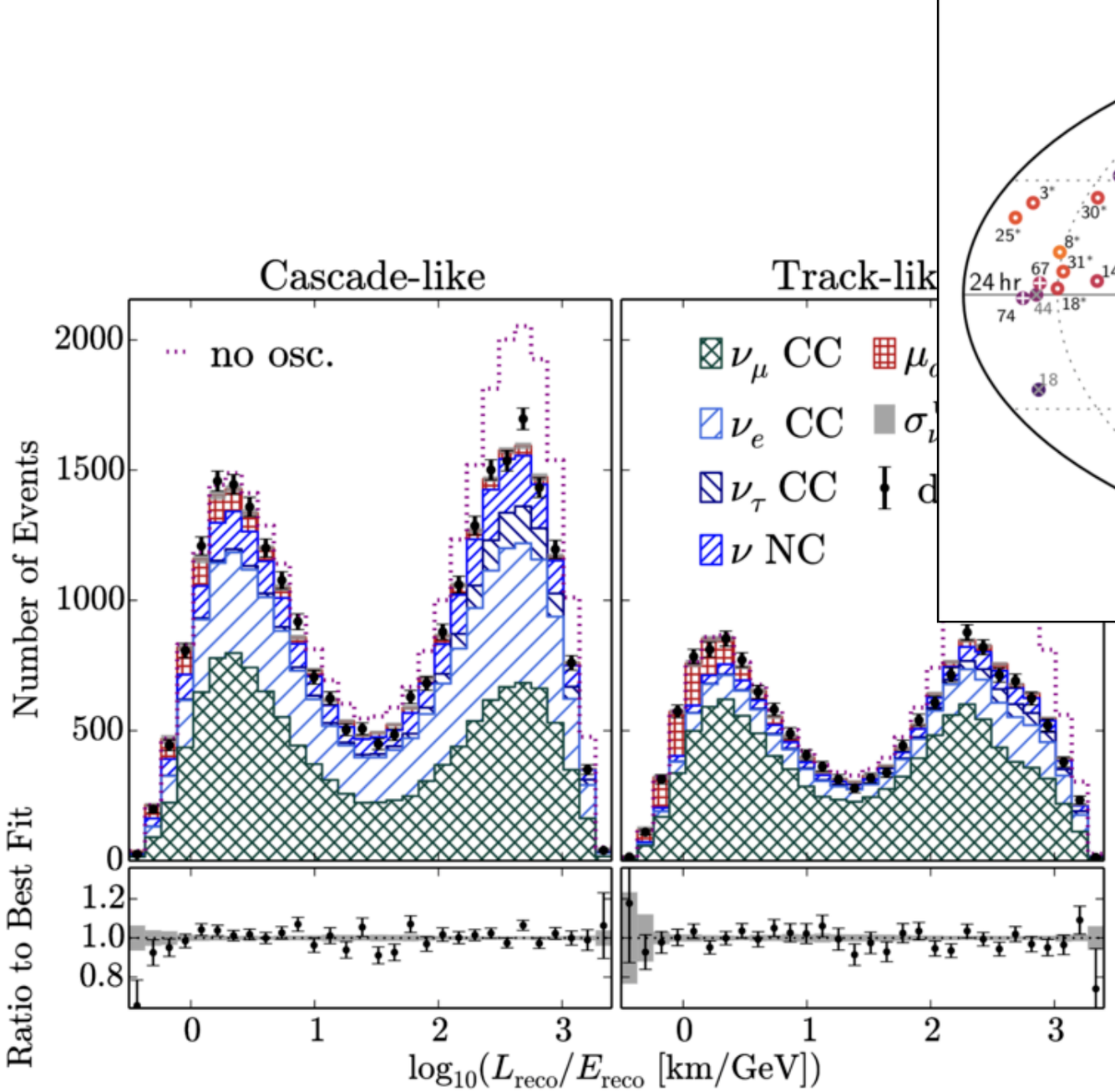
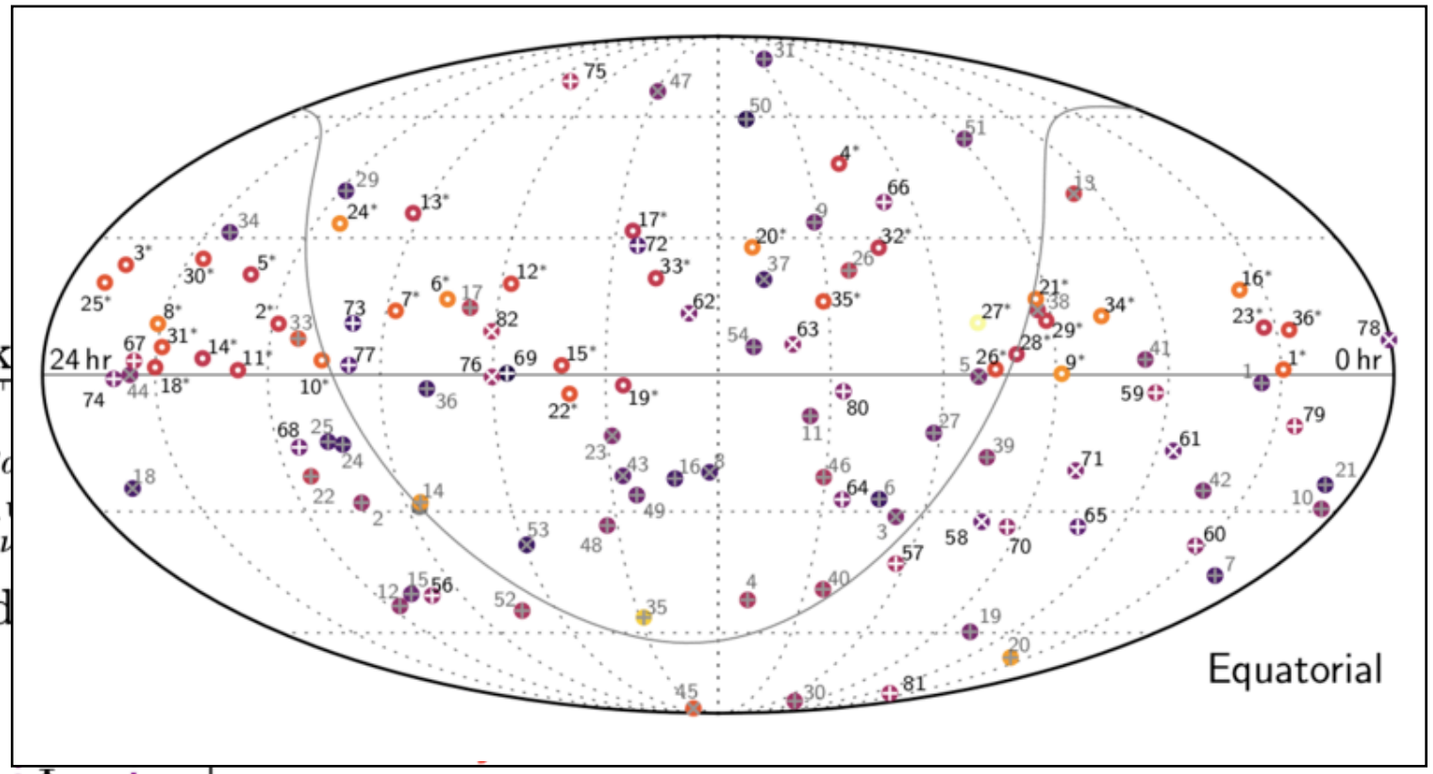
Status and prospects

of the IceCube neutrino telescope





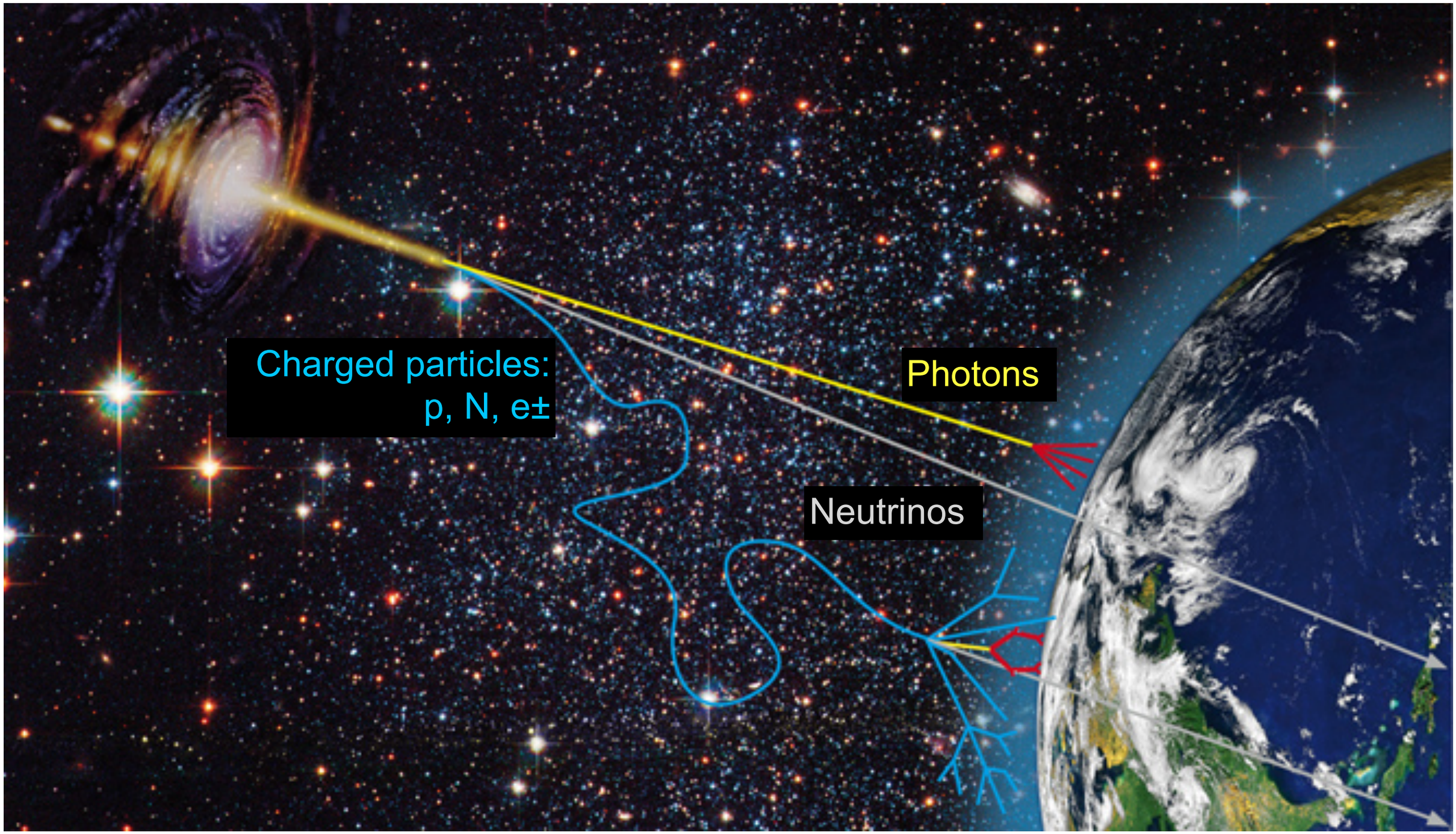
Markus Ackermann
for the IceCube collaboration

PAHEN 2017 workshop, Naples
Sep 25, 2017 — Sep 26, 2017

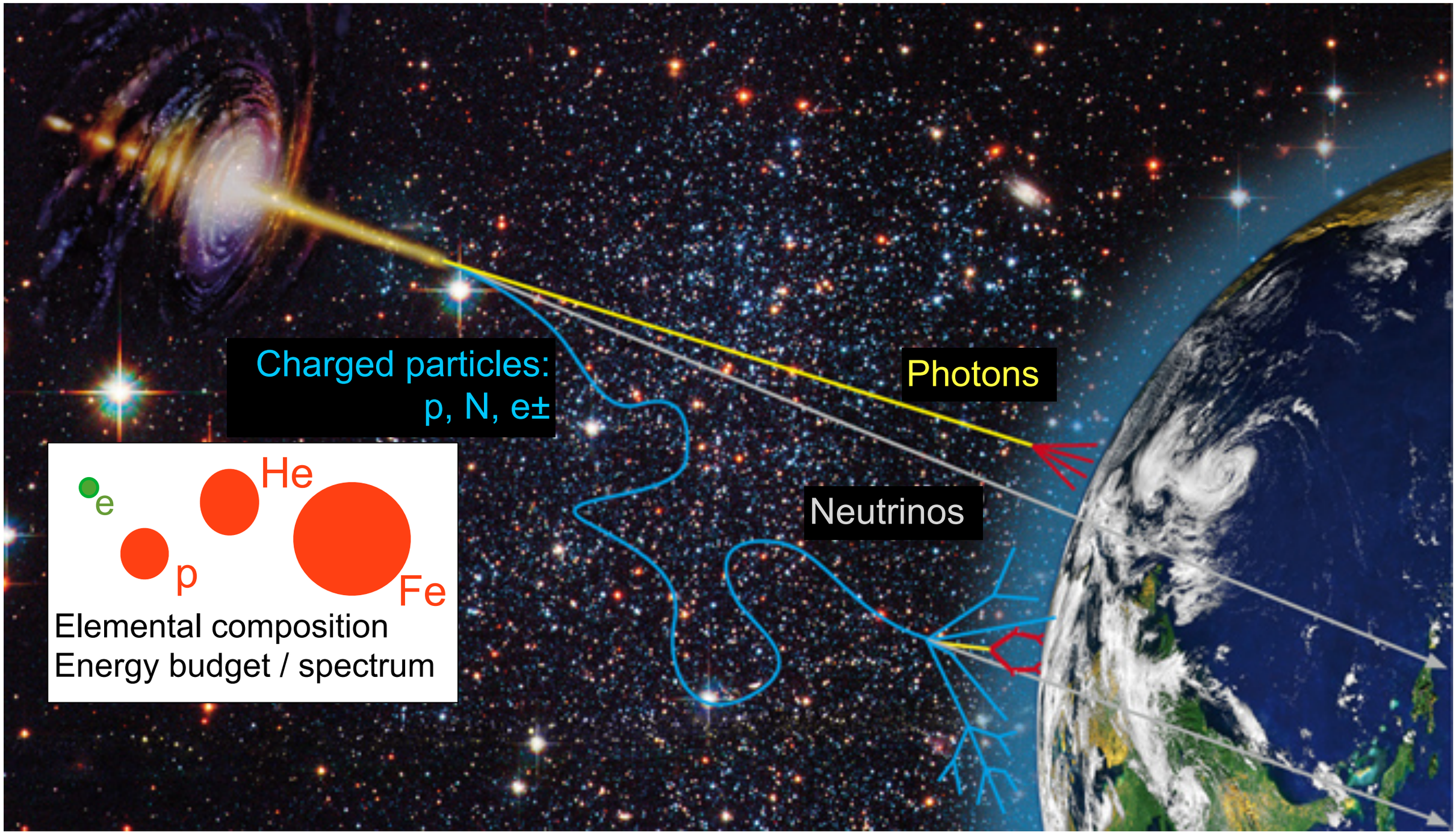
HELMHOLTZ ASSOCIATION

DESY

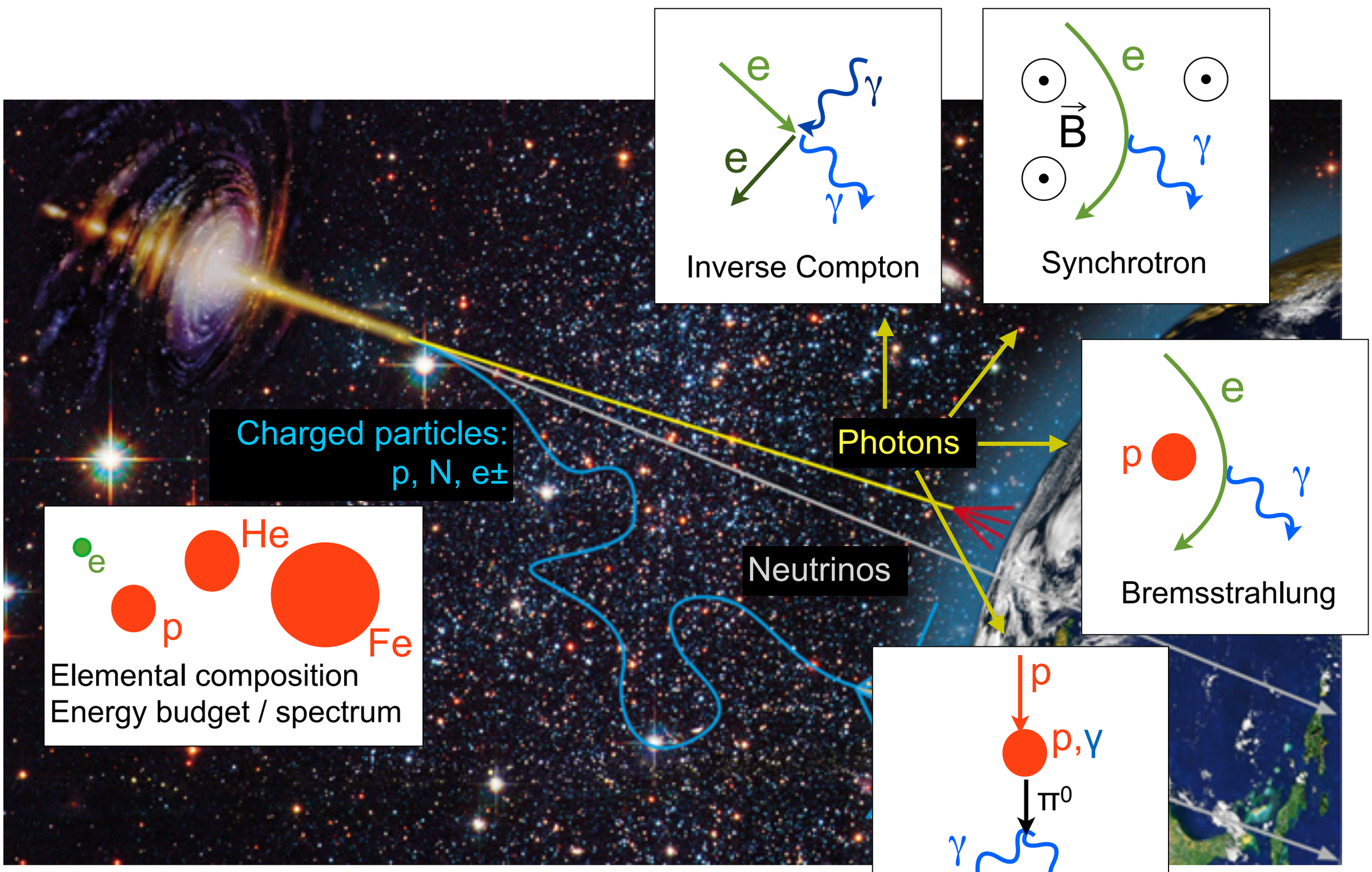
Neutrinos as astrophysical messengers



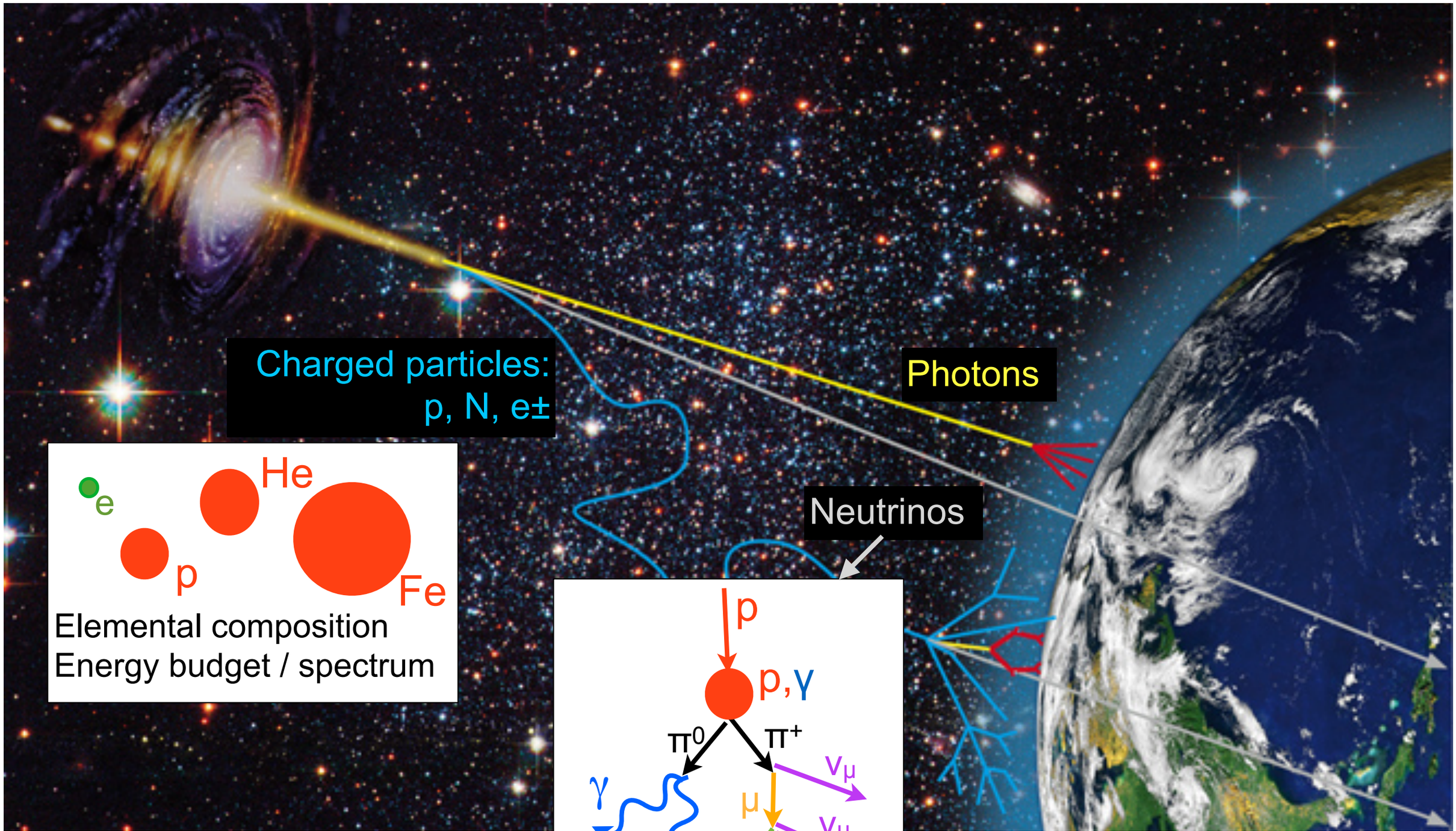
Neutrinos as astrophysical messengers



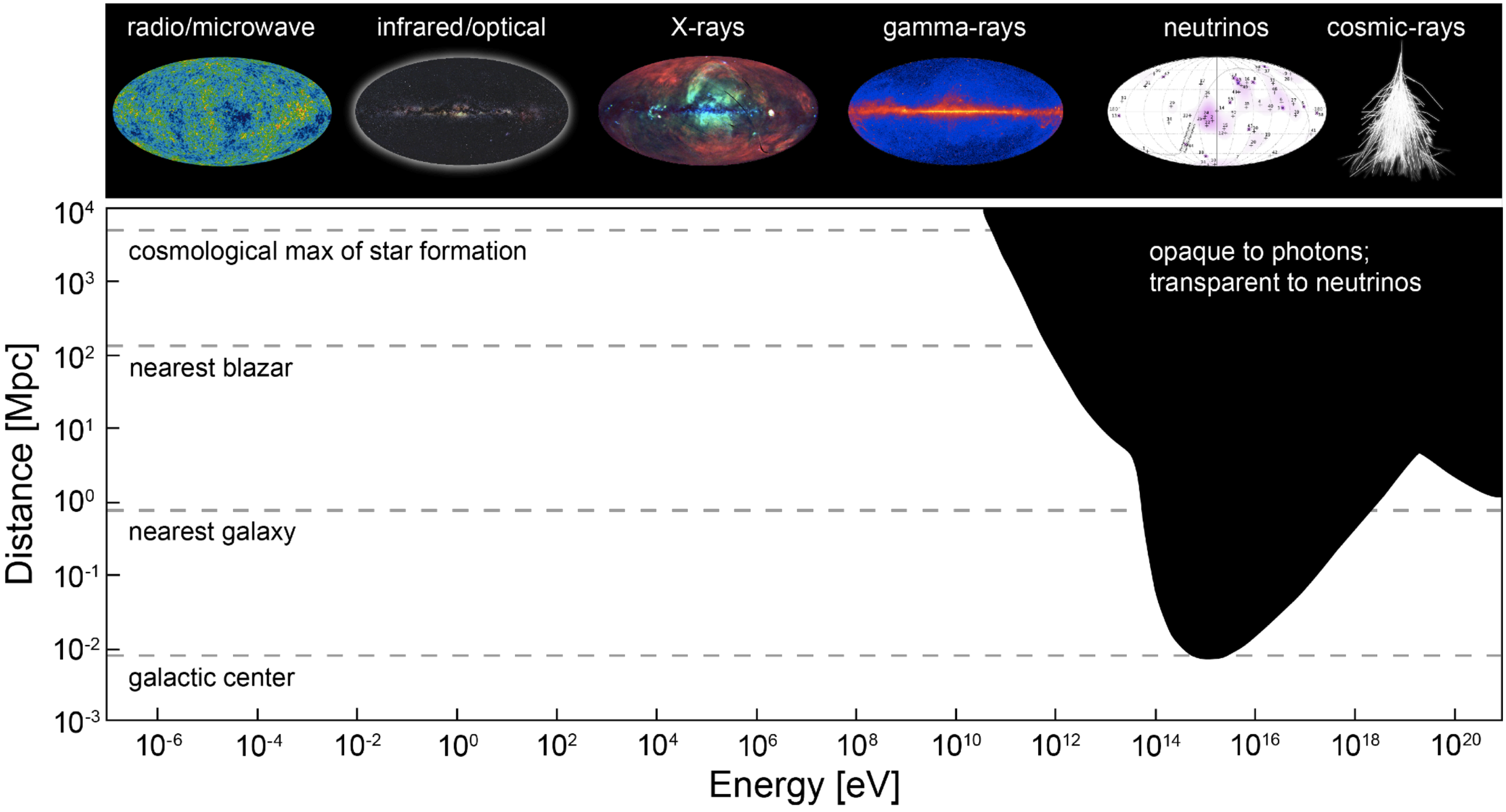
Neutrinos as astrophysical messengers



Neutrinos as astrophysical messengers

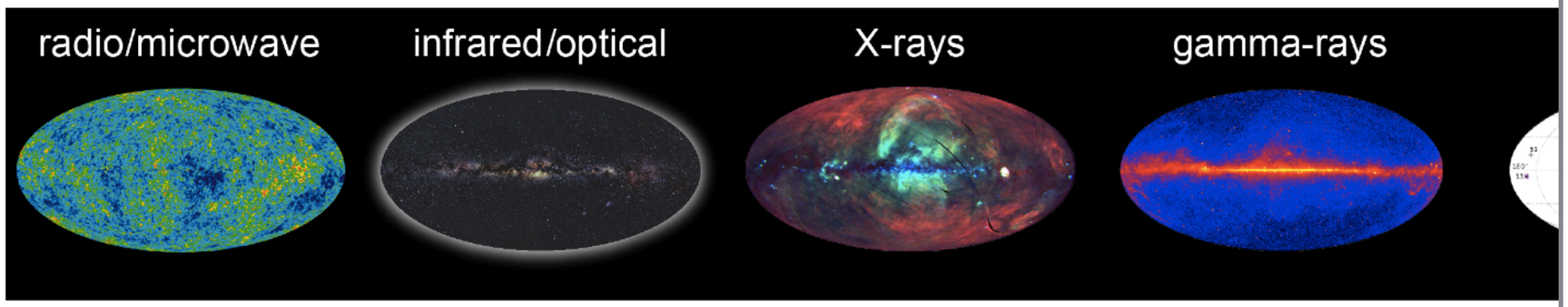


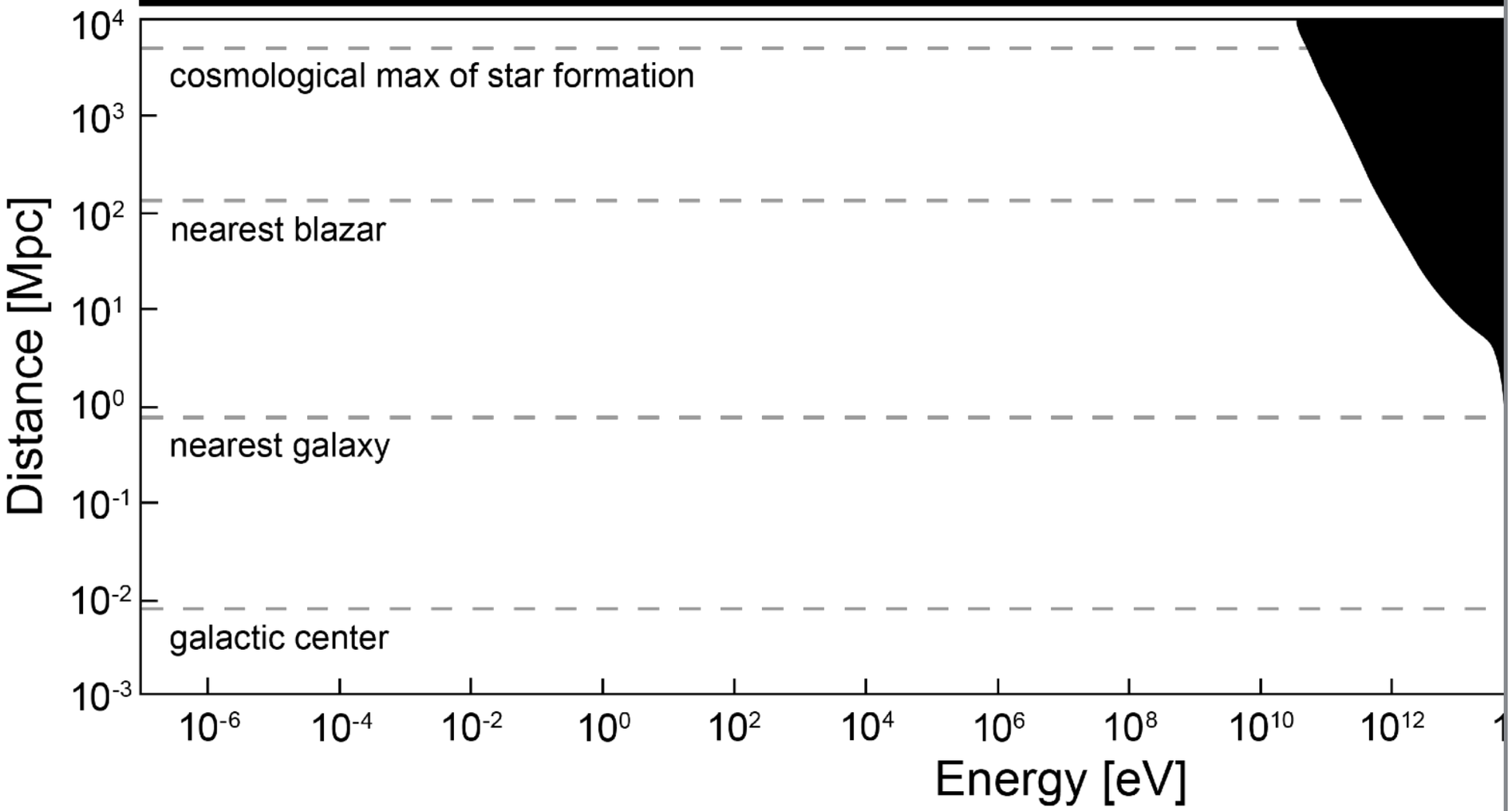
The uniqueness of neutrinos

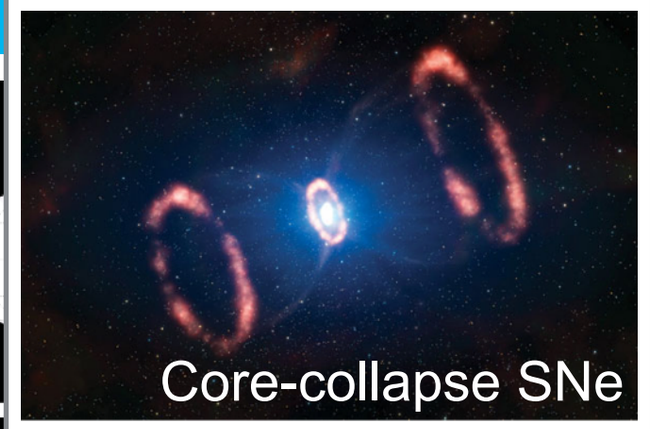


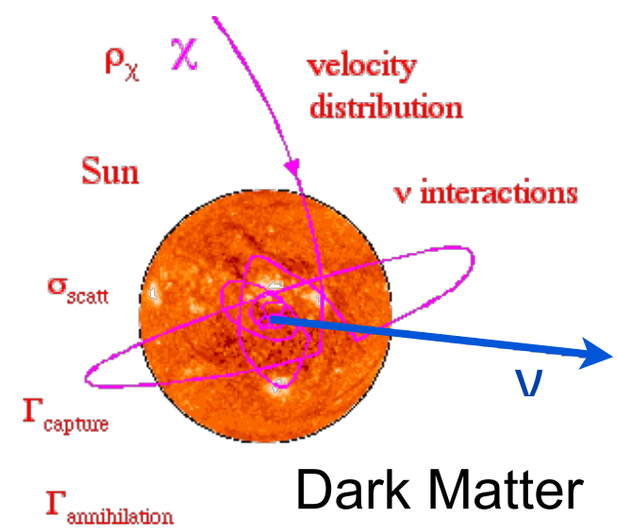
- Neutrinos allow us to **peek beyond** the gamma-ray horizon…
- … and into environments **opaque to electromagnetic radiation**.

The uniqueness of neutrinos





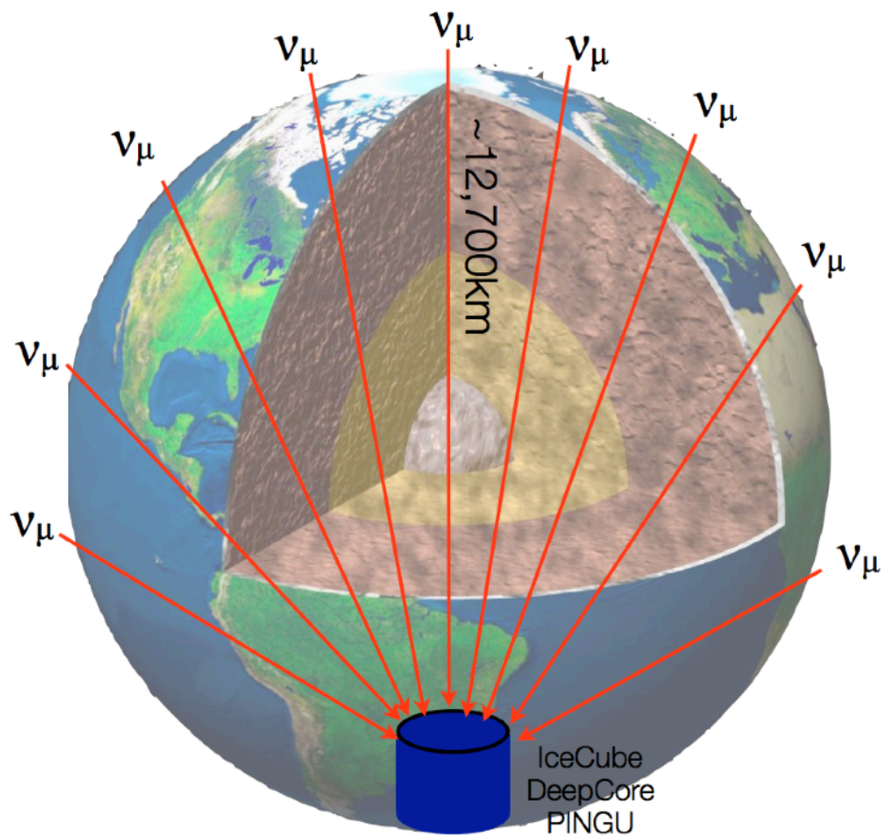




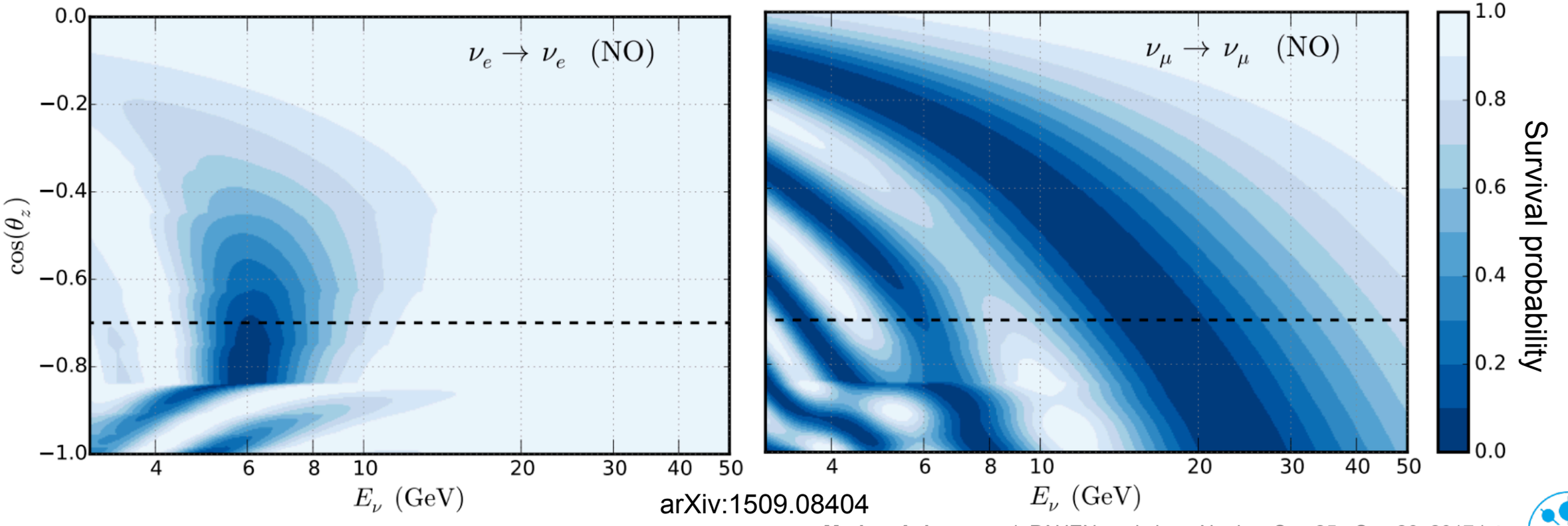
- Neutrinos allow us to **peek beyond** the gamma-ray horizon…
- … and into environments **opaque to electromagnetic radiation**.

Particle physics with neutrino telescopes

- **Atmospheric neutrinos** can be used to measure **oscillation parameters** and the **neutrino cross-section** at high energies.

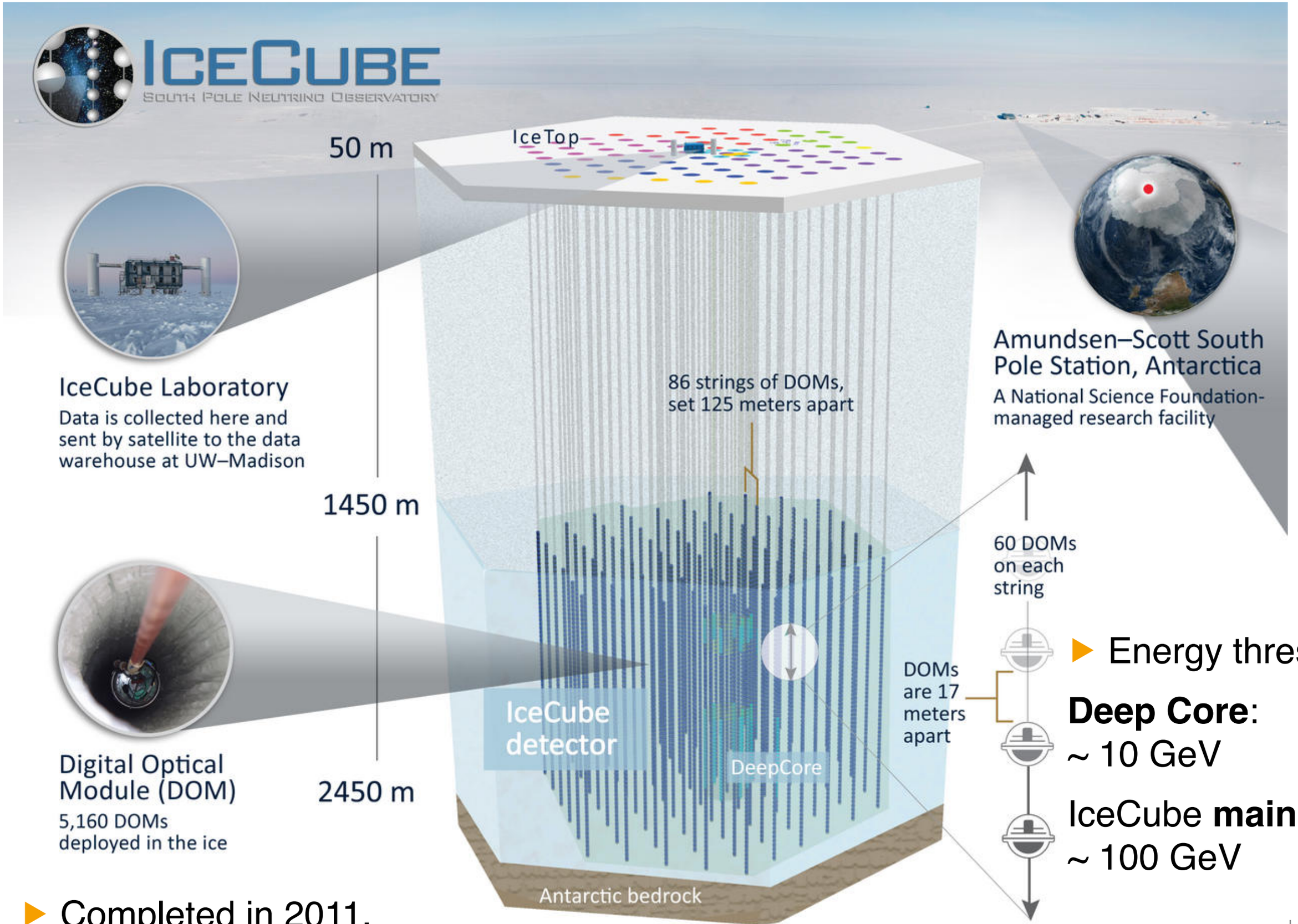


- Atmospheric and astrophysical neutrinos help to **constrain new physics**:
  - Search for sterile neutrinos
  - DM annihilation/decay
  - Search for exotic particles



arXiv:1509.08404

IceCube - the world's largest neutrino observatory



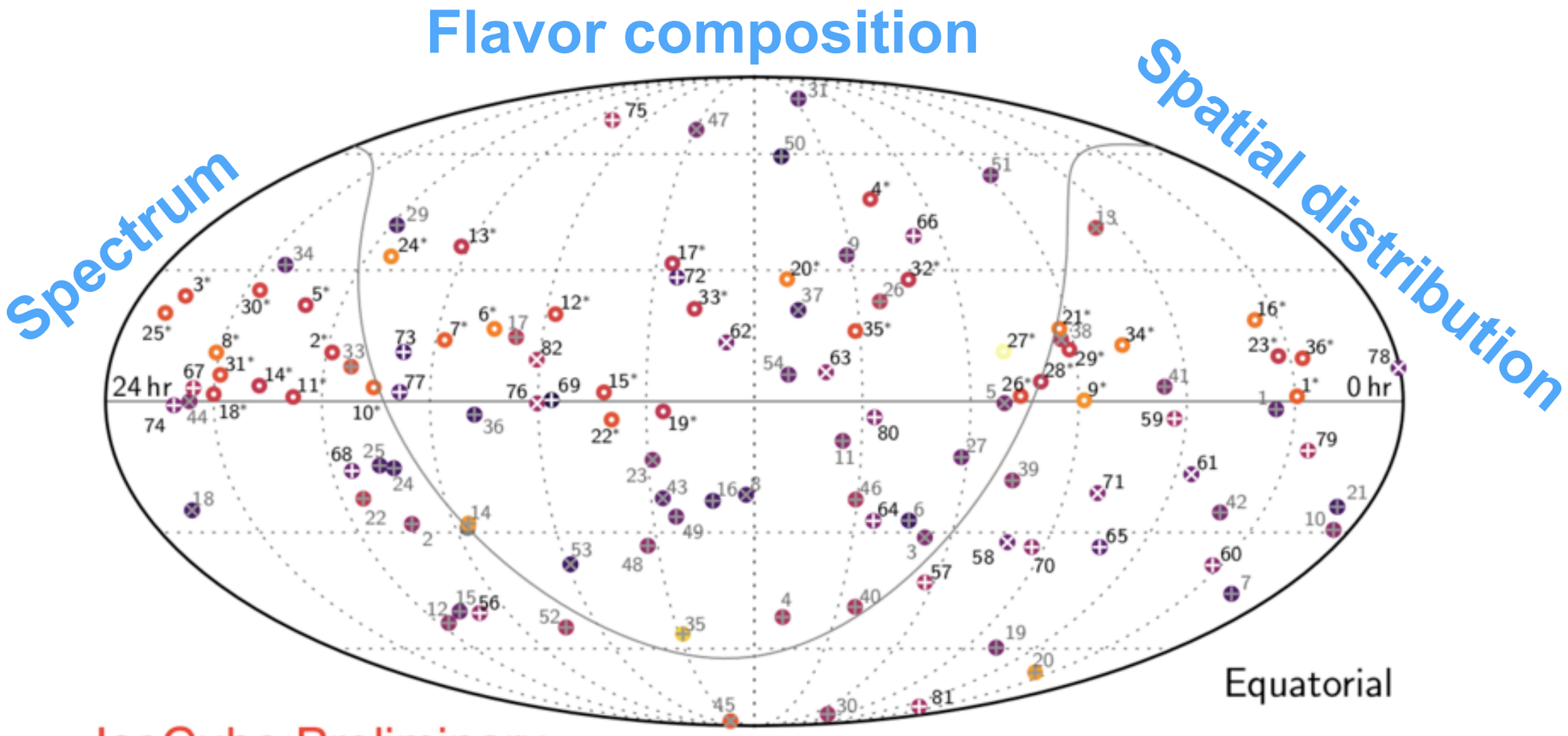
- Completed in 2011.

- Energy thresholds:

Deep Core:
~ 10 GeV

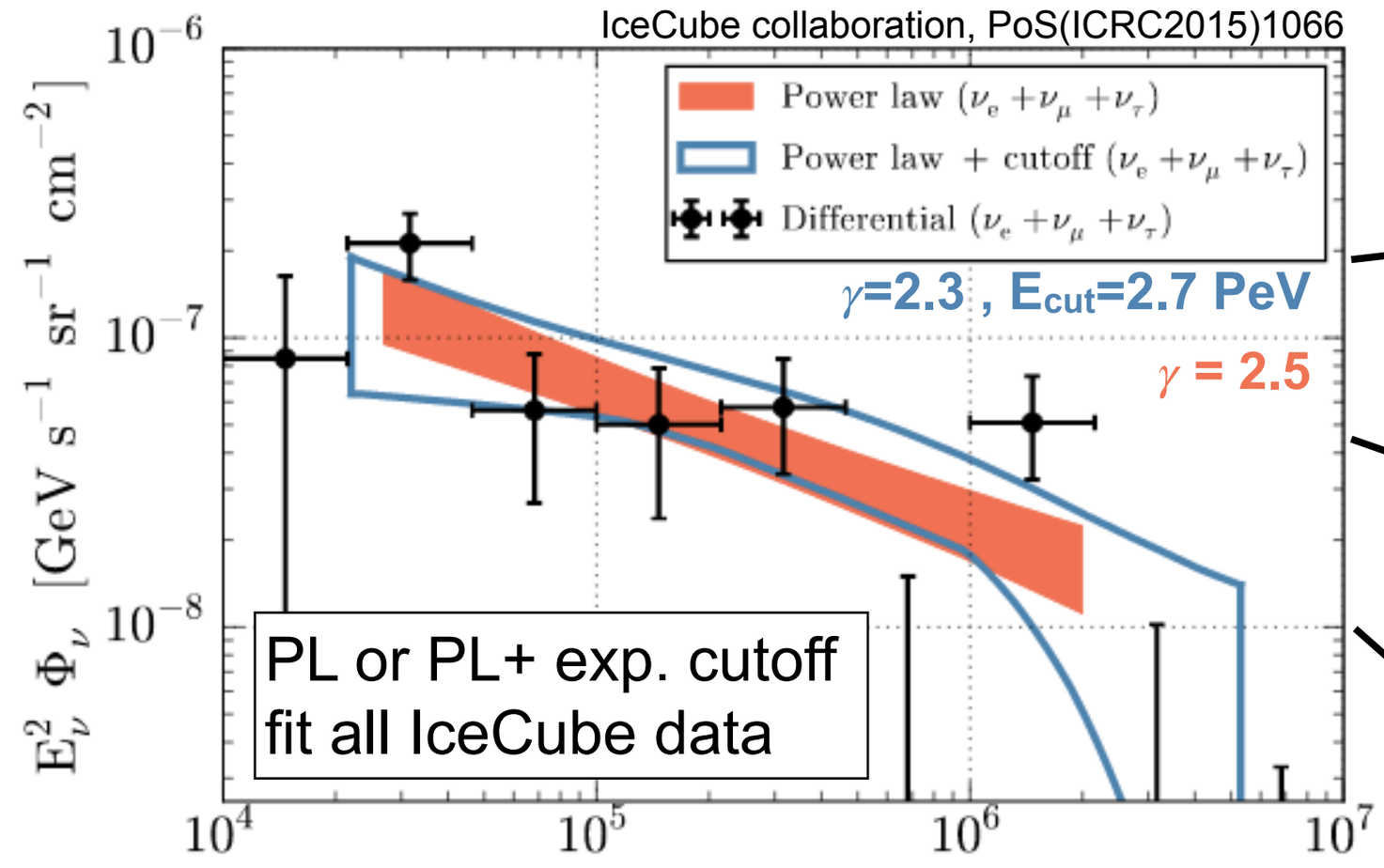
IceCube **main array**:
~ 100 GeV

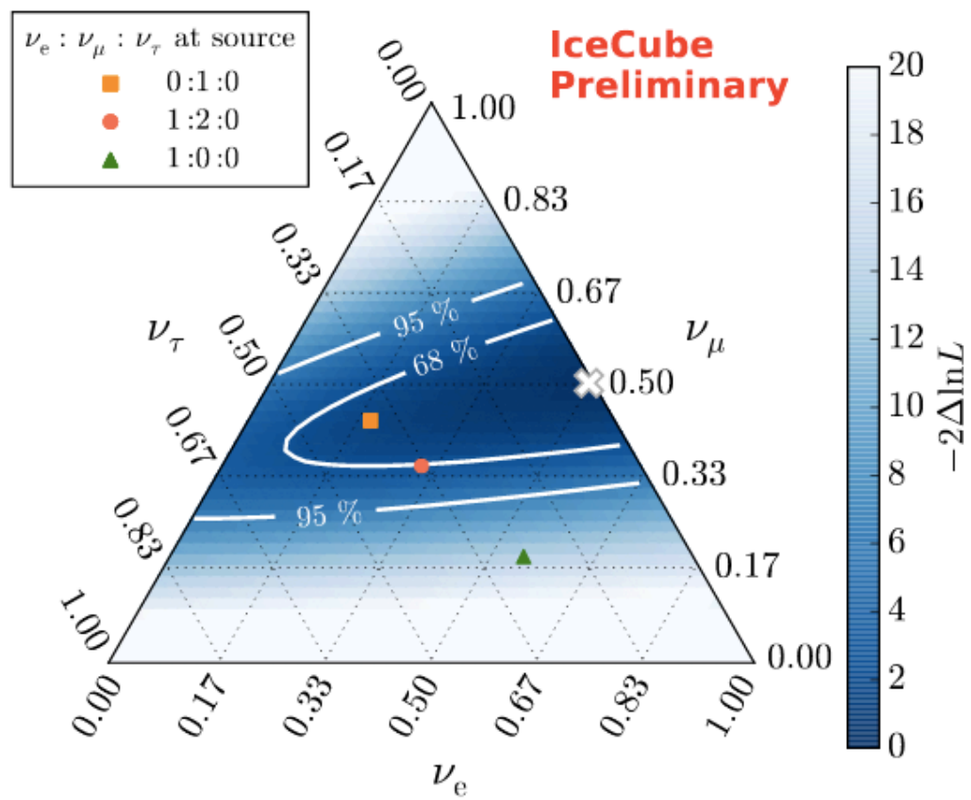
What are the properties of the cosmic neutrino flux ?

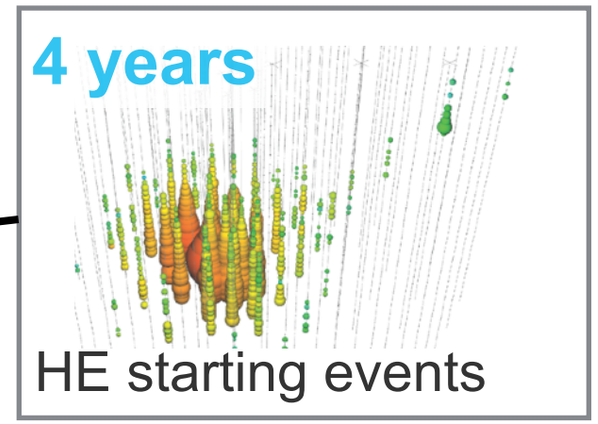


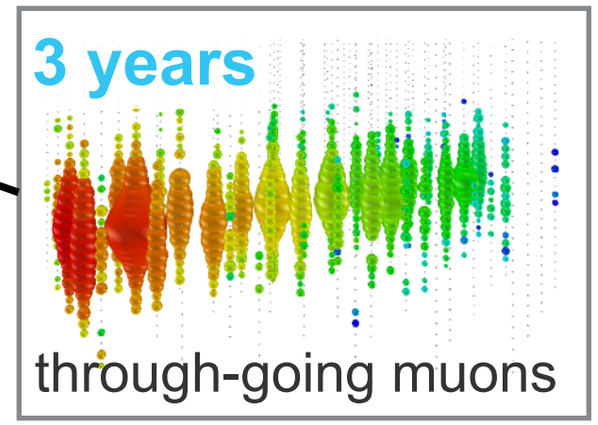
IceCube high-energy events >~ 30 TeV (2010 - 2016)

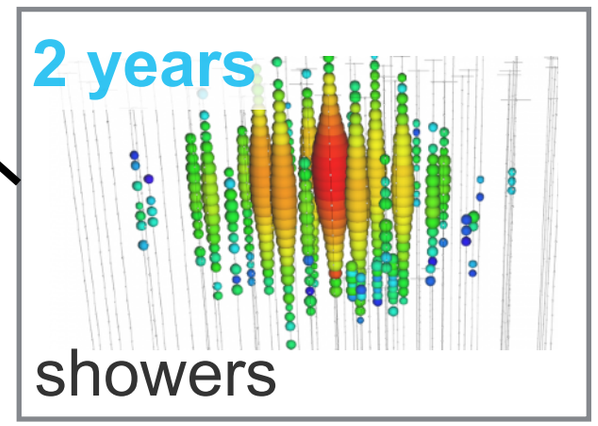
Cosmic neutrinos 2 years ago…





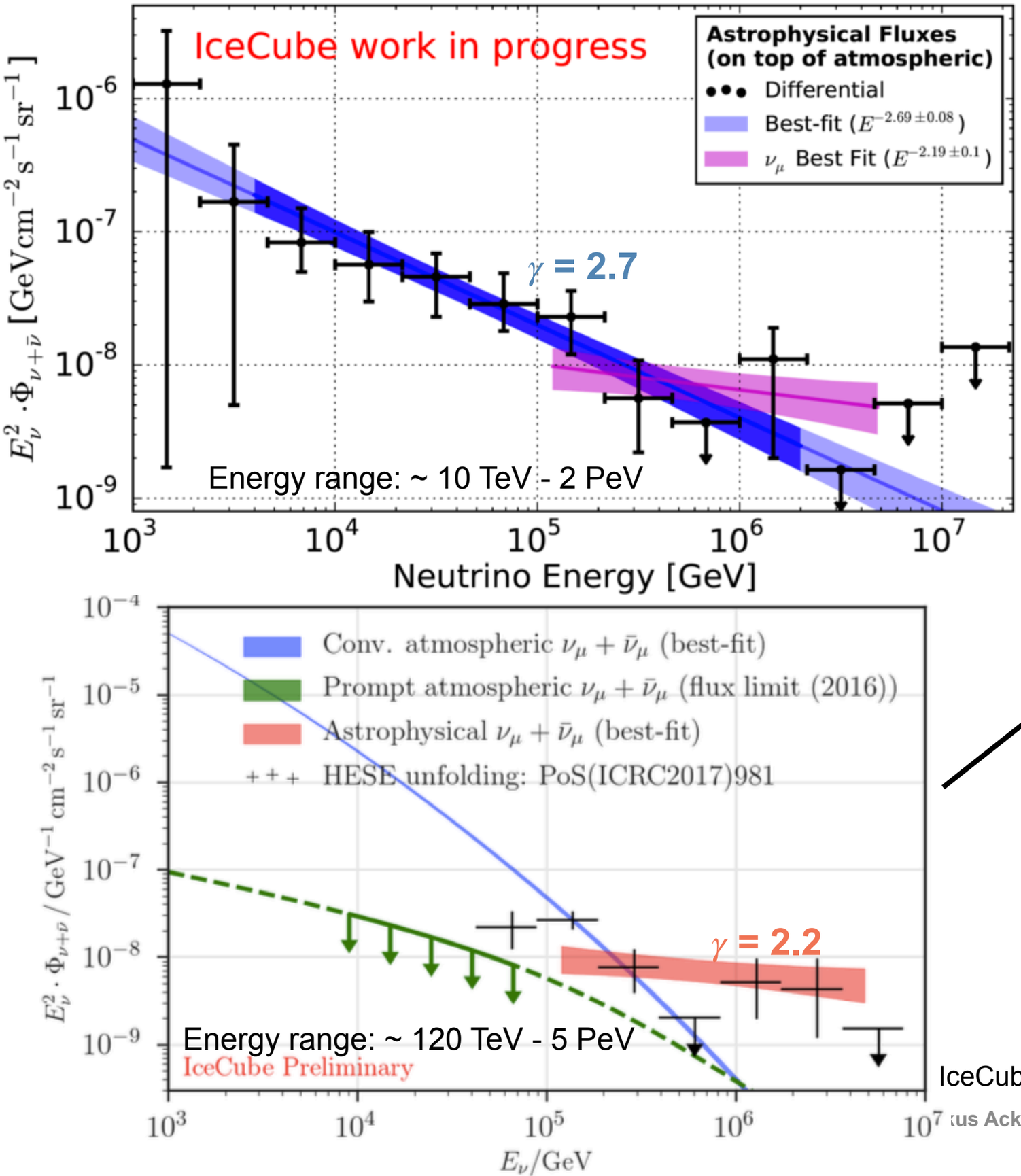




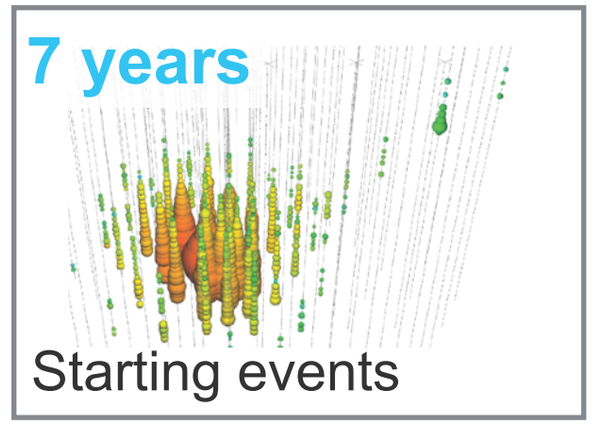


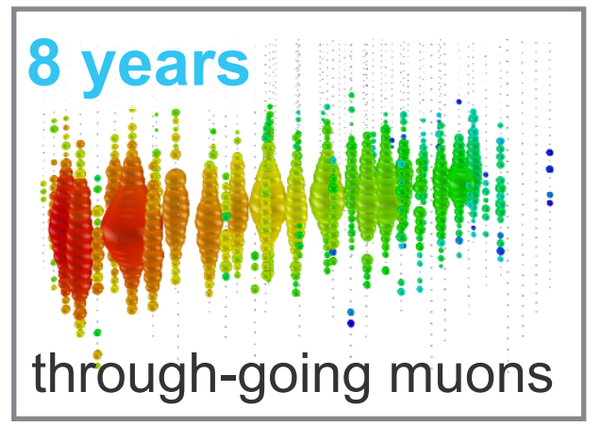
- **Global analysis** of multiple event samples from IceCube.
- **No** indications **for anisotropies** or point sources.
- **No** neutrinos **beyond PeV** energies

Cosmic neutrinos today



IceCube collaboration, TeVPA 2017

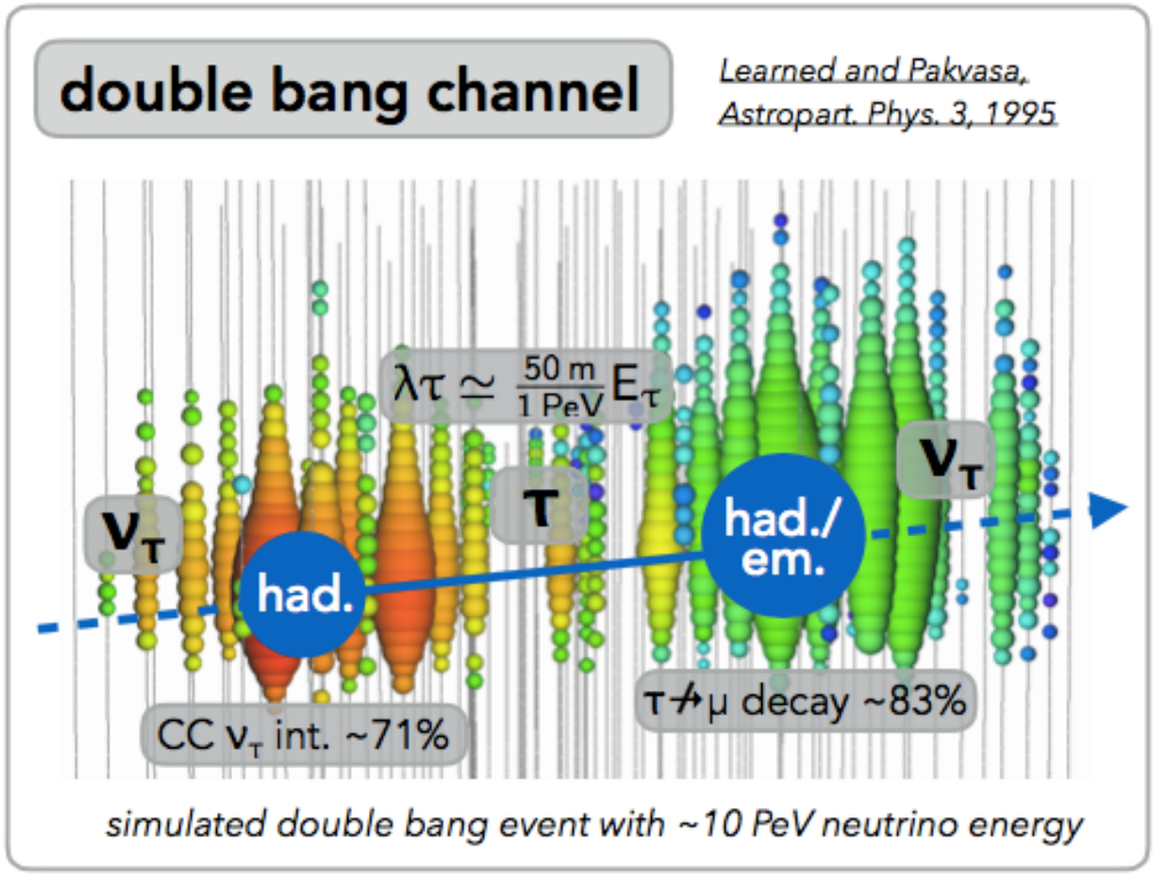




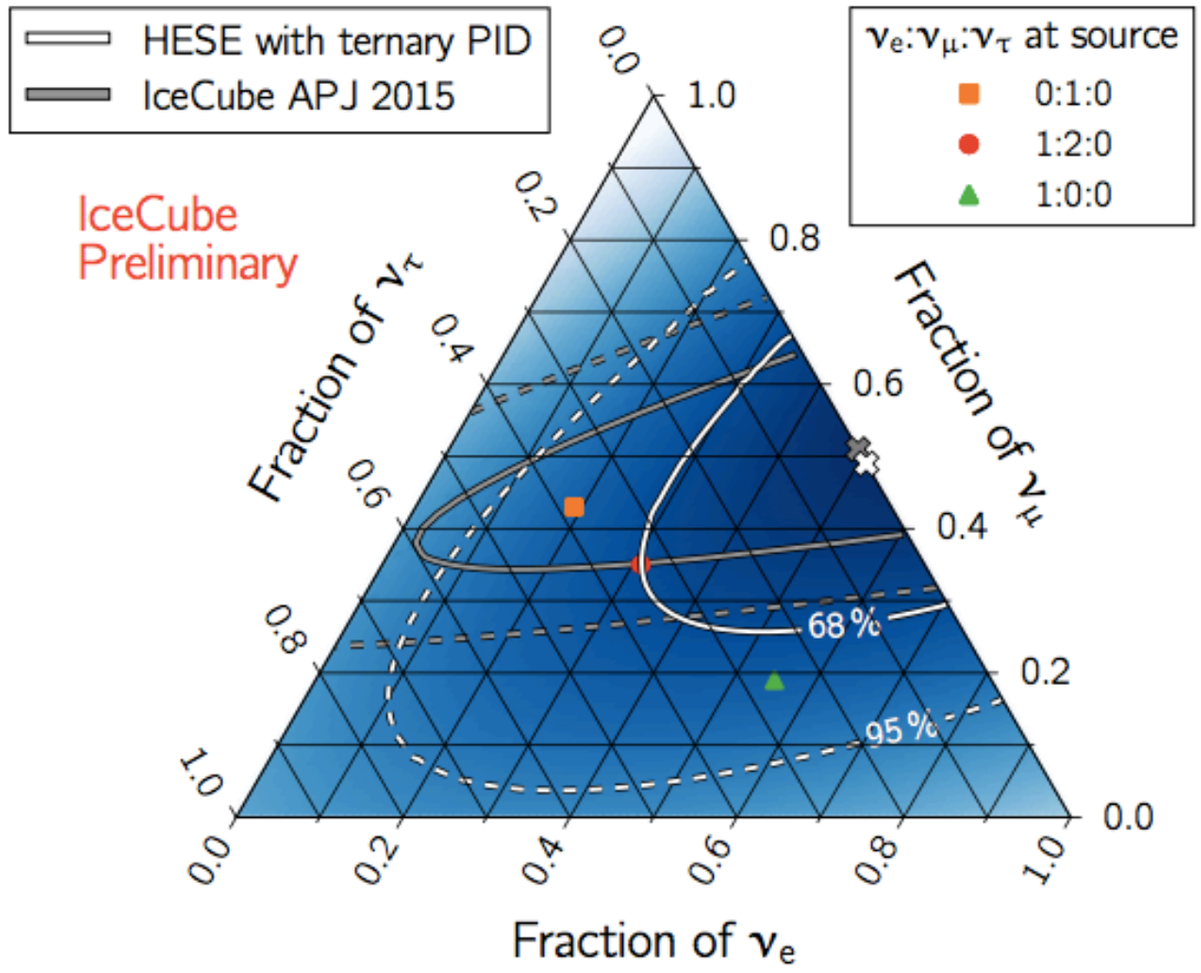
- Potential **spectral hardening** above 100 TeV.
- **Global analysis** will be updated soon.

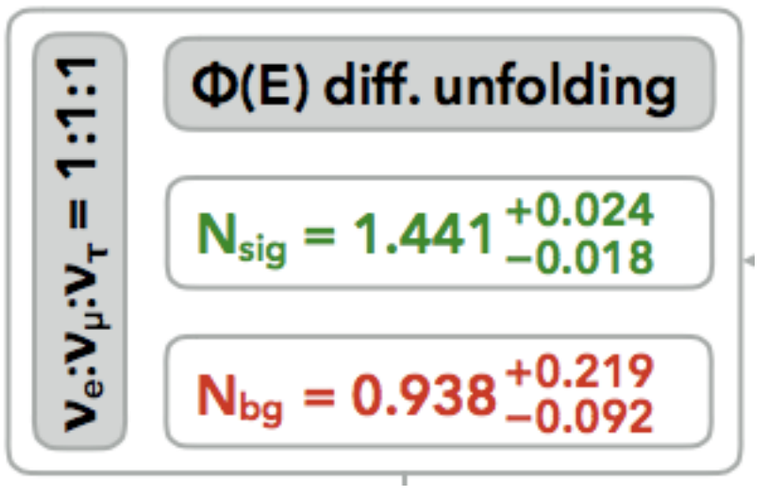
IceCube collaboration, ICRC 2017

Astrophysical tau neutrinos



IceCube collaboration, ICRC 2017

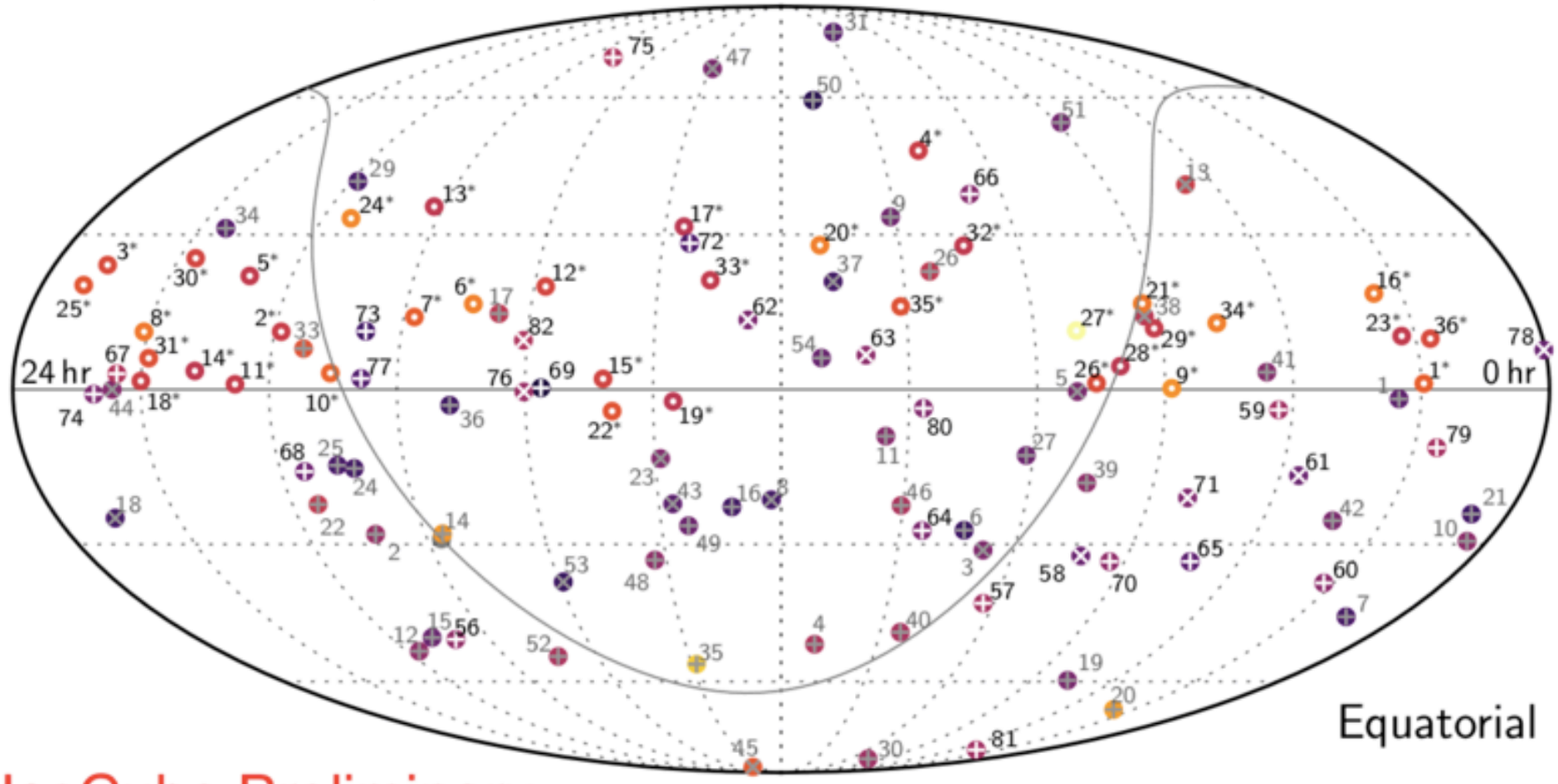




- Search for **characteristic ν^τ signature**.
- Sensitive to $\nu\tau$ **with E > 100 TeV**.
- **No $\nu\tau$ candidate** found in starting event sample. Consistent with fluctuation.
- Future analysis will be extended to other data samples: **up to 50% more** expected $\nu\tau$ candidates.

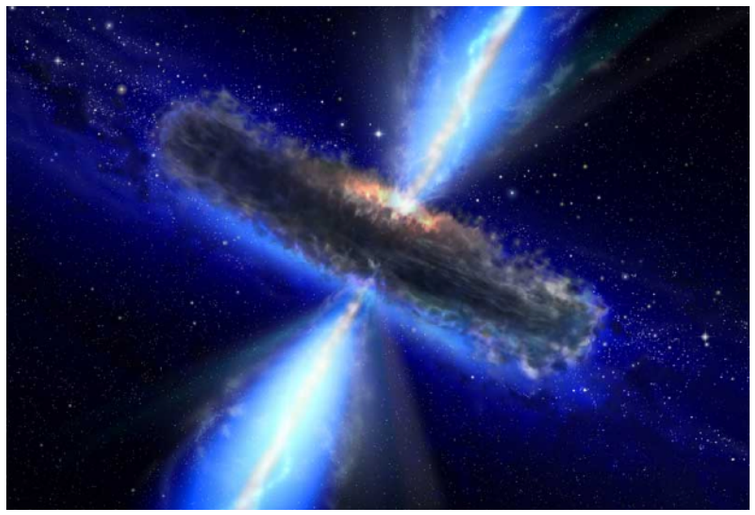
Distribution of high-energy neutrinos on the sky

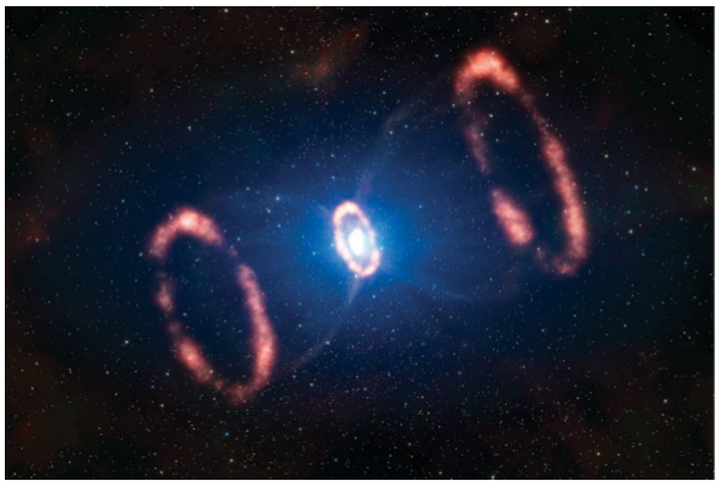
IceCube collaboration, ICRC 2017



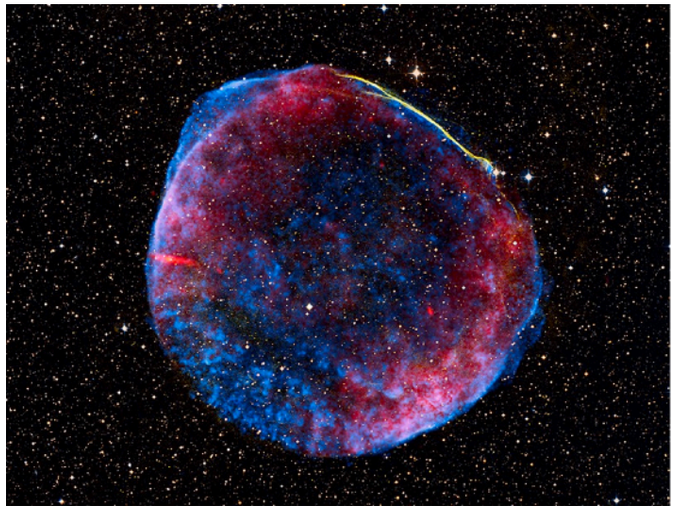
IceCube high-energy events >~ 30 TeV (2010 - 2016)

- **Compatible** with an **isotropic** distribution
  - points to extragalactic origin of cosmic neutrinos
- **No significant clustering** of high-energy events
- **No significant correlation** with electromagnetic or gravitational wave transients

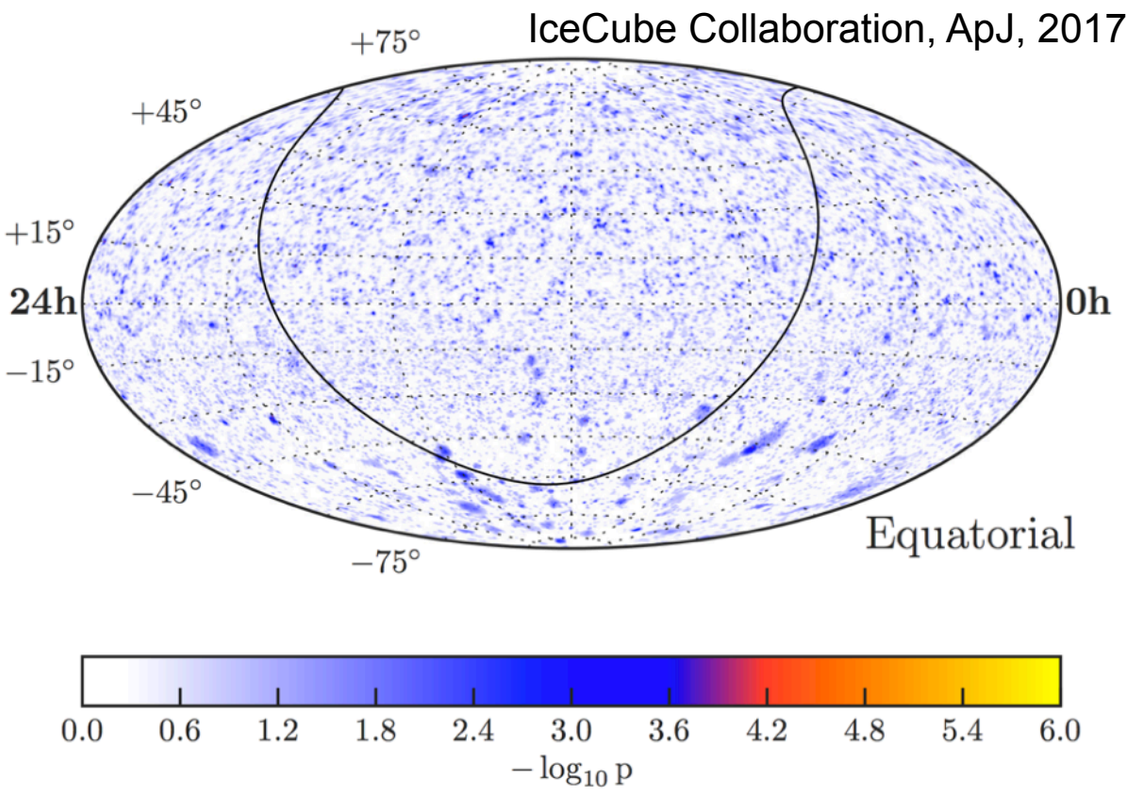




Where do they come from?

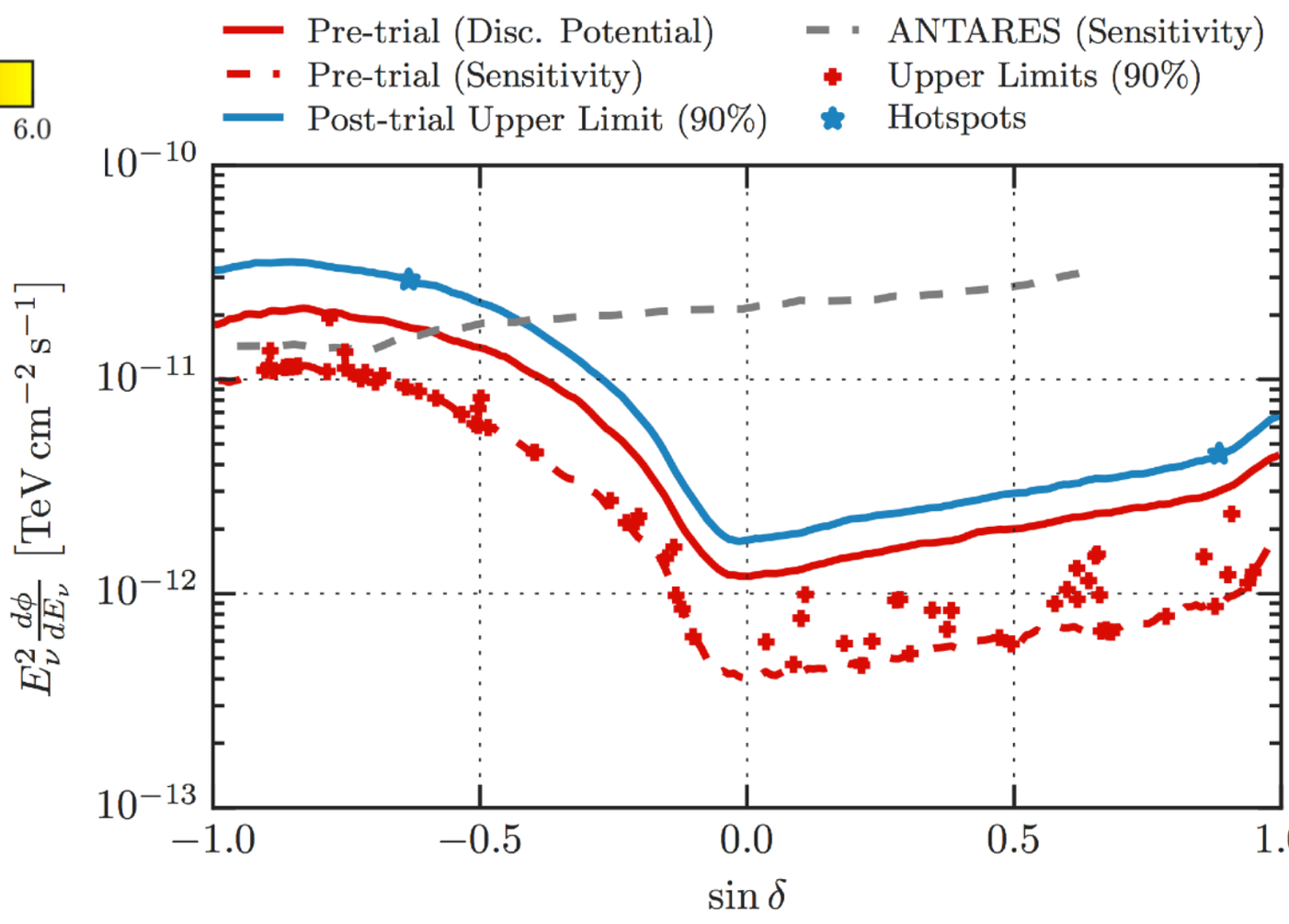


Cosmic neutrino sources



- Search for neutrino sources on **large sample of 712,830** dominantly atmospheric neutrinos/muons
  - Collected between 2008 and 2015.
- **Search for a local excess** of events over atmospheric backgrounds.

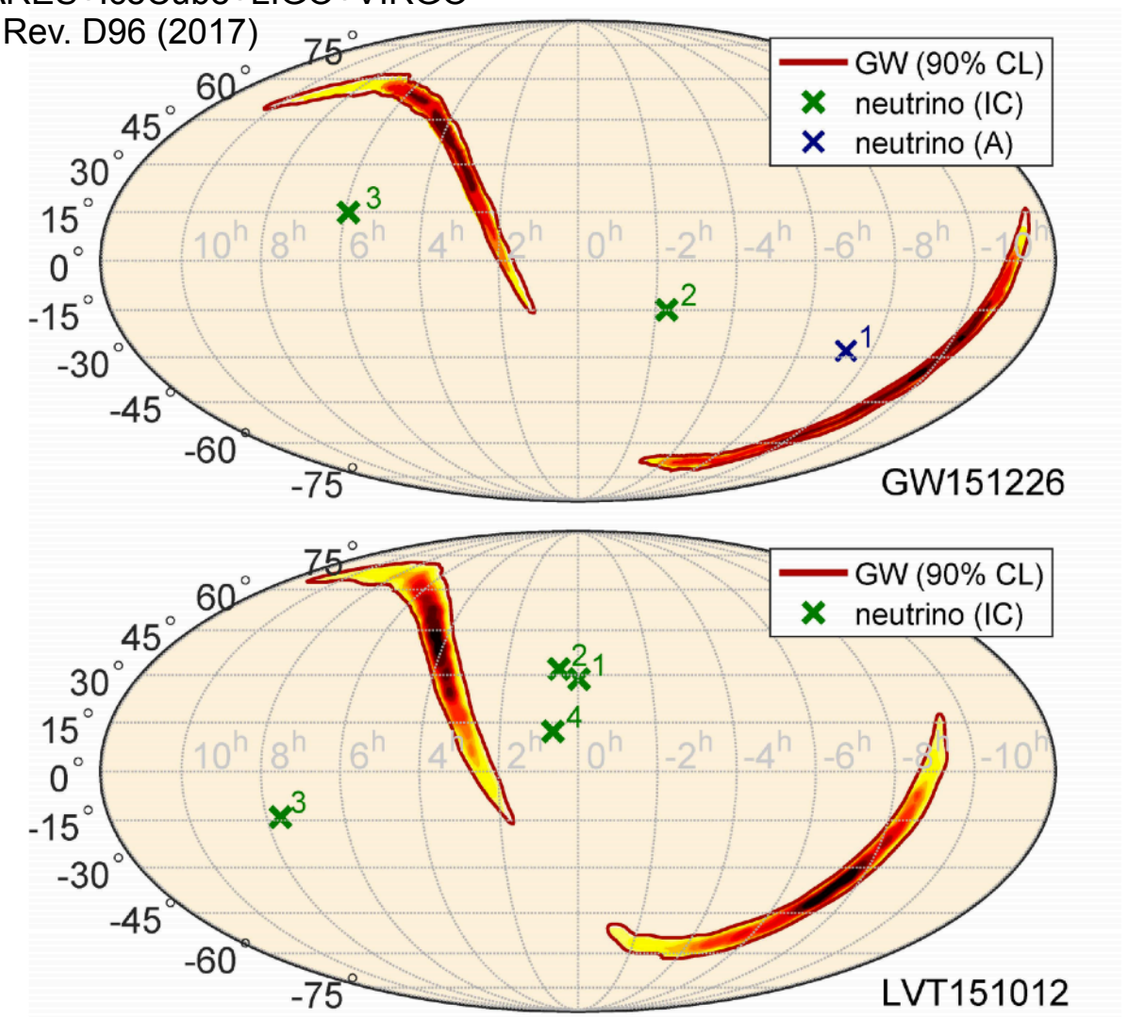
- **No point source** found.
- **No extended source** found.



Transient sources

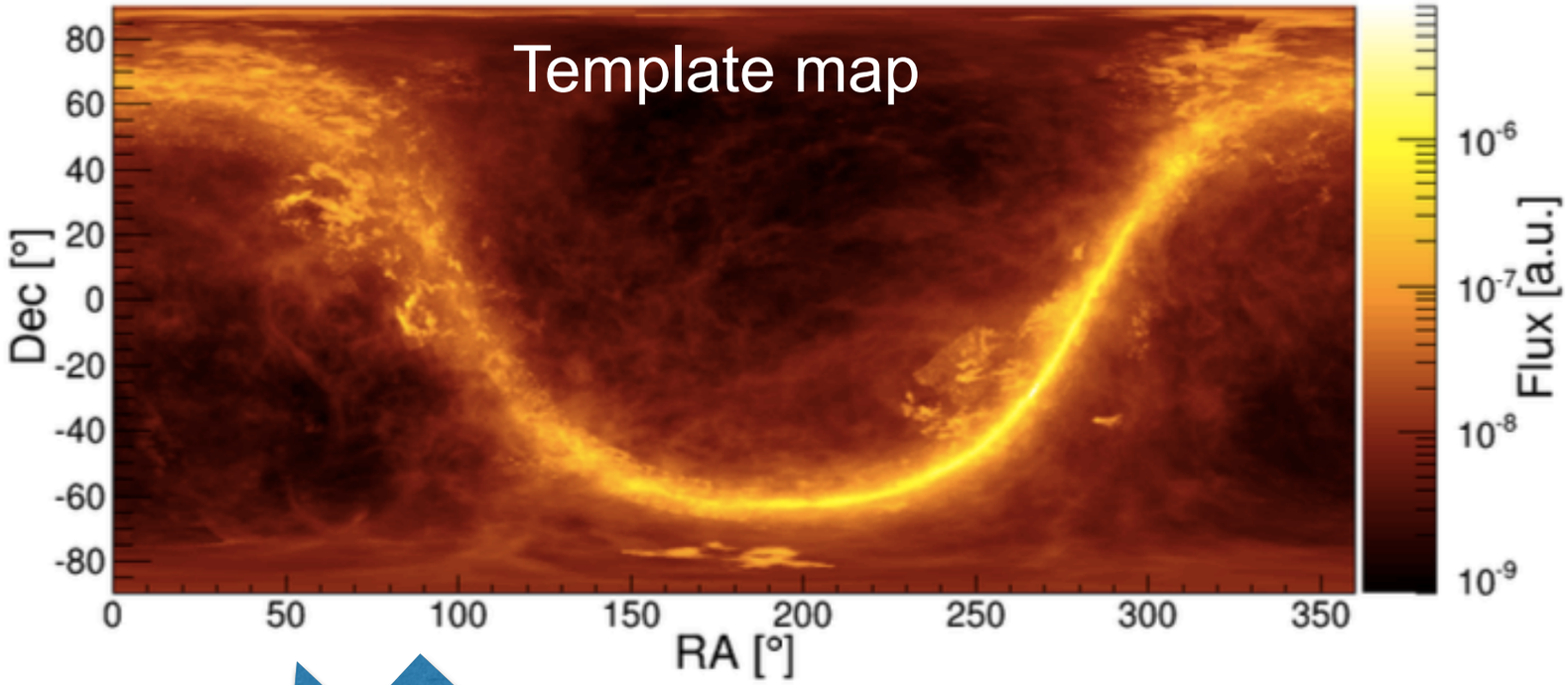
- Search for correlations of neutrinos with observed light curves in various electromagnetic (EM) wave bands
- IceCube high-energy neutrinos trigger EM follow-up observations.
- Search for correlations of neutrino events with interesting EM or gravitational-wave transients
- **No significant correlation found** with:
  - Gamma-ray bursts
  - Blazar flares
  - Fast radio bursts
  - Gravitational wave events
  - Supernovae

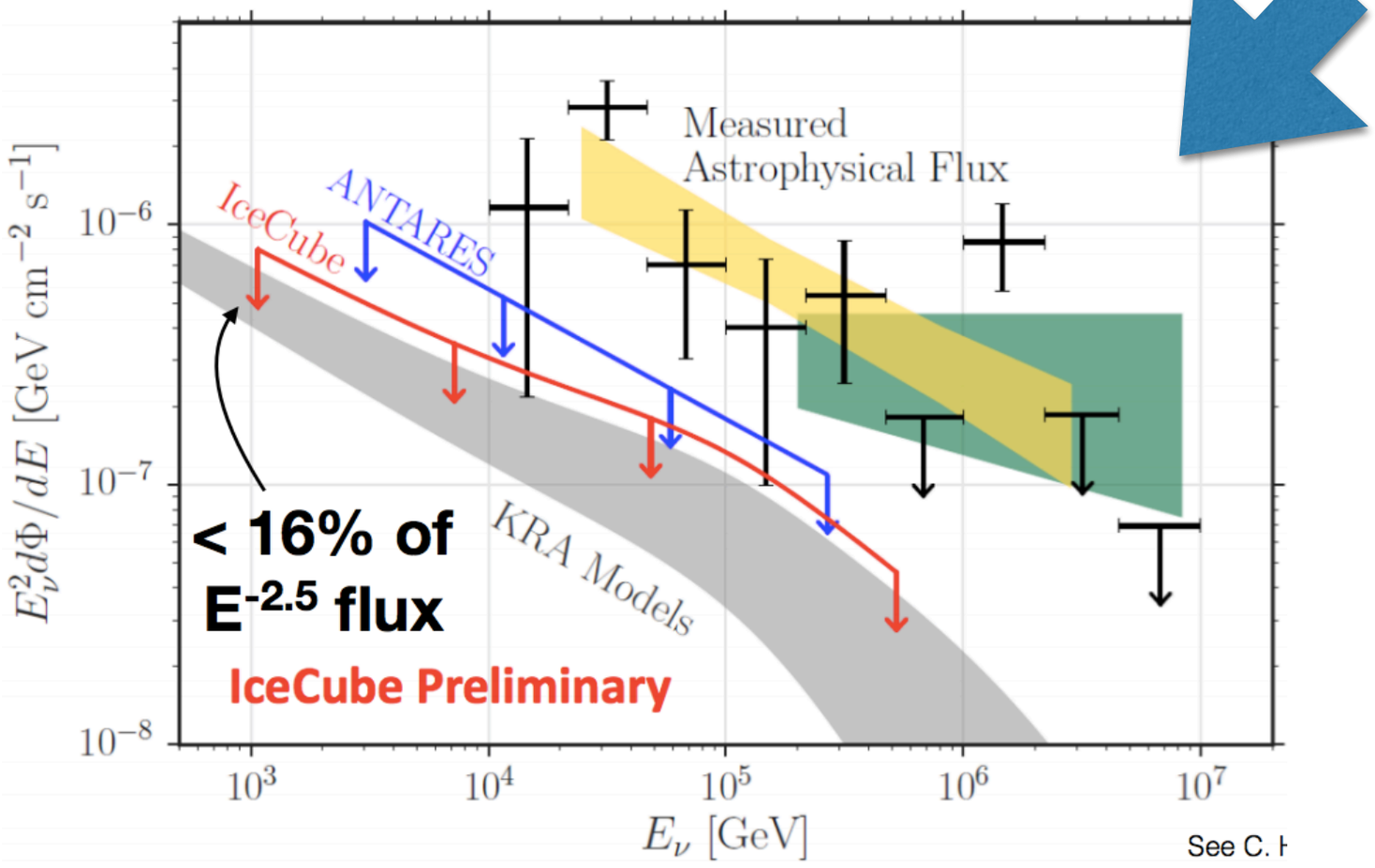
ANTARES+IceCube+LIGO+VIRGO
Phys.Rev. D96 (2017)



Neutrinos from the Galactic plane

- Neutrinos from the **interactions of cosmic rays** with interstellar gas.
- Expected spatial distribution **well understood** from gamma-ray data.
- Intensity above 10 TeV uncertain.





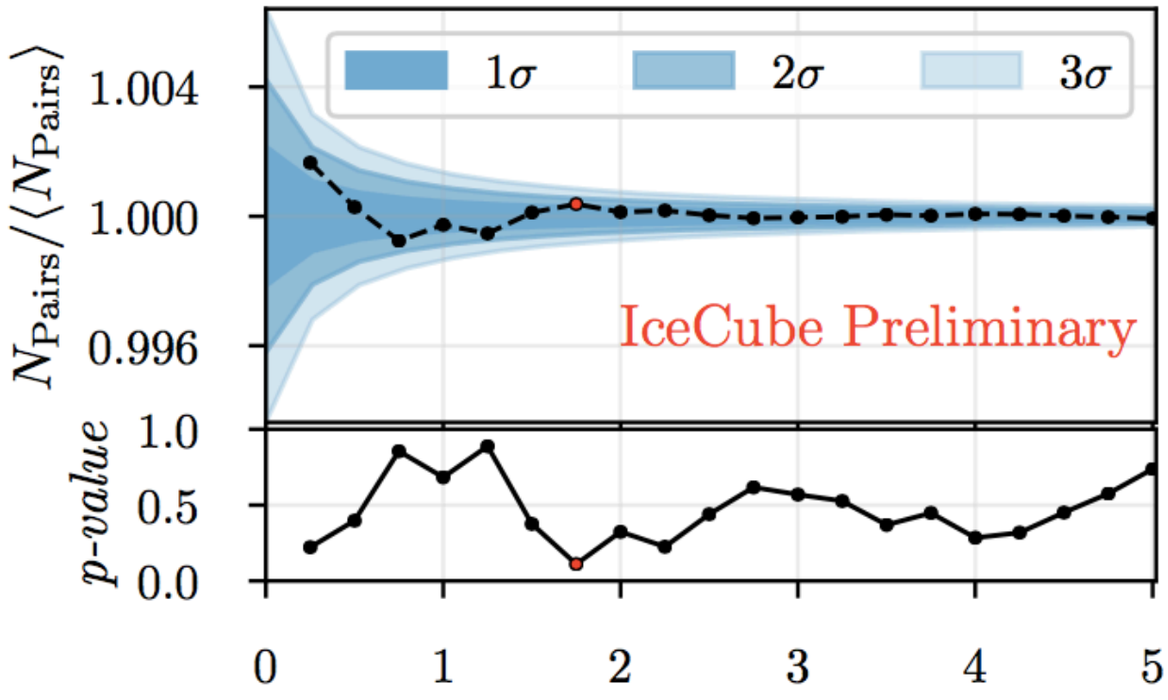
See C. I

- Analysis of **correlation with template map** derived from interstellar gas distribution.
- **No correlation** found.
- Only **small fraction** of signal can **originate from CR interactions** in the Galaxy.

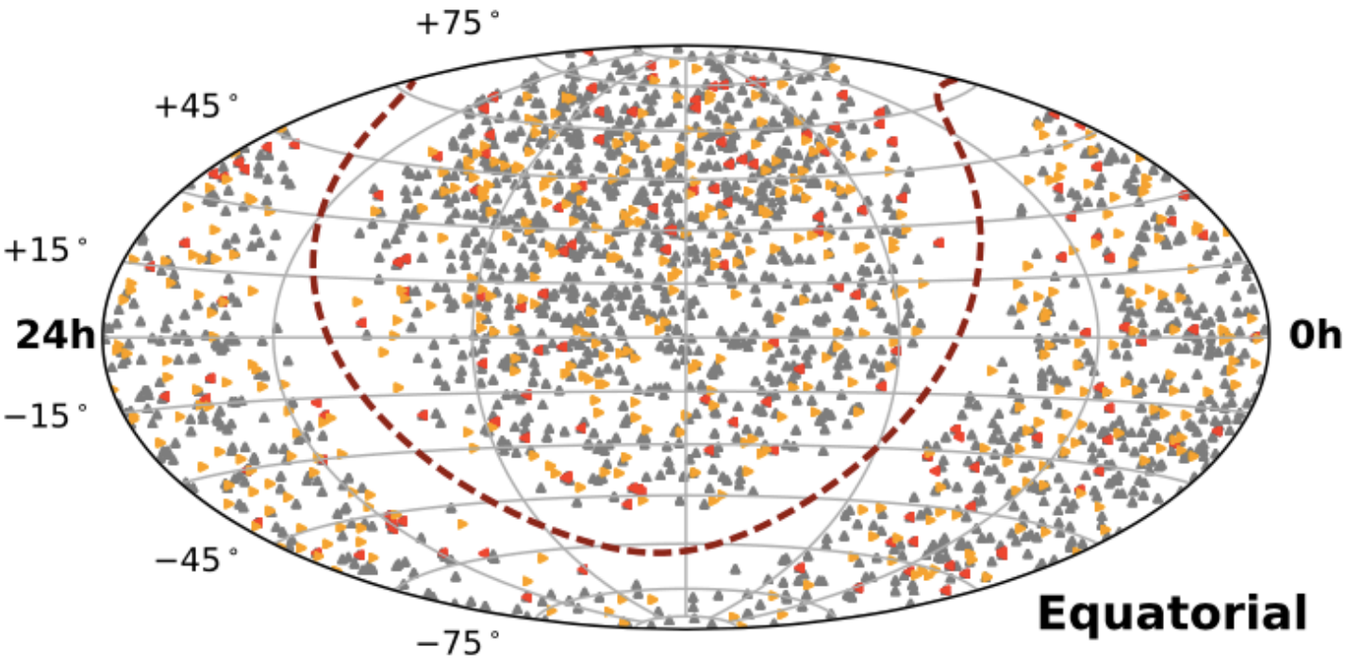
Cross-correlation & auto-correlation searches

- **Cross- and autocorrelation** searches enhance detection power for **weak neutrino sources.**
- **No significant** autocorrelation.
- **No correlation** to gamma-ray blazars.
- **No correlation** with Gamma-Ray Bursts (GRB).

2pt-autocorrelation



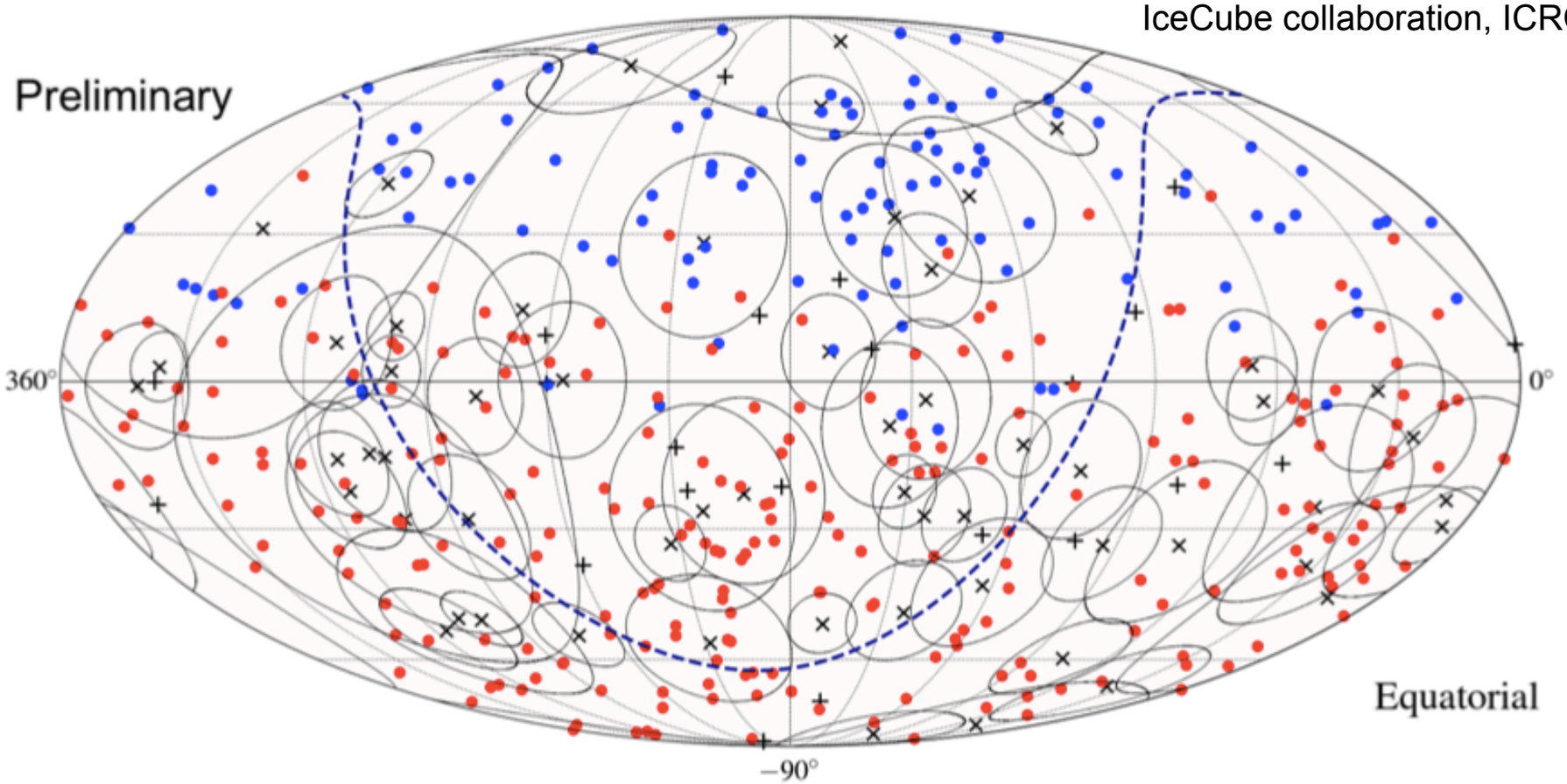
IceCube collaboration, ICRC 2017



2FHL, 3LAC and 2WHSP blazars X-Correlation search

- The neutrino sky is dominated by **low-luminosity, high-density source populations.**

Cross-correlation with ultra-high-energy cosmic rays



D	High-energy tracks		High-energy cascades	
	n_s	pre-trial p-value	n_s	pre-trial p-value
3°	0.9	0.44	45.5	2.7×10^{-2}
6°	-	underfluctuation	71.5	1.0×10^{-2}
9°	-	underfluctuation	84.7	1.5×10^{-2}

- **~3σ correlation** seen on previous dataset for shower-type events.
- **Reduced to about ~2σ** with new IceCube/CR data added.
- **No evidence** for correlation from muon tracks.

Cosmogenic neutrinos

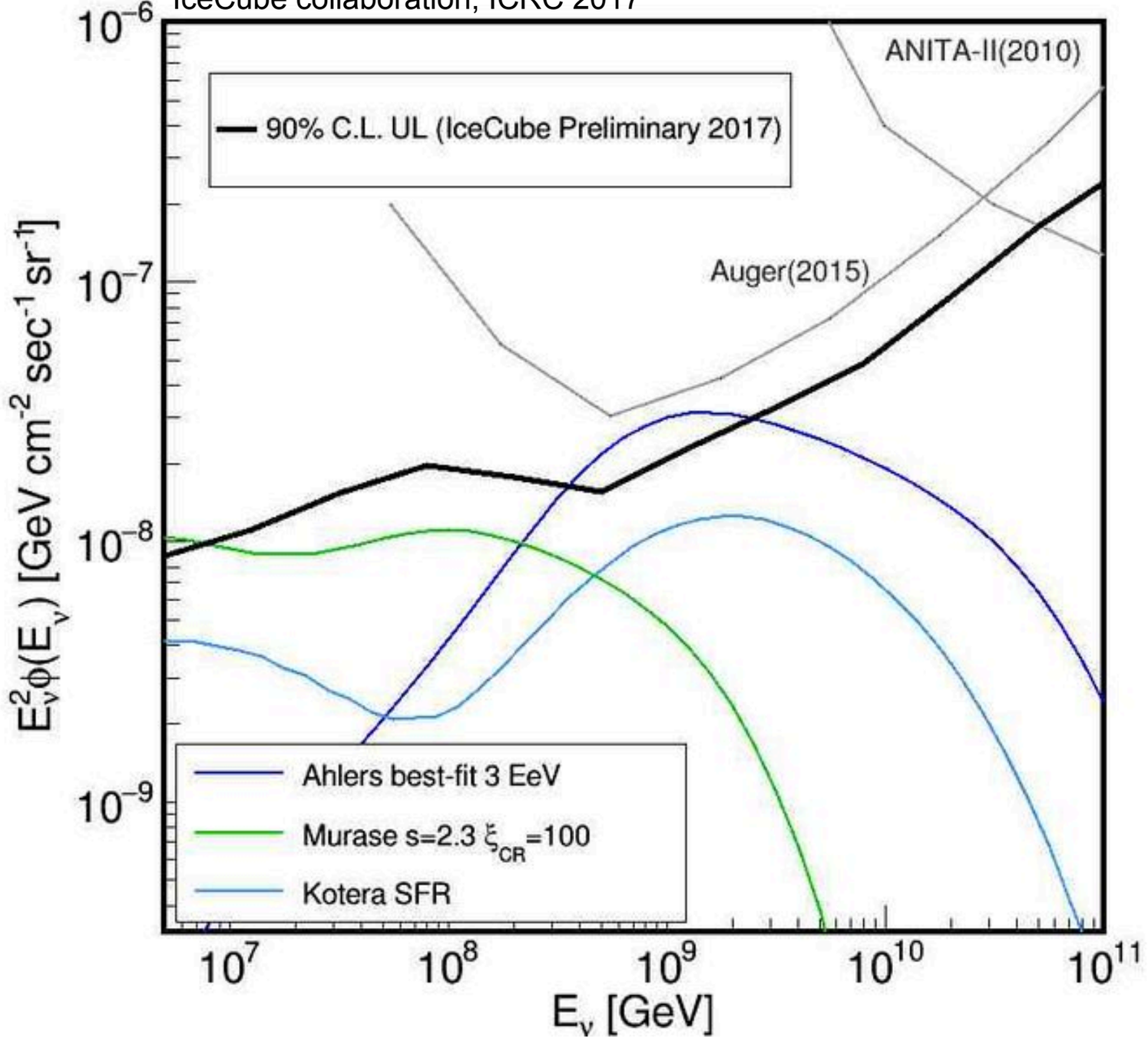
- Neutrinos from the **interactions** of ultra-high-energy cosmic rays **with CMB and extragalactic photon** fields.

- Neutrino spectrum expected to peak at **~ 100 PeV - 10 EeV.**

- Astrophysical neutrino flux only observed **up to few PeV.**

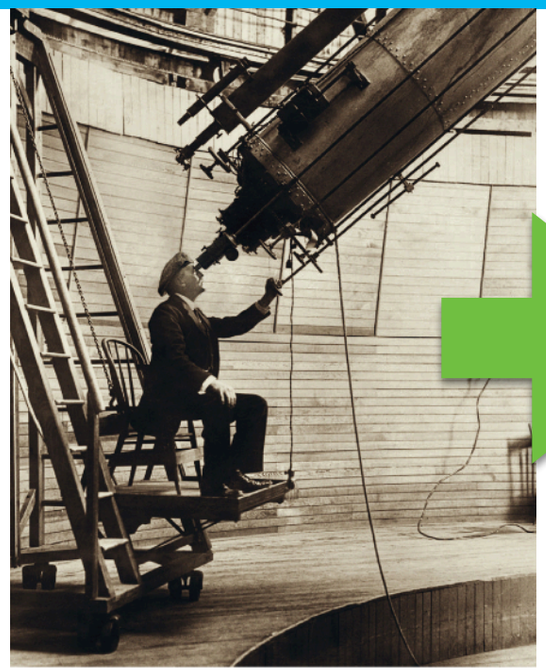
- Cosmogenic neutrinos are an **unlike origin** of this flux
  - Constraints on cosmogenic flux can be obtained.

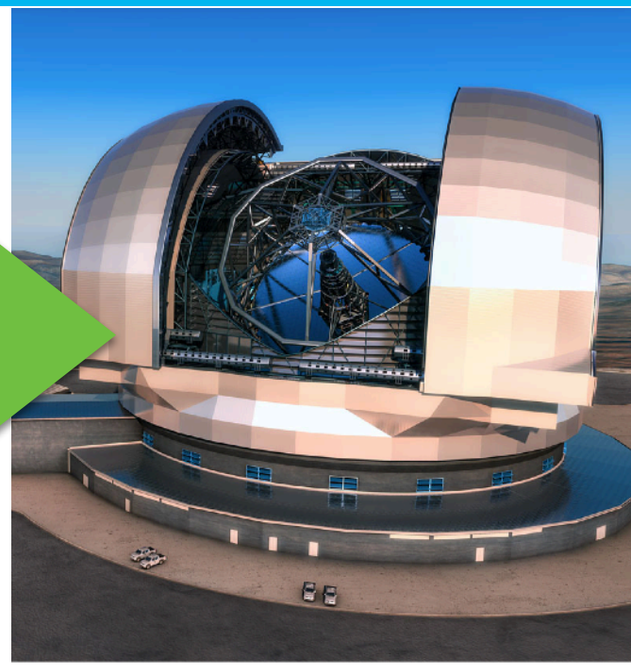
IceCube collaboration, ICRC 2017



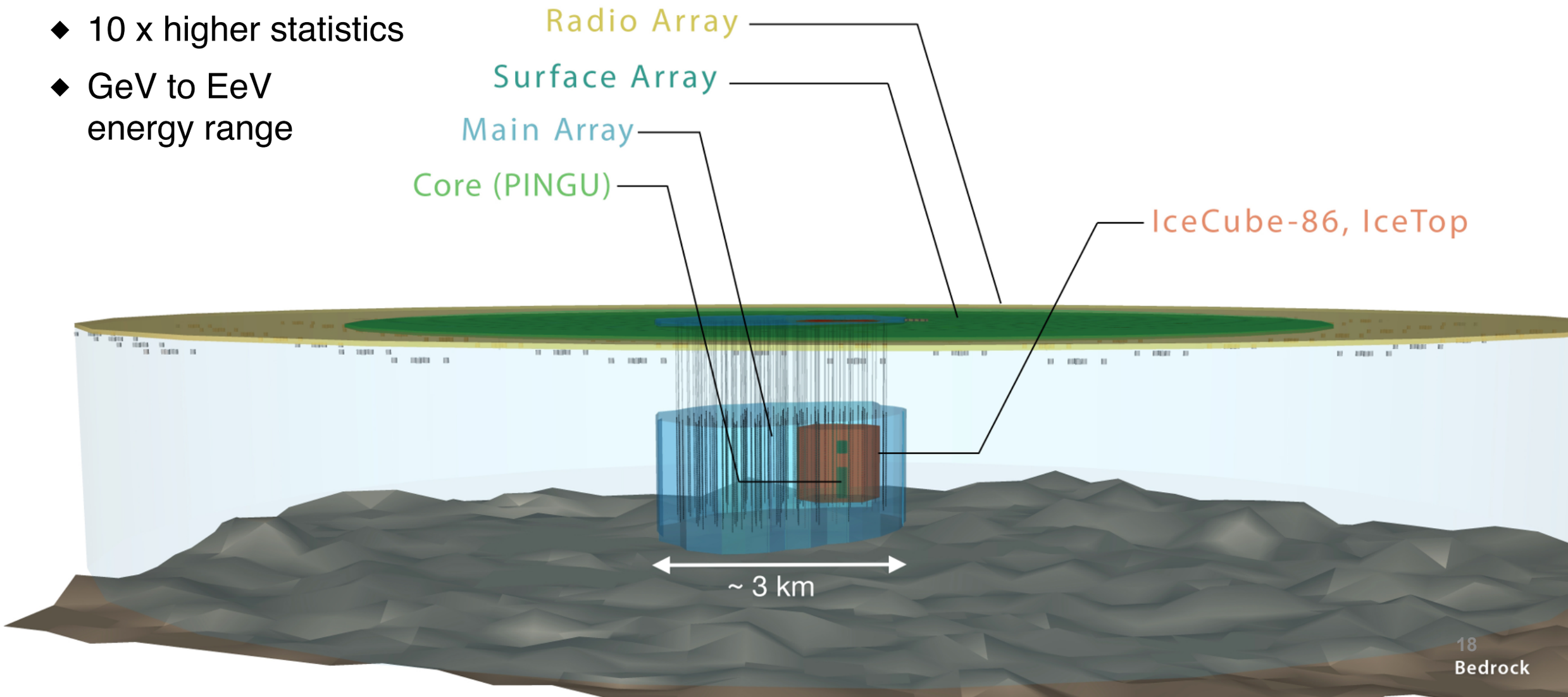
The future of neutrino astronomy at the South Pole

- Future IceCube data will help to **constrain properties of the cosmic neutrino flux**
  …and hopefully find indications for their origin.

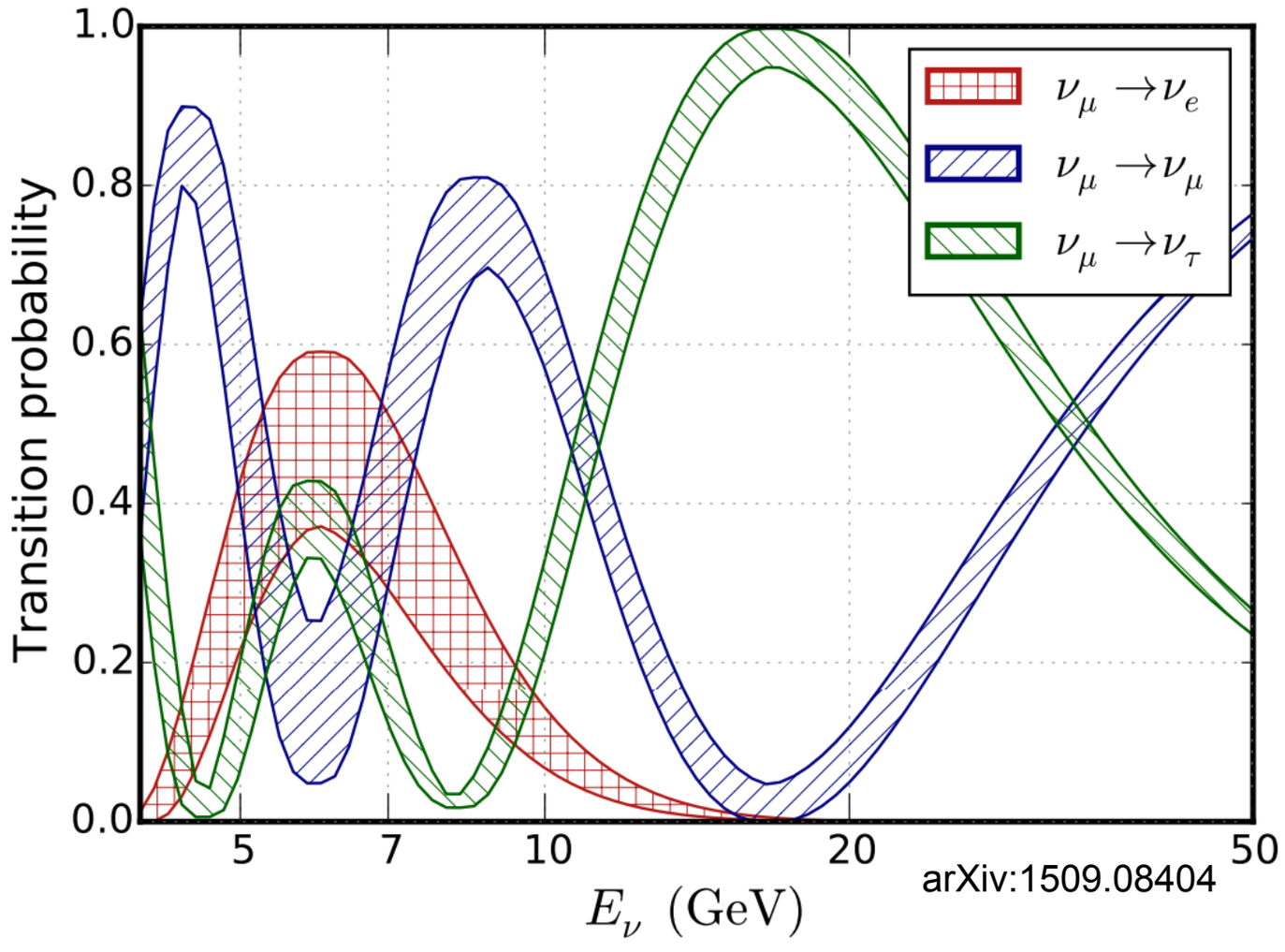




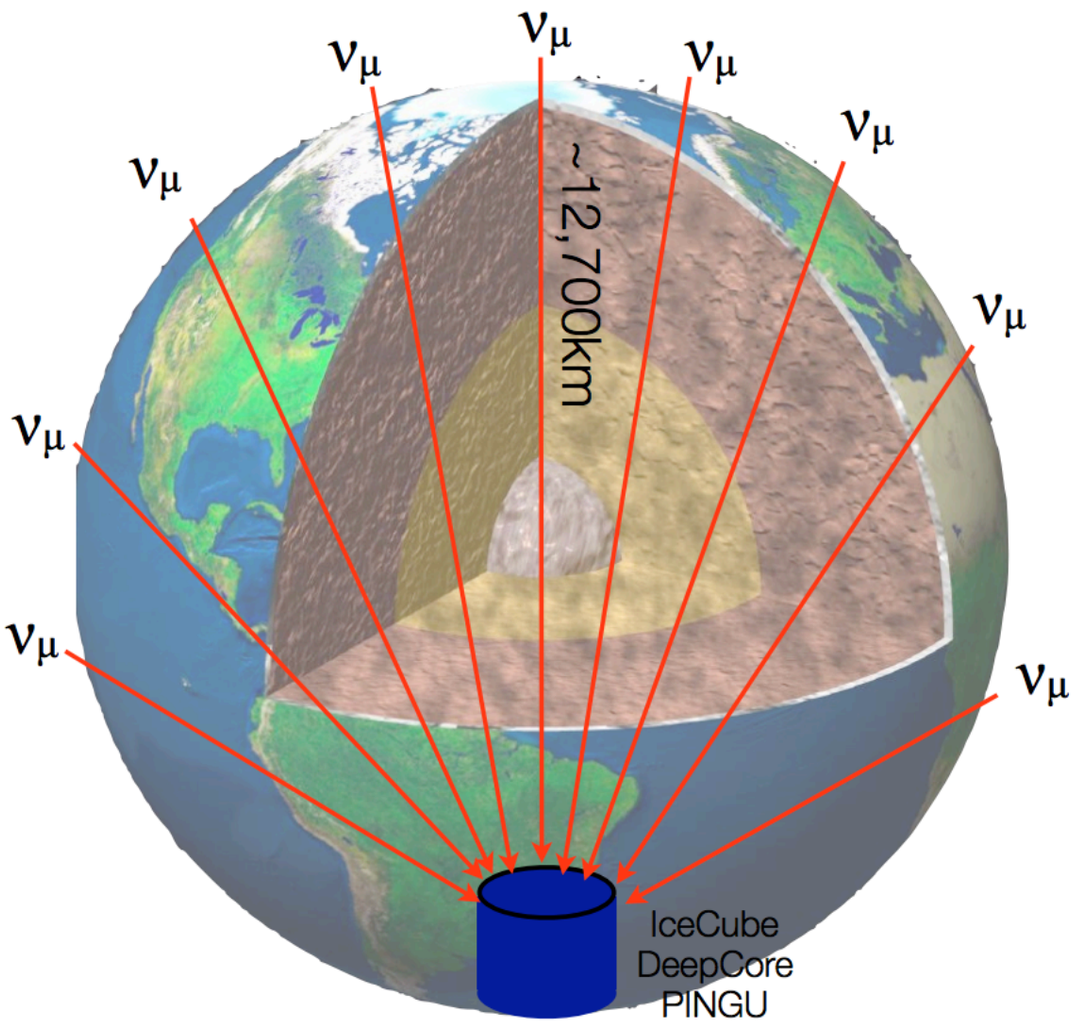
- IceCube-Gen2 will allow **precision studies** of cosmic neutrinos.
  - 5 x better source sensitivity
  - 10 x higher statistics
  - GeV to EeV energy range



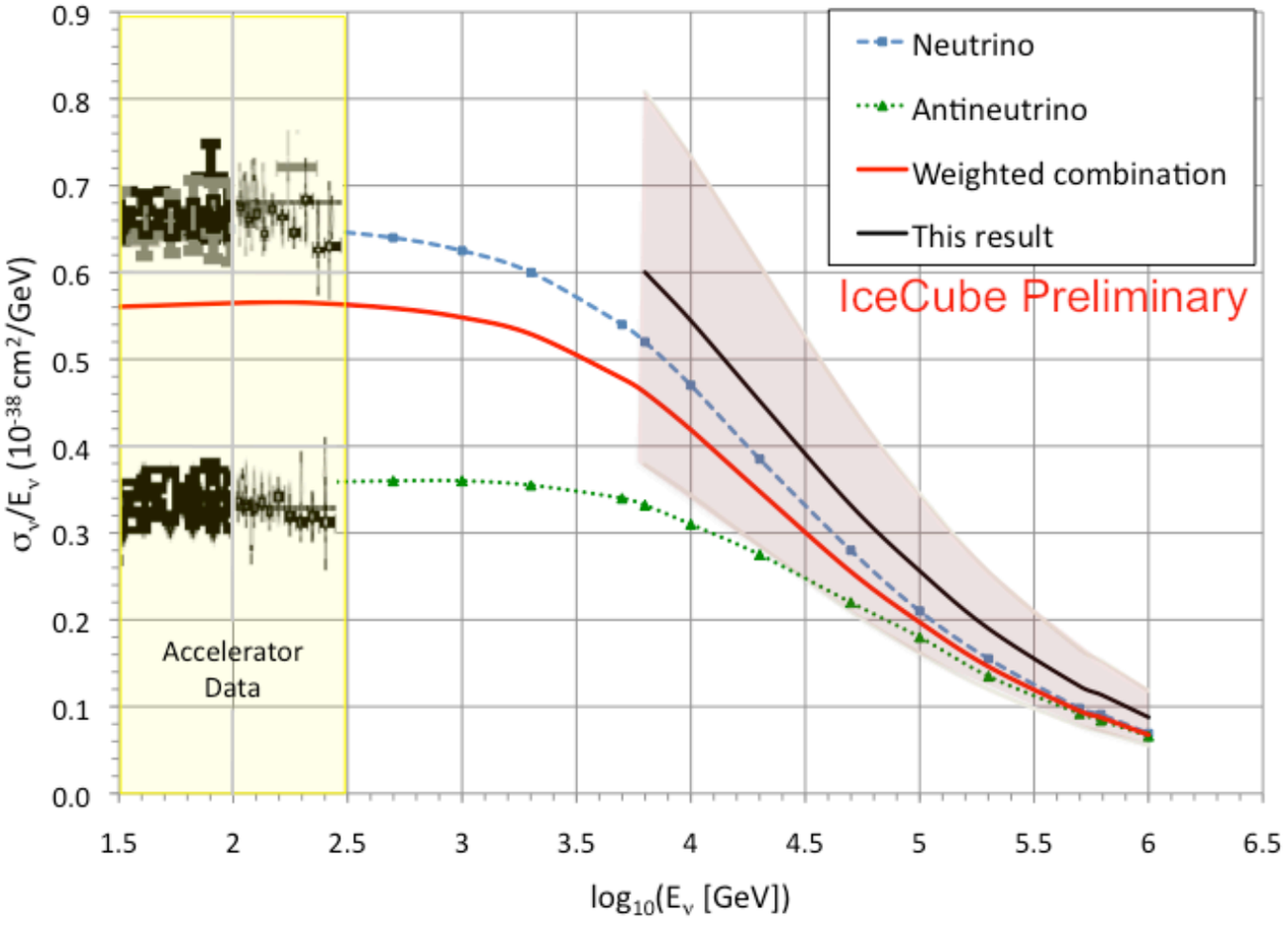
What can we learn **now** about fundamental properties of neutrinos from neutrino telescopes?



Measurement of the neutrino-nucleon scattering cross-section.

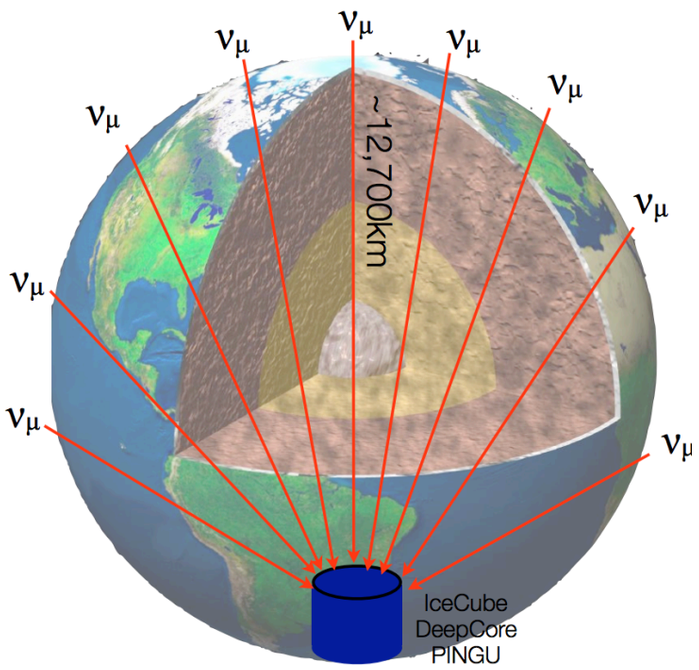


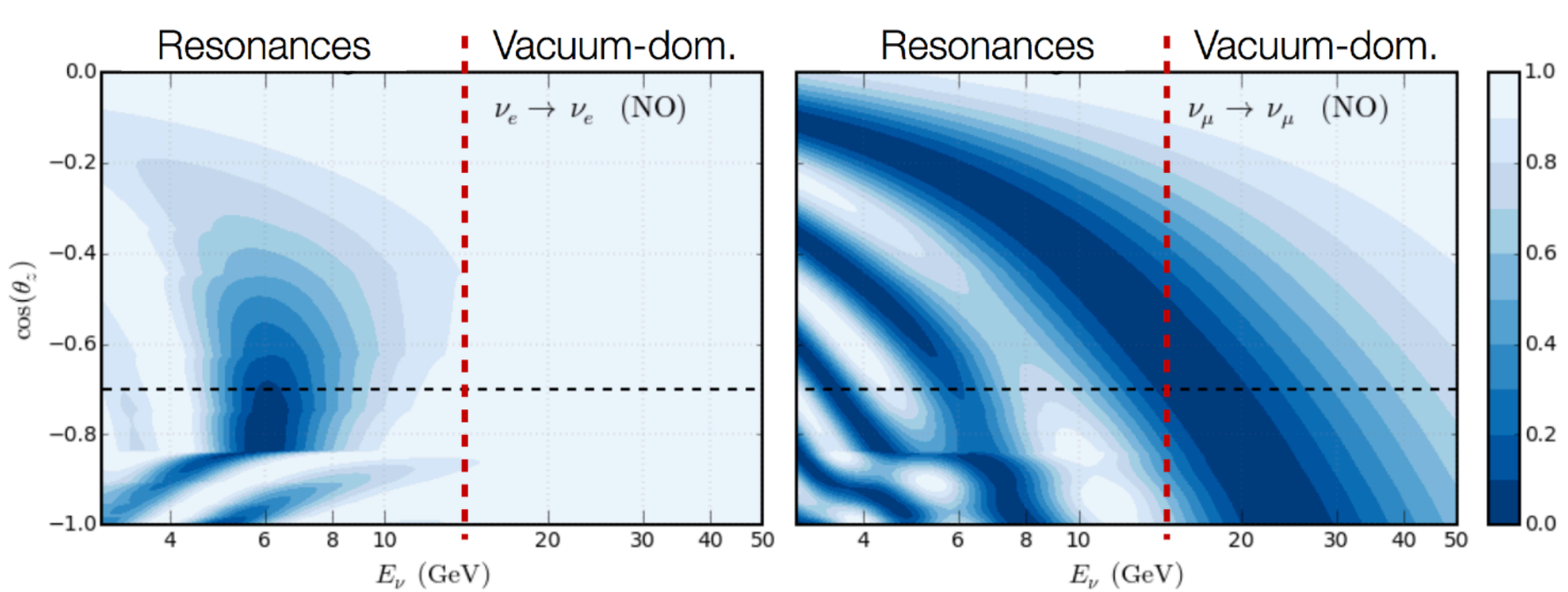
First measurement of neutrino-nucleon cross-section between 6.3 TeV and 980 TeV

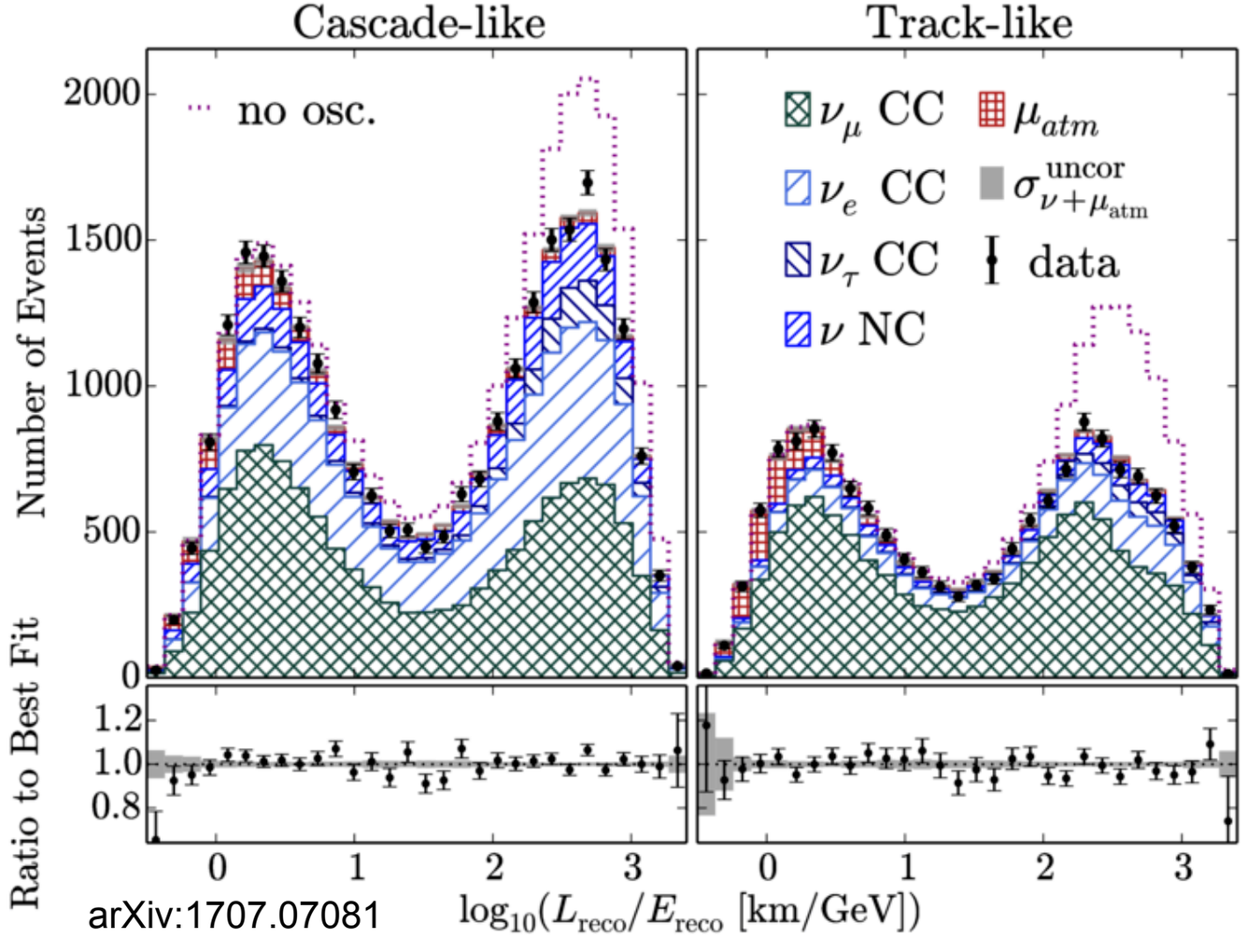


- High-statistics **"beam" of atmospheric neutrinos** with baselines from ~ 20 km to ~ 12700 km for measurement of **oscillation parameters**.
- Energy range from **~ 10 GeV to 1 PeV.**
- Earth as target allows measurement of **neutrino-nucleon scattering cross-section.**

Measurement of atmospheric neutrino oscillation parameters



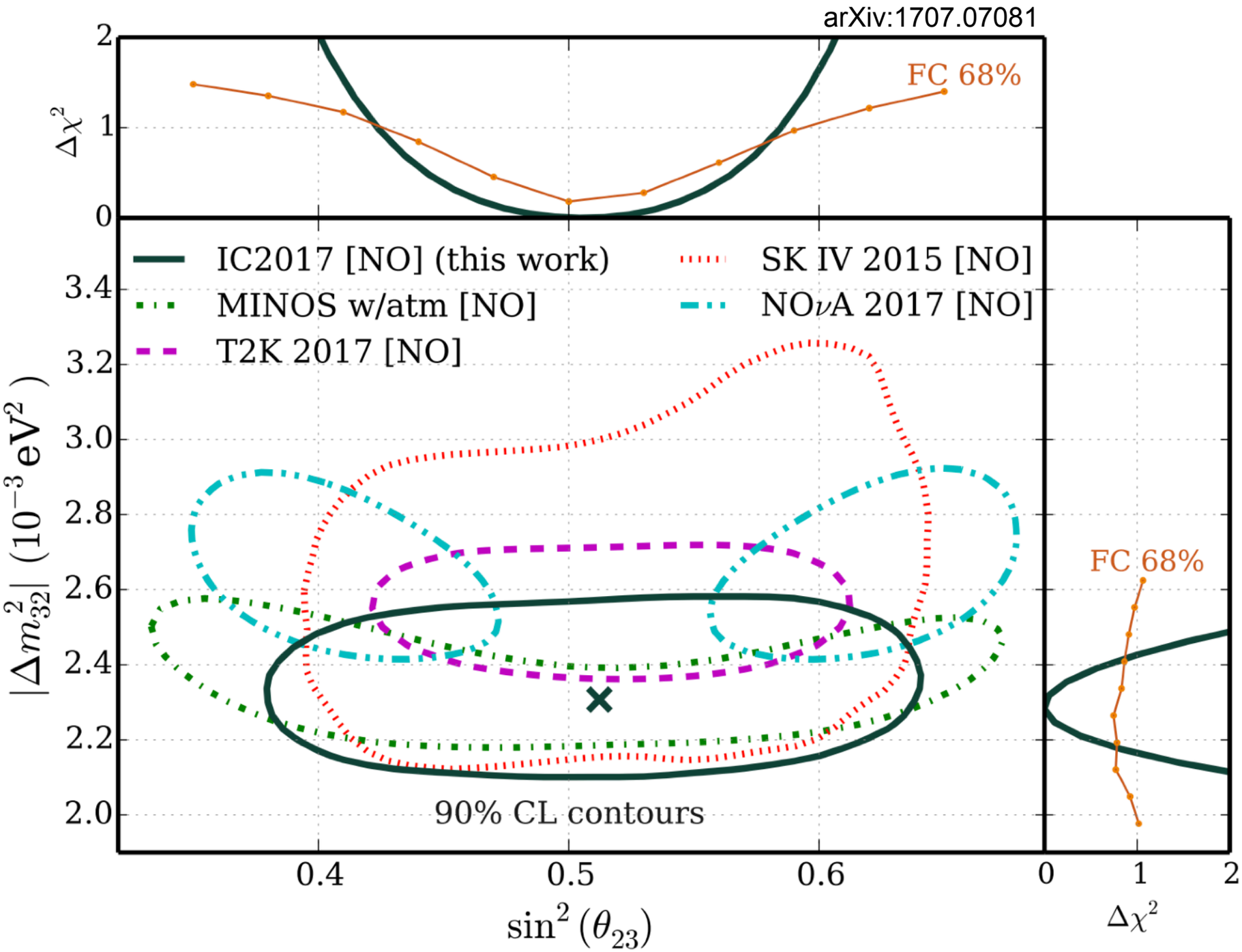




arXiv:1707.07081

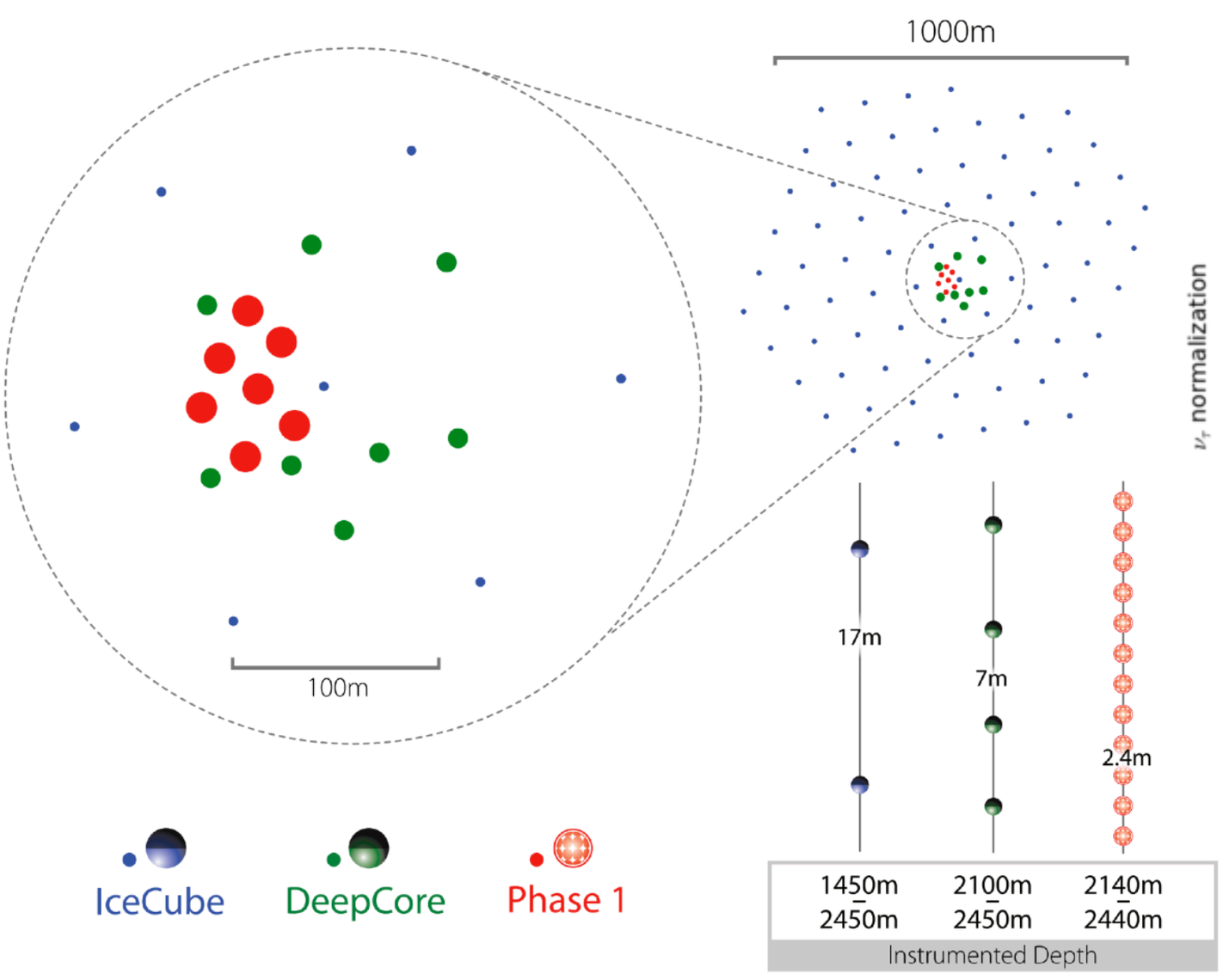
- IceCube probes **oscillation physics** at a range of baselines and energies **not accessible** to long-baseline / reactor neutrino experiments.
- Measure **atmospheric parameters** (Δm^2_{atm}, θ_{23}) at high energies.
- **Tau-neutrino appearance** also accessible.

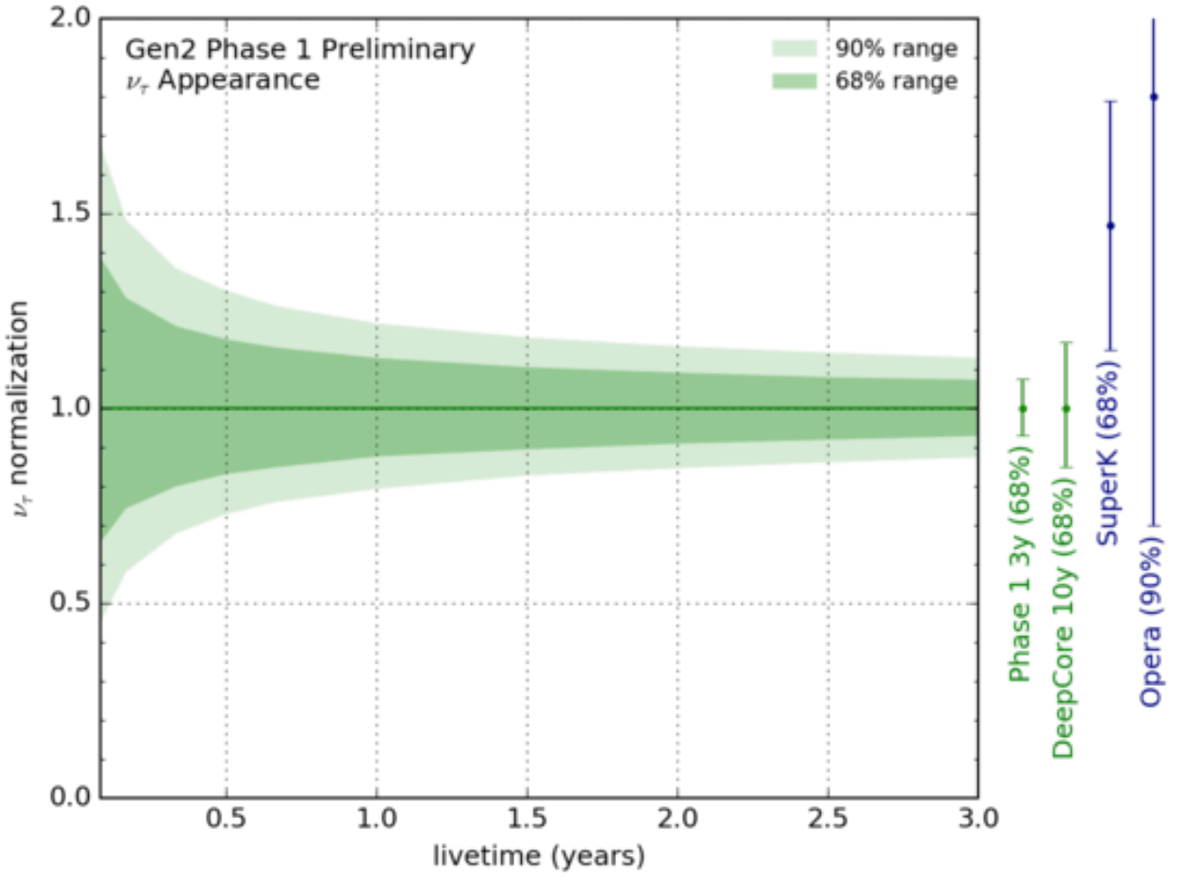
Measurement of atmospheric neutrino oscillation parameters

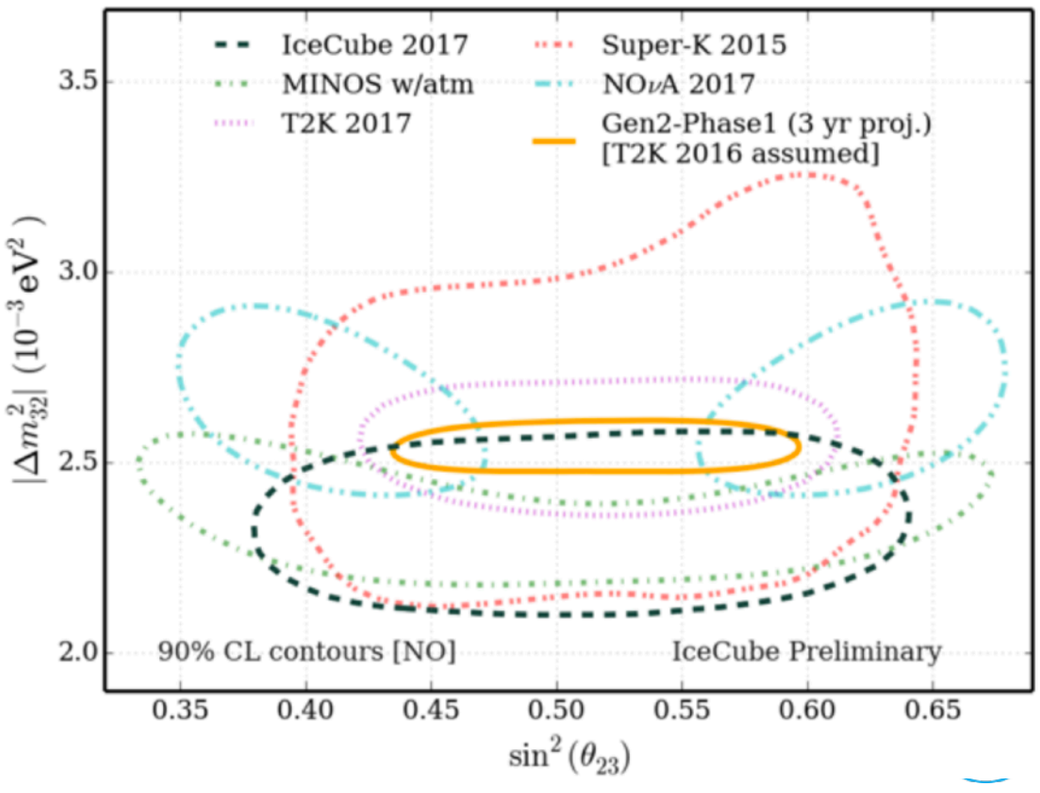


- Best fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\text{eV}^2$, $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

The next step: IceCube Gen2 - Phase 1







- **7 new strings** in the DeepCore footprint.
- **Proposed to NSF** and international funding agencies.
- Newly deployed **calibration devices** will also improve reconstruction of high-energy events.

Markus A

Summary

- **New IceCube data helps to characterize spectrum and flavor composition of the cosmic neutrino flux.**
  - Cosmic neutrinos observed between ~ 10 TeV and several PeV.
  - Possible spectral hardening above 100 TeV.
  - No tau neutrino identified so far — compatible with a statistical fluctuation.
- **The origin of the neutrino flux remains elusive.**
  - No evidence for point sources or transients.
  - No evidence for correlation with the Galactic plane / UHECRs / Gamma-ray Blazars / GRBs.
  - Points to an origin from low-luminosity / high-density sources.
- **IceCube is a valuable particle physics instrument.**
  - Measurement of the neutrino-nucleon scattering cross section at TeV energies.
  - Strongest oscillation parameter constraints from atmospheric neutrinos observations.
- **The Future: IceCube-Gen2.**
  - IceCube-Gen2 Phase1 — if funded — would significantly improve measurements of oscillation parameters and reconstruction of high-energy cosmic neutrinos.
  - Full IceCube-Gen2 could allow precision observations of the cosmic neutrino flux. at the end of the next decade.

Backup

Nuissance parameters for oscillations fit

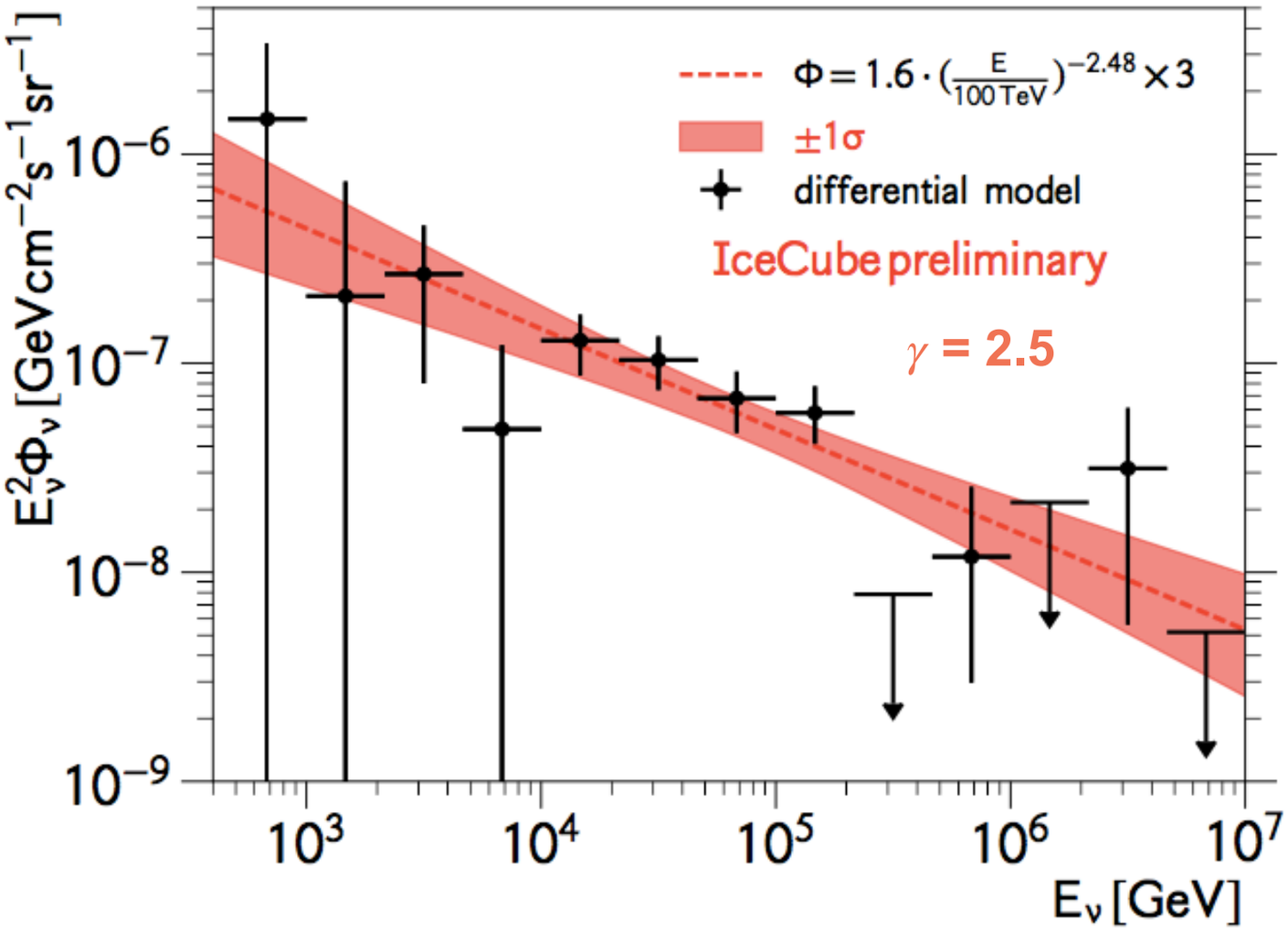
arXiv:1707.07081

Parameters	Priors	Best Fit NO	Best Fit IO
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent [42]	0.00±1.00	-0.56	-0.59
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent [42]	0.00±1.00	-0.55	-0.57
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
Detector parameters			
overall DOM efficiency [%]	100±10	102	102
relative DOM efficiency, lateral [σ]	0.0±1.0	0.2	0.2
relative DOM efficiency, head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

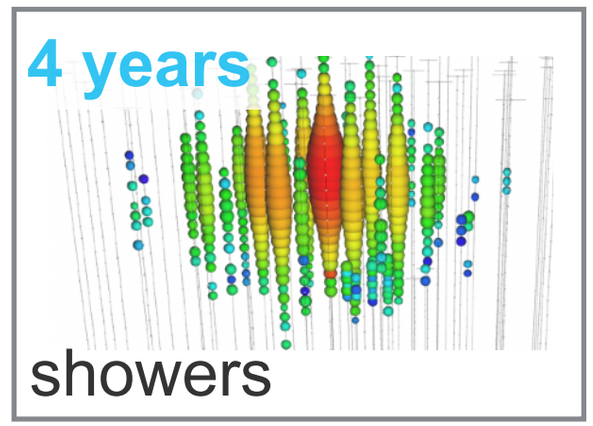
- Held fixed due to lack of impact on fit: $\Delta m^2_{21} = 7.53\times10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 2.17 \times 10^{-2}$, and $\delta_{CP} = 0°$

Cosmic neutrinos today

IceCube collaboration, ICRC 2017

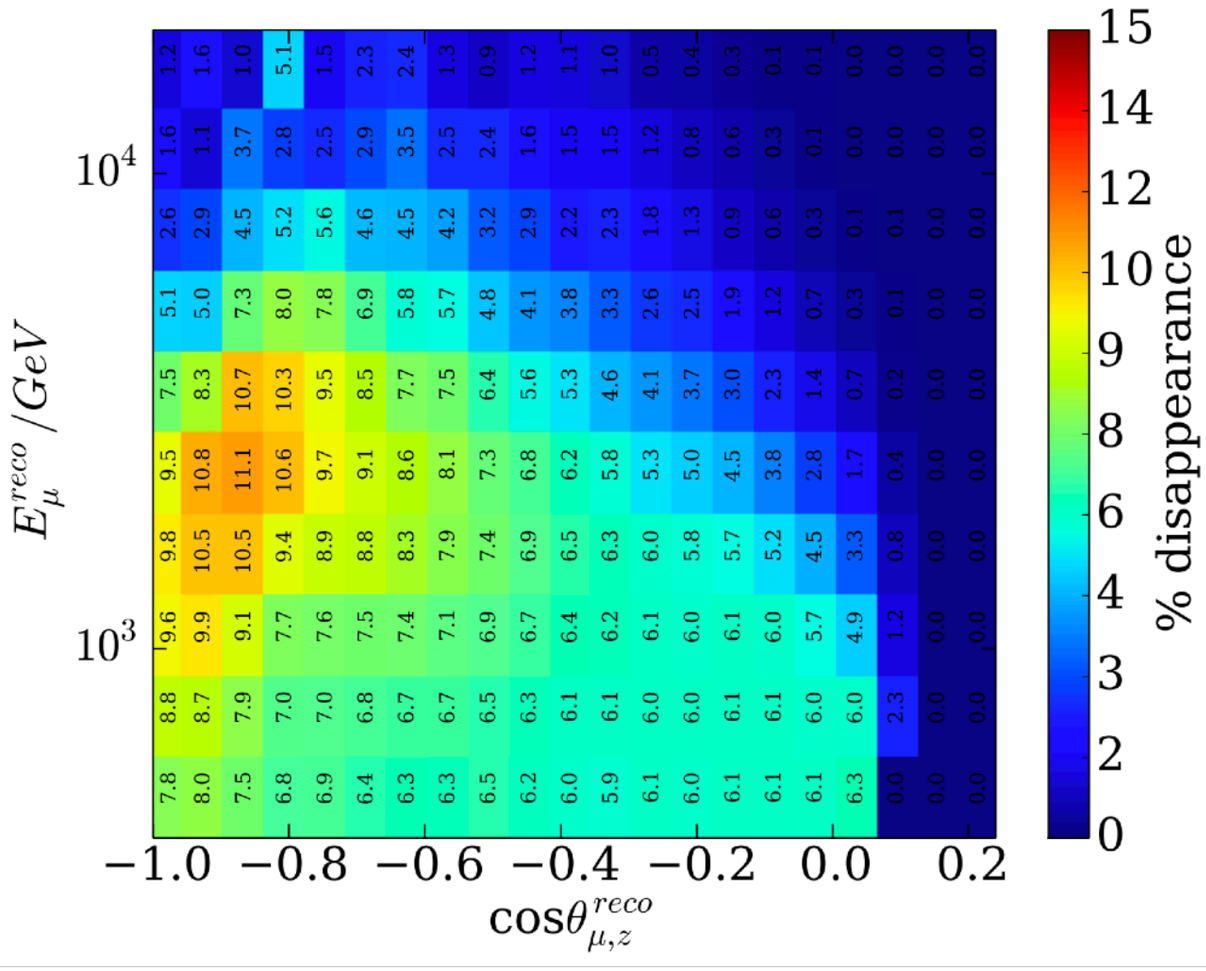


Energy range: 12 TeV - 2.1 PeV



Constraints on sterile neutrinos

- **Distortions of the zenith distribution** of O(TeV) atmospheric neutrinos in the presence of **sterile neutrinos**.
- Strong exclusion limits **exclude favored region** from short-baseline appearance experiments at 99% CL.



IceCube collaboration, PRL, 2016