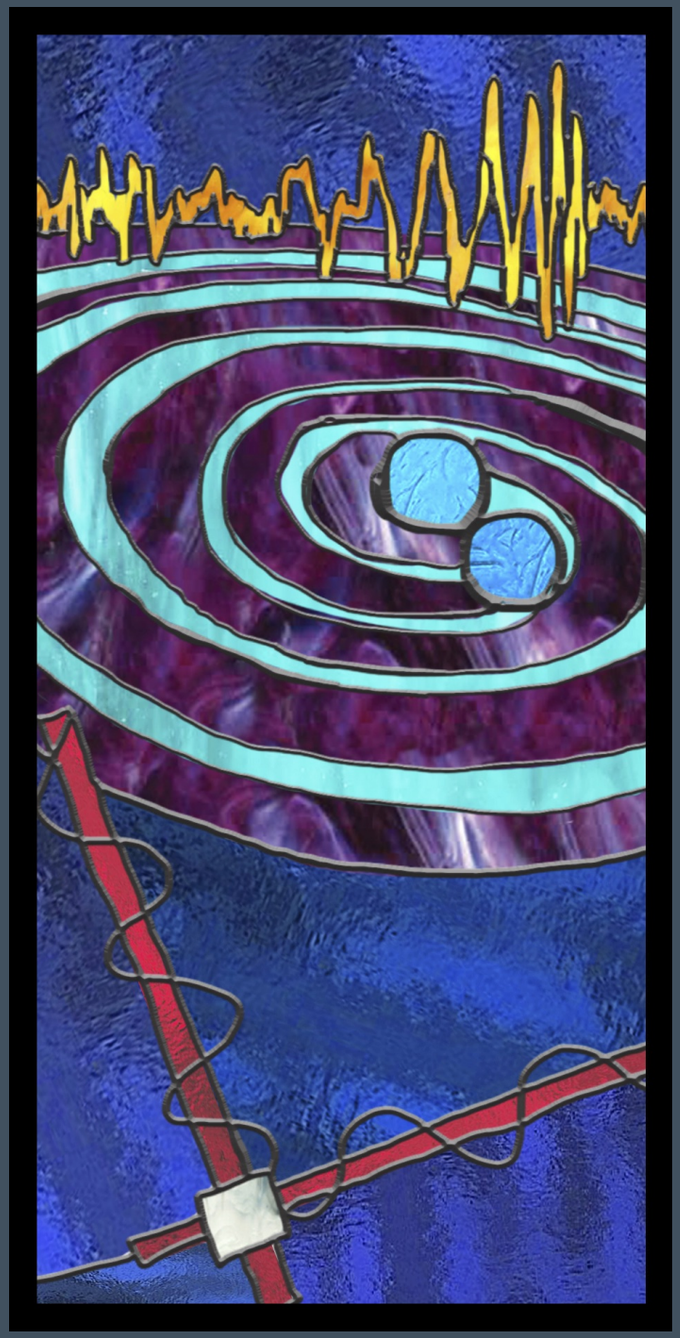

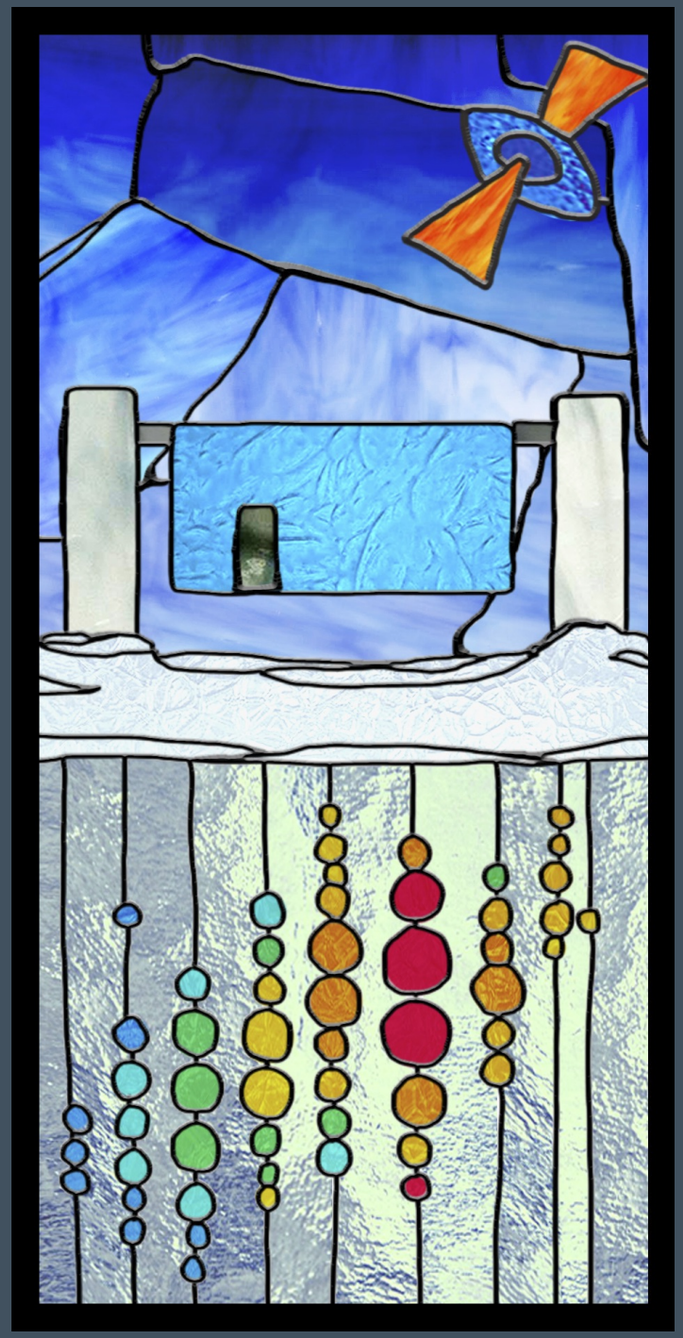

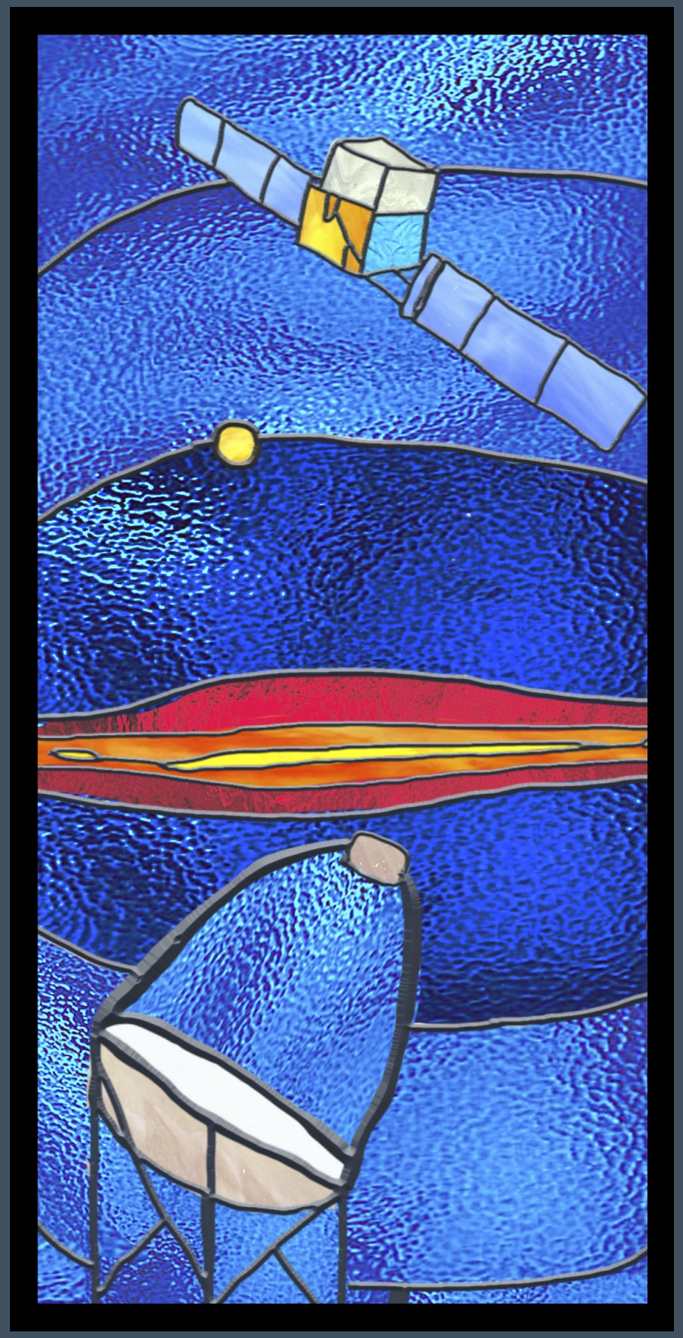

Neutrino Astrophysics

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

MSc Day, October 13, 2021

Who are we?

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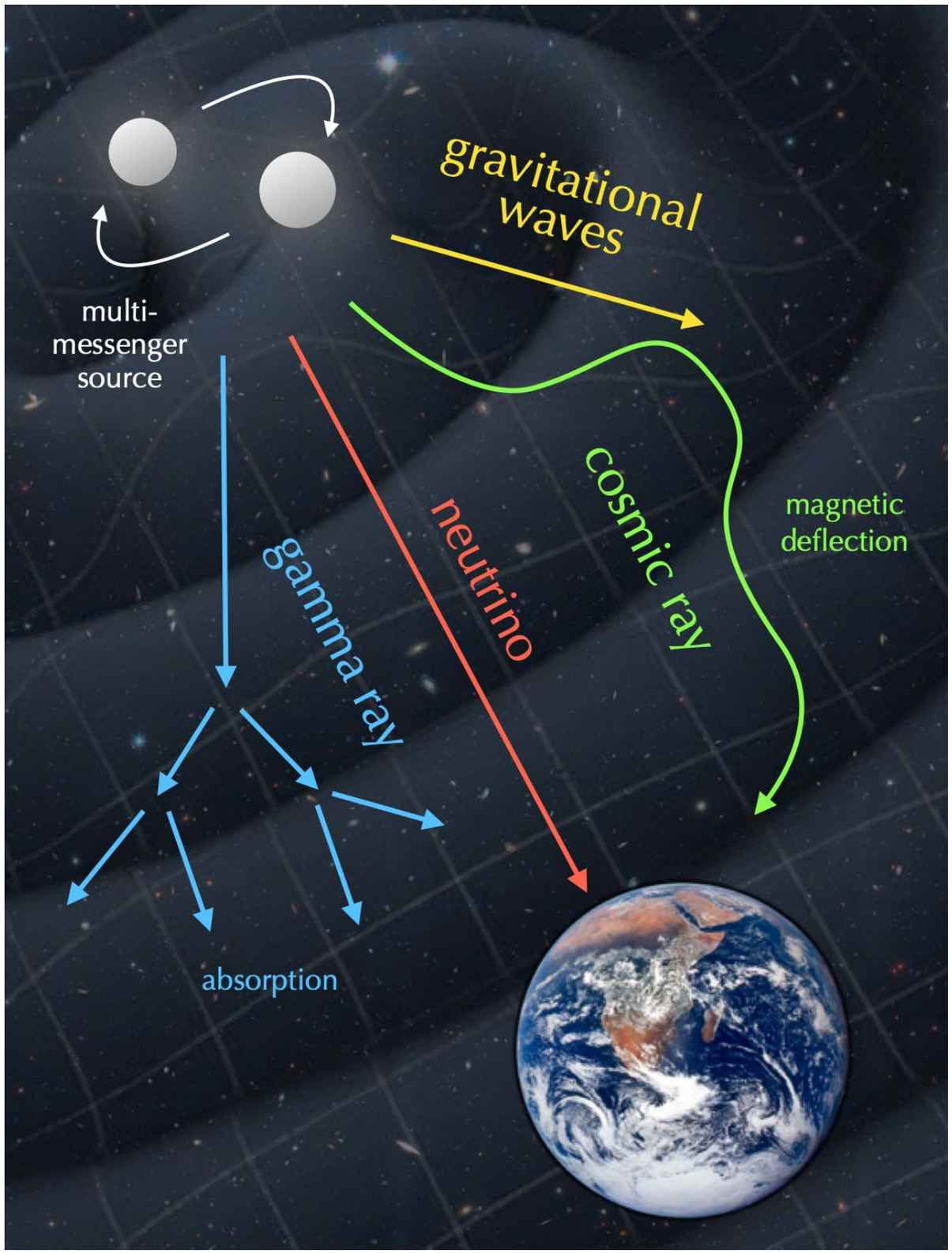
The Elusive Neutrino

- **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

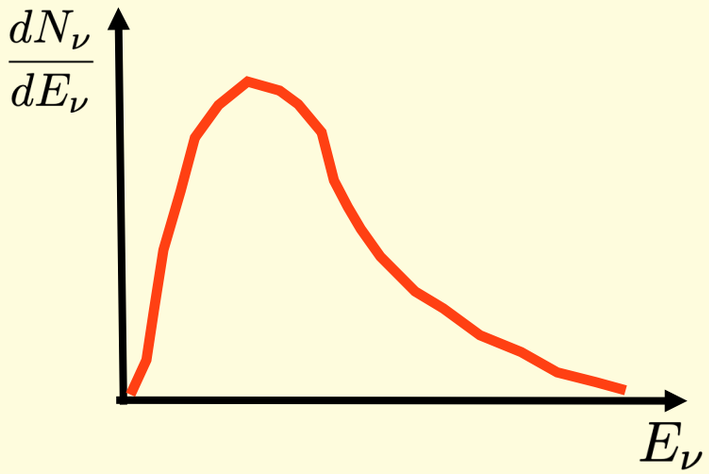
coincident with
photons and gravitational waves

BUT, very difficult to detect!

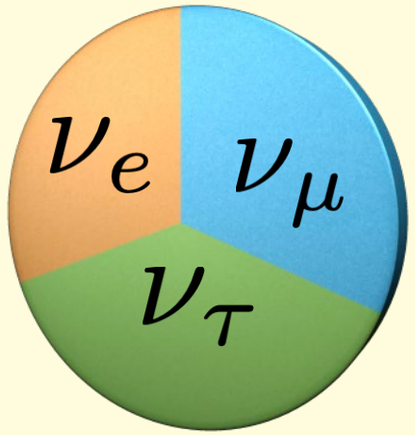
Powerful Probes in Astrophysics

Neutrinos provide us with:

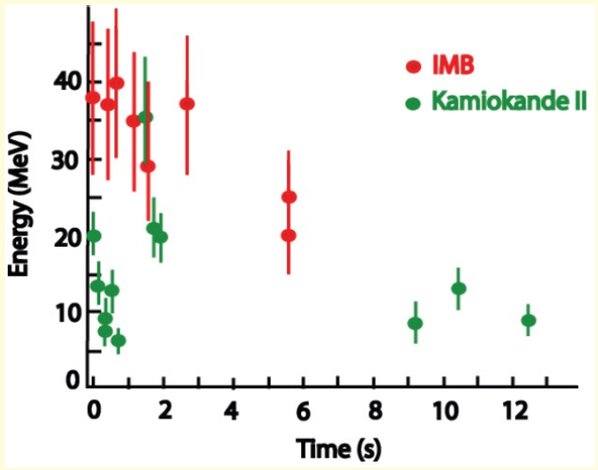
1. Energy Distribution



2. Flavor Ratios

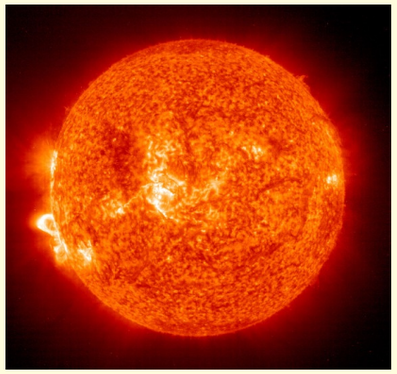


3. Light Curve

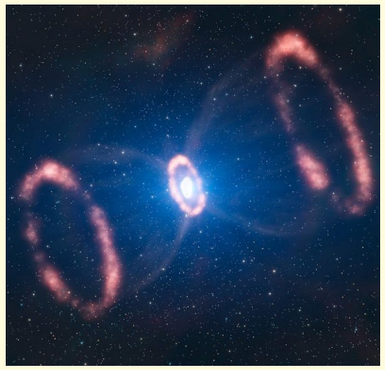


Neutrinos are copiously produced in astrophysical sources, e.g.

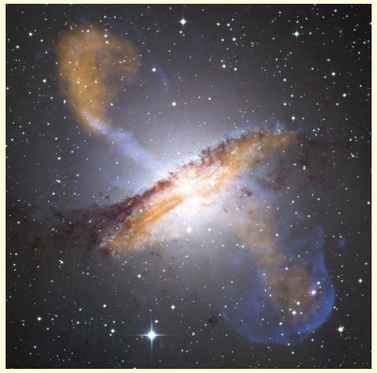
The Sun



Supernovae



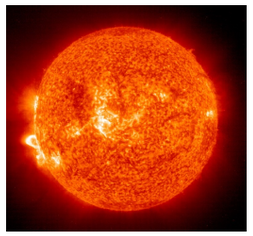
Active Galaxies

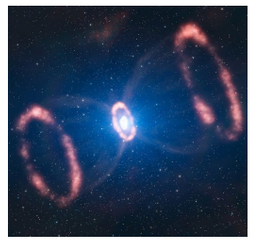


Gamma-ray Bursts

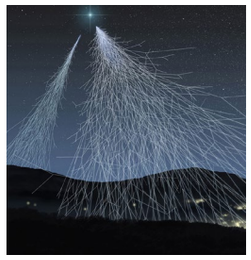
Non-Anthropogenic Neutrino Fluxes

The Sun





SN 1987A



atmosphere

cosmic neutrinos

energy scale

atomic masses

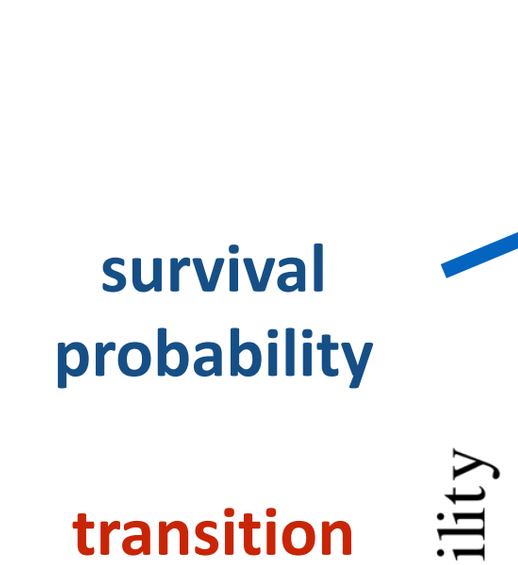
particle accelerators

penalty kick

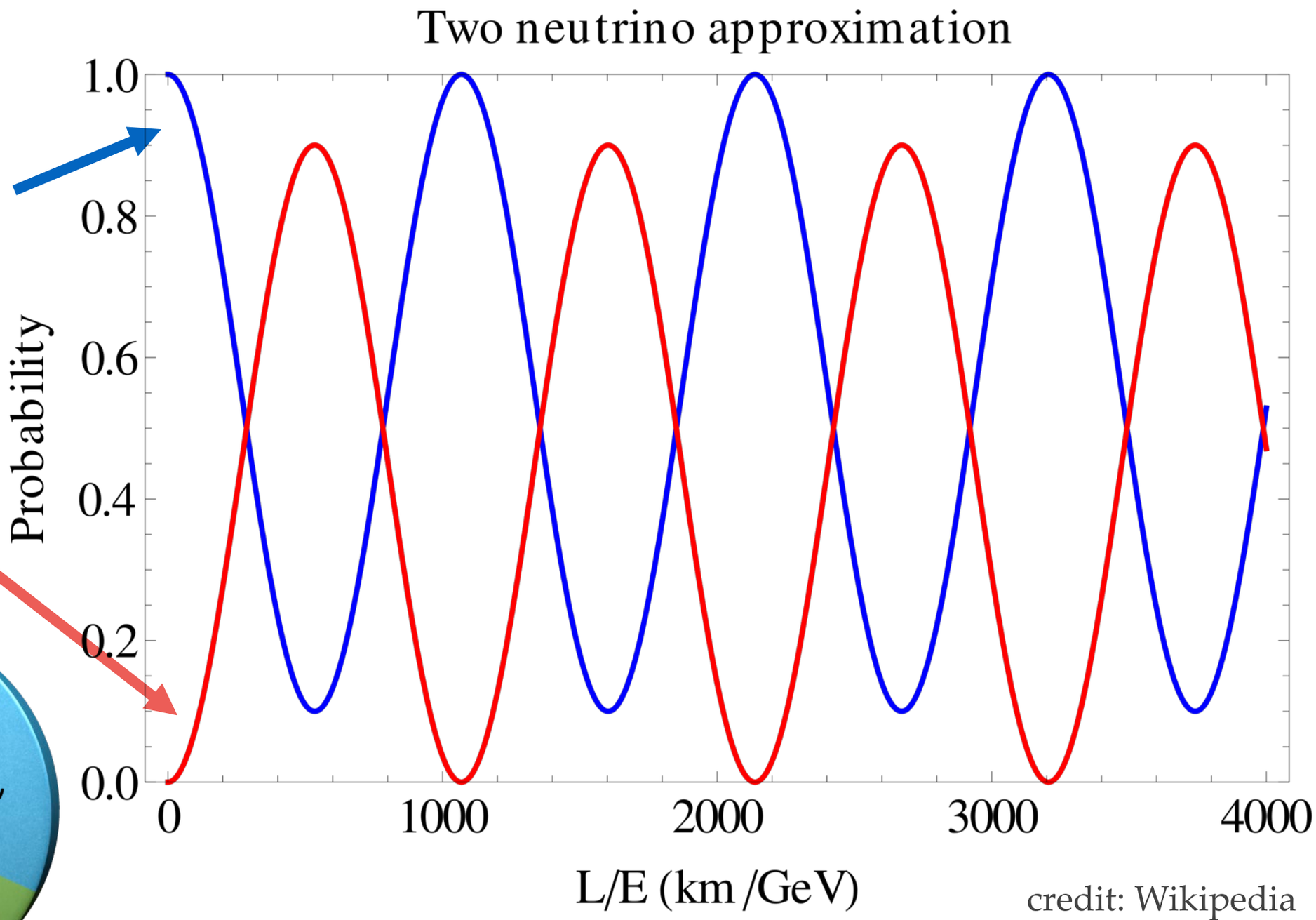
Neutrino Flavor Oscillations

survival probability

transition probability

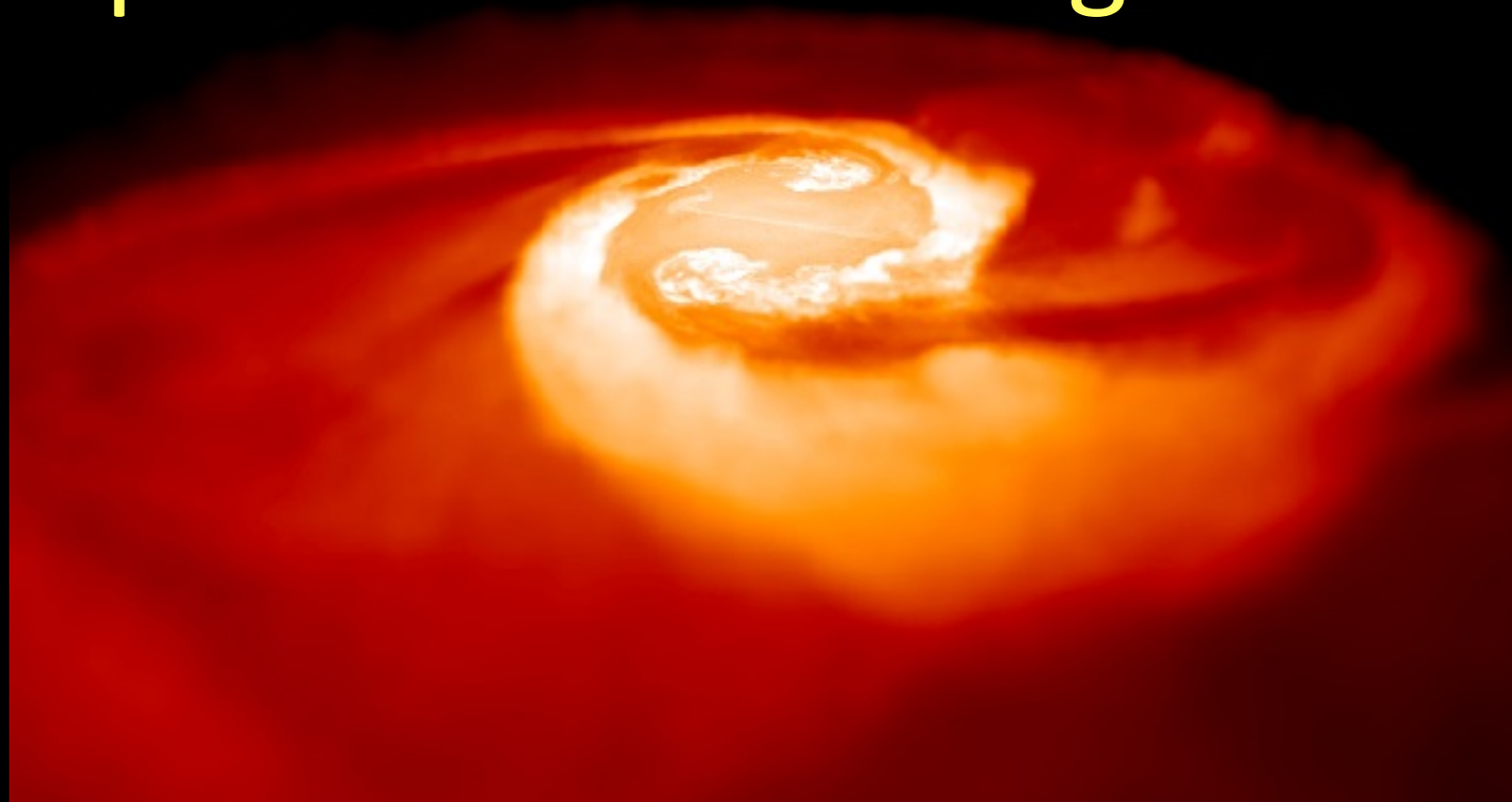


(mass state)



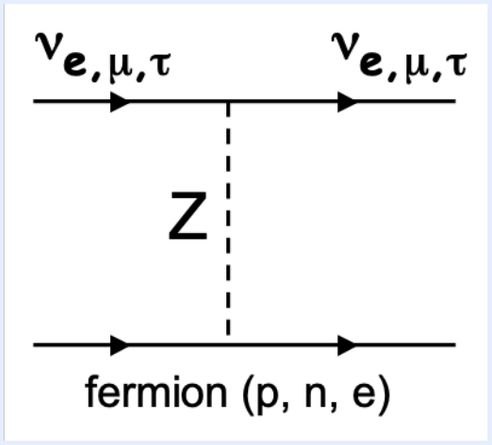
Neutrino oscillate between flavors in time/distance.

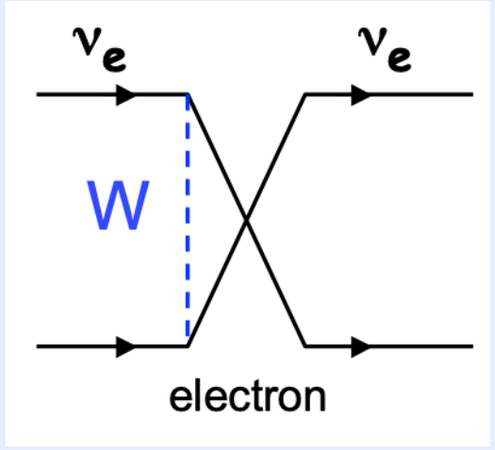
Neutrinos in Supernovae and Mergers



Neutrino Interactions

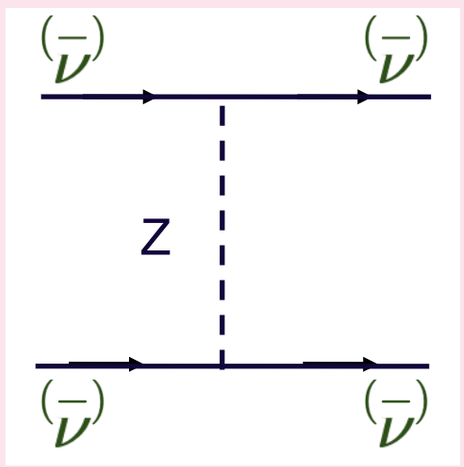
Understood phenomenon.





Neutrinos interact with neutrons, protons and electrons.

We still need to learn a lot about this process!

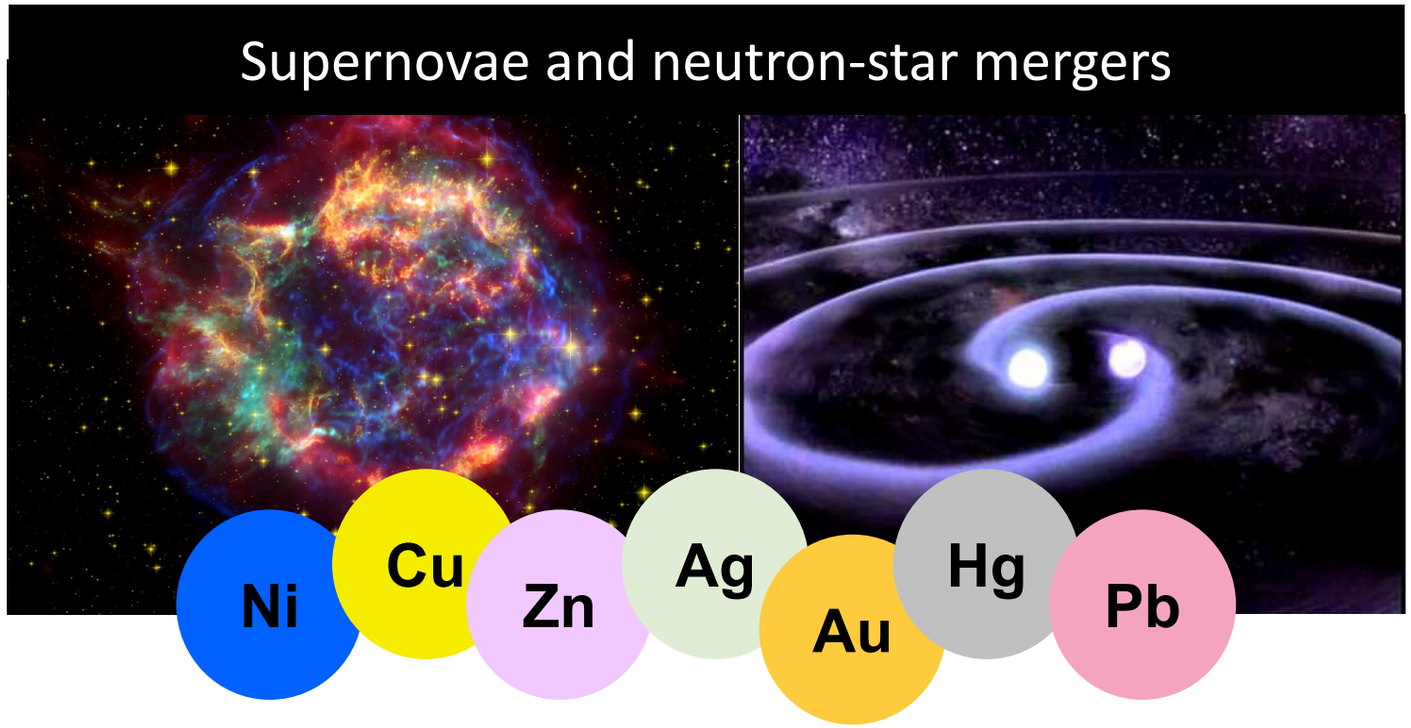


$\nu - \nu$ interactions

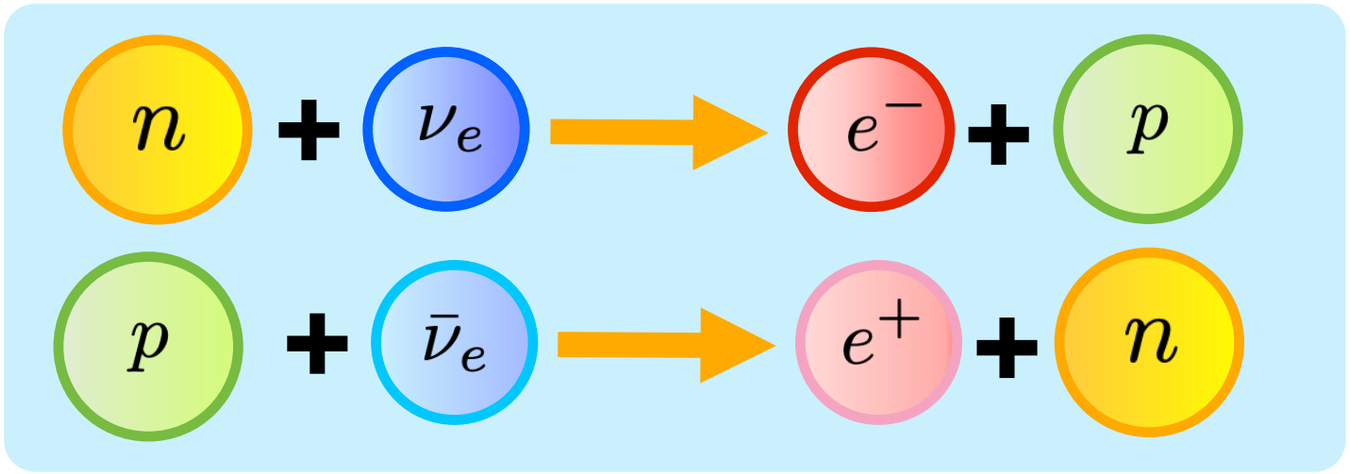
Non-linear phenomenon!

Stellar Nucleosynthesis

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

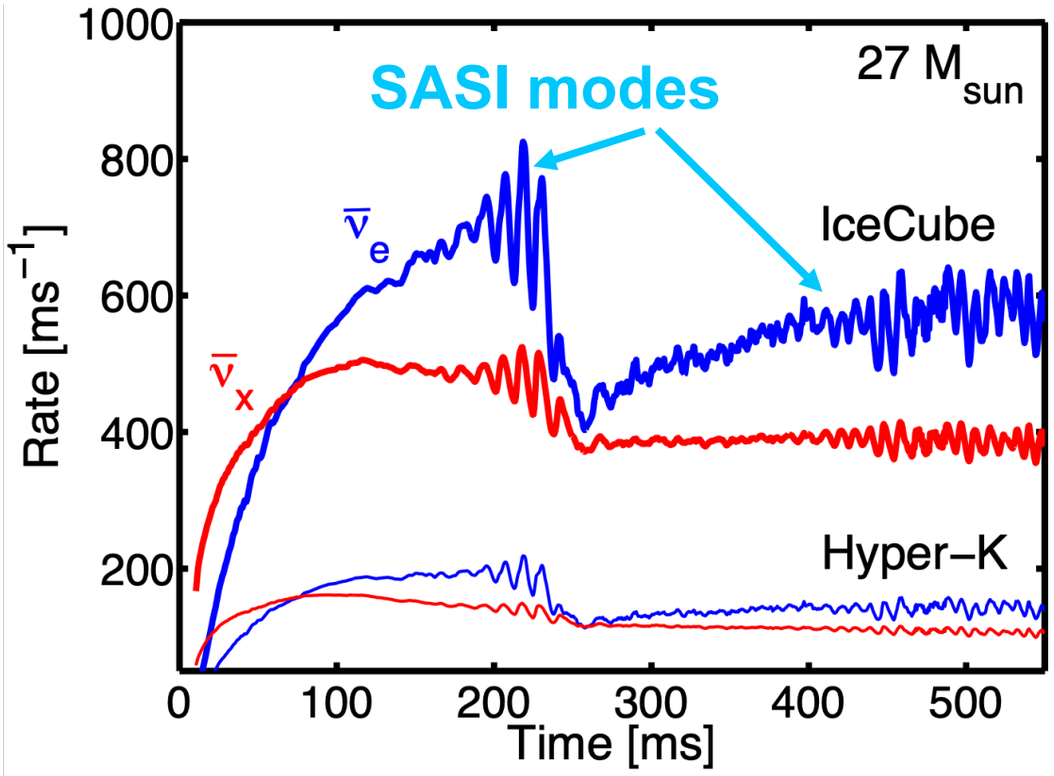


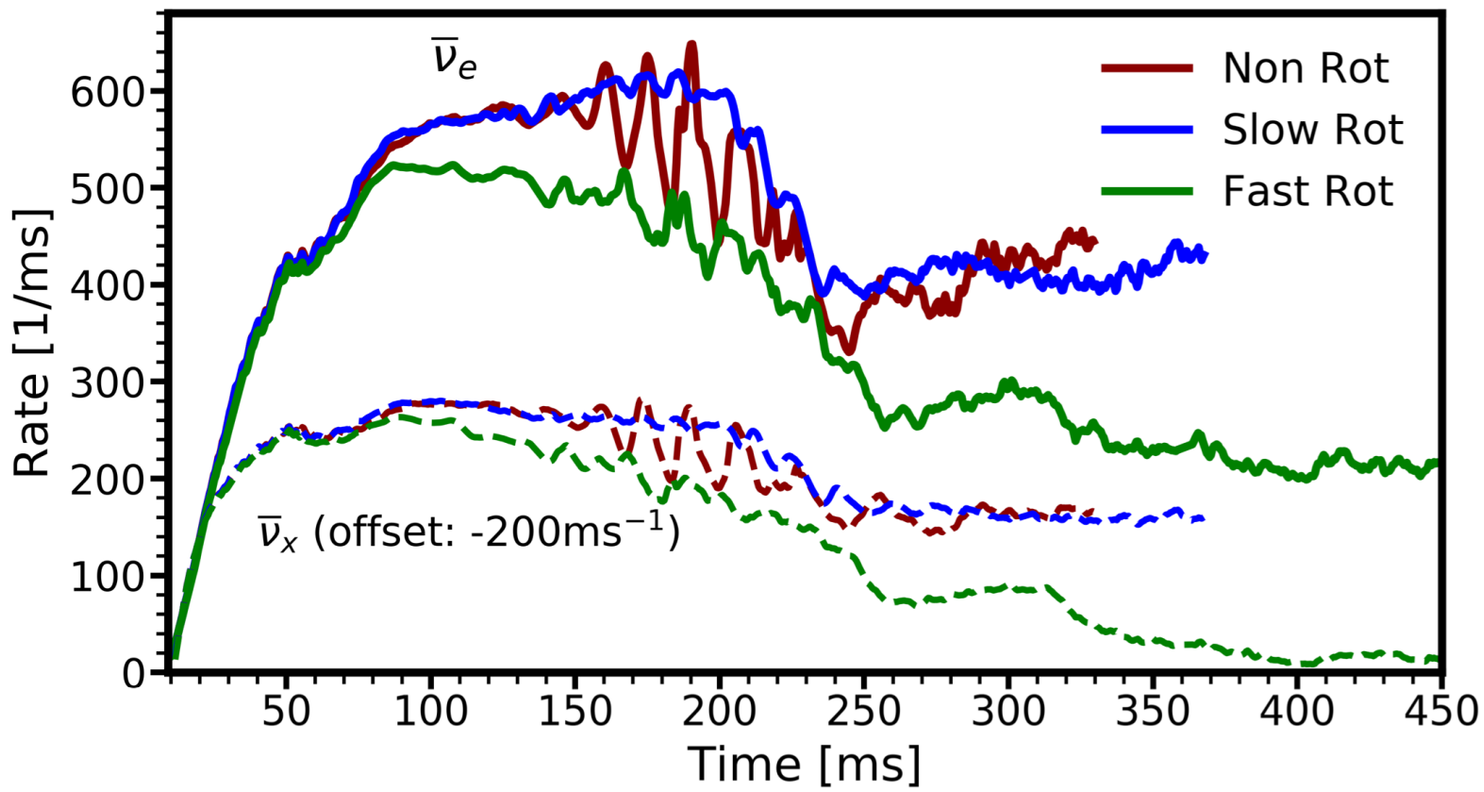
Synthesis of new elements could not happen without neutrinos.



Probe of Supernova Dynamics

Predicted neutrino "lightcurves":



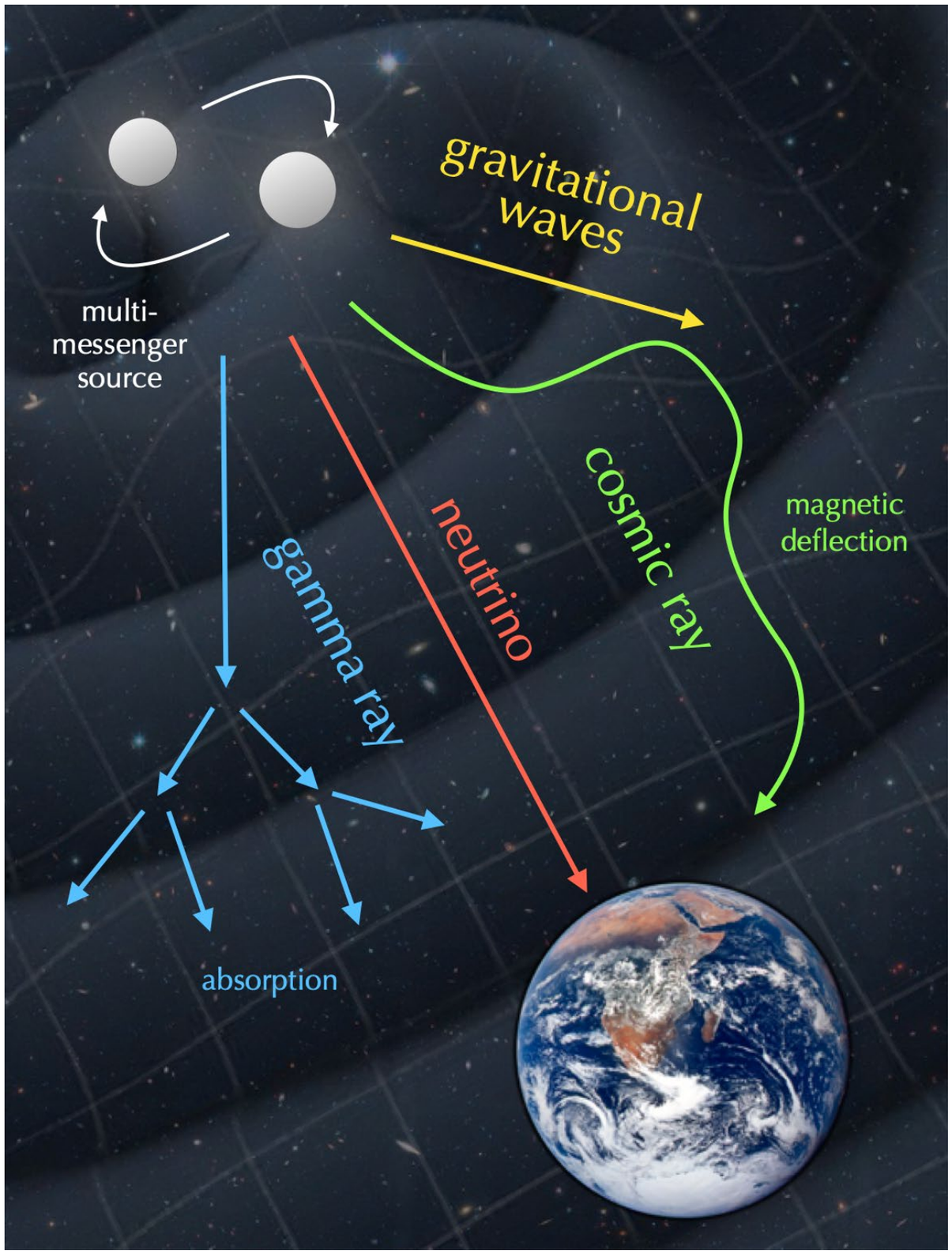


[Tamborra et al., **PRD** 90, 123001 (2014) & **PRD** 98, 123001(2018)]

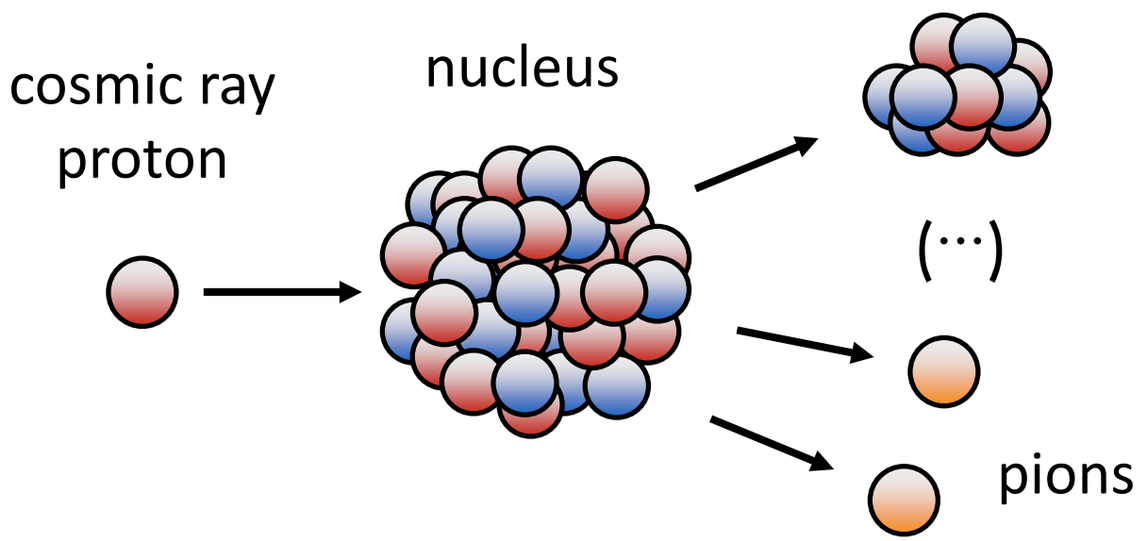
Neutrinos **probe explosion mechanism of a supernova and its rotation.**
Complementary information from detection of gravitational waves.

Neutrinos In & From Cosmic Accelerators

Multi-Messenger Astronomy



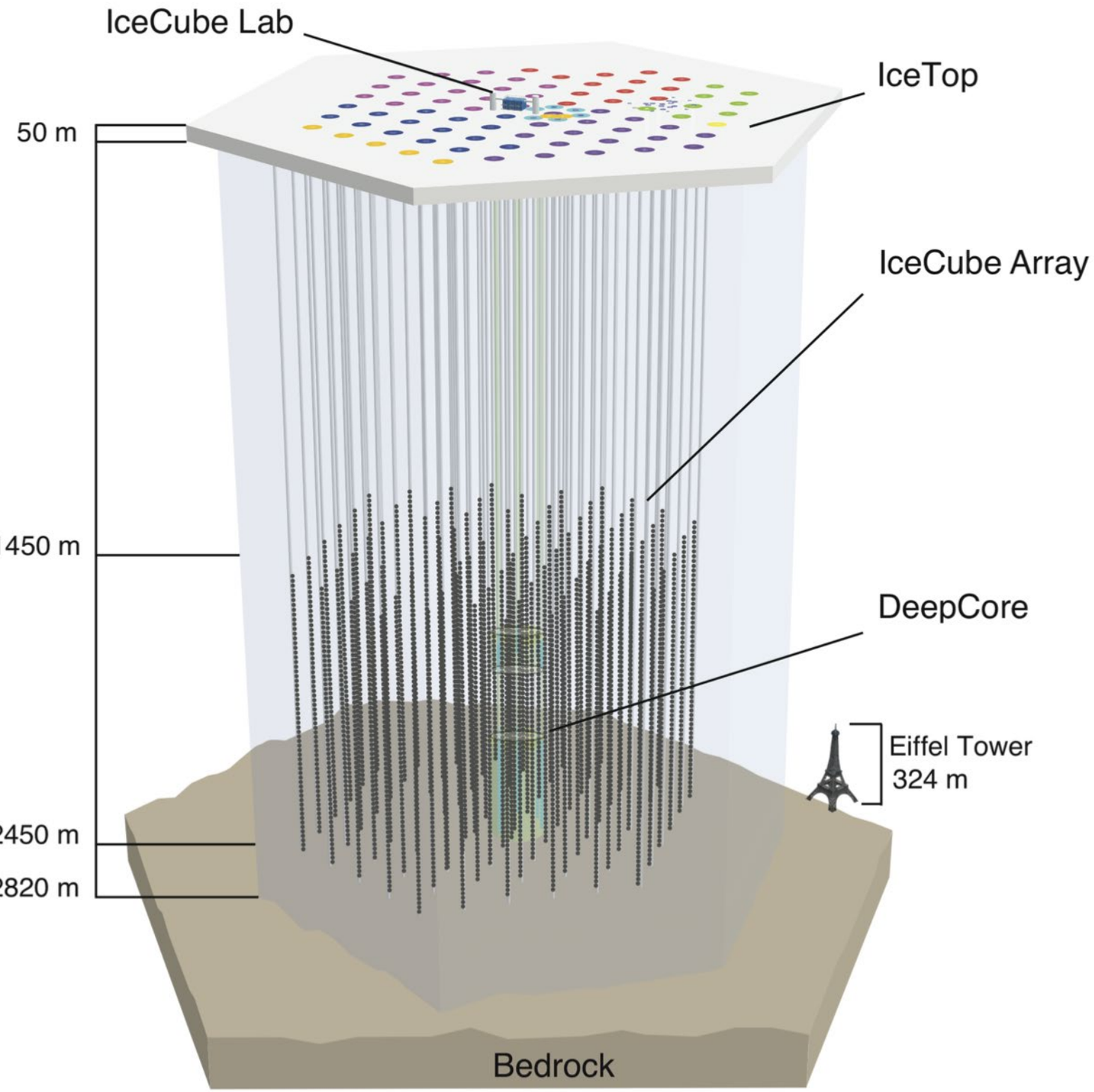
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.



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

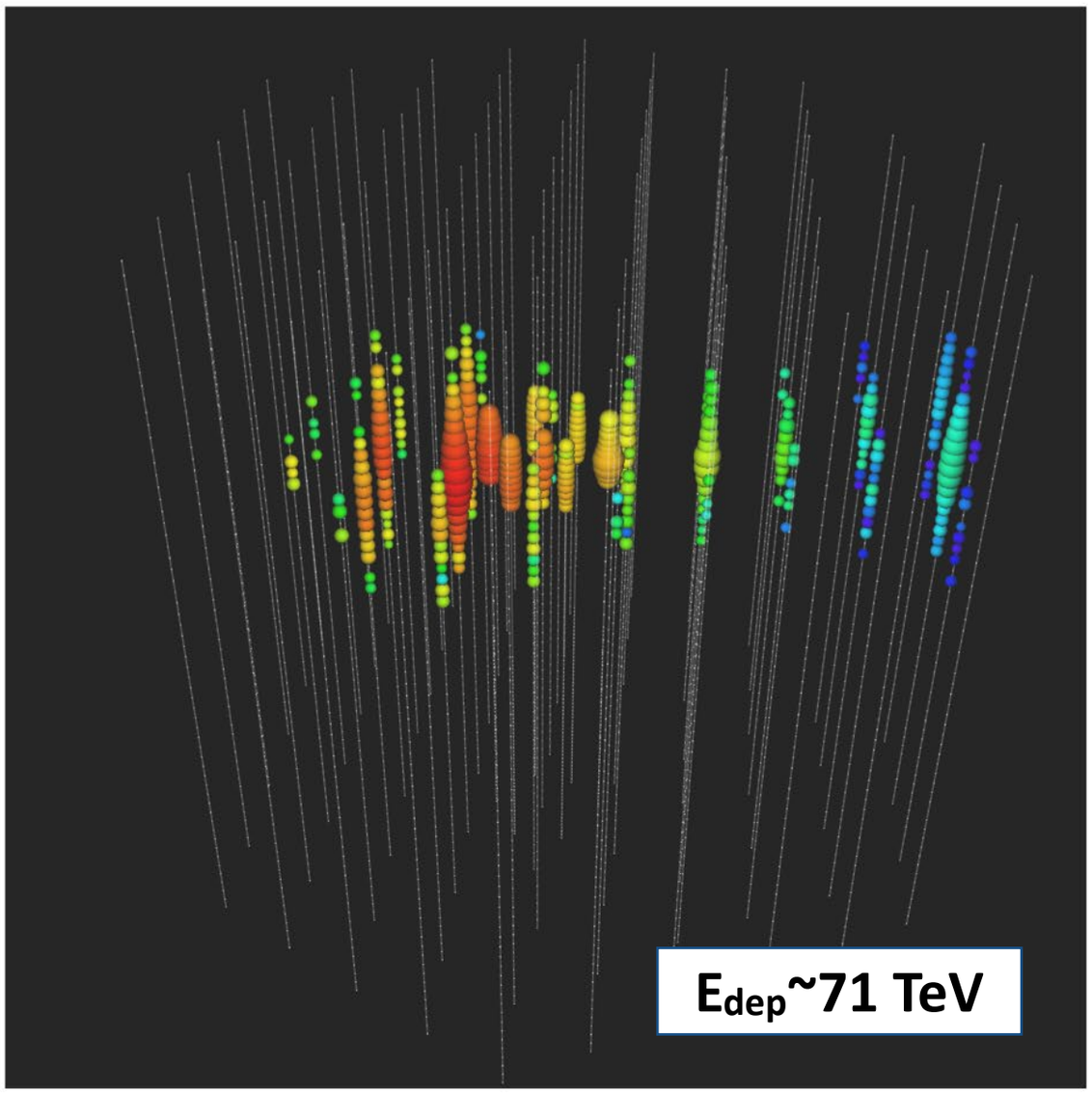


- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km^3 of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections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

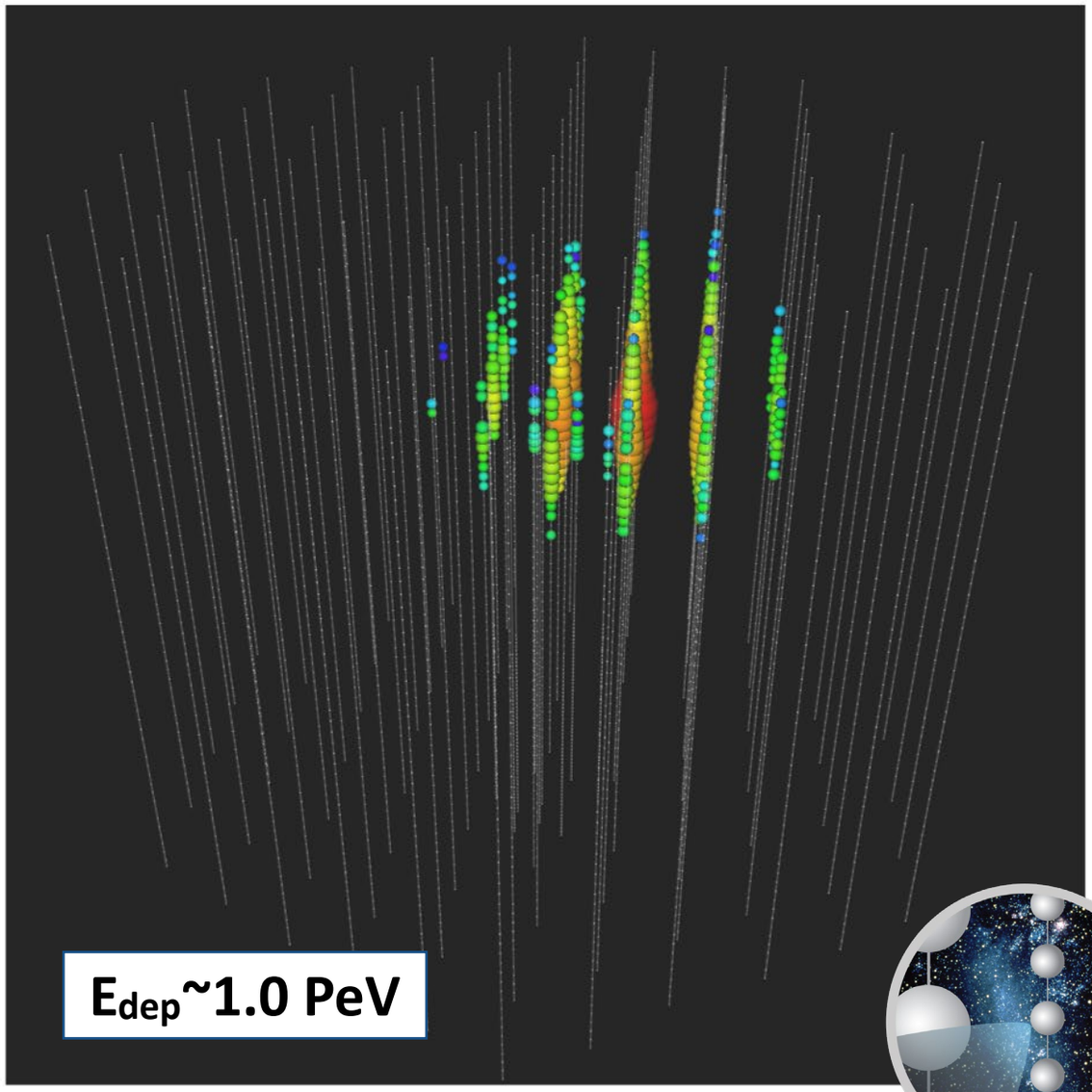
Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering)

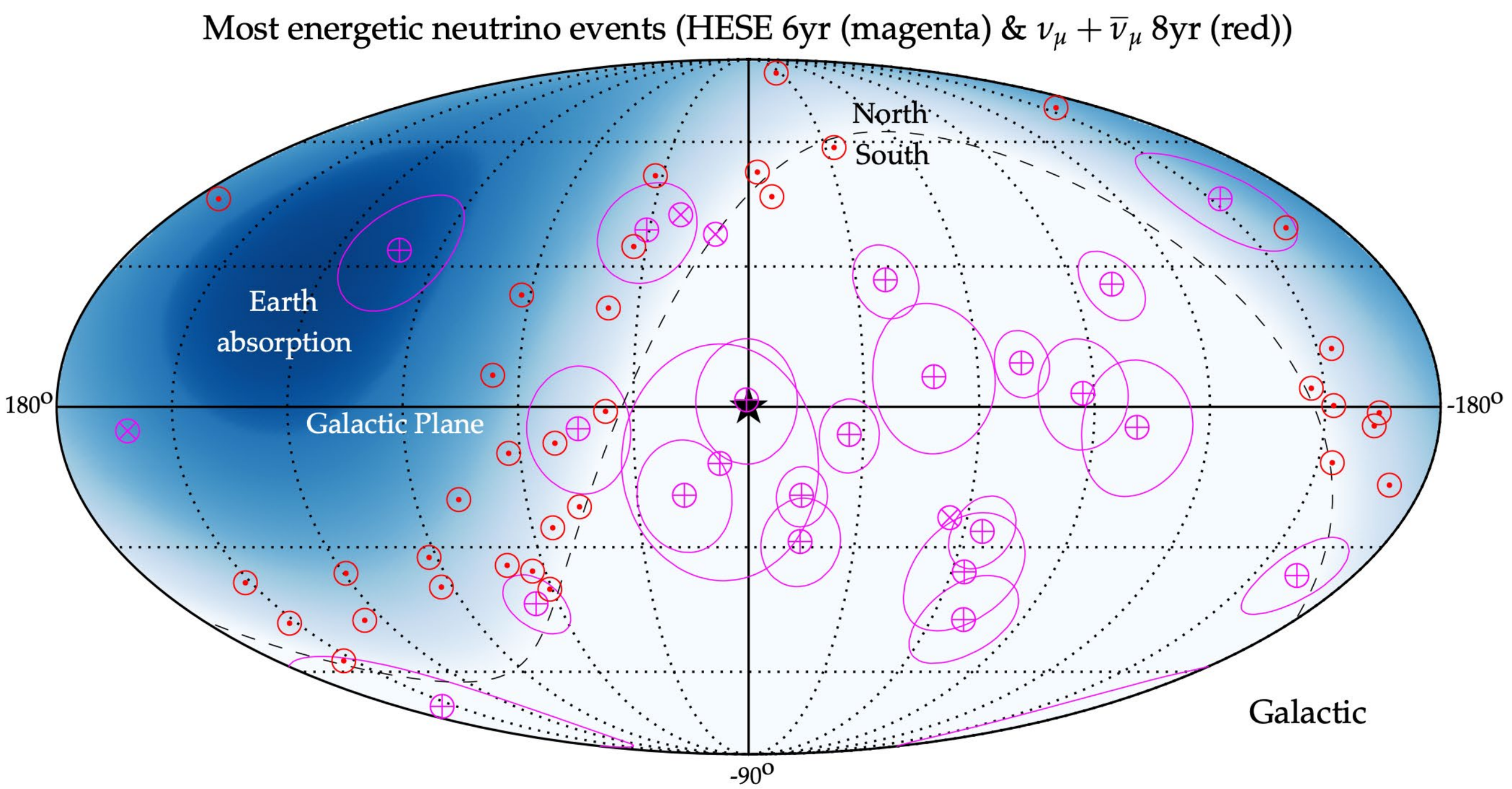


"cascade event" (from all flavours)



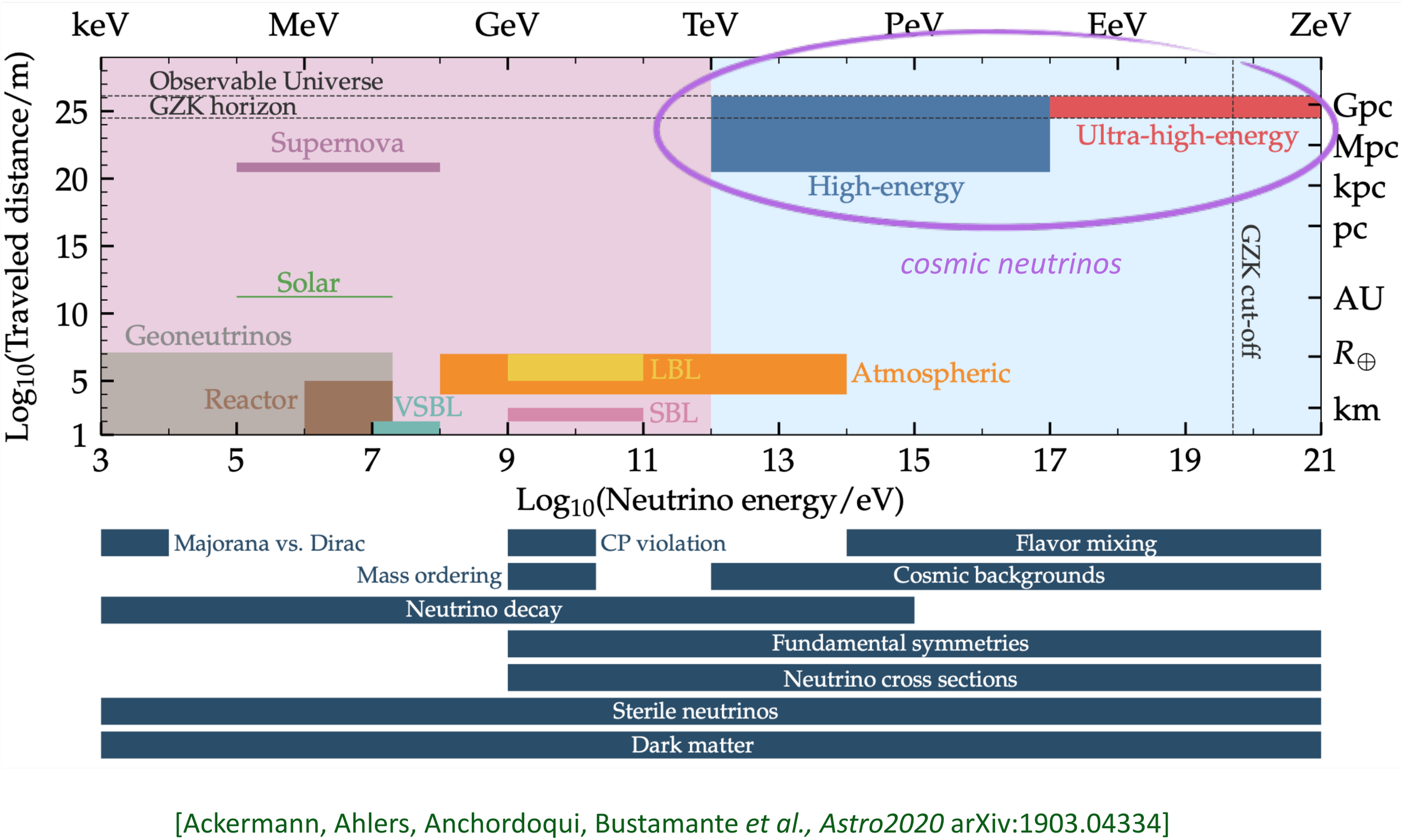
["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

Status of Neutrino Astronomy



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

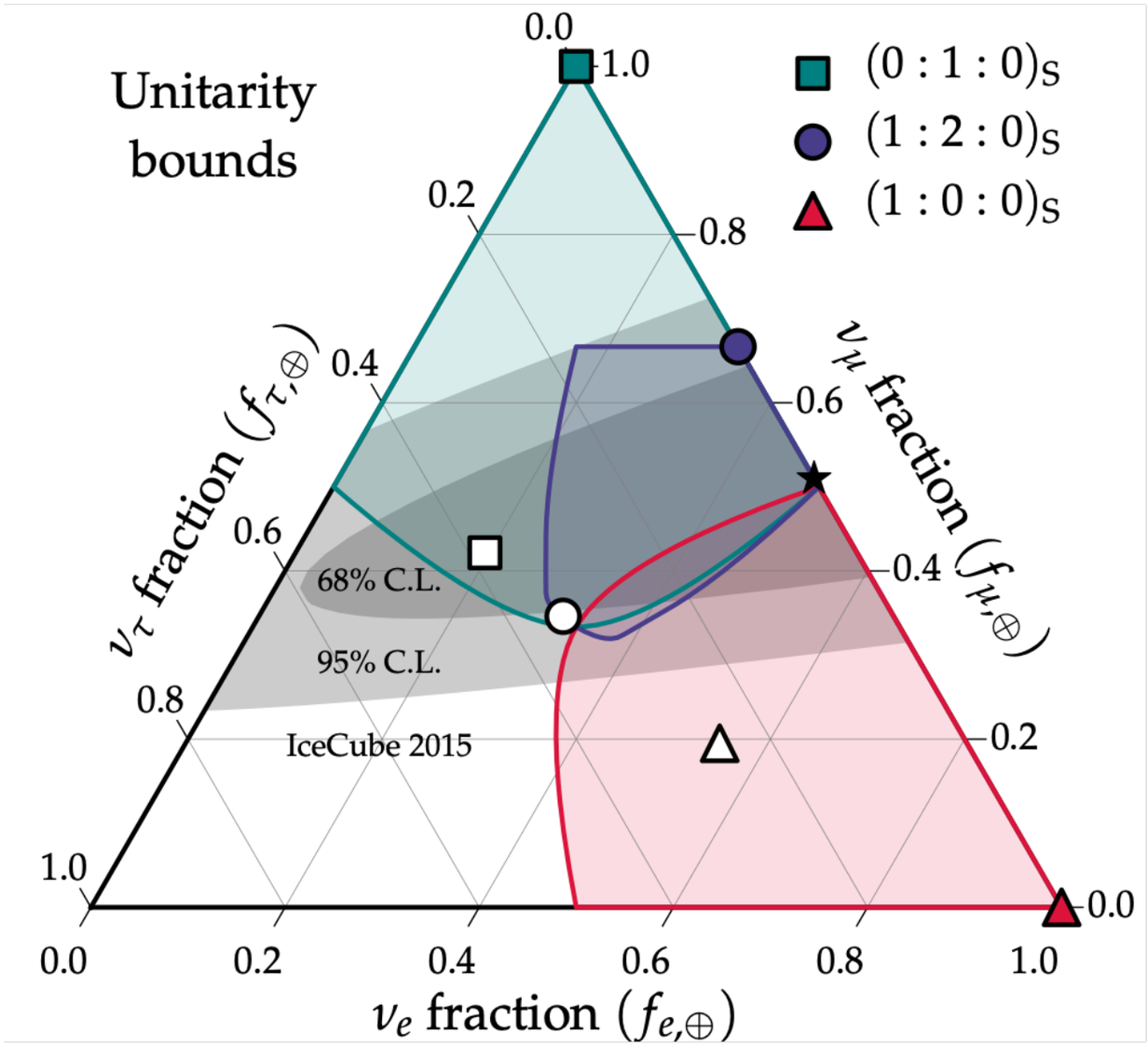
Probe of Fundamental Physics



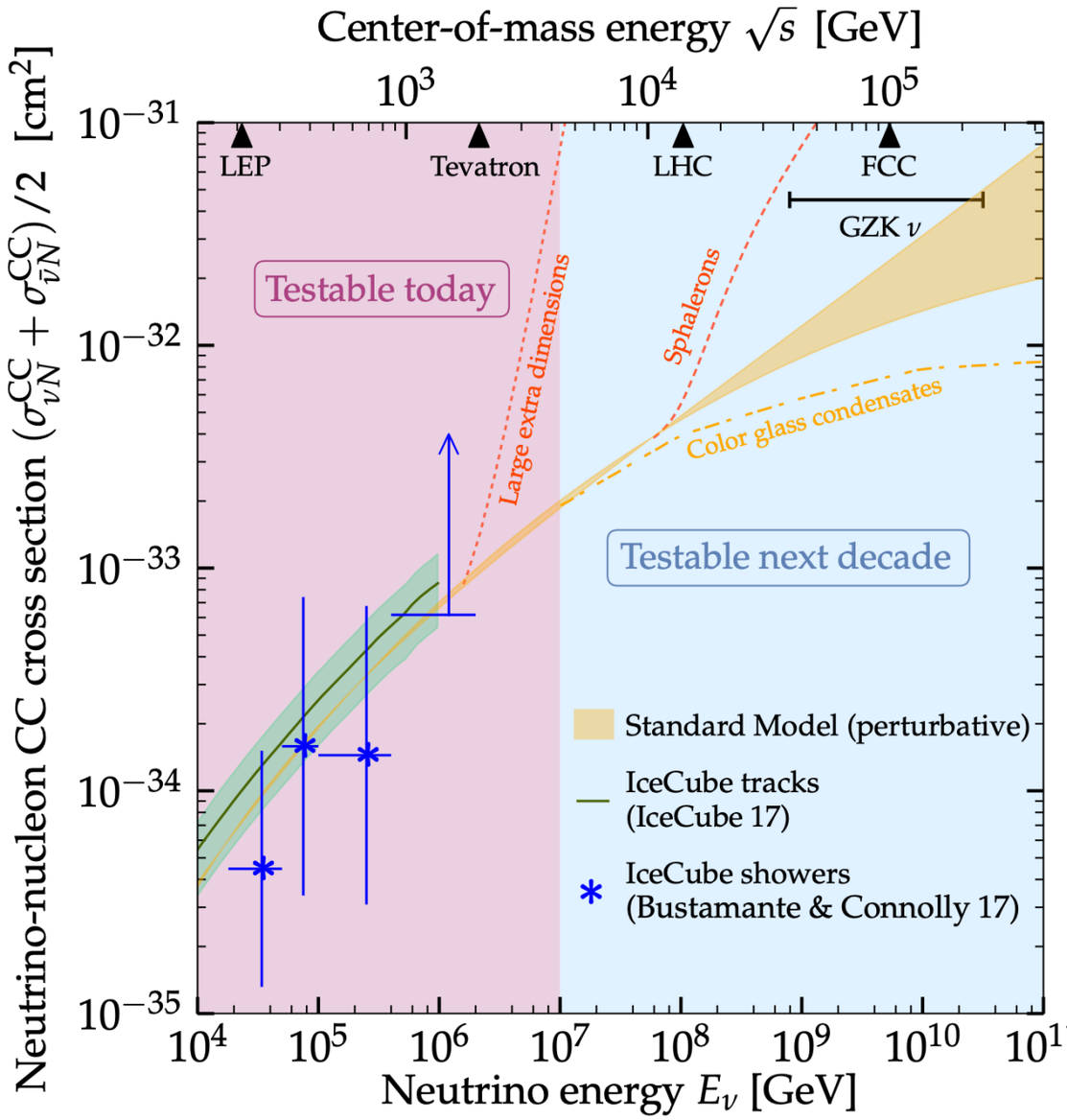
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al., Astro2020* arXiv:1903.04334]

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:

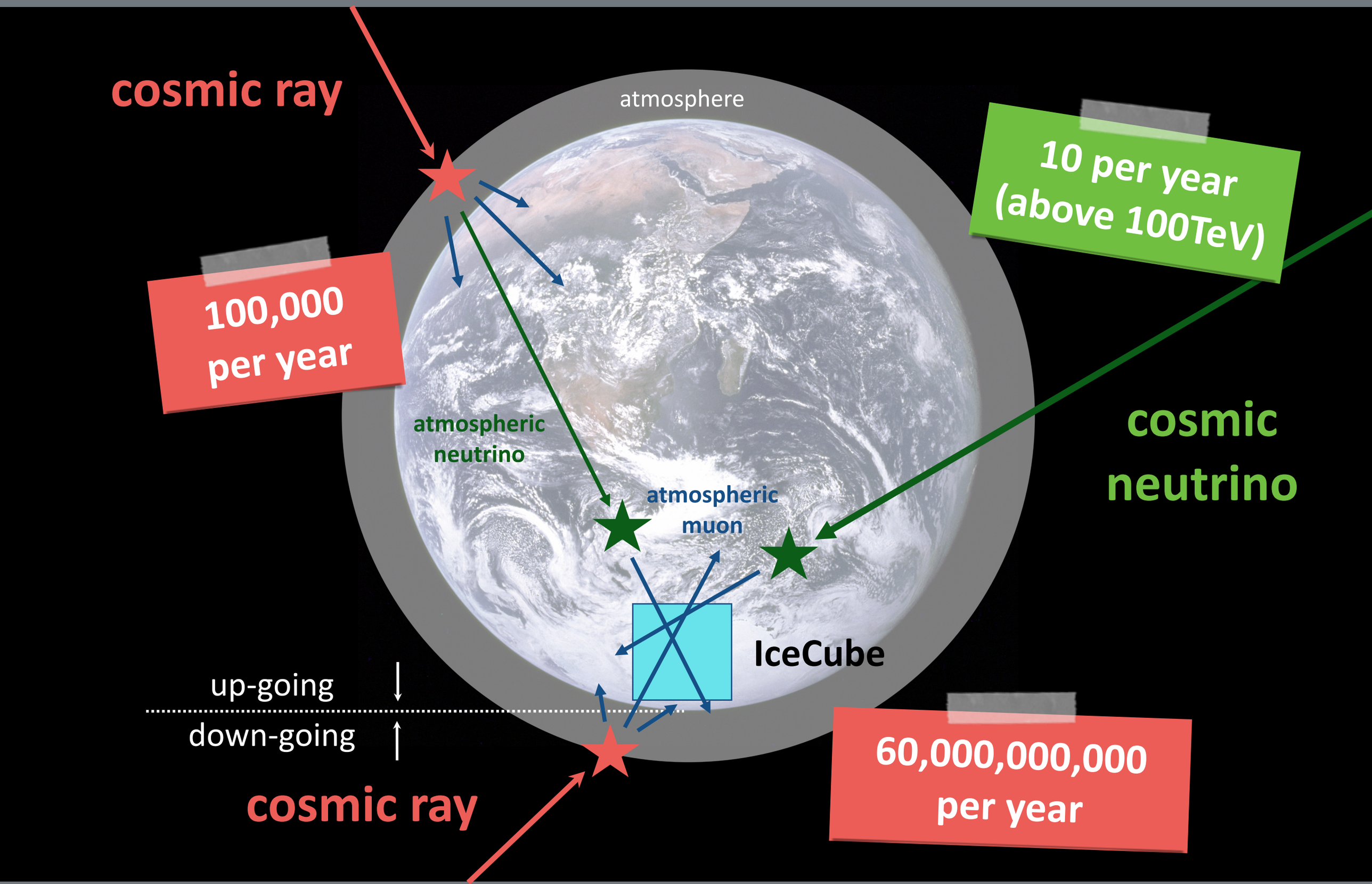
- **impact on stellar evolution**
- **potential to probe astrophysical environments**
- **fundamental neutrino properties**
- **direct probe of the origin of cosmic rays**
- **observation in neutrino telescopes or experiments**

Thank you

for your attention!

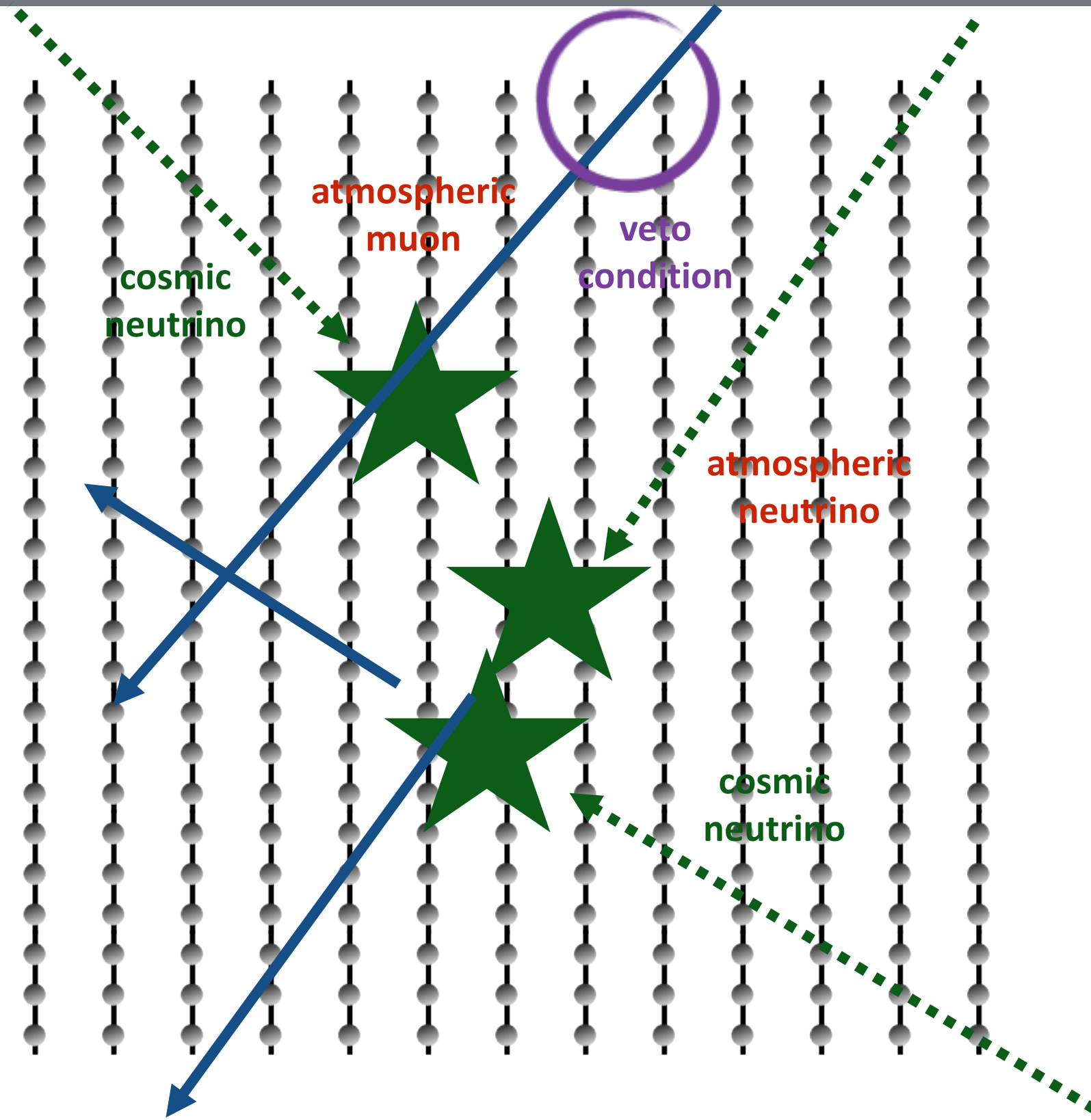
Backup Slides

Neutrino Selection I

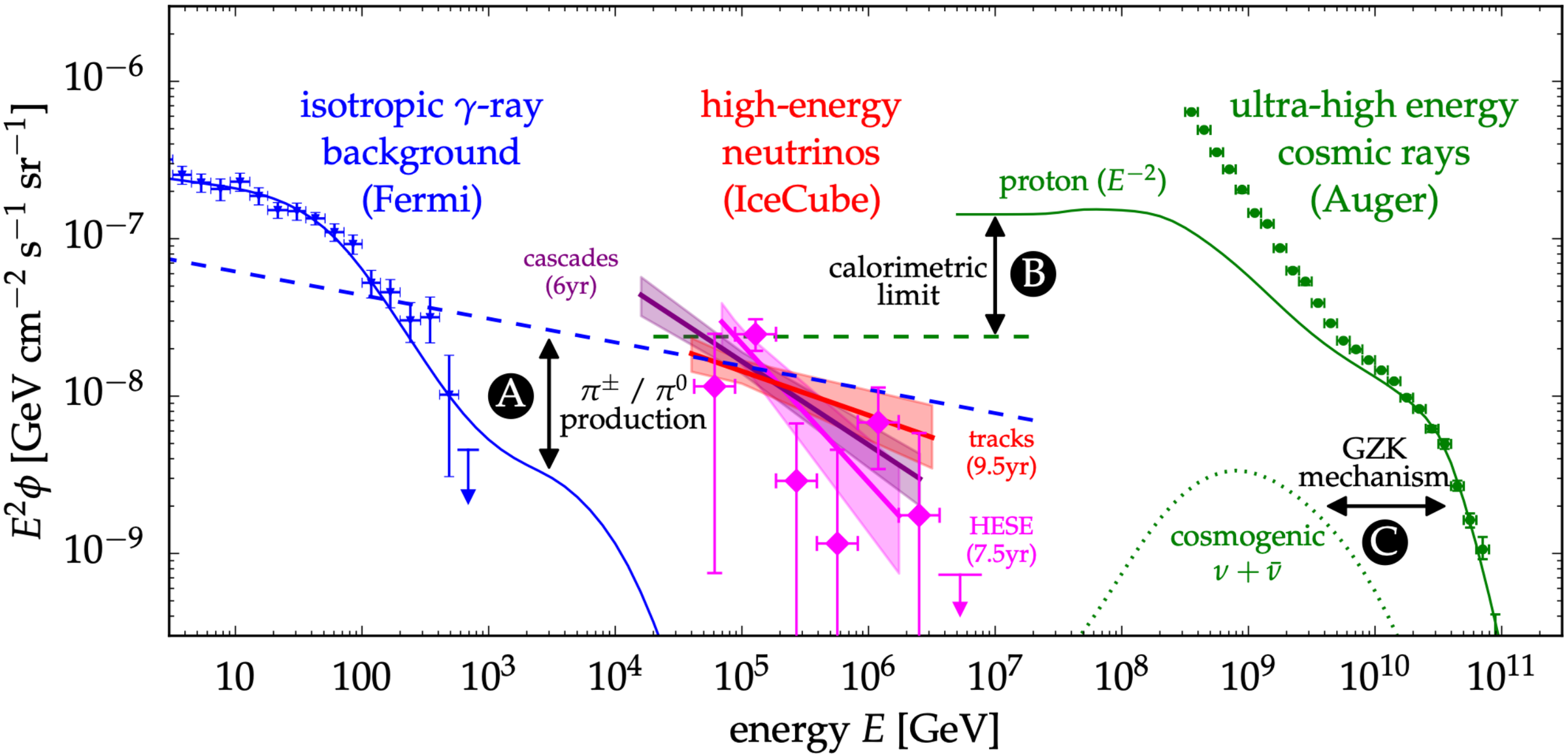


Neutrino Selection II

- 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



Multi-Messenger Interfaces



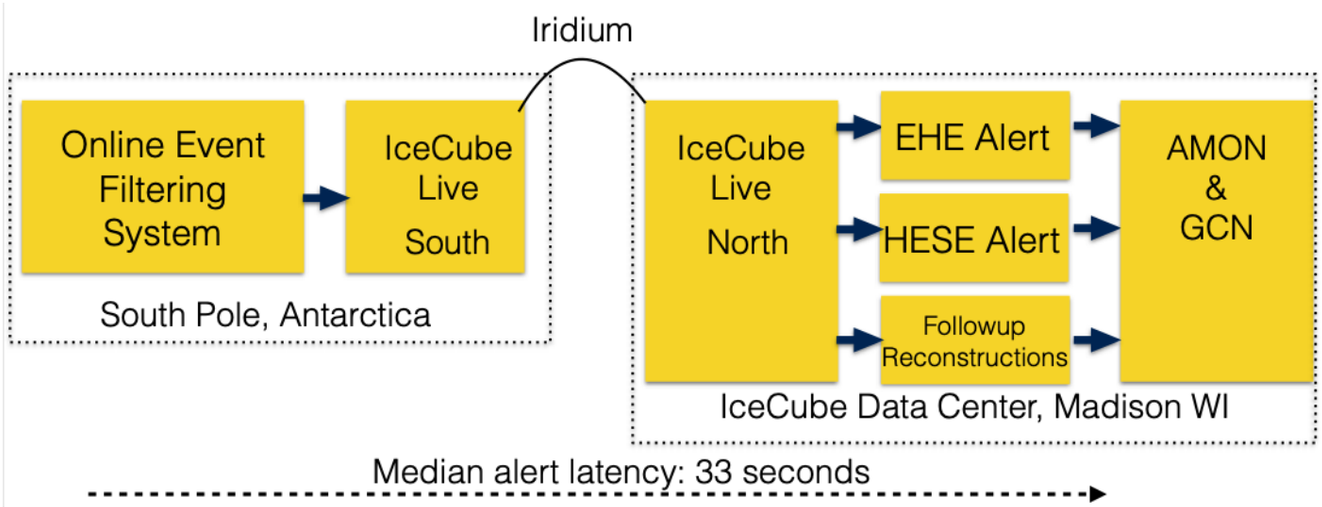
γ

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

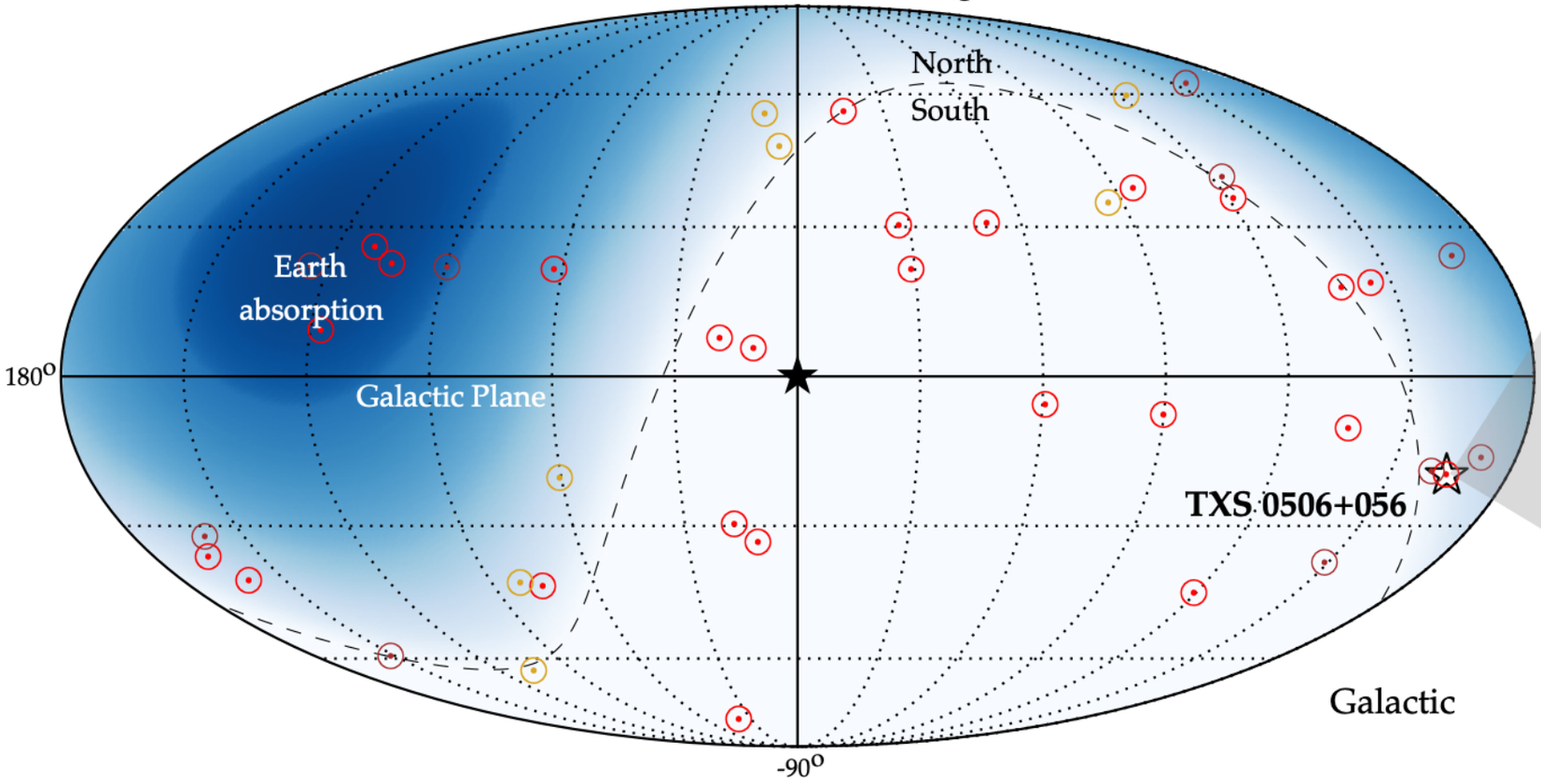
Realtime Neutrino Alerts

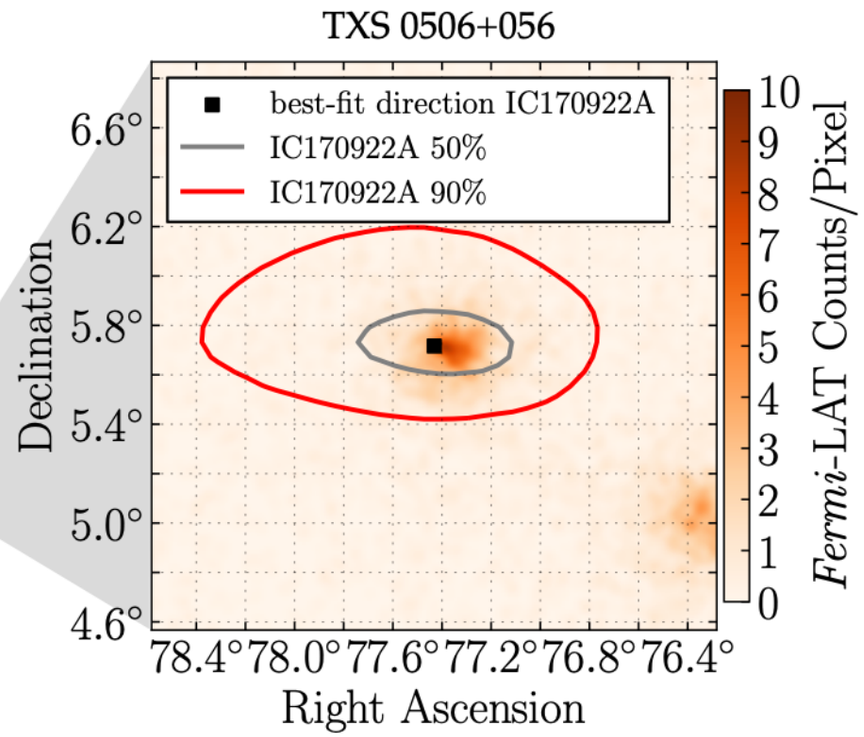
Low-latency (<1min) **public neutrino alert system** established in April 2016.

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

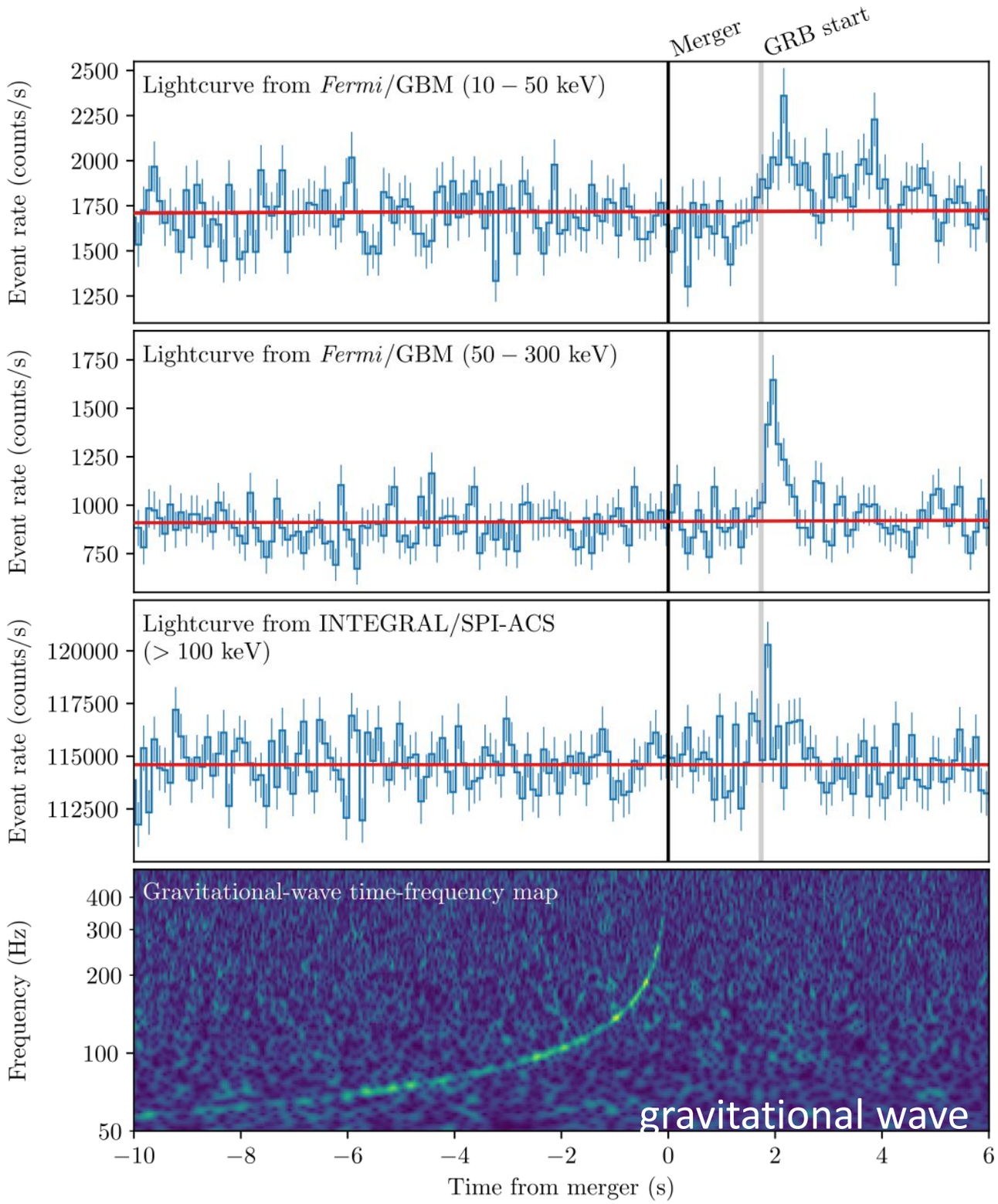


Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))

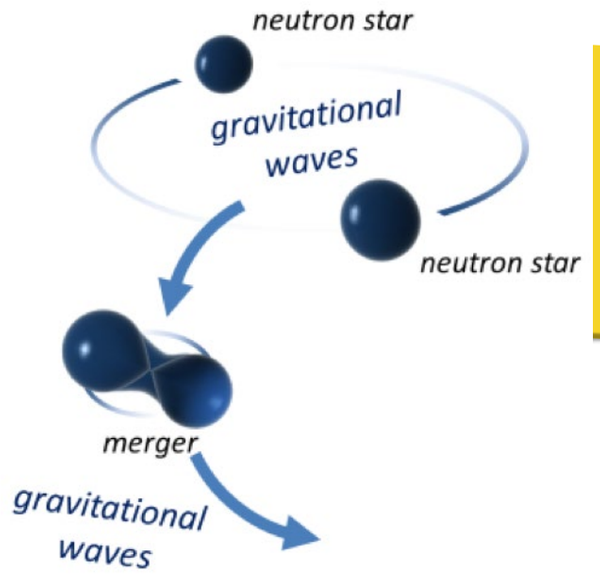




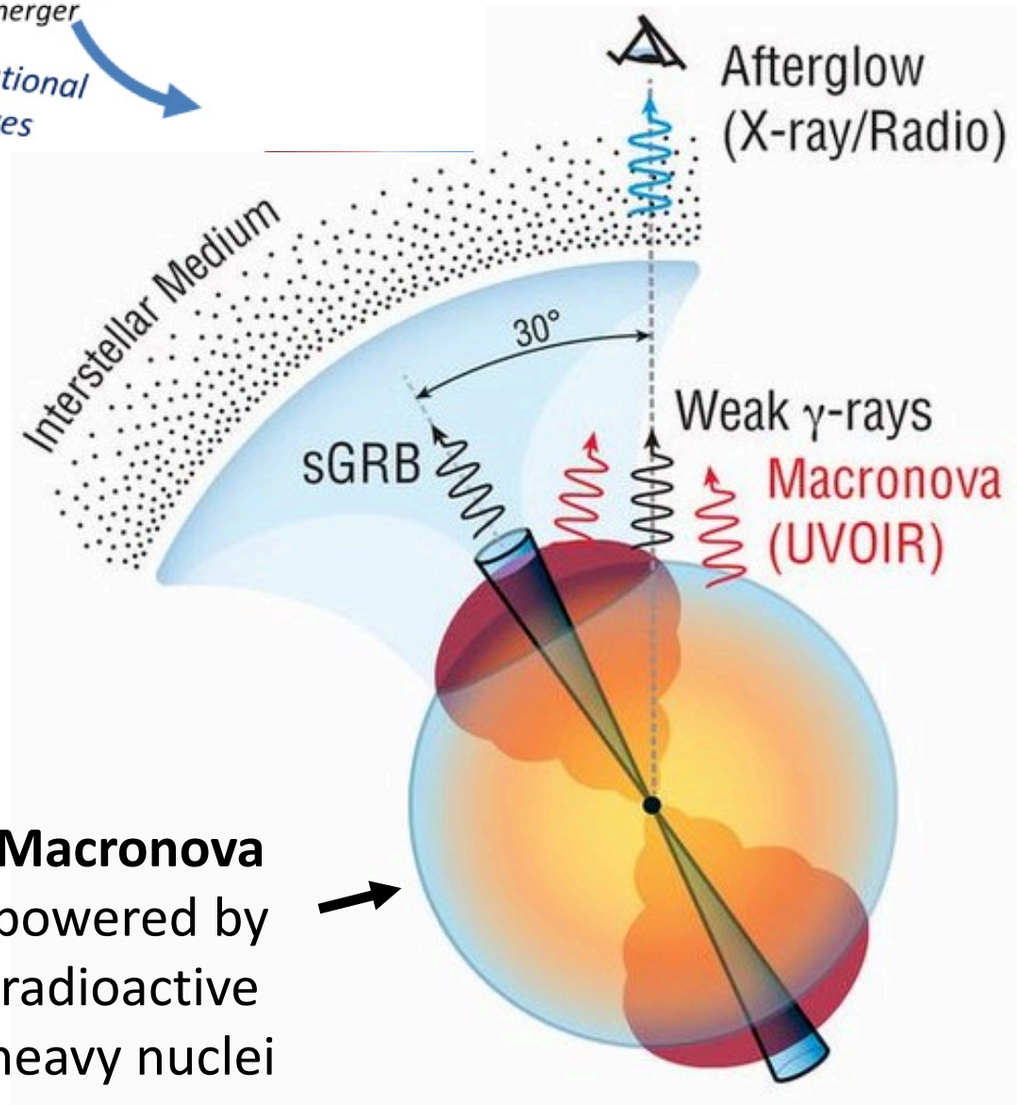
GRBs and Gravitational Waves



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

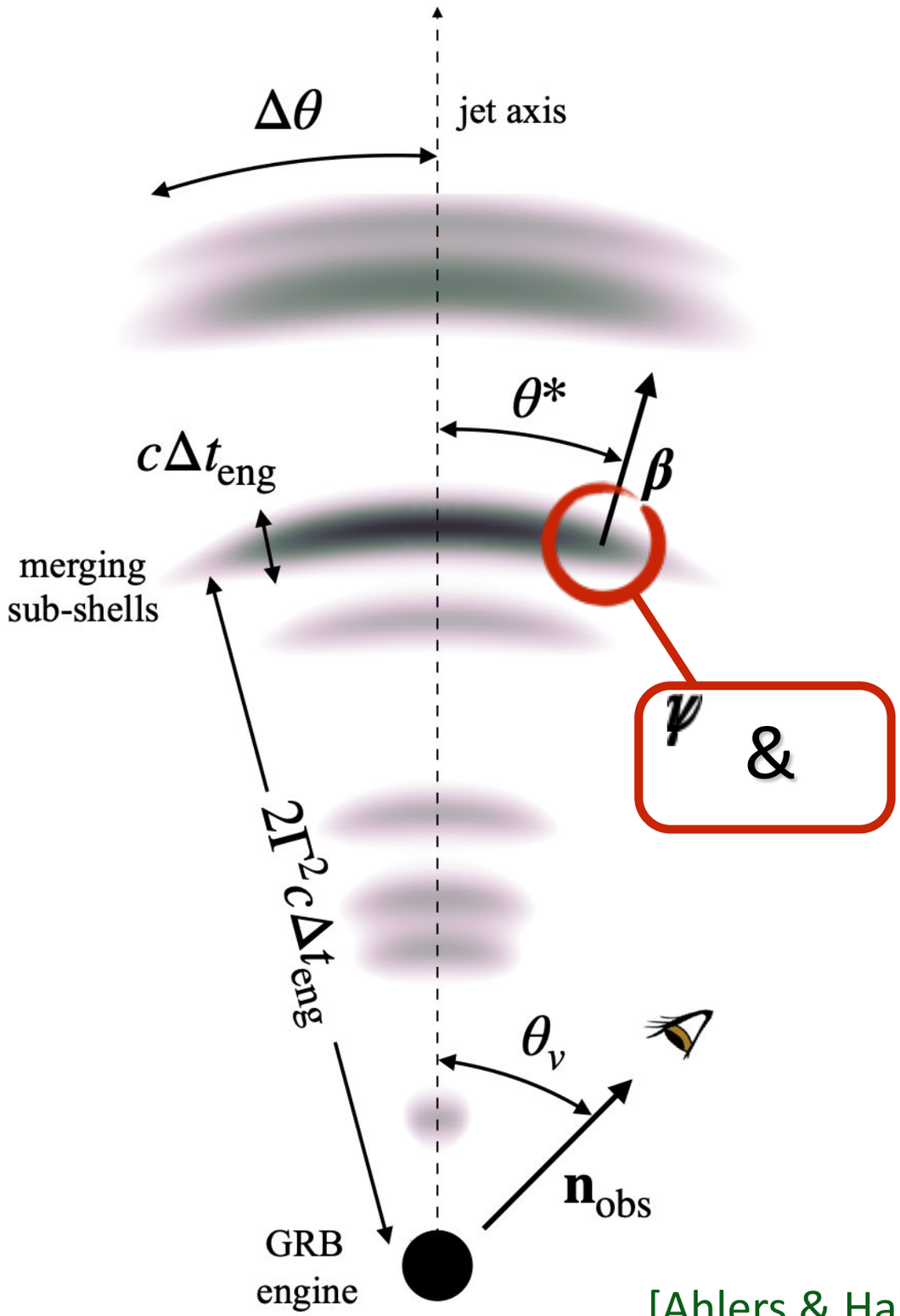


GW 170817
&
GRB 170817A

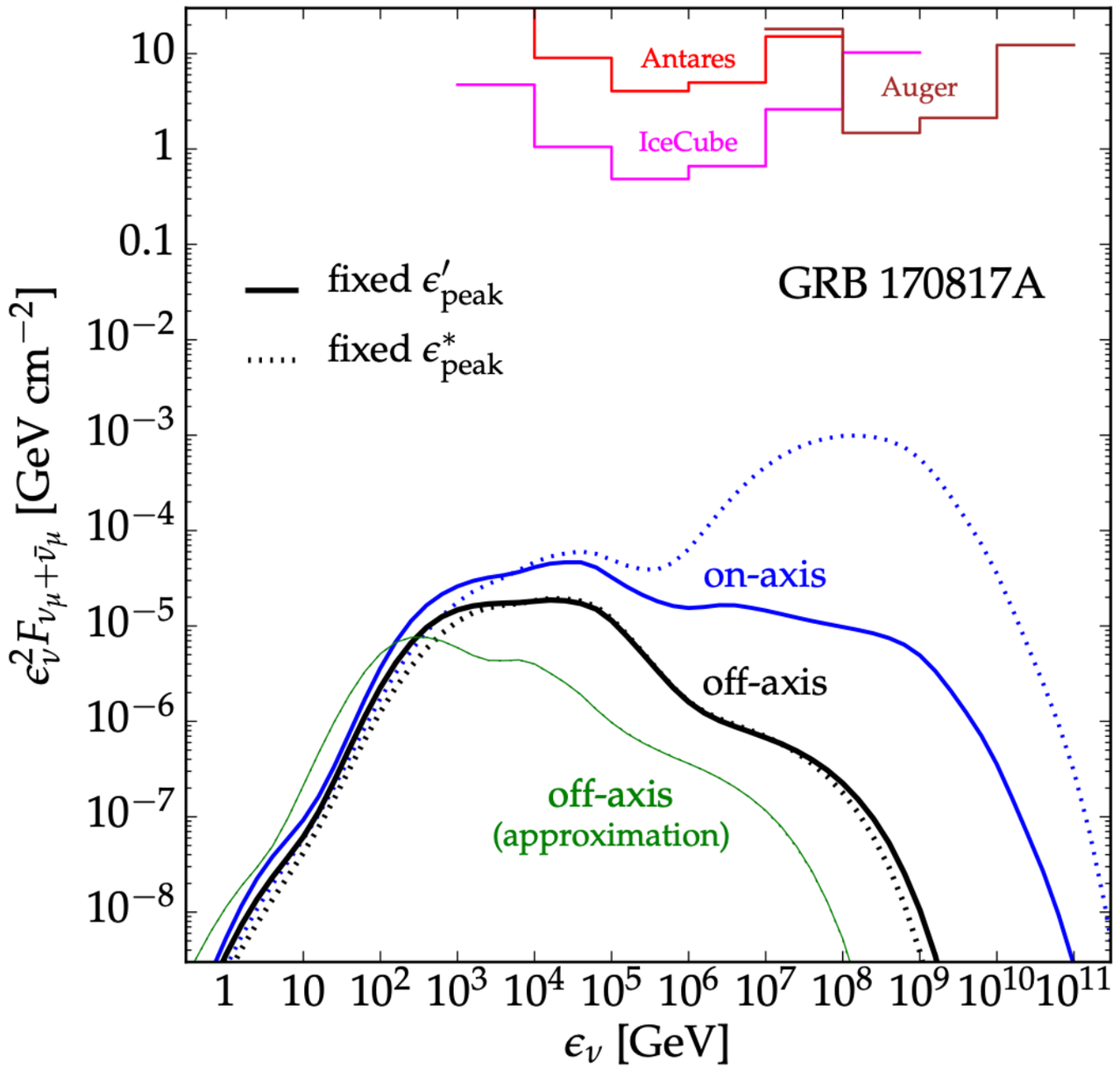


Macronova
powered by
radioactive
heavy nuclei

GRB 170817A - Revisited



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



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