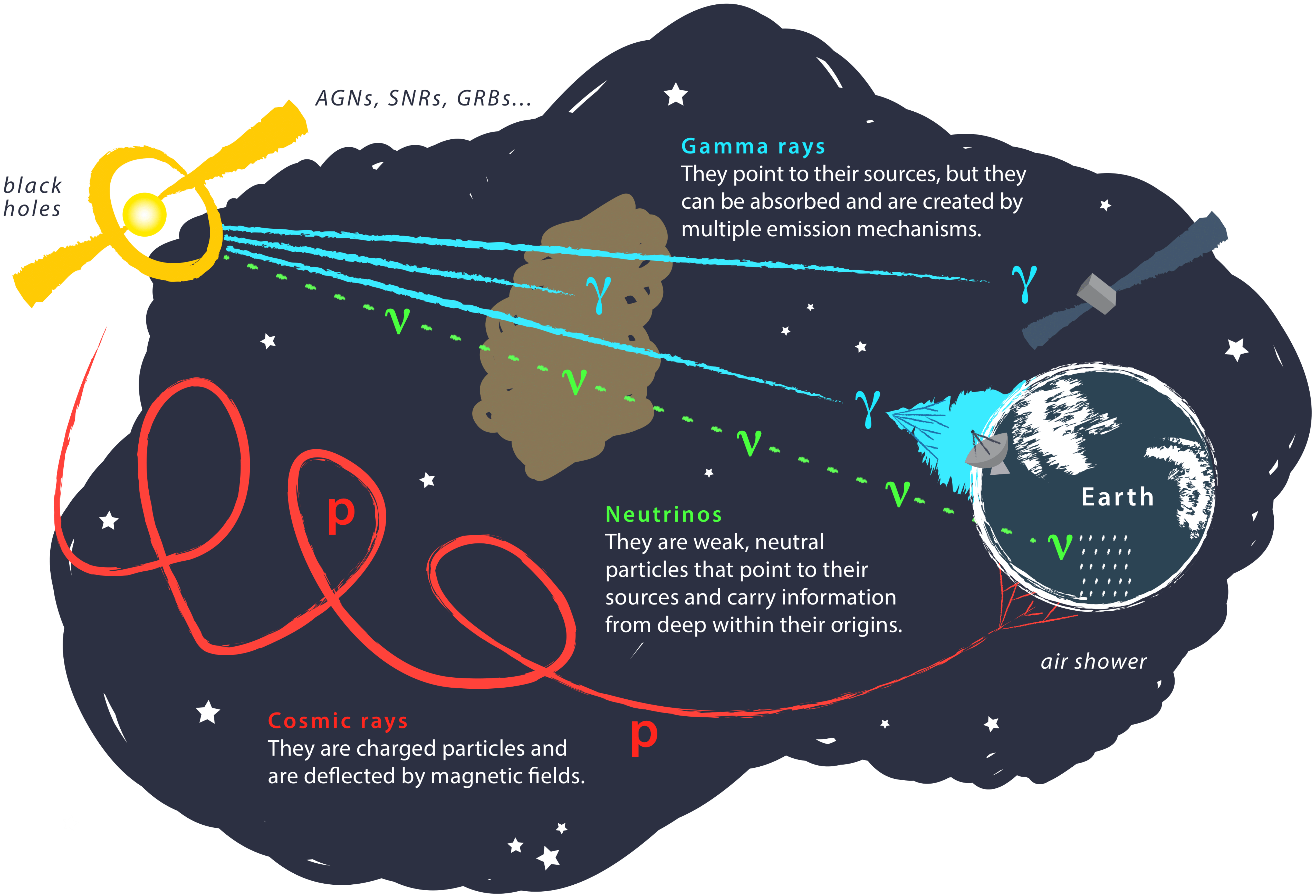
High-Energy Neutrino Observation Highlights from IceCube

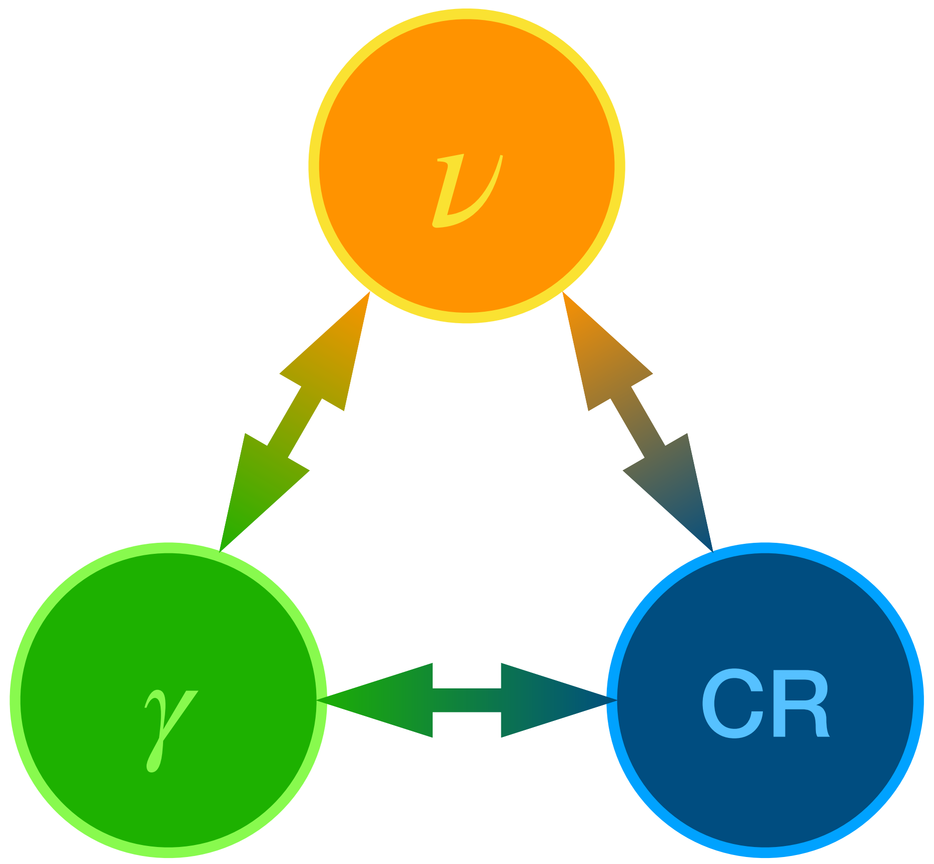
Qinrui Liu
for the IceCube collaboration

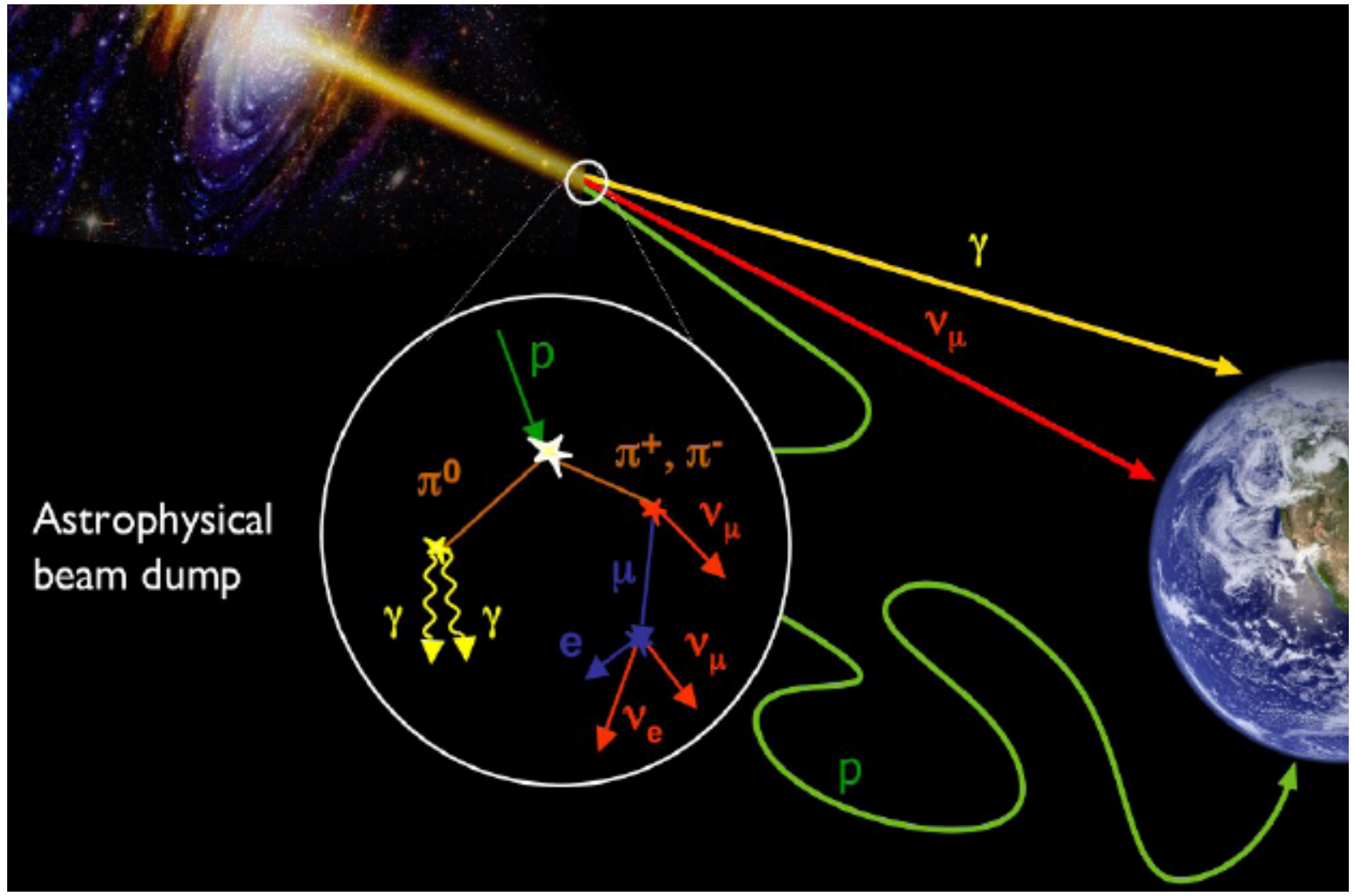
TeVPA 2021
Oct 28th, Chengdu, China

Neutrinos as Astronomical Messengers



Neutrinos as Astronomical Messenger

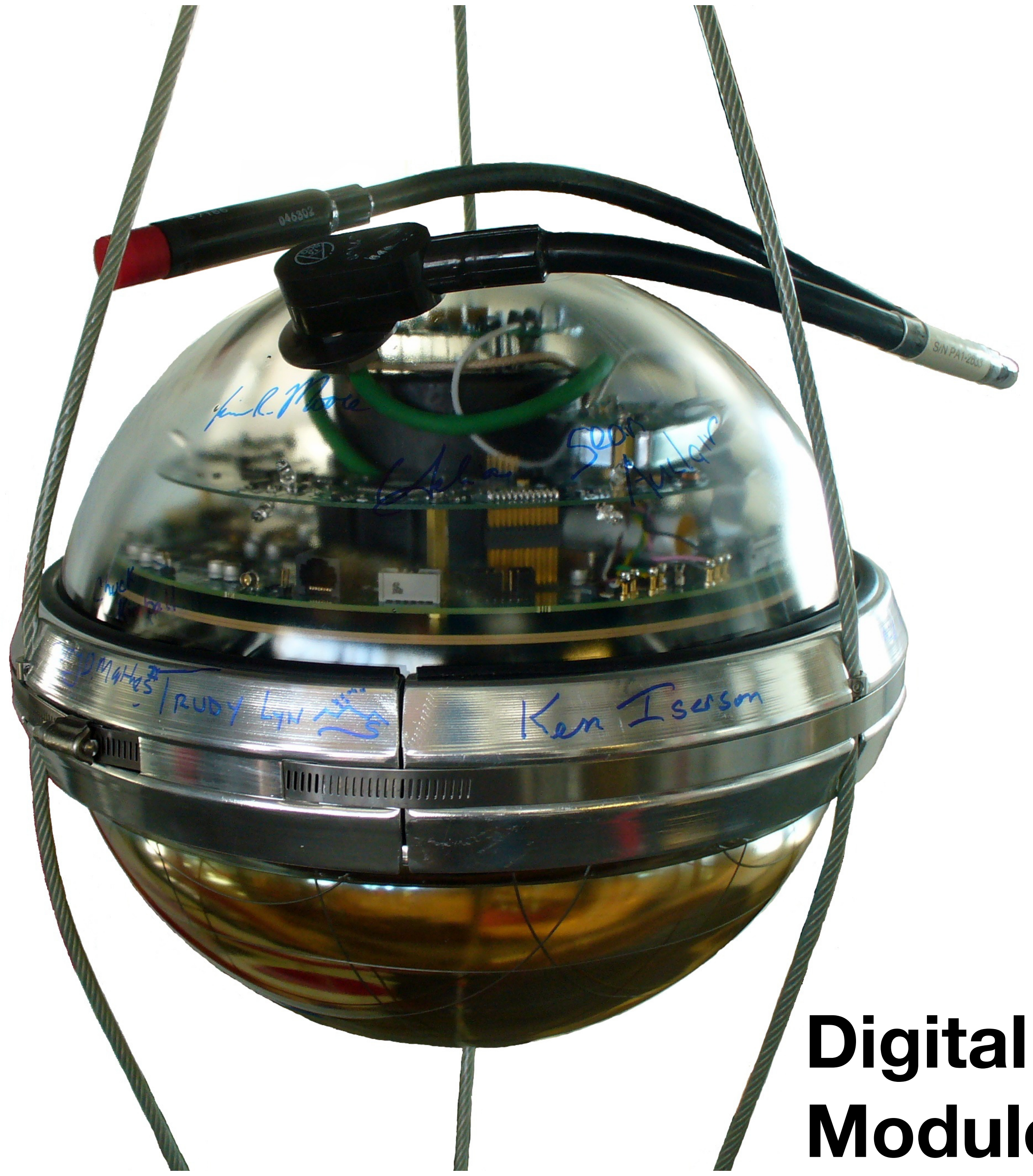




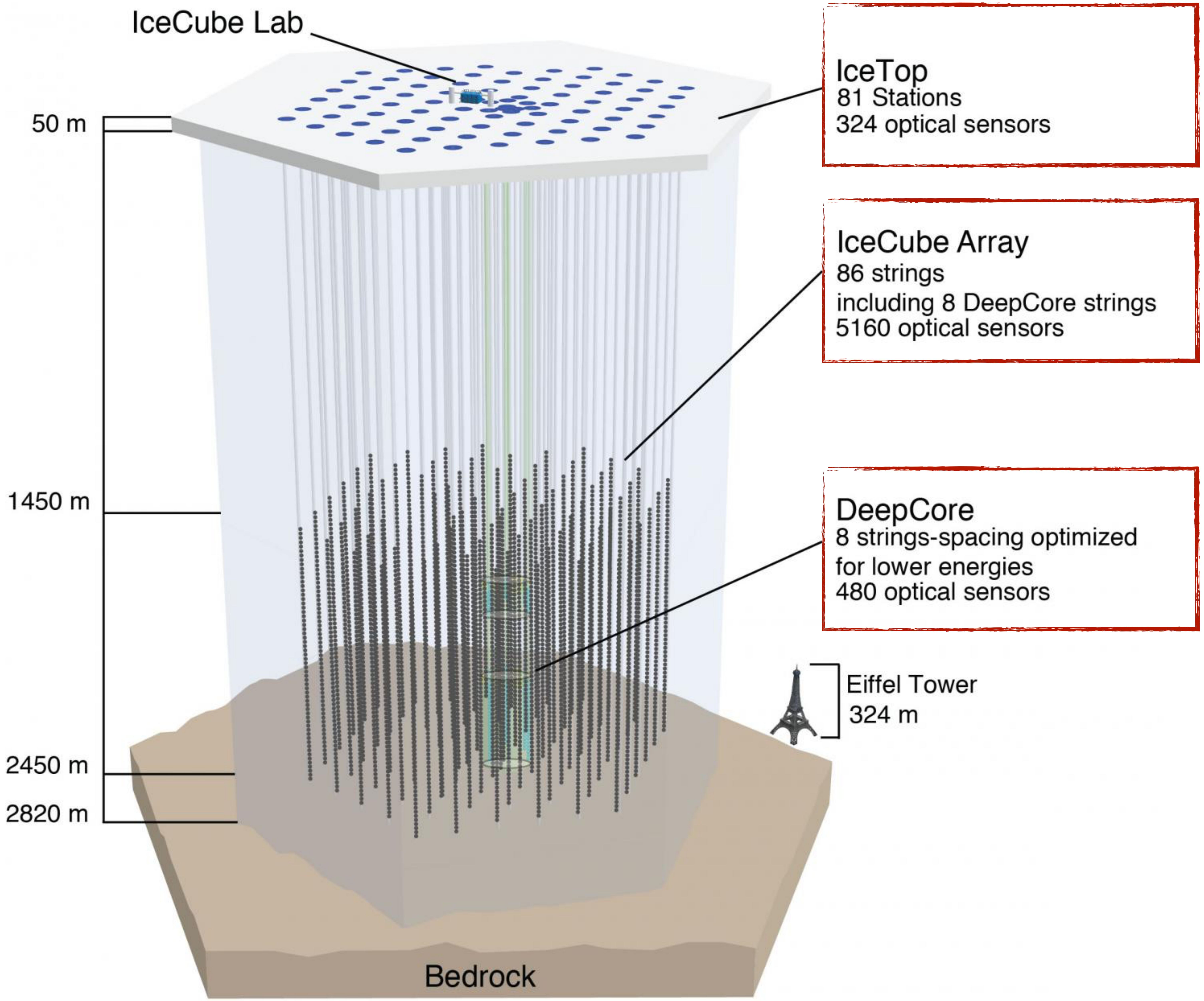
- Hadronic cosmic rays (p) interact with gas (p) or radiation (γ).
- Correlated cosmic ray/neutrino/gamma ray flux.
- ν: "Smoking-gun" of cosmic ray accelerators.
- Difficult to detect, a giant detector is needed.

The IceCube Neutrino Observatory

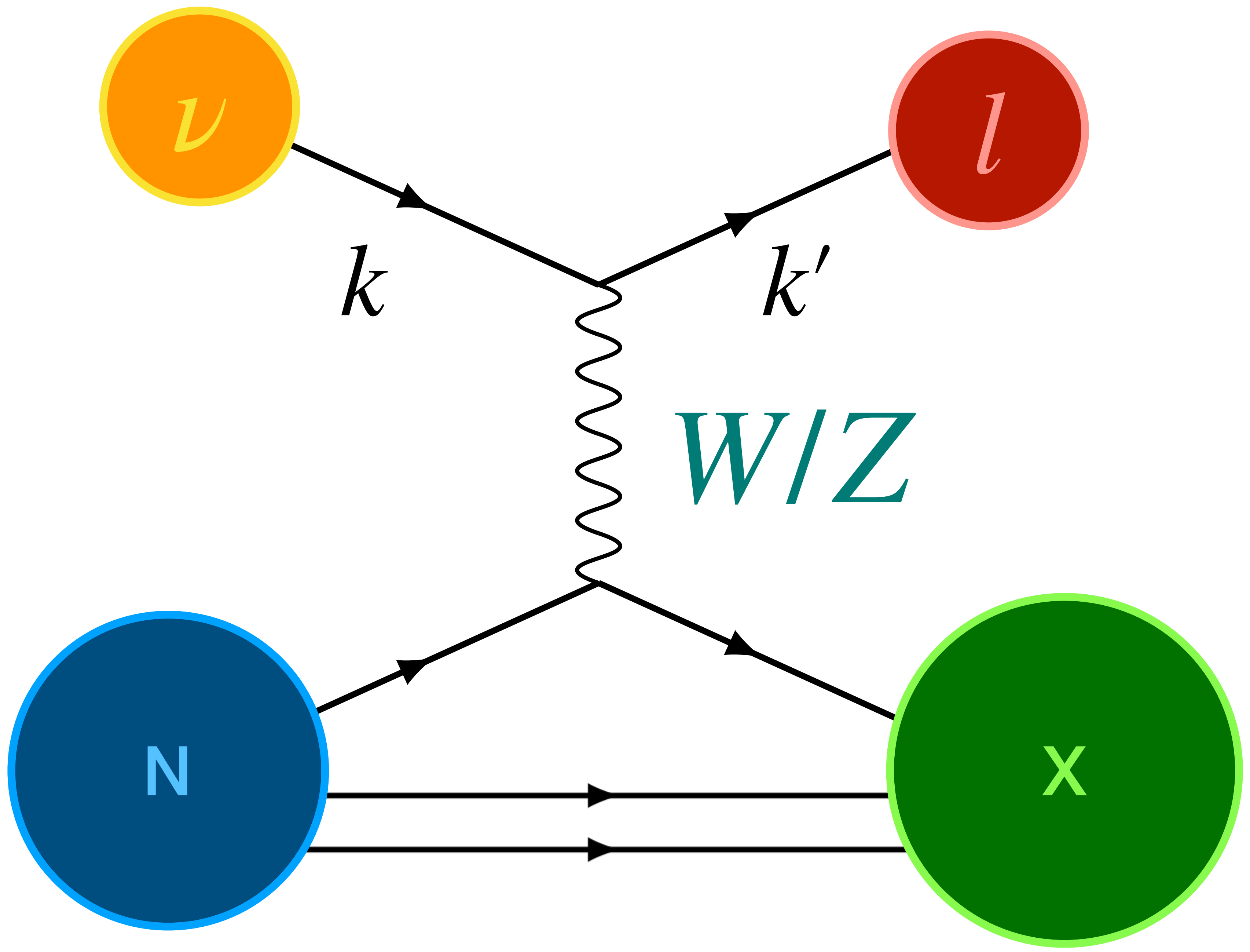
- $1\ \mathrm{km}^3$ Cherenkov detector at the geographic South Pole.
- A collaboration of more than 50 institutes over 13 countries with more than 300 scientists



Digital Optical Module (DOM)

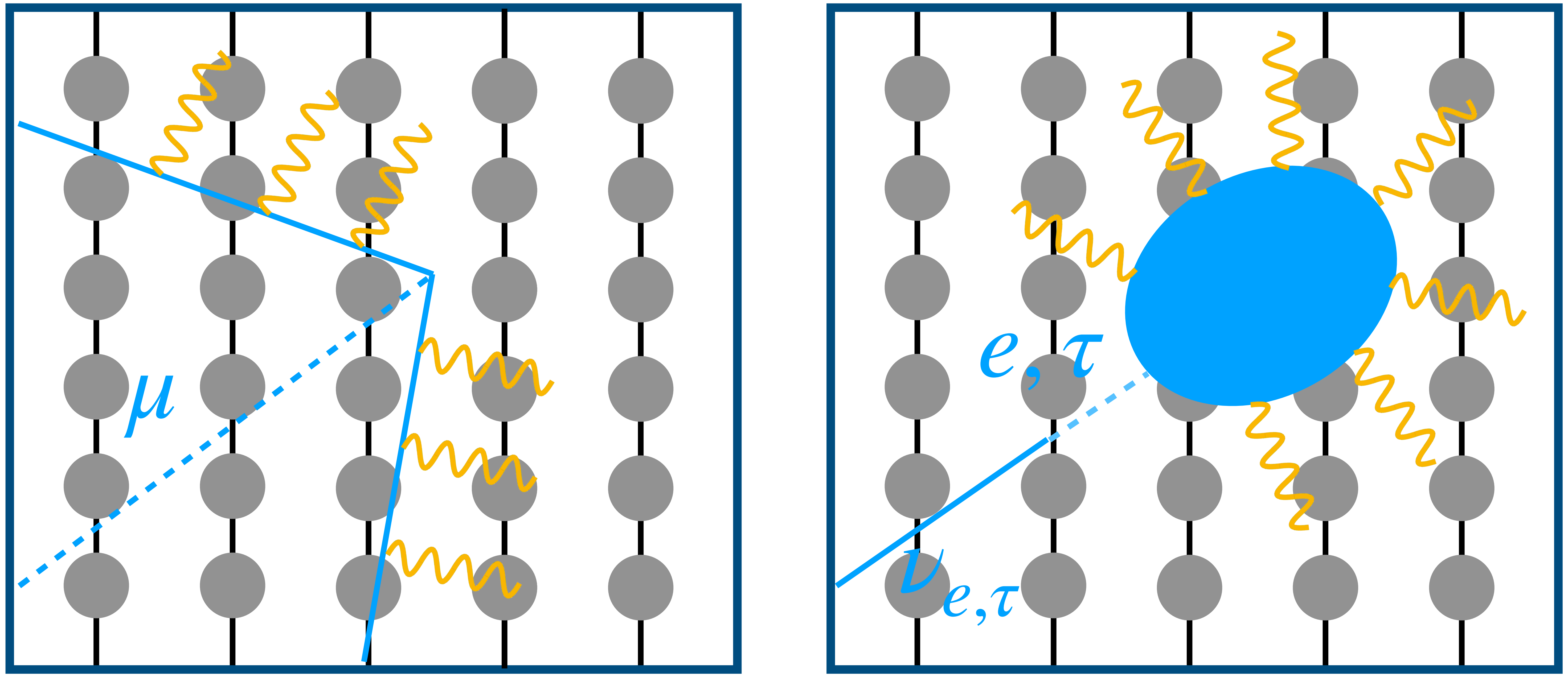


“See” a Neutrino



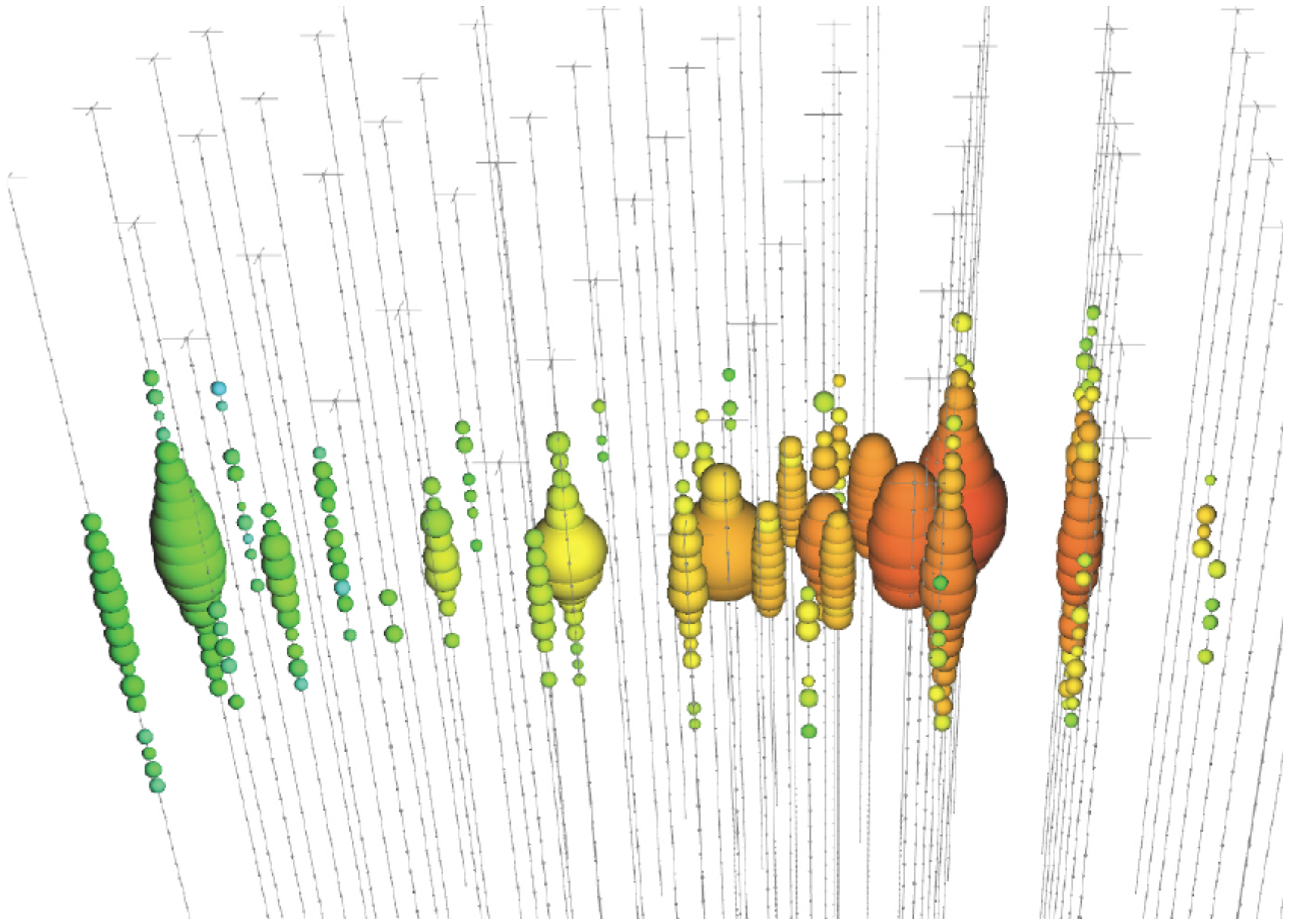
- Deep inelastic scattering of neutrinos and nucleus in transparent media, including “charged” (W) and “neutral” (Z) current interactions.
- Collecting Cherenkov light of the secondary particles.

Cherenkov radiation



Event Morphologies

Charged Current ν_μ

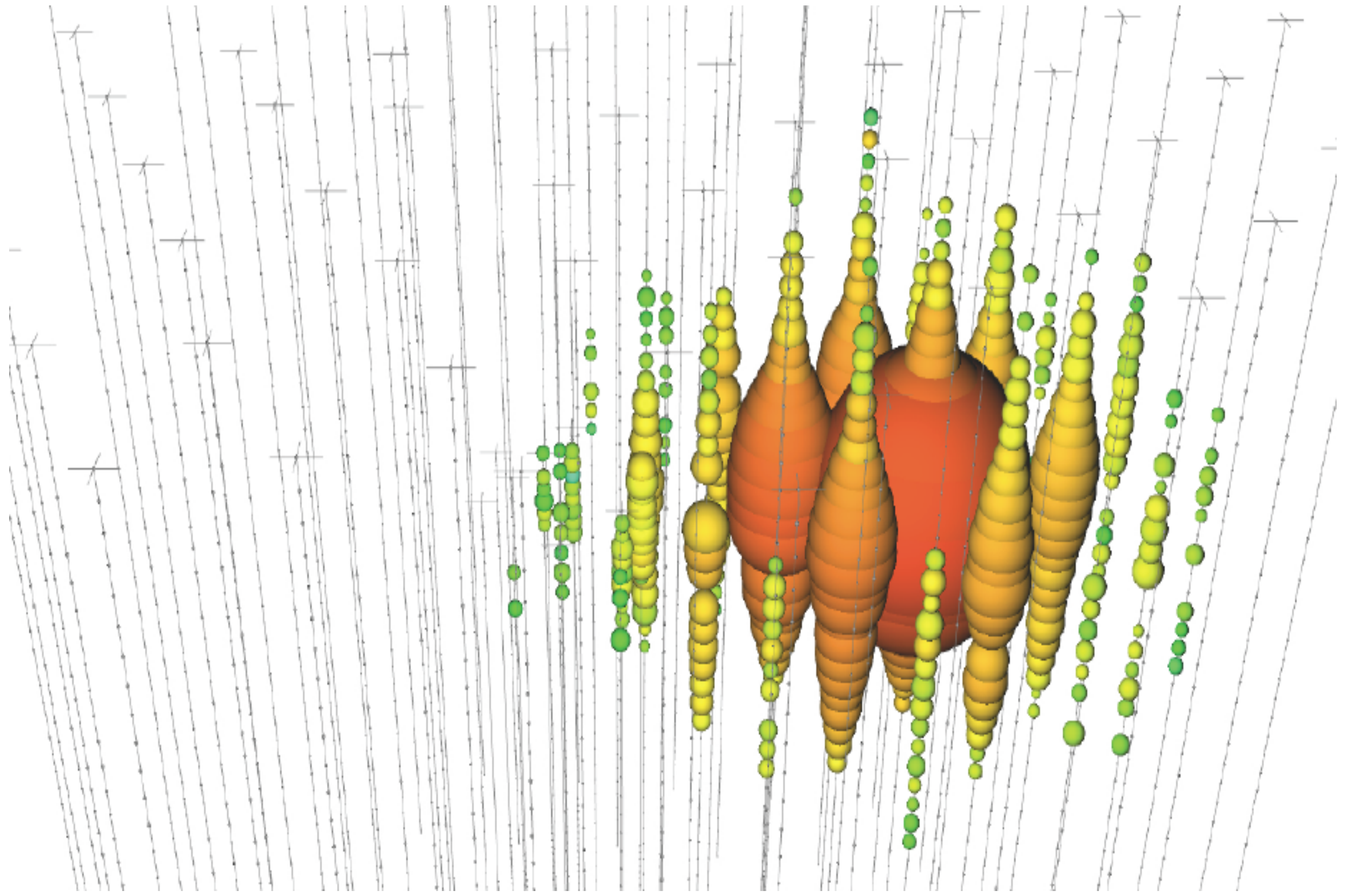


$$\nu_\mu + N \rightarrow \mu + X$$

Track (data)

Angular resolution $\sim 0.5^\circ$
Energy resolution factor of ~2

Neutral Current / Charged Current ν_e

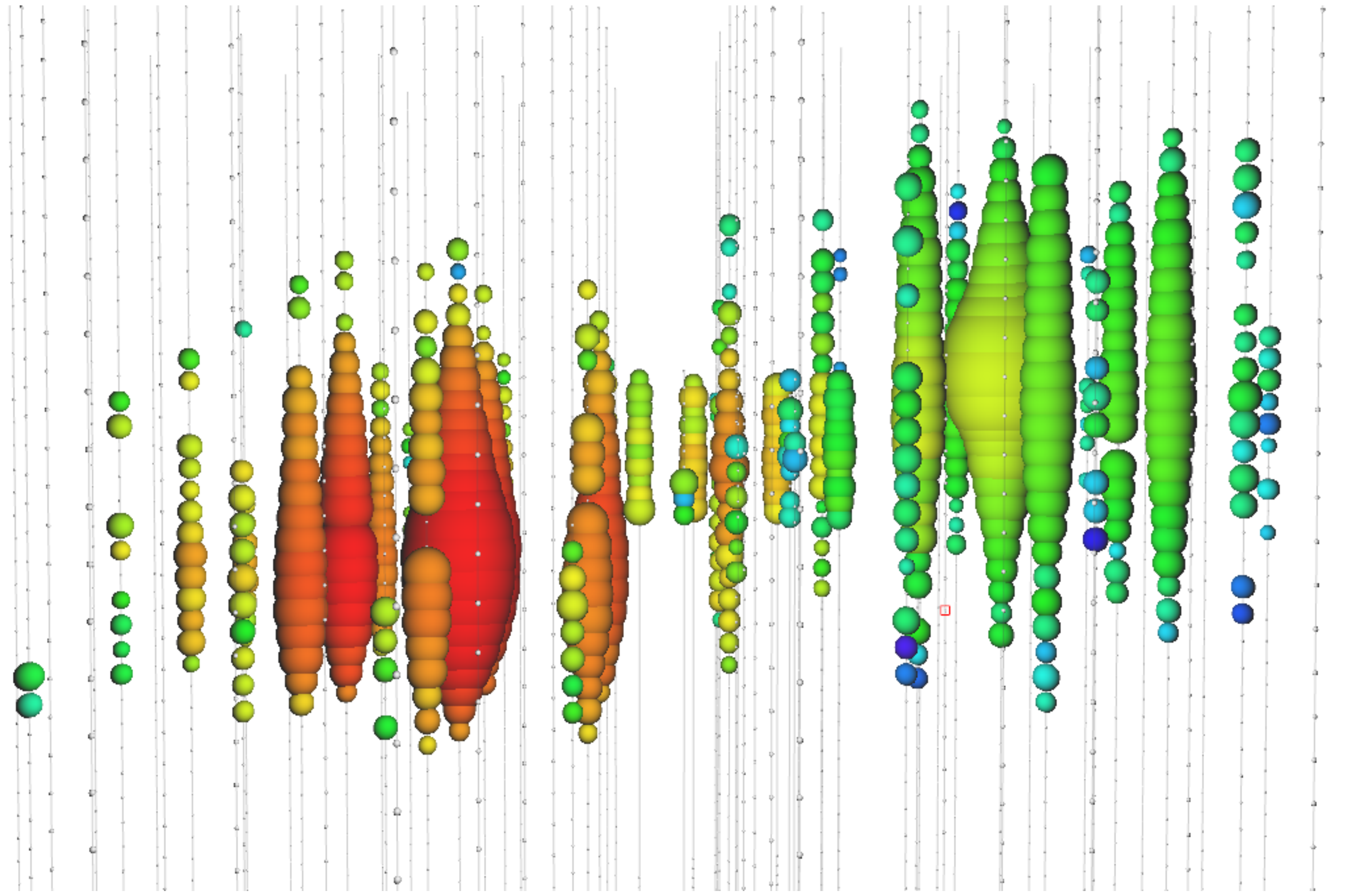


$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + N$$

Cascade (data)

Angular resolution $\sim 10^\circ \; (\gtrsim 100\,\mathrm{TeV})$
Energy resolution $\sim 15\,\%$

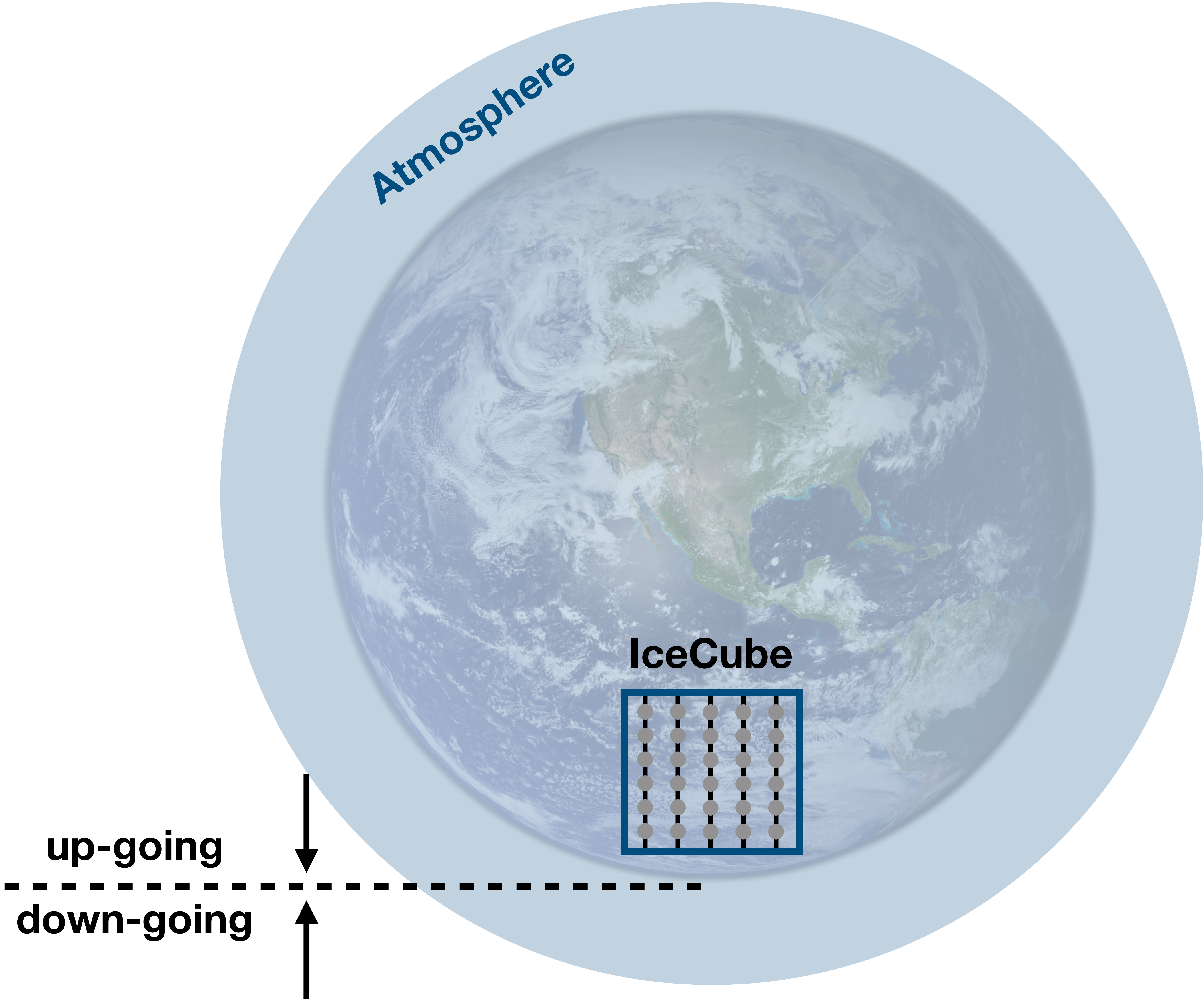
Charged Current ν_τ



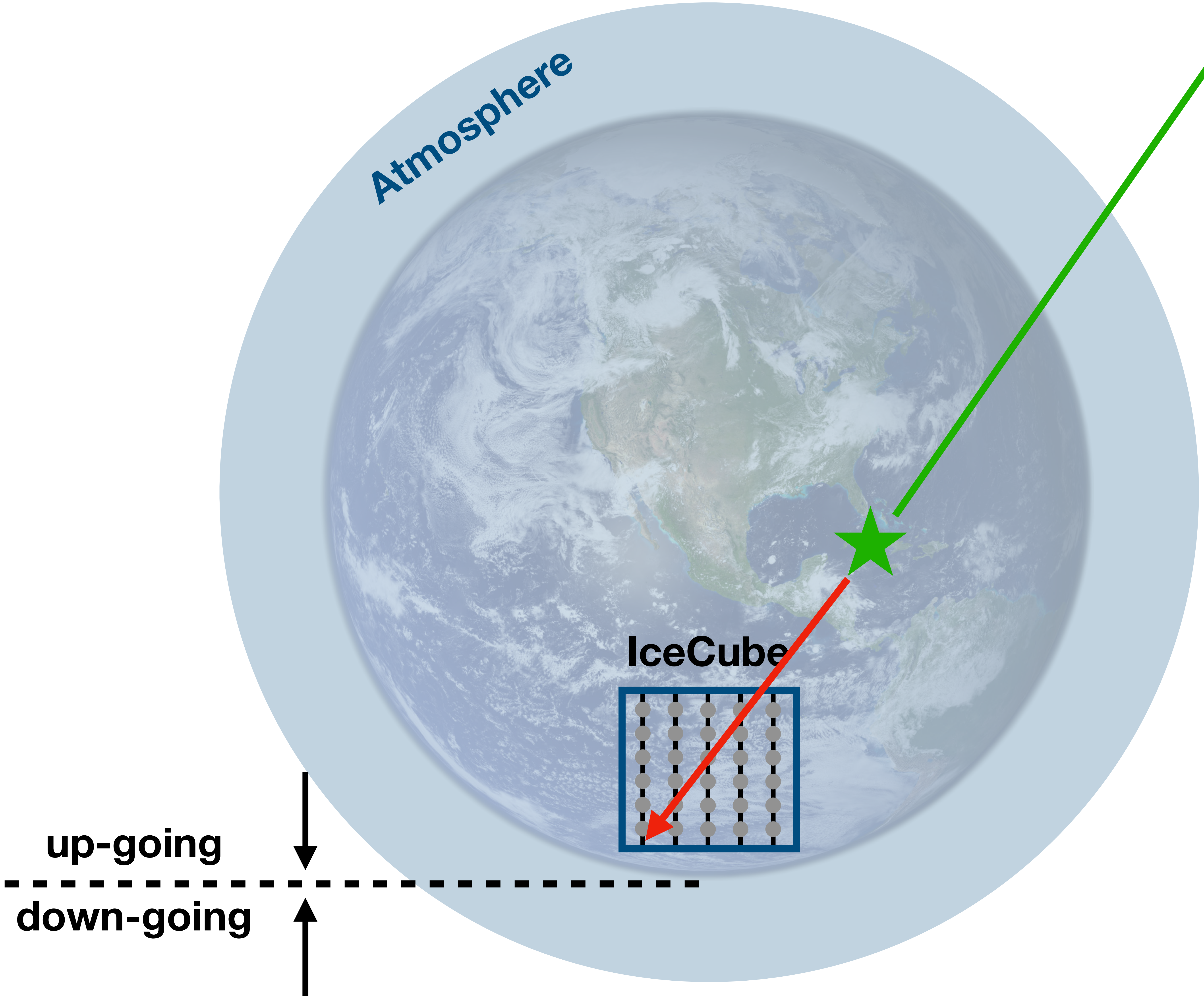
$$\nu_\tau + N \rightarrow \tau + X$$

"Double-Bang" (simulation)

IceCube Events

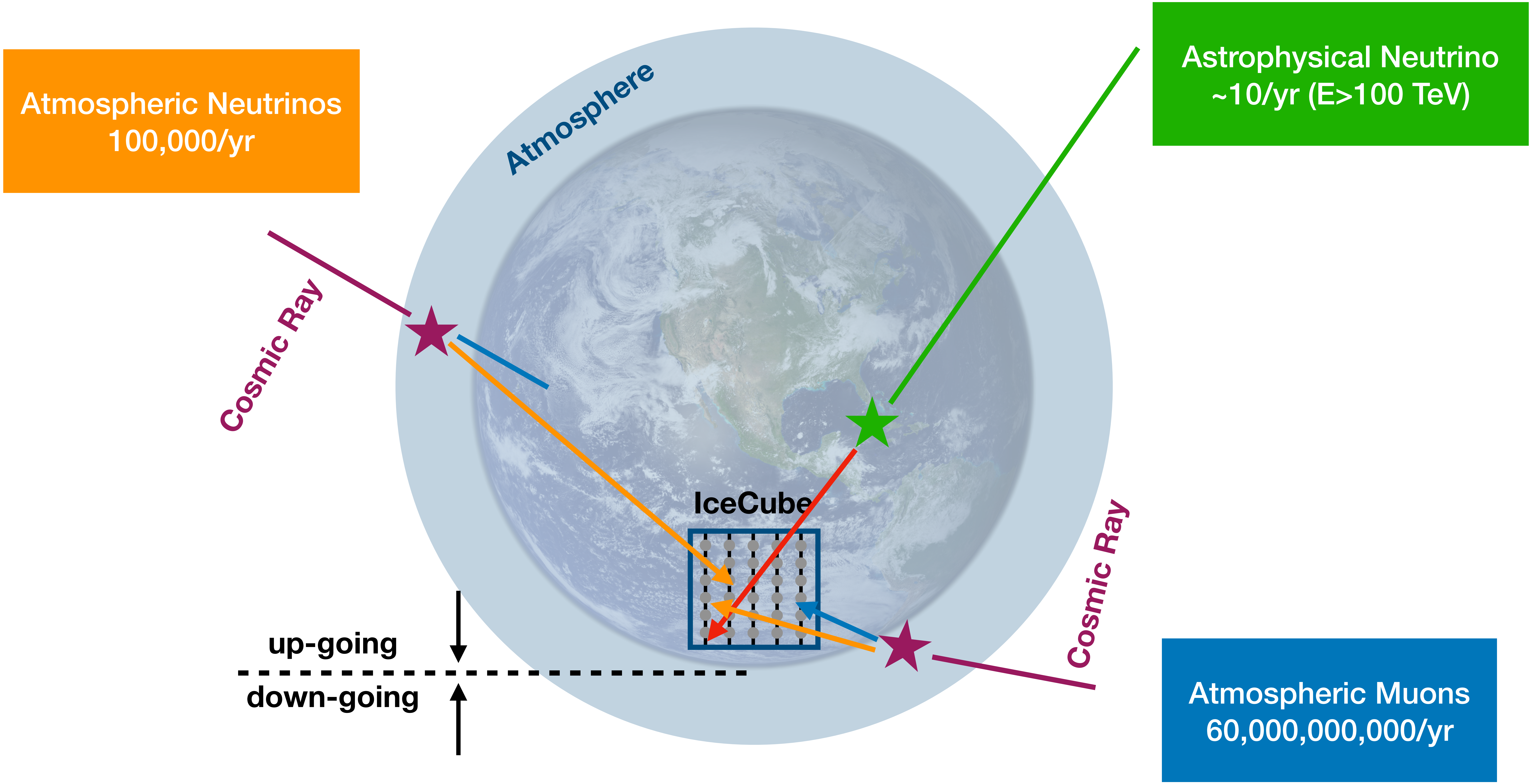


IceCube Events



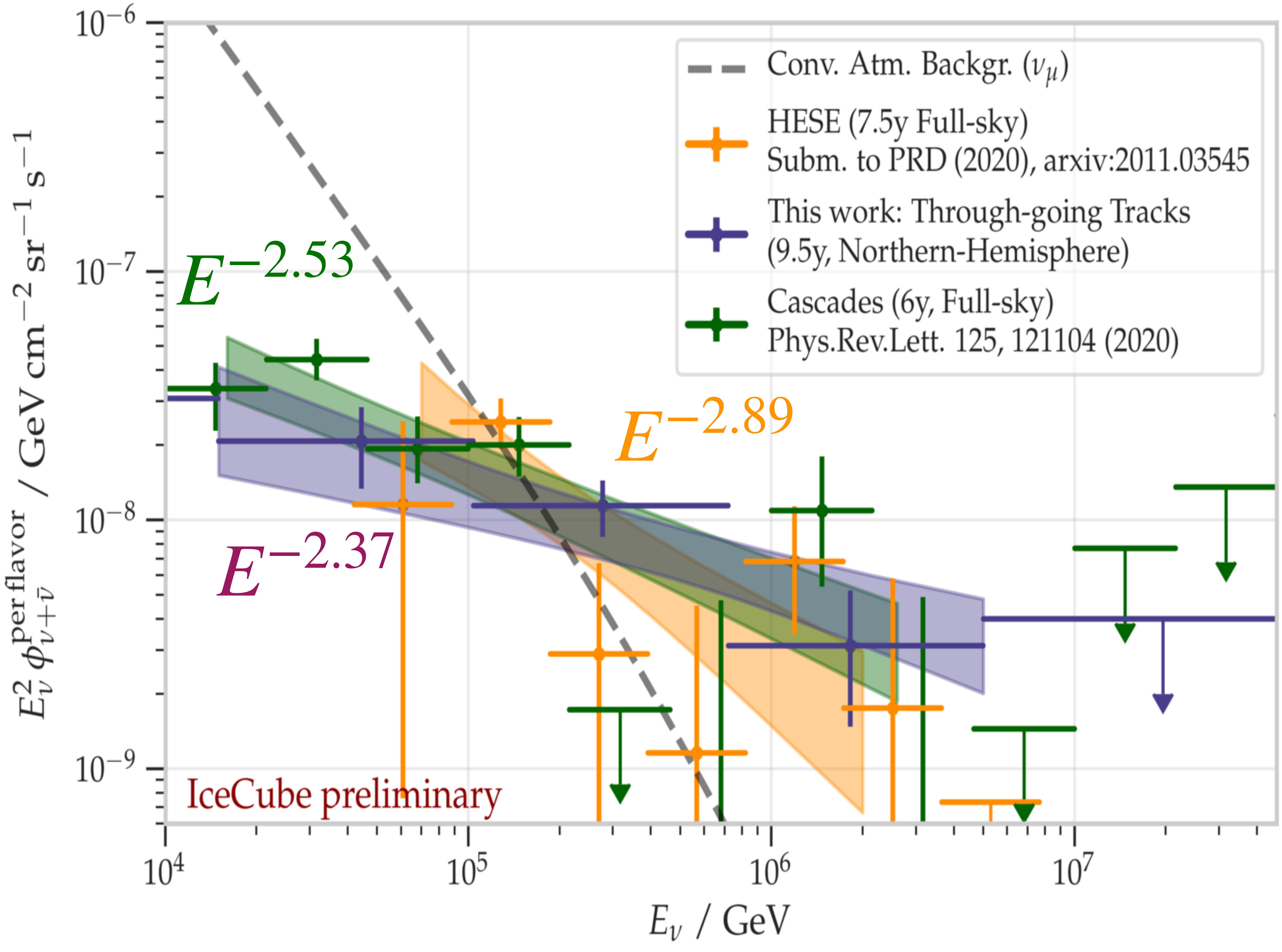
Astrophysical Neutrino
~10/yr (E>100 TeV)

IceCube Events



Diffuse Cosmic Neutrino Flux

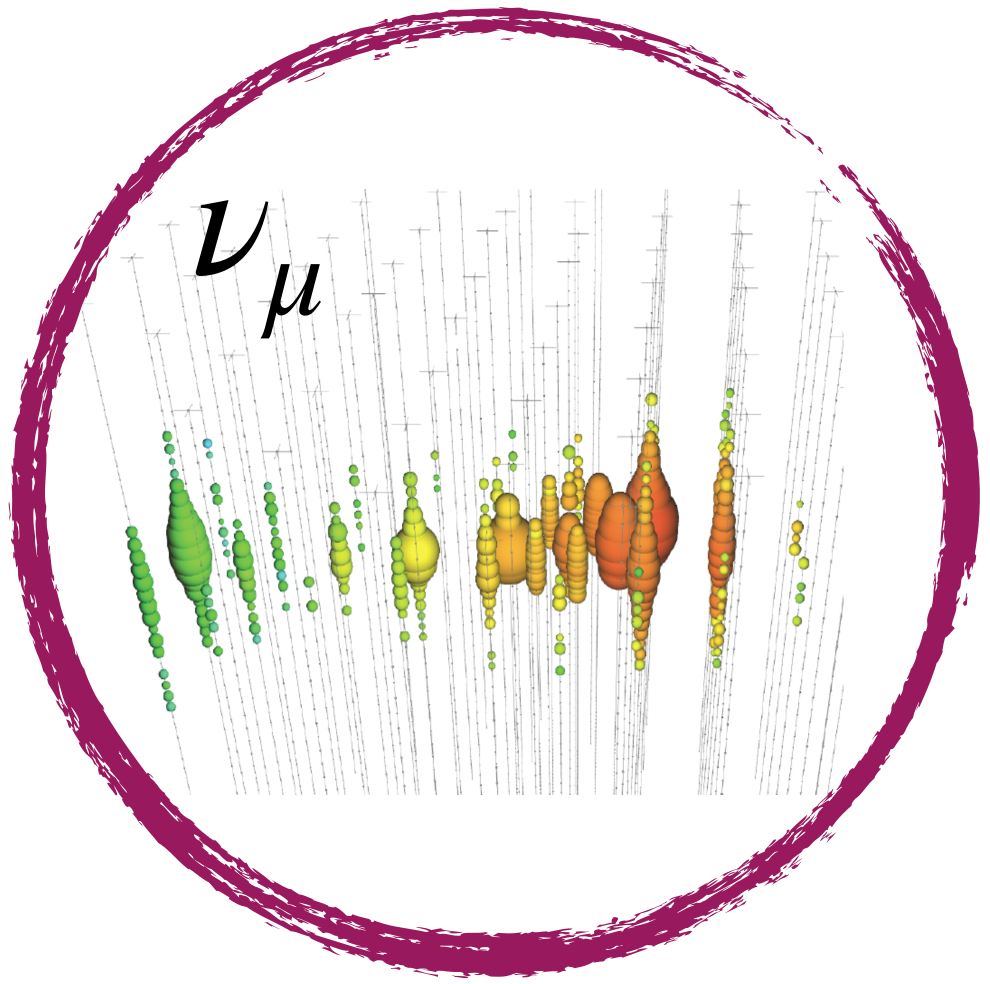
What do we know about the observed cosmic neutrino flux?

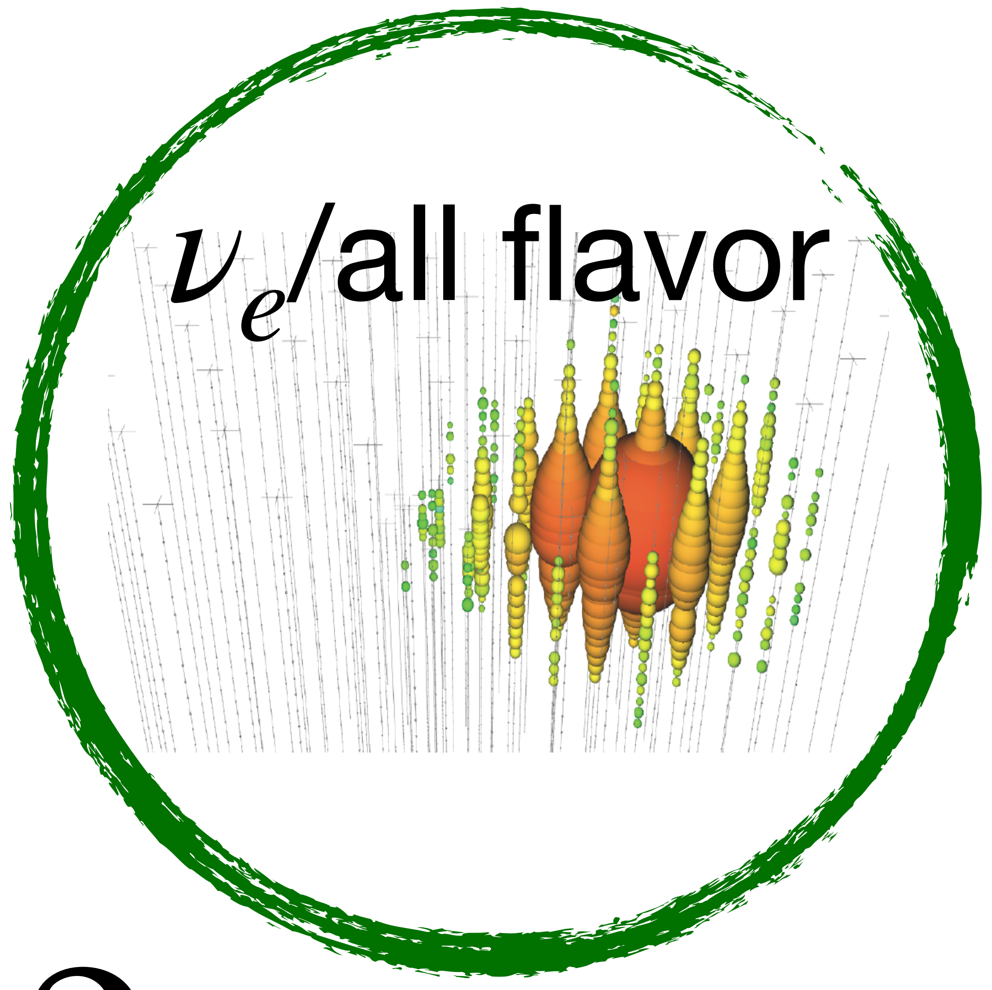


- Observation established in multiple channels in IceCube
  - High-energy starting events (HESE): vertex inside detector, all flavor & all sky
  - Through-going tracks: vertex outside detector, ν_μ & Northern sky
  - Cascades: $\nu_e + \nu_\tau$ dominant & all sky
- Power-law spectra

Tau Neutrino Candidate

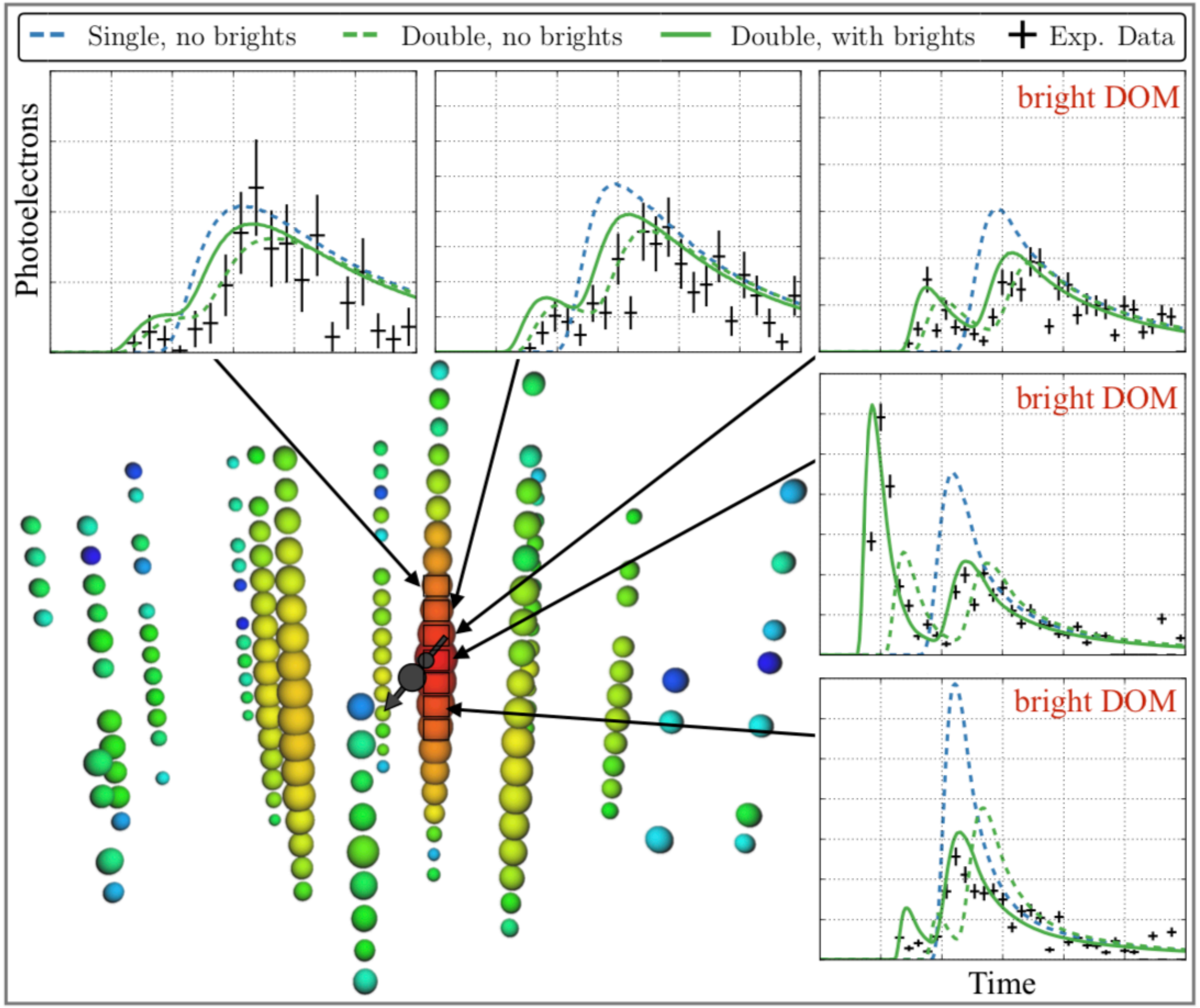
NuTau: D. Cowen





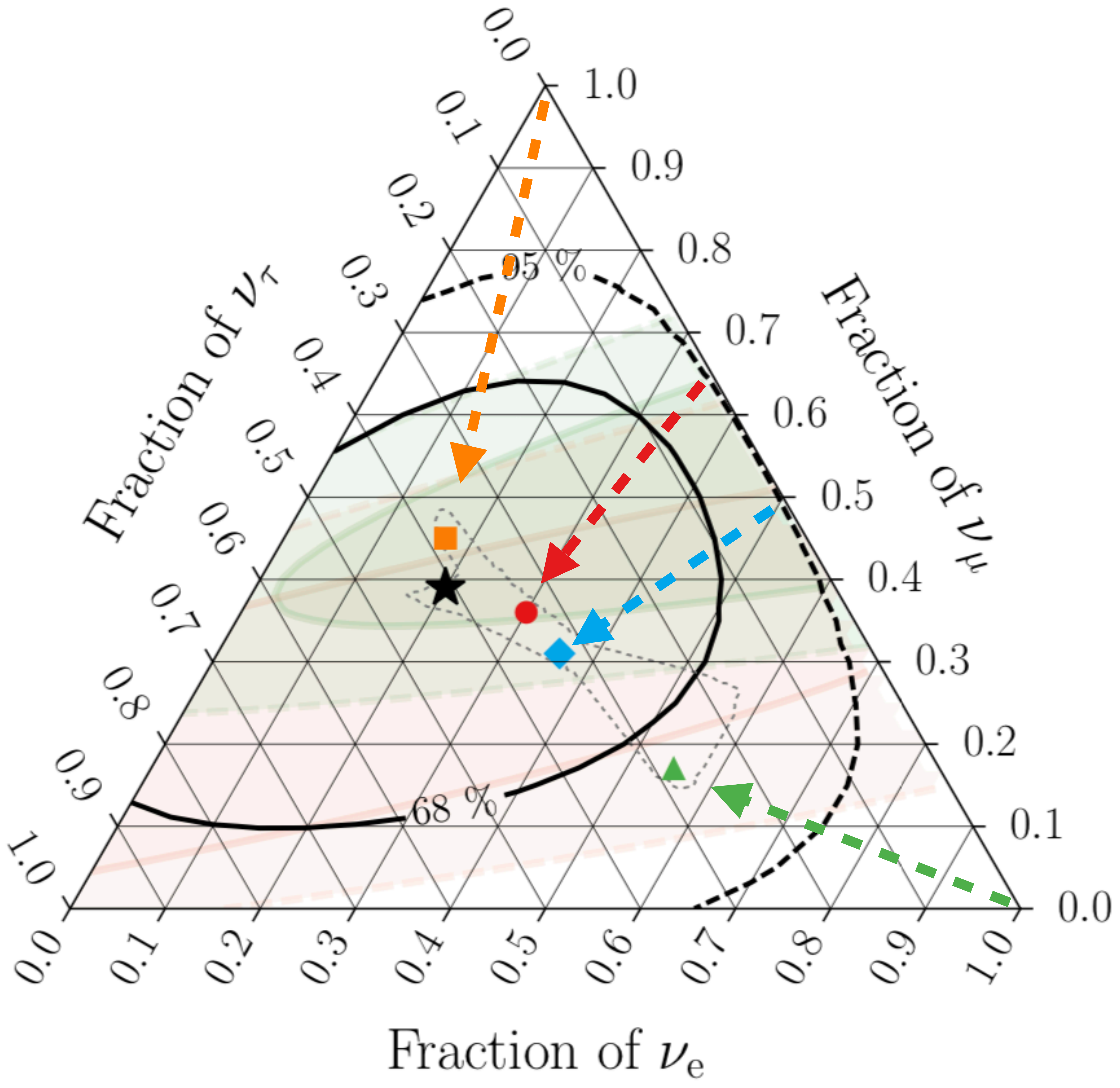
ν_τ?

- Double-cascade: Charged Current ν_τ interactions signal with a later signal from τ decay.
- The Cherenkov light can be distinguished in single DOMs.
- Two candidate events were observed. "Tauness": $\gtrsim 97\,\%$ and $75\,\%$

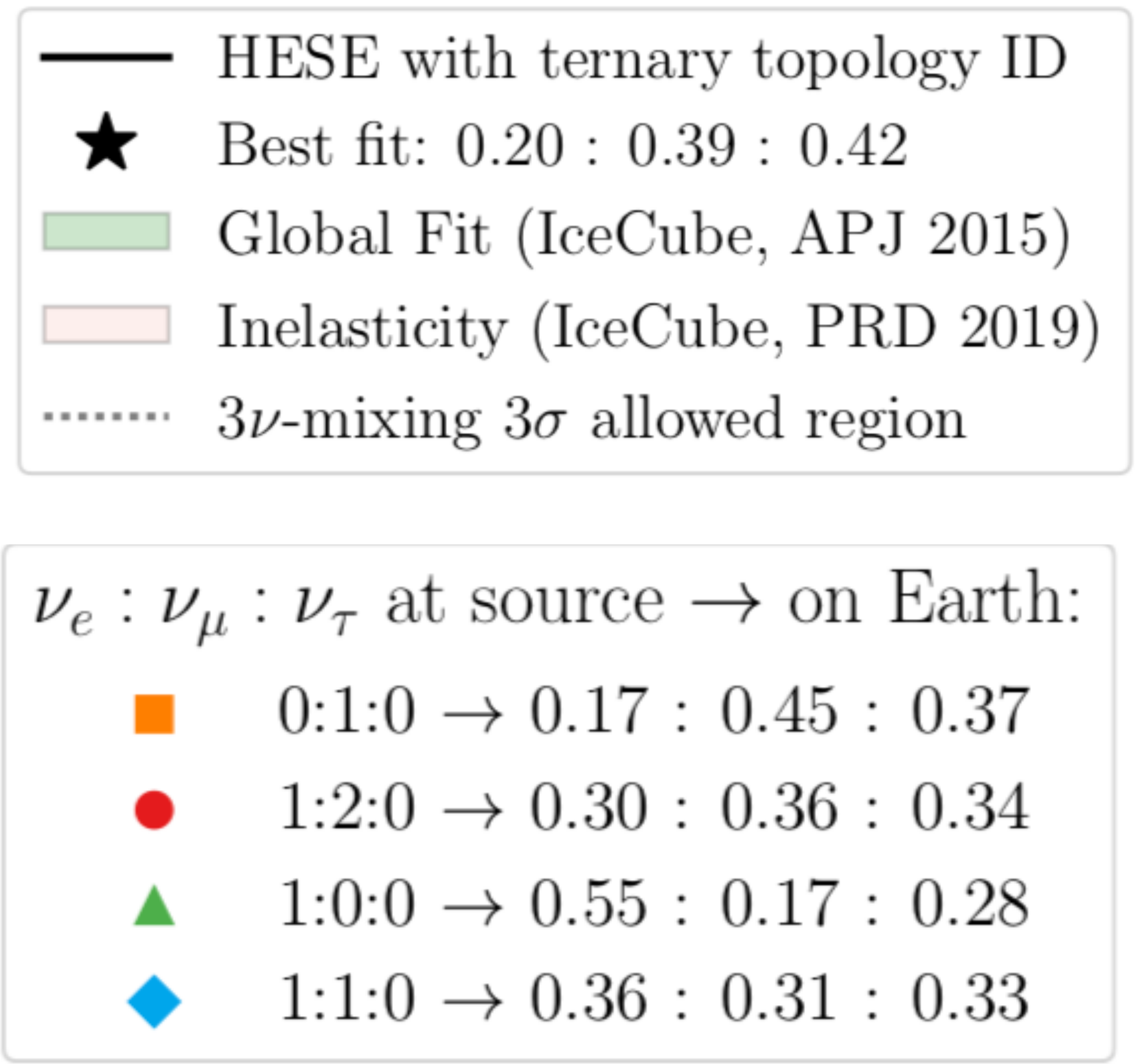


IceCube [2011.03561]

Neutrino Flavor Composition



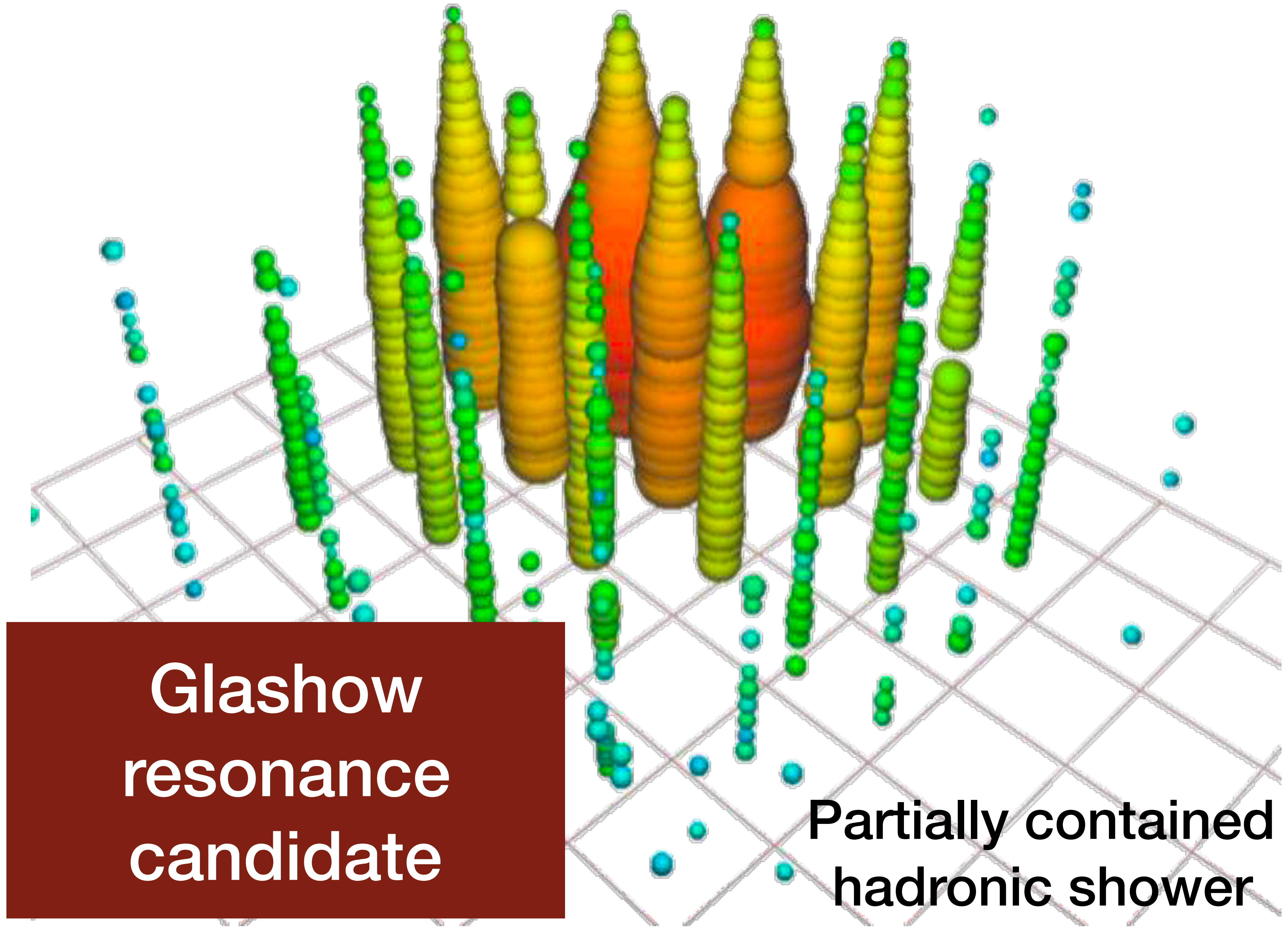
- Measuring the oscillation-averaged cosmic neutrino flavor combination at Earth.
- Important for study of neutrino production and propagation.

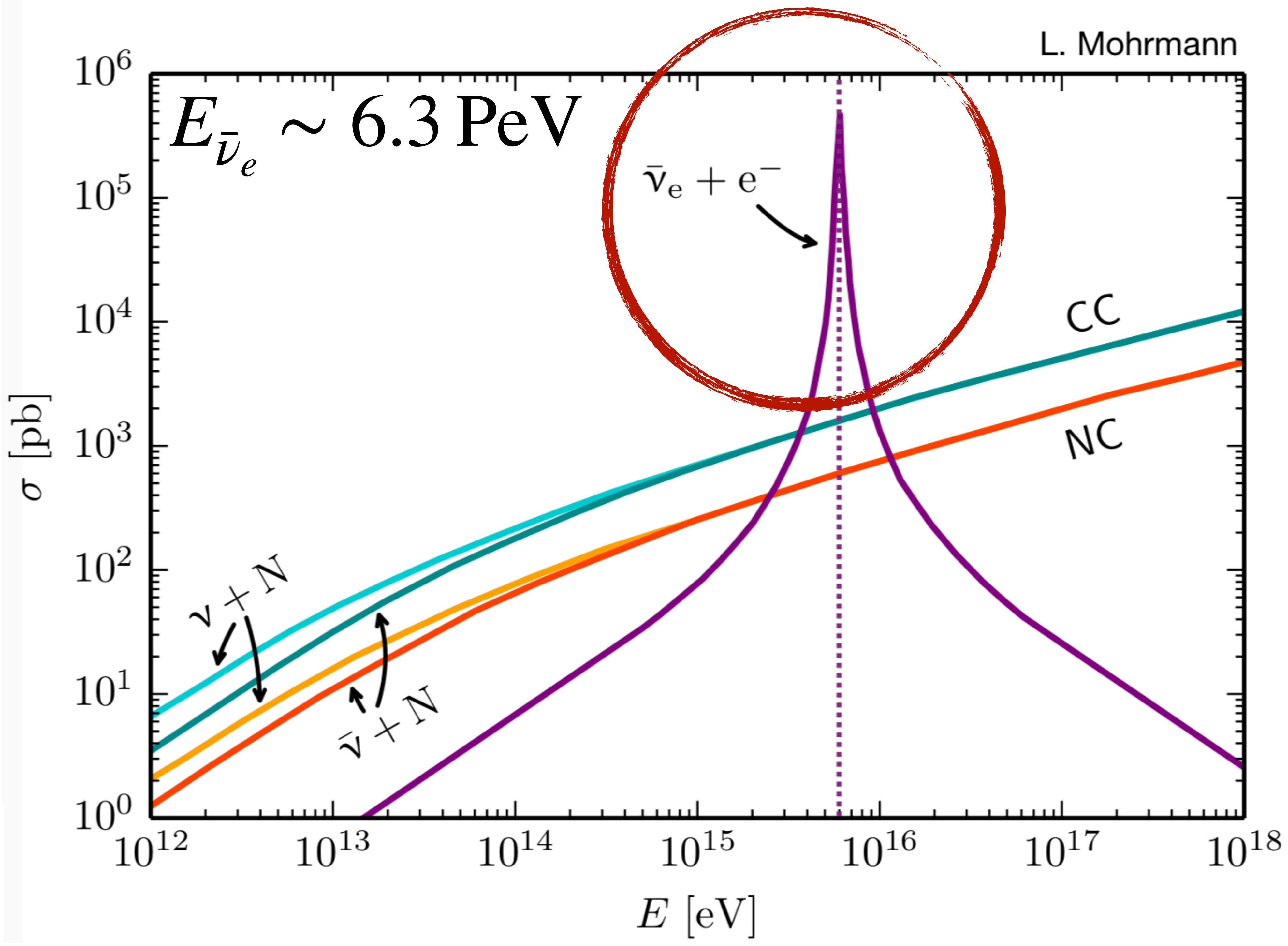


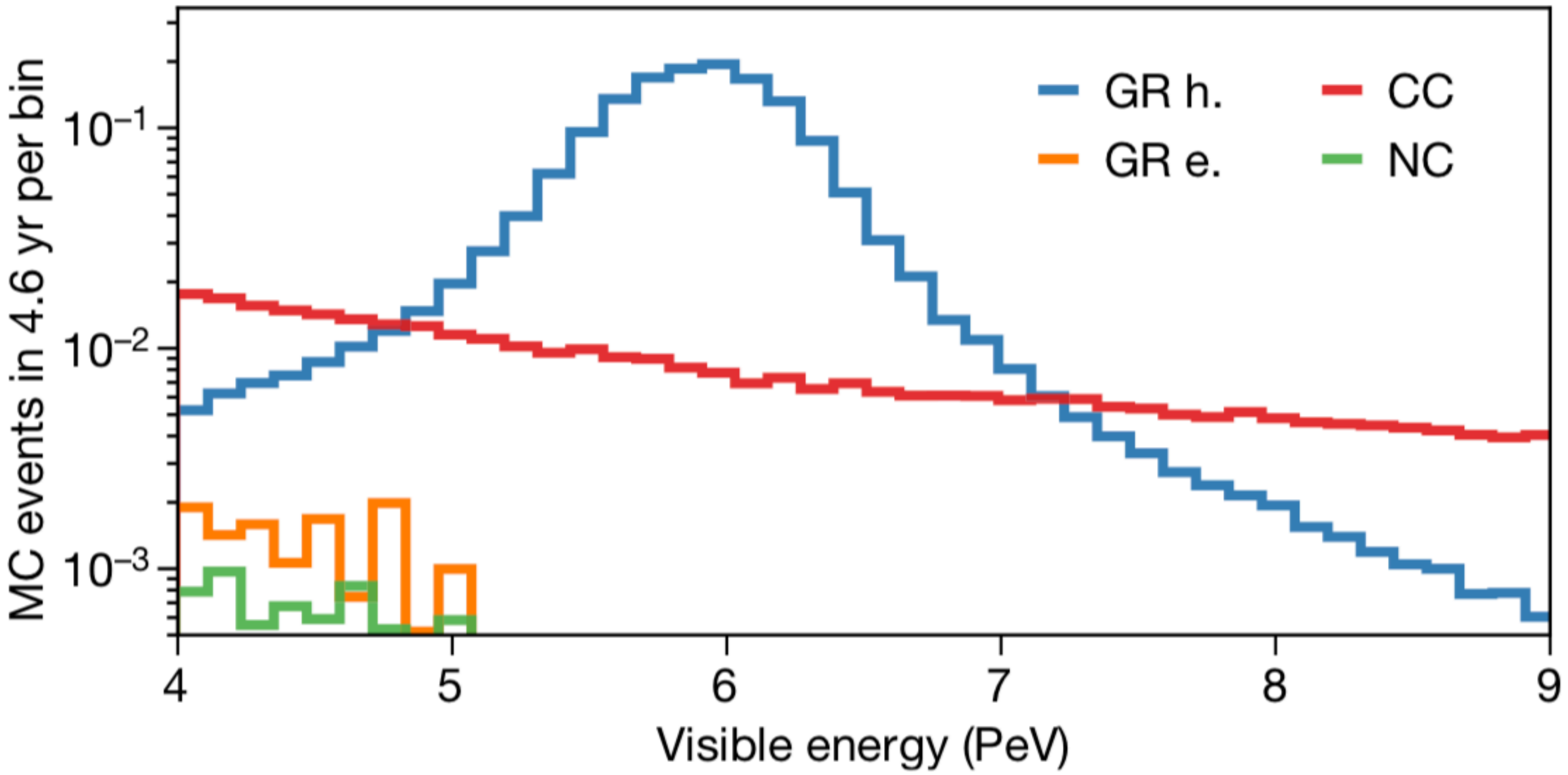
IceCube [2011.03561]

Glashow Resonance

- Resonant interaction $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$
- Disentangle antineutrinos from the total neutrino flux.



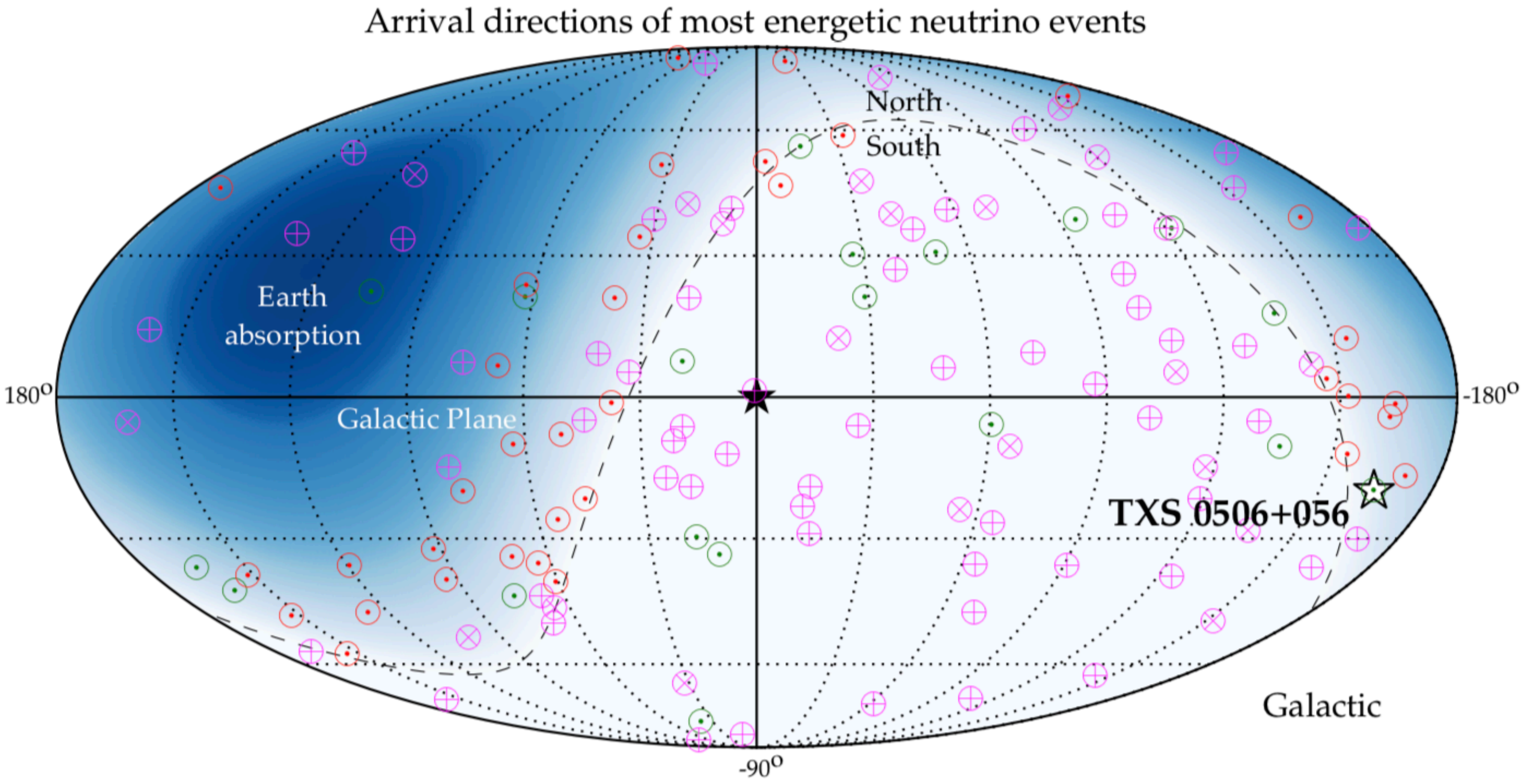




IceCube Nature 591 (2021) 7849

Origin of Cosmic Neutrinos

Where are neutrinos from?



Consistency of arrival direction with the isotropic distribution implies that the observed neutrino flux is predominantly extragalactic in origin.

Neutrino Source Searches

No source class confirmed as the main contributor yet.

- All-sky scan

  Neutrino self-clustering in sky by scanning pixels

- Targeted extragalactic/galactic catalog/candidate searches

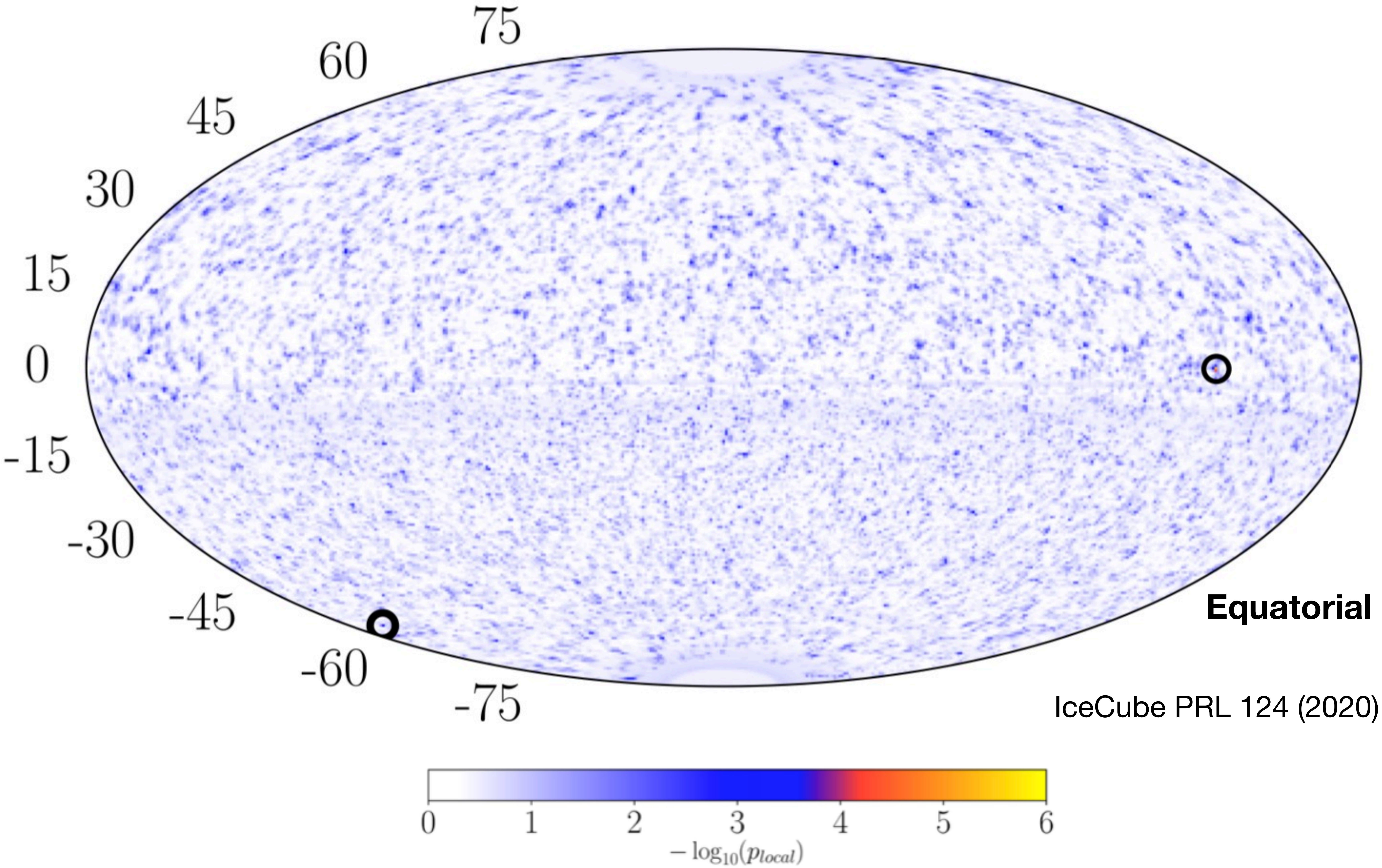
  Source catalogs/regions, testing different emission hypotheses with diverse methods: steady, time-dependent, stacking…

- Realtime alerts, realtime follow-up analyses

  Alert system for follow-up observations of alert telescopes.
  Fast response analysis: following alerts from neutrino, multi-wavelengths and gravitational wave observations.

Multimessenger efforts!

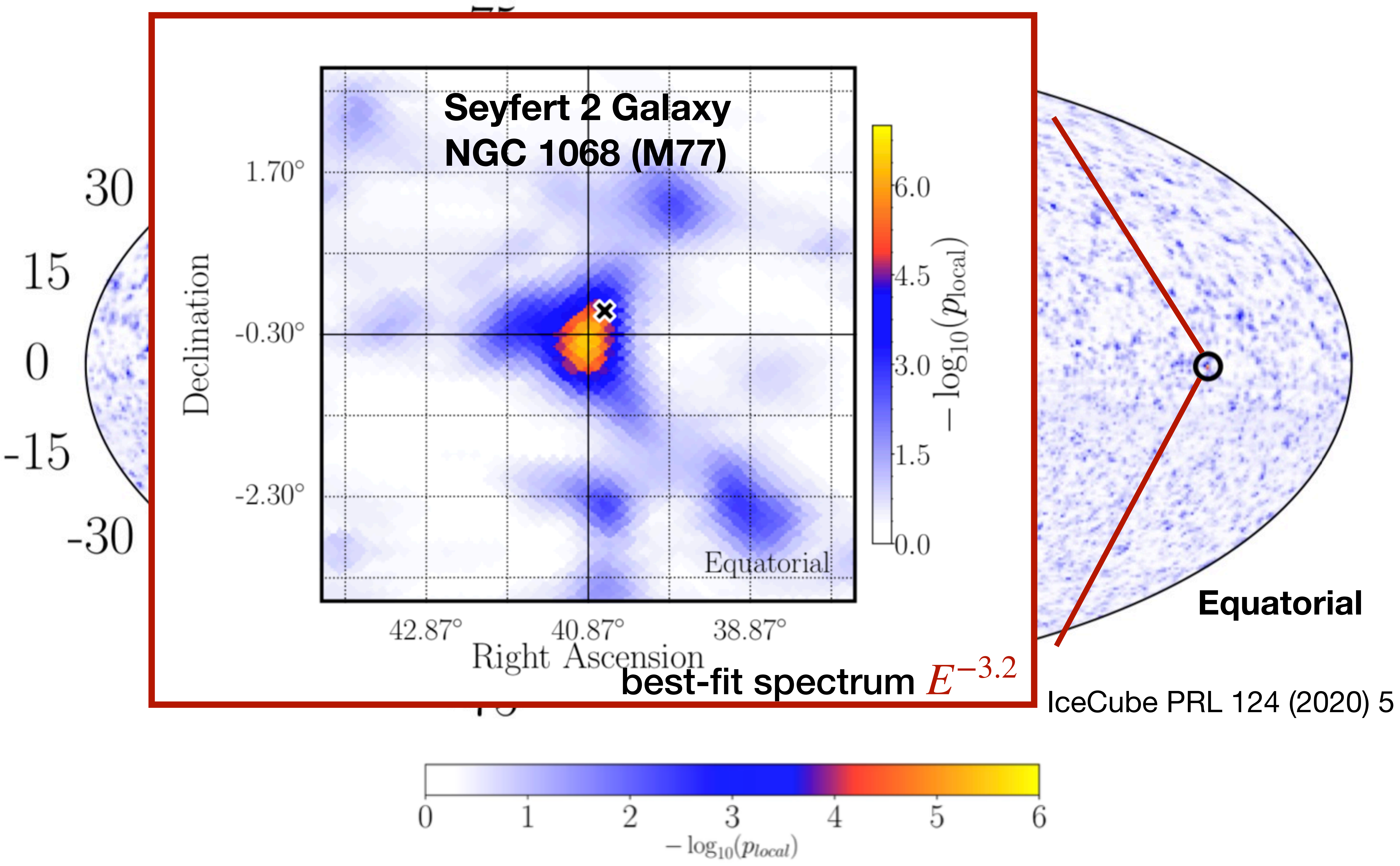
10-Year Steady Neutrino Source Search



IceCube PRL 124 (2020) 5

No significant point sources found in the time-integrated all-sky search and known catalog search.

10-Year Steady Neutrino Source Search



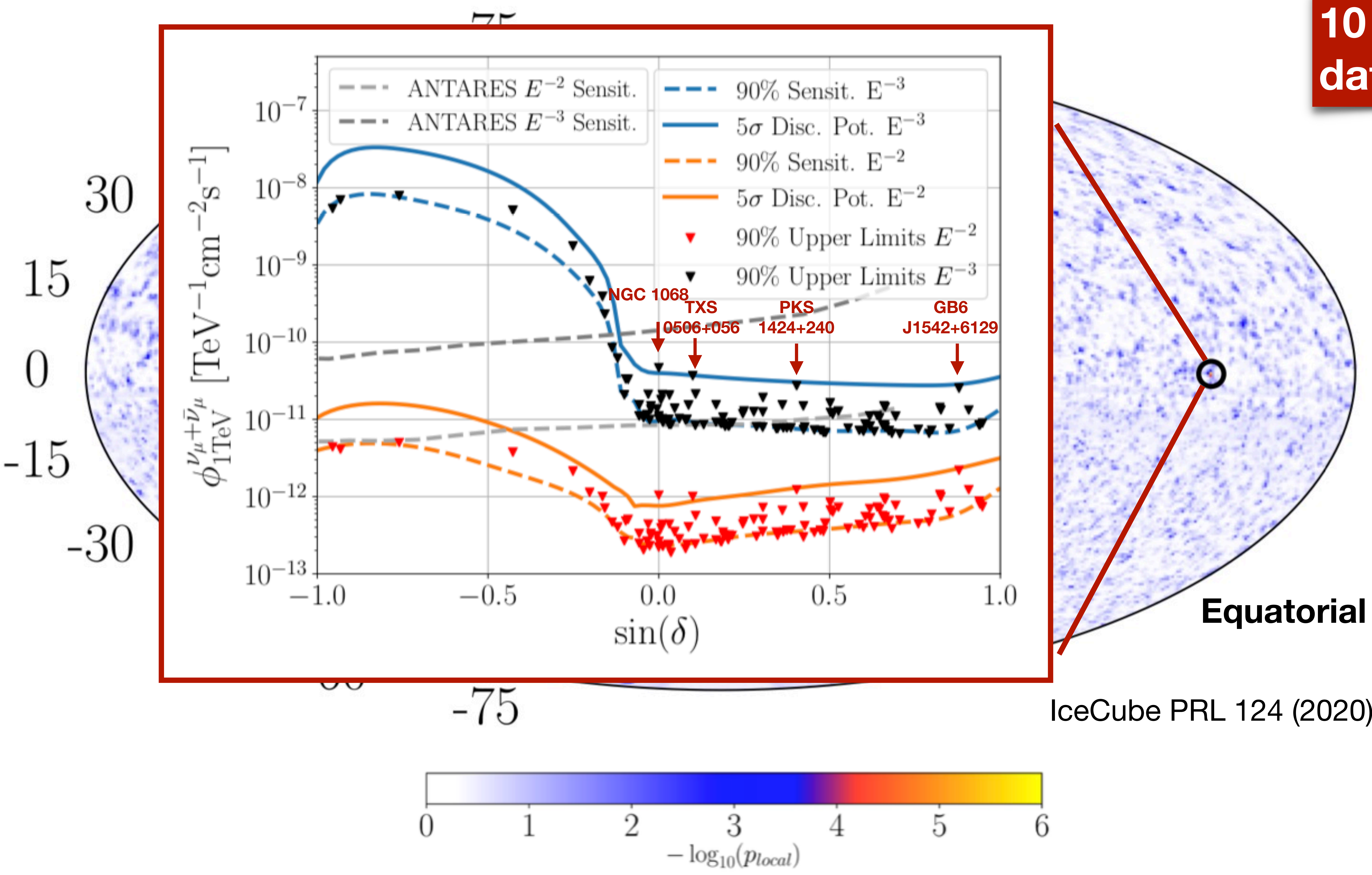
best-fit spectrum $E^{-3.2}$

IceCube PRL 124 (2020) 5

Hottest spot coincides with NGC 1068 (d~14 Mpc), 2.9σ significance (post-trial)

10-Year Steady Neutrino Source Search

10 yr point-source data now public!



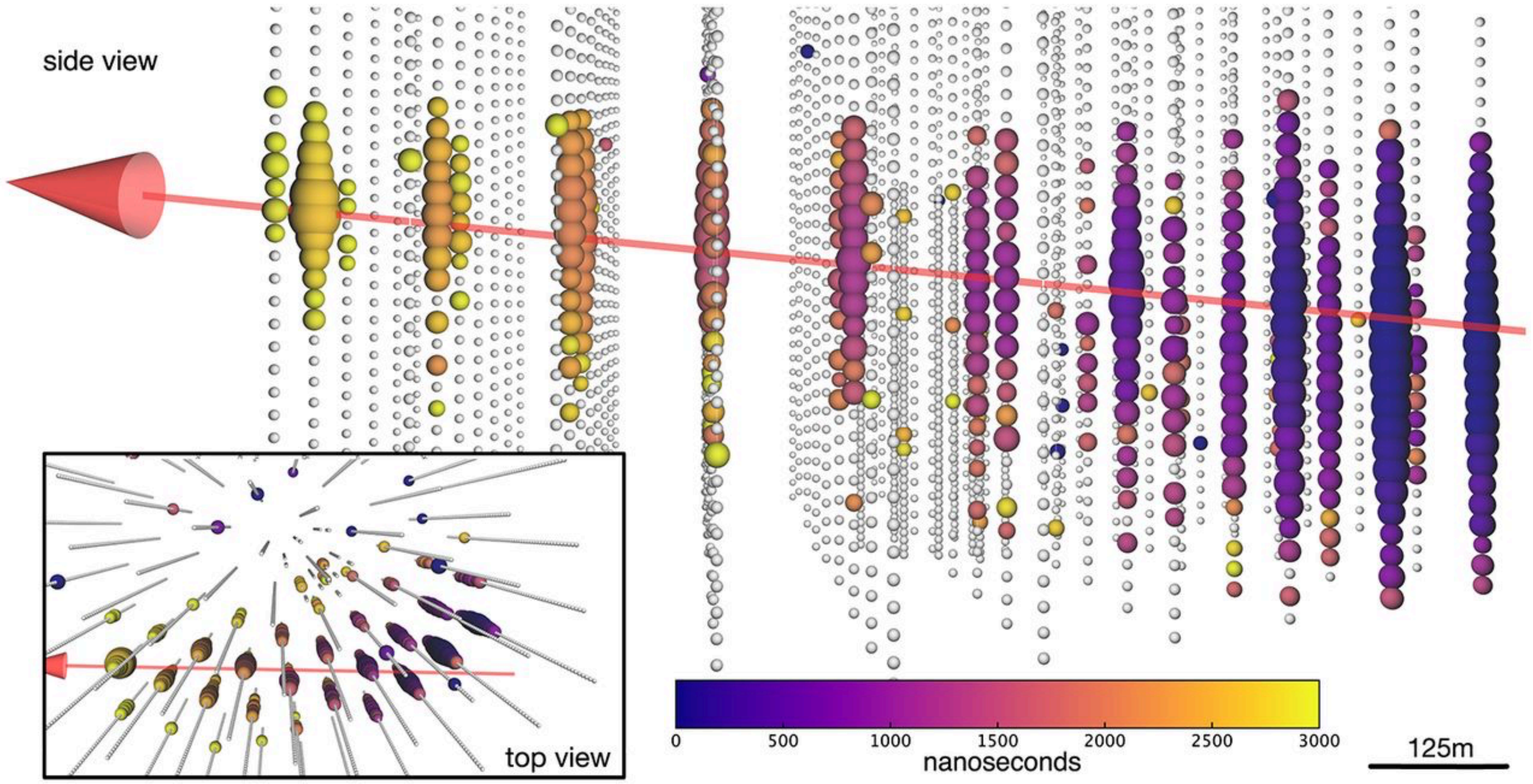
IceCube PRL 124 (2020) 5

4 sources in the Northern Sky with pre-trial p-values < 0.01.

TXS 0506+056

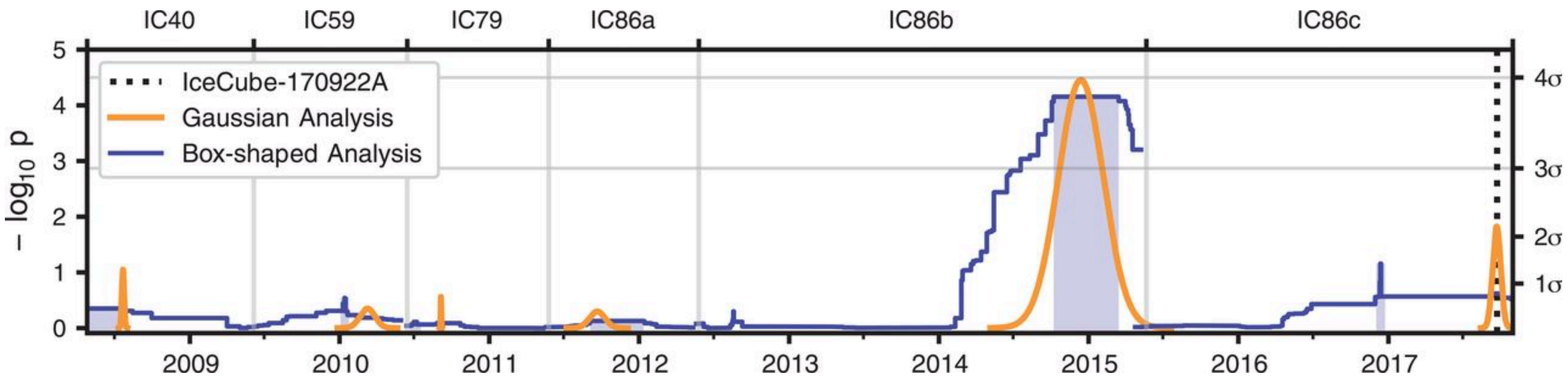
- Up-going muon track, energy ~ 290 TeV.
- In coincidence with a flaring blazar TXS 0506+056.
- One of the most luminous blazar in gamma rays, z=0.34 (1.7 Gpc).

A multi-messenger campaign !



Realtime alert: IC170922A

Neutrino Flare in Archival Search

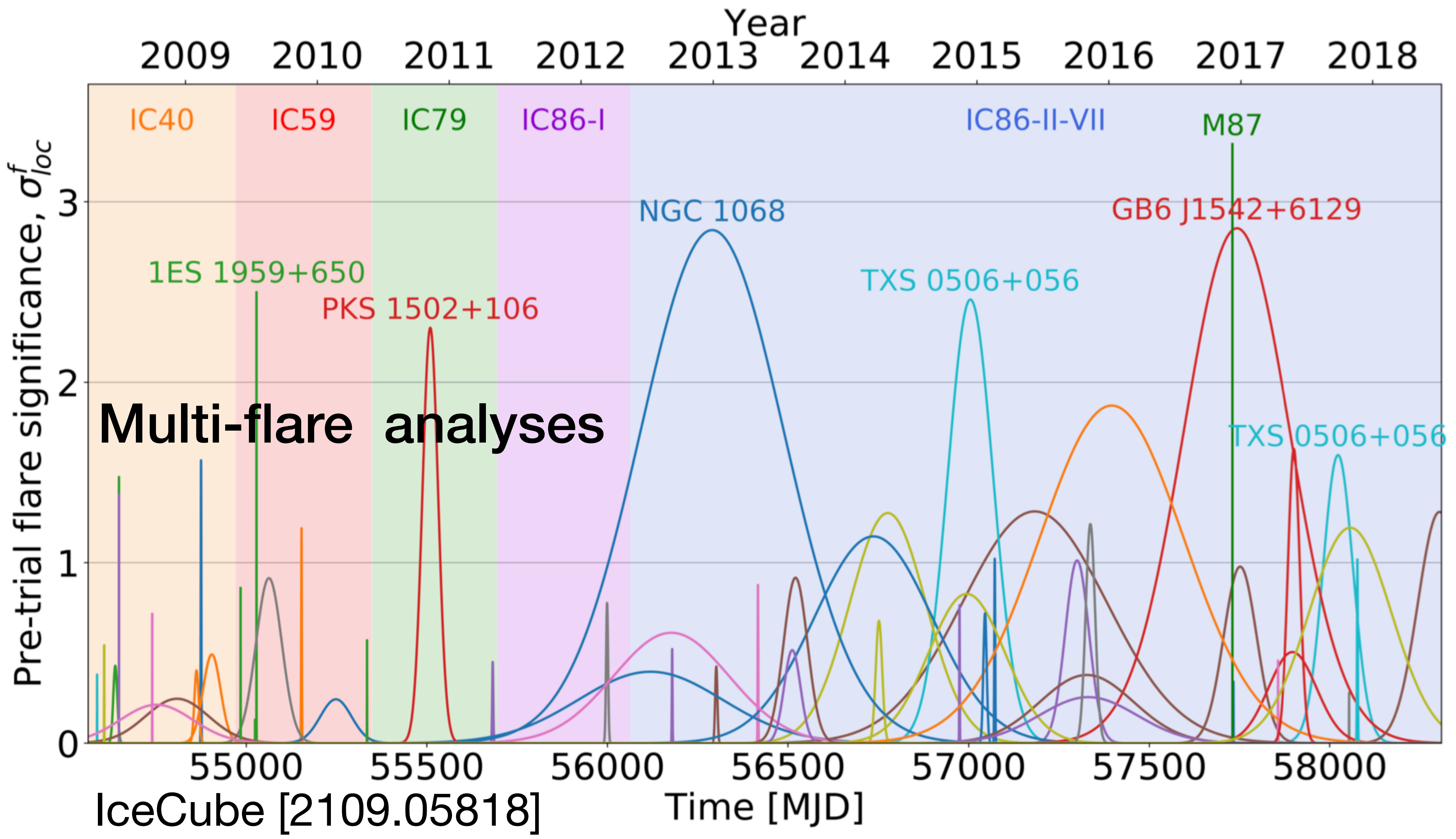


- 3.5σ evidence for a neutrino flare independent of the 2017 alert.
- 13 ± 5 neutrino events in 2014/15 in 158 days.
- Spectrum $E^{-2.1}$.

IceCube++ Science 361 (2018) 6398
IceCube Science 361 (2018) 6398

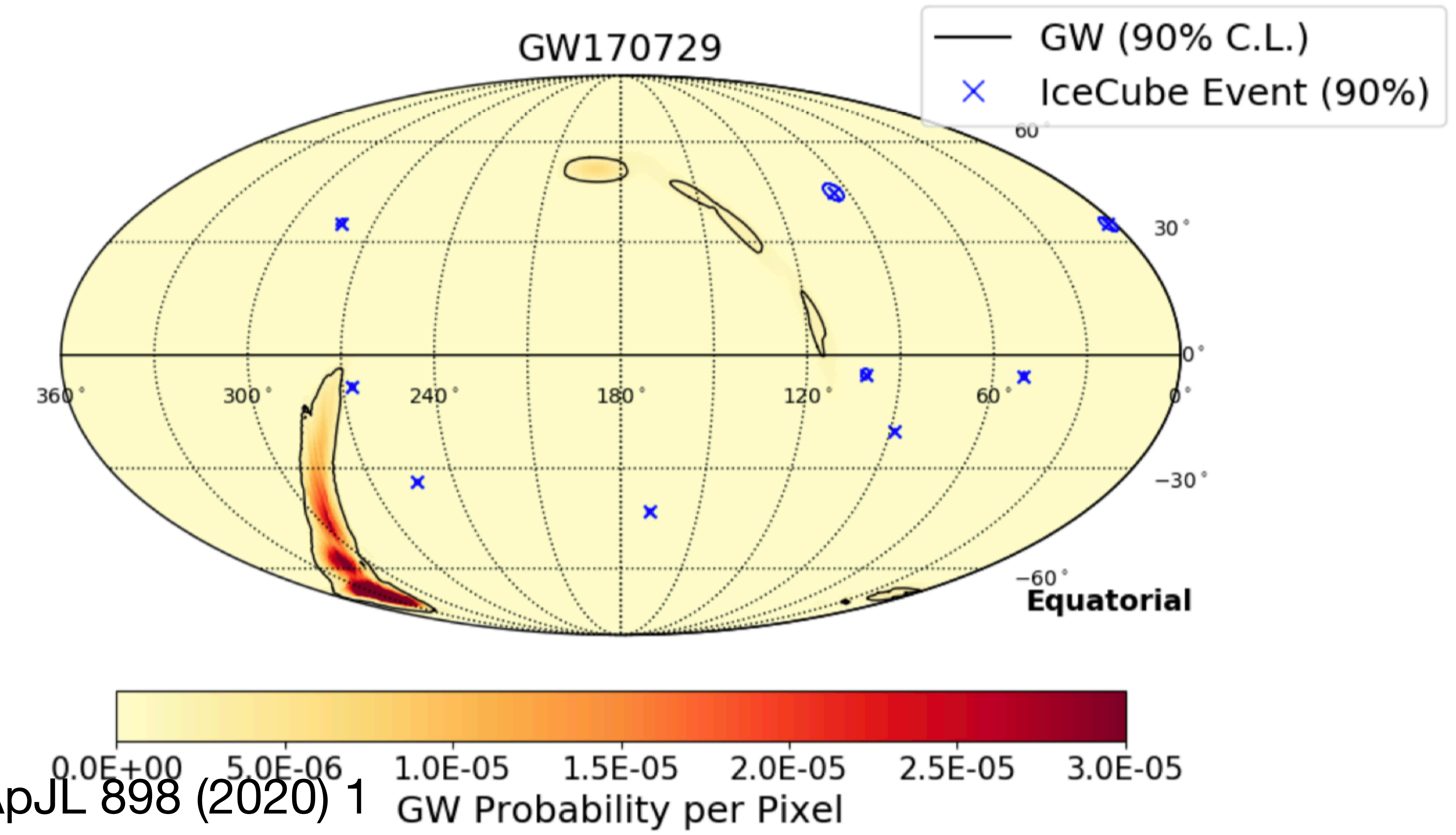
Recent Searches on Neutrino Sources

New methods & various candidates



IceCube [2109.05818]
IceCube (ICRC2021) 1128

GW follow-up



IceCube ApJL 898 (2020) 1
IceCube (ICRC2021)950

Time-dependent/transient searches:

sub-TeV transient IceCube [2011.05096]
All-sky IceCube ApJ 911(2021)1
GRB IceCube (ICRC2021)1118

Stacking searches:

Infrared galaxies IceCube [2107.03149]
Radio AGN IceCube (ICRC2021)1133

Realtime follow-ups:

VHE gamma-ray IceCube (ICRC2021)960
Realtime transient IceCube ApJ 910 (2021)

Blazars: C. Lagunas
Galaxy Cluster: M. Un Nisa
GW: A. Balagopal V

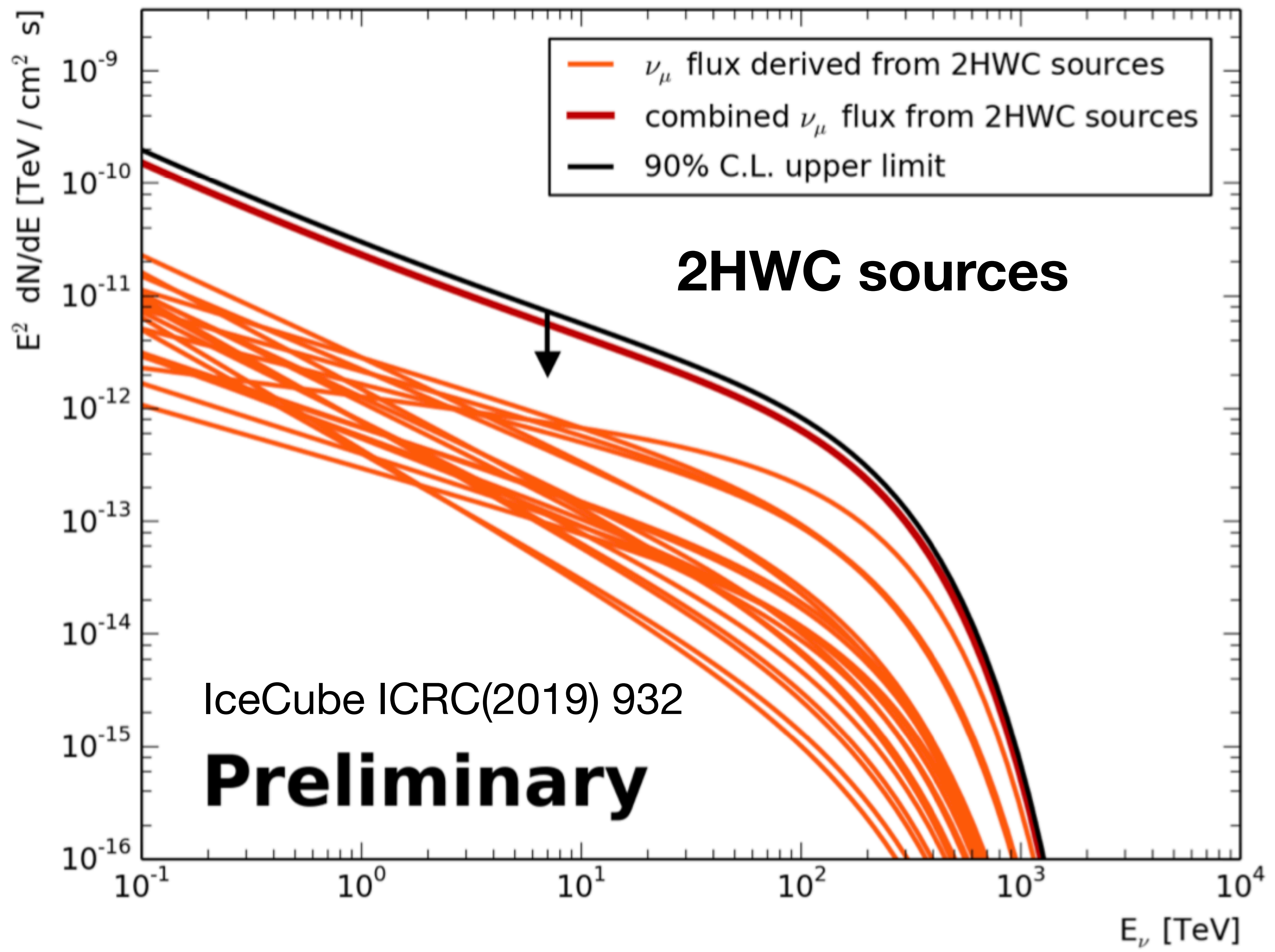
Many results/ongoing searches for neutrino emission not shown!

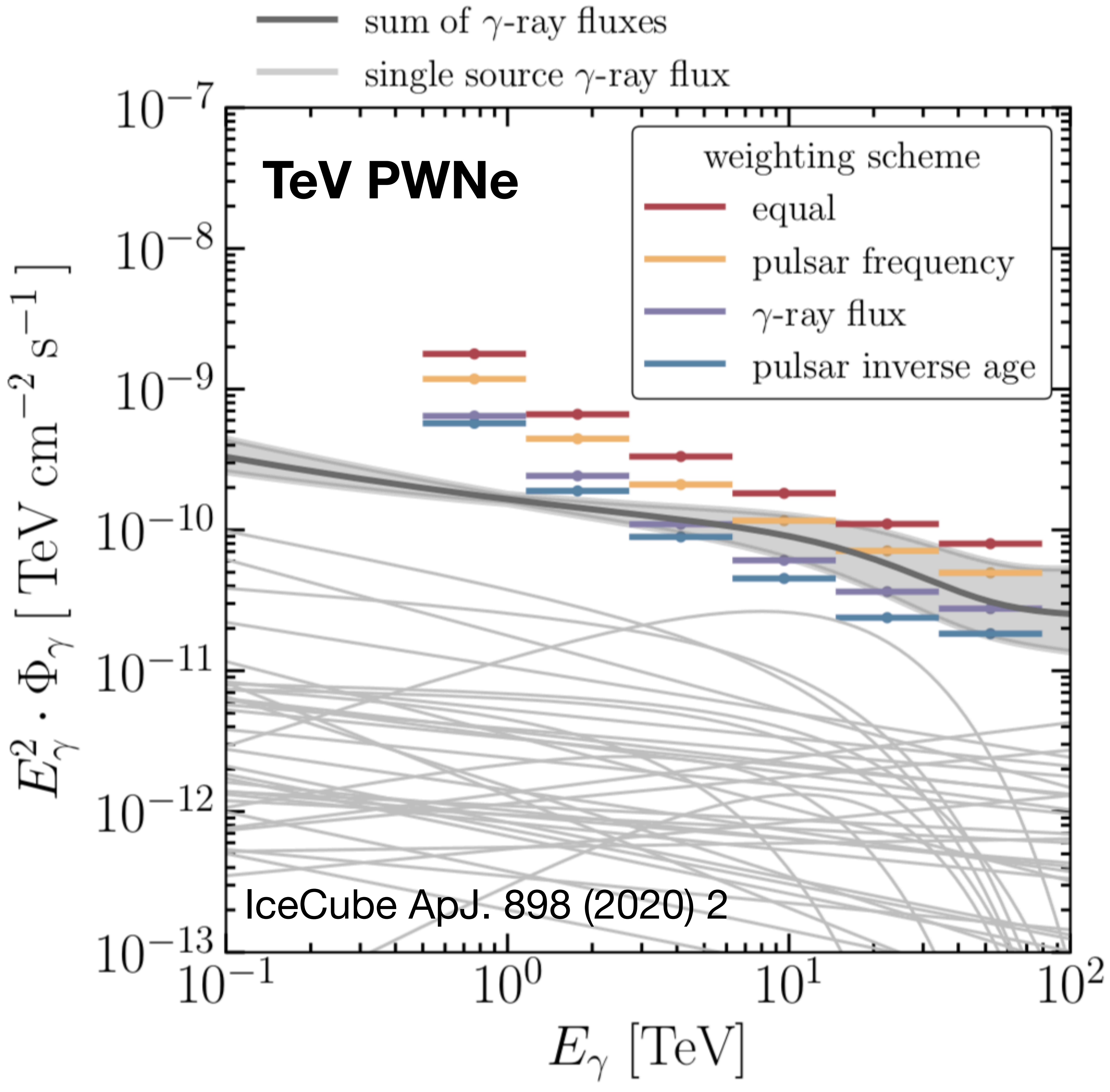
Galactic Sources

- HE cosmic neutrinos are predominantly extragalactic in origin. Galactic $\lesssim 14\,\%$ above 1TeV.
- Galactic cosmic rays reach PeV, guaranteed neutrino flux is expected from the Milky Way.
- Rich results of gamma-ray observation beyond TeV. Hints for hadronic origin besides leptonic origin?
- Identification of Galactic neutrino sources can unveil the origin of Galactic cosmic rays.

Galactic Sources

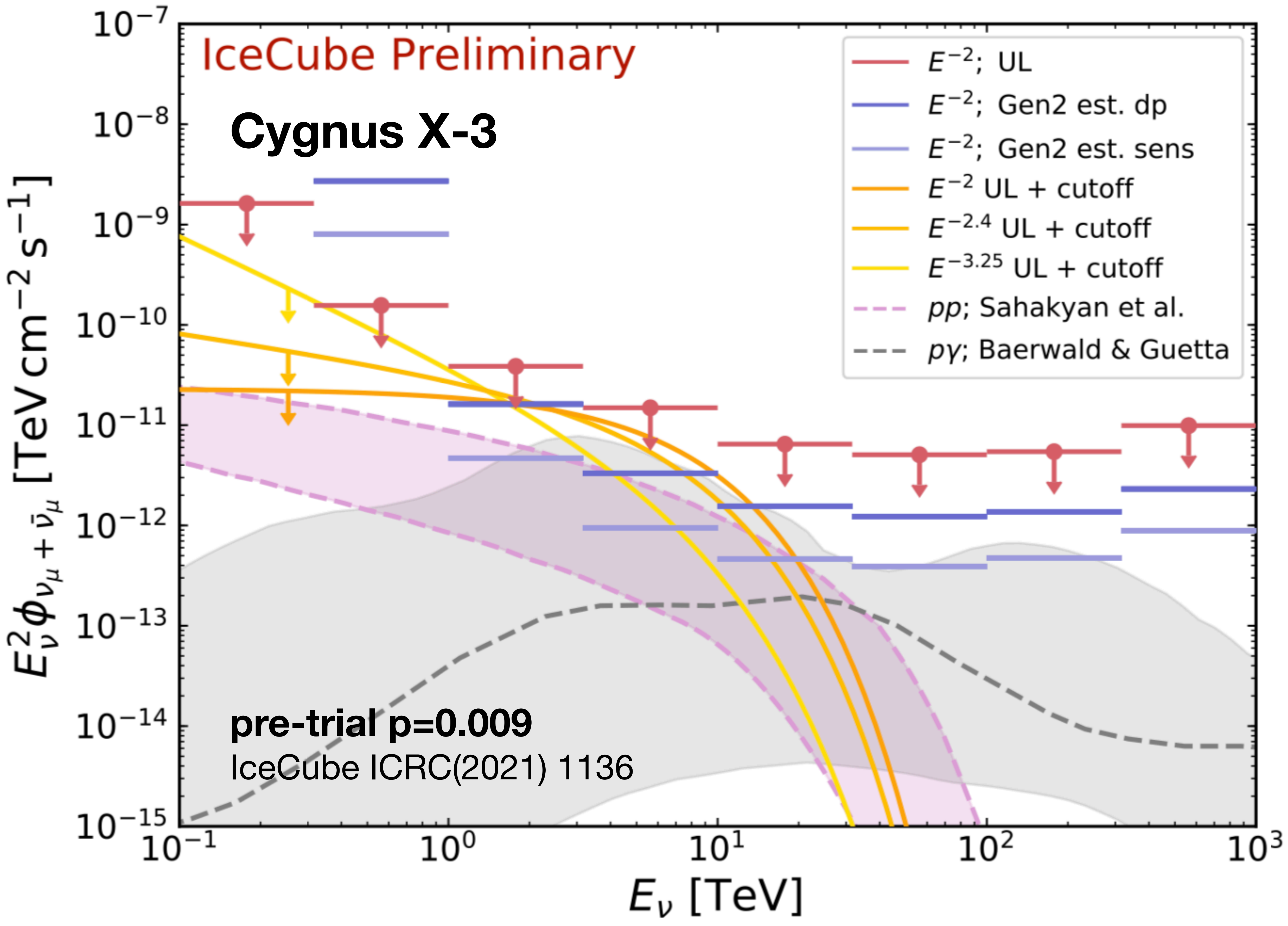
- HE cosmic neutrinos are predominantly extragalactic in origin. Galactic $\lesssim 14\,\%$ above 1TeV.
- Galactic cosmic rays reach PeV, guaranteed neutrino flux is expected from the Milky Way.
- Rich results of gamma-ray observation beyond TeV. Hints for hadronic origin besides leptonic origin?
- Identification of Galactic neutrino sources can unveil the origin of Galactic cosmic rays.





Stacking searches for high-energy emitter catalogs

Galactic Sources



- No Galactic source exceeds 3σ significance on neutrino emission yet.
- Some warm local spots have been found, e.g. RX J1713.7-3946, MGRO J1908+06, Cygnus X-3…

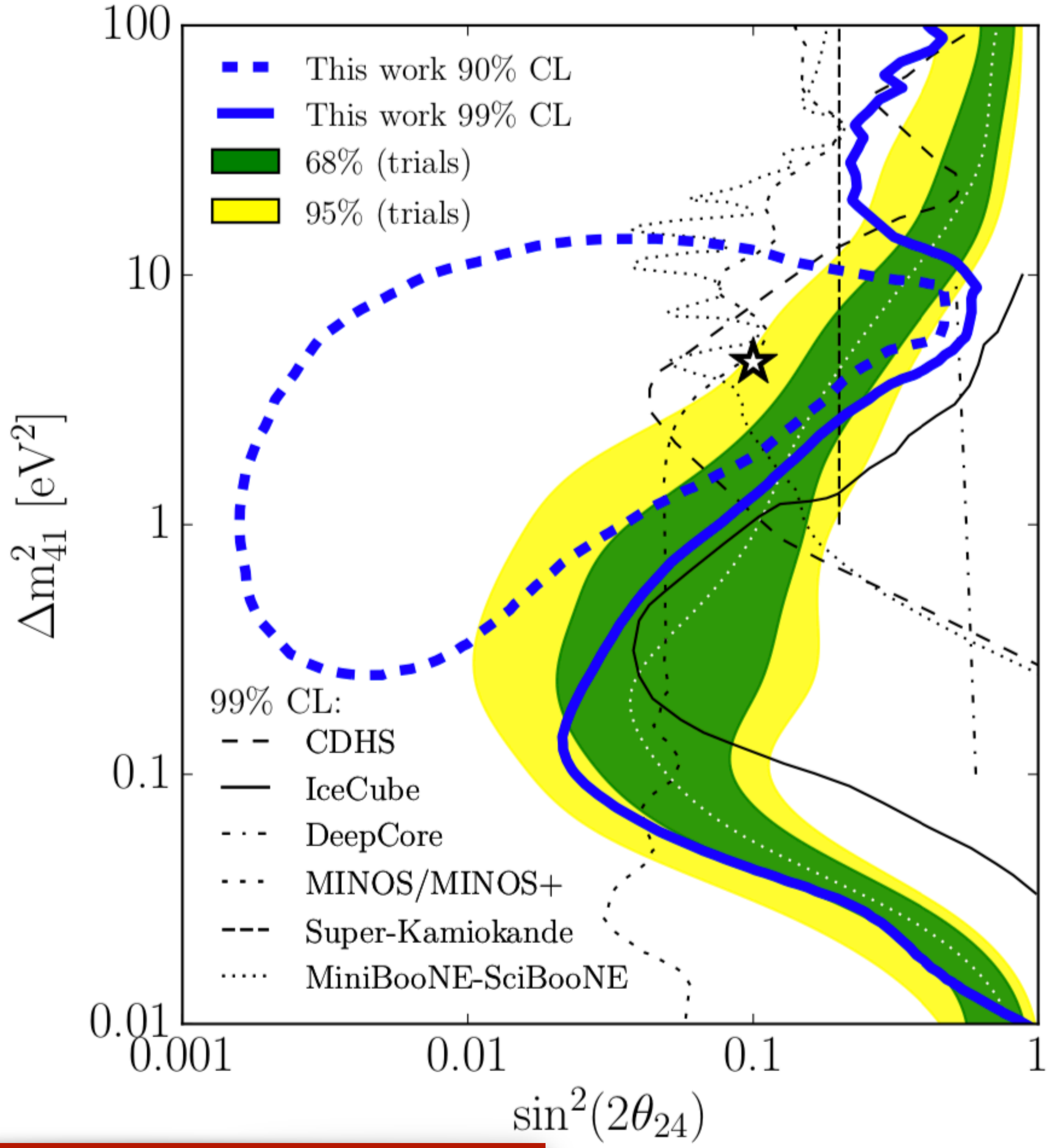
More searches on the diffuse emission, extended regions, (un)identified gamma-ray sources…

Probing Particle Physics

What can we study in parallel with astrophysics?

The cosmic & atmospheric neutrinos also provide an excellent opportunity to study particle physics.

- (Non)standard oscillations & interactions
  - Oscillation IceCube PRL 120 (2018) 7
  - Cross section IceCube Nature 551 (2017), PRD 104 (2021)
  - Inelasticity IceCube PRD 99(2019)3
  - Lorentz violation IceCube Nature Phys. 14 (2018) 9
  - Non-standard interactions IceCube [2106.07755]
  - Sterile neutrinos IceCube PRL 125 (2020) 14
- Indirect Dark Matter
  - Sun IceCube EPJC 77 (2017) 3
  - Earth IceCube EPJC 77 (2017) 2
  - Halo ANTARES+IceCube PRD 102 (2020)
- Exotic signals
  - monopole IceCube [2109.13719]



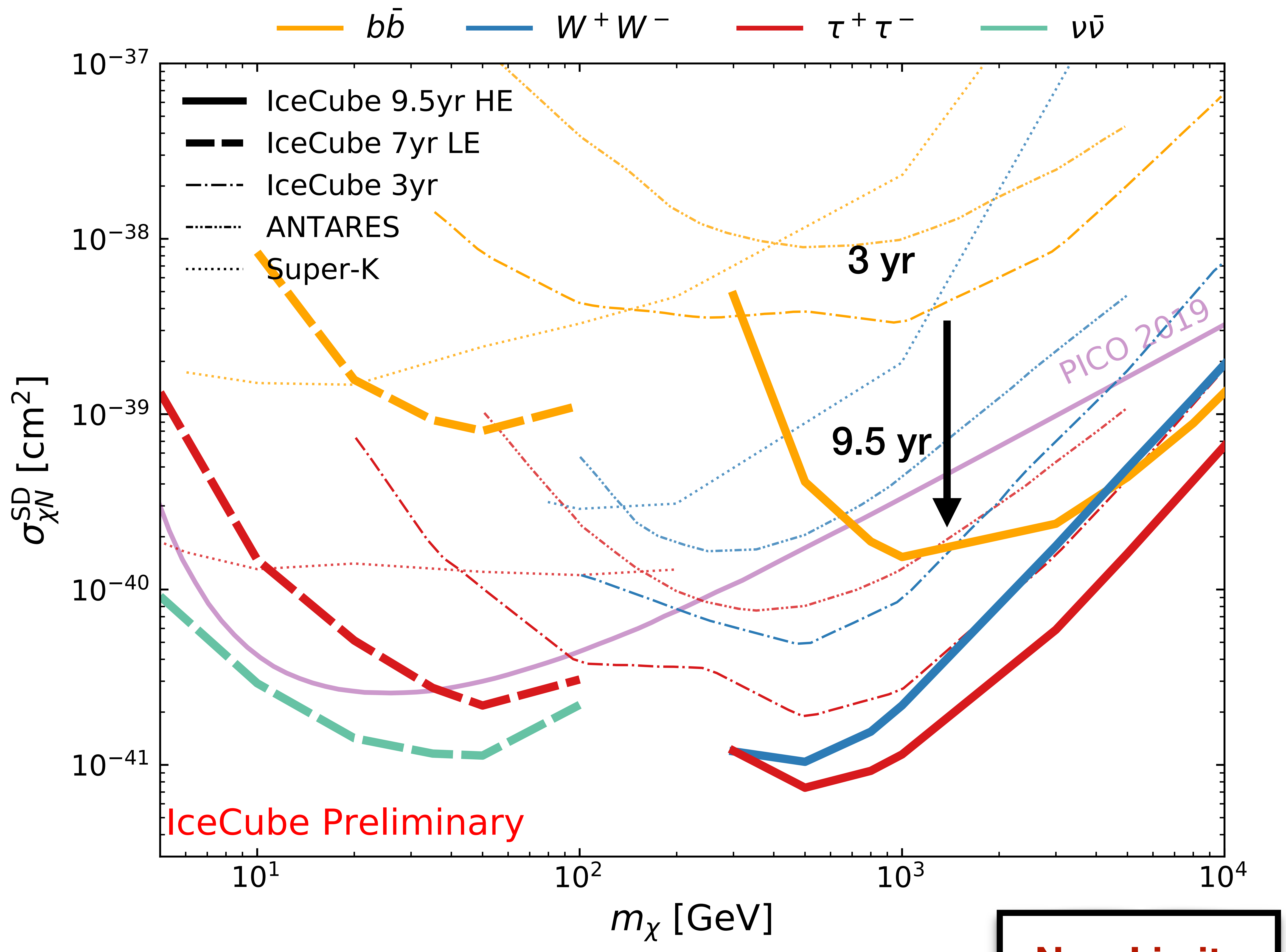
8 yr sterile neutrinos

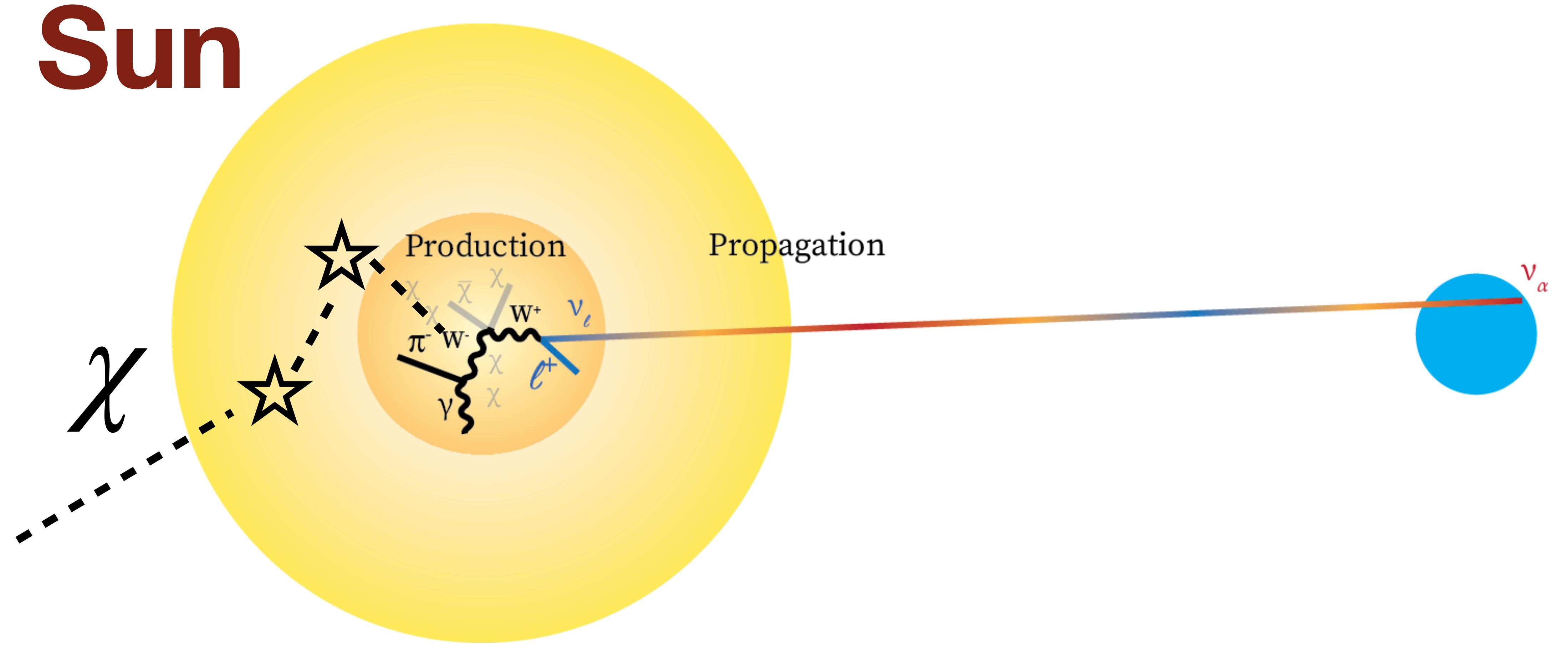
IceCube PRL 125 (2020) 14

More updated analyses with more years of data!

NSI: G. Parker
Sterile neutrinos: A. Garcia

Dark Matter in Sun



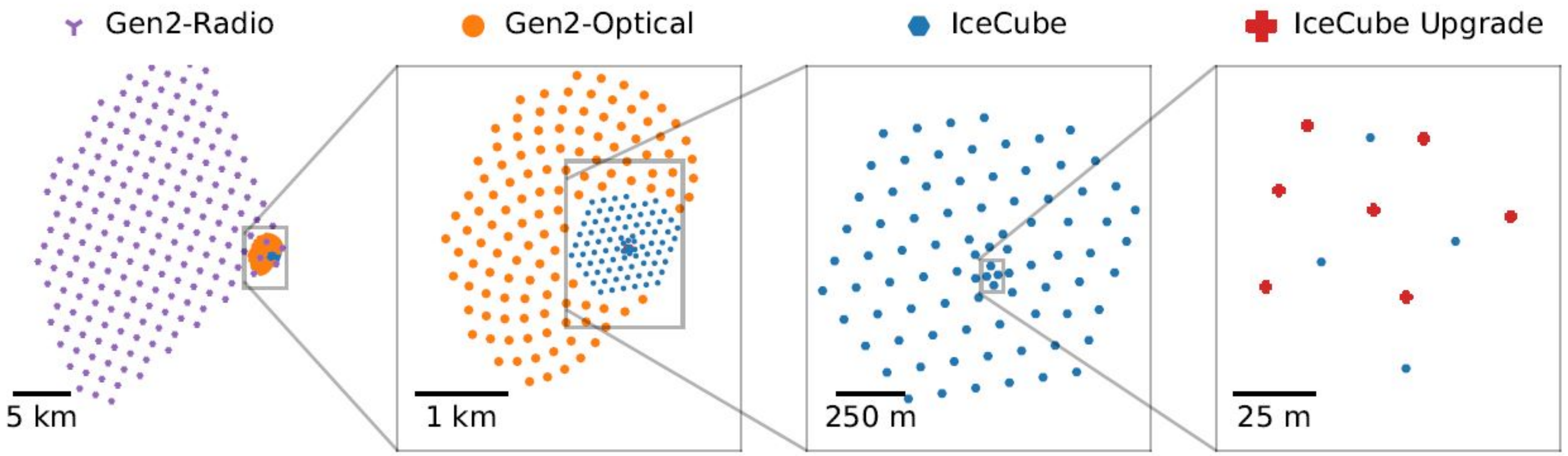


- **No WIMPs found** with 9.5 yr high-energy & 7 yr low-energy data.
- New **world-leading limits** for spin-dependent DM-nucleon scattering for mass $\gtrsim \mathcal{O}(10)$ GeV.
- Limits **improved** up to **50x** compared to IceCube 3 yr results.
- Implemented new neutrino spectra including latest **EW** calculations.

Bauer, Rodd, Webber JHEP 2021
QL, Lazar, Argüelles, Kheirandish JCAP 2020

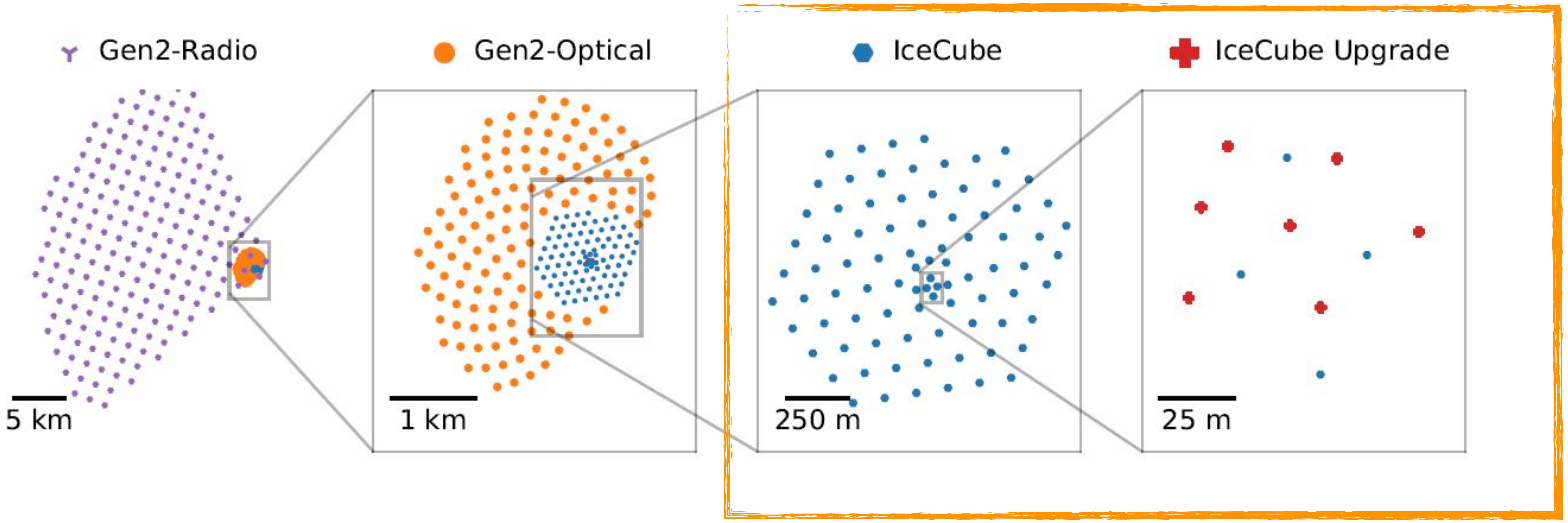
New Limits

The Future



Gen2-Radio
Gen2-Optical
IceCube
IceCube Upgrade
5 km
1 km
250 m
25 m

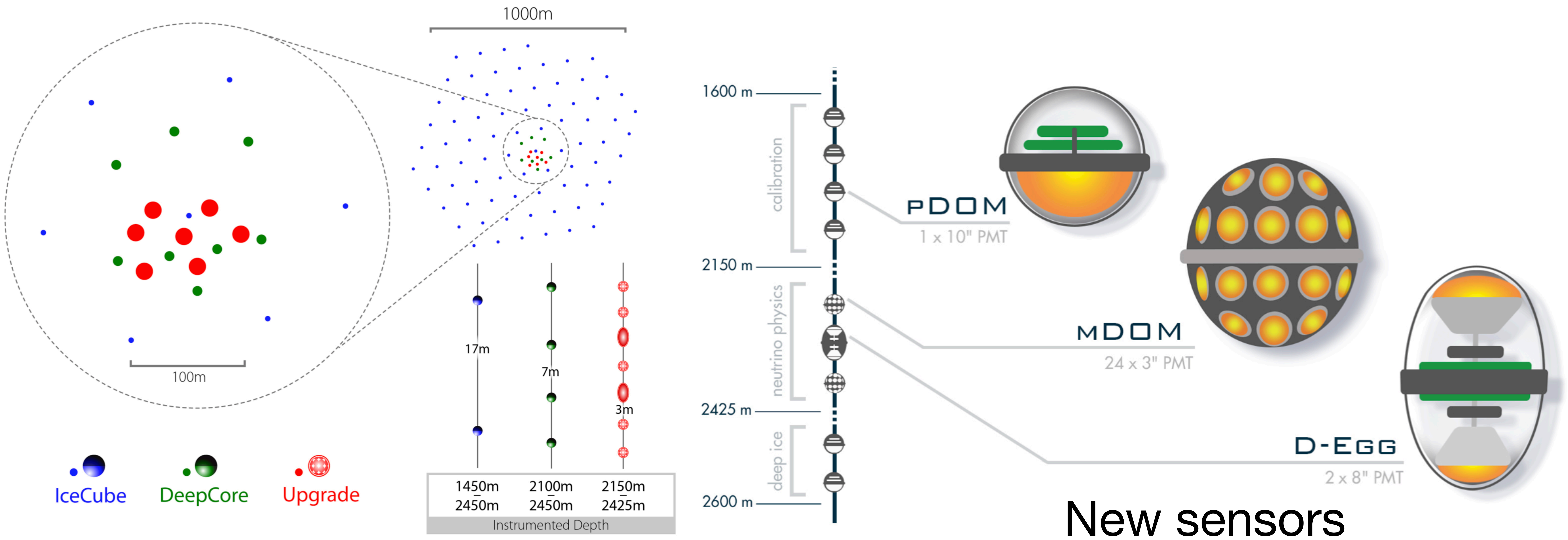
The Future



7 new denser strings

New design of DOMs

Funded and planned deployment in 2024/25



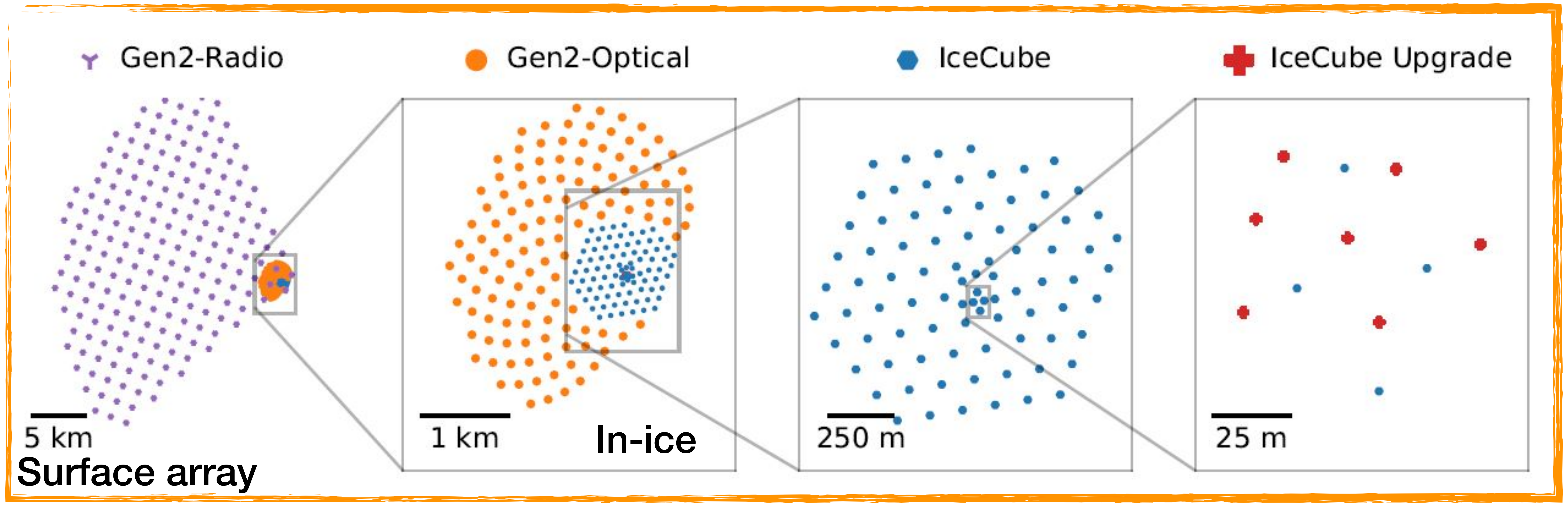
New sensors

- Improved calibration of ice, reduced systematic uncertainties.
- Improved angular and energy reconstructions.
- Precision measurement of atmospheric neutrino oscillations.

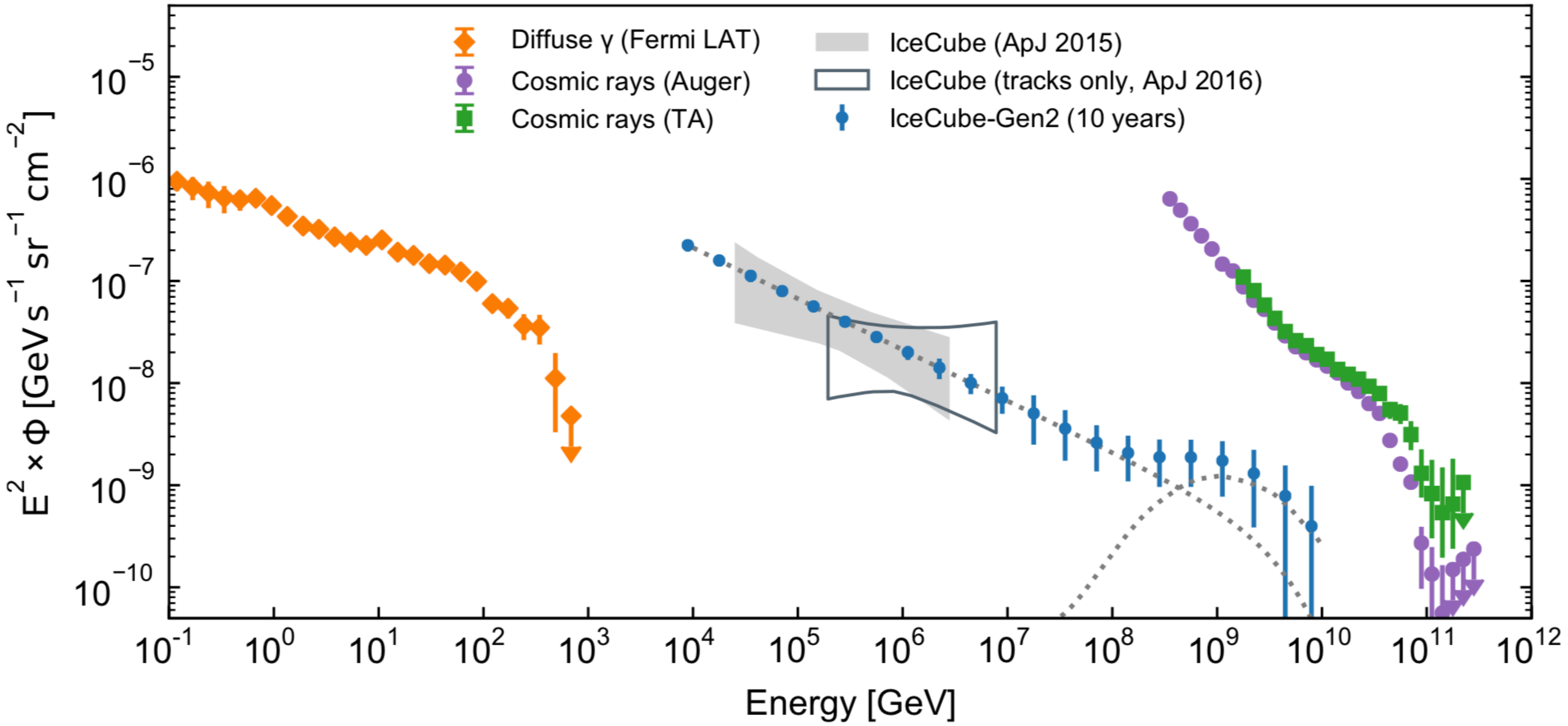
D-Egg: C. Hill

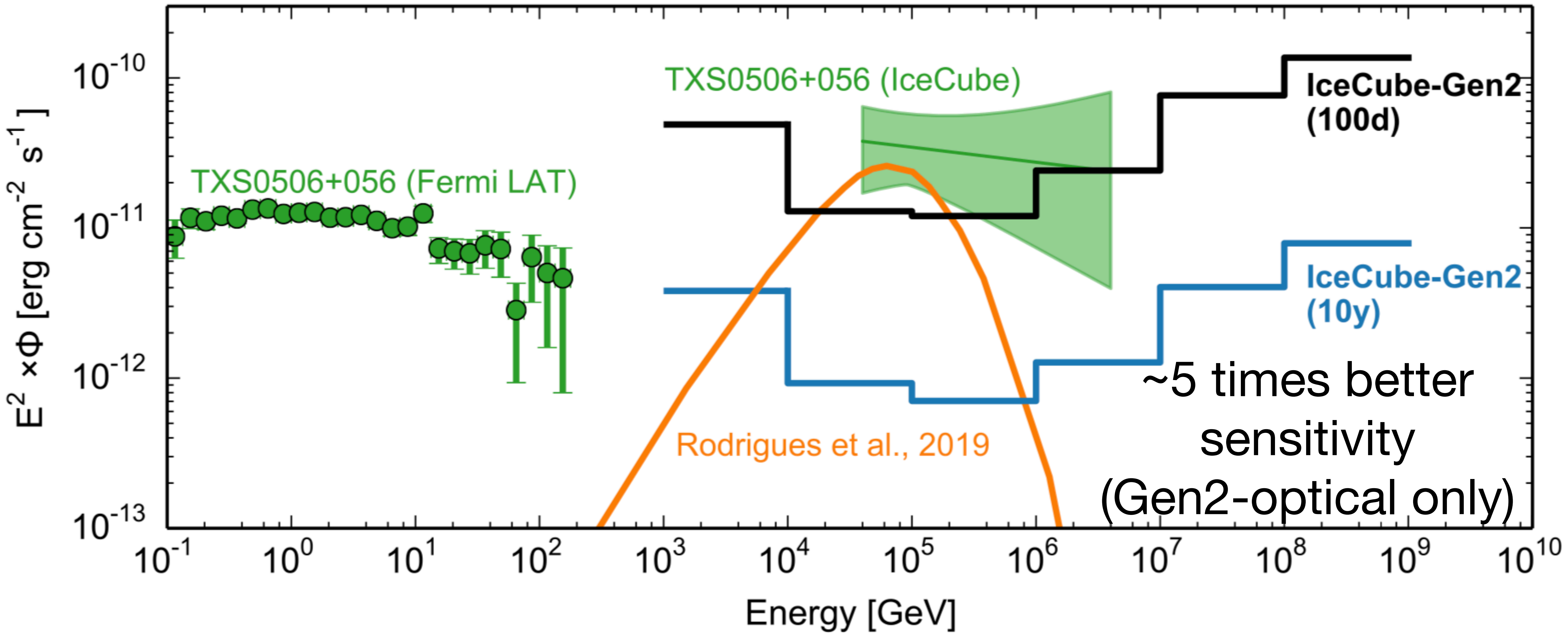
IceCube ICRC(2019) 1031

The Future

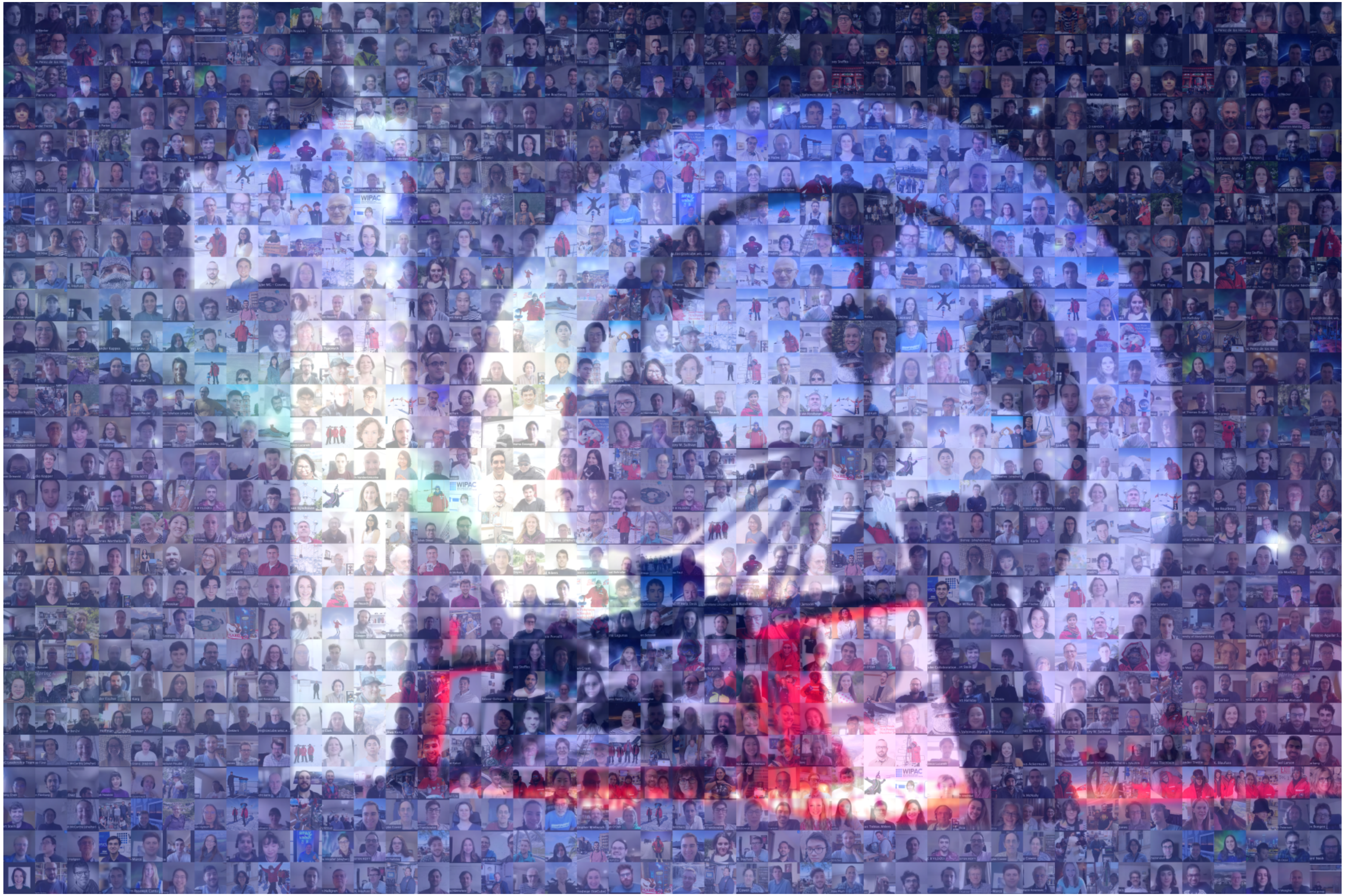


- Proposed $1\,\mathrm{km}^3$ IceCube -> $8\,\mathrm{km}^3$ Gen2-Optical -> $500\,\mathrm{km}^2$ Gen2-Radio.
- Sensitivity to cosmic neutrinos at GeV ~ EeV.
- Improved sensitivity to neutrino source searches.





IceCube-Gen2 White Paper [2008.04323]



Summary

- Fruitful results of the high-energy cosmic neutrino flux detection in the past 10 yrs.
- First evidence of high-energy neutrino source in 2017 - TXS 0506+056.
- We are finding more interesting candidates, e.g. NGC 1068.
- Extensive analyses searching for neutrino sources, with important multi-messenger input.
- There are many particle physics topics can be explored with the neutrino flux observed by IceCube.
- The next-generation detectors with improved sensitivities will advance searches in the upcoming years.

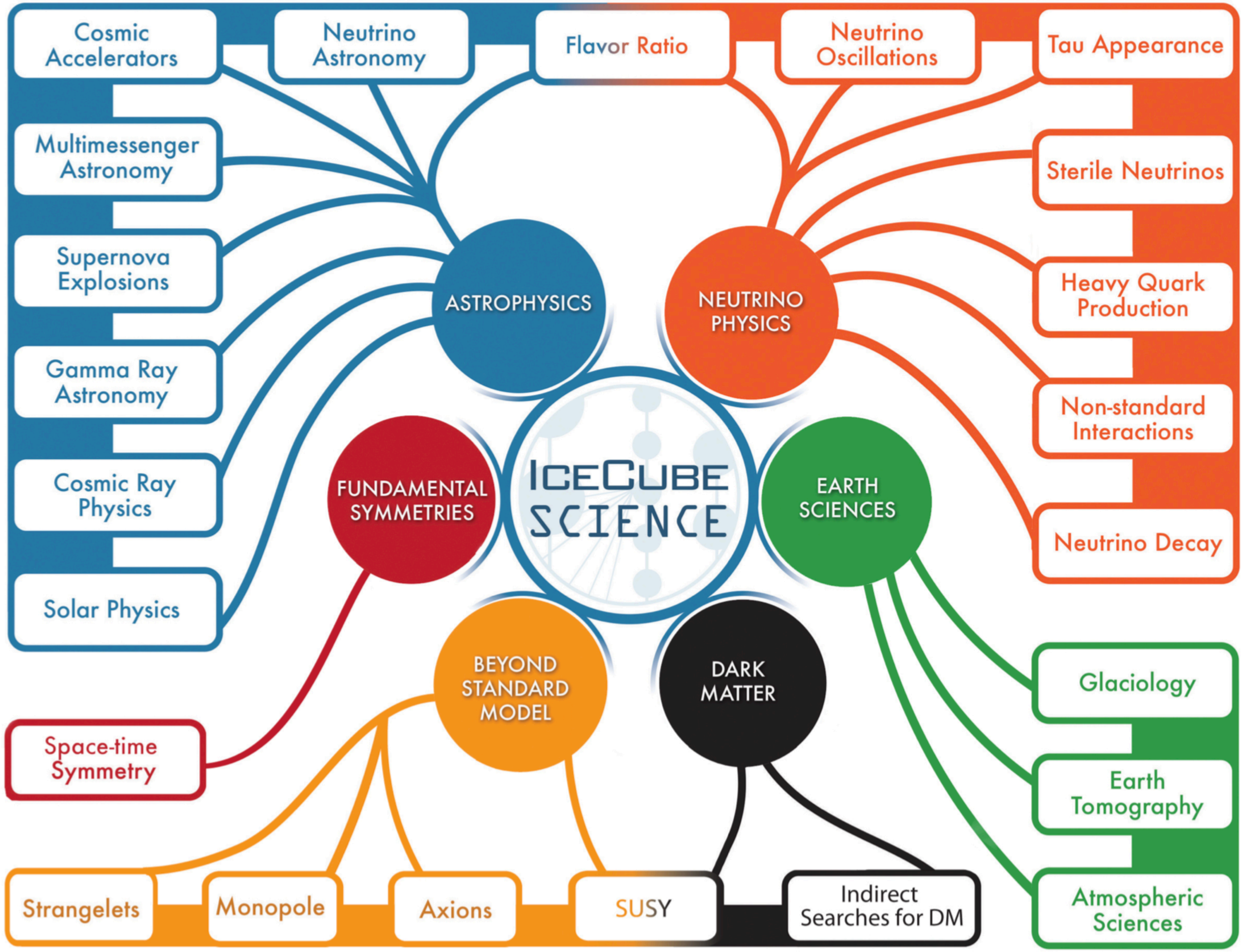
Thank you!

Stay Tuned…

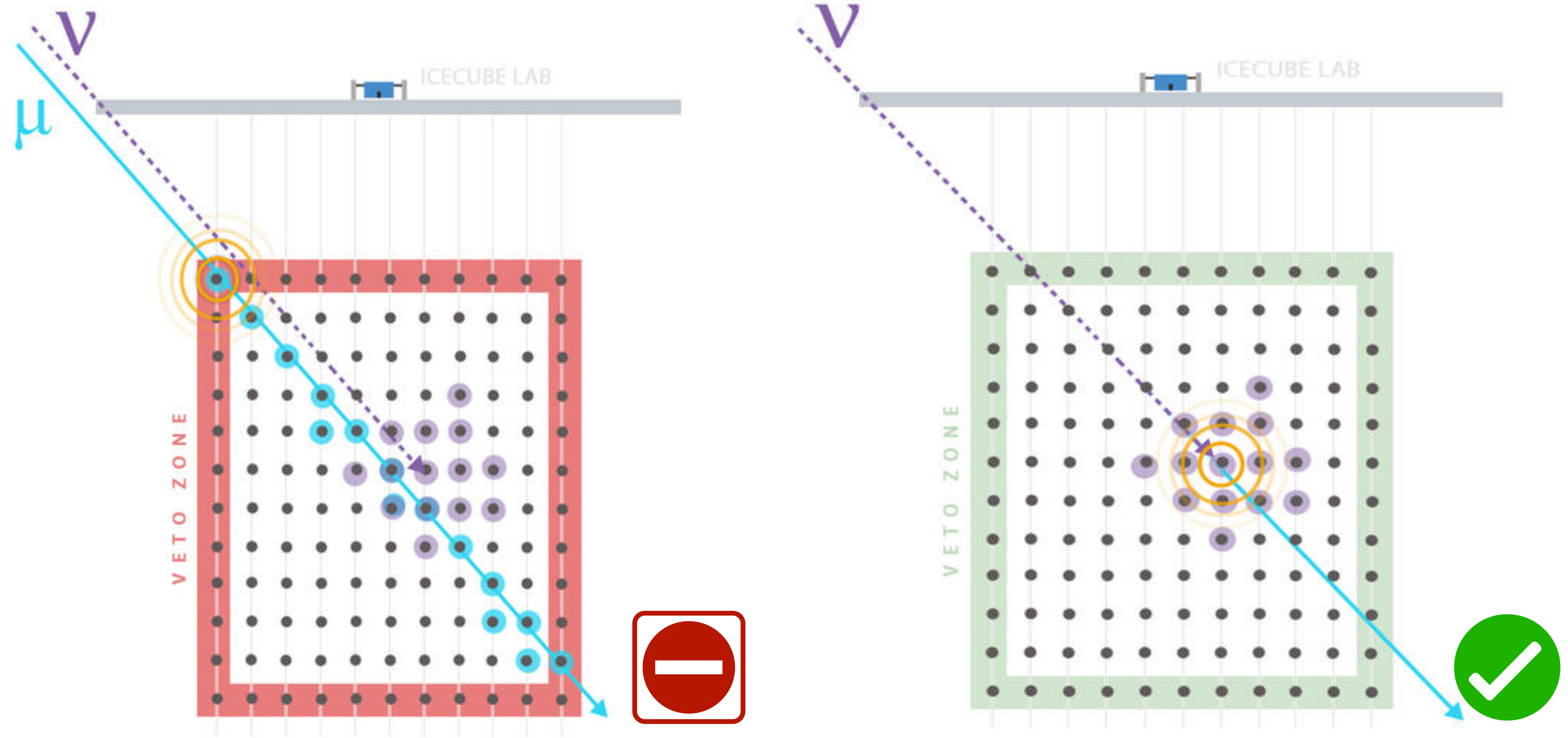
Bonus Slides

IceCube Collaboration

IceCube Science



Event Selection



- Earth is a natural filter for up-going events.
- The outer layer of the detector acts as the veto region for Atmospheric muons and coincident atmospheric neutrinos.
- Cosmic neutrino events be selected as ones starting inside the detector (e.g. HESE).

Multi-messenger Connection

Accelerated cosmic ray beam (p) interact with gas (p) or radiation (γ).

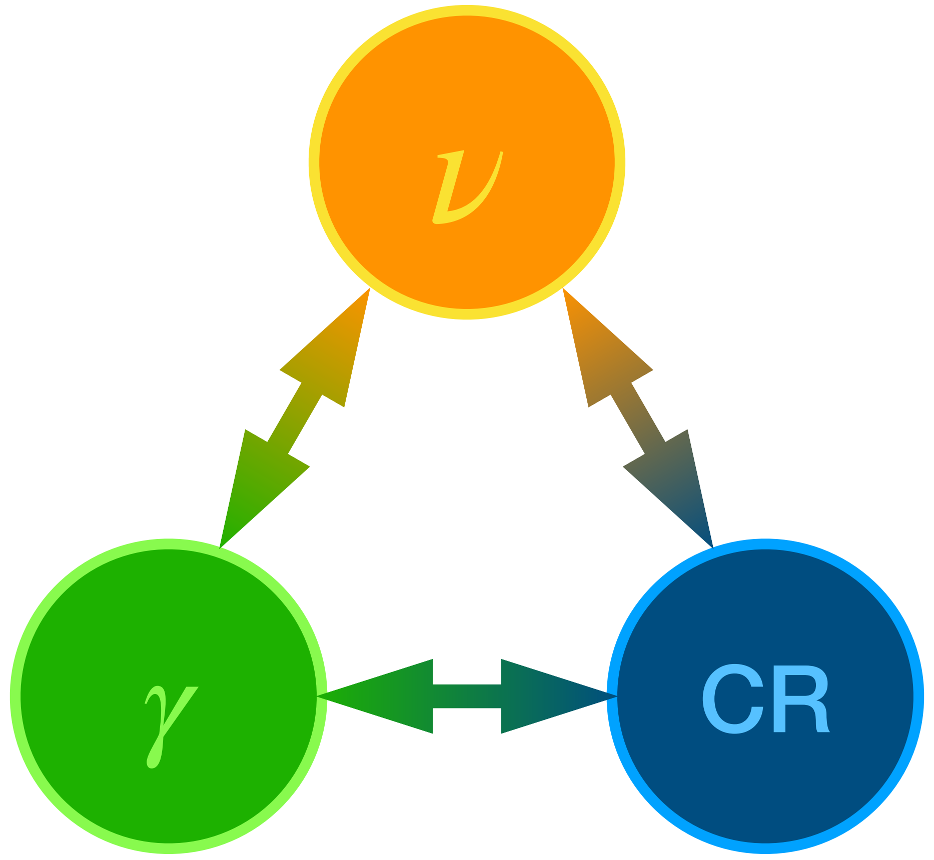
$$p + p \rightarrow n_\pi \left[\pi^0 + \pi^+ + \pi^-\right] + X$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$$\begin{cases} \pi^+ \rightarrow \nu_\mu + \mu^+ \rightarrow \nu_\mu + \left(e^+ + \nu_e + \bar{\nu}_\mu\right) \\ \pi^- \rightarrow \bar{\nu}_\mu + \mu^- \rightarrow \bar{\nu}_\mu + \left(e^- + \bar{\nu}_e + \nu_\mu\right) \\ \pi^0 \rightarrow \gamma + \gamma \end{cases}$$

ν "Smoking-gun" of cosmic-ray accelerators

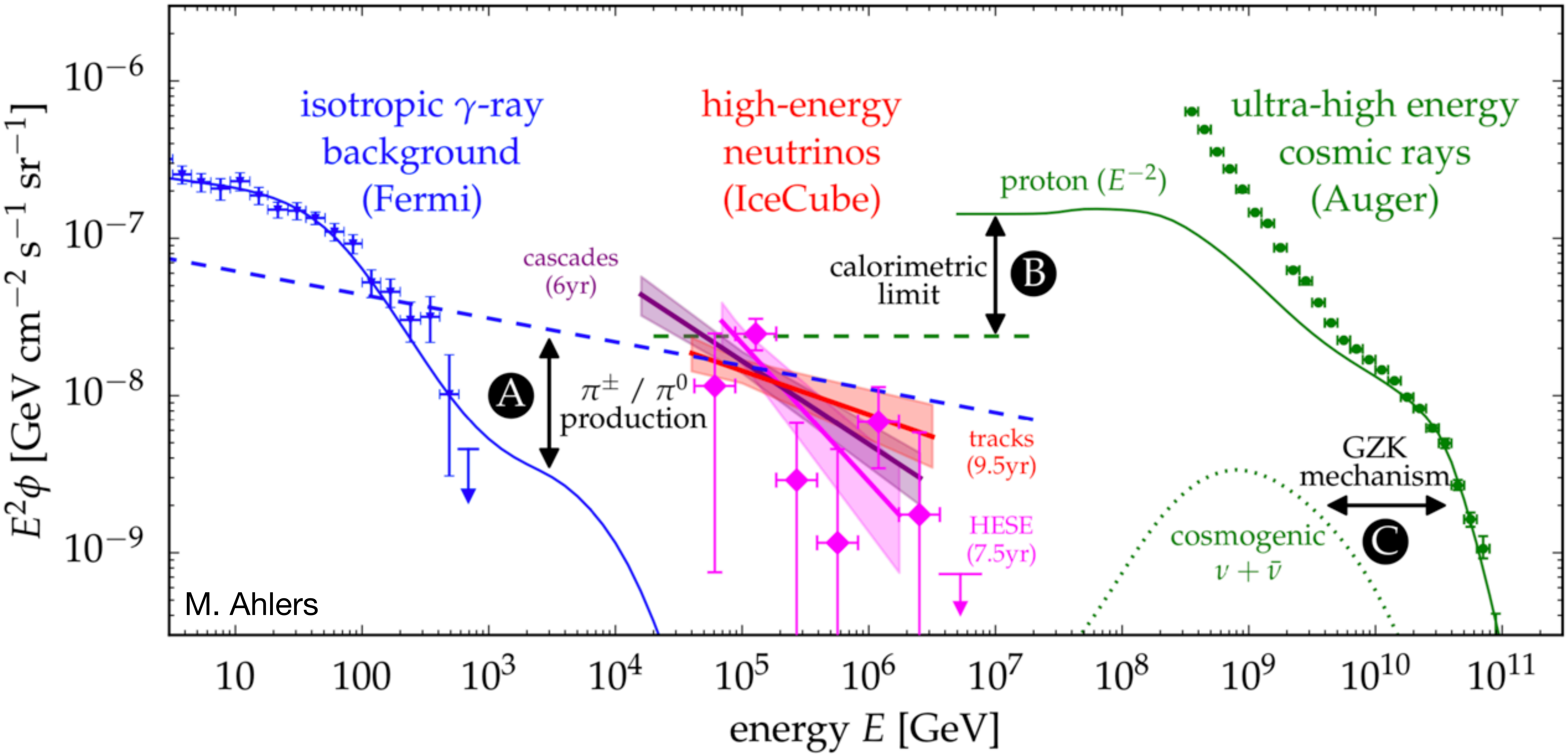
Correlated neutrinos~gamma rays~cosmic rays emission rate at source



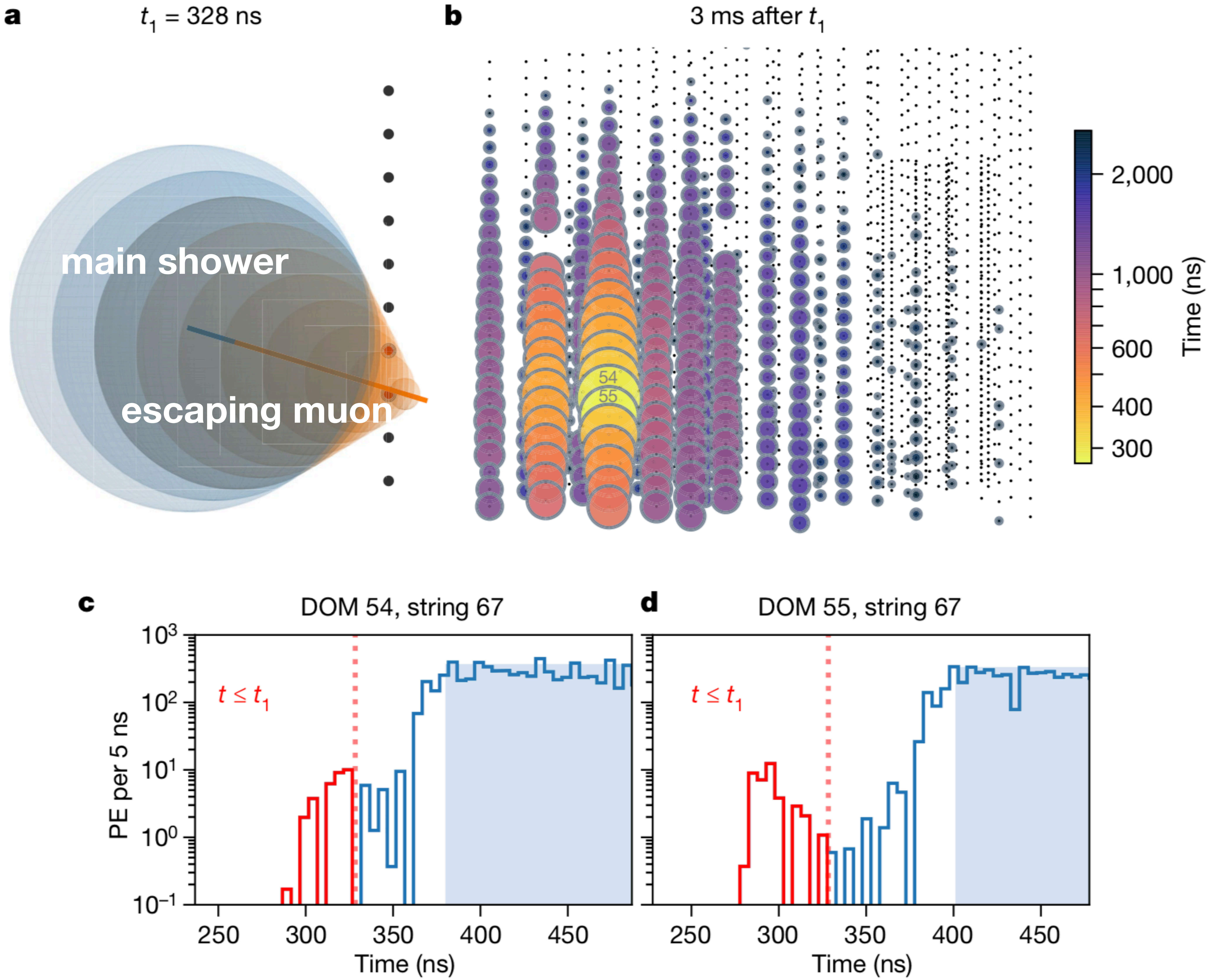
$$\frac{1}{3}\sum_{\nu_\alpha} E_\nu^2 Q_{\nu_\alpha} \simeq \frac{K_\pi}{4} E_\gamma^2 Q_\gamma \simeq \frac{1}{4} f_\pi \frac{K_\pi}{1 + K_\pi} E_p^2 Q_p$$

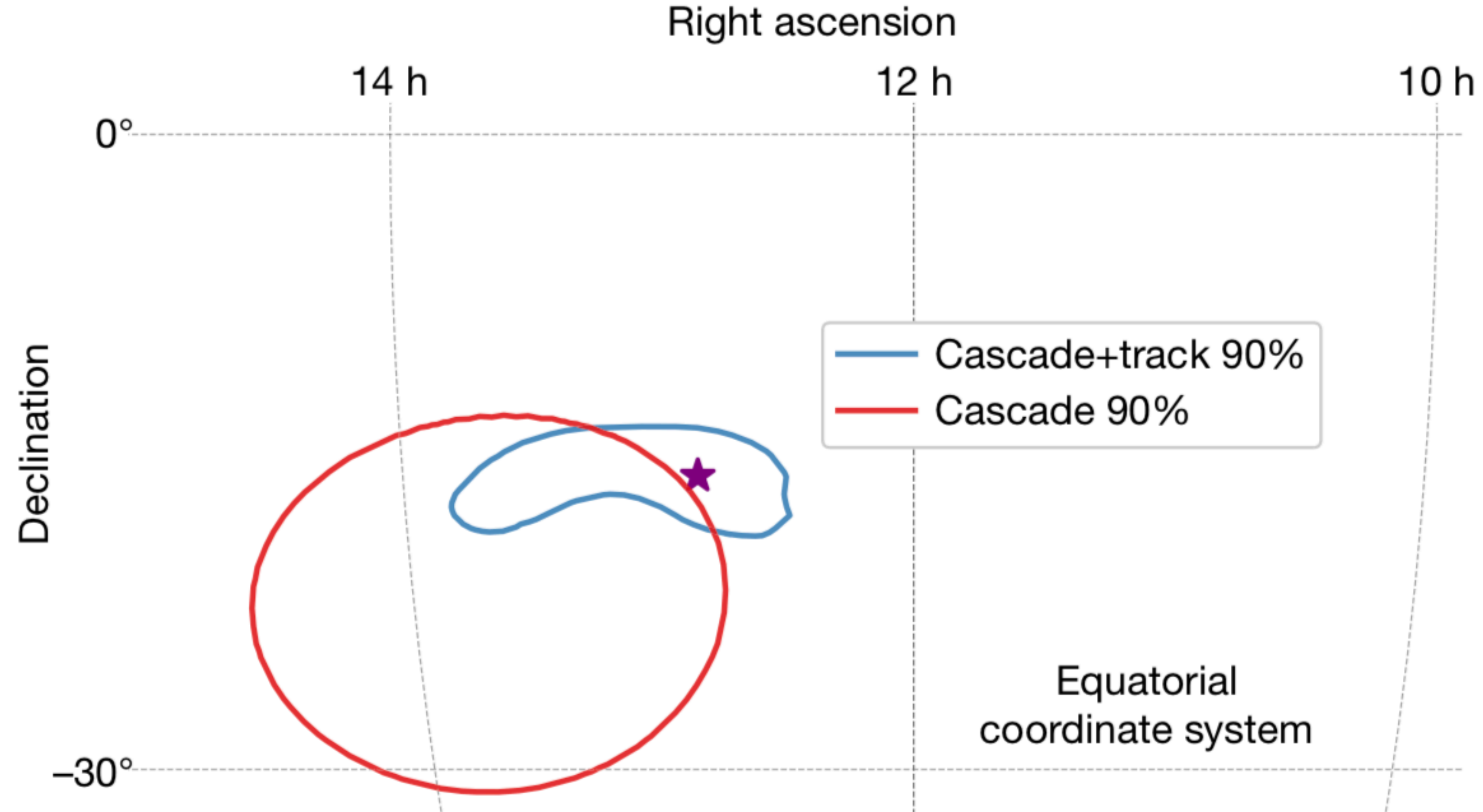
$$E_\nu \simeq \frac{1}{2} E_\gamma \simeq \frac{1}{20} E_p$$

Multi-messenger Connection

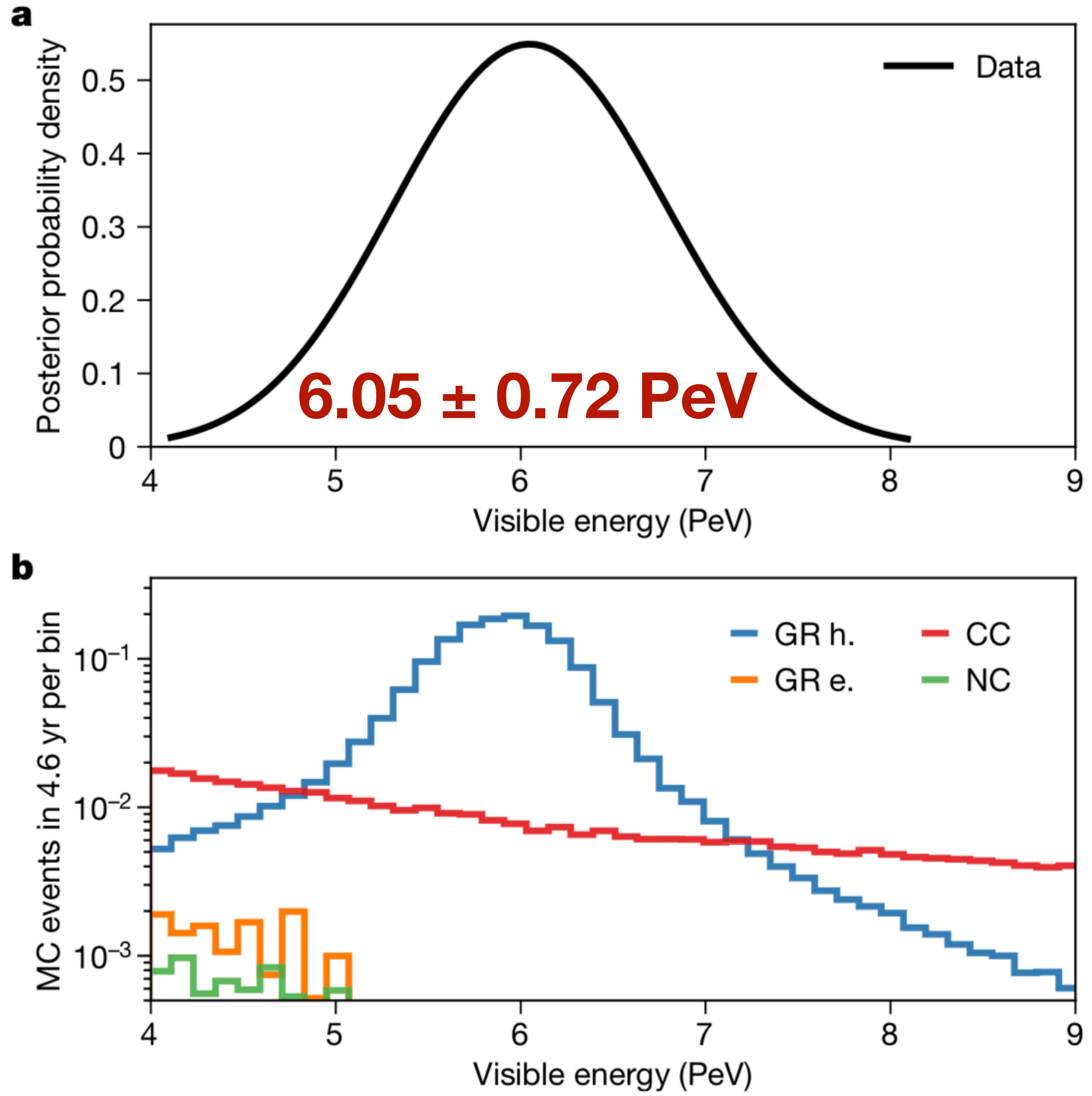


Glashow Resonance





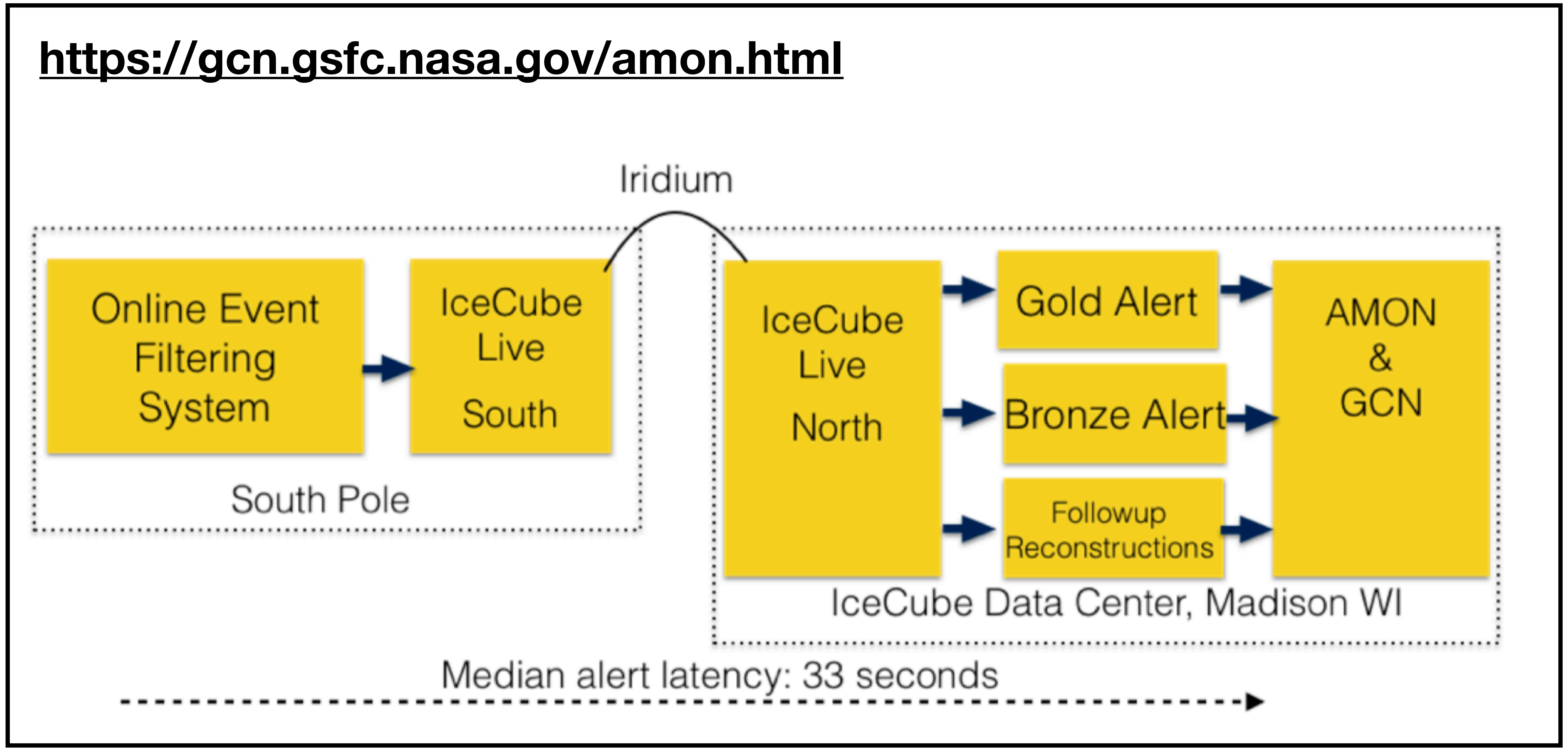
Directional reconstructions under two hypotheses



IceCube Nature 591 (2021) 7849

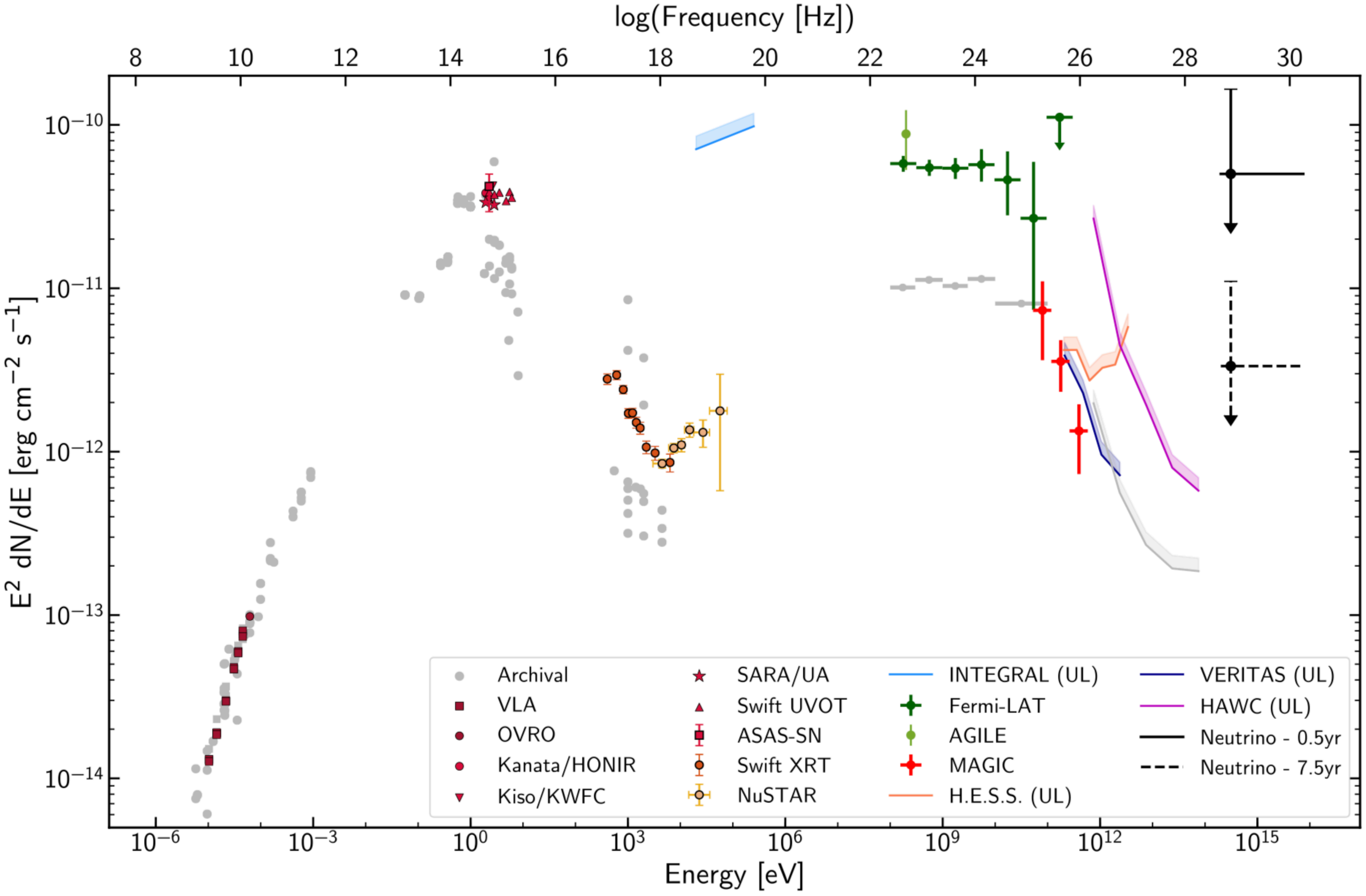
Realtime Alerts

- A public real-time alert system for followup multimessenger observation since 2016
- Information is shared as a GCN alert within 1 min after detection
- A new set of neutrino selection since 2019
  - "Gold" channel: ~10 alerts/yr, $\geq$50% astrophysical signalness
  - "Bronze" channel: ~20 alerts/yr, 30%-50% astrophysical signalness

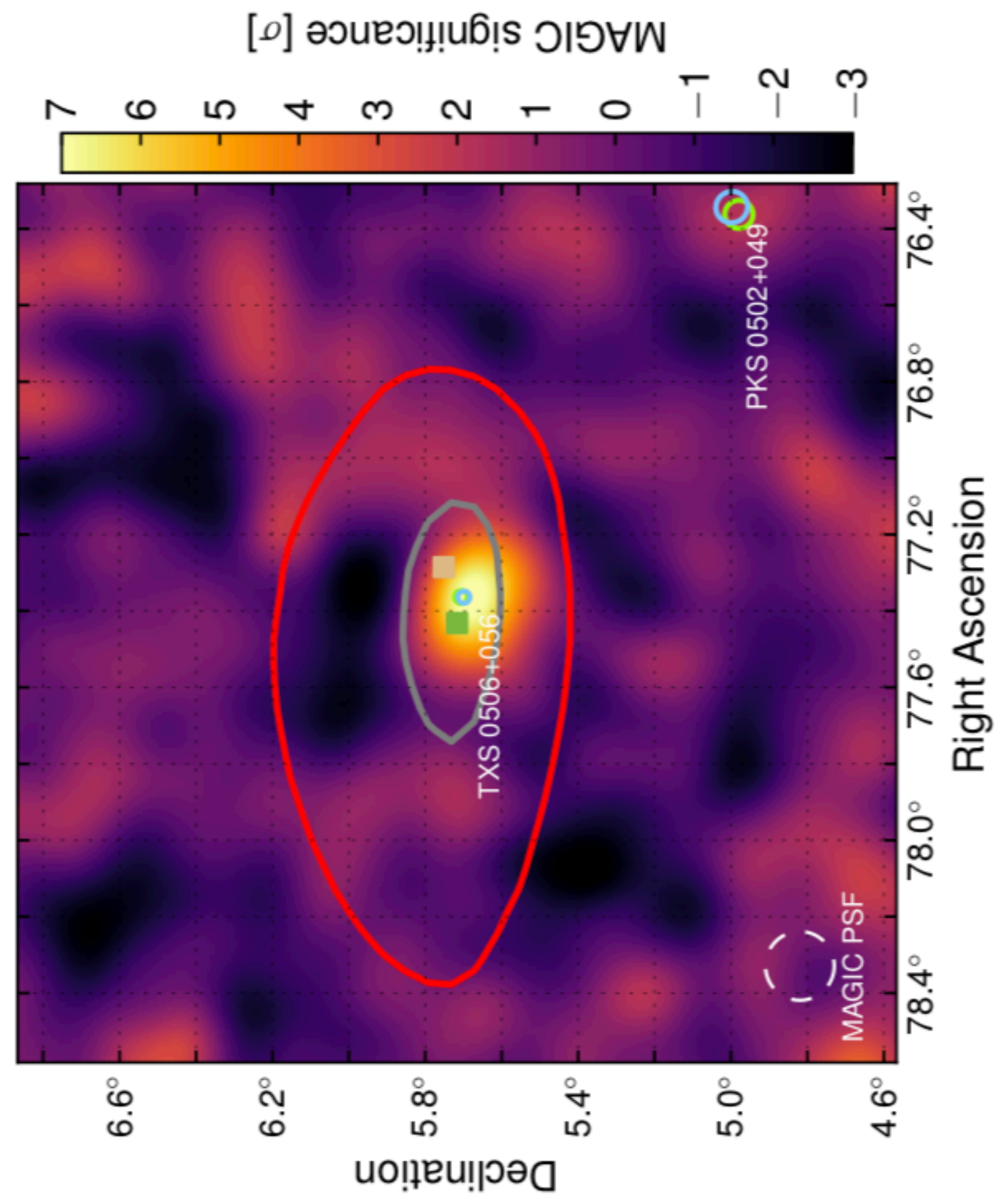


IceCube ICRC(2019) 1021

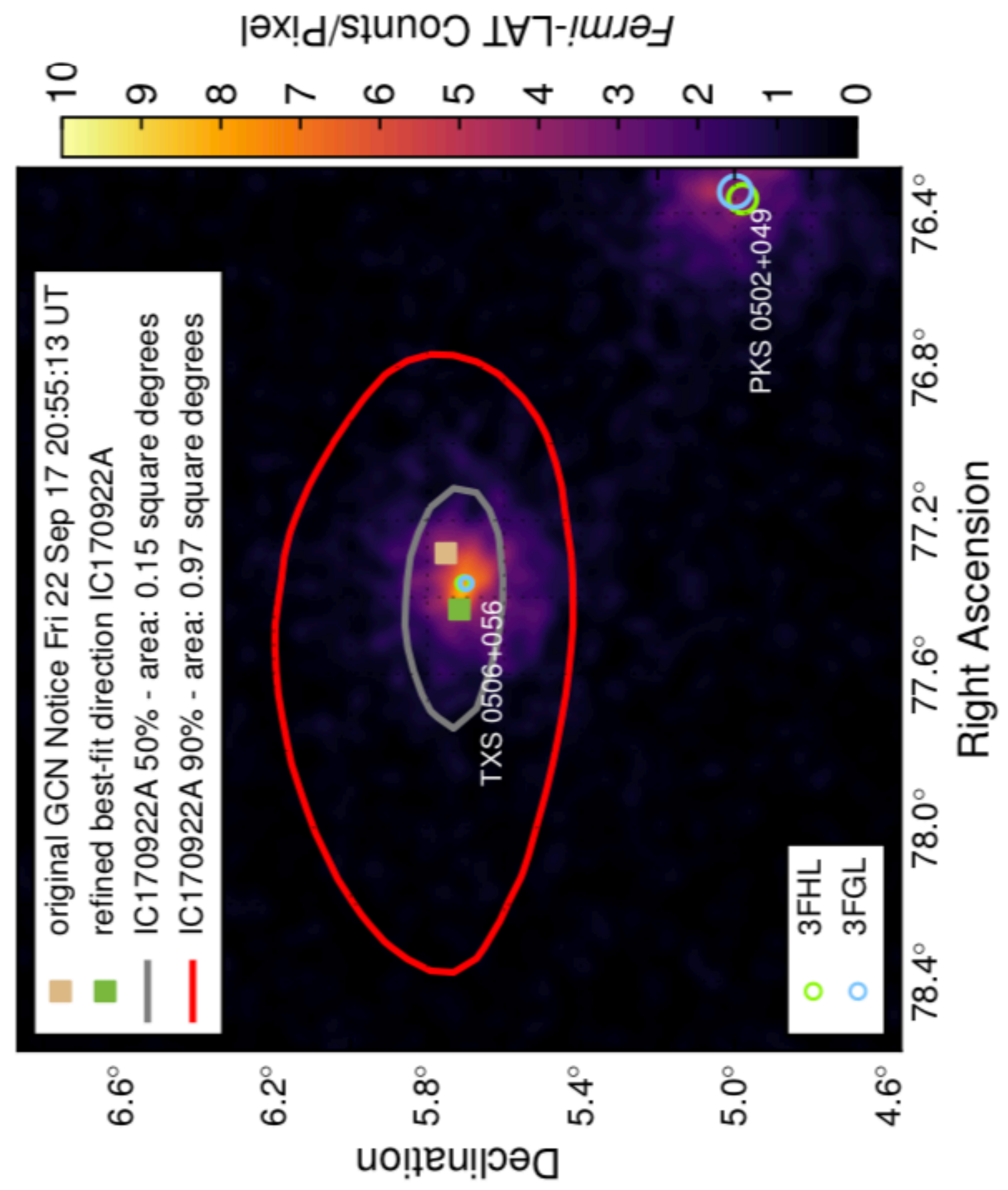
TXS 0506+056



SED in the direction of IceCube-170922A within 14 days

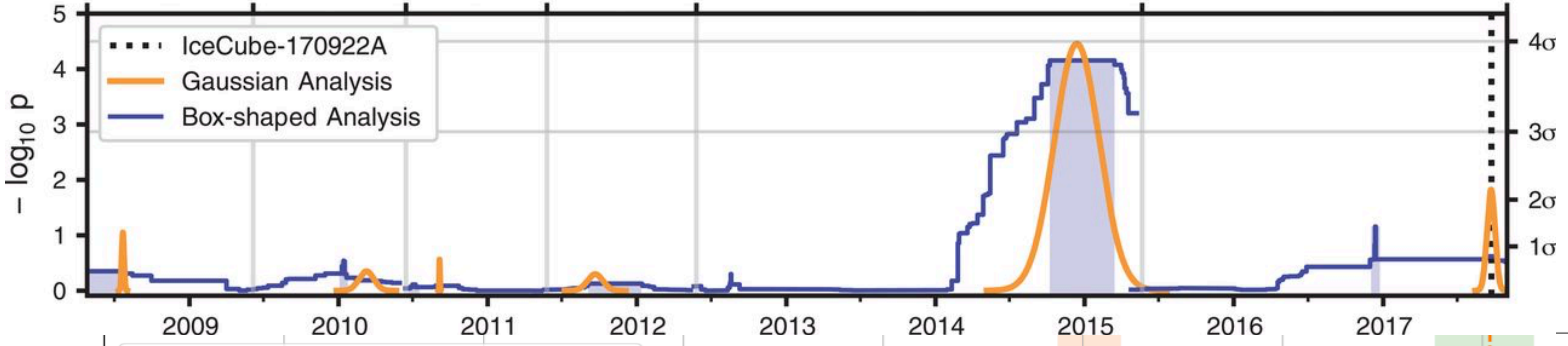


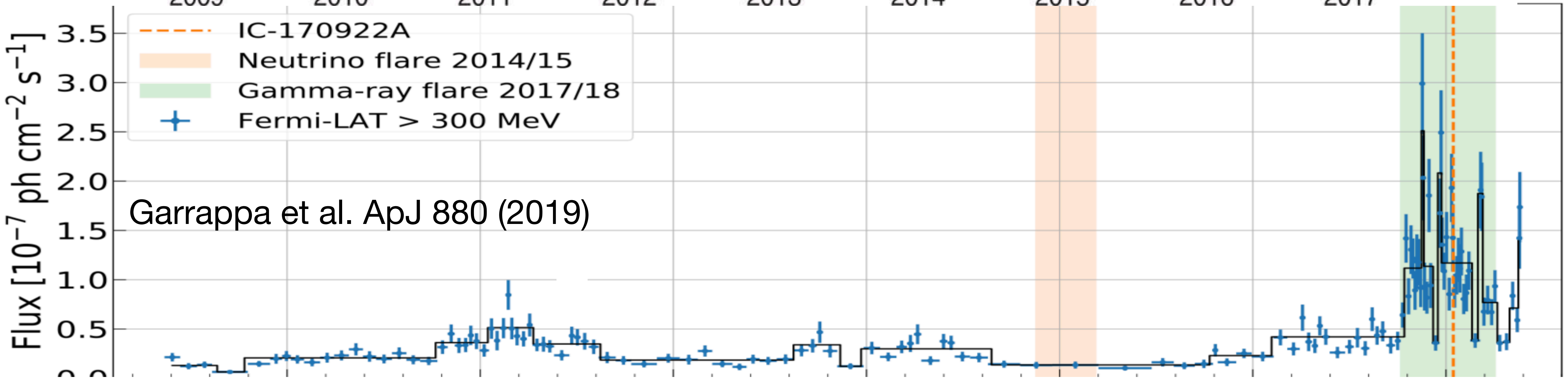
MAGIC detected > 100 GeV gamma rays

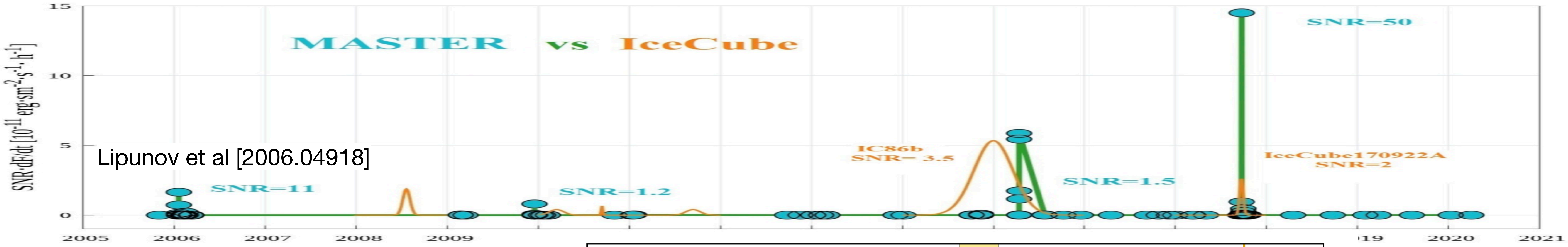


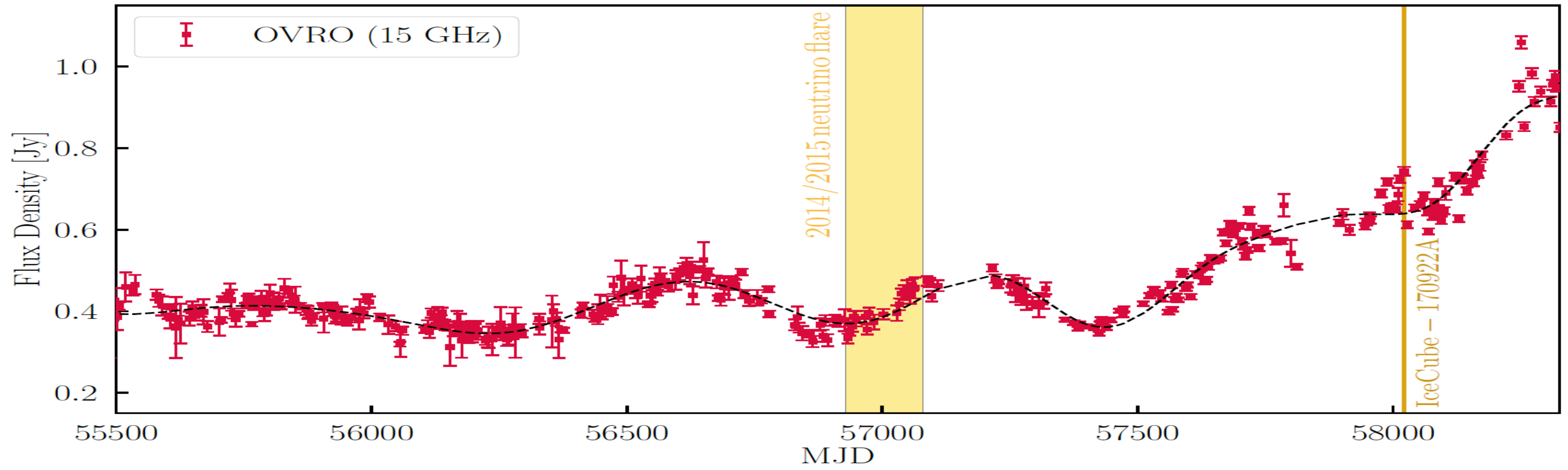
Fermi detected a flaring blazar within 0.06 degrees.

IceCube++ Science 361 (2018) 3698


IceCube-170922A
Gaussian Analysis
Box-shaped Analysis
$-\log_{10} p$
4σ
3σ
2σ
1σ
2009
2010
2011
2012
2013
2014
2015
2016
2017

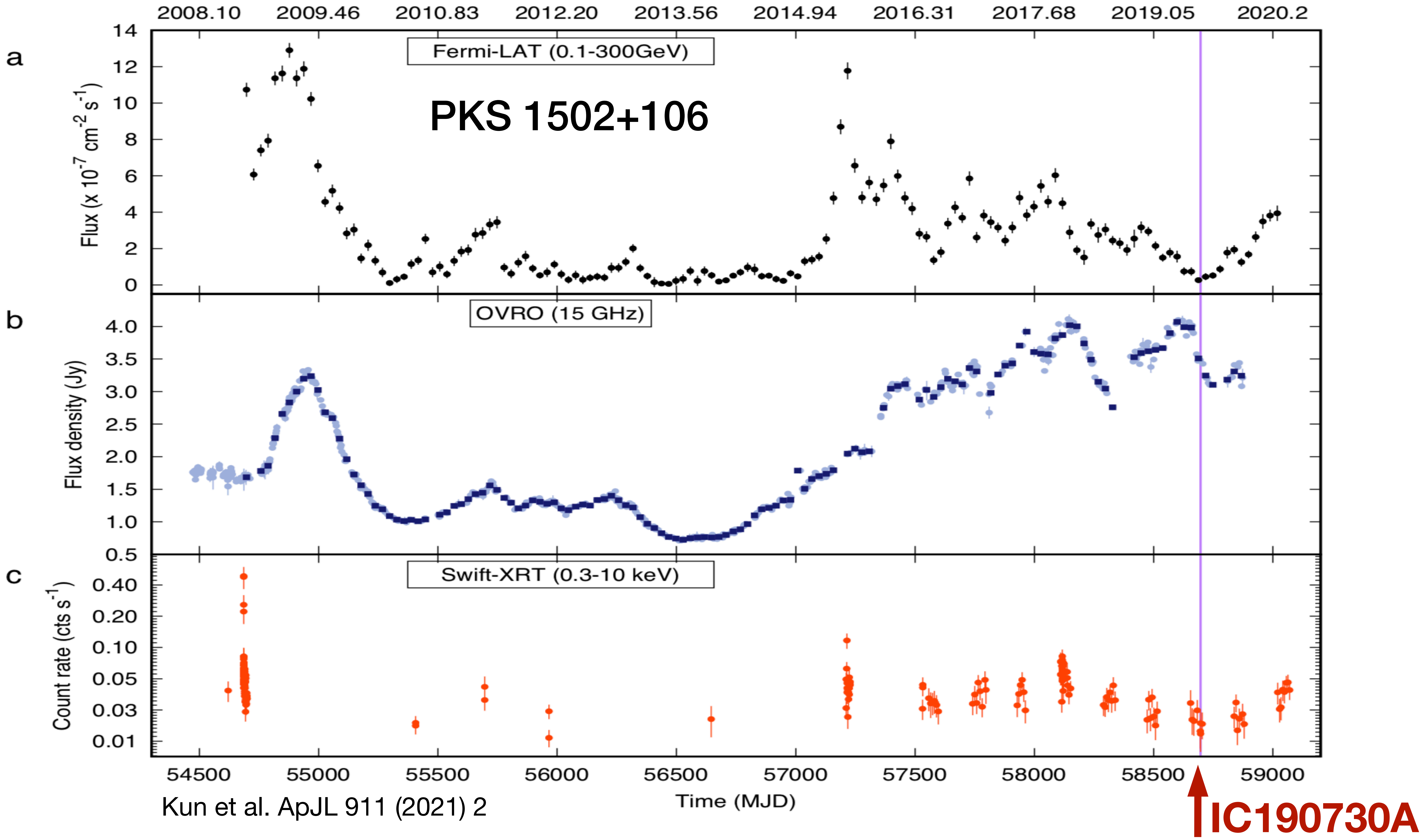

IC-170922A
Neutrino flare 2014/15
Gamma-ray flare 2017/18
Fermi-LAT > 300 MeV
Flux [10^{-7} ph cm^{-2} s^{-1}]
Garrappa et al. ApJ 880 (2019)


MASTER vs IceCube
SNR=50
IC86b
SNR= 3.5
IceCube170922A
SNR=2
SNR=11
SNR=1.2
SNR=1.5
Lipunov et al [2006.04918]
2005
2006
2007
2008
2009
2020
2021


OVRO (15 GHz)
2014/2015 neutrino flare
IceCube – 170922A
Flux Density [Jy]
MJD
55500
56000
56500
57000
57500
58000

TXS 0506+056

IC190730A

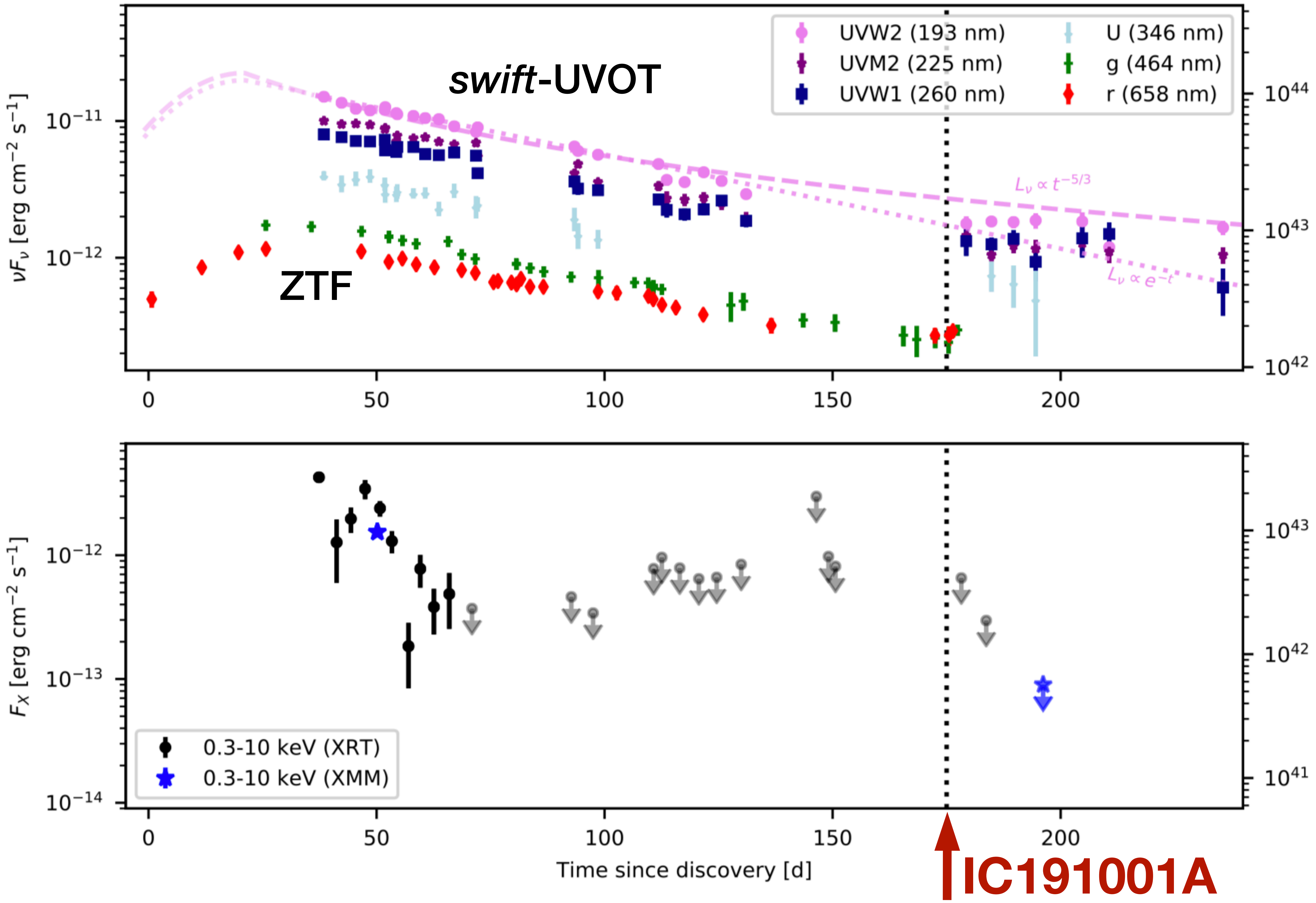


Kun et al. ApJL 911 (2021) 2

- coincident with AGN PKS 1502+106
- Radio outburst

IC191001A

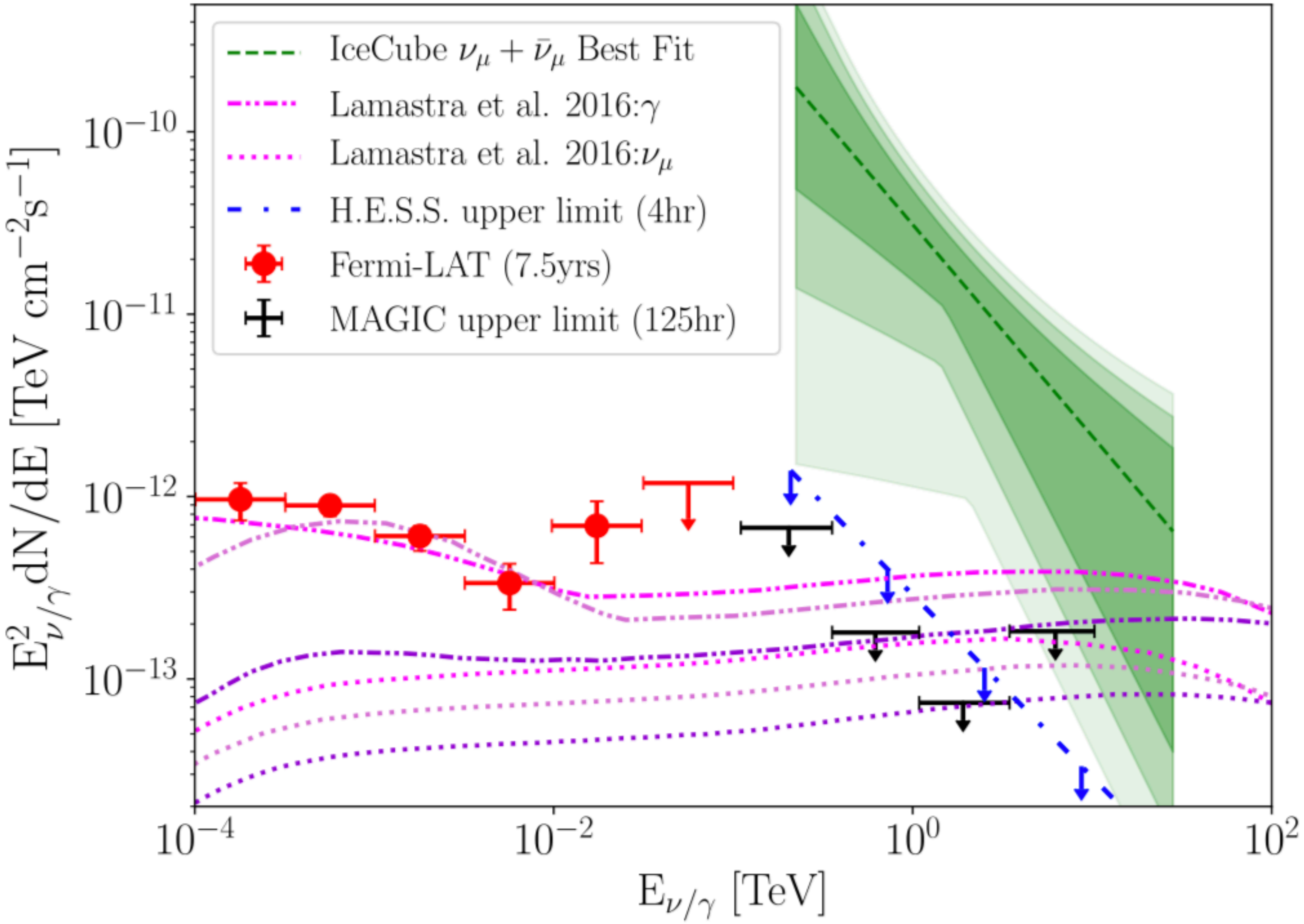
Multi-wavelength light-curve of AT2019dsg

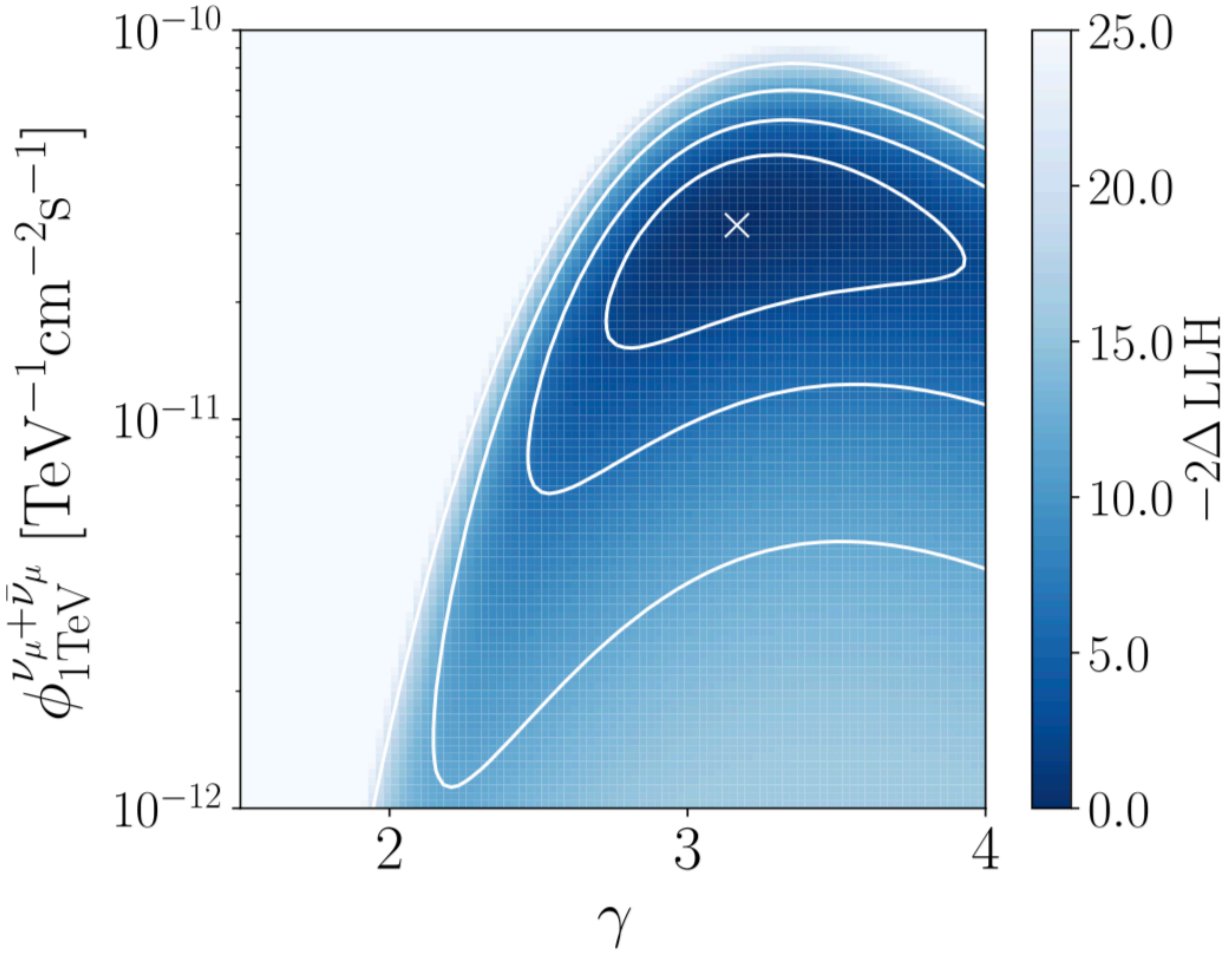


- Coincident with TDE AT2019dsg (d~230 Mpc) discovered by Zwicky Transient Facility (ZTF)
- Radio TDE coincident with IC1901001A 0.5% chance probability

Stein et al. Nature Astron. 5 (2021) 5

NGC 1068

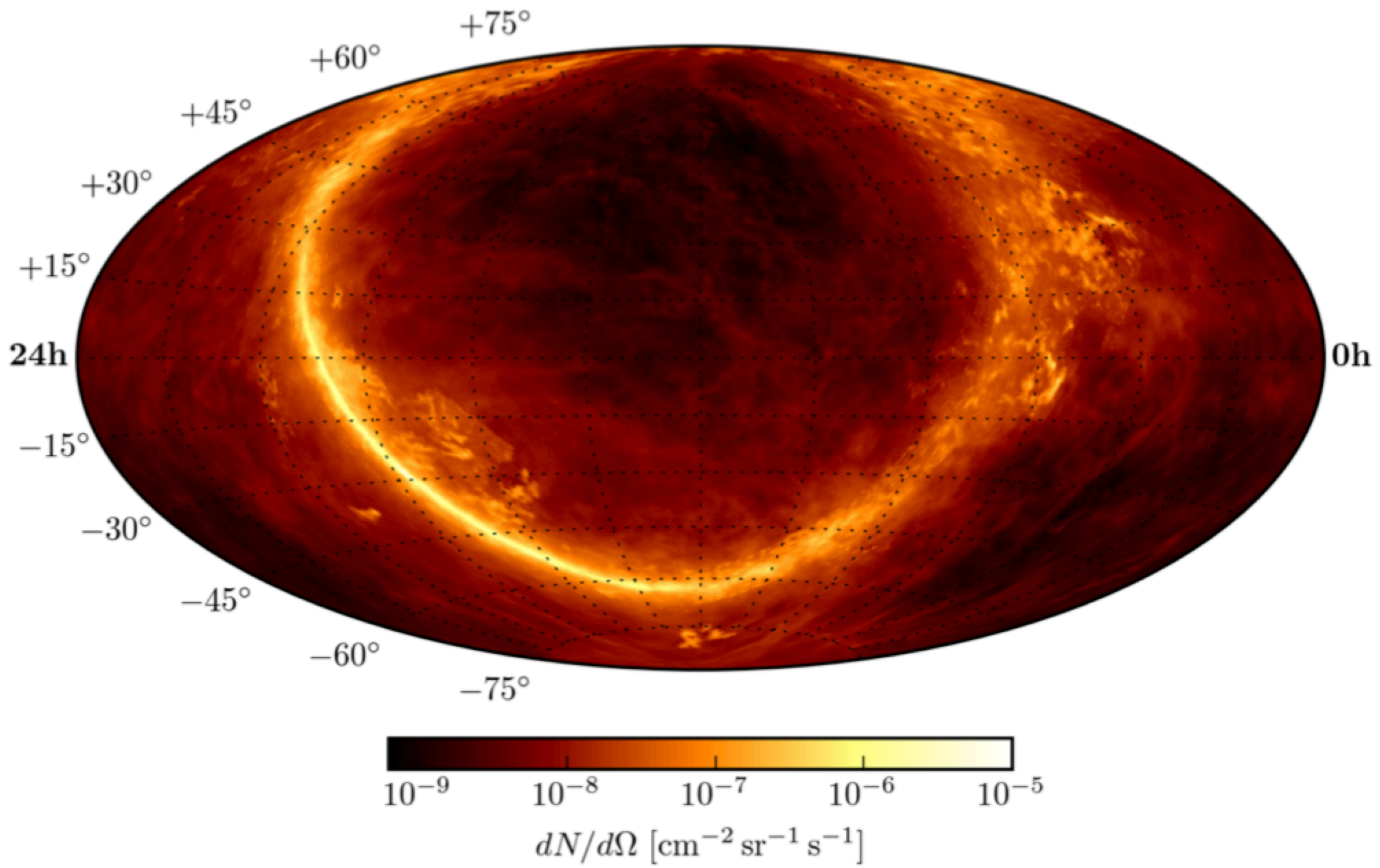




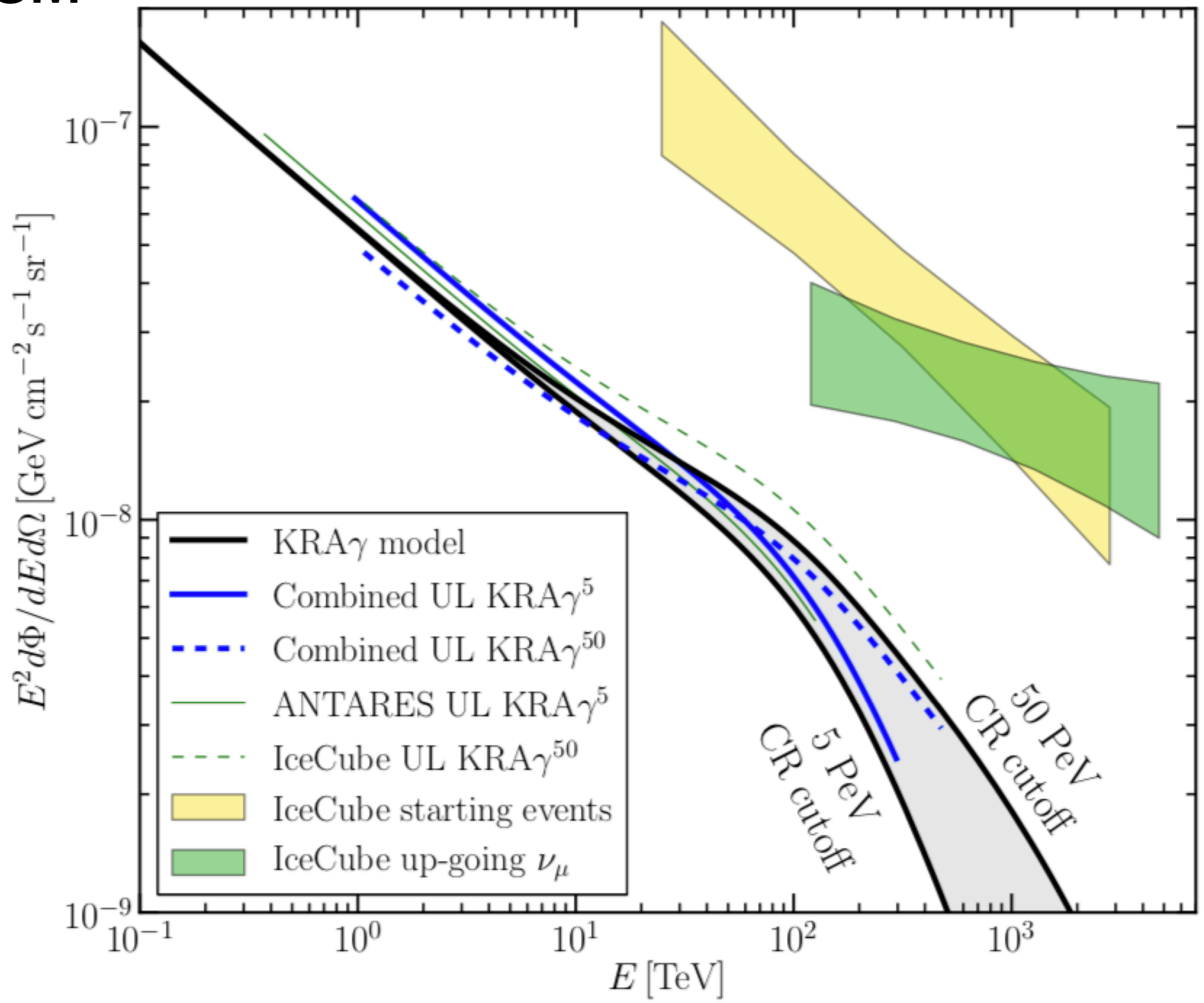
IceCube PRL 124 (2020) 5

Diffuse Galactic Neutrinos

Guaranteed Galactic flux from CR interactions with the ISM



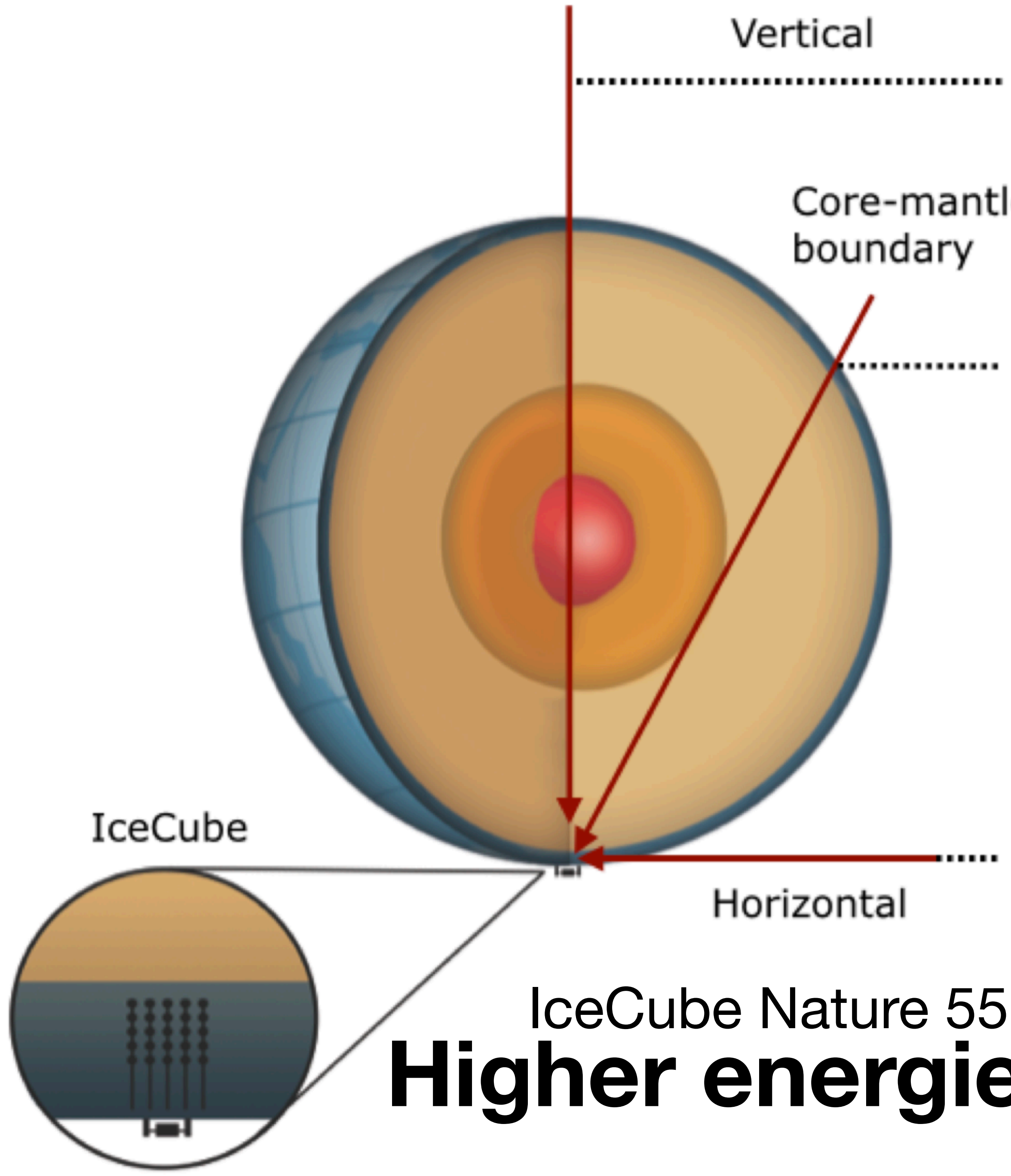
Energy integrated neutrino flux per unit of solid angle of the KRA_γ^5 model

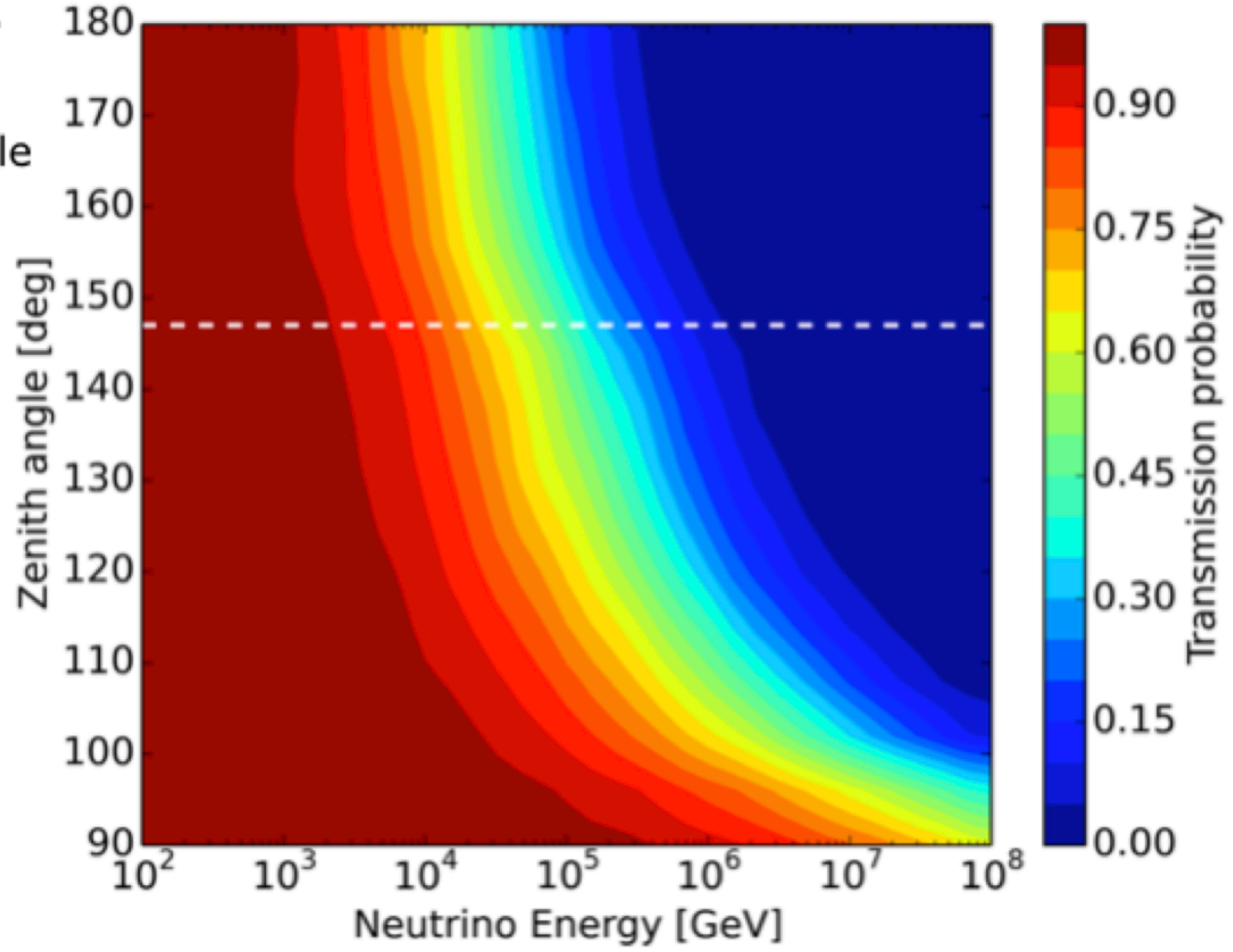


Upper limits on the Galactic diffuse gamma-ray emission compared to predicted neutrino flux from KRAγ.

ANTARES & IceCube ApJL 868 (2018) 2

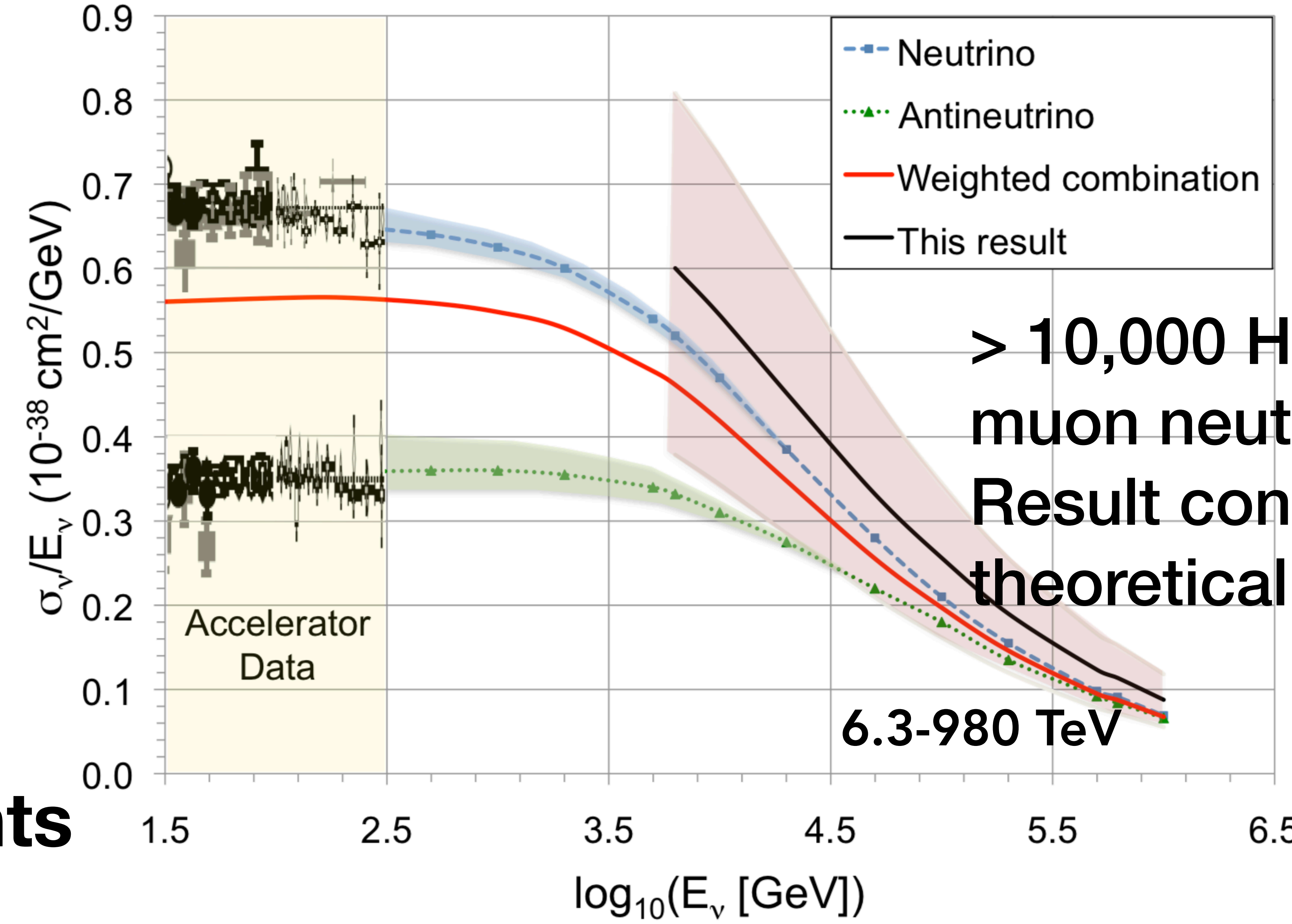
Cross section & Inelasticity



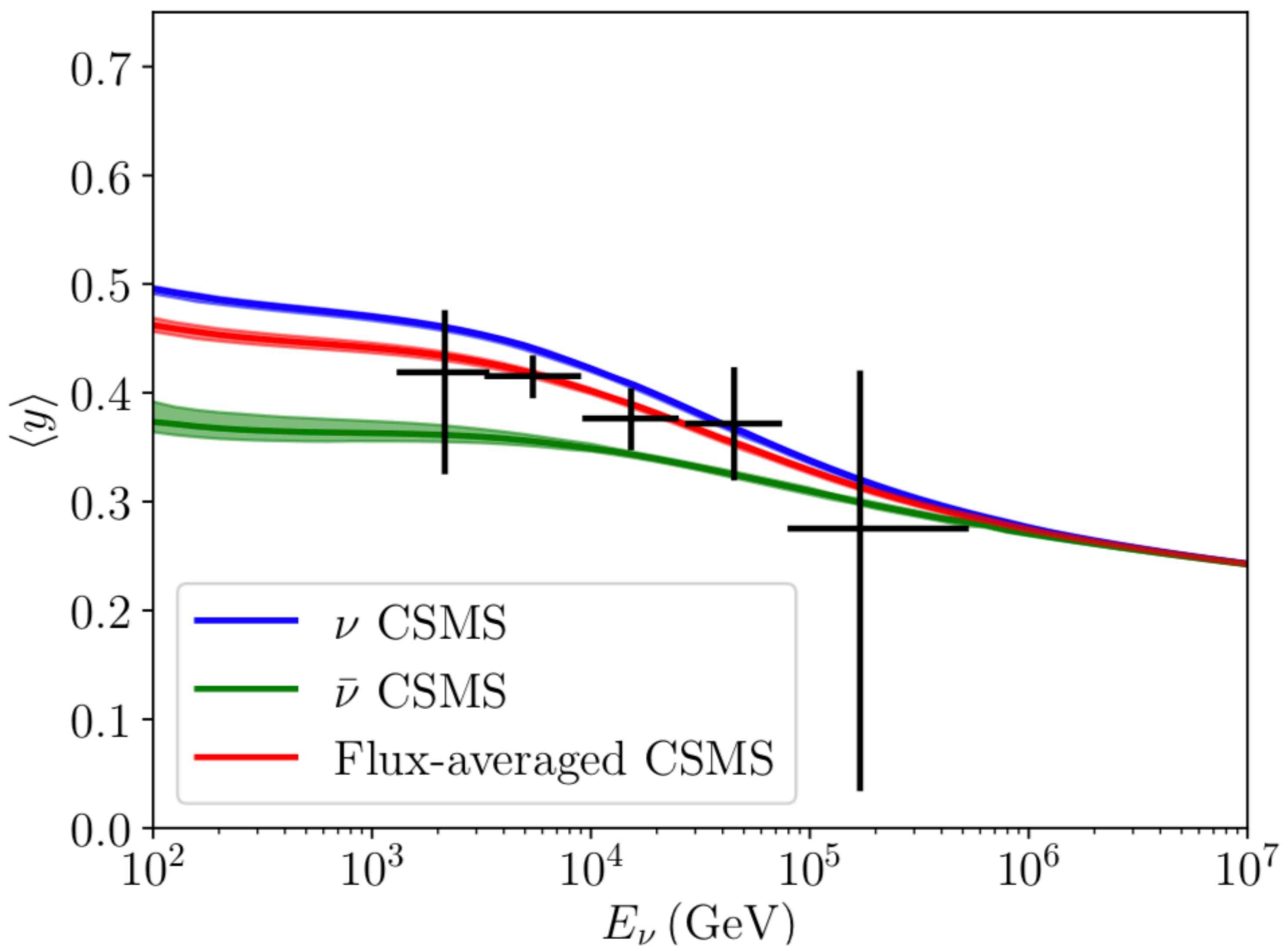


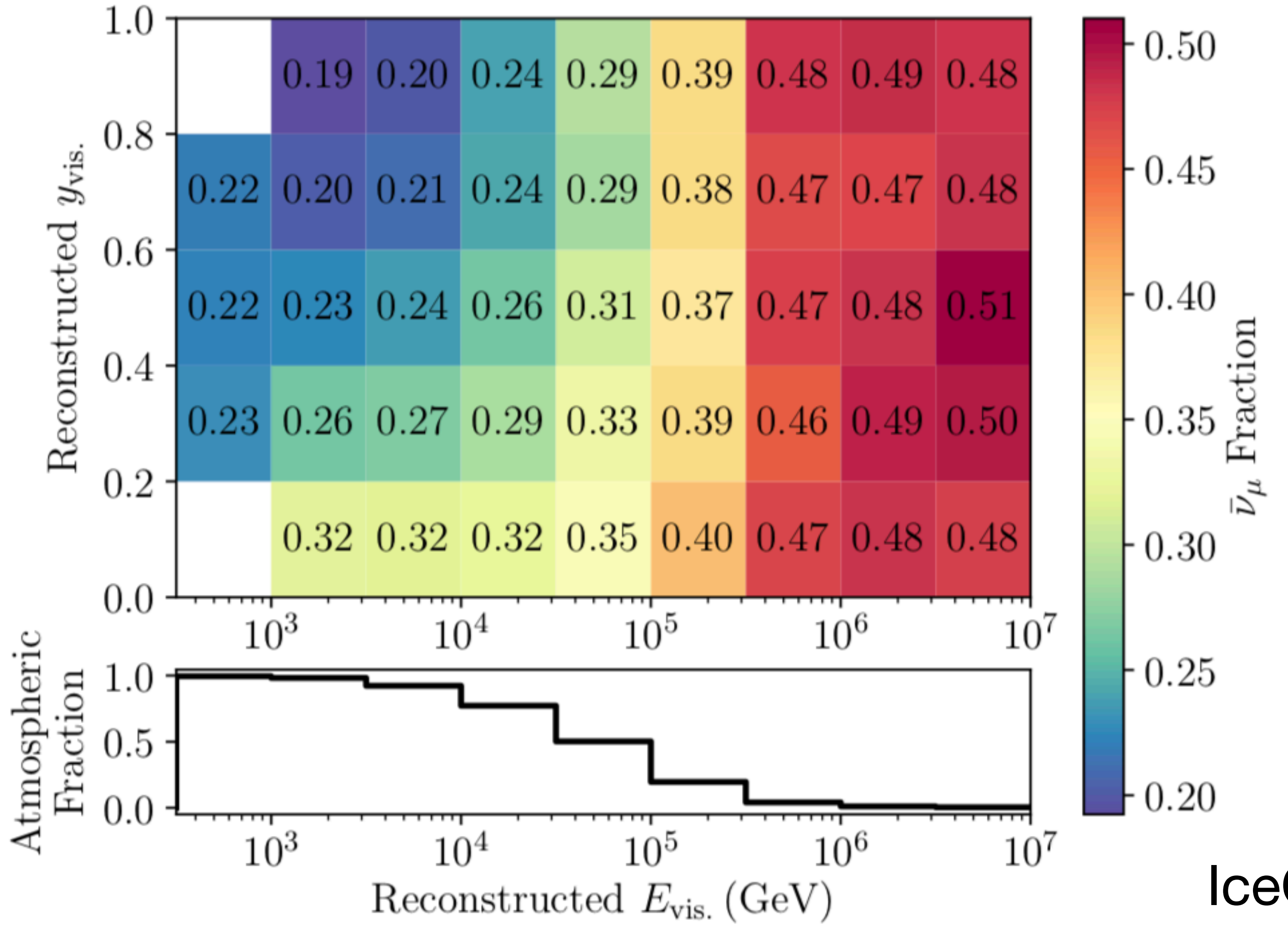
IceCube Nature 551 (2017)

Higher energies than previous measurements



> 10,000 HE up-going muon neutrino events. Result consistent with theoretical prediction.

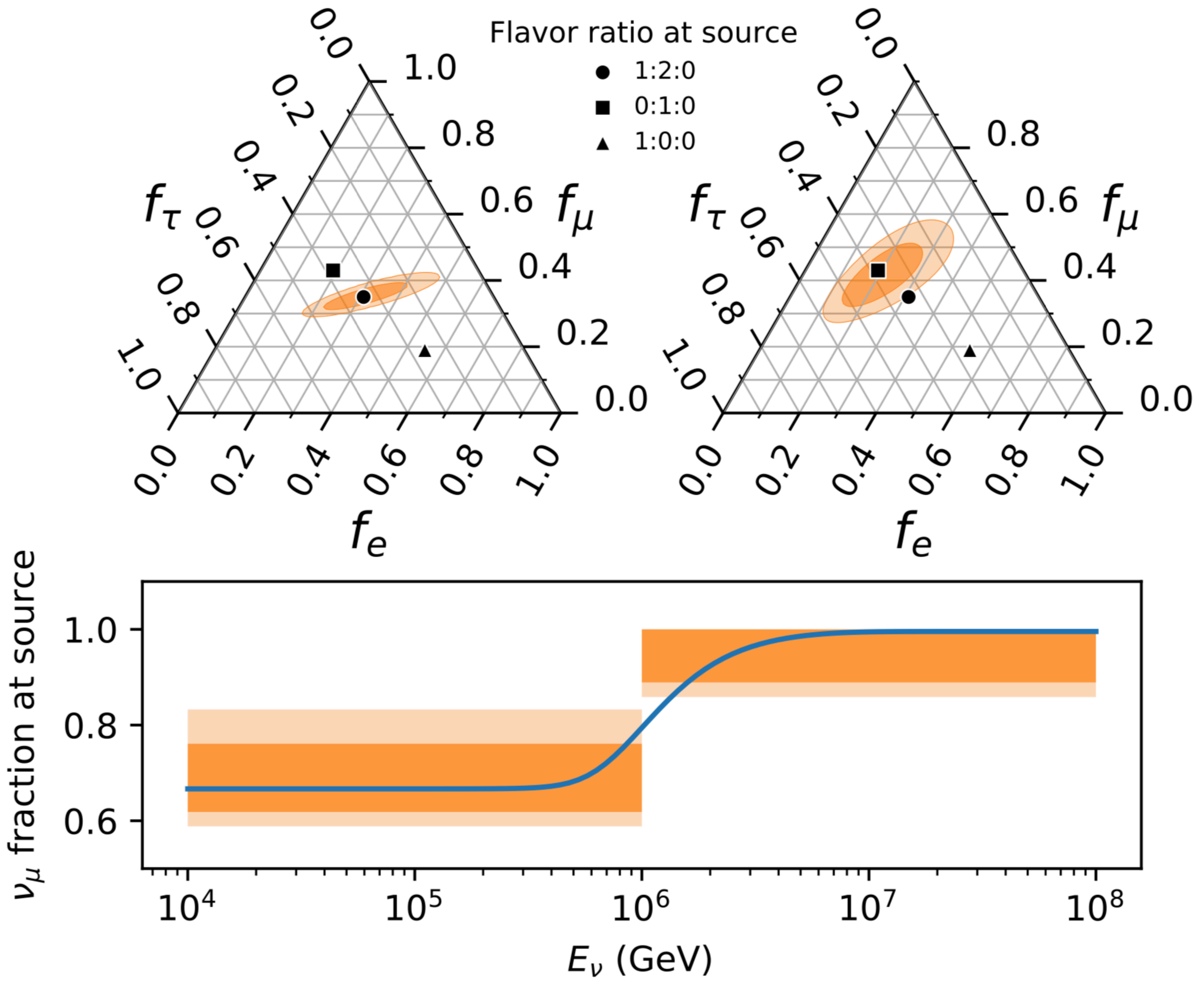


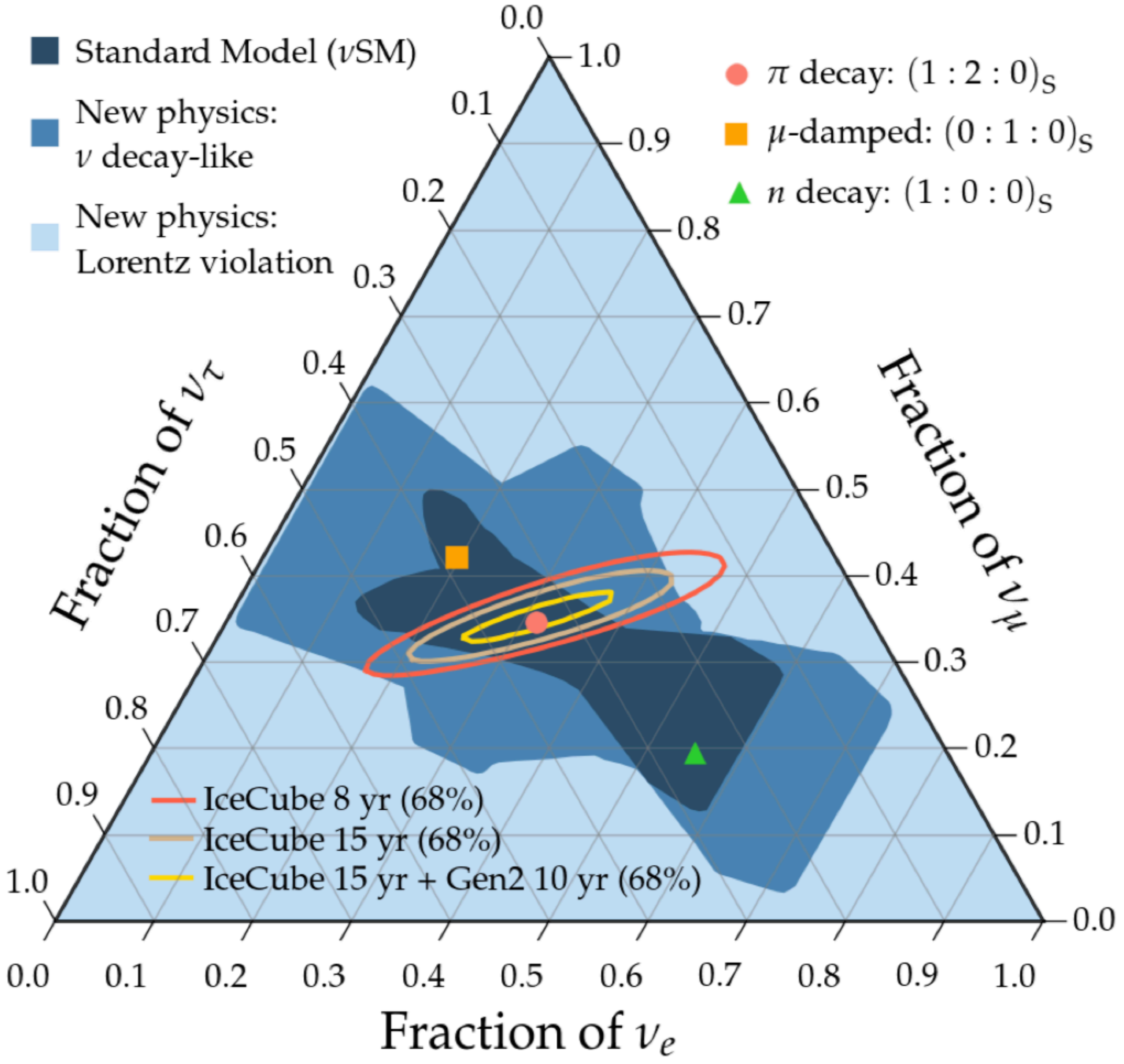


- Fraction of energy transferred to hadrons in neutrino interactions.
- Result consistent with prediction.
- Zero charm production.

IceCube PRD 99(2019)3

Flavor Composition

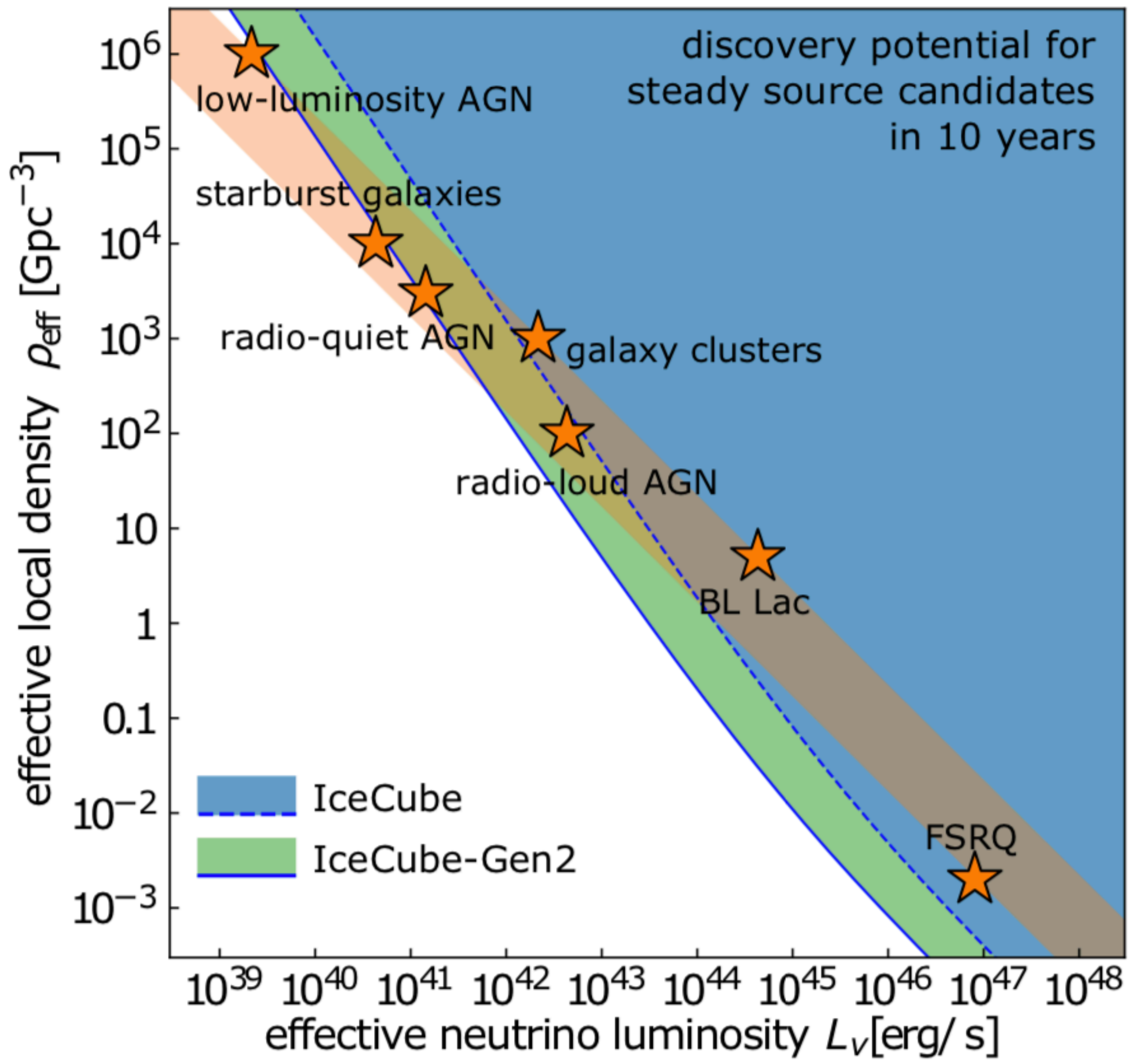


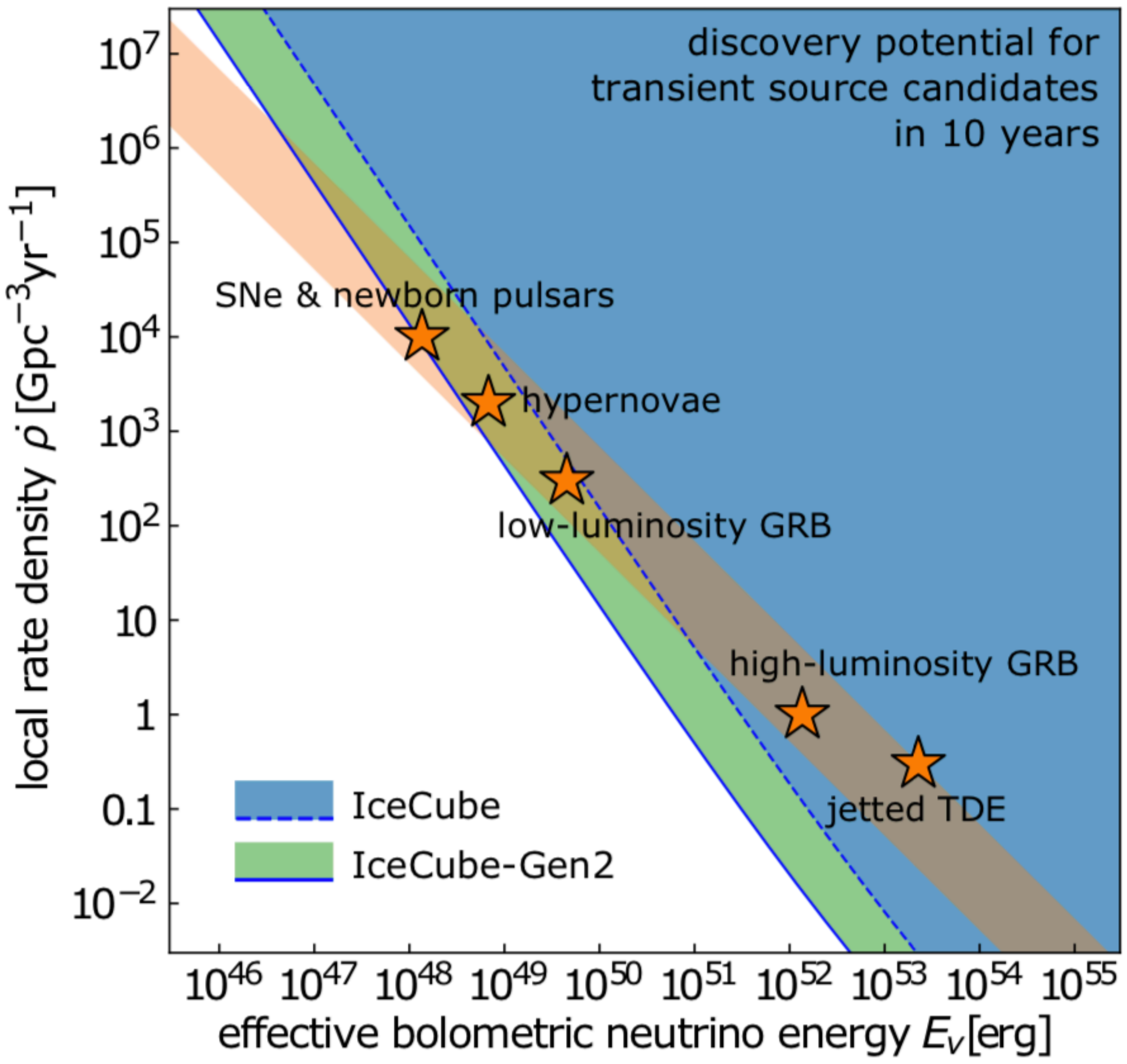


- Precision measurement of flavor composition.
- Sensitivity to energy-dependent flavor composition.

IceCube-Gen2 White Paper [2008.04323]

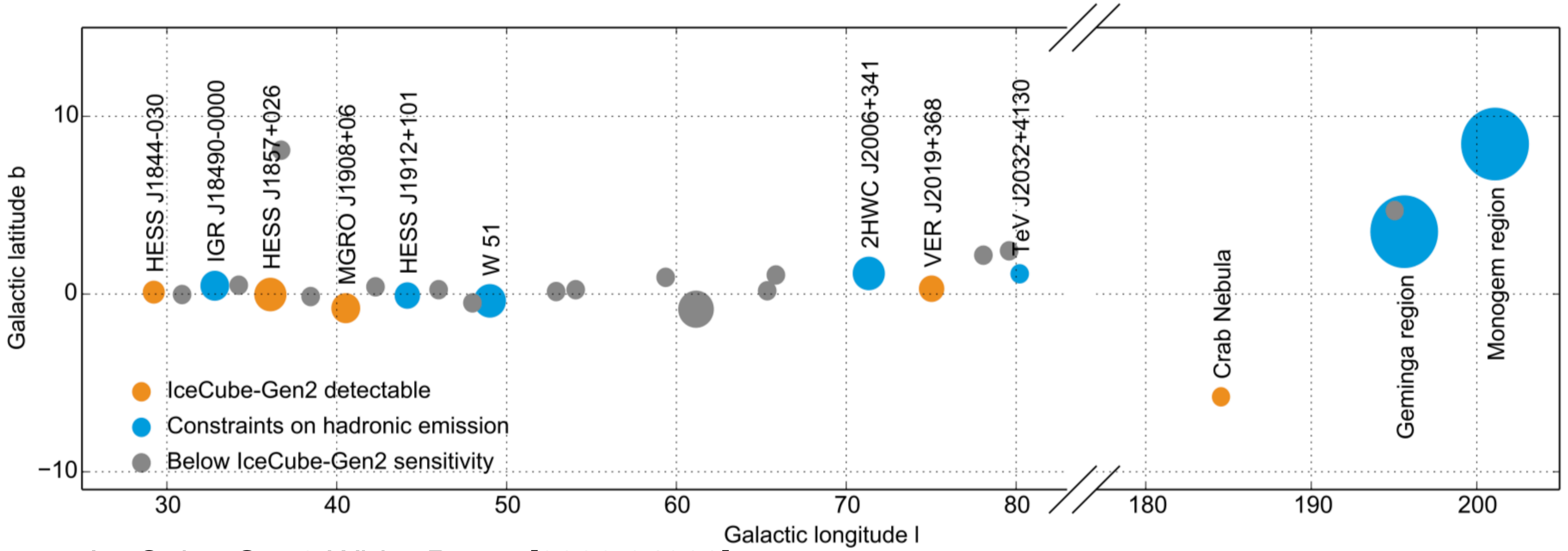
Source Population





IceCube-Gen2 White Paper [2008.04323]

Galactic Sources

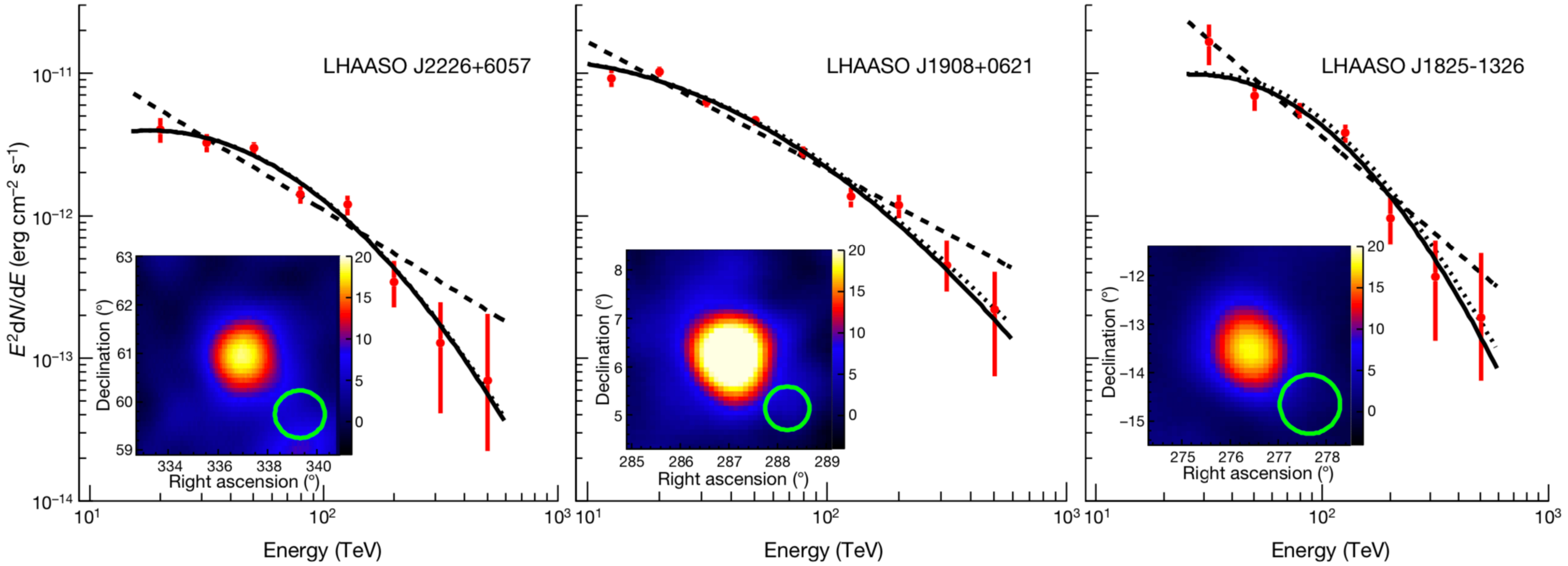


IceCube-Gen2 White Paper [2008.04323]

Detectability of Northern Sky TeV Galactic gamma-ray sources detected by HAWC assuming solely hadronic origin of TeV gamma rays.

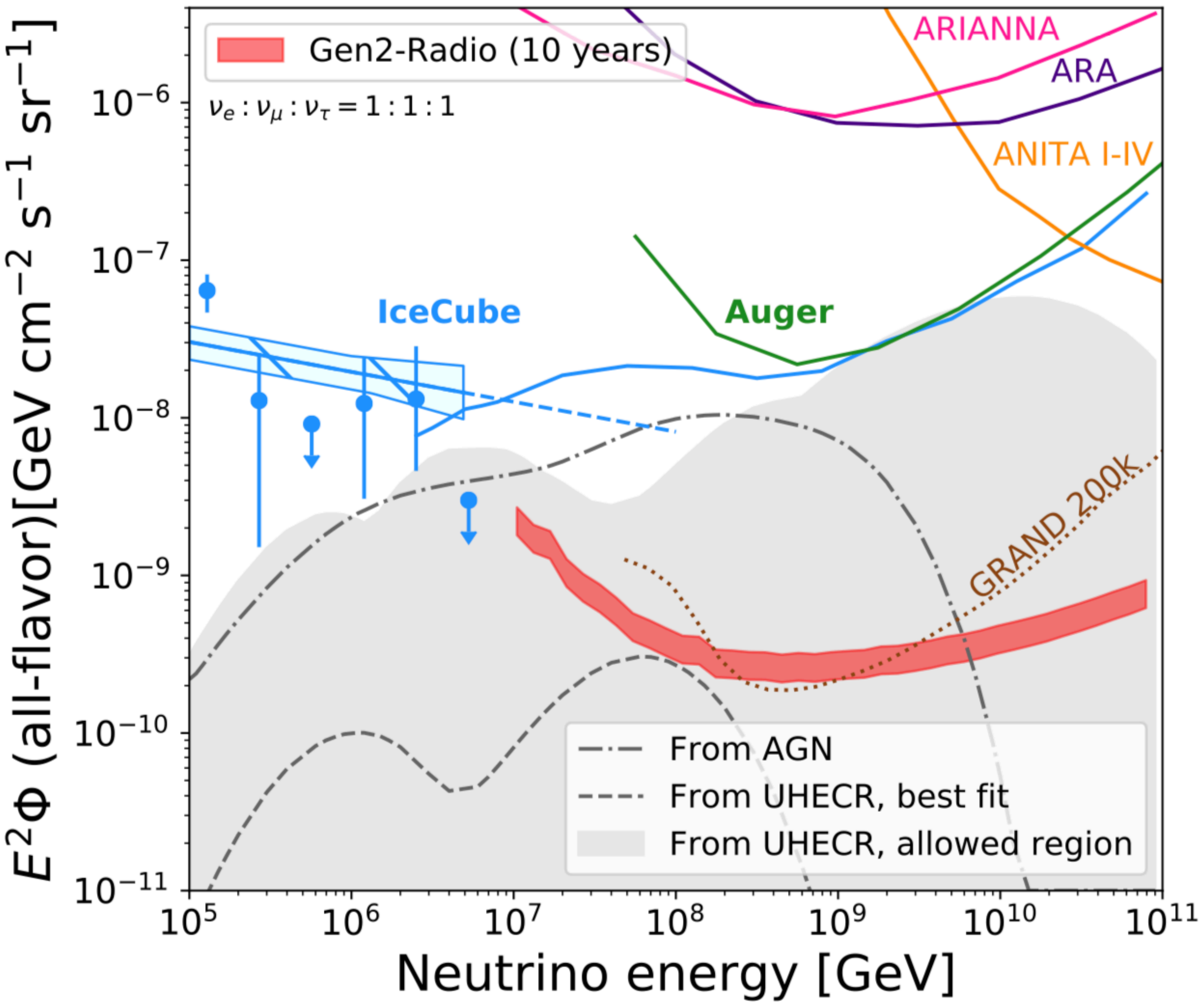
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

- LHASSO detected sources beyond 100 TeV.
- Indication of hadronic processes



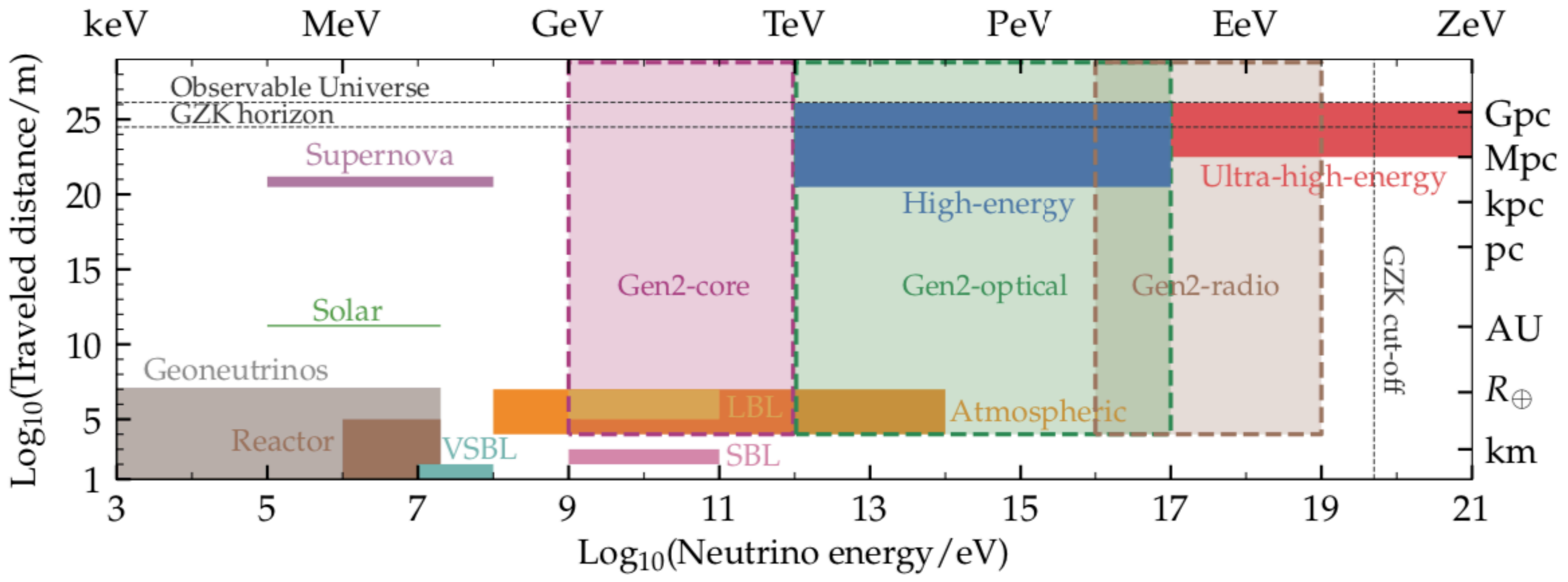
UHE neutrinos

PeV-EeV neutrino flux



IceCube-Gen2 White Paper [2008.04323]

Next-Generation Neutrino Telescopes



Ultra-high-energy:

- Detecting extensive air shower.
- Explore cosmogenic neutrinos, sources and interactions at extreme energies.
- RNO-G, GRAND, POEMMA…

High-energy:

- Larger volume, better sensitivity, complementary field of view
- KM3NET, Baikal-GVD, P-ONE: view of the Southern sky

Development of experiments on other messengers is also happening.

IceCube-Gen2 White Paper [2008.04323]