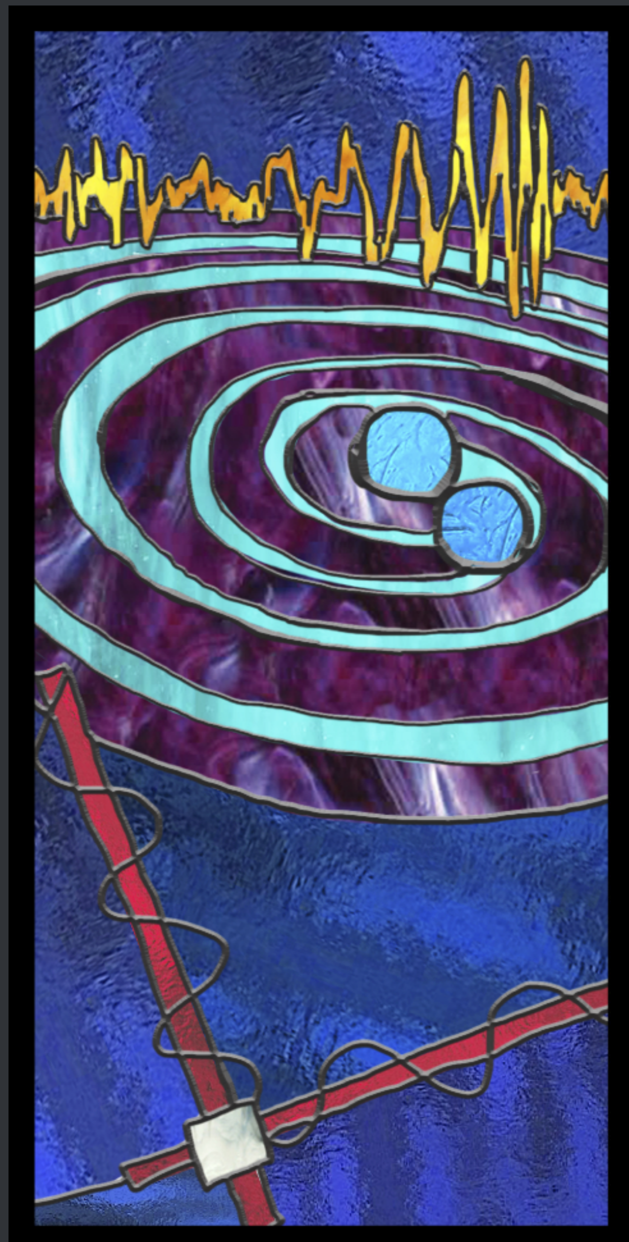
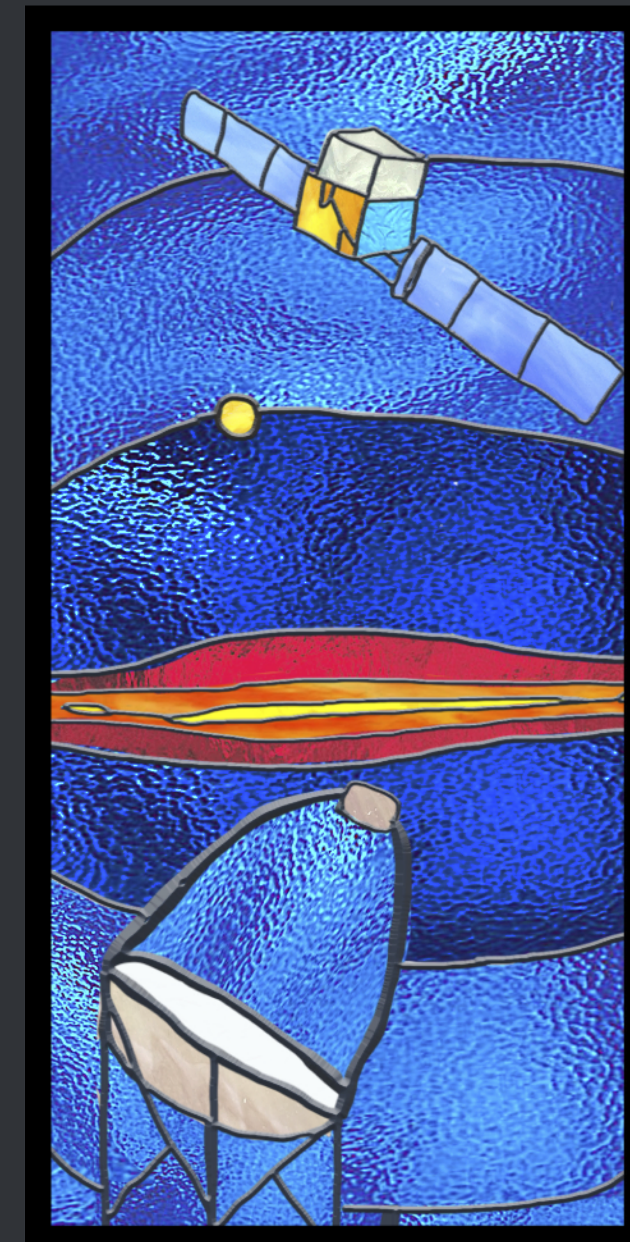




Extragalactic Neutrinos

Markus Ahlers

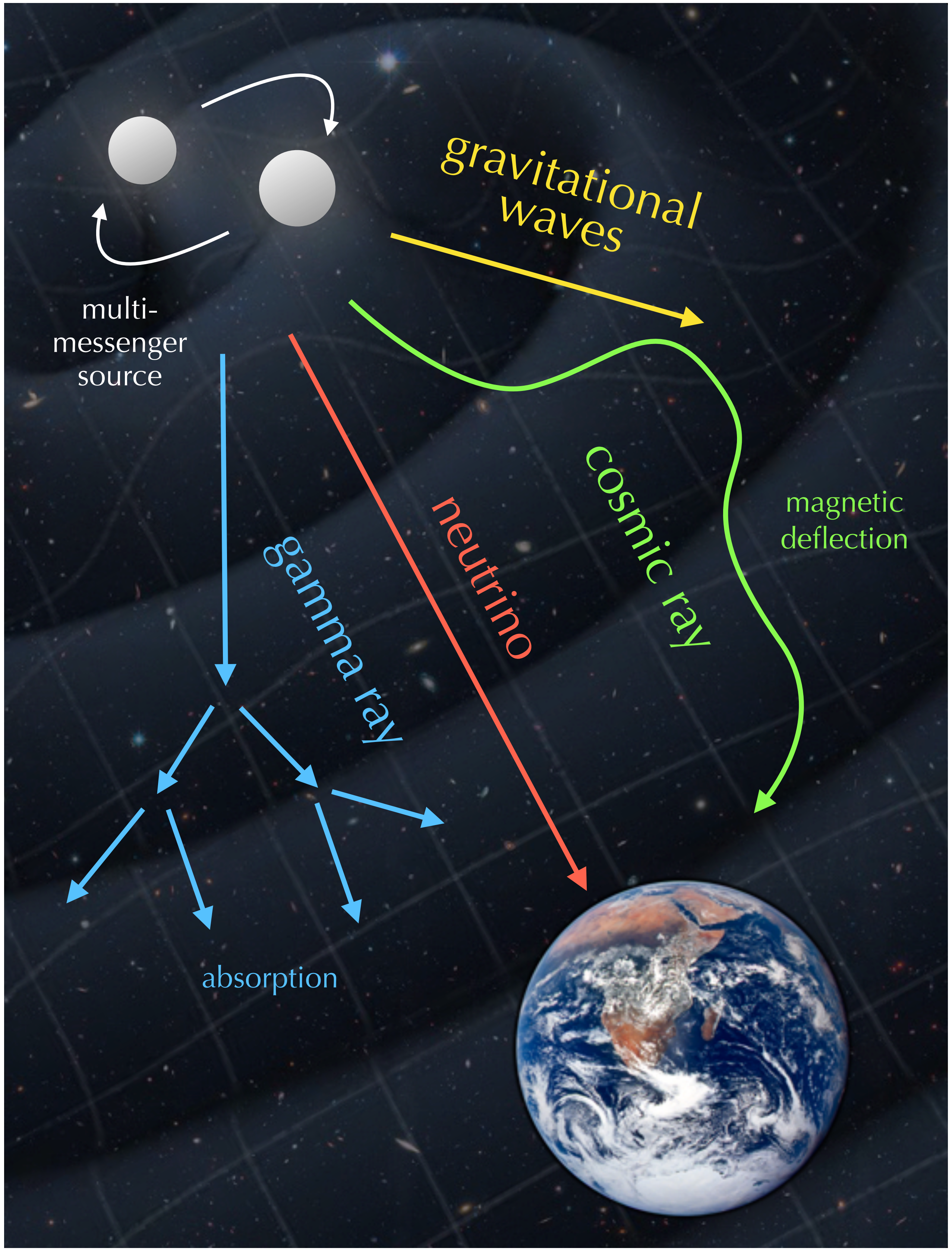
Neutrinos in the MM Era 2022

Louvain-la-Neuve, Belgium

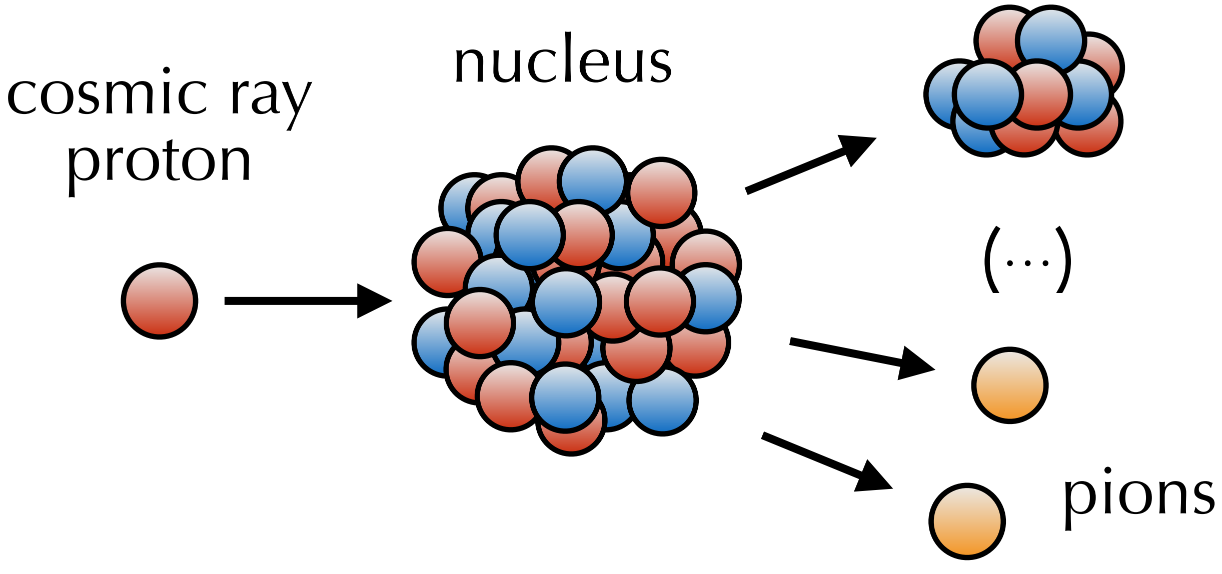
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Multi-Messenger Paradigm



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



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

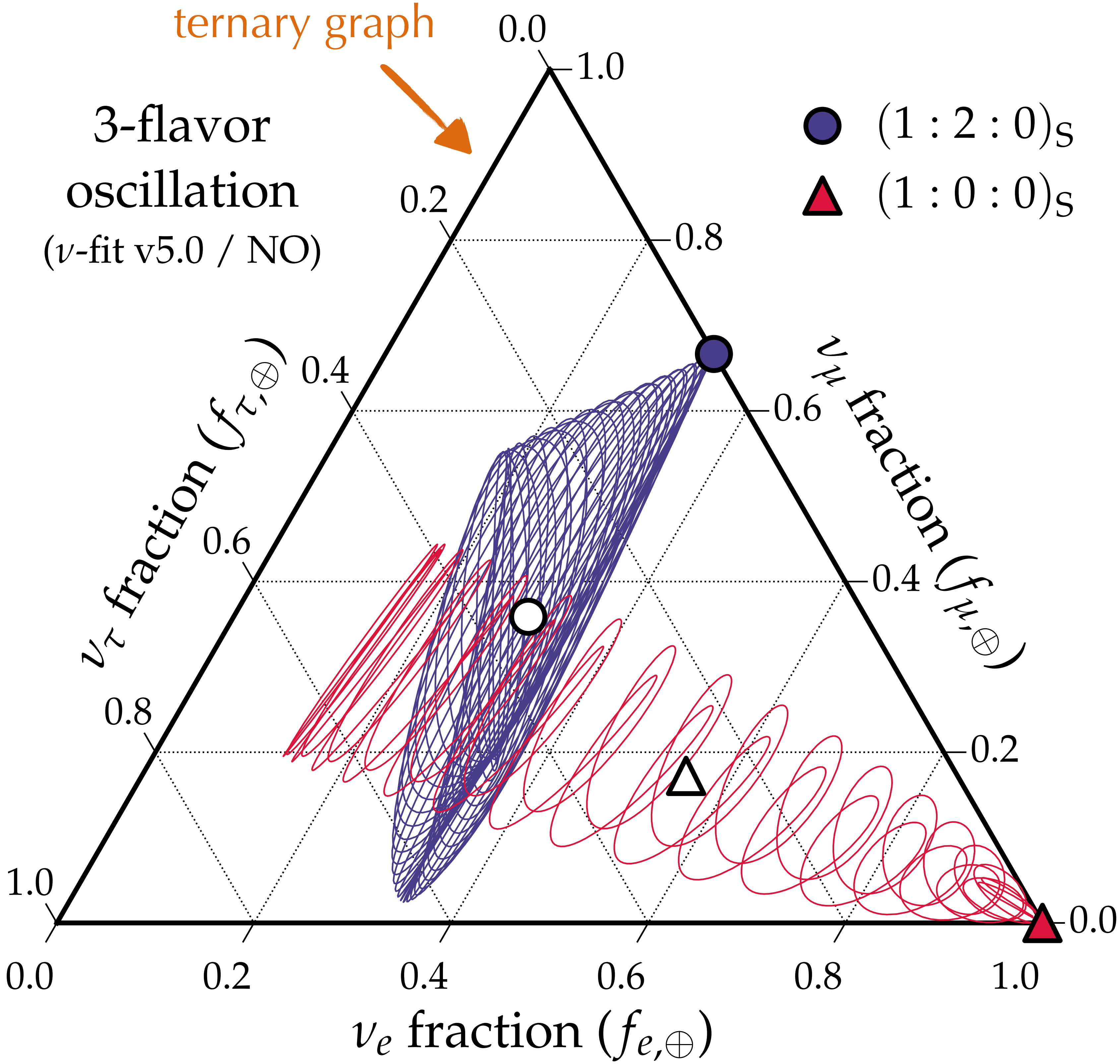
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^0 \rightarrow \gamma + \gamma$$

$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

Astrophysical Flavours

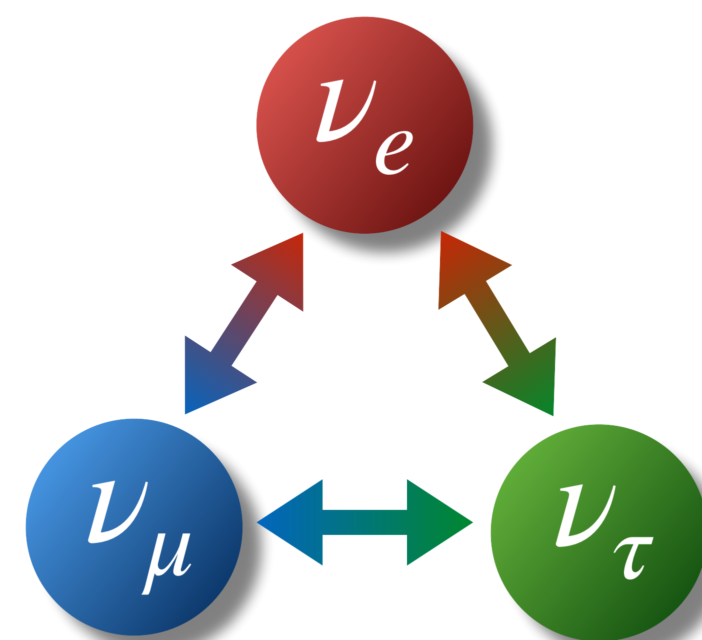
3-flavor oscillation
(ν-fit v5.0 / NO)

ternary graph

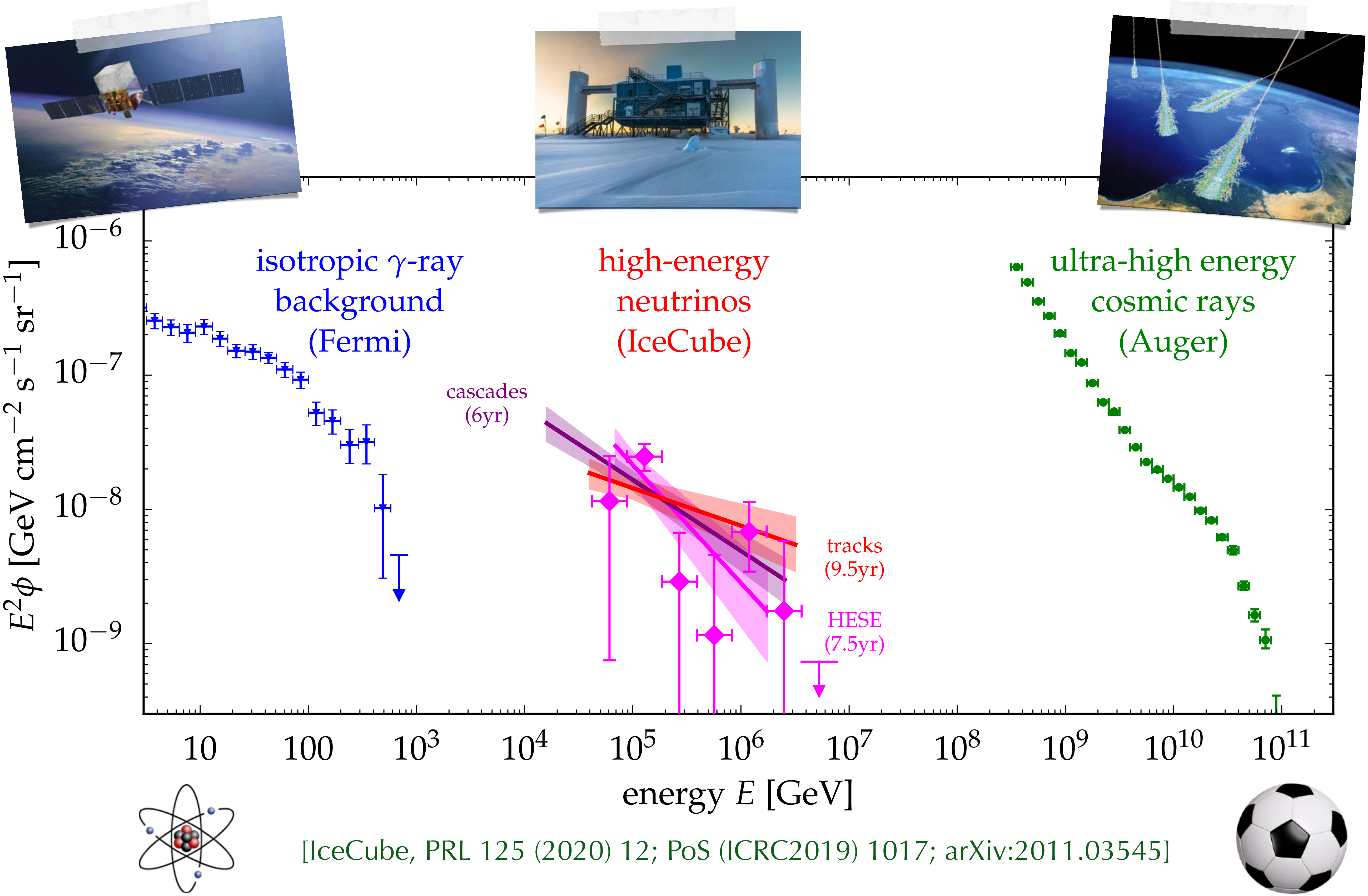


flavor ratios
on production

Superposition of flavor and mass states induce oscillations.

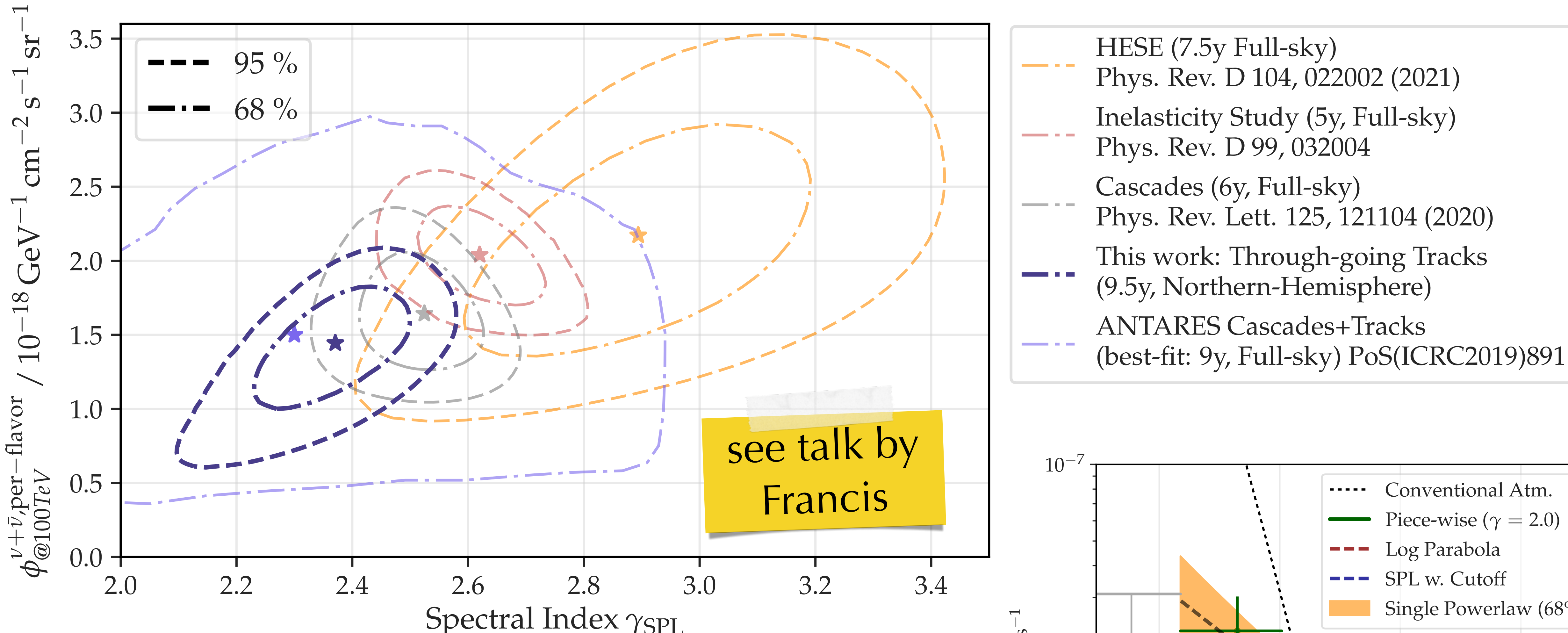


Diffuse TeV-PeV Neutrinos



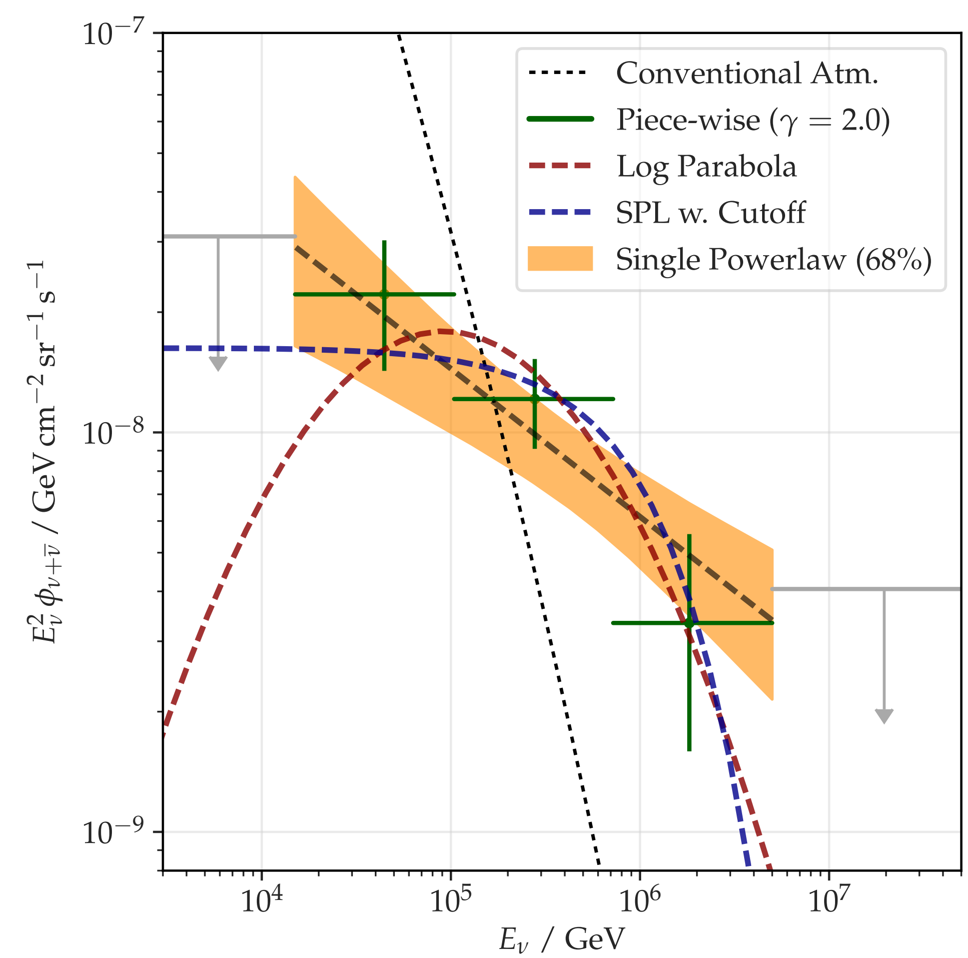
[IceCube, PRL 125 (2020) 12; PoS (ICRC2019) 1017; arXiv:2011.03545]

Isotropic Diffuse Flux

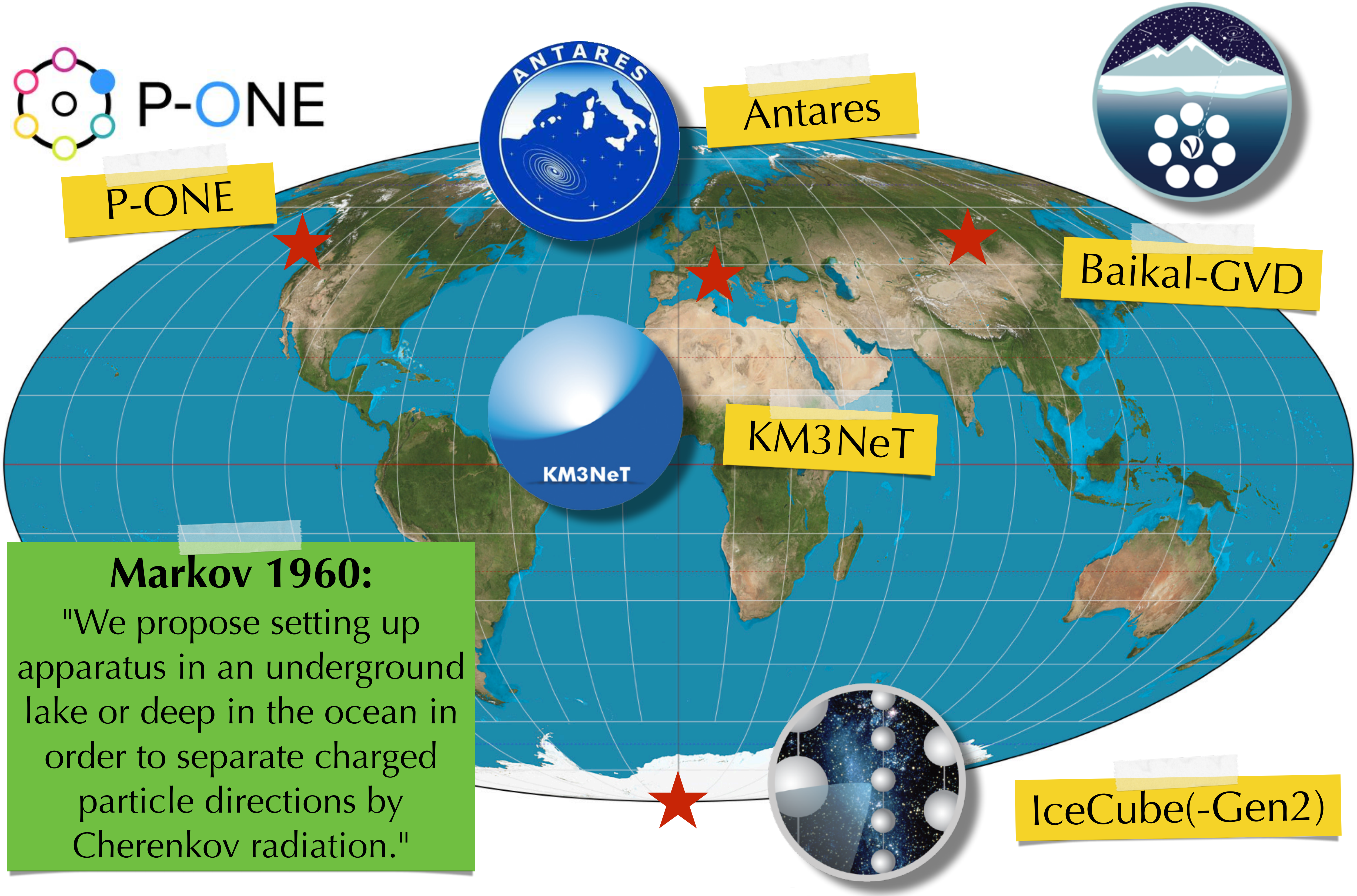


[IceCube, ApJ (2022) 928]

- Diffuse flux agrees across analyses (within their overlapping energy regions).
- However, mild tensions though for a "vanilla" single power-law flux.



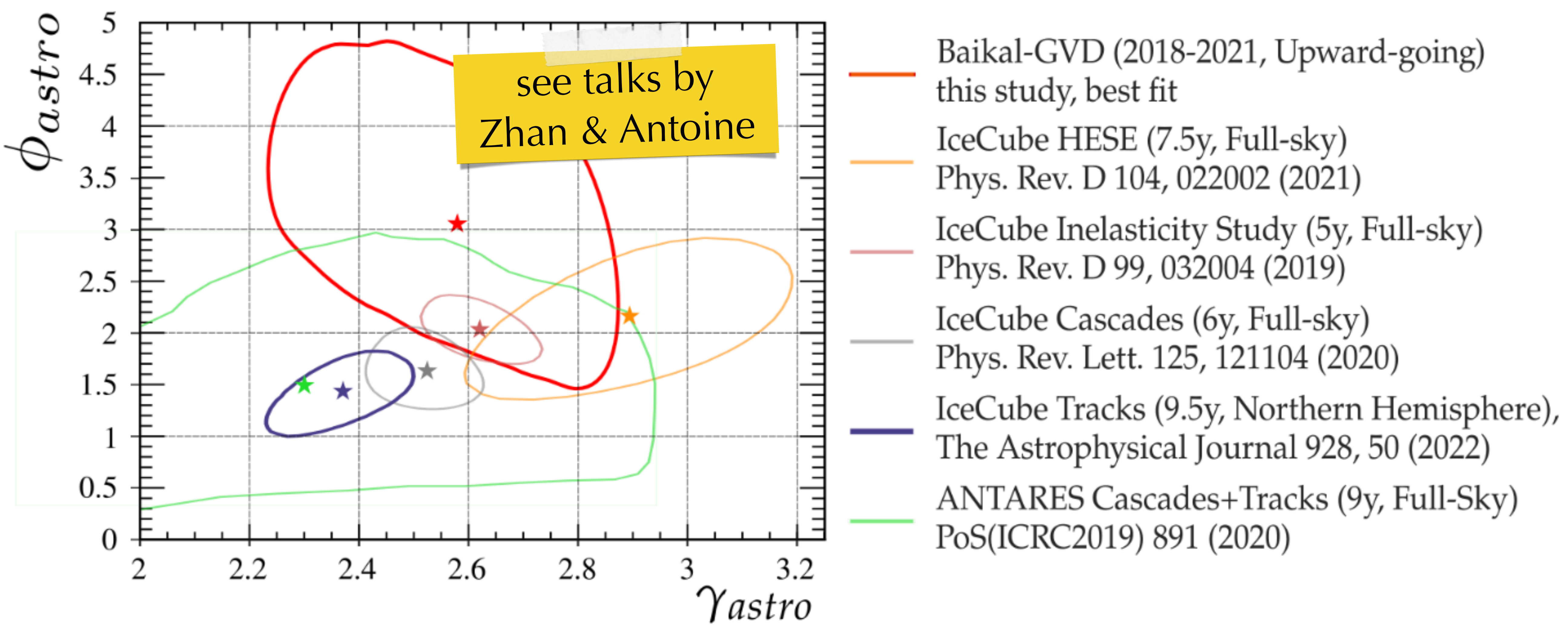
Optical Cherenkov Telescopes



Markov 1960:

"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation."

Isotropic Diffuse Flux



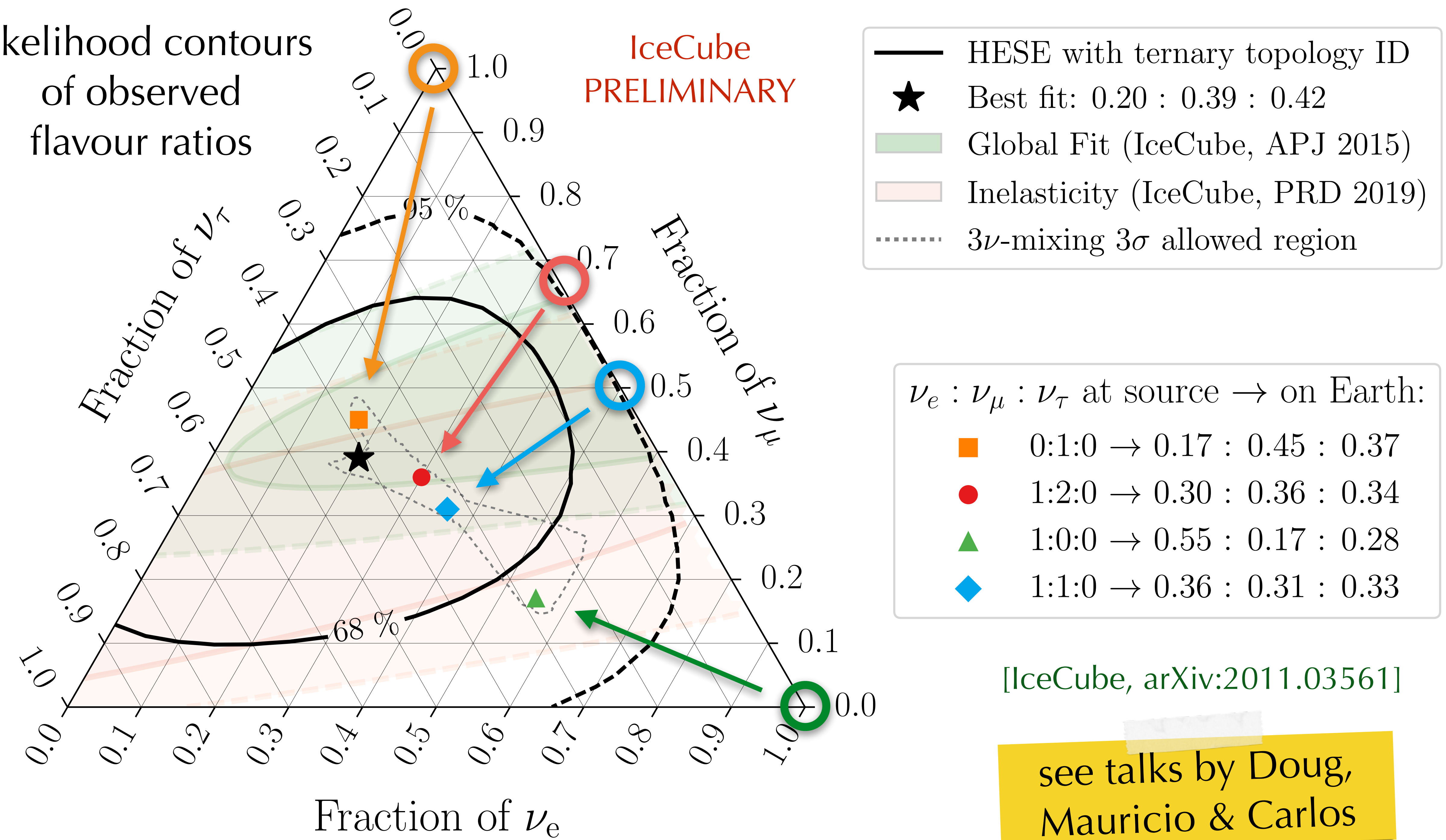
[ANTARES, PoS (ICRC2019) 891 & PoS (ICRC2021) 1121; Baikal-GVD, arXiv:2210.01650]

- Independent probe of diffuse flux by Baikal-GVD and KM3NeT.
- Complementary field of view allows to decipher anisotropies, e.g. by Galactic diffuse emission.

Astrophysical Flavours

Cosmic neutrinos visible via their oscillation-averaged flavour.

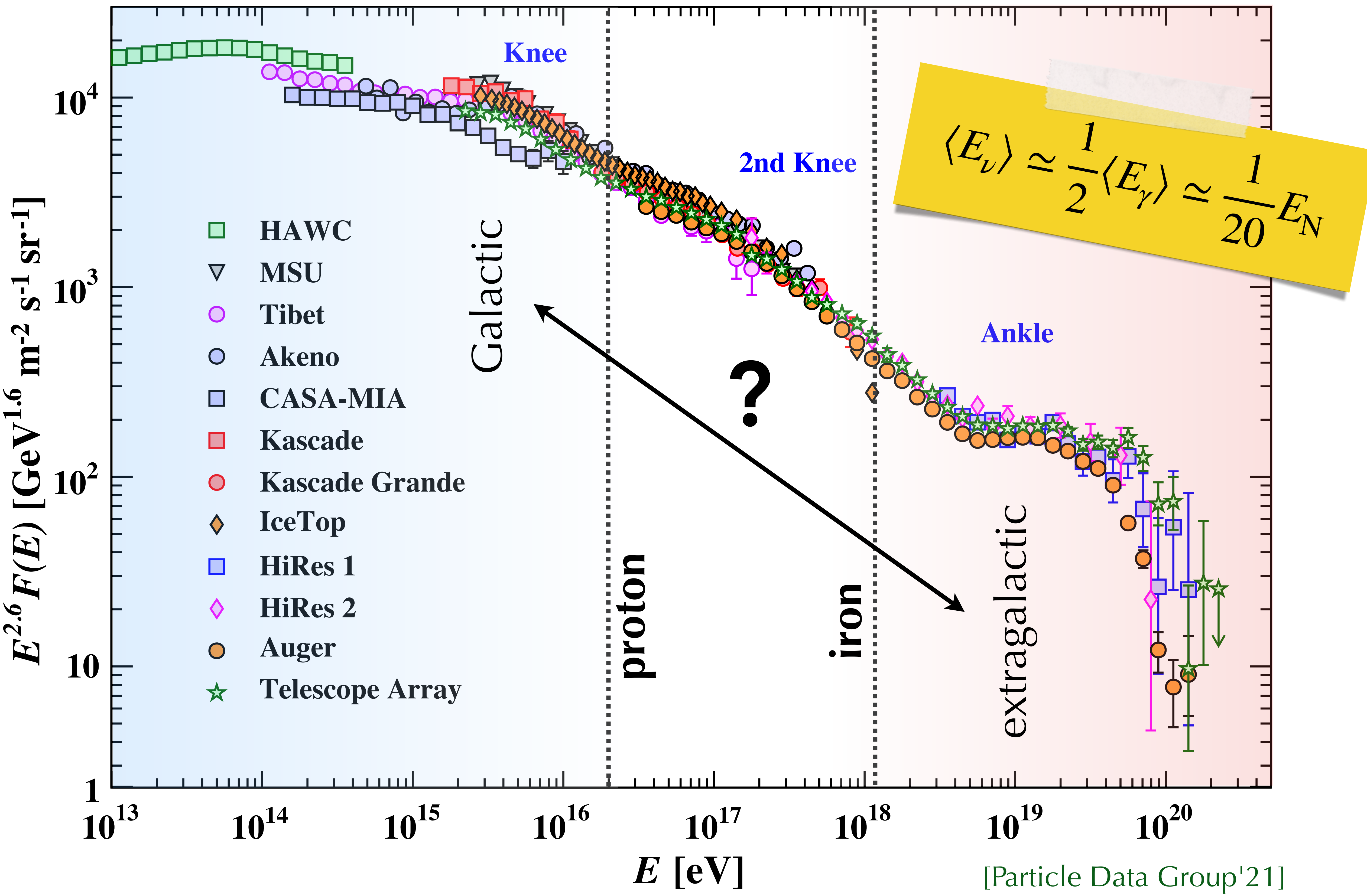
Likelihood contours of observed flavour ratios



[IceCube, arXiv:2011.03561]

see talks by Doug, Mauricio & Carlos

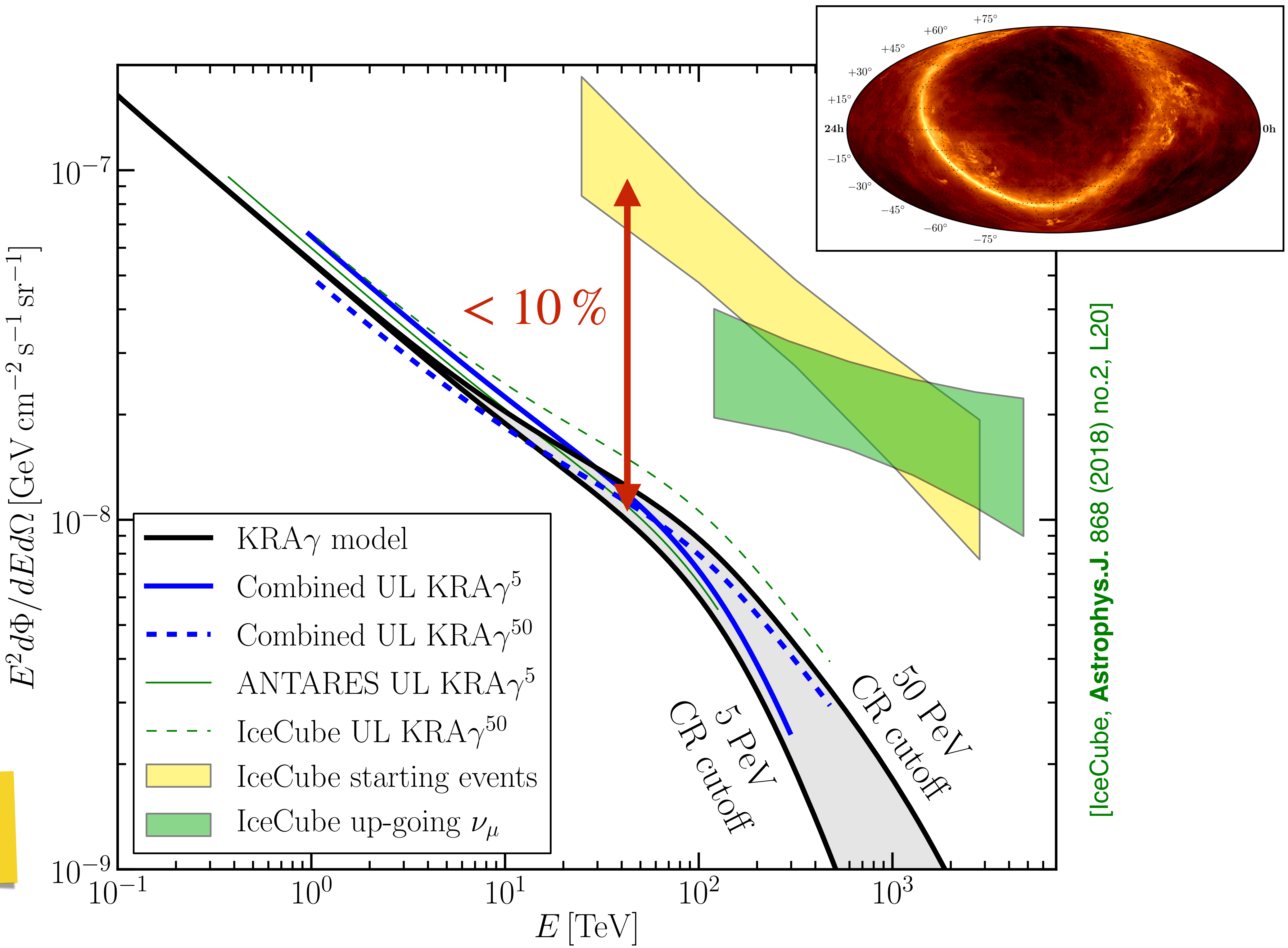
Very-High Energy Cosmic Rays



[Particle Data Group'21]

Galactic Neutrino Emission

ICECUBE



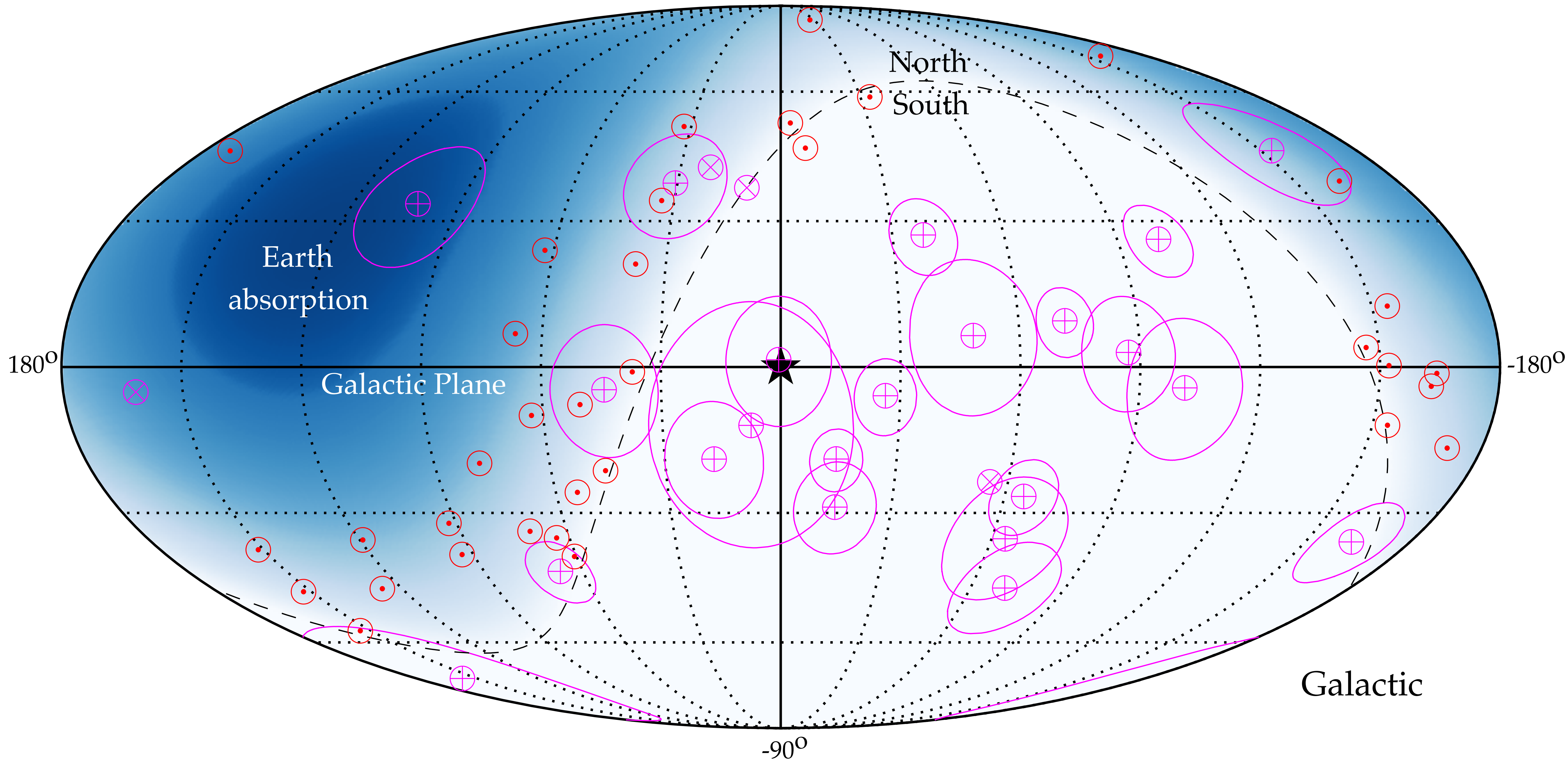
[IceCube, **Astrophys.J.** 868 (2018) no.2, L20]

see talk by Andrii

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

Status of Neutrino Astronomy

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



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Point Source vs. Diffuse Flux

Populations of extragalactic neutrino sources can be visible

individual sources

or by the

combined isotropic emission.

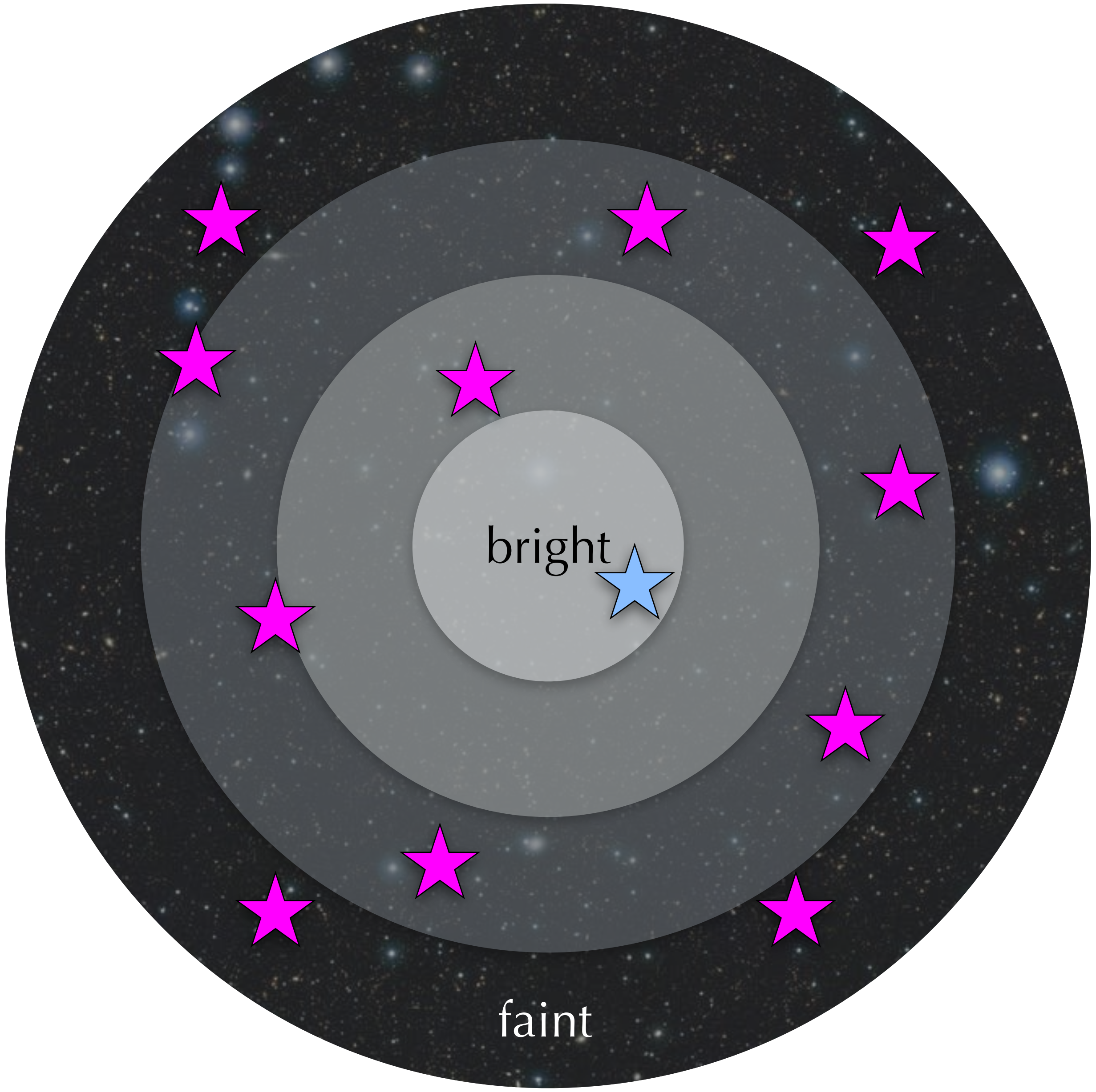
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

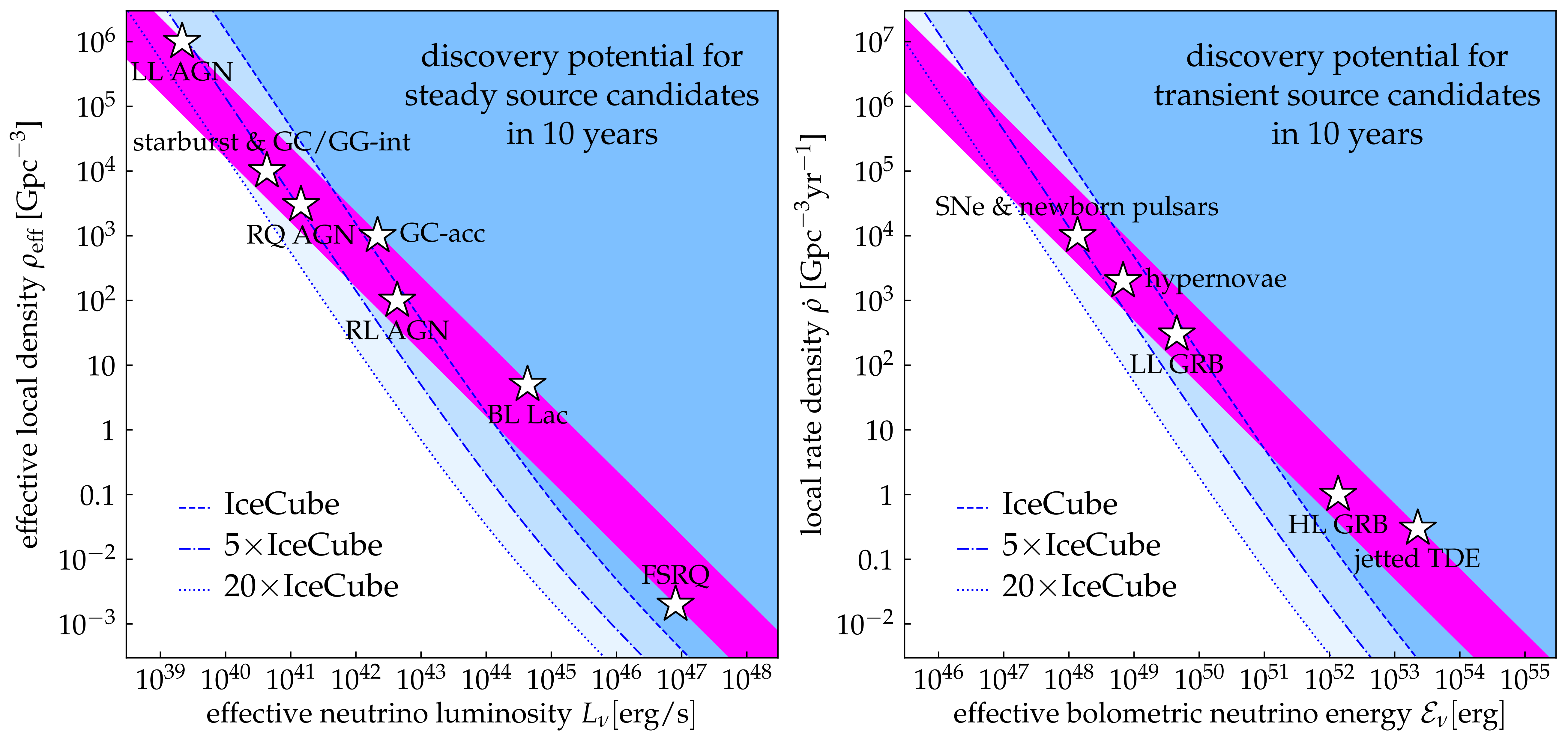
source luminosity.

"Observable Universe"
with far (faint) and near (bright) sources.



Hubble horizon

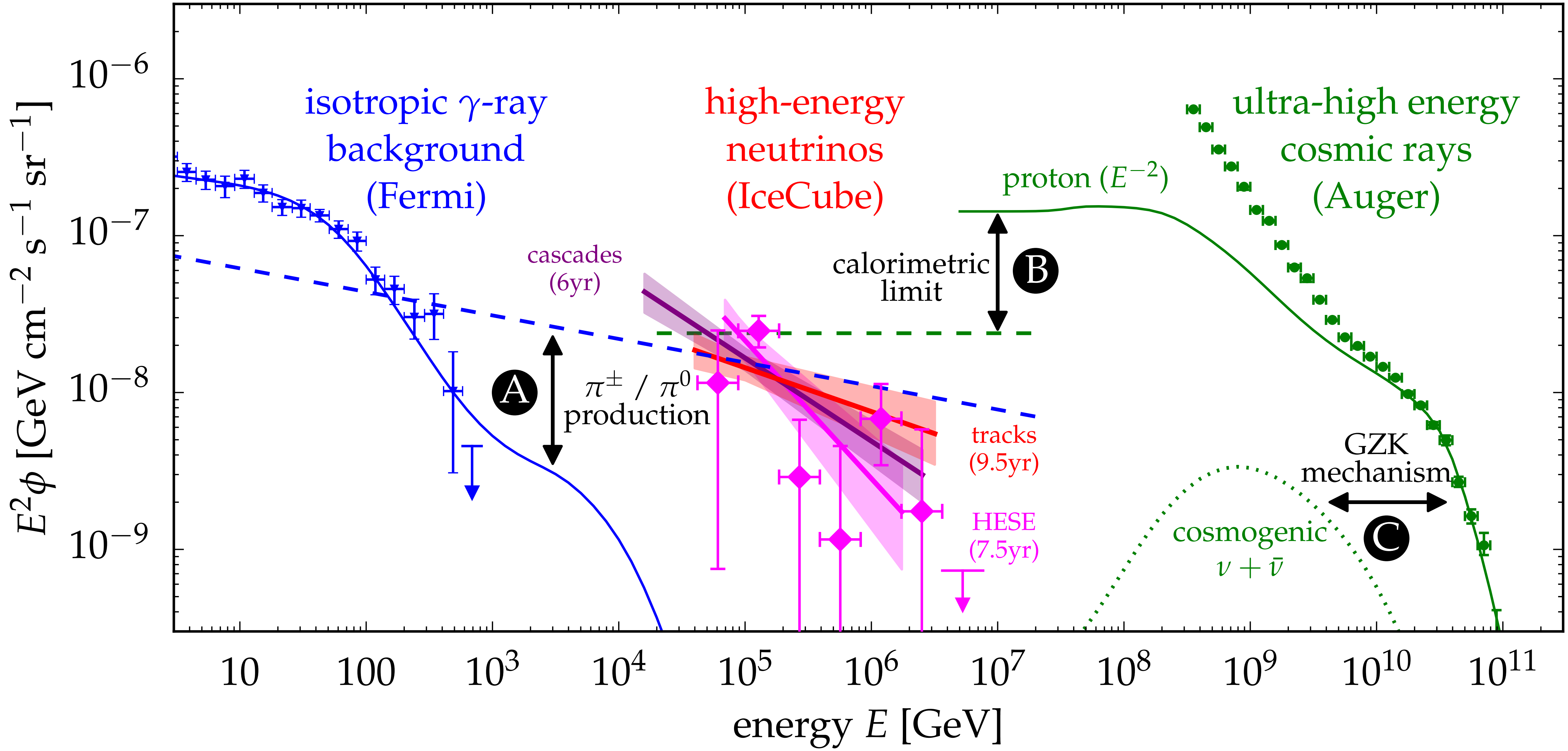
Point Source vs. Diffuse Flux



[Murase & Waxman'16; Ackermann *et al.*'19]

Rare sources - blazars, HL GRBs or jetted TDEs - can not be the dominant sources of TeV-PeV neutrino emission (magenta band).

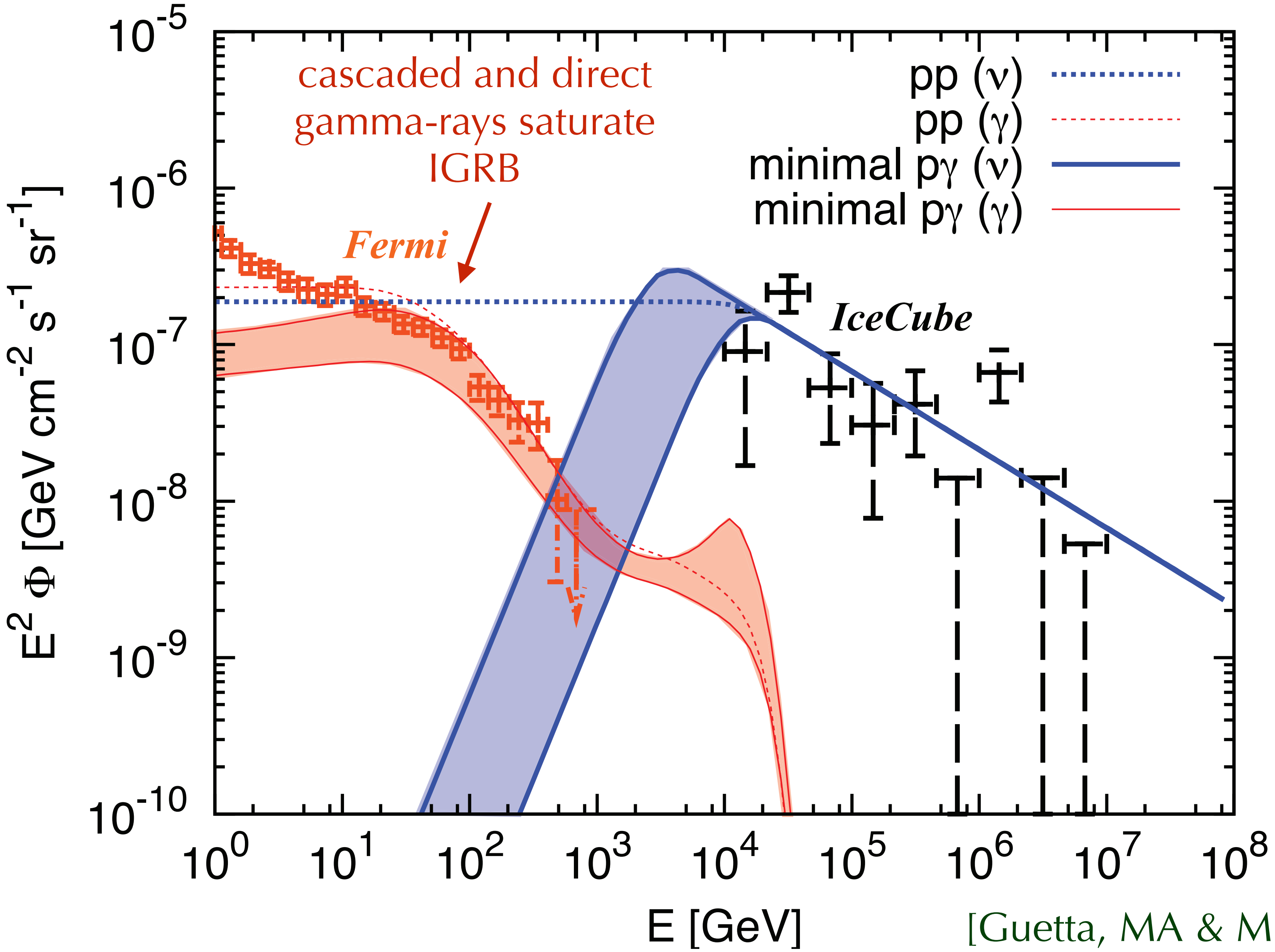
Multi-Messenger Interfaces



The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) or radiation (pγ) saturate the isotropic diffuse gamma-ray background.



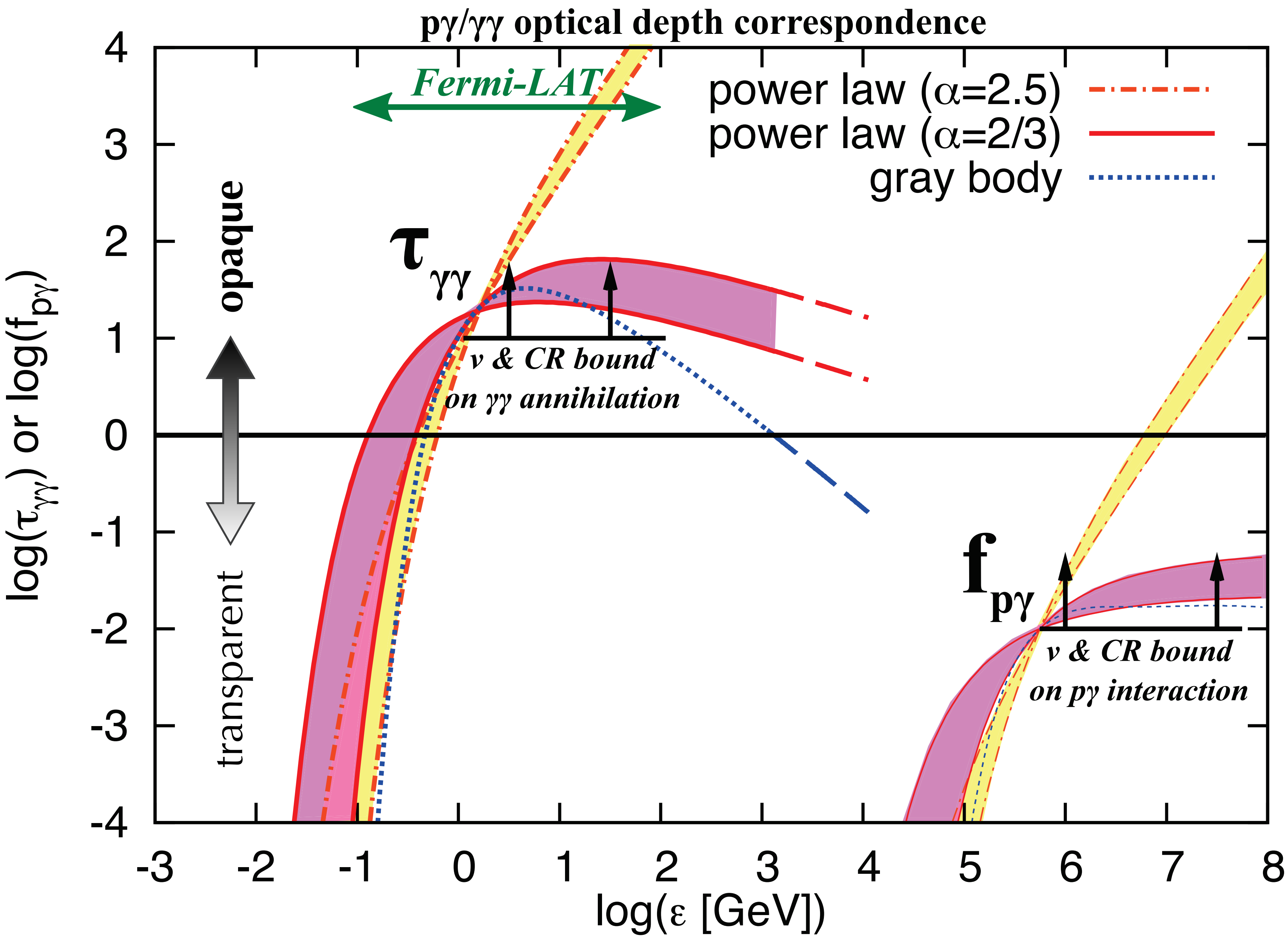
[Guetta, MA & Murase'16]

[see also Murase, MA & Lacki'13; Tamborra, Ando & Murase'14; Ando, Tamborra & Zandanel'15]

[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15; Palladino, Fedynitch, Rasmussen & Taylor'19]

Hidden Sources?

Efficient production of 10 TeV neutrinos in $p\gamma$ scenarios require sources with **strong X-ray backgrounds** (e.g. AGN core models).



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

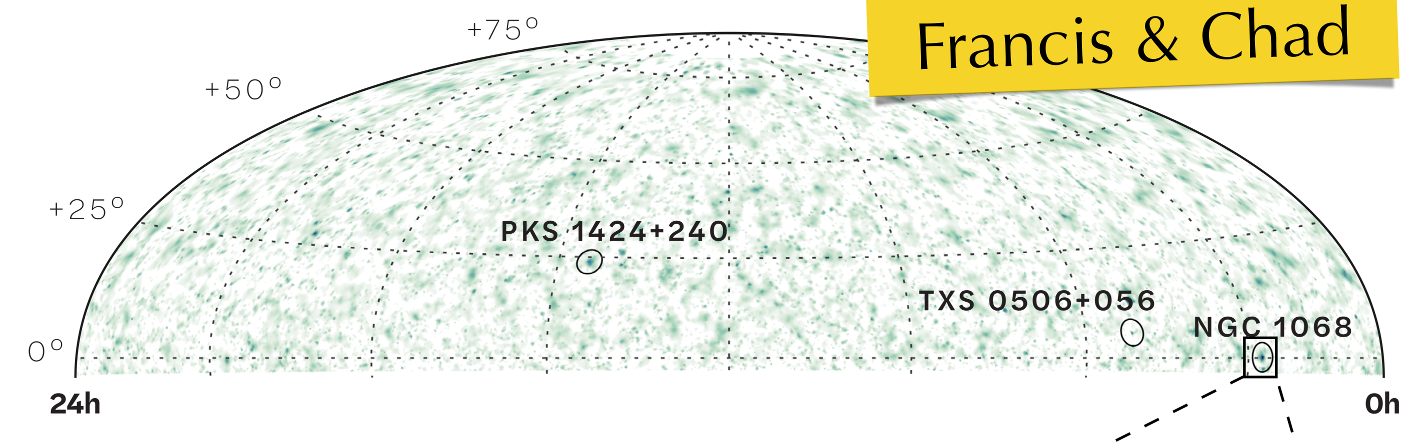
$$\tau_{\gamma\gamma} \simeq 1000 f_{p\gamma}$$

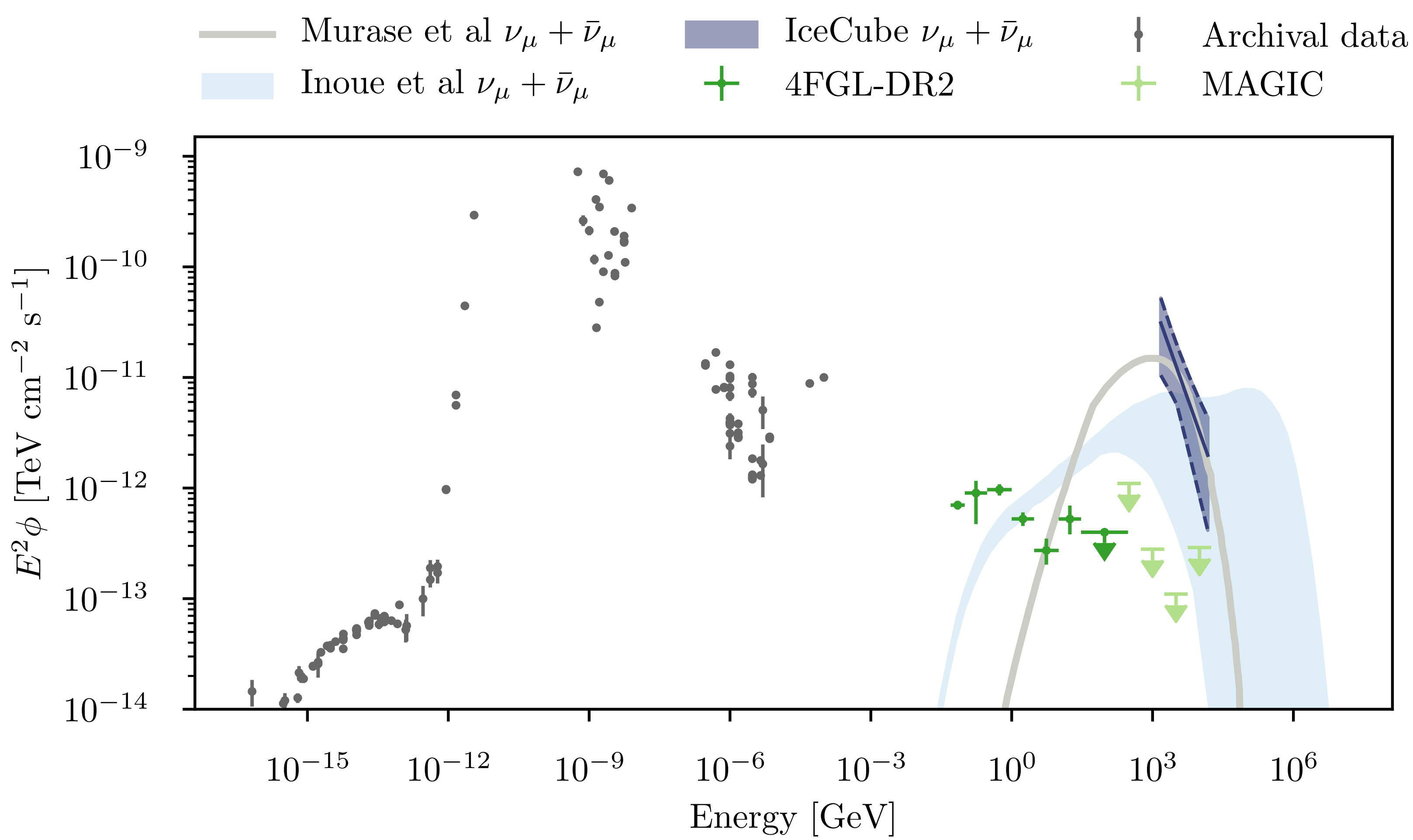
[Guetta, MA & Murase'16]

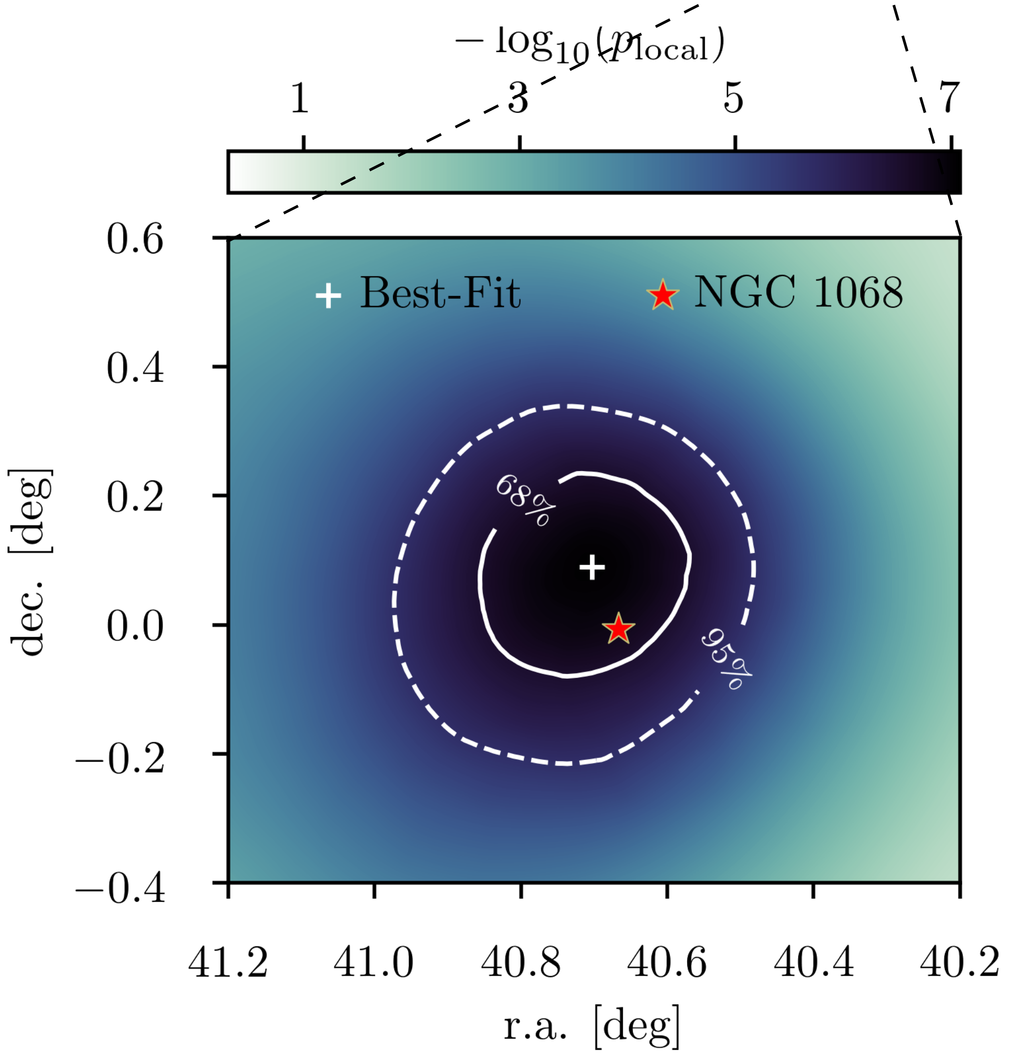
Excess from NGC 1068

see talks by Francis & Chad

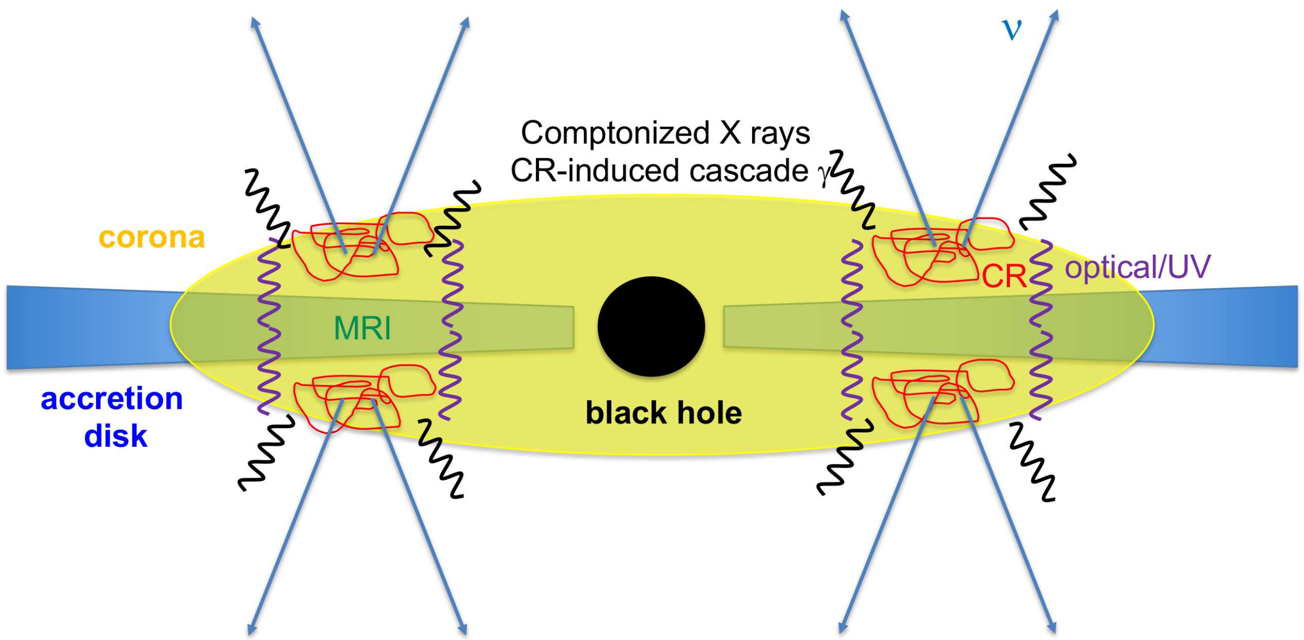
Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** has now a **significance of 4.2σ** *(trial-corrected for 110 sources)*.



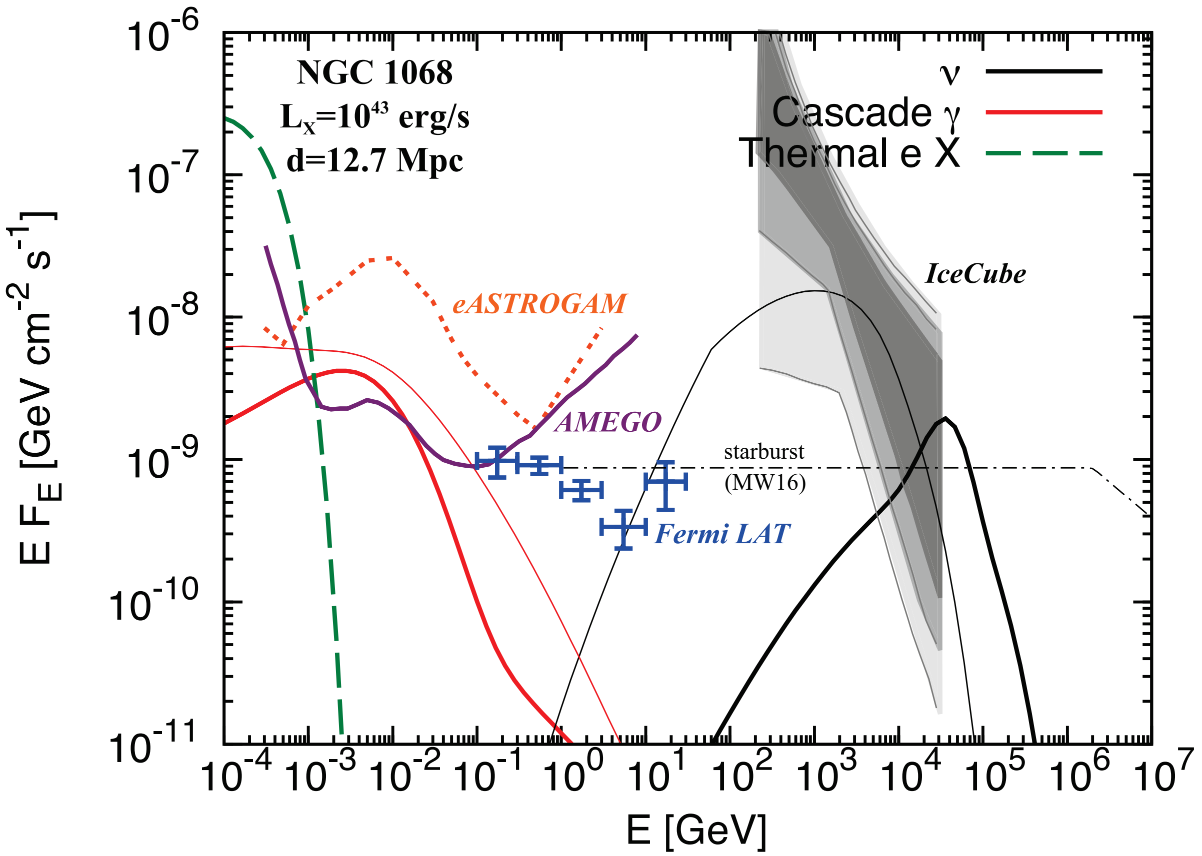




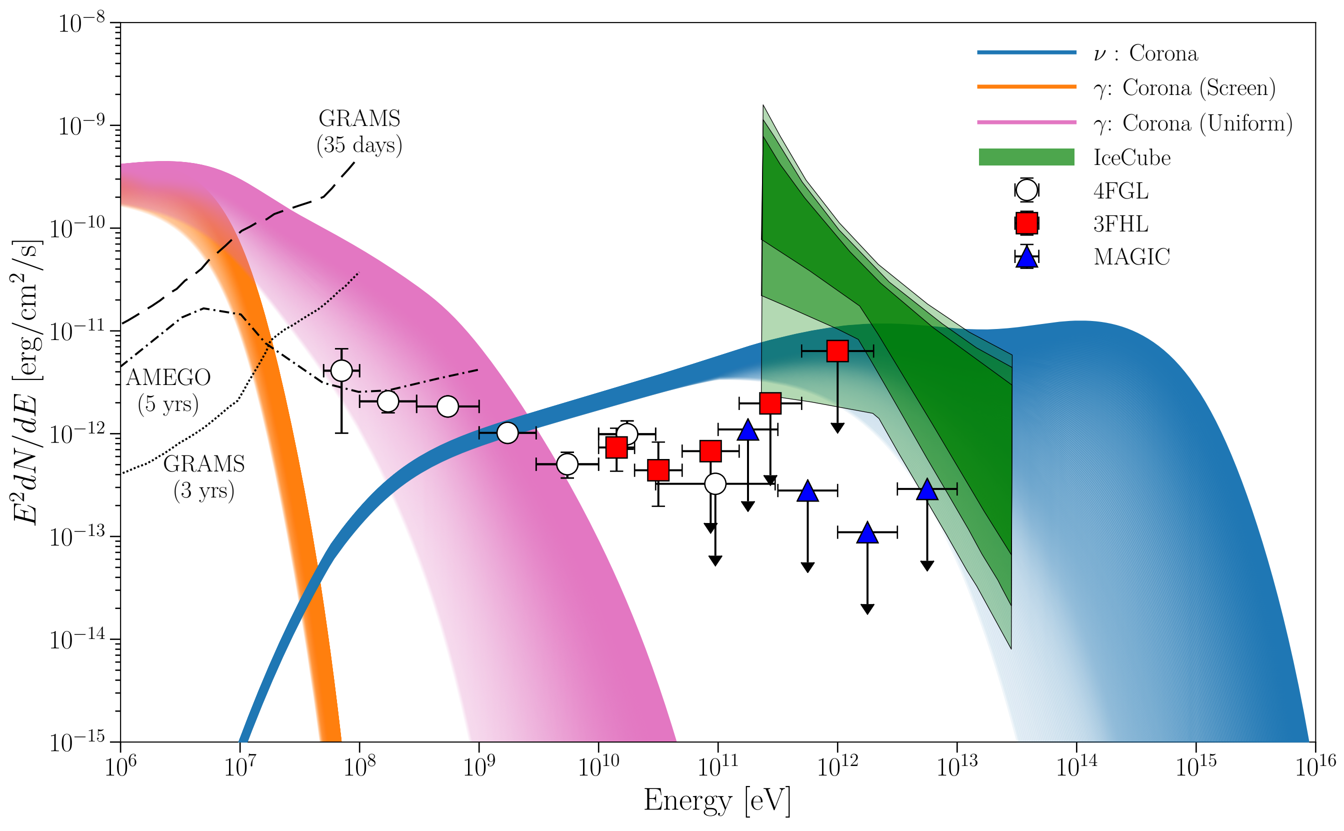
[IceCube, PRL 124 (2020) 5 **(2.9σ post-trial)**; Science 378 (2022) 6619 **(4.2σ post-trial)**]



- **Soft spectrum** ($\gamma = 3.2 \pm 0.2$) within 1.5-15 TeV indicates peak or cutoff in ν emission.
- Effective **absorption** of accompanying γ-rays in X-ray photons of **AGN corona.**



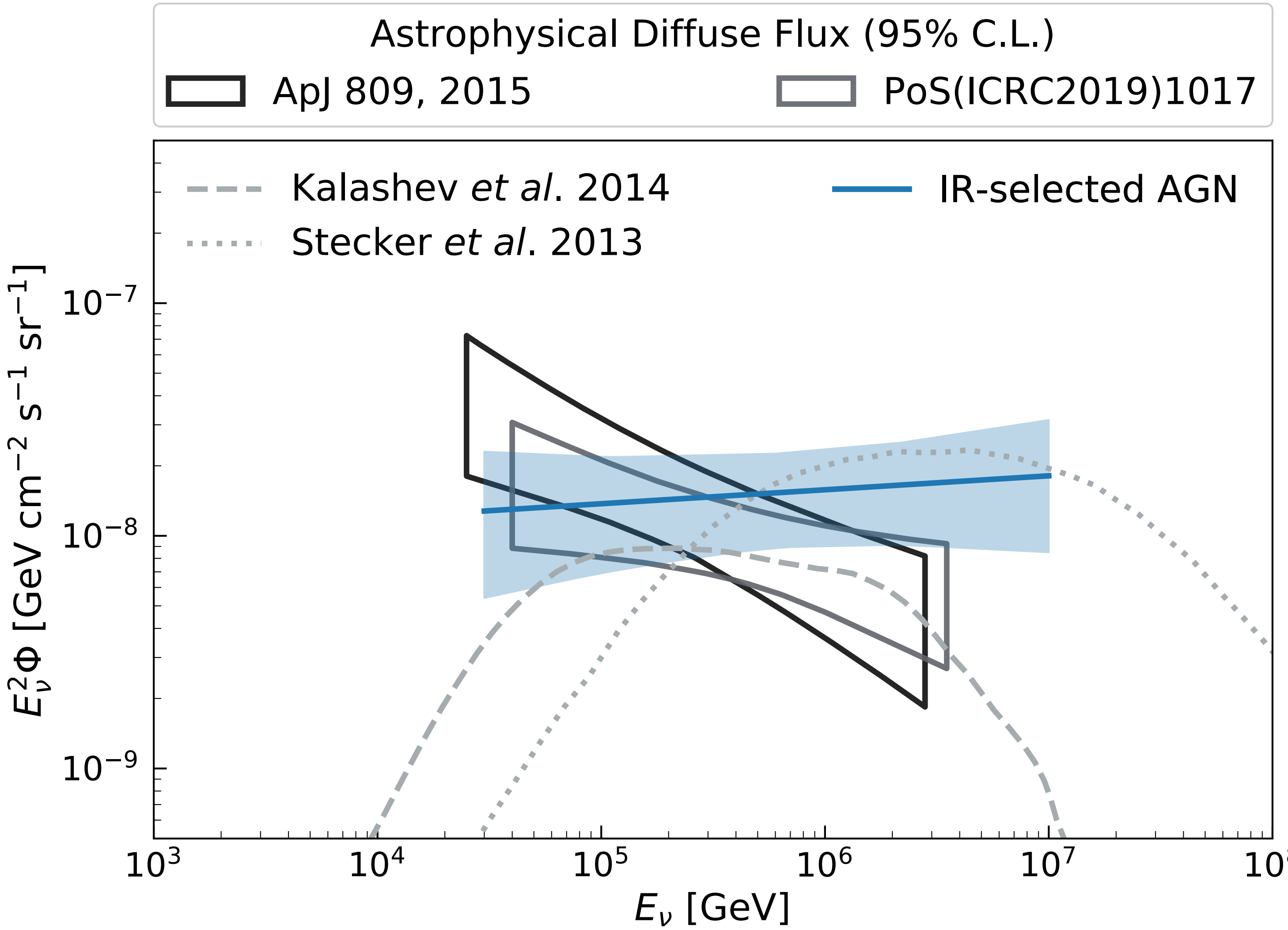
[Murase, Kimura & Meszaros '20]



[Inoue, Khangulyan & Doi '20]

AGN Core Stacking

- Hadronic γ-rays in **cores of AGNs** are suppressed due to pair production in X-ray background.
- IceCube finds a **2.6σ excess** for 32,249 AGN selected by their IR emission.

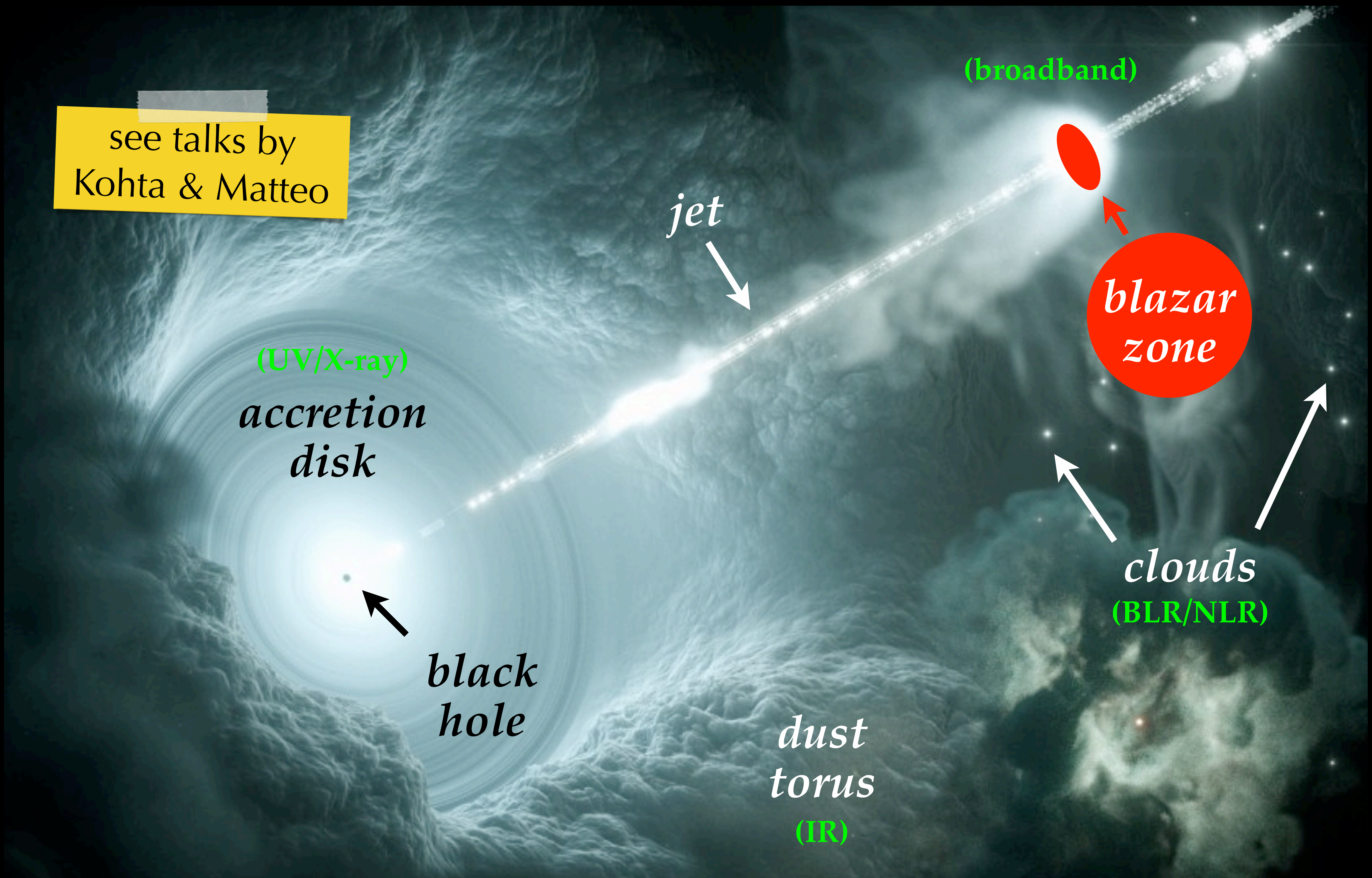


[IceCube, PRD 106 (2022) 2]

TABLE I. Properties of the AGN samples created for the analysis. The surveys used for the cross-match to derive each sample, the final number of selected sources, cumulative X-ray flux in the 0.5-2 keV energy range from the selected sources [44] and the completeness (fraction of total X-ray flux from all AGN in the Universe contained in the sample) are listed.

	Radio–selected AGN	IR–selected AGN	LLAGN
Matched catalogues	NVSS + 2RXS + XMMSL2	AllWISE + 2RXS + XMMSL2	AllWISE + 2RXS
Nr. of sources	9749	32249	15887
Cumulative X-ray flux [erg cm^{-2} s^{-1}]	7.71×10^{-9}	1.43×10^{-8}	7.26×10^{-9}
Completeness	$5^{+5}_{-3}\%$	$11^{+12}_{-7}\%$	$6^{+7}_{-4}\%$

Blazars

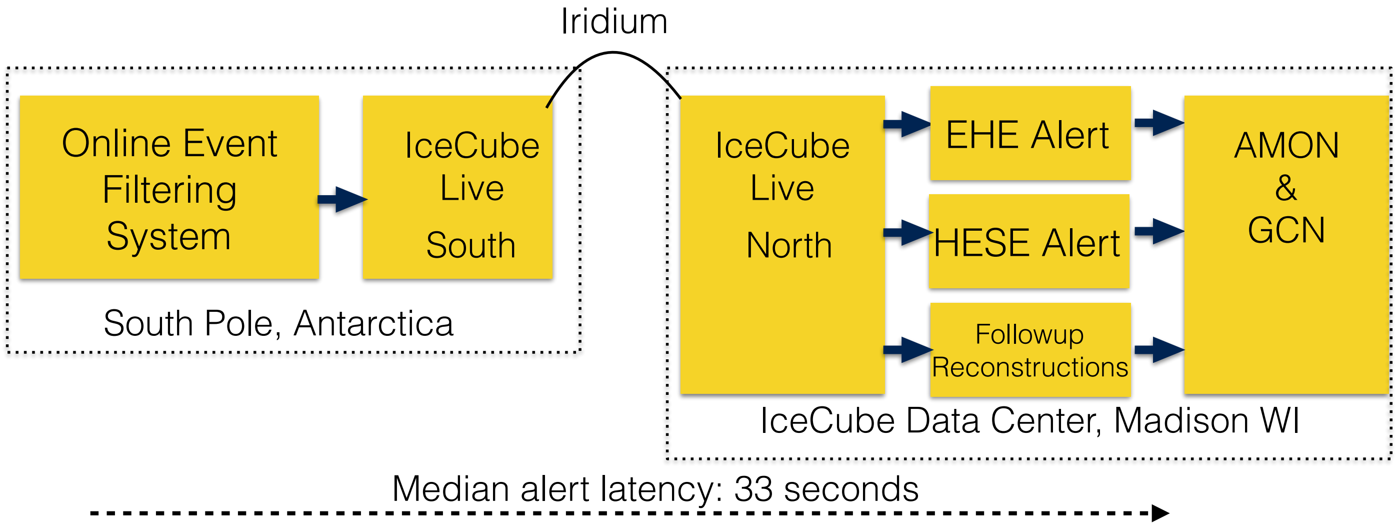


Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

Realtime Neutrino Alerts

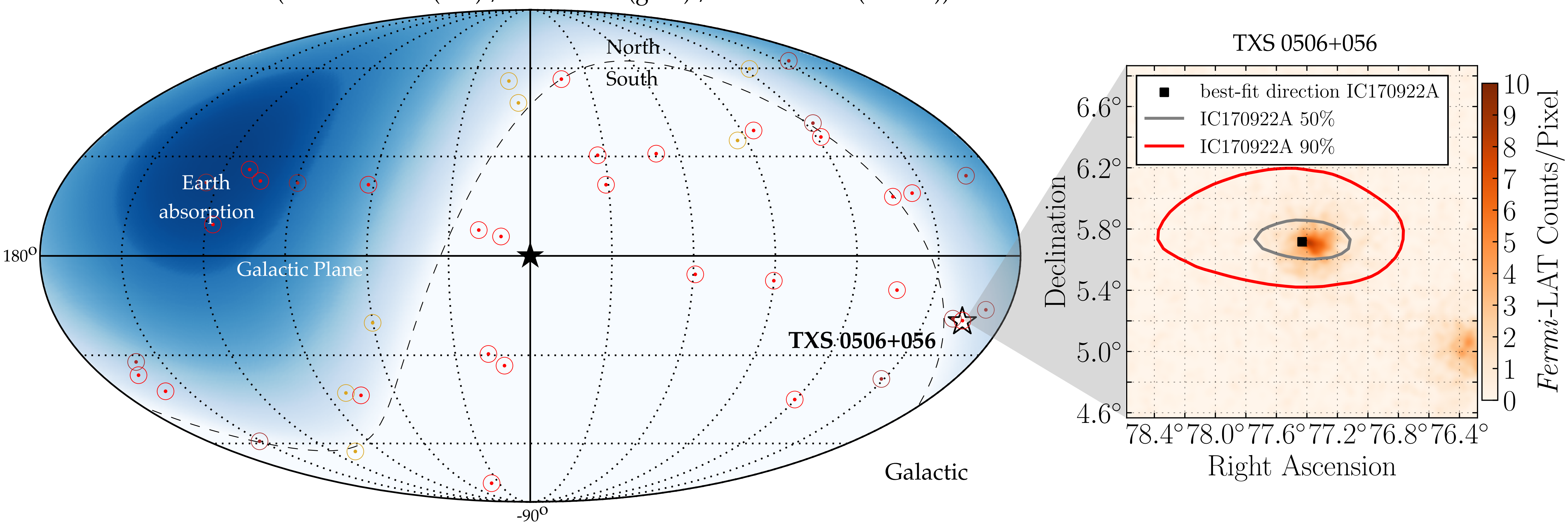
Low-latency (<1min) **public neutrino alert system** established in April 2016.

- ✦ **Gold alerts:** ~10 per year
  >50% signalness
- ✦ **Bronze alerts:** ~20 per year
  30-50% signalness

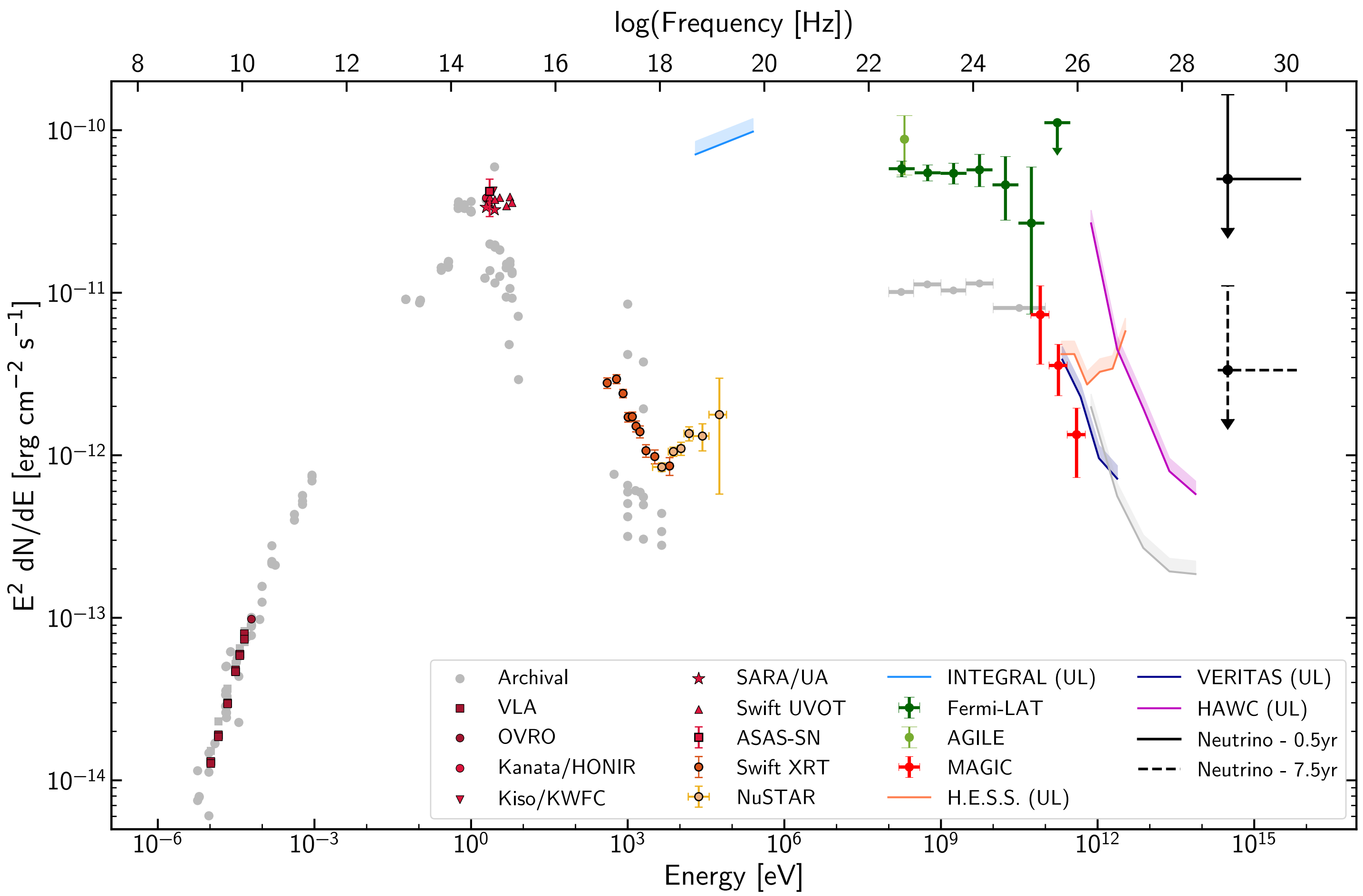


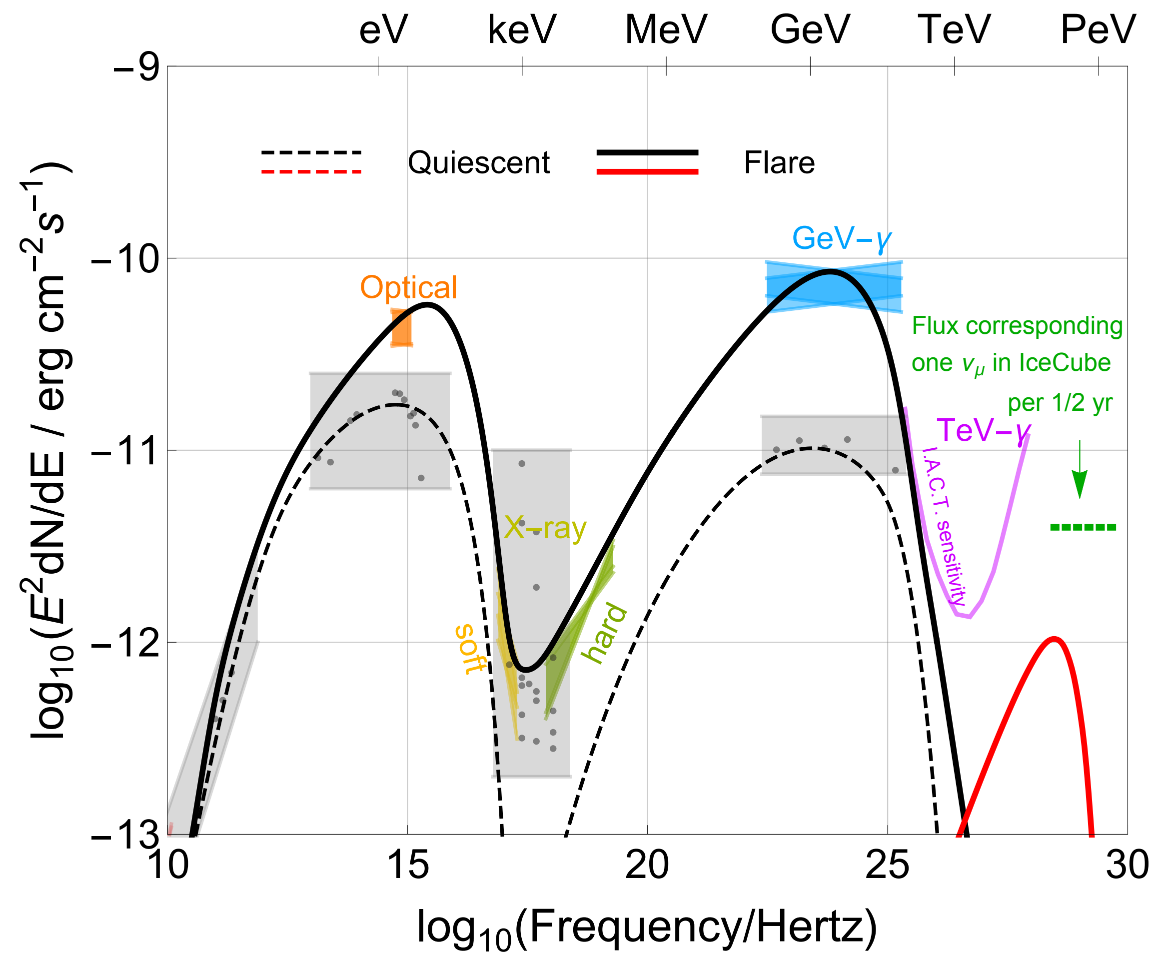
[IceCube, PoS (ICRC2019) 1021]

Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))



TXS 0506+056





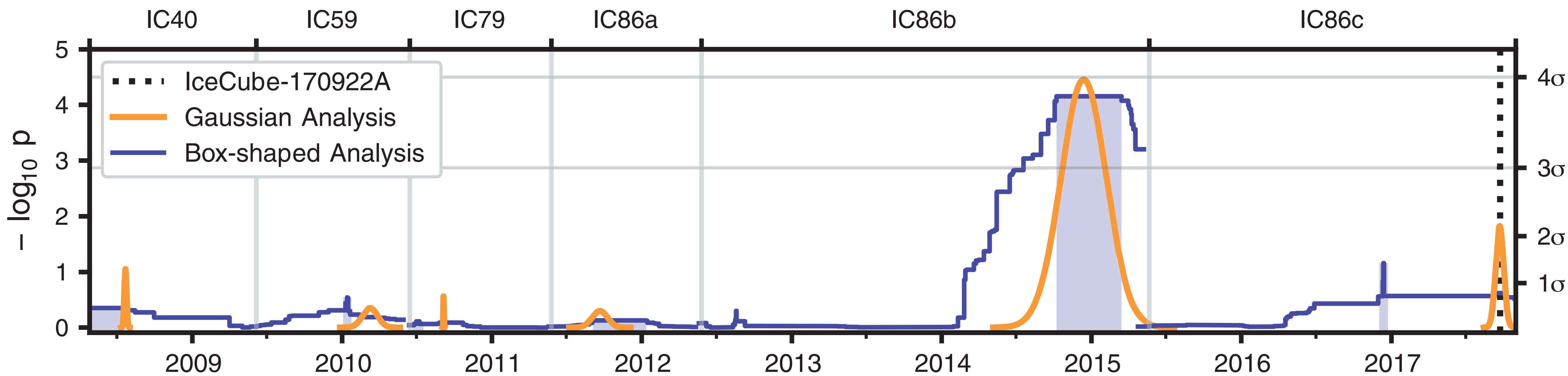
[IceCube++, Science 361 (2018) 6398] [Gao *et al.*'18]

- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- Photon SED can be modelled by lepto-hadronic or proton-synchrotron models.

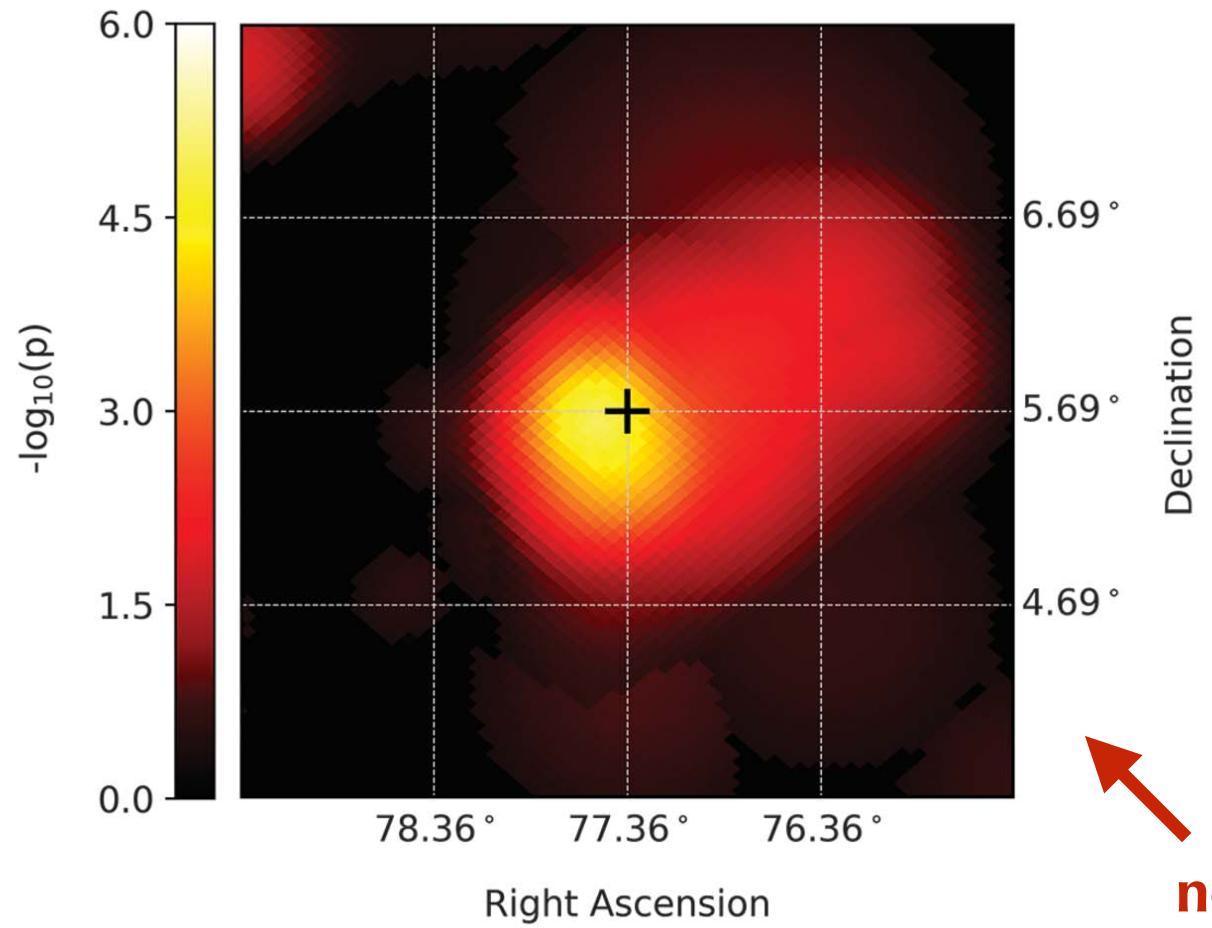
[Keivani *et al.*'18.; Gao *et al.*'18; Cerruti *et al.*'18; Zhang, Fang & Li'18; Gokus *et al.*'18; Sahakyan'18]

[Murase, Oikonomo & Petropoulou'18; see also: Strotjohann, Kowalski & Franckowiak'18]

Neutrino Flare in 2014/15



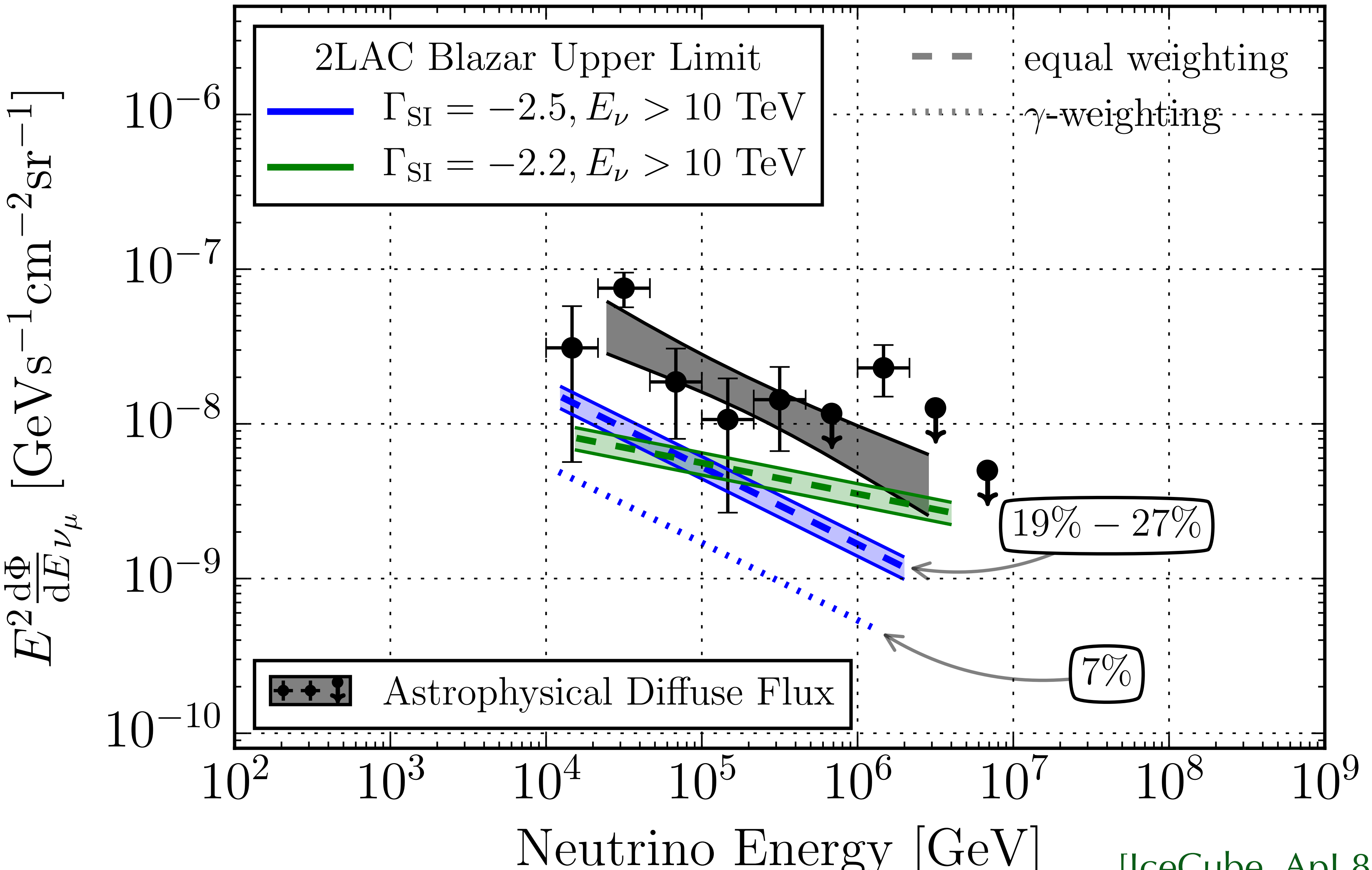
[IceCube, Science 361 (2018) 6398]



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

neutrino "morphology" of 2014/15 flare

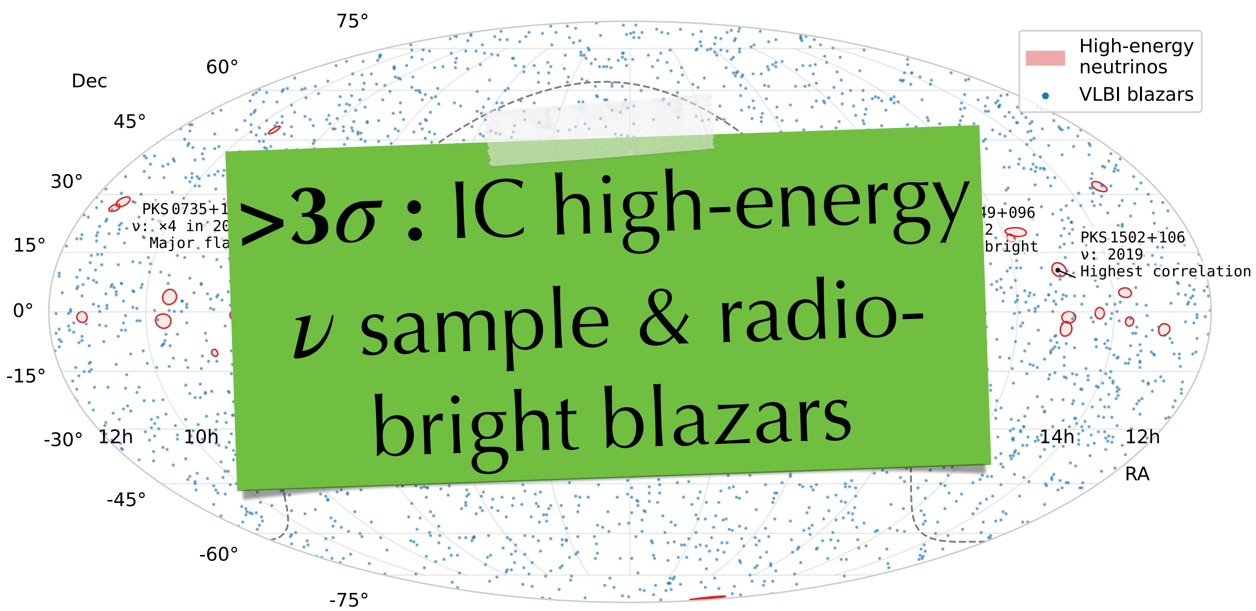
Fermi-LAT Blazar Stacking



[IceCube, ApJ 835 (2017) 45]

Combined contribution of Fermi-LAT blazars (2LAC) **below 30%** of the isotropic TeV-PeV neutrino observation.

Blazar Stacking Revisited

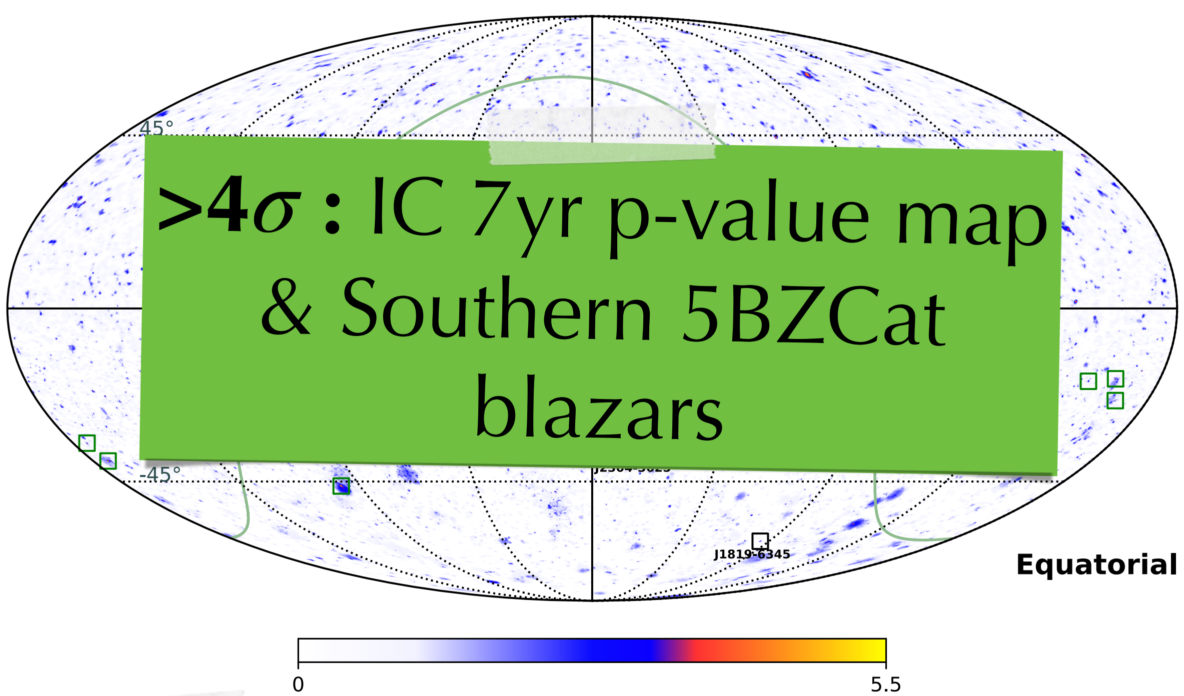


>3σ : IC high-energy ν sample & radio-bright blazars

[Plavin, Kovalev, Kovalev & Troitsky '20 & '22]

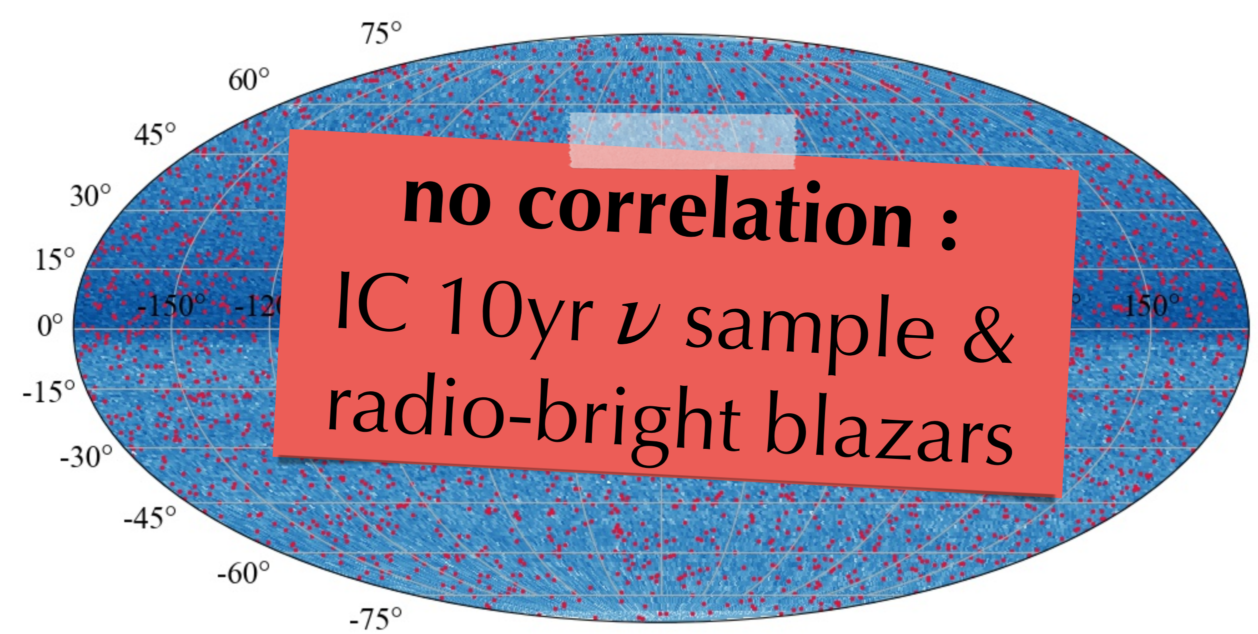
3σ : IC 7yr p-value map & radio-bright blazars

[Plavin, Kovalev, Kovalev & Troitsky '21]



>4σ : IC 7yr p-value map & Southern 5BZCat blazars

[Buson et al.'22]



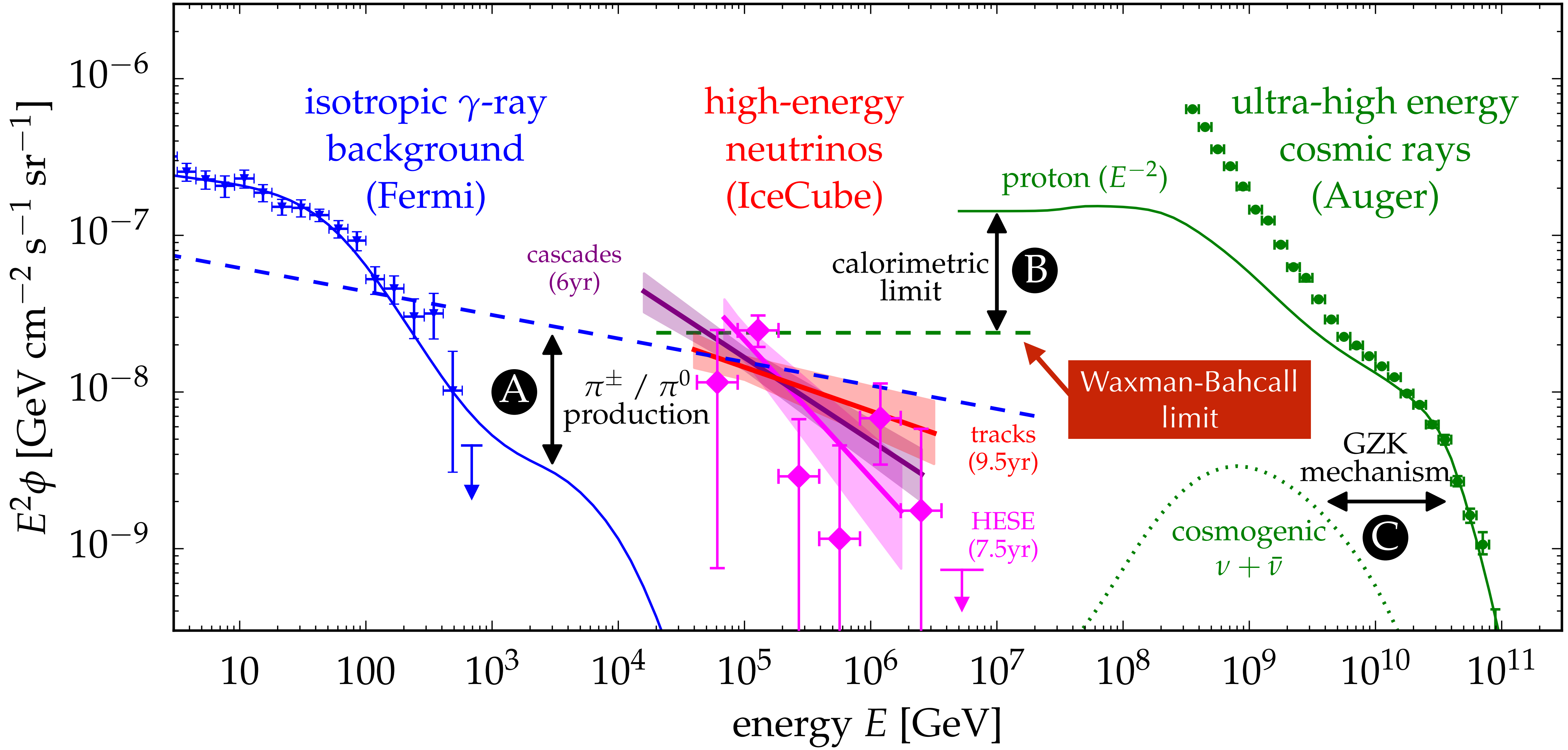
no correlation : IC 10yr ν sample & radio-bright blazars

[Zhou, Kamionkowski & Liang '21]

see talk by Sasha

[see also Hooper, Linden & Vieregg'19; Luo & Zhang '20; Hovatta *et al.* '21]

Multi-Messenger Interfaces



The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

Waxman-Bahcall Limit

- 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 : redshift evolution factor) :

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

- Limited by **pion production efficiency**: $f_\pi \lesssim 1$ [Waxman & Bahcall'98]

- Similar UHE **nucleon emission rate** density (local minimum at $\Gamma \simeq 2.04$) :

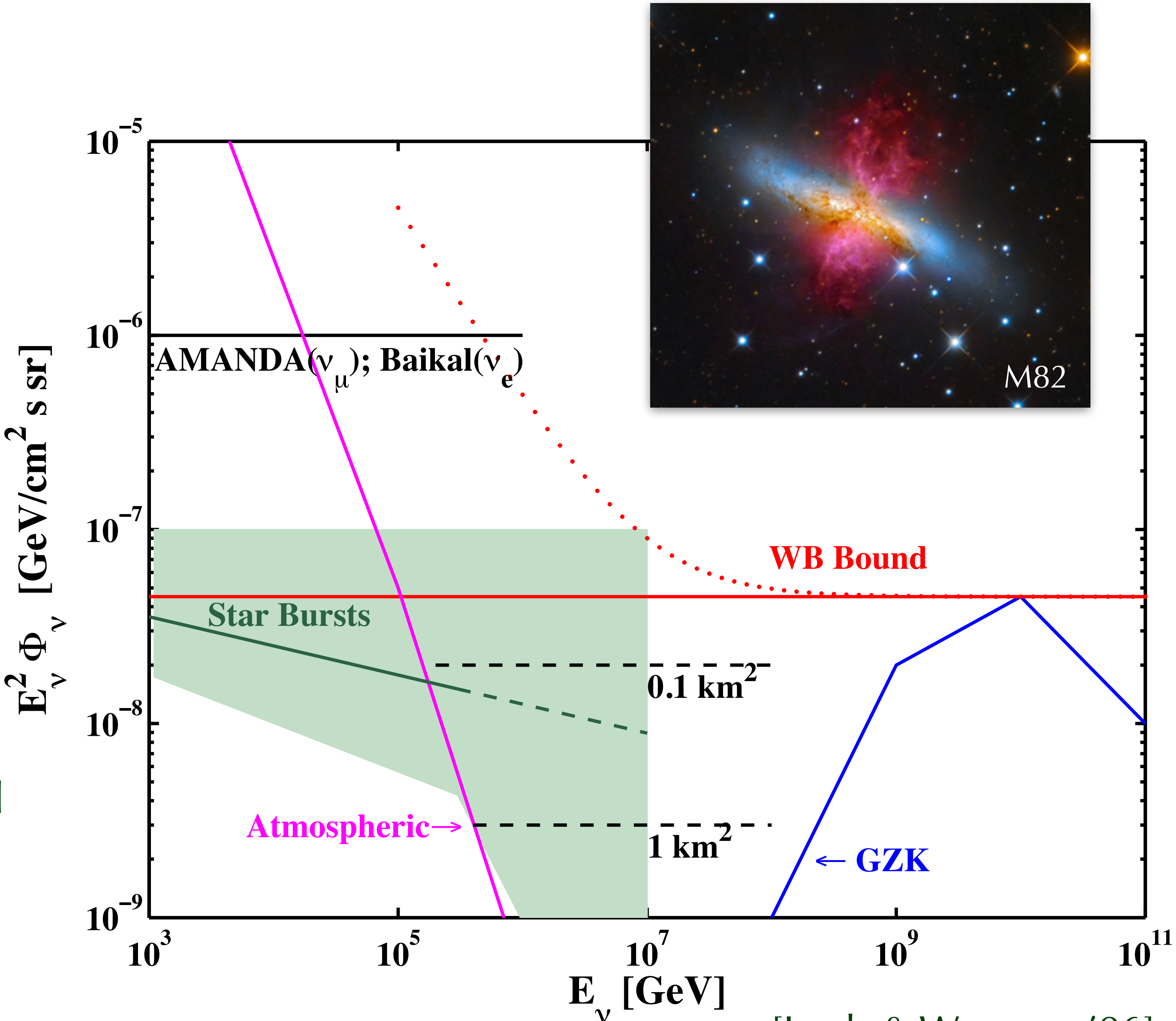
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43} \mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

[Auger'16; see also Jiang, Zhang & Murase'20]

- **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).

Starburst Galaxies

- High rate of **star formation** and SN explosions enhances (UHE) CR production.
- Low-energy cosmic rays remain magnetically confined and eventually collide in **dense environment**.
- In time, efficient **conversion of CR energy density into γ-rays and neutrinos**. [Loeb & Waxman '06]
- Power-law neutrino spectra with high-energy softening from CR leakage and/or acceleration.

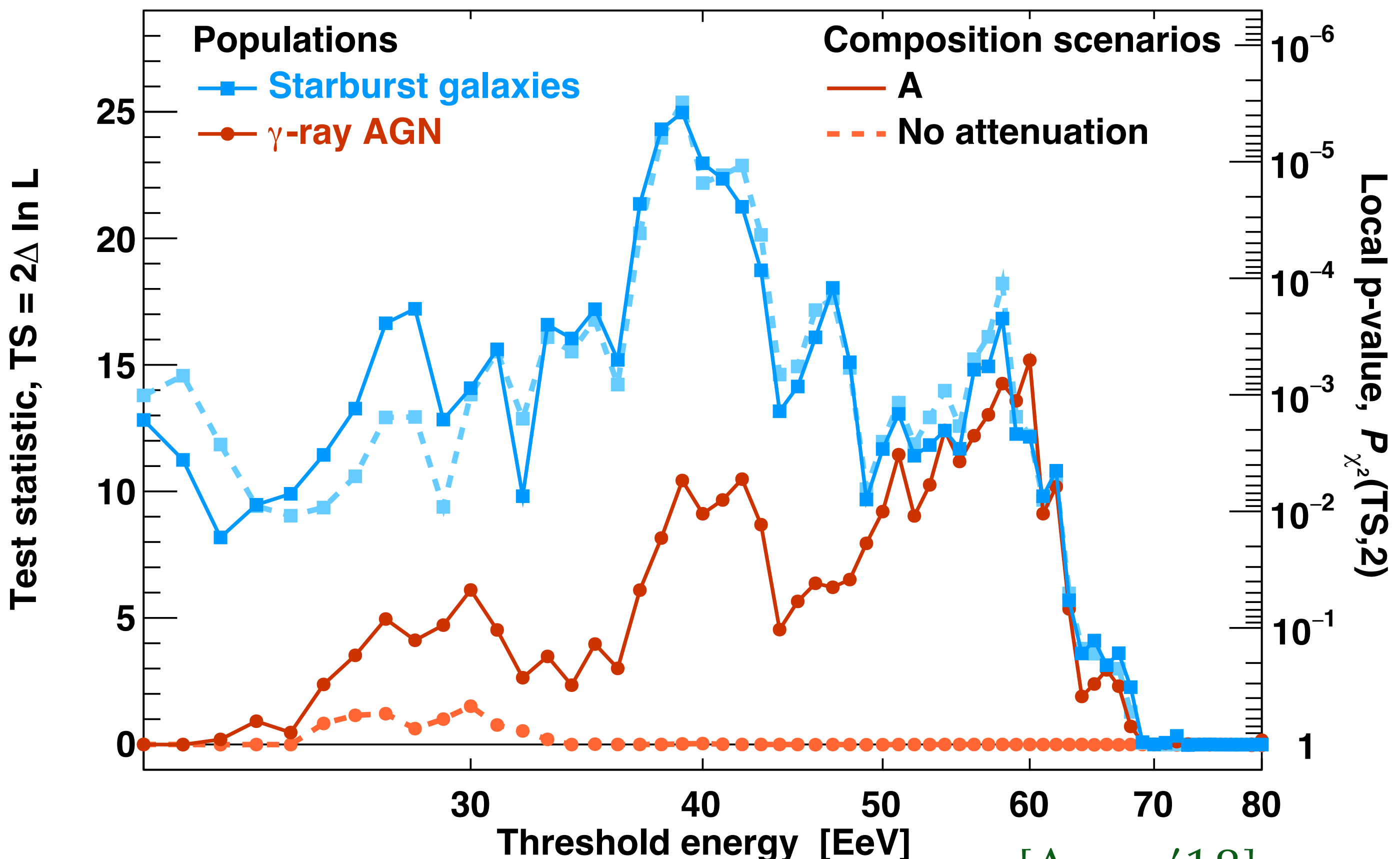


[Loeb & Waxman '06]

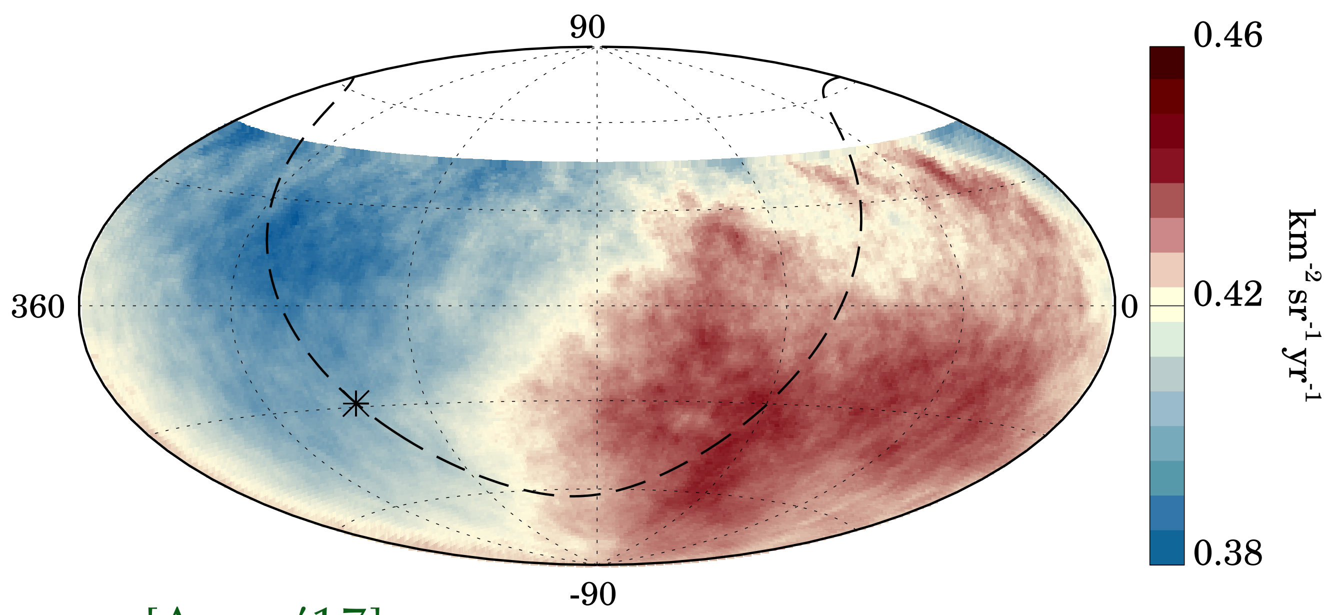
[Romero & Torres'03; Liu, Wang, Inoue, Crocker & Aharonian'14; Tamborra, Ando & Murase'14]
[Palladino, Fedynitch, Rasmussen & Taylor'19; Peretti, Blasi, Aharonian, Morlino & Cristofari'19]
[Ambrosone, Chianese, Fiorillo, Marinelli, Miele & Pisanti'20]

UHE CR Anisotropy

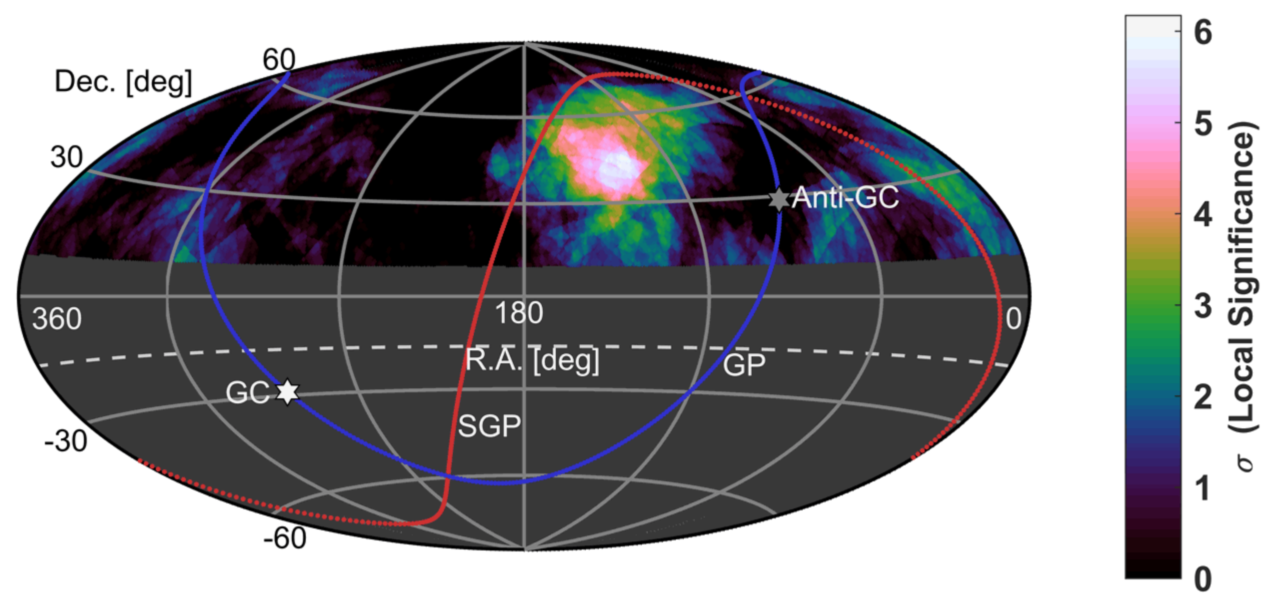
- UHE CR arrival direction above 8EeV show strong (6.5%) **dipole anisotropy** (5.2σ). [Auger'17]
- Arrival directions of UHE CRs above 40 EeV show **correlation with local starburst galaxies** (4σ).
- Indications for **medium-scale anisotropy** above 16 EeV in Northern Hemisphere (3.7σ) [TA'18]



[Auger'18]



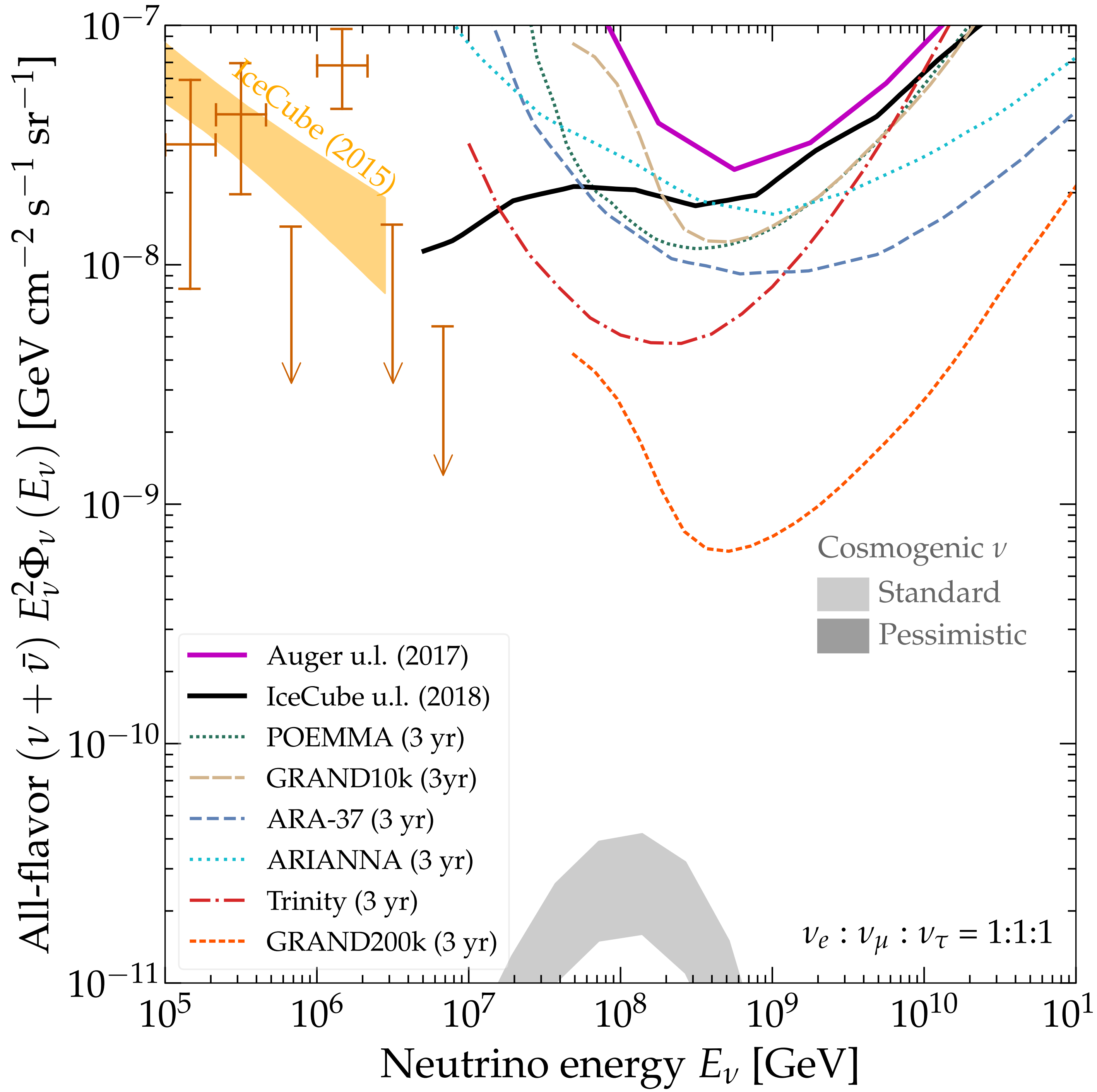
[Auger'17]



[TA'18]

Cosmogenic Neutrinos

- Cosmogenic (GZK) neutrinos produced in UHE CR interactions peak in the EeV energy range.
- 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.
- Absolute flux level serves as **independent measure of UHE CR composition** beyond 40EeV.

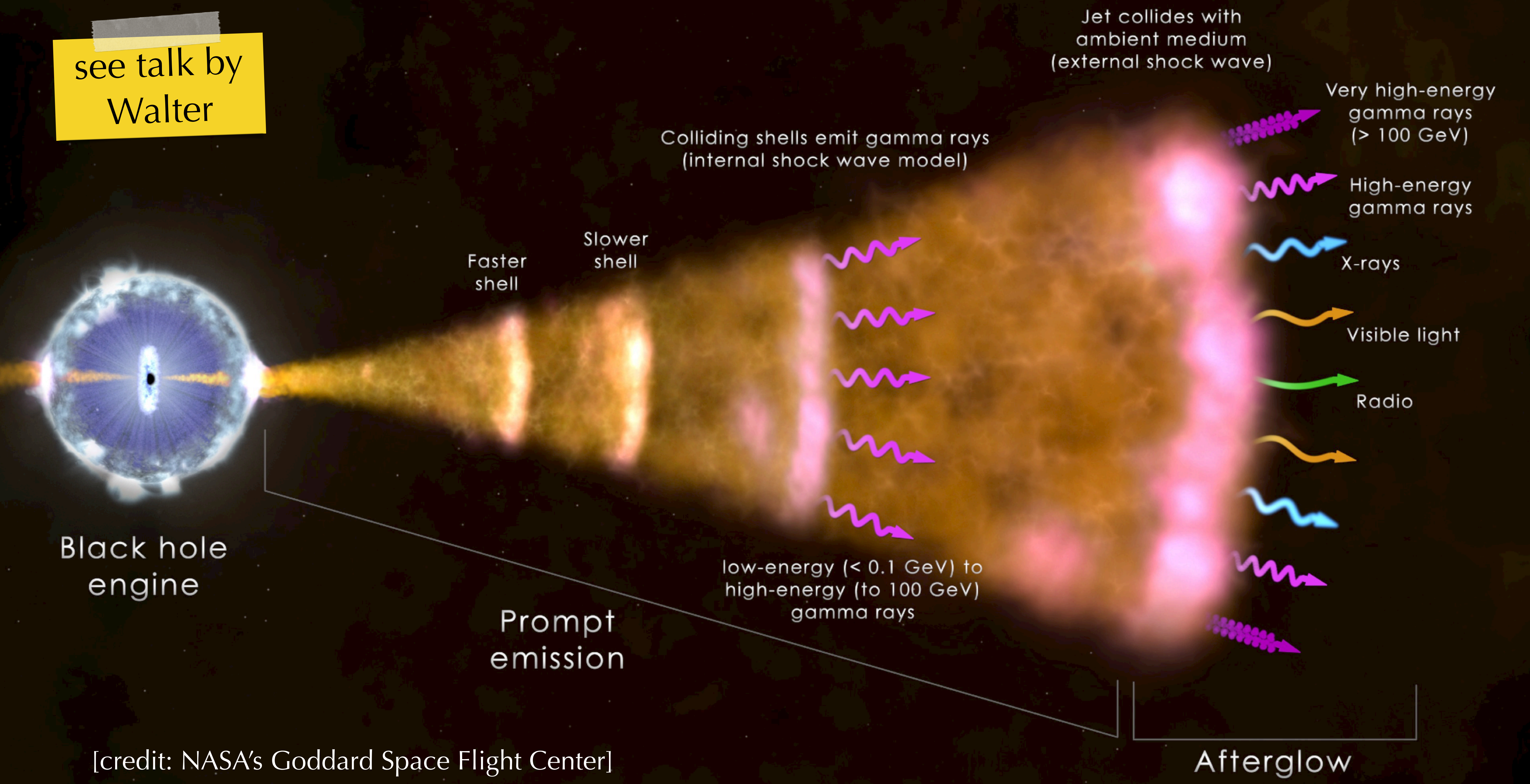


[Alves Batista *et al.*'19]

Gamma-Ray Bursts

High-energy neutrino emission is predicted by cosmic ray interactions with radiation at various stages of the GRB evolution.

see talk by Walter

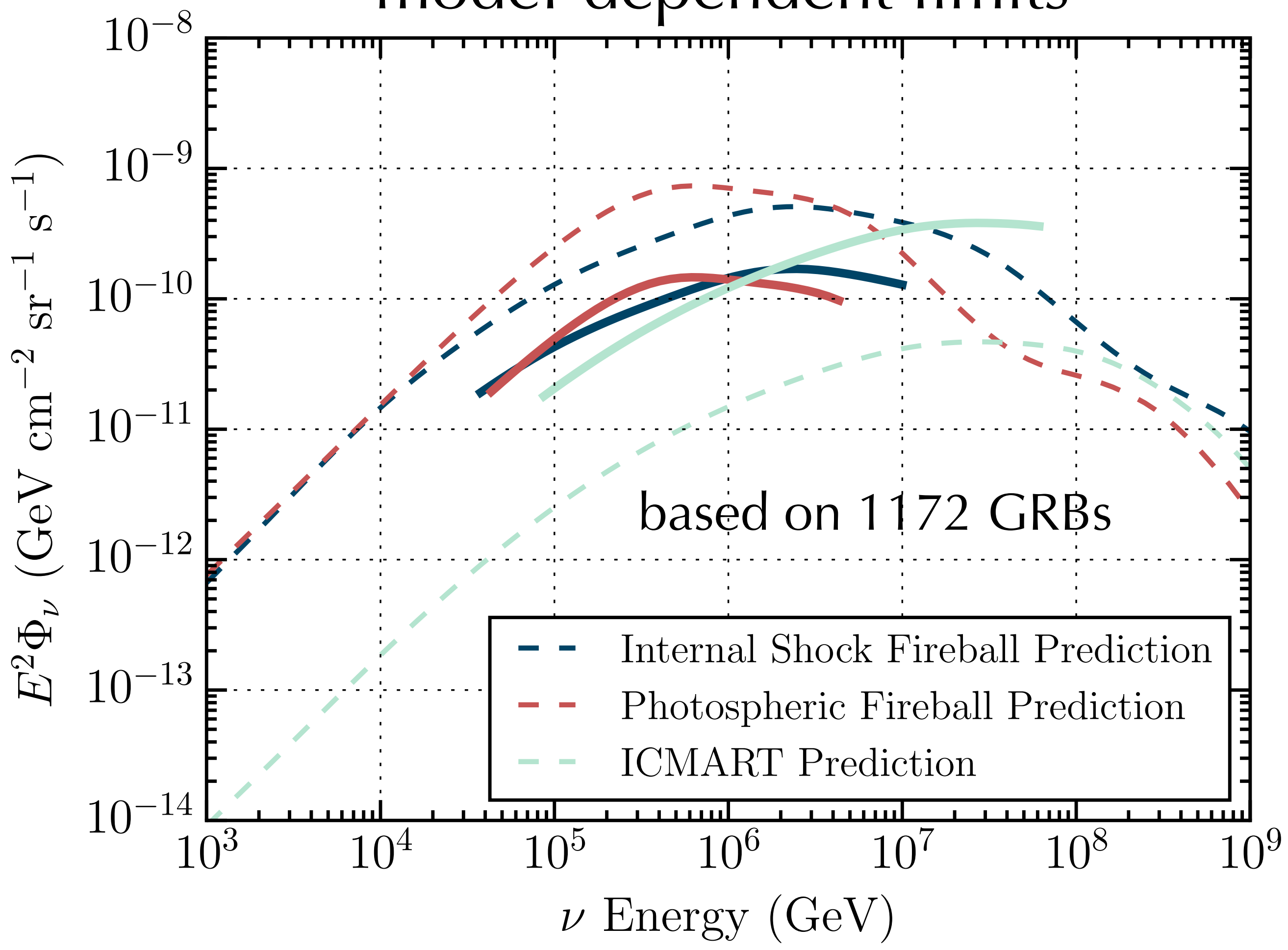


[credit: NASA's Goddard Space Flight Center]

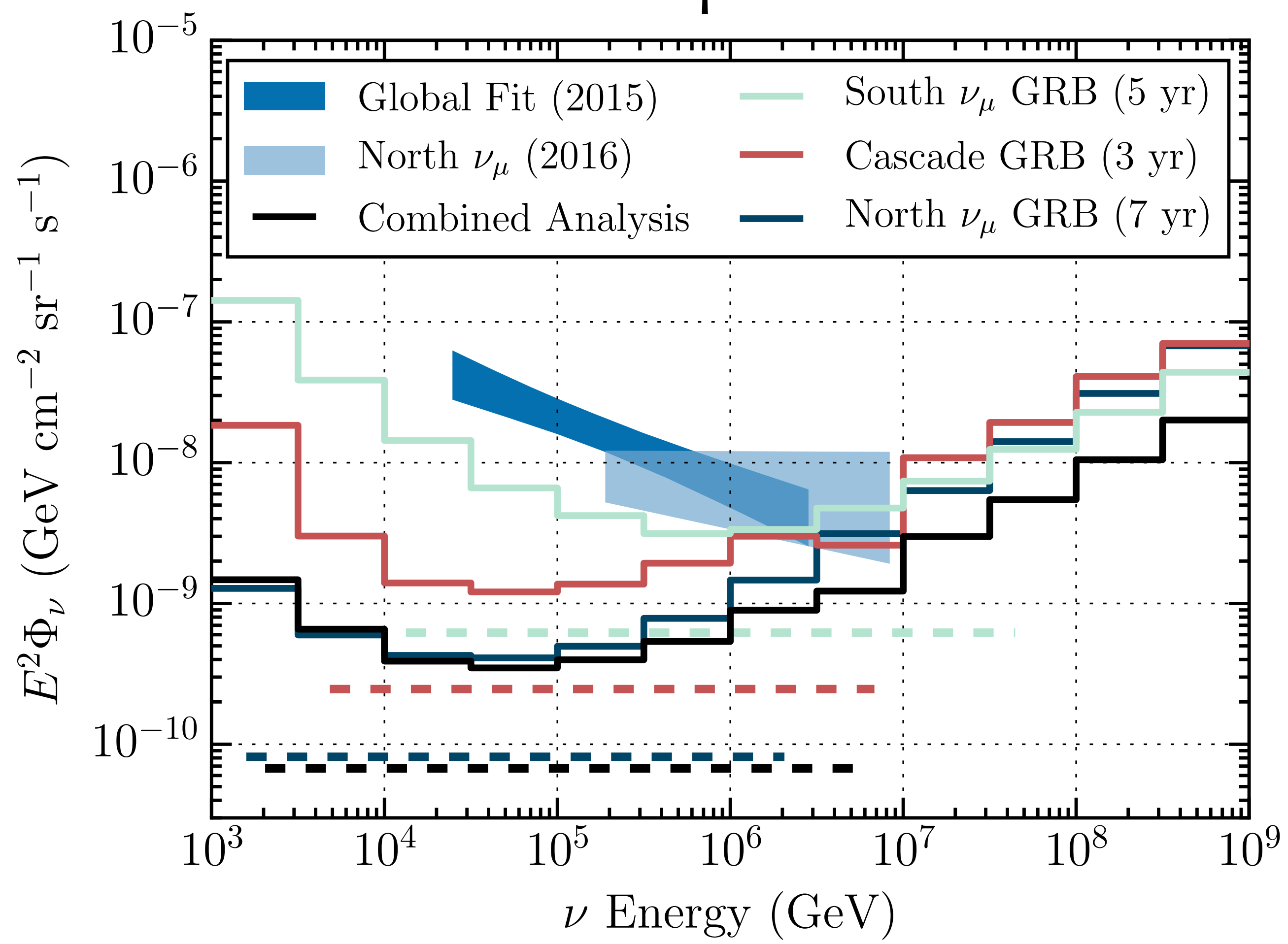
GRB Limits

- IceCube routinely follows up on γ-ray bursts. [IceCube, ApJ 843 (2017) 2]
- Search is most sensitive to "prompt" (<100s) neutrino emission.
- Neutrino predictions based on the assumption of **cosmic ray acceleration in internal shocks**. [Waxman & Bahcall '97]

model-dependent limits

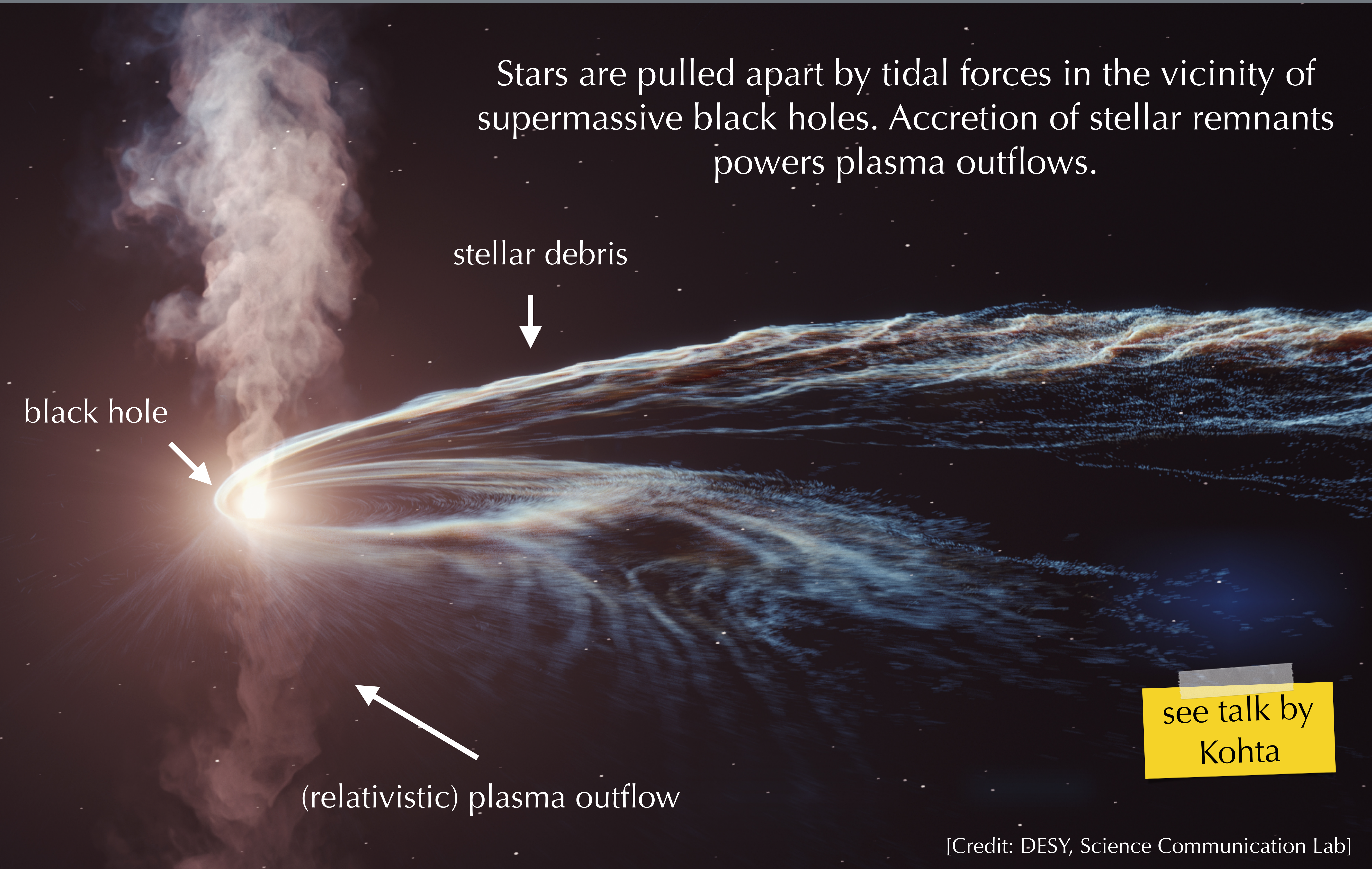


model-independent limits



Tidal Disruption Events

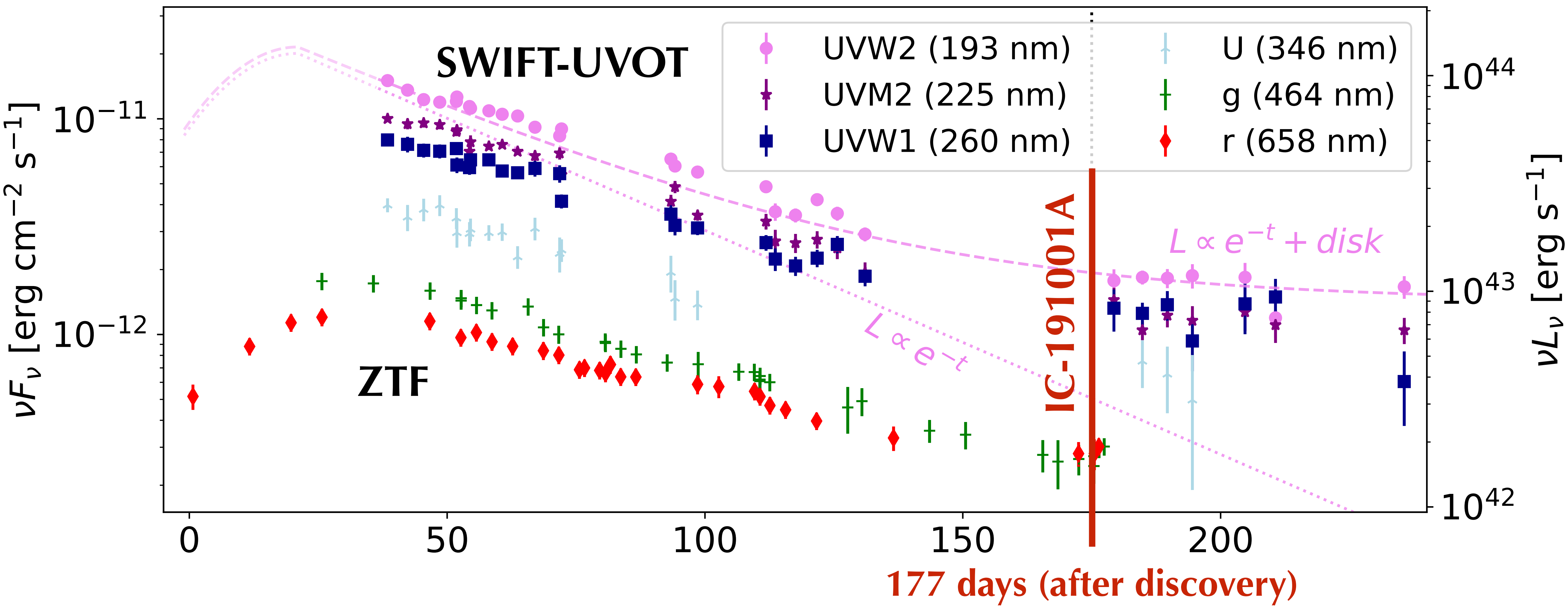
Stars are pulled apart by tidal forces in the vicinity of supermassive black holes. Accretion of stellar remnants powers plasma outflows.



see talk by Kohta

[Credit: DESY, Science Communication Lab]

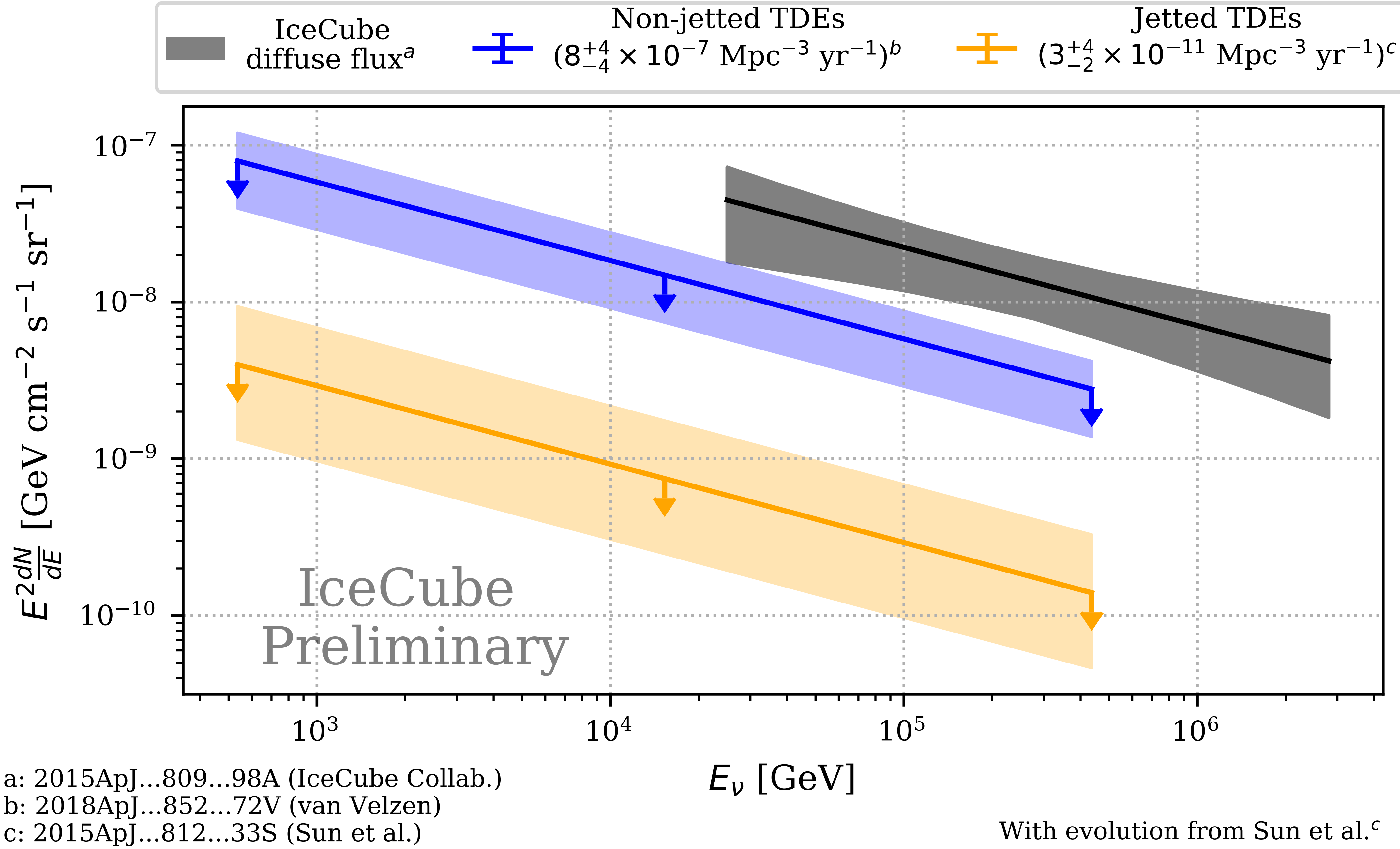
Tidal Disruption Events



[Stein et al. Nature Astronomy 5 (2021) 5]

- Association of alert IC-191001A with radio-emitting TDE AT2019dsg
- Plot shows data from Zwicky-Transient Facility and SWIFT-UVOT.
- Chance for random correlation of TDEs and IceCube alerts is 0.5%.

TDE Limits



[IceCube, PoS (ICRC2019) 1016]

Limits derived based on stacking of 3 jetted and 13 non-jetted TDEs.
Correspond to <1.3% and <26% of diffuse flux.

Summary

- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**
- So far, **no discovery** of point sources, but many **interesting candidates,** in particular, **TXS 0506+056** and **NGC 1068.**
- Intensity of cosmic neutrinos is comparable to that of ultra-high energy cosmic-rays (*Auger/TA*) and γ-rays (*Fermi-LAT*), expected from the **multi-messenger paradigm**.
- Essential for future discoveries are **multi-messenger partners** facilitating low-latency studies.
- In parallel, development of **neutrino telescopes for the next decade** with complementary FoV and/or increased sensitivity and energy coverage.

  (Baikal-GVD, KM3NeT, P-ONE, RNO-G, IceCube-Gen2, ARA, ARIANNA, GRAND,…)

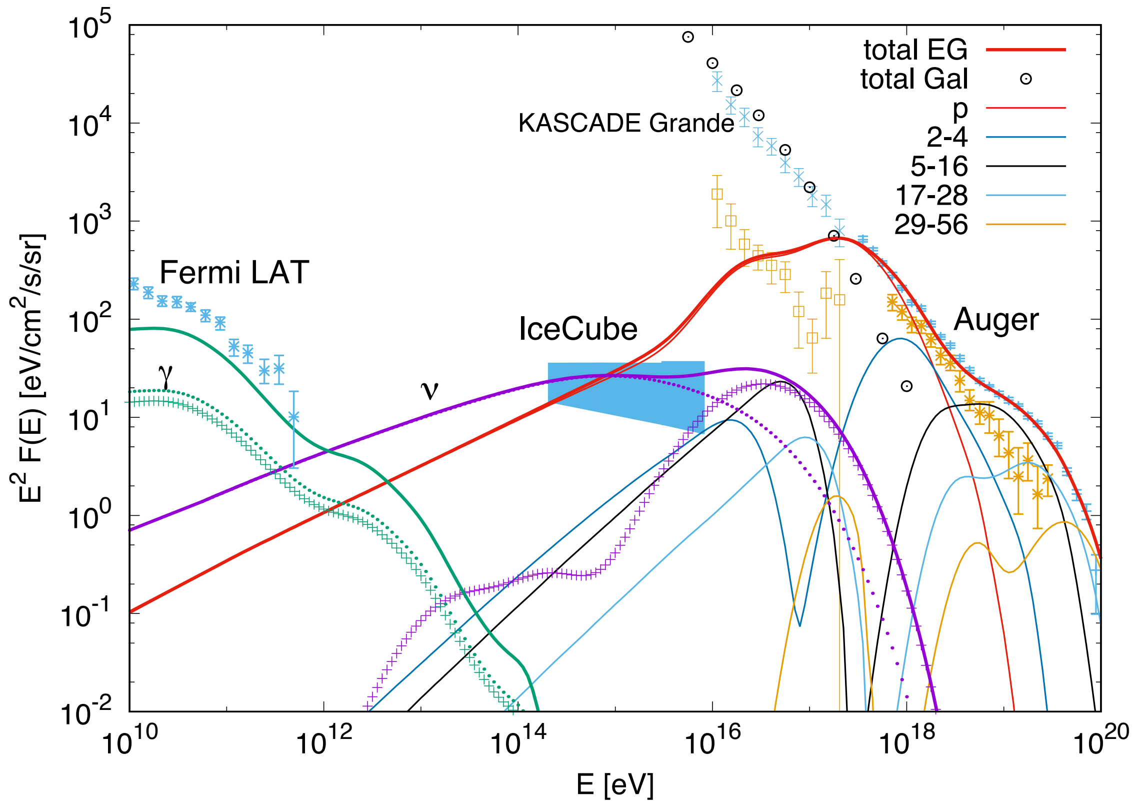
Backup Slides

Cosmic Ray Calorimeters

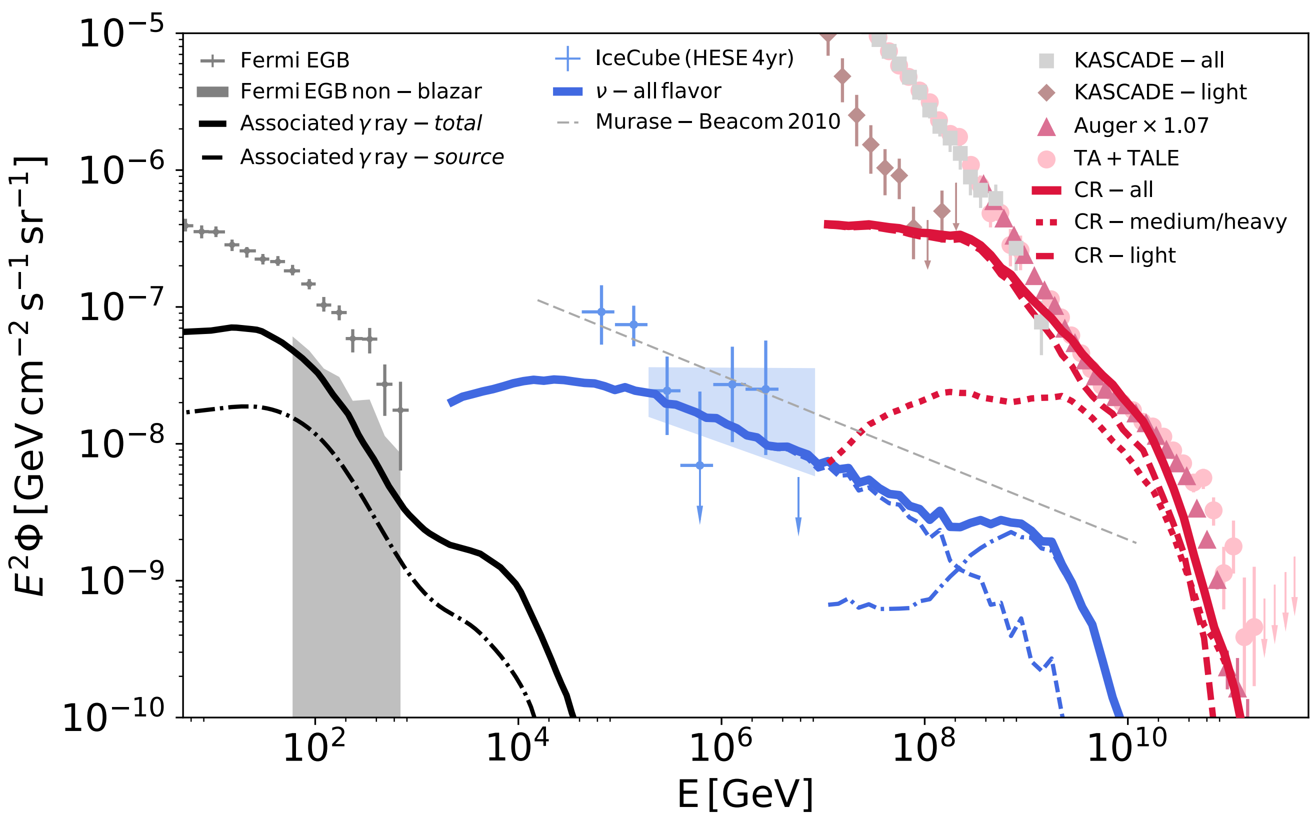
- Competing requirements for efficient CR acceleration and subsequent interaction can be accommodated in **multi-zone models**.
- Magnetic confinement in CR calorimeters, such as **starburst galaxies**, could provide a unified origin of UHE CRs and TeV–PeV neutrinos.

[Loeb & Waxman '06]

- "*Grand Unification*" of UHE CRs, γ-rays and neutrinos?

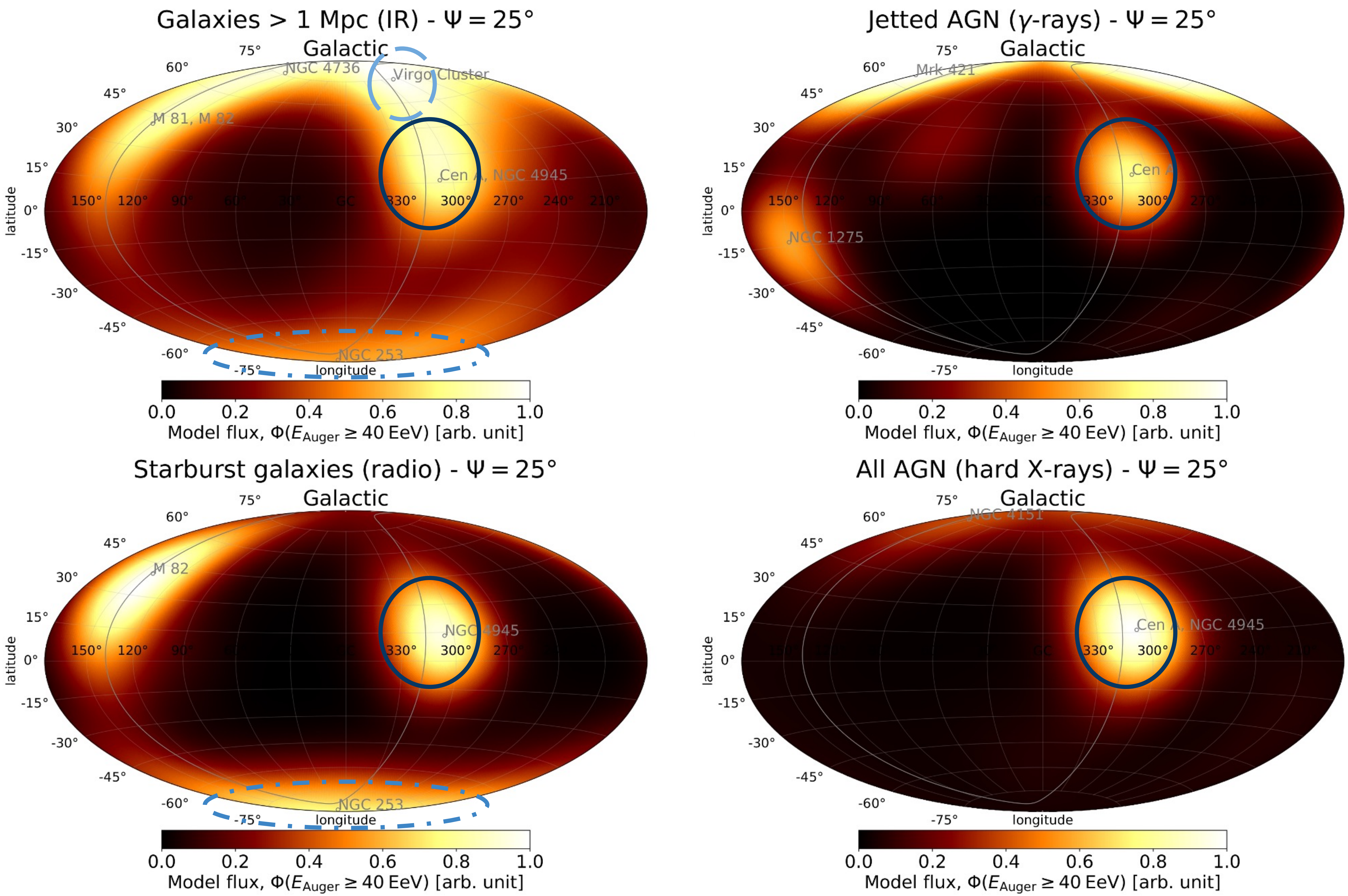


[Kachelriess, Kalashev, Ostapchenko & Semikoz'17]

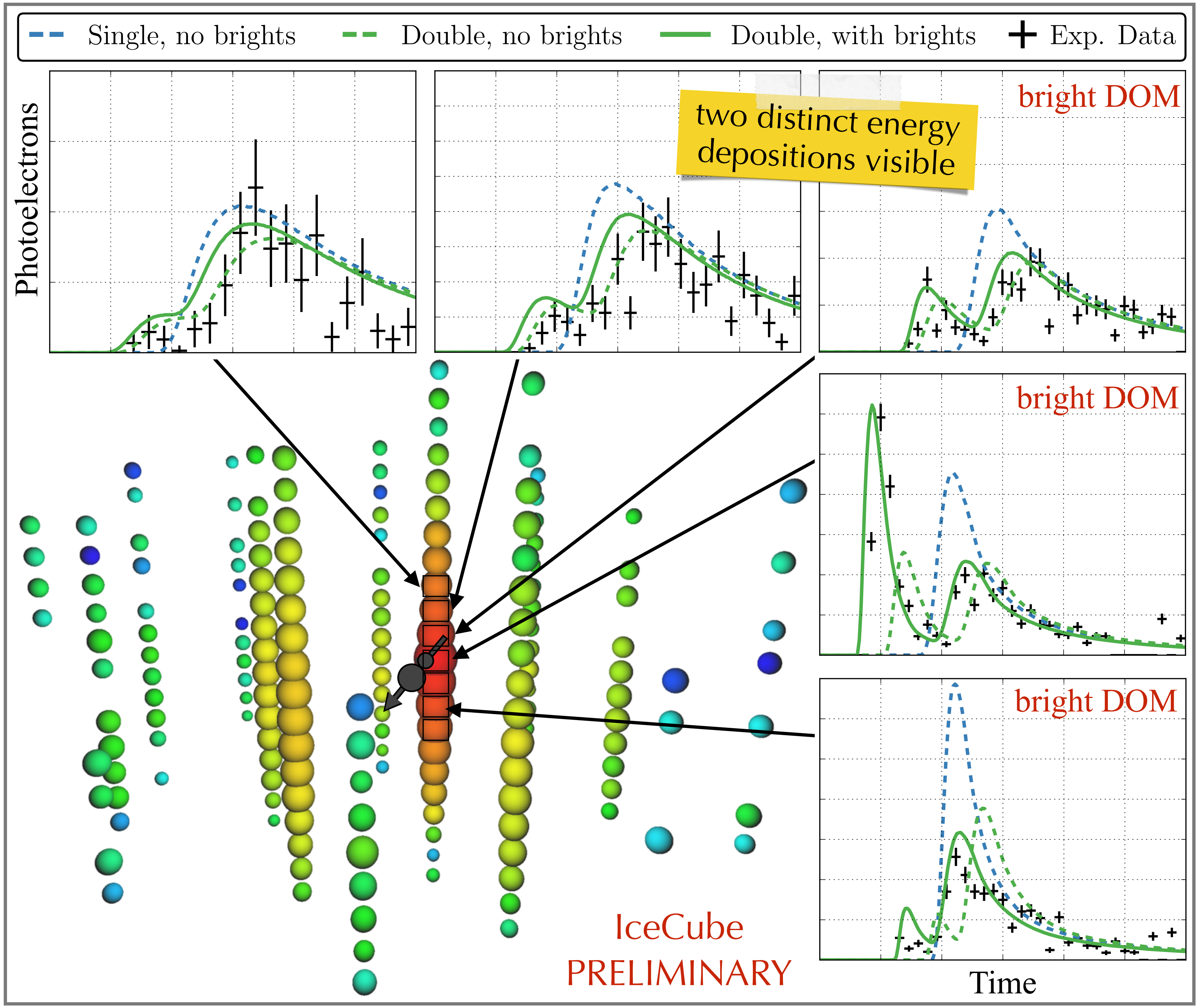


[Fang & Murase'17]

UHE CR Anisotropy



[Auger Collaboration'22]



[IceCube, arXiv:2011.03561]

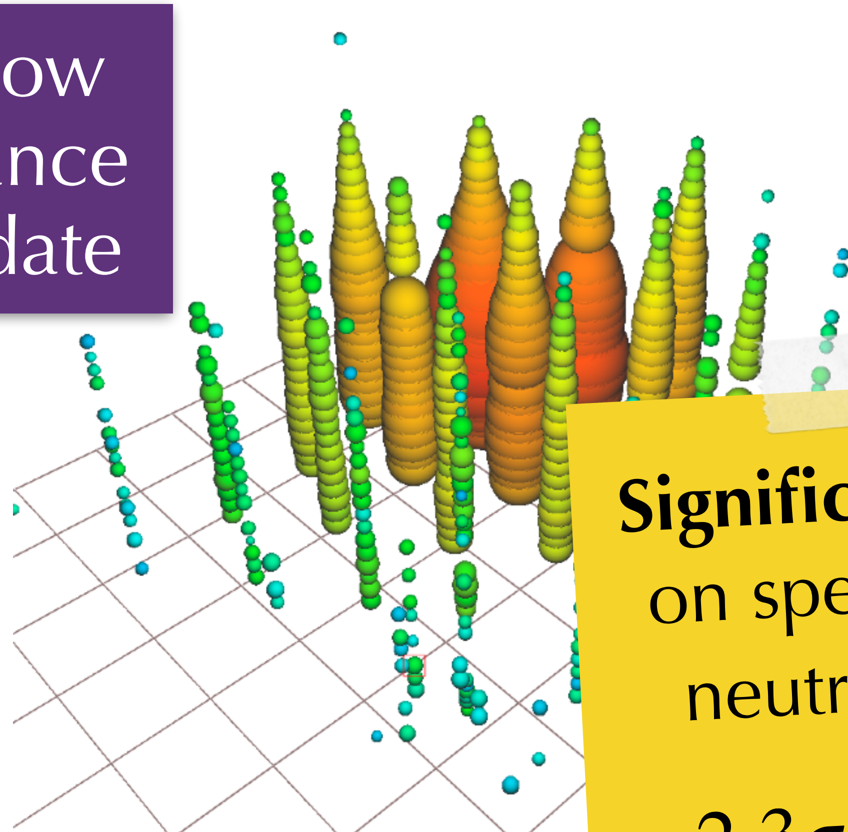
tau neutrino candidate

ICECUBE

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

Astrophysical Flavours

Glashow resonance candidate



Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

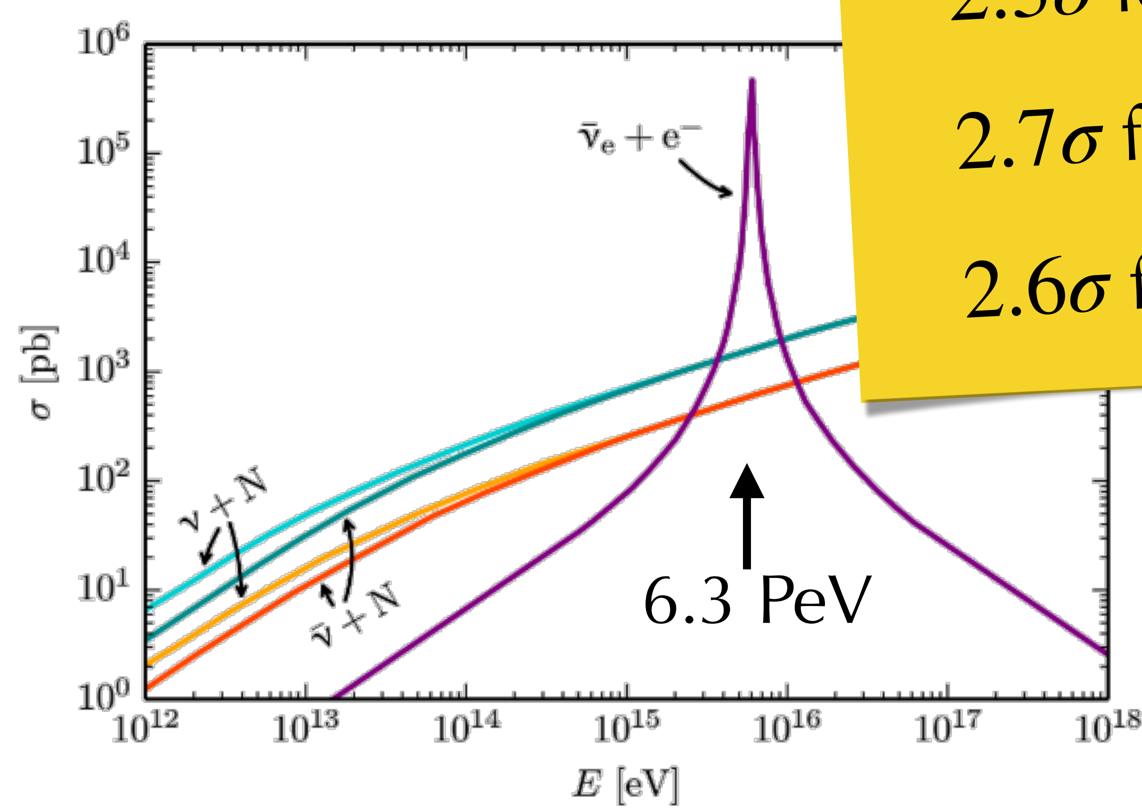
$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$

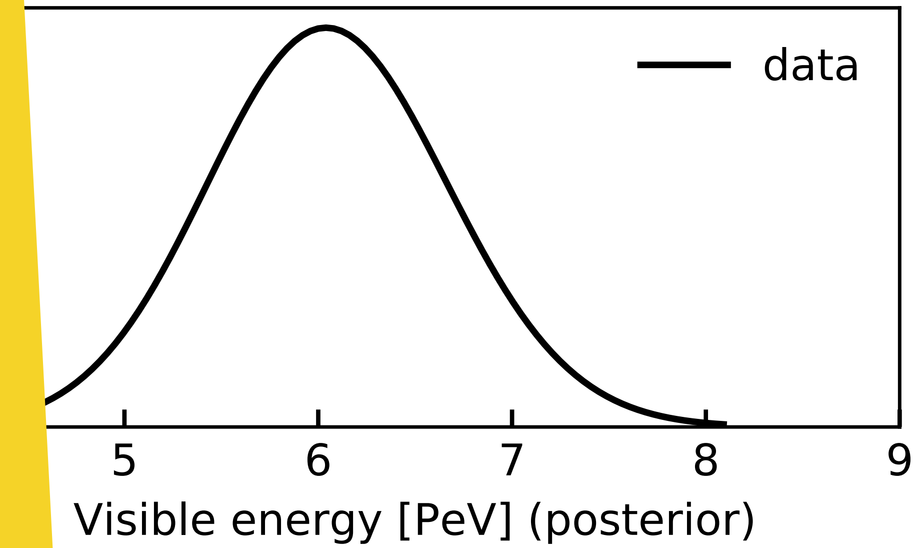
Significance depends on spectral index of neutrino flux: $E^{-\gamma}$

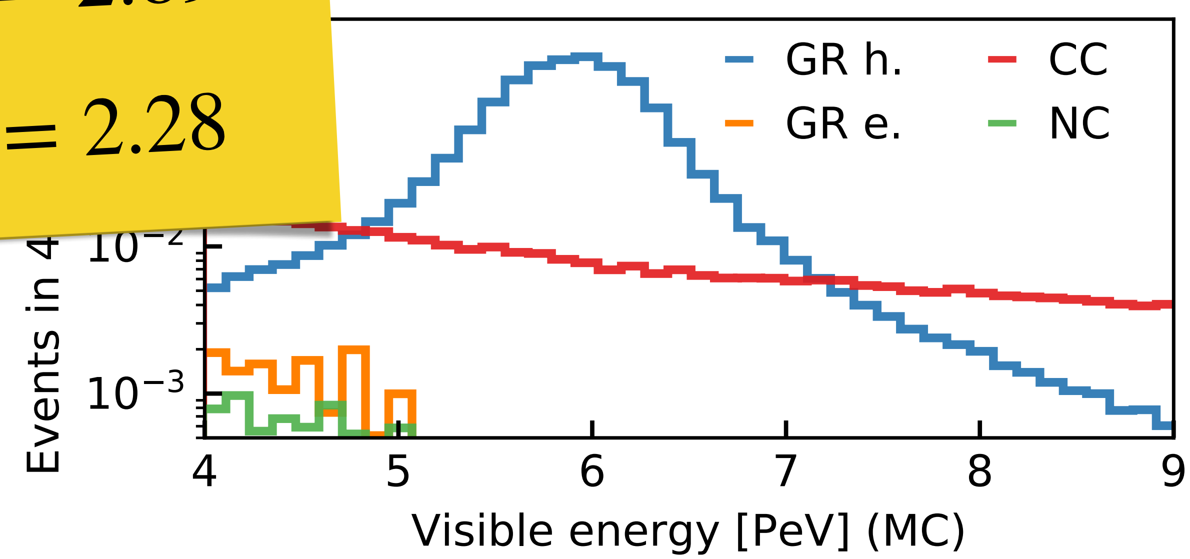
2.3σ for $\gamma = 2.49$

2.7σ for $\gamma = 2.89$

2.6σ for $\gamma = 2.28$

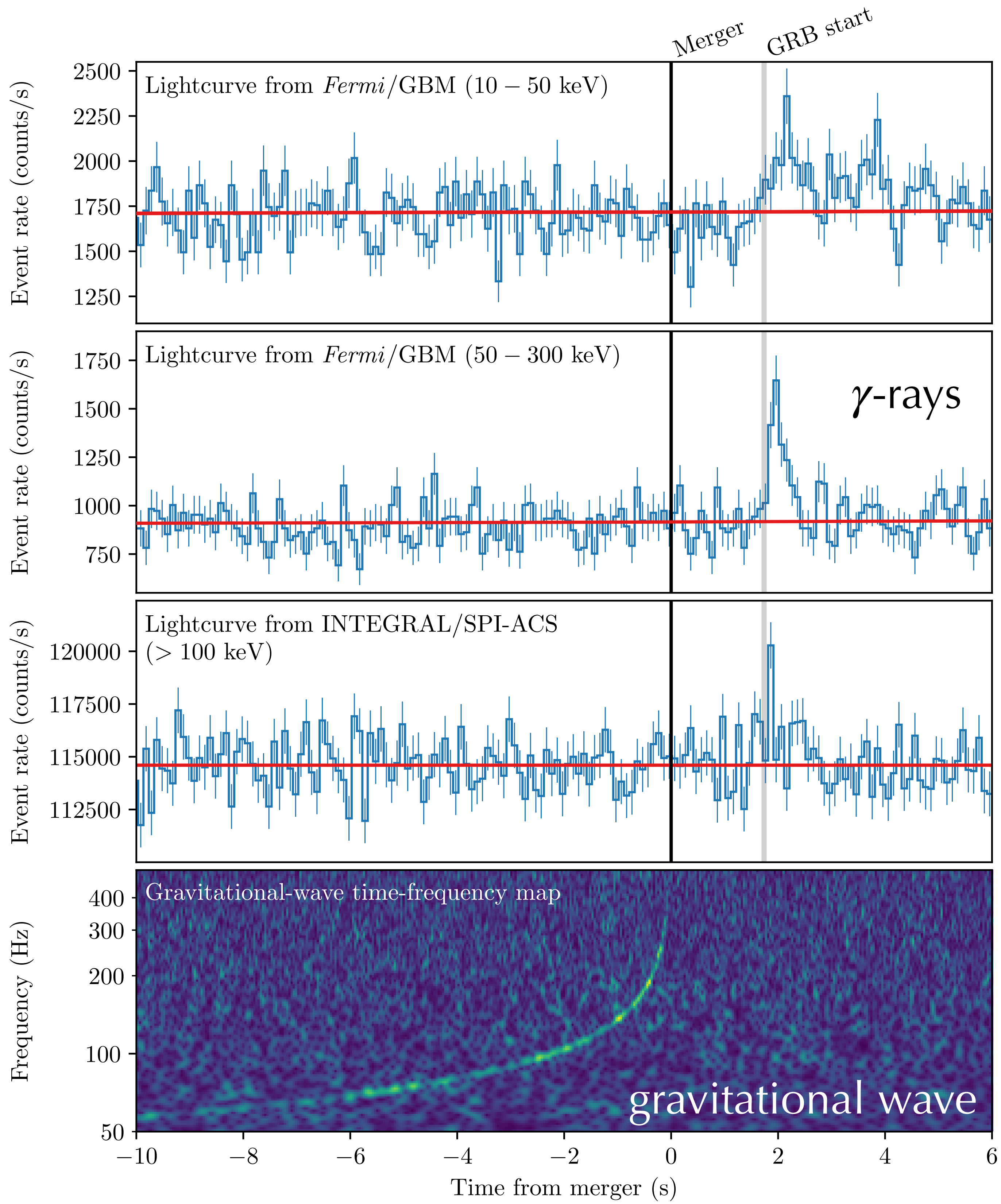




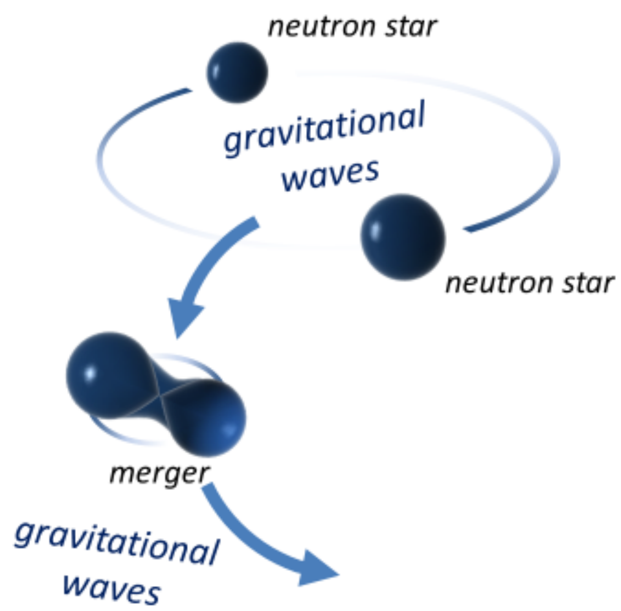


[IceCube, Nature 591 (2021) 220-224]

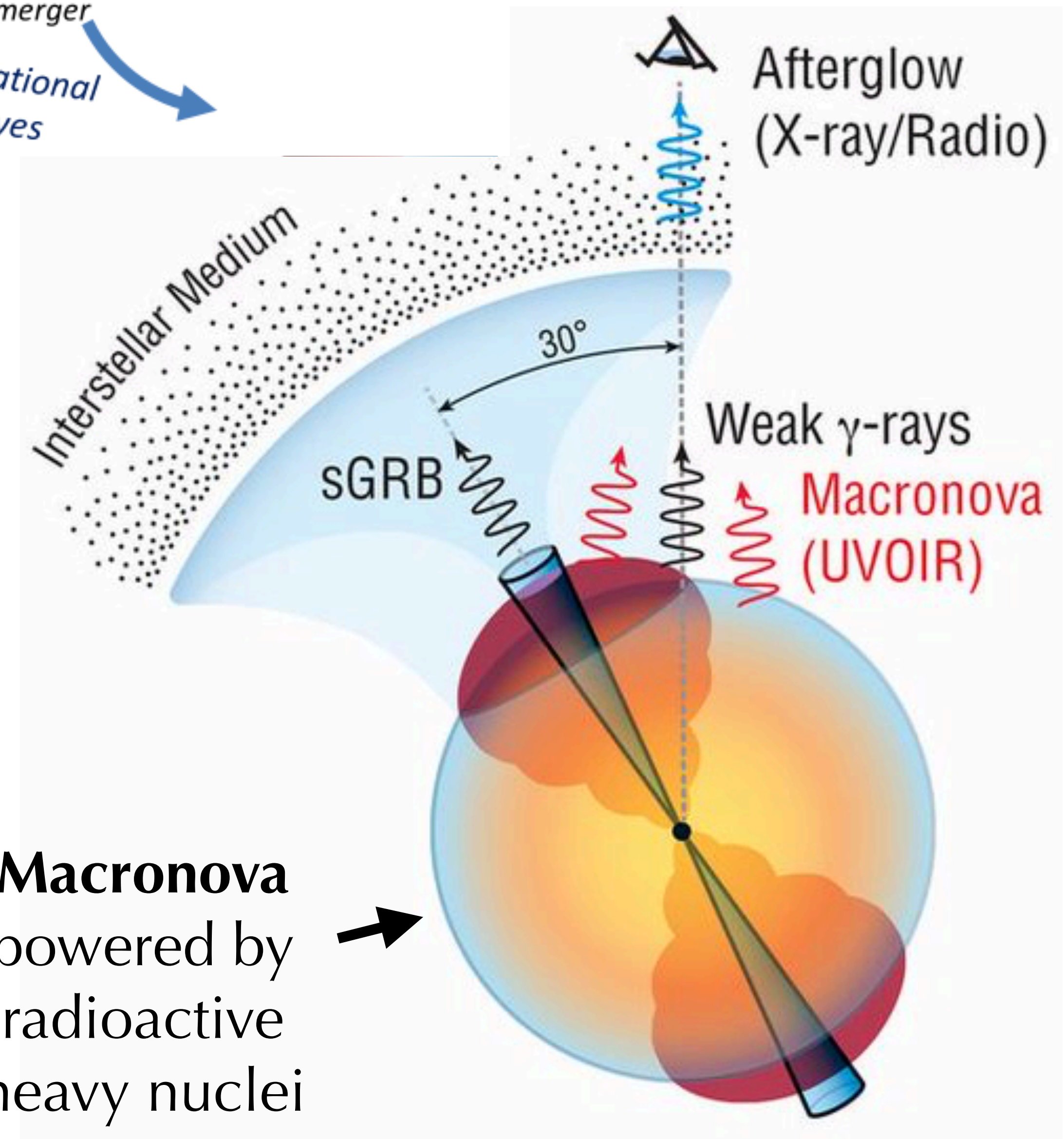
GRBs and Gravitational Waves



[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]

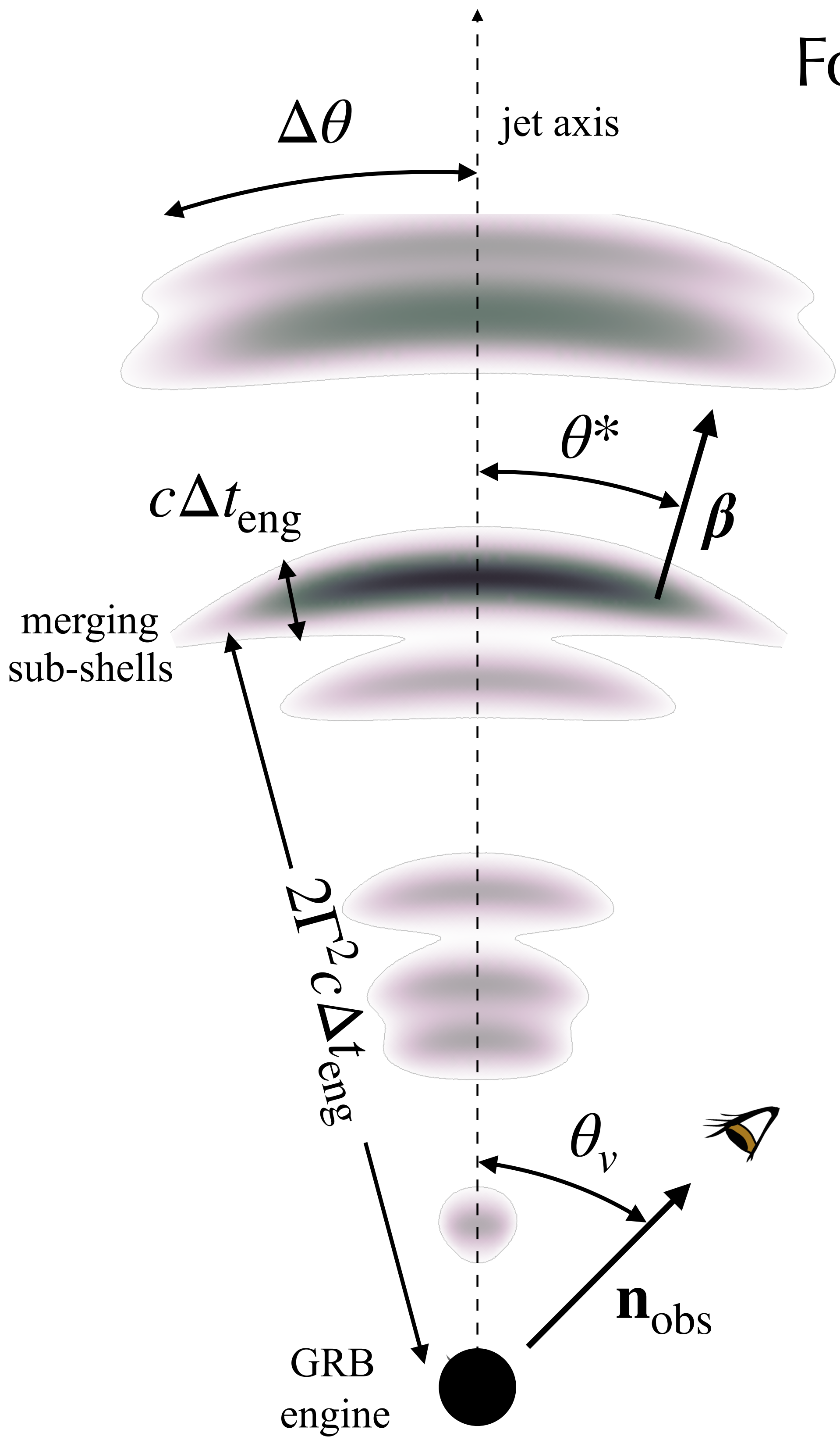


GW 170817
&
GRB 170817A

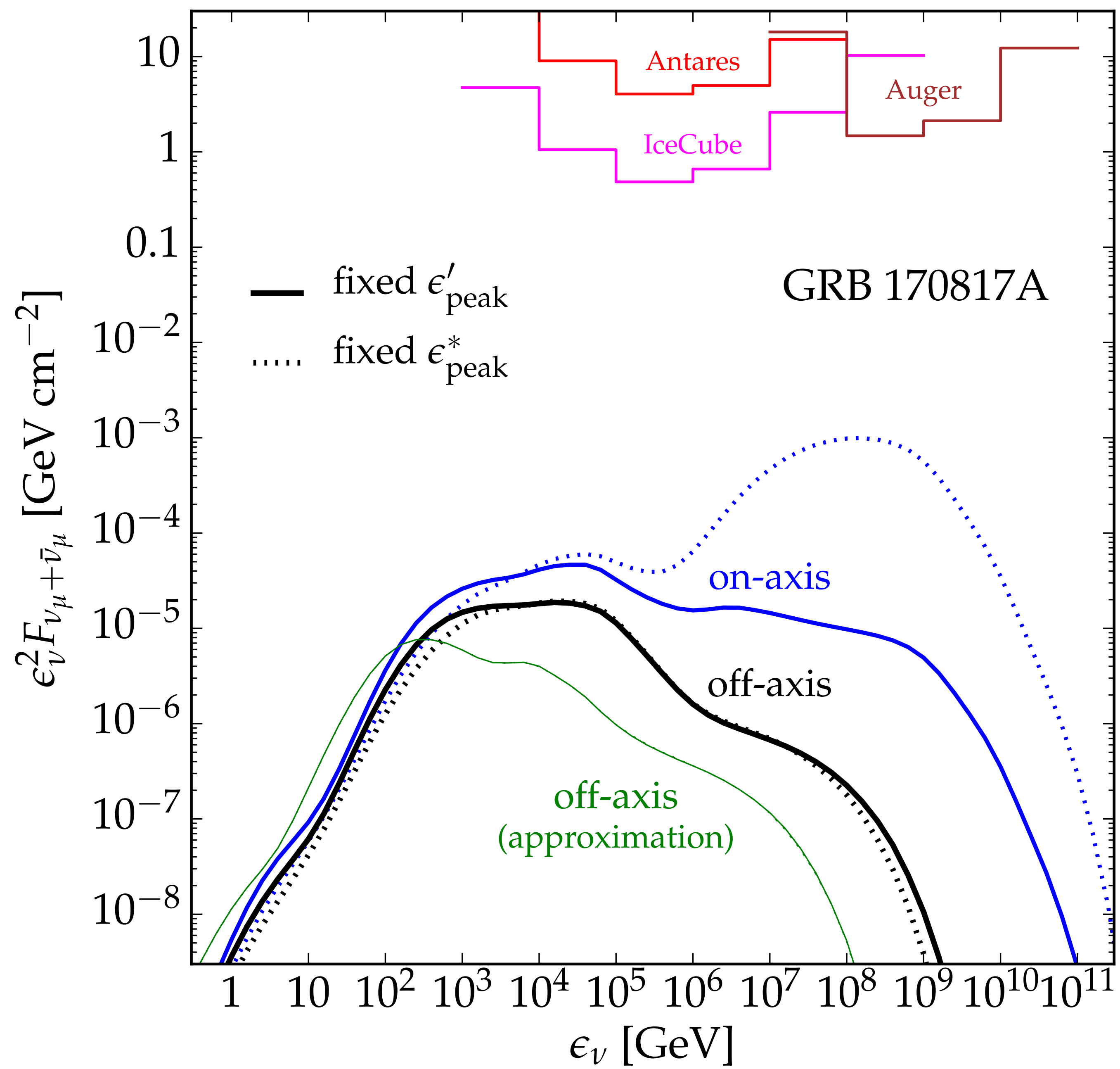


Macronova powered by radioactive heavy nuclei

GRB 170817A - Revisited

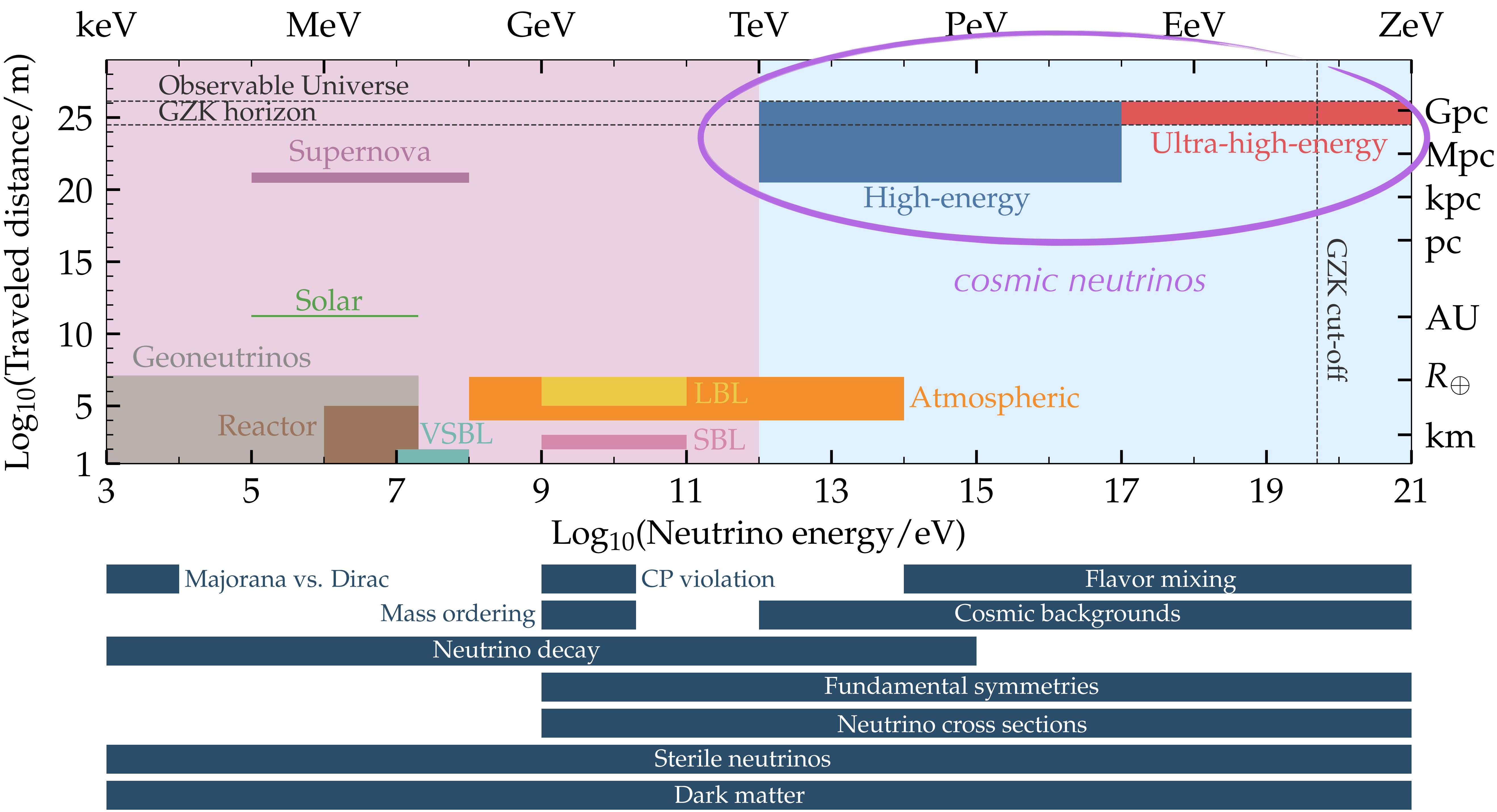


Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



[MA & Halser MNRAS 490 (2019) 4]

Probe of Fundamental Physics



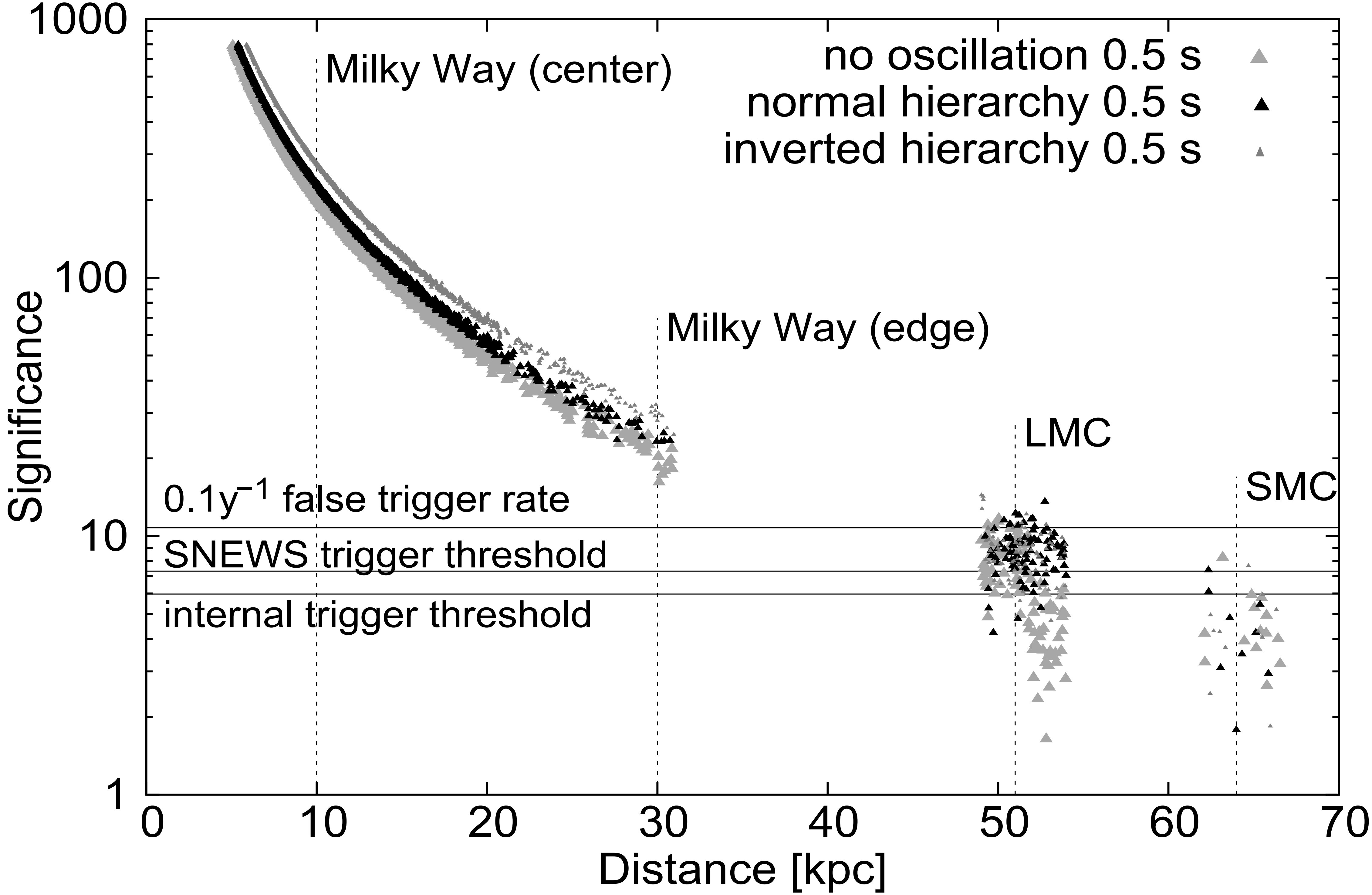
[Ackermann, MA, Anchordoqui, Bustamante *et al., Astro2020* arXiv:1903.04334]

Supernova Forecast

From K. Scholberg, J. Phys G 45:2017

Detector	Type	Mass (kt)	Location	Events [10 kpc]
IceCube	**long string**	**600**	**South Pole**	**1,000,000**
*Hyper-K**	*H_2O*	*374*	*Japan*	*75,000*
*DUNE**	*Ar*	*40*	*USA*	*3,000*
Super-K	H_2O	32	Japan	7,000
*JUNO**	*C_nH_{2n}*	*20*	*China*	*6,000*
NOvA	C_nH_{2n}	15	USA	4,000
LVD	C_nH_{2n}	1	Italy	300
KamLAND	C_nH_{2n}	1	Japan	300
SNO+	C_nH_{2n}	0.8	Canada	300
Baksan	C_nH_{2n}	0.33	Russia	50
Daya Bay	C_nH_{2n}	0.33	China	100
Borexino	C_nH_{2n}	0.3	Italy	100
MicroBooNE	Ar	0.17	USA	17
HALO	Pb	0.08	Canada	30

Supernova Neutrino Detection



Supernova Neutrino Detection

Reaction	# Targets	# Signal Hits	Signal Fraction	Reference
$\bar{\nu}_e + p \to e^+ + n$	$6 \cdot 10^{37}$	134 k (157 k)	93.8 % (94.4 %)	Strumia & Vissani (2003)
$\nu_e + e^- \to \nu_e + e^-$	$3 \cdot 10^{38}$	2.35 k (2.25 k)	1.7 % (1.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$3 \cdot 10^{38}$	660 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\nu_{\mu+\tau} + e^- \to \nu_{\mu+\tau} + e^-$	$3 \cdot 10^{38}$	700 (720)	0.5 % (0.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_{\mu+\tau} + e^- \to \bar{\nu}_{\nu+\tau} + e^-$	$3 \cdot 10^{38}$	600 (570)	0.4 % (0.4 %)	Marciano & Parsa (2003)
$\nu_e + {}^{16}O \to e^- + X$	$3 \cdot 10^{37}$	2.15 k (1.50 k)	1.5 % (0.9 %)	Kolbe et al. (2002)
$\bar{\nu}_e + {}^{16}O \to e^+ + X$	$3 \cdot 10^{37}$	1.90 k (2.80 k)	1.3 % (1.7 %)	Kolbe et al. (2002)
$\nu_{all} + {}^{16}O \to \nu_{all} + X$	$3 \cdot 10^{37}$	430 (410)	0.3 % (0.3 %)	Kolbe et al. (2002)
$\nu_e + {}^{17/18}O/{}^2_1H \to e^- + X$	$6 \cdot 10^{34}$	270 (245)	0.2 % (0.2 %)	Haxton (1999)

Notes. The approximate number of targets in a 1 km^3 ice detector, the detected number of hits at 10 kpc distance and their fraction in stars are given in the second, third and fourth column, respectively. In order to indicate the effect of neutrino oscillations in the star, signal hits and fractions are presented both assuming a normal neutrino hierarchy (Scenario A) and - in brackets - assuming an inverted hierarchy (Scenario B). The numbers are taken from the Garching model using the equation of state by Lattimer & Swesty (1991) and averaging over 0.8 s.

Model	Reference	Progenitor mass ($M_\odot$)	$\#\nu$'s $t < 380$ ms	$\#\nu$'s all times
"Livermore"	(Totani et al., 1997)	20	0.174×10^6	0.79×10^6
"Garching LS-EOS 1d"	(Kitaura et al., 2006)	8 – 10	0.069×10^6	-
"Garching WH-EOS 1d"	(Kitaura et al., 2006)	8 – 10	0.078×10^6	-
"Garching SASI 2d"	(Marek et al., 2009)	15	0.106×10^6	-
"1987A at 10 kpc"	(Pagliaroli et al., 2009b)	15 – 20		$(0.57 \pm 0.18) \times 10^6$
"O-Ne-Mg 1d"	(Hüdepohl et al., 2010)	8.8	0.054×10^6	0.17×10^6
"Quark Star (full opacities)"	(Dasgupta et al., 2010)	10	0.067×10^6	-
"Black Hole LS-EOS"	(Sumiyoshi et al., 2007)	40	0.395×10^6	1.03×10^6
"Black Hole SH-EOS"	(Sumiyoshi et al., 2007)	40	0.335×10^6	3.40×10^6

Notes. Number of recorded DOM hits in IceCube ($\approx \#\nu$'s) for various models of the supernova collapse and progenitor masses assuming a distance of 10 kpc, approximately corresponding to the center of our Galaxy. A normal neutrino hierarchy is assumed.

Supernovae in IceCube

Inverse β-decay

$$\bar{\nu}_e + p \to e^+ + n$$

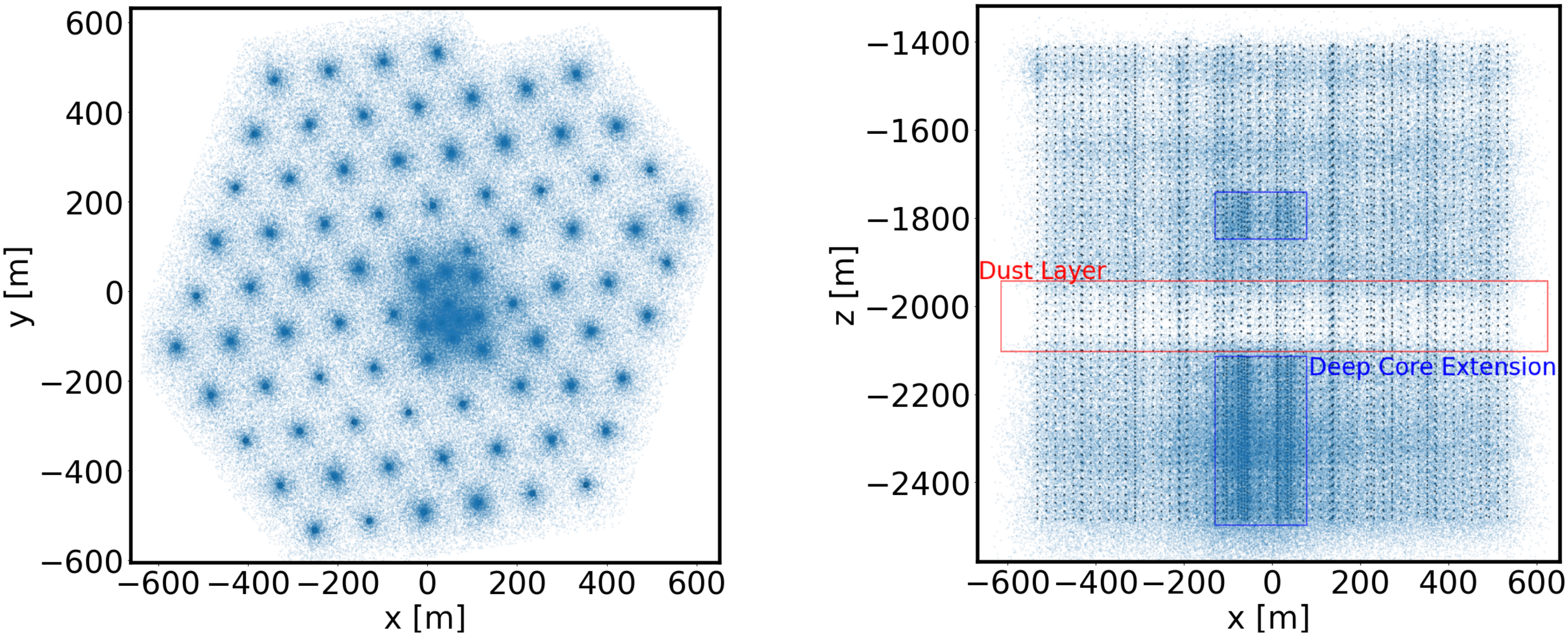
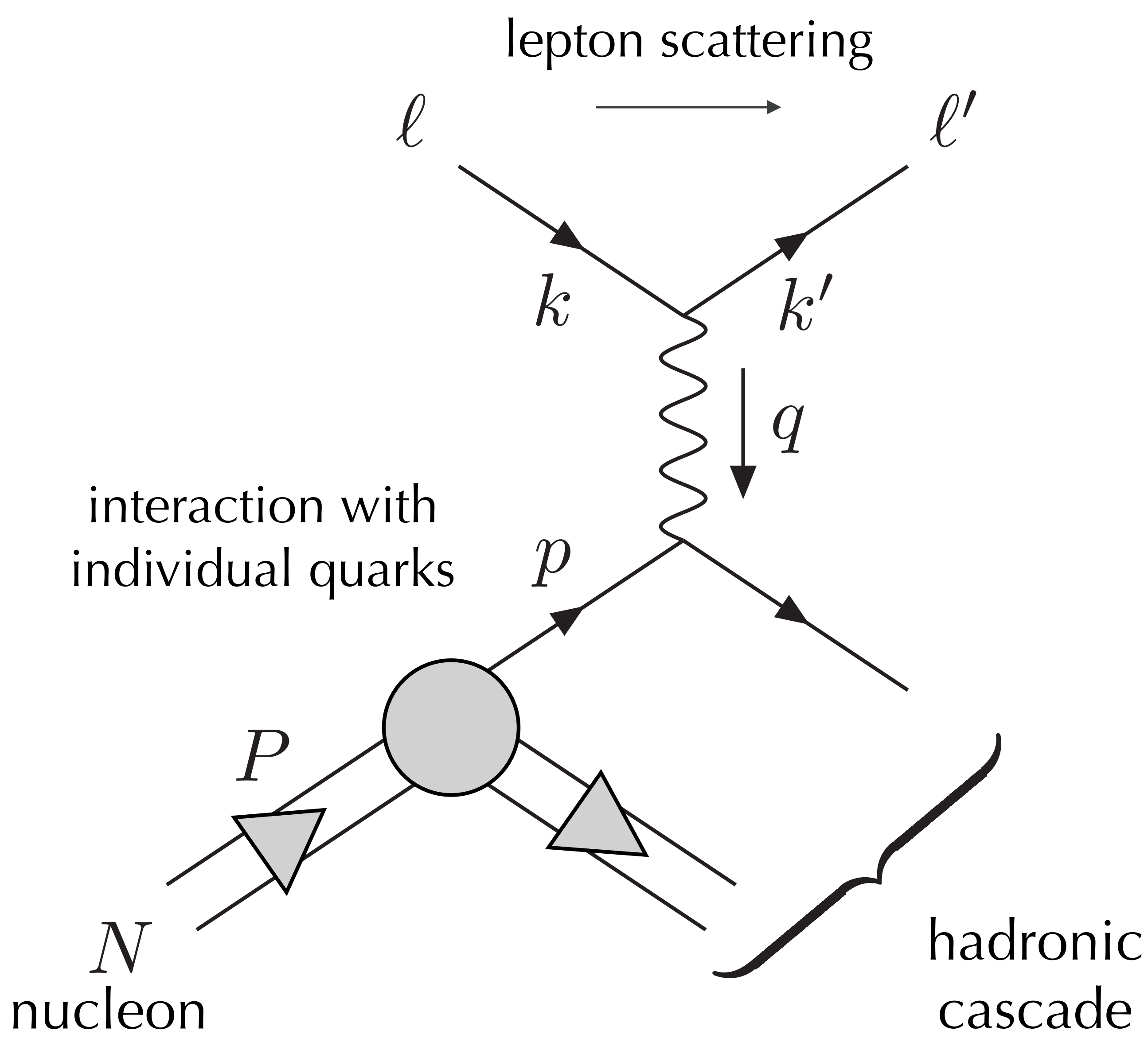


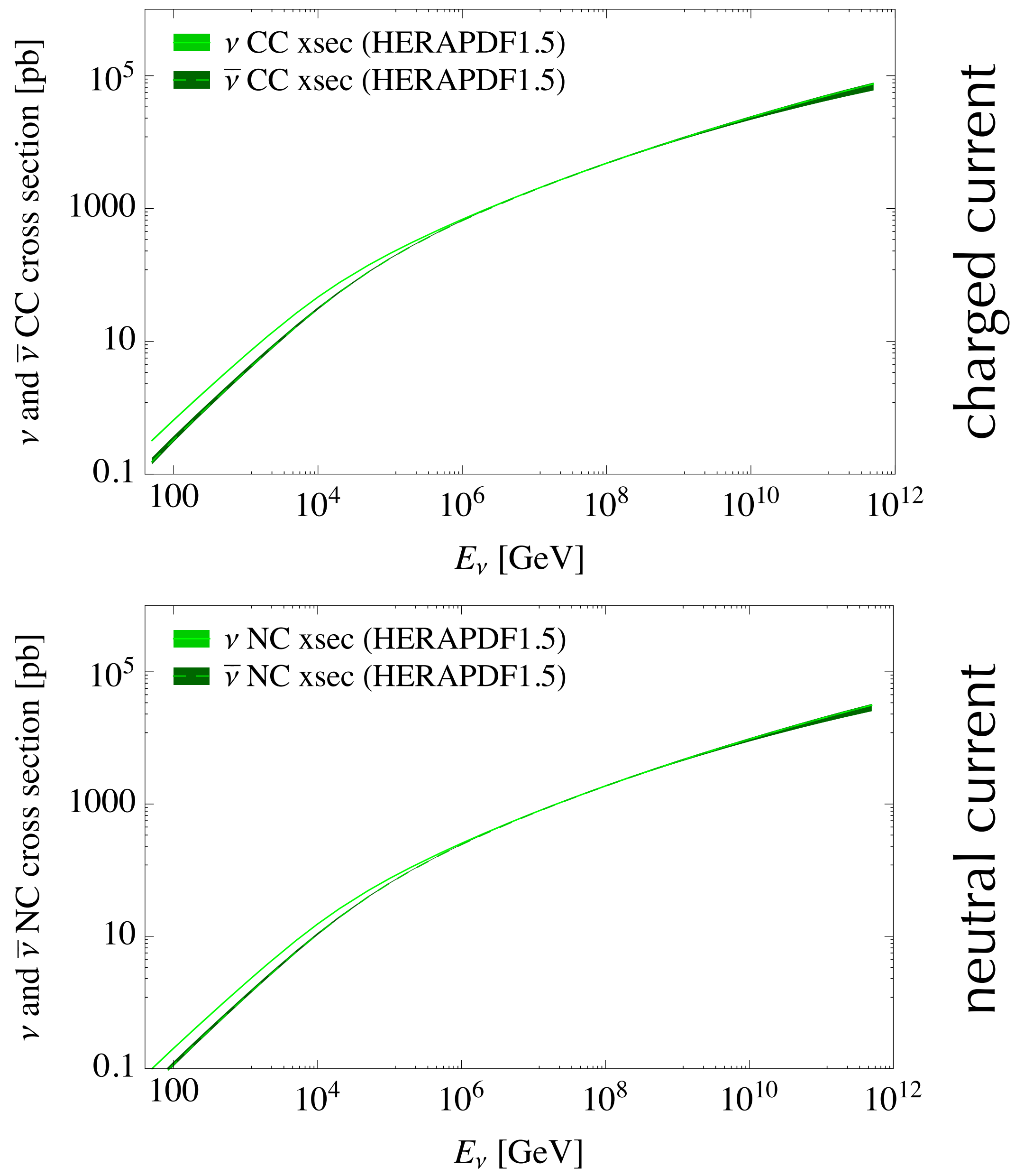
Figure 1: Top and side view of $\sim 3.4 \times 10^5$ simulated supernova ν interaction vertices registered by IceCube DOMs. The dust layer between -1950 m and -2050 m and the denser DeepCore subarray are clearly visible.

[IceCube, PoS (ICRC2019) 1177]

Neutrino Interactions

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





[Cooper-Sarkar, Mertsch & Sarkar'11]

Detector Requirements

Neutrino **charged and neutral current (CC & NC) interactions** are visible by Cherenkov emission of relativistic secondaries in transparent media.

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

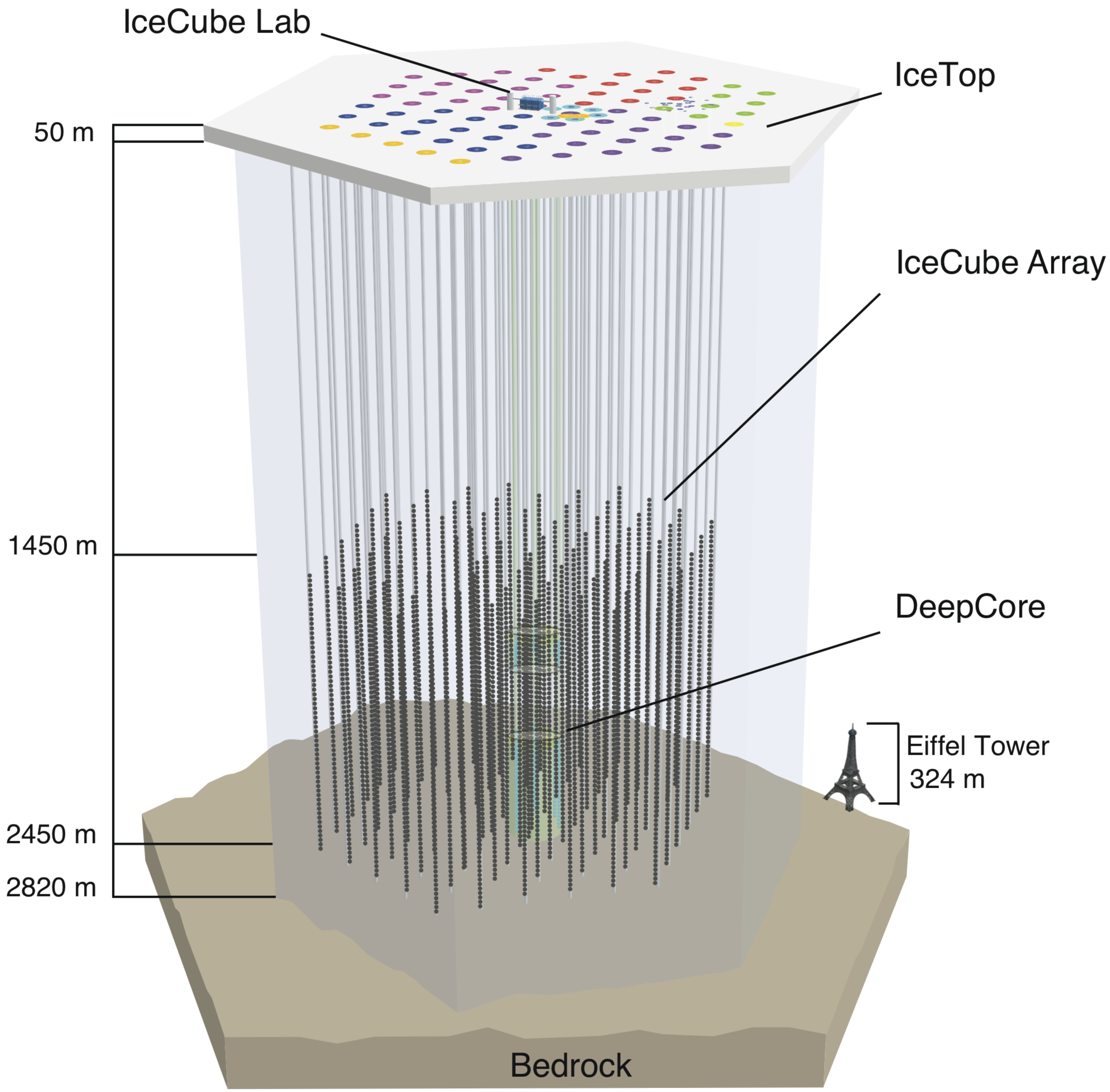
- **flux of neutrinos** : $$\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5\mathrm{yr}}$$
- **cross section** : $$\sigma_{\nu N} \sim 10^{-8}\sigma_{pp} \sim 10^{-33}\mathrm{cm}^2$$
- **targets**: $$N_N \sim N_A \times V/\mathrm{cm}^3$$

→ **rate of events** :

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

minimum detector size: 1km³

IceCube Observatory

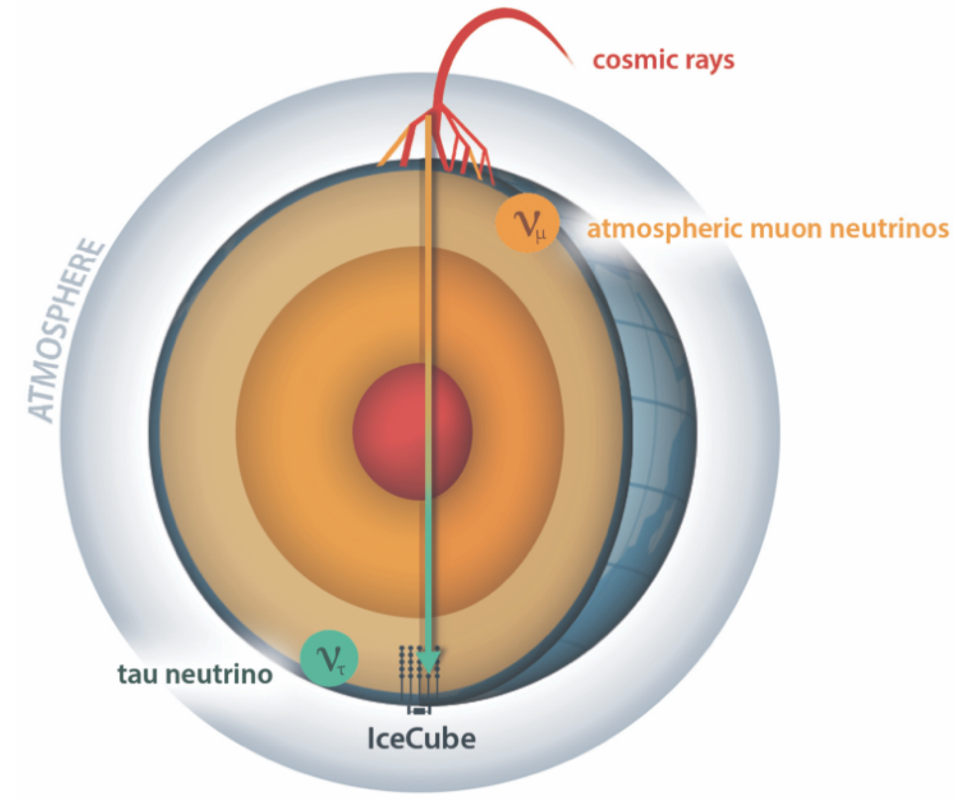


- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

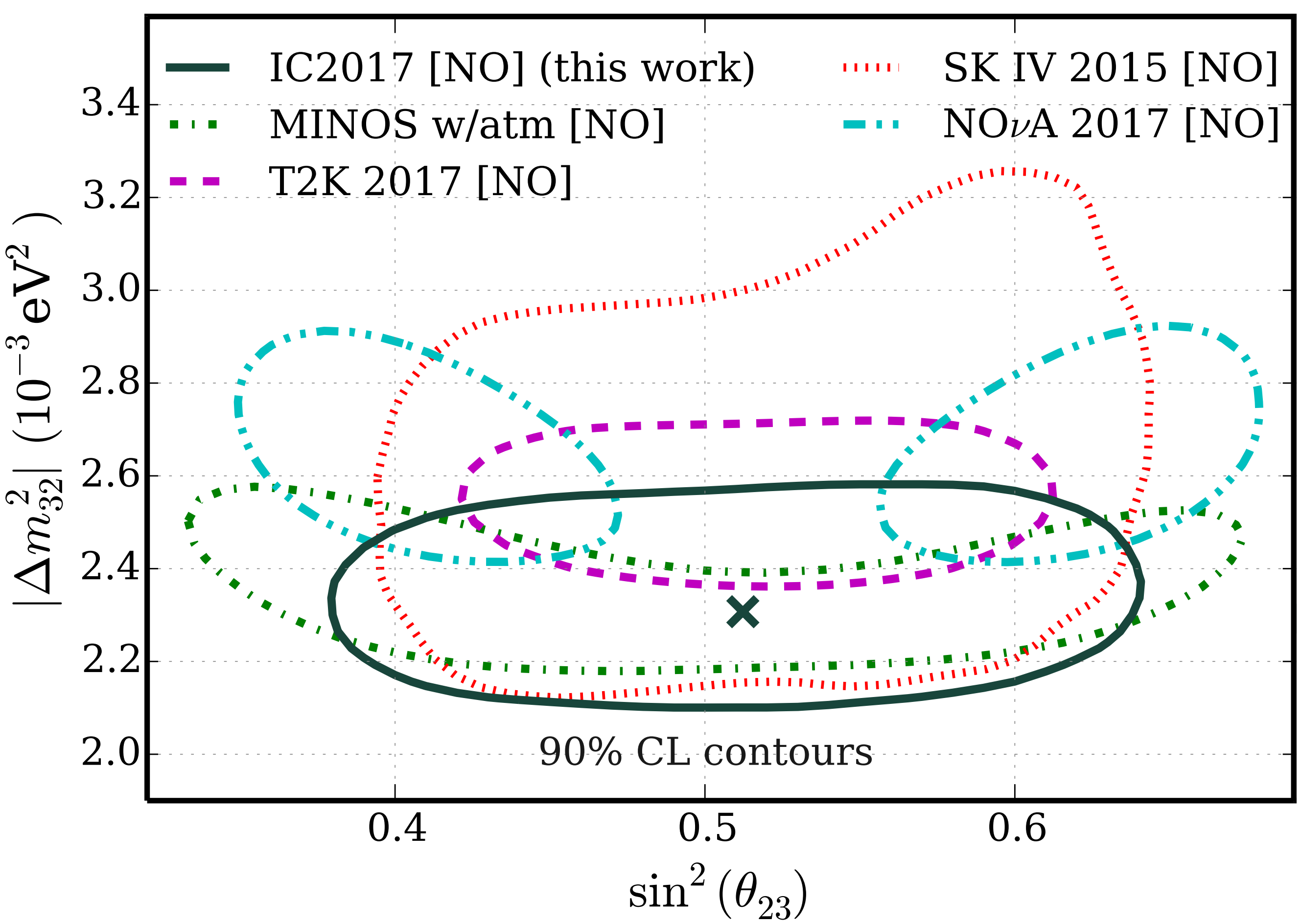
Atmospheric Neutrino Oscillations

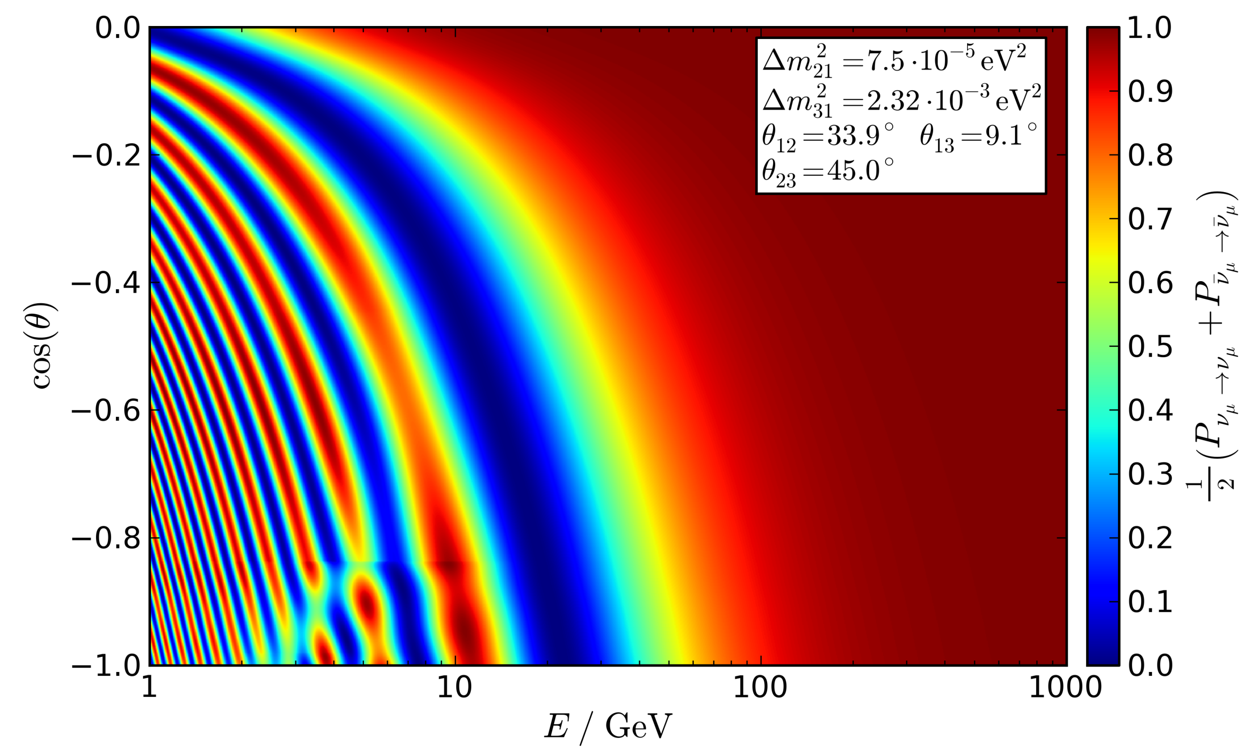
- **Muon neutrino disappearance** in the 1-100 GeV range allows for precision measurement of atmospheric mixing parameters.

- Oscillation analyses with DeepCore data.



[IceCube, PRL 120 (2018) 7]

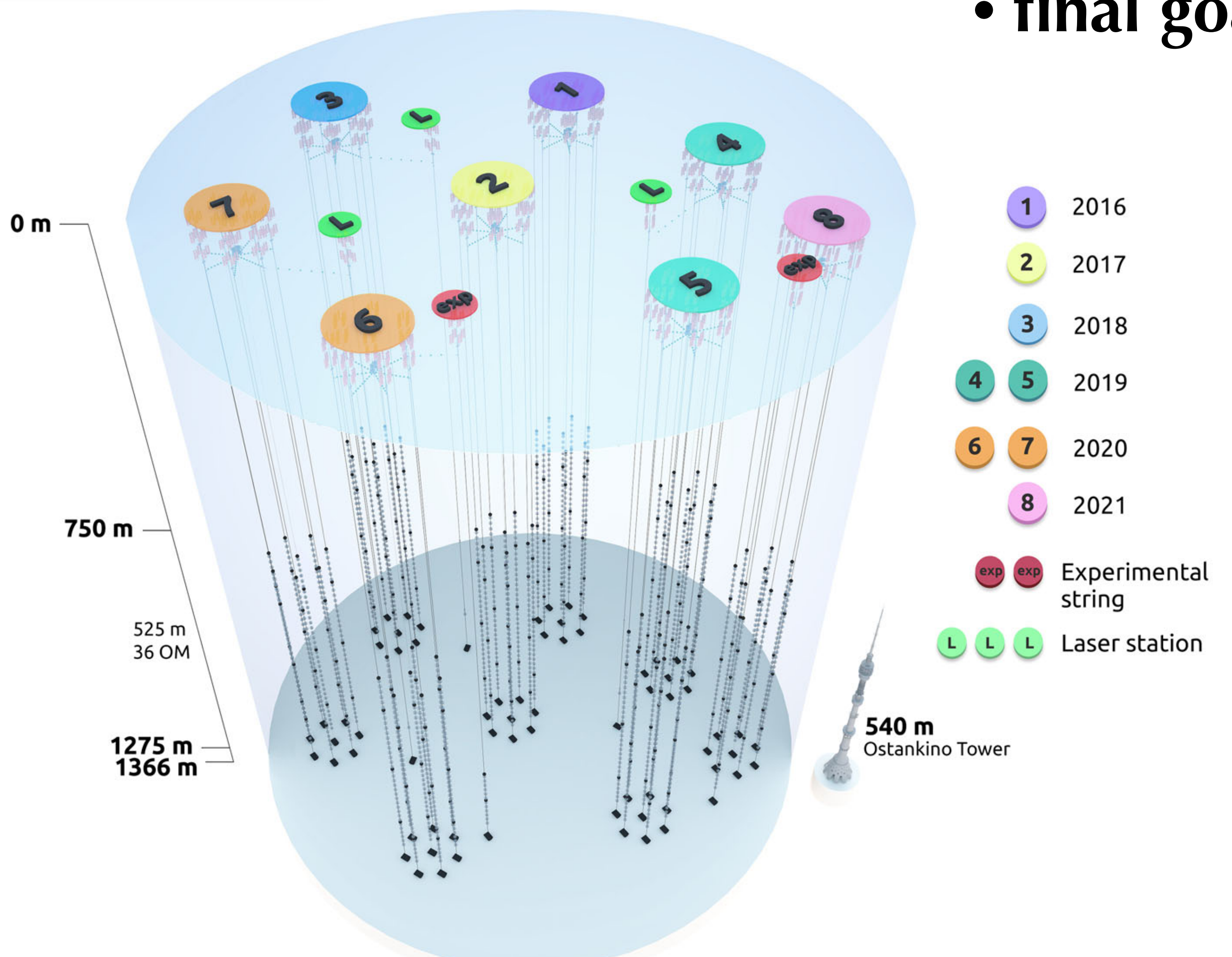


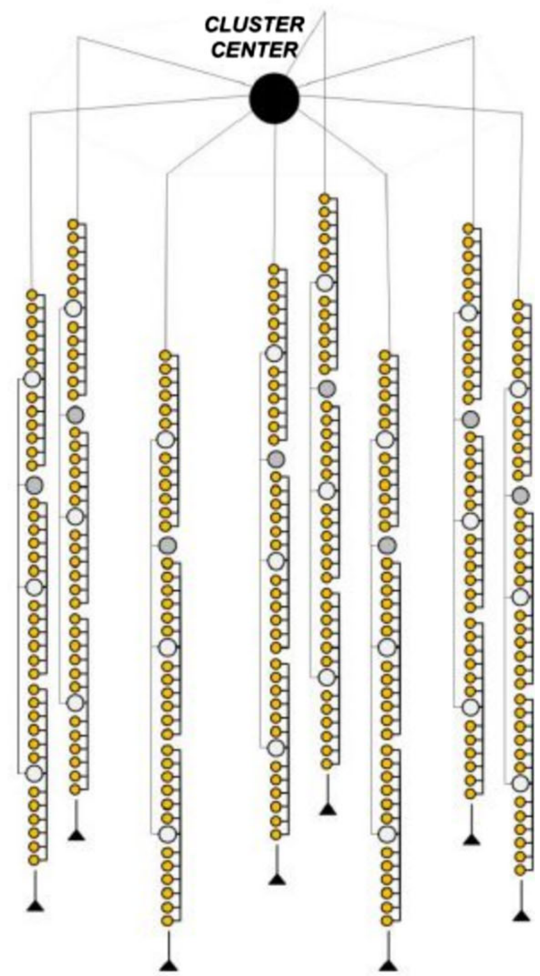


Outlook: Baikal-GVD

BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status April 2022: 10 clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

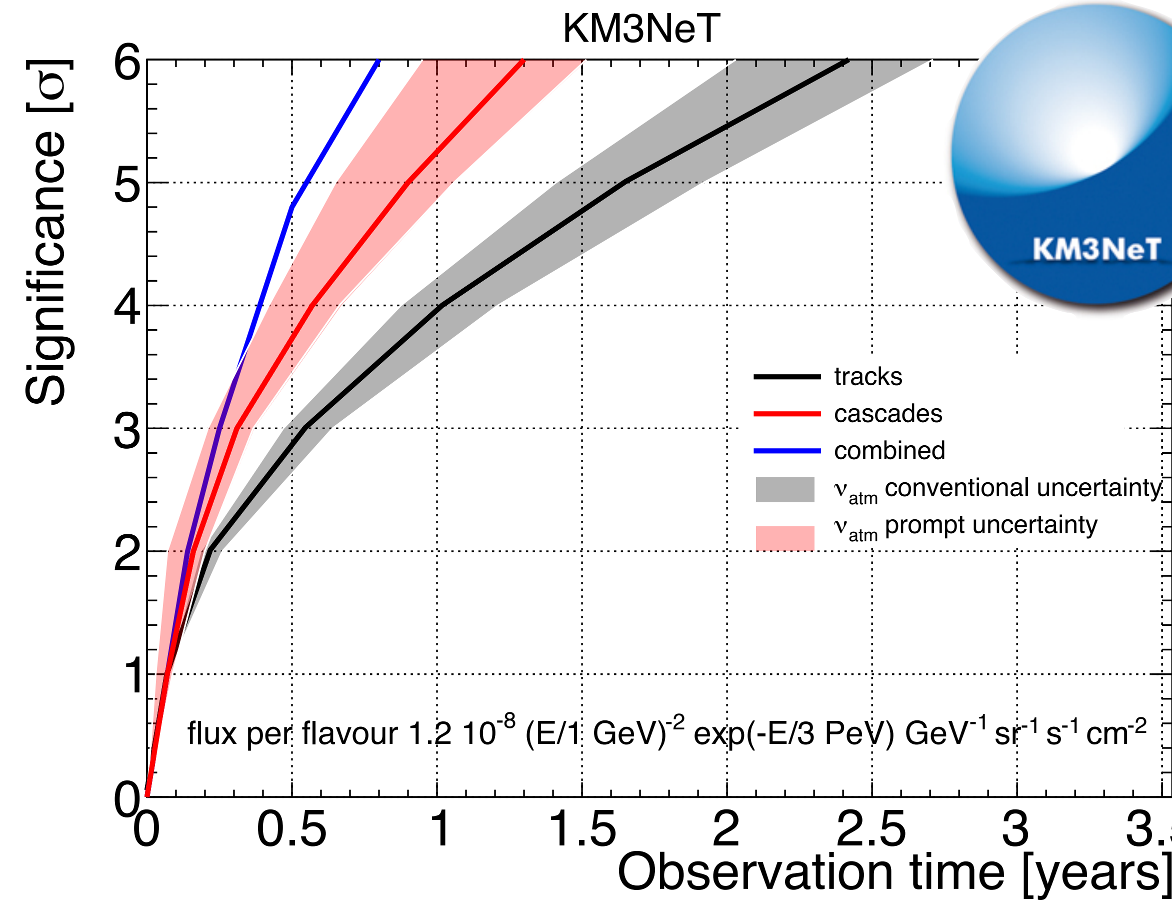




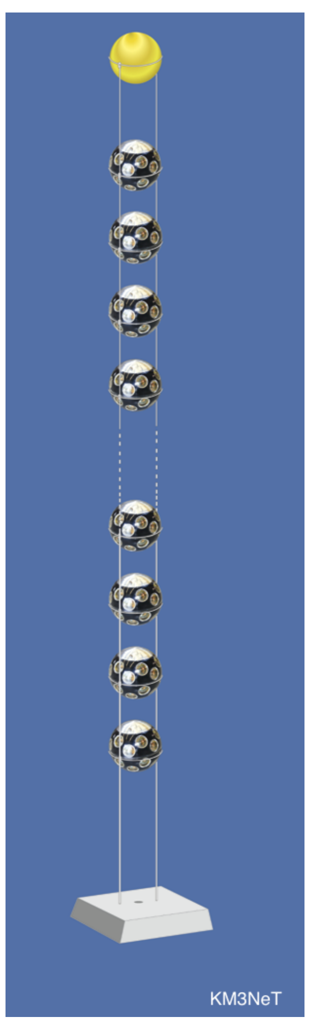
~157 TeV cascade e

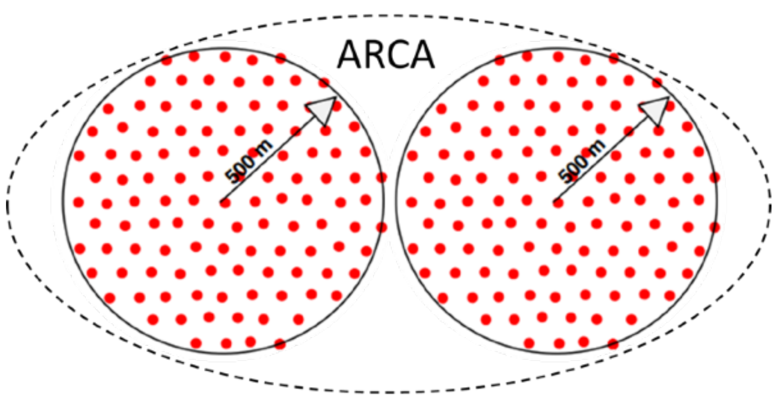
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status April 2022: 8 (ARCA) DUs**
- **ORCA** : optimized for low-energy (GeV) and oscillation analyses



detection unit with multi-PMT DOMs



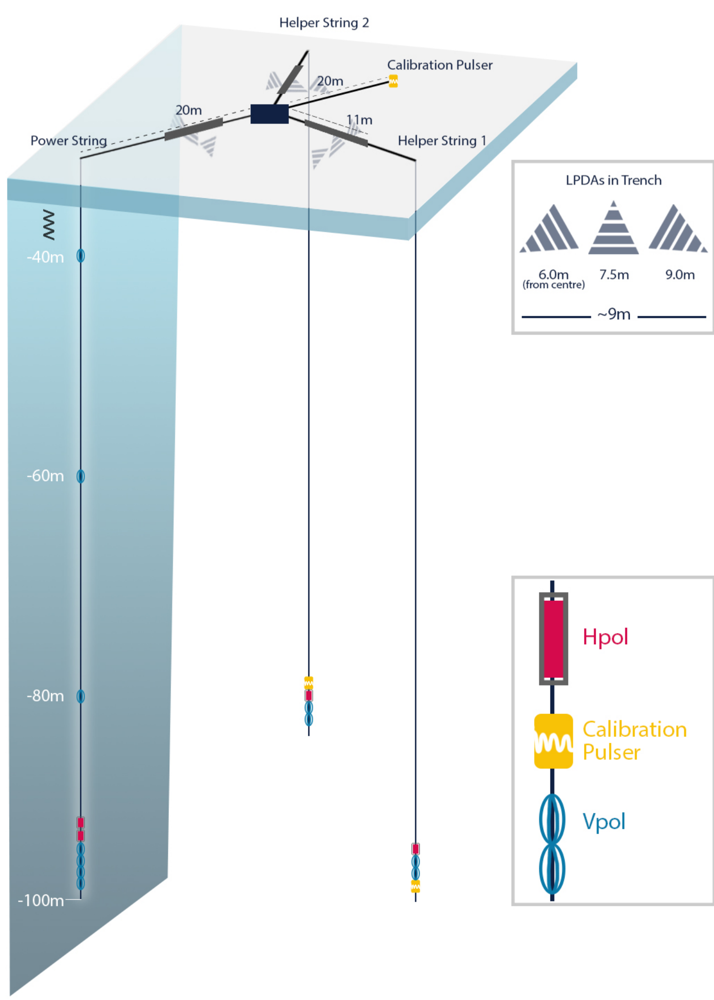


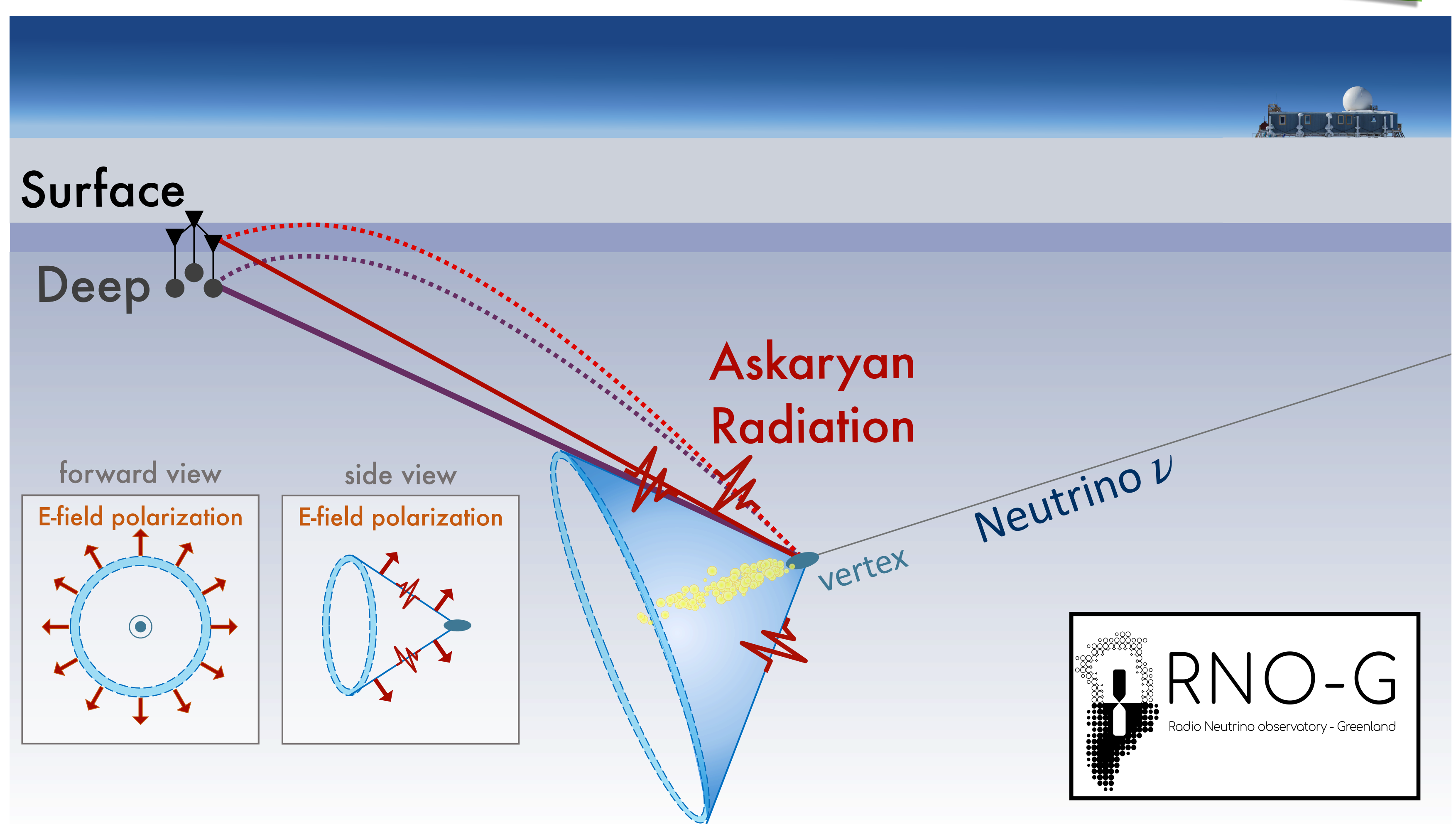
- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

Outlook: RNO-G

- Detection principle of **ANITA, ARA & ARIANNA** (Antarctica)
- **Under construction:** Radio Neutrino Observatory-Greenland (**RNO-G)**

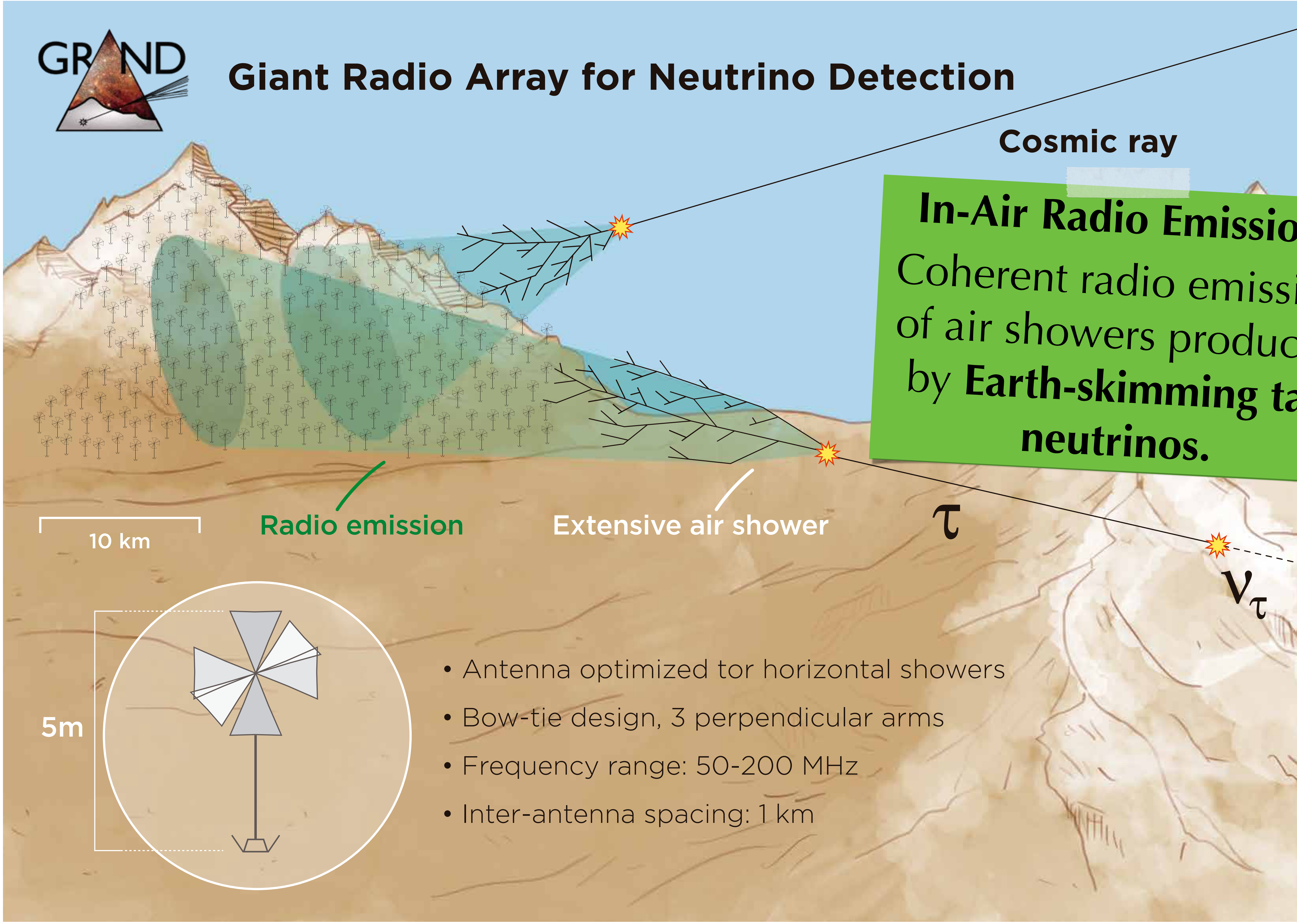
Askaryan effect:
Neutrino emission above 10 PeV can be observed via **coherent radio emission of showers** in radio-transparent media.





[RNO-G JINST 16 (2021) 3]

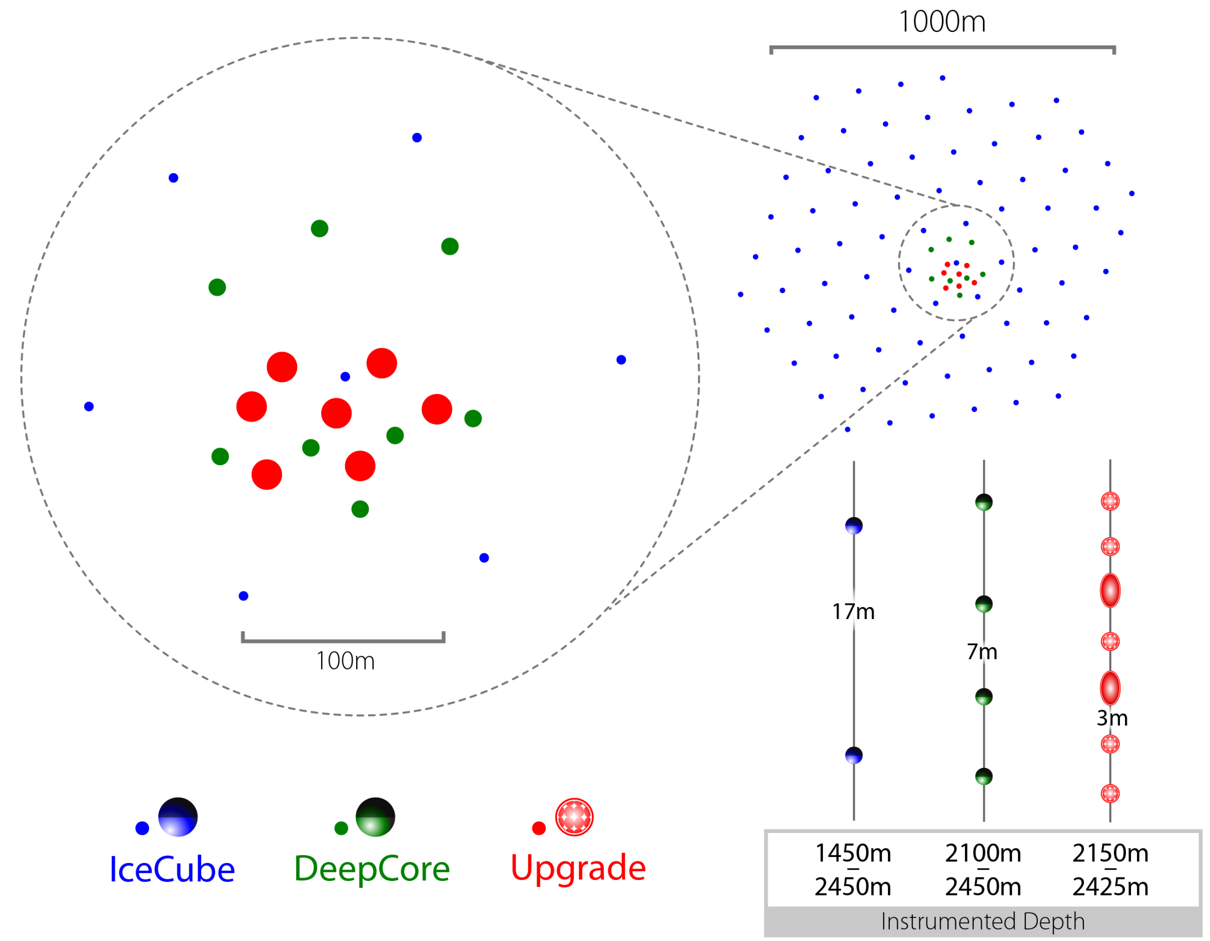
Vision: GRAND

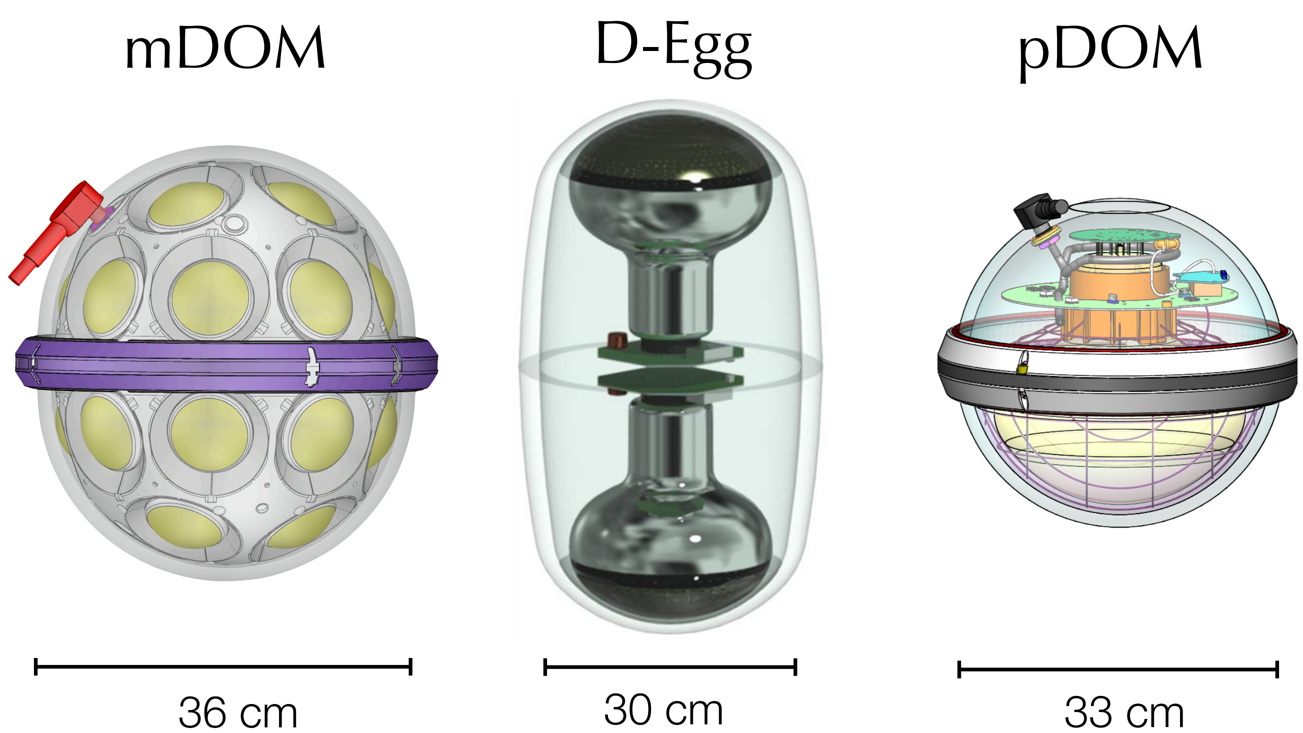


[GRAND SCPMA 63 (2020) 1]

Outlook: IceCube Upgrade

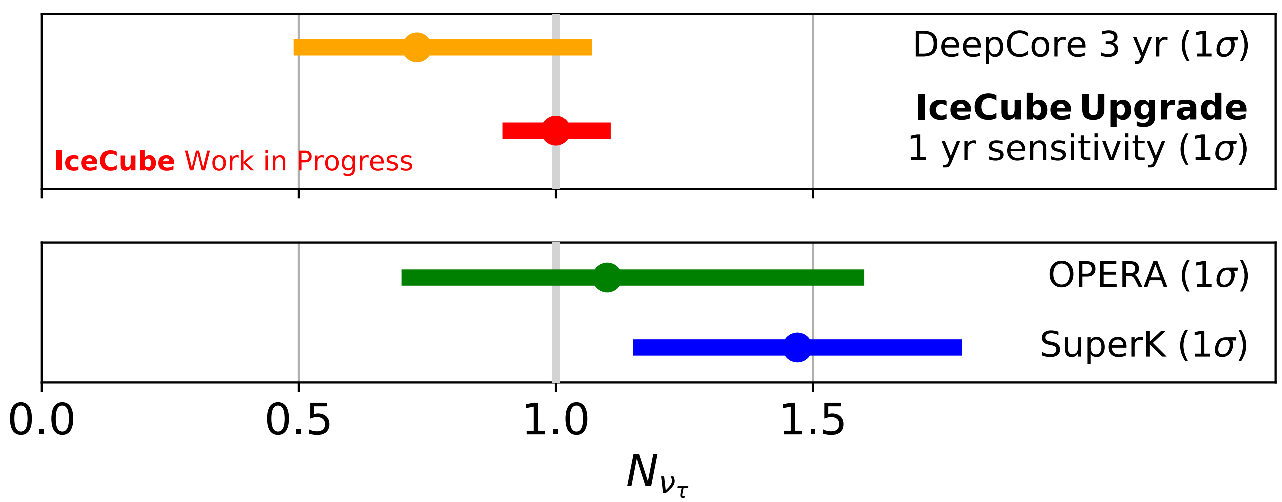
- **7 new strings** in the DeepCore region (~20m inter-string spacing)
- **New sensor designs**, optimized for ease of deployment, light sensitivity & effective area
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts
- In parallel, **IceTop surface enhancements** (scintillators & radio antennas) for CR studies.
- **Aim: deployment in 2025/26**

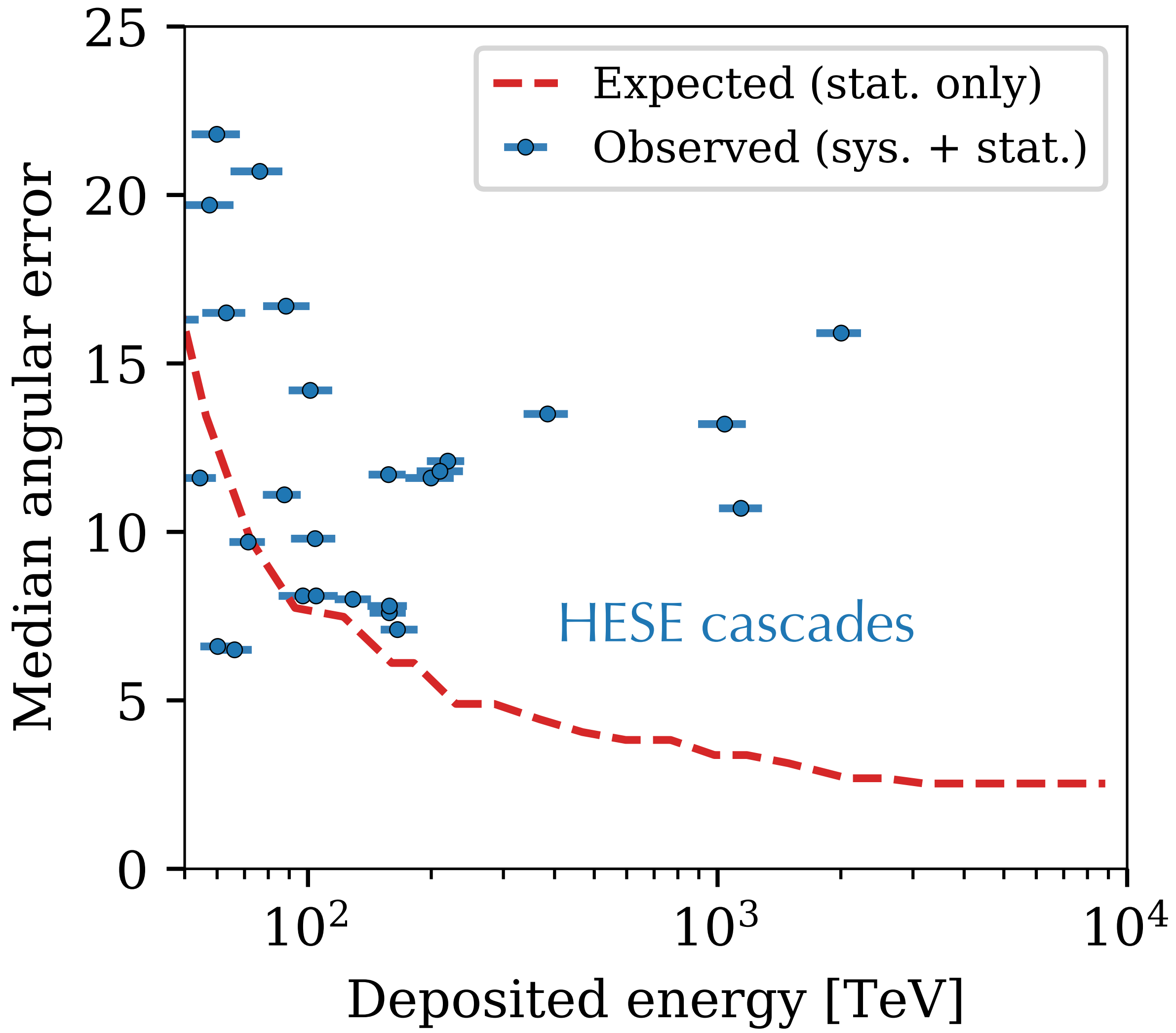


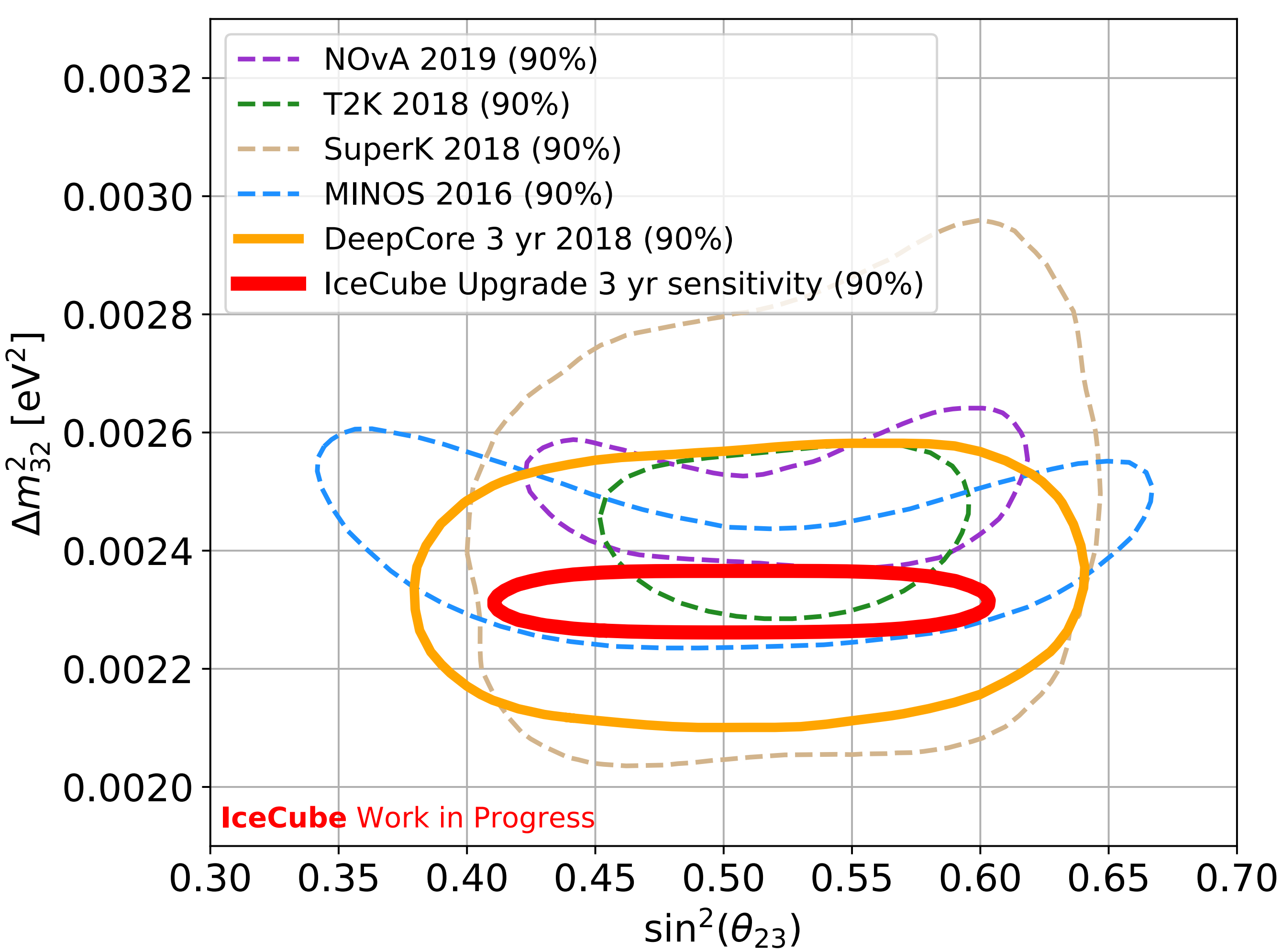


Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance
- **Improved energy and angular reconstructions** of IceCube data







[IceCube, PoS (ICRC2019) 1031]