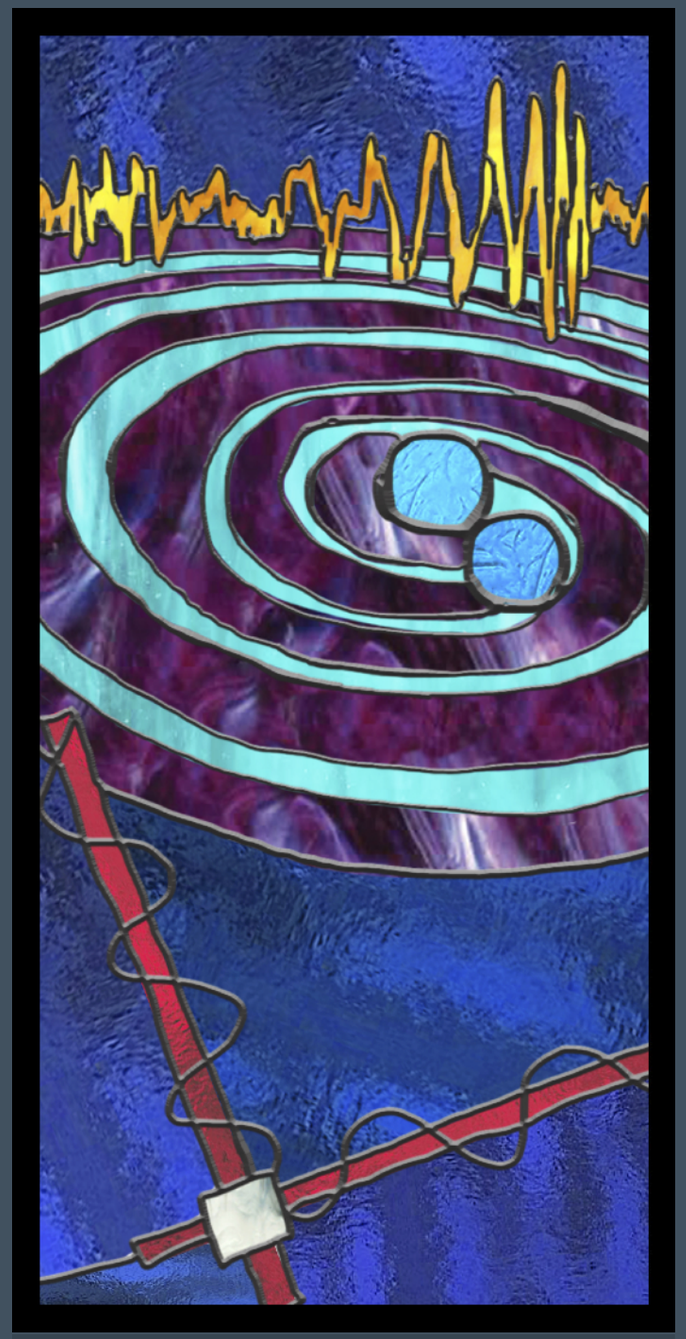

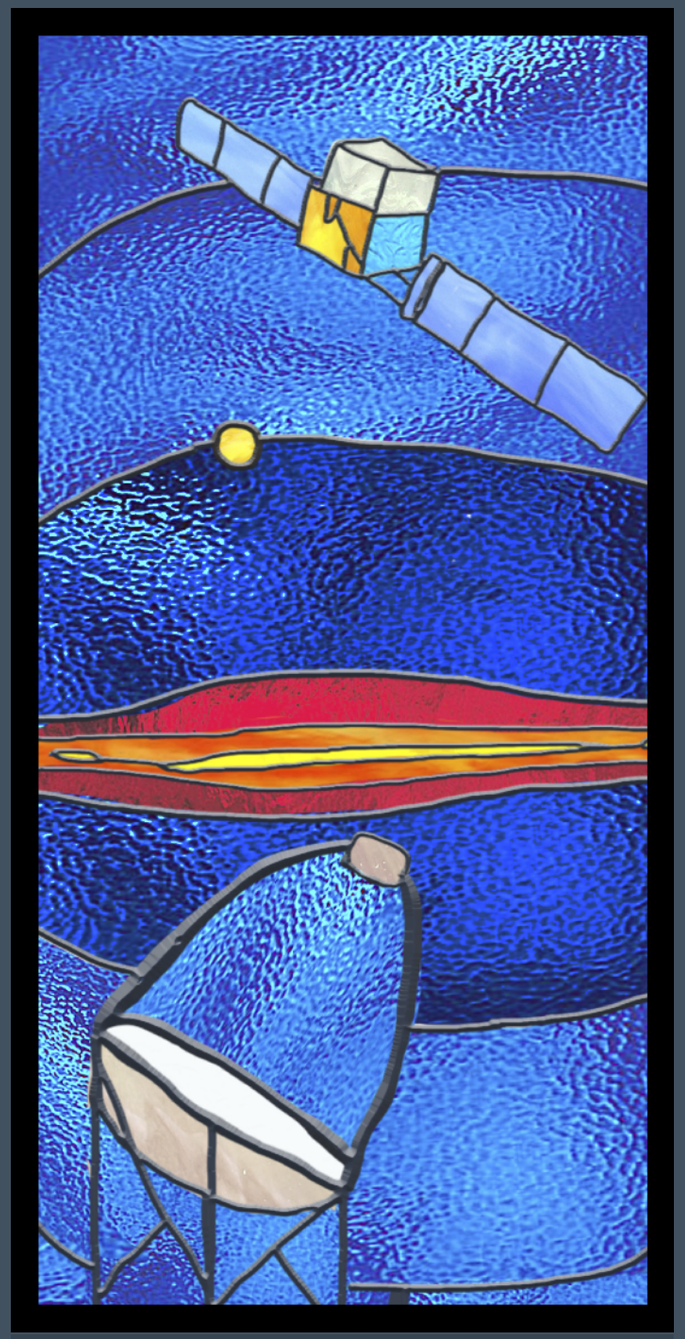

Neutrino Astrophysics

Markus Ahlers, Mauricio Bustamante, D. Jason Koskinen & Irene Tamborra

MSc Day, October 9, 2020

Who are we?

Prof.
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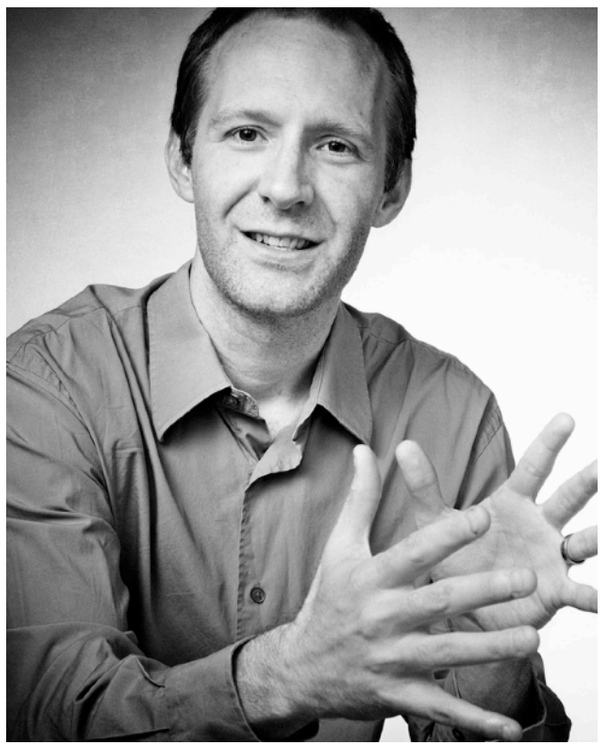

Asst. Prof.
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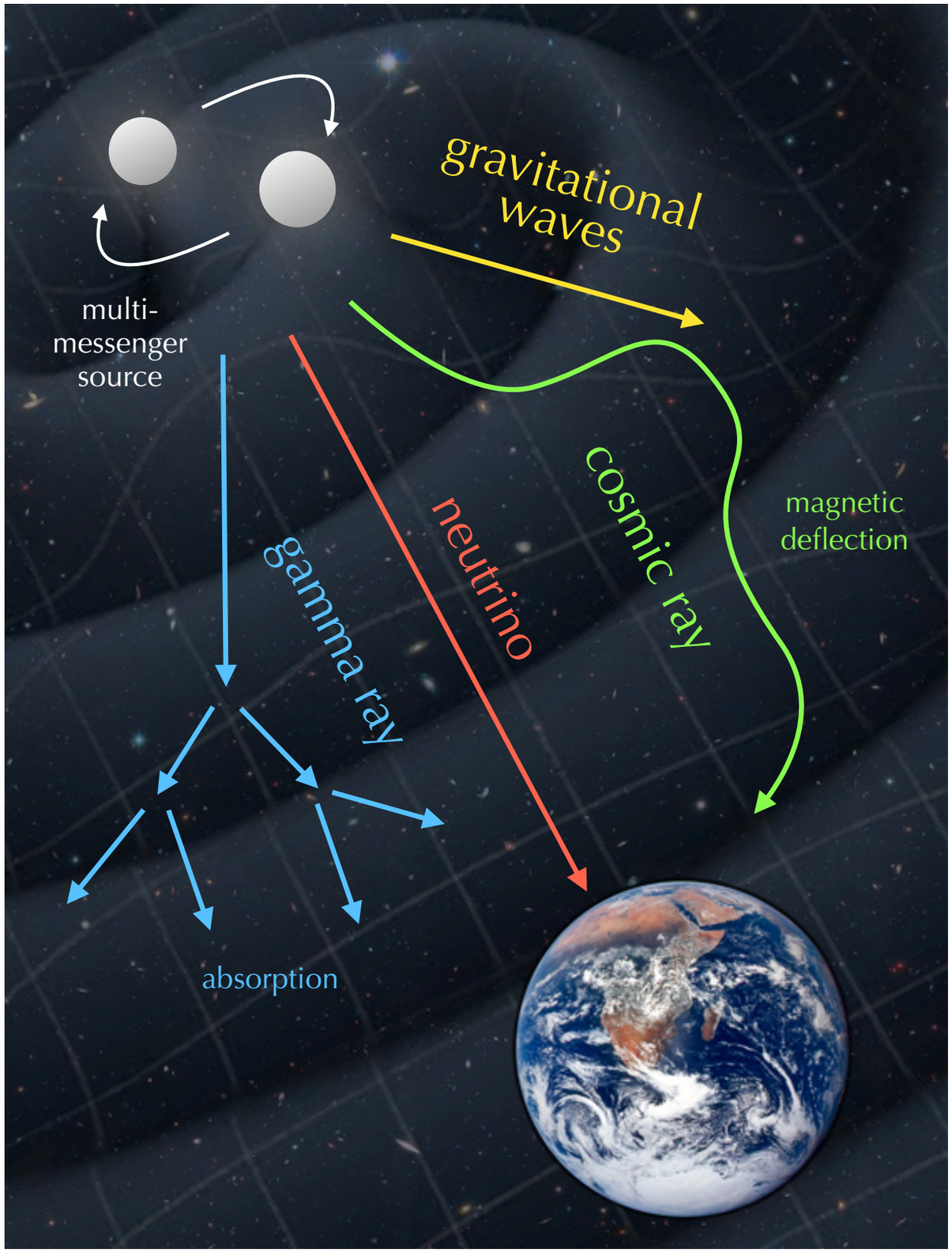
The Elusive Neutrino

- **three neutrino flavours**
- very small masses *(unknown origin)*
- large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **unique probe of high-energy astrophysics**

Standard Model of Particle Physics

(+ Higgs boson)

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

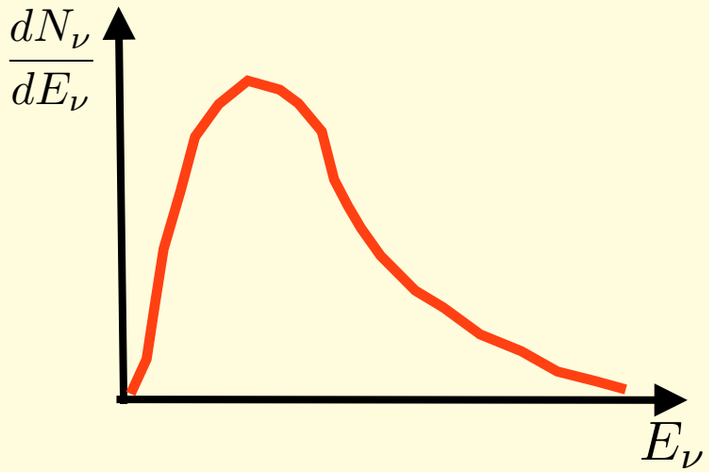
coincident with
photons and gravitational waves

BUT, very difficult to detect!

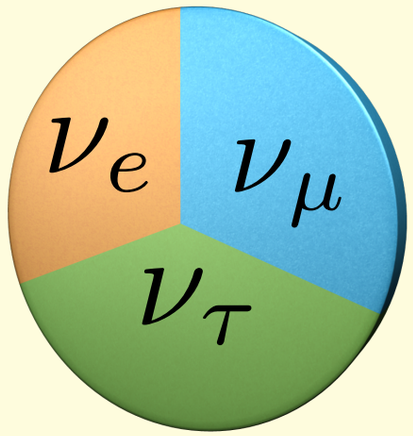
Powerful Probes in Astrophysics

Neutrinos provide us with:

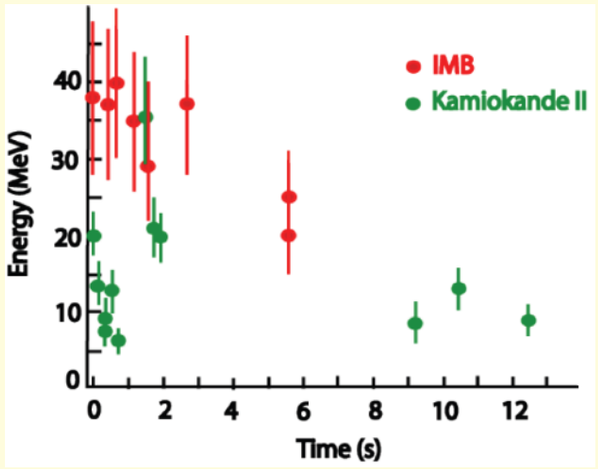
1. Energy Distribution



2. Flavor Ratios

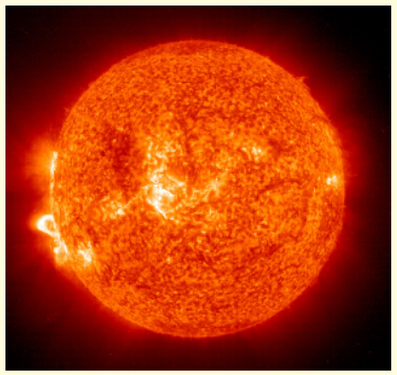


3. Light Curve

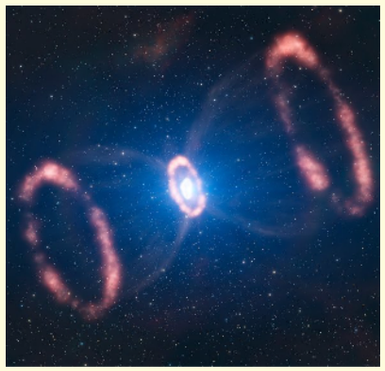


Neutrinos are copiously produced in astrophysical sources, e.g.

The Sun



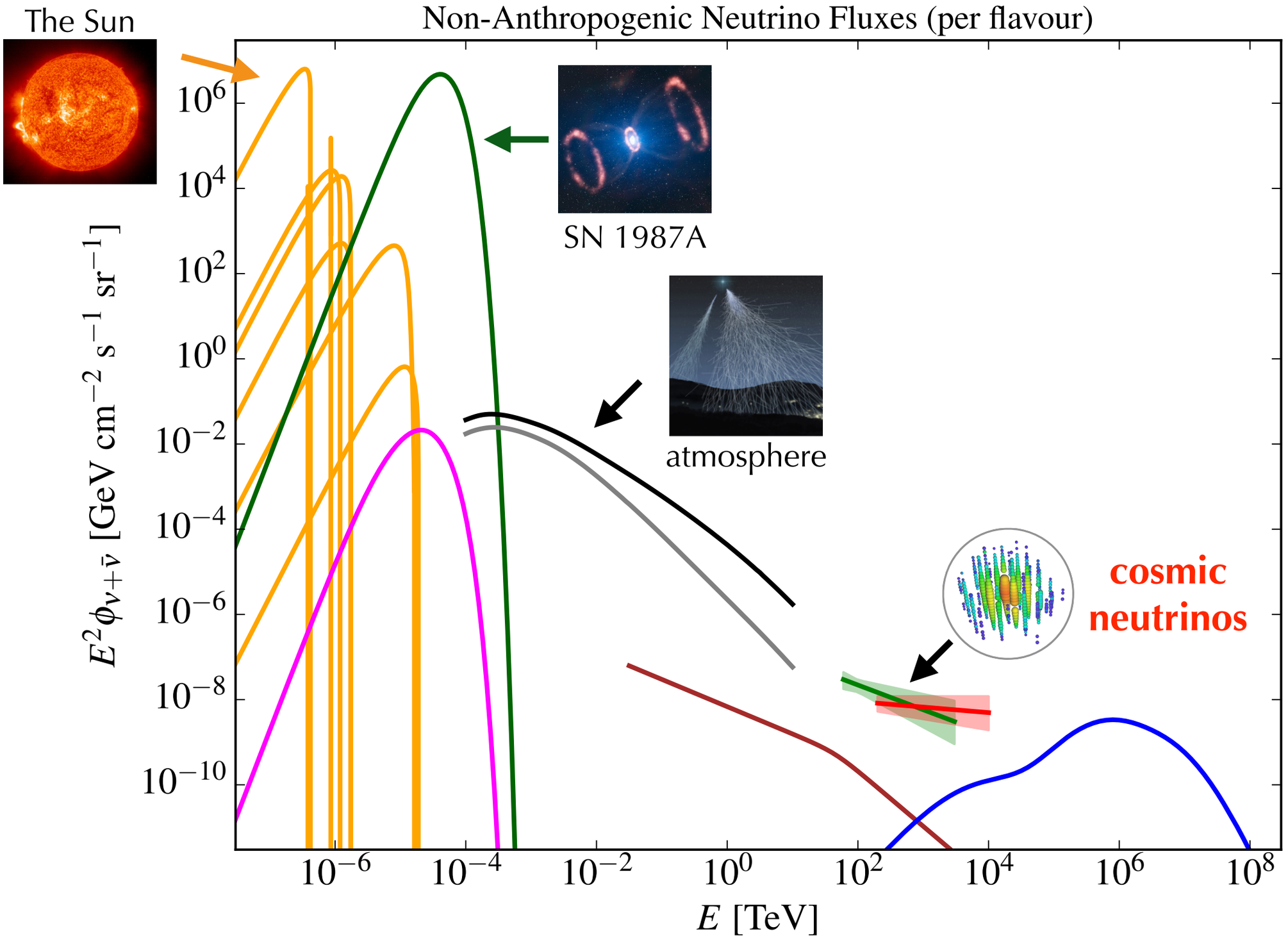
Supernovae



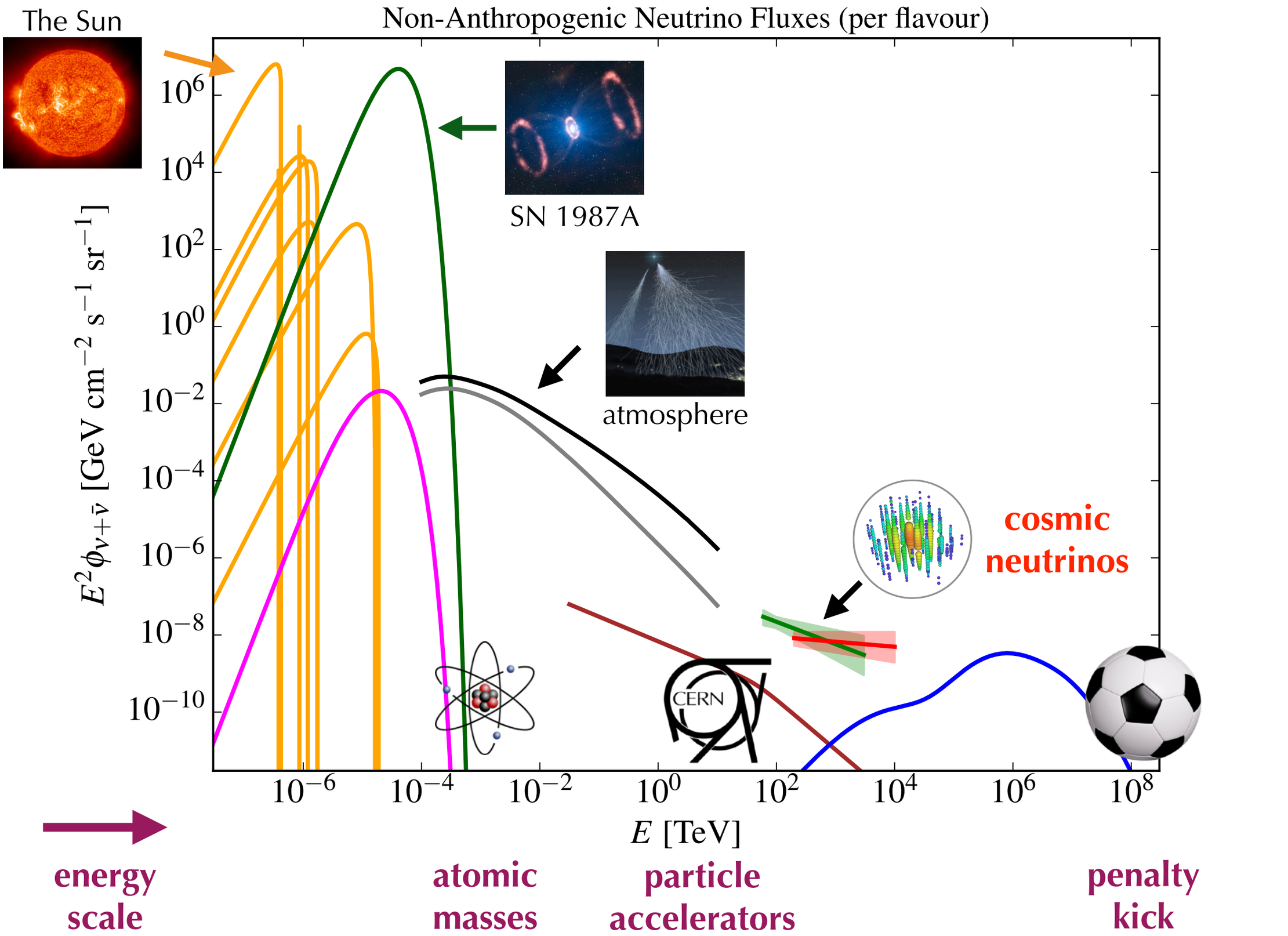
Active Galaxies

Gamma-ray Bursts

Non-Anthropogenic Neutrino Fluxes



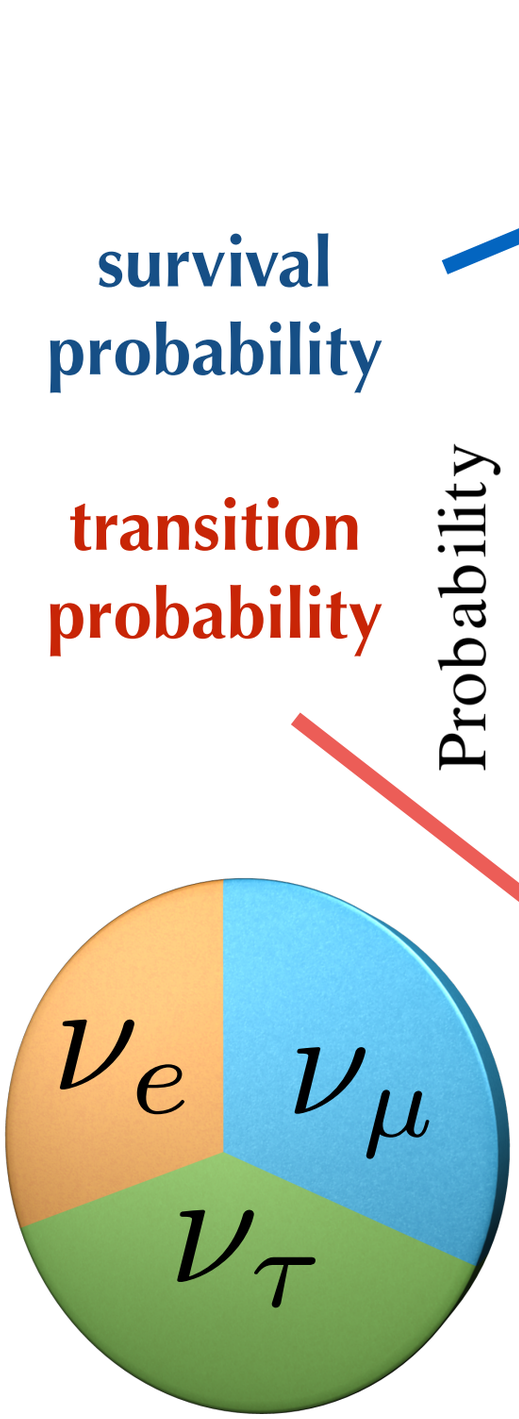
Non-Anthropogenic Neutrino Fluxes



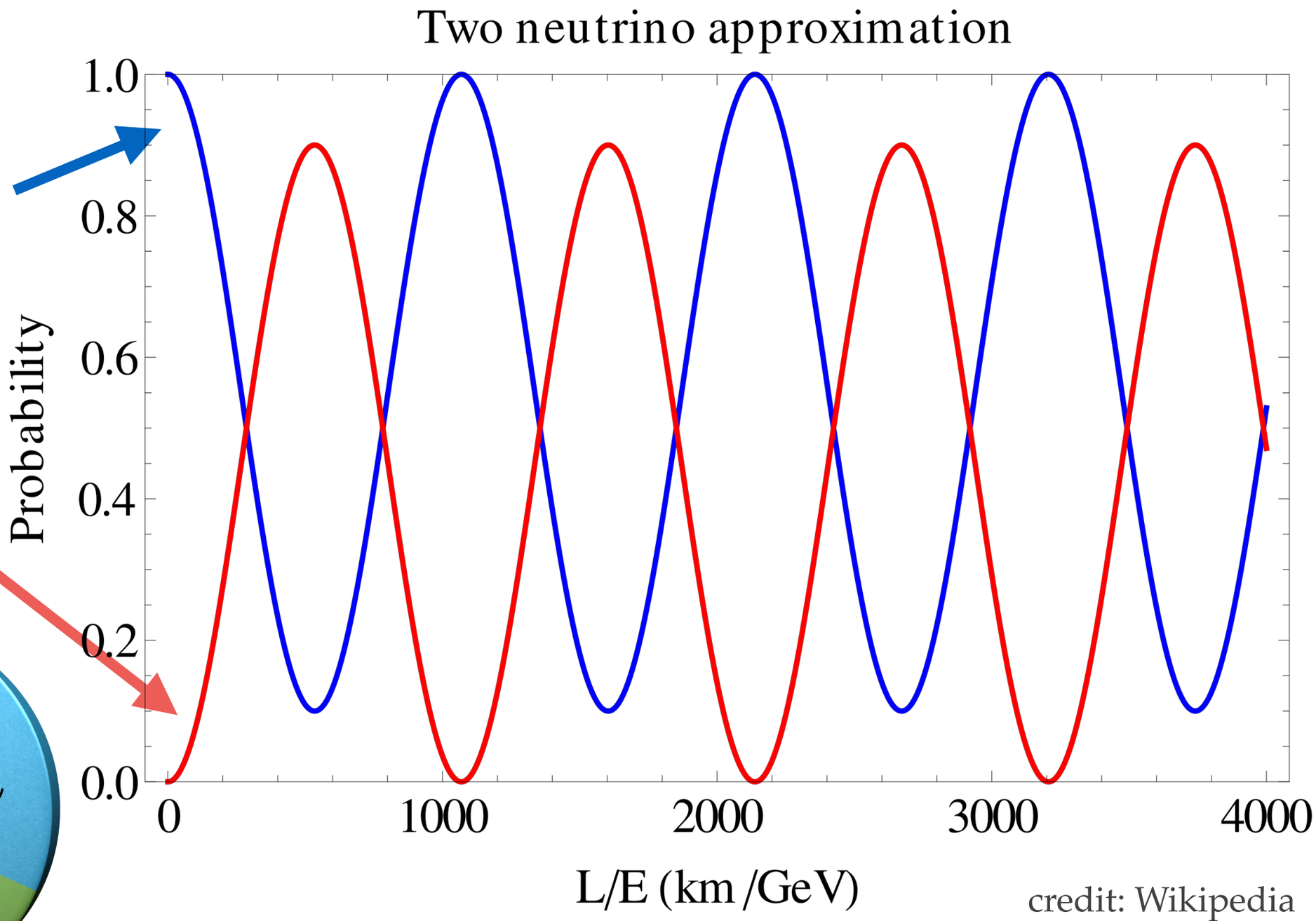
Neutrino Flavor Oscillations

survival probability

transition probability

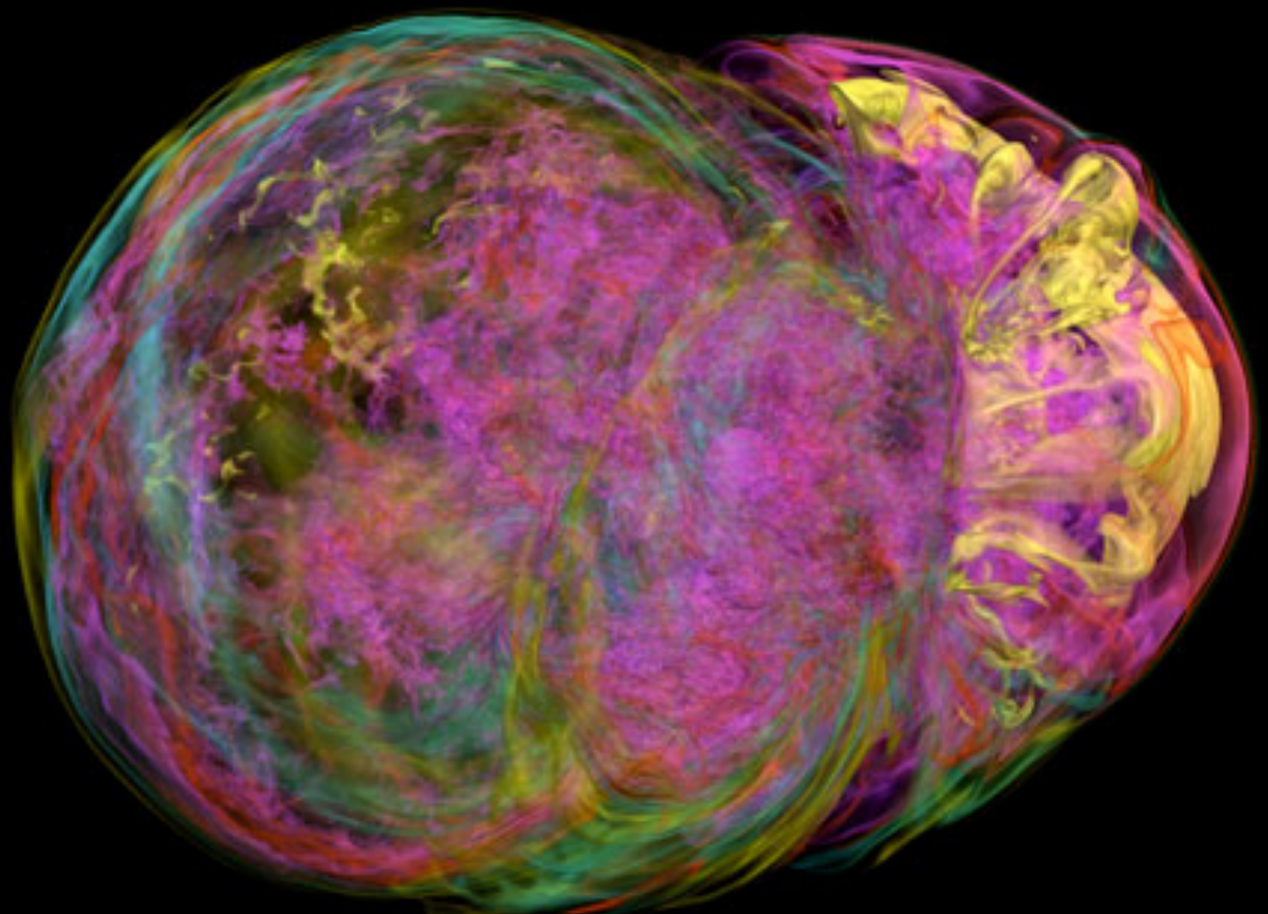


(mass state)

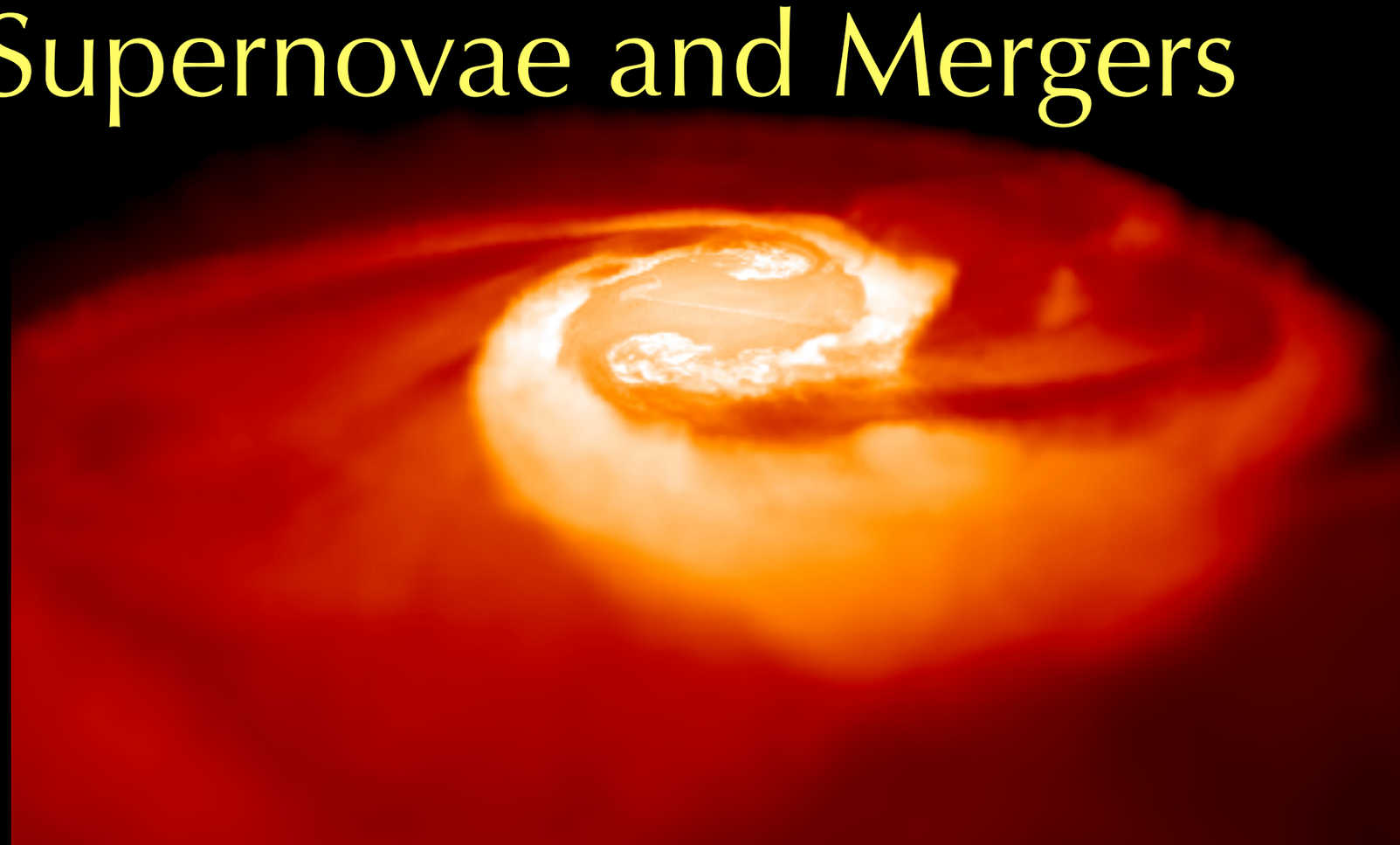


credit: Wikipedia

Neutrino oscillate between flavors in time/distance.

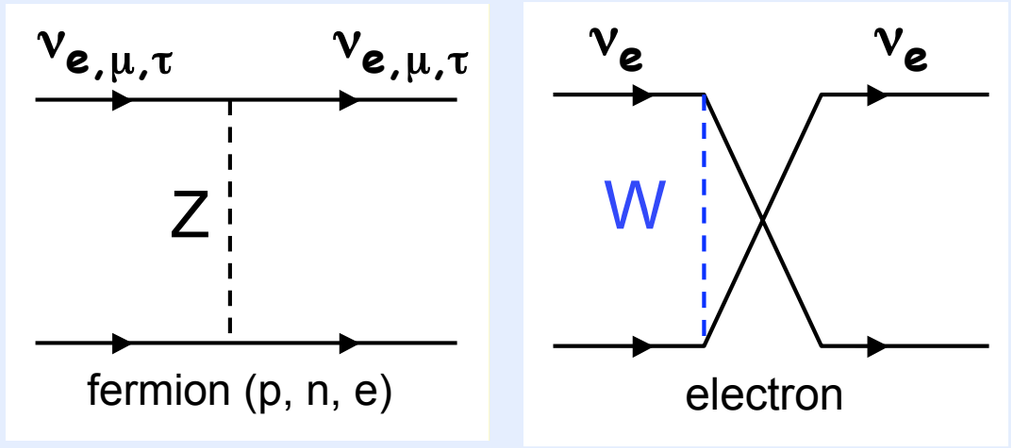


Neutrinos in Supernovae and Mergers



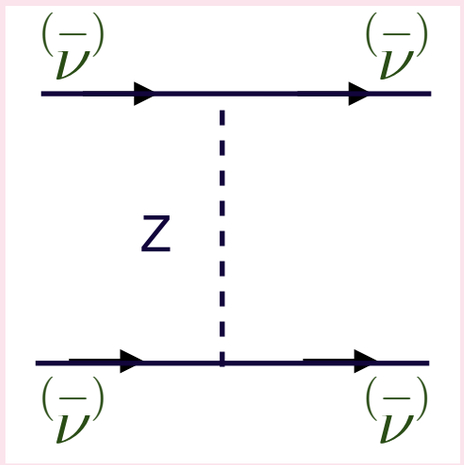
Neutrino Interactions

Understood phenomenon.



Neutrinos interact with neutrons, protons and electrons.

We still need to learn a lot about this process!

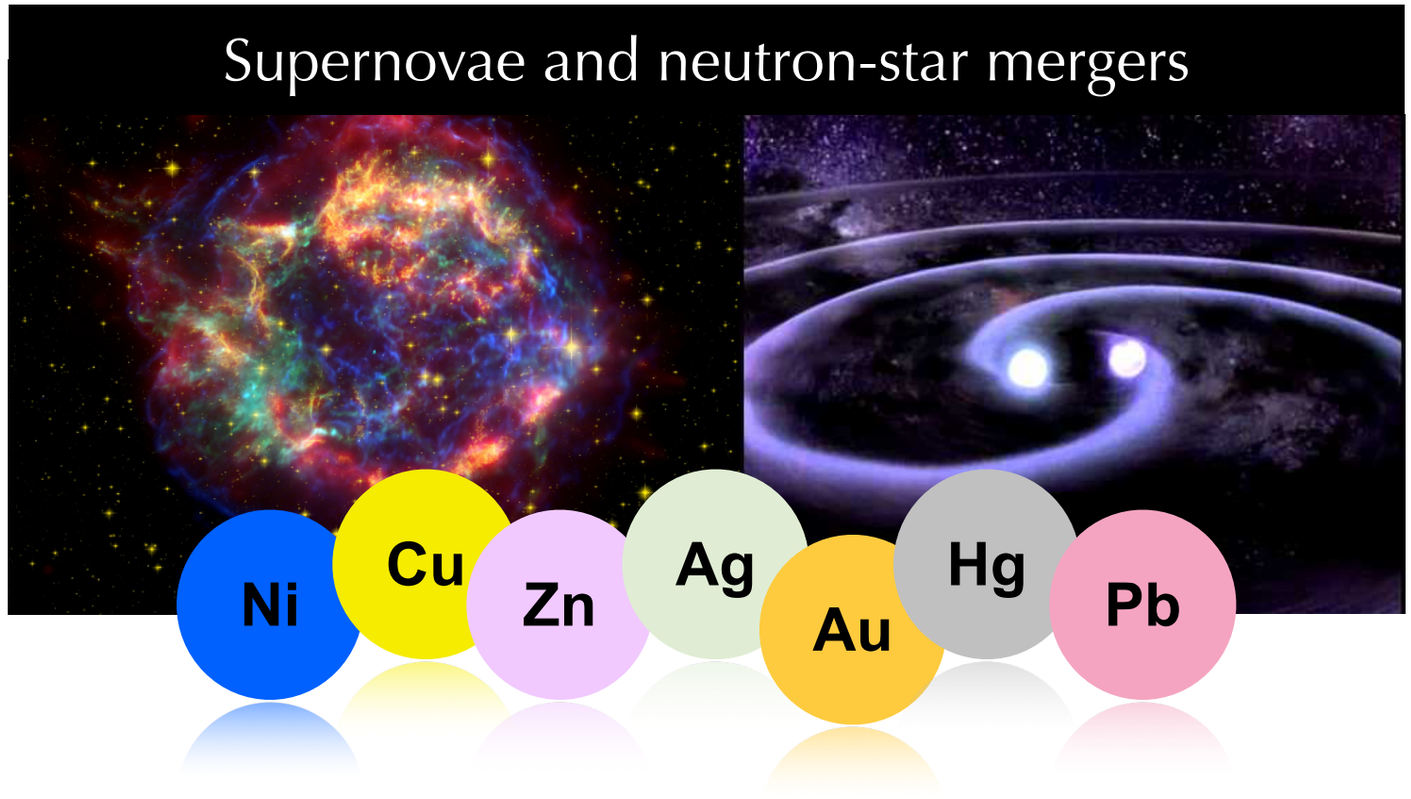


$\nu - \nu$ interactions

Non-linear phenomenon!

Stellar Nucleosynthesis

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



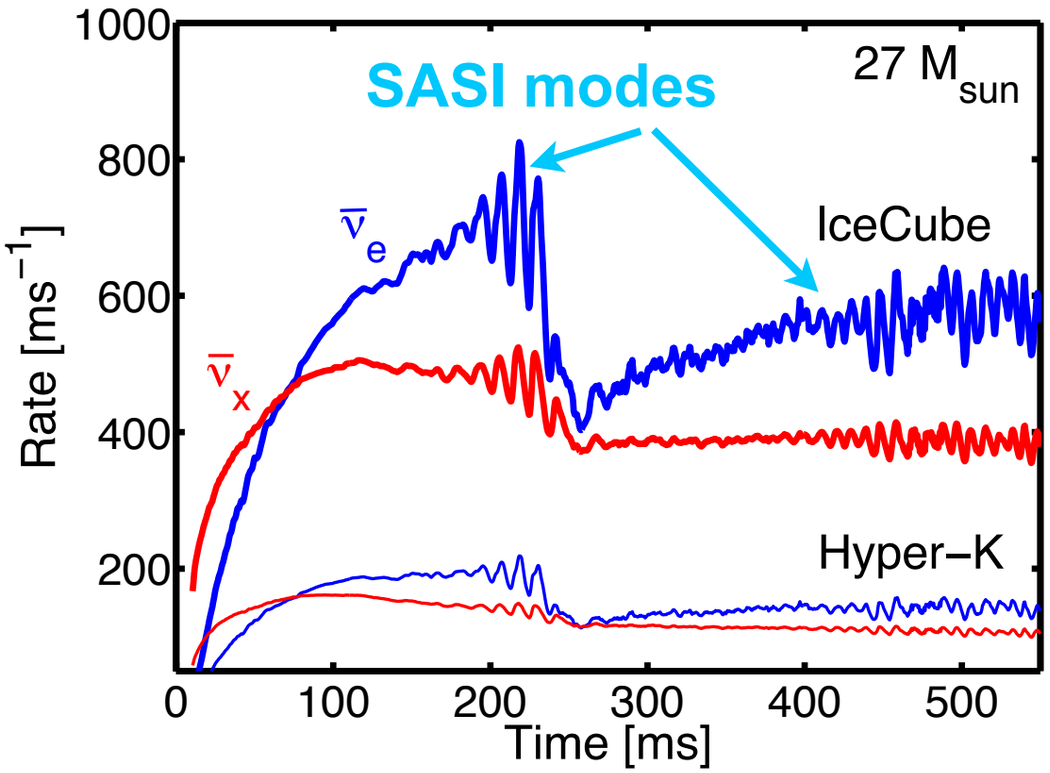
Synthesis of new elements could not happen without neutrinos.

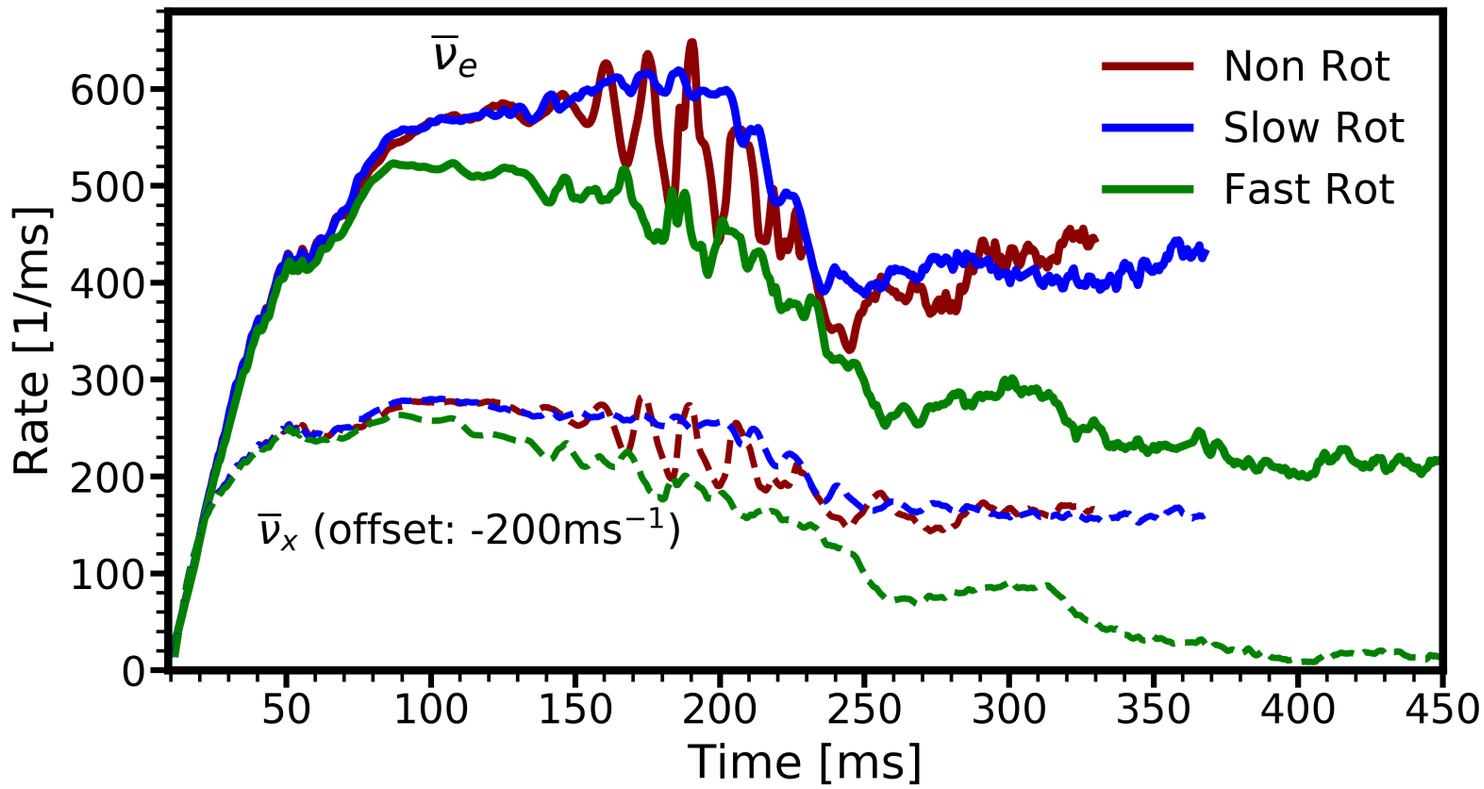
$$n + \nu_e \rightarrow e^- + p$$

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

Probe of Supernova Dynamics

Predicted neutrino "lightcurves":





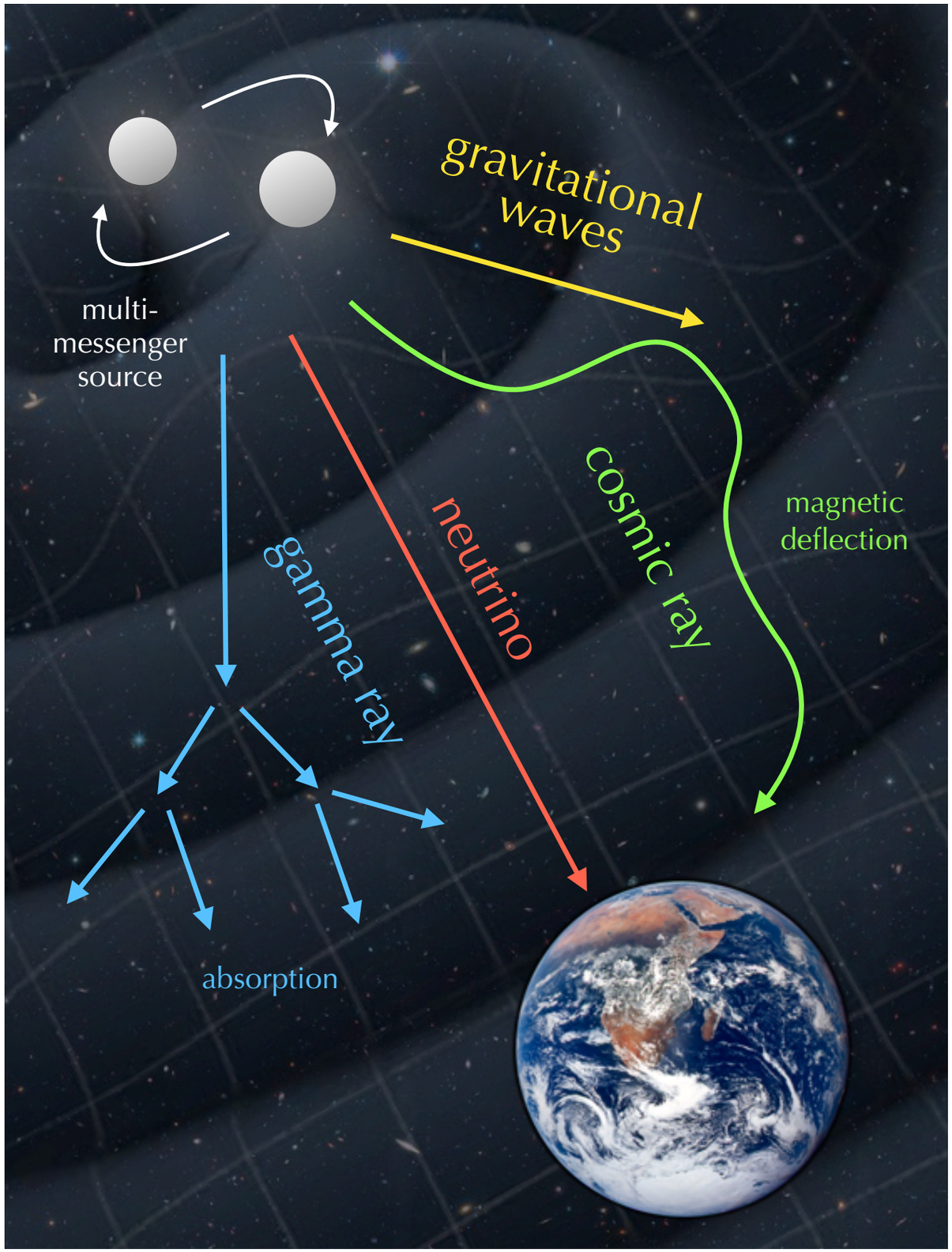
[Tamborra et al., **PRD** 90, 123001 (2014) & **PRD** 98, 123001(2018)]

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

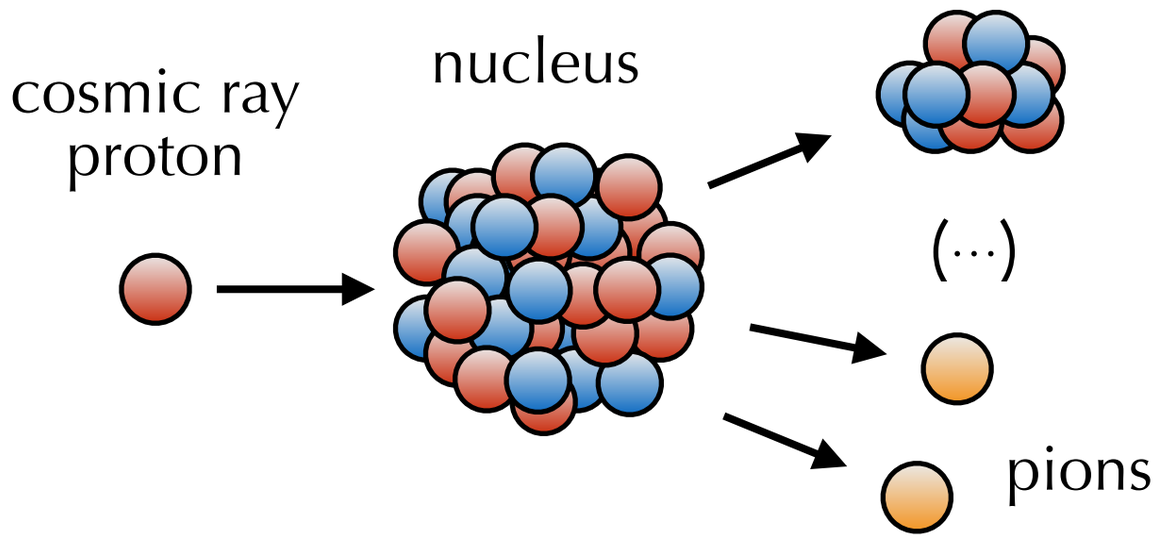
Complementary information from detection of gravitational waves.

Neutrinos In & From Cosmic Accelerators

Multi-Messenger Astronomy



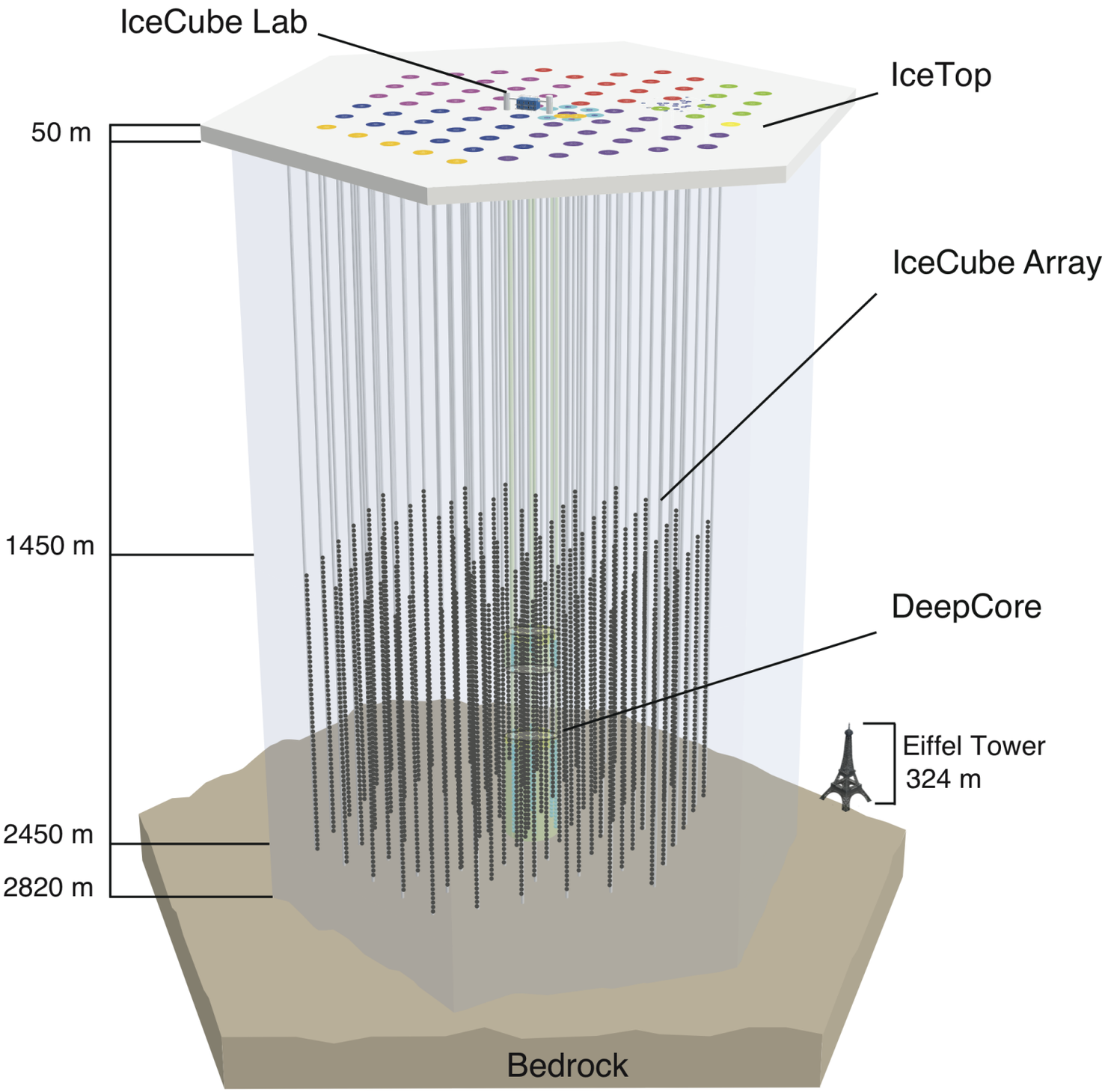
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.



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

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

IceCube Observatory

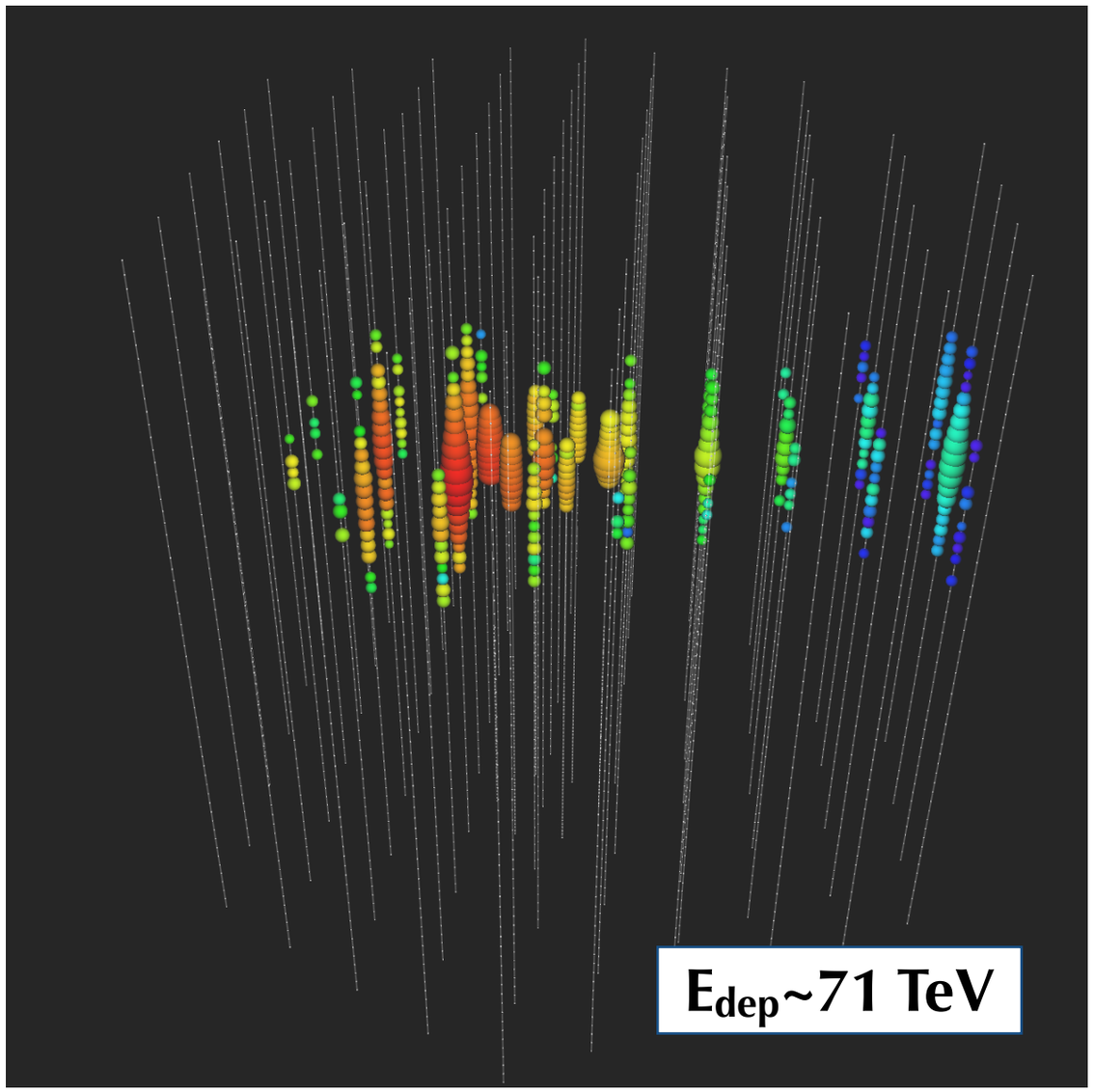


- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections
- price tag: ~**2 DKK per ton**

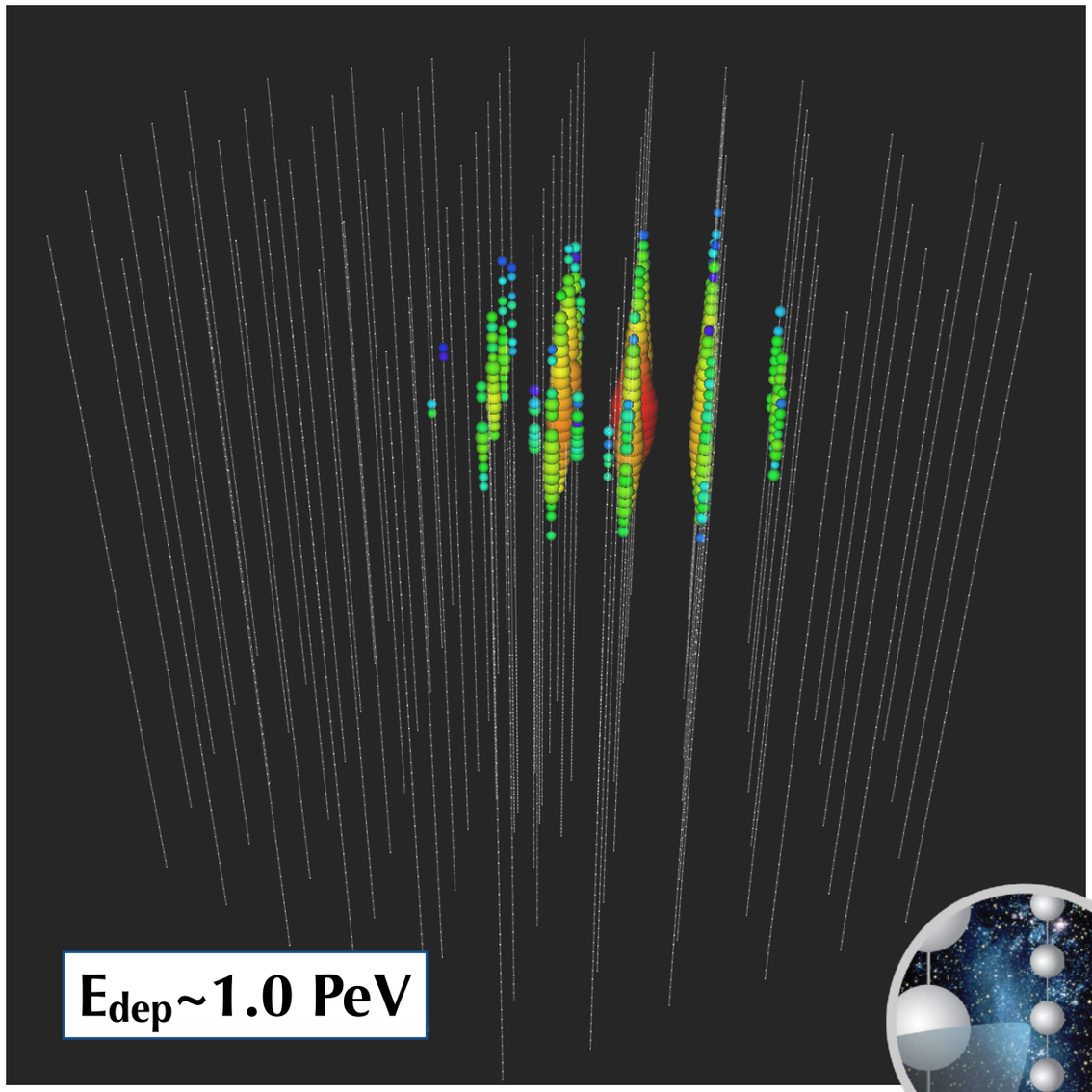
Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering)



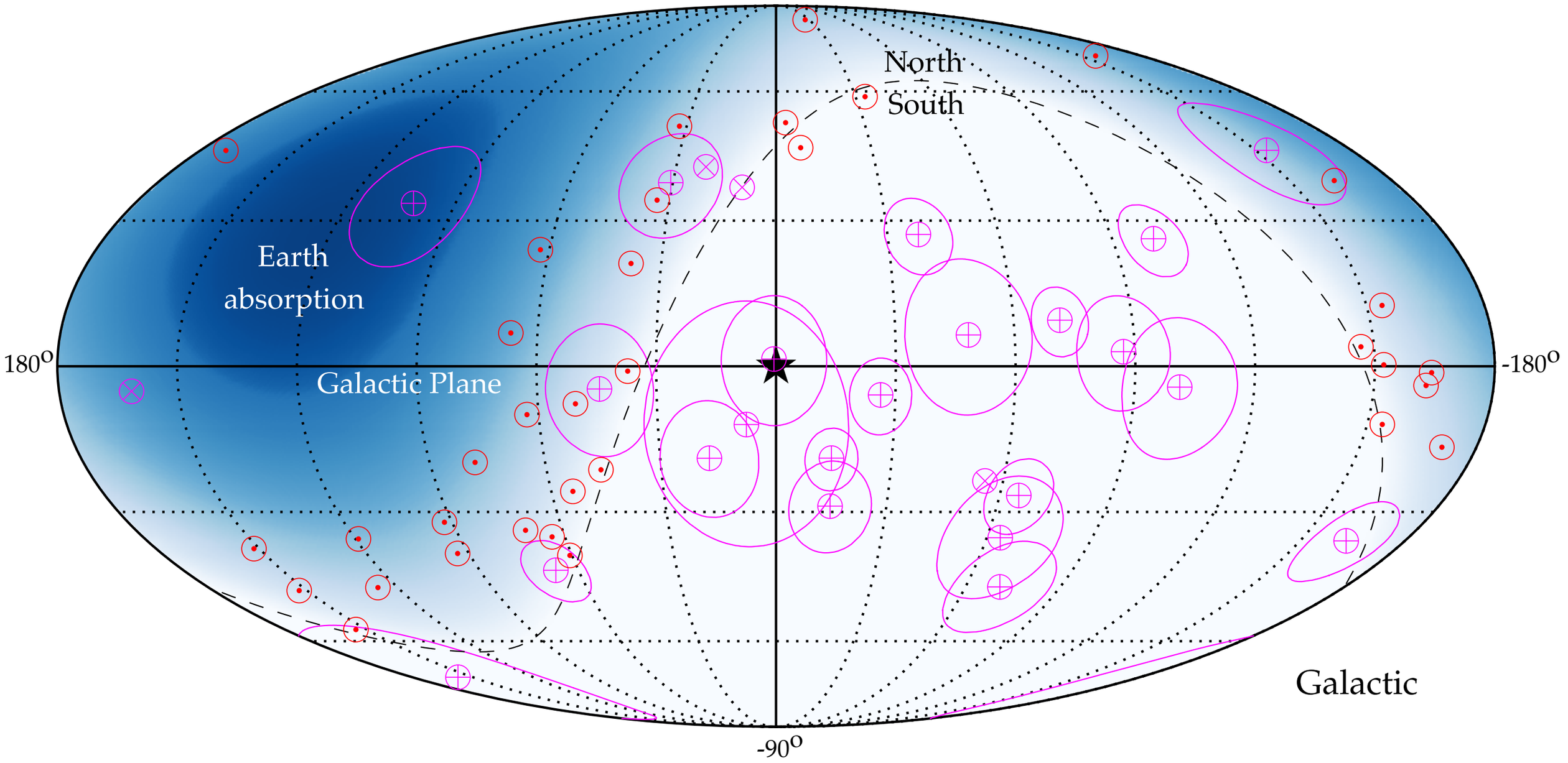
"cascade event" (from all flavours)



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

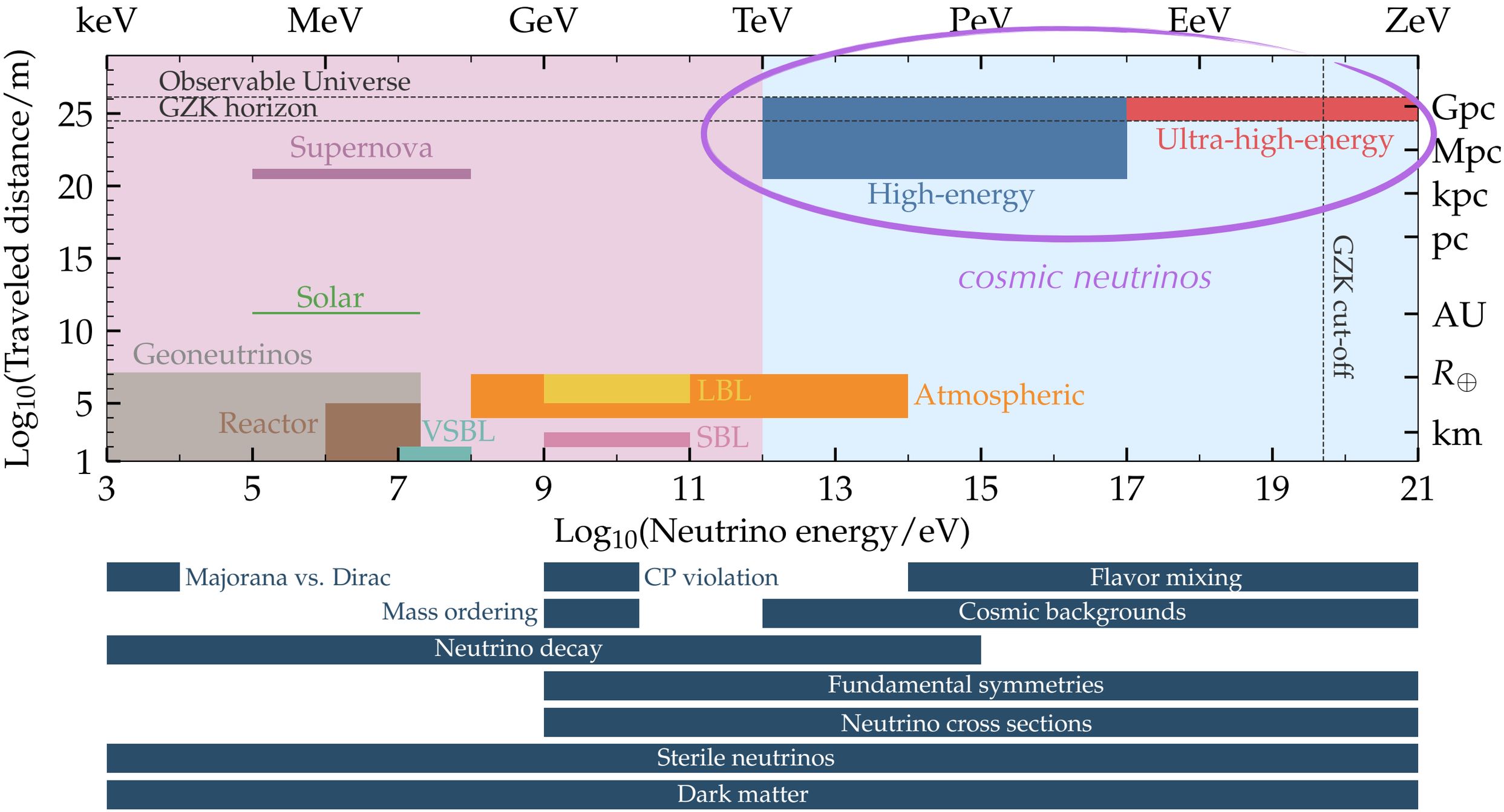
Status of Neutrino Astronomy

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*).

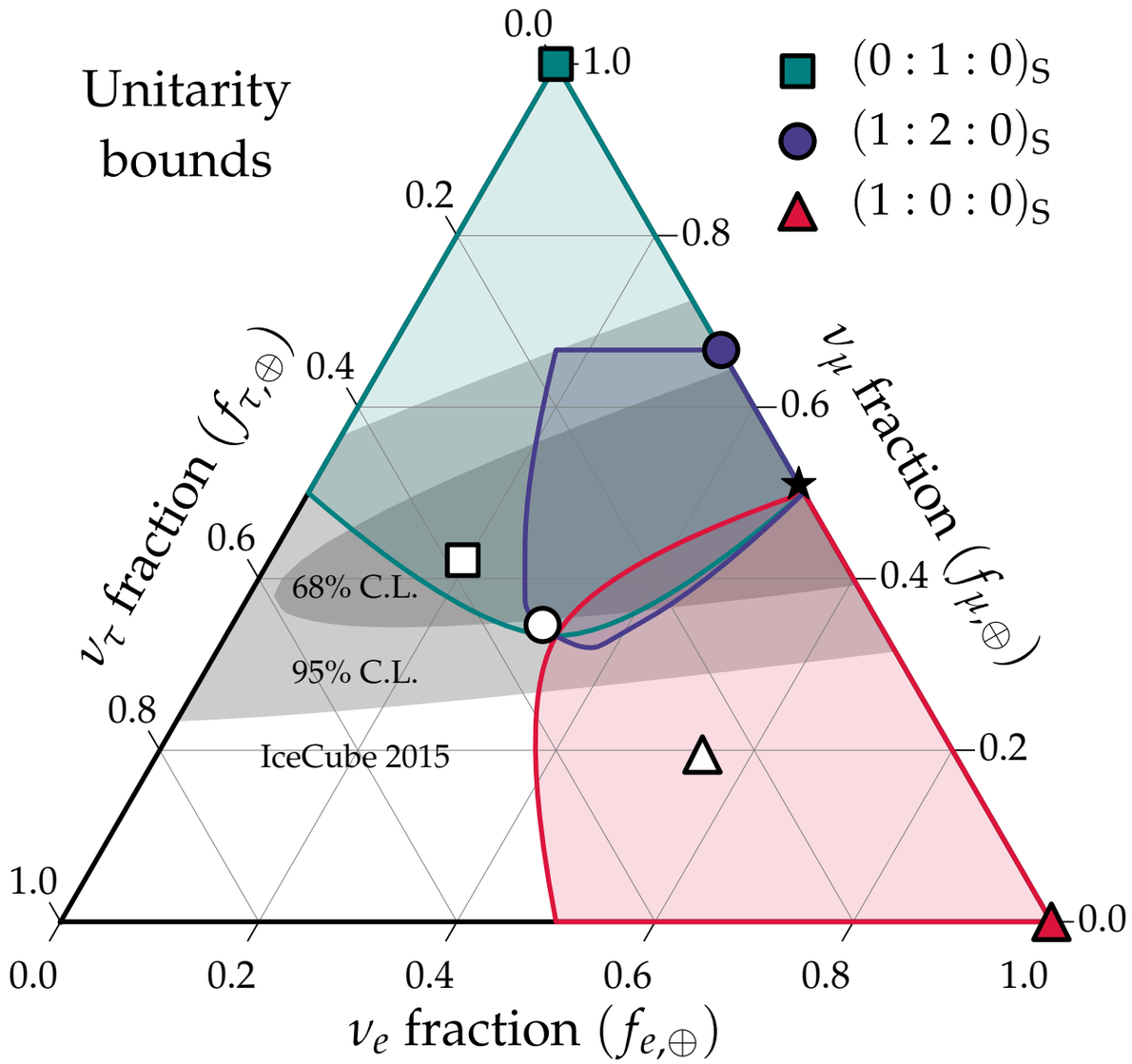
Probe of Fundamental Physics



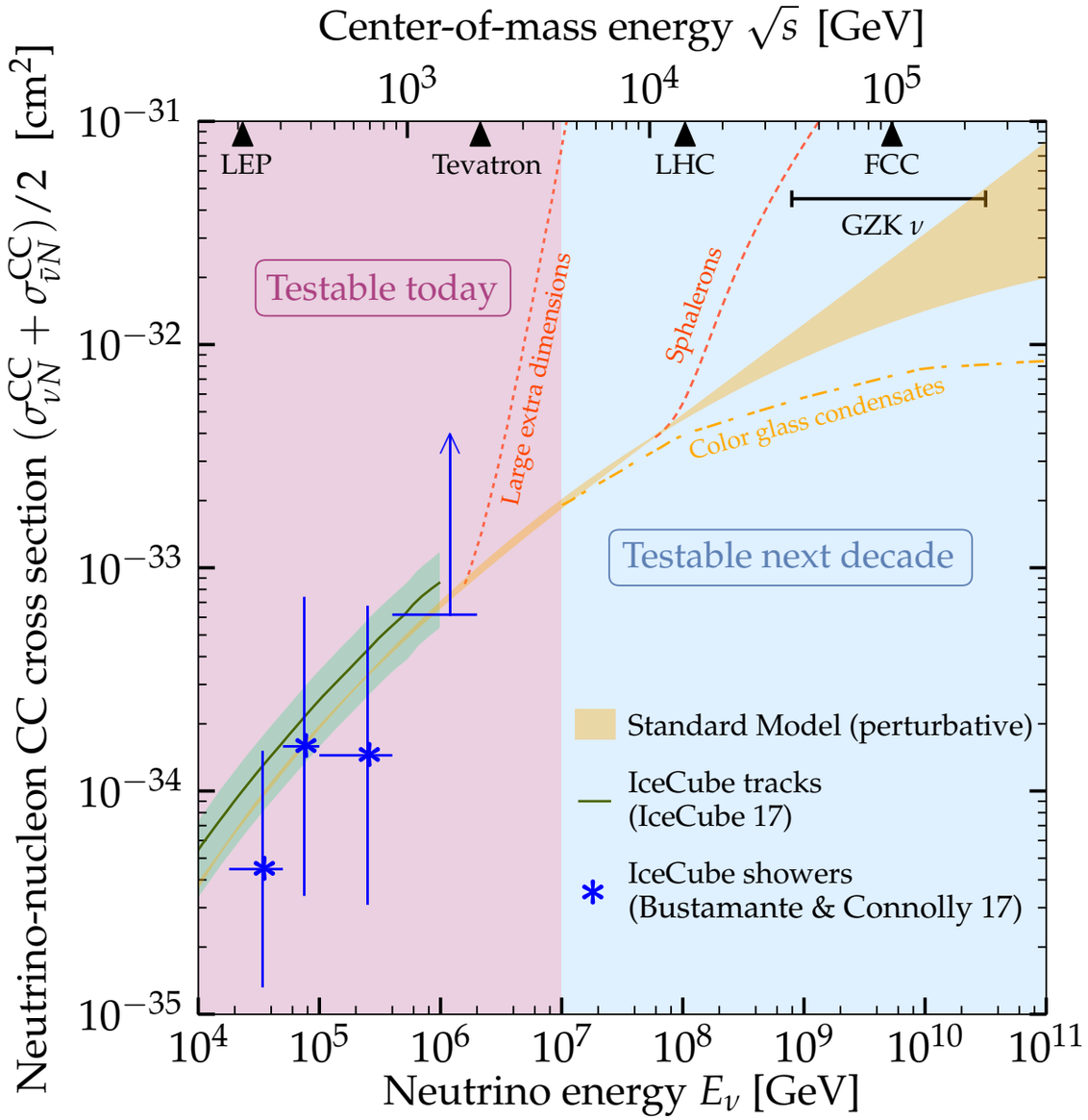
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04334]

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, Ahlers, Anchordoqui, Bustamante *et al.*, *Astro2020* arXiv:1903.04333 & arXiv:1903.04334]

Summary

Neutrinos:

- Fundamental in most energetic phenomena in our Universe.
- Ideal messengers.
- Carry imprints of engine and population of extreme transients.
- Affect element formation in astrophysical sources.
- Their flavor conversions are crucial but yet to be fully grasped.

M.Sc. projects in Neutrino Astrophysics can cover various aspects:

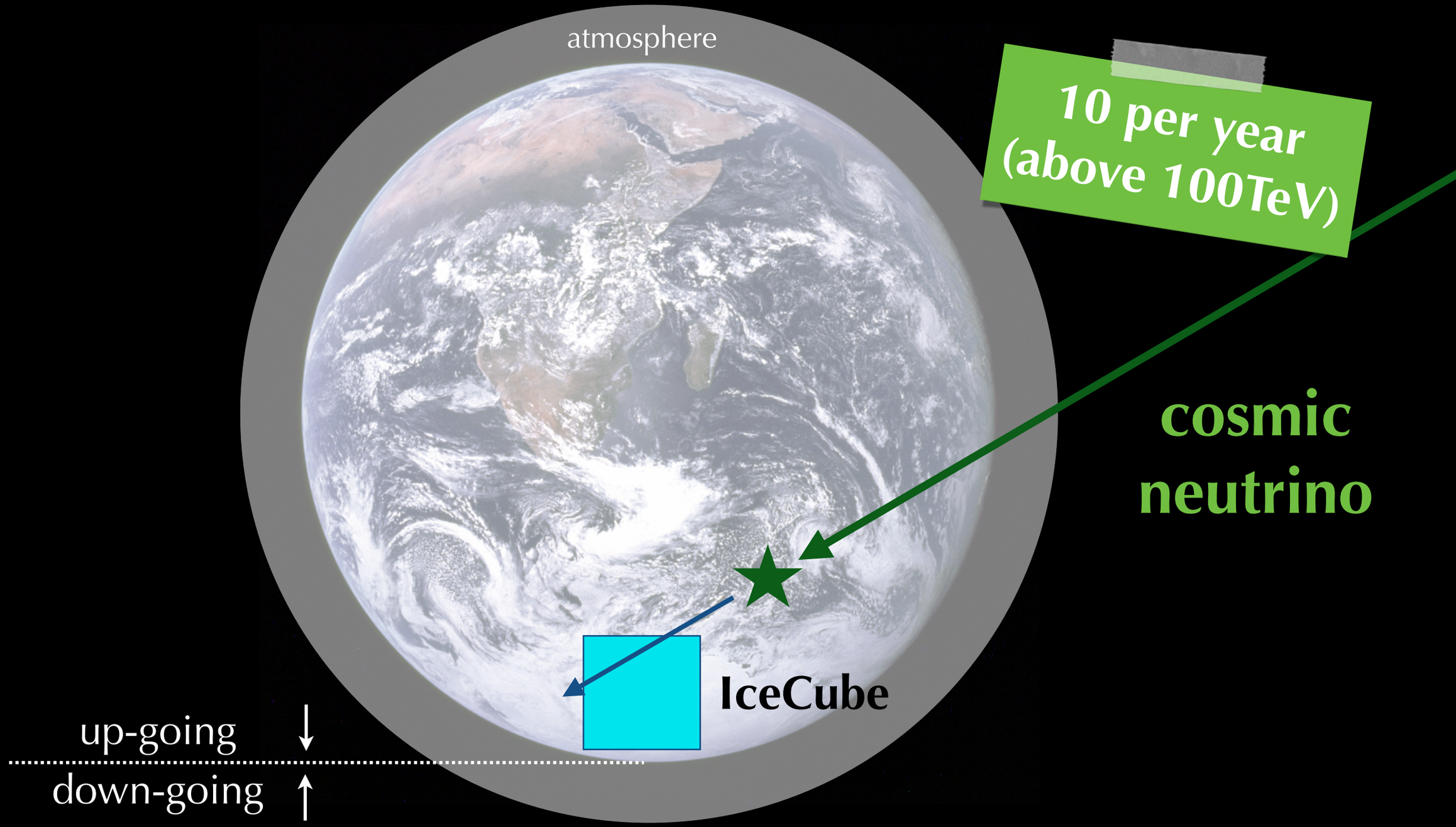
- **impact on stellar evolution**
- **potential to probe astrophysical environments**
- **fundamental neutrino properties**
- **direct probe of the origin of cosmic rays**
- **observation in neutrino telescopes or experiments**

Thank you

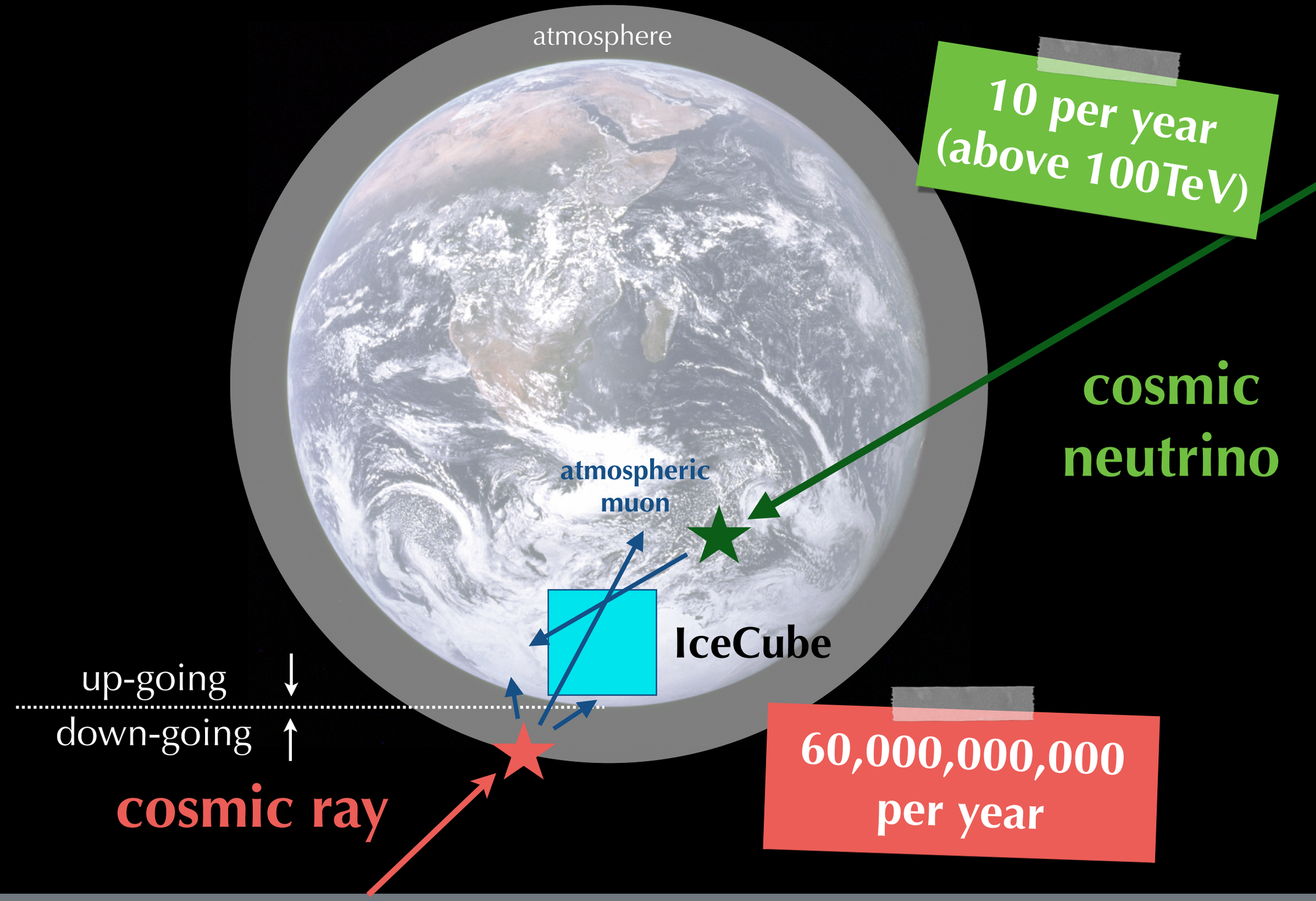
for your attention!

Backup Slides

Neutrino Selection I



Neutrino Selection I



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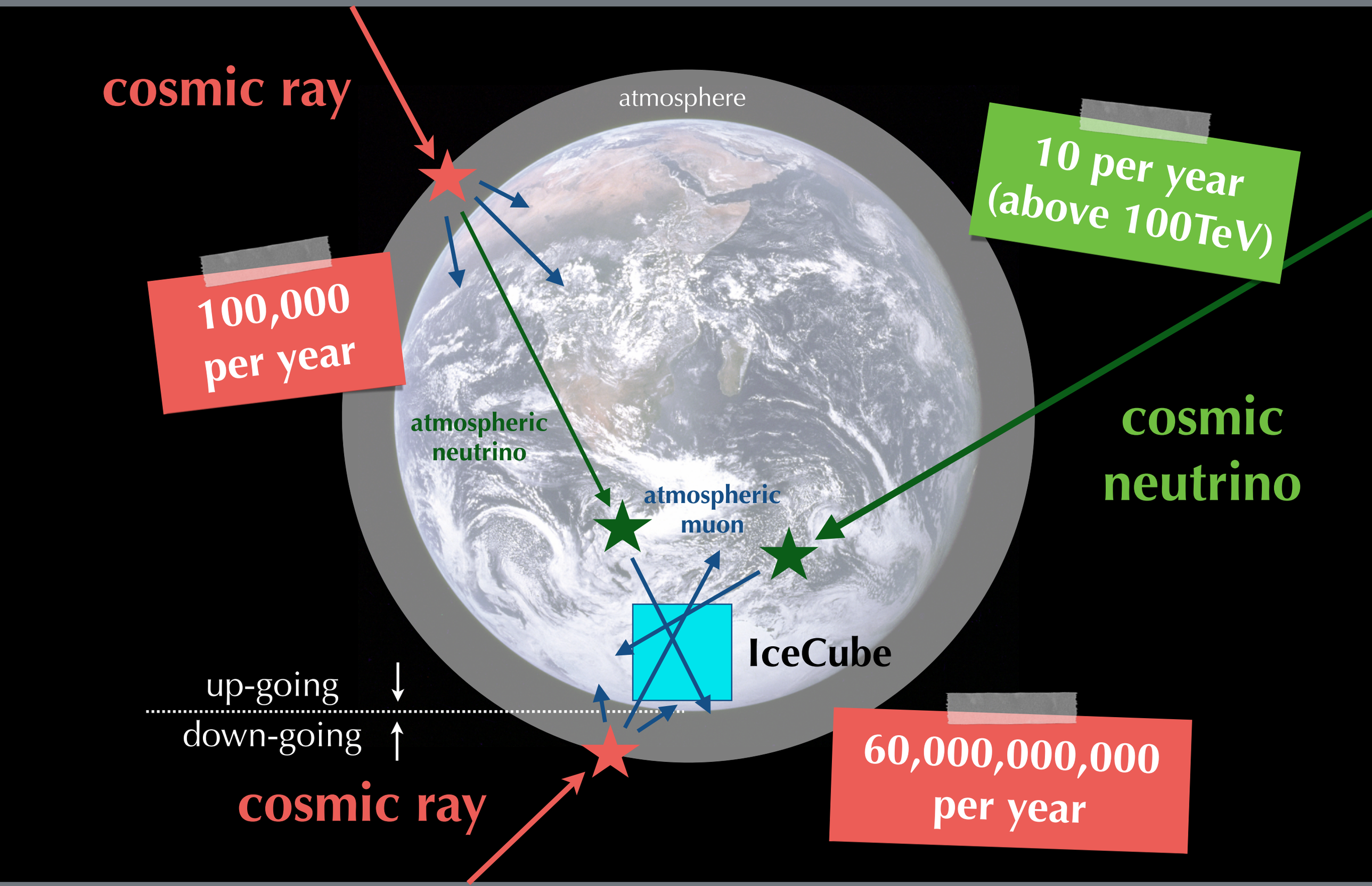
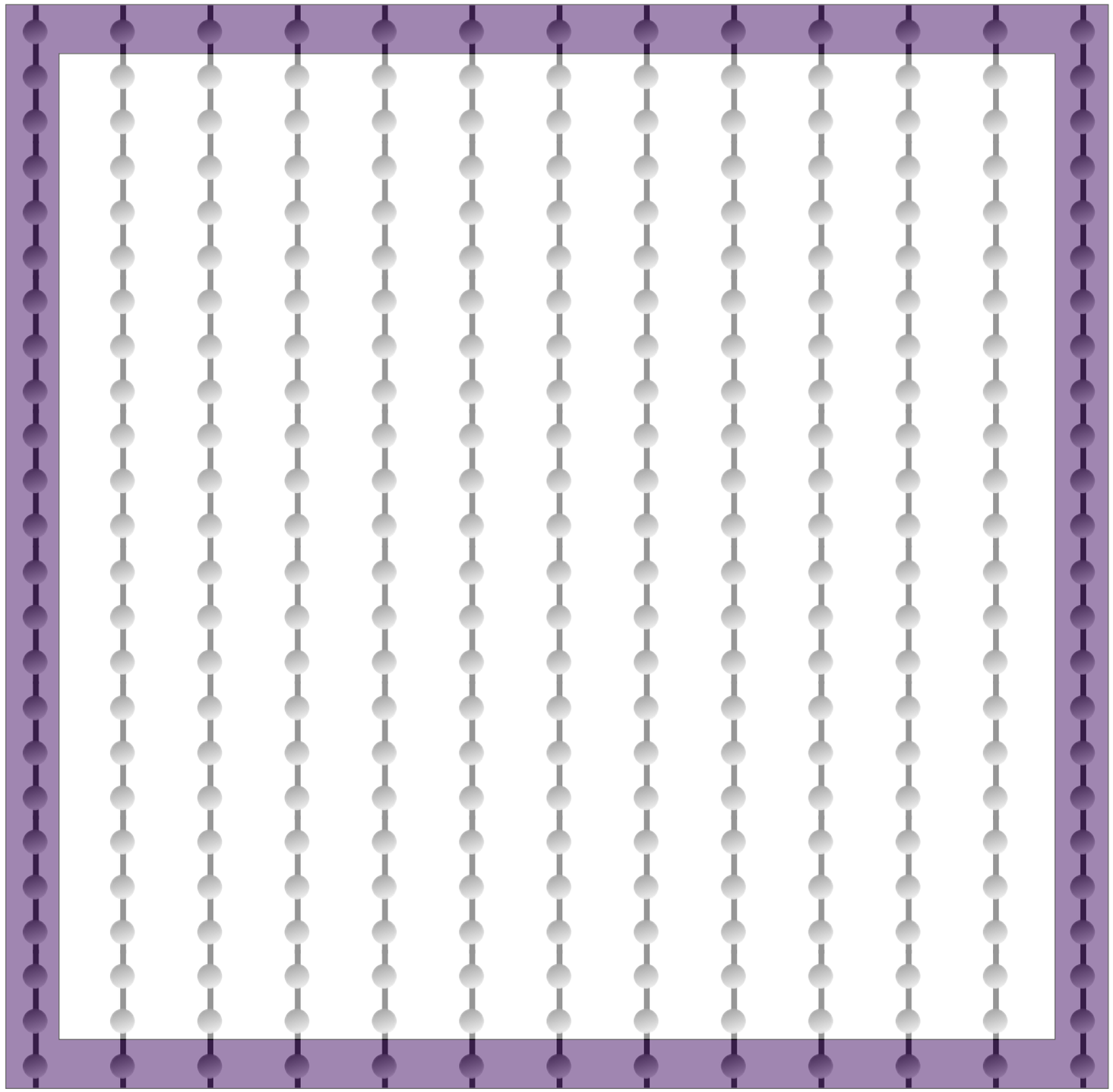


Neutrino Selection II

- 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



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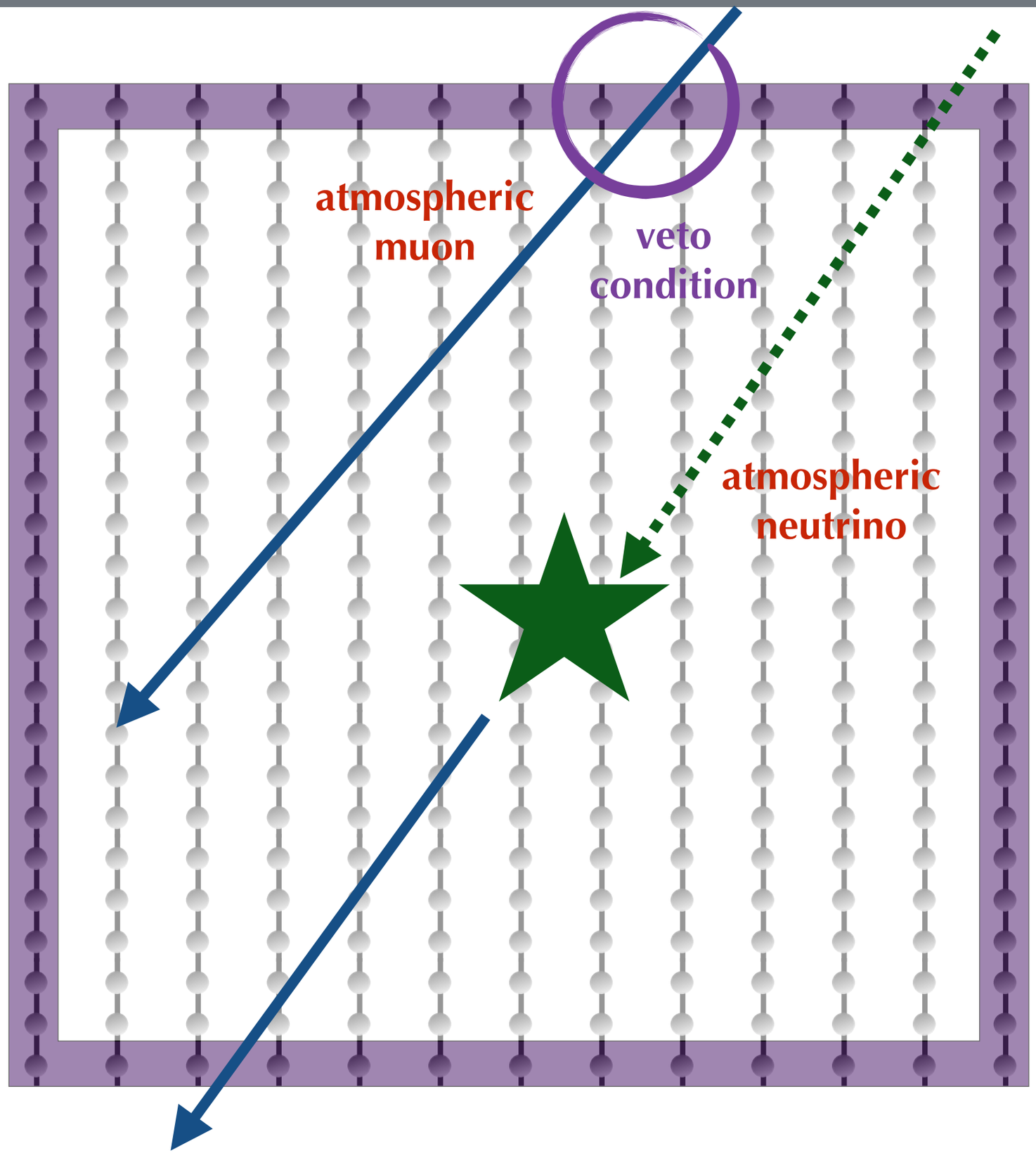

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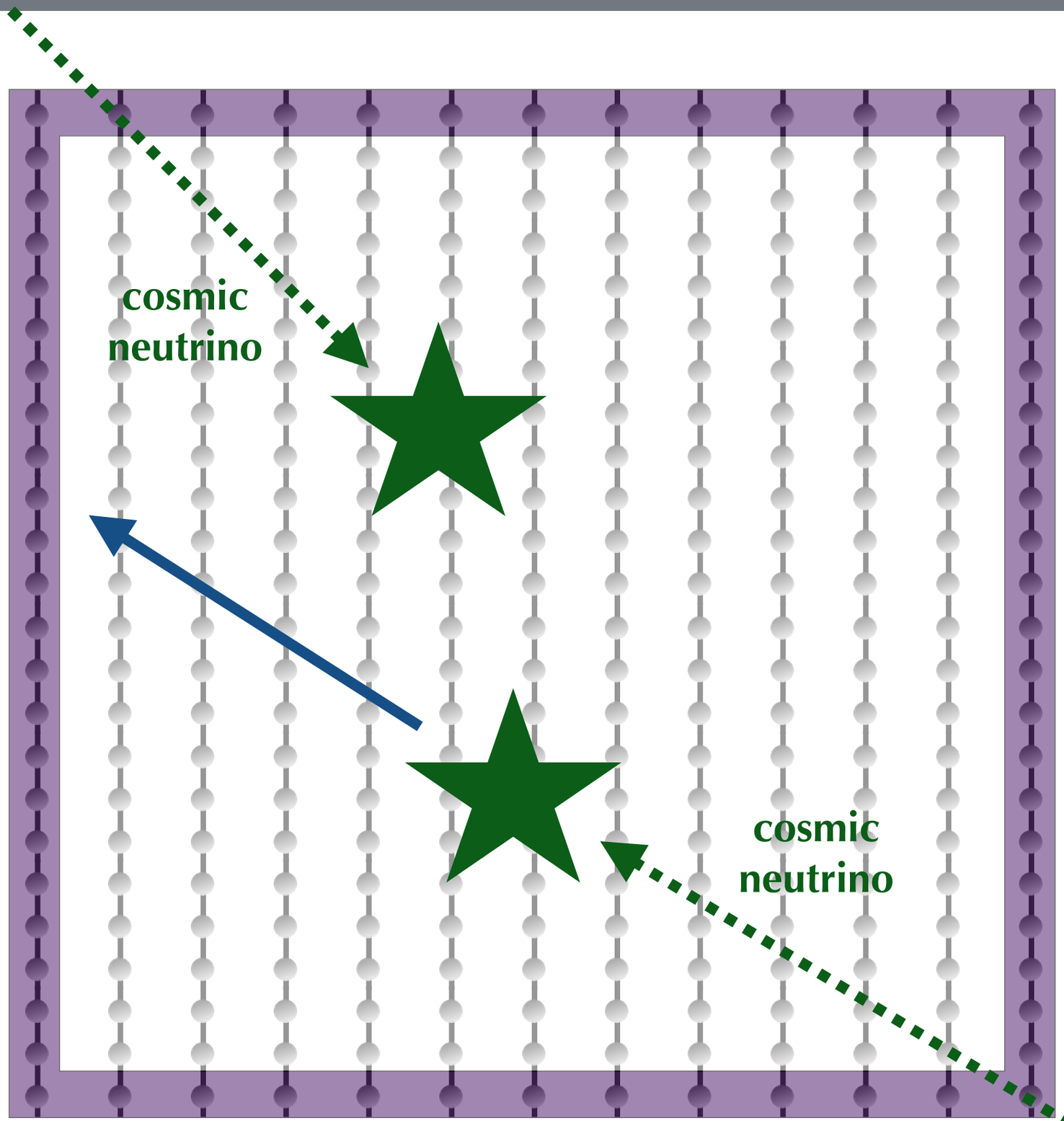
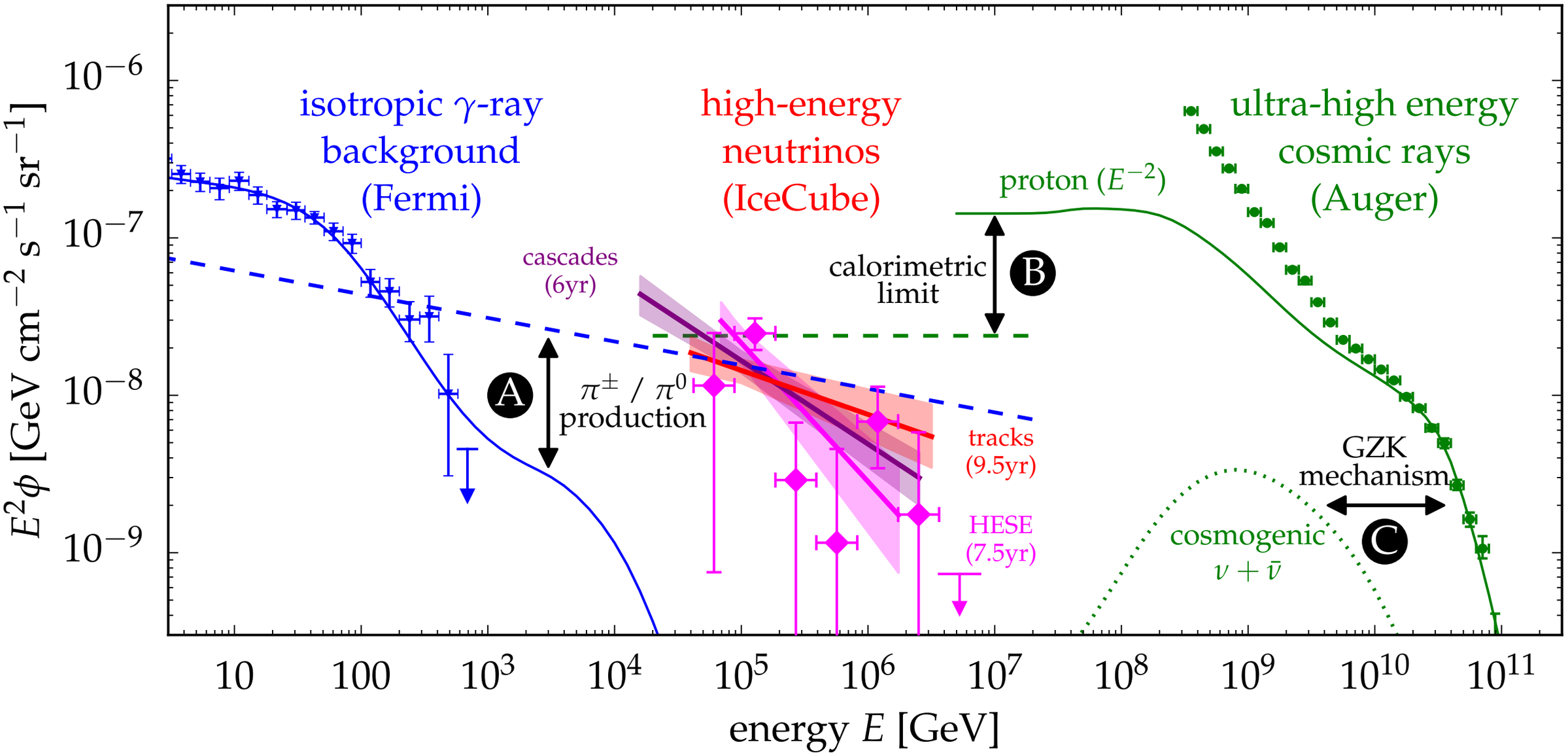


Multi-Messenger Interfaces

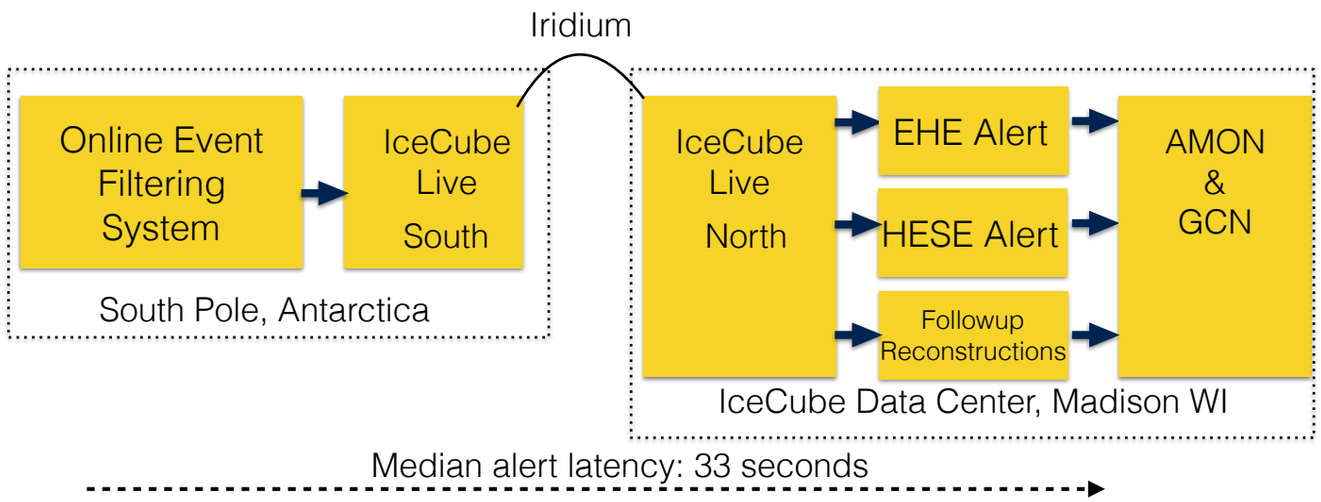


The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

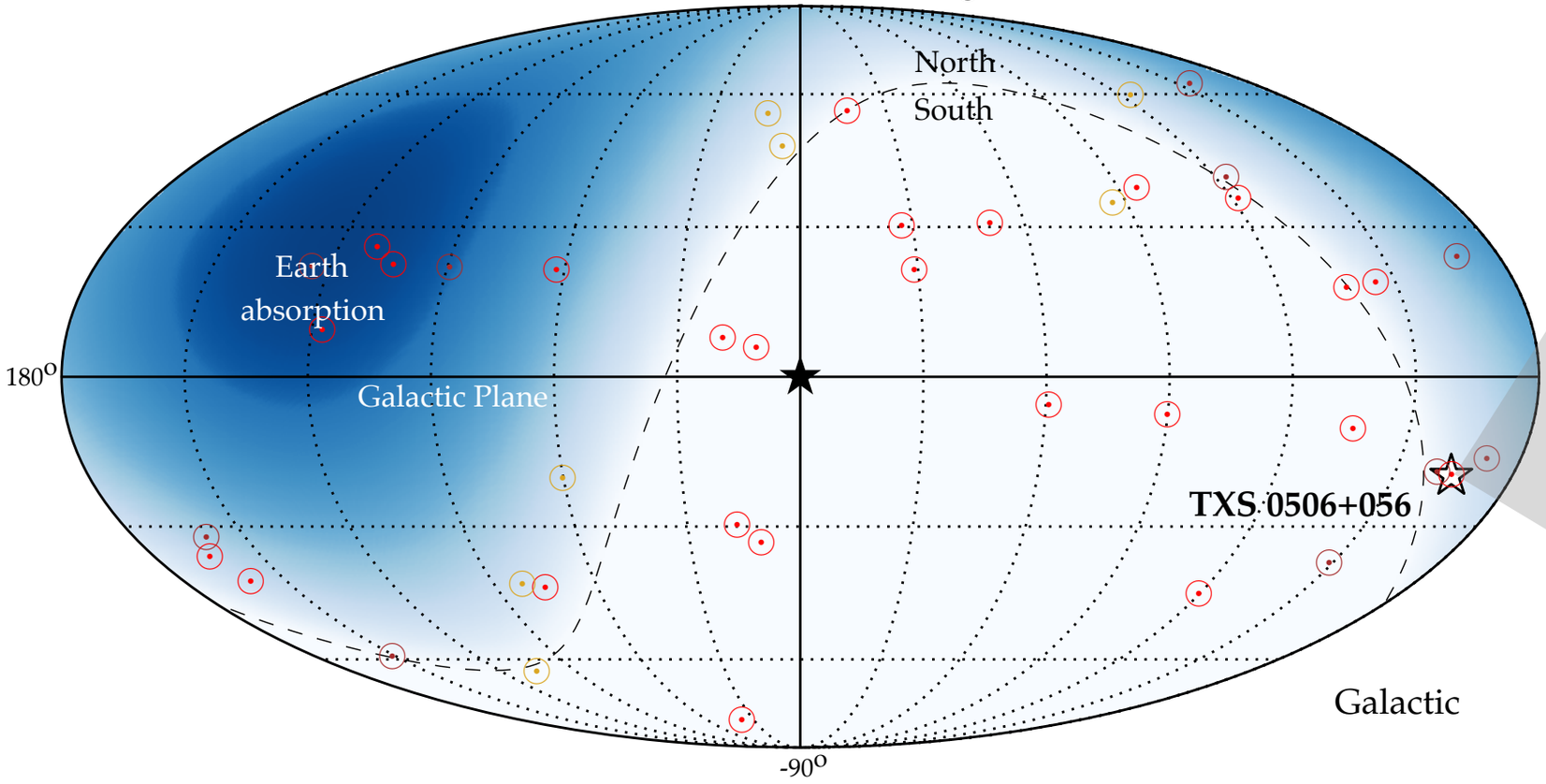
Realtime Neutrino Alerts

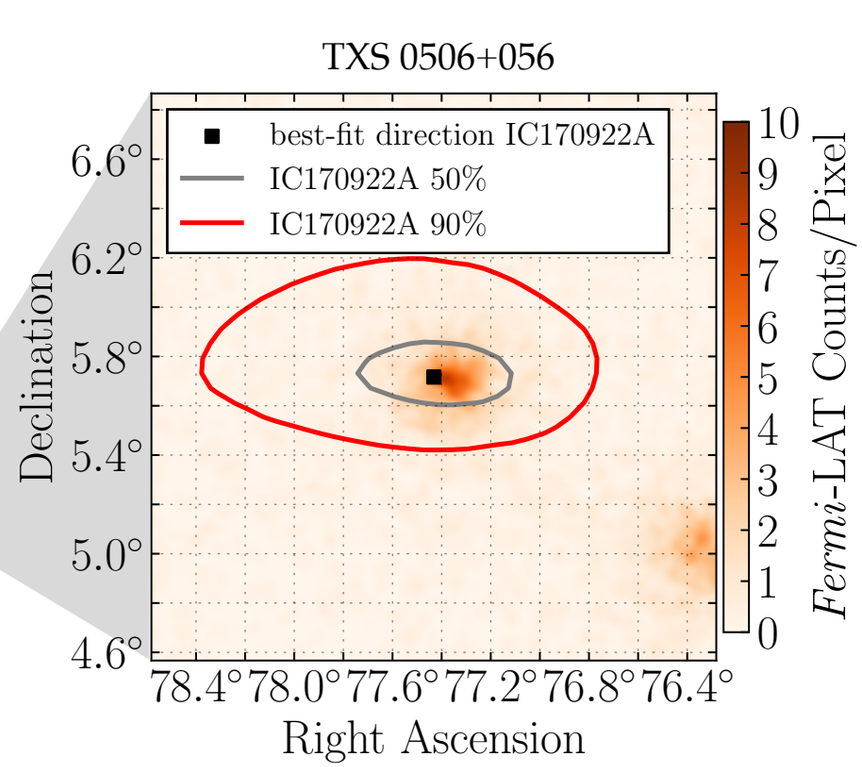
Low-latency (<1min) **public neutrino alert system** established in April 2016.

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

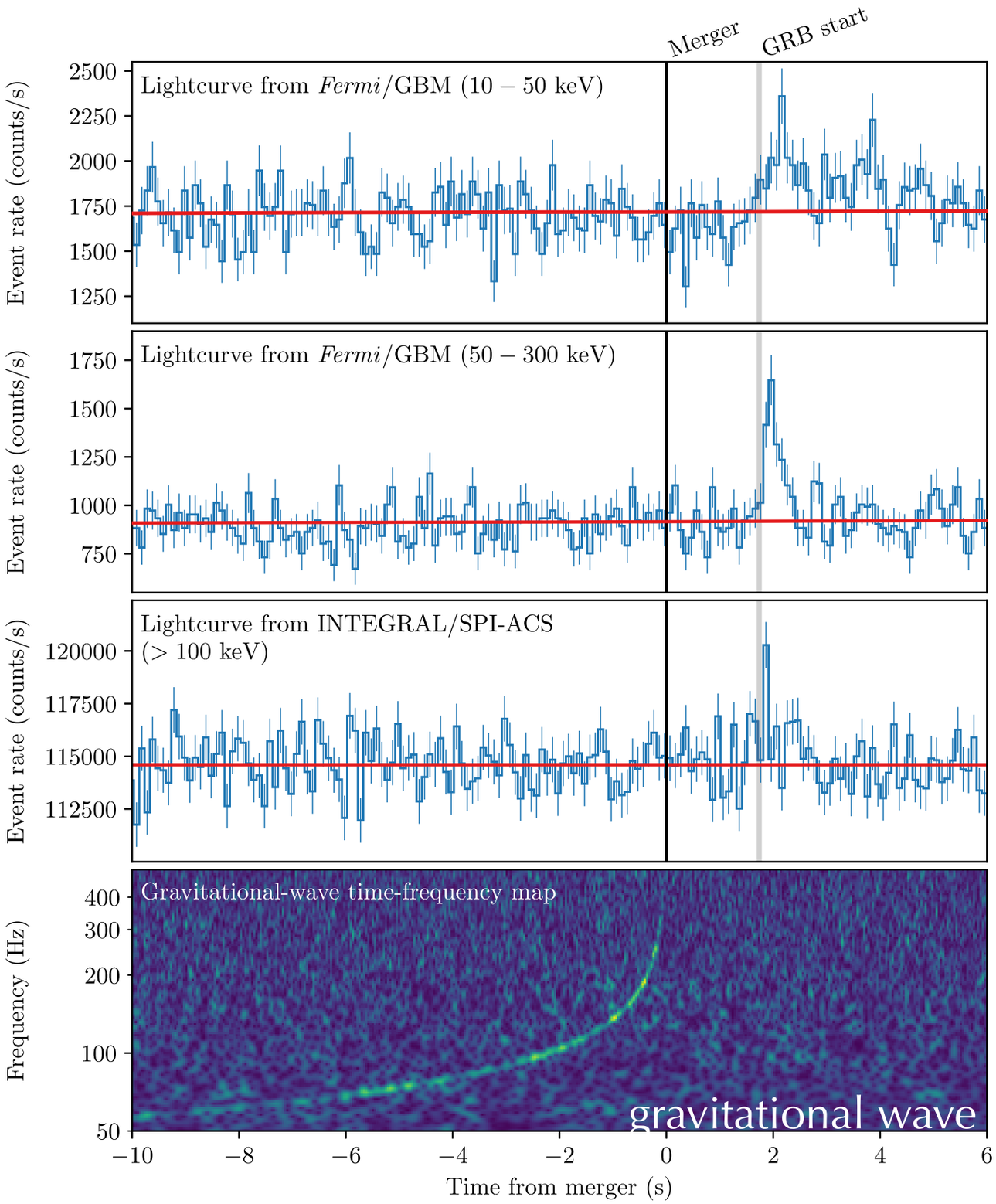


Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))

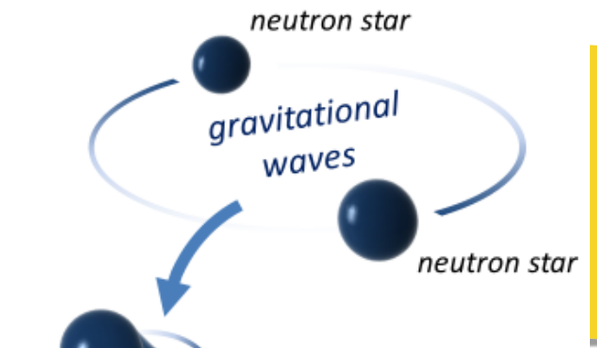




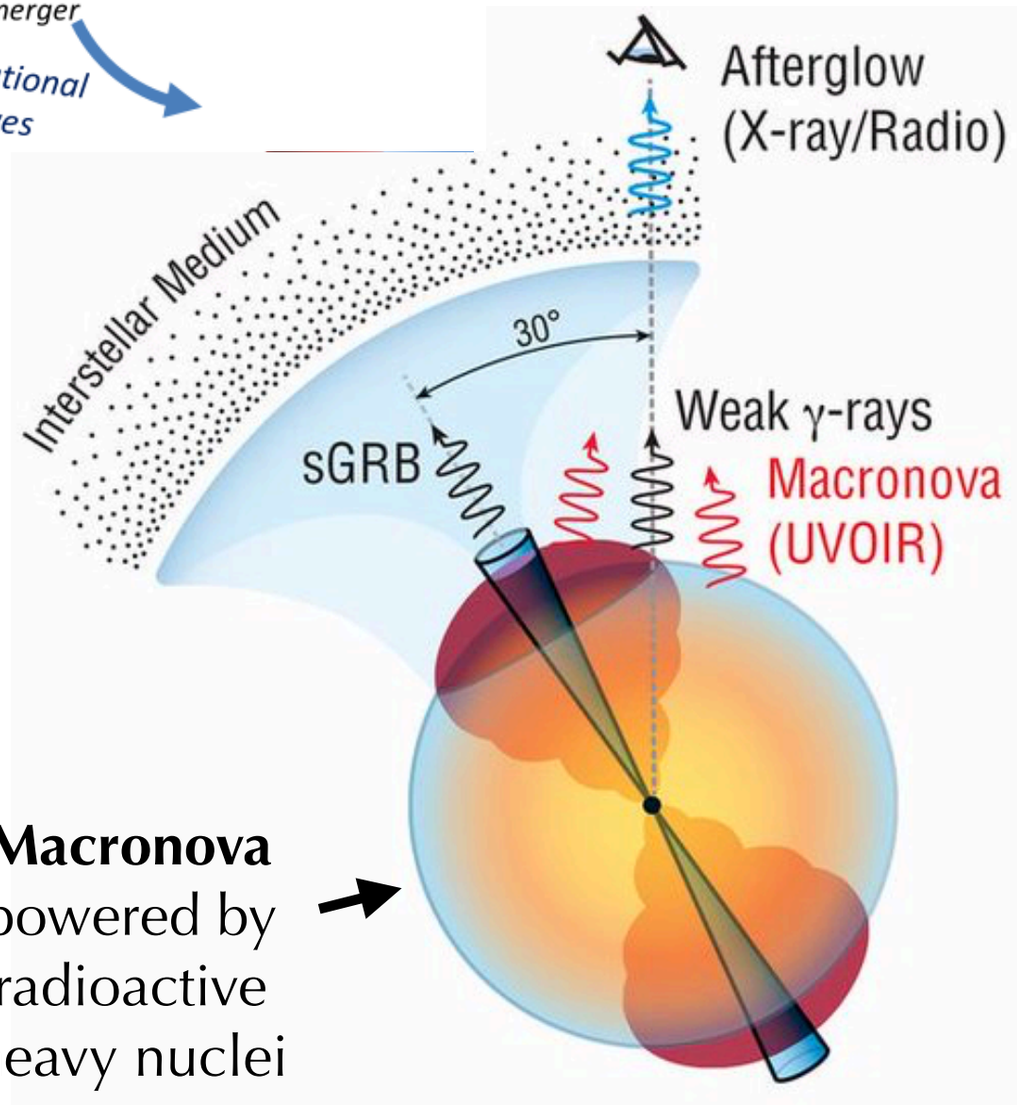
GRBs and Gravitational Waves



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

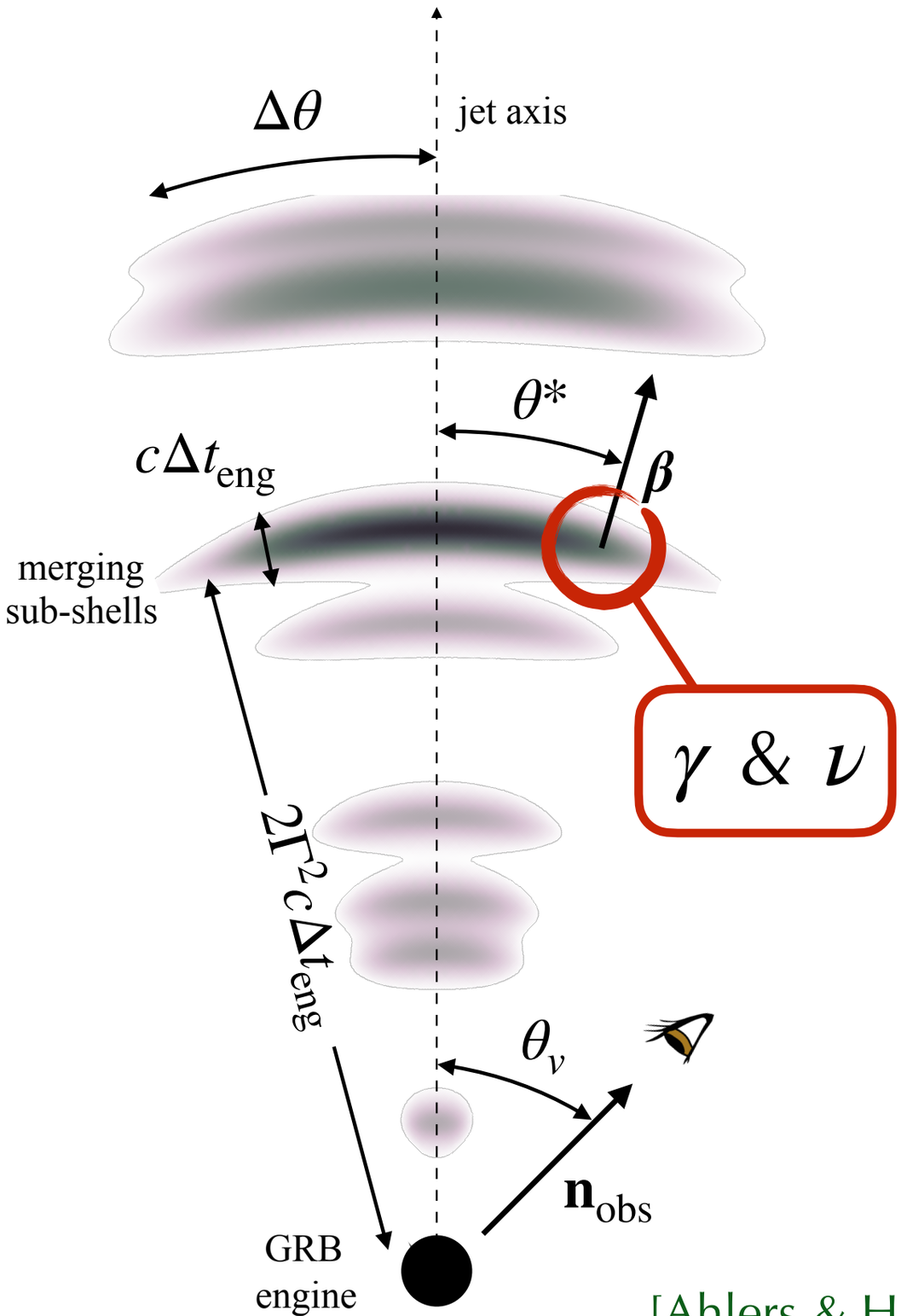


GW 170817
&
GRB 170817A

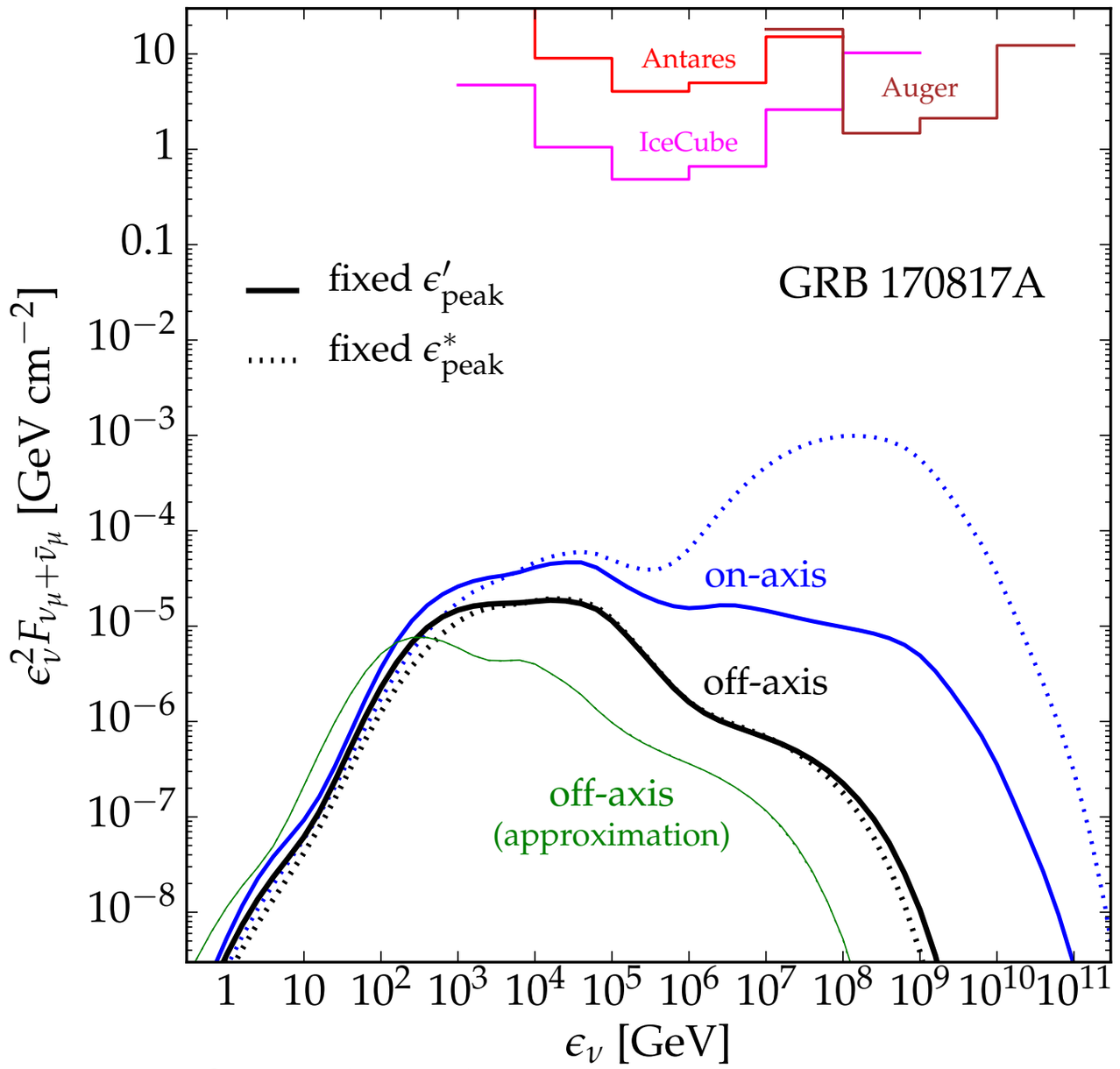


Macronova powered by radioactive heavy nuclei

GRB 170817A - Revisited



Revised neutrino emission in the from
off-axis emission of structured jets.



[Ahlers & Halser **MNRAS** 490 (2019)]