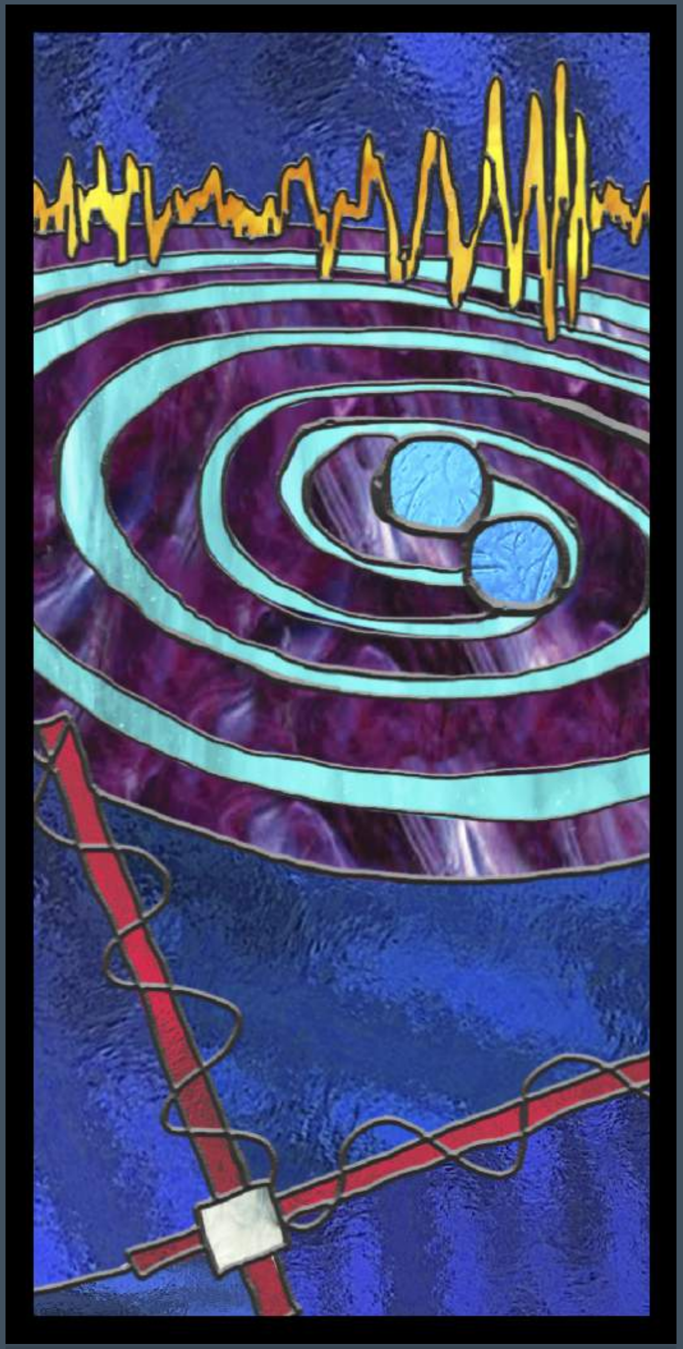
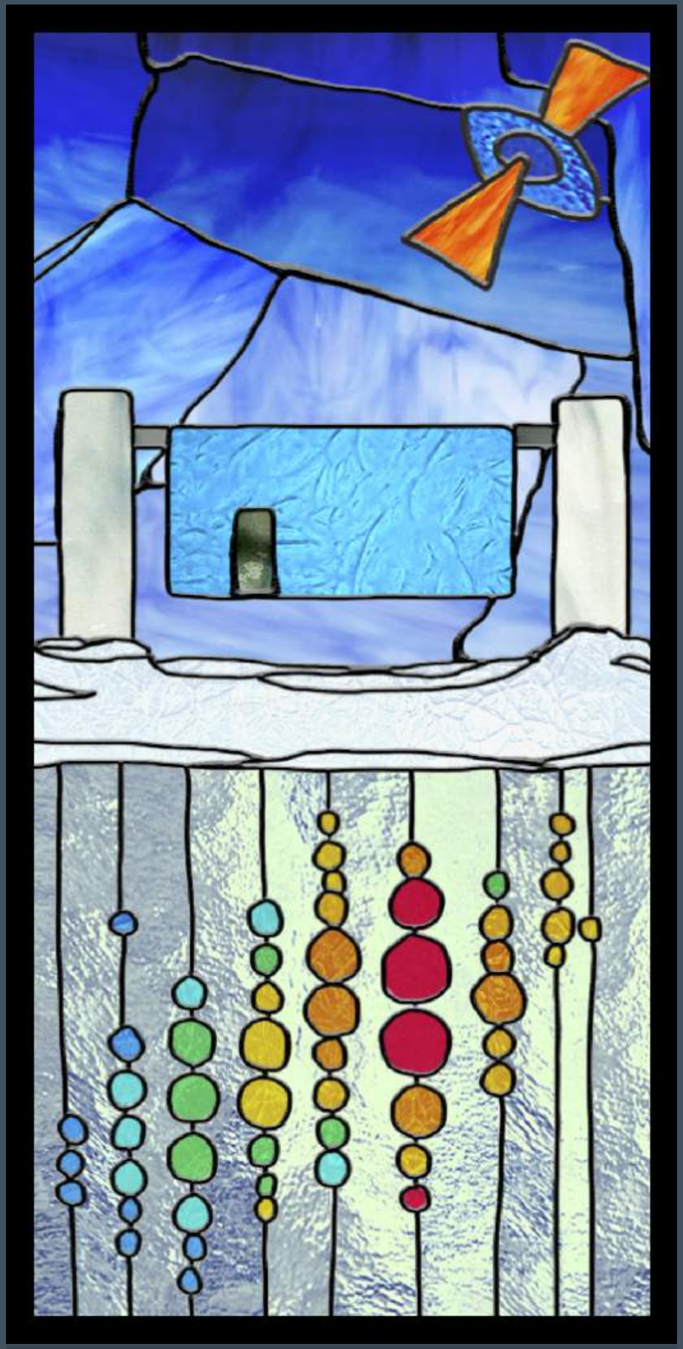
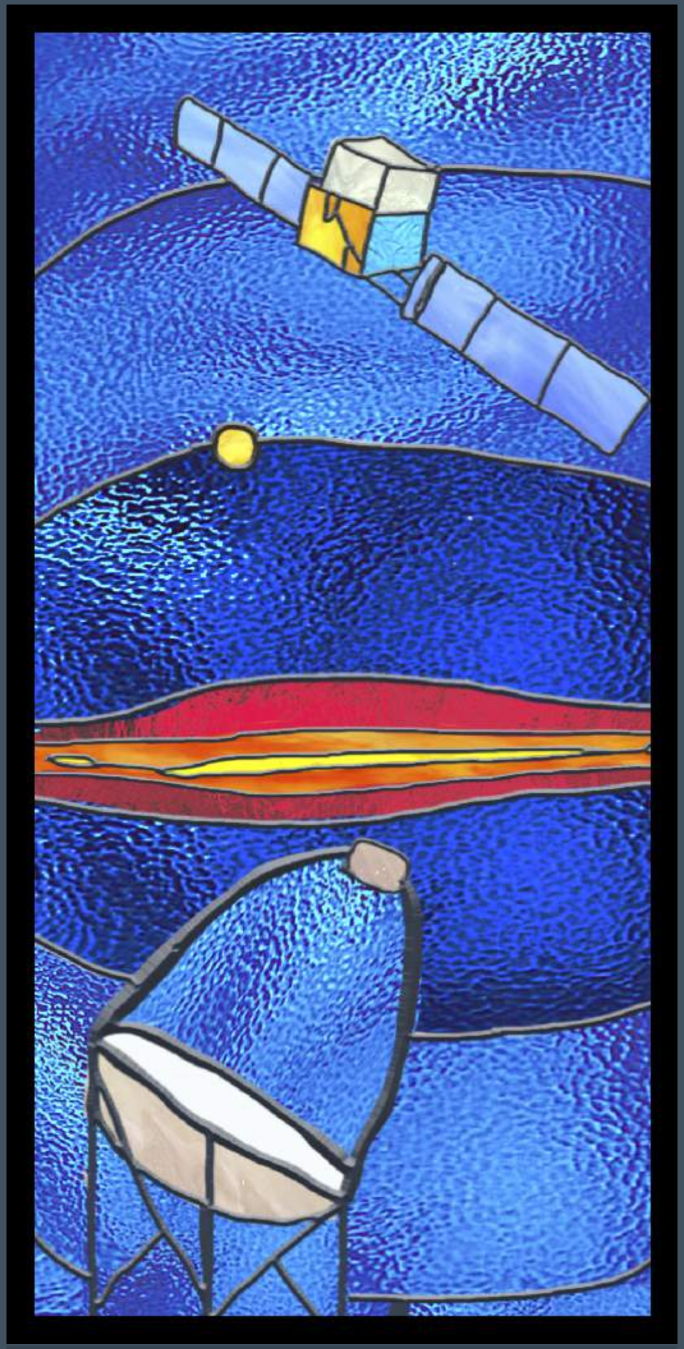






Neutrinos on the Rocks

VILLUM FONDEN

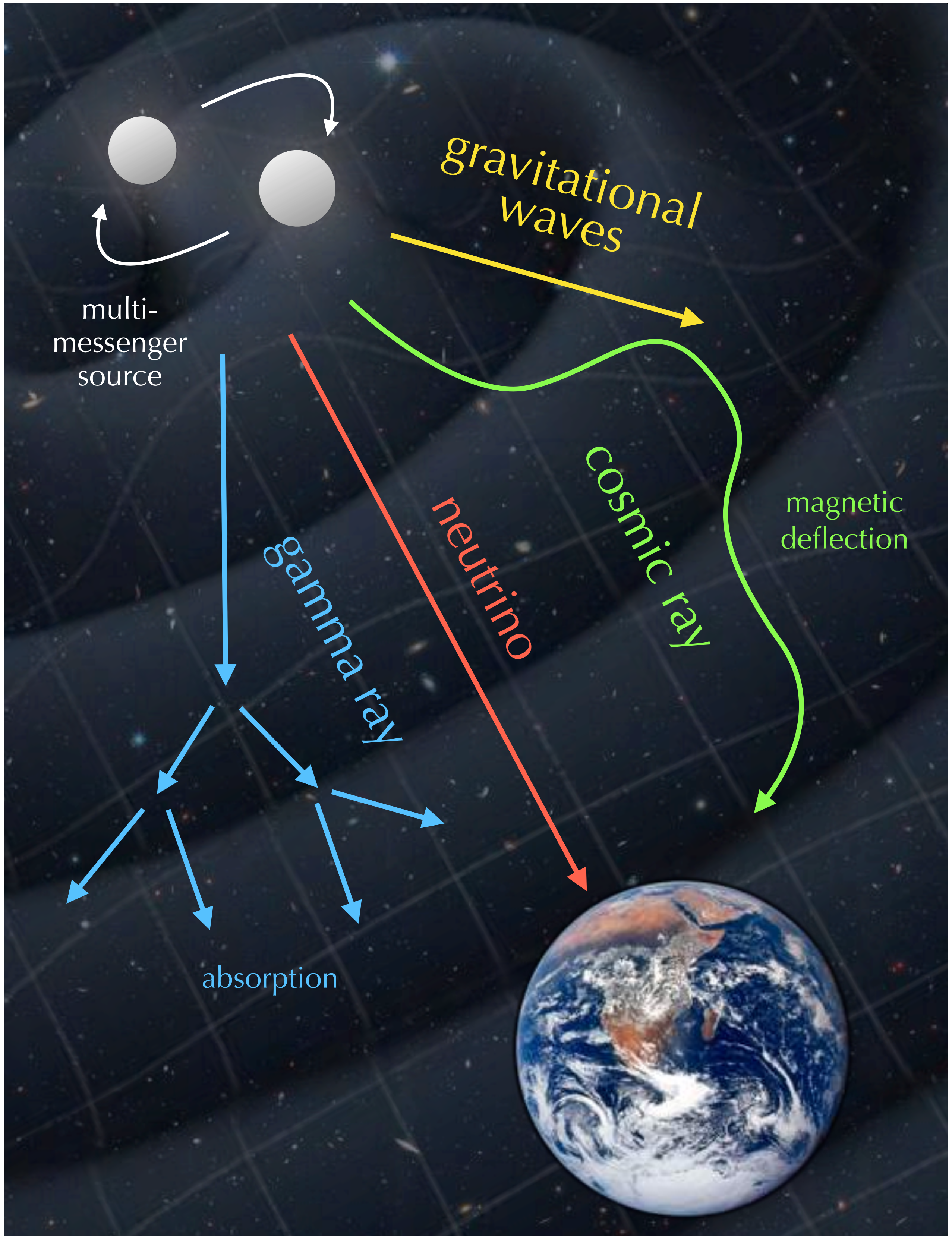
Markus Ahlers, NBI Copenhagen

IAP Online Seminar

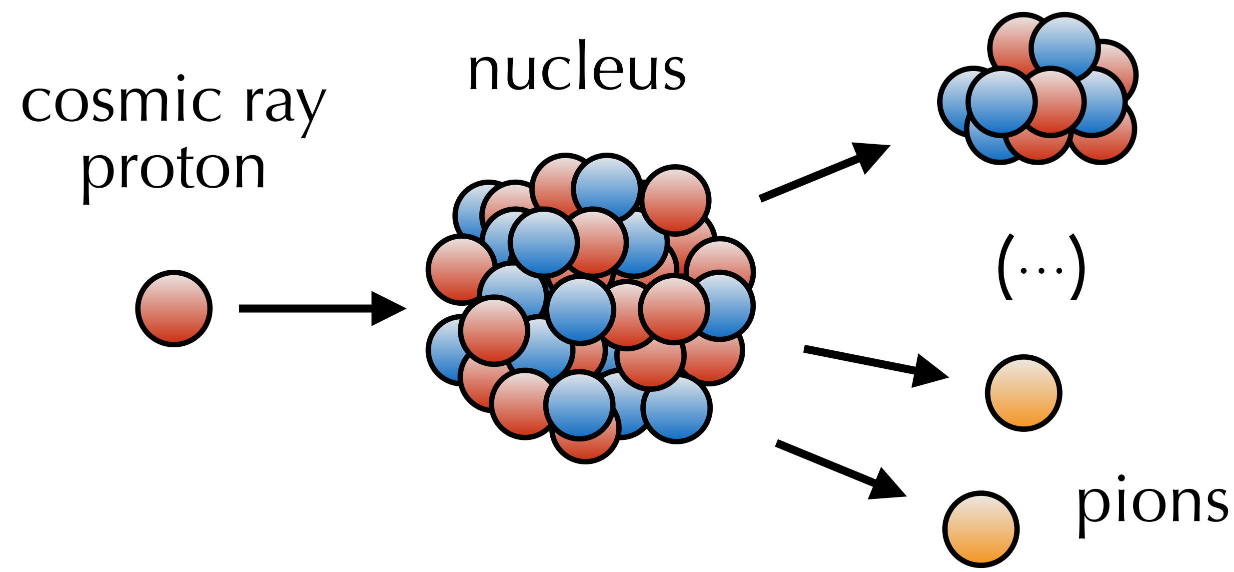
October 30, 2020

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



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

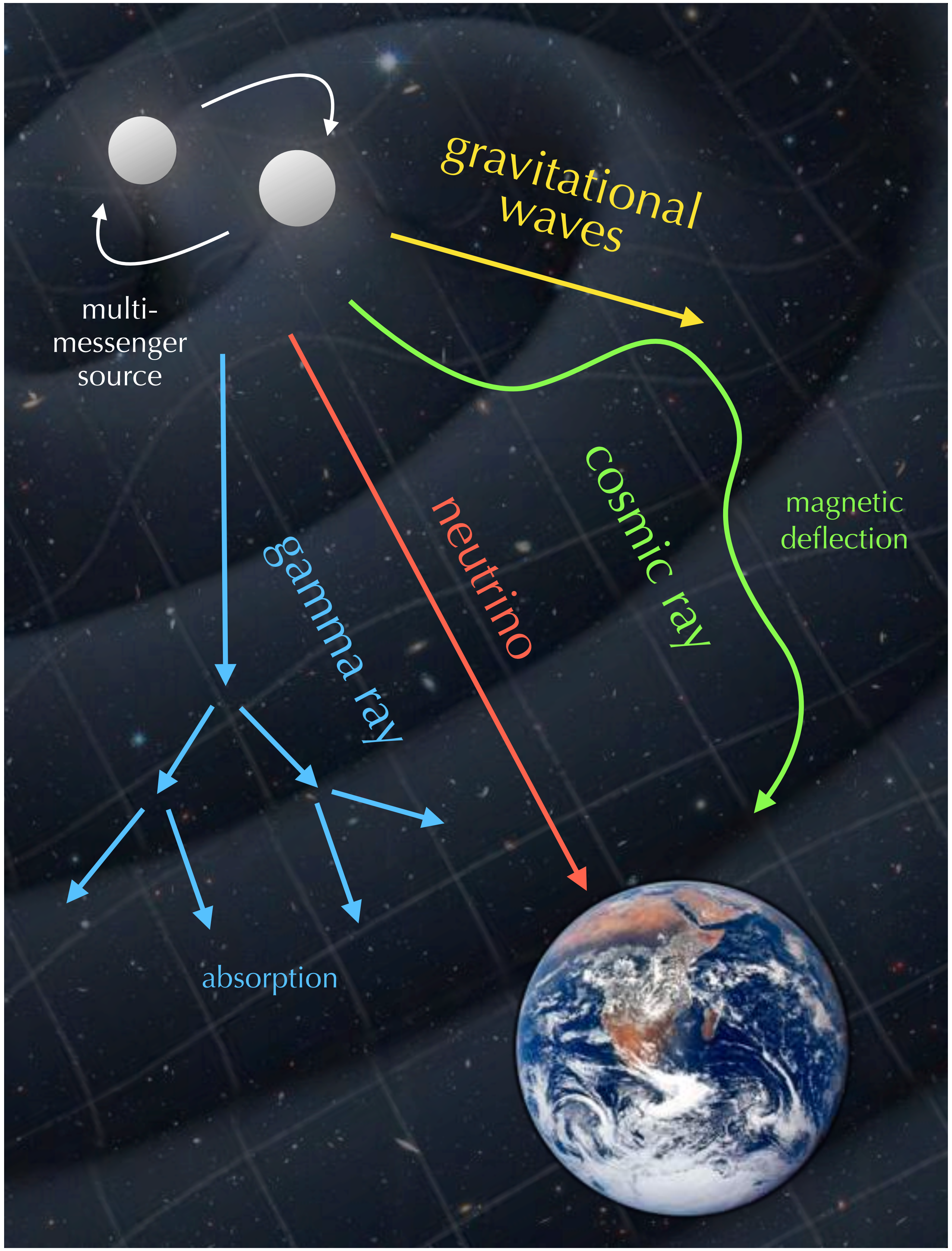


Secondary **neutrinos** and **gamma-rays** from pion decays:

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

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

Multi-Messenger Astronomy



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

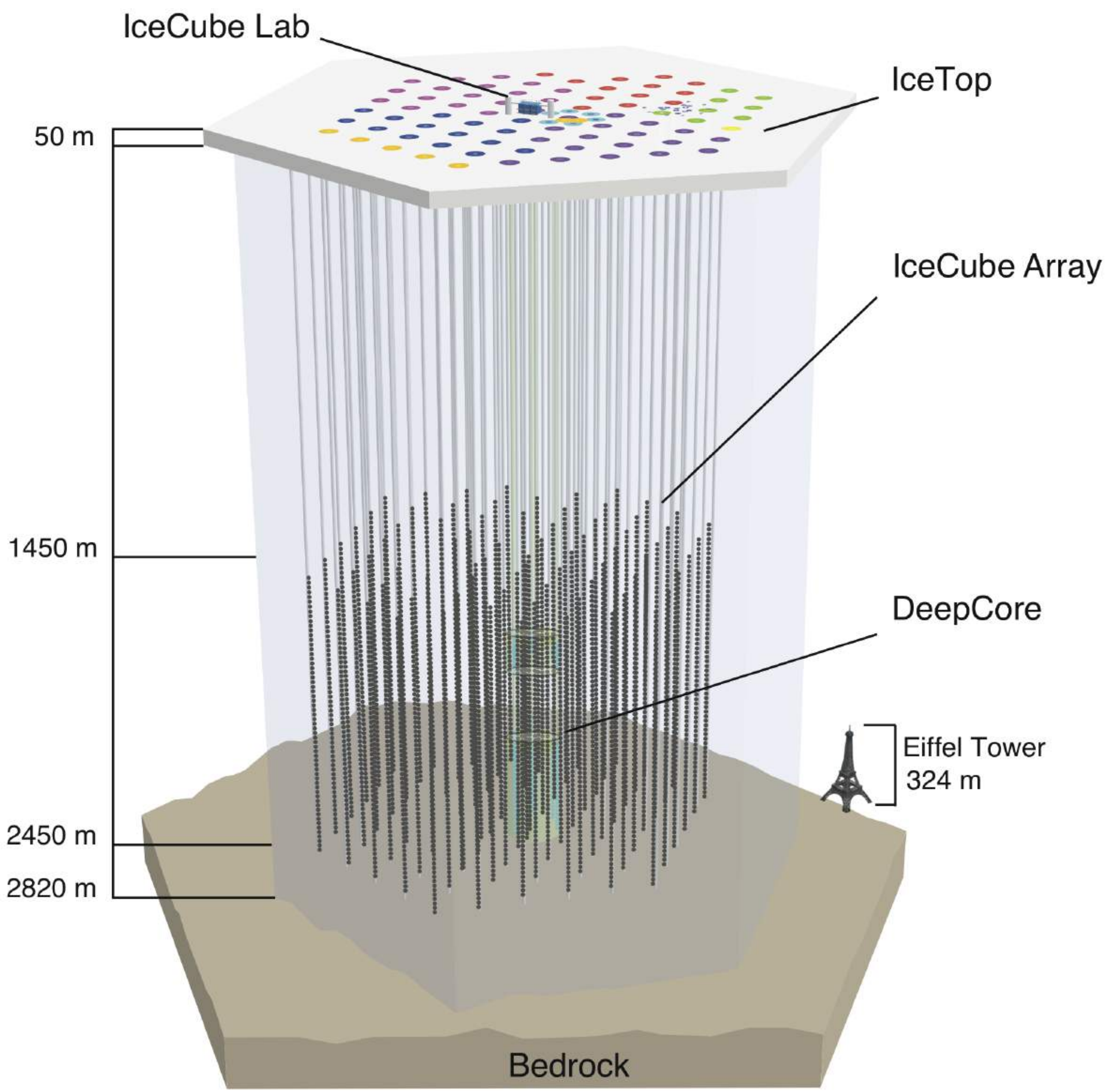
coincident with
photons and gravitational waves

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

BUT, very difficult to detect!

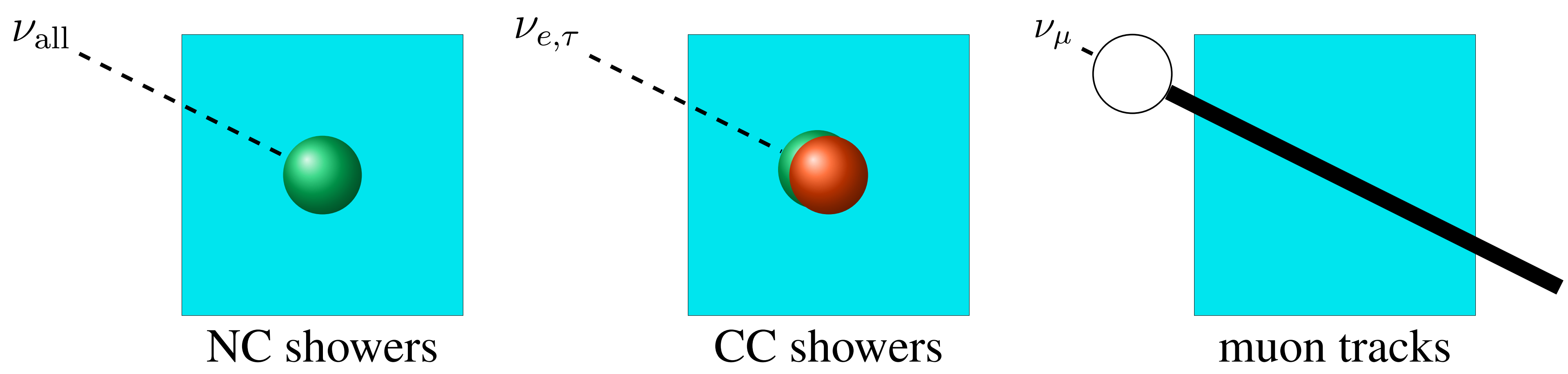
IceCube Observatory



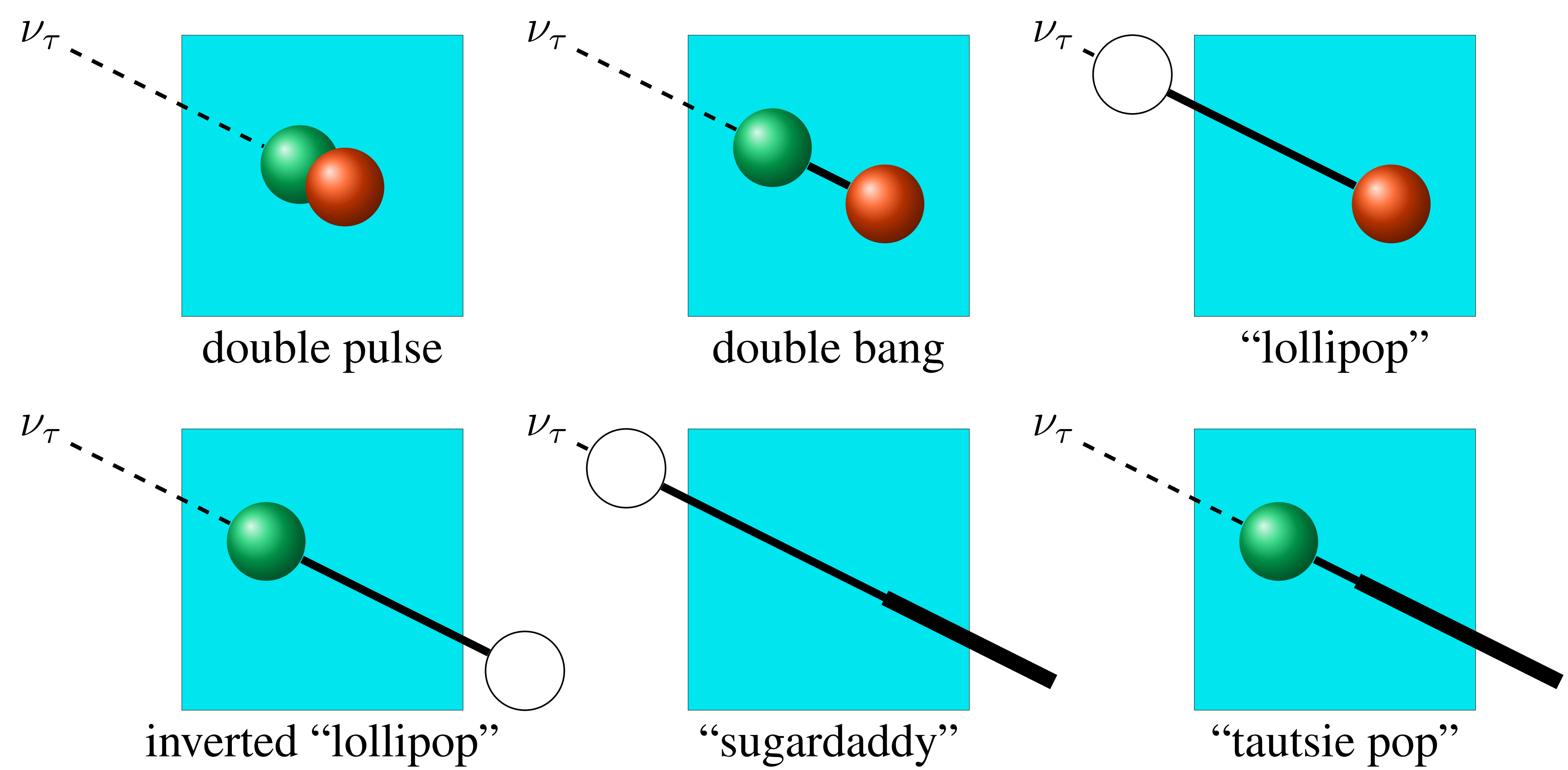
- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- price tag: **1/4 € per ton**

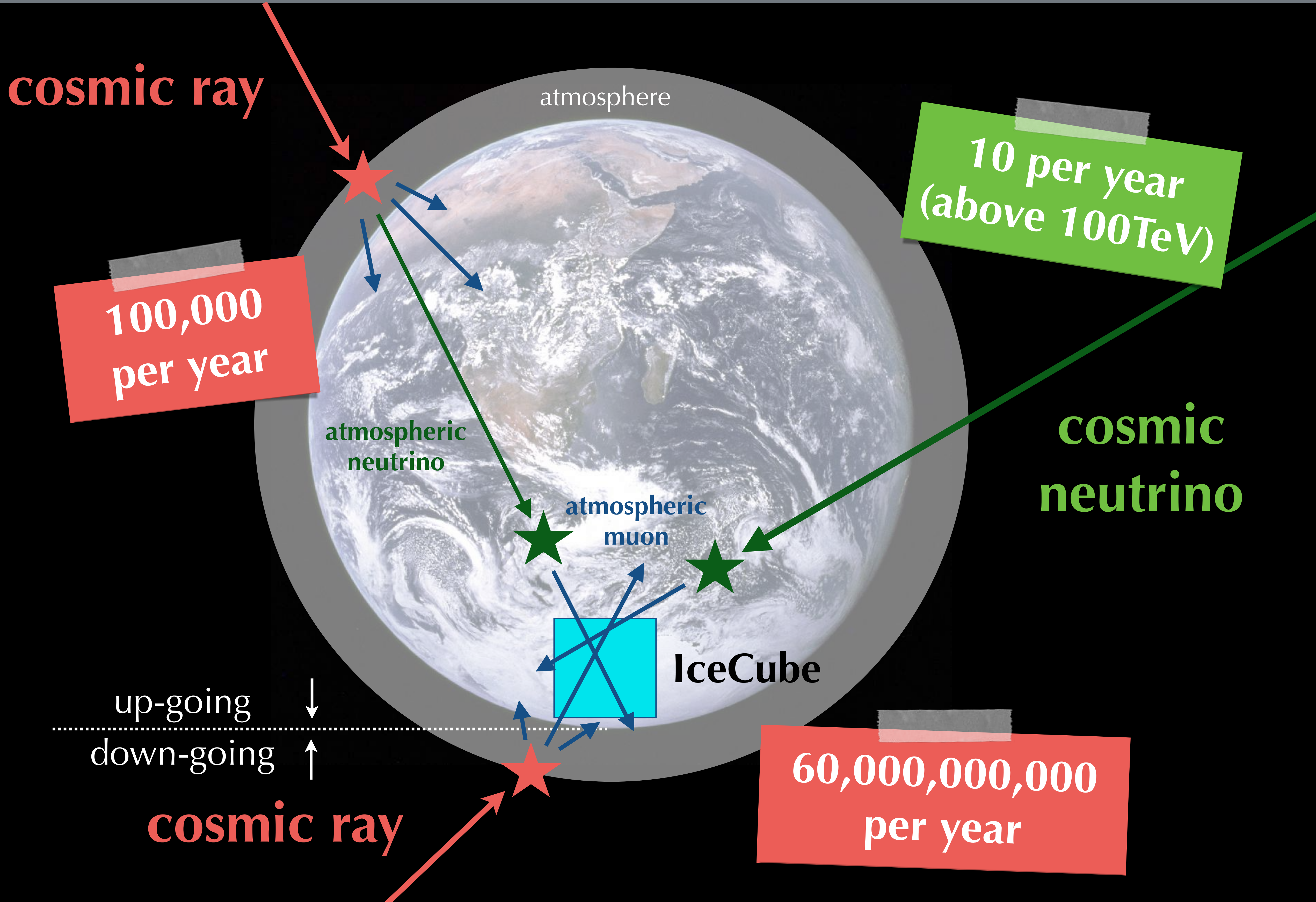
Optical Cherenkov Detection

"cascades"
&
"tracks"



rare events
from CC ν_τ
interactions

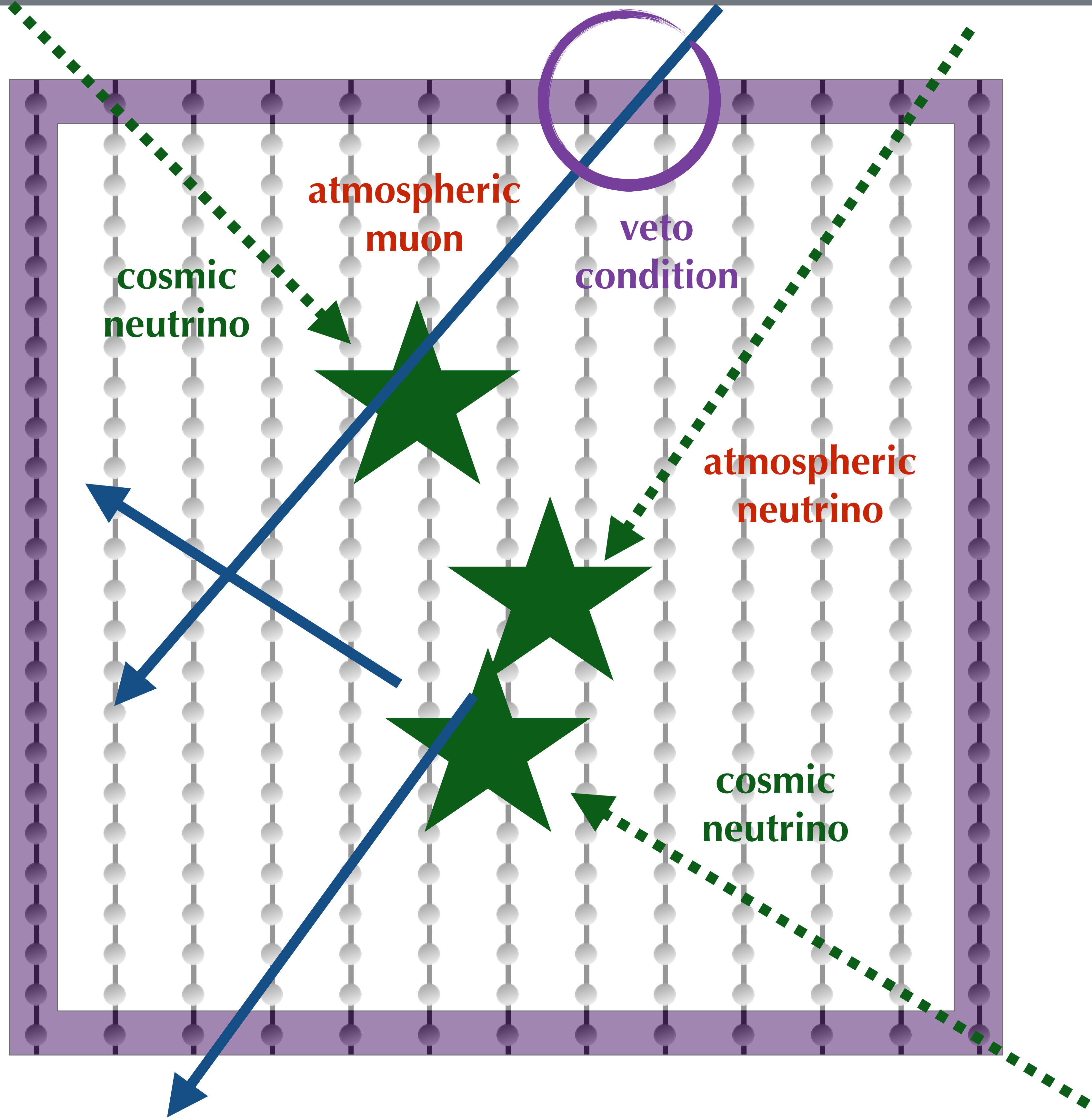




cosmic ray
atmosphere
10 per year
(above 100TeV)
100,000
per year
atmospheric
neutrino
cosmic
neutrino
atmospheric
muon
IceCube
up-going
down-going
cosmic ray
60,000,000,000
per year

Neutrino Selection II

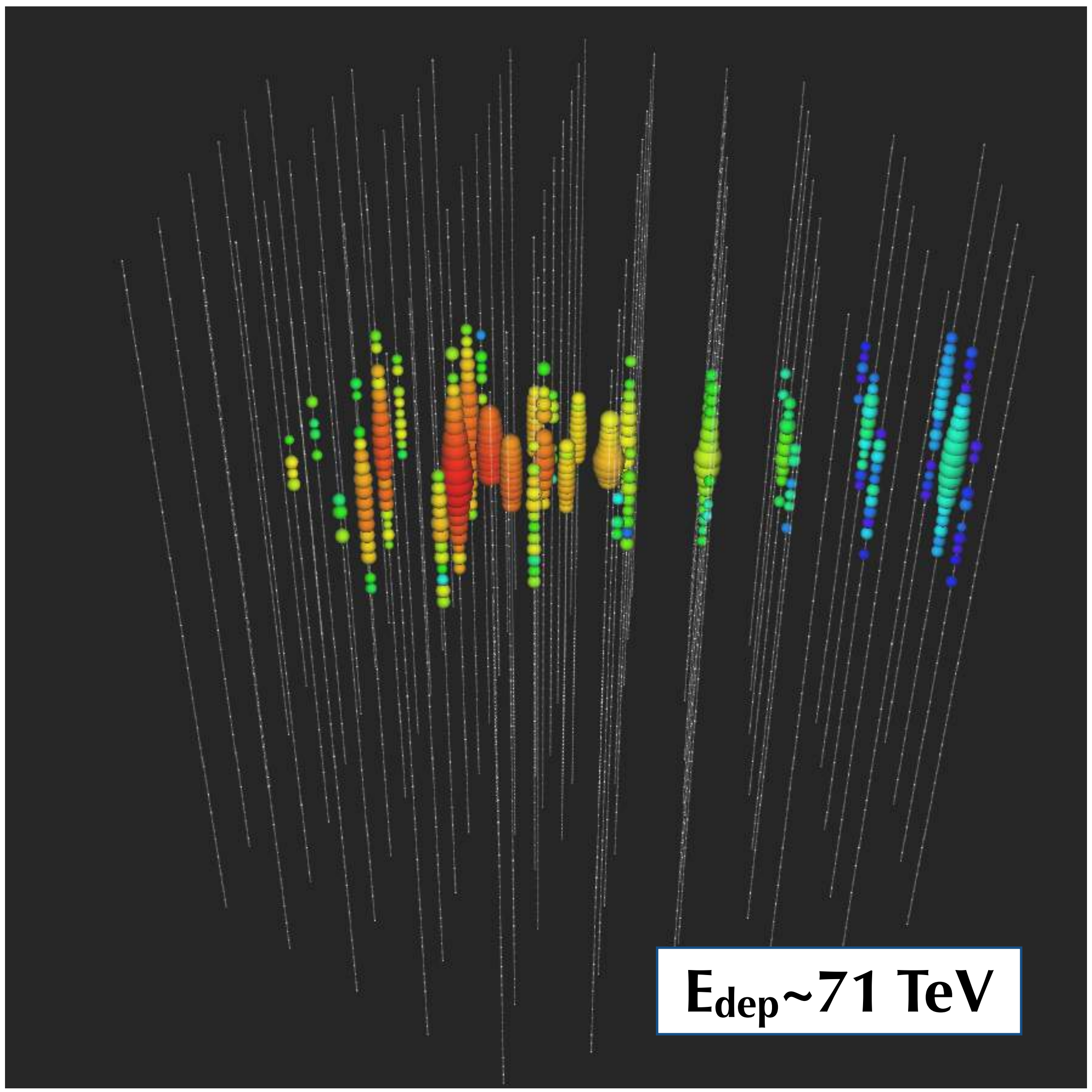
- Outer layer of optical modules used as virtual **veto region.**
- **Atmospheric muons** pass through veto from above.
- **Atmospheric neutrinos** coincidence with atmospheric muons.
- **Cosmic neutrino** events can start inside the fiducial volume.
- **High-Energy Starting Event** (HESE) analysis

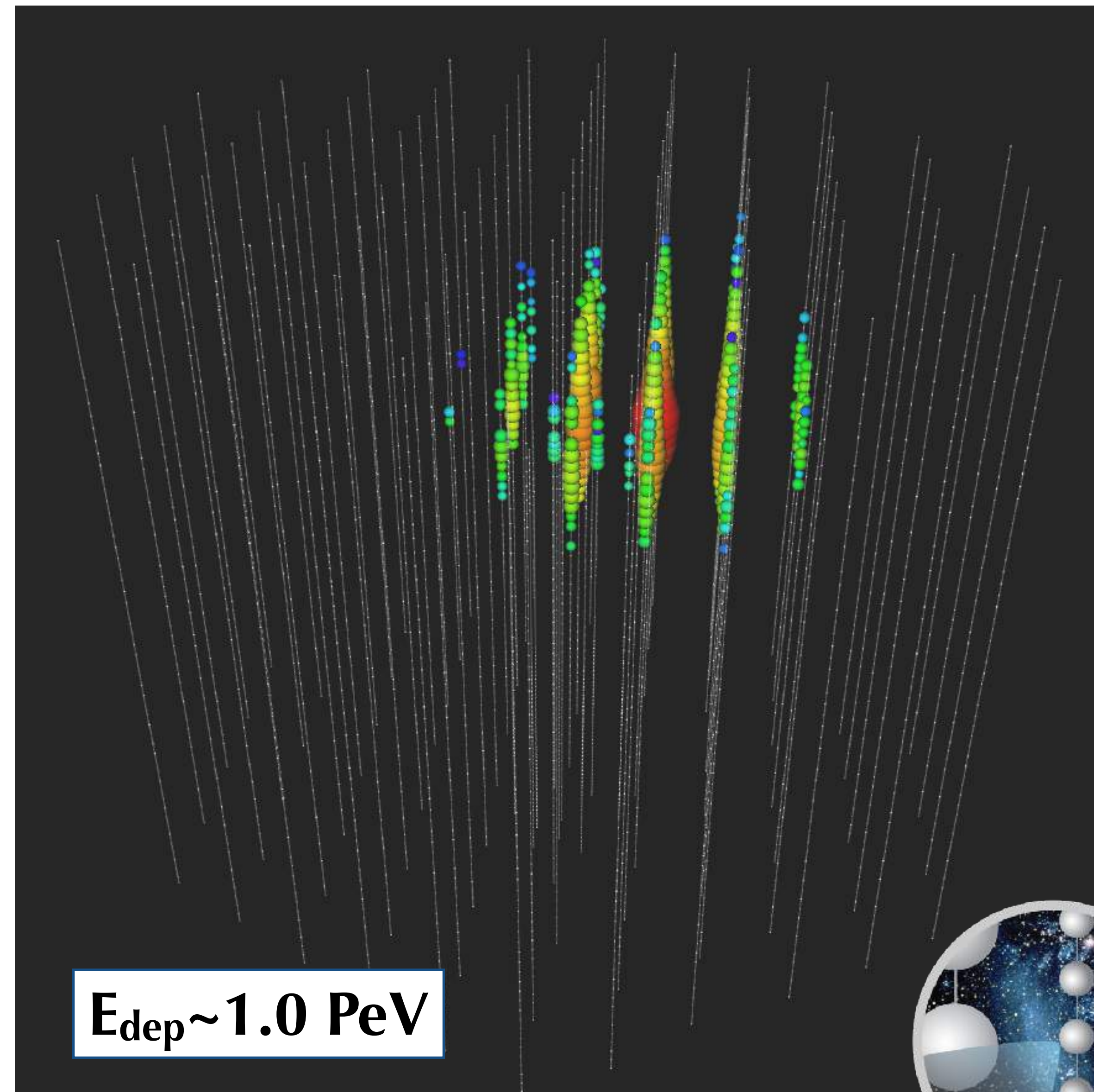


Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

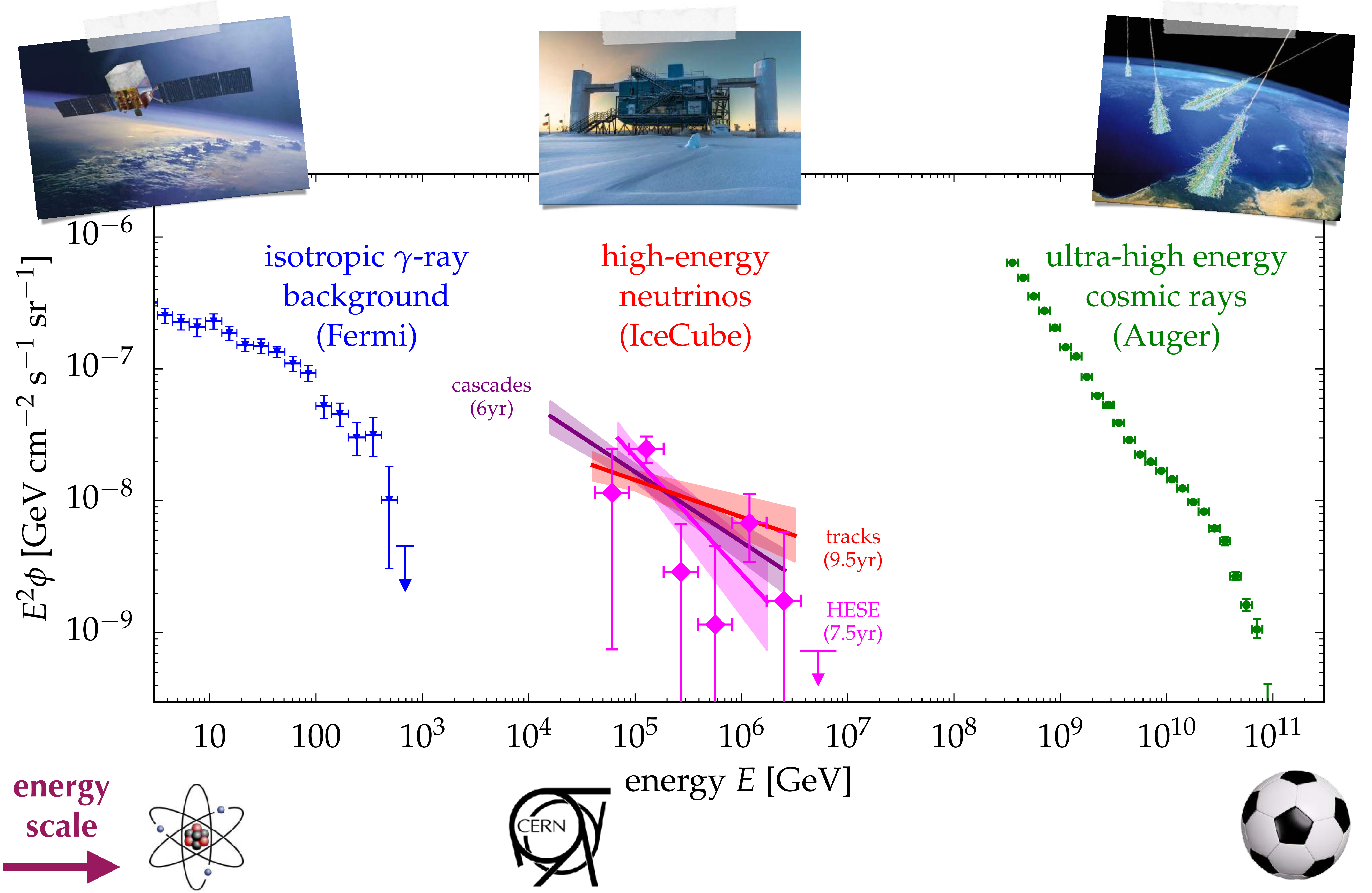
"track event" (from ν_μ scattering) **"cascade event"** (from all flavours)

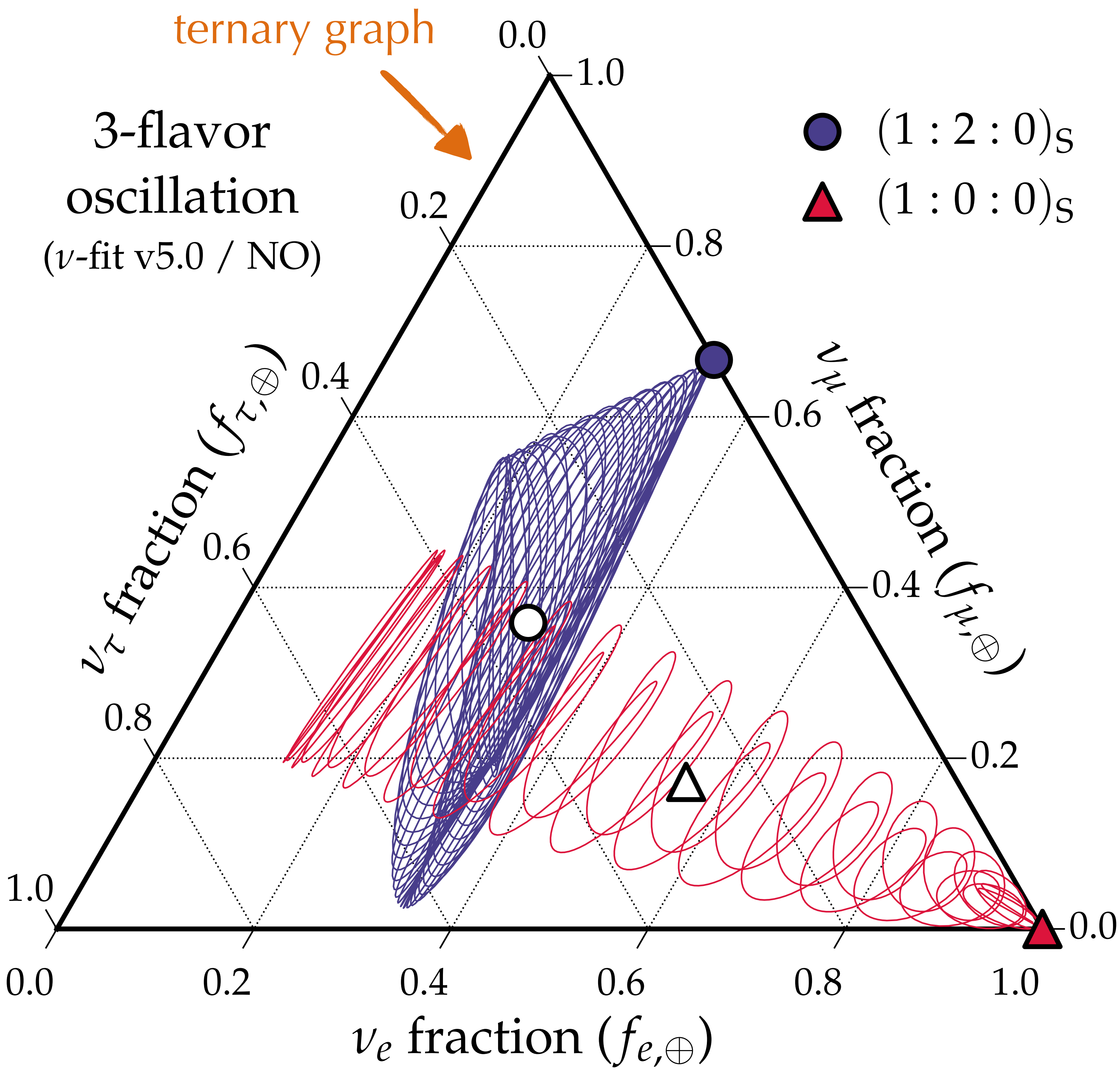




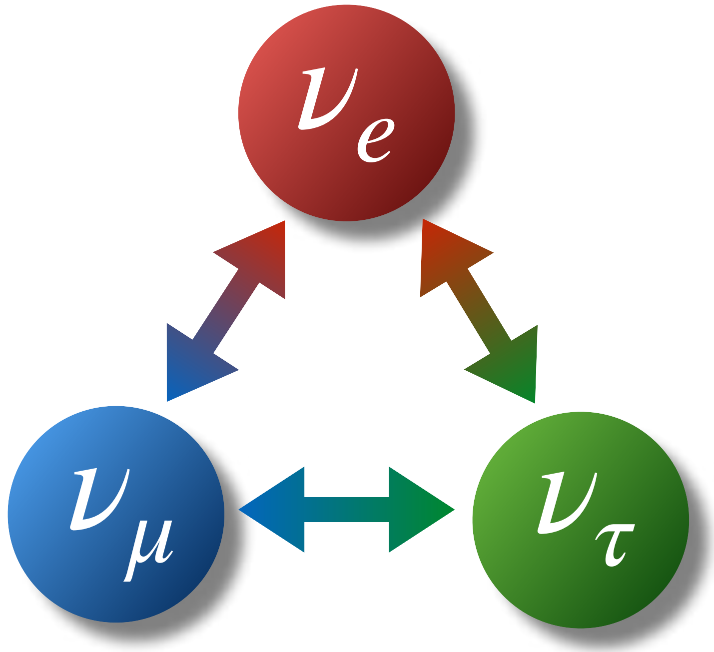
["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

Diffuse TeV-PeV Neutrinos

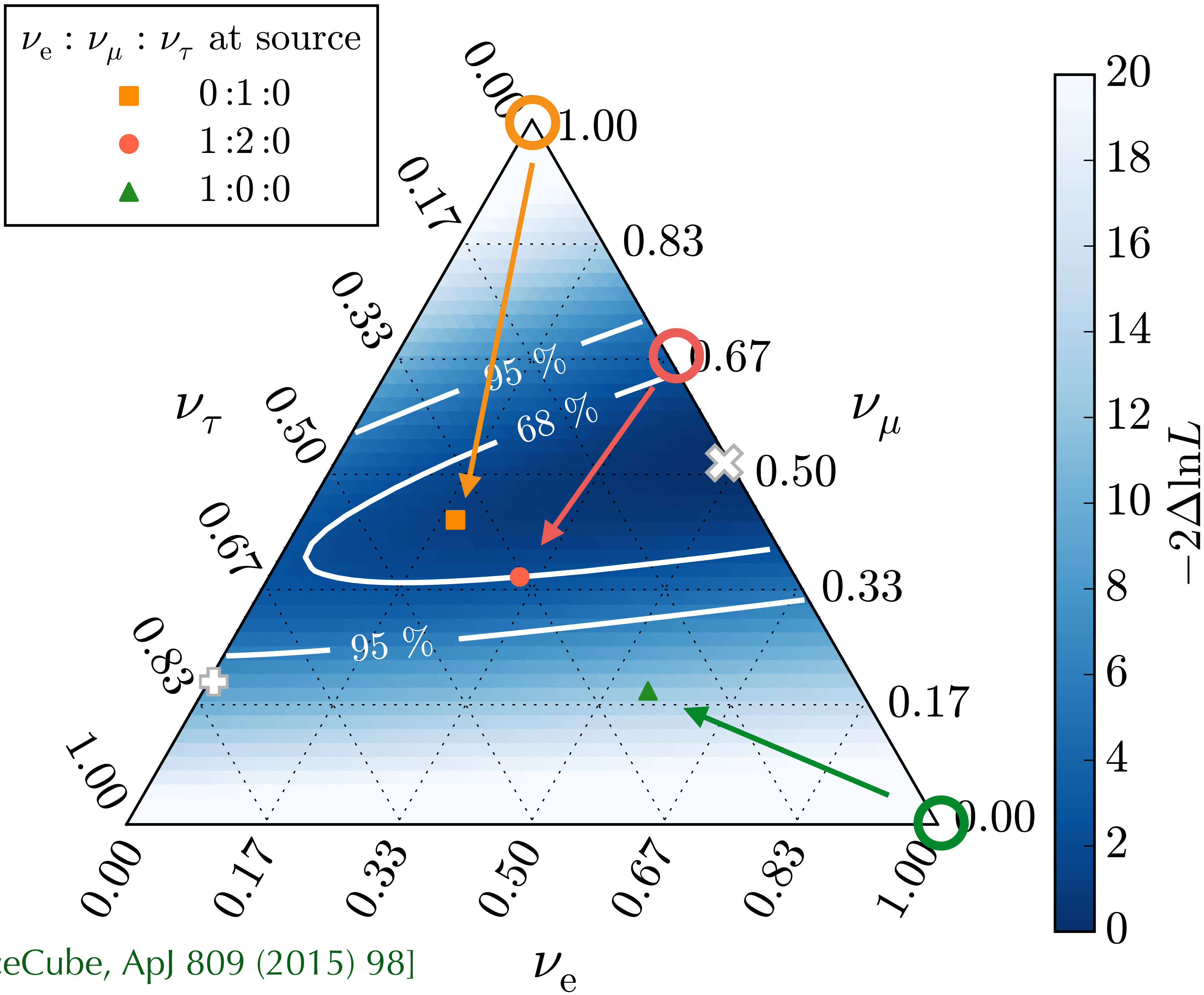




Superposition of flavor and mass states induce oscillations.

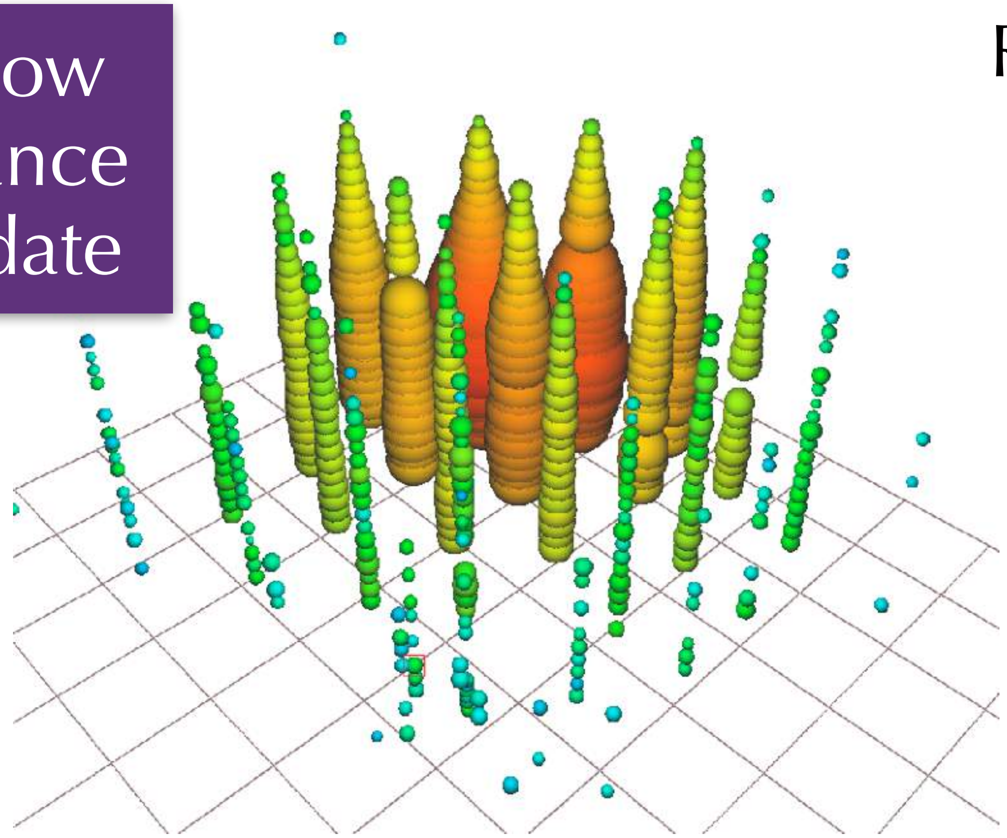


Cosmic neutrinos visible via their oscillation-averaged flavor.



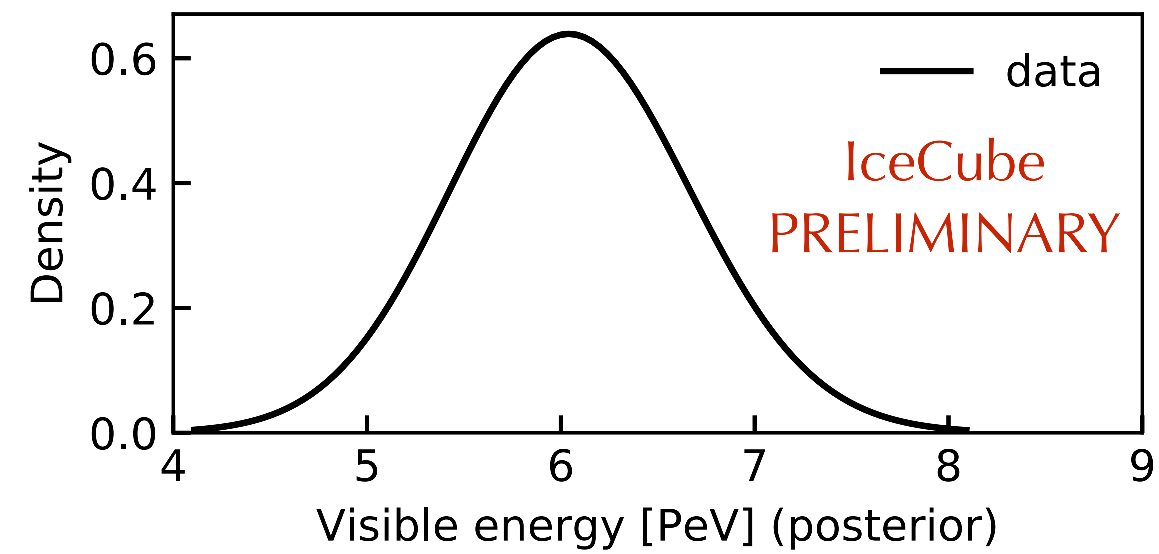
[IceCube, ApJ 809 (2015) 98]

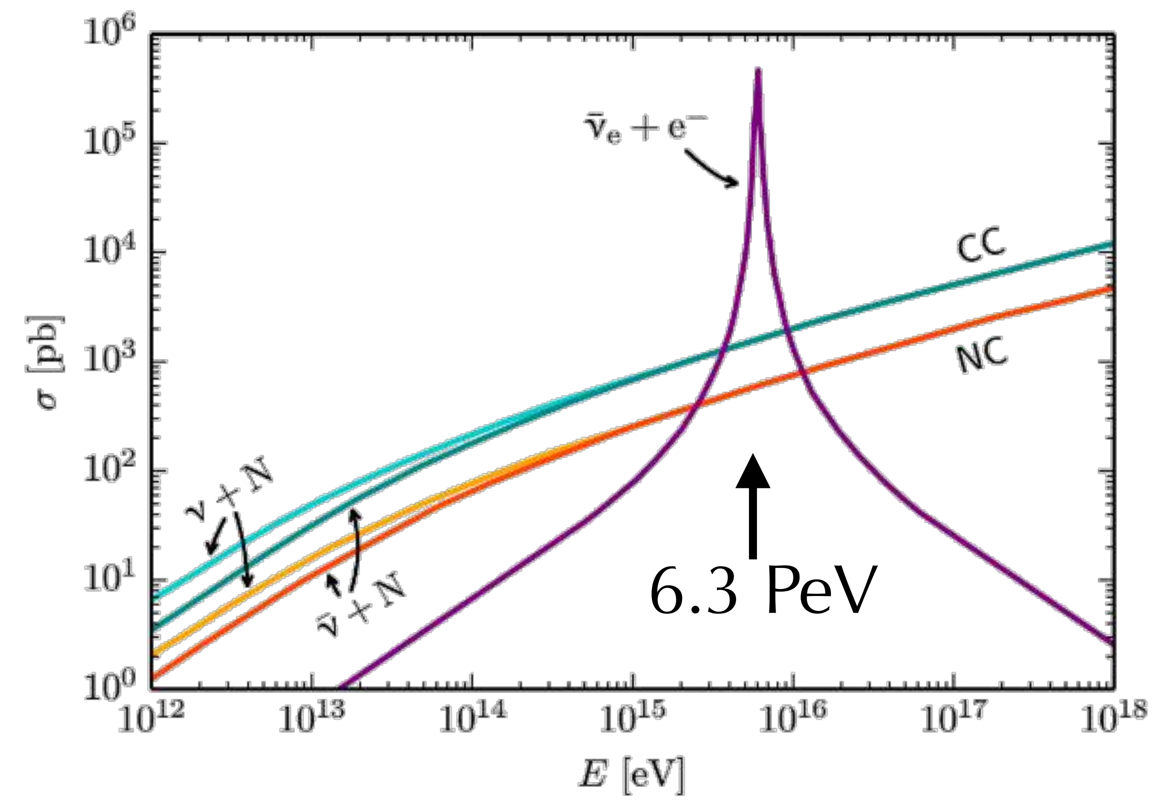
Glashow resonance candidate

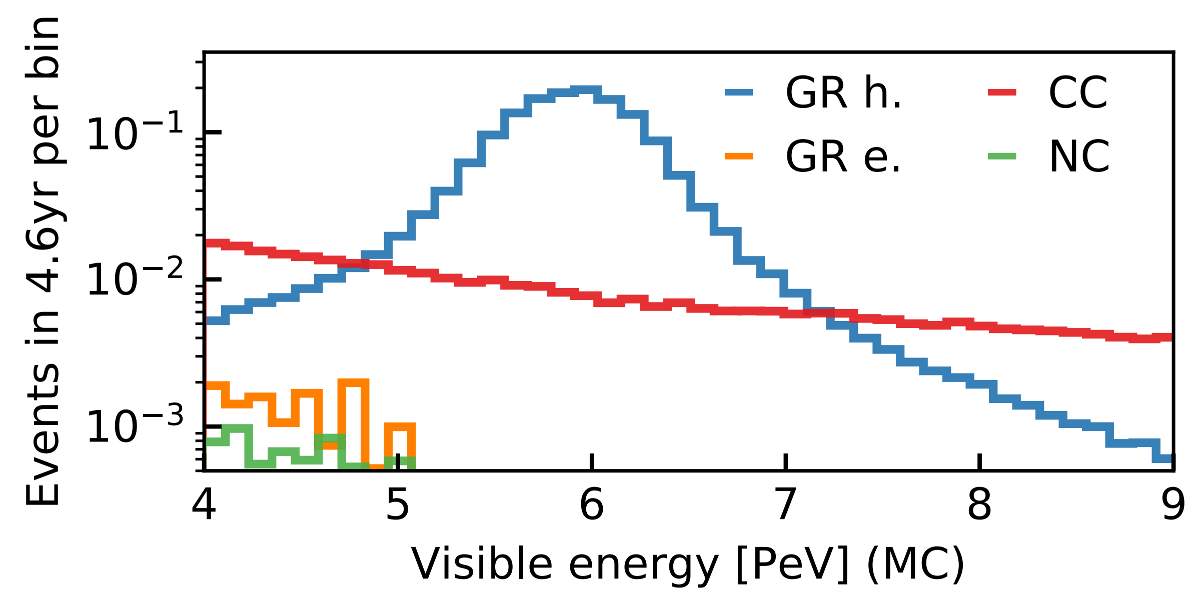


Resonant interaction of **electron anti-neutrinos** with electrons at 6.3PeV:

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

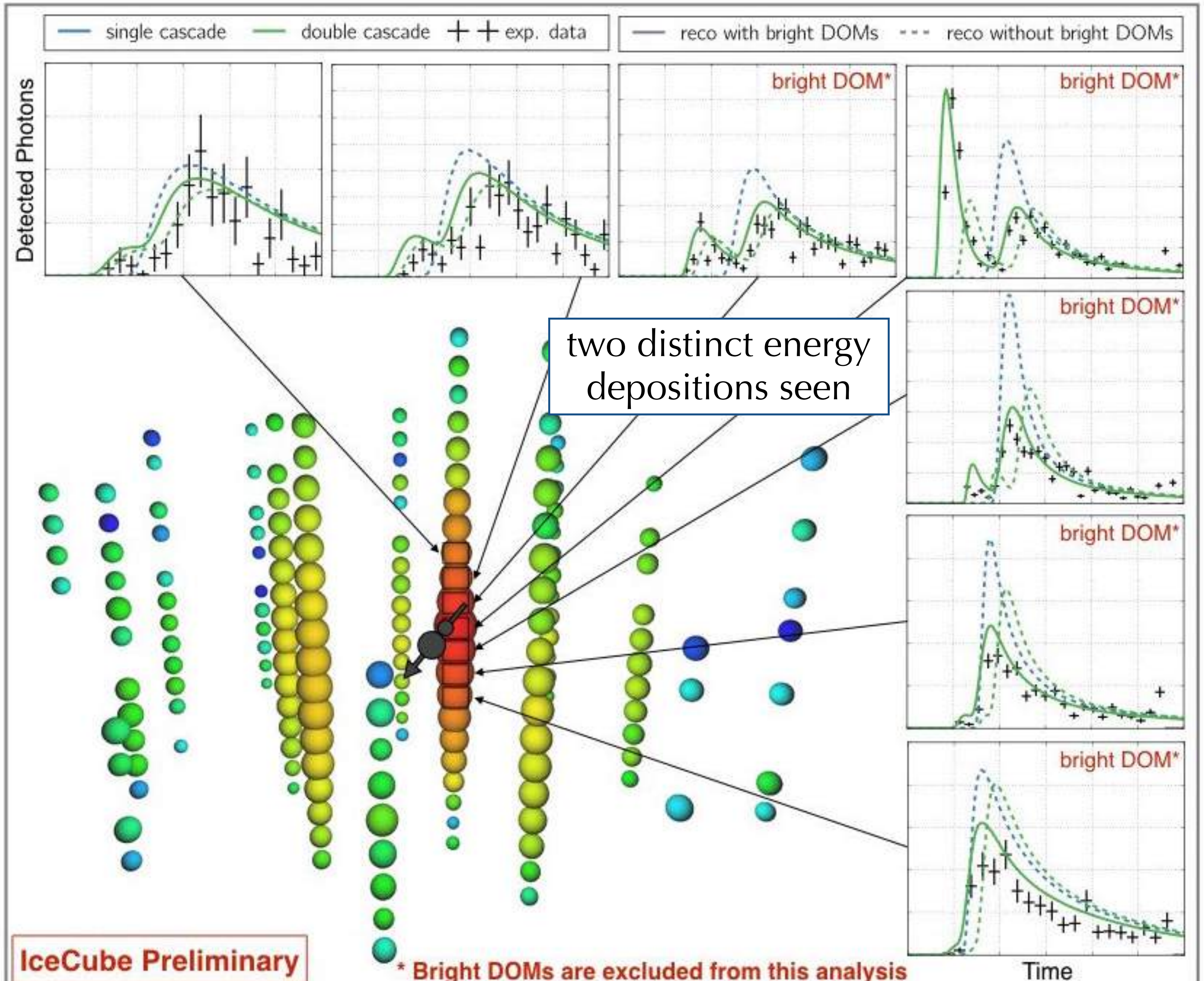




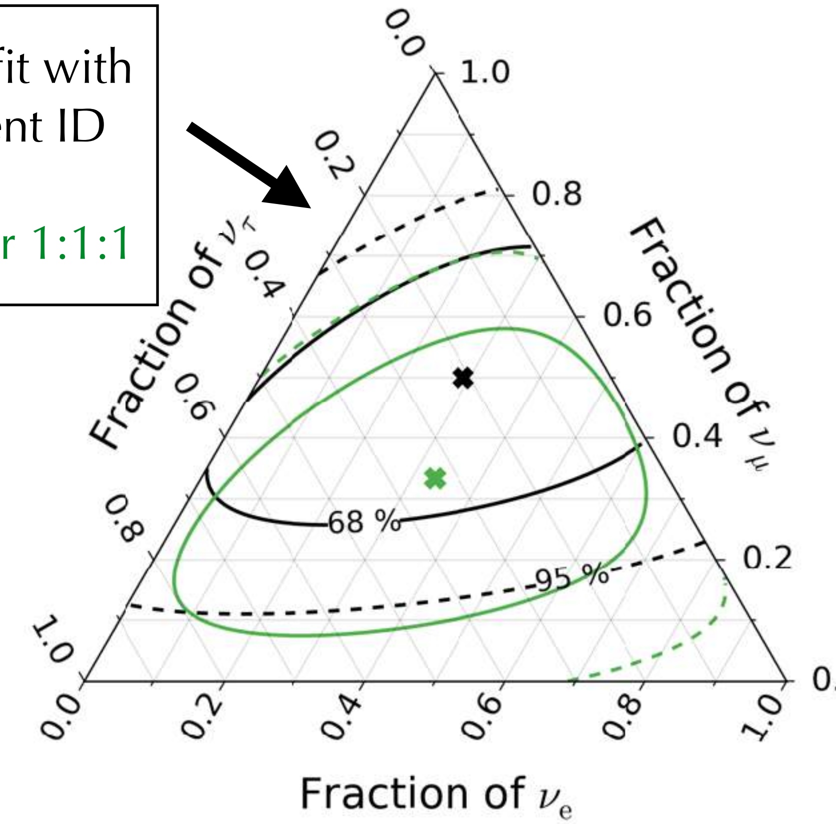


Astrophysical Flavours

tau neutrino candidate



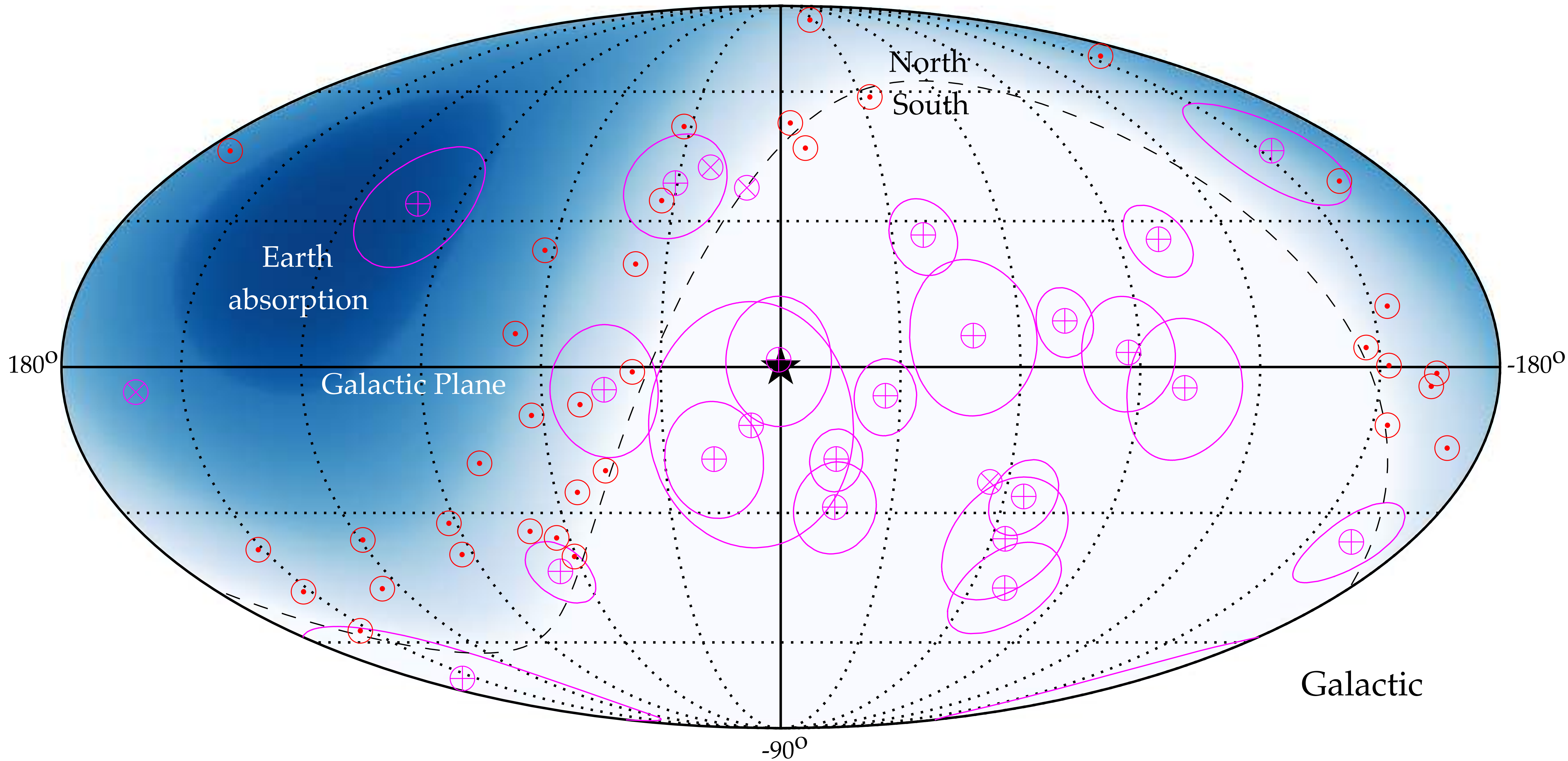
HESE 7.5yr fit with ternary event ID & sensitivity for 1:1:1



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

Status of Neutrino Astronomy

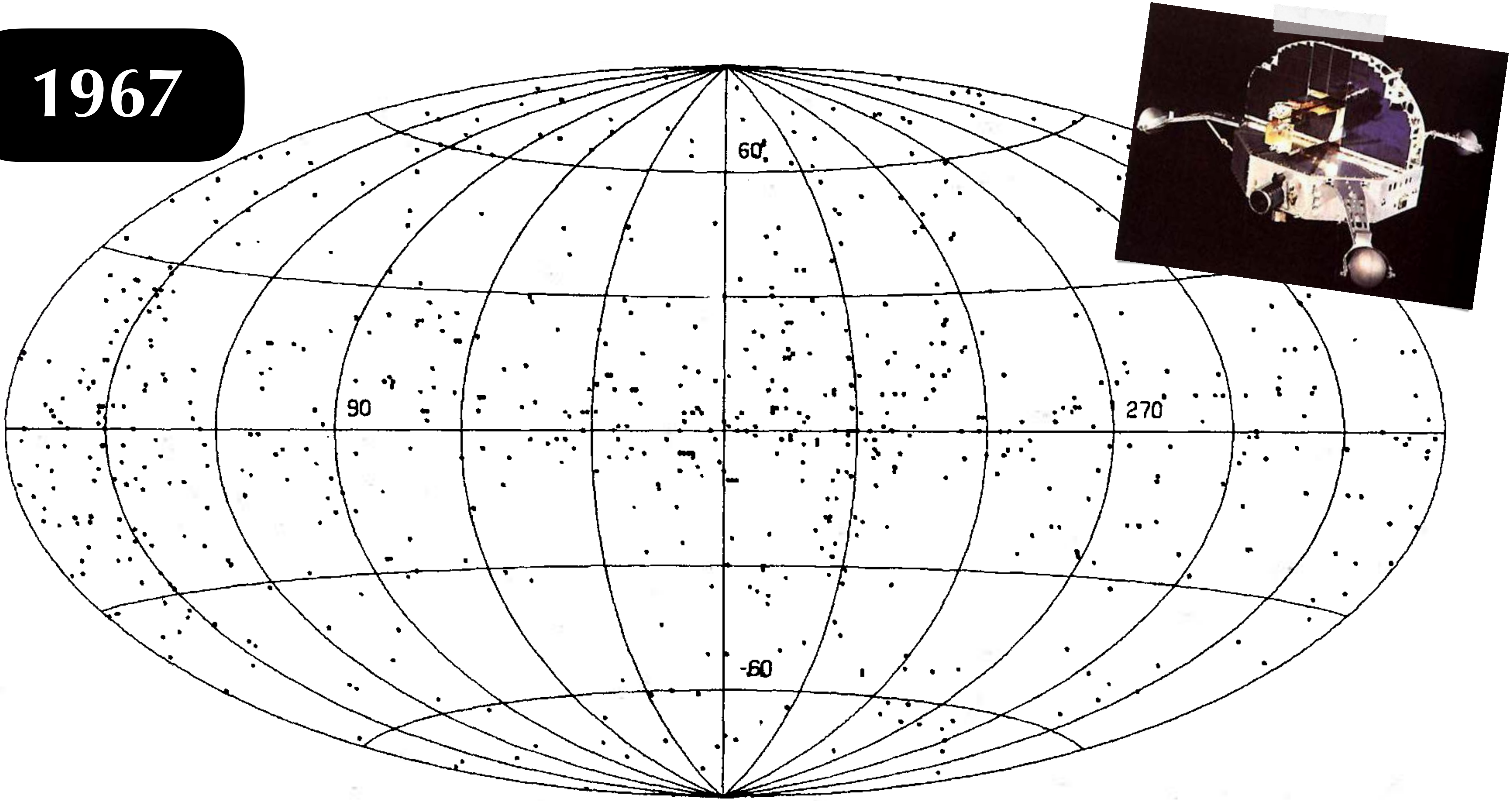
Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \overline{\nu}_\mu$ 8yr (red))



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

Status of Neutrino Astronomy

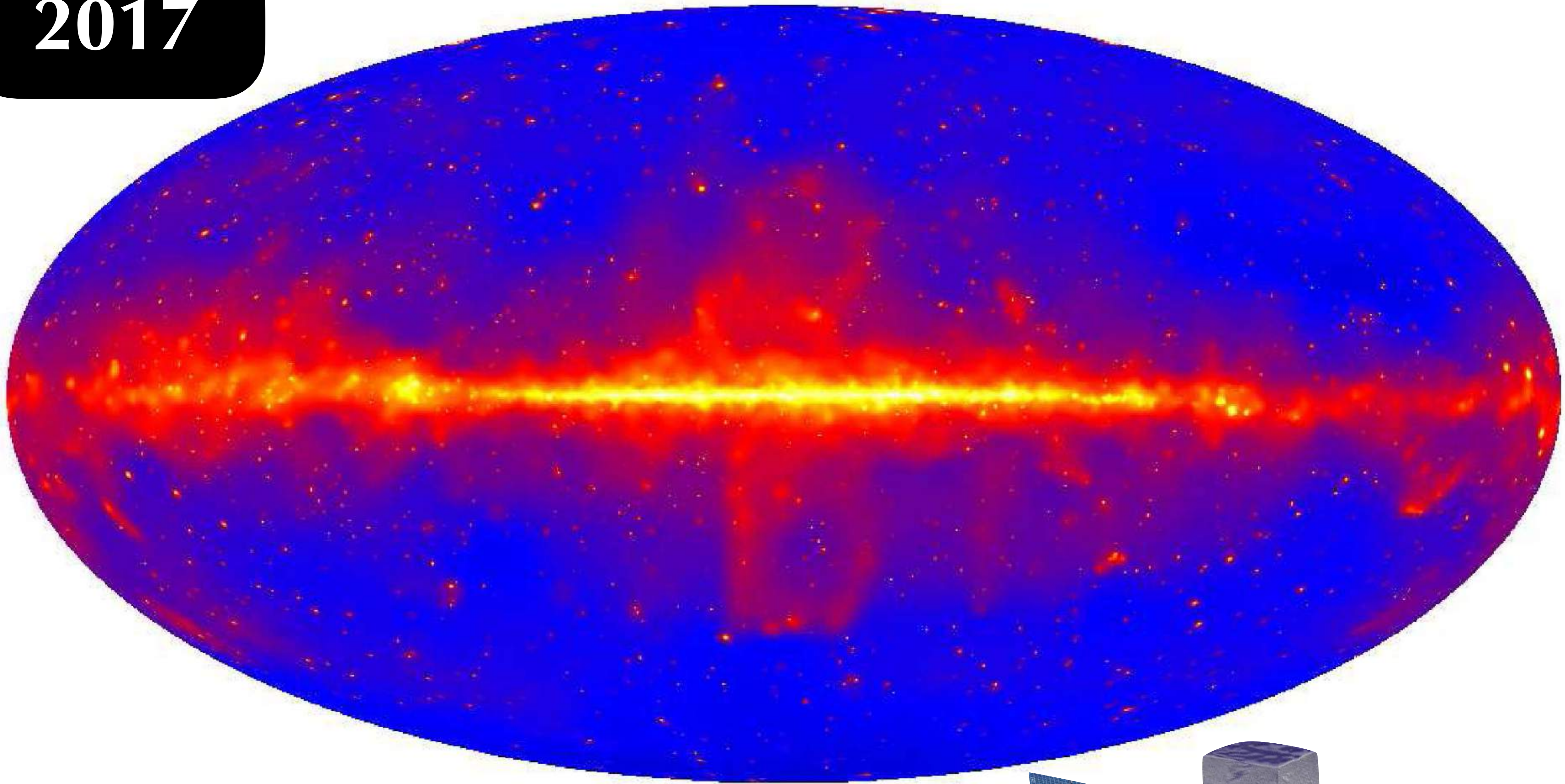
1967



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

Status of Neutrino Astronomy

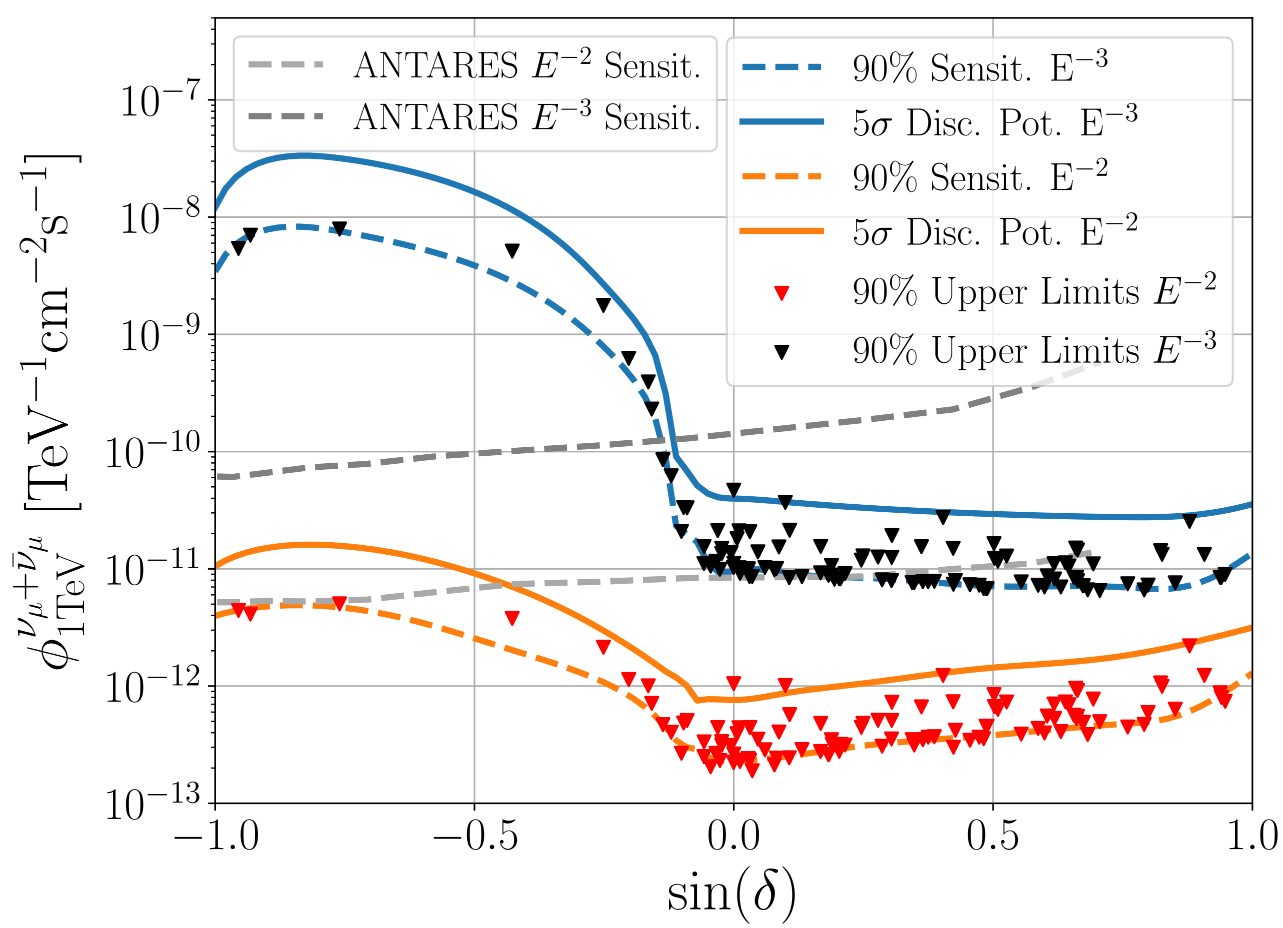
2017

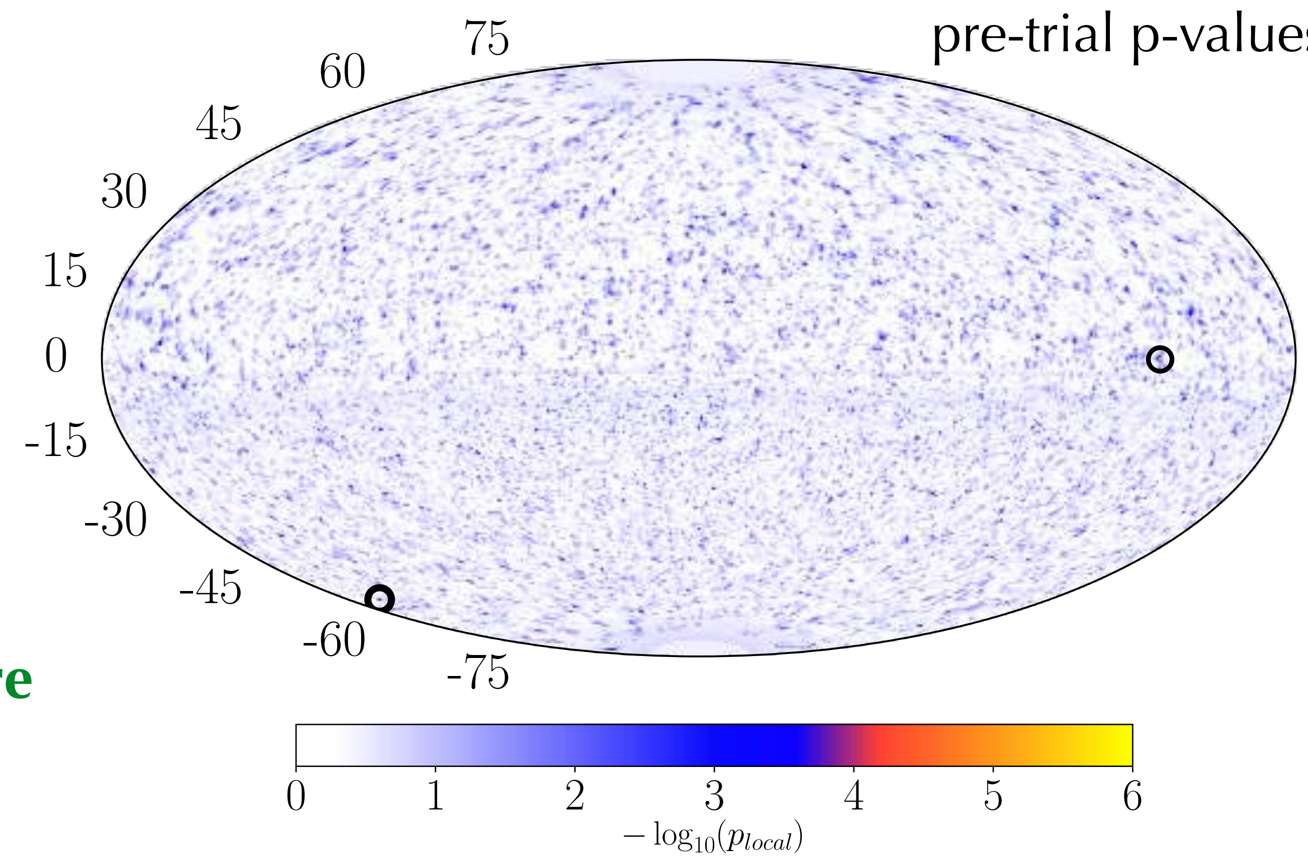


Fermi-LAT gamma-ray count map

IceCube and ANTARES/KM3NeT with complementary field of views.

Southern Hemisphere | Northern Hemisphere





[IceCube, PRL 124 (2020) 051103]

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

Point Source vs. Diffuse Flux

Populations of extragalactic neutrino sources can be visible

individual sources

or by the

combined isotropic emission.

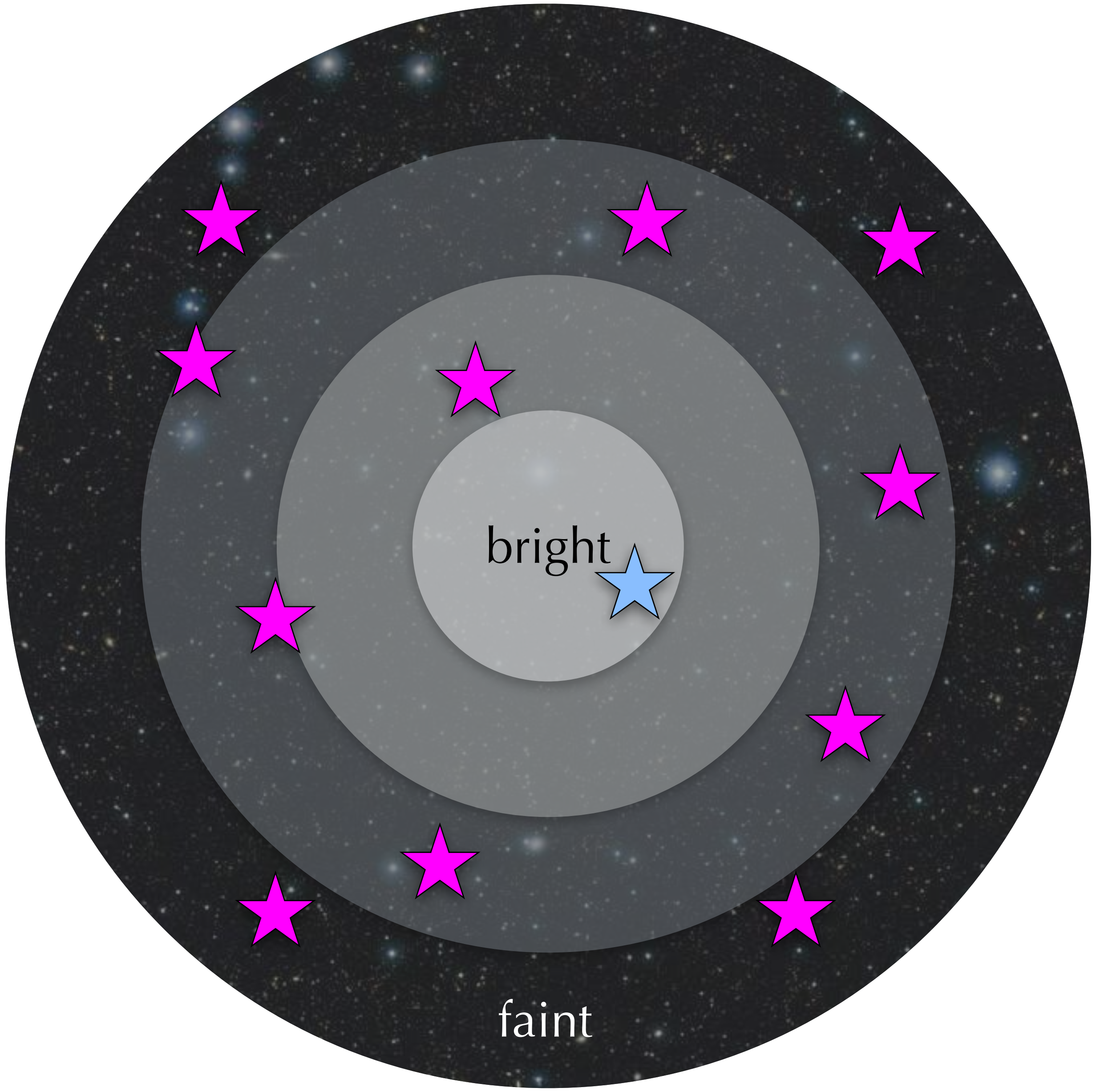
The relative contribution can be parametrized (*to first order*) by the average

local source density

and

source luminosity.

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

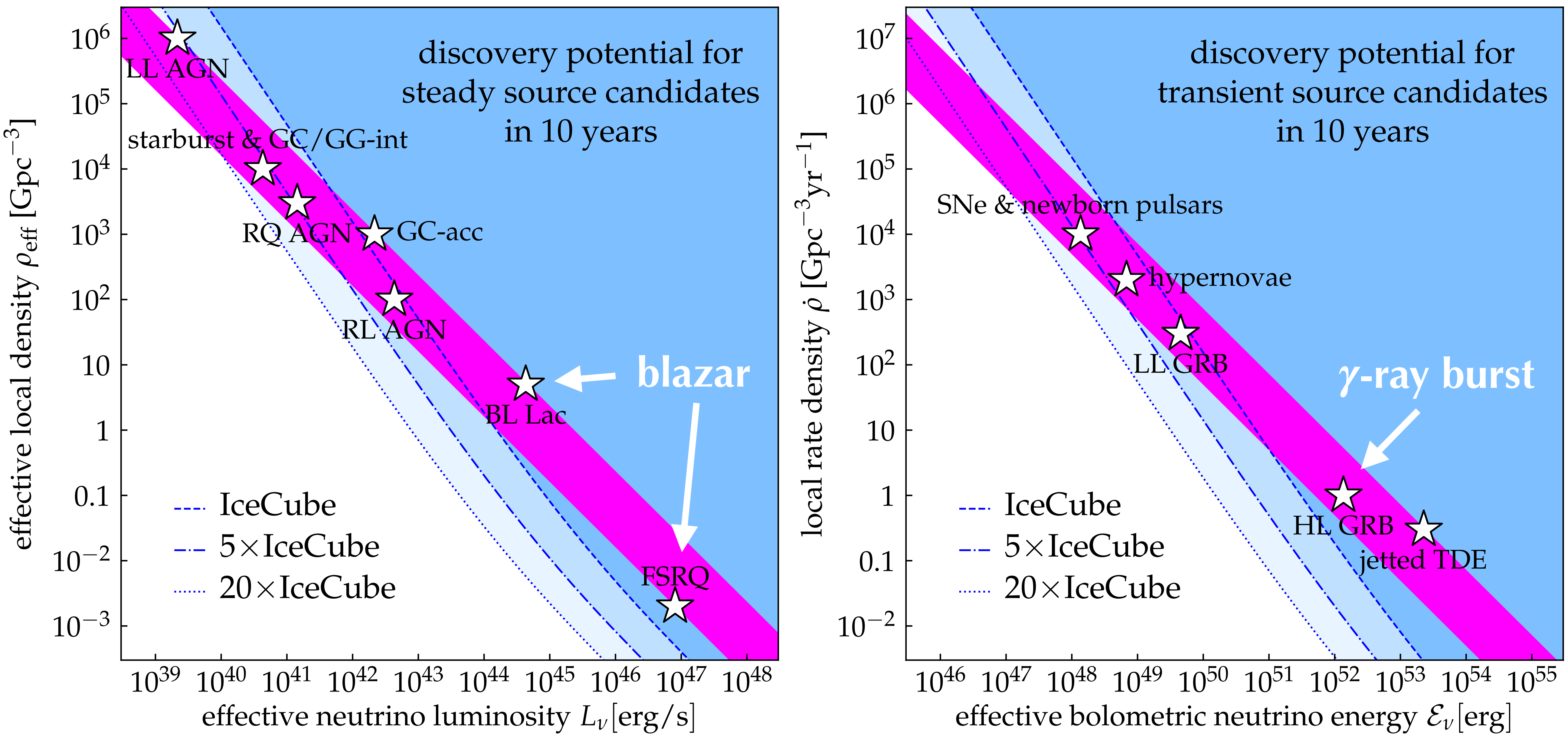


Hubble horizon

Point Source vs. Diffuse Flux

Neutrino sources are hiding in plain sight.

Point Source vs. Diffuse Flux

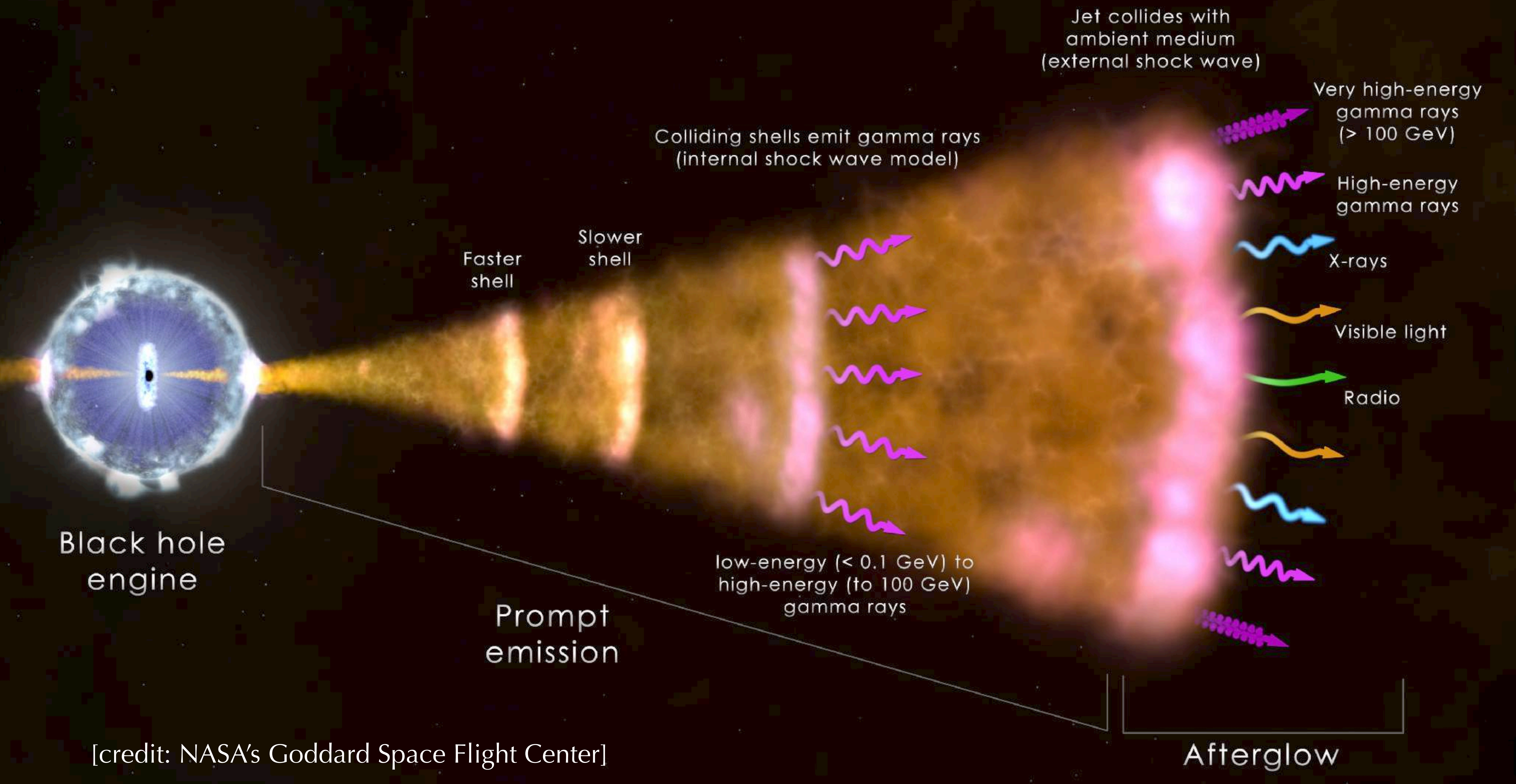


[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04334]

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

Gamma-Ray Bursts

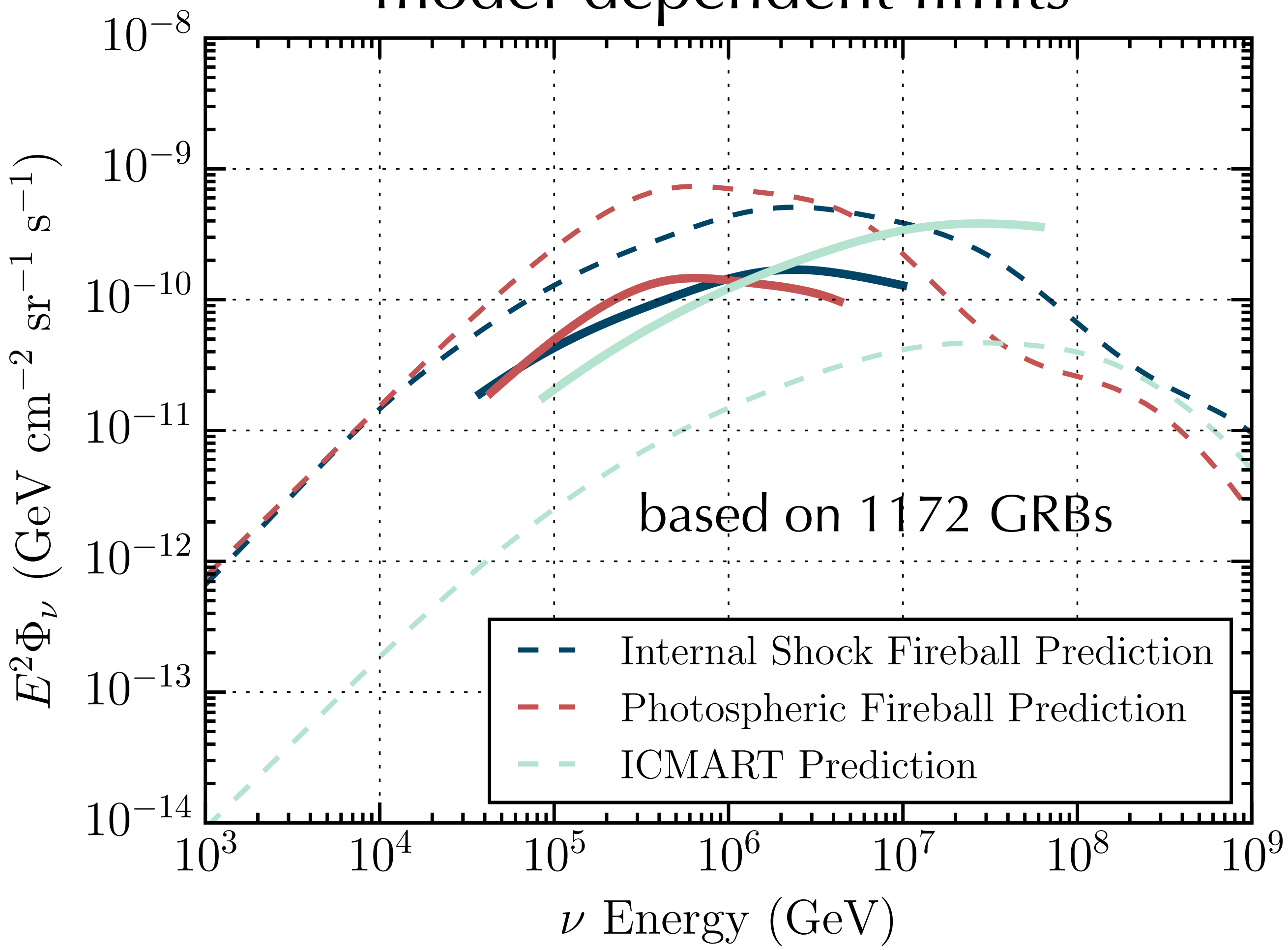
High-energy neutrino emission is predicted by cosmic ray interactions with radiation at various stages of the GRB evolution.



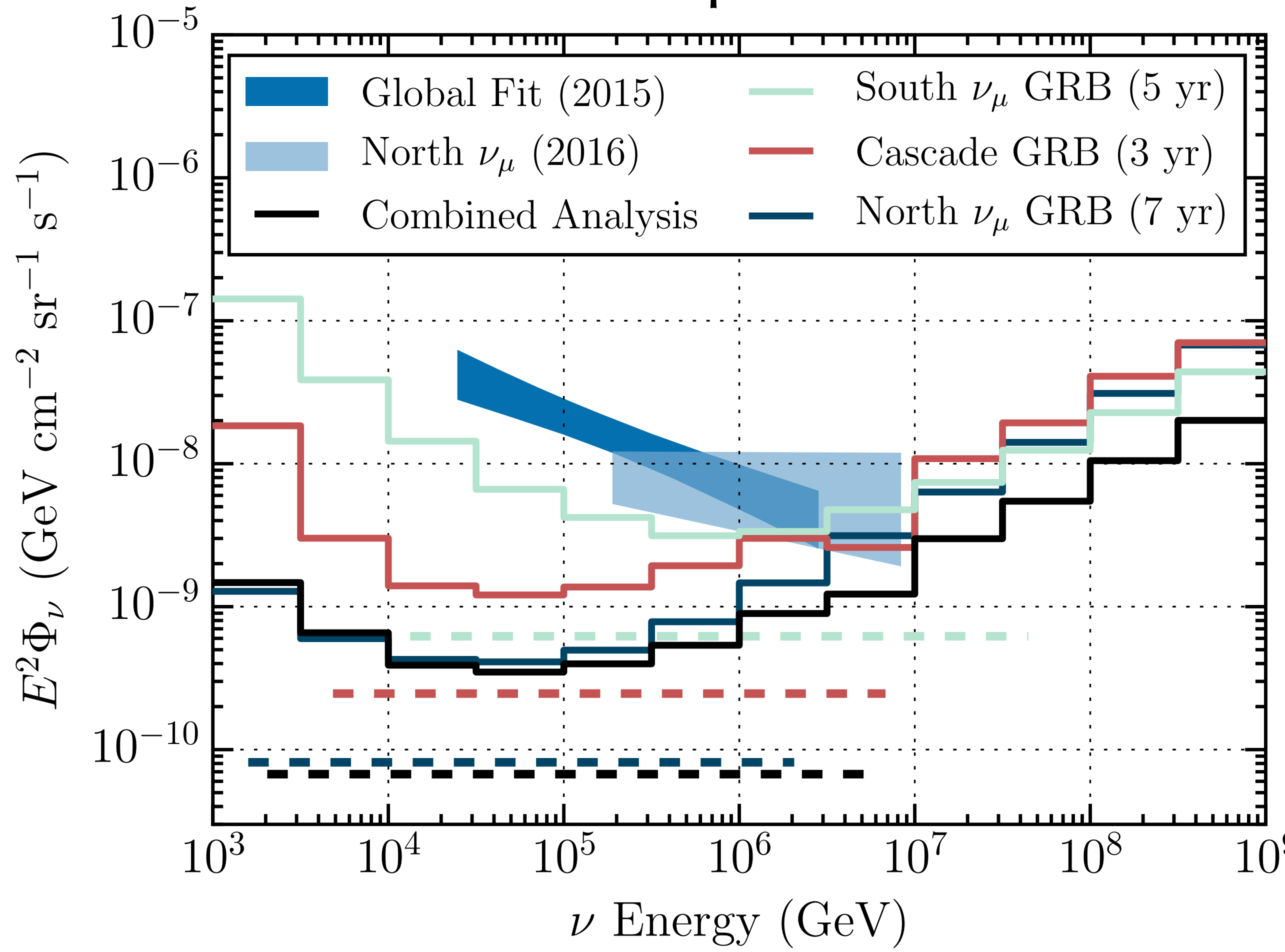
[credit: NASA's Goddard Space Flight Center]

- 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]

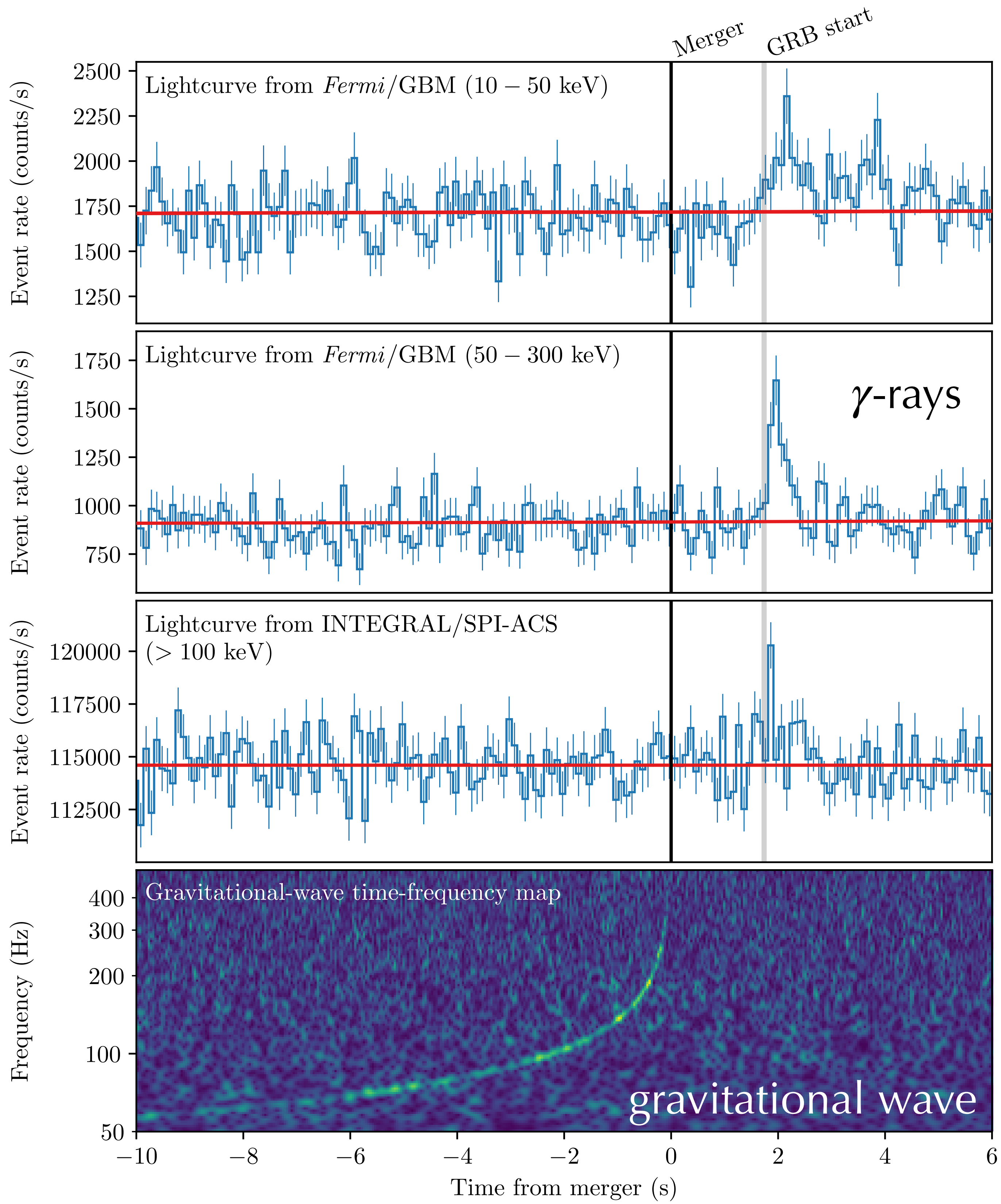
model-dependent limits



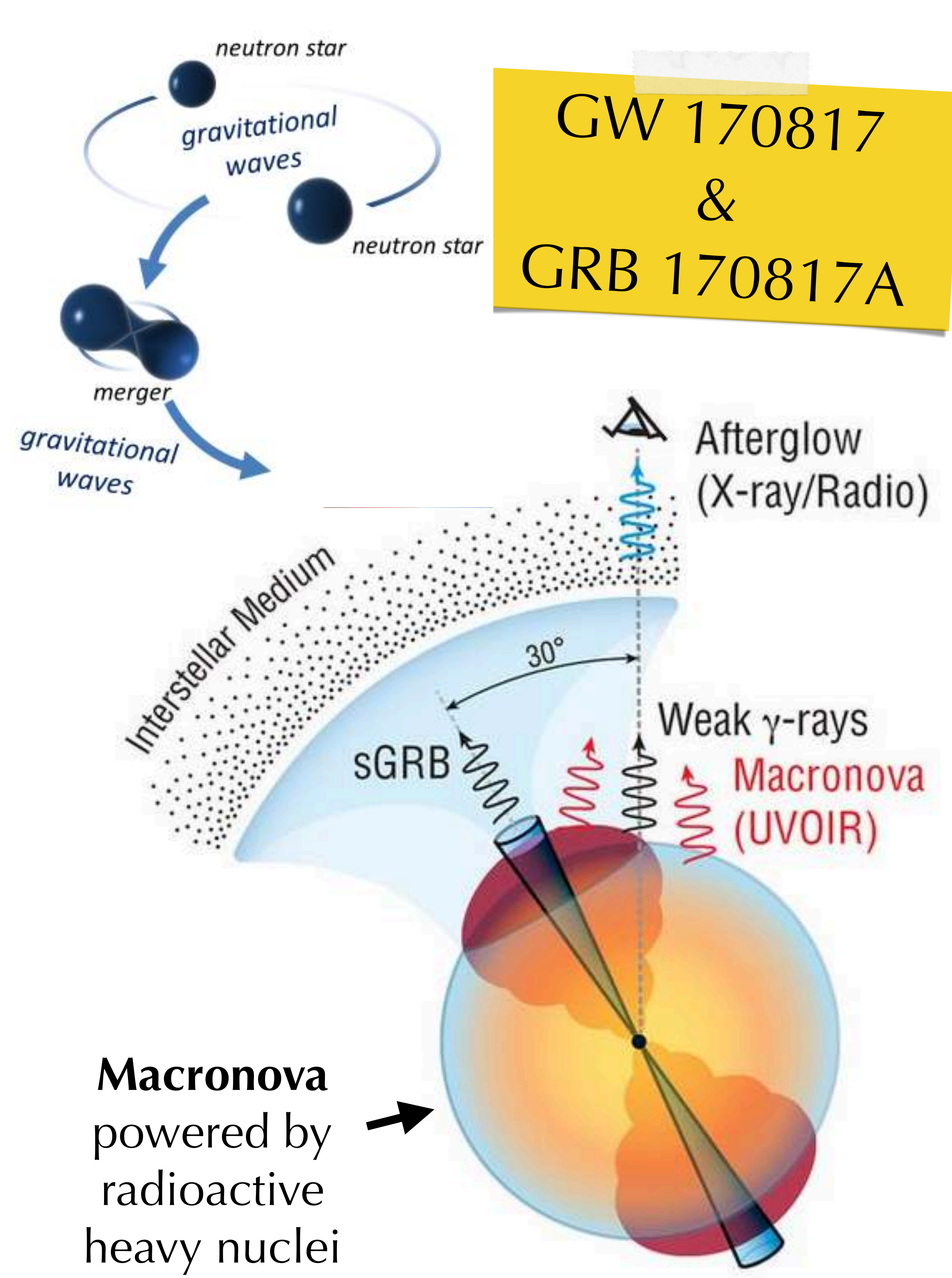
model-independent limits



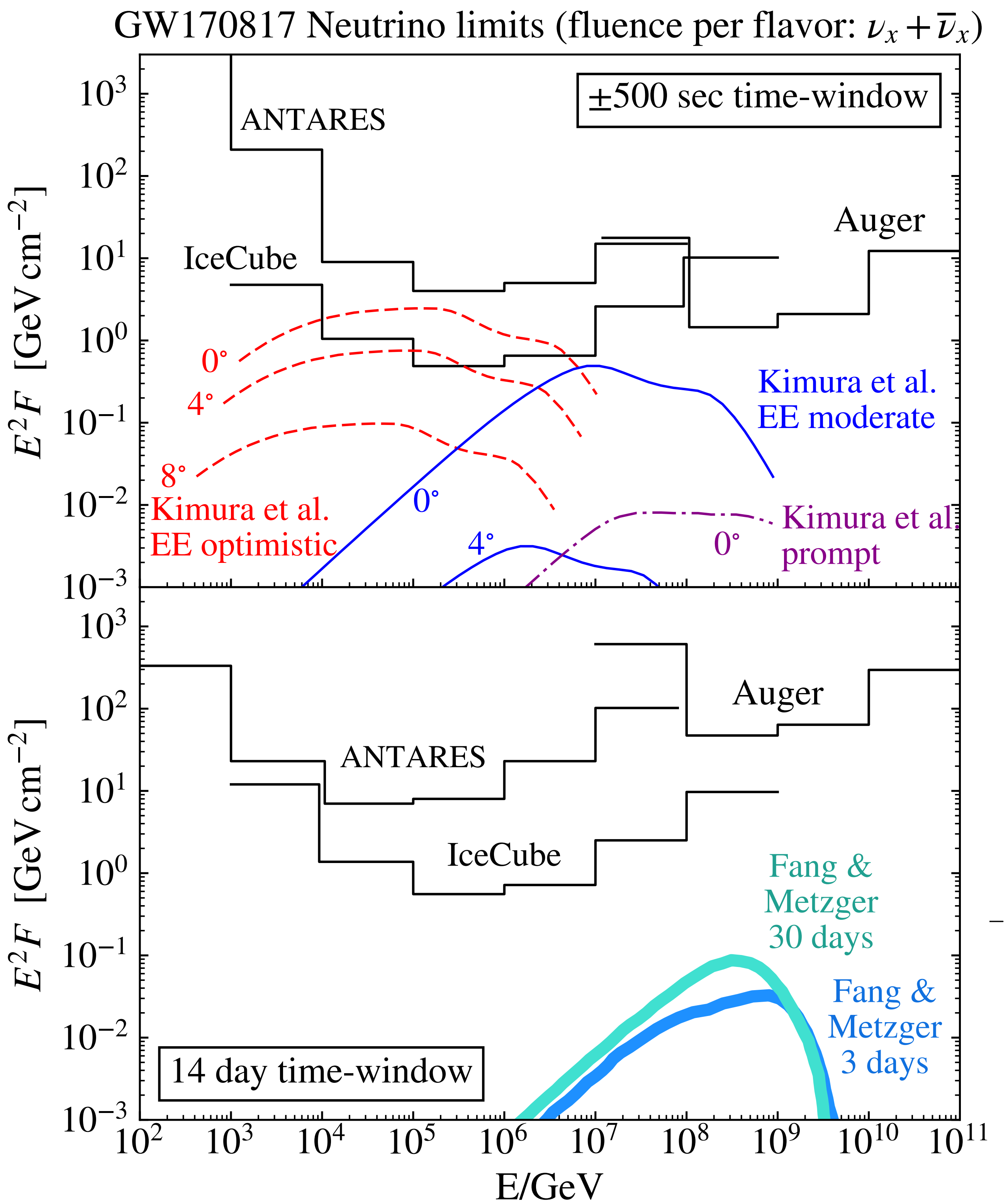
GRBs and Gravitational Waves



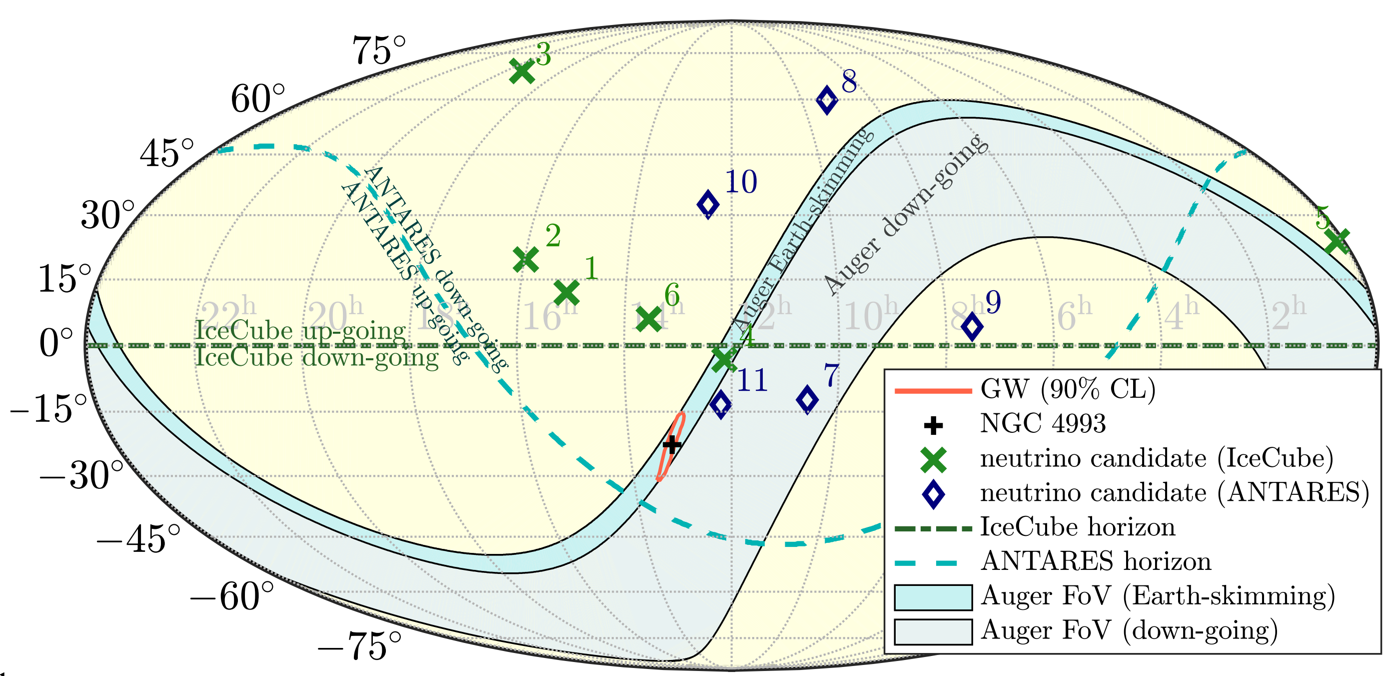
[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]



GRB 170817A



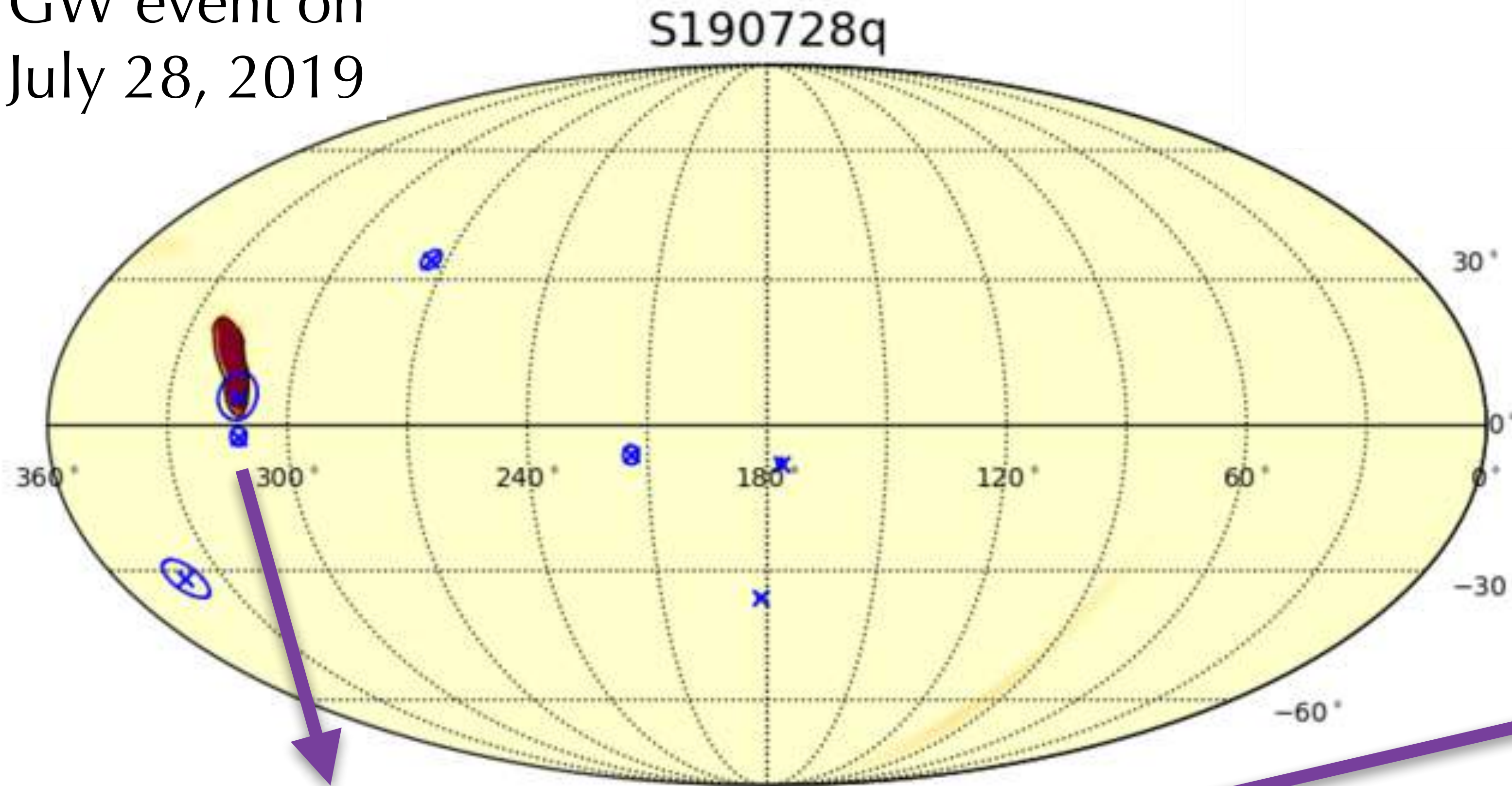
- No coincident neutrinos observed by IceCube, ANTARES or Auger.
- Consistent with predicted neutrino flux from internal shocks and **off-axis viewing angle.**



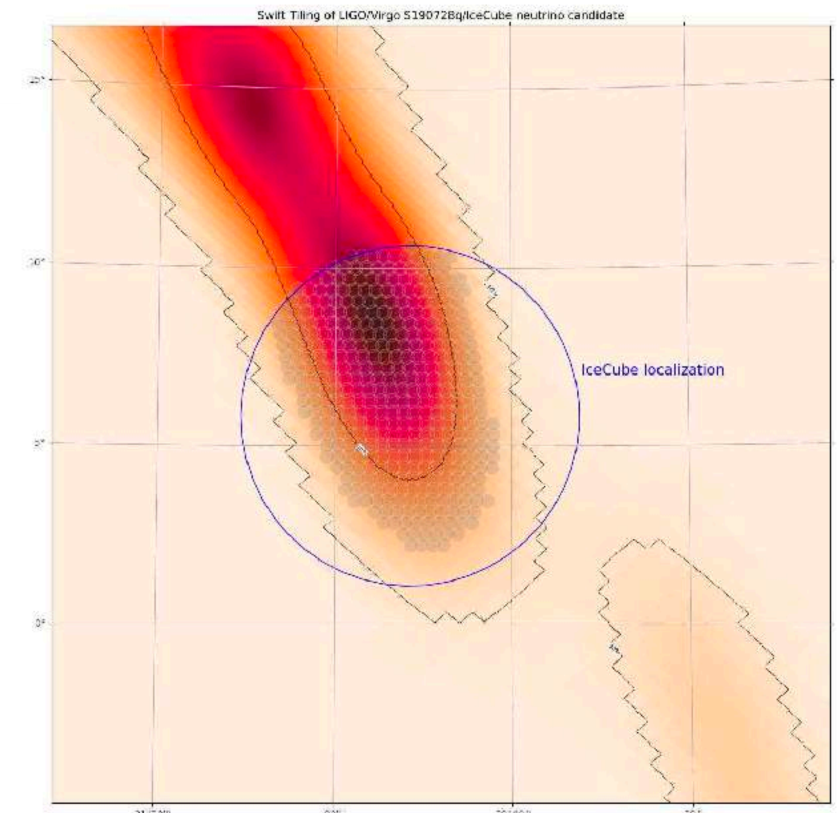
[ANTARES, IceCube, Auger & LVC, ApJ 850 (2017) 2]

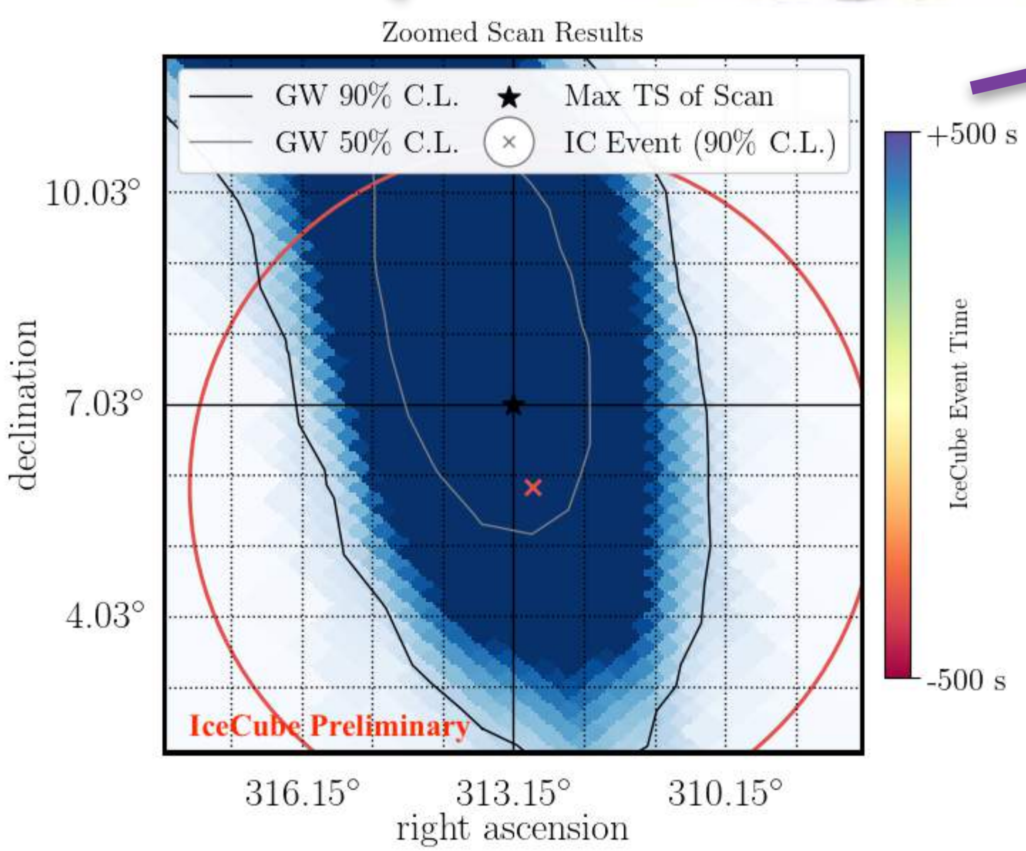
Gravitational Wave Follow-Up

GW event on July 28, 2019



Swift-XRT search tiling

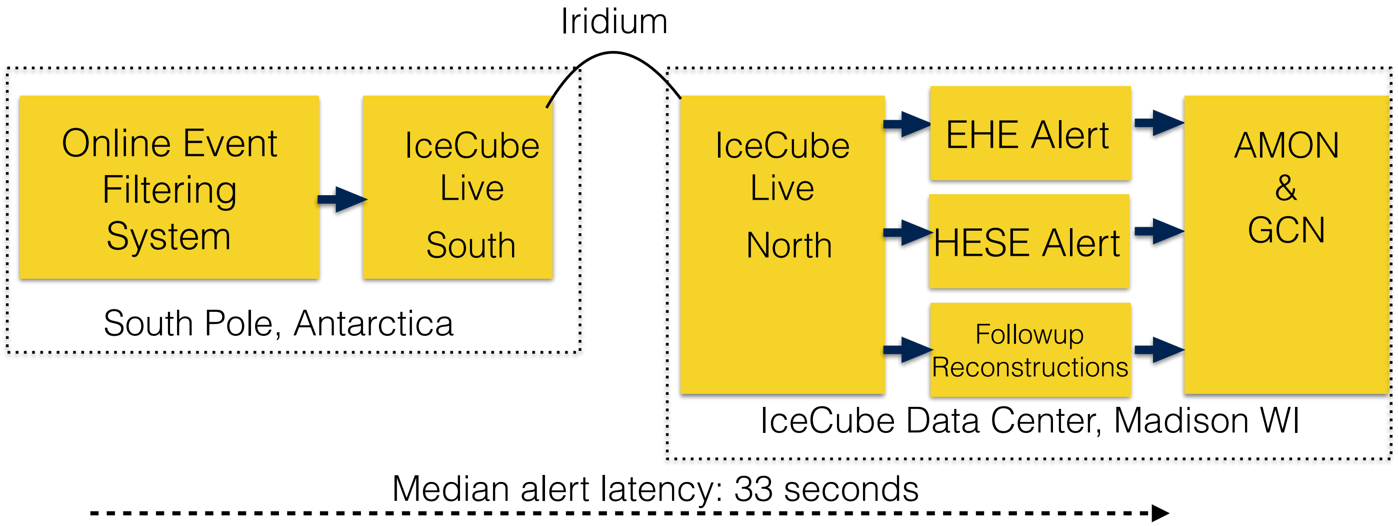


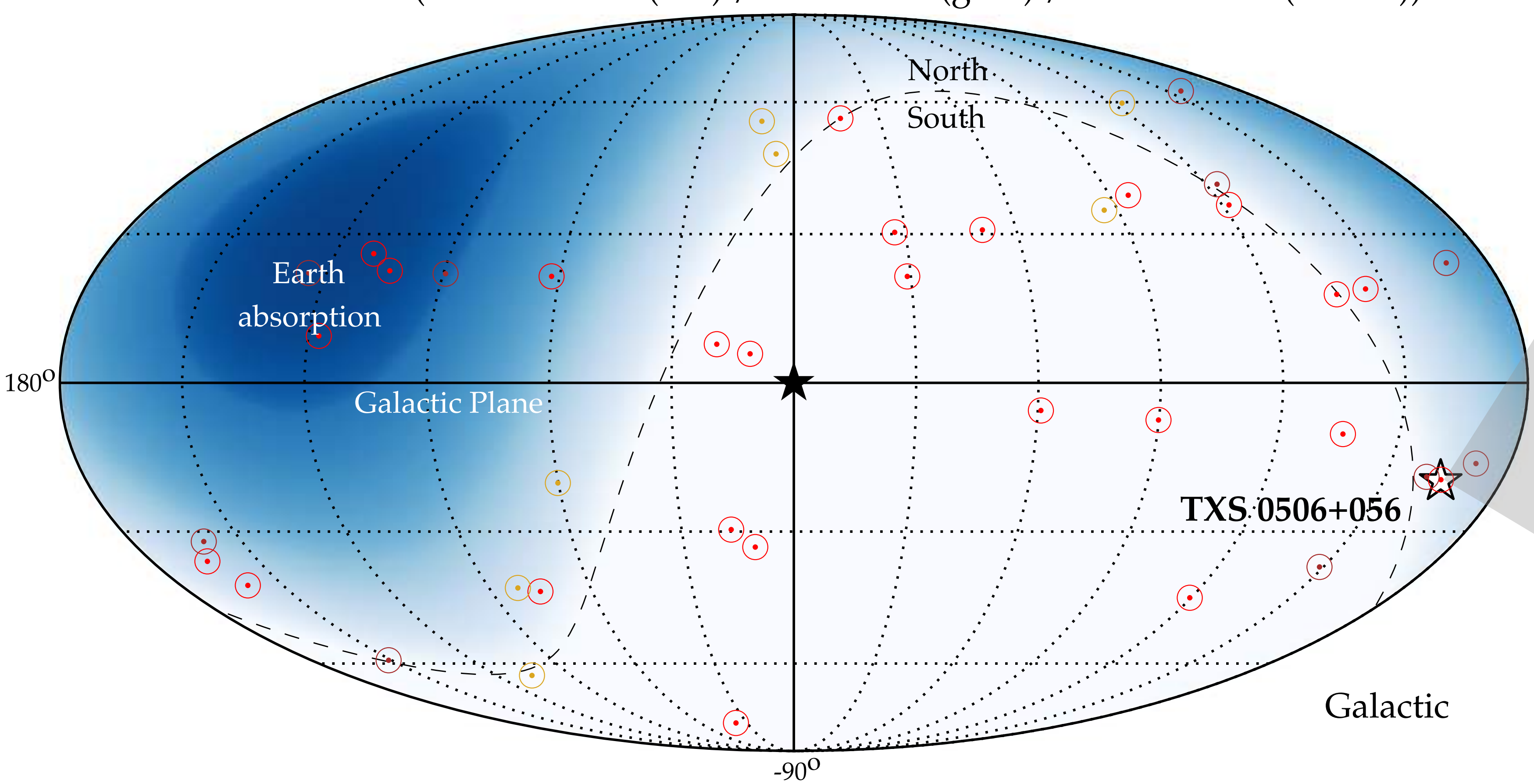


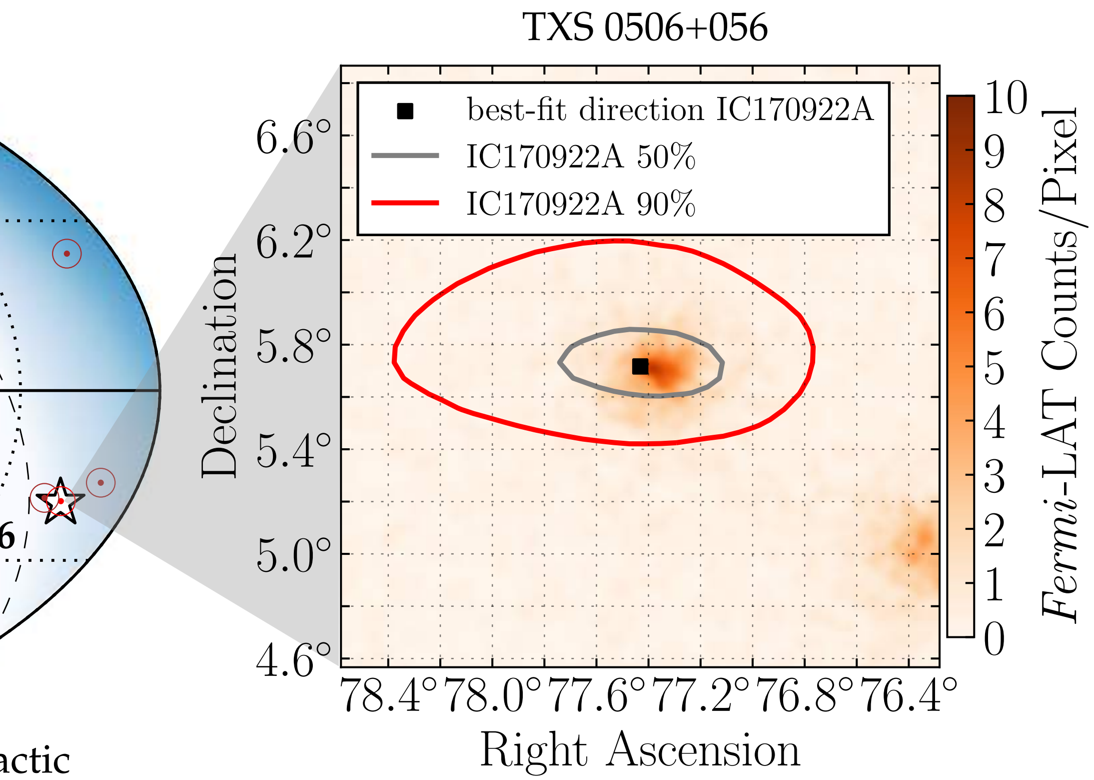
- IceCube responds to public LIGO/Virgo alerts with low latency.
- Astrophysical neutrino candidates released if background probability <1%.
- Neutrino information allows to tailor EM follow-up of pointing observatories.

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

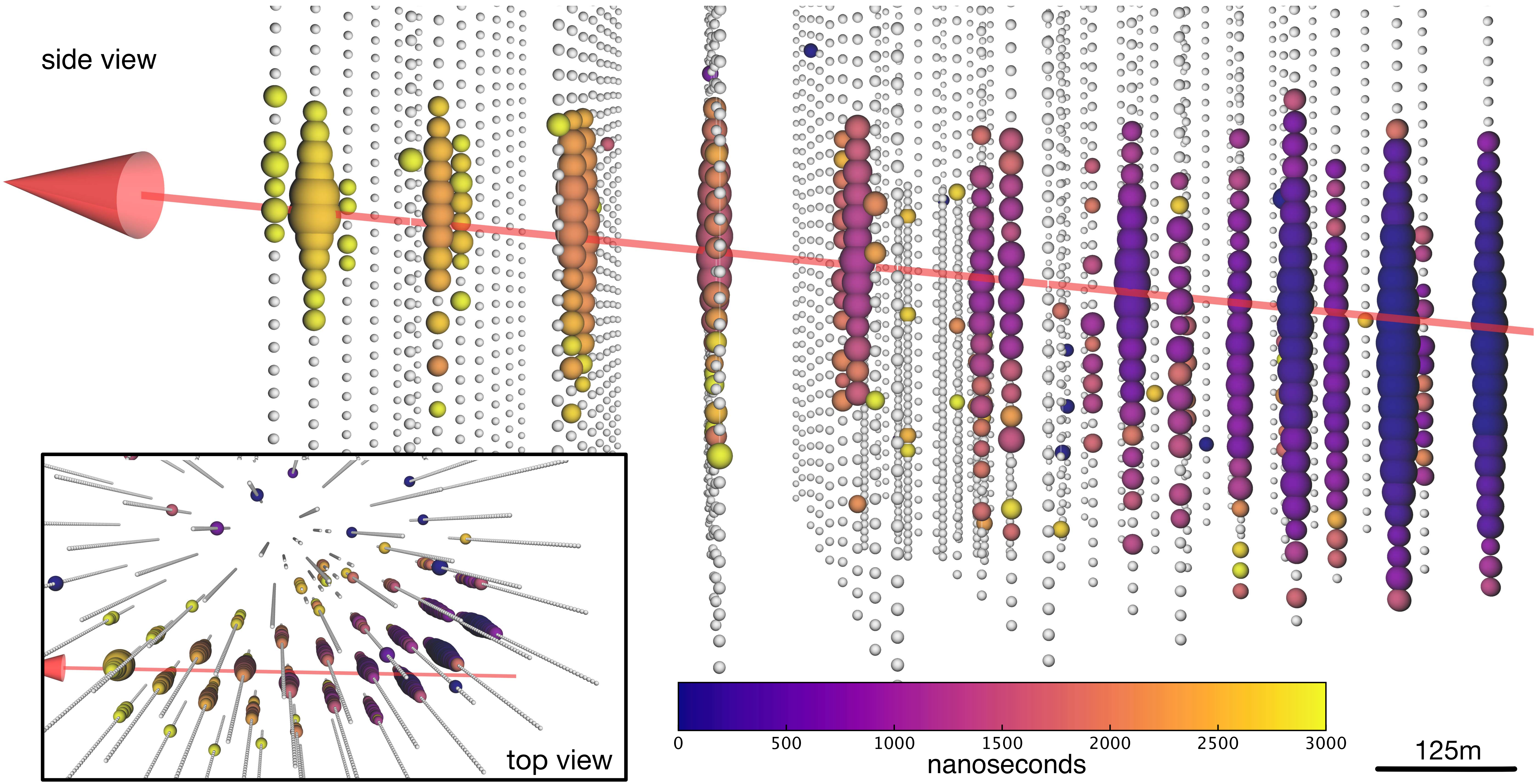






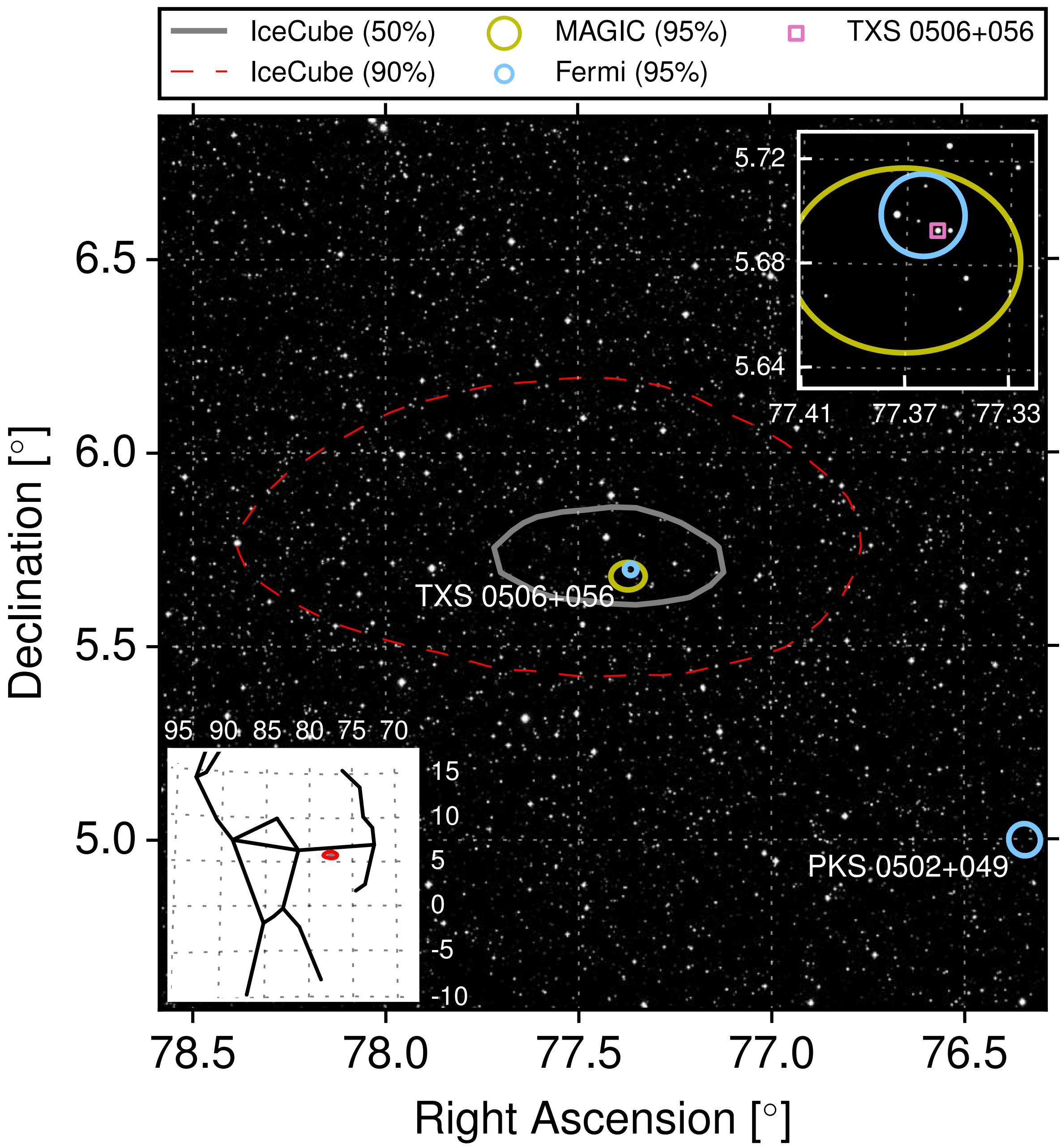
Realtime Neutrino Alerts

IC-170922A



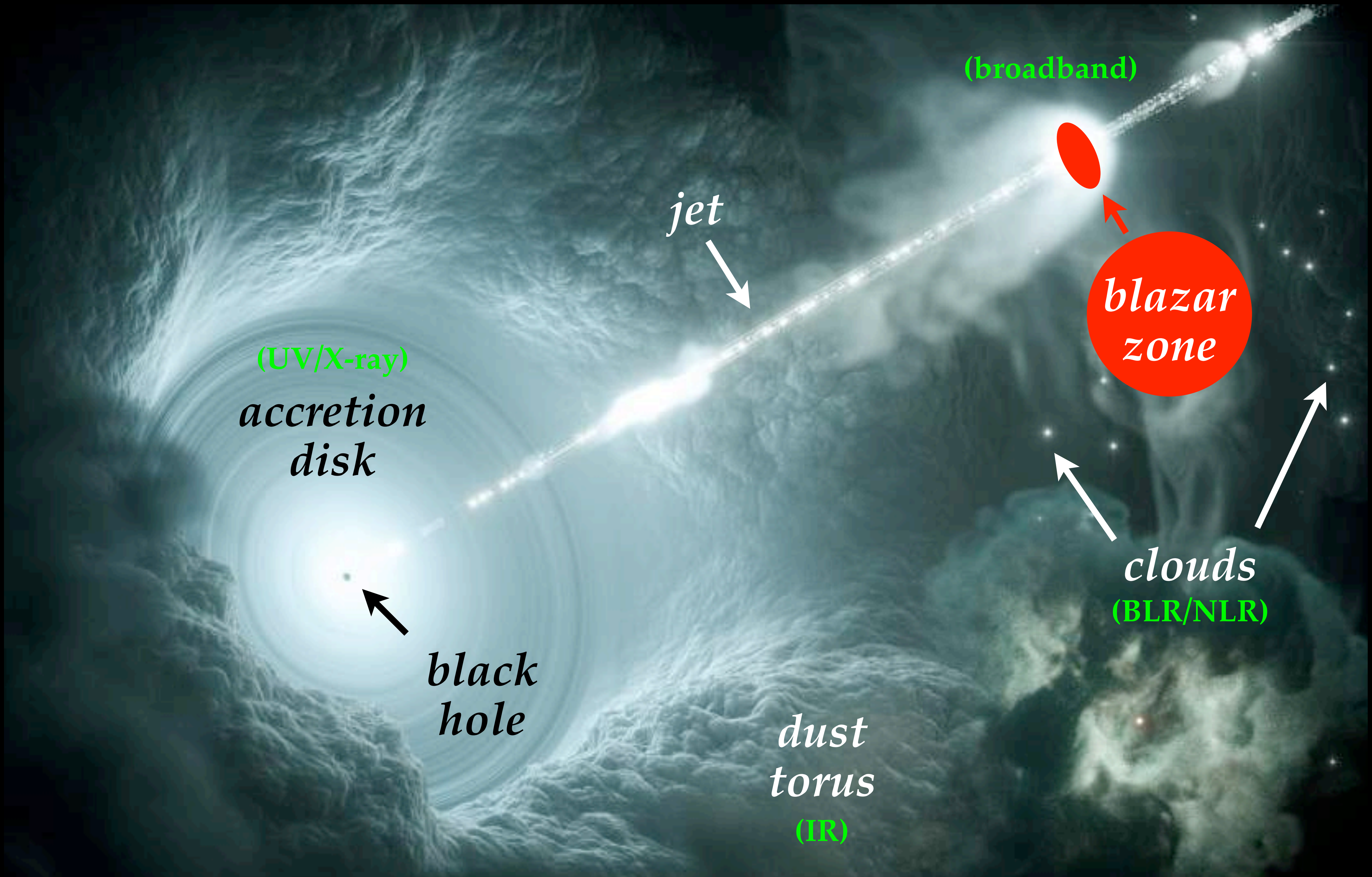
up-going muon track (5.7° below horizon) observed September 22, 2017
best-fit neutrino energy is about 300 TeV

TXS 0506+056



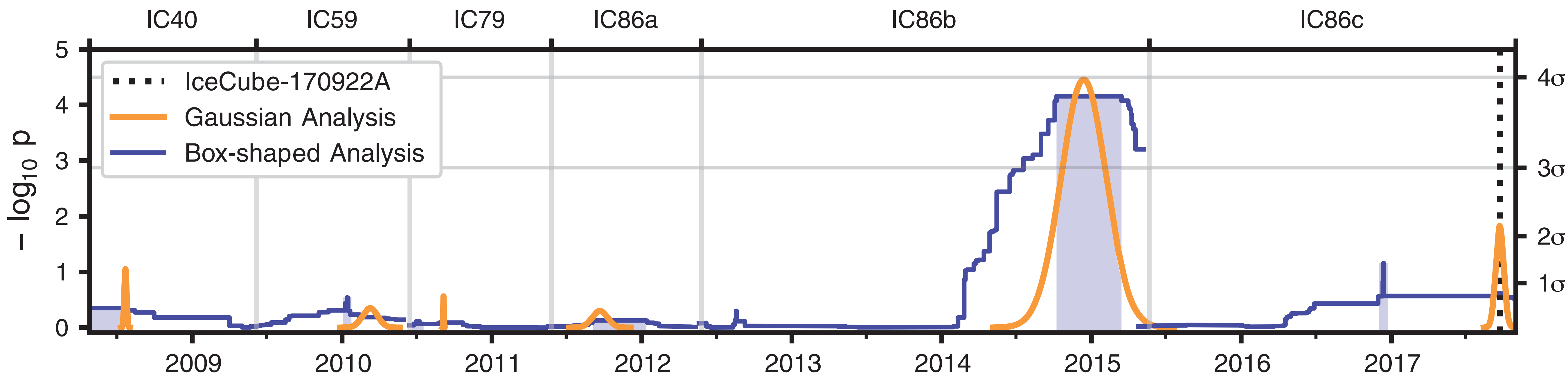
- IC-170922A observed in coincident with **flaring blazar TXS 0506+056**.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the most luminous BL Lac objects in gamma-rays.

Blazars as Neutrino Factories

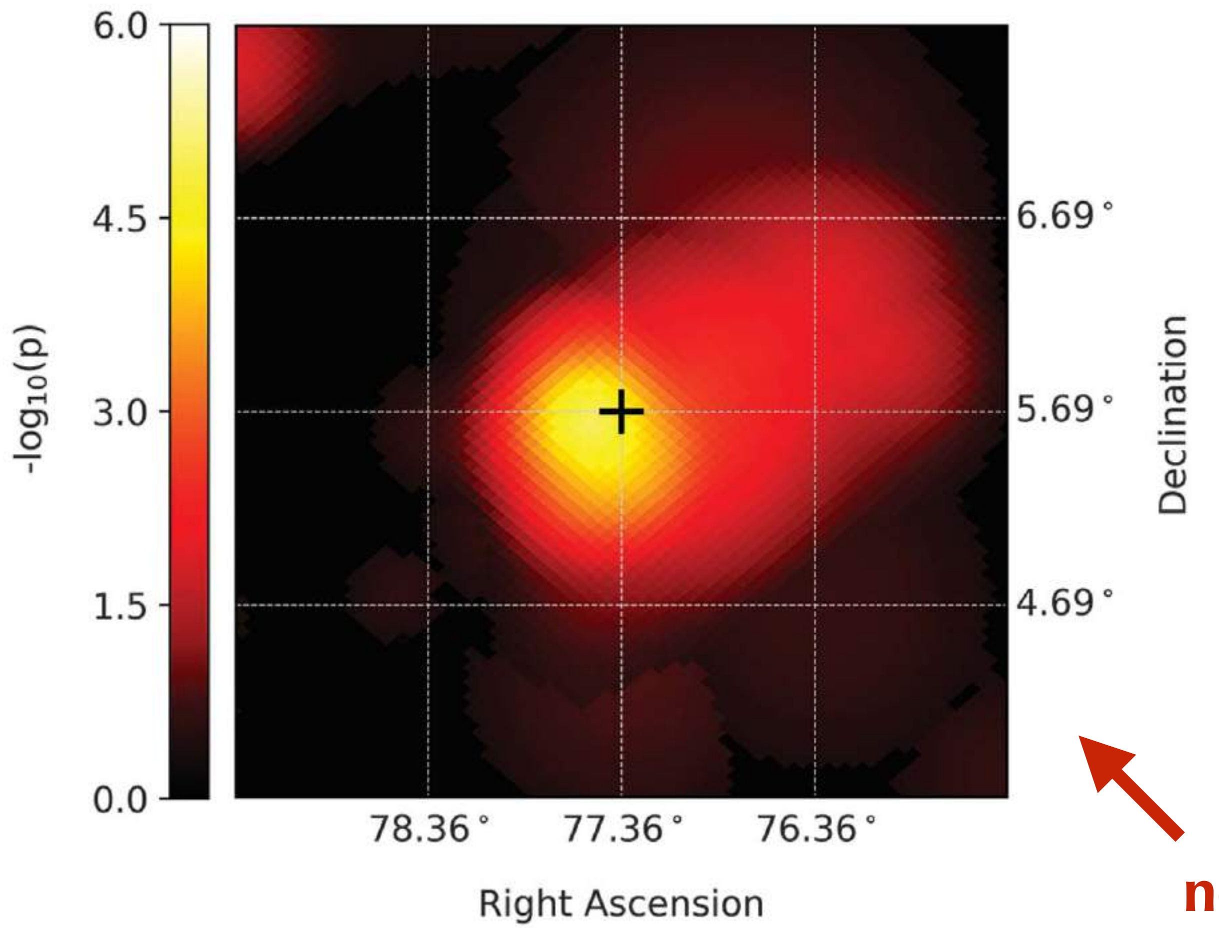


Active galaxy powered by accretion onto a supermassive black hole with **relativistic jets pointing into our line of sight**.

Neutrino Flare in 2014/15



[IceCube, Science 361 (2018) no.6398, 147-151]

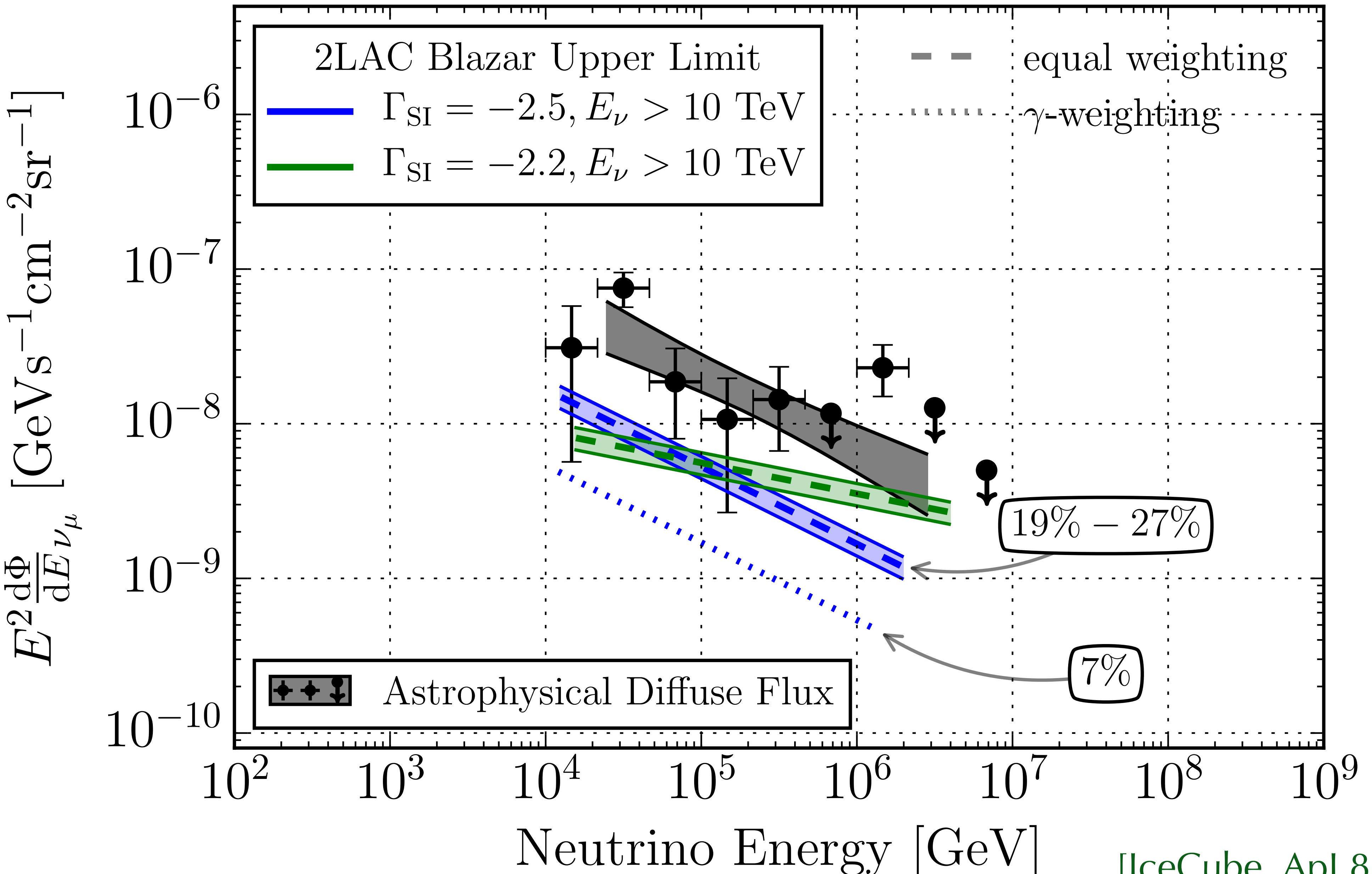


- Independent 3.5σ evidence for a **neutrino flare** (13±5 events) in 2014/15.

- Neutrino luminosity over 158 days is about **four times that of gamma-rays** (Fermi-LAT).

neutrino "morphology" of flare

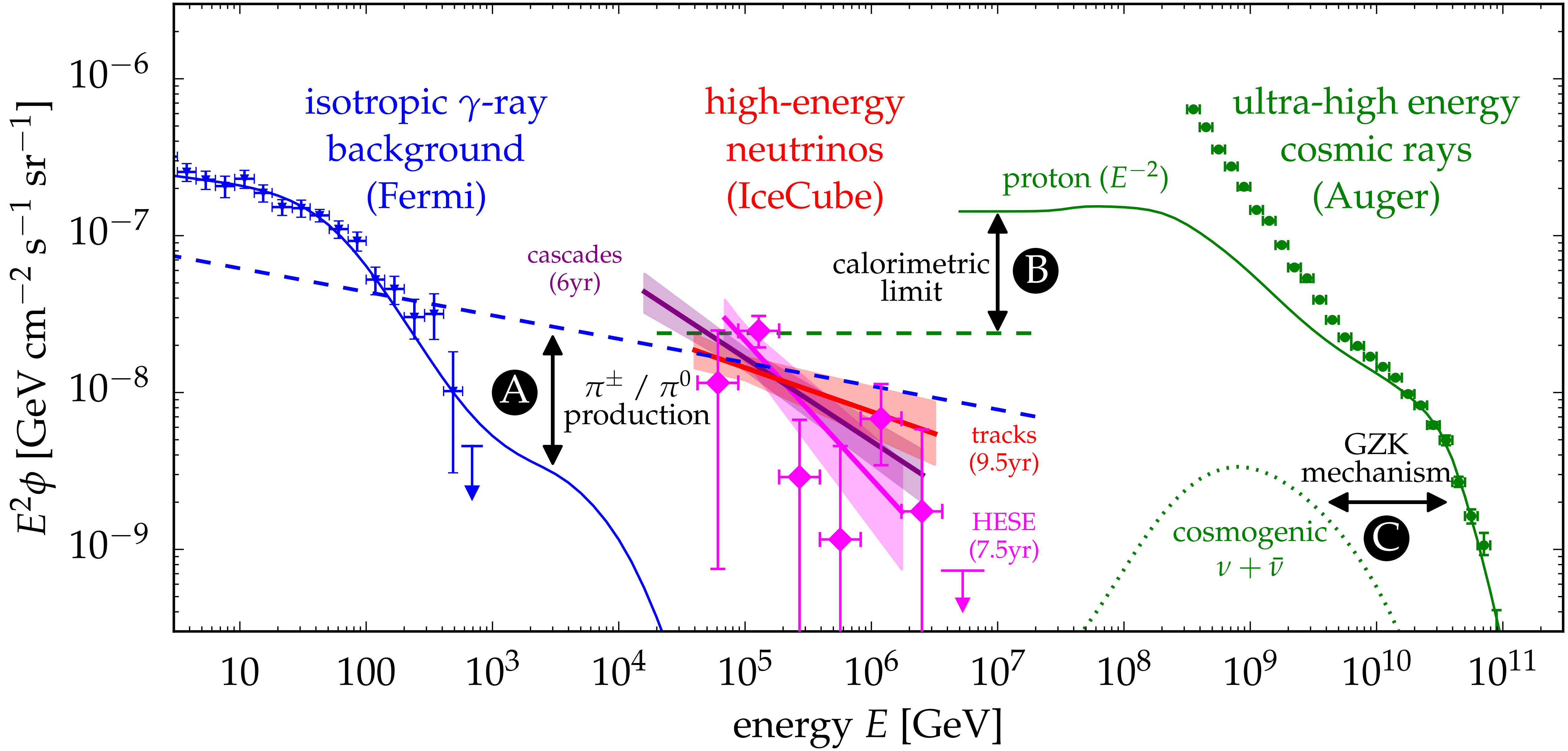
Blazar Origin of the Isotropic Flux?



[IceCube, ApJ 835 (2017) 45]

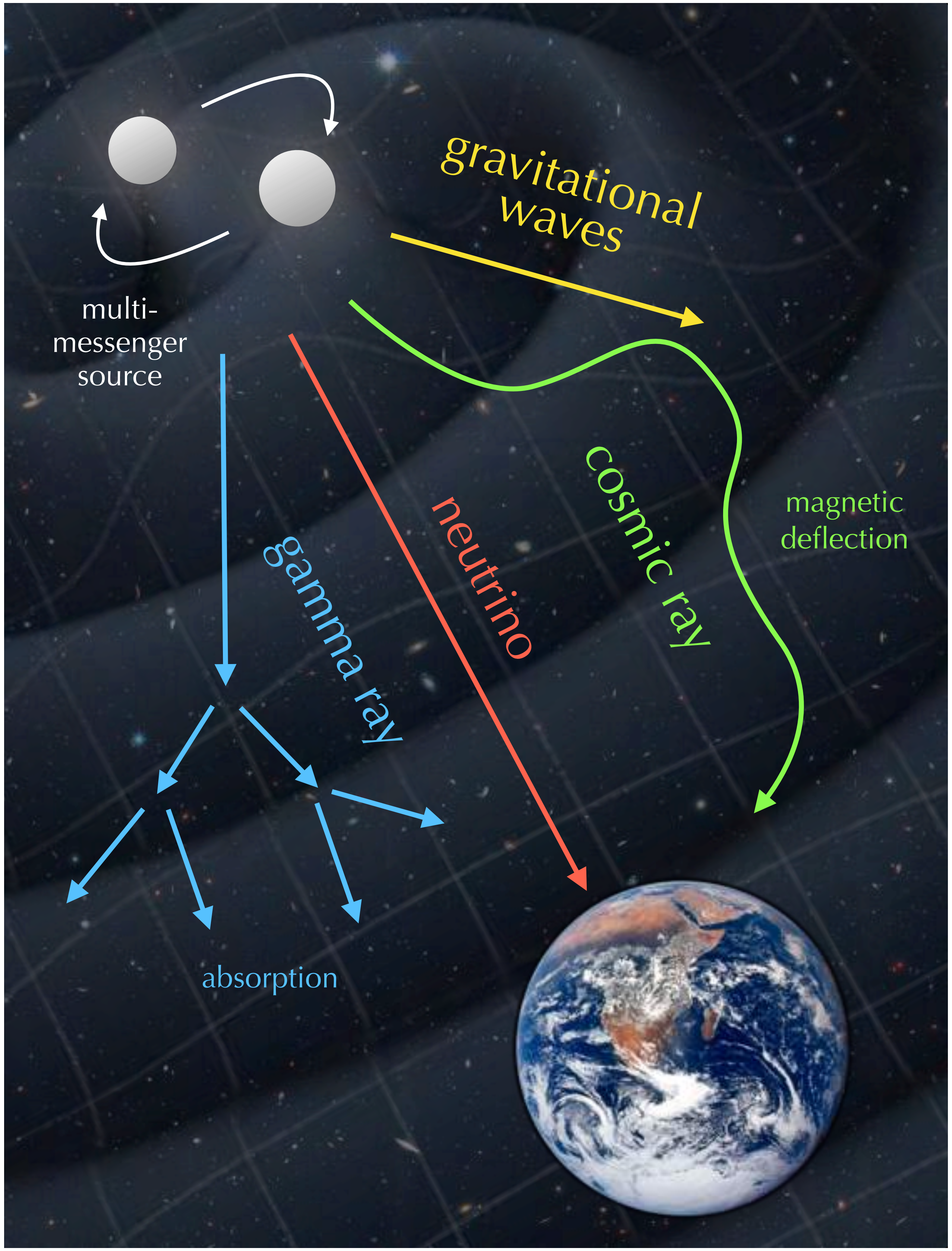
Combined contribution of Fermi-LAT blazars **below 30%** of the isotropic TeV-PeV neutrino observation.

Multi-Messenger Interfaces



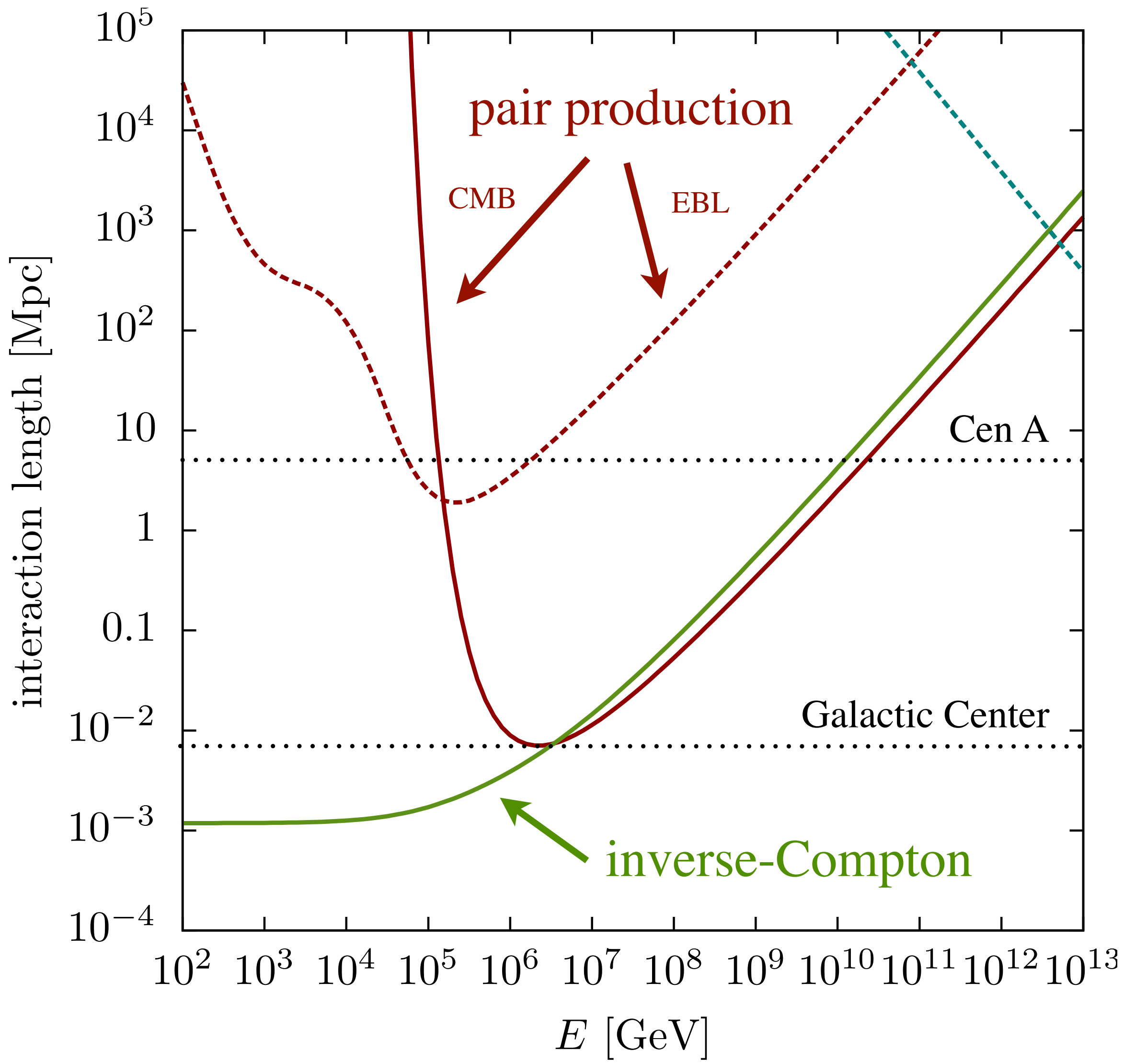
The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

Hadronic Gamma-Rays

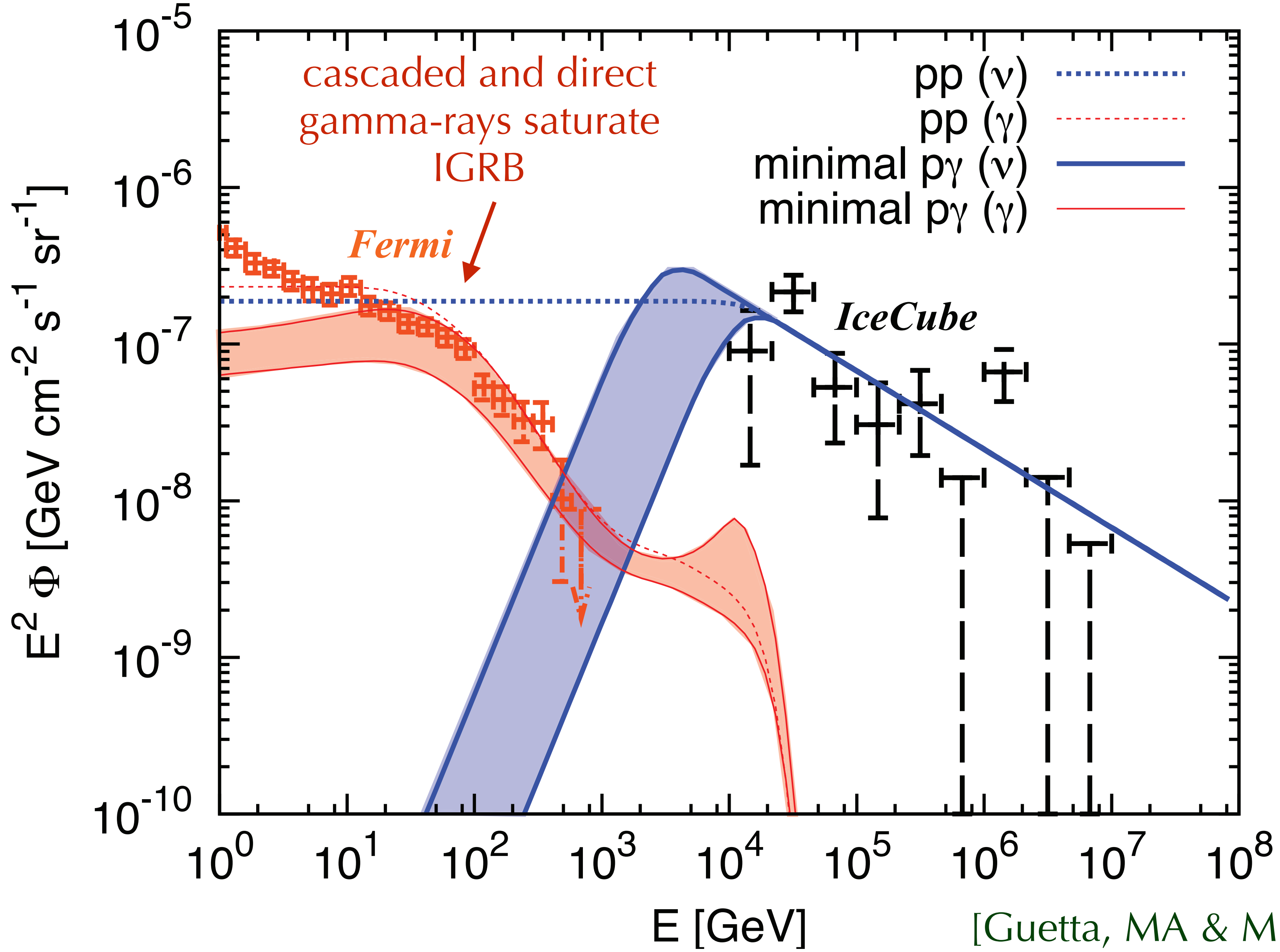


Secondary **neutrinos** and **gamma-rays** from pion decays:

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



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



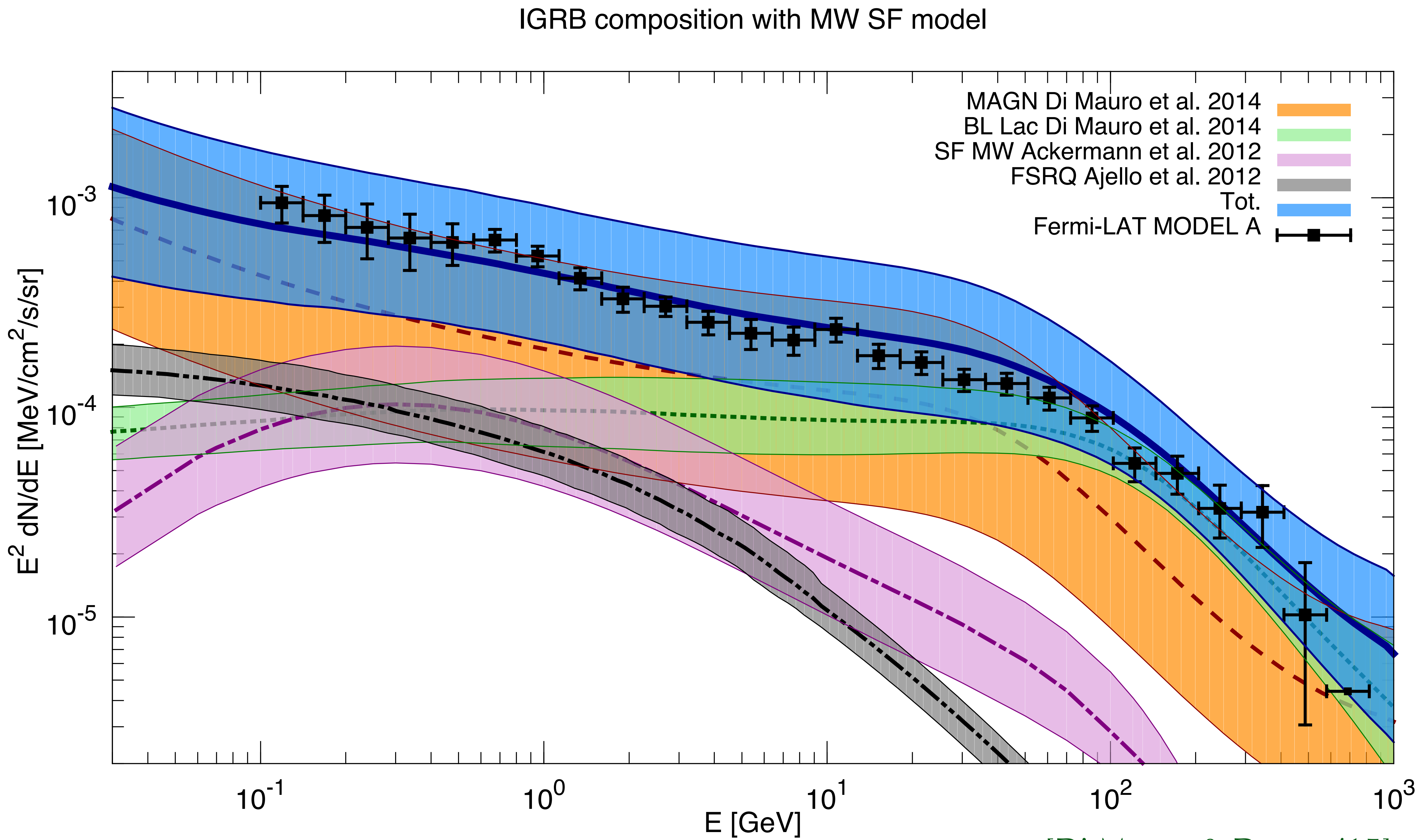
[Guetta, MA & Murase'16]

[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]

Isotropic Diffuse Gamma-Ray BGR

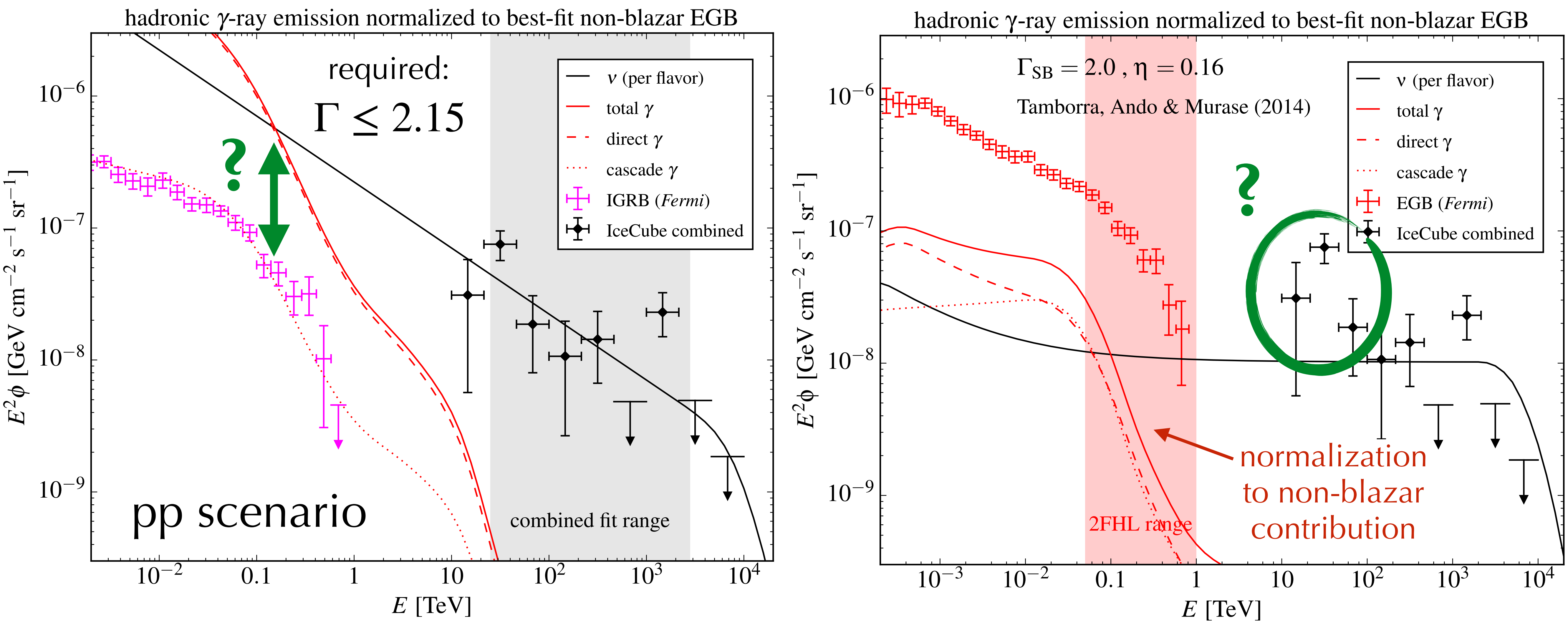
There is little room in the **isotropic diffuse γ-ray background** (IGRB) for "extra" γ-ray contributions.



[Di Mauro & Donato'15]

Hadronic Gamma-Rays

Neutrino production via cosmic ray interactions with gas (pp) in general overproduce γ-rays in the Fermi-LAT range.



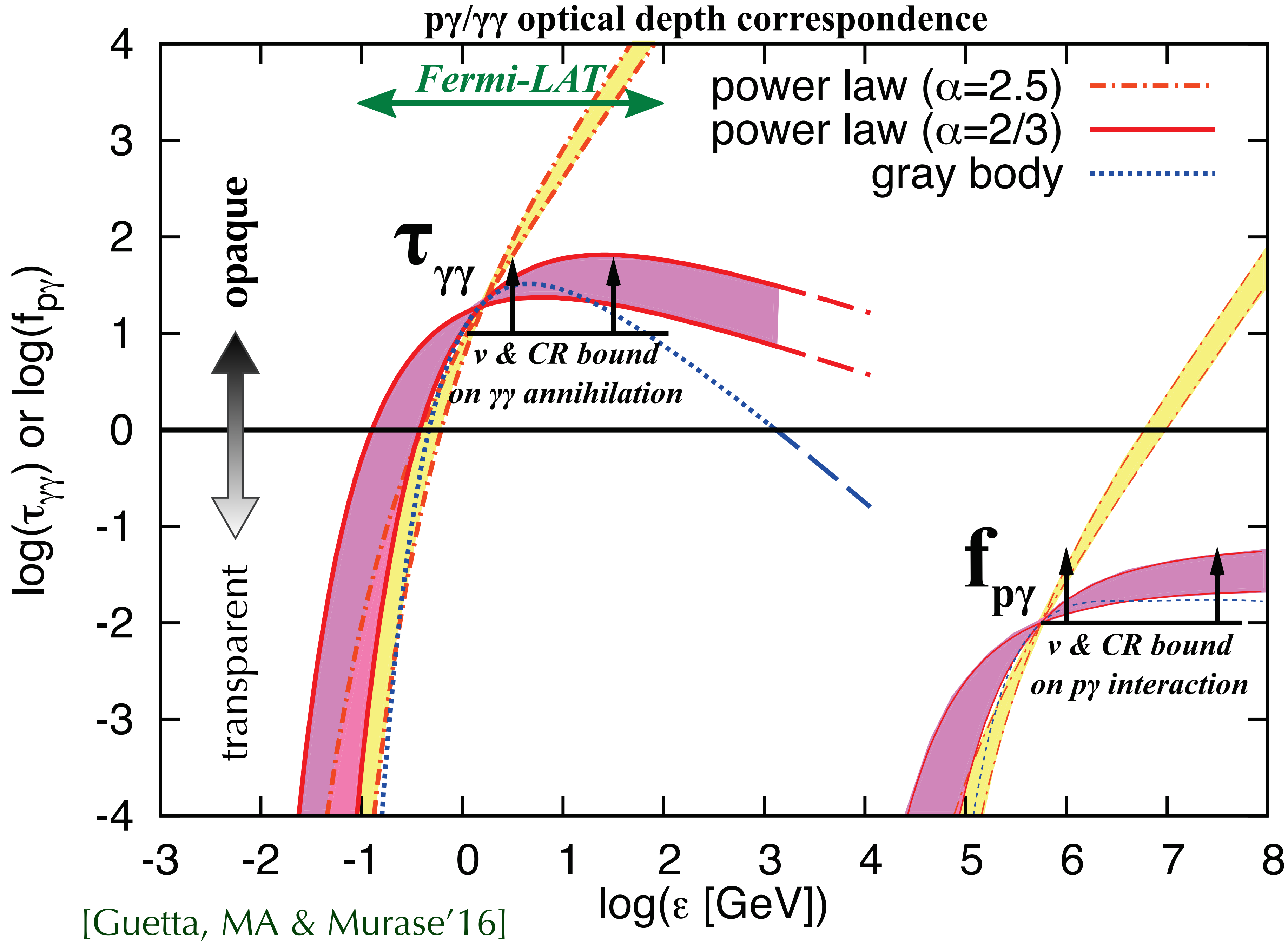
[Bechtol, MA, Ajello, Di Mauro & Vandenbrouke'15]

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

[Guetta, MA & Murase'16; 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 cores or chocked GRBs).



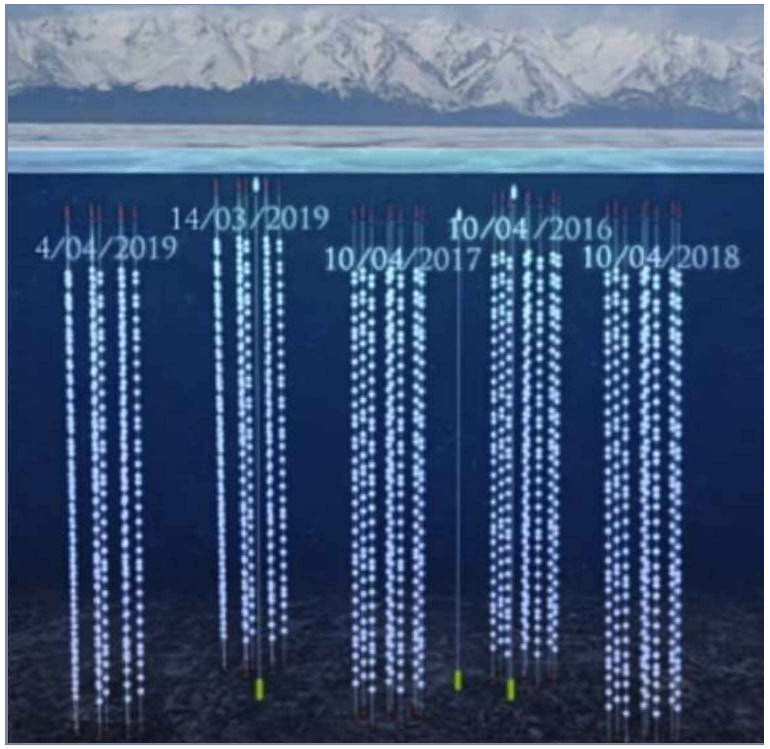
[Guetta, MA & Murase'16]

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

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

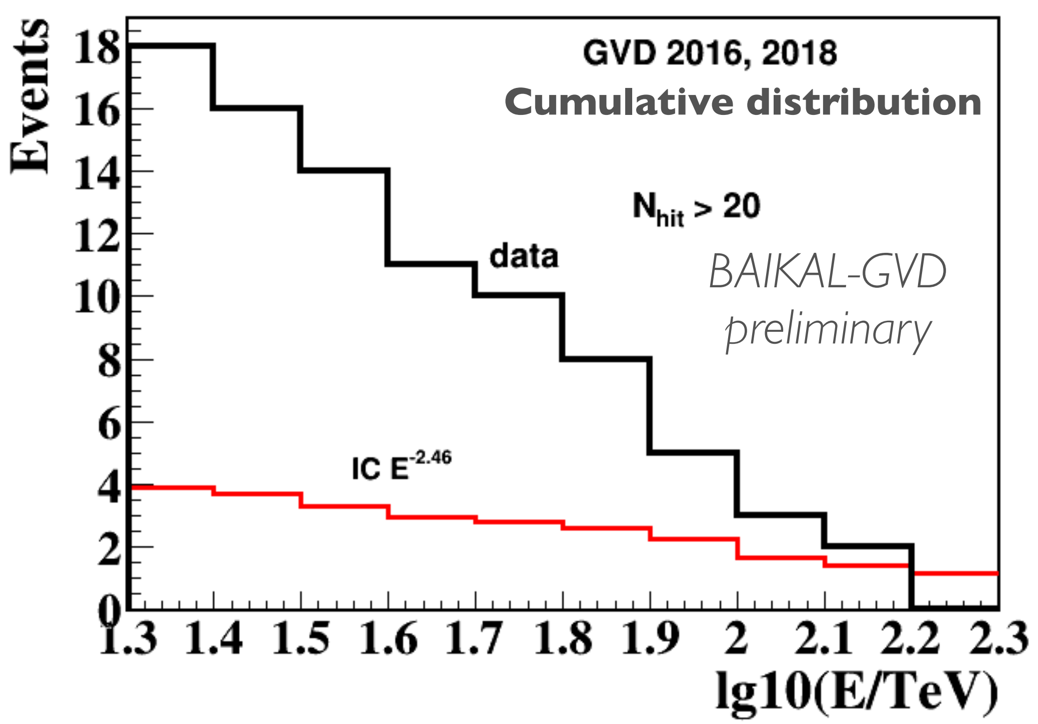
Outlook: Baikal-GVD

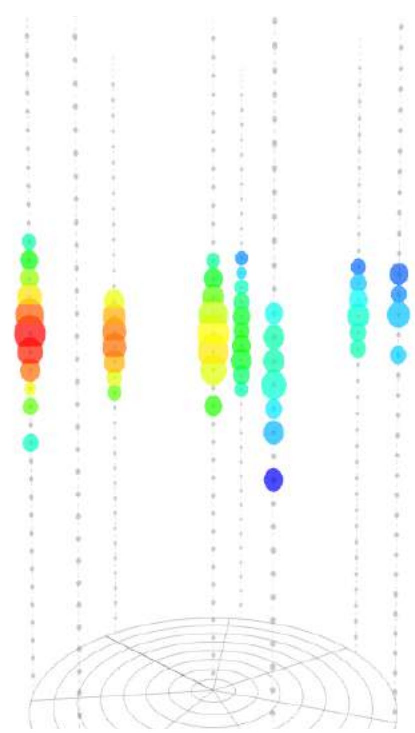
BAIKAL-GVD



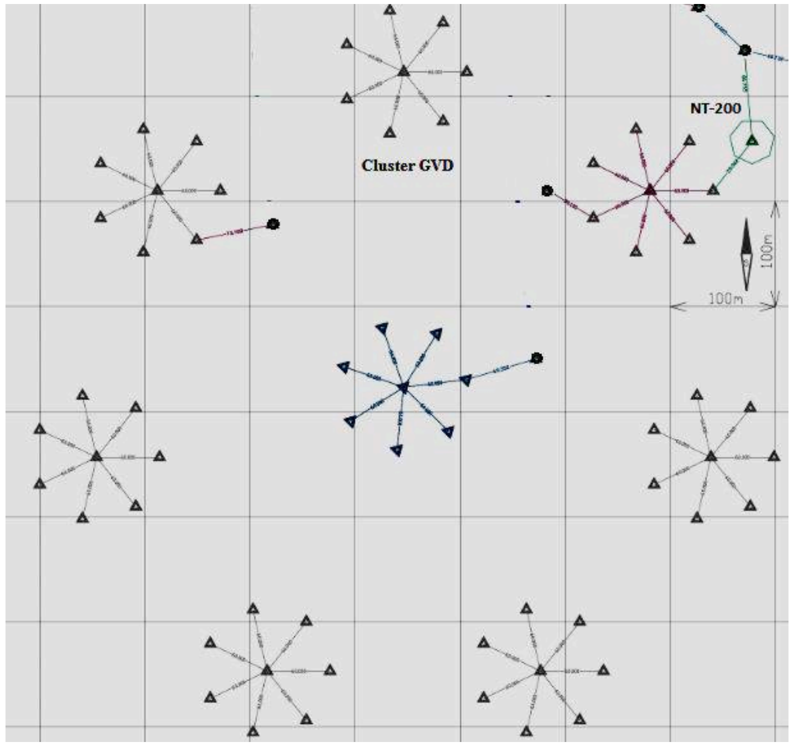
detector outline in 2019

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- since April 2020: 7 clusters
- **final goal**: 27 clusters (~1.4 km³)





~157 TeV cascade event

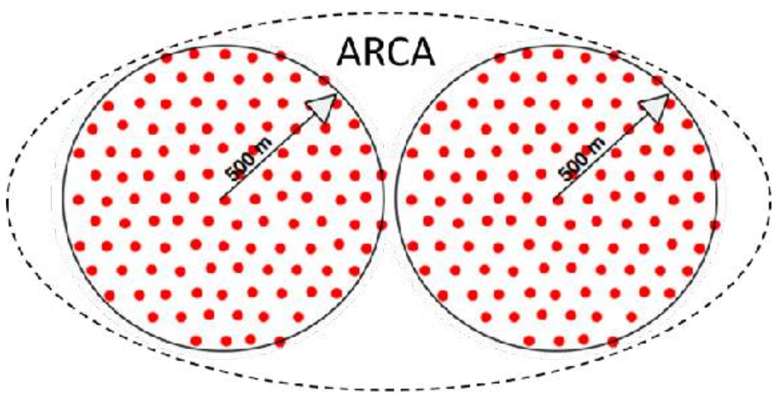


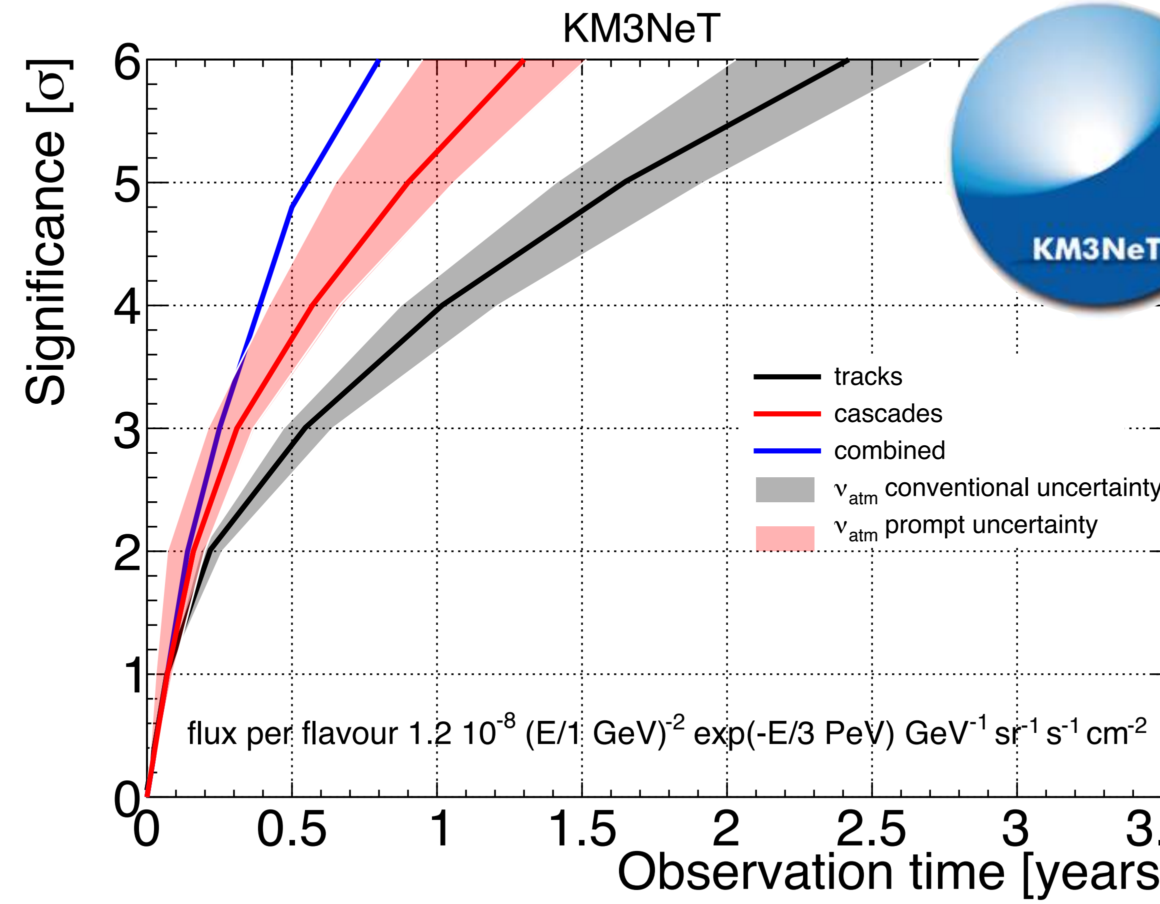
GVD-Phase 1

Outlook: KM3NeT/ARCA

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

detection unit with multi-PMT DOMs

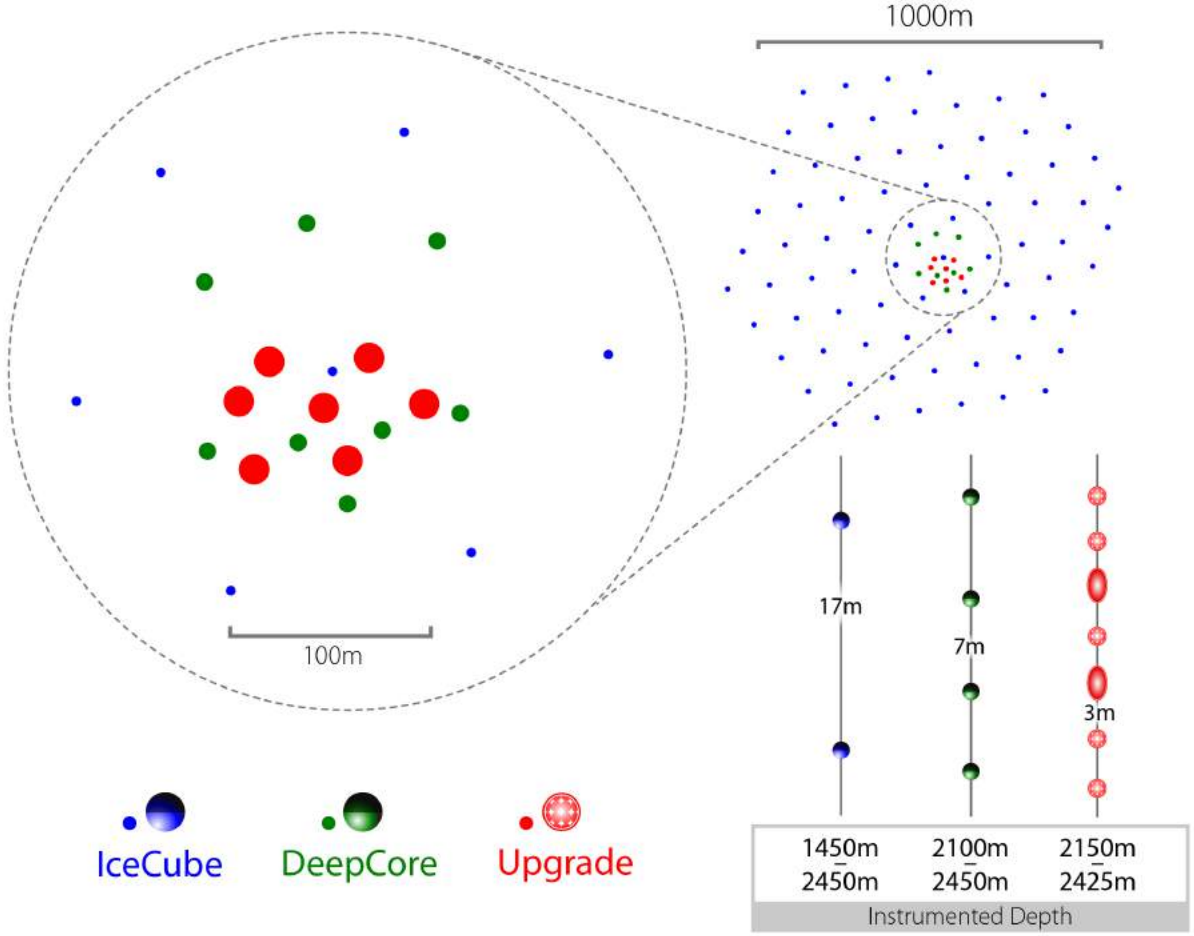




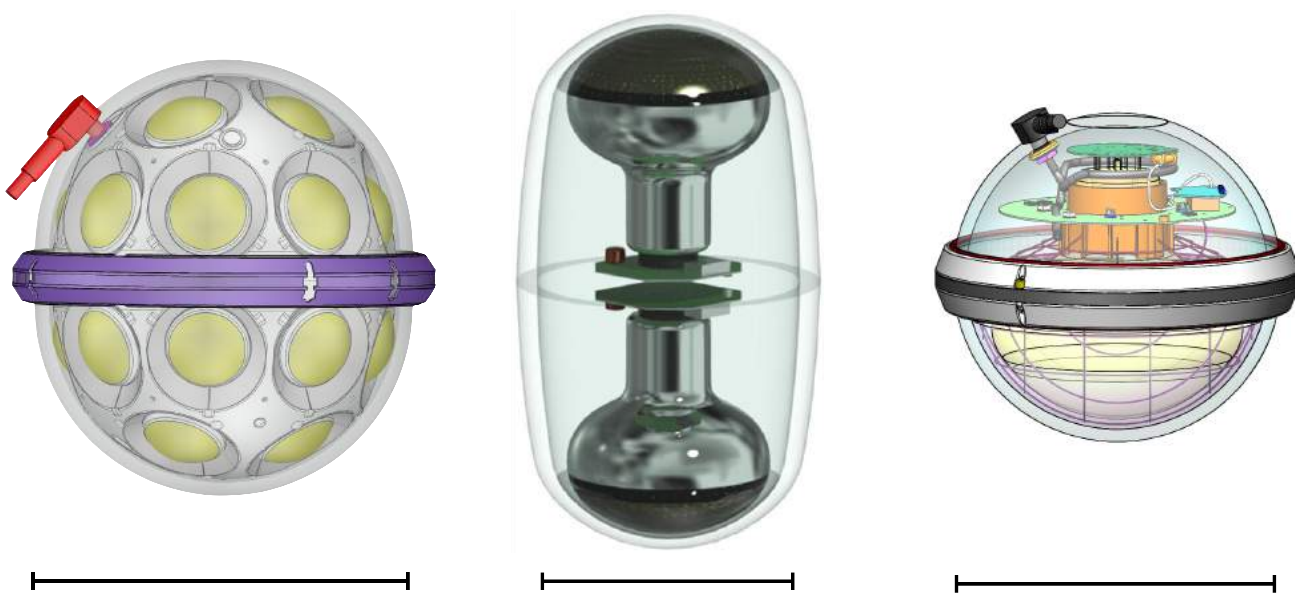
- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

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
- Midscale NSF project with an estimated total cost of $23M
- Additional $9M in capital equipment alone from partners
- **Aim: deployment in 2023/24**



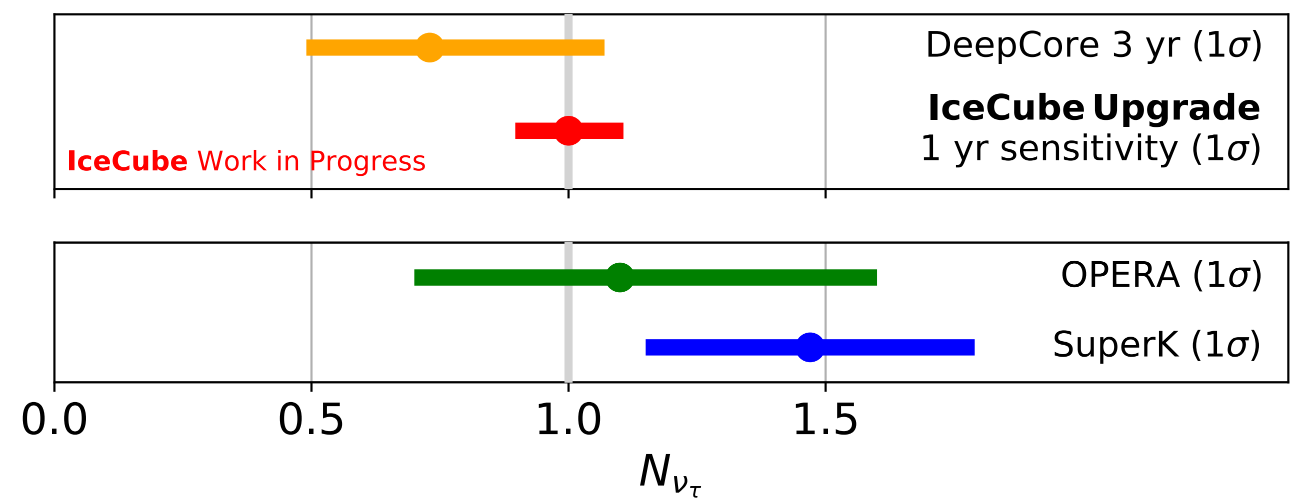
mDOM D-Egg pDOM

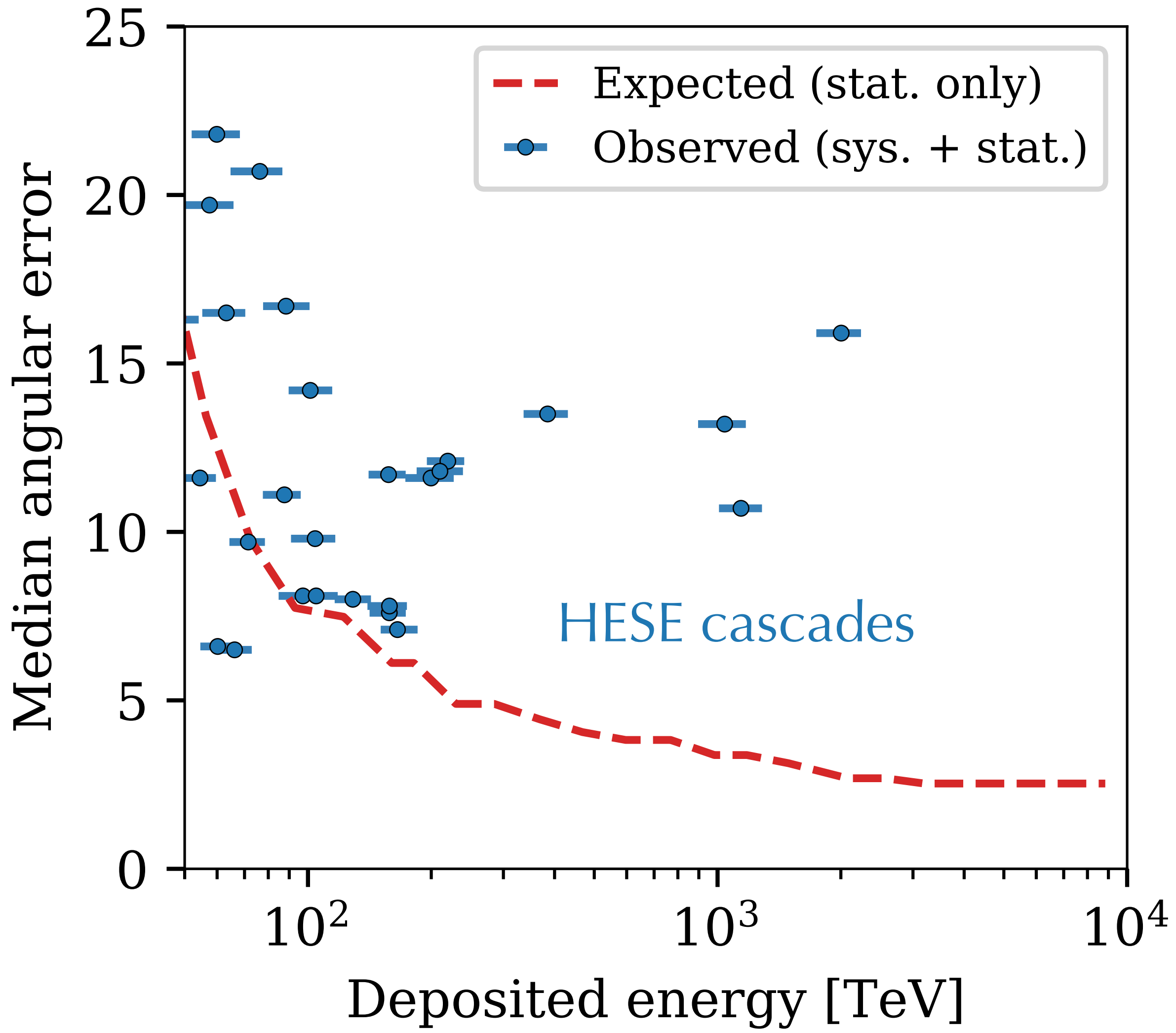


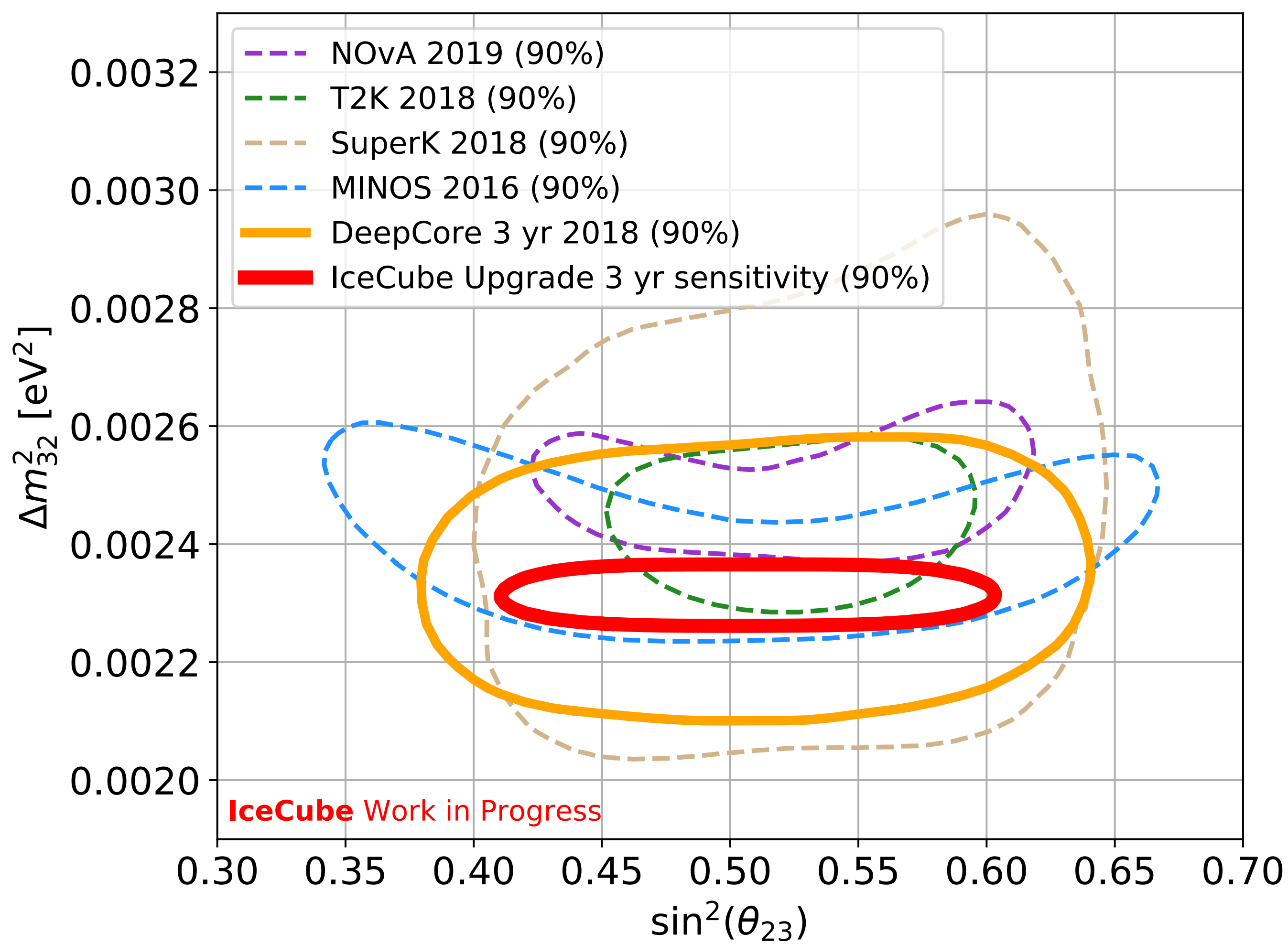
36 cm 30 cm 33 cm

Outlook: IceCube Upgrade

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

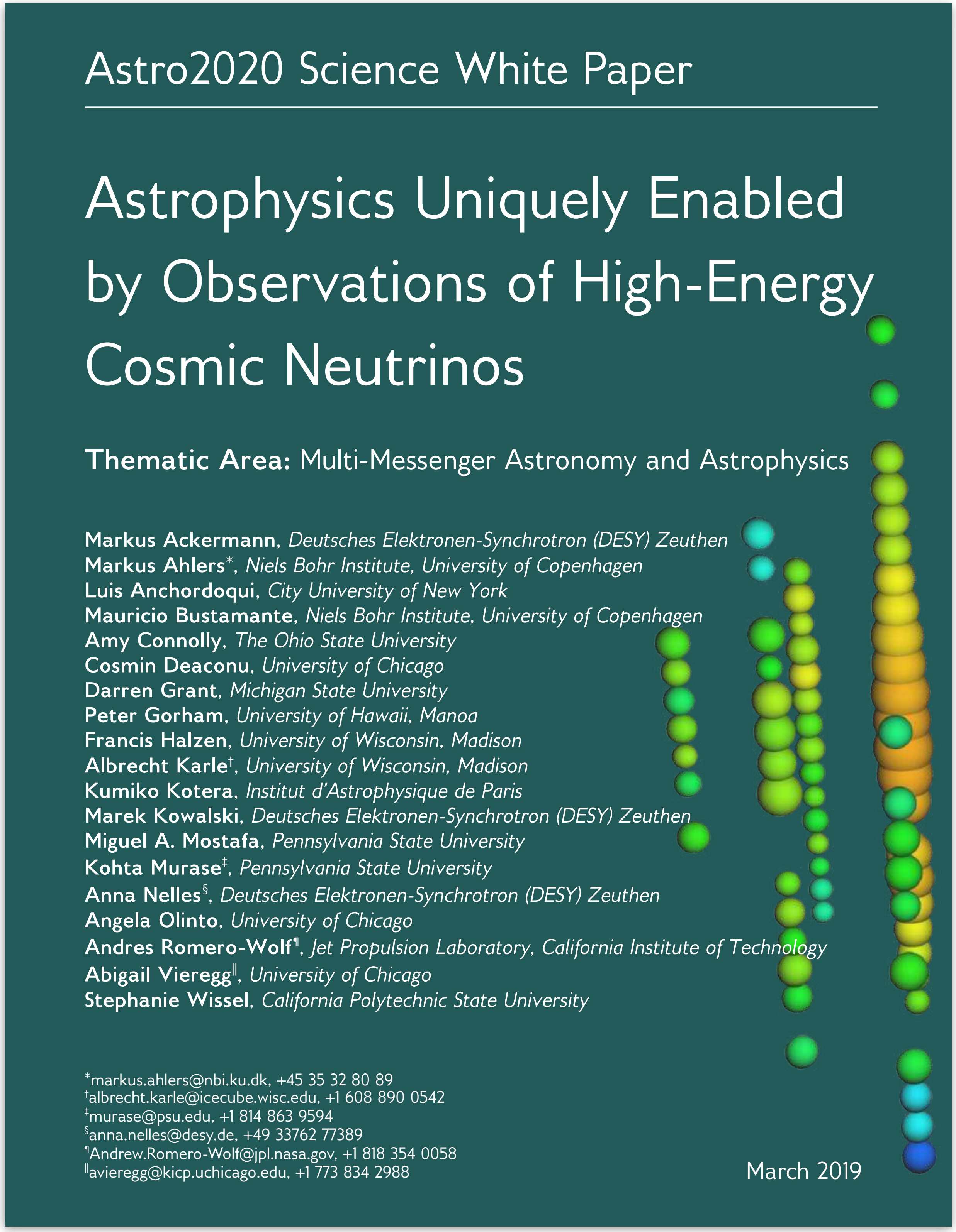






[IceCube, PoS(ICRC2019) 1177]

Astro2020 Decadal Survey


Astro2020 Science White Paper

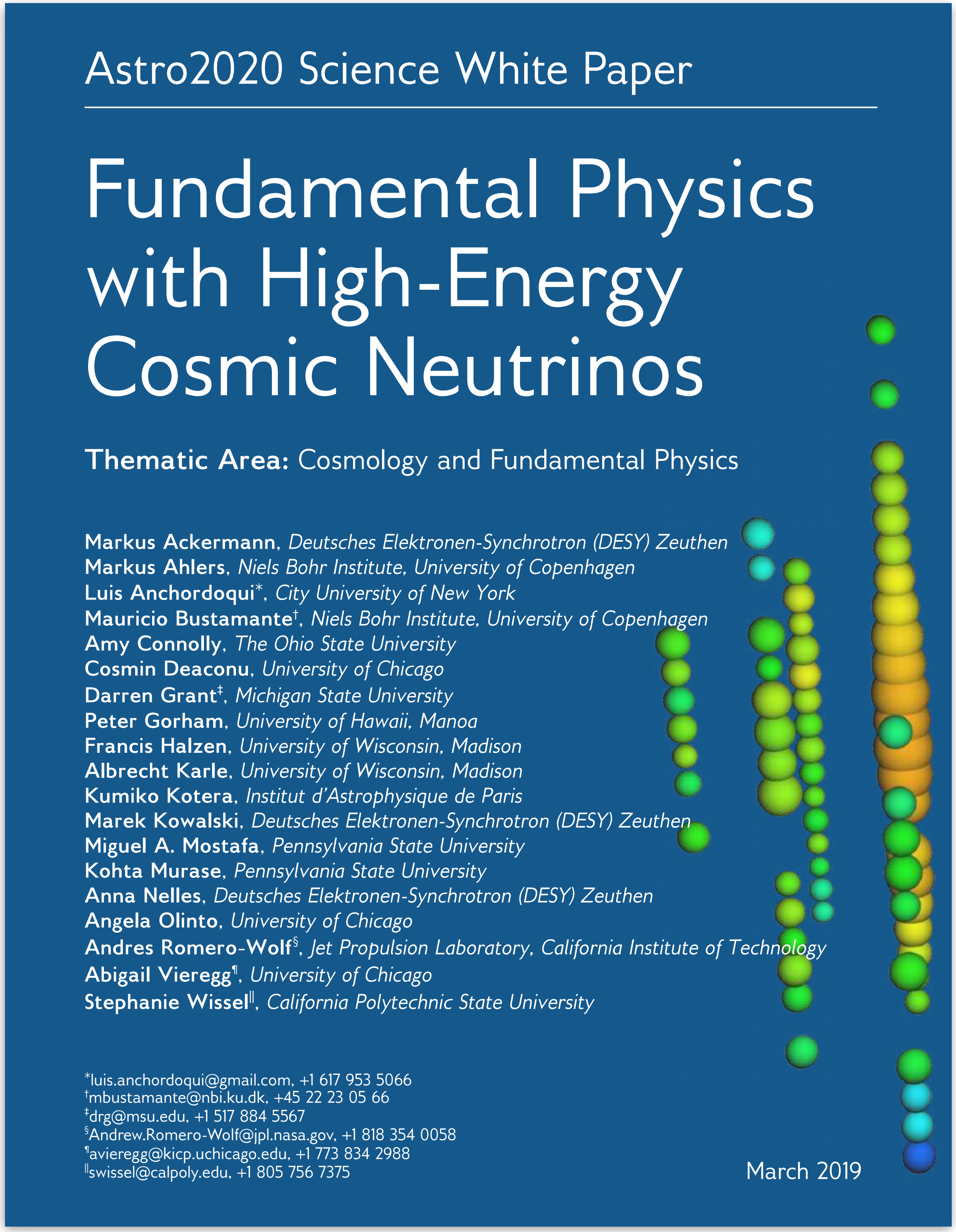
Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos

Thematic Area: Multi-Messenger Astronomy and Astrophysics

Markus Ackermann, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Markus Ahlers[*], *Niels Bohr Institute, University of Copenhagen*
Luis Anchordoqui, *City University of New York*
Mauricio Bustamante, *Niels Bohr Institute, University of Copenhagen*
Amy Connolly, *The Ohio State University*
Cosmin Deaconu, *University of Chicago*
Darren Grant, *Michigan State University*
Peter Gorham, *University of Hawaii, Manoa*
Francis Halzen, *University of Wisconsin, Madison*
Albrecht Karle[†], *University of Wisconsin, Madison*
Kumiko Kotera, *Institut d'Astrophysique de Paris*
Marek Kowalski, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Miguel A. Mostafa, *Pennsylvania State University*
Kohta Murase[‡], *Pennsylvania State University*
Anna Nelles[§], *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Angela Olinto, *University of Chicago*
Andres Romero-Wolf[¶], *Jet Propulsion Laboratory, California Institute of Technology*
Abigail Vieregg[‖], *University of Chicago*
Stephanie Wissel, *California Polytechnic State University*

[*] markus.ahlers@nbi.ku.dk, +45 35 32 80 89
[†] albrecht.karle@icecube.wisc.edu, +1 608 890 0542
[‡] murase@psu.edu, +1 814 863 9594
[§] anna.nelles@desy.de, +49 33762 77389
[¶] Andrew.Romero-Wolf@jpl.nasa.gov, +1 818 354 0058
[‖] avieregg@kicp.uchicago.edu, +1 773 834 2988

March 2019


Astro2020 Science White Paper

Fundamental Physics with High-Energy Cosmic Neutrinos

Thematic Area: Cosmology and Fundamental Physics

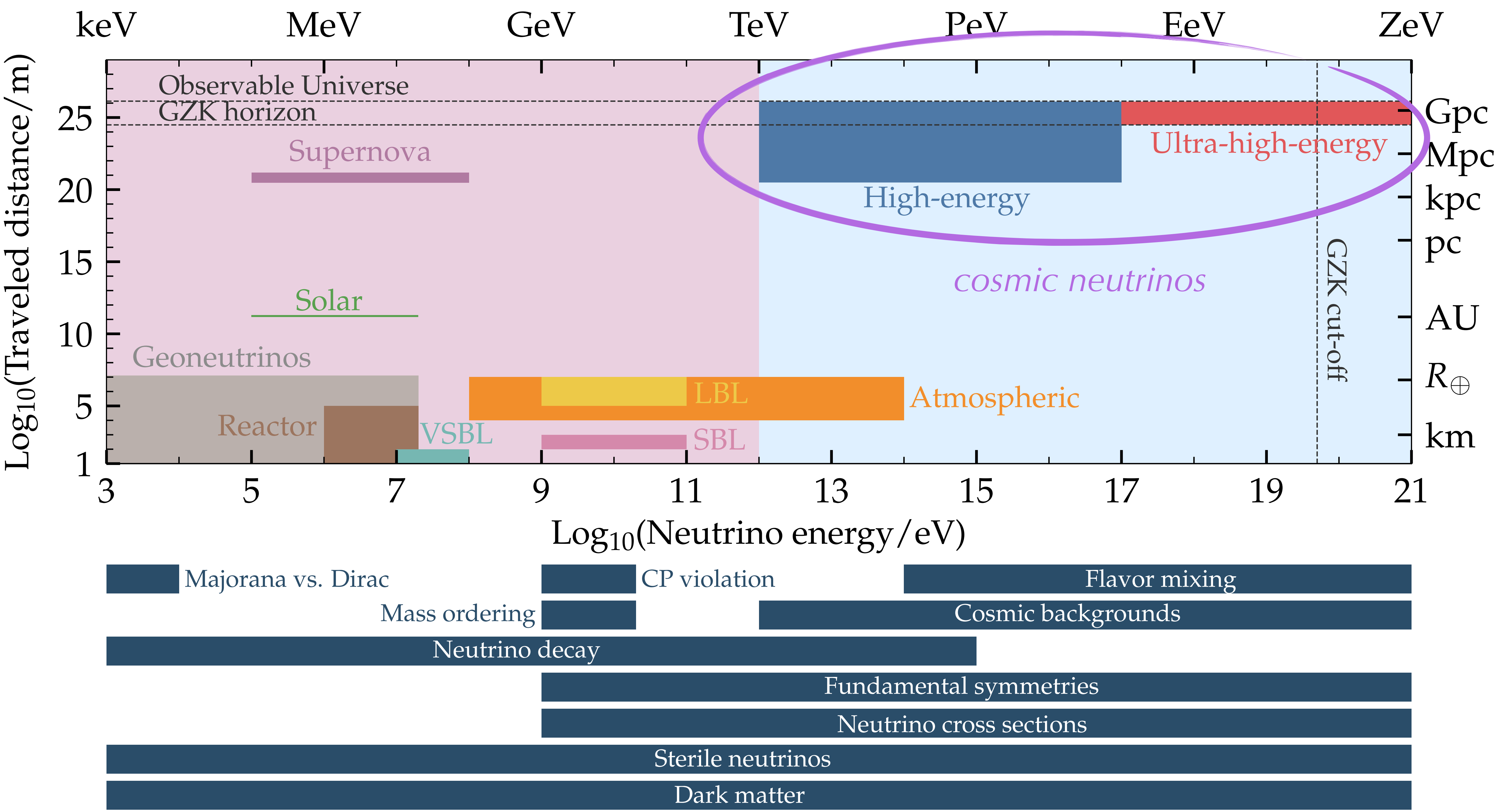
Markus Ackermann, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Markus Ahlers, *Niels Bohr Institute, University of Copenhagen*
Luis Anchordoqui[*], *City University of New York*
Mauricio Bustamante[†], *Niels Bohr Institute, University of Copenhagen*
Amy Connolly, *The Ohio State University*
Cosmin Deaconu, *University of Chicago*
Darren Grant[‡], *Michigan State University*
Peter Gorham, *University of Hawaii, Manoa*
Francis Halzen, *University of Wisconsin, Madison*
Albrecht Karle, *University of Wisconsin, Madison*
Kumiko Kotera, *Institut d'Astrophysique de Paris*
Marek Kowalski, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Miguel A. Mostafa, *Pennsylvania State University*
Kohta Murase, *Pennsylvania State University*
Anna Nelles, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Angela Olinto, *University of Chicago*
Andres Romero-Wolf[§], *Jet Propulsion Laboratory, California Institute of Technology*
Abigail Vieregg[¶], *University of Chicago*
Stephanie Wissel[‖], *California Polytechnic State University*

[*] luis.anchordoqui@gmail.com, +1 617 953 5066
[†] mbustamante@nbi.ku.dk, +45 22 23 05 66
[‡] drg@msu.edu, +1 517 884 5567
[§] Andrew.Romero-Wolf@jpl.nasa.gov, +1 818 354 0058
[¶] avieregg@kicp.uchicago.edu, +1 773 834 2988
[‖] swissel@calpoly.edu, +1 805 756 7375

March 2019

[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04333 & arXiv:1903.04334]

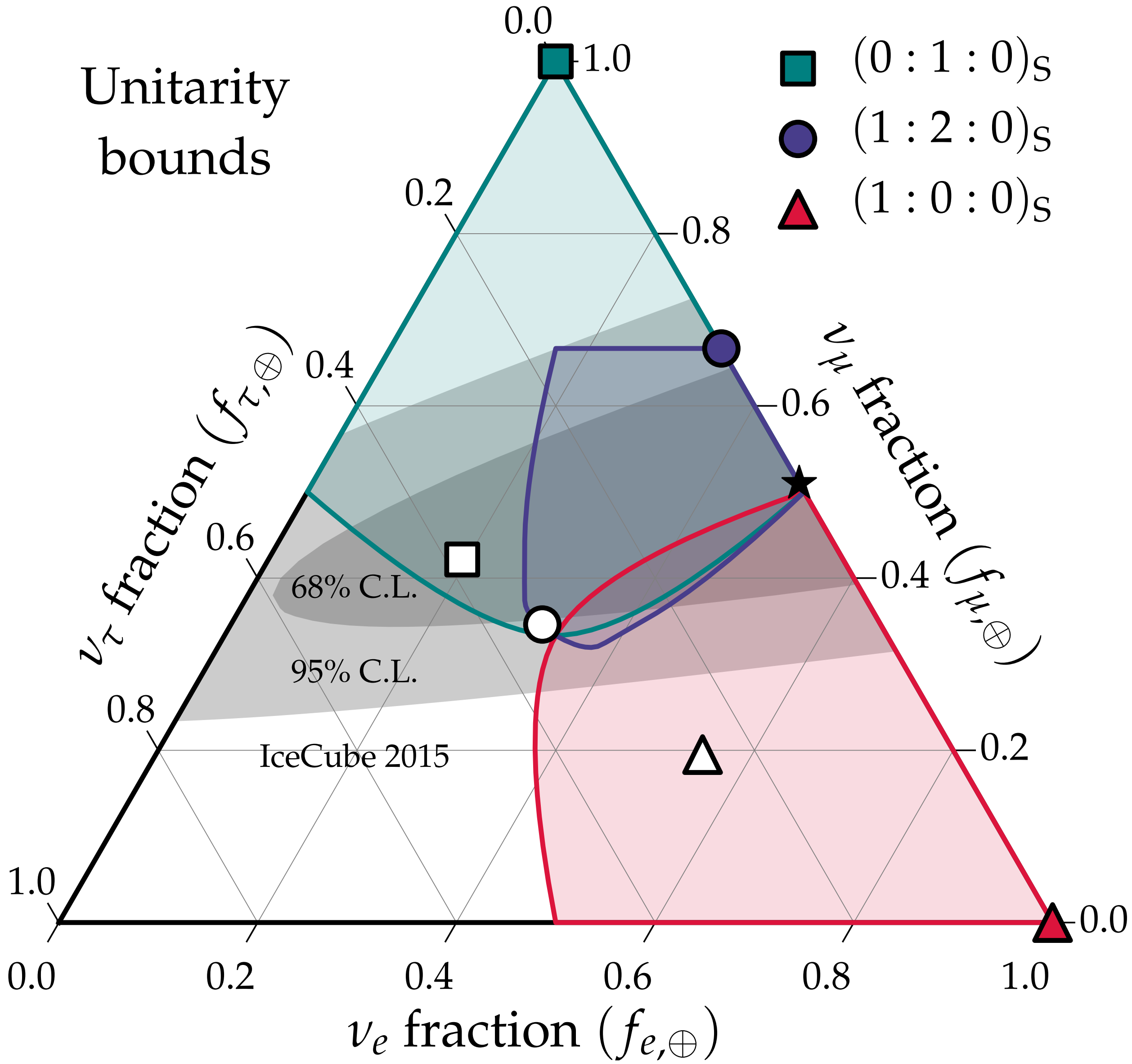
Probe of Fundamental Physics



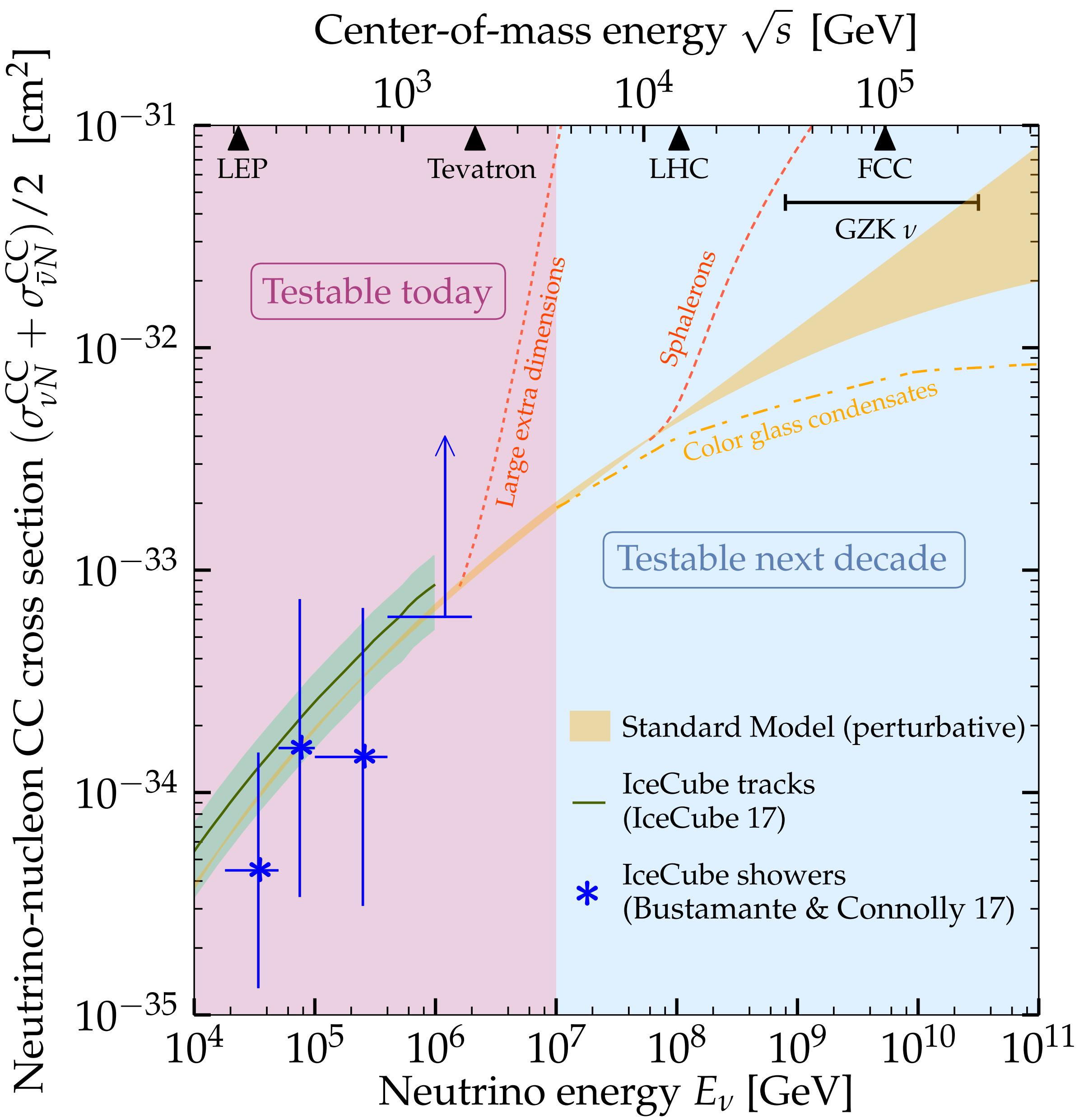
[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04334]

Probe of Fundamental Physics

Probe of exotic neutrino mixing, e.g. in **Lorentz-invariance violating** extensions of the neutrino Standard Model.



Probe of **neutrino-nucleon cross sections** at very-high energies.

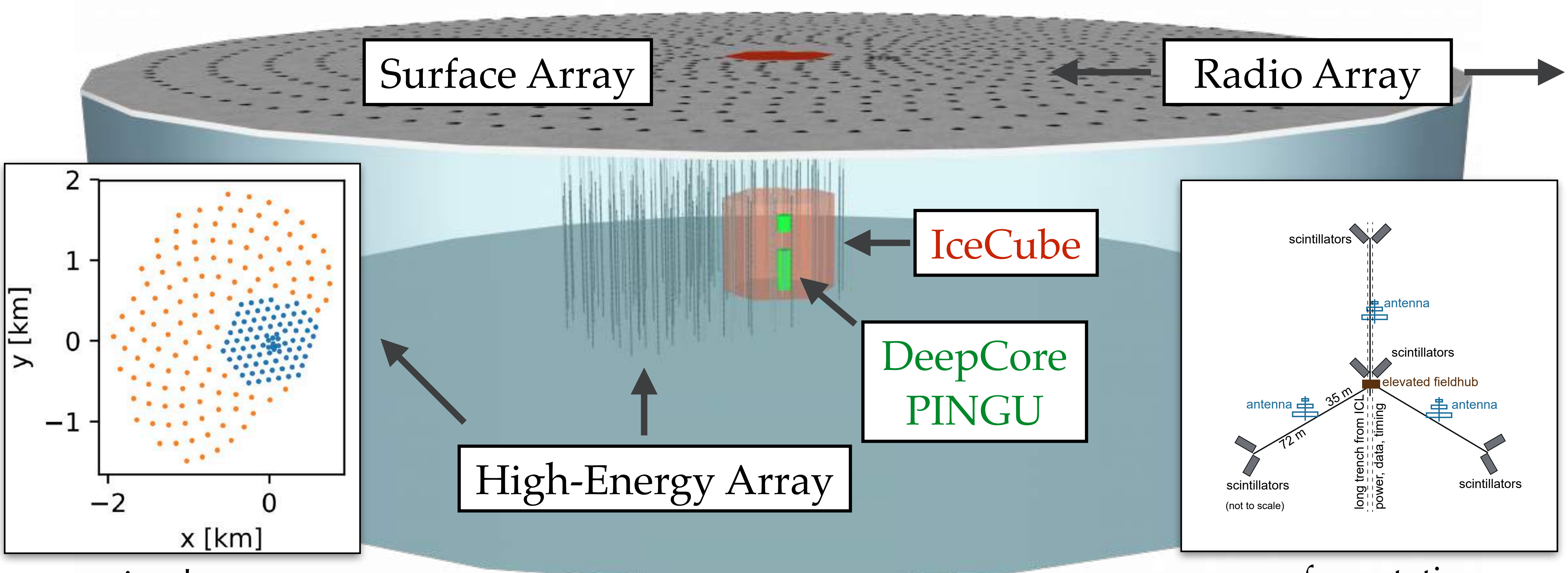


[Ackermann, MA, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04333 & arXiv:1903.04334]

Vision: IceCube-Gen2

- **Multi-component facility** (low- and high-energy & multi-messenger)
- **In-ice optical Cherenkov array** with 120 strings and 240m spacing
- **Surface array** (scintillator panels & radio antennas) for cosmic ray veto
- **Askaryan radio array** for >10PeV neutrino detection

[Ackermann et al. arXiv:2008.04323]

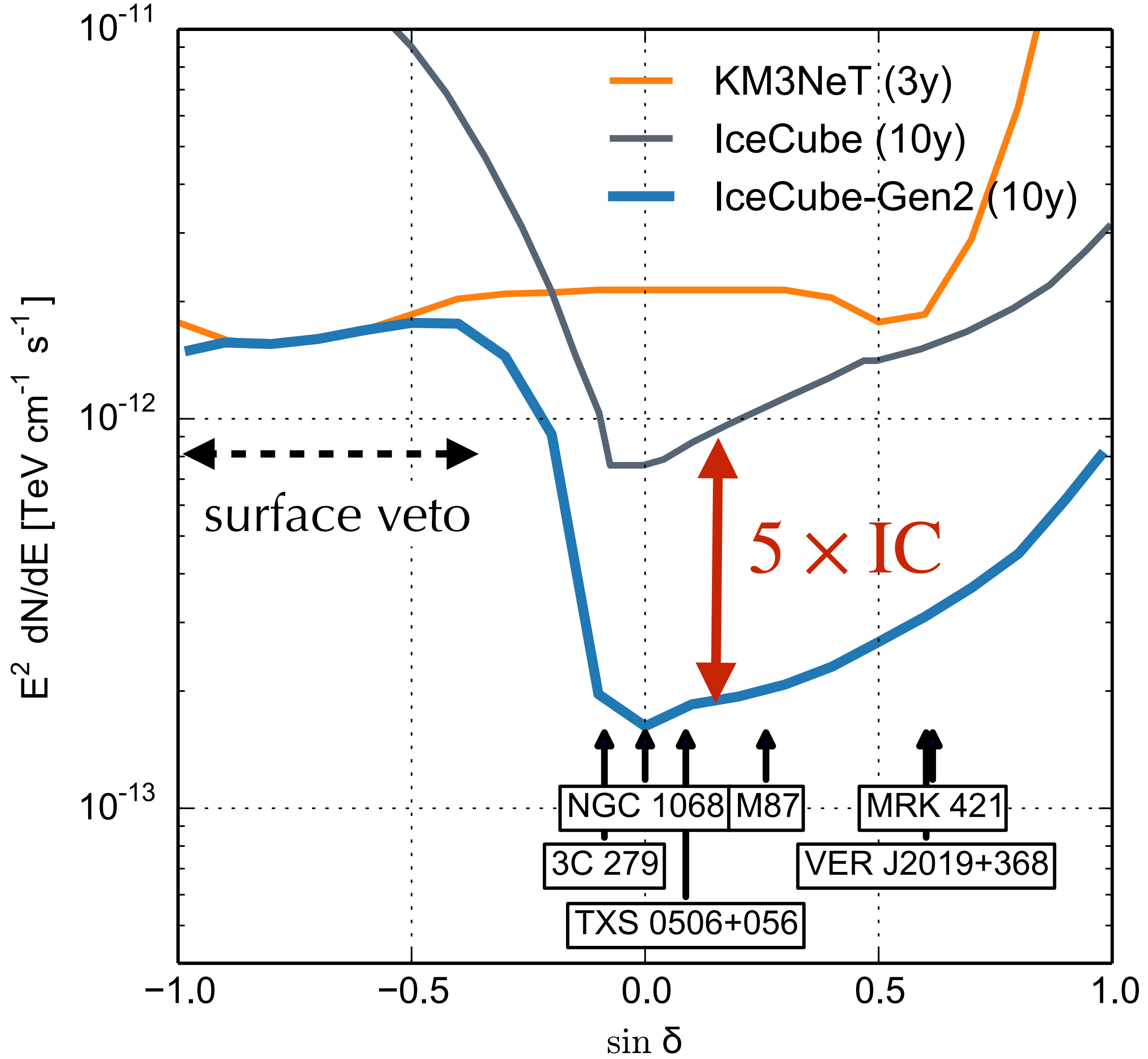


string layout

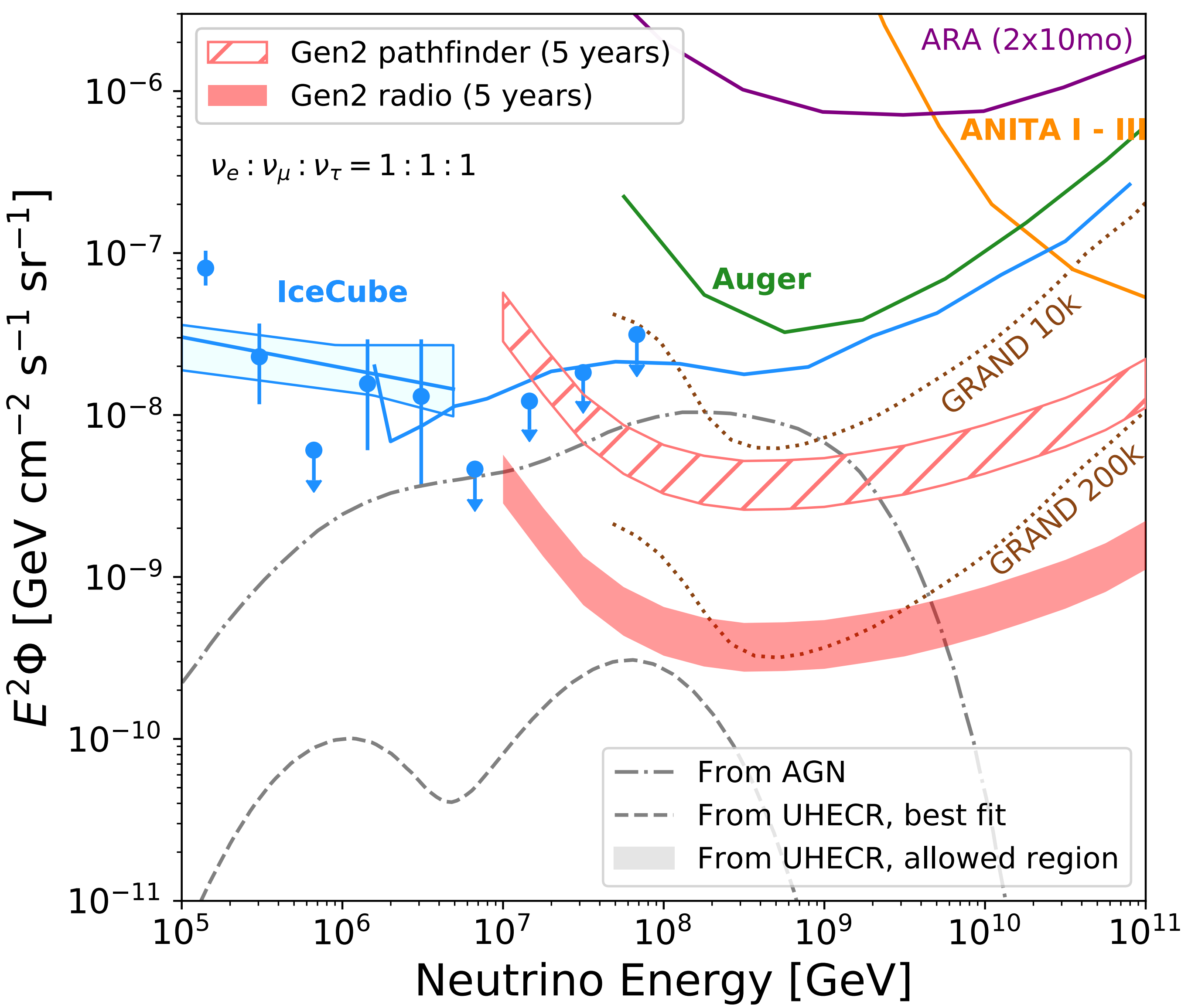
surface station

Vision: IceCube-Gen2

Improved sensitivity for neutrino point sources to find the origin of the isotropic TeV-PeV flux



Precision measurement of **PeV-EeV neutrino fluxes** with extended in-ice optical and surface radio array



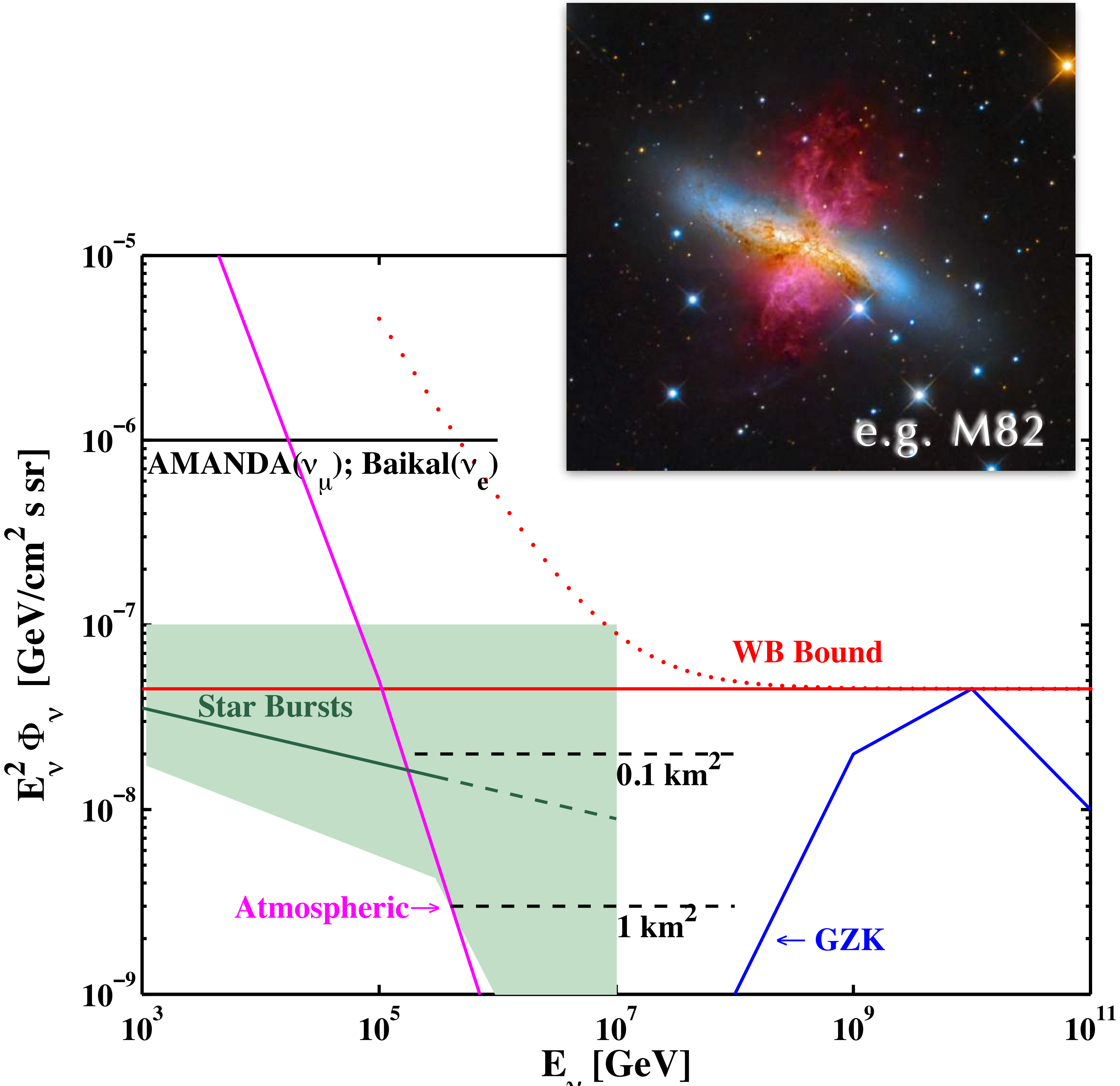
Summary

- Neutrino astronomy has reached an important milestone by the discovery of an **isotropic flux of high-energy (TeV-PeV) neutrinos.**
  - *Consistent with point-source limits?*
  - *Consistent multi-messenger picture?*
- So far, **no significant point sources**, except blazar TXS 0506+056.
  - *Are there more sources like TXS?*
  - *How do we find them?*
- Essential for future discoveries are **multi-messenger partners** facilitating low-latency studies.
  - *Fermi-LAT, Magic, H.E.S.S., HAWC, Swift-XRT, VERITAS, LIGO/Virgo,…*
- In parallel, development of **next-generation neutrino telescopes** with increased sensitivity and energy coverage.

Backup Slides

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.



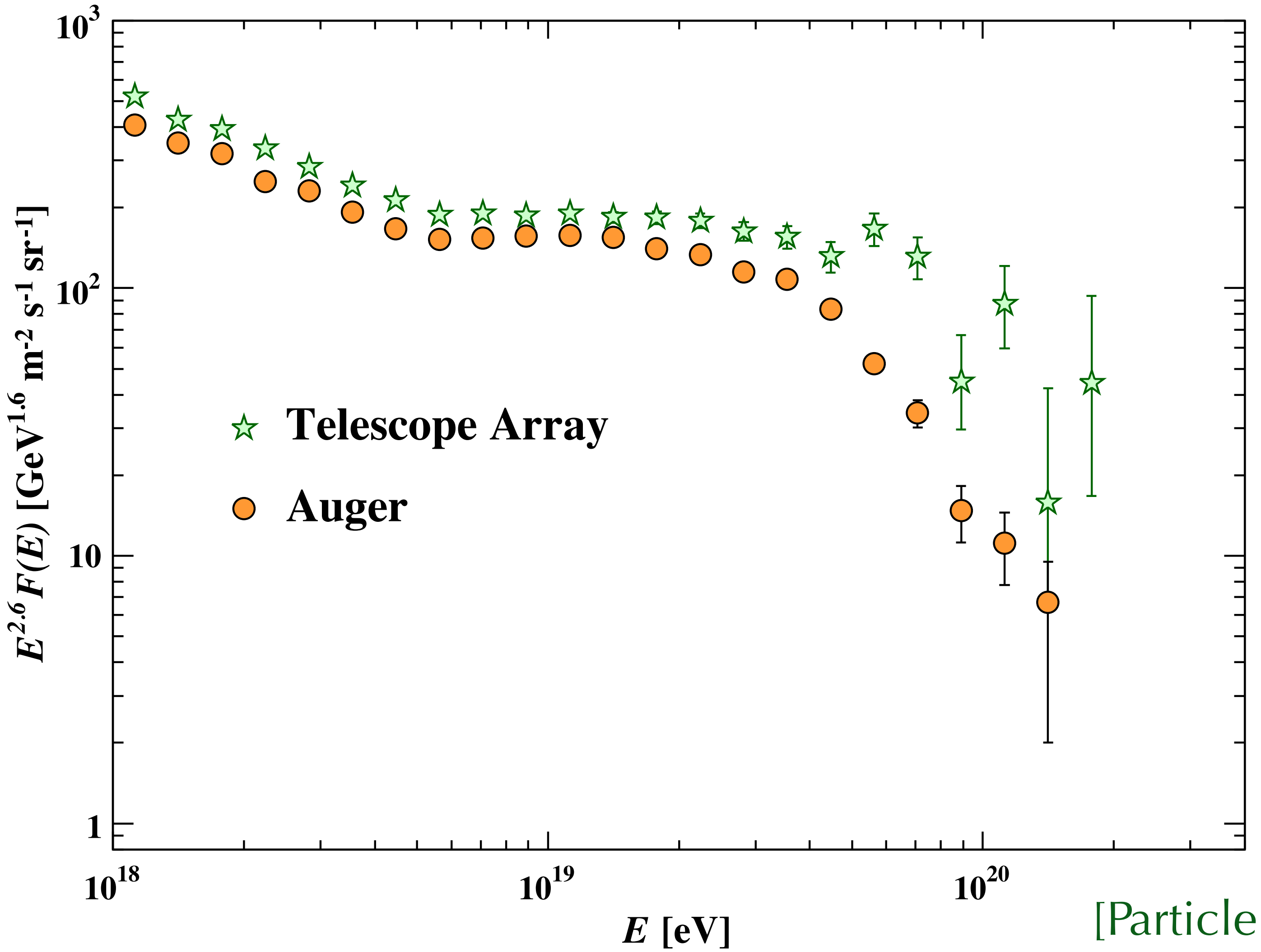
[Loeb & Waxman '06]

Cosmogenic Neutrinos

- 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).



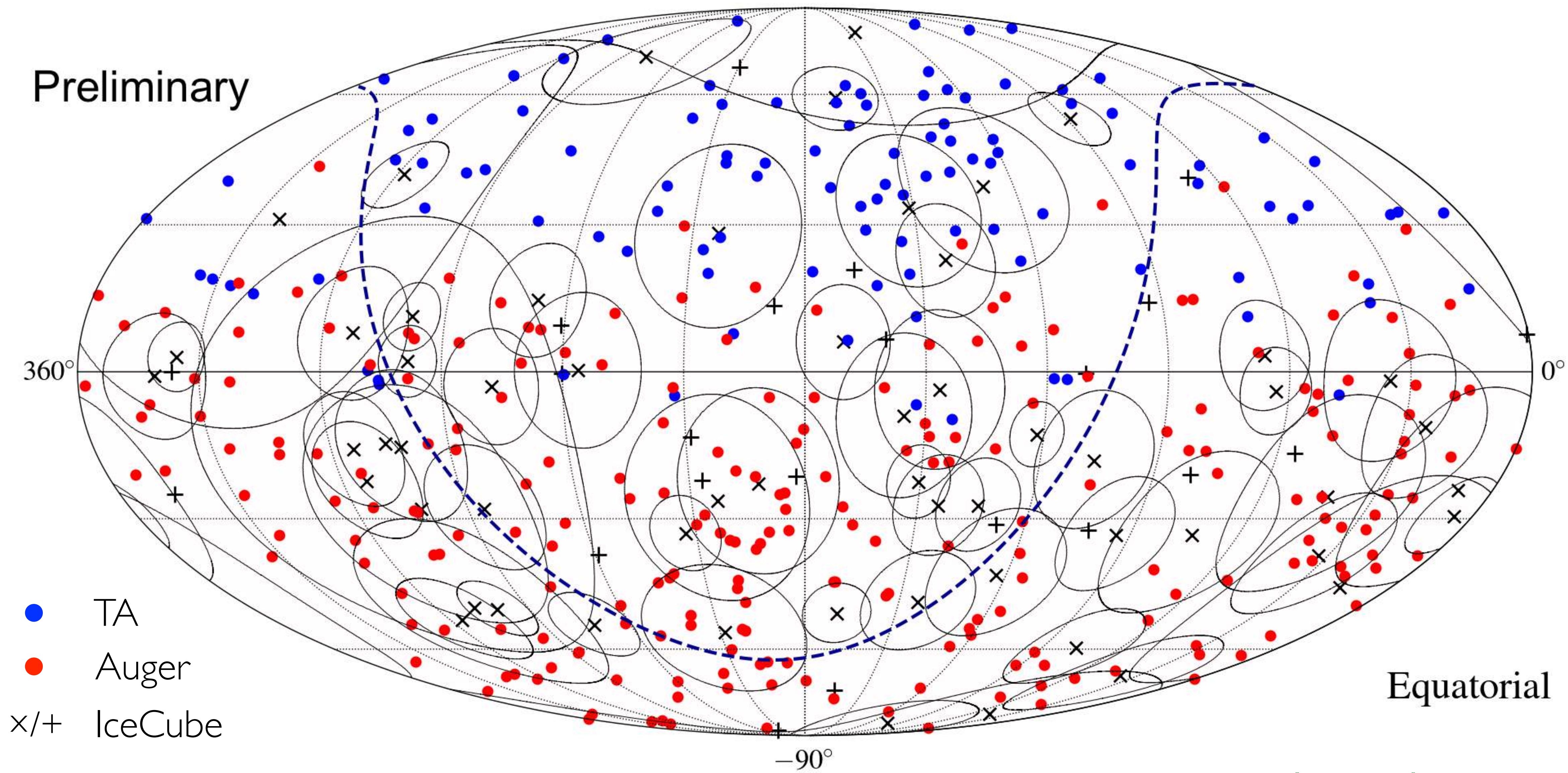
[Particle Data Group'19]

- Suppression feature observed in spectra with high significance, but could also be related to intrinsic cutoff of sources.

- Testable by **cosmogenic neutrinos**. [Berezinsky&Zatsepin'70]

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]

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) :

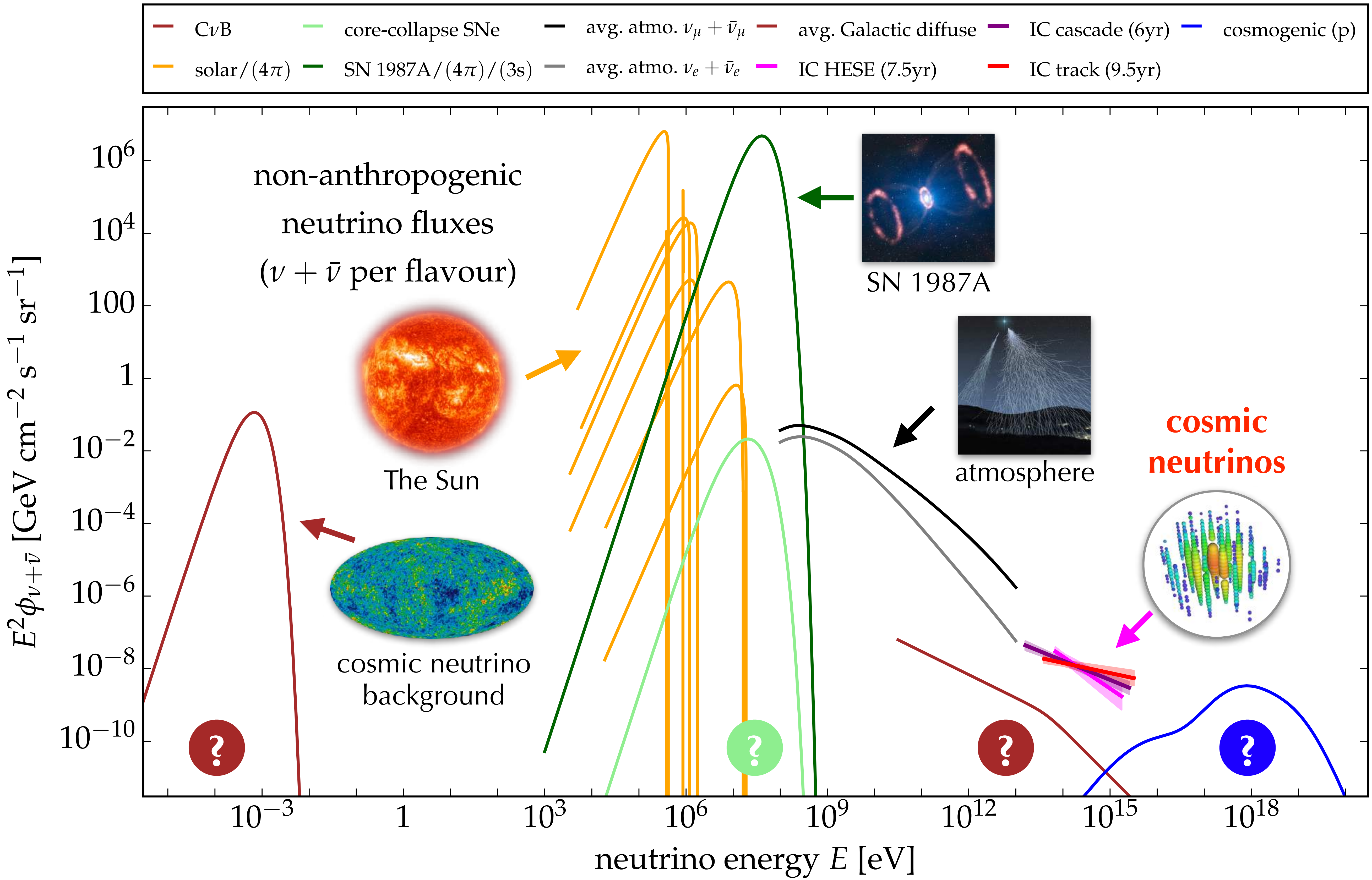
$$E_\nu^2 \phi_\nu(E_\nu) \simeq f_\pi \underbrace{\frac{\xi_z K_\pi}{1+K_\pi}}_{\mathcal{O}(1)} \underbrace{1.5 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}}_{\sim\ \text{IceCube diffuse}}$$

➜ 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]

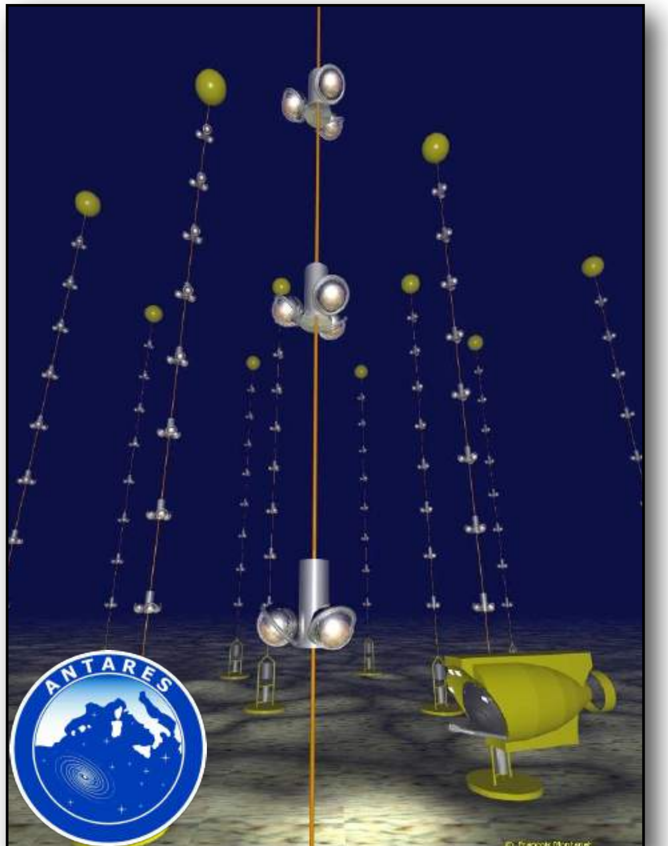
$$[E_N^2 Q_N(E_N)]_{10^{19.5}\mathrm{eV}} \simeq 2.2 \times 10^{43}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$$

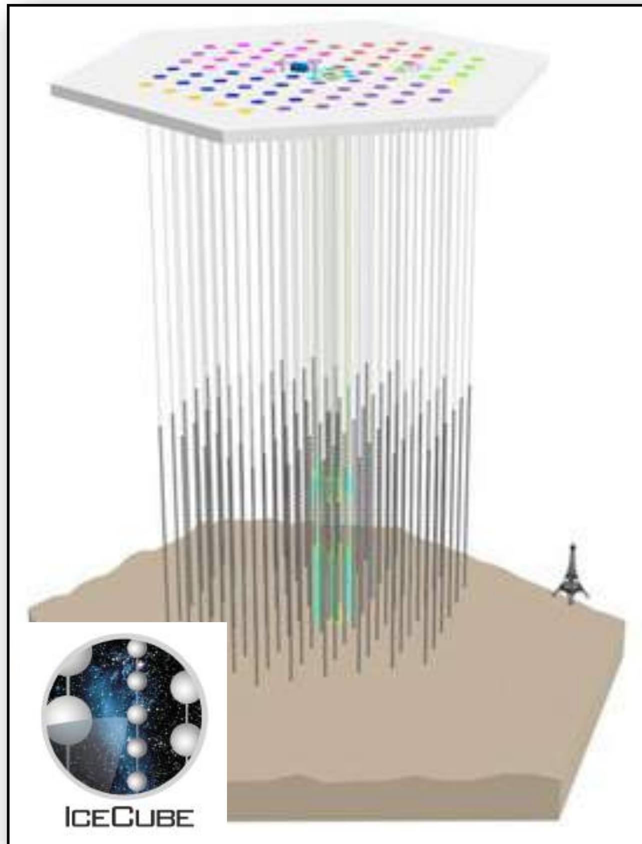
- Sources of UHECRs could be embedded in "calorimetric" environments ($f_\pi = 1$), producing a large flux of neutrinos, *e.g.*, **starburst galaxies** or **galaxy clusters**.

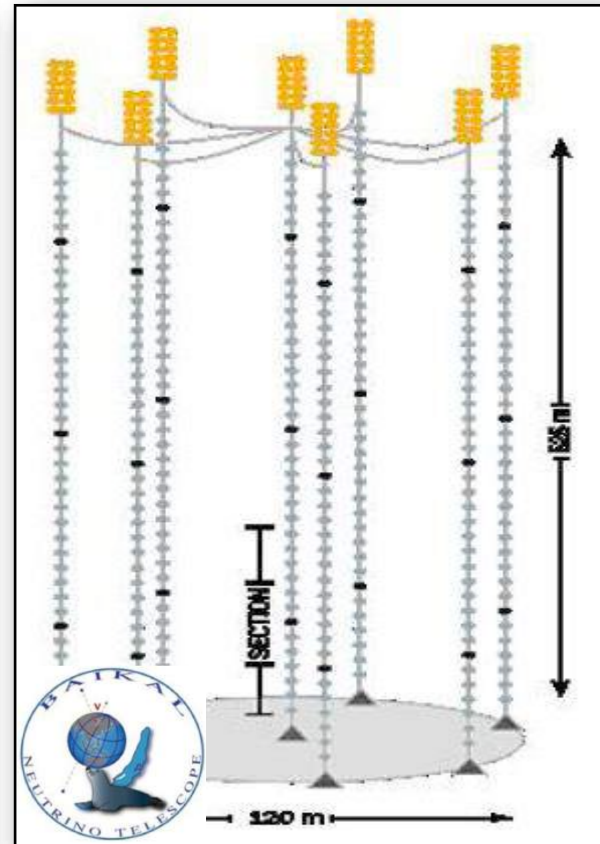

CνB
core-collapse SNe
avg. atmo. $\nu_\mu + \bar{\nu}_\mu$
avg. Galactic diffuse
IC cascade (6yr)
cosmogenic (p)
solar/(4π)
SN 1987A/(4π)/(3s)
avg. atmo. $\nu_e + \bar{\nu}_e$
IC HESE (7.5yr)
IC track (9.5yr)
non-anthropogenic
neutrino fluxes
($\nu + \bar{\nu}$ per flavour)
SN 1987A
The Sun
atmosphere
cosmic
neutrinos
cosmic neutrino
background
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^6
10^4
100
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-3}
1
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
neutrino energy E [eV]

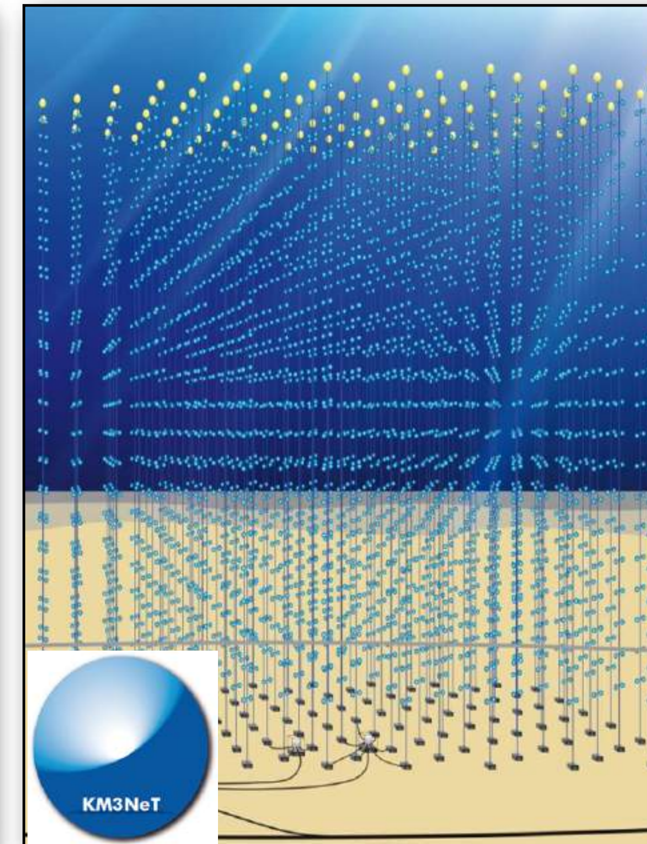
Cherenkov Observatories

Antares | IceCube | Baikal-GVD | KM3NeT/ARCA







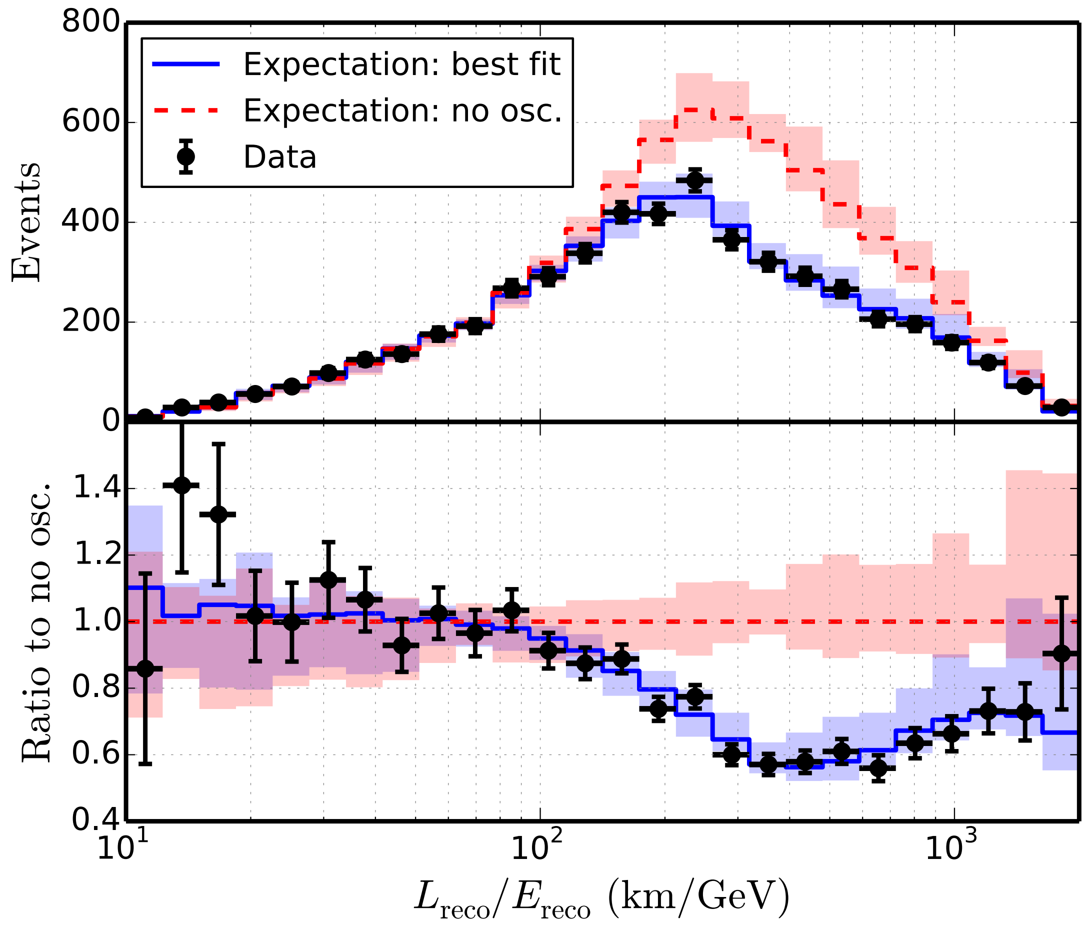


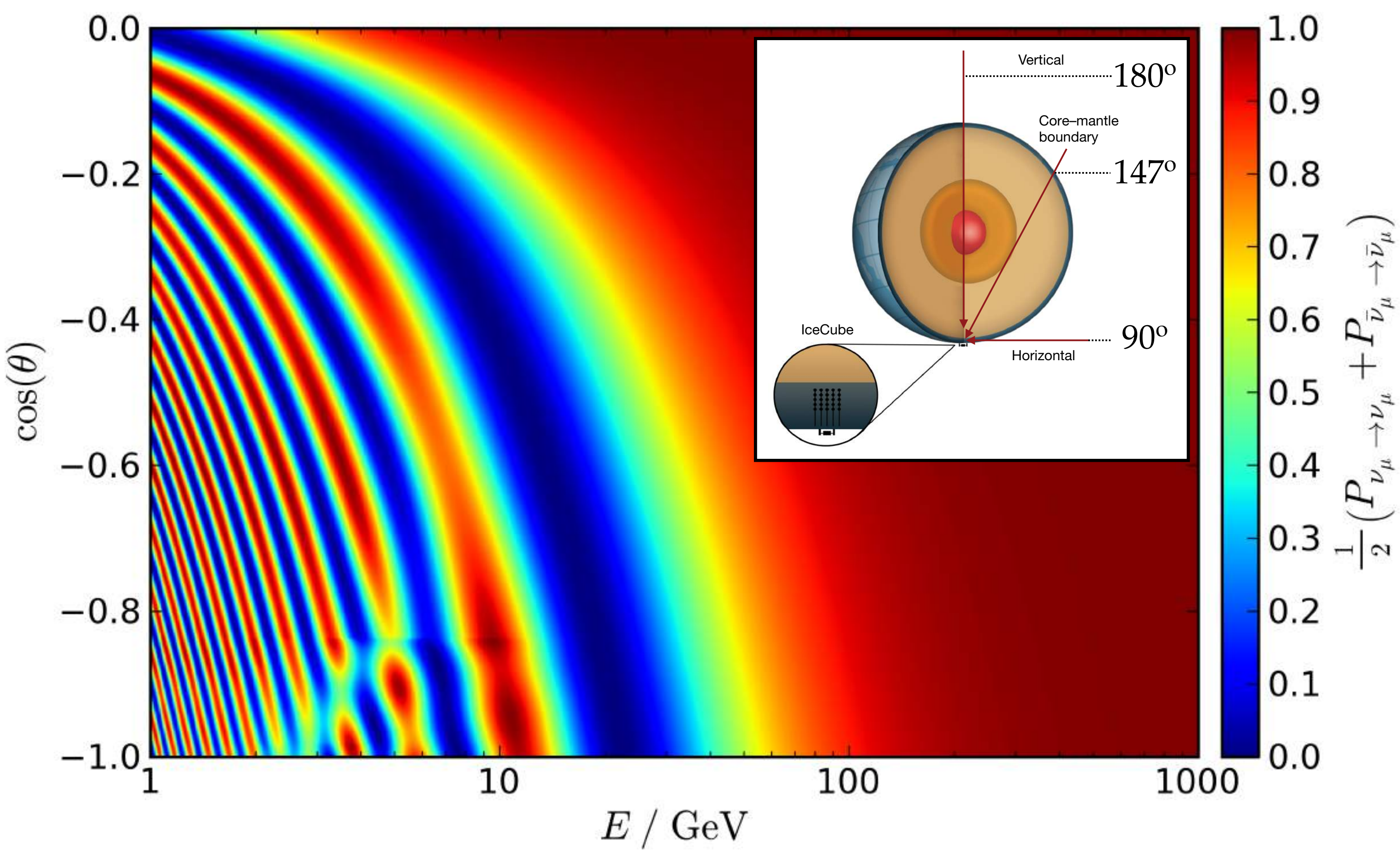
Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (5 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km³	~1 km³	~0.4 km³ (Phase 1) ~1km³	~0.1 km³ (Phase 1) ~1 km³
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

- Atmospheric neutrinos with energy E are observed with different zenith angles that correspond to different oscillation baselines L (*lower right plot*).

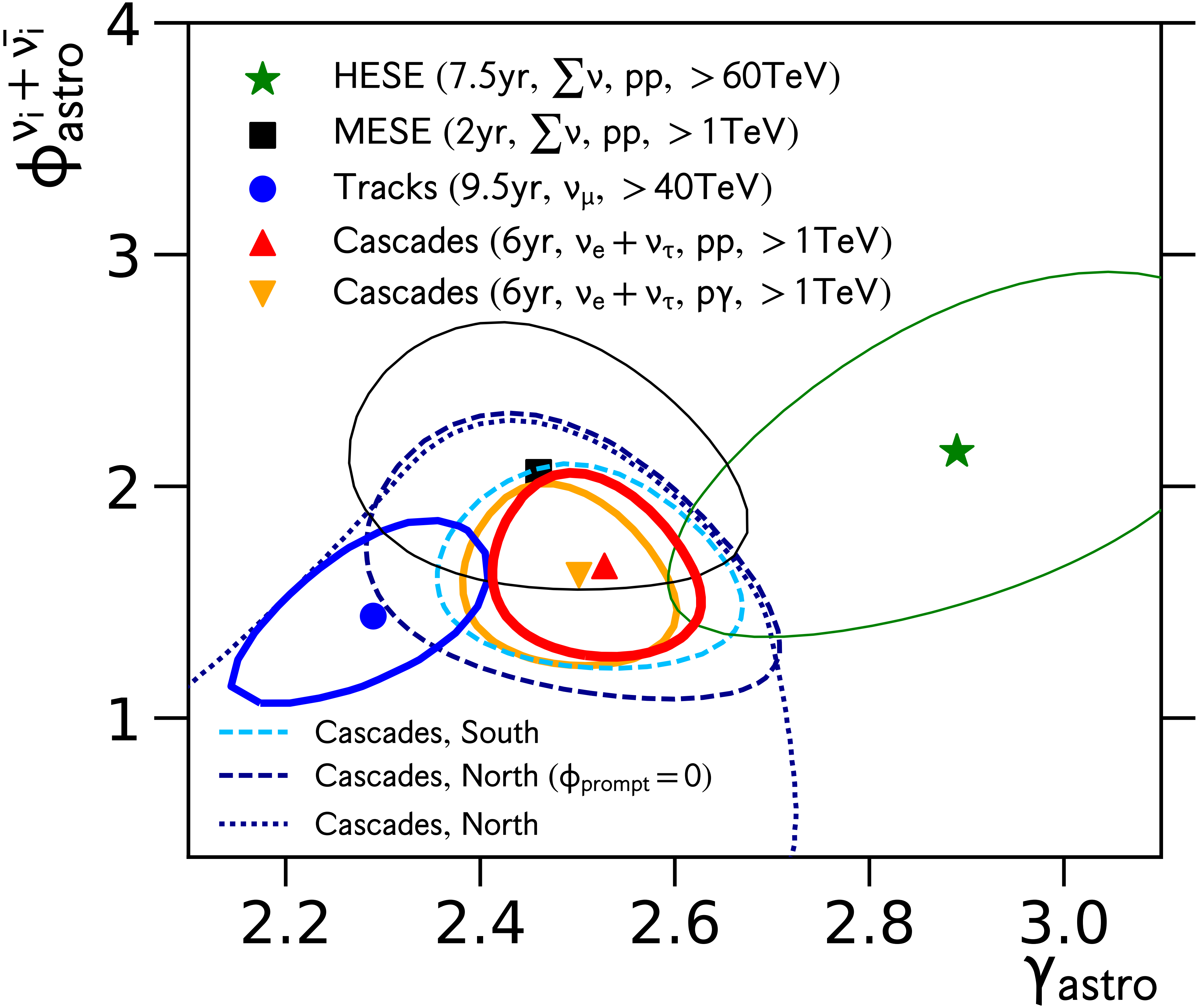
- Arranging the data into bins of L/E one can study the **disappearance** of atmospheric neutrinos (*lower left plot*):

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$





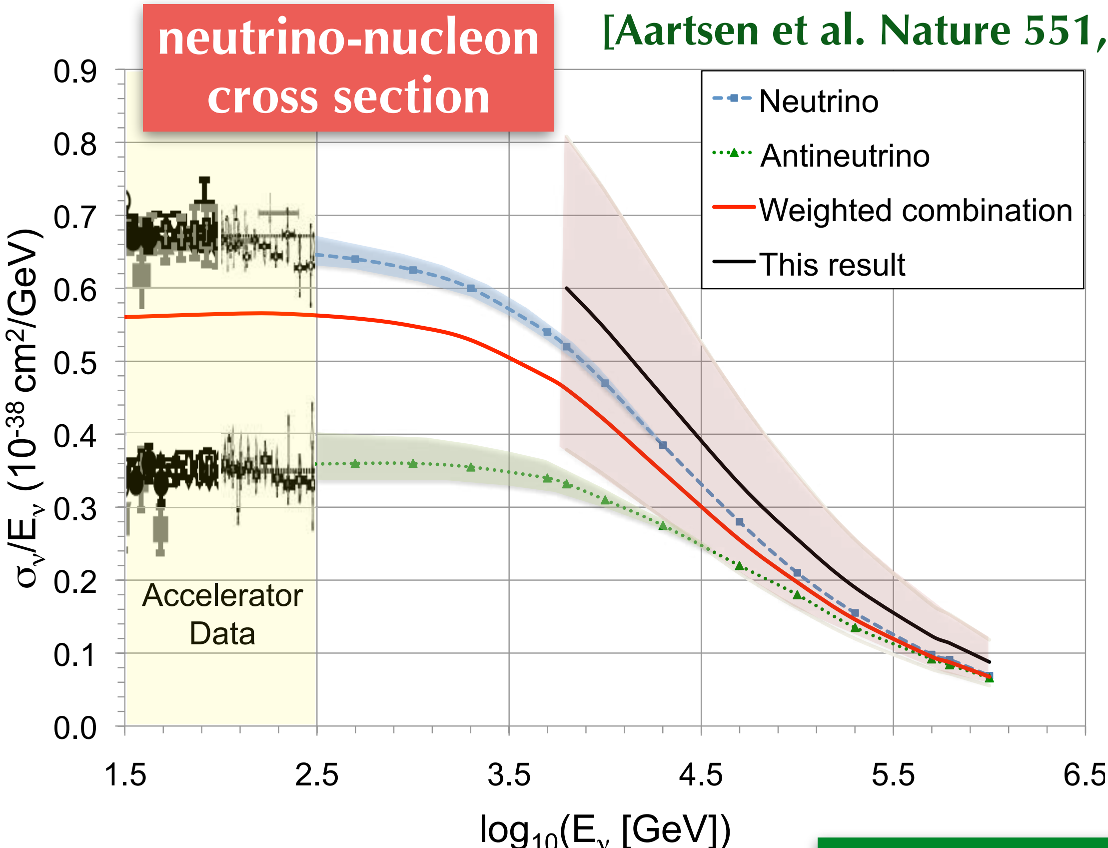
Power-Law Fits

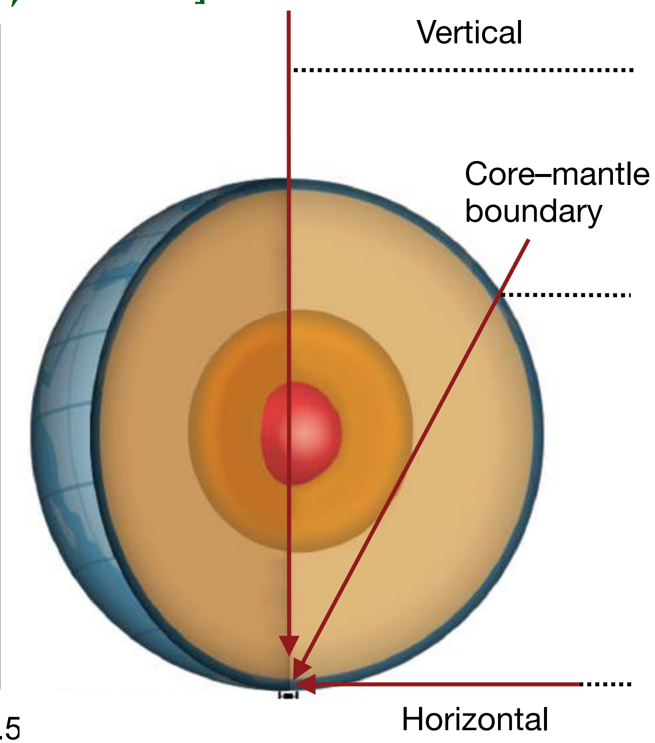


Neutrino Physics

neutrino-nucleon cross section

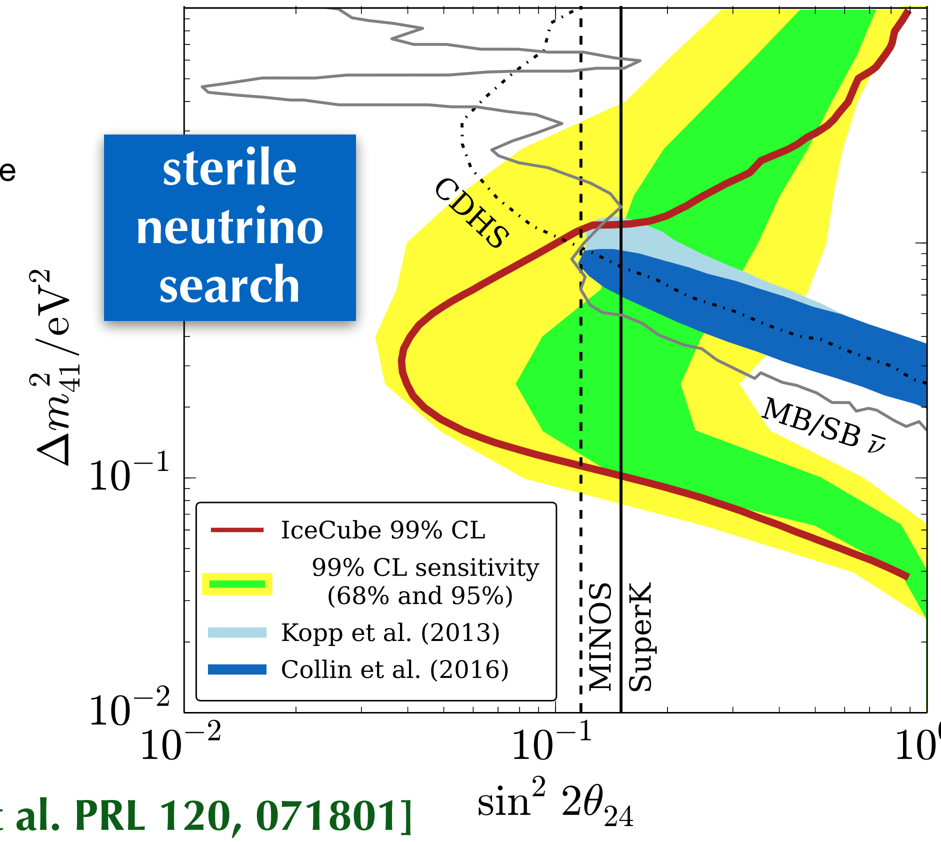
[Aartsen et al. Nature 551, 596-600]





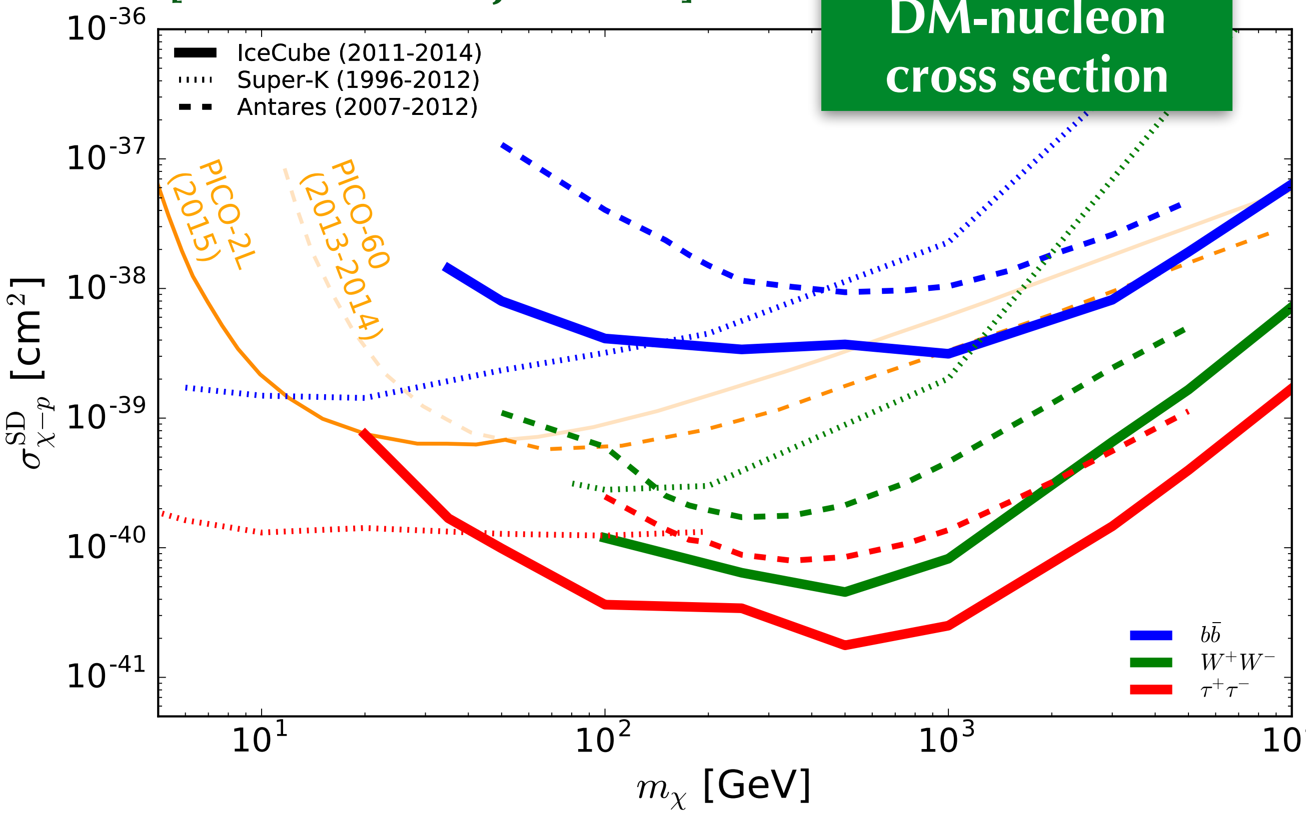
[Aartsen et al. PRL 117, 071801]

sterile neutrino search



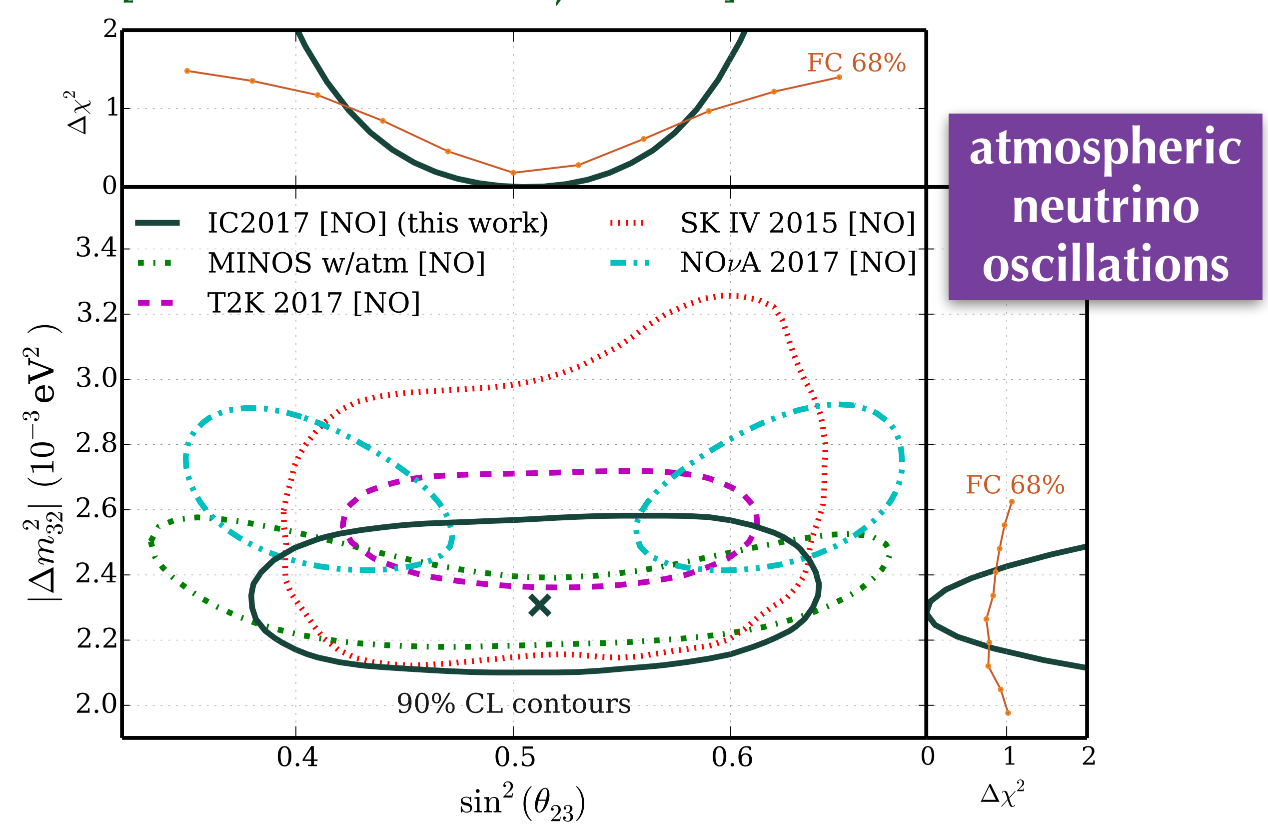
[Aartsen et al. EPJ C77 146]

spin-dependent DM-nucleon cross section

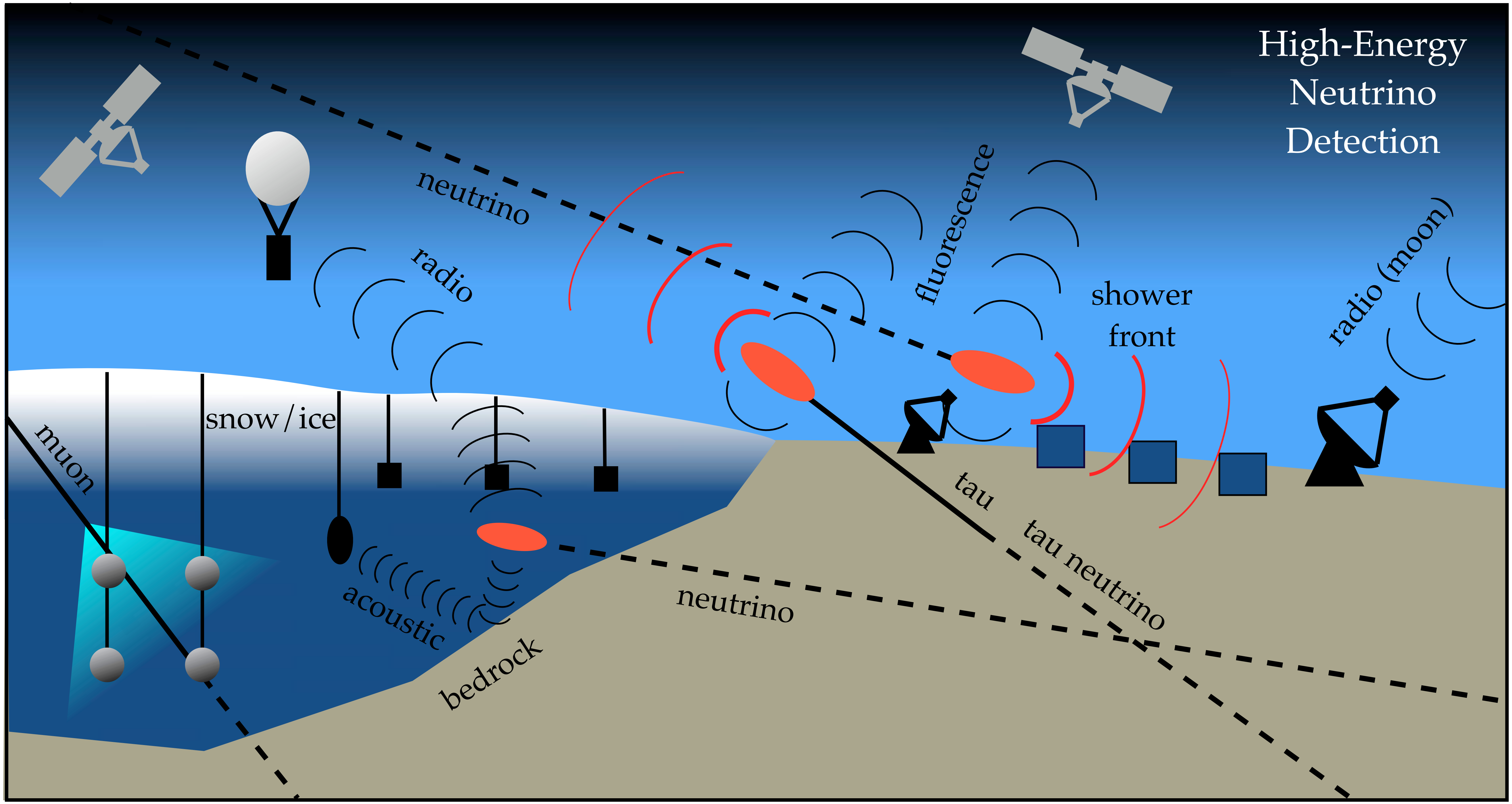


[Aartsen et al. PRL 120, 071801]

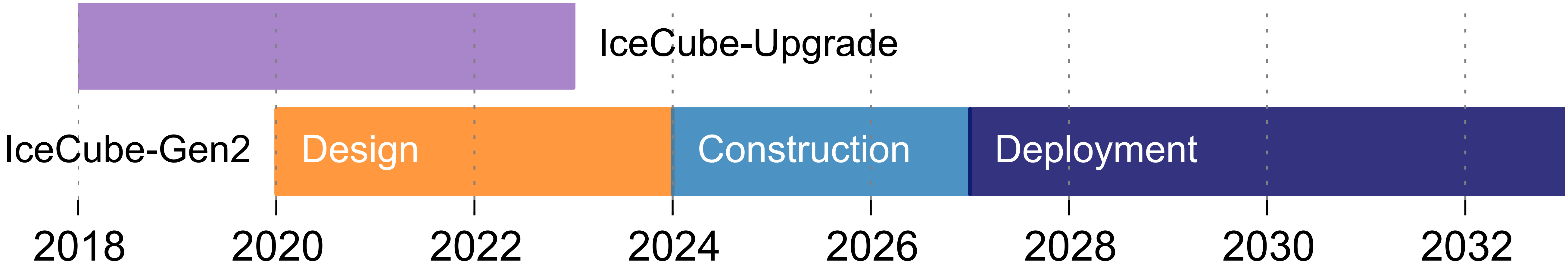
atmospheric neutrino oscillations

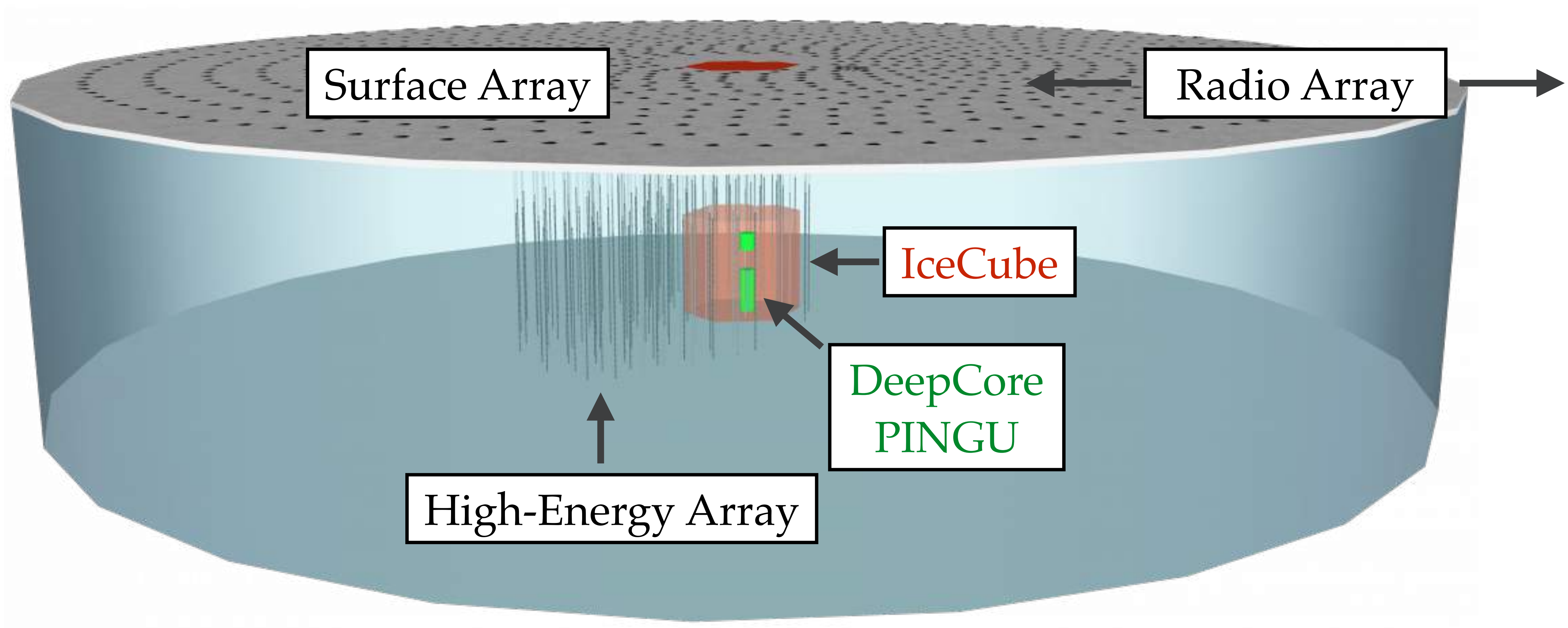


Detection Principles



IceCube-Gen2 Timeline



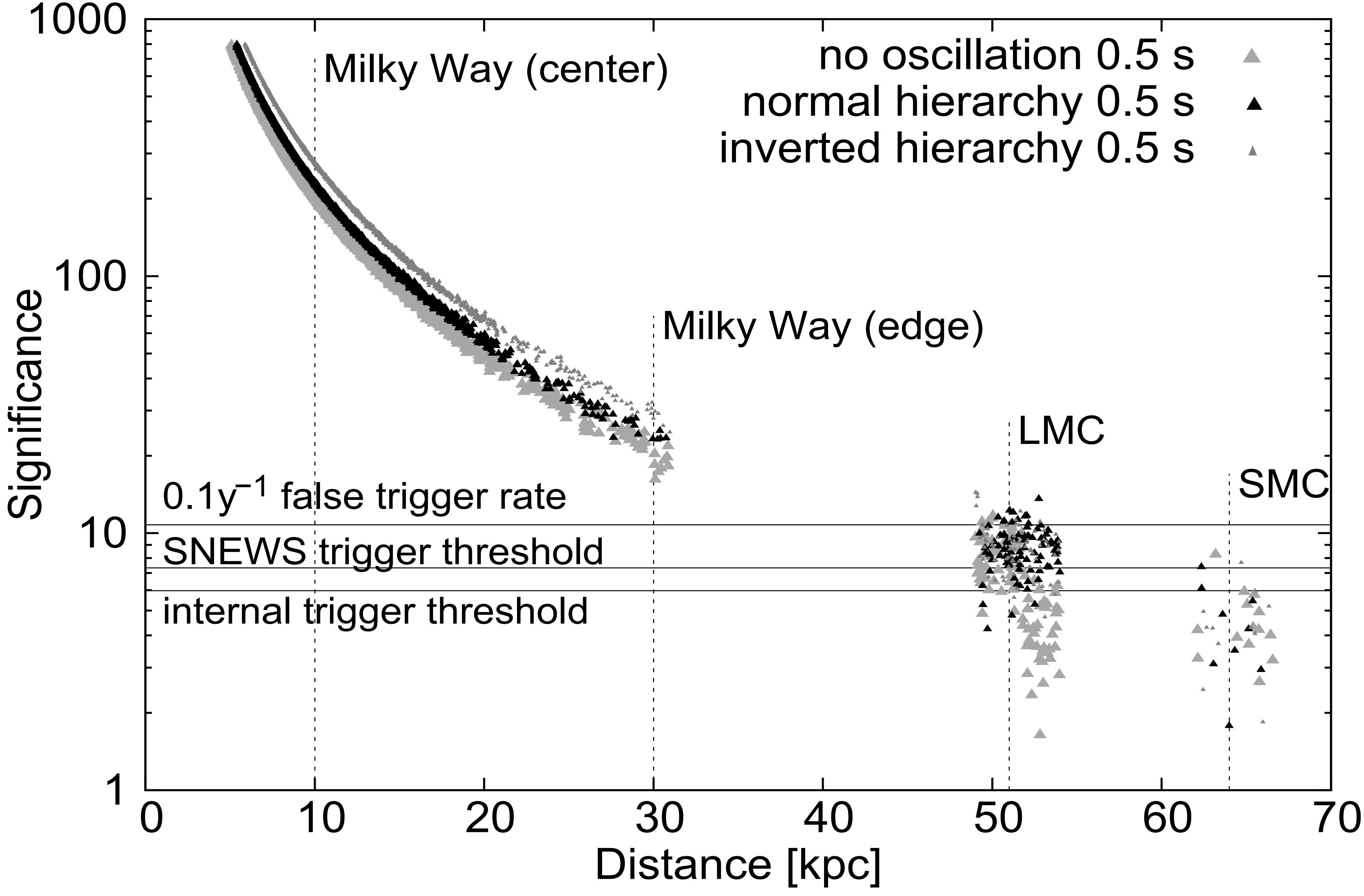


Supernova Forecast

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

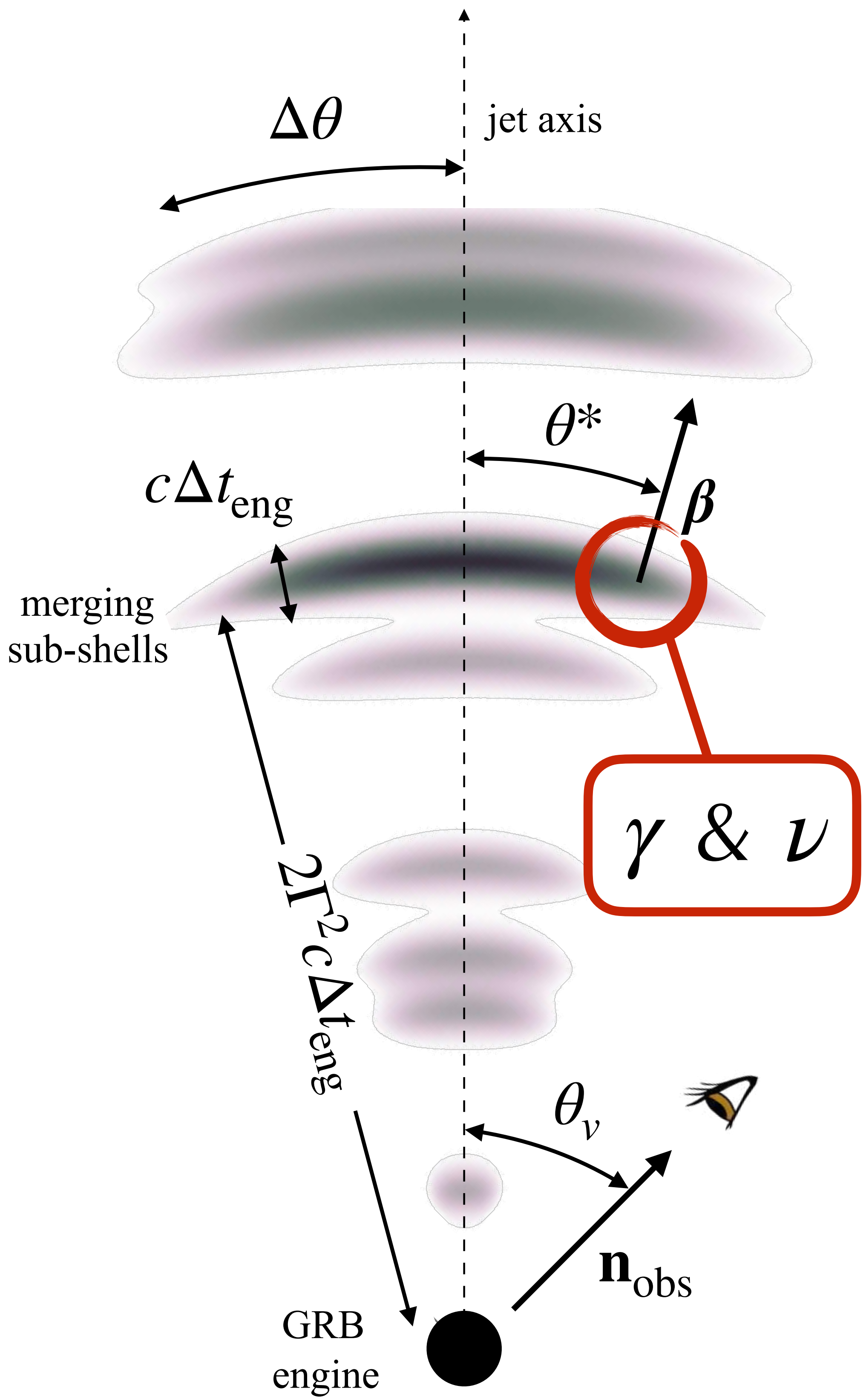
Reaction	# Targets	# Signal Hits	Signal Fraction	Reference
$\bar{\nu}_e + p \to e^+ + n$	$6 \cdot 10^{37}$	134 k (157 k)	93.8 % (94.4 %)	Strumia & Vissani (2003)
$\nu_e + e^- \to \nu_e + e^-$	$3 \cdot 10^{38}$	2.35 k (2.25 k)	1.7 % (1.4 %)	Marciano & Parsa (2003)
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	$3 \cdot 10^{38}$	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.

Scaling of Off-Axis Emission



- Observed emission of surface elements along the internal shocks are scaled in energy and intensity via the **relativistic Doppler factor**:

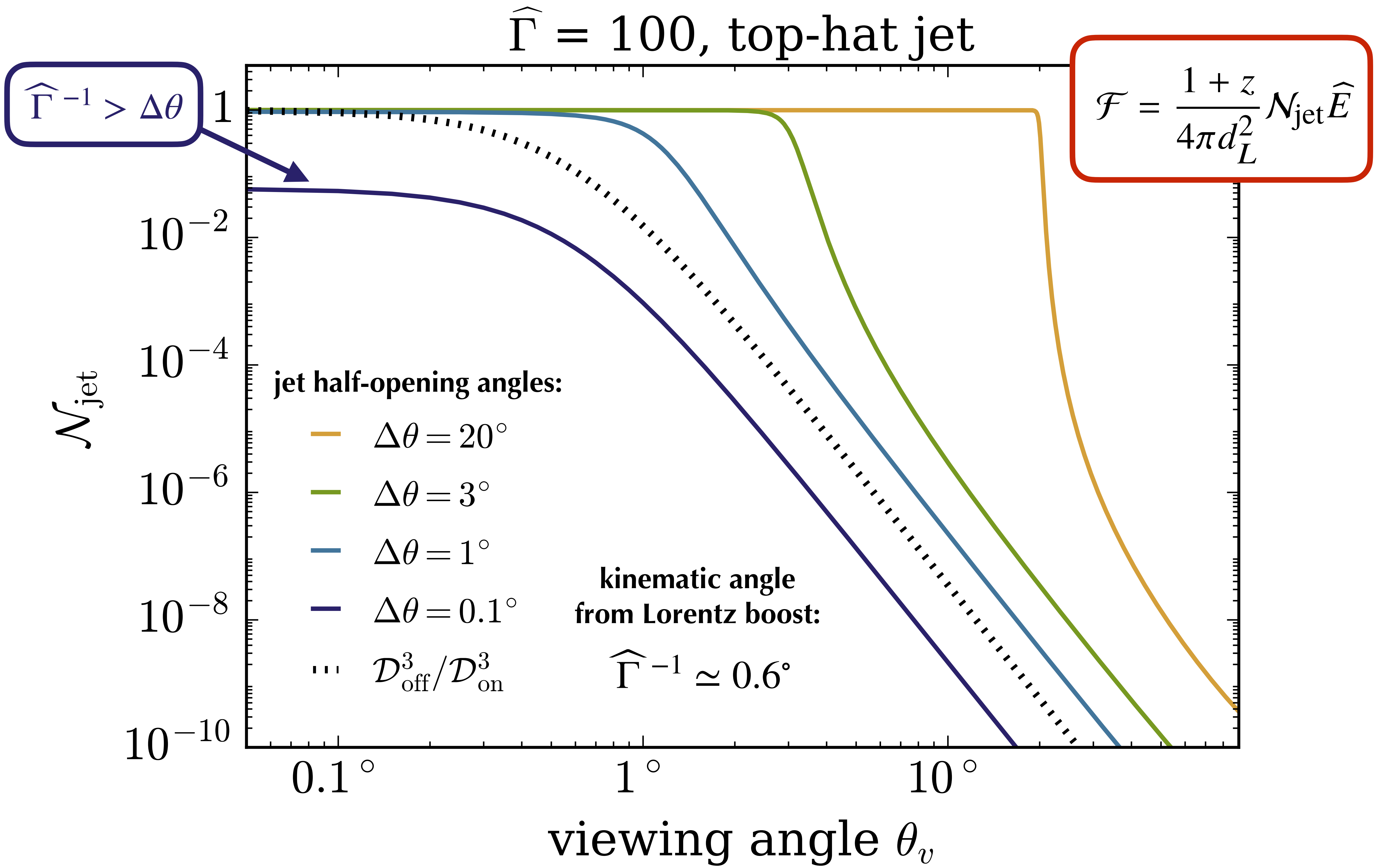
$$\mathcal{D} = [\Gamma(1 - \boldsymbol{\beta}\cdot\mathbf{n}_{\mathrm{obs}})]^{-1}$$

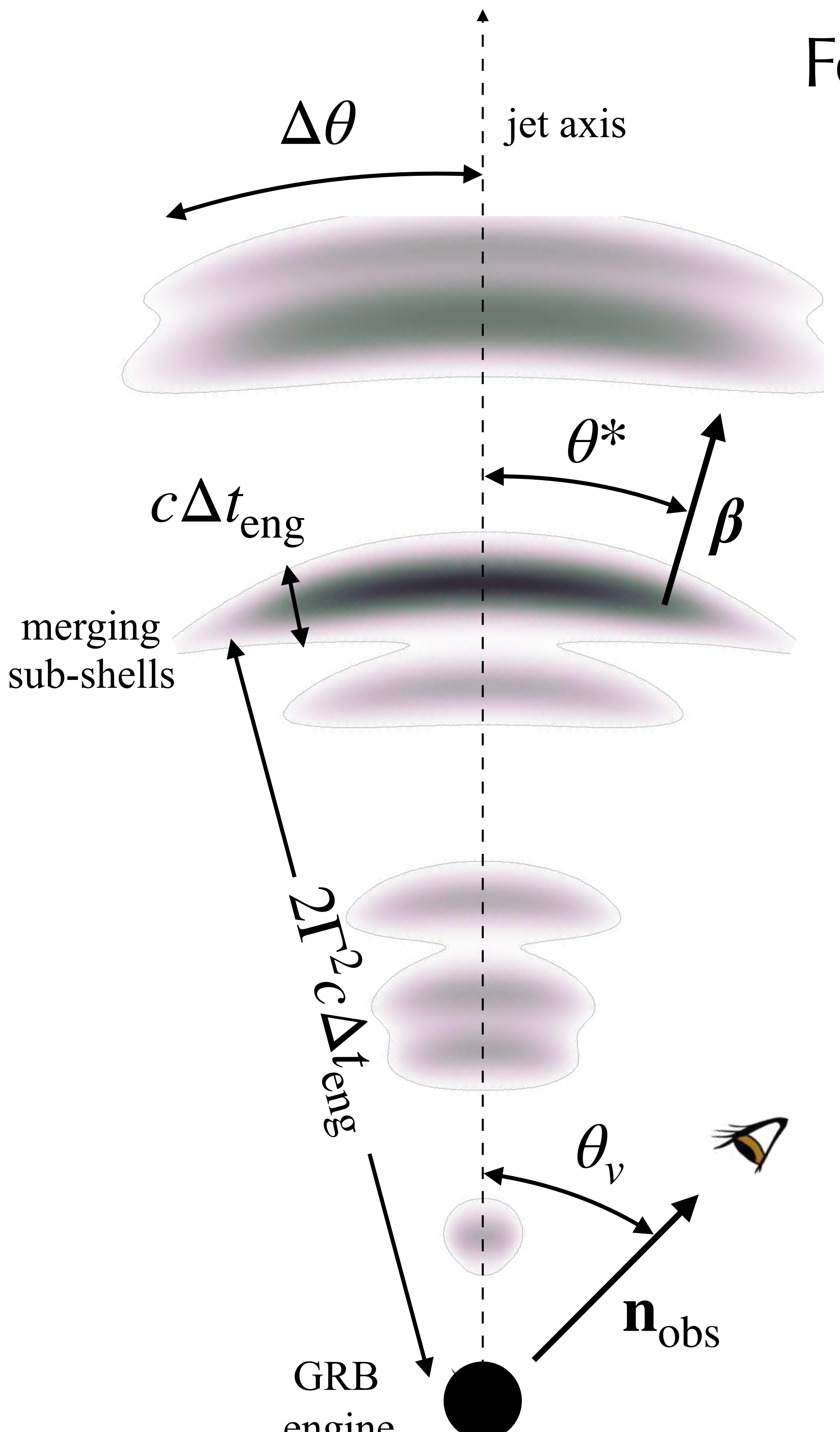
- The GRB fluence $\mathcal{F}$ [GeVcm^{-2}] can be expressed as:

$$\mathcal{F} = \frac{1+z}{4\pi d_L^2}\int \mathrm{d}\Omega^* \frac{\mathcal{D}^3(\Omega^*)}{\Gamma(\theta^*)}\frac{\mathrm{d}E^*}{\mathrm{d}\Omega^*}$$

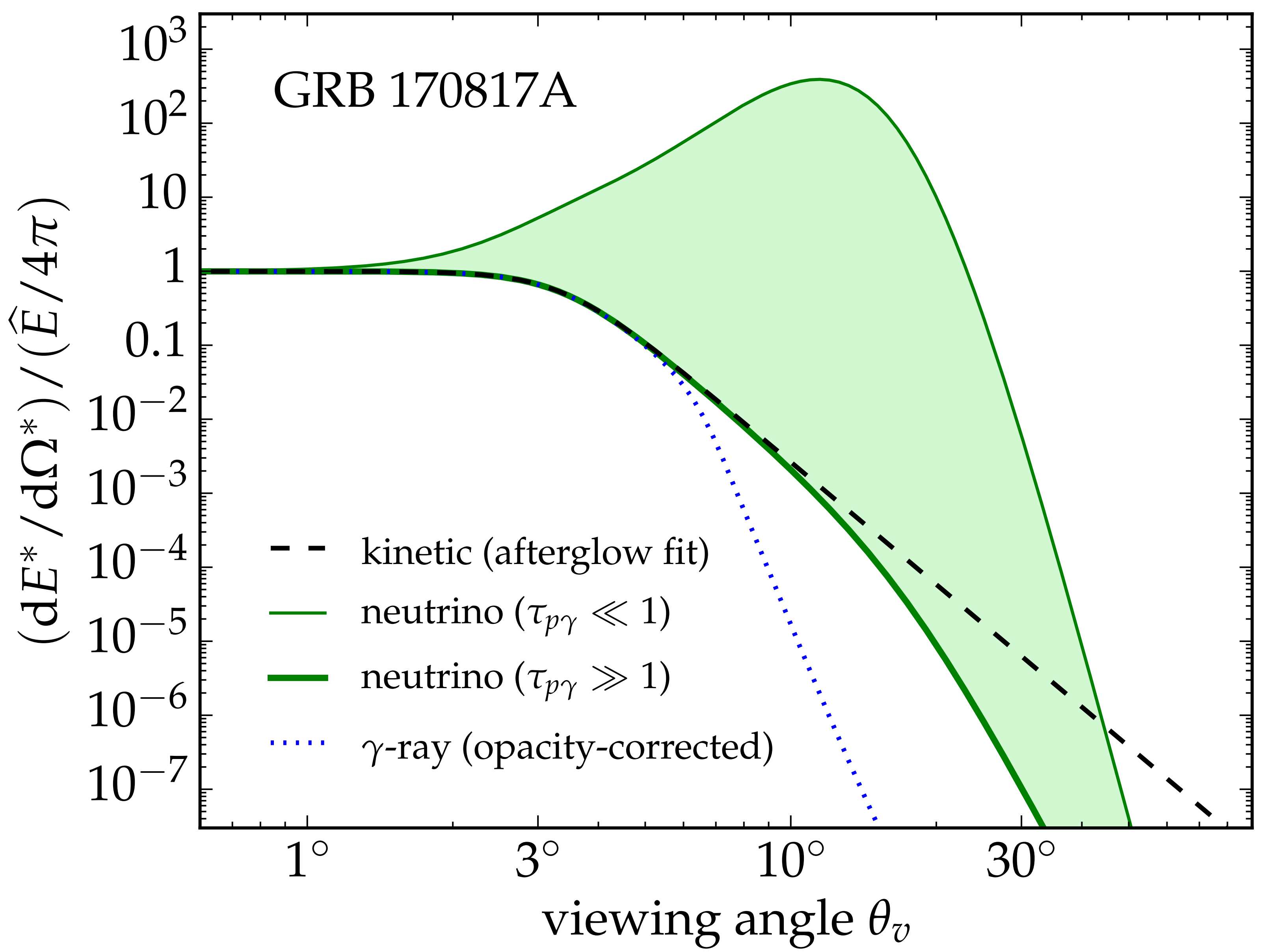
[MA & Halser MNRAS 490 (2019) 4]

Scaling of Off-Axis Fluence

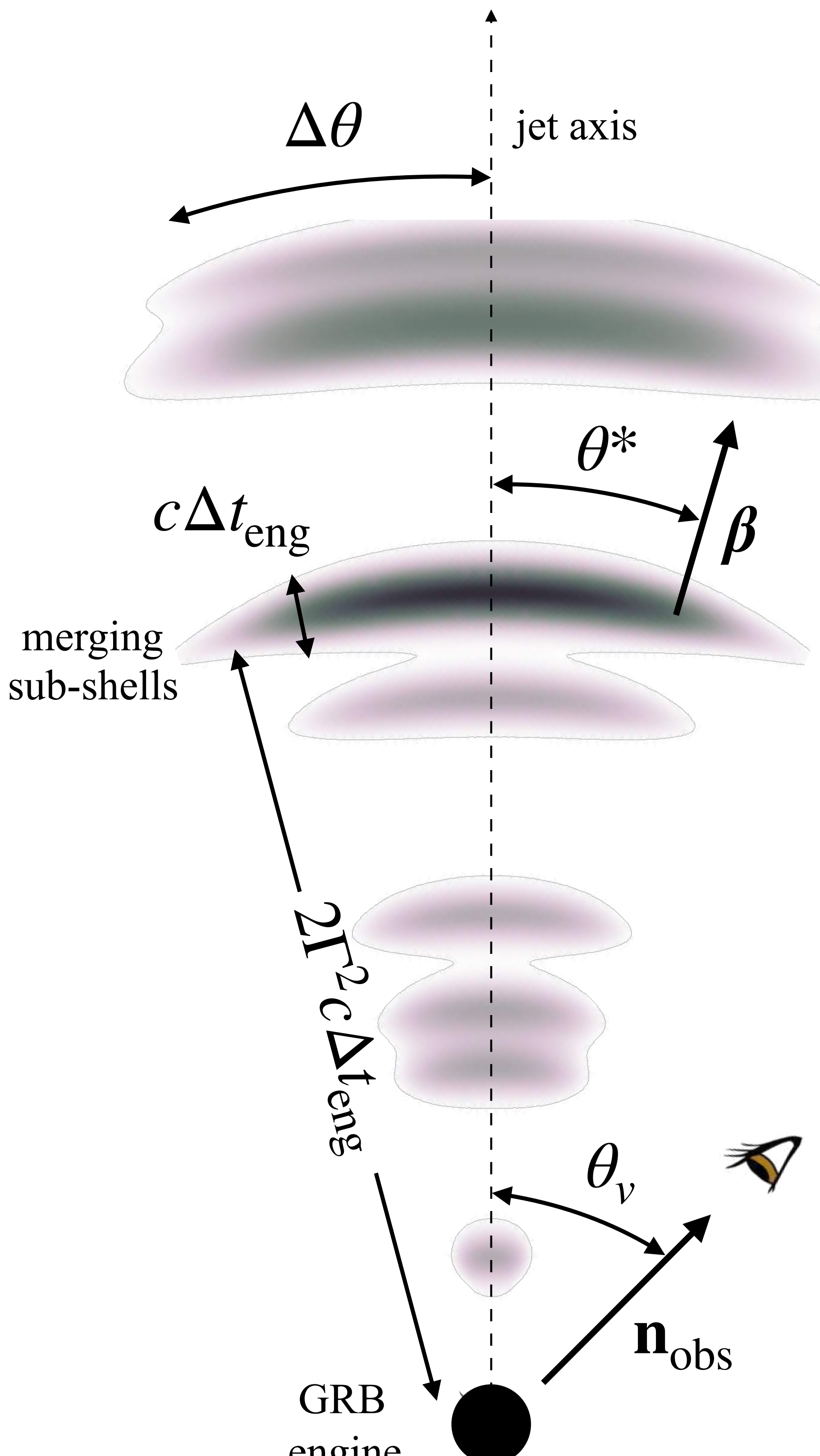




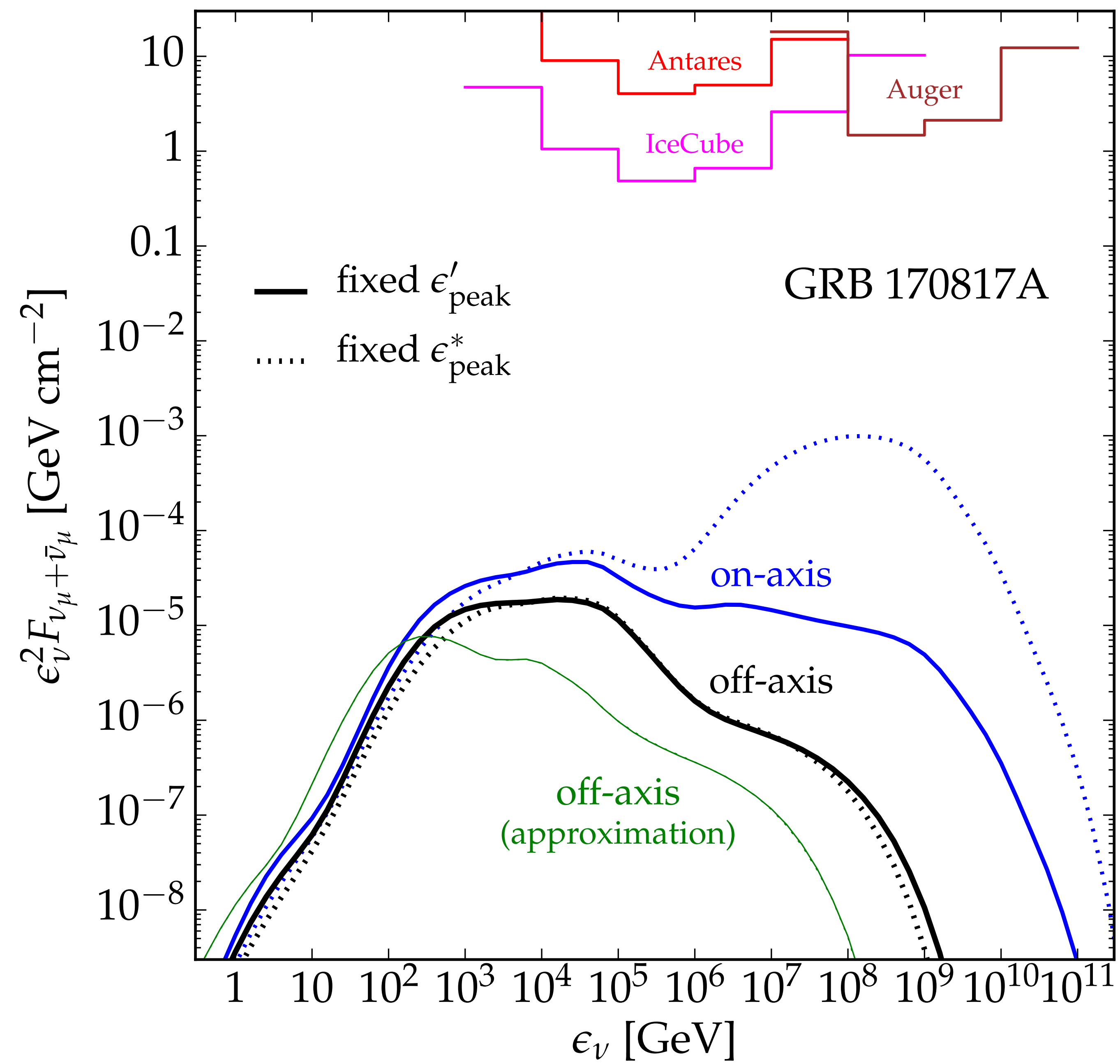
Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



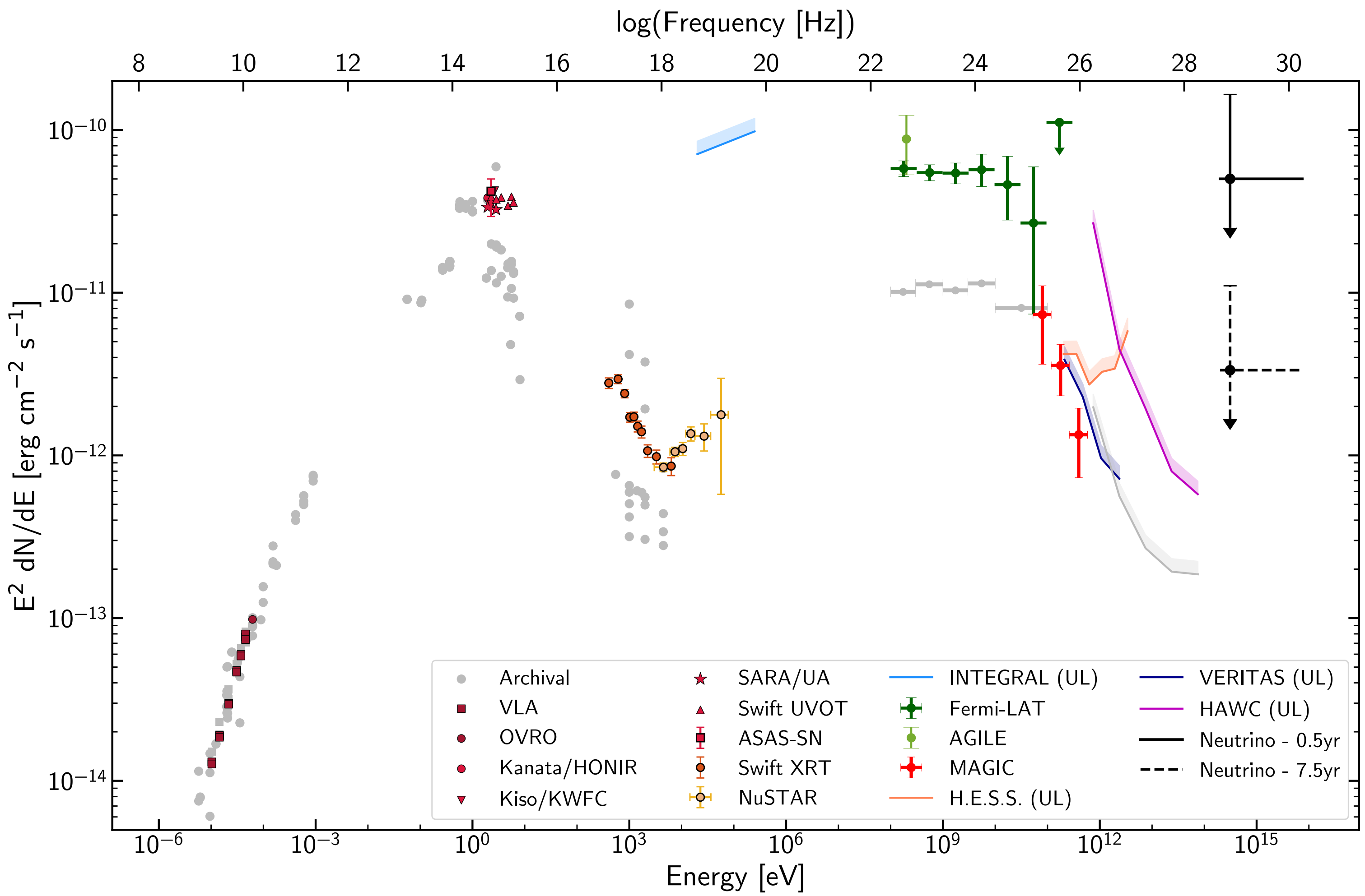
[MA & Halser MNRAS 490 (2019) 4]

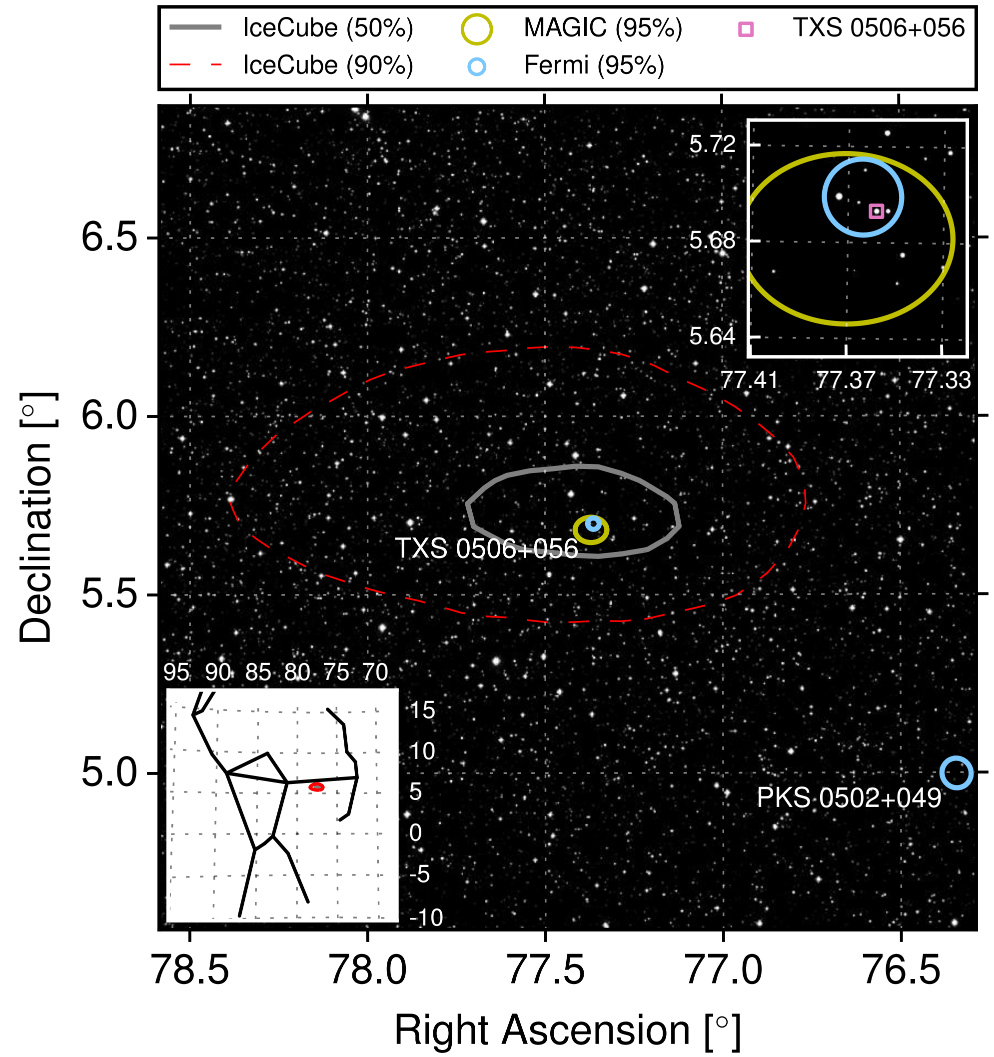


Formalism can be extended to **off-axis emission of structured jets** as in the case of GRB 170817A.



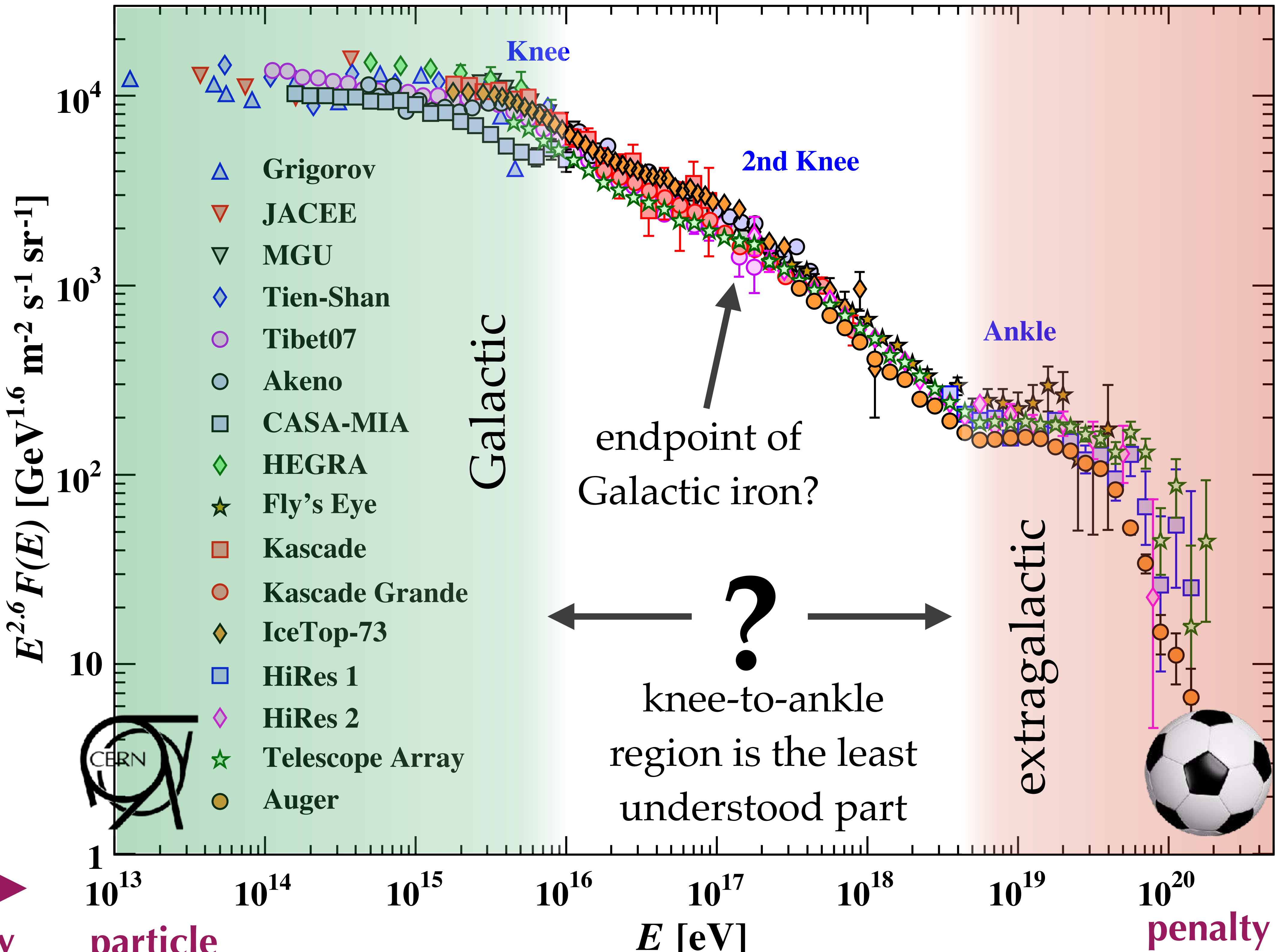
[MA & Halser MNRAS 490 (2019) 4]





- 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]

Very-High Energy Cosmic Rays



energy scale

particle accelerators

penalty kick