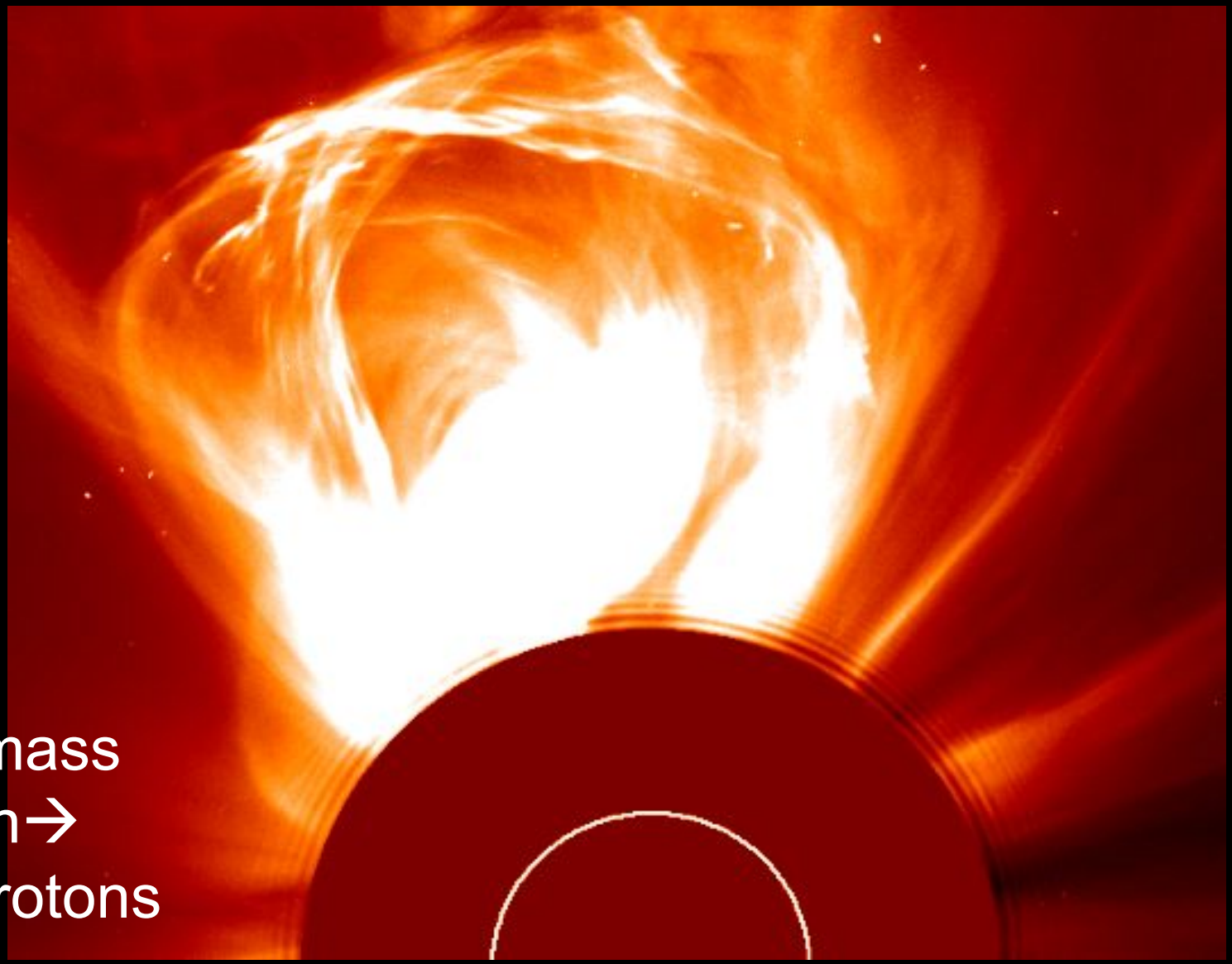
gravitational energy from collapsing star converted into particle acceleration

LHC filling the orbit of Mercury

neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect

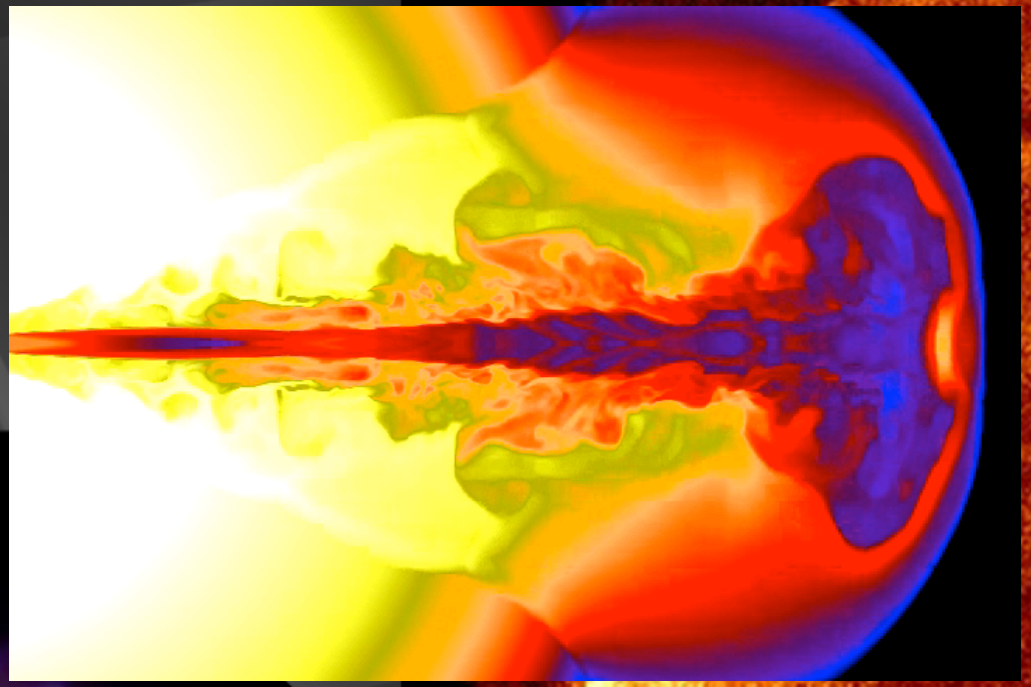
the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

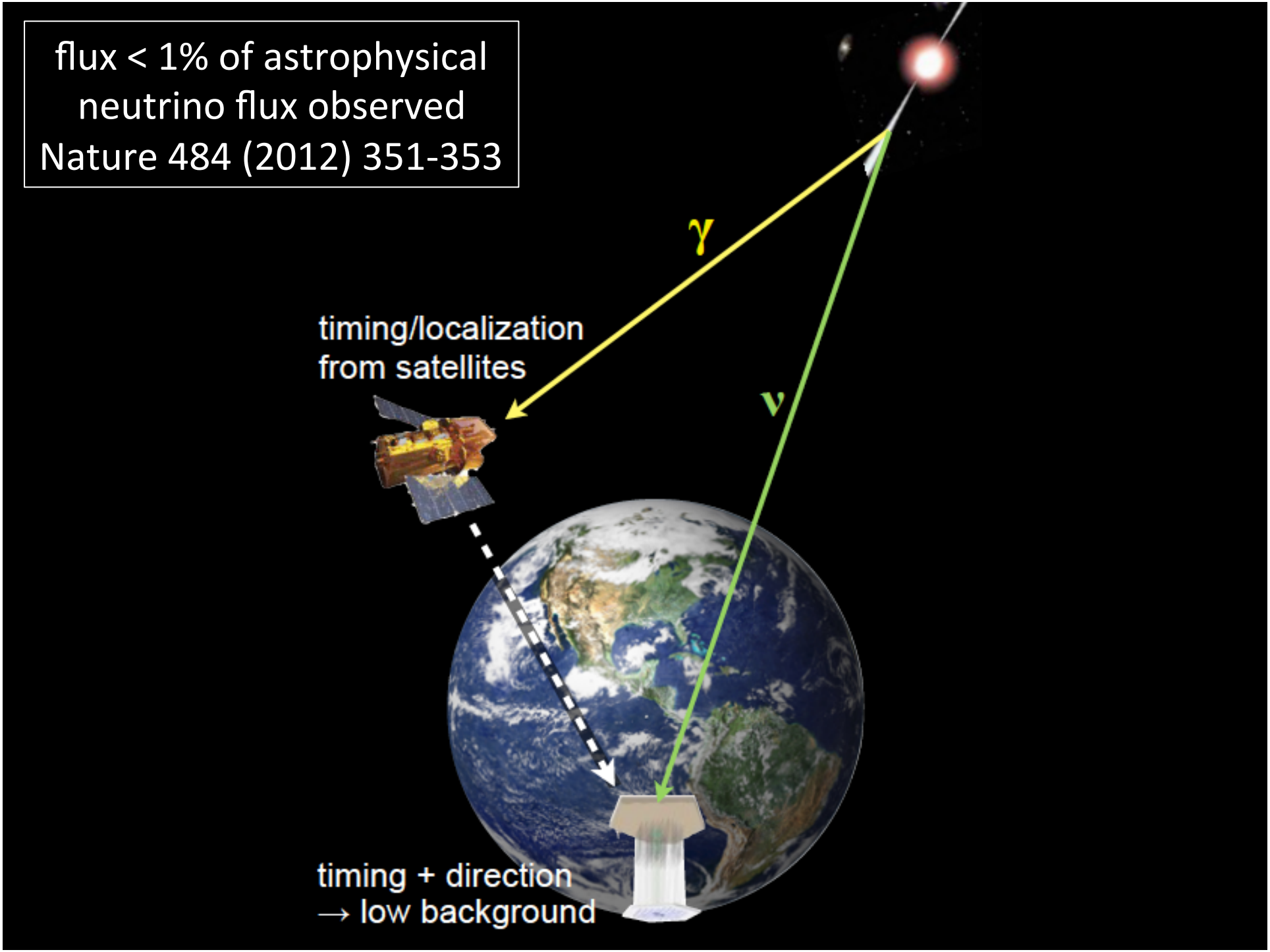
supernova remnants

Chandra
Cassiopeia A

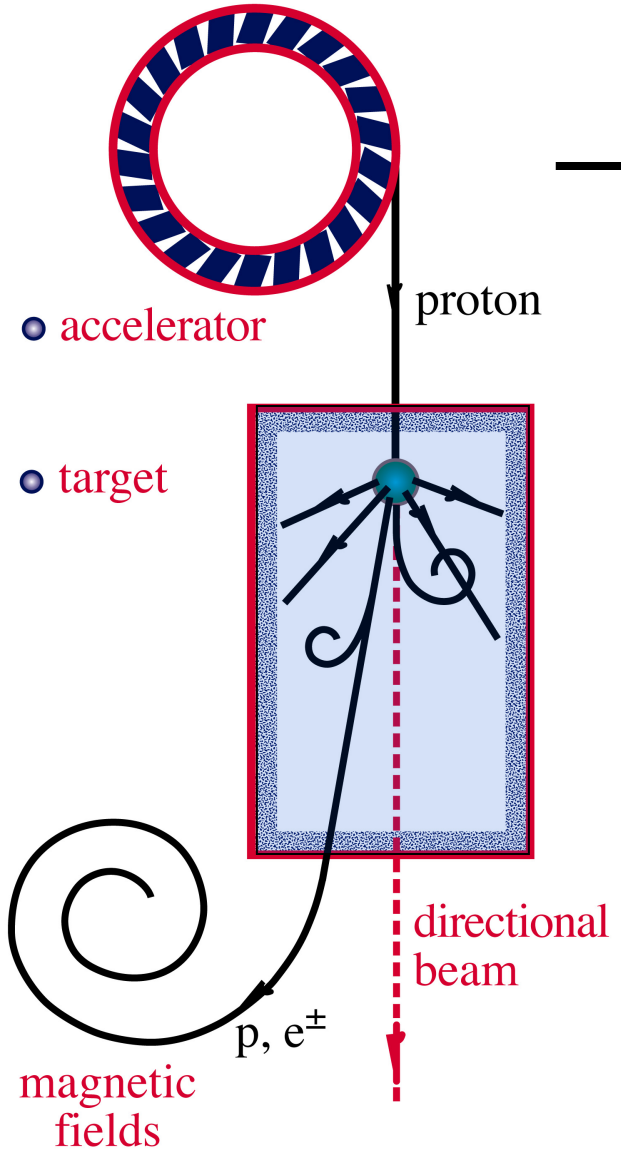


gamma ray bursts

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



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

$\rightarrow p + \pi^0$

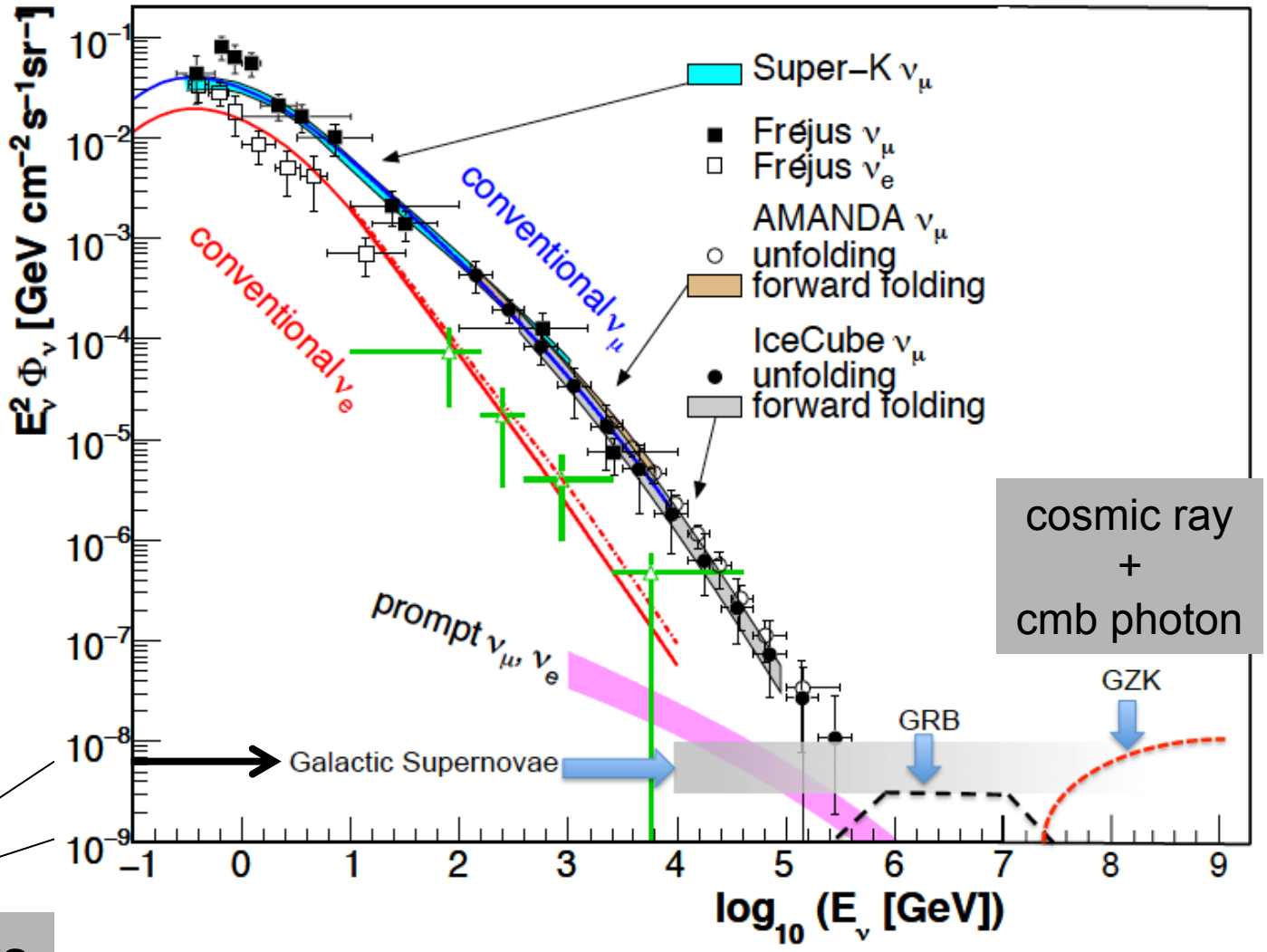
~ cosmic ray + gamma

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

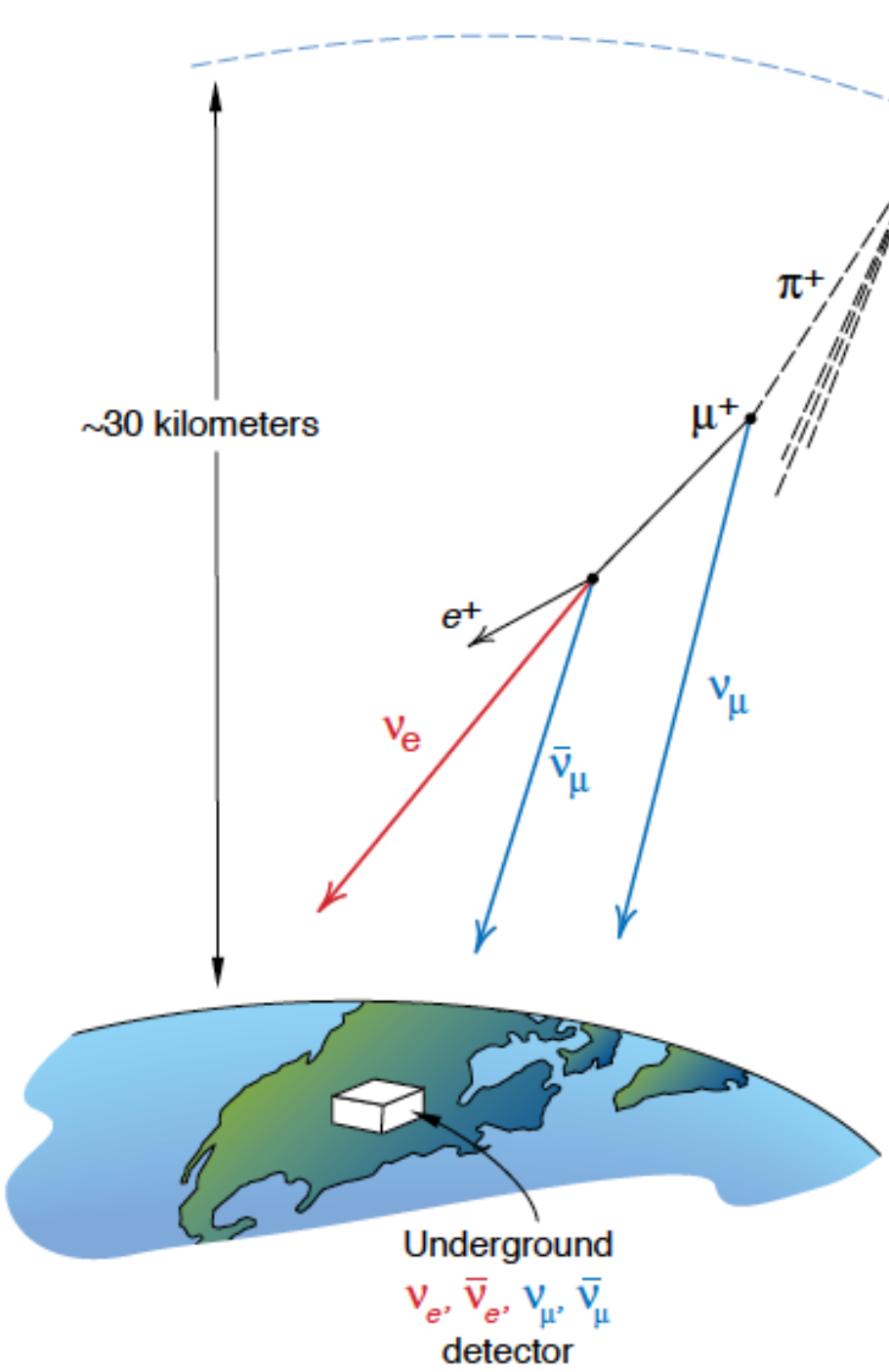


cosmic ray + cmb photon

atmospheric

cosmic

100 TeV



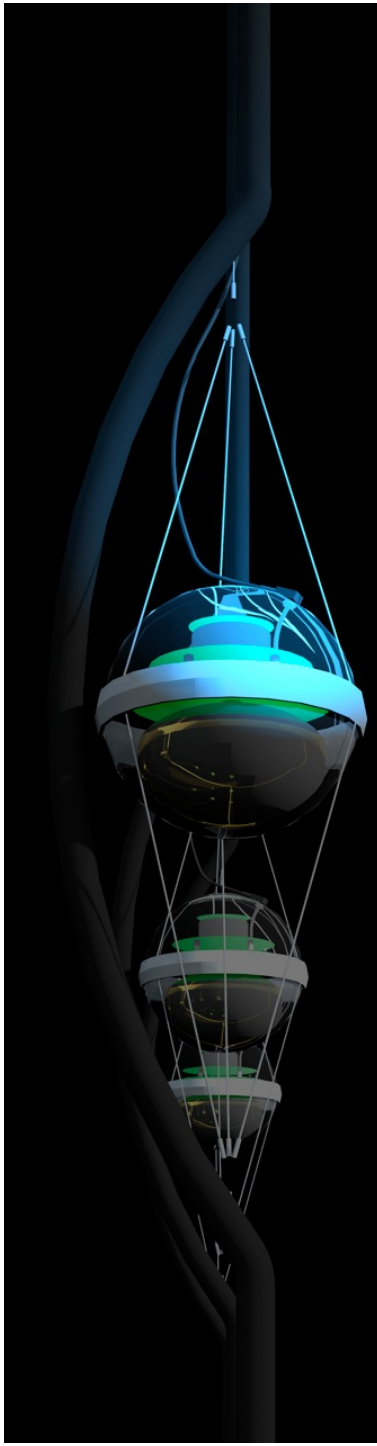
atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

not only π, also K, D,…

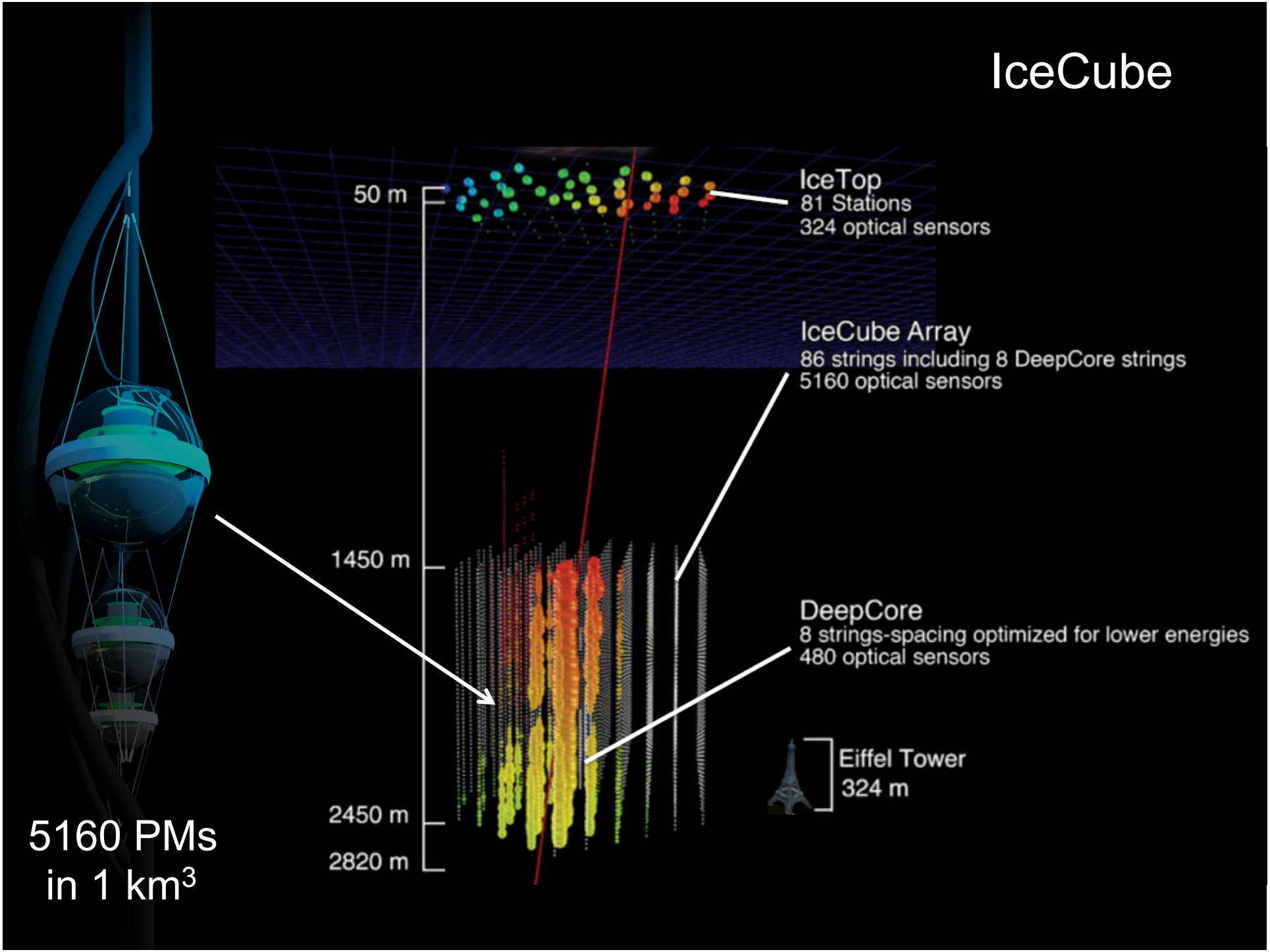


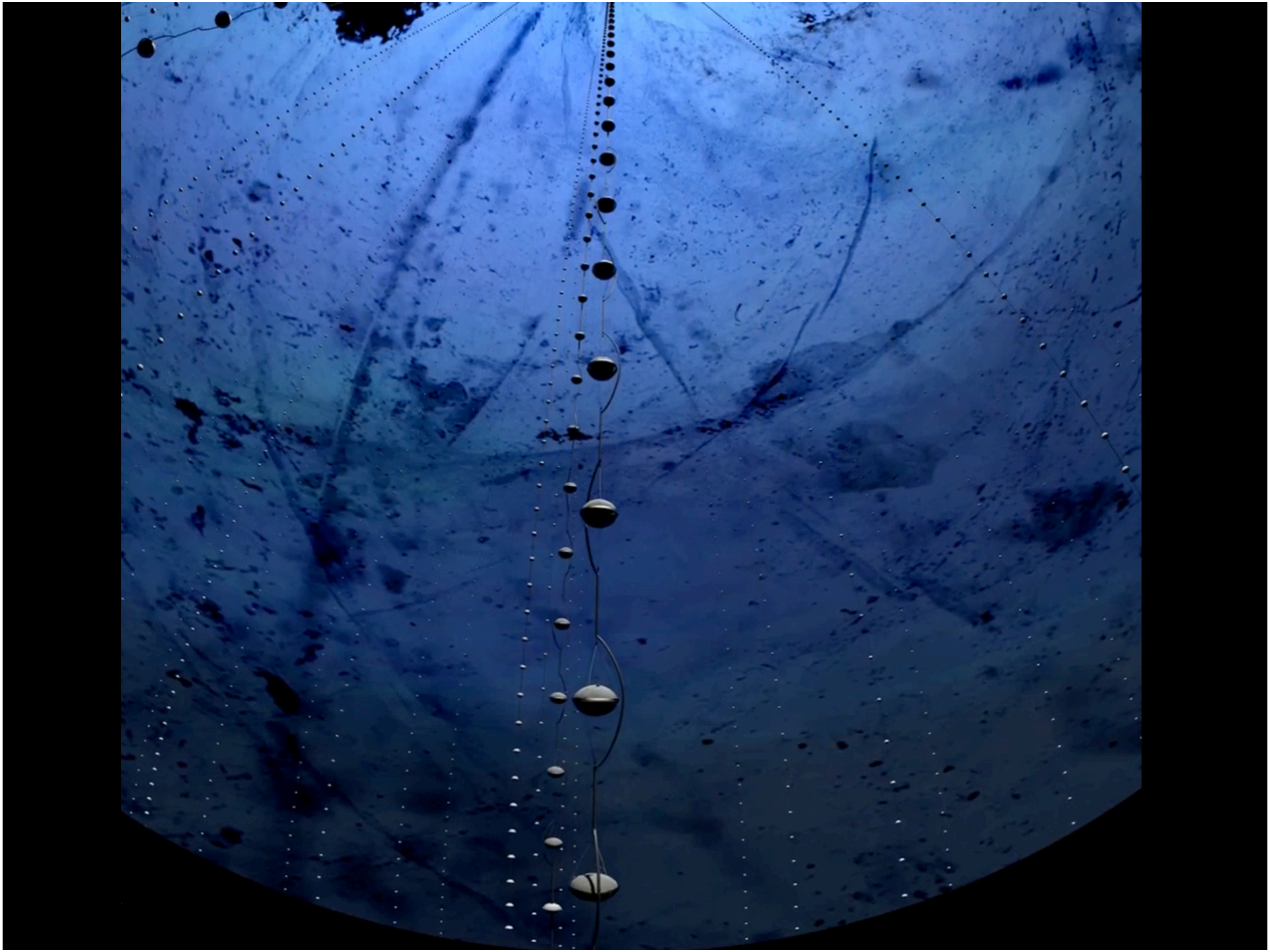
IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

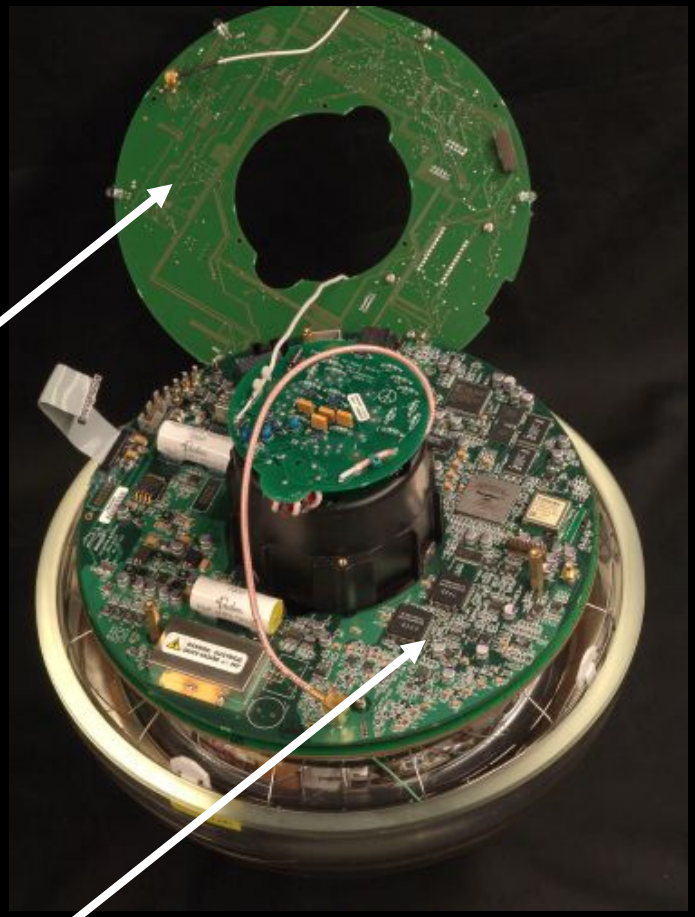
IceCube.wisc.edu


IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3



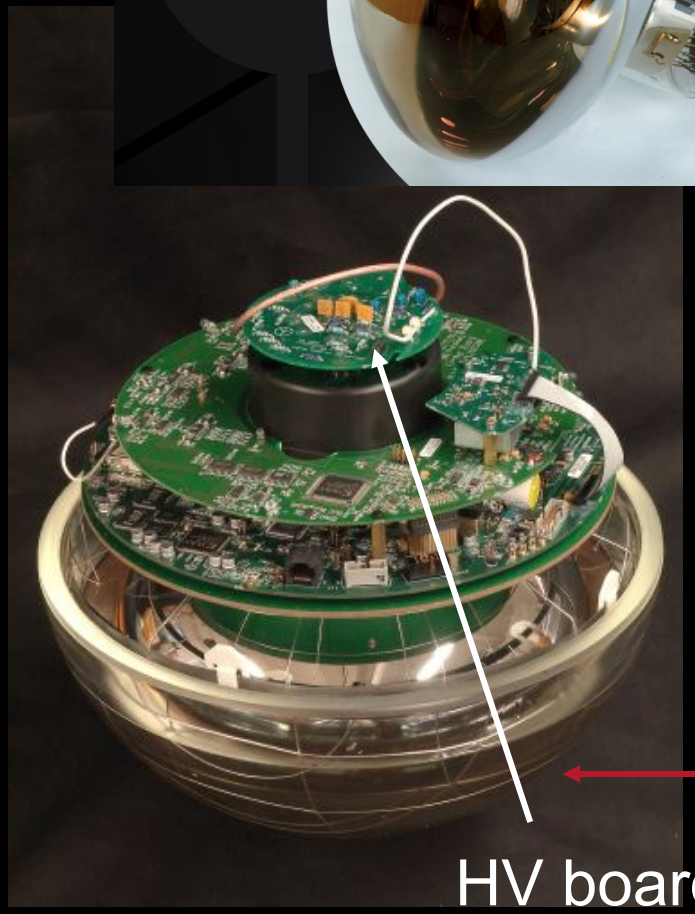
architecture of independent DOMs

10 inch pmt



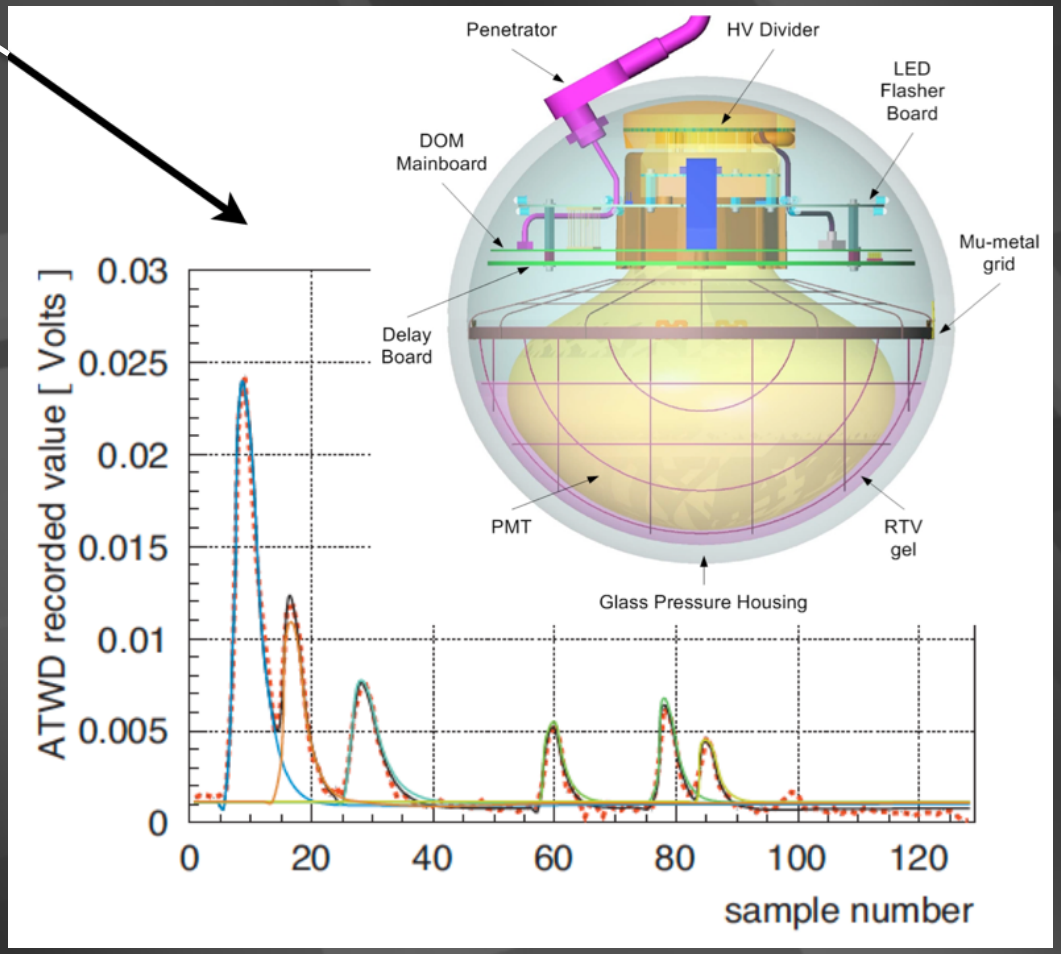
LED
flasher
board

main
board

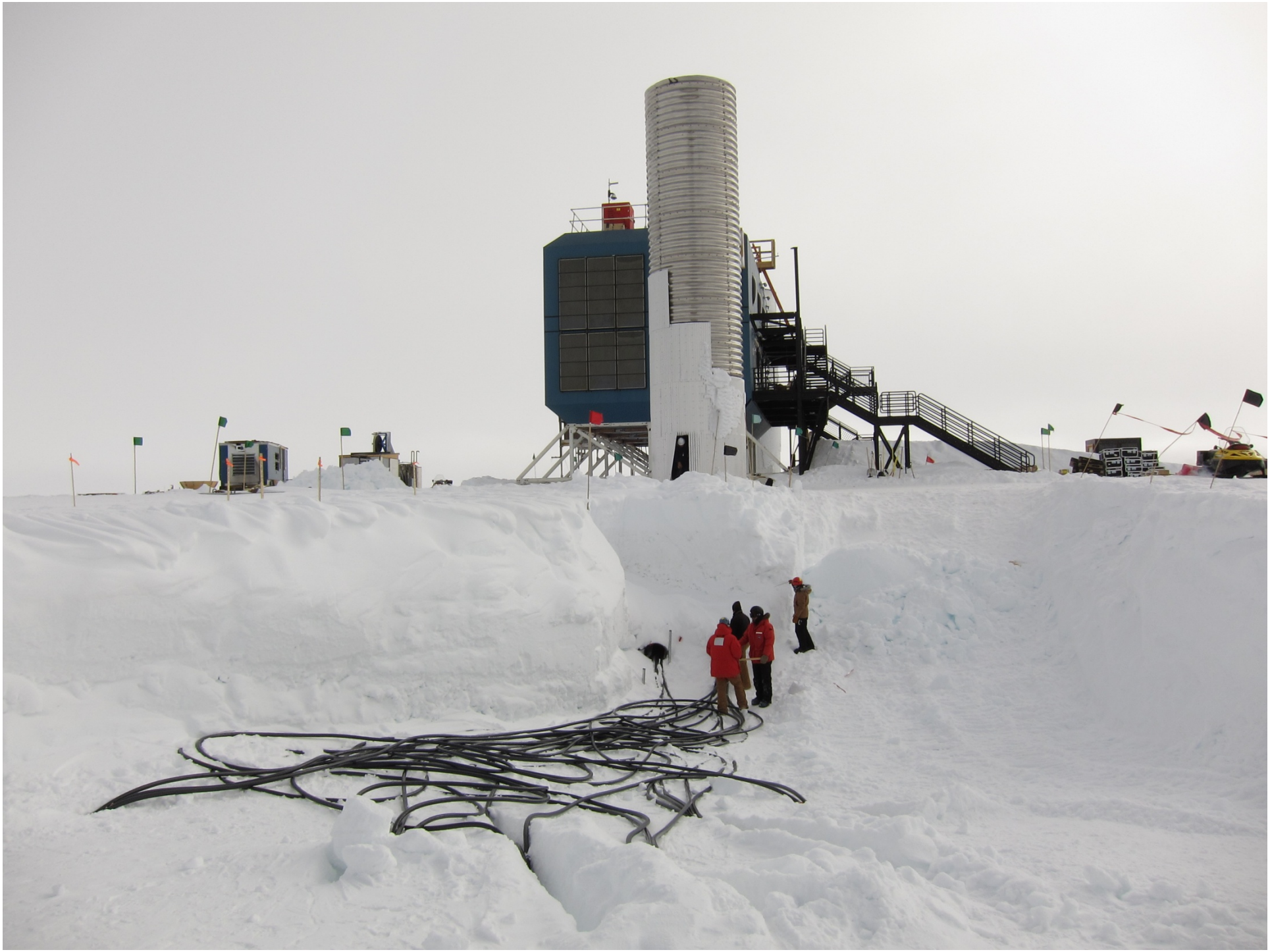


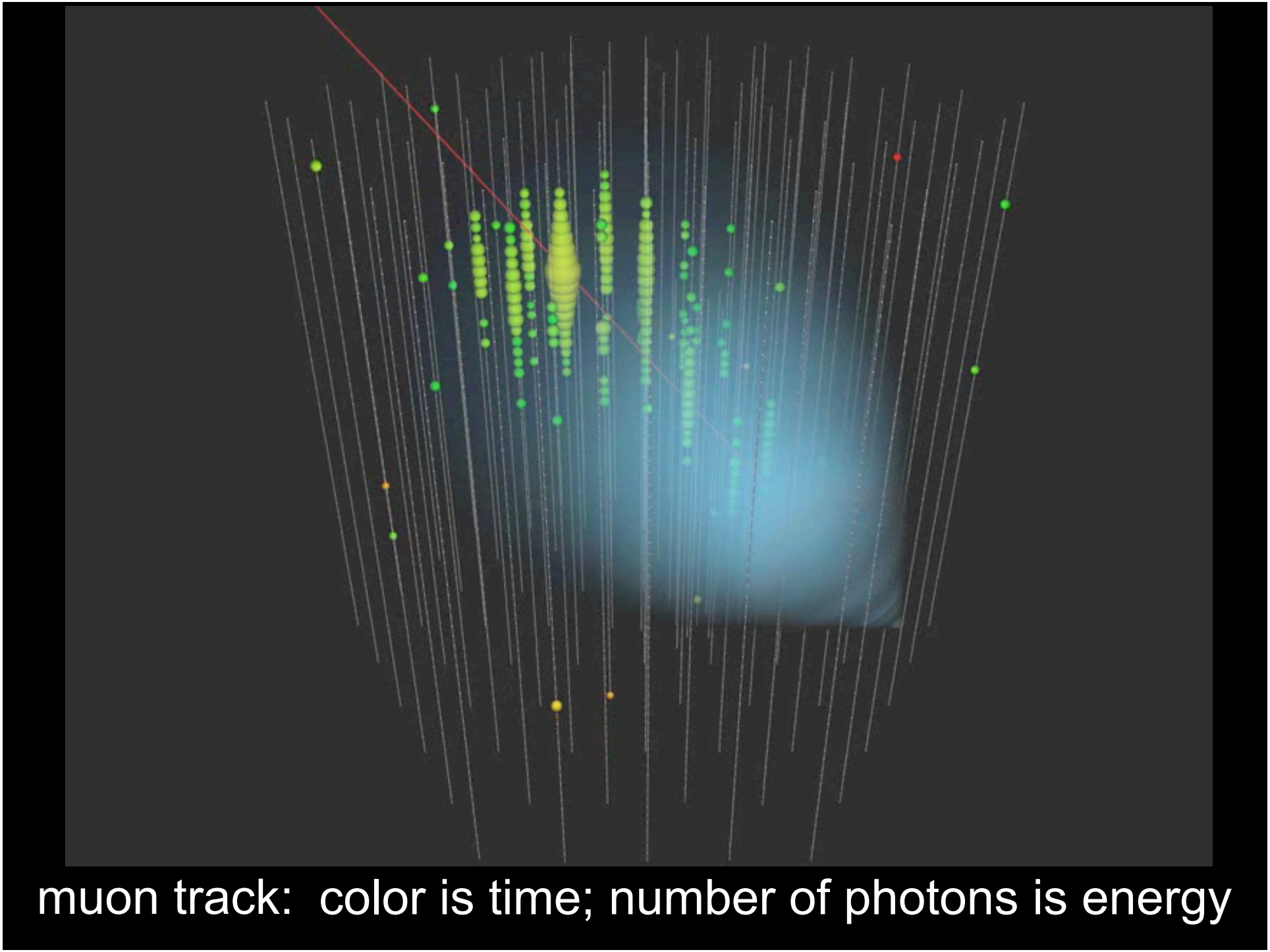
HV board

… 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…





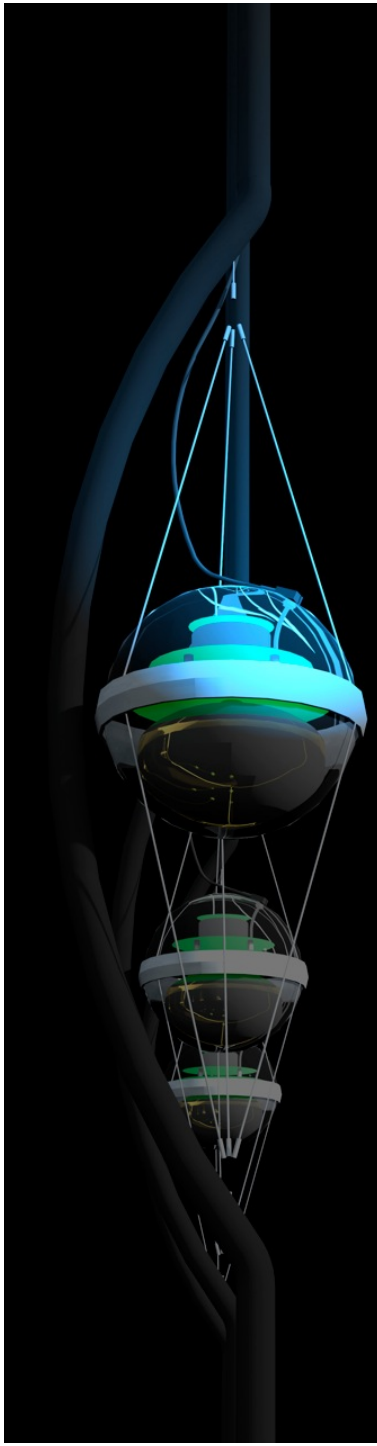
muon track: color is time; number of photons is energy

events detected per year:

- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ < 10^{2}

* 3000 per second

** 1 every 6 minutes



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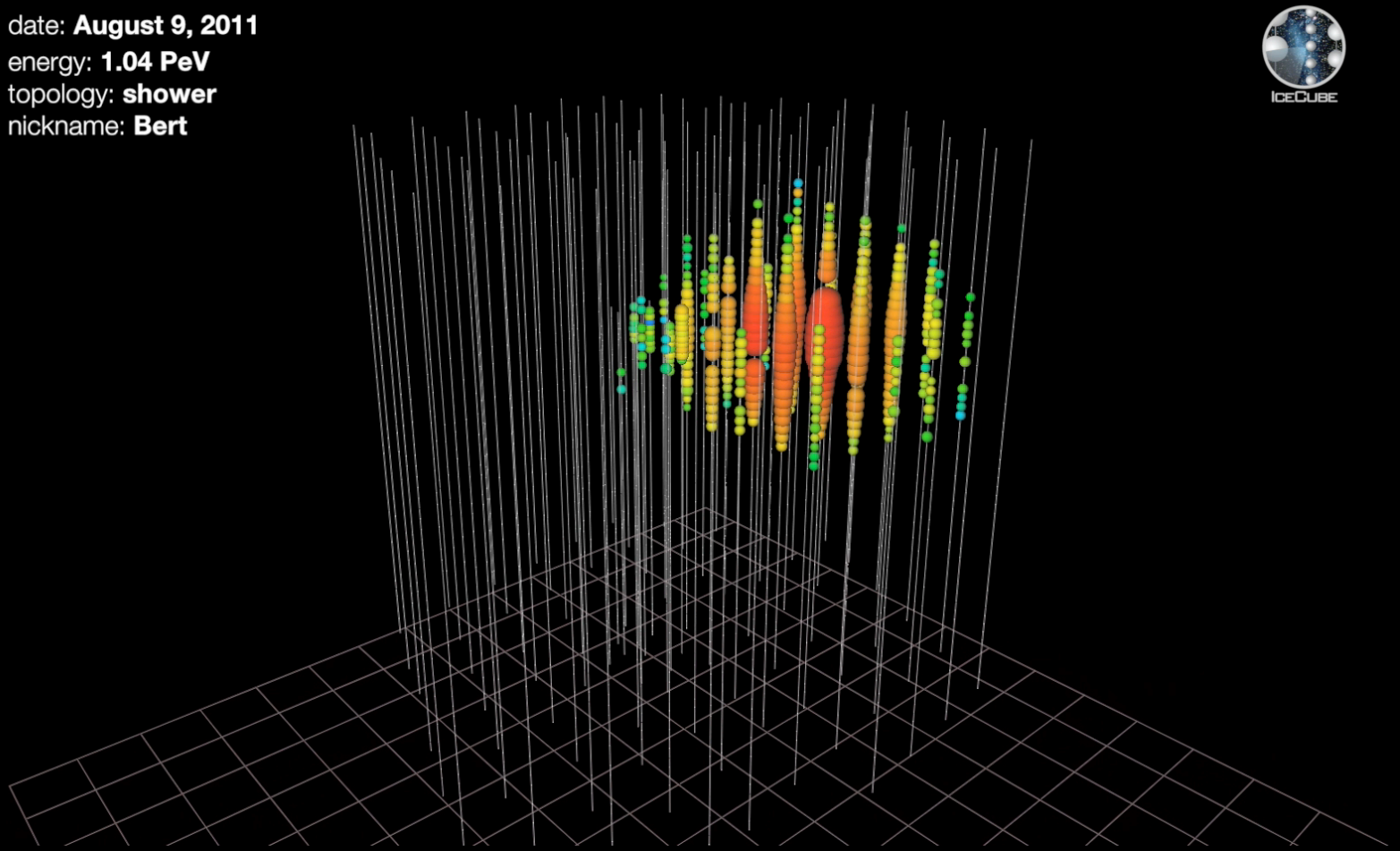
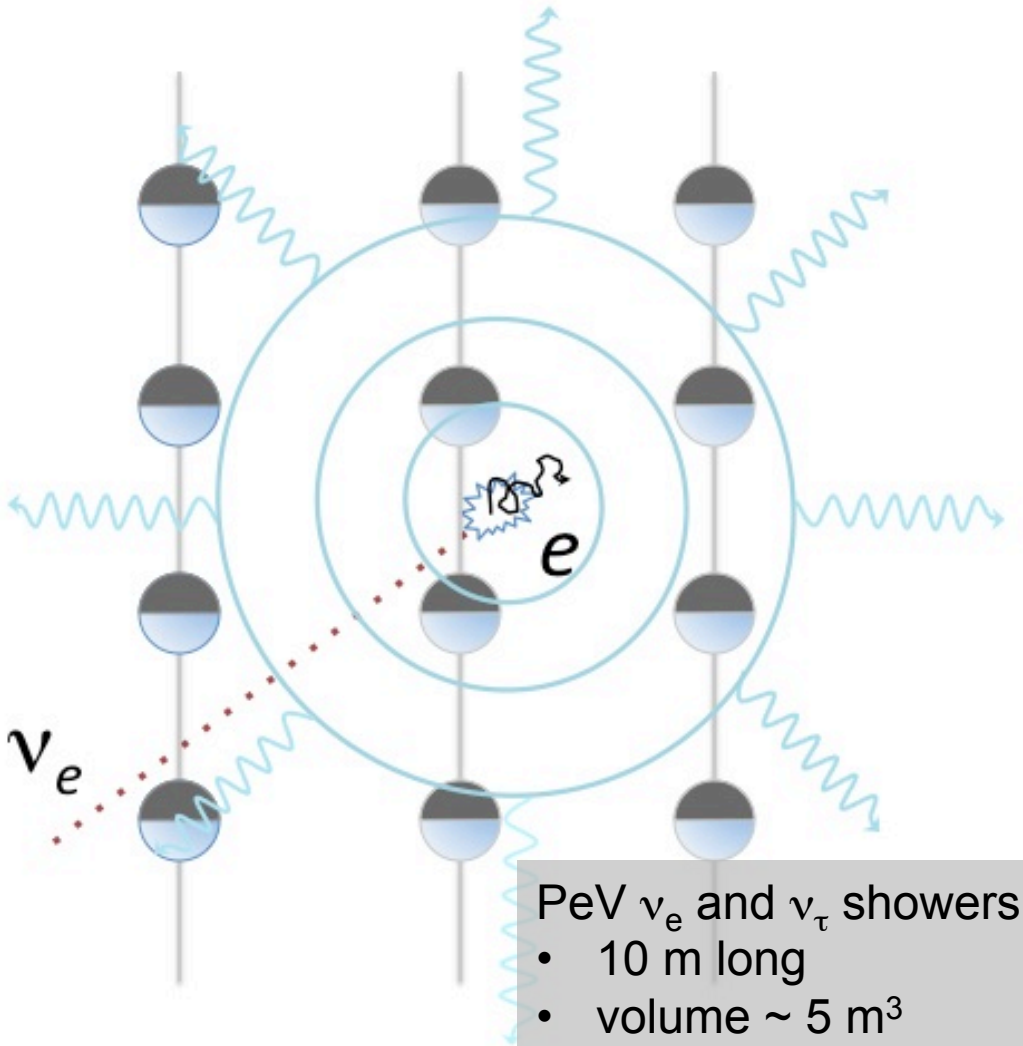
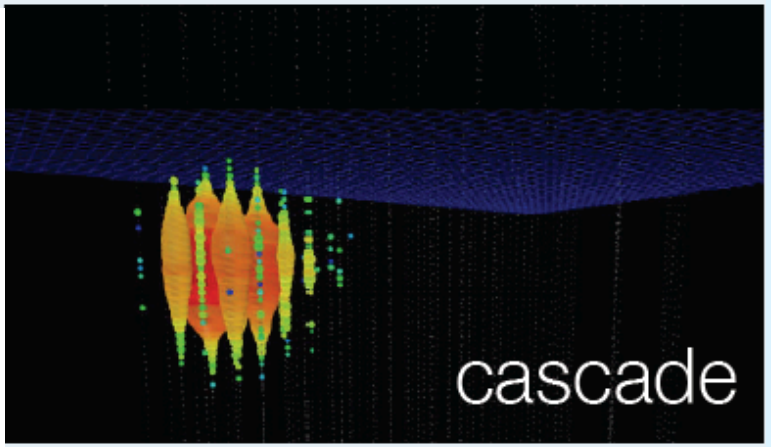
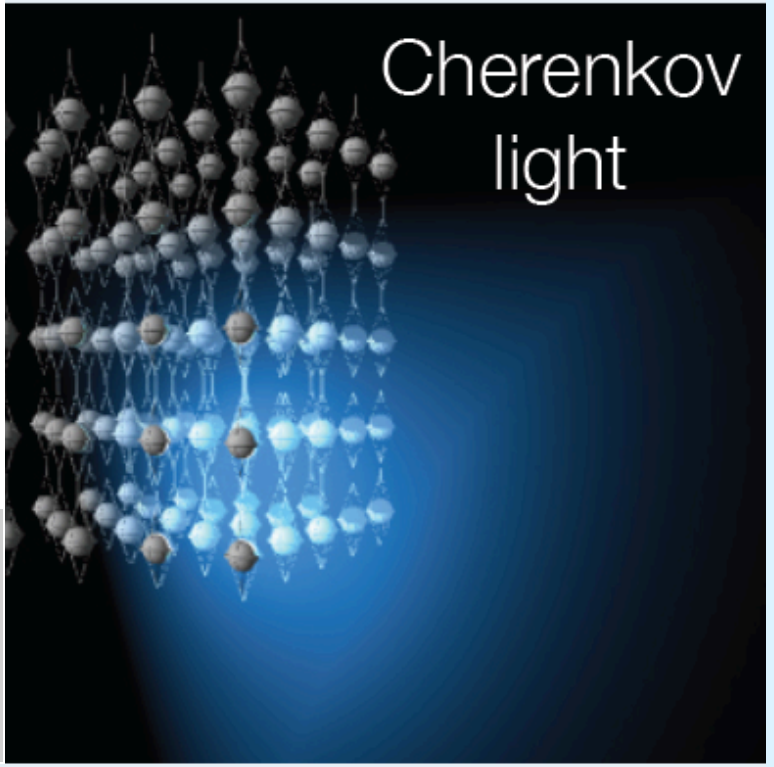
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

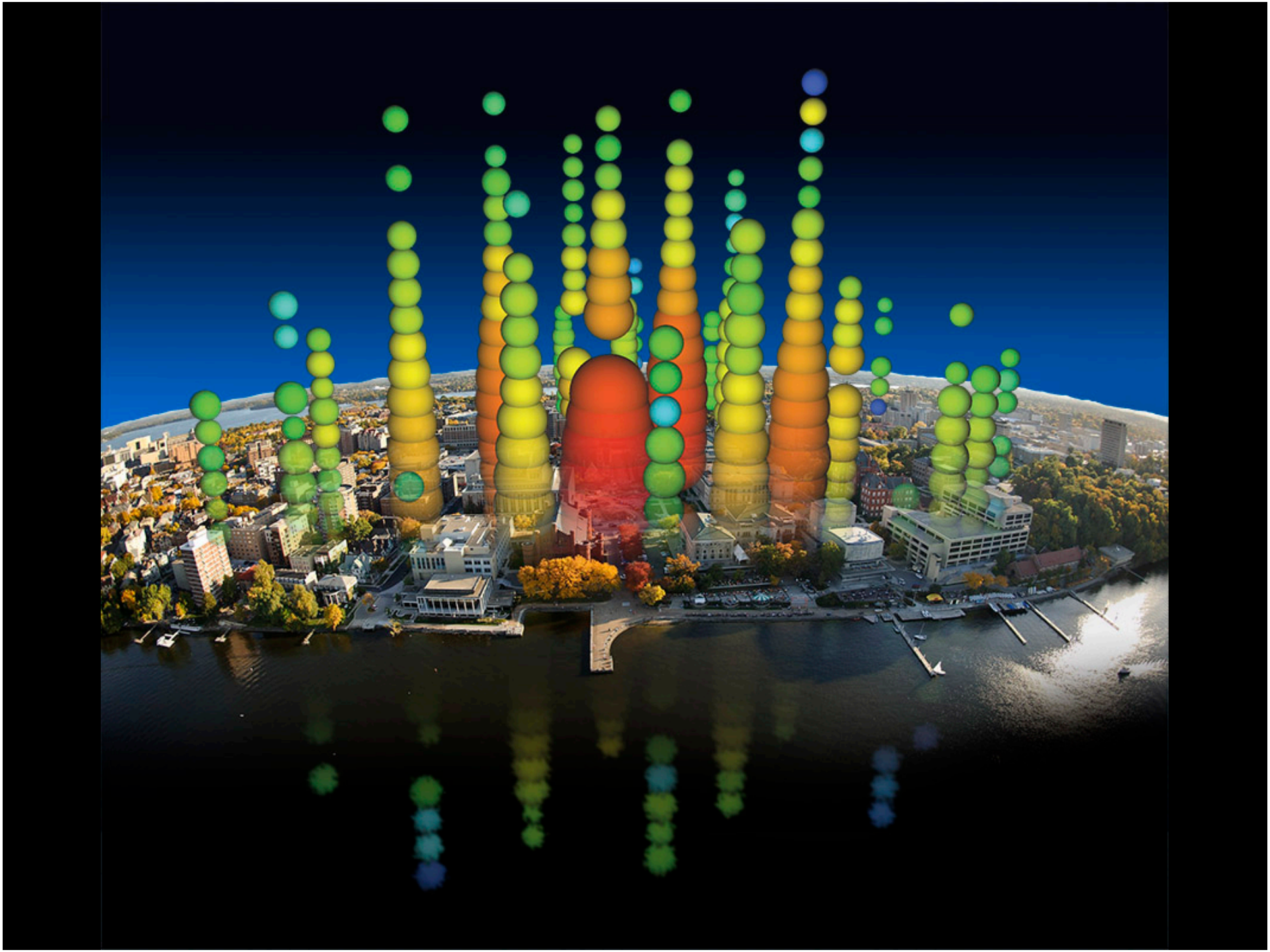


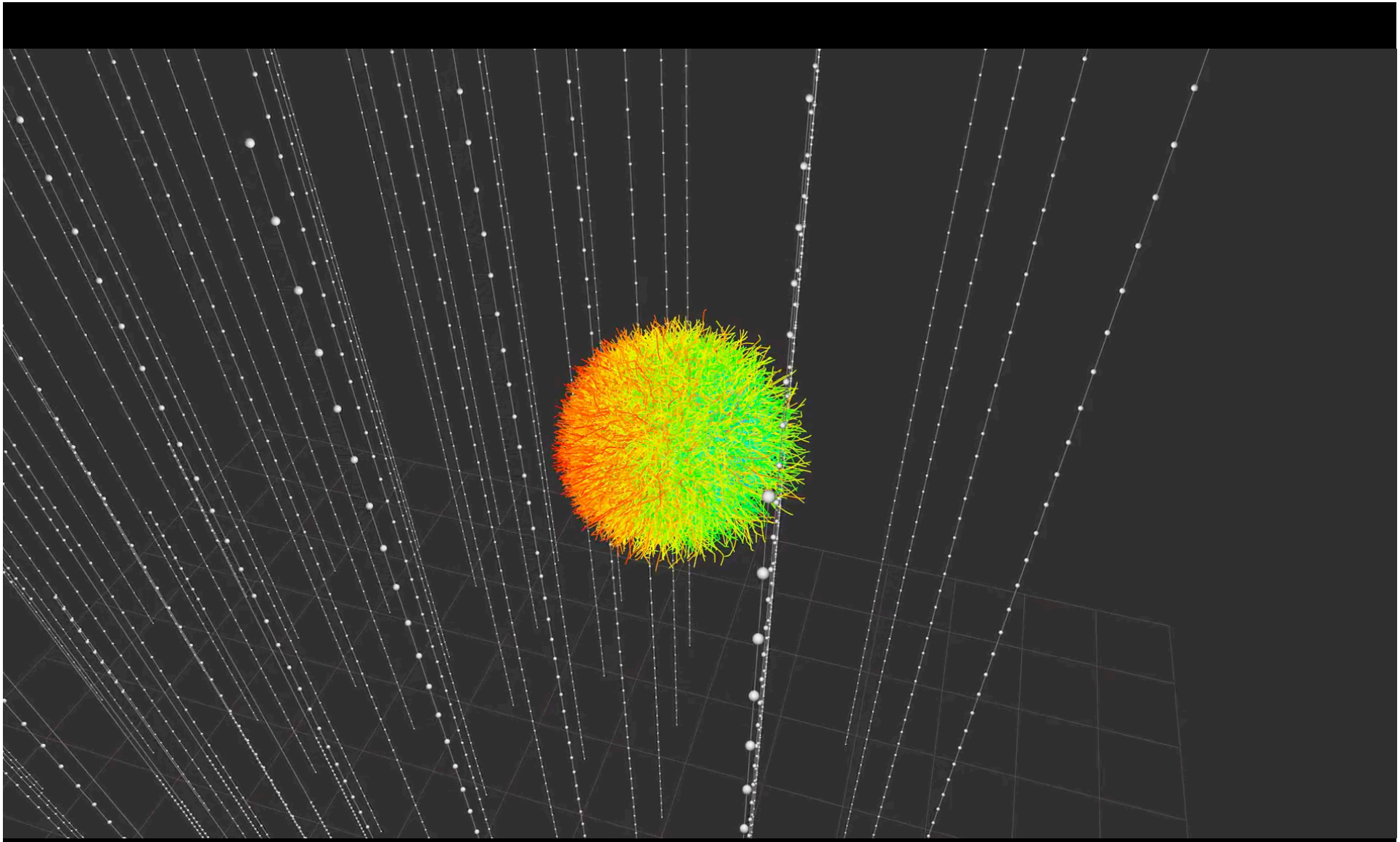




PeV ν_e and ν_τ showers:

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



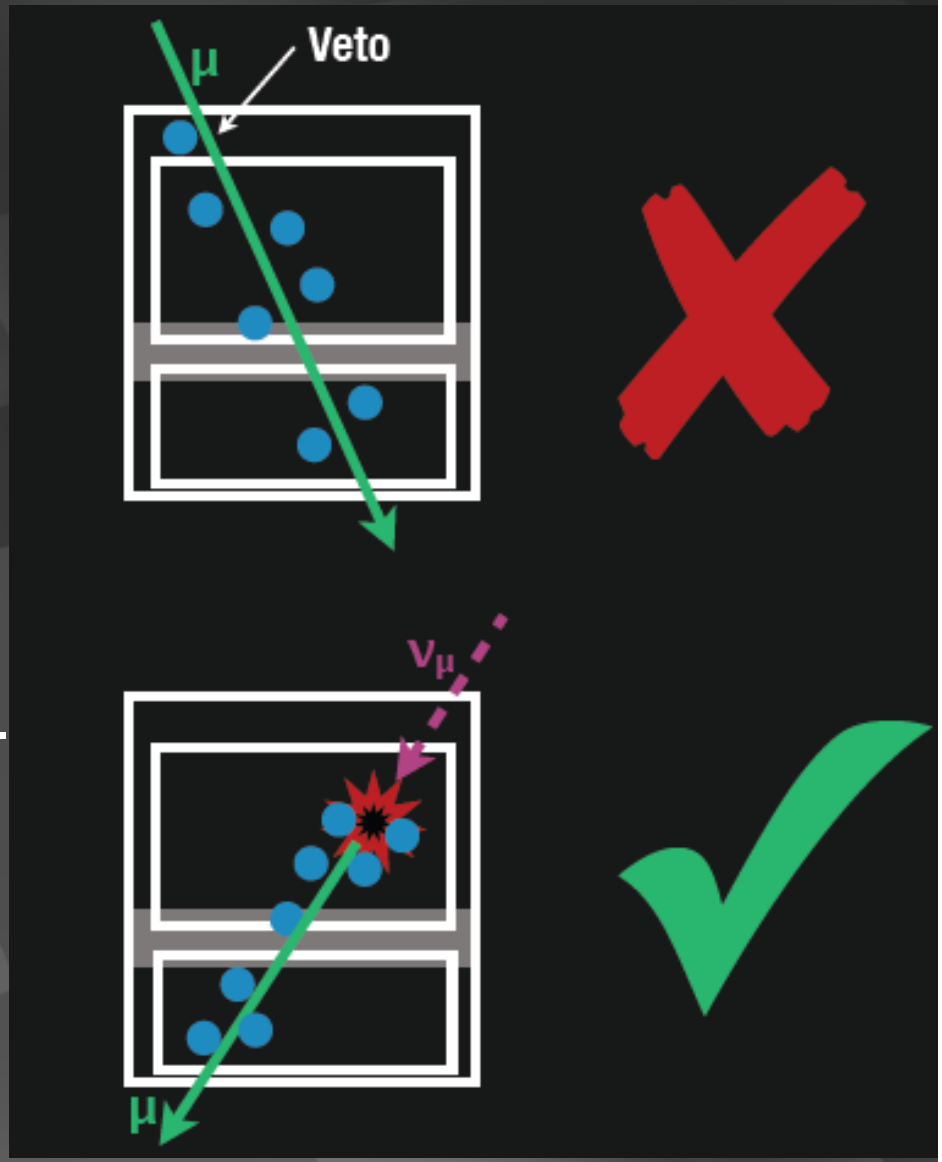


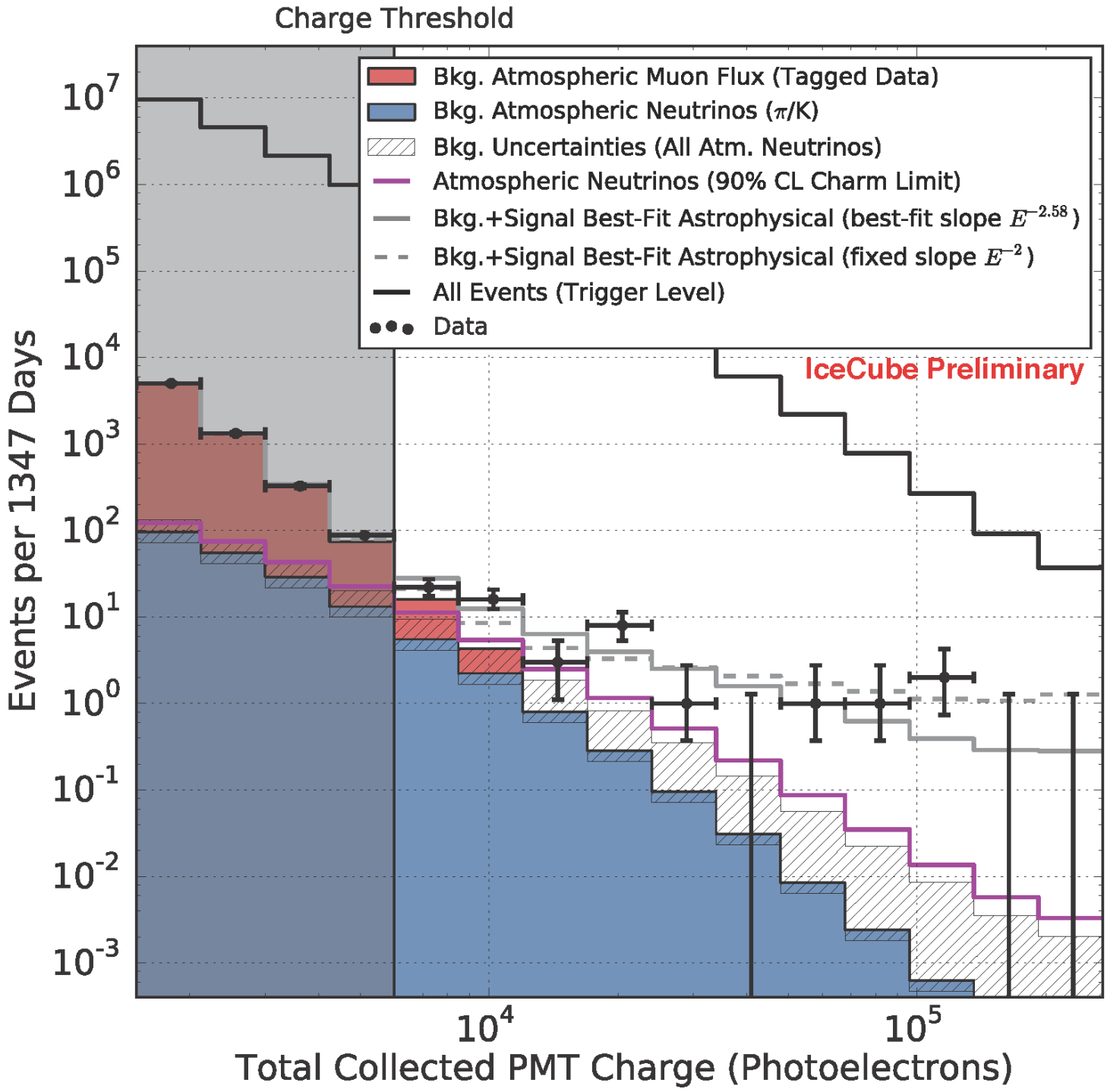
size = energy

color = time = direction

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



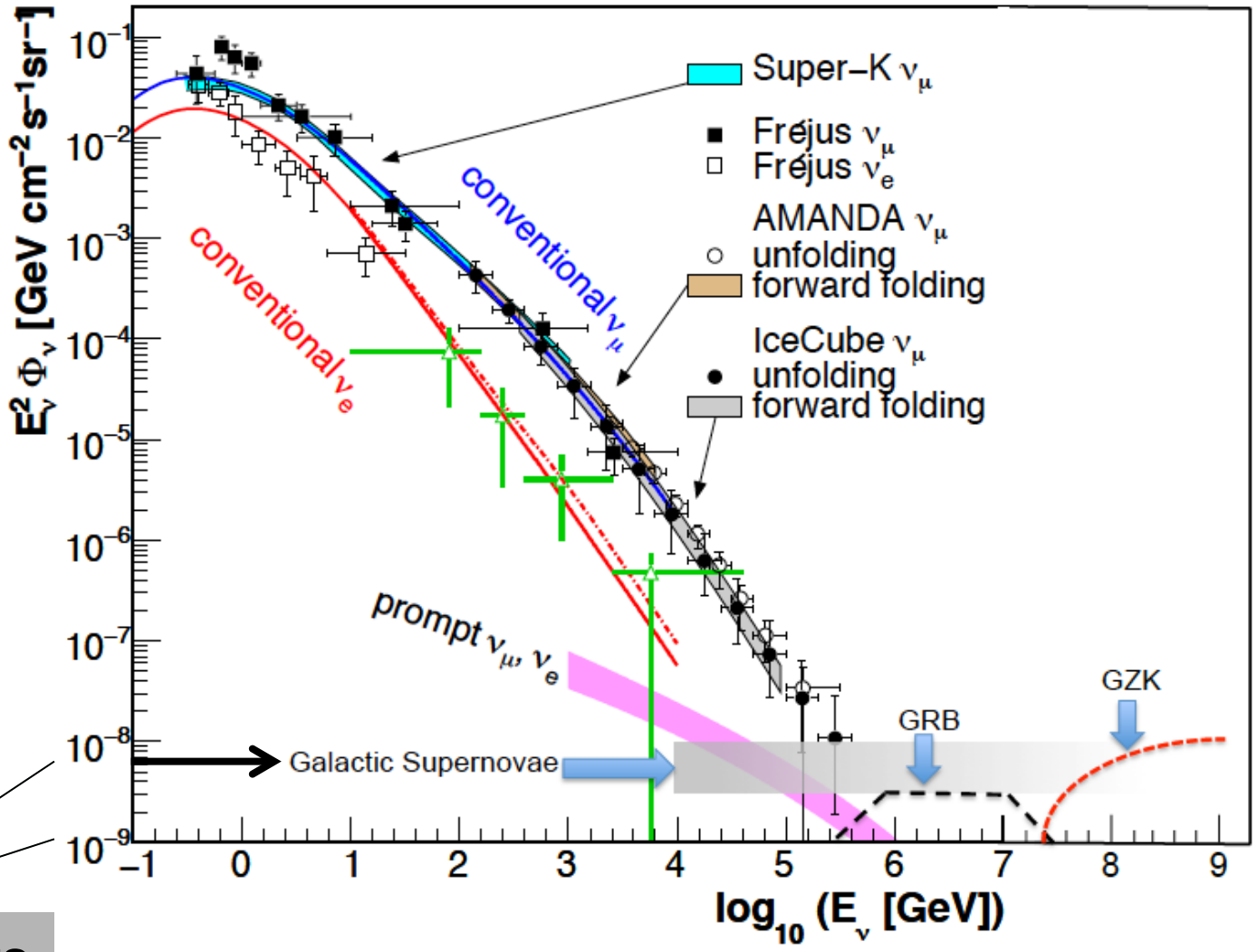

Charge Threshold
Bkg. Atmospheric Muon Flux (Tagged Data)
Bkg. Atmospheric Neutrinos (π/K)
Bkg. Uncertainties (All Atm. Neutrinos)
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
All Events (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

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

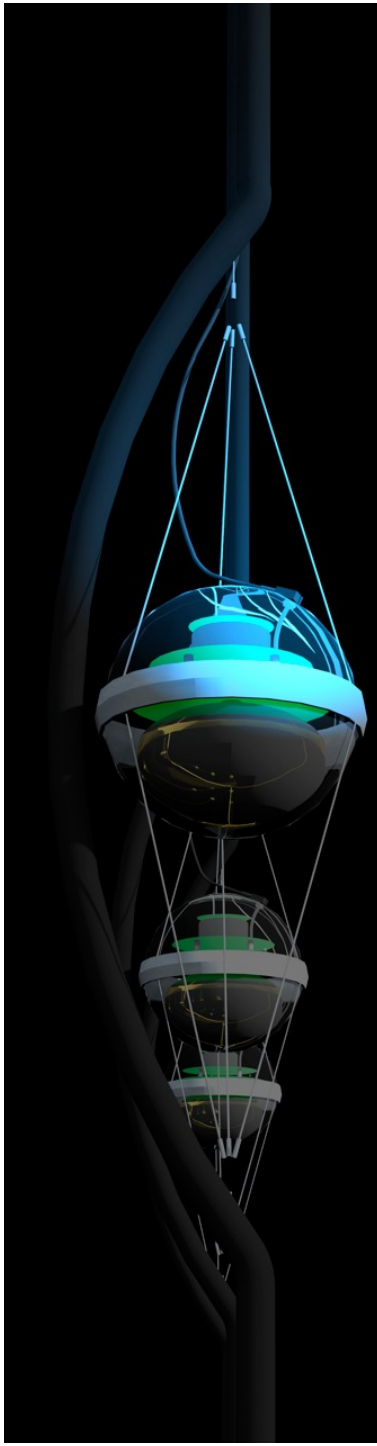
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV



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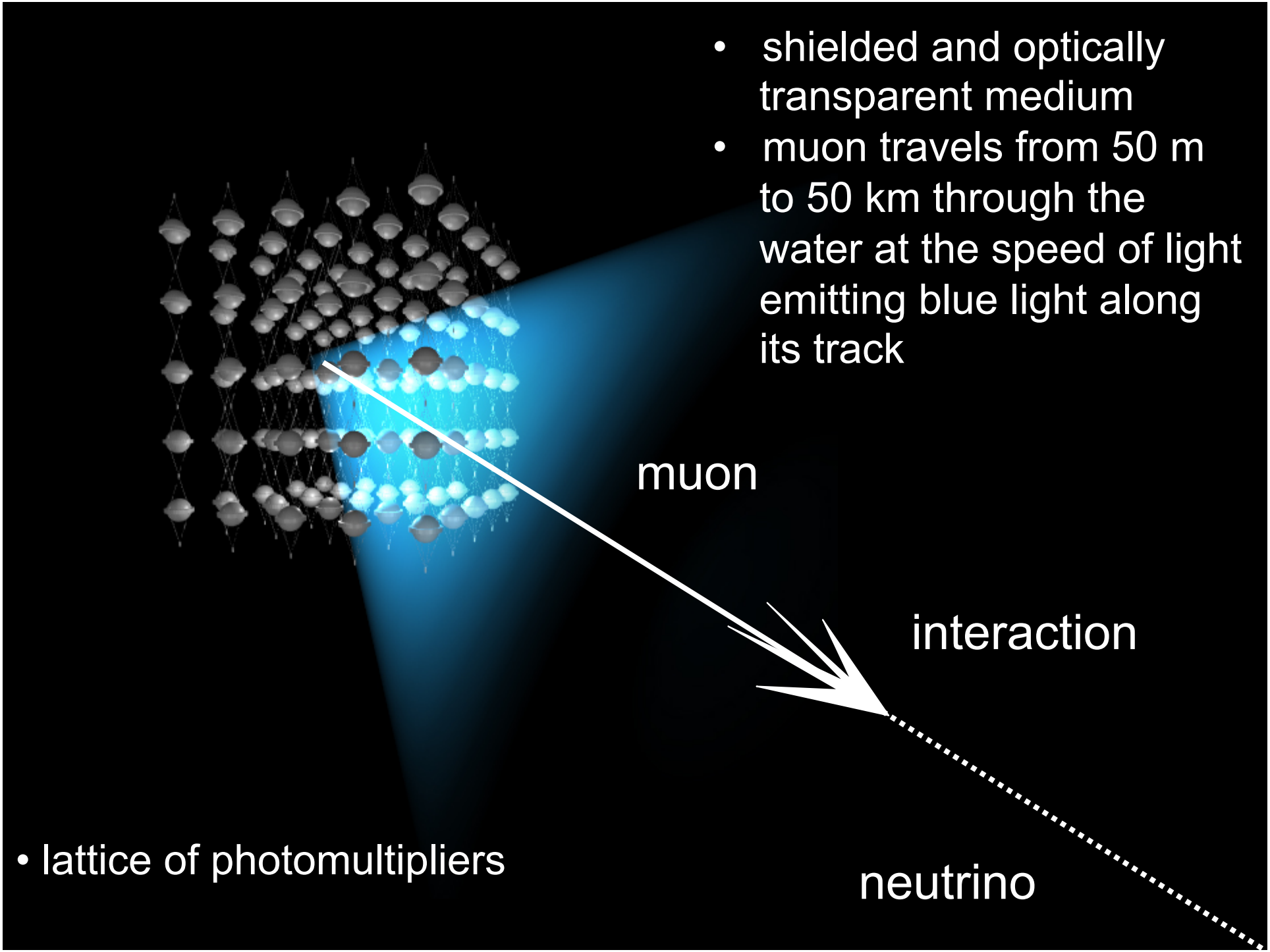
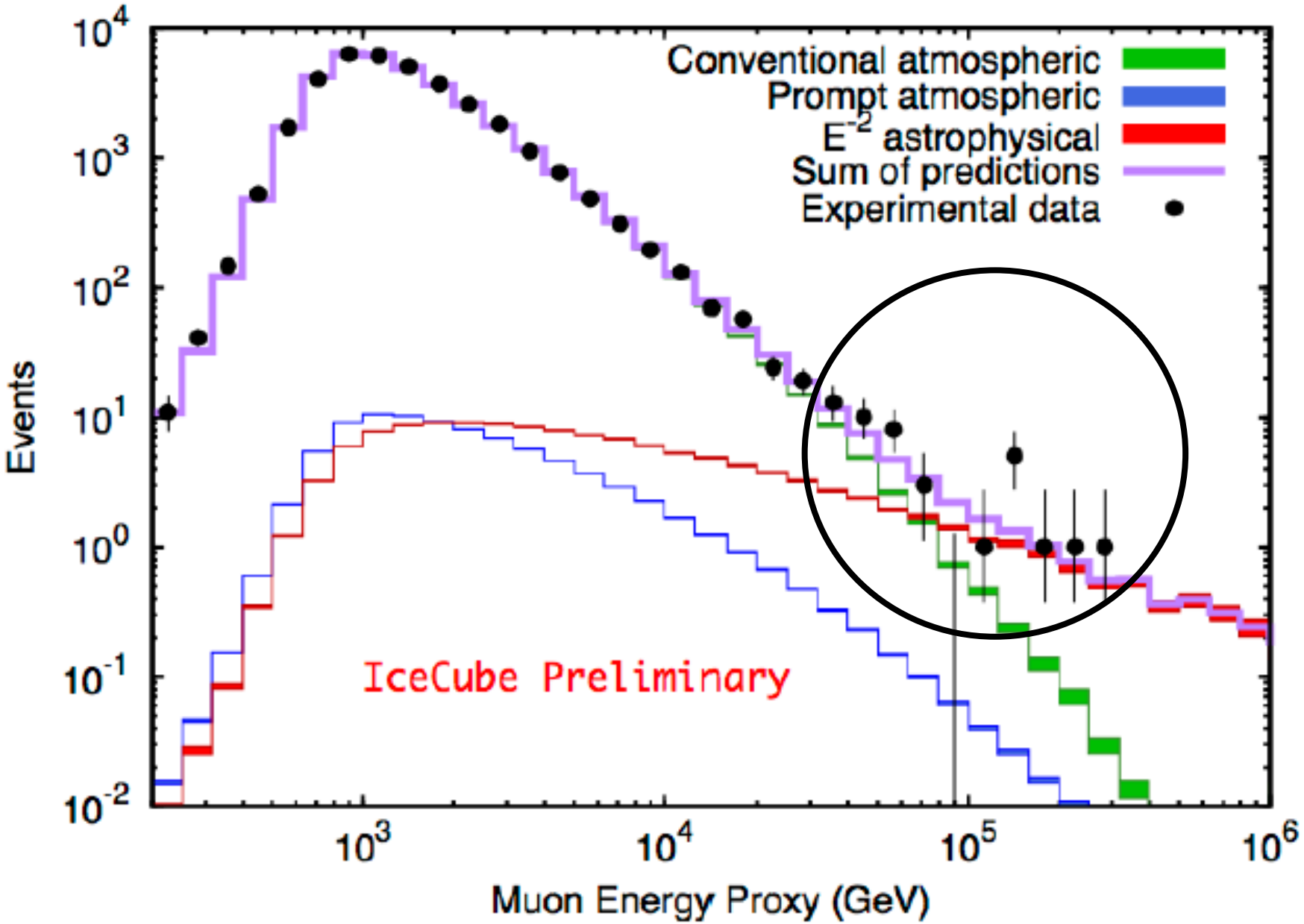
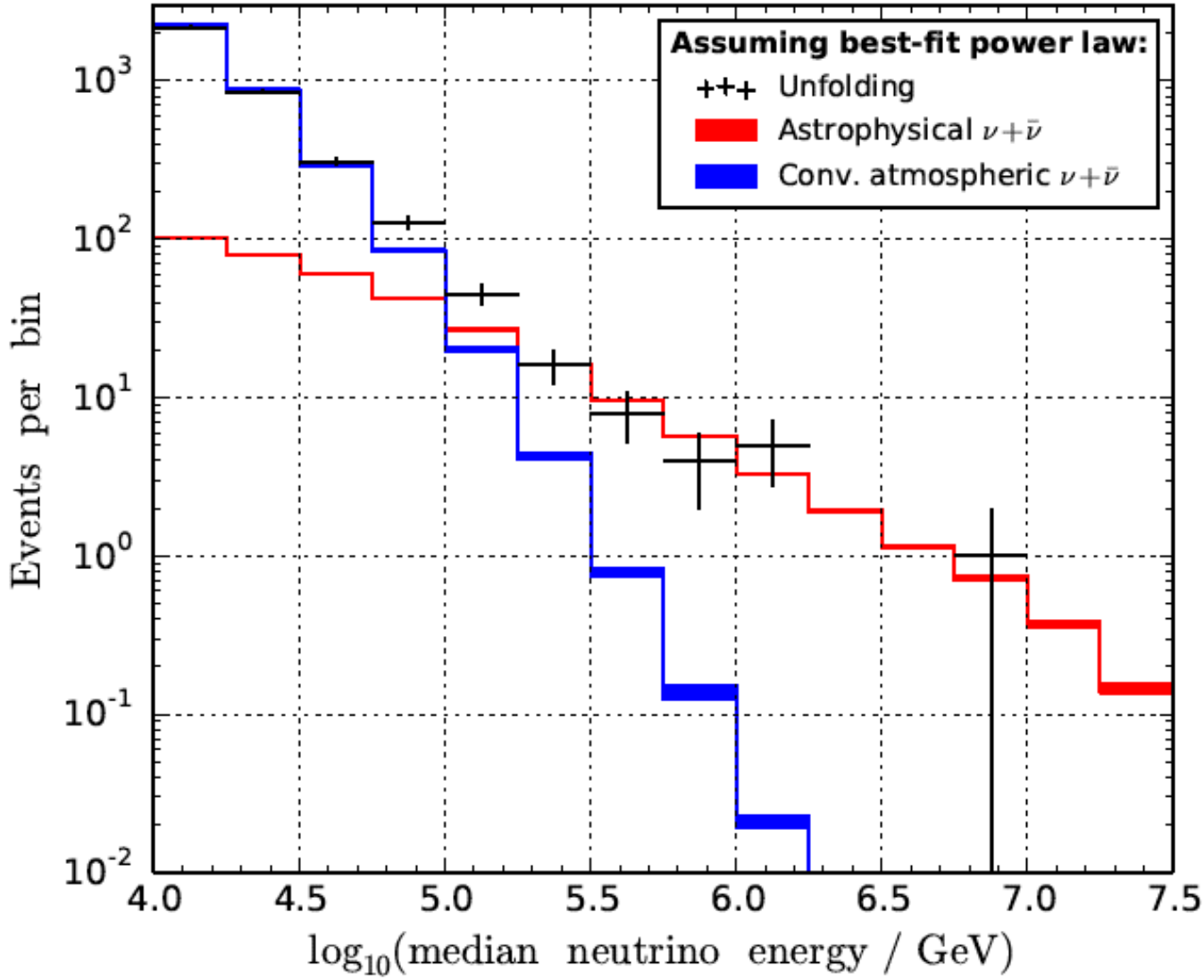

• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
• lattice of photomultipliers
neutrino

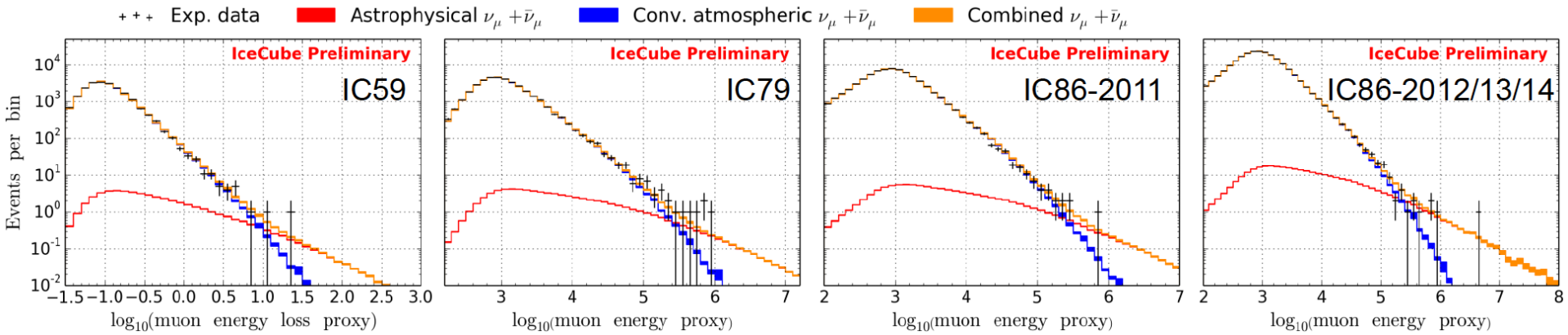
cosmic neutrinos in 2 years of data at 3.7 sigma

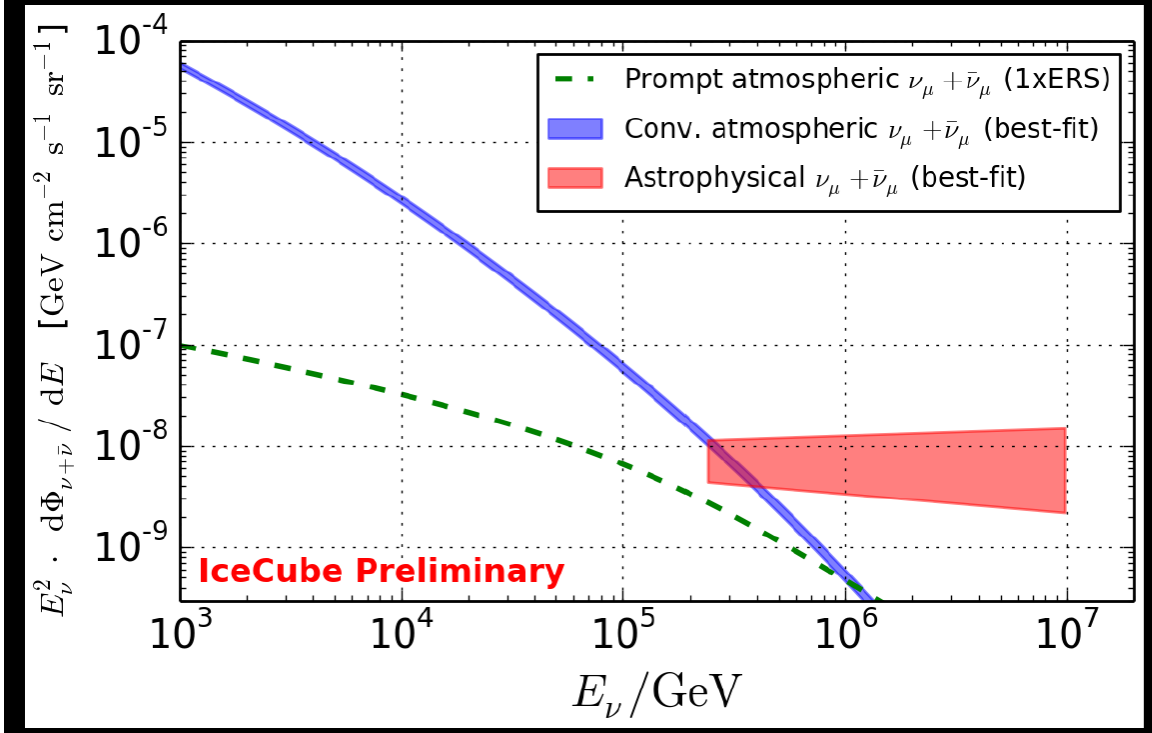


muon neutrinos through the Earth → 5.6 sigma



for 5.5 years of data: 3.7→ 6 sigma and E^{-2} above 200 TeV !





- Best-fit astrophysical normalization:

  $(0.9^{+0.3}_{-0.25})\ 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

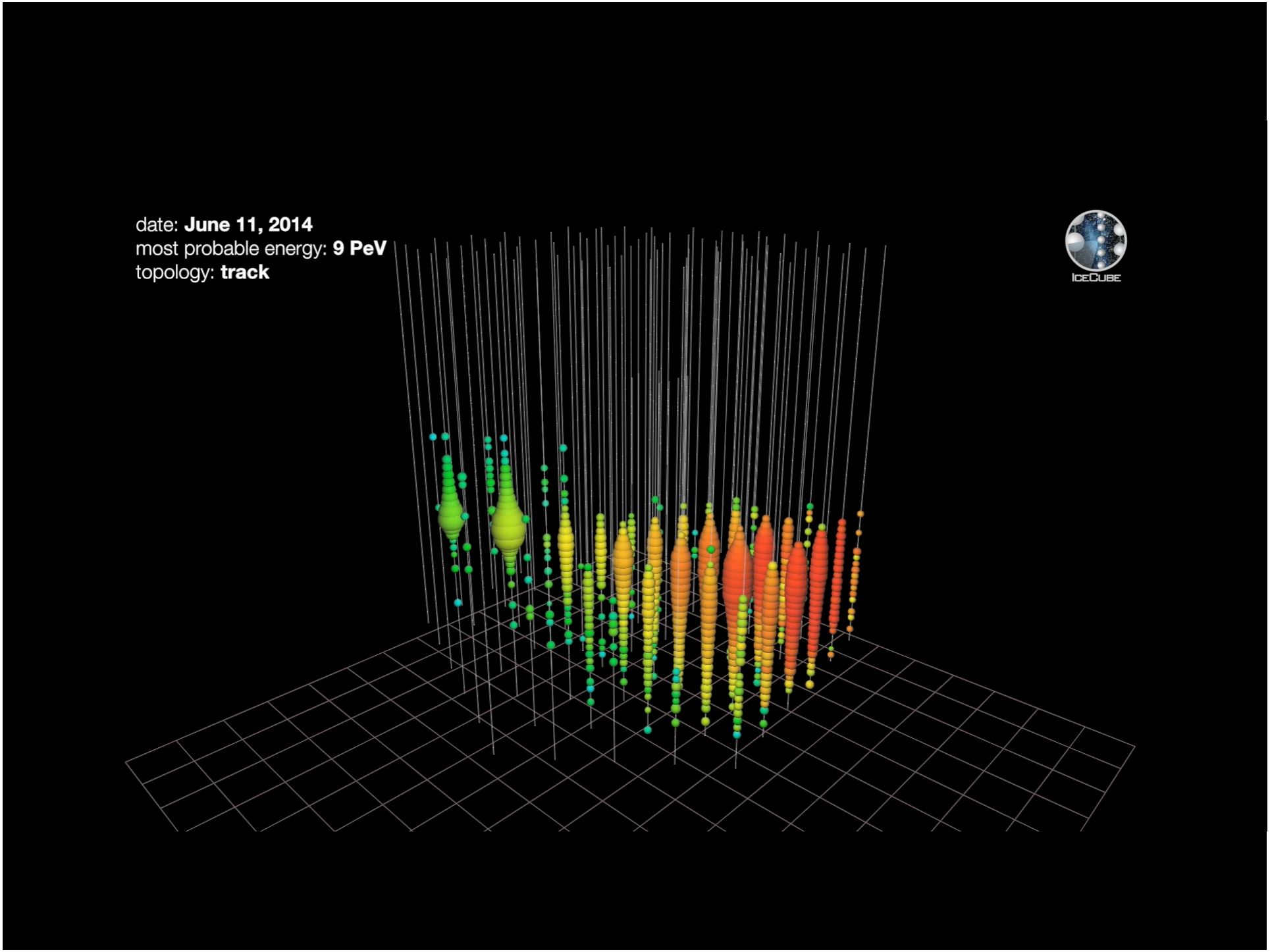
- Best-fit spectral index:

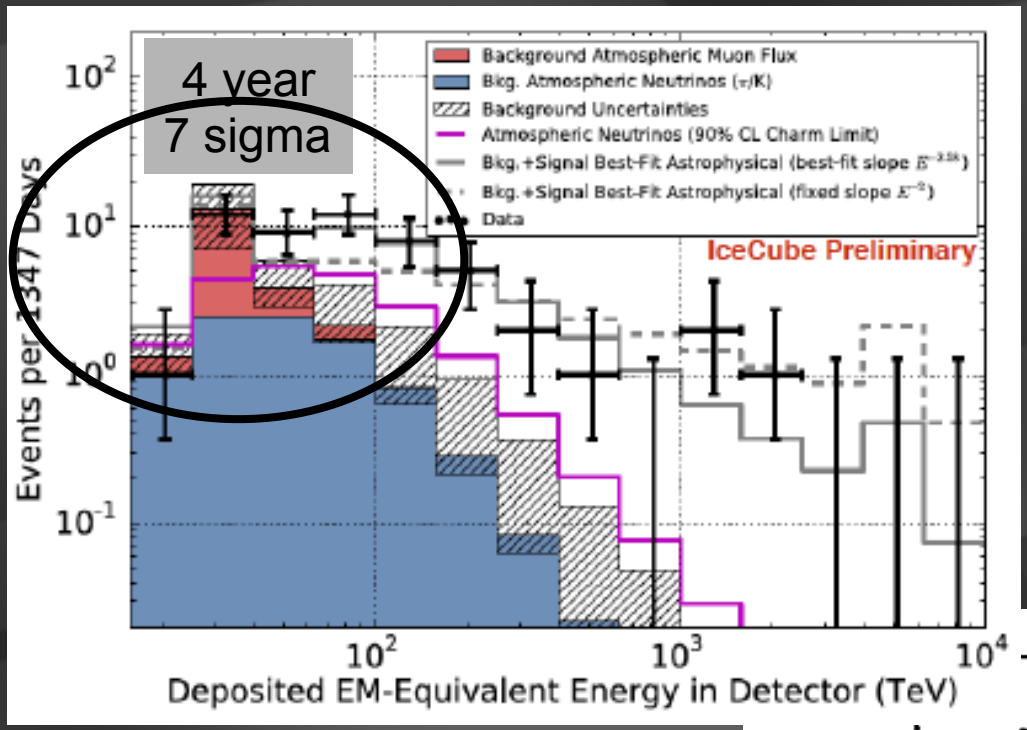
  $\gamma_{\mathrm{astro}} = 2.13 \pm 0.13$

- Energy ranges:

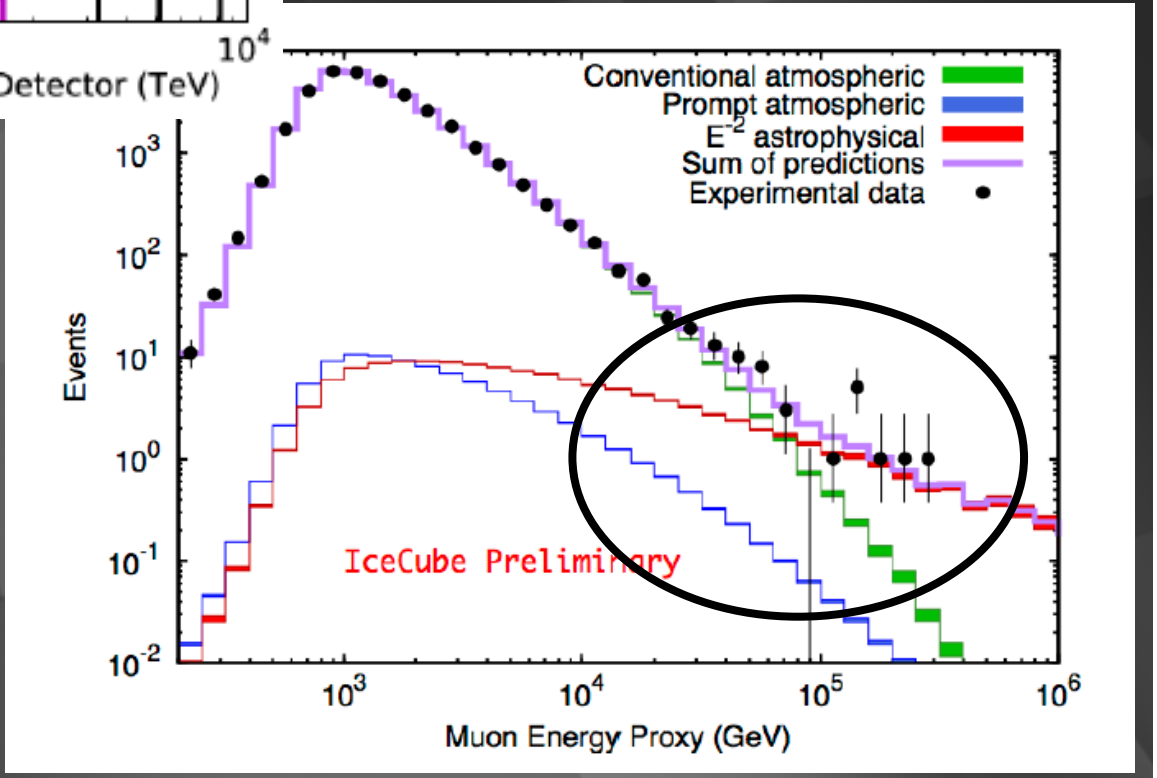
  $240\ \mathrm{TeV} - 10\ \mathrm{PeV}$

- Atmospheric-only hypothesis excluded by 6.0σ


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



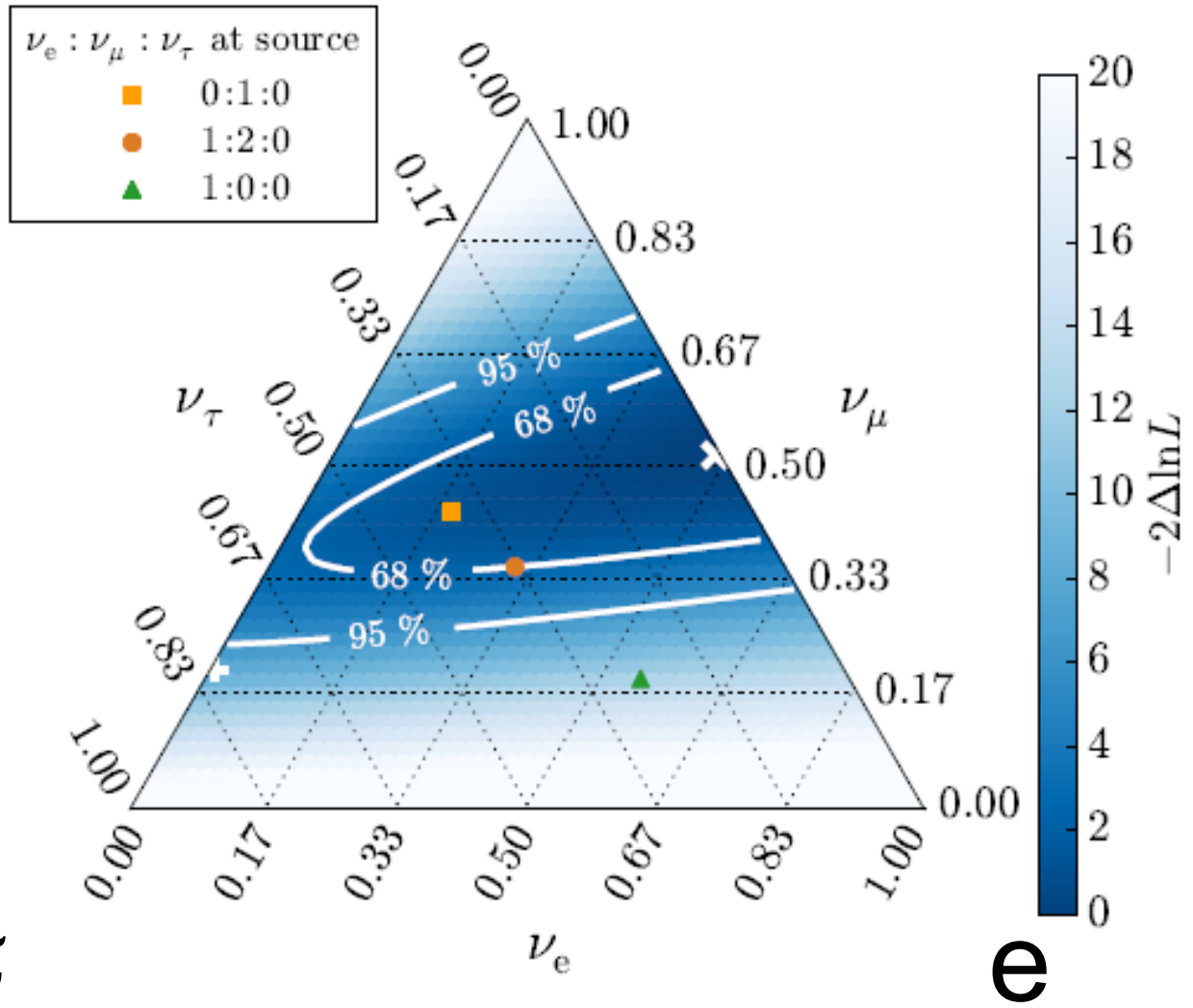
confirmation!
flux of muon neutrinos
through the Earth



neutrinos of all flavors
interacting inside
IceCube

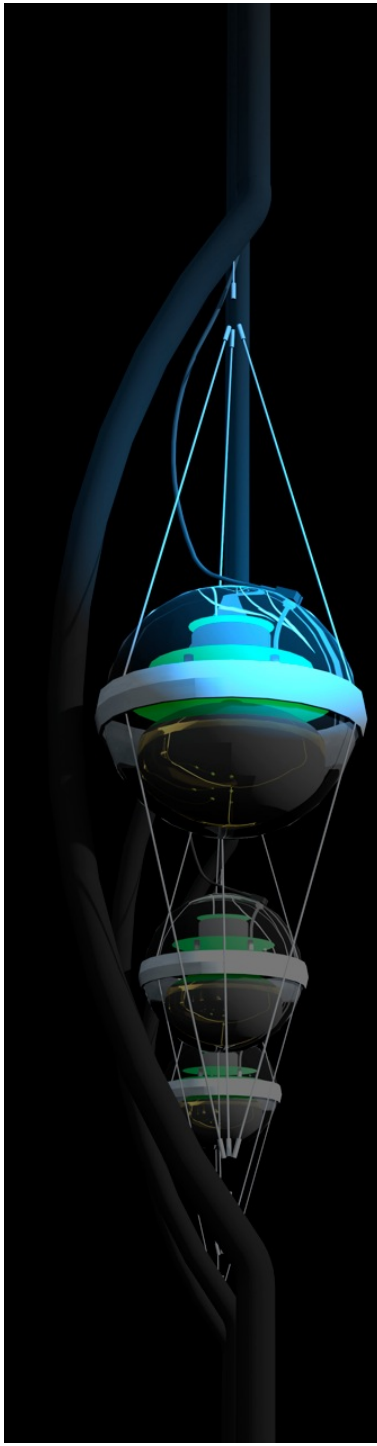
oscillate over cosmic distances to 1:1:1

μ



τ

e



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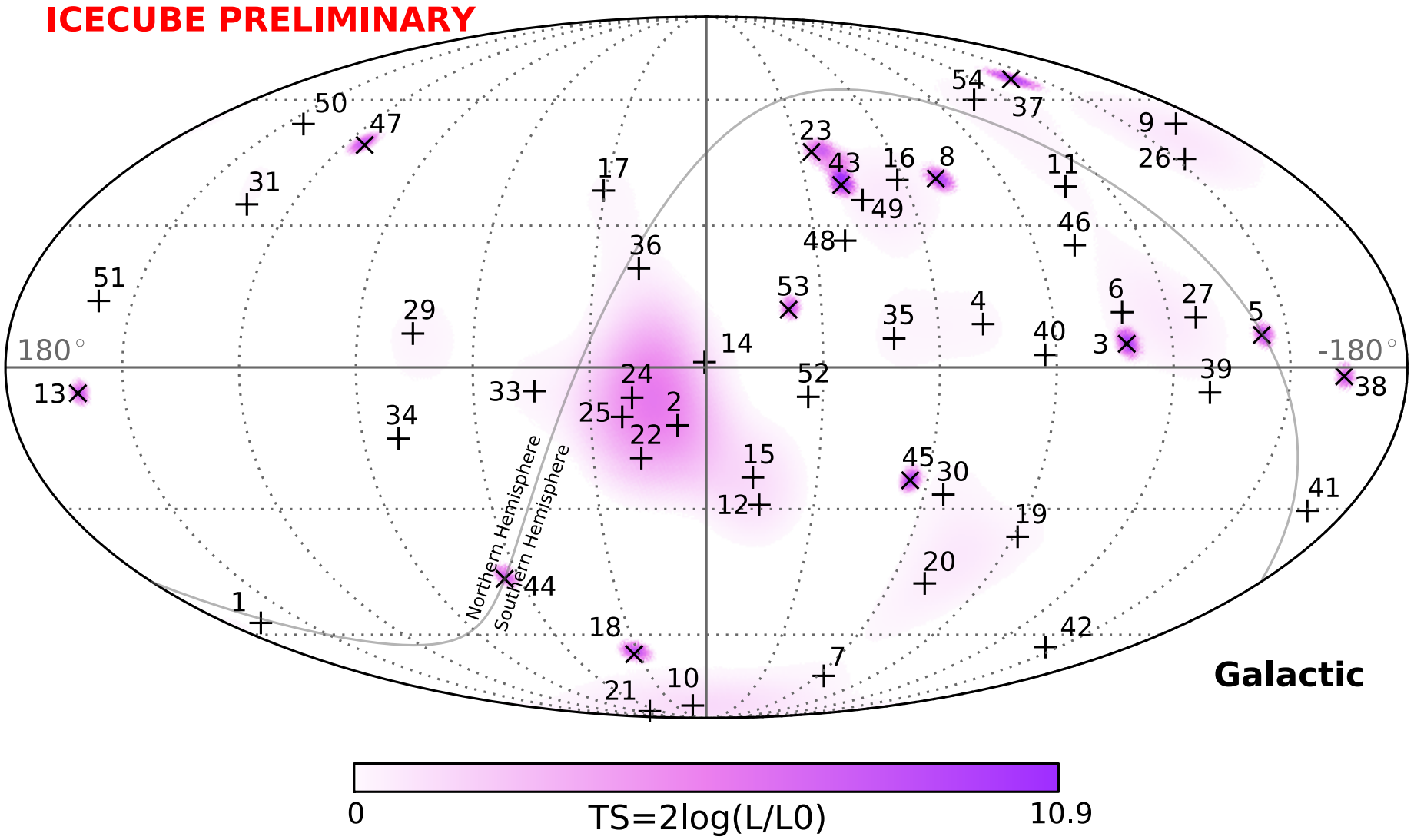
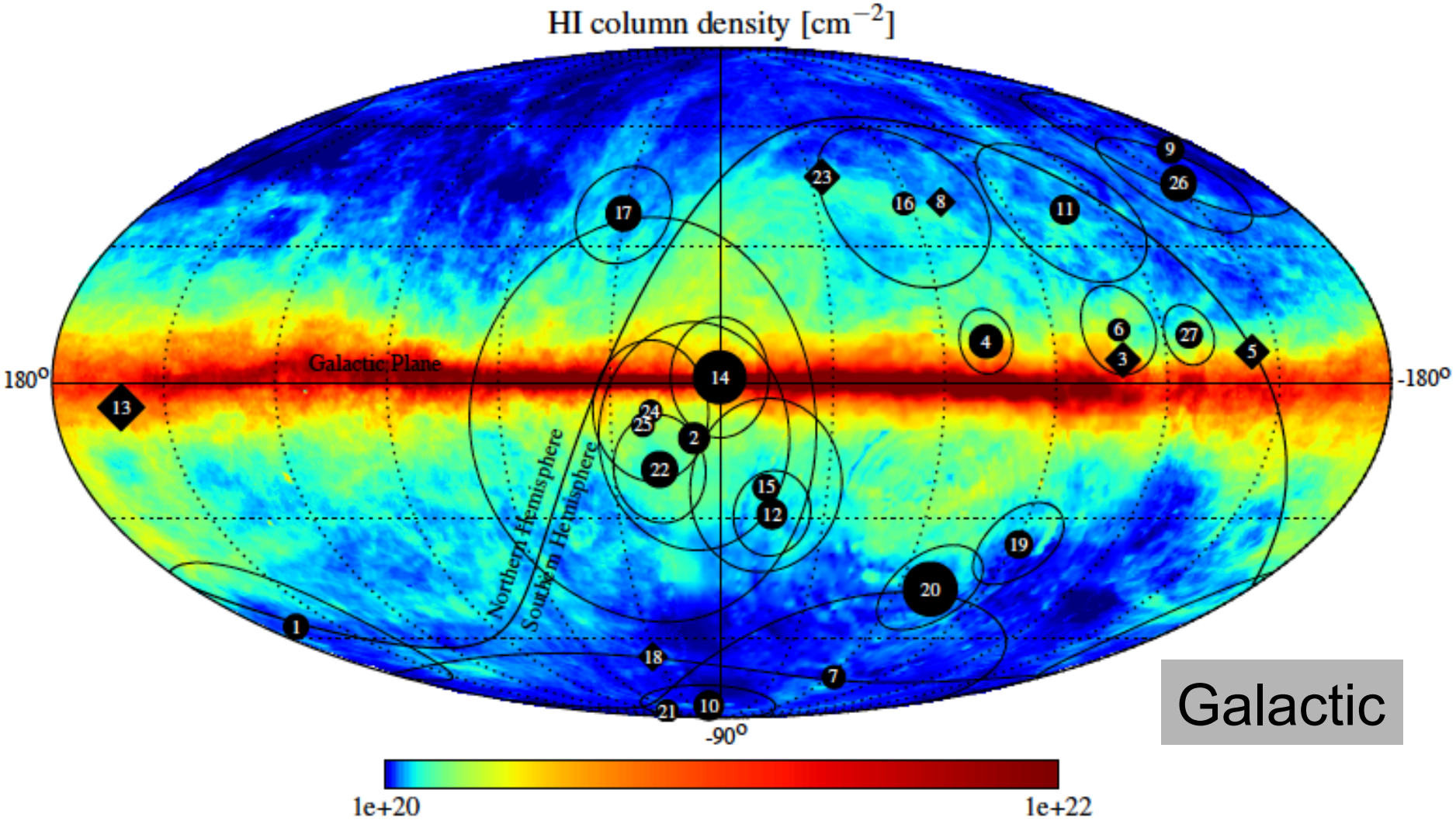
4 year HESE

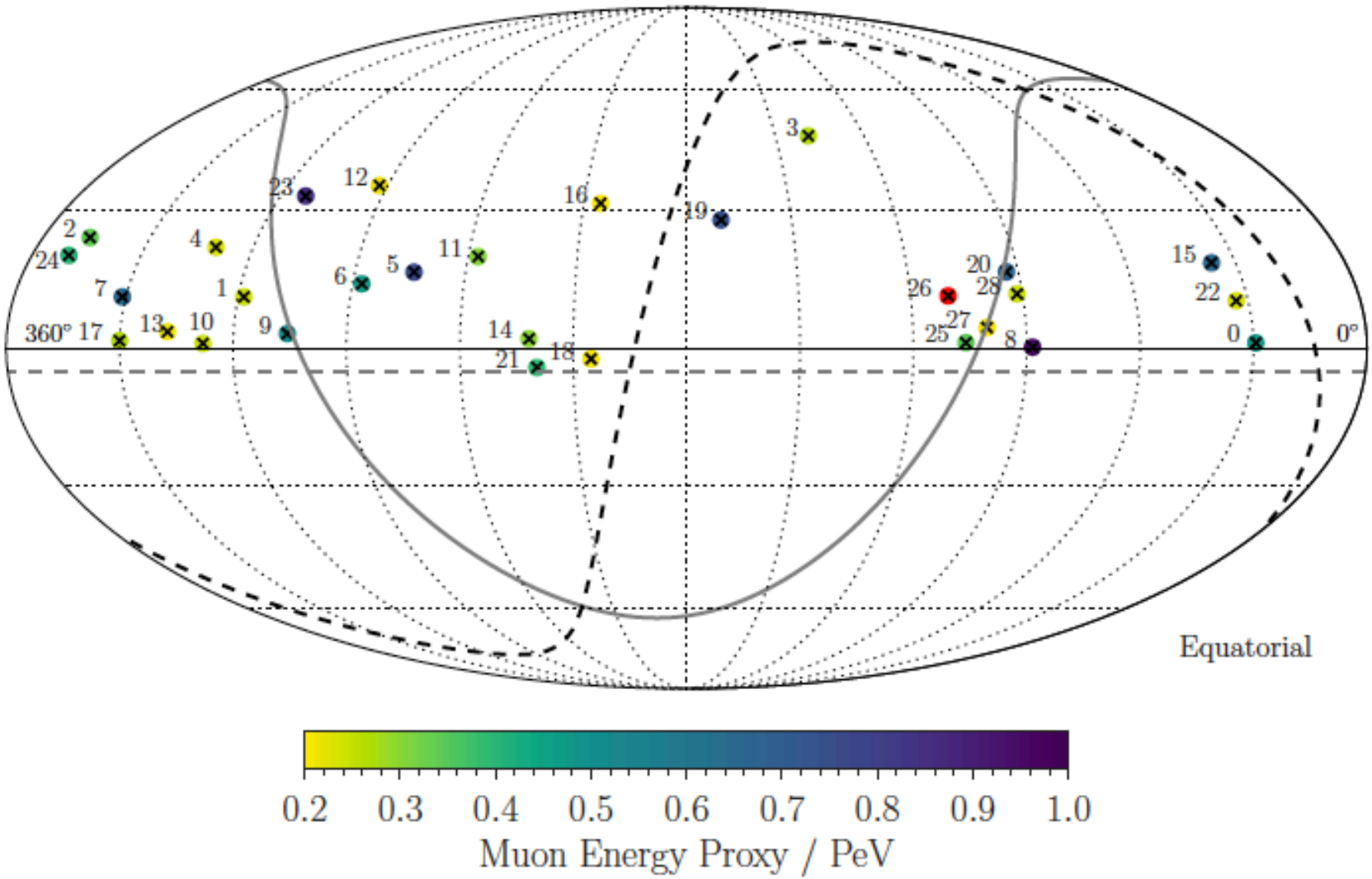


where do they come from?

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

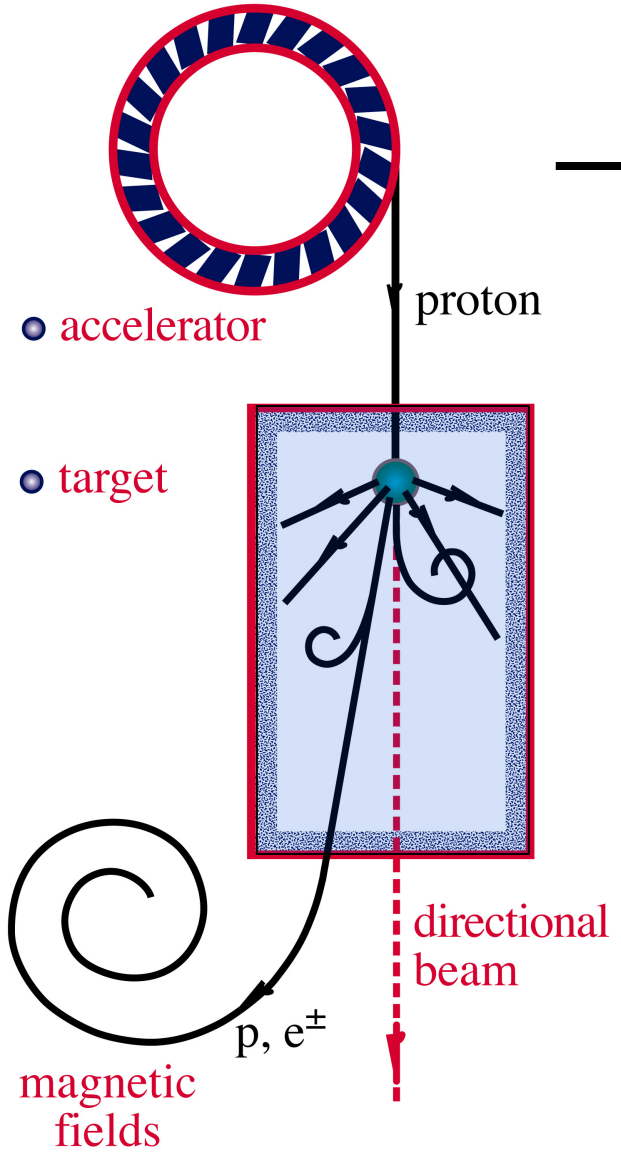


equatorial map of muon neutrinos reconstructed with 0.3 degree resolution



- 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

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

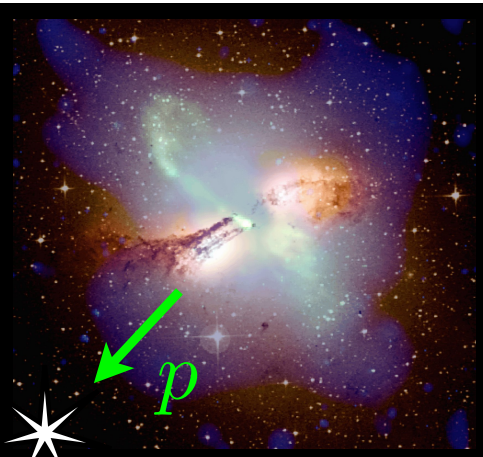
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

hadronic gamma rays ?

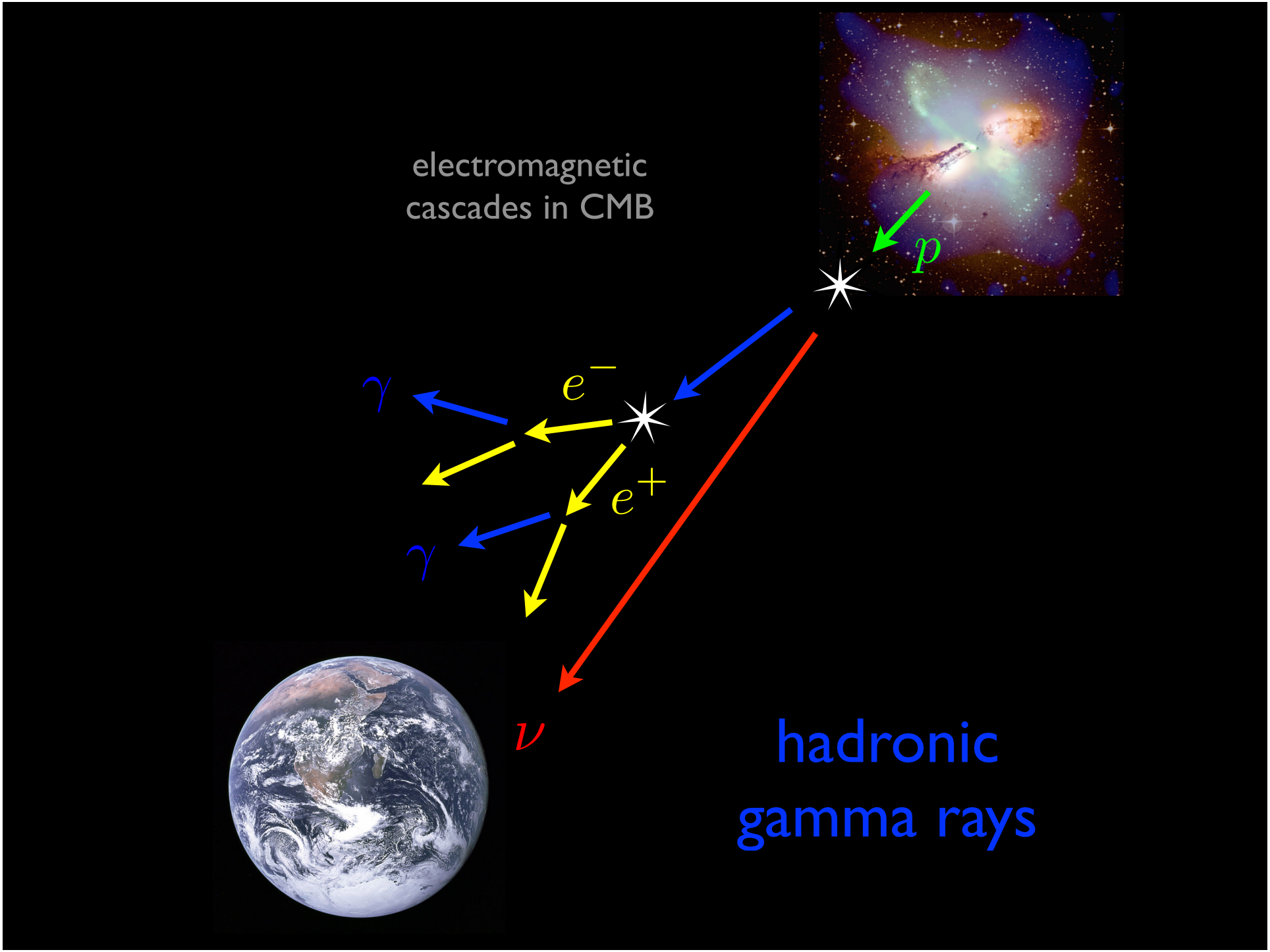
$\pi^+ = \pi^- = \pi^0$

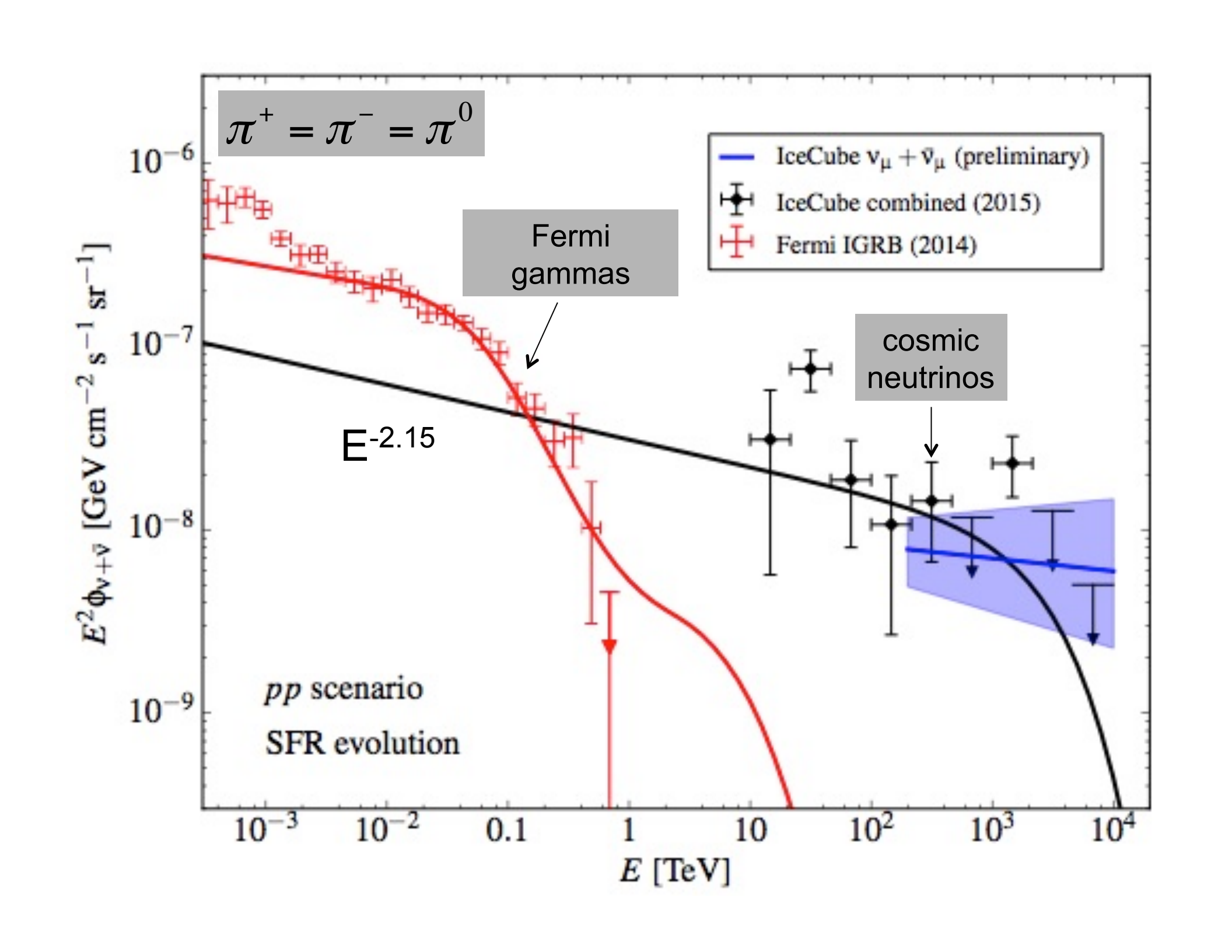


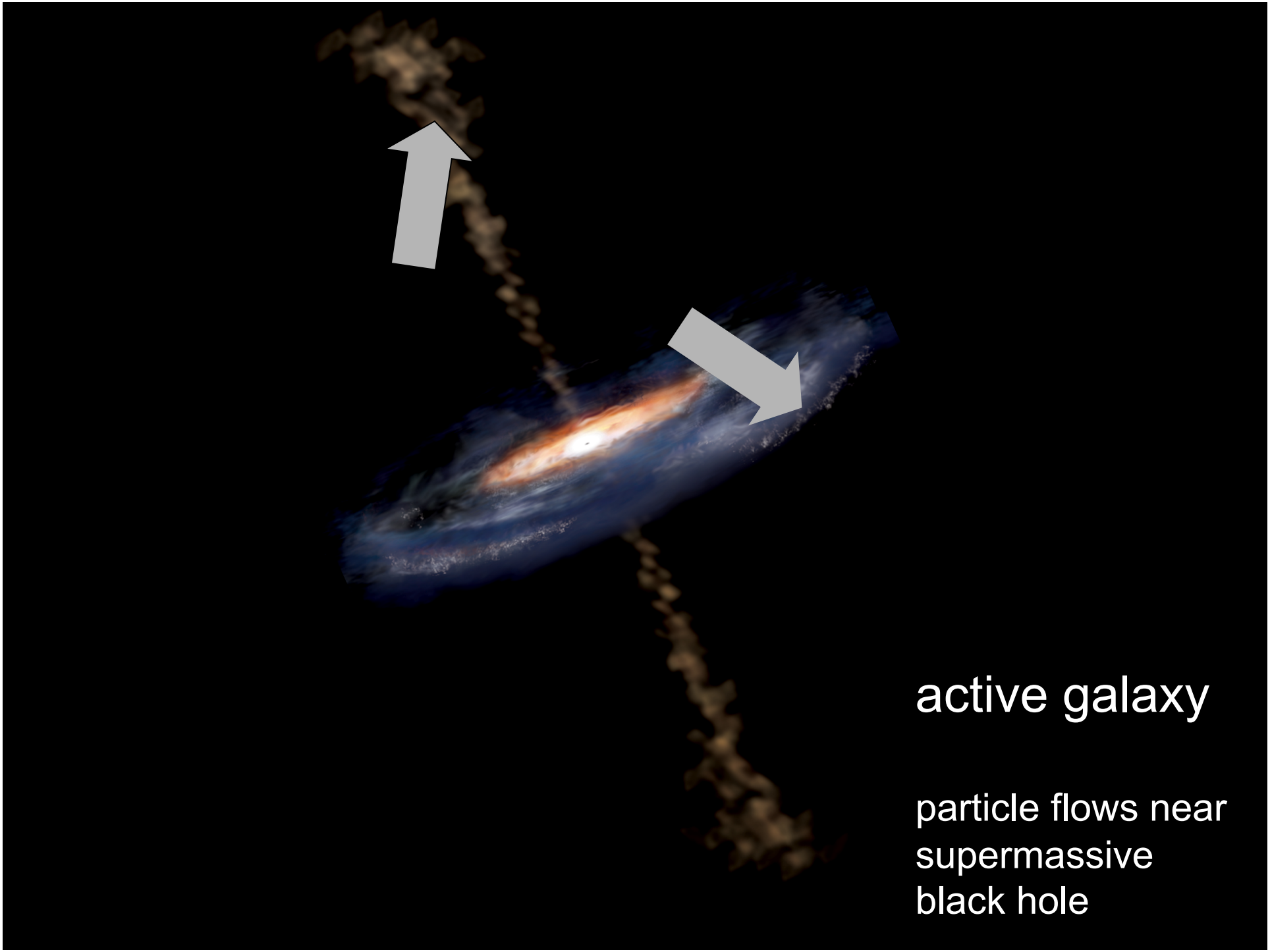
γ

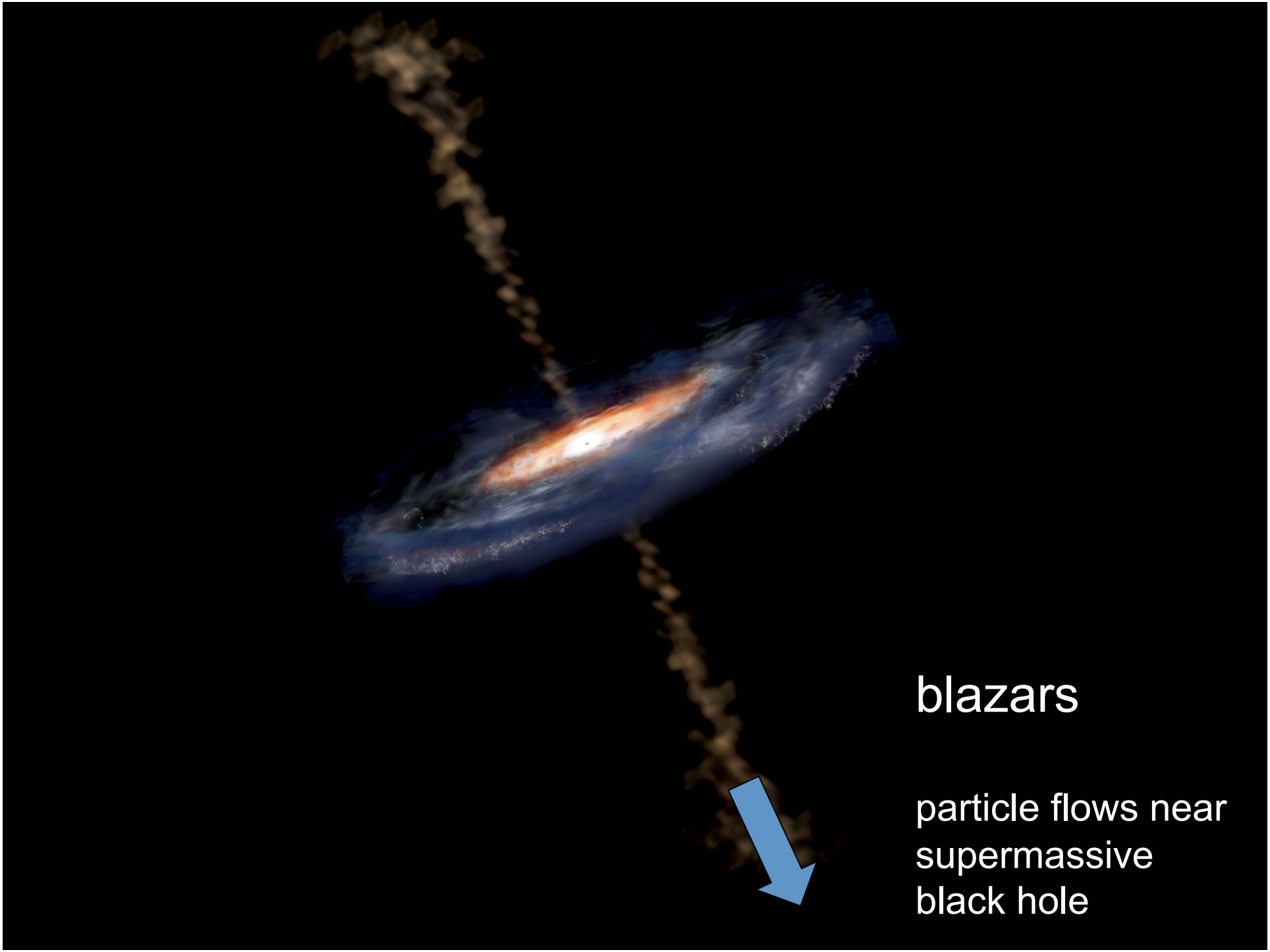
ν

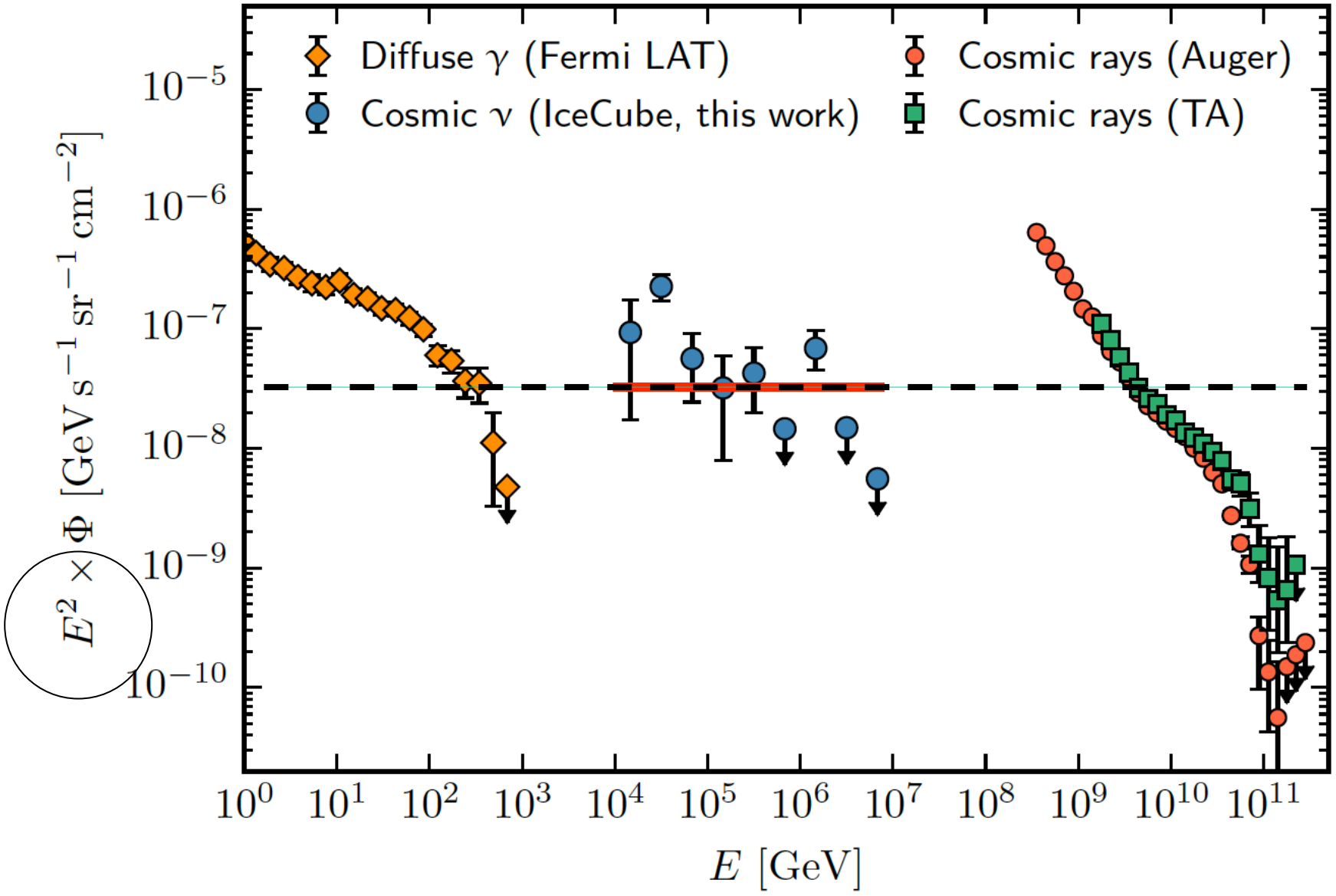
hadronic
gamma rays


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


$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\phi_{\nu+\bar{\nu}}$ [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
10^4


active galaxy
particle flows near
supermassive
black hole


blazars
particle flows near
supermassive
black hole



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

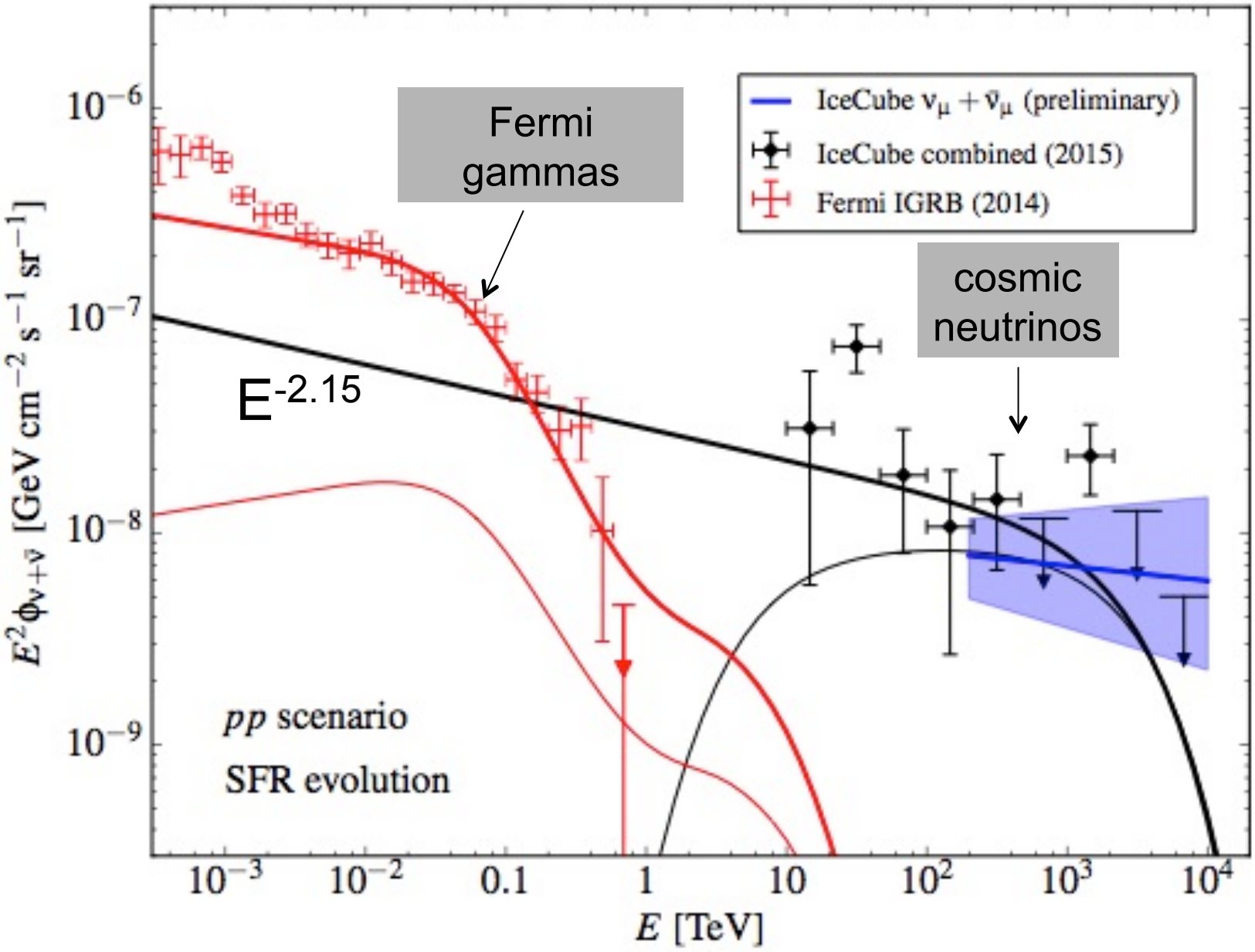
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

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

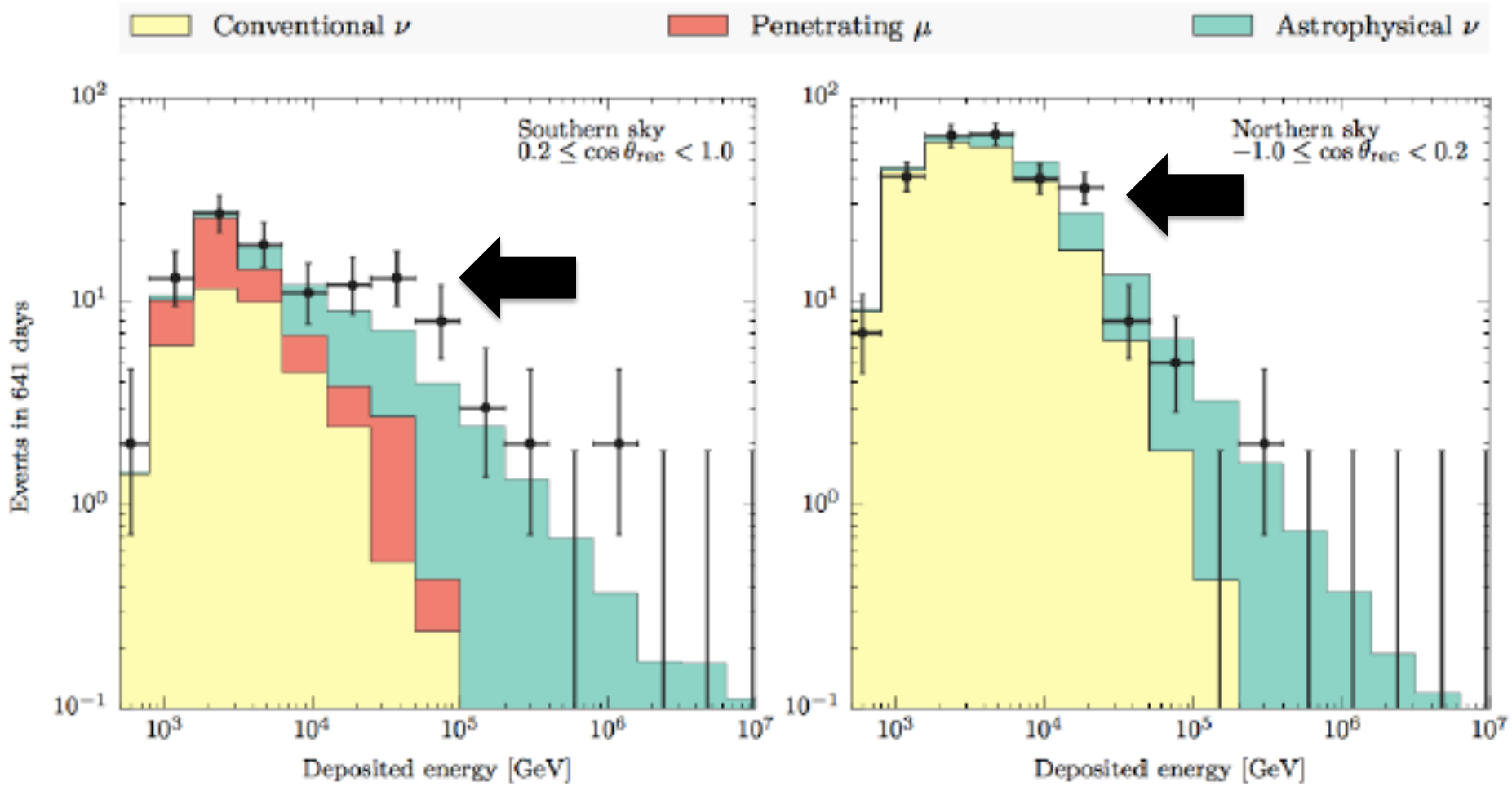
- at some level common Fermi-IceCube sources: galaxies (blazars? see talk by M. Ackermann)

- there is more

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

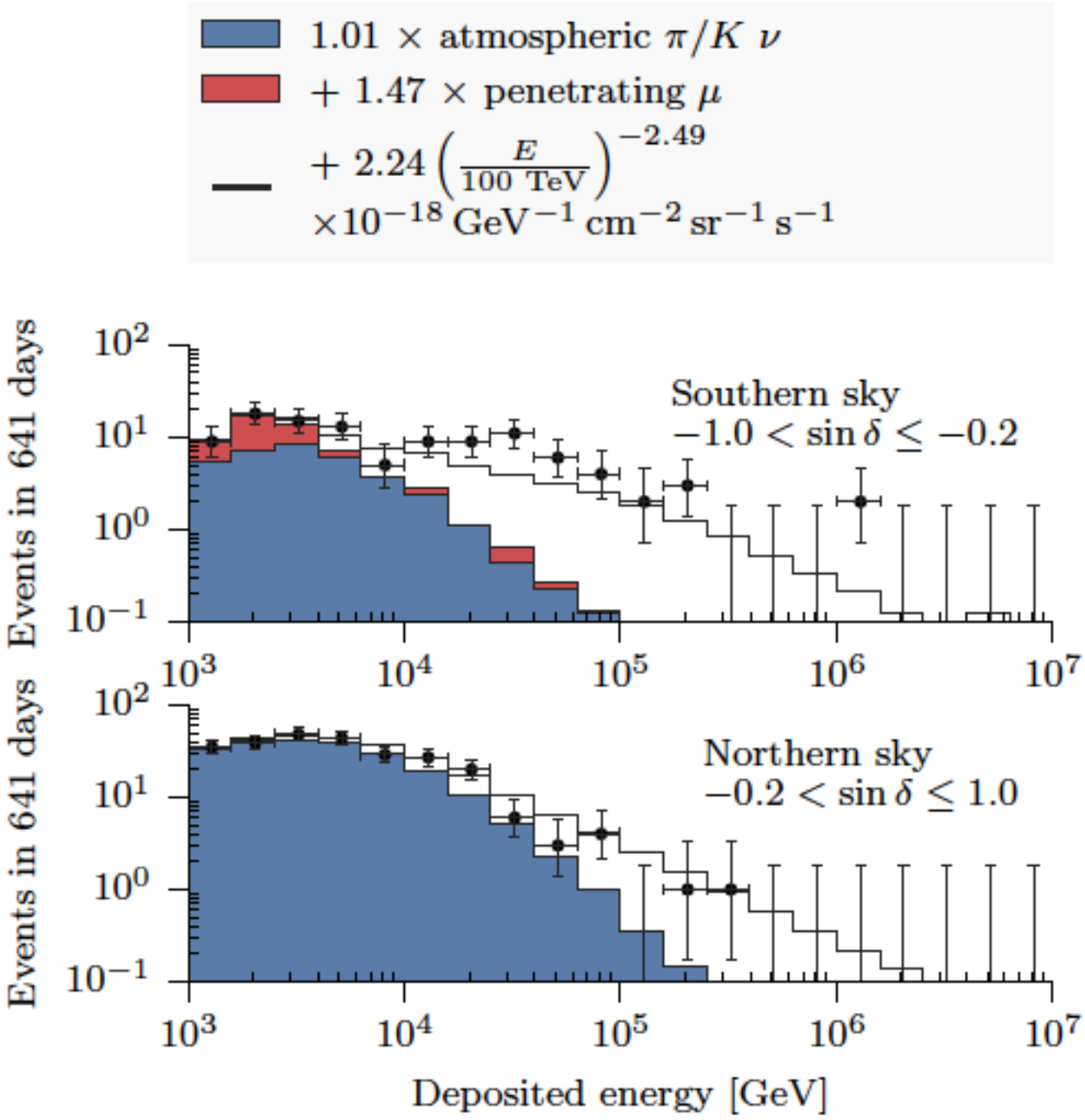

Fermi gammas
cosmic neutrinos
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
10^4

towards lower energies: a second component?

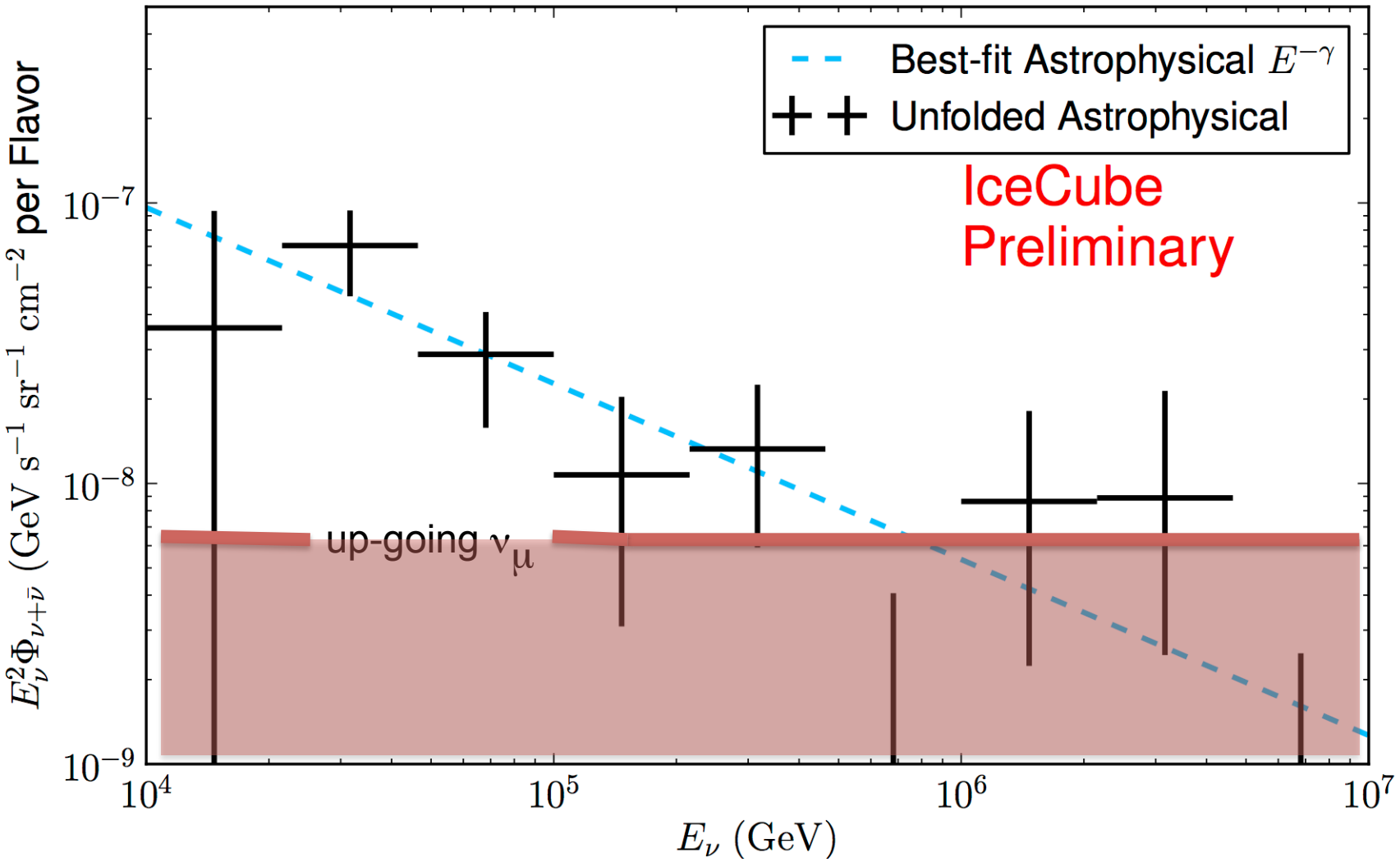


warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
$+ 2.24 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.49}$
$\times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$
Southern sky
$-1.0 < \sin\delta \leq -0.2$
Northern sky
$-0.2 < \sin\delta \leq 1.0$
Events in 641 days
Events in 641 days
Deposited energy [GeV]

yet lower energies….



did not talk about:

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

Conclusions

- more to come from IceCube: many analyses have not exploited more than one year of data
- analyses are not in the background-dominated regime
- next-generation detector Gen-2: 10 km^3

    1. discovery → astronomy (also KM3NeT, GVD)
    2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
    3. potential for discovery

- neutrinos are never boring!

The IceCube–PINGU Collaboration

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