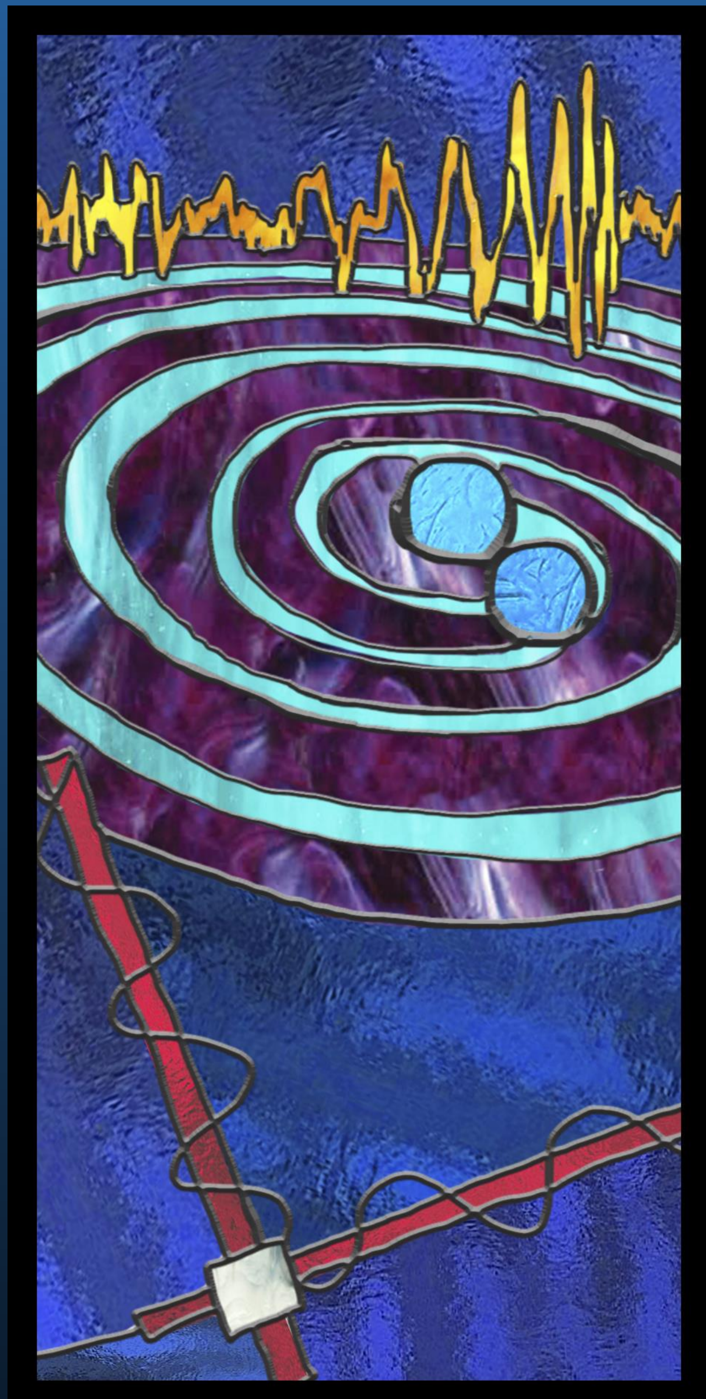
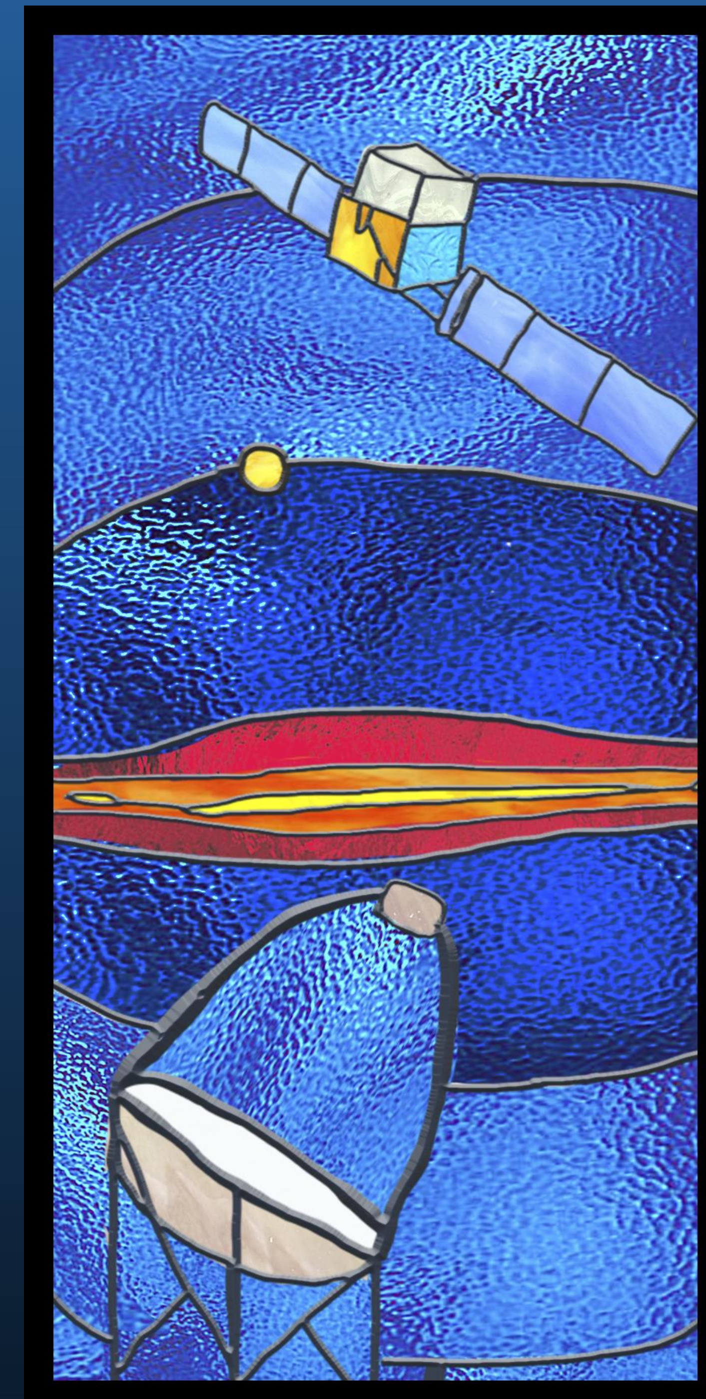
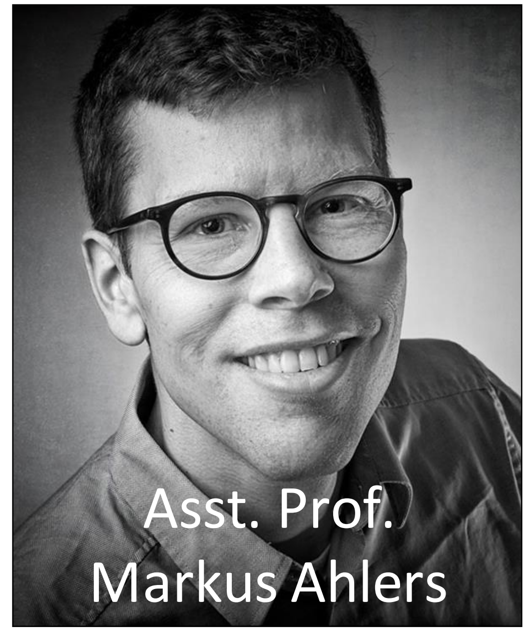




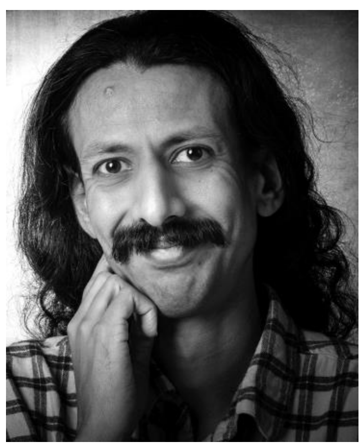
Particle Astrophysics

Markus Ahlers, Mauricio Bustamante & Irene Tamborra

Who are we?



+ many excellent Master & Bachelor students


Shashank Shalgar


Annika Rudolph


Enrico Peretti


Damiano Fiorillo


Ersilia Guarini


Tetyana Pitik


Marie Cornelius Hansen


Pedro Dedin


Kathrine Mørch Groth


Victor Valera

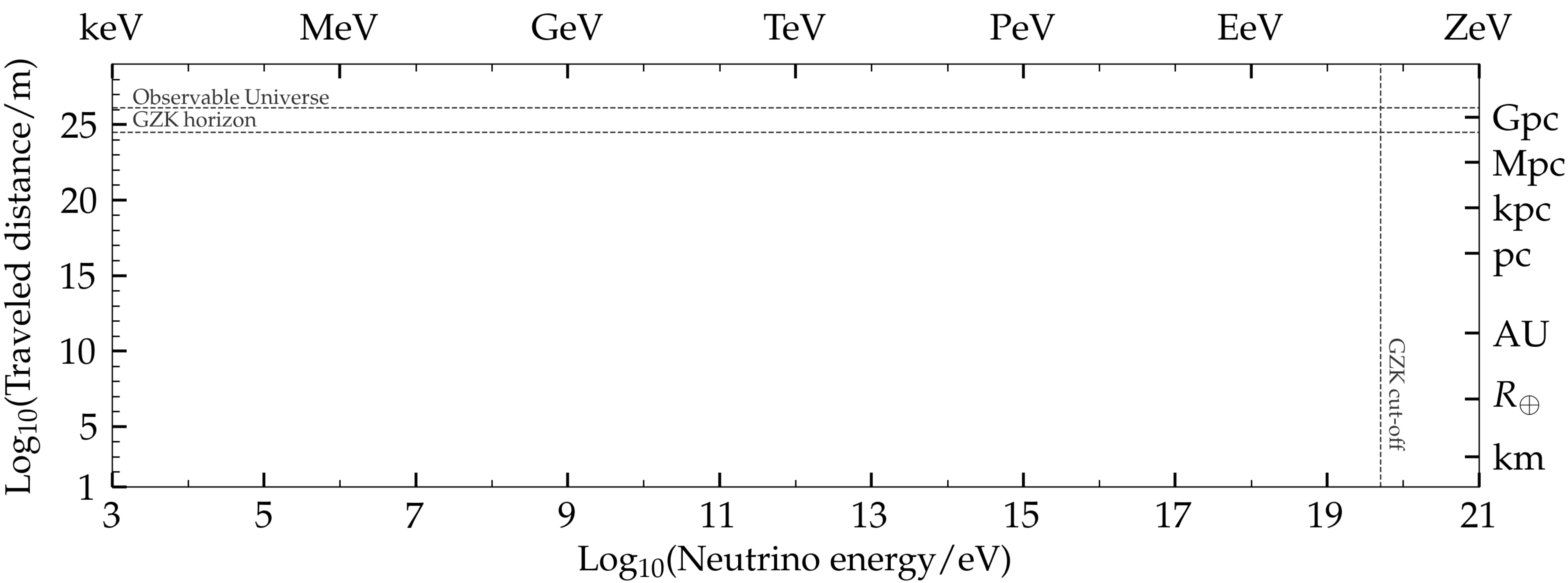

Bernanda Telalovic

The Elusive Neutrino

- **Three neutrino flavours**
- Very small masses *(unknown origin)*
- Large mixing between flavor and mass states *(unknown mechanism)*
- Second most abundant particle in the Universe *(impact on cosmology)*
- **Unique probe of high-energy particle physics & astrophysics**

Standard Model of Particle Physics

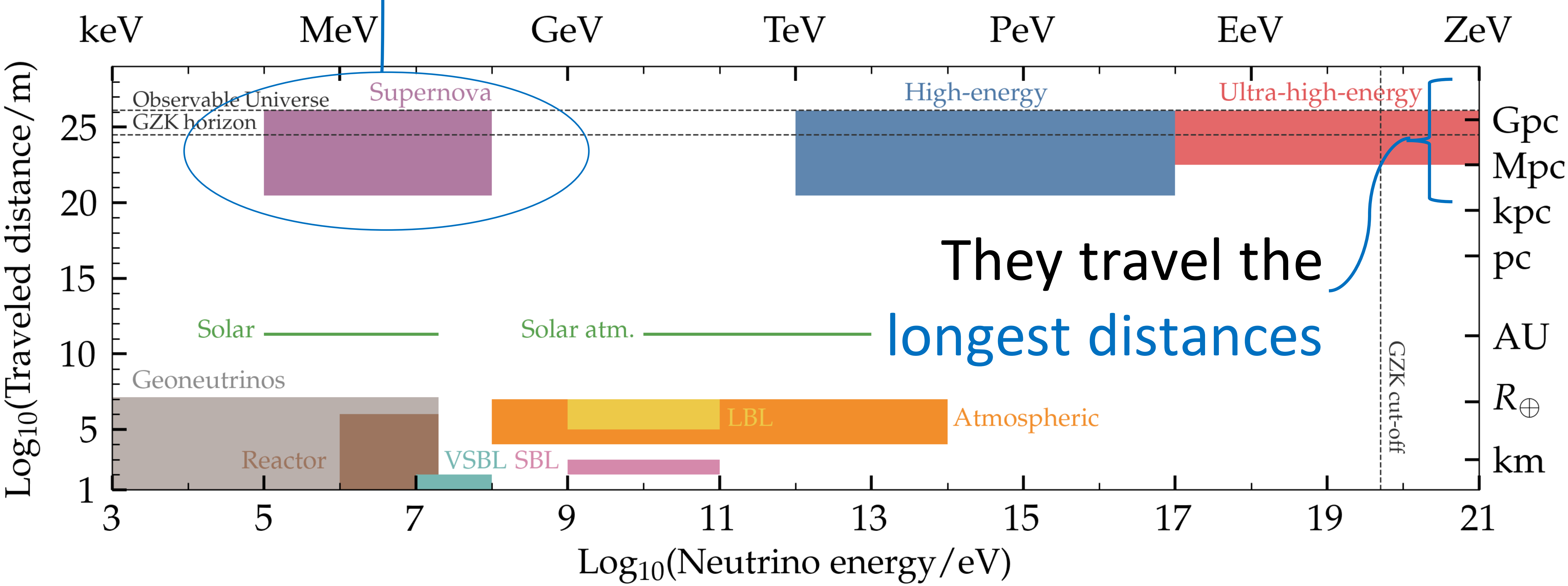
(+ Higgs boson)



Ackermann, **Bustamante**, *et al.*, Snowmass 2021

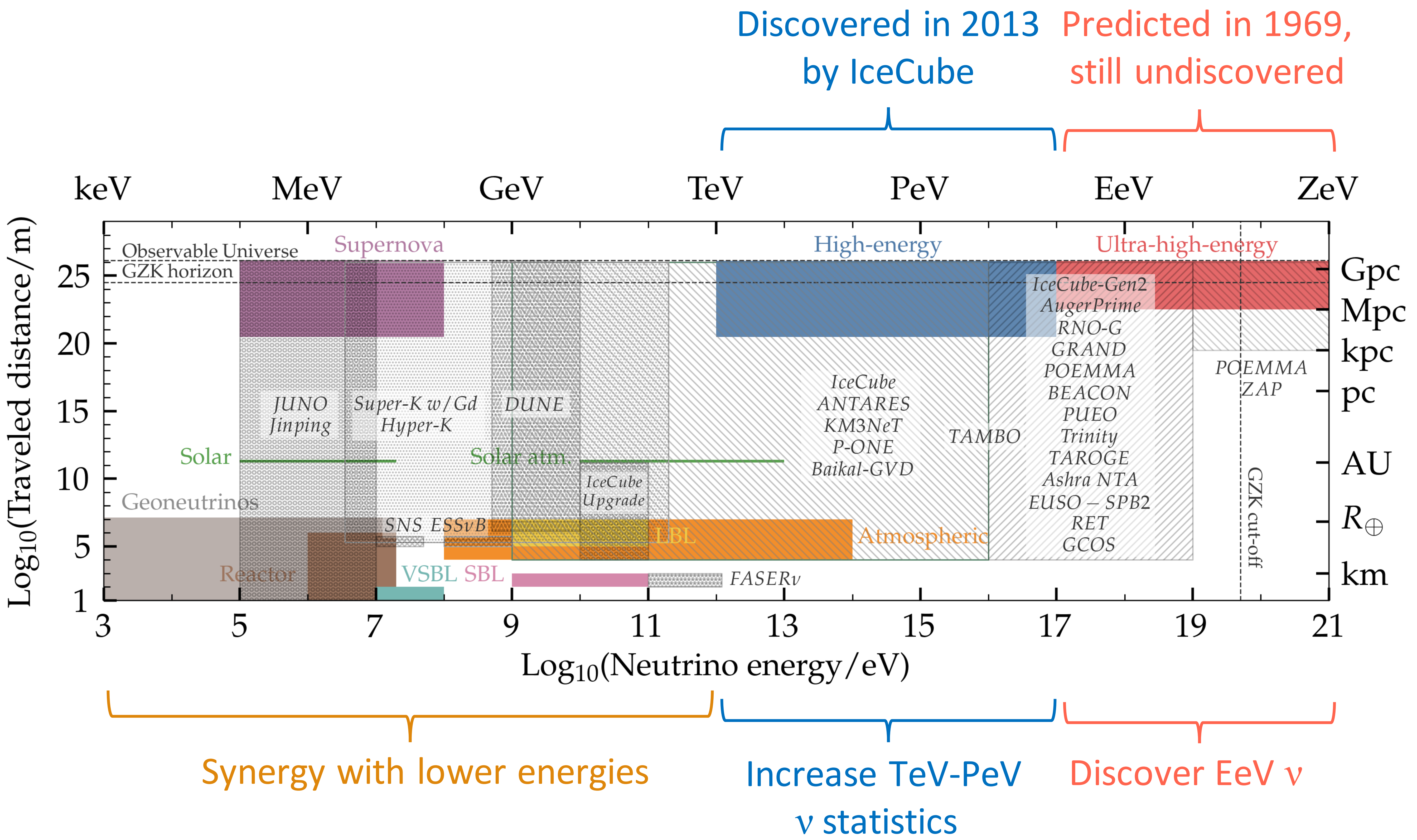
They probe the densest matter

They have the highest energies



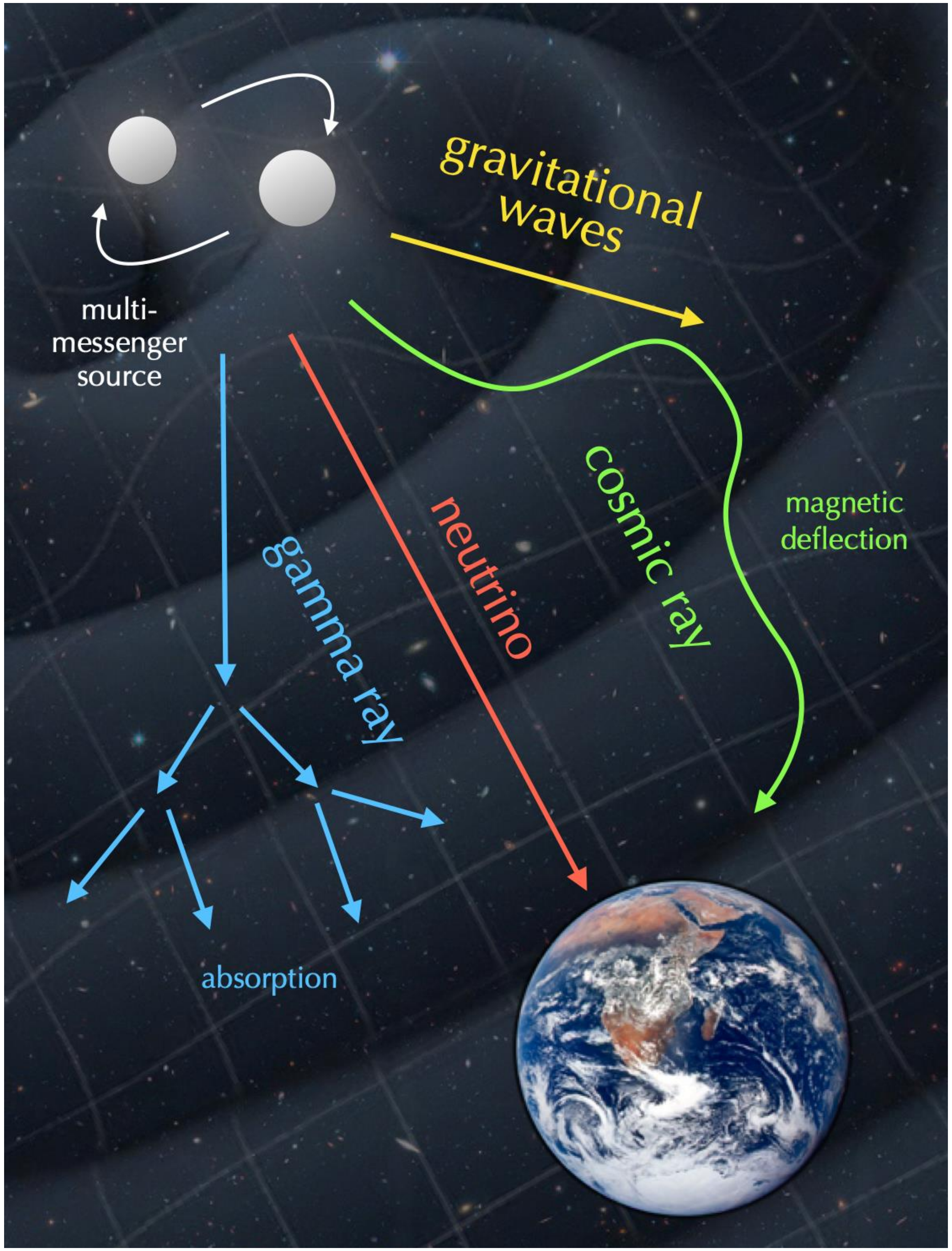
They travel the longest distances

Ackermann, **Bustamante**, *et al.*, Snowmass 2021



Ackermann, **Bustamante**, *et al.*, Snowmass 2021

Neutrinos as Cosmic Messengers



Unique abilities of **cosmic neutrinos**:

no deflection in magnetic fields
(unlike cosmic rays)

no absorption in cosmic backgrounds
(unlike gamma-rays)

smoking-gun of
unknown sources of cosmic rays

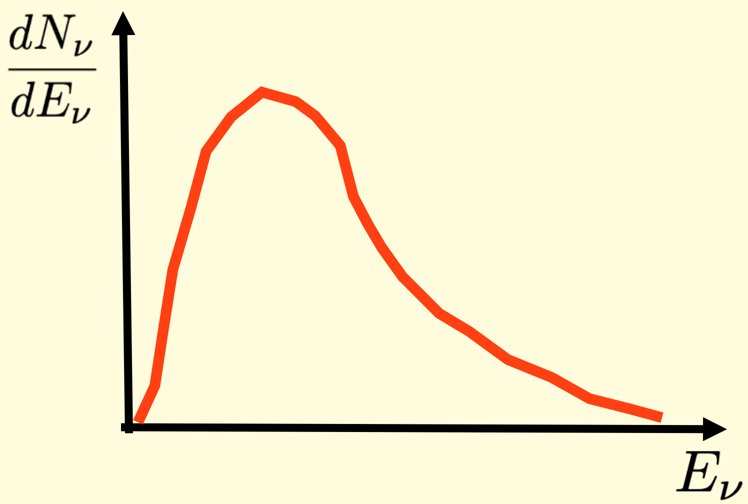
coincident with
photons and gravitational waves

BUT, very difficult to detect!

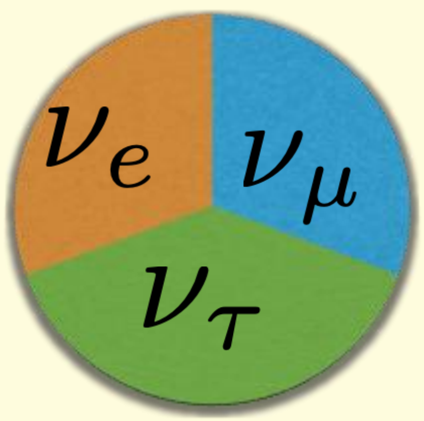
Powerful Probes in Astrophysics

Neutrinos provide us with:

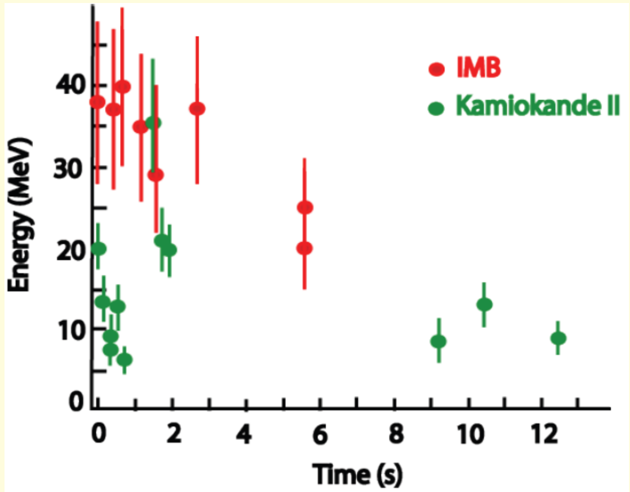
1. Energy Distribution



2. Flavor Ratios

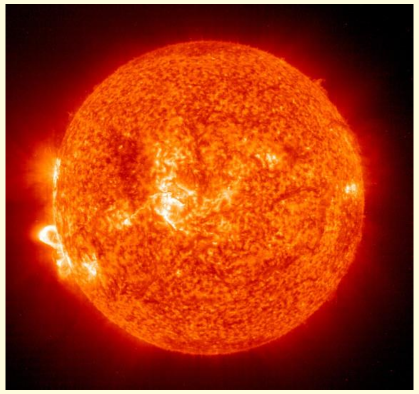


3. Light Curve

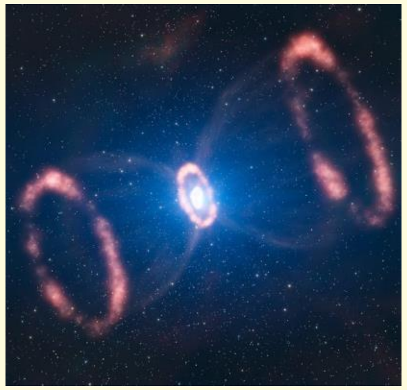


Neutrinos are copiously produced in astrophysical sources, e.g.

The Sun



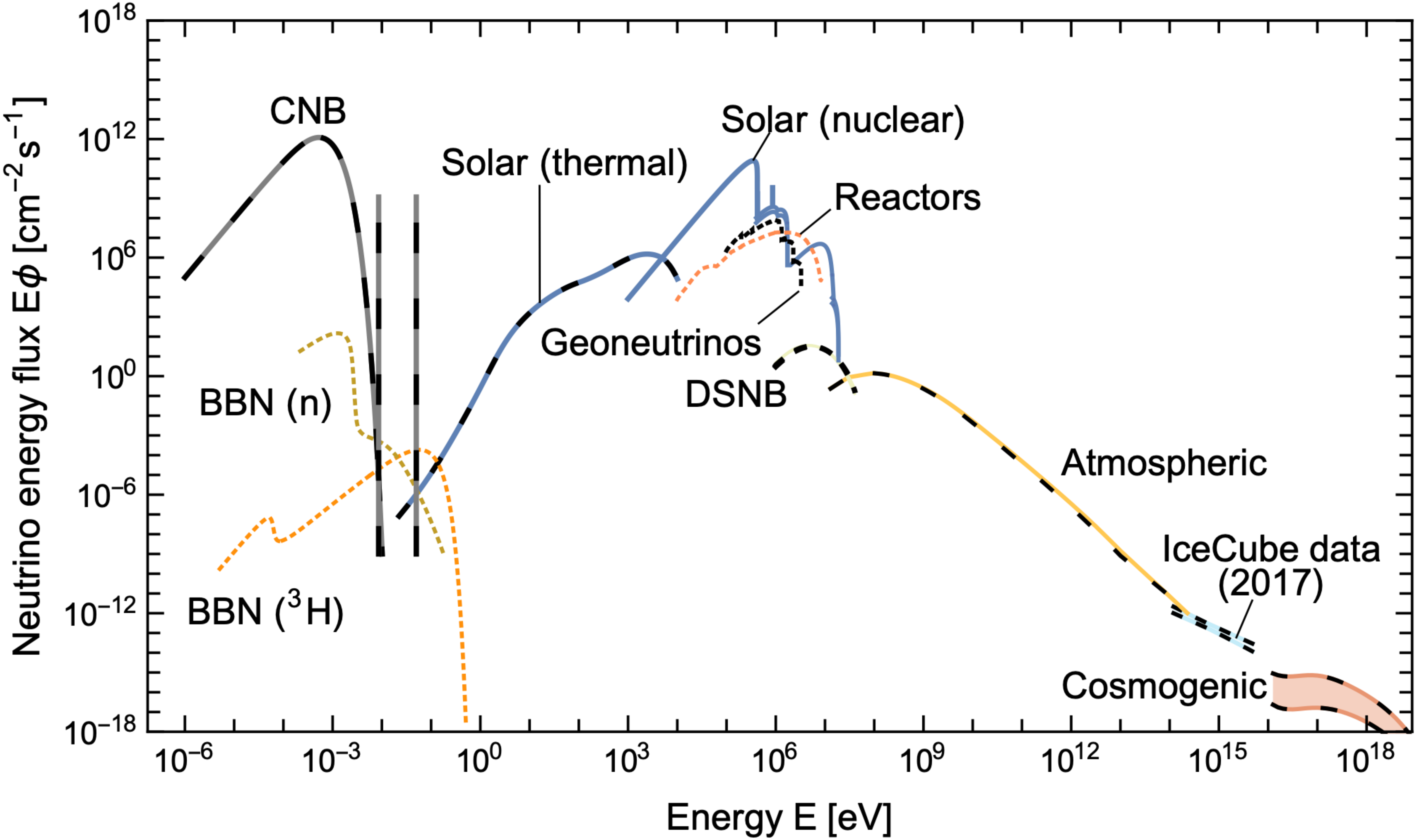
Supernovae



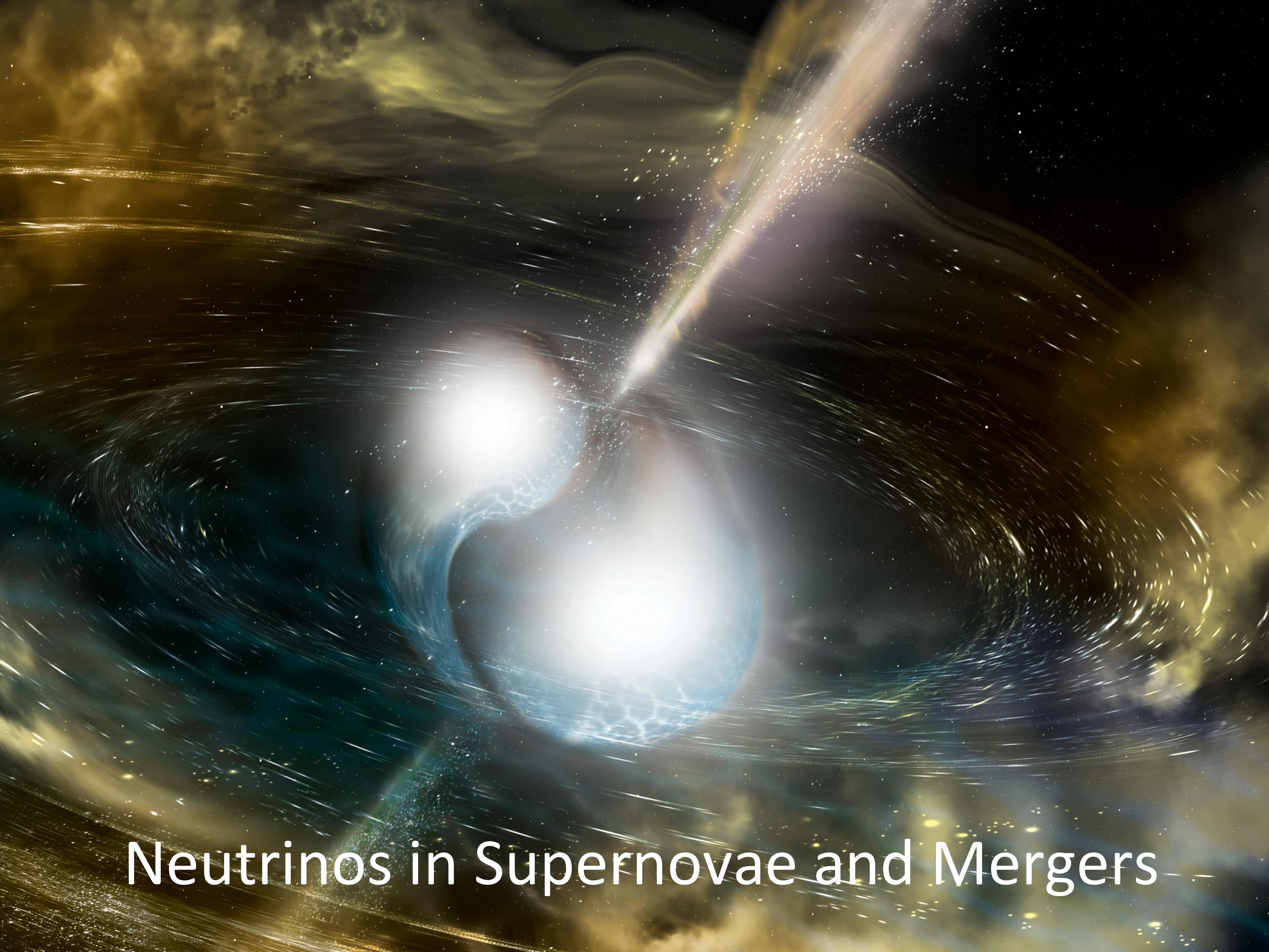
Active Galaxies

Gamma-ray Bursts

Grand Unified Neutrino Spectrum



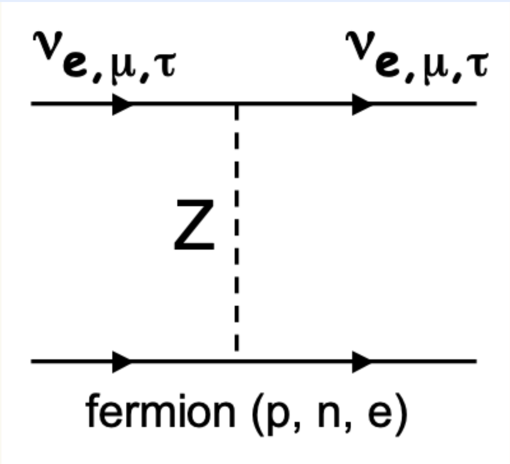
[Vitagliano, Tamborra & Raffelt, *Rev. Mod. Phys.* 92 (2020)]

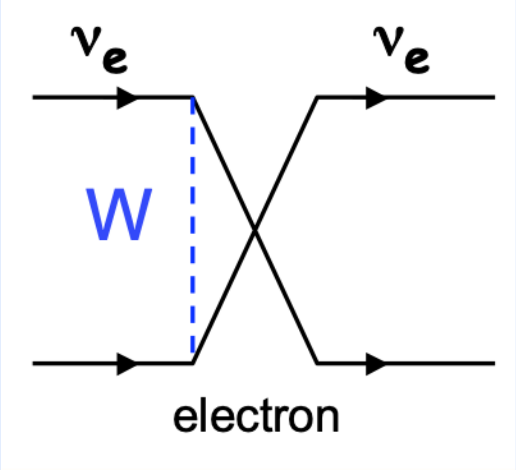


Neutrinos in Supernovae and Mergers

Neutrino Interactions

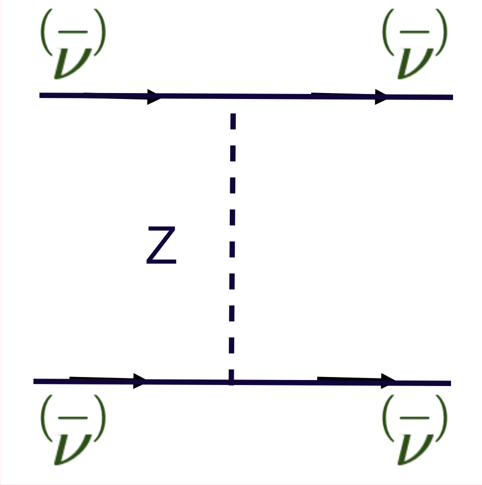
Understood phenomenon





Neutrinos interact with neutrons, protons and electrons.

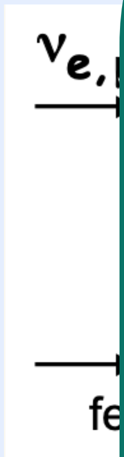
We still need to learn a lot about this process!



$\nu - \nu$ interactions

Non-linear phenomenon!

Neutrino Interactions



ns,

Large body of work on flavor conversions in compact objects:

Neutrino Flavor Conversion, Advection, and Collisions: The Full Solution
Shalgar & **Tamborra**, 2207.04058

Supernova Neutrino Decoupling Is Altered by Flavor Conversion
Shalgar & **Tamborra**, 2206.00676

Enhancement or damping of fast neutrino flavor conversions due to collisions
Hansen, **Shalgar**, **Tamborra**, *PRD* 2022

Neutrino Flavor Pendulum Reloaded: The Case of Fast Pairwise Conversion
Padilla-Gay, **Tamborra**, Raffelt, *PRL* 2022

Symmetry breaking induced by pairwise conversion of neutrinos in compact sources
Shalgar, **Tamborra**, *PRD* 2021

On the characteristics of fast neutrino flavor instabilities in three-dimensional core-collapse supernova models
Abbar, Capozzi, Glas, Janka, **Tamborra**, *PRD* 2021

Neutrino flavor mixing breaks isotropy in the early universe
Hansen, **Shalgar**, **Tamborra**, *JCAP* 2021

New Developments in Flavor Evolution of a Dense Neutrino Gas
Tamborra, **Shalgar**, *Ann. Rev. Nucl. Part. Sci.* 2021

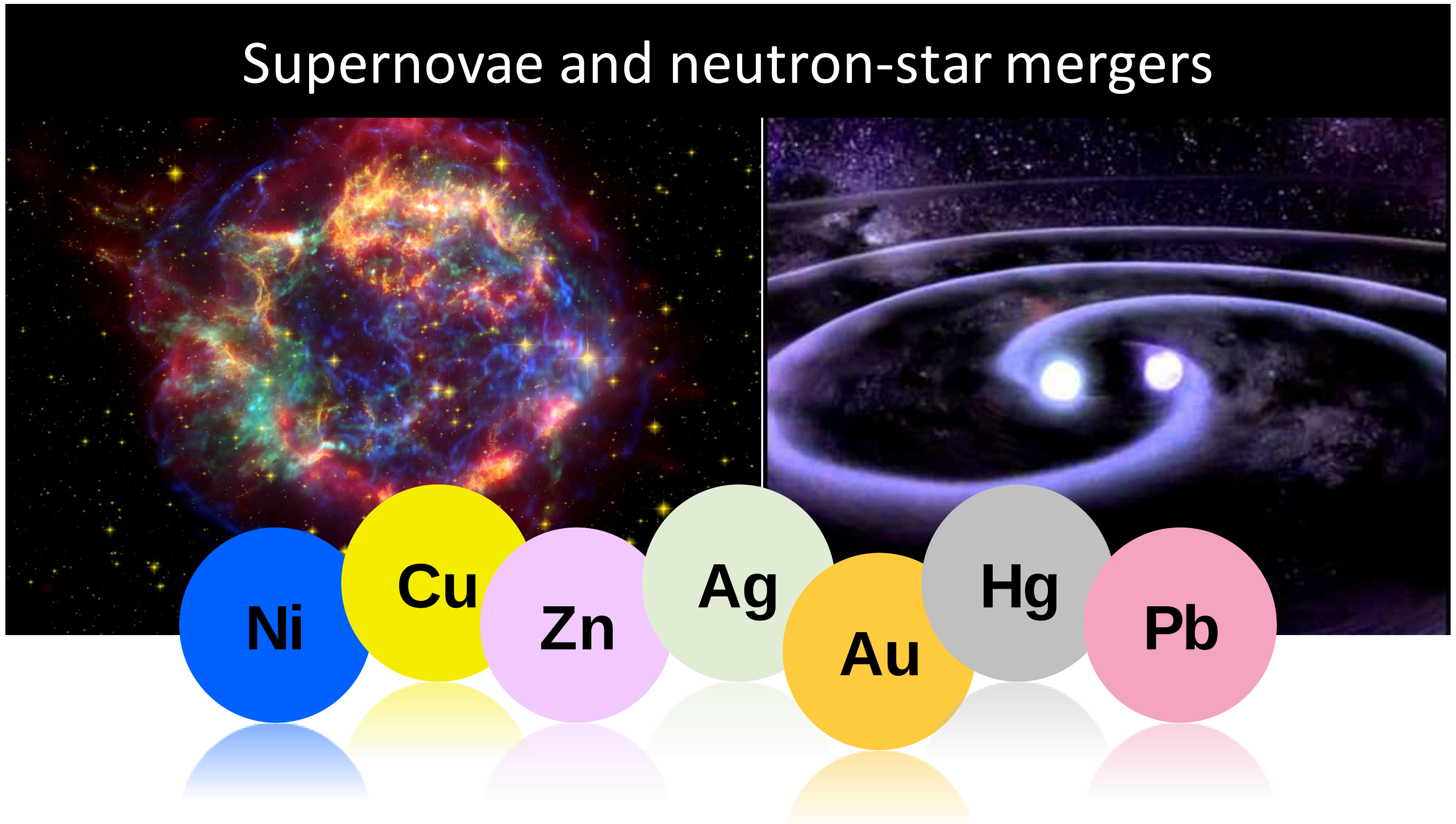
A change of direction in pairwise neutrino conversion physics: The effect of collisions
Shalgar, **Tamborra**, *PRD* 2021

Fast neutrino flavor conversion, ejecta properties, and nucleosynthesis in newly-formed hypermassive remnants of neutron-star mergers
George, Wu, **Tamborra**, Ardevol-Pulpillo, Janka, *PRD* 2020

Multi-Dimensional Solution of Fast Neutrino Conversions in Binary Neutron Star Merger Remnants
Padilla-Gay, **Shalgar**, **Tamborra**, *JCAP* 2021

Stellar Nucleosynthesis

Elements heavier than iron are born in supernovae and neutron-star mergers.



contact:
Tamborra

Synthesis of new elements could not happen without neutrinos.

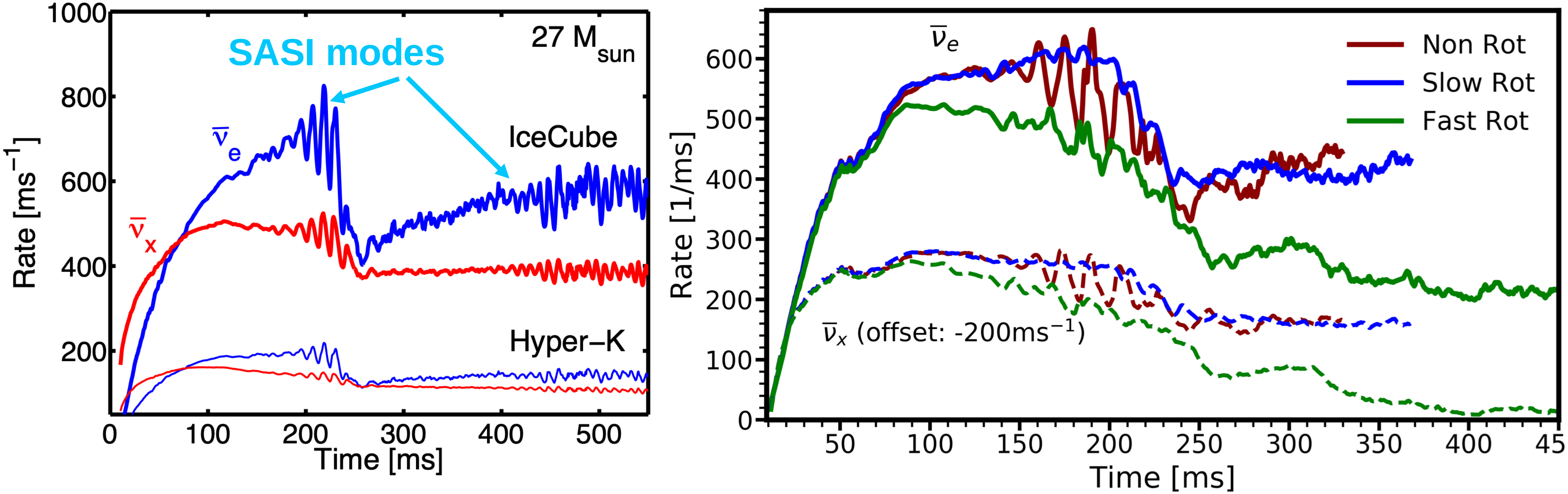
$$n + \nu_e \rightarrow e^- + p$$

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

Probe of Supernova Dynamics

contact: Tamborra

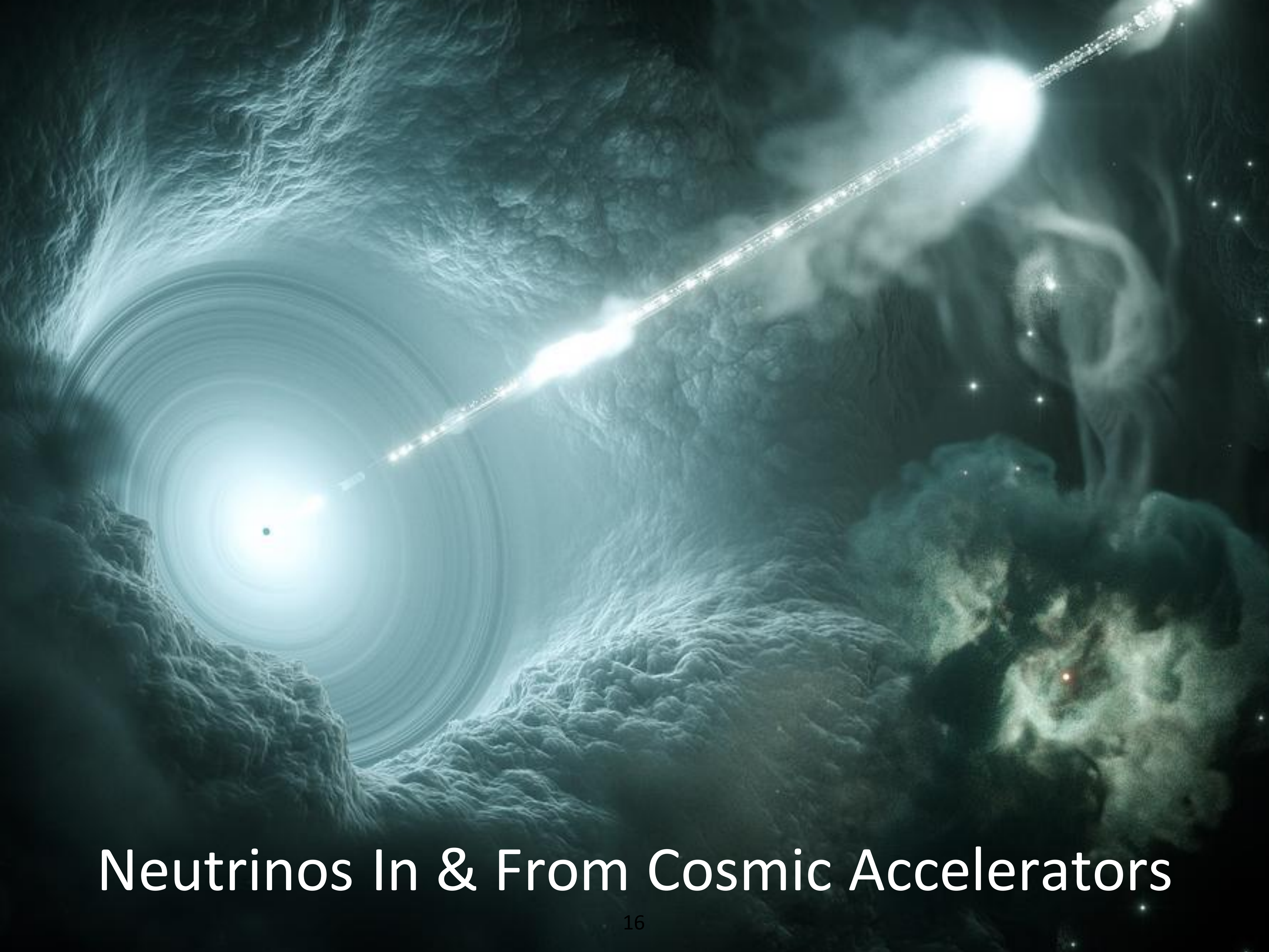
Predicted neutrino "lightcurves":



[Tamborra et al., **PRD** 90, 123001 (2014) & **PRD** 98, 123001(2018)]

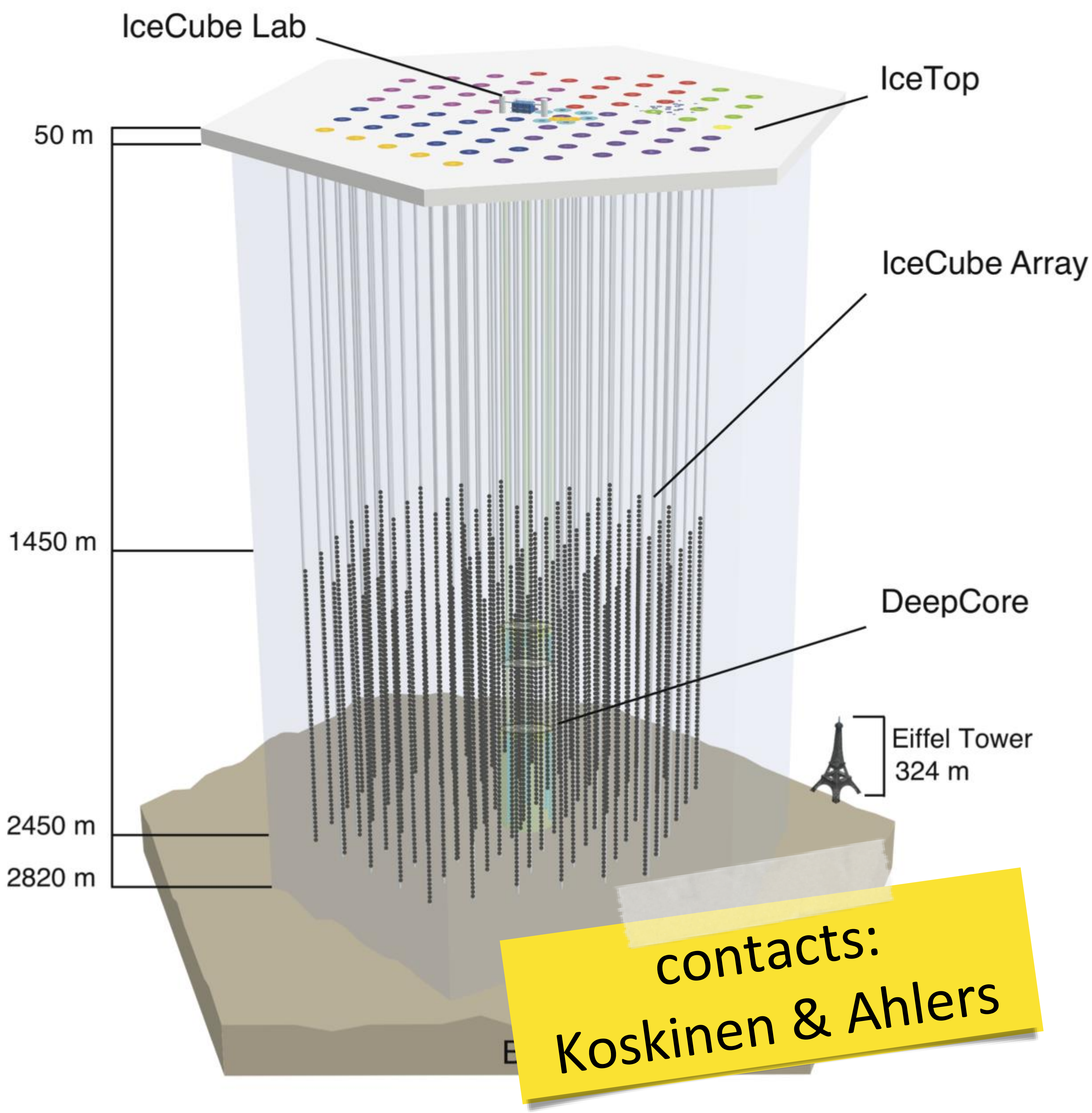
Neutrinos **probe explosion mechanism of a supernova and its rotation.**

Complementary information from detection of gravitational waves.



Neutrinos In & From Cosmic Accelerators

IceCube Observatory

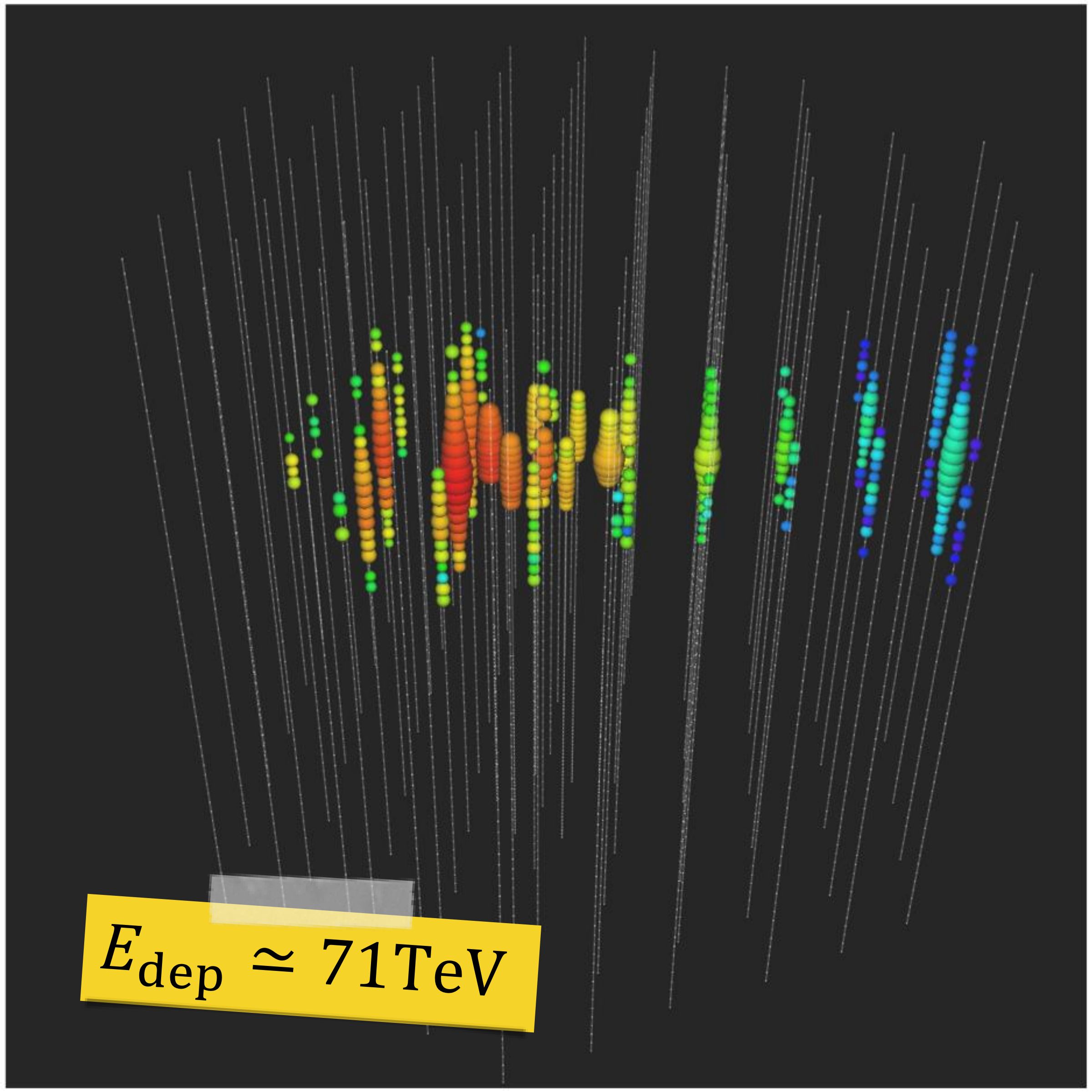


- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- price tag: ~**2 DKK per ton**

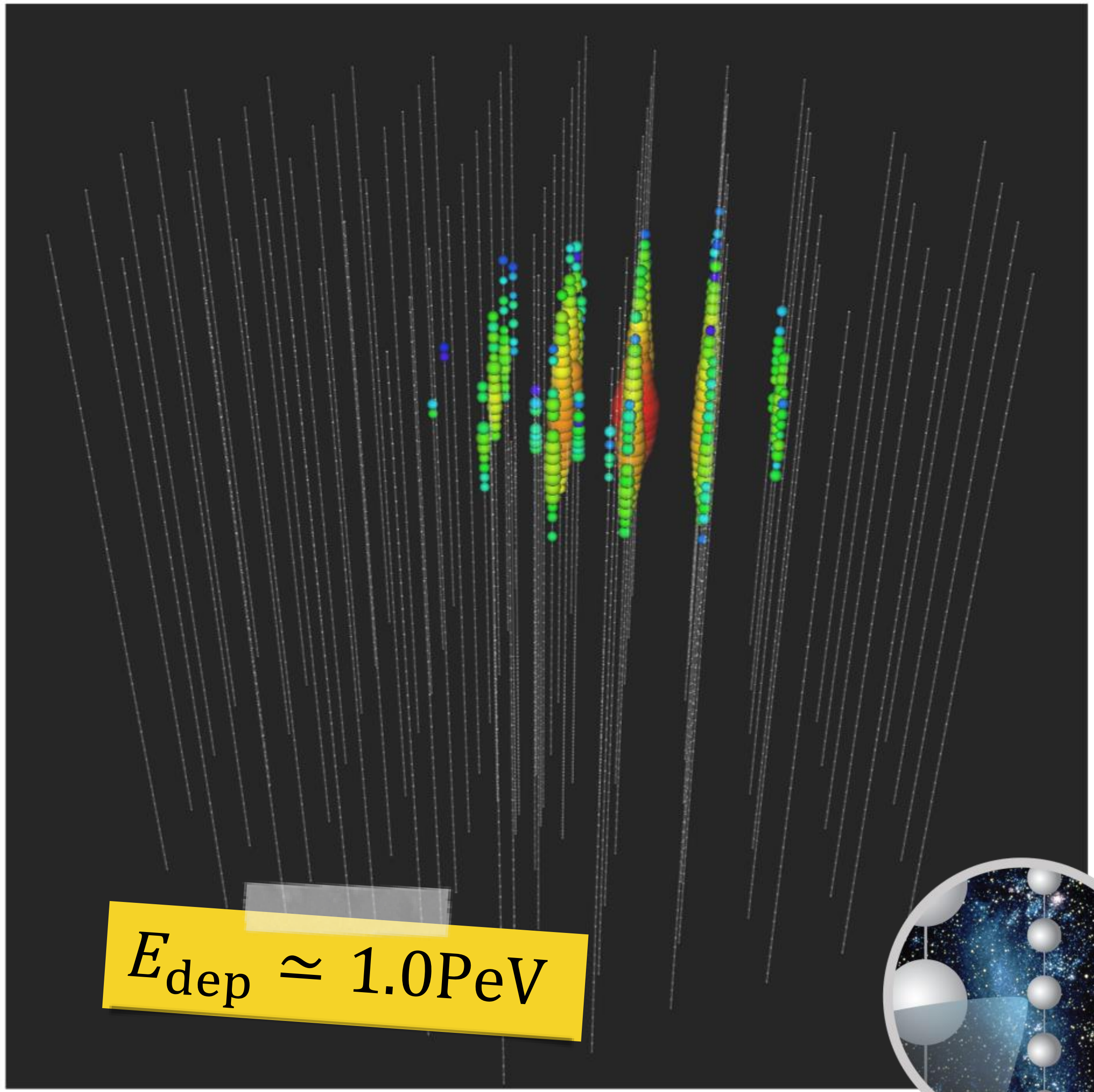
Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube in 2013.

"track event" (*e.g.* ν_μ CC interactions)



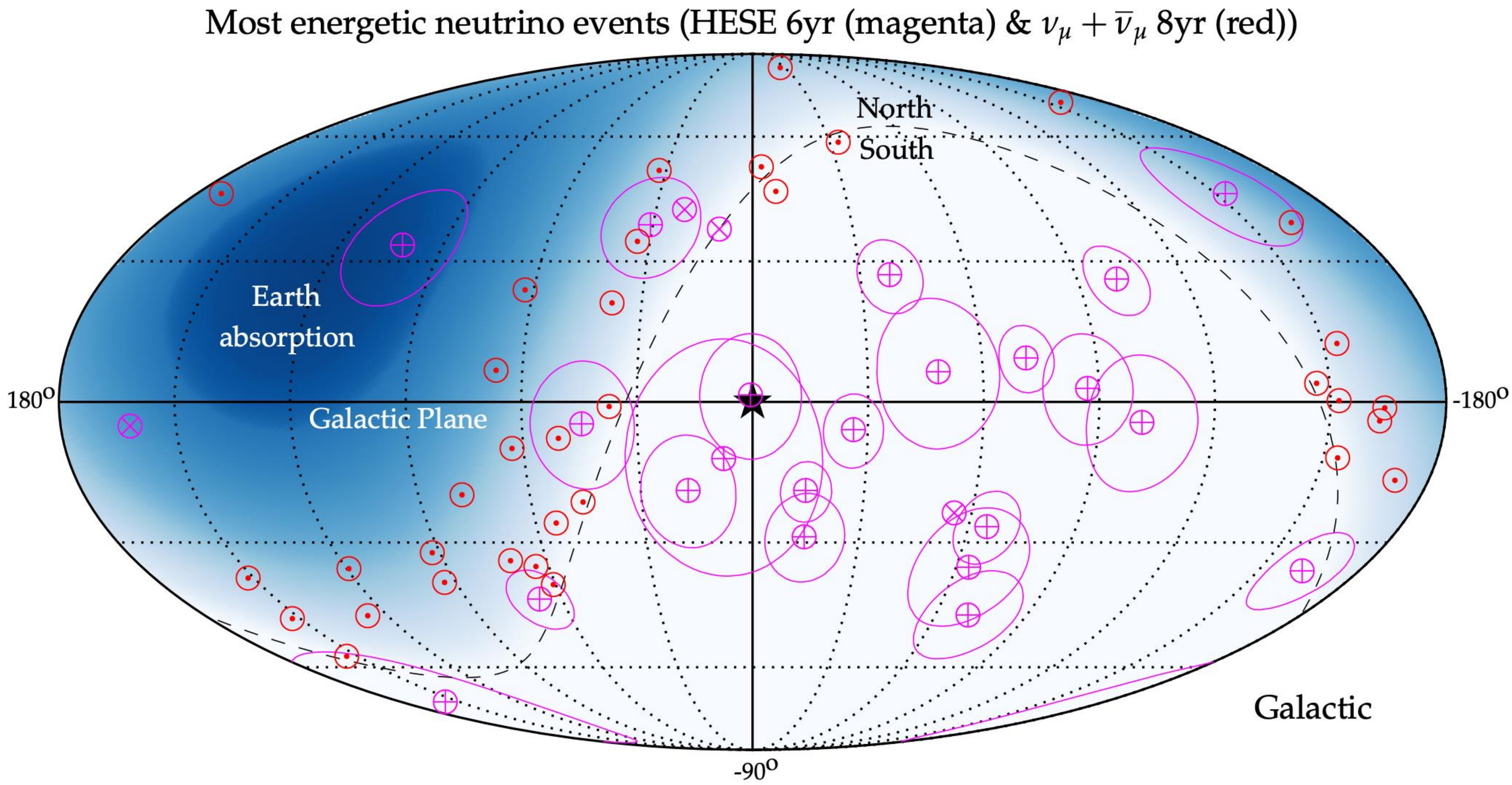
"cascade event" (*e.g.* NC interactions)



(colors indicate arrival time of Cherenkov photons from **early** to **late**)

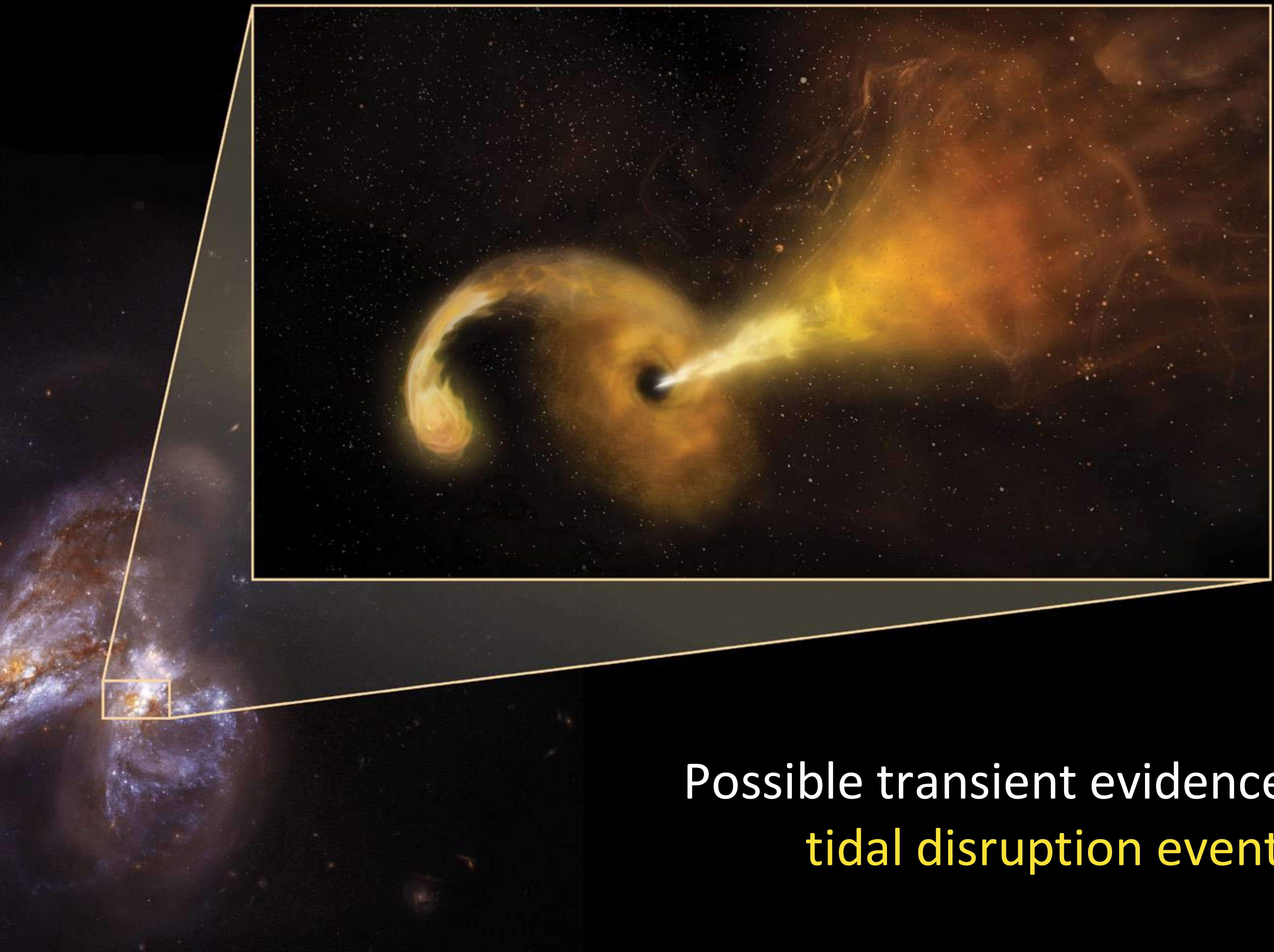
ICECUBE

Status of Neutrino Astronomy

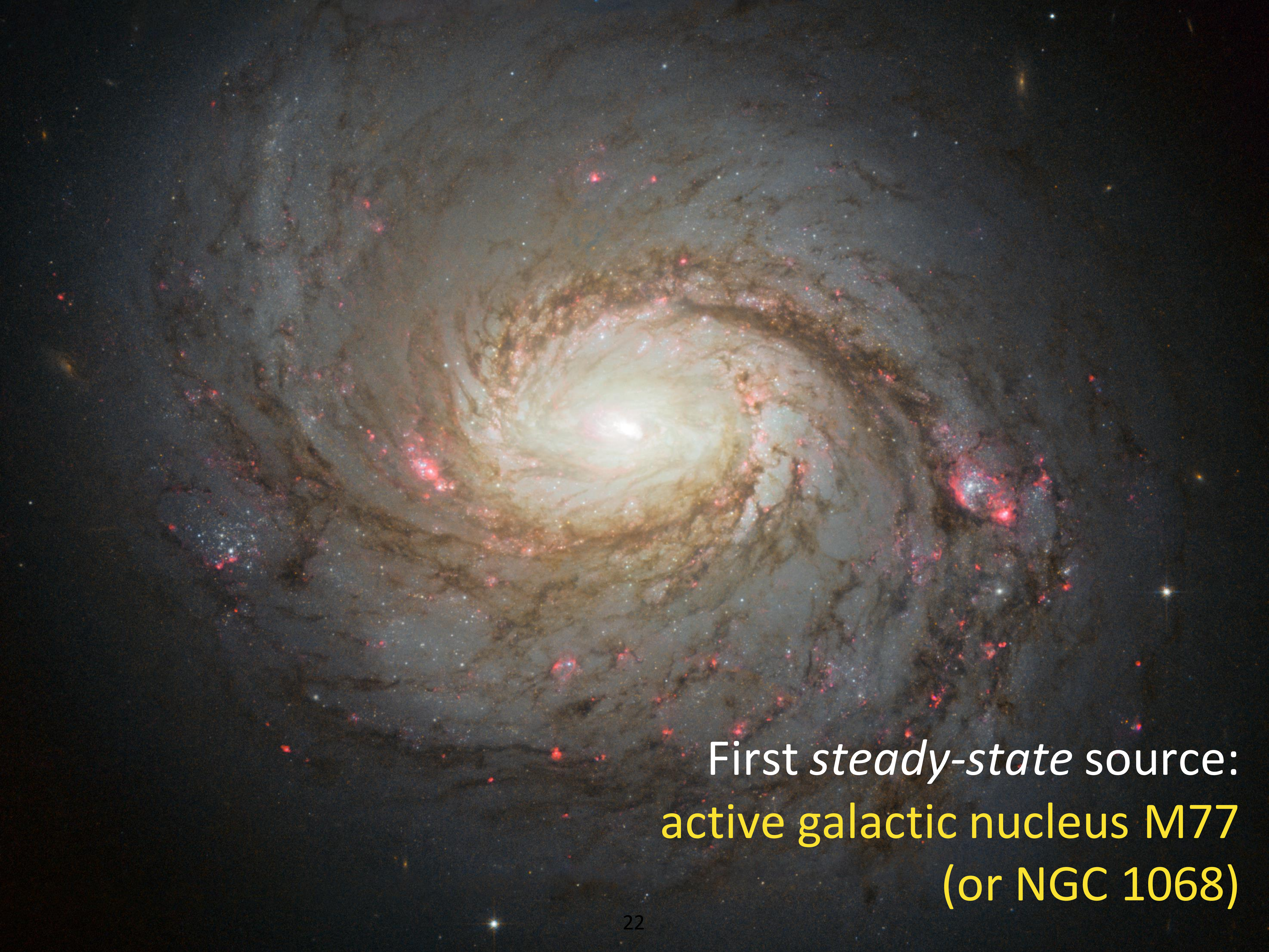


No significant steady or transient emission from known Galactic and extragalactic high-energy sources (*except for one candidate*).

First *transient* source of high-energy neutrinos (2017):
blazar TXS 0506+056



Possible transient evidence:
tidal disruption events

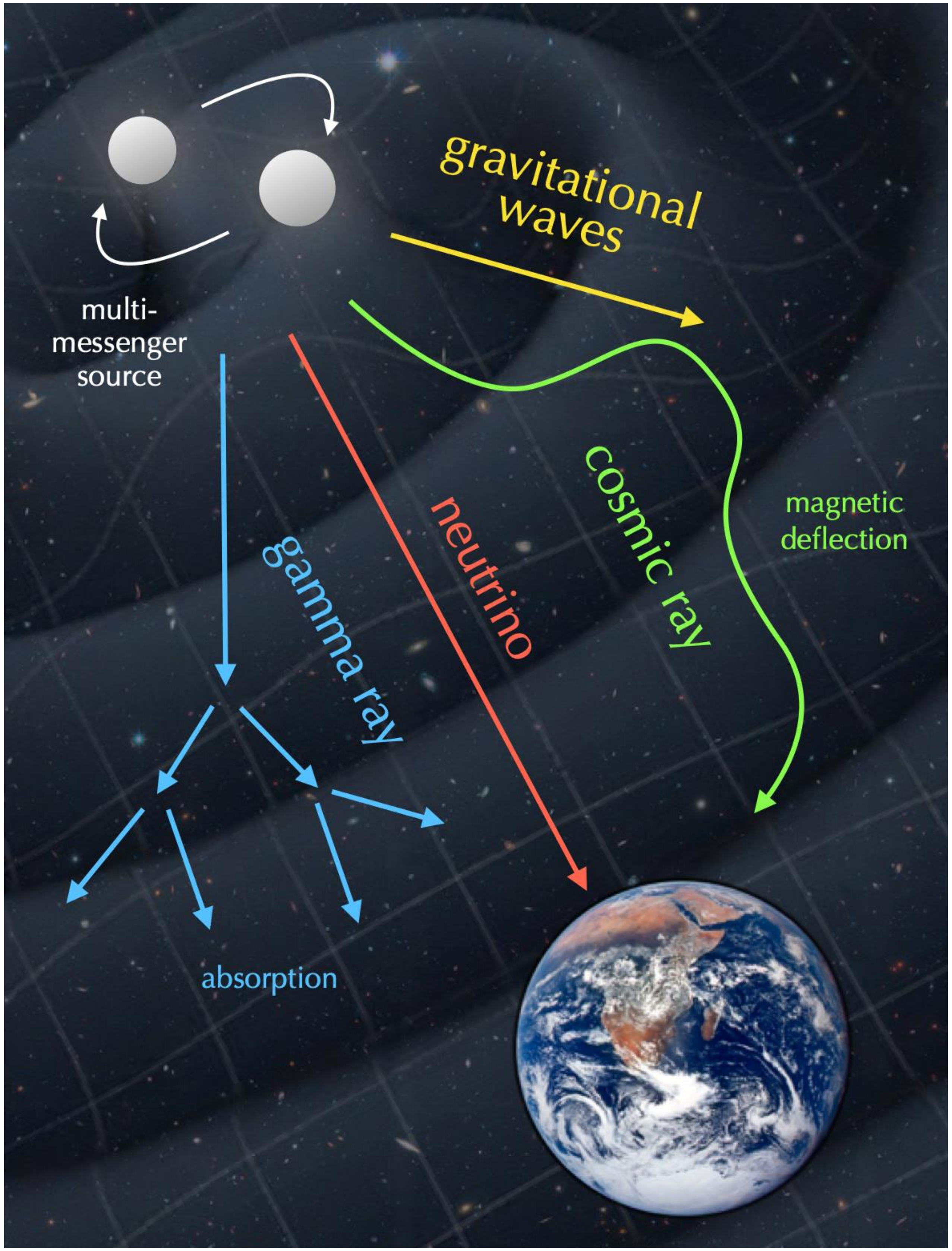


First *steady-state* source:

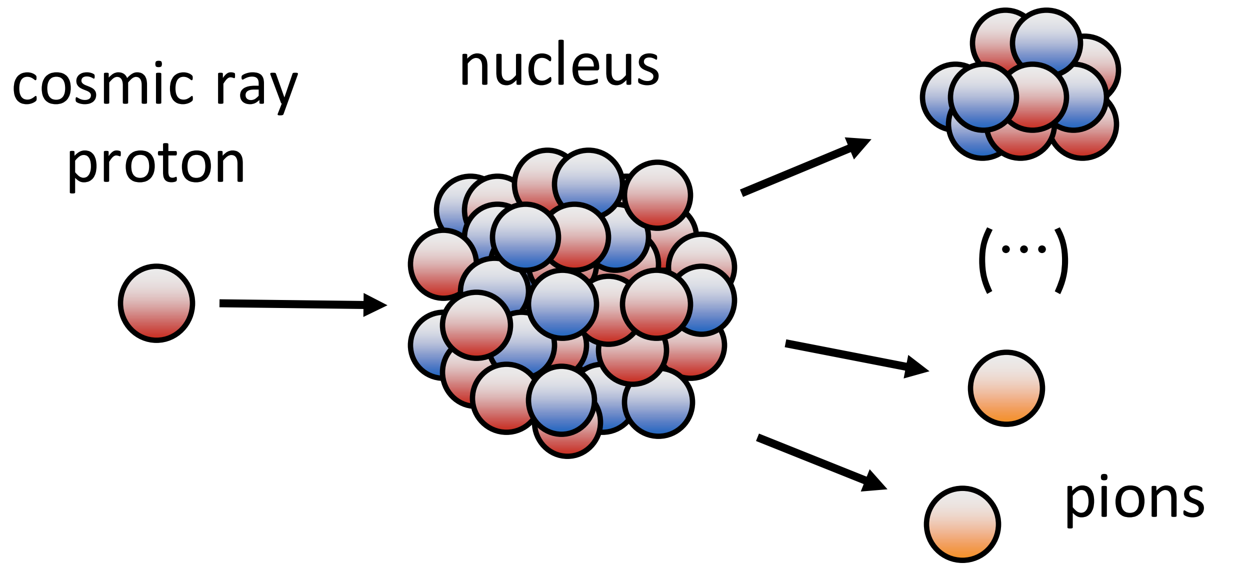
active galactic nucleus M77

(or NGC 1068)

Multi-Messenger Astronomy



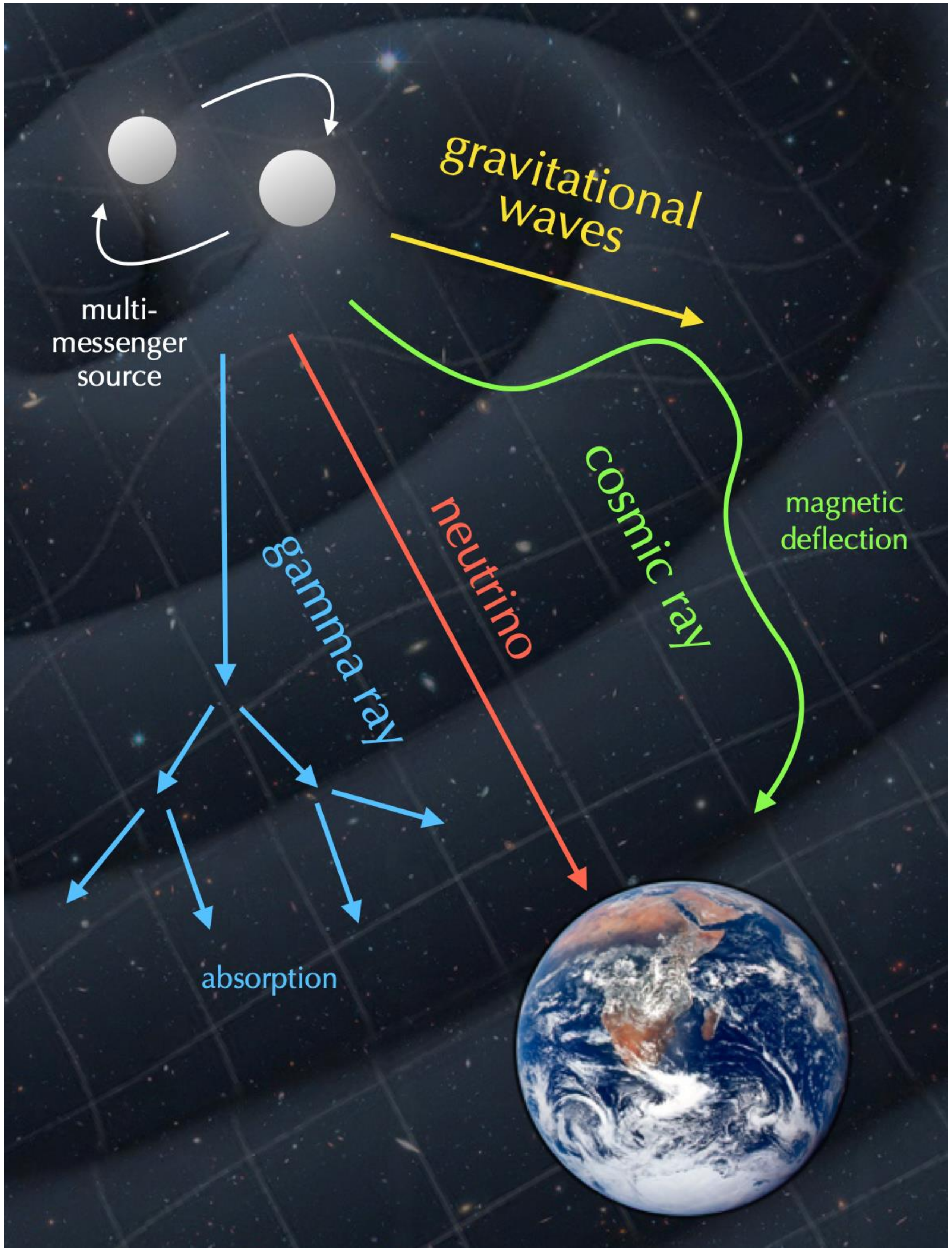
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.



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

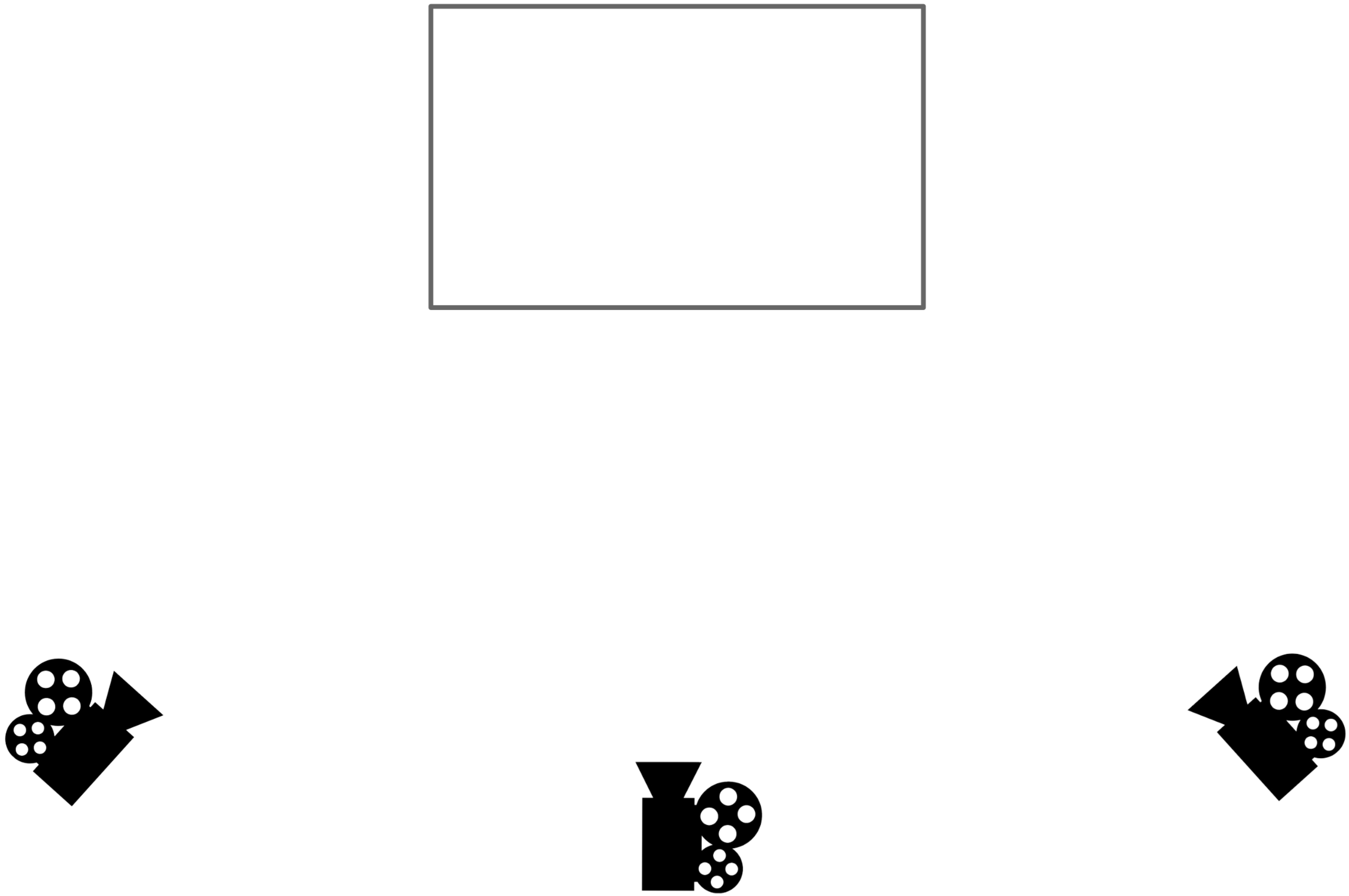


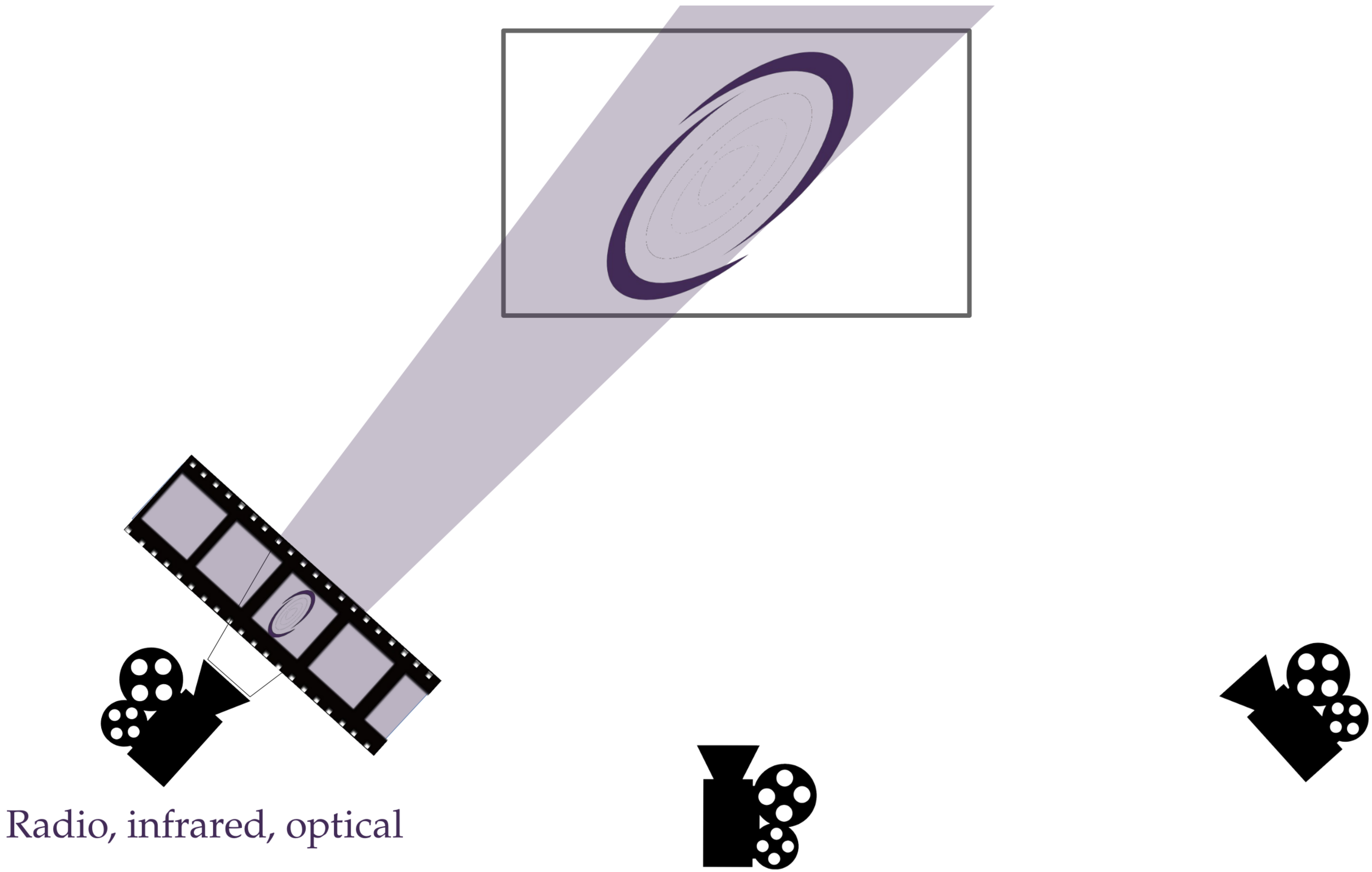
What are the sources and mechanisms that are responsible for energetic cosmic messengers?

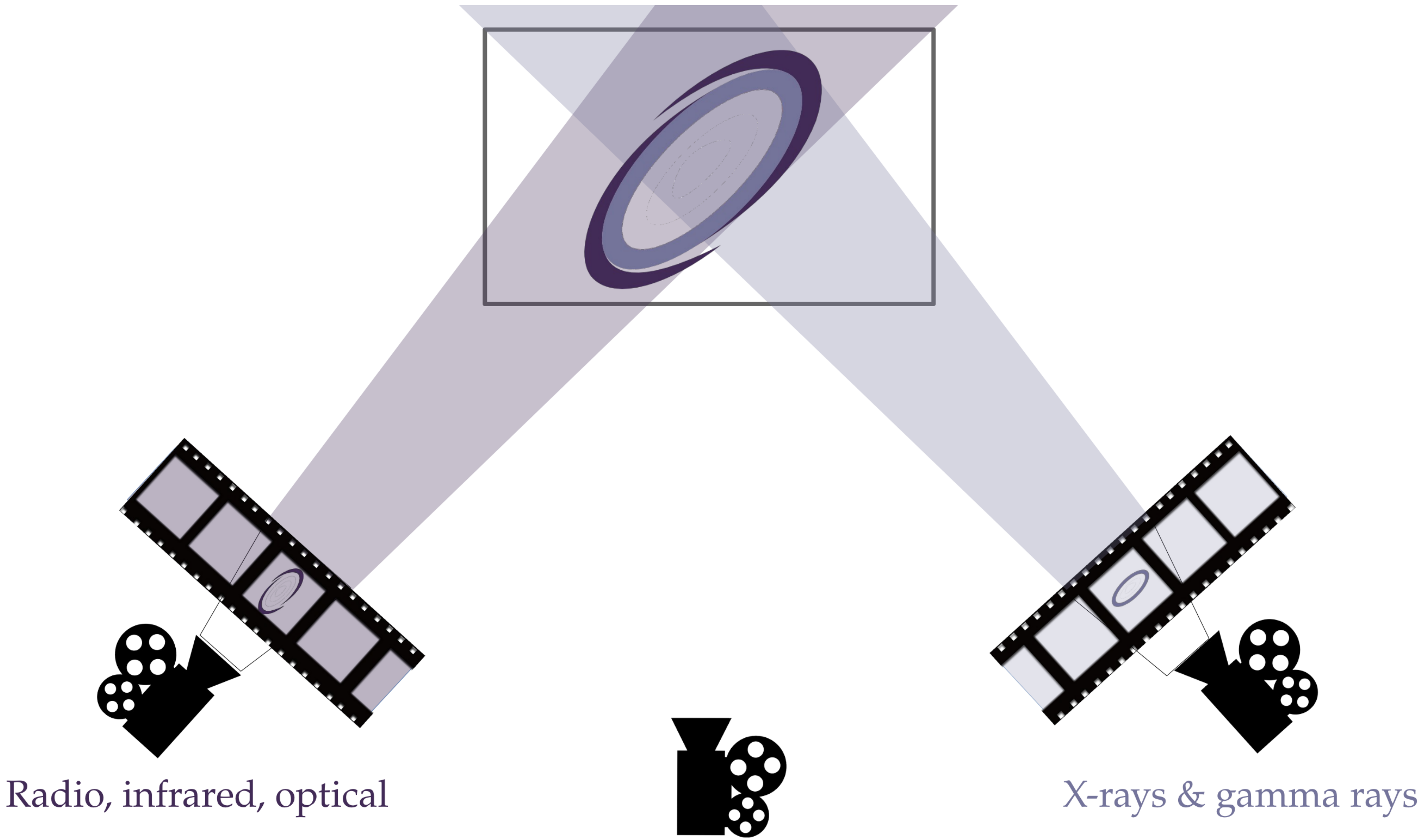
How do energetic messengers probe their environment on astrophysical and cosmic scales?

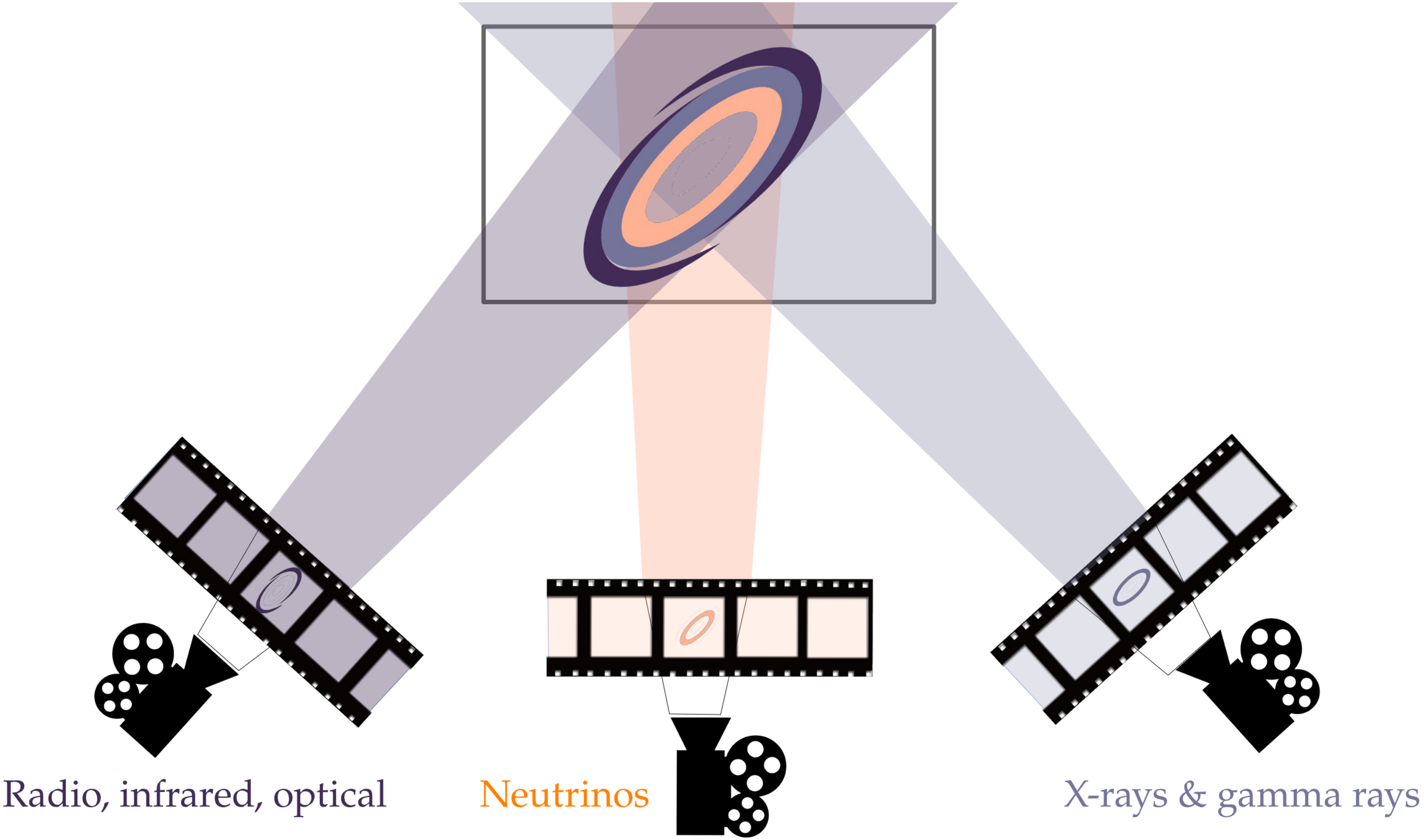
What are the best strategies for the observation and analysis of multi-messenger data?

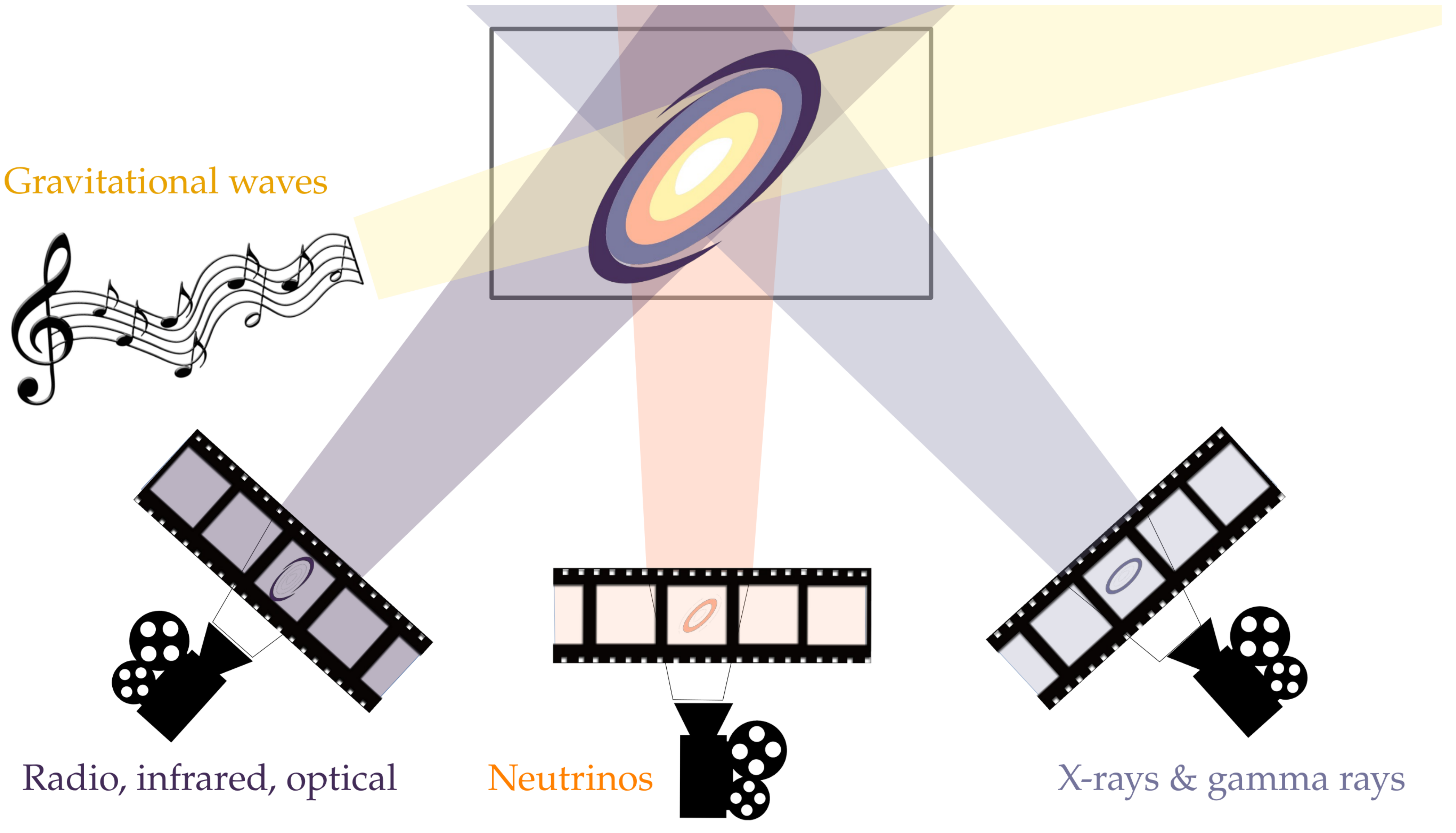
What new can we learn about fundamental particle physics and cosmology?



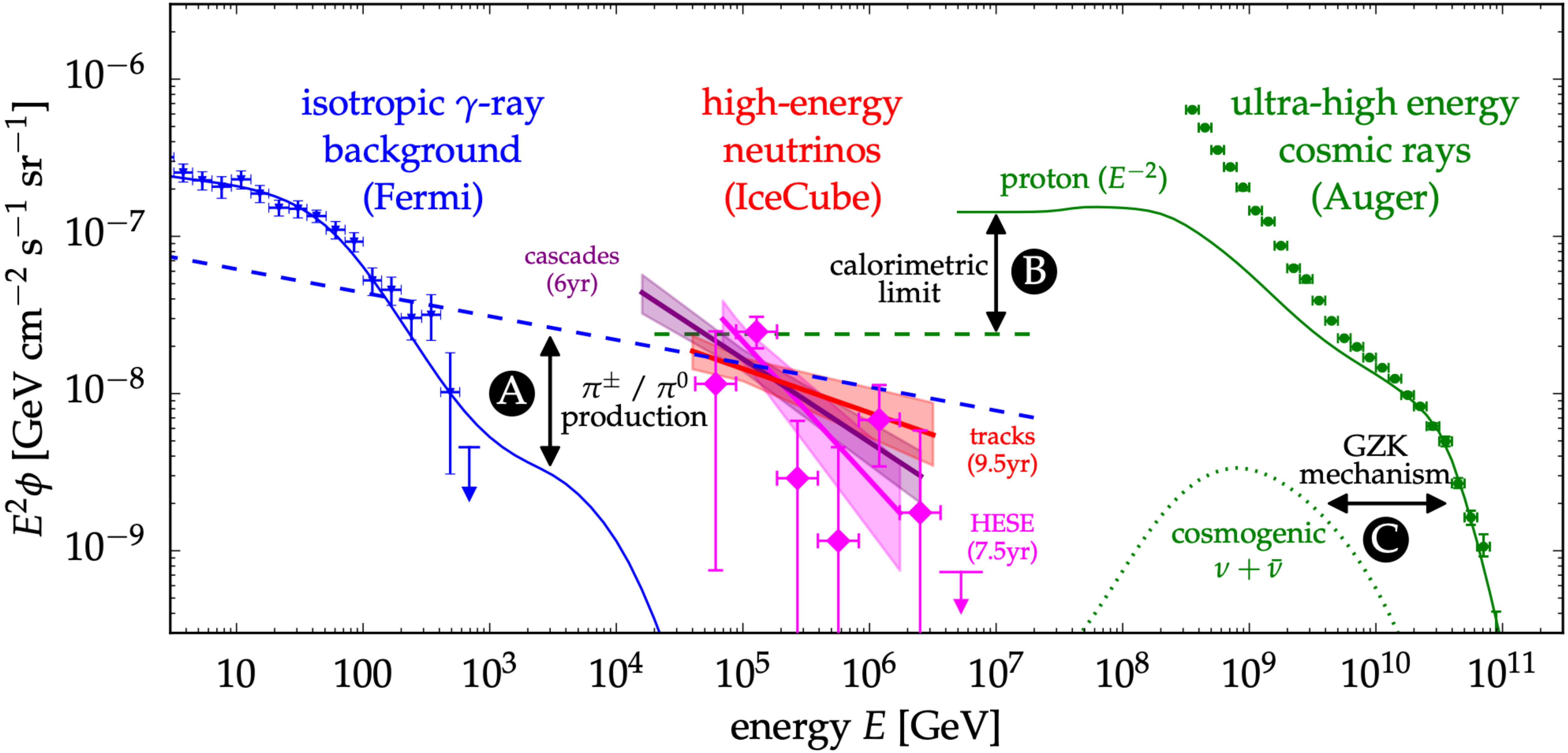

Radio, infrared, optical


Radio, infrared, optical
X-rays & gamma rays


Radio, infrared, optical
Neutrinos
X-rays & gamma rays


Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

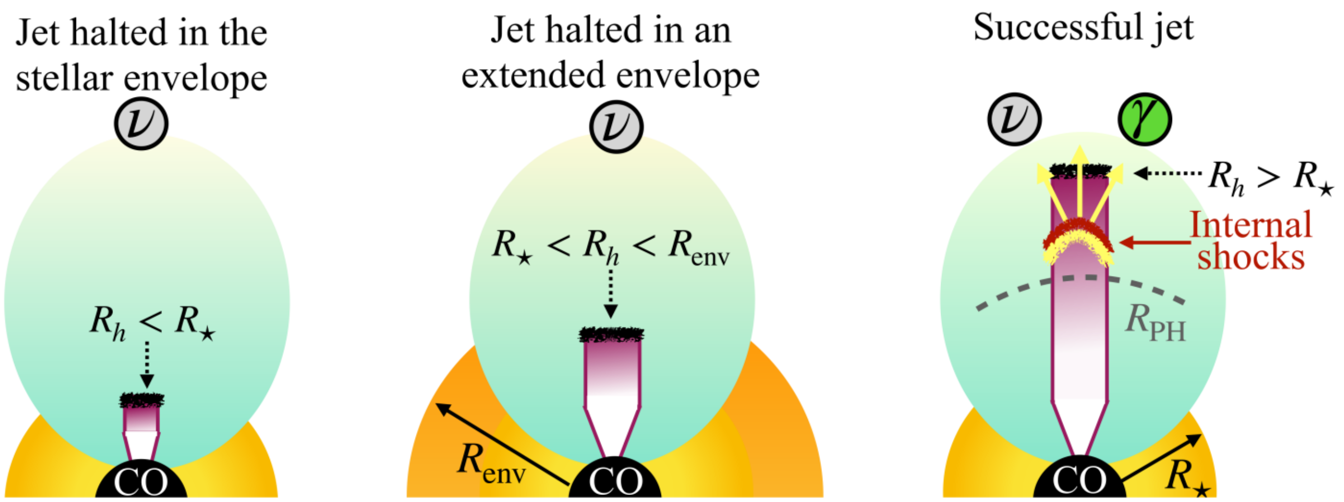
Multi-Messenger Interfaces

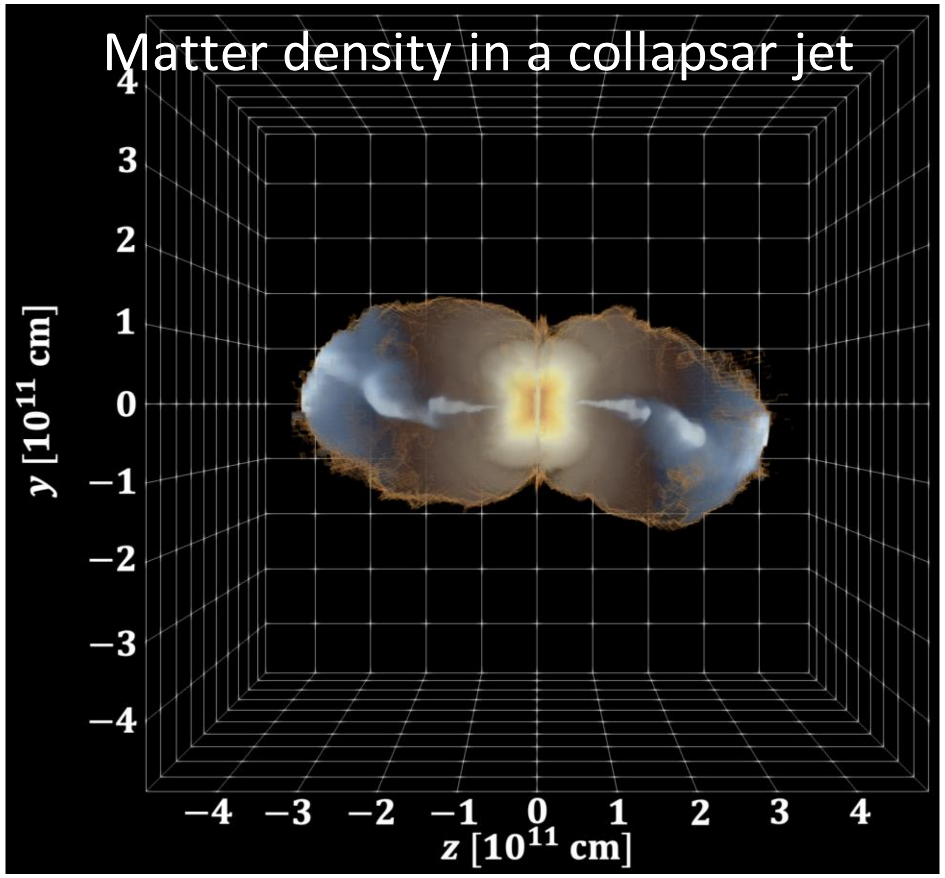


The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

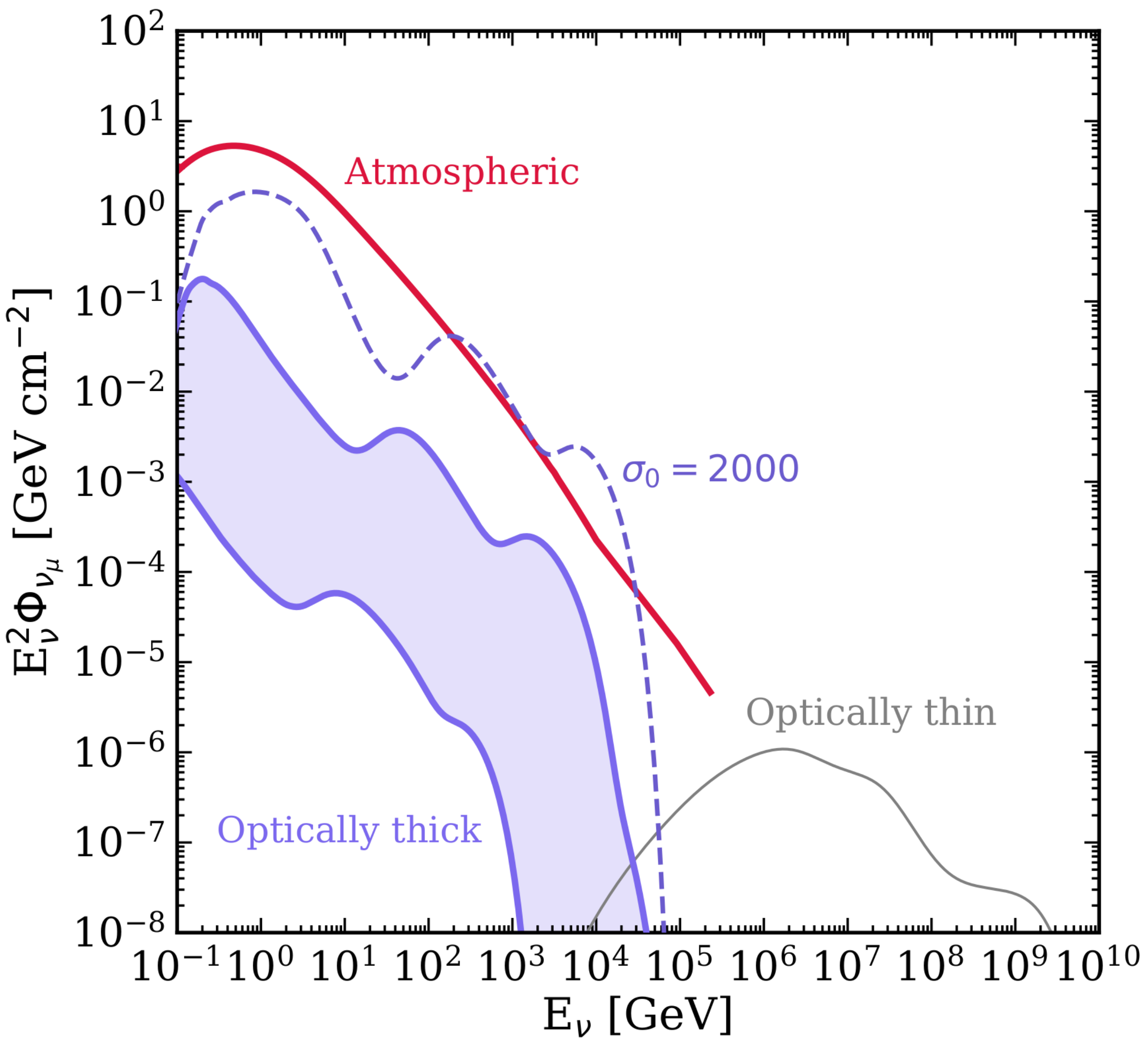
Sophisticated source modeling

Conditions at the sources (*e.g.*, density) determine whether neutrinos or neutrinos + gamma-rays are emitted





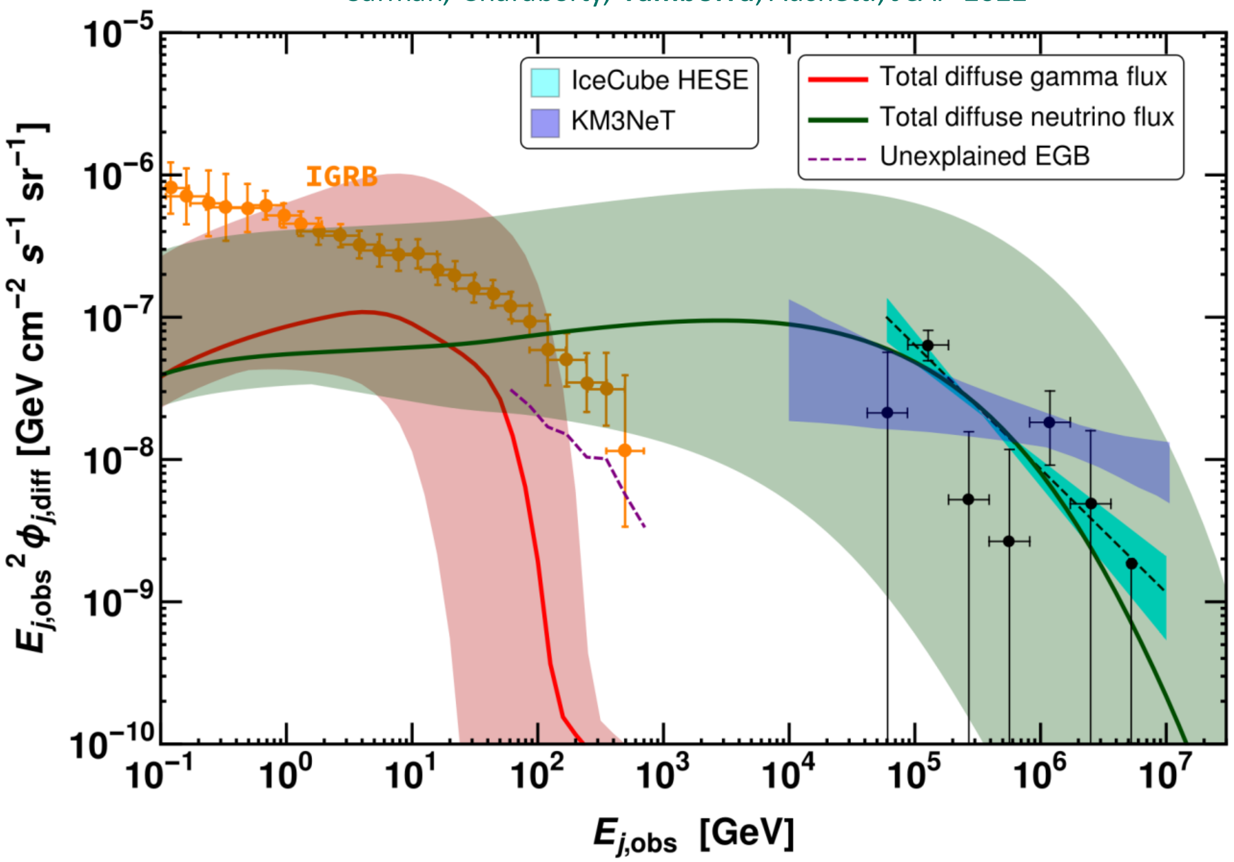
Guarini, Tamborra, Gottlieb, *PRD* 2022



Sophisticated source modeling

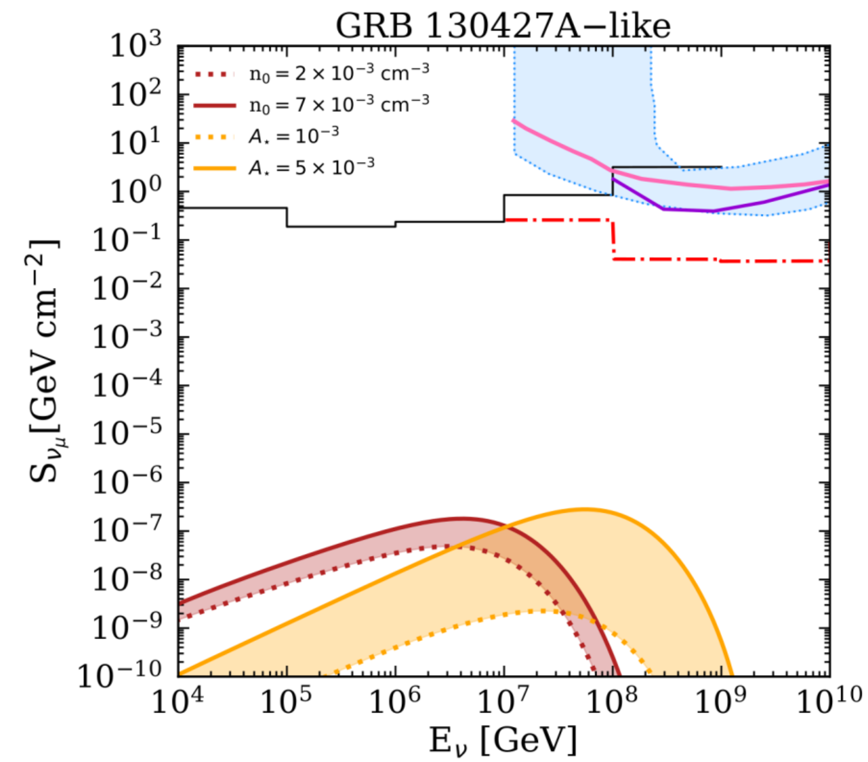
Young supernovae

Sarmah, Charaborty, **Tamborra**, Auchettl, *JCAP* 2022



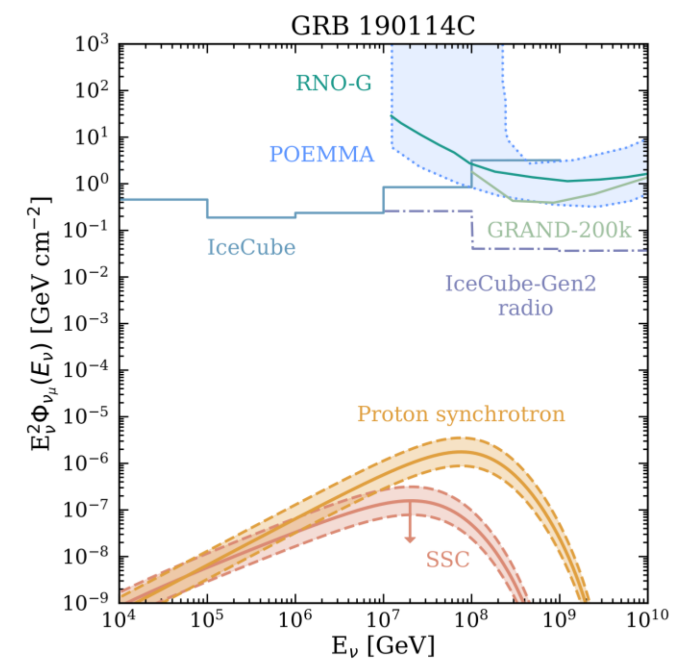
Gamma-ray-burst afterglows

Guarini, **Tamborra**, Bégué, **Pitik**, Greiner, *JCAP* 2022



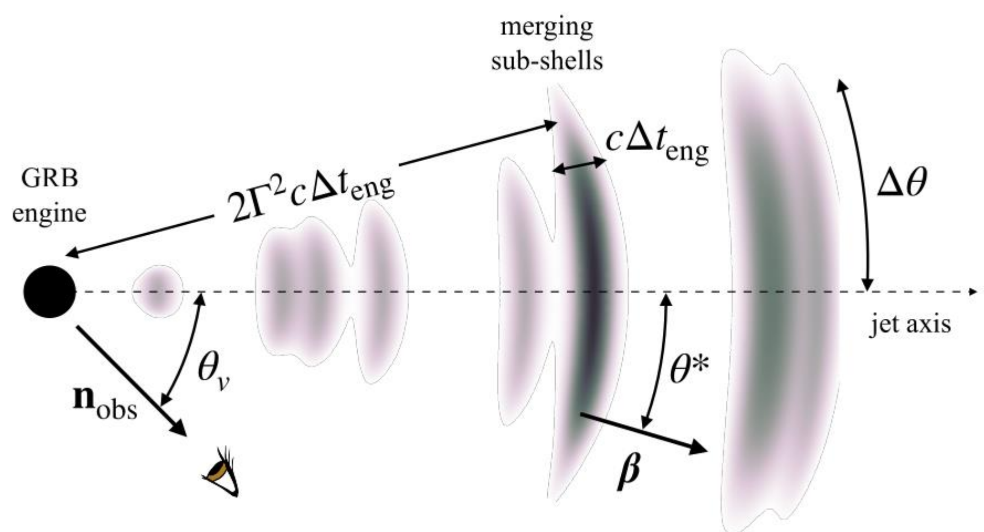
Very-high-energy GRBs

Guarini, **Tamborra**, Bégué, **Pitik**, **Rudolph**, 2301.10256



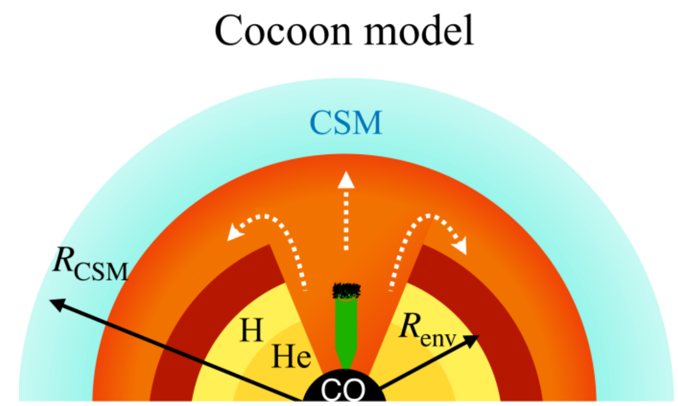
Structured GRB jets

Ahlers & Halser, *MNRAS* 2019



Luminous Fast Blue Optical Transients

Guarini, **Tamborra**, Margutti, *ApJ* 2022



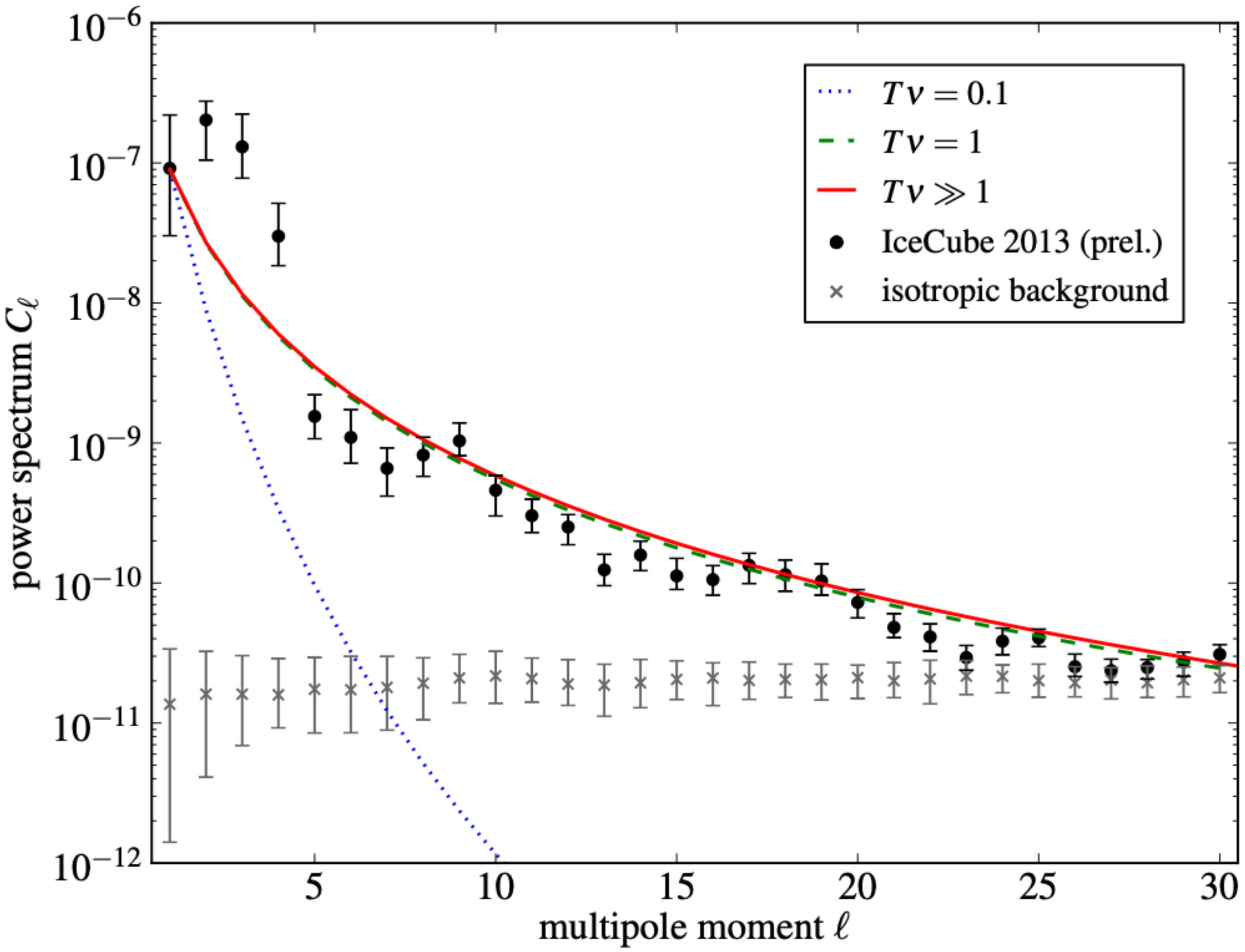
Cosmic Ray Anisotropy

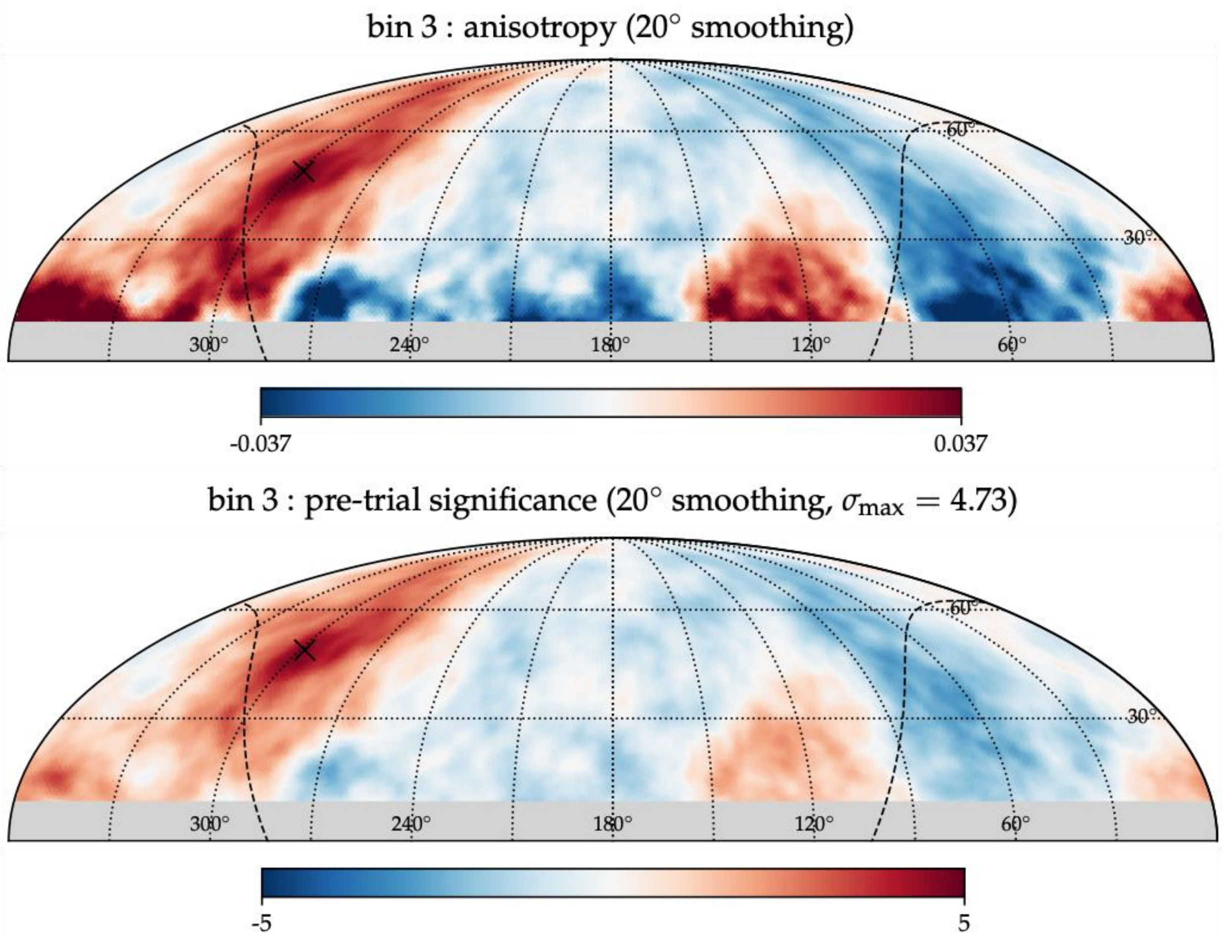
“Deciphering the Dipole Anisotropy of Galactic Cosmic Rays”

[**Ahlers,** *PRL* 2016]

“Anomalous Anisotropies of Cosmic Rays from Turbulent Magnetic Fields”

[**Ahlers,** *PRL* 2014]





“Large- and Medium-Scale Anisotropies in the Arrival Directions of Cosmic Rays observed with KASCADE-Grande”

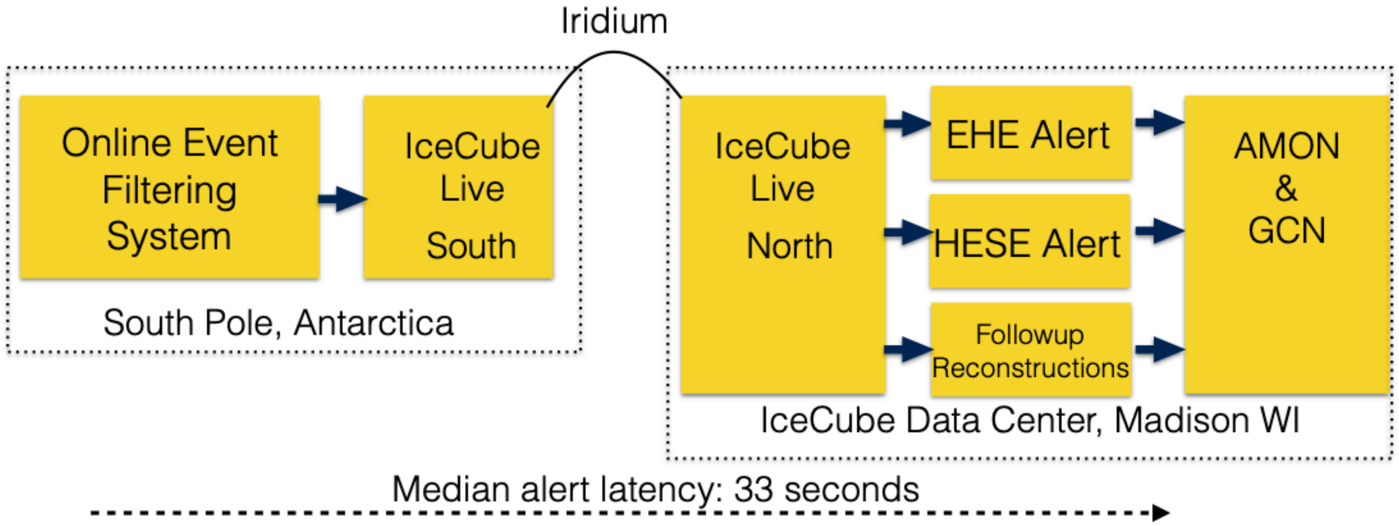
[**Ahlers,** *ApJL* 2019]

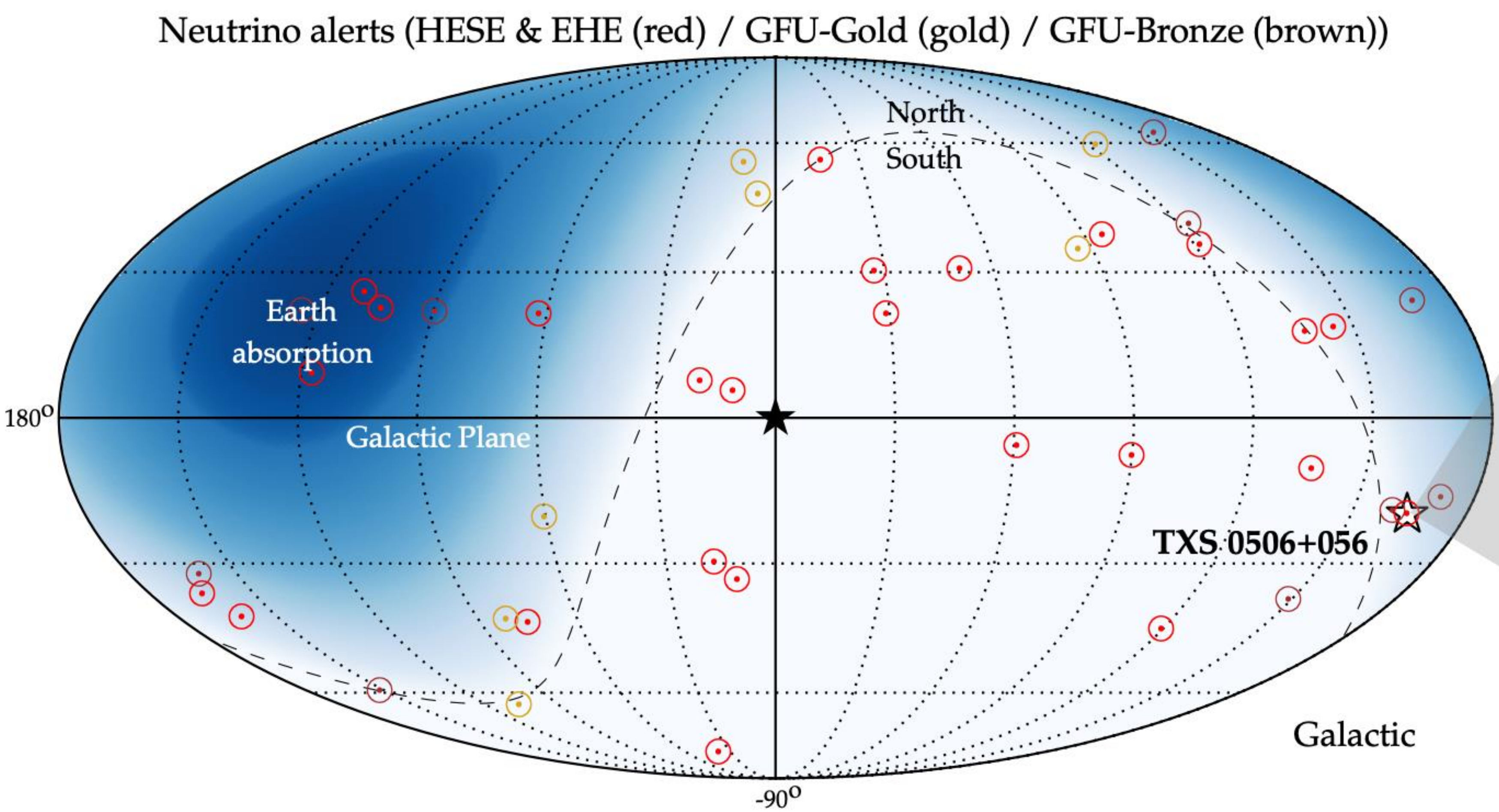
“Searching for All-Scale Anisotropies in the Arrival Directions of CRs above the Ankle”

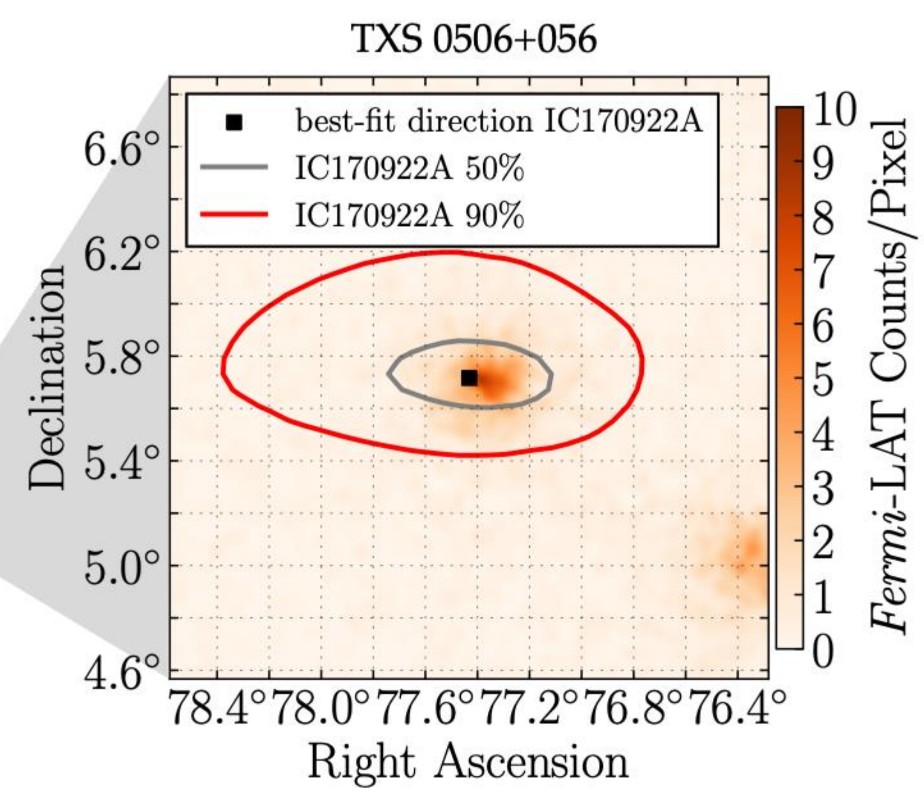
[**Ahlers,** *ApJ* 2018]

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

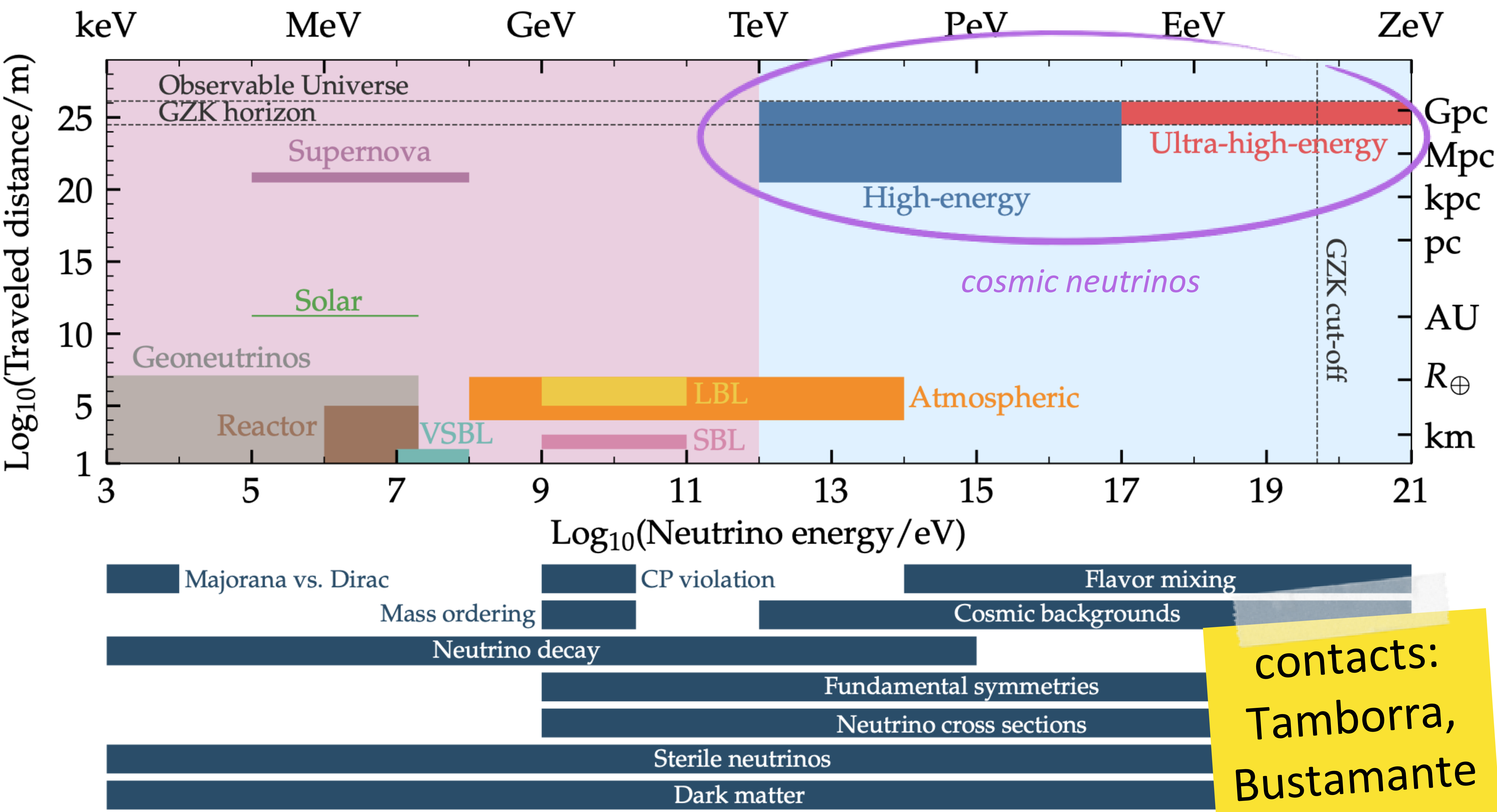
- **Gold alerts:** ~10 per year >50% signalness
- **Bronze alerts:** ~20 per year 30-50% signalness







Probe of Fundamental Physics



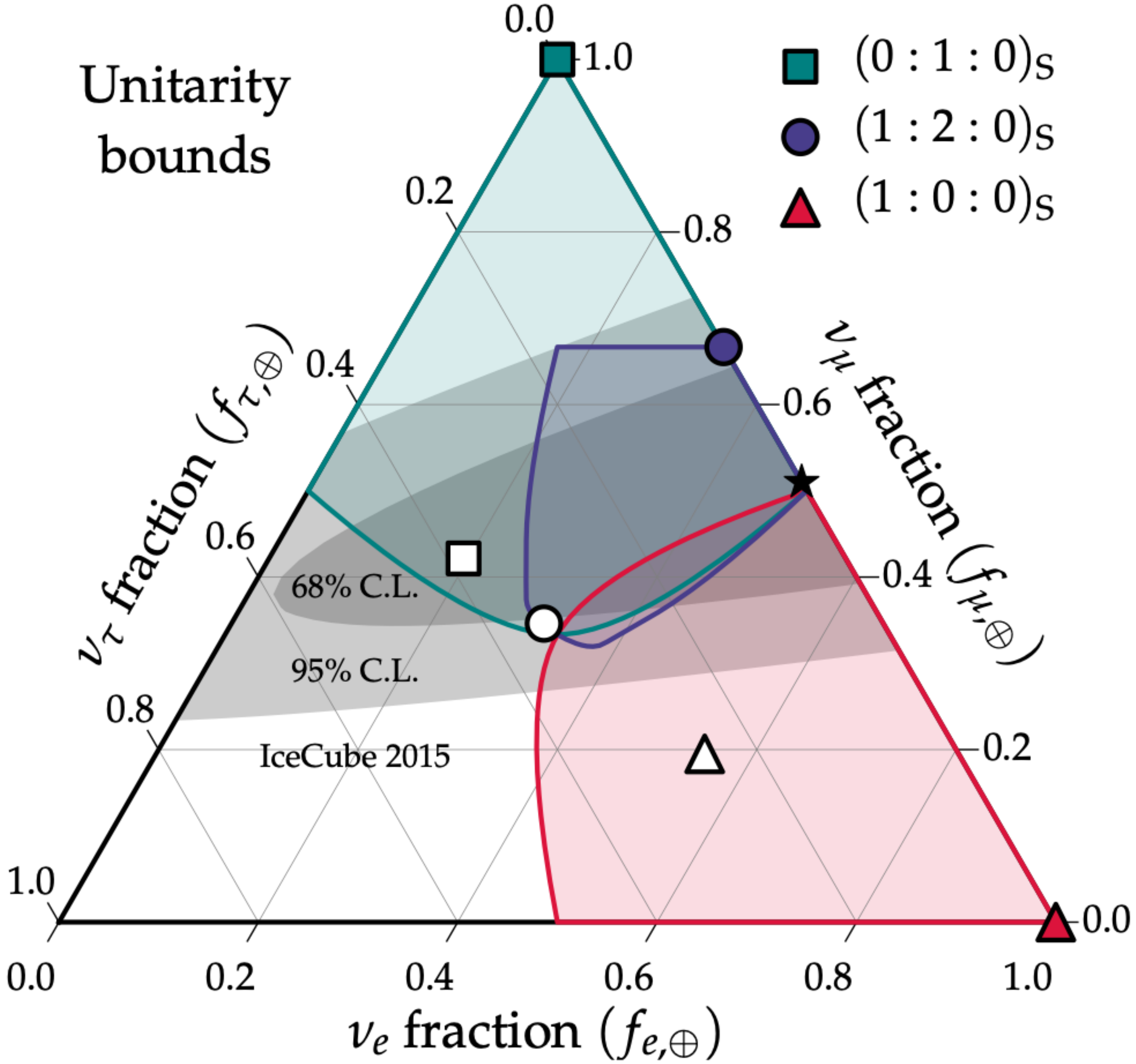
contacts: Tamborra, Bustamante & Ahlers

[Ackermann, **Ahlers**, Anchordoqui, **Bustamante** *et al., Bull. Am. Astron. Soc.* 2019]
[Ackermann, **Bustamante** *et al.*, JHEAp 2022]
[Argüelles, **Bustamante**, Kheirandish, Palomares-Ruiz, Salvadó, *PoS ICRC* 2020]
[**Ahlers**, Helbing, De los Heros, *Eur. Phys. J. C* 2018]

Flavor is a powerful probe...

... of fundamental physics

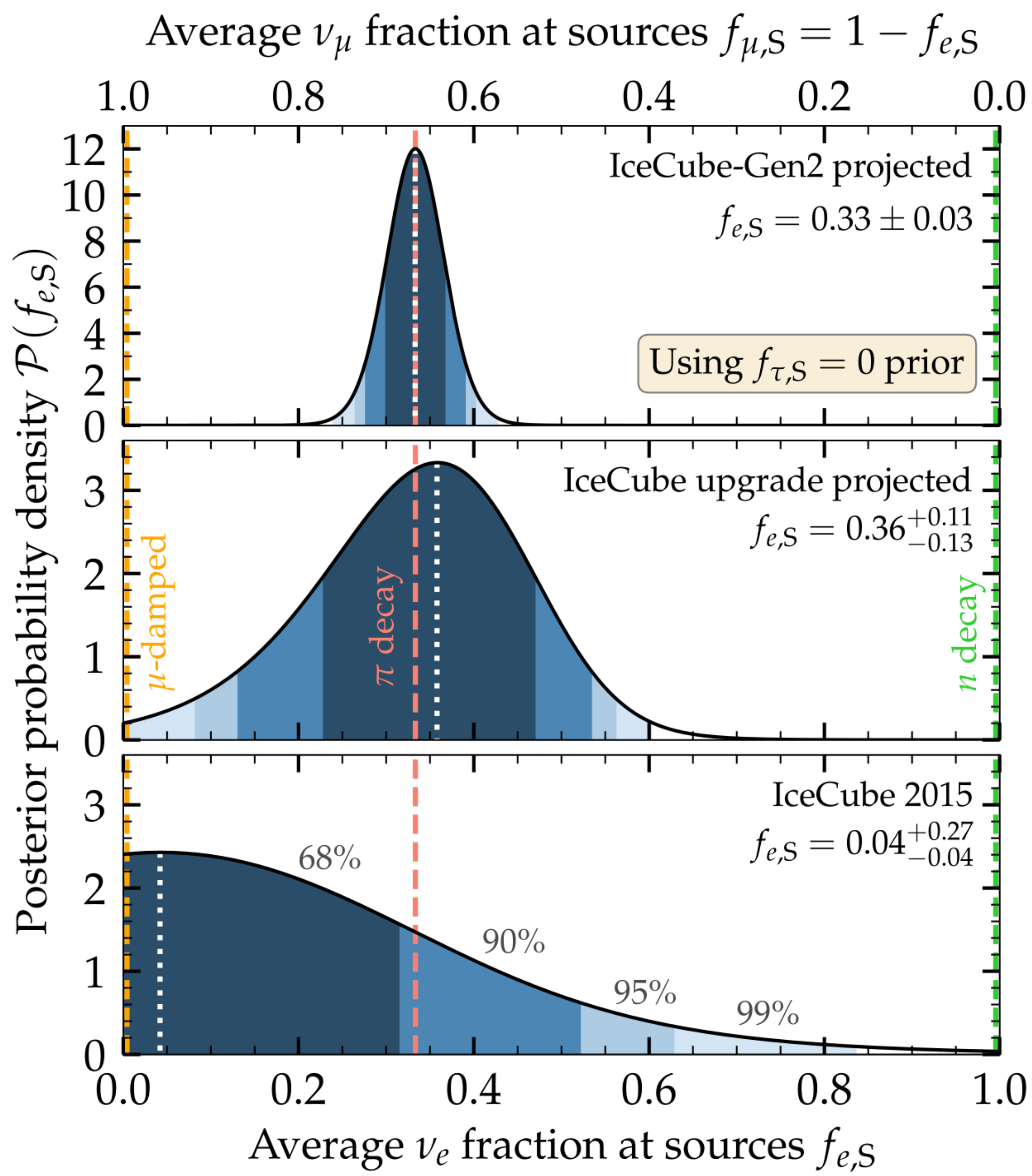
(*e.g.*, non-unitary neutrino mixing, Lorentz-violating extensions of the Standard Model)



[**Ahlers**, **Bustamante** & Mu, *PRD* 2018]
[**Bustamante** & Agarwalla, *PRL* 2019]
[**Ahlers**, **Bustamante** & Willesen, *JCAP 2021*]

... of astrophysics

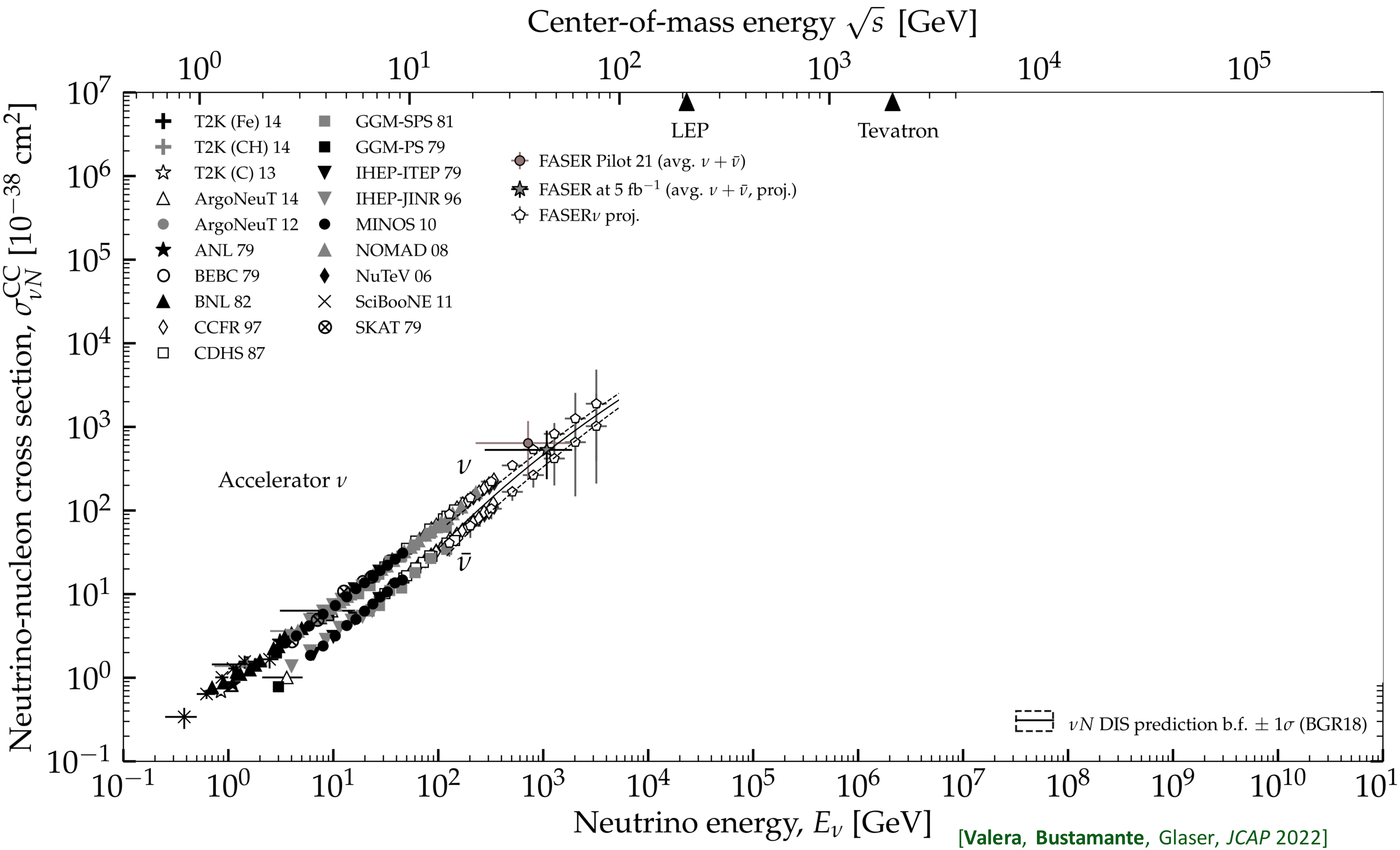
(*e.g.*, inferring the neutrino production mechanism at the sources)



[**Bustamante** & **Ahlers**, *PRL* 2019]
[**Bustamante** & **Tamborra**, *PRD* 2020]
[Song, Li, Argüelles, **Bustamante**, Vincent, *JCAP* 2021]

[Ackermann, **Ahlers**, Anchordoqui, **Bustamante** *et al., Bull. Am. Astron. Soc.* 2019]
[Ackermann, **Bustamante** *et al.*, JHEAp 2022]
[Argüelles, **Bustamante**, Kheirandish, Palomares-Ruiz, Salvadó, *PoS ICRC* 2020]
[**Ahlers**, Helbing, De los Heros, *Eur. Phys. J. C* 2018]

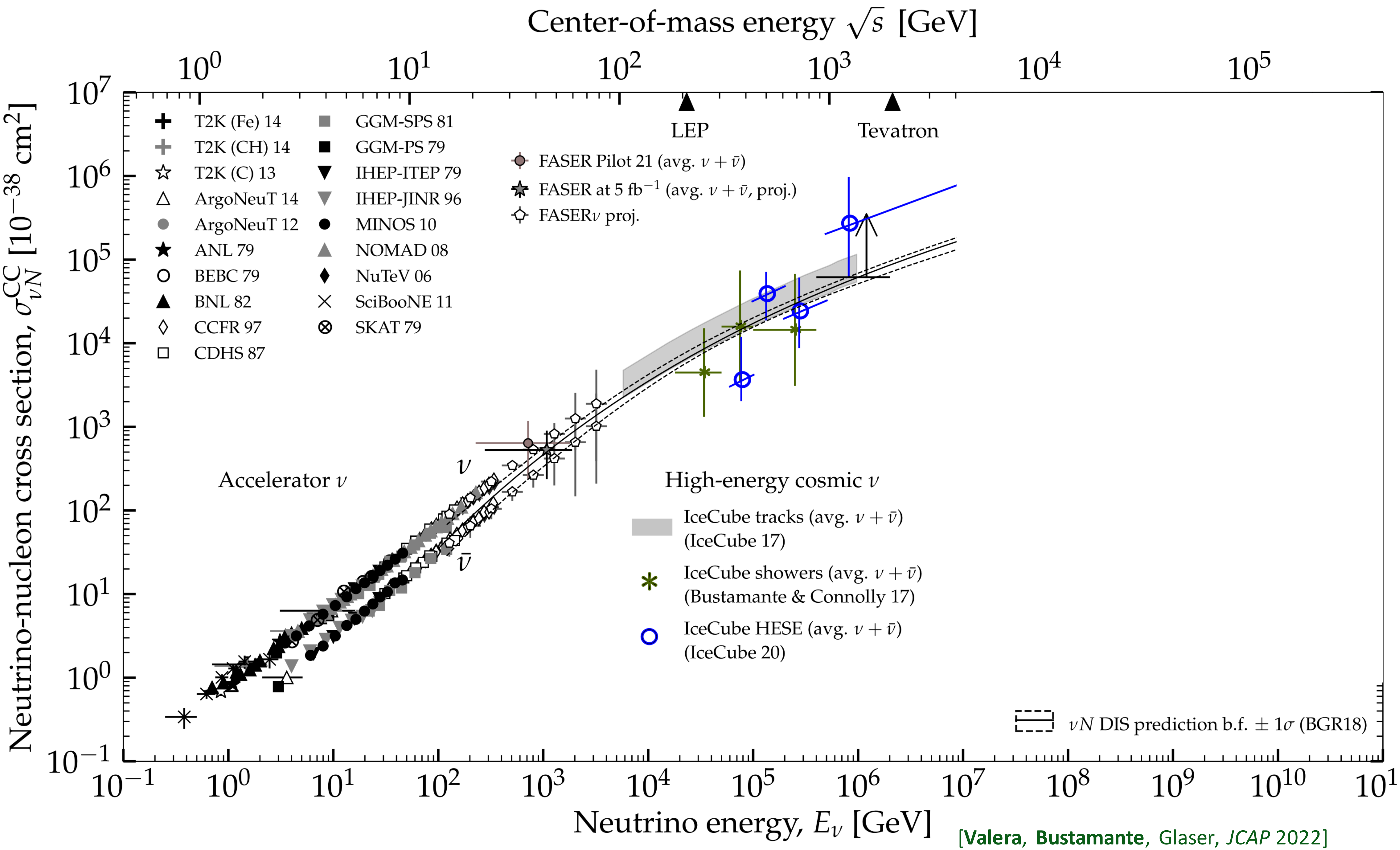
Measuring neutrino-matter int.



[**Valera**, **Bustamante**, Glaser, *JCAP* 2022]

[**Bustamante** & Connolly, *PRL* 2019]

Measuring neutrino-matter int.



[**Valera**, **Bustamante**, Glaser, *JCAP* 2022]

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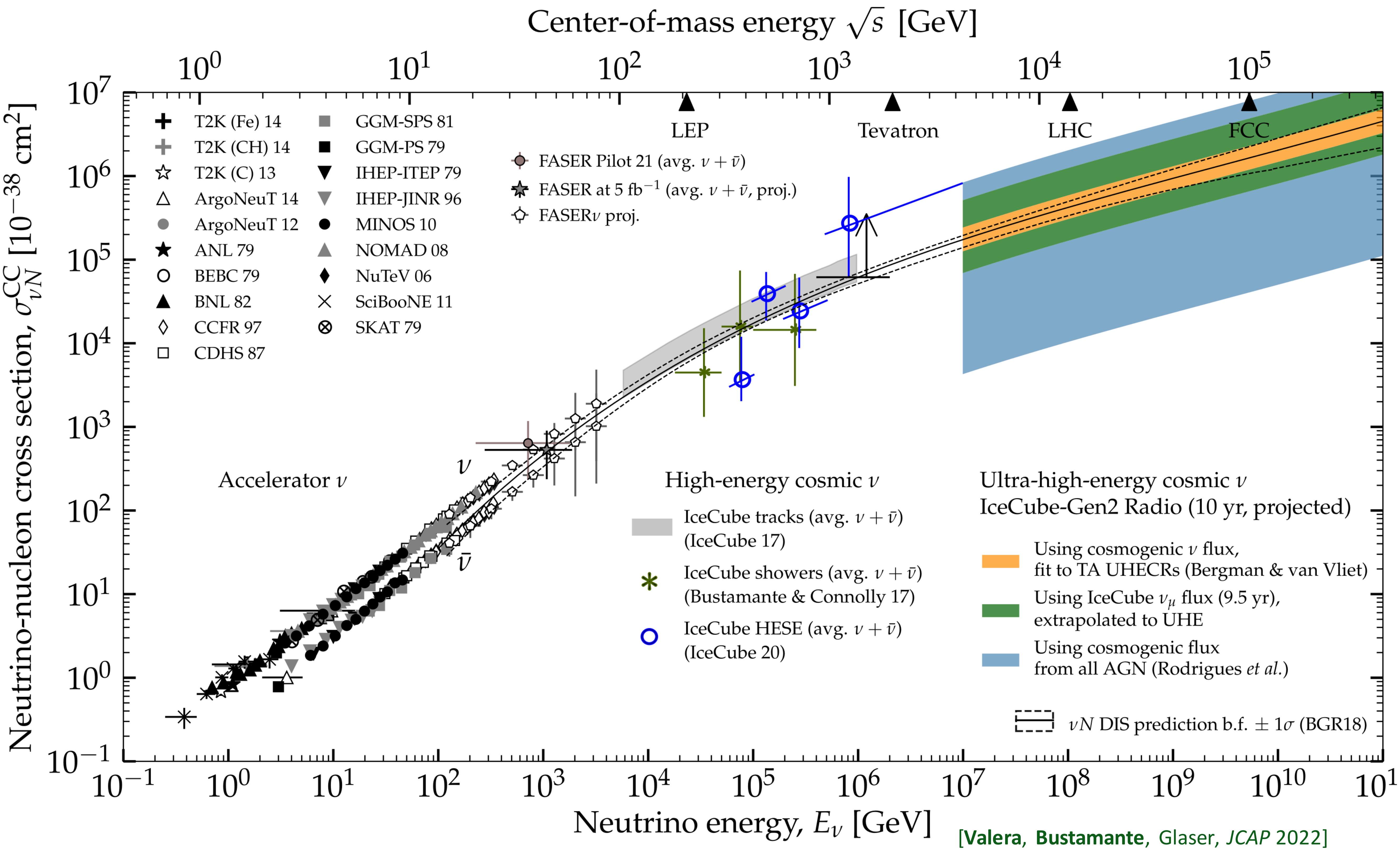


[**Valera**, **Bustamante**, Glaser, *JCAP* 2022]

[**Bustamante** & Connolly, *PRL* 2019]

Planning next-gen ν detectors

Multiple TeV-EeV neutrino telescopes under planning and construction

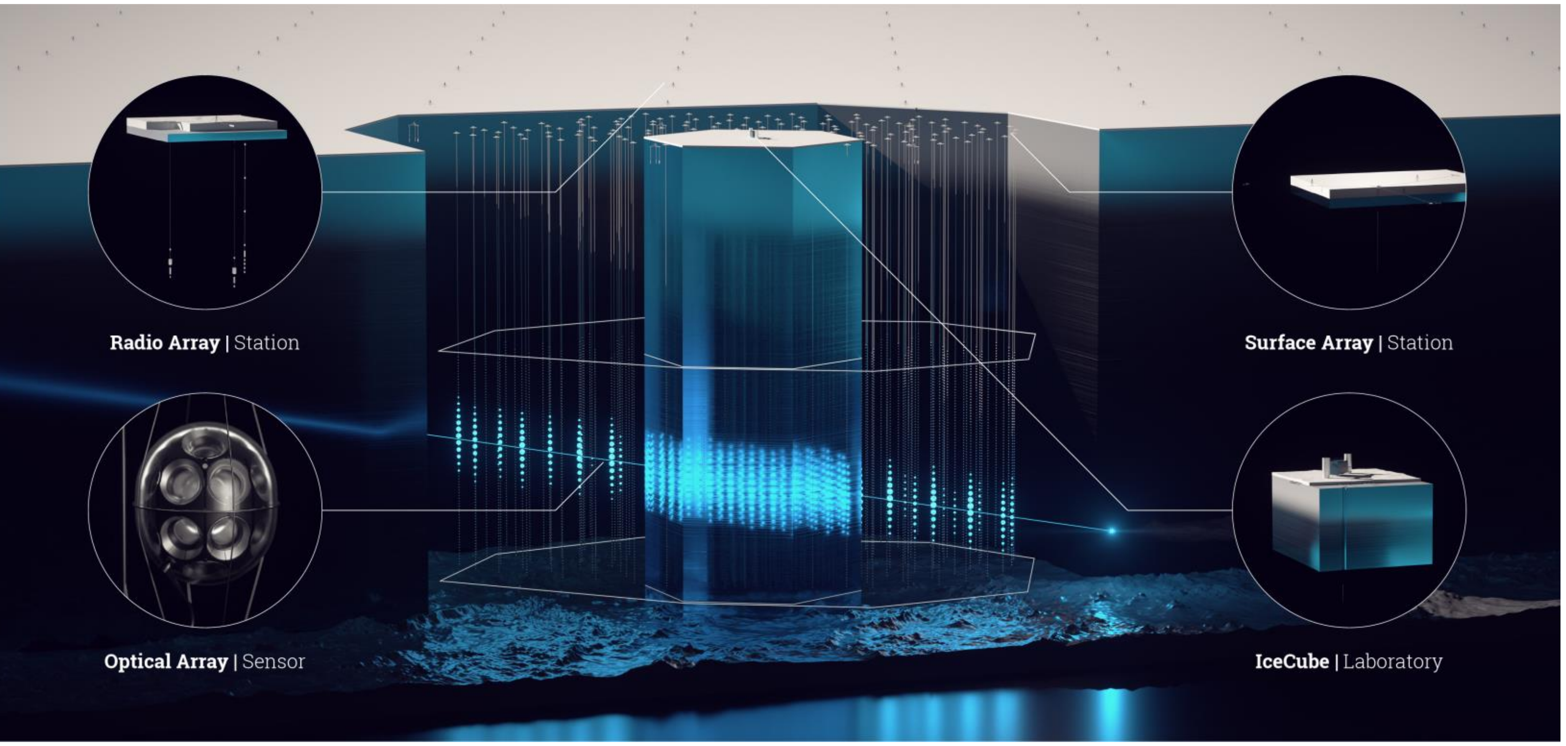
				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediterranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

[Mammen et al. (inc. **Bustamante**), *J. Phys. G* 2022]

See also:
[Ackermann, **Bustamante**, *et al.*, *JHEAp* 2022]
[Alves Batista *et al.* (inc. **Bustamante, Tamborra**) 2110.10074]

Planning next-gen ν detectors

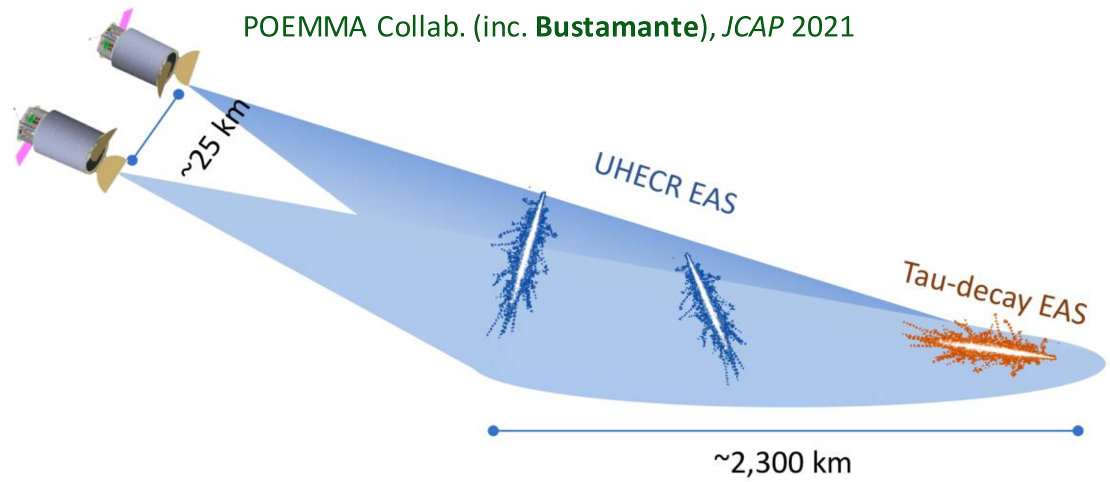


◀ IceCube-Gen2

IceCube-Gen2 Collab. (inc. **Ahlers** & **Bustamante**), *J. Phys. G* 2021
Point UHE sources: **Fiorillo**, **Bustamante**, **Valera**, 2205.15985
Diffuse UHE flux: **Valera**, Bustamante, Glaser, 2210.03756
TeV-PeV spectral shape: **Fiorillo**, **Bustamante**, 2301.00024

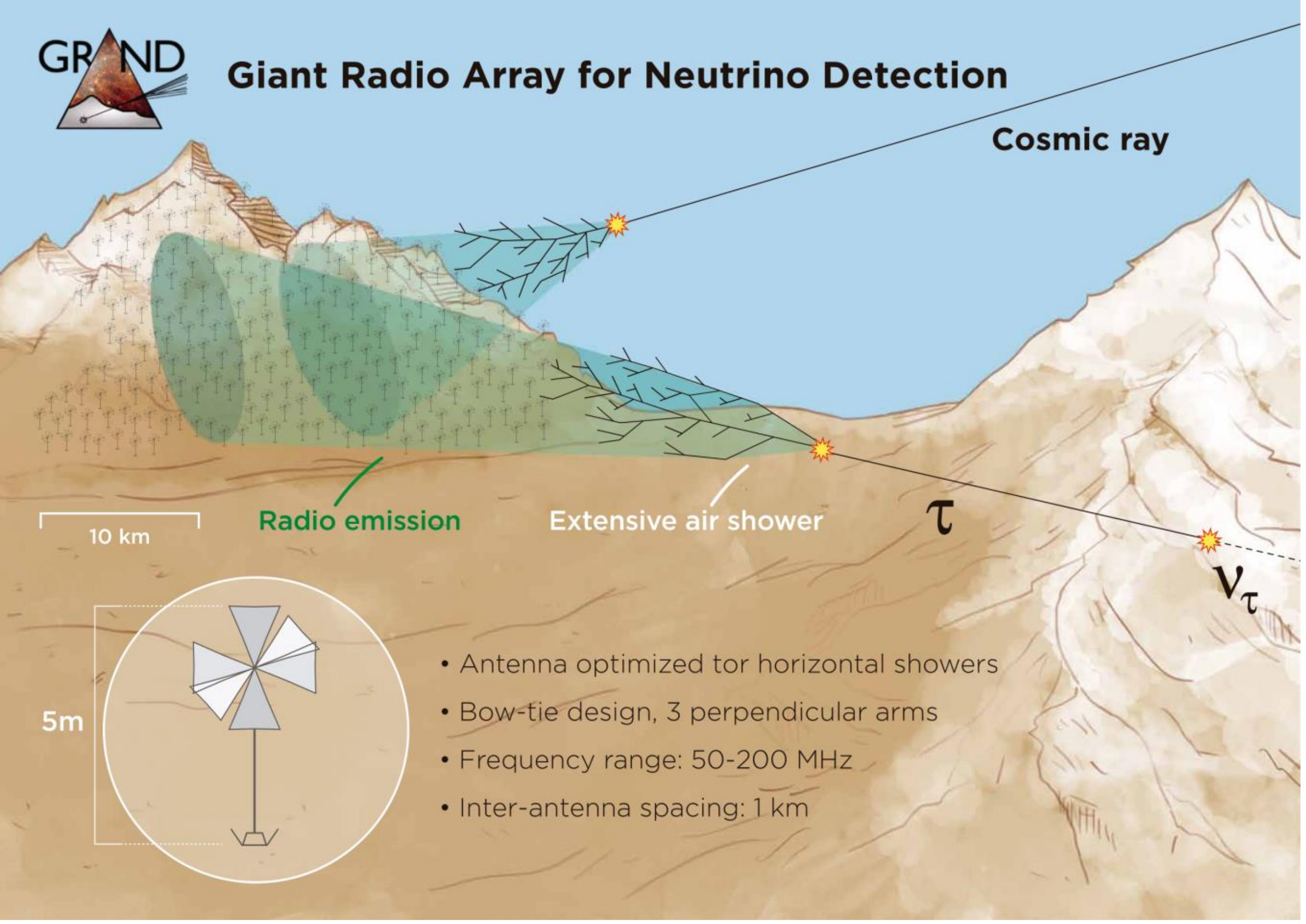
POEMMA-Limb

POEMMA Collab. (inc. **Bustamante**), *JCAP* 2021



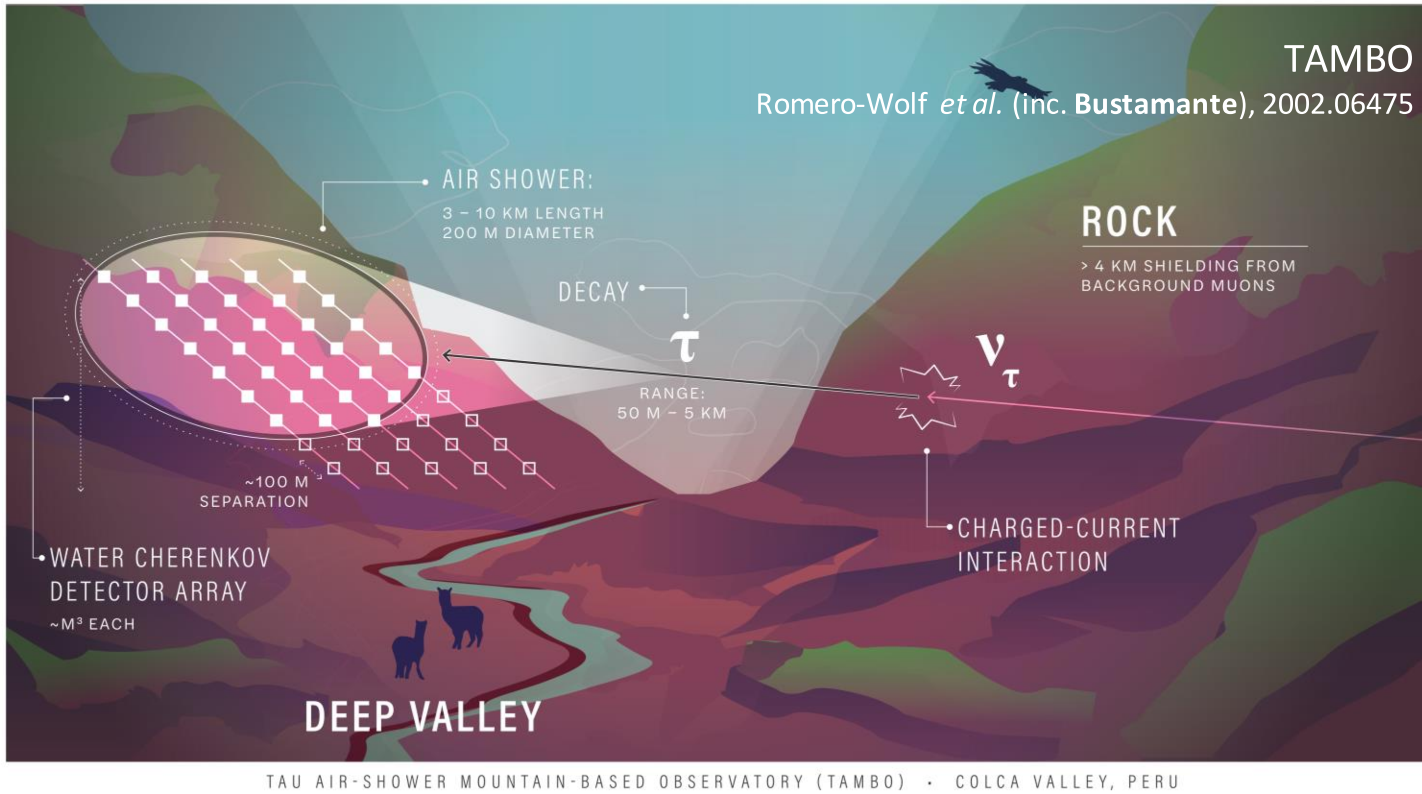
◀ GRAND

GRAND Collab. (inc. **Bustamante**), *Sci. China Phys. Mech. Astron. 2020*



TAMBO

Romero-Wolf *et al.* (inc. **Bustamante**), 2002.06475



NBIA Neutrino Summer School

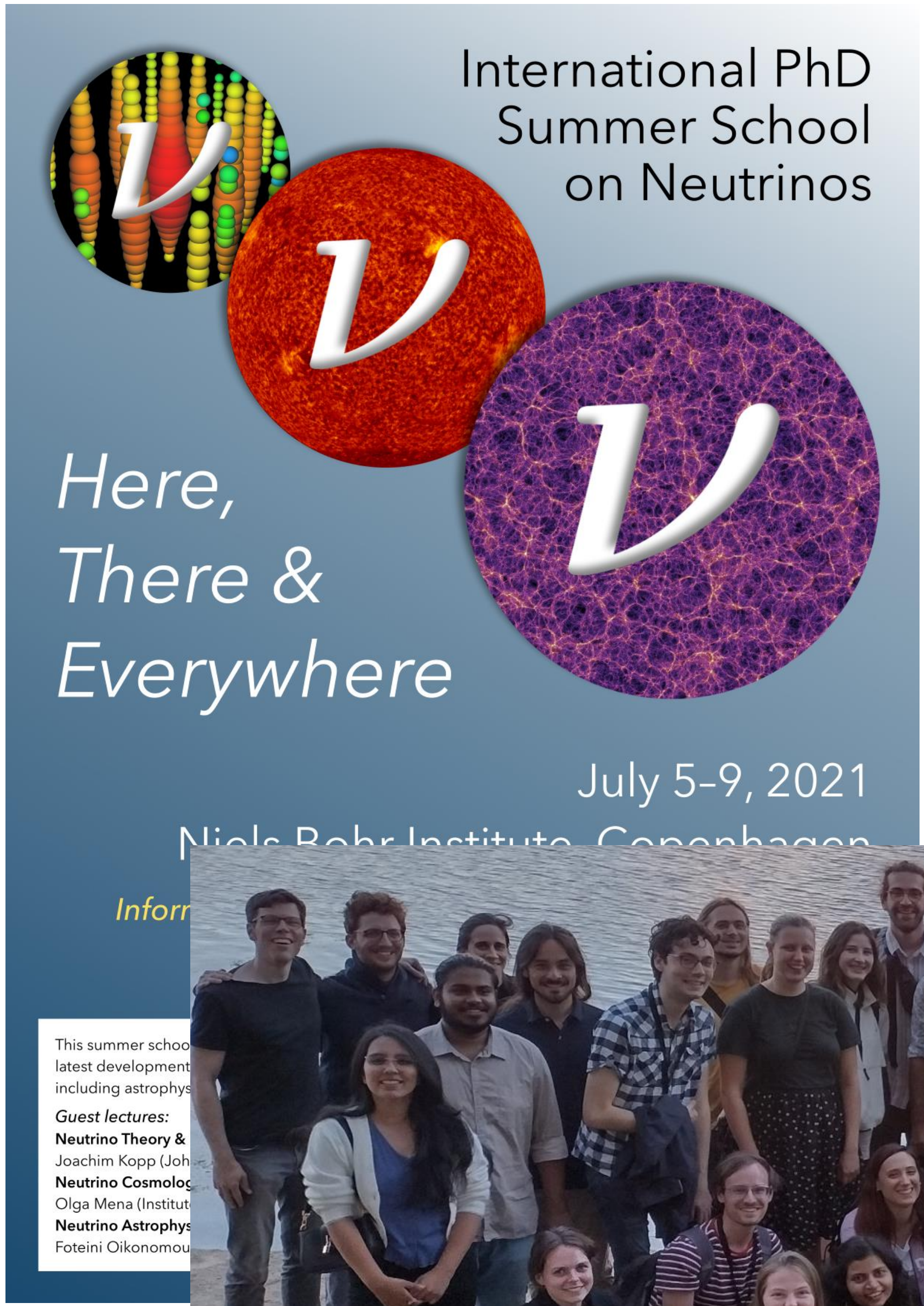
2021 (online)

2022 (in person)

- One-week long
- International lecturers:
  - Neutrino phenomenology
  - Neutrino astrophysics
  - Neutrino cosmology
- Local topical seminars
- Student talks
- Organized by:
  - Markus Ahlers
  - Mauricio Bustamante

NBIA Neutrino Summer School

2021 (online)



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Student posters!

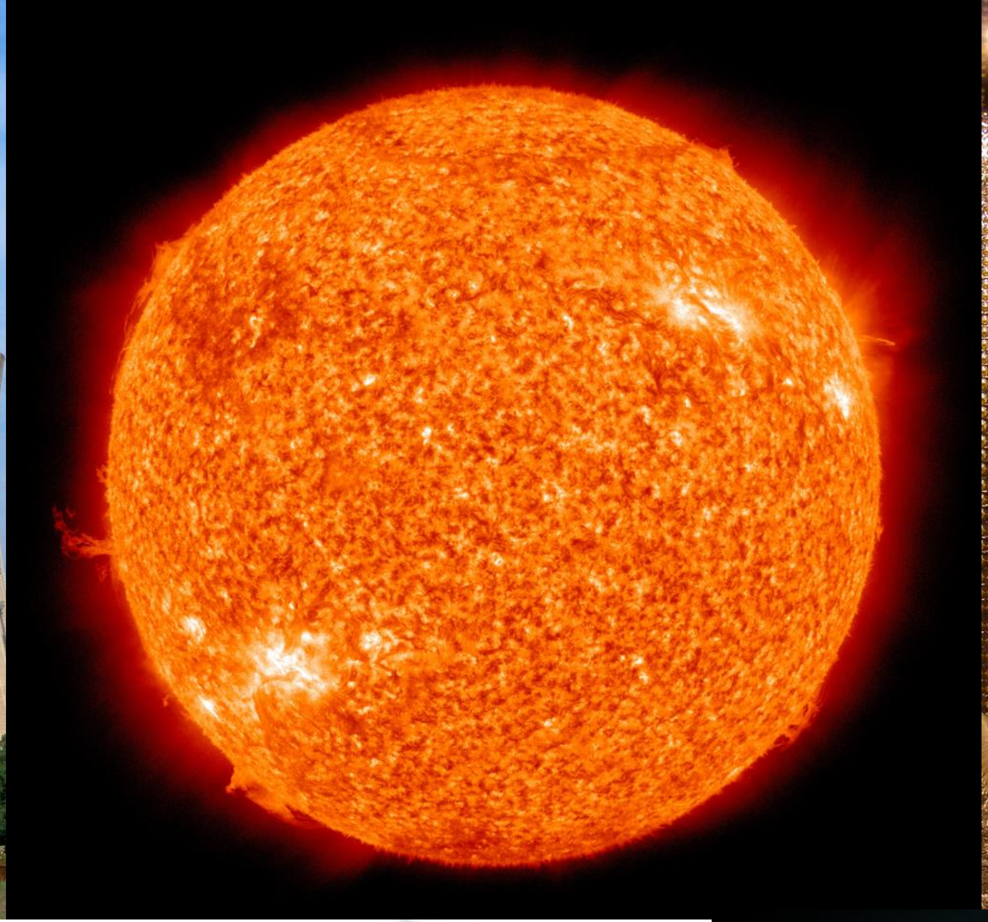
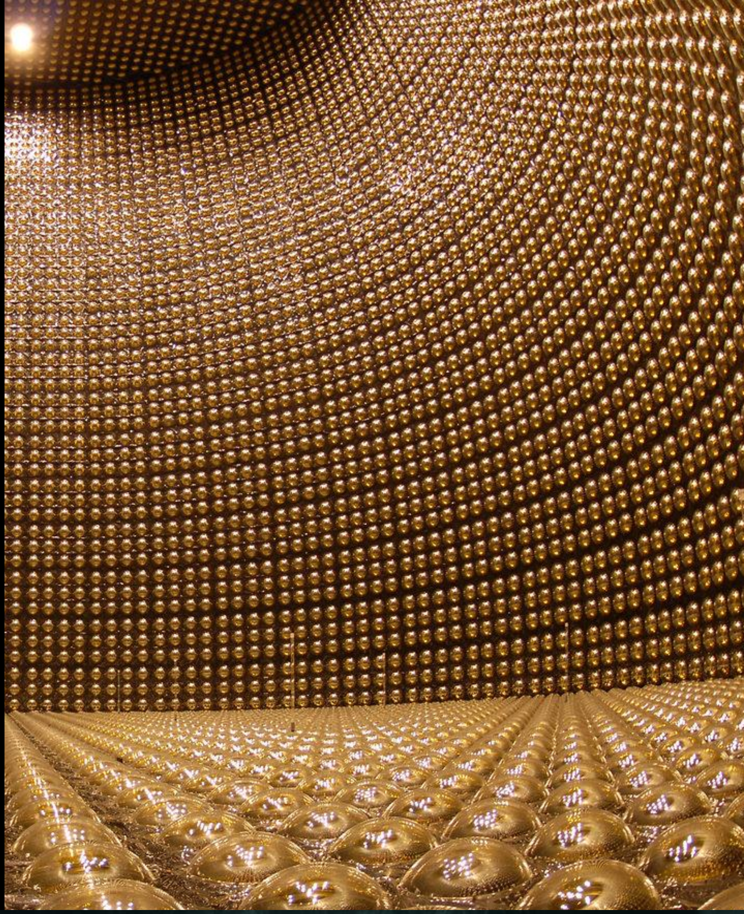
Ersilia Guarini

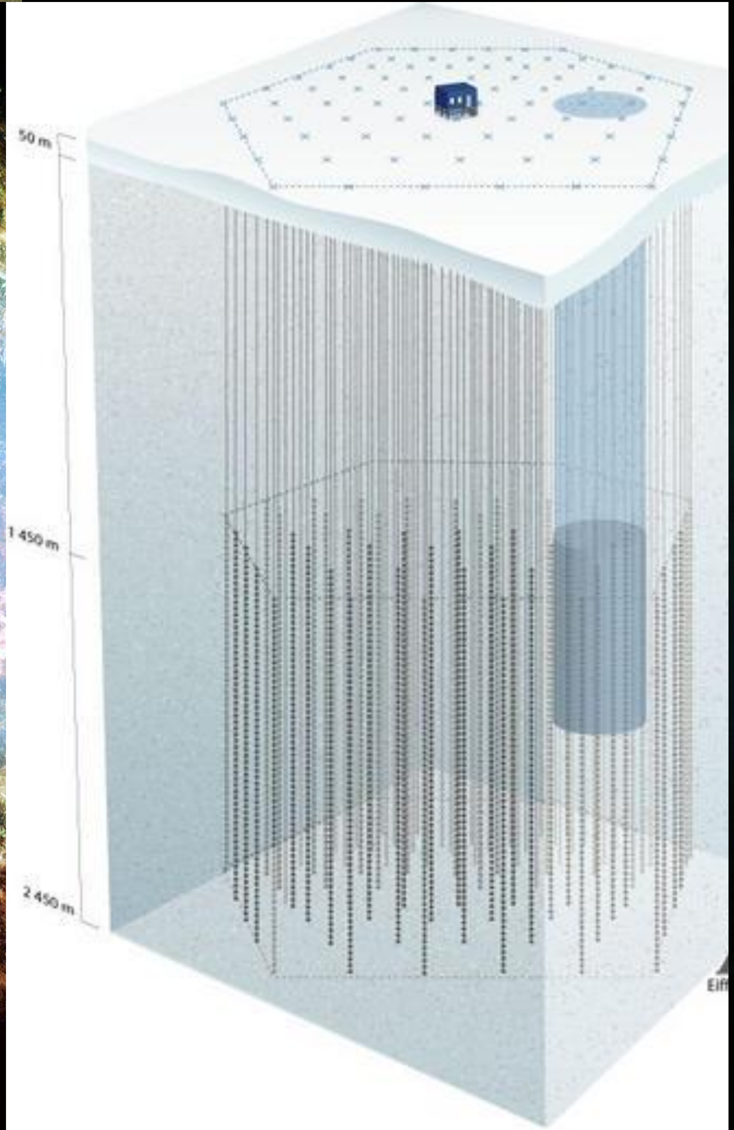
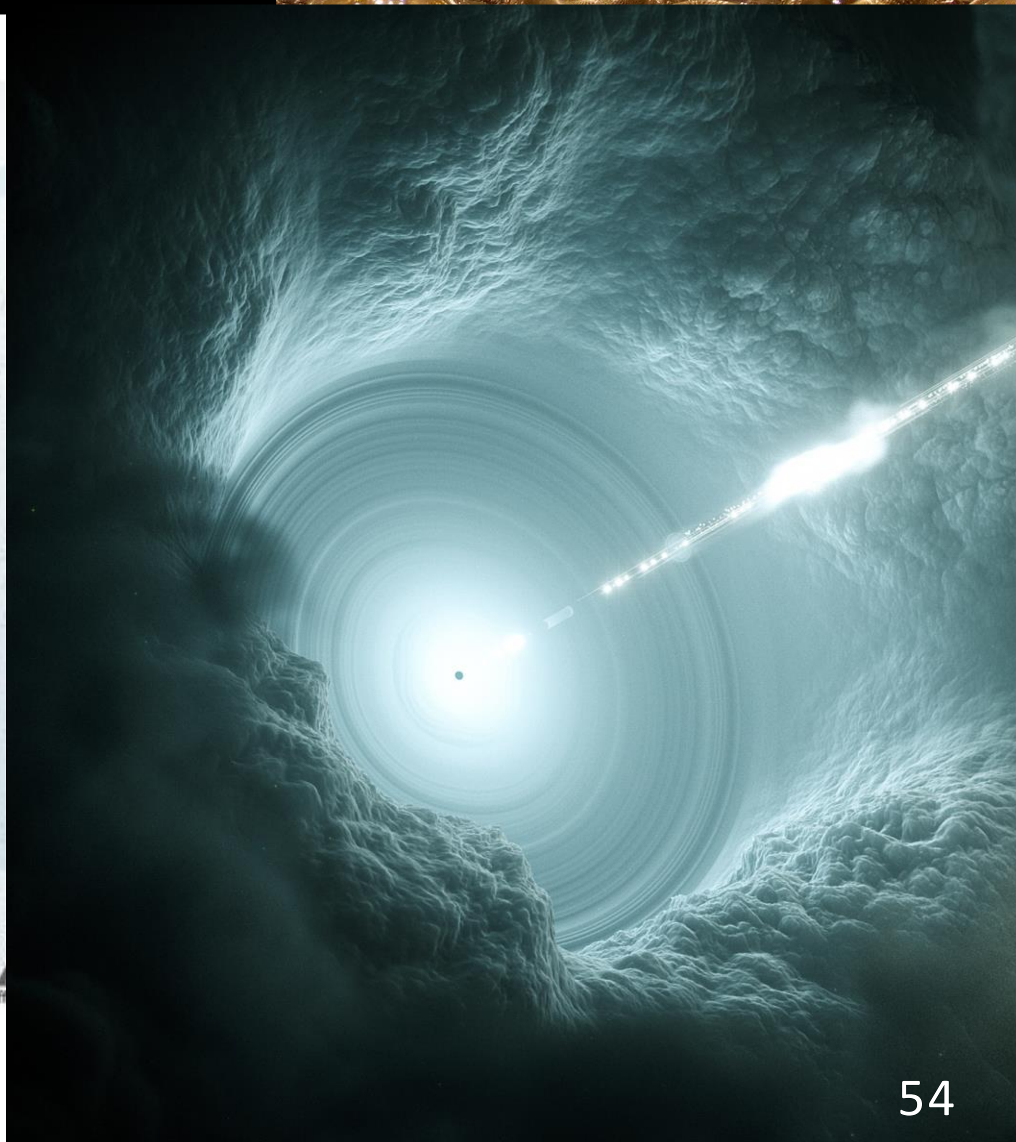
Pedro Dedin

Kathrine
Mørch Groth

Victor Valera

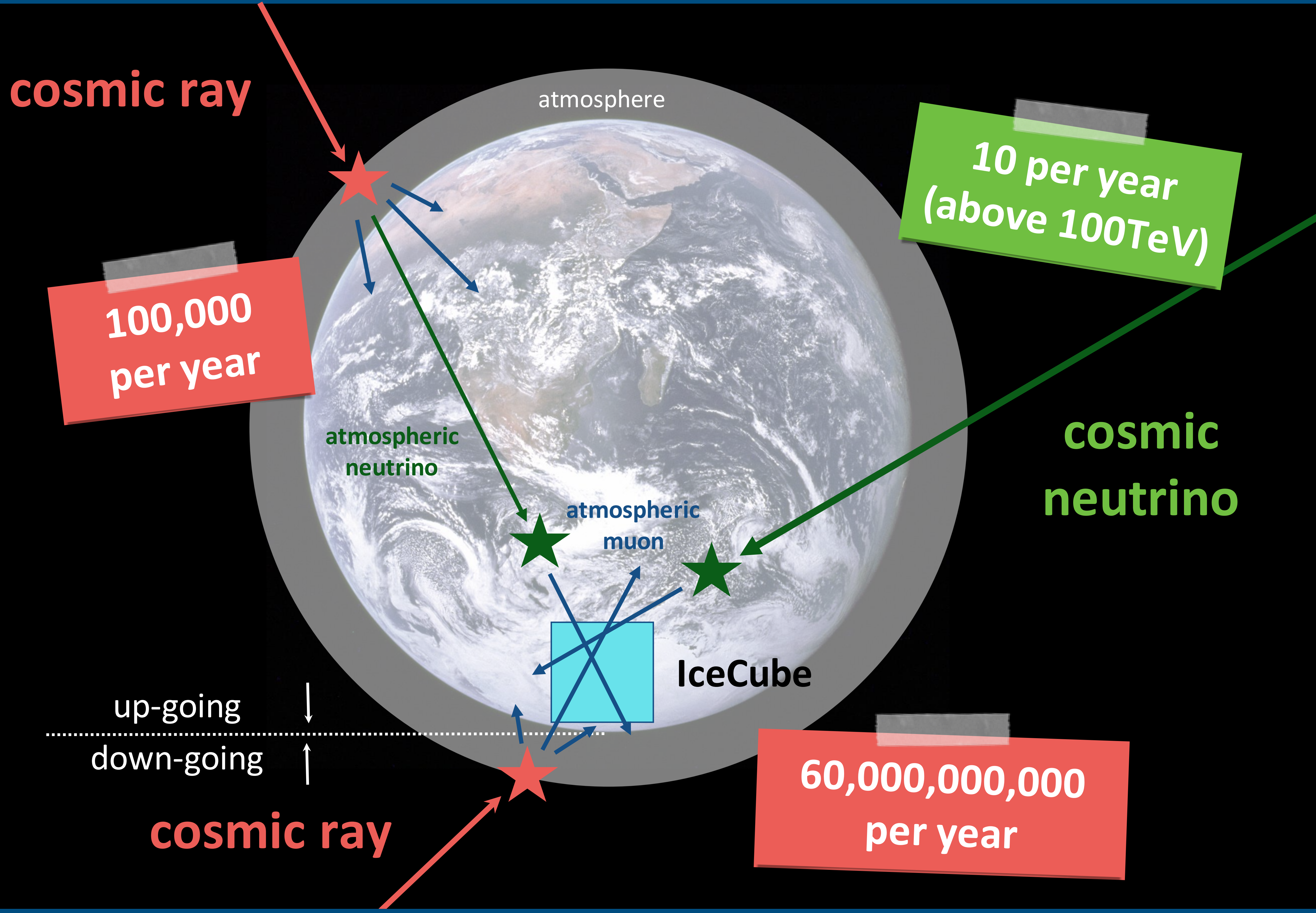
Ask them for the details I skipped!



50 m
1 450 m
2 450 m


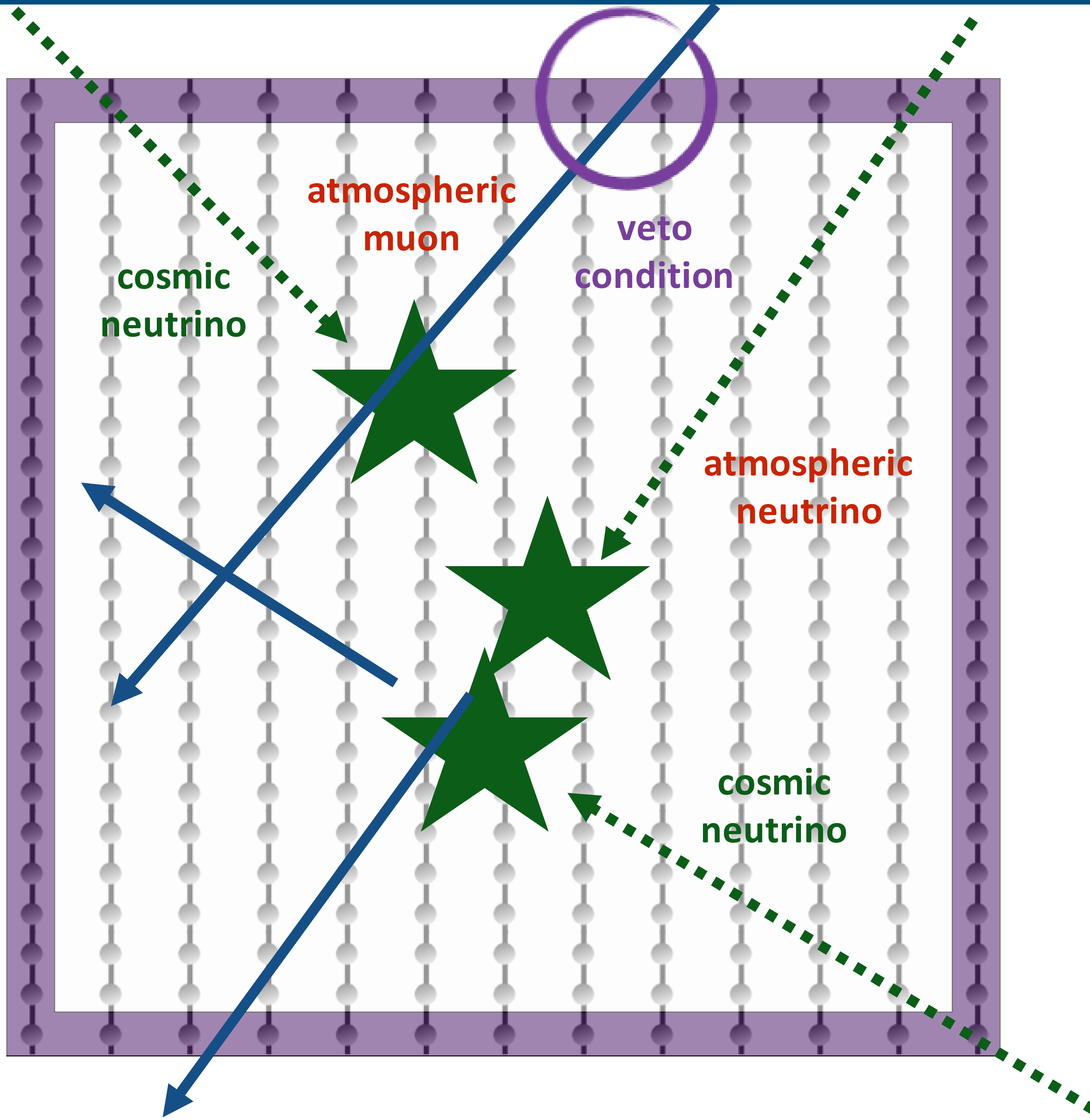
Backup Slides

Neutrino Selection I

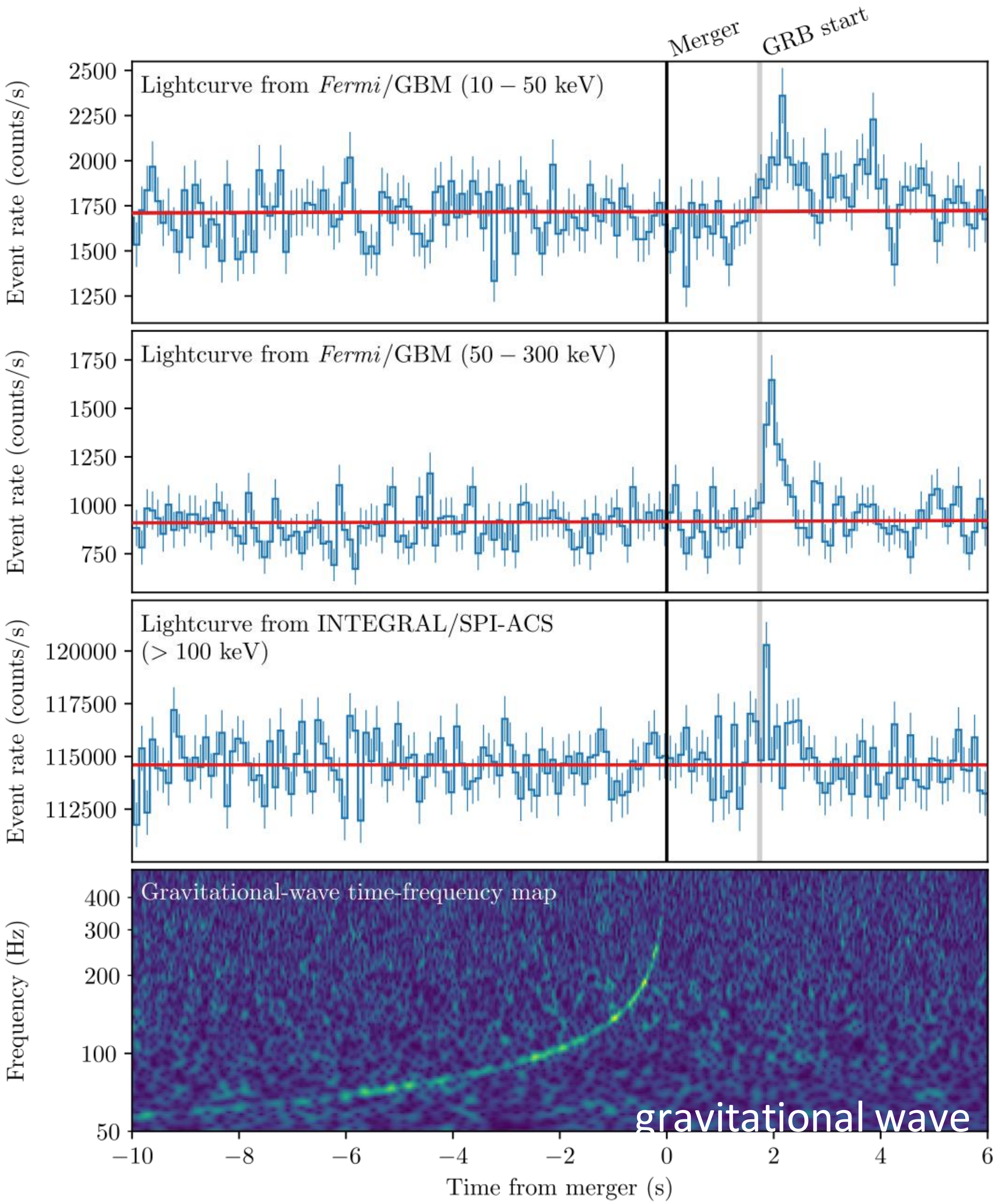


Neutrino Selection II

- 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

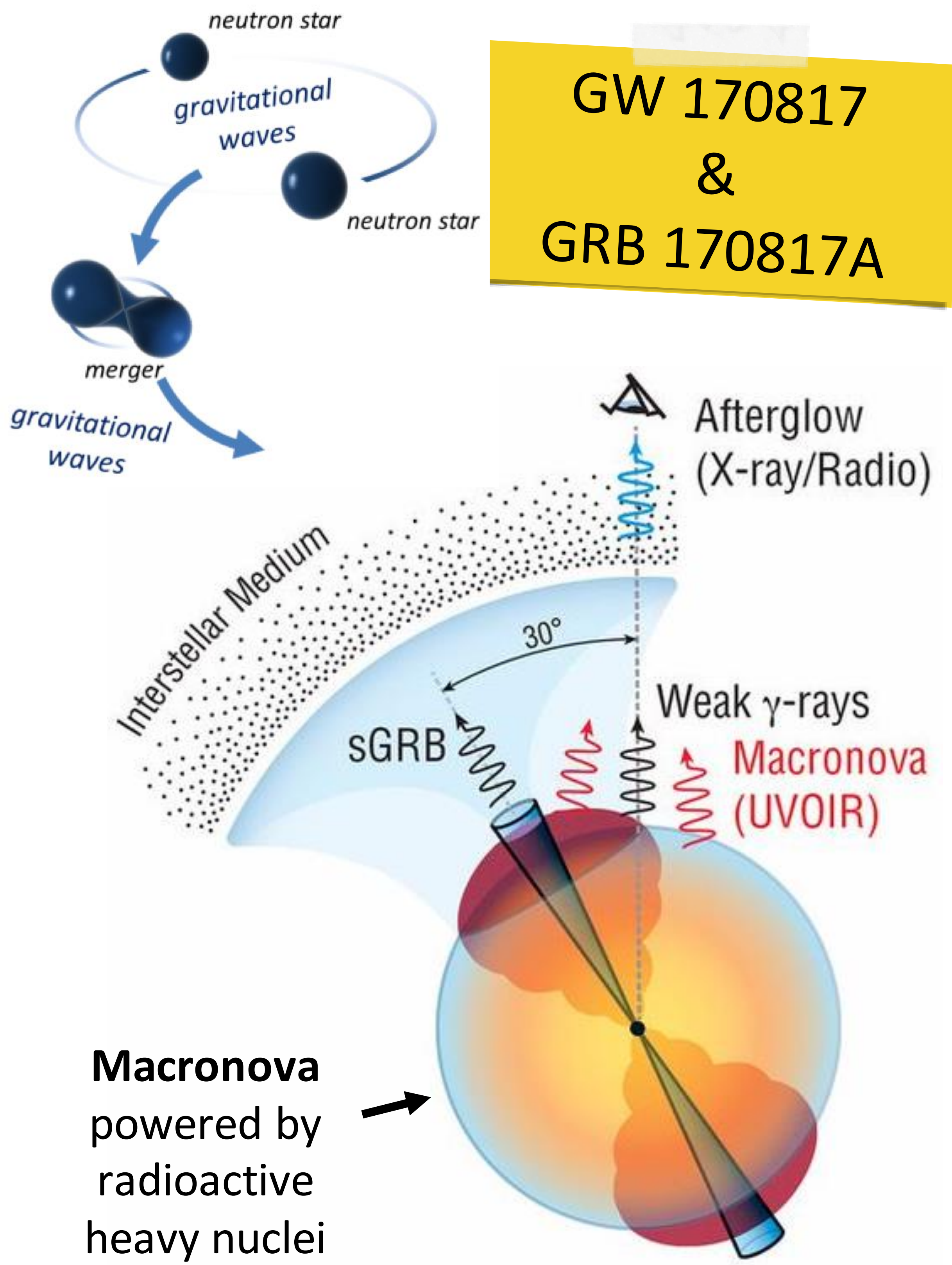


GRBs and Gravitational Waves



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

GW 170817
&
GRB 170817A



Macronova powered by radioactive heavy nuclei