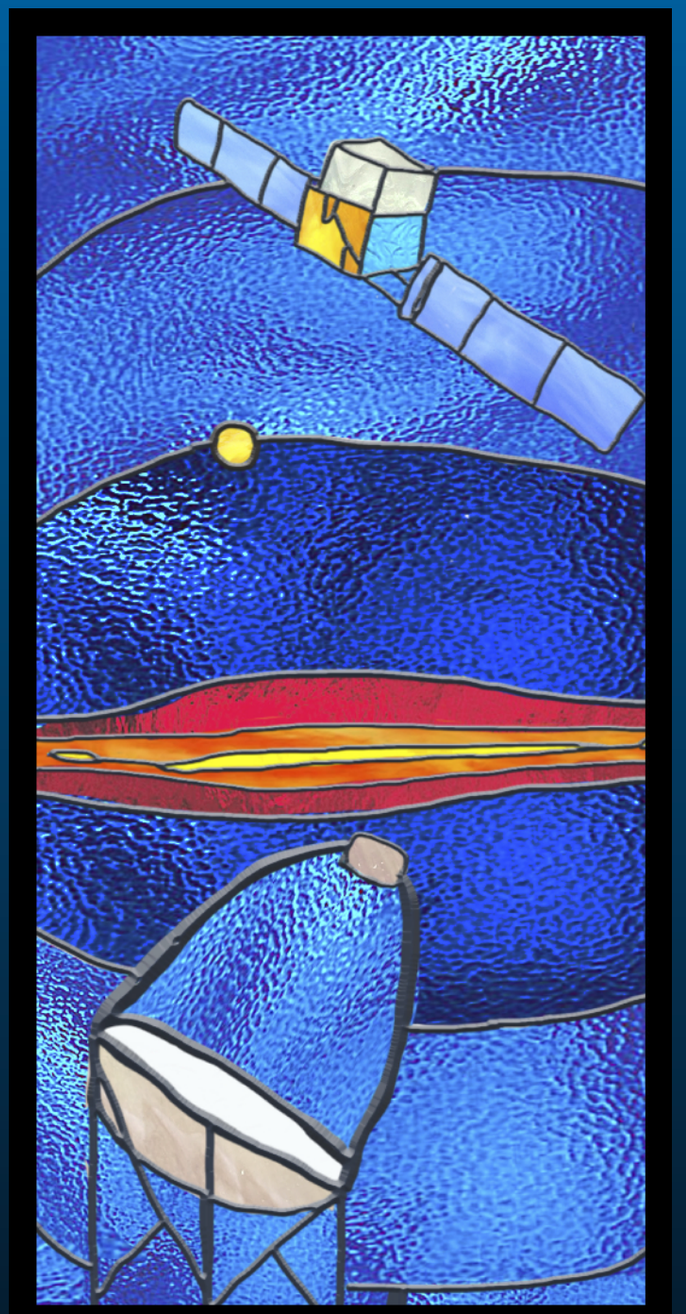
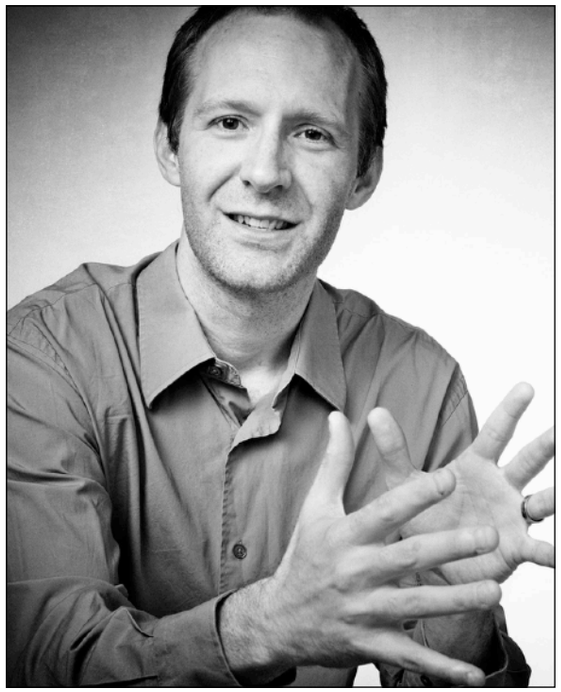




Particle Astrophysics

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

Who are we?



Assoc. Prof. D. Jason Koskinen

Prof. Irene Tamborra

Assoc. Prof. Oleg Ruchayskiy

Asst. Prof. Mauricio Bustamante

+ many excellent Post-Docs, PhDs, Master & Bachelor students

Asst. Prof. Markus Ahlers

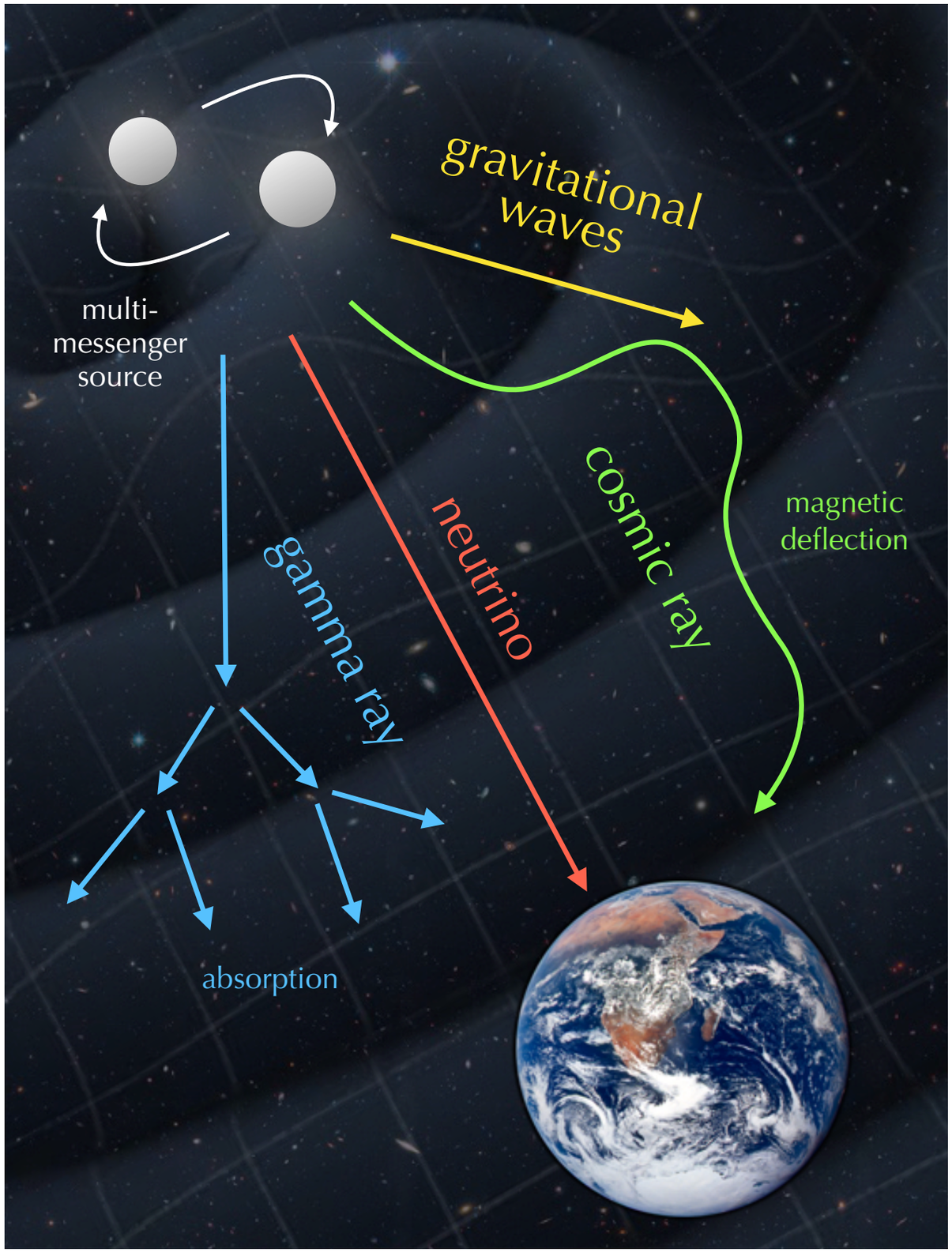
The Elusive Neutrino

- **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

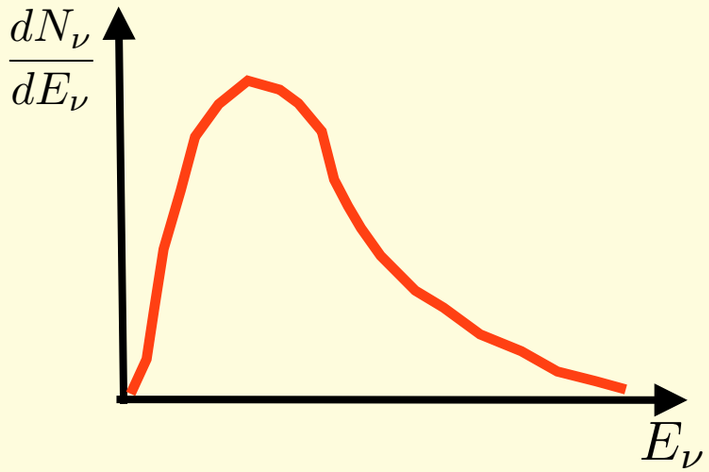
coincident with
photons and gravitational waves

BUT, very difficult to detect!

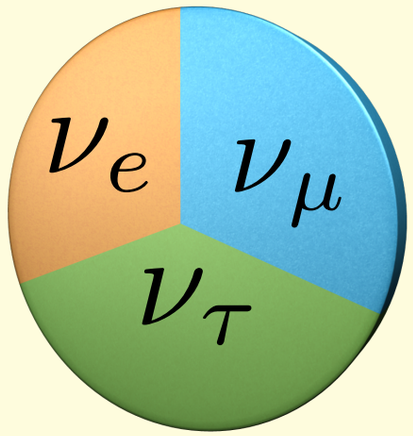
Powerful Probes in Astrophysics

Neutrinos provide us with:

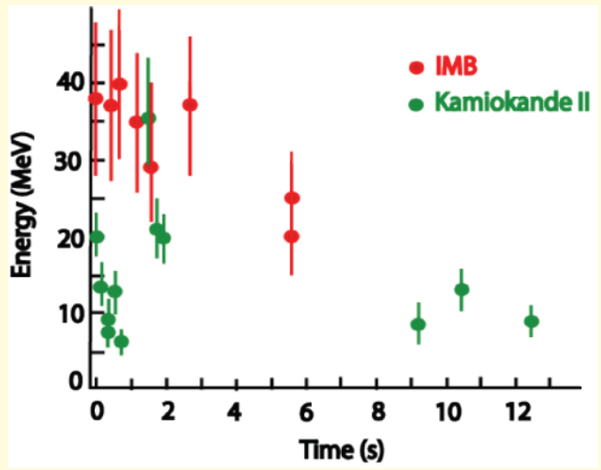
1. Energy Distribution



2. Flavour Ratios

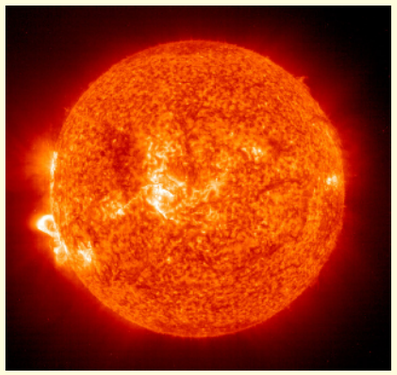


3. Light Curve

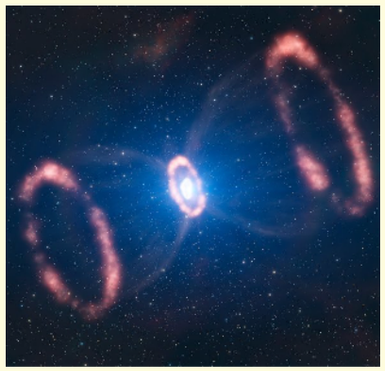


Neutrinos are copiously produced in astrophysical sources, e.g.

The Sun



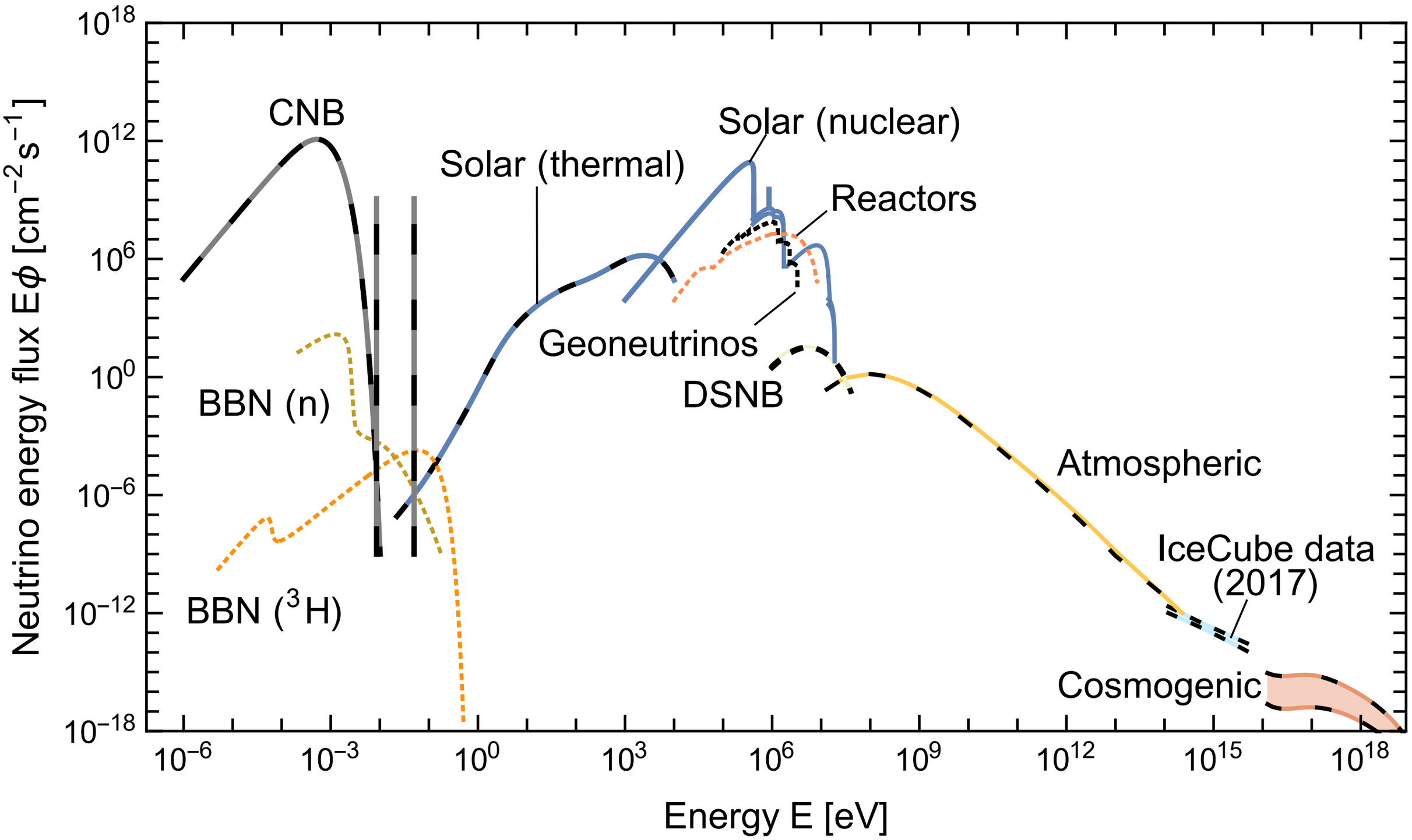
Supernovae



Active Galaxies

Gamma-ray Bursts

Grand Unified Neutrino Spectrum



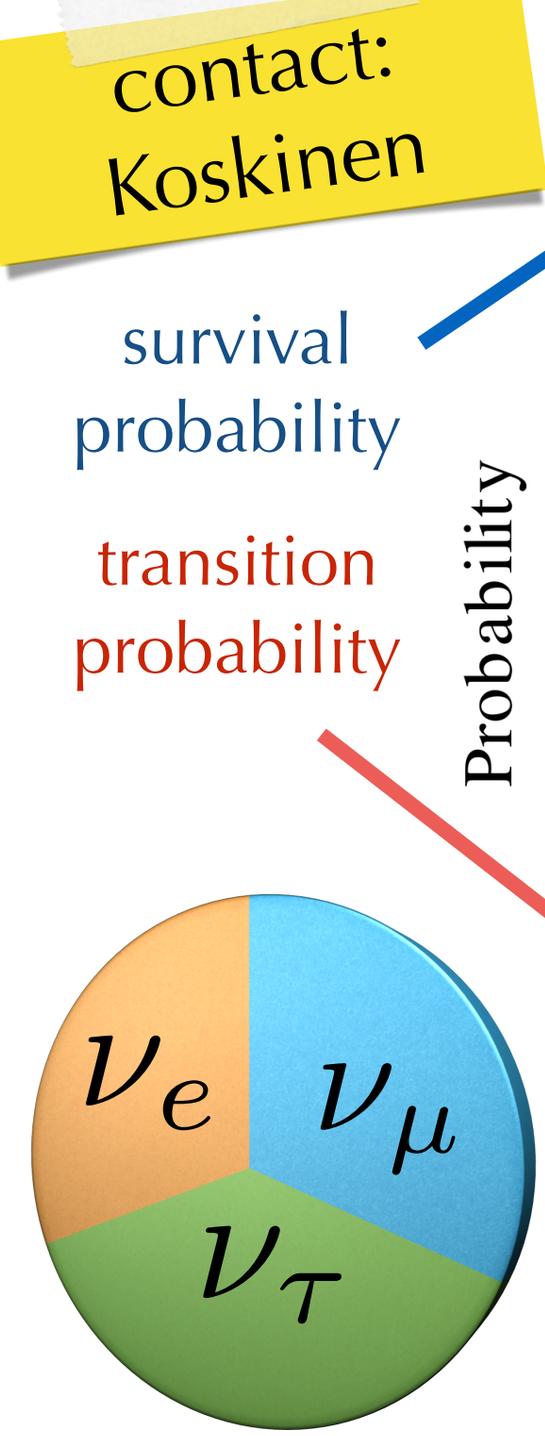
[Vitagliano, Tamborra & Raffelt Rev.Mod.Phys. 92 (2020)]

Neutrino Flavour Oscillations

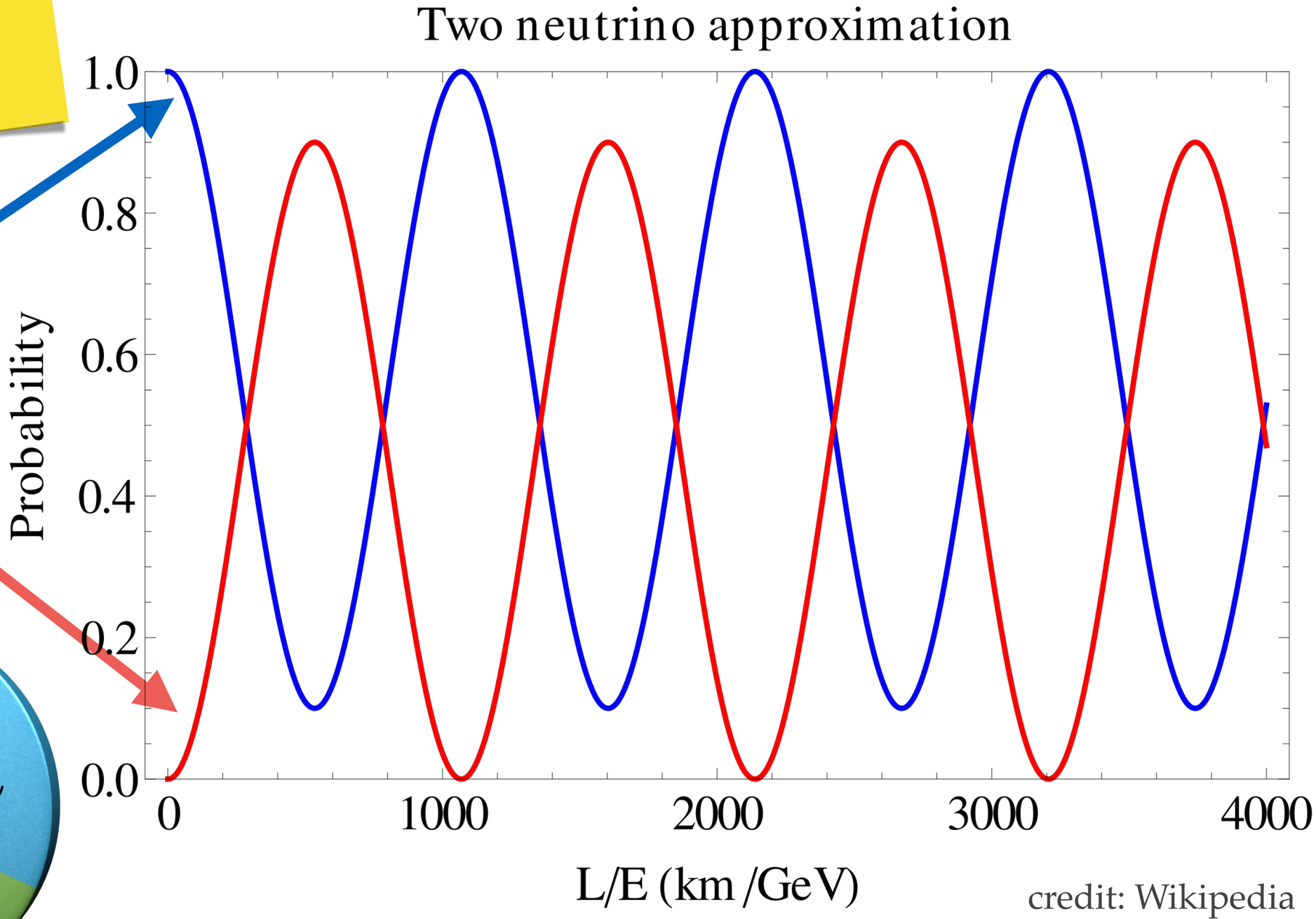
contact: Koskinen

survival probability

transition probability



(mass state)



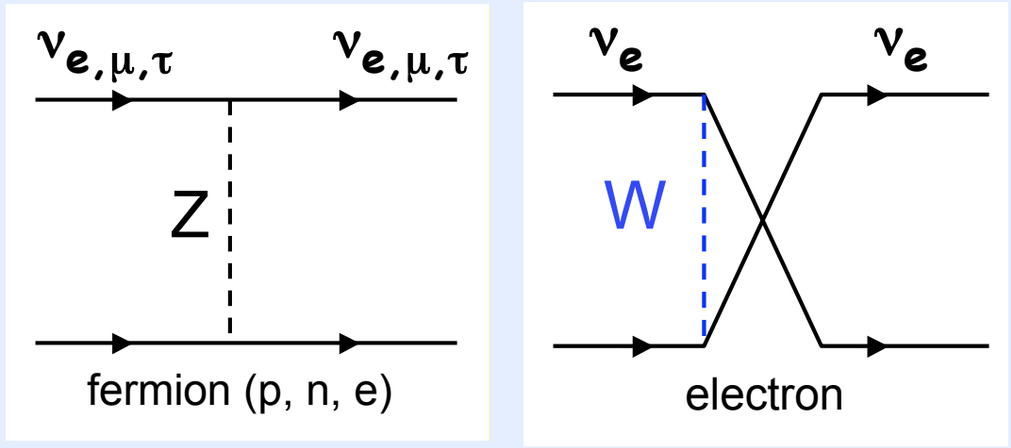
credit: Wikipedia

Neutrino oscillate between flavours in time/distance.

Neutrinos in Supernovae and Mergers

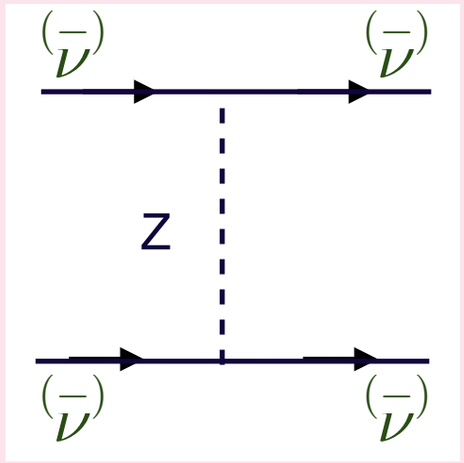
Neutrino Interactions

Understood phenomenon.



Neutrinos interact with neutrons, protons and electrons.

We still need to learn a lot about this process!

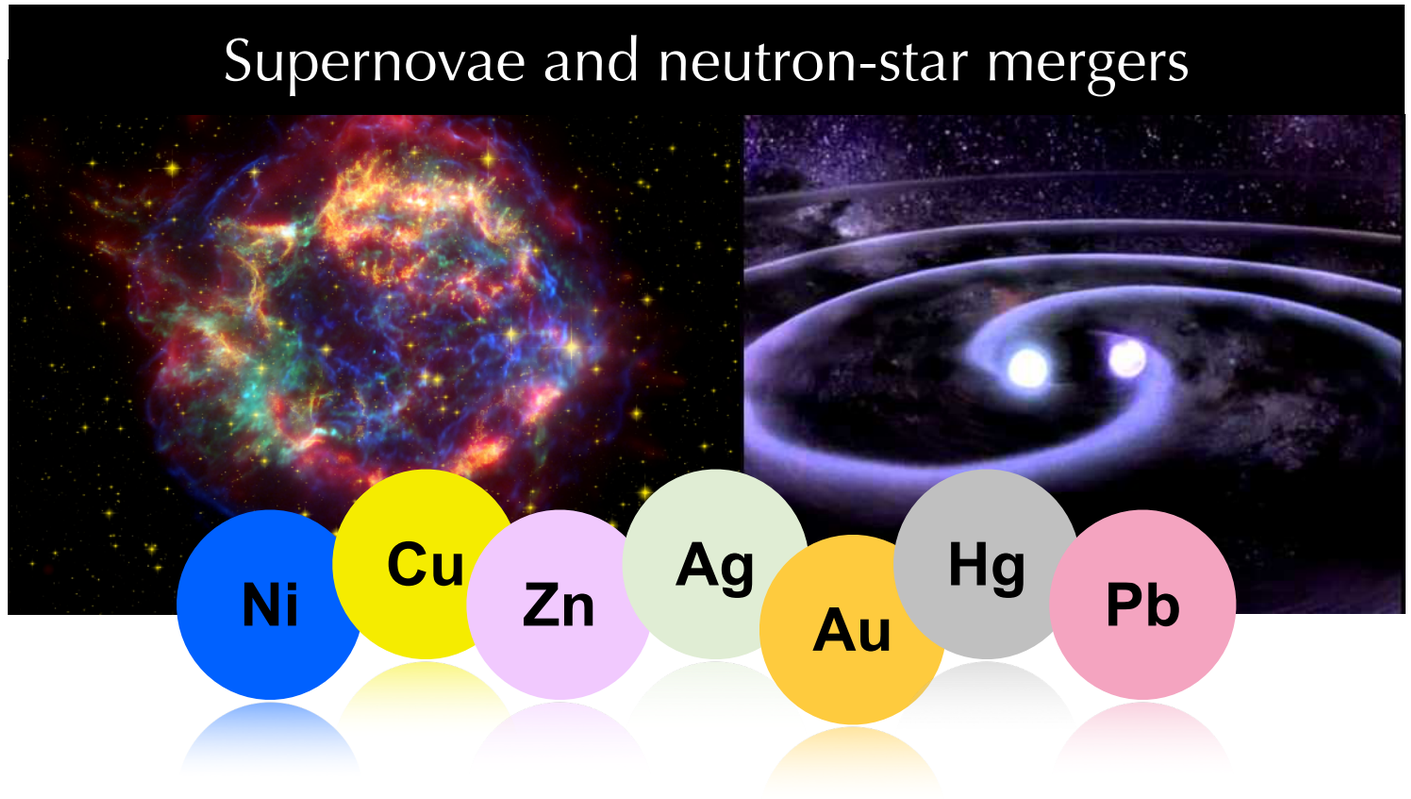


$\nu - \nu$ interactions

Non-linear phenomenon!

Stellar Nucleosynthesis

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



contact: Tamborra

Synthesis of new elements could not happen without neutrinos.

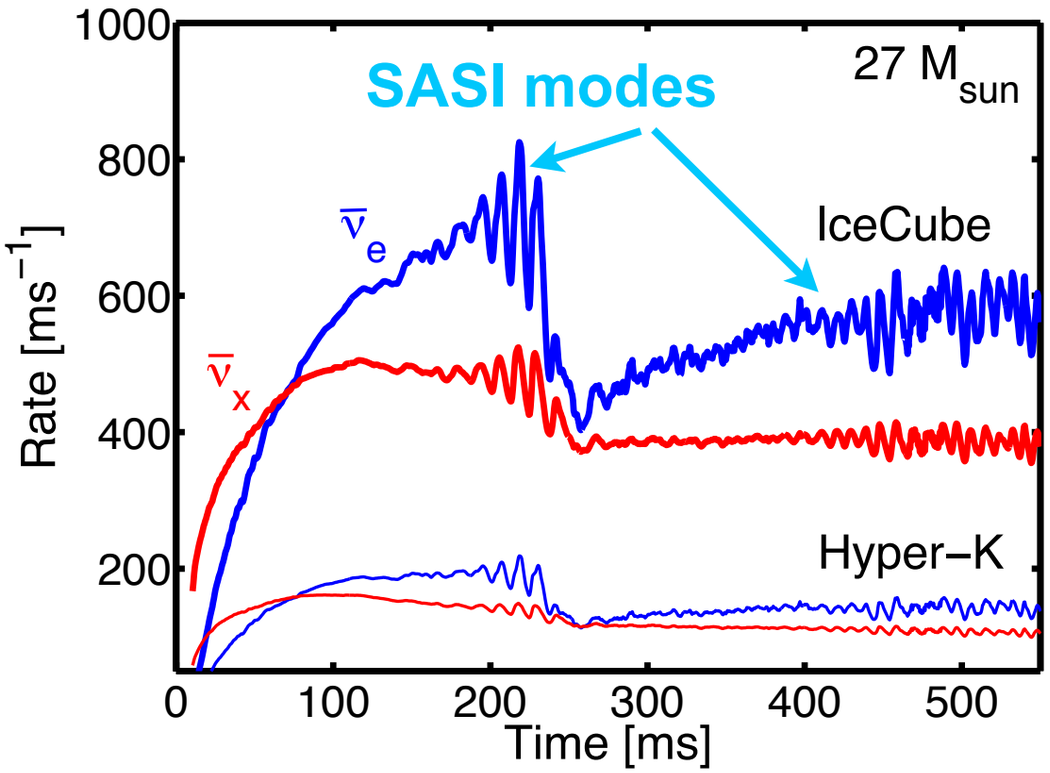
$$n + \nu_e \rightarrow e^- + p$$

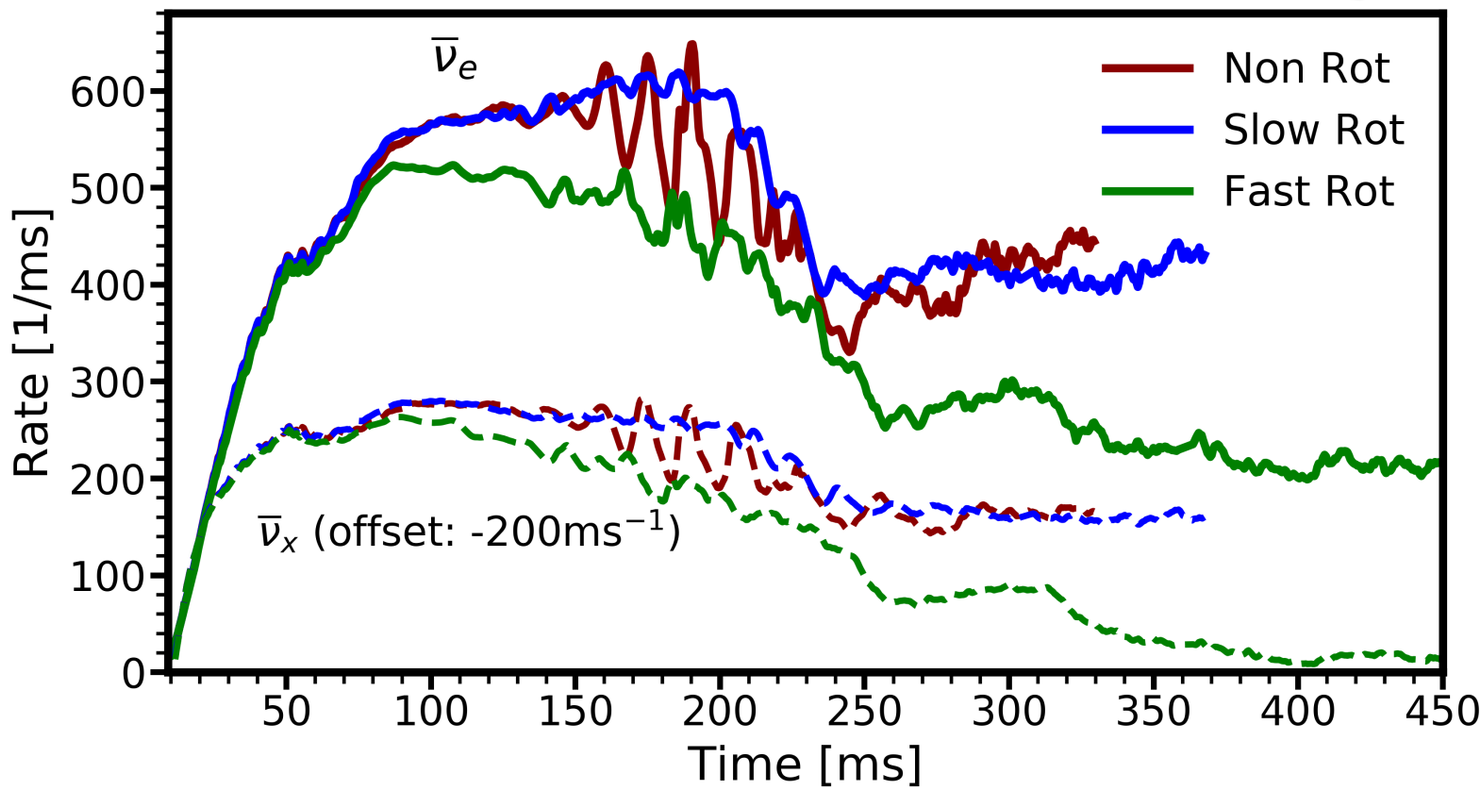
$$p + \bar{\nu}_e \rightarrow e^+ + n$$

Probe of Supernova Dynamics

contact: Tamborra

Predicted neutrino "lightcurves":



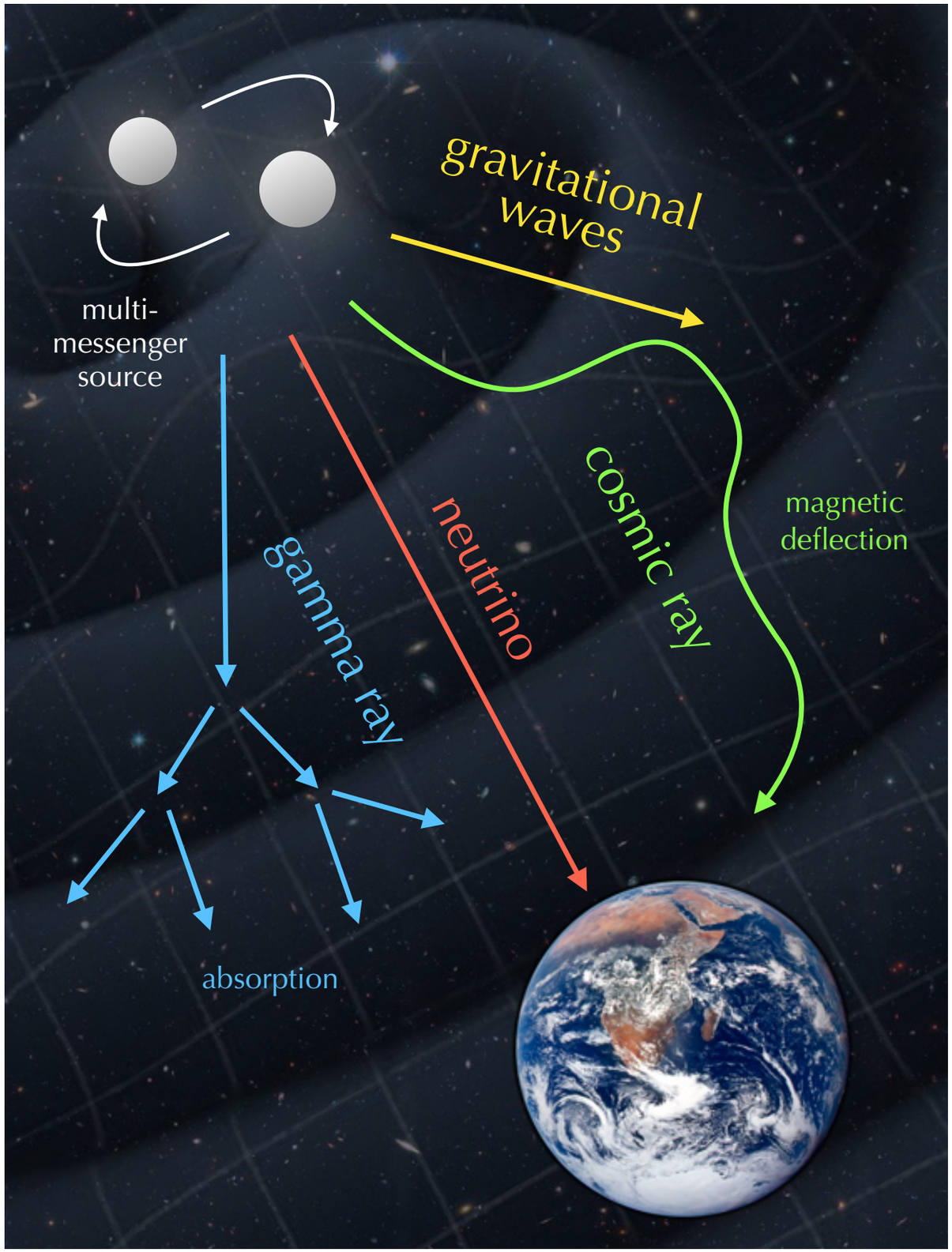


[Tamborra et al., **PRD** 90, 123001 (2014) & **PRD** 98, 123001(2018)]

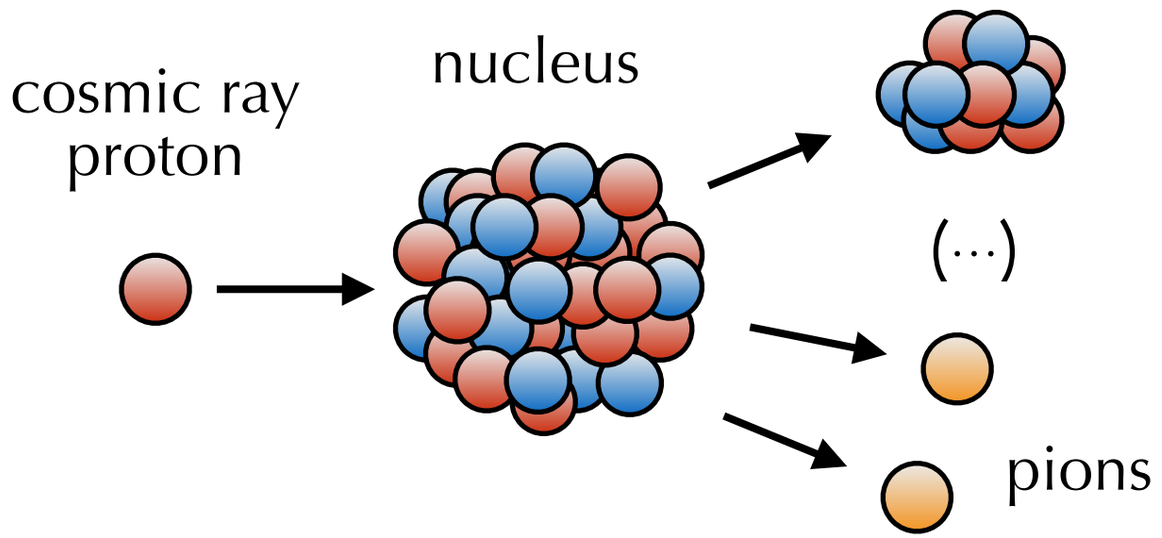
Neutrinos **probe explosion mechanism of a supernova and its rotation.**
Complementary information from detection of gravitational waves.

Neutrinos In & From Cosmic Accelerators

Multi-Messenger Astronomy



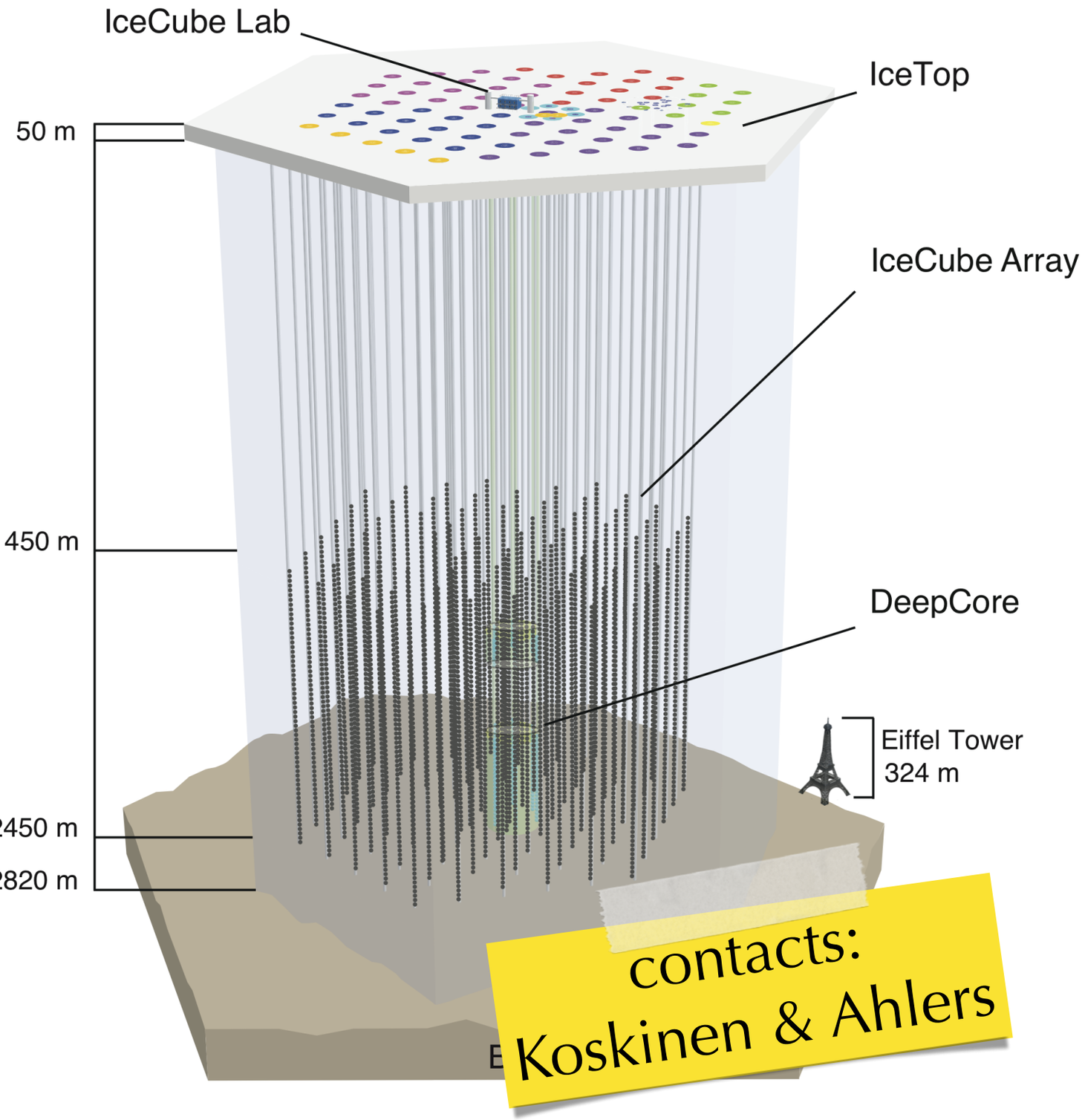
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.



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

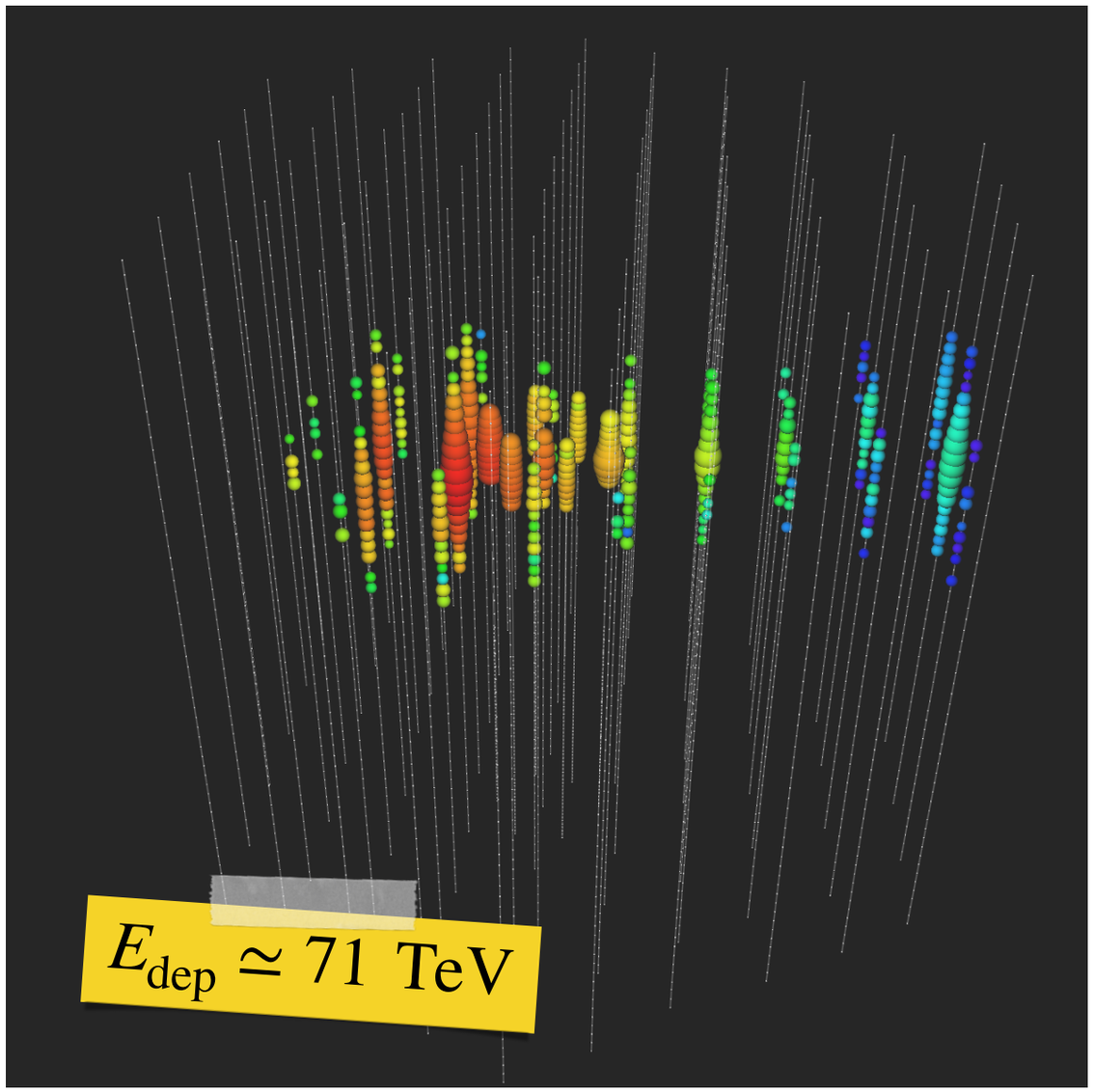


- **Giga-ton Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at 53 international institution
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections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

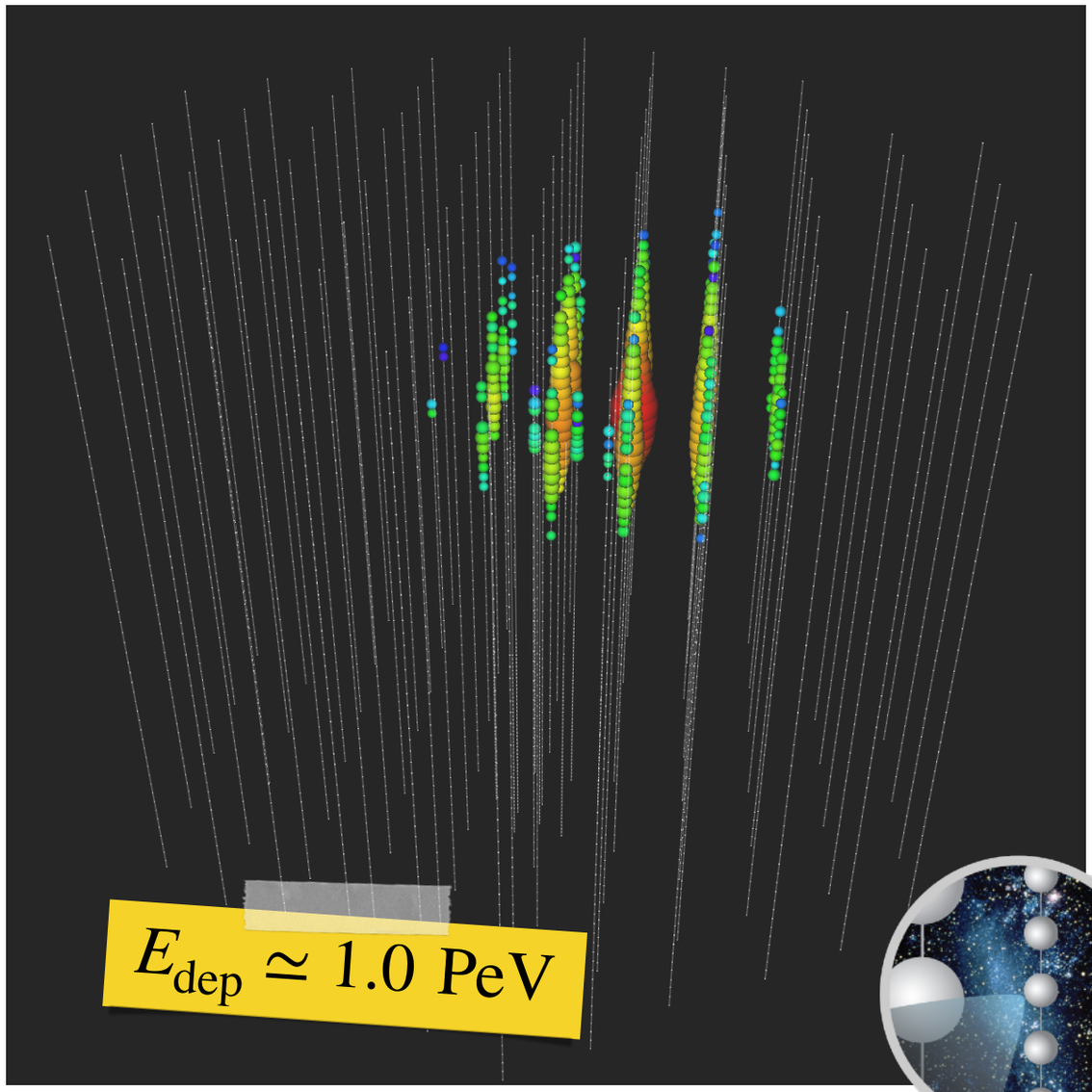
Breakthrough in 2013

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

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



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

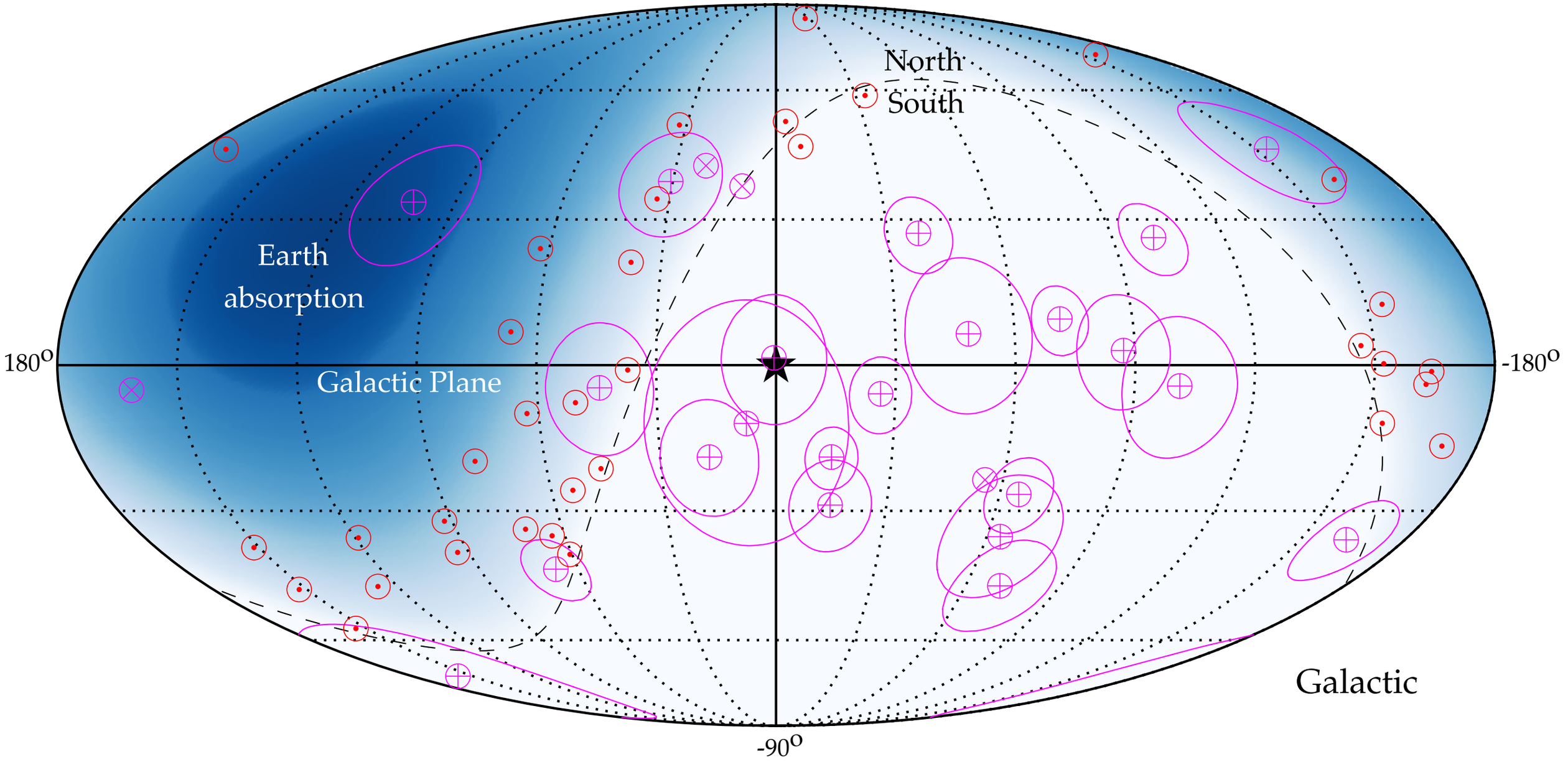


(colours indicate arrival time of Cherenkov photons from **early** to **late**)

ICECUBE

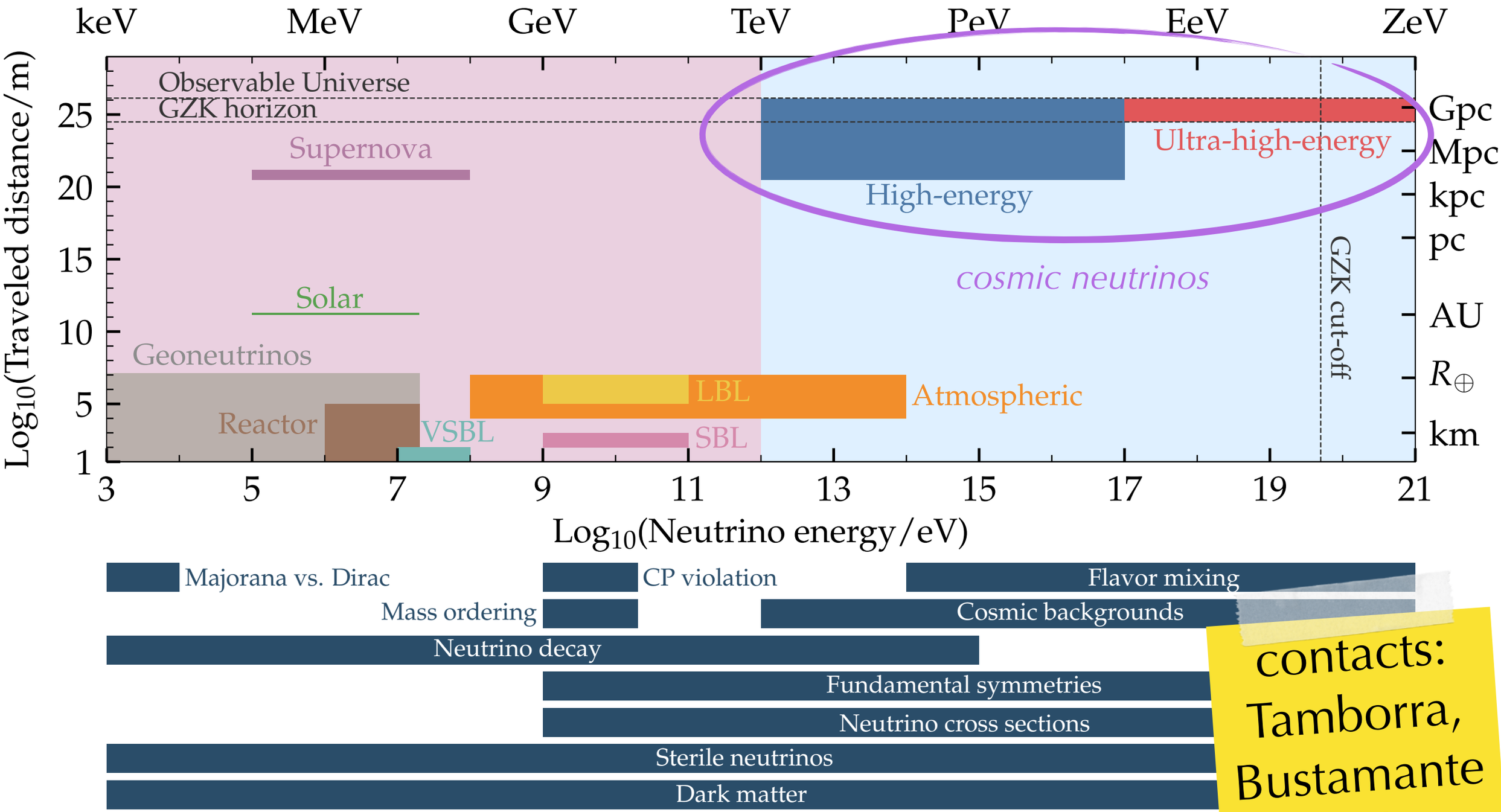
Status of Neutrino Astronomy

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

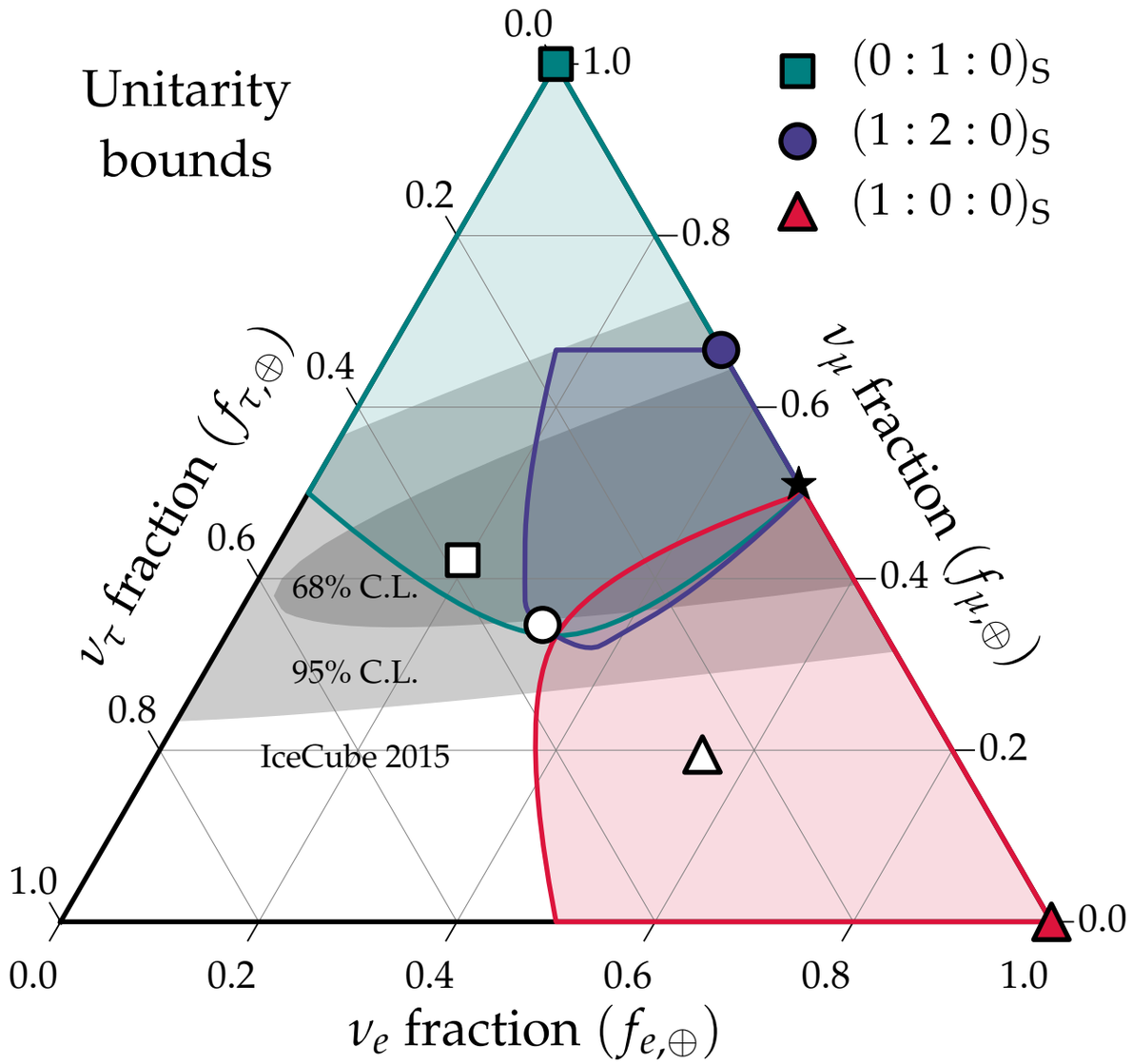


contacts: Tamborra, Bustamante & Ahlers

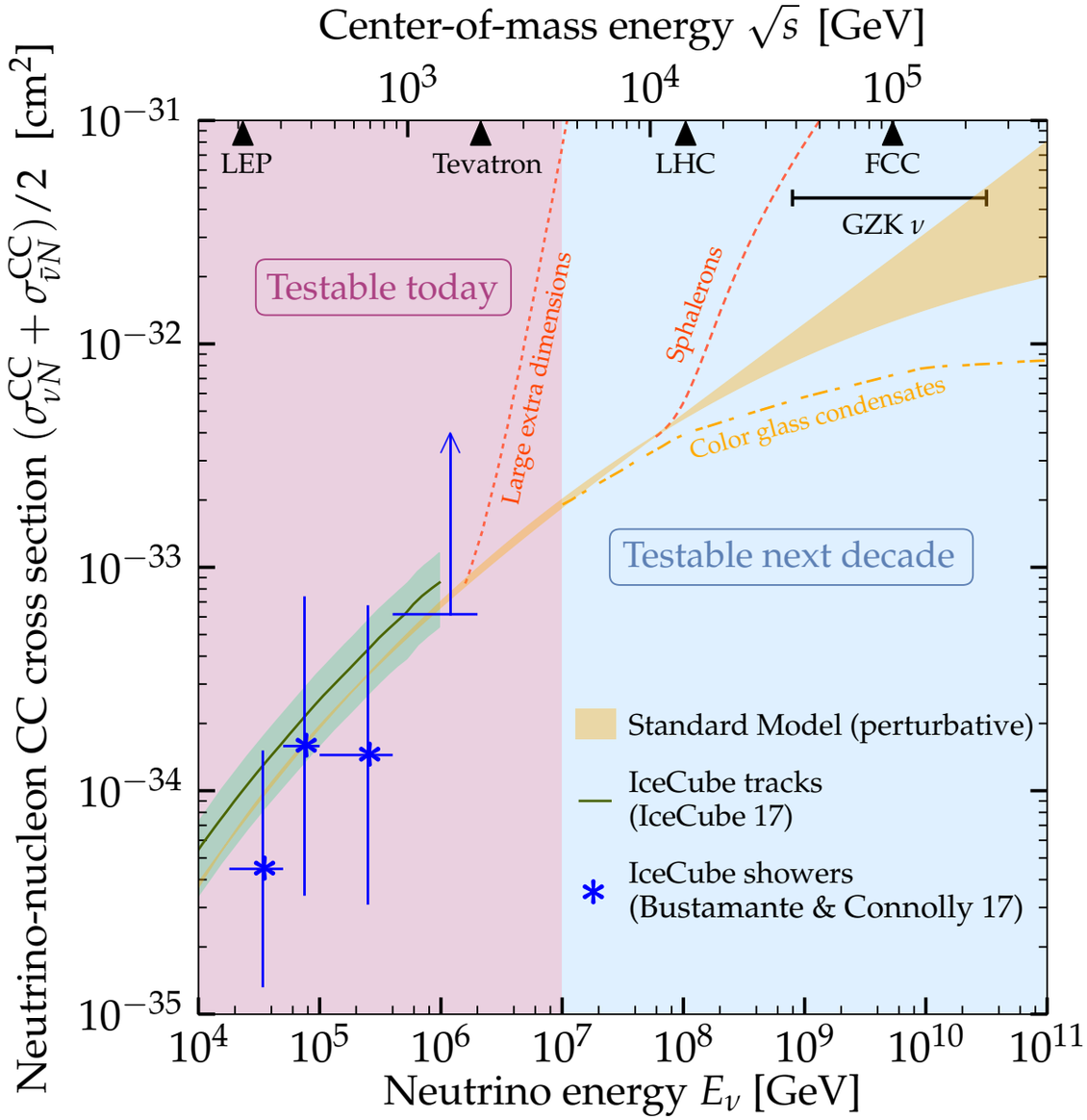
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al.*, Bull. Am. Astron. Soc. 51 (2019)]

Probe of Fundamental Physics

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



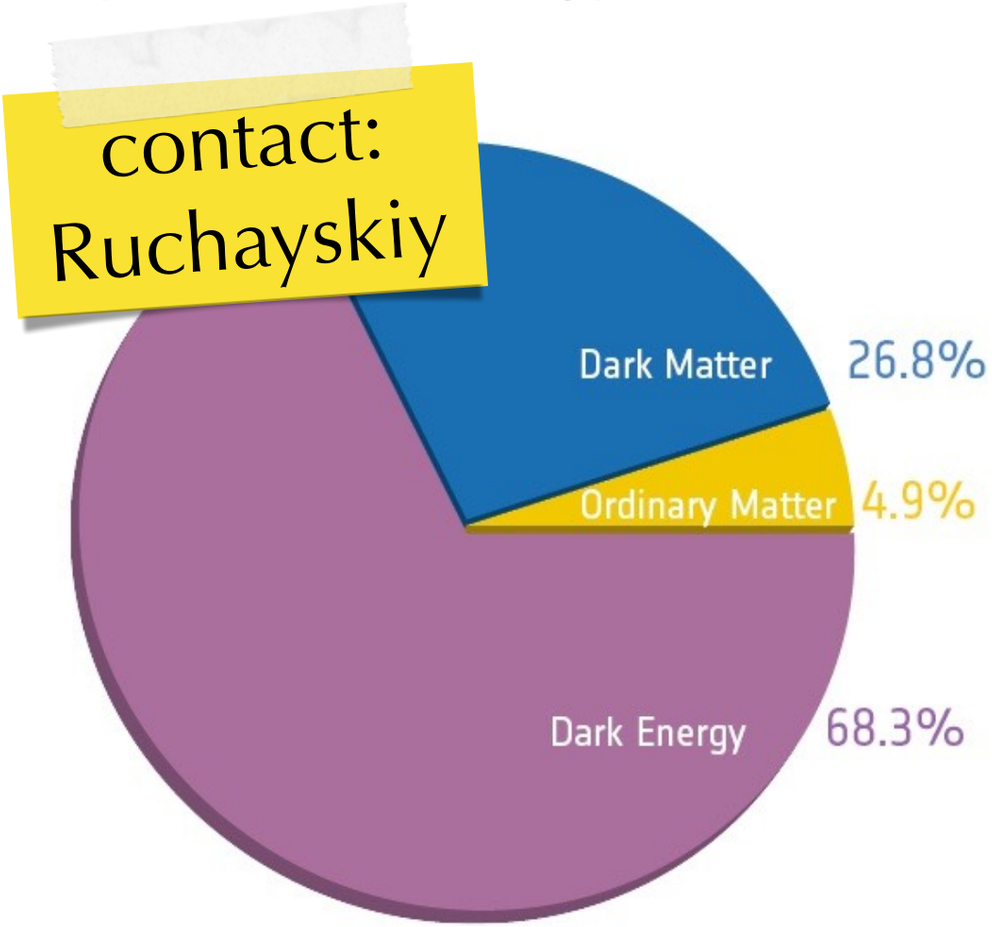
Probe of **neutrino-nucleon cross sections** at very-high energies.

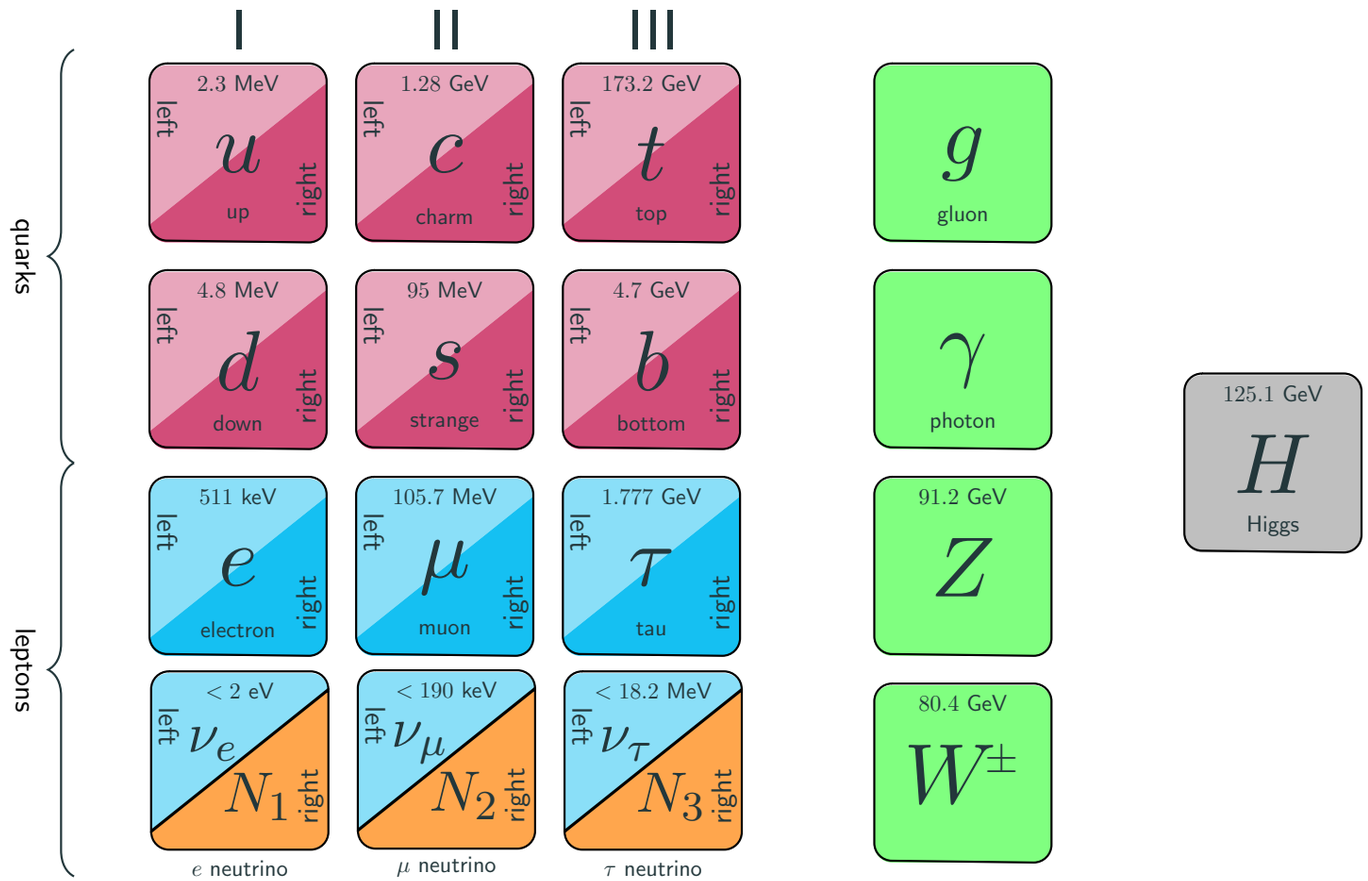


[Ahlers, Bustamante & Mu, *Phys.Rev.D* 98 (2018) 12, Ackermann *et al.*, Bull. Am. Astron. Soc. 51 (2019)]

Heavy Neutral Leptons

- also known as "right-handed neutrinos" or "heavy sterile neutrinos"
- candidates for (warm) dark matter and/or mediators of leptogenesis
- *possible astrophysical signatures:* X-ray emission, Lyman-α forest
- *phenomenology of direct experimental searches:* SHiP, ATLAS @ CERN





[Boyarsky, Drewes, Lasserre, Mertens & Ruchayskiy, Prog.Part.Nucl.Phys. 104 (2019)]

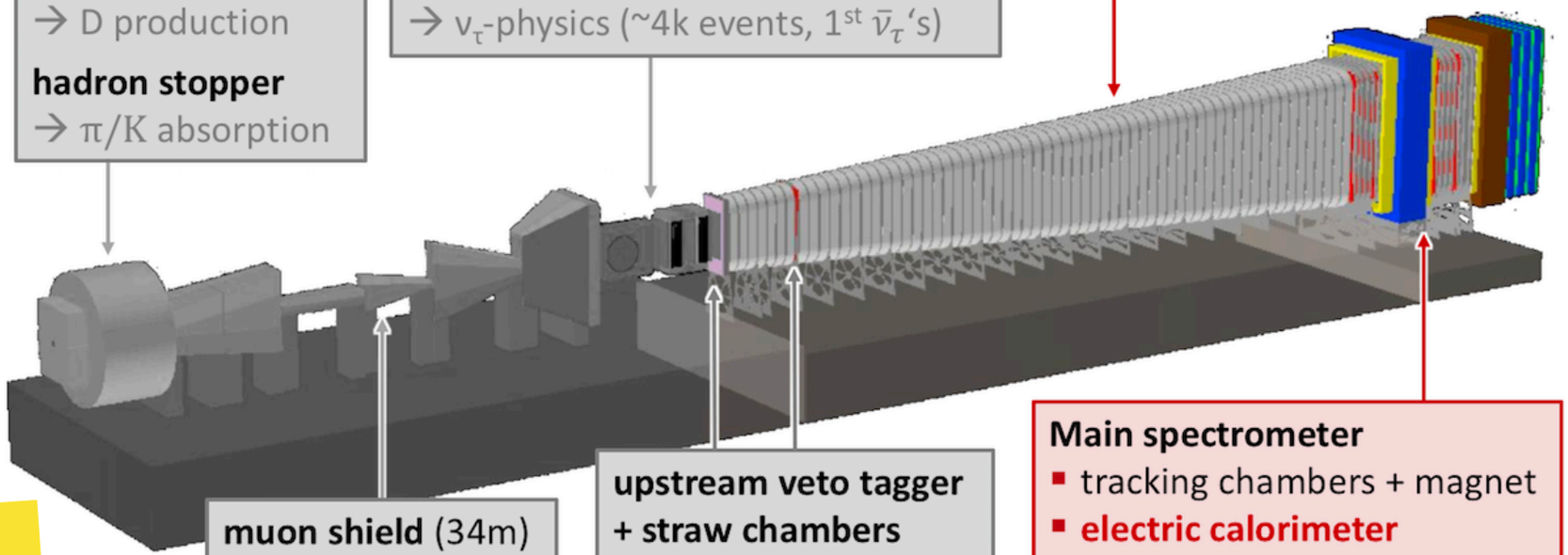
SHiP Experiment

fixed target
- 58cm Mo-TZM
+ 58cm W ($\widehat{=} 10\lambda$)
→ D production

hadron stopper
→ π/K absorption

Emulsion spectrometer
- OPERA-like lead-emulsion-bricks
- muon spectrometer
→ ν_τ-physics (~4k events, 1st $\bar{\nu}_\tau$'s)

evacuated decay vessel (50m)
+ Surround Background Tagger

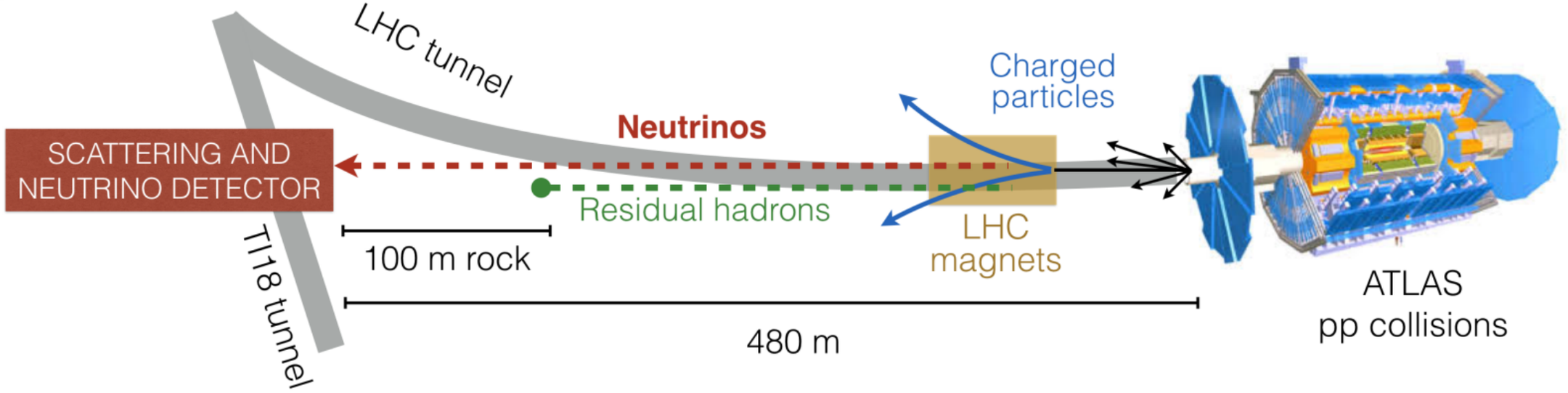


muon shield (34m)
- 1.8 kt Fe
→ active shield & passive absorber

upstream veto tagger
+ straw chambers
→ veto **ν** events
+ residual **μ**'s

Main spectrometer
- tracking chambers + magnet
- **electric calorimeter**
- muon filters

contact: Ruchayskiy



Summary

Neutrinos in Particle Astrophysics and Cosmology:

- *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 flavour conversions are crucial but yet to be fully grasped*

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

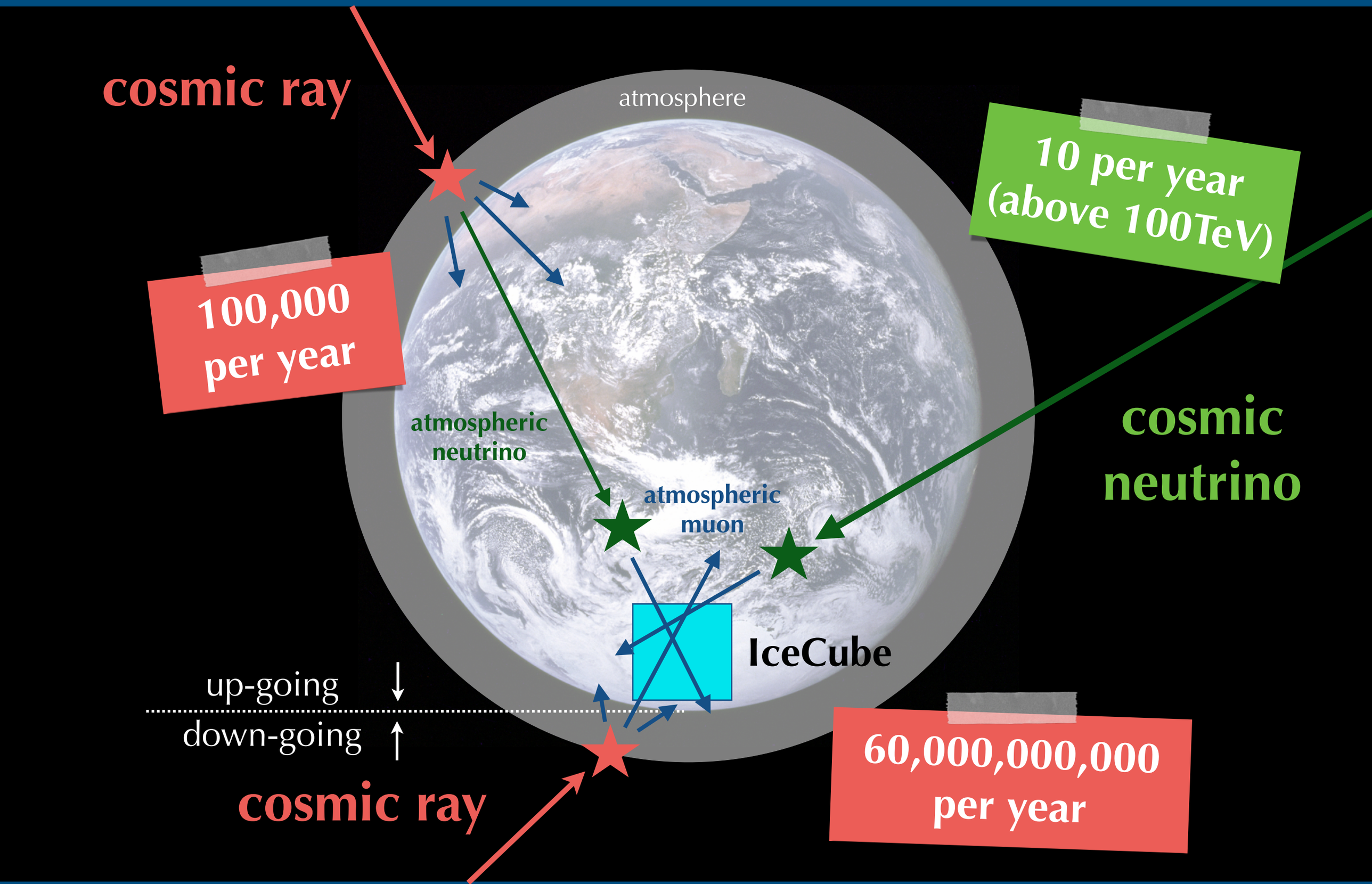
- *impact on stellar evolution*
- *potential to probe astrophysical environments*
- *fundamental neutrino properties*
- *direct probe of the origin of cosmic rays*
- *observation in neutrino telescopes or experiments*

Thank you

for your attention!

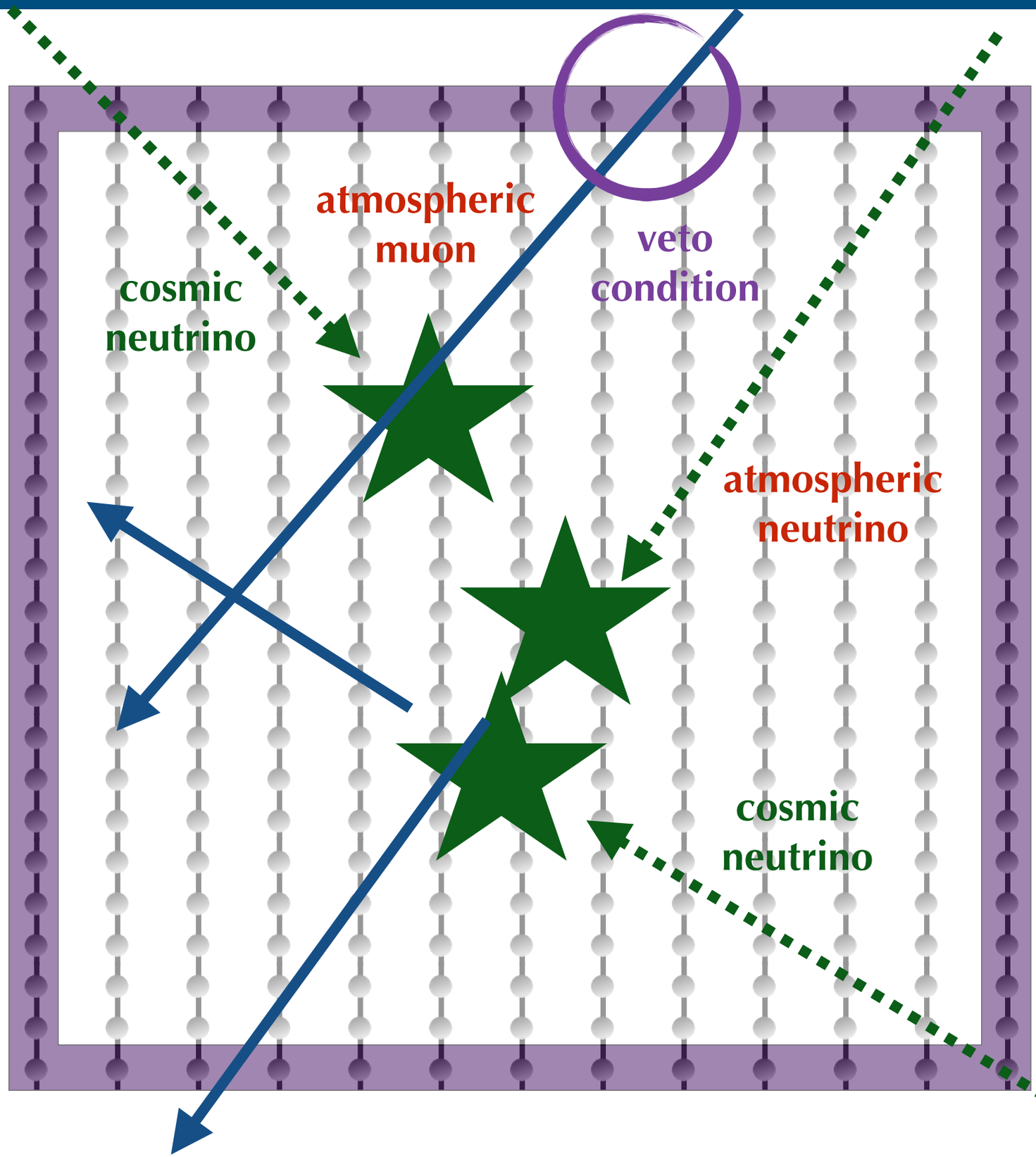
Backup Slides

Neutrino Selection I

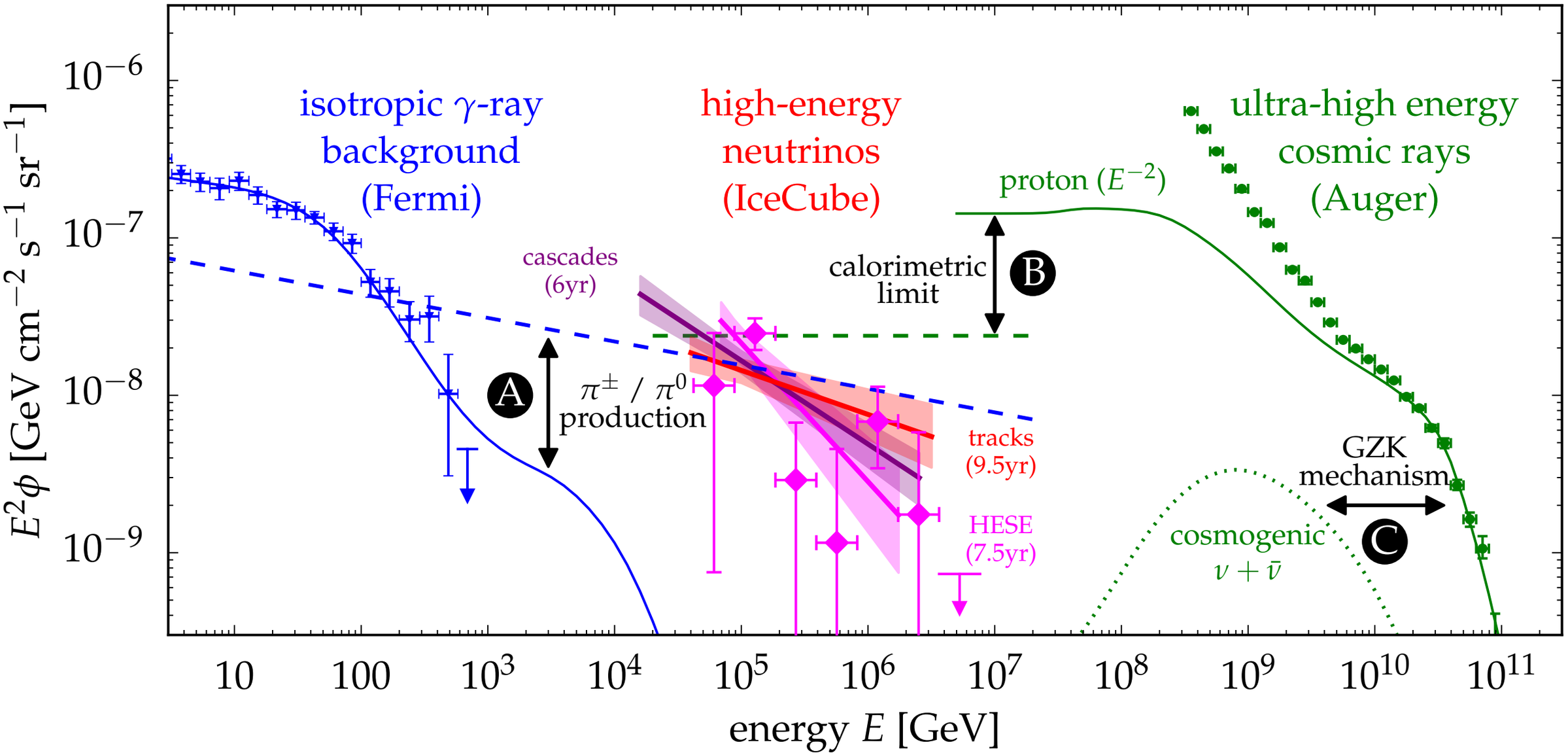


Neutrino Selection II

- 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

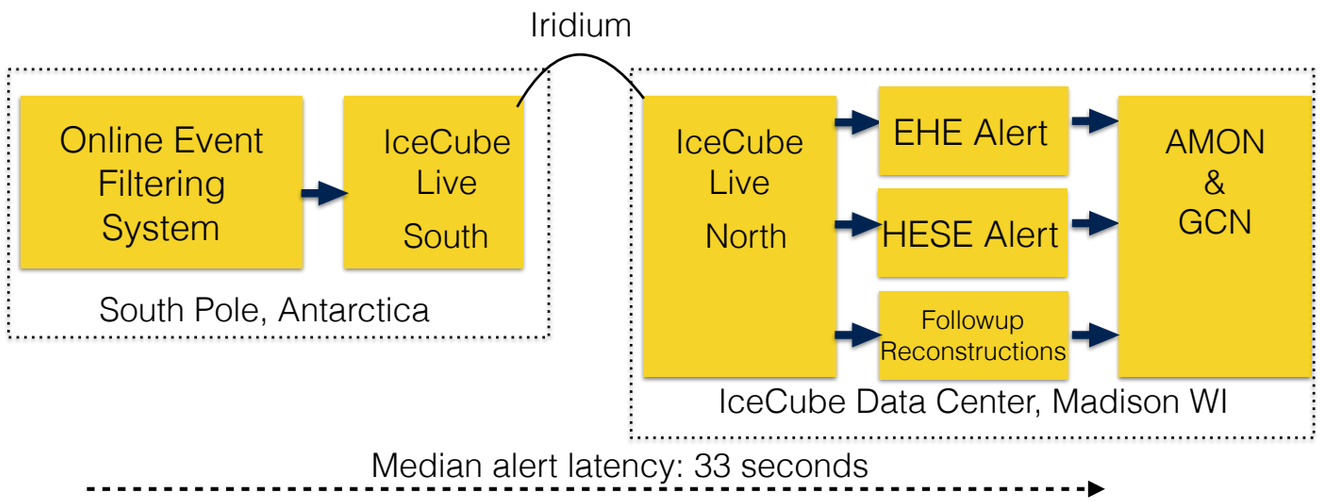


The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

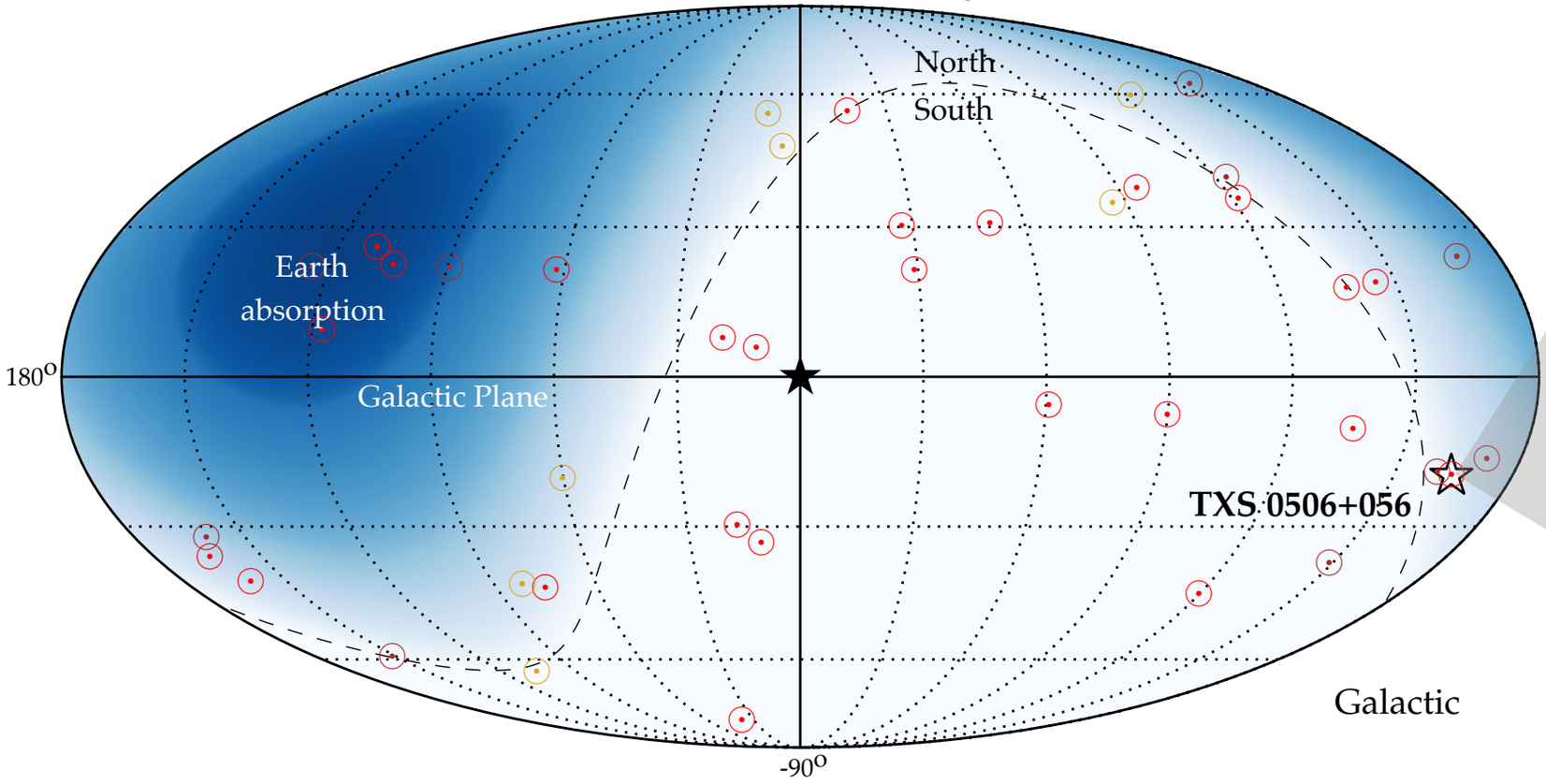
Realtime Neutrino Alerts

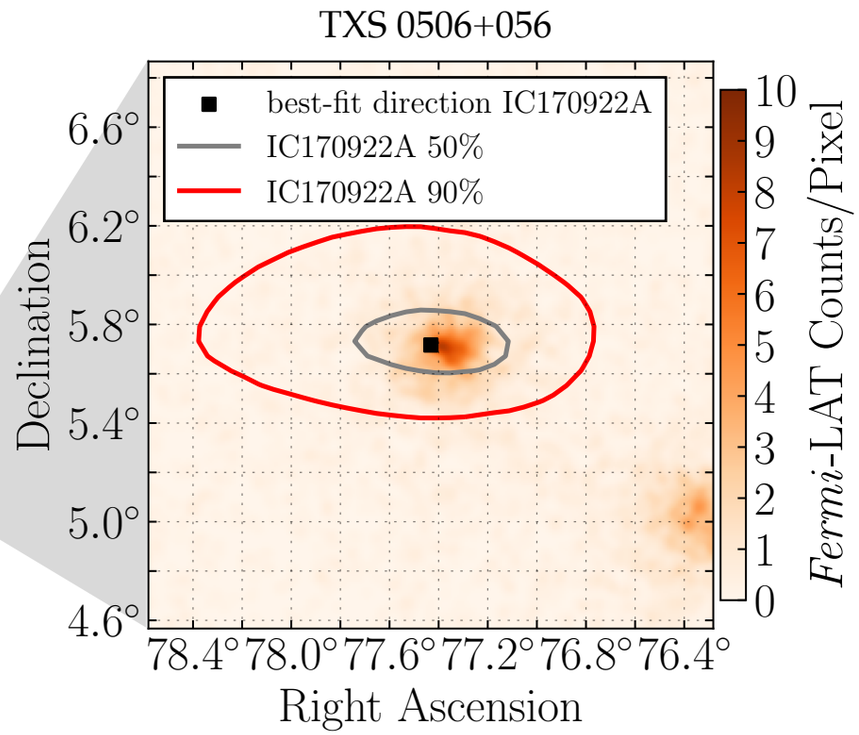
Low-latency (<1min) **public neutrino alert system** established in April 2016.

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

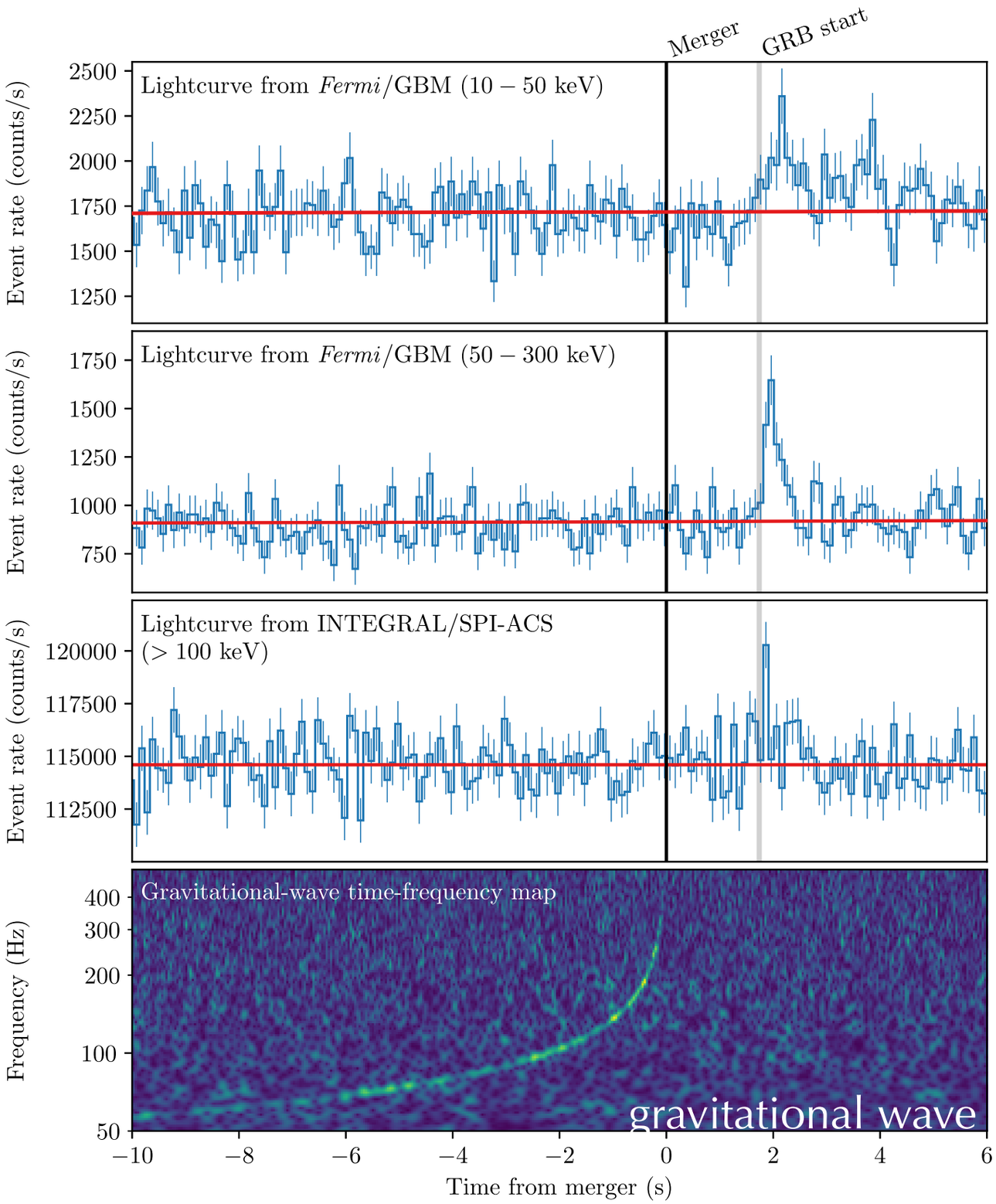


Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))

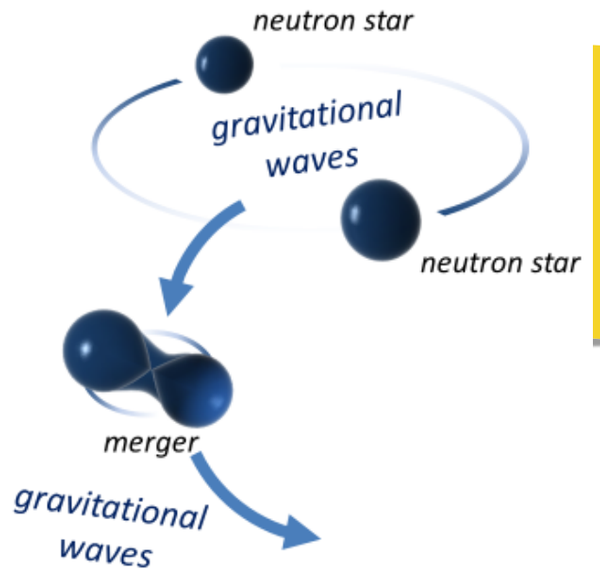




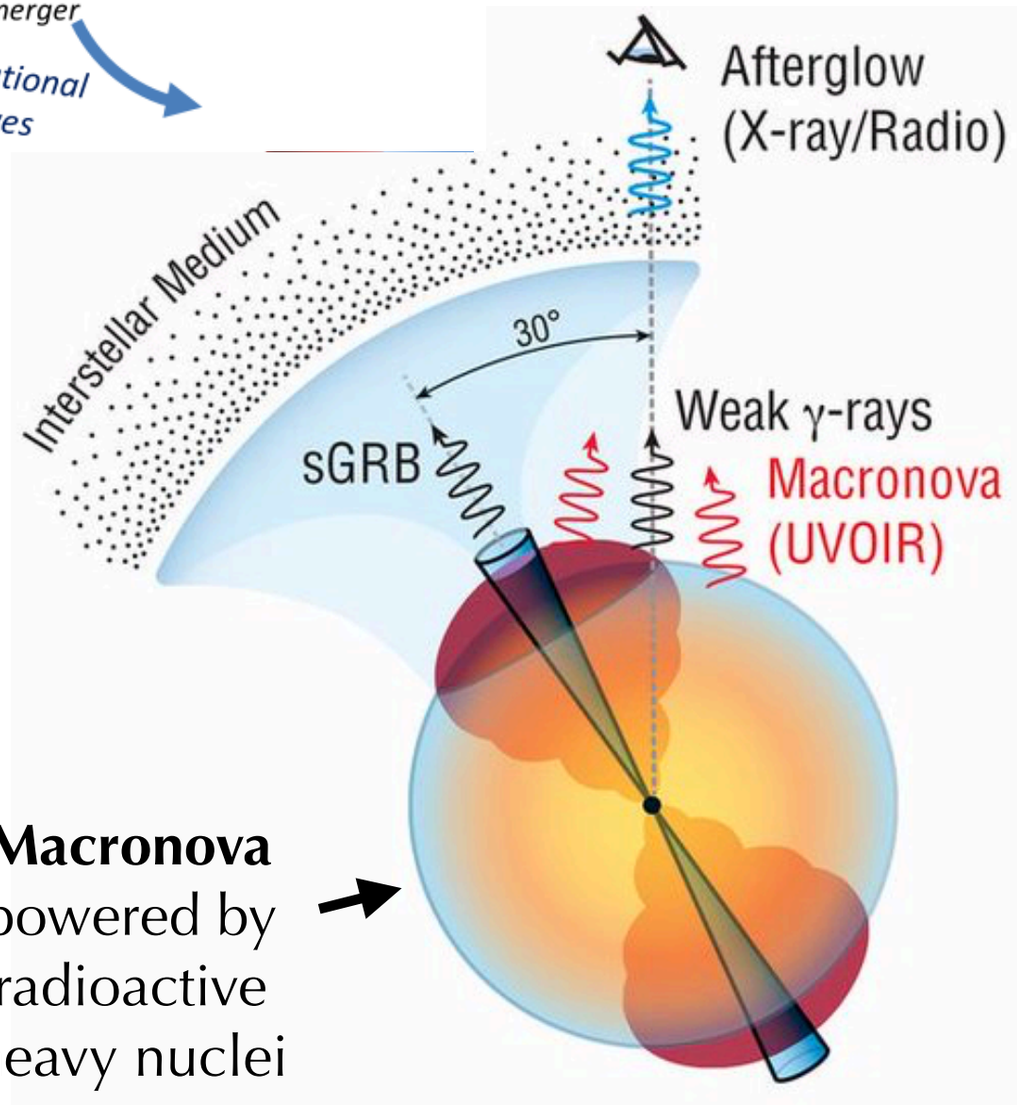
GRBs and Gravitational Waves



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



GW 170817
&
GRB 170817A



Macronova powered by radioactive heavy nuclei