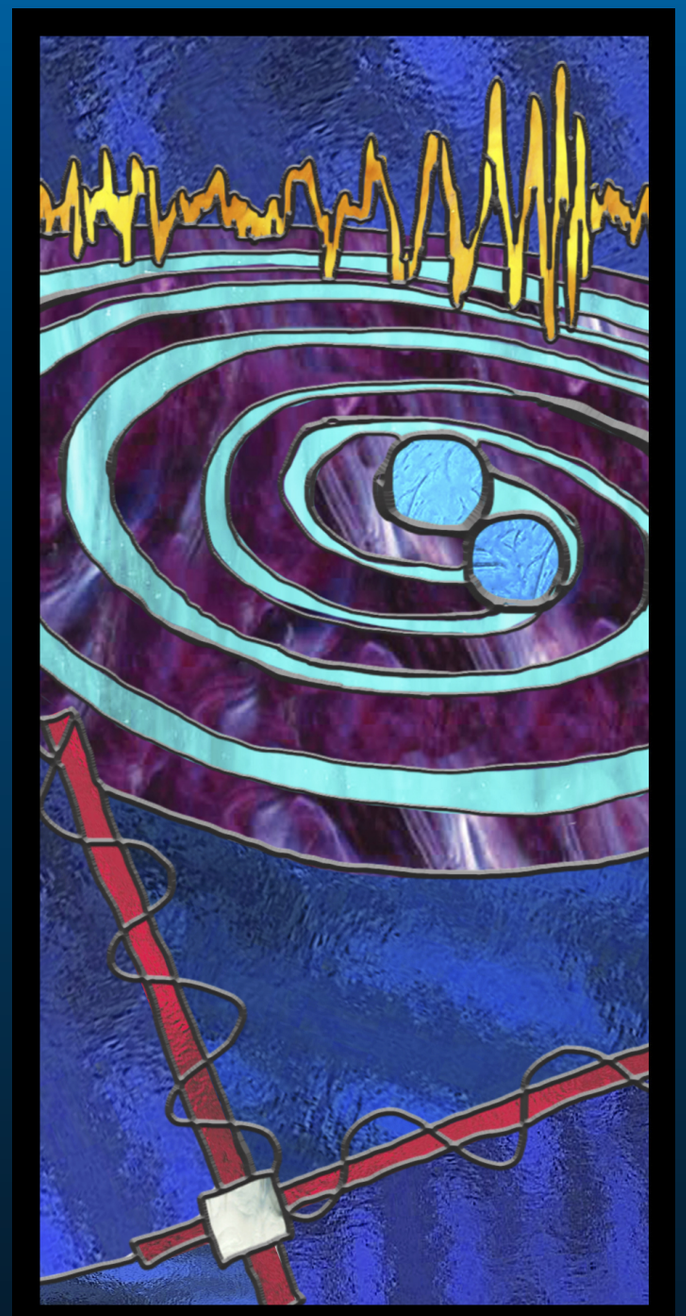
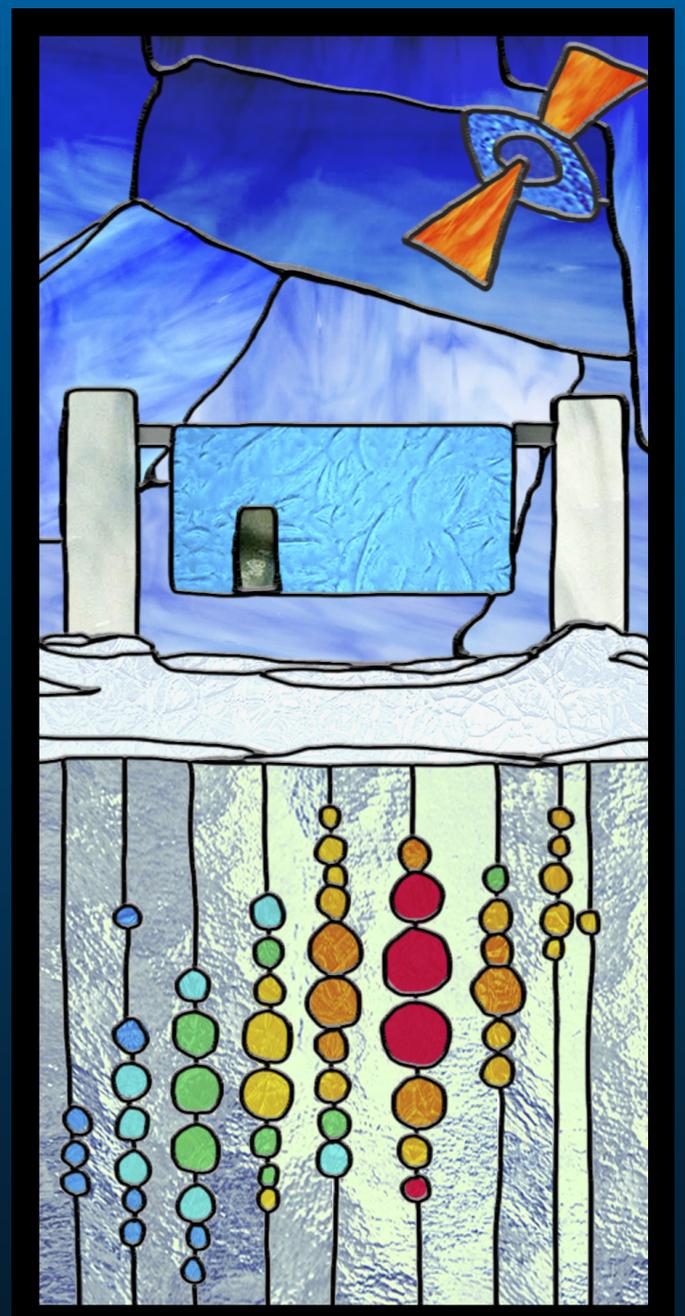
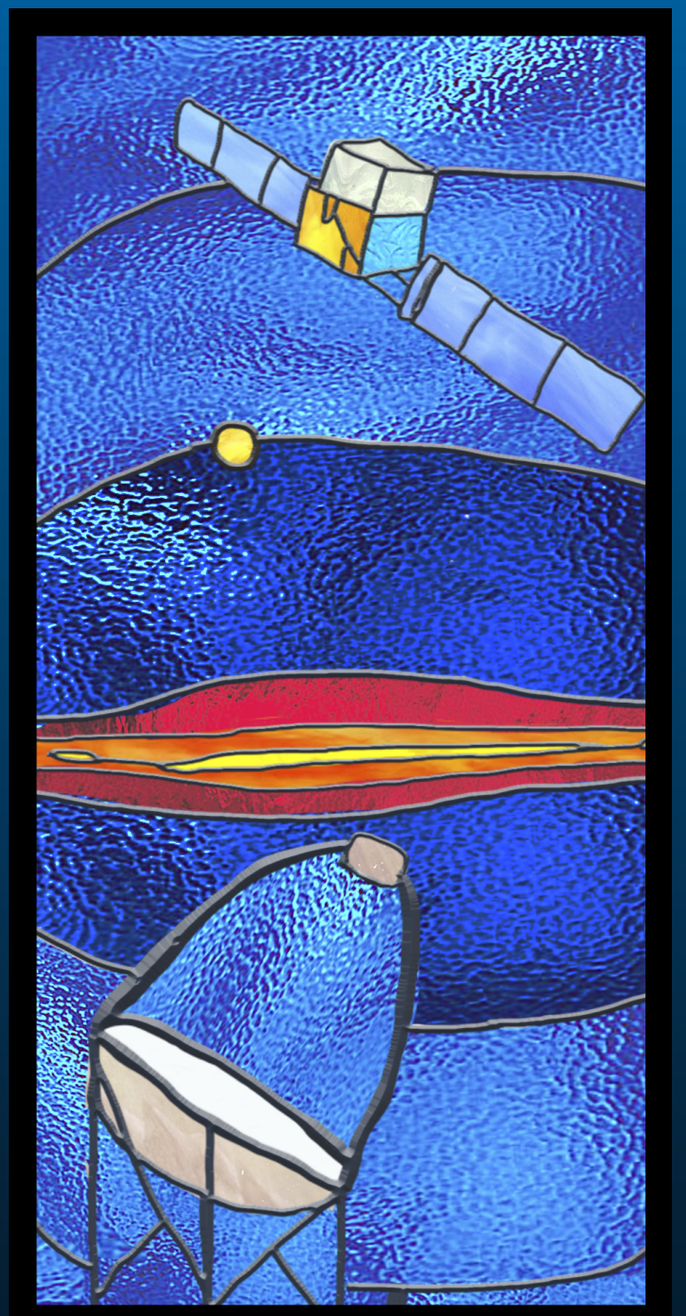
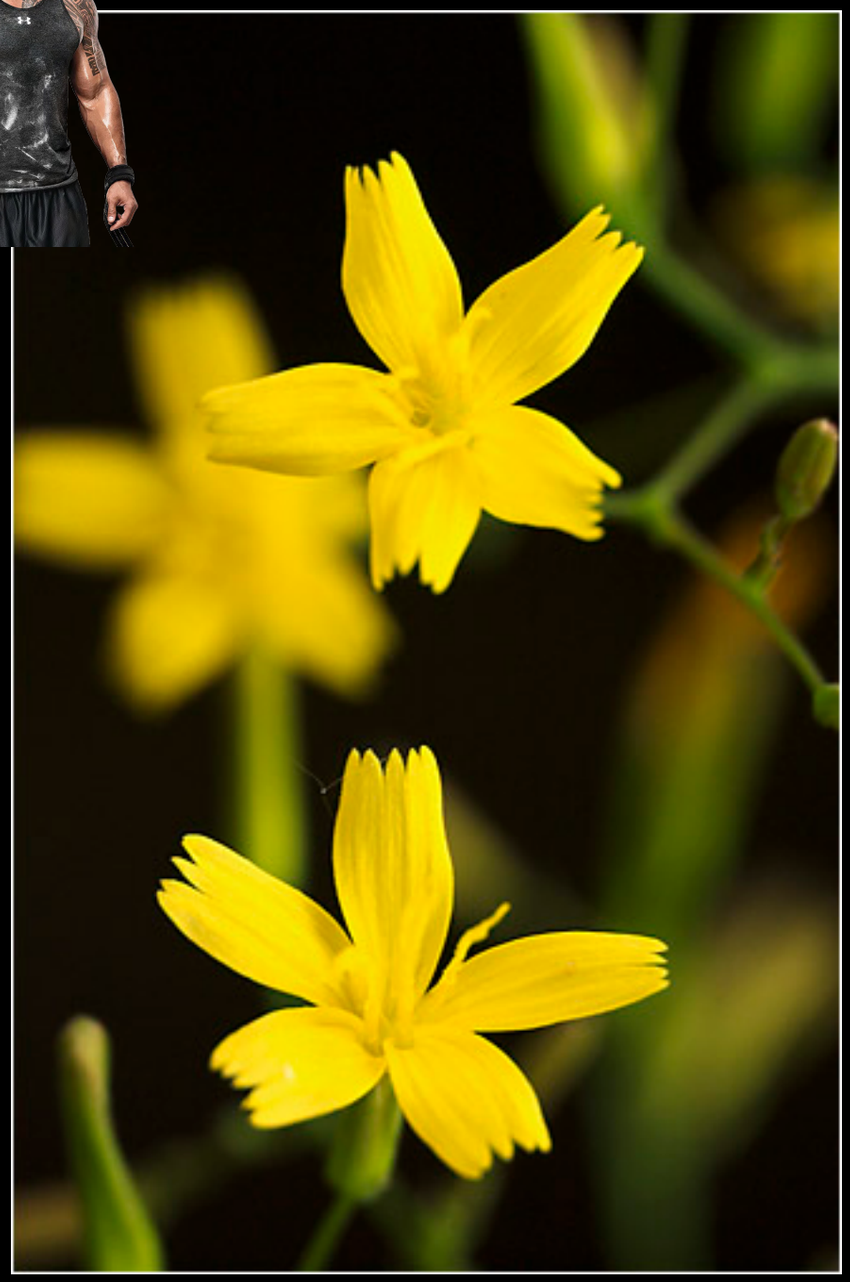




Particle Astrophysics

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

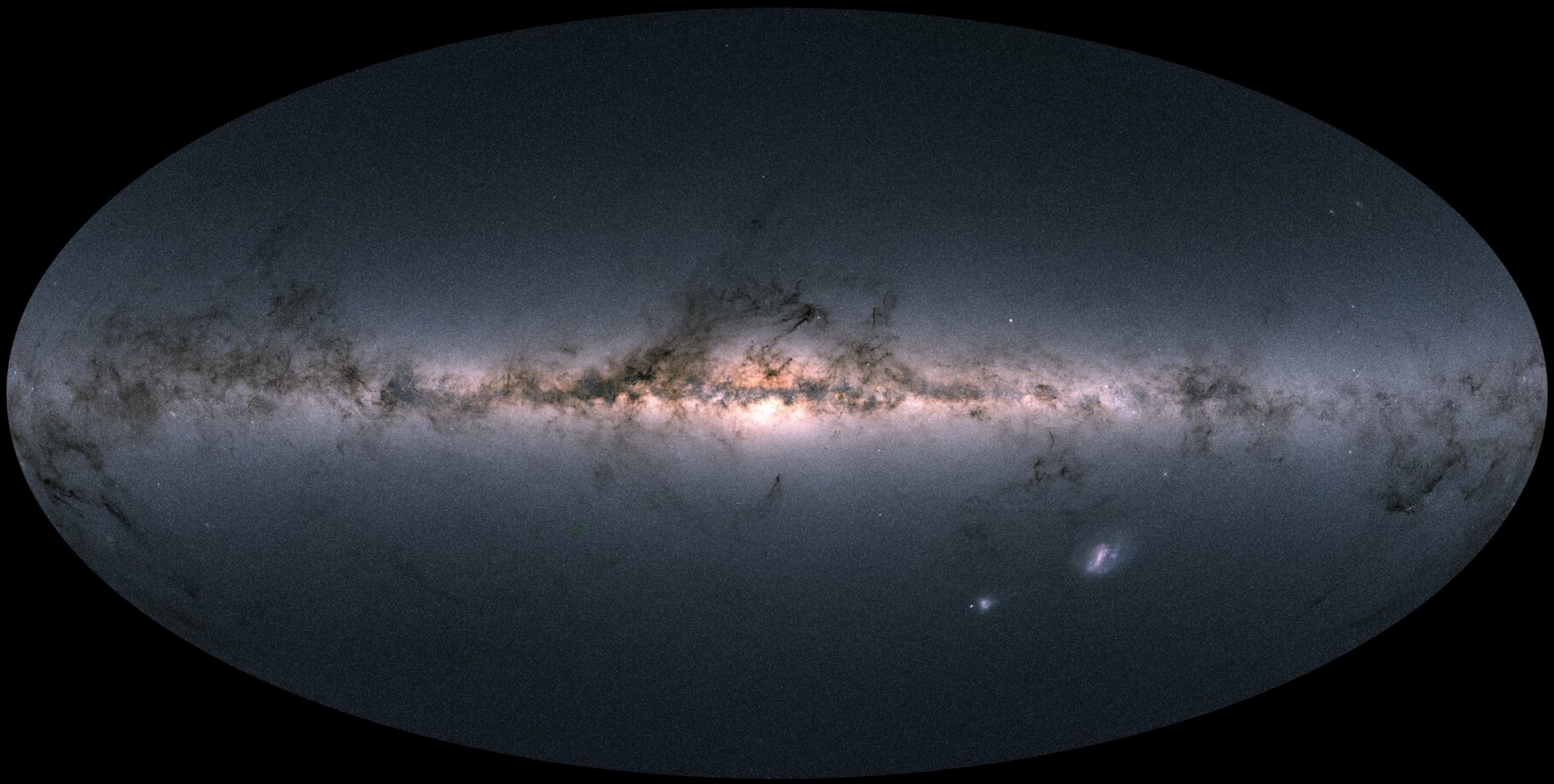
Optical light



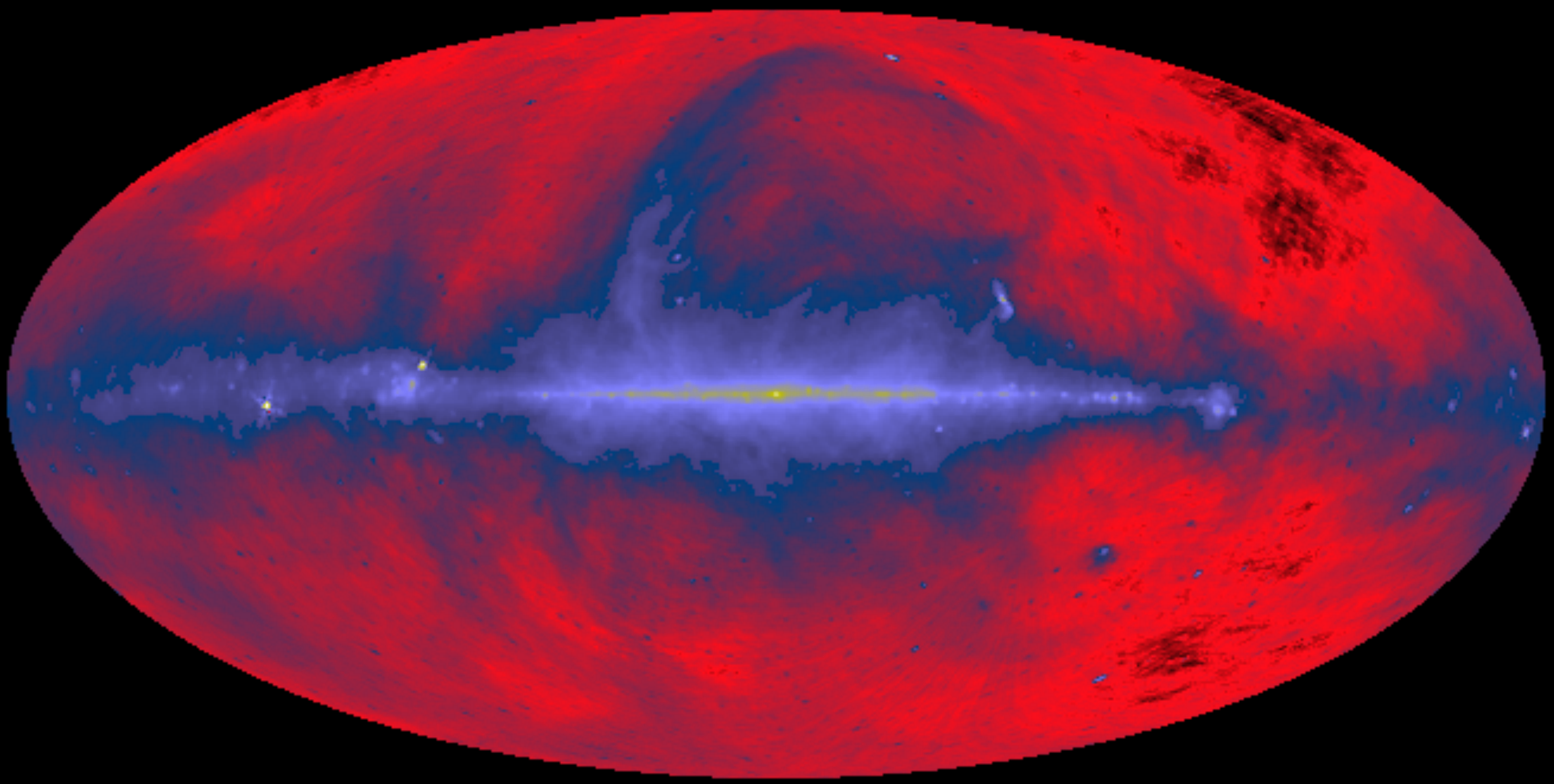
Ultraviolet light

Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

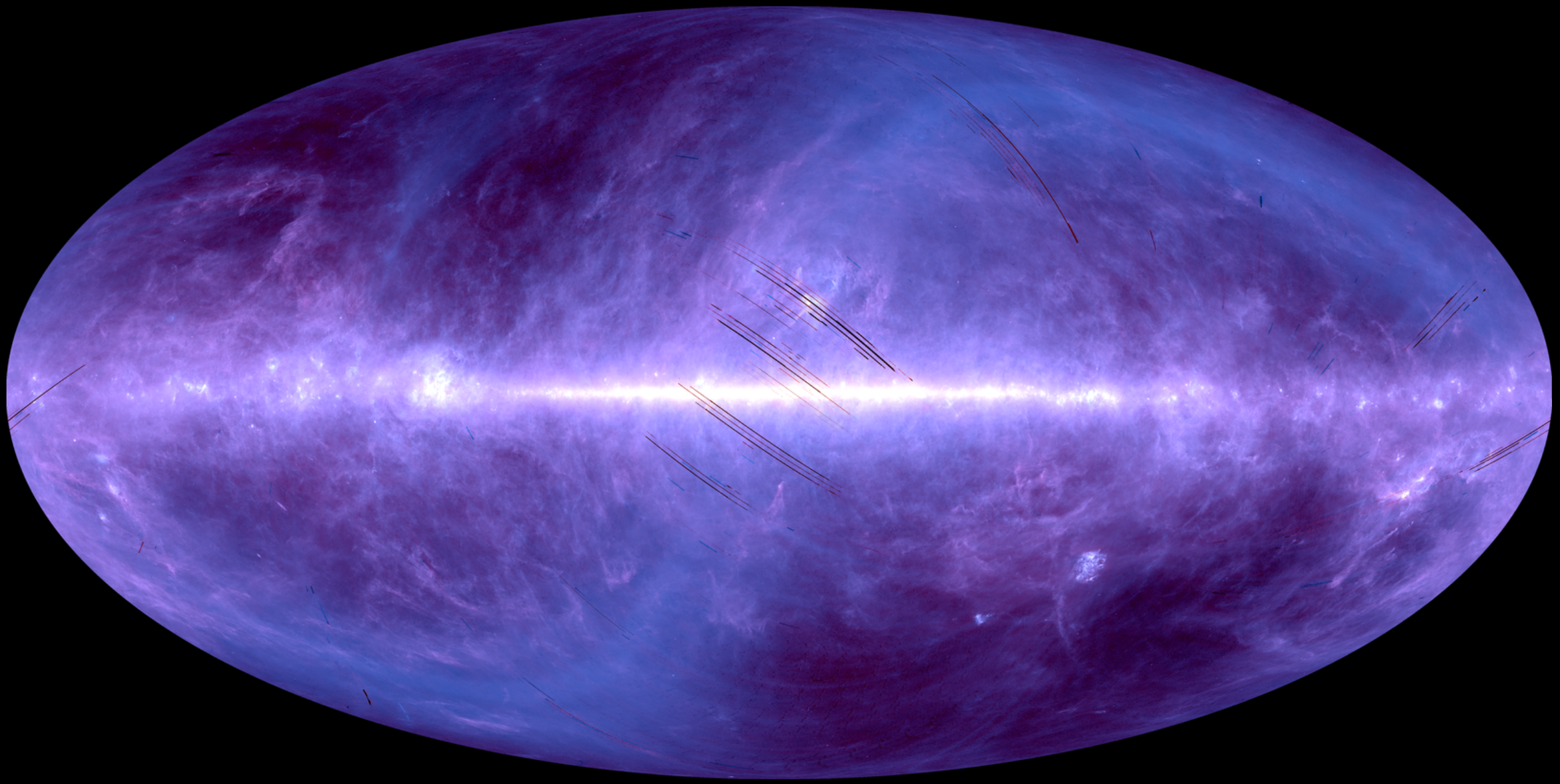
Optical light



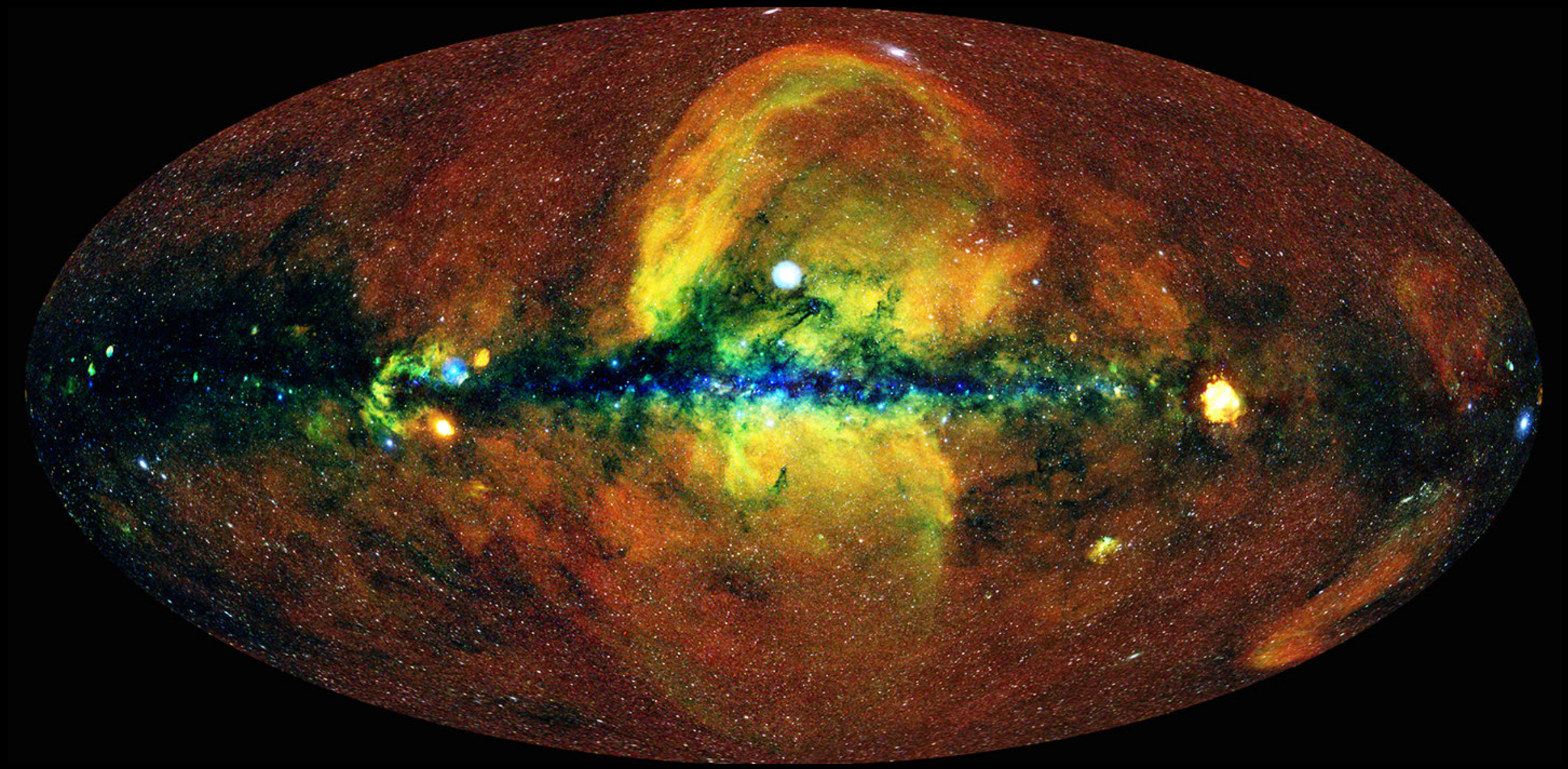
Radio waves



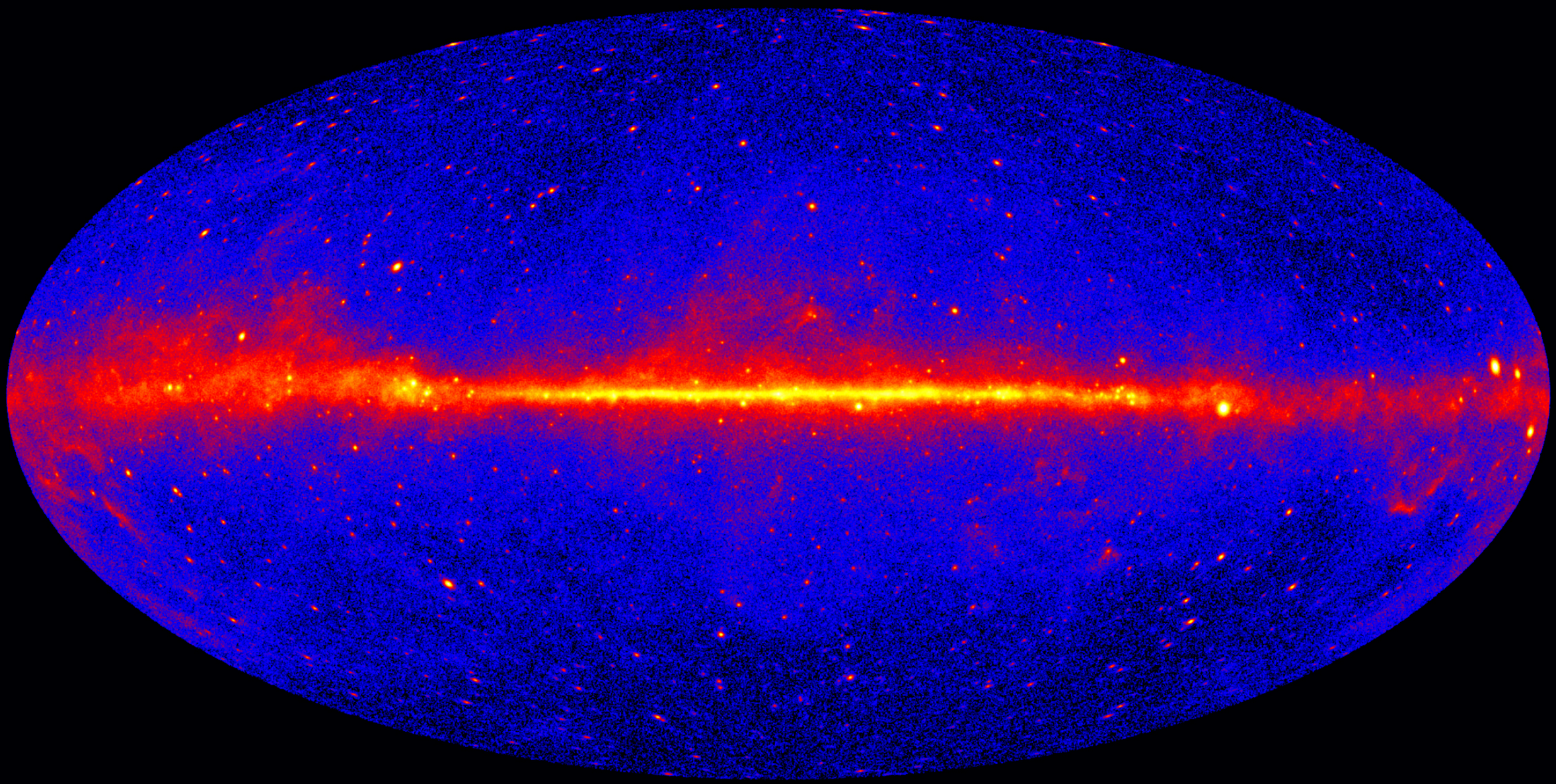
Infrared



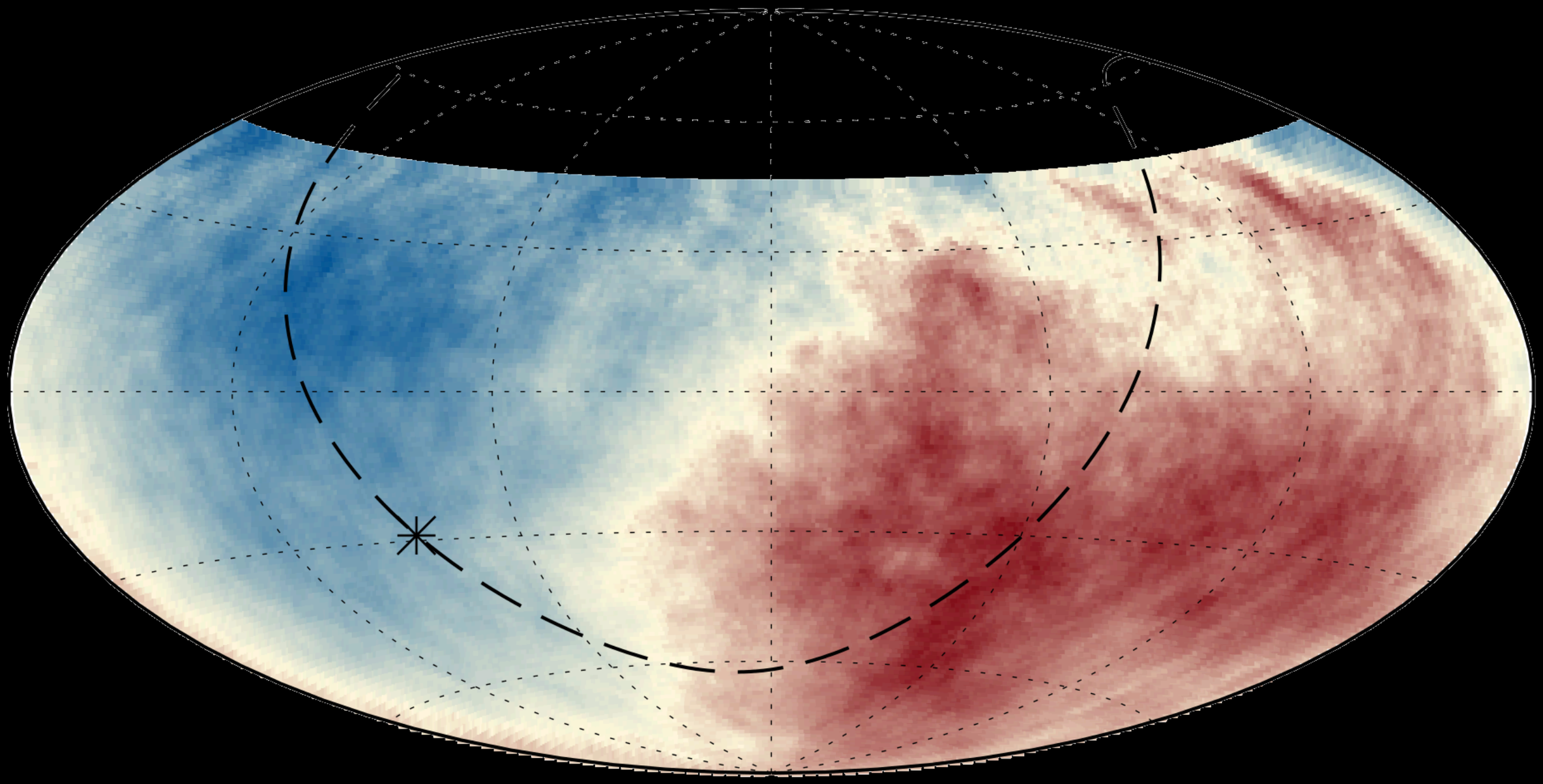
X-rays



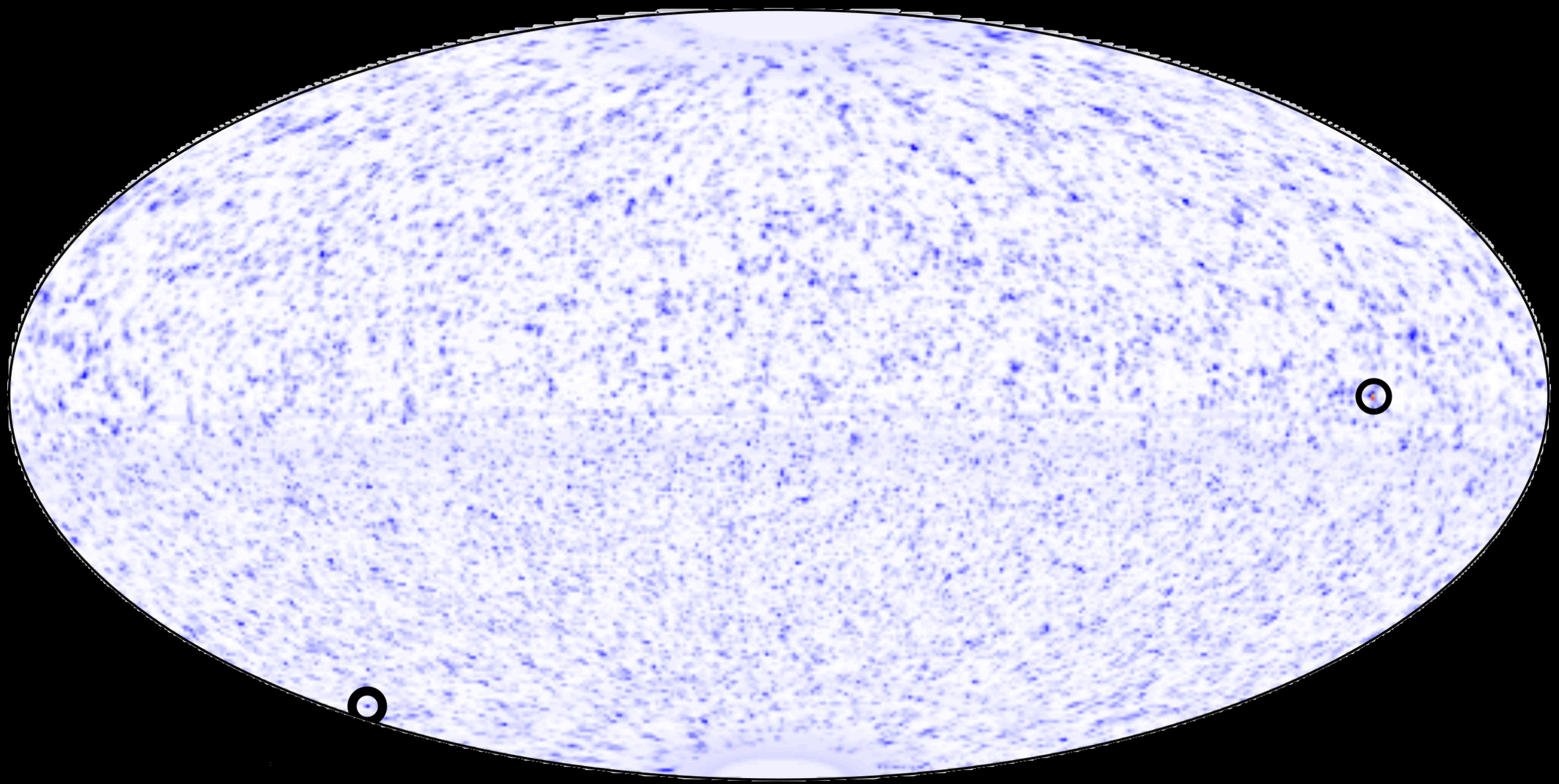
Gamma rays



Ultra-high-energy cosmic rays



Neutrinos



Neutrinos are elementary particles,

= indivisible

electrically neutral,

= no electric charge

very light,

= so light that we don't know their mass!

and superbly antisocial

= barely interact with matter

The Elusive Neutrino

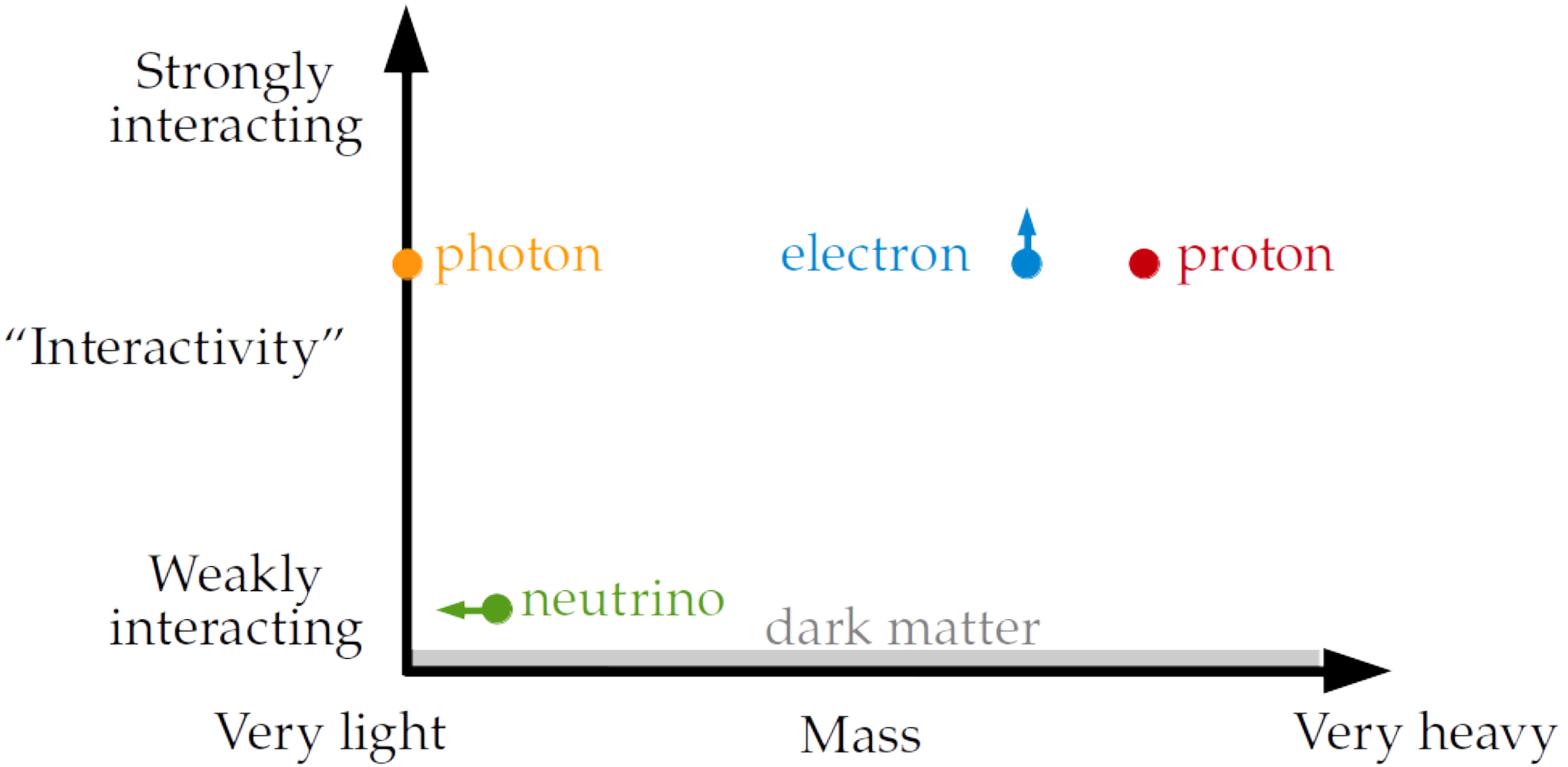
- **Three neutrino flavours**
- Very small masses *(unknown origin)*
- Large mixing between flavour and mass states *(unknown mechanism)*
- 2nd most abundant particle in the Universe *(impact on cosmology)*
- **Unique probe of high-energy astrophysics**

Standard Model of Particle Physics

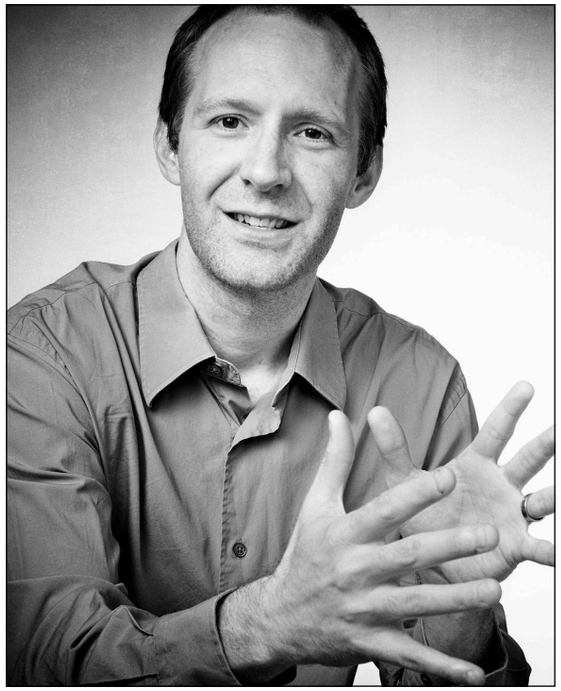
(+ Higgs boson)

The Elusive Neutrino

Neutrinos are *very* light and *very* antisocial



Who are we?



Assoc. Prof. D. Jason Koskinen

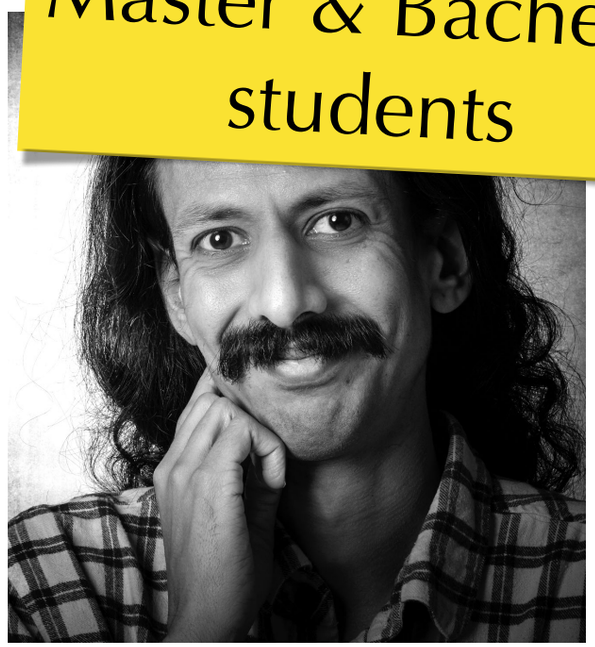
Prof. Irene Tamborra

Ass

+ many excellent Postdocs, PhDs, Master & Bachelor students

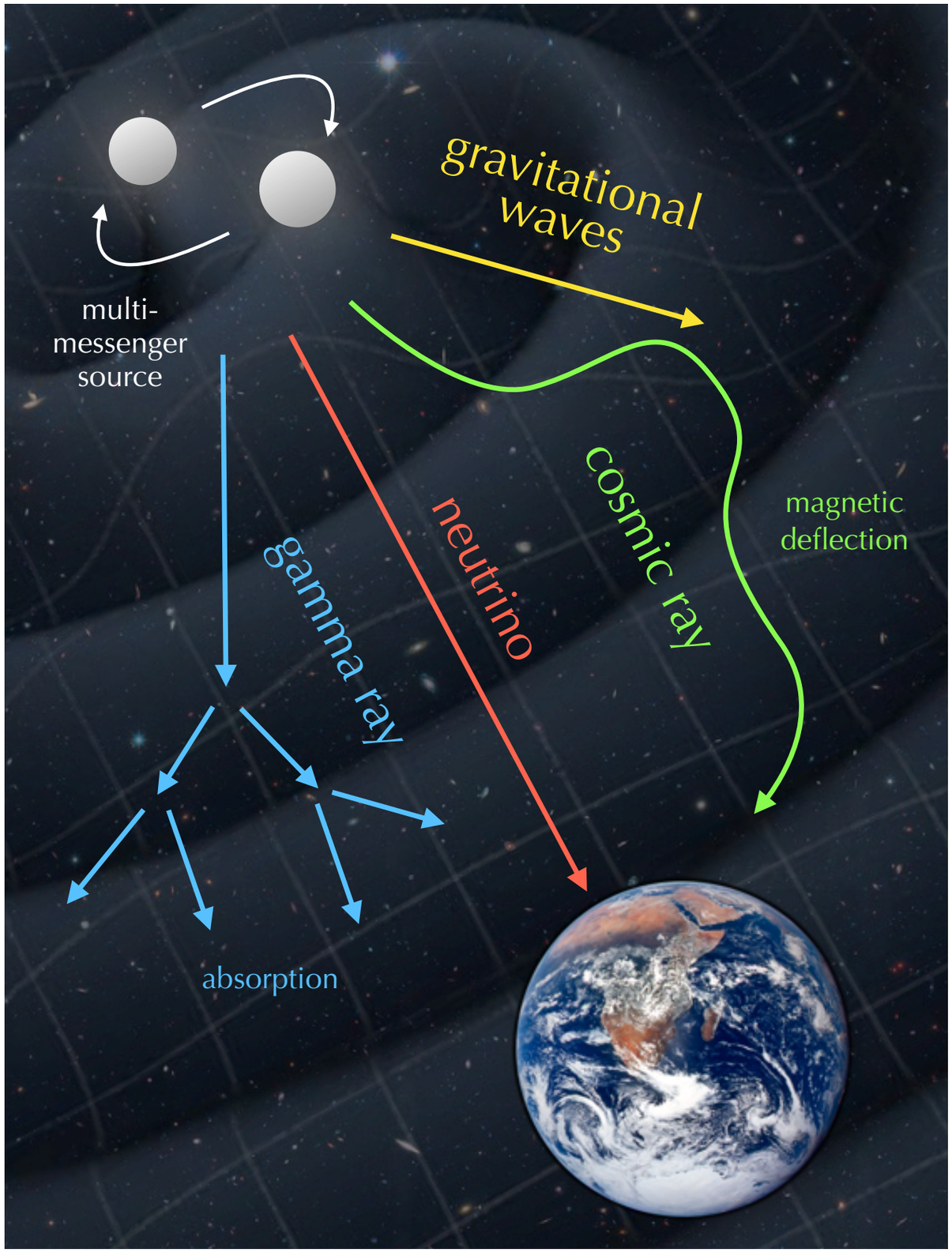
Asst. Prof. Mauricio Bustamante

Asst. Prof. Markus Ahlers



Asst. Prof. Shashank Shalgar

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

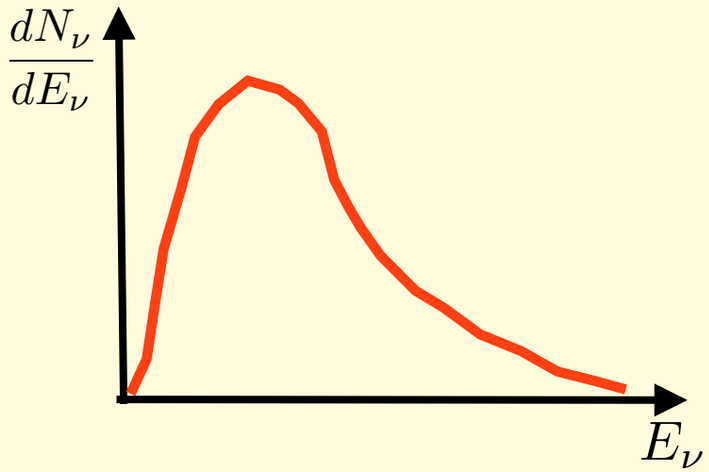
coincident with
photons and gravitational waves

BUT, very difficult to detect!

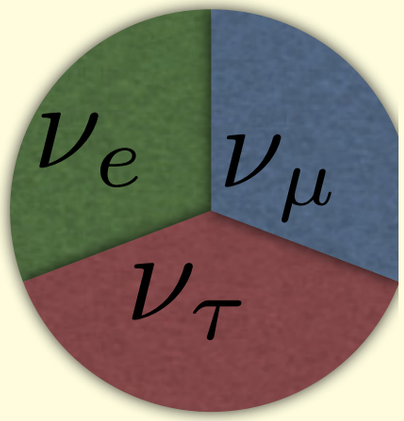
Powerful Probes in Astrophysics

Neutrinos provide us with:

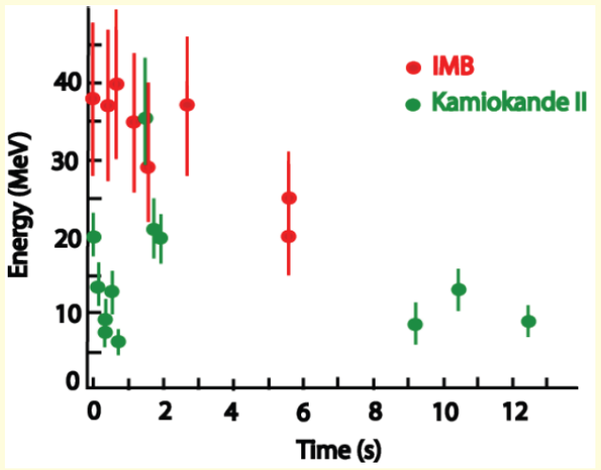
1. Energy Distribution



2. Flavour Ratios

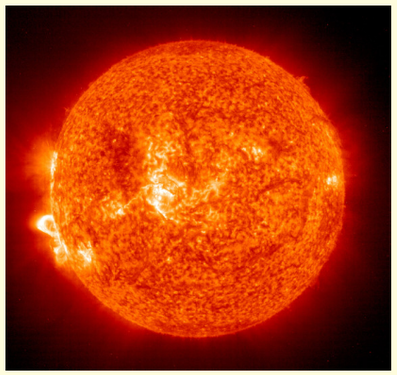


3. Light Curve

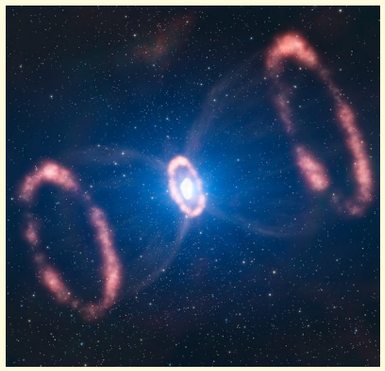


Neutrinos are copiously produced in astrophysical sources, e.g.,

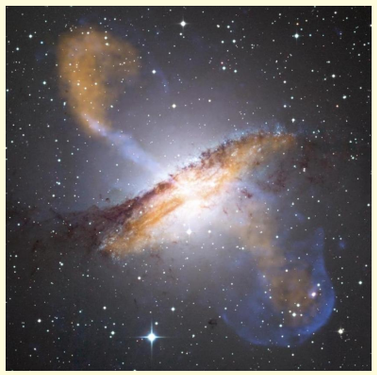
The Sun



Supernovae

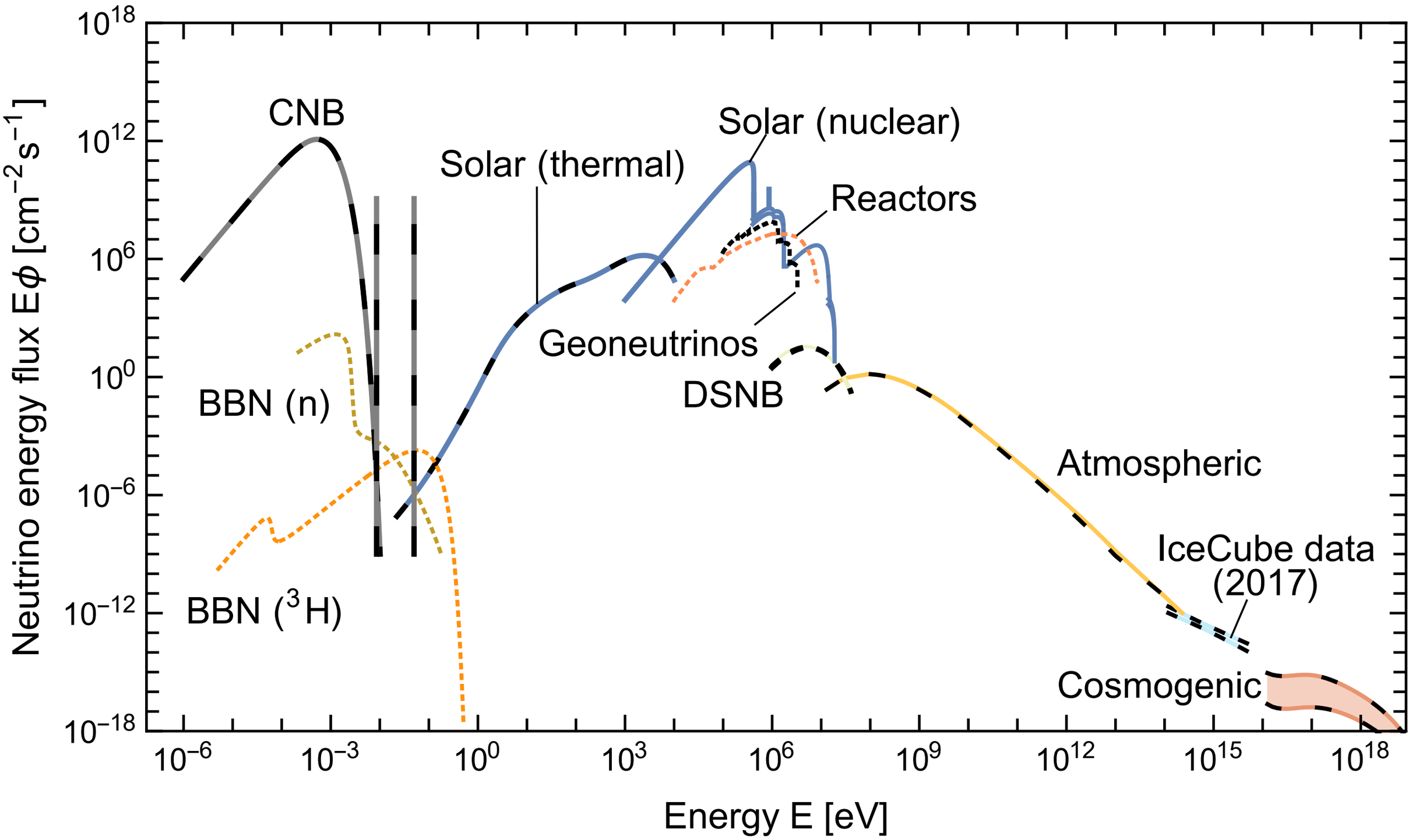


Active Galaxies



Gamma-ray Bursts

Grand Unified Neutrino Spectrum



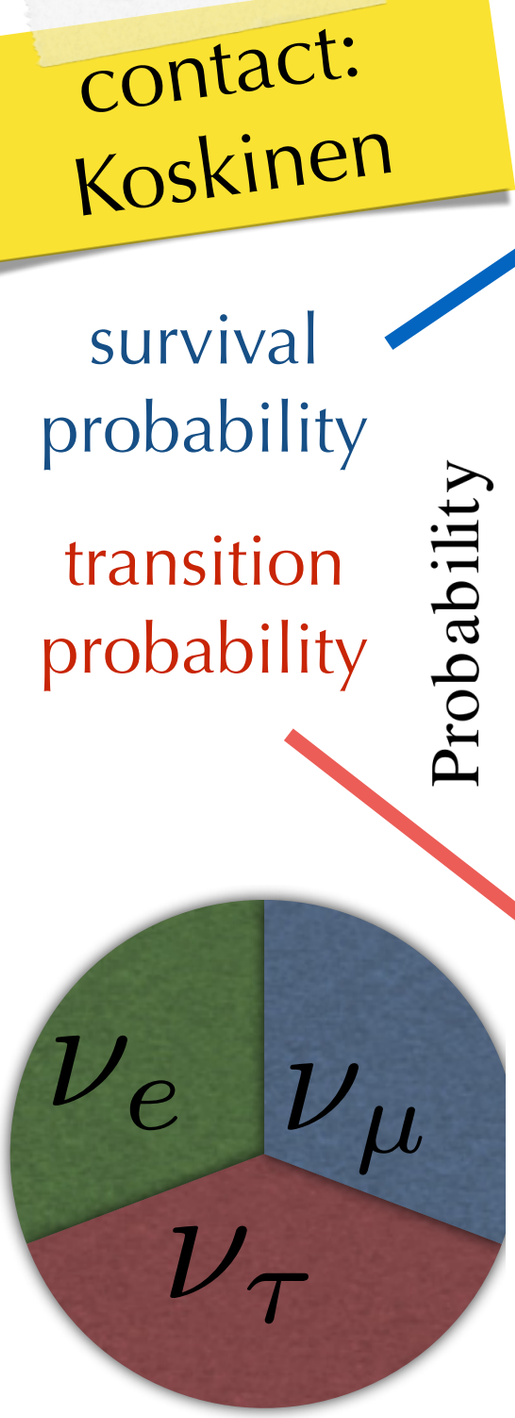
[Vitagliano, Tamborra & Raffelt *Rev. Mod. Phys.* 92 (2020)]

Neutrino Flavour Oscillations

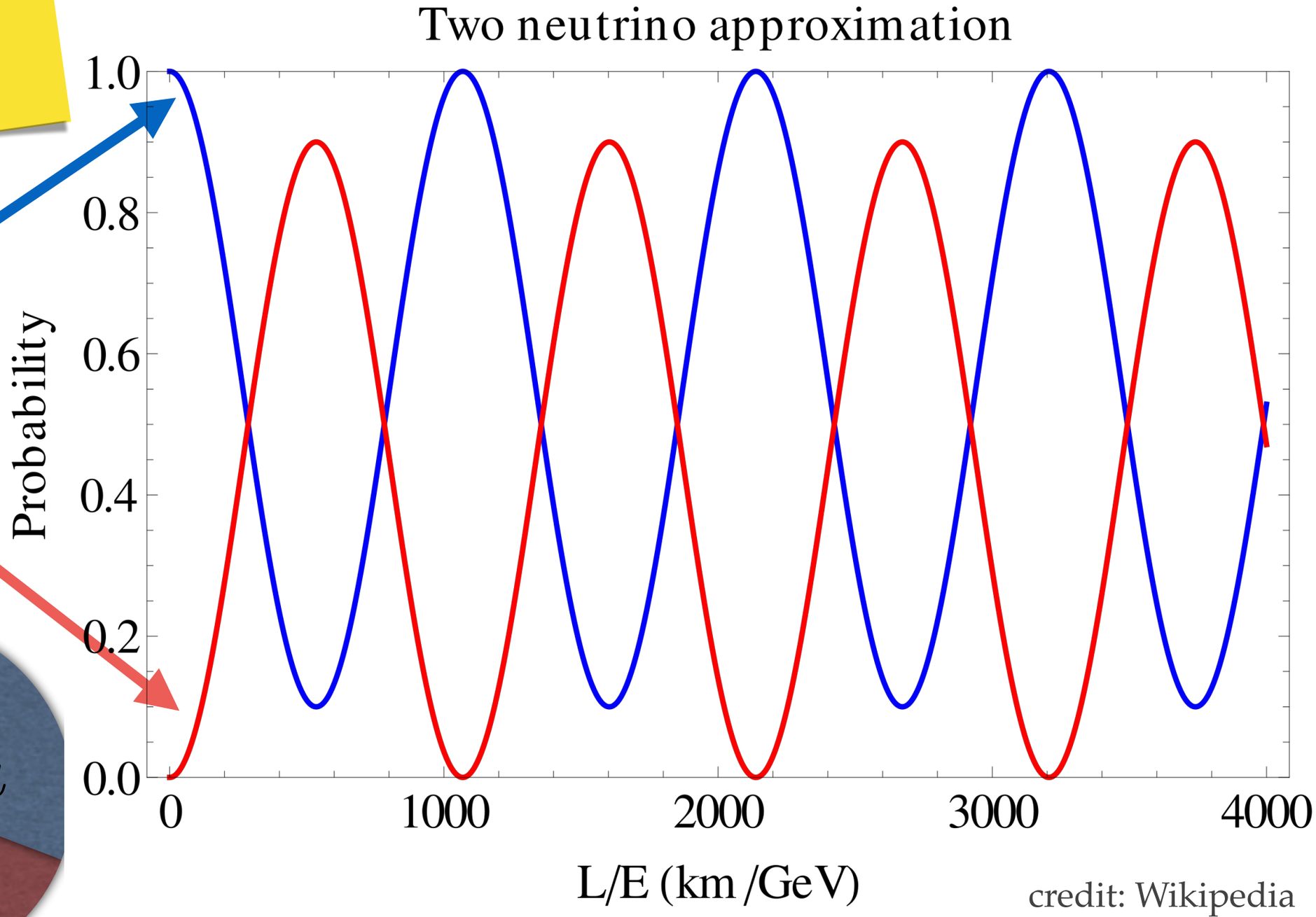
contact: Koskinen

survival probability

transition probability



(mass state)



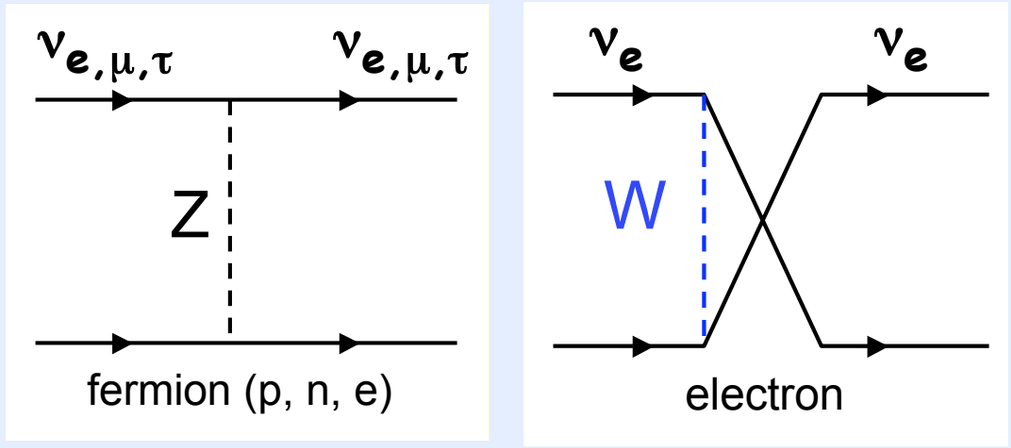
credit: Wikipedia

Neutrino oscillate between flavours in time/distance.

Neutrinos in Supernovae and Mergers

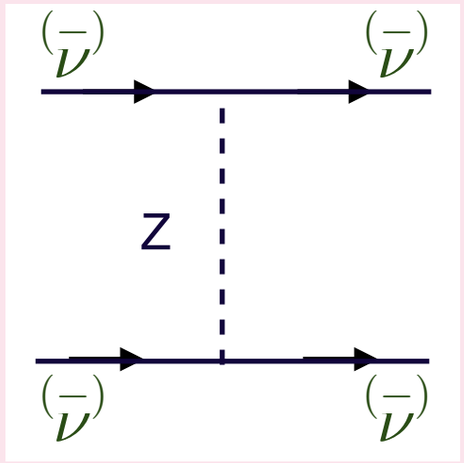
Neutrino Interactions

Understood phenomenon.



Neutrinos interact with neutrons, protons and electrons.

We still need to learn a lot about this process!

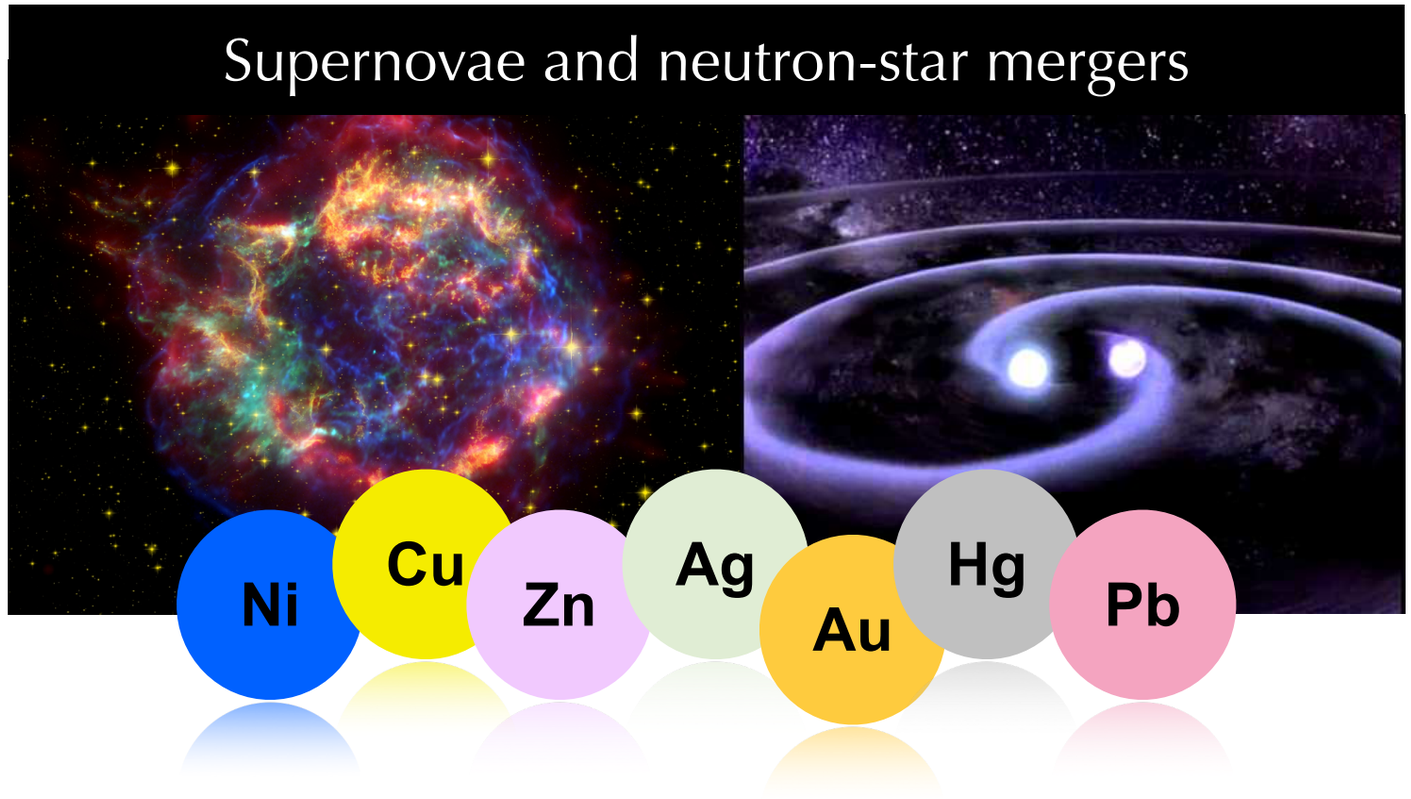


$\nu - \nu$ interactions

Non-linear phenomenon!

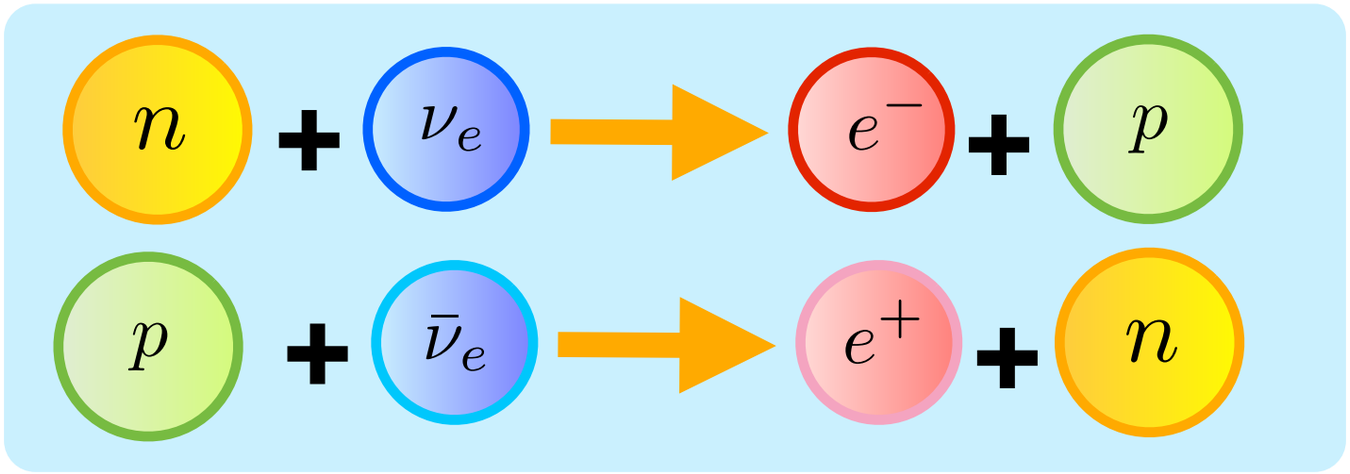
Stellar Nucleosynthesis

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



contact: Tamborra

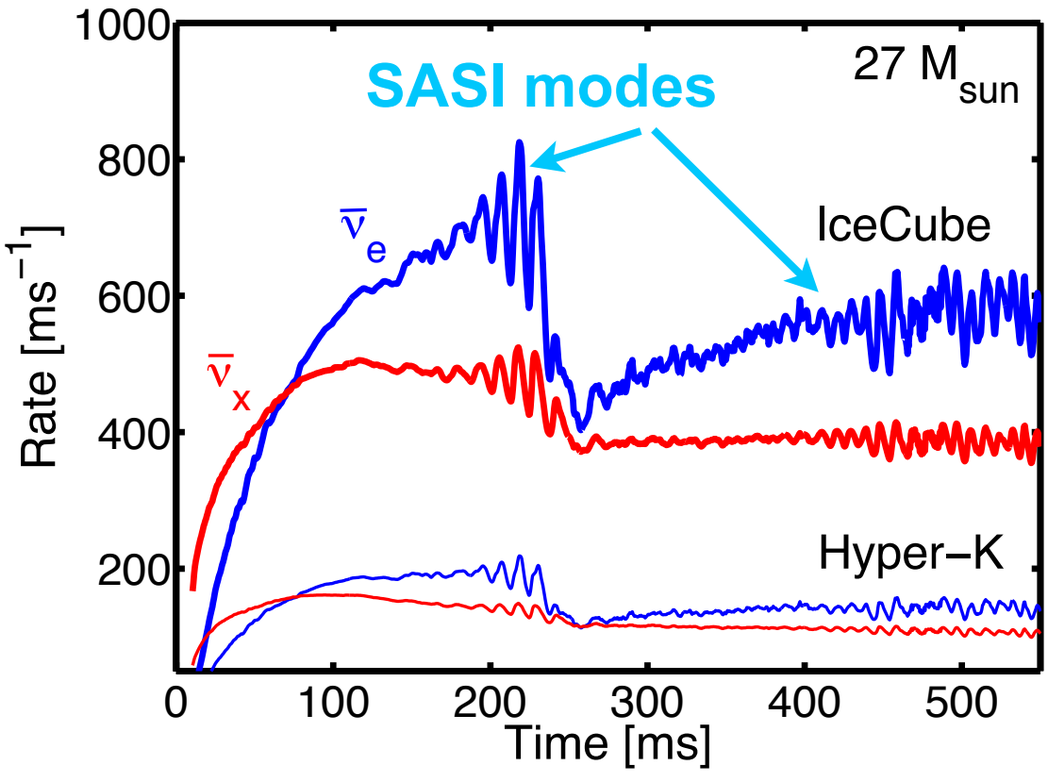
Synthesis of new elements could not happen without neutrinos.

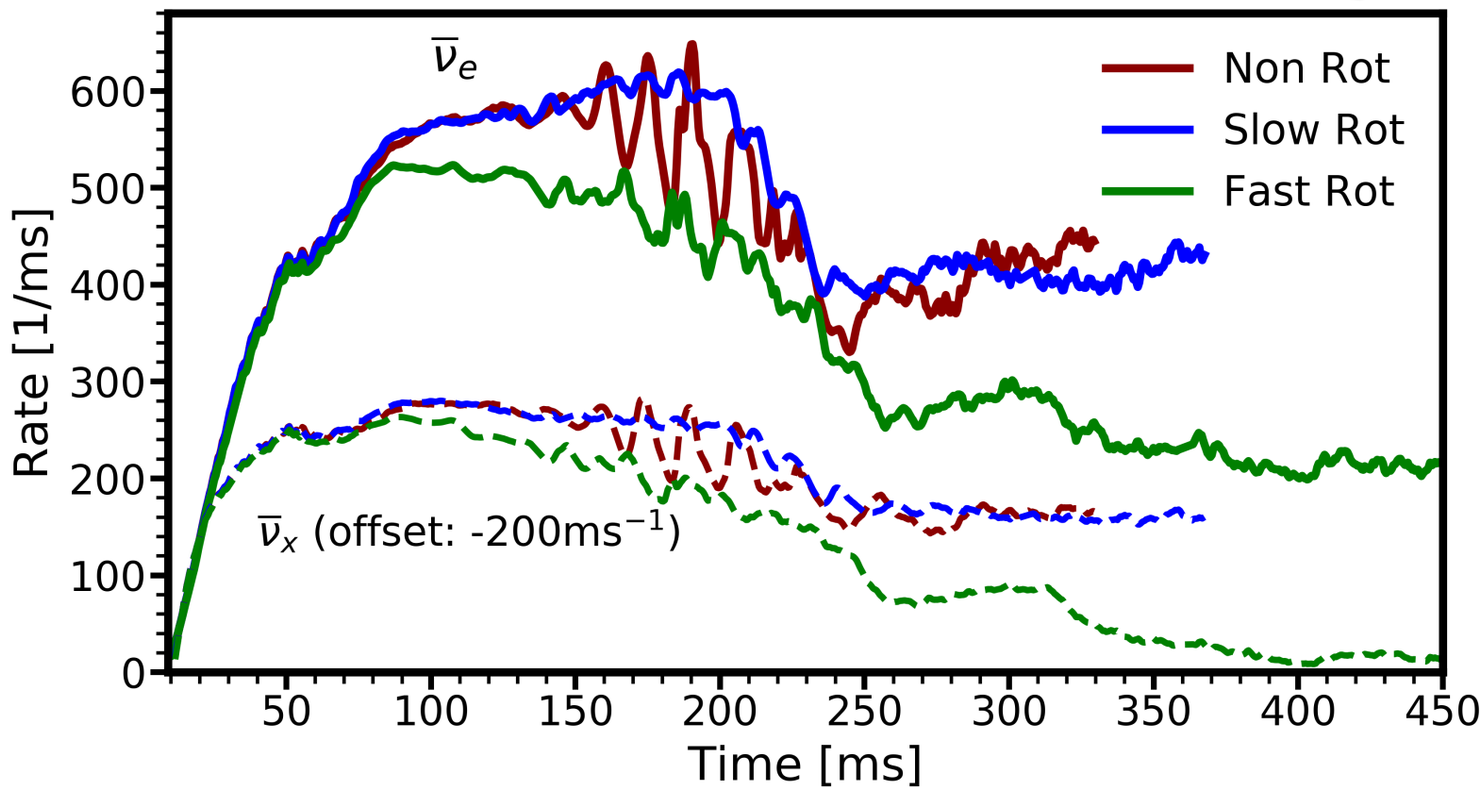


Probe of Supernova Dynamics

contact: Tamborra

Predicted neutrino "lightcurves":



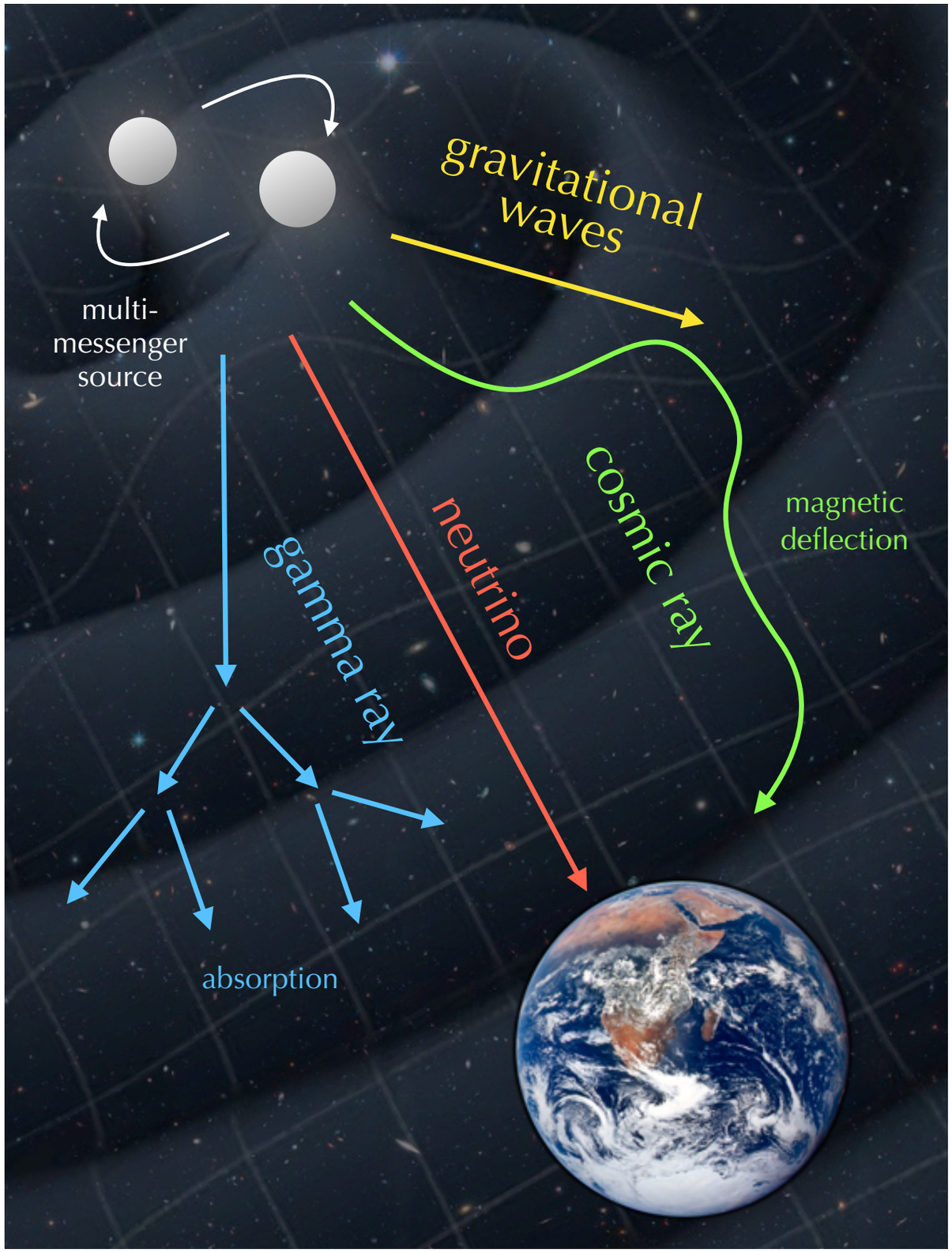


[Tamborra et al., *PRD* 90, 123001 (2014) & *PRD* 98, 123001(2018)]

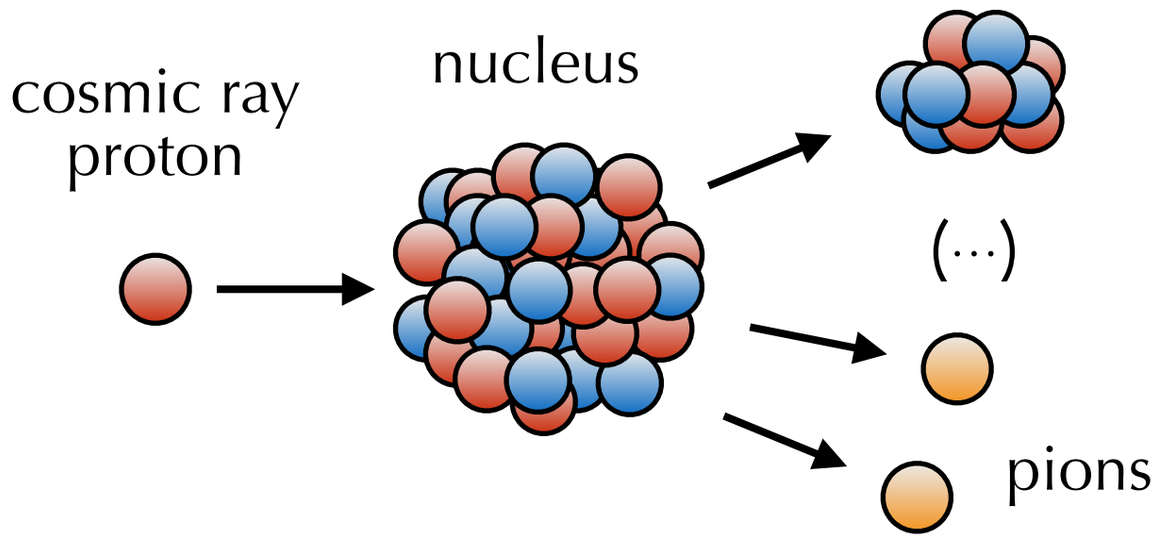
Neutrinos **probe explosion mechanism of a supernova and its rotation.**
Complementary information from detection of gravitational waves.

Neutrinos In & From Cosmic Accelerators

Multi-Messenger Astronomy



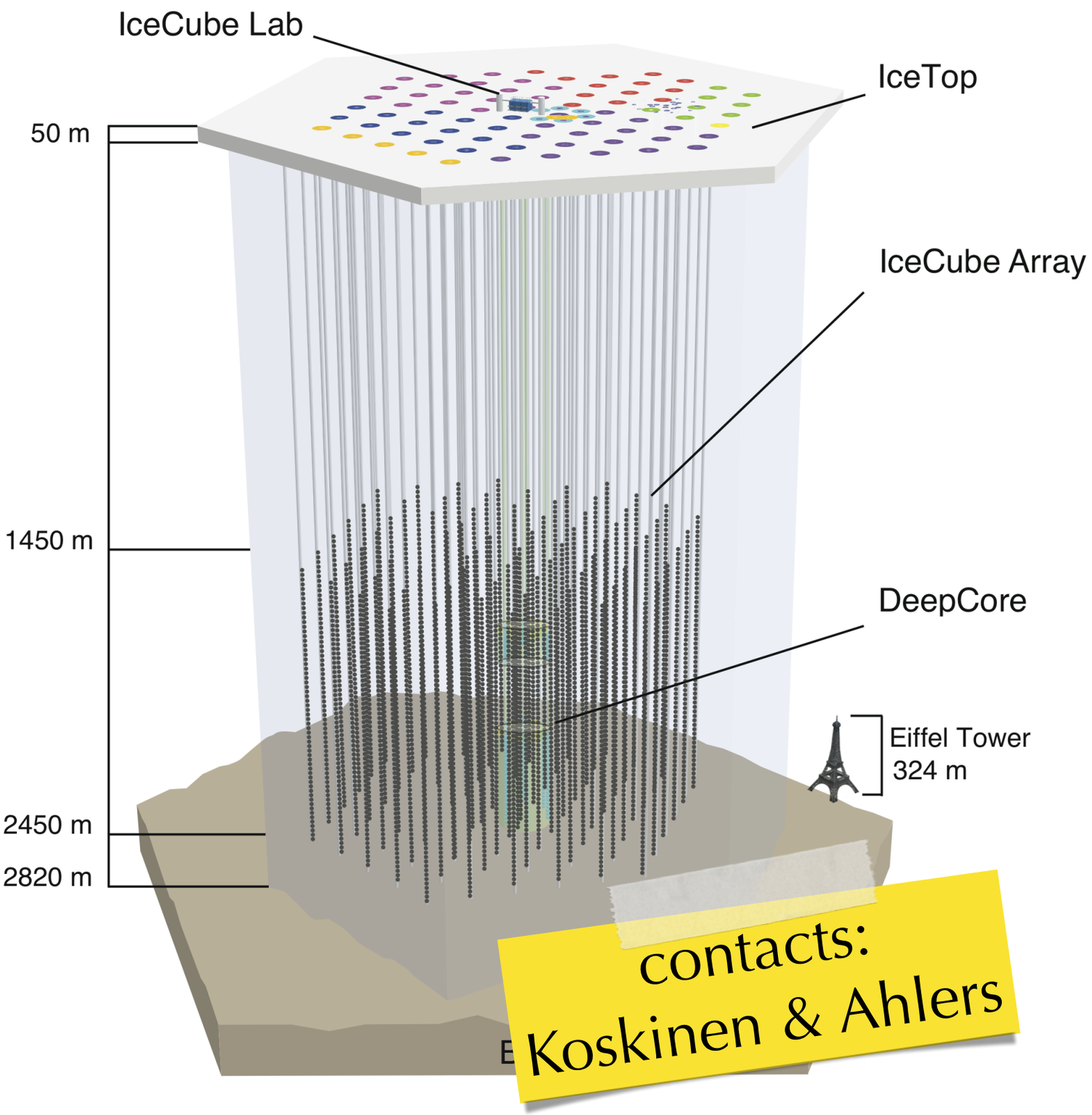
Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.



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

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

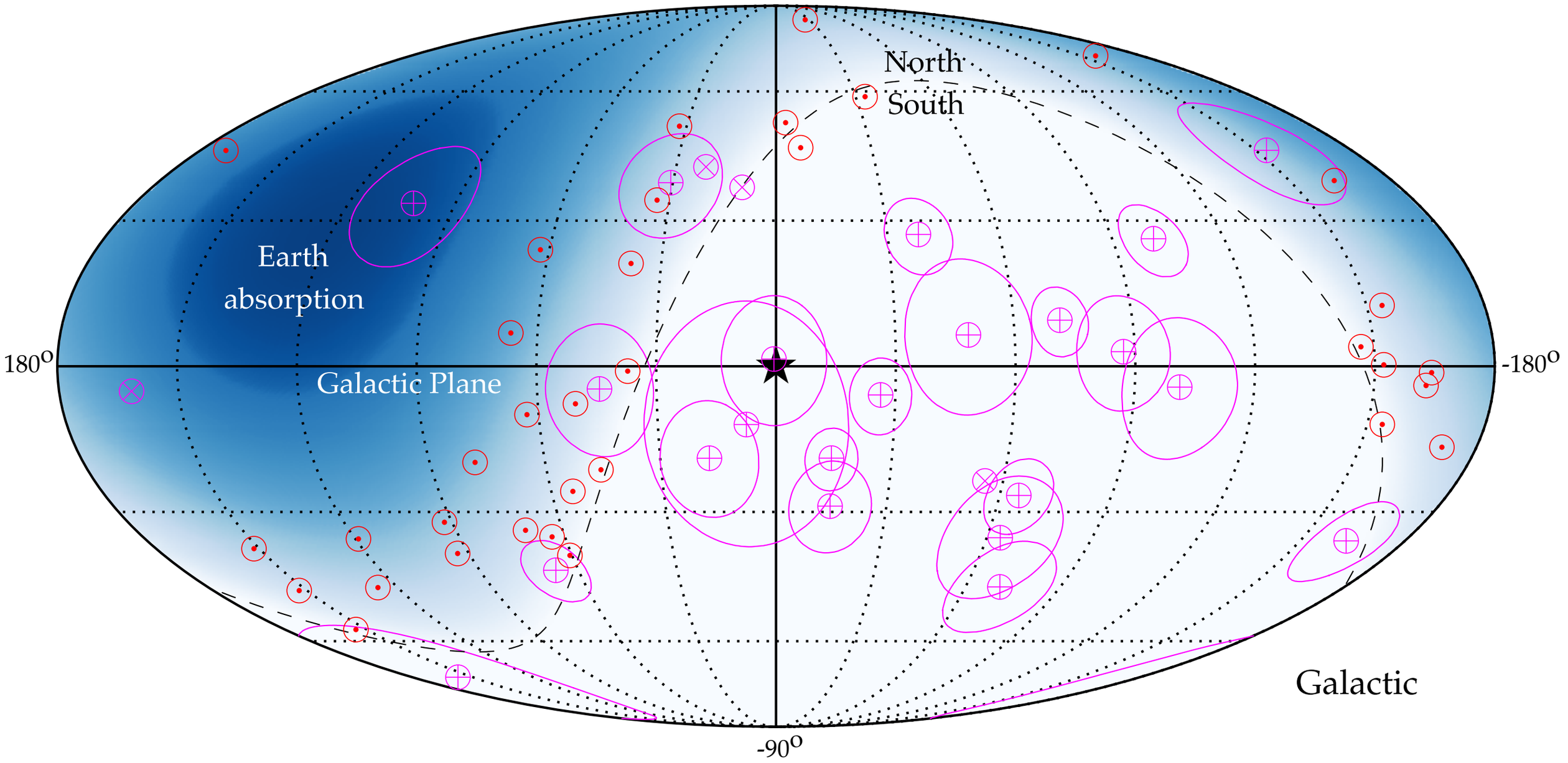
IceCube Observatory



- **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**

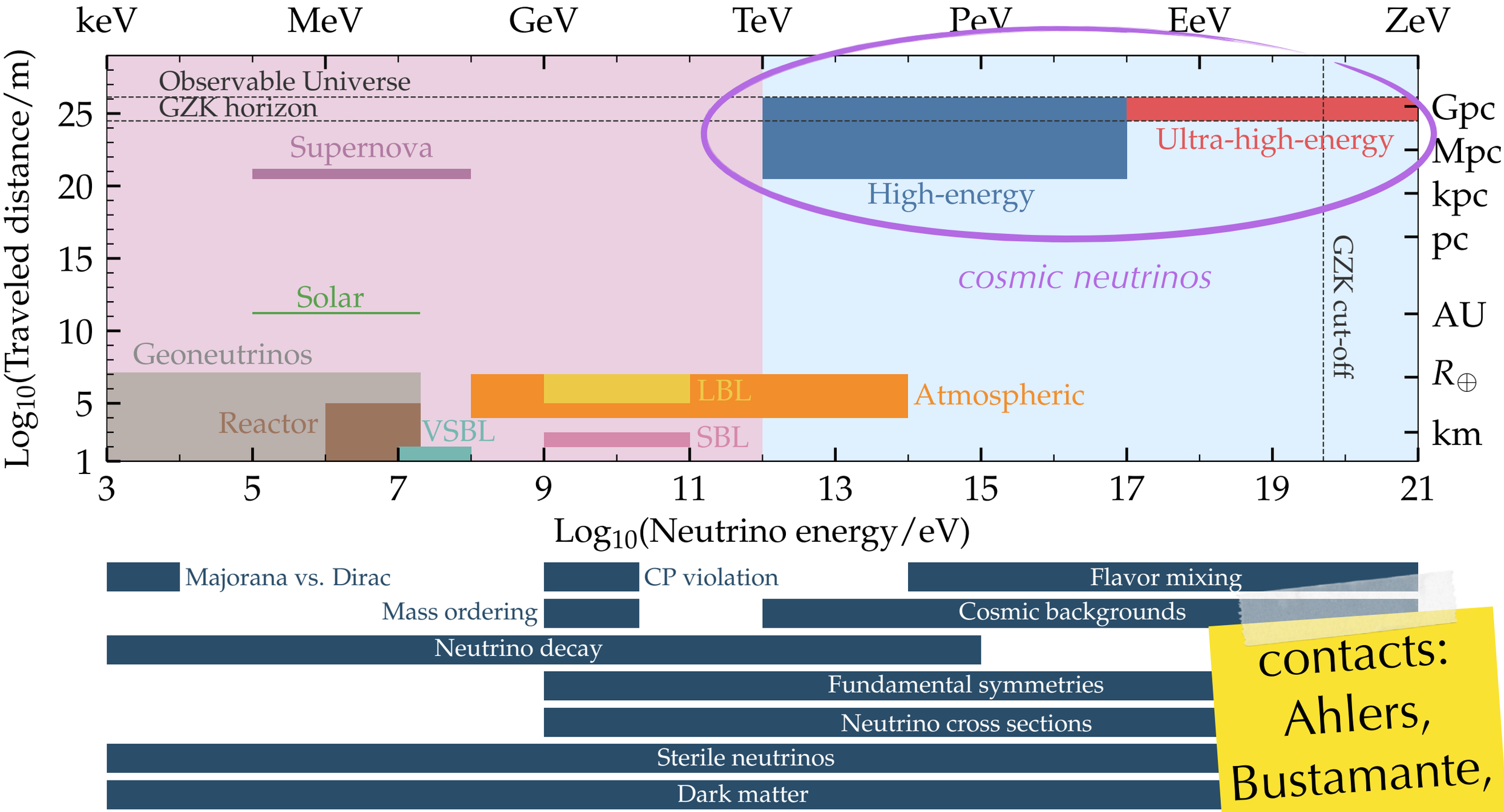
Status of Neutrino Astronomy

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

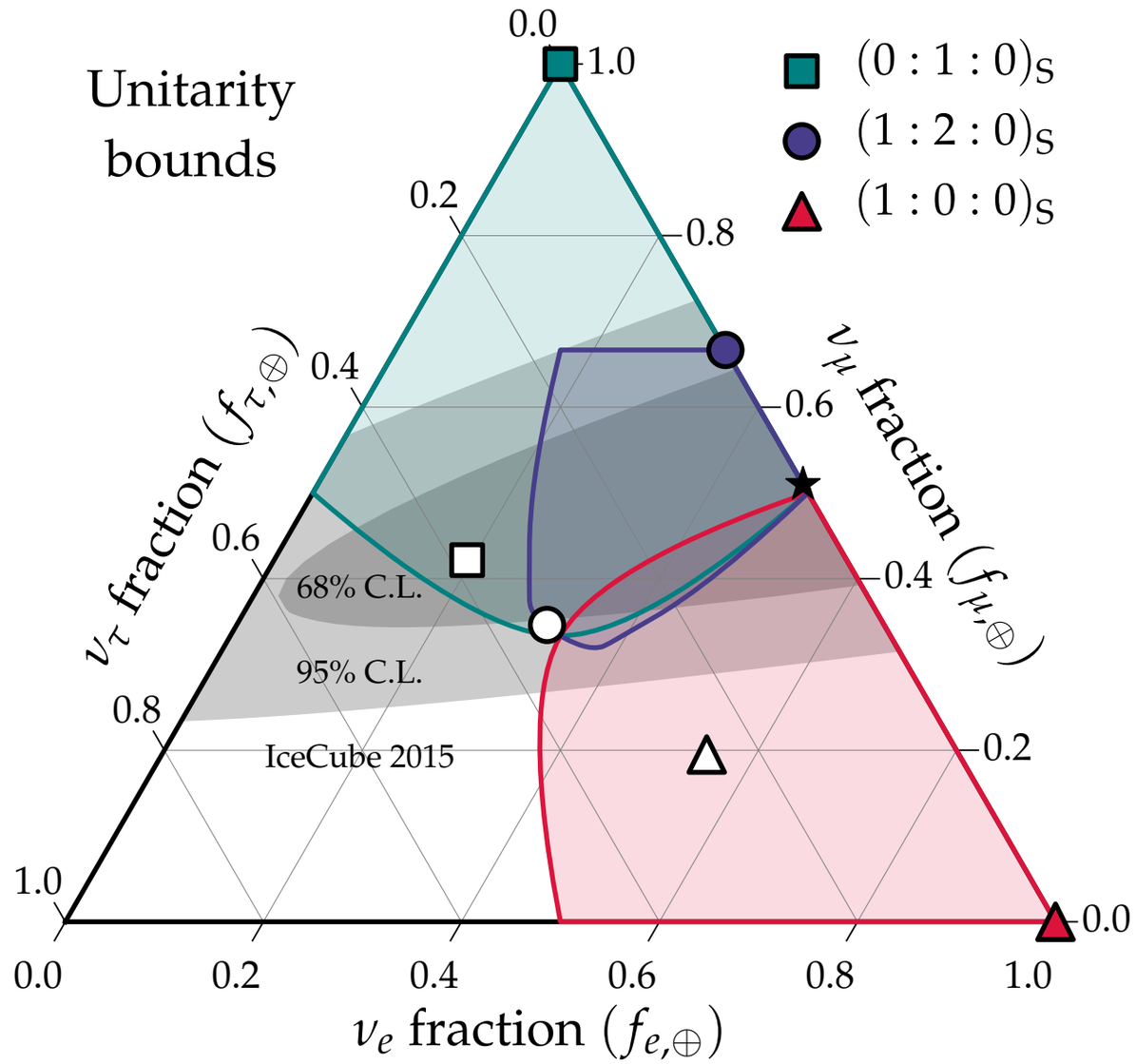


contacts: Ahlers, Bustamante, Tamborra

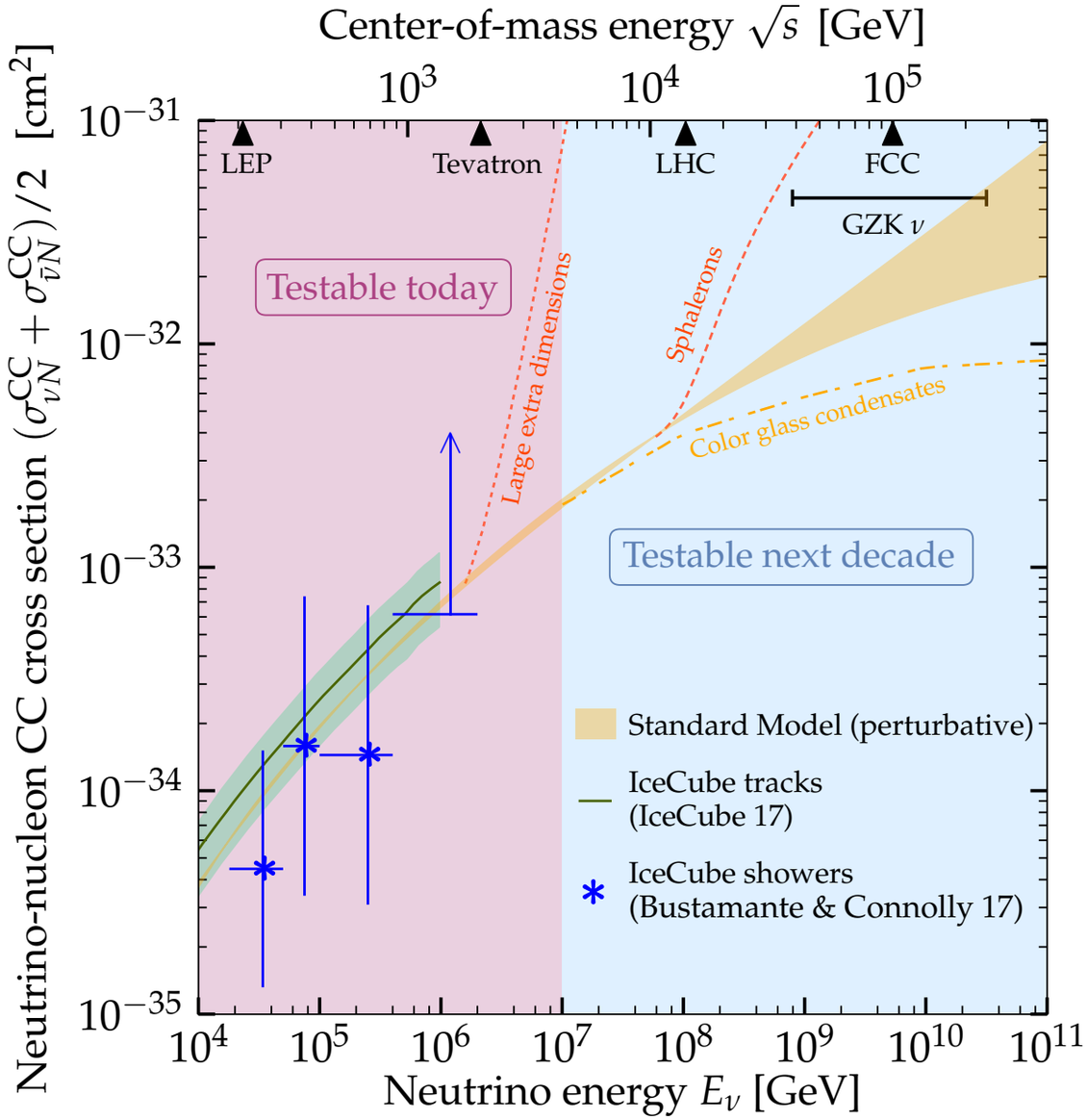
[Ackermann, Ahlers, Anchordoqui, Bustamante *et al.*, Bull. Am. Astron. Soc. 51 (2019)]

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)]

New particles. New probes

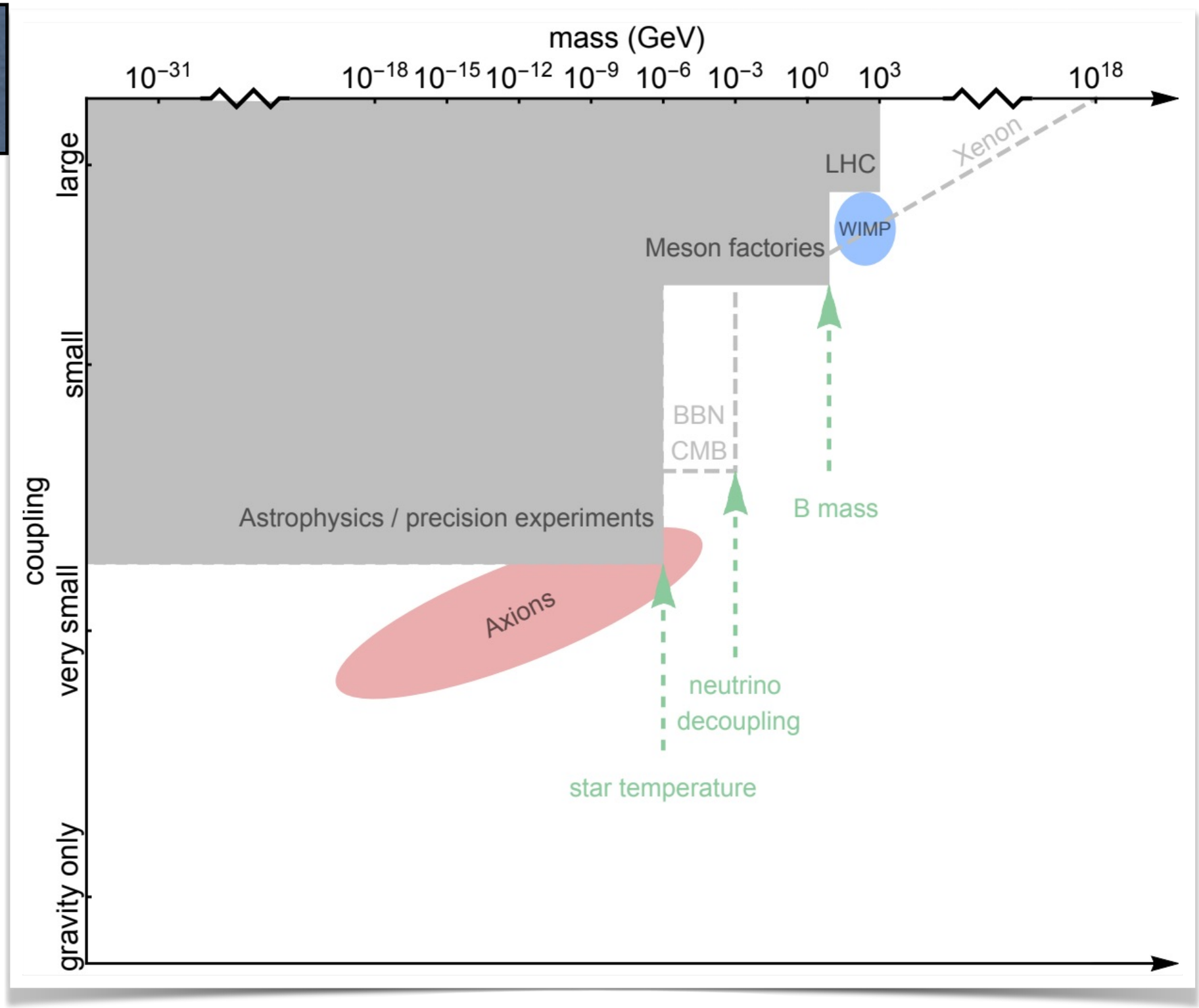
Hidden particles
Dark sectors

How can we probe for the existence of new particles?

What particles can we search for?

What is "**feebly** interacting massive particles"?

contact:
Oleg Ruchayskiy

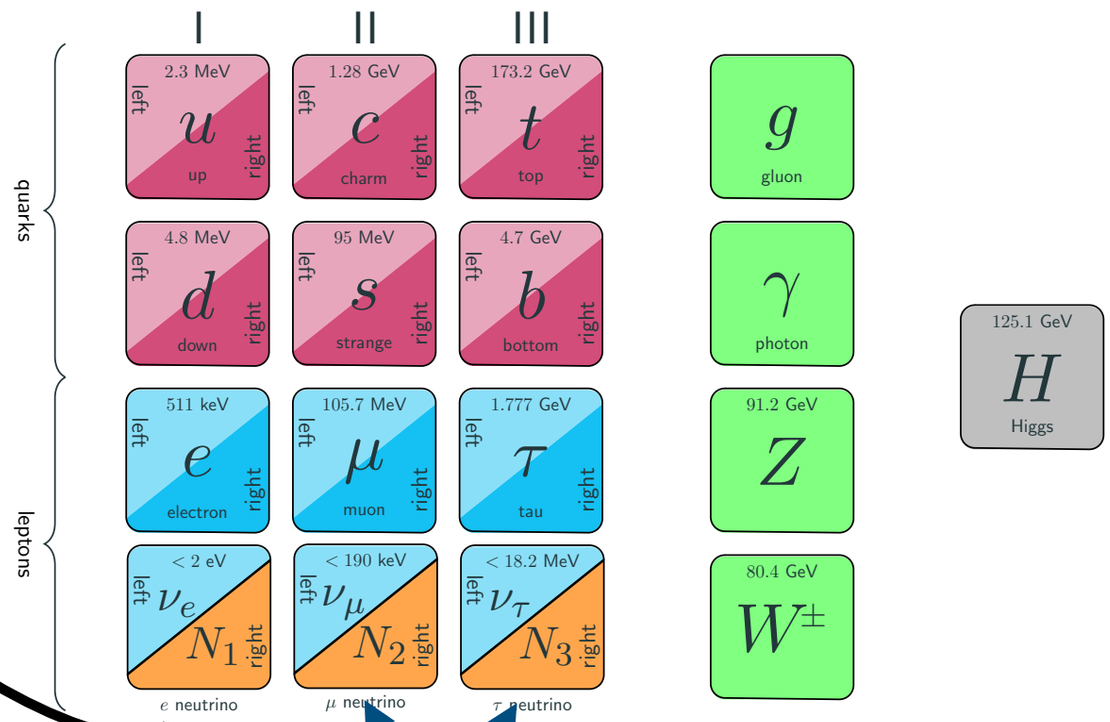


Example: Heavy Neutral Leptons

— The group is working on physics beyond the Standard Model with **feebly interacting** particles (feebly = weaker-than-neutrinos)
— Theoretical developments (what are they good for) and experimental searches (how to find them at CERN and beyond)

Sterile neutrino dark matter

- Astrophysical searches: X-ray, Lyman-α
- Production mechanisms: Leptogenesis, Einstein-Cartan gravity

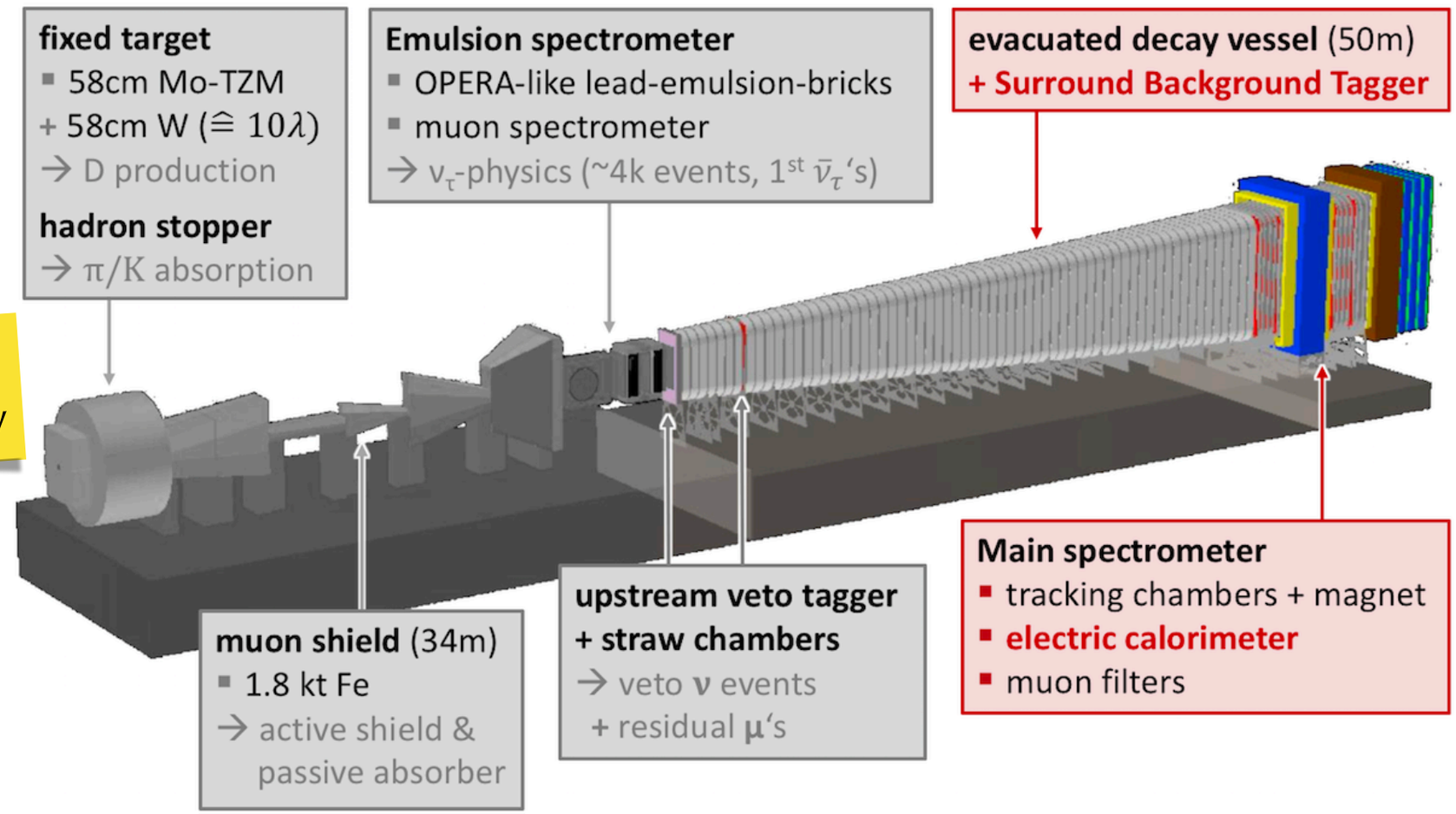


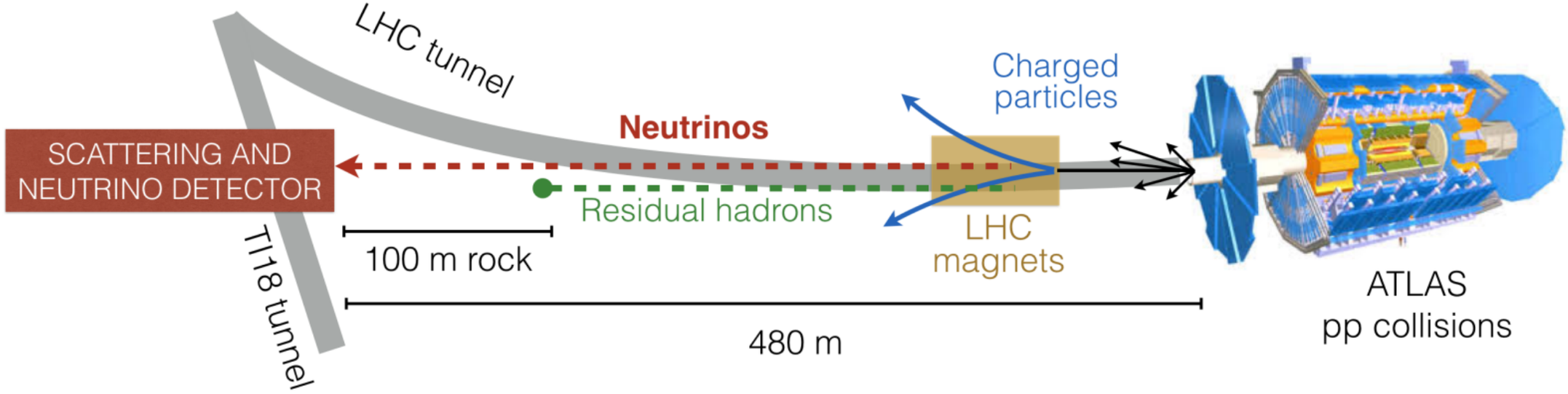
Heavy Neutral Leptons
(also known as right-handed neutrinos, heavy sterile neutrinos)

- Phenomenology of direct experimental searches: SHiP, ATLAS, SND
- Indirect searches and EFT
- Baryon asymmetry of the Universe: Leptogenesis

Search in CERN (SHiP and SND)

contact:
Oleg 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 flavor 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*

contacts:
Ahlers,
Bustamante,
Tamborra

Summary

Dark particles. Dark sectors. Dark matter

- *Particles beyond-the-Standard-model* ***exist***
- *These particles can be interacting* ***weaker than neutrinos***
- *They can be searches in* ***lab*** *and in* ***space***
- *Their signals are always subtle, require ingenuity*

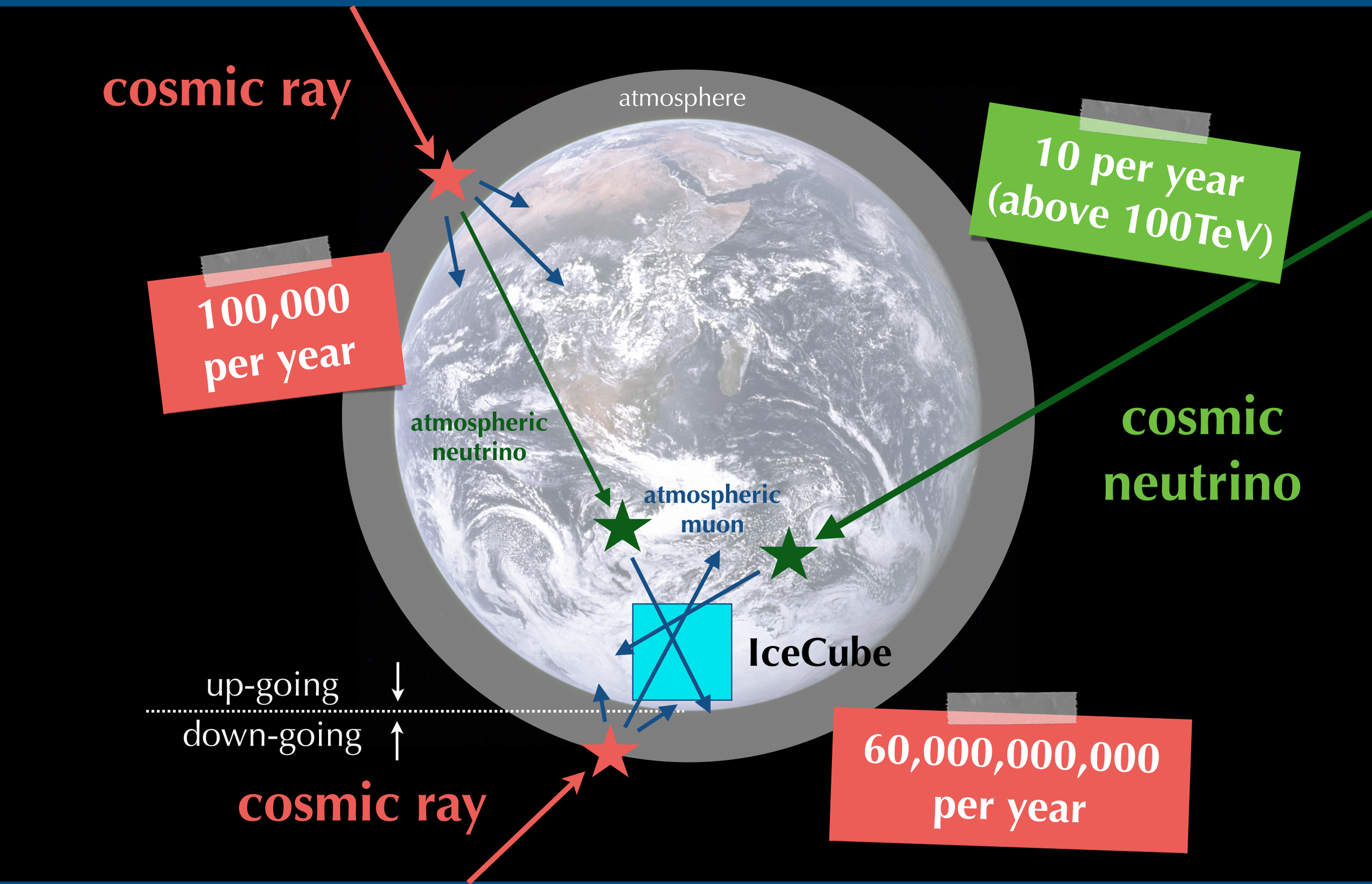
M.Sc. projects in Particle Astrophysics can cover various aspects:

- *New probes of feebly interacting particles — there is still space for ideas!*
- *New methods of data analysis (large-scale AI tools , including popular nowadays LLMs)*
- *Lots of small cool projects to start you research*

contact:
Oleg Ruchayskiy

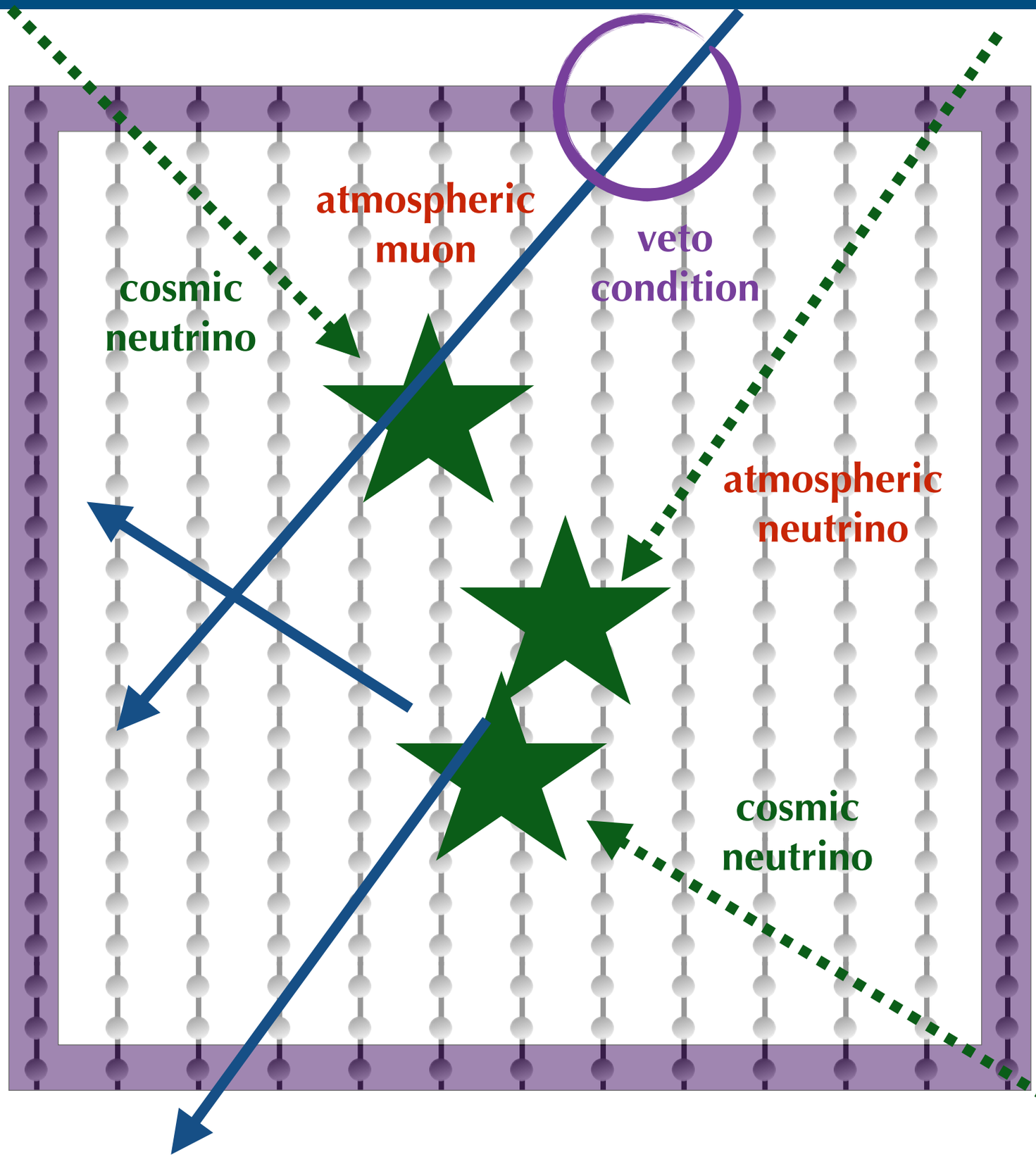
Backup Slides

Neutrino Selection I

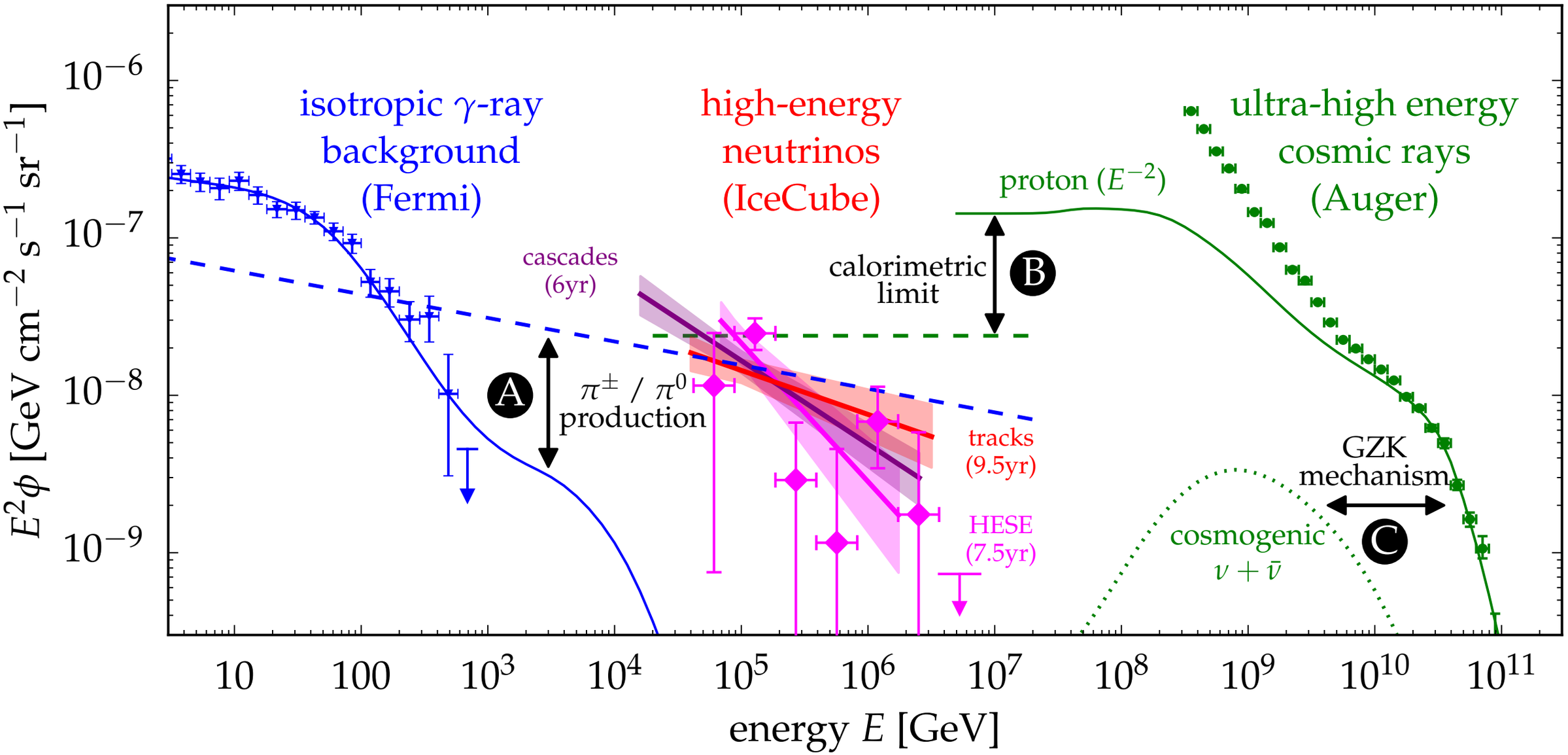


Neutrino Selection II

- 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

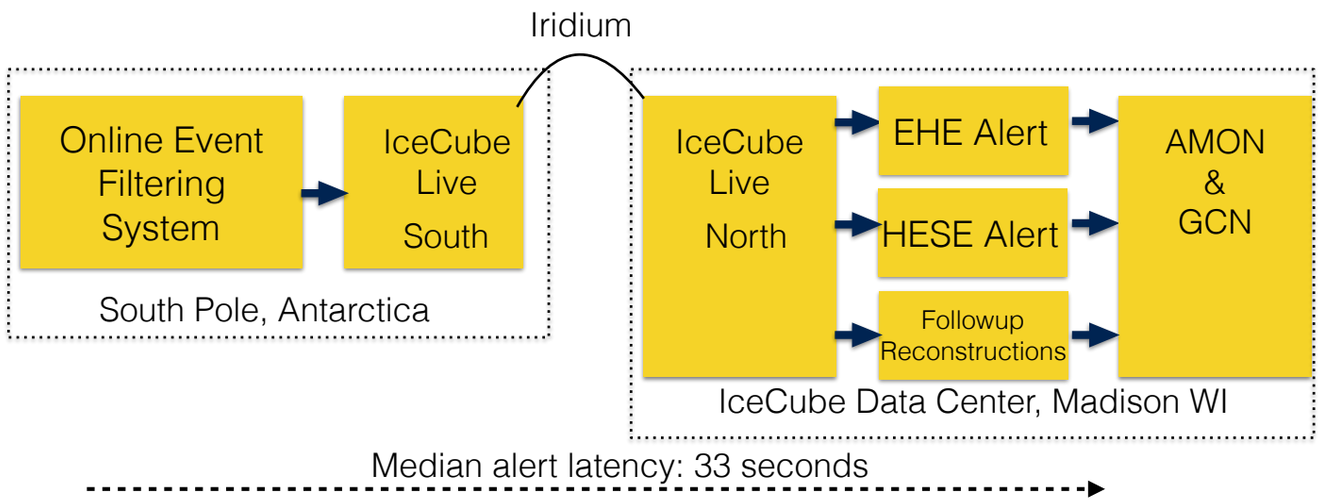


The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.

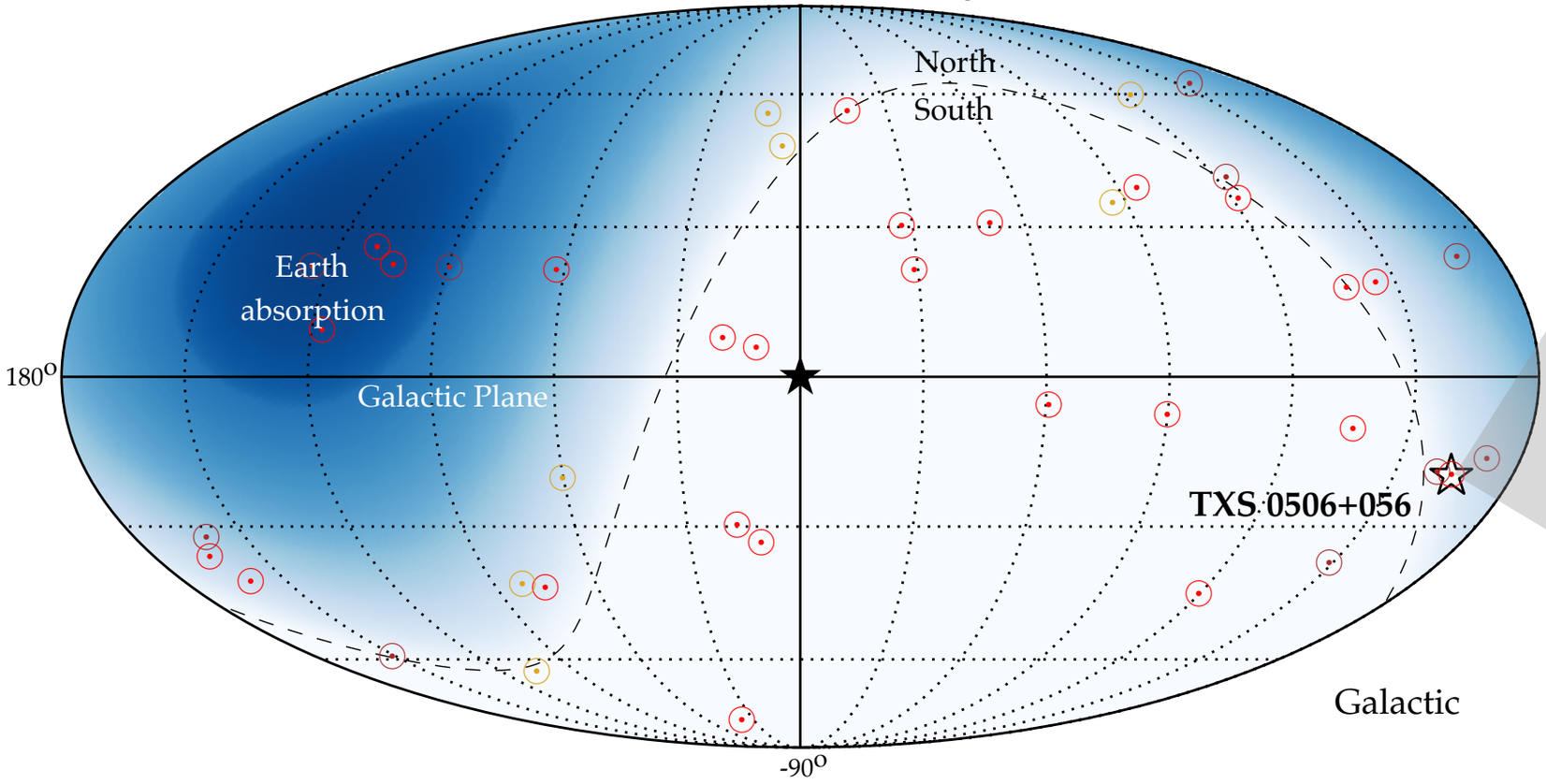
Realtime Neutrino Alerts

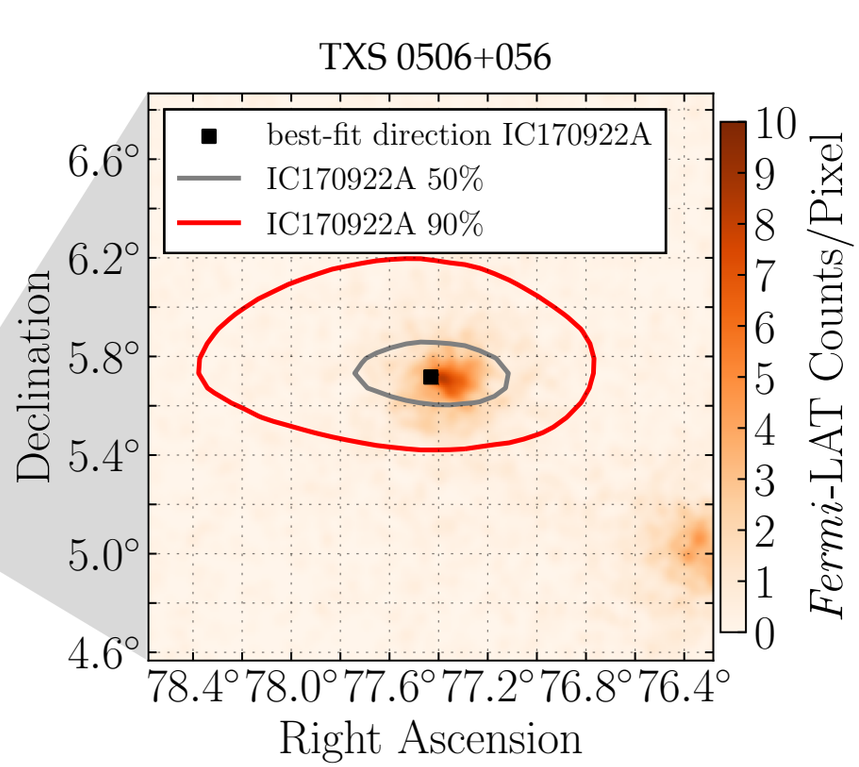
Low-latency (<1min) **public neutrino alert system** established in April 2016.

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

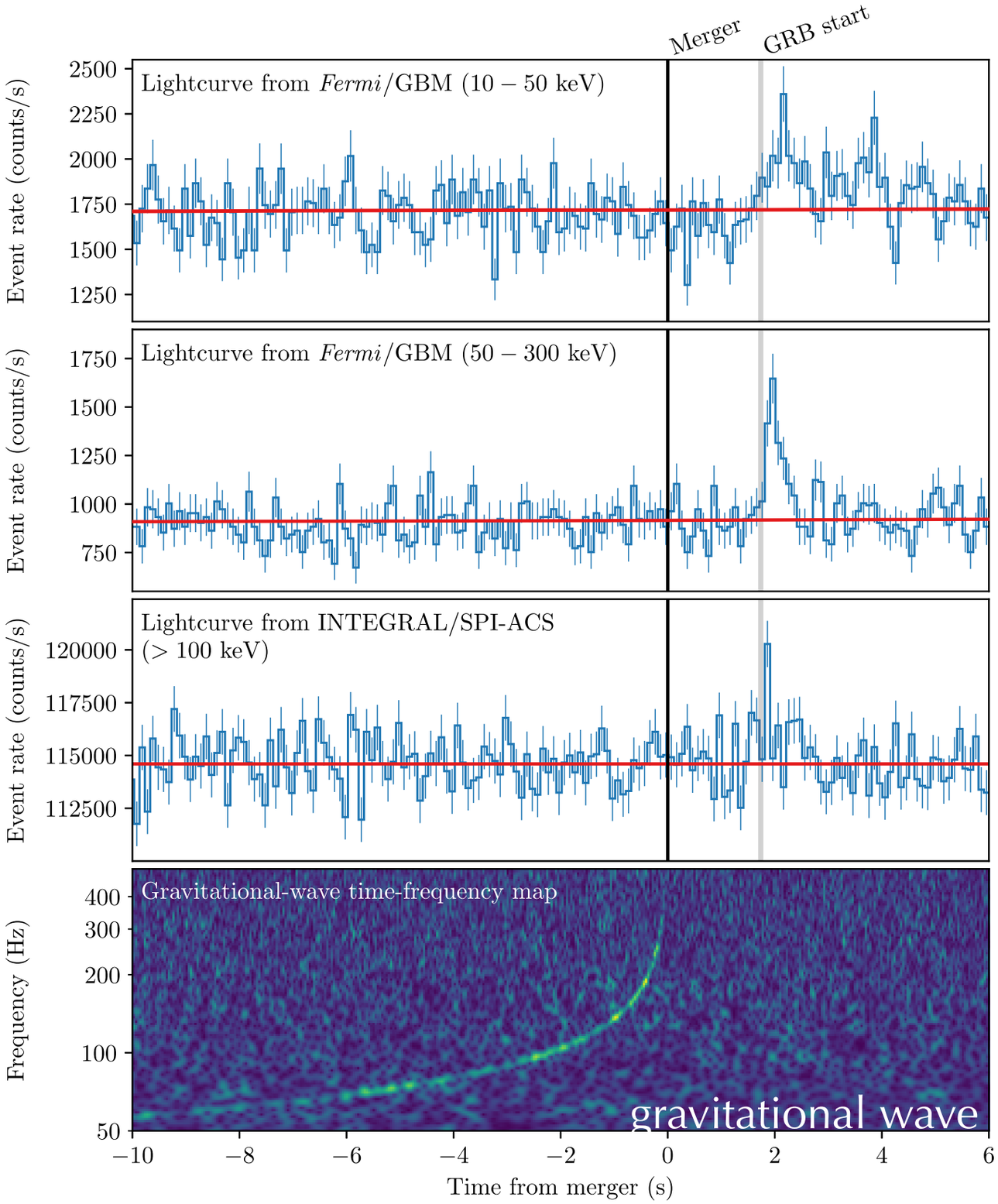


Neutrino alerts (HESE & EHE (red) / GFU-Gold (gold) / GFU-Bronze (brown))

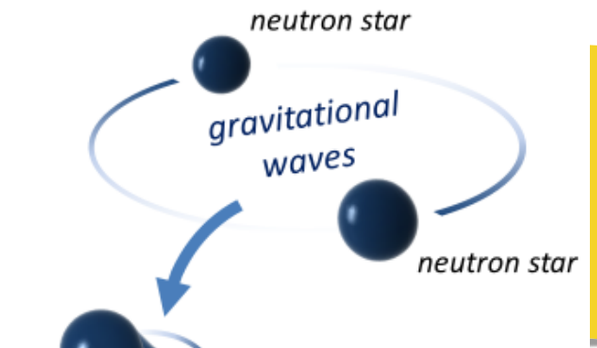




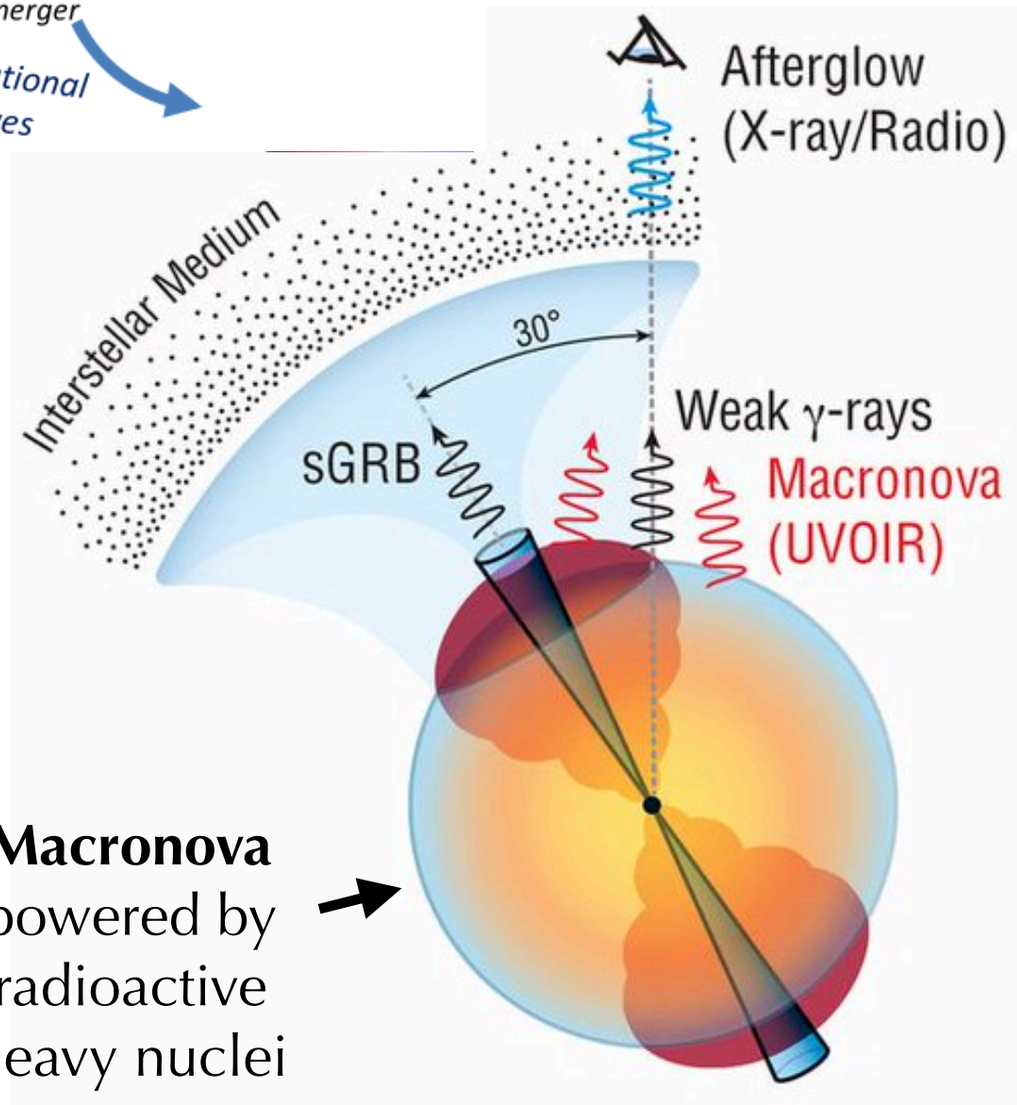
GRBs and Gravitational Waves



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



GW 170817
&
GRB 170817A



Macronova powered by radioactive heavy nuclei