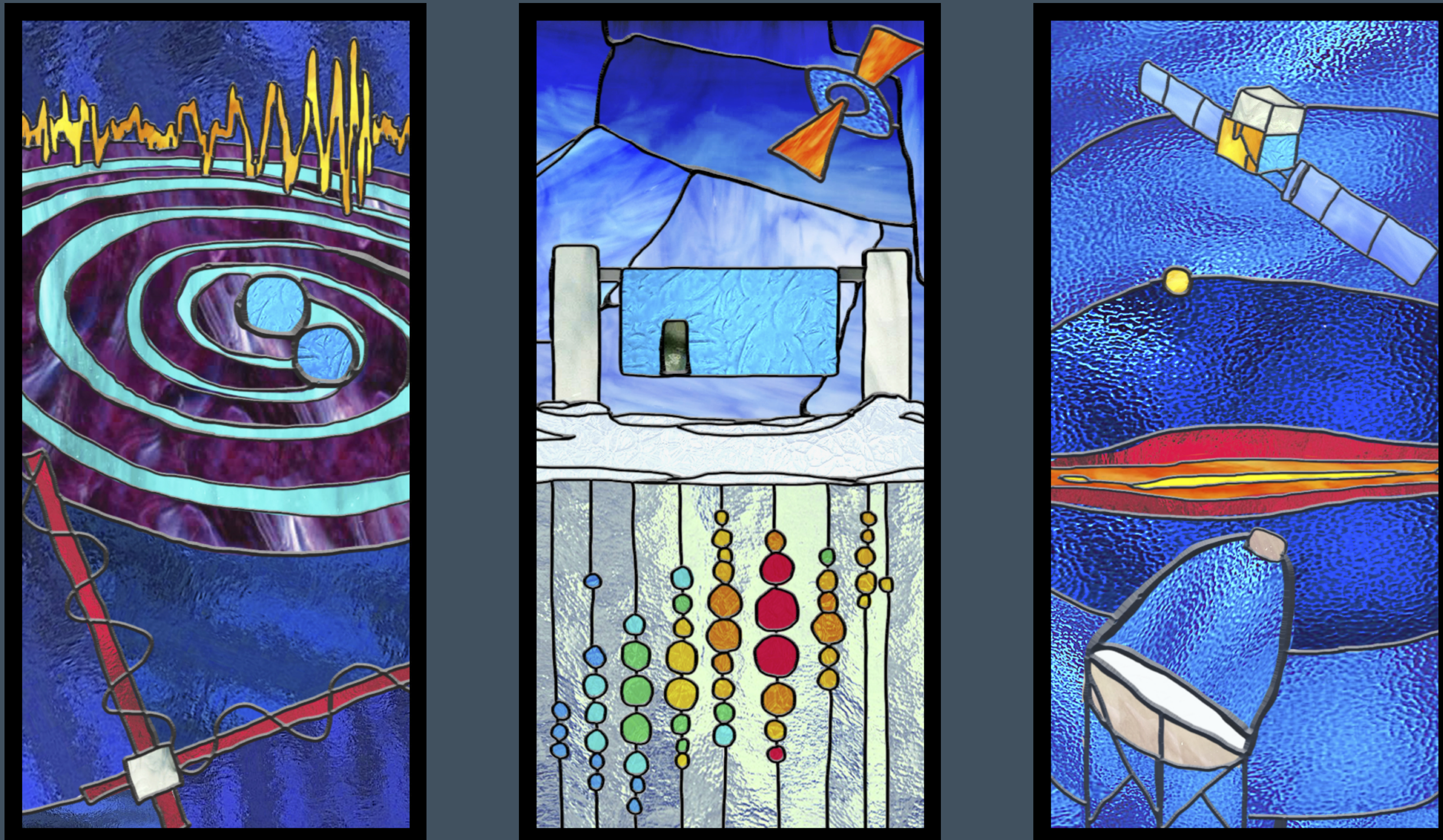


IceCube: Neutrinos and Multi-Messenger Astronomy

VILLUM FONDEN

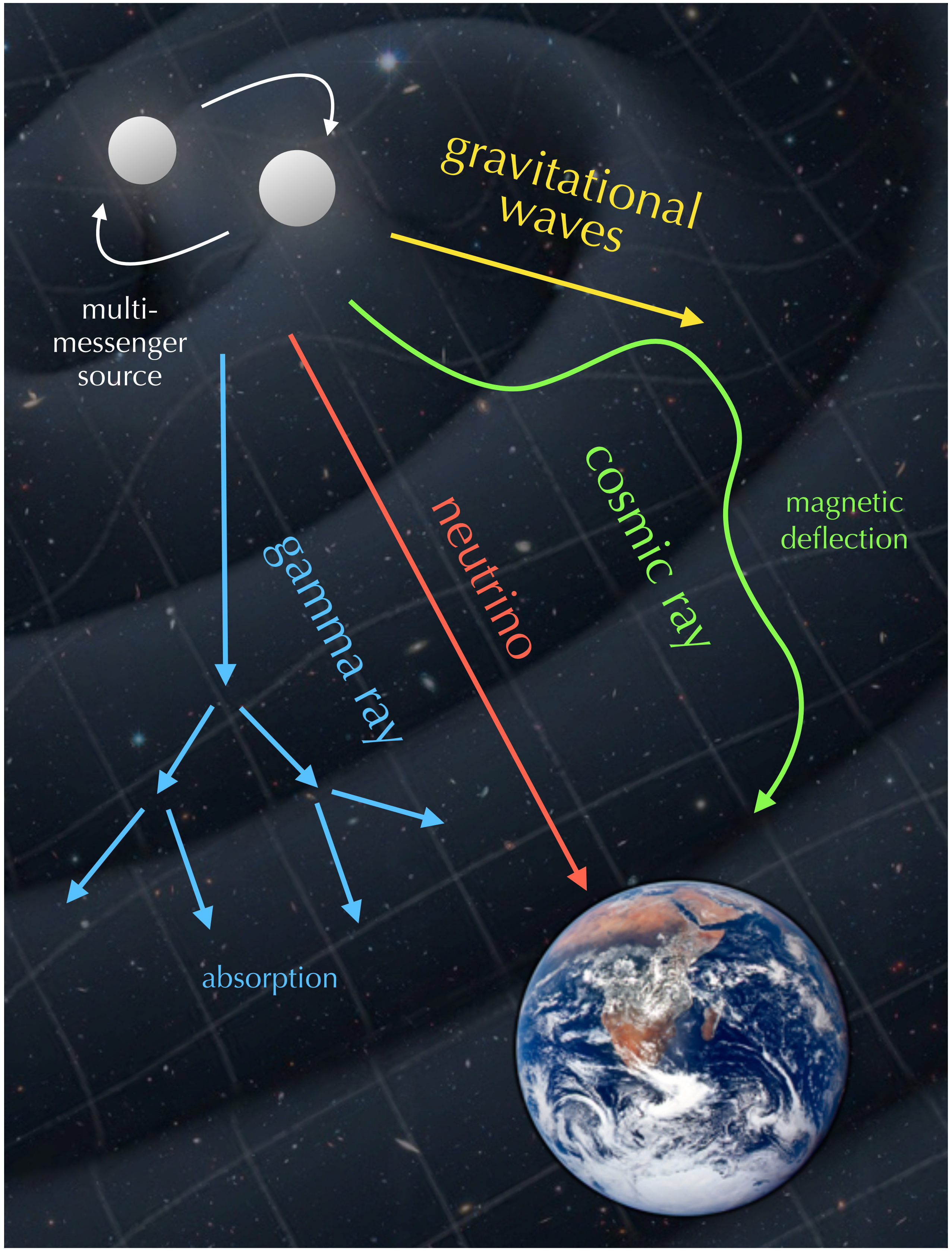
Markus Ahlers

Annual Meeting of the DFS

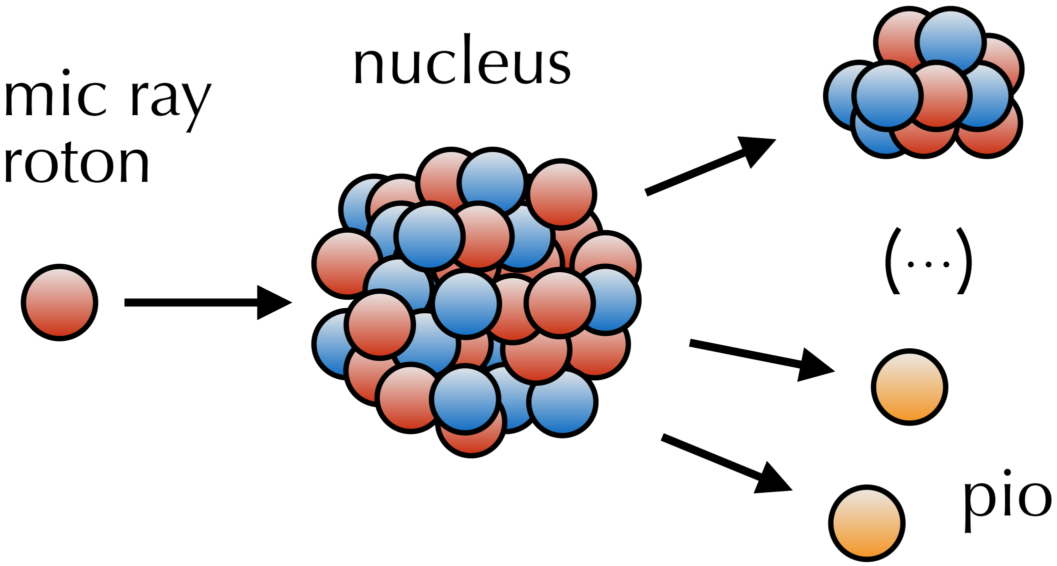
May 28, 2019

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

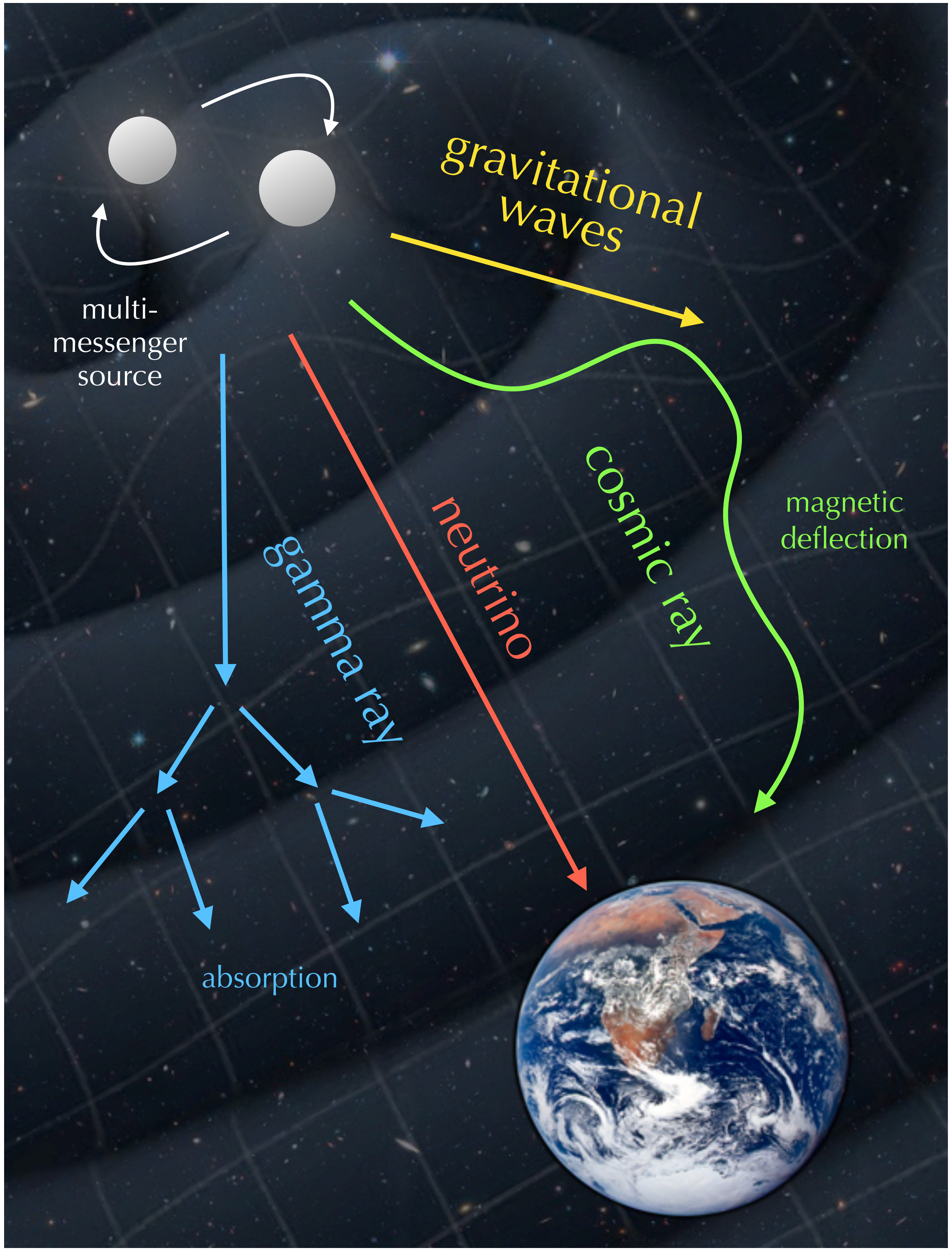


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^0 \rightarrow \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

Multi-Messenger Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields (unlike cosmic rays)

no absorption in cosmic backgrounds (unlike gamma-rays)

smoking-gun of unknown sources of cosmic rays

coincident with photons and gravitational waves

BUT, very difficult to detect!

Detector Requirements

High-energy neutrino collisions with nuclei via
deep-inelastic charged and neutral current interactions.

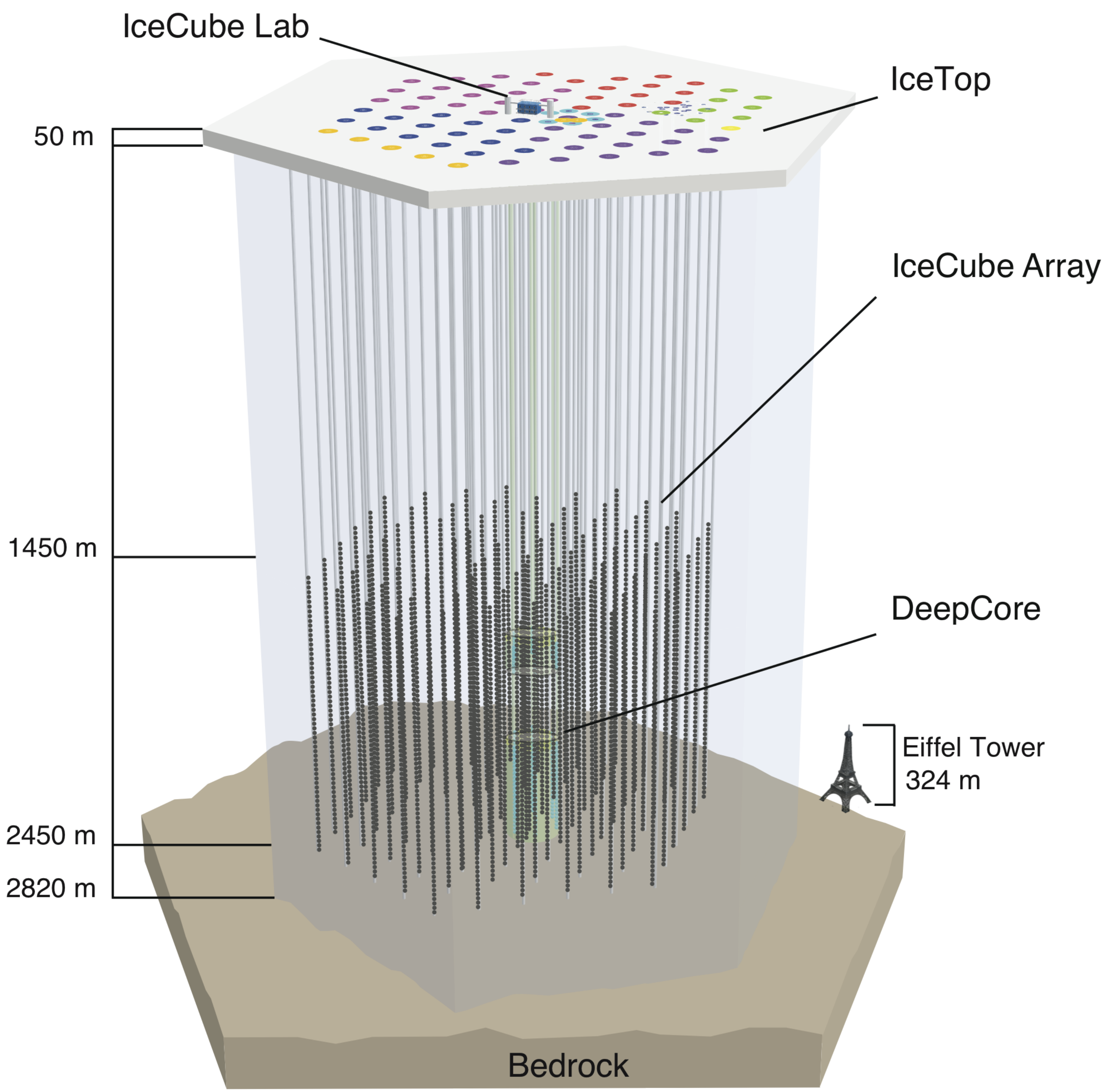
- *back-of-the-envelope* ($E_\nu \sim 1\mathrm{PeV} = 10^{15}$ eV):

- **flux of neutrinos** : $$\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5\mathrm{yr}}$$
- **cross section** : $$\sigma_{\nu N} \sim 10^{-8}\sigma_{pp} \sim 10^{-33}\mathrm{cm}^2$$
- **targets**: $$N_N \sim N_A \times V/\mathrm{cm}^3$$

➜ **rate of events** :

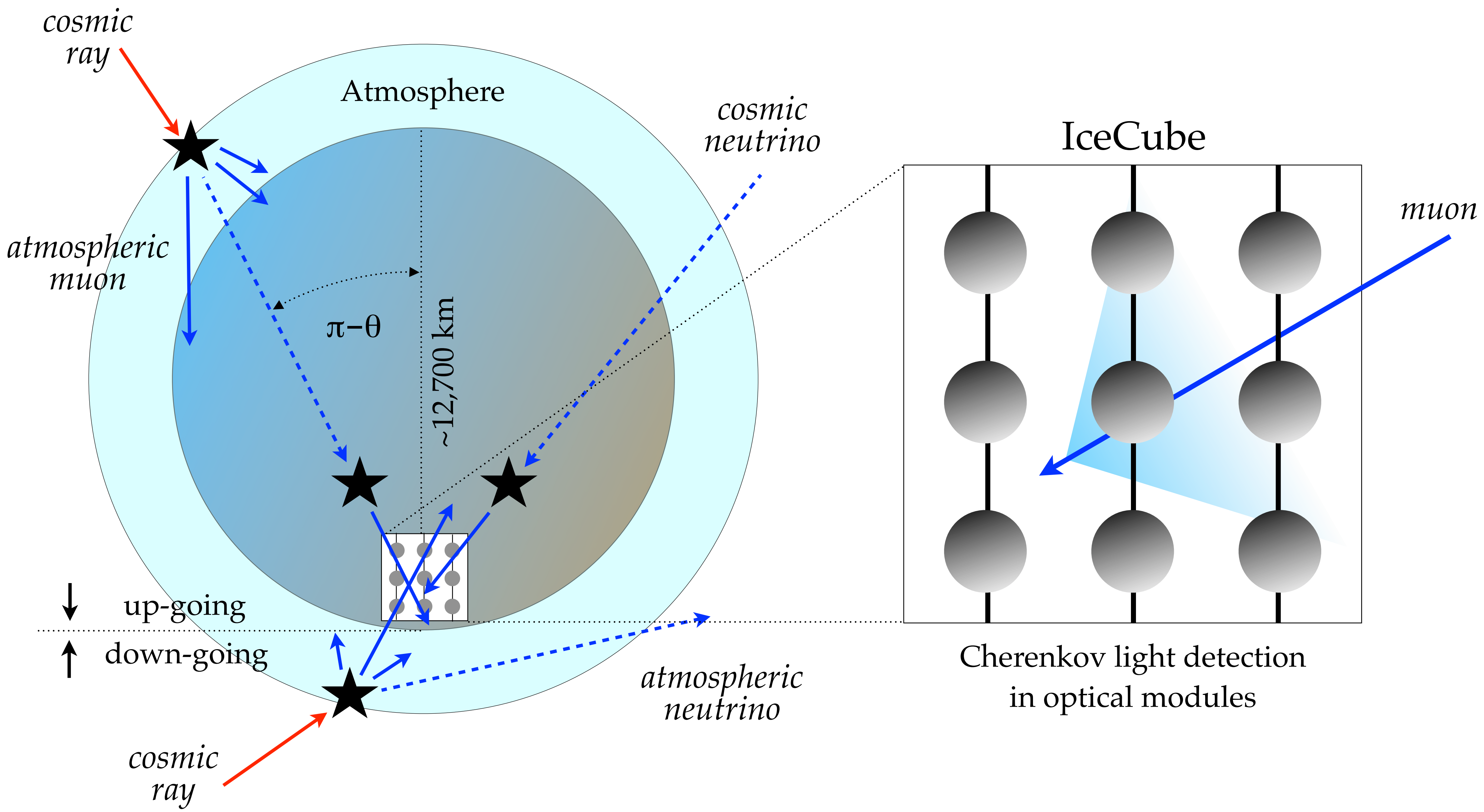
$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$

IceCube Observatory



- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 47 intl. institution
- Digital optical modules (DOMs) attached to strings instrumenting **1 km³ of clear glacial ice**
- 7-year construction: 2004–2011
- price: **2 DKK per ton**
- **NBI member since 2013:**
  - *tau neutrino appearance*
  - *non-standard oscillations*
  - *low-energy transients*
  - *multi-messenger analyses*

Detection Methods I

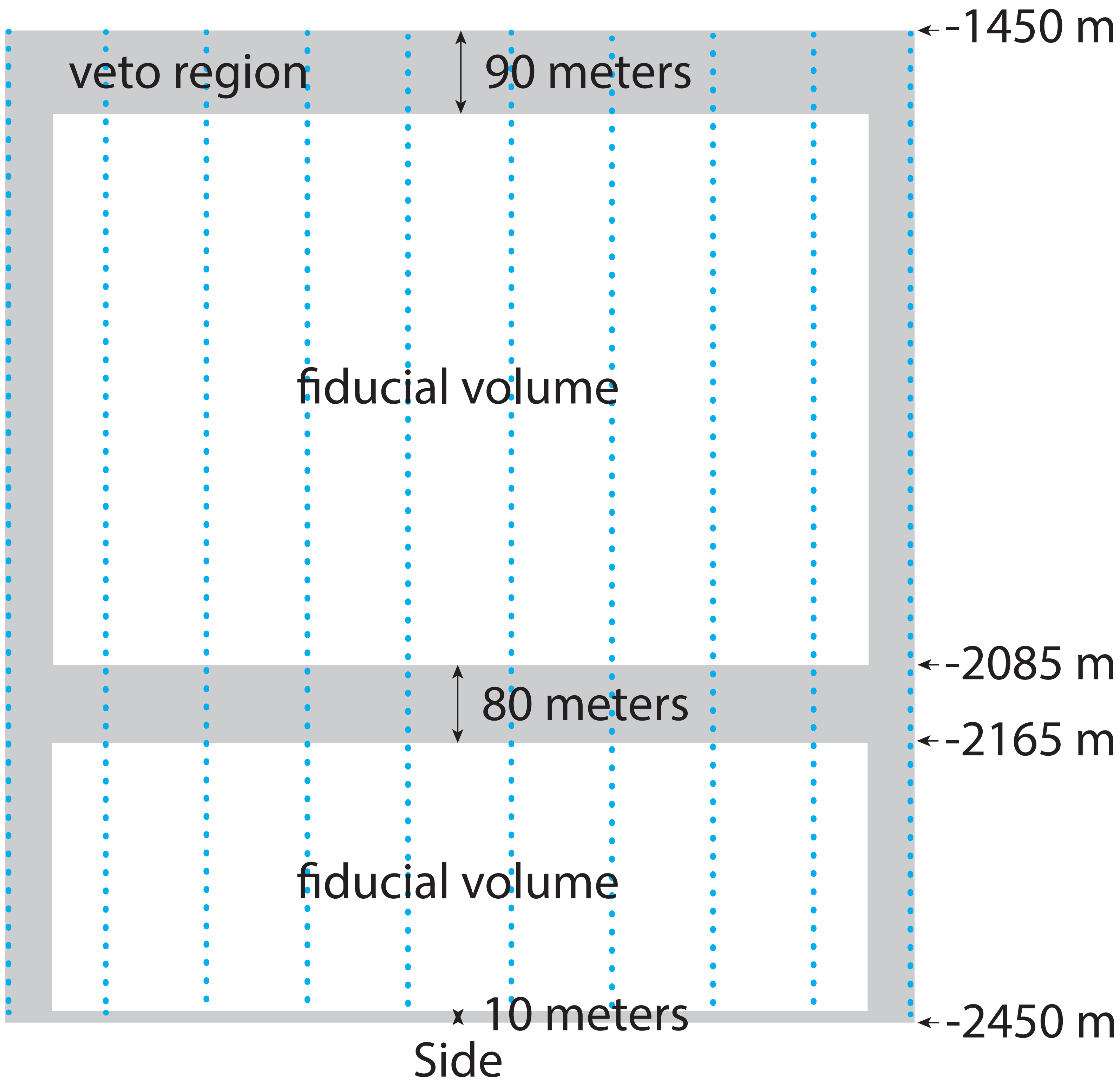


➜ Selecting **up-going muon tracks** reduces atmospheric muon background:

$$\underbrace{10,000,000,000}_{\text{atmospheric muons (from above)}} : \underbrace{100,000}_{\text{atmospheric neutrinos}} : \underbrace{10}_{\text{cosmic neutrinos}}$$

Detection Methods II

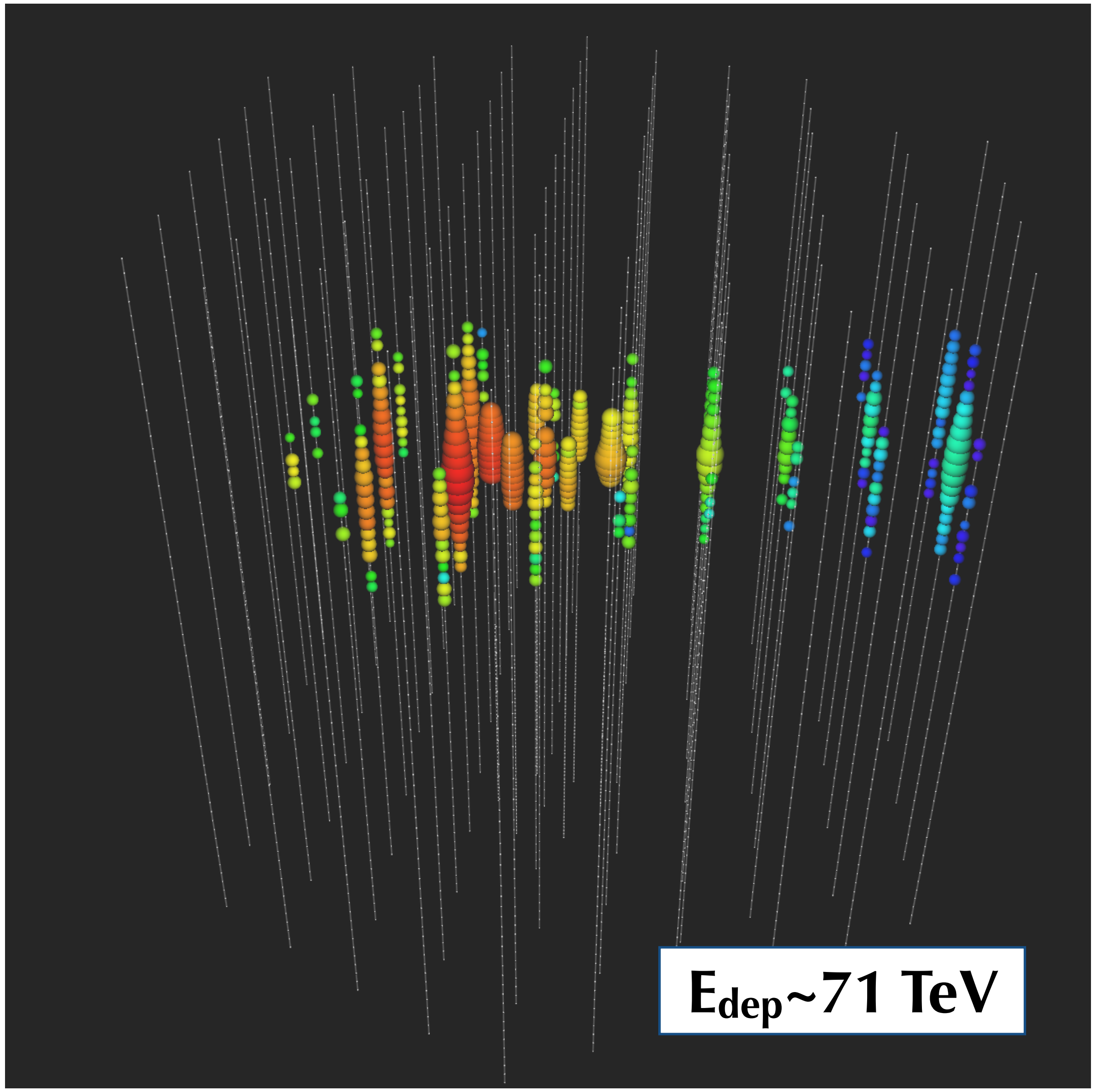
- Outer layer of optical modules used as virtual **veto region** (gray area)
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis

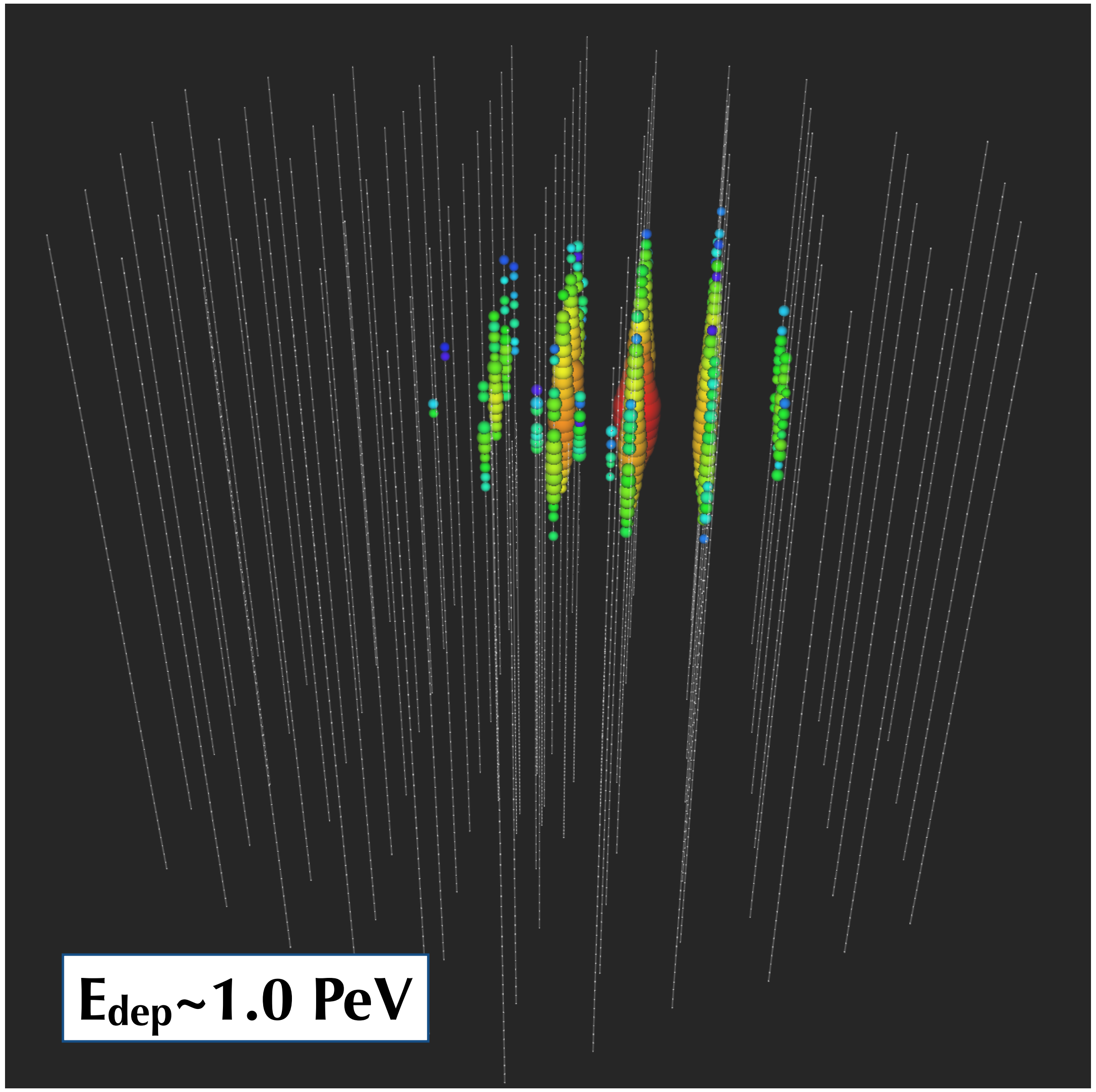


Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering) **"cascade event"** (from all flavours)

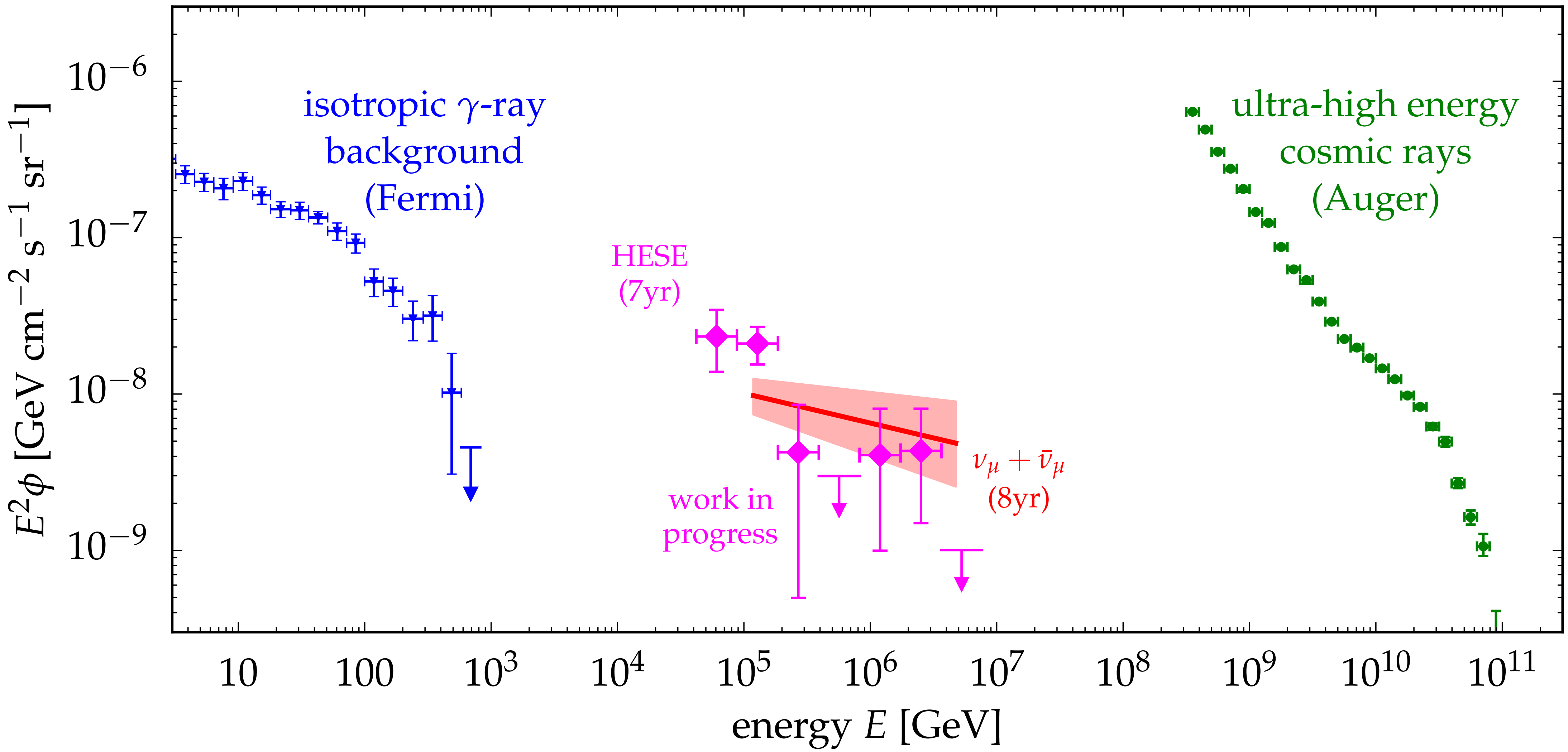




["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

Diffuse TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (7yrs):** [Science 342 (2013); work in progress]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (8yrs):** [Astrophys.J. 833 (2016); update ICRC 2017]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption



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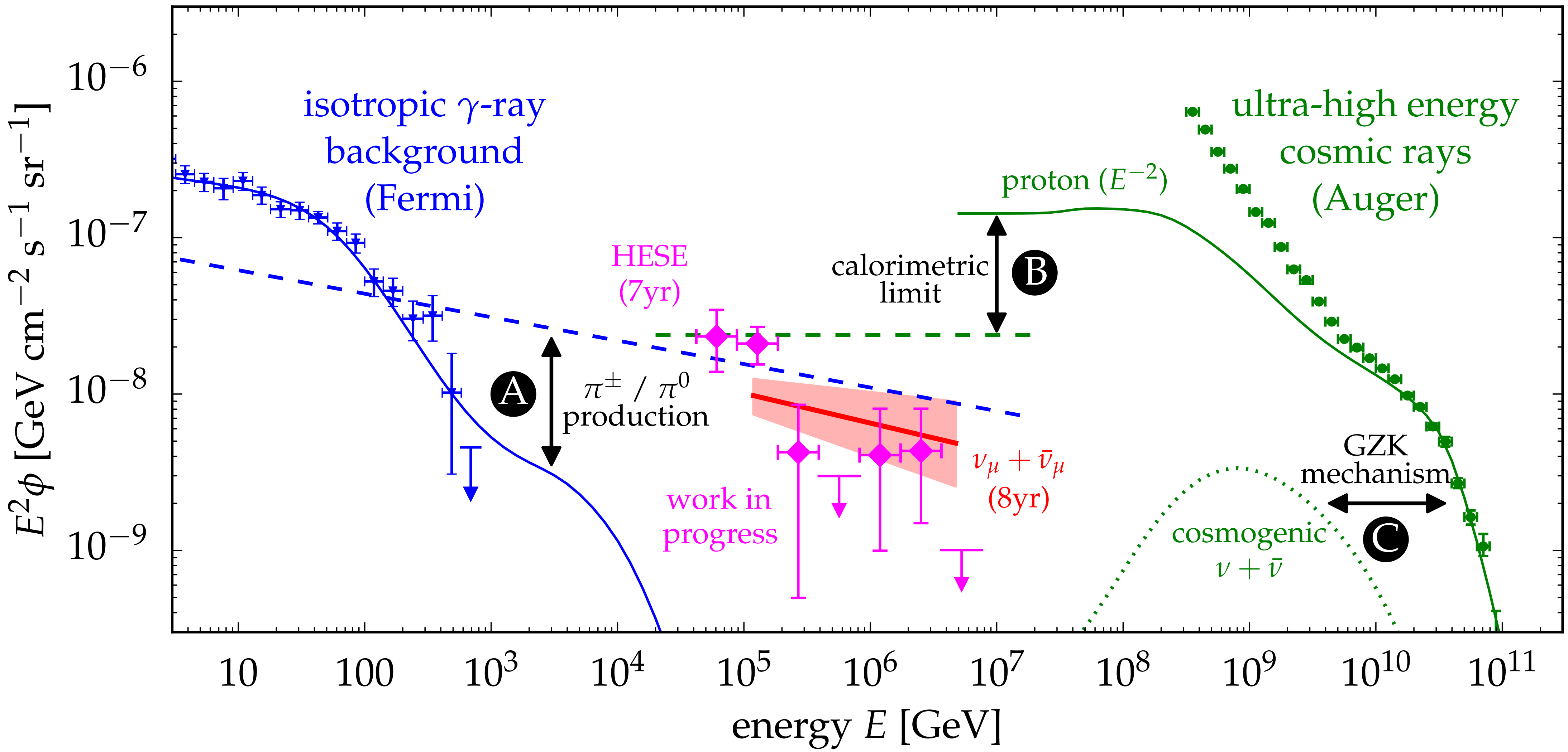
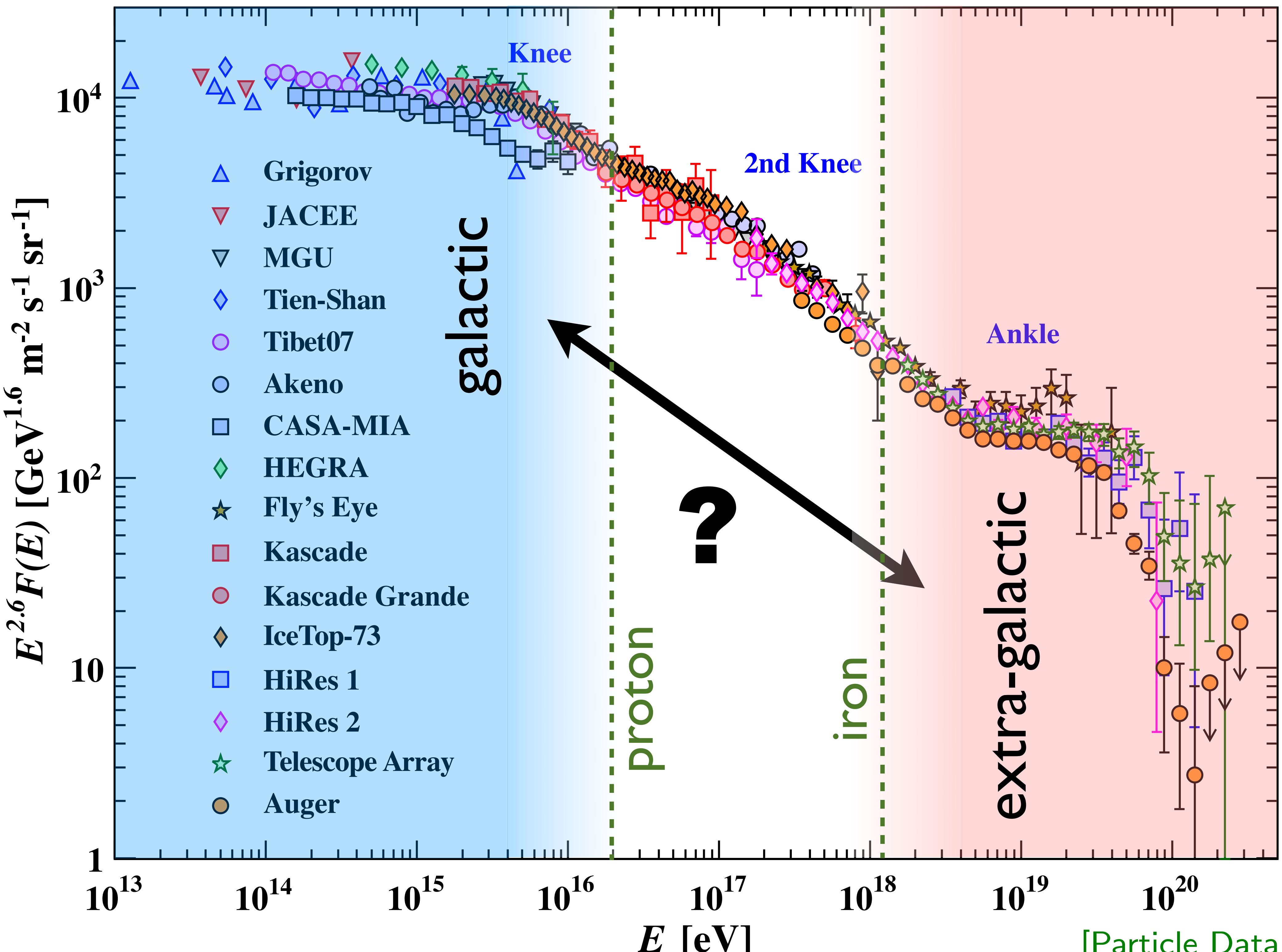


Primary Cosmic Rays for PeV Neutrinos

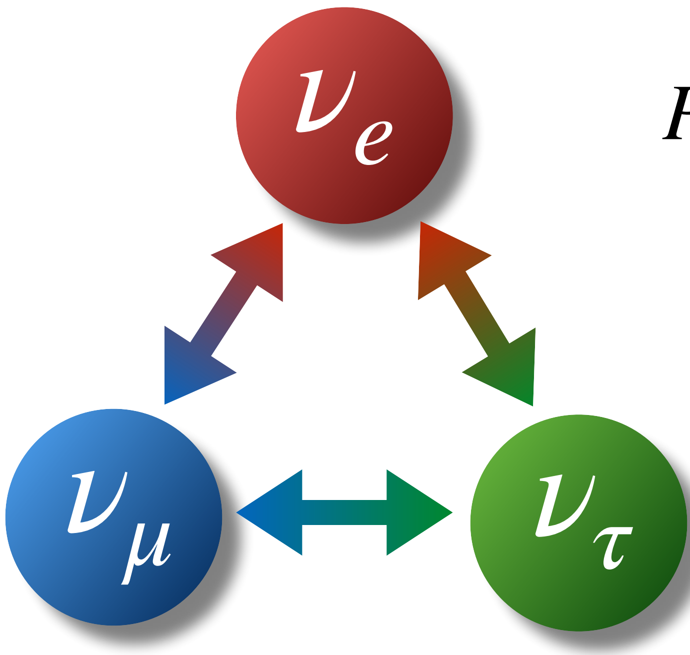
1 PeV neutrino ↔ 20-30 PeV cosmic ray nucleon



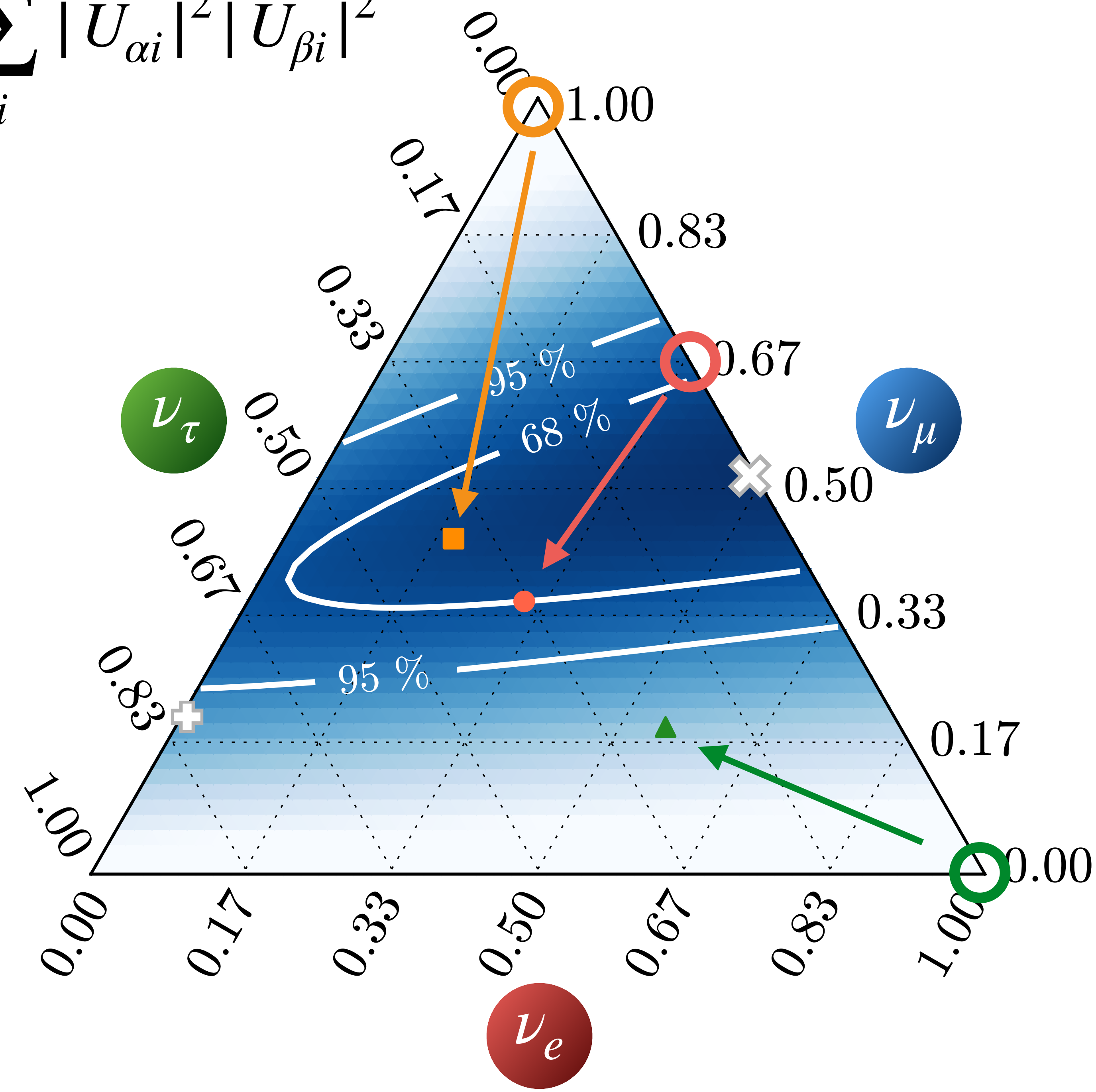
[Particle Data Group'13]

Astrophysical Flavours

Oscillation of neutrino flavours between source and observatory.



$$P_{\nu_\alpha \to \nu_\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

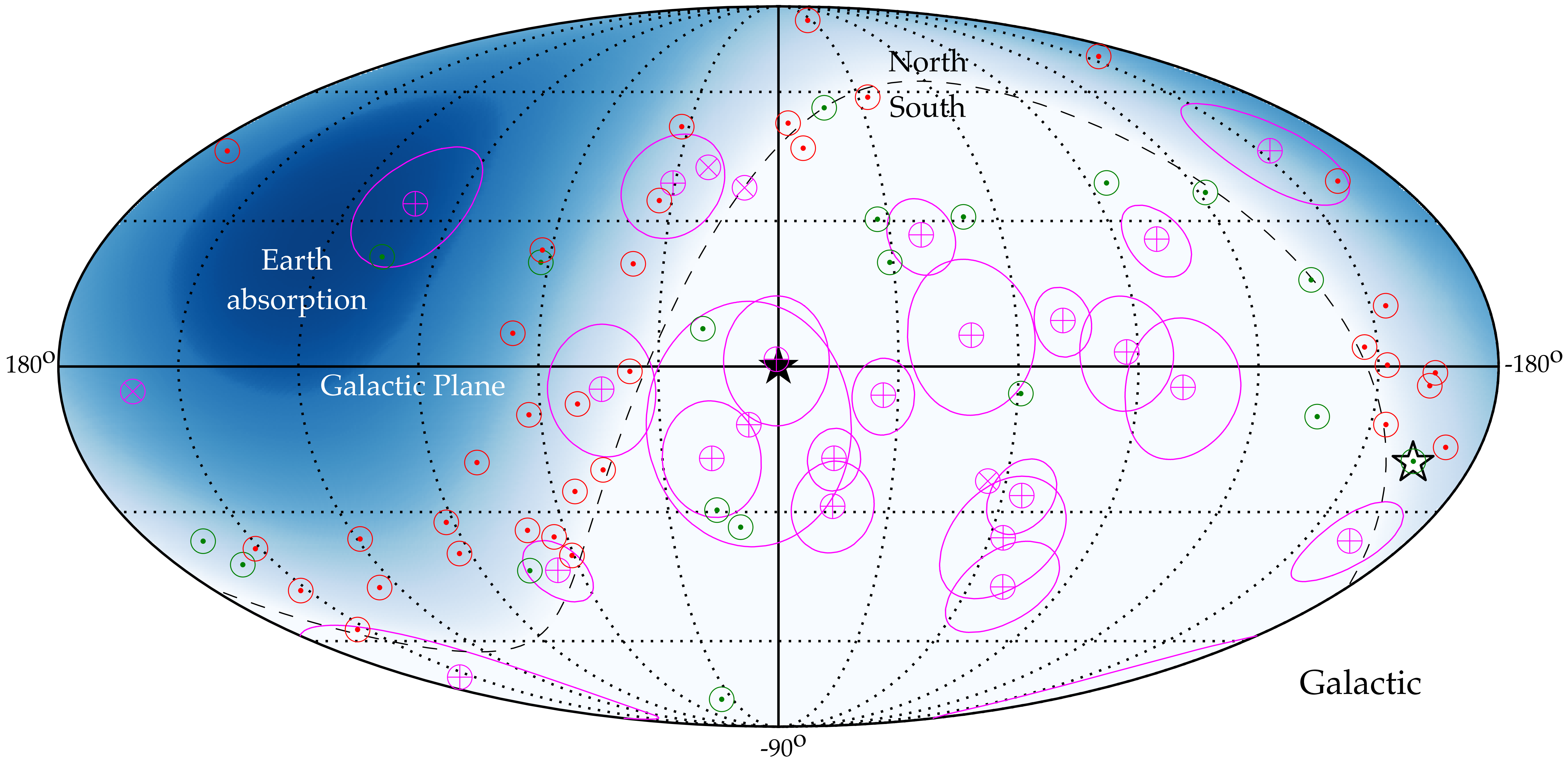


- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  - *pion & muon decay:* $1:2:0$
  - *muon-damped decay:* $0:1:0$
  - *neutron decay:* $1:0:0$

Cosmic neutrinos visible via their oscillation-averaged flavour.

Status of Neutrino Astronomy

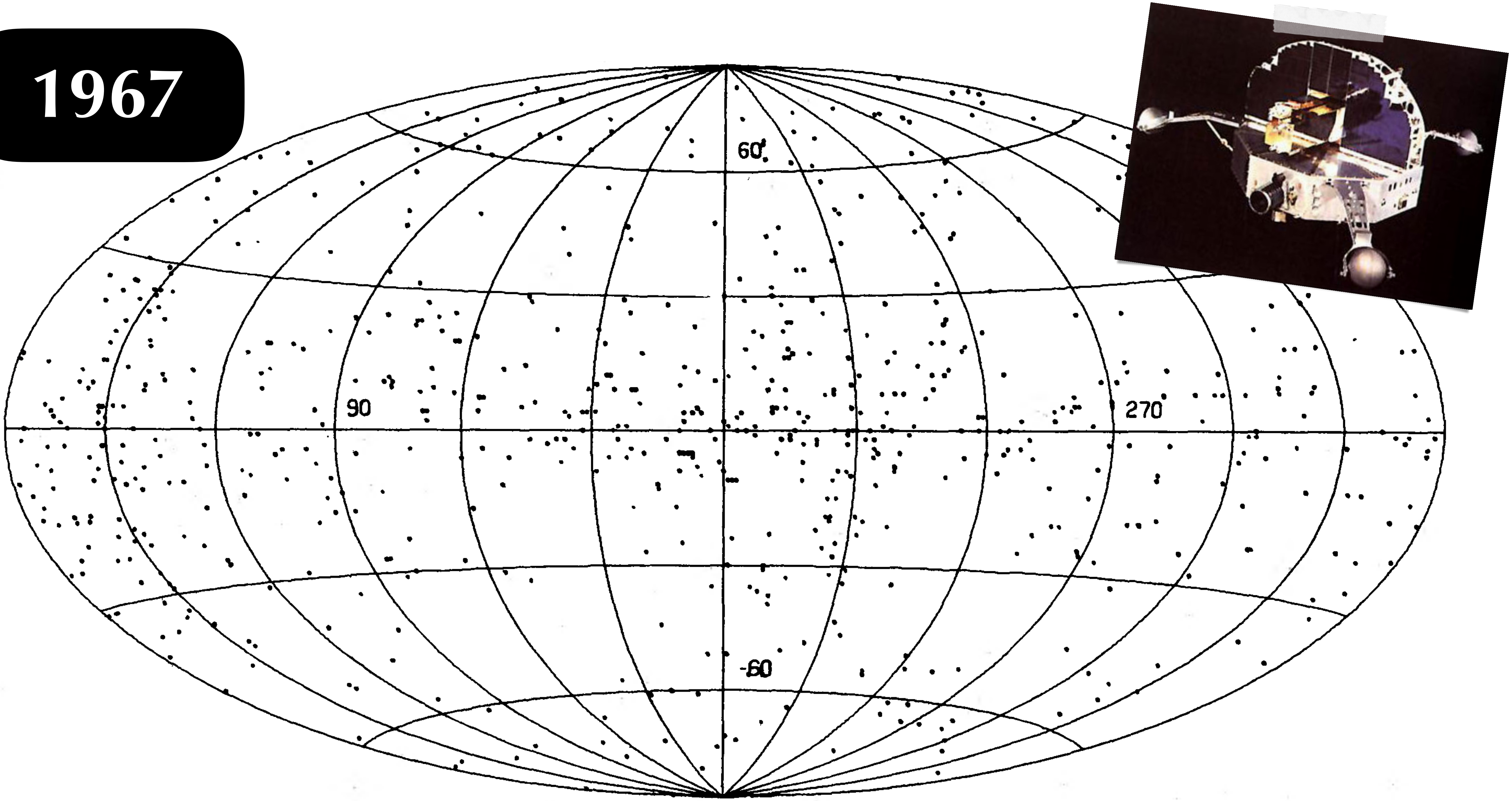
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red) + public alerts (green))



No significant steady or transient emission from known Galactic and extragalactic high-energy sources (except for one candidate).

Status of Neutrino Astronomy

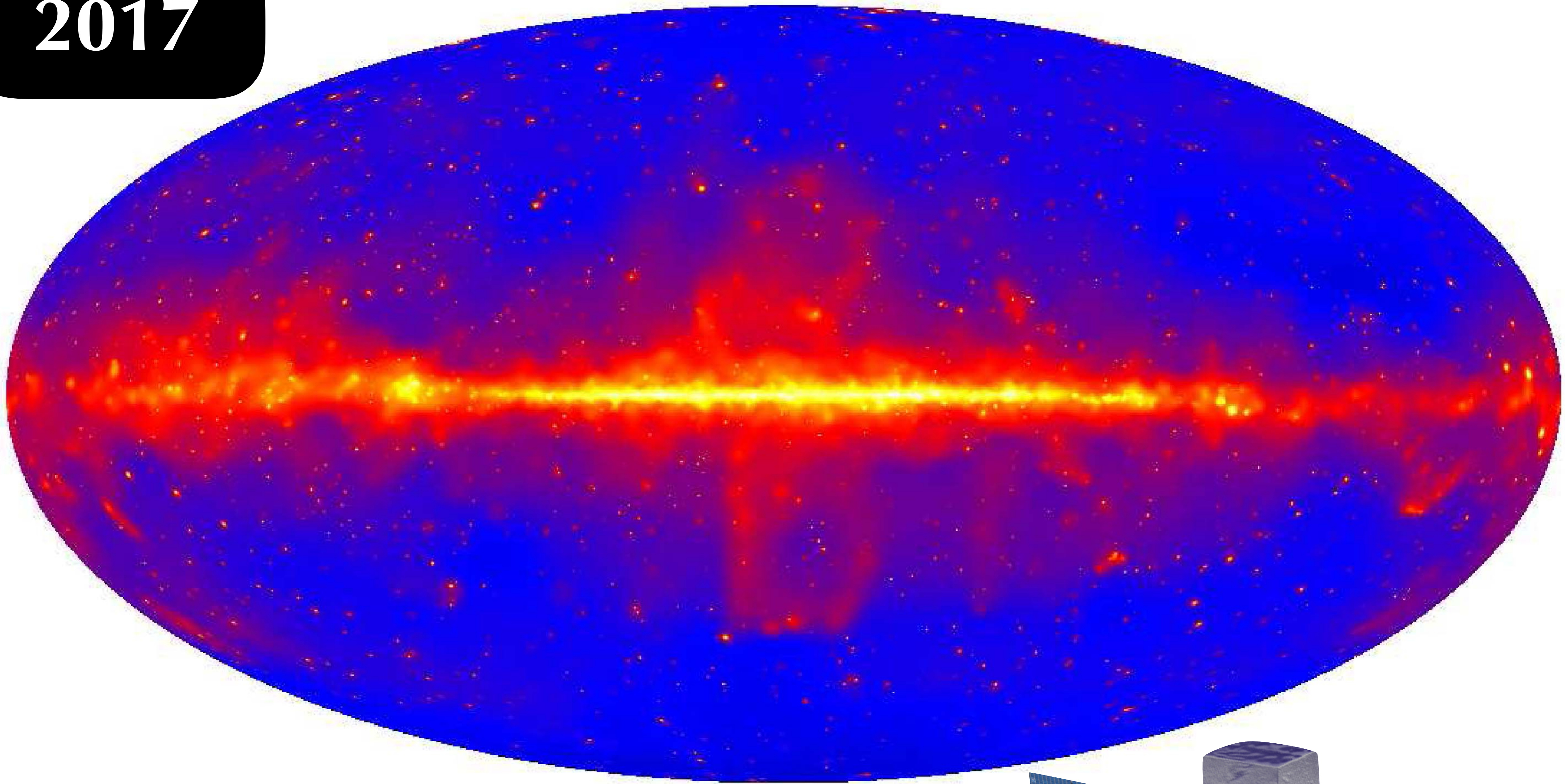
1967



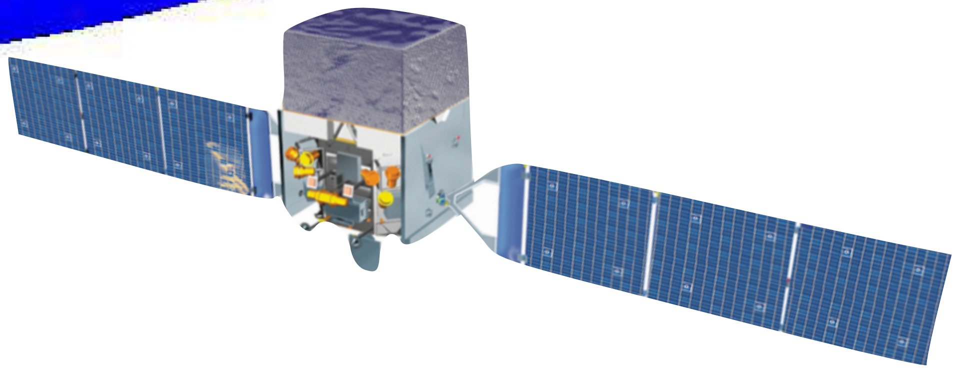
Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

Status of Neutrino Astronomy

2017



Fermi-LAT gamma-ray count map

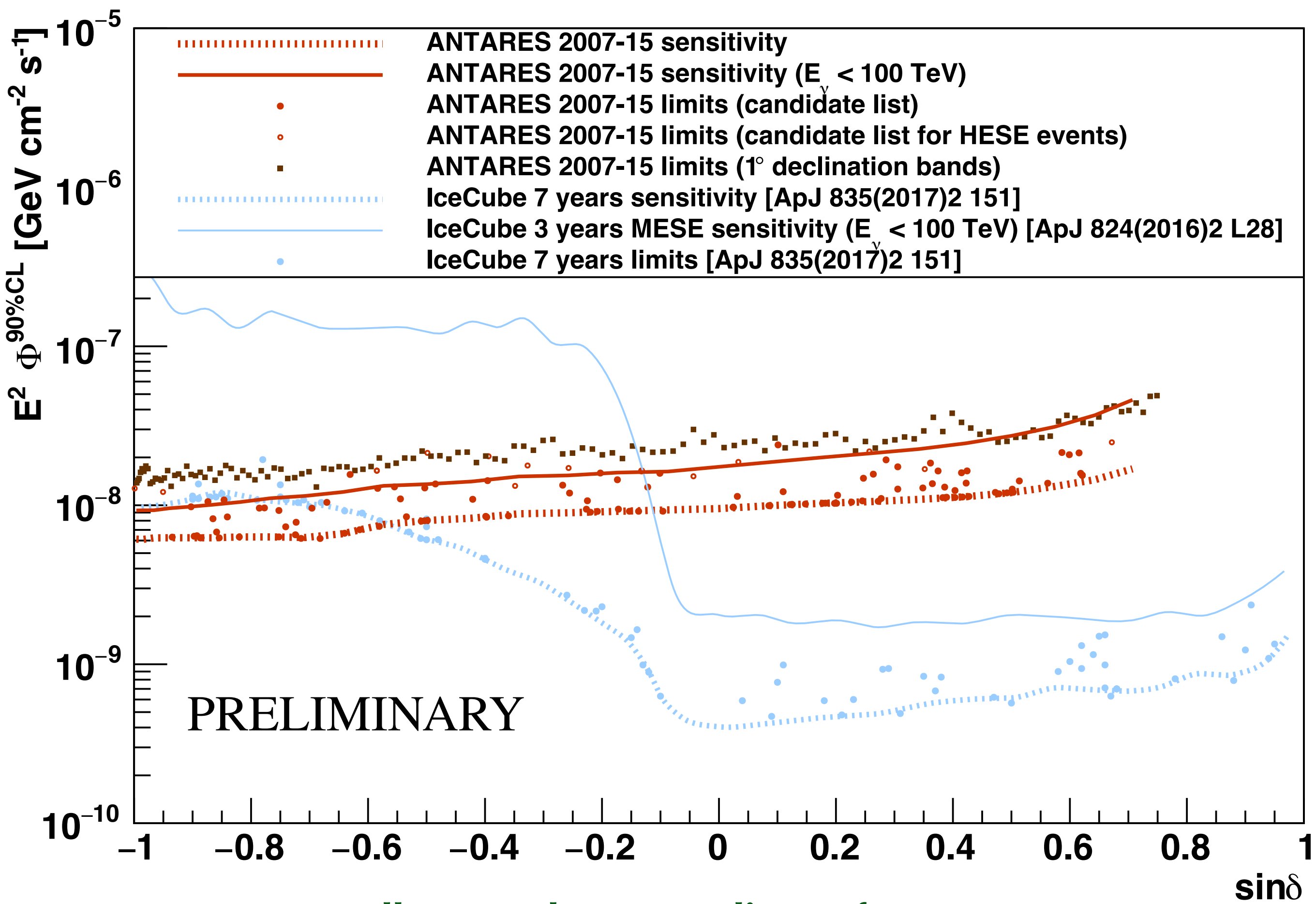


Search for Neutrino Sources

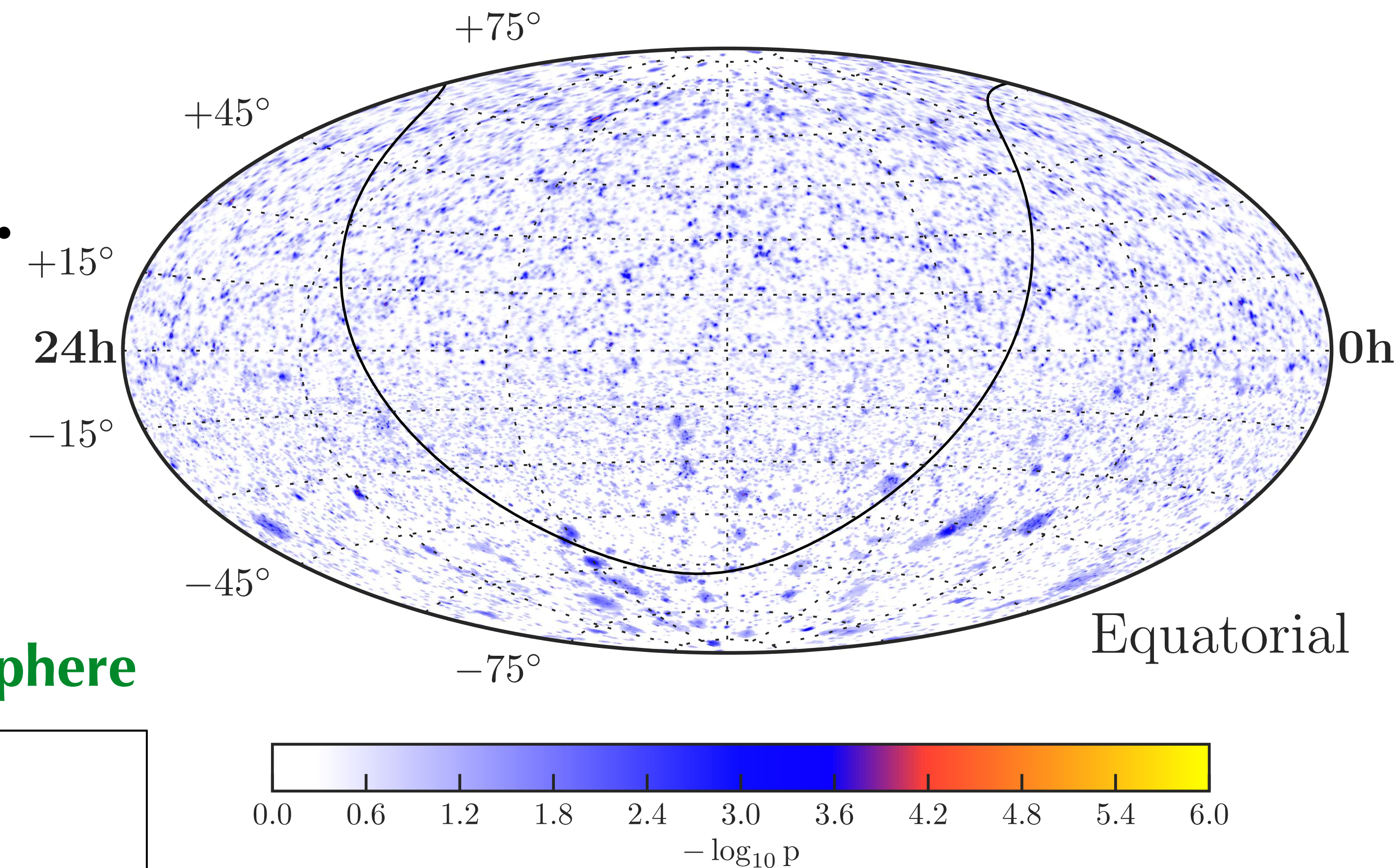
IceCube and ANTARES/KM3NeT with complementary field of views.

ICECUBE

Southern Hemisphere | Northern Hemisphere



[Albert et al., Proceedings of ICRC 2017]



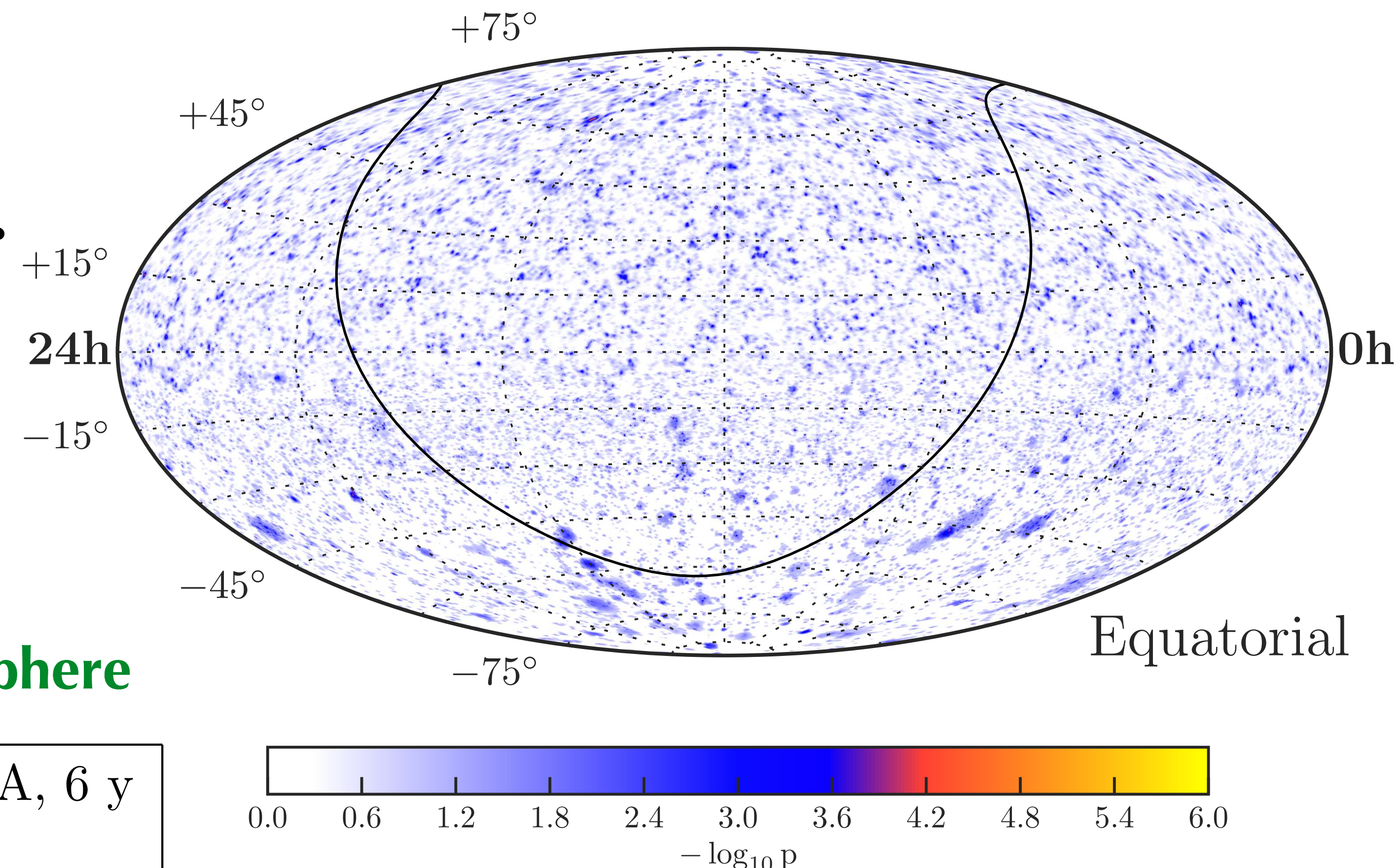
[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

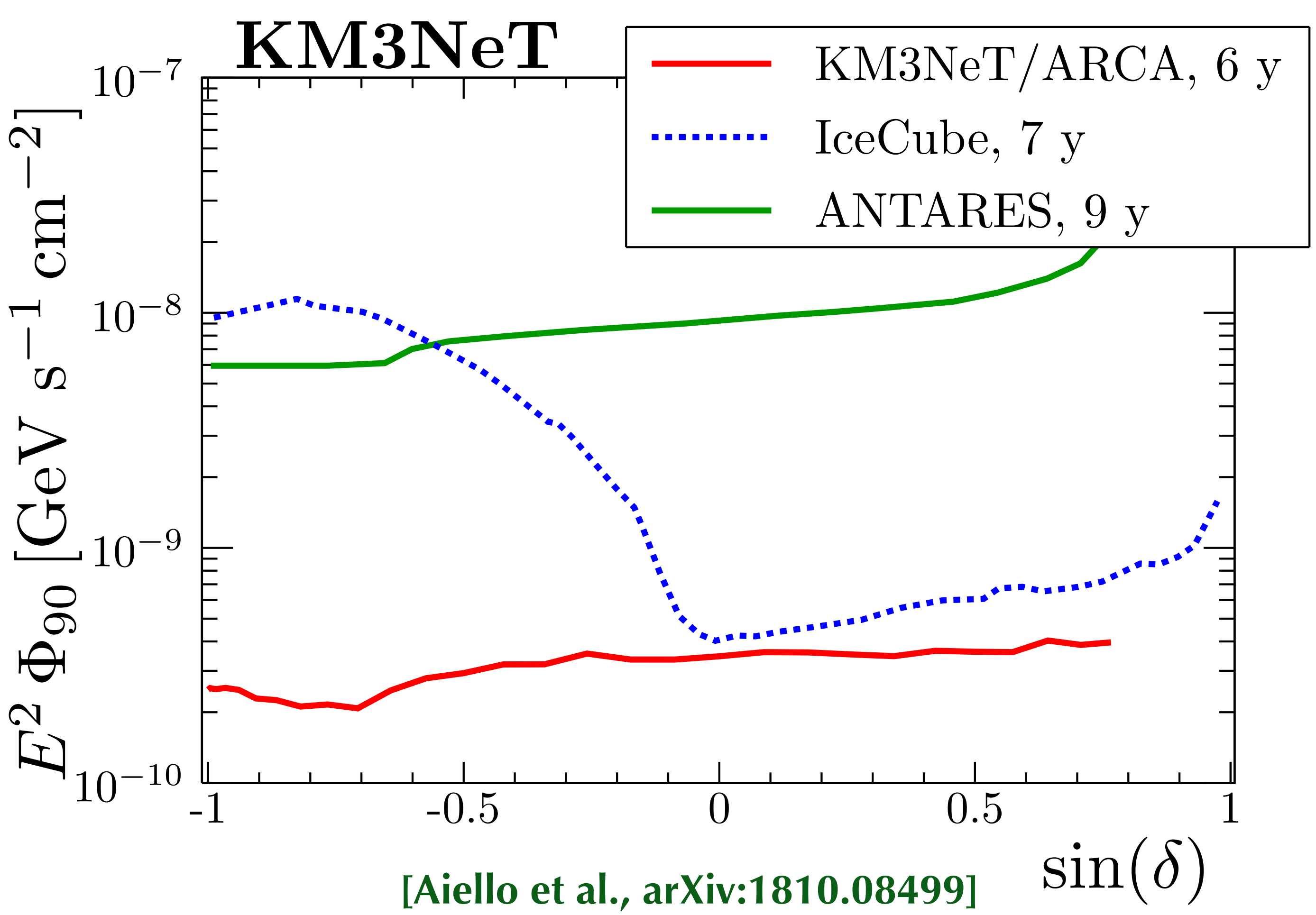
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere



[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]



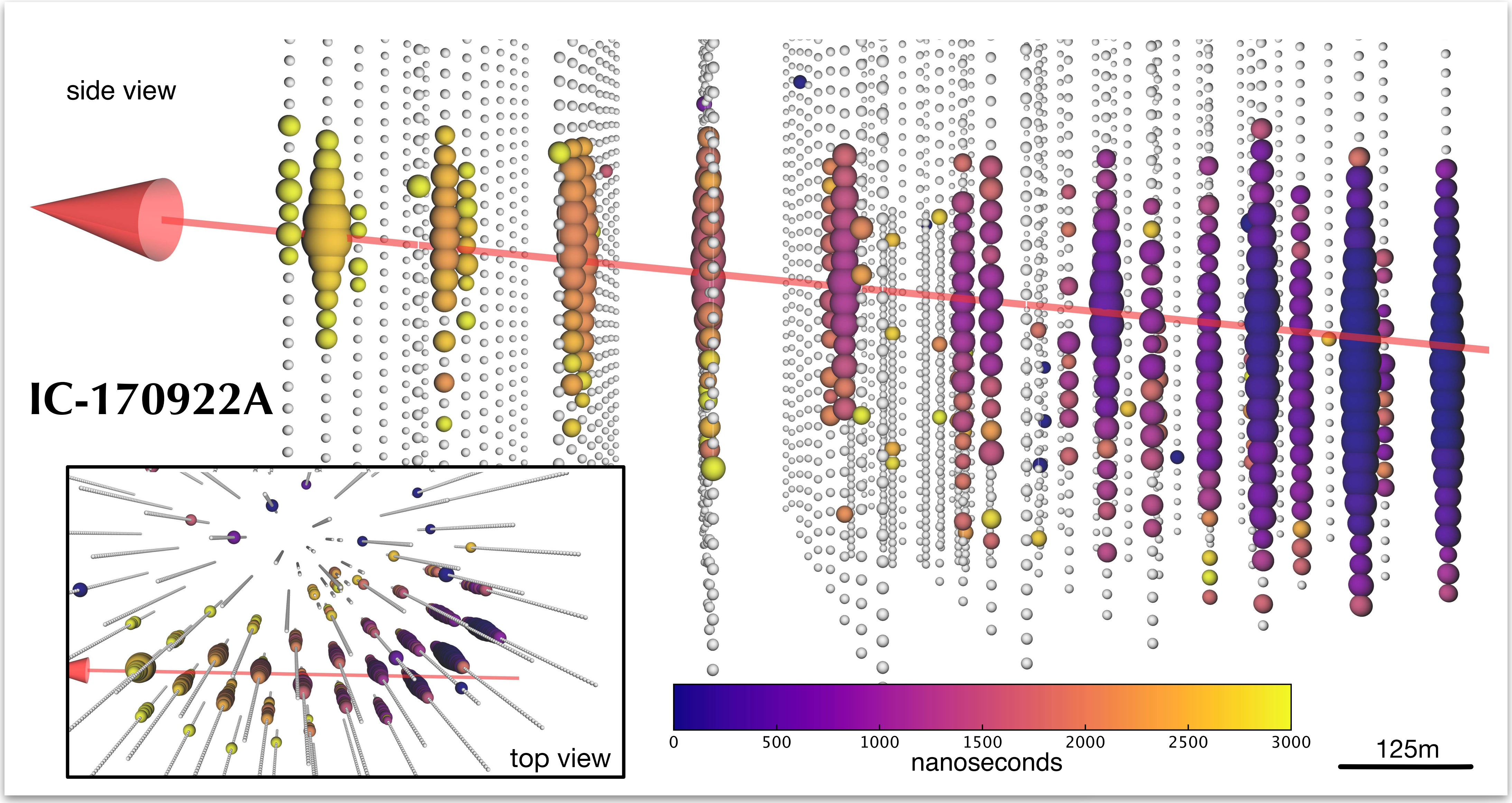
[Aiello et al., arXiv:1810.08499]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

Realtime Neutrino Alerts

IceCube issues realtime neutrino alerts* to multi-messenger partner for rapid follow-up.

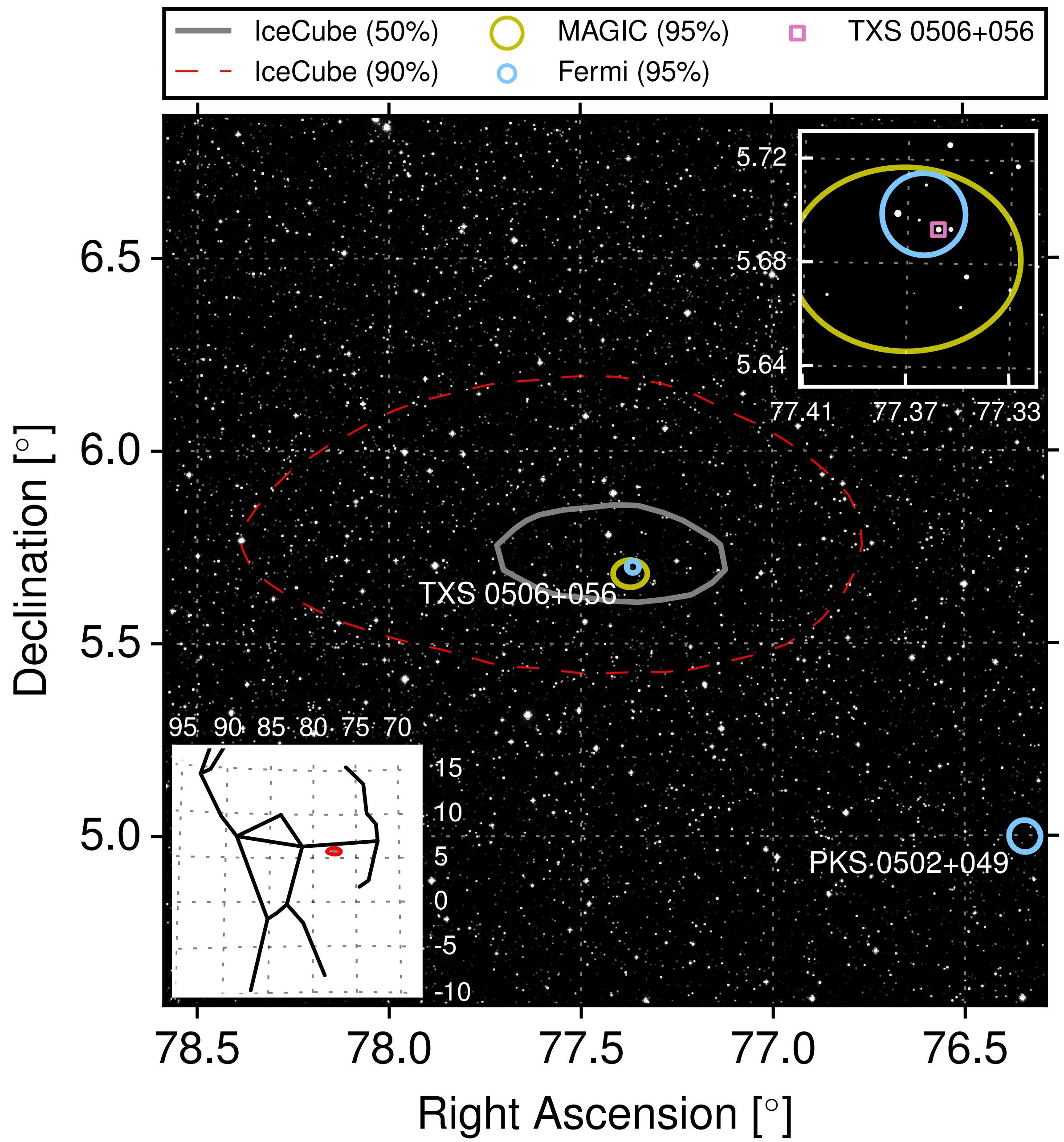
[* high-energy muon tracks (likely astrophysical) with good angular resolution (0.5-2deg)]



up-going muon track (5.7° below horizon) observed September 22, 2017

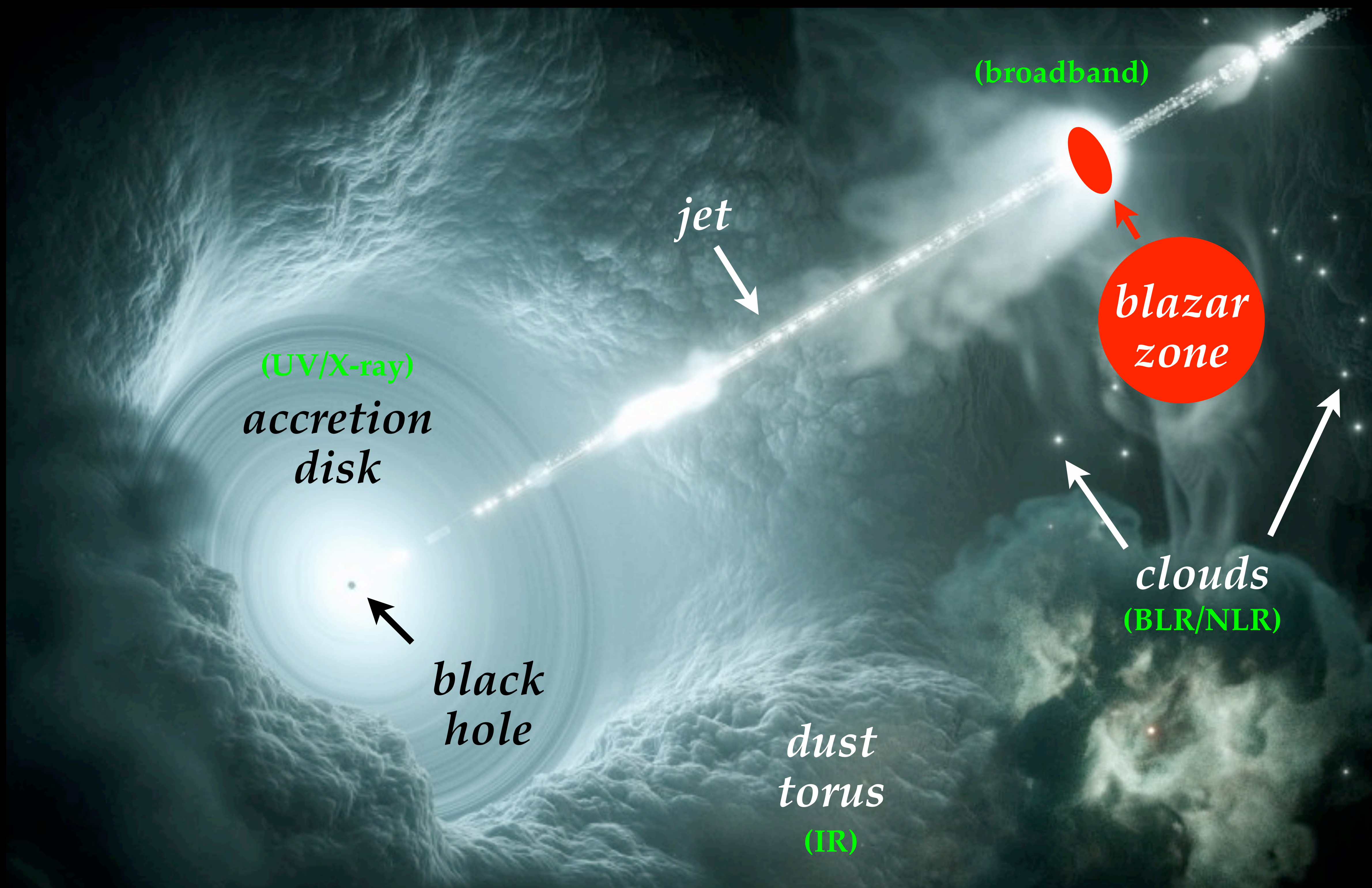
best-fit neutrino energy is about 300 TeV

TXS 0506+056



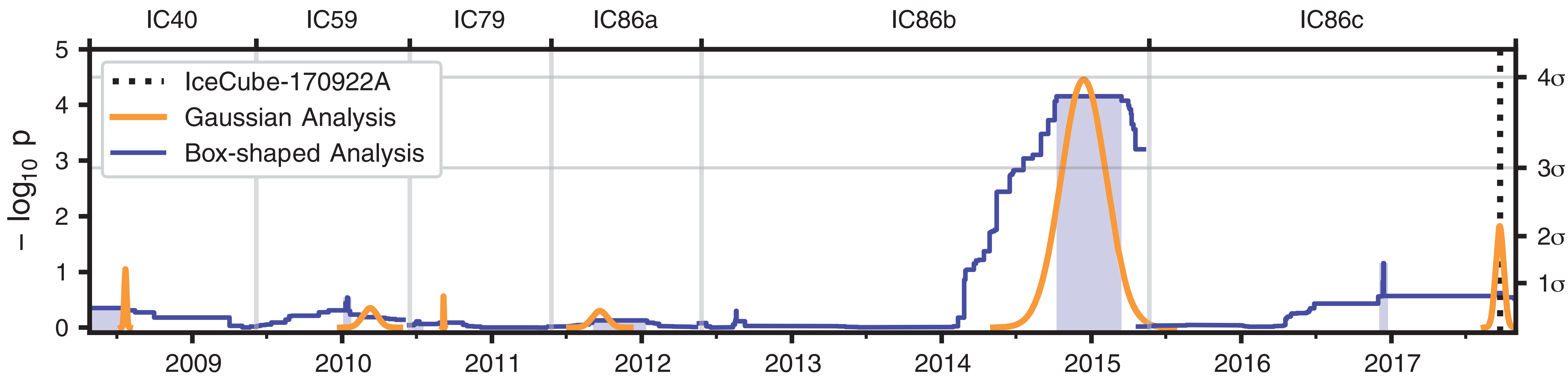
- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

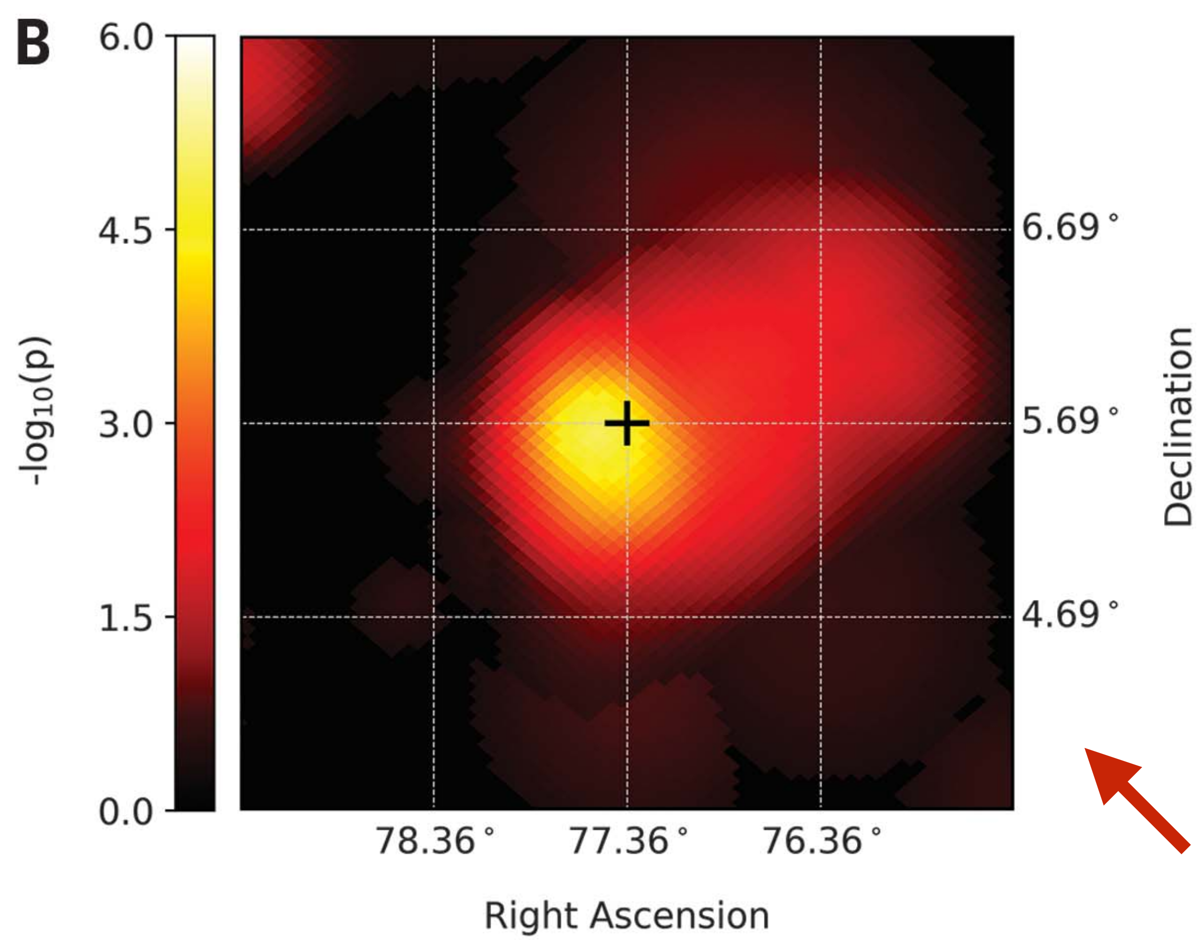
Blazars as Neutrino Factories



Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

Neutrino Flare in 2014/15

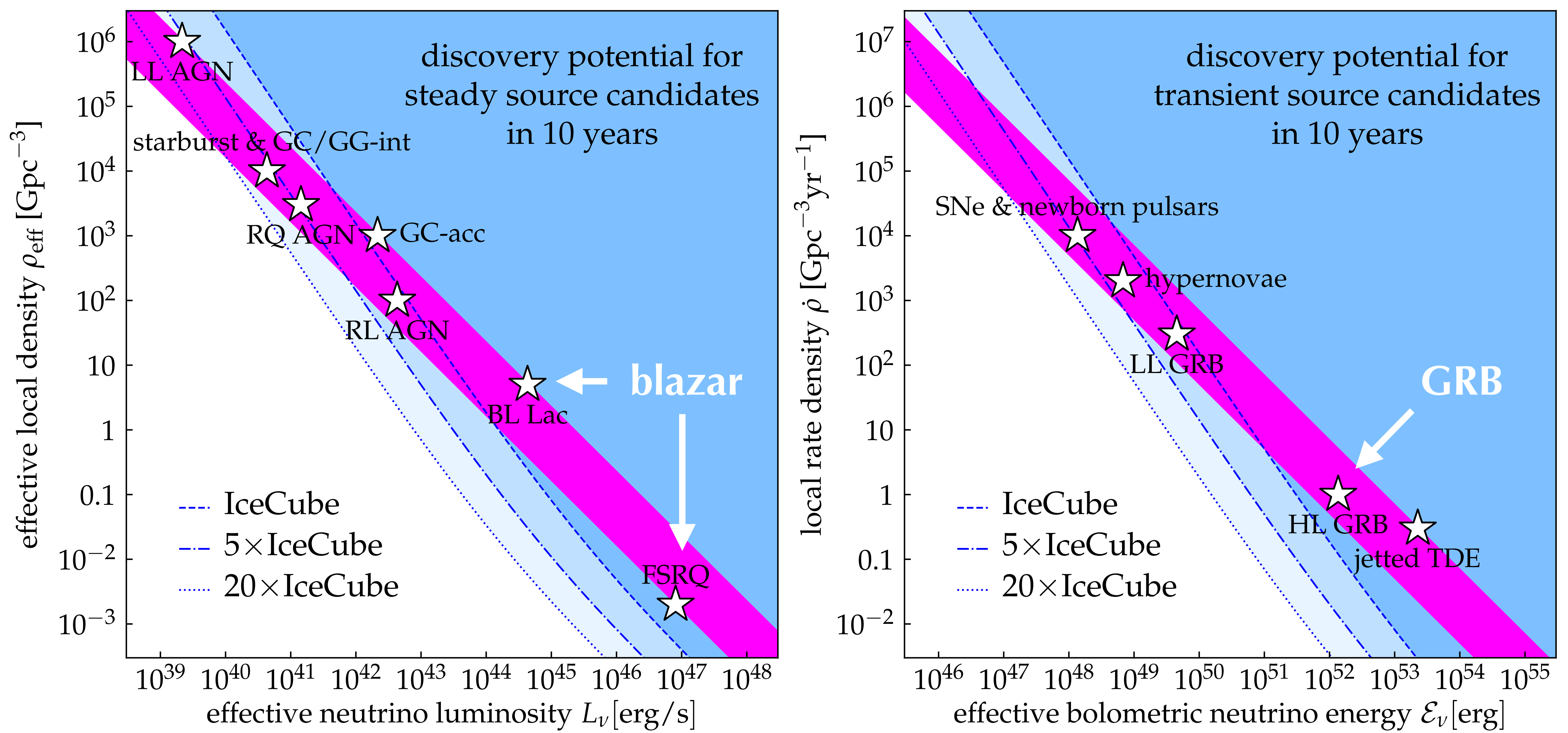




- Independent 3.5σ evidence for a **neutrino flare** (13±5 events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times that of gamma-rays** (Fermi-LAT).

neutrino morphology of flare

Are Blazars the only Sources?

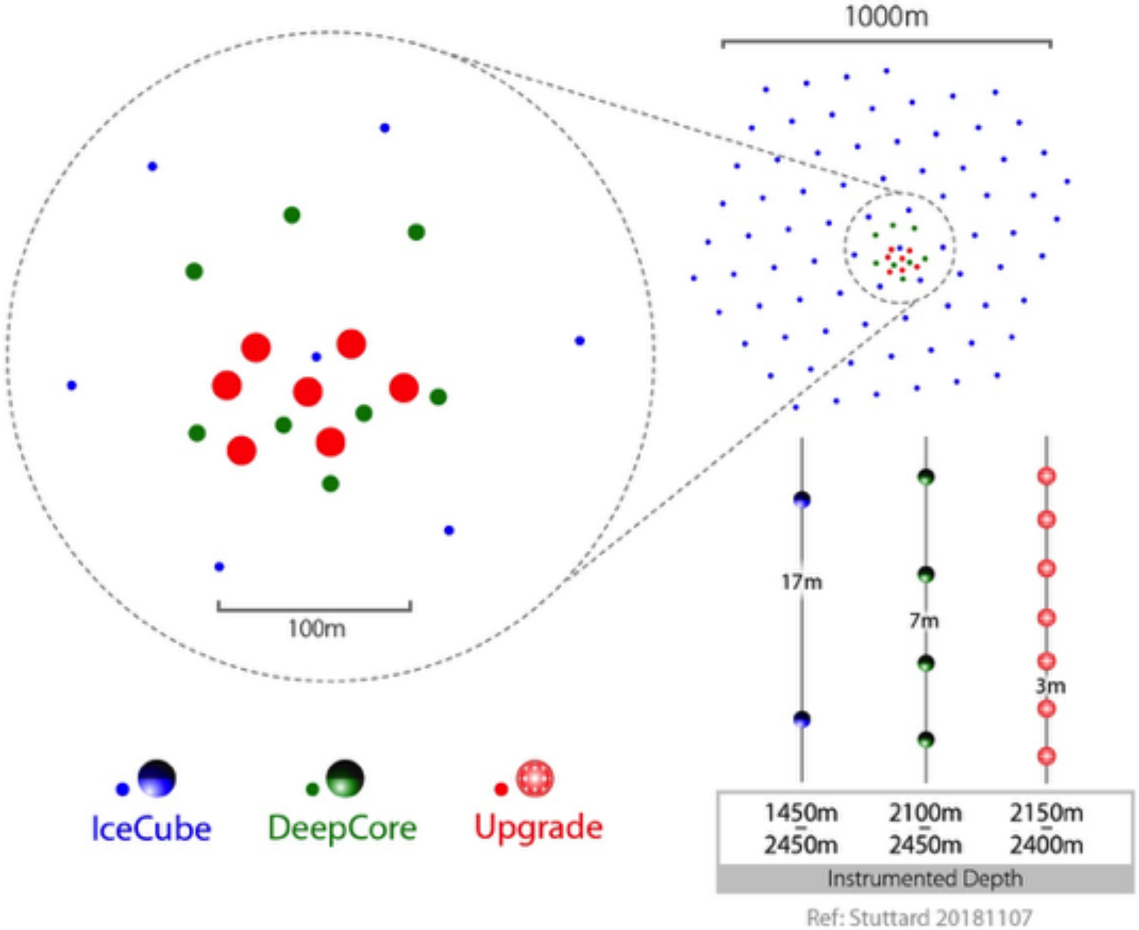


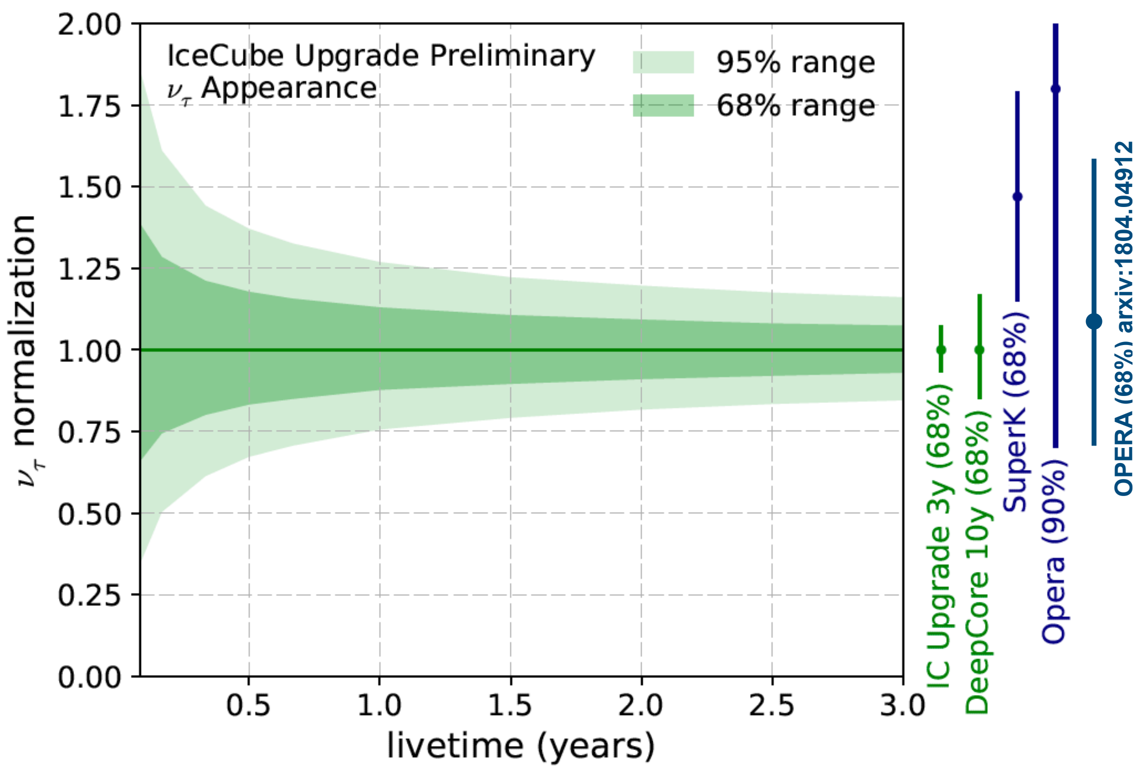
[Ackermann, MA, Anchordoqui, Bustamante et al., arXiv:1903.04333]

Rare sources, like blazars or gamma-ray bursts, can not be the dominant sources of TeV-PeV neutrino emission (magenta band).

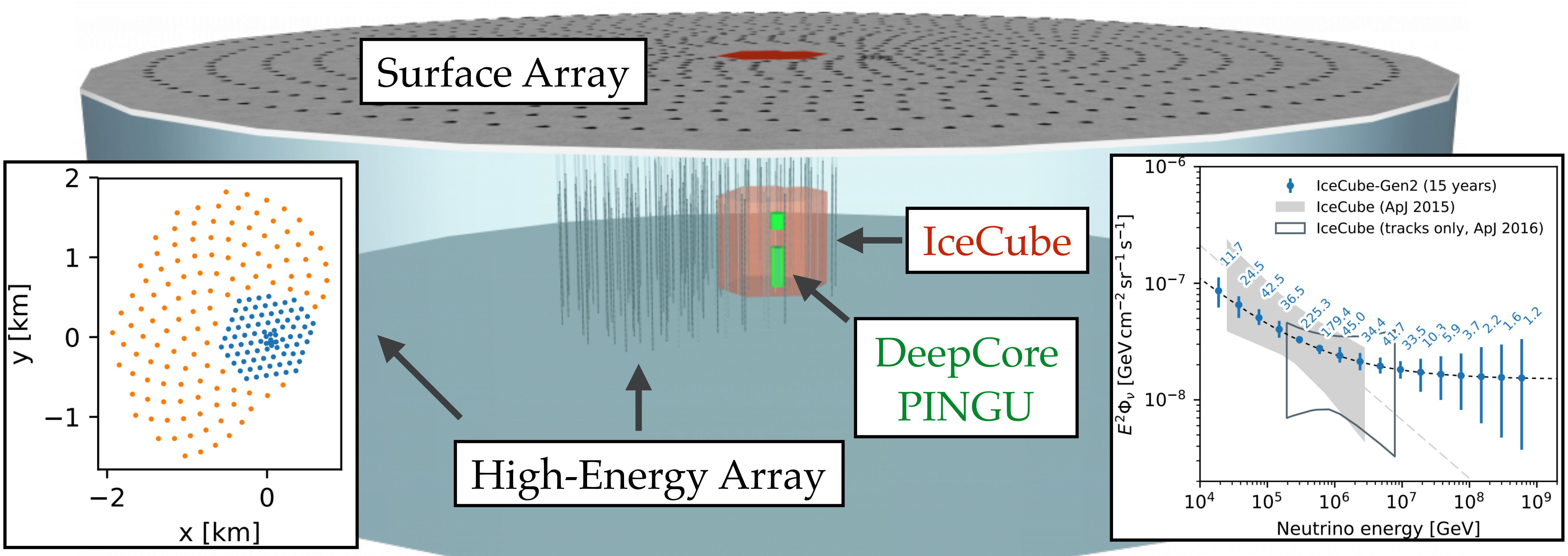
Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.
- **Precision measurement** of atmospheric neutrino oscillation.
- Midscale NSF project with an estimated total cost of $23M.
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2022/23**





- **Multi-component facility** (low- and high-energy & multi-messenger).
- In-ice **high-energy Cherenkov array** with 6-10 km³ volume.
- **Under investigation:** Surface arrays for in-ice radio (Askaryan) and cosmic ray veto (air Cherenkov and/or scintillator panels).



[Aartsen et al., Proceedings of ICRC 2017]

Summary

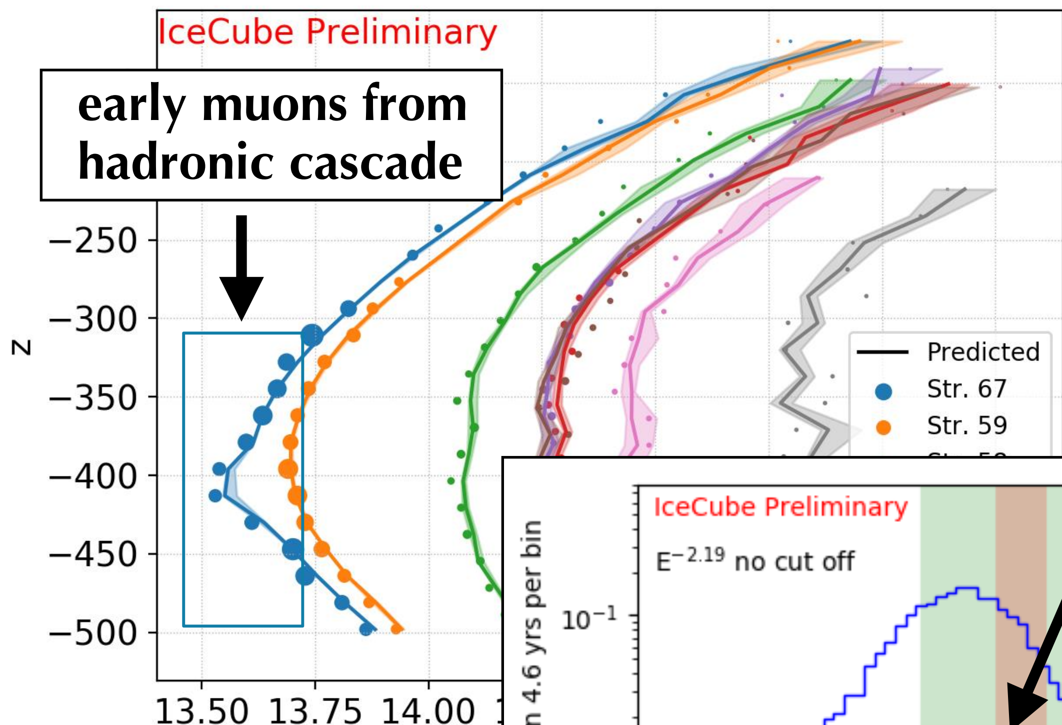
- The future of high-energy neutrino astronomy is bright:
  - Diffuse TeV-PeV neutrino flux of unknown origin.
  - Intensity comparable to cosmic-ray and gamma-ray observations.
  - First compelling evidence of neutrino emission from blazars.
- With next-generation telescopes we will go from discovery to astronomy!
- Many more avenues:

  supernova neutrinos, GZK neutrinos, BSM physics, sterile neutrinos, dark matter indirect signals, cosmic rays (spectrum & anisotropy), …

Thank you for your attention!

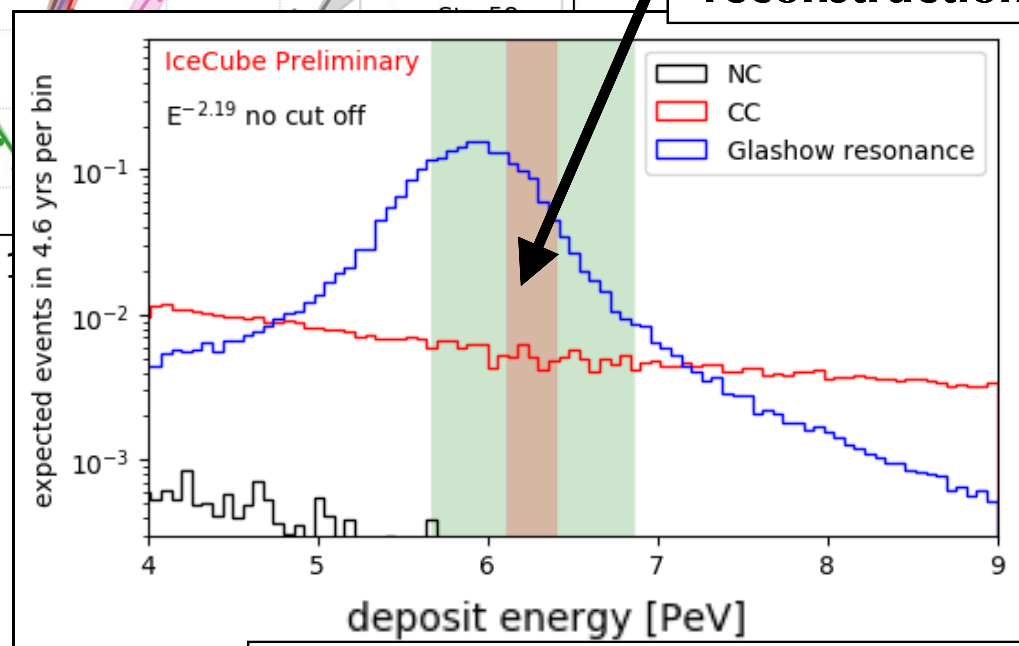
Backup Slides

Astrophysical Flavour Studies

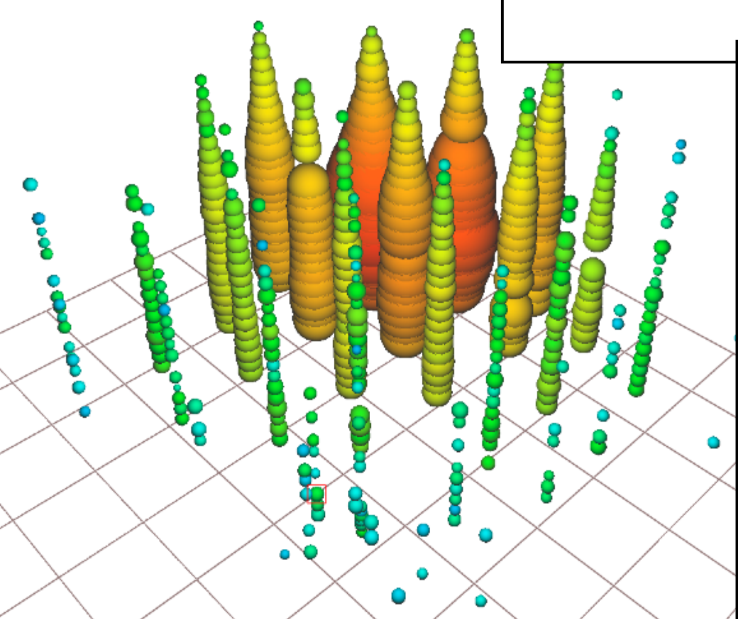


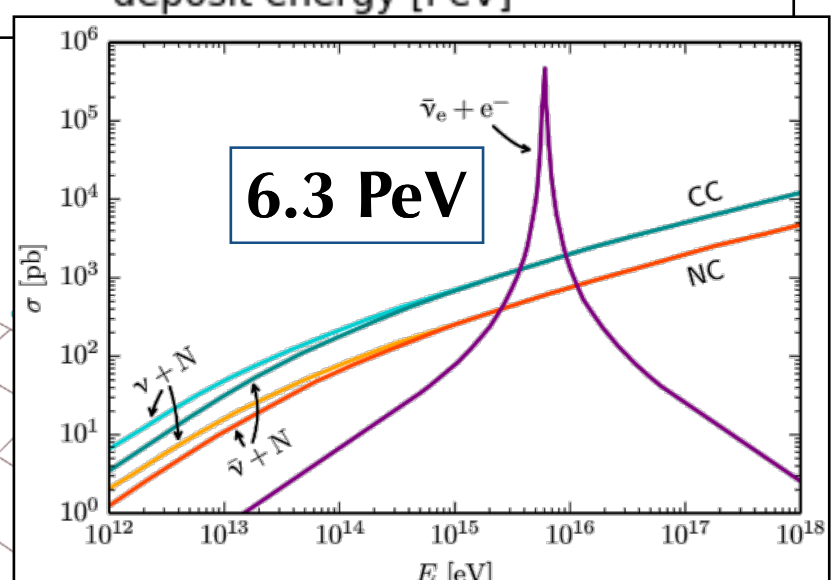
early muons from hadronic cascade

energy reconstruction

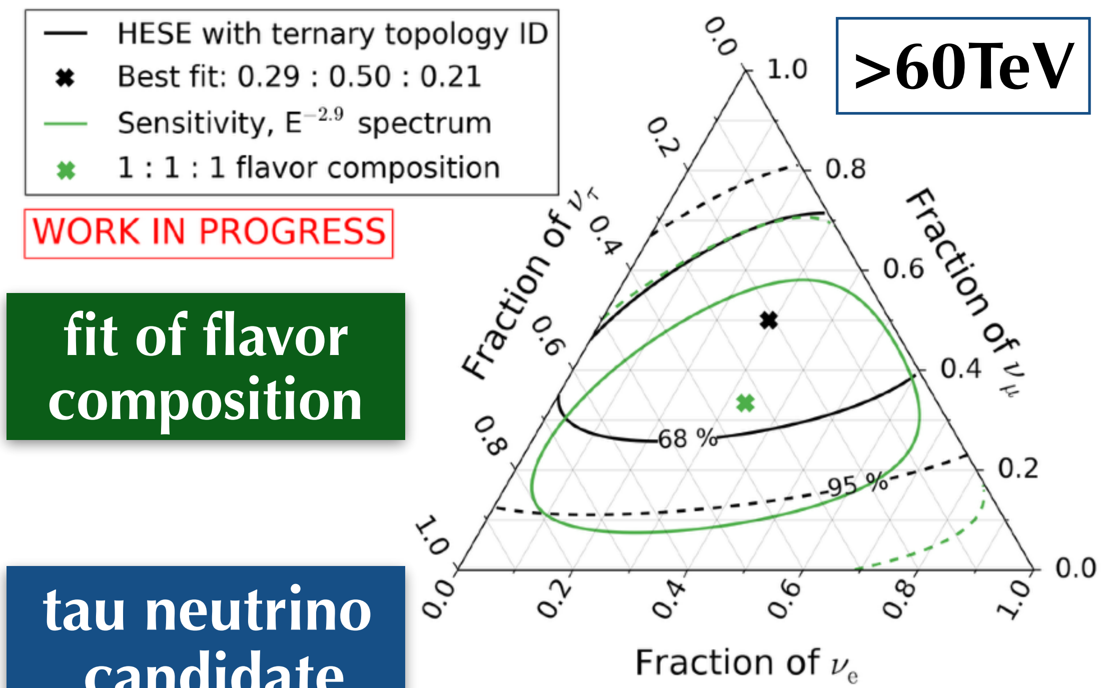


Glashow resonance candidate





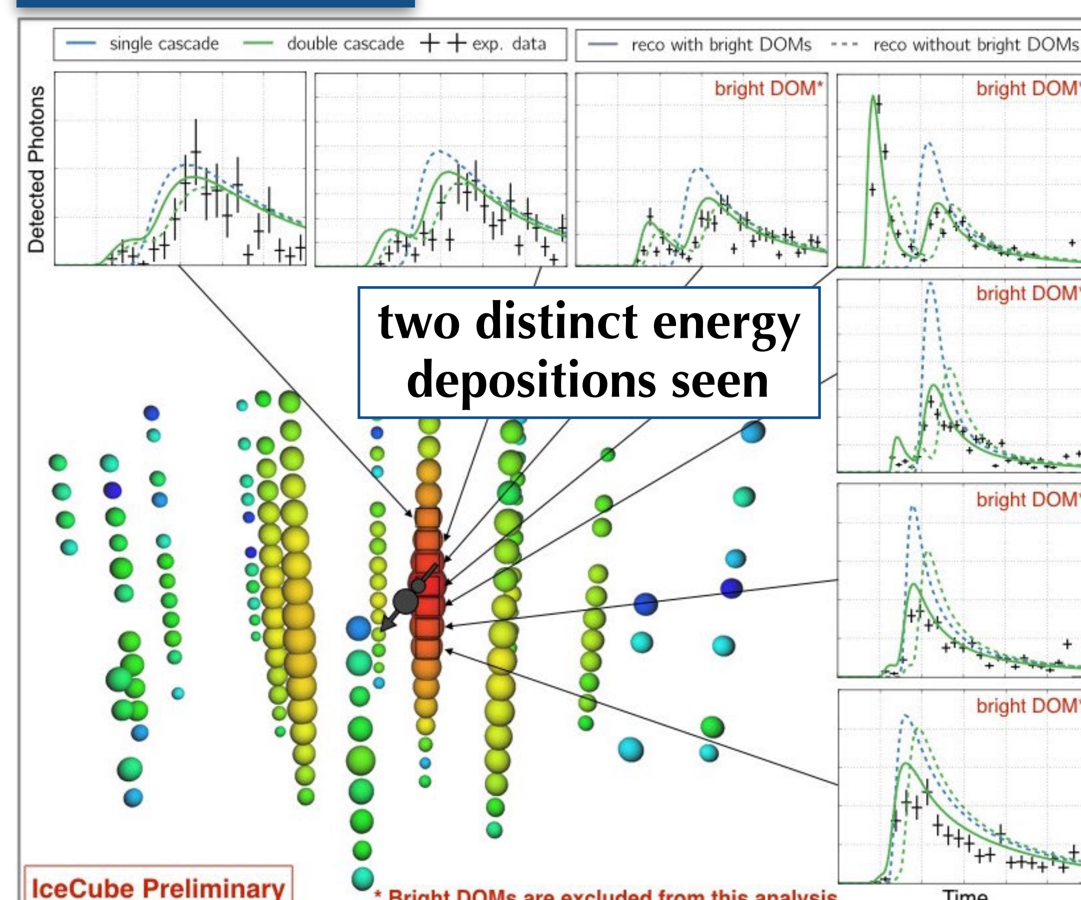
6.3 PeV



>60TeV

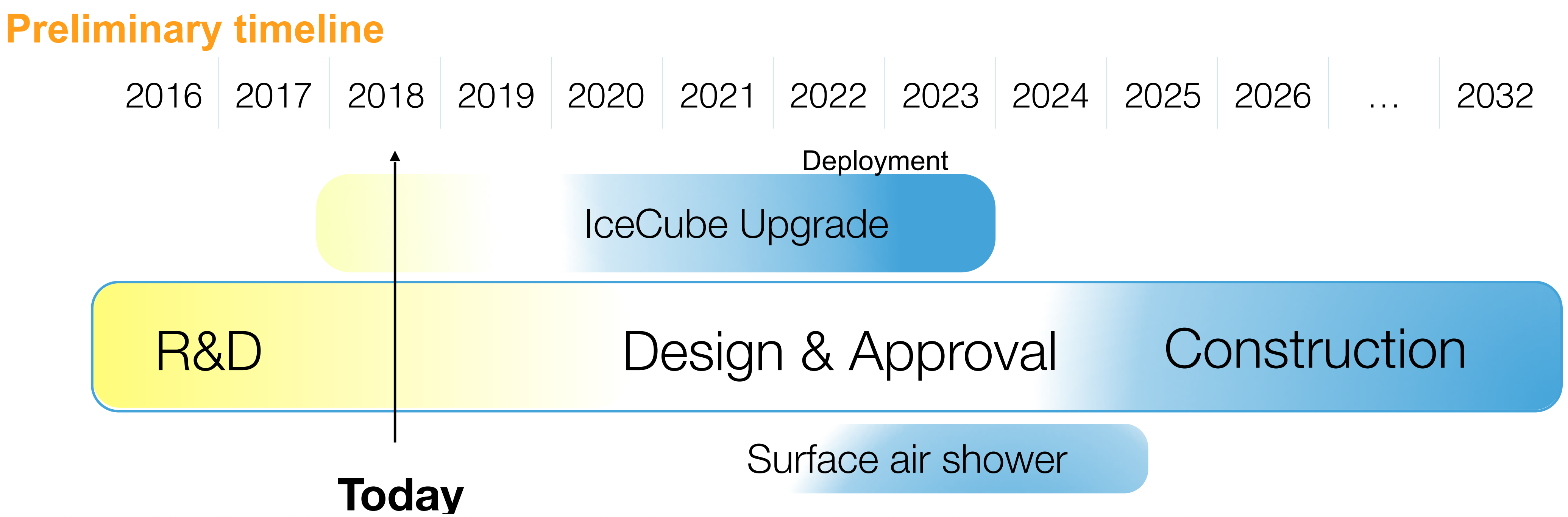
fit of flavor composition

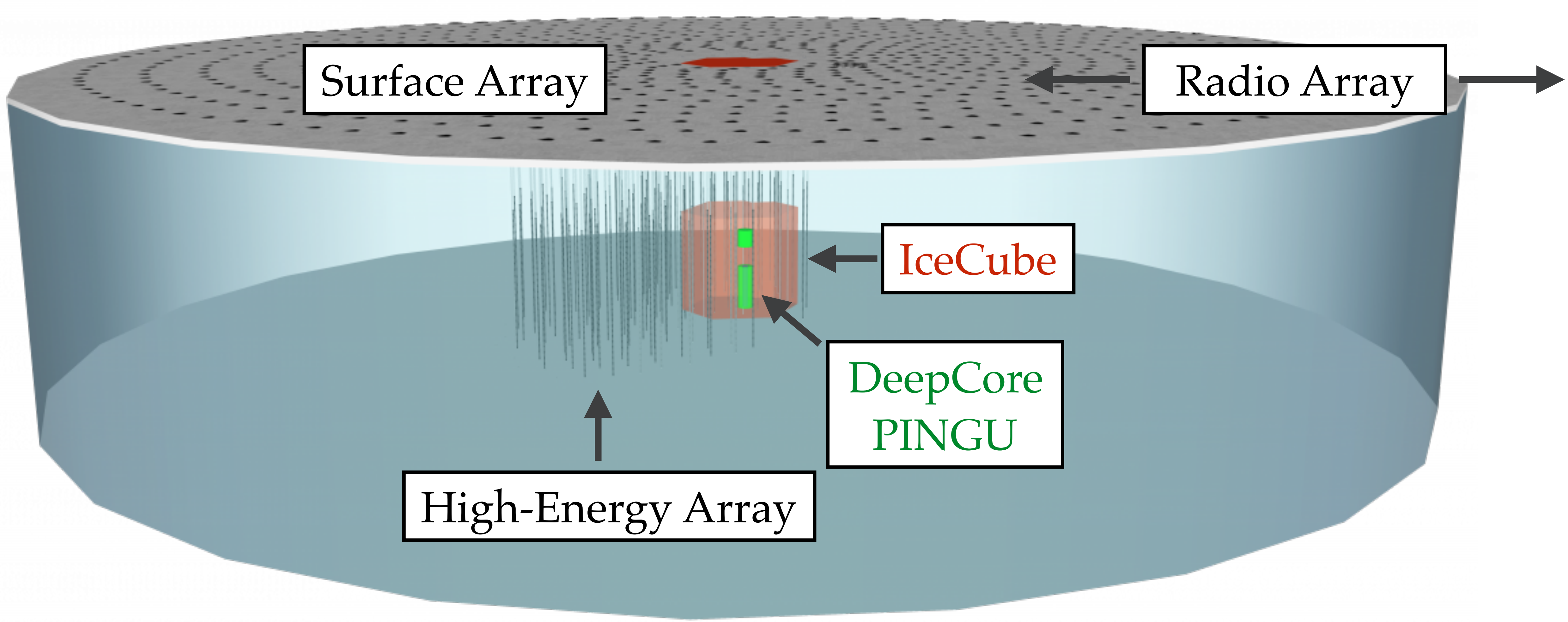
tau neutrino candidate



two distinct energy depositions seen

IceCube-Gen2 Timeline

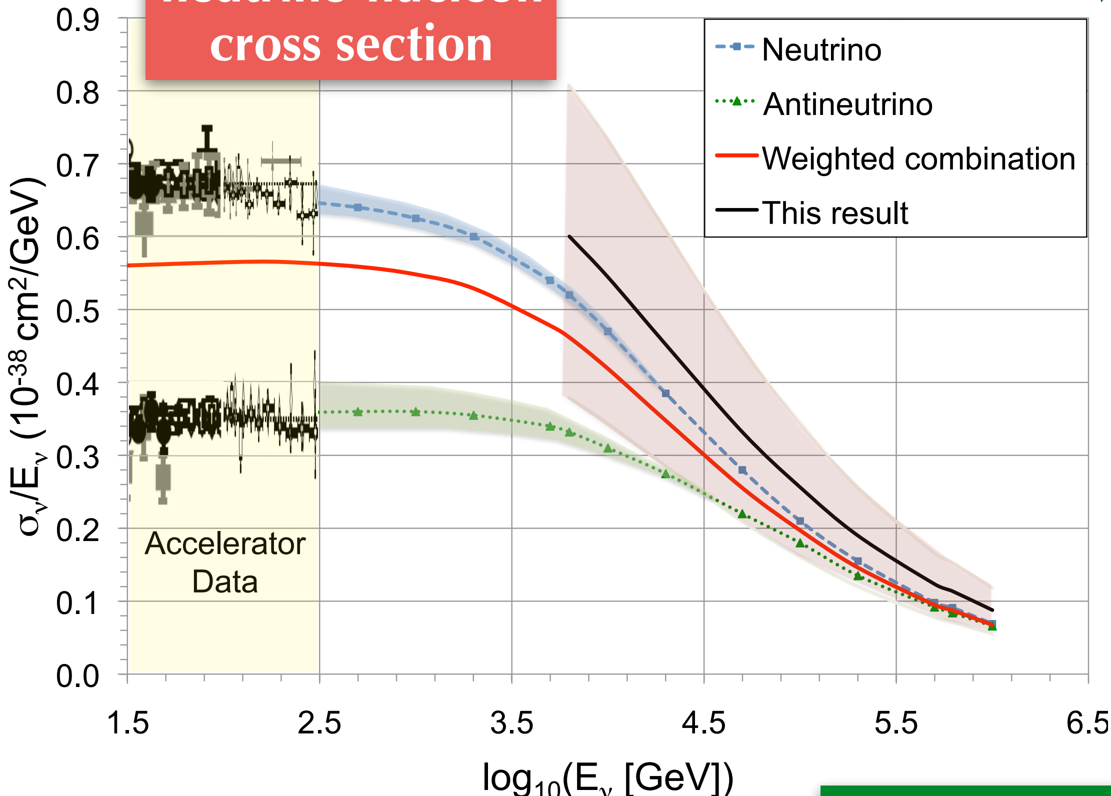


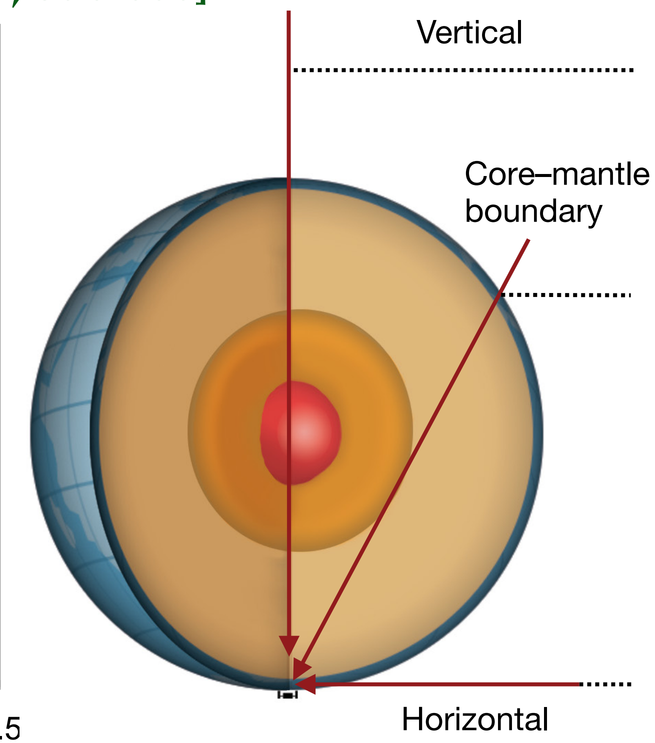


Neutrino Physics

neutrino-nucleon cross section

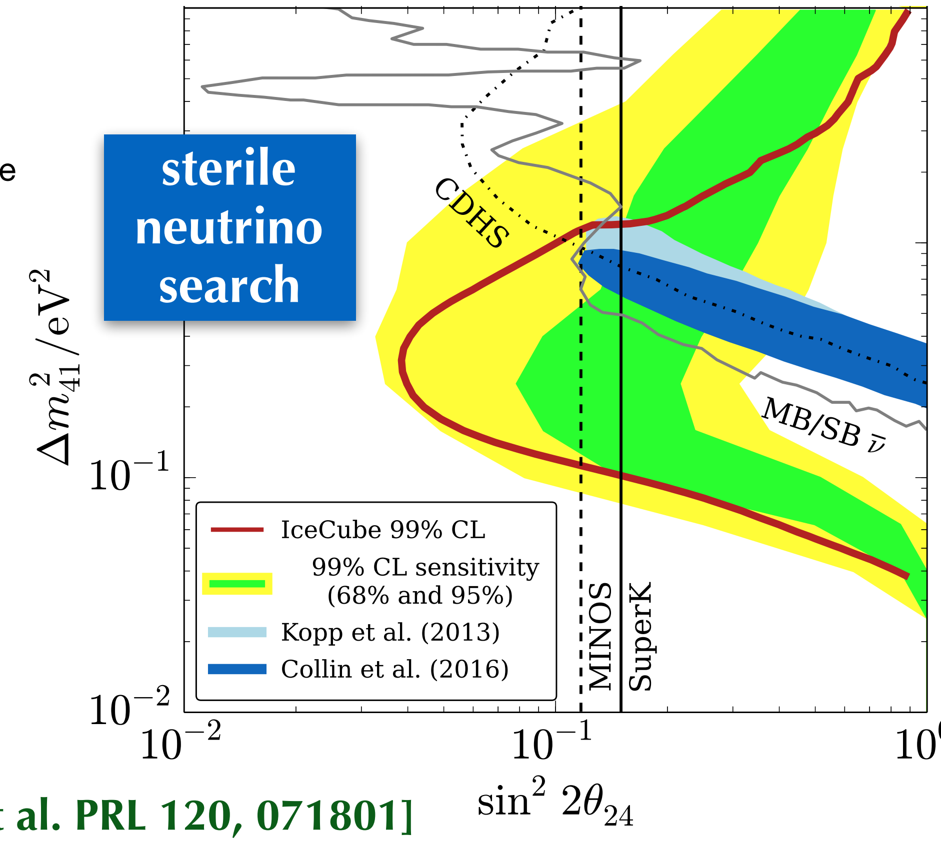
[Aartsen et al. Nature 551, 596-600]





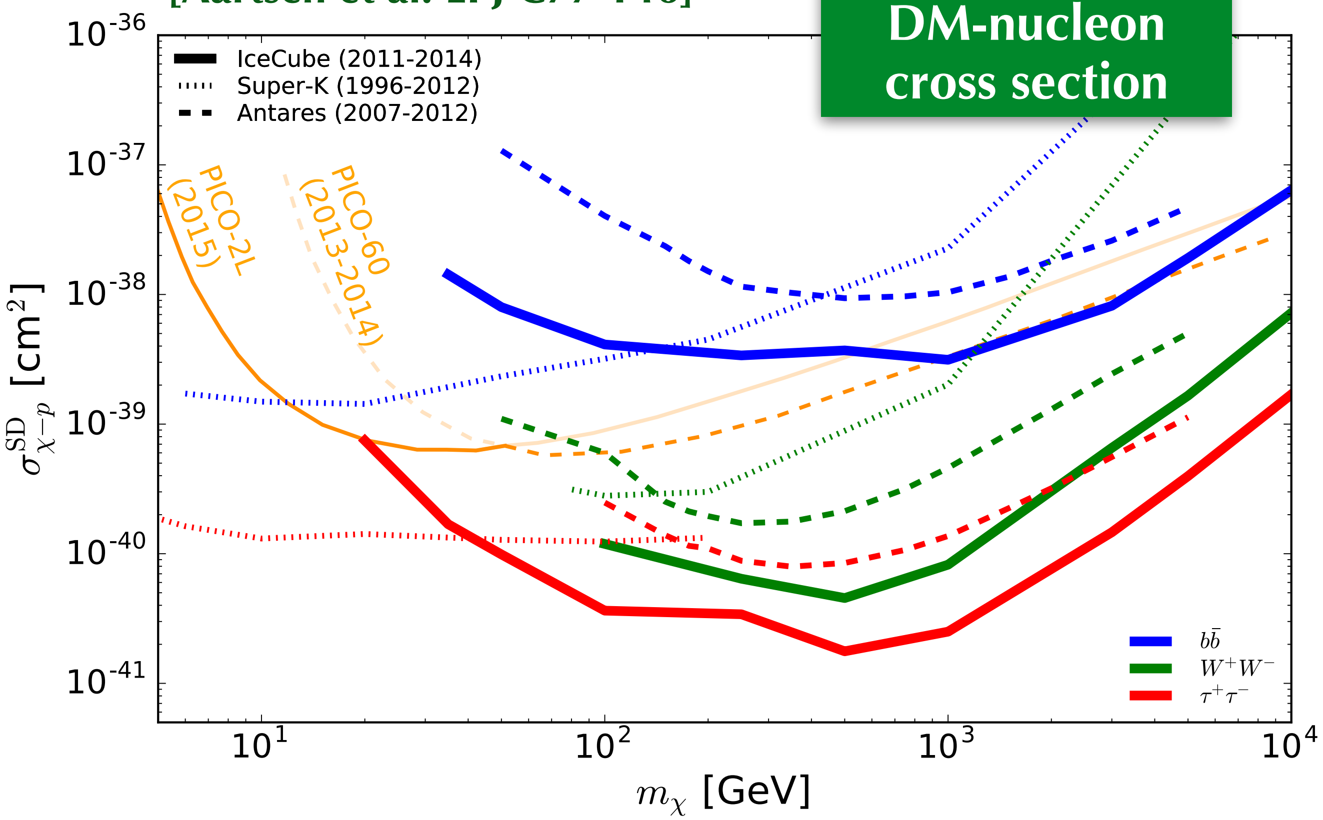
sterile neutrino search

[Aartsen et al. PRL 117, 071801]



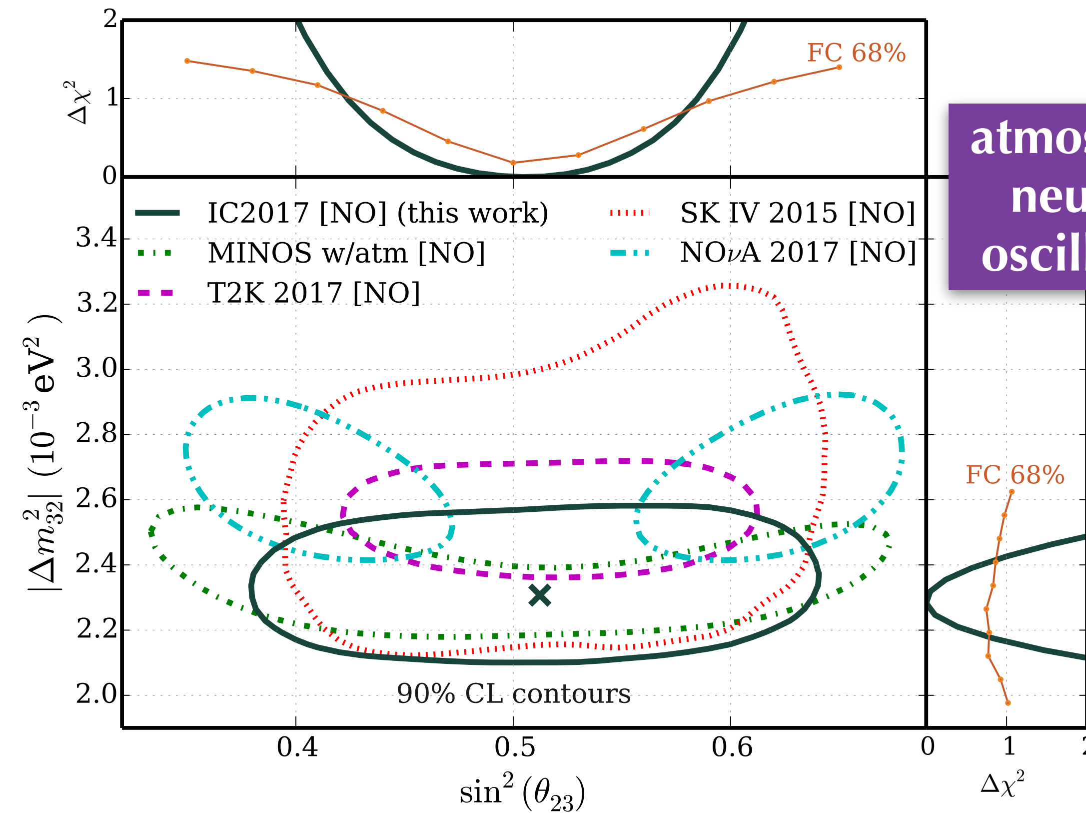
spin-dependent DM-nucleon cross section

[Aartsen et al. EPJ C77 146]



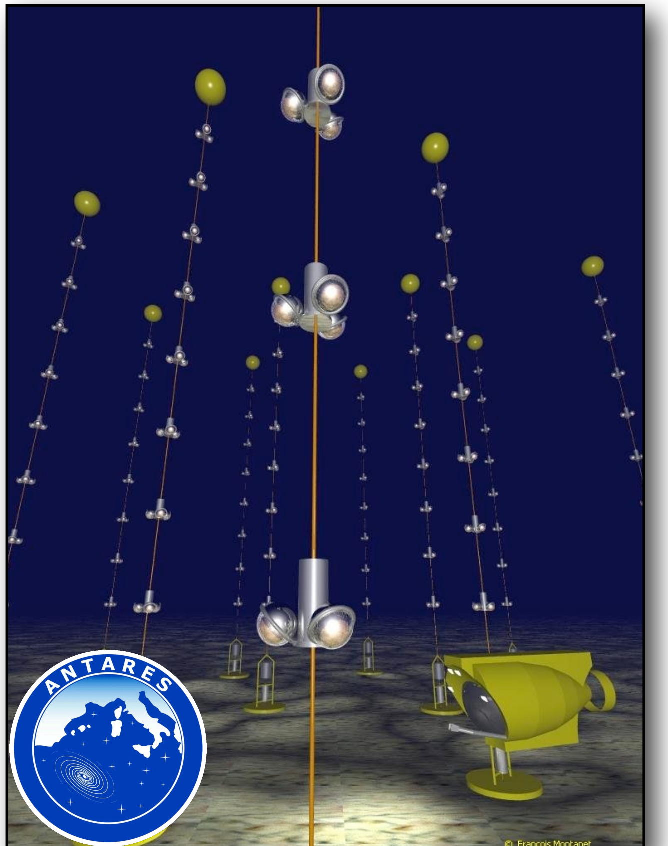
atmospheric neutrino oscillations

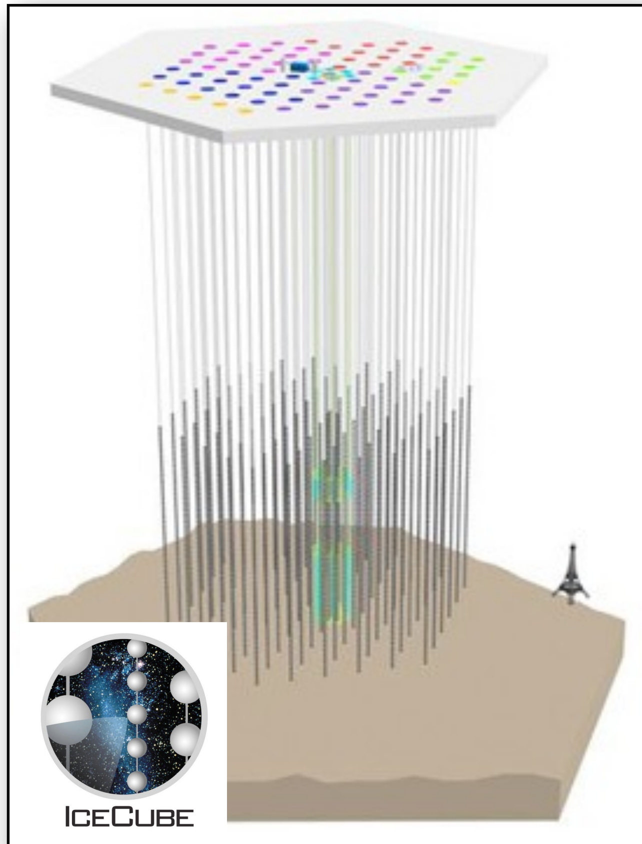
[Aartsen et al. PRL 120, 071801]

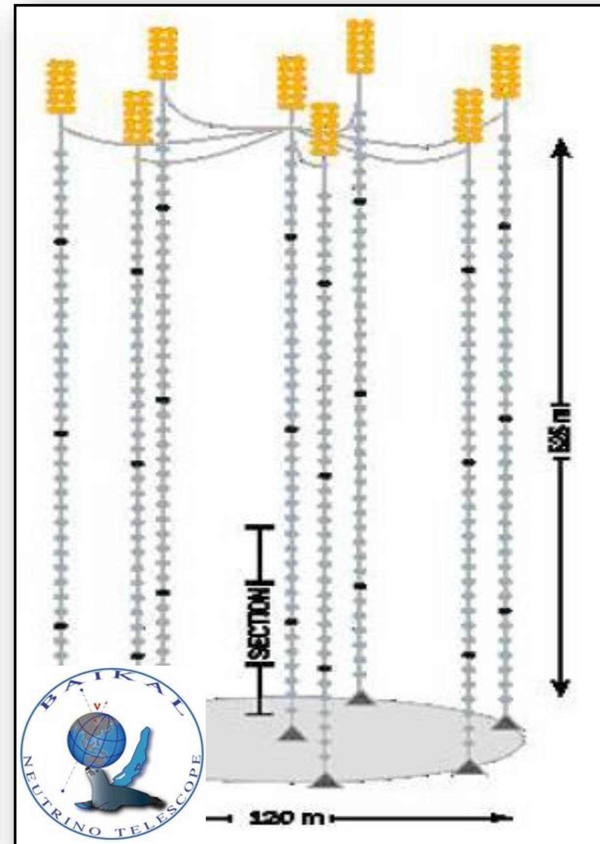


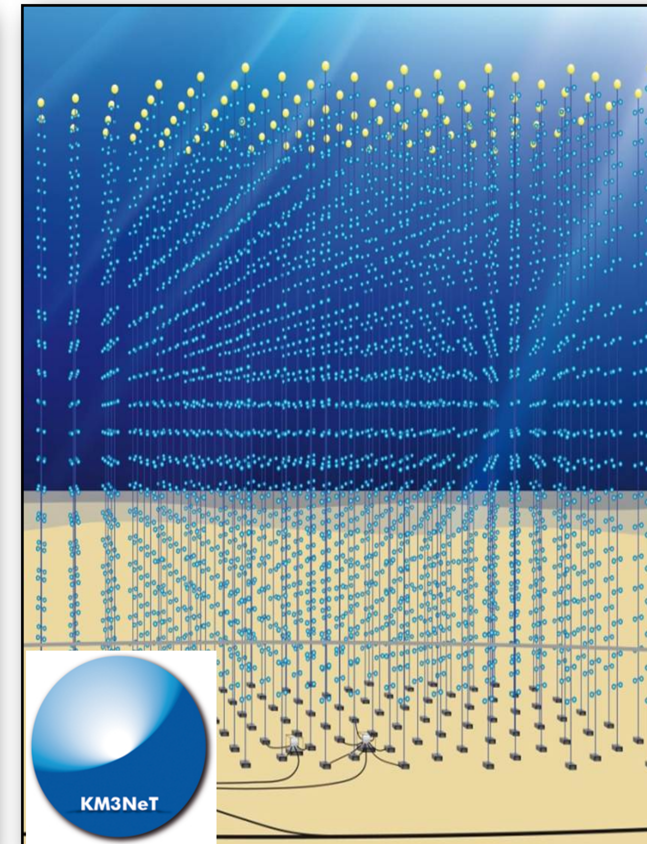
Cherenkov Observatories

Antares	IceCube	Baikal-GVD	KM3NeT/ARCA



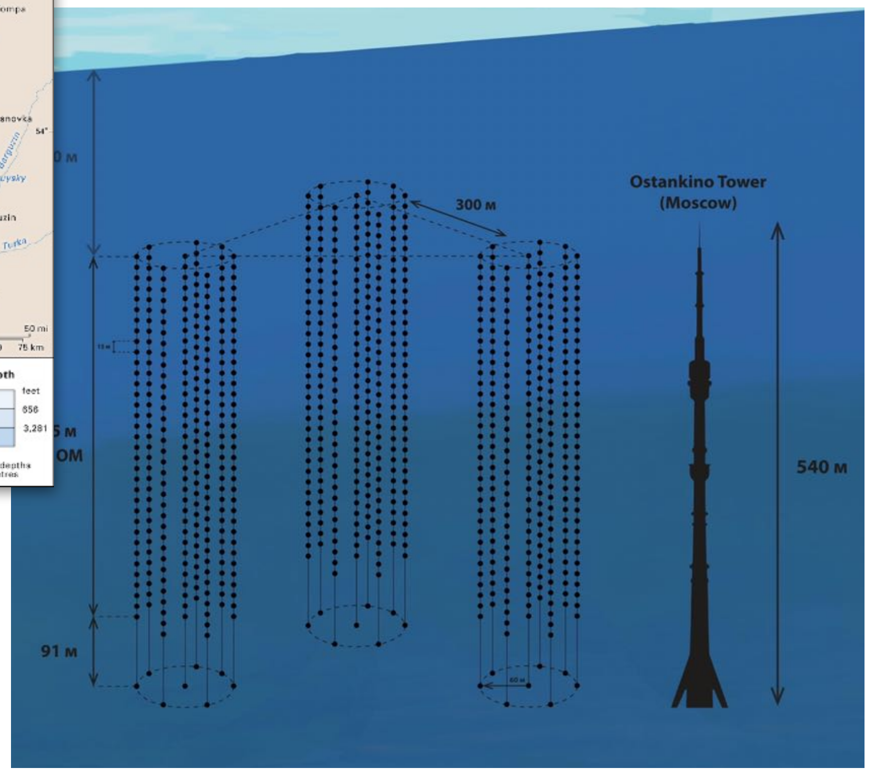






Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (3 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km³	~1 km³	~0.4 km³ (Phase 1) ~1km³	~0.1 km³ (Phase 1) ~1 km³
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

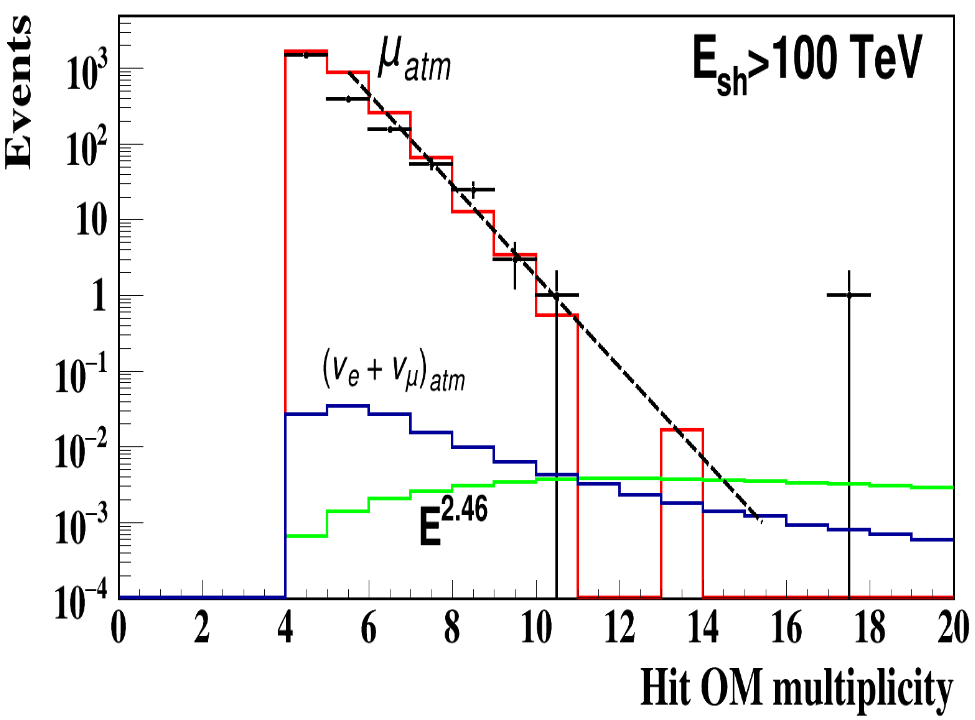
Outlook: Baikal-GVD



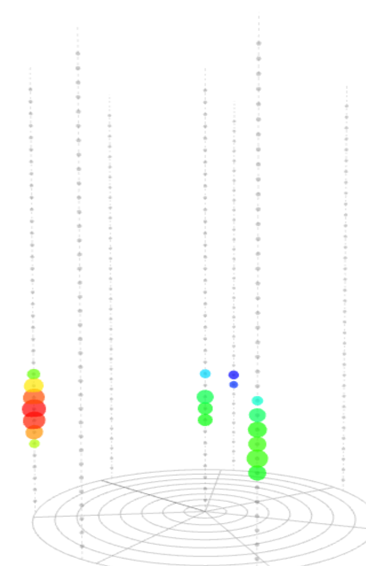
BAIKAL-GVD

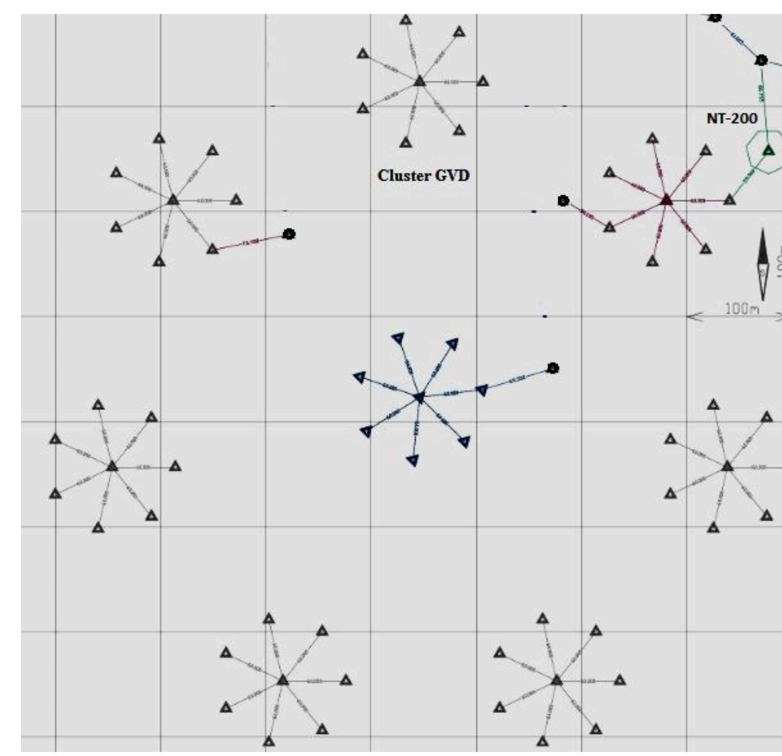
present detector outline (2018)

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- 3 clusters deployed 2016–18
- **final goal**: 27 clusters (~1.4 km³)



first physics results: cascade spectrum / cascade event in 2015 data

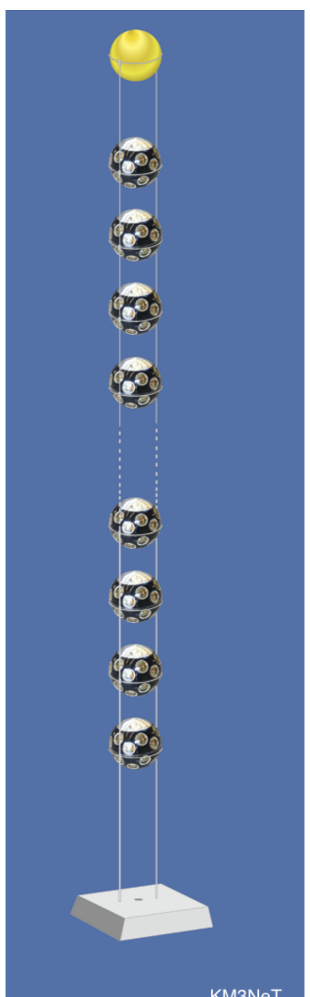




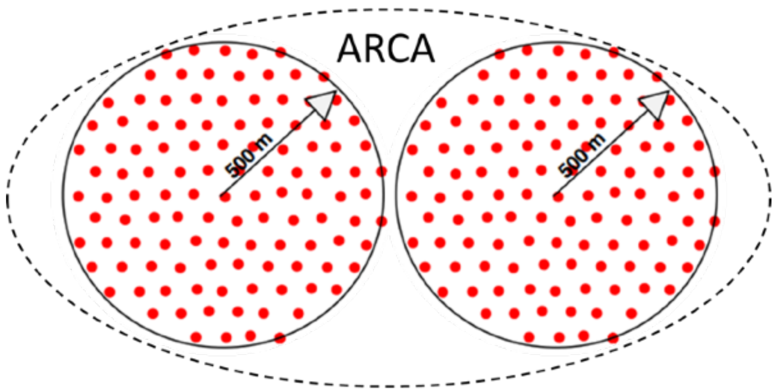
GVD-Phase 1

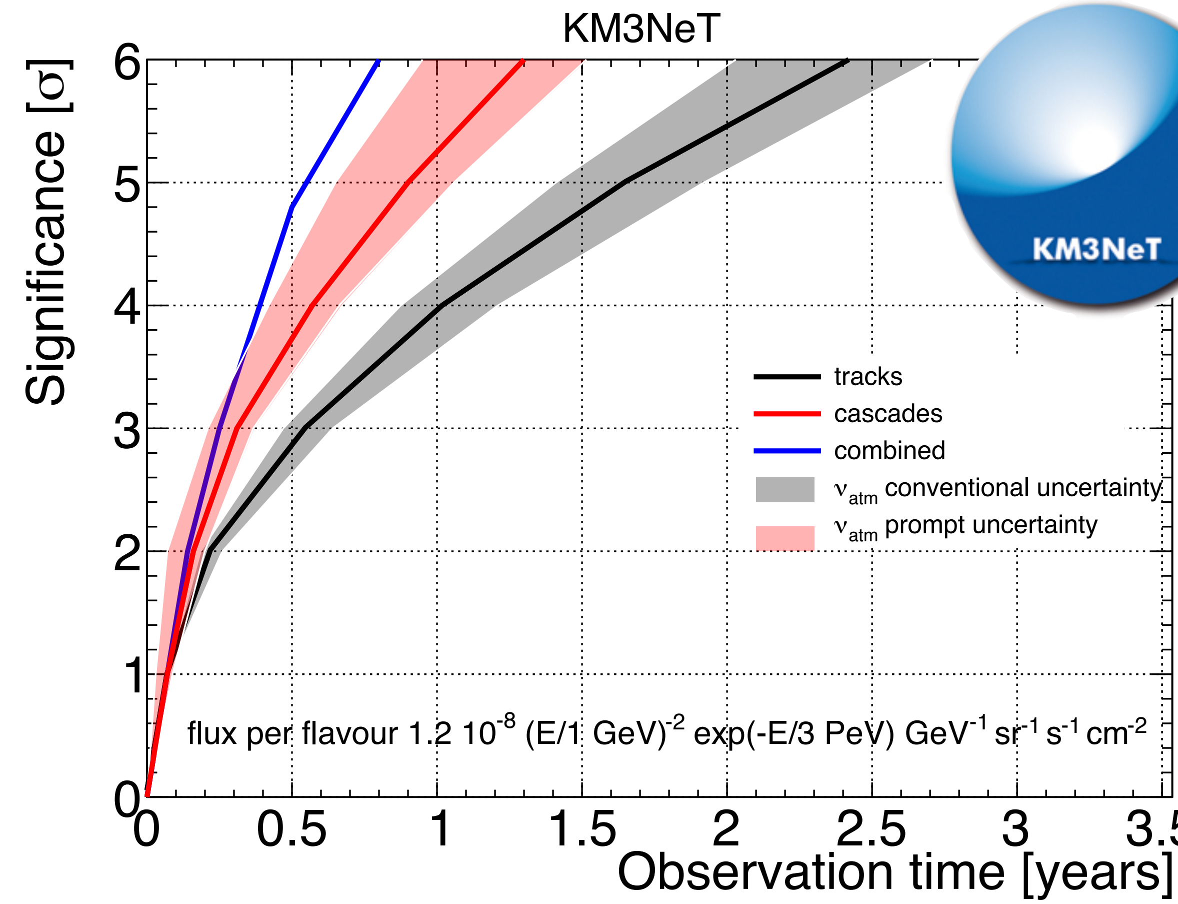
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km³)
- 3 DU deployed off the coast of Italy (1 DU recovered after shortage)
- 2 DUs operated until March 2017



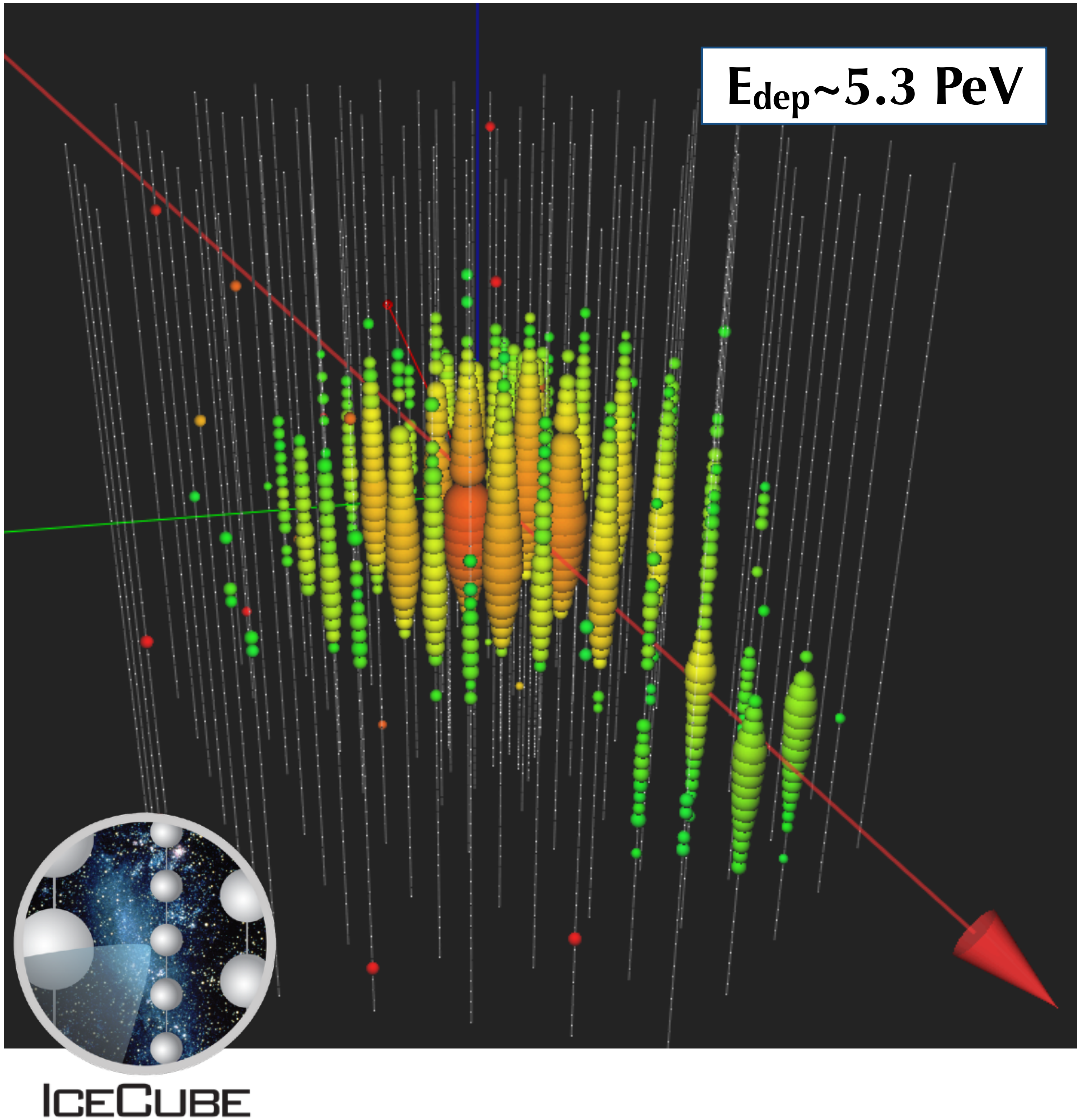
detection unit with multi-PMT DOMs





- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

HESE Alert IC-190331A



- HESE alert on March 31, 2019
- deposited energy: 5.3 PeV
- **brightest HESE event, so far**
- down-going muon neutrino
- RA 337.785° +/- 2.240°
- DEC -21.075° +/- 3.064°
- Follow-up by Fermi-LAT / AGILE (gamma-ray), NuSTAR (X-ray), MASTER / SARA (optical)
- **No obvious EM counterpart.**