Which flavour do you want your neutrino? A conversation over ice cream
21 August 2019, CERN

Astrophysical neutrinos and neutrino telescopes

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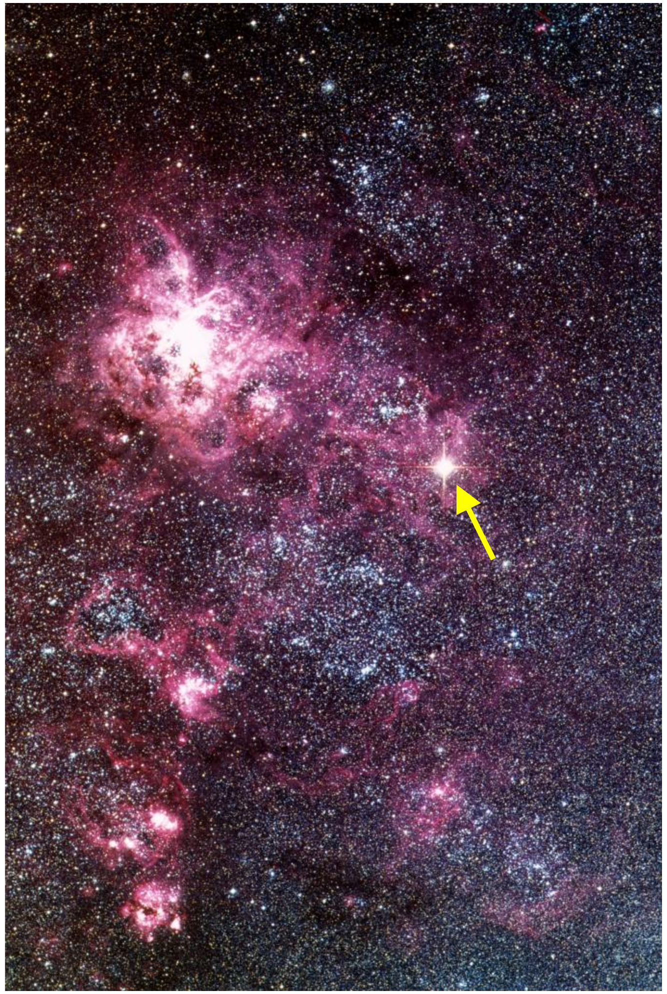
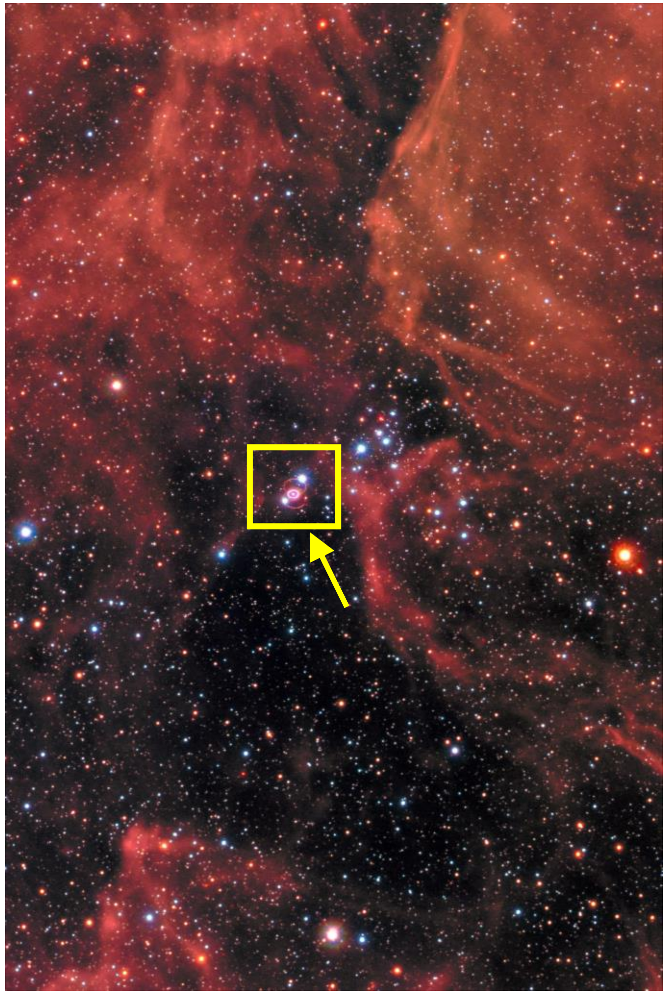
DPNC, University of Geneva

Contents

- Neutrinos as messengers
- How large a neutrino telescope?
- The discovery of cosmic neutrinos
- Where do they come from?

The birth of neutrino astronomy: supernova 1987 A





- 1987: SN1987A explosion in Large Magellanic cloud resulted in 25 neutrino events

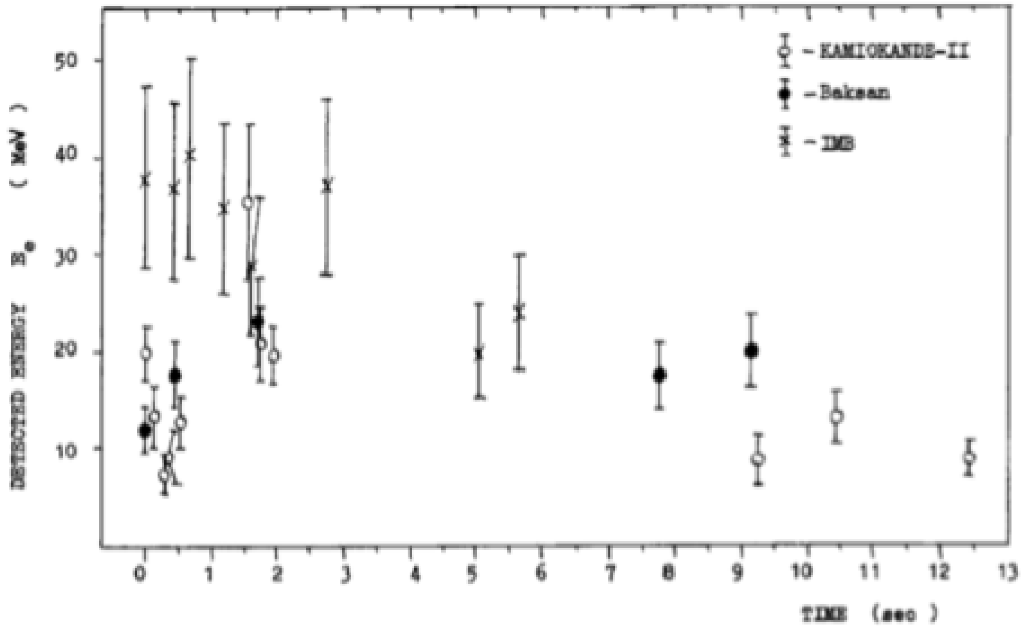
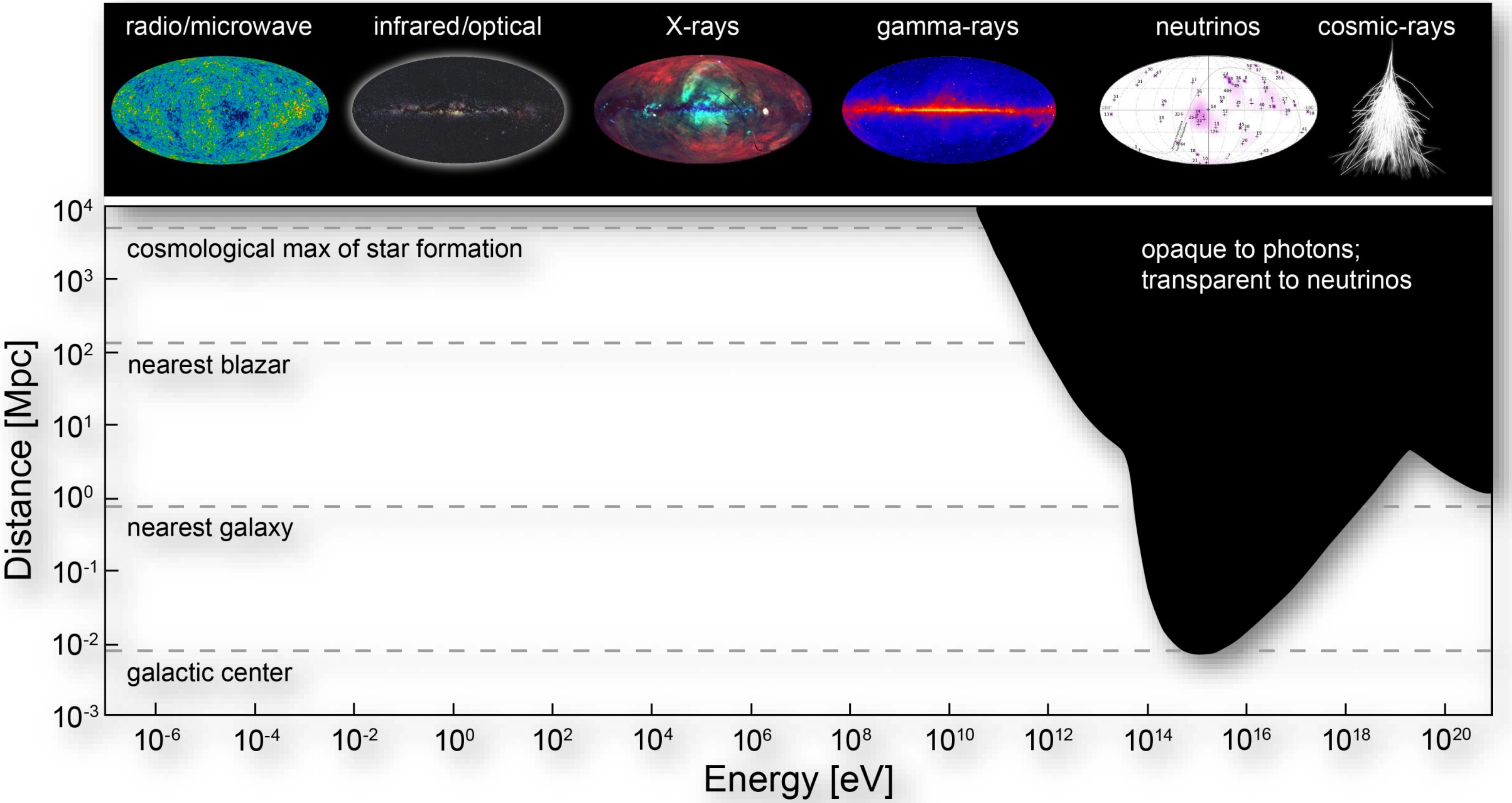


Fig. 3. Energies of all events detected at 7:35 UT on February 23, 1987 versus time. $t=0.0$ is set as to be the time of the first event of each signal observed.

Exploring the extreme universe



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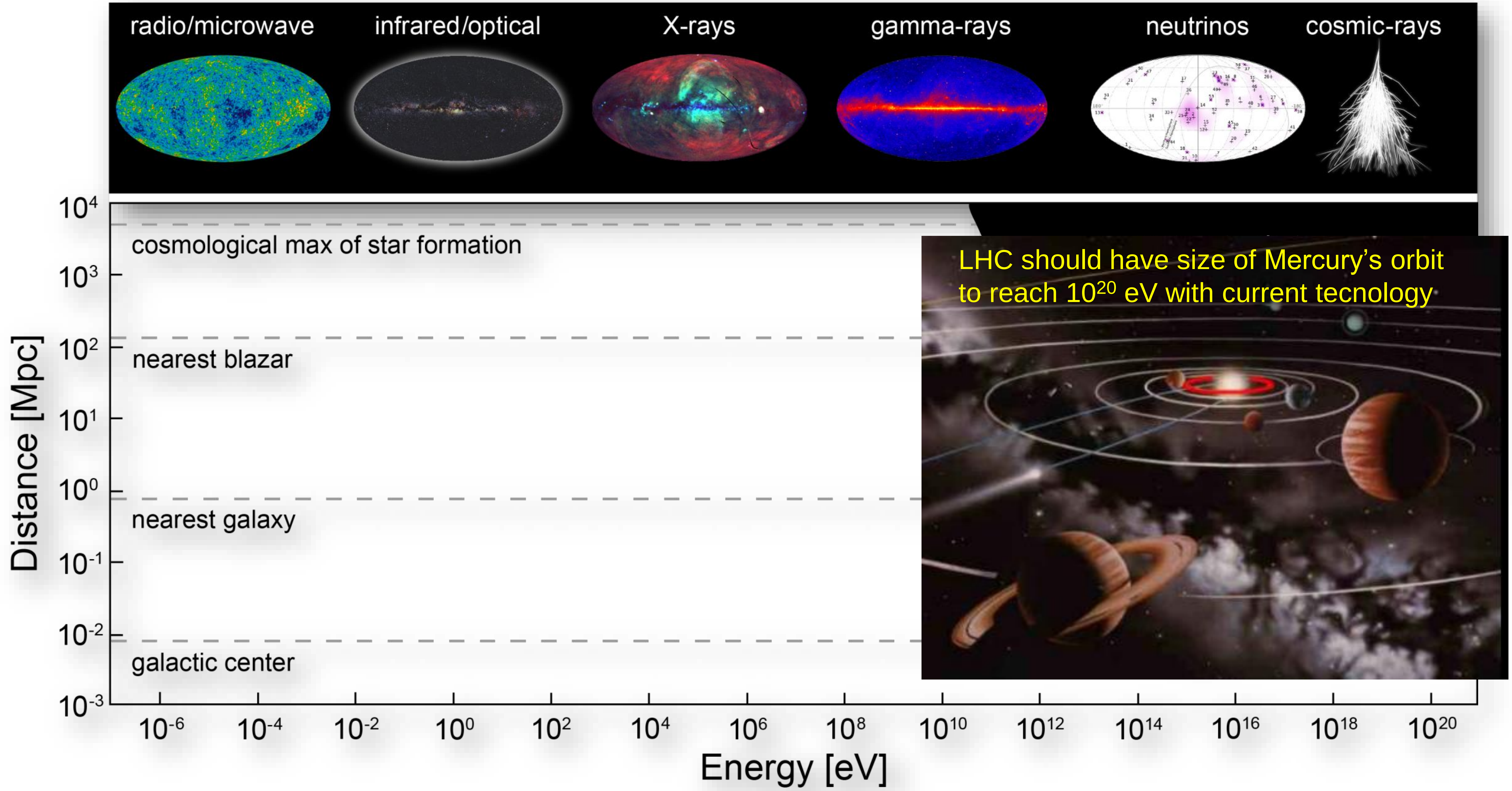
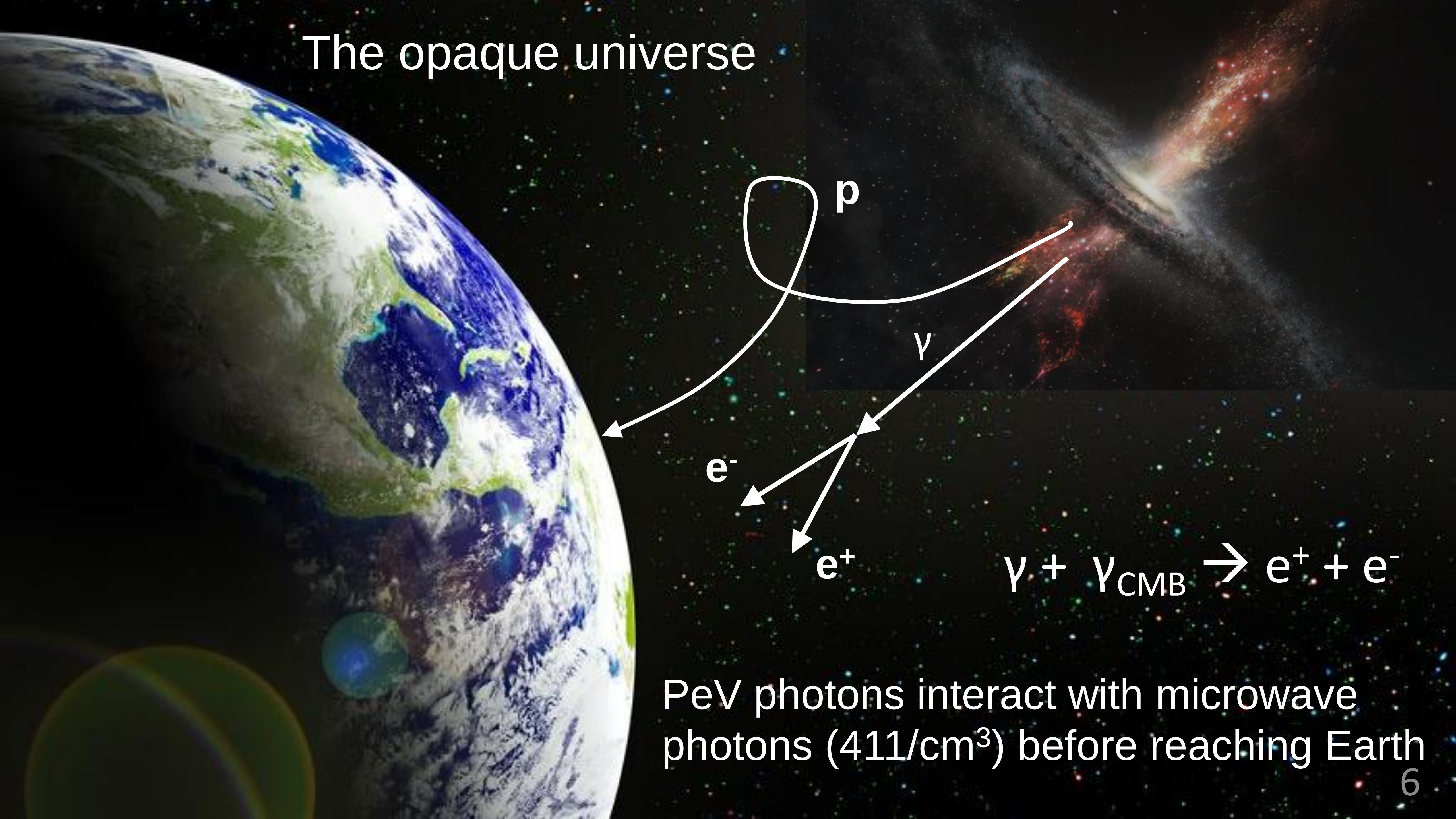


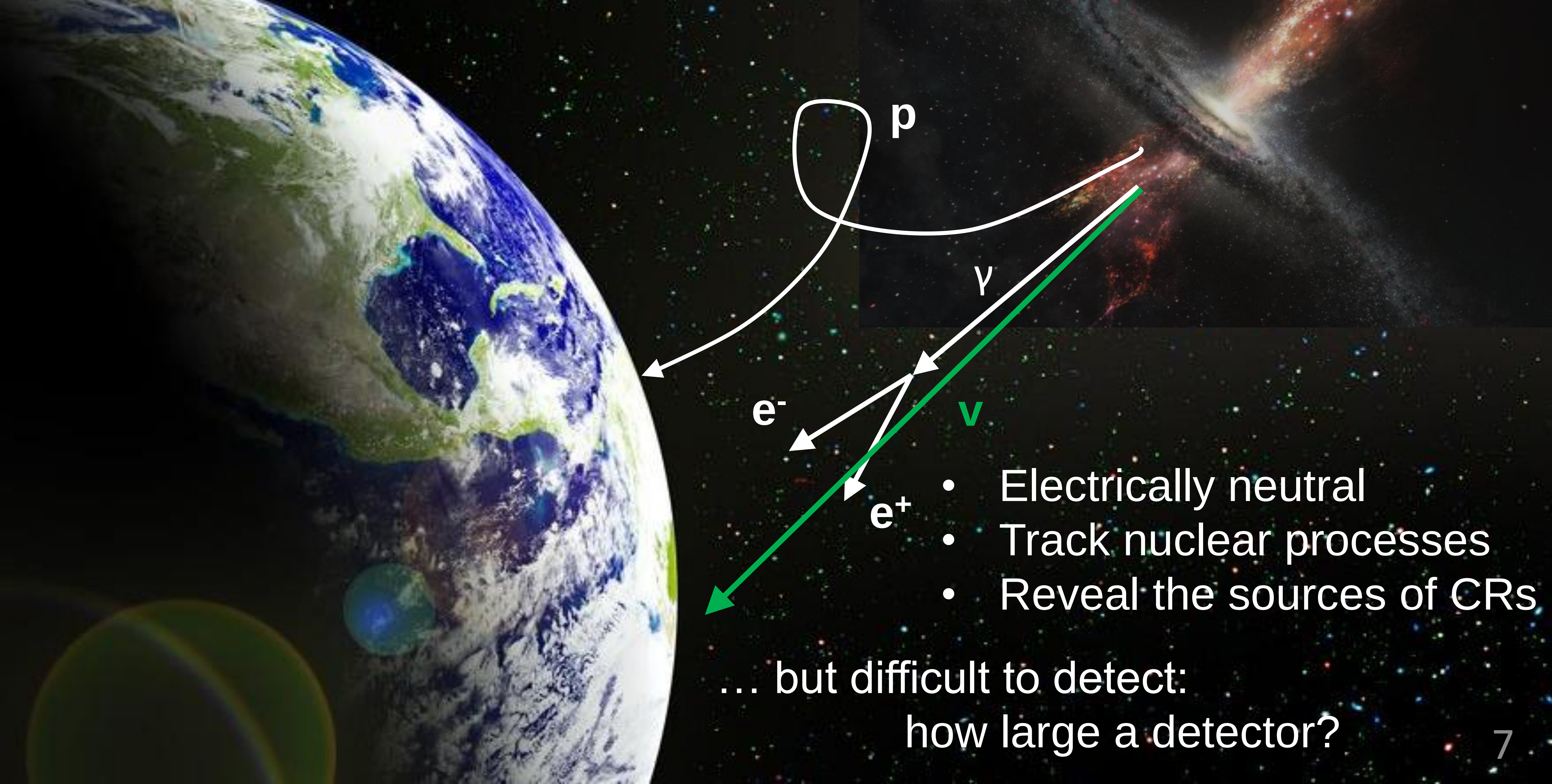
The opaque universe



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

PeV photons interact with microwave photons (411/cm^3) before reaching Earth

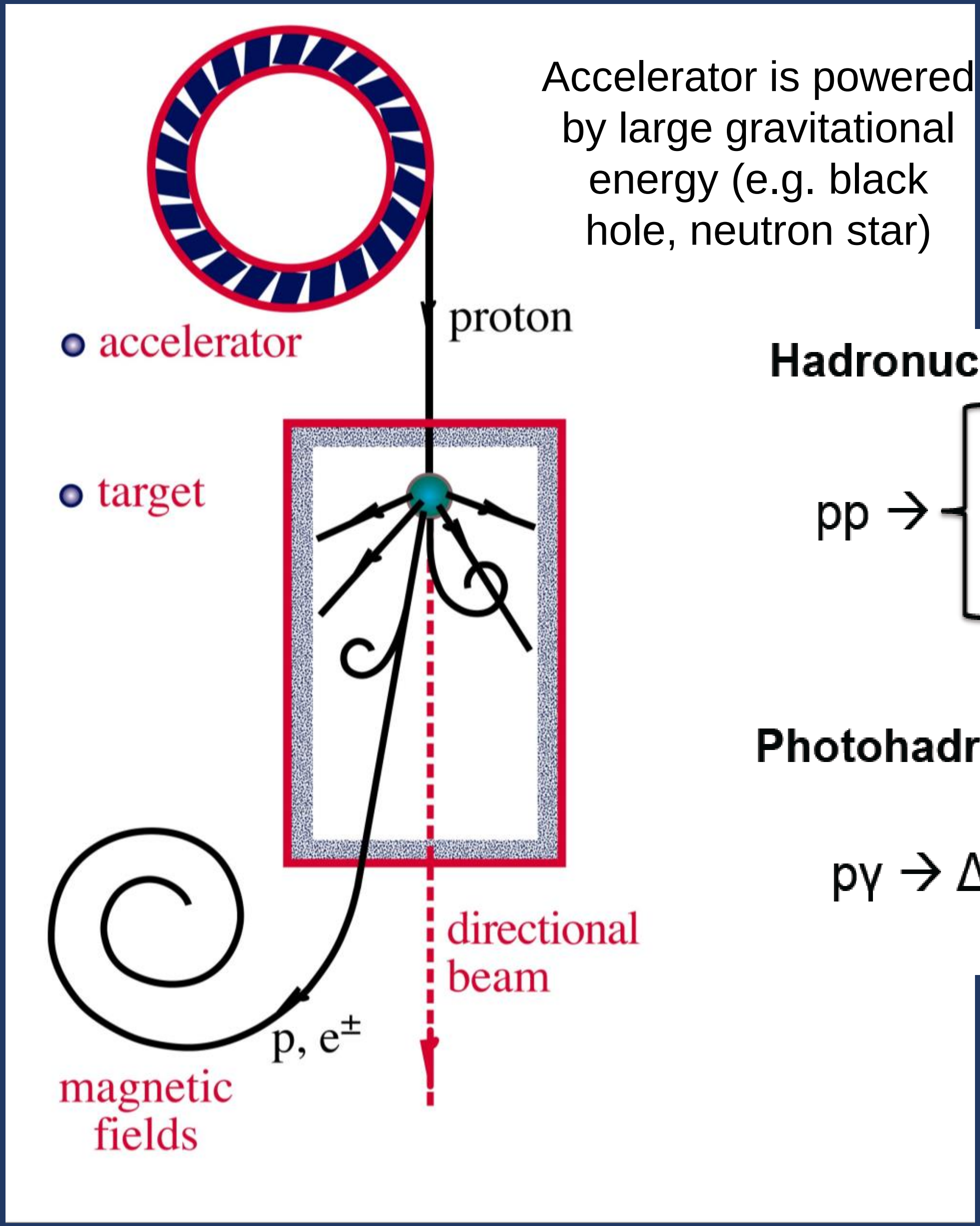
Neutrinos: a probe of the universe



- Electrically neutral
- Track nuclear processes
- Reveal the sources of CRs

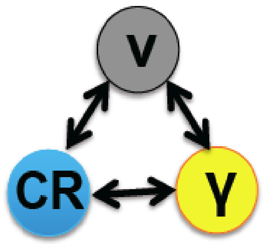
… but difficult to detect:
how large a detector?

The generic messenger Source: the Cosmic Beam Dump



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



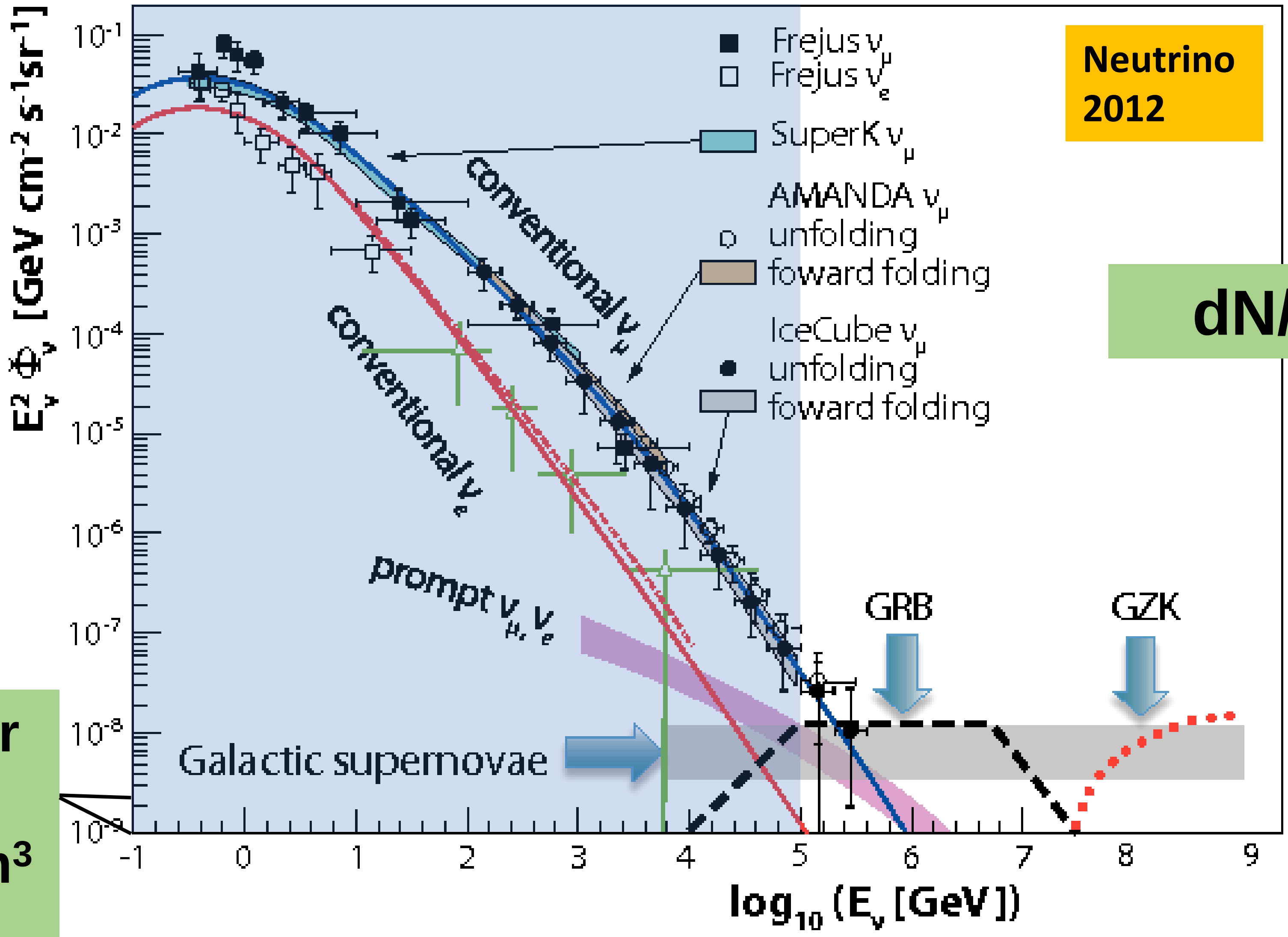
Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Cosmic neutrino fluxes

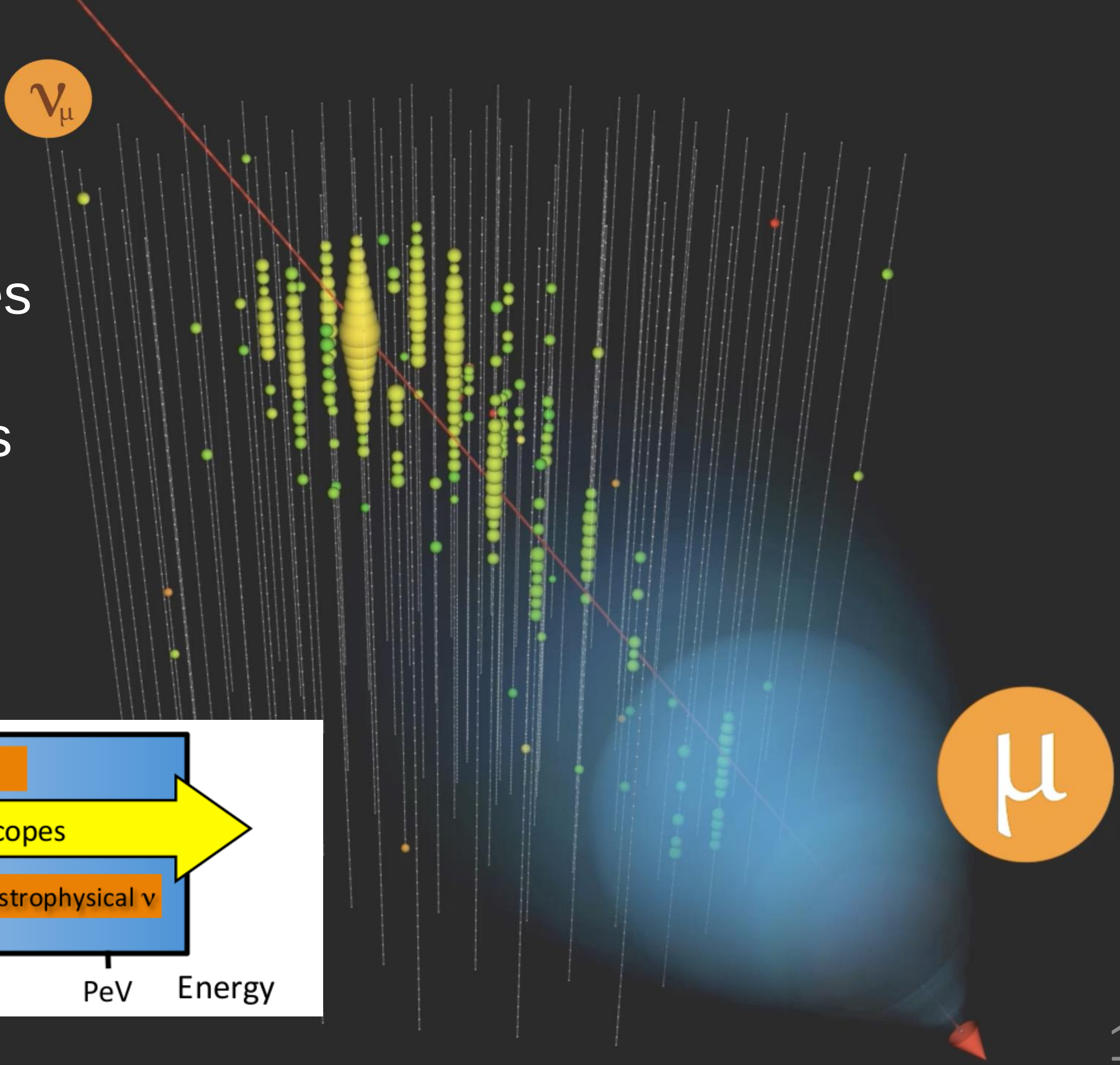


dN/dE ~ E^{-2}

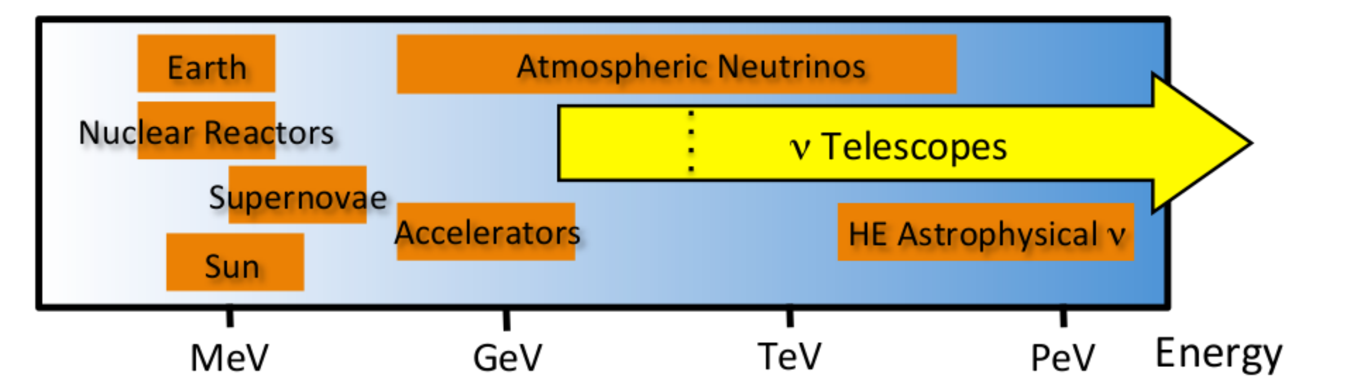
1-10 events/year > 50 TeV for a fully efficient km^3 detector

Atmospheric **50 TeV** **Cosmic**

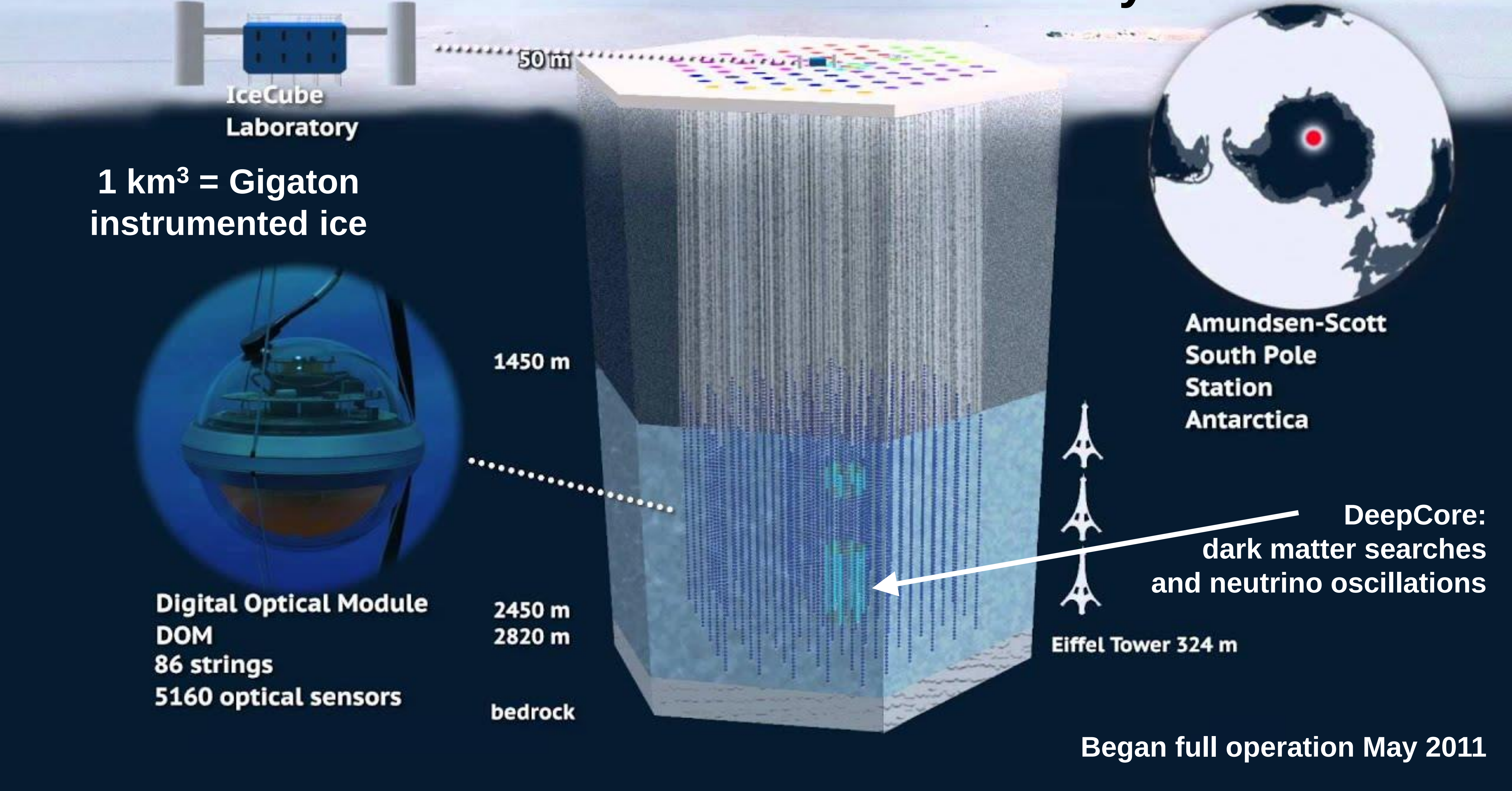
Principle of detection



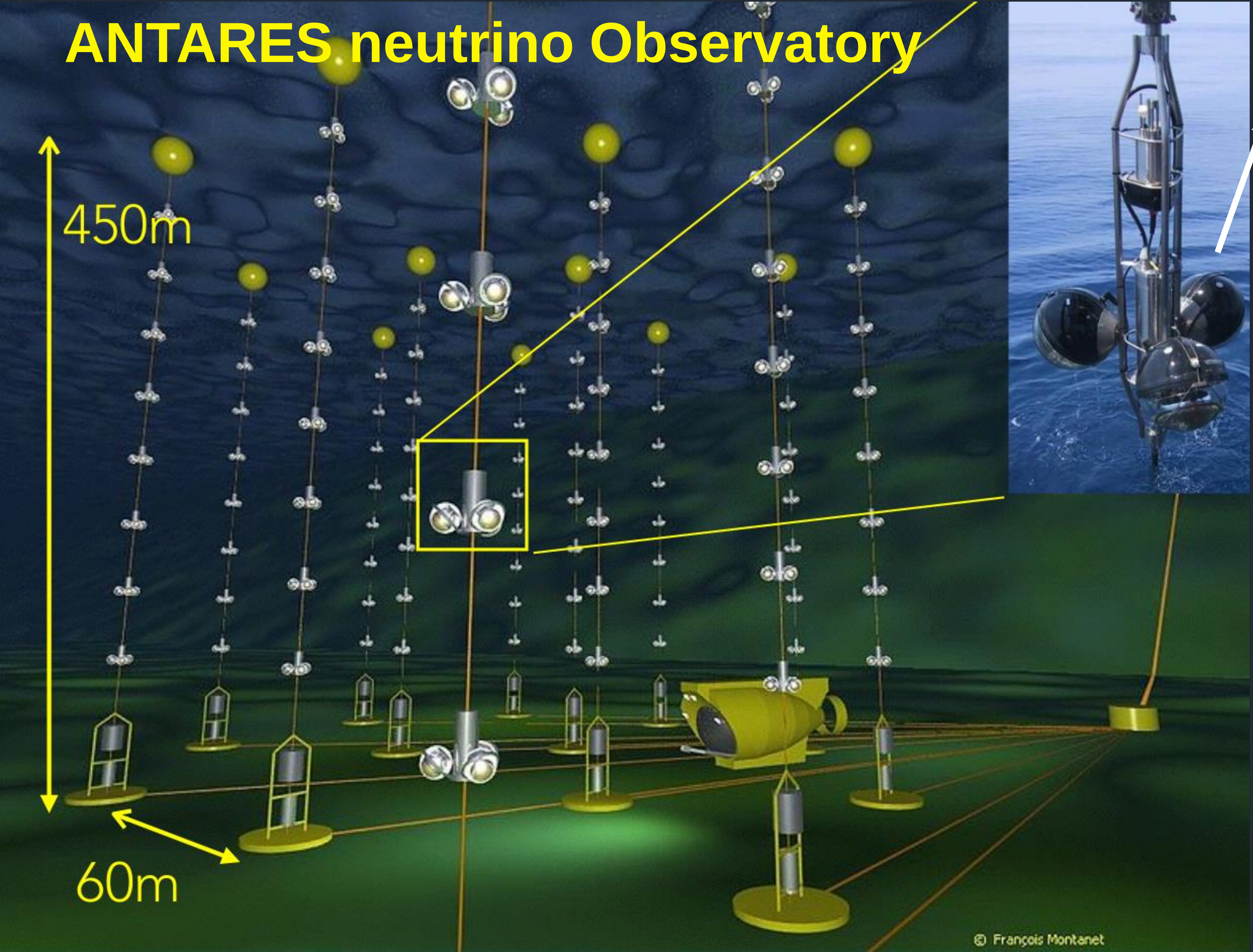
- A muon neutrino produces a muon
- Lattice of photomultipliers to detect cone of Cherenkov light



IceCube neutrino Observatory



ANTARES neutrino Observatory



Optical sensor:
1PMT of 10 inches

- Depth 2475 m in Mediterranean Sea
- 12 lines of PMTs
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs
- Volume 0.01 km3

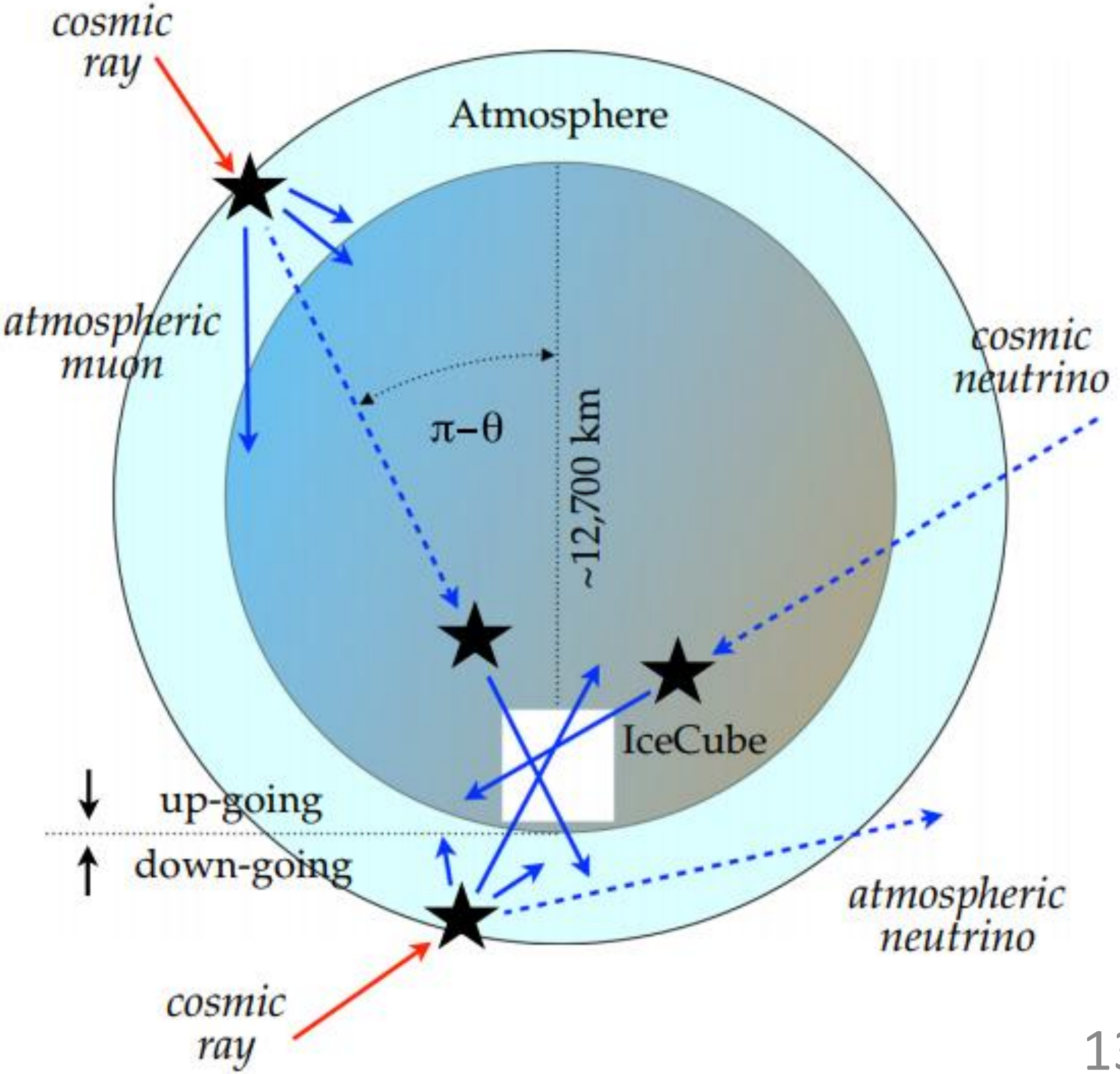
Began full operation in 2008
Duty cycle ~95%

Signal and background

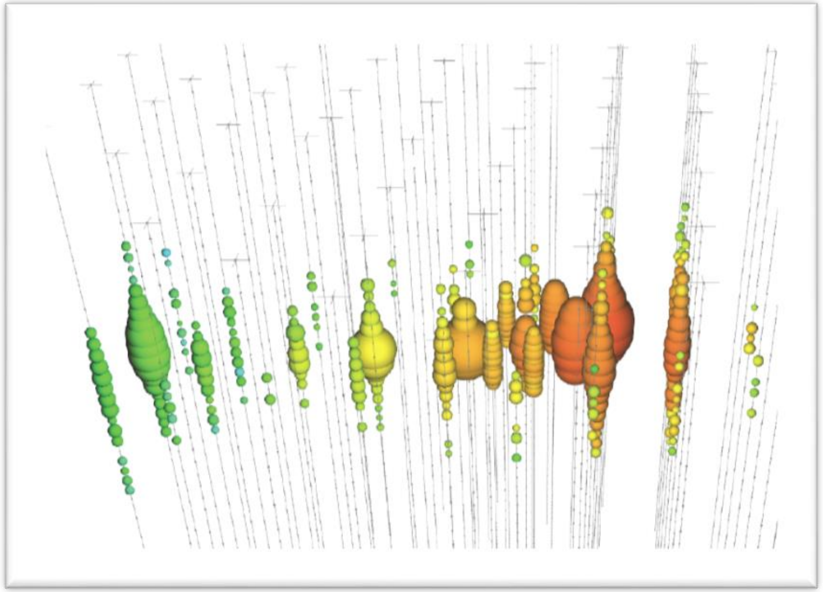
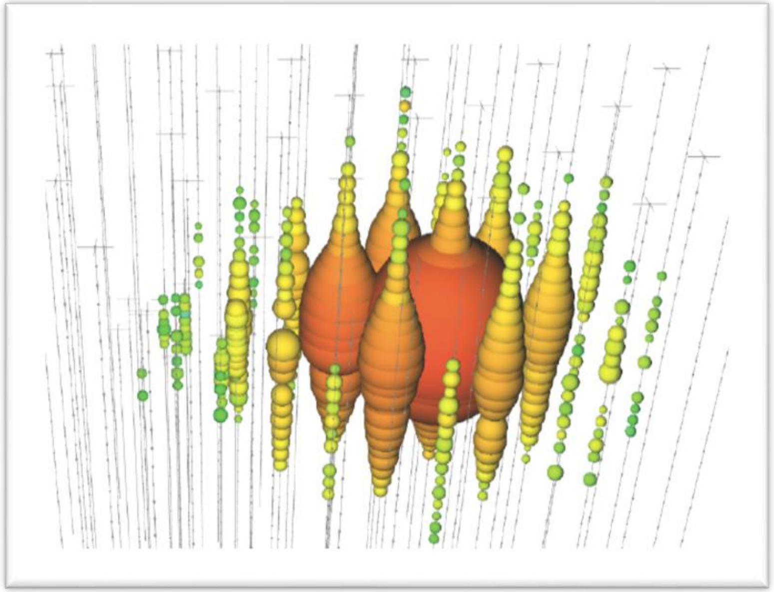
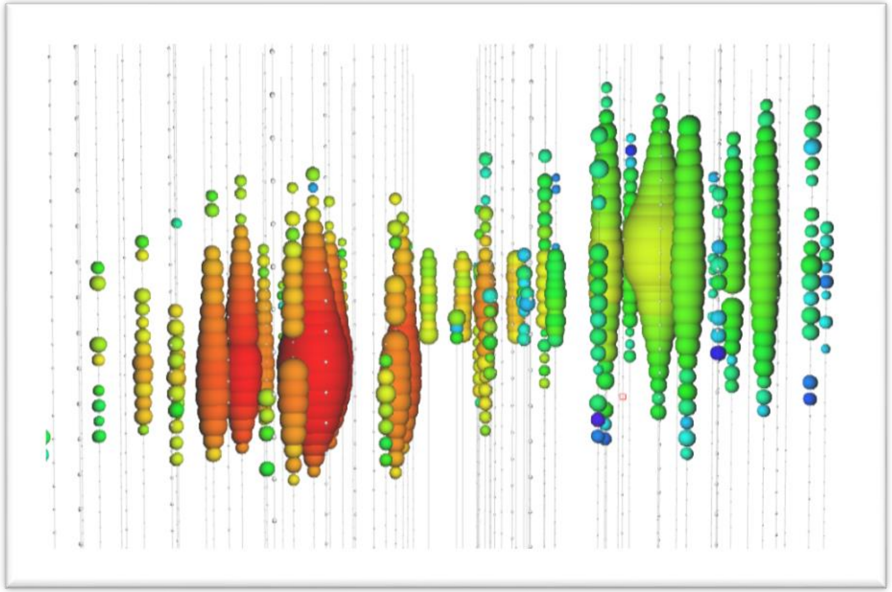
- 2 kinds of backgrounds:
    - Atmospheric μ
    - Atmospheric ν

- 3 components in neutrino flux:
    - Conventional atmospheric **ν** from K/Pi decays in air-showers
    - Prompt atmospheric **ν** from decays of charmed hadrons in air-showers
    - Astrophysical **ν**, power-law energy spectrum

- Muons detected per year:
    - Atmospheric μ ~ 10^{11} (3000 per second)
    - Atmospheric ν → μ ~ 10^{5} (1 every 6 minutes)
    - Cosmic ν → μ ~ 1-10 (> 50 TeV)



Event topologies

Tracks	Cascades	Double-cascades
		

Tracks

- ν_μ charged-current (CC) interactions
- Atmospheric μ
- ν_τ CC interactions with muonic tau decay
- Good angular resolution: < 0.3° (>100 TeV)
- Energy resolution: x2

Cascades

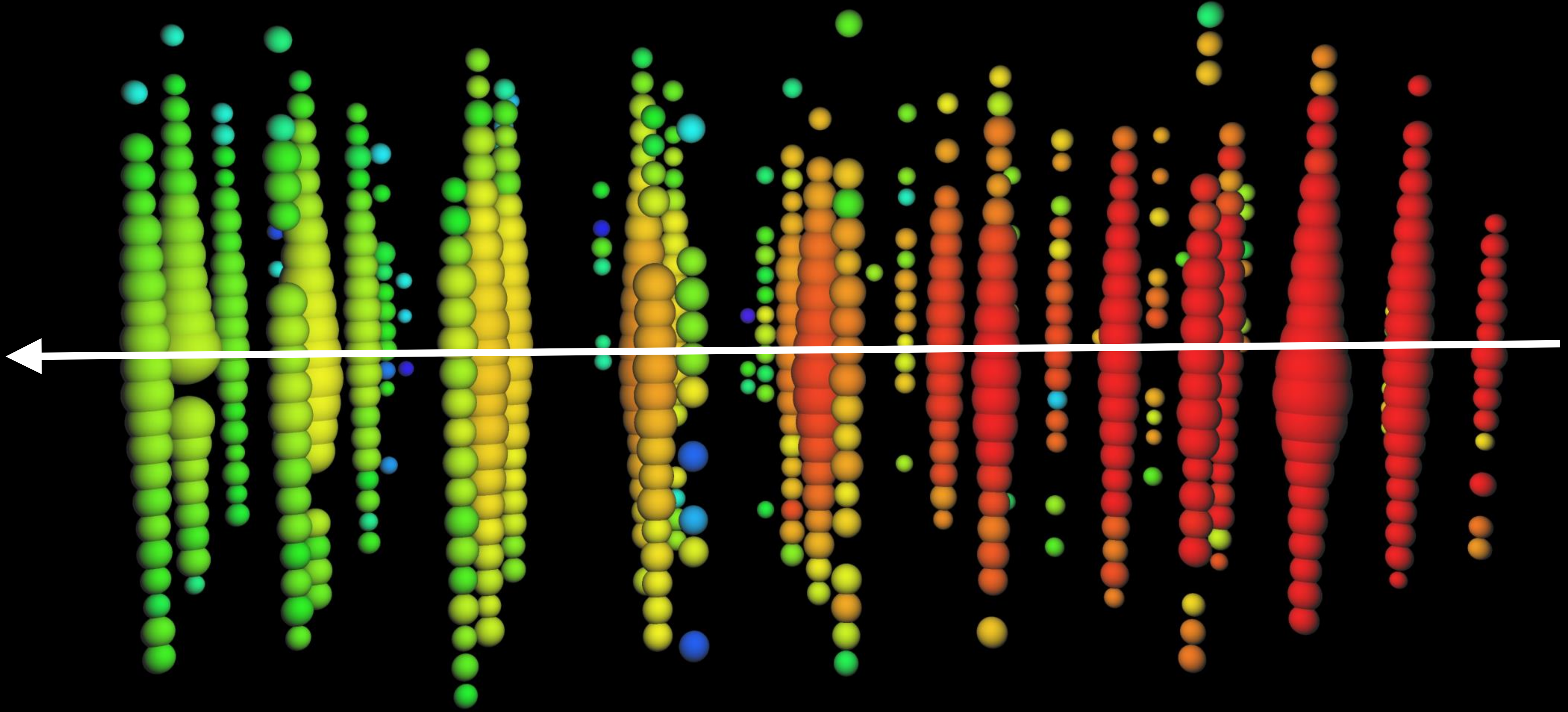
- All neutral-current (NC) interactions
- ν_e, ν_τ CC interactions
- Angular resolution: ~10° (> 100 TeV)
- Good energy resolution: ~15%

Double-cascades

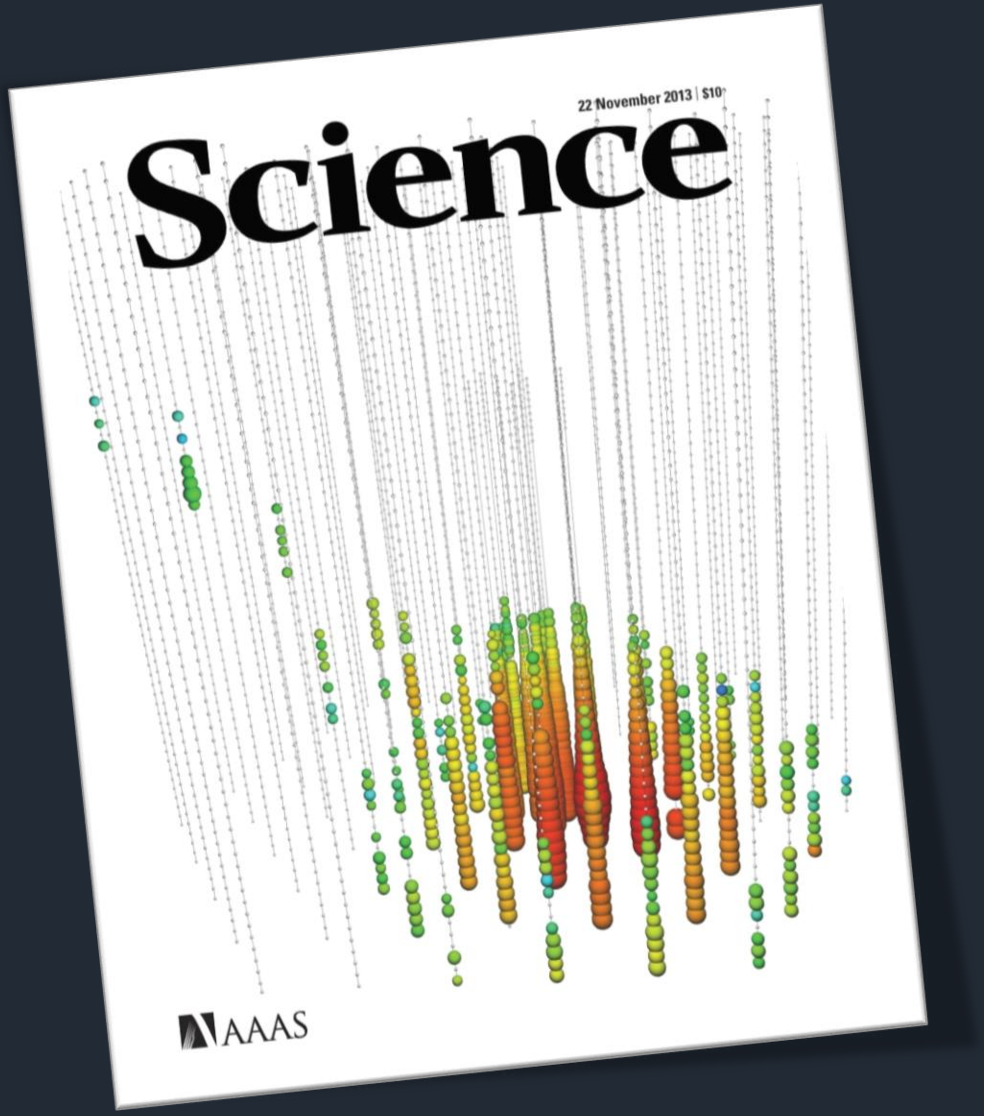
- Very high-energy ν_τ CC interactions with hadronic/electronic tau decay
- ~2 expected in 6 years

Track-like event
(28 Oct 2010)

Muon energy: ~604 TeV
Neutrino energy: ~880 TeV
Radius ~ number of photons
Time: red → purple



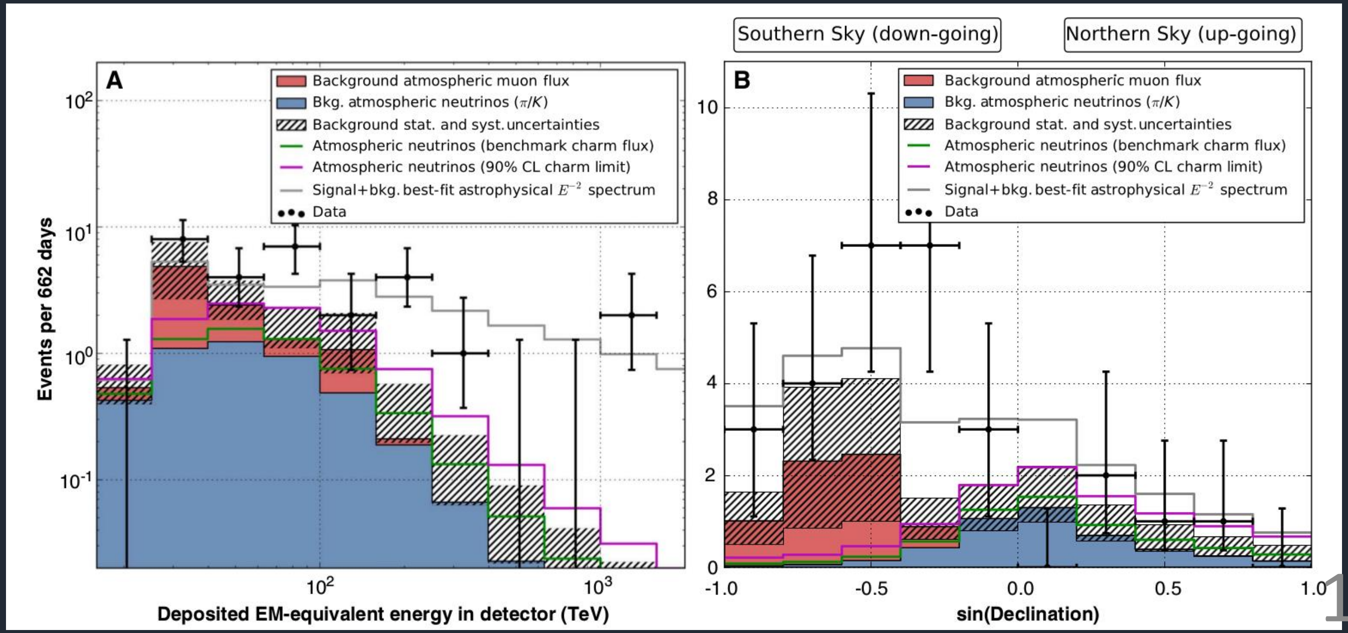
The discovery of cosmic neutrinos



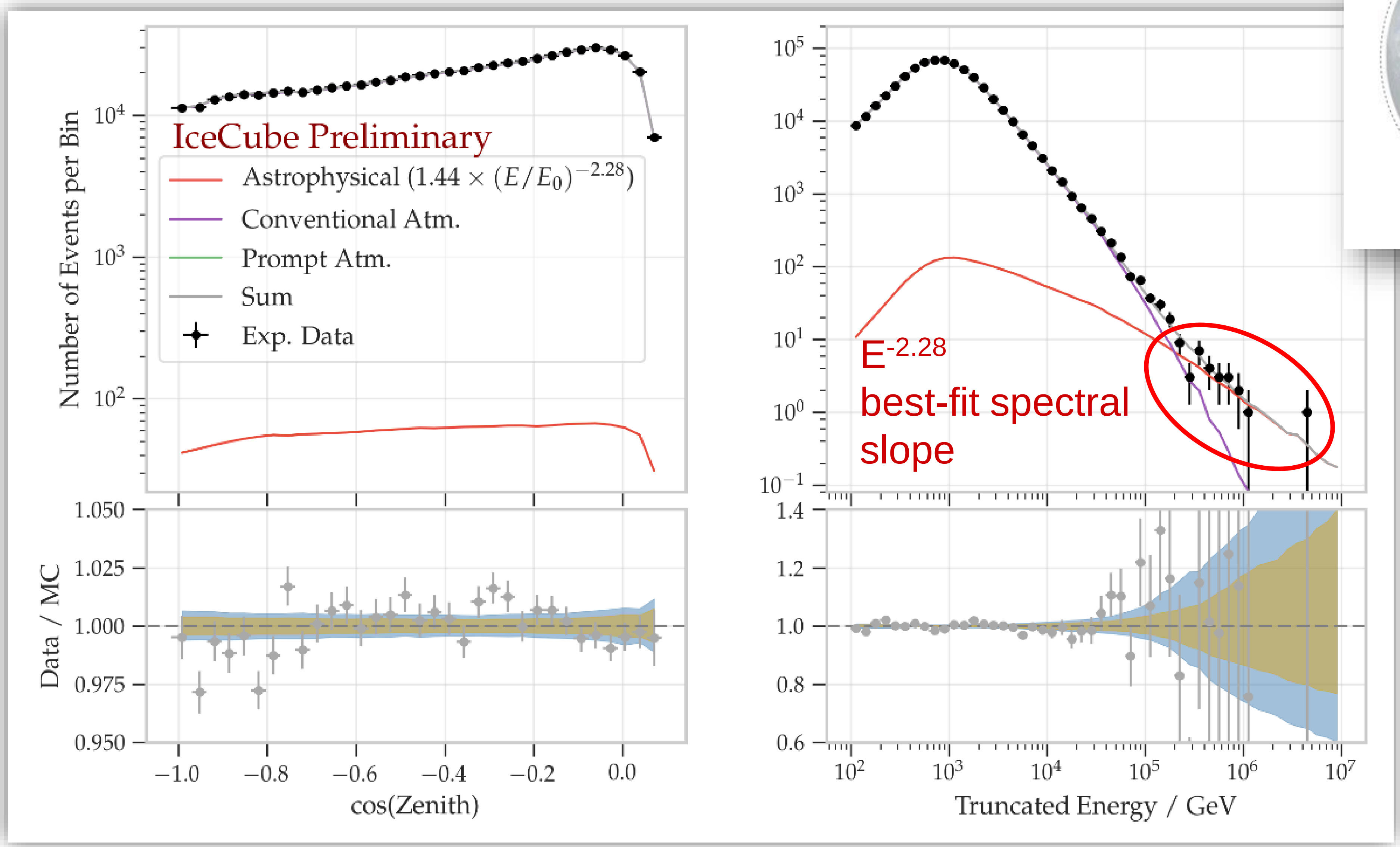
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

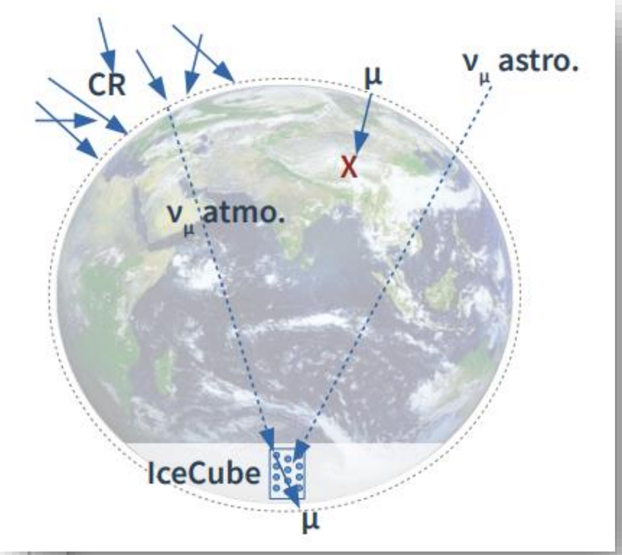
IceCube Collaboration*

- 2-year dataset (May 2010 to May 2012)
- 28 neutrino events detected
- expected atmospheric background: $10.6^{+5.0}_{-3.6}$
- 30 < E < 1200 TeV



Astrophysical neutrinos, 9 years of data





- Independent analysis using thorough-going muon events from the Northern Hemisphere

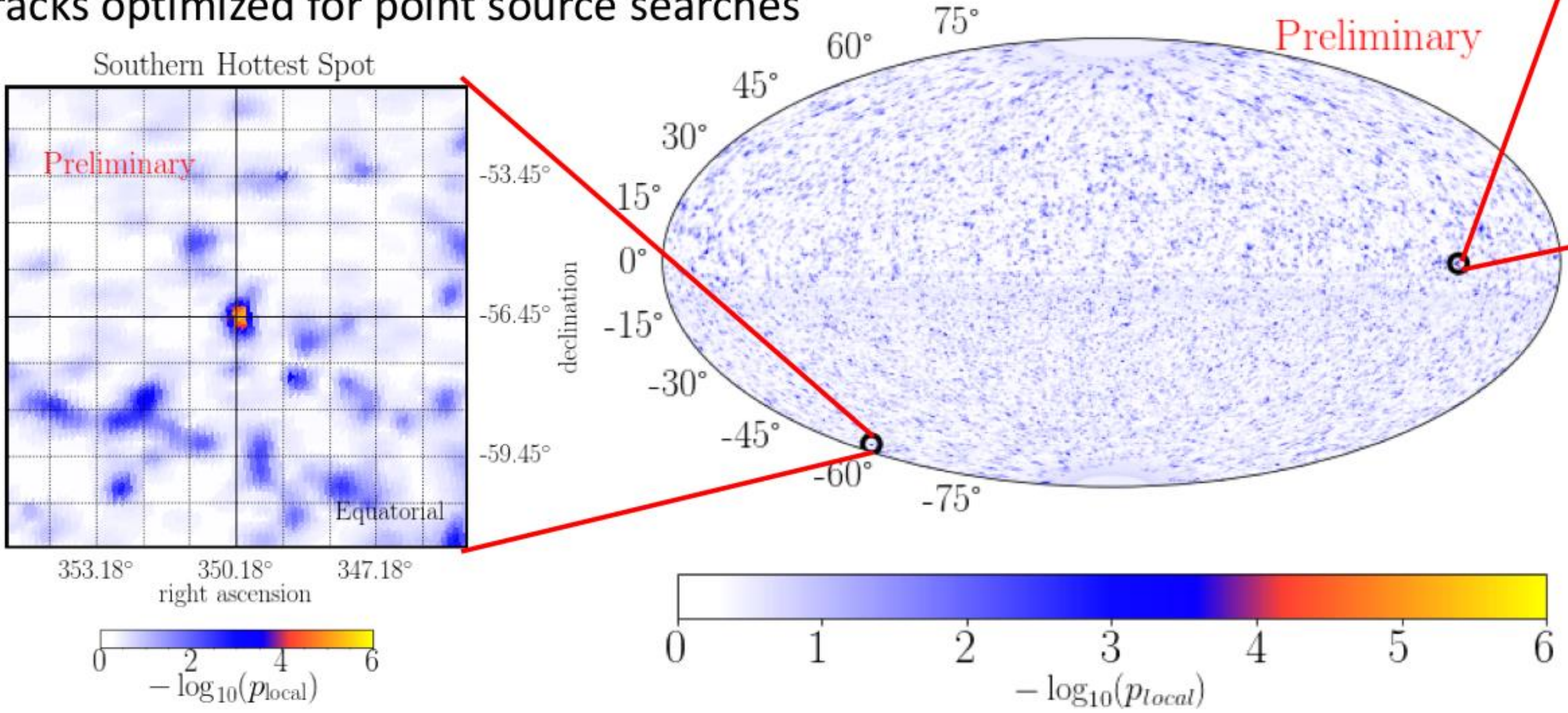
Excess of a high-energy component clearly visible

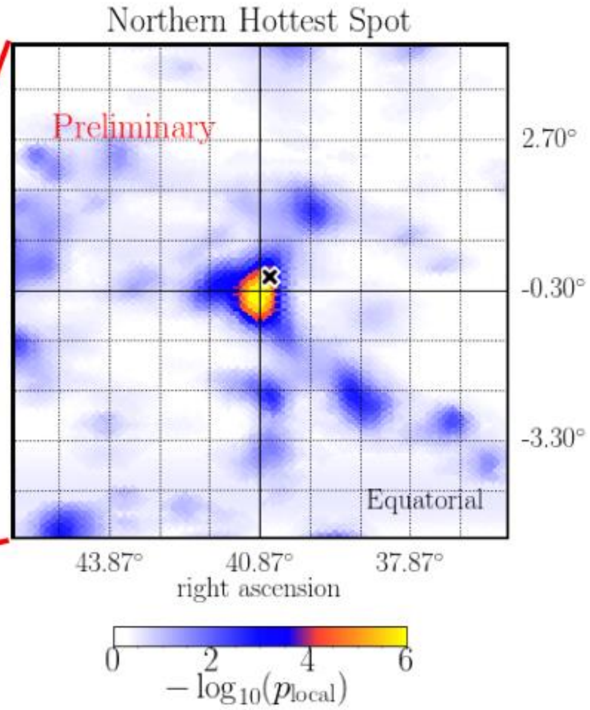
… but where do they come from?

All sky combined 10 year search

- 1.1M neutrino candidates
- ~1-10 cosmic neutrino/year expected above 50 TeV

Using high energy through-going tracks and tracks optimized for point source searches



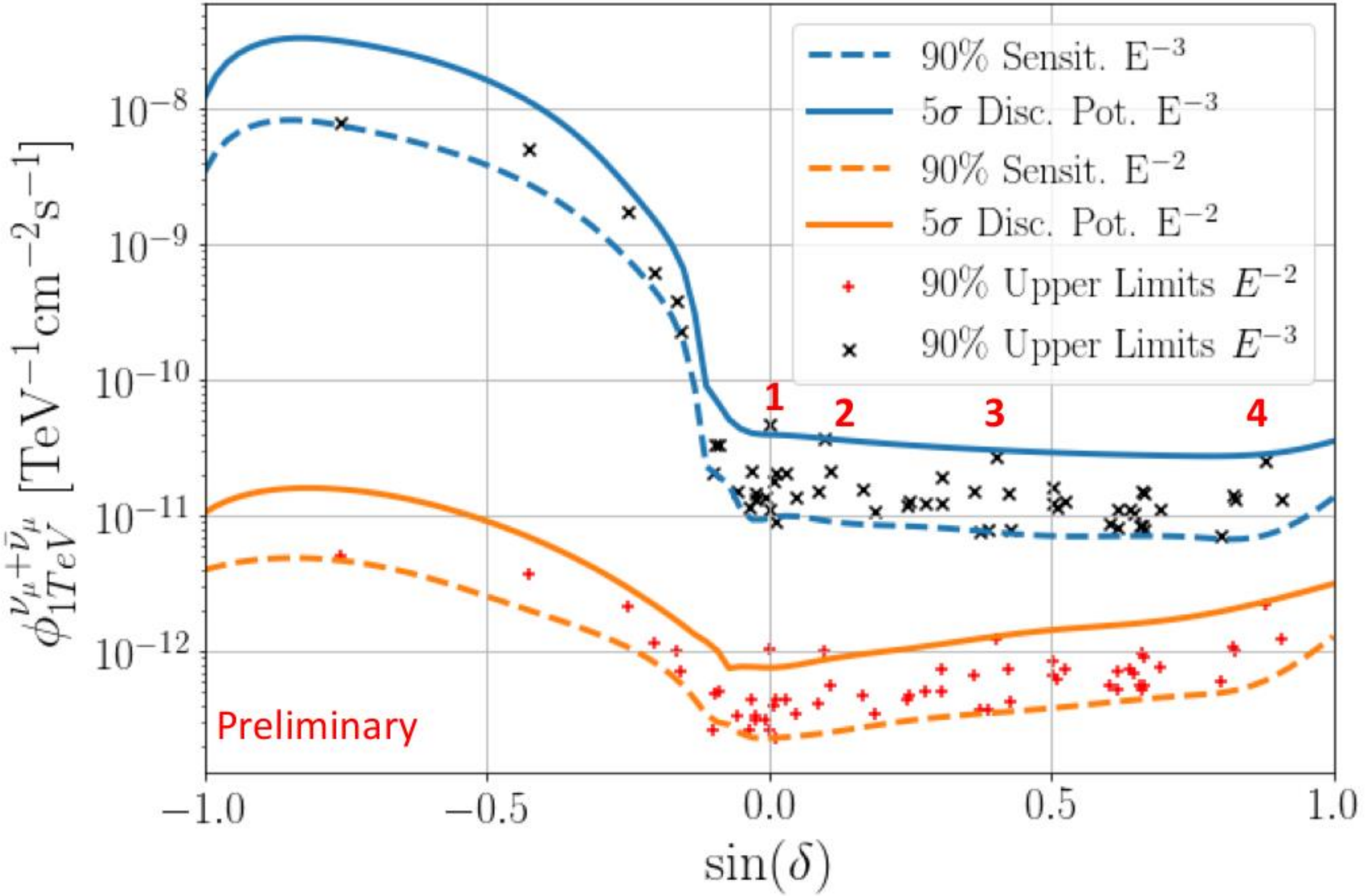


Hottest spot in Northern Hemisphere coincides with 2.9 σ excess at the position of NGC 1068 → evidence of non-uniform map

… but where do they come from?

All sky combined 10 year search

Source list of 110 Galactic and Extragalactic objects



1. NGC 1068
2. TXS 0506 + 056
3. PKS 1424 + 240
4. GB6 J1542+6129

Source list search is incompatible with background at 3.3σ (2.25σ without TXS 0506)

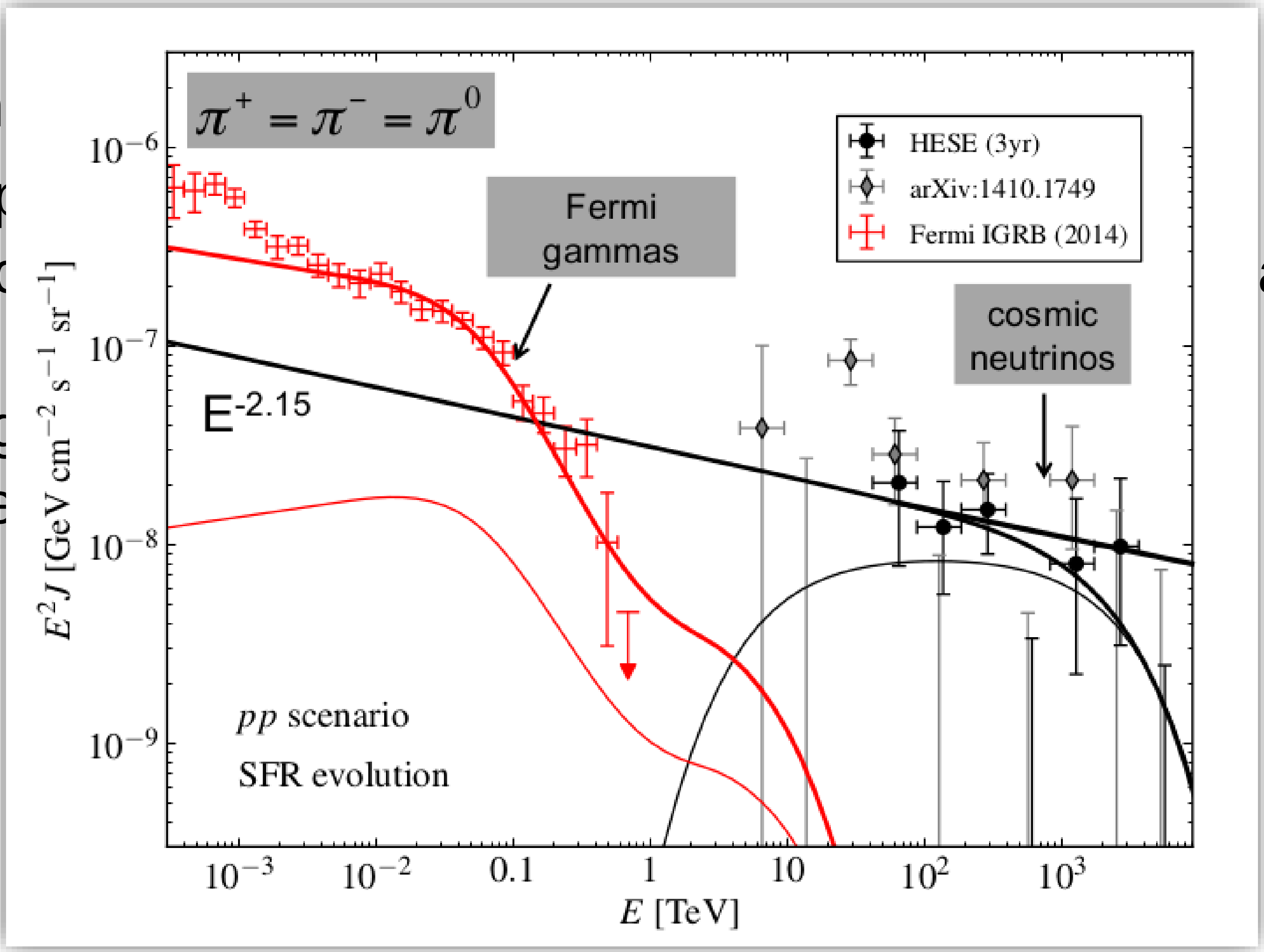
Lessons so far

- Diffuse flux of neutrinos of astrophysical origin
- A Galactic component cannot be excluded
    - But galactic neutrino searches for emission from the Galactic plane revealed no significant correlations so far
- Where are the gammas counterpart of PeV neutrinos from same sources?

  →multi-messenger searches

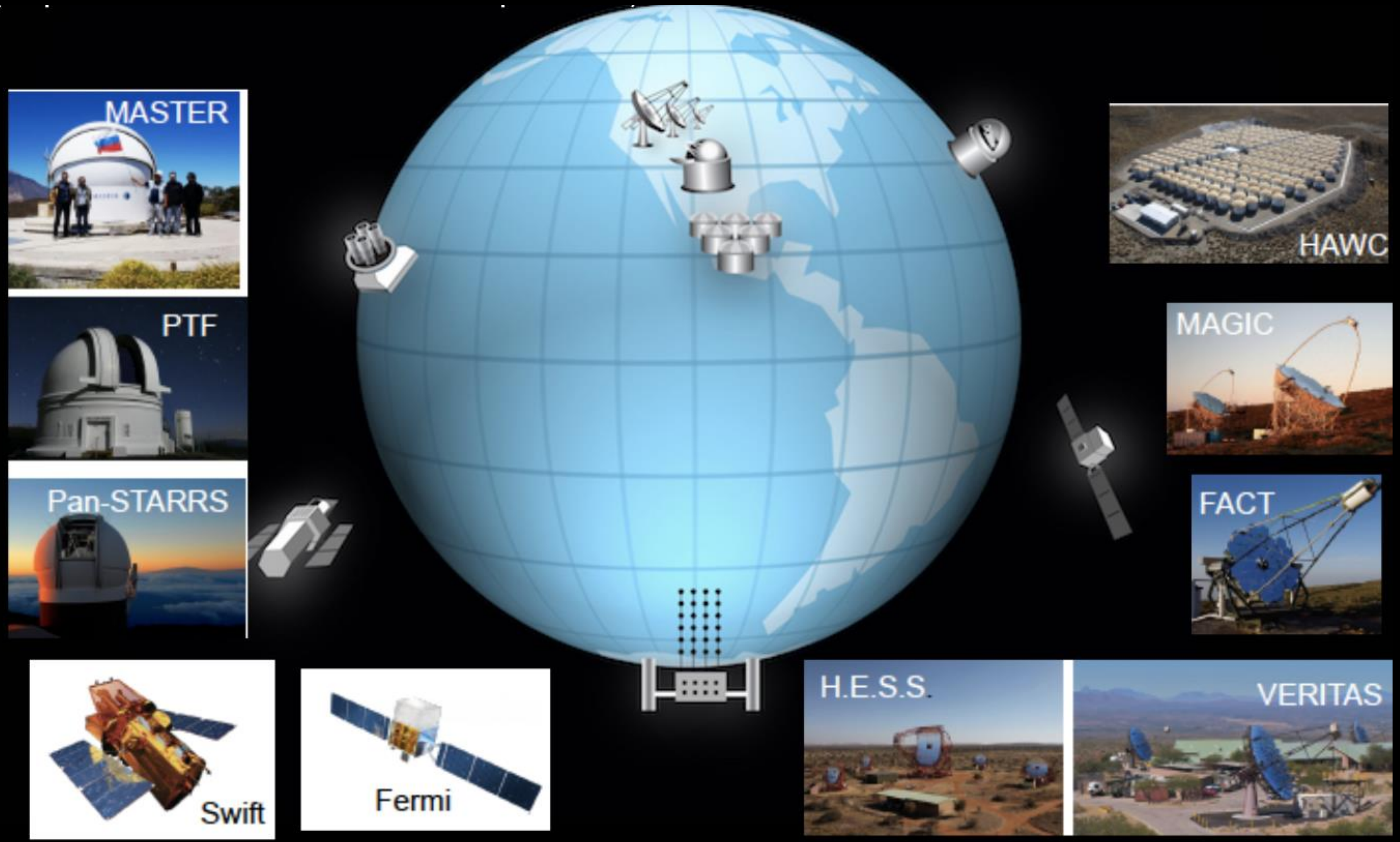
Lessons so far

- Diffuse flux of n
- A Galactic comp
  - But galac … actic plane revealed
- Where are the g … e sources?
  - →multi-me



IceCube Realtime Public Alerts

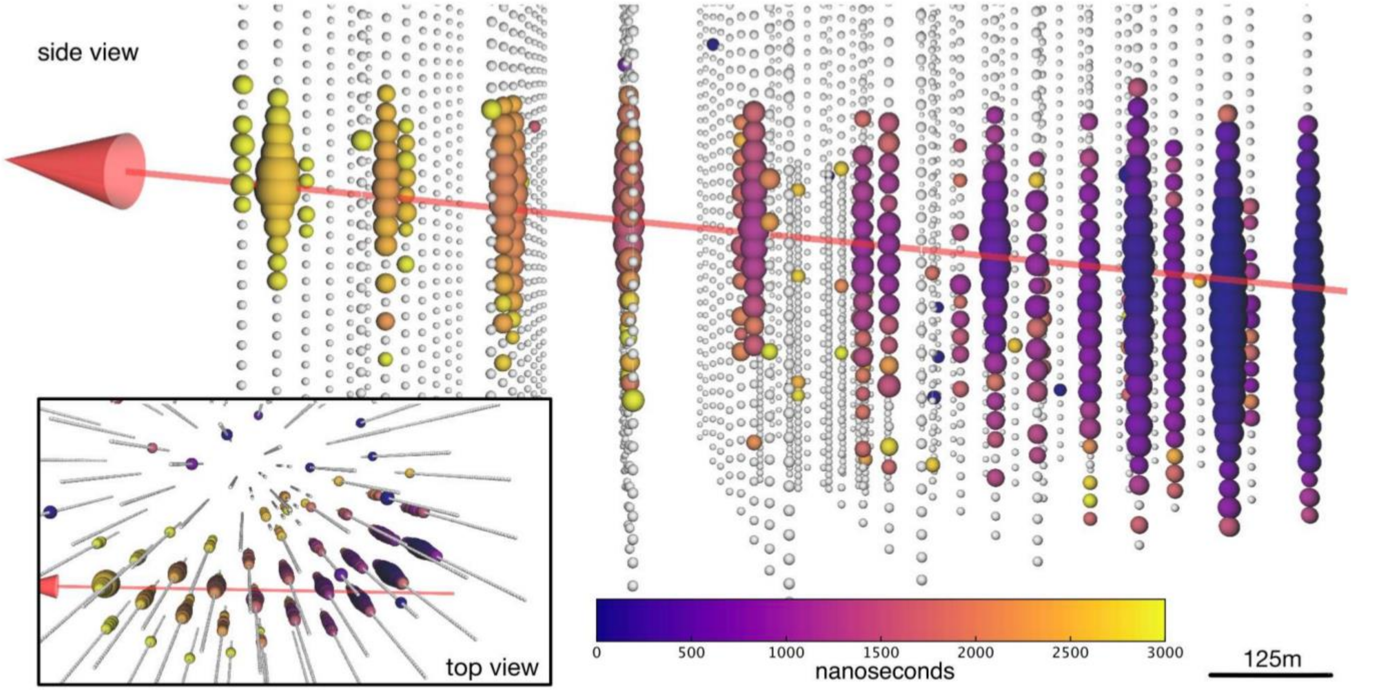
- Operating since 2016
- ~ 8 public track alerts per year with $E>10^{14}$ eV
- ~ 3 have probability of being of cosmic origin > 50% (depends on assumed cosmic spectrum)
- Alerts transmitted via satellite to GCN (Gamma-ray Coordination Network) in < 1 min



2017 September 22: Alert event IceCube-170922A

- 23.7 ± 2.8 TeV muon energy loss in the detector
  → most probable neutrino energy ~ 290 TeV (> 180 TeV, 90%CL)
- Signalness: 56.5 %

RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)



TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon

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28 Sept 2017, Fermi-LAT gamma-ray observations

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on ***28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

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Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

4 Oct 2017, MAGIC VHE gamma-ray observations

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

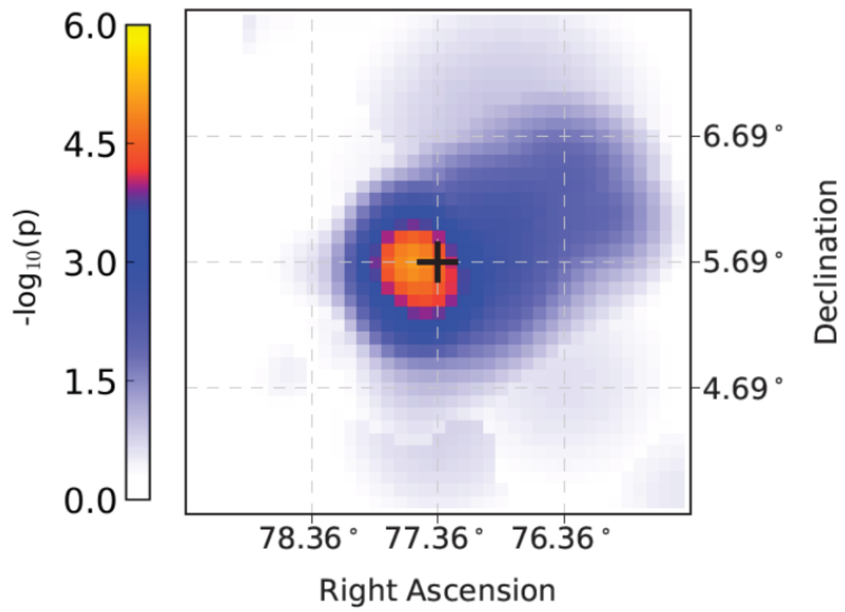
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

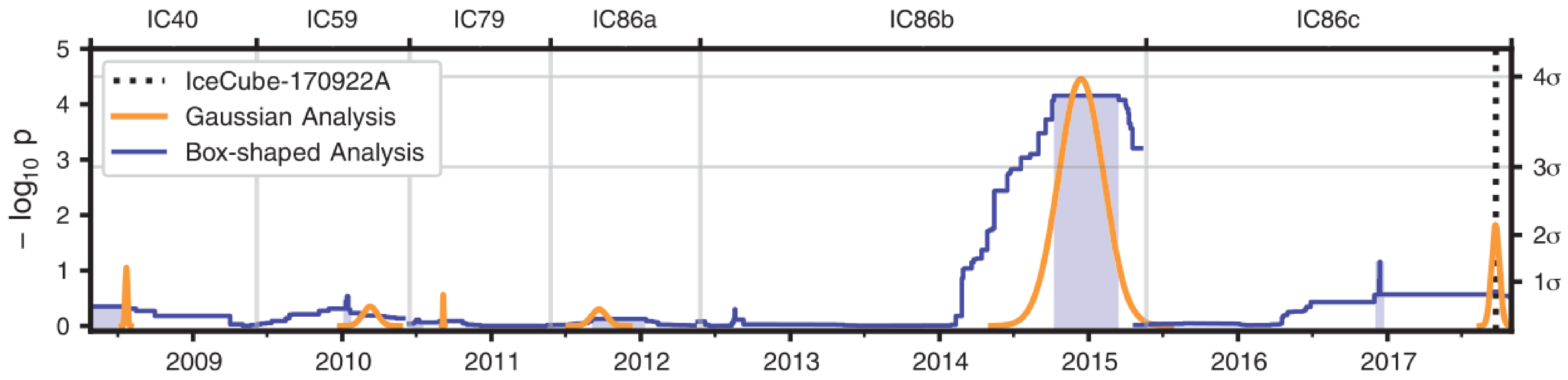
> 400 GeV γ-rays from the blazar

Follow-up detections of IC170922 based on public telegrams

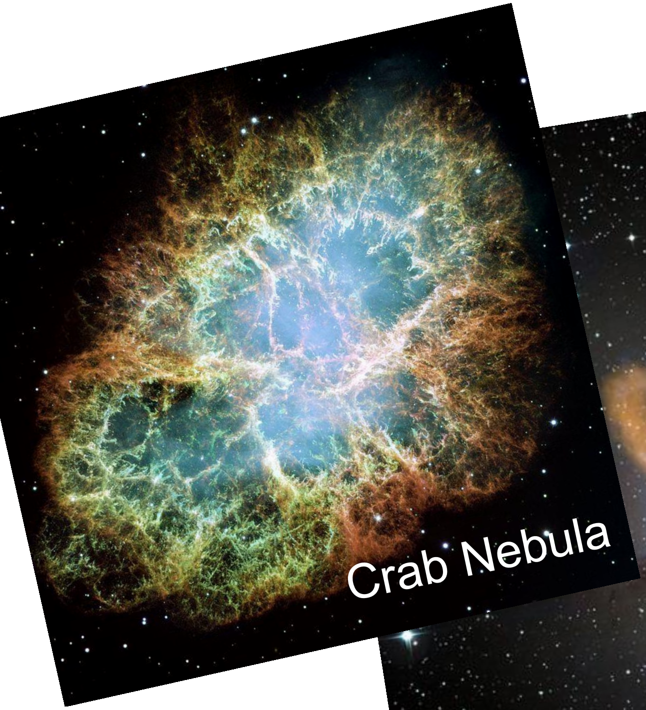
Looking at neutrinos from TXS 0506+056 back in time

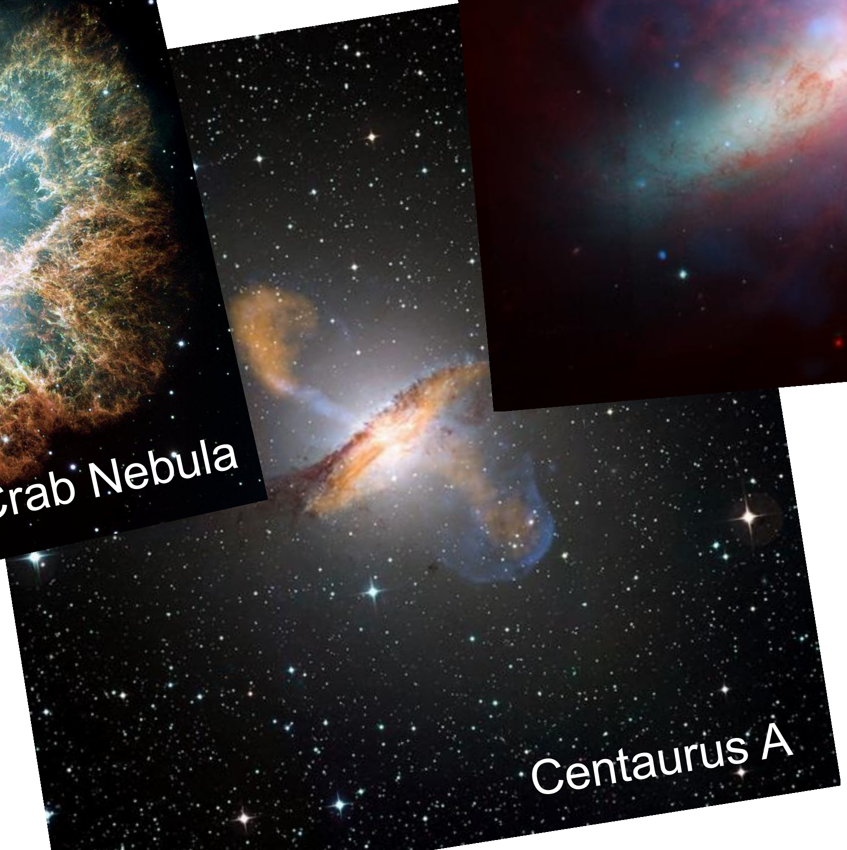
- Analysis of 9.5 yr in 6 independent periods
- 150 day flare in Dec 2014 of 19 events
- Inconsistent with background at 3.5σ
- Spectrum $E^{-2.1}$

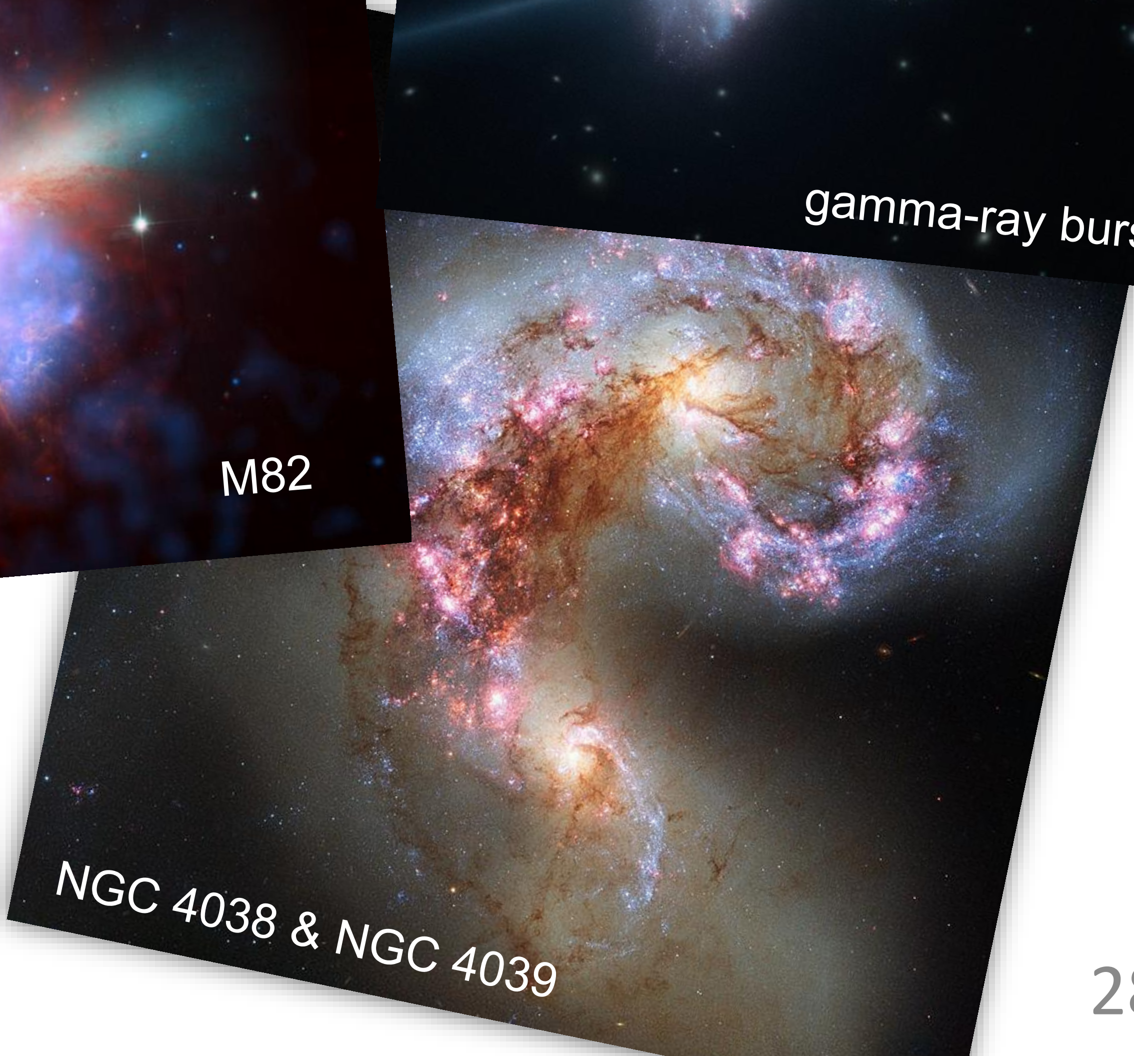


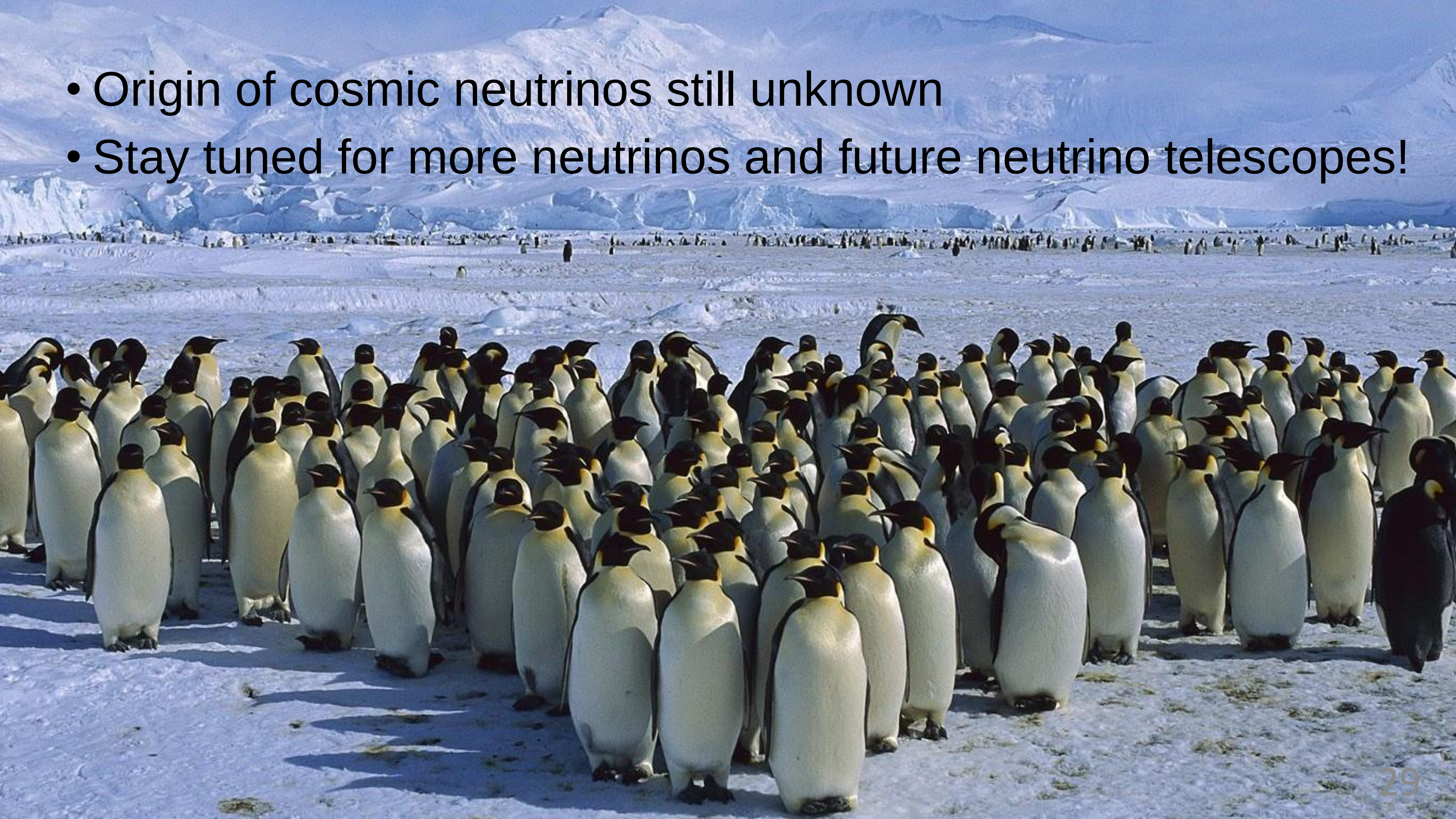


- Are blazars the sources of the diffuse neutrinos and CRs?
- Or galaxy mergers?
- Starbust galaxies?
- Gamma ray bursts?
- Neutron stars?





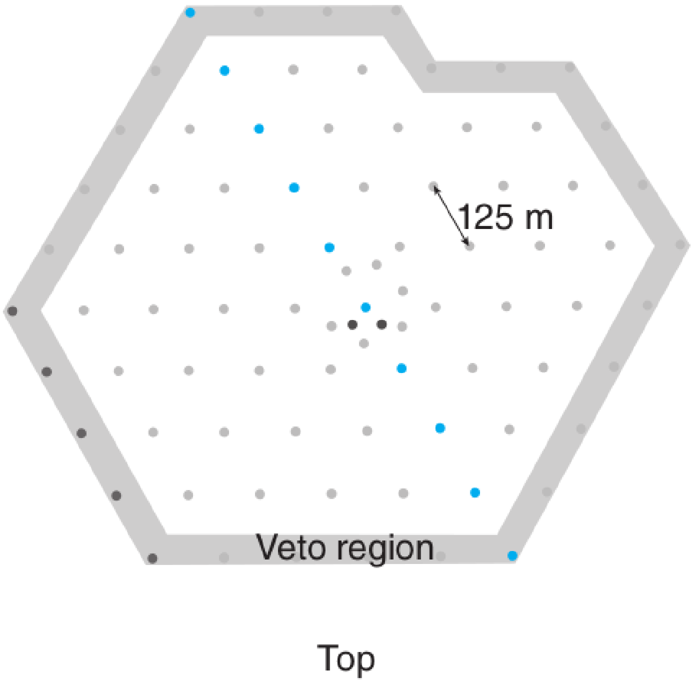


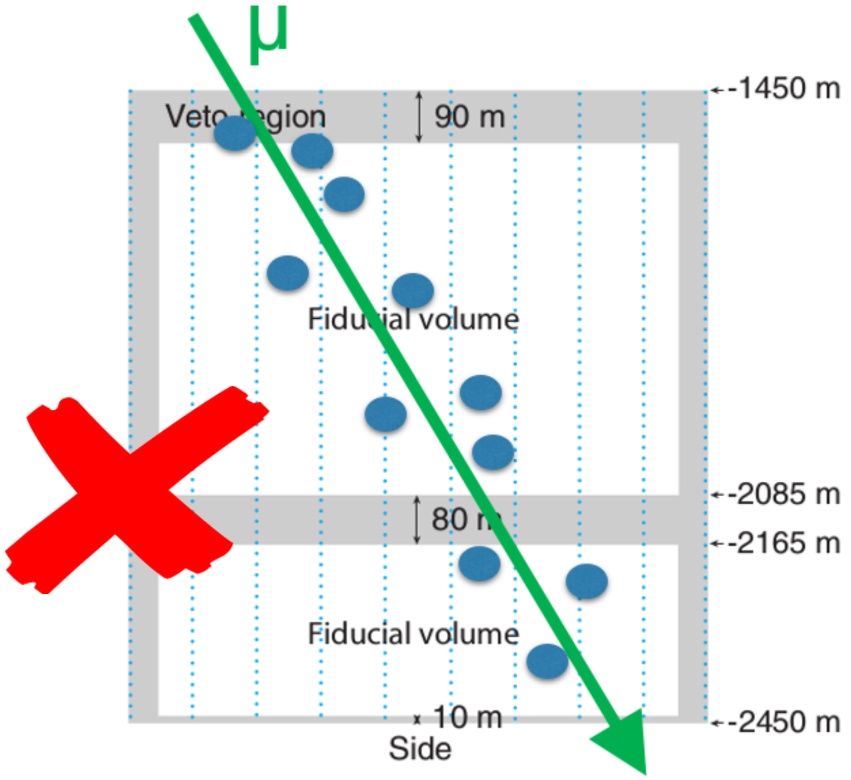


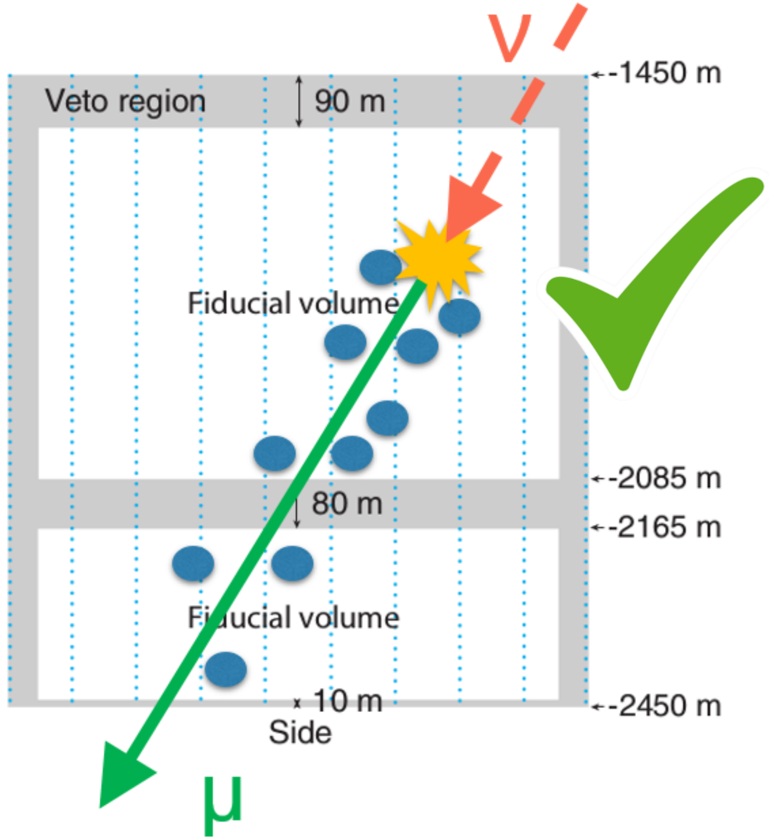
- Origin of cosmic neutrinos still unknown
- Stay tuned for more neutrinos and future neutrino telescopes!

Backup

High-Energy Starting Events (HESE)

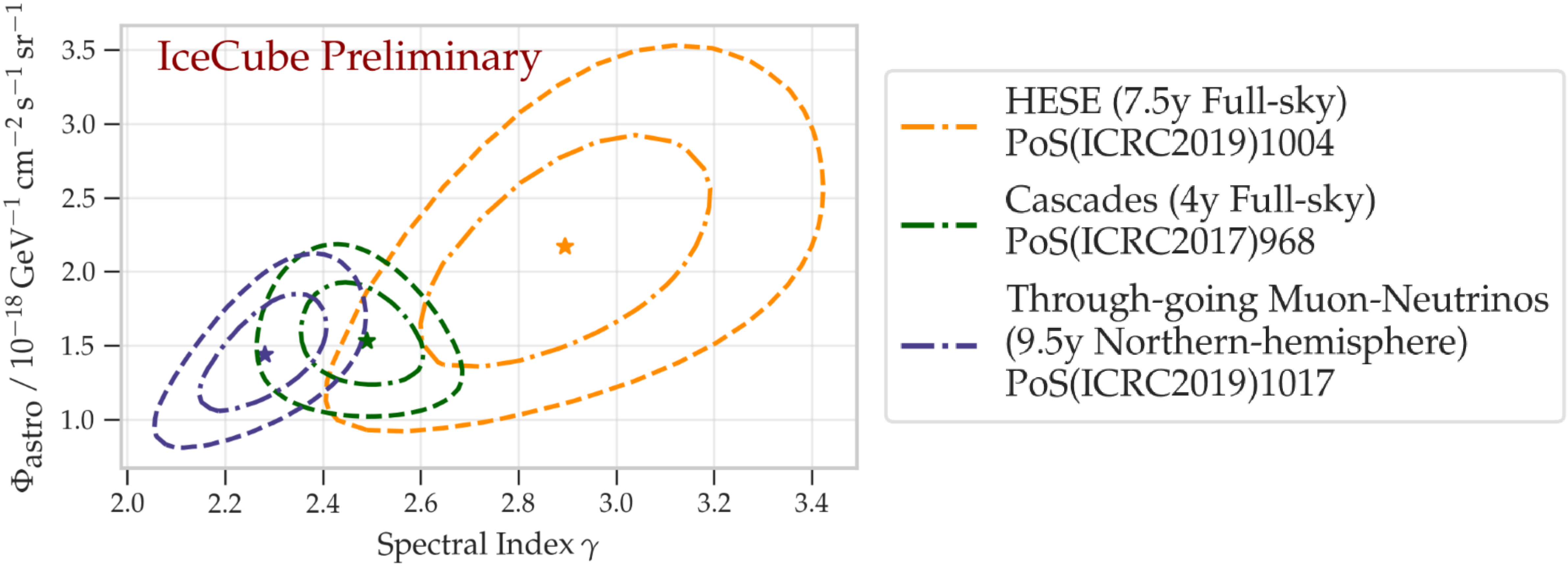






- No light in the veto region
- Active veto for atmospheric μ entering from outside the detector
- Indirect veto for atmospheric ν that are typically accompanied by muons
- All sky, all flavors
- Selection on Q_{tot} > 6000 p.e.
- Sensitive above 60 TeV

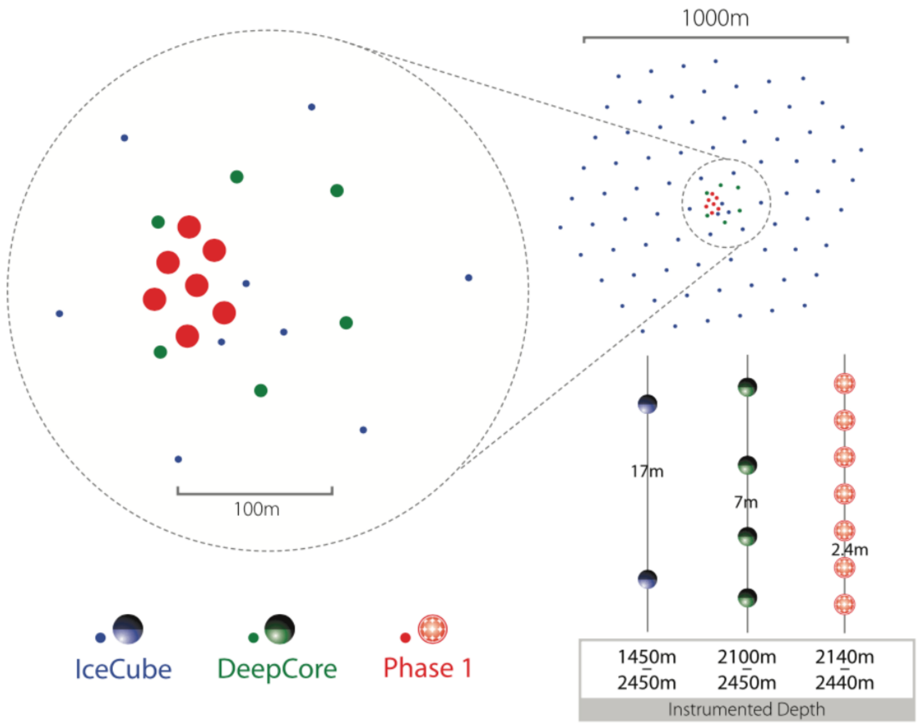
Single power law astrophysical neutrino spectra

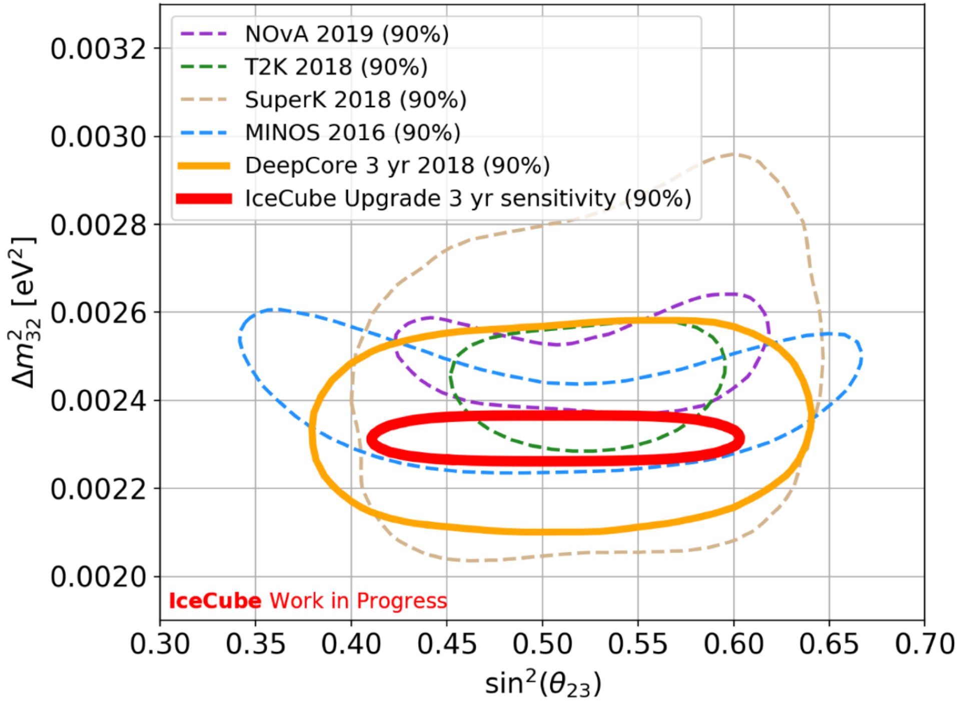


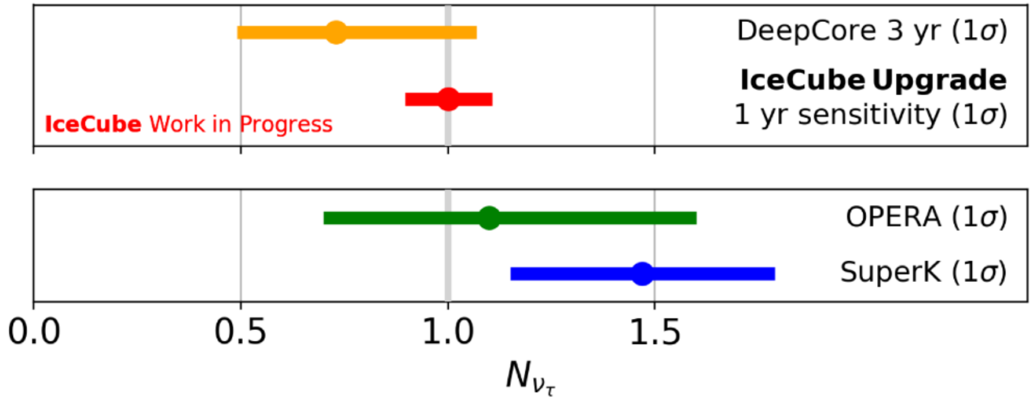
- Single power law may not be possible, e.g. contribution of sources of different nature to fluxes?

Outlook: IceCube upgrade

- 7 new strings in the DeepCore region (~20m inner-string spacing)
- Planned to deploy in 2022-2023
- New multi-PMT sensors
- New calibration devices
- Precision measurement of atmospheric neutrino oscillation

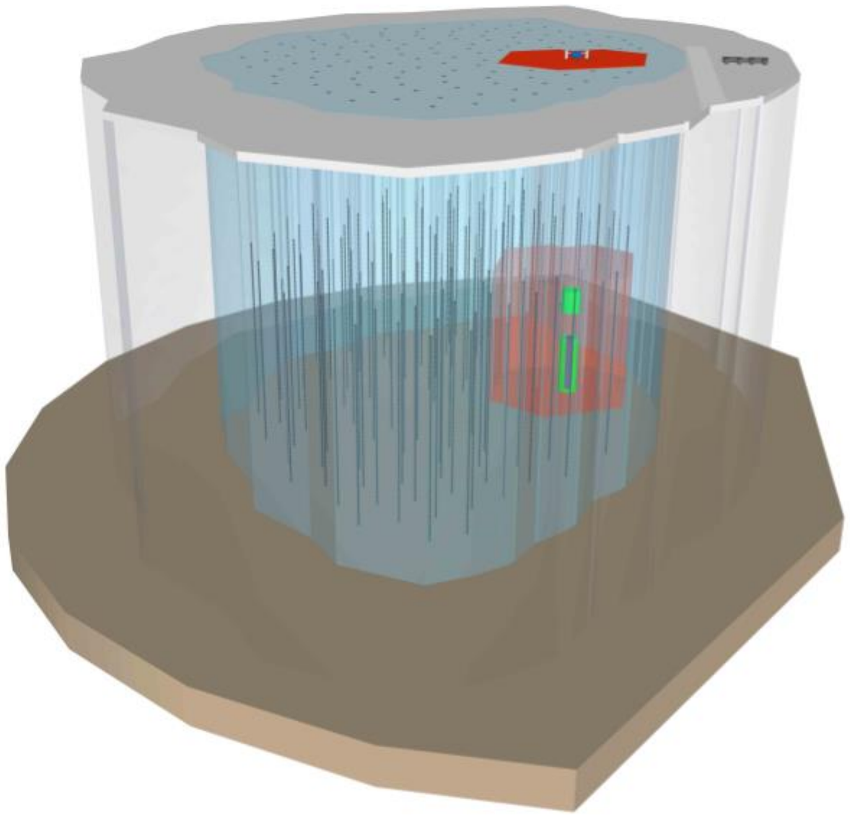


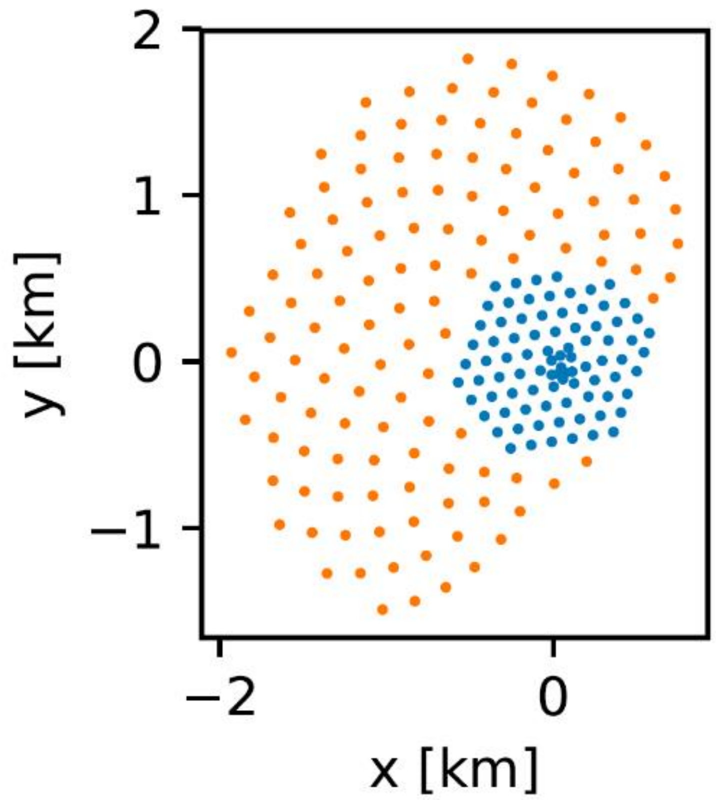




The upgrade will have world-leading sensitivity to tau neutrino appearance

The future: IceCube-Gen2



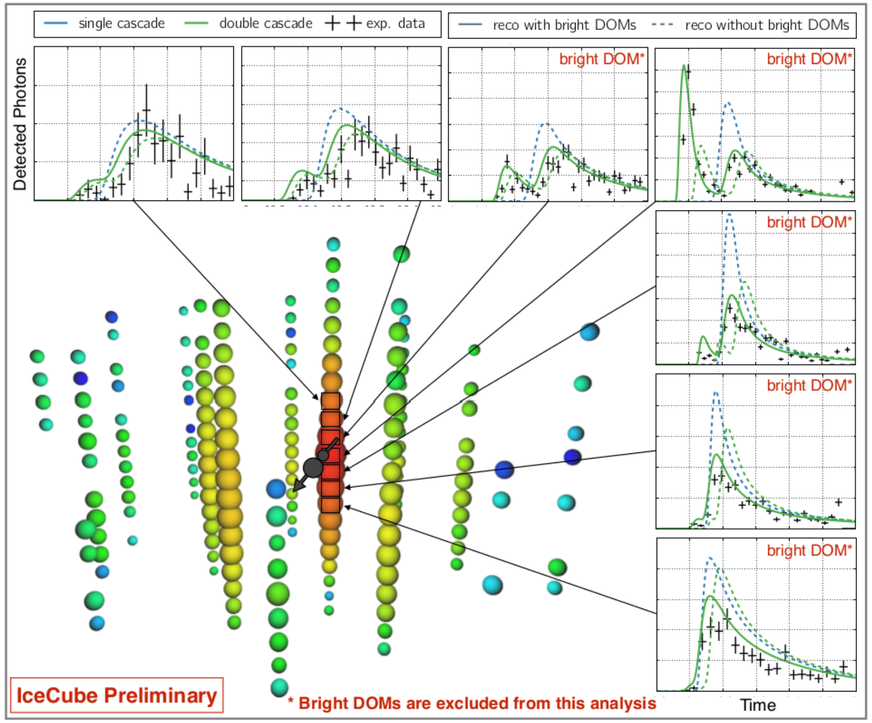


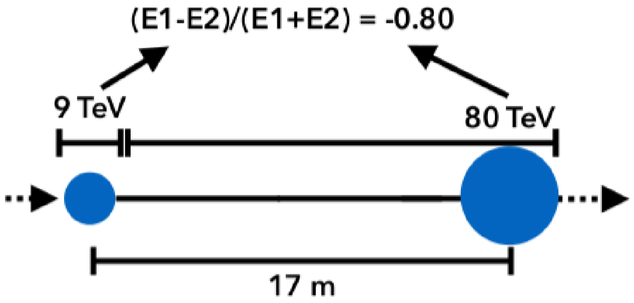
- Multi-component facility (low- and high-energy and multi-messenger)
- In-ice high-energy Cherenkov array with 6-10 km^3 volume
- Will be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array

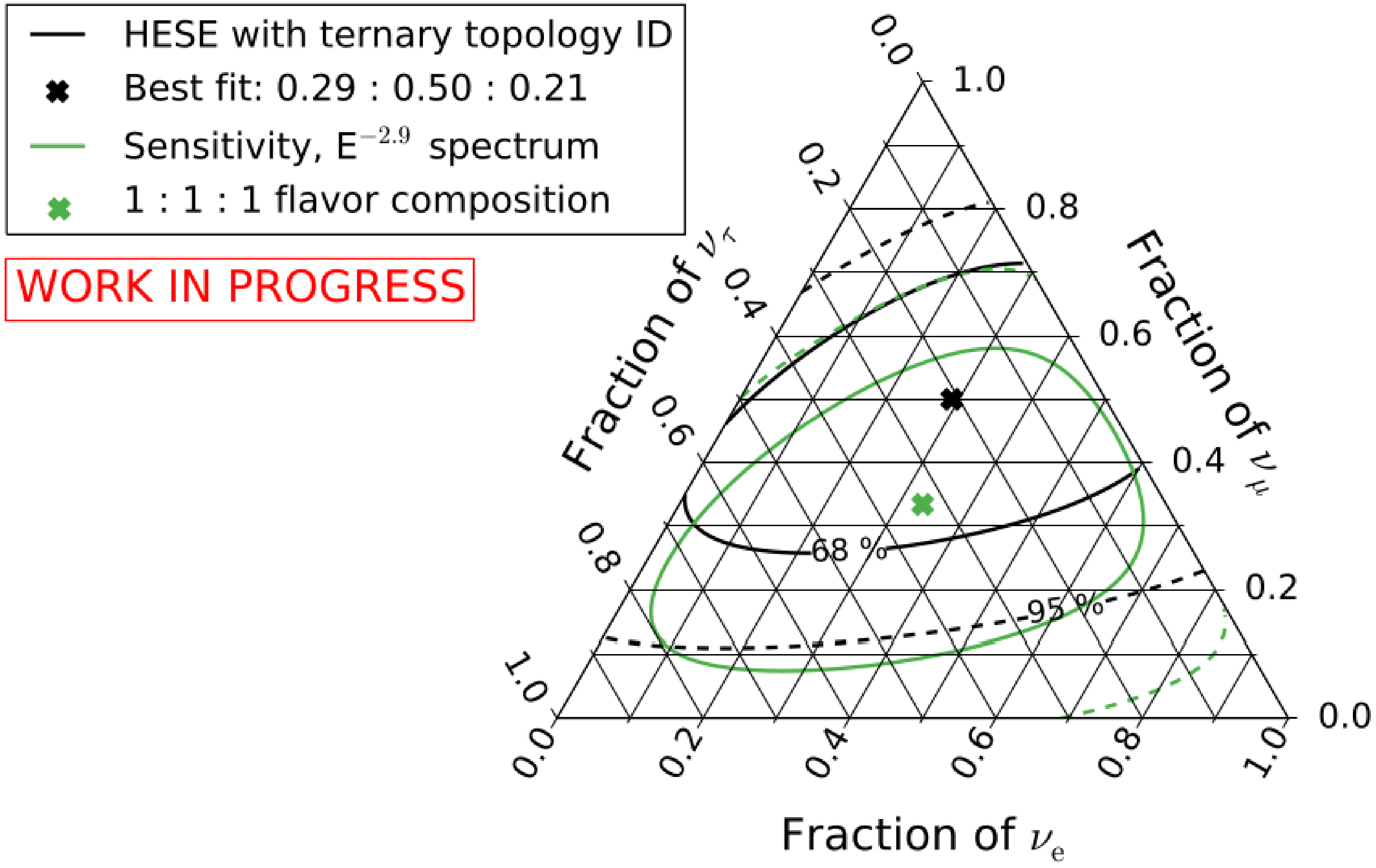
Flavor composition

Best-fit $\nu_e:\nu_\mu:\nu_\tau$ = 0.29:0.50:0.21

"Double-double"
Observed 2014

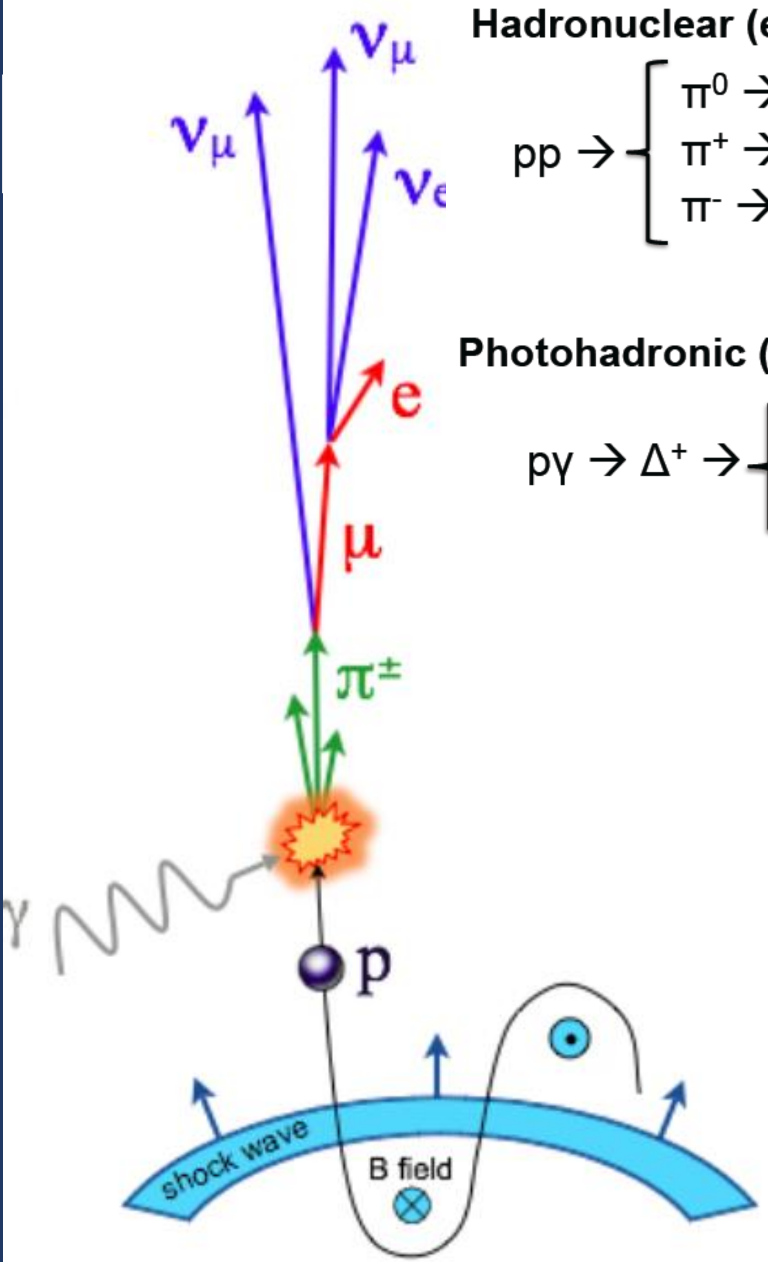






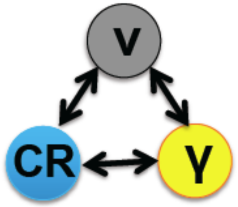
- First best-fit non zero in each flavor component!
- First probe of neutrino oscillations over cosmological baselines and at TeV energies
- Consistent with previous measurement and expectation of 1:1:1 for astrophysical neutrinos

The generic messenger Source: the Cosmic Beam Dump



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e\, \nu_\mu\, \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\, e^+ \nu_e\, \bar{\nu}_\mu\, \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

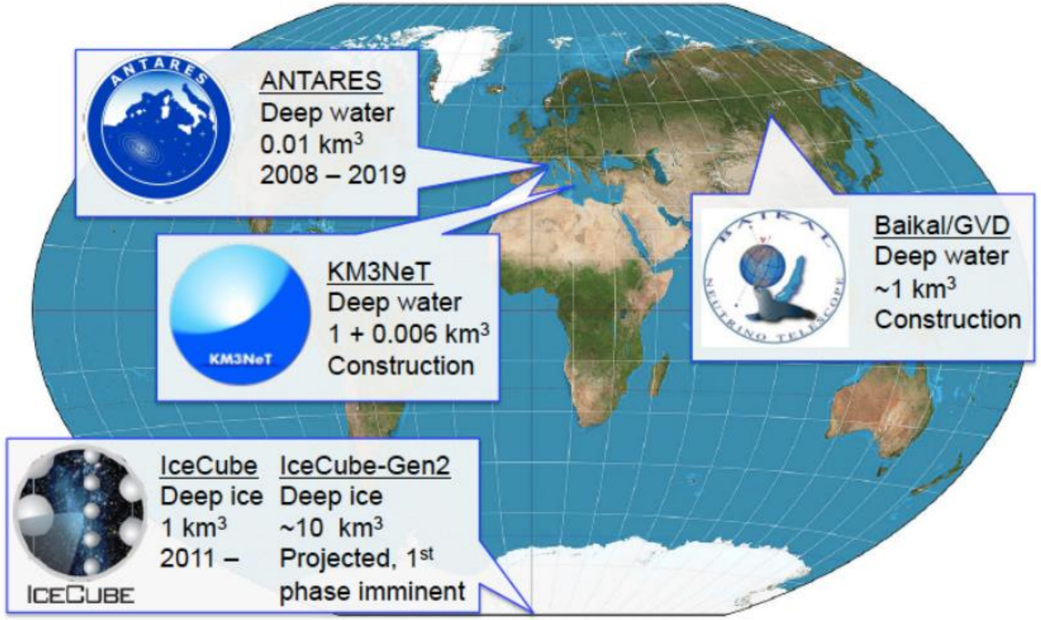
pion-muon decay

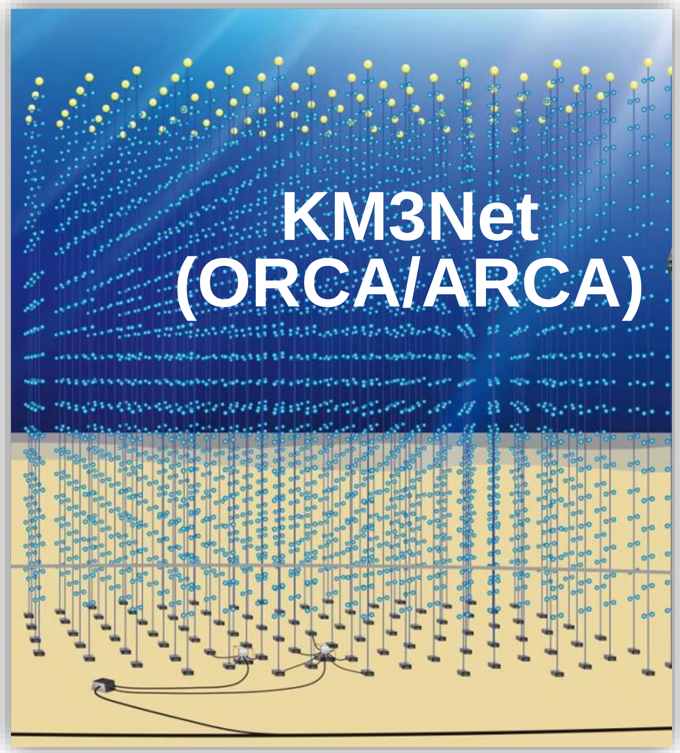
$$\nu_e : \nu_\mu : \nu_\tau \sim 1:2:0$$

Oscillations average out over cosmic baselines

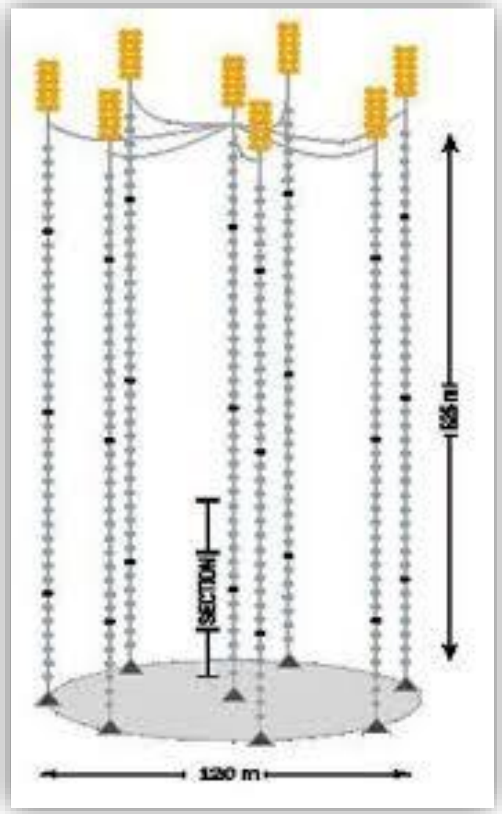
$$\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$$

The future

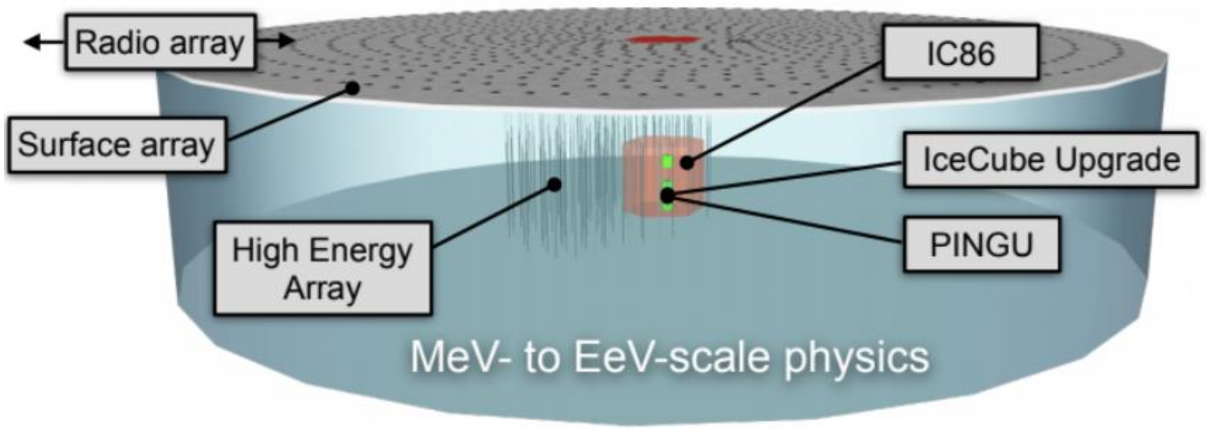




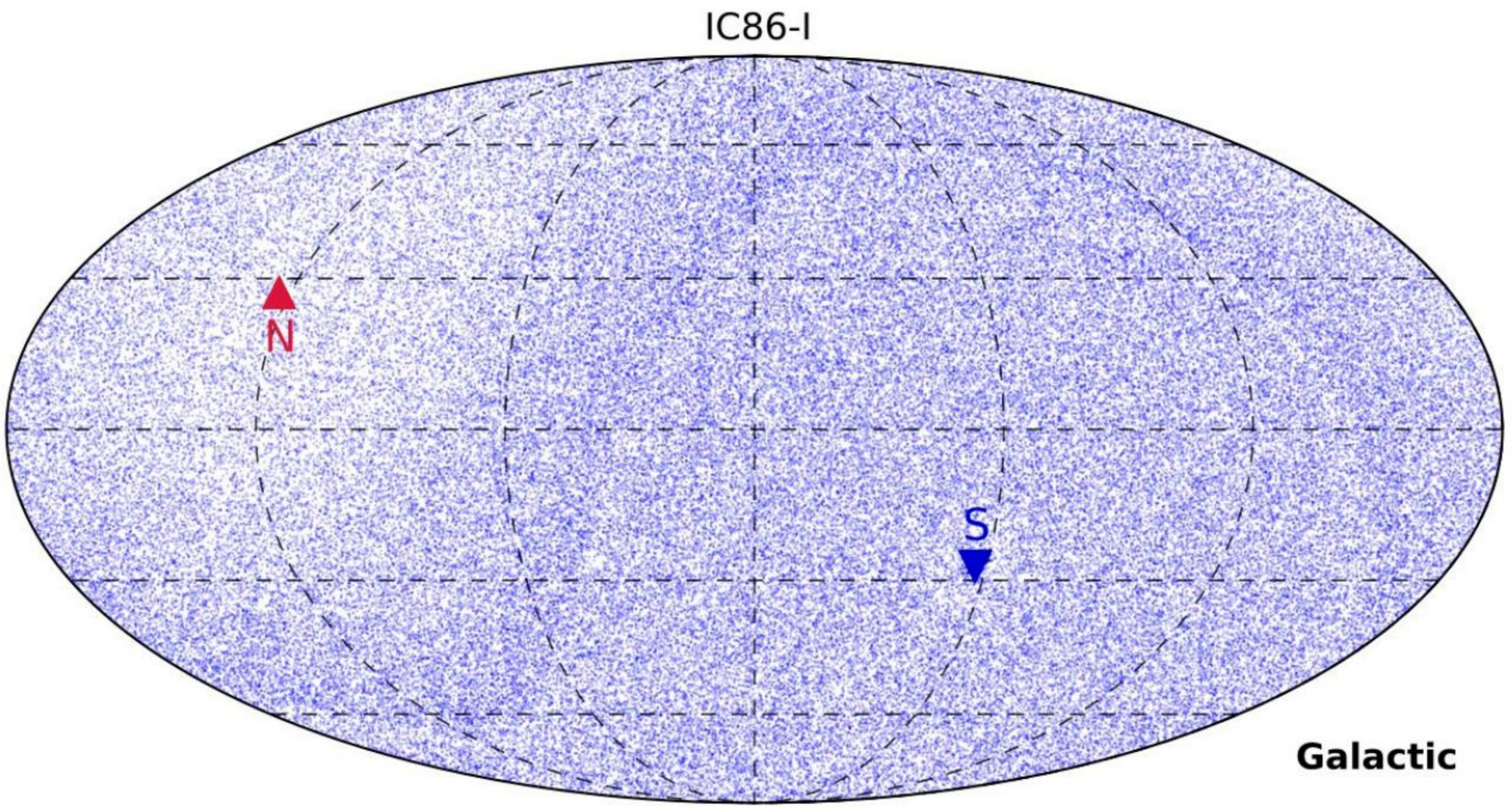
Baikal-GVD



IceCube-Gen2



… but where do they come from?



- 1 year of data
- 138322 neutrino candidates
- ~1-10 cosmic neutrino/year expected above 50 TeV
- Structure in map due to neutrino absorption by Earth