

Deep-sea telescopes: a new window to our Universe

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APC PhD Seminar

January 23rd 2025

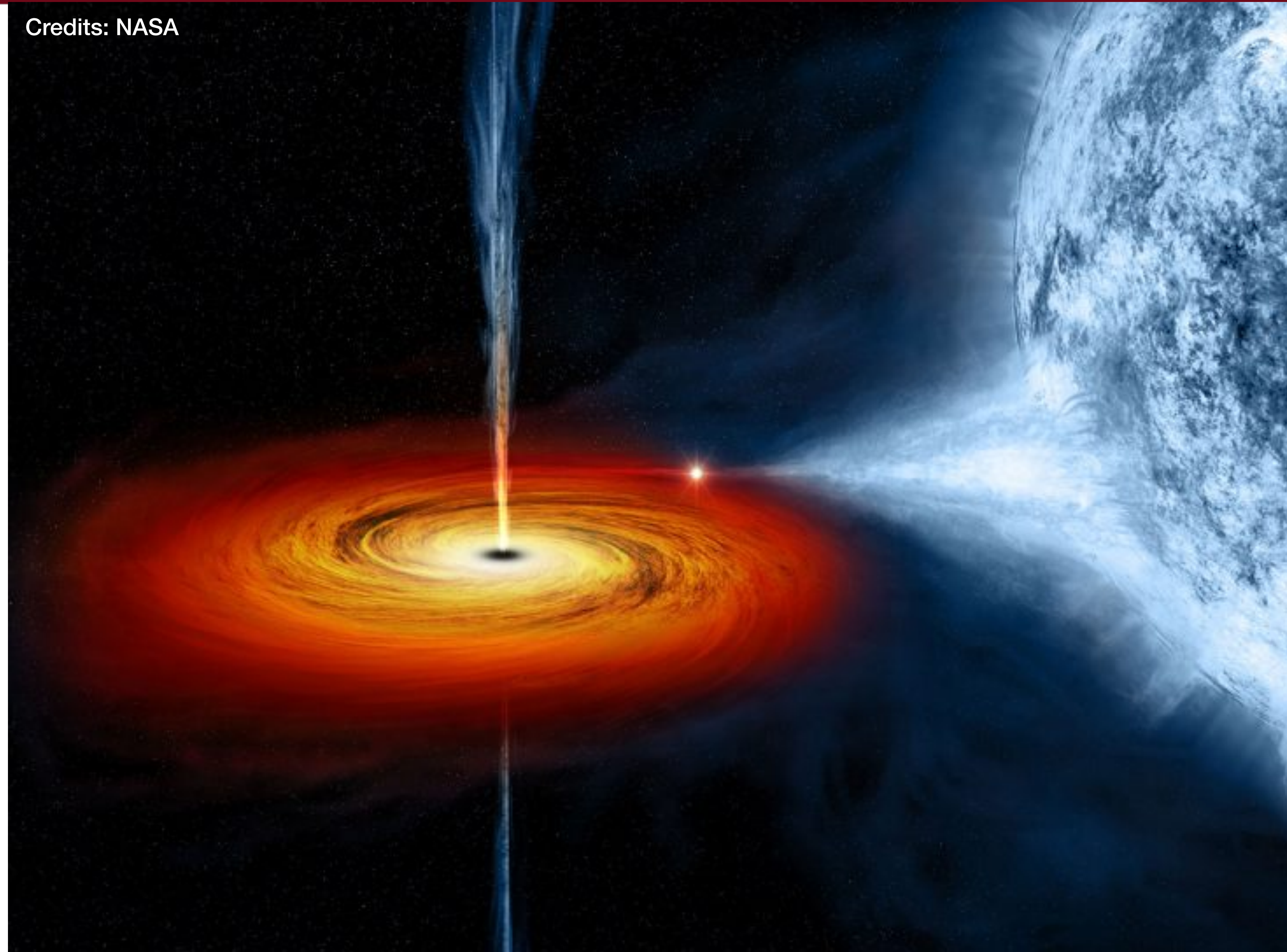
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Outline

- **Introduction**
- **Classical astronomy**
- **Neutrinos**
- **Multi-messenger astronomy**
- **Neutrino telescopes**
- **The KM3NeT Collaboration**

Credits: NASA

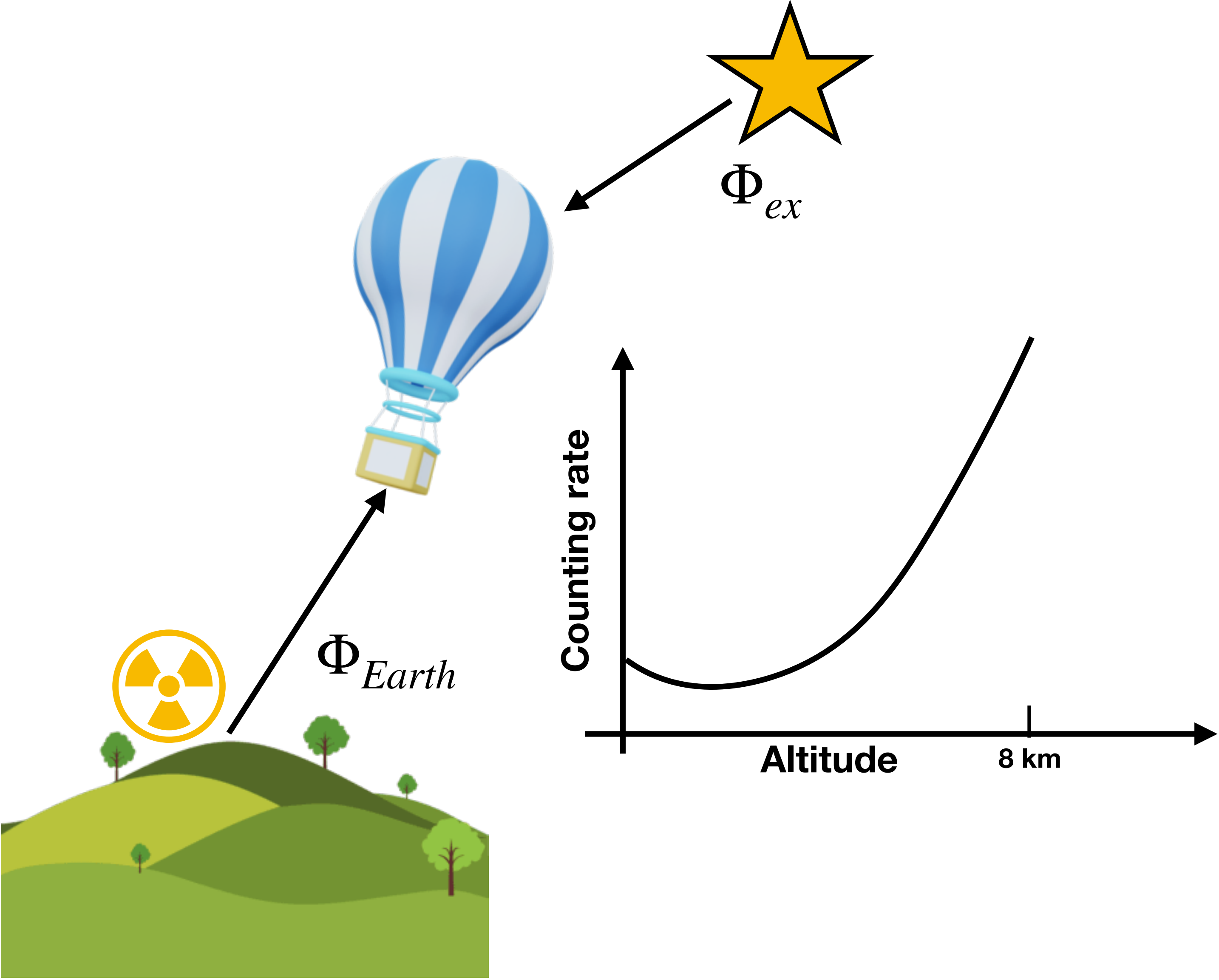


Introduction



Victor Franz Hess

Physics Nobel Prize 1936



Introduction

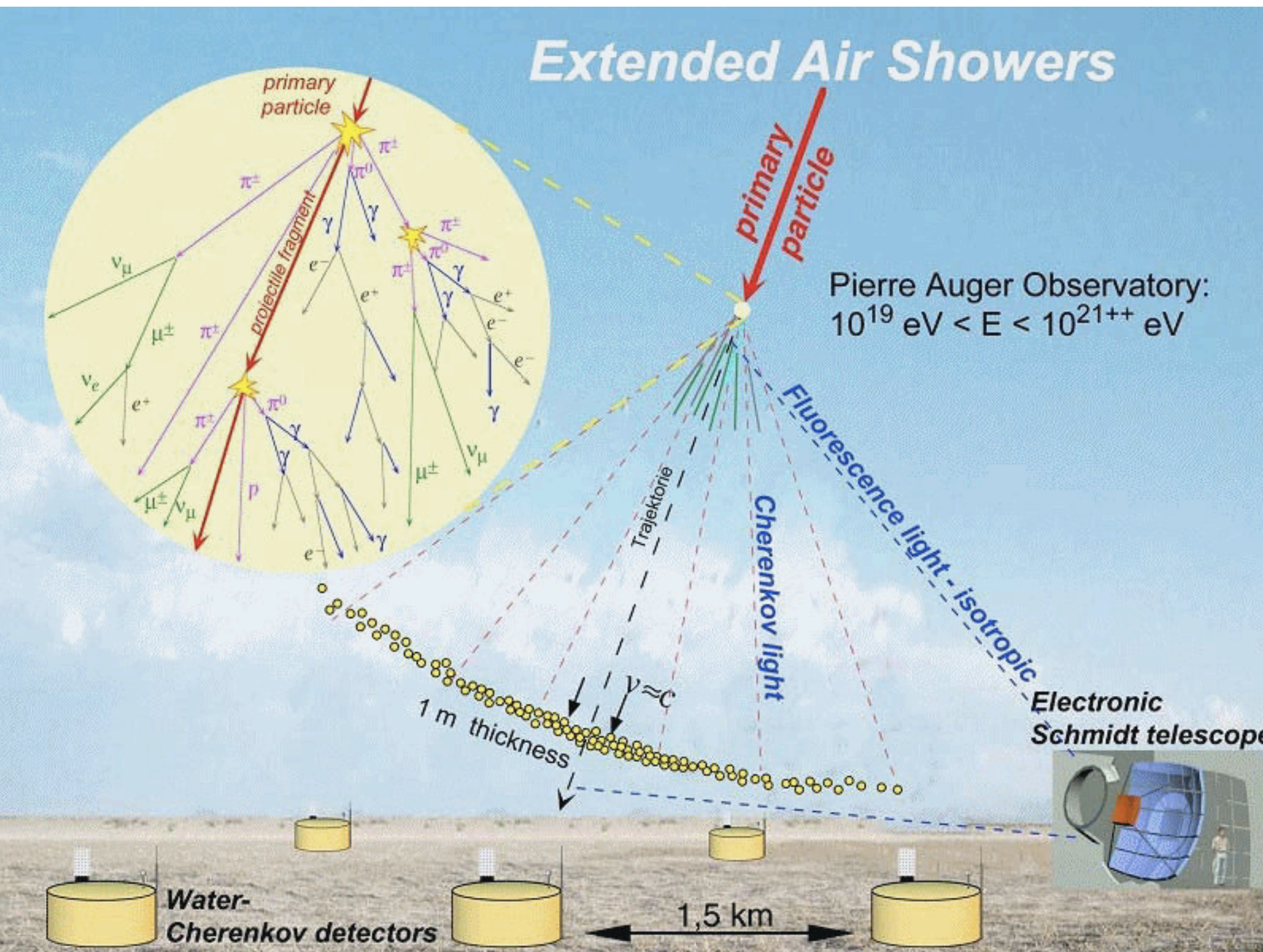
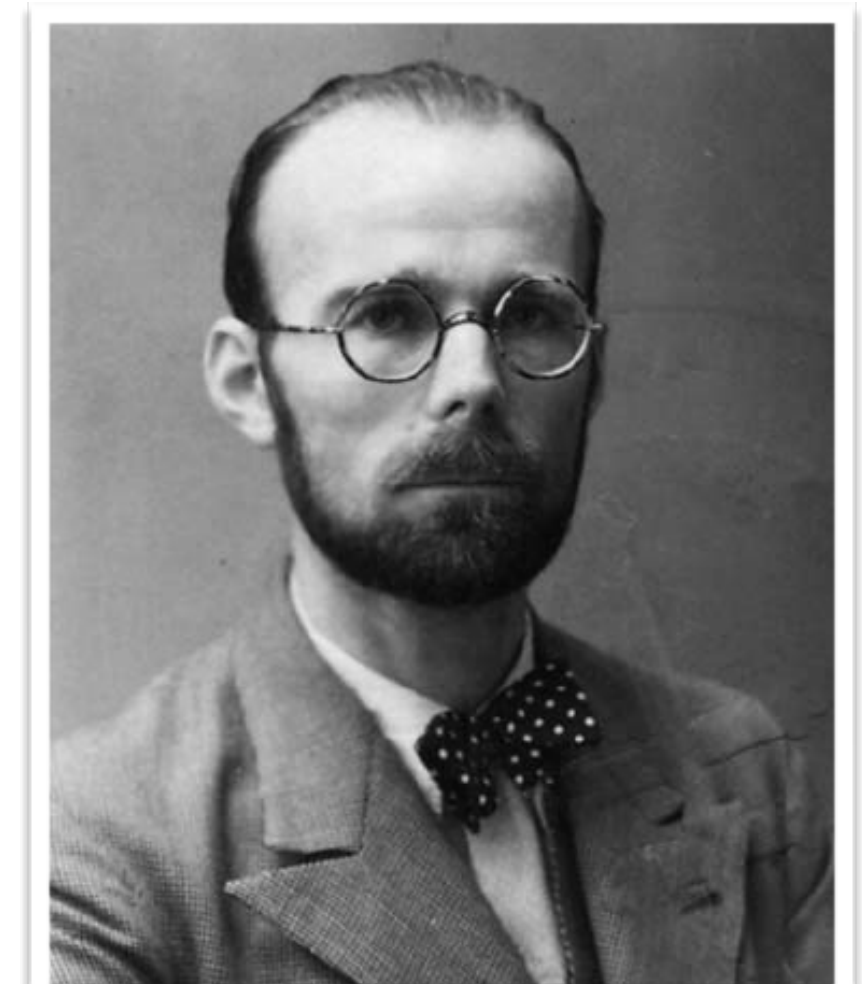


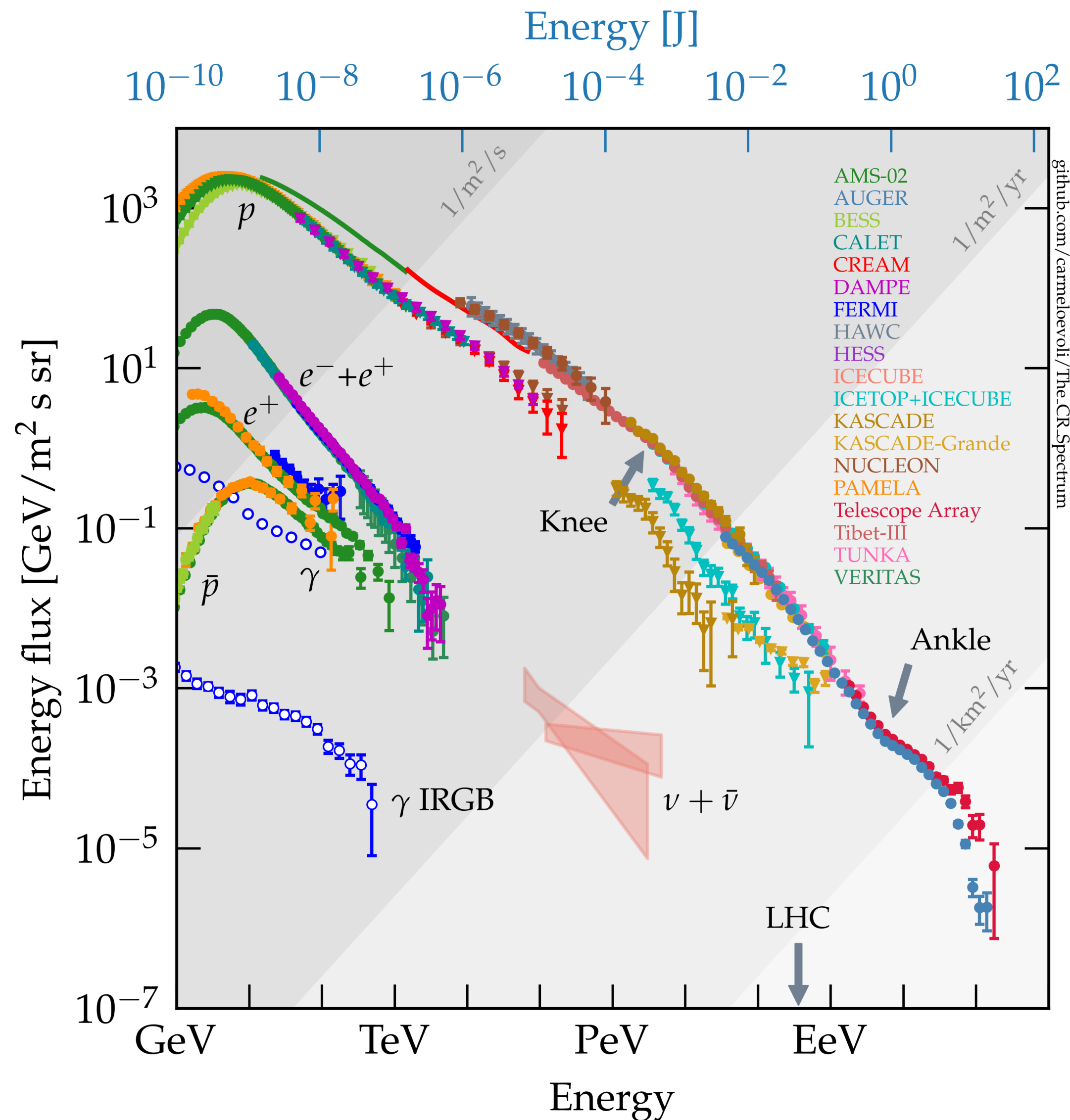
Image Credits: Pierre Auger Observatory

- Inelastic collisions of energetic particles in the atmosphere produce a cascade of secondary particles (EAS)
- Main components:
 - electro-magnetic cascades of electrons, positrons and gamma-rays
 - hadronic cascades of mesons and baryon
 - muons
 - neutrinos

1938: Auger discovers extended air showers by coincident measures in ground based arrays



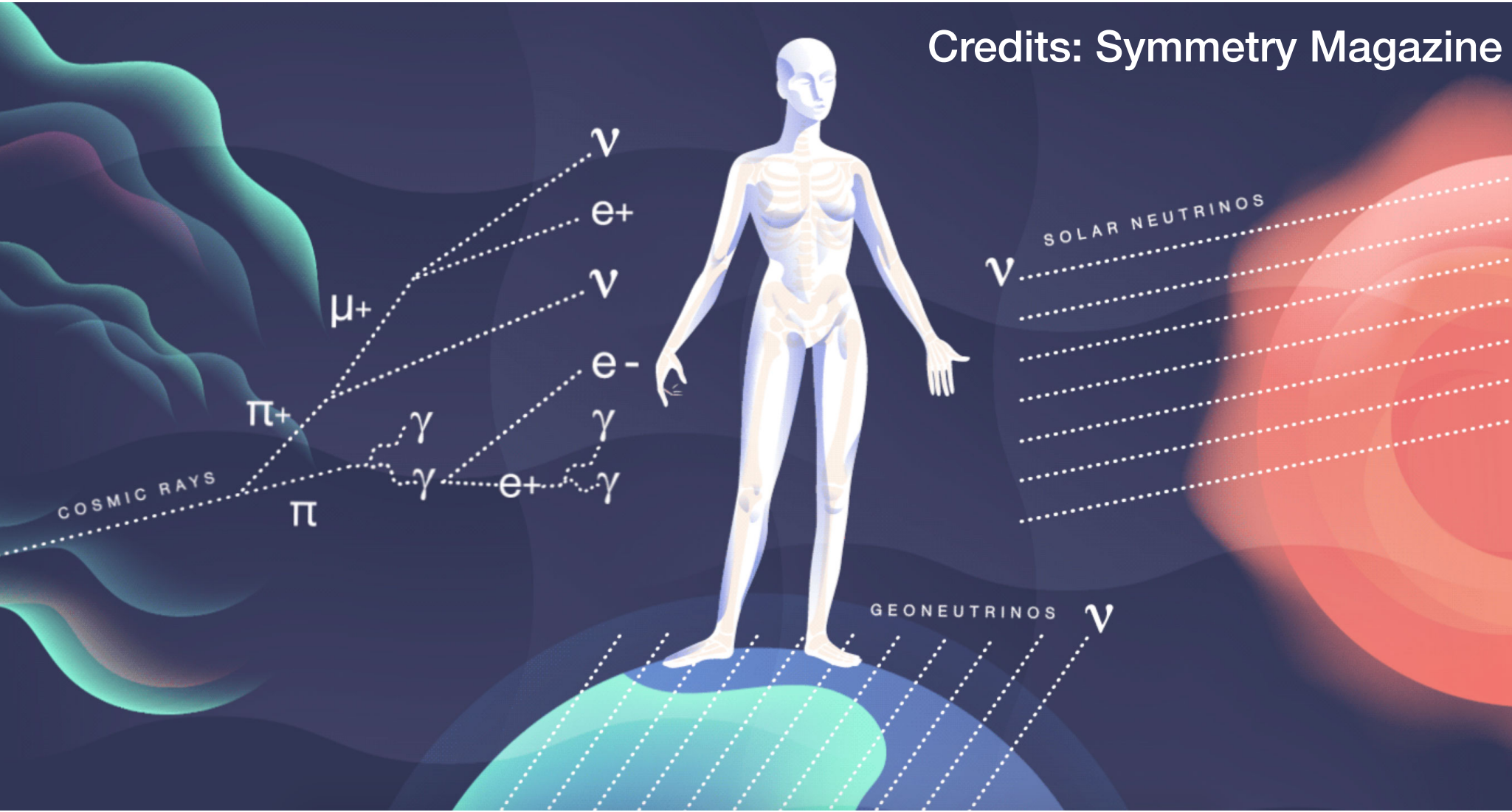
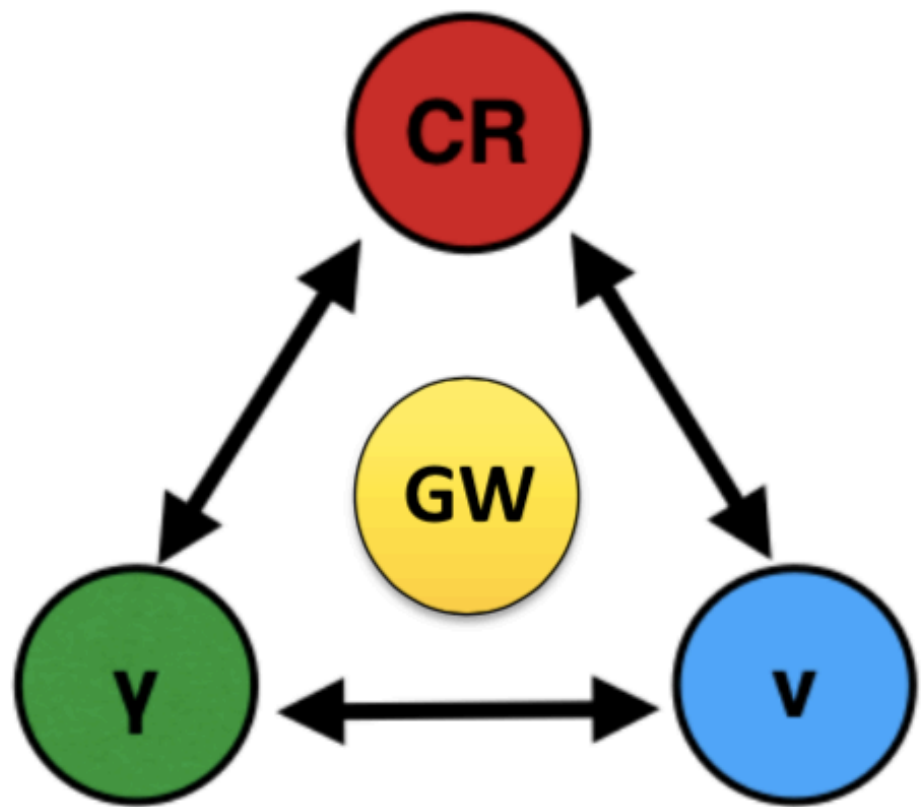
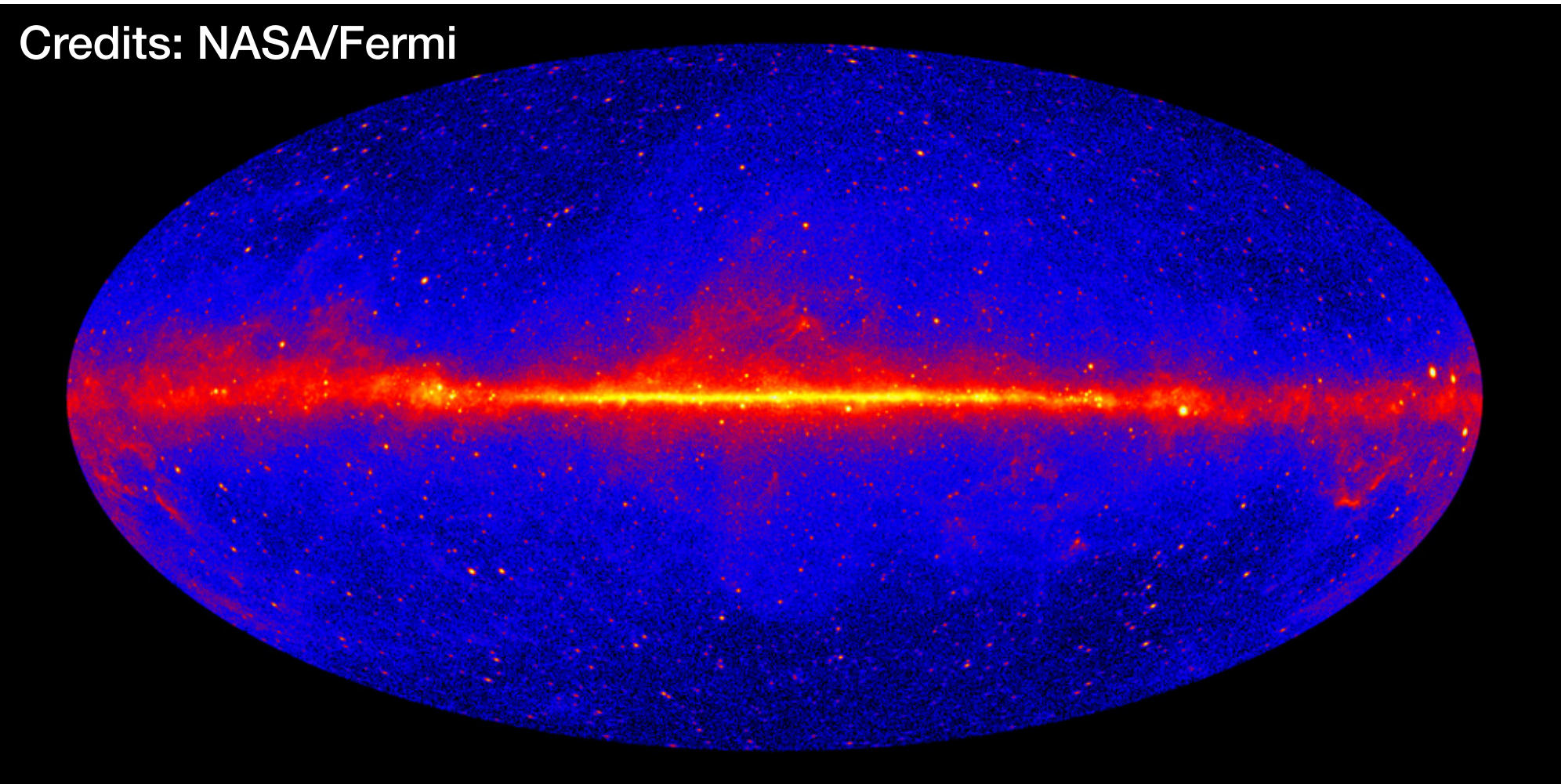
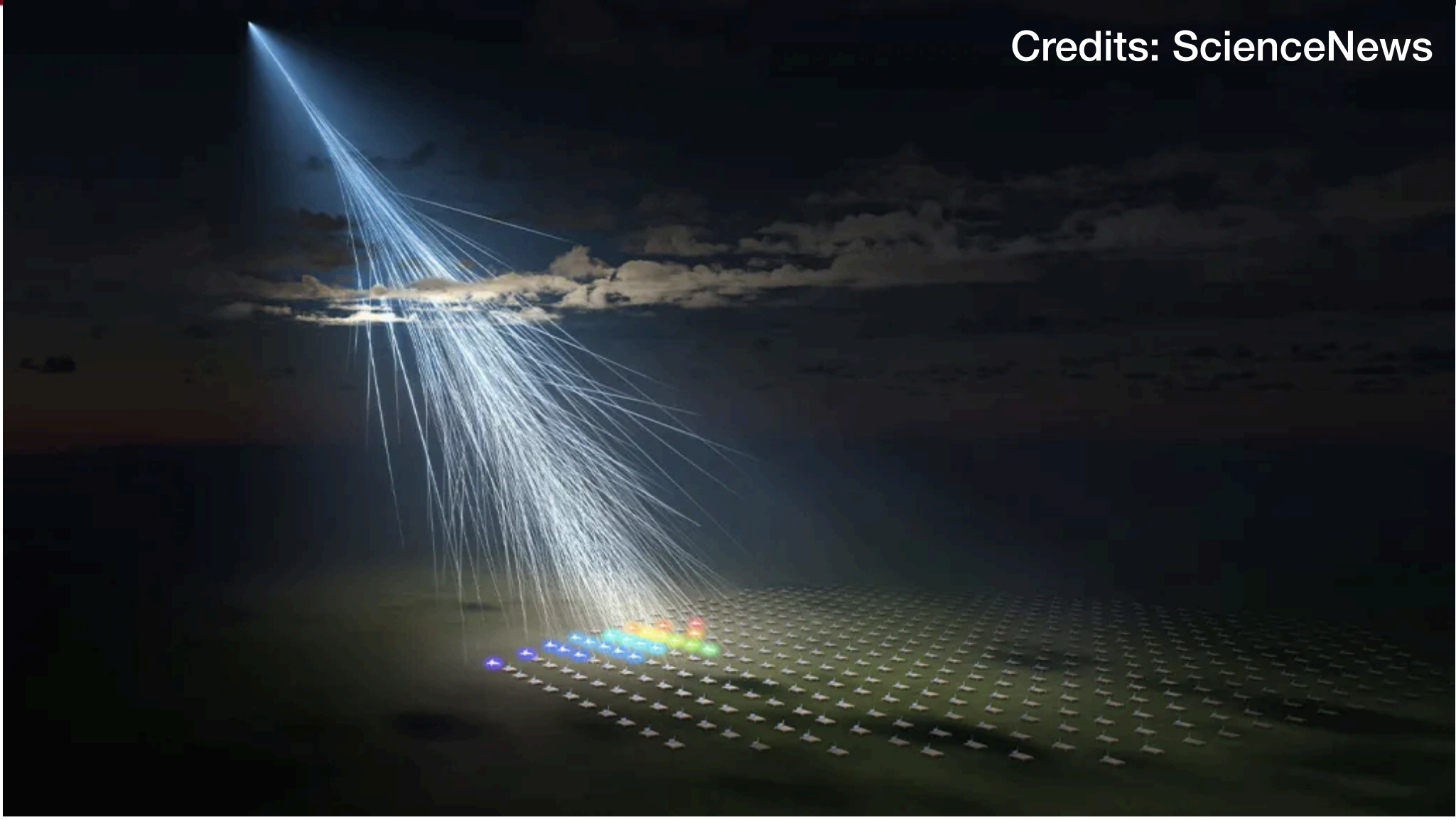
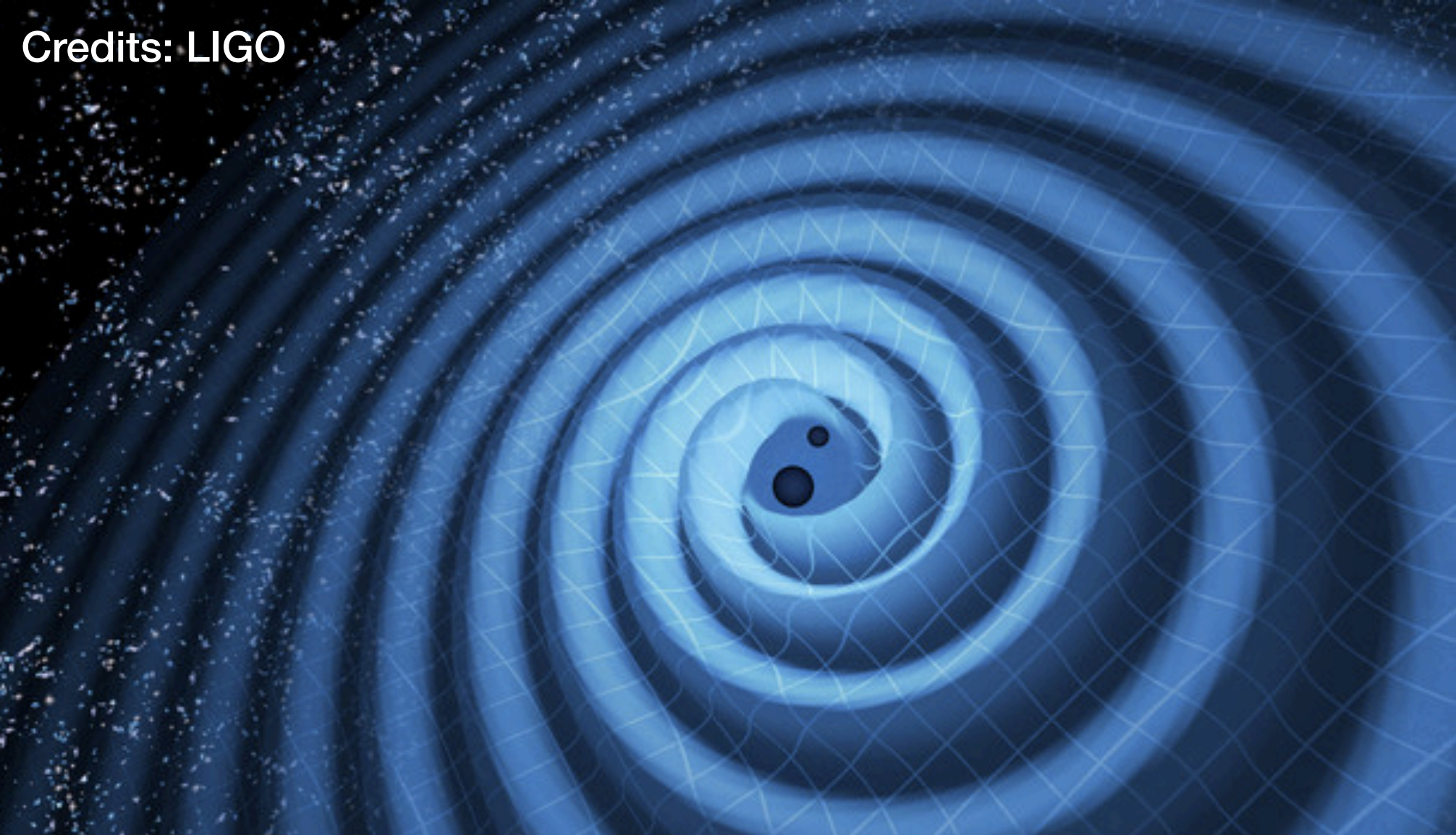
Introduction



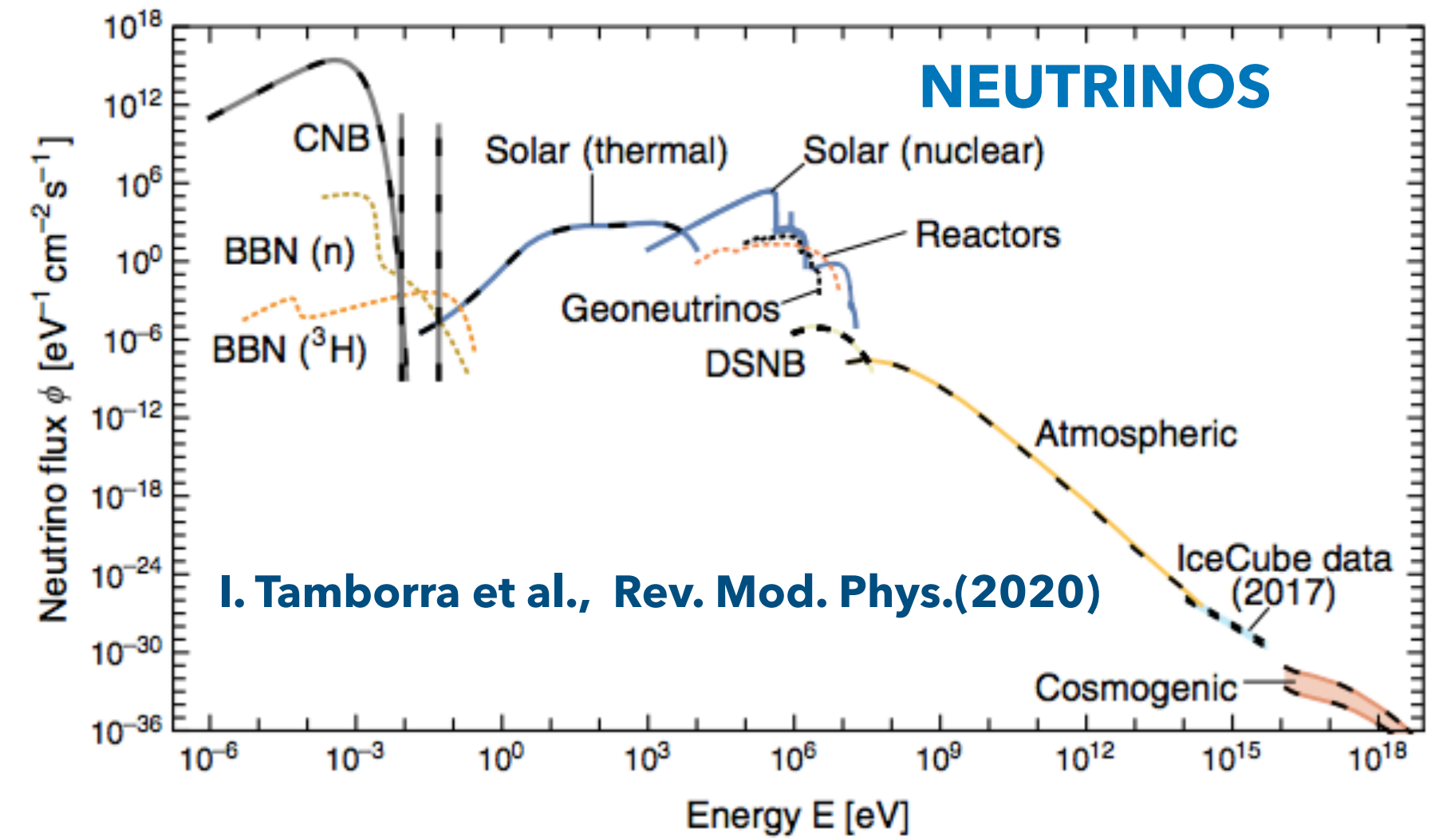
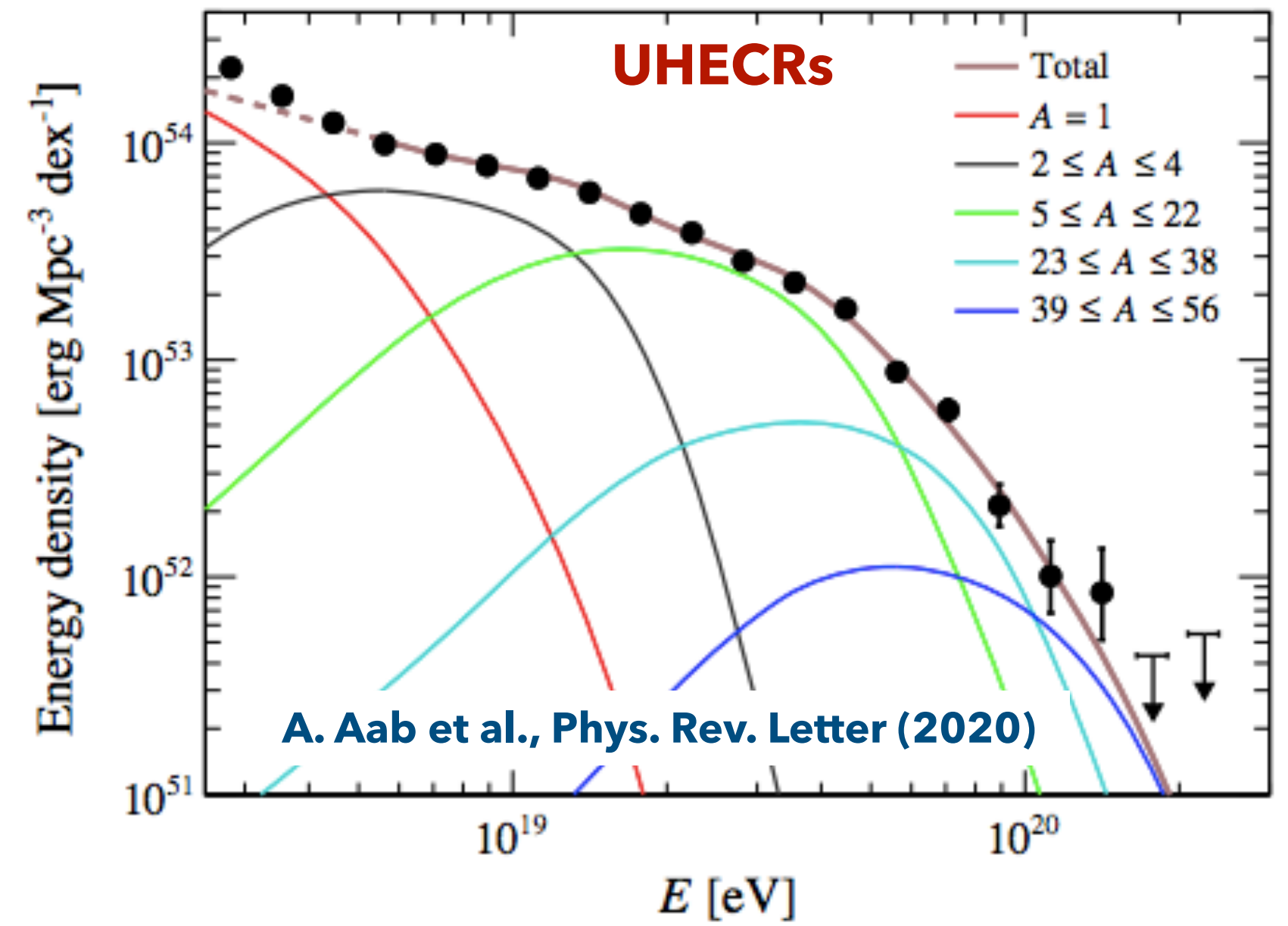
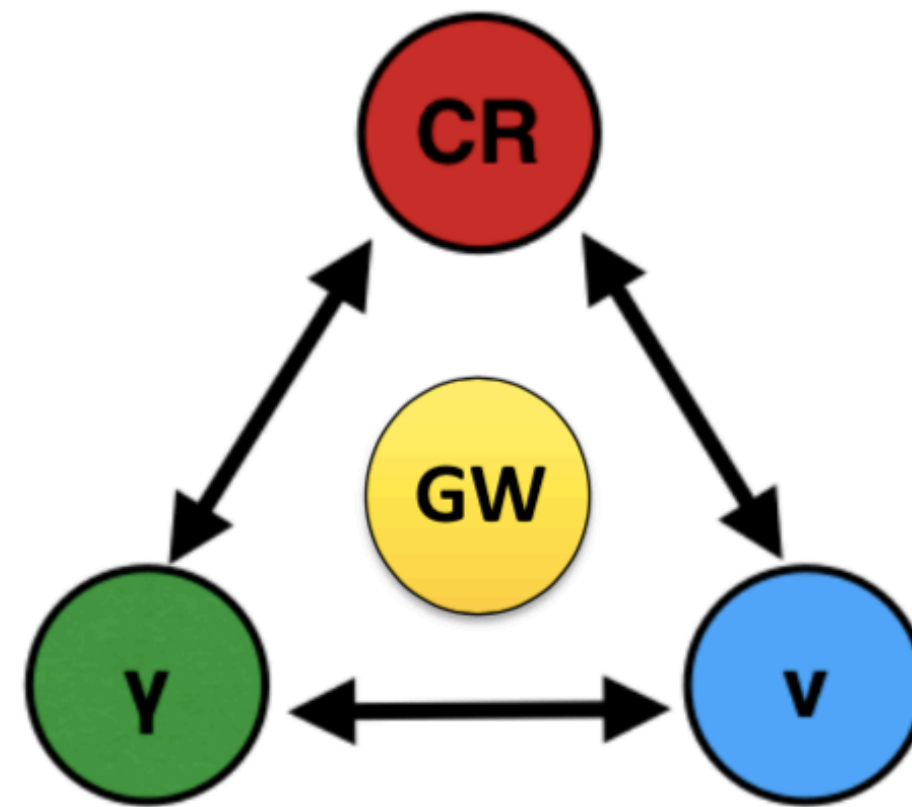
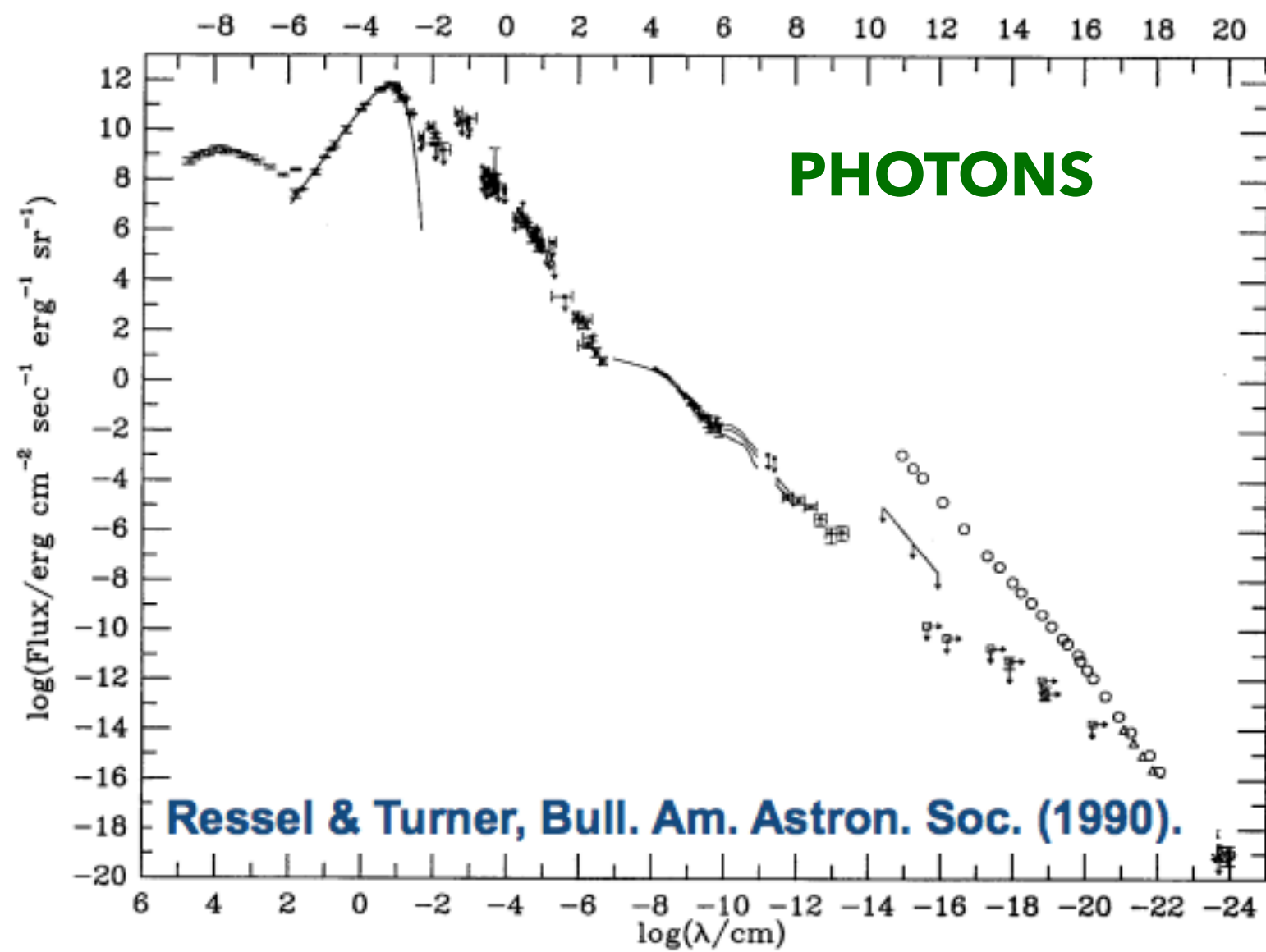
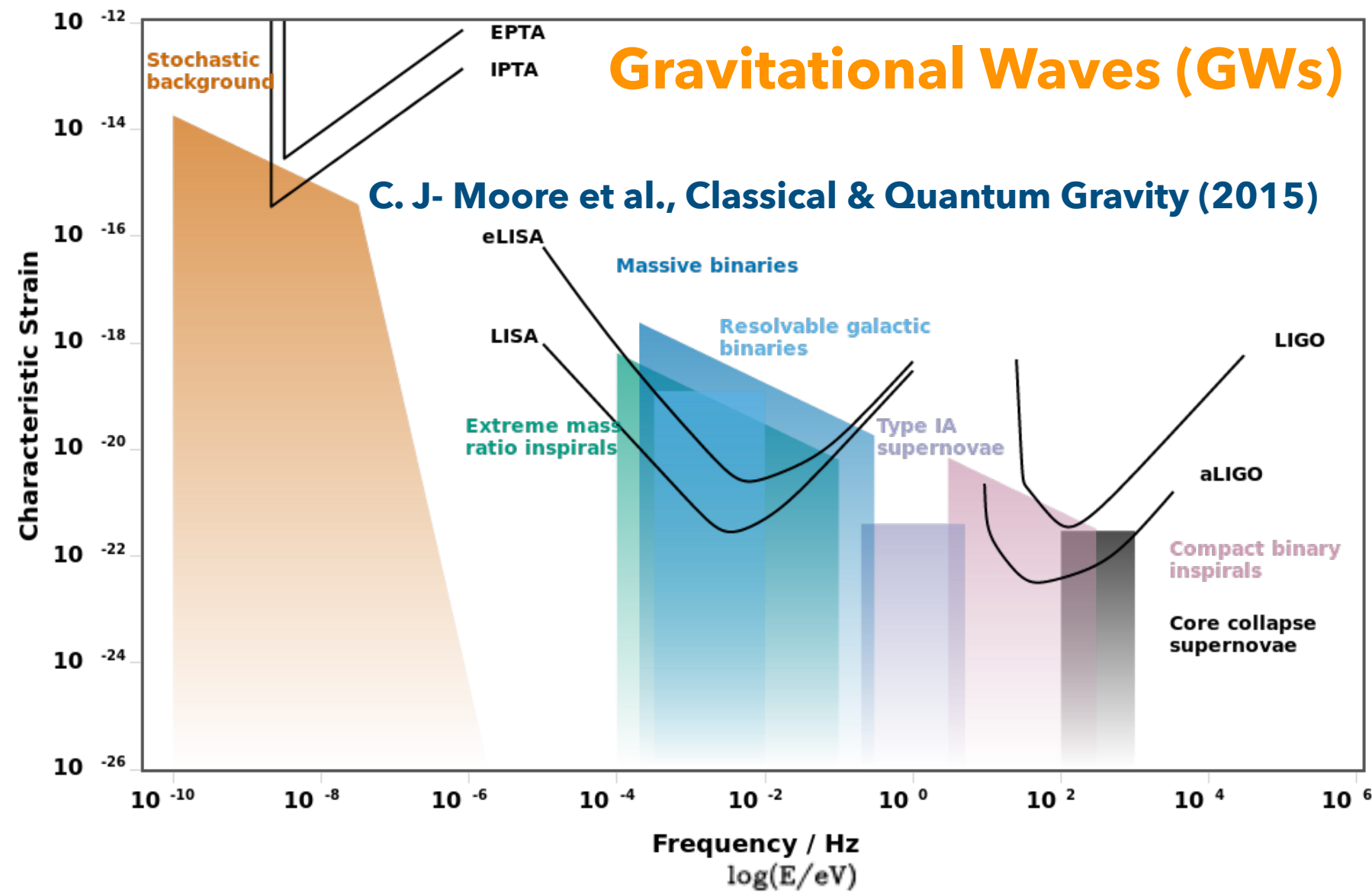
Evoli, C. The Cosmic-Ray Energy Spectrum, 2020

- **Cosmic rays are made up of:**
 - **85 % of protons**
 - **12 % of α particles**
 - **1-2 % of electrons and heavy nuclei**
- **The energy flux extends over at least 12 decades in energy with a corresponding decline in intensity of over more than 10 decades**
- **At high energy (around 10^9 GeV) the Extra-Galactic component start dominating the arrival flux**
- **Beyond the PeV, indirect measurements are necessarily to be performed, exploiting EAS**

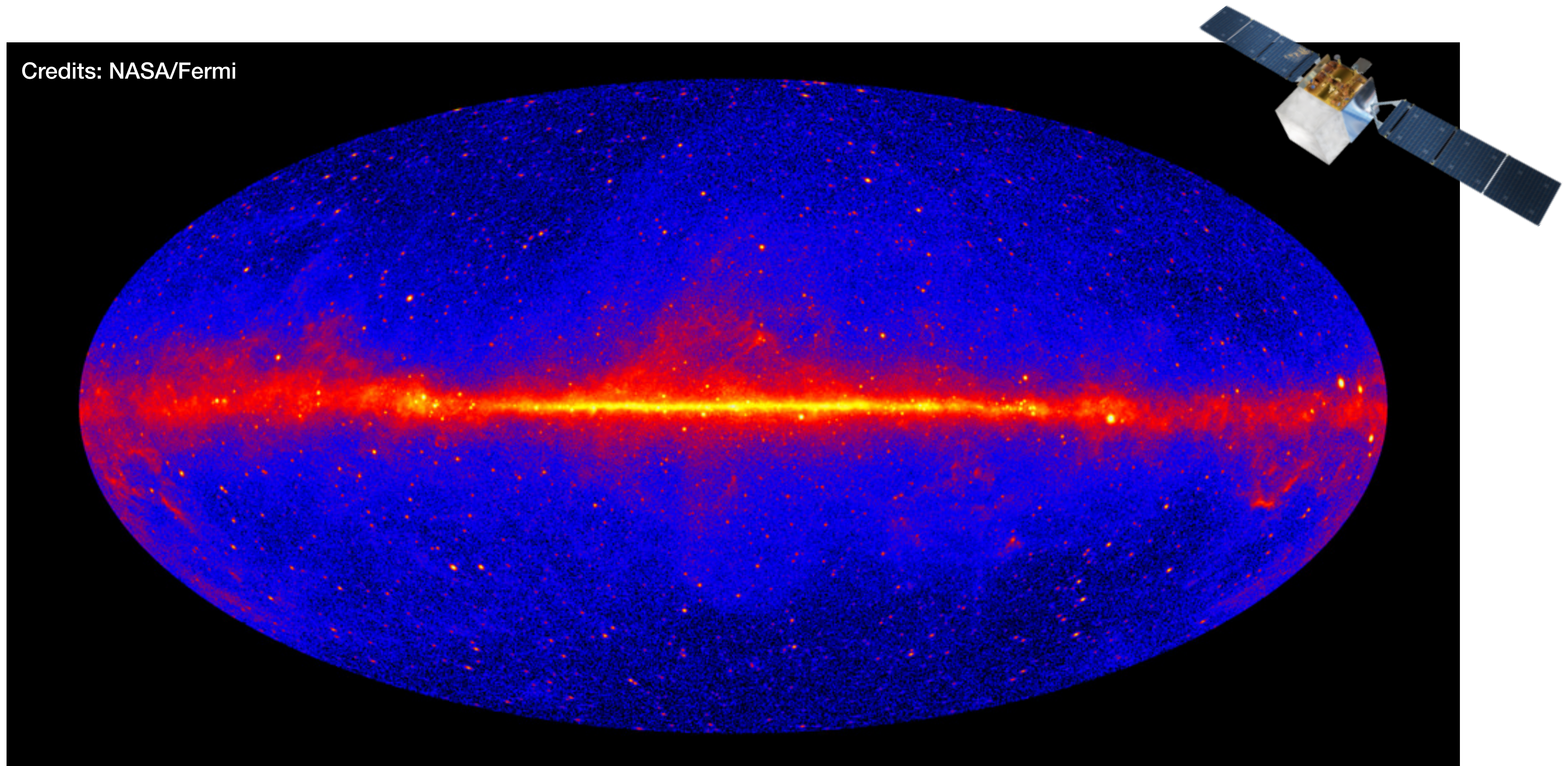
Introduction



Introduction

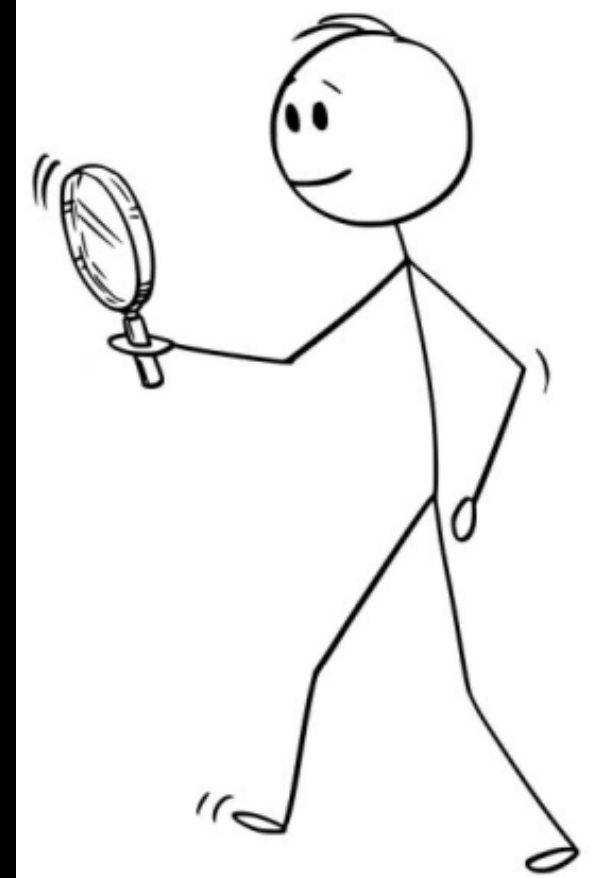
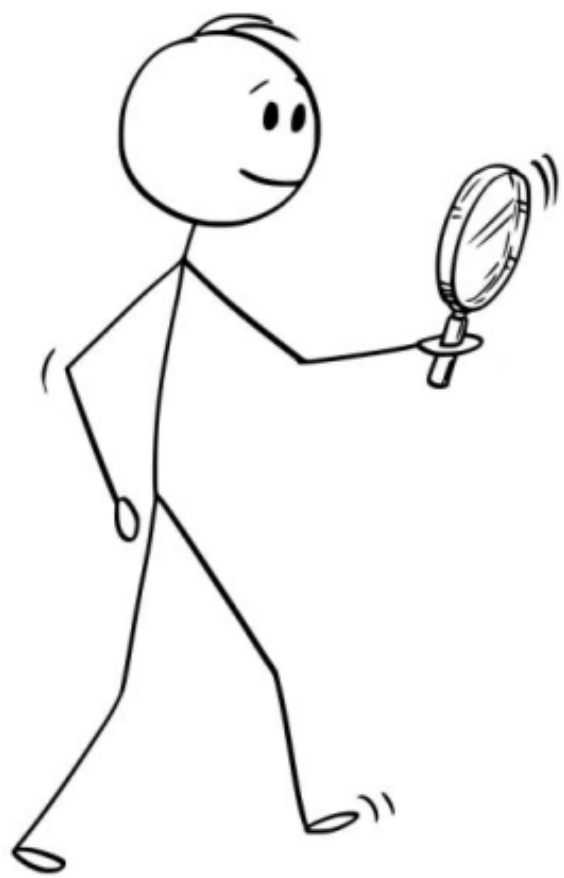
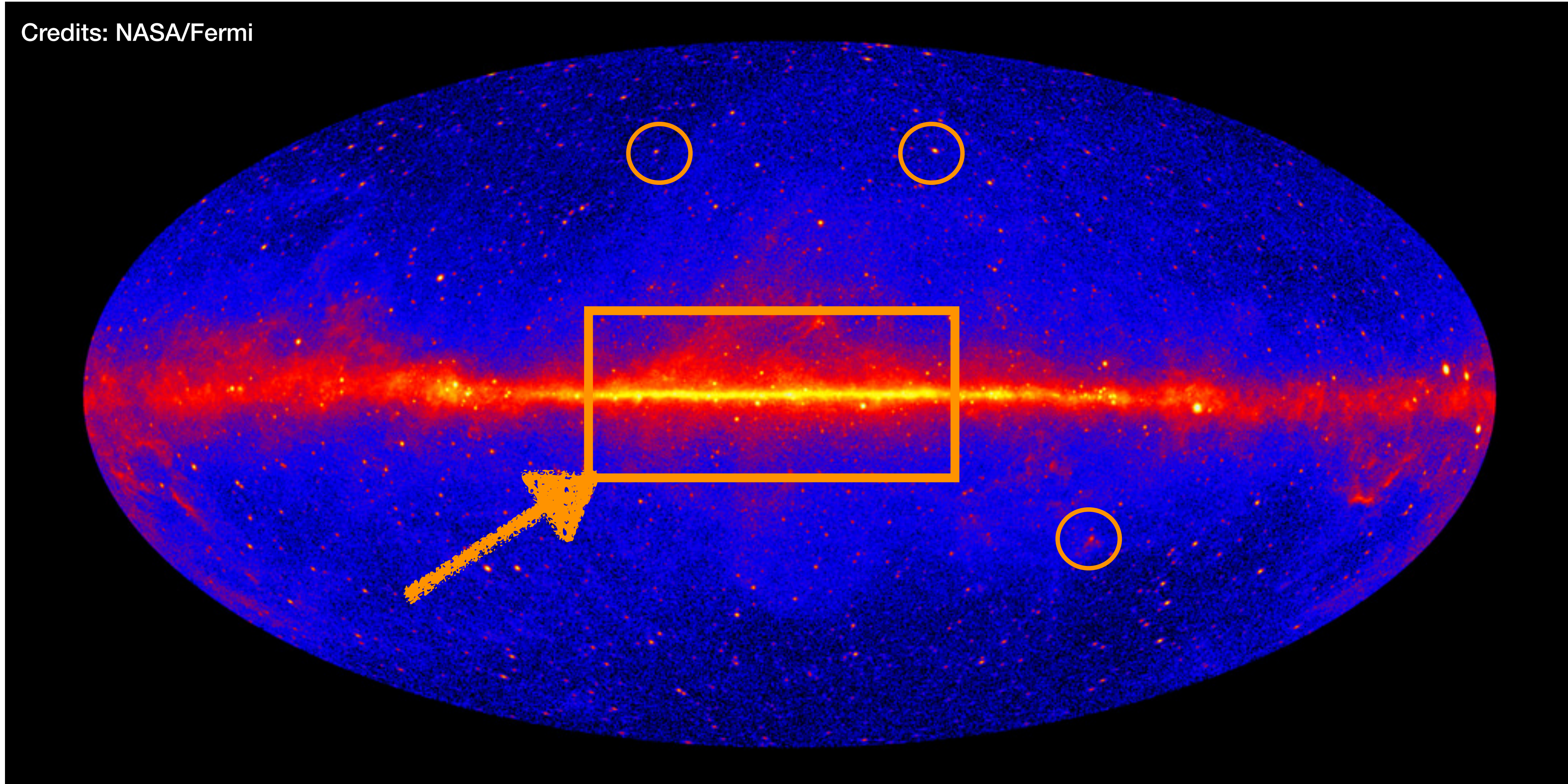


Classical astronomy



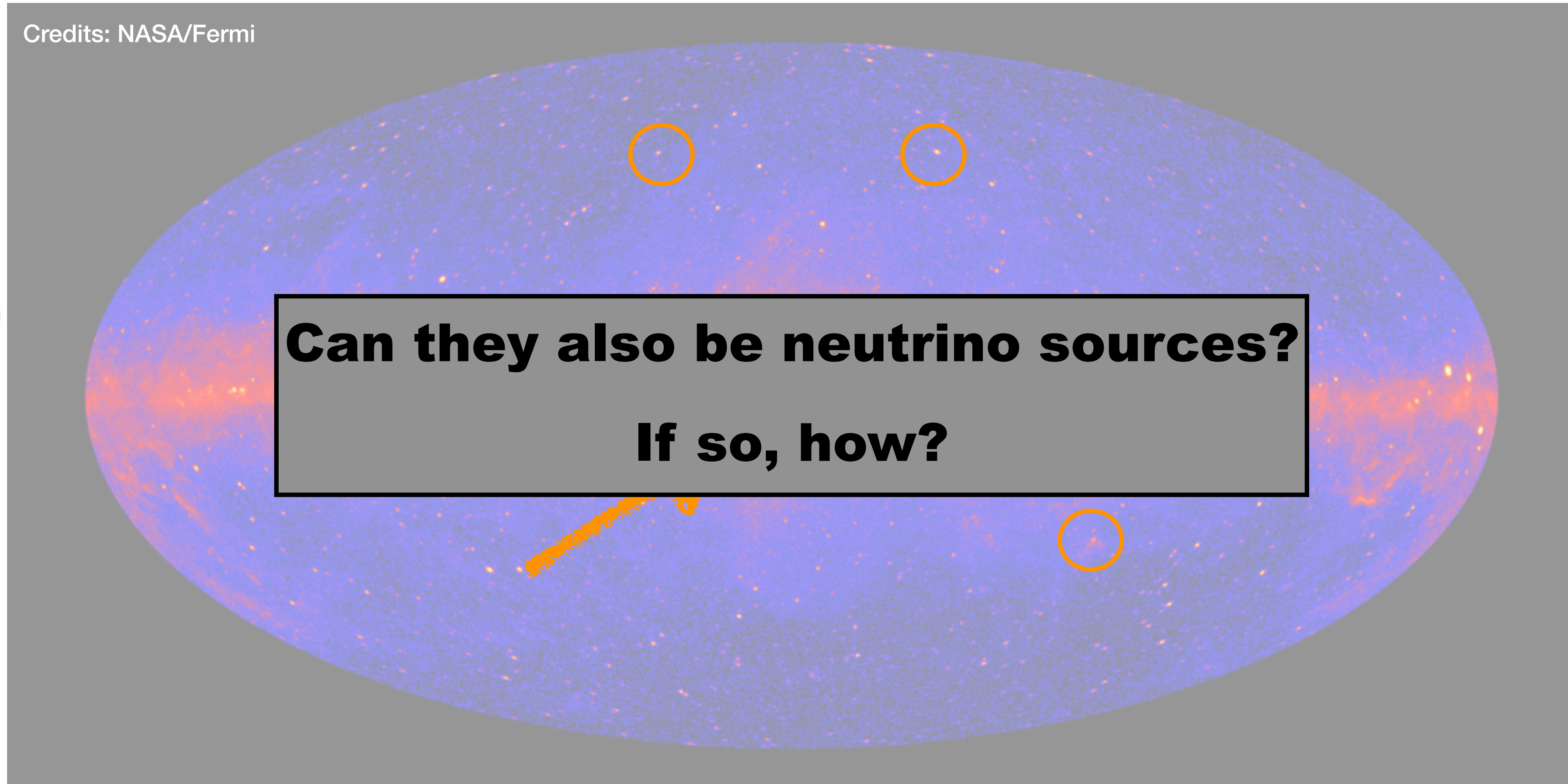
What's there?

Credits: NASA/Fermi



The main question

Credits: NASA/Fermi



**Can they also be neutrino sources?
If so, how?**



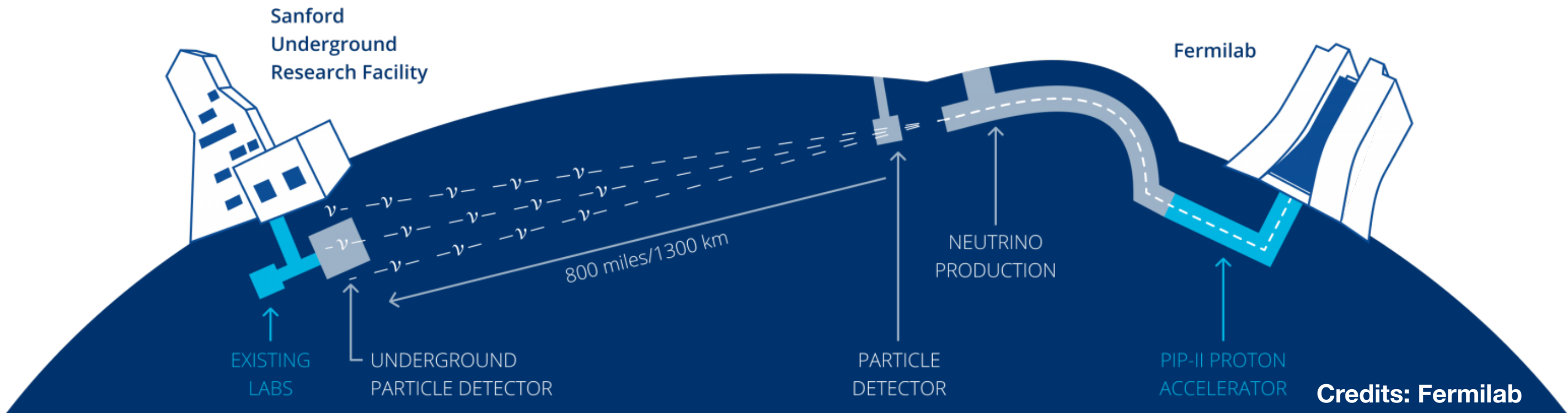
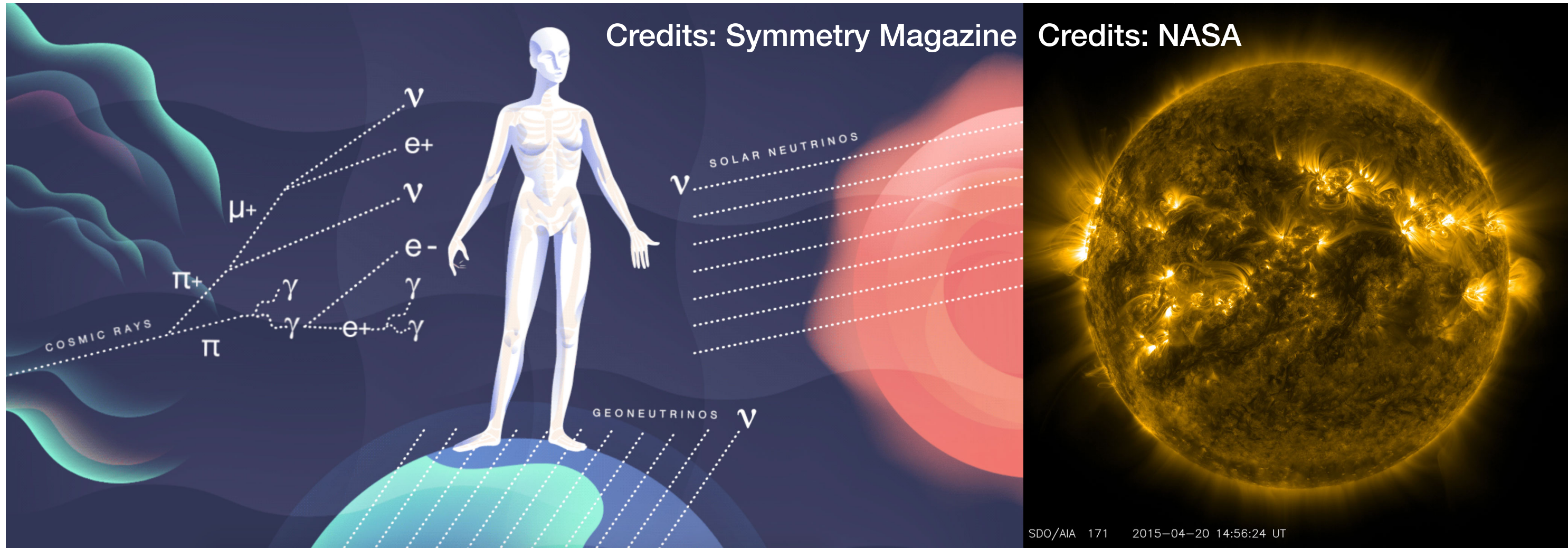
Source of neutrinos

- **Natural**

- **Big Bang**
- **Sun**
- **Earth**
- **Atmosphere**
- **Galactic**
- **Extragalactic**

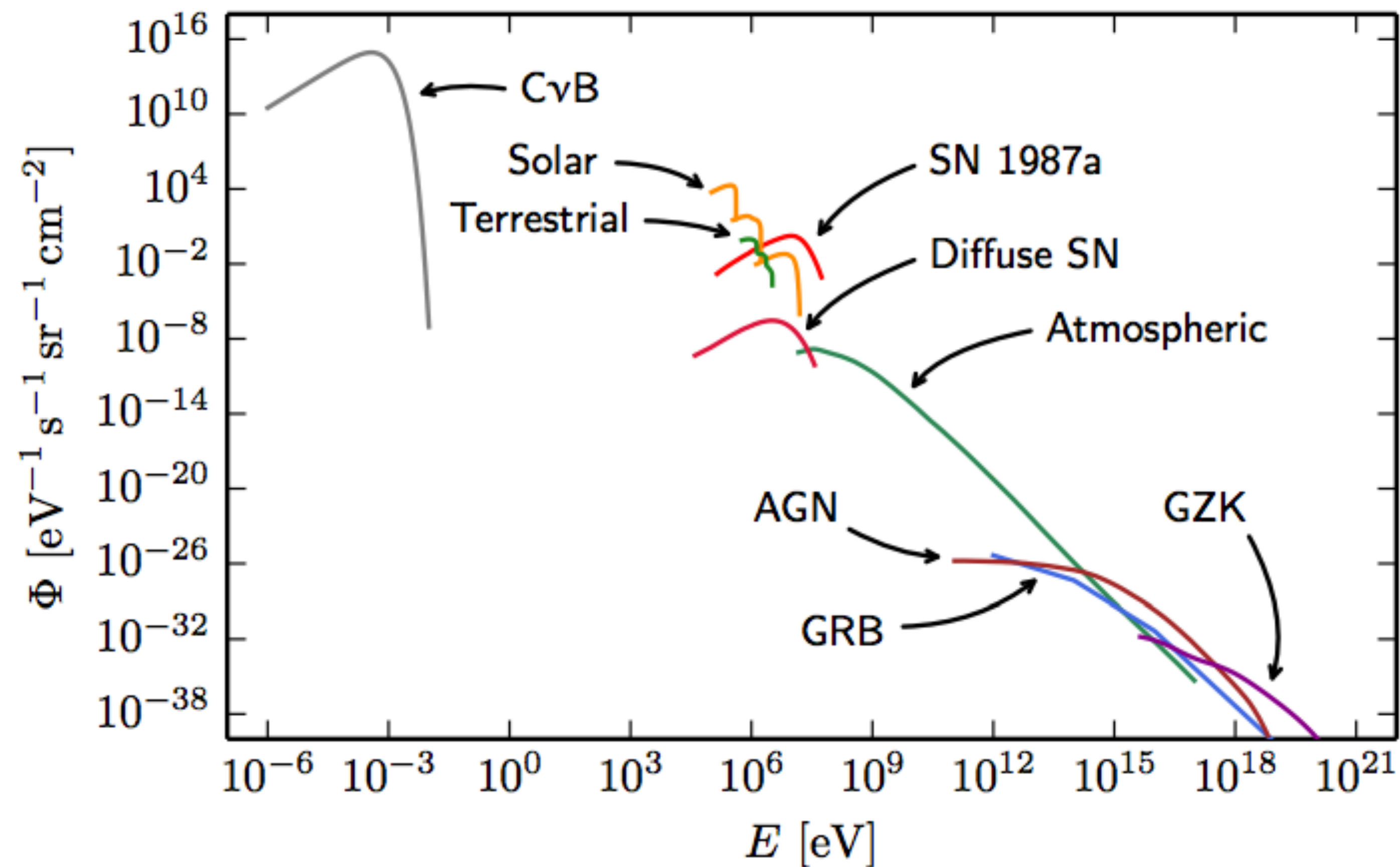
- **Man-made**

- **Accelerators**
- **Nuclear reactors**



Neutrino fluxes

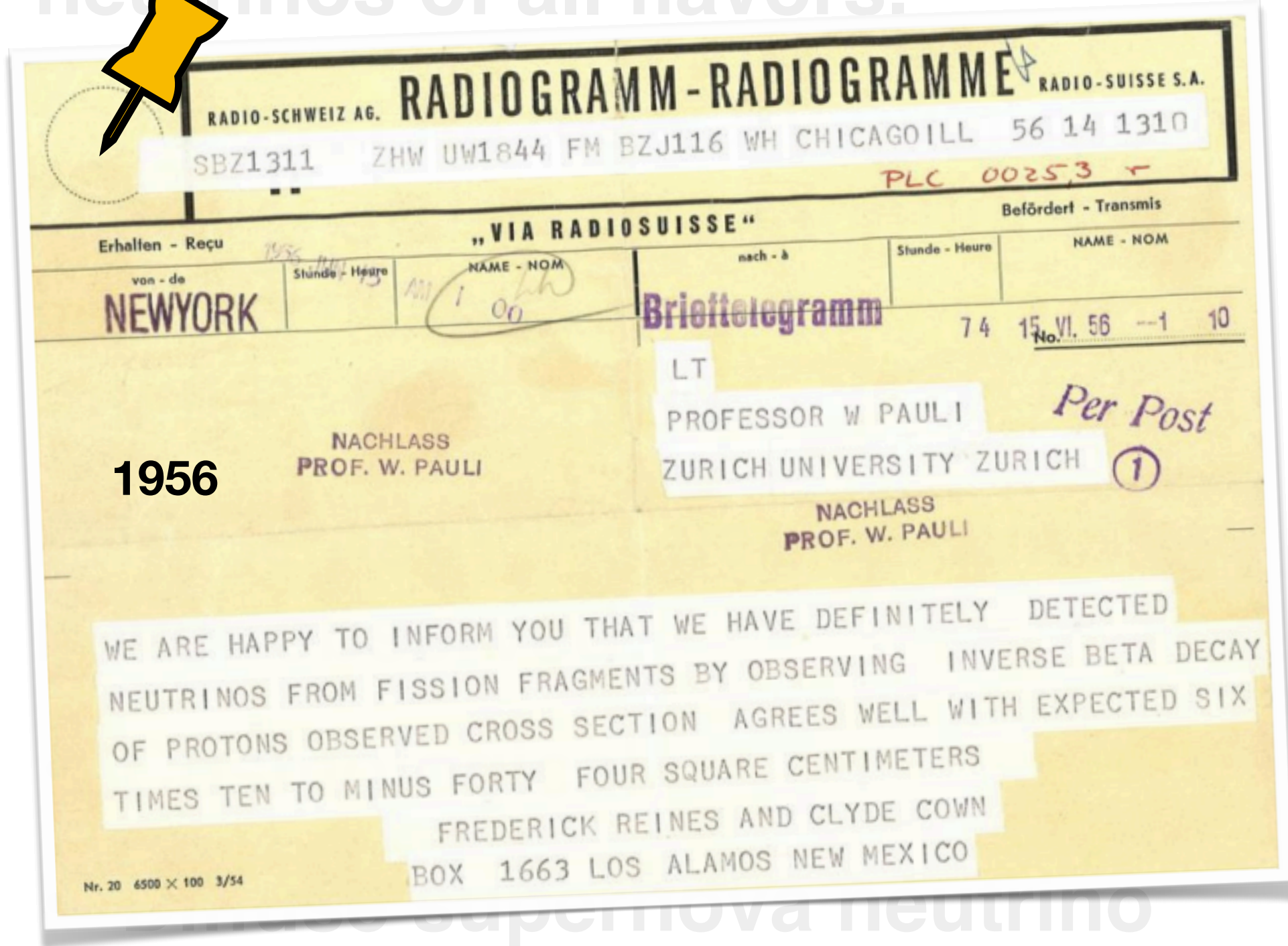
- **Variety of natural and man-made sources produce neutrinos**
- **Expected fluxes vary over more than 30 orders of magnitudes and go from below meV up to multi PeV energies**
- **Diffuse neutrino background not yet observed:**
 - **Cosmological**
 - **Diffuse supernova neutrino background**



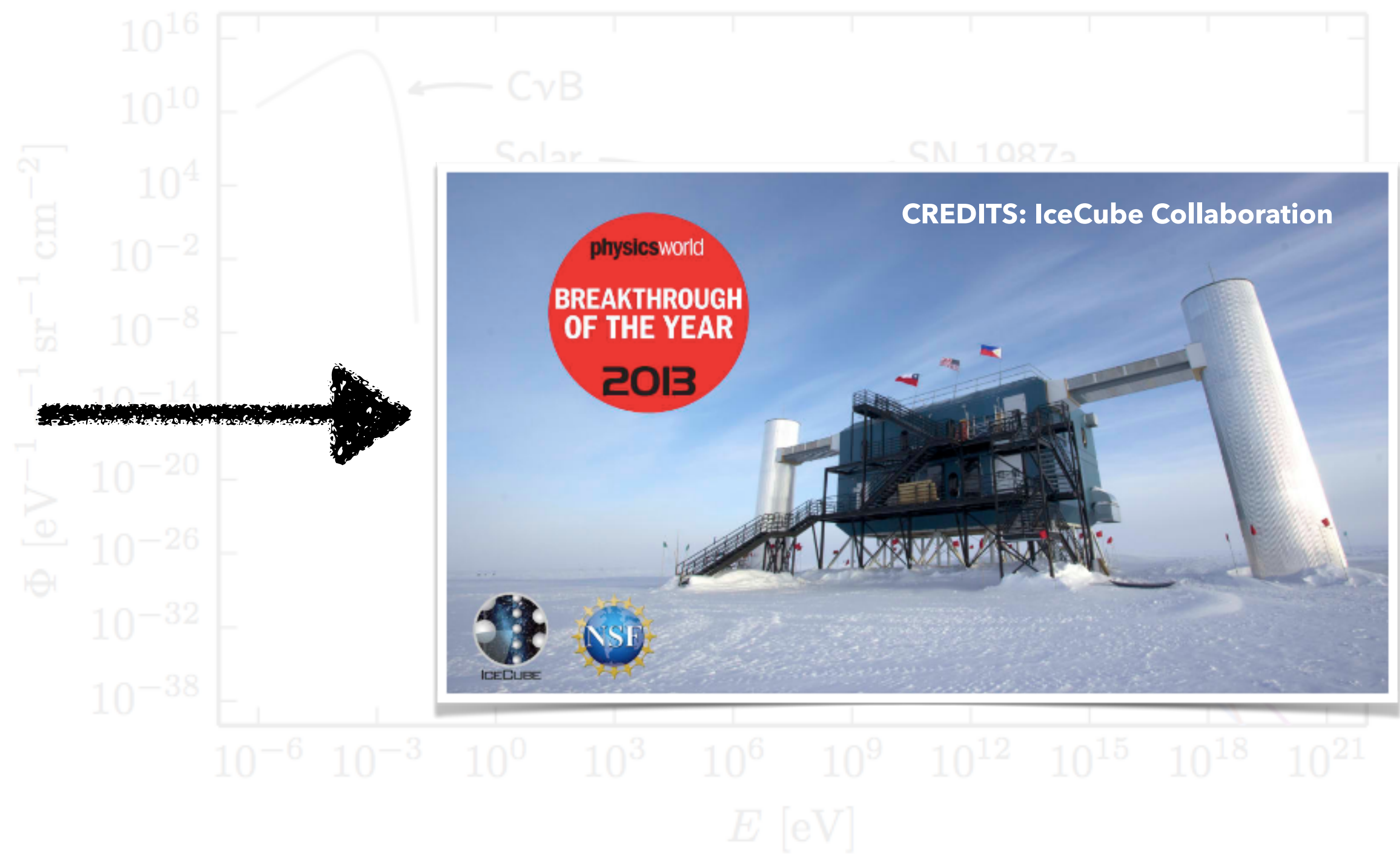
Mohrmann, Lars Bastian. *Characterizing Cosmic Neutrino Sources – A Measurement of the Energy Spectrum and Flavor Composition of the Cosmic Neutrino Flux Observed with the IceCube Neutrino Observatory*. PhD thesis, Humboldt University, Berlin, 2015.

Neutrino fluxes

- Variety of natural and man-made sources produce neutrinos of all flavors.

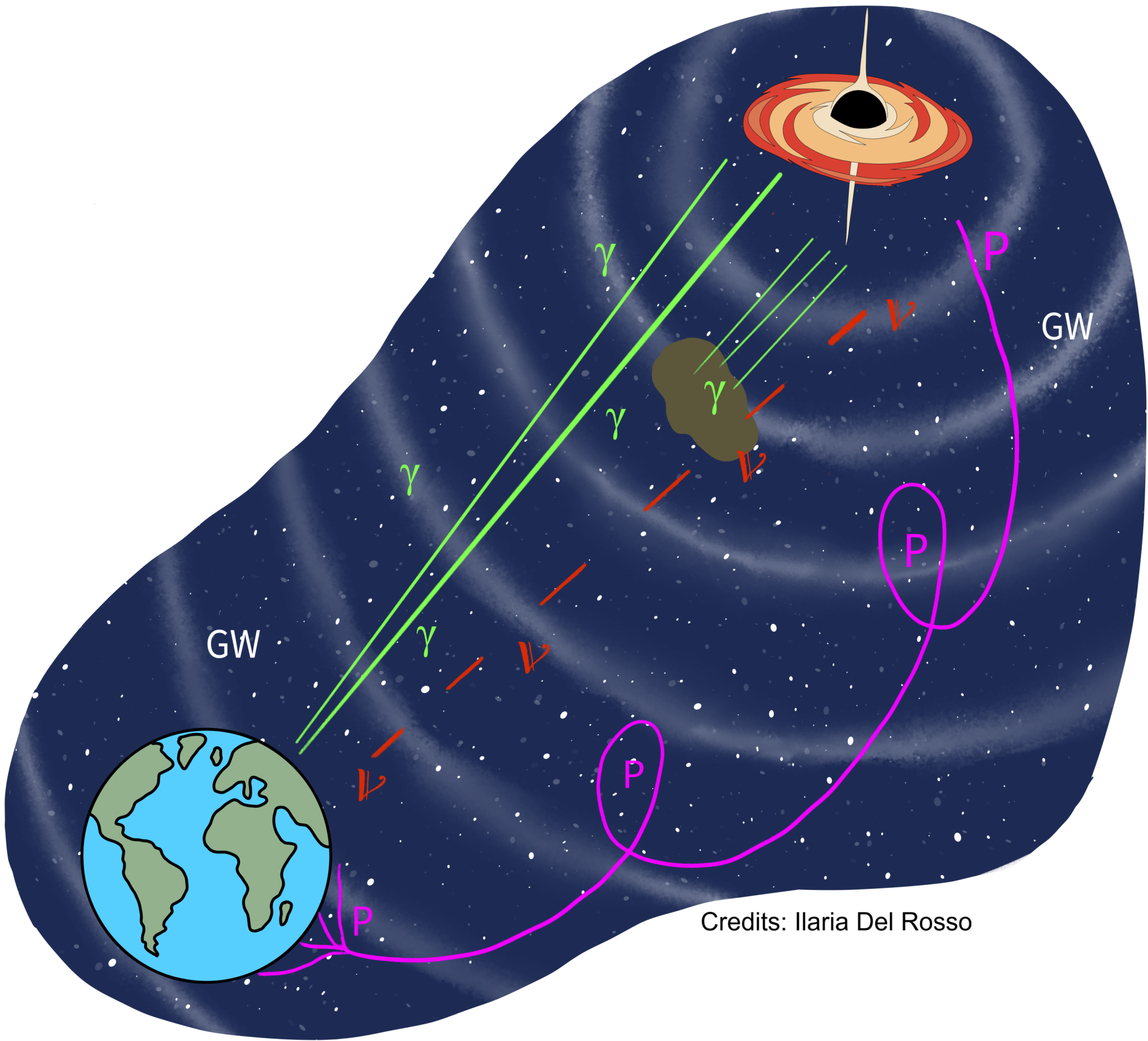


background



Mohrmann, Lars Bastian. *Characterizing Cosmic Neutrino Sources – A Measurement of the Energy Spectrum and Flavor Composition of the Cosmic Neutrino Flux Observed with the IceCube Neutrino Observatory*. PhD thesis, Humboldt University, Berlin, 2015.

The sky is full of messengers
What can they tell us?



Multi-messenger astronomy

Cosmic rays

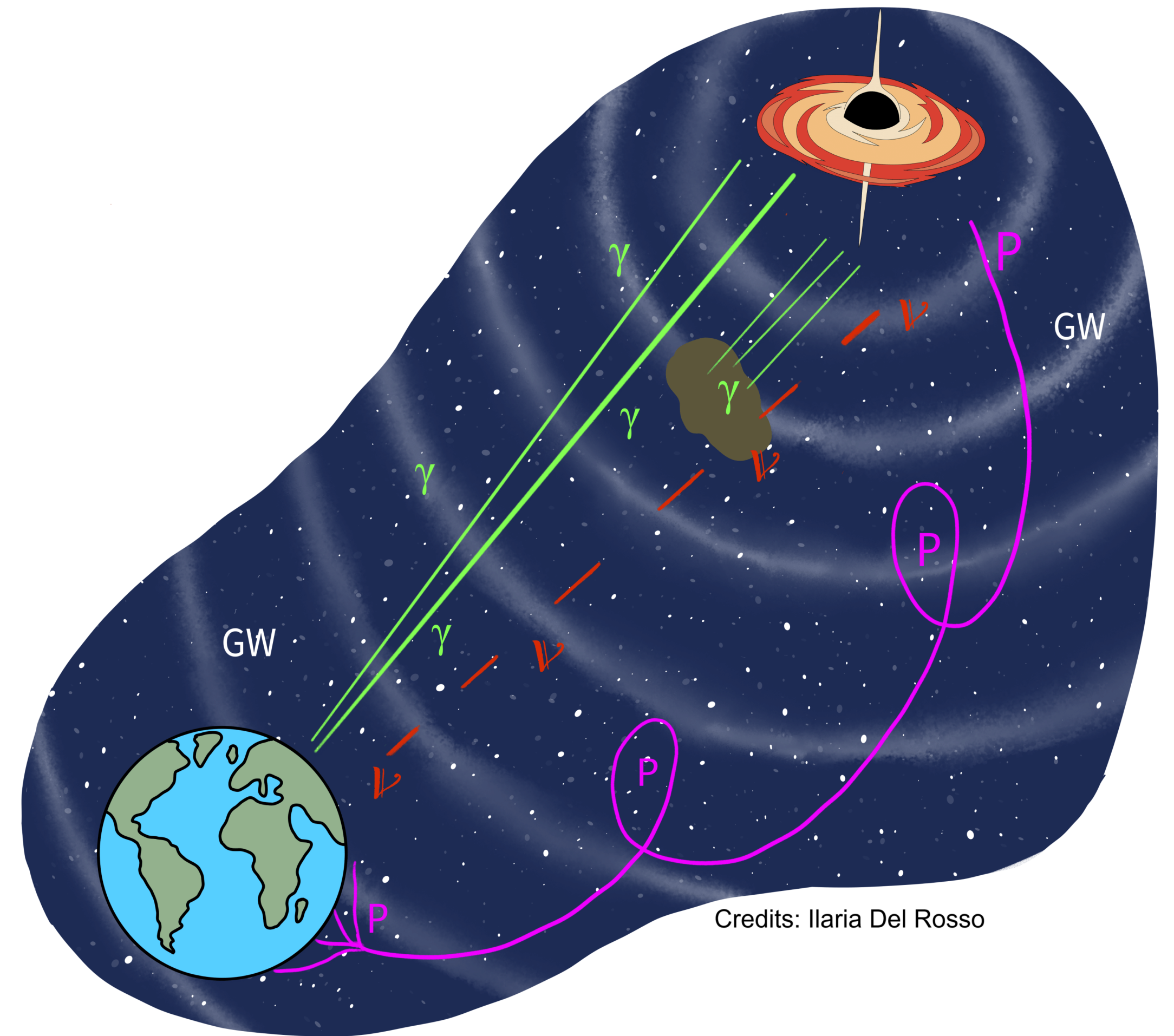
are deflected by magnetic fields

Gamma rays

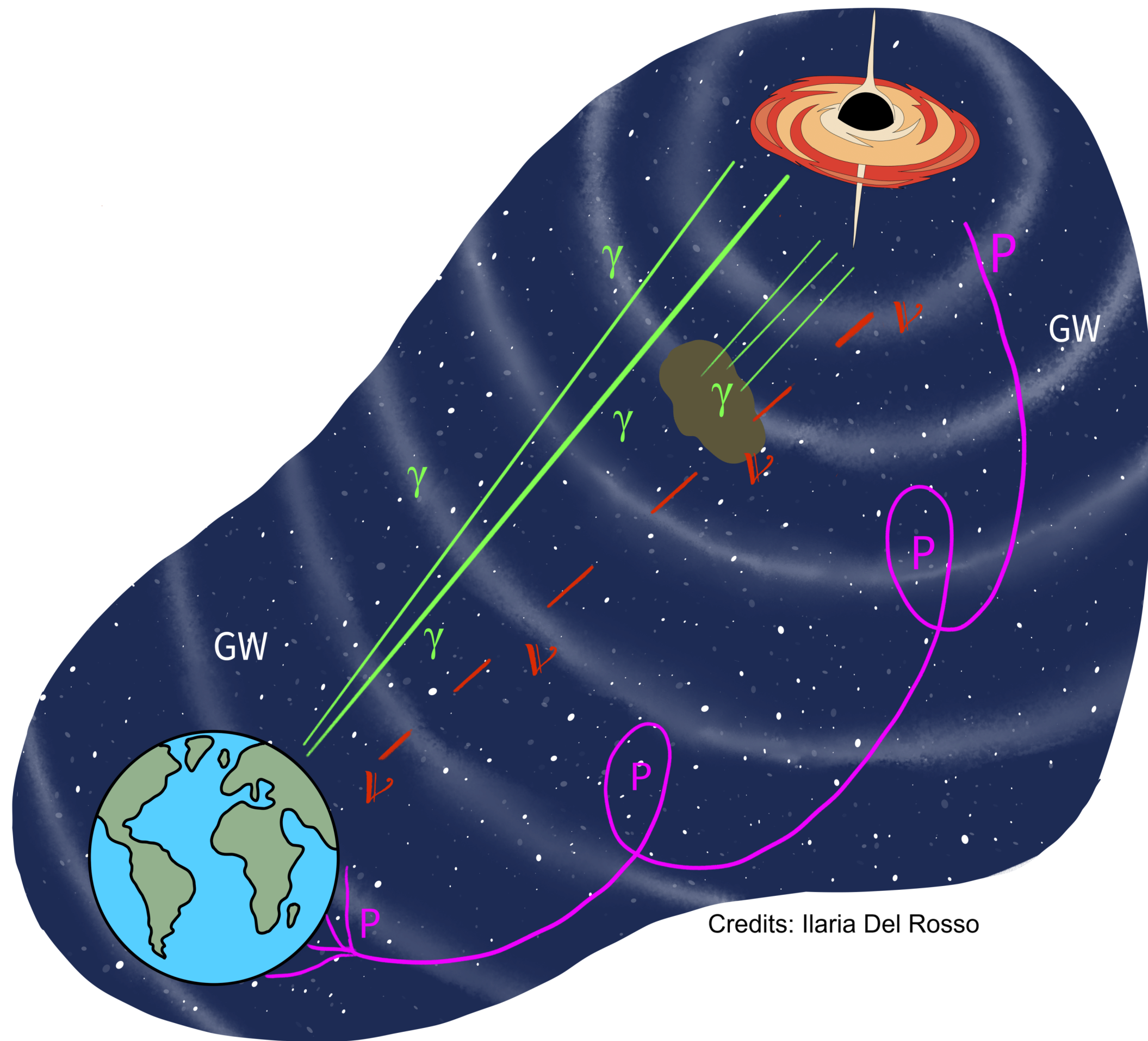
absorbed and generated by multiple emission mechanism

Gravitational waves

emerging field and... source localization needs a network of detectors

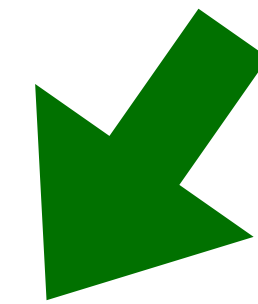


Neutrinos in multi-messenger astronomy



Neutrinos as ideal messengers

- **stable and electrically neutral**
- **weakly interacting particle**
- **produced only via hadronic processes**



Advantages

- **are undeflected and trace back their production site**
- **probes for UHECRs acceleration**

Challenges

- **low fluxes**
- **background contamination from atmospheric muons and neutrinos**

Neutrinos production mechanisms: hadronic processes

Photo-mesons interactions

$$p + \gamma \longrightarrow p' + \pi^0 \longrightarrow p' + 2\gamma$$

$$p + \gamma \longrightarrow n + \pi^+$$

$$p + \gamma \longrightarrow p' + \pi^+ + \pi^-$$

$$\pi^\pm \longrightarrow \mu^\pm \bar{\nu}_\mu^{(-)}$$

$$\mu^\pm \longrightarrow e^\pm \bar{\nu}_\mu^{(-)} \bar{\nu}_e^{(-)}$$

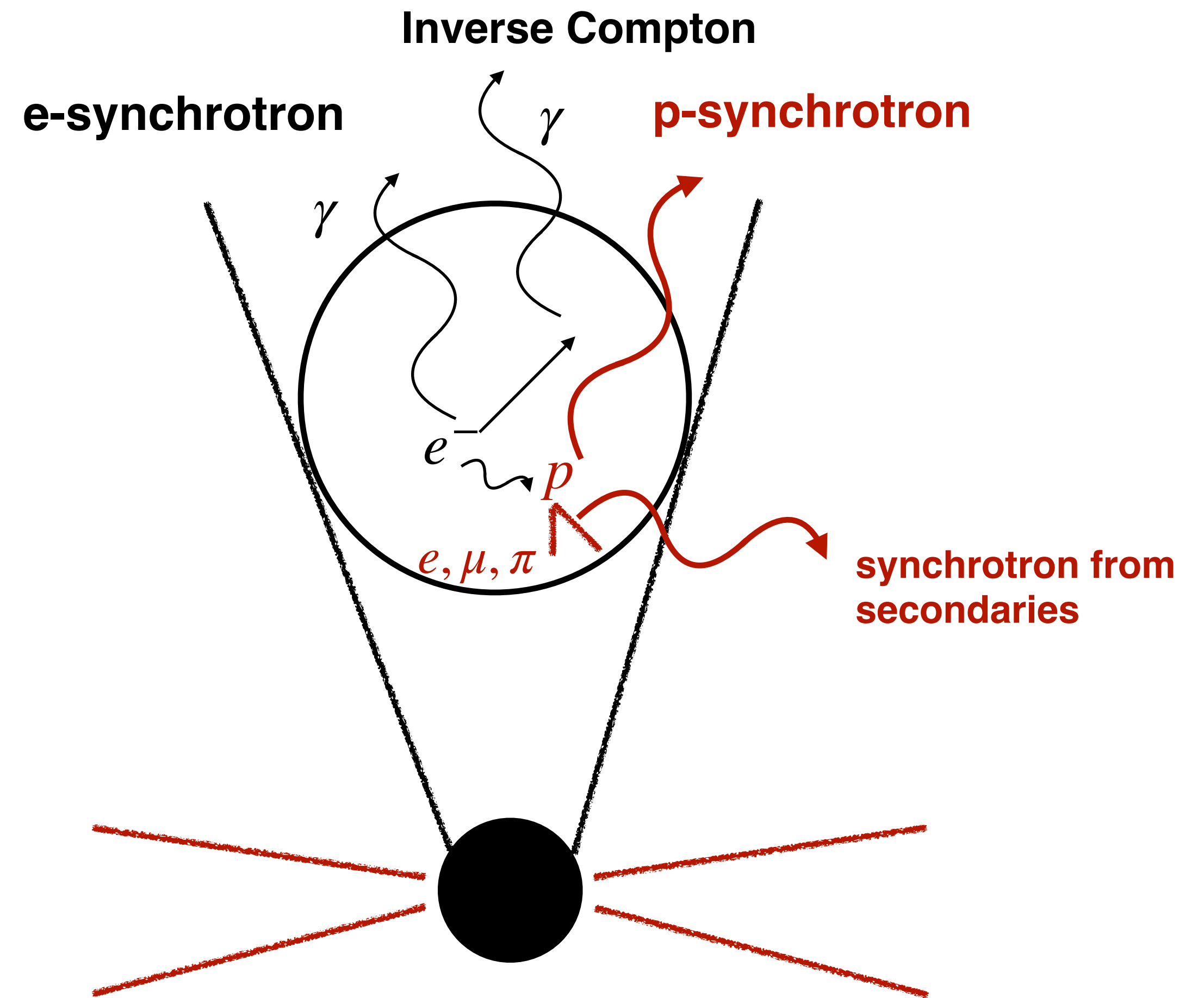
Astrophysical beam dump

$$p + p \longrightarrow \pi^\pm K^\pm \pi^0 K^0 p n \longrightarrow \nu \bar{\nu} \dots$$

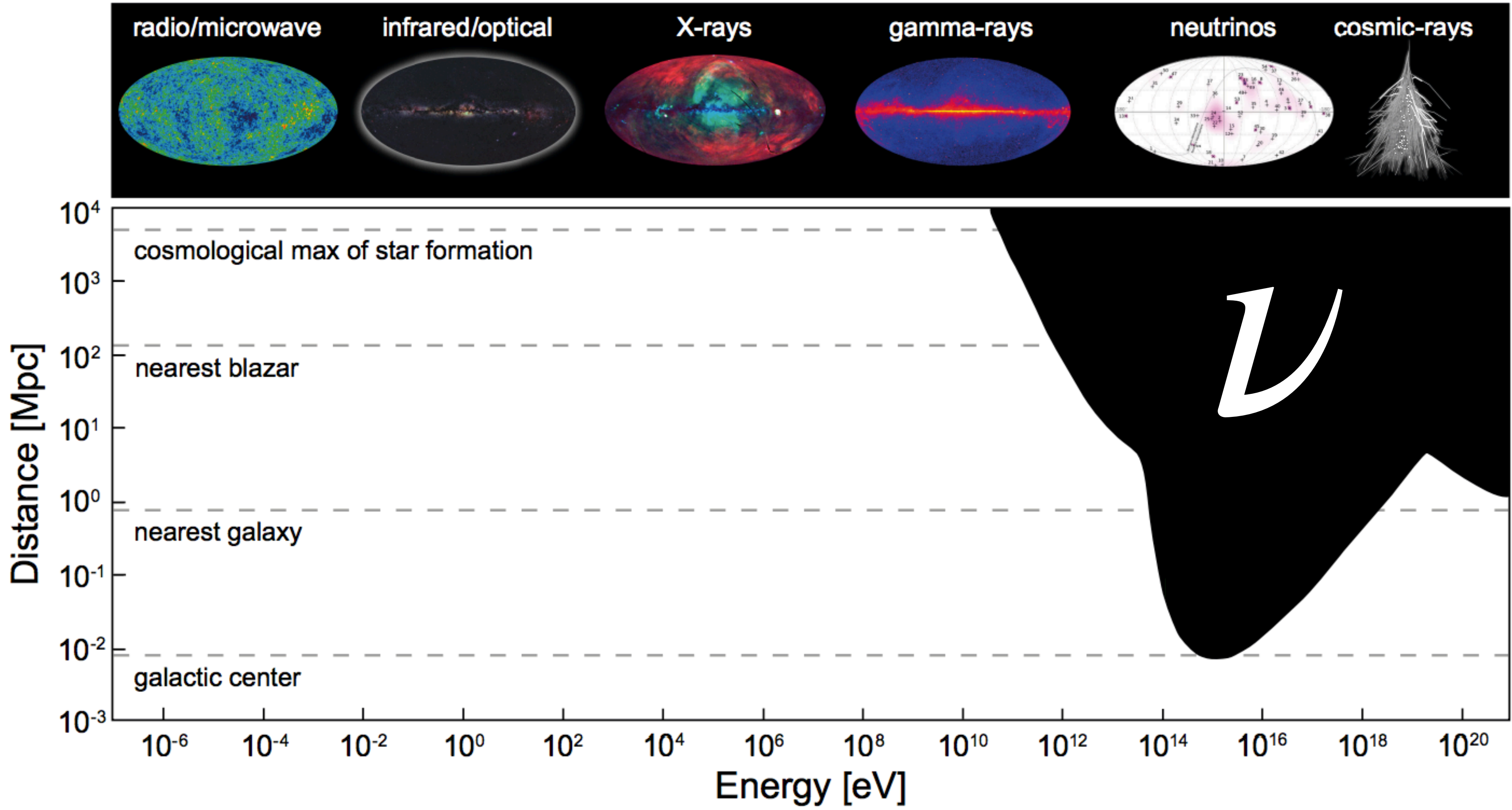
But also... Bethe-Heitler pair production

$$p + \gamma \longrightarrow p' e^+ e^-$$

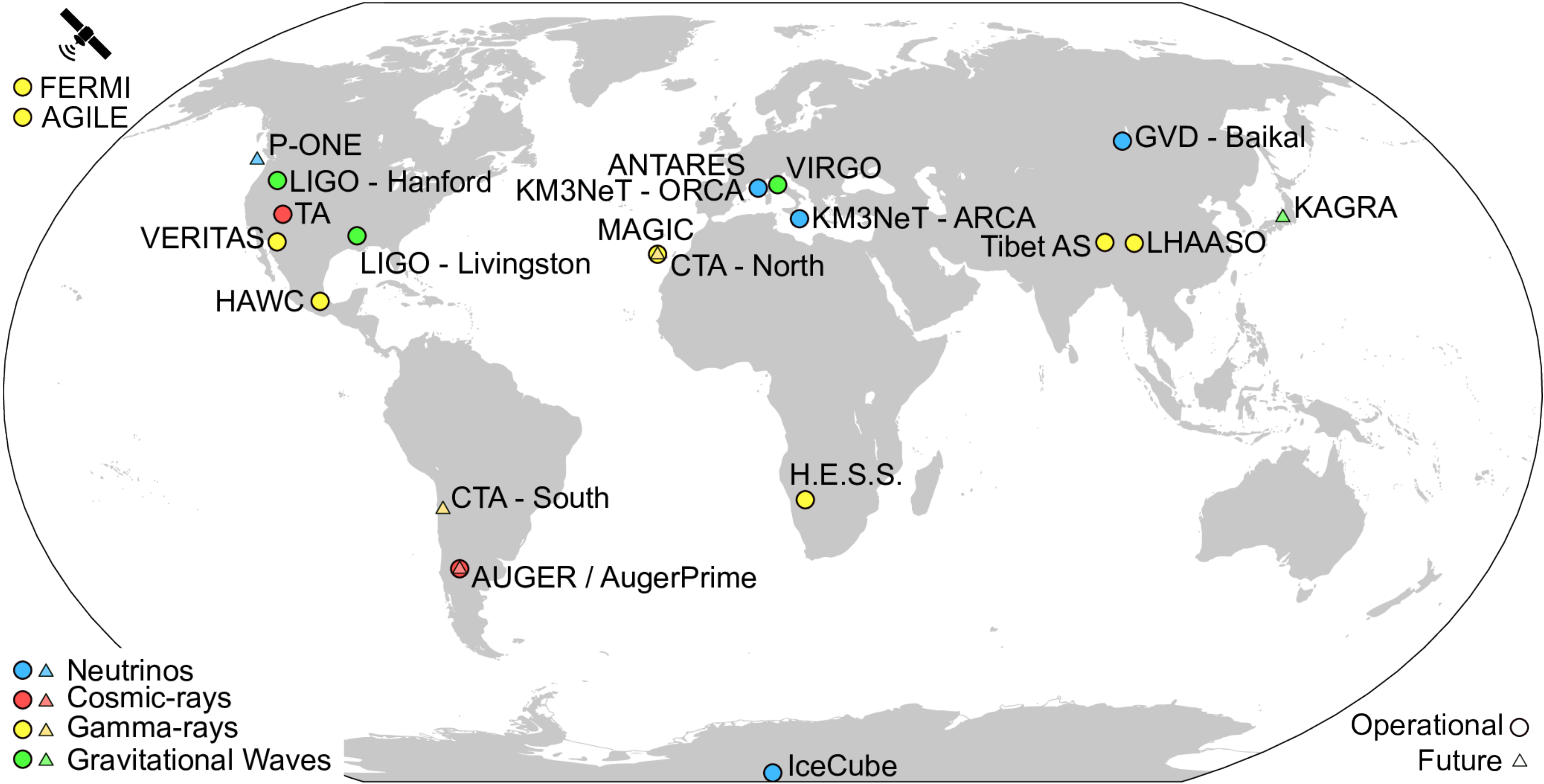
No neutrino in this case!



The high-energy Universe

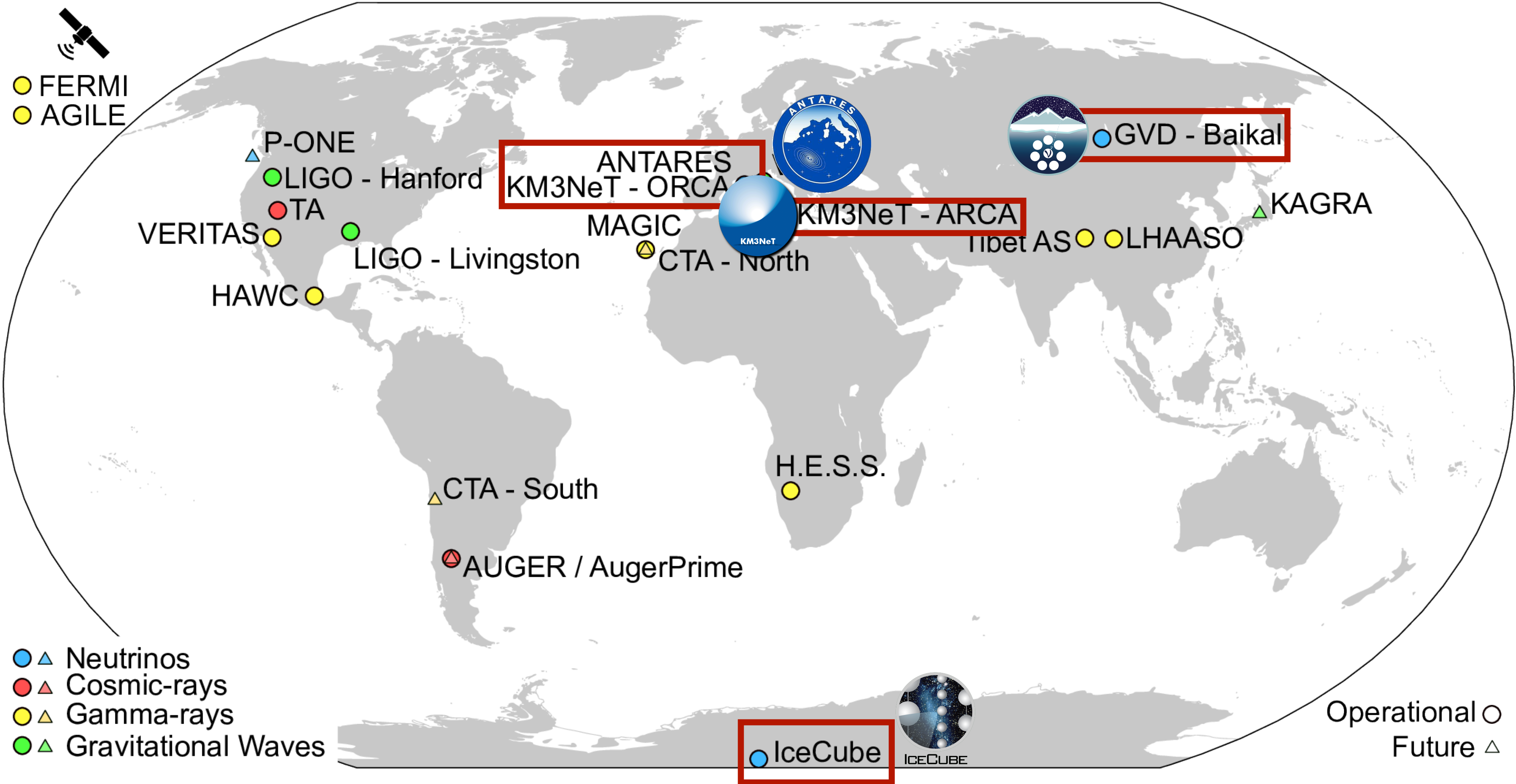


Muti-messenger facilities in the world



Francisco Salesa Greus and Agustín Sánchez Losa, "Multimessenger Astronomy with Neutrinos," *Universe* 7, no. 11 (2021): 397

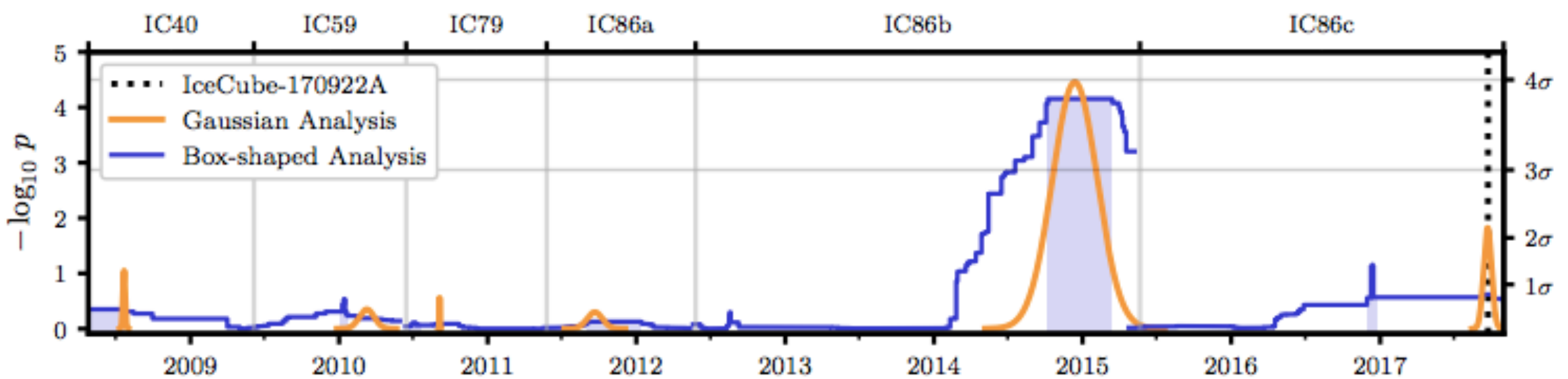
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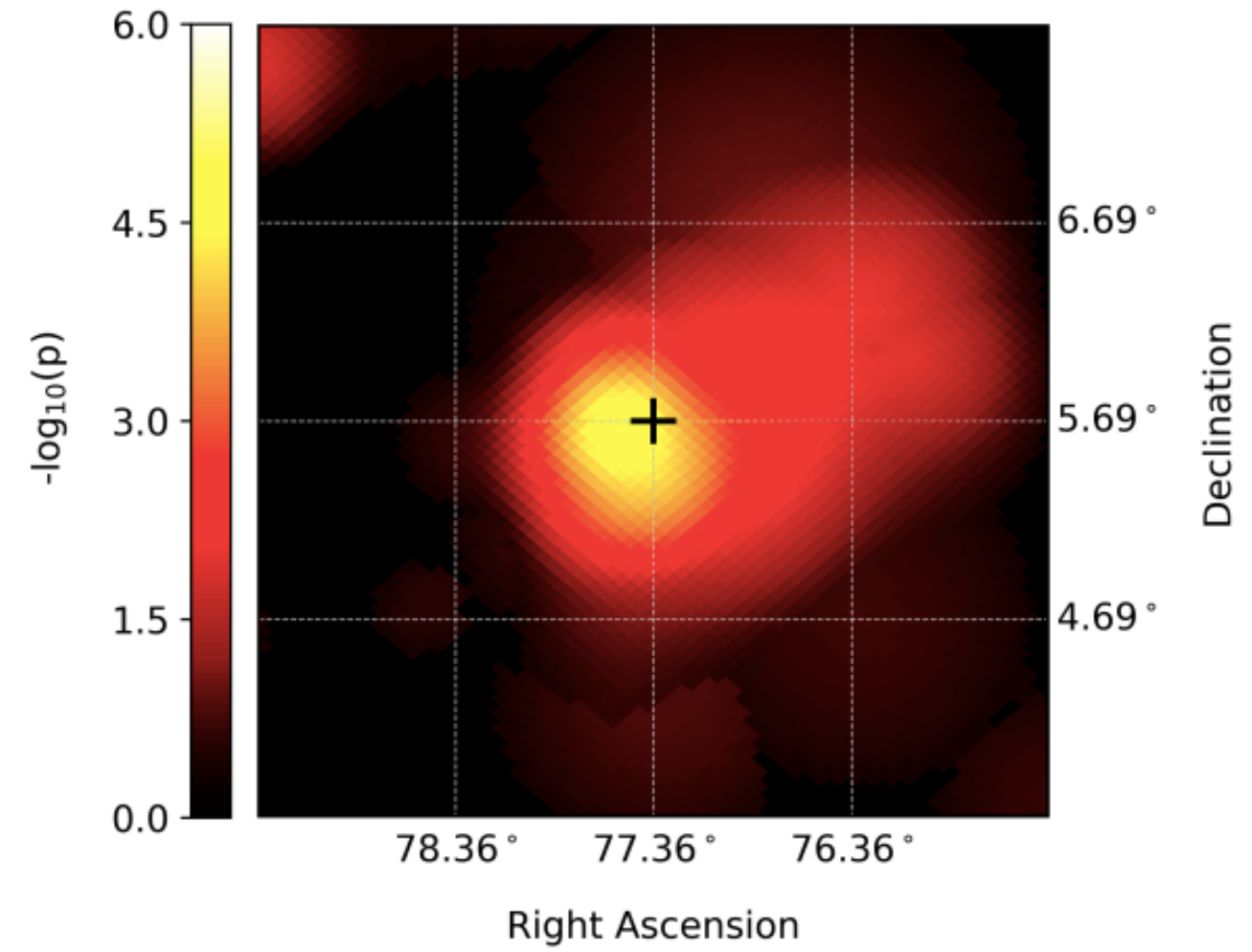
Multi-messenger milestones

TXS 0506+056



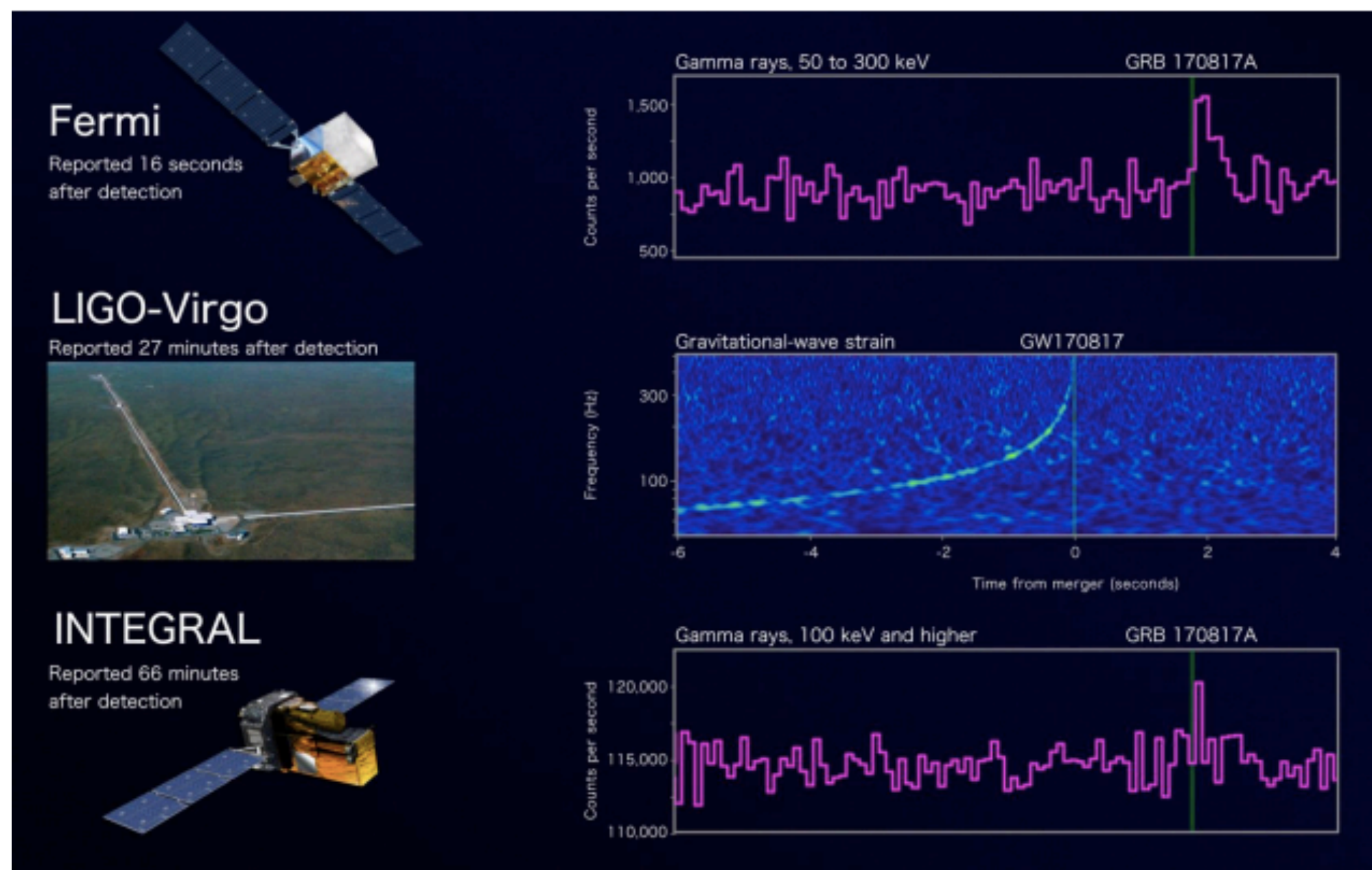
IceCube Collaboration, Science 361, 147-151 (2018)

NEUTRINO ALERT:
22 September 2017 IceCube reported the observation of a 290 TeV neutrino coming from the direction of the γ -ray emitter TXS 0506+056



SEARCH IN ARCHIVAL ICECUBE DATA:
Excess of high-energy neutrino events at source position between September 2014 and March 2015: 3.5σ evidence, prior to the 2017 alert, assuming a time variable flux.

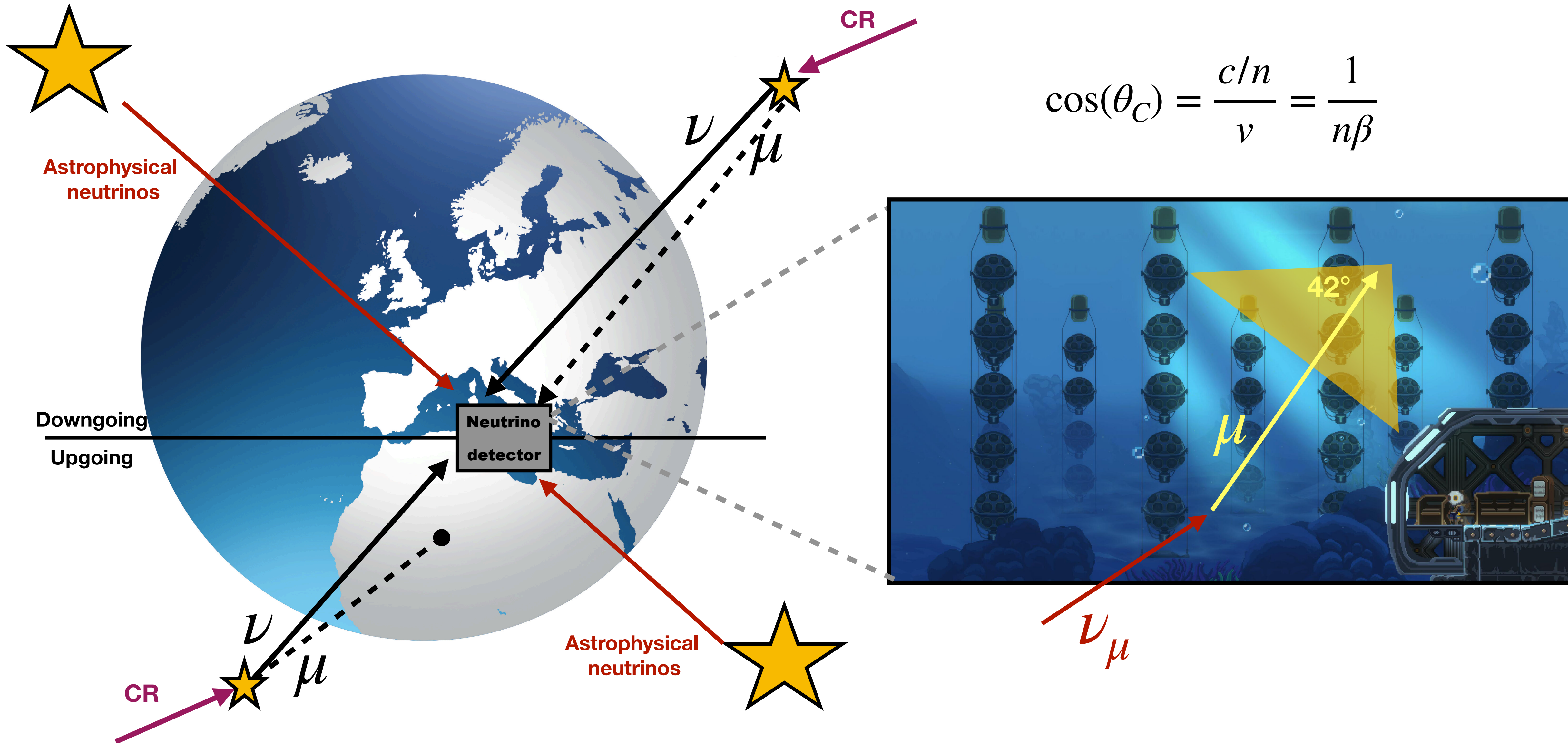
GW170817 AND GRB 170817A



Abbott et al., ApJ (2017), ESA

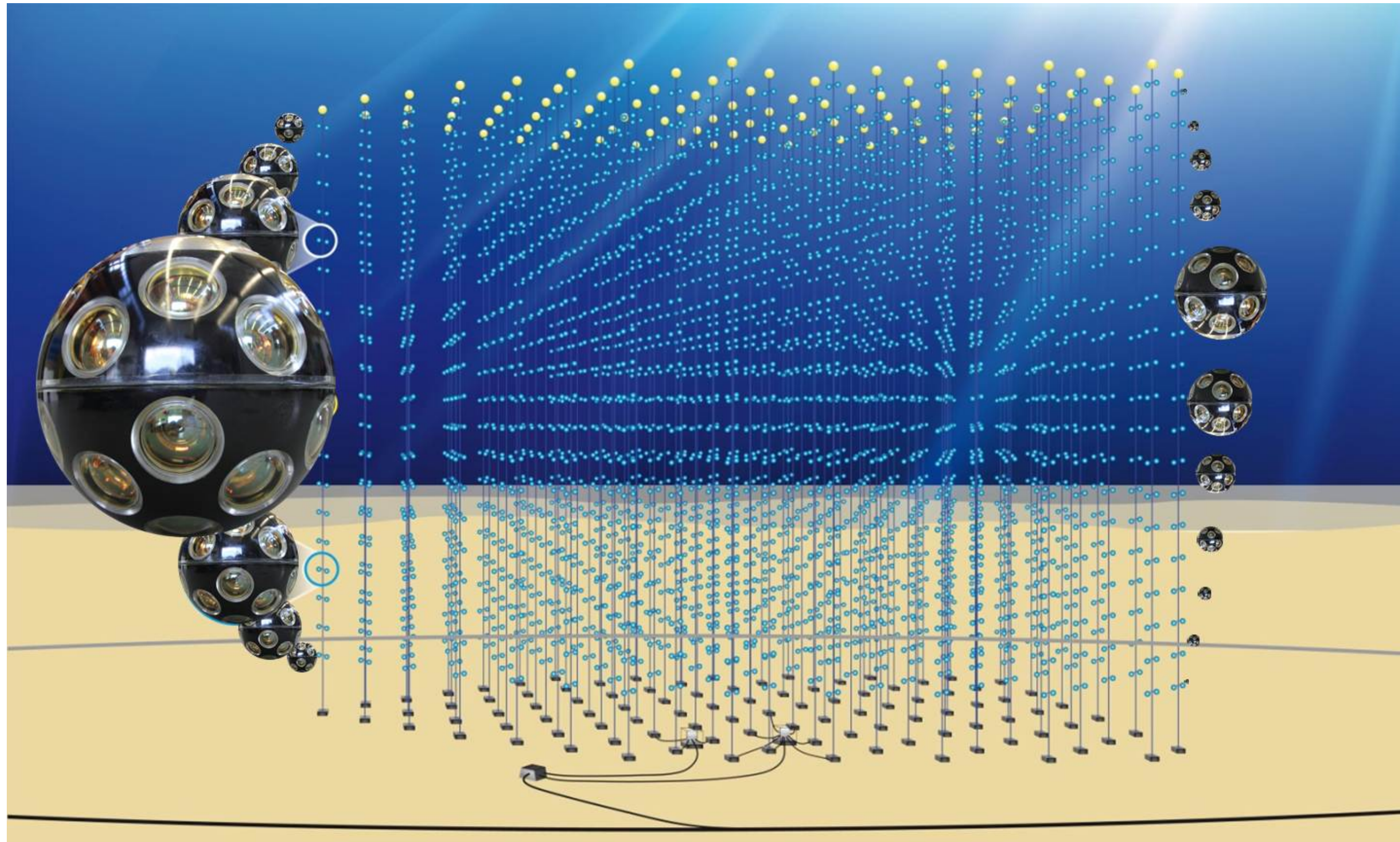
- JOINT OBSERVATION OF GW170817 AND GRB 170817A:**
1. First spatial and temporal coincidence between a GW and a GRB
 2. Evidence that the merger of two neutron stars can produce short bursts of gamma-rays

Cherenkov telescopes



$$\cos(\theta_C) = \frac{c/n}{v} = \frac{1}{n\beta}$$

Deep-sea neutrino telescopes



Go to the very deep-sea

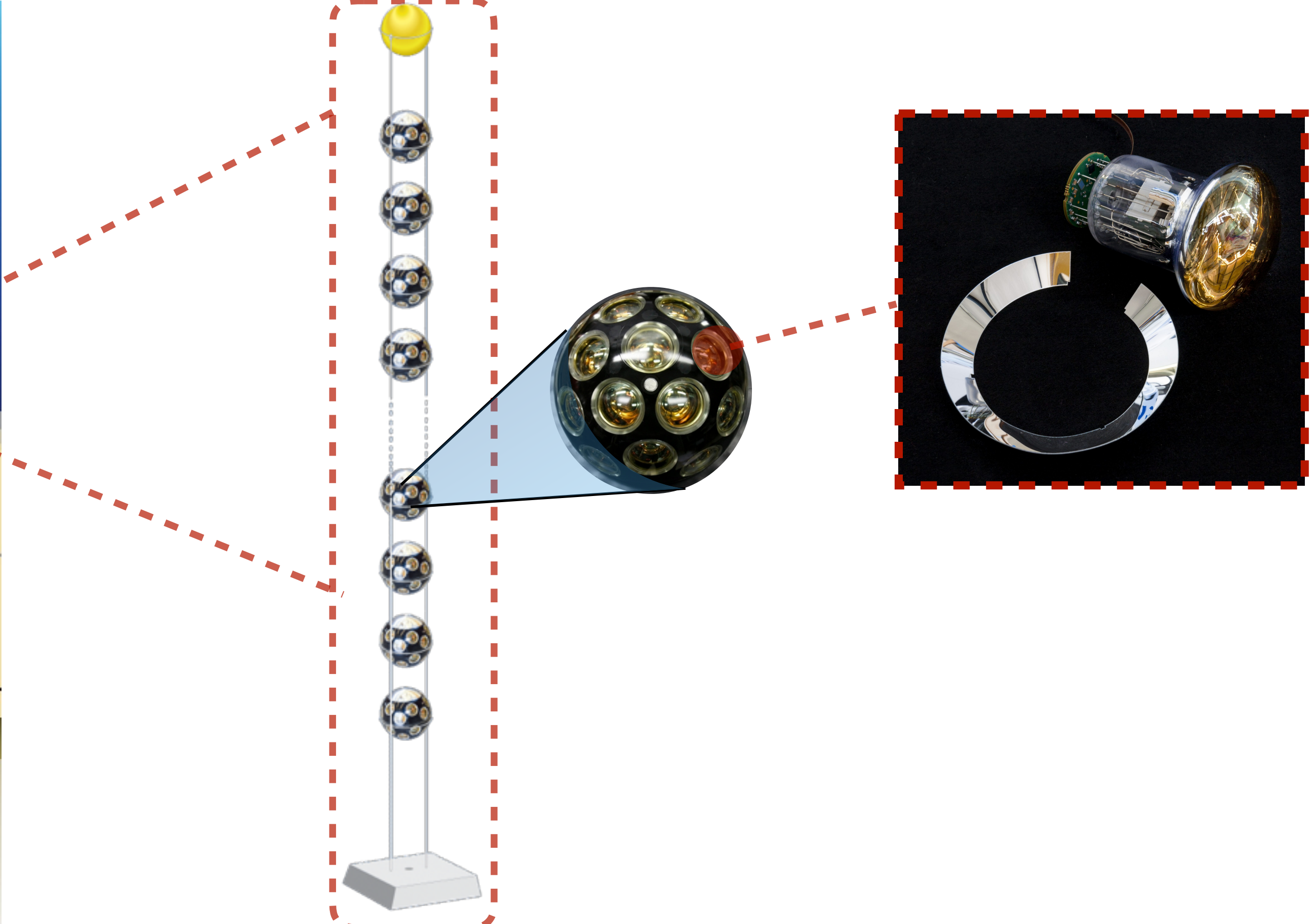
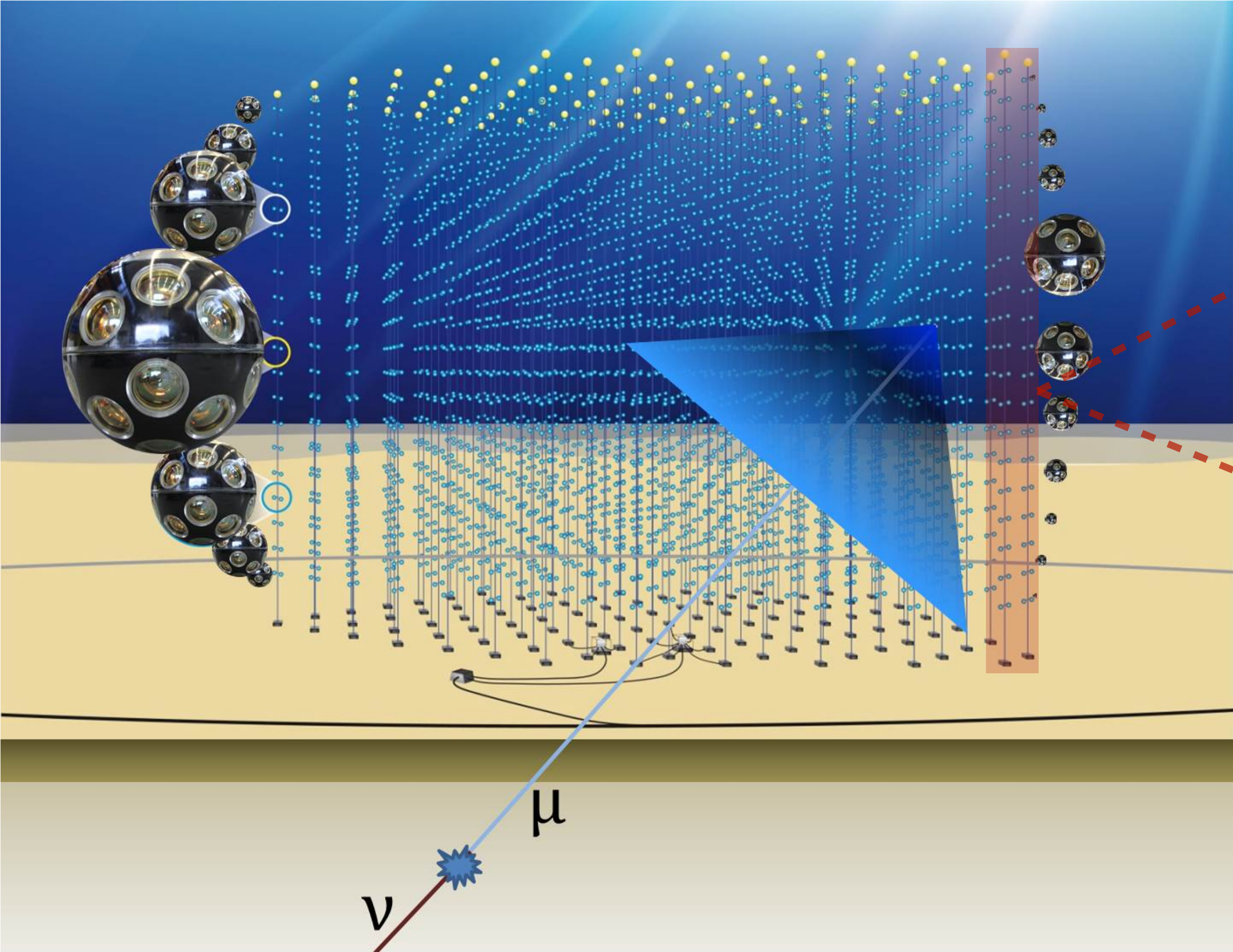


Create a huge grid of photo sensors

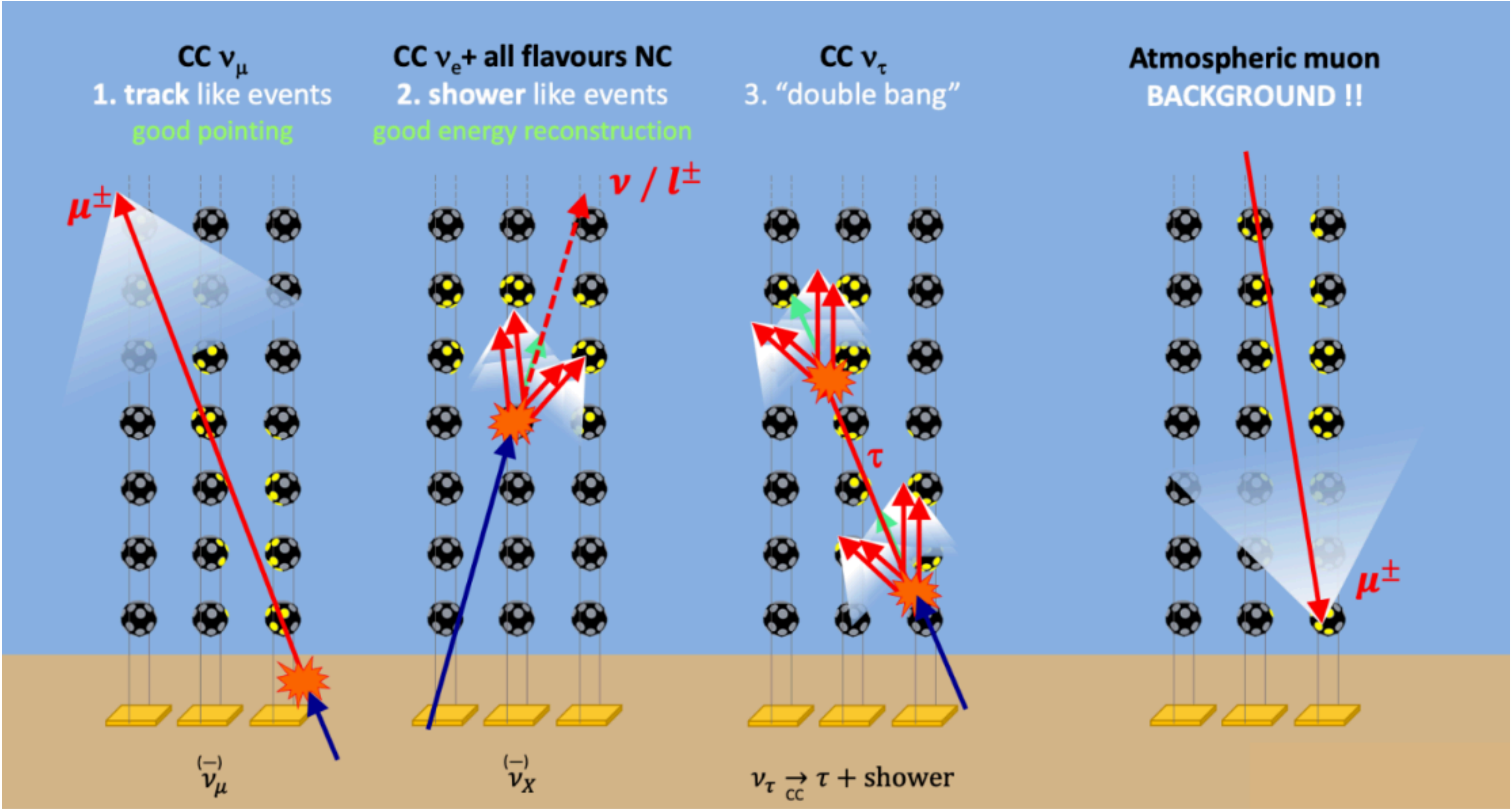


Detect light induced by the passage of neutrinos in seawater

Deep-sea neutrino telescopes: the technology



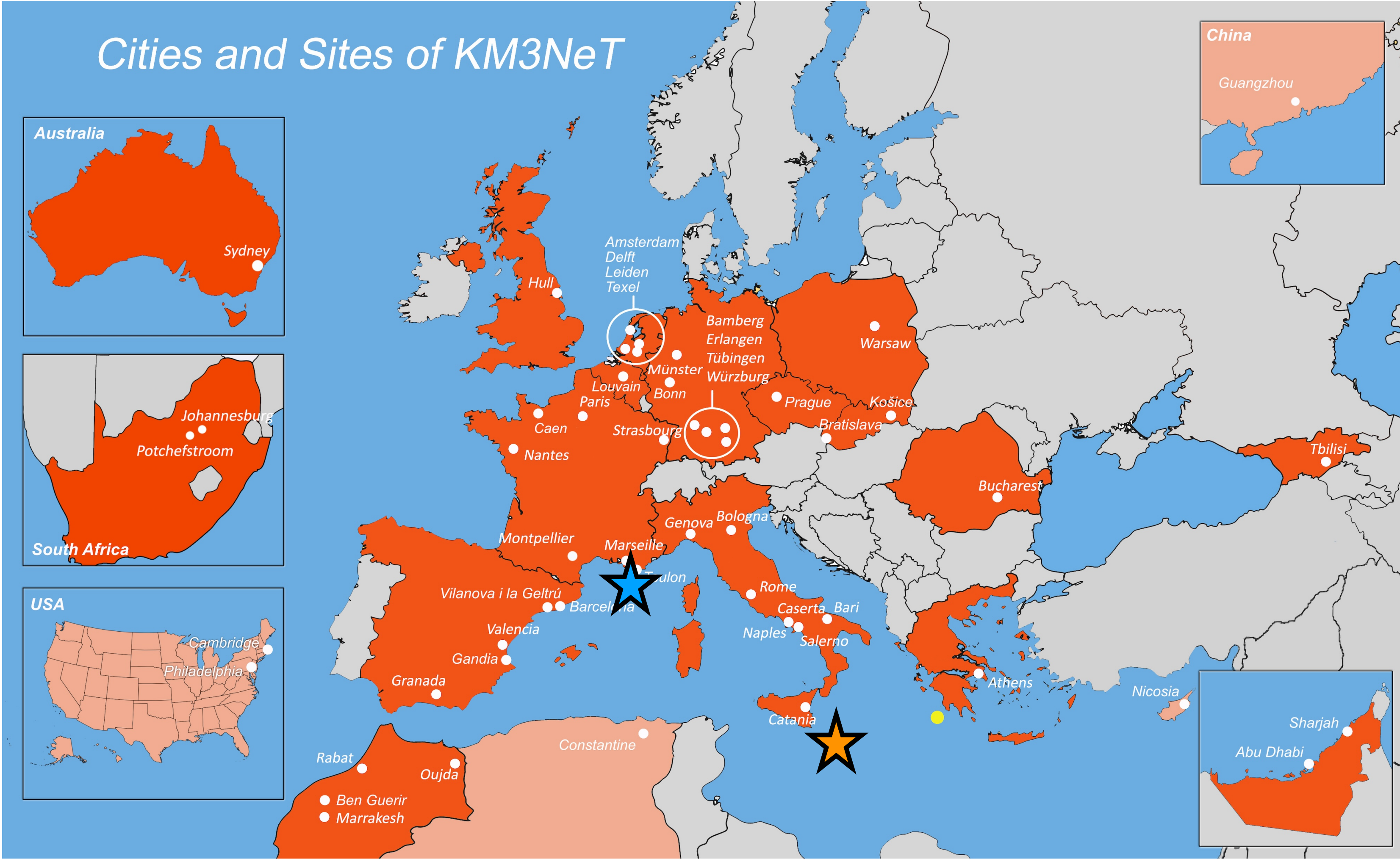
Event topologies



$$\text{CC} : \bar{\nu}_l^{(-)} + N \longrightarrow l^\pm + X$$

$$\text{NC} : \bar{\nu}_l^{(-)} + N \longrightarrow \bar{\nu}_l^{(-)} + X$$

KM3NeT: a next generation neutrino telescope



KM3NeT in numbers:

- 5 continents
- 21 countries
- >50 groups
- 2 DETECTORS

ARCA

Astroparticle
Research with
Cosmics in the
Abyss

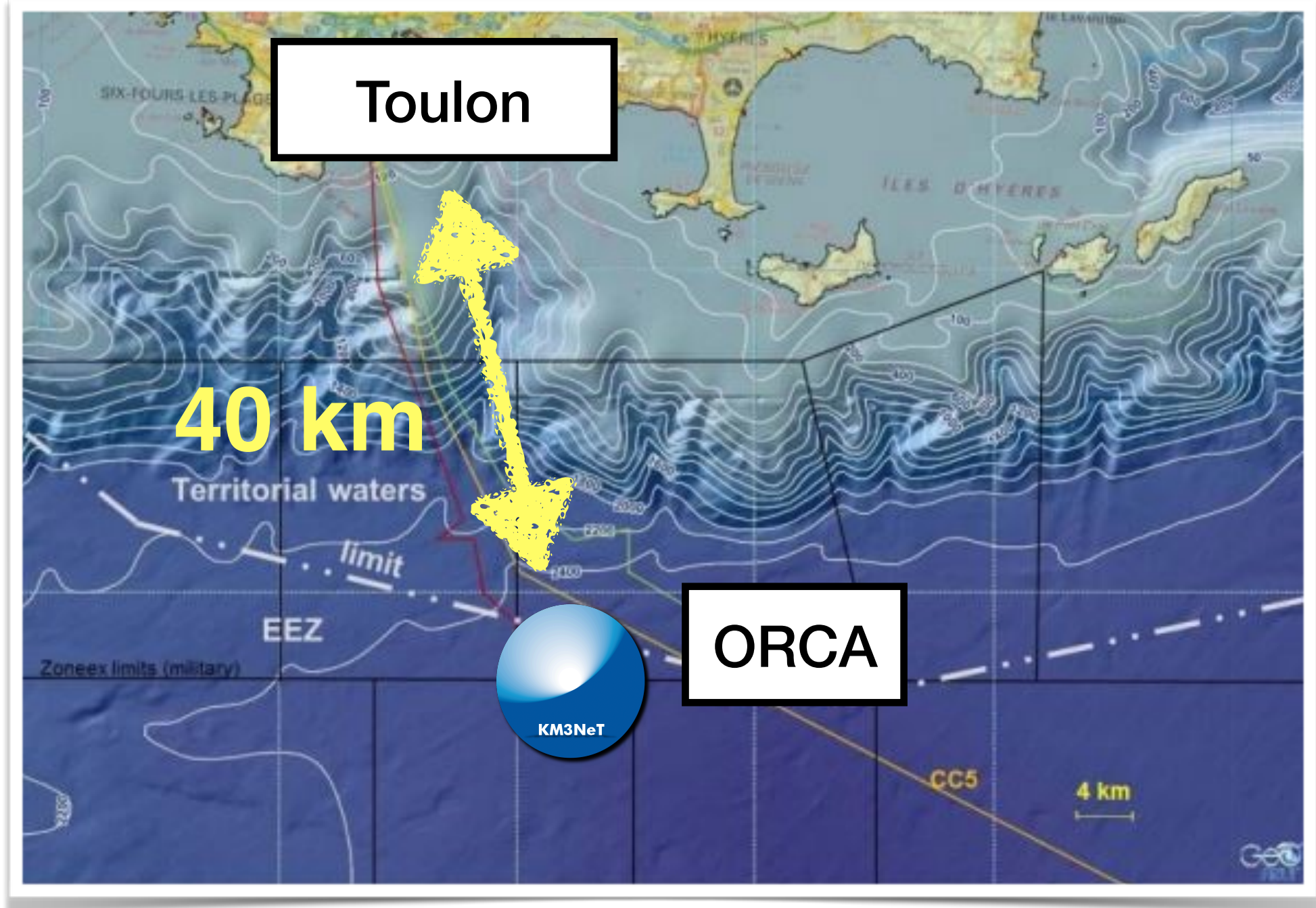
ORCA

Oscillation
Research with
Cosmics in the
Abyss

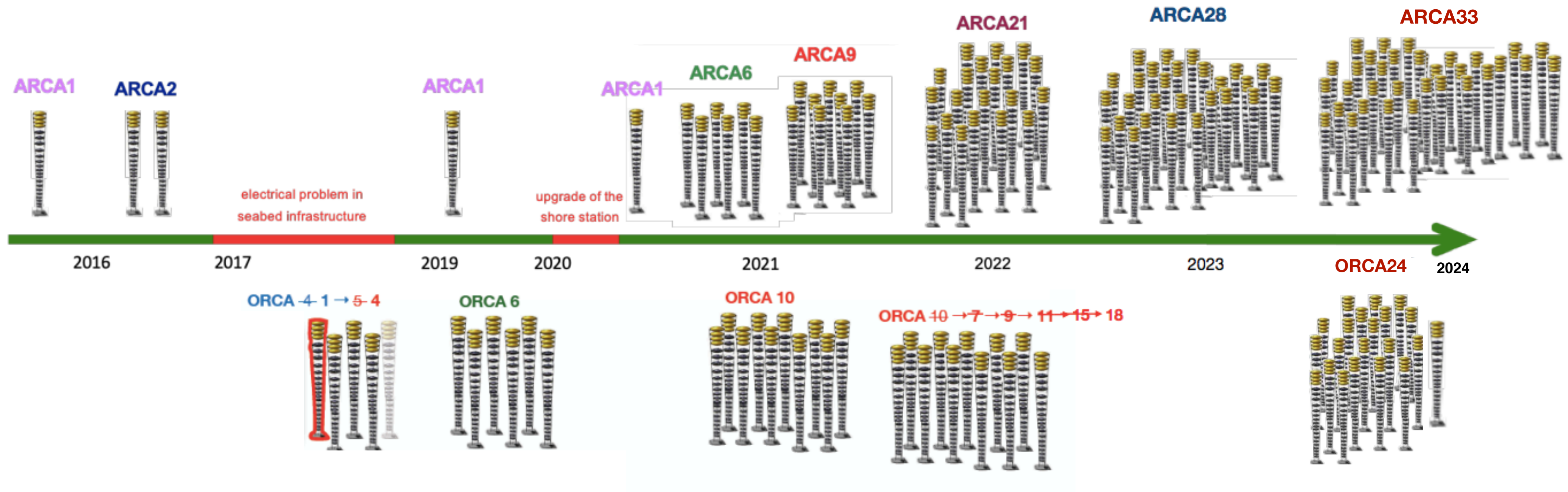
Also optimized for low-energy astronomy analyses!

KM3NeT: sites location

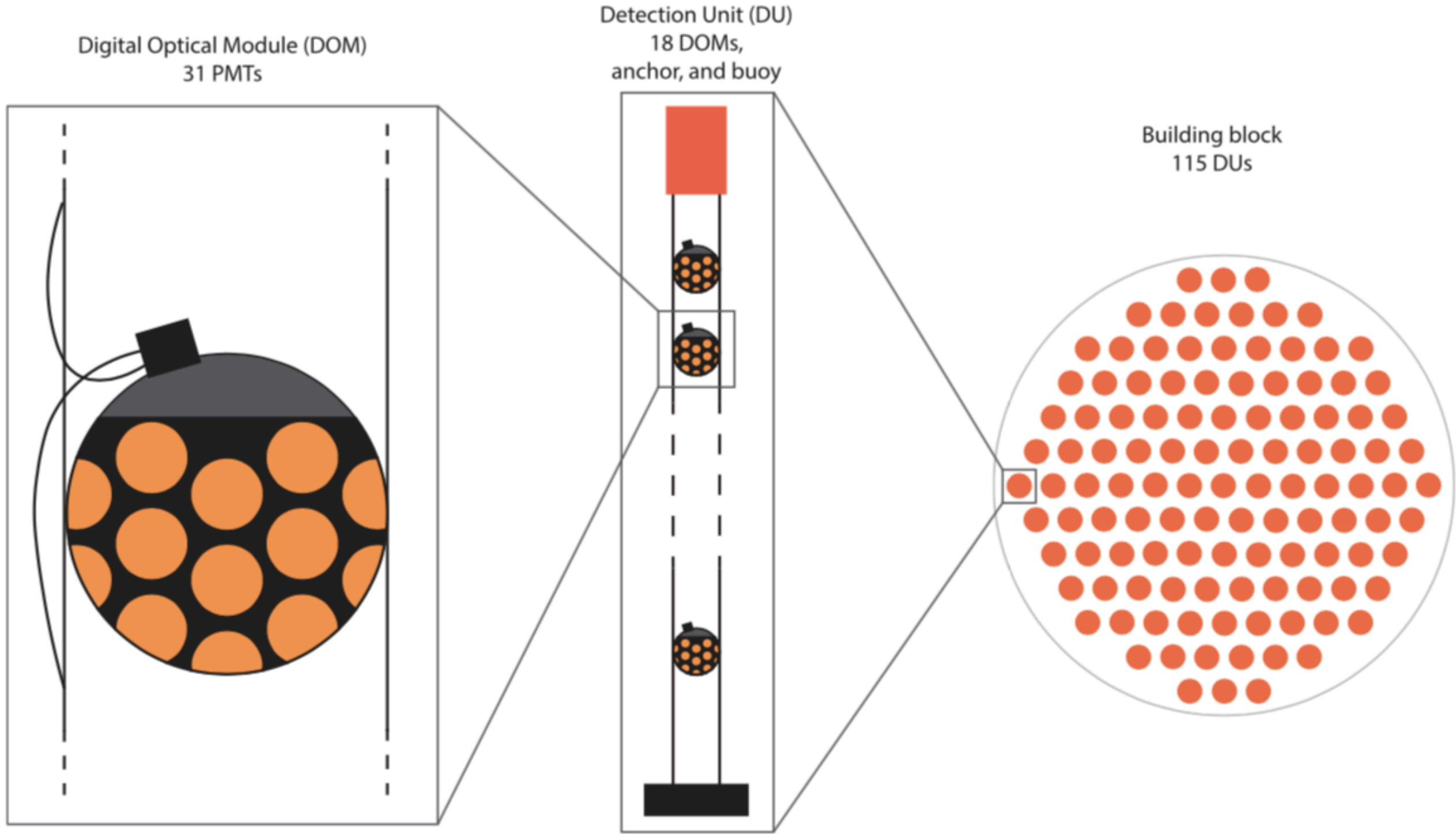
- Deep infrastructure under construction in the Mediterranean Sea
- Two instrument sites: ORCA (France) and ARCA (Italy)



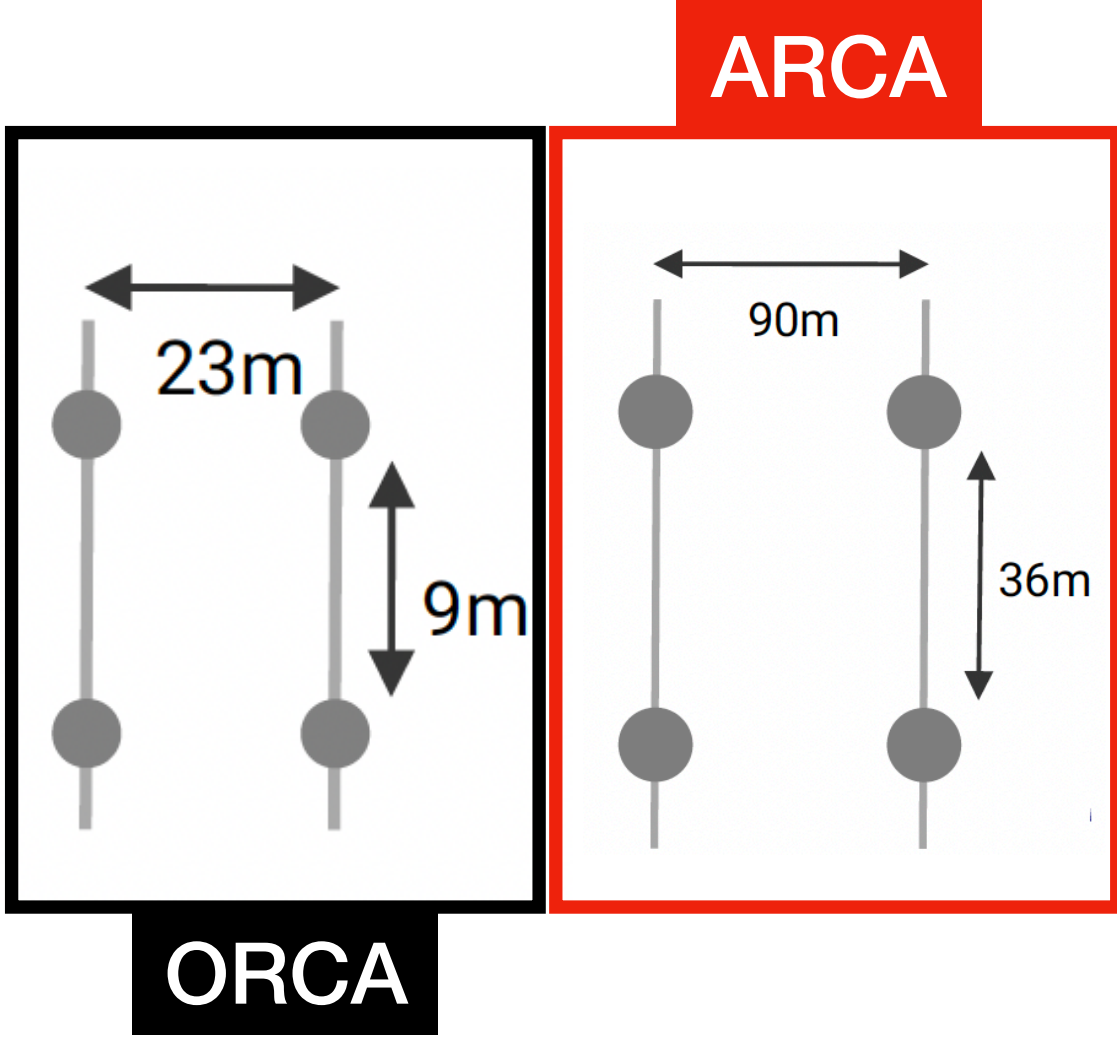
KM3NeT: construction timeline



KM3NeT: the building block



**TWO detectors,
SAME technology
DIFFERENT layout
and...
DIFFERENT physics objectives!**

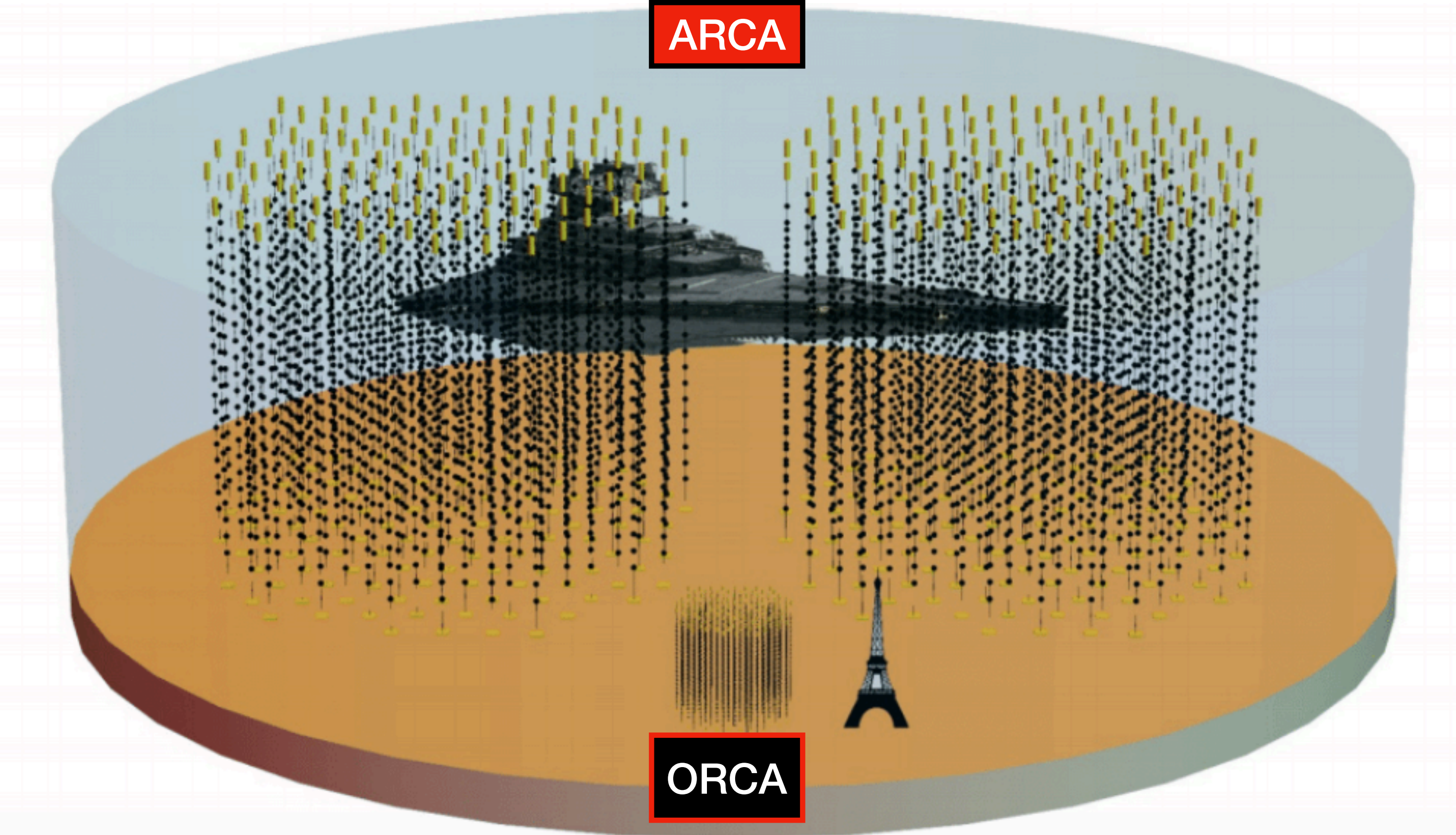


KM3NeT Collaboration (2024). *Astronomy potential of KM3NeT/ARCA*.
European Physical Journal C, 84(9), 885.

Building Block: 115 DUs

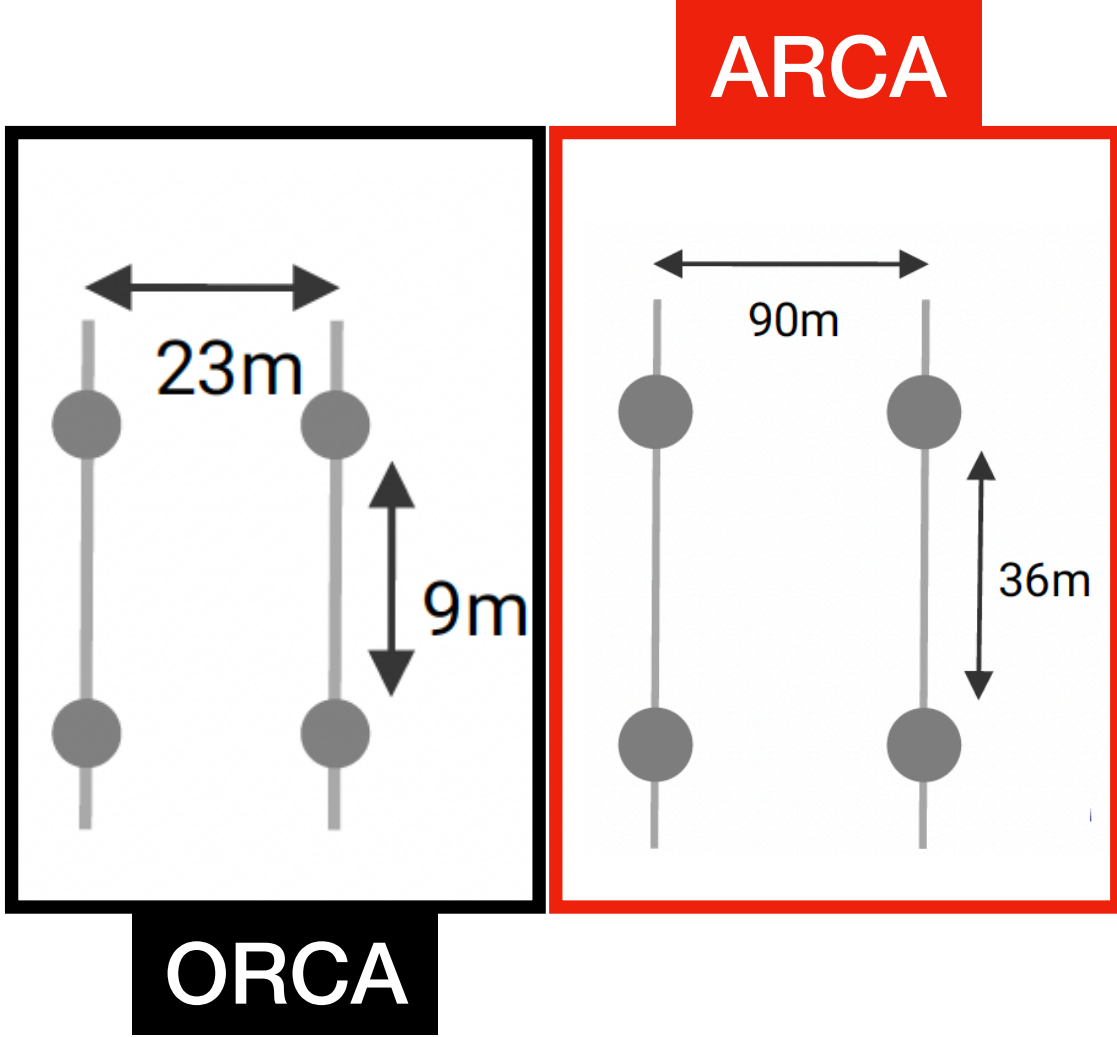
**KM3NeT/ARCA final configuration: 230 DUs
instrumenting about a km³ volume**

KM3NeT: the building block



CREDITS: KM3NeT Collaboration

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DIFFERENT layout
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Building Block: 115 DUs

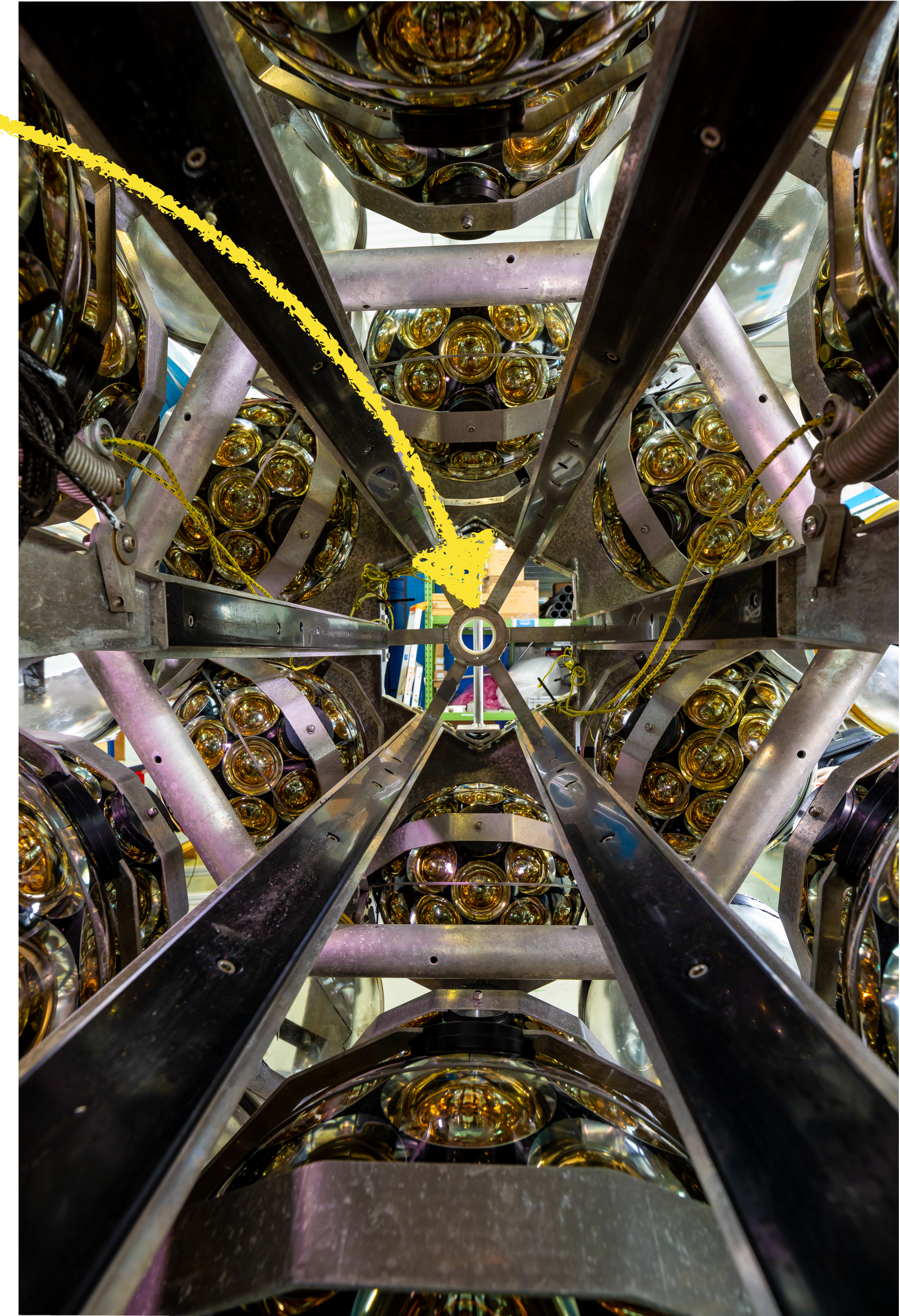
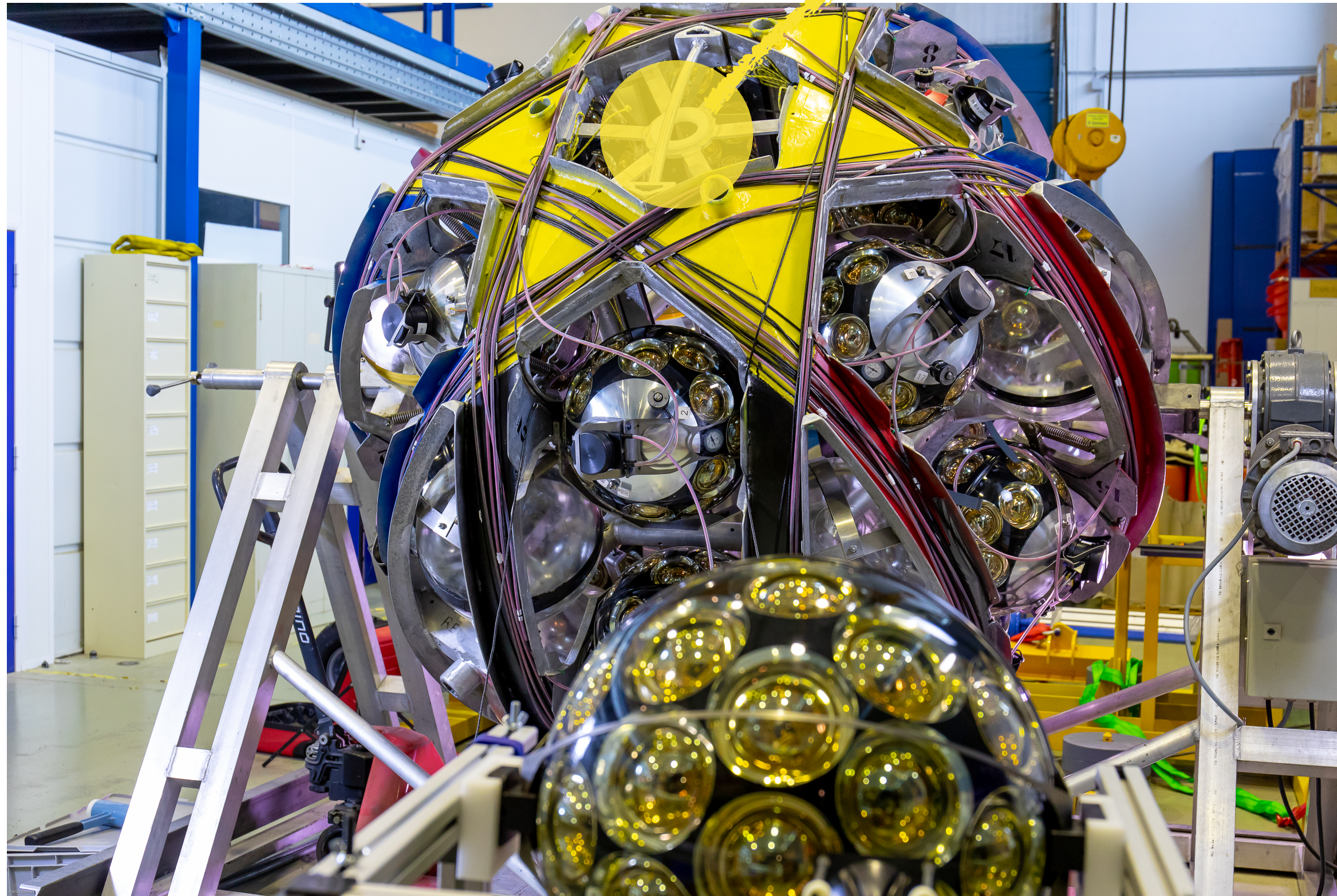
**KM3NeT/ARCA final configuration: 230 DUs
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Deep-sea neutrino telescopes: the construction



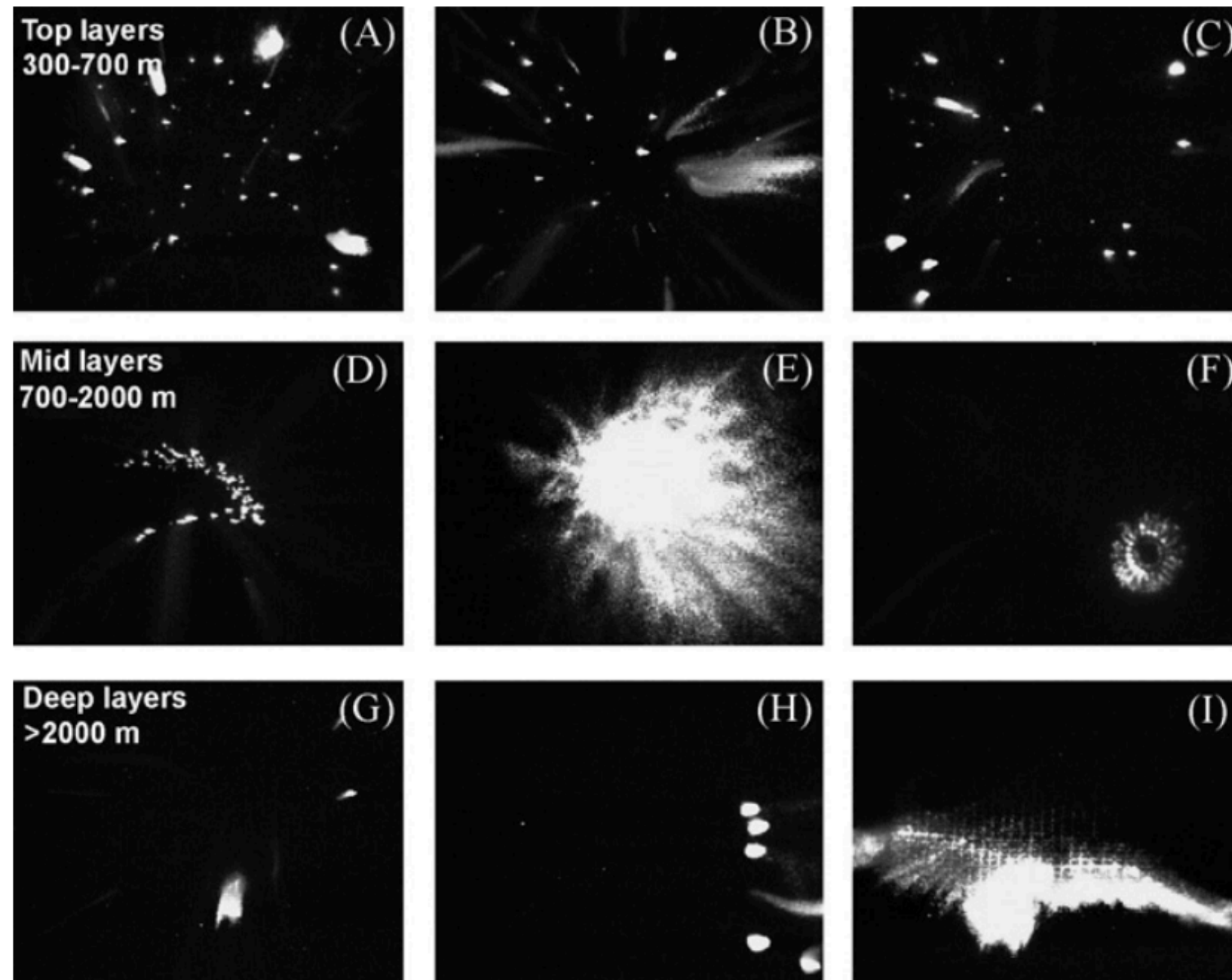
CLICK HERE!

A matter of perspective



KM3NeT: background rejection

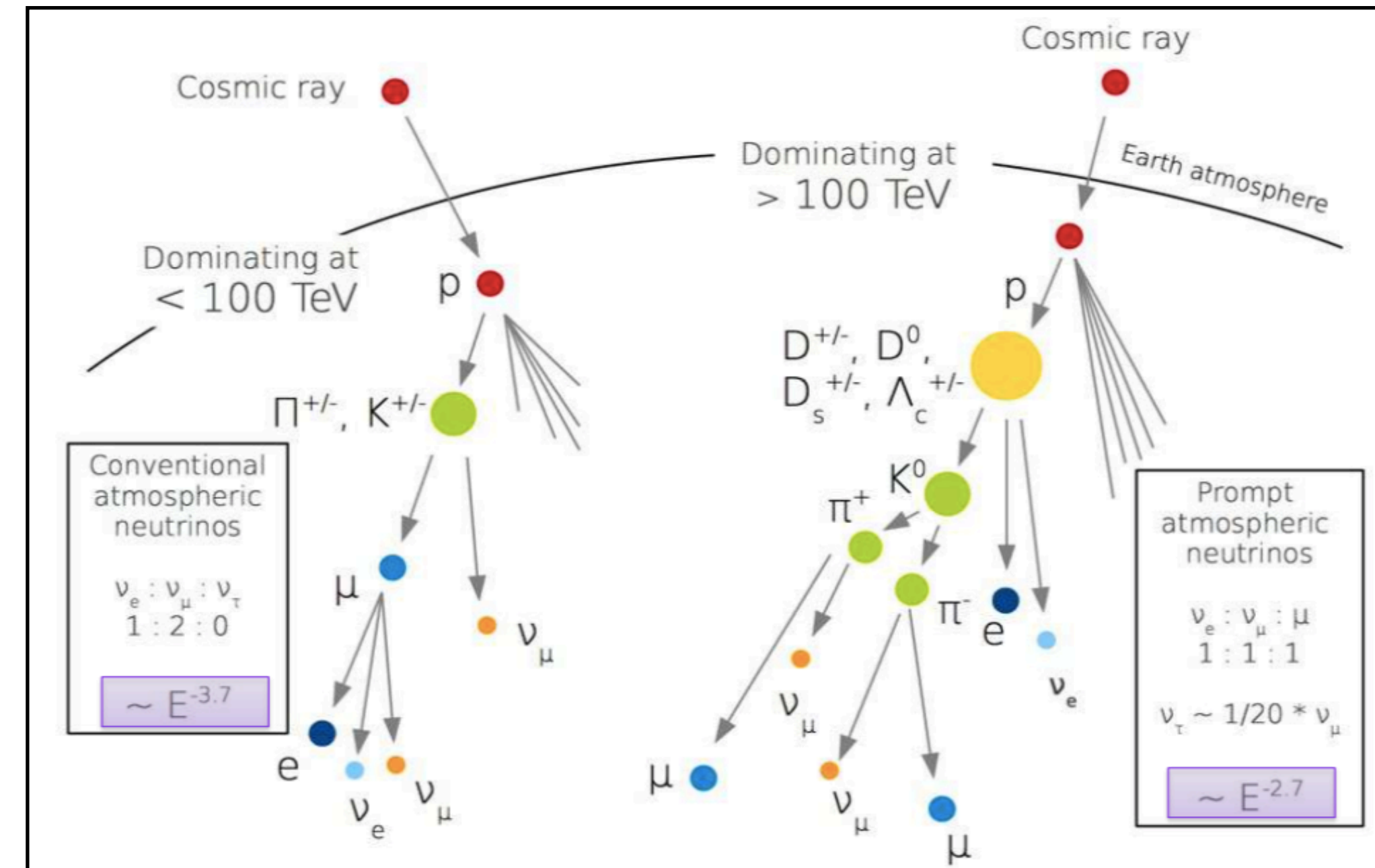
OPTICAL BACKGROUND: Bioluminescence + ^{40}K decay



Heger, A. Et al. (2008). *Deep-sea pelagic bioluminescence over the Mid-Atlantic Ridge*. *Deep Sea Research Part II: Topical Studies in Oceanography*, 55(1–2), 126–136.

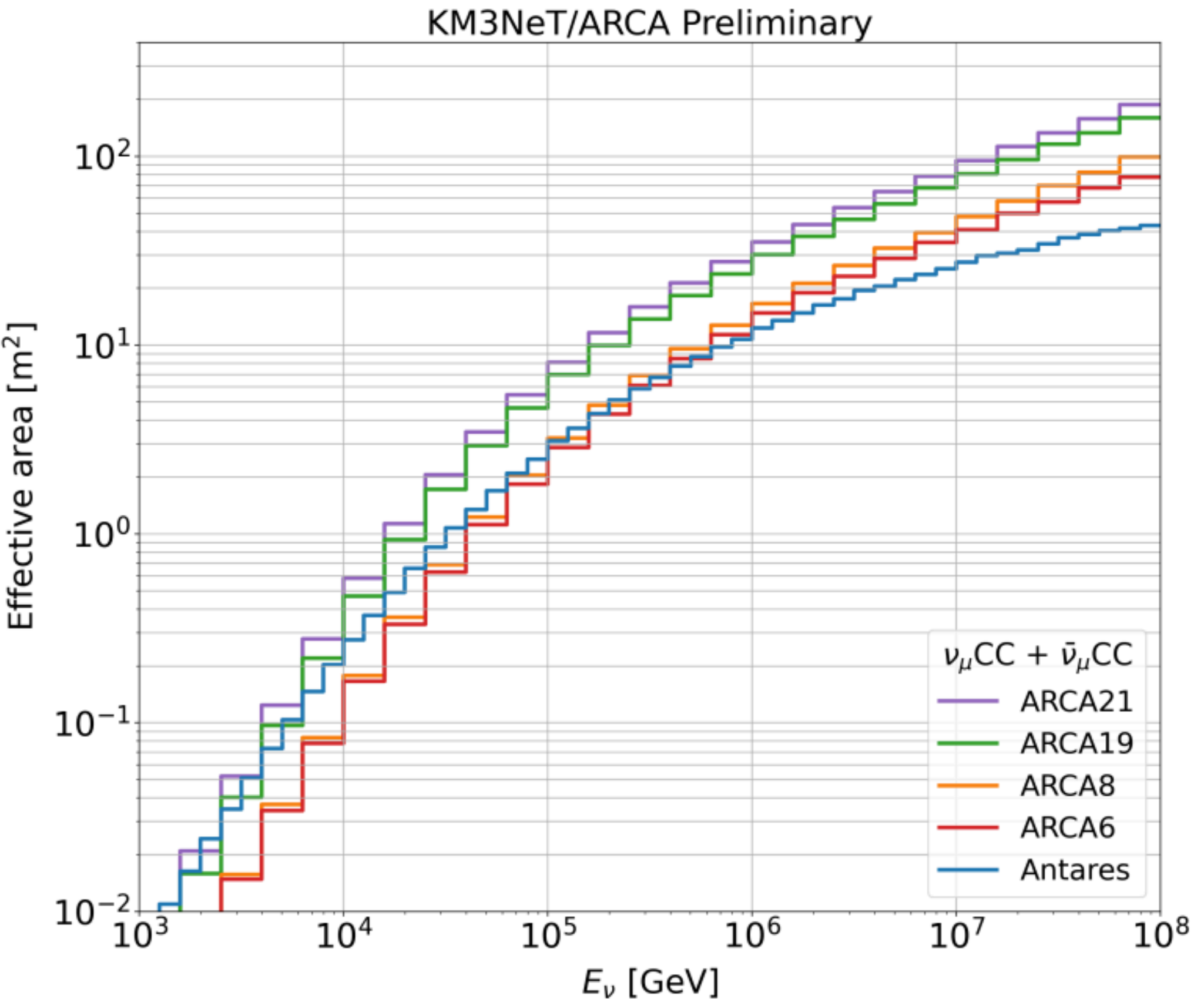
- Hits produced in the apparatus by these processes are not correlated
- Removed at analysis level considering space-time coincidences between hits

PHYSICAL BACKGROUND: μ atmospheric and atmospheric ν_μ



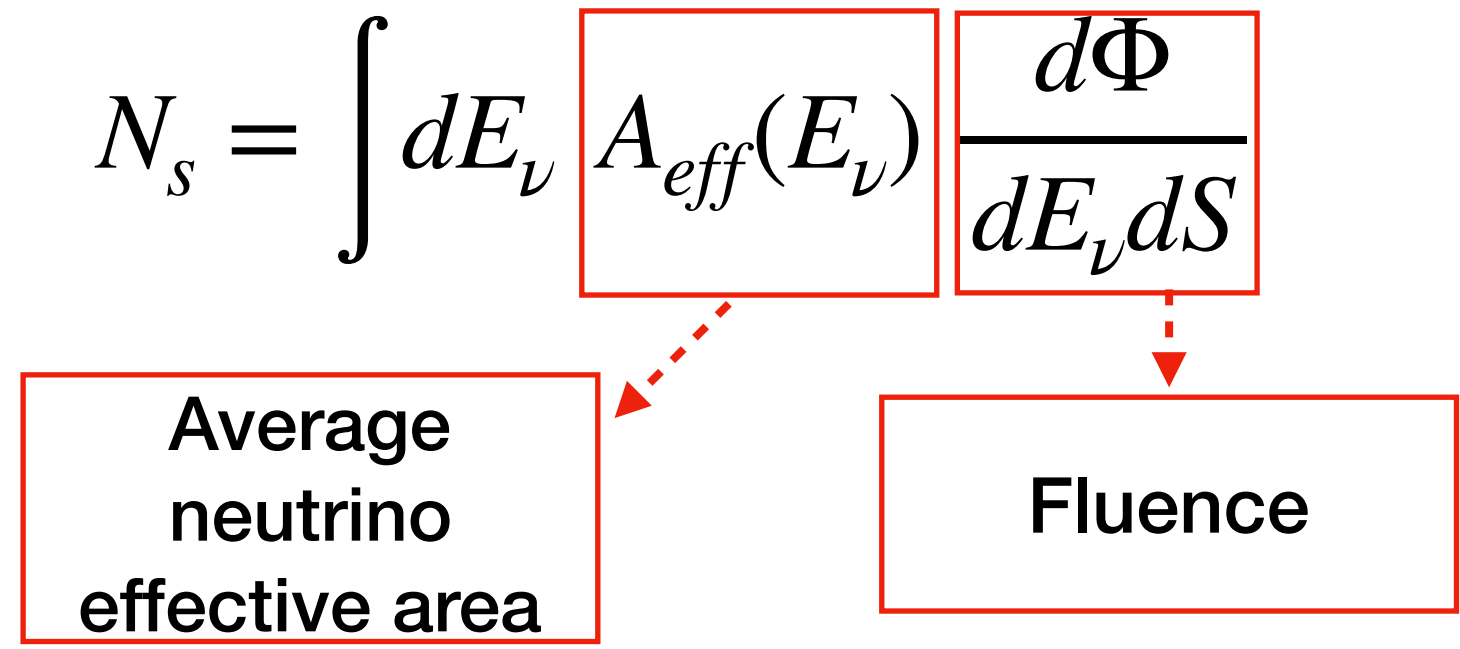
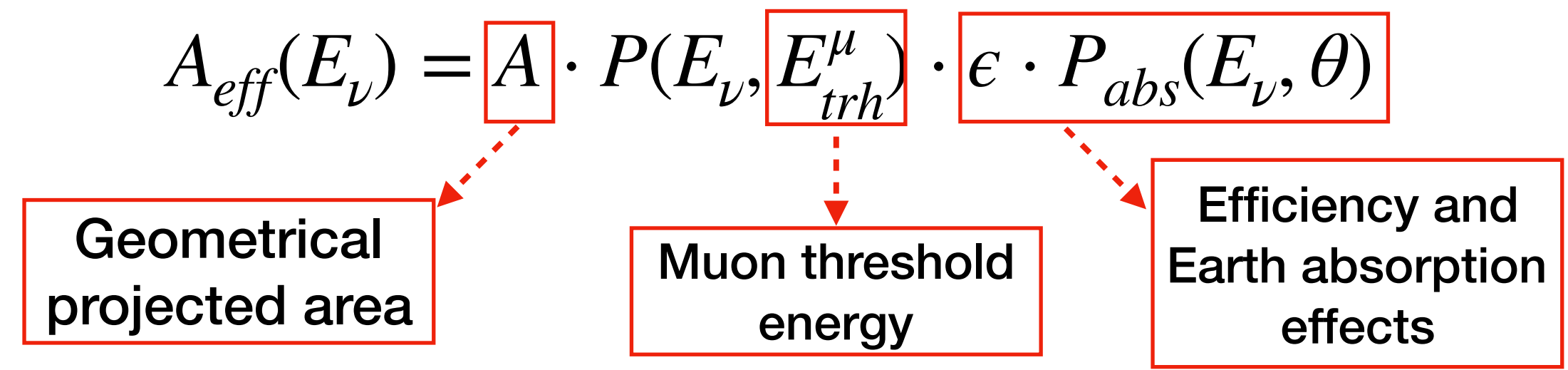
- Atmospheric muons and associated neutrinos are the main sources of background in the detector
- This contribution is reduced selecting events coming from below detector horizon

KM3NeT/ARCA: effective area

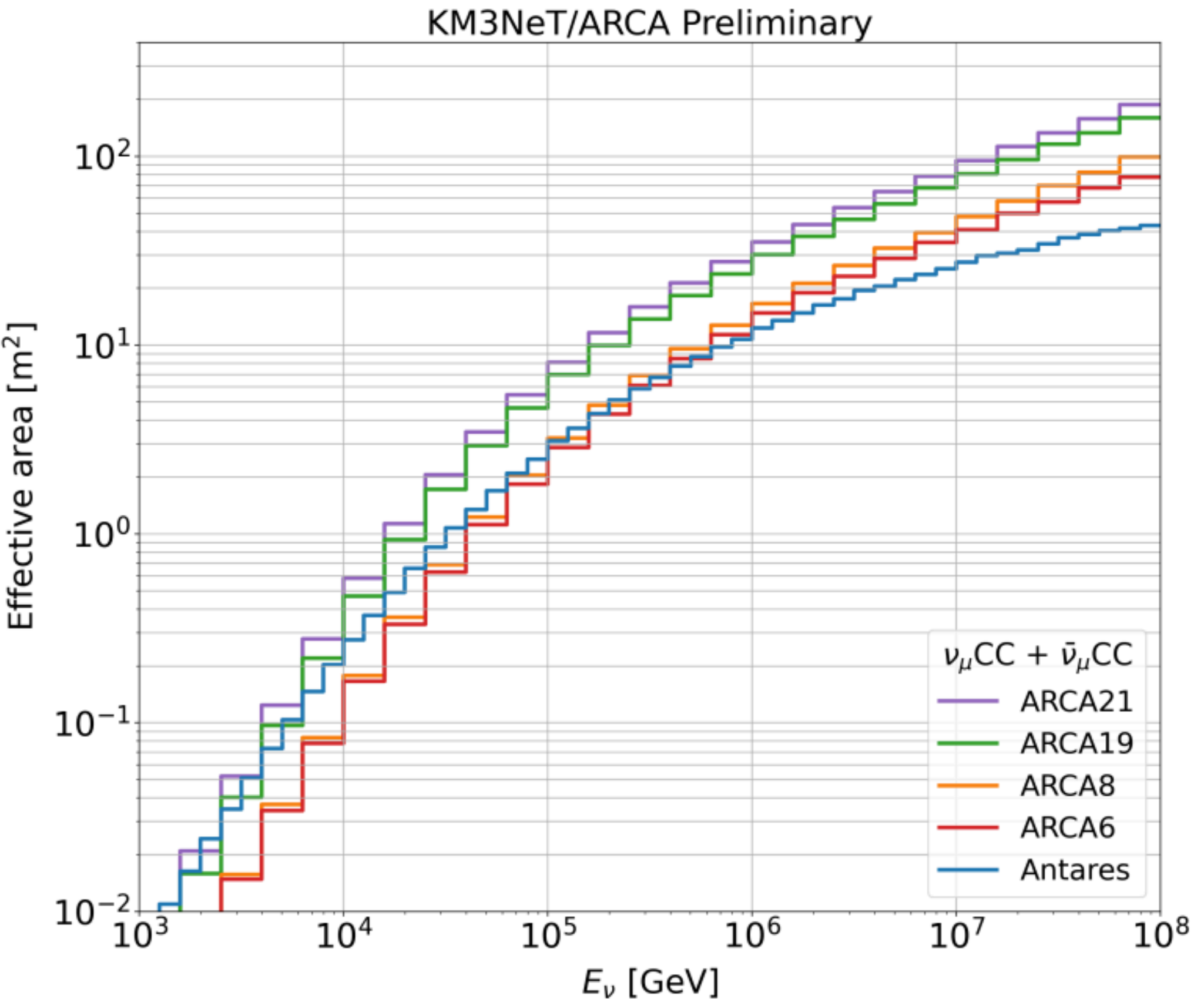


Muller, R., Heijboer, A., & van Eeden, T. (2023). *Search for cosmic neutrino point sources and extended sources with 6-21 lines of KM3NeT/ARCA. PoS, ICRC2023, 1018.*

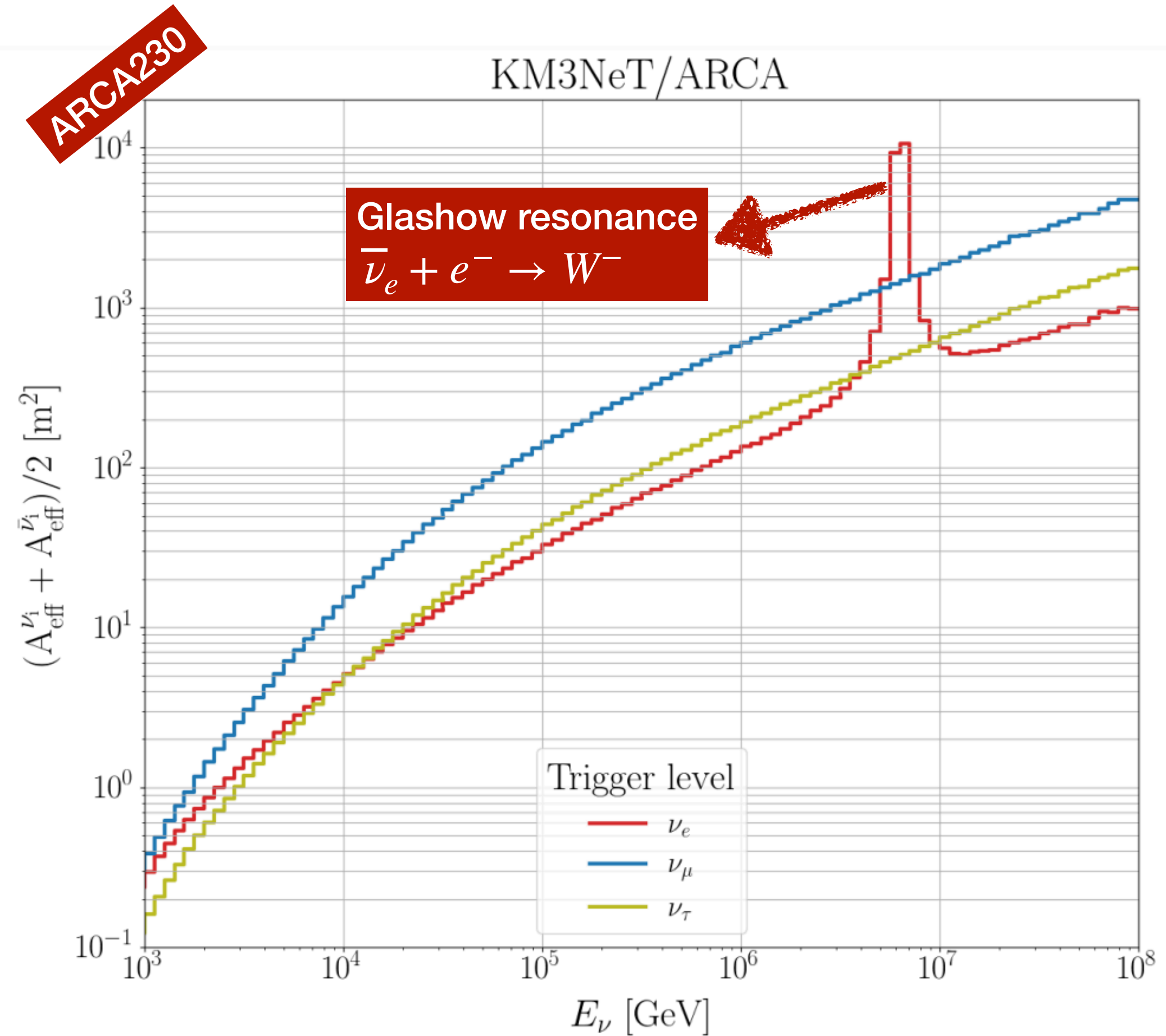
The effective area represents the area of a hypothetical detector that has a 100% neutrino detection efficiency.



KM3NeT/ARCA: effective area

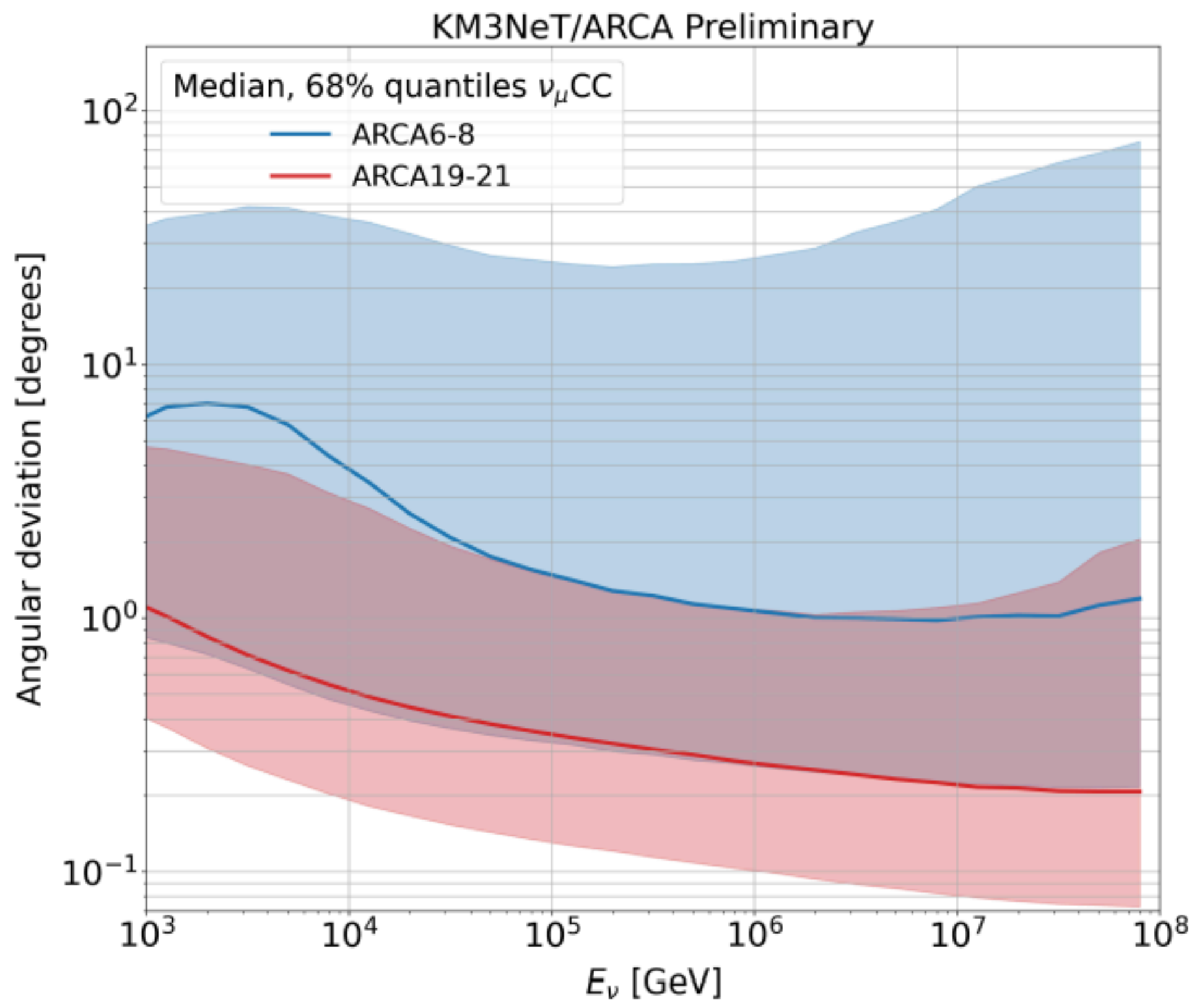


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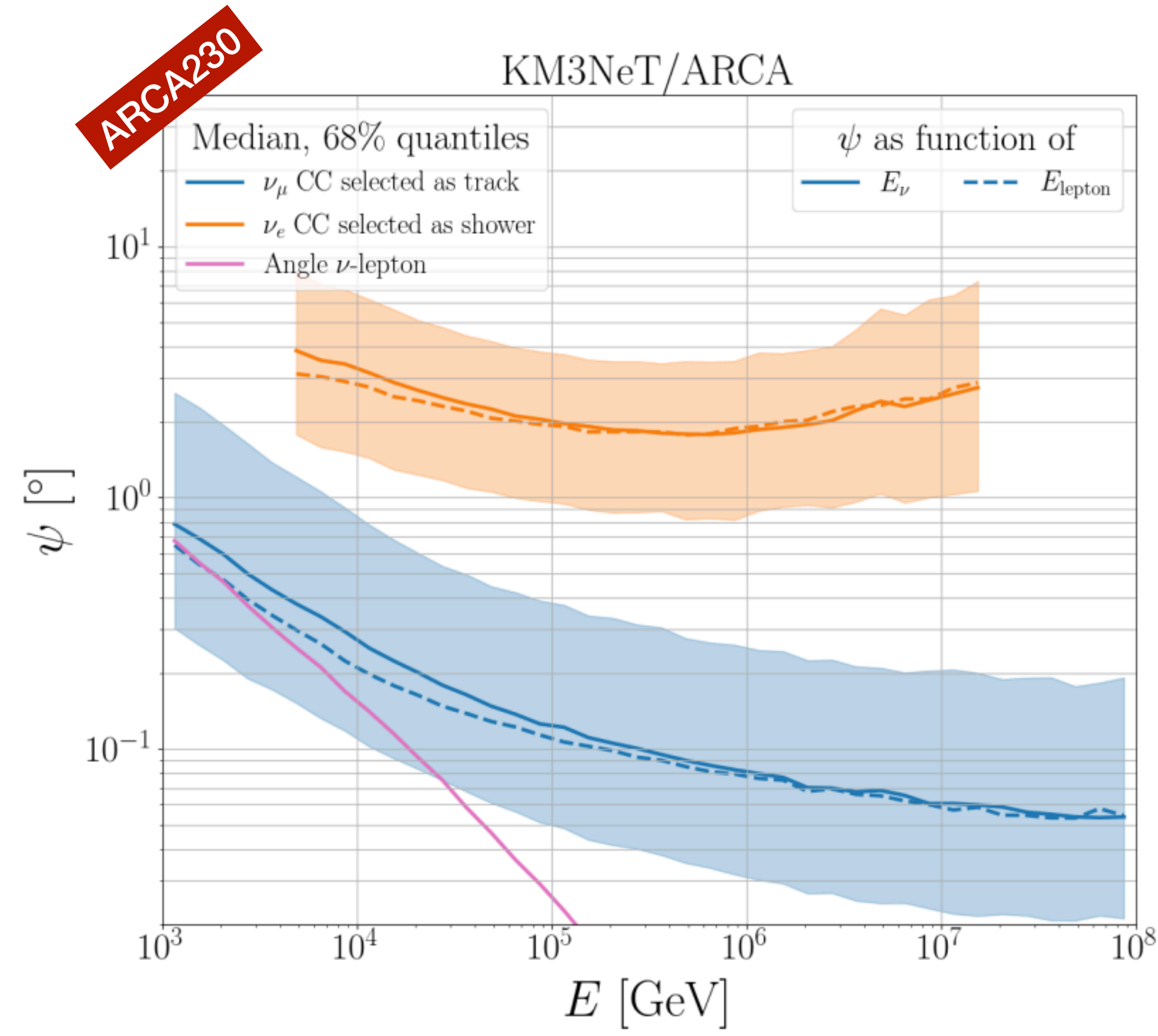


KM3NeT Collaboration (2024). *Astronomy potential of KM3NeT/ARCA*. *European Physical Journal C*, 84(9), 885.

KM3NeT/ARCA: angular resolution

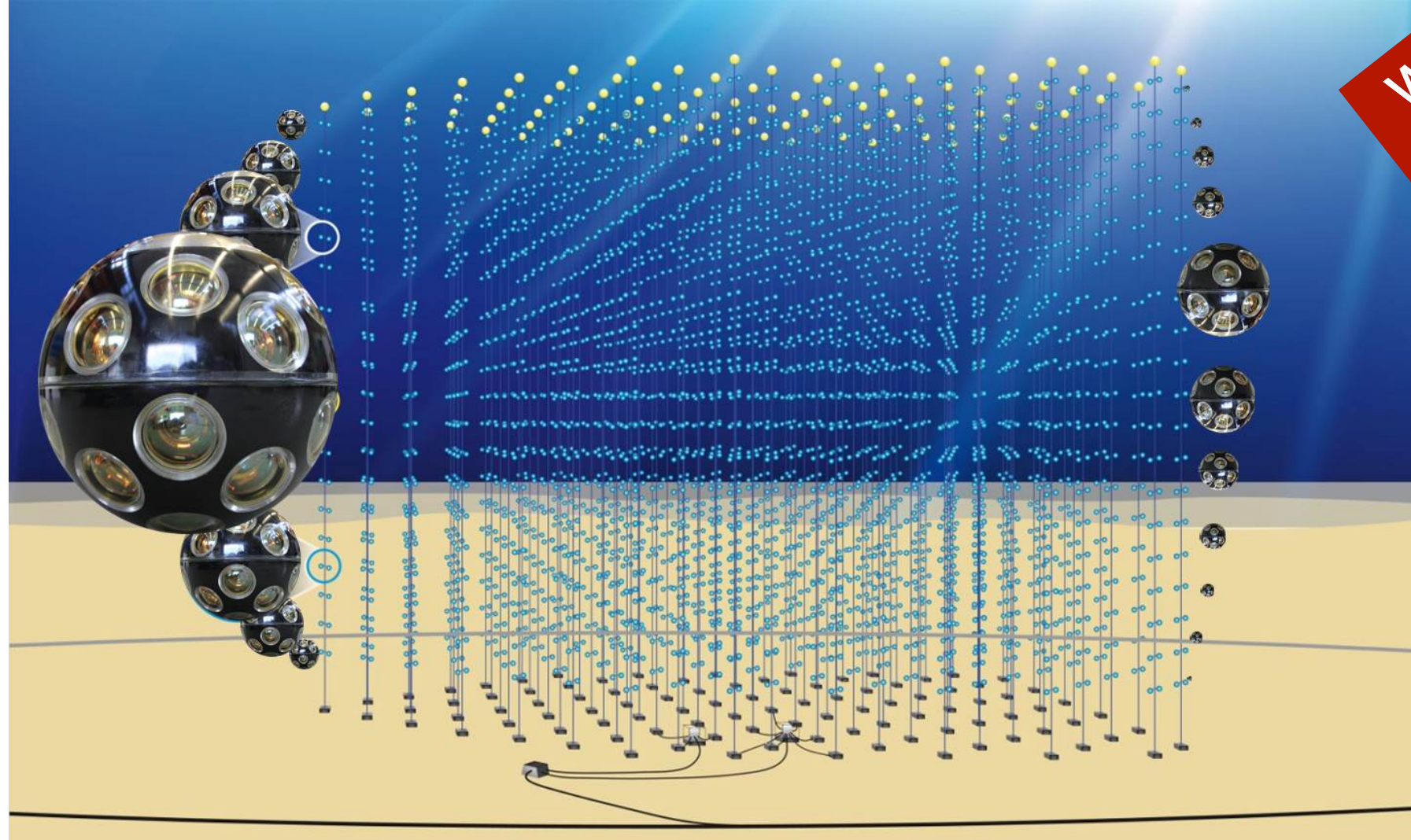


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KM3NeT Collaboration (2024). *Astronomy potential of KM3NeT/ARCA*. *European Physical Journal C*, 84(9), 885.

KM3NeT: alert follow-up strategies



Work in progress

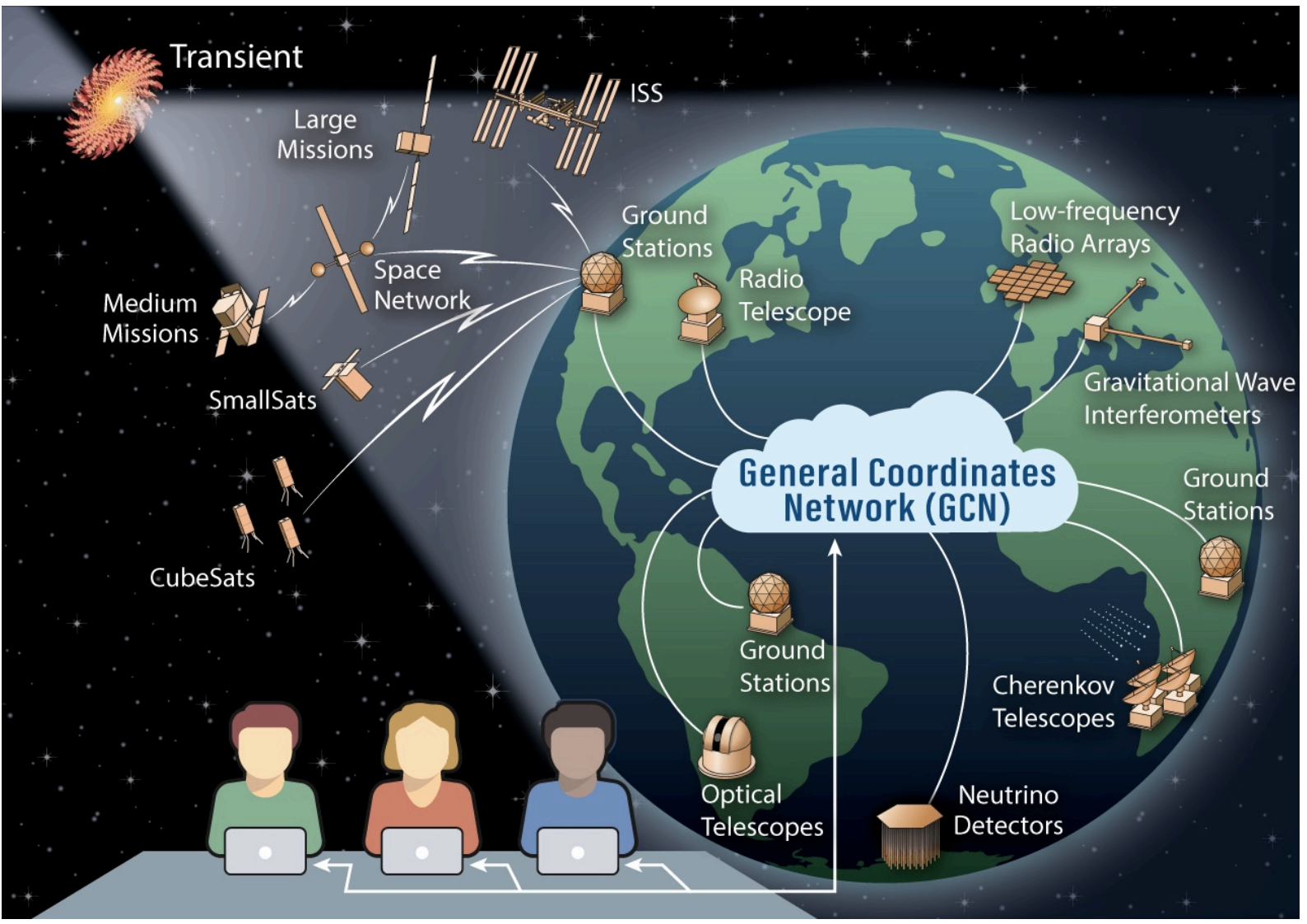
Sending alerts to external communities for follow-ups



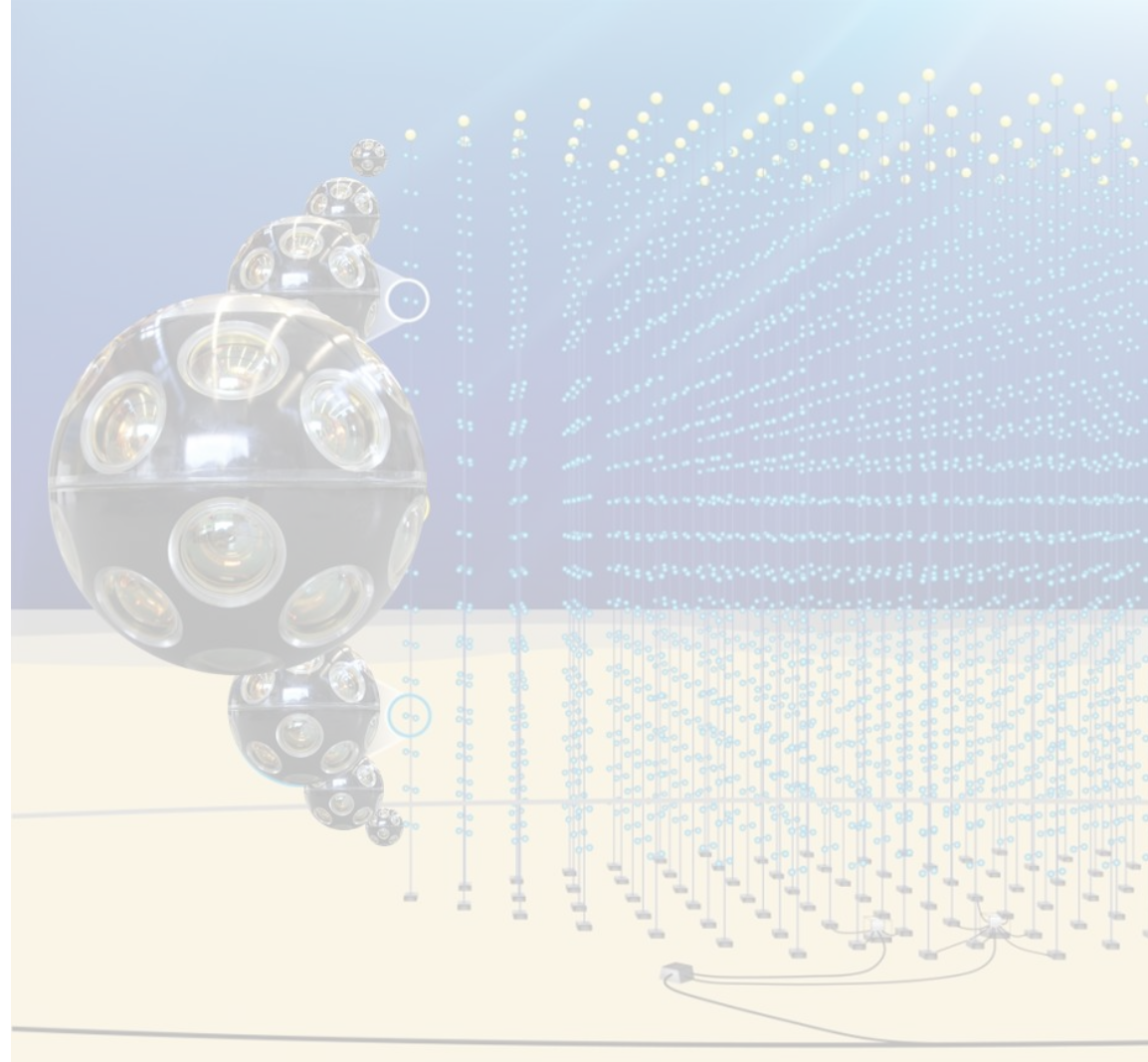
Follow-up of EM/GW/neutrino alerts



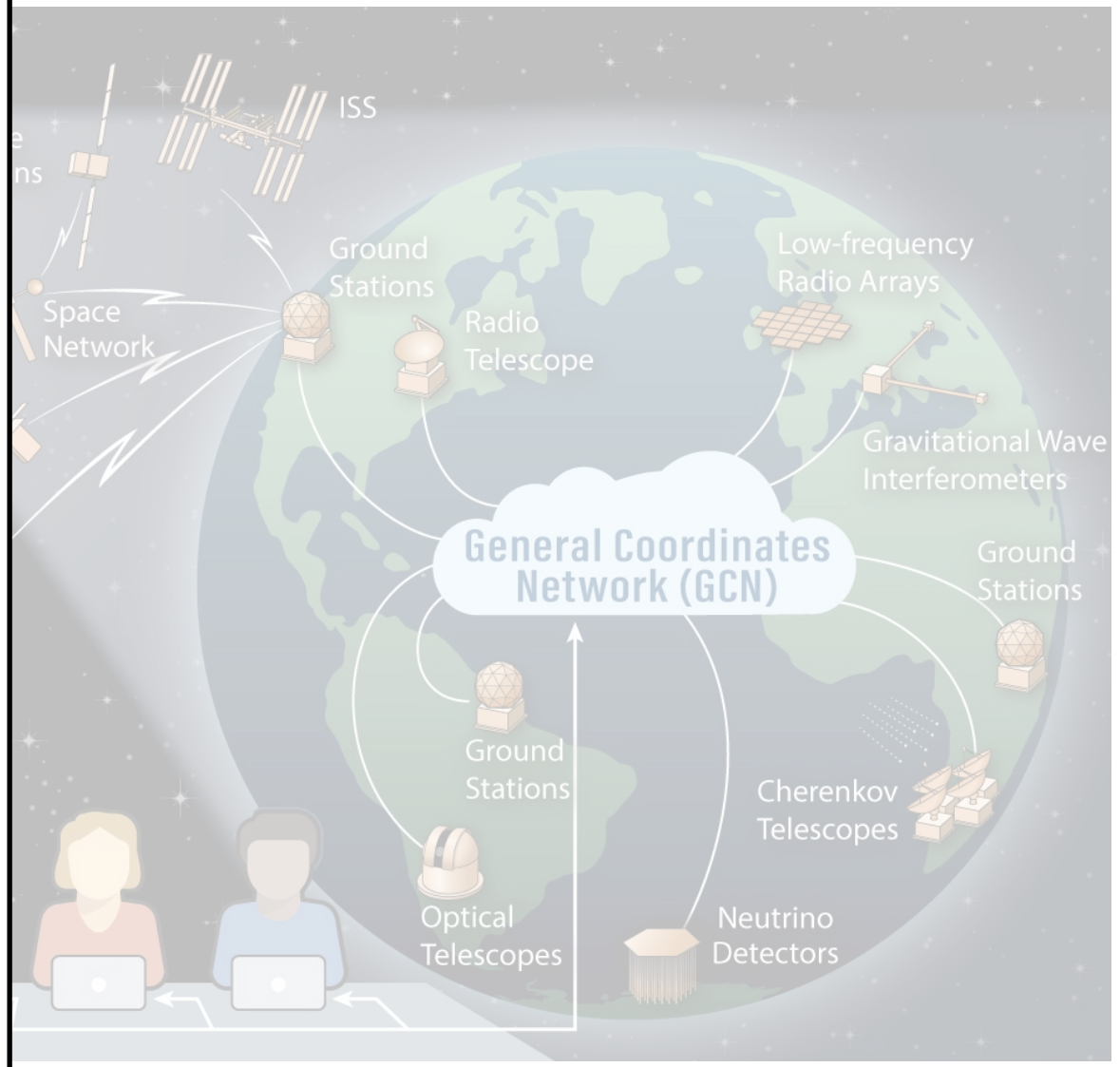
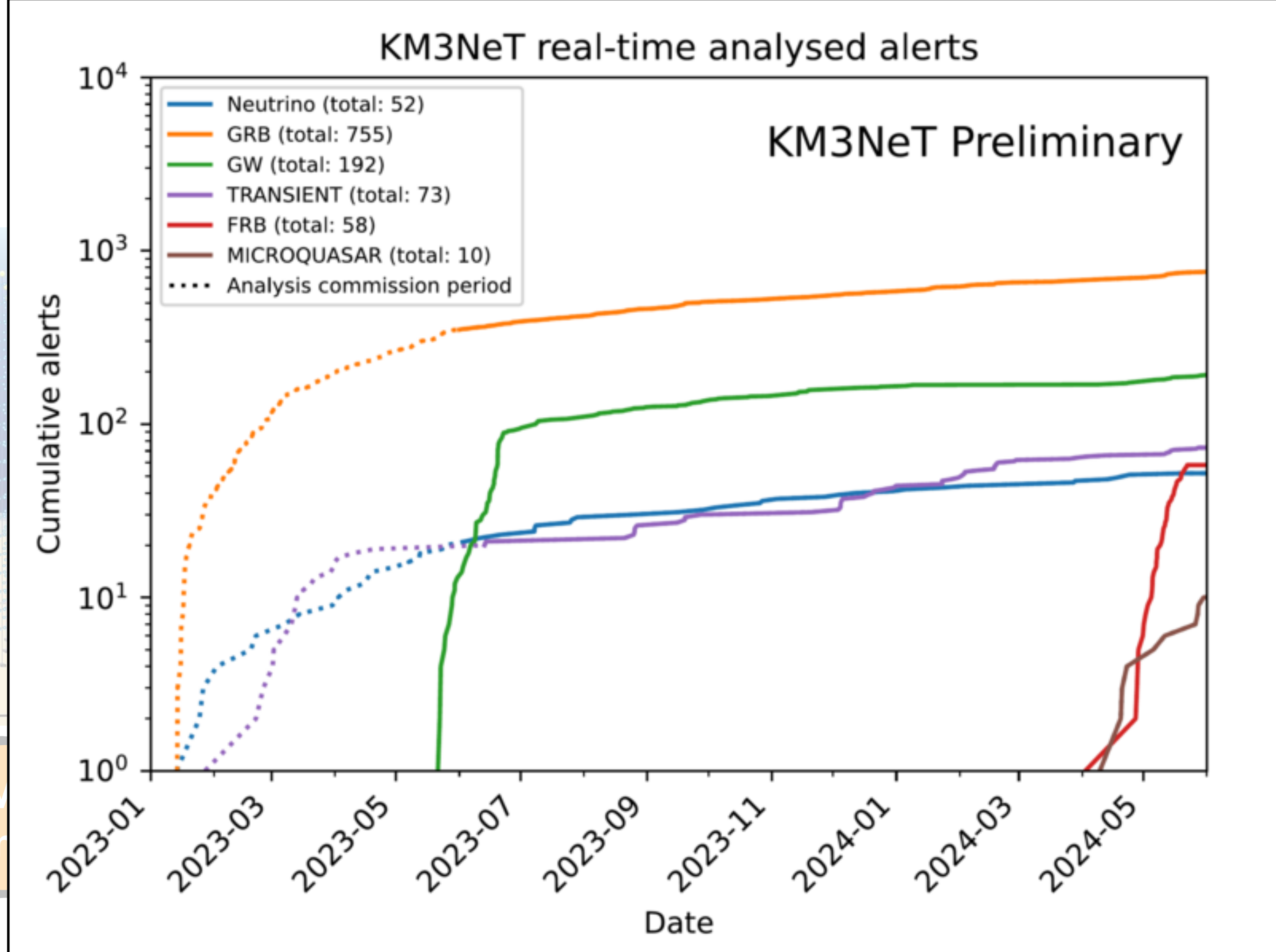
**KM3NeT/ARCA and KM3NeT/ORCA
Data Acquisition level**



KM3NeT: alert follow-up strategies



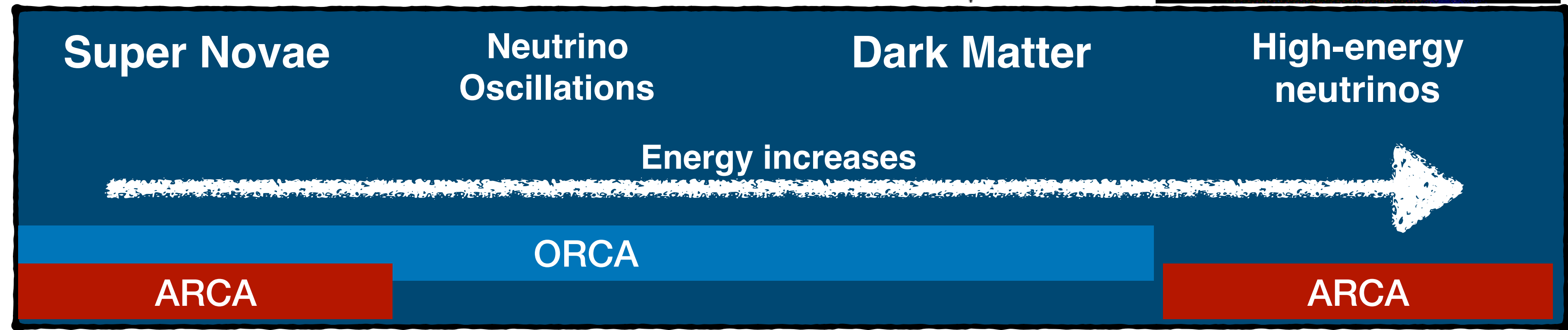
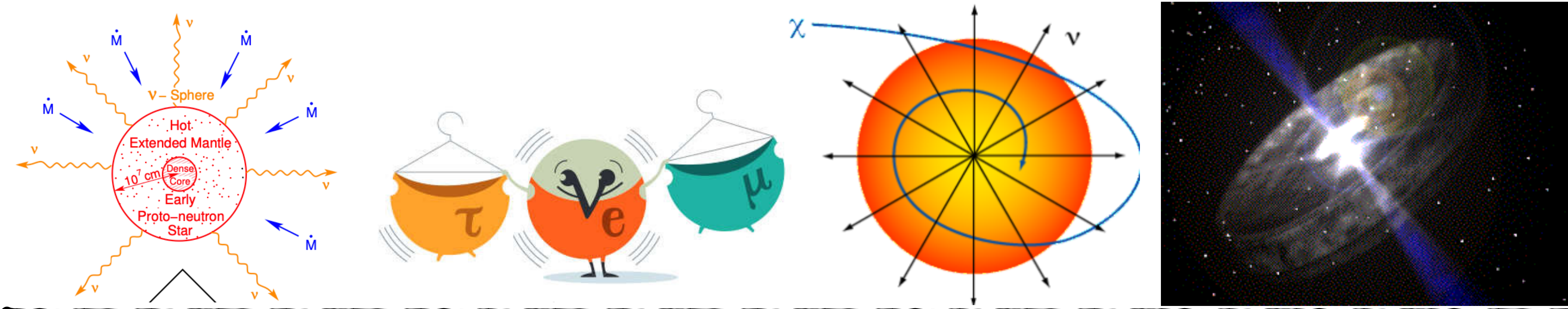
KM3NeT/ARCA and KM3NeT Data Acquisition



Del Rosso, I. (2024). Results of the follow-up of external triggers with KM3NeT. Zenodo. <https://doi.org/10.5281/zenodo.13899346>

All the physics we can do

- **KM3NeT is gonna be a real multipurpose laboratory**
- **There is an exciting future ahead!**
- **Are you curious? Visit our website: km3net.org**



An important announcement!

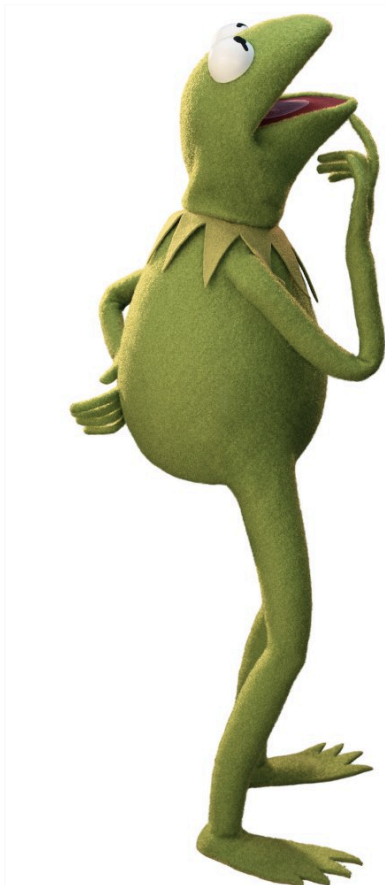
'Fantastic' particle could be most energetic neutrino ever detected

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

By [Davide Castelvecchi](#)



An observatory still under construction at the bottom of the Mediterranean Sea has spotted what could be the most energetic neutrino ever detected. Such ultra-high-energy neutrinos – tiny subatomic particles that travel at nearly the speed of light – have been known to exist for



25 giugno 2024

Una particella "fantastica" potrebbe essere il neutrino più energetico mai rilevato

di Davide Castelvecchi/Nature



Cinque rivelatori ARCA a bordo di una nave, pronti per l'impiego (© KM3NeT Collaboration)

An important announcement!


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An observatory still under construction... what could be the most energetic neutrino... tiny subatomic particles that travel at n...



Save the date!
February 12th 2025
starting from 4.50 p.m. CET
International streaming on YouTube:
KM3NeTneutrino Channel
Announcement of the detection!

ere il neutrino



Cinque rivelatori ARCA a bordo di una nave, pronti per l'impiego (© KM3NeT Collaboration)



Thanks for your attention!

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