

Multi-messenger astronomy



Harm
Schoorlemmer.
Topical lectures
July 2026

Radboud University



Program

<https://indico.nikhef.nl/event/7880/>

- Lectures on cosmic rays: Teresa
- Lectures on detection: Charles
- Lectures on gamma-rays: Jim
- Lectures on neutrinos: Juan
- Hands-on detection: Charles
- Hands-on public data: Harm
- Presentations: You
- Social Event: Pim van Dillen

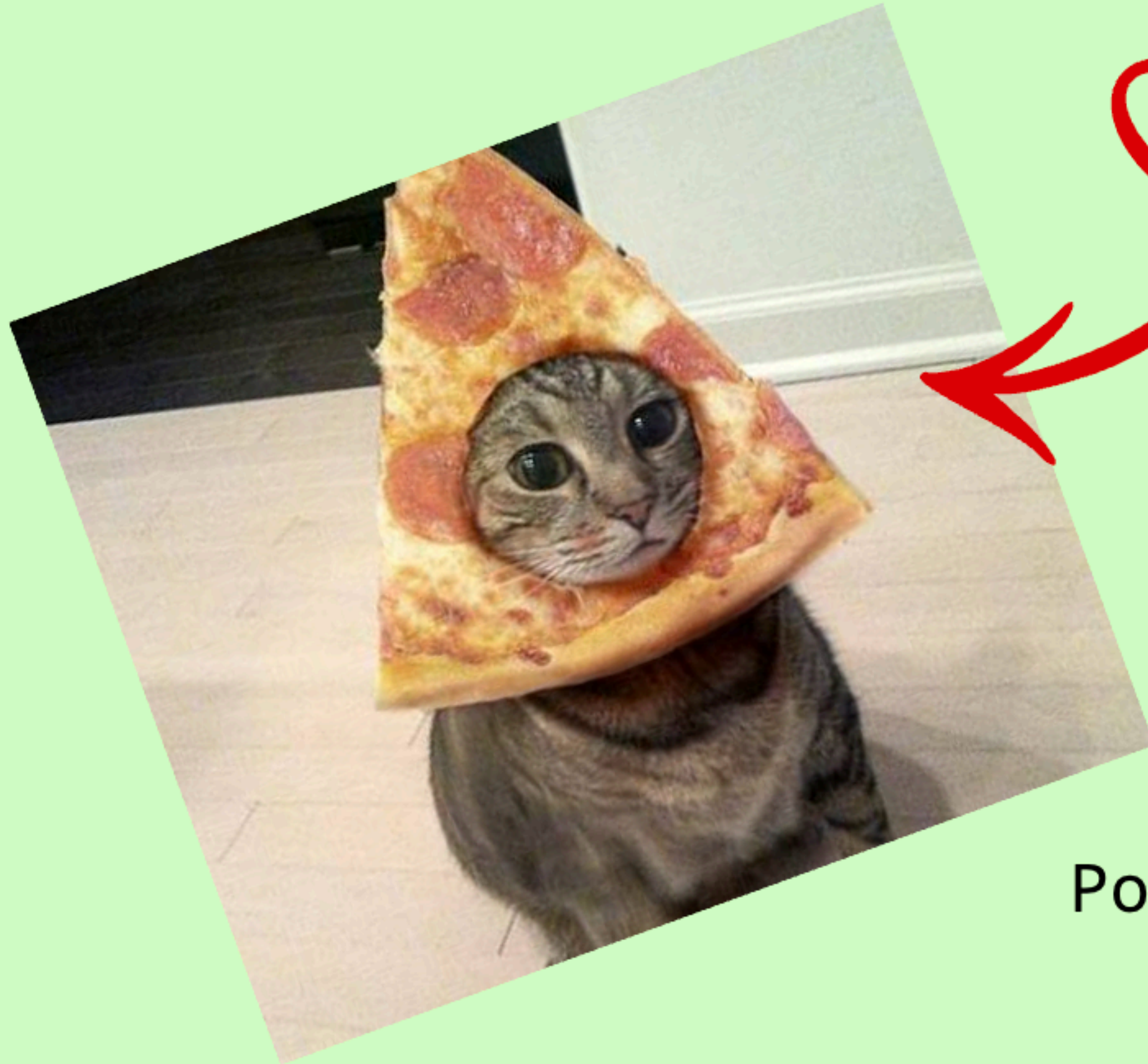
MONDAY, 6 JULY			
10:00	→ 11:00	Introduction Speaker: Harm Schoorlemmer (Radboud University Nijmegen)	🕒 1h 📄
11:00	→ 11:30	Break	🕒 30m
11:30	→ 12:30	Cosmic rays and sources 1 Speaker: Teresa Bister	🕒 1h 📄
12:30	→ 13:30	Lunch	🕒 1h
13:30	→ 14:30	Cosmic ray detection: KORSTMOS Speaker: Charles Timmermans	🕒 1h 📄
14:30	→ 15:00	Break	🕒 30m
15:00	→ 17:00	Hands on cosmic ray detection	🕒 2h 📄
TUESDAY, 7 JULY			
09:30	→ 10:30	Gamma Rays 1 Speaker: Prof. Jim Hinton (Max Planck Institut fuer Kernphysik)	🕒 1h 📄
10:30	→ 11:00	Break	🕒 30m
11:00	→ 12:00	Gamma Rays 2 Speaker: Jim Hinton (Max Planck Institut fuer Kernphysik)	🕒 1h 📄
12:00	→ 13:00	Lunch	🕒 1h
13:00	→ 14:00	Cosmic rays and sources 2 Speaker: Teresa Bister	🕒 1h 📄
14:00	→ 14:30	Break	🕒 30m
14:30	→ 15:30	Using public events Speaker: Harm Schoorlemmer (Radboud University Nijmegen)	🕒 1h 📄
15:30	→ 17:30	Hands on: Public events	🕒 2h 📄
18:00	→ 21:00	Possible Social Event	🕒 3h
WEDNESDAY, 8 JULY			
09:30	→ 10:30	Preparation for presentations	🕒 1h 📄
10:30	→ 11:00	Break	🕒 30m
11:00	→ 12:00	Neutrino Astronomy 1 Speaker: Dr Juan Aguilar (Université Libre de Bruxelles)	🕒 1h 📄
12:00	→ 13:00	Lunch	🕒 1h
13:00	→ 14:00	Neutrino Astronomy 2 Speaker: Juan Aguilar (Université Libre de Bruxelles)	🕒 1h 📄
14:00	→ 14:30	Break	🕒 30m
15:00	→ 17:00	Presentationa	🕒 2h 📄

Social event

By:



When: Tomorrow (Tuesday 7th Juli)
Whats included: Food & Prison Island



Times

Food: ~18:00
Activity: 19:00

Possibility for drinks afterwards!
(own costs)

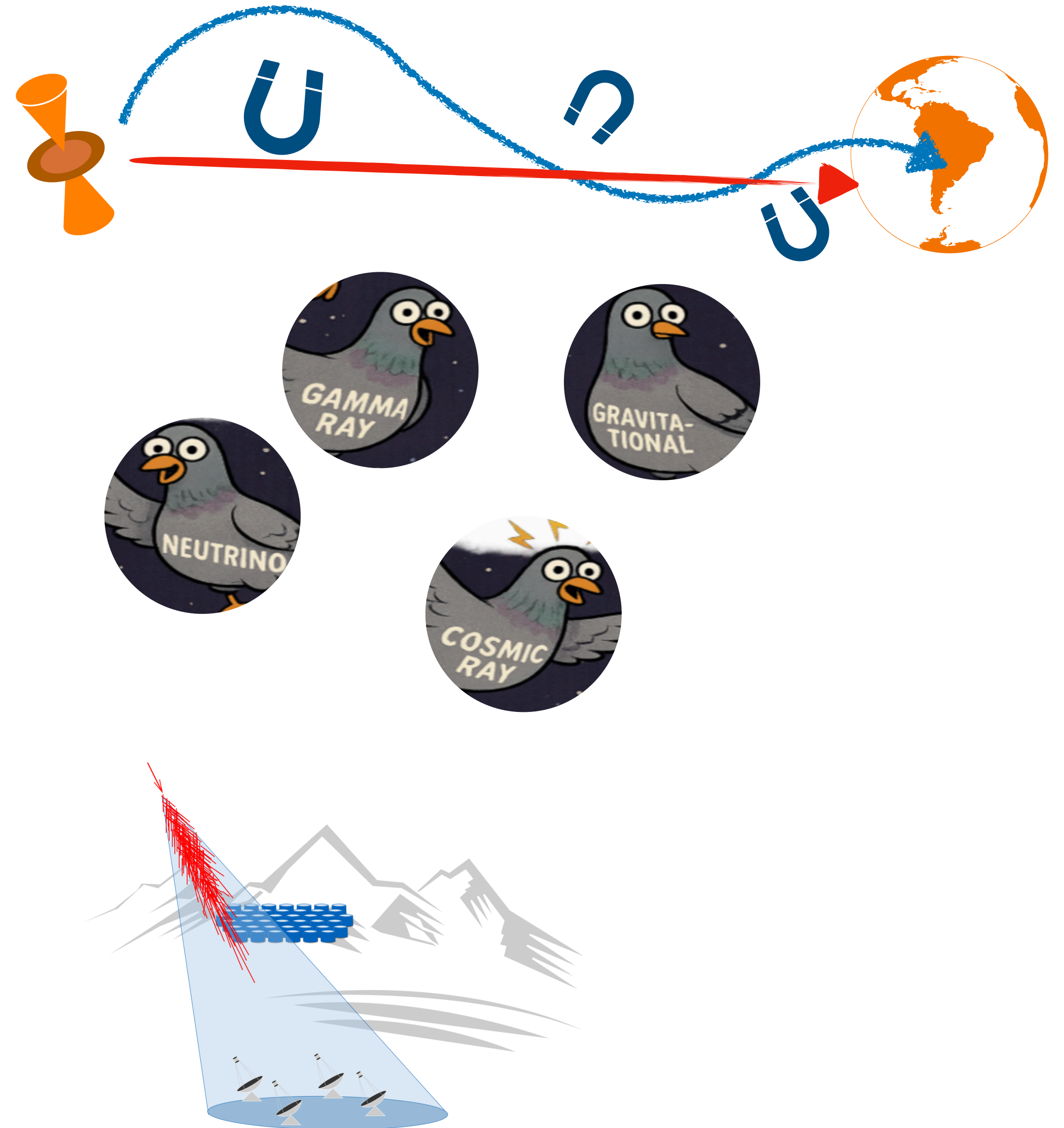
Sign up in teams on the sheet!



phdcouncil@nikhed.nl

Multi-messenger astronomy

- Messengers: are particles (including photons) or gravitational waves
- An astrophysical object/event can cause signals in multiple type of messengers
- Often these messengers are observed by different observatories
- Observatories have increased their sensitivity and accuracy over the last decades



Cosmic rays: Accelerated charged particles by astrophysical processes

Maximum energy for a particle with charge Ze in static electric field $\mathcal{E}$, accelerated over length L

$$E_{\max} = Ze\mathcal{E}L$$

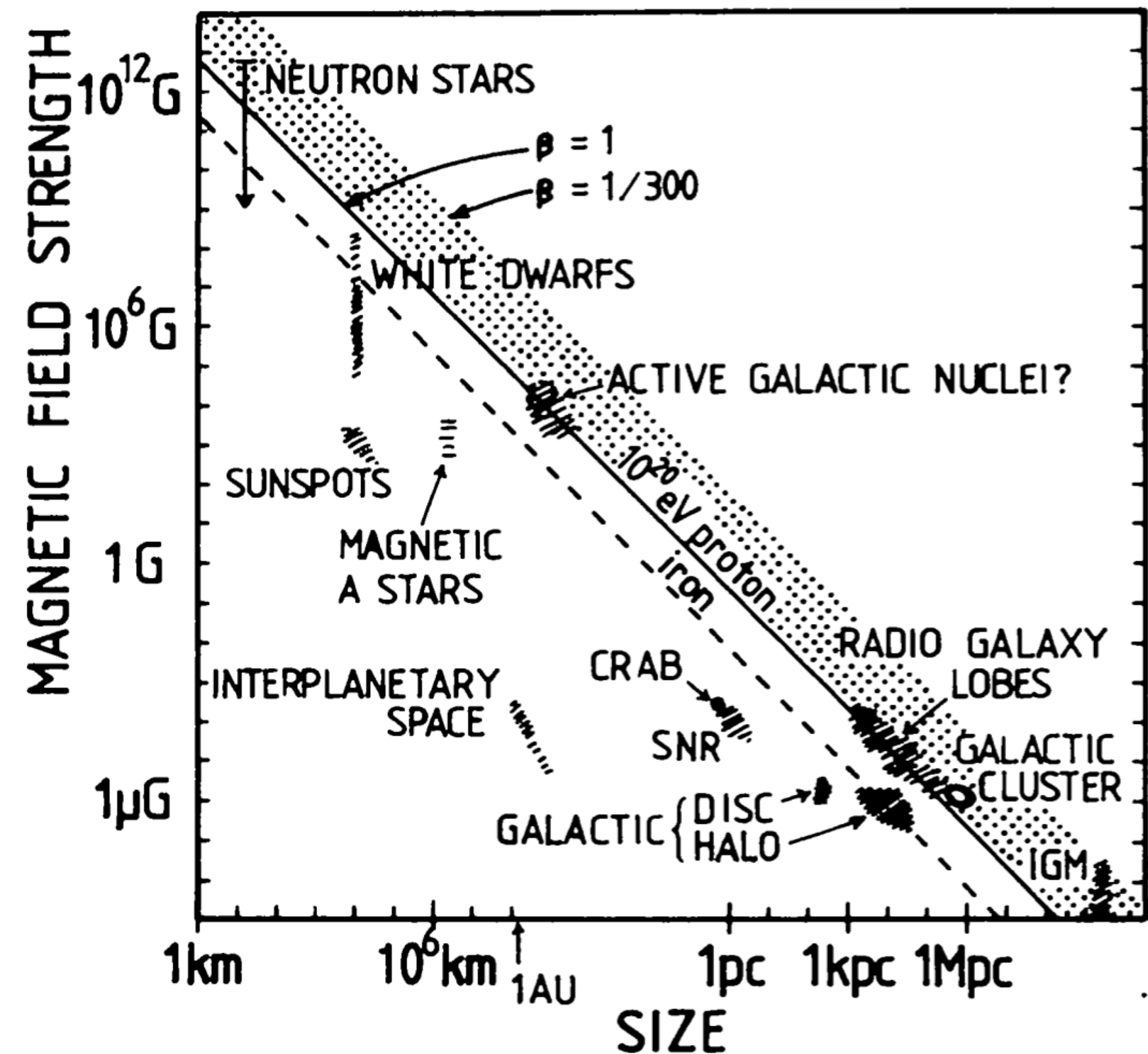
Plasmas are conductive, quickly cancelling static electric-fields. However, magnetic fields are everywhere inducing electric fields:

$$\mathcal{E} = \vec{\beta} \times \vec{B} \quad \text{with } \vec{\beta} = \vec{v}/c \text{ the plasma velocity}$$

The resulting maximum reachable energy

$$E_{\max} = ZeL\beta B$$

(See also talk by Teresa)



A.M. Hillas *Ann. Rev. A&A*

Propagating charged particles through space

Charged particles are deflected by the Lorentz force in **galactic** and **inter-galactic** magnetic fields

Gyroradius in a magnetic field: $r = \frac{\beta \gamma m_0 c}{qB}$

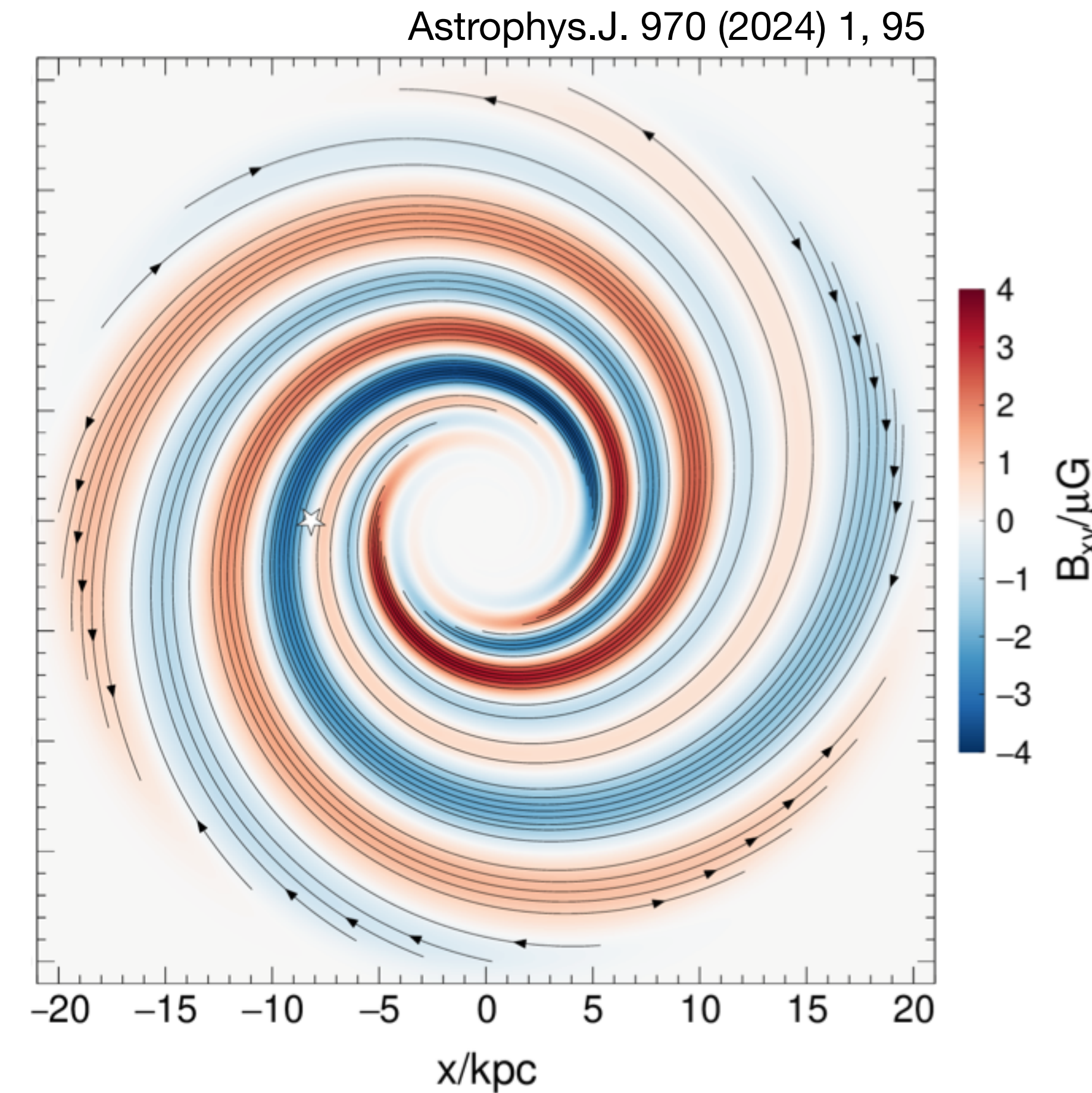
higher energy:
less deflection

lower charge:
less deflection

Large scale astrophysical magnetic fields:

- Coherent component → deflection (back tracking possible)
- Random / Turbulent → scattering

Effects of astrophysical magnetic fields, see also talk by Teresa



Production of energetic neutral particles

Caused by interactions of energetic charged particles with either **matter** or **radiation fields**

Hadronic

Proton proton interacties (or different hadrons)

$$p_{cr} + p \rightarrow \text{hadrons}$$

Photomeson interacties (photo-hadronic)

$$p_{cr} + \gamma \rightarrow \text{mesons (pions)}$$

Production of mostly pions, which decay to make secondary photons and neutrinos

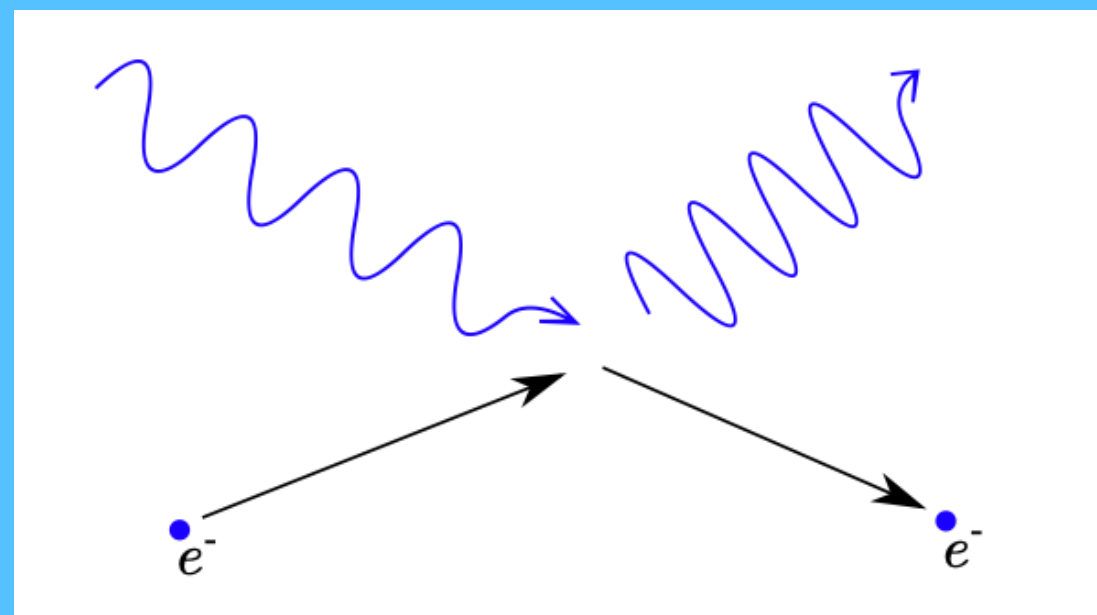
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

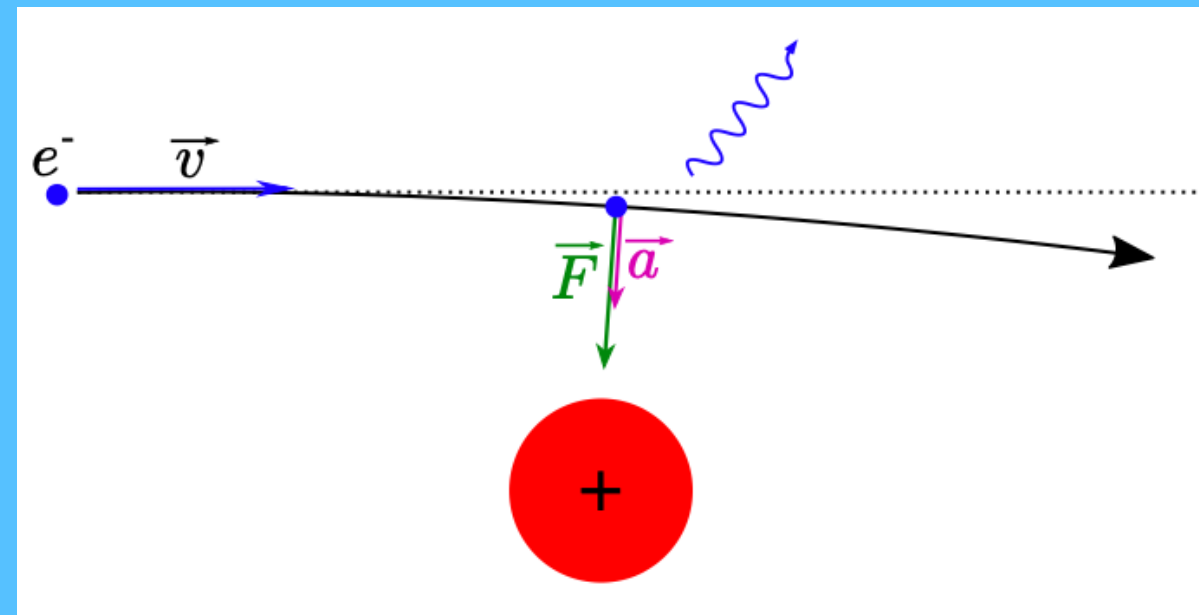
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Leptonic

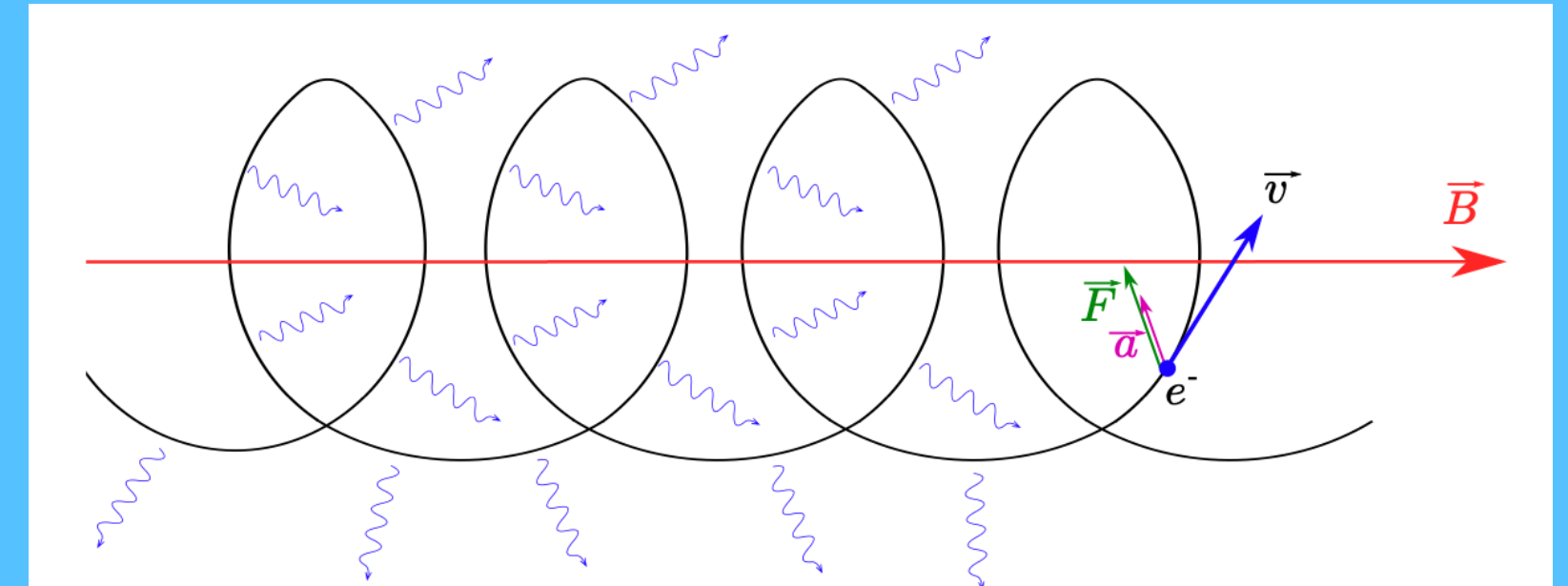
Inverse Compton scattering



Bremsstrahlung



Synchrotron radiation



No neutrino production!

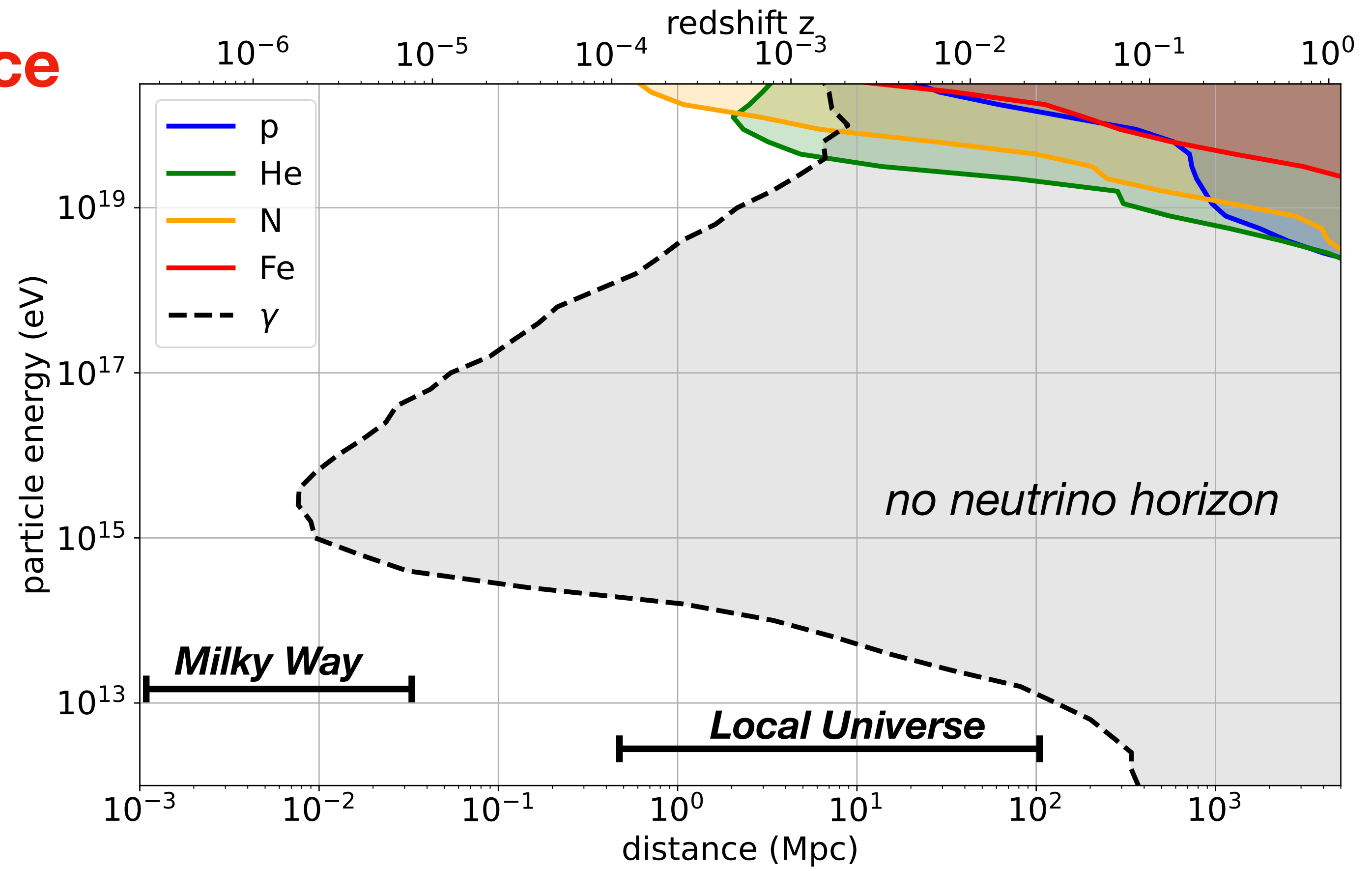
Propagating particles through space

The universe is filled with $\epsilon \sim 1 \times 10^{-3}$ eV photons the Cosmic Microwave Background radiation

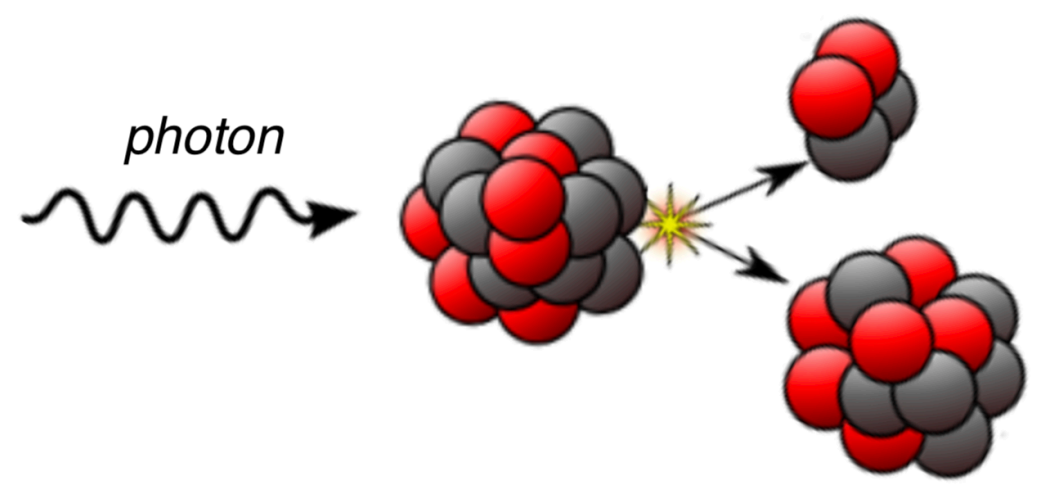
Interactions Pion production (Greisen-Zatsepin-Kuzmin):

$$\gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\gamma_{CMB} + p \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

$$E_{GZK} = \frac{m_{\pi}(m_p + m_{\pi})}{2\epsilon} \approx 7 \times 10^{19} eV$$


For heavier nuclei, photo disintegration becomes important at similar energy scale



Photons, will pair-produce with Extra-galactic Background Light

$$\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$$

above an energy of:

$$E_{\gamma} E_{EBL} > 2(m_e c^2)^2$$

Electrons will loose energy near the source, due to inverse compton scattering



Charged particle
that gets
accelerated

Get deflected in
magnetic fields

Can lose
energy in
interactions with
radiation fields



Caused by
cosmic ray
hadronic
interactions

Not deflected in
magnetic fields

"No"
interactions



Caused by cosmic
ray **hadronic &
leptonic**
interactions

Not deflected in
magnetic fields

Lose energy in
radiation fields



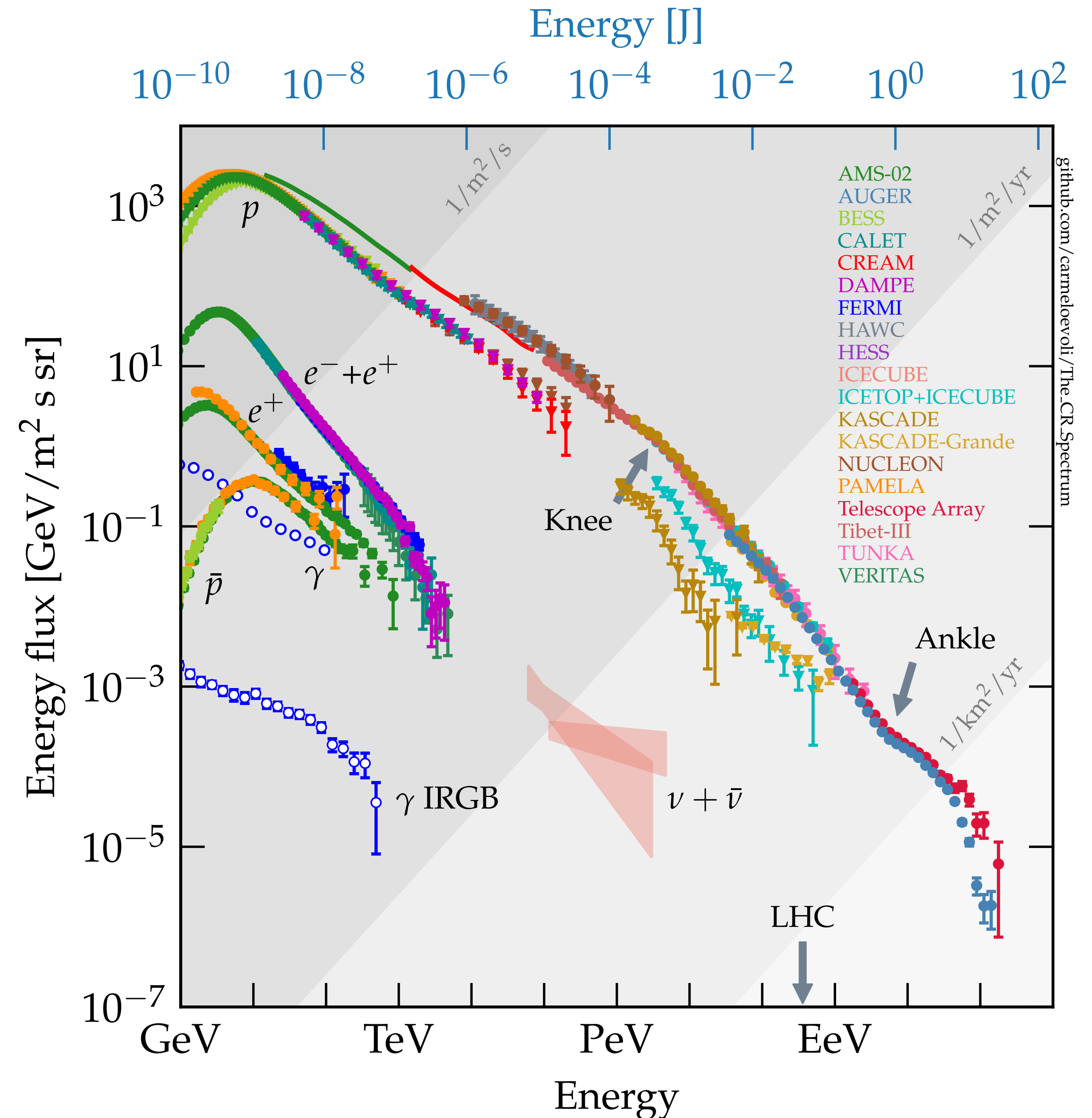
Caused by
merger of
compact
objects

Not deflected in
magnetic fields

"No"
interactions

Lets take stock: Energy of particles arriving at Earth

- Several species of particles, protons and other atomic nuclei are most common
- Electrons up to roughly a TeV
- Photons (γ -rays) have been observed up to a few PeV (not shown)
- Neutrinos are observed in the TeV-PeV range

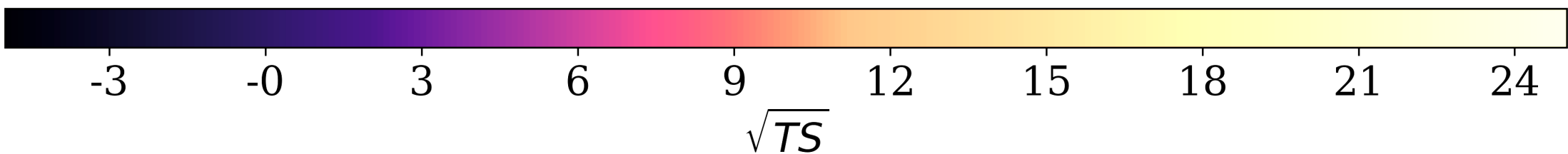
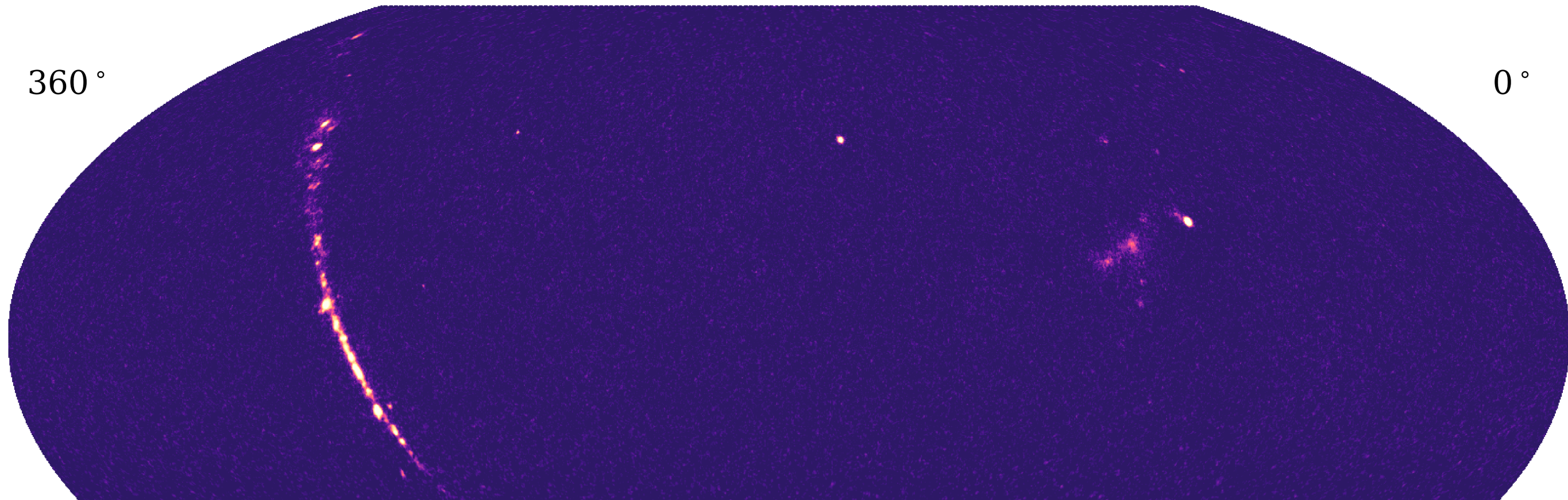


Lets take stock: arrival directions

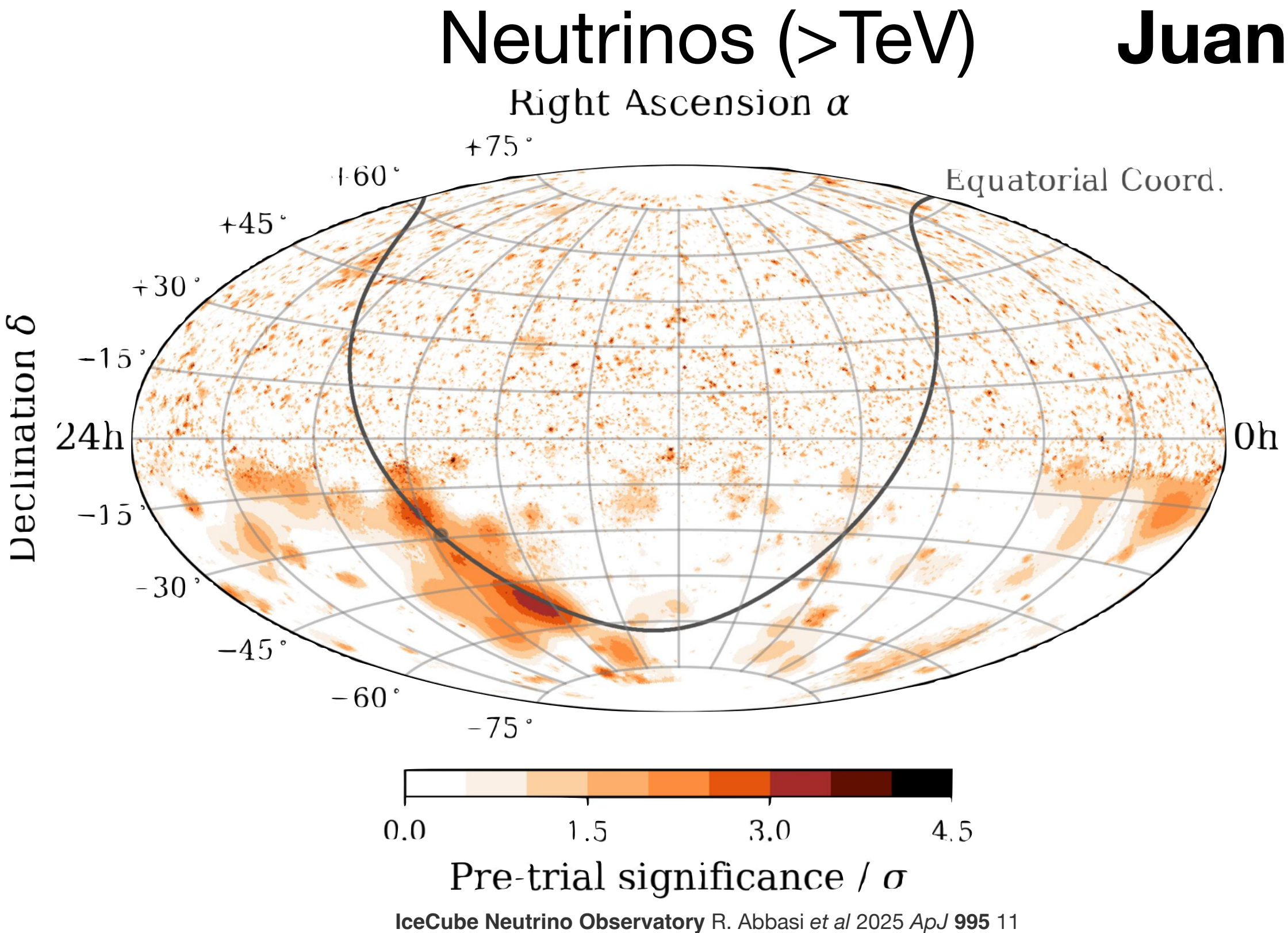
Neutrinos (>TeV) Juan

photons (> TeV) Jim

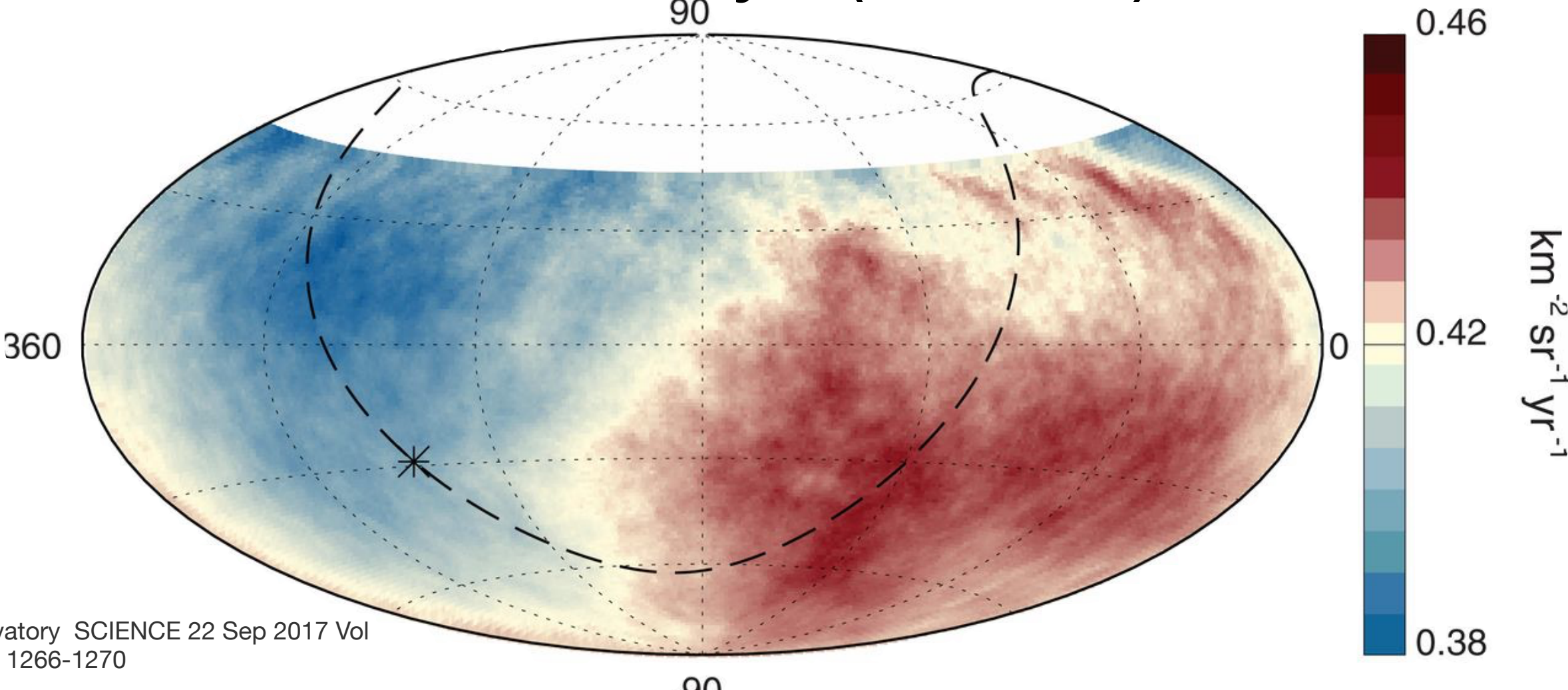
All-sky view; 0°; 2090 days



HAWC Collaboration (2025)



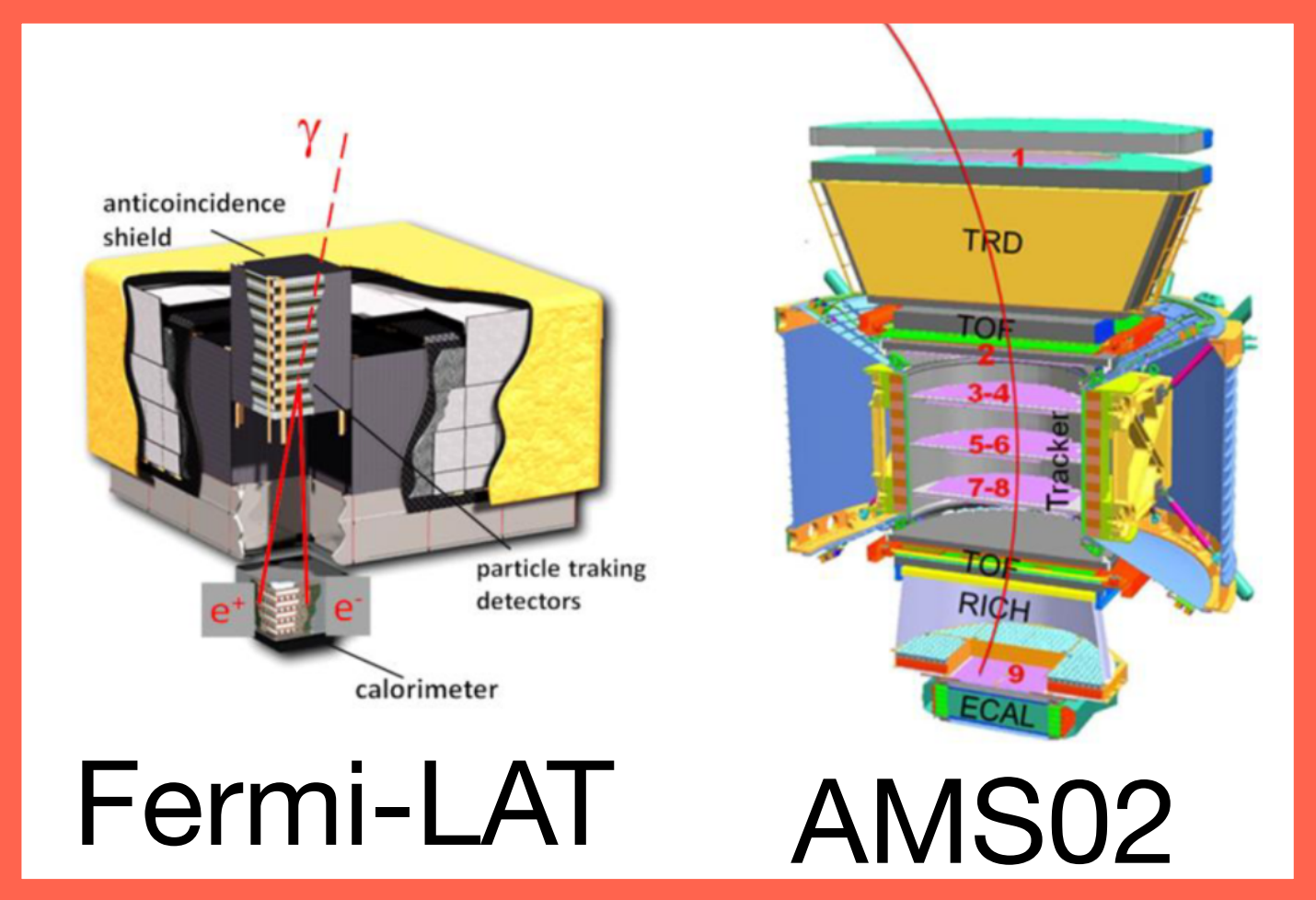
Cosmic rays (>8 EeV) Teresa



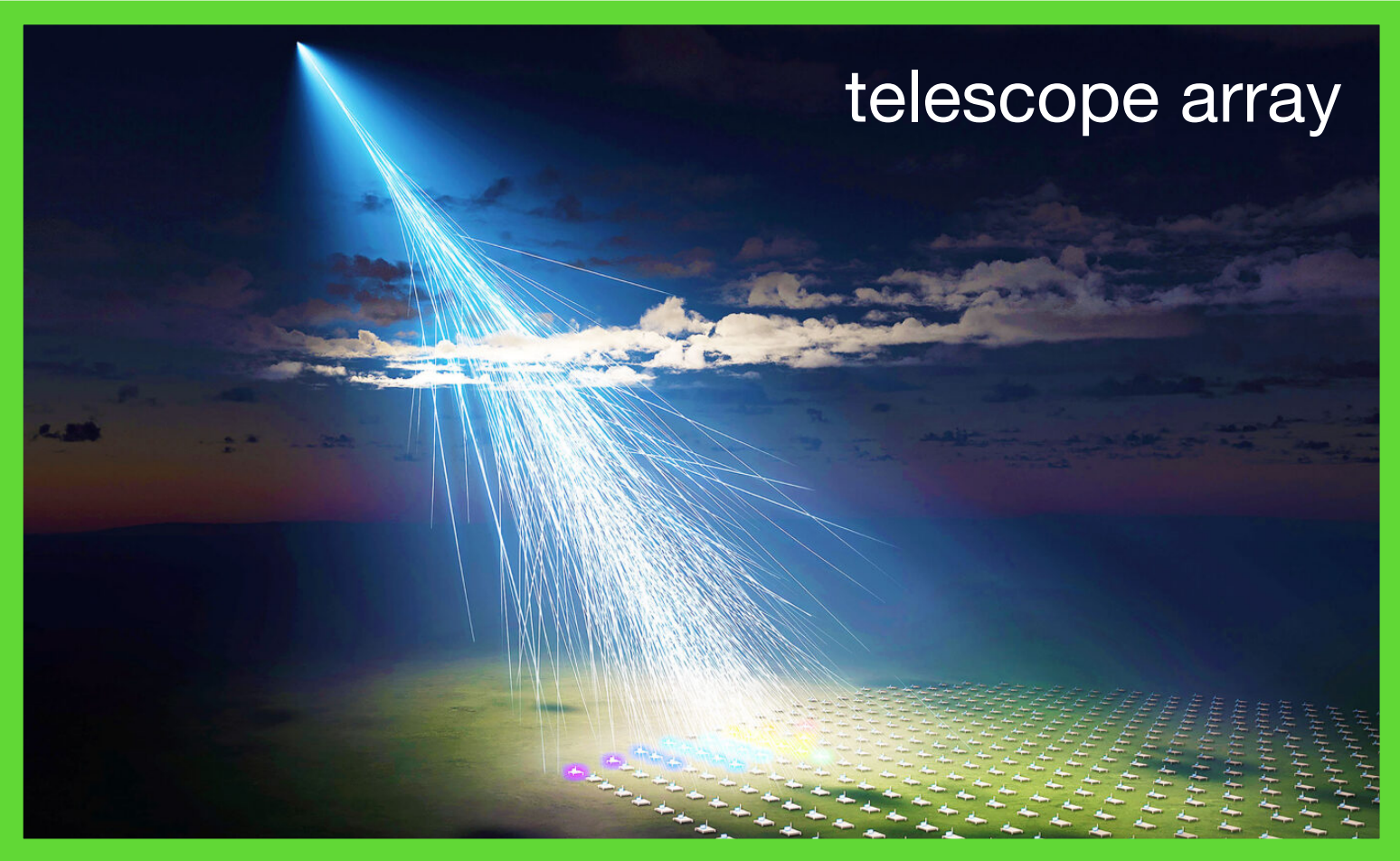
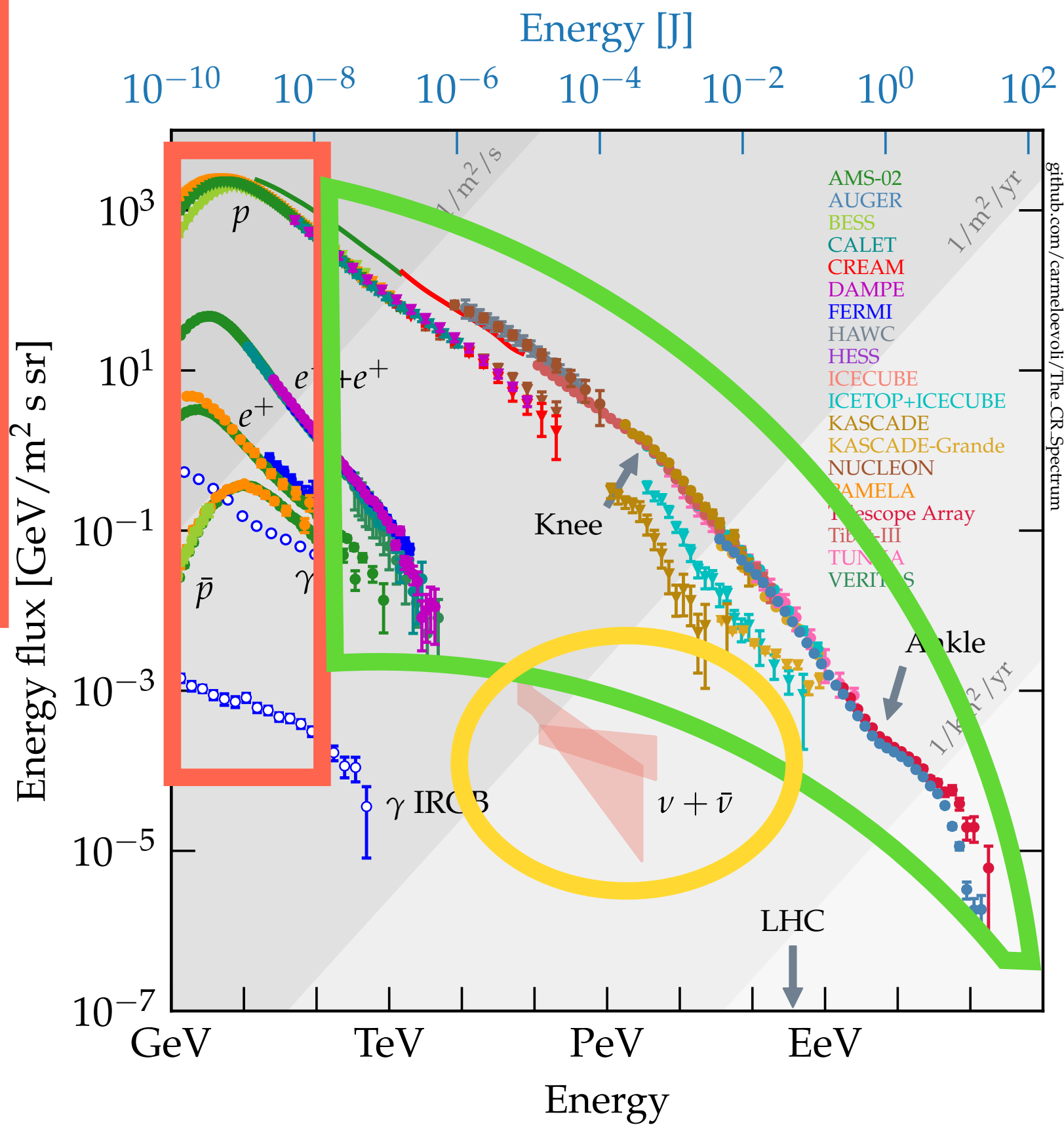
How to observe...

We will focus (mainly) on “high” energy...

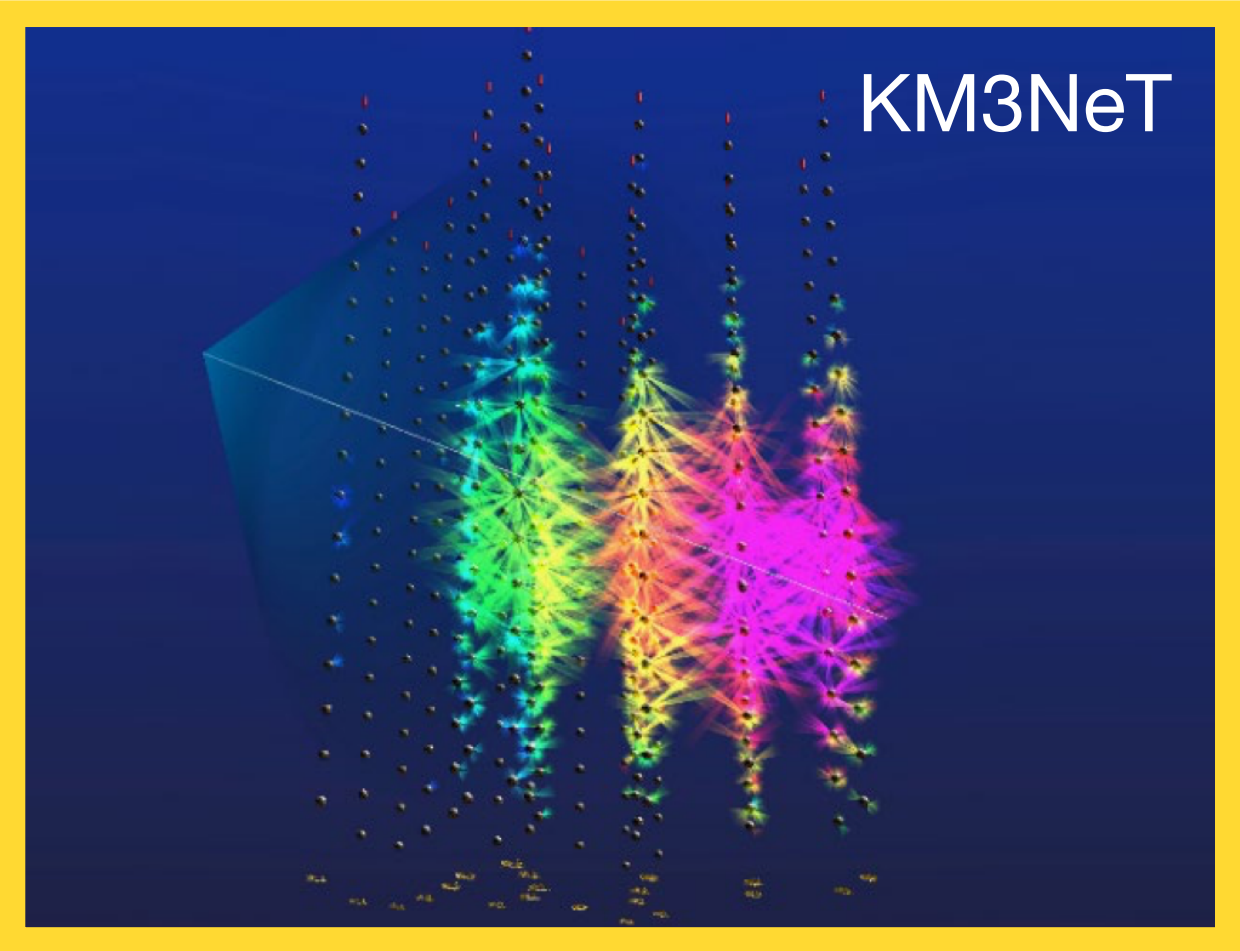
Particle Detectors in Space



“Low” Energy

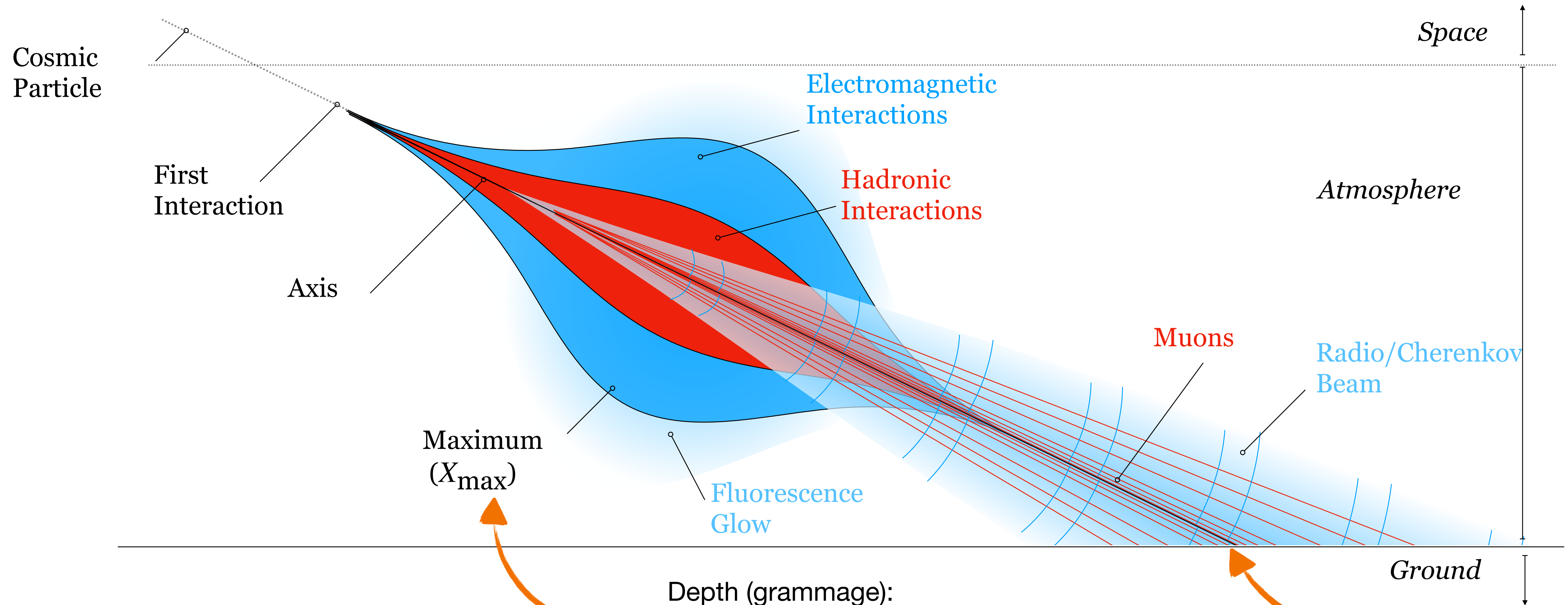


Particle interaction in the atmosphere



Particle interactions in water

Particle interaction in the Atmosphere: Air showers



Air shower measurements can be used to estimate: particle type, energy, and direction

Depth (grammage):

$$X(r) = \int_{\infty}^r \rho(r') dr'$$

with r' along the direction of the incoming (cosmic) particle

Core: intercept axis with ground

Air shower detection

- Particle detectors: Scintillators, water-Cherenkov Detectors
- Emission detectors: Cherenkov-light telescopes, Fluorescence light telescopes, radio-wave emission
- Different (array) configurations for targeting specific energy regimes and particle types
- Techniques are often combined for optimal results

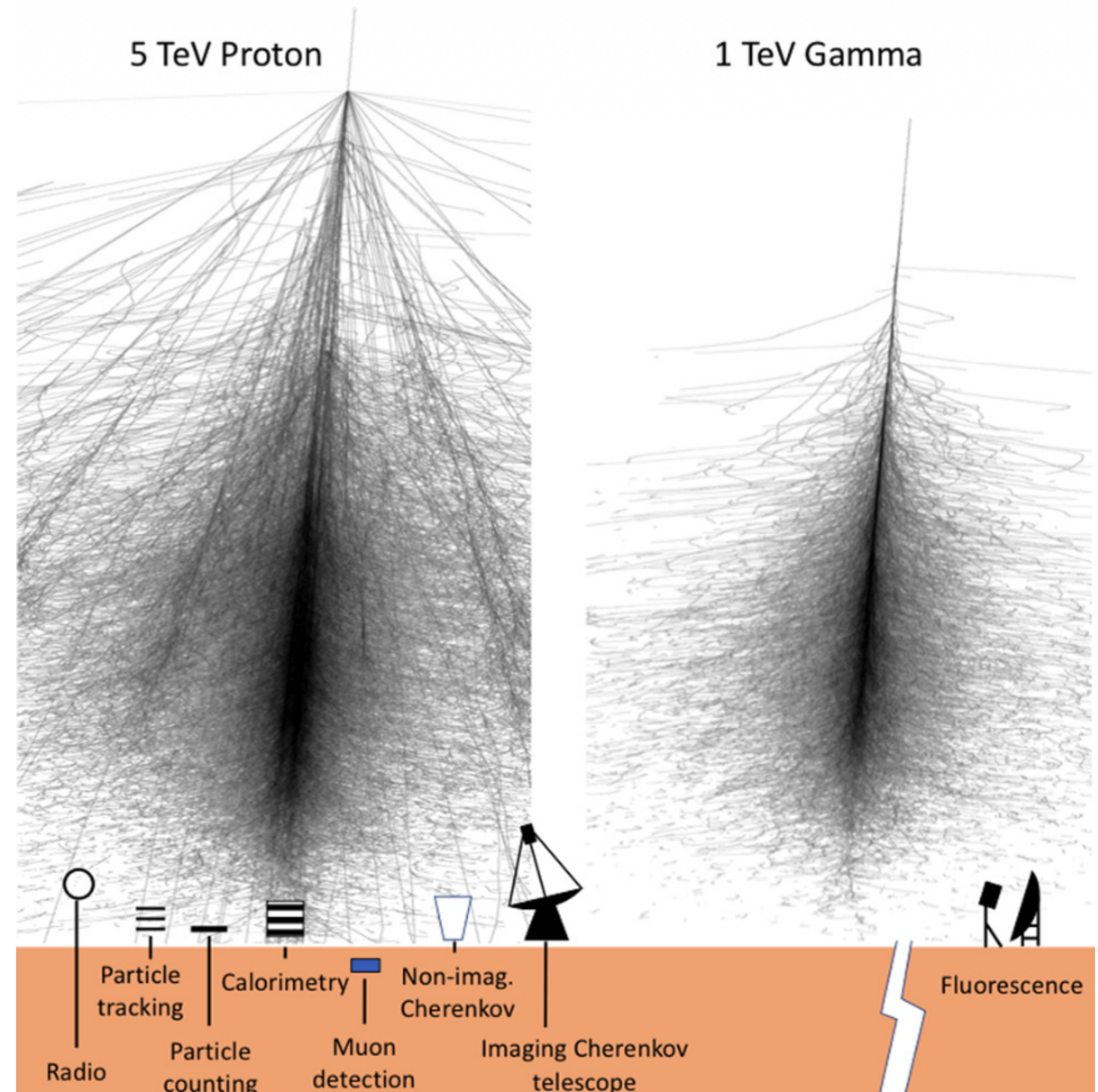
Recommended reading

Detectors for high-energy messengers from the Universe

W. Hofmann, J. Hinton*

Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany

Nuclear Inst. and Methods in Physics Research, A 907 (2018) 31–45



Air shower detection

Ultra-High-Energy Cosmic Rays

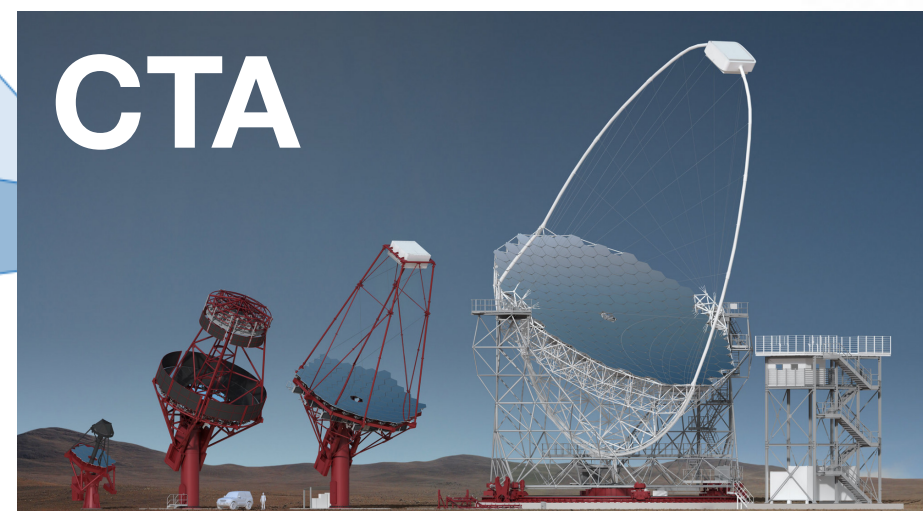
Gamma-ray astronomy

High Altitude Particle Detectors
(dense arrays)

Cherenkov Beam



Imaging Atmospheric Cherenkov Telescopes



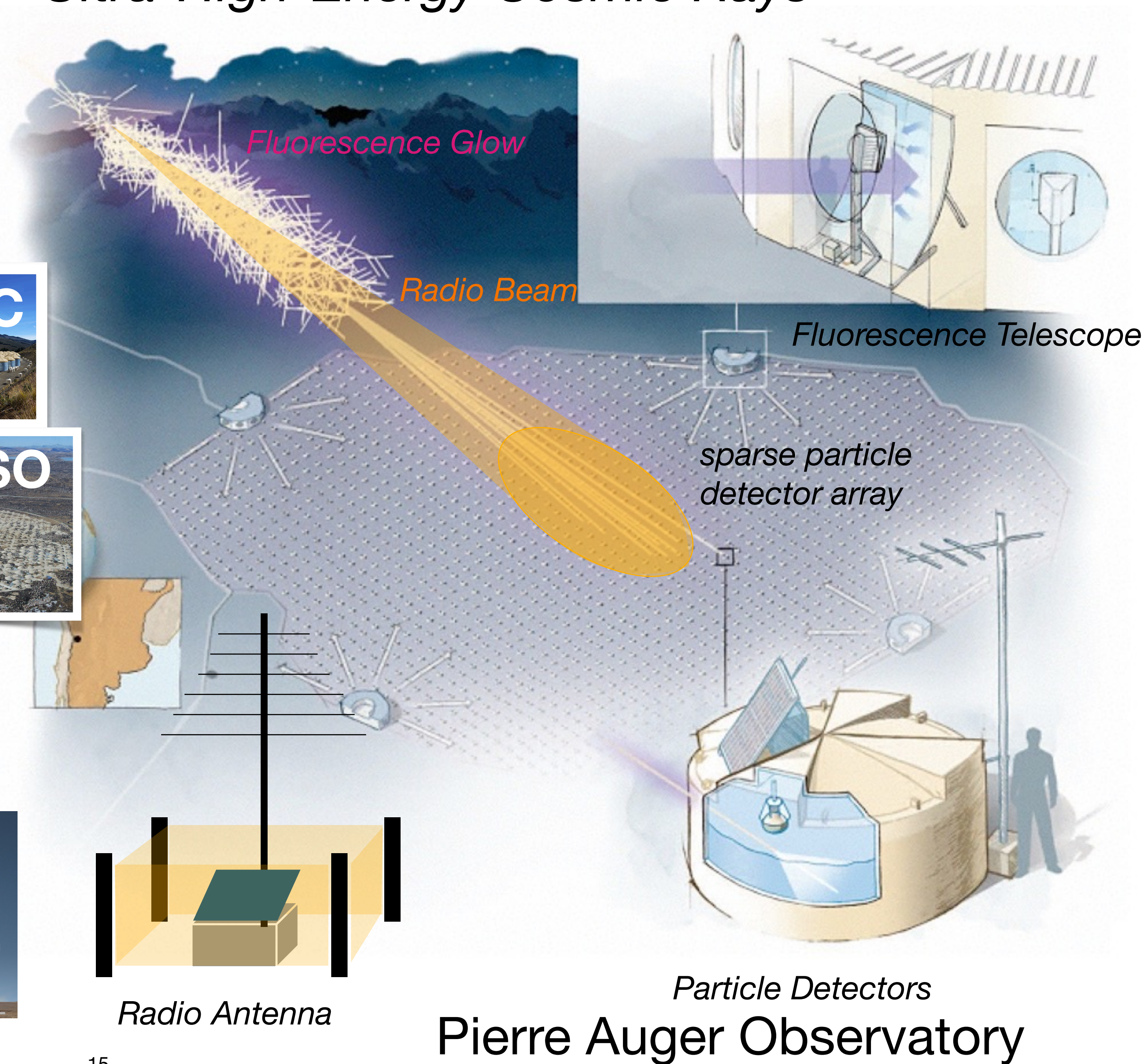
CTA



HAWC



LHAASO



Neutrino detection

- Neutrino interacts in water or ice
- Charged particles caused by the interaction can be observed by a grid of water-Cherenkov detectors
- Depending on the neutrino type, we can have different topologies of sensor hits:
 - Tracks
 - Cascades

Recommended reading

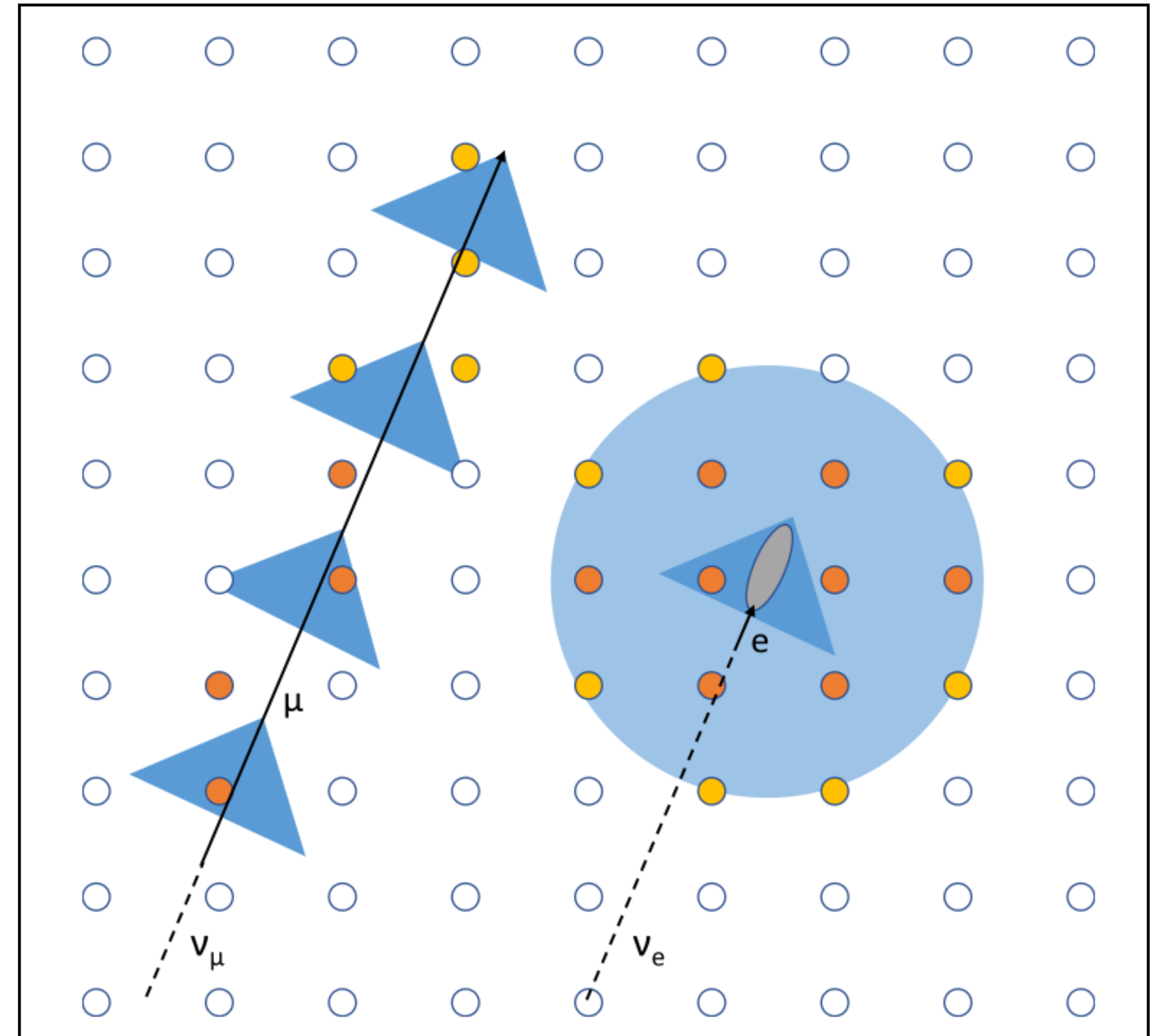
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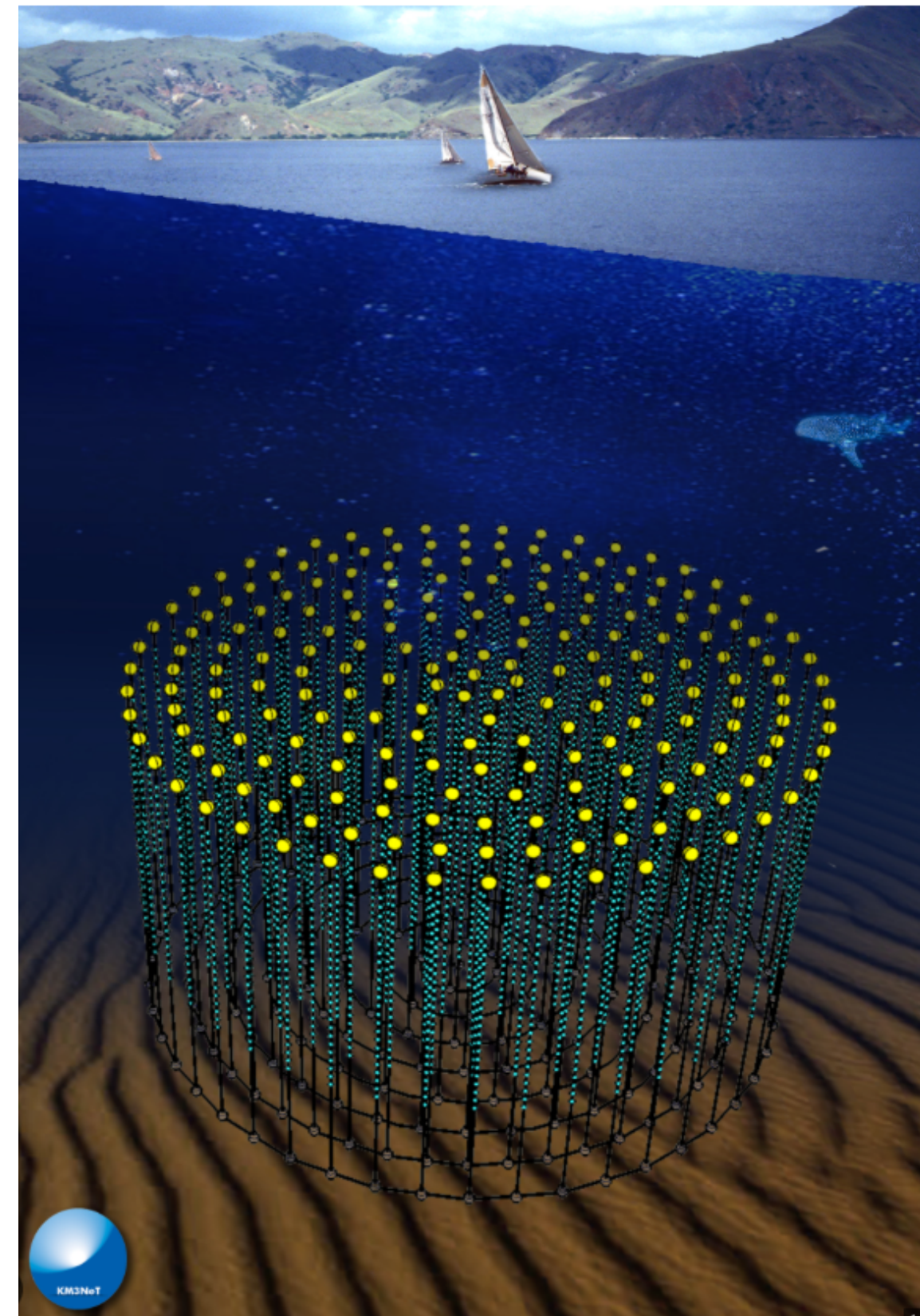
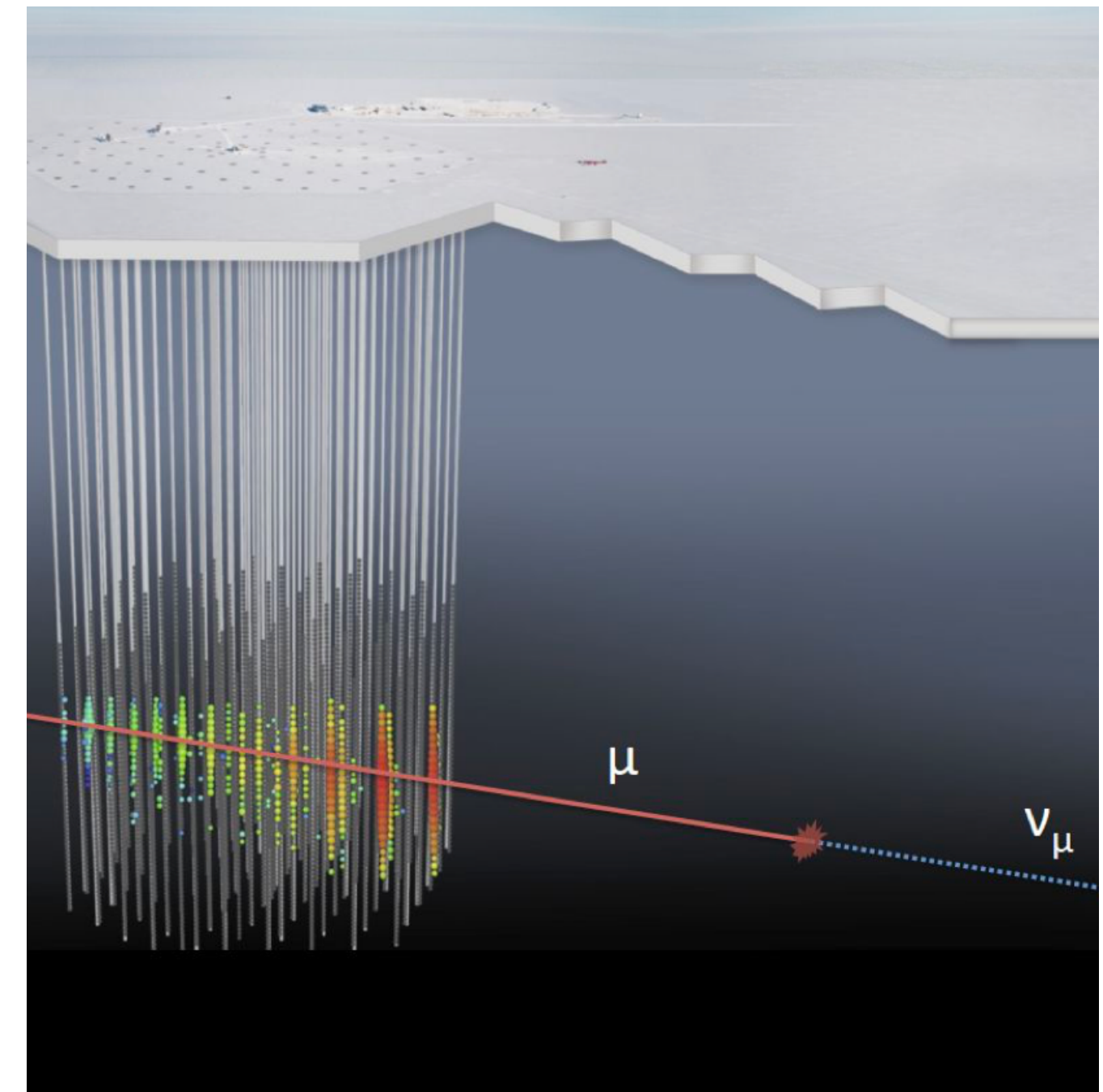
water-Volume



Neutrino detection

- Neutrino interacts in water or ice
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IceCube

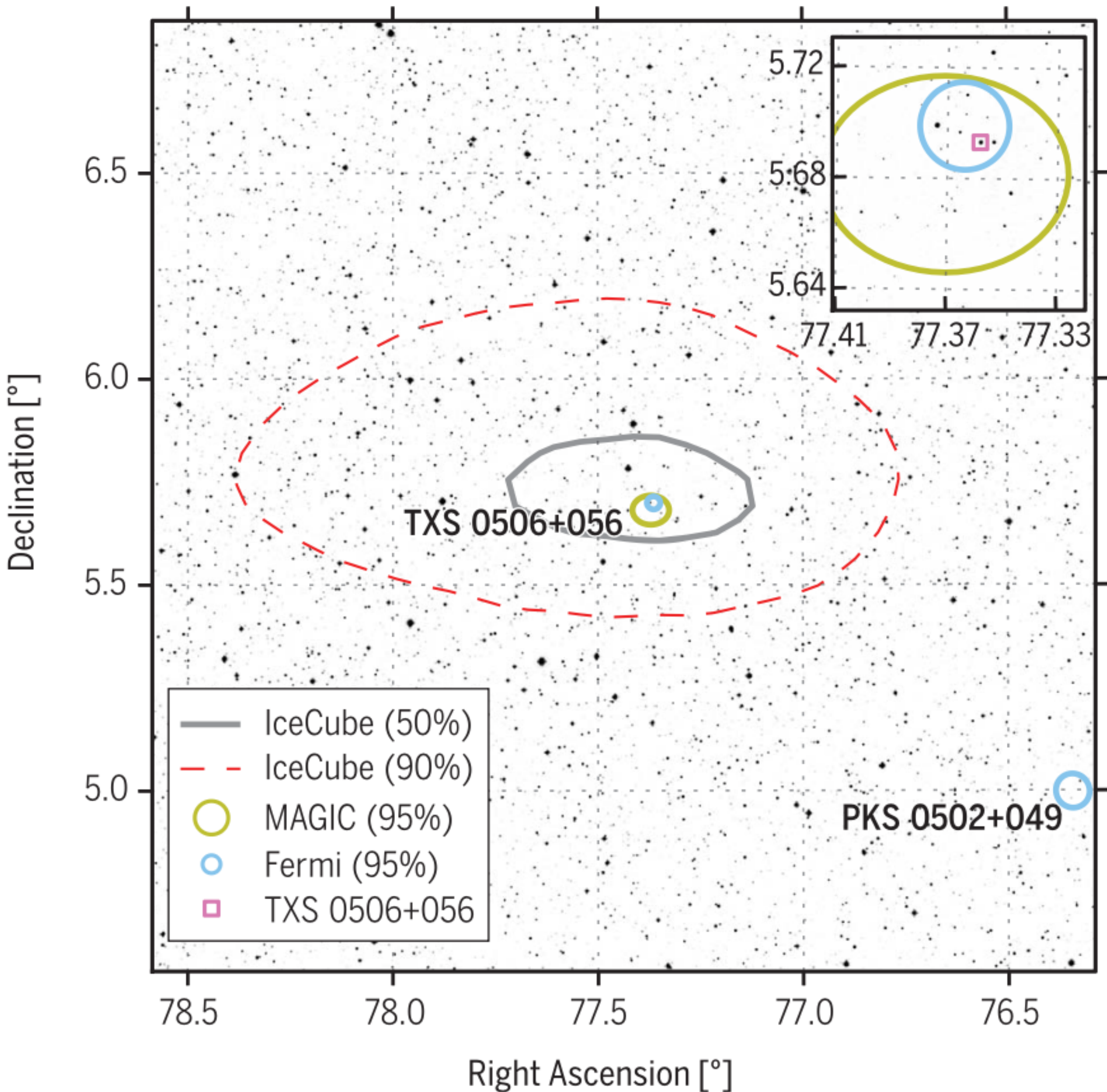
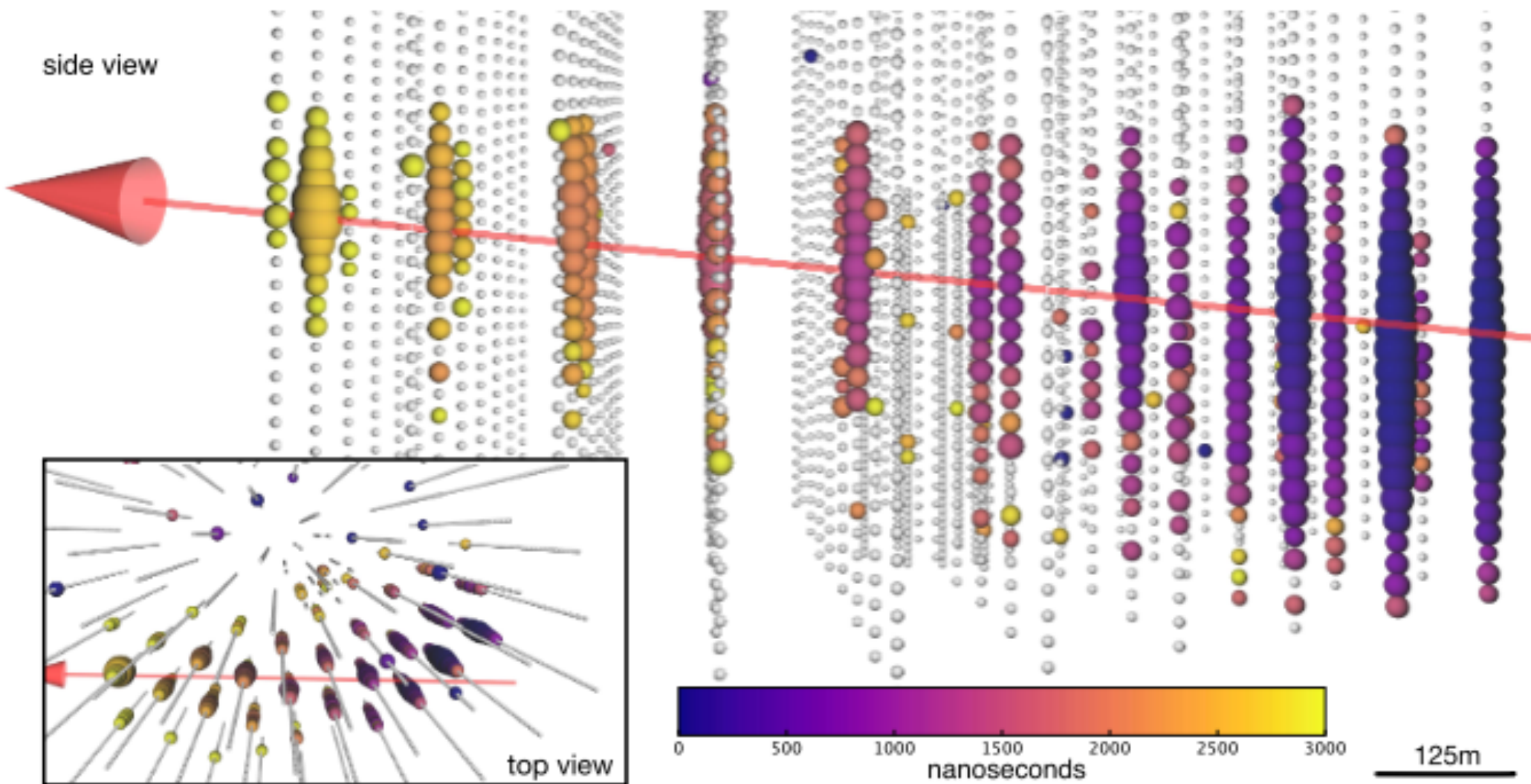


KM3NeT

Multi-messenger observations

TXS 0506+056: Neutrino & Photon observations

IceCube neutrino observatory found a high-energy event in coincidence with a gamma-ray flaring blazar



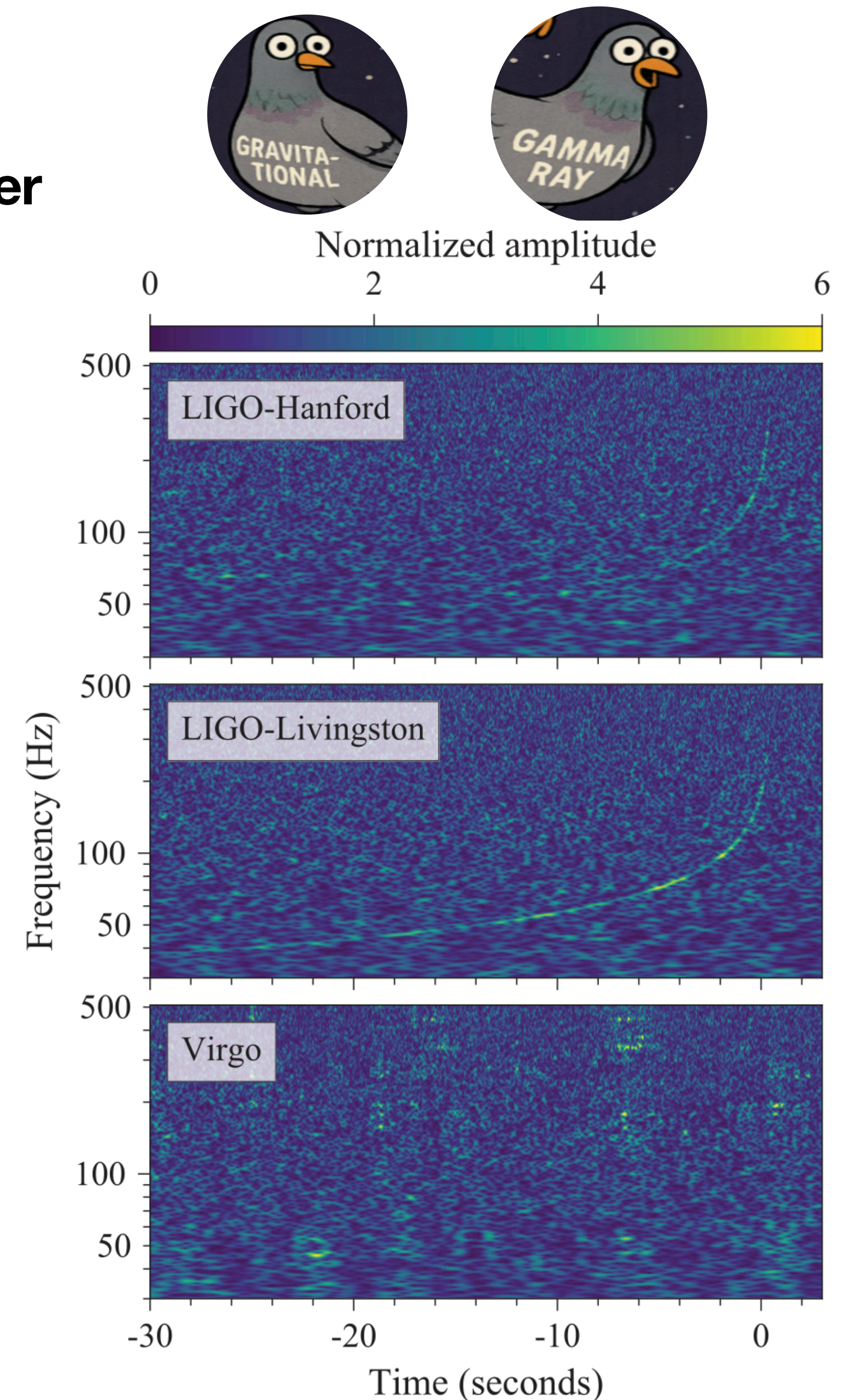
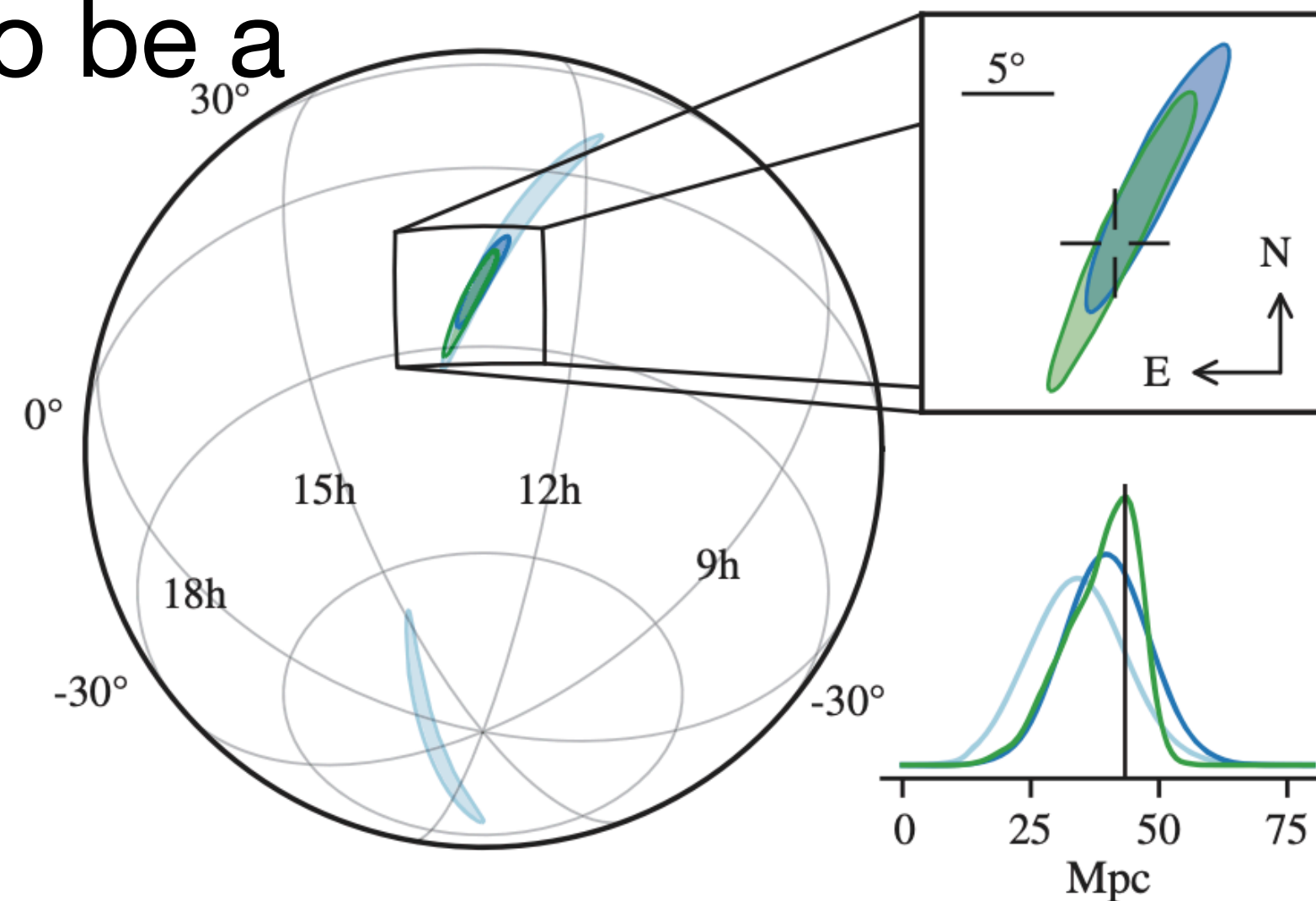
Multi-messenger observations

GW170817: Gravitational wave of neutron-neutron star merger in coincidence with a gamma-ray burst (GRB 170817A)

Gravitational wave detected, followed by a gamma-ray burst

Exact localisation of the merger event

Confirmation of neutron-neutron star mergers to be a source of GRBs

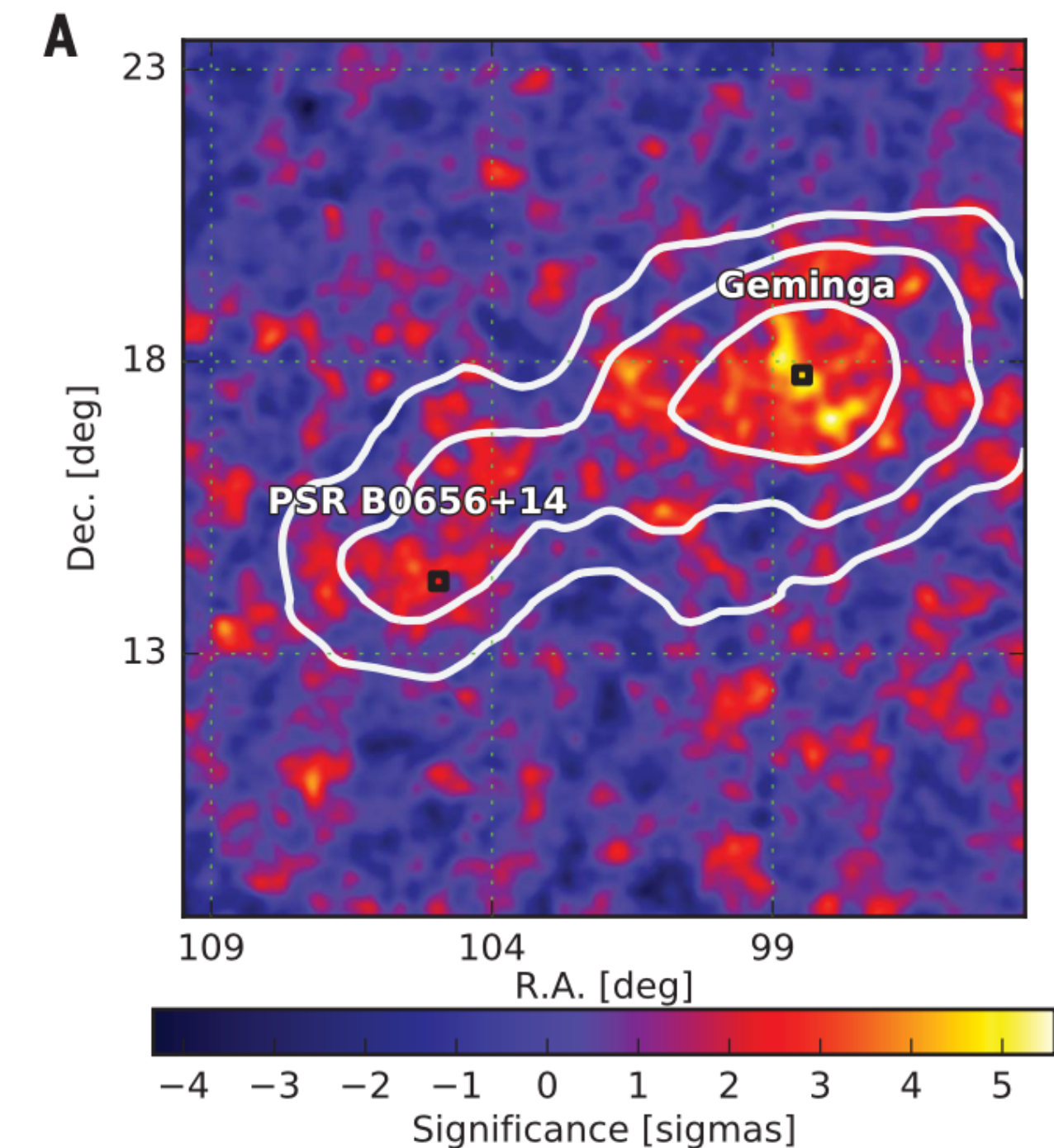


Multi-messenger observations

Observation of gamma ray halo around a nearby pulsar “Geminga” and positrons by AMS02

Positron excess seen by spaced based observatories (AMS02/PAMELA) could be explained by a local astrophysical source or annihilating dark matter

*Gamma-ray Halo around pulsar:
Electrons and positrons leaving the
source, can they make it to Earth/
AMS02?*



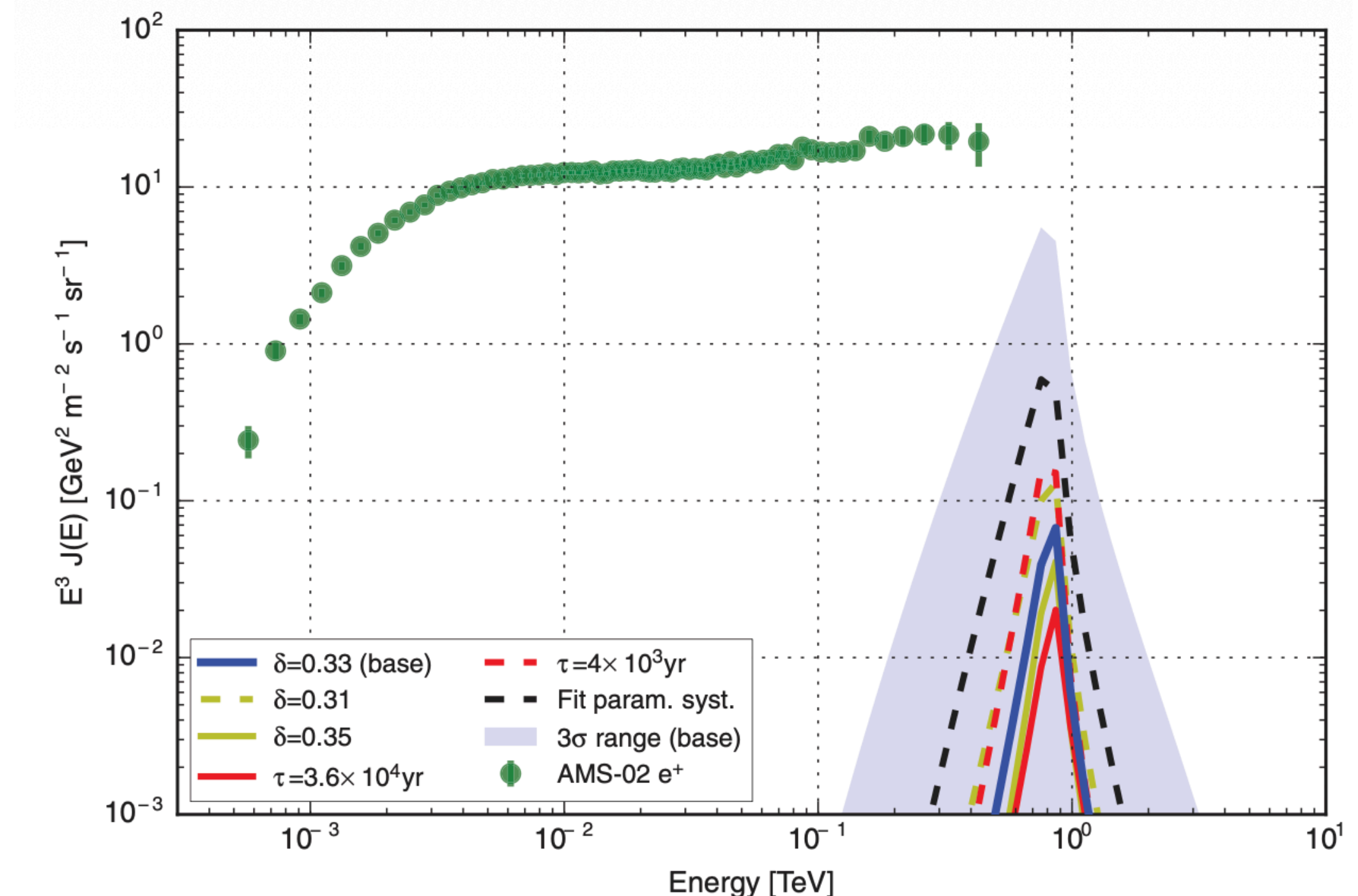
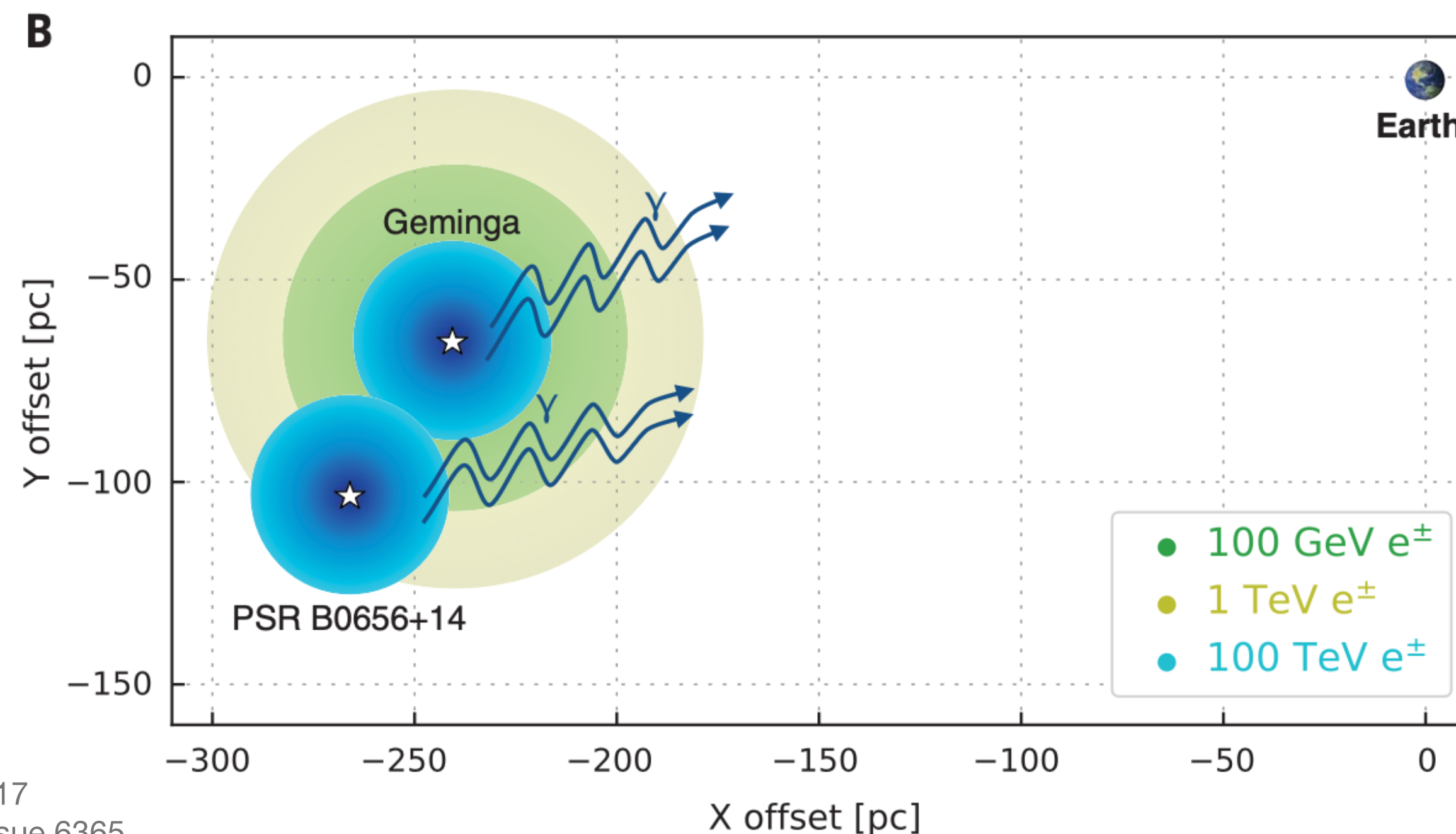
Multi-messenger observations

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*Gamma-ray Halo around pulsar:
Electrons and positrons leaving the
source, can they make it to Earth/
AMS02?*

No!
(under certain assumptions)



Concluding remarks ...

In the last decades we have witnessed the birth of gravitational wave and neutrino astronomy

We have increased our sensitivity for cosmic and gamma-ray observations

Multimessenger astronomy has started

Challenges

Different sensitivities of observatories

Matching energy ranges for different messengers

Differences in propagation of the messengers

