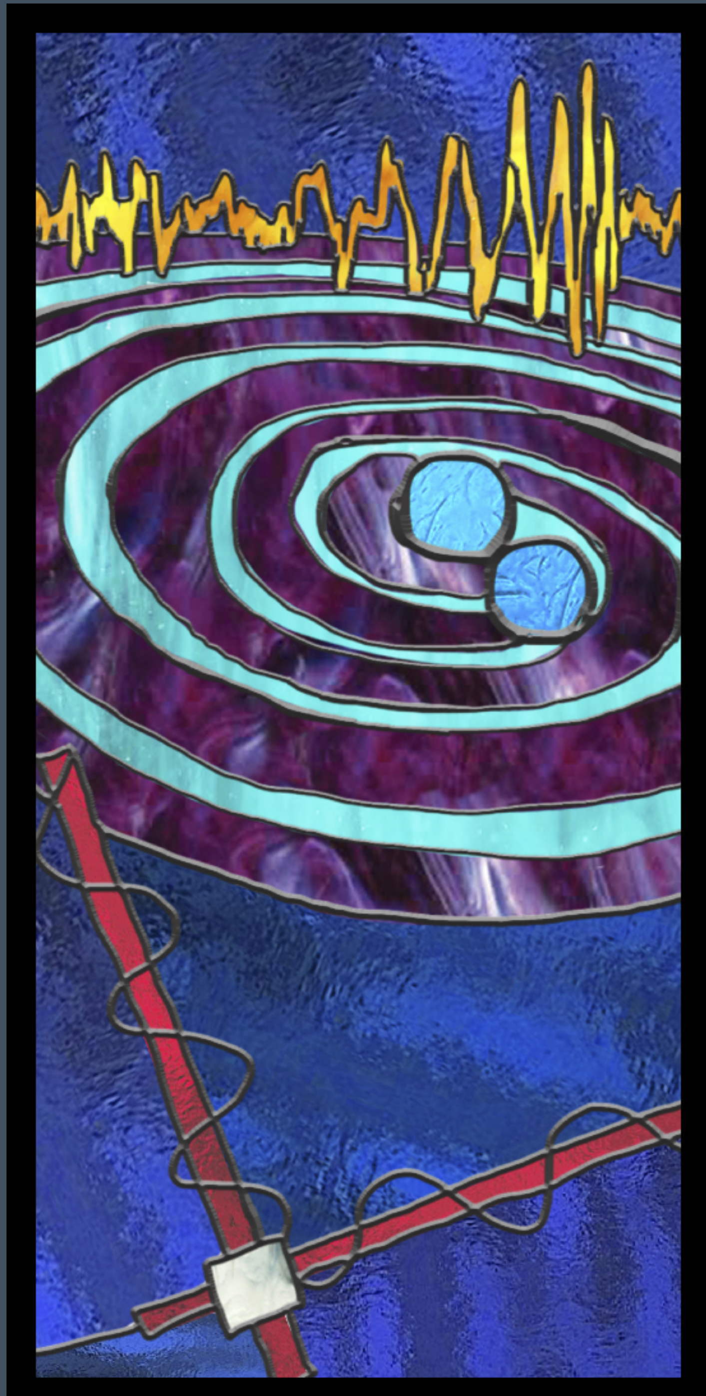
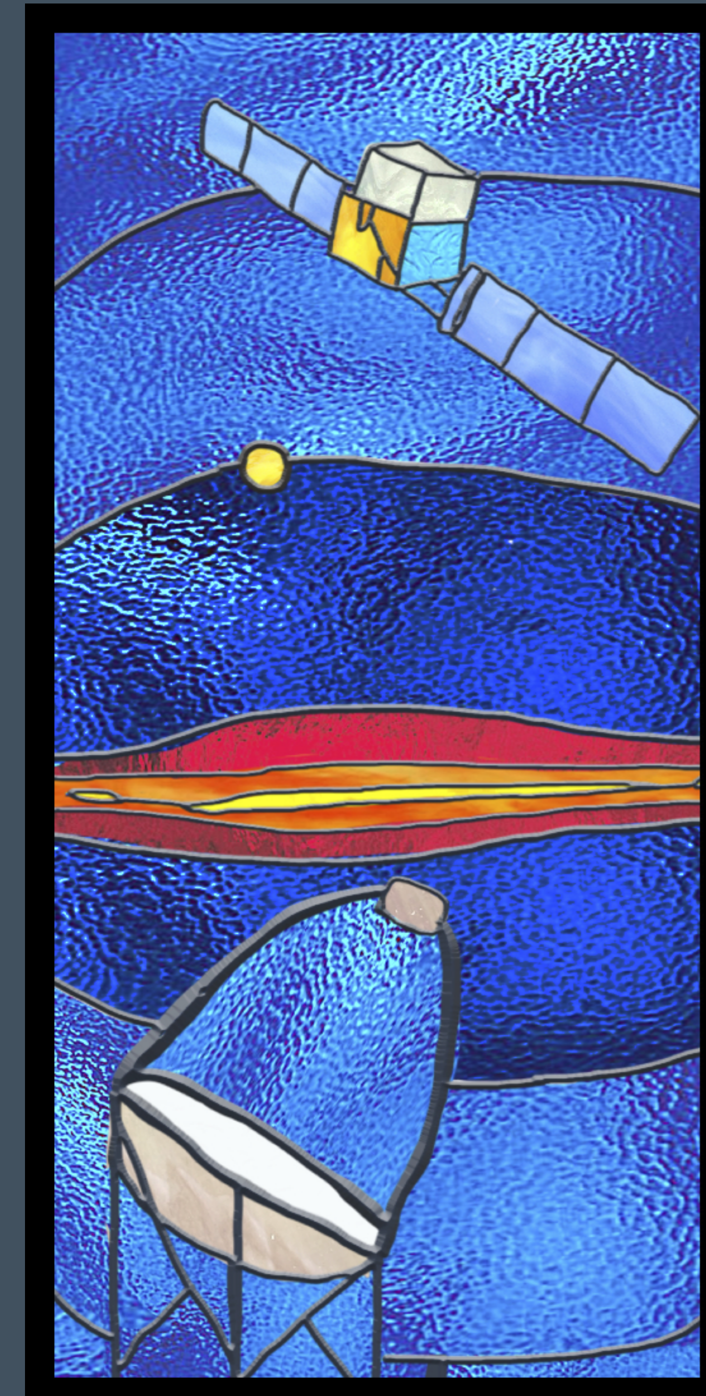




High-Energy Messengers: Present & Future

VILLUM FONDEN

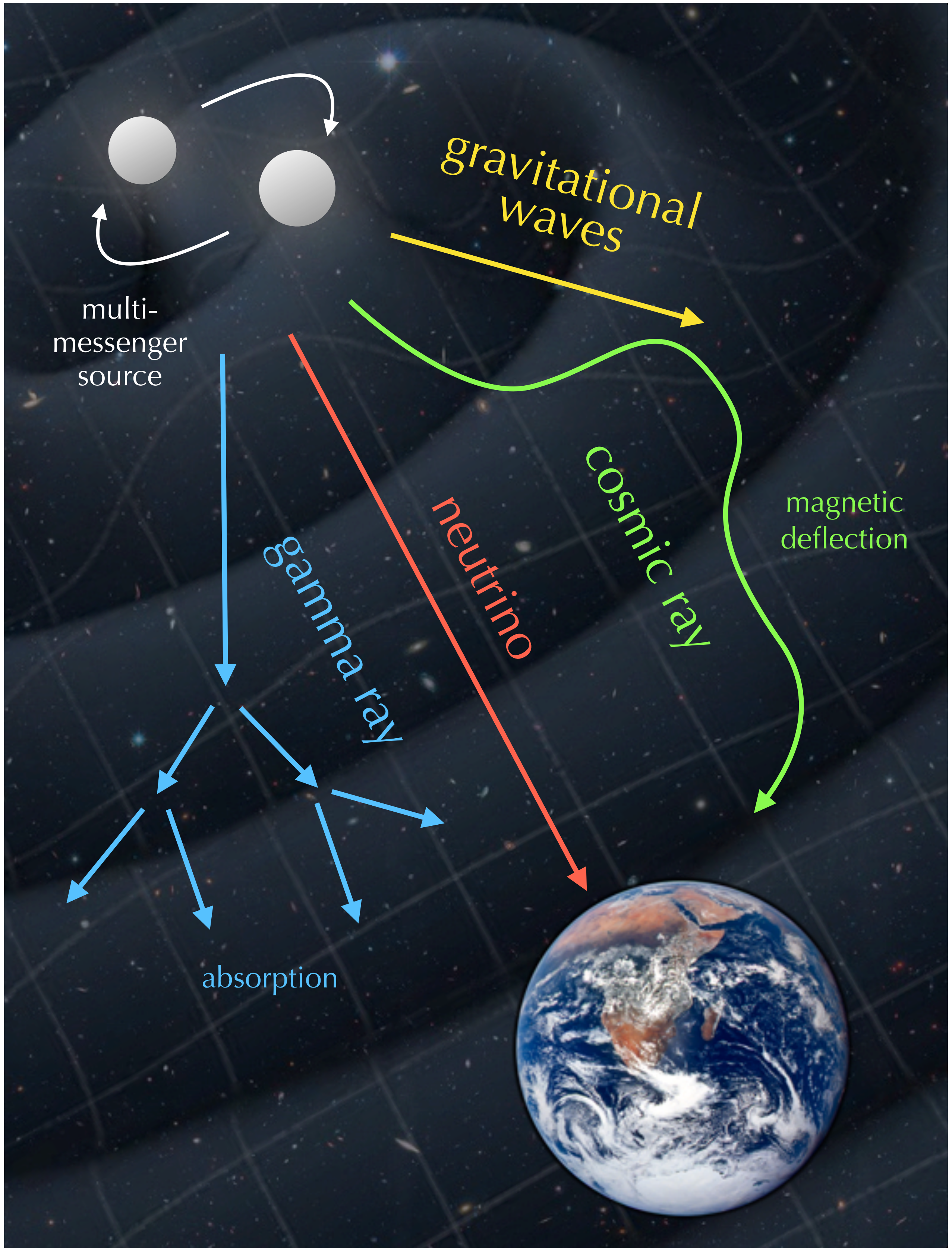
Markus Ahlers

WIN2019, Bari

June 6, 2019

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



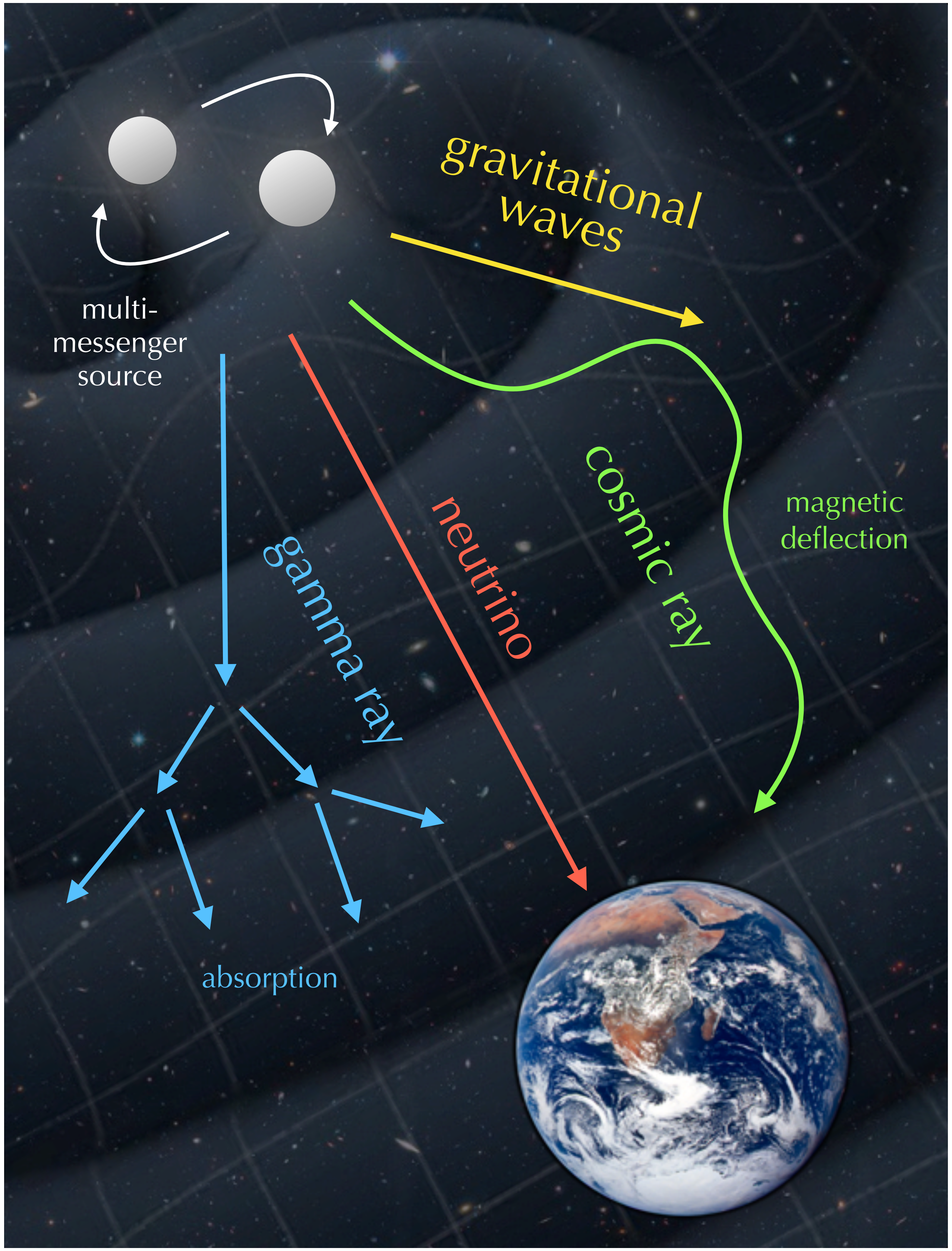
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

Inelastic **cosmic ray collisions with gas or radiation** create a flux of secondary pions/kaons.

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

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

Multi-Messenger Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

no absorption in cosmic backgrounds
(unlike gamma-rays)

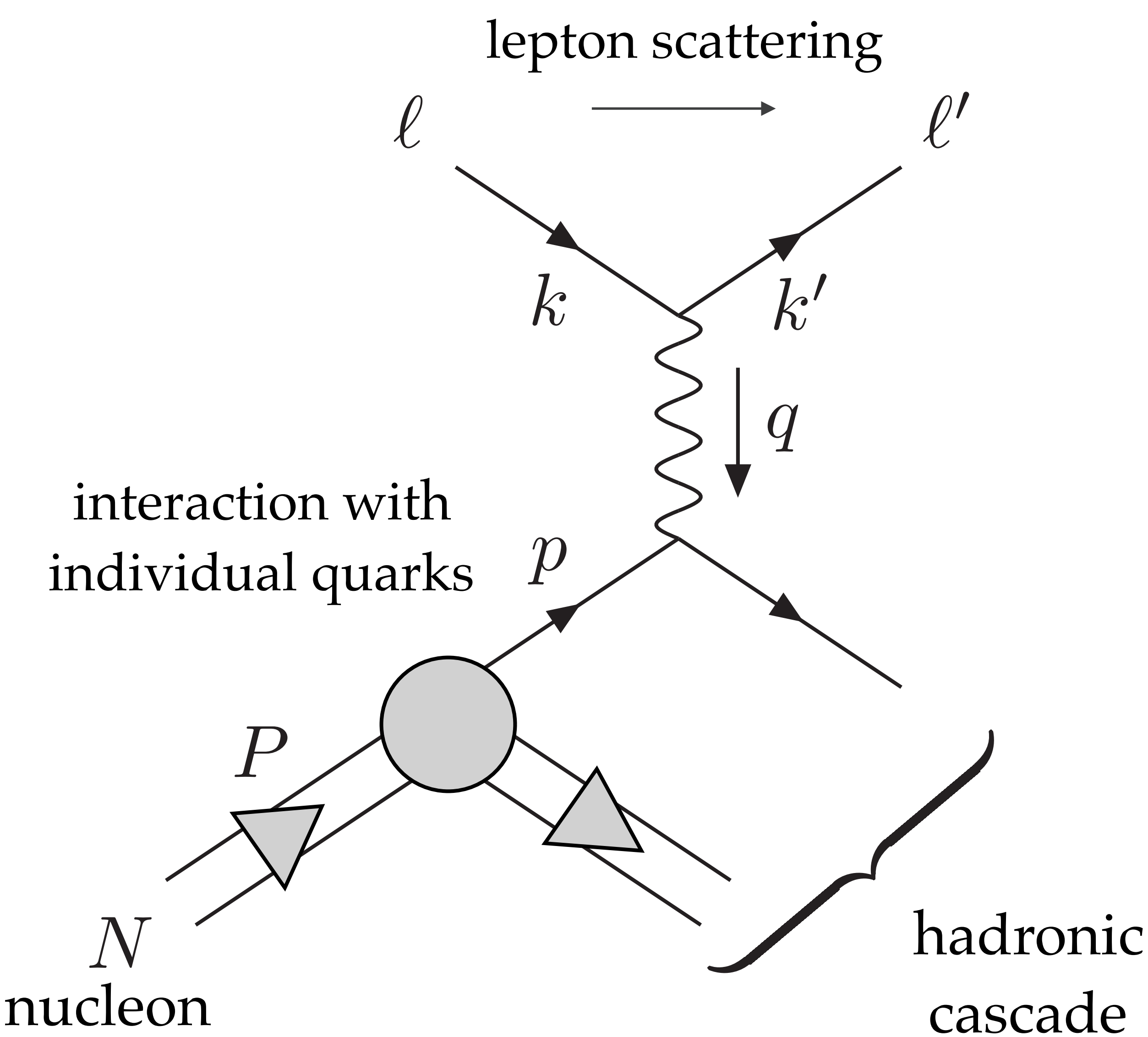
smoking-gun of
unknown sources of cosmic rays

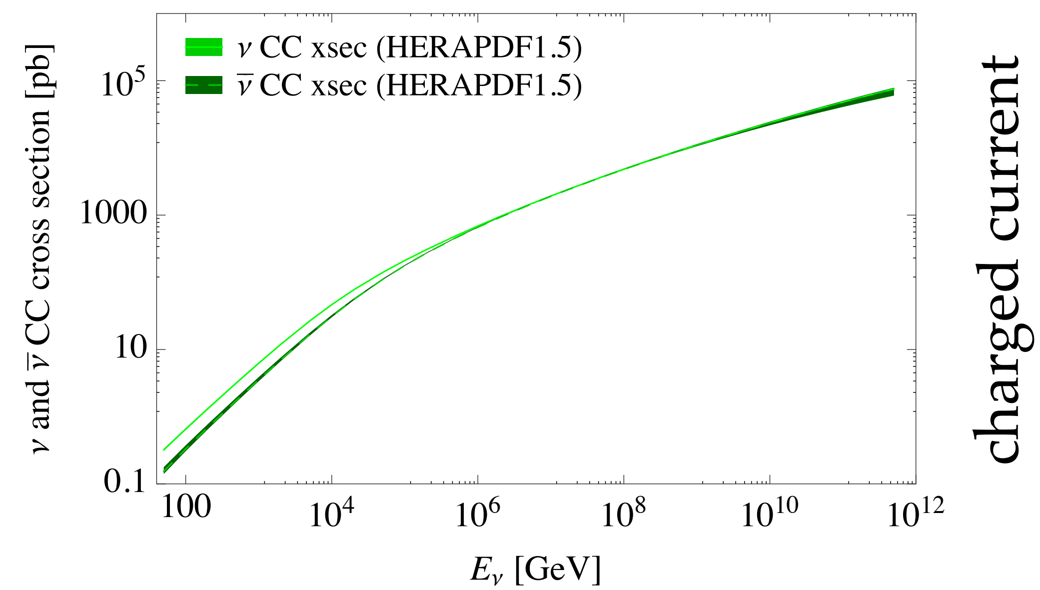
coincident with
photons and gravitational waves

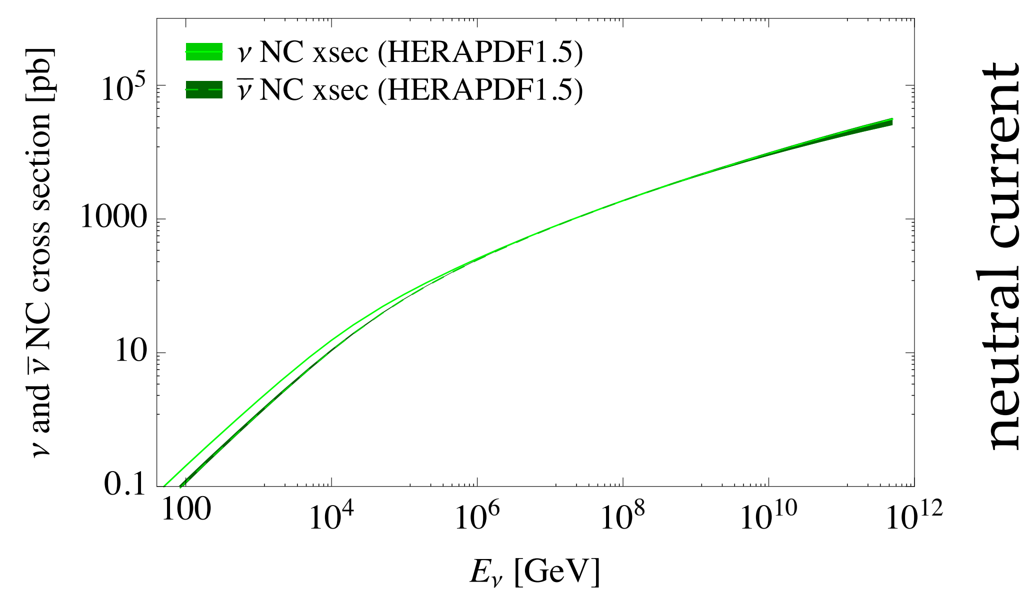
…but difficult to detect…

High-Energy Neutrino Interaction

- Low-energy (<10GeV) neutrino interaction with matter in quasi-elastic or resonant interactions.
- High-energy neutrinos interact with nuclei via **deep inelastic scattering.**







[Cooper-Sarkar, Mertsch & Sarkar'11]

Detector Requirements

Secondary charged particle are visible via optical Cherenkov emission in **transparent media**.

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**: $$N_N \sim N_A \times V/\mathrm{cm}^3$$

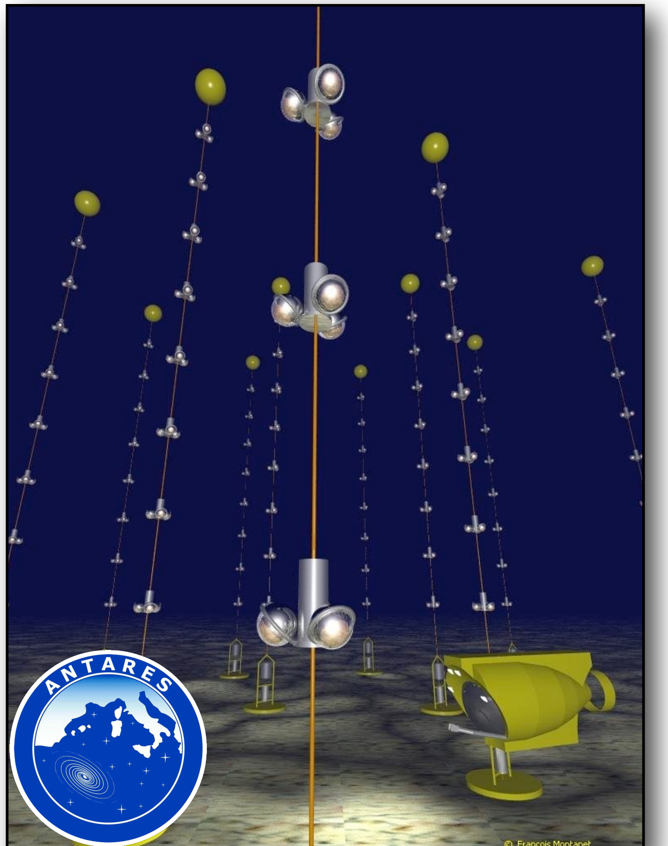
→ **rate of events** :

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

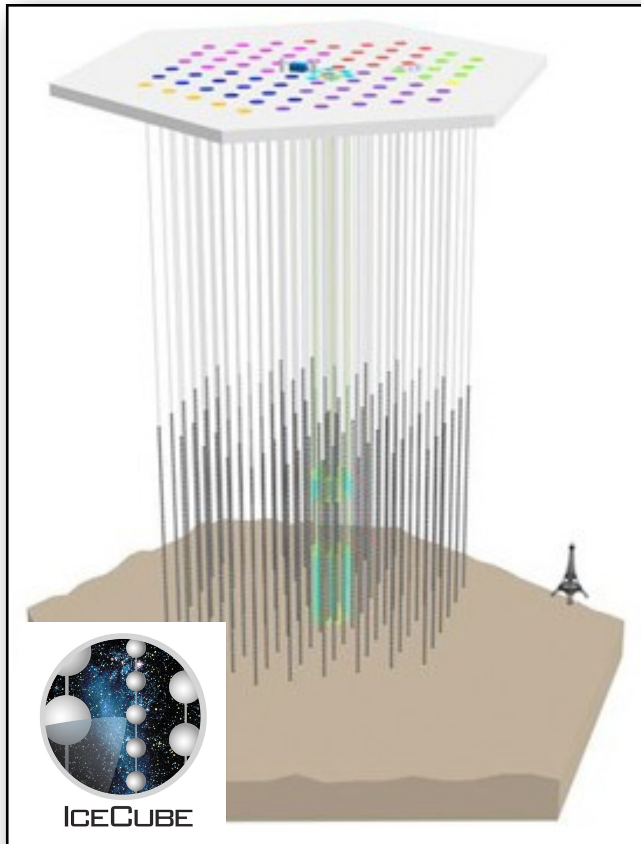
minimum detector size : 1km^3

Cherenkov Observatories

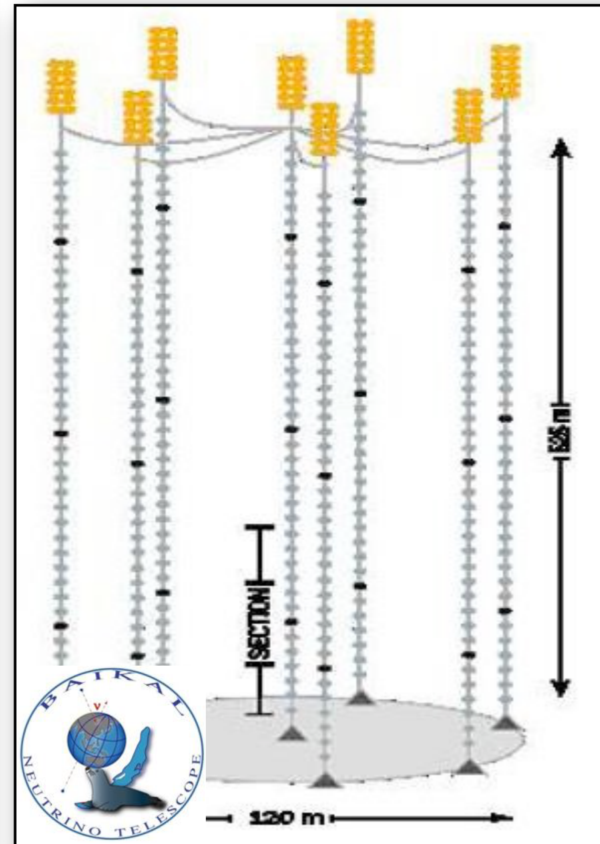
ANTARES



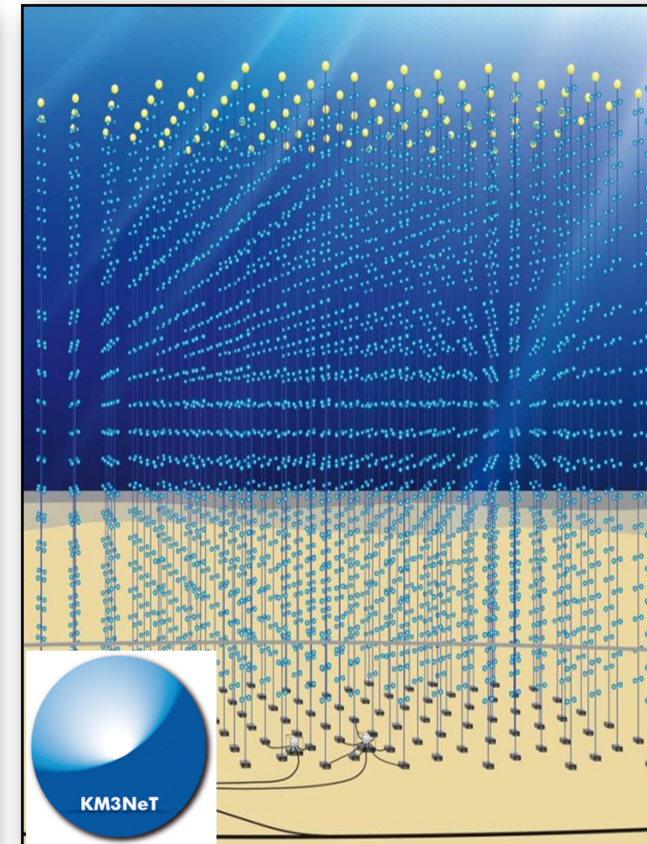
IceCube



Baikal-GVD

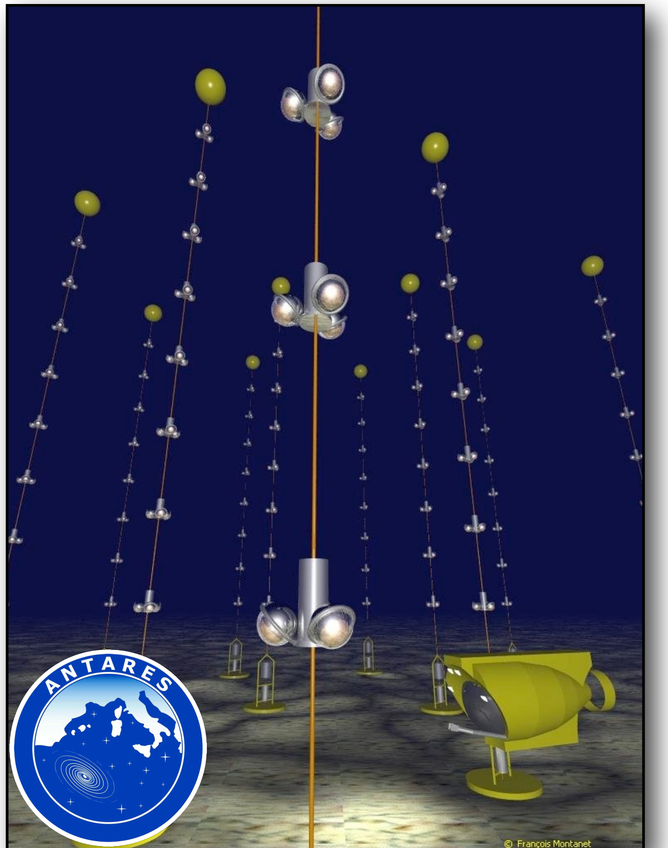
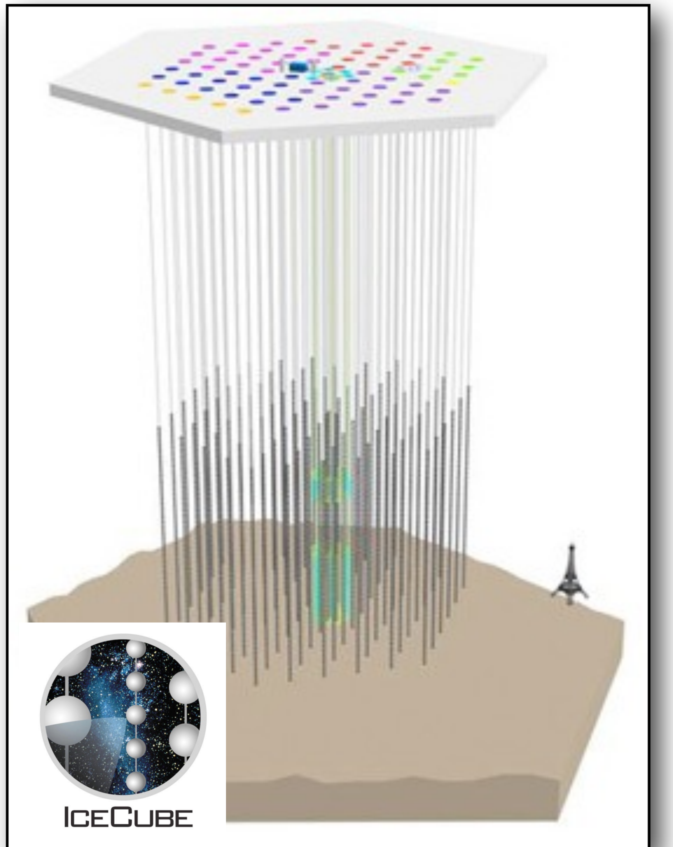
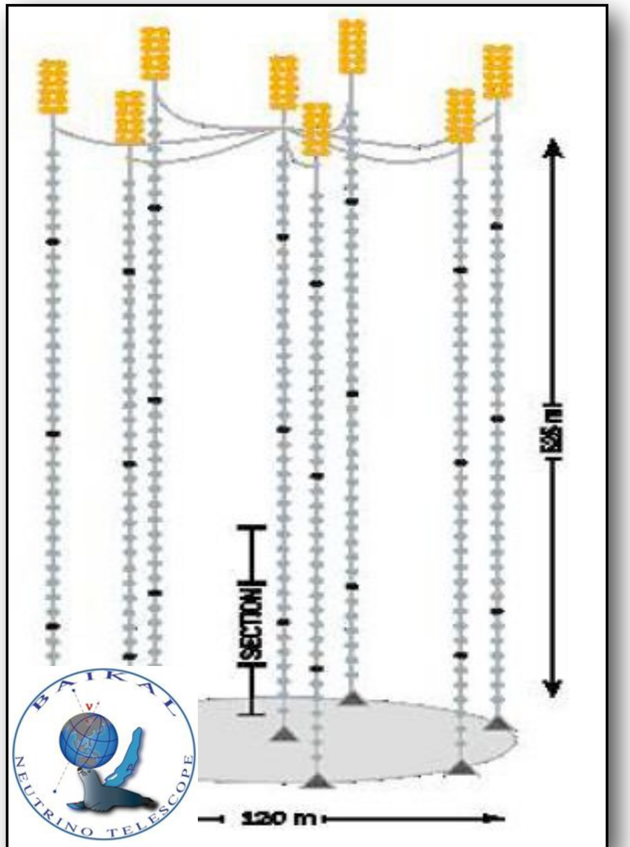
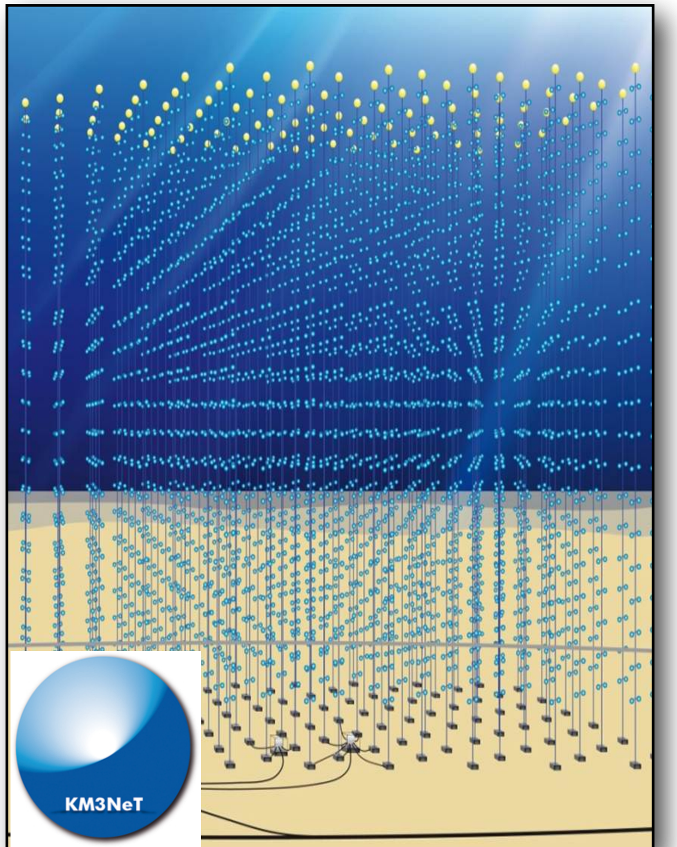


KM3NeT/ARCA



Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2020	fully instrumented since 2011	under construction (5 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km^3	~1 km^3	~0.4 km^3 (Phase 1) ~1km^3	~0.1 km^3 (Phase 1) ~1 km^3
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

Cherenkov Observatories

ANTARES	IceCube	Baikal-GVD	KM3NeT/ARCA
 	 	 	
Mediterranean	South Pole	Lake Baikal	Mediterranean
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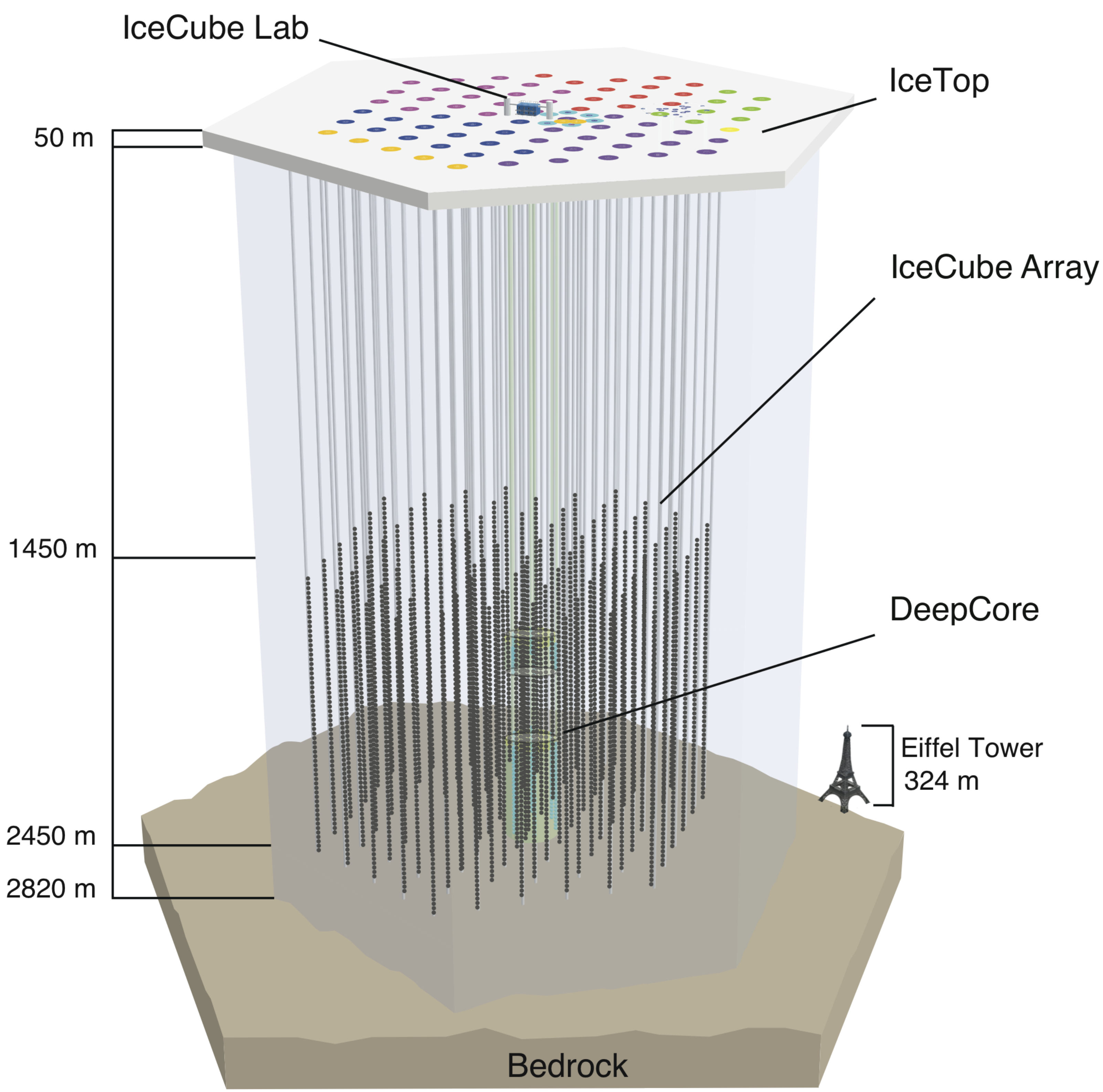
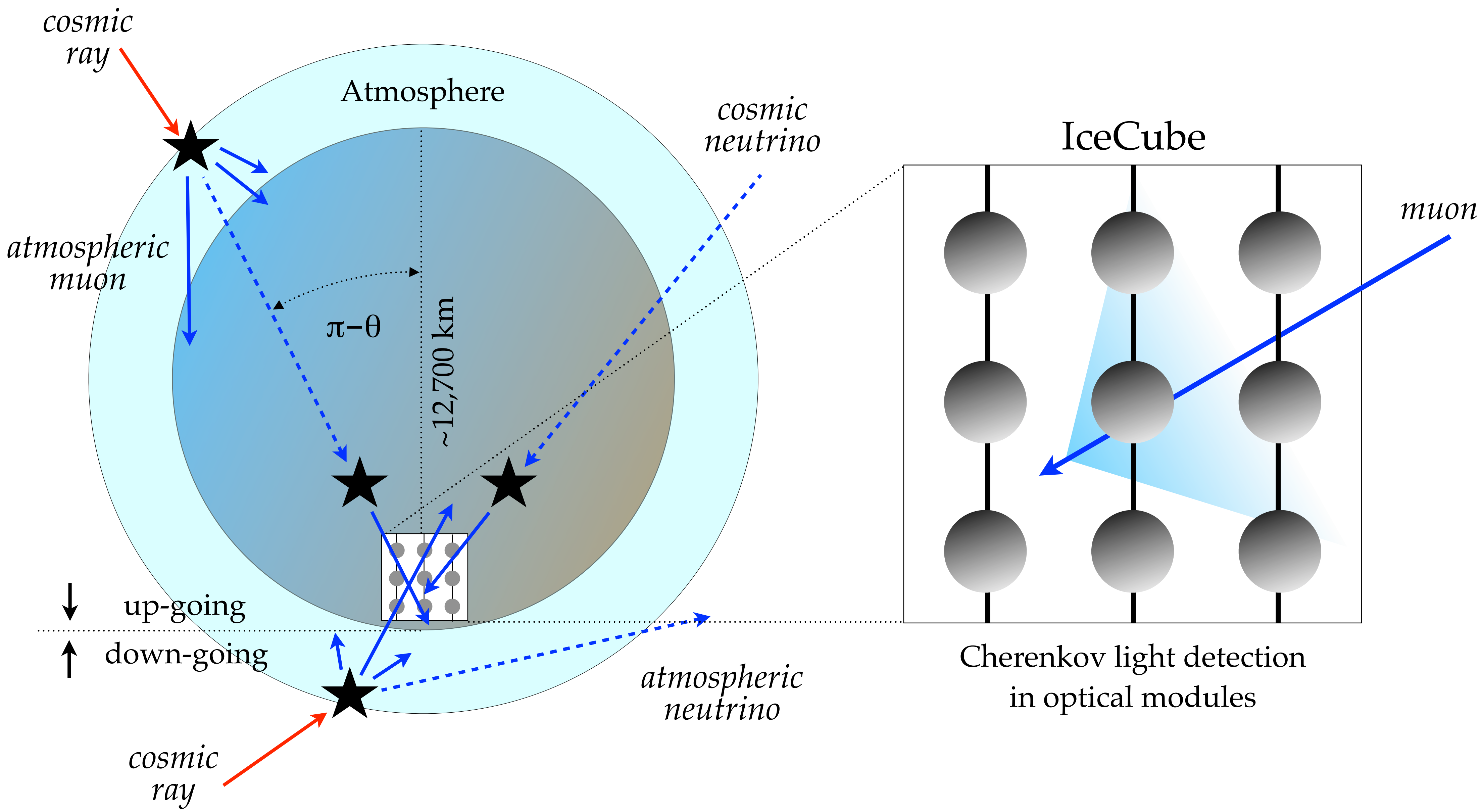
ANTARES/KM3NeT talk
by Pasquale Migliozzi
(Tuesday)

IceCube Observatory



- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 47 intl. institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- 7-year construction phase (2004–2011)
- price: **$0.3 per ton**

Detection Methods I

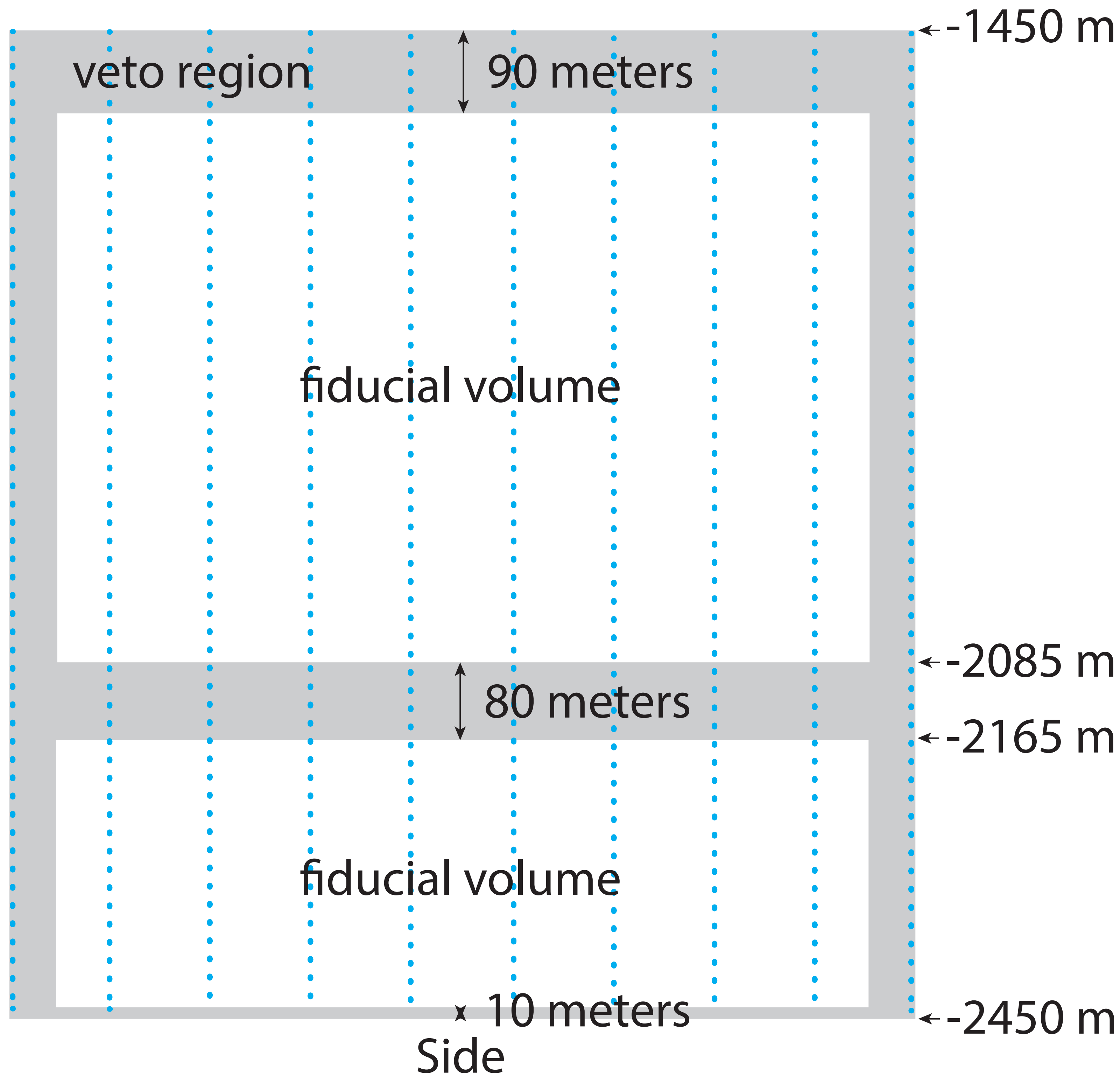


➜ Selecting **up-going muon tracks** reduces atmospheric muon background:

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

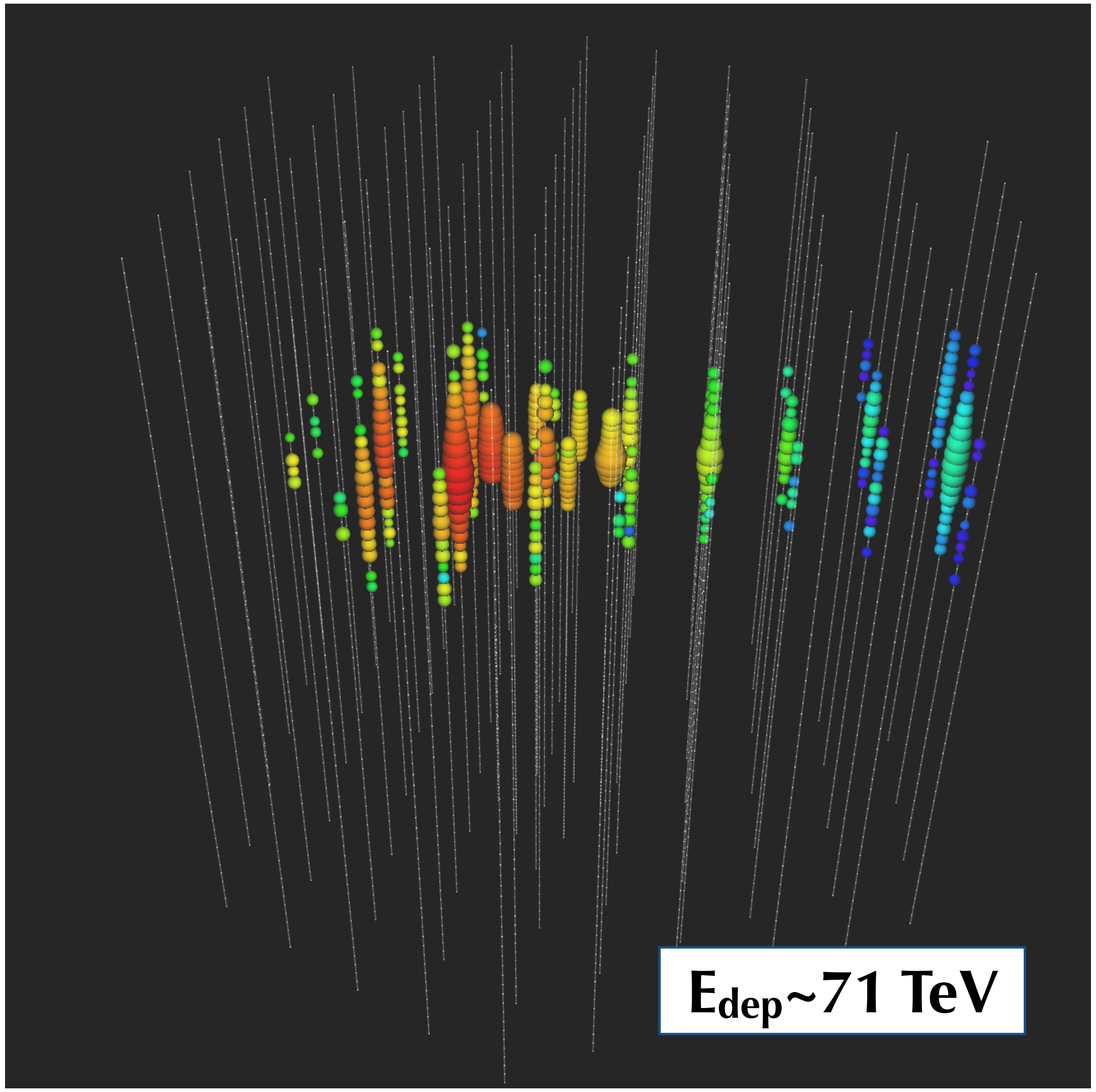
Detection Methods II

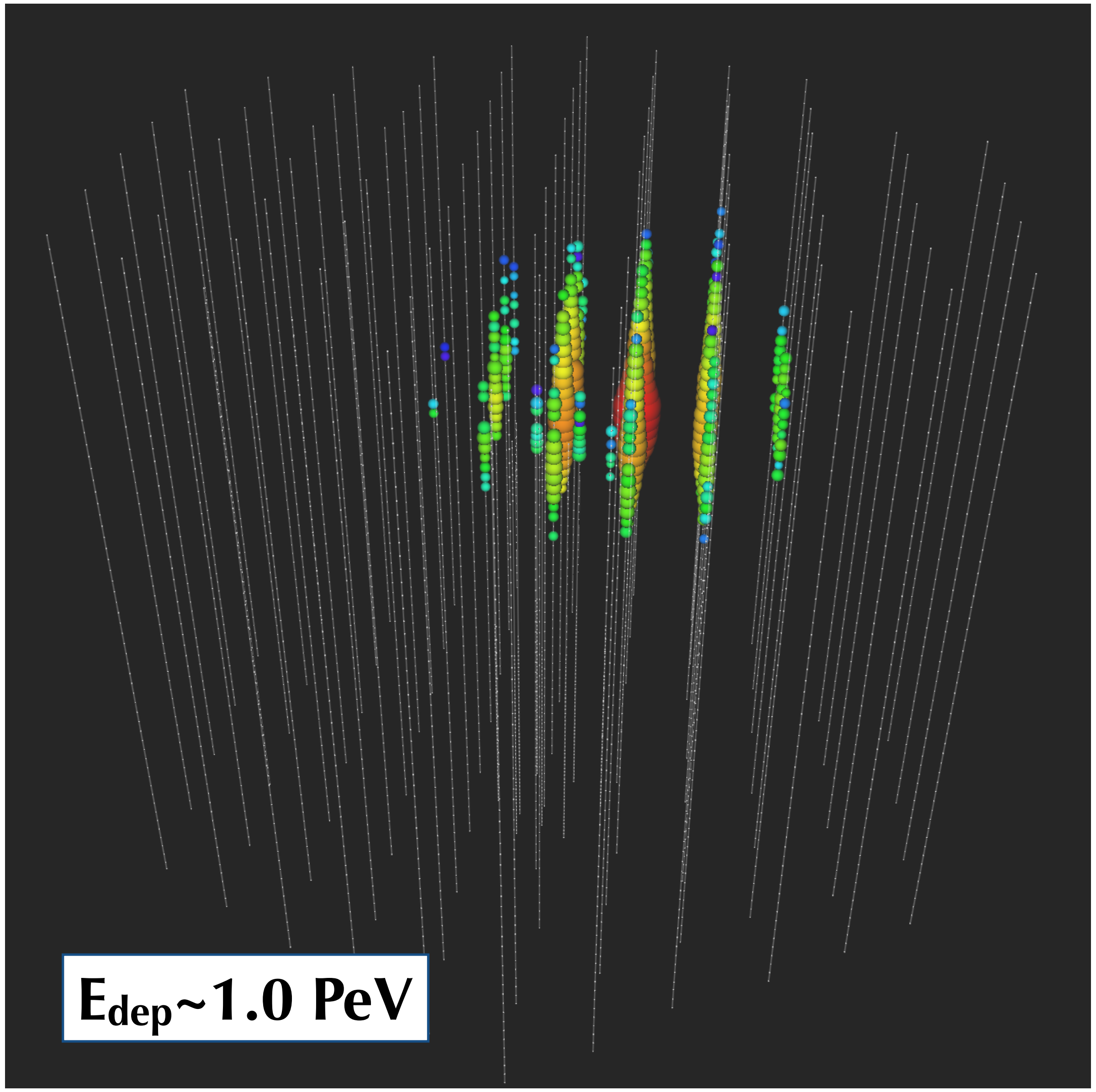
- Outer layer of optical modules used as virtual **veto region** (gray area)
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE)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



First observation of high-energy astrophysical neutrinos by IceCube.

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

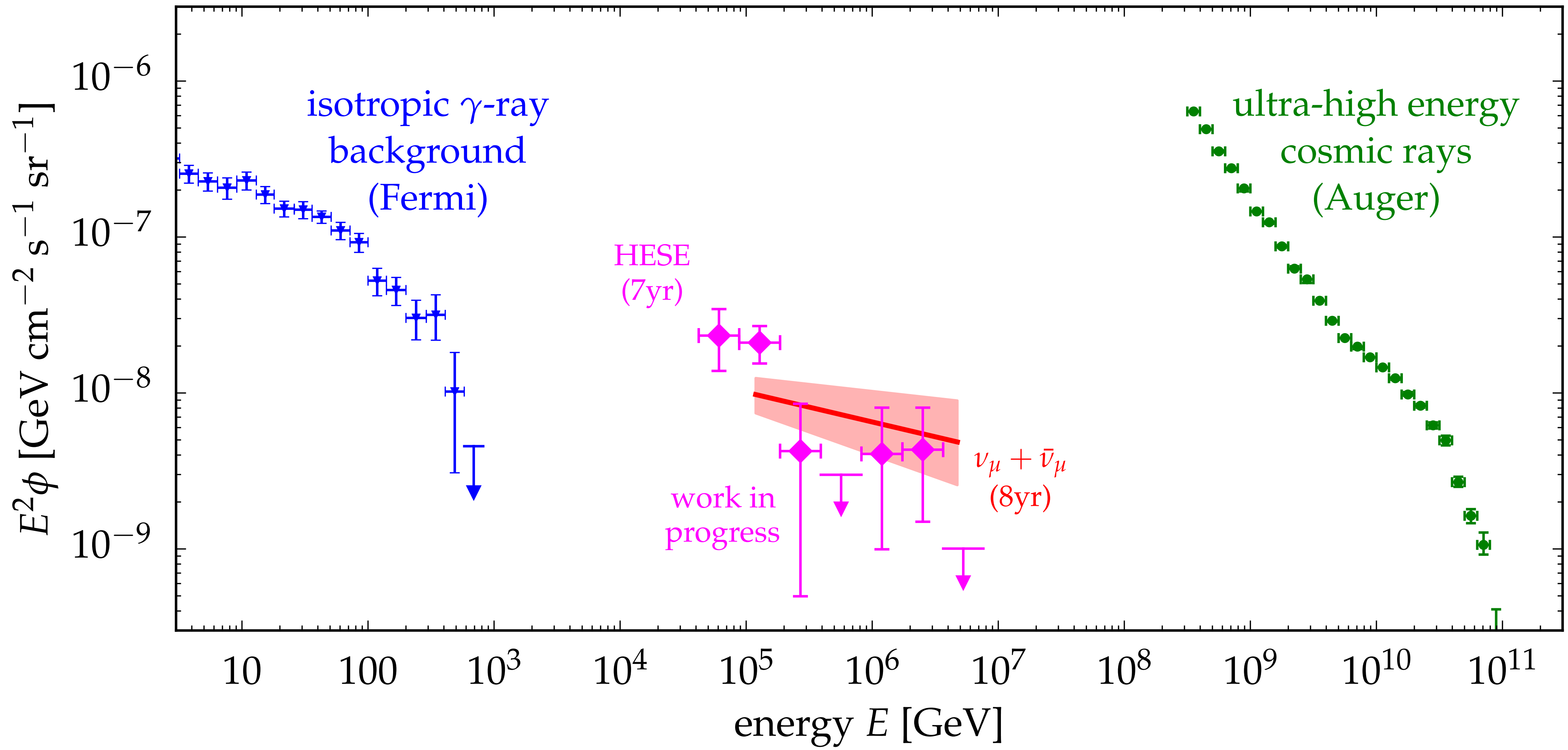




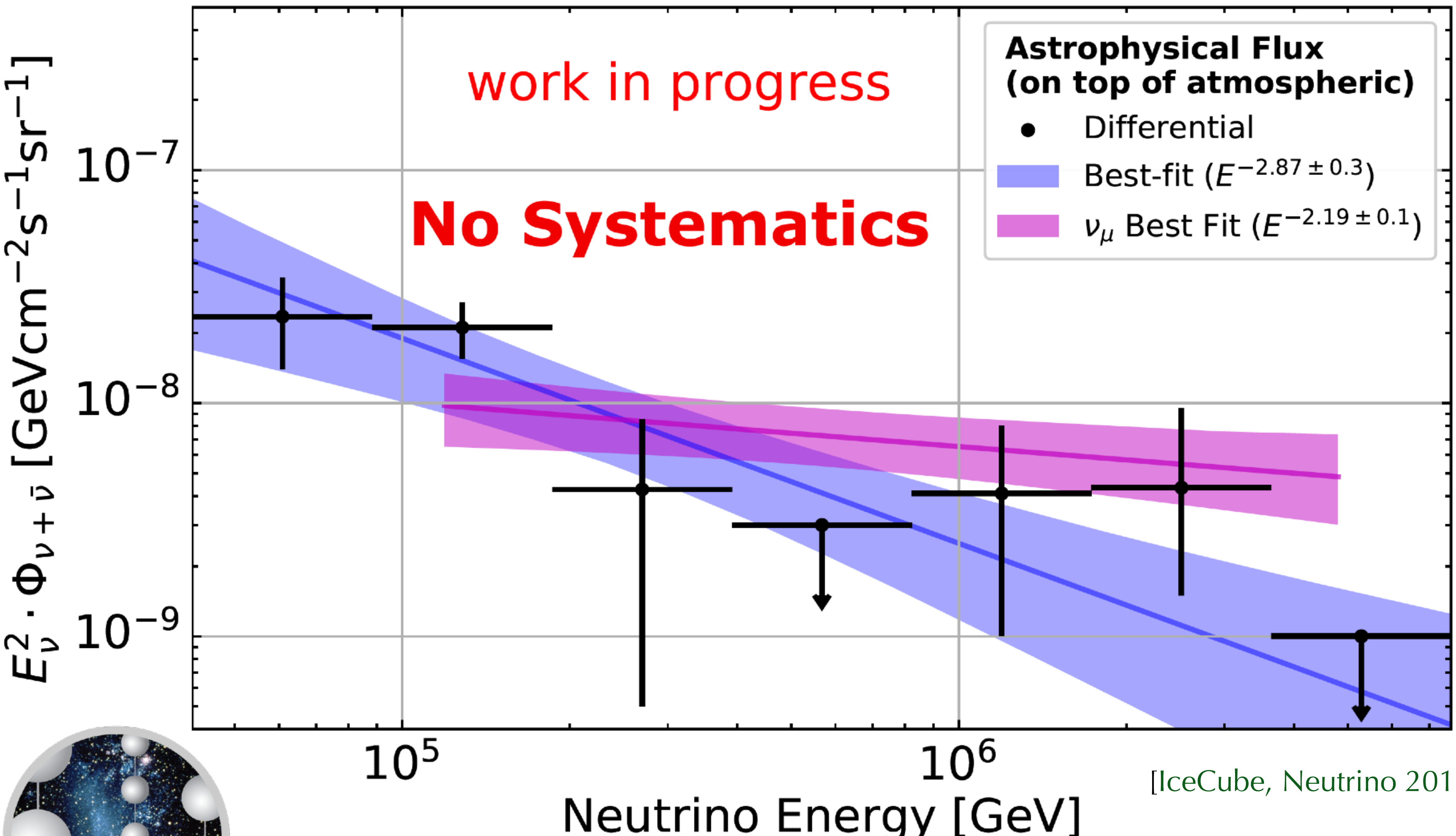
["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

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



Power-Law Comparison



[IceCube, Neutrino 2018]

Similar intensity, but mild tension between power-law fits

Indications for spectral breaks?

Astrophysical Flavours

- Energy resolution of detectors is limited and neutrino source is distant.

$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin^2\Delta_{ij}}_{\to 1/2} + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin 2\Delta_{ij}}_{\to 0}$$

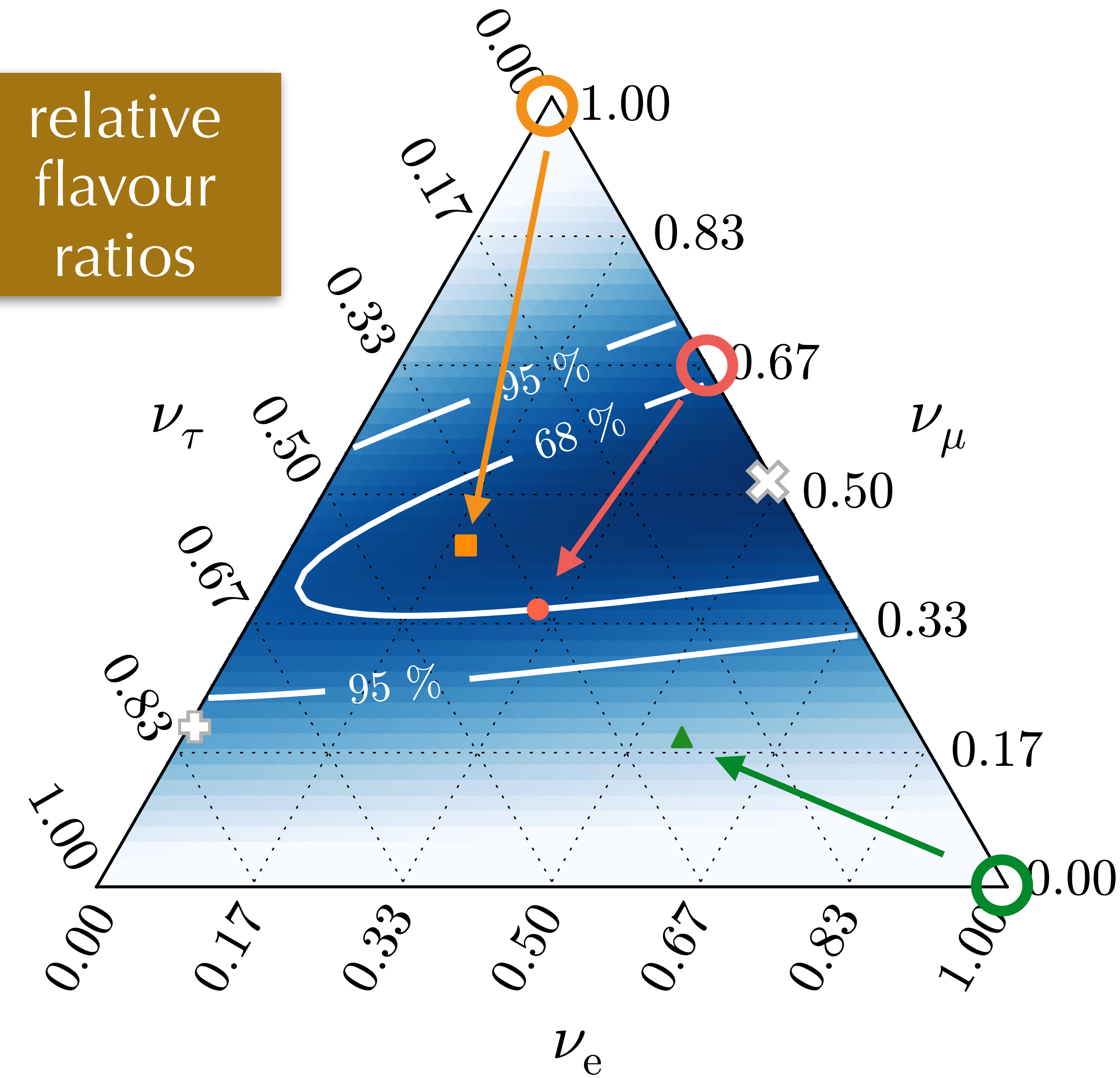
➜ oscillation-averaged probability:

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

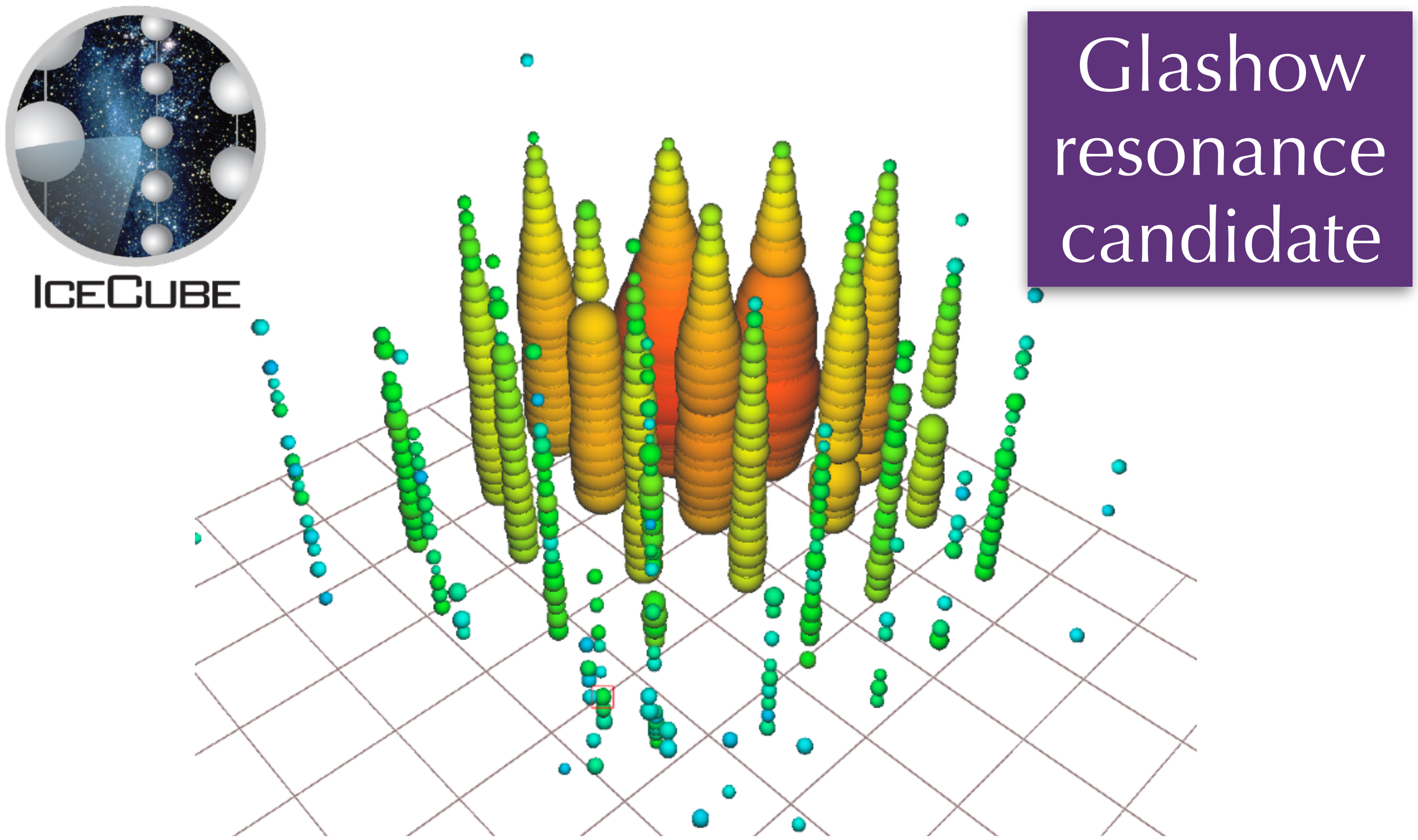
- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  - *pion & muon decay:* $1:2:0$
  - *muon-damped decay:* $0:1:0$
  - *neutron decay:* $1:0:0$

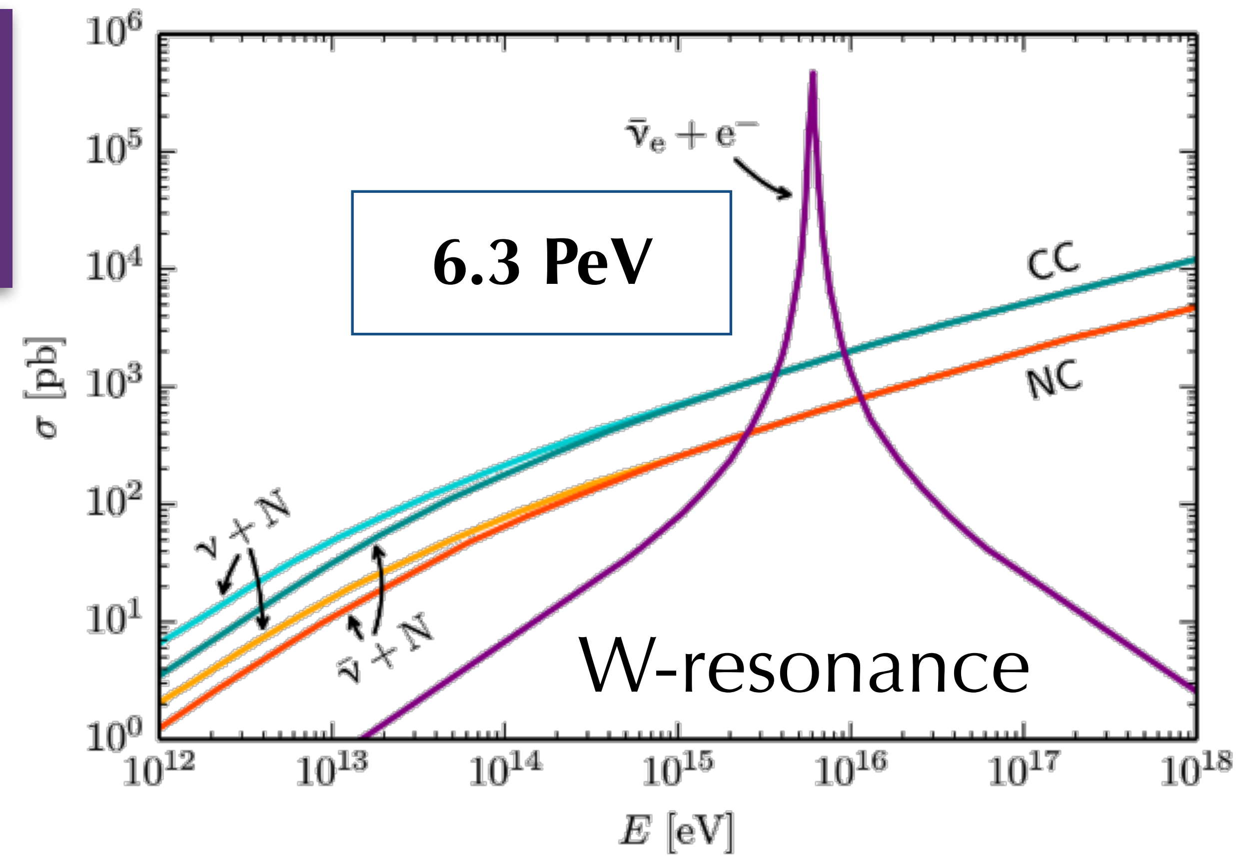
[**Astrophys.J.** 809 (2015) no.1, 98]

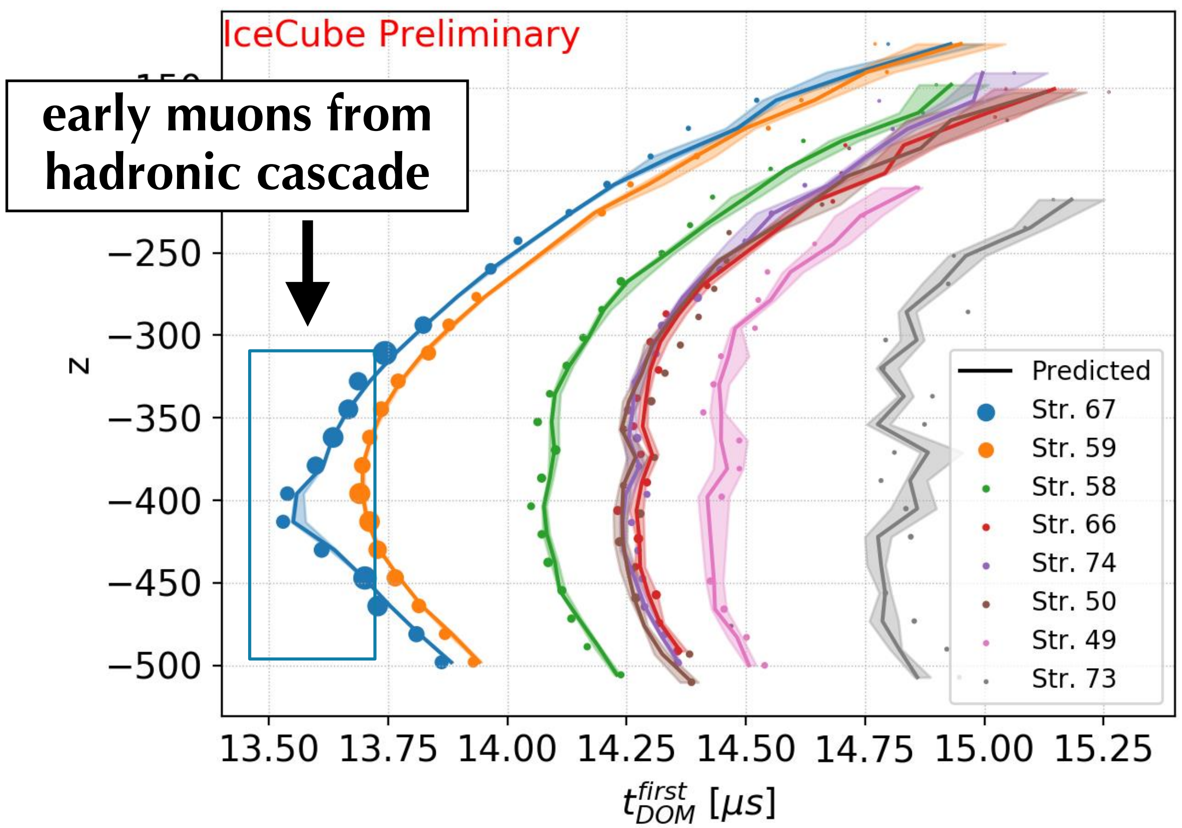
relative flavour ratios

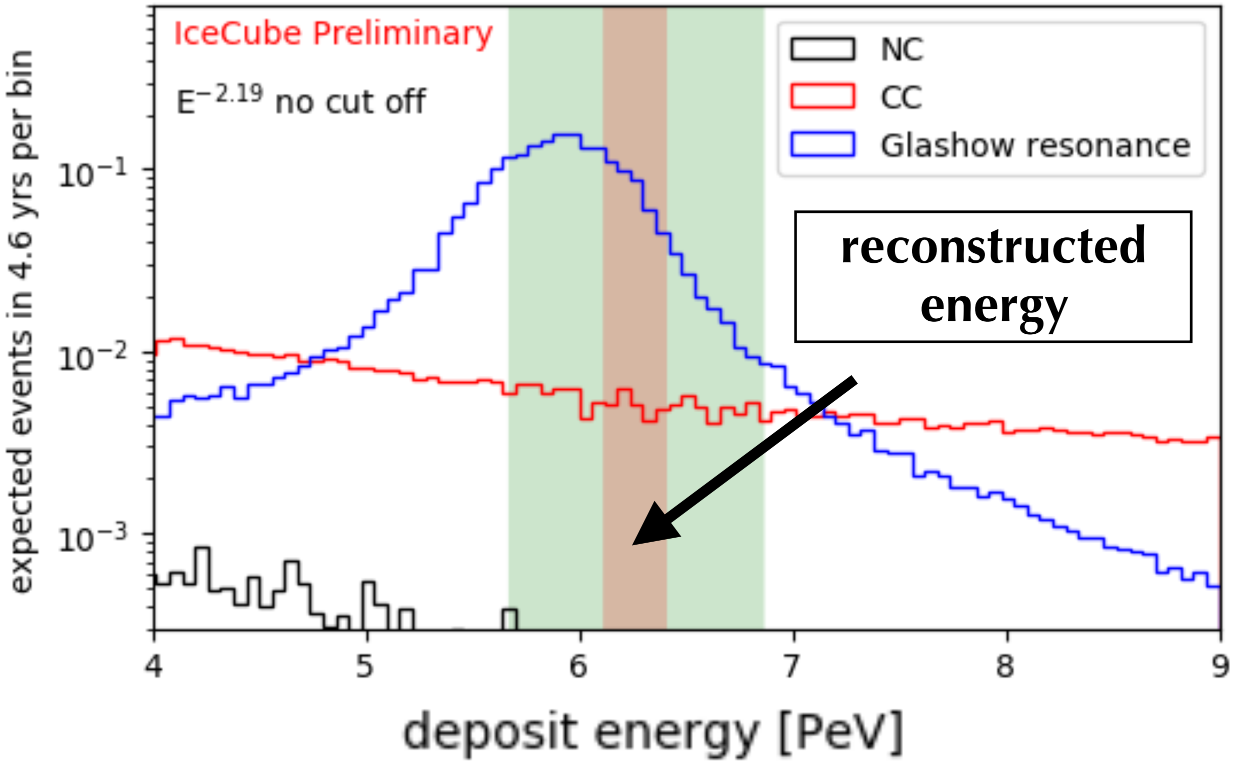


Astrophysical Flavours



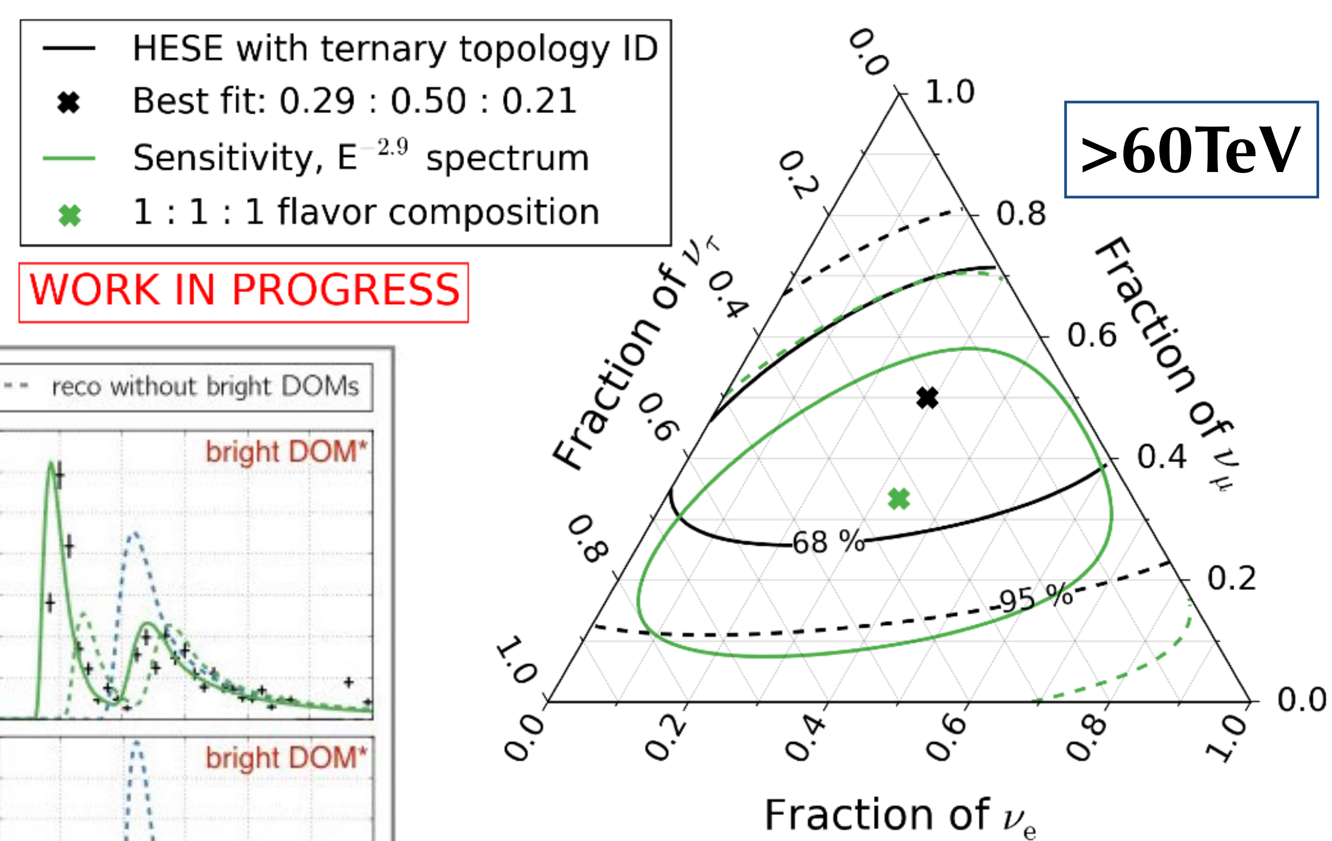


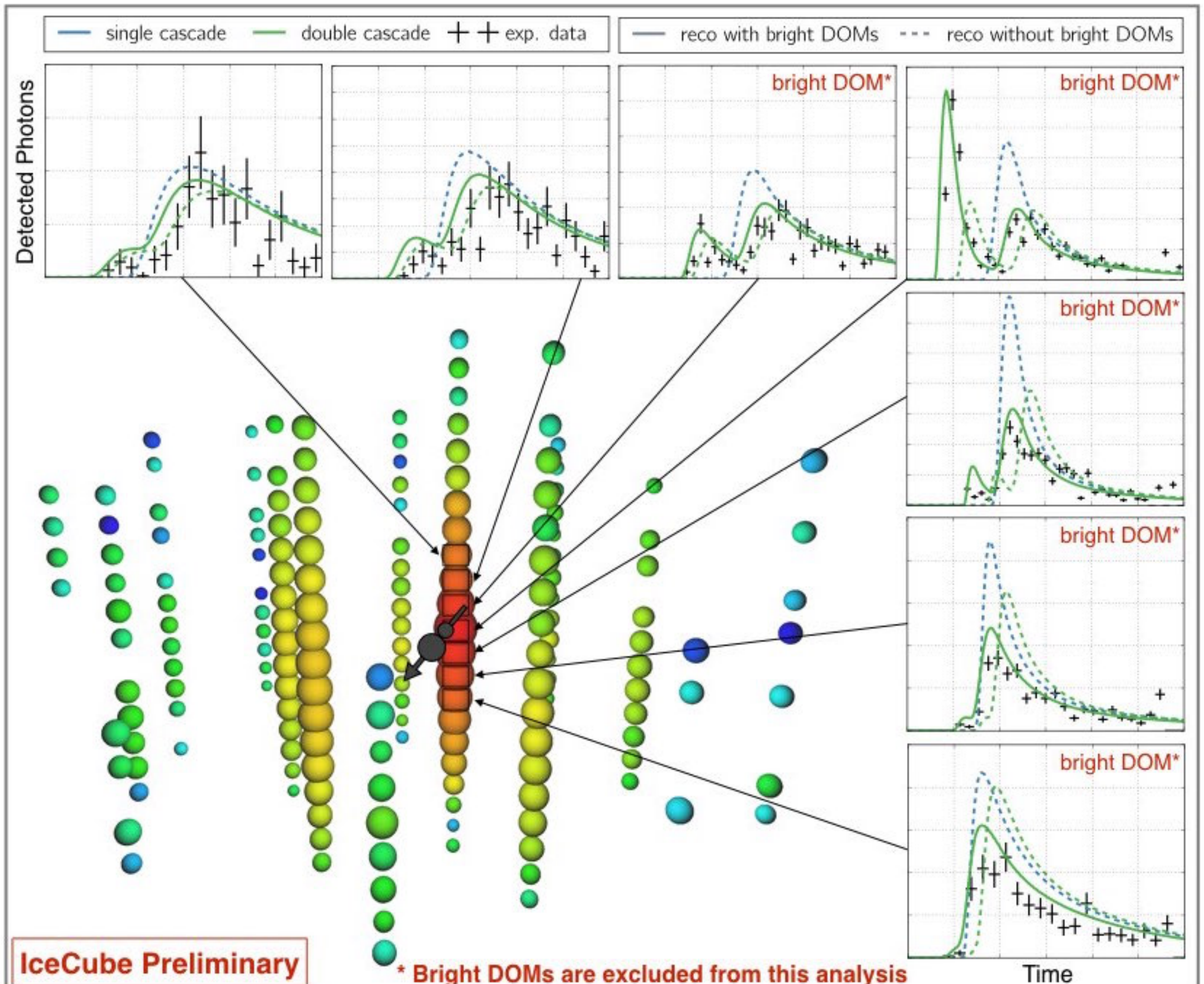




Astrophysical Flavours

tau neutrino candidate

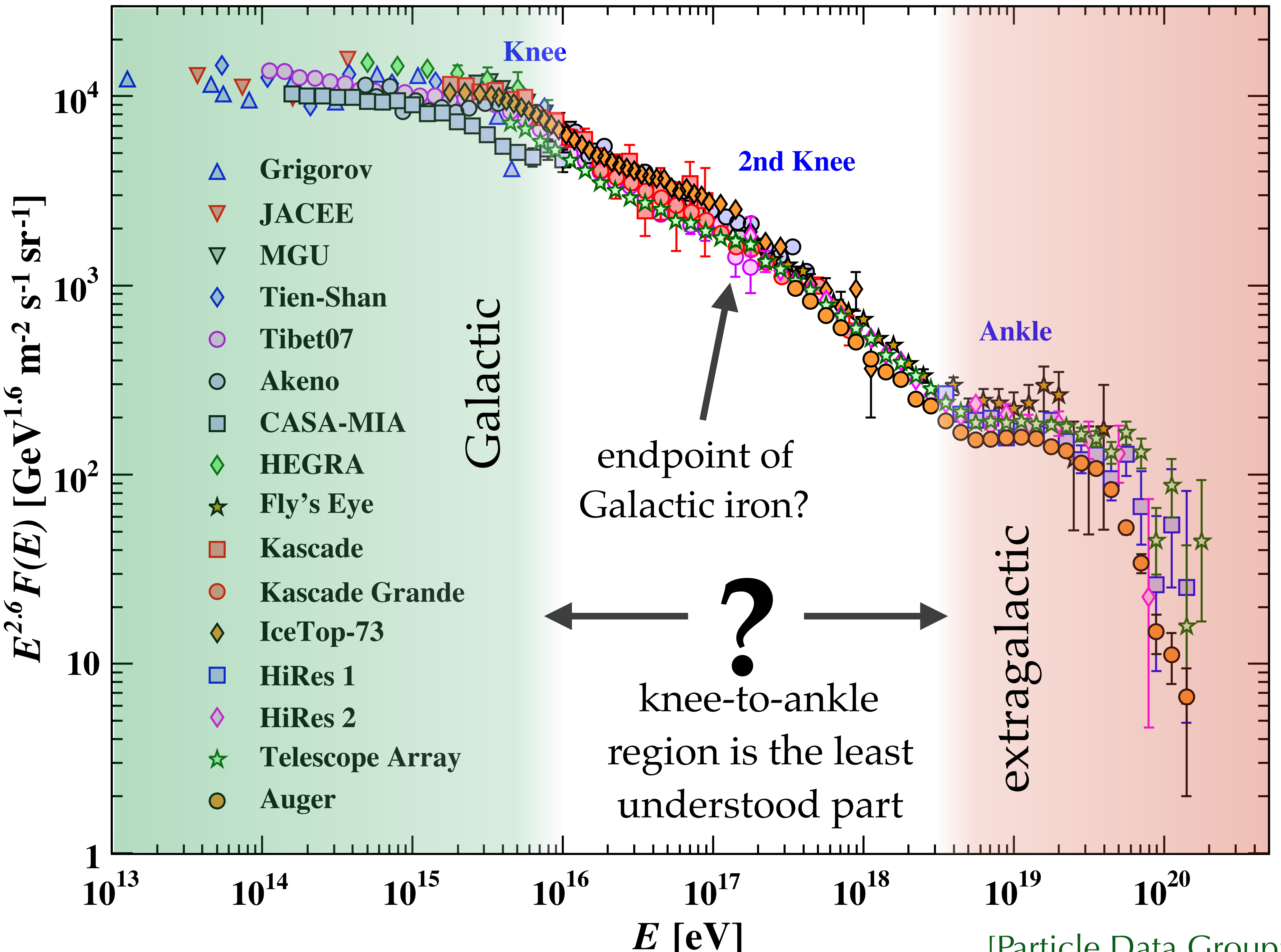




- Tau neutrino charged current interactions can produce **second hadronic cascades** from tau decays ("double-bangs").
- Arrival time of **delayed Cherenkov photons** is visible in individual DOMs.

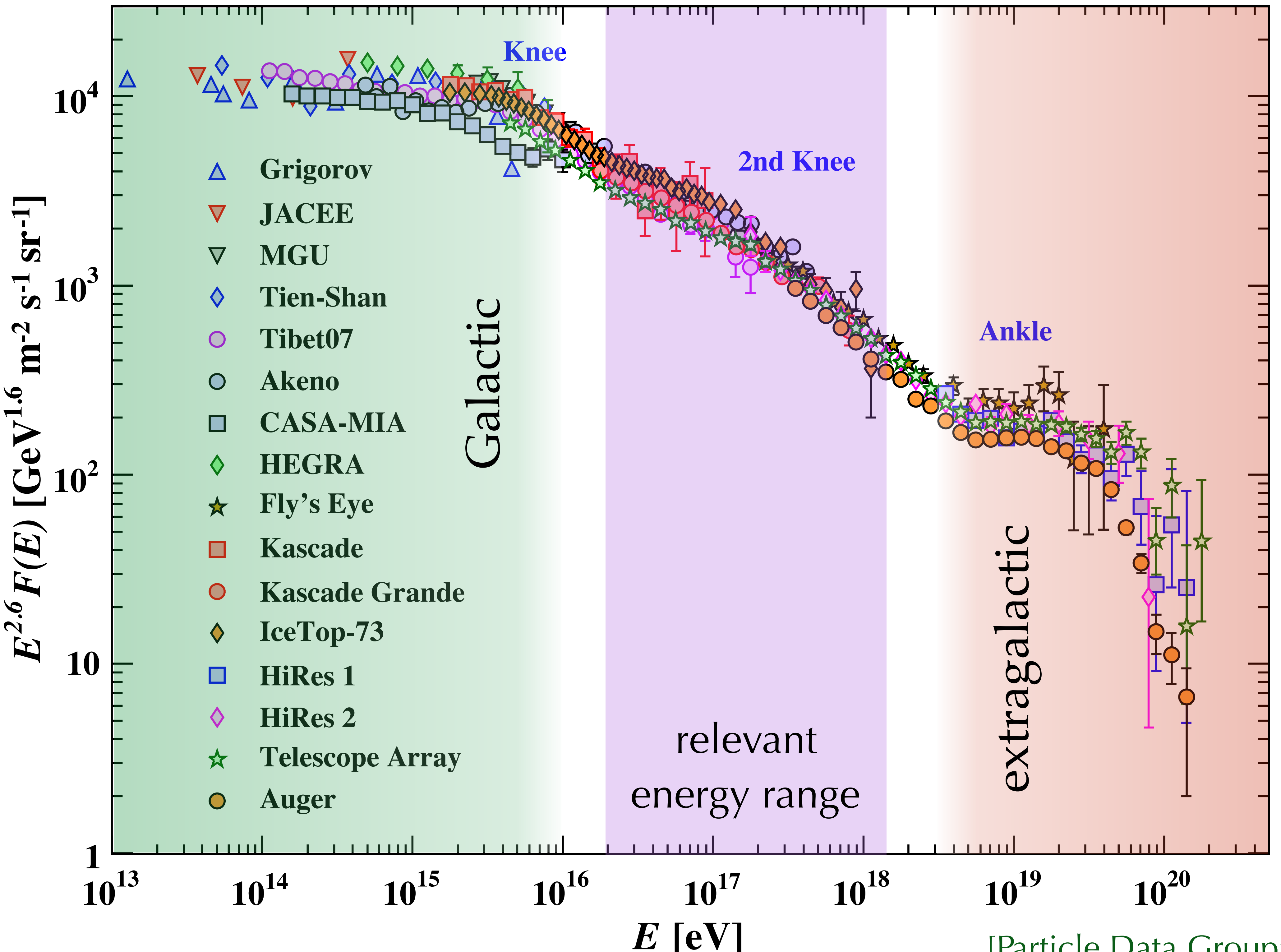
Very-High Energy Cosmic Rays

1 PeV neutrinos require collisions of 20-30 PeV cosmic ray nucleons.



[Particle Data Group'19]

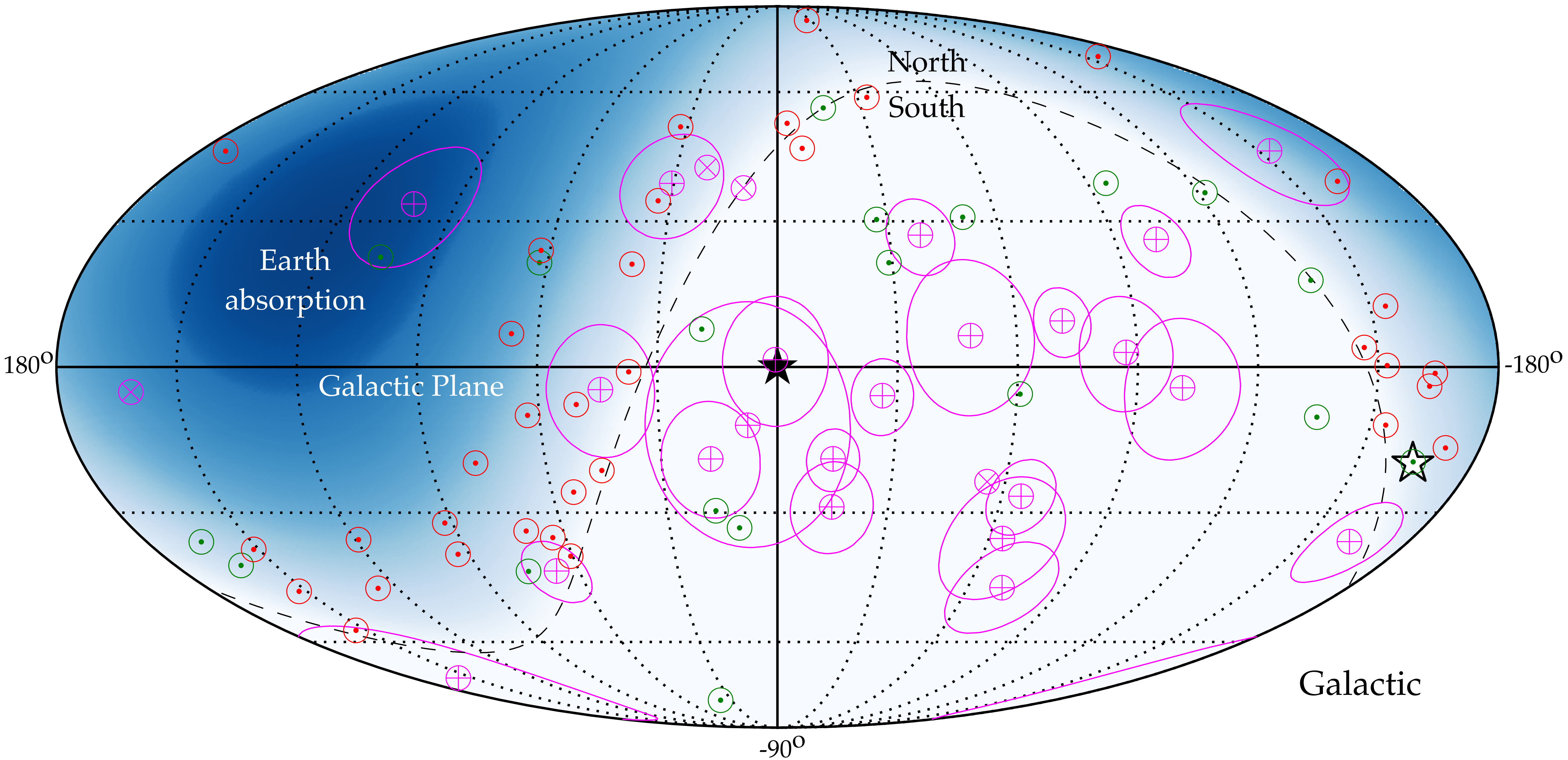
1 PeV neutrinos require collisions of 20-30 PeV cosmic ray nucleons.



[Particle Data Group'19]

Status of Neutrino Astronomy

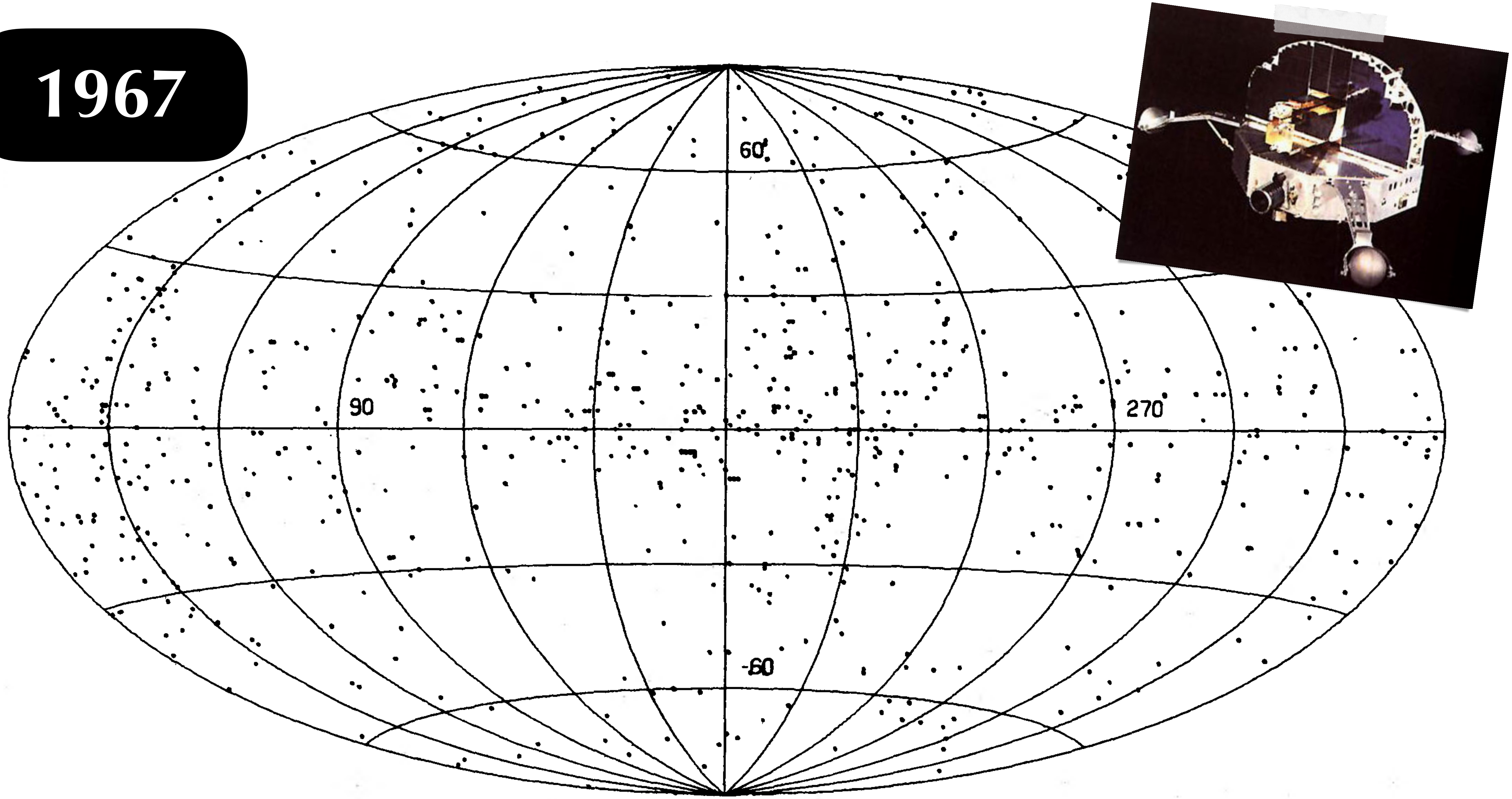
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red) + public alerts (green))



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

Status of Neutrino Astronomy

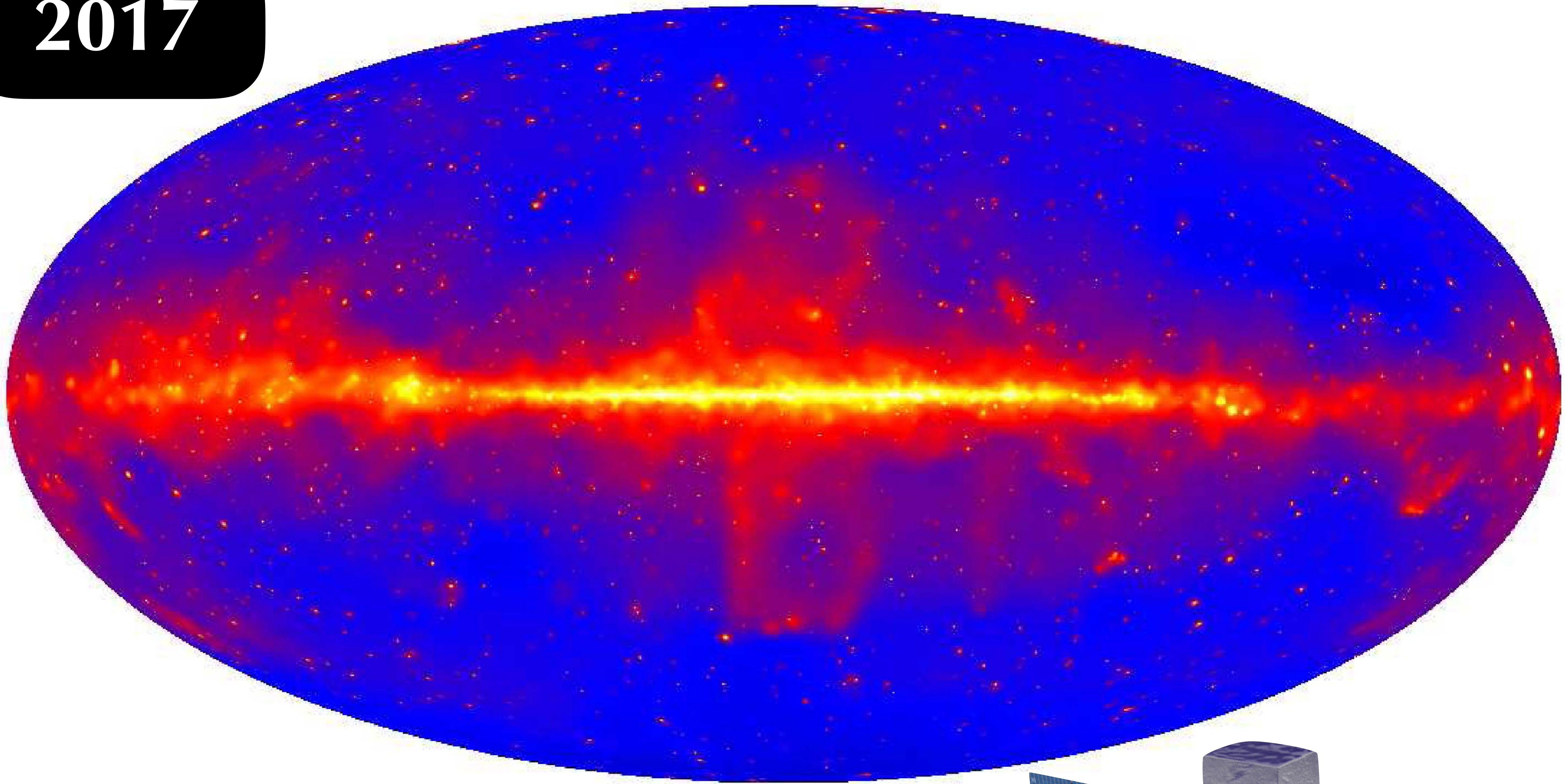
1967



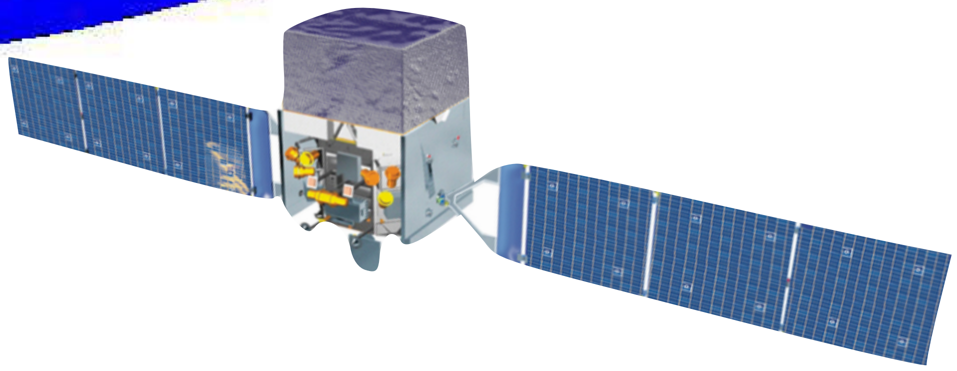
Orbiting Solar Observatory (OSO-3) (Clark & Kraushaar'67)

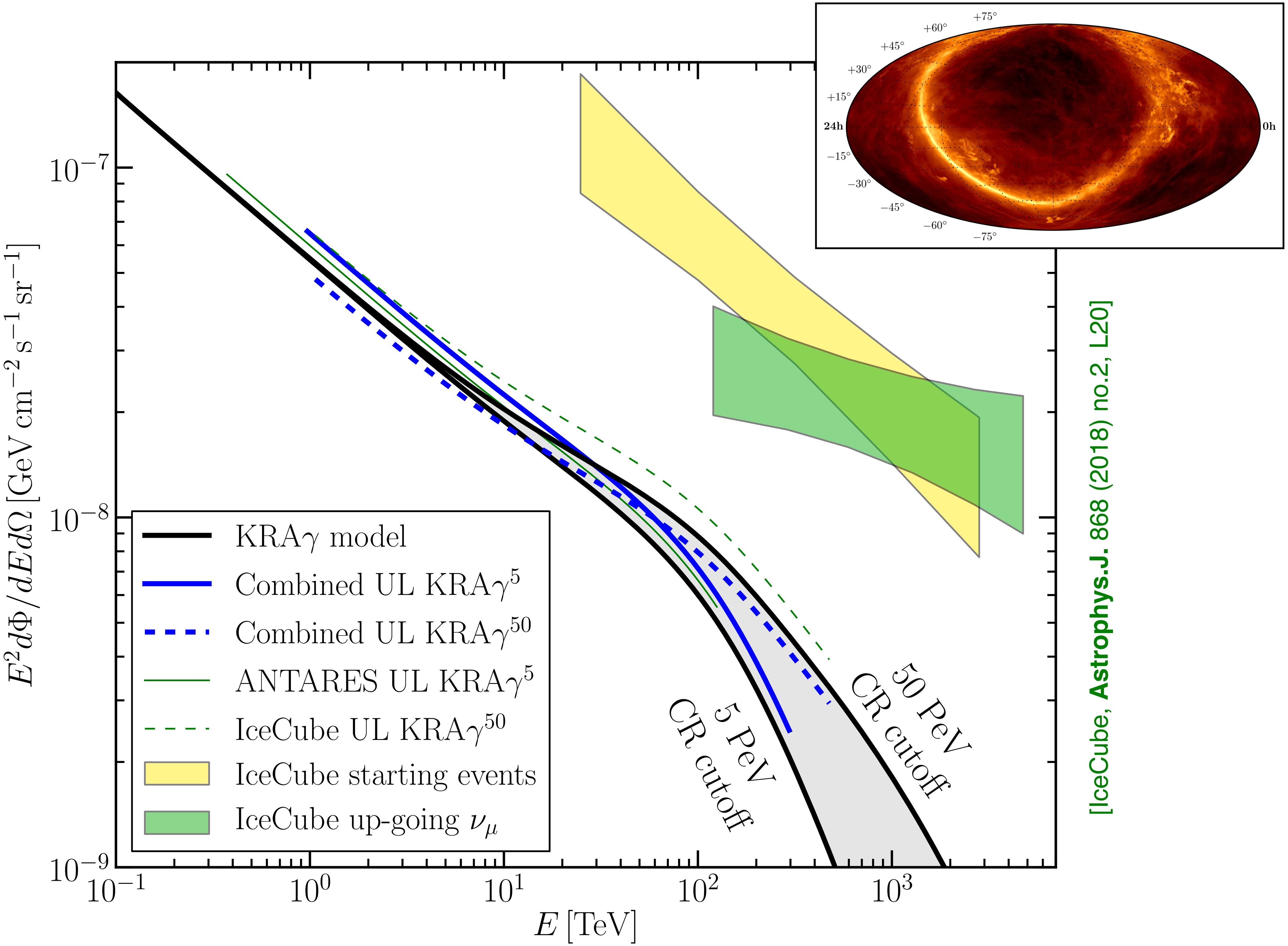
Status of Neutrino Astronomy

2017



Fermi-LAT gamma-ray count map





[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

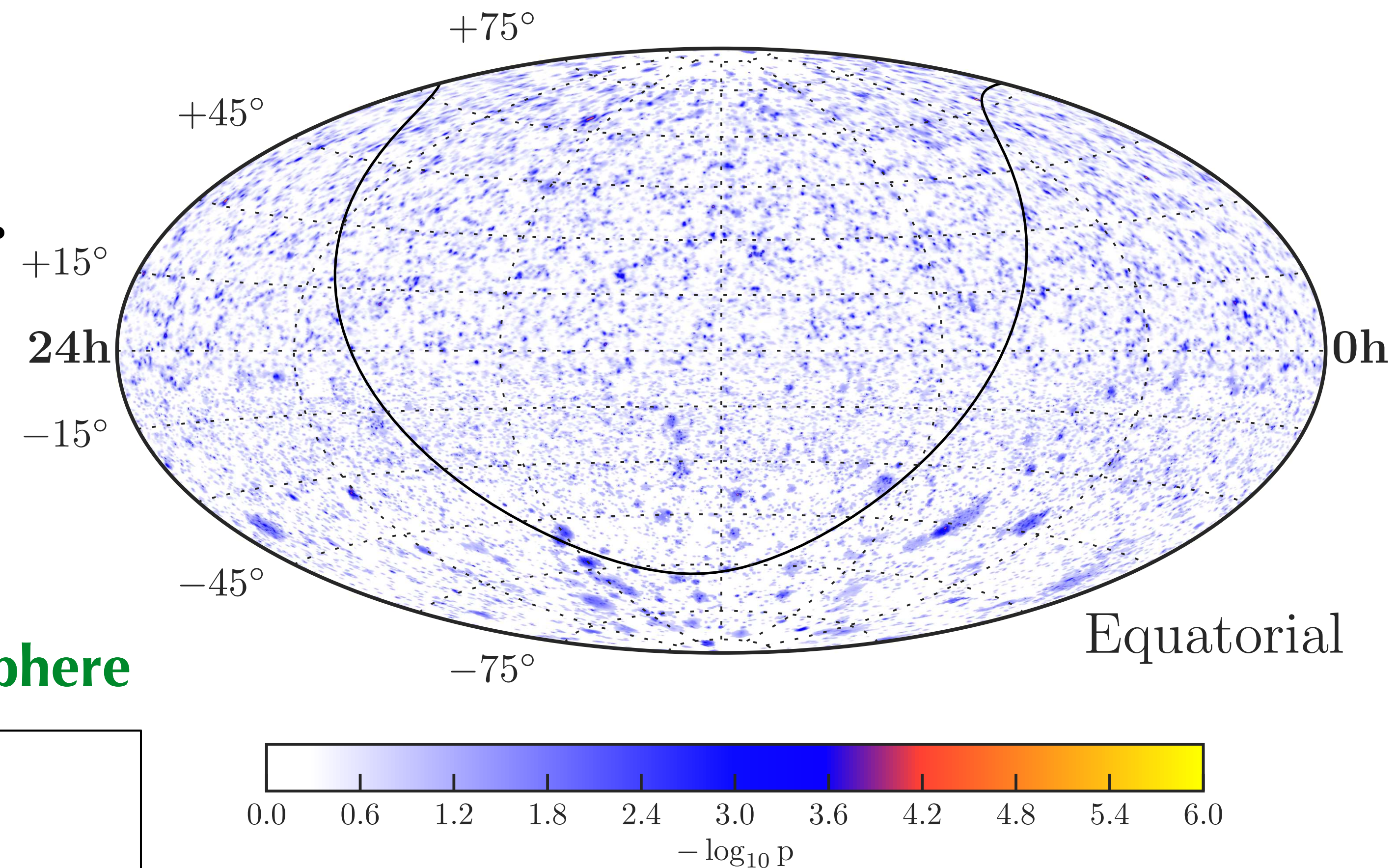
Contribution of Galactic diffuse emission at 10TeV-PeV is subdominant.

Extragalactic Source Candidates

- association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
  [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14;Moharana & Razzaque'15]
- association with diffuse γ-ray background [Murase, MA & Lacki'13]
  [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
- active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
  [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
  [Padovani & Resconi'14; Petropoulou *et al.*'15; Padovani *et al.*'16; Kadler *et al.*'16; Wang & Loeb'16]
- gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  [Senno, Murase & Meszaros'16; Denton & Tamborra'18; Boncioli, Biehl & Winter'18]
- galaxies with intense star-formation (*e.g.* starbursts)
  [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13; Murase, MA & Lacki'13]
  [Anchordoqui, Paul, da Silva, Torres& Vlcek'14; Tamborra, Ando & Murase'14; Chang & Wang'14]
  [Liu, Wang, Inoue, Crocker & Aharonian'14; Senno, Meszaros, Murase, Baerwald & Rees'15]
  [Chakraborty & Izaguirre'15; Emig, Lunardini & Windhorst'15; Bechtol *et al.*'15]
- galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
- tidal disruption events (TDE) [Wang, Liu, Dai & Cheng'11; Senno, Murase & Més'aros'17]
  [Guépin, Kotera, Barausse, Fang & Murase'17; Biehl, Boncioli, Lunardini & Winter'17]

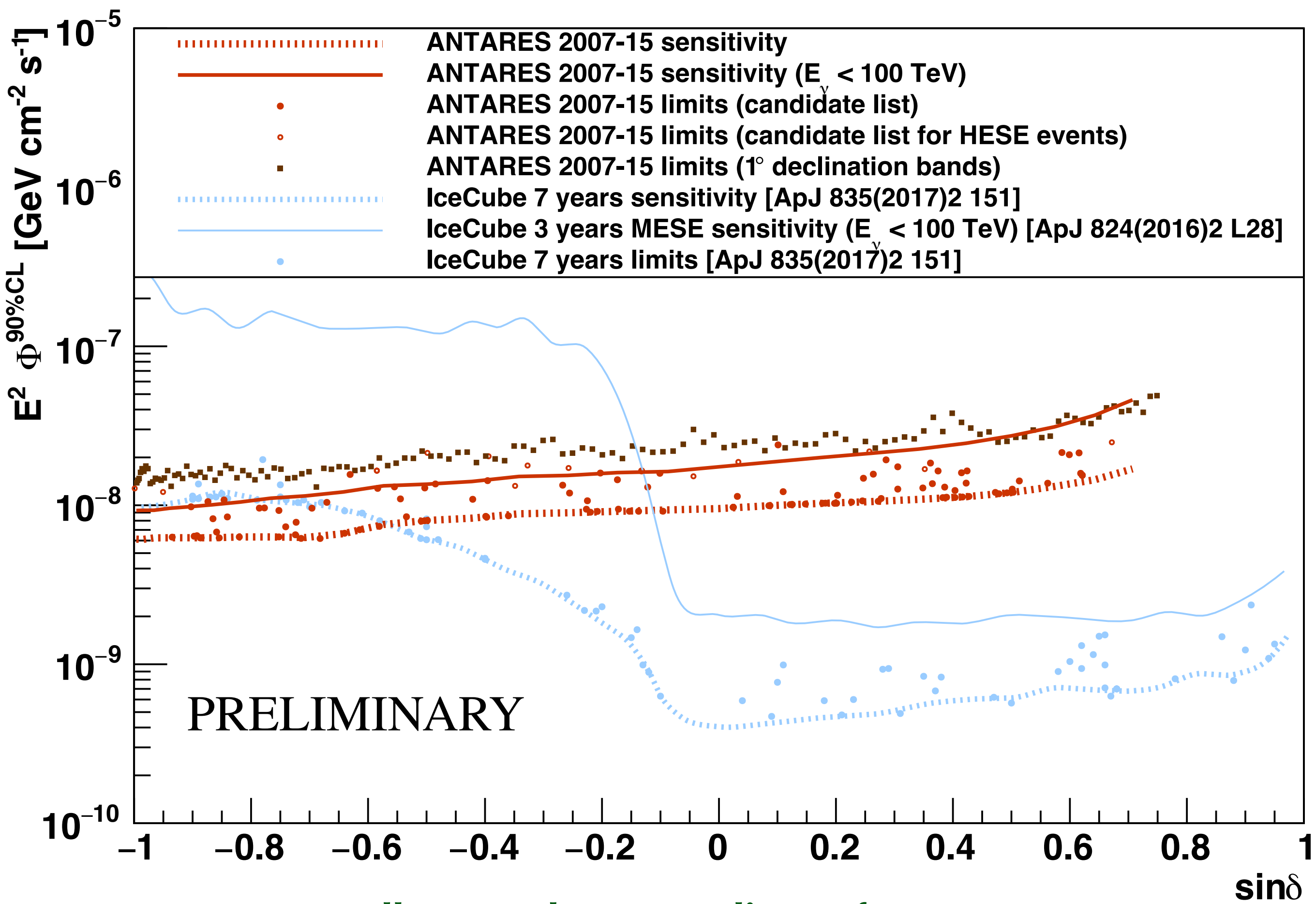
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.



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

Southern Hemisphere | Northern Hemisphere

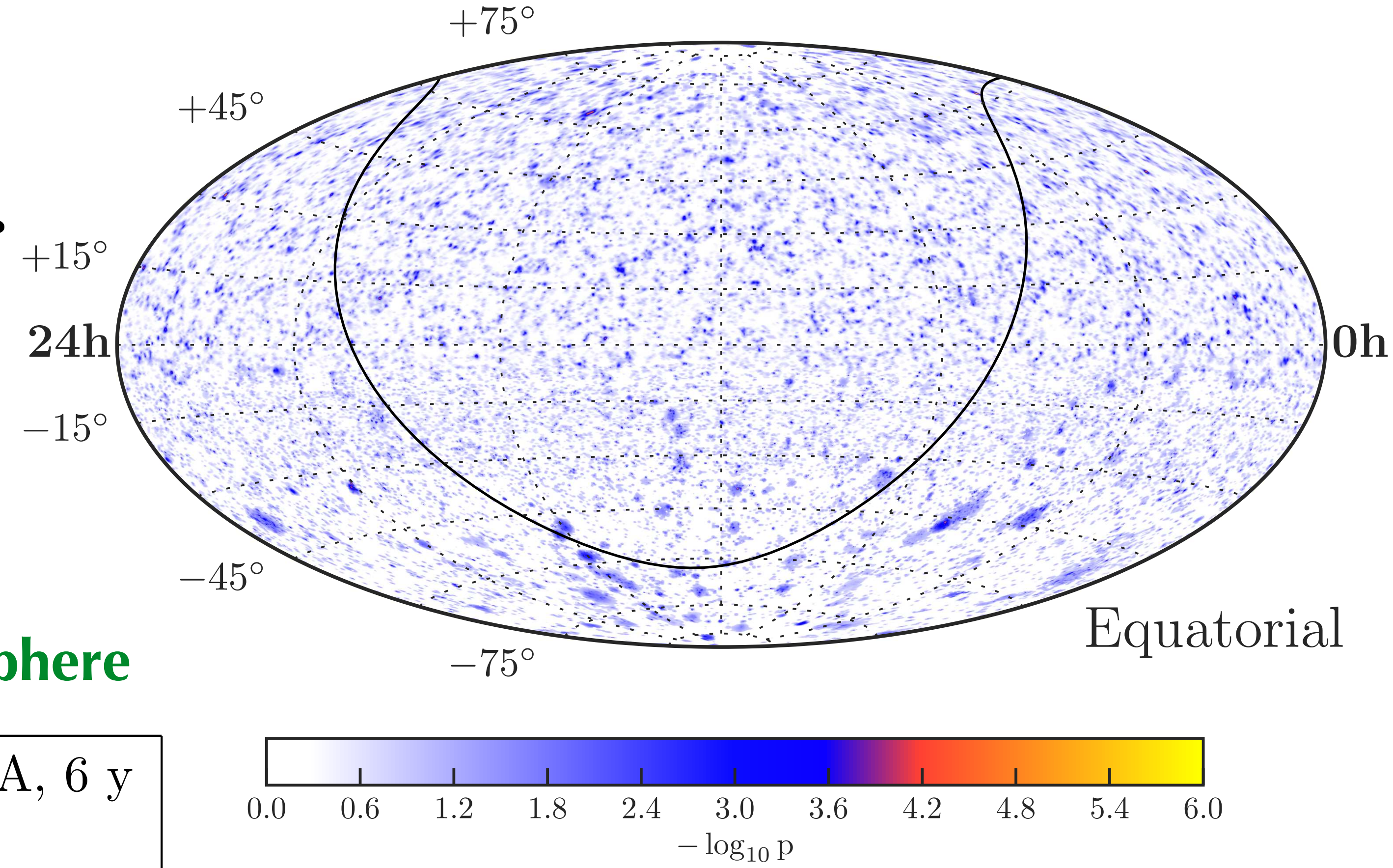


[Albert et al., Proceedings of ICRC 2017]

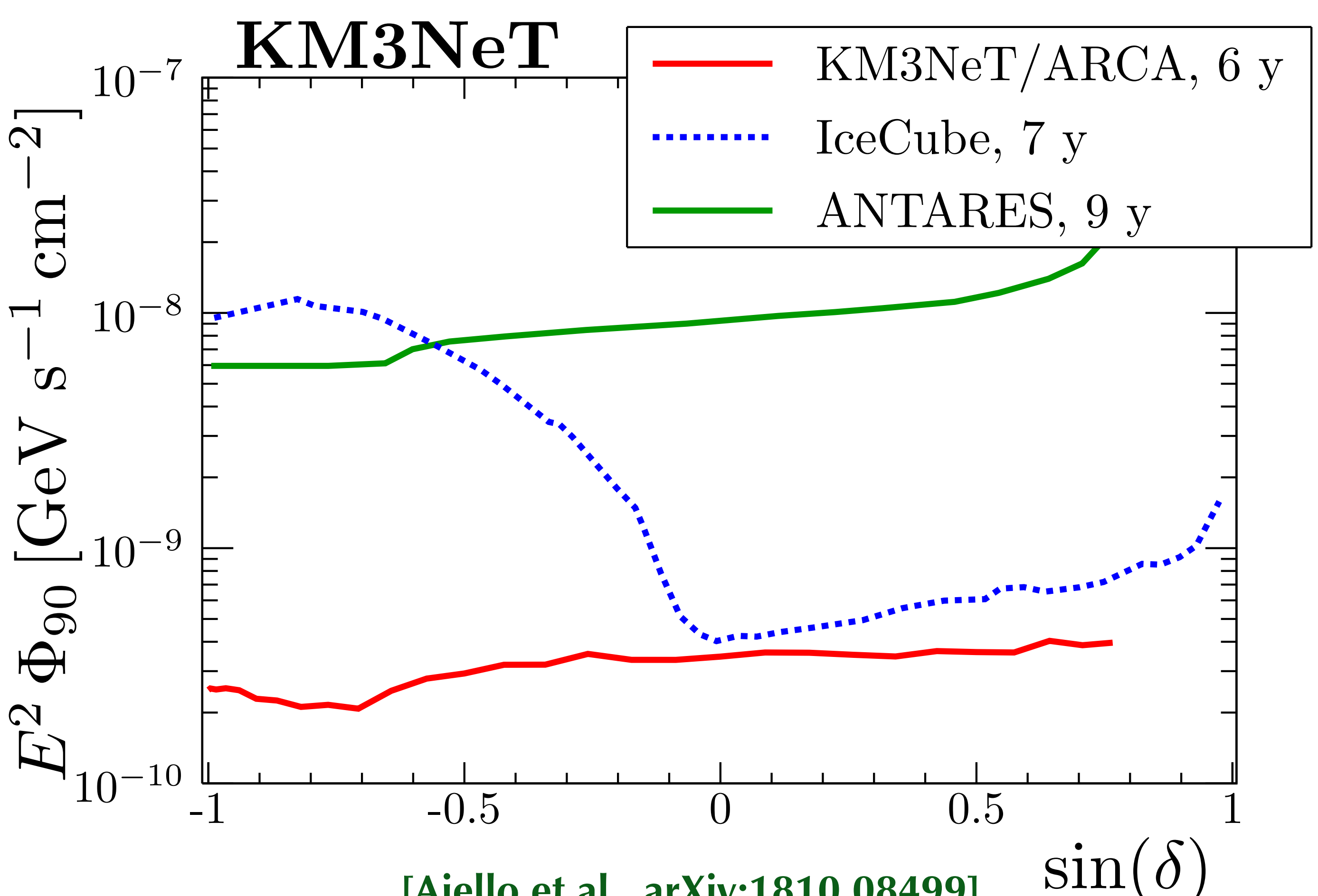
- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere



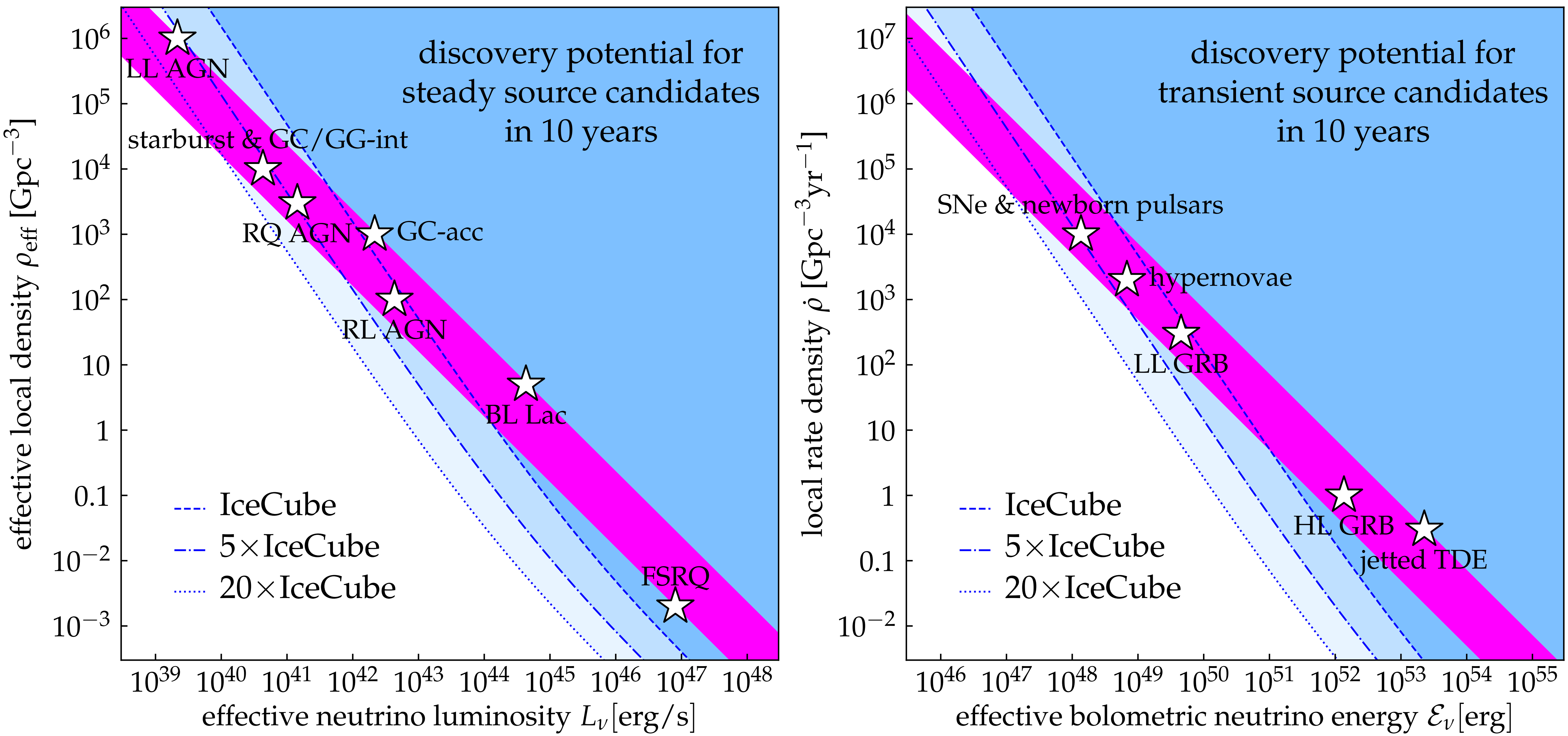
[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]



[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.

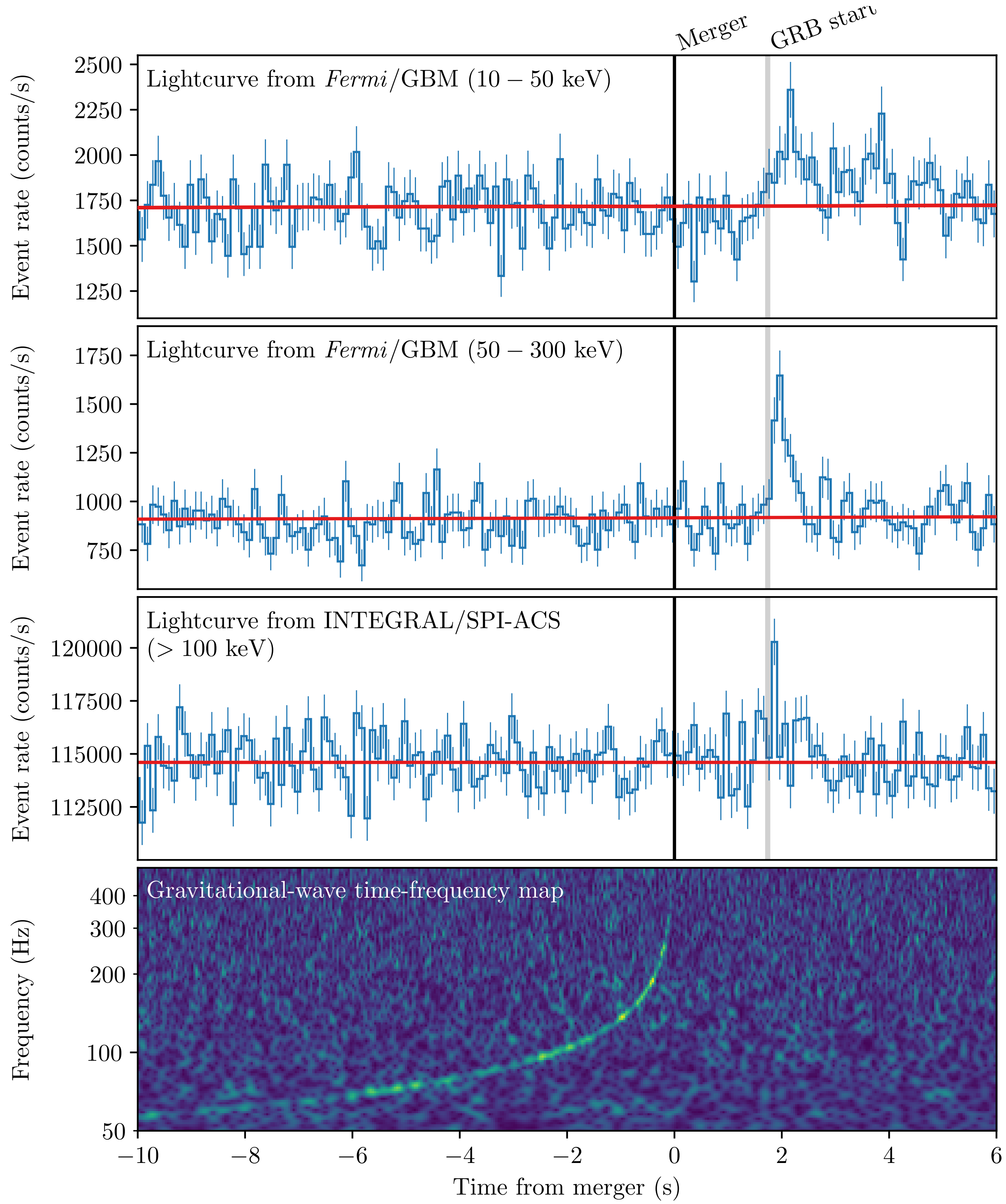
Where are the Sources?



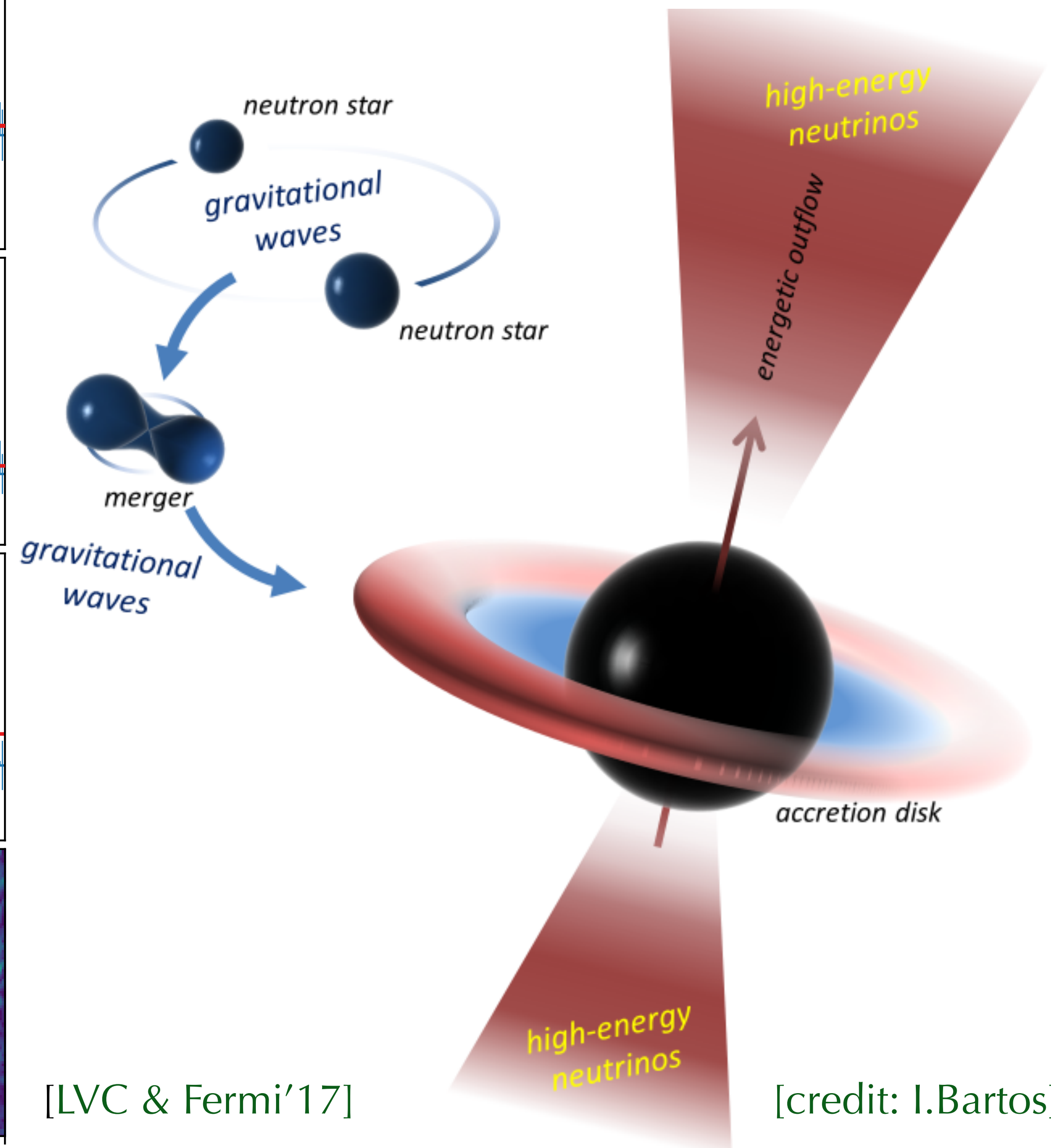
[Ackermann *et al.*, Astro2020]

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

Gravitational Wave Follow-Up



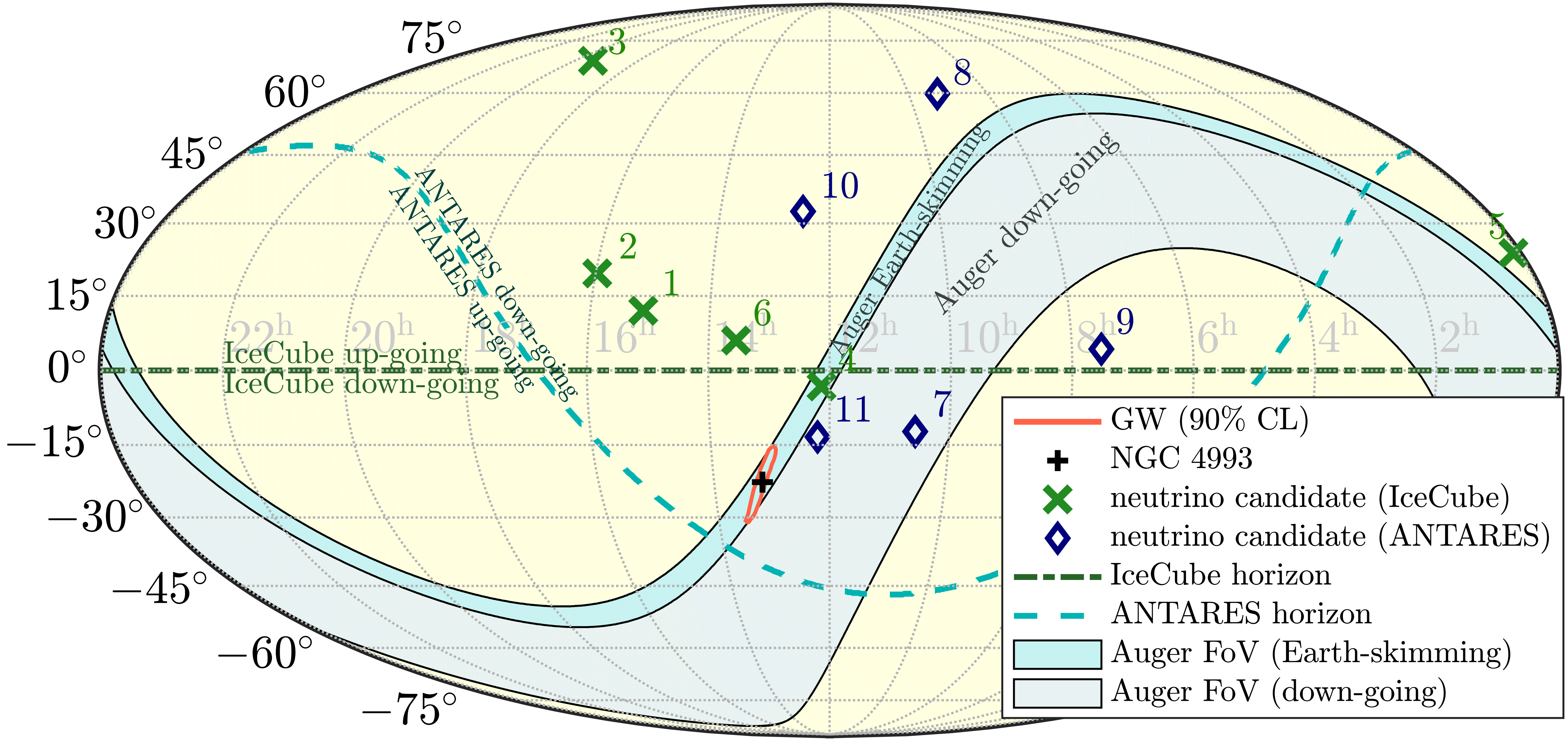
[LVC & Fermi'17]



[credit: I.Bartos]

First binary neutron star merger observed in gravitational waves (GW170817) coincident with a short gamma-ray burst (GRB 170817A).

Gravitational Wave Follow-Up



[**Astrophys.J.** 850 (2017) no.2, L35]

- Search for neutrino emission from GRB 170817A by ANTARES, IceCube & Pierre Auger.
- **No neutrino candidates** found within +/-500s and the GW 90% angular uncertainty region.
- LVC O3 science run (since April 1) : **near real-time follow-up by IceCube**

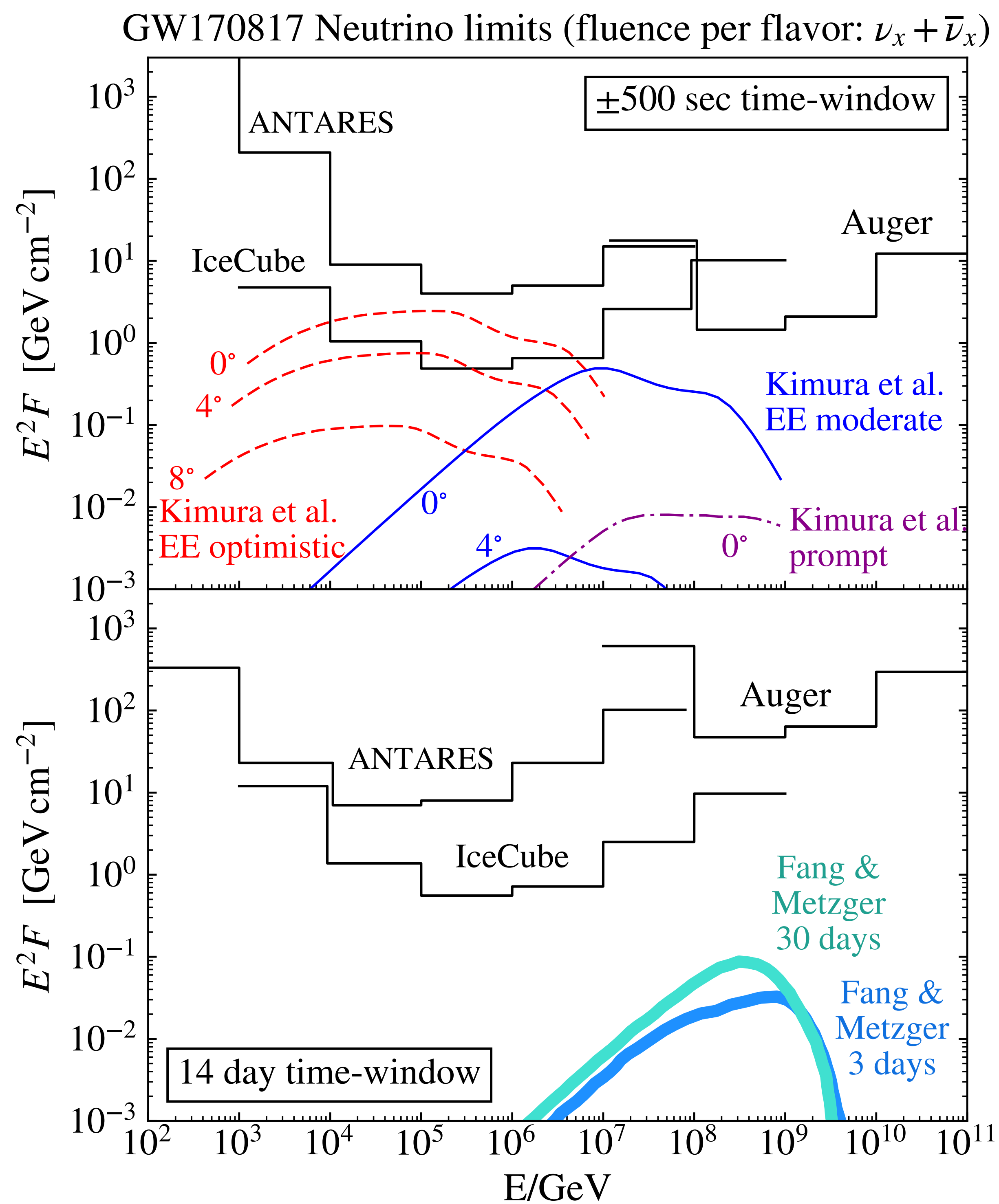
- Cosmic ray acceleration expected in internal shocks of short duration gamma-ray burst.
- Short-term neutrino production in scattering off photons (top panel).
- Non-observation consistent with off-axis emission:

$$F_{\mathrm{off}}(E_\nu) = \frac{\delta(\theta)}{\delta(0^\circ)} F_{\mathrm{on}}\left(\frac{\delta(0^\circ)}{\delta(\theta)} E_\nu\right)$$

- Doppler factor:

$$\delta(\theta) = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

- Long-term neutrino emission from remnant pulsar wind (bottom panel).

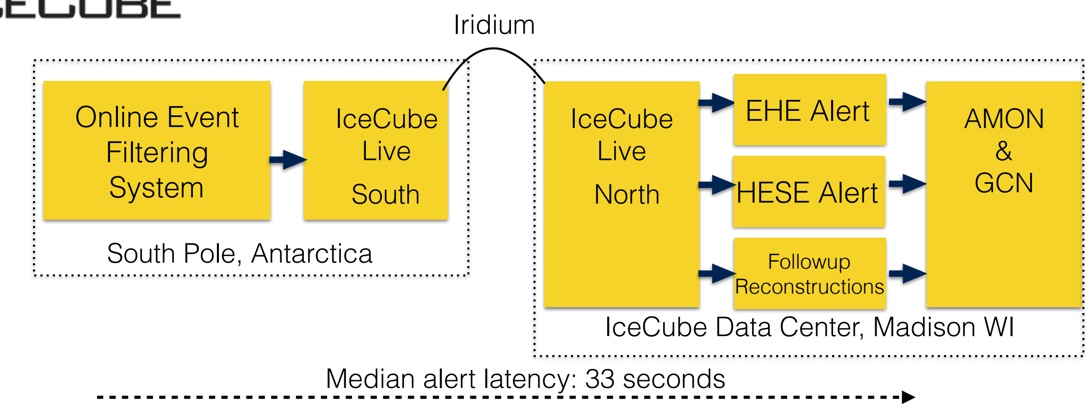


[**Astrophys.J.** 850 (2017) no.2, L35]

Realtime Neutrino Alerts

ICECUBE

IceCube and ANTARES issue realtime neutrino alerts to multi-messenger partners for rapid follow-up.



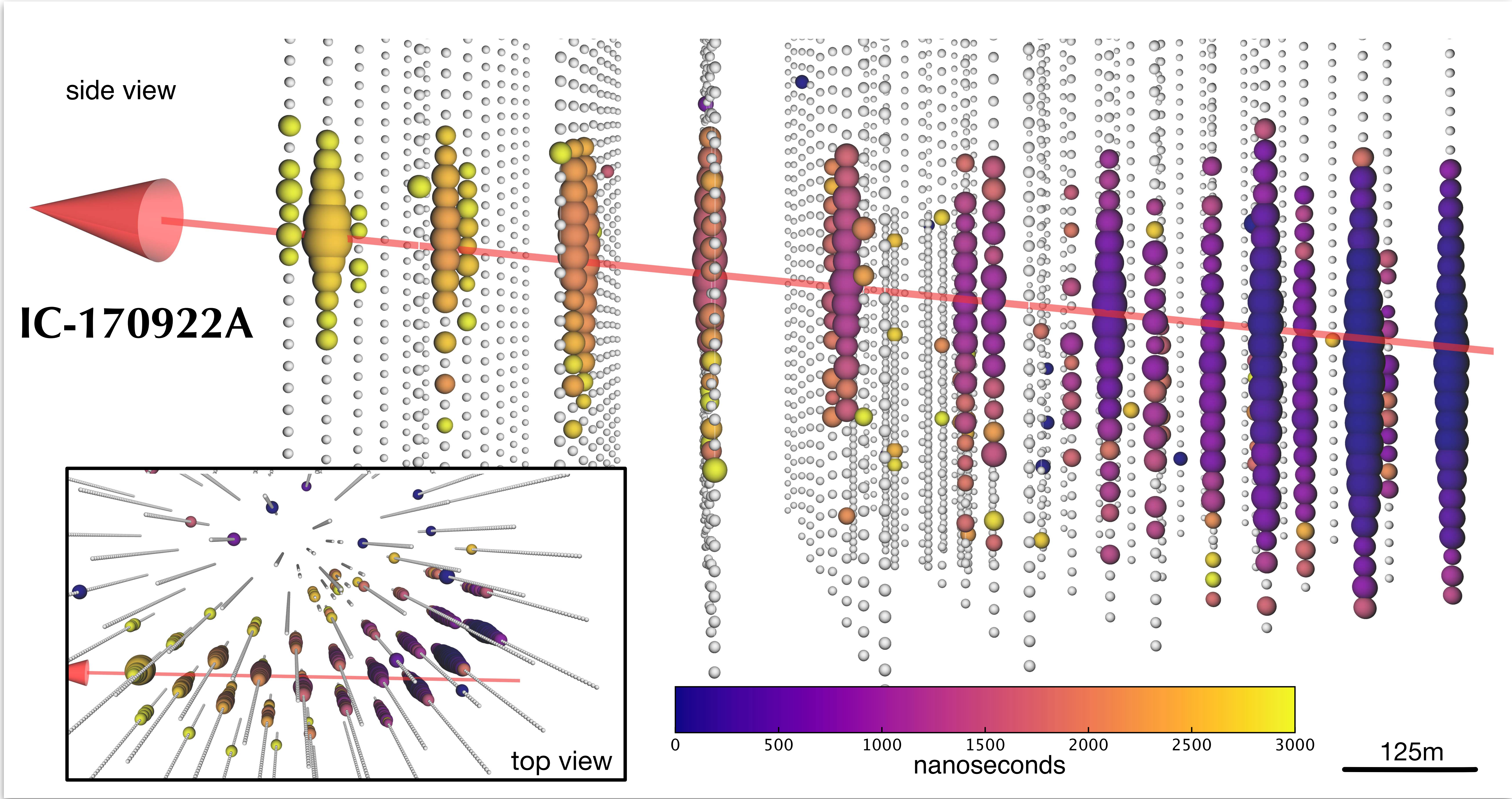
- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- **high-energy starting tracks** (>60TeV)
  - 4.8 alerts/year (1.1 signal/year)
- **through-going muons** (>100TeV)
  - 4-5 alerts/year (2.5-4 signal/year)

[Blaufuss et al., Proceedings of ICRC 2017]

- time to issue alert: 5s
- median angular resolution 0.5deg
- **neutrino doublets**
  - 0.04 alerts/year
- **neutrinos from local galaxies** (>1TeV)
  - 10 alerts/year
- **high-energy neutrinos** (>5TeV)
  - 20 alerts/year
- **very high-energy neutrinos** (>30TeV)
  - 3-4 alerts/year

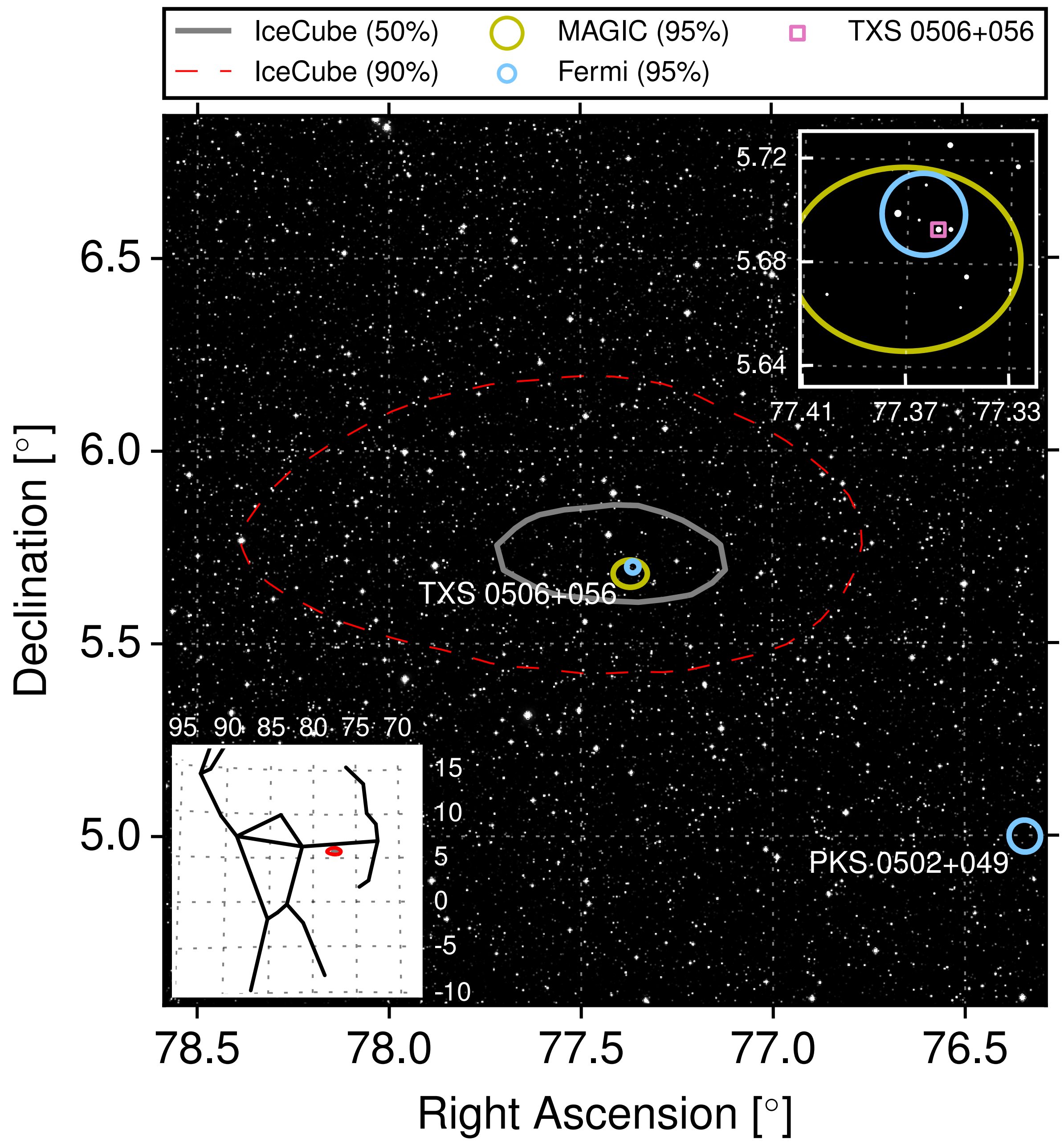
[Dornic et al., Proceedings of ICRC 2017]

Realtime Neutrino Alerts



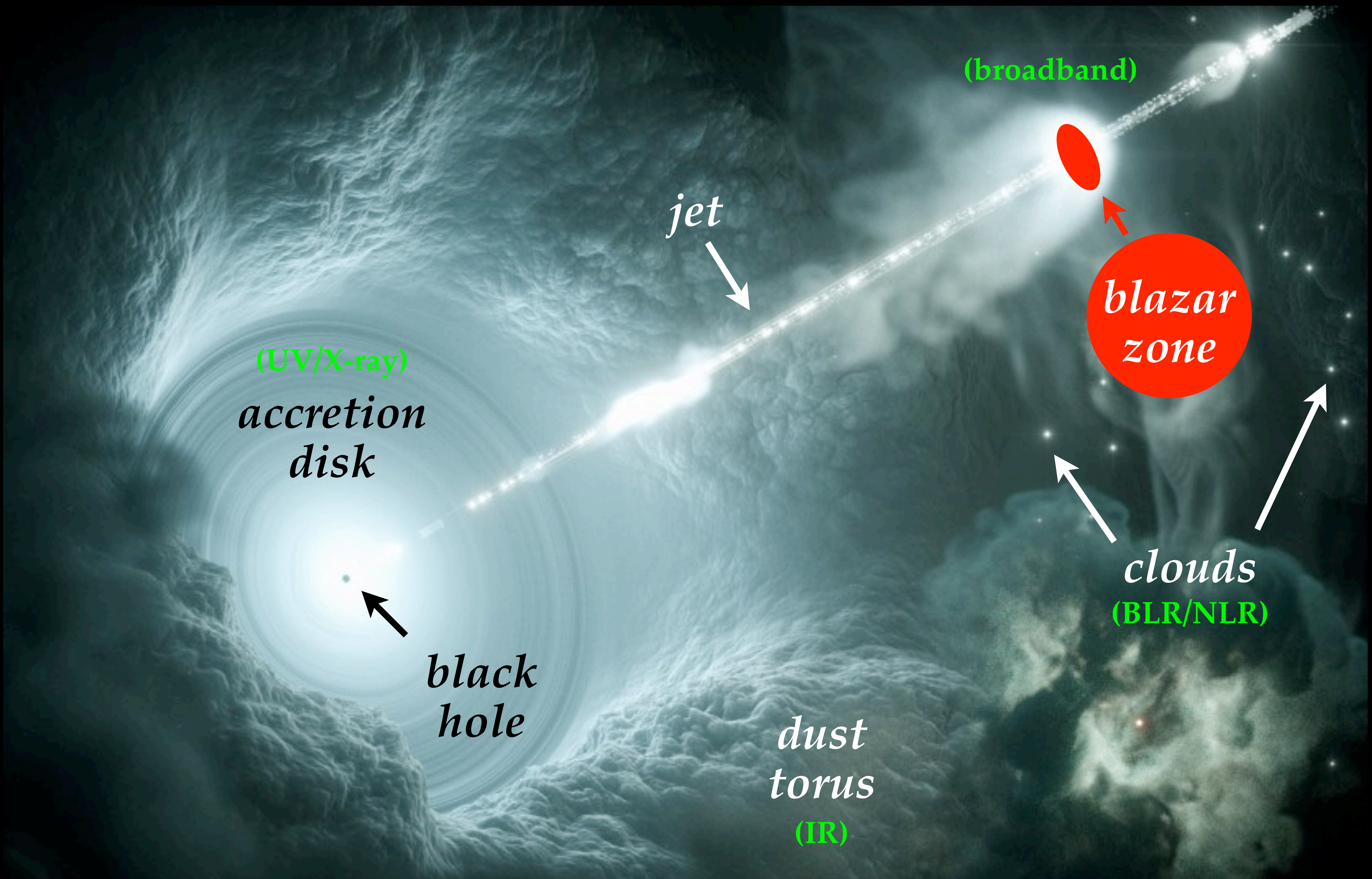
up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

TXS 0506+056



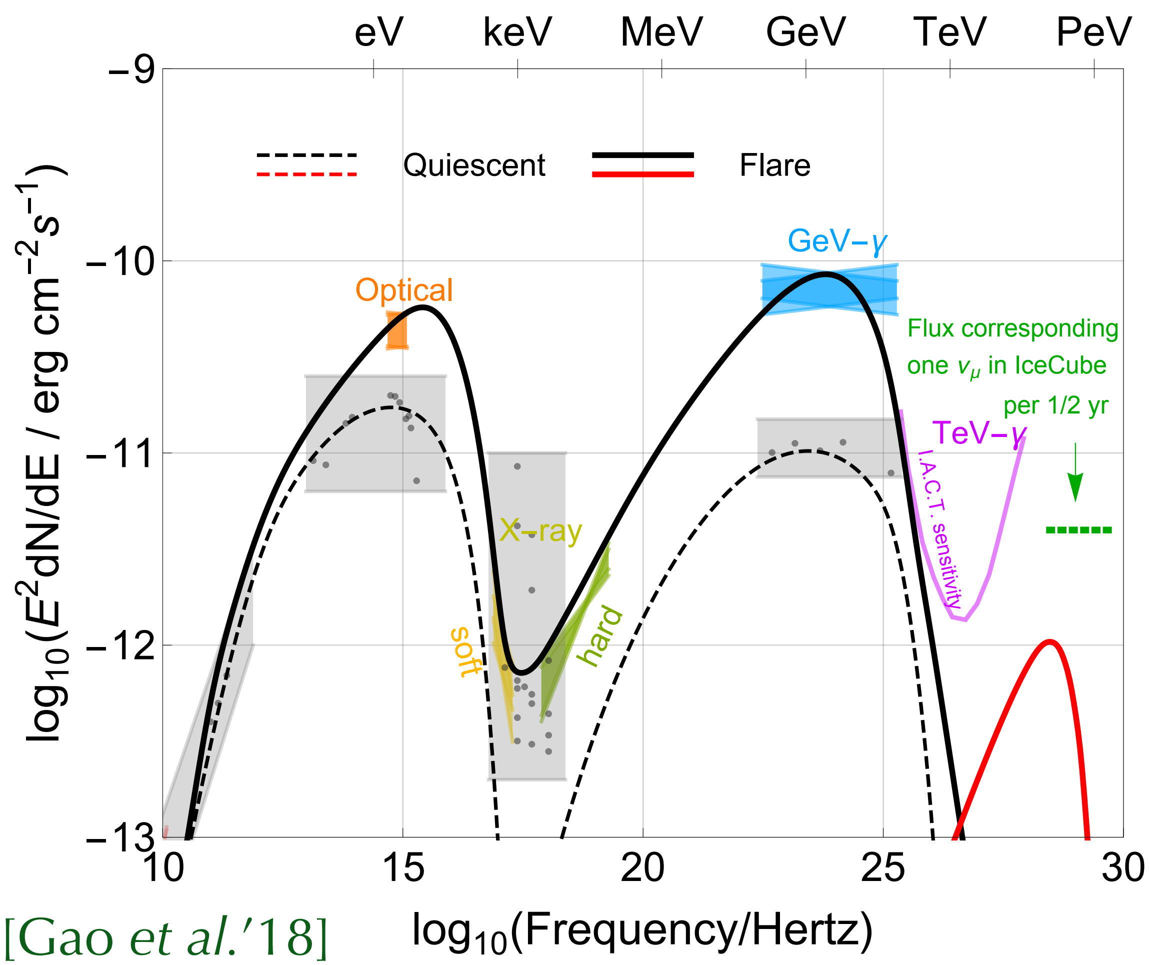
- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the **3σ-level**.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Blazars as Neutrino Factories

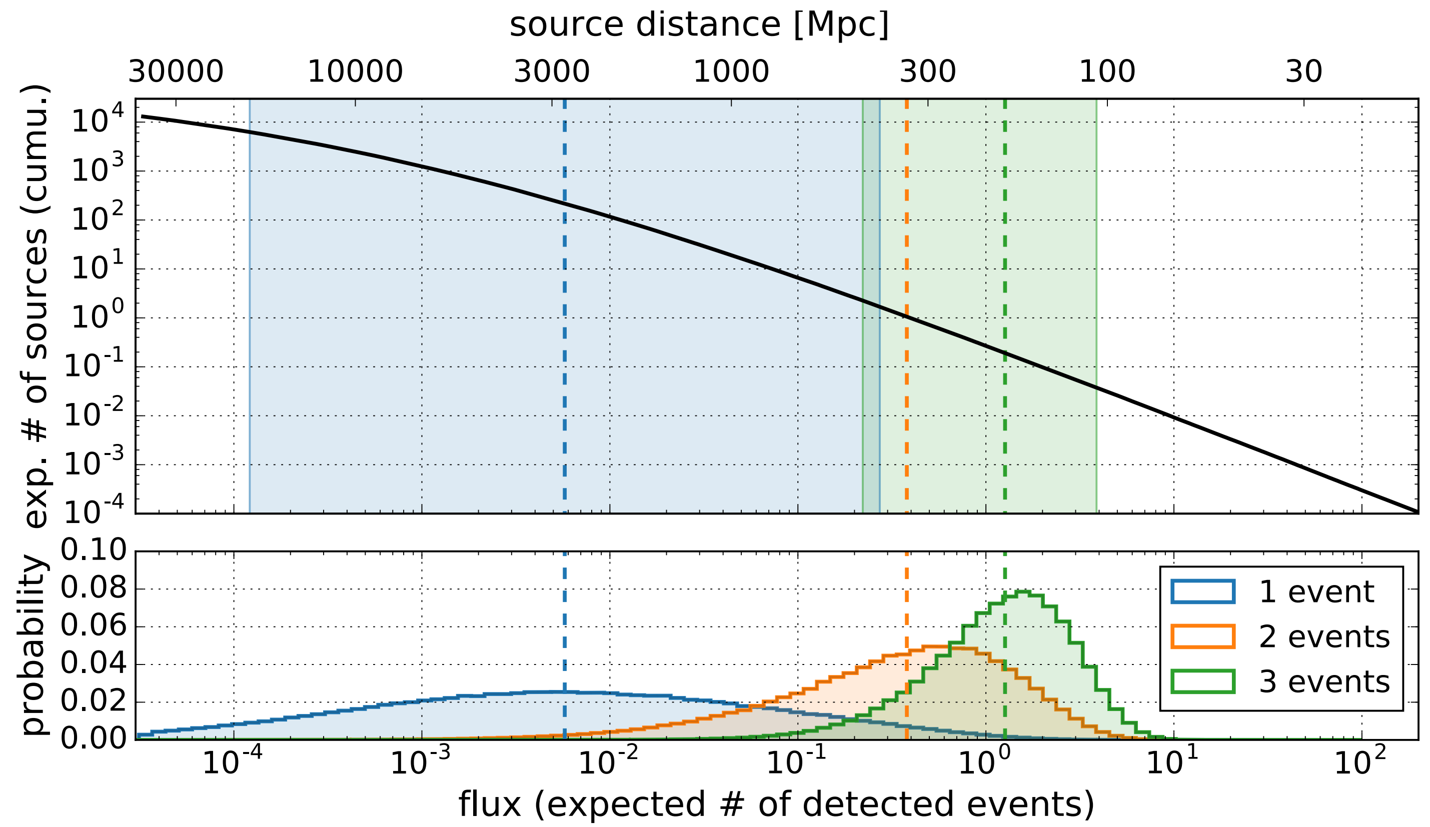


Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

Neutrino Flare in 2017



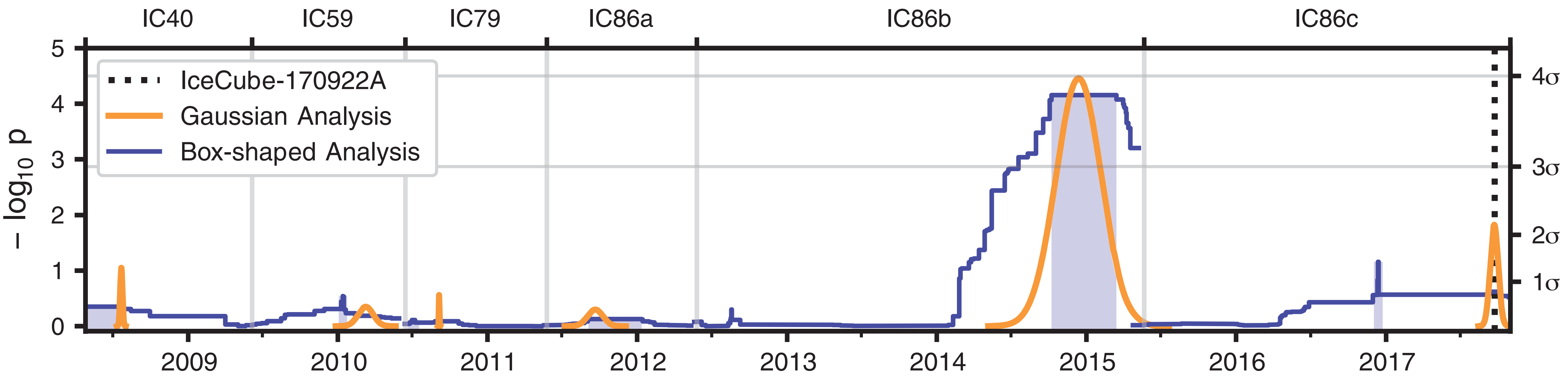
[Gao *et al.*'18]

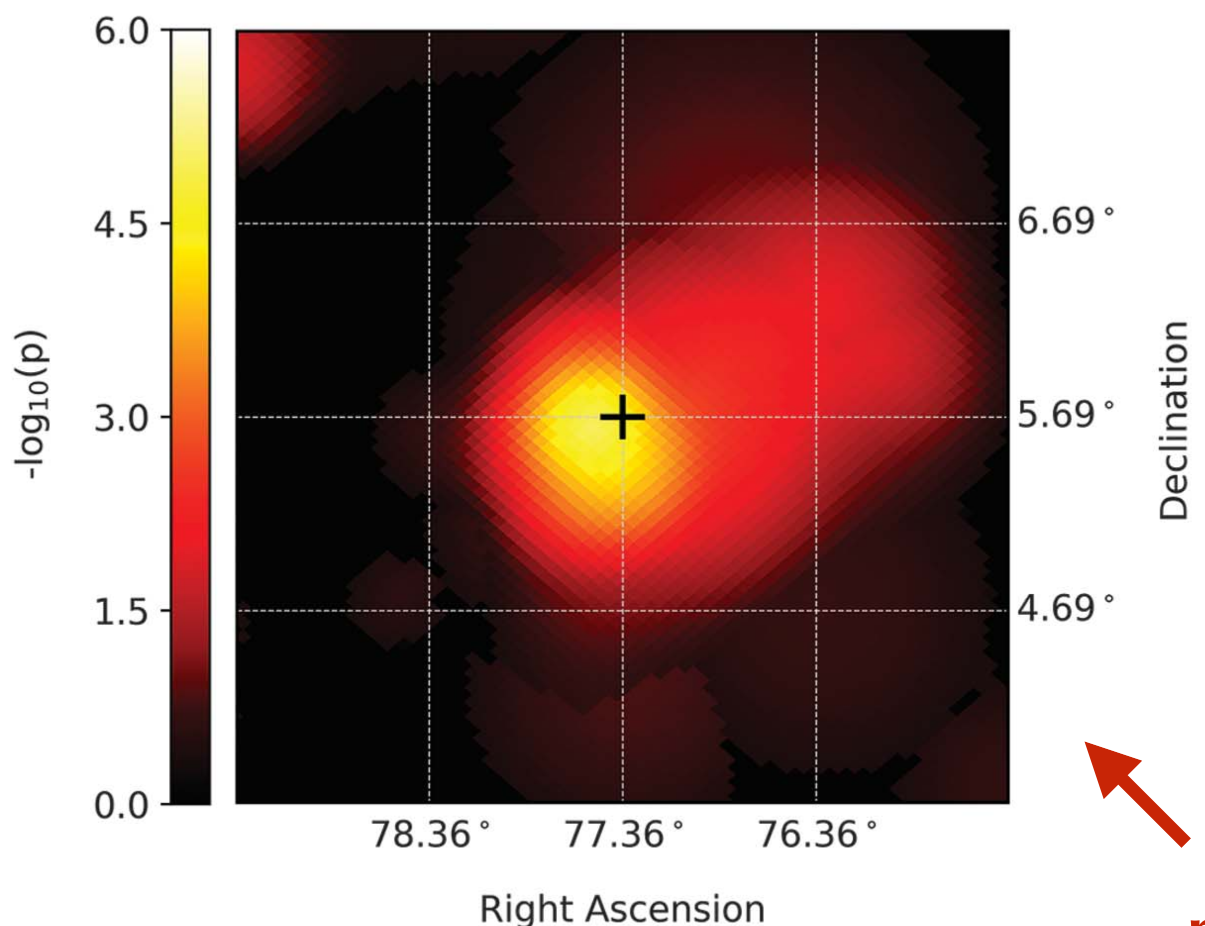


[Strotjohann, Kowalski & Franckowiak'18]

- Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.
  [Keivani *et al.*'18.; Gao *et al.*'18; Cerruti *et al.*'18; Zhang, Fang & Li'18; Gokus *et al.*'18; Sahakyan'18]
- Neutrino flux limited to **less than one event** by theoretically feasible cosmic ray luminosity and X-ray data. [Murase, Oikonomo & Petropoulou'18]
- **Eddington bias**: expected number of events expected from BL Lacs observed by one event in the range **0.006 - 0.03** [Strotjohann, Kowalski & Franckowiak'18]

Neutrino Flare in 2014/15

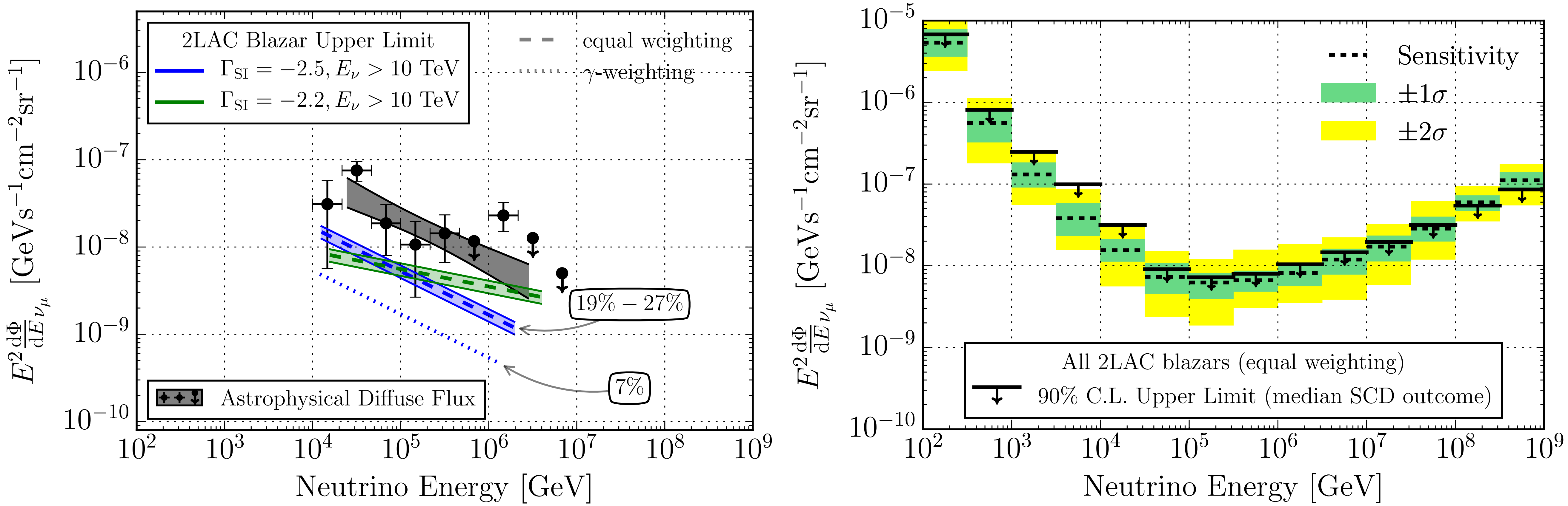




- Independent 3.5σ evidence for a **neutrino flare** (13±5 events) in 2014/15.
- Neutrino luminosity over 158 days is about **four times brighter than gamma-ray emission** (Fermi-LAT).
- on average, **1000 times brighter** than 2017 neutrino flux

neutrino "morphology" of 2014/15 flare

Are Blazars the TeV-PeV Sources?



[IceCube'17]

- Blazar stacking limits derived from Fermi-LAT AGN catalogue (2LAC).
- Upper limit on the diffuse flux at the level of 30% assuming all blazar classes contribute. [IceCube'17]
- Energy of IC-170922A in the region of strongest differential upper limit.

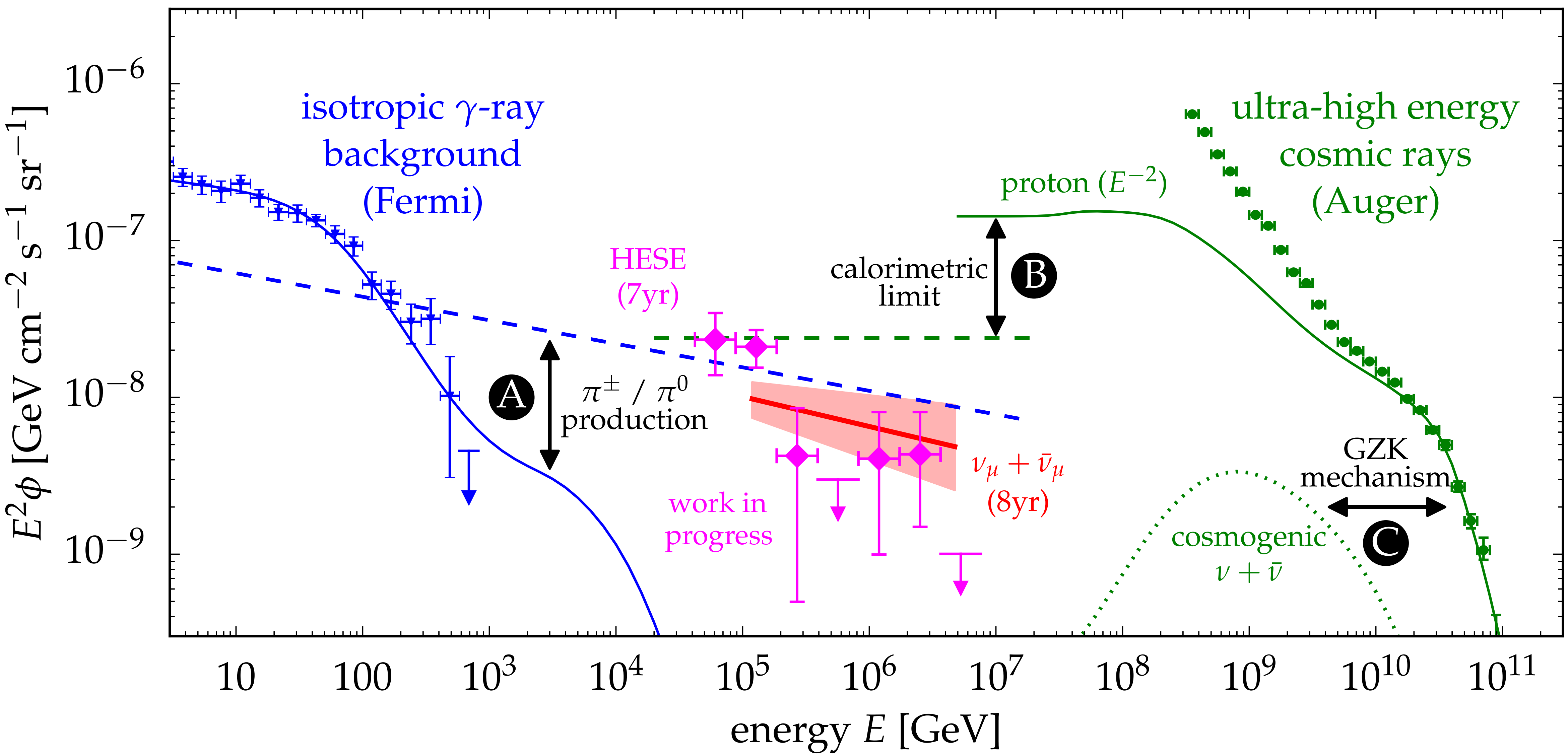
Multi-Messenger Interfaces

Further progress on diffuse emission via multi-messenger relations:

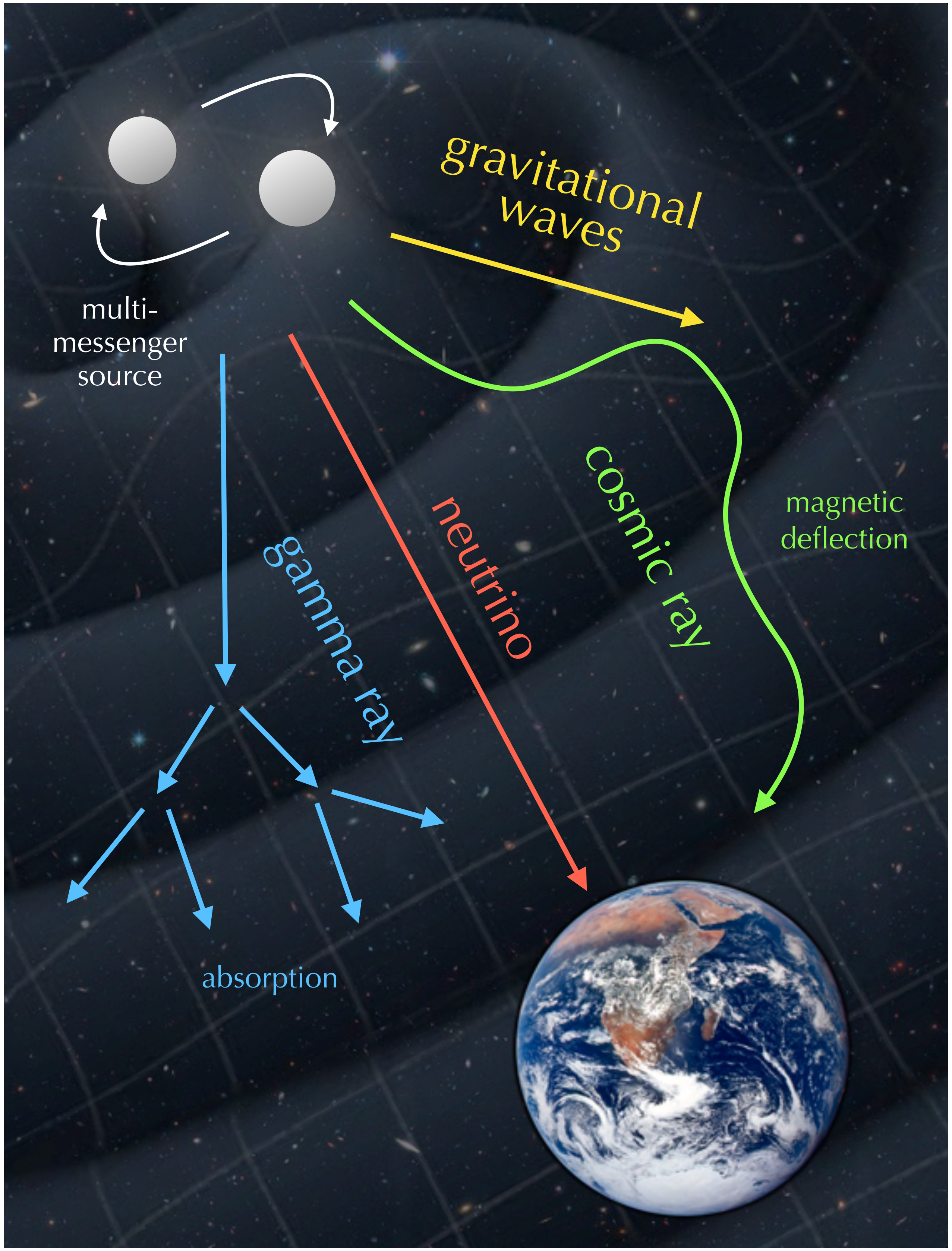
(A) **Joint production** of gamma-rays and neutrinos in CR interactions.

(B) Low-rigidity CRs trapped in **calorimetric environments** (e.g. starburst galaxies).

(C) **GZK neutrinos** from UHE CR propagation in cosmic backgrounds.

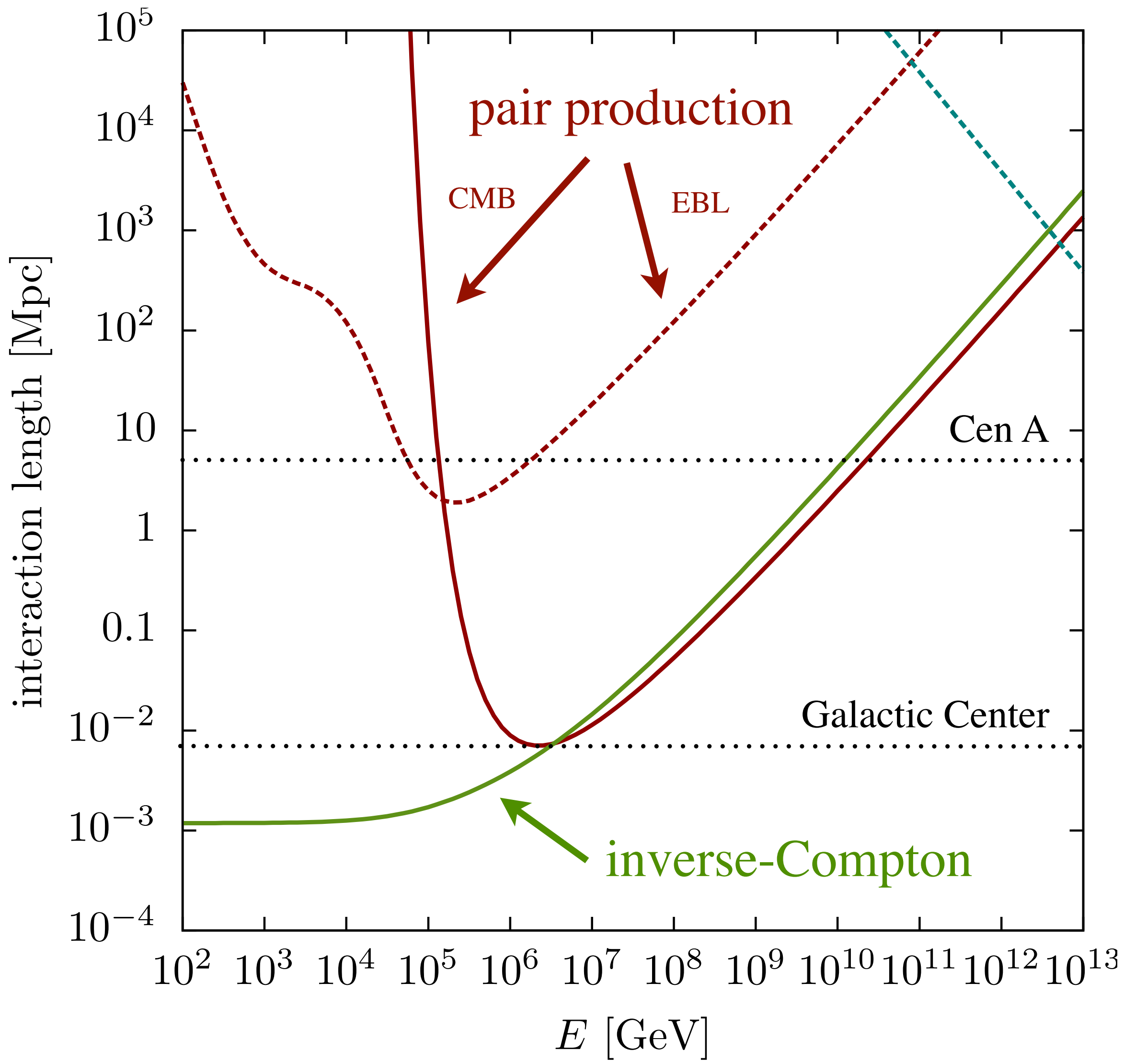


Hadronic Gamma-Rays



- Joint production of gamma-rays and neutrinos from cosmic ray collisions.

- TeV gamma-rays initiate electro-magnetic cascades in collisions with cosmic microwave background.



Hadronic Gamma-Rays

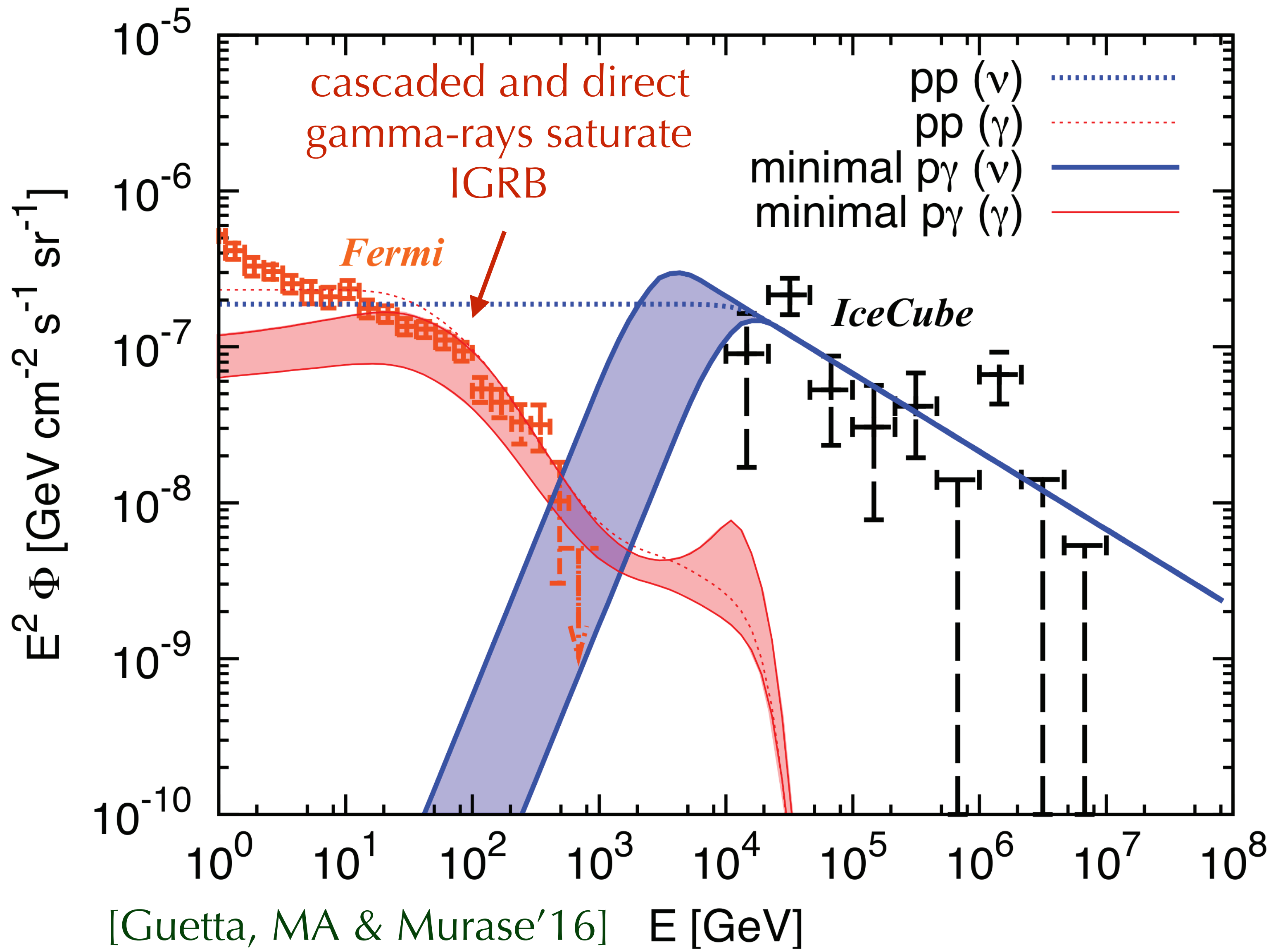
- Gamma-ray emission from EM cascades ends up in the sub-TeV range observed with **Fermi-LAT**.
- In addition, CR interactions with gas (pp) predict extended **power-law spectra** of neutrinos and gamma-rays.
- Cosmic ray **spectral index strongly constrained** by the isotropic diffuse gamma-ray background (IGRB):

[Murase, MA & Lacki'13]

$$\Gamma \leq 2.15$$

- IceCube best-fit (HESE 7.5yr):

$$\Gamma \simeq 2.87 \pm 0.3$$



[Guetta, MA & Murase'16]

[Murase, MA & Lacki'13]
[Tamborra, Ando & Murase'14;Ando, Tamborra & Zandanel'15]
[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15]
[Palladino, Fedynitch, Rasmussen & Taylor'19]

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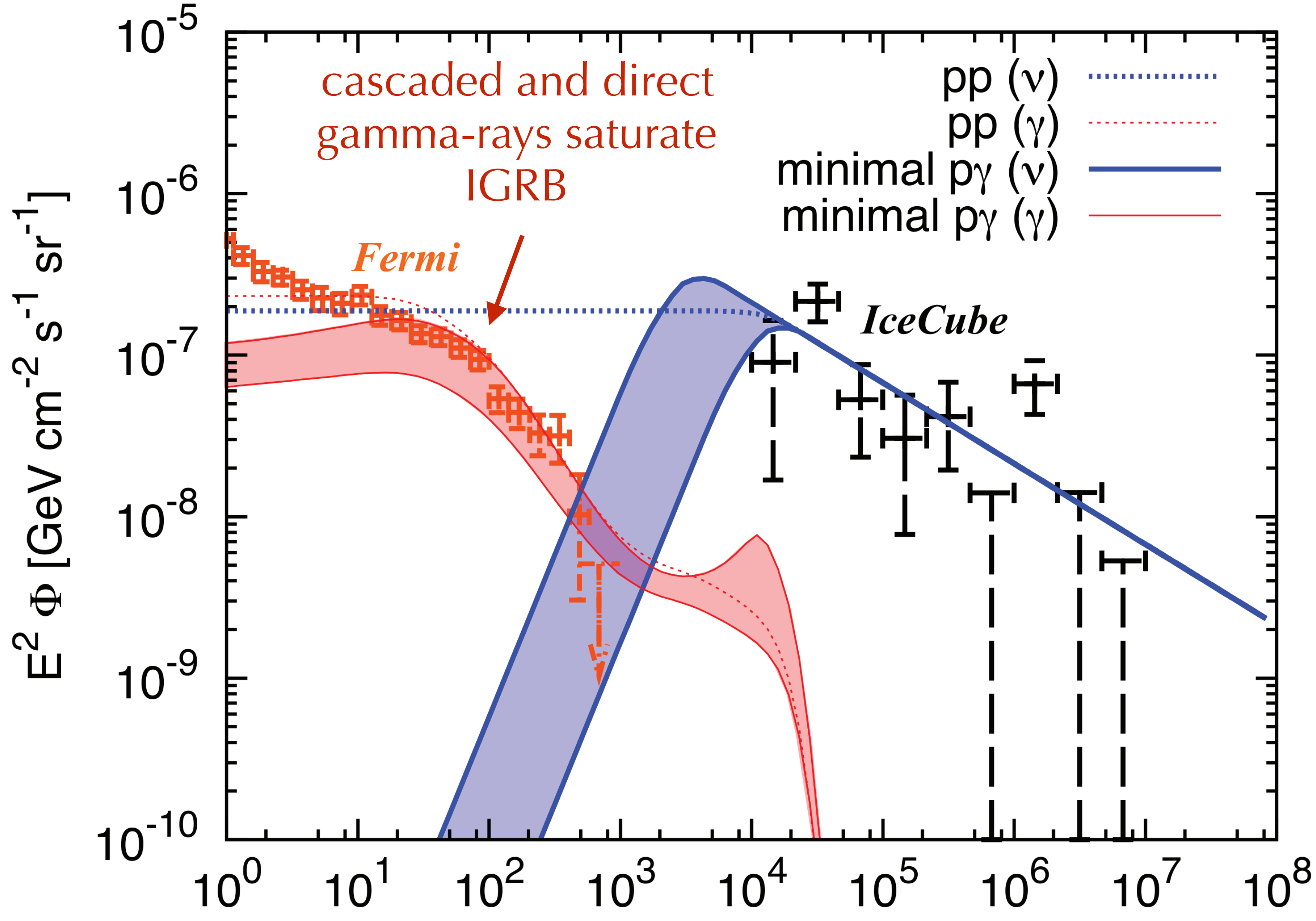

[Guetta, MA & M…rase’16]

Talk by Andrea Palladino (Tuesday)

[Murase, MA & Lacki’13]
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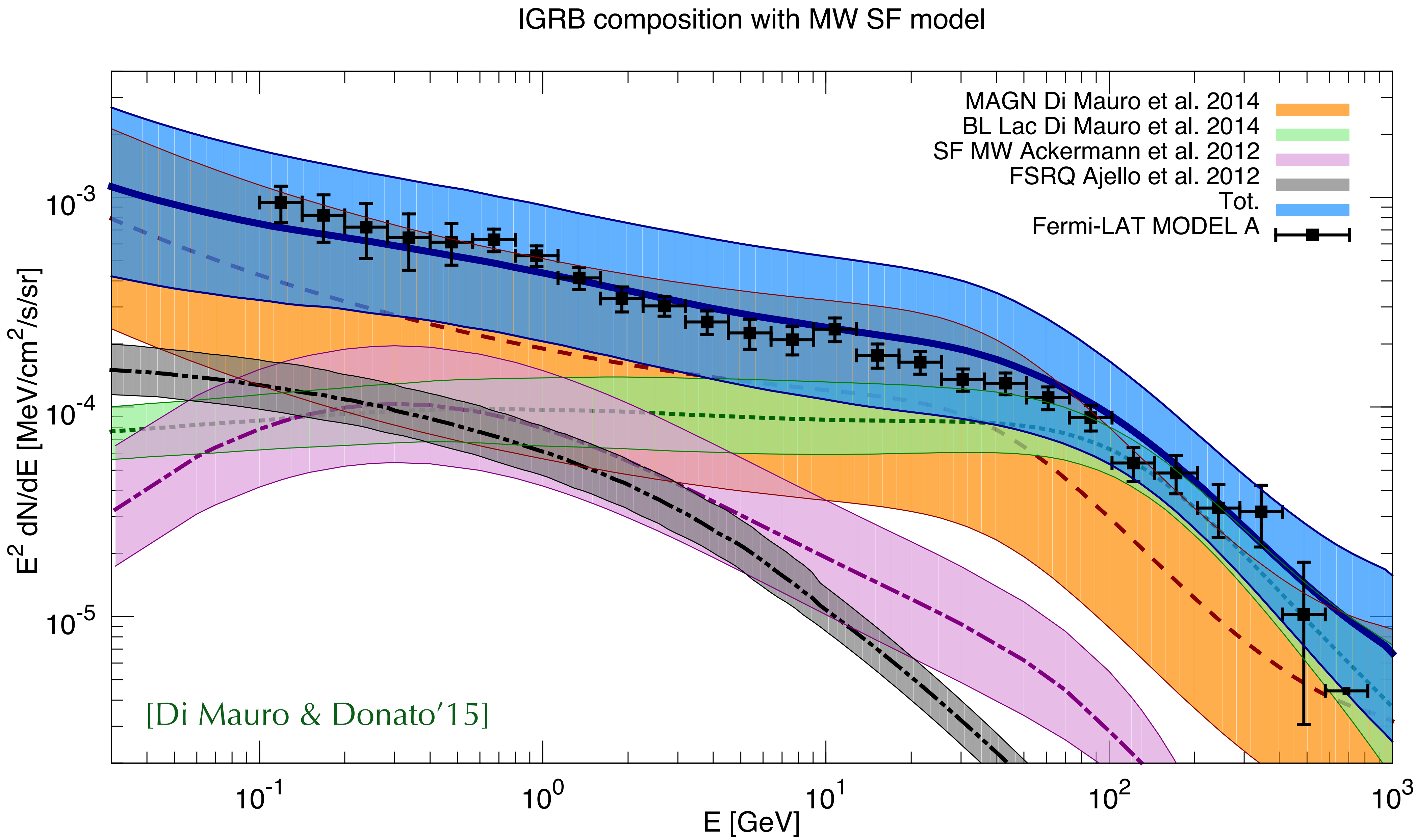
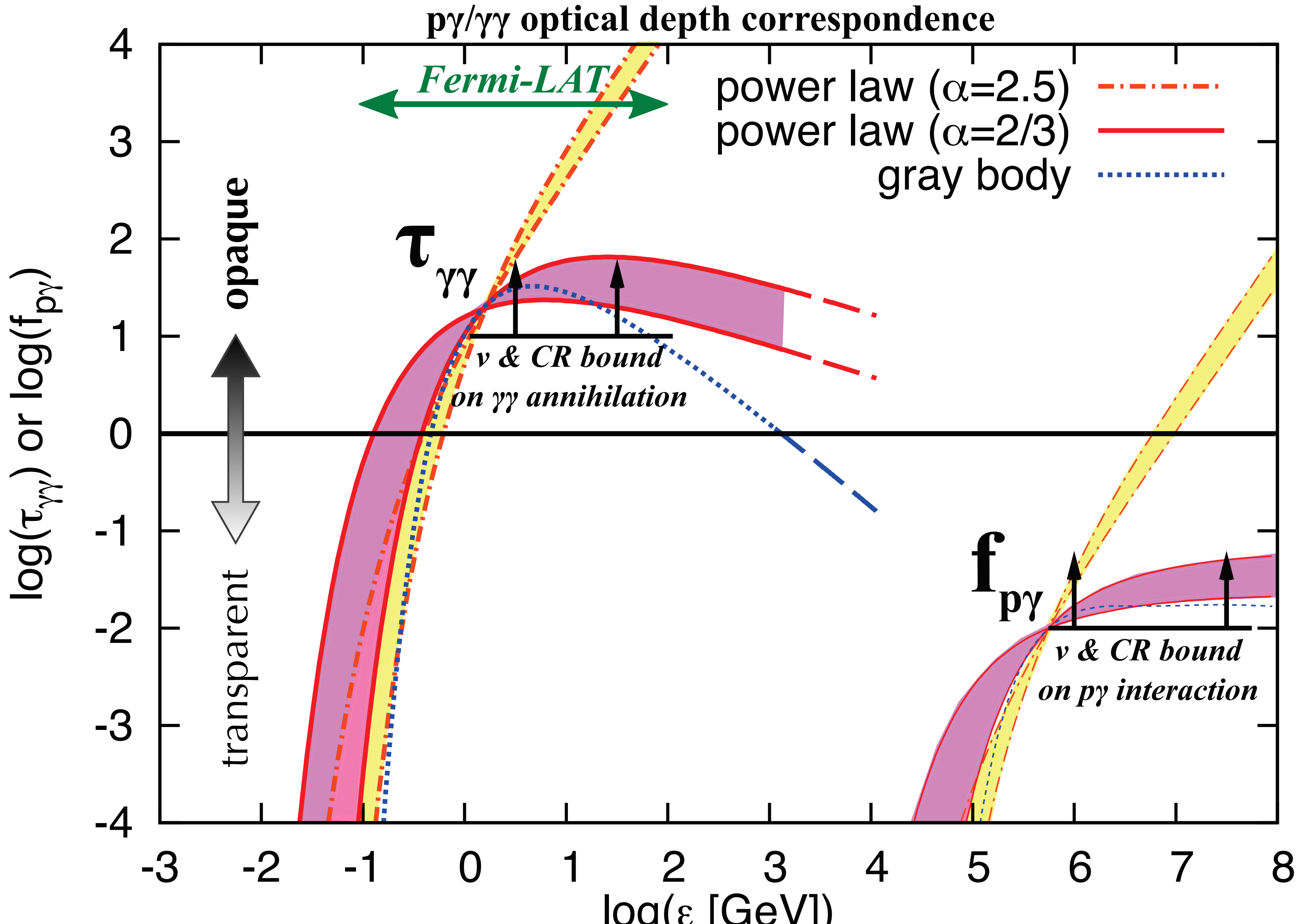
Isotropic Diffuse Gamma-Ray BGR



- **Isotropic diffuse gamma-ray background** (IGRB) consists of unidentified point-like sources and diffuse contributions.
- Extrapolation of identified (bright) gamma-ray sources allows to model the emission.
- large contribution (>50%) from unidentified blazars (BL Lac) at E>50 GeV

Hidden Sources?

Efficient production of 10 TeV neutrinos requires **strong X-ray backgrounds.**



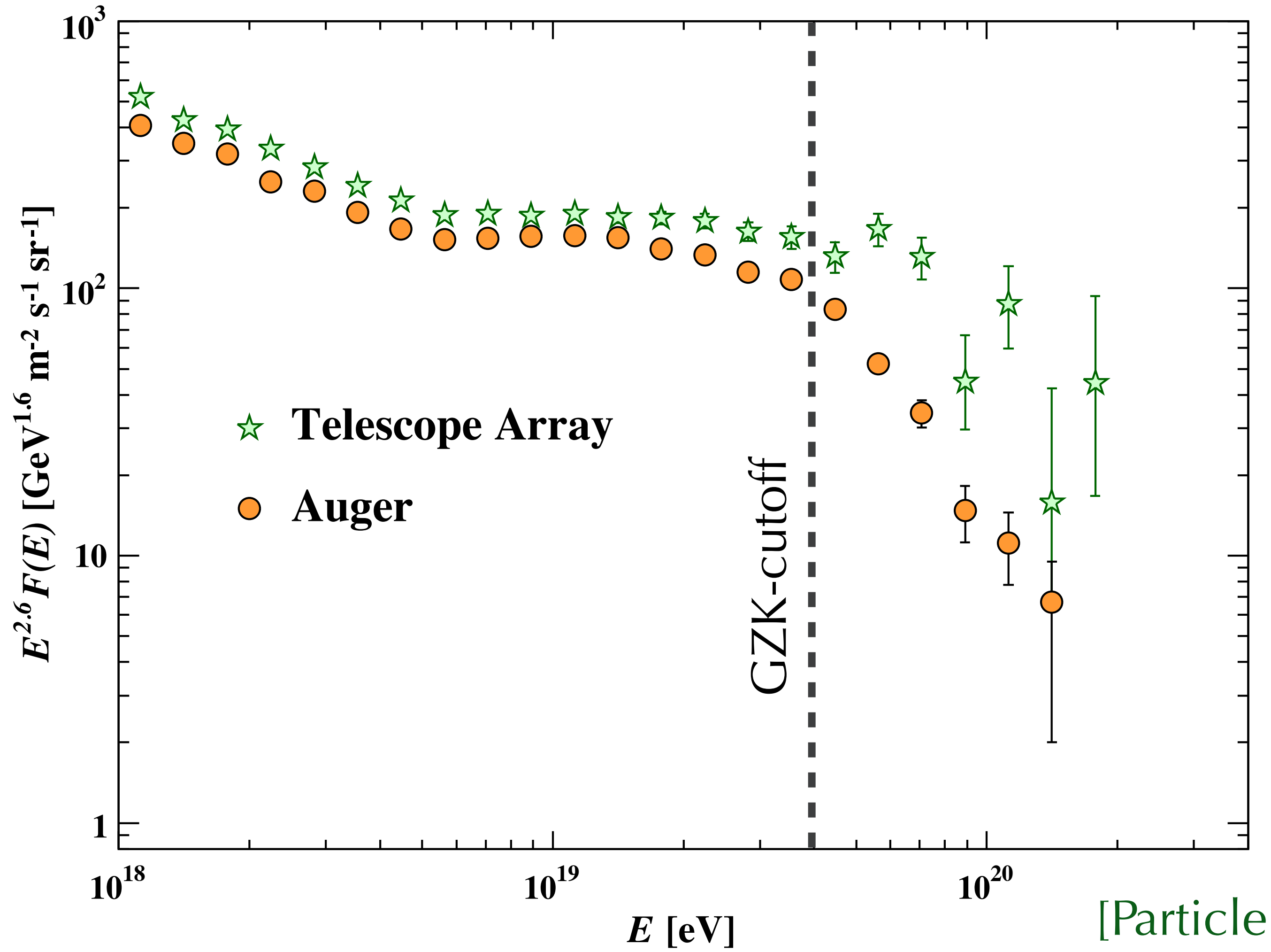
[Guetta, MA & Murase'16]

High pion production efficiency implies strong internal **gamma-ray absorption in Fermi-LAT energy range**:

$$\tau_{\gamma\gamma} \simeq 1000\, f_{p\gamma}$$

UHE CR Spectrum

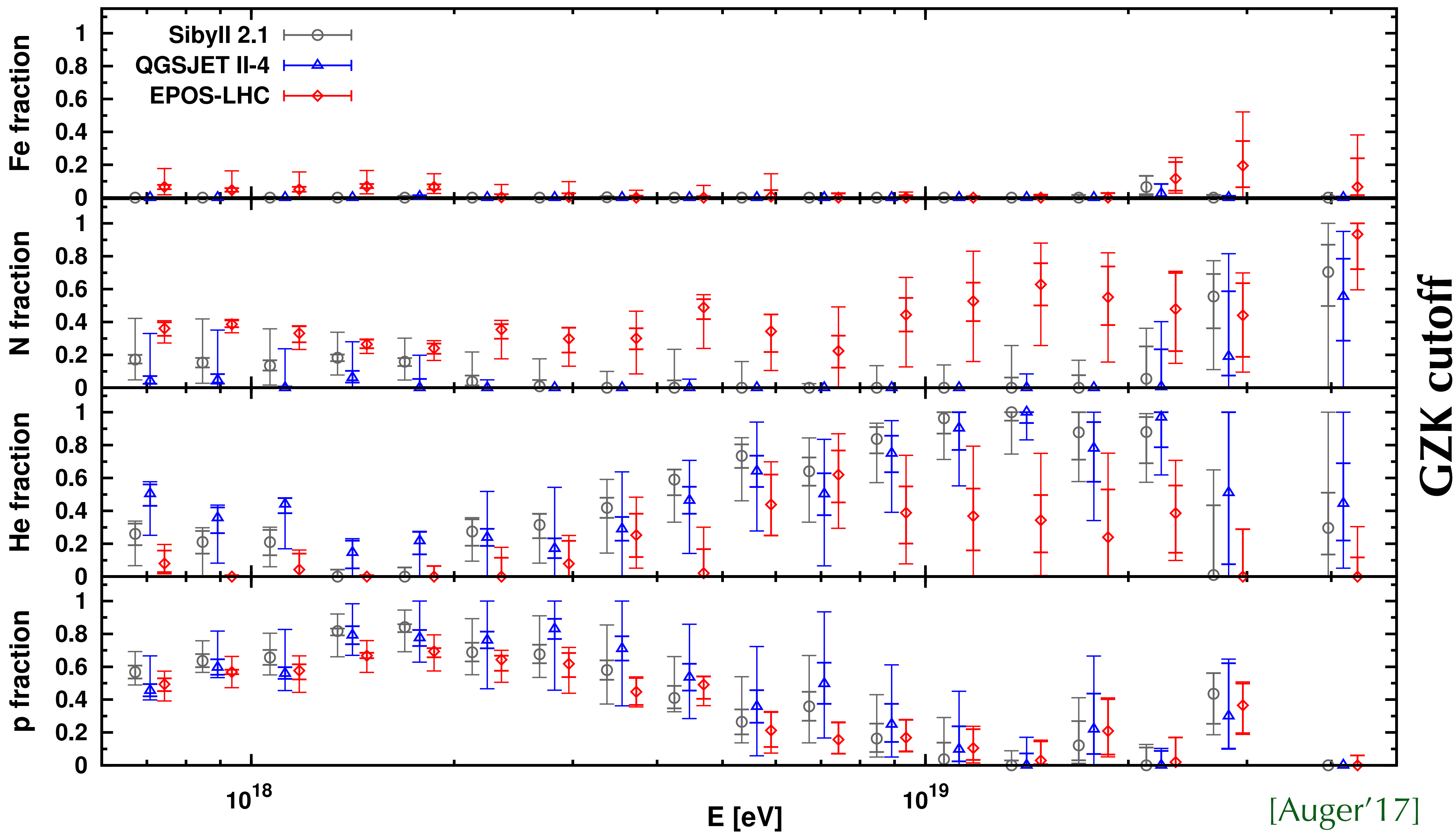
- **Ultra-High Energy (UHE) CR** spectrum (>EeV) expected to show suppression due to resonant interactions with cosmic microwave background beyond ~40EeV (GZK-cutoff). [Greisen & Zatsepin'66;Kuzmin'66]
- UHE CRs above 40EeV limited to local Universe (~200Mpc).
- **Window for UHE CR astronomy** for light composition (high rigidity).



[Particle Data Group'19]

- Suppression feature observed in spectra with high significance.
- However, could also be related to **intrinsic cutoff** of UHE CR sources.
- **Testable by GZK neutrinos**. [Berezinsky & Zatsepin'70]

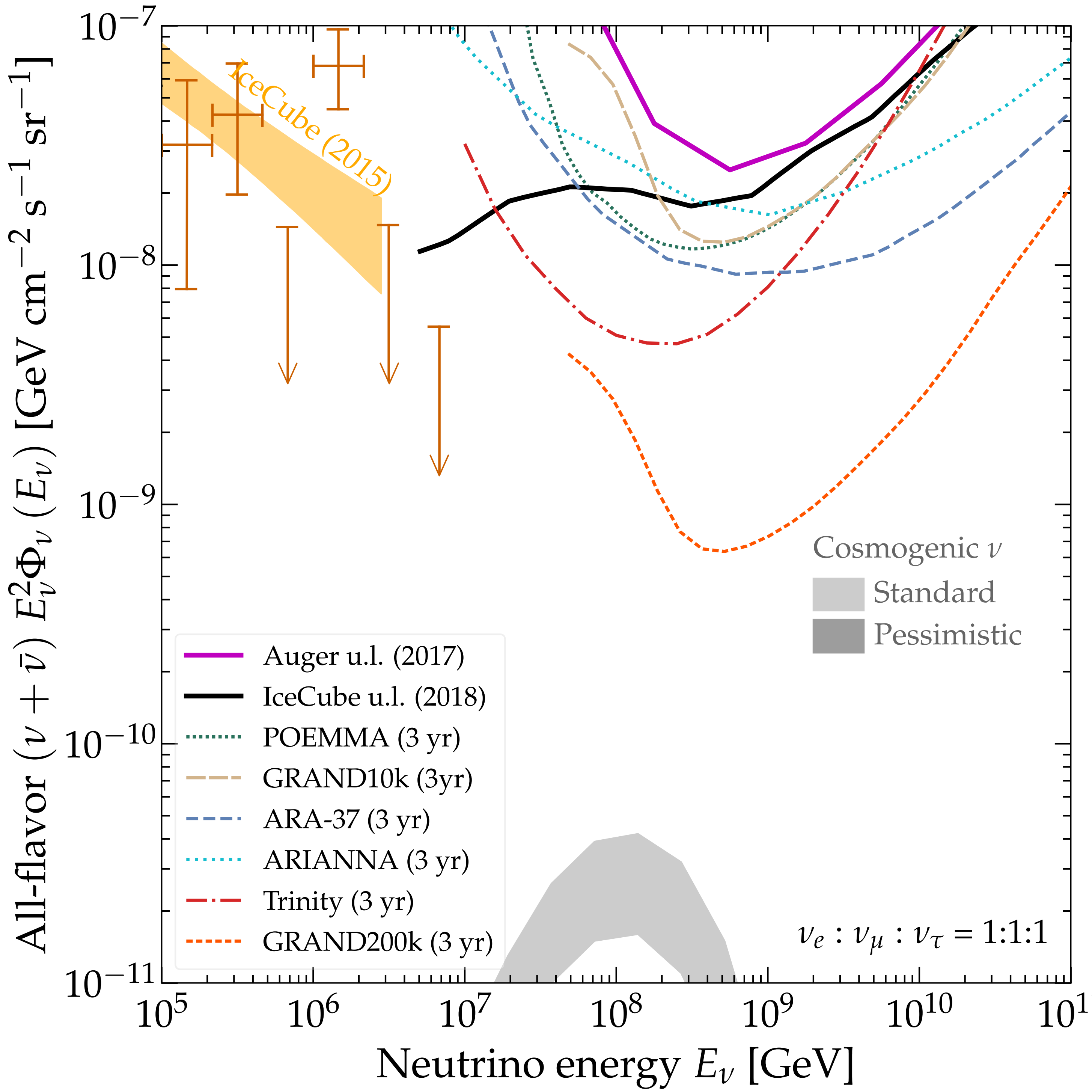
- **Composition of UHE CR** determined by fits of shower maxima (X_{max}) distribution.
- Large systematic uncertainties in hadronic interaction models
- **Auger**: significant contribution of heavy nuclei above the ankle.



[Auger'17]

GZK Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
  [Berezinsky&Zatsepin'70]
- Target of proposed in-ice **Askaryan** (ARA & ARIANNA), air shower **Cherenkov** (GRAND) or **fluorescence** (POEMMA & Trinity) detectors.
- Optimistic predictions based on high proton fraction and high maximal energies.
  [e.g. MA *et al.*'10; MA & Halzen'12]
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.



[Alves Batista *et al.*'19]

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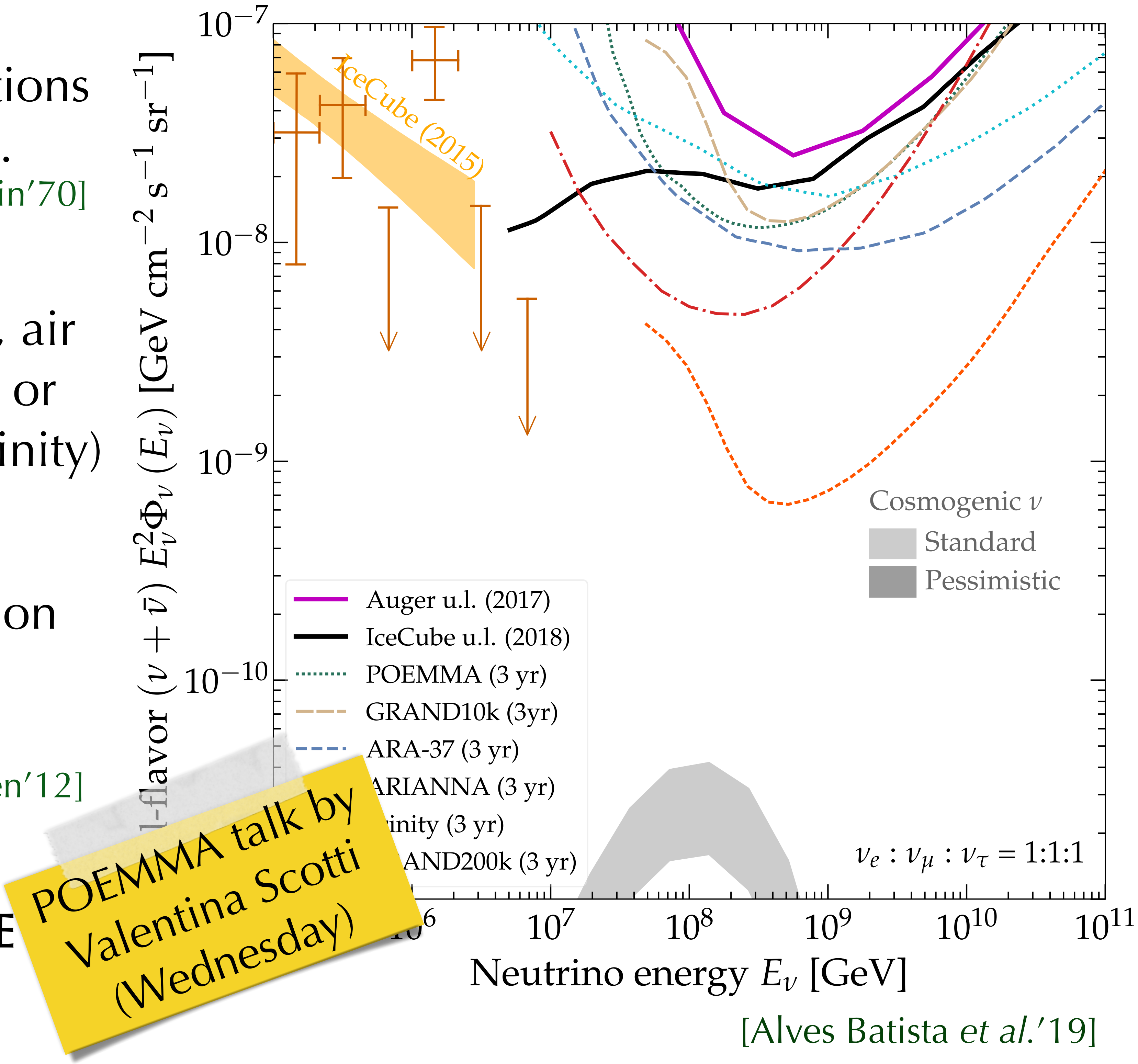
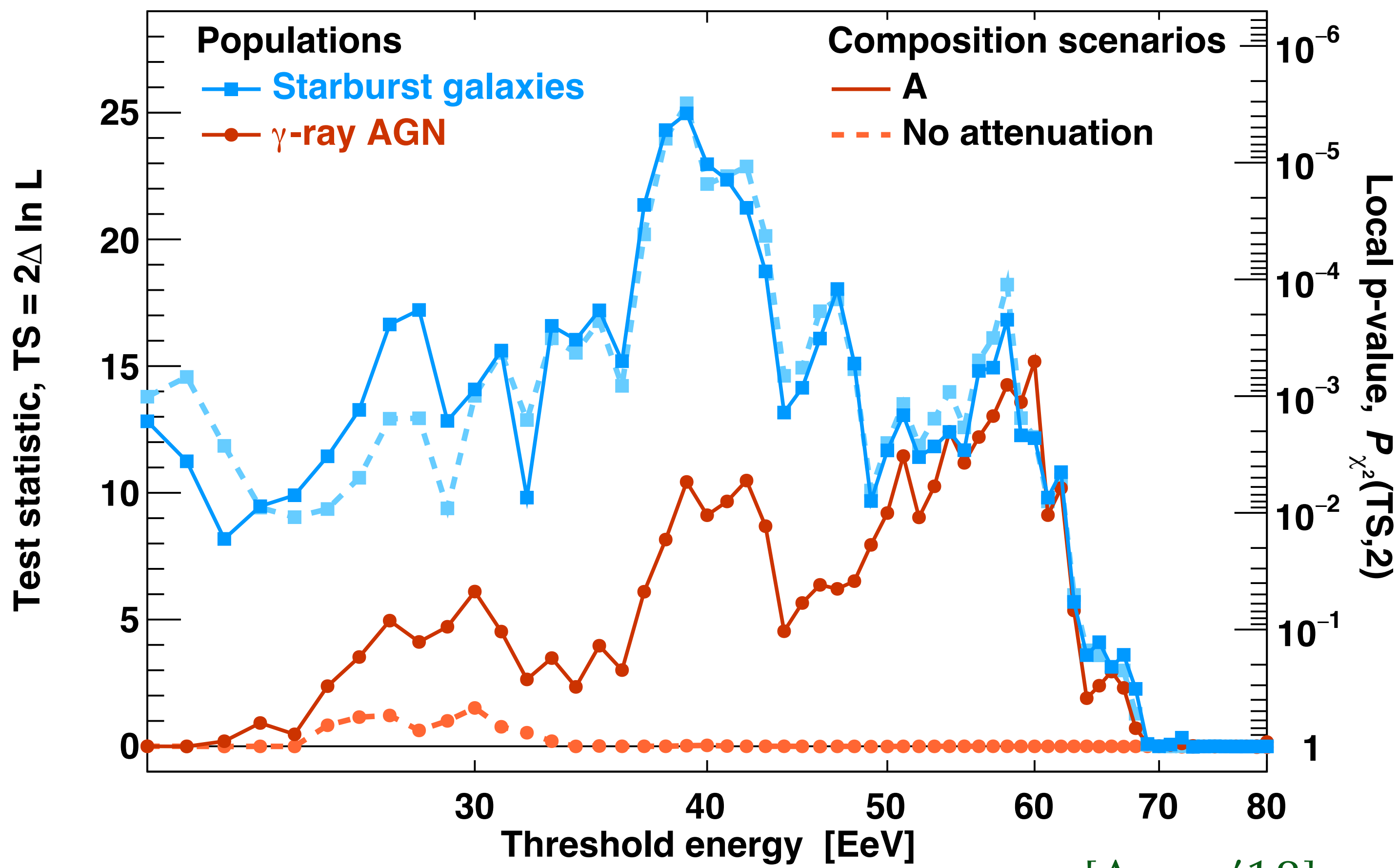
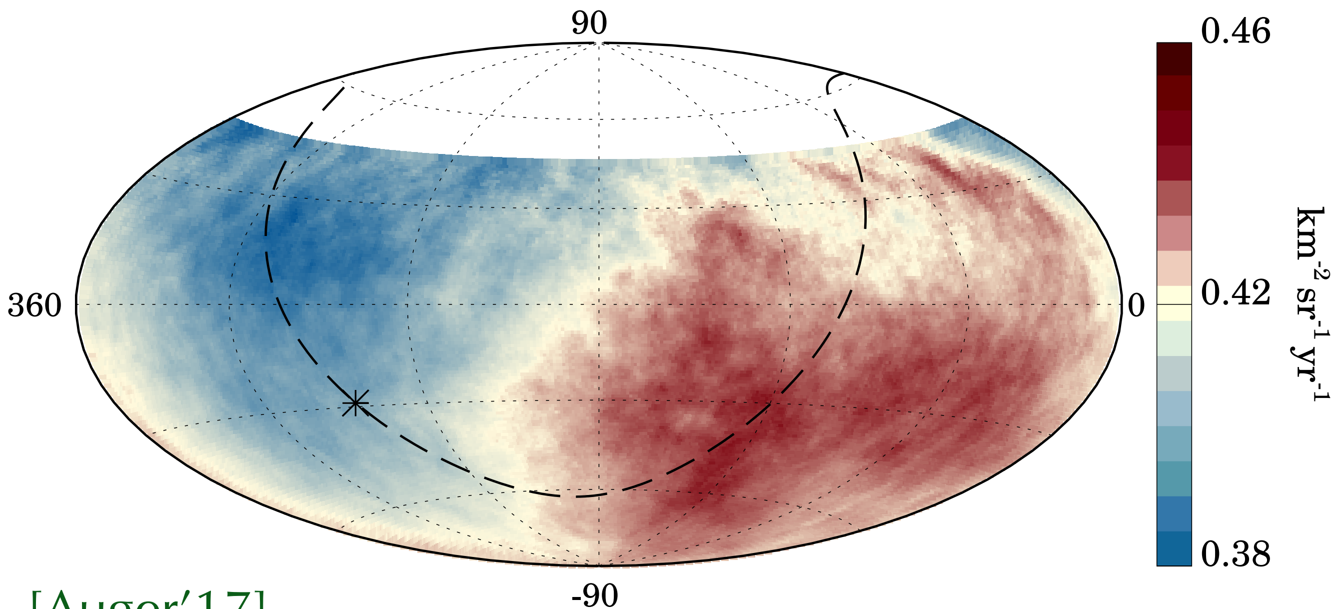


[Alves Batista *et al.*'19]

- UHE CR arrival direction above 8EeV show **strong** (6.5%) **dipole anisotropy** (5.2σ). [Auger'17]
- Arrival directions of UHE CRs above 40 EeV show **correlation with local starburst galaxies** (4σ). [Auger'18]
- **Indications for medium-scale anisotropy** above 16 EeV in Northern Hemisphere (3.7σ) [TA'18]



[Auger'18]



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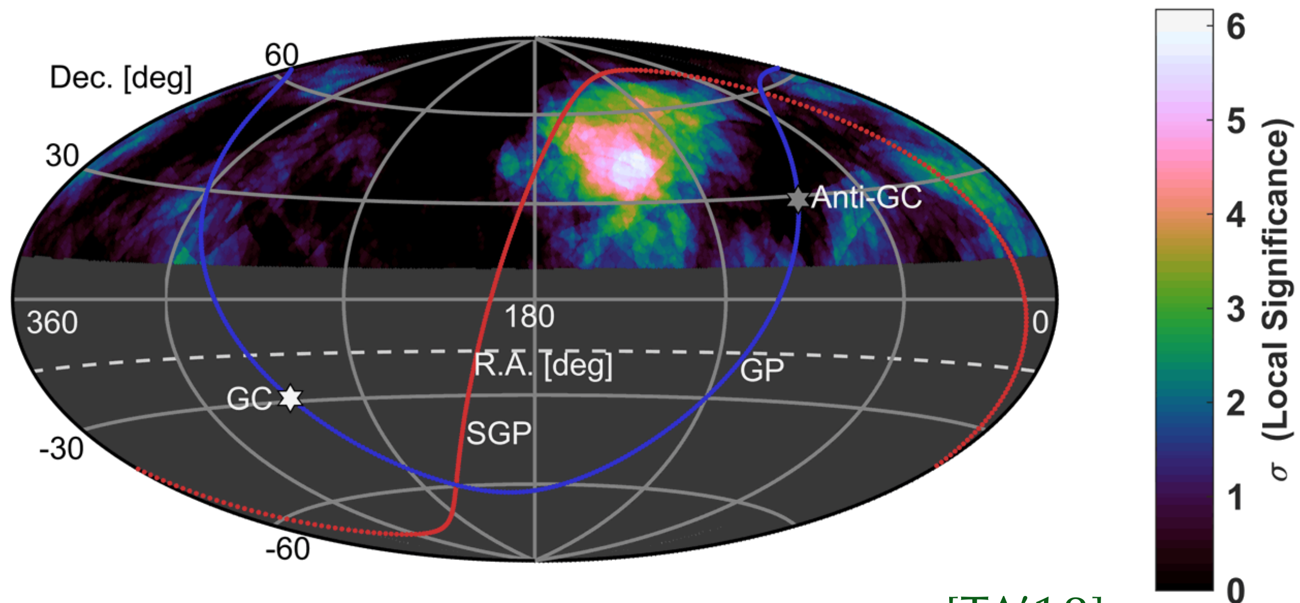

[TA'18]

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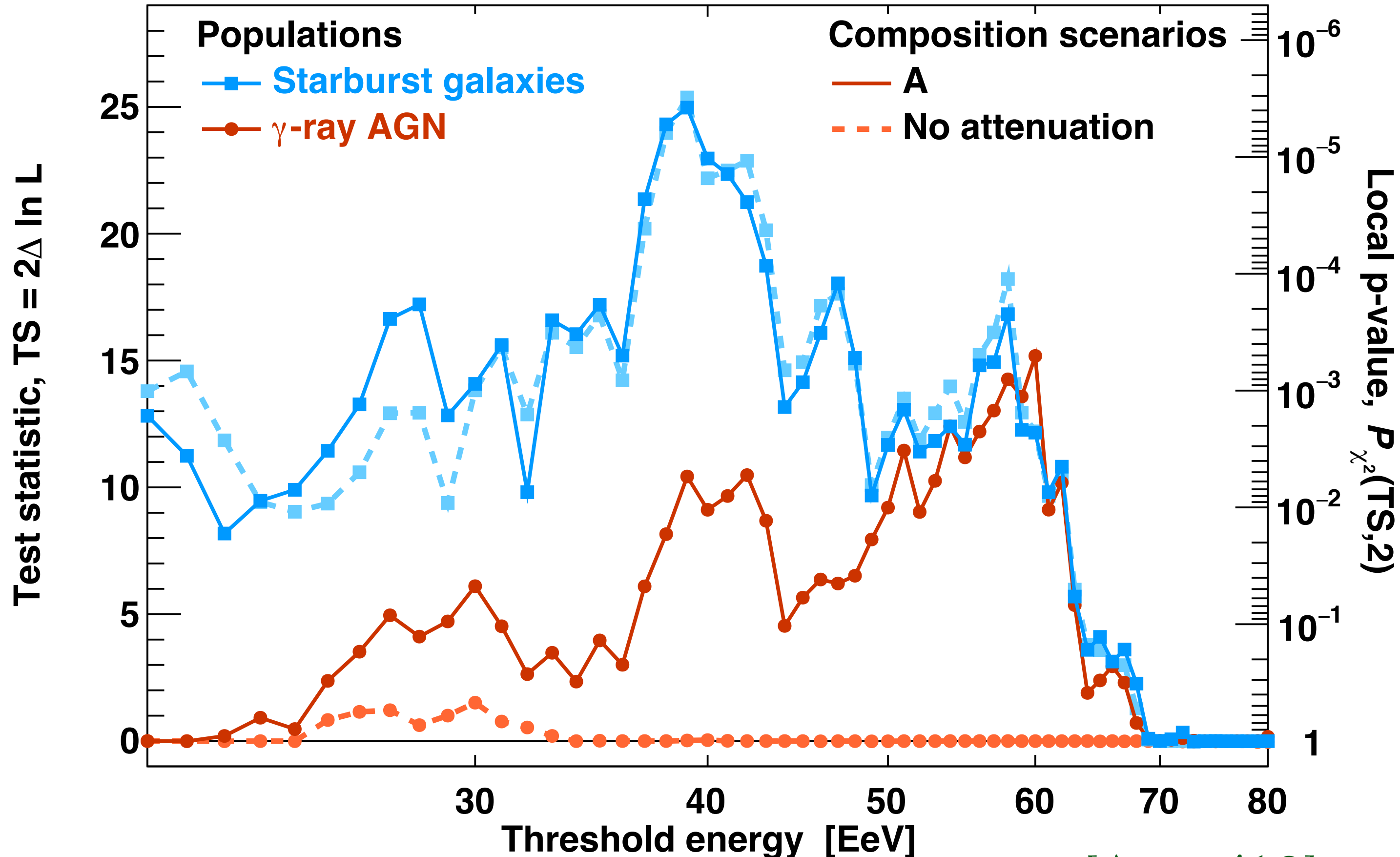
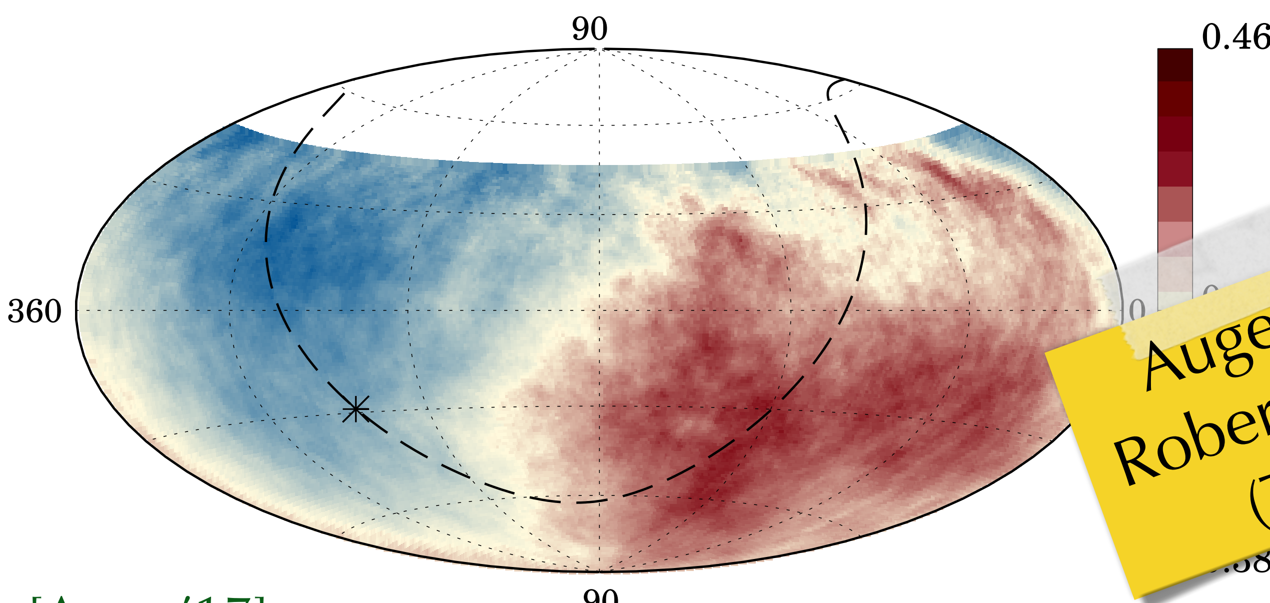
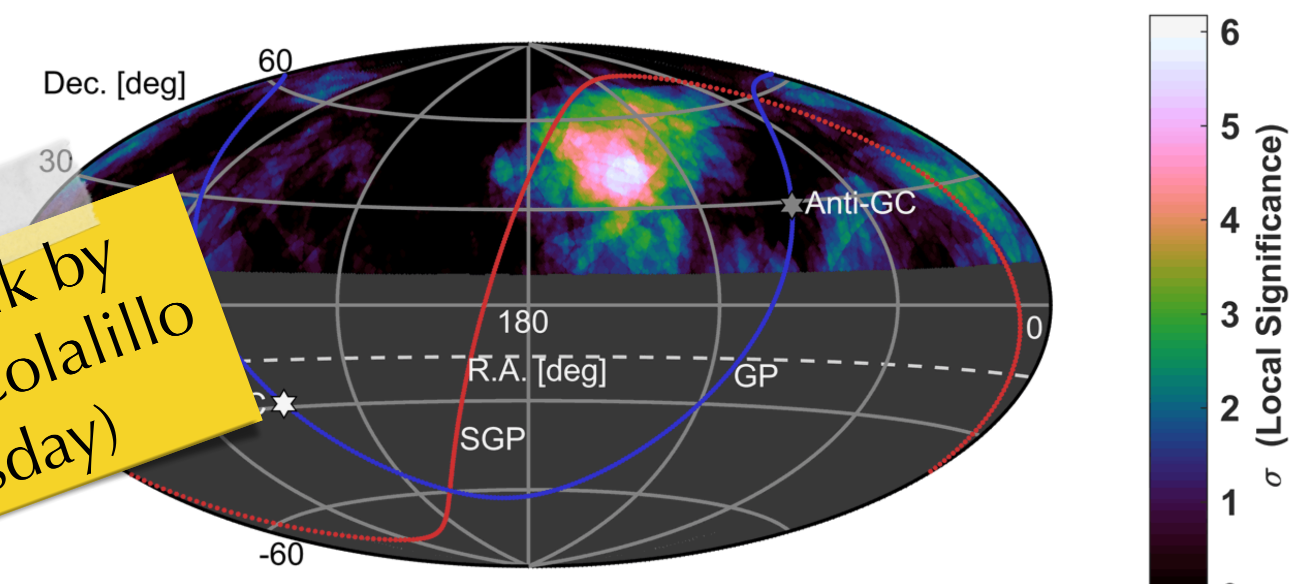


[Auger'18]



[Auger'17]

Auger talk by Roberta Colalillo (Tuesday)



[TA'18]

Cosmic Ray Calorimeters

- UHE CR proton emission rate density: [e.g. MA & Halzen'12]

$$[E_p^2 Q_p(E_p)]_{10^{19.5}\mathrm{eV}} \simeq 8\times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- neutrino flux can be estimated as (ξ_z : factor accounting for redshift evolution) :

$$E_\nu^2\phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}}_{\sim\ \text{IceCube diffuse}}$$

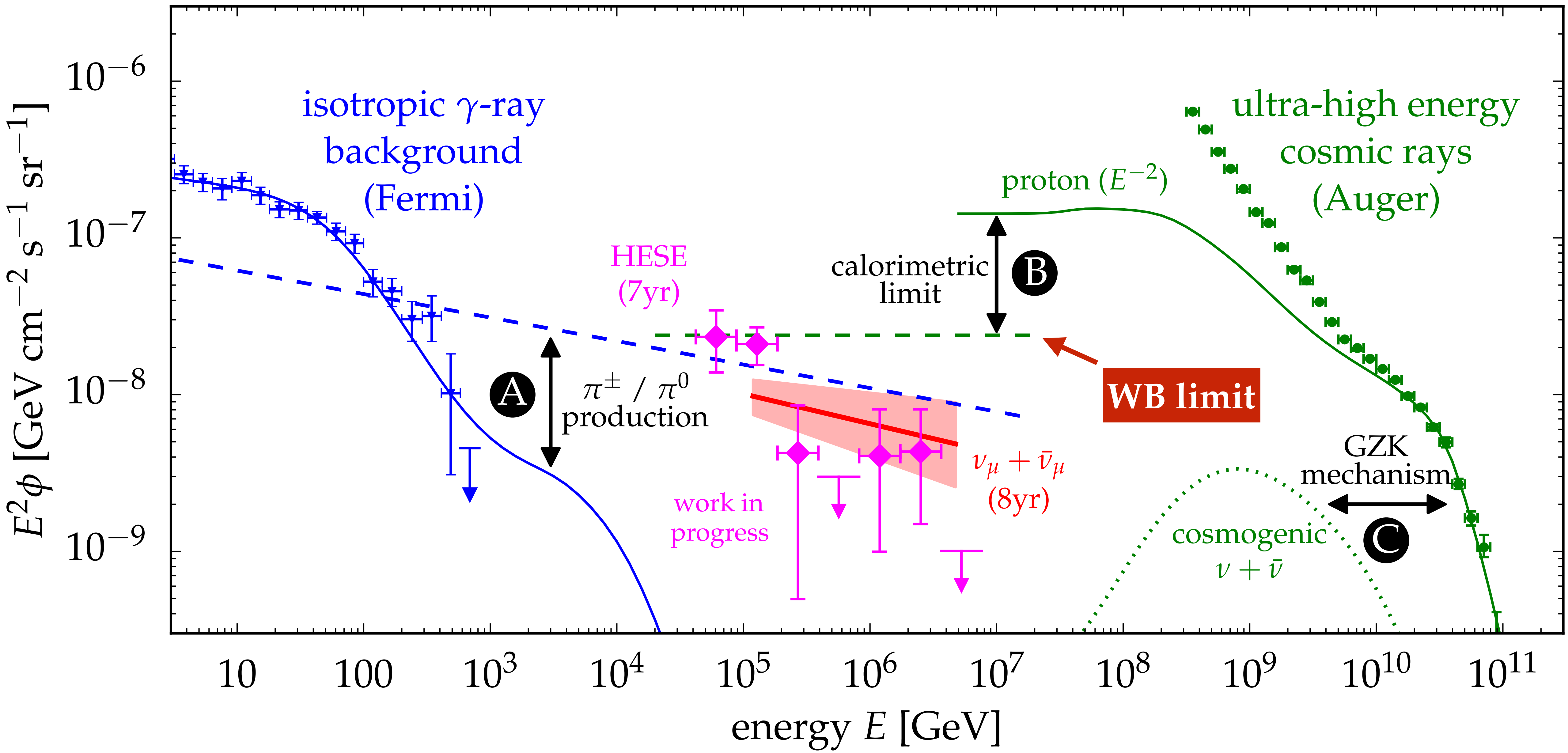
➜ limited by pion production efficiency: $f_\pi \leq 1$ [Waxman & Bahcall'98]

- **similar** UHE nucleon emission rate density (local minimum at $\Gamma \simeq 2.04$) [Auger'16]

$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2\times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

- Sources of UHECRs could be embedded in "calorimetric" environments ($f_\pi = 1$), producing a large flux of neutrinos, *e.g.*, **starburst galaxies** or **galaxy clusters**.

Waxman-Bahcall Limit

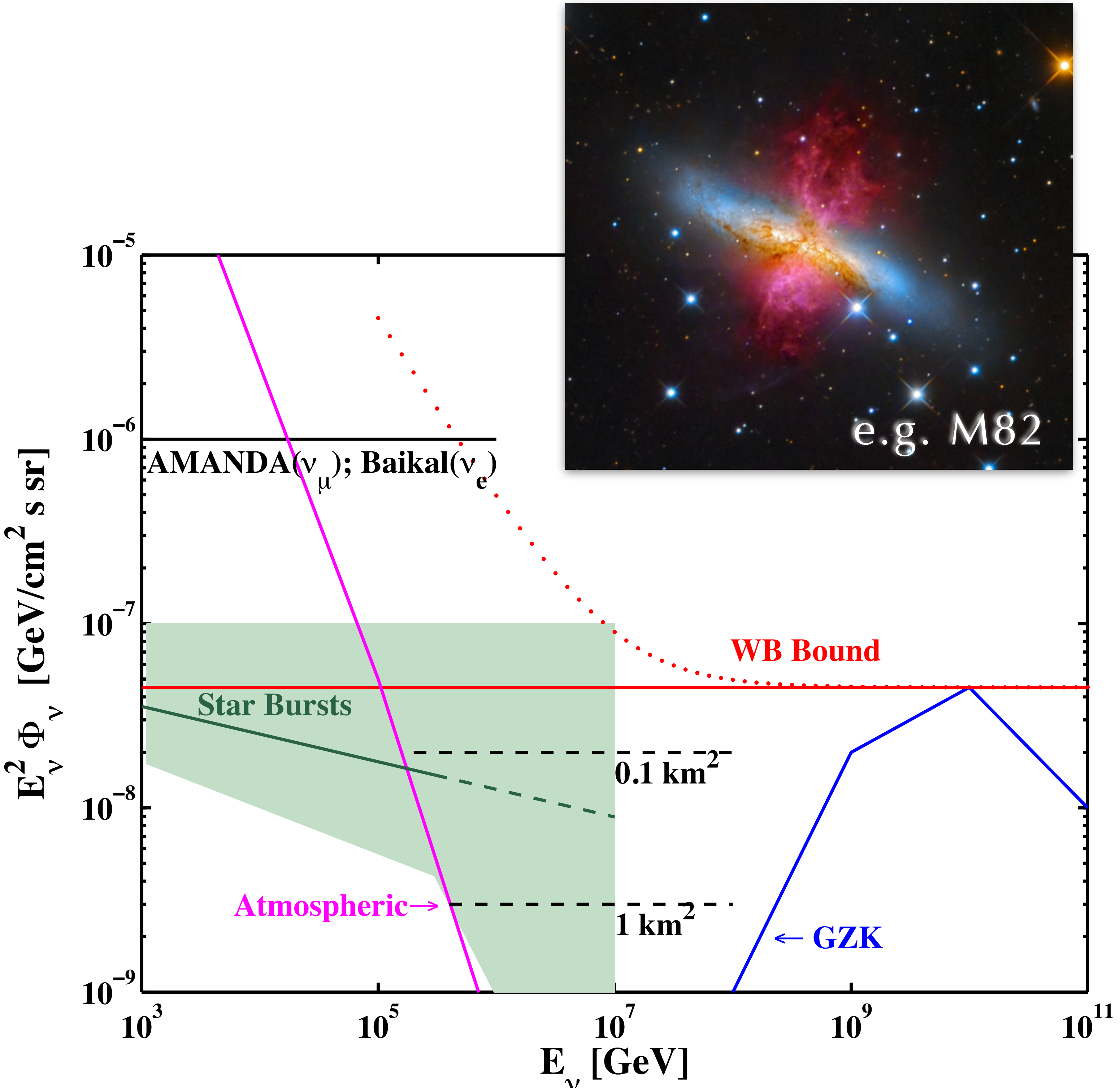


Observed neutrino flux close to Waxman-Bahcall (WB) limit:

Common origin of TeV-PeV neutrinos and UHE CRs?

Starburst Galaxies

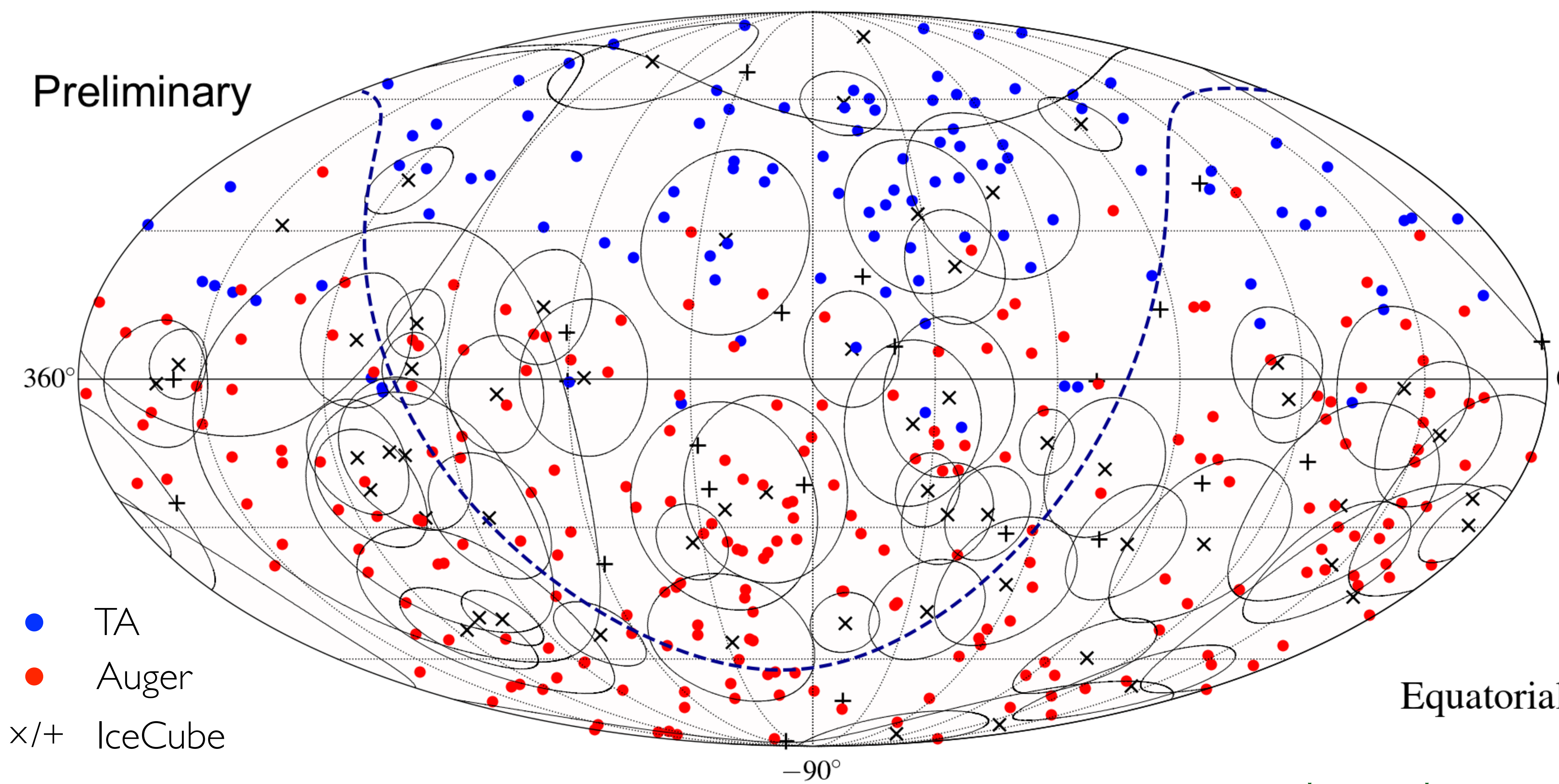
- **Intense star formation enhances UHE CR production**, e.g. by gamma-ray bursts.
- Low-energy cosmic rays remain magnetically confined and eventually **collide in dense environment**.
- In time, efficient **conversion of CR energy density into gamma-rays and neutrinos**.
  [Loeb & Waxman '06]
- Expect power-law neutrino spectra with high-energy break from CR leakage.



[Loeb & Waxman '06]

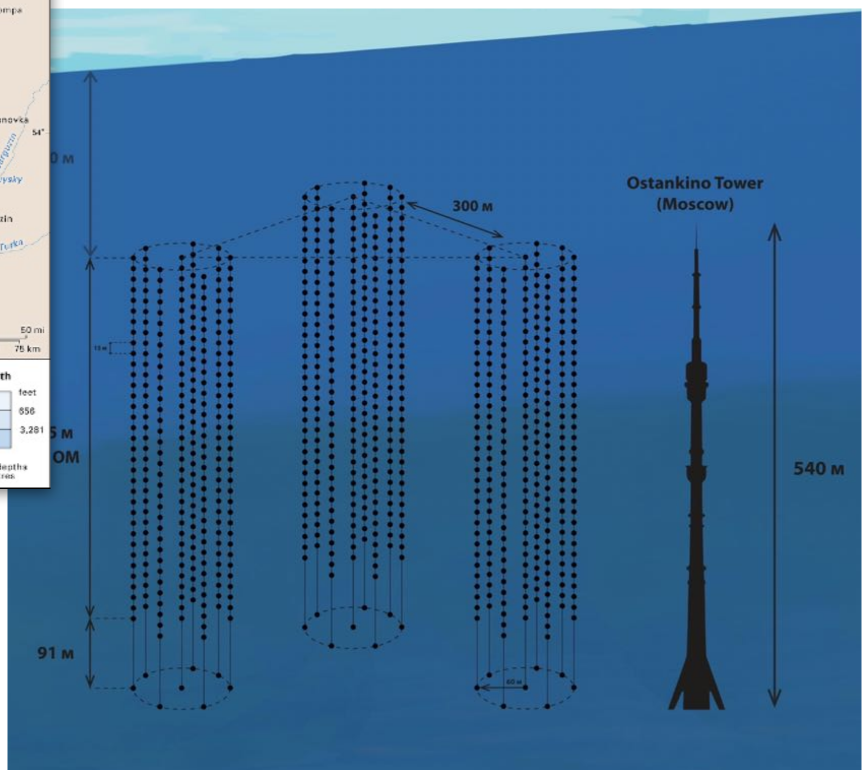
UHE CR Composition

- **No significant cross-correlation** found between UHE CRs and HE neutrinos.
- Galactic and extragalactic magnetic fields can introduce **significant angular deflections and time delays:** $\Delta t \simeq d(\Delta\psi)^2$
- Maximal cross-correlation **limited by GZK horizon** : $\lambda_{\rm GZK}/\lambda_{\rm Hubble} \simeq 5\,\%$



[Auger, IceCube & Telescope Array'17]

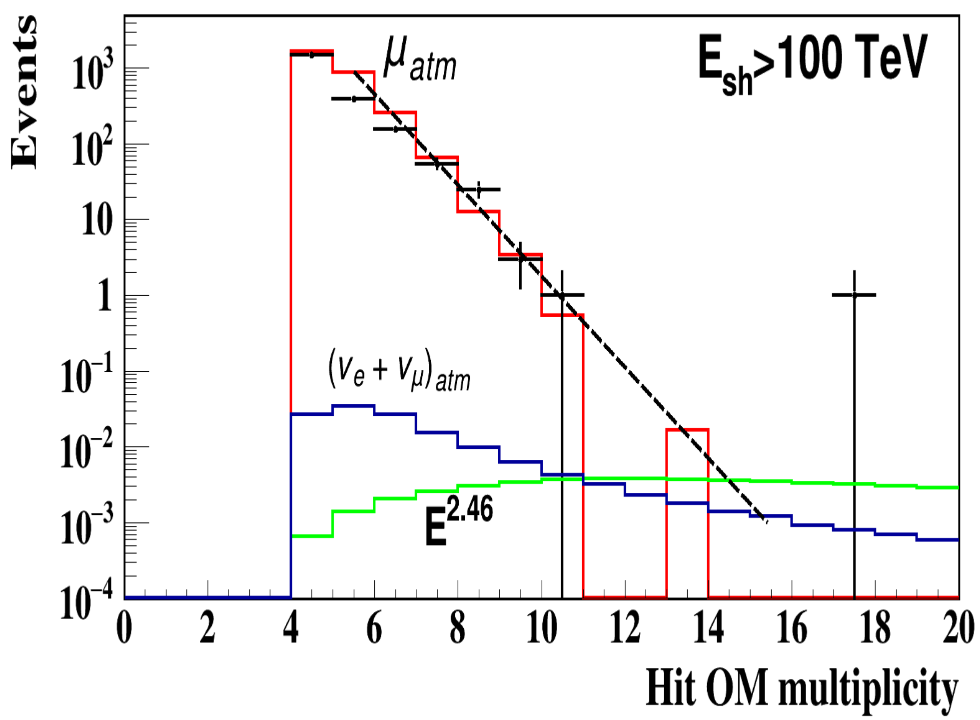
Outlook: Baikal-GVD



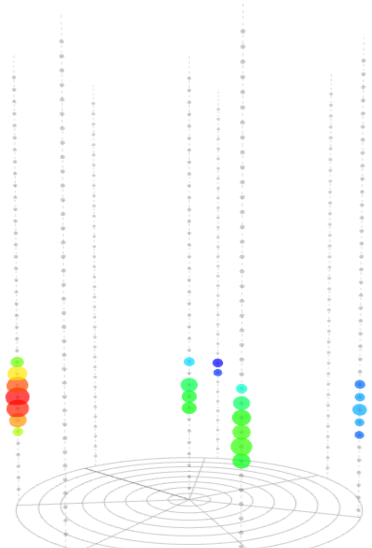
present detector outline (2018)

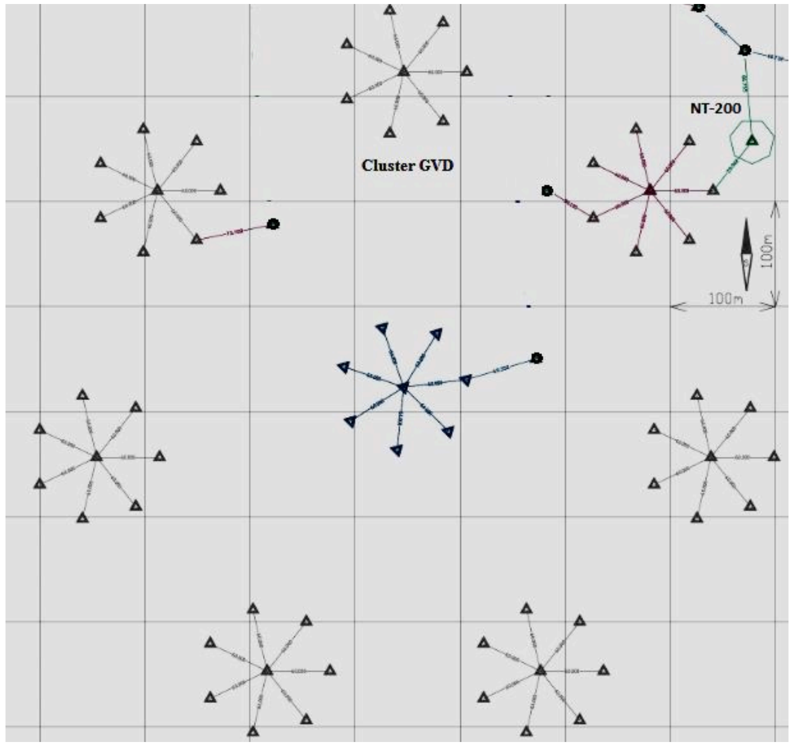
BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- 5 clusters deployed 2016–19
- **final goal**: 27 clusters (~1.4 km³)



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



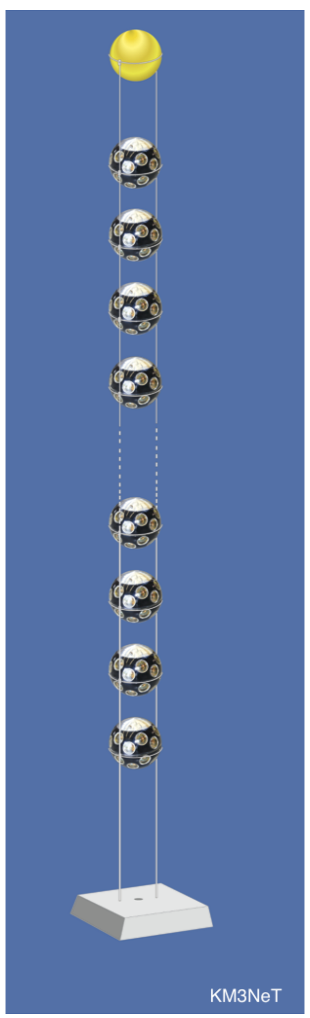


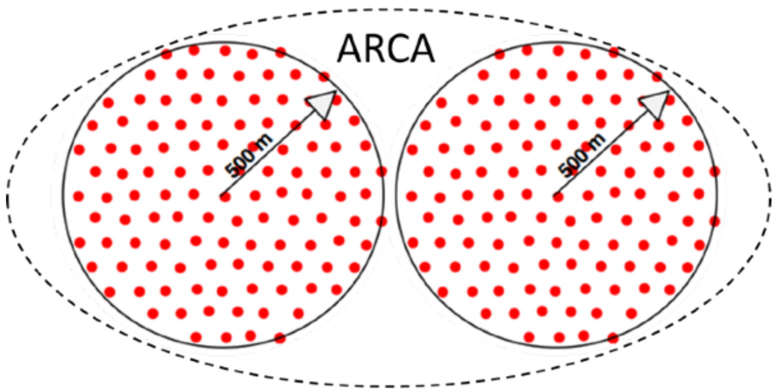
GVD-Phase 1

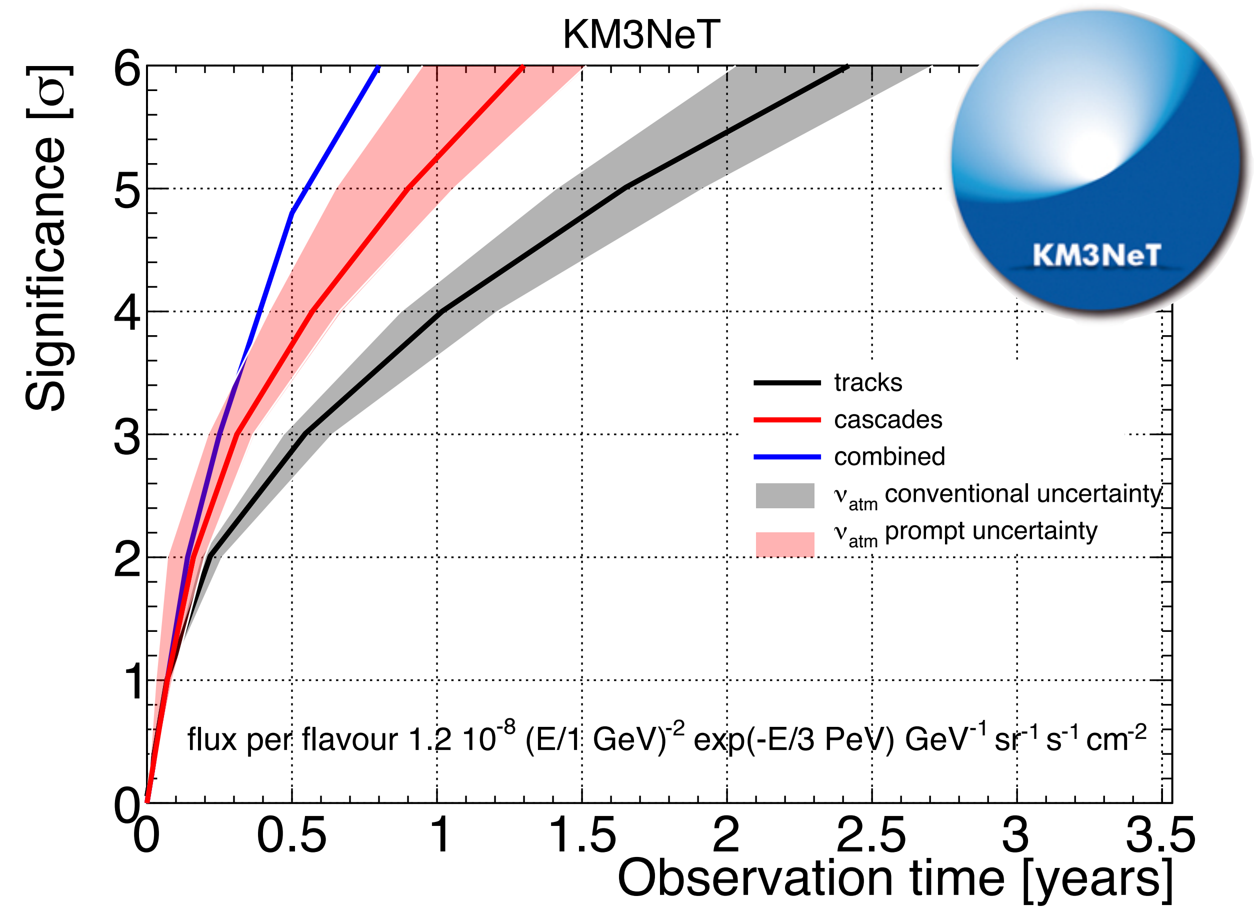
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km^3)
- 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



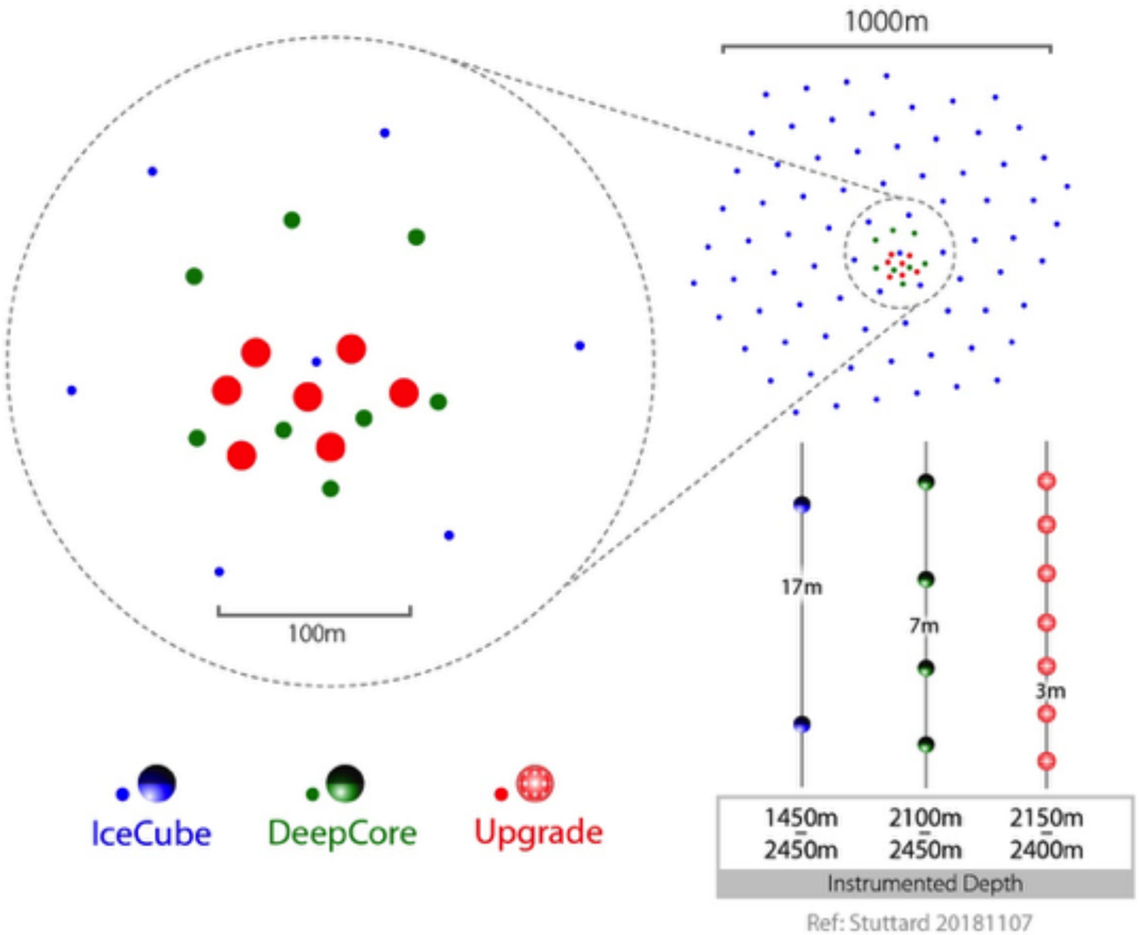


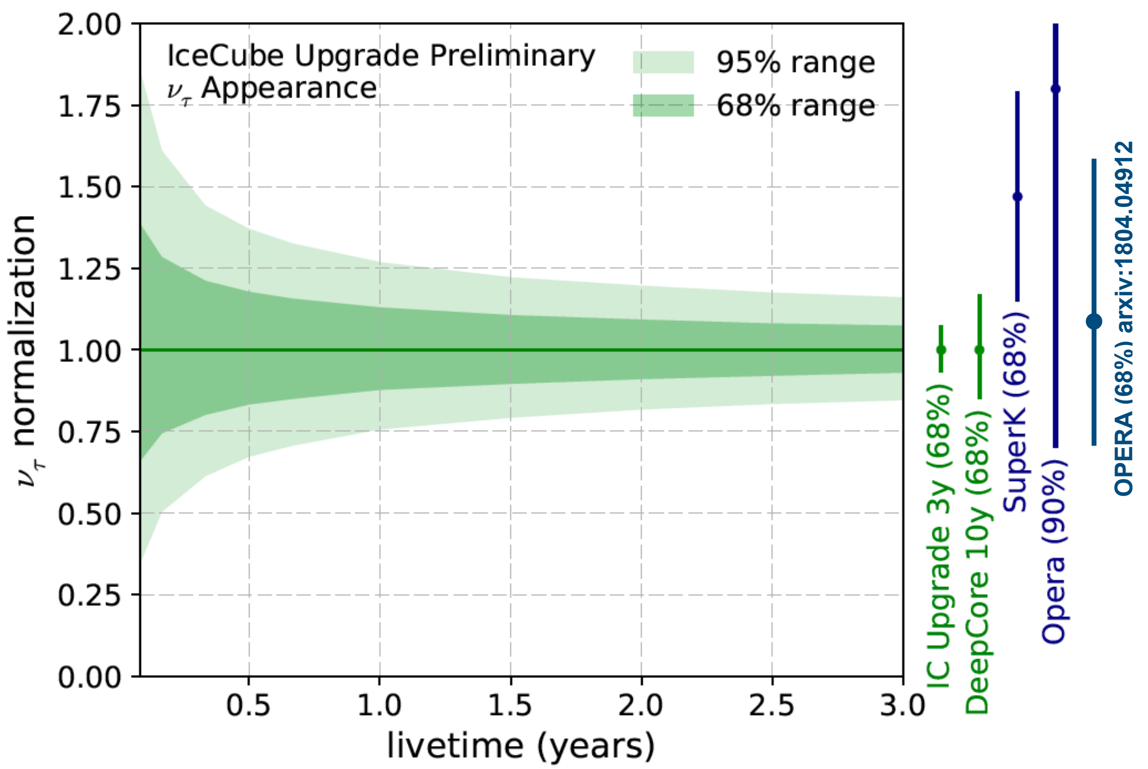


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Outlook: IceCube Upgrade

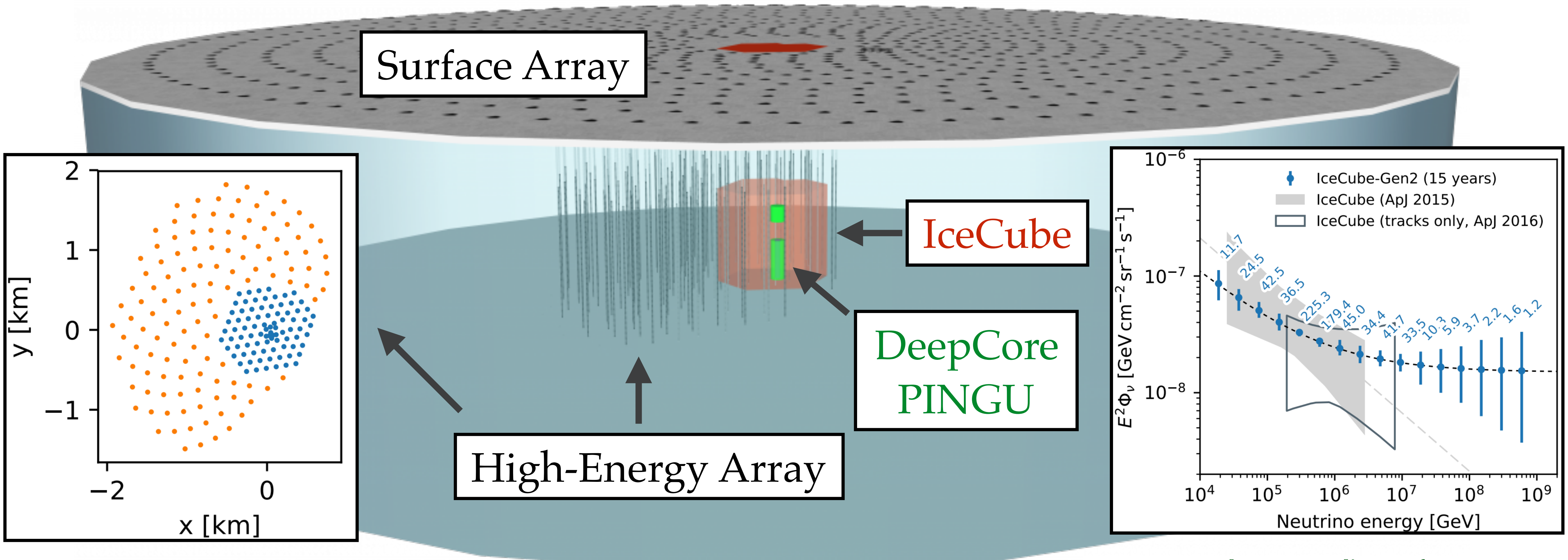
- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.
- **Precision measurement** of atmospheric neutrino oscillation.
- Midscale NSF project with an estimated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





Vision: IceCube-Gen2

- **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

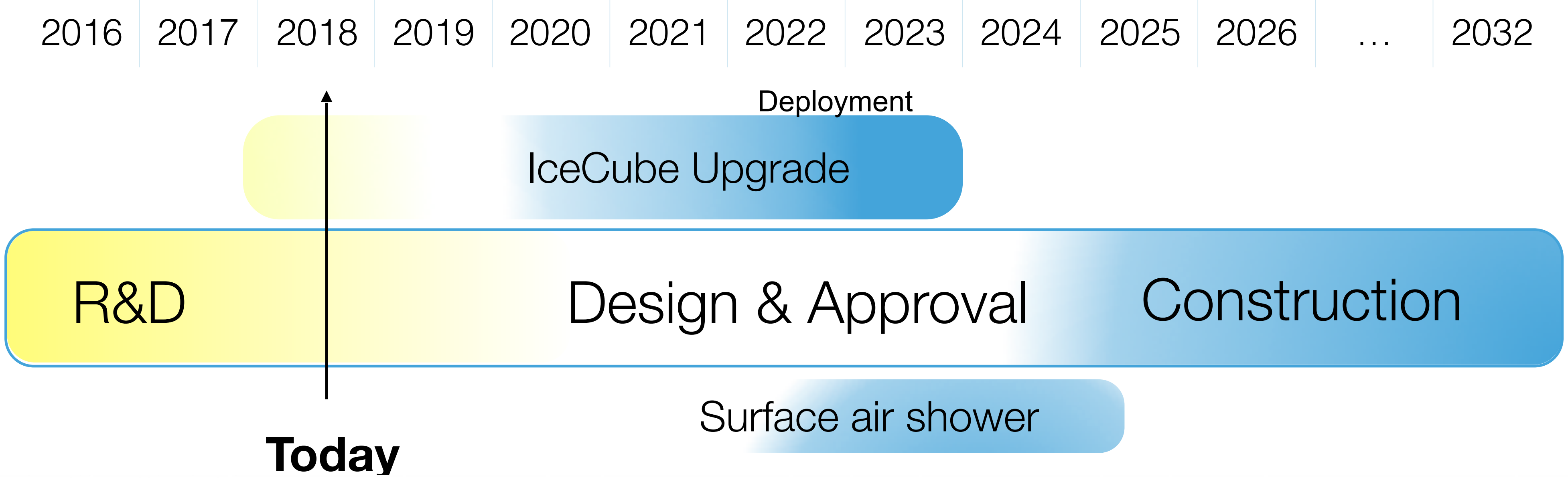
- The future of high-energy multi-messenger astronomy is bright:
  - TeV-PeV neutrino emission (of unknown origin) with intensity comparable to ultra-high energy cosmic-rays and gamma-rays.
  - First observation of binary neutron star merger in gravitational waves and photons.
  - First compelling evidence of neutrino emission from gamma-ray blazars.
- Real-time multi-messenger campaigns involving photons, gravitational waves and neutrinos are becoming routine.
- With next-generation telescopes we will go from discovery to astronomy.

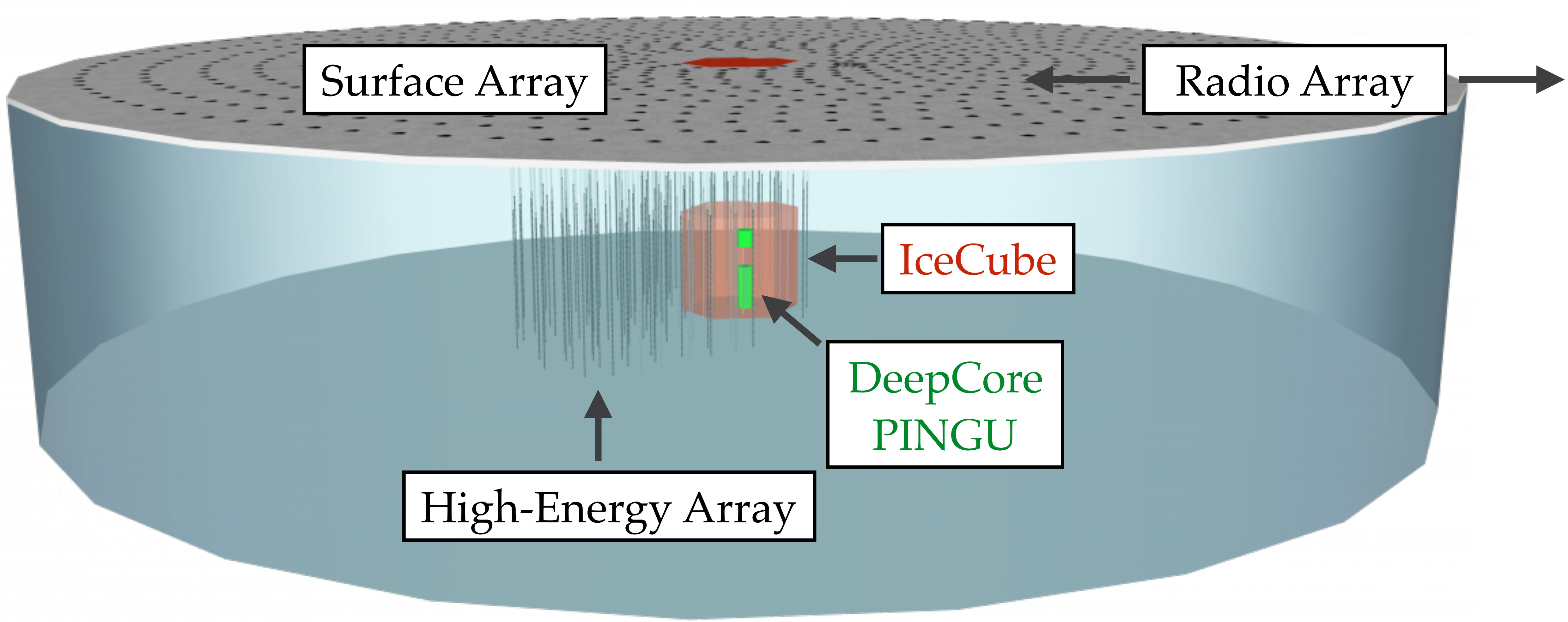
Thank you for your attention!

Backup Slides

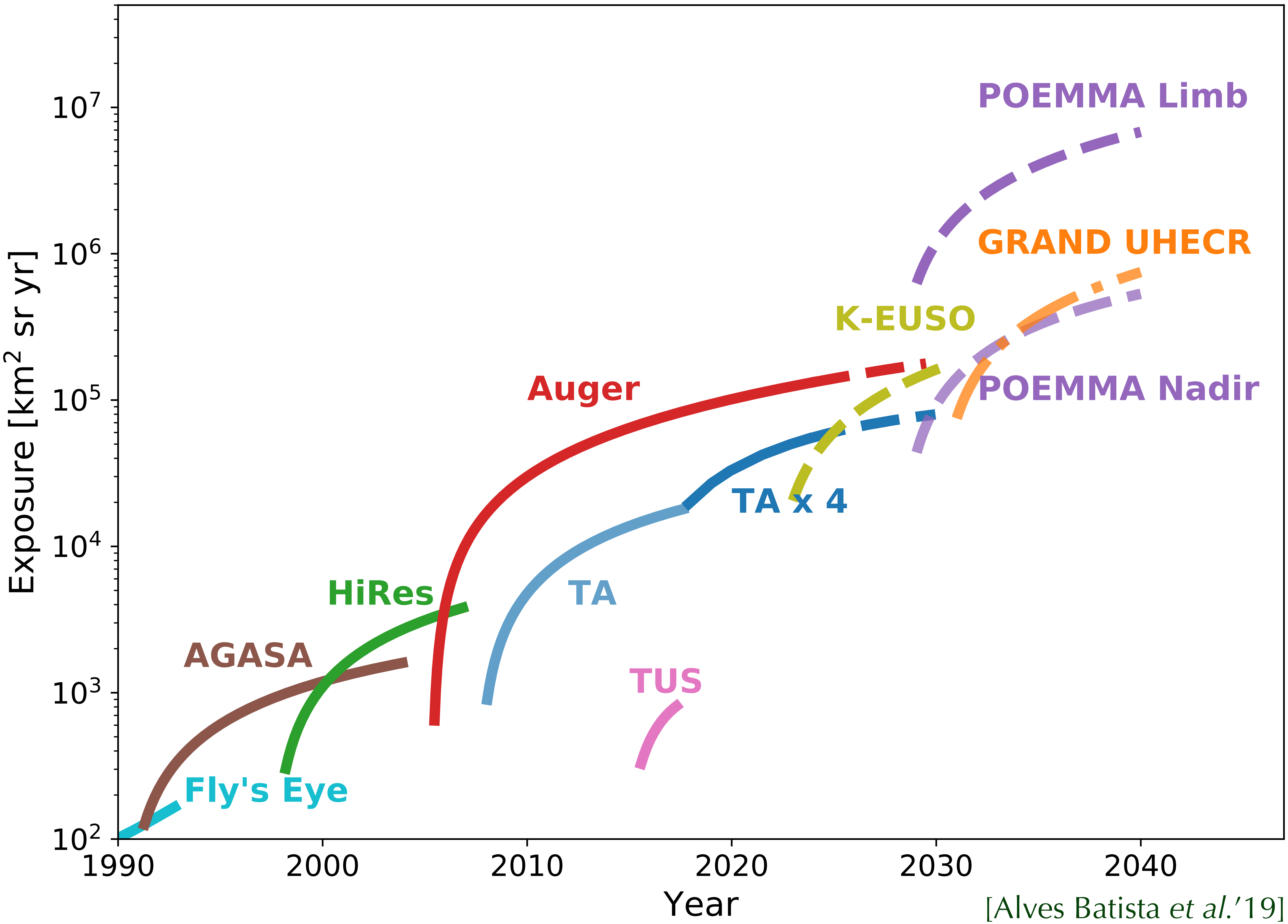
IceCube-Gen2 Timeline

Preliminary timeline



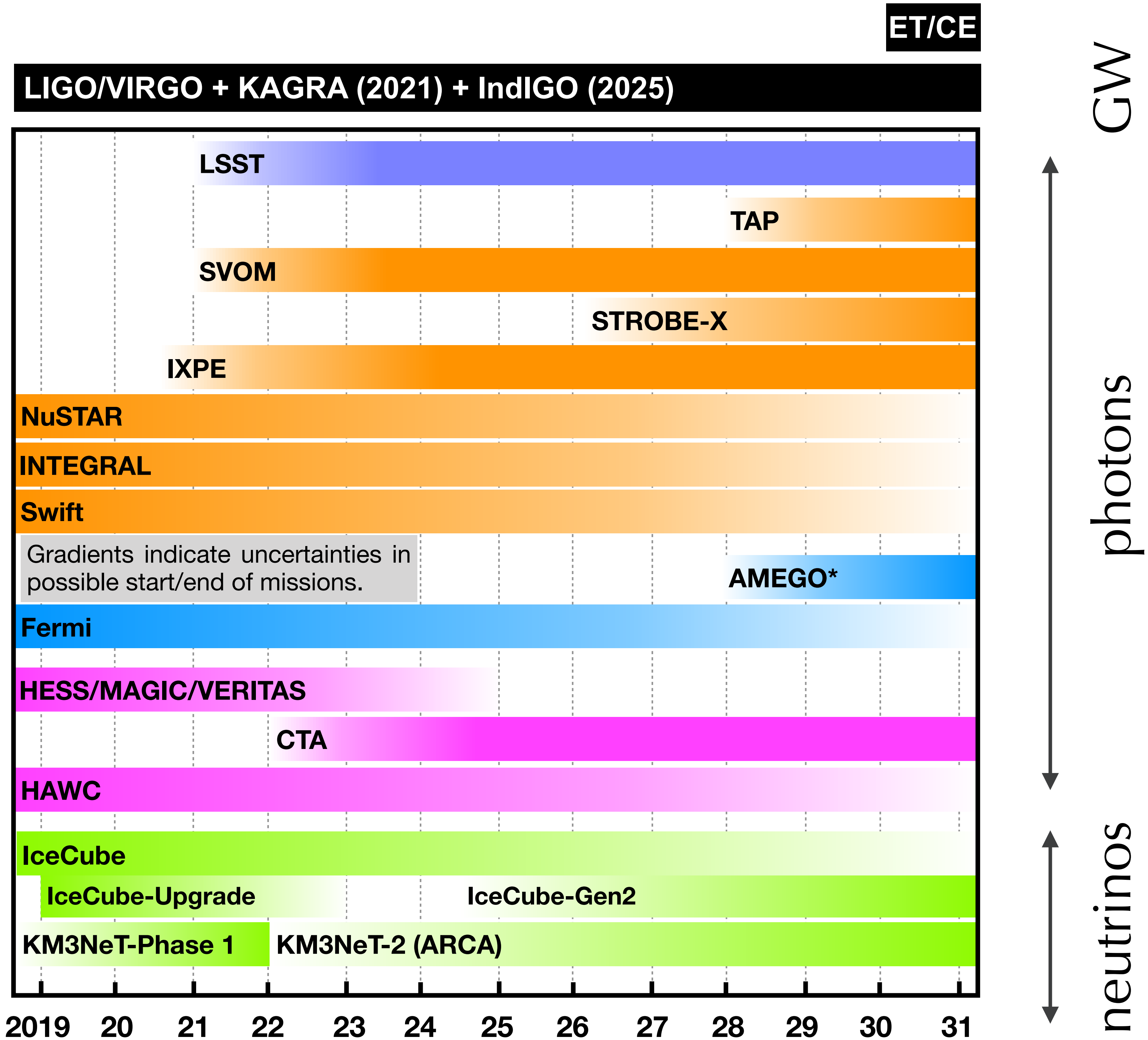


Outlook: UHE CR Observatories



[Alves Batista *et al.*'19]

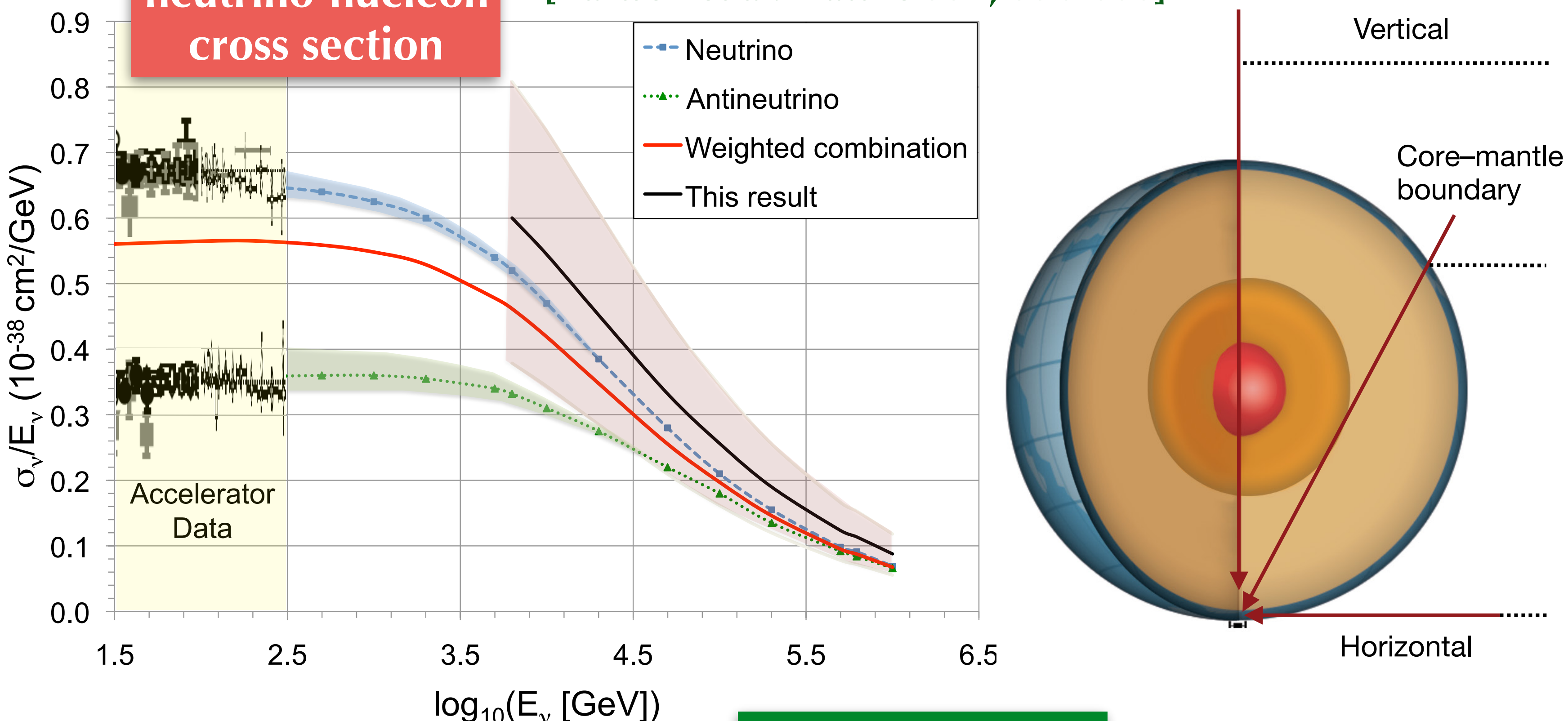
Future Multi-Messenger Landscape



[Buson *et al.* *Astro2020*]

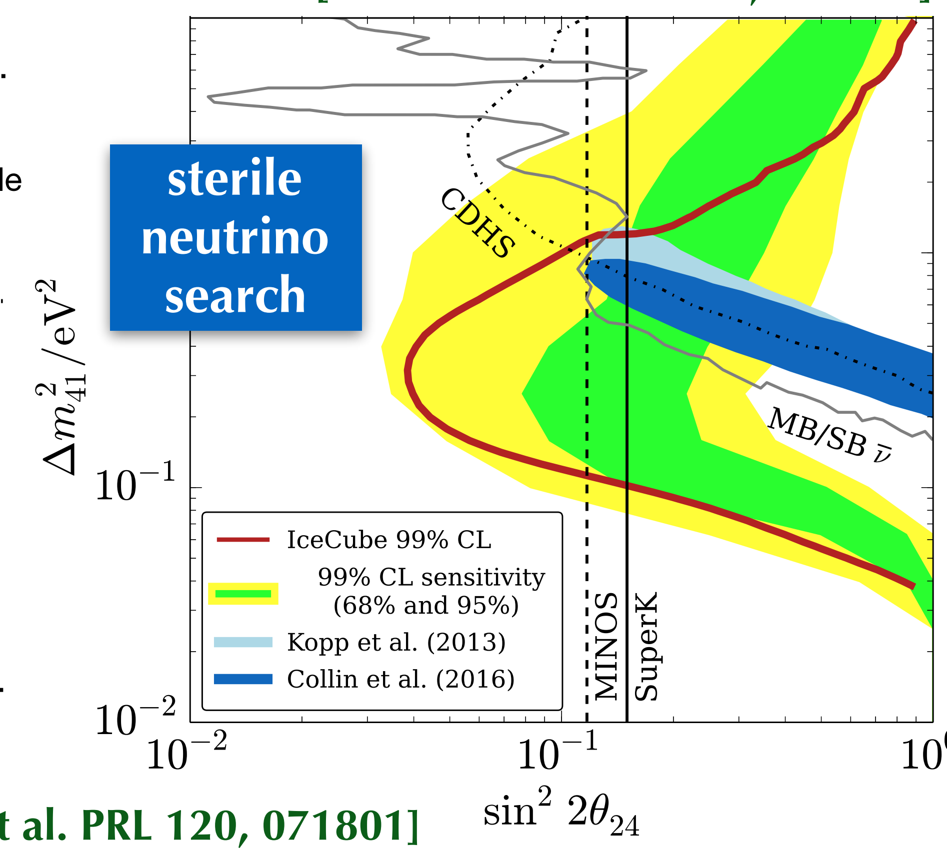
neutrino-nucleon cross section

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



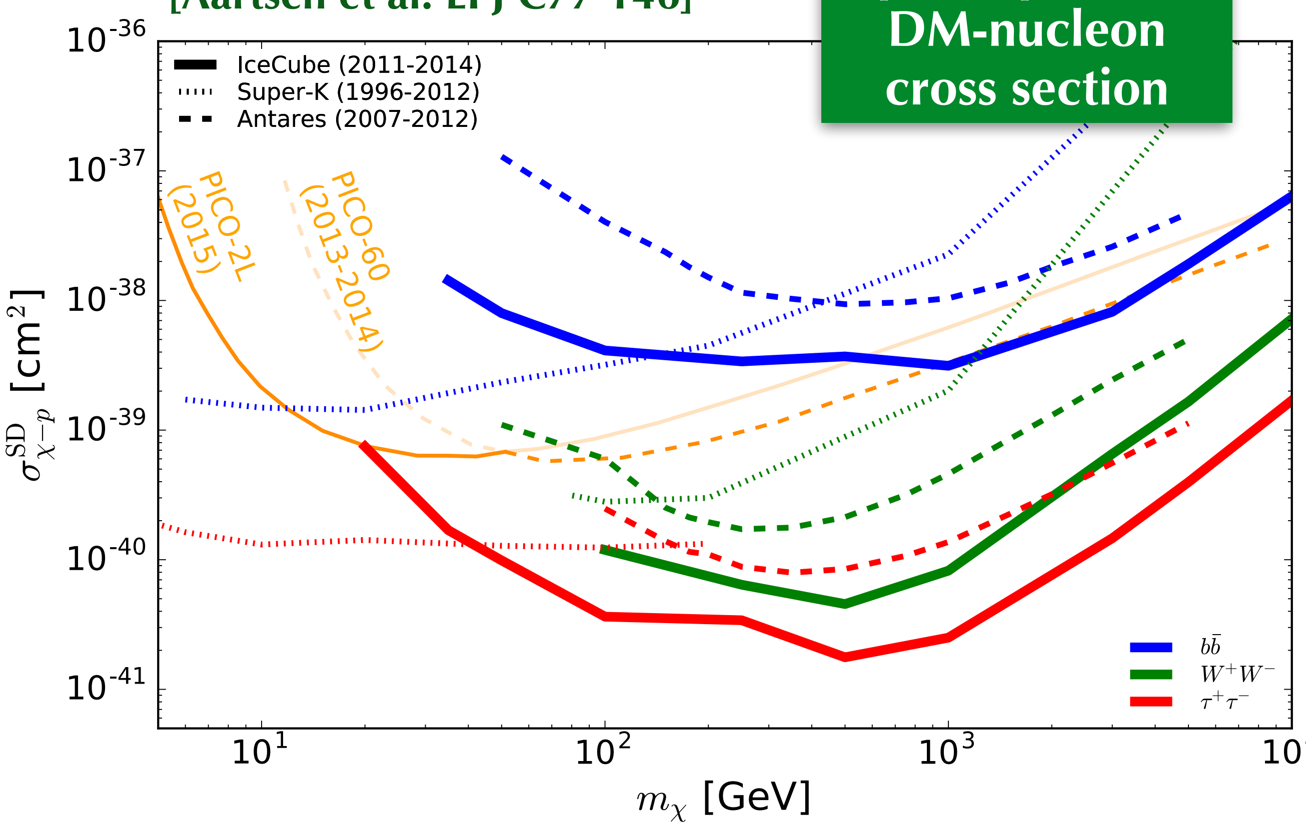
sterile neutrino search

[Aartsen et al. PRL 117, 071801]



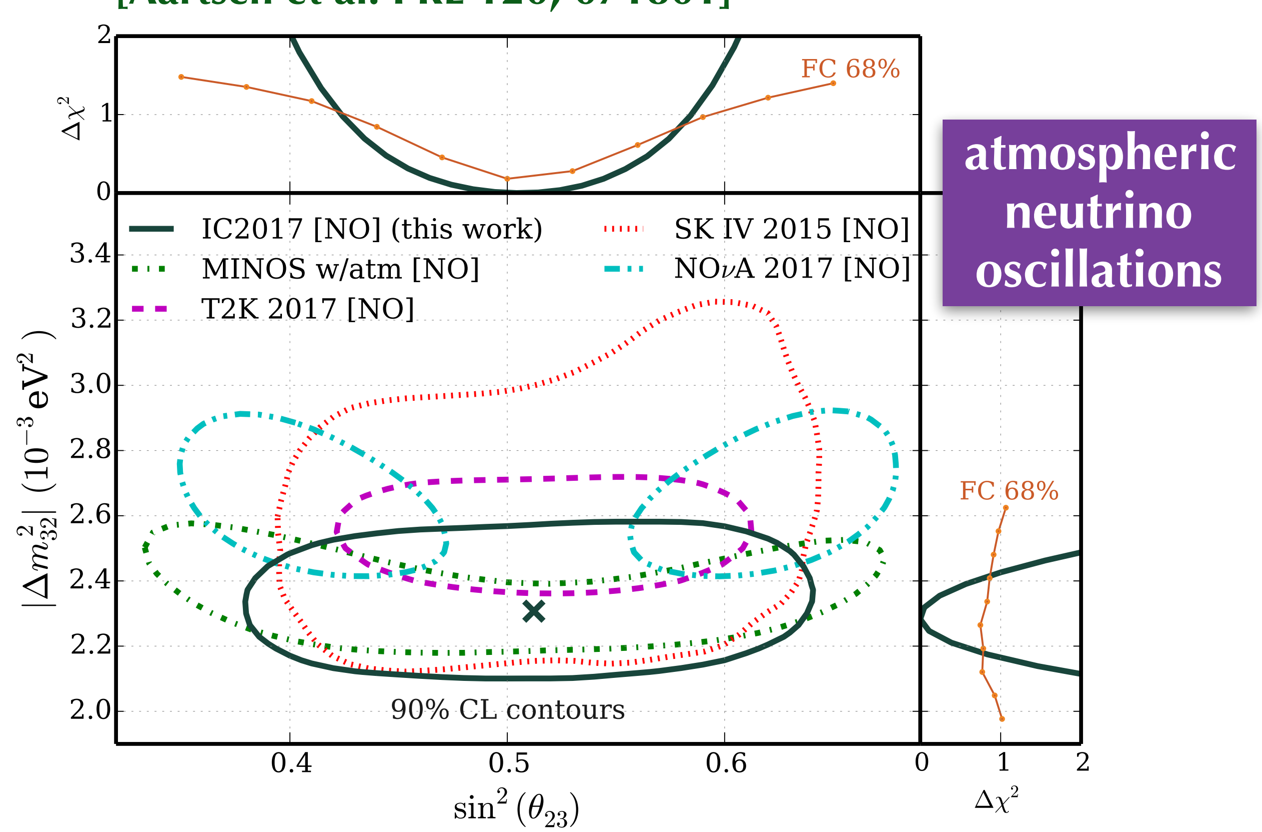
spin-dependent DM-nucleon cross section

[Aartsen et al. EPJ C77 146]

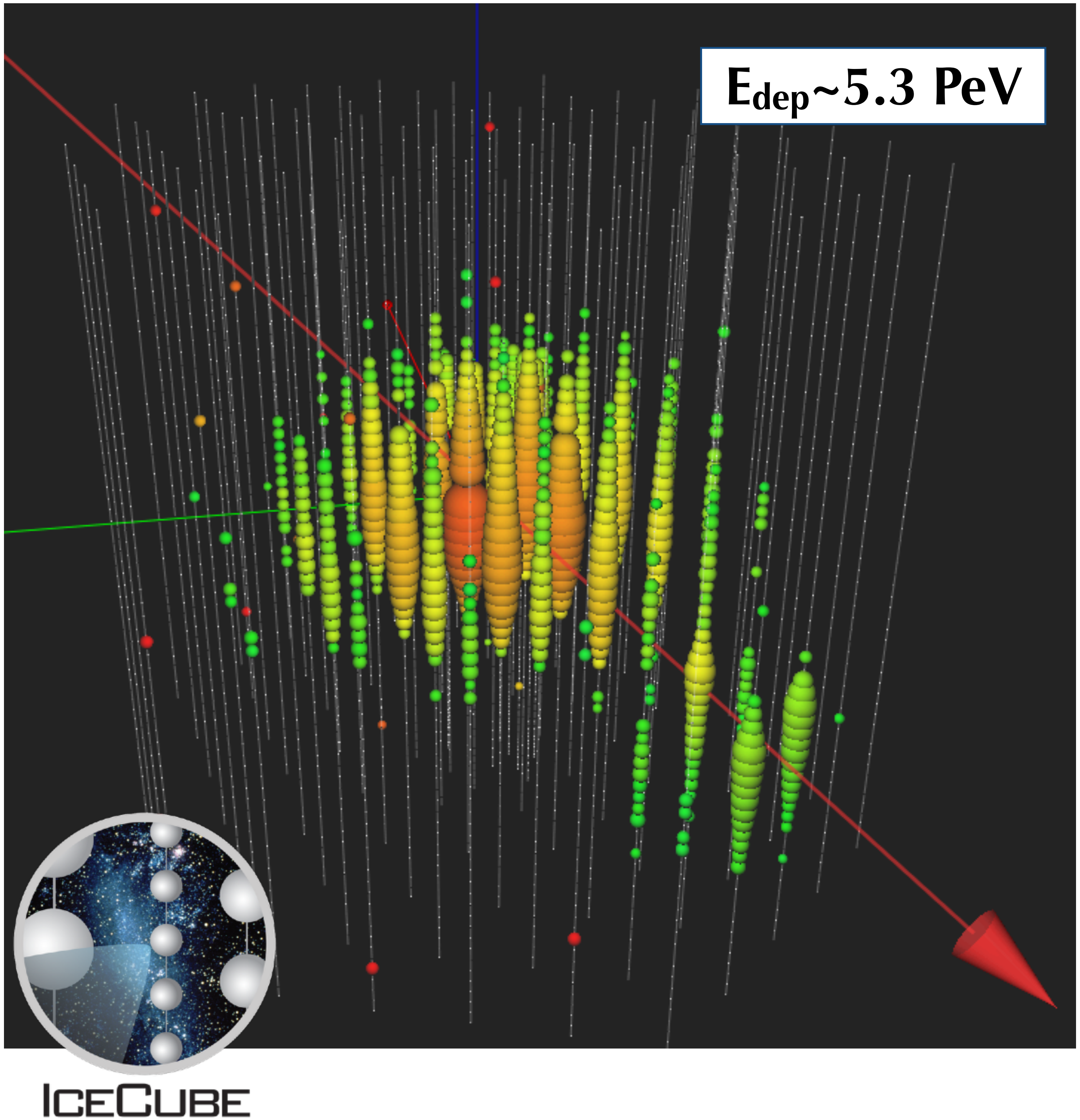


atmospheric neutrino oscillations

[Aartsen et al. PRL 120, 071801]



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.**