



Multimessenger Astrophysics

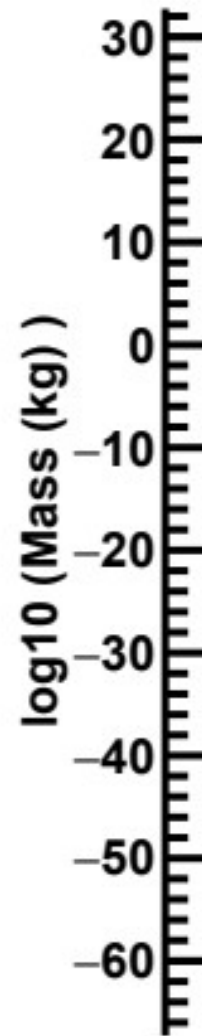
Vitor de Souza
University of São Paulo
vitor@ifsc.usp.br

AP^QEMA

$$E^2 = p^2 c^2 + m^2 c^4$$

$$E = kT$$

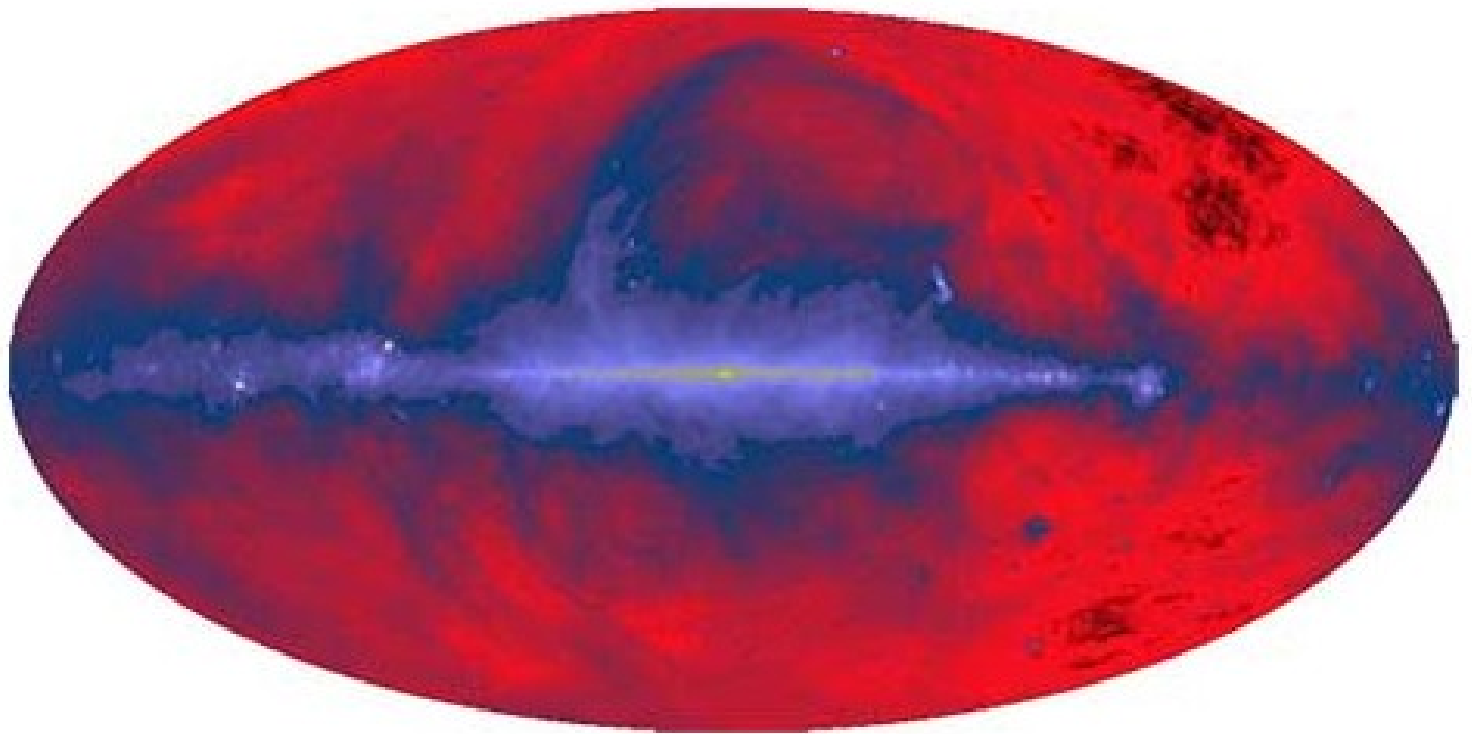
$$E = h\nu = \frac{hc}{\lambda}$$



$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joule}$$

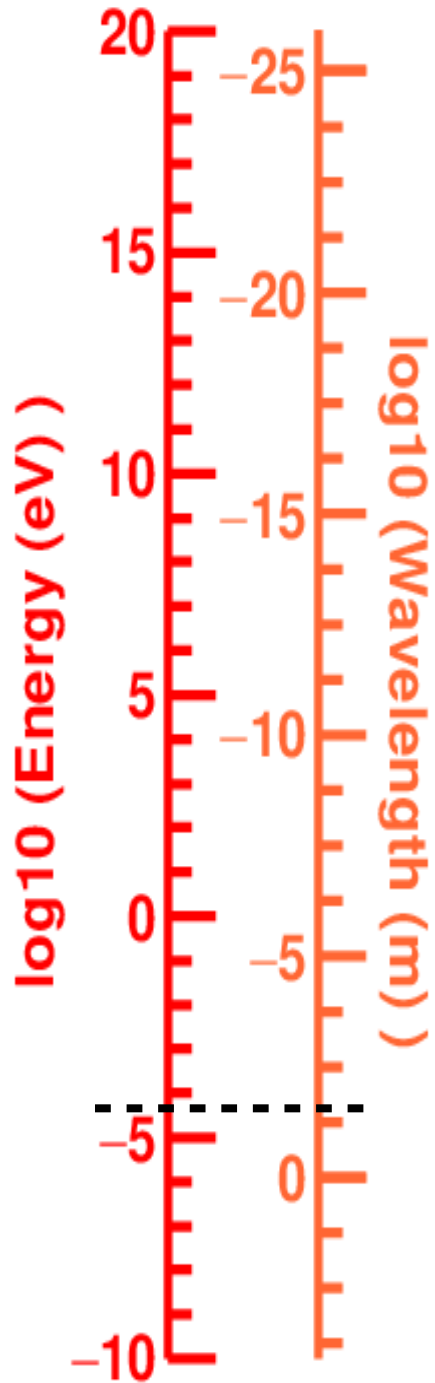
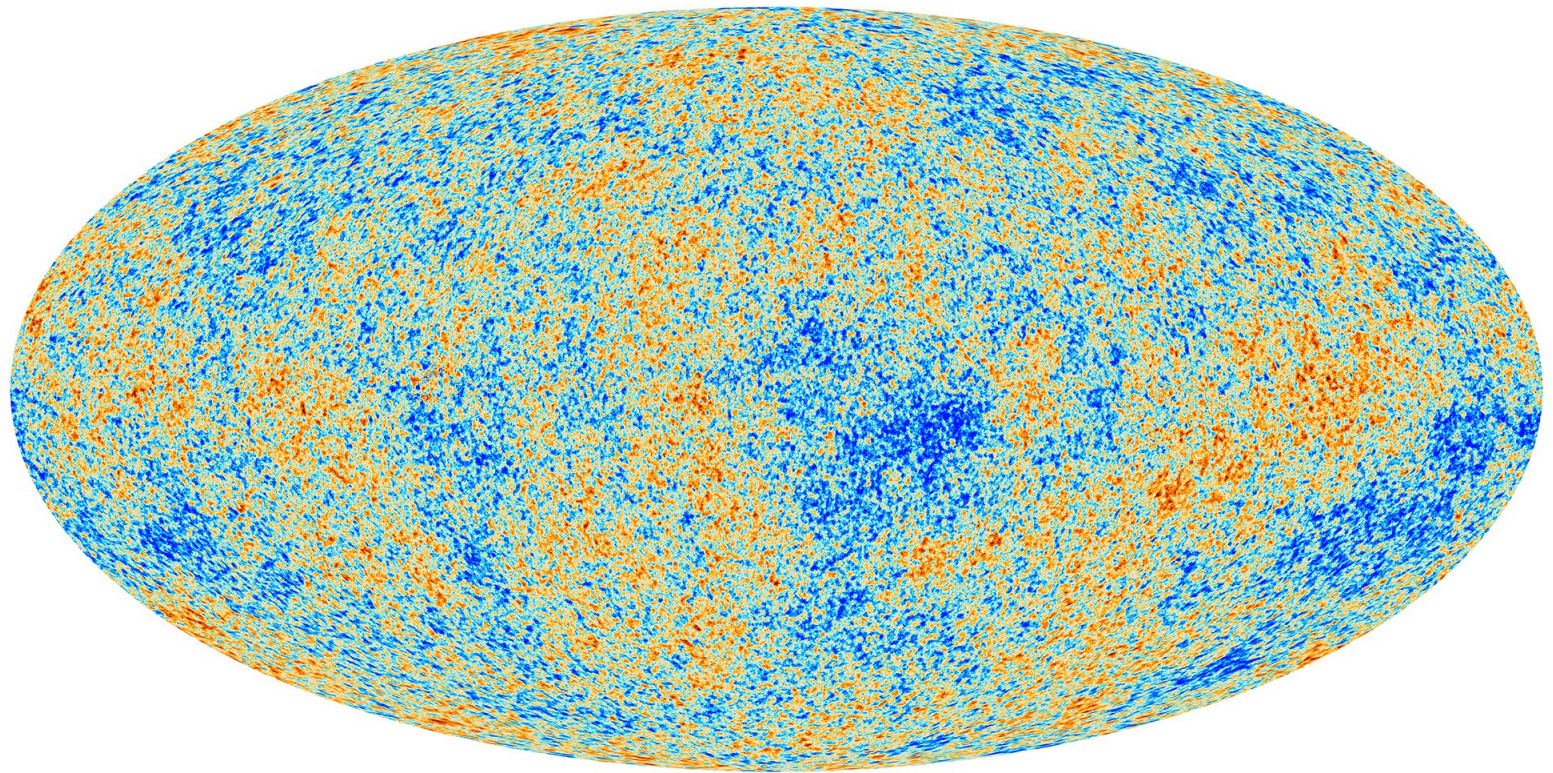
Radio waves

$$E \sim 10^{-6} \text{ eV} \Leftrightarrow \lambda \sim 1 \text{ m}$$



Microwaves

$$E \sim 10^{-4} \text{ eV} \Leftrightarrow \lambda \sim 10^{-2} \text{ m}$$



Planck

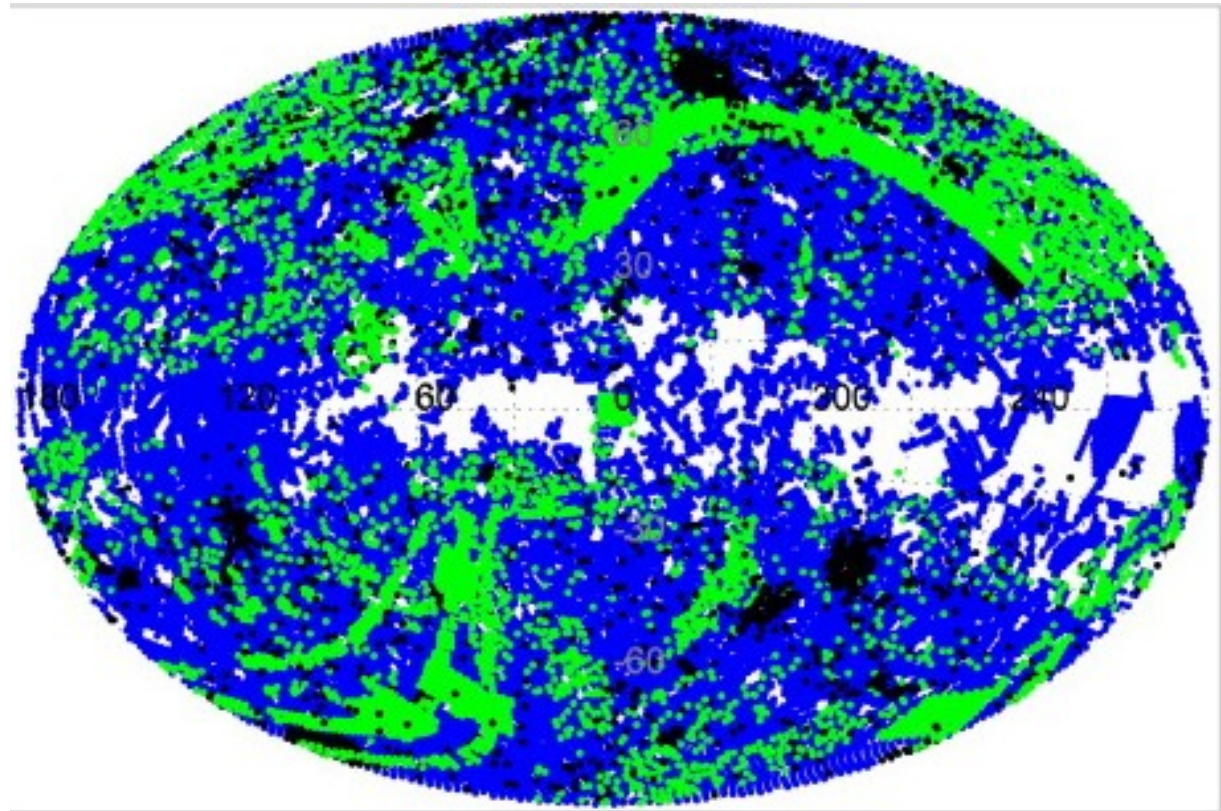
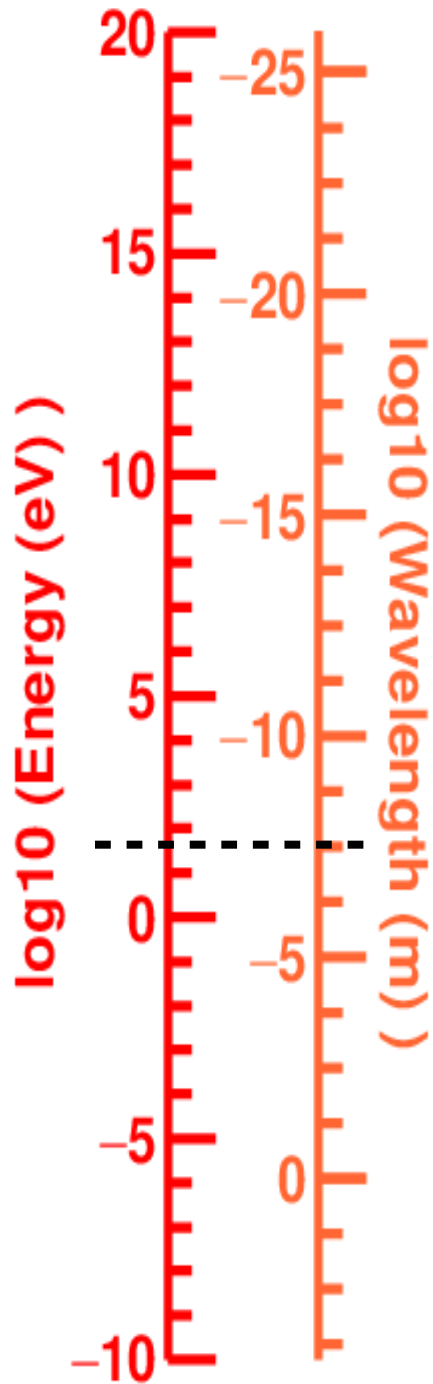
Visible light

$$E \sim 1 \text{ eV} \Leftrightarrow \lambda \sim 10^{-6} \text{ m}$$



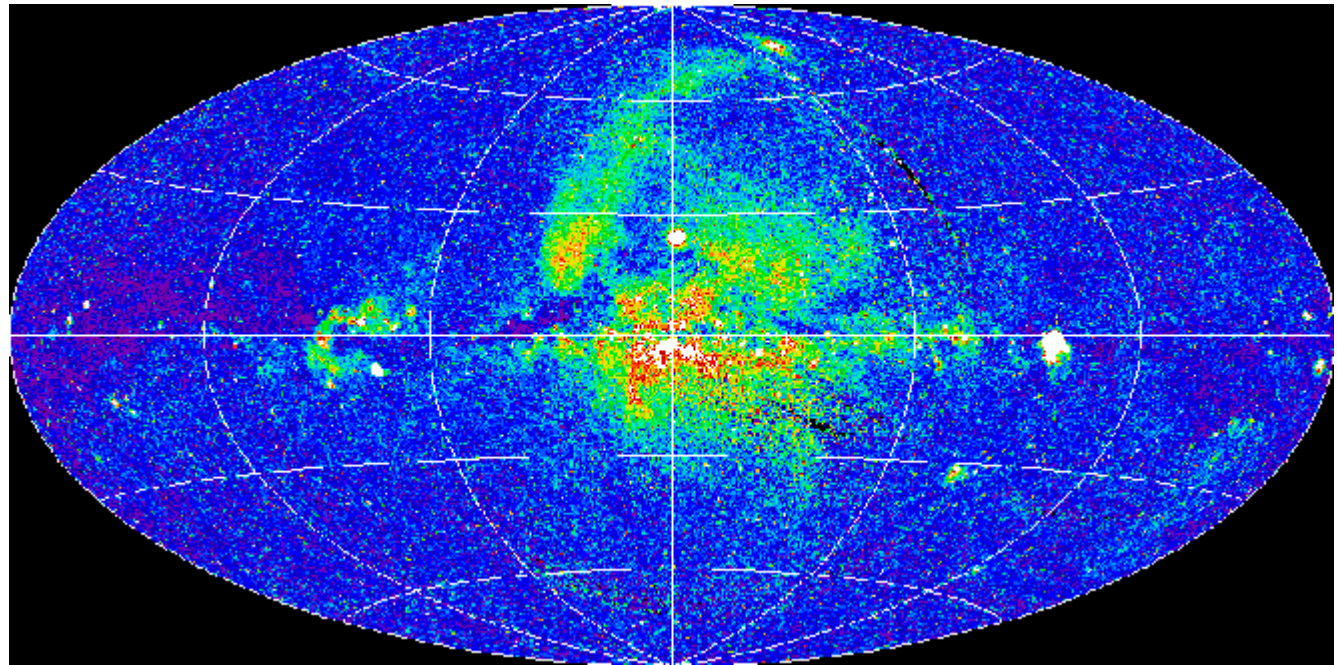
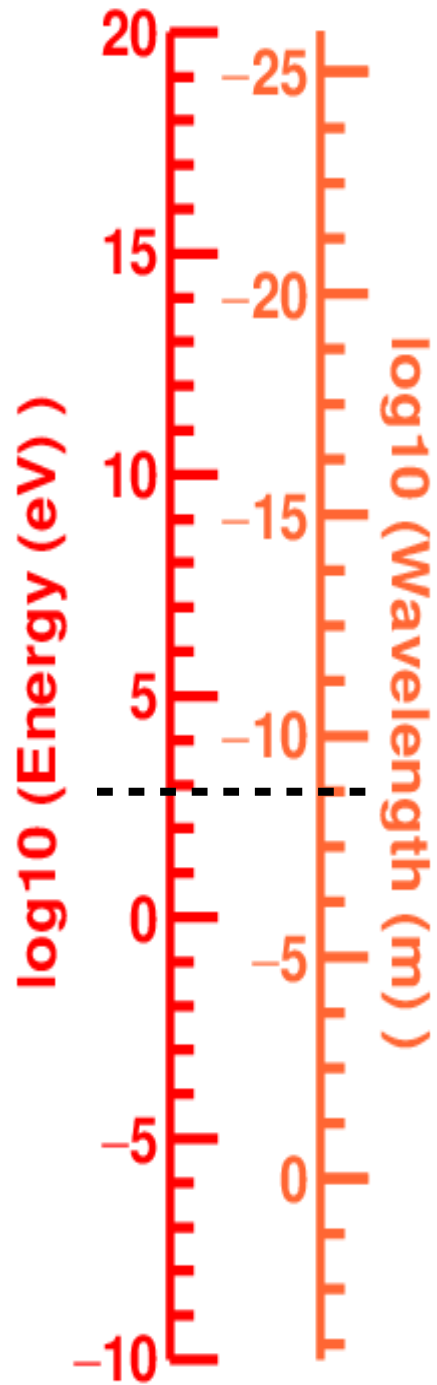
Ultraviolet

$$E \sim 100 \text{ eV} \Leftrightarrow \lambda \sim 10^{-8} \text{ m}$$



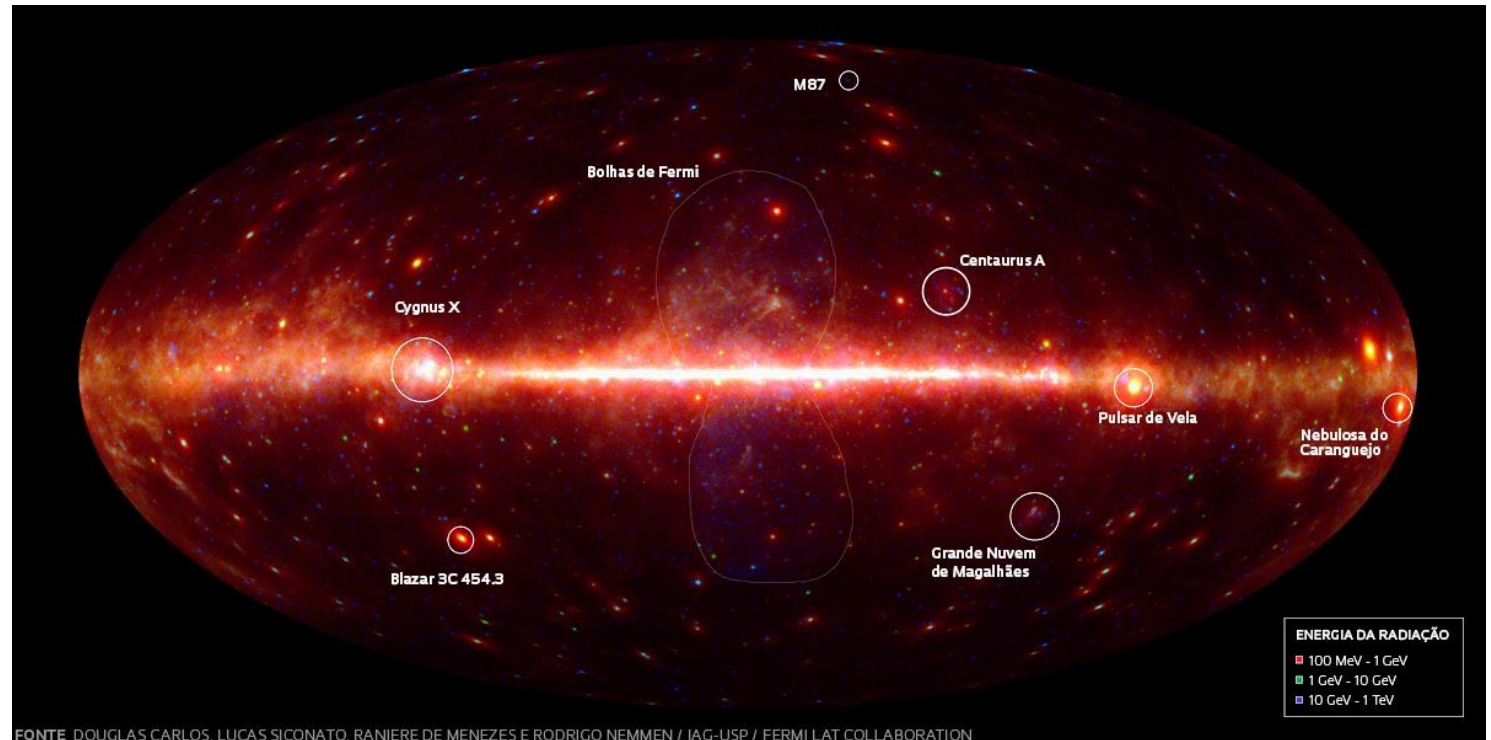
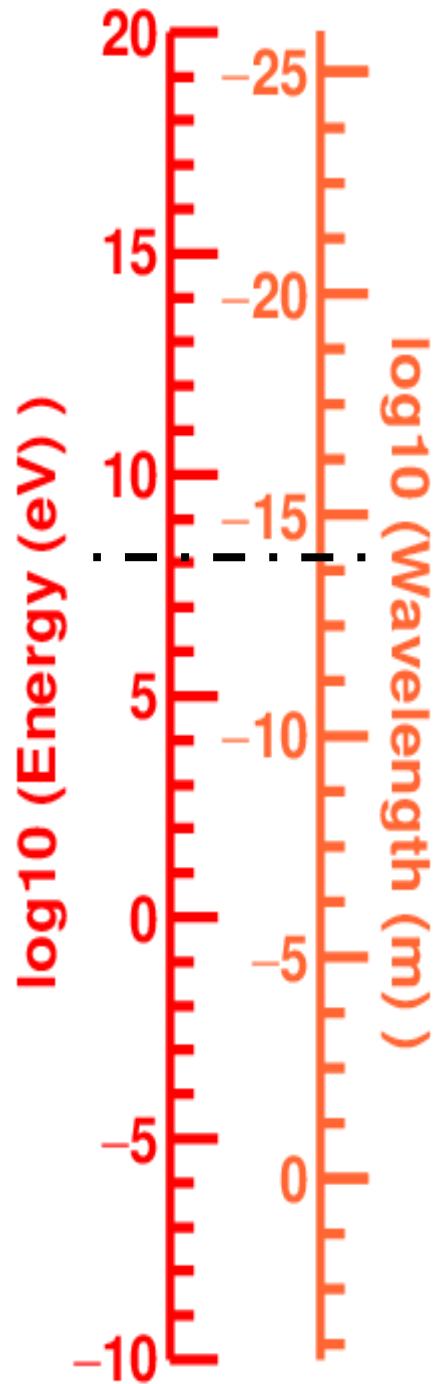
X-rays

$$E \sim 1500 \text{ eV} \Leftrightarrow \lambda \sim 10^{-9} \text{ m}$$



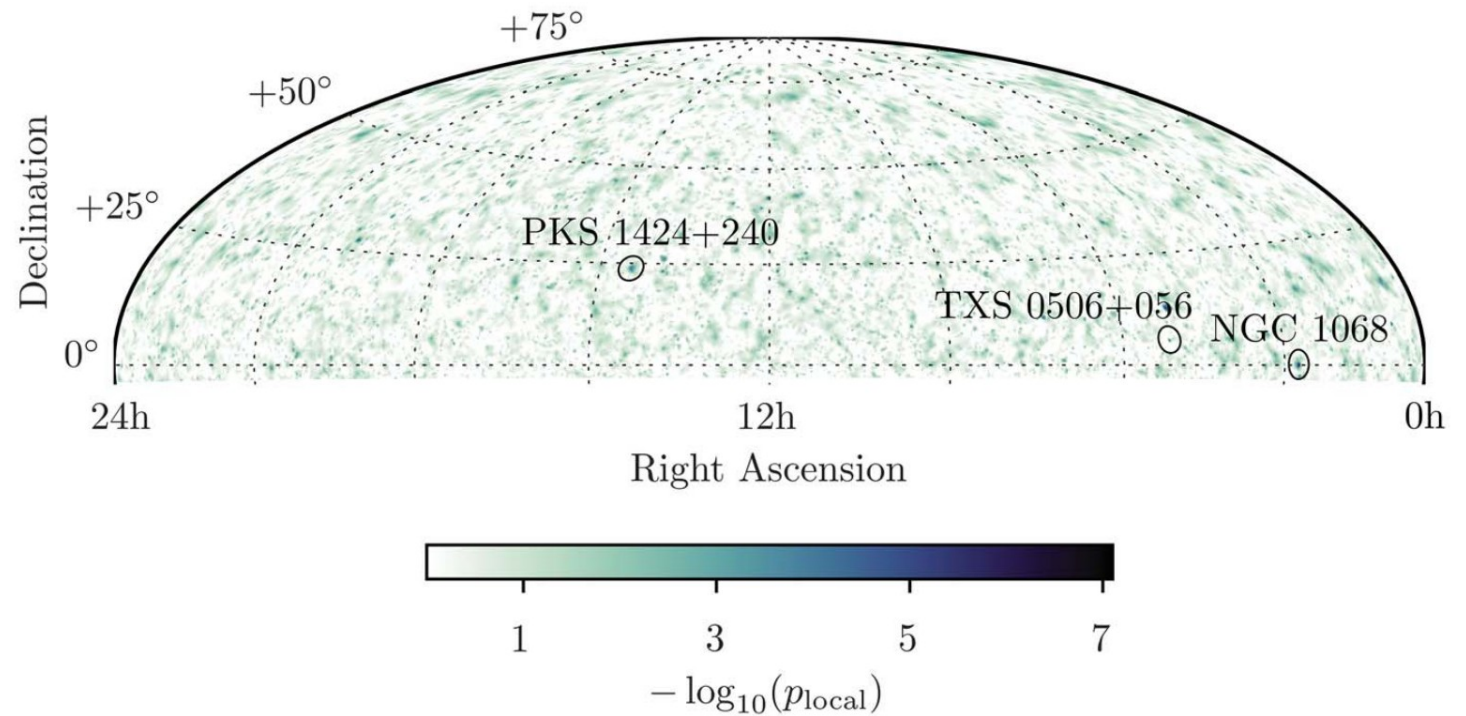
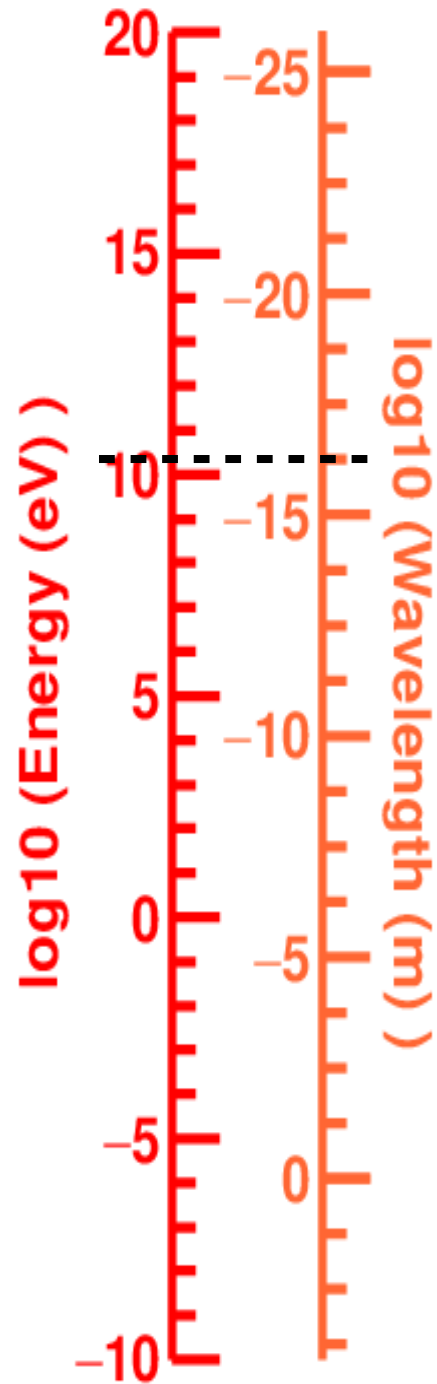
Gamma-rays

$$E > 10^8 \text{ eV} \Leftrightarrow \lambda < 10^{-14} \text{ m}$$



Neutrinos TeV

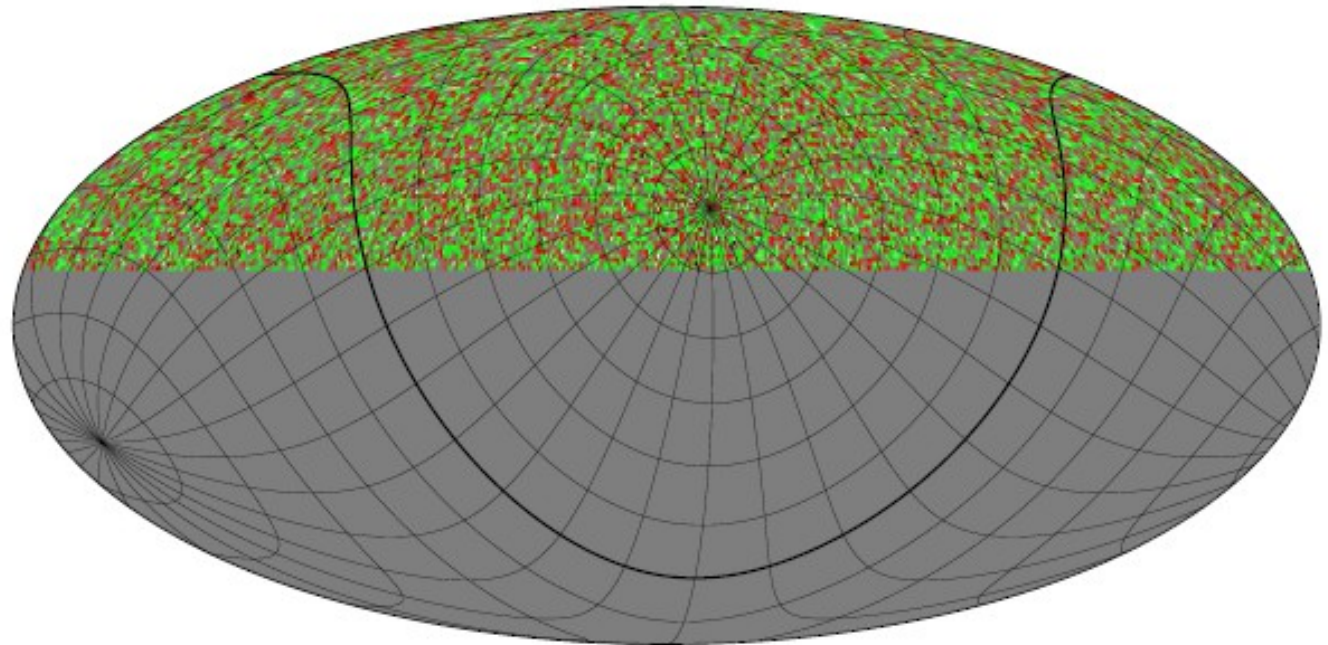
$$E > 10^{12} \text{ eV} \Leftrightarrow \lambda < 10^{-17} \text{ m}$$



IceCube Collaboration

Charged Particles Cosmic rays

$$E > 10^{15} \text{ eV} \Leftrightarrow \lambda < 10^{-21} \text{ m}$$

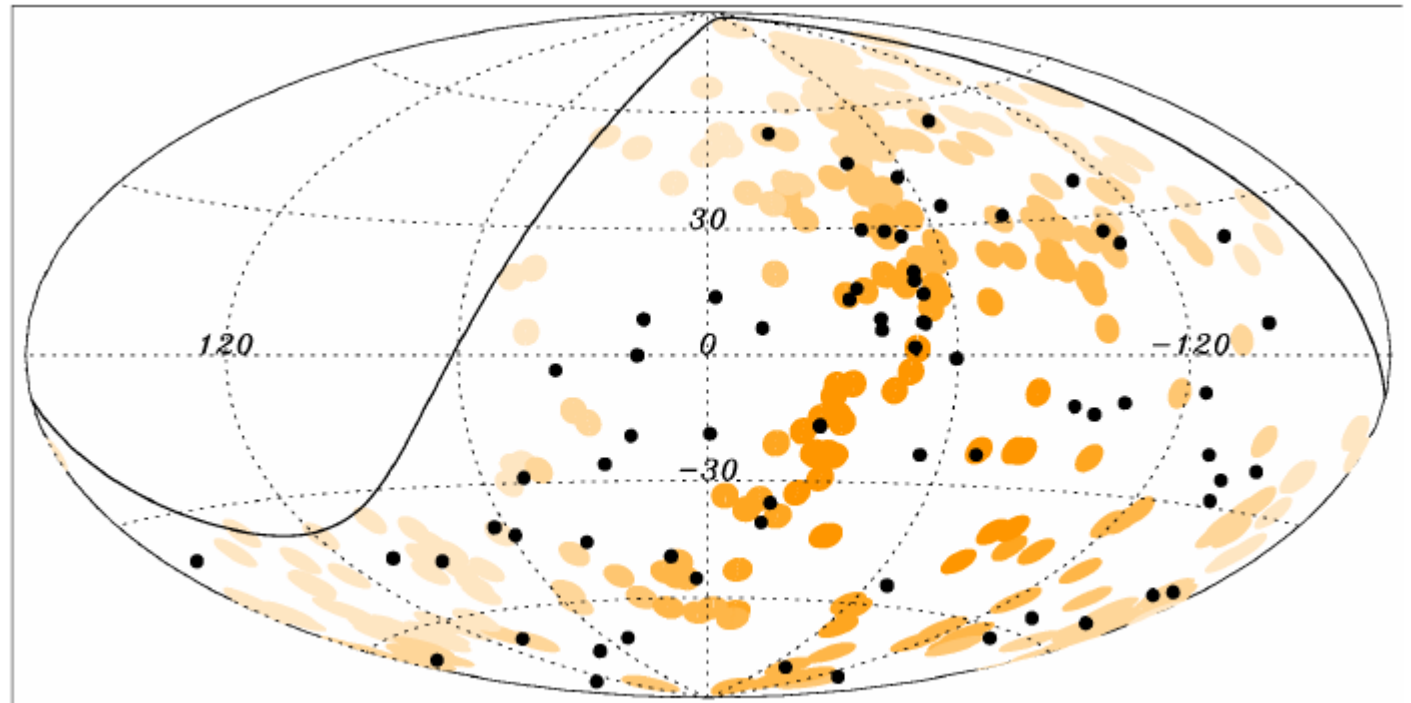


KASCADE

Charged Particles

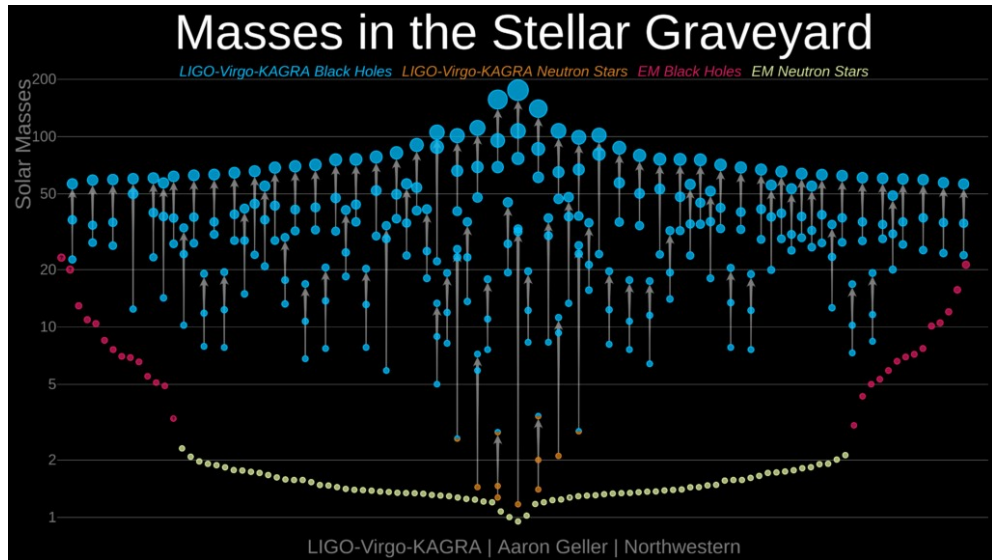
Cosmic rays

$$E > 10^{19} \text{ eV} \Leftrightarrow \lambda < 10^{-25} \text{ m}$$



Cosmic rays EeV = $E > 10^{18} \text{ eV}$

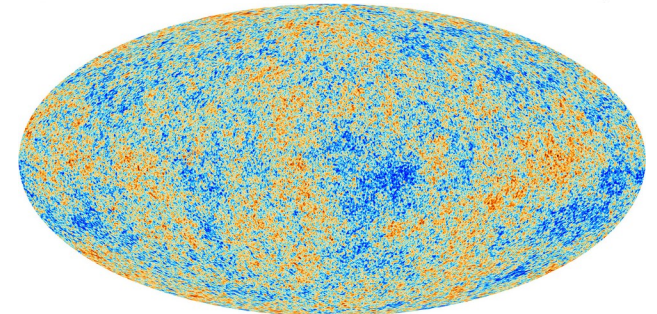
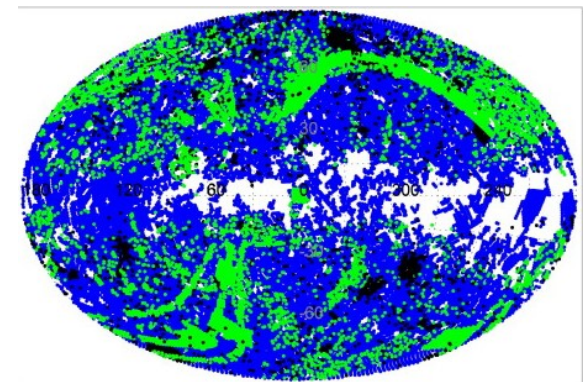
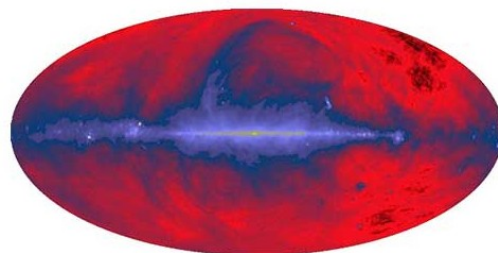
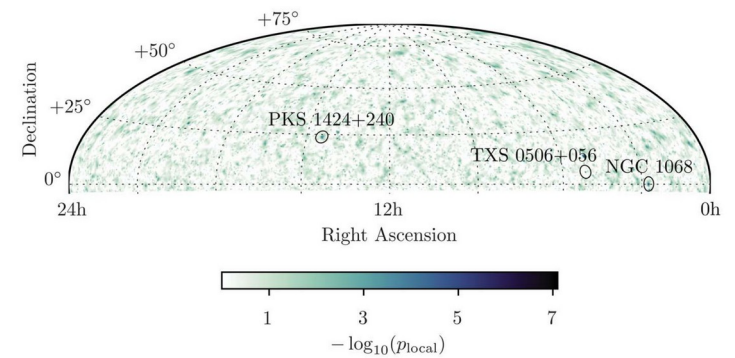
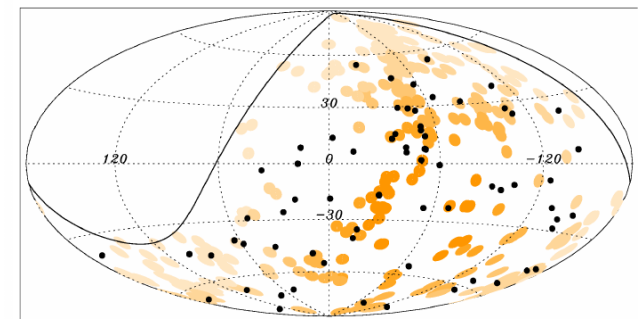
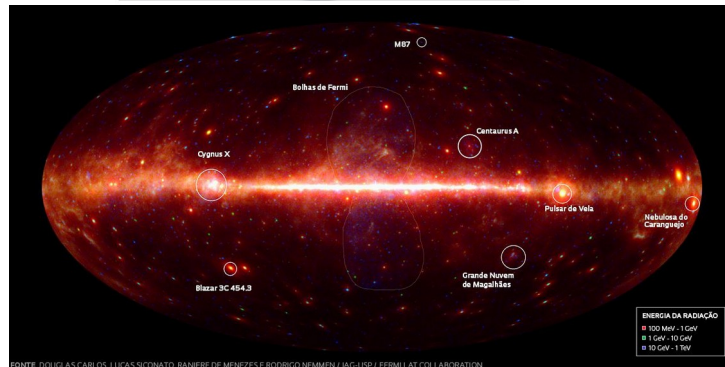
Gravitational waves



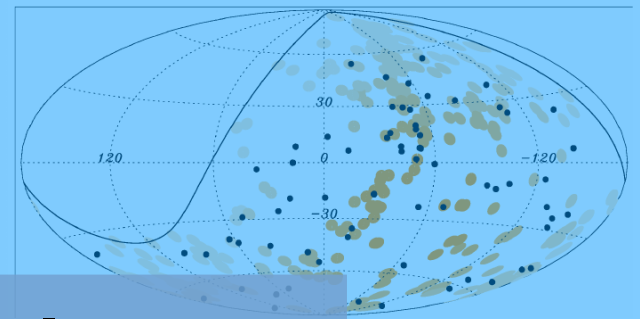
$$E_{\text{released}} > 10^{65} \text{ eV}$$

LIGO-Virgo-Kagra

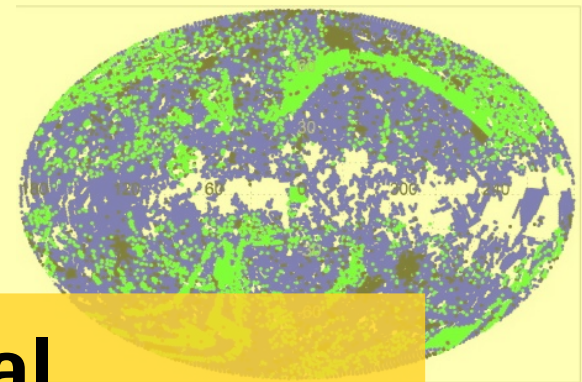
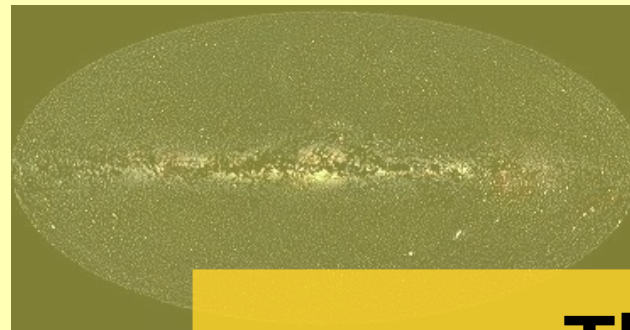
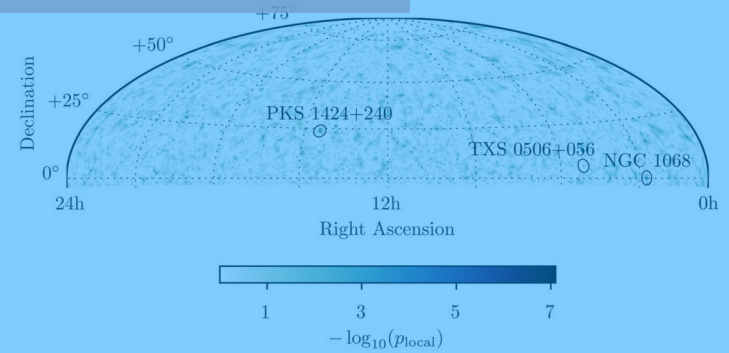
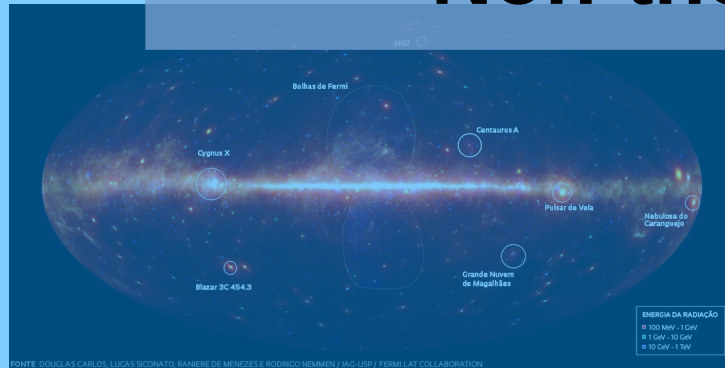
$\log_{10}(\text{Energy (eV)})$



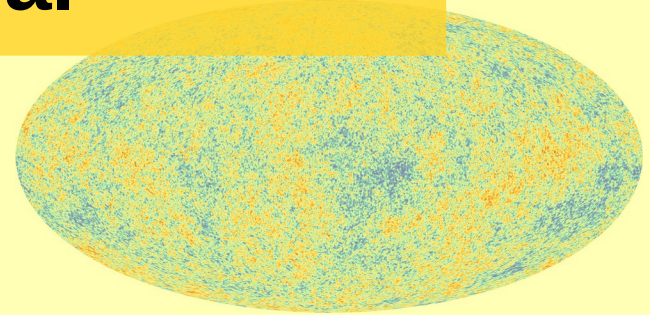
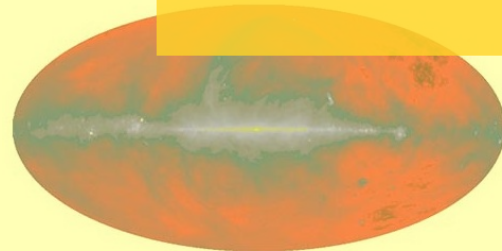
log10 (Energy (eV))



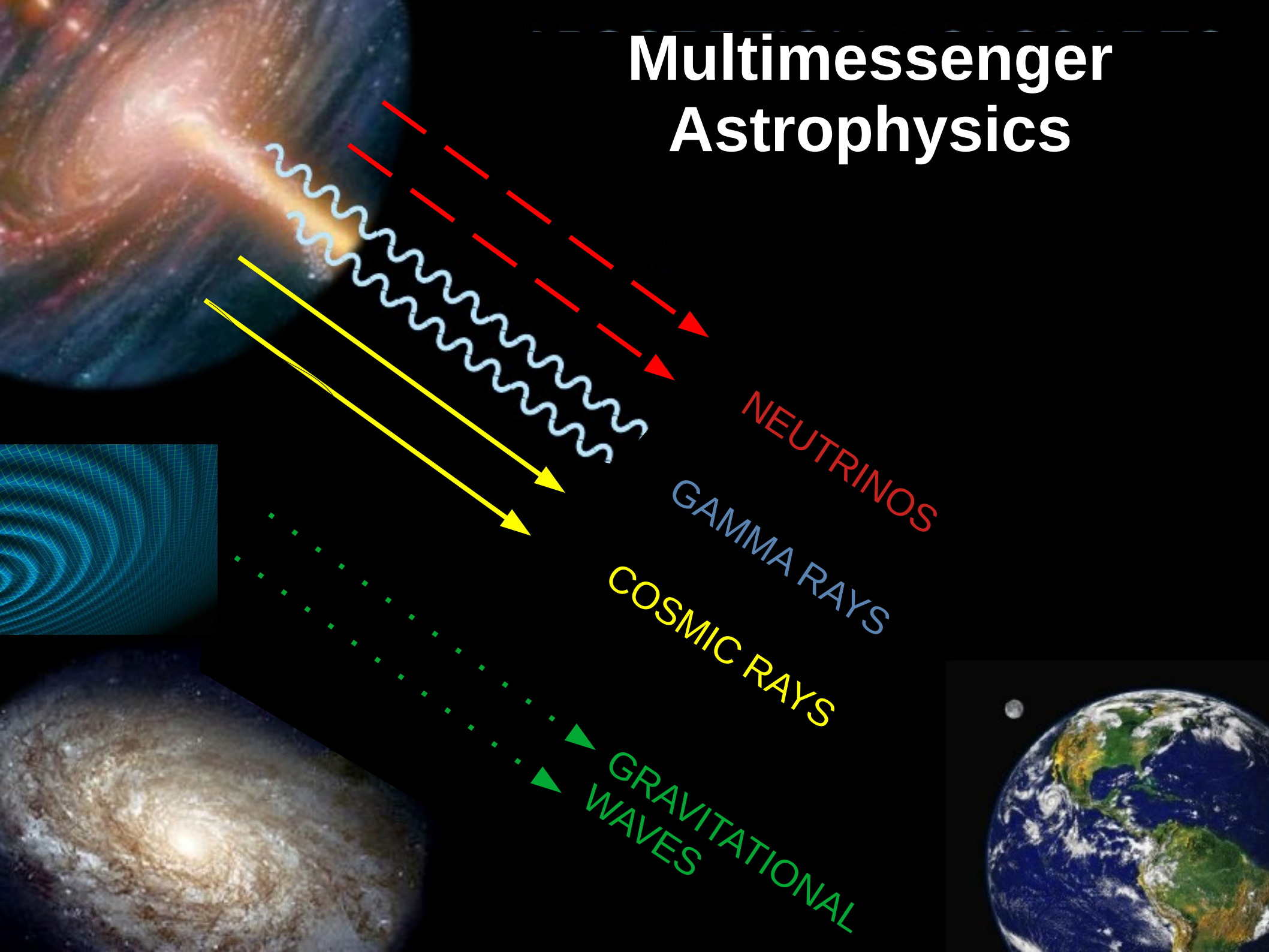
Non-thermal



Thermal



Multimessenger Astrophysics

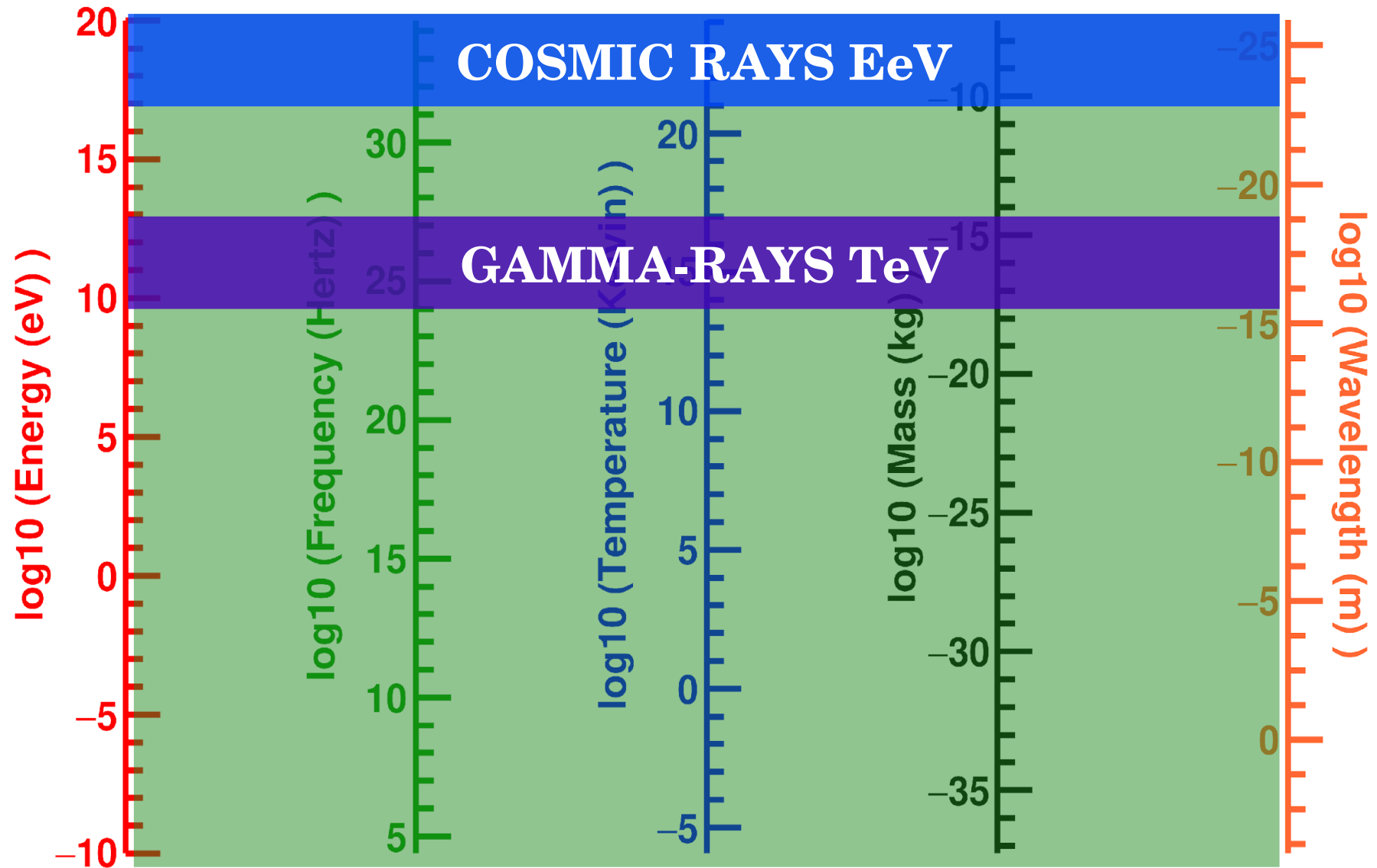


Why ?

Because Multimessenger Astrophysics:

- Probes the highest energetic phenomena
- Highlights physics of the four forces
- Searches for the dark components
- Teaches acceleration mechanisms
- Tests of our current knowledge

Probes to the highest energetic phenomena

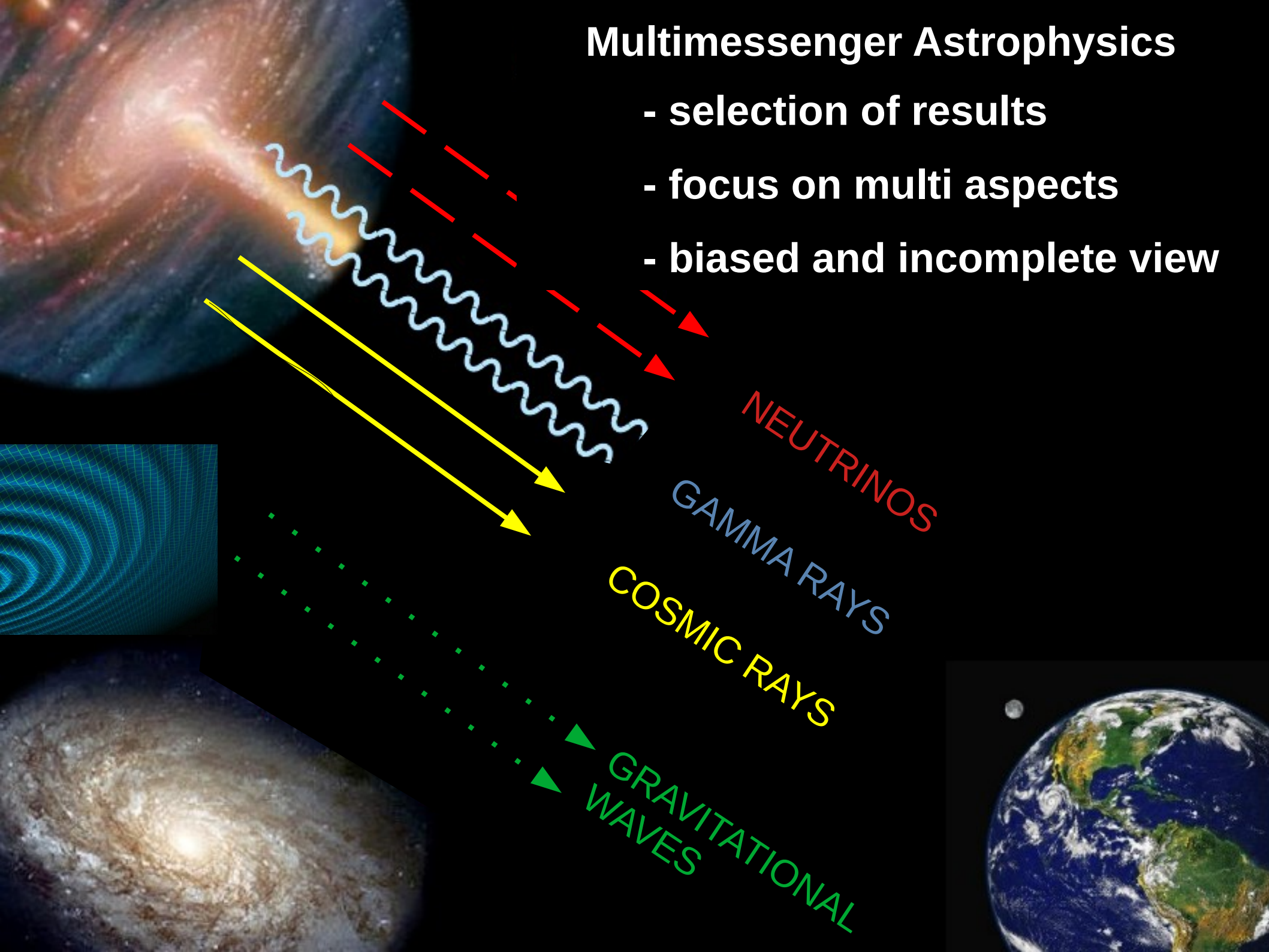


HOME OF THE FOUR FORCES

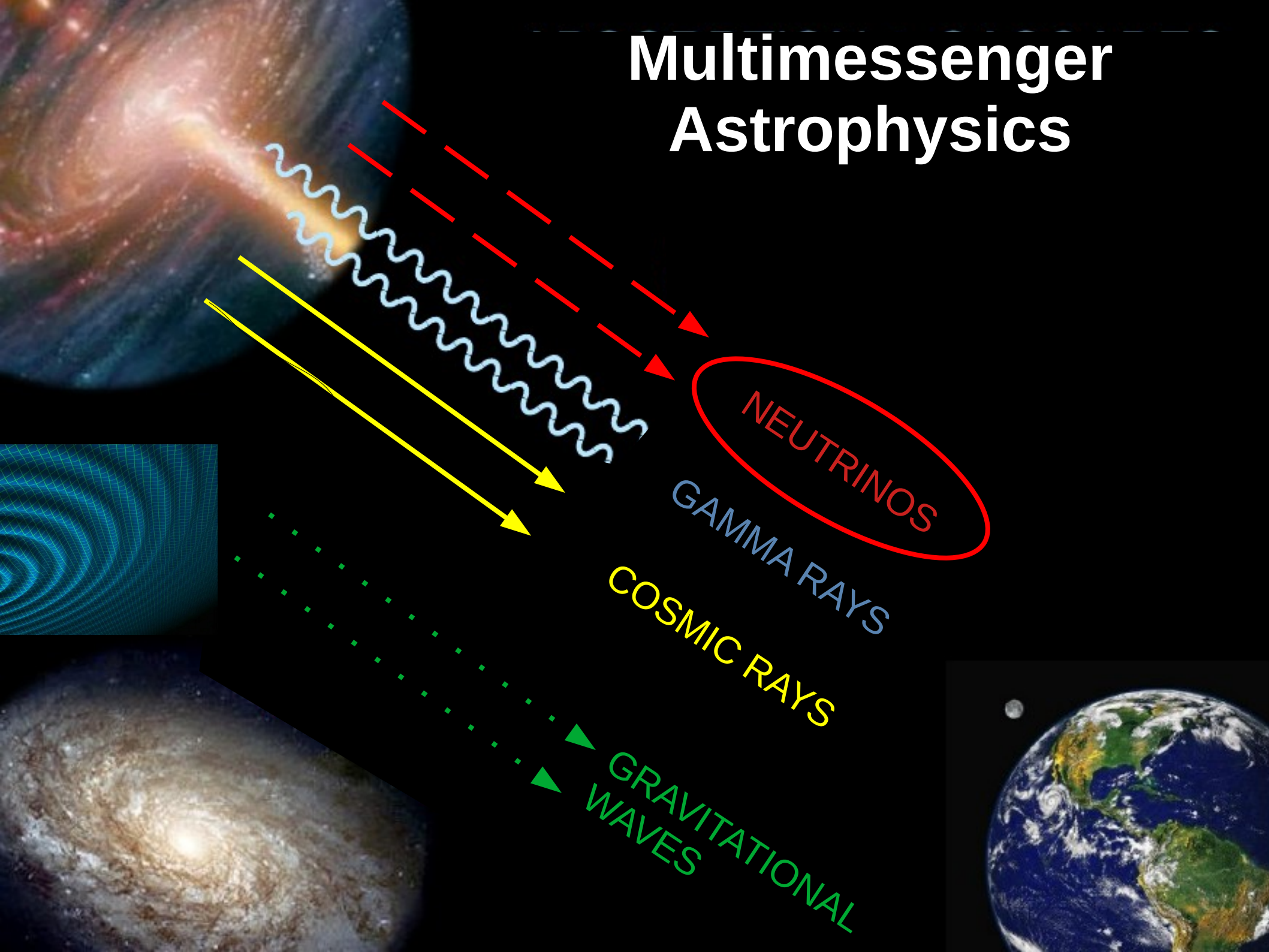


Multimessenger Astrophysics

- selection of results
- focus on multi aspects
- biased and incomplete view



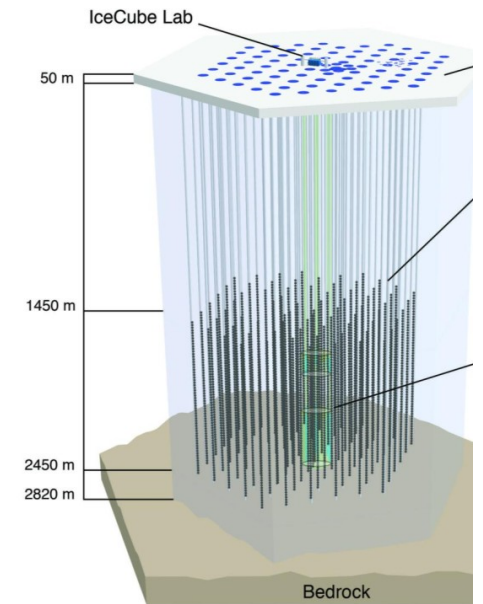
Multimessenger Astrophysics



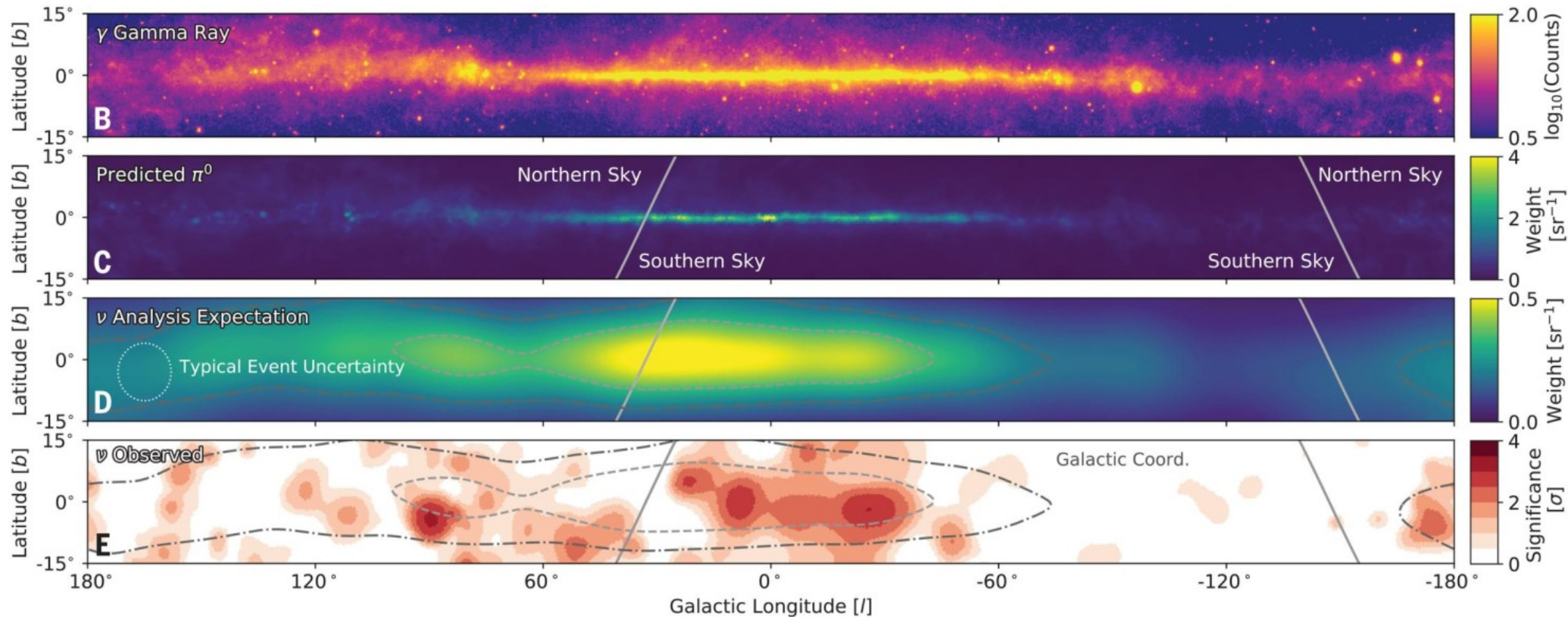
IceCube

Galactic neutrinos

Lisa Schumacher (ICHEP 2024)



No evidence of correlation with known
TeV gamma-ray sources

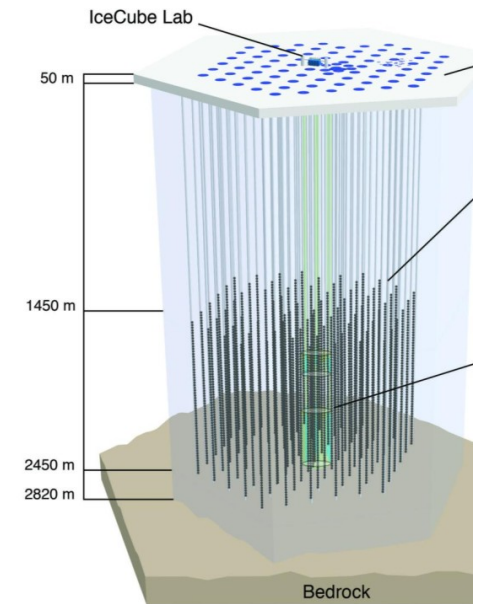


IceCube

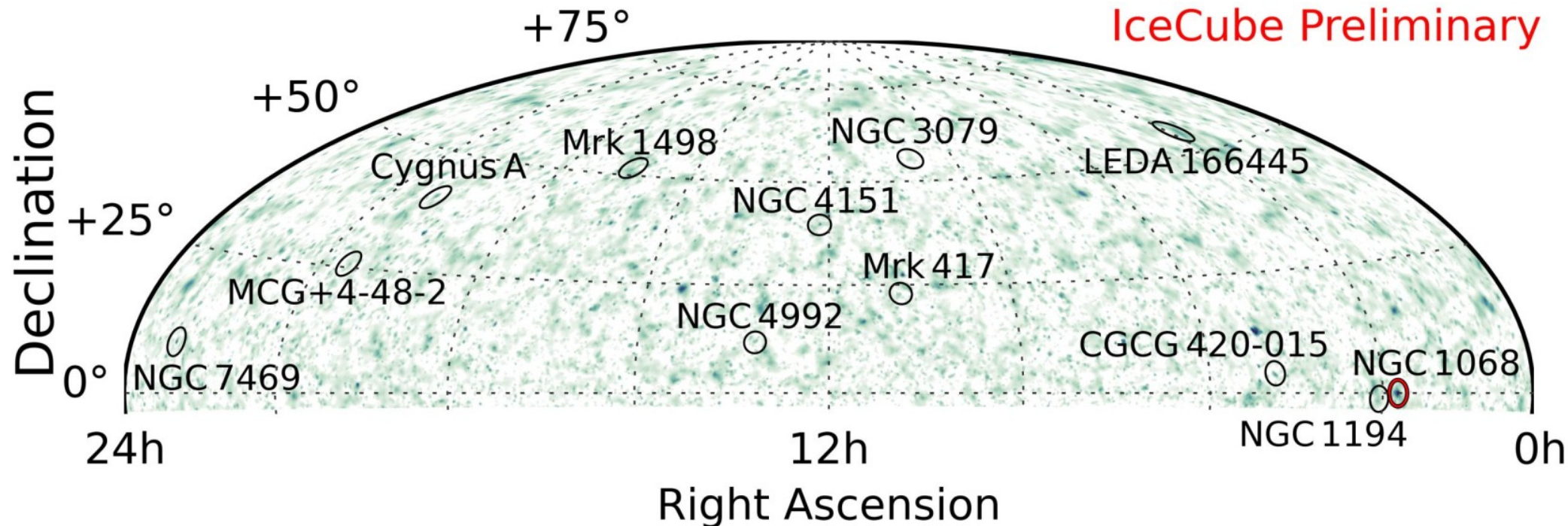
Extragalactic neutrinos

Lisa Schumacher (ICHEP 2024)

Correlation ??



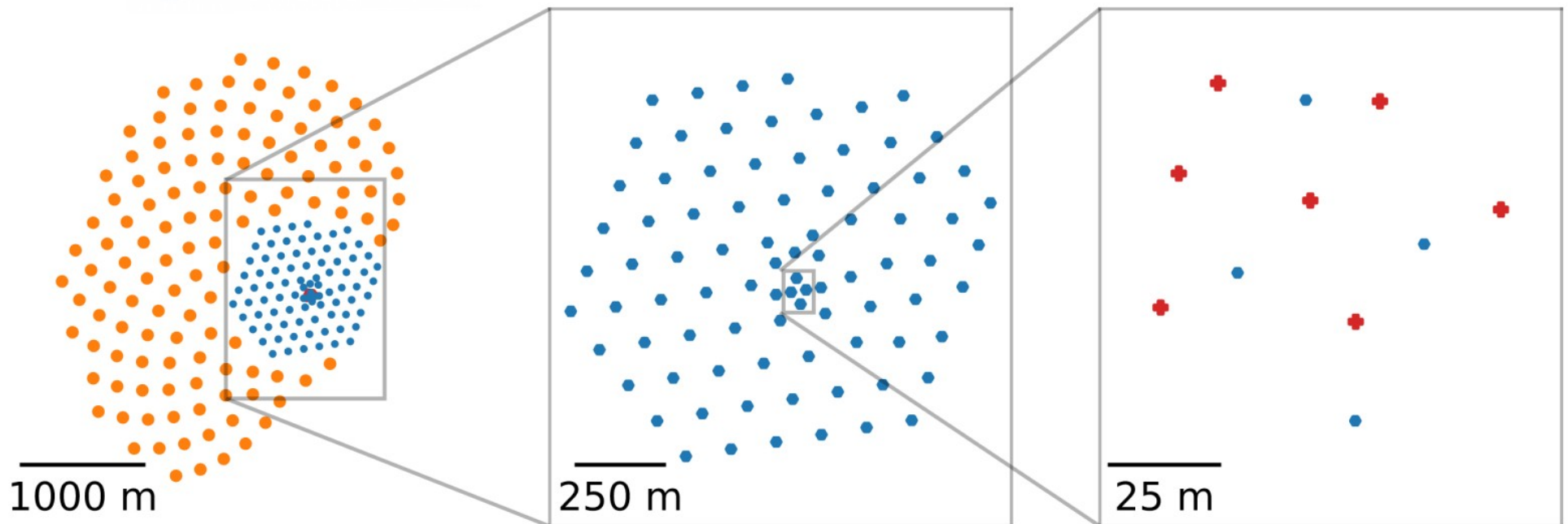
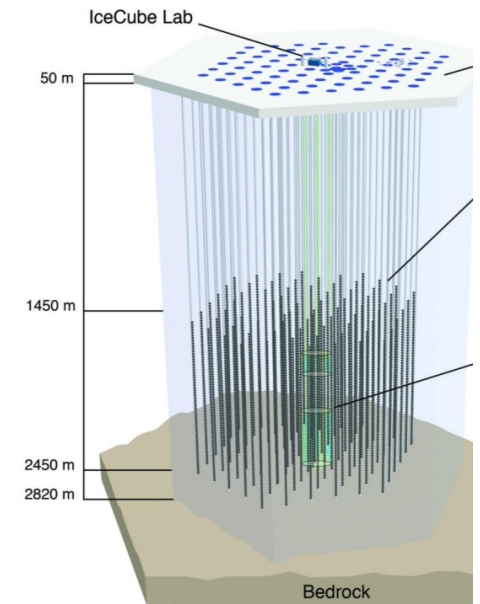
IceCube Preliminary



IceCube

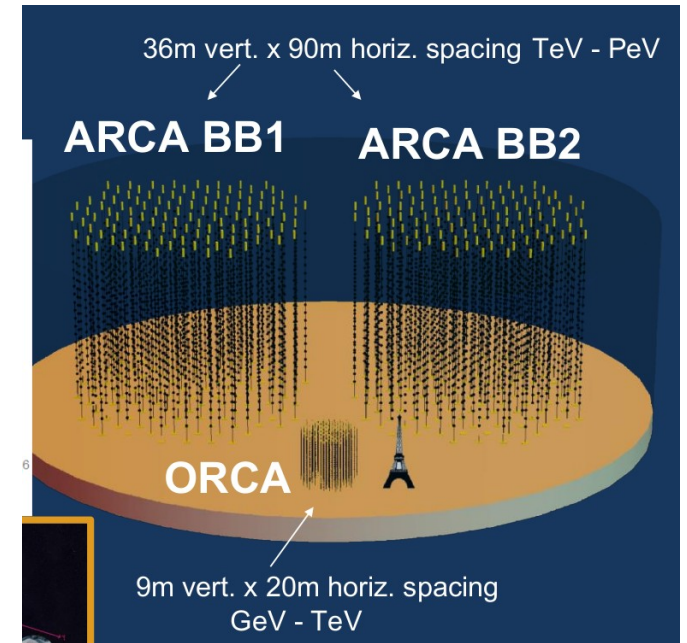
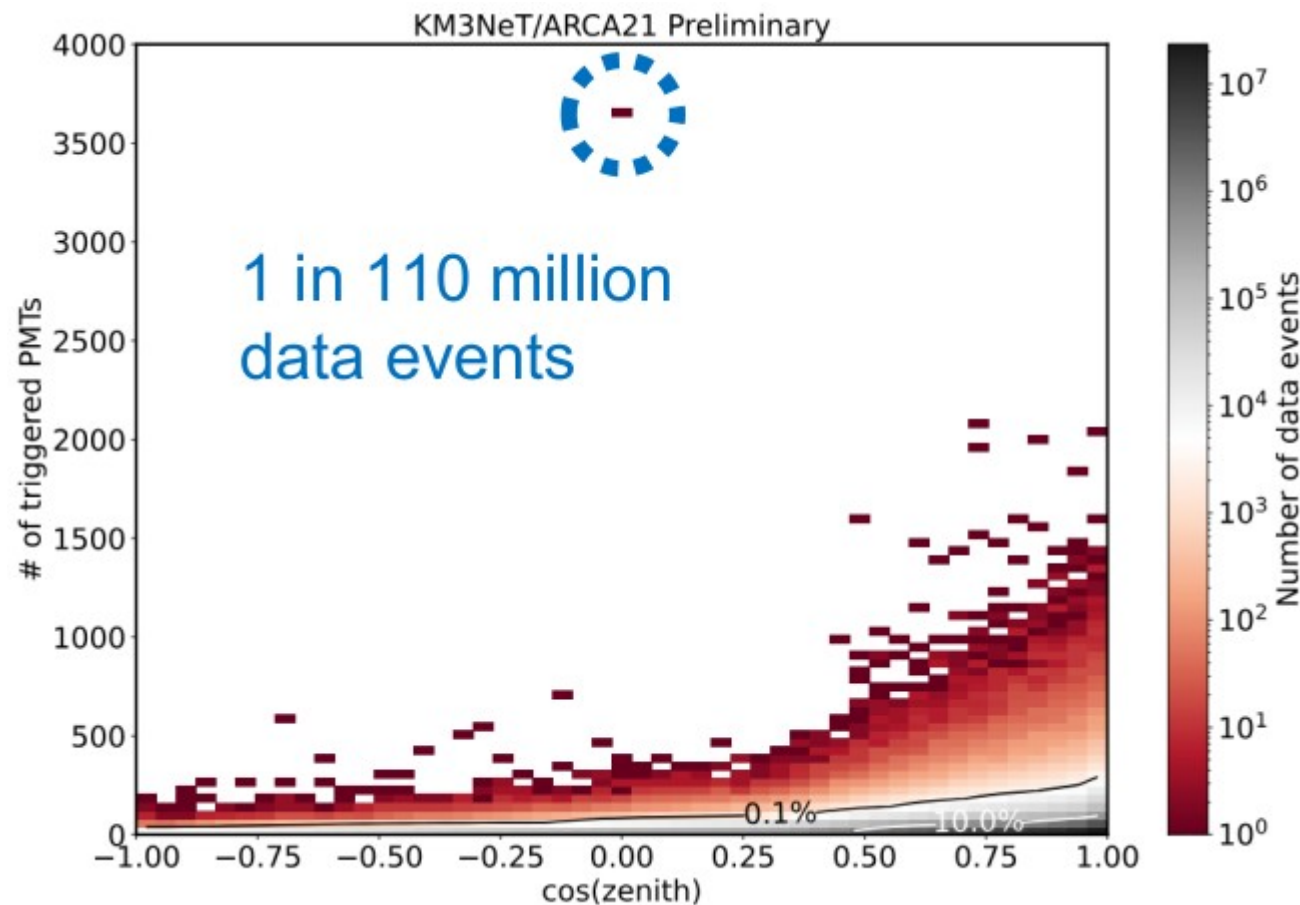
Upgrades

Lisa Schumacher (ICHEP 2024)



News from KM3NeT / ARCA

Paschal Coyle (ICHEP 2024)



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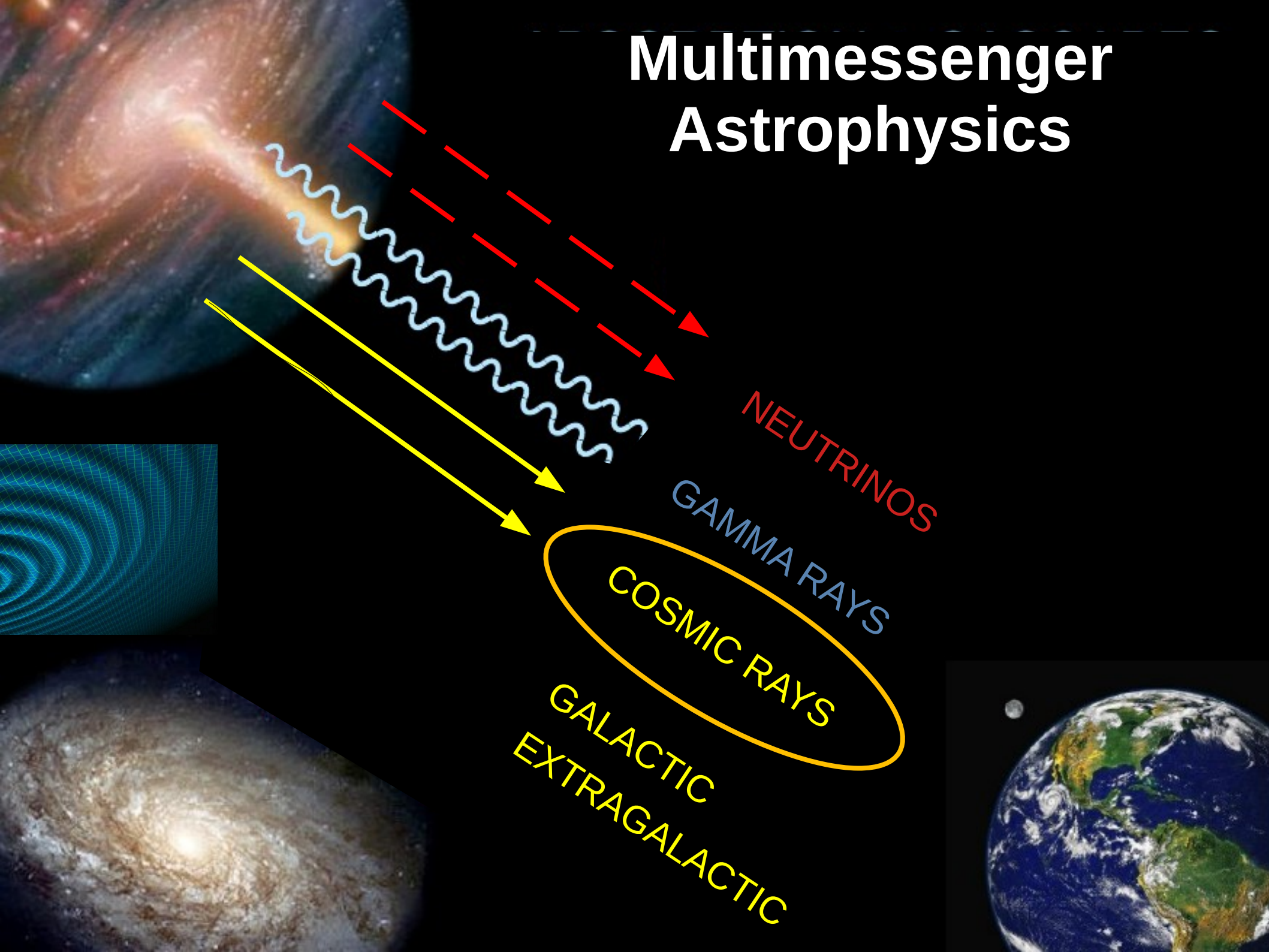
NEWS | 21 June 2024

‘Fantastic’ particle could be most energetic neutrino ever detected

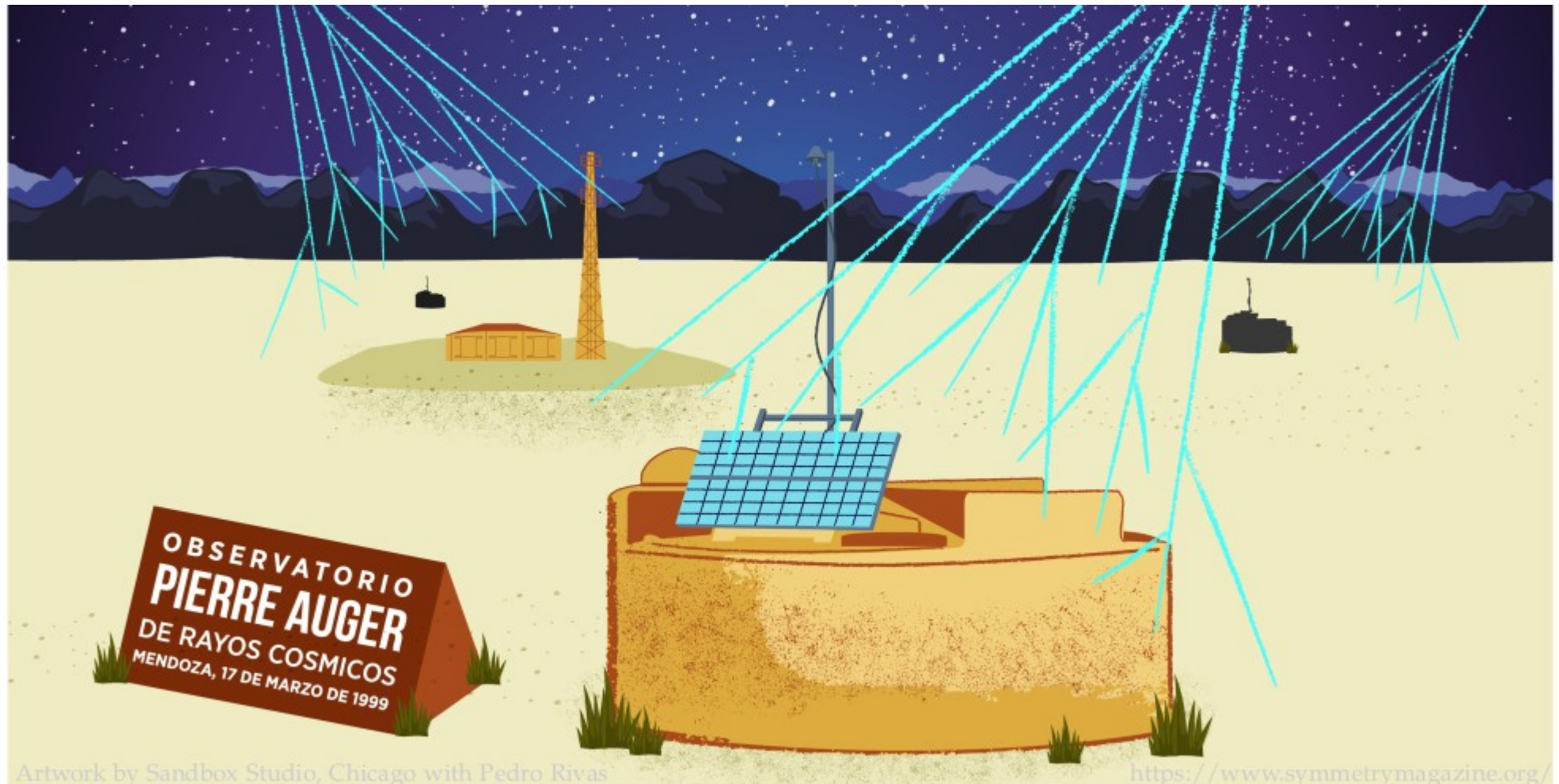
The ultra-high-energy neutrino was spotted by deep-sea detectors and could point to a massive cosmic event.

By [Davide Castelvecchi](#)

Multimessenger Astrophysics



Pierre Auger Observatory



Artwork by Sandbox Studio, Chicago with Pedro Rivas

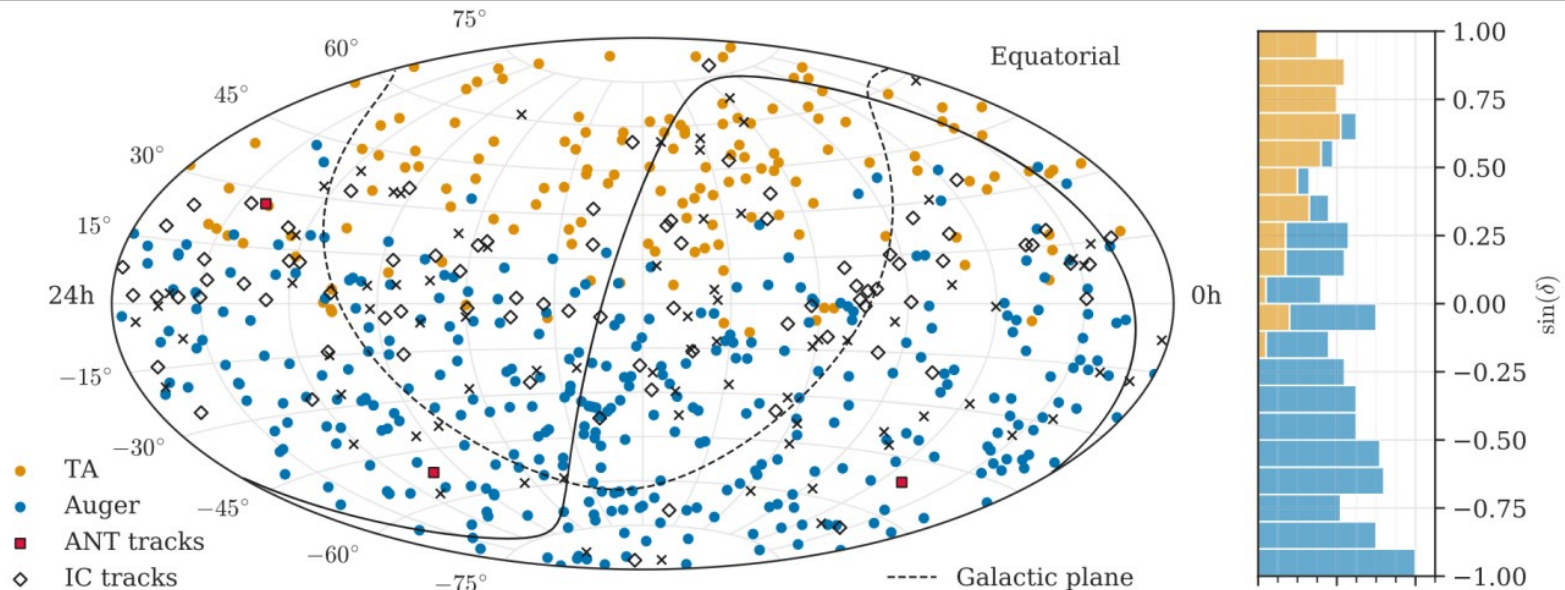
<https://www.symmetrymagazine.org/>

Extragalactic cosmic rays

Pierre Auger Observatory

Alexey Yushov (ICHEP 2024)

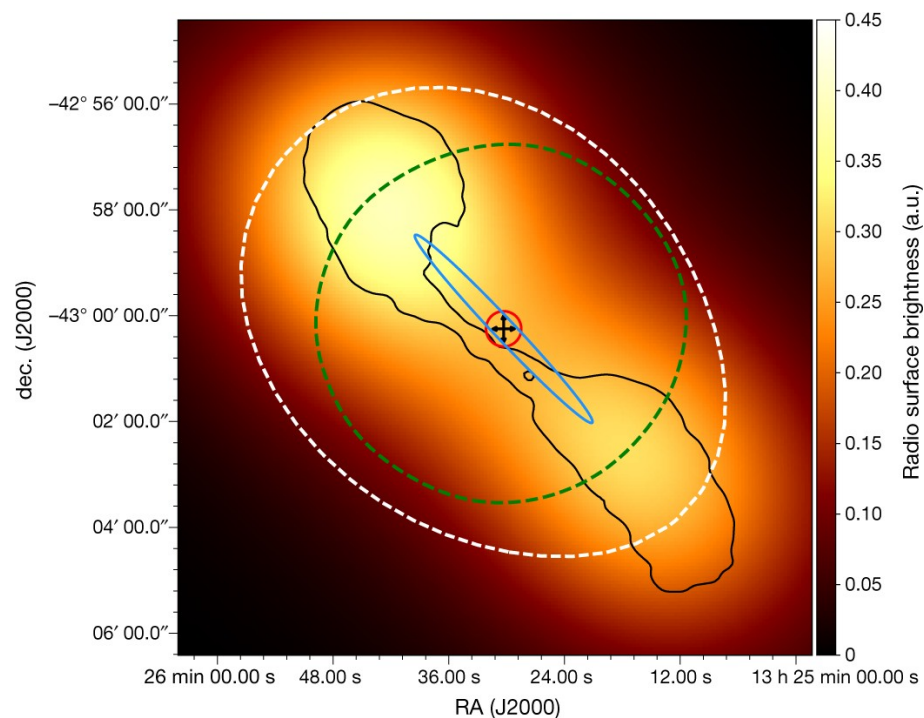
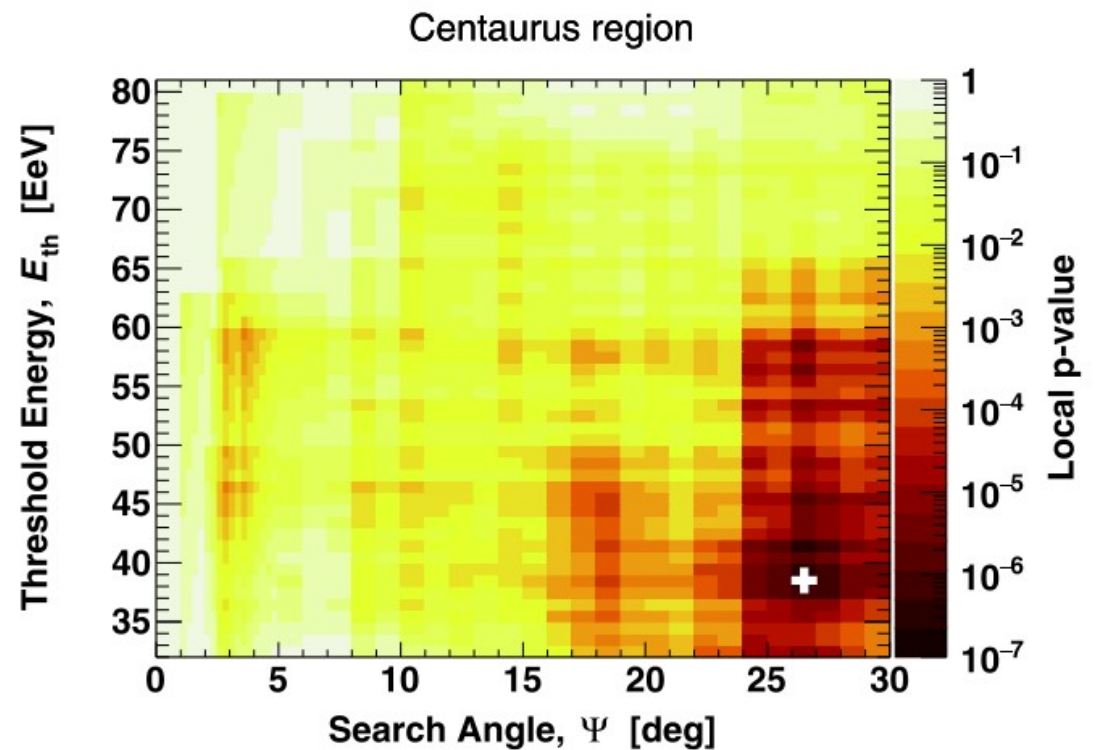
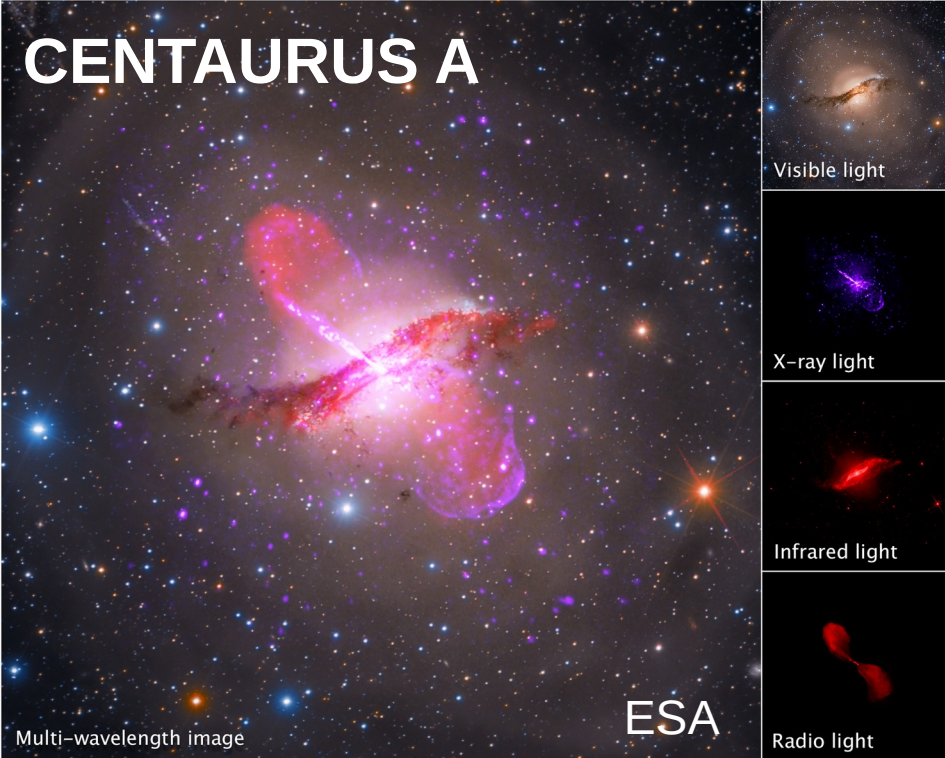
UHECR correlation (Auger $E > 52$ EeV) with IceCube and ANTARES neutrinos



No correlation of extragalactic cosmic rays and neutrinos found

The Astrophysical Journal, 952:91 (11pp), 2023

No photons (10 EeV) found correlating with Gravitational Wave events either



Pierre Auger Observatory

The Astrophysical Journal, 935:170 (24pp), 2022

Nobs = 215

Nexp = 152.0 from isotropy

p-value = 4.5×10^{-5}

H.E.S.S Observatory

Nature volume 582, 356–359 (2020)

Extragalactic cosmic rays

Pierre Auger Observatory

Alexey Yushov (ICHEP 2024)

AugerPrime upgrade: to run until 2035

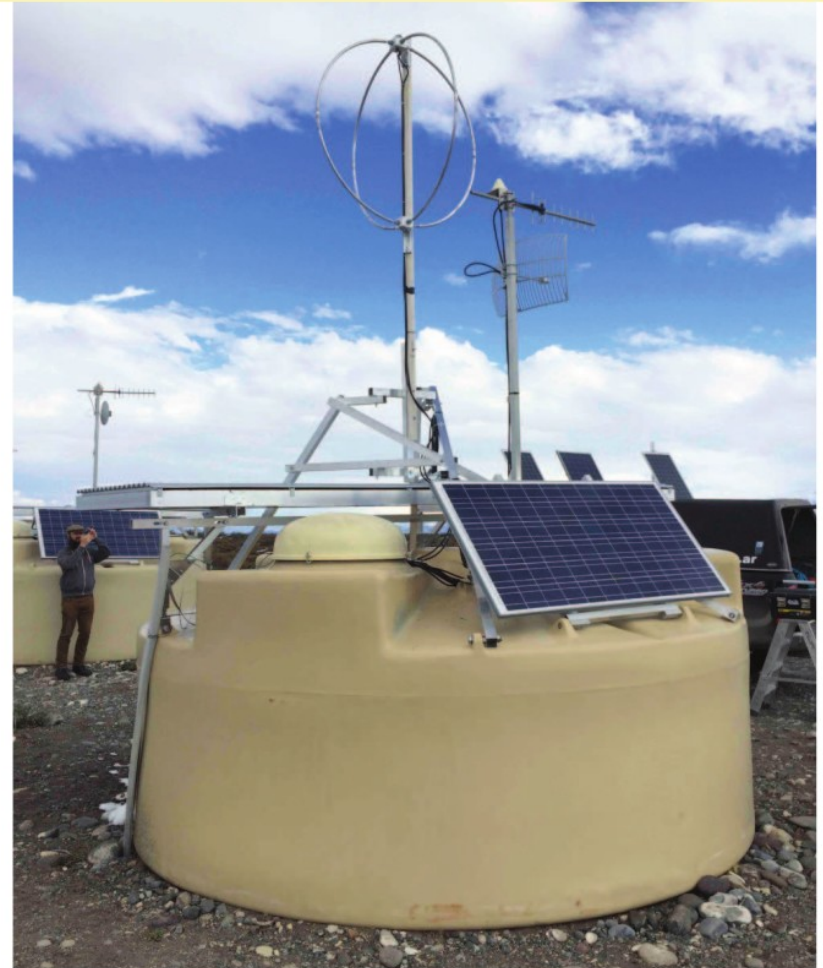
More details: talks of Martin Schimassek (today in Upgrade session) & Lukas Nellen (Computing, July 19)

For each WCD

- + new electronics
- + small PMT
- + 3.8 m^2 scintillator detectors
- + radio antenna

SD (750 m) of 23.5 km^2 area

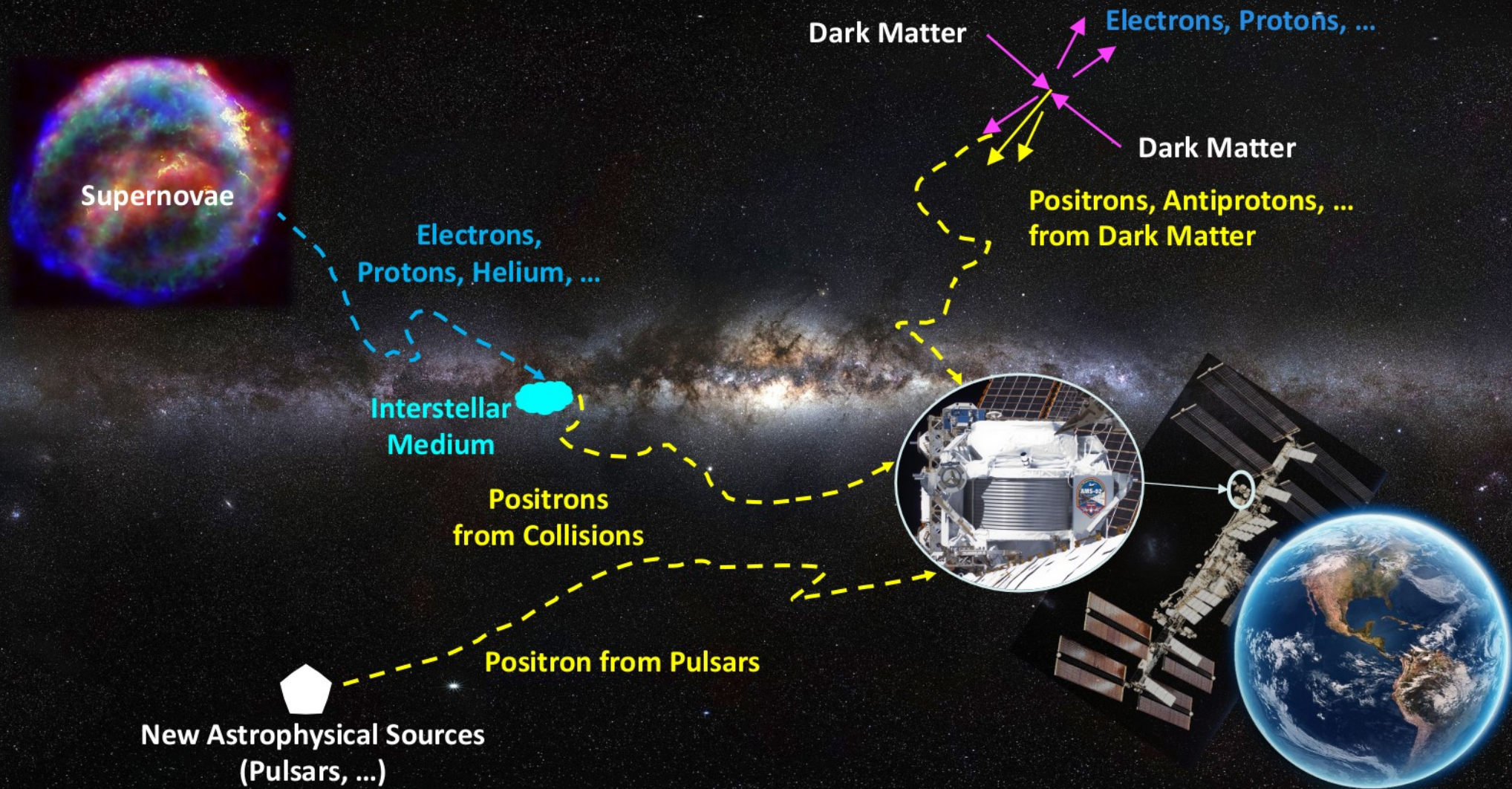
- + underground muon detectors



Galactic cosmic rays: AMS

Andrei Kounine (ICHEP 2024)

Latest Physics Results from AMS: Study of Positrons & Electrons

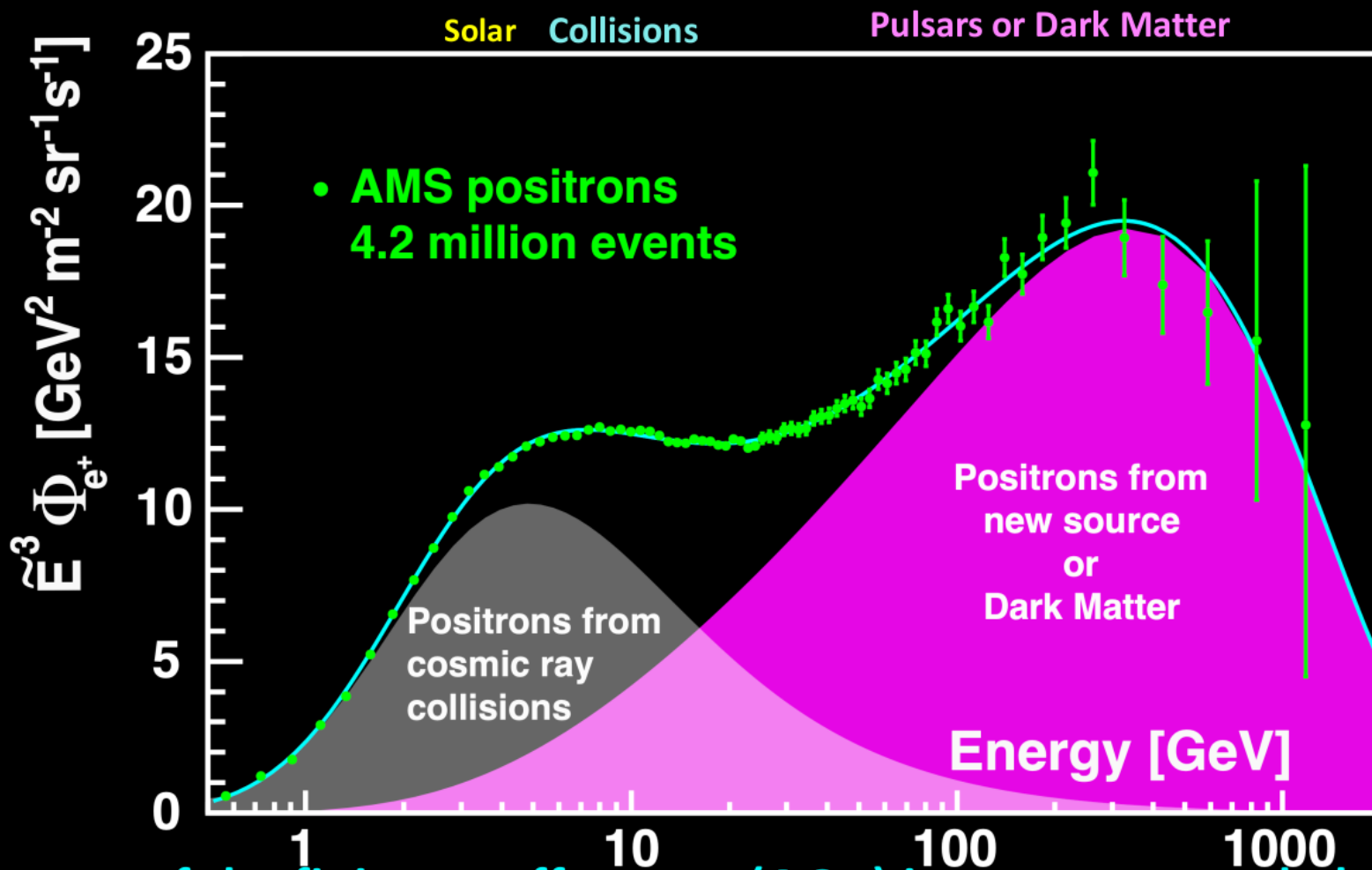


Galactic cosmic rays: AMS

Andrei Kounine (ICHEP 2024)

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter both with a cutoff energy E_s .

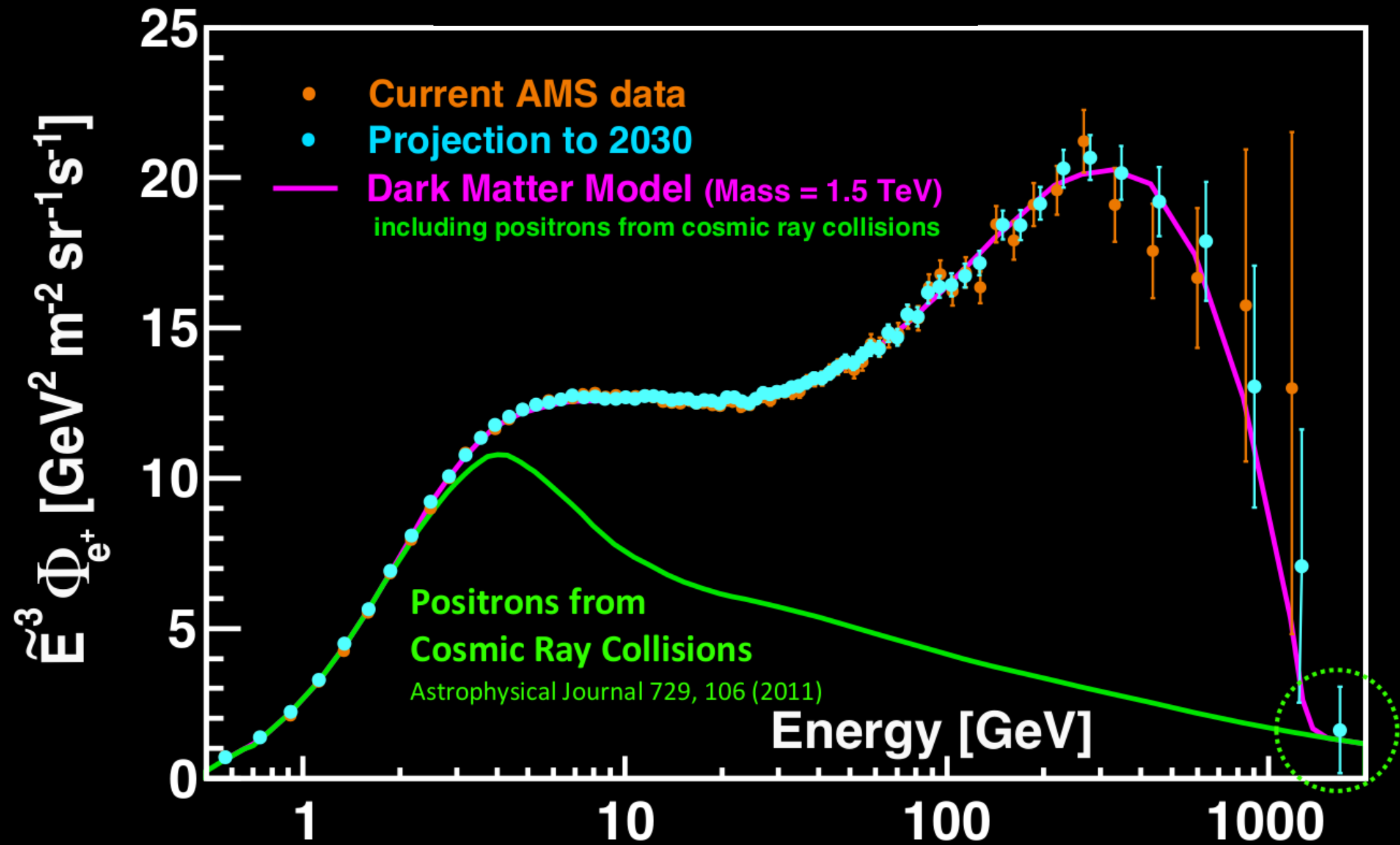
$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2} \left[C_d (\hat{E}/E_1)^{\gamma_d} + C_s (\hat{E}/E_2)^{\gamma_s} \exp(-\hat{E}/E_s) \right]$$



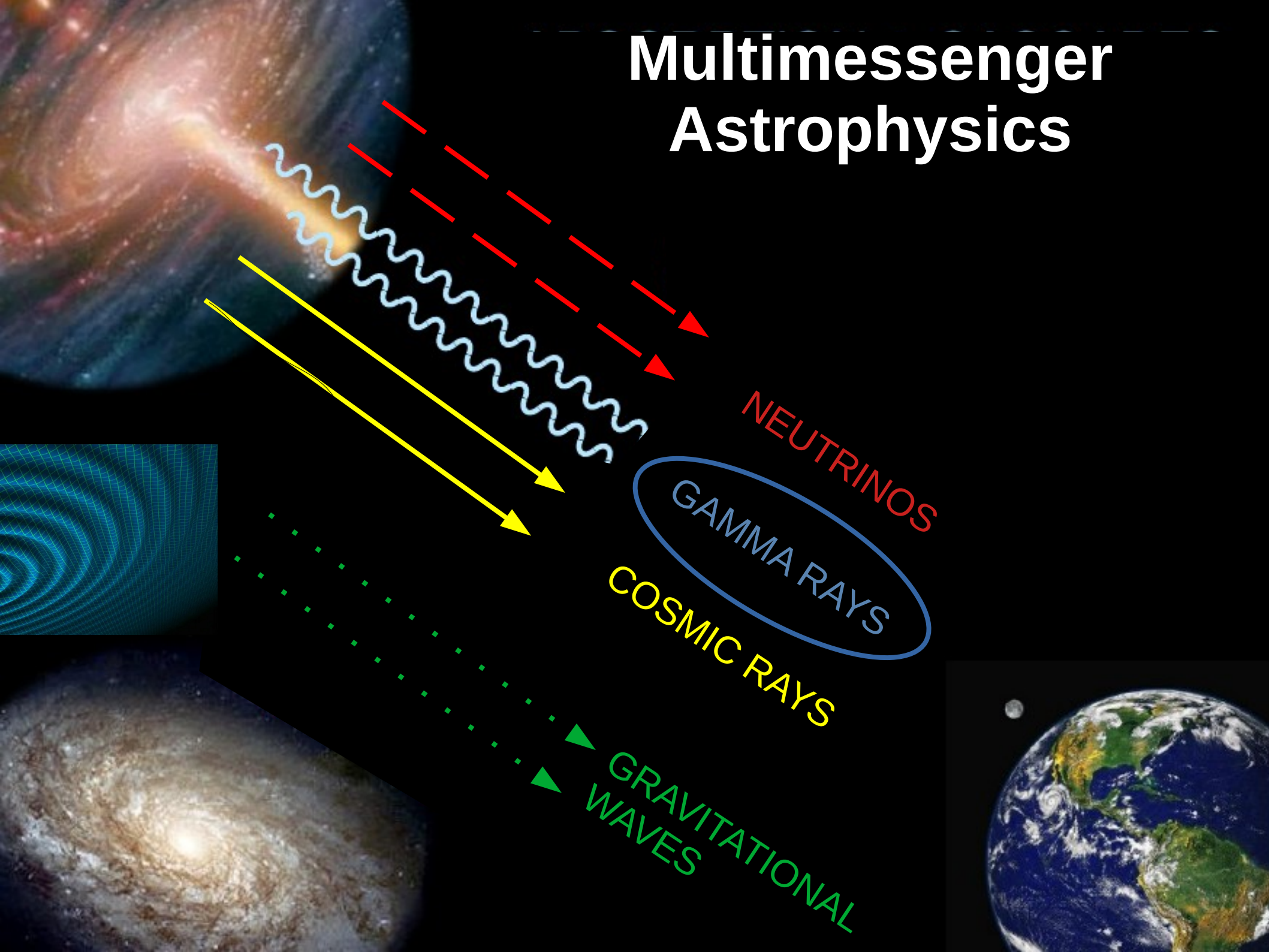
The existence of the finite cutoff energy (4.8σ) is an unexpected observation

Galactic cosmic rays: AMS

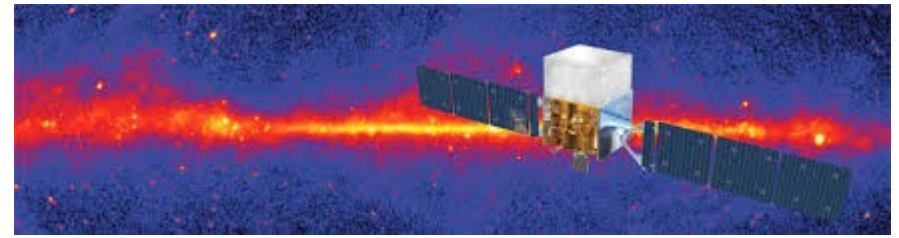
Andrei Kounine (ICHEP 2024)



Multimessenger Astrophysics

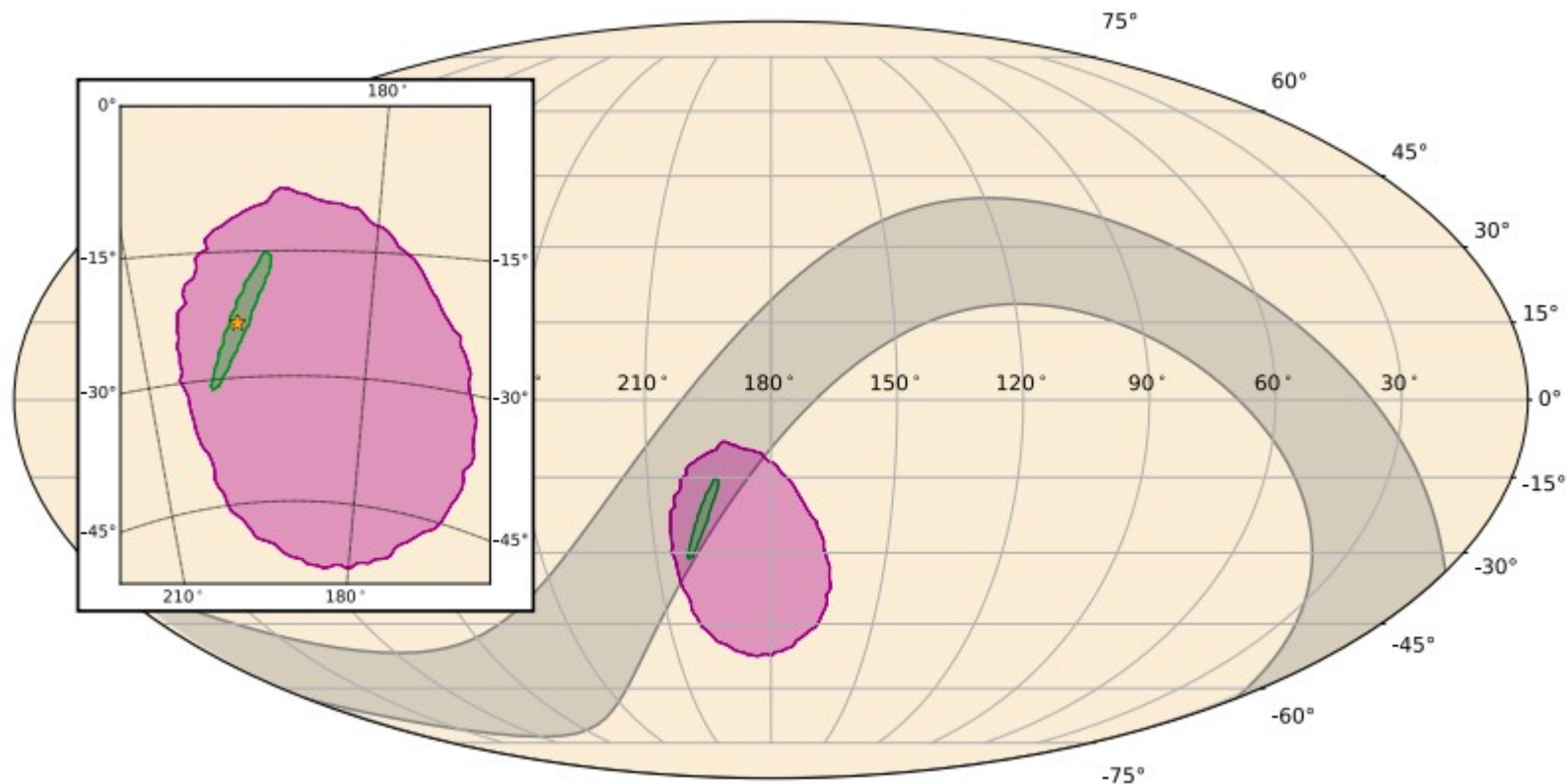


GeV gamma-ray Fermi-LAT



All-sky monitor

Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A



LIGO Scientific Collaboration, Virgo Collaboration, Fermi Gamma-Ray Burst Monitor, INTEGRAL

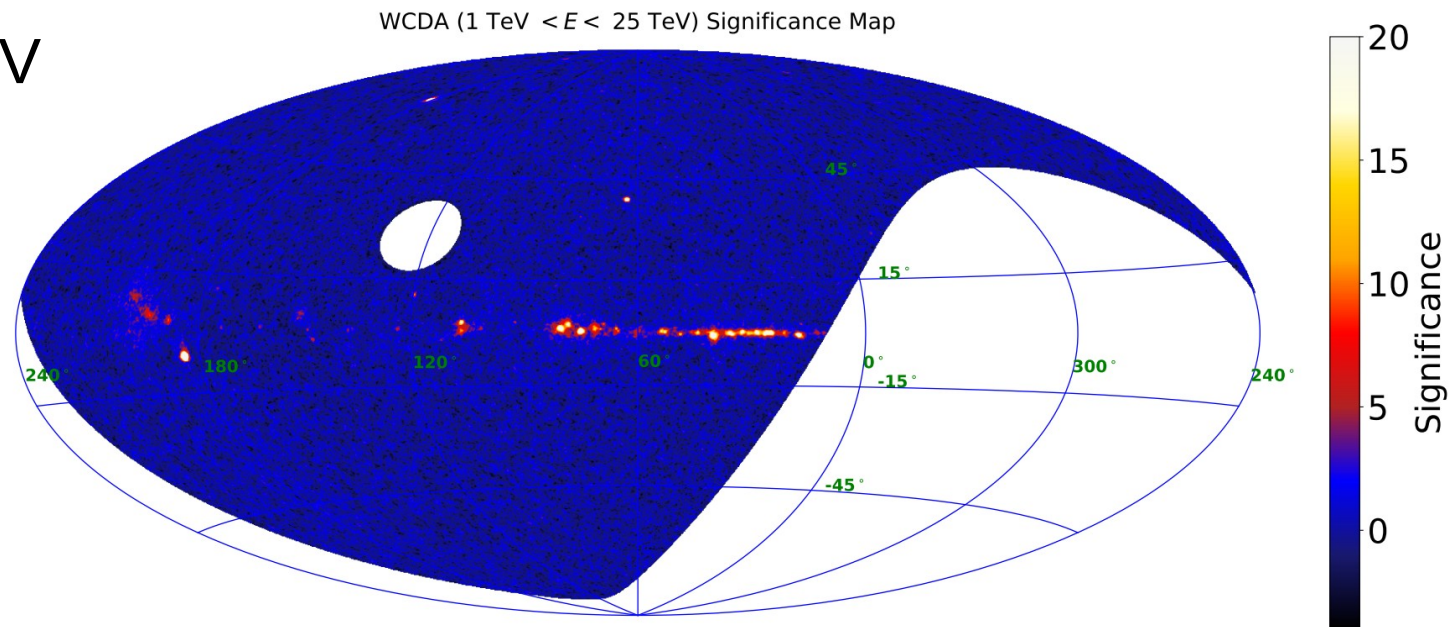
The Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20

> 100 TeV gamm-ray LHAASO

HIGH ENERGY
WIDE-FIELD OF VIEW

Sources by LHAASO

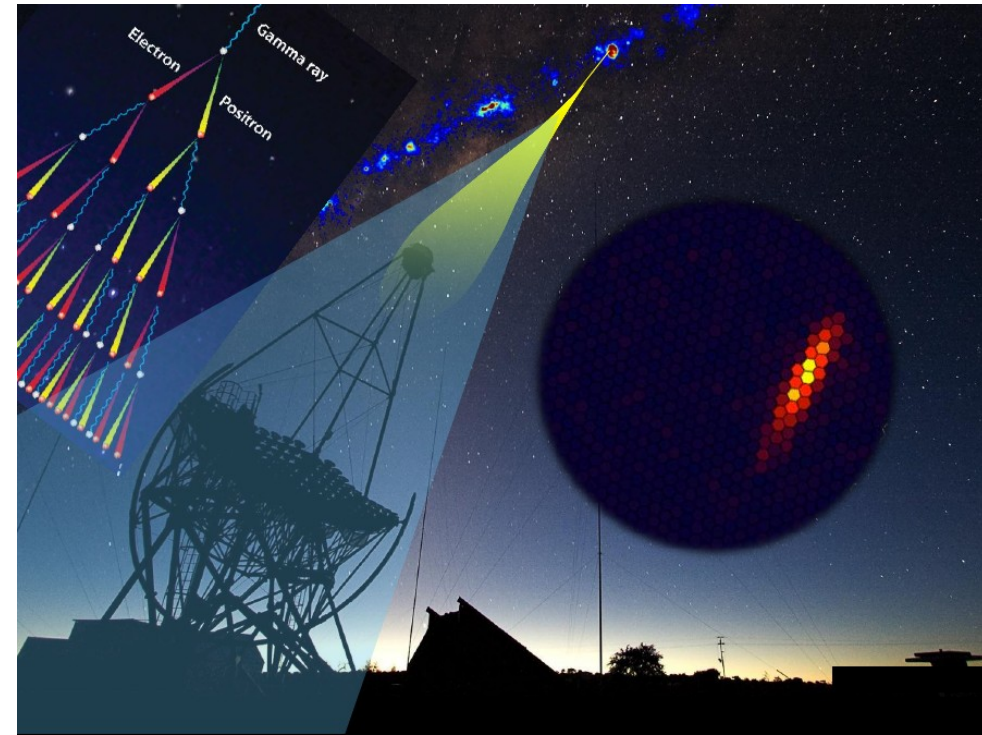
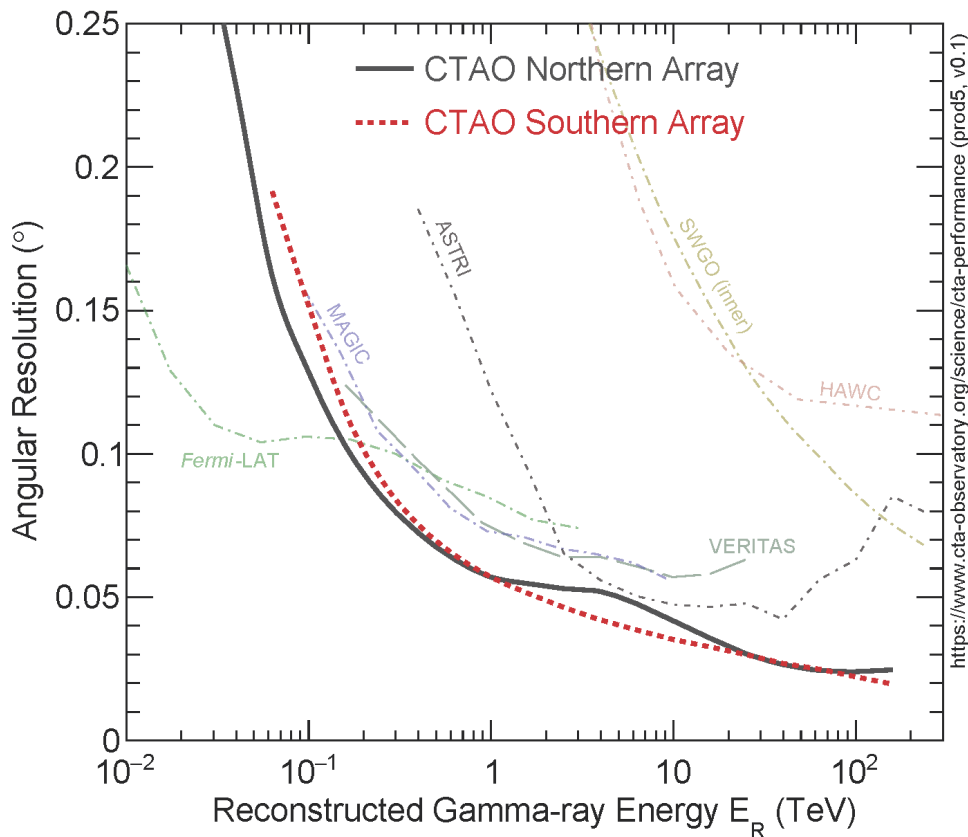
- Observed 90
- Discovered 32 (TeV)
- 43 above 100 TeV
- 7 “dark” sources



GeV - TeV gamma-ray



Wide energy range
Improved angular resolution
Precision measurements



CTA observation modes

very deep field



deep field



deep field



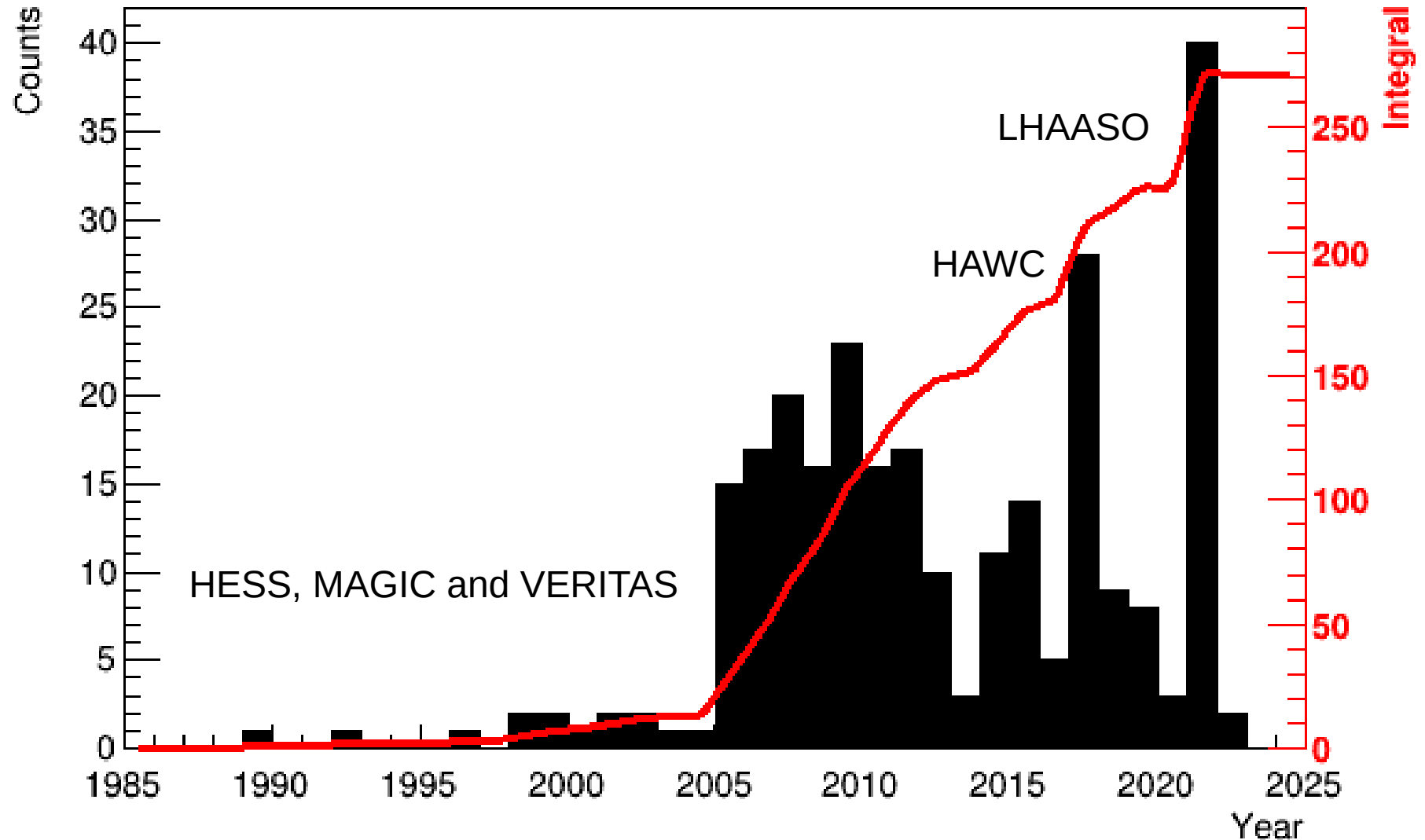
monitoring



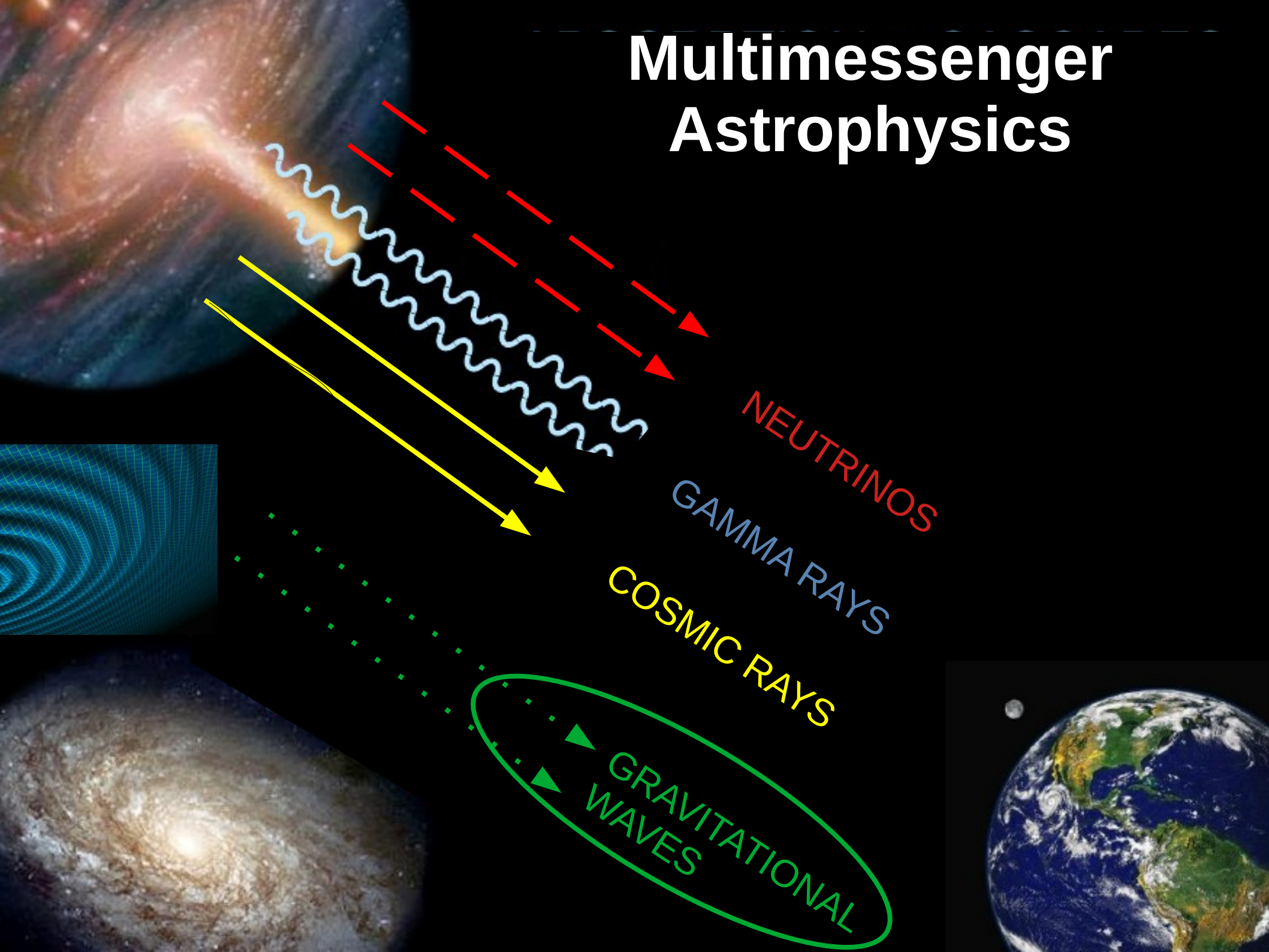
survey mode



CTAO will detect over 1000 TeV-sources



Multimessenger Astrophysics



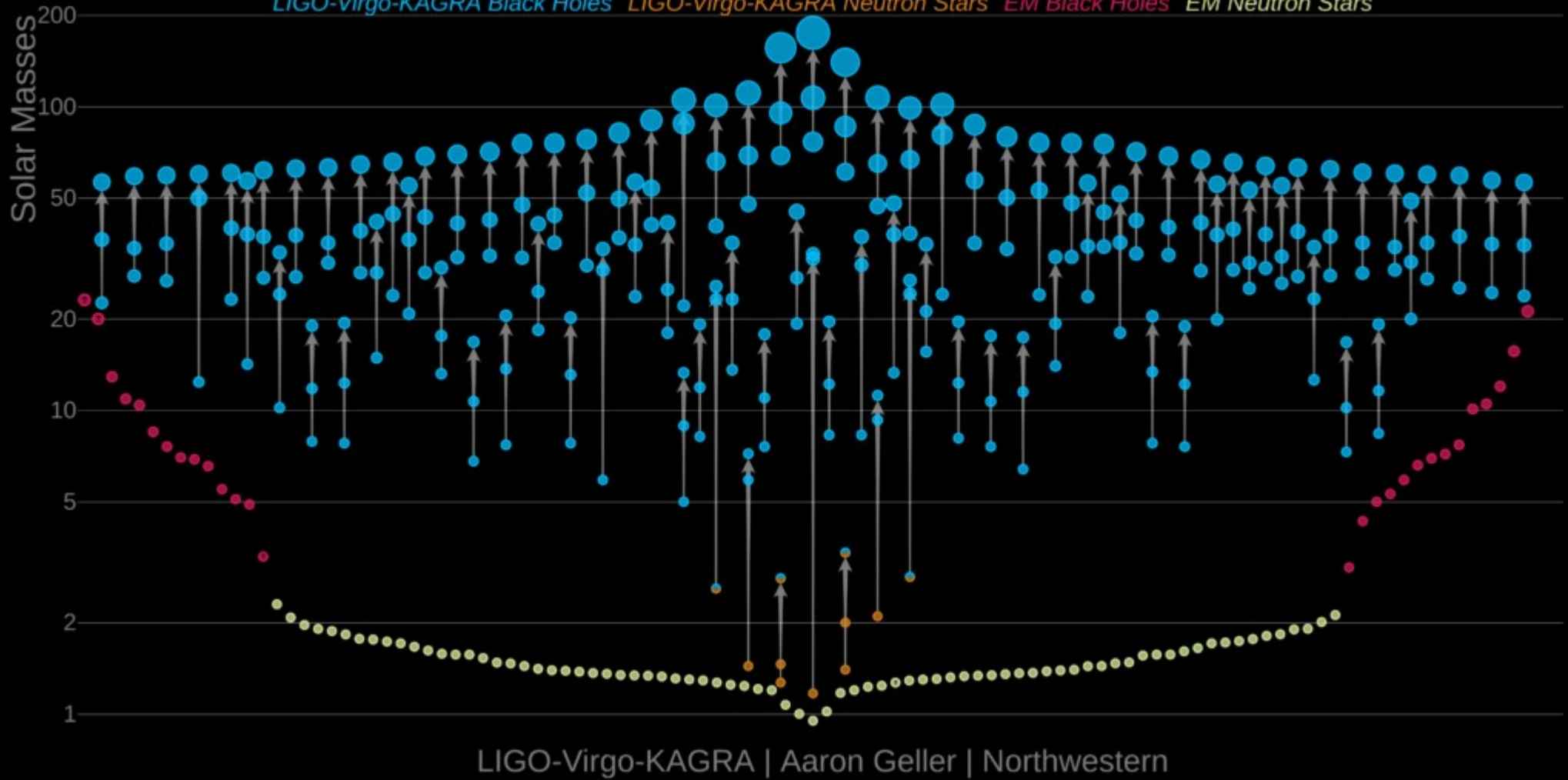
LIGO-Virgo-KAGRA

Nicolas Arnaud (ICHEP 2024)

Gravitational wave events

Masses in the Stellar Graveyard

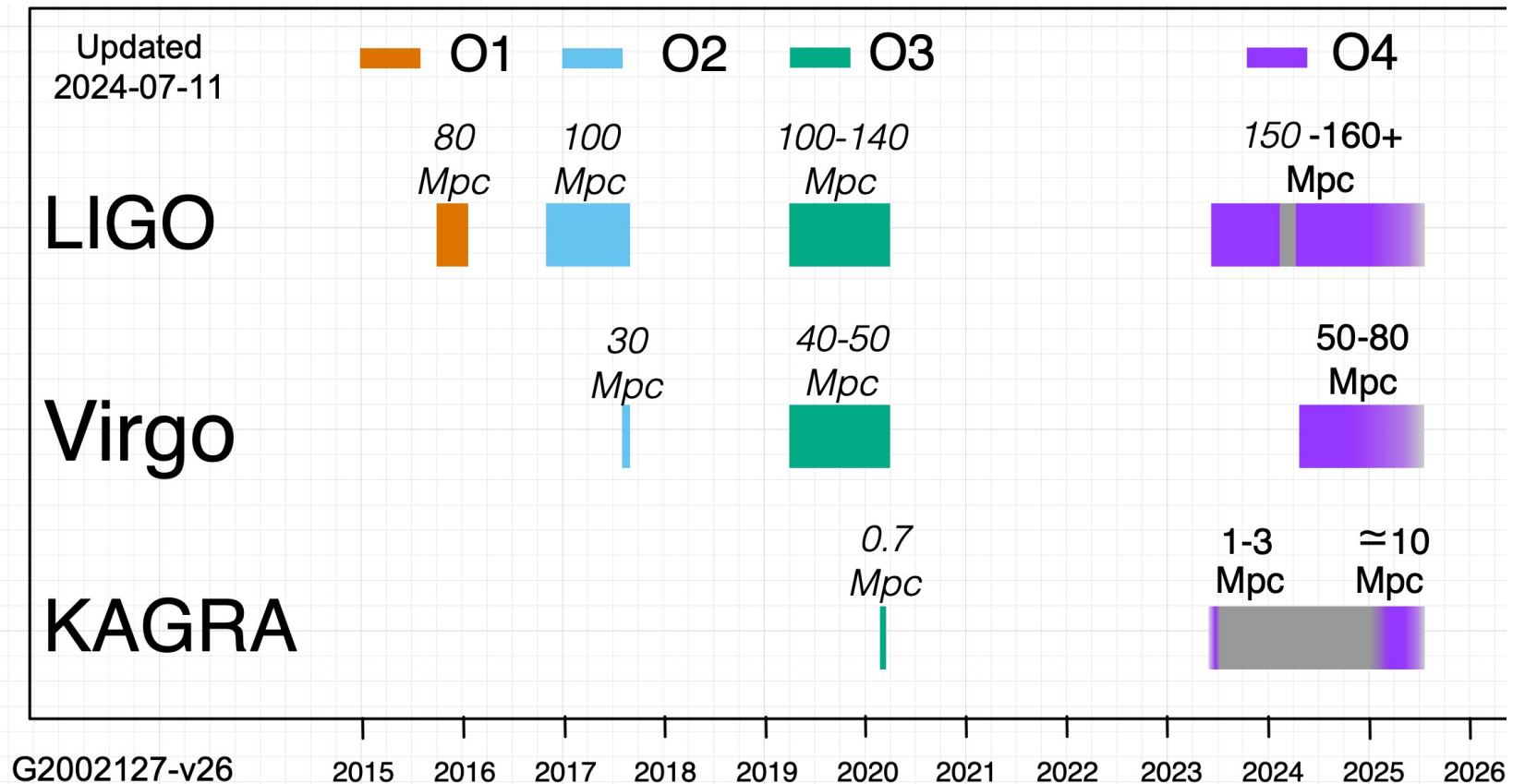
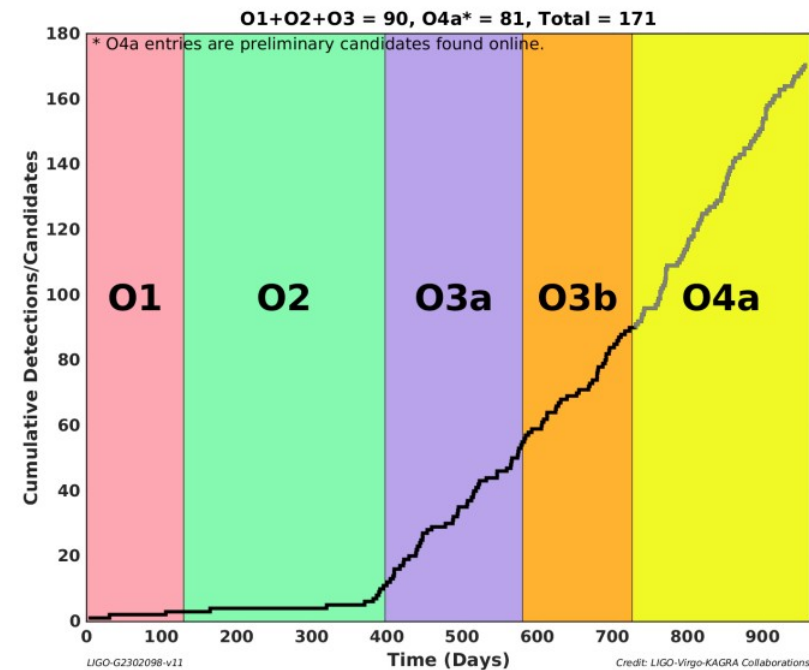
LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



LIGO-Virgo-KAGRA

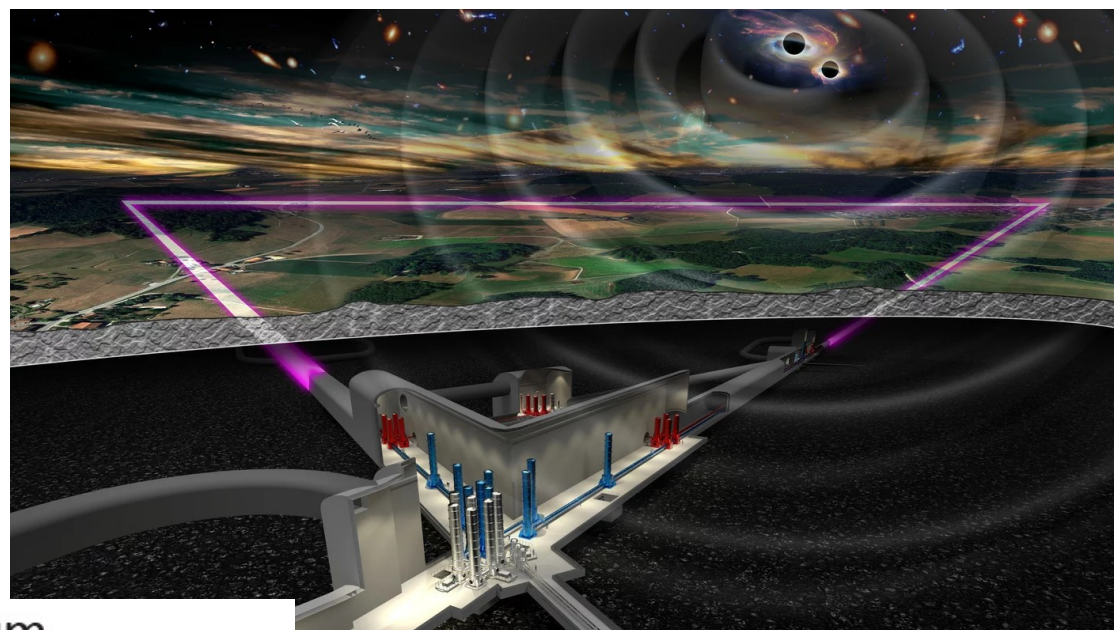
Nicolas Arnaud (ICHEP 2024)

<https://observing.docs.ligo.org/plan/>



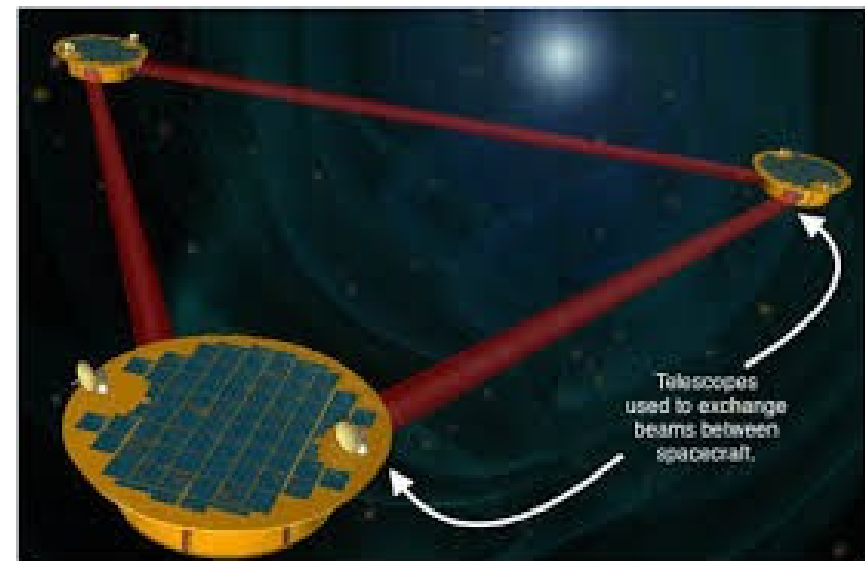
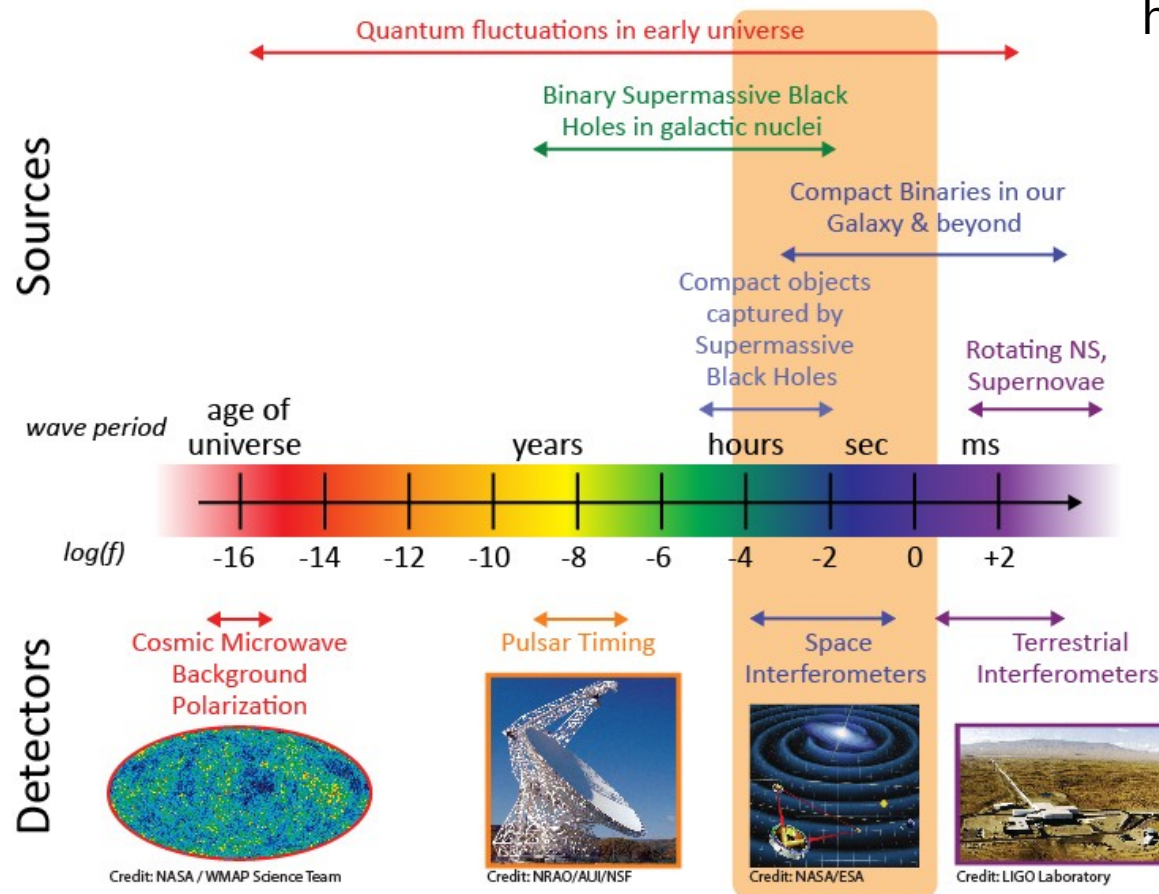
Future GW: Einstein Telescope LISA Telescope

<https://lisa.nasa.gov/>



<https://www.aei.mpg.de/einsteintelelescope>

The Gravitational Wave Spectrum

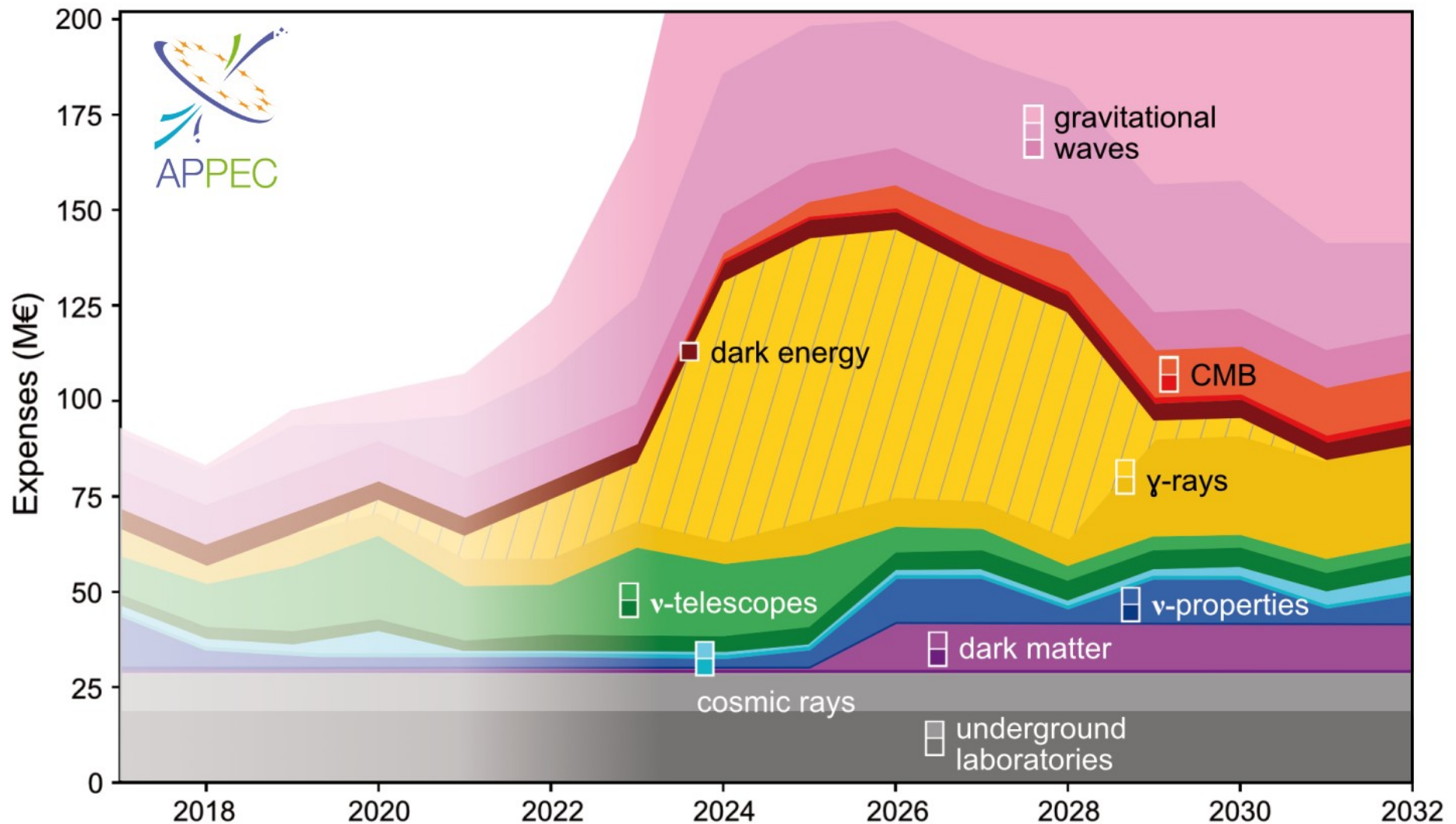


USA 2020 Decadal Survey Priorities:

- Pathways to habitable worlds
- New windows on the dynamic universe
 - Probe the nature of black holes and neutron stars - and the explosive events that gave rise to them - and understand what happened in the earliest moments in the birth of the universe.
- Drivers of galaxy growth

The report says the highest-priority sustaining activity for NASA is the space-based time-domain and **multi-messenger program** - comprised of small- and medium-scale missions. NASA should also pursue a new line of probe missions.

European Astroparticle Physics Strategy Recommendation



Take away message

Multimessenger Astrophysics

- Probes the highest energetic phenomena
- Highlights physics of the four forces
- Searches for the dark components
- Teaches acceleration mechanisms
- Tests of our current knowledge

Multi-bright and multi-challenge future !