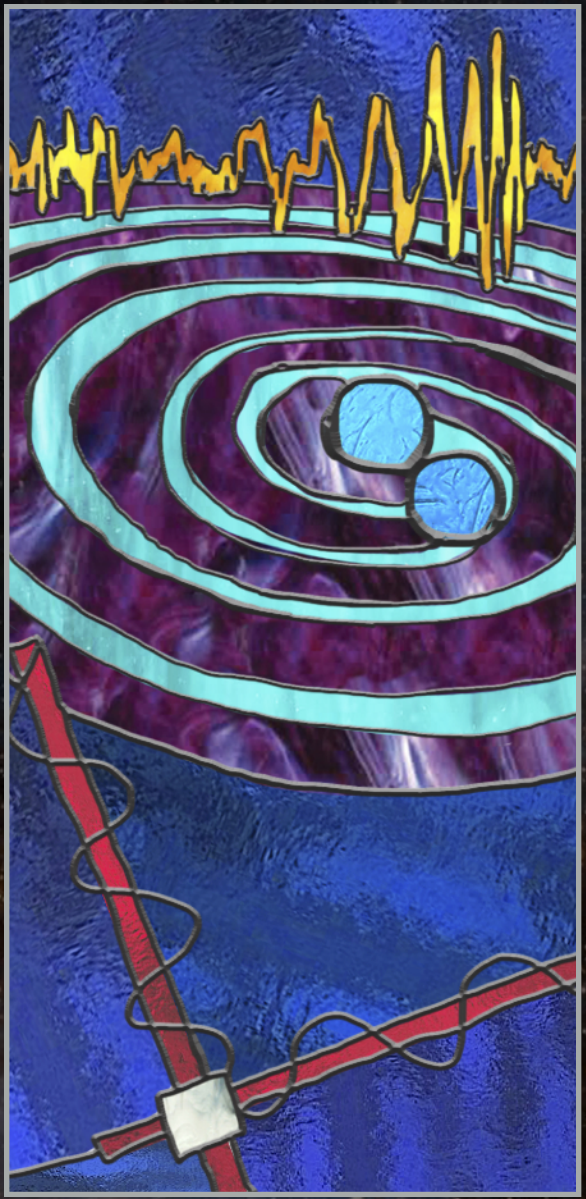
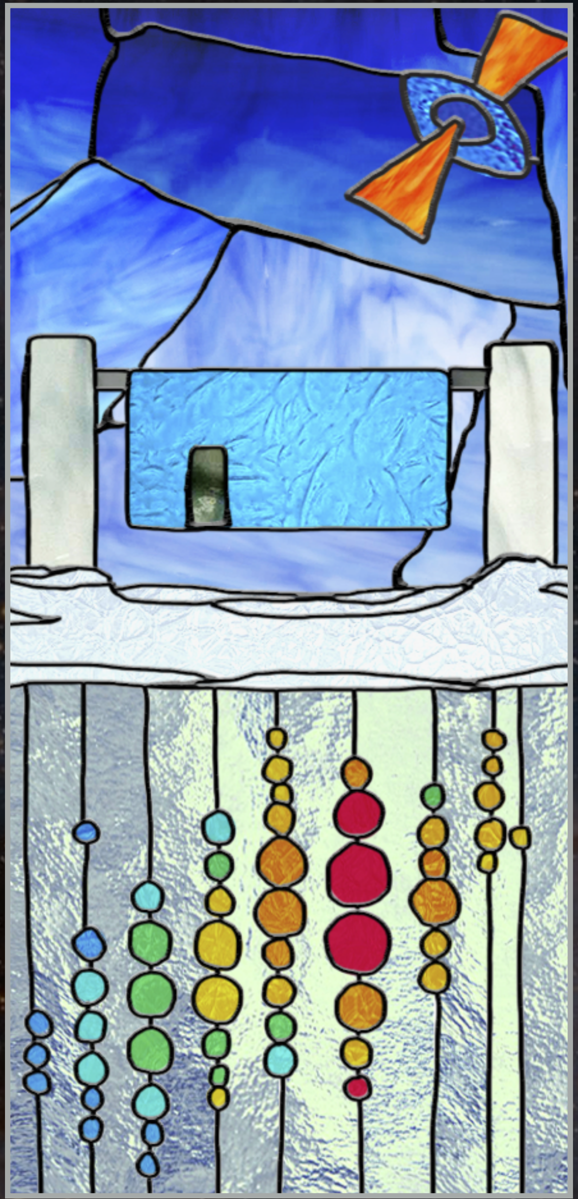
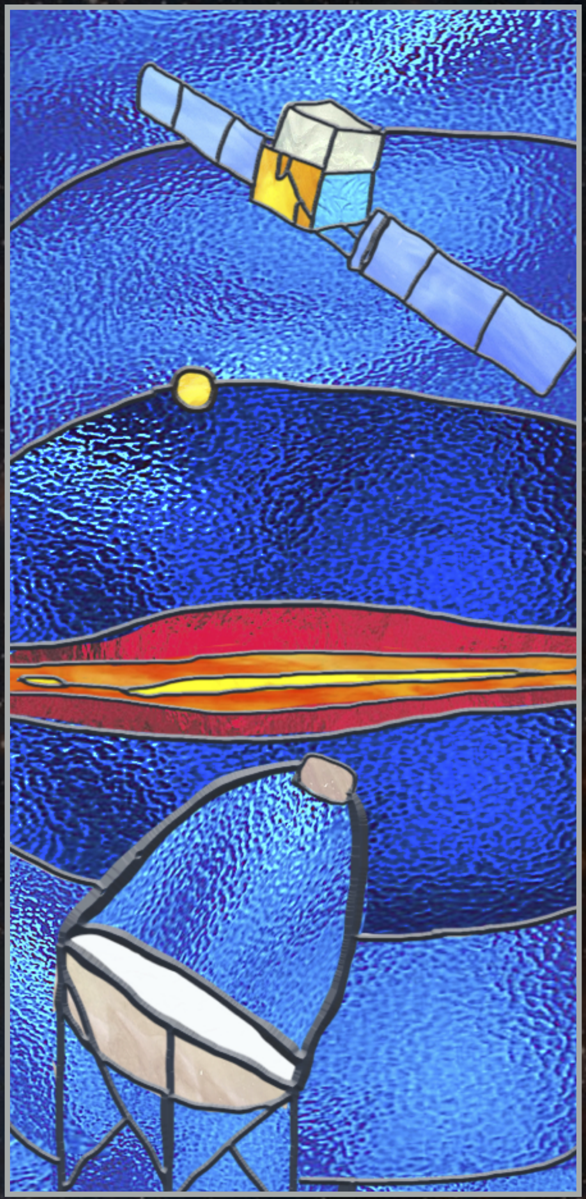




Neutrino Astronomy: Physics, Status & Outlook
Part II

Markus Ahlers
Niels Bohr Institute

Georges Lemaître Chair 2023

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Extragalactic Populations

Populations of extragalactic neutrino sources visible as

individual sources

and by

combined isotropic emission.

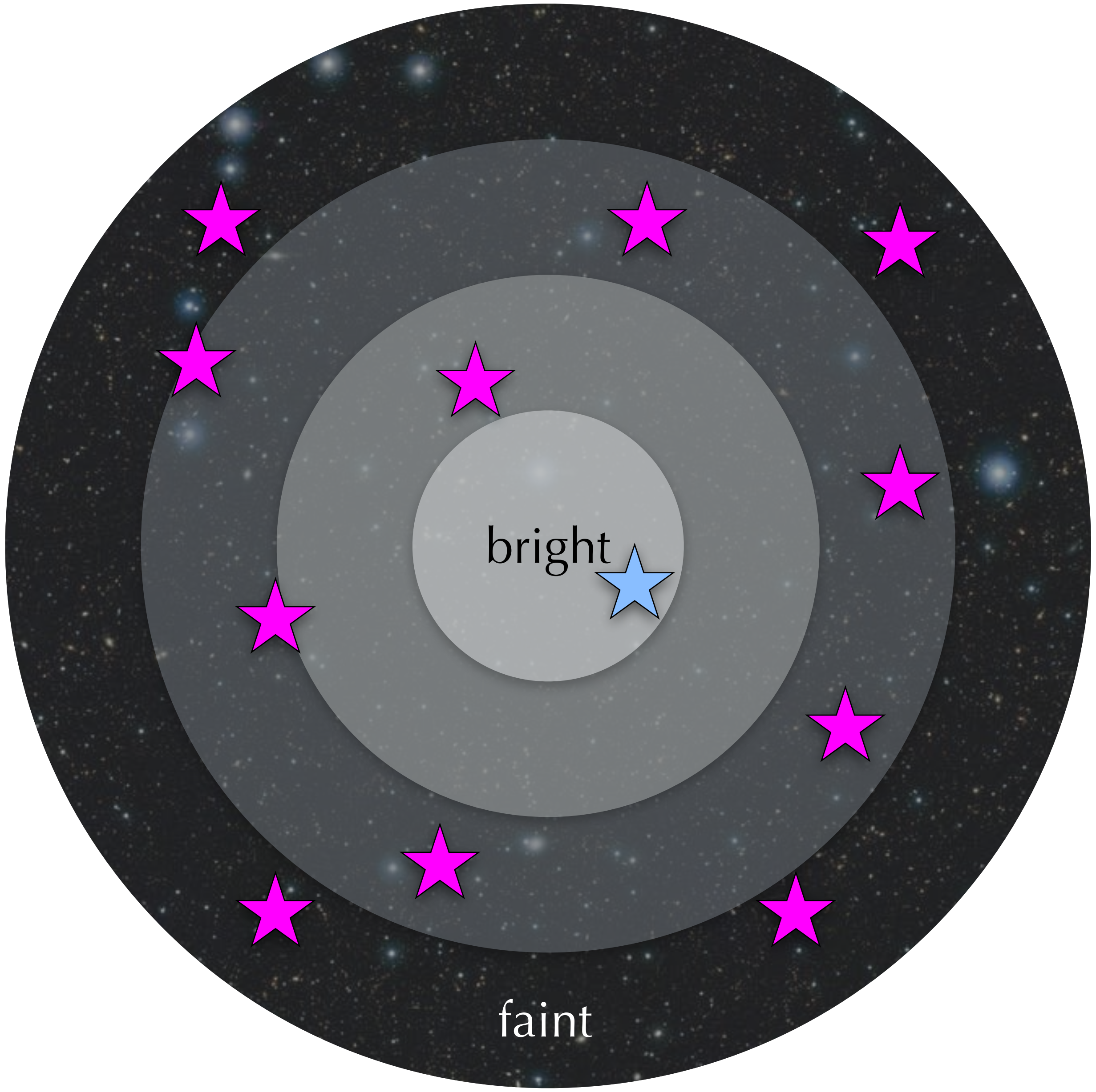
The relative contribution can be parametrized (*to first order*) by the average

local source density $\rho_{\rm eff}$

and

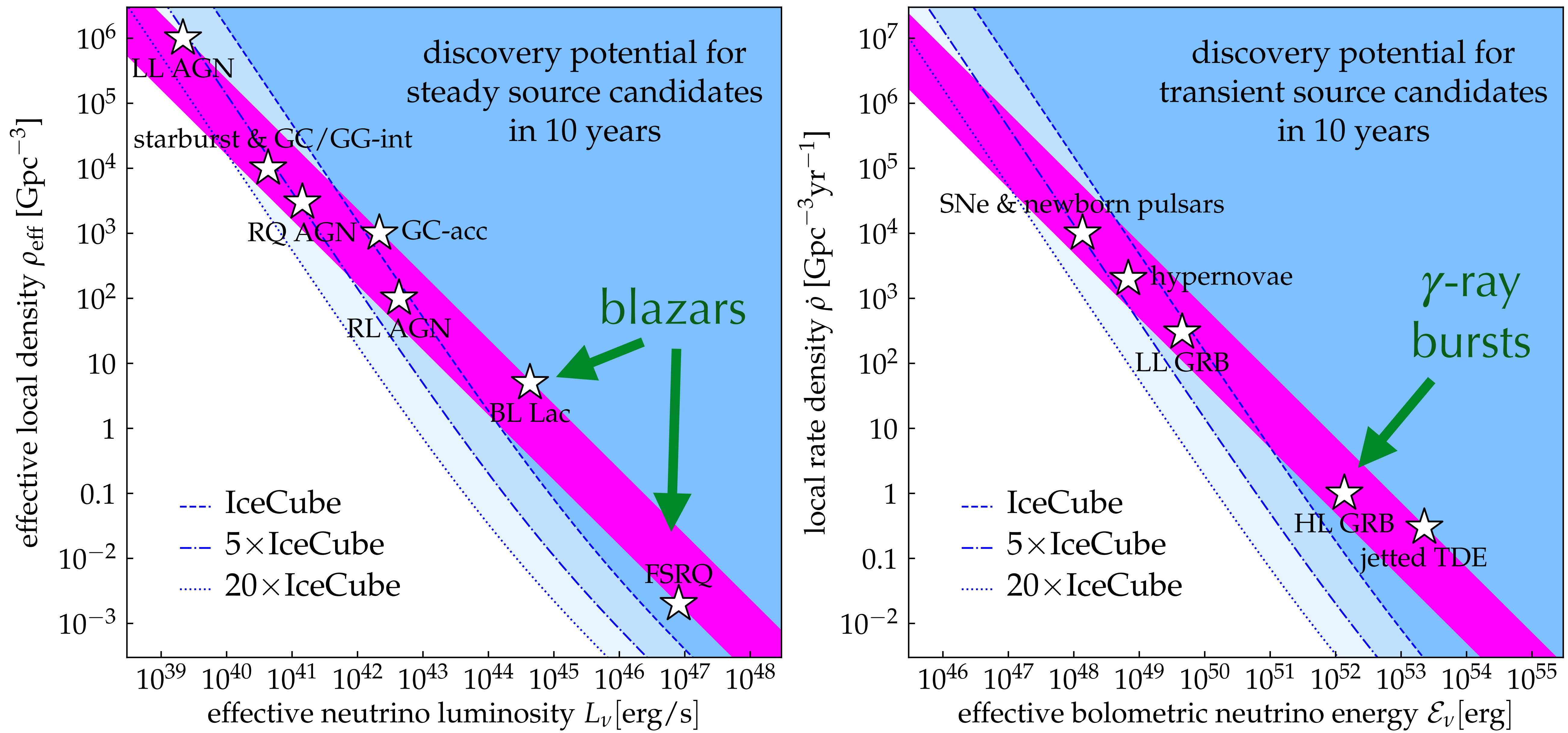
source luminosity L_ν

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



Hubble-Lemaître horizon

Point Source vs. Diffuse Flux

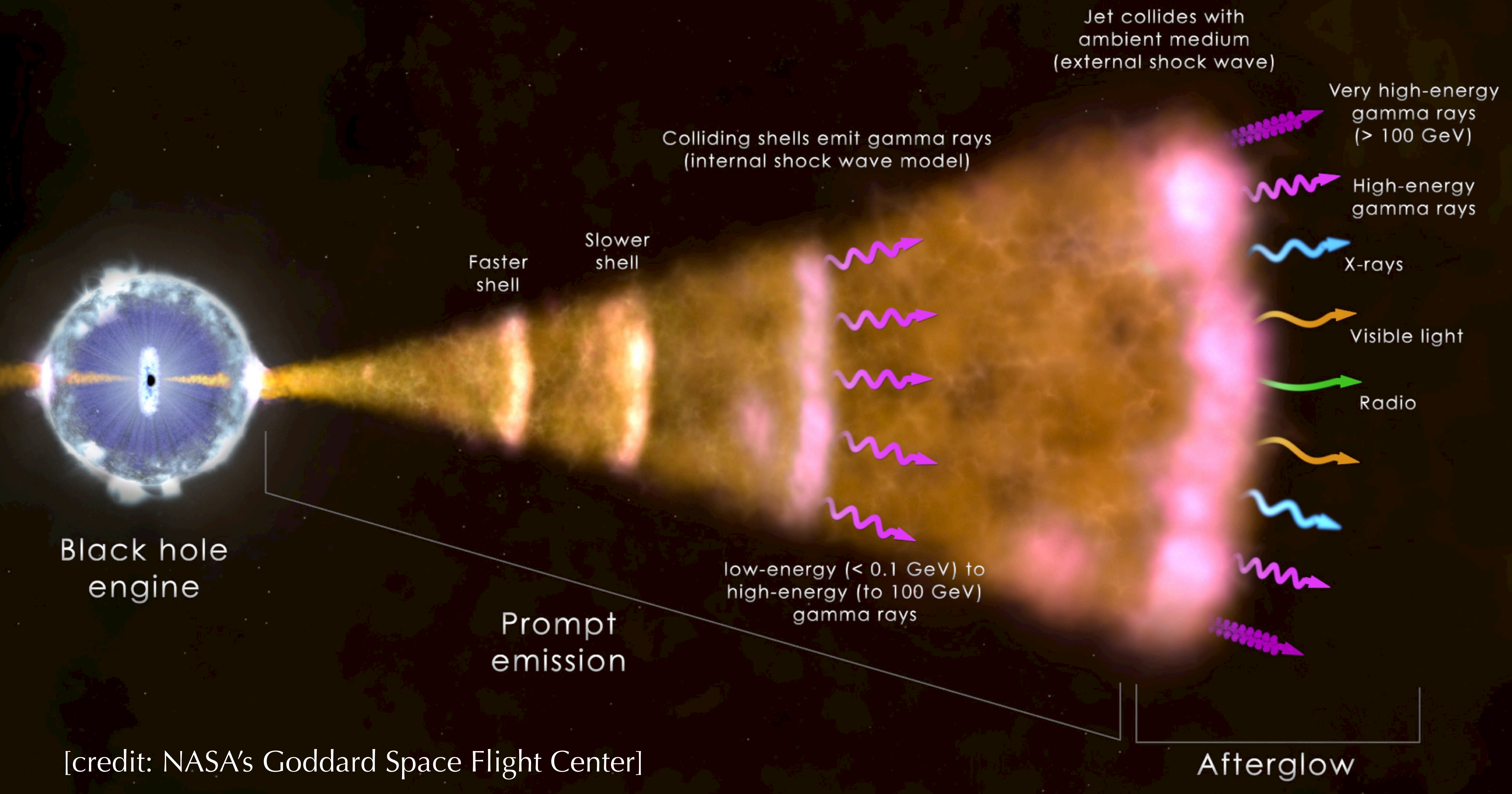


[Murase & Waxman'16; Ackermann *et al.'19*]

Rare sources - blazars, high-luminosity GRBs or jetted TDEs - 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.

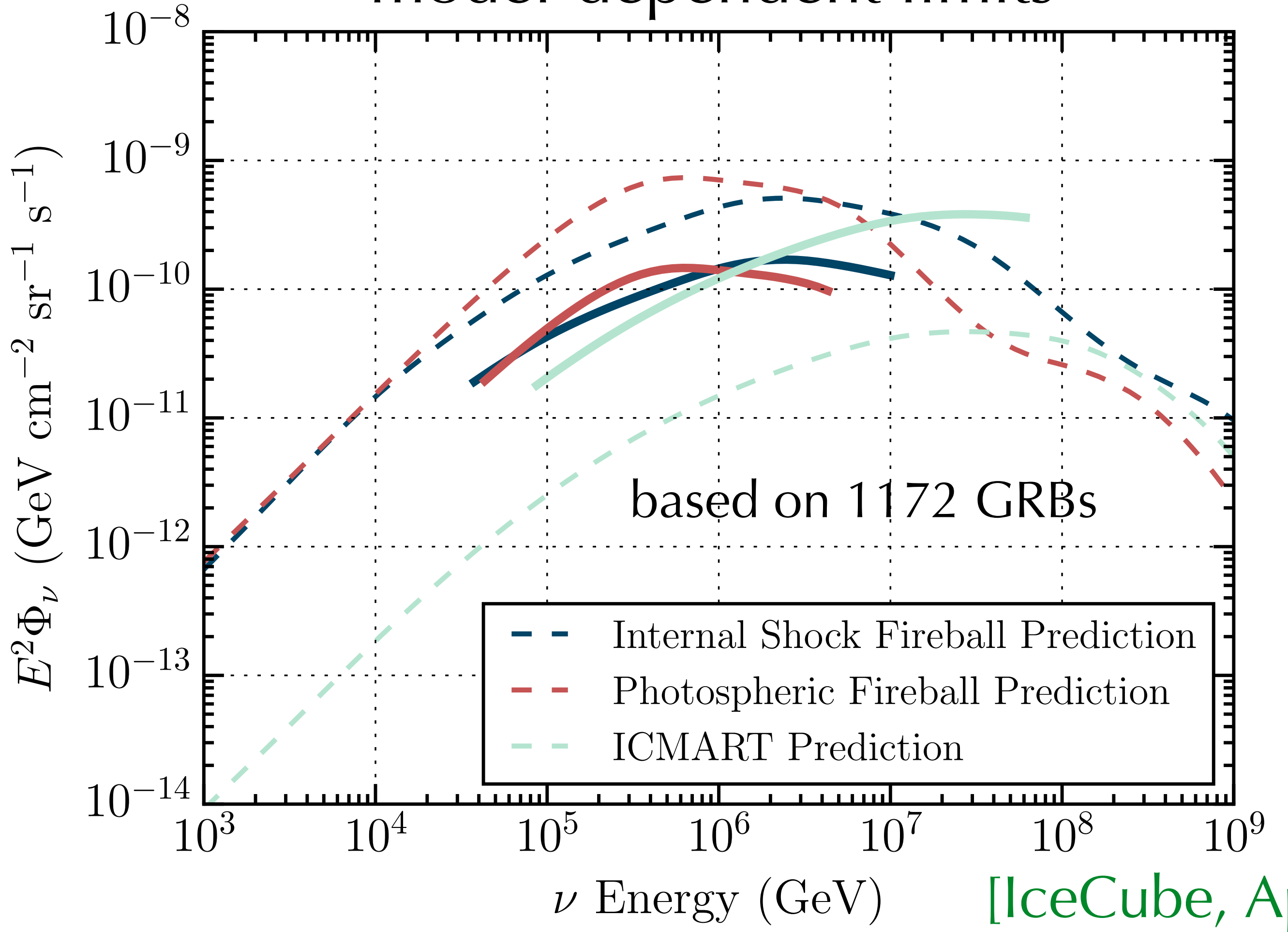


[credit: NASA's Goddard Space Flight Center]

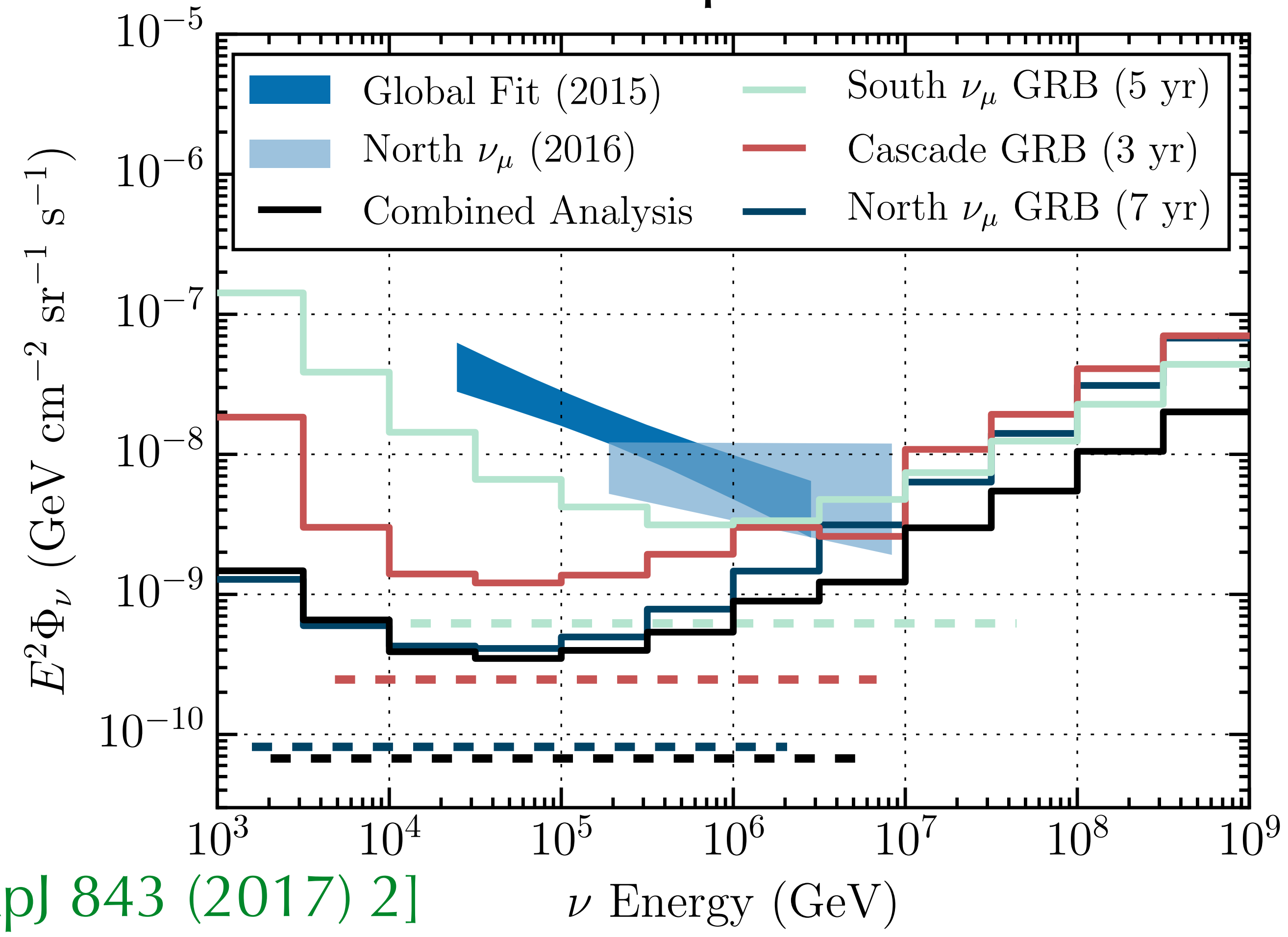
GRB Neutrino Limits

- IceCube routinely follows up on γ-ray bursts. [IceCube, ApJ 843 (2017) 2]
- Search is most sensitive to "prompt" (<100s) neutrino emission. [Waxman & Bahcall '97]
- Contribution to diffuse flux **below 1%** for "prompt" phase and **below 27%** for neutrino emission within 3h. [IceCube, ApJ 939 (2022) 2]

model-dependent limits



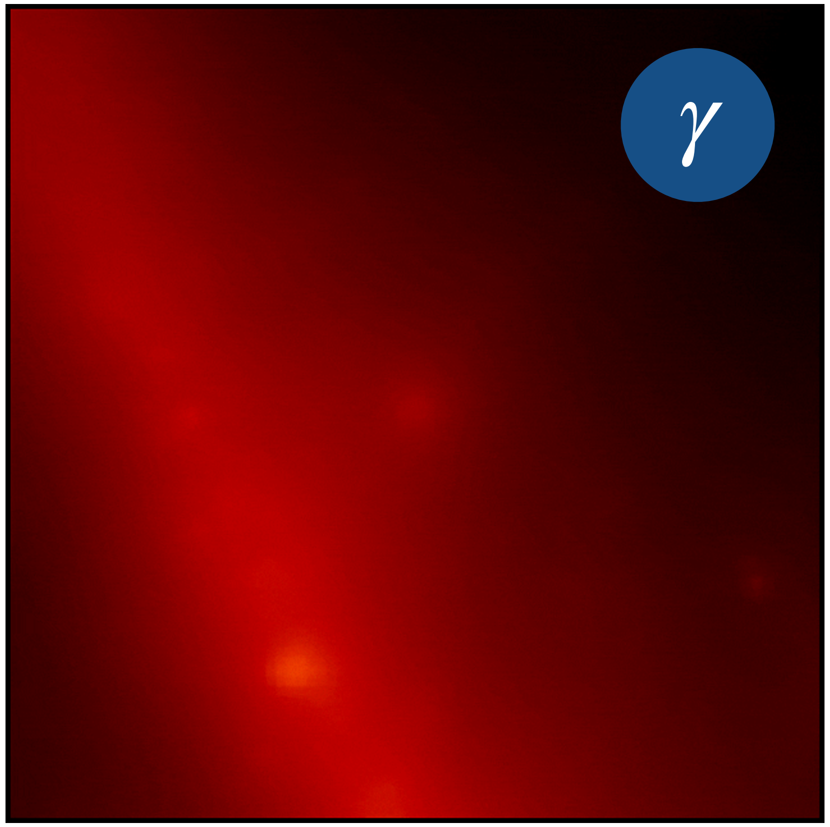
model-independent limits



[IceCube, ApJ 843 (2017) 2]

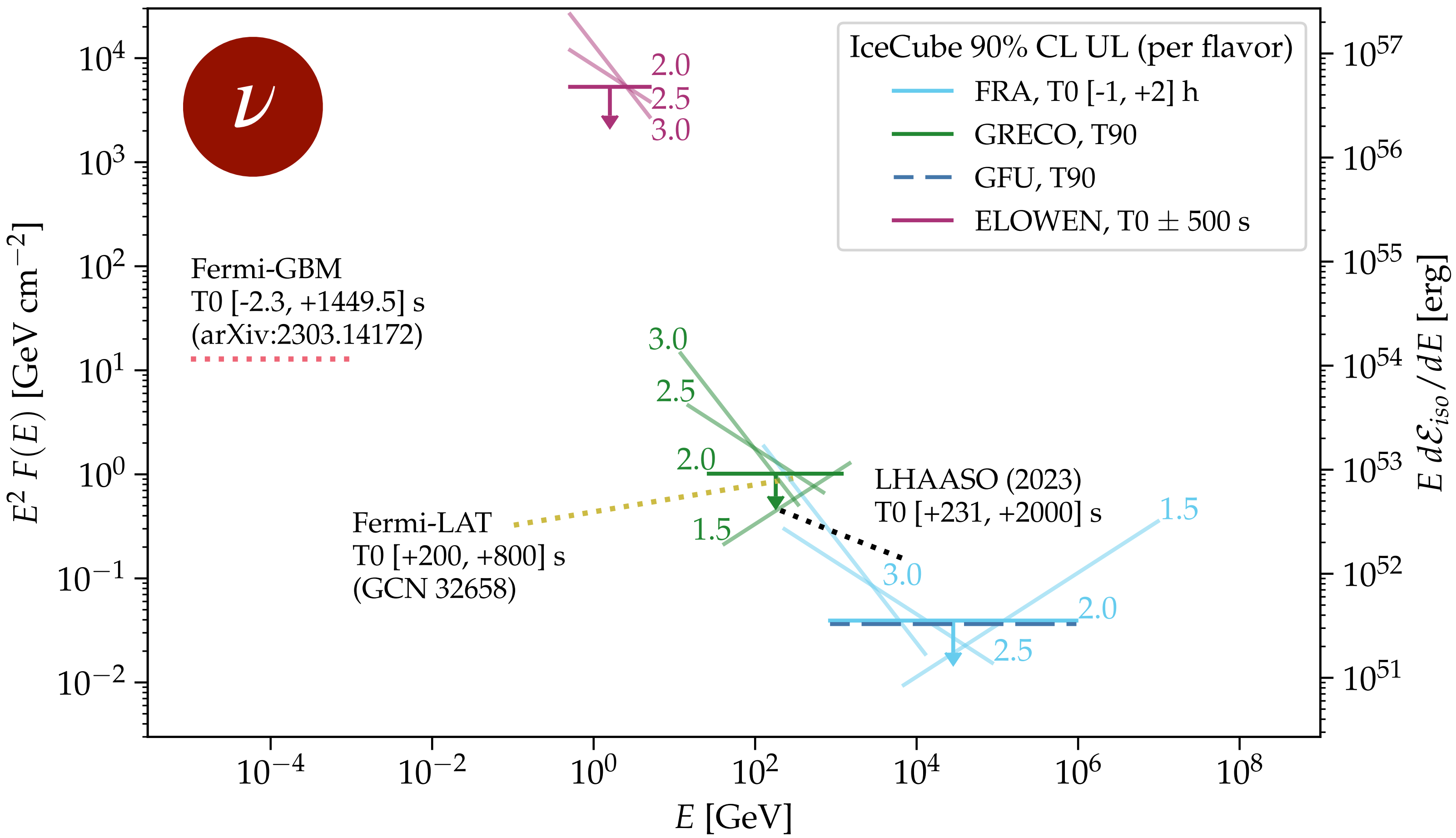
GRB 221009A - The "BOAT"

GRB seen by Fermi-LAT over 10h



(credit: NASA/DOE/Fermi-LAT)

Neutrino Upper Limits from IceCube



[γ-ray observations by Fermi **ApJL** 952 (2023) & LHAASO **Science** 9 (2023)]

- "*Brightest-Of-All-Time*" GRB 221009A ($D_L \simeq 740$ Mpc but $E_{\rm iso} \simeq 10^{55}$erg)
- MM observations in ApJL focus issue
- broadband limits on ν's: $10\text{MeV} - 1\text{PeV}$

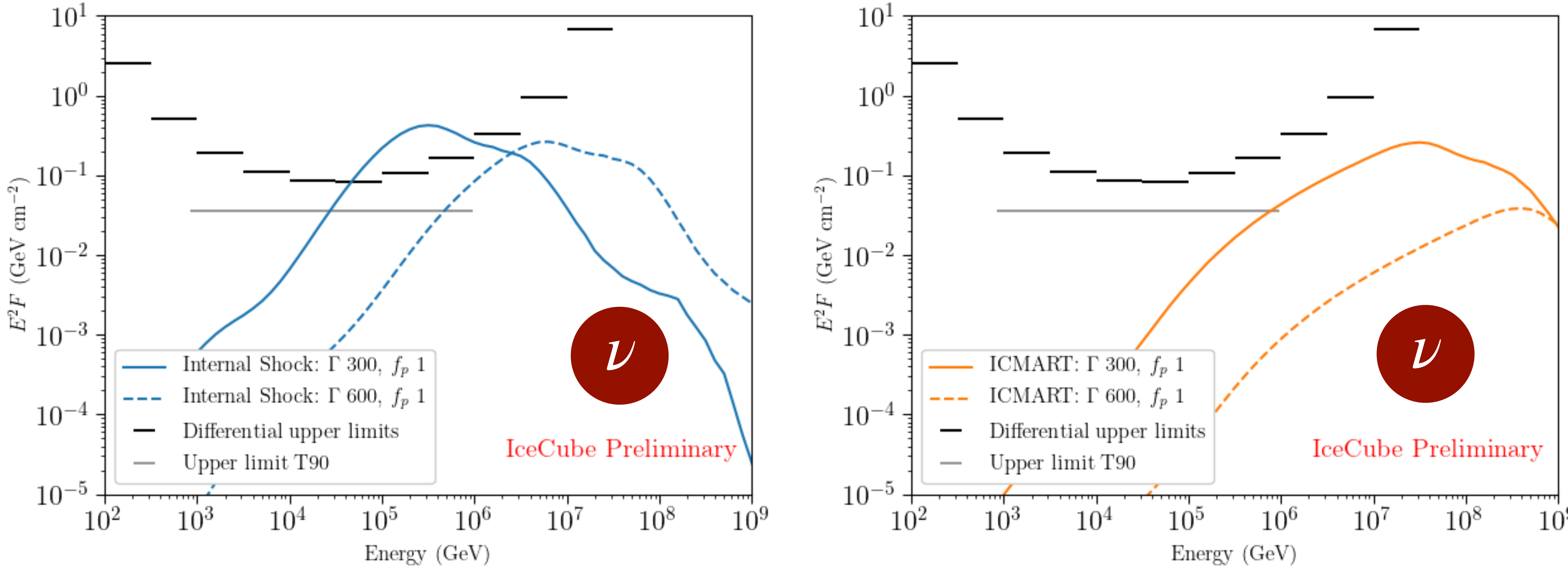
"*Limits on Neutrino Emission from GRB 221009A from MeV to PeV using the IceCube Neutrino Observatory*"

[IceCube **ApJL** 946 (2023)]

[IceCube PoS-ICRC2023-1511]

GRB 221009A - The "BOAT"

Predicted neutrino spectra for internal shock model (left) and ICMART (right)



[Bahcall & Waxman'99; Zhang & Yan'11; Hummer, Baerwald & Winter'11; MA, Gonzalez-Garcia & Halzen'11]

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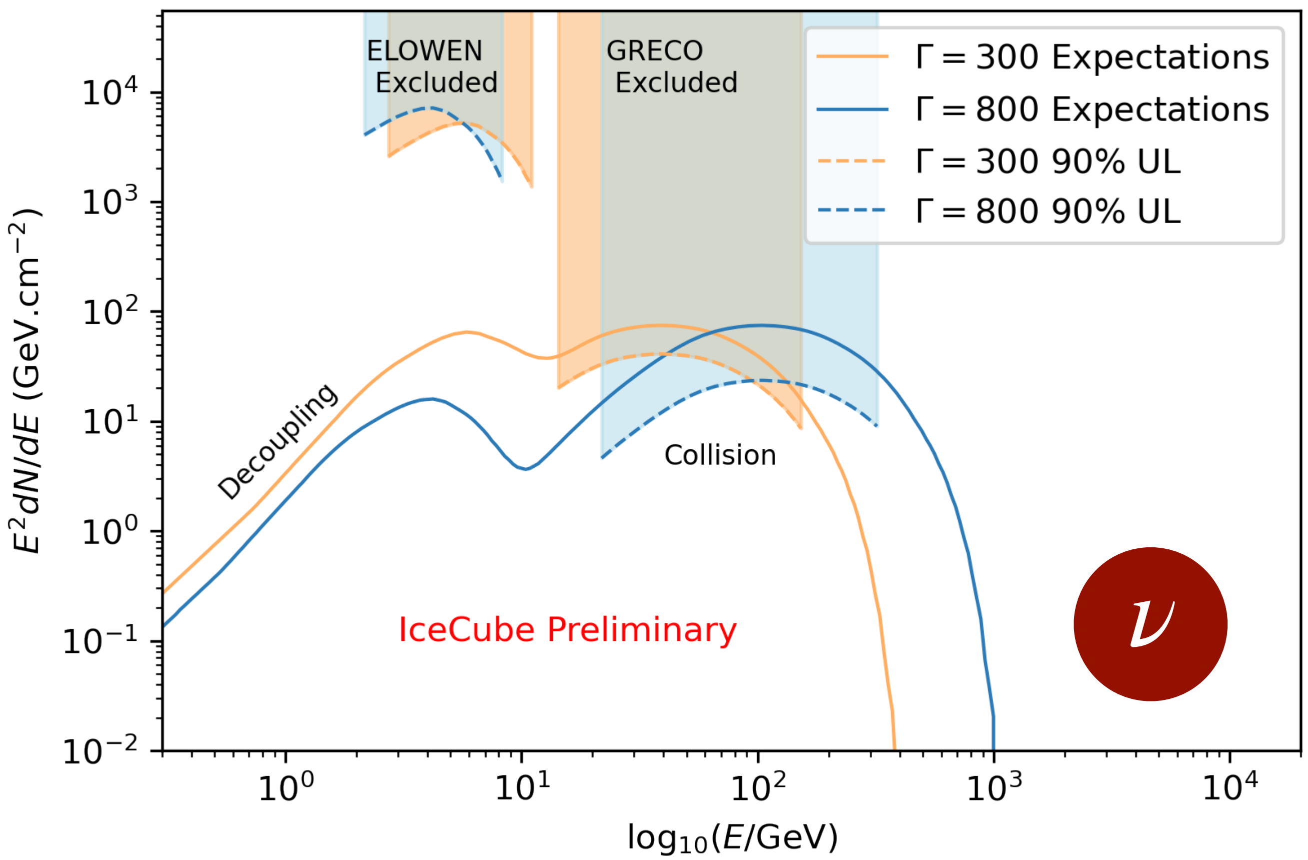

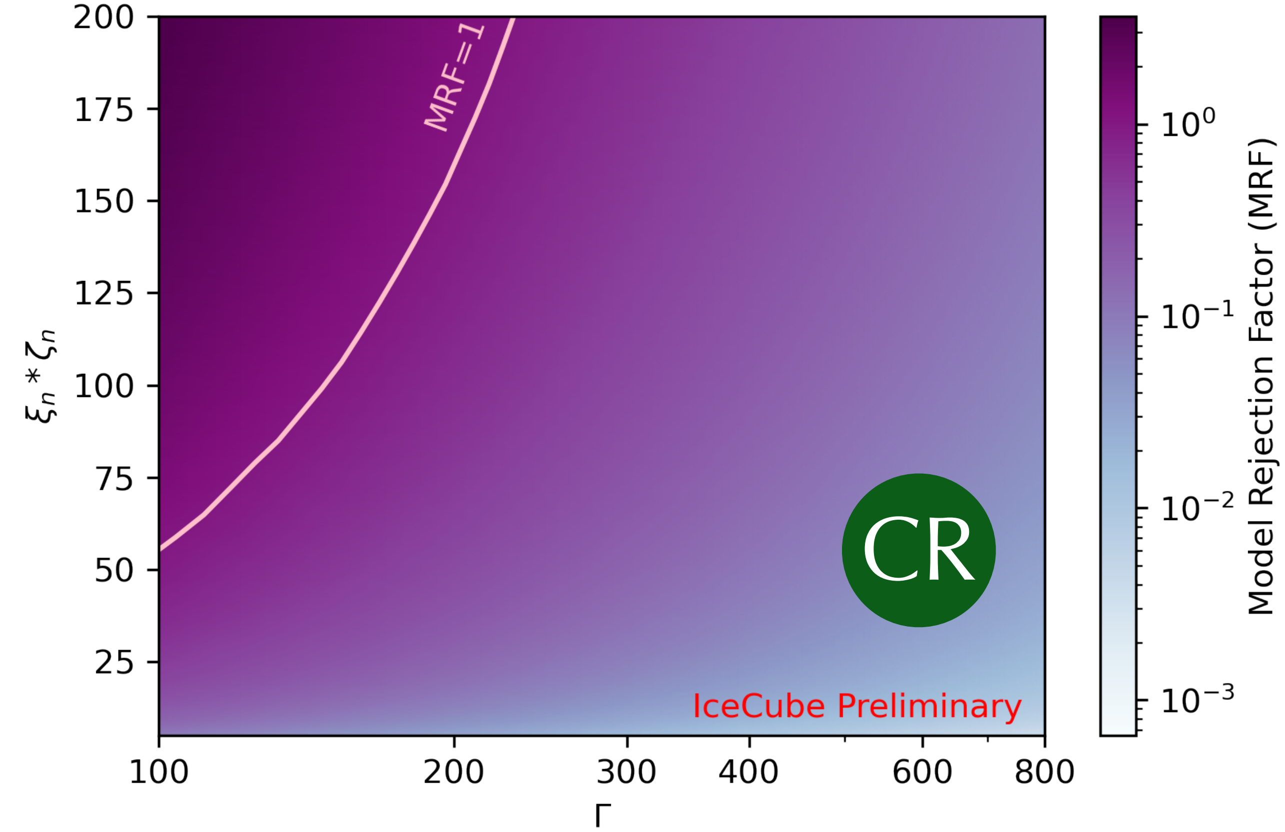

[IceCube PoS-ICRC2023-1511; Murase, Mukhopadhyay, Kheirandish, Kimura & Fang, ApJL 941 (2022) 1]

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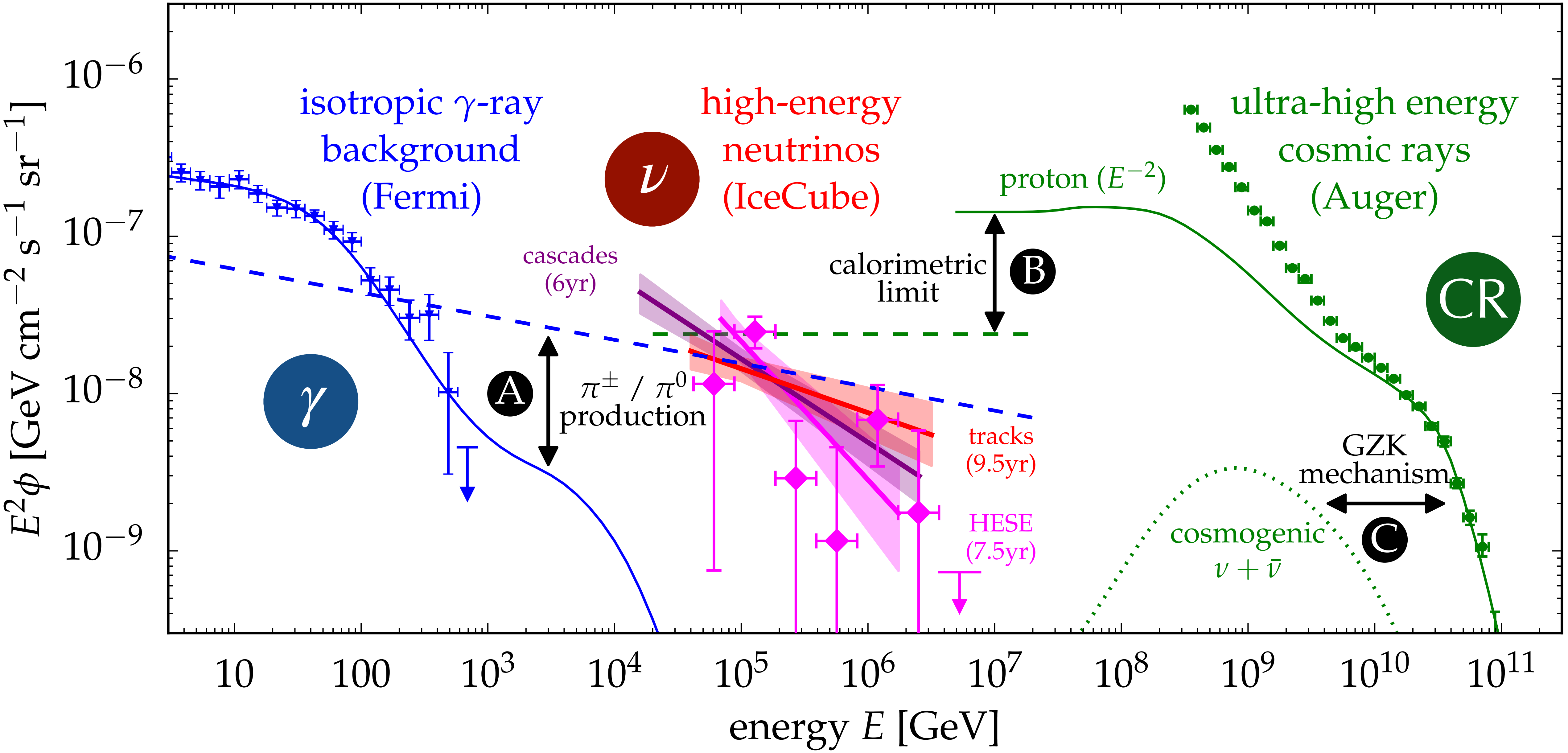
[IceCube **ApJL** 946 (2023)]

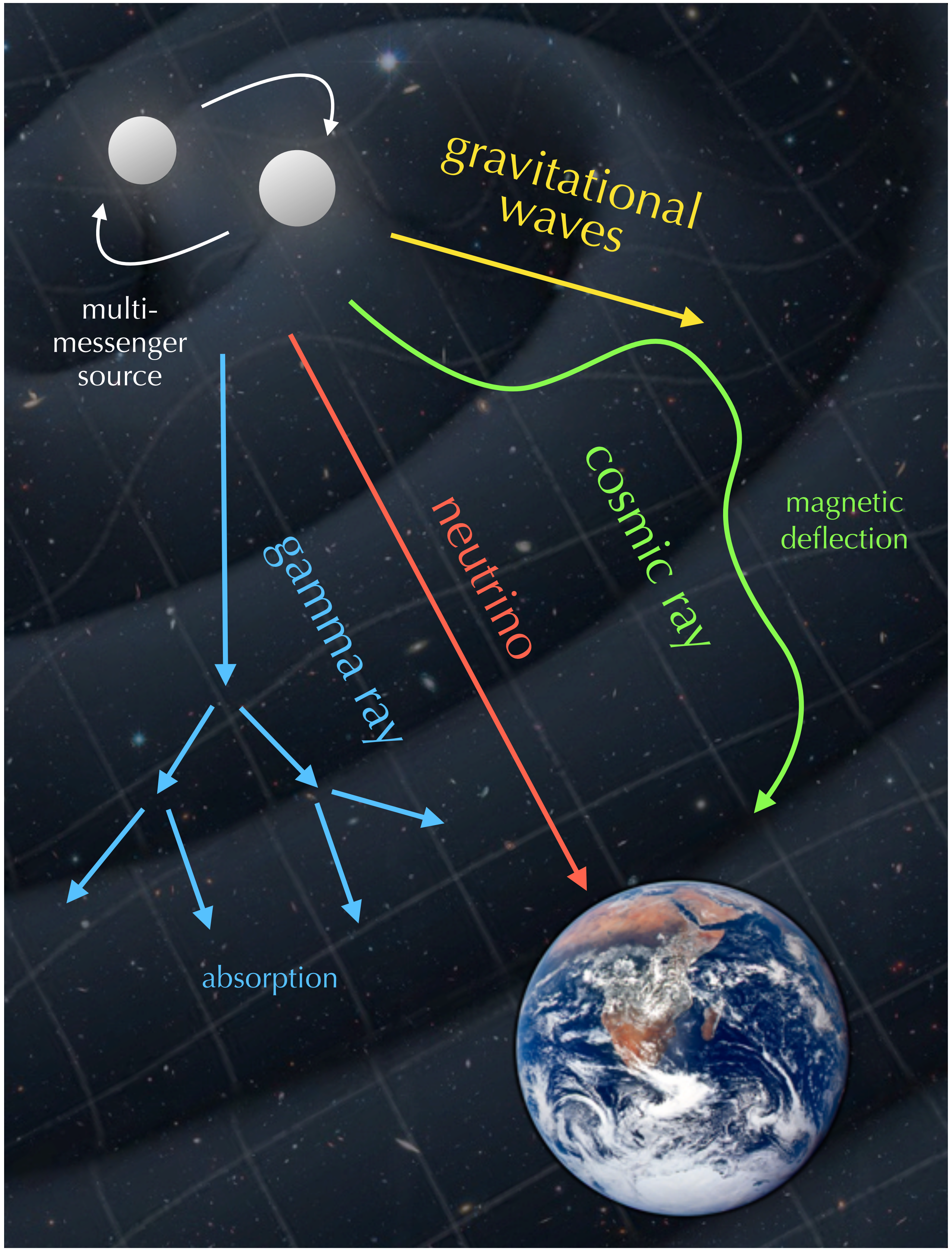
[IceCube PoS-ICRC2023-1511]

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.

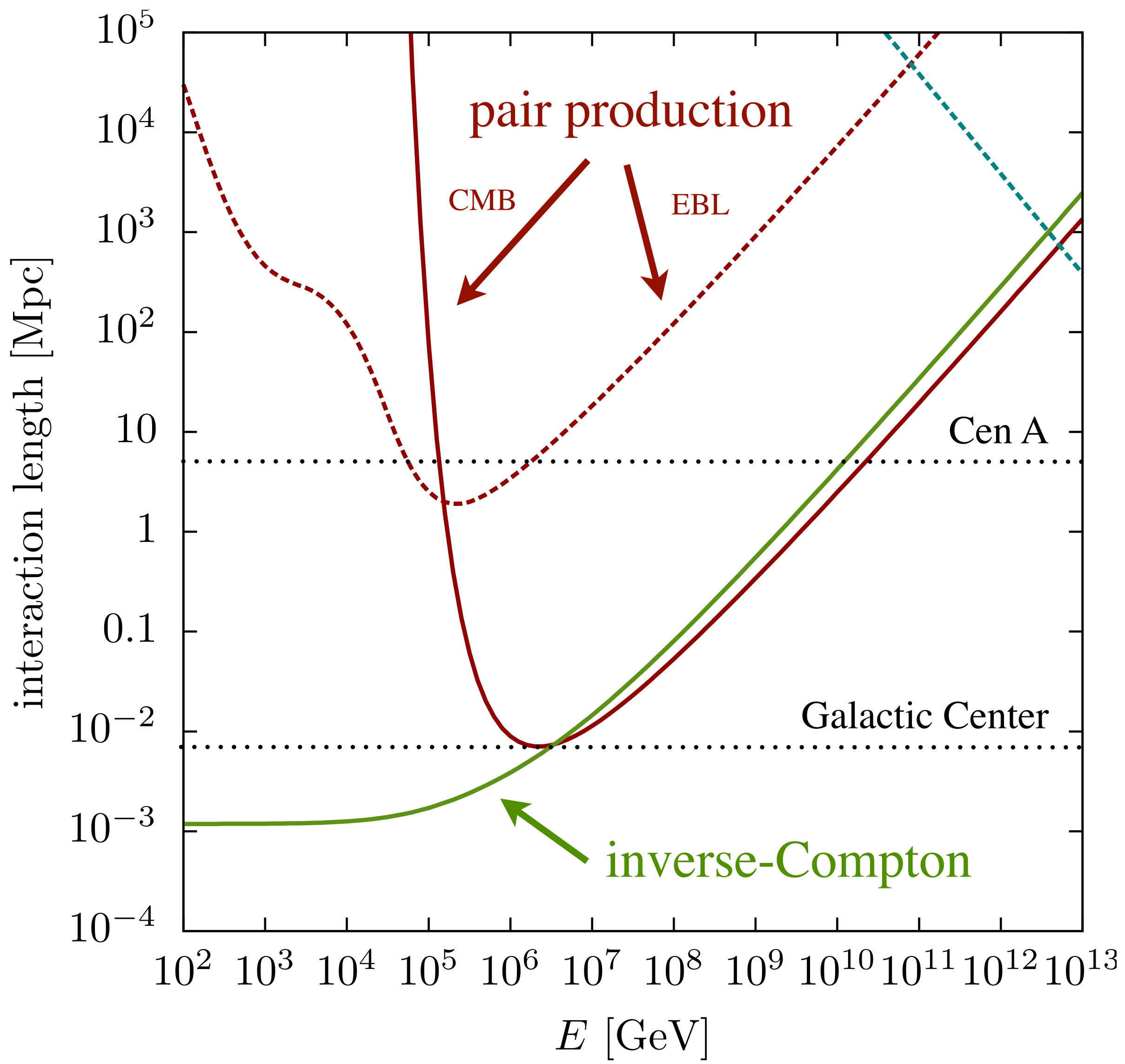
Hadronic Gamma-Rays



EM cascades from interactions in cosmic radiation backgrounds:

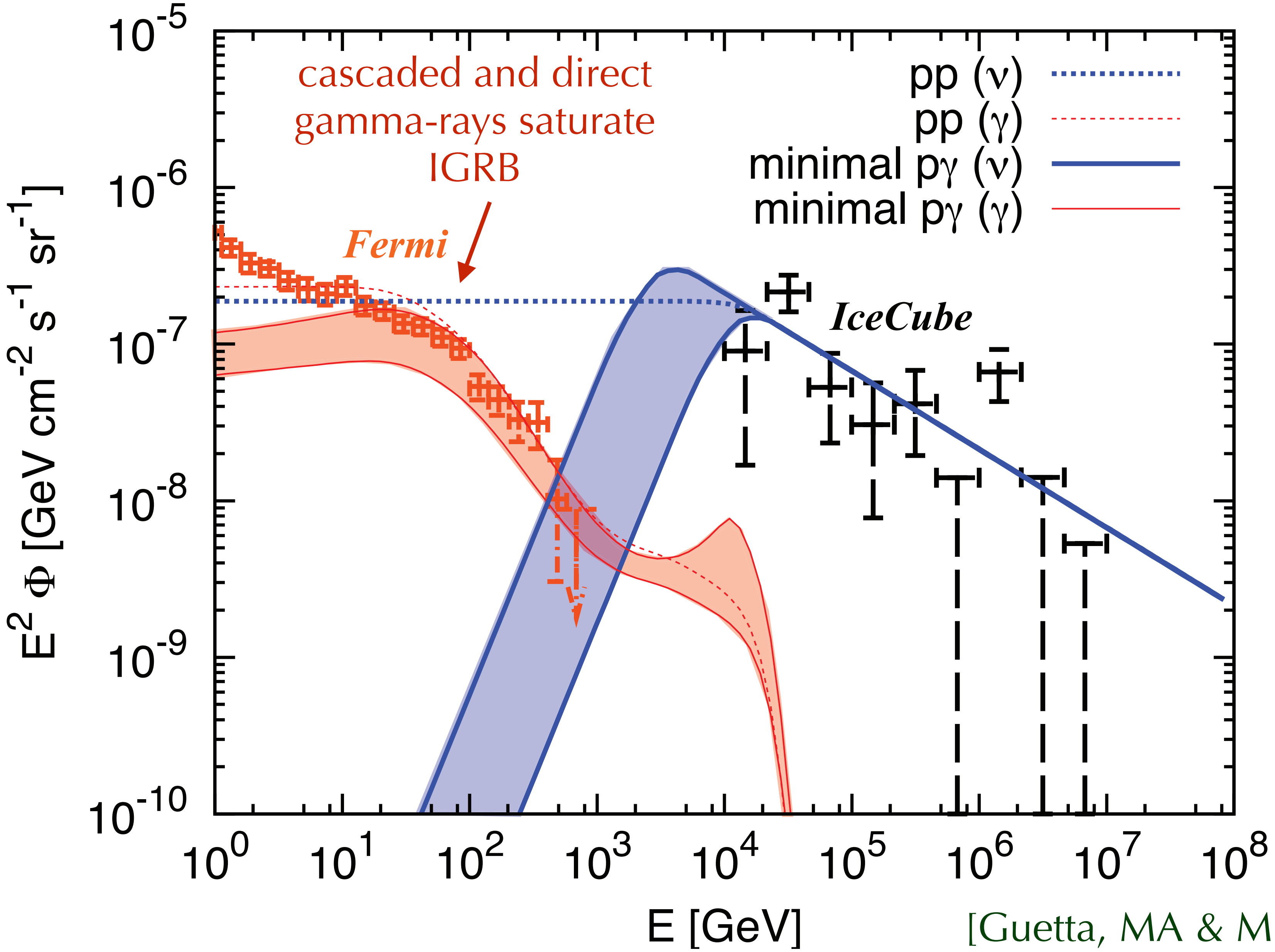
$$\gamma + \gamma_{\rm bg} \to e^+ + e^- \quad \text{(PP)}$$

$$e^\pm + \gamma_{\rm bg} \to e^\pm + \gamma \quad \text{(ICS)}$$



Hadronic Gamma-Rays

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



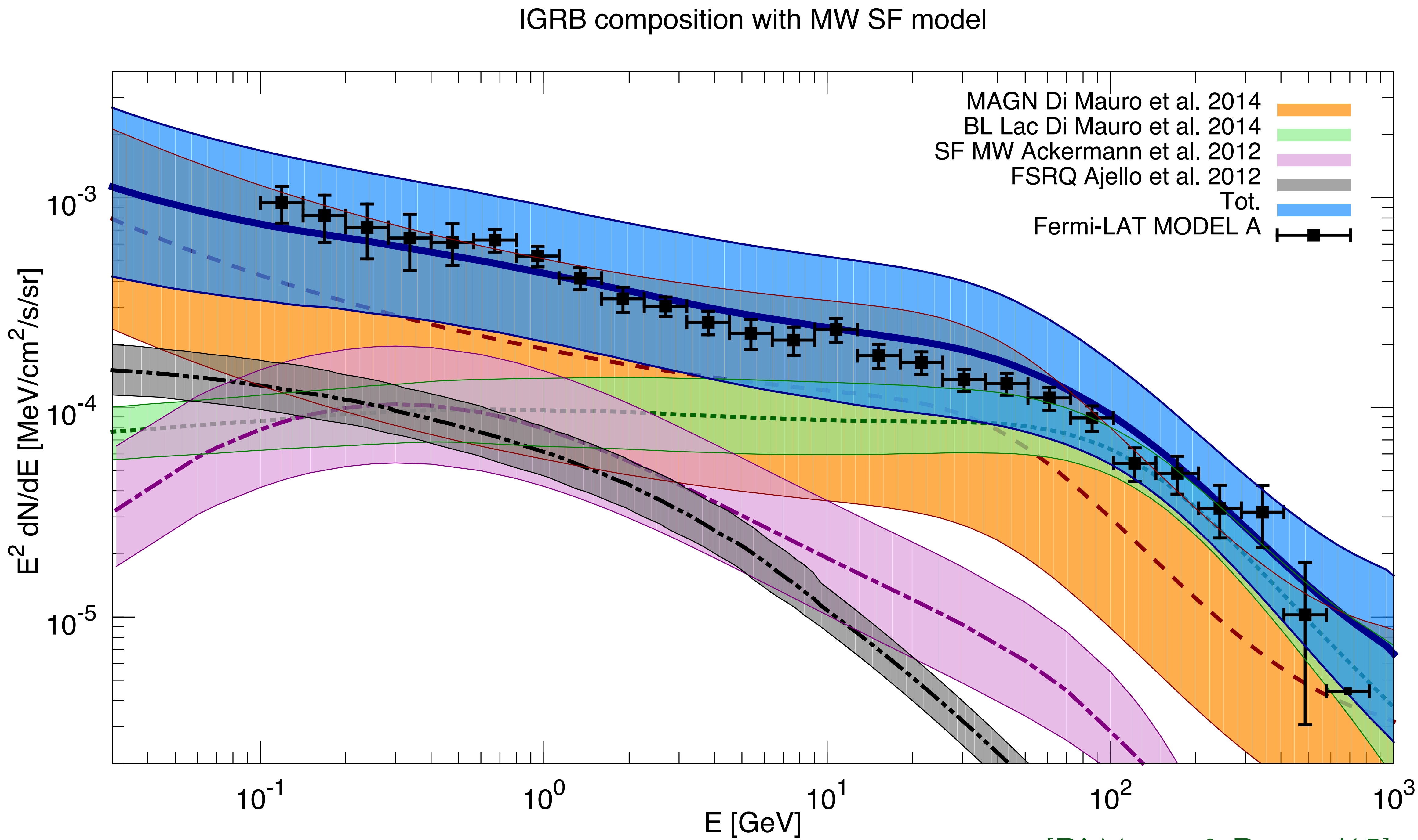
[Guetta, MA & Murase'16]

[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]

Isotropic Diffuse γ-ray Background

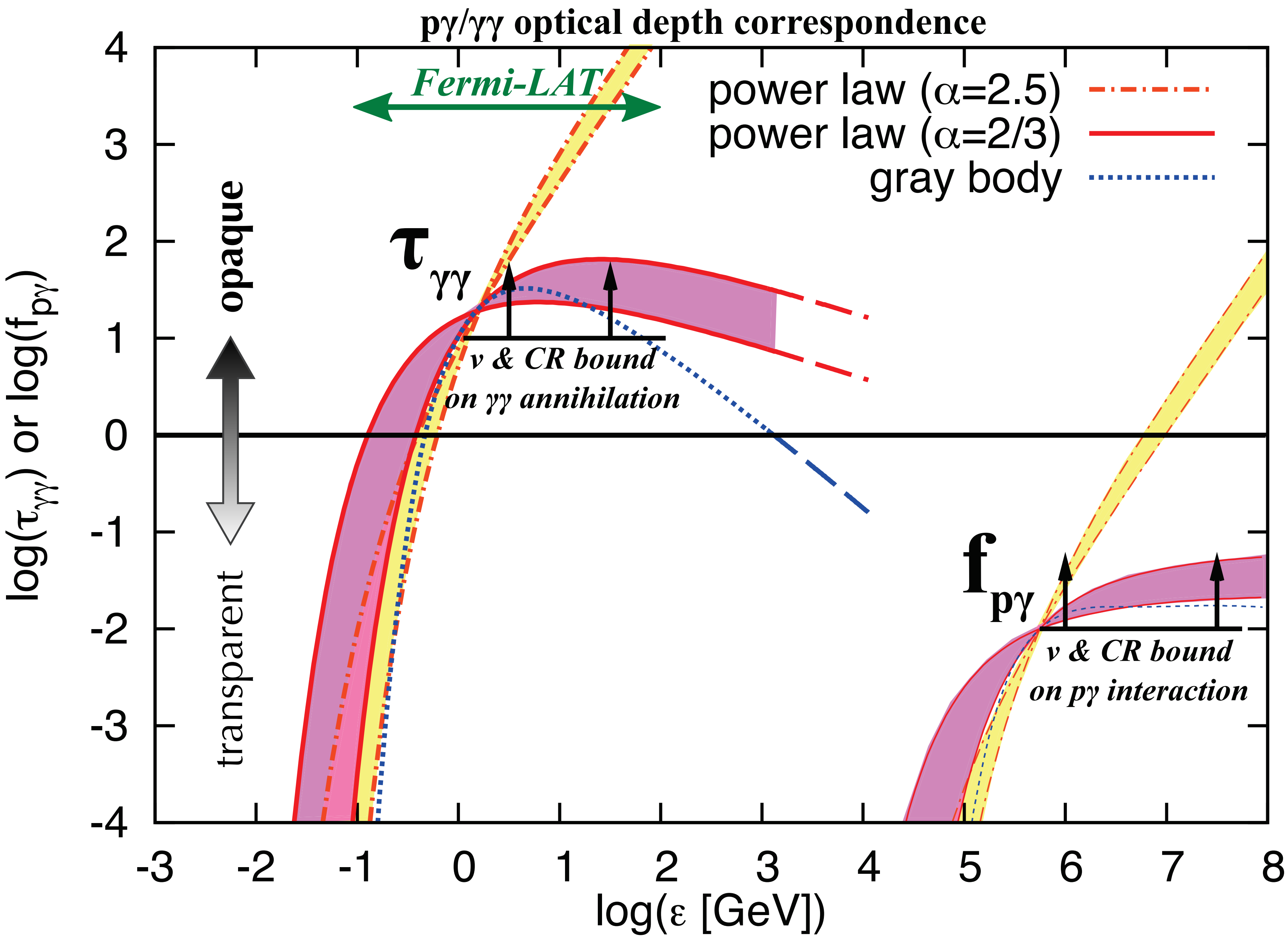
- There is little room in the i**sotropic diffuse γ-ray background** (IGRB) for "extra" γ-ray contributions.



[Di Mauro & Donato'15]

Hidden Sources?

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



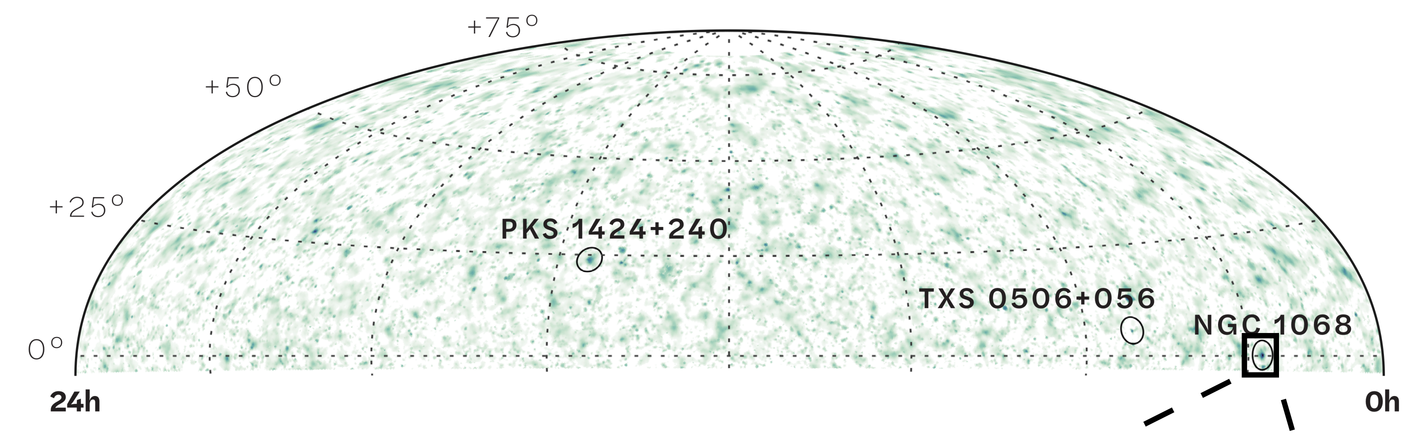
High pion production efficiency implies strong internal ***γ*-ray absorption in Fermi-LAT energy range:**

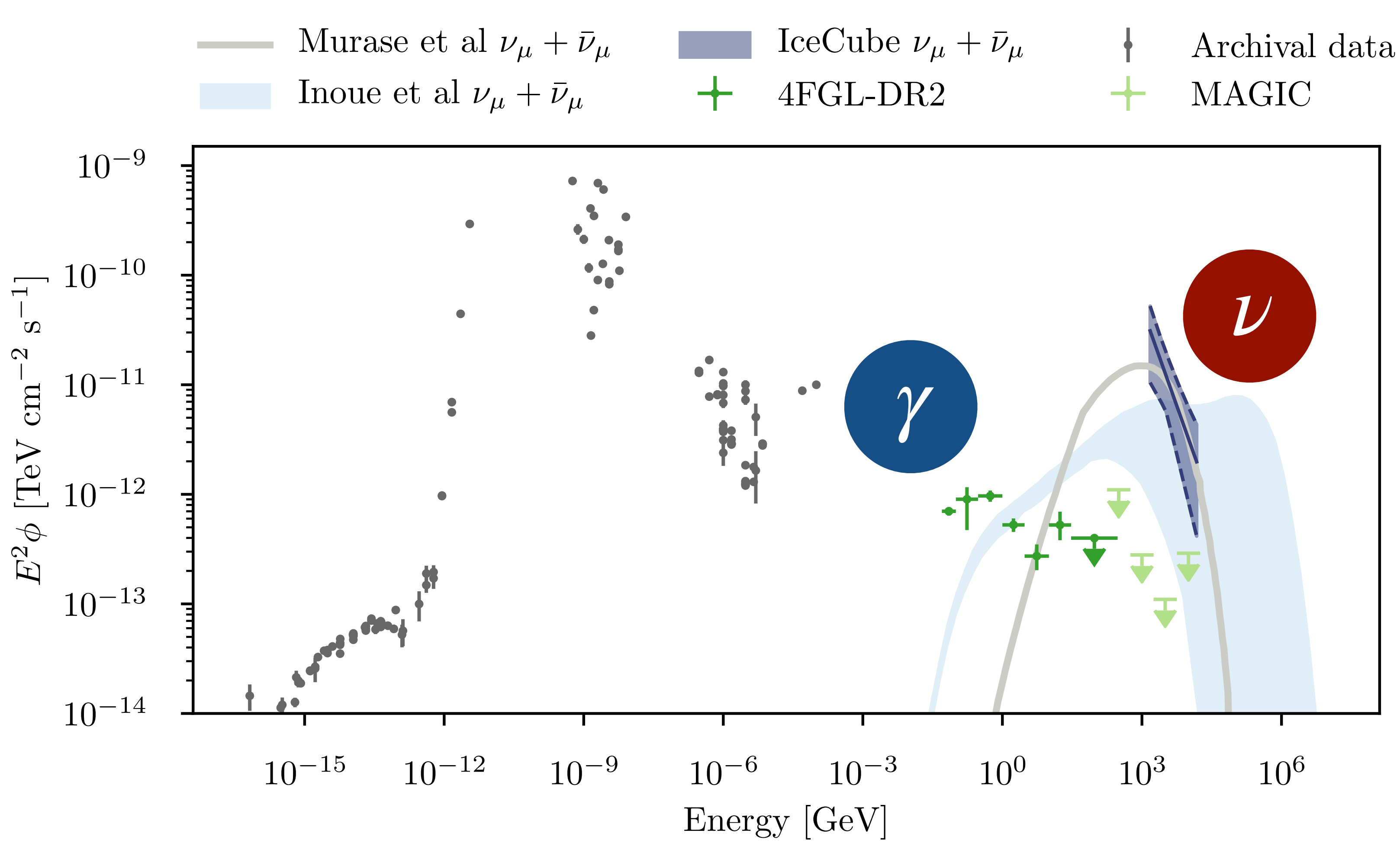
$$\tau_{\gamma\gamma} \simeq 1000 f_{p\gamma}$$

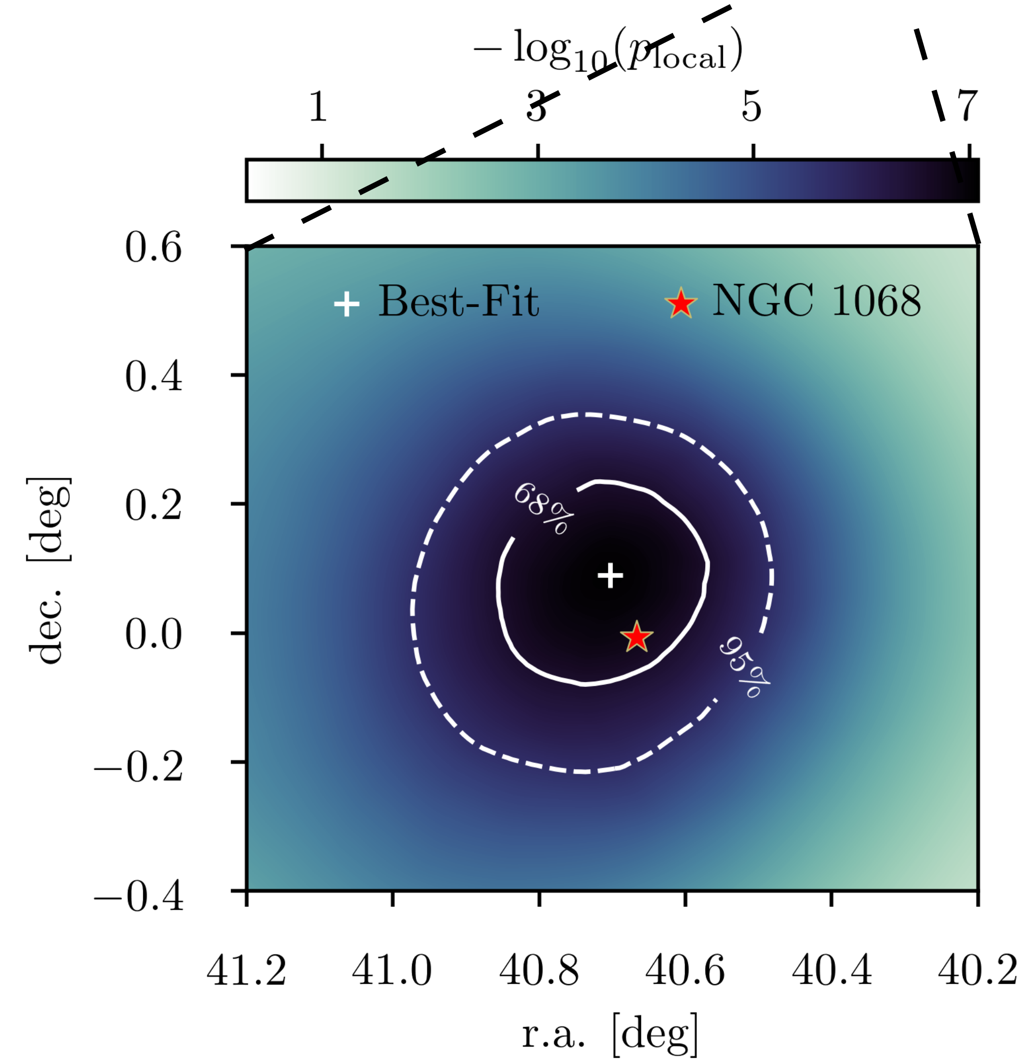
[Guetta, MA & Murase'16]

Excess from NGC 1068

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

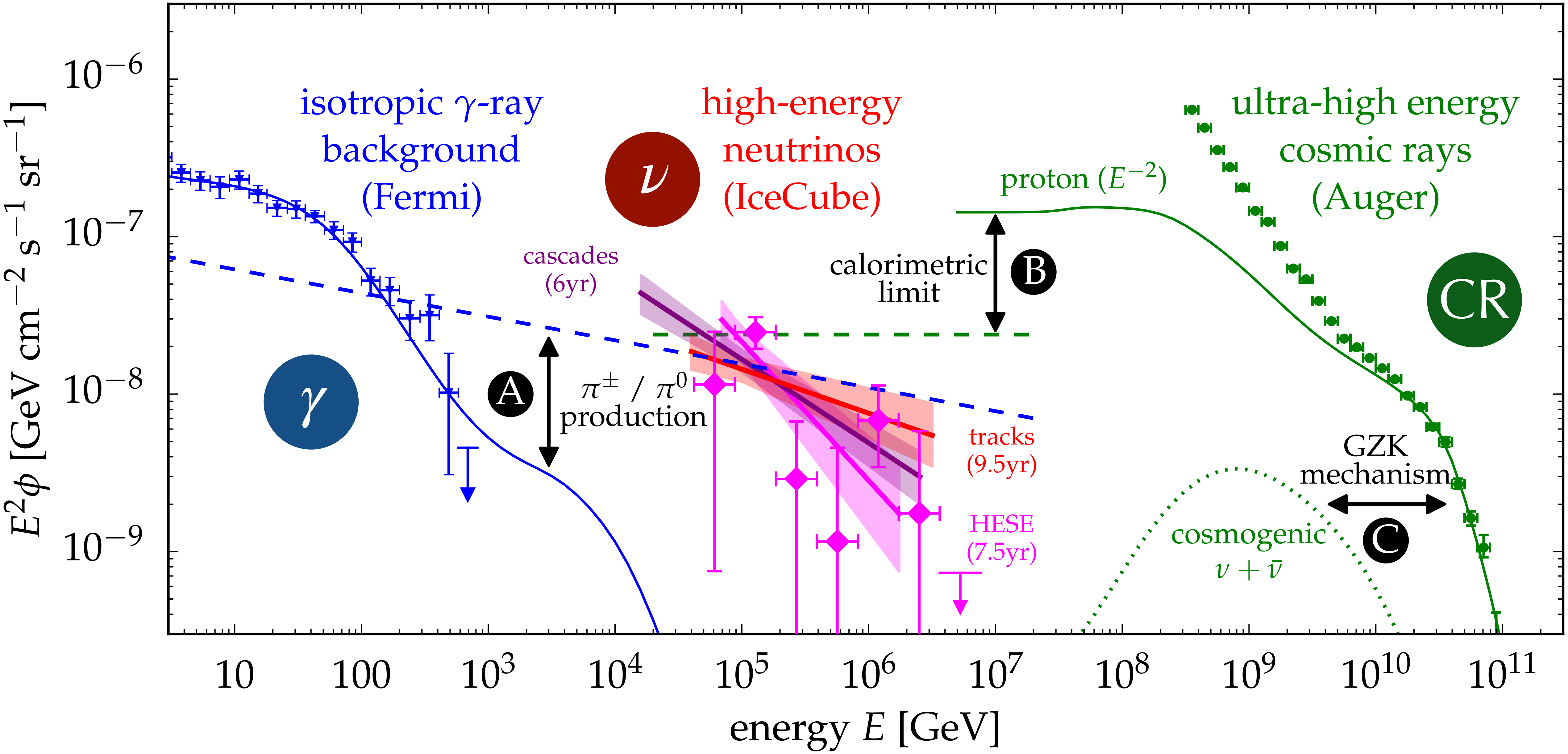






[IceCube, PRL 124 (2020) 5 **(2.9σ post-trial)**; Science 378 (2022) 6619 **(4.2σ post-trial)**]

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]

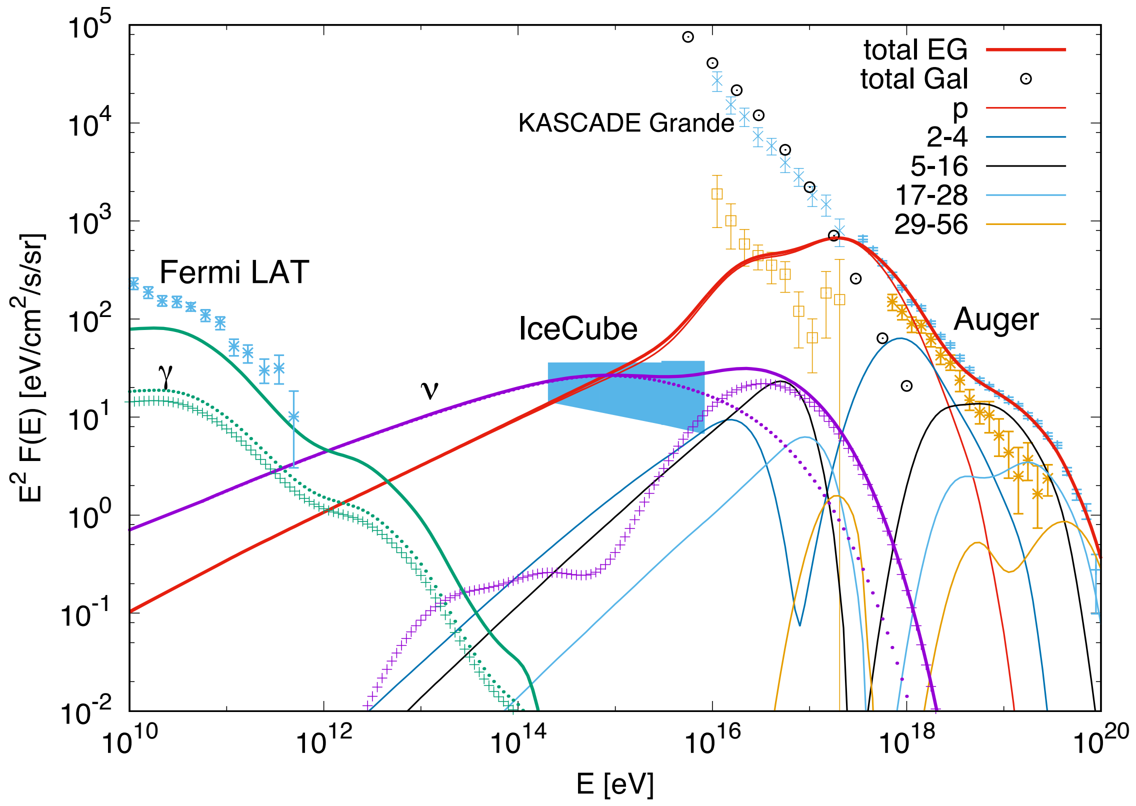
- **Competition** between pion production efficiency (*dense target*) and CR acceleration efficiency (*thin target*).

Cosmic Ray Calorimeters

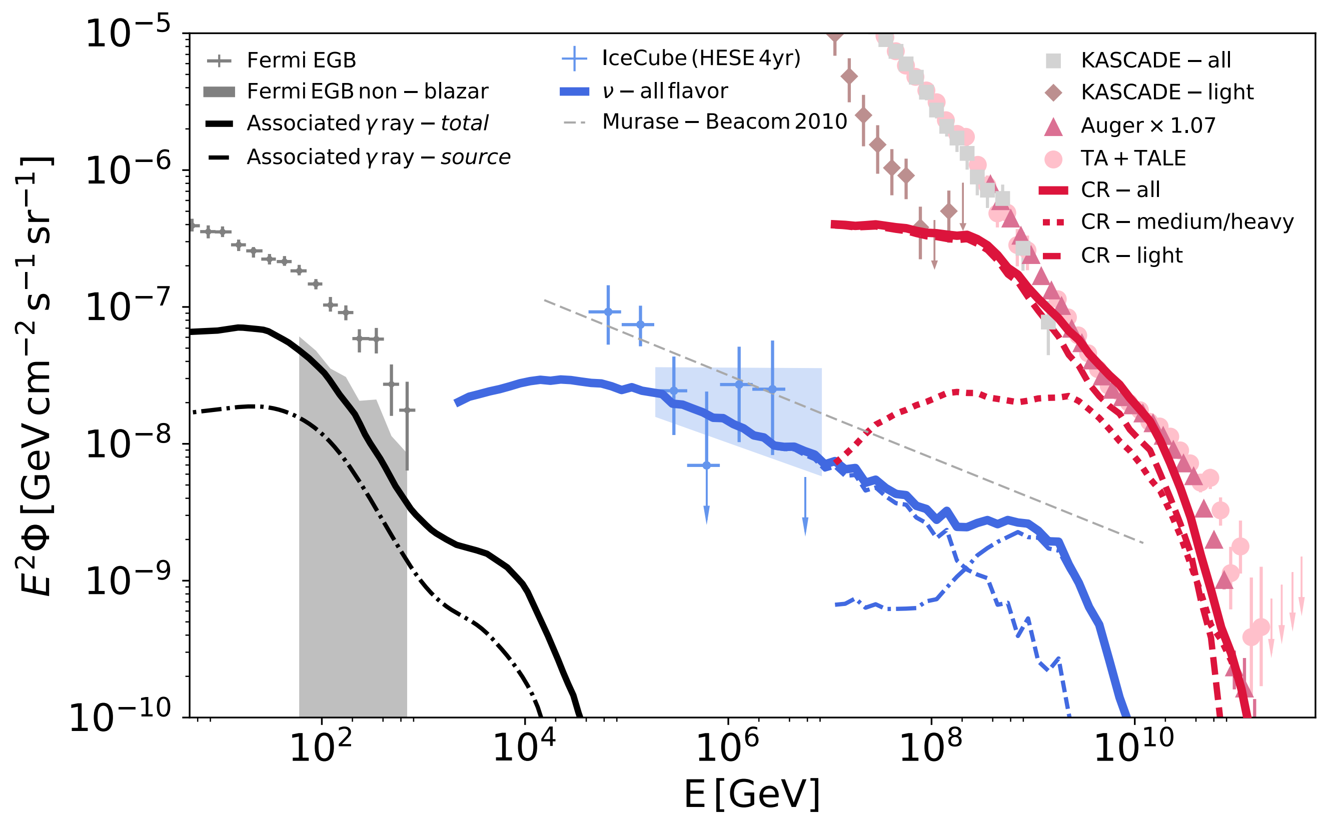
- Competing requirements for efficient CR acceleration and subsequent interaction can be accommodated in **multi-zone models**.
- Magnetic confinement in CR calorimeters, such as **starburst galaxies**, could provide a unified origin of UHE CRs and TeV–PeV neutrinos.

[Loeb & Waxman '06]

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



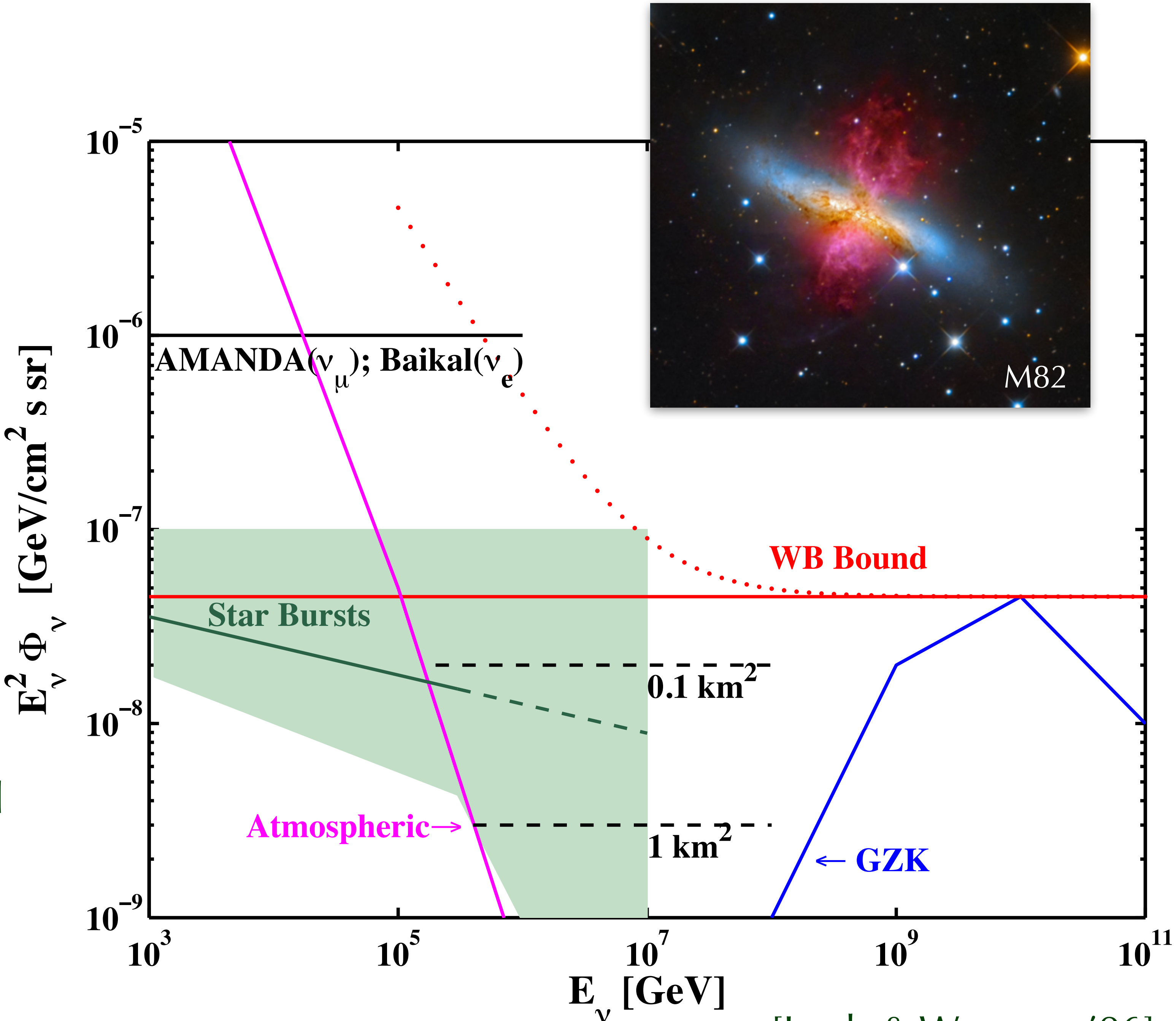
[Kachelriess, Kalashev, Ostapchenko & Semikoz'17]



[Fang & Murase'17]

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.

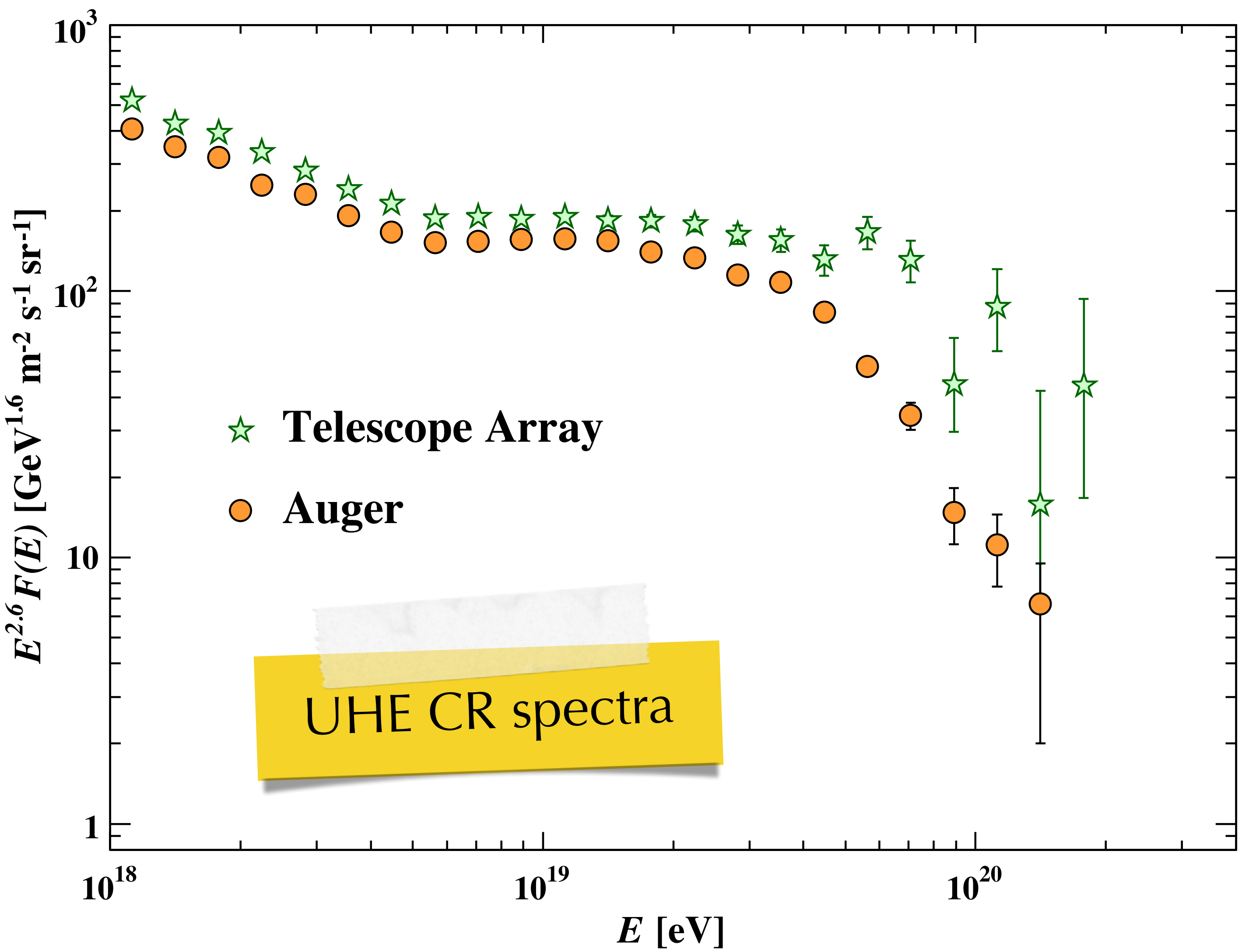


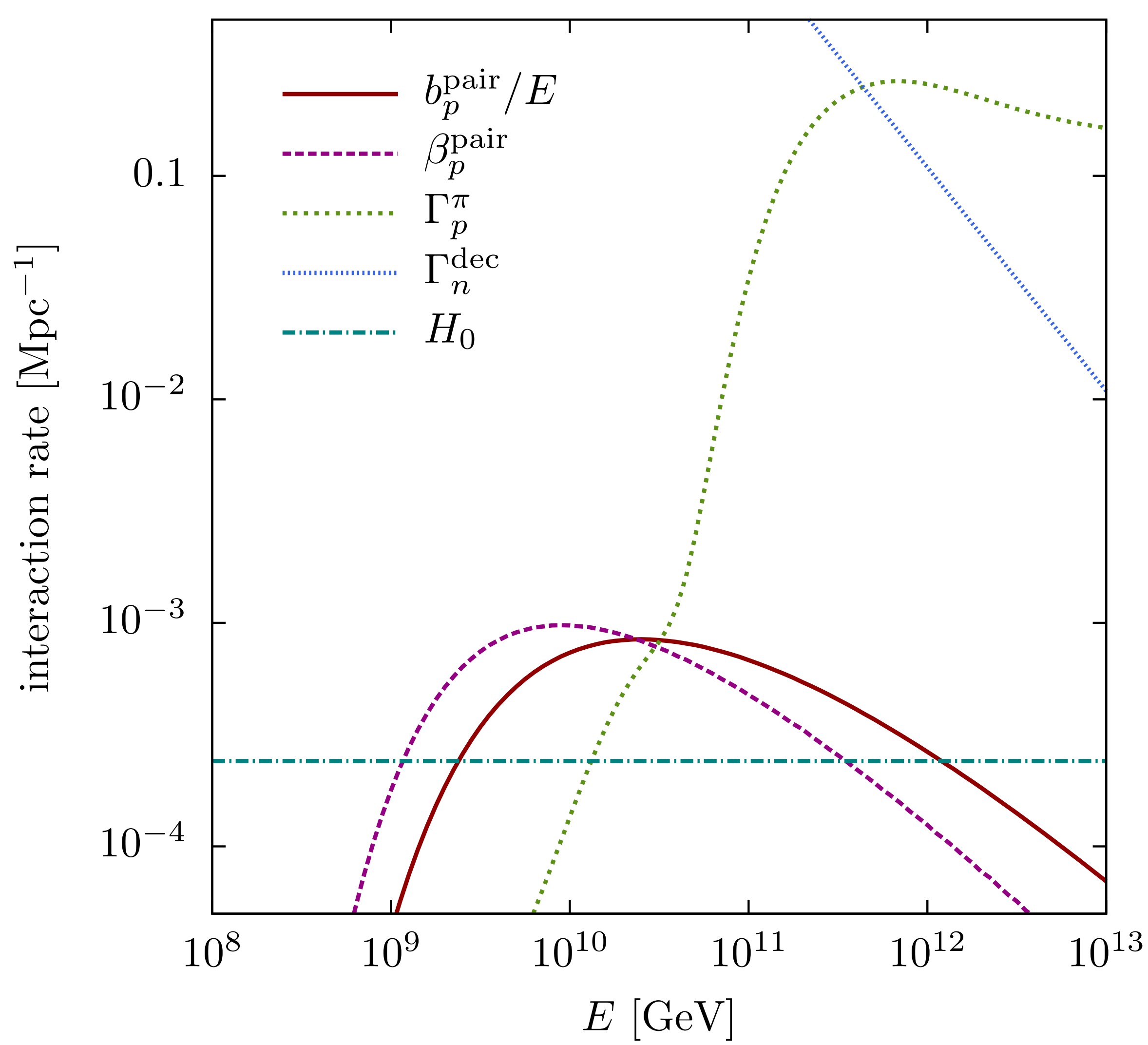
[Loeb & Waxman '06]

[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]

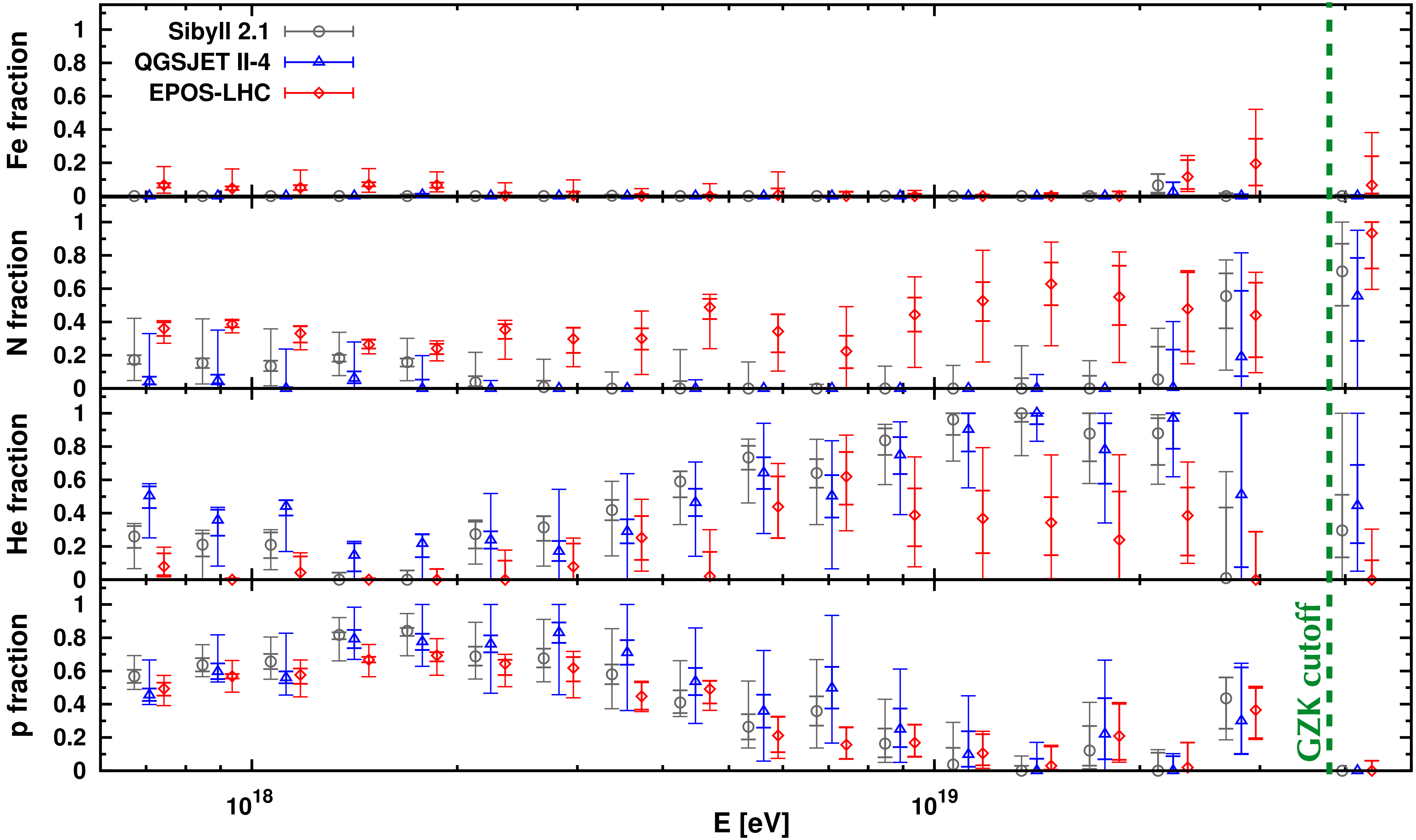
GZK Cutoff

- UHE CR spectrum expected to show *GZK cutoff* due to interactions with cosmic microwave background. [Greisen & Zatsepin'66; Kuzmin'66]
- resonant interactions $p + \gamma_{\rm CMB} \to \Delta^+ \to X$ lead to $E_{\rm GZK} \simeq 40$ EeV
- UHE CR propagation limited to less than about 200 Mpc.





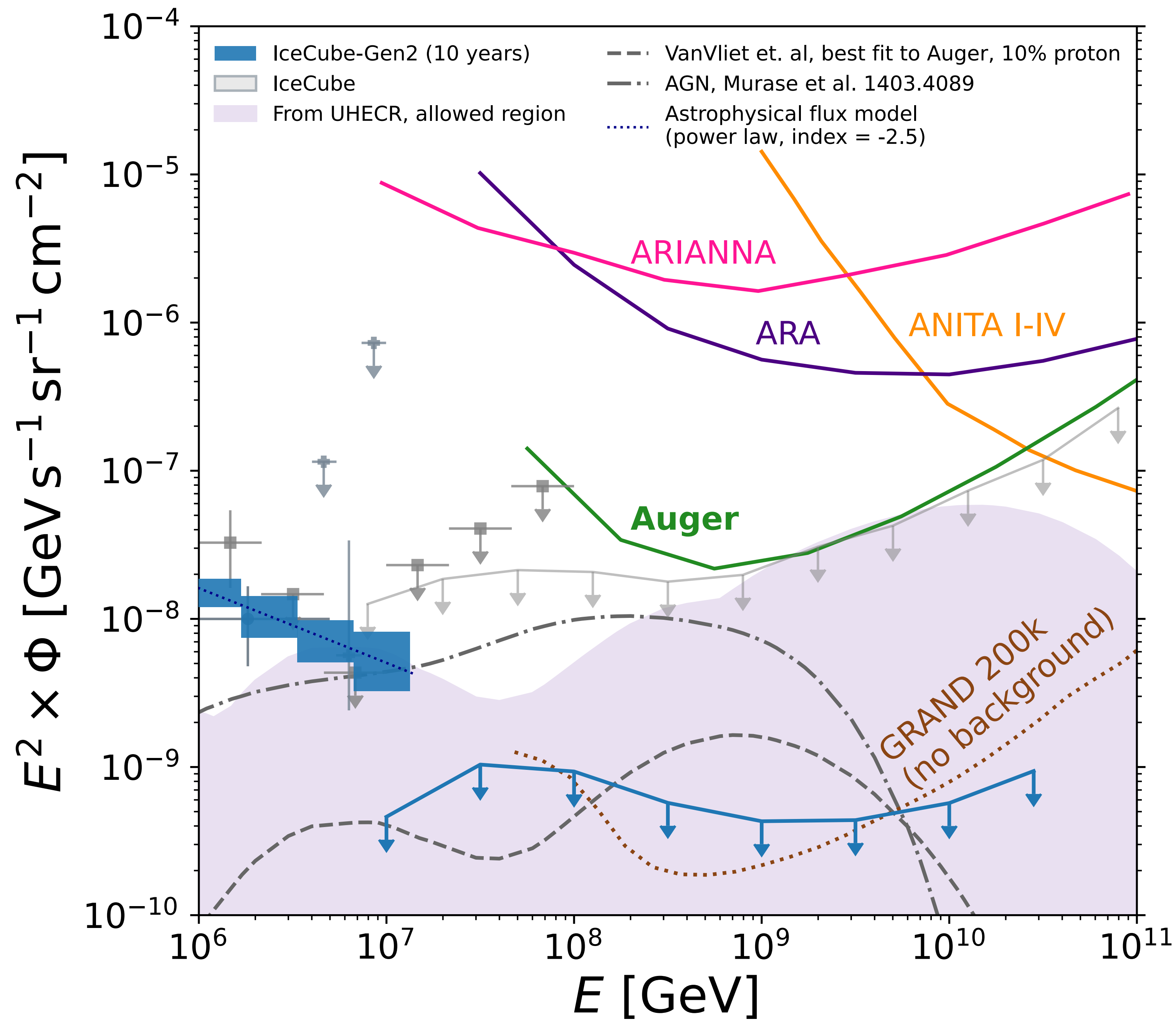
UHE CR Composition



Composition of UHE CRs is uncertain; depends on details of CR interactions in atmosphere.

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.

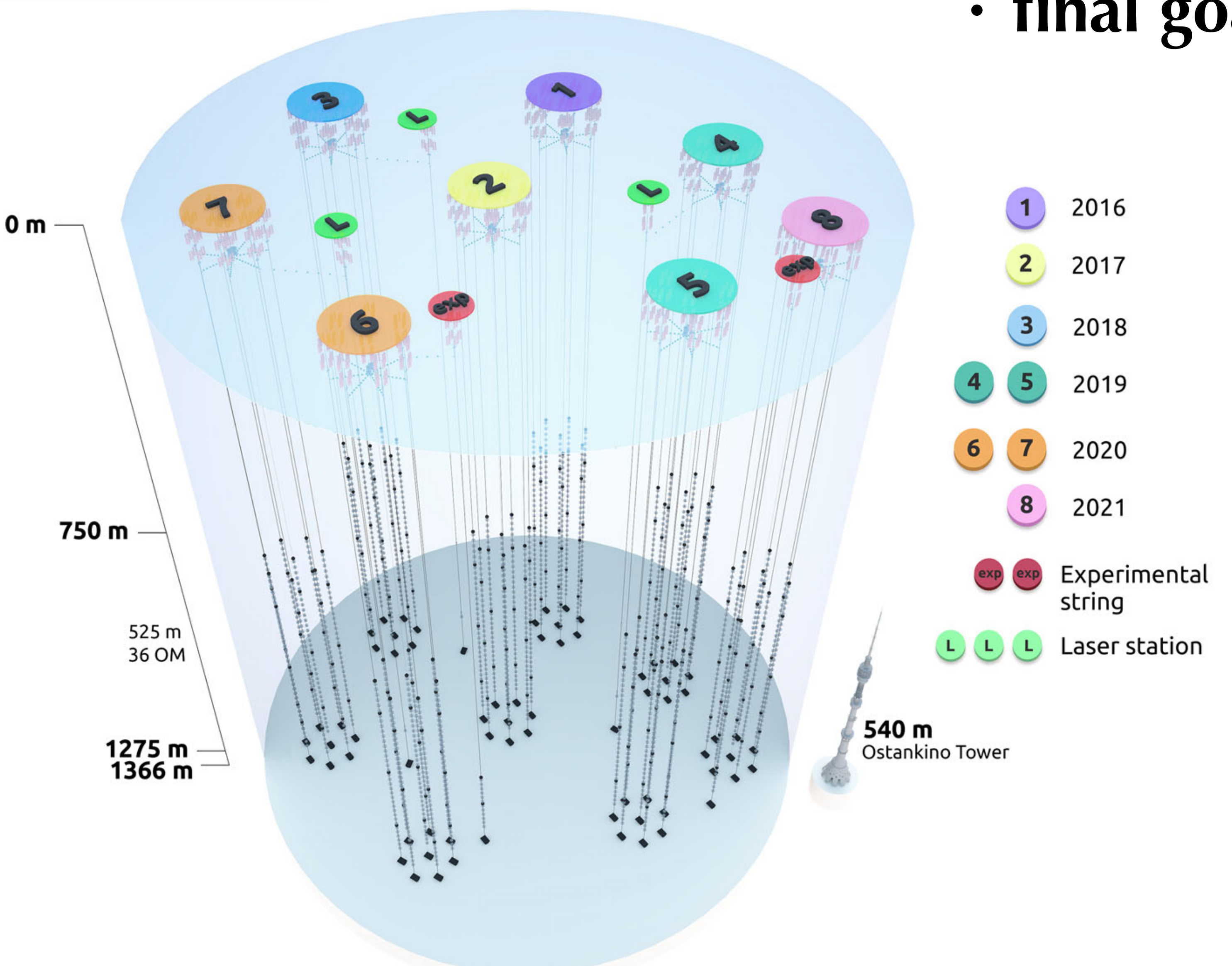


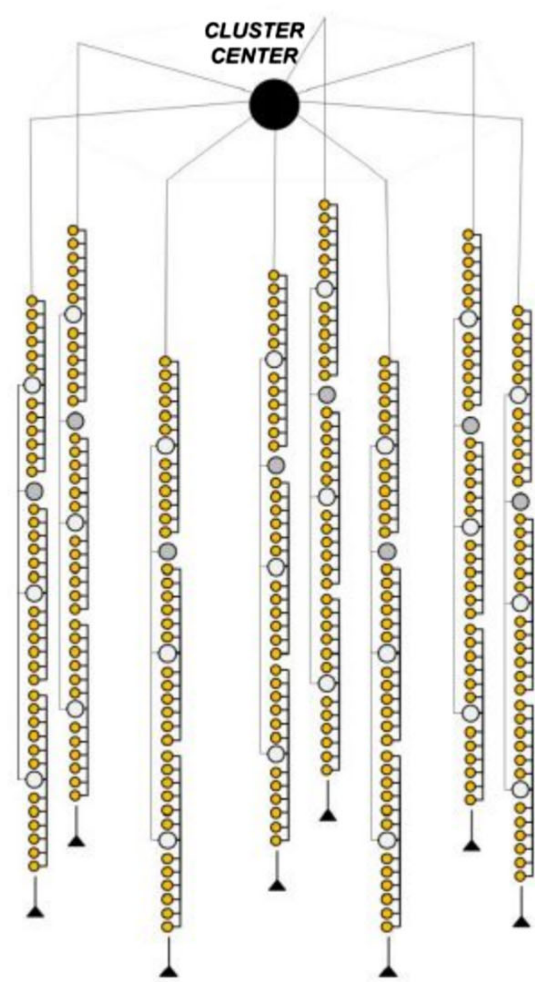
[IceCube-Gen2 *Technical Design Report*]

Outlook: Baikal-GVD

BAIKAL-GVD

- **GVD Phase 1:** 8 clusters with 8 strings each were completed in 2021
- **status March 2024: 11(+1) clusters**
- **final goal**: 27 clusters ($\sim 1.4\,\mathrm{km}^3$)

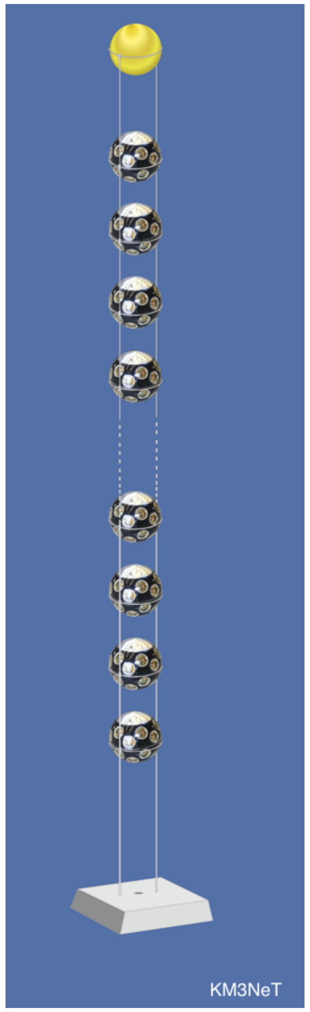


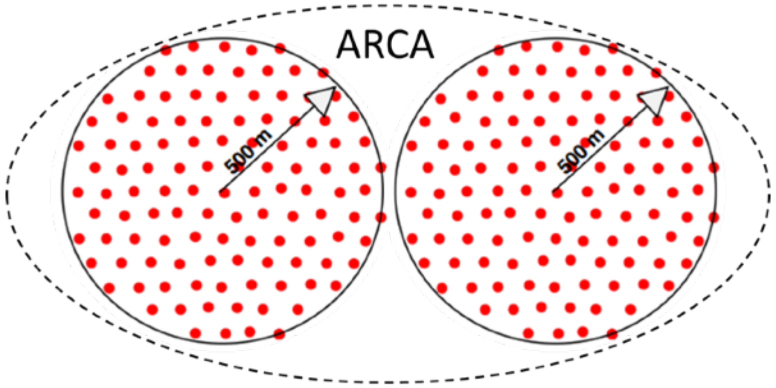


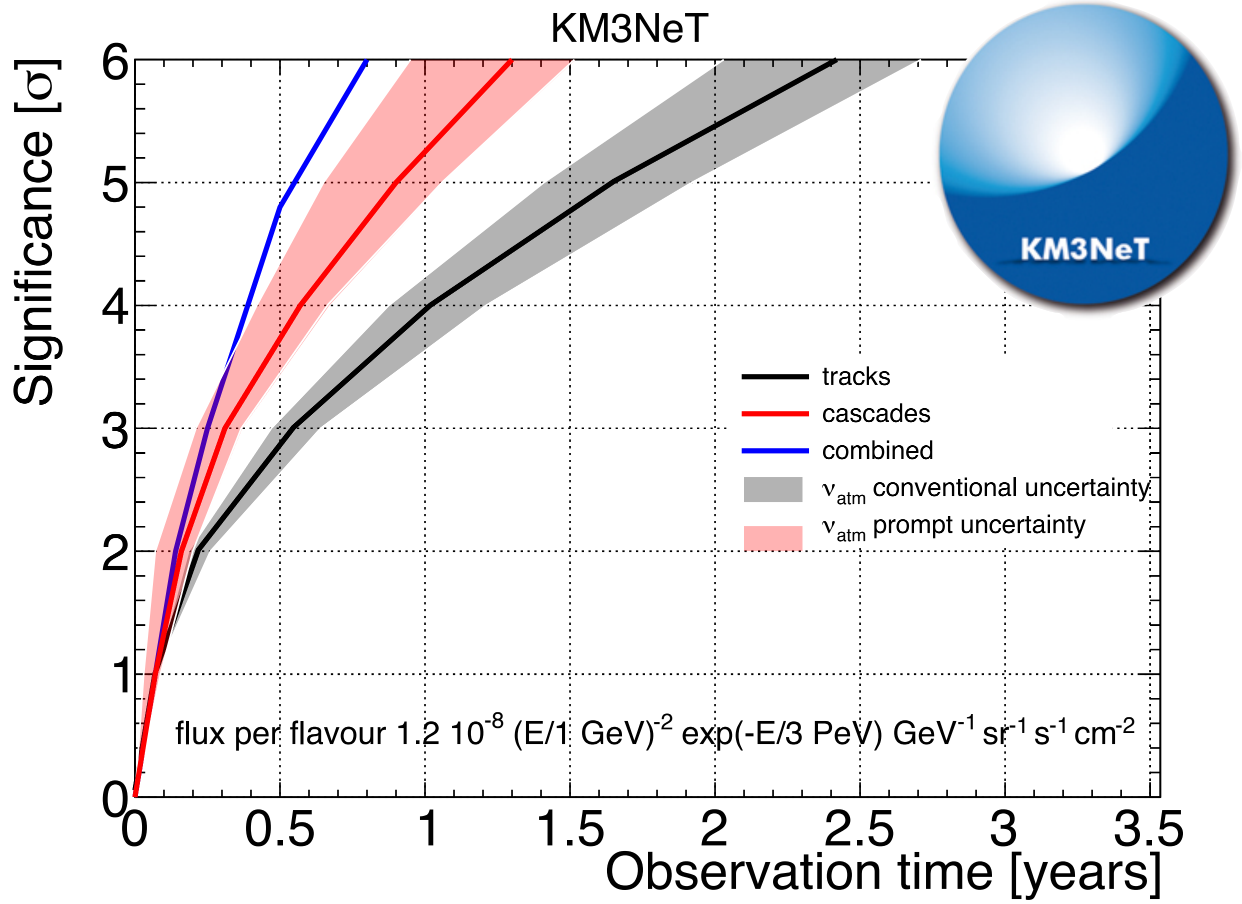
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- **status March 2024: 28 (ARCA) DUs**
- **ORCA** : optimized for low-energy (GeV) and oscillation analyses

detection unit with multi-PMT DOMs





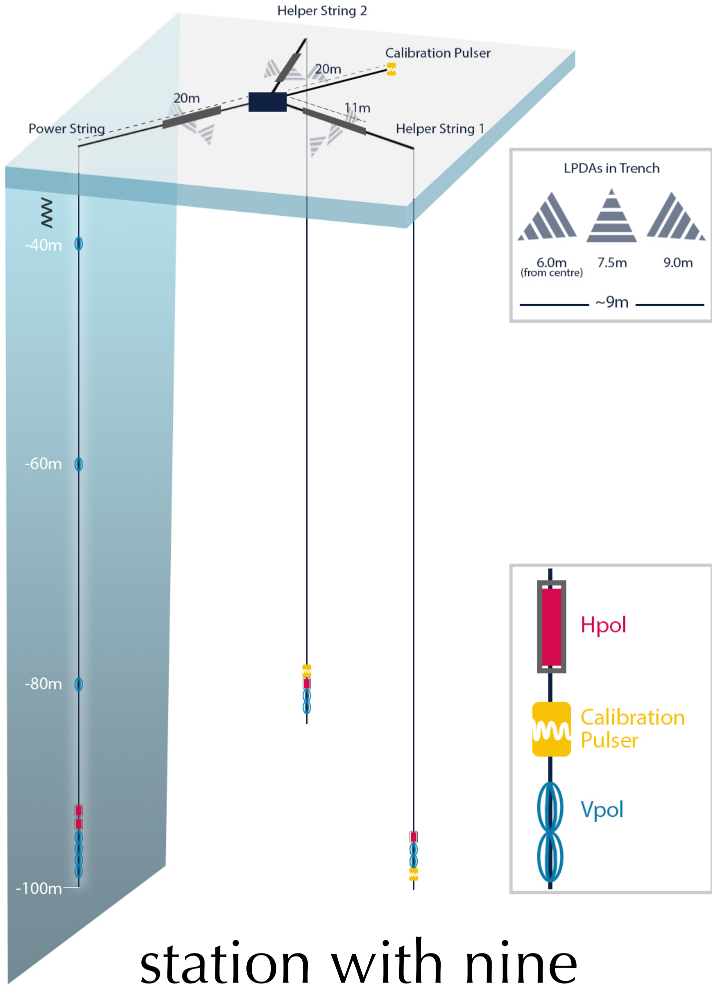


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

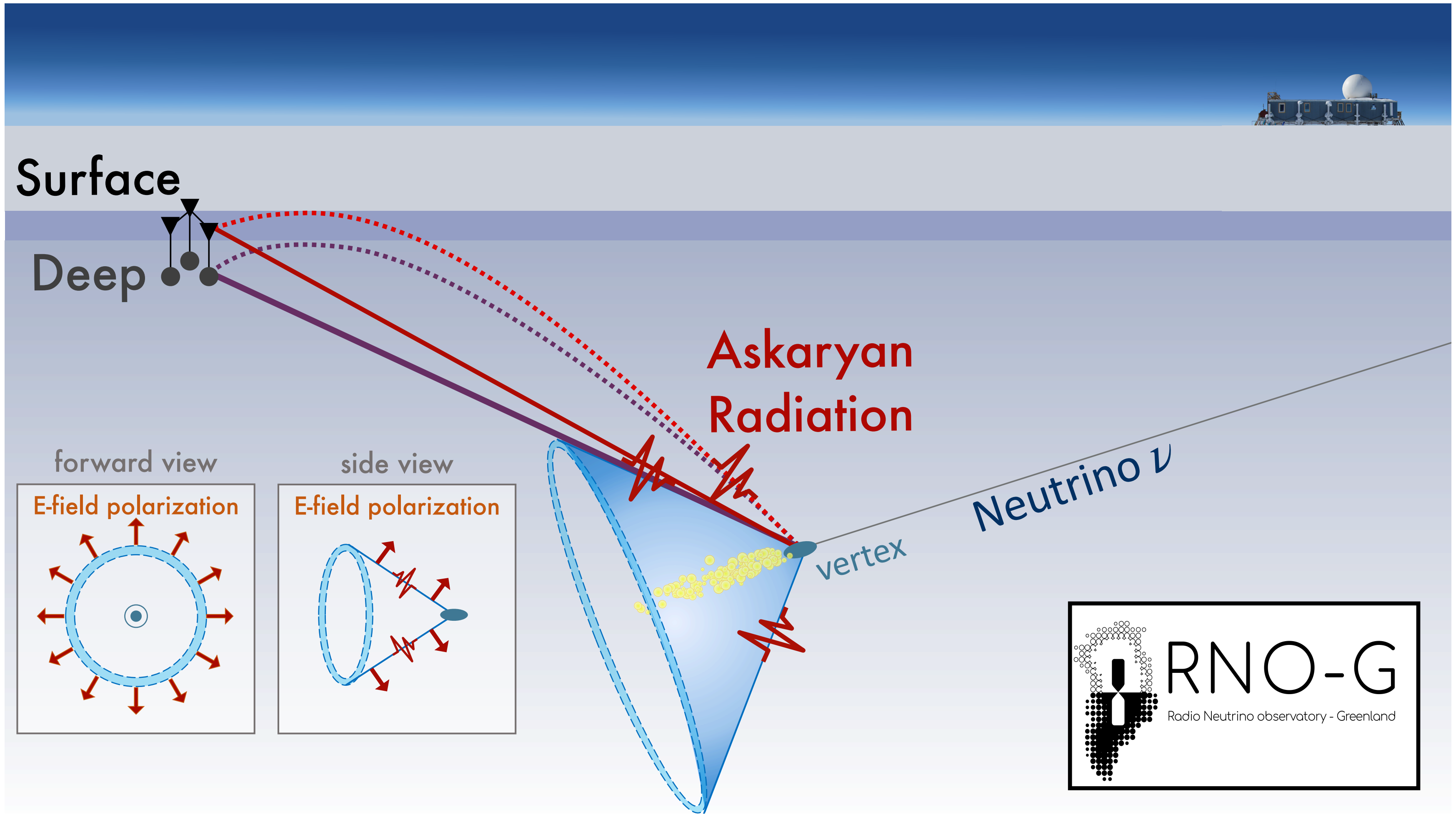
Outlook: RNO-G

- Detection principle of **ANITA, ARA & ARIANNA** (Antarctica)
- **Under construction:** Radio Neutrino Observatory-Greenland (**RNO-G**)
- **status March 2024:** 7 of 35 stations deployed

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



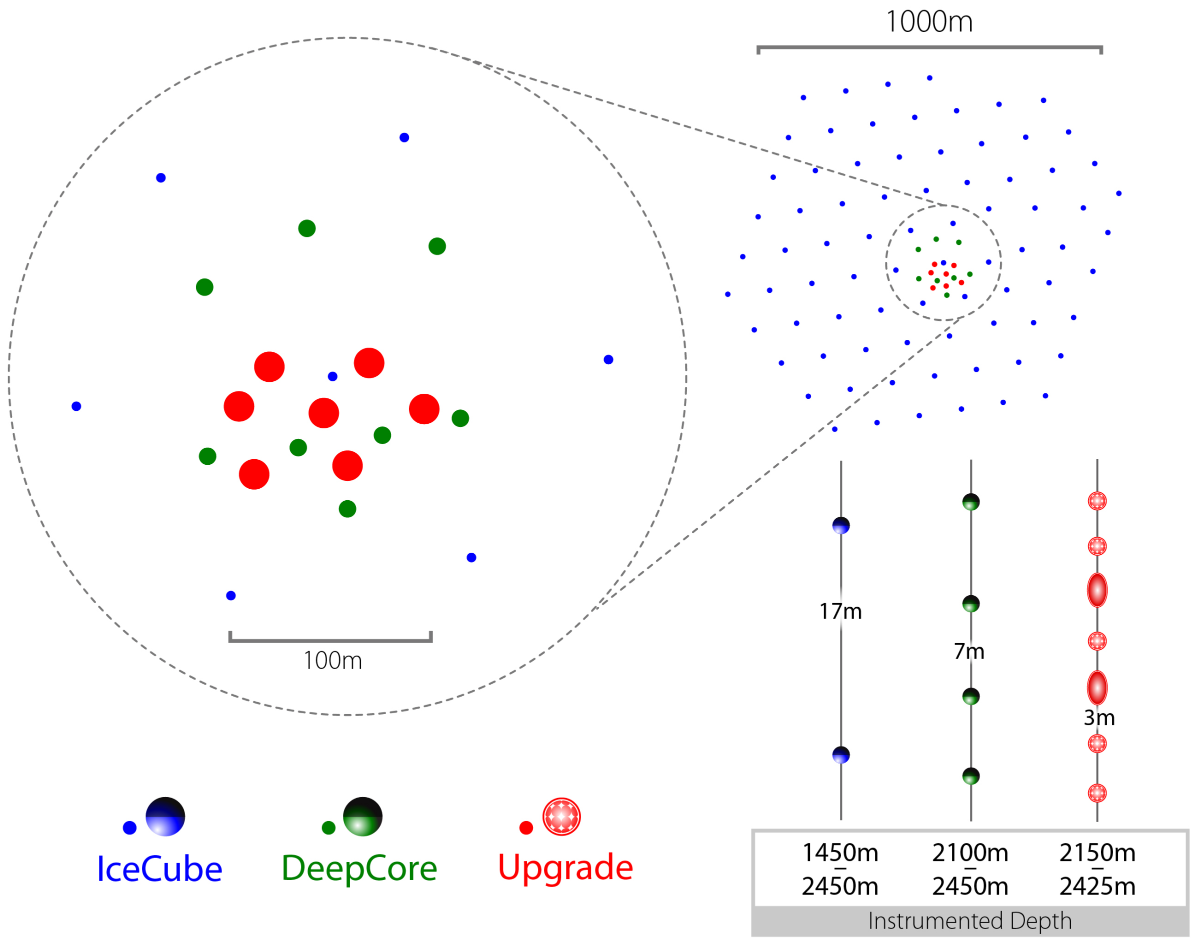
station with nine deep & surface antennas

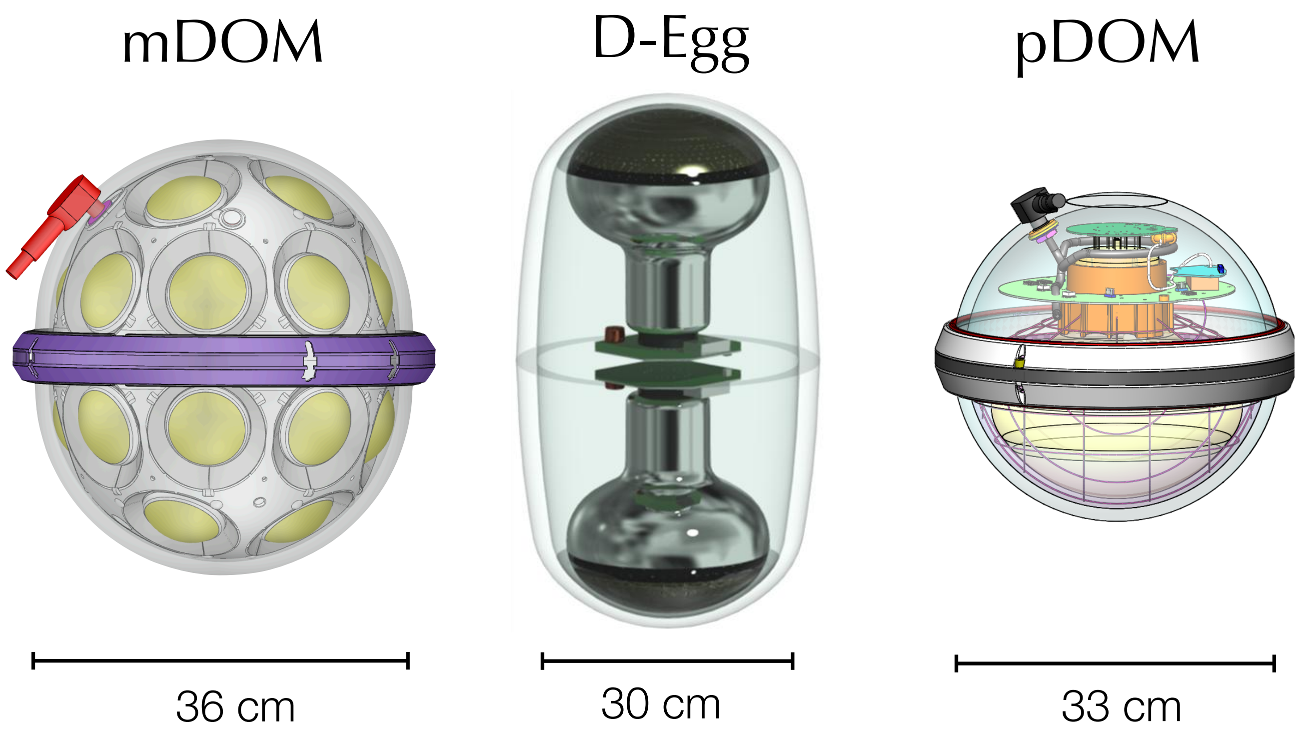


[RNO-G JINST 16 (2021) 3]

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**

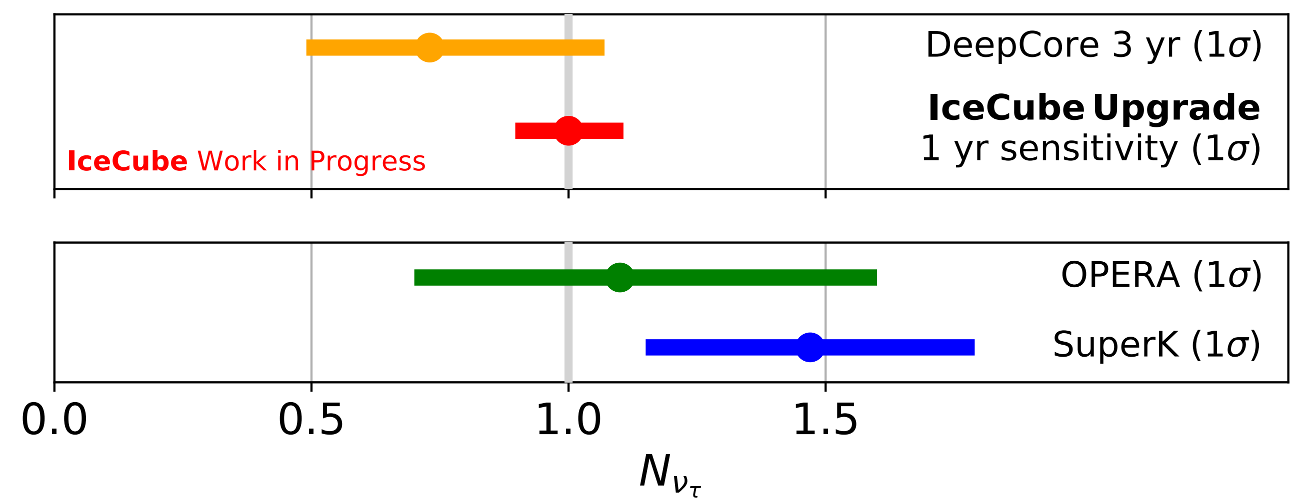


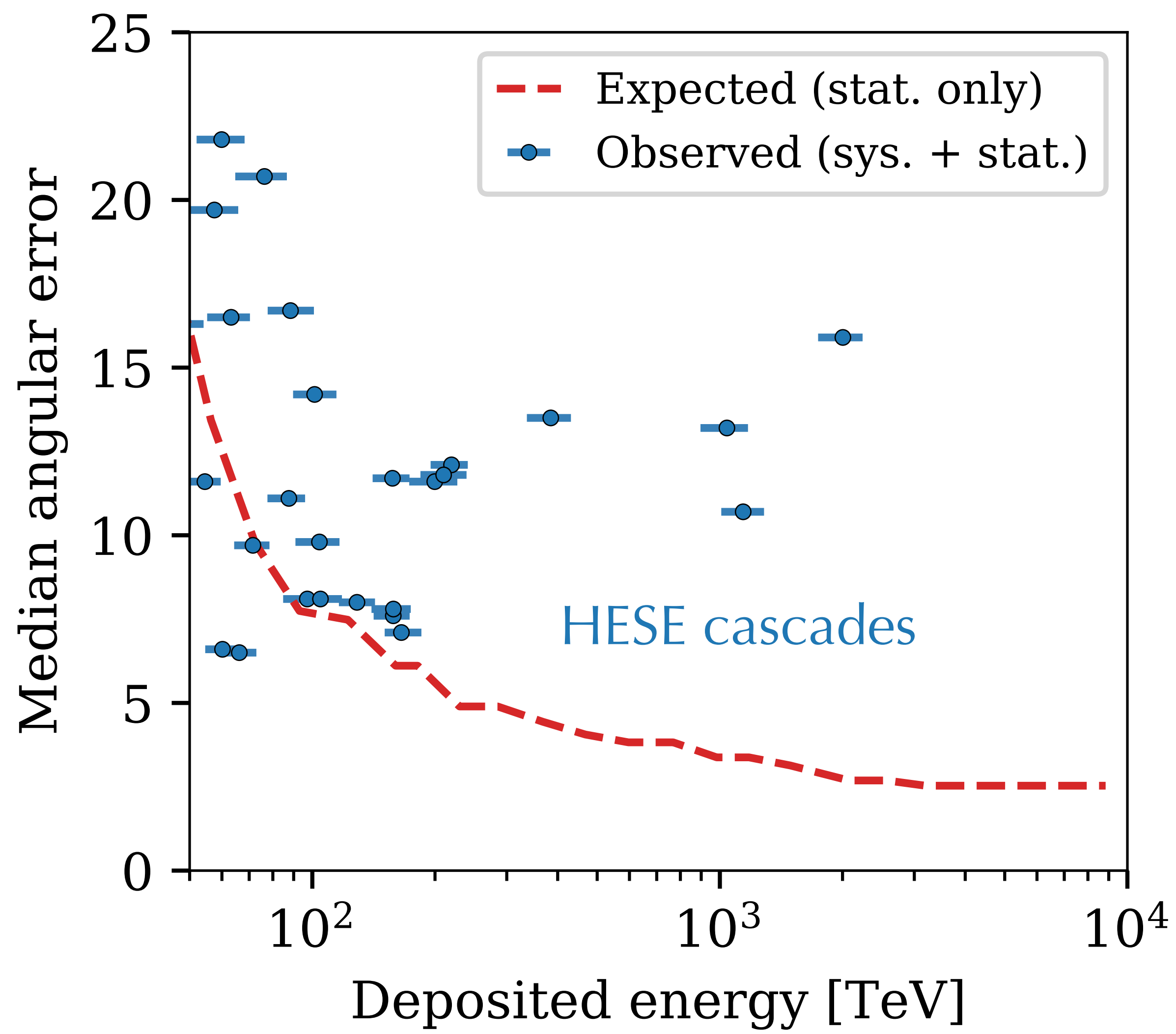


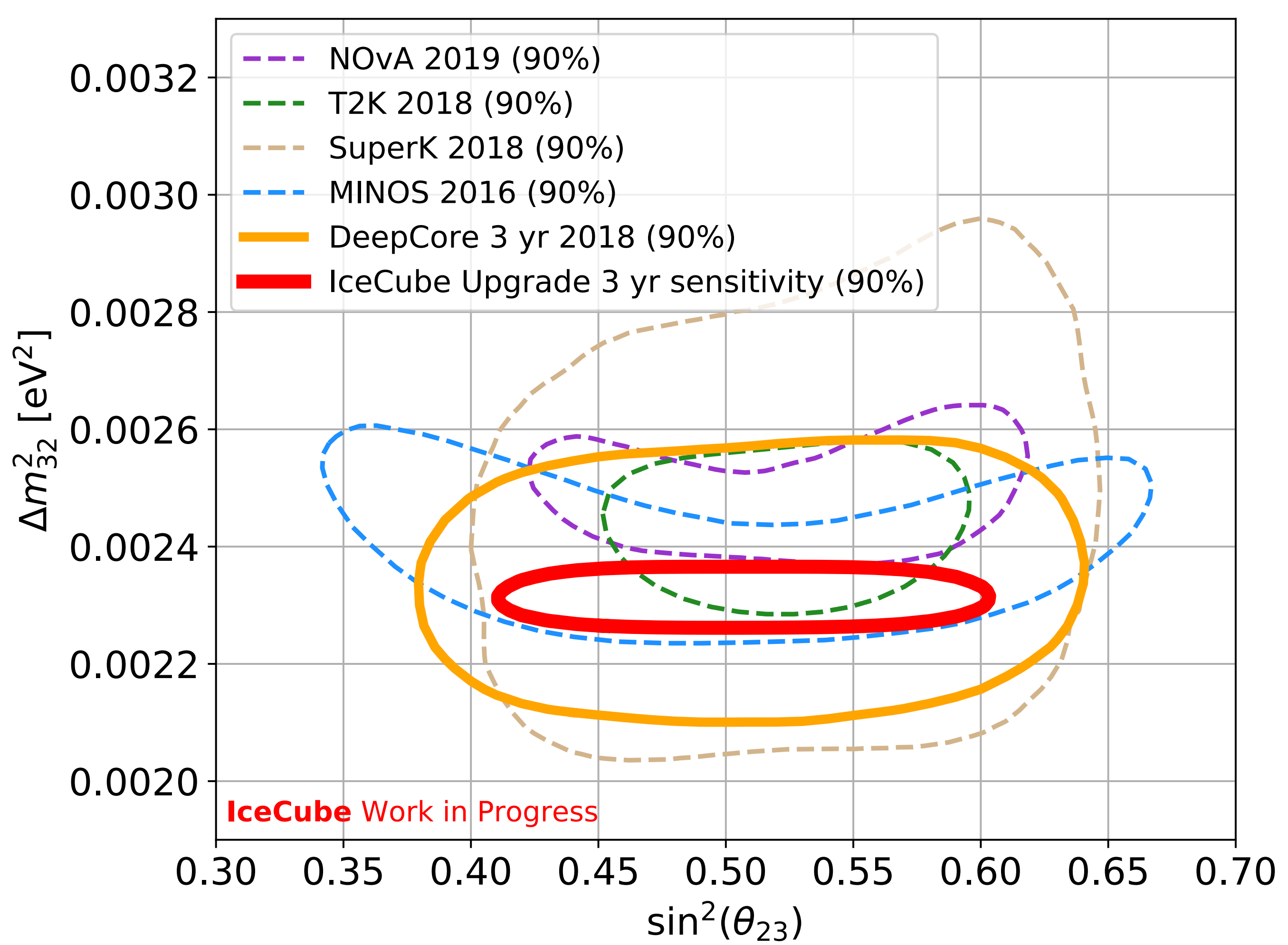
Outlook: IceCube Upgrade

- **Precision measurement** of atmospheric neutrino oscillations and tau neutrino appearance

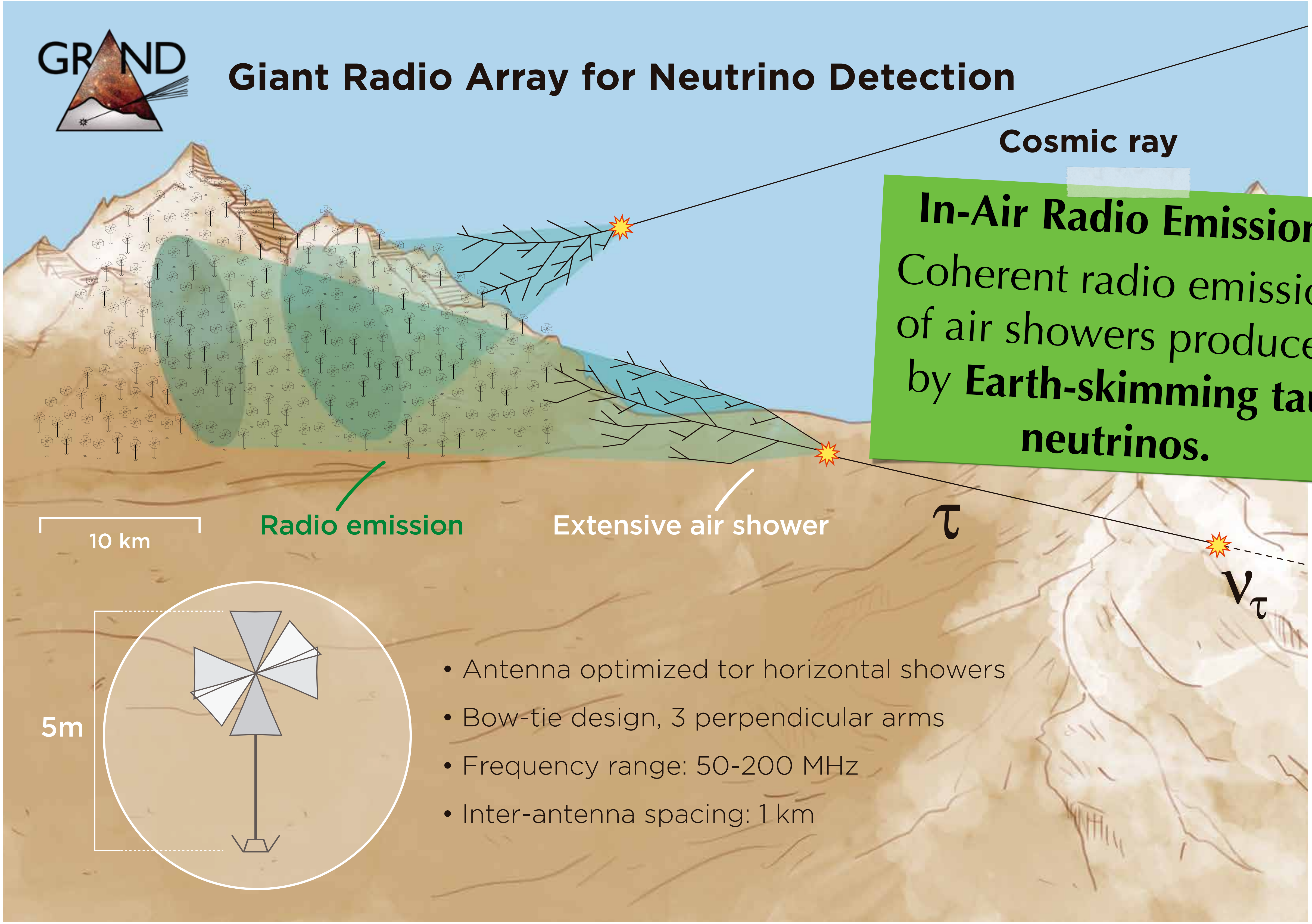
- **Improved energy and angular reconstructions** of IceCube data





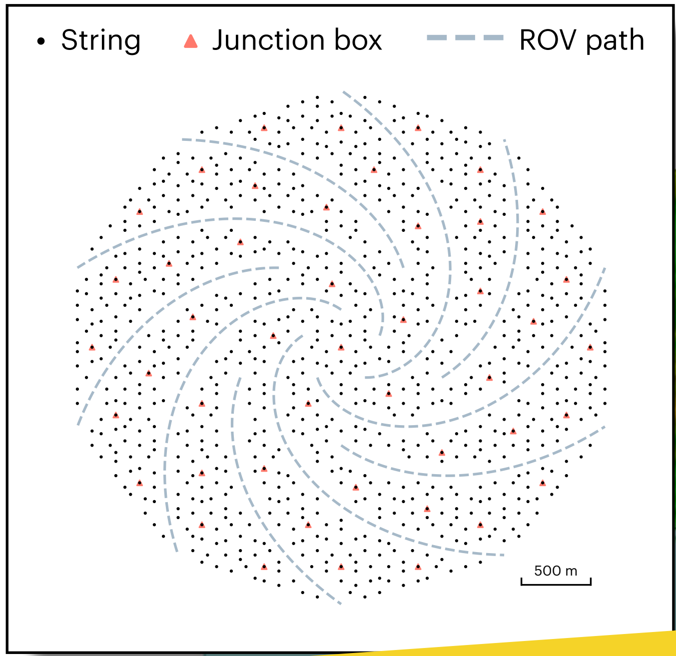


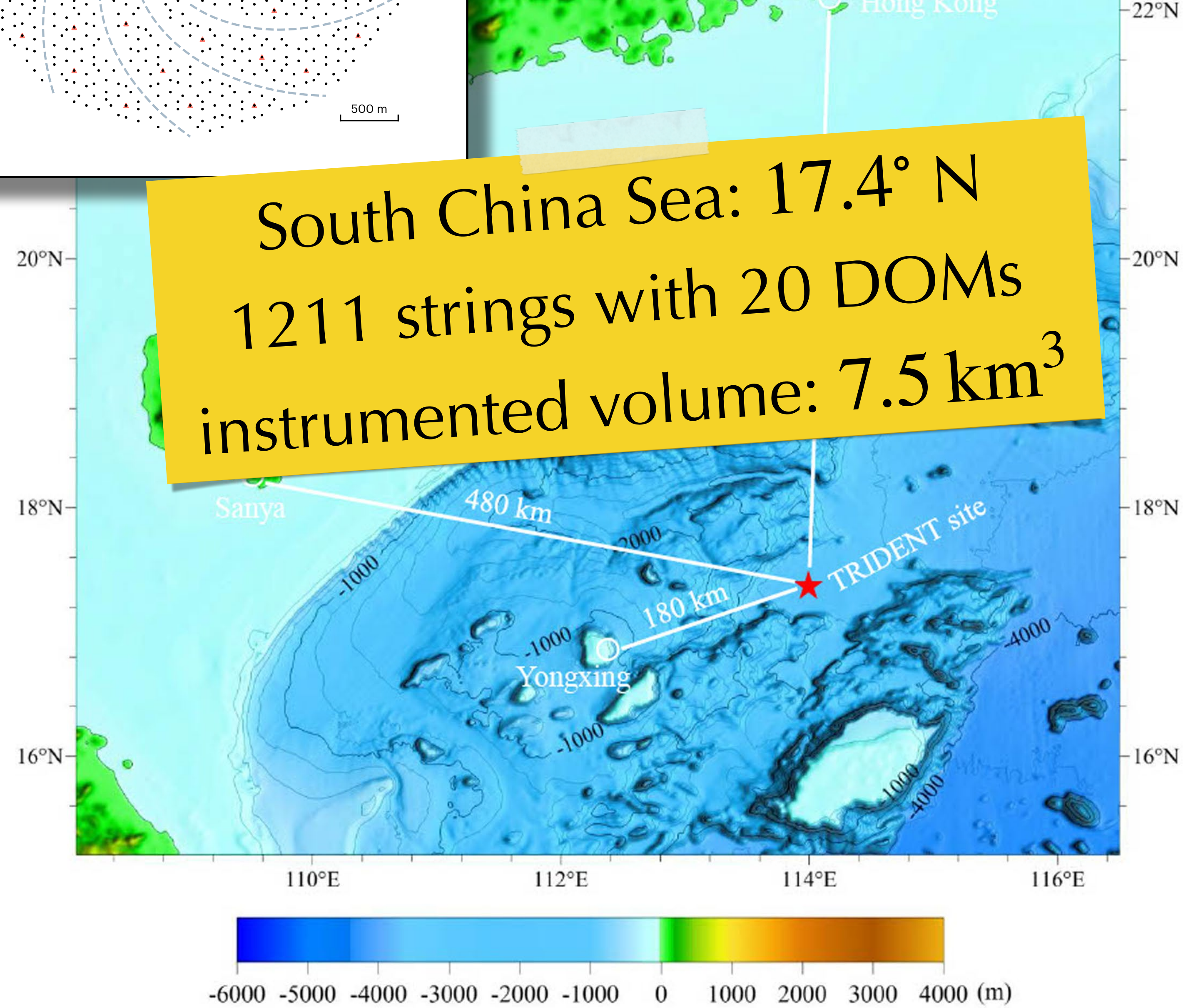
[IceCube, PoS (ICRC2019) 1031]



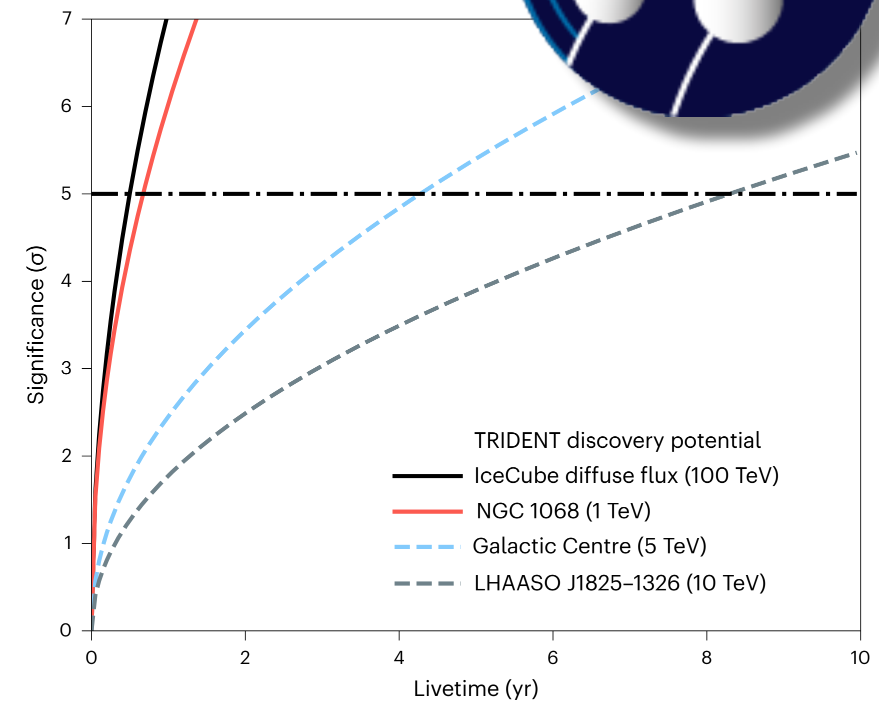
[GRAND SCPMA 63 (2020) 1]

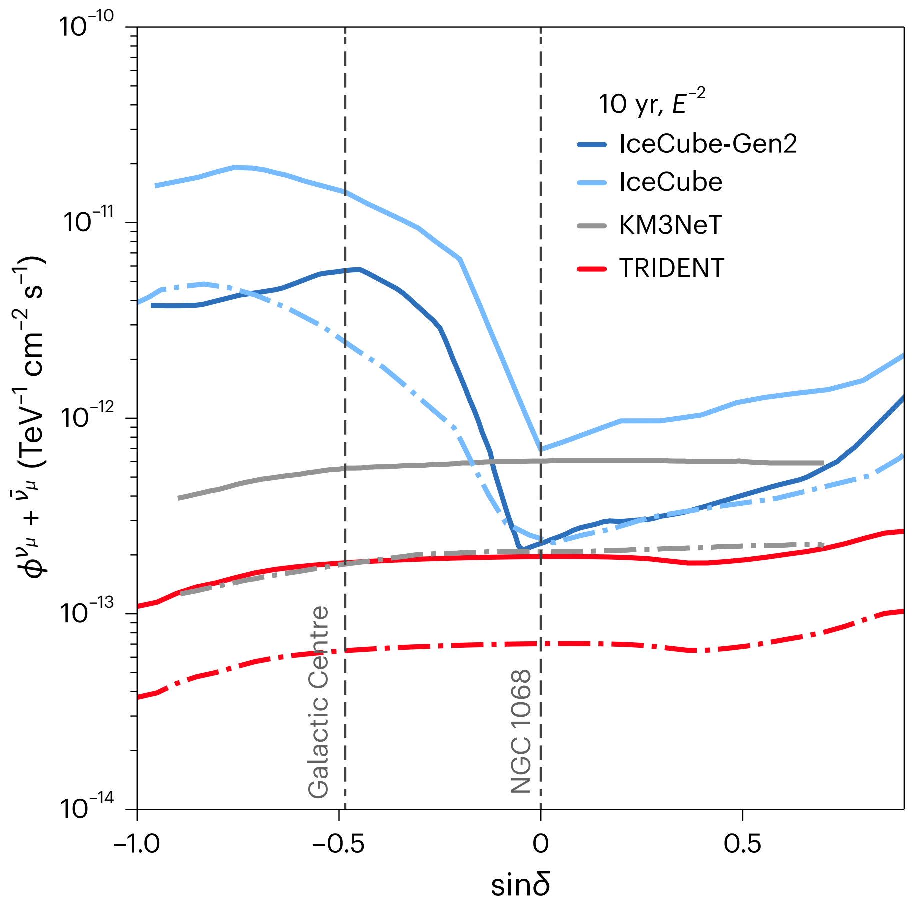
Vision: TRIDENT





South China Sea: 17.4° N
1211 strings with 20 DOMs
instrumented volume: 7.5 km^3

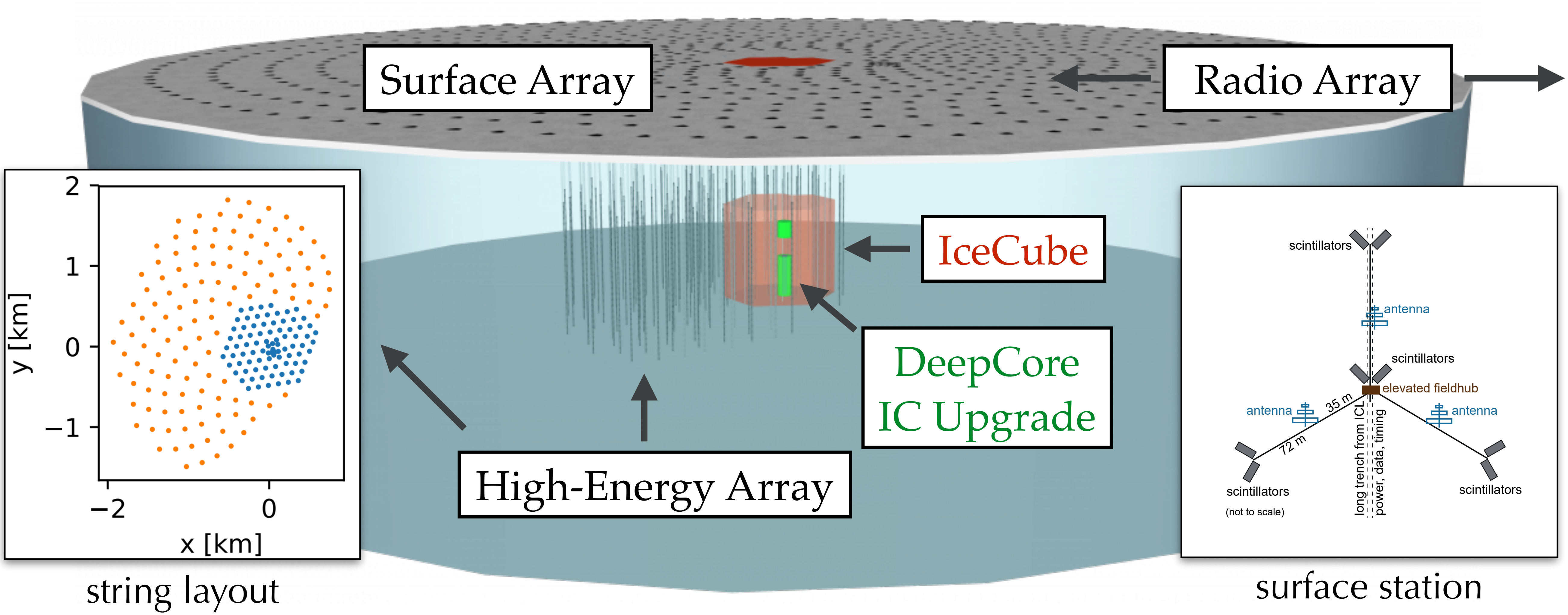




[TRIDENT Nature Astron. 7 (2023) 12]

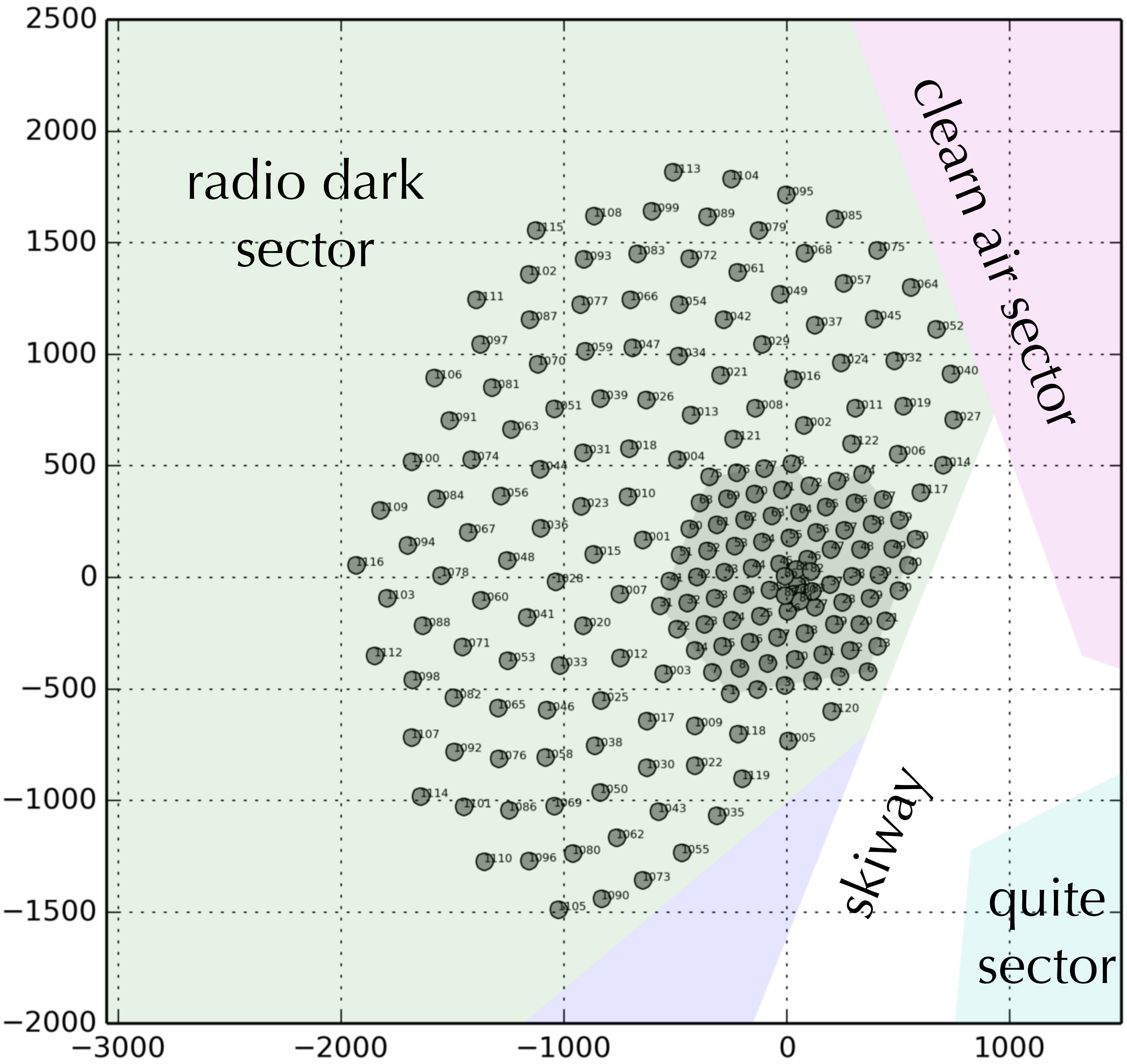
Vision: IceCube-Gen2

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



[IceCube-Gen2 *Technical Design Report:* icecube-gen2.wisc.edu/science/publications/tdr/]

Vision: IceCube-Gen2



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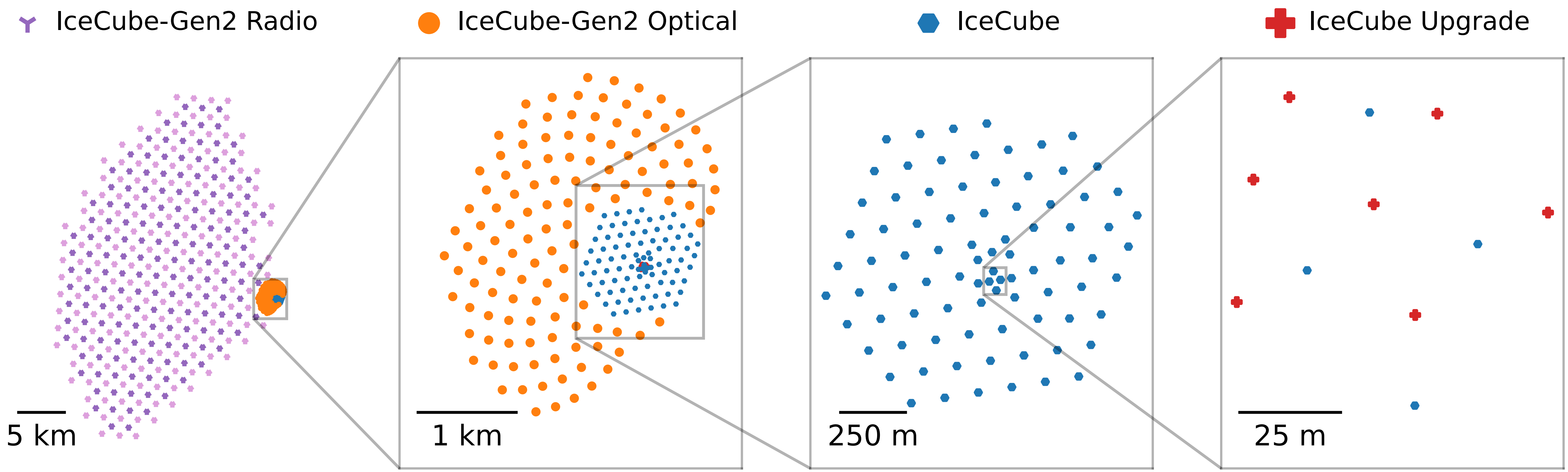
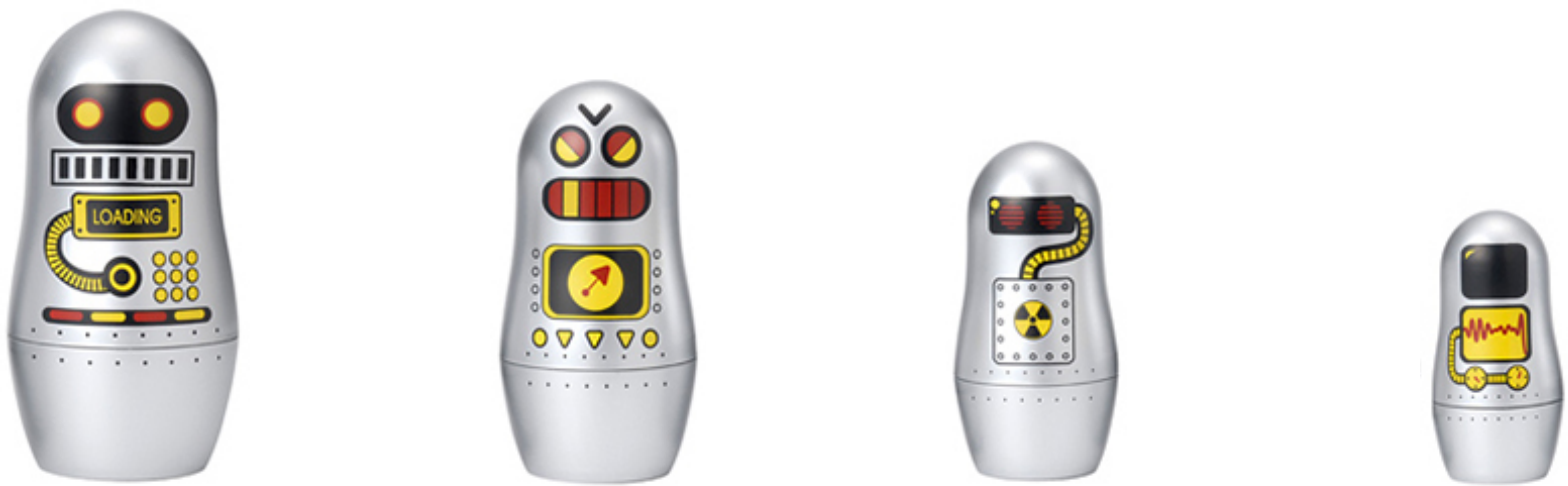
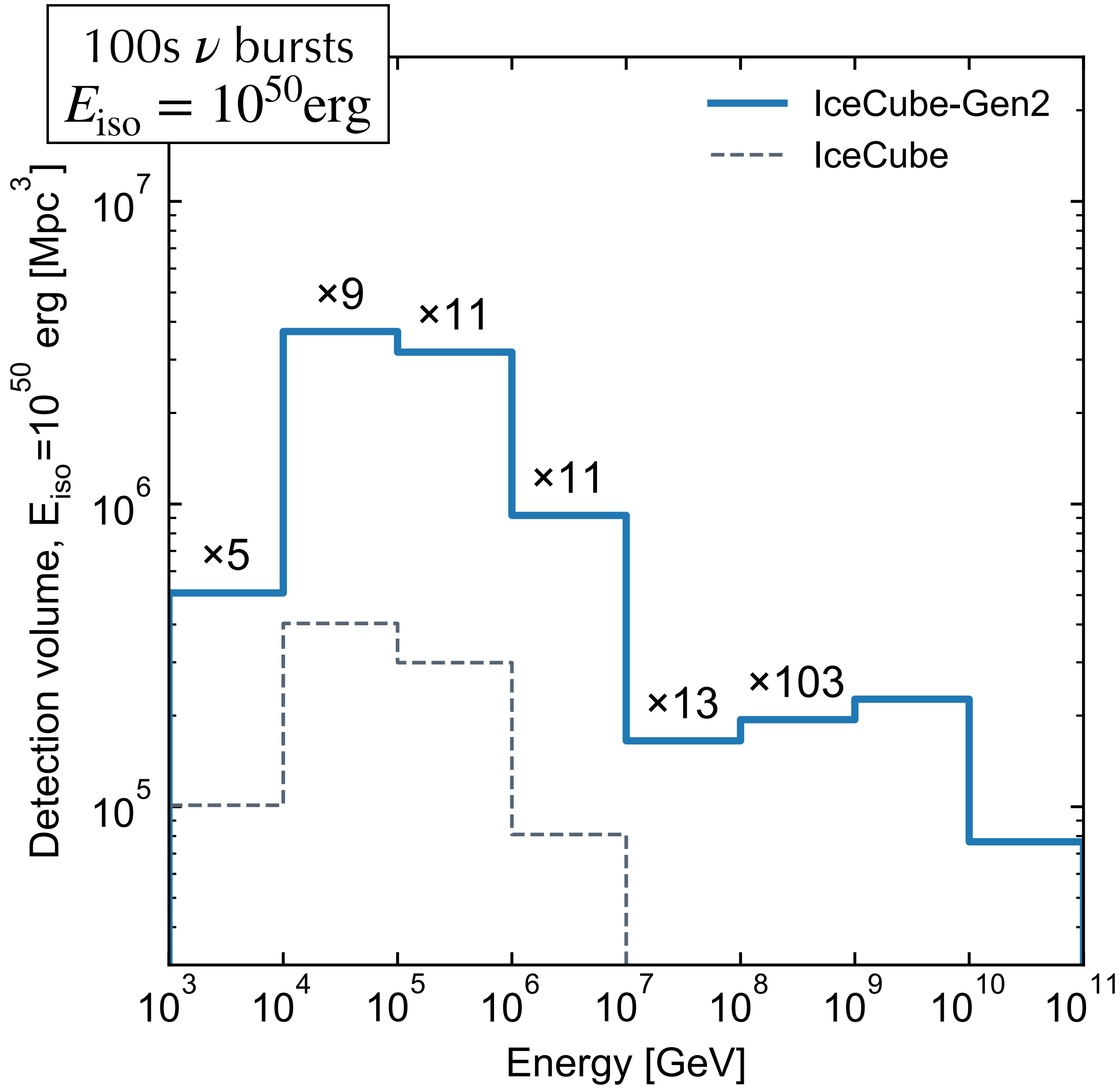


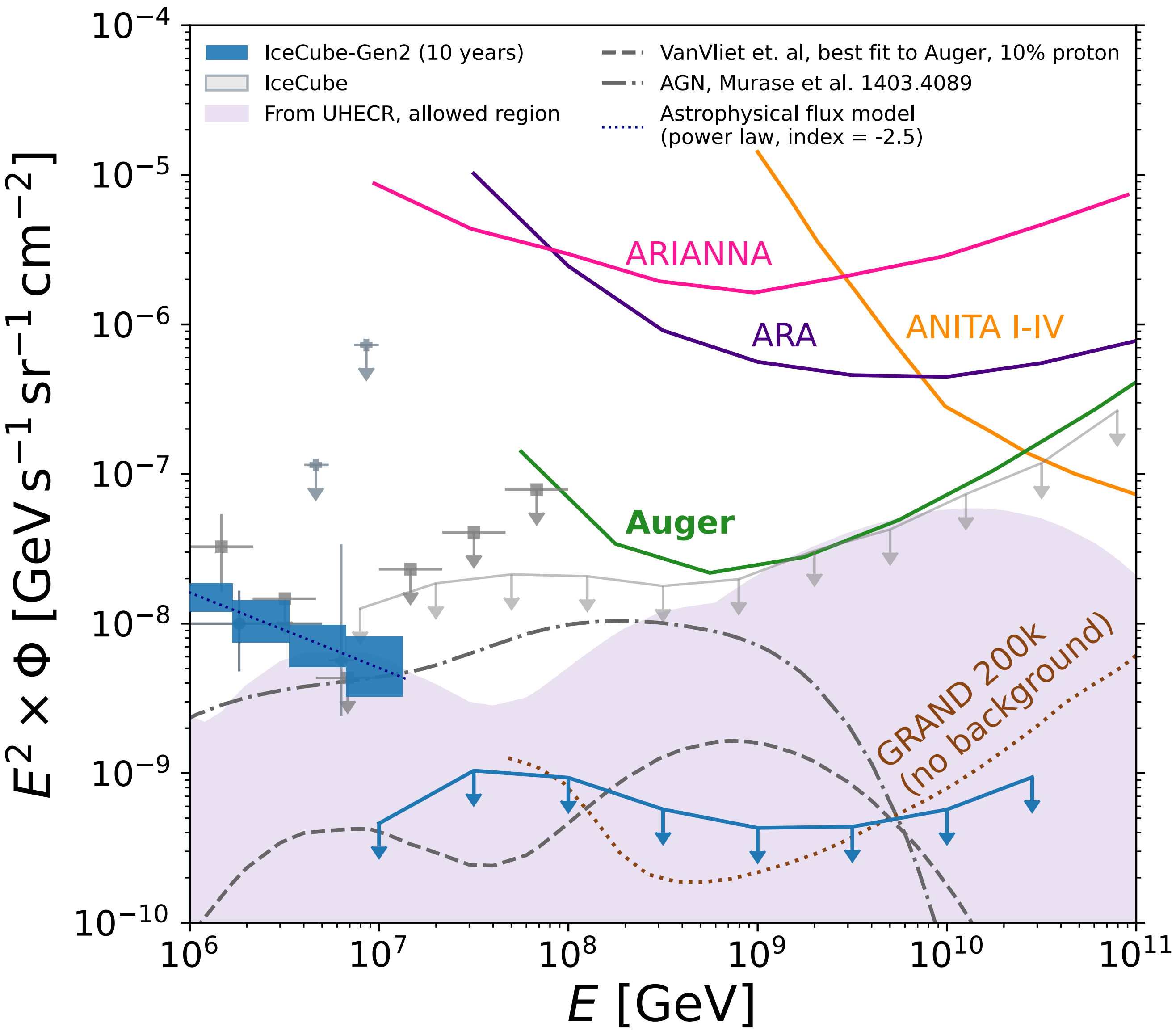


Vision: IceCube-Gen2

Improved sensitivity for neutrino 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



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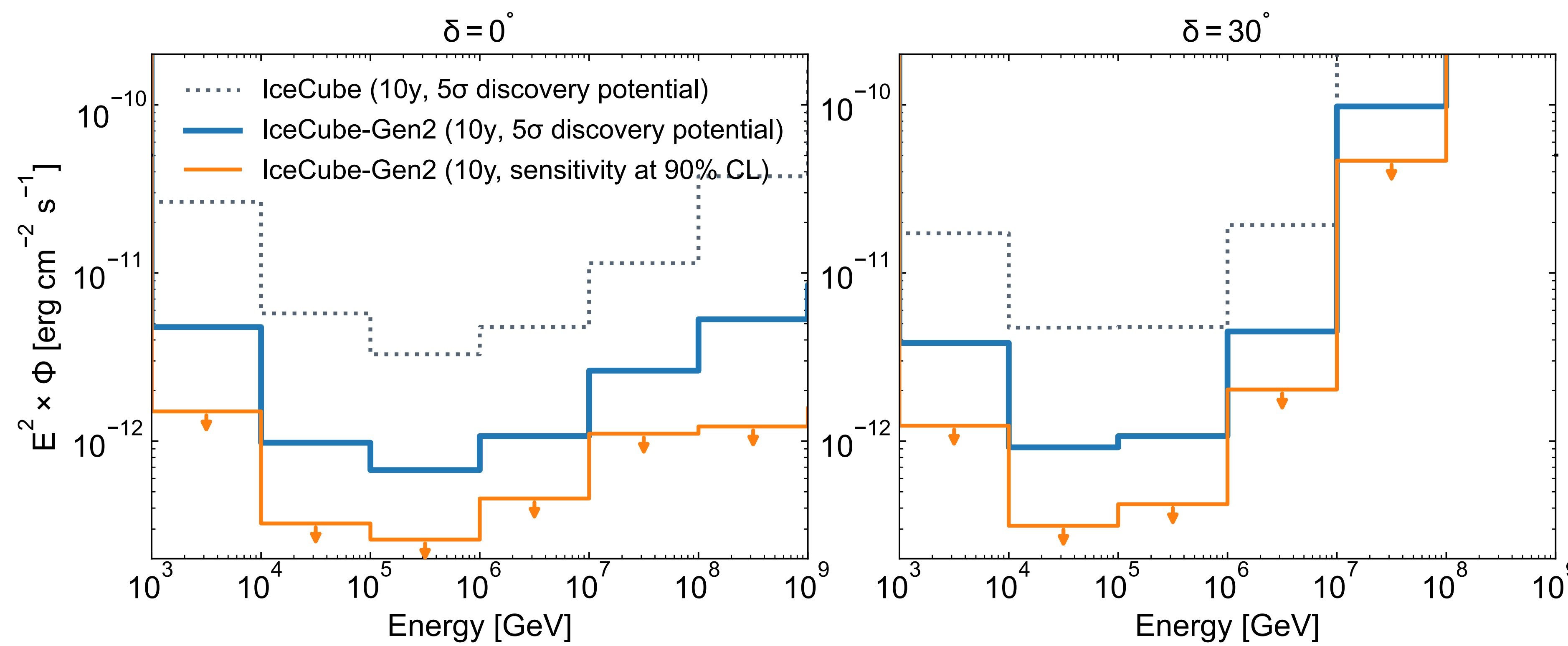
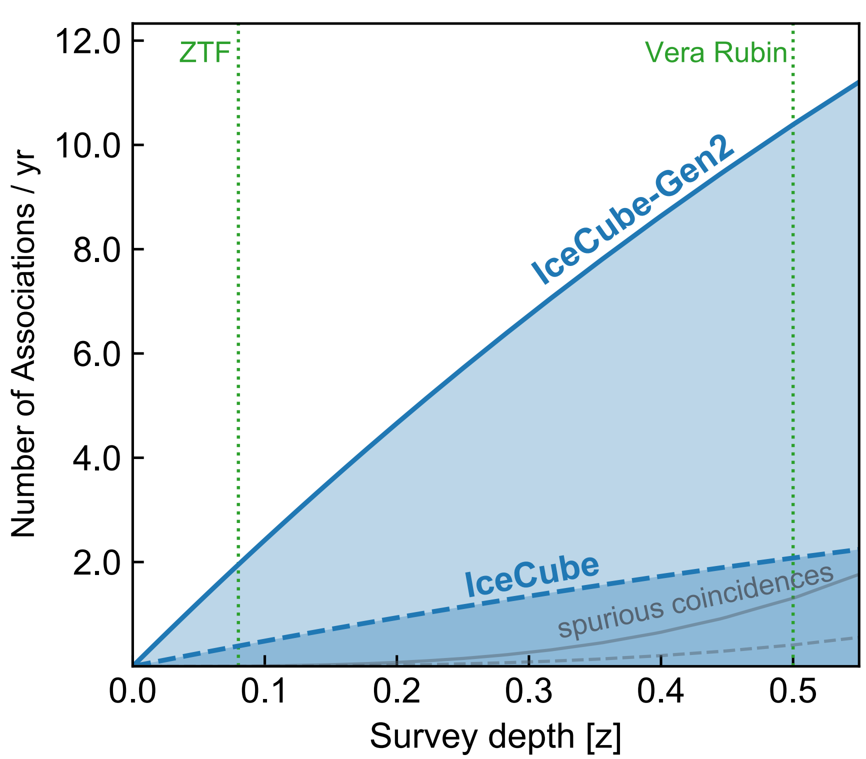
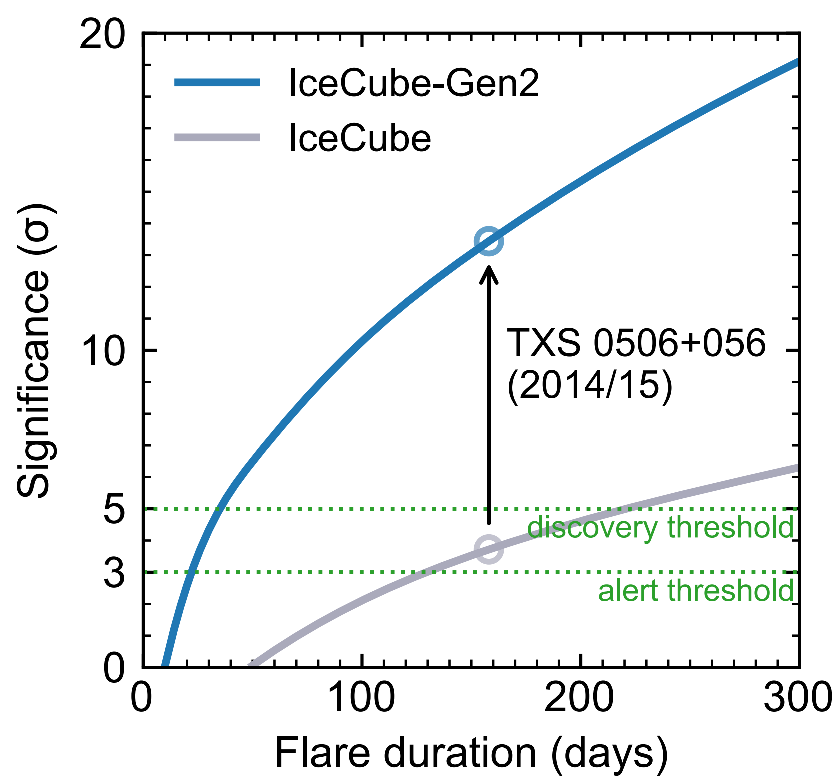
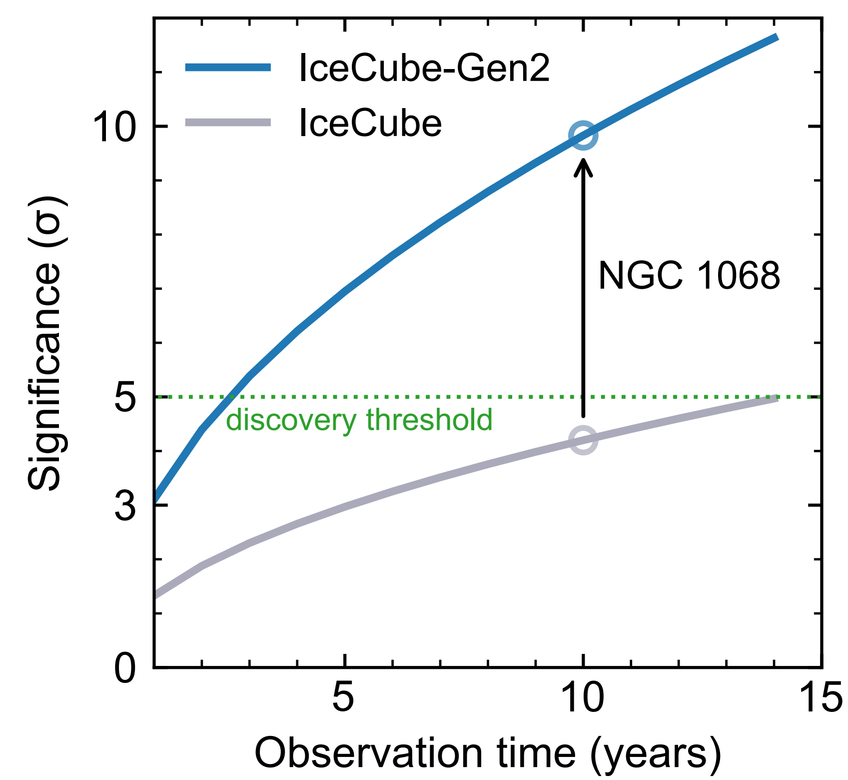
Vision: IceCube-Gen2

Discovery potentials of IceCube vs. IceCube-Gen2









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