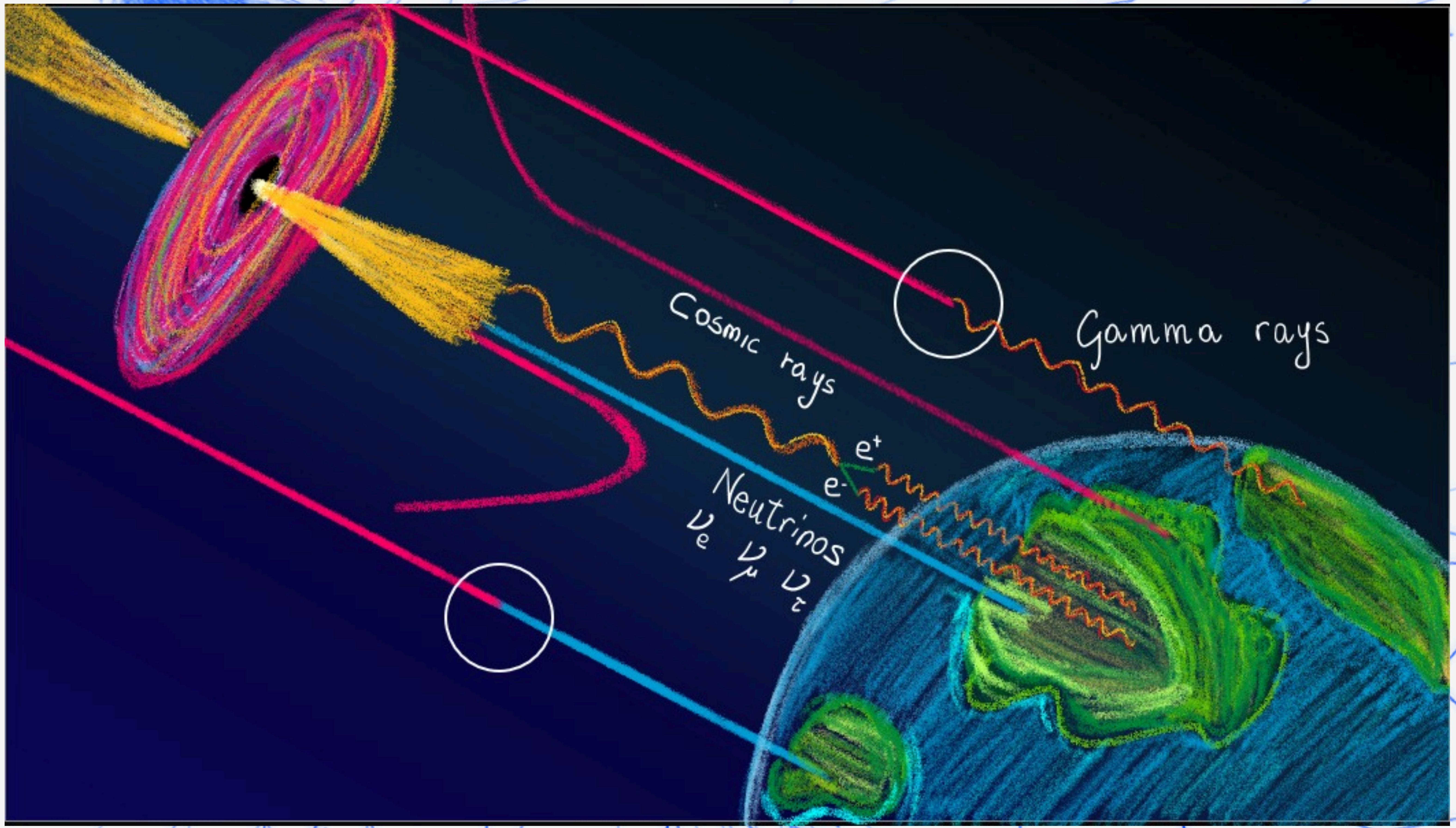
EXPERIMENTAL ASPECT OF MULTI-MESSENGER ASTROPHYSICS



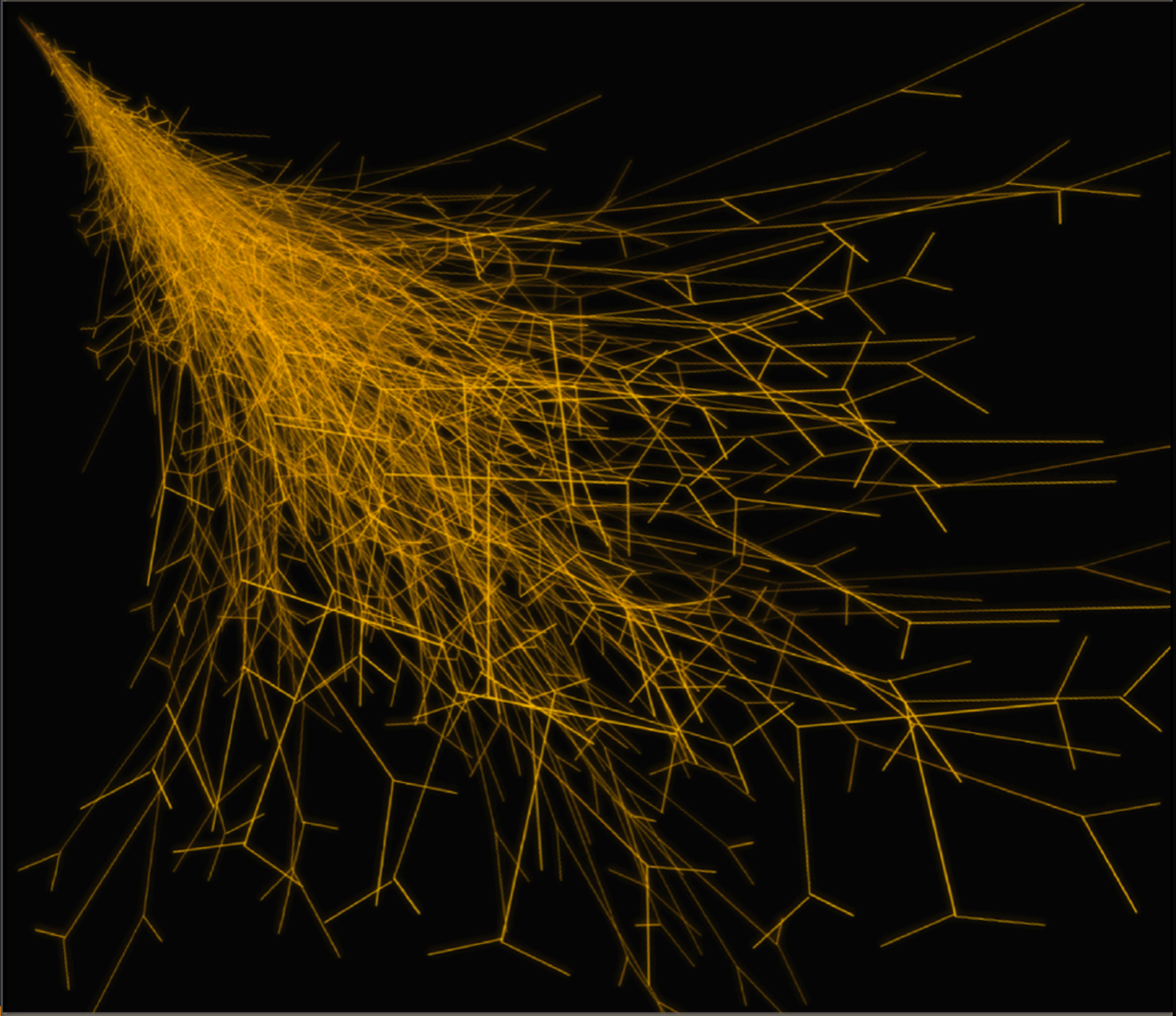
COSMIC-RAY AND NEUTRINOS

@ IPDASC, Orsay

24/07/2025

Antonio Condorelli

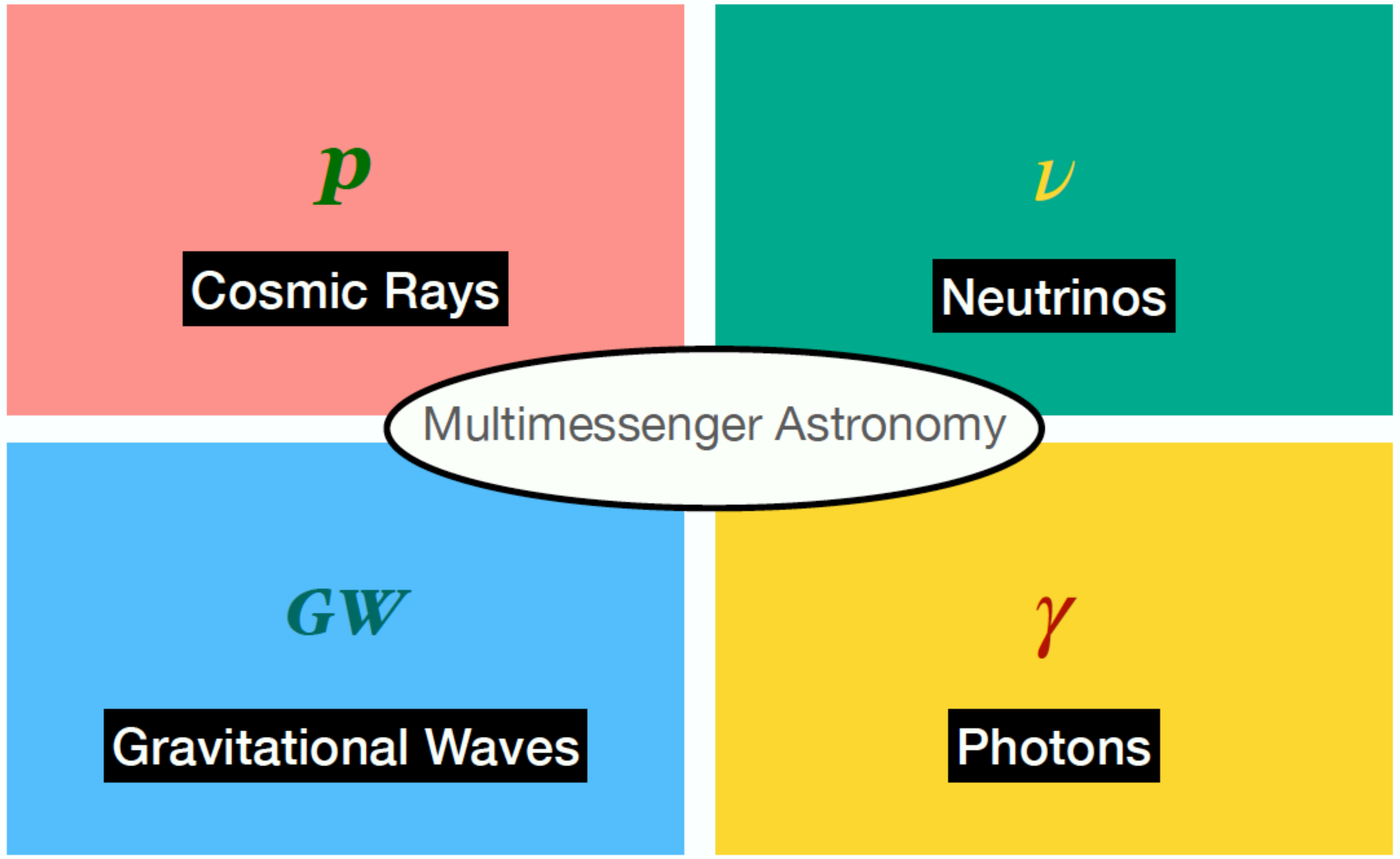
APC, CNRS, FRANCE



Outline

Multi-messenger astronomy

Pierre Auger Observatory



IceCube

LIGO Site in site in Livingston, La

Fermi Gamma-ray Space Telescope

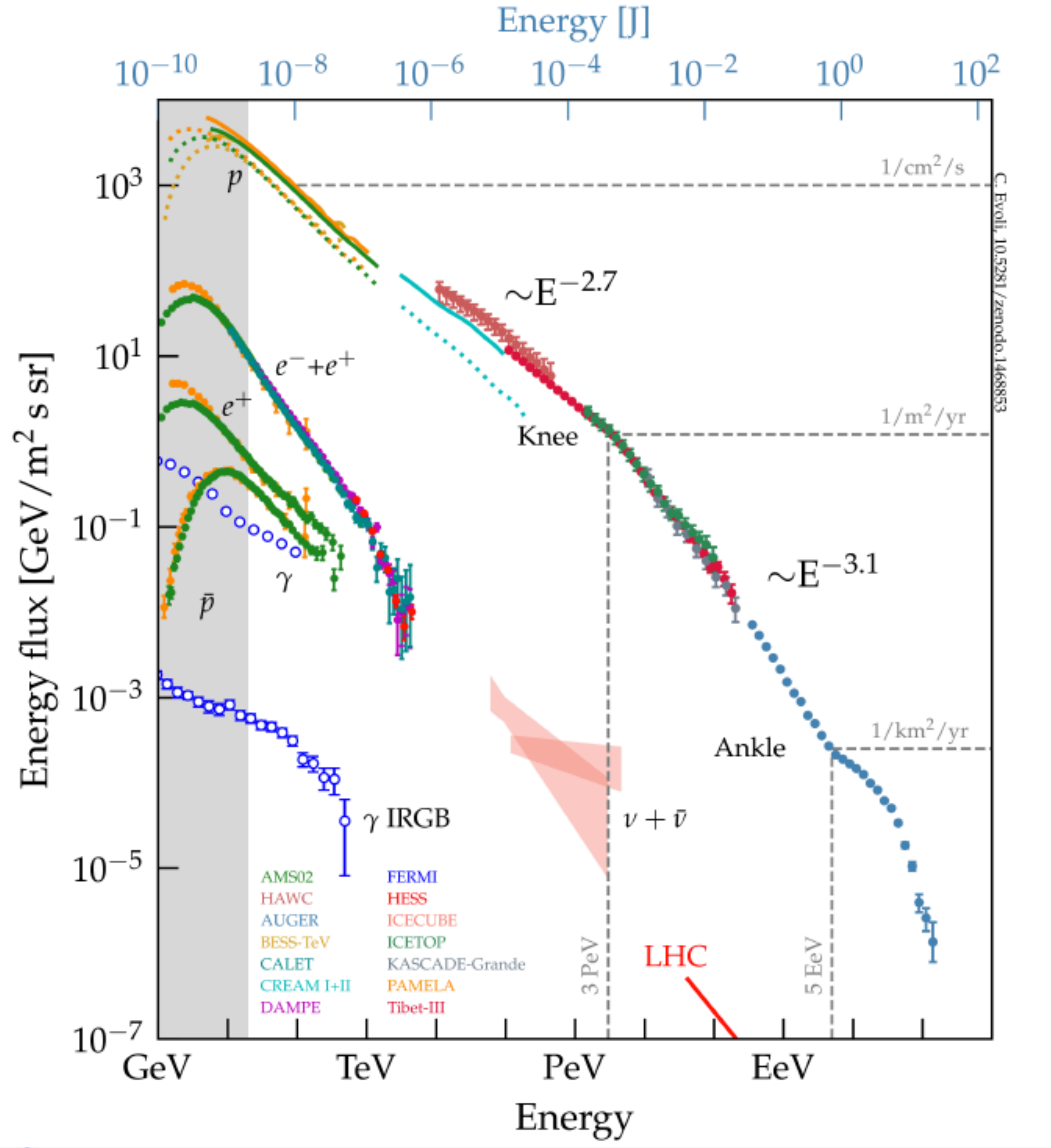
Source: S. Saffi, LIGO LABORATORIES, NASA's Goddard Space Flight Center/Chris Smith (USRA/GESTAR), Moreno Baricevic, IceCube/NSF

The cosmic ray spectrum

Cosmic rays (CR): charged particles from the Universe.

CR spectrum spans over several order of magnitude in energy and flux;

- Several detection techniques are needed;
- Power law: it reflects acceleration mechanism;
- Features can be addressed to propagation and/ or re-acceleration processes.



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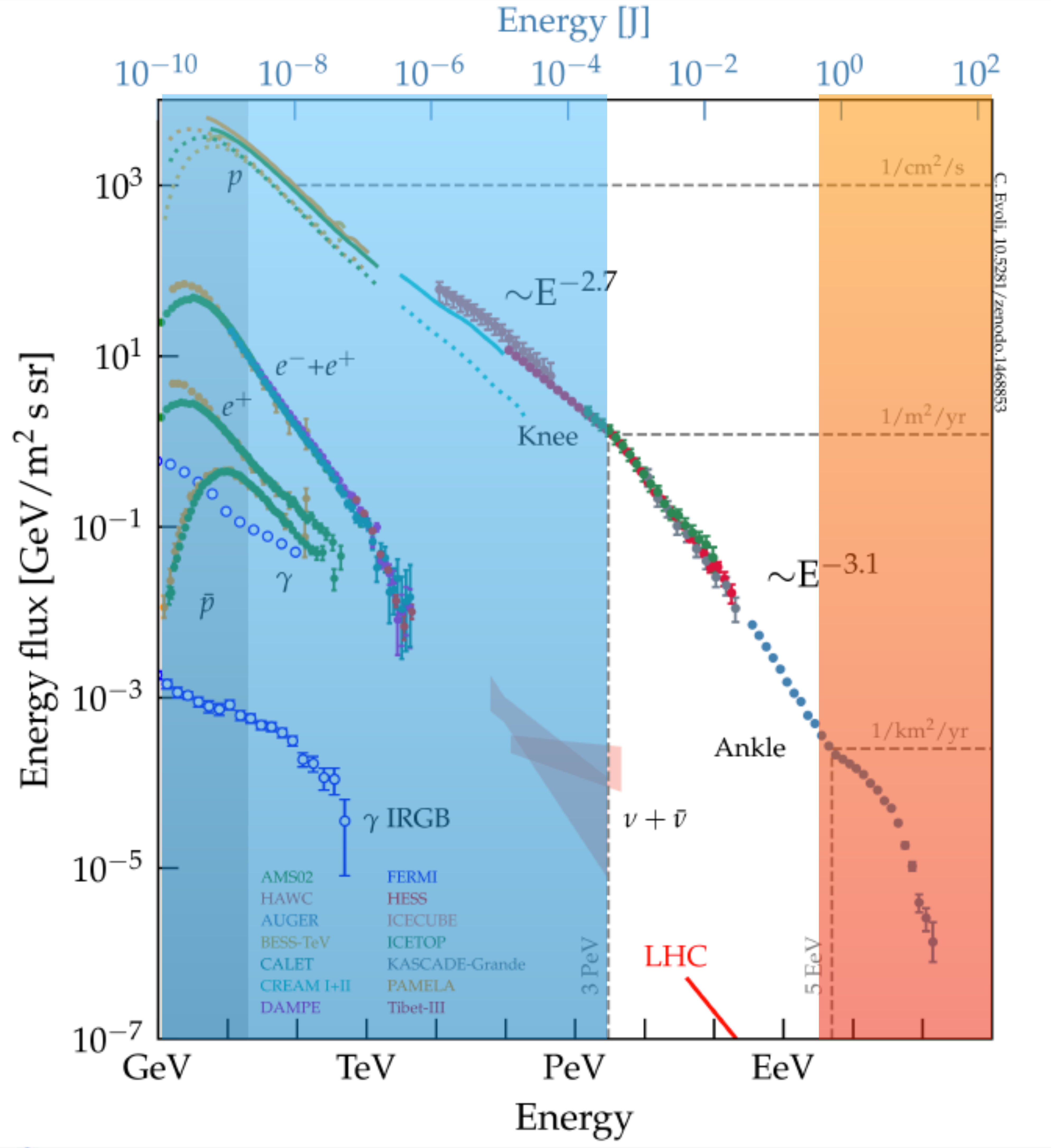
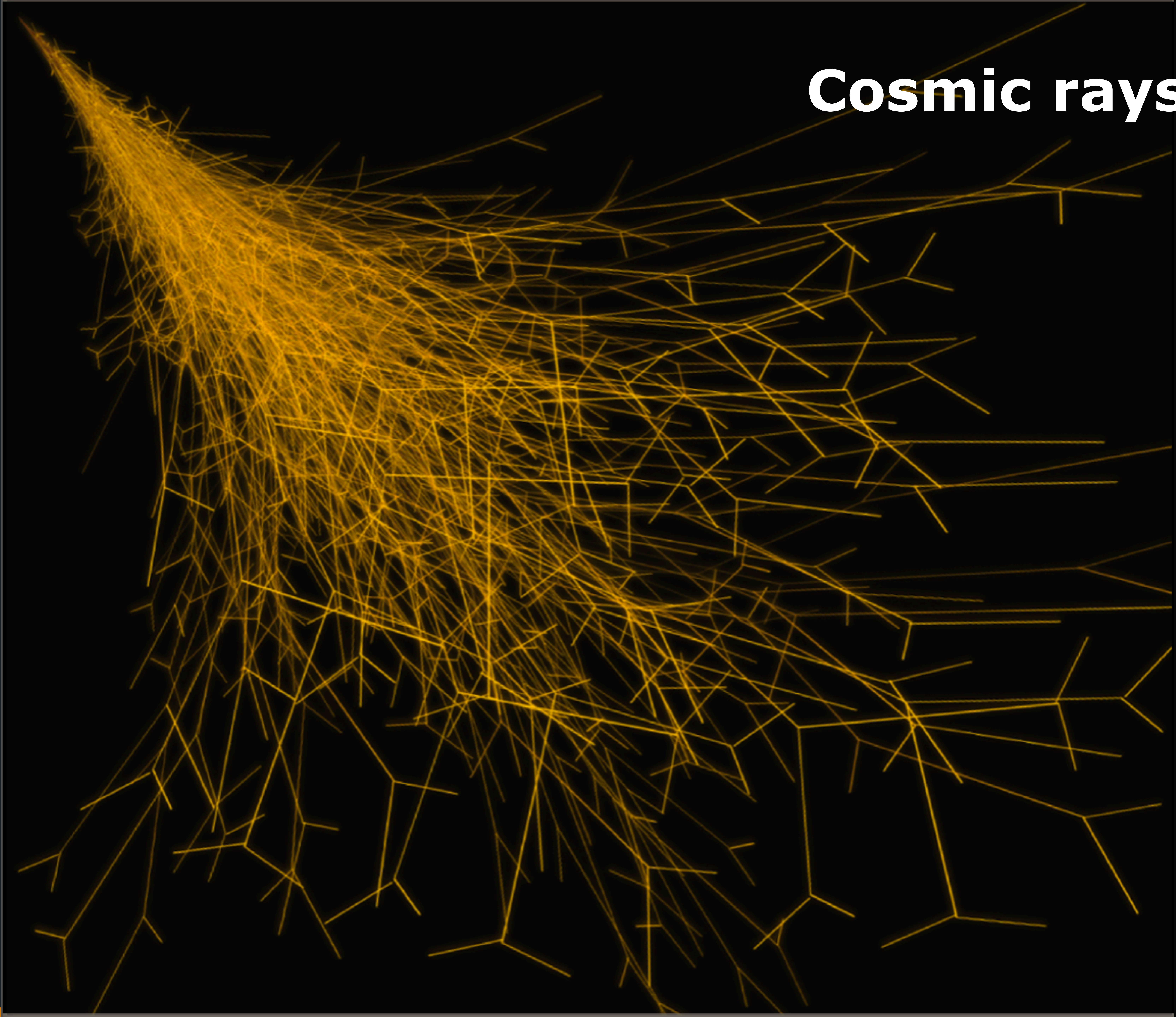


Cosmic rays lower



How do we identify a particle?

How do we identify a particle?

For all charged cosmic rays – e^+, e^-, p, $\bar{p}$, and nuclei from the Periodic Table:

- **Charge (Z)** and **charge sign**
- **Rigidity**: $R = P/Z$ (in GV)
- **Velocity**: $\beta = v/c$
- **Energy**: E (in GeV)
- **Mass**: $M = p/(\gamma\ \beta\ c)$
- **Flux**: $N\_events/(s \cdot sr \cdot m^2 \cdot GeV)$

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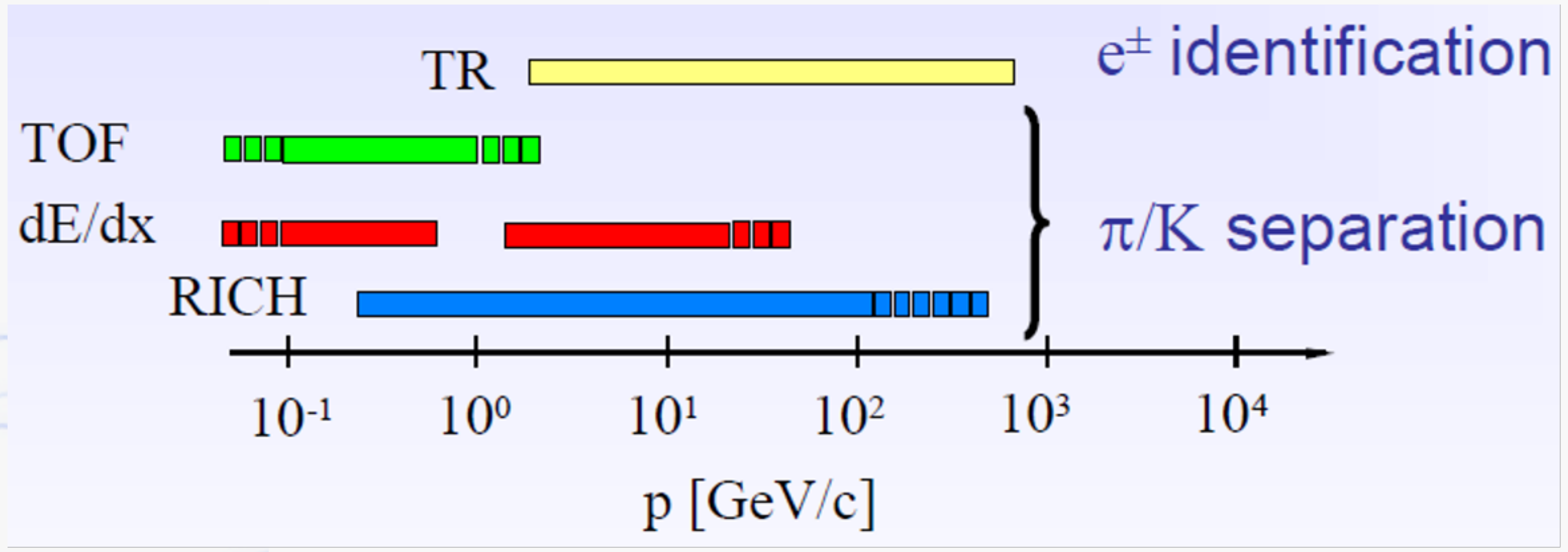
The information that can be analyzed includes:

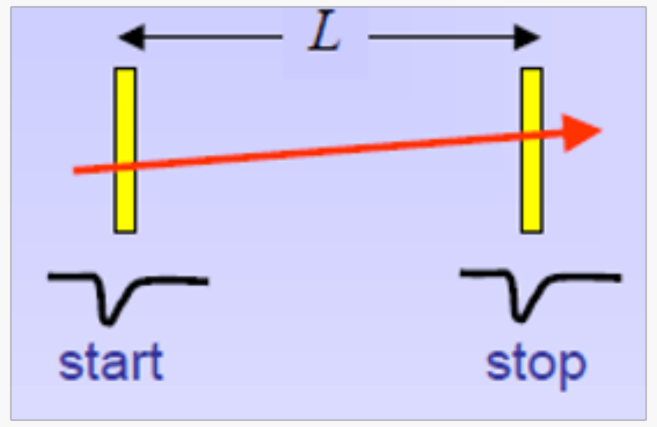
- Energy released in the detector, total or partial;
- Time of flight over a defined distance;
- Shape of the generated signal (rise and fall time);
- Curvature in the presence of **B;**
- Specific emissions of electromagnetic radiation.

Identification techniques

- **Interaction with Matter:** Cosmic rays a, they interact in various ways, primarily through:
  - **Ionization:** Knocking electrons off atoms, creating electron-ion pairs.
  - **Excitation:** Raising electrons to higher energy levels, leading to photon emission.
  - **Scintillation:** Causing certain materials to emit light (photons).
  - **Cherenkov Radiation:** Emission of light when a charged particle travels faster than the speed of light in a medium.
- **Signal Conversion:** These interactions convert the particle's energy into a measurable signal (electrical current, light pulses).



Identification techniques



Time-of-Flight (TOF) Detectors:

- **Purpose:** Measure the particle's velocity (beta=v/c).
- **Principle:** Consist of two or more scintillator layers separated by a known distance.
  time difference–> velocity can be calculated.

$$t = \frac{L}{\beta c} \longrightarrow \beta = \frac{L}{tc}$$

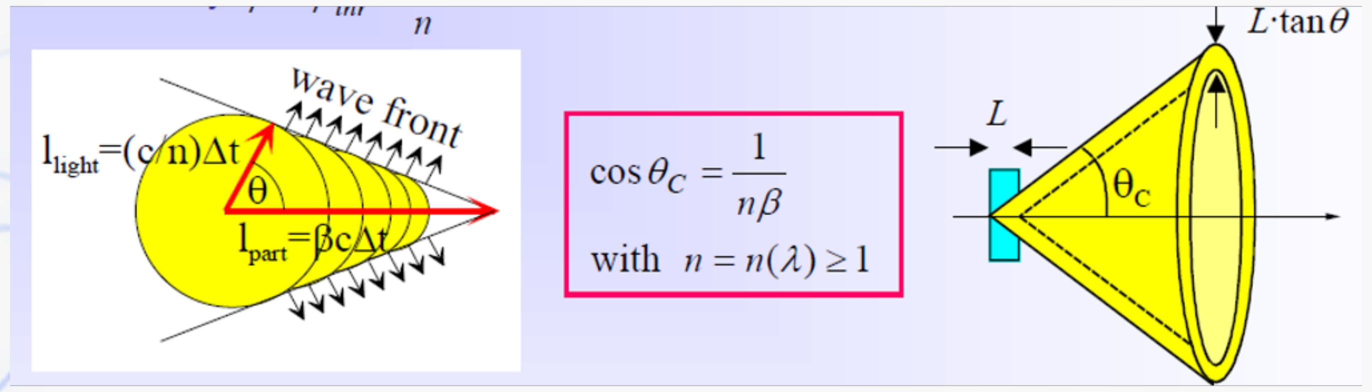
$$p = m_0 \beta \gamma \longrightarrow m_0 = p\sqrt{\frac{c^2 t^2}{L^2} - 1}$$

$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2 \left(\frac{dt}{t} + \frac{dL}{L} \right)$$

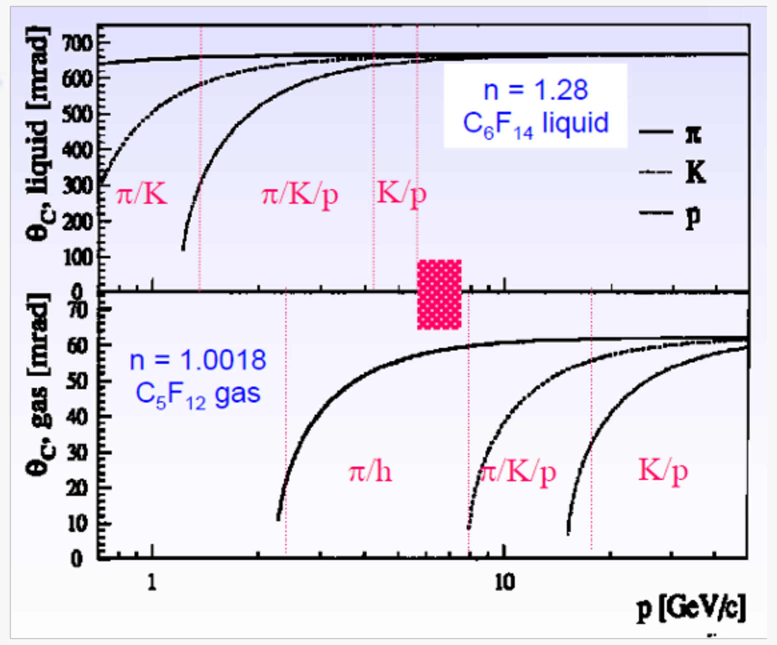
$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right) = \frac{L}{c}\left(\sqrt{1 + m_1^2 c^2 / p^2} - \sqrt{1 + m_2^2 c^2 / p^2}\right) \approx \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

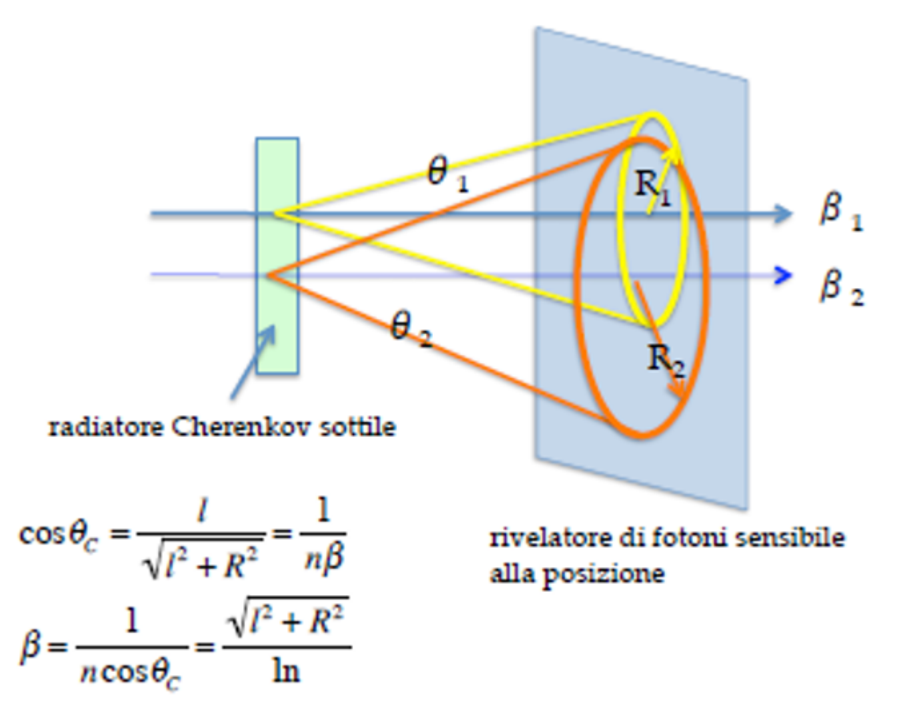
Cherenkov Detectors:

- **Purpose:** Measure velocity and charge.
- **Principle:** When a charged particle travels faster than the speed of light in a given transparent medium, it emits Cherenkov light. The angle and intensity of this light are dependent on the particle velocity and charge.

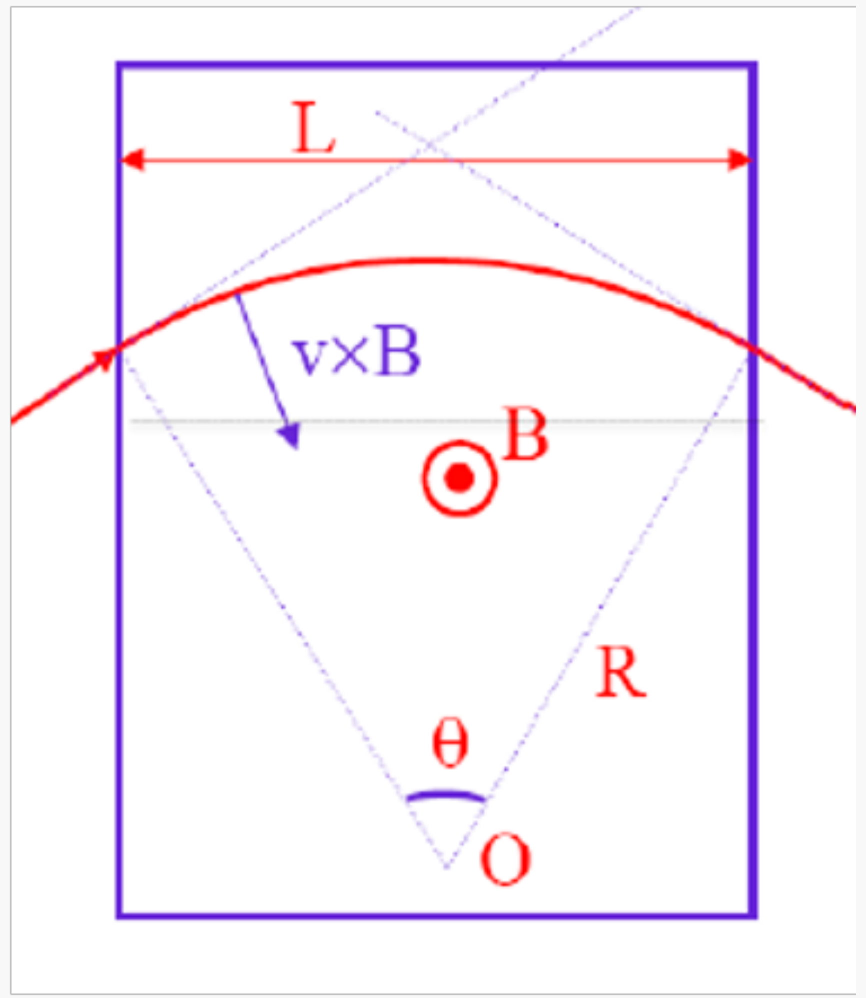


$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right) = \cos^{-1}\left(\frac{E}{pc}\frac{1}{n}\right) = \cos^{-1}\left(\frac{\sqrt{p^2 + m^2}}{pc}\frac{1}{n}\right)$$





Identification techniques

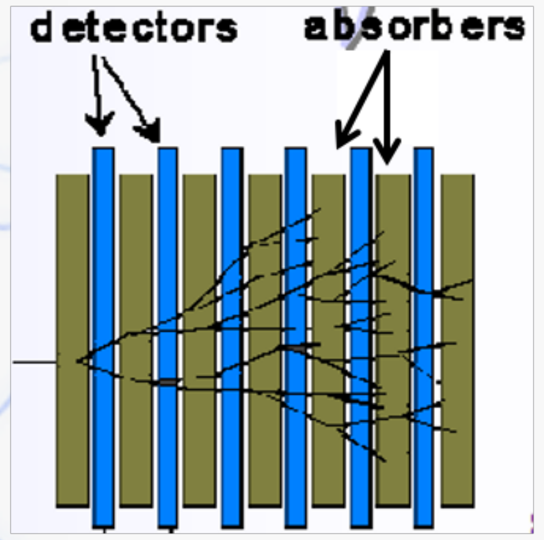


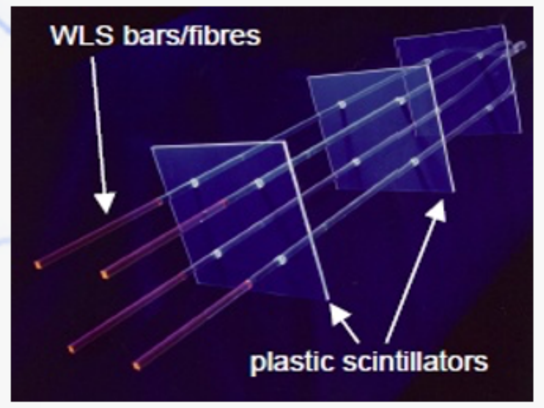
$$p_T\ (\mathrm{GeV/c}) = 0.3B\rho$$

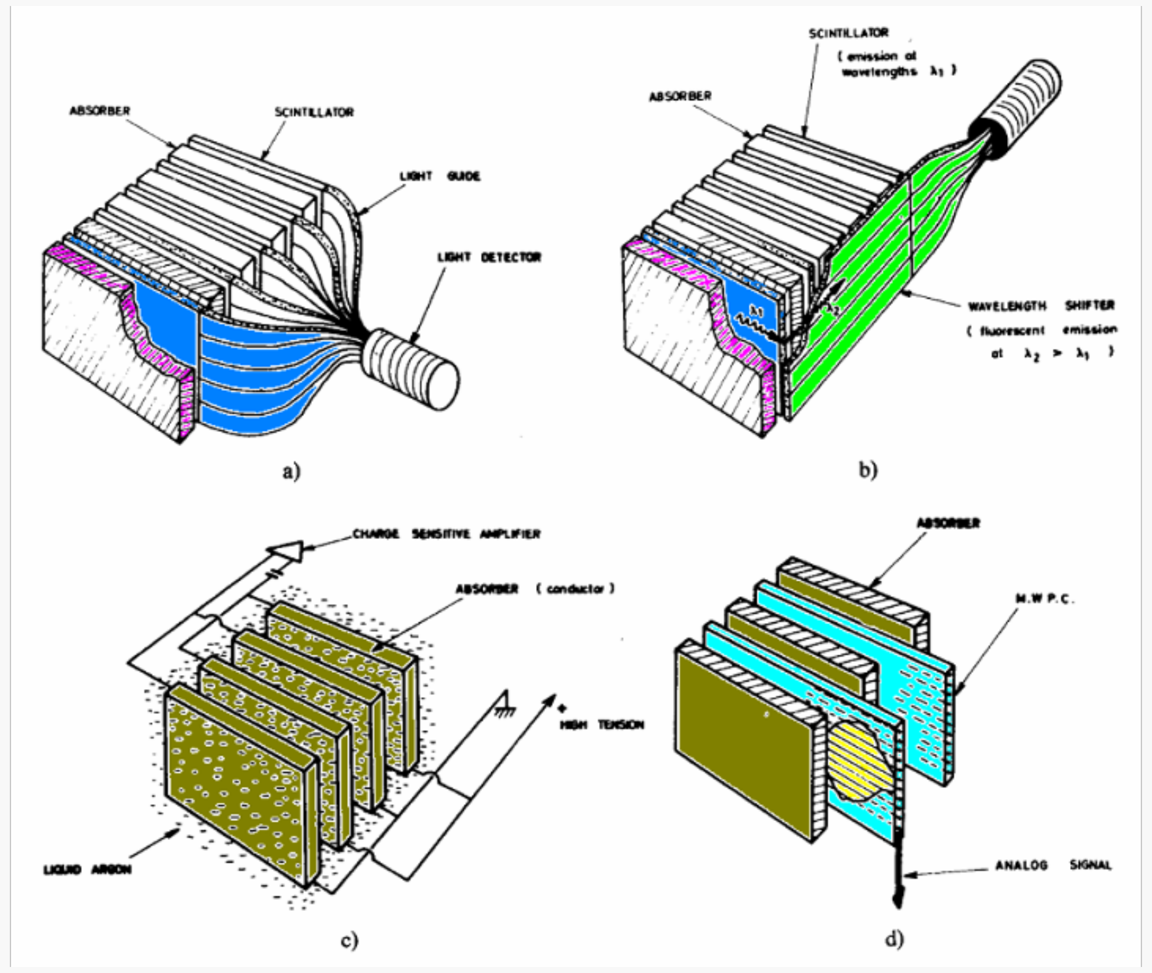
Tracking Detectors:

- **Purpose:** Determine the particle trajectory (path).
- **Examples:** Silicon strip detectors, drift chambers, scintillating fiber trackers.
- **Principle:** Measure ionization points along the path, allowing reconstruction of the track. A magnetic field is often used to bend the trajectory of charged particles.

Calorimeters:







- **Purpose:** Measure the particle total energy.
- **Examples:** Electromagnetic and hadronic calorimeters.
- **Principle:** The particle interacts and produces a "shower" of secondary particles. The total energy deposited in the calorimeter layers is proportional to the incident particle's energy.
- **Material:** Often alternating layers of dense absorber (e.g., lead, tungsten) and active detector material (e.g., scintillators, silicon).

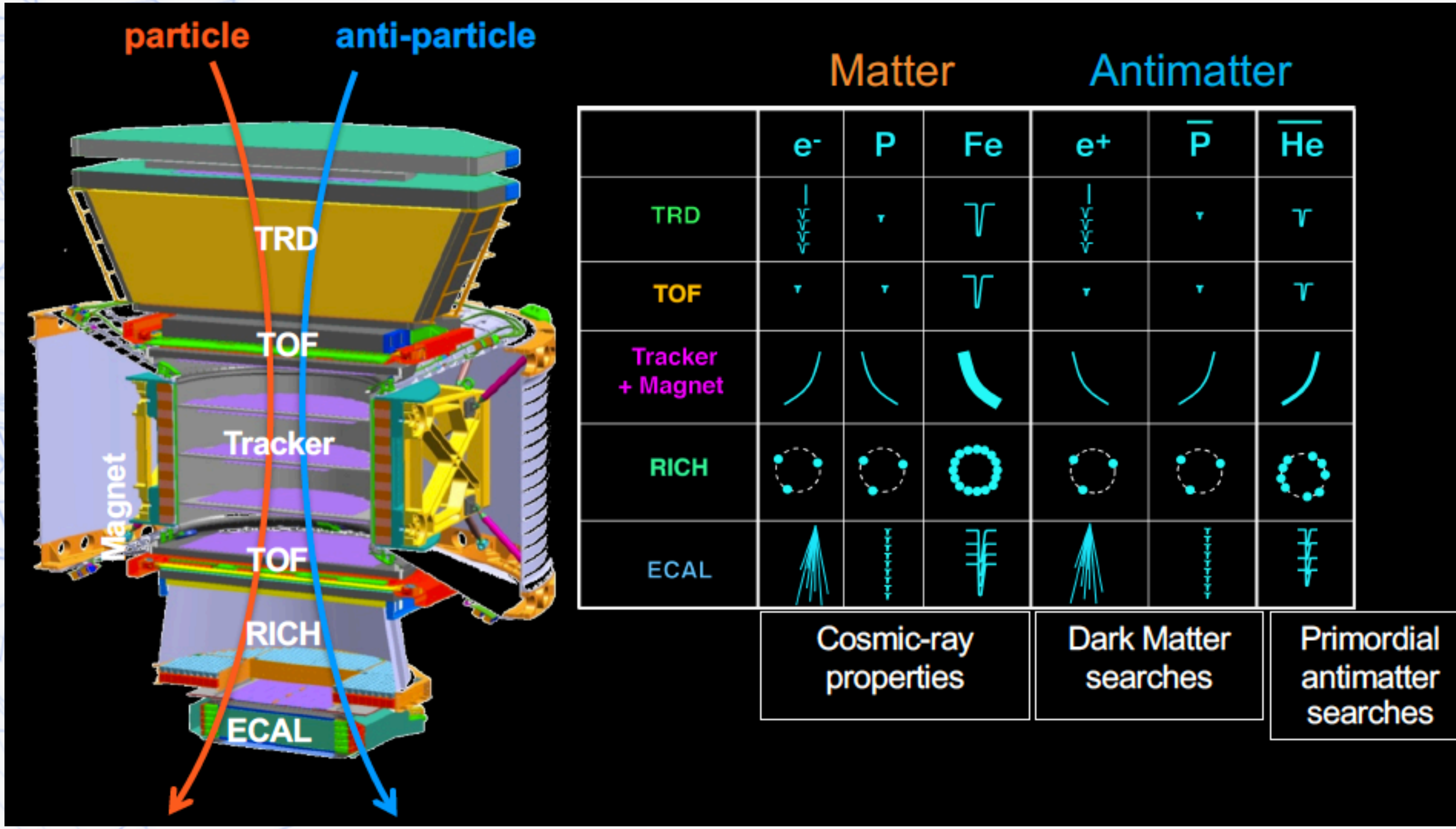
How do we identify a charge particle?

Near Earth Orbit:
altitude 400 Km
inclination 52°
period 92 min

AMS (Alpha-Magnetic Spectrometer experiment) installed on the ISS in May 2011.

Continuous operations through the ISS lifetime (at least 2030)
AMS: direct detection of cosmic rays from the International Space Station

AMS provides precision, long-duration measurements of charged cosmic rays to study the Origin of the Cosmos, the physics of Dark matter and Antimatter.



How do we identify a particle?

Measure Energy / Momentum

Measure Mass (β/γ + E/p)

Measure Sign of Charge

Hadron / Lepton Separation

Measure Charge

How do we identify a charge particle?

Measure Energy / Momentum

- Calorimetry
- Magnetic spectrometry
- Time of flight
- Cherenkov
- Transition radiation

Measure Sign of Charge

- Magnetic spectrometry + time of flight
- Topology of annihilation (tracking / calorimetry)

Measure Charge

- dE/dx (tracking / scintillation)
- Number of photons in Cherenkov radiation

Measure Mass (β/γ + E/p)

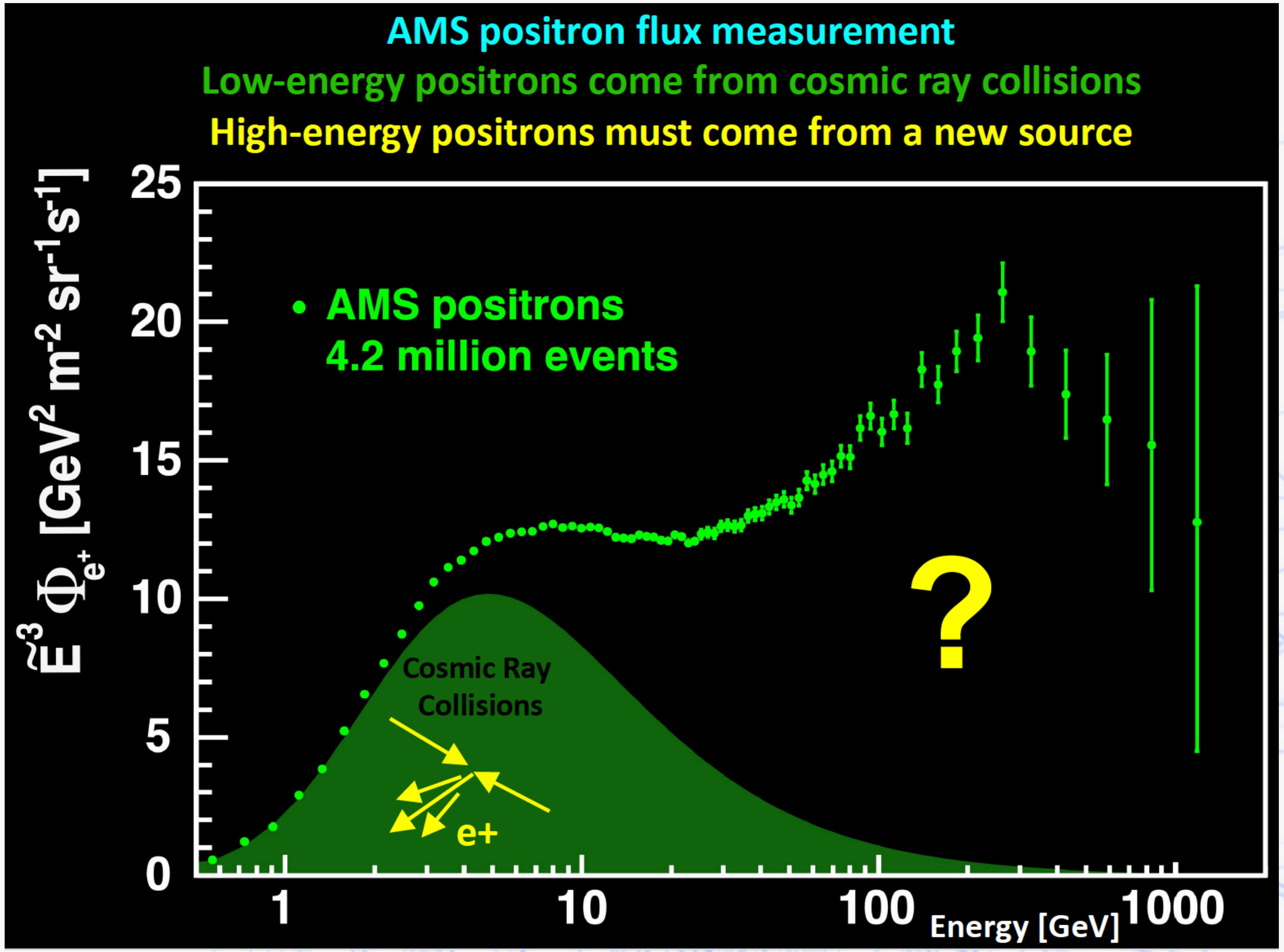
- Time of flight
- Cherenkov
- Transition radiation

Hadron / Lepton Separation

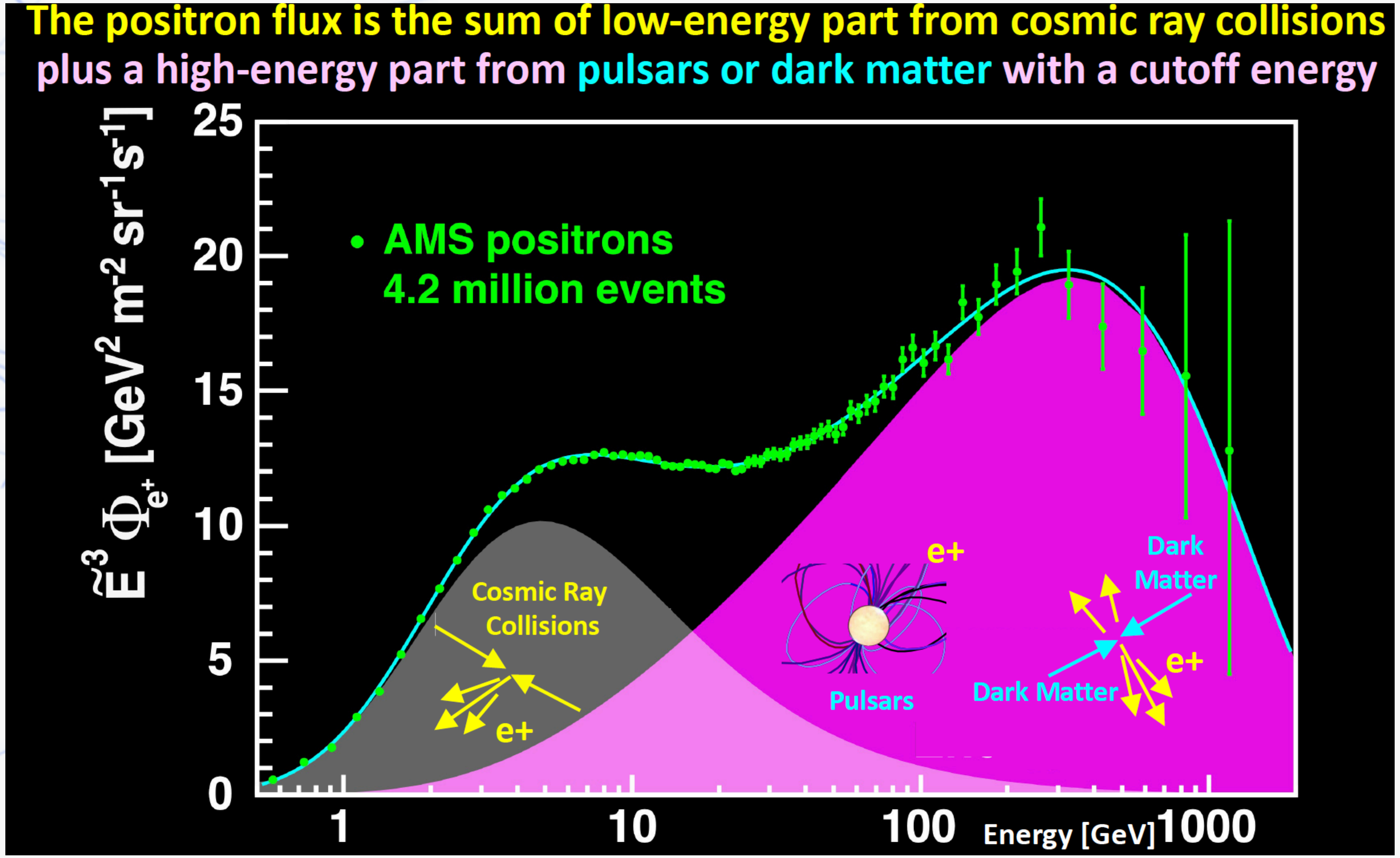
- Transition radiation
- Shower development topology (imaging calorimetry)
- Energy / momentum match
- Neutrons produced in hadronic shower (neutron detector)
- Calorimeter back-scattering timing measurement (?)

Current knowledge of cosmic ray

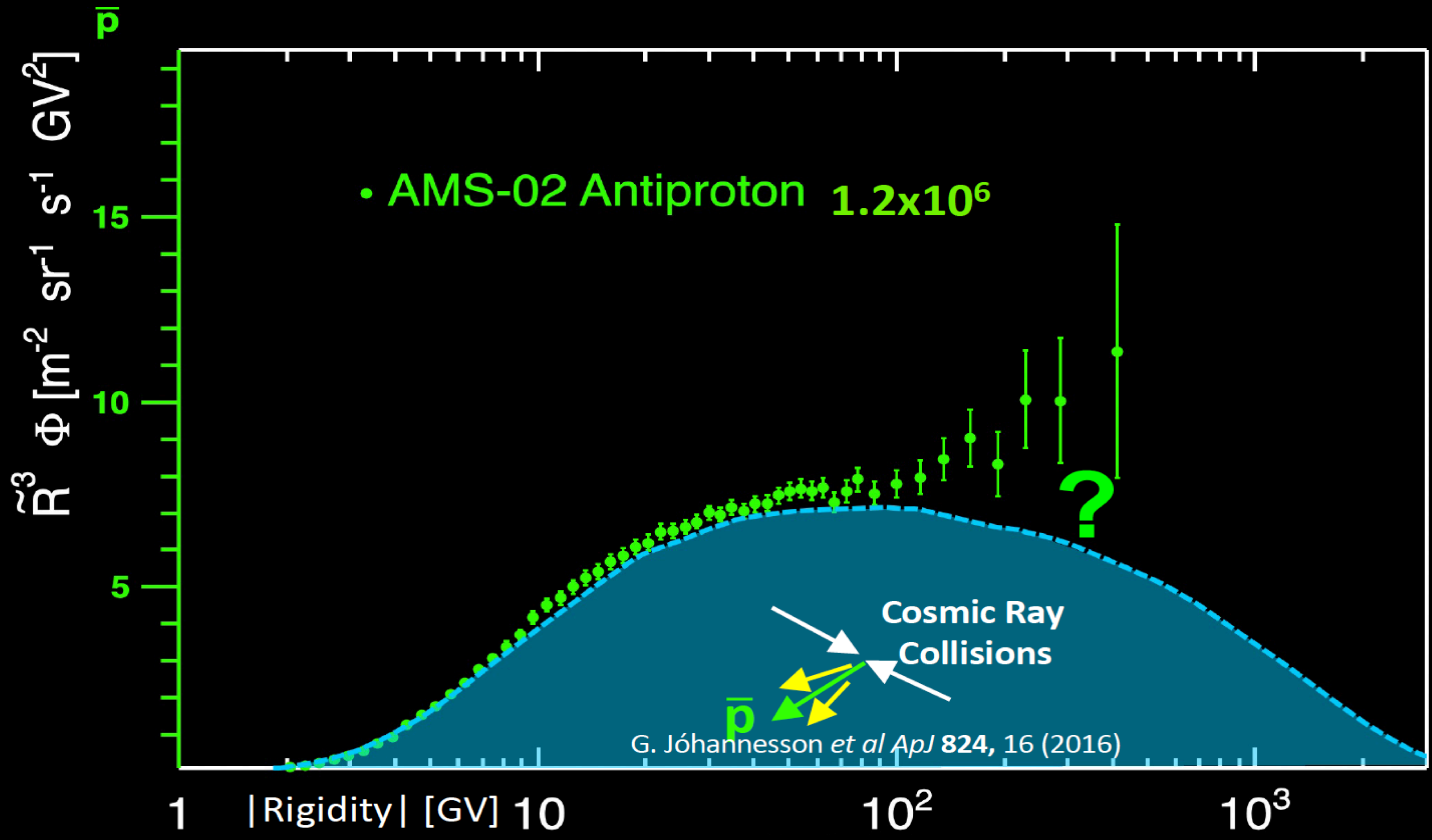
From M. Paniccia et al. at the last ECRS



why there are two classes of spectra in both primary and secondary cosmic-ray nuclei?



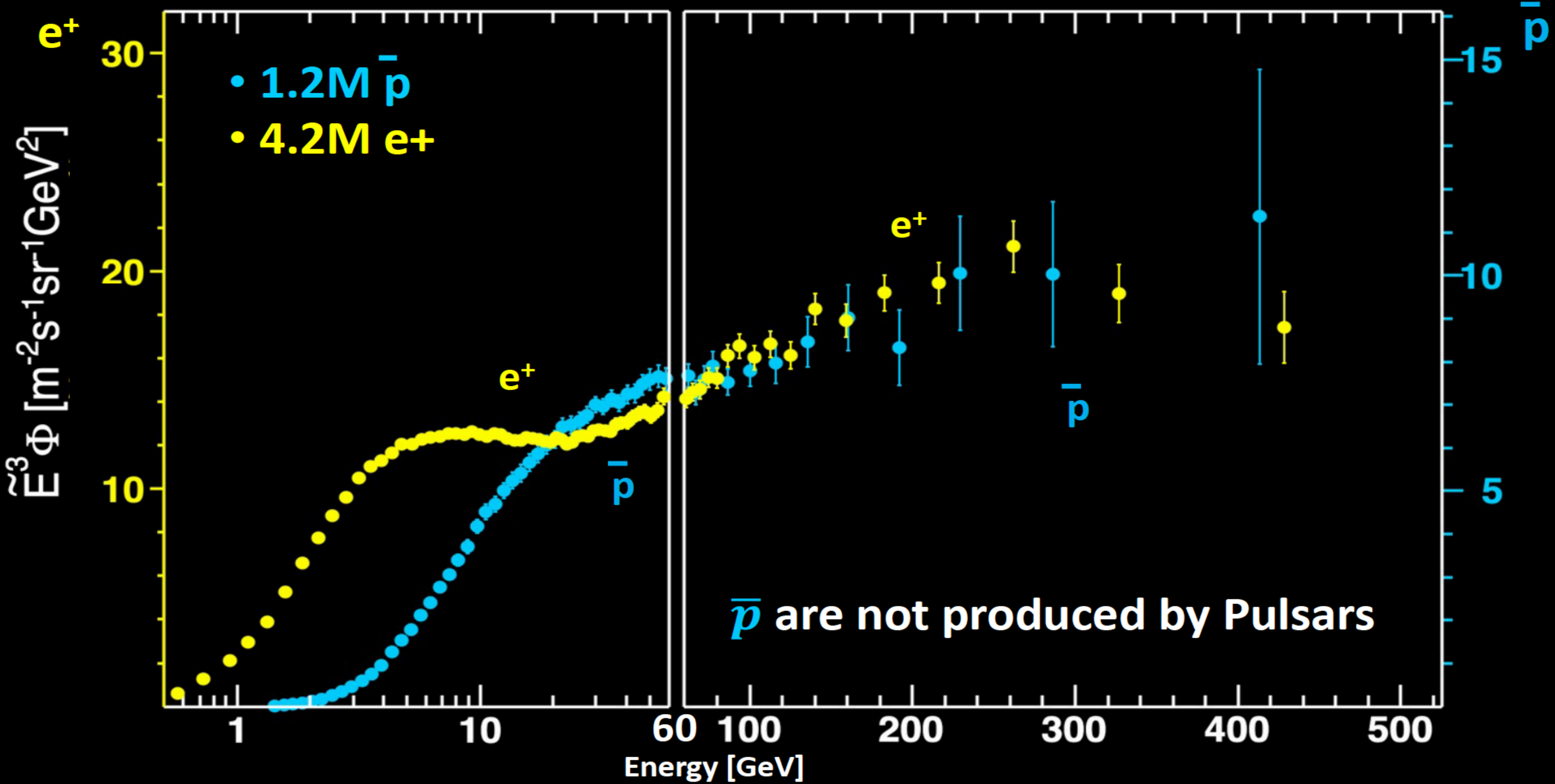
Cosmic Antiprotons



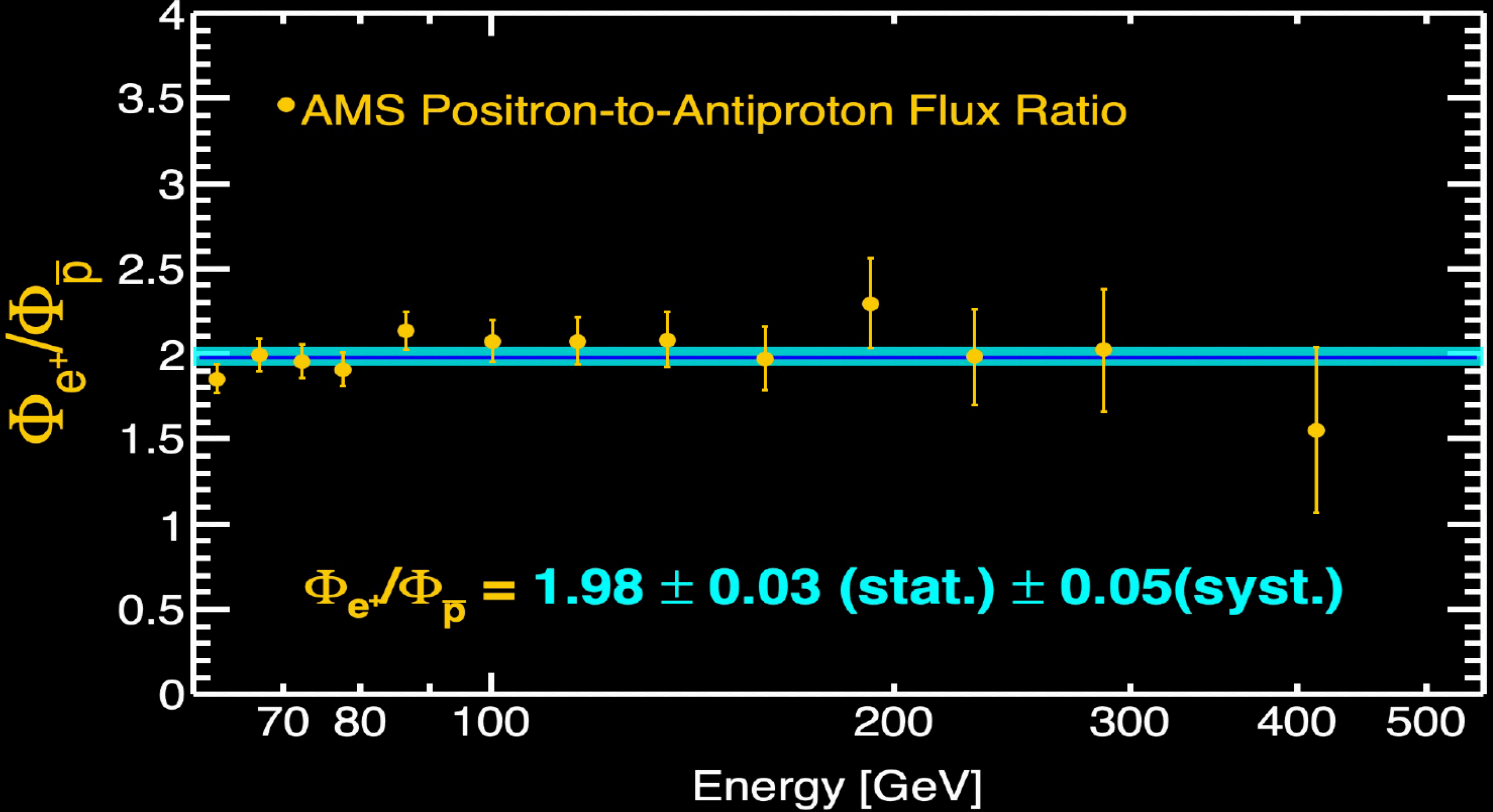
$\bar{p}$ are not produced by pulsars nor > 60 GV from cosmic ray collisions

Cosmic Antiprotons and Positrons

Above 60 GeV, the $\bar{p}$ and e^+ fluxes have identical energy dependence



The positron-to-antiproton flux ratio is independent of energy.



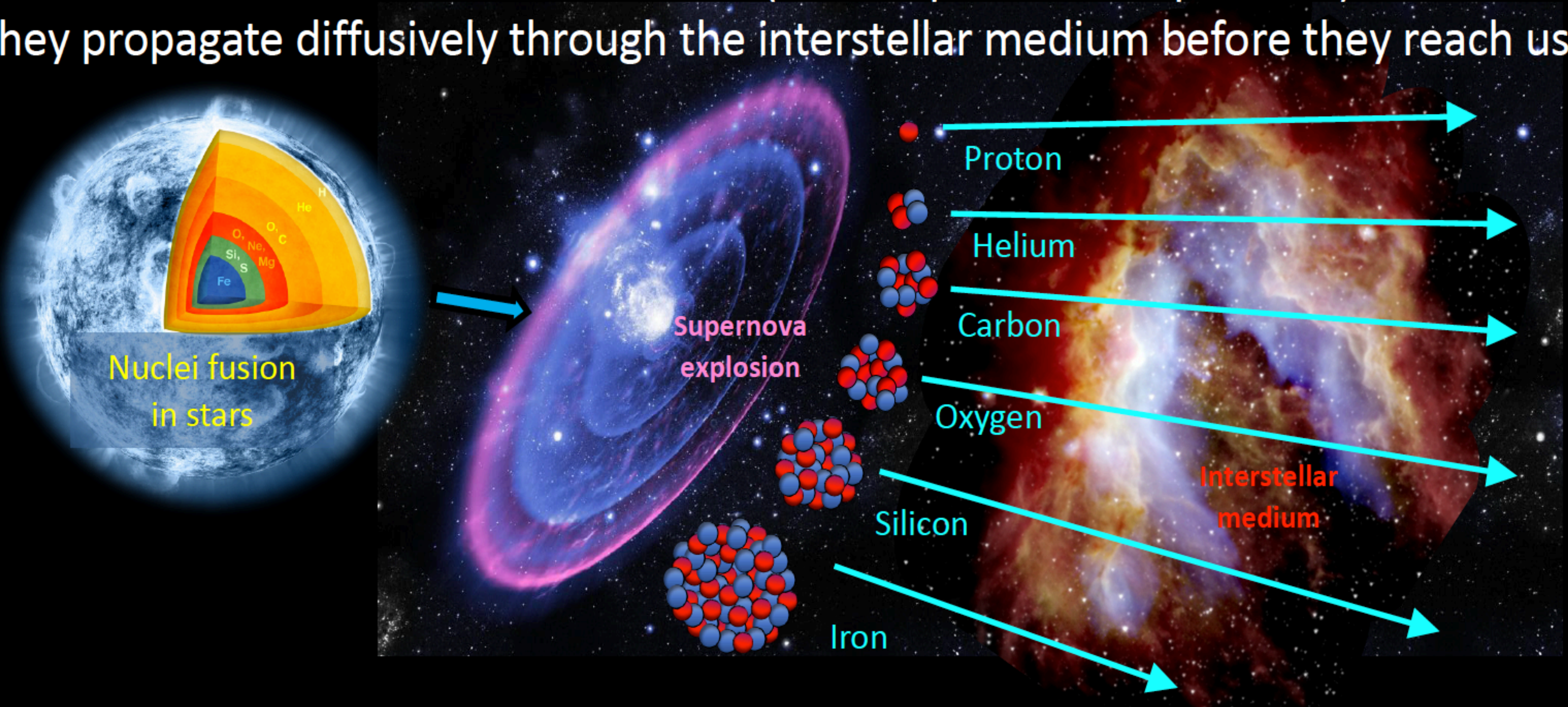
Latest AMS Results on Primary Cosmic Rays

See dedicated talk in Today CRD session:

Unique properties of Cosmic Ray Nuclei: Results from the Alpha Magnetic Spectrometer - V. Choutko

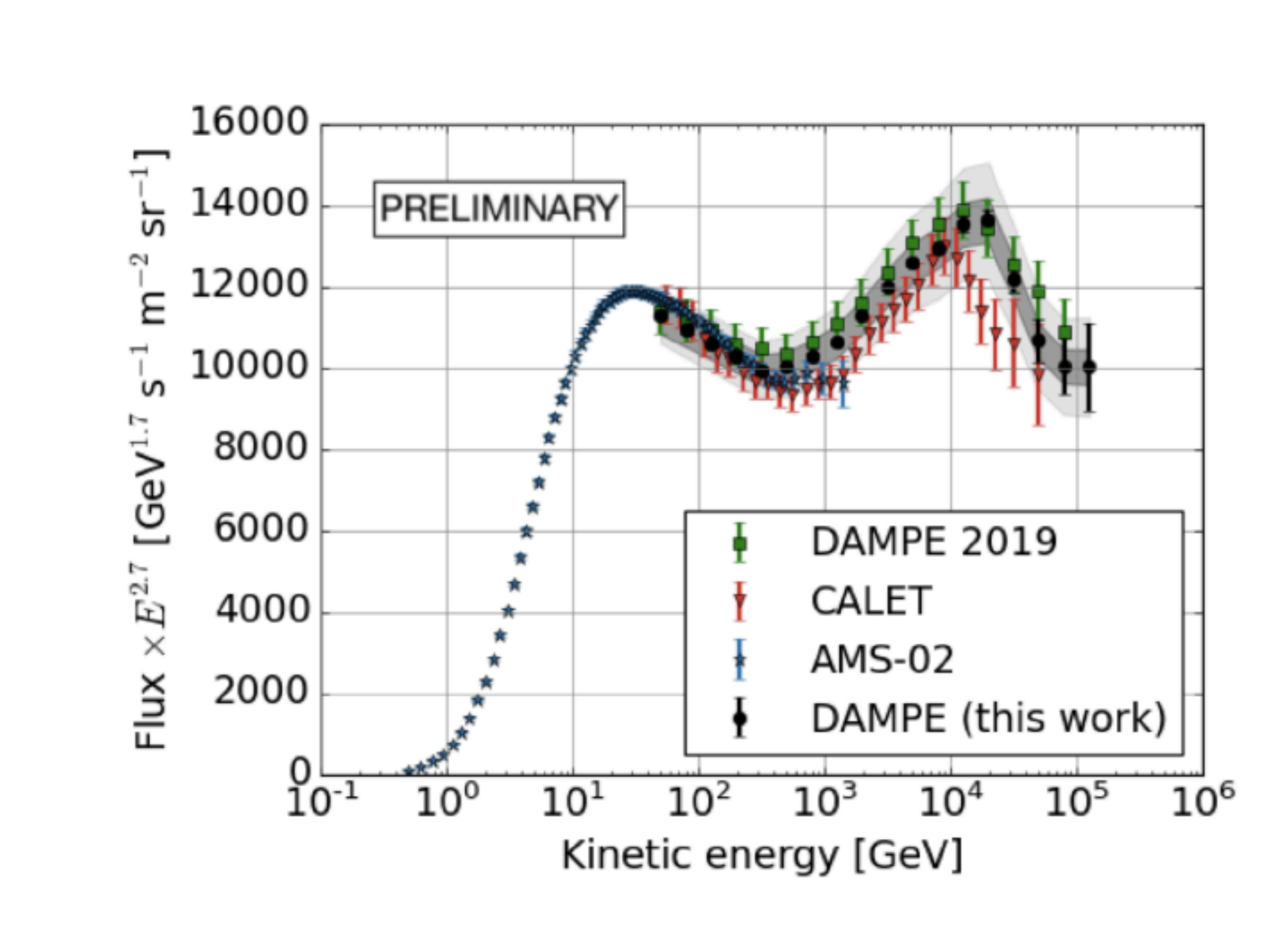
Primary cosmic rays p, He, C, O, ..., Si, ..., Fe produced during the lifetime of stars and accelerated by diffusive shock acceleration (as in Supernovae explosions)

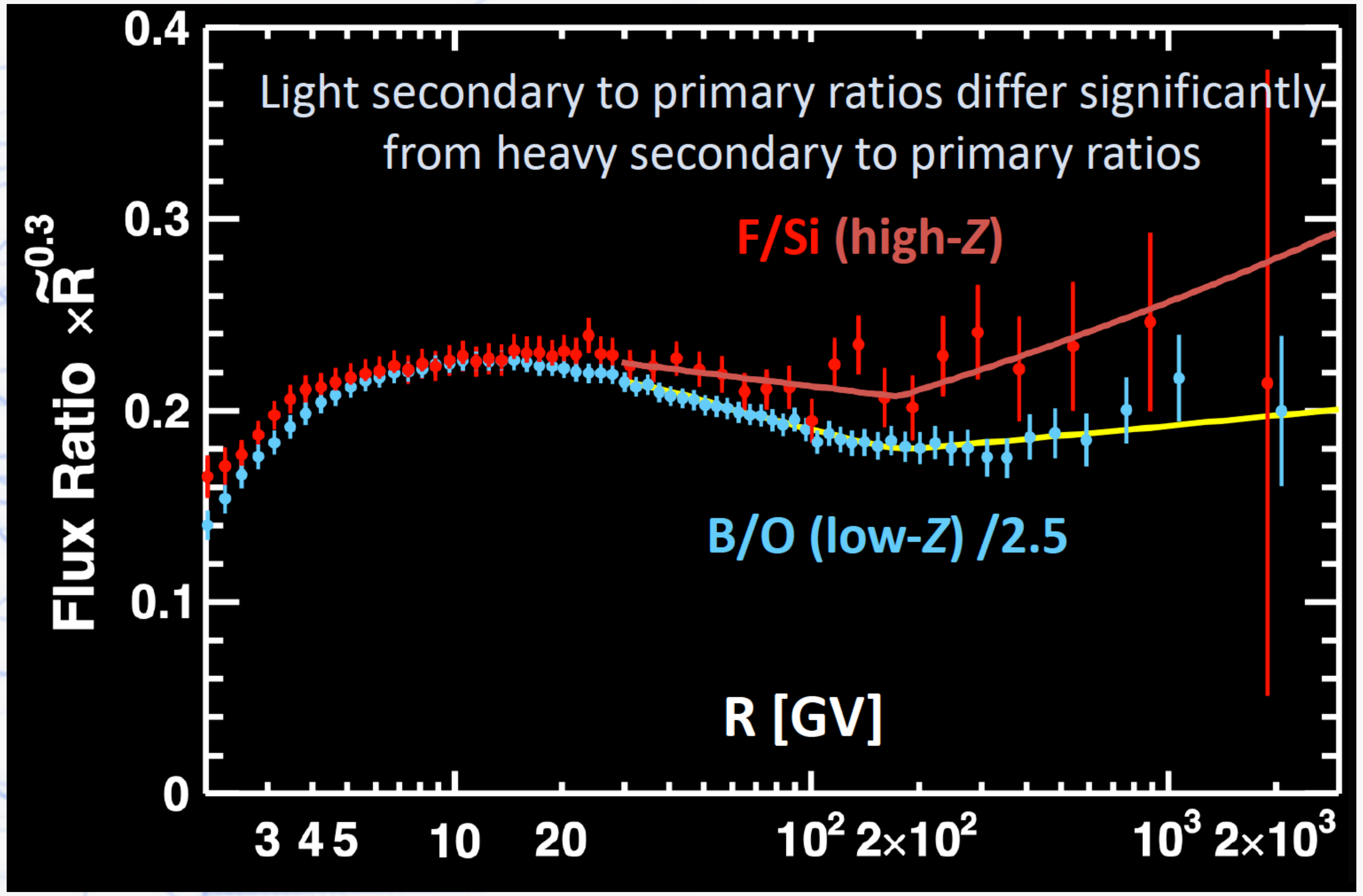
They propagate diffusively through the interstellar medium before they reach us.

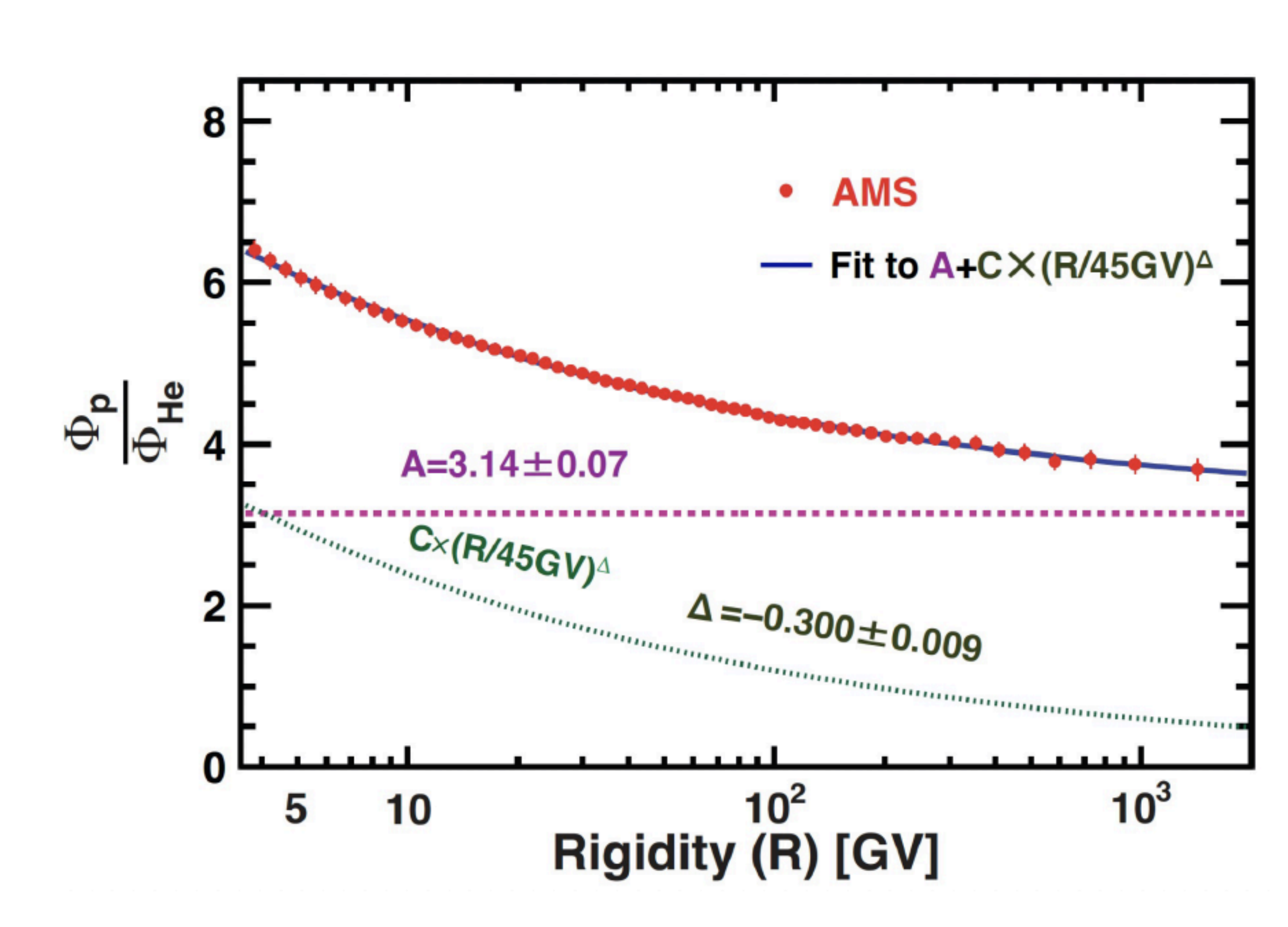


Measurements of primary cosmic ray fluxes are fundamental to understanding the origin, acceleration, and propagation processes of cosmic rays in the Galaxy.

How do we identify a charge particle?



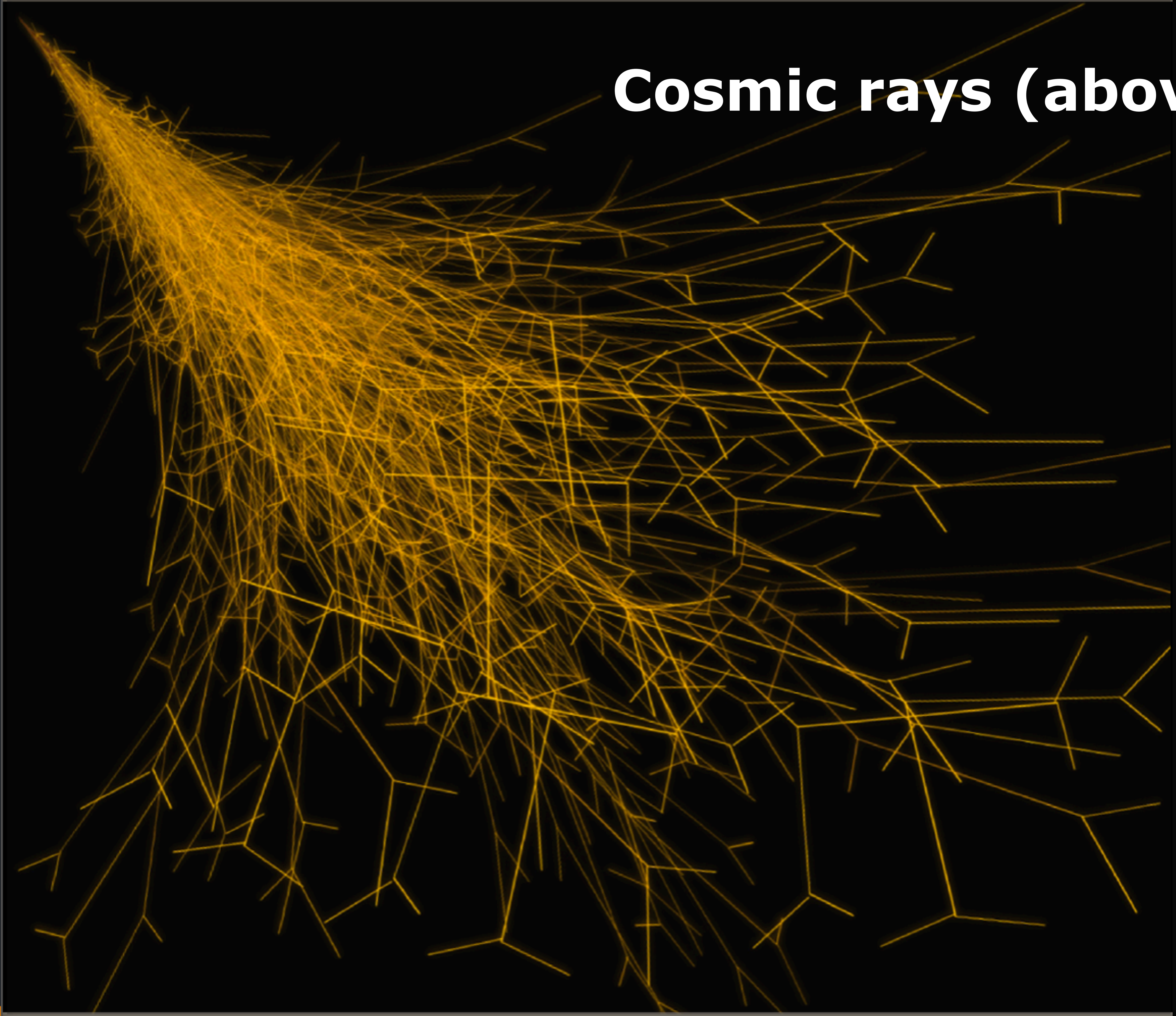




Why hardening at 200 GeV?
do light and heavy cosmic-ray nuclei propagate in the same way?

–> related to propagation properties in the Galaxy

Cosmic rays (above the knee)



Running & future experiments

Cosmic rays

- Pierre Auger Observatory
- Telescope Array
- IceCube/IceTop
- GRAPES 3
- LHAASO
- TibetAs
- Yakutsk

\+ GCOS

\+ POEMA

\+ SKA

Gamma rays

- HAWC
- ALPACA
- LHAASO
- TibetAsγ
- IceCube
- Pierre Auger Observatory

\+ SWGO

\+ CTAO

\+ PEPS

\+ HiScore

Neutrinos

- IceCube
- KM3Net
- Baikal-GDV
- Pierre Auger Observatory

\+ P-One

\+ TRIDENT

\+ GRAND

\+ RNO-G

Not covered here: dark matter searches, direct measurements and space detectors, ...

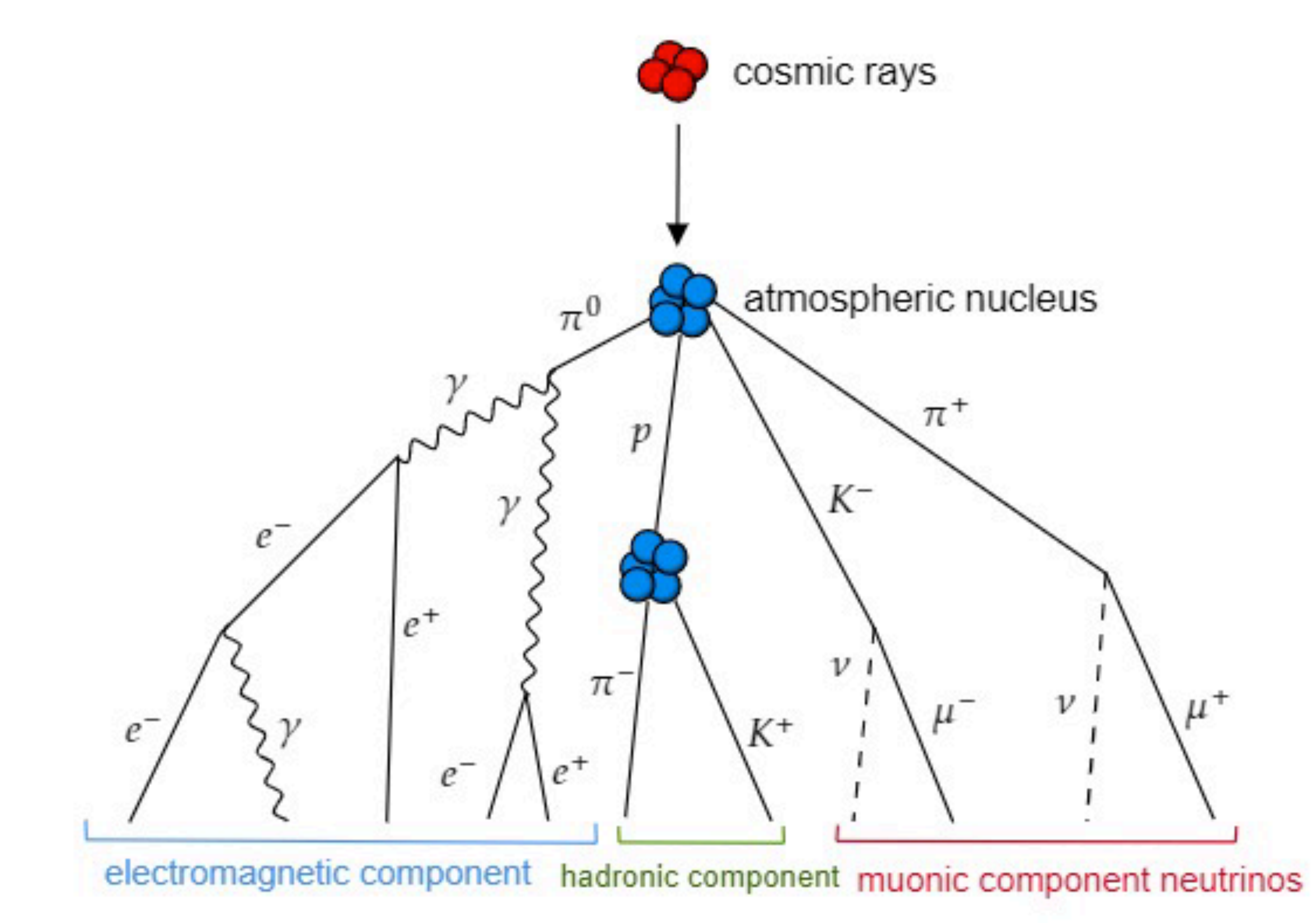
What do they have in common?

Indirect detection: Extensive Air Shower (EAS)

The collision of cosmic rays with the atmospheric molecules produces a cascade of particles, called Extensive Air Shower (EAS).

The particles of an EAS initiated by a proton or a nucleus can be roughly divided into three components:

- Hadronic (mostly pions)
- Electromagnetic (e^+, e^-, γ)
- Penetrant (muons and neutrinos)



A key information to infer about properties of the primary particle is the depth of the shower maximum

$$X_{max} \propto lg(E/A)$$

The Pierre Auger Observatory

Hybrid detector

Fluorescence detector (FD)
duty cycle 15%
24+3 fluorescence telescopes

Surface detector (SD)
duty cycle 100%
1660 water-Cherenkov detectors

Radio detector (RD)

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Hybrid detector

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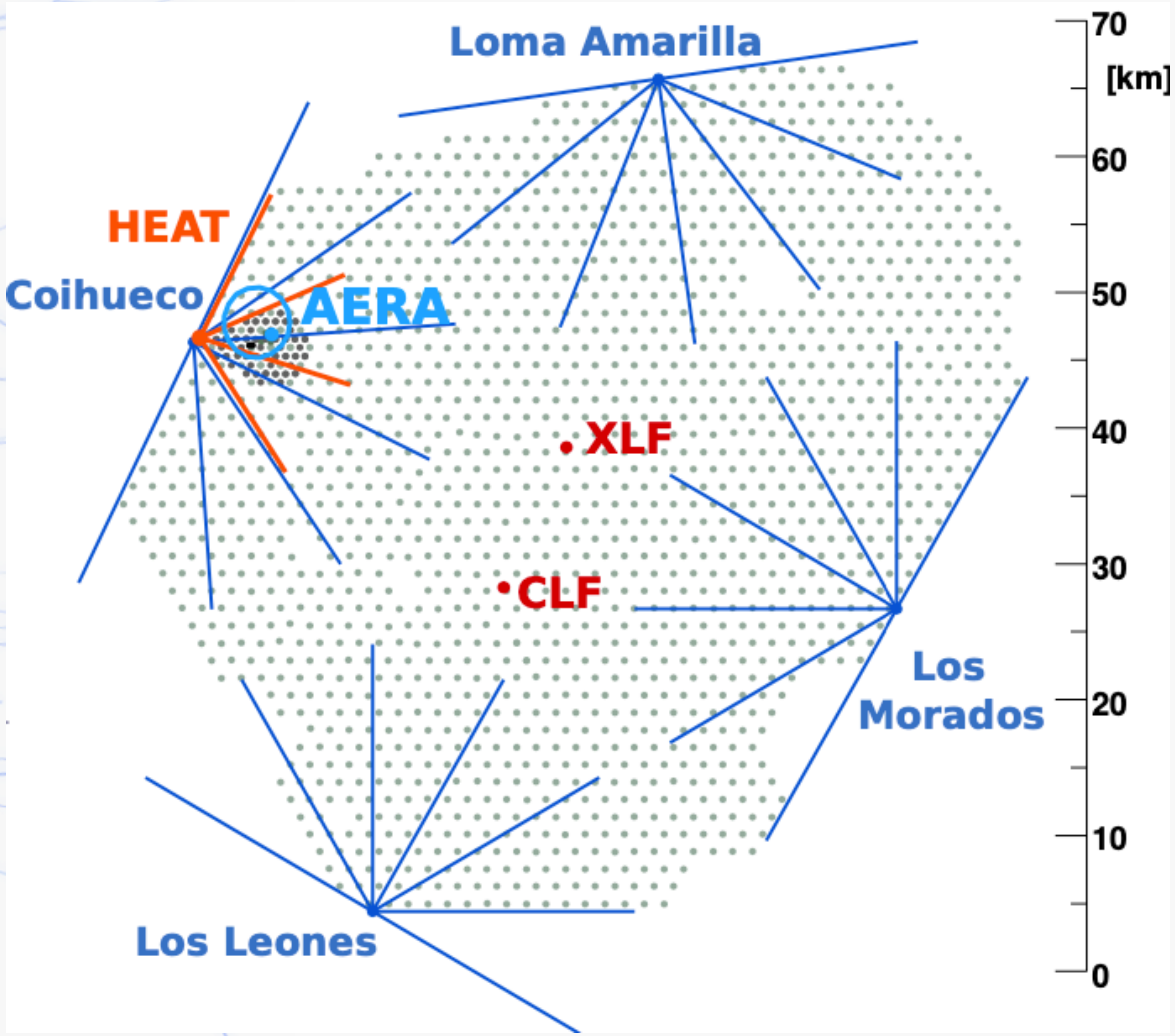
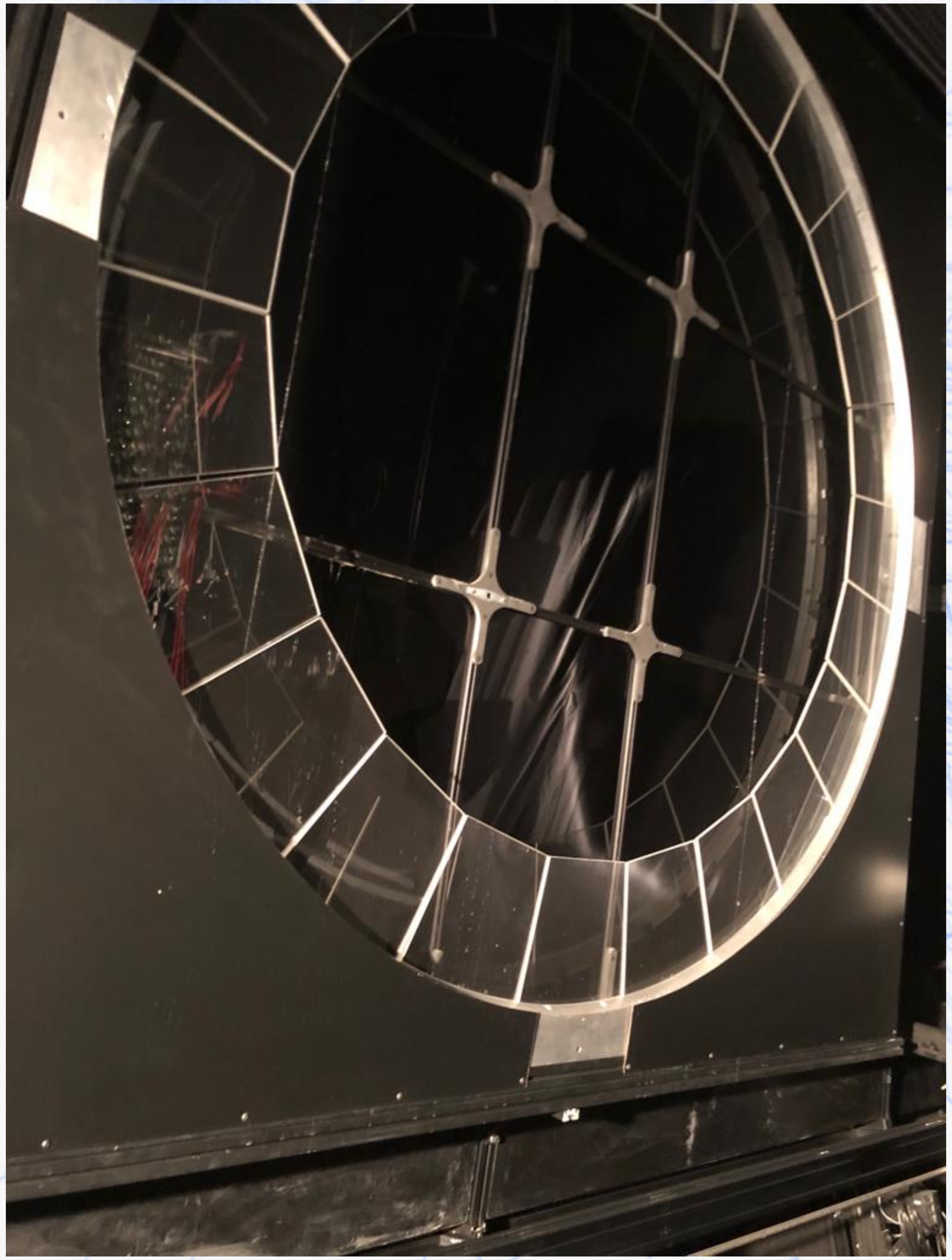
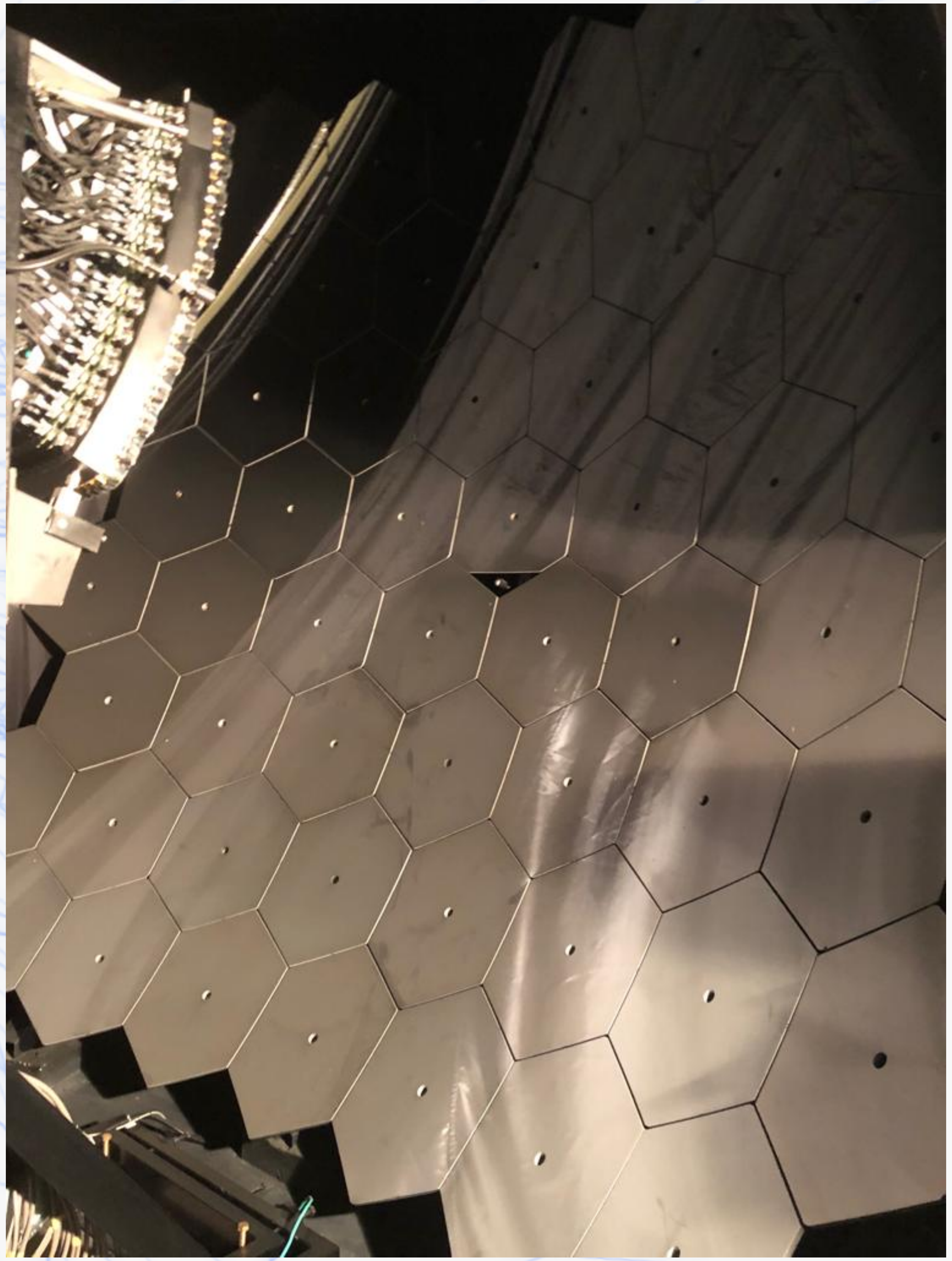
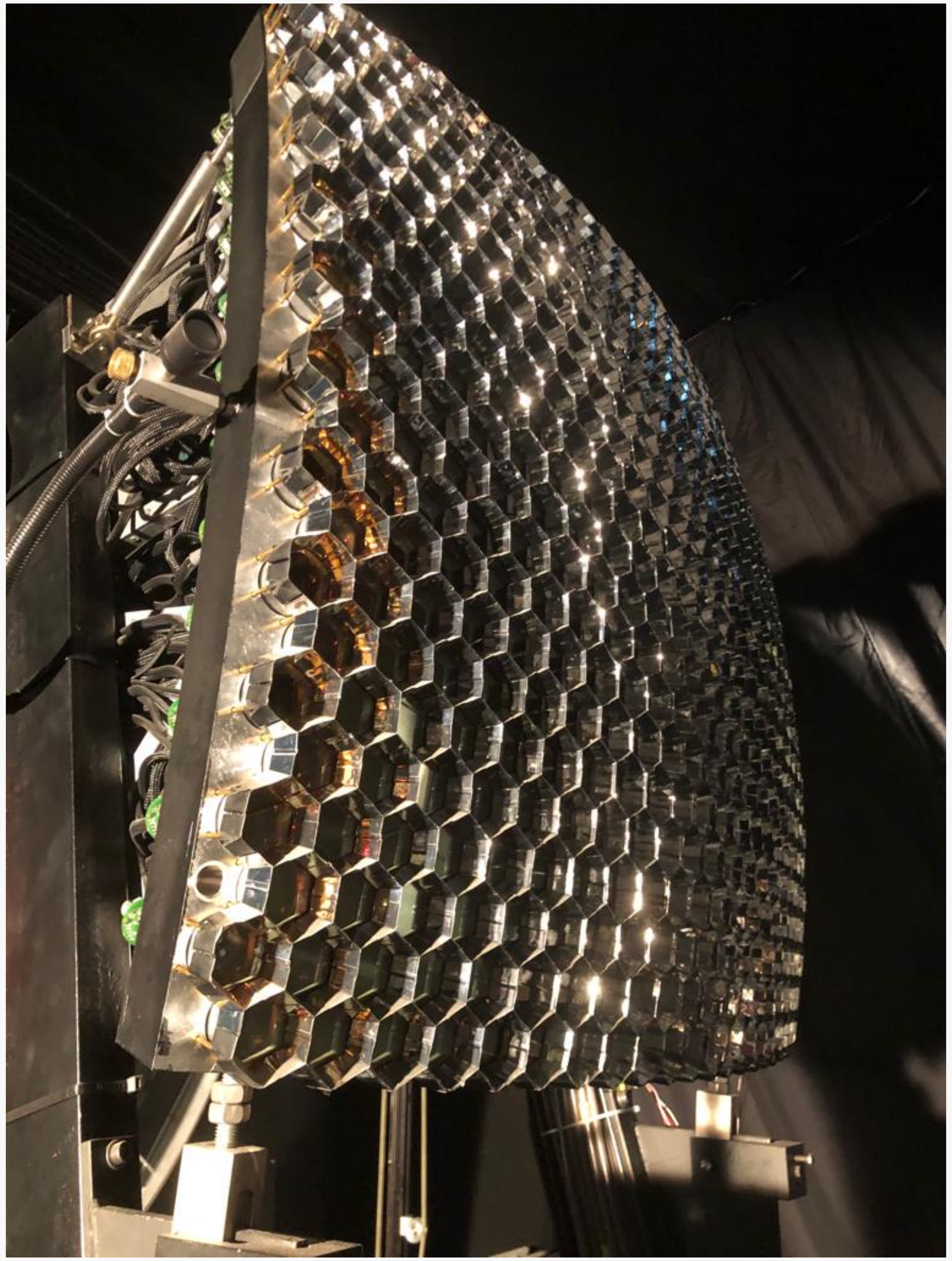


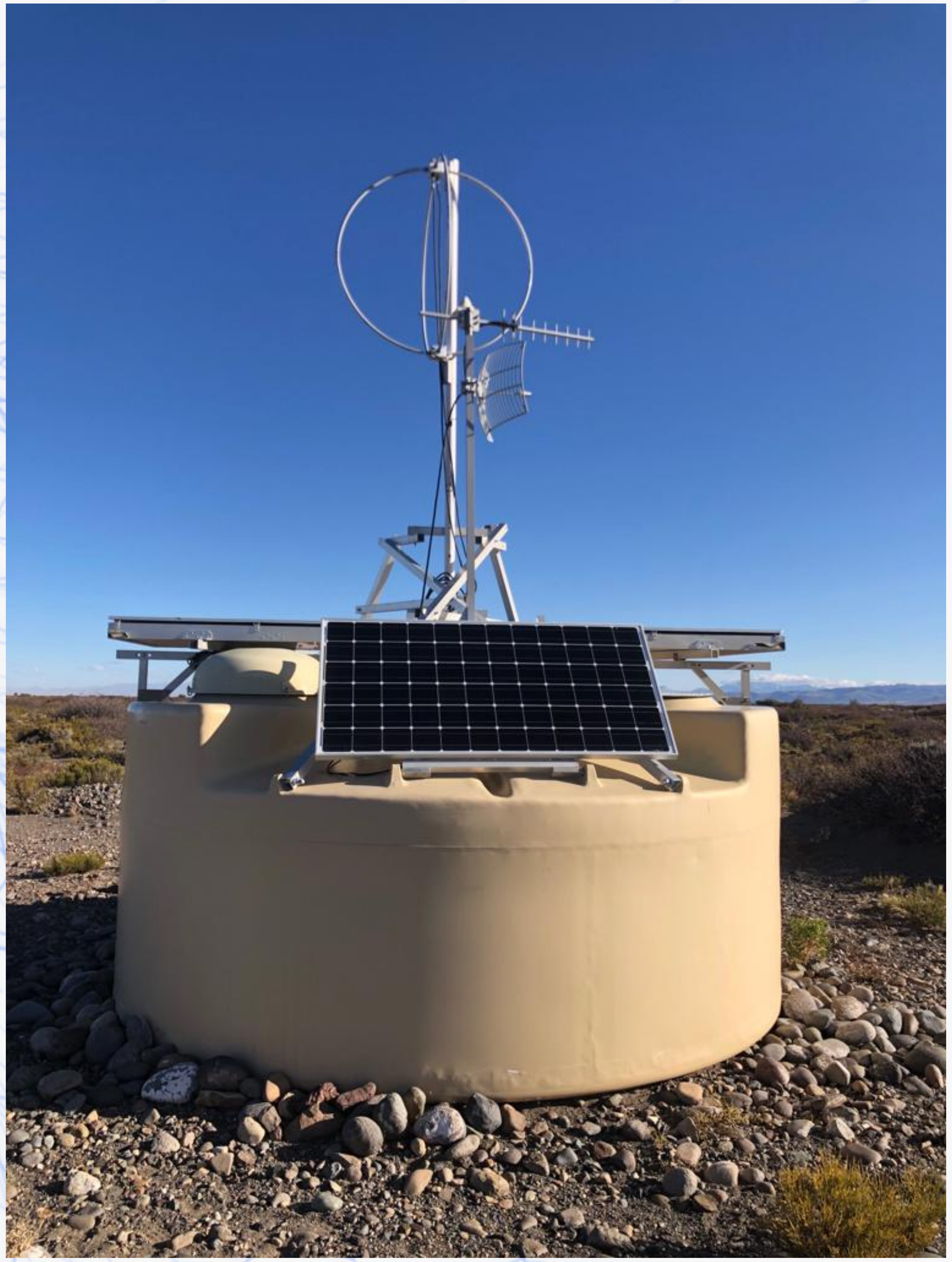
The hybrid detection







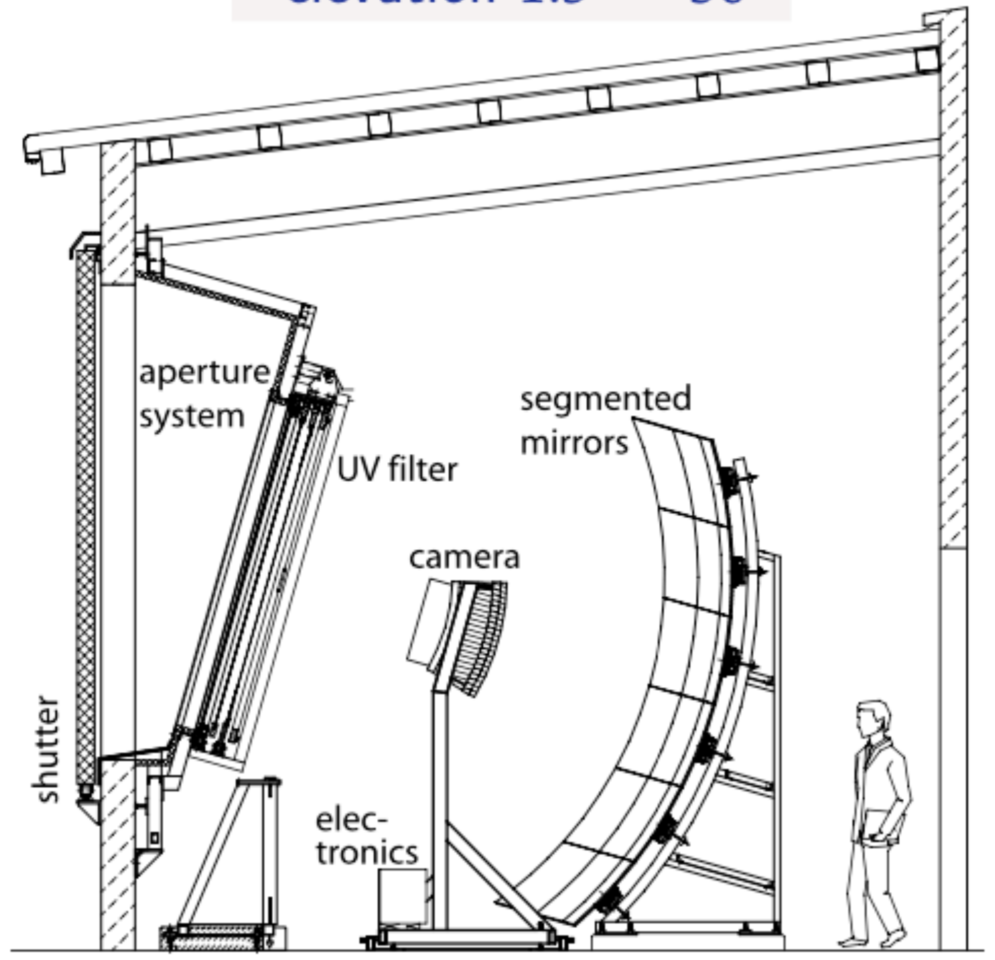
The hybrid detection



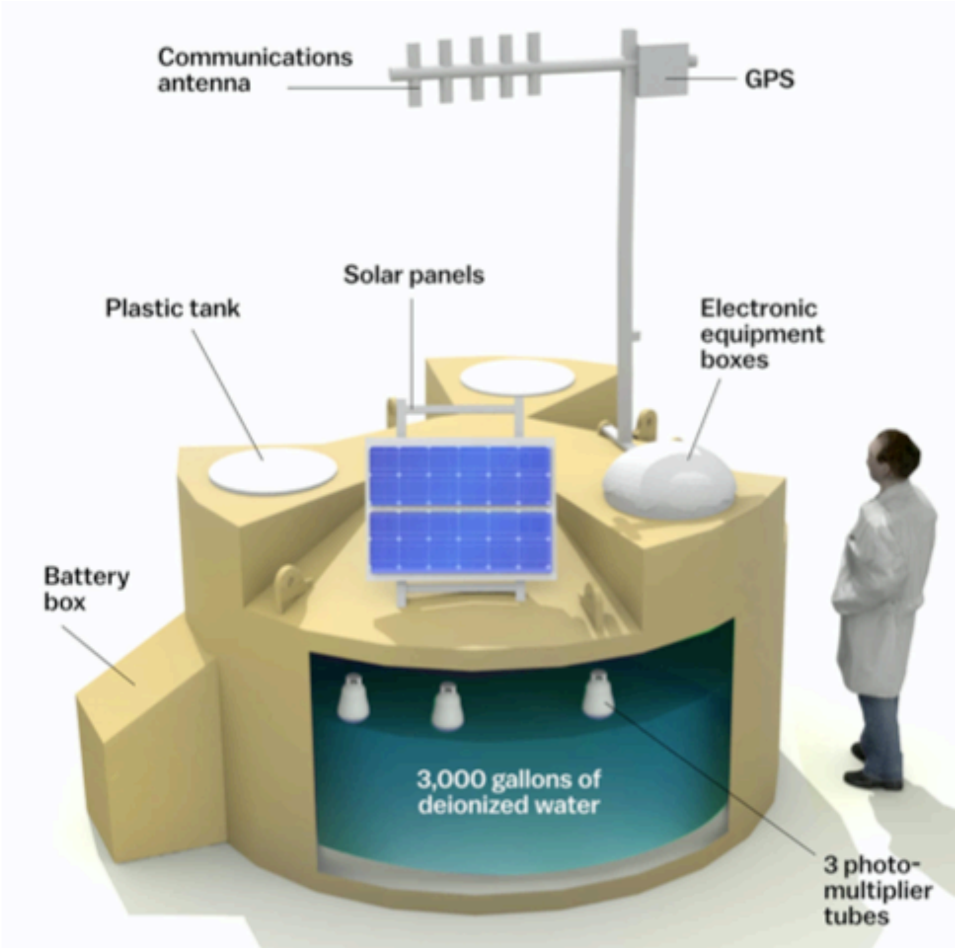
The hybrid detection

FD telescopes at Los Morados

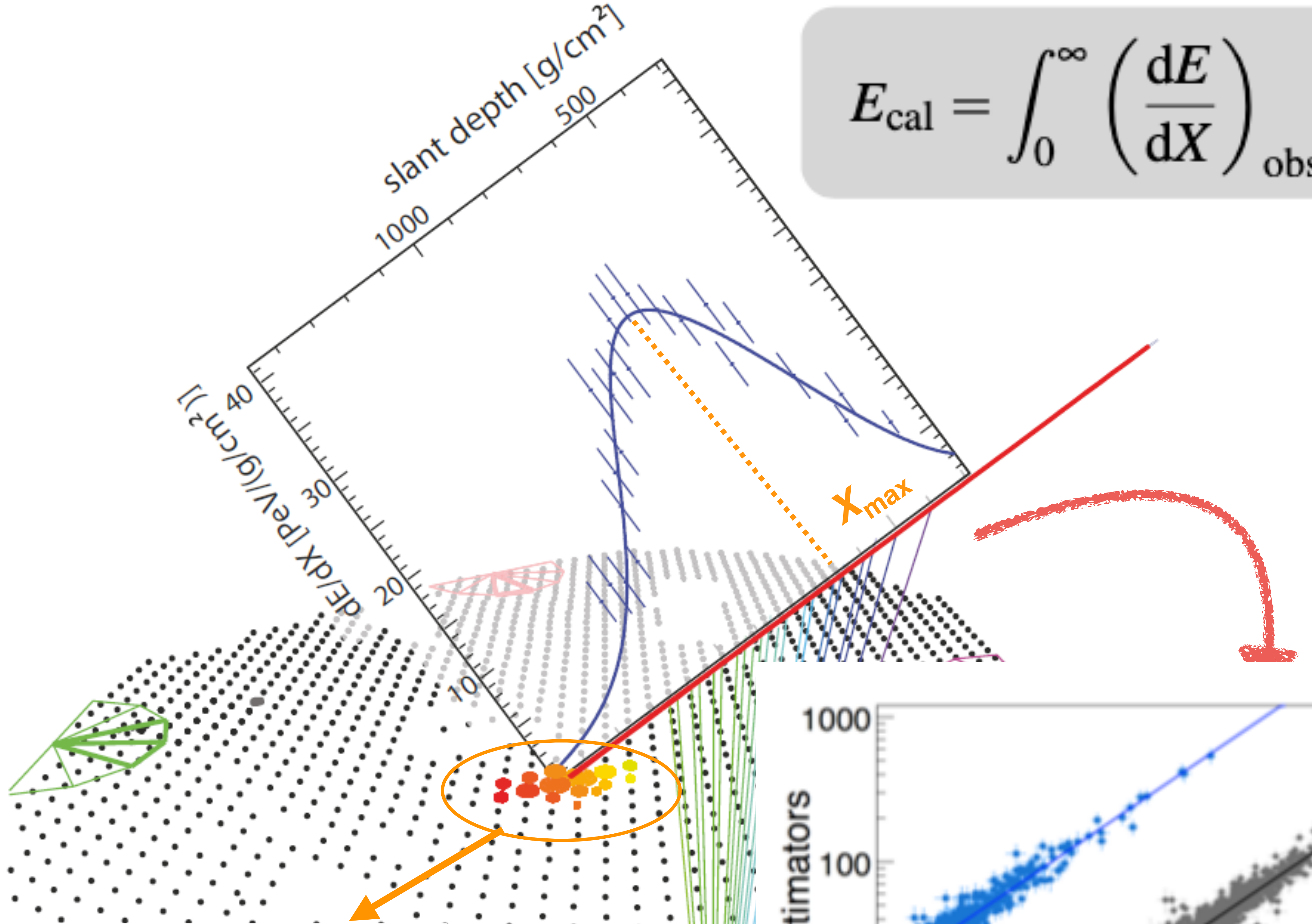
elevation 1.5° – 30°

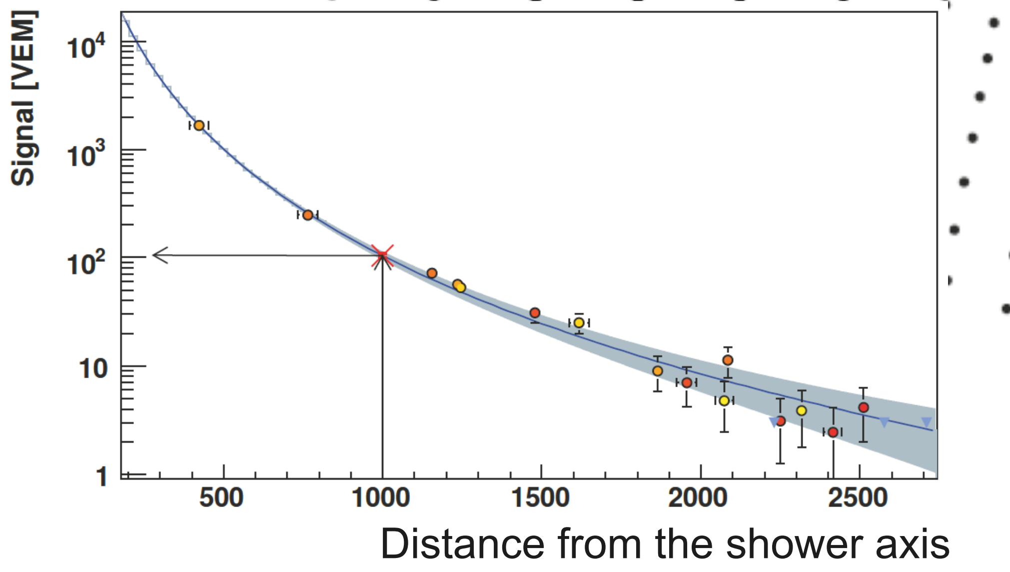


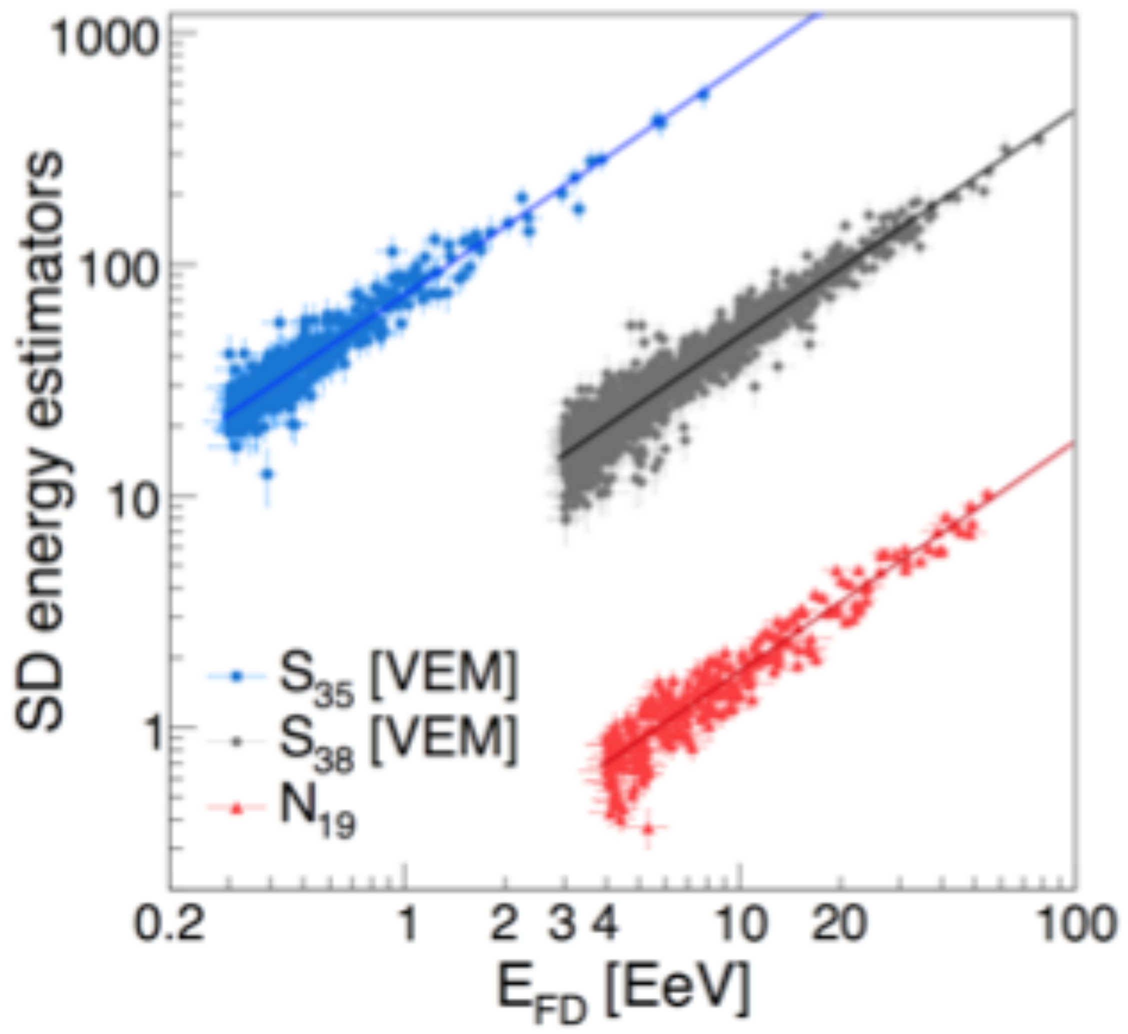
Water-Cherenkov station



$$E_{\text{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\text{obs}} \mathrm{d}X$$

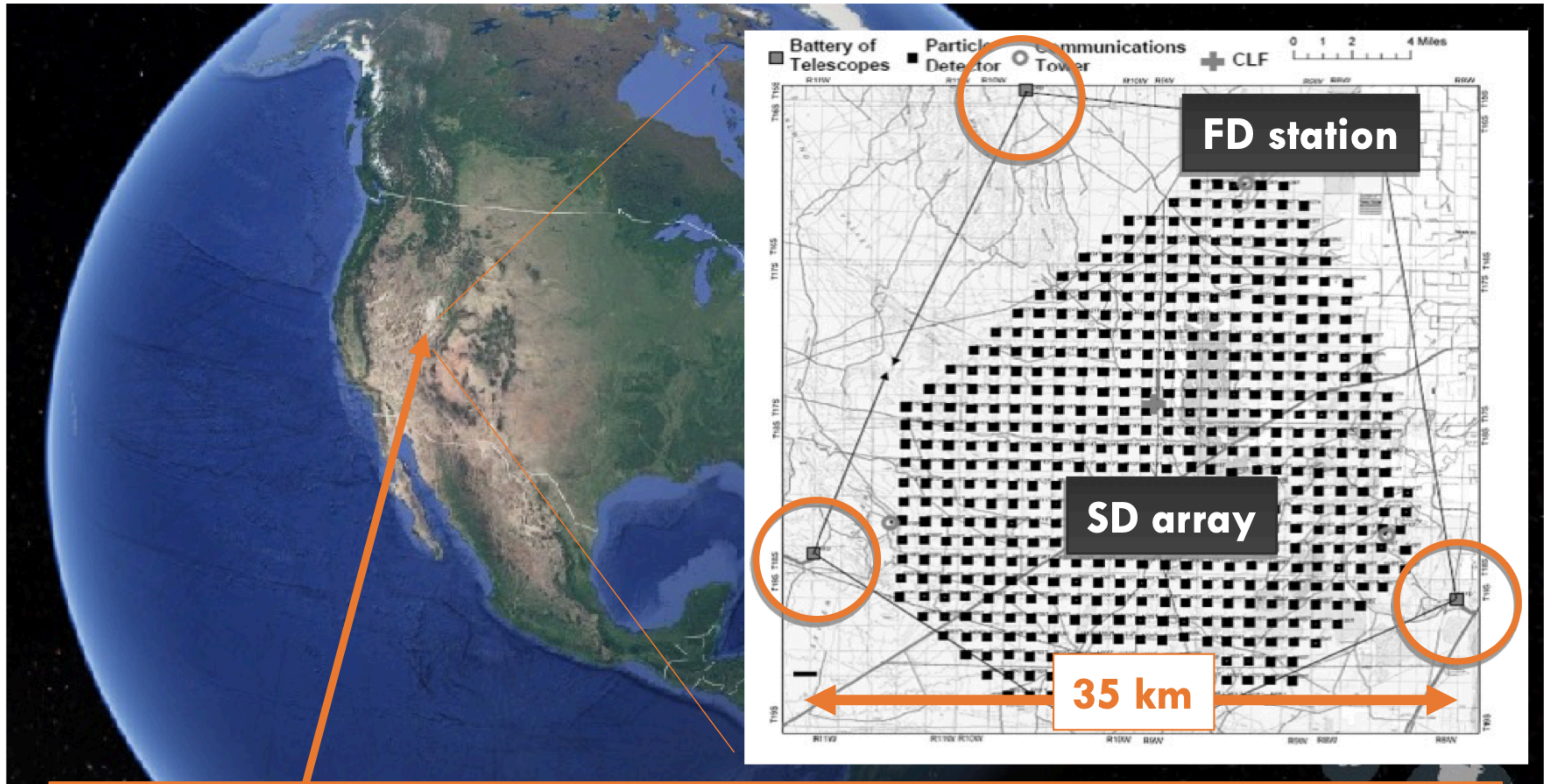






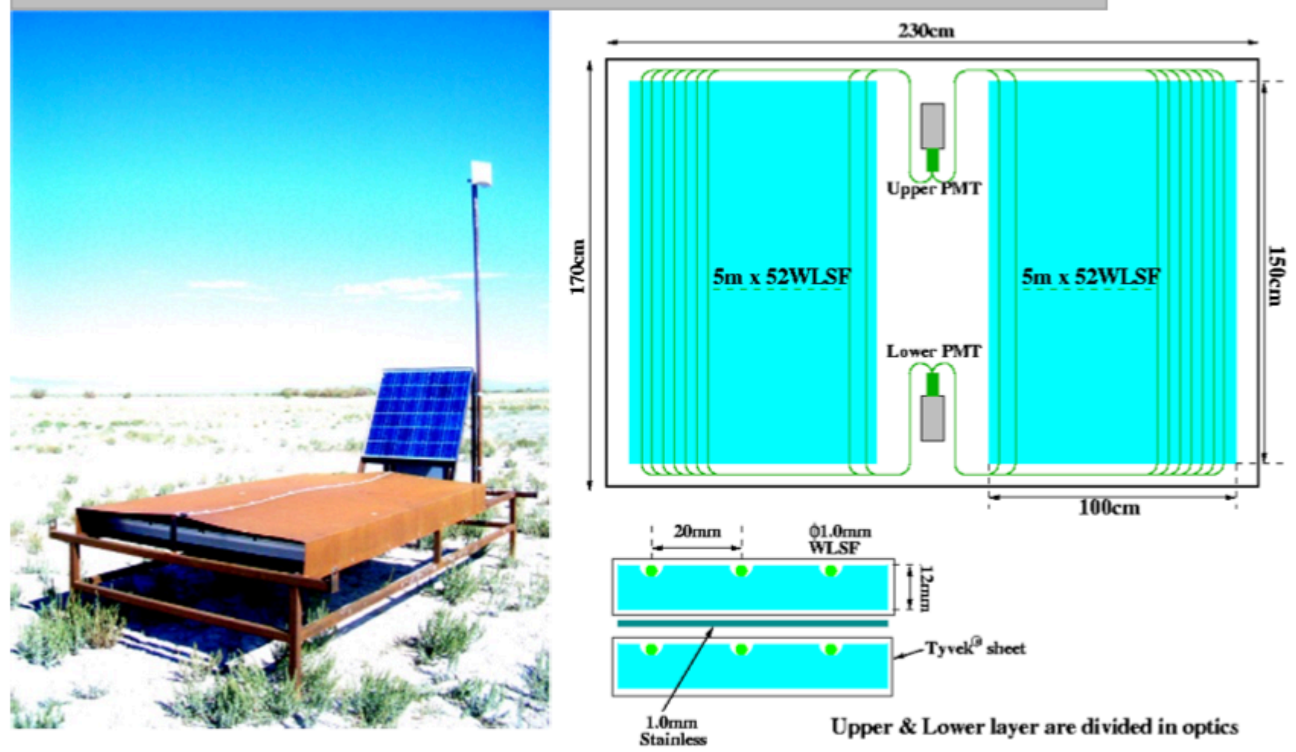
Telescope Array

- The largest cosmic ray observatory in the northern hemisphere



- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers **~700 km^2**
- 38 telescopes at 3 stations to observe the sky above the array

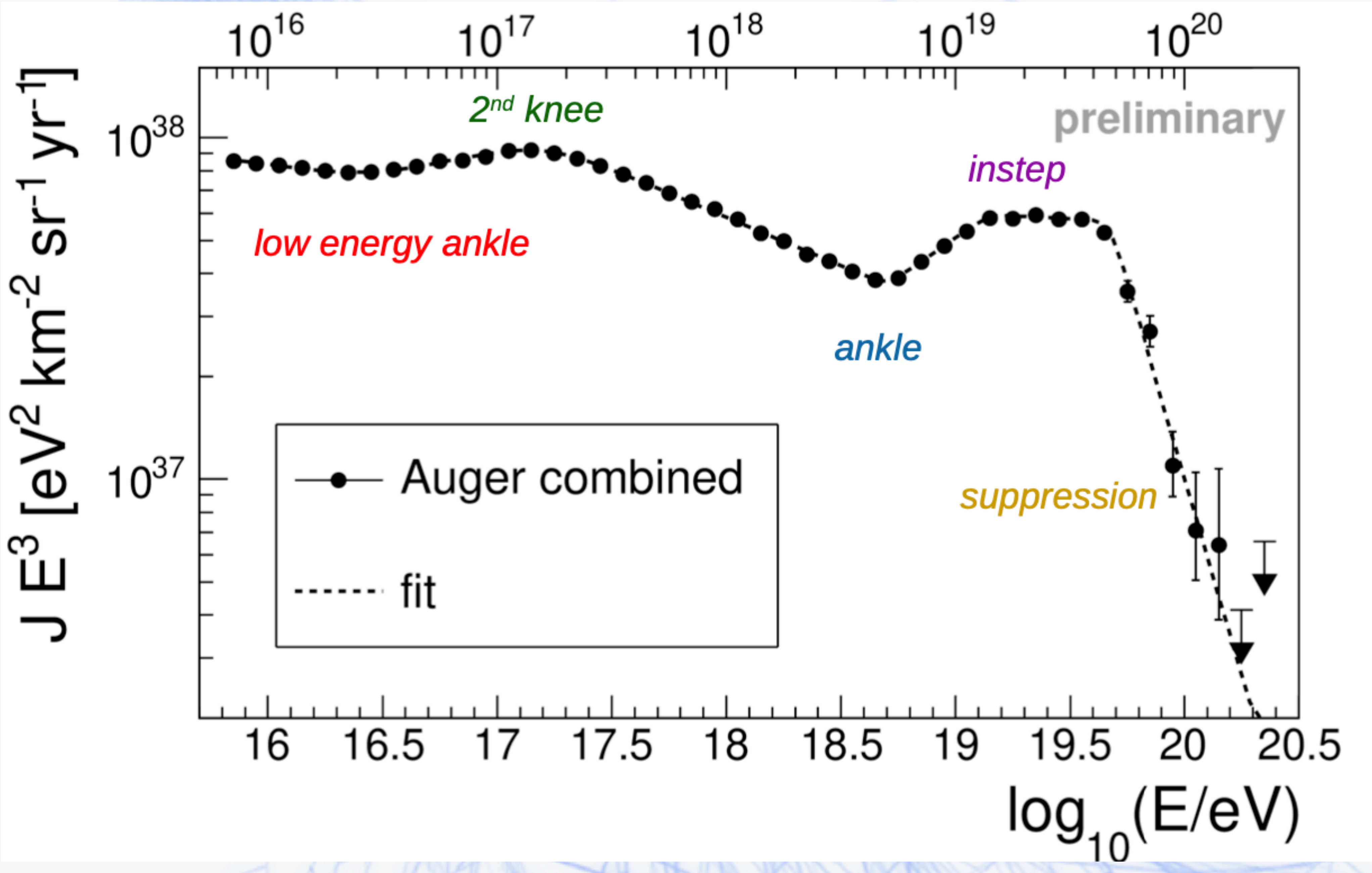
Surface Detector: Plastic Scintillator



Fluorescence Detector: PMT camera

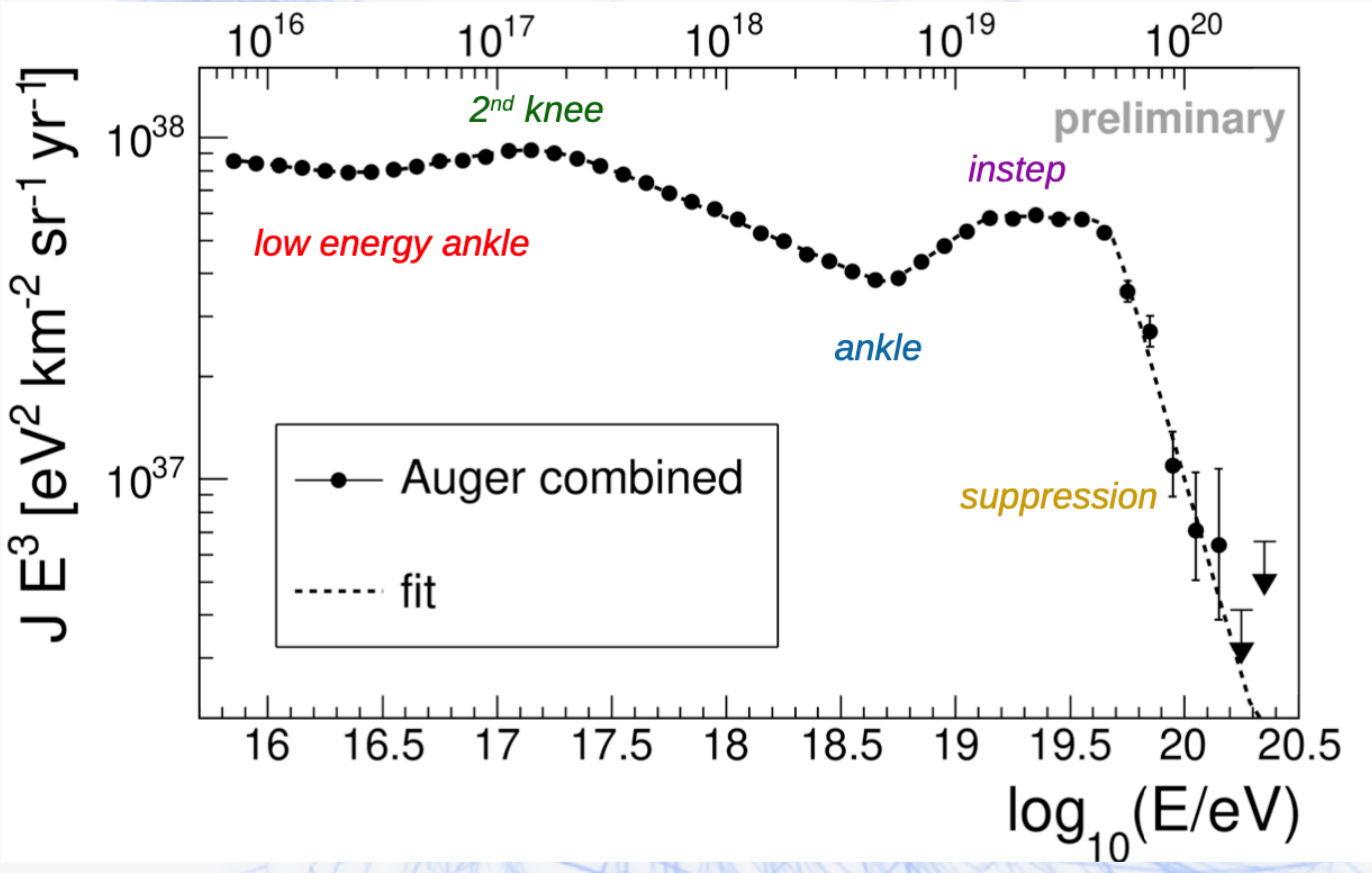
UHECR observables

Energy spectrum

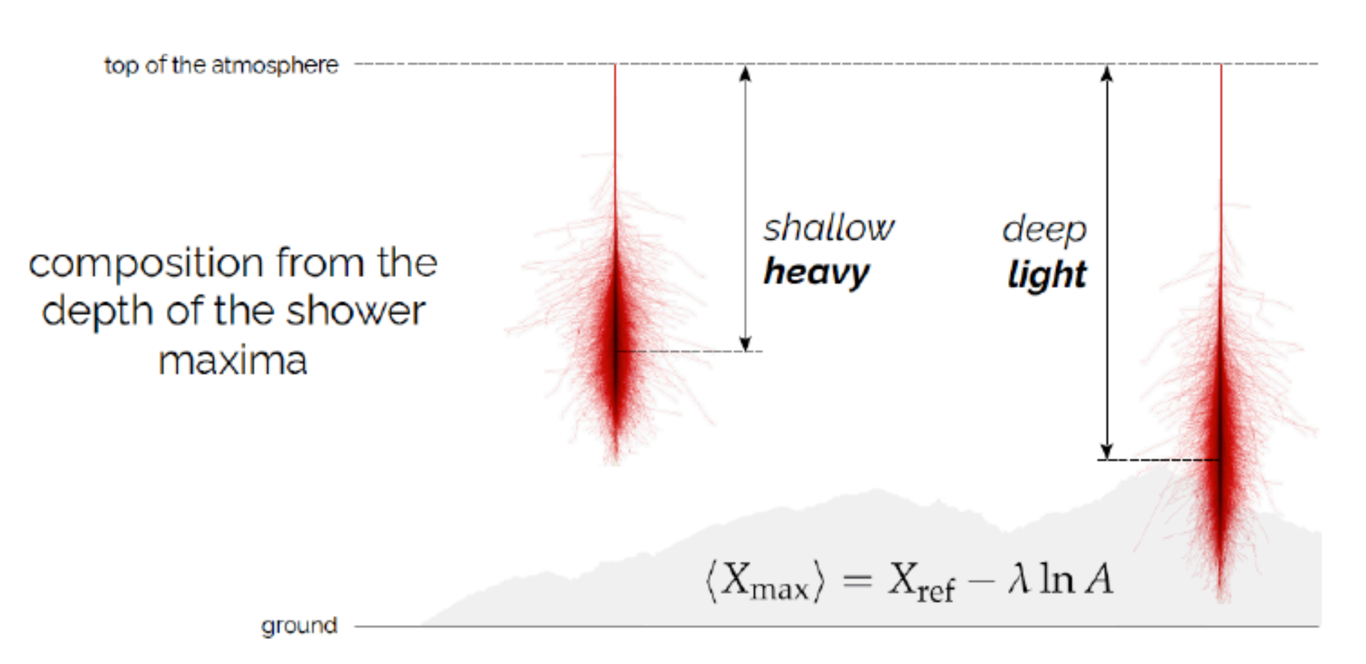


UHECR observables

Energy spectrum

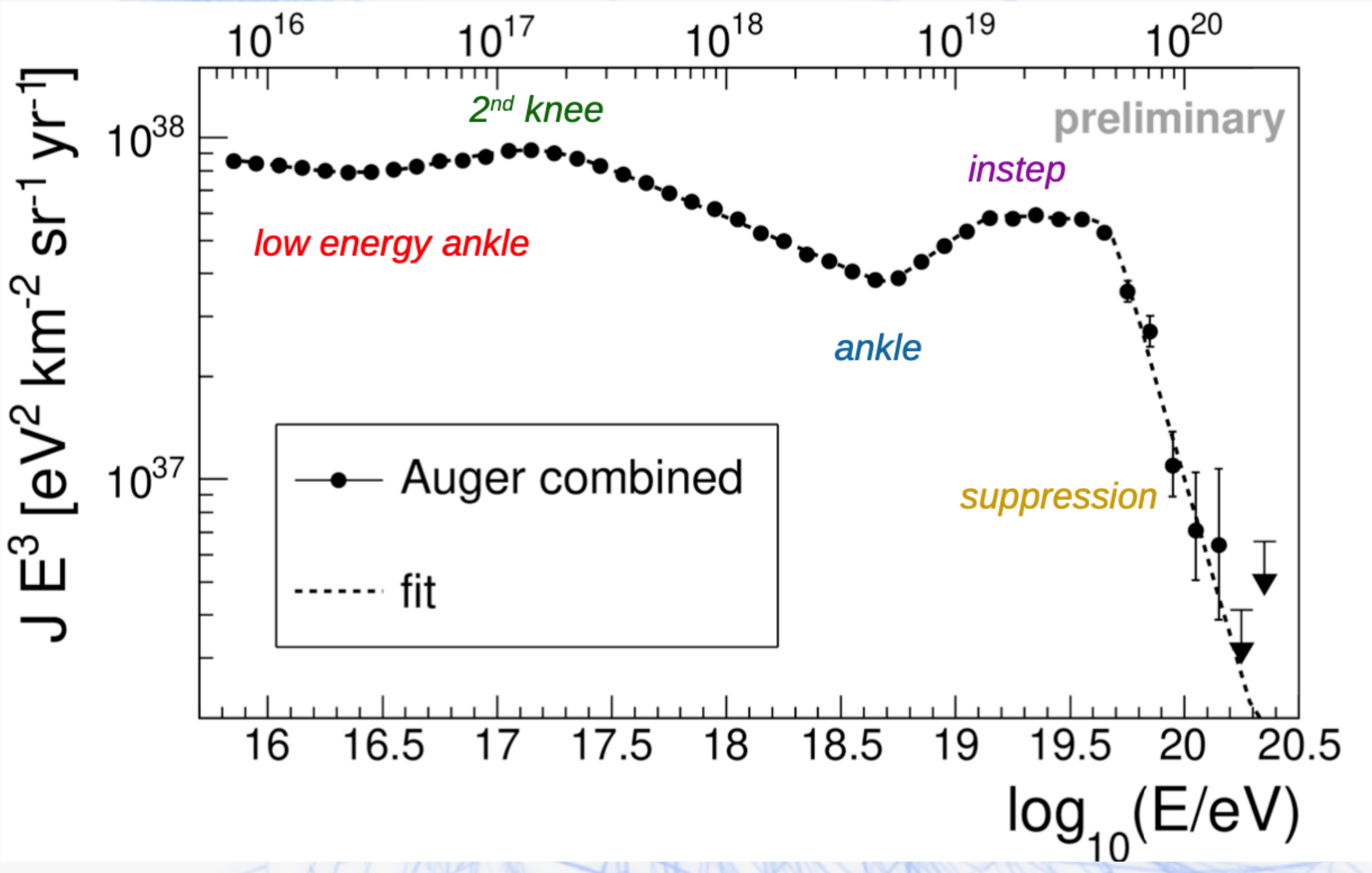


Mass Composition

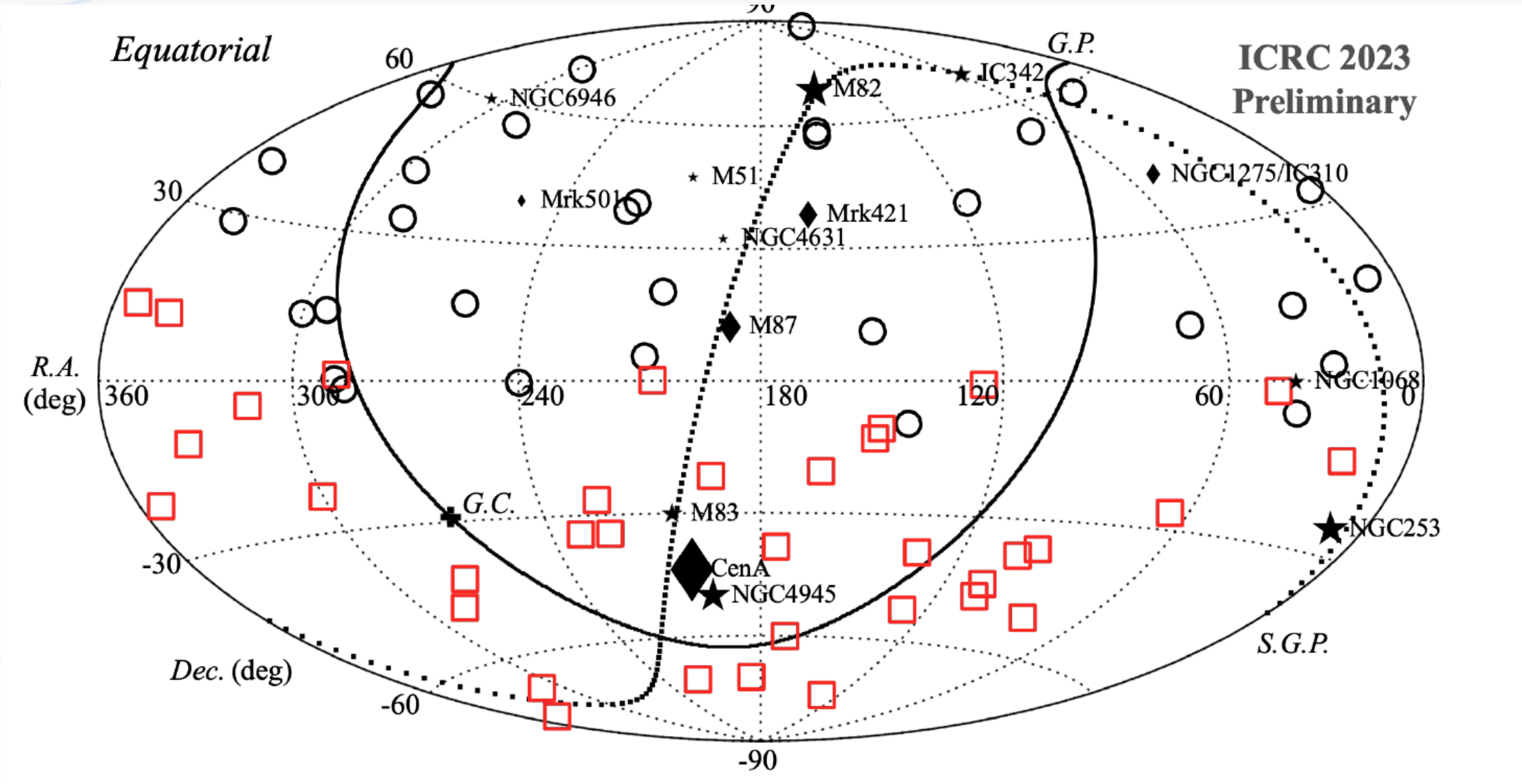


UHECR observables

Energy spectrum

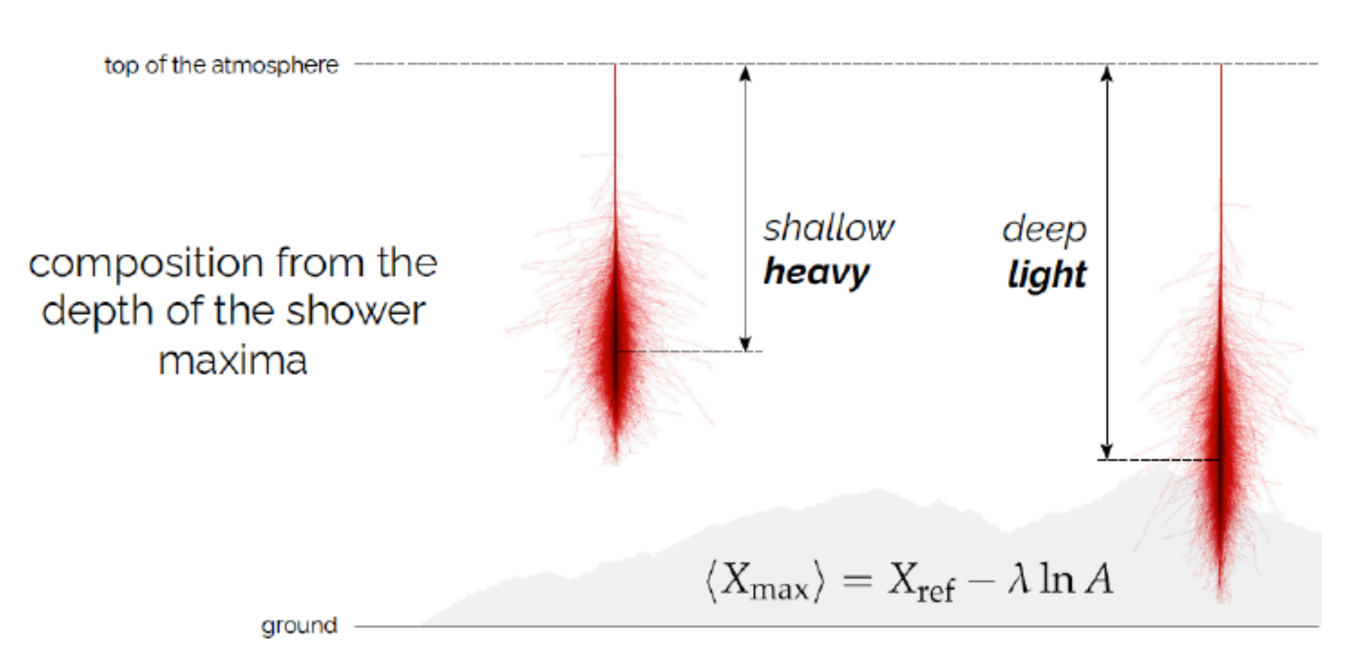


Arrival direction



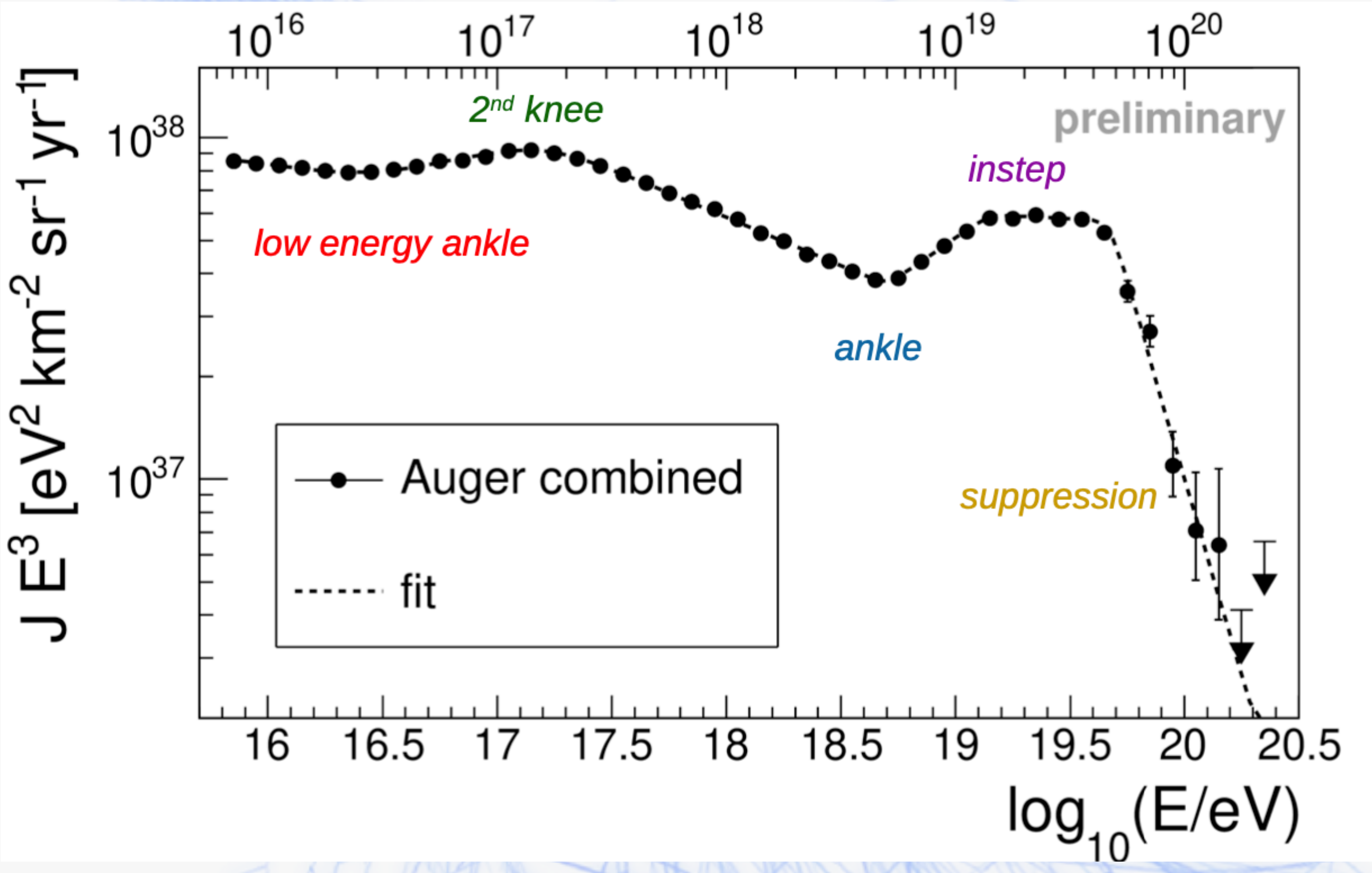
TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

Mass Composition

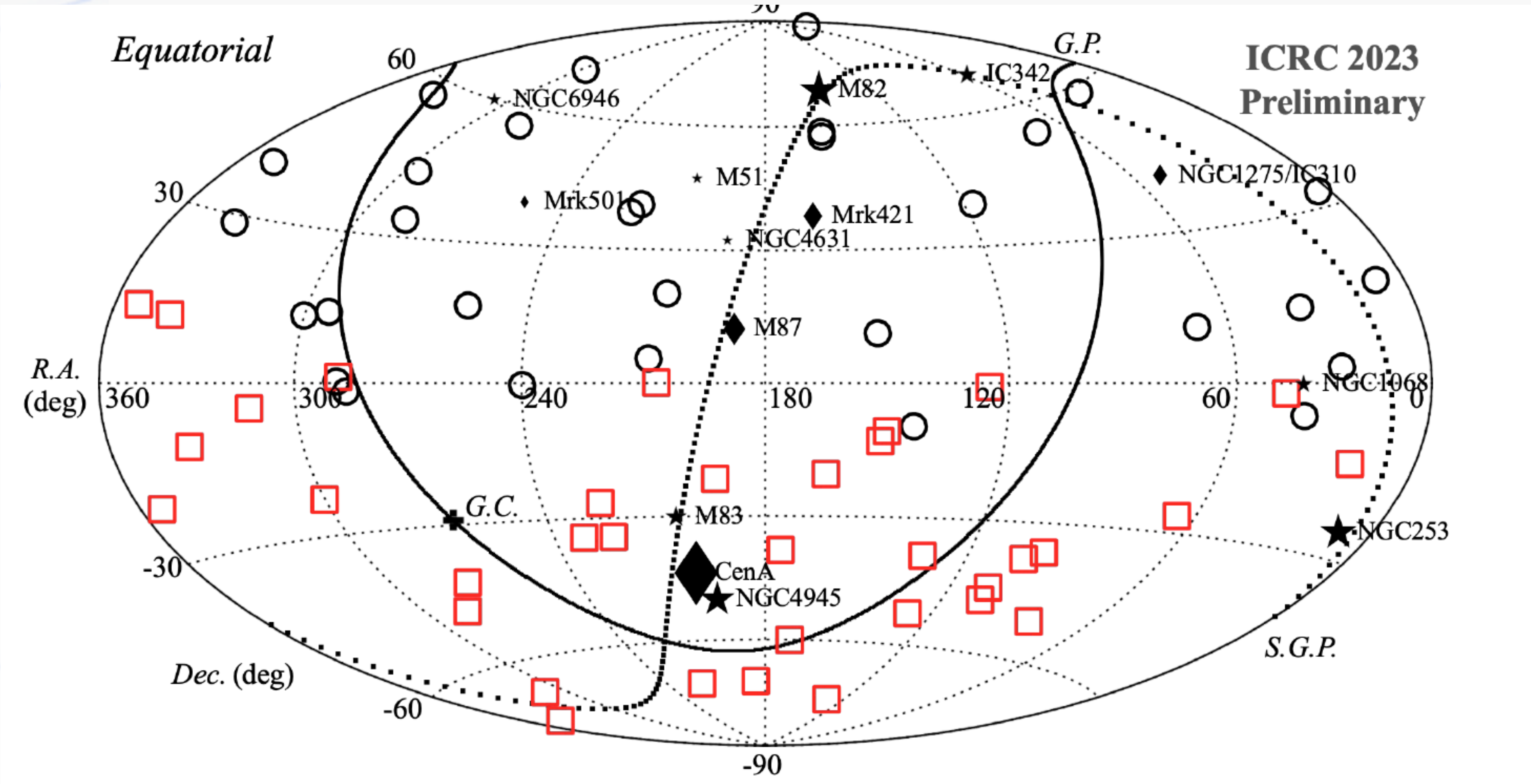


UHECR observables

Energy spectrum



Arrival direction



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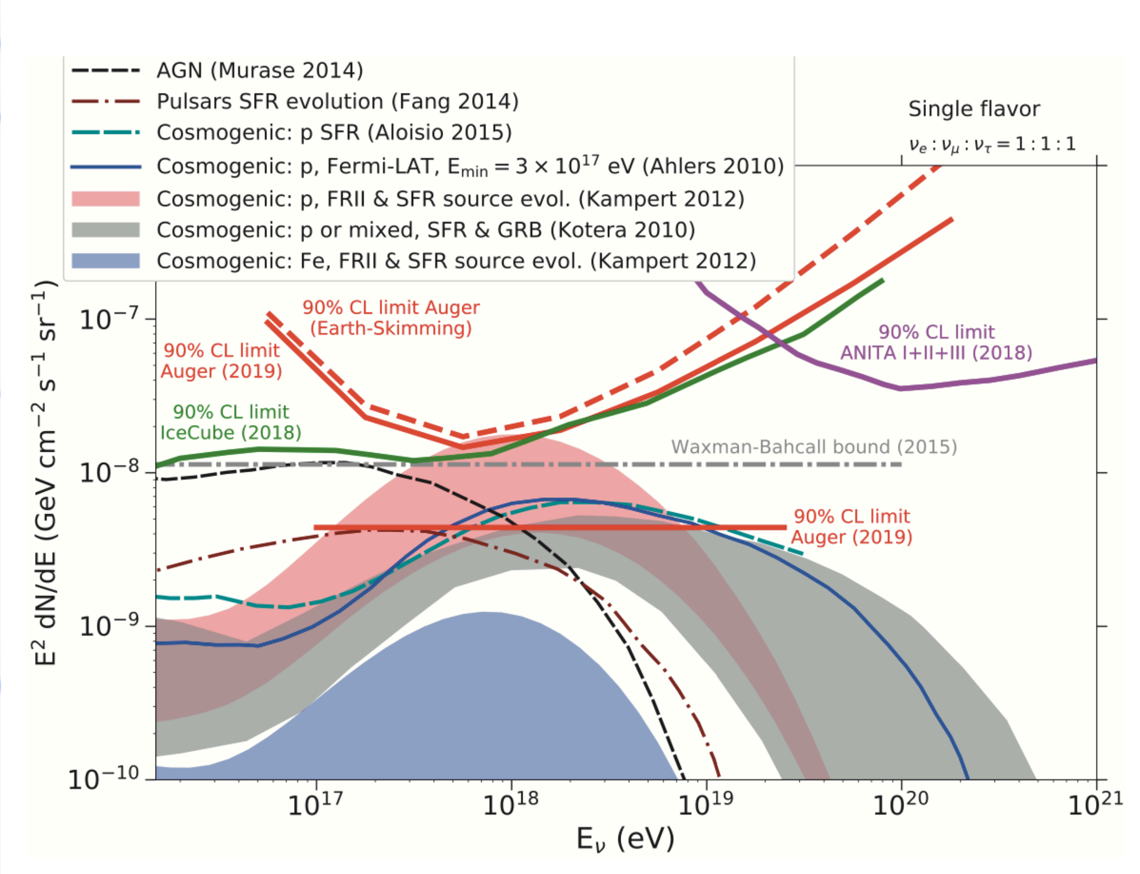
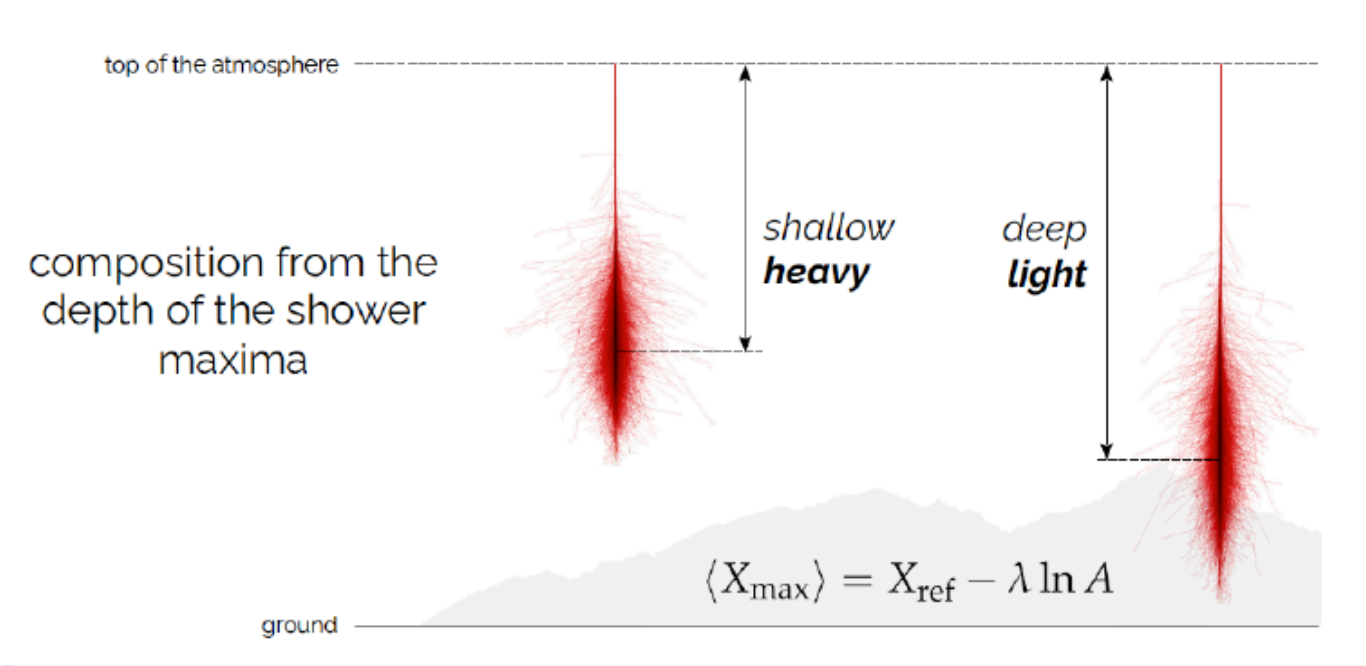
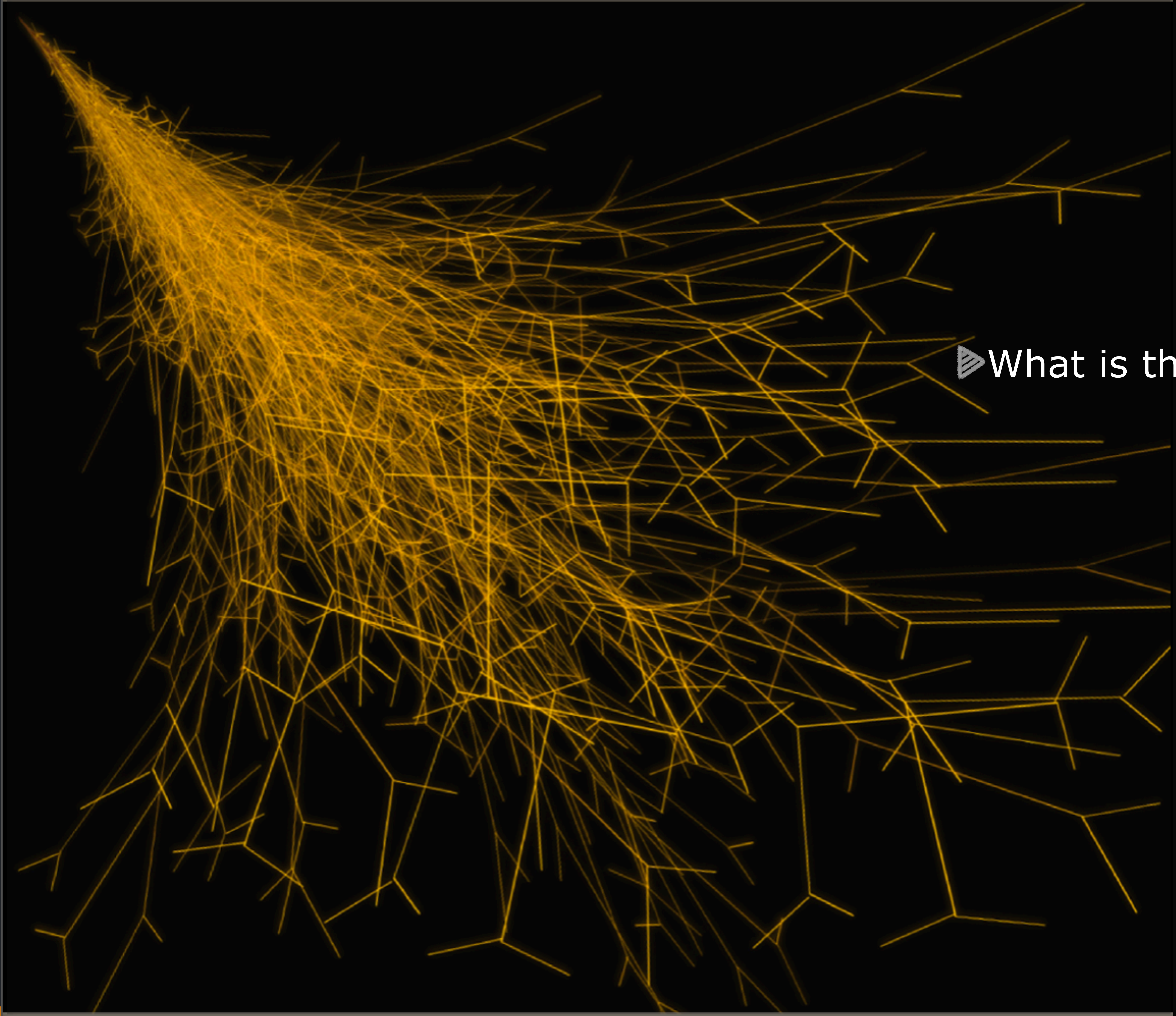
Secondary fluxes



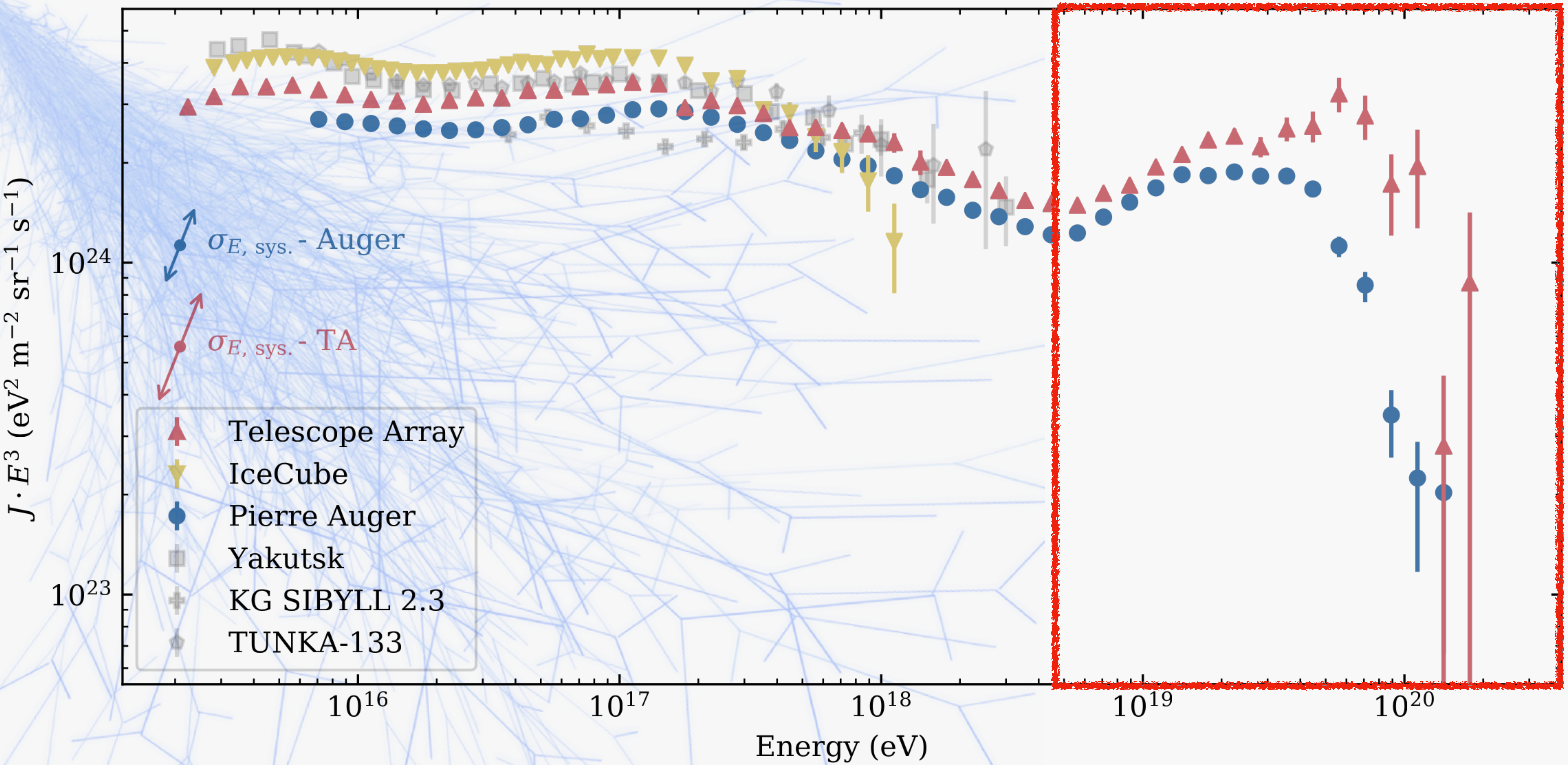
Mass Composition





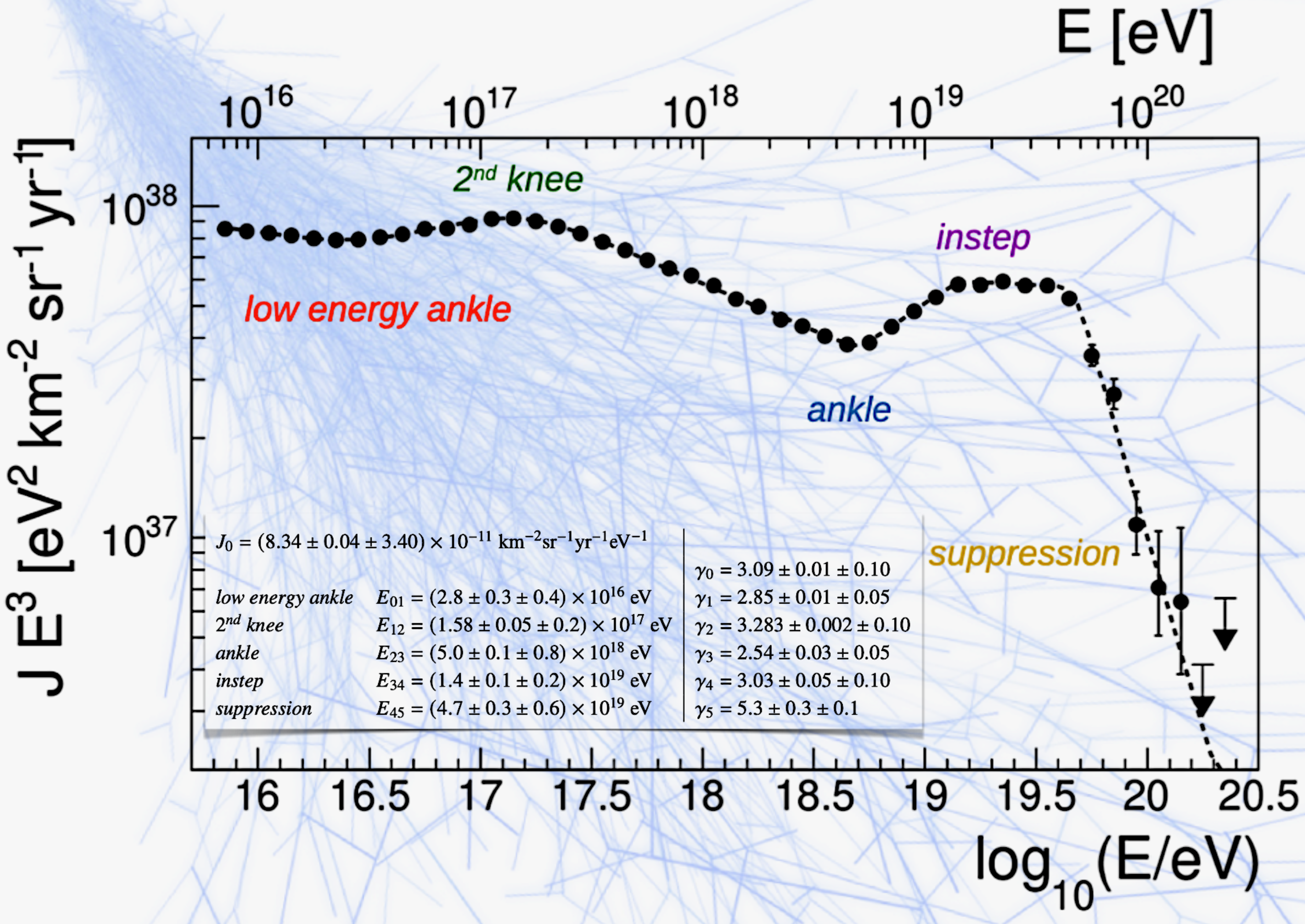
- What is the status of the art **today**?

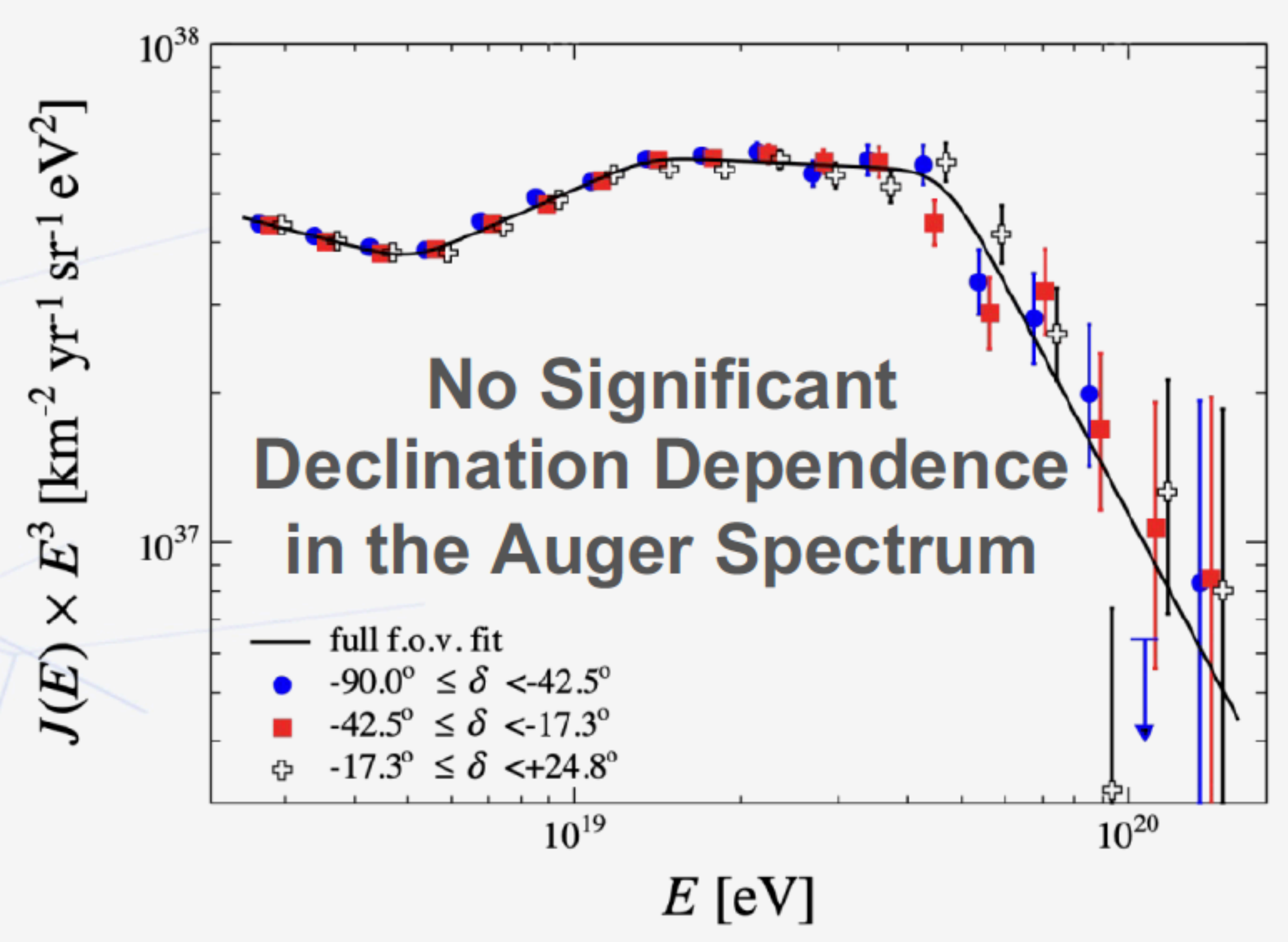
Current UHECR Picture: Energy Spectrum

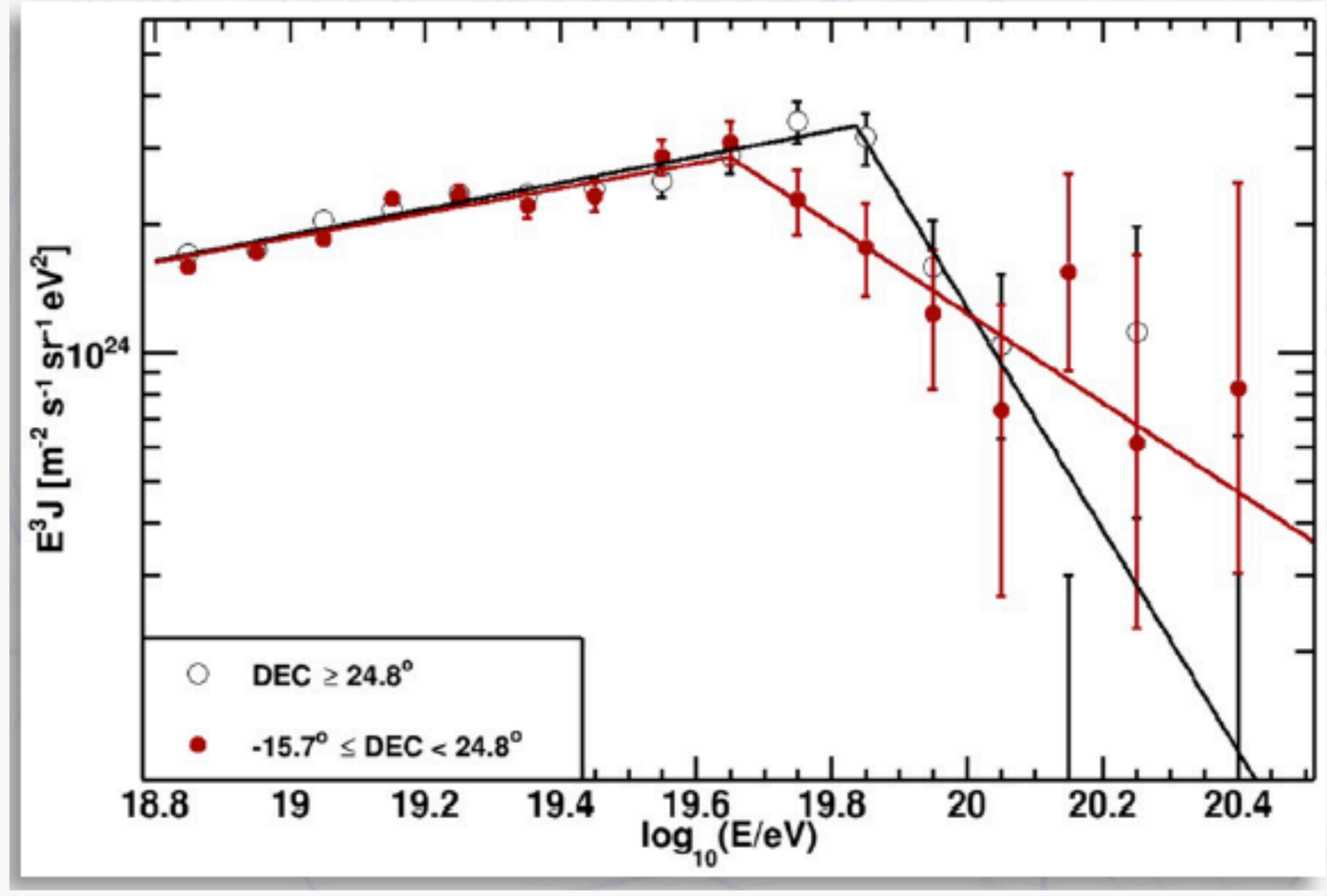


Differences in the UHECR spectra as measured as two experiments!

Current UHECR Picture: Energy Spectrum

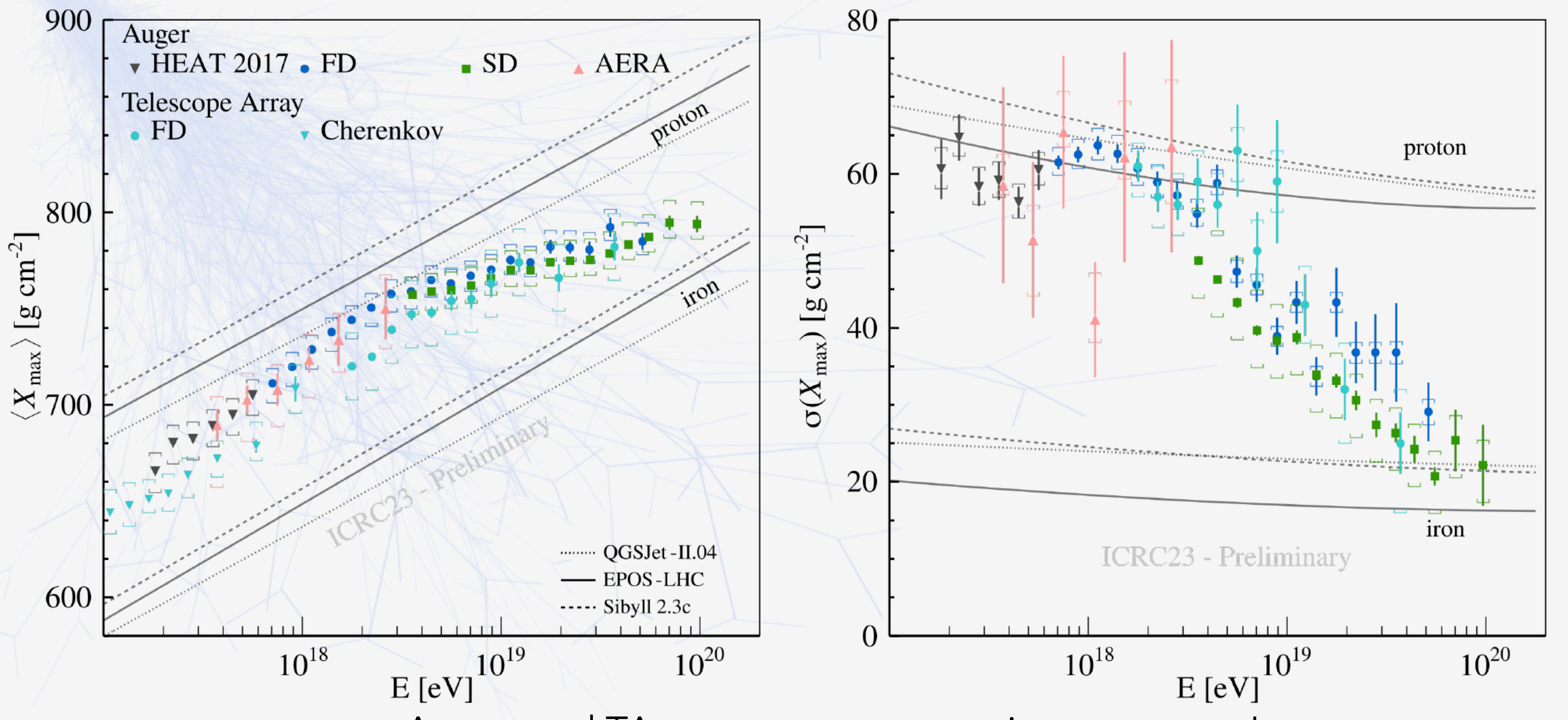






Differences in fluorescence yield, invisible energy, etc…
Possible astrophysical explanation?

Current UHECR Picture: Mass composition



(A. Yushkov for Auger/TA
Pos ICRC2023 249, PRD in preparation)

Auger and TA measurements are in agreement!

Crosscheck –> Bring Auger best fit mass fractions into TA detector simulations and then compare –> still in agreement.

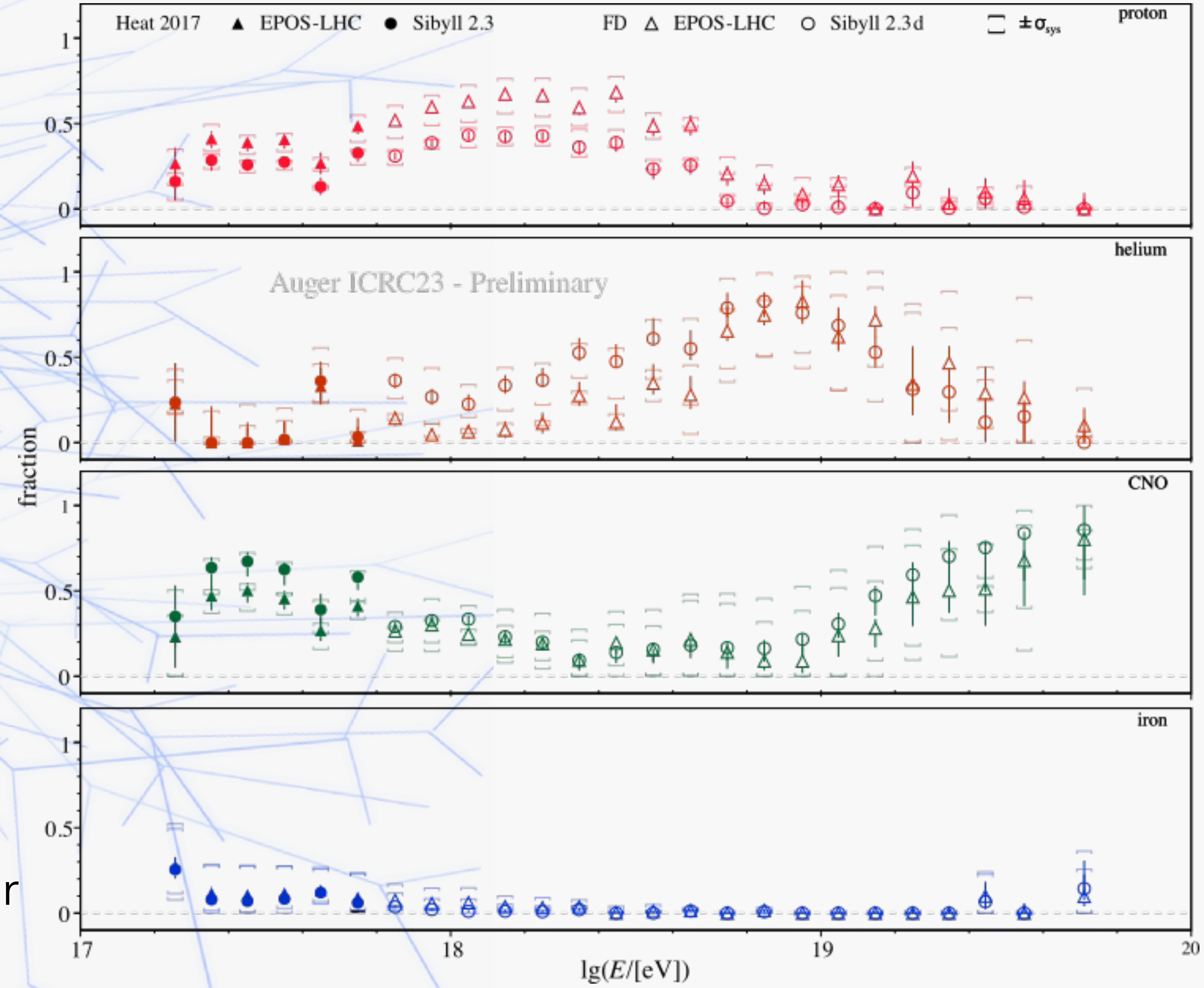
Current UHECR Picture: Mass composition

Protons: as expected from lnA, peak around 2-3 EeV.
→ Only form a weak majority at this energy, but dominate the flux nowhere.

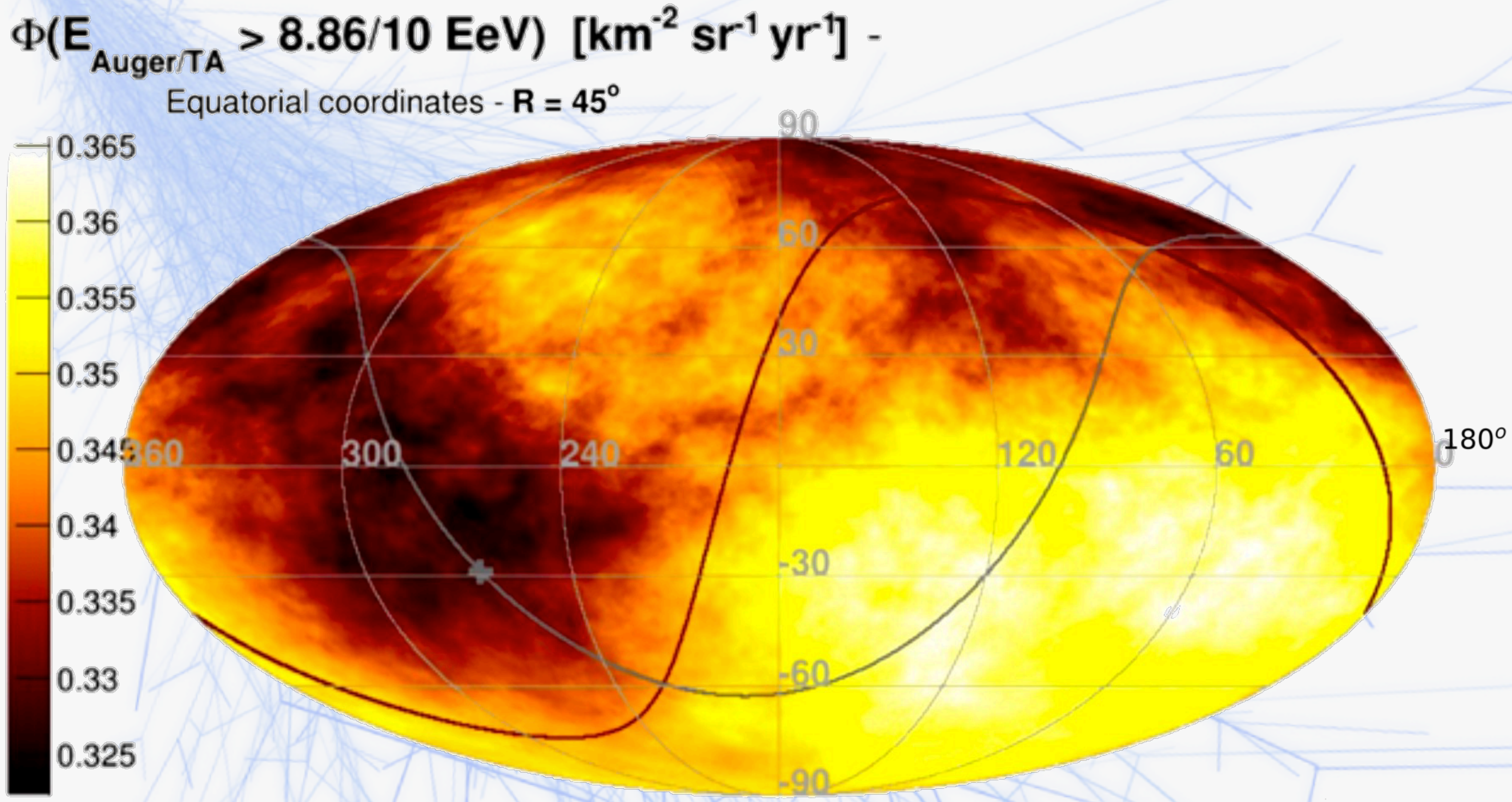
Helium: peaks at ~ 8 EeV
→ roughly ~ 4 times higher energy than protons

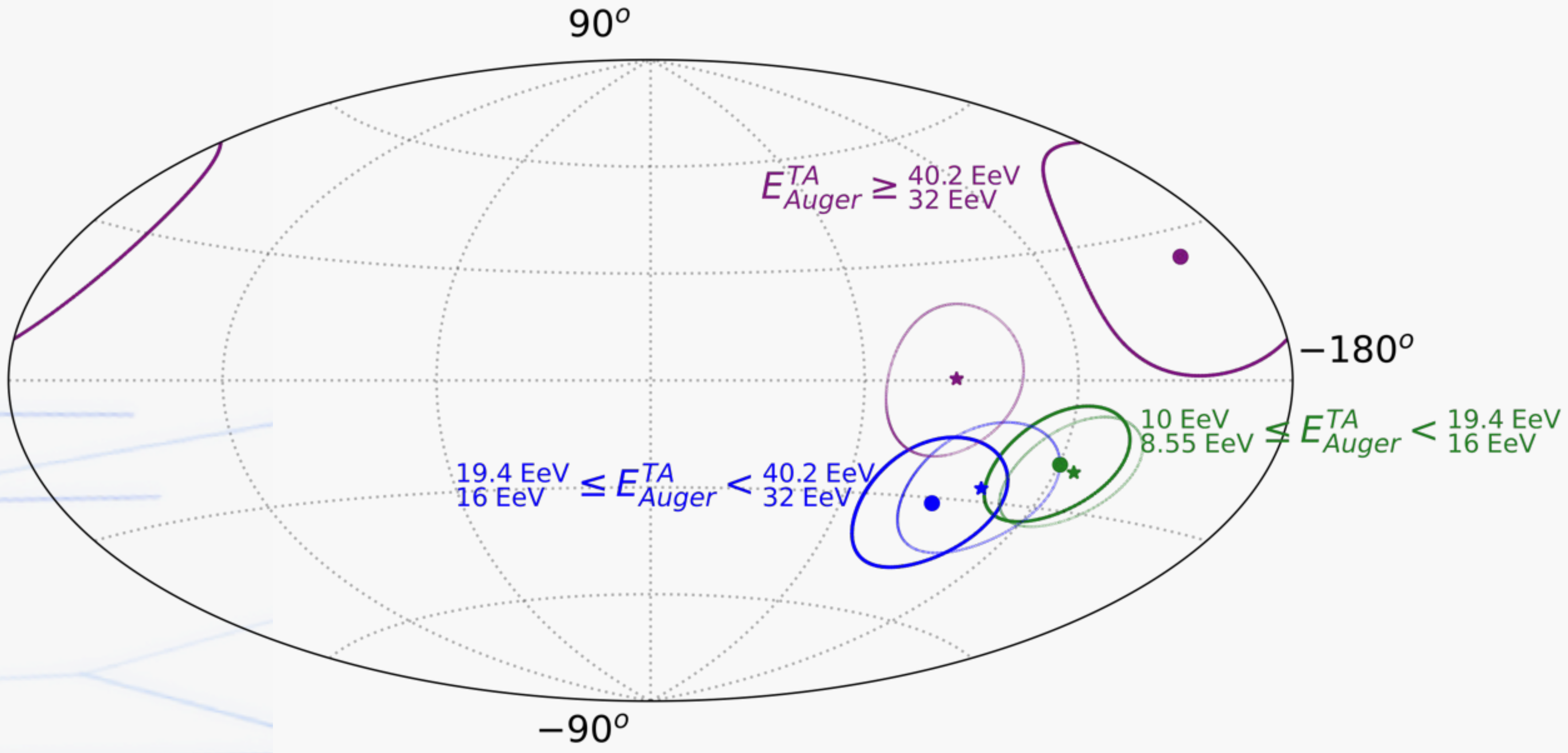
CNO: fraction continues to climb up to ~ 50 EeV
and may continue beyond

Iron: fitted fraction compatible with zero over nearly the full energy range
→ small fraction allowed at low/high energy



Current UHECR Picture: Arrival direction



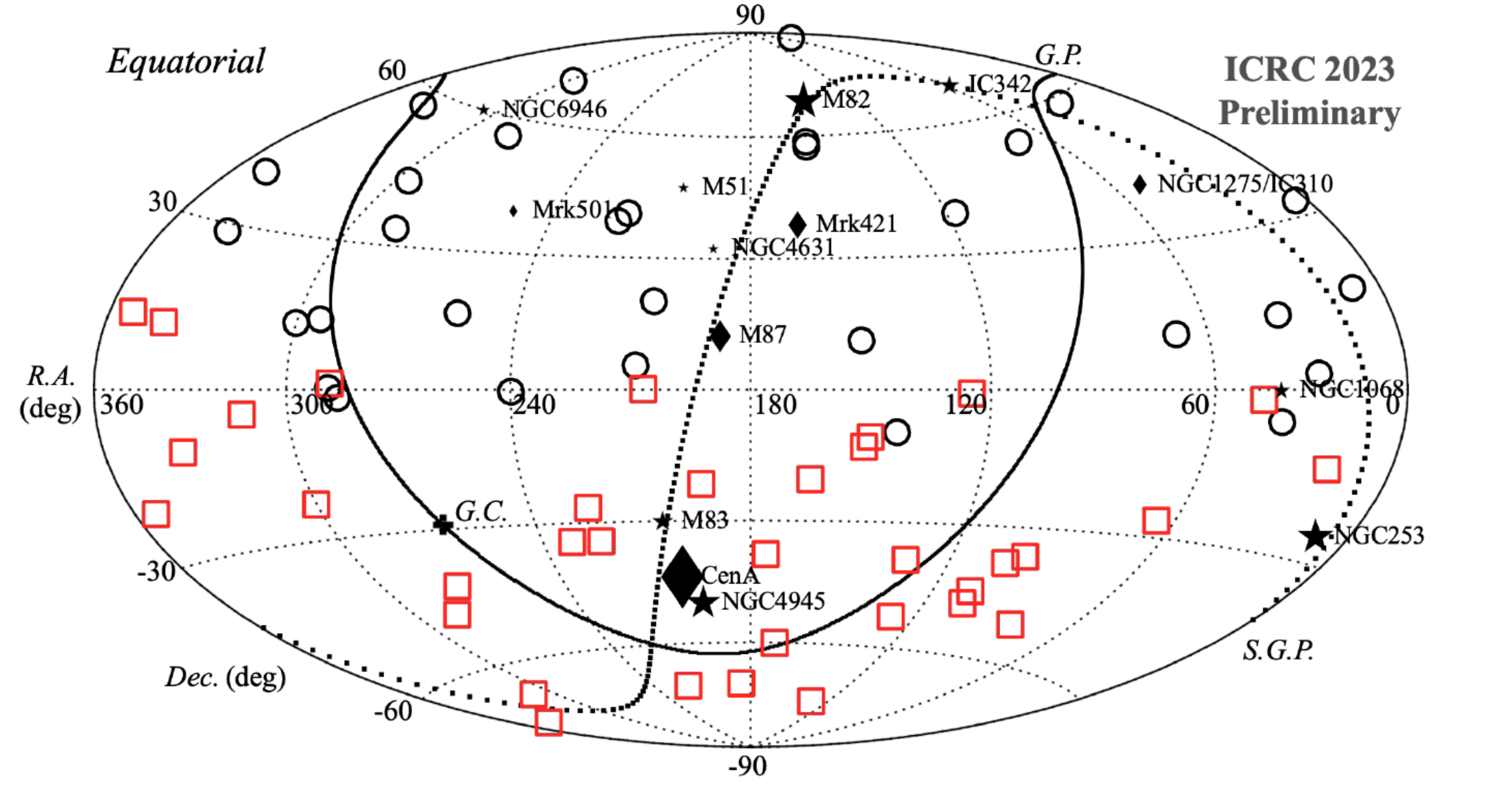


The above flux map is immediately interpretable

- ➢ equal sensitivity anywhere in the sky
- ➢ upper limits uniform over the sky
- ➢ no need for methods to re-weight individual exposures

Confirm the presence of a dipole pointing away from the GC

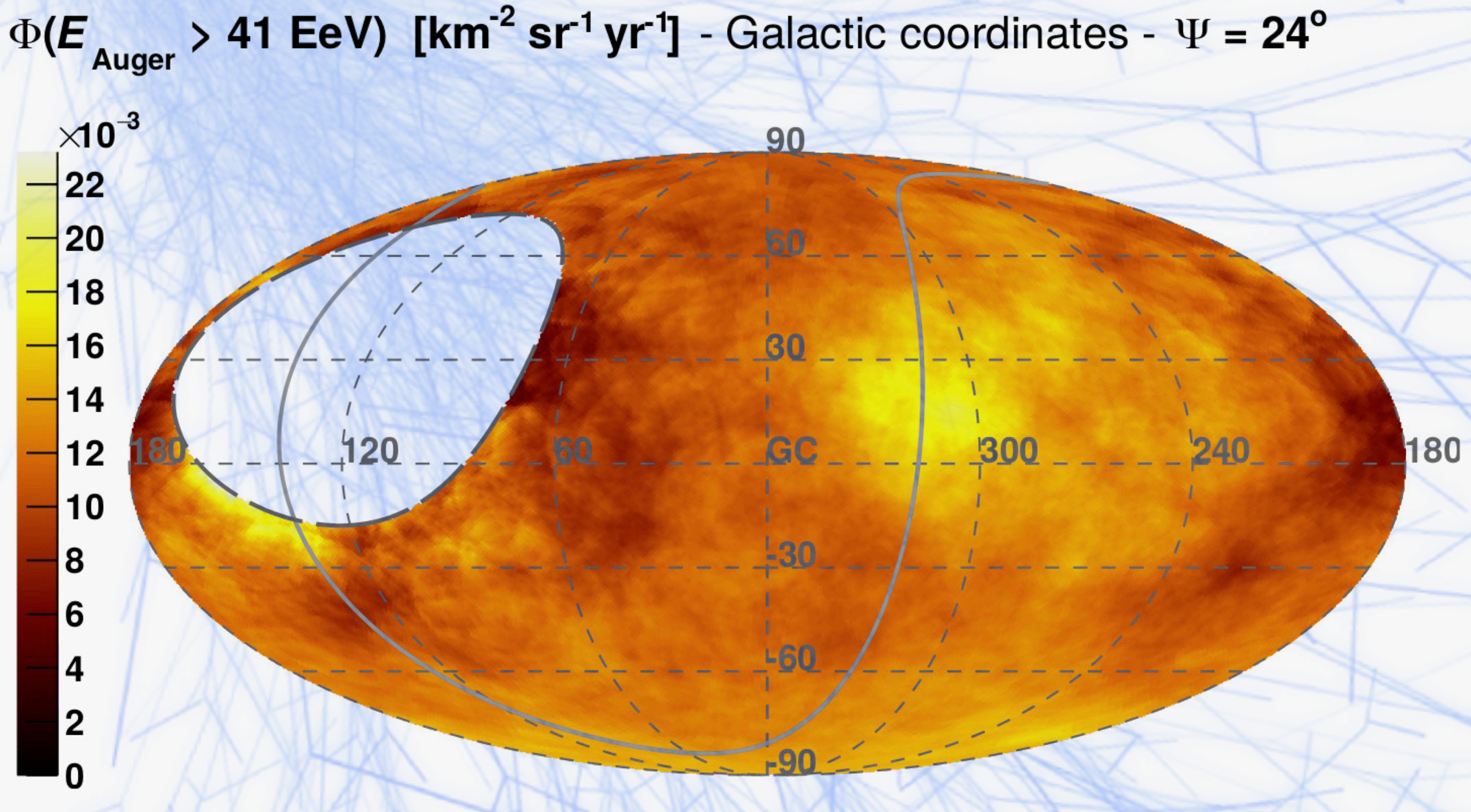
Current UHECR Picture: Arrival direction



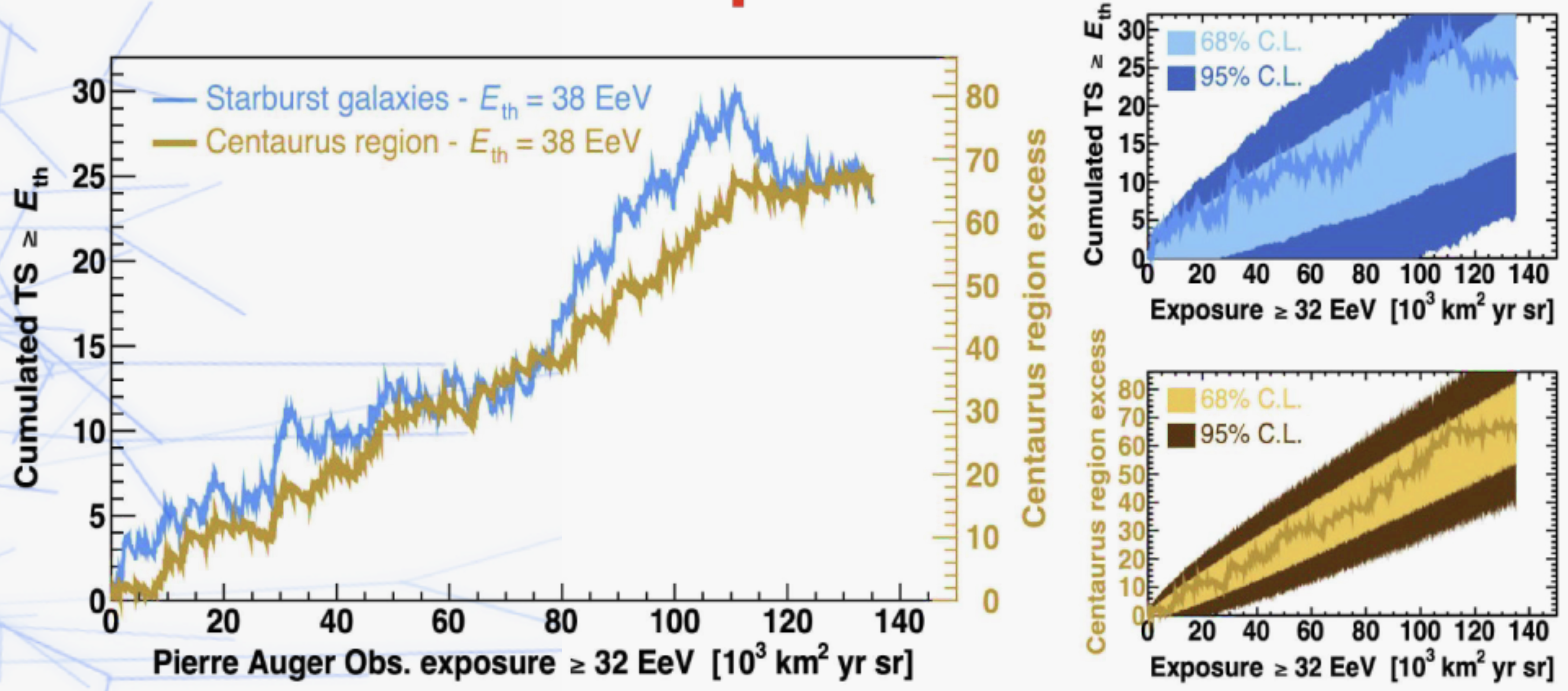
TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

No Obvious Sources above 100 EeV in TA or Auger –>This level of isotropy strongly disfavours Protons at the highest energies event at extremely high EGMF strengths.

Narrowing down Source Candidates In Southern Sky



~90% isotropic distribution



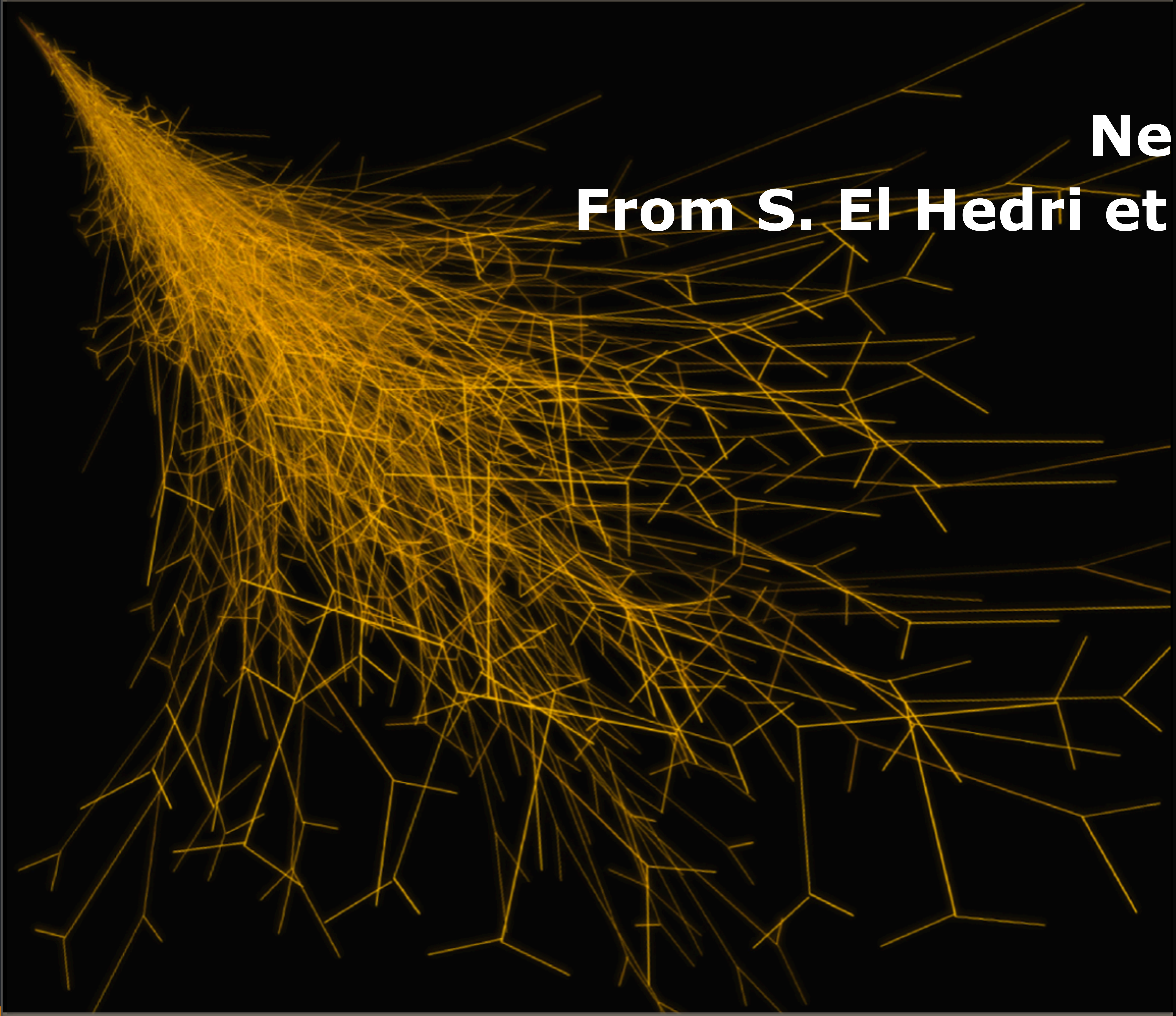
Correlation with catalogues of SBGs (3.8 σ) and AGN (3.5 σ)

➢Correlation mostly driven by CenA region

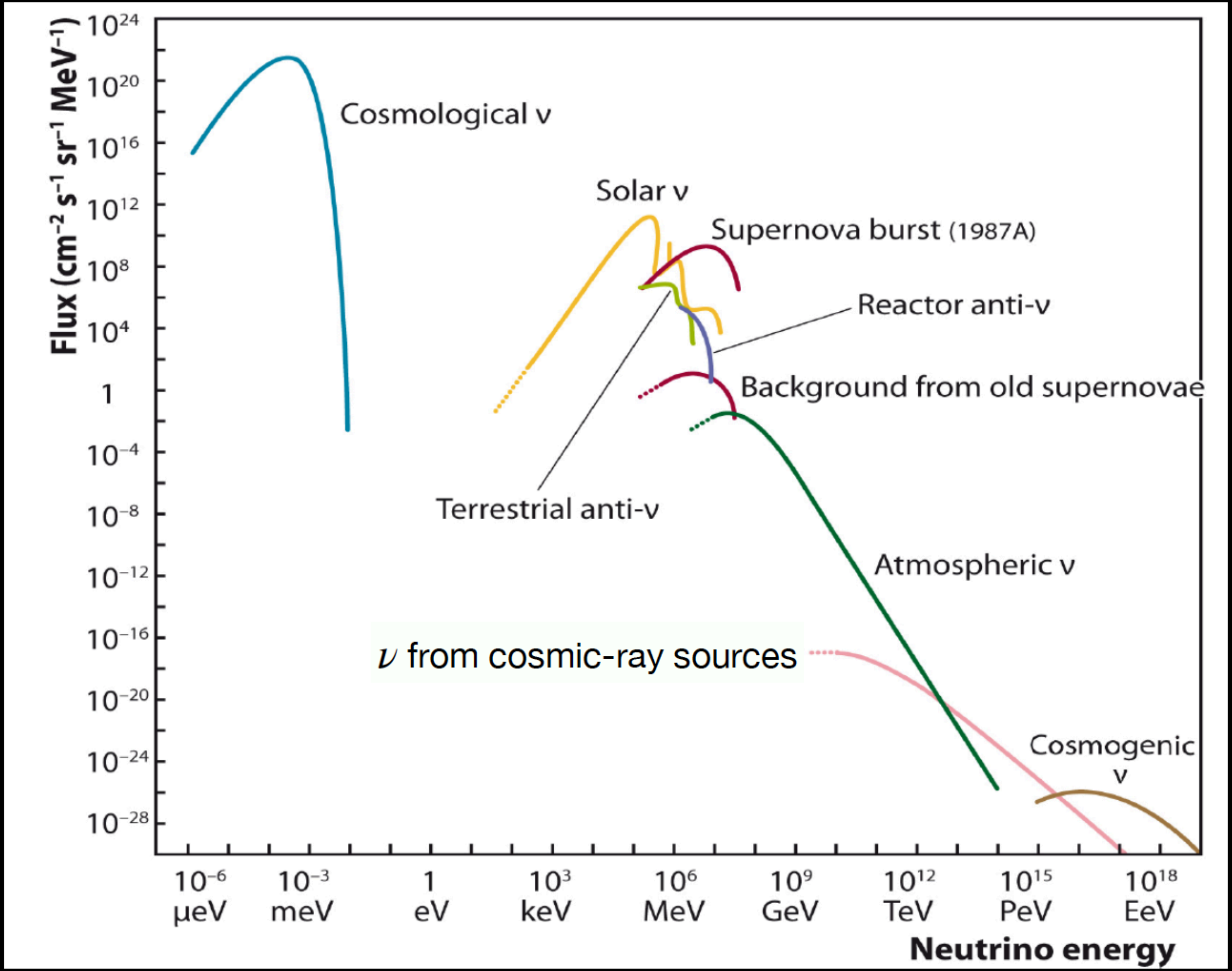
➢Still 90% of isotropic flux –> what does it mean in terms of astrophysical sources?

Question:
What did you expect for secondaries?

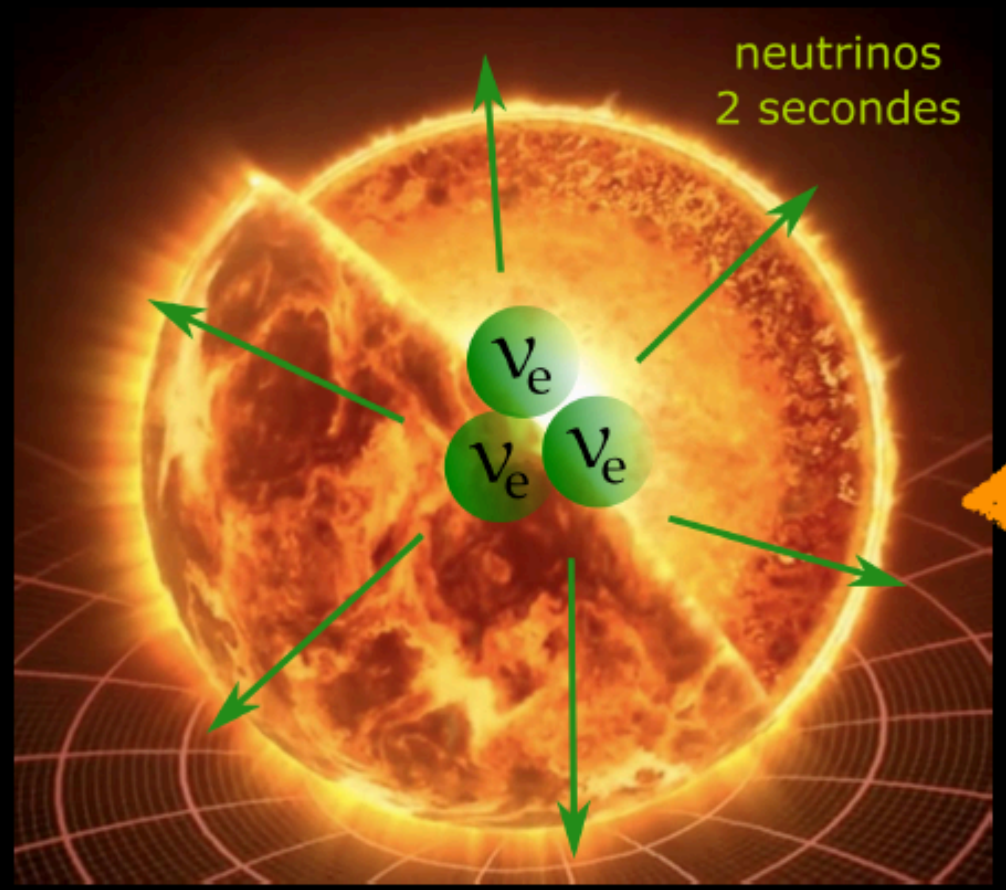
Neutrinos
From S. El Hedri et al. at the last SFP

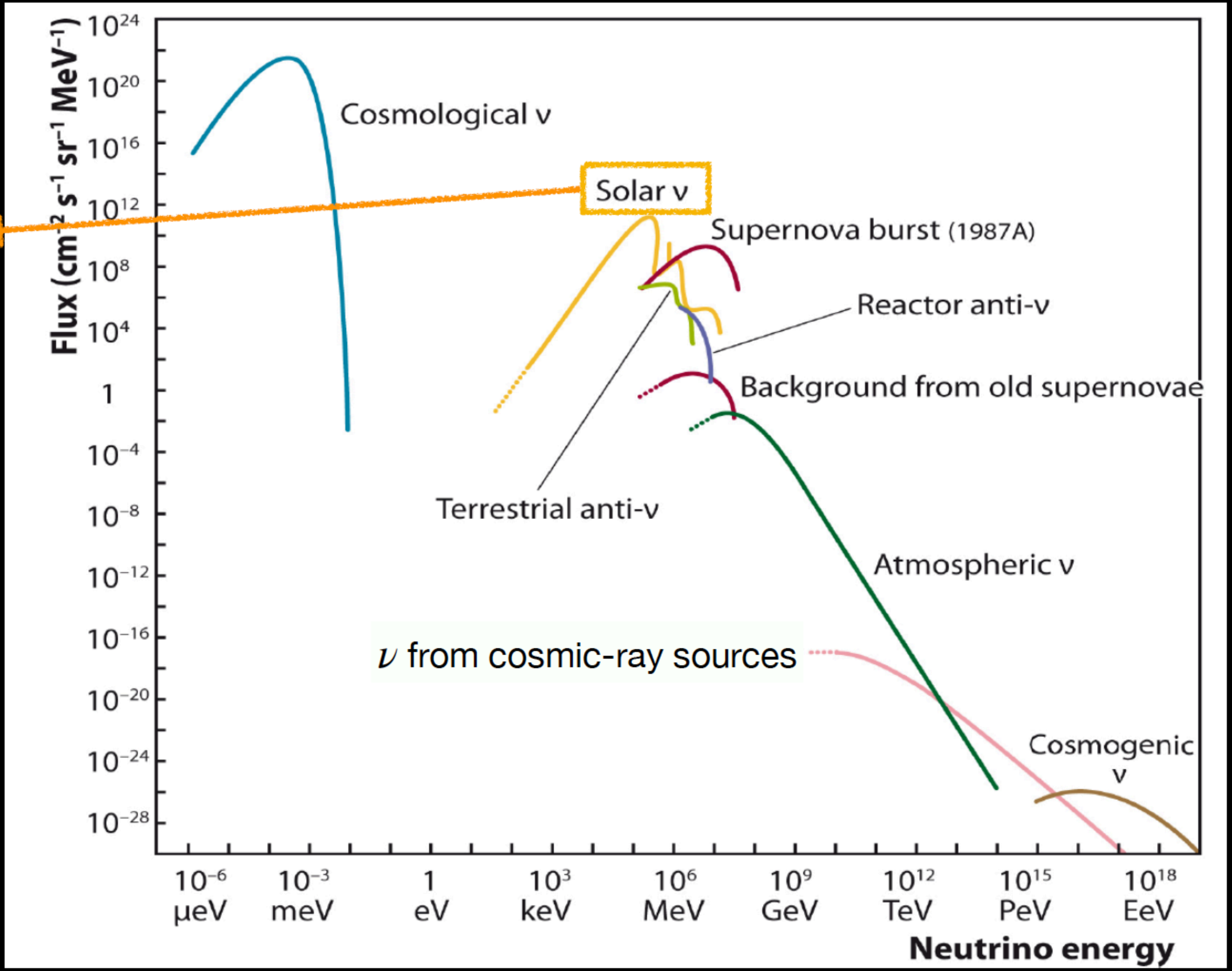


Astrophysical Neutrinos — Why? Where? How?

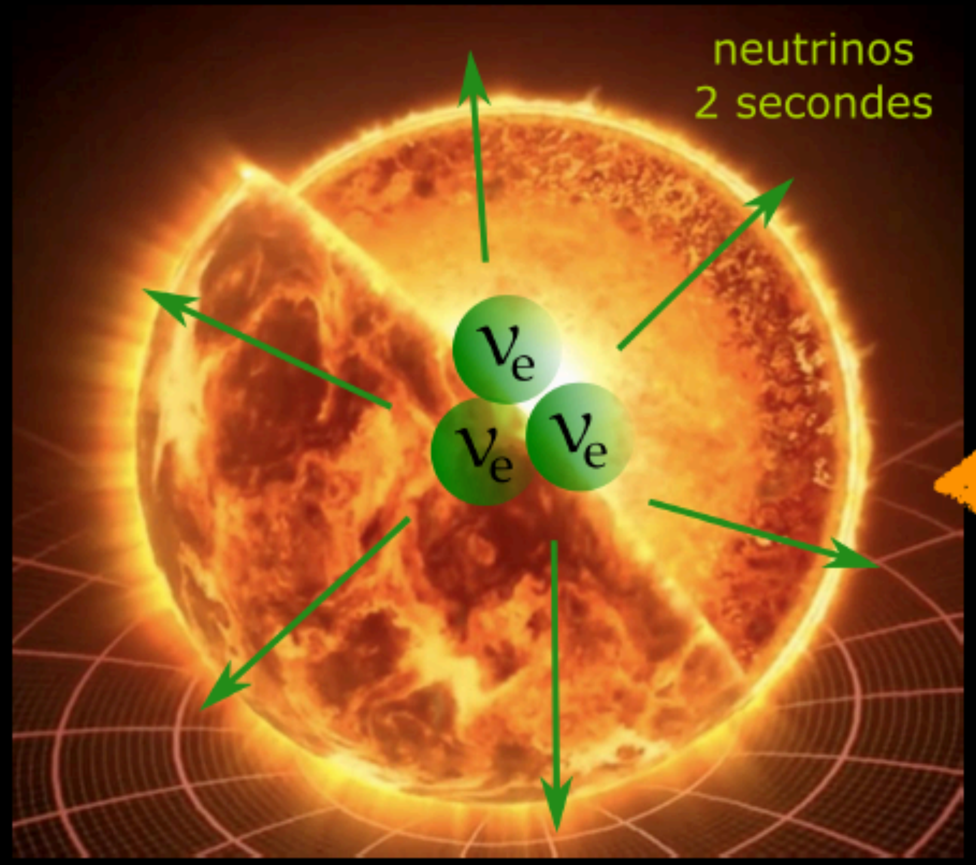


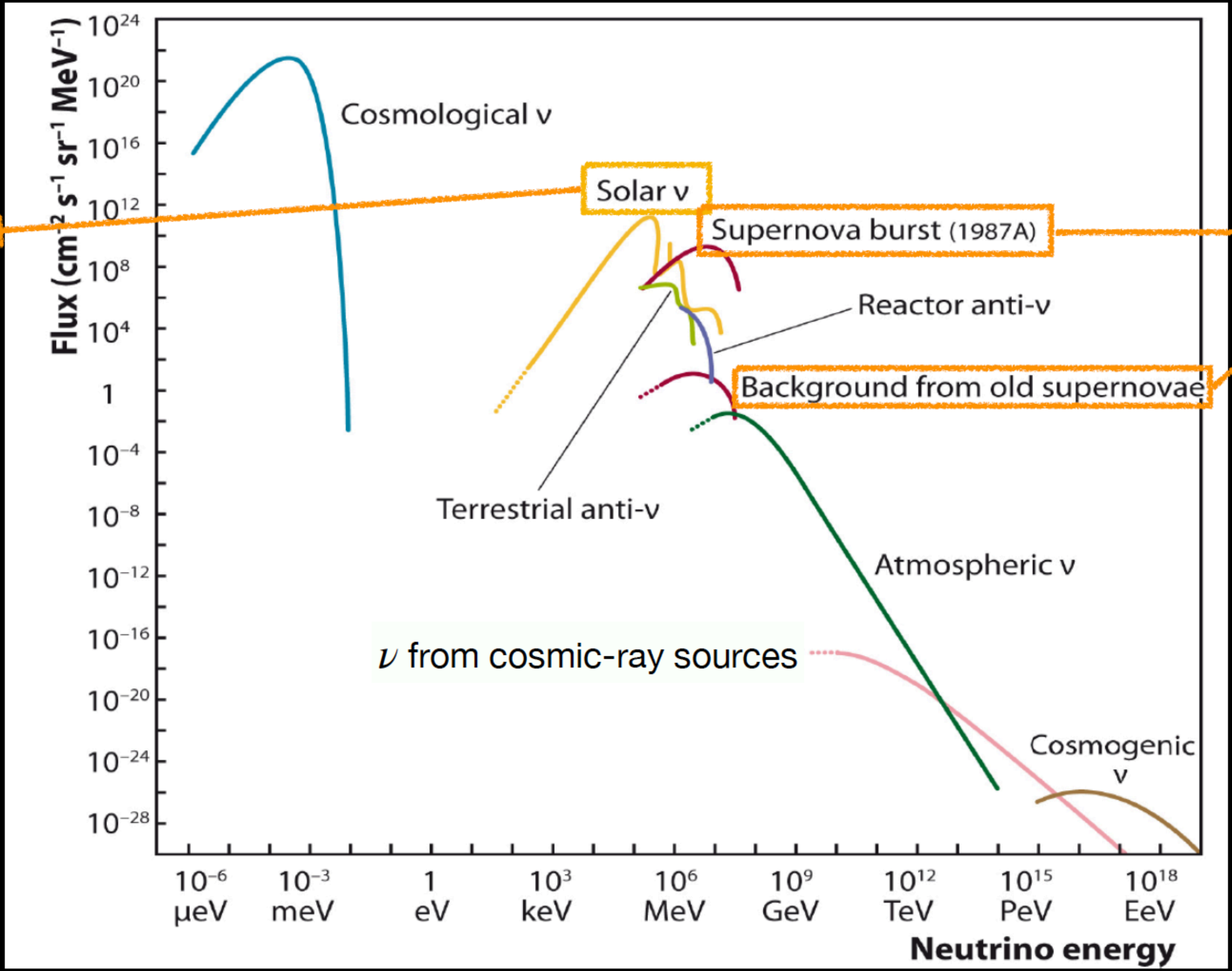
Astrophysical Neutrinos — Why? Where? How?

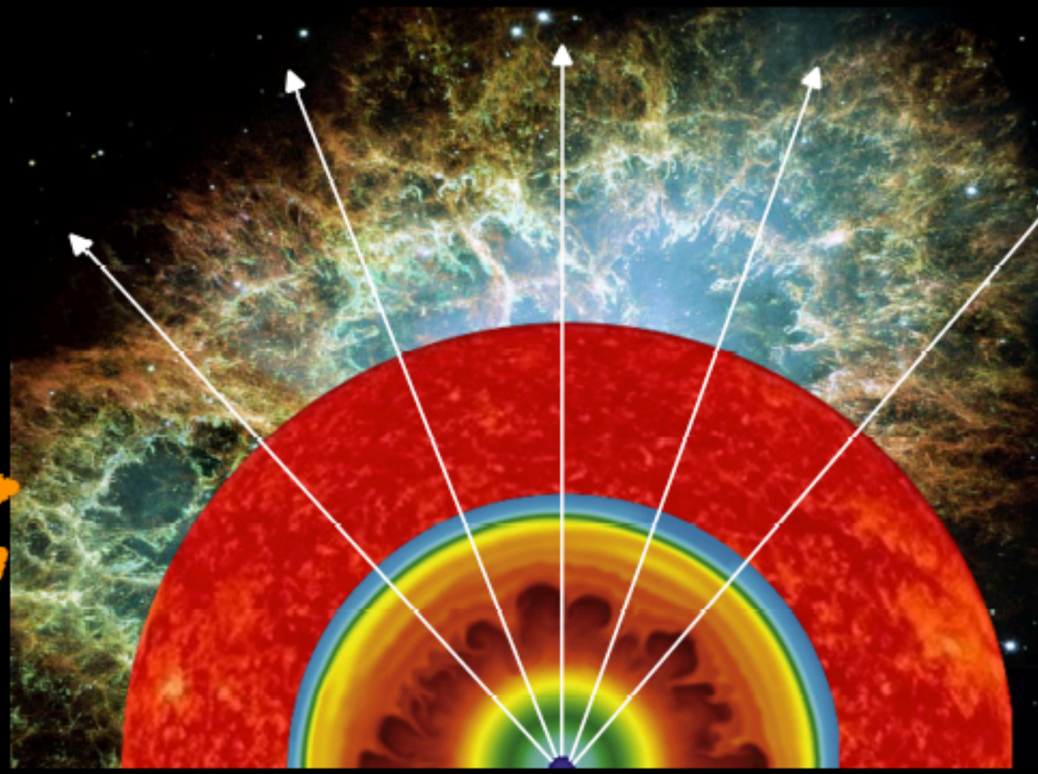




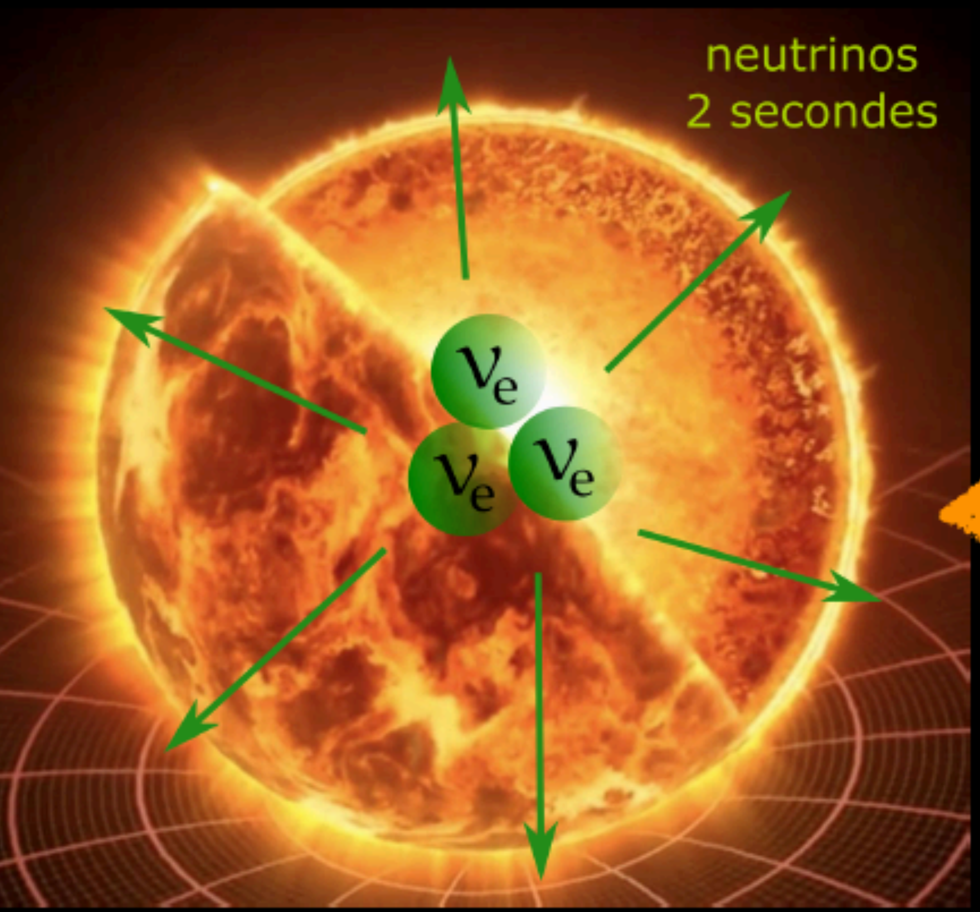
Astrophysical Neutrinos — Why? Where? How?

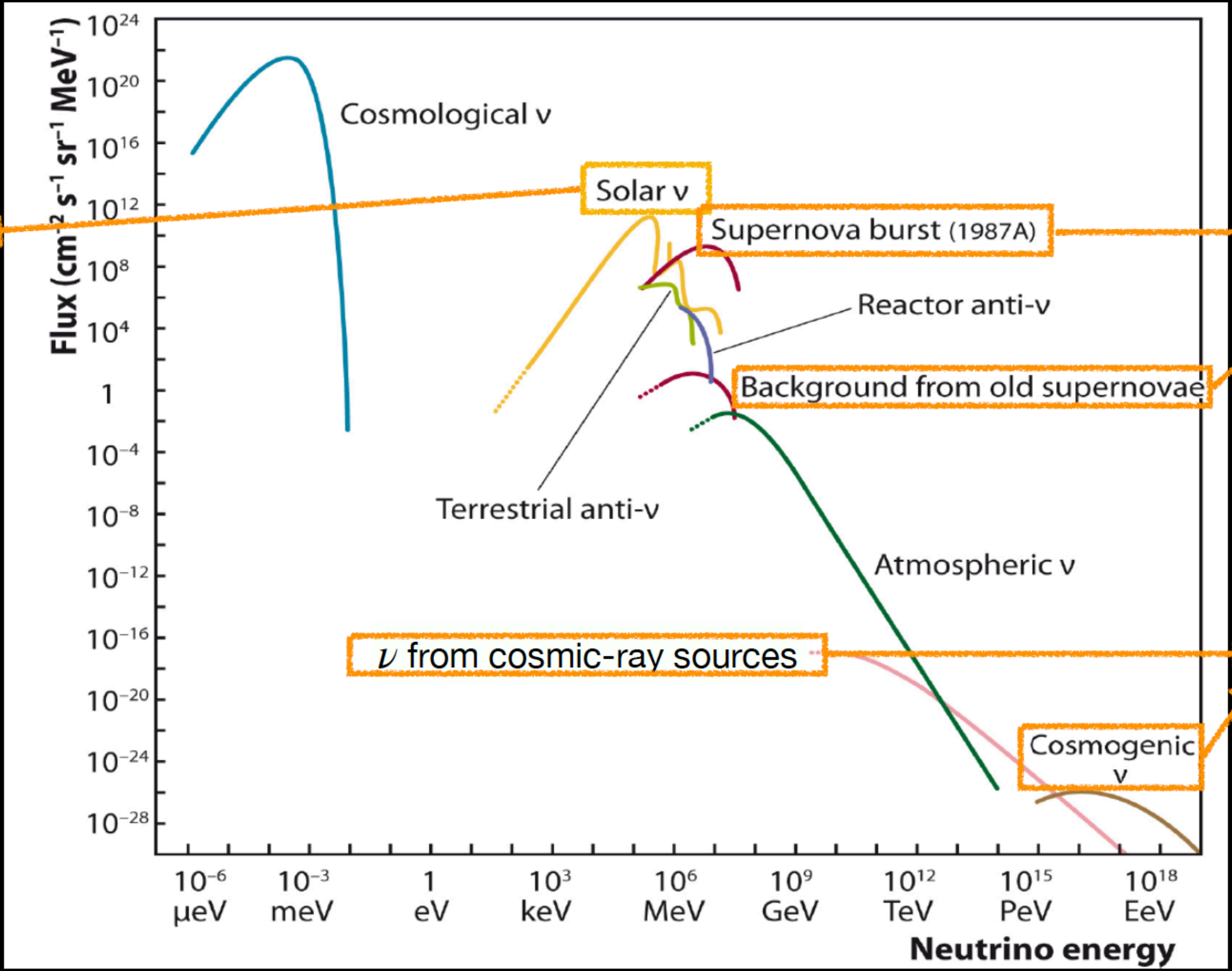


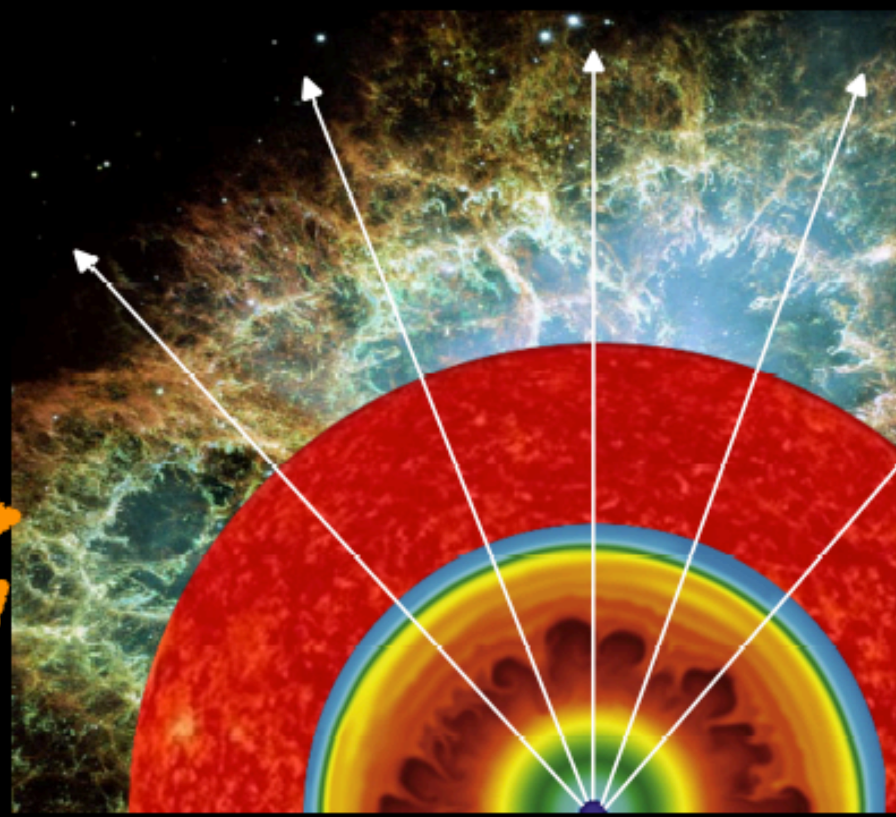


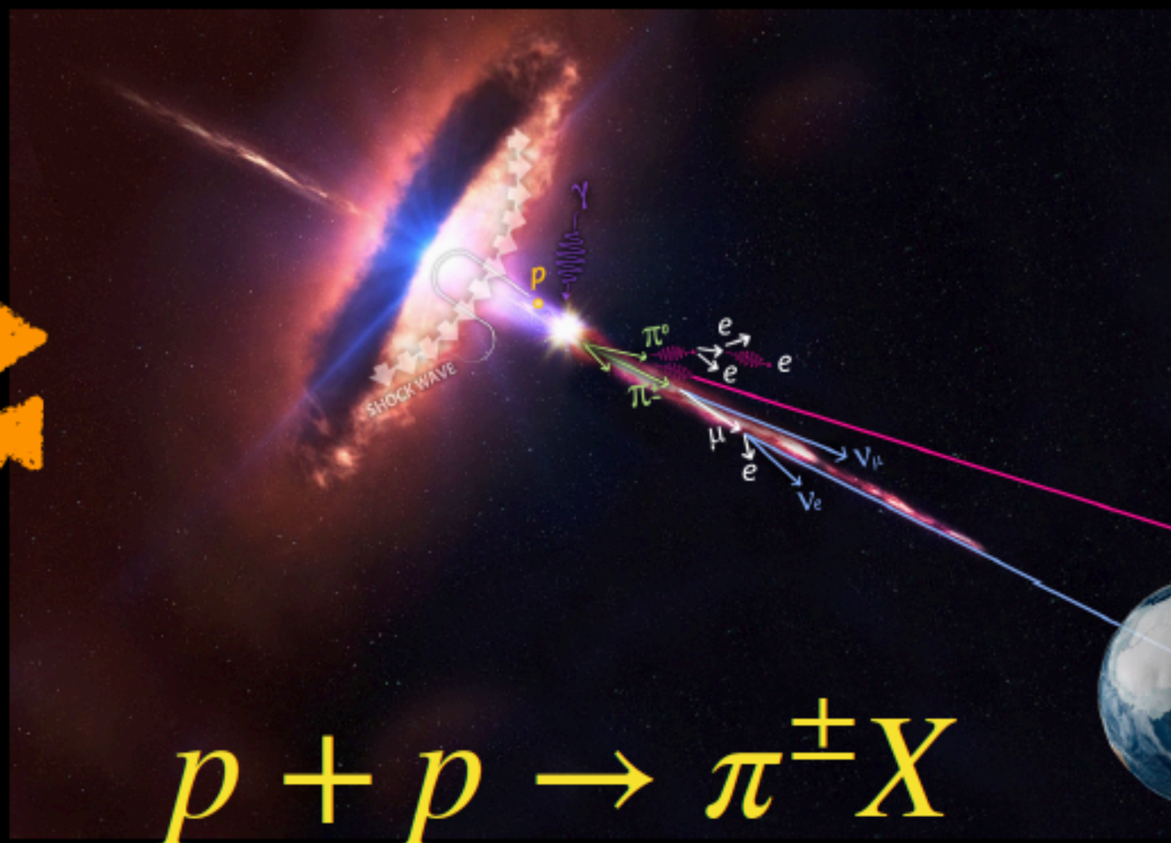


Astrophysical Neutrinos — Why? Where? How?





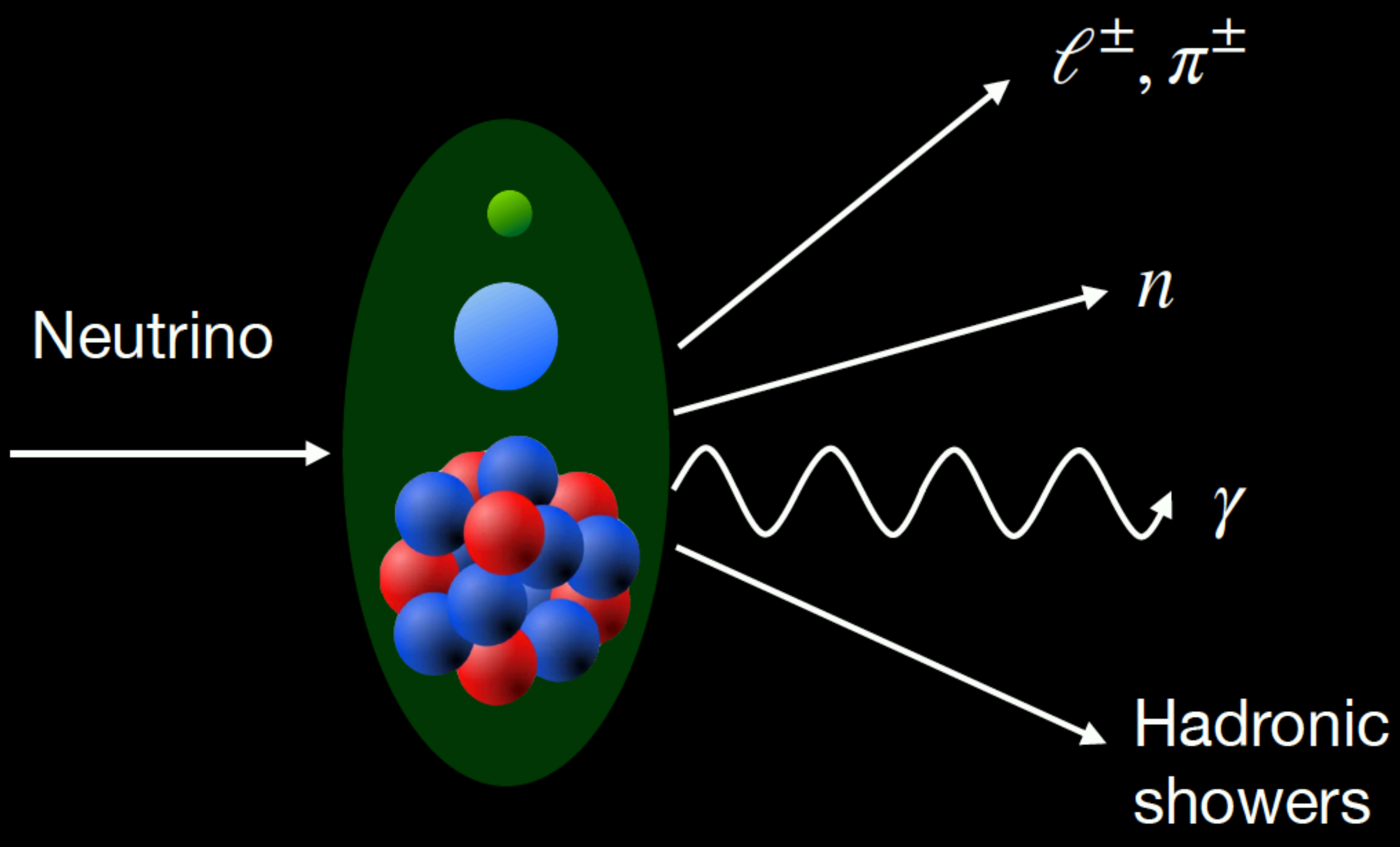


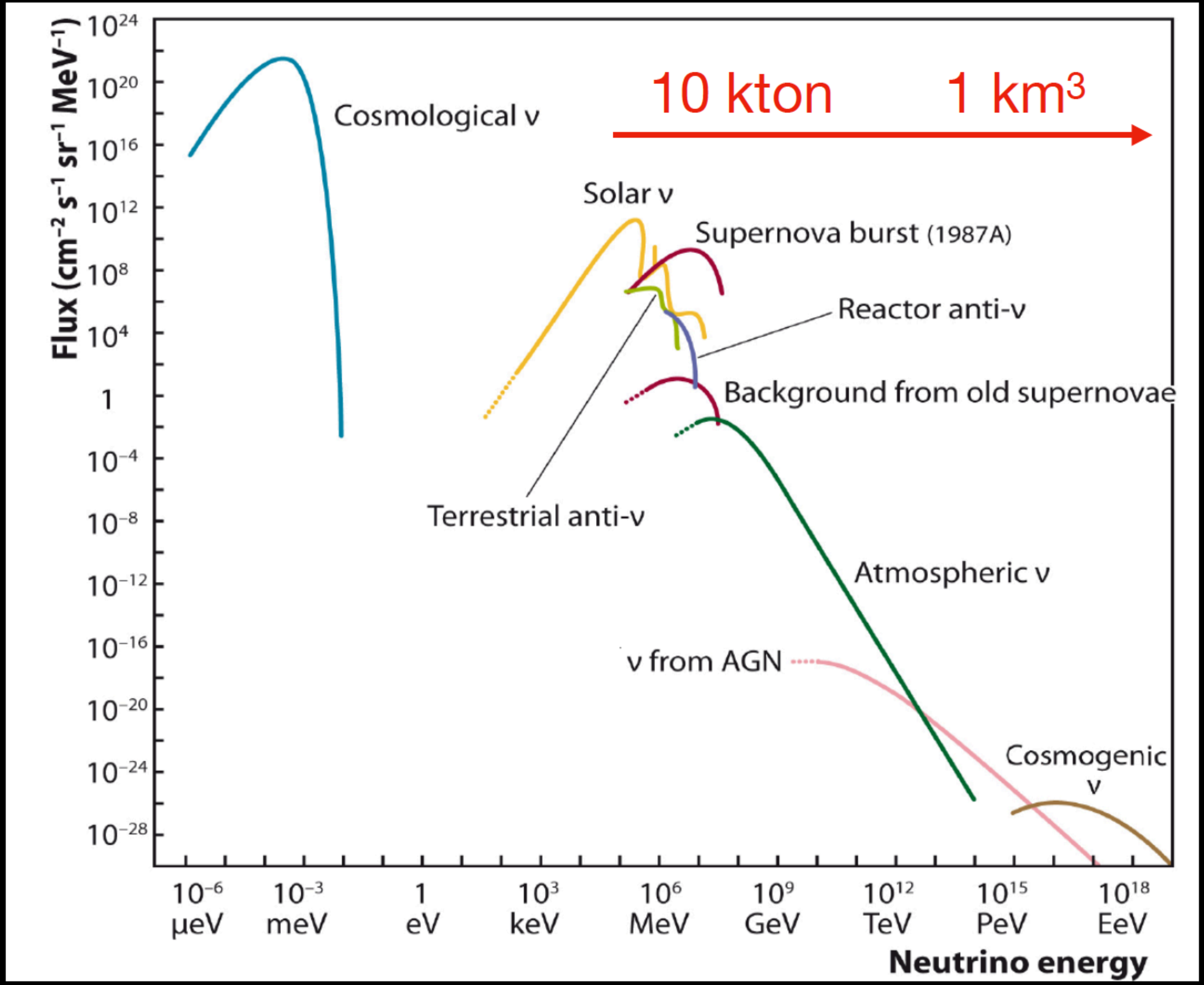


$$p + p \rightarrow \pi^{\pm} X$$

$$p + \gamma \rightarrow \pi^{\pm} + n$$

Astrophysical Neutrinos — Why? Where? How?

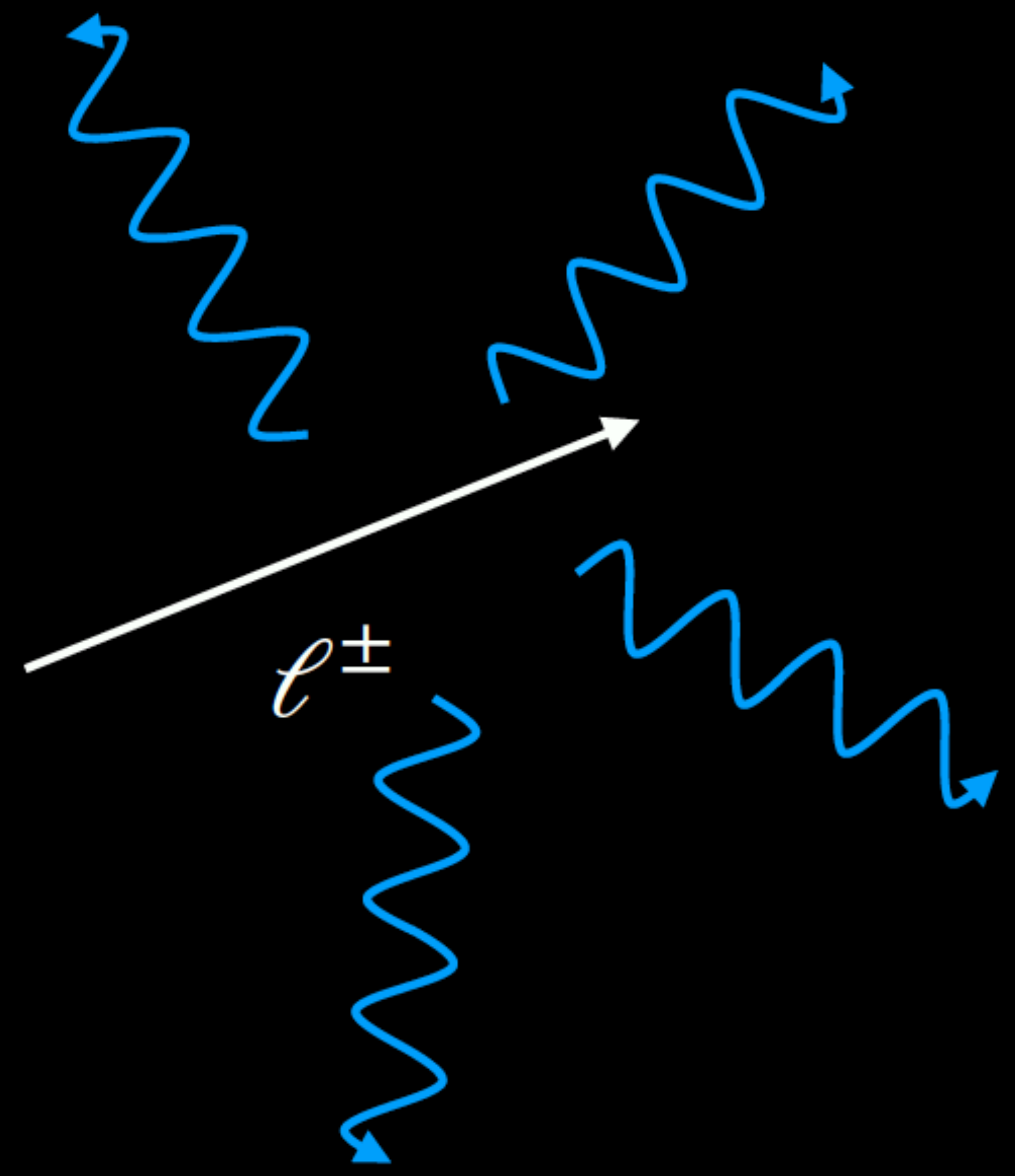




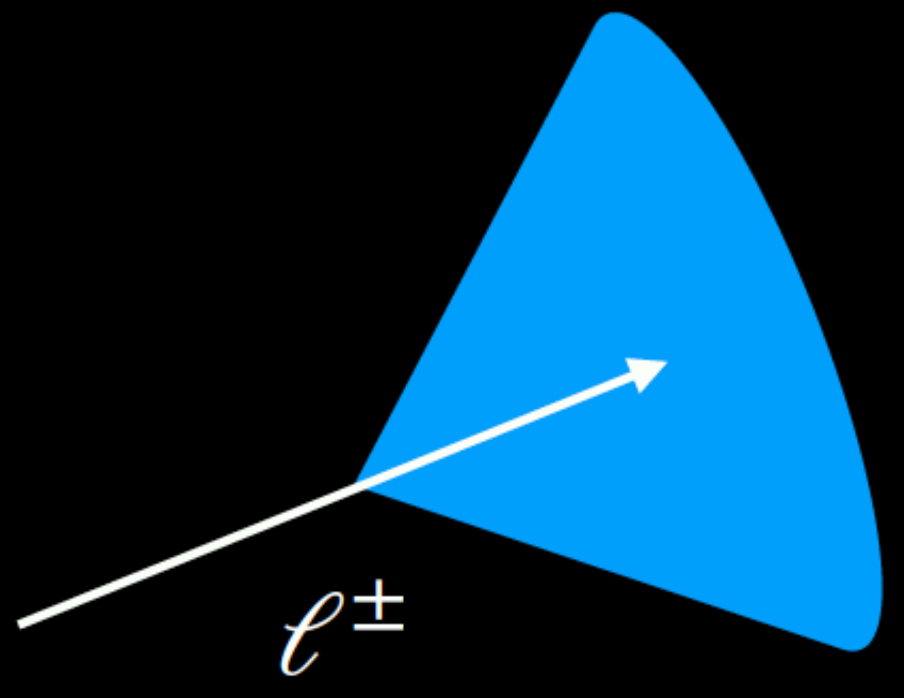
→Underground/water detectors

Astrophysical neutrinos: detection principle

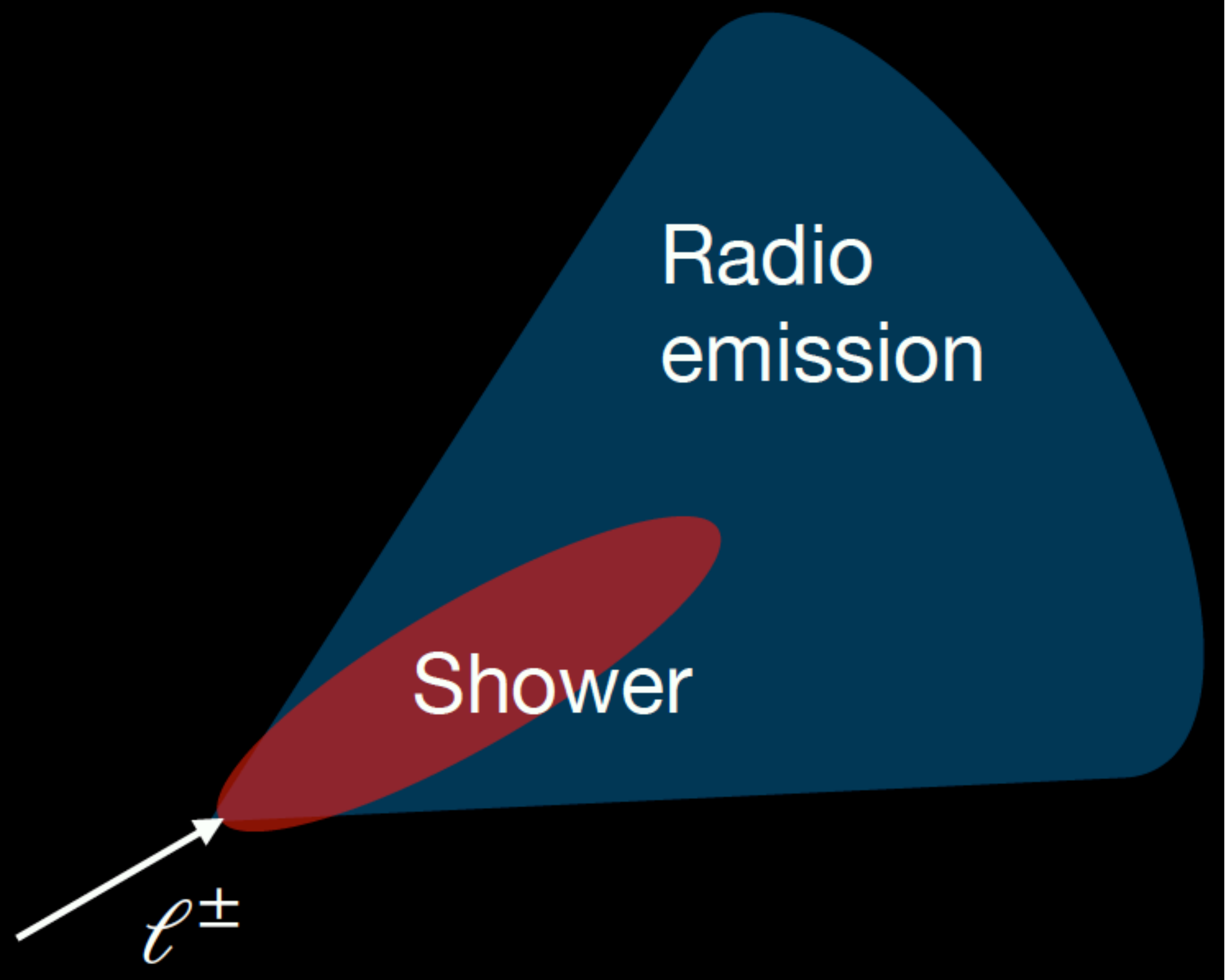
10 MeV	TeV-PeV	100 PeV-1EeV
10 kton	1 km^3	> 100 000 km^2



Liquid scintillators
e.g. JUNO



Water Cherenkov
e.g. Super-Kamiokande, IceCube



Radiodetectors
e.g. GRAND

Astrophysical neutrinos: detection principle

10 MeV	TeV-PeV	100 PeV-1EeV
10 kton	1 km^3	> 100 000 km^2

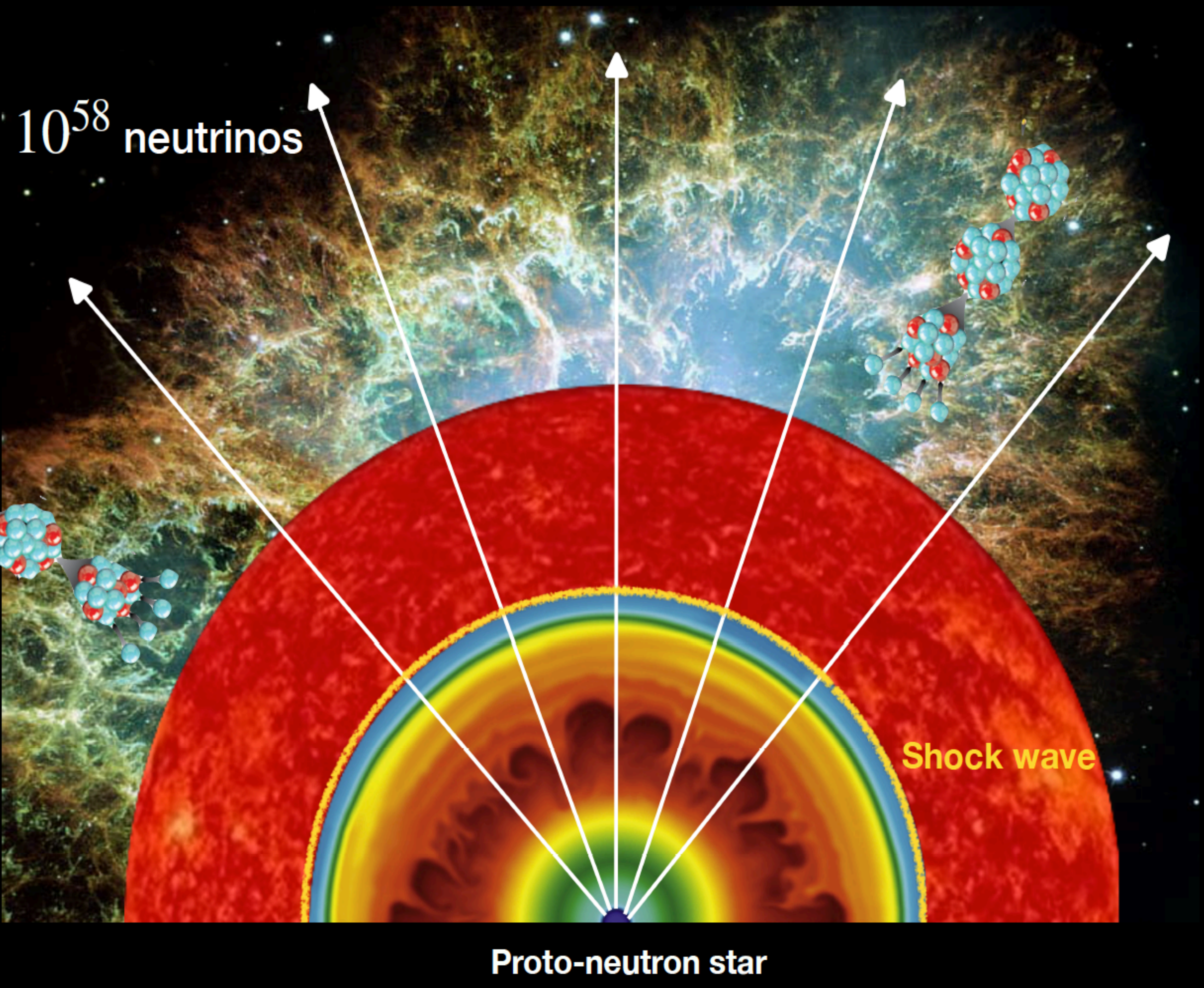
Liquid scintillators
e.g. JUNO

Water Cherenkov
e.g. Super-Kamiokande, IceCube

Radiodetectors
e.g. GRAND

Core-collapse supernova explosions

Extreme, complex, and not-fully-understood phenomena

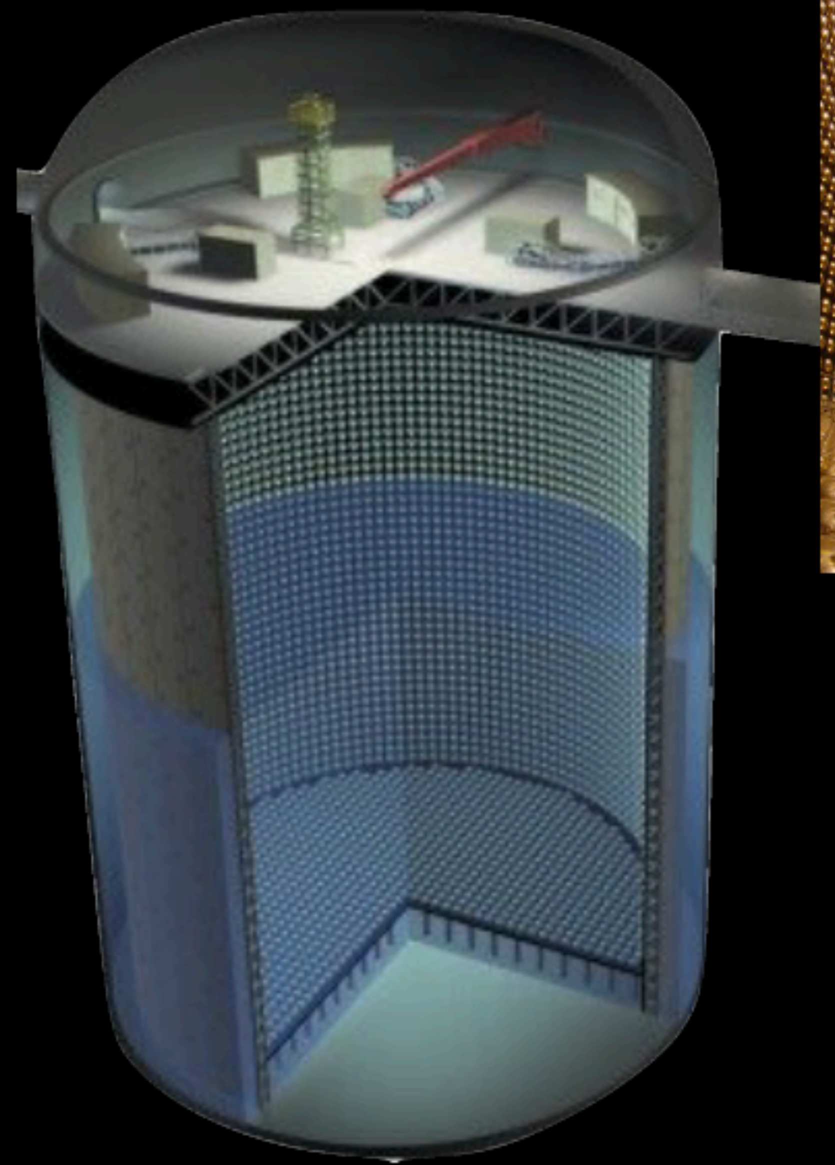


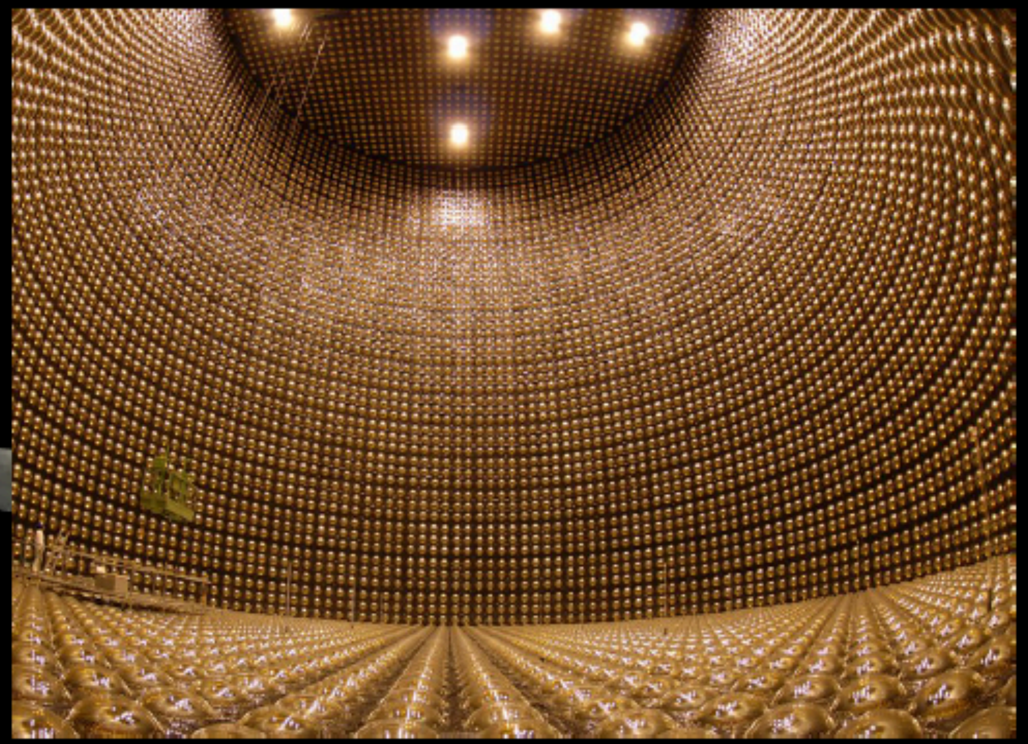
- End of life of heavy star: collapse leading to an explosion or a stellar black hole
- Explosion conditions not fully understood
  $\Rightarrow$ Need to observe the core of the star
- Short & intense CCSN neutrino burst
- Neutrino rates and energies are characteristic of the CCSN phases

Main CCSN neutrino observatories

Super-Kamiokande

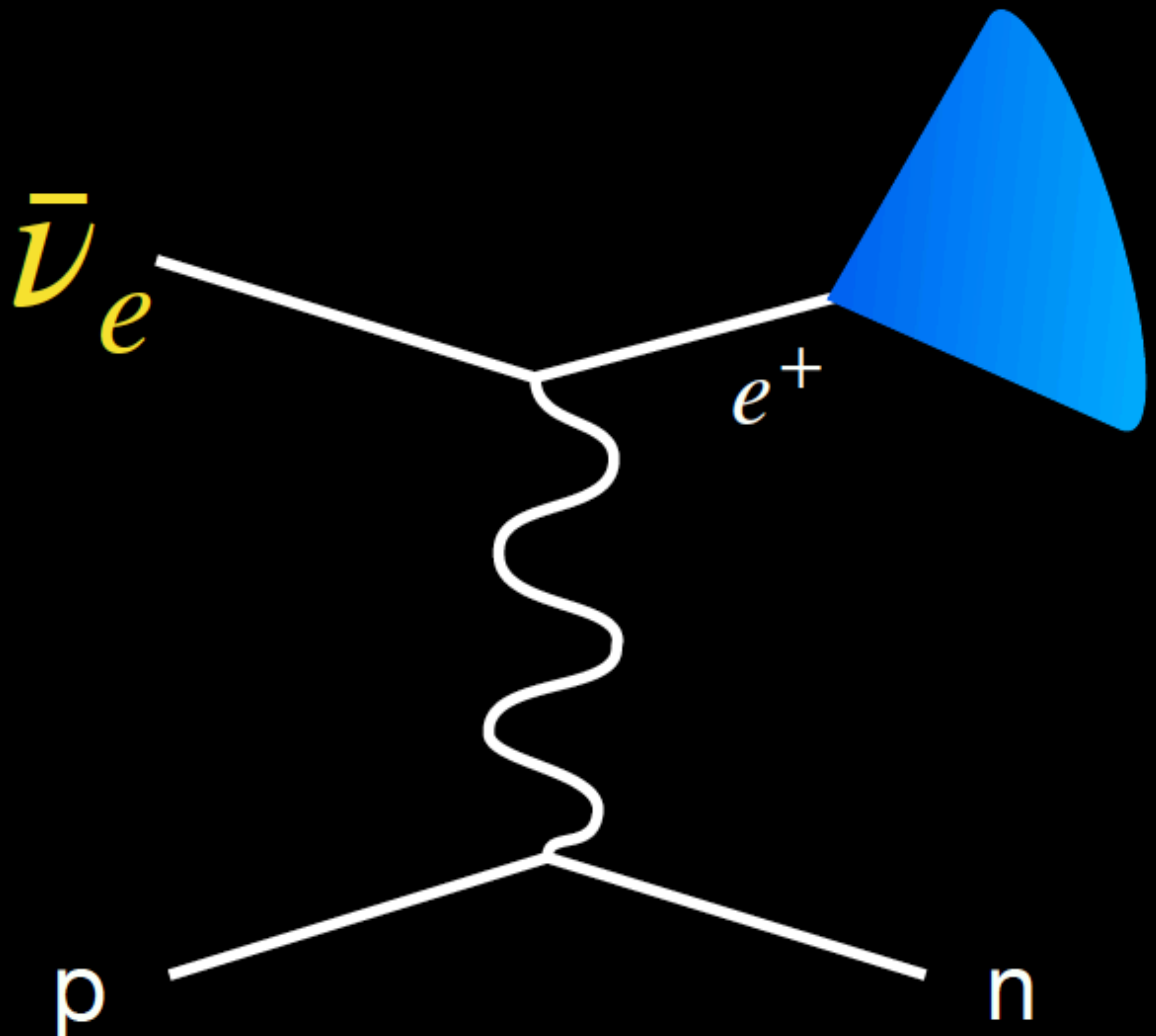
32 kton
11129 PMTs
1km overburden





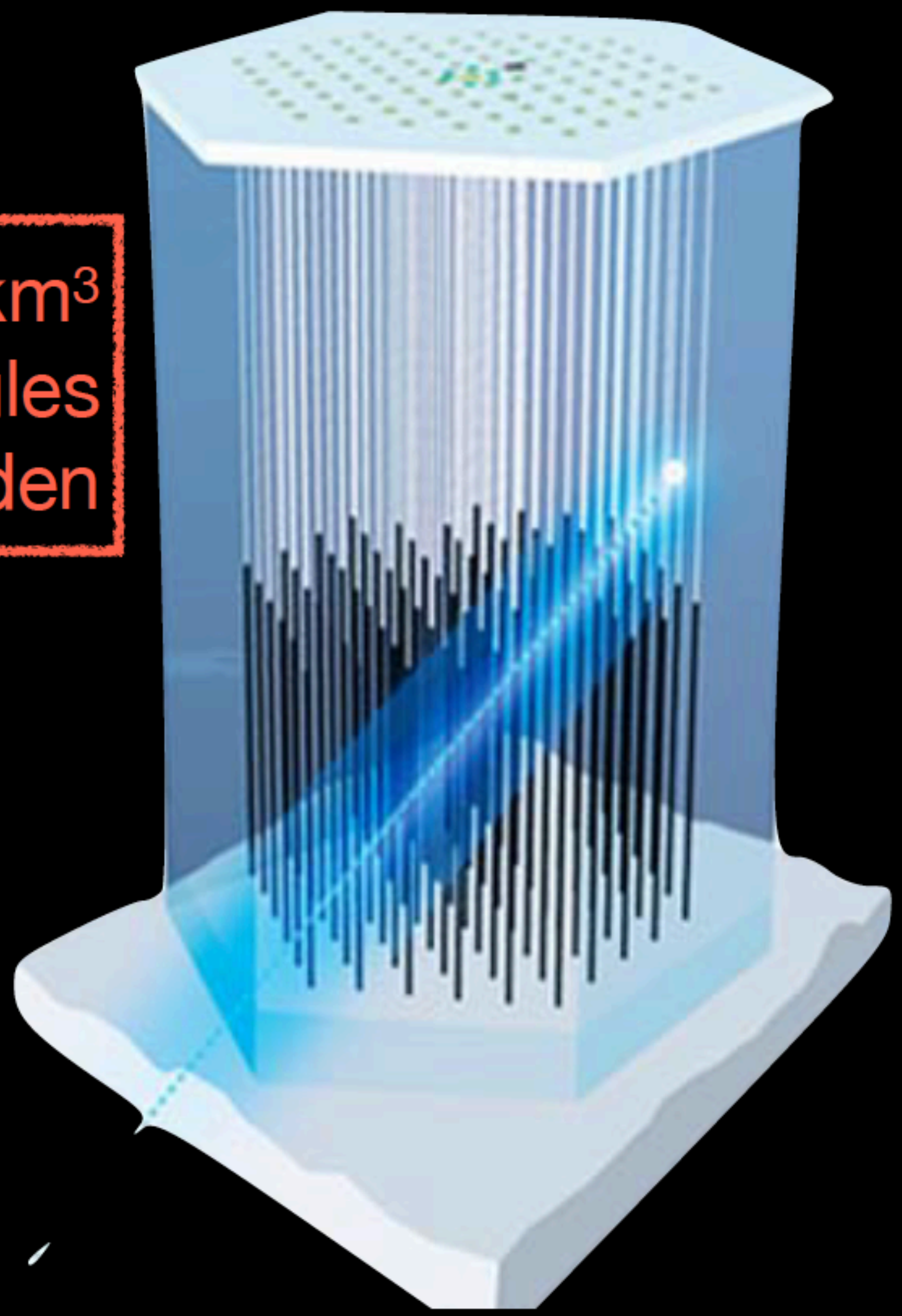
D. Guetta et al, Astrophys. J. Lett. 955 (2023) 1, L9

- 14% energy resolution @ 10 MeV
- Negligible background



IceCube

1 km^3
5160 optical modules
1.5 km overburden



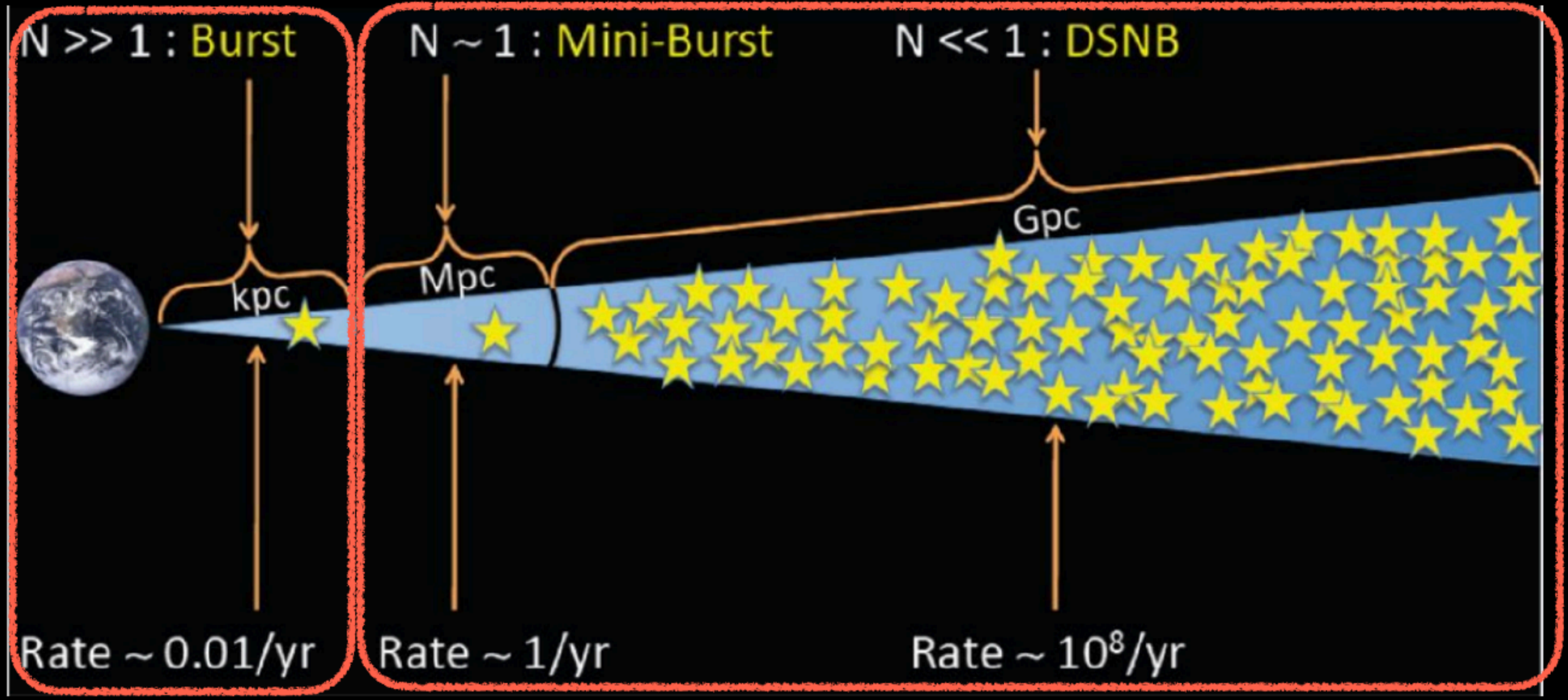
- No resolution, 1.5 MHz background
- 10^6 events for a CCSN @ 10 kpc

Supernovae in multi-messager astro: SNEWS

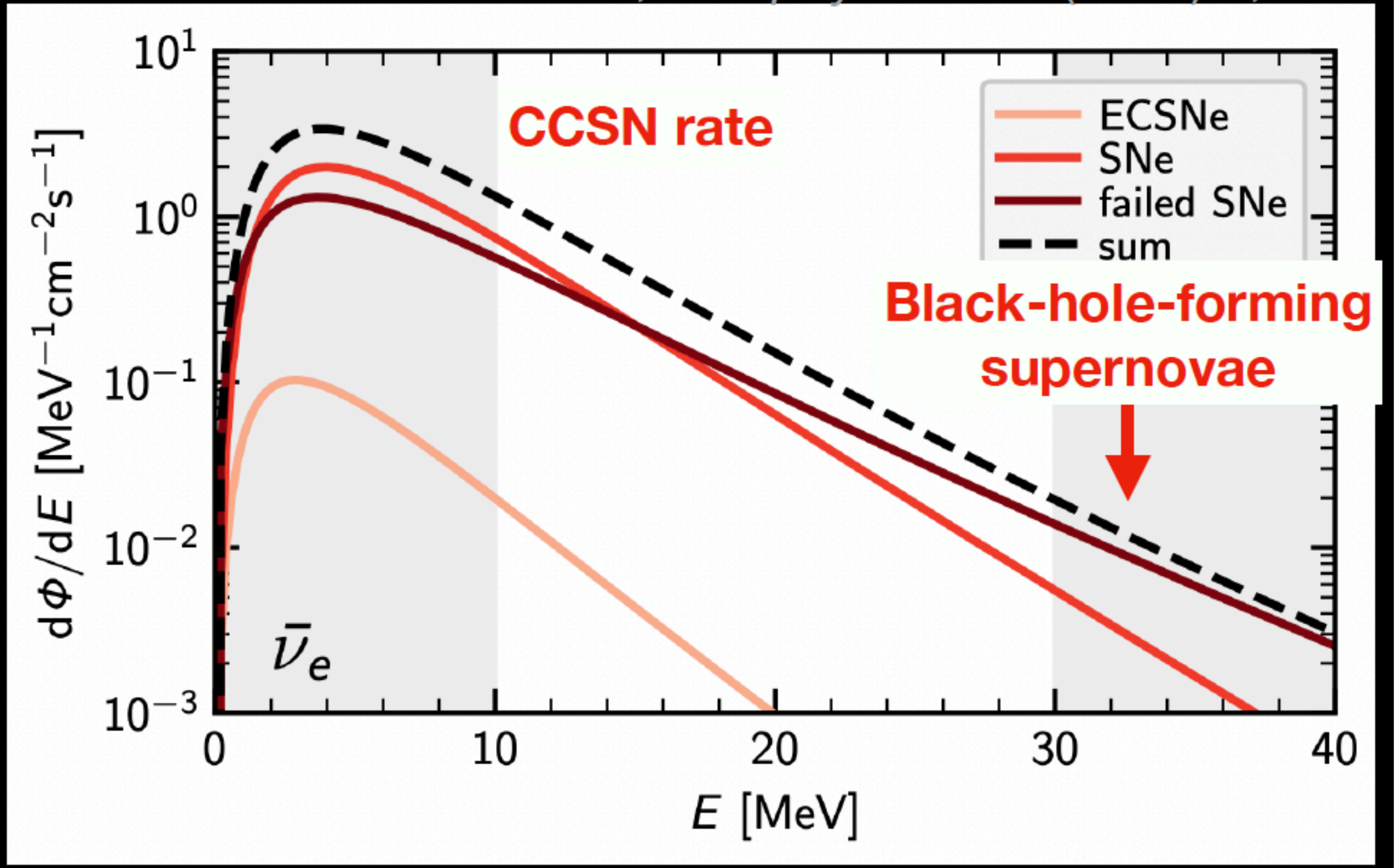
Use neutrino detectors to locate the supernova

SuperNova Early Warning System

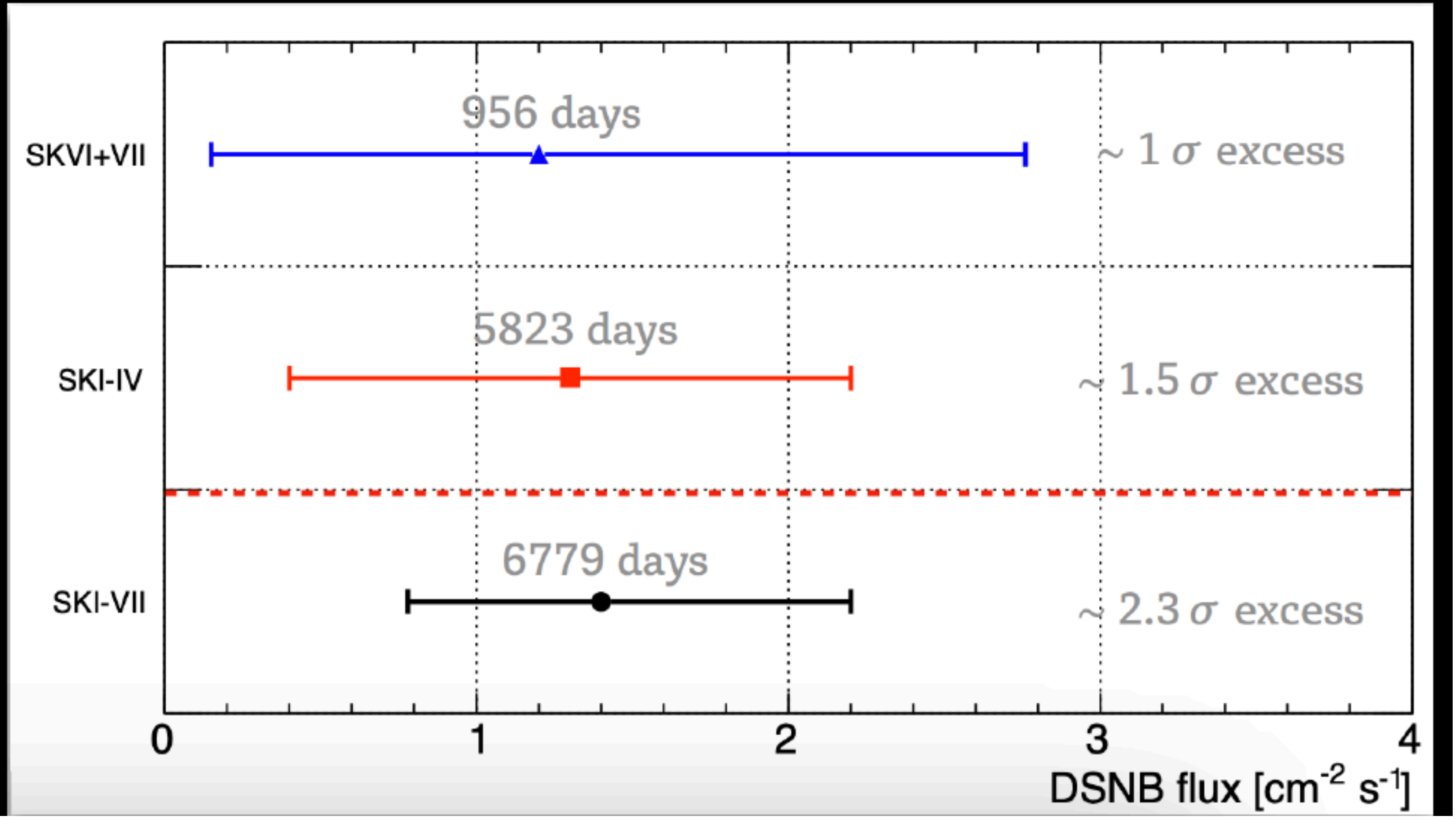
The Diffuse Supernova Neutrino Background



D. Kresse et al, *Astrophys.J.* 909 (2021) 2, 169



- Permanent CCSN neutrino signal
  Only 2-3 events/s in Super-Kamiokande…
- Enhance detectability by tagging neutrons from $\bar{\nu}_e$ interactions ⇒ SuperK-Gd since 2020

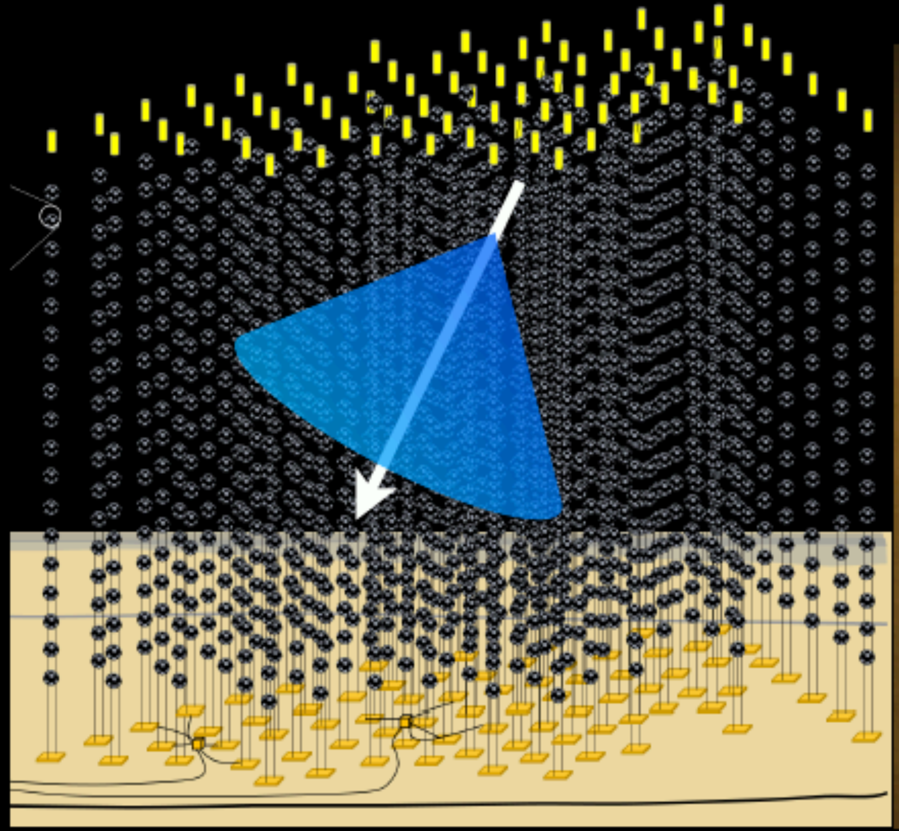


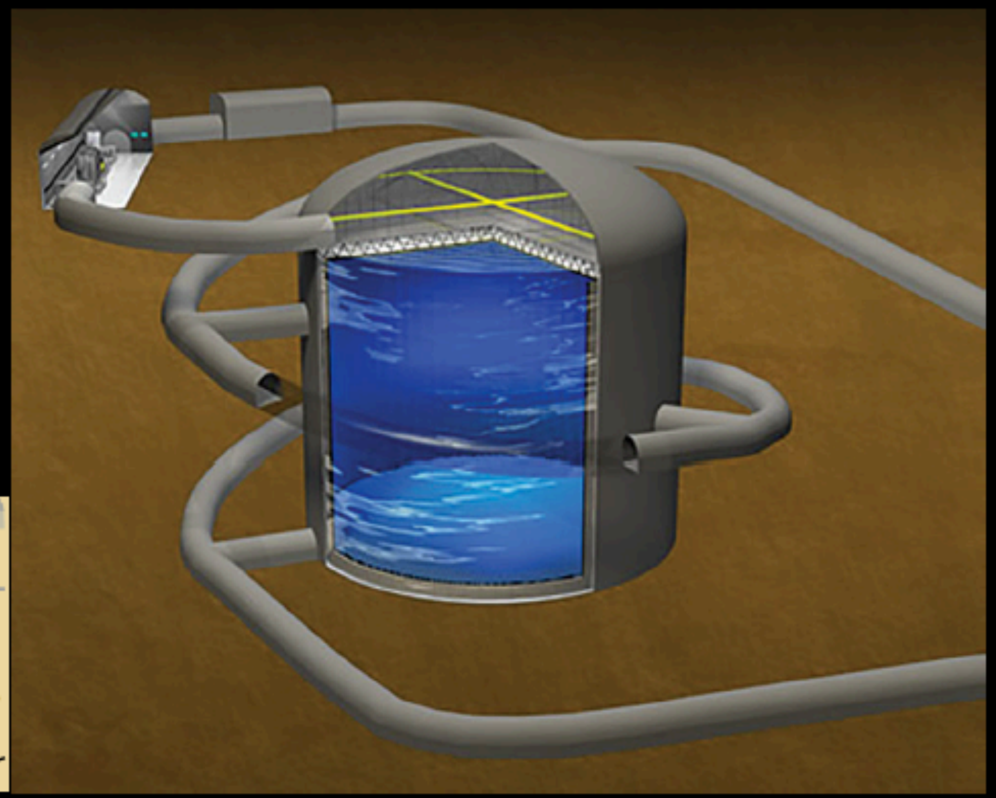
M. Harada for the Super-Kamiokande collaboration
Neutrino 2024

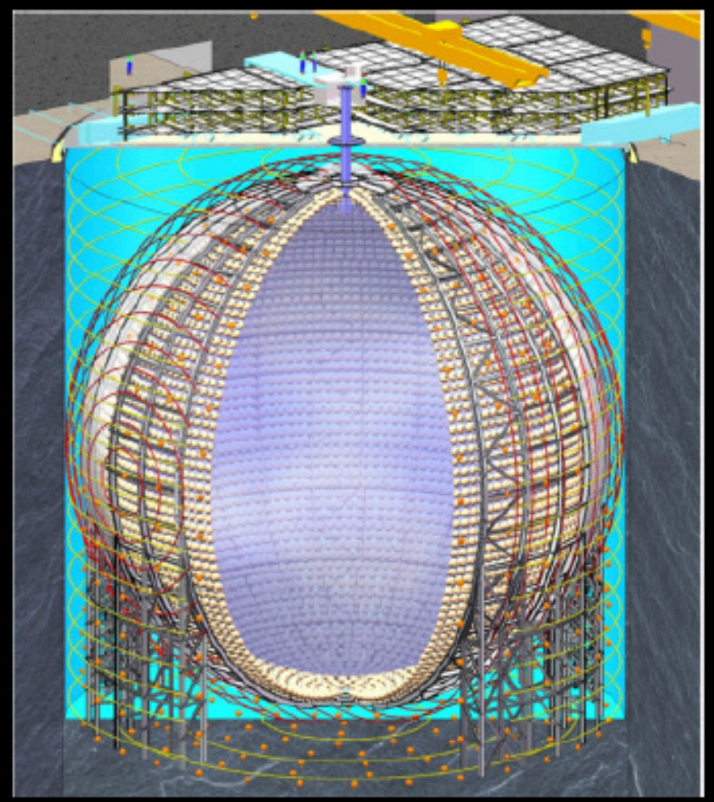
The 2030s: multi-flavor probing of supernovae

Water Cherenkov & scintillator detectors

Sensitivity to $\bar{\nu}_e$ through IBD





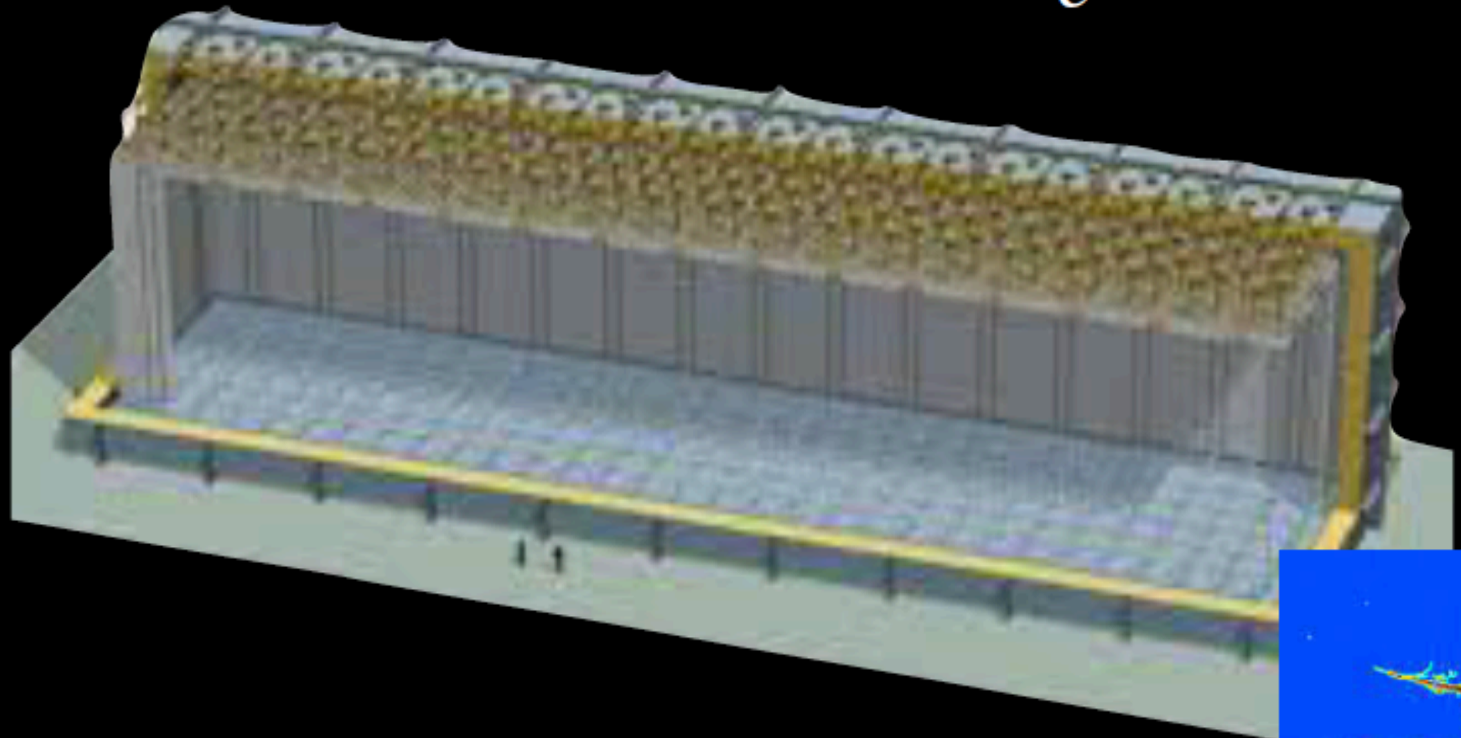


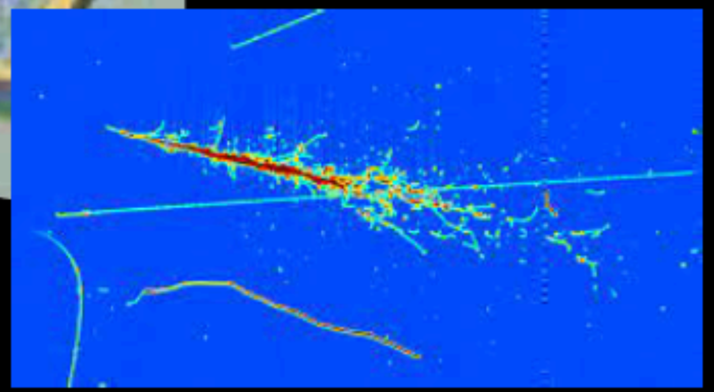
IceCube, Hyper-Kamiokande, JUNO

Noble gas detectors

DUNE

Sensitivity to ν_e

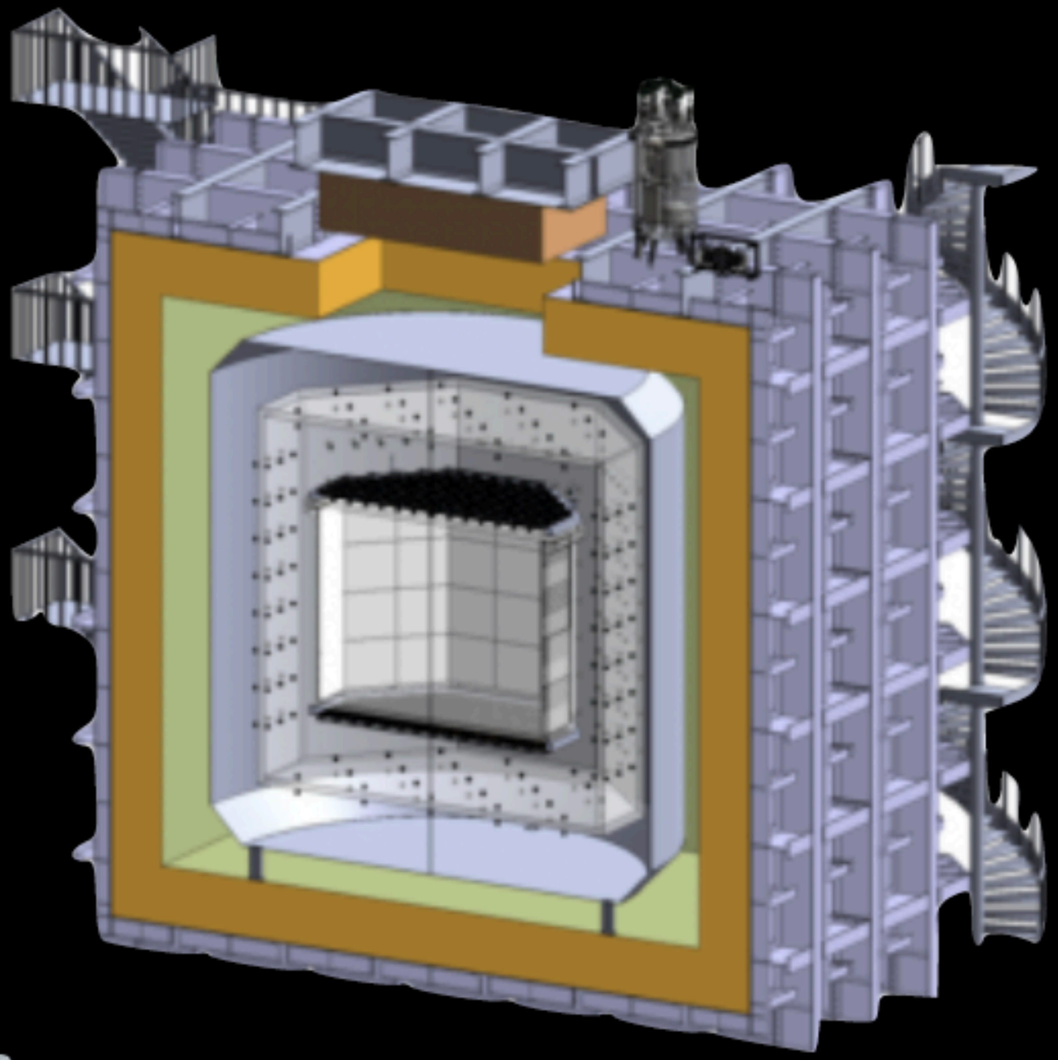




2000-3000 events
@ 10 kpc for 40 kton

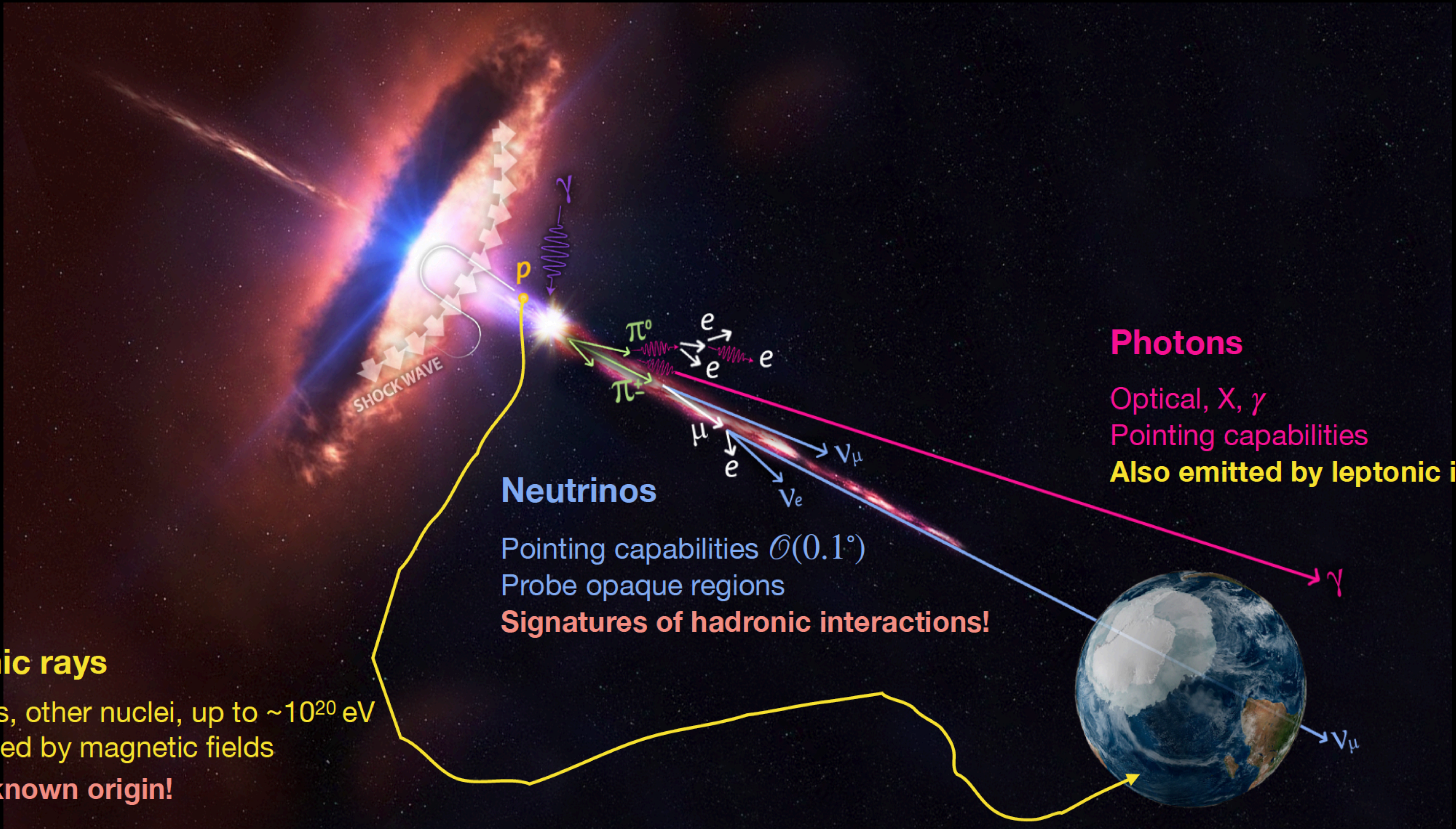
DARWIN, ARGO

Sensitivity to all ν



700-1700 events
@ 10 kpc

Neutrinos and the origin of cosmic rays



Photons

Optical, X, γ
Pointing capabilities
Also emitted by leptonic interactions

Neutrinos

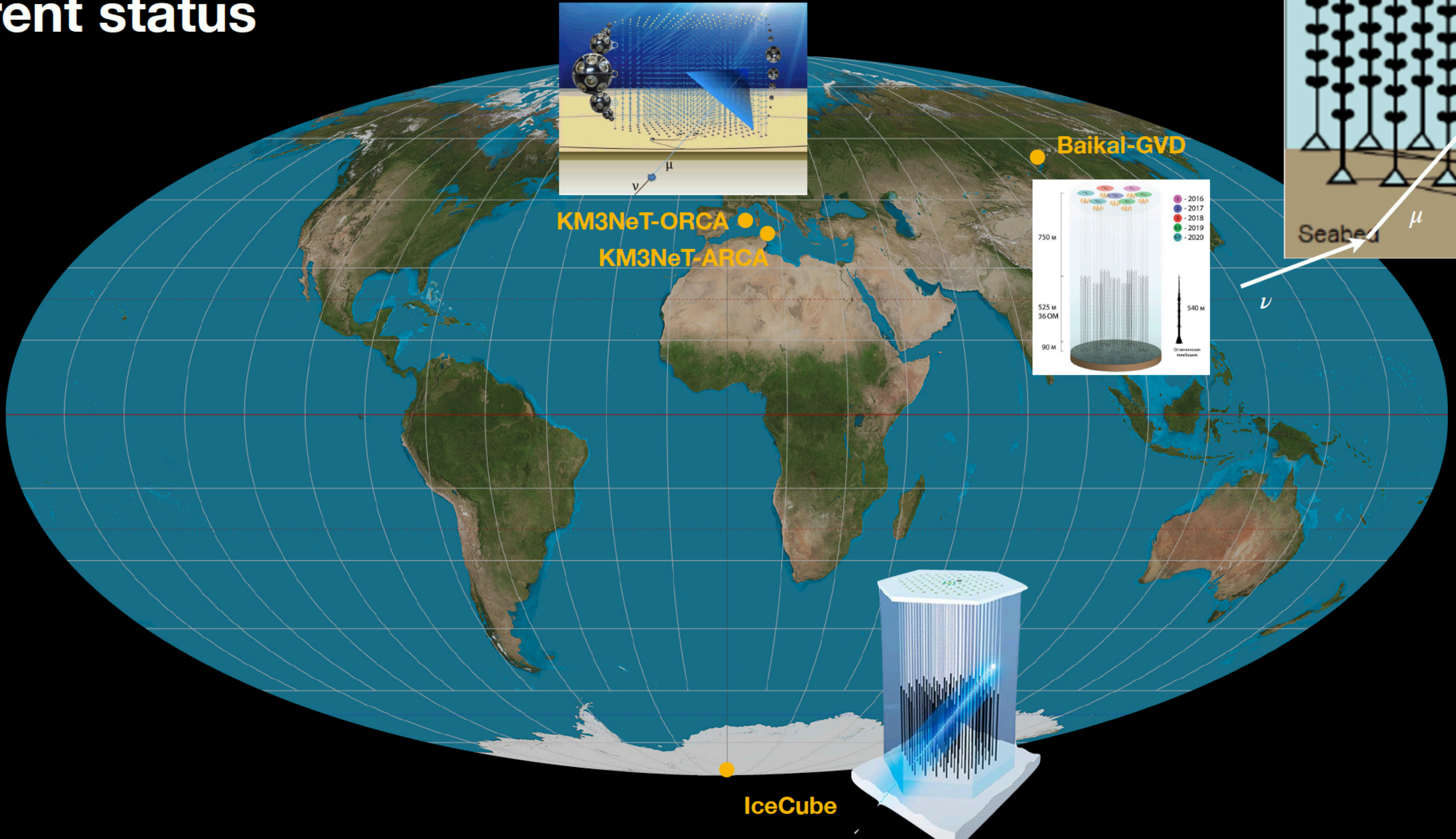
Pointing capabilities $\mathcal{O}(0.1°)$
Probe opaque regions
Signatures of hadronic interactions!

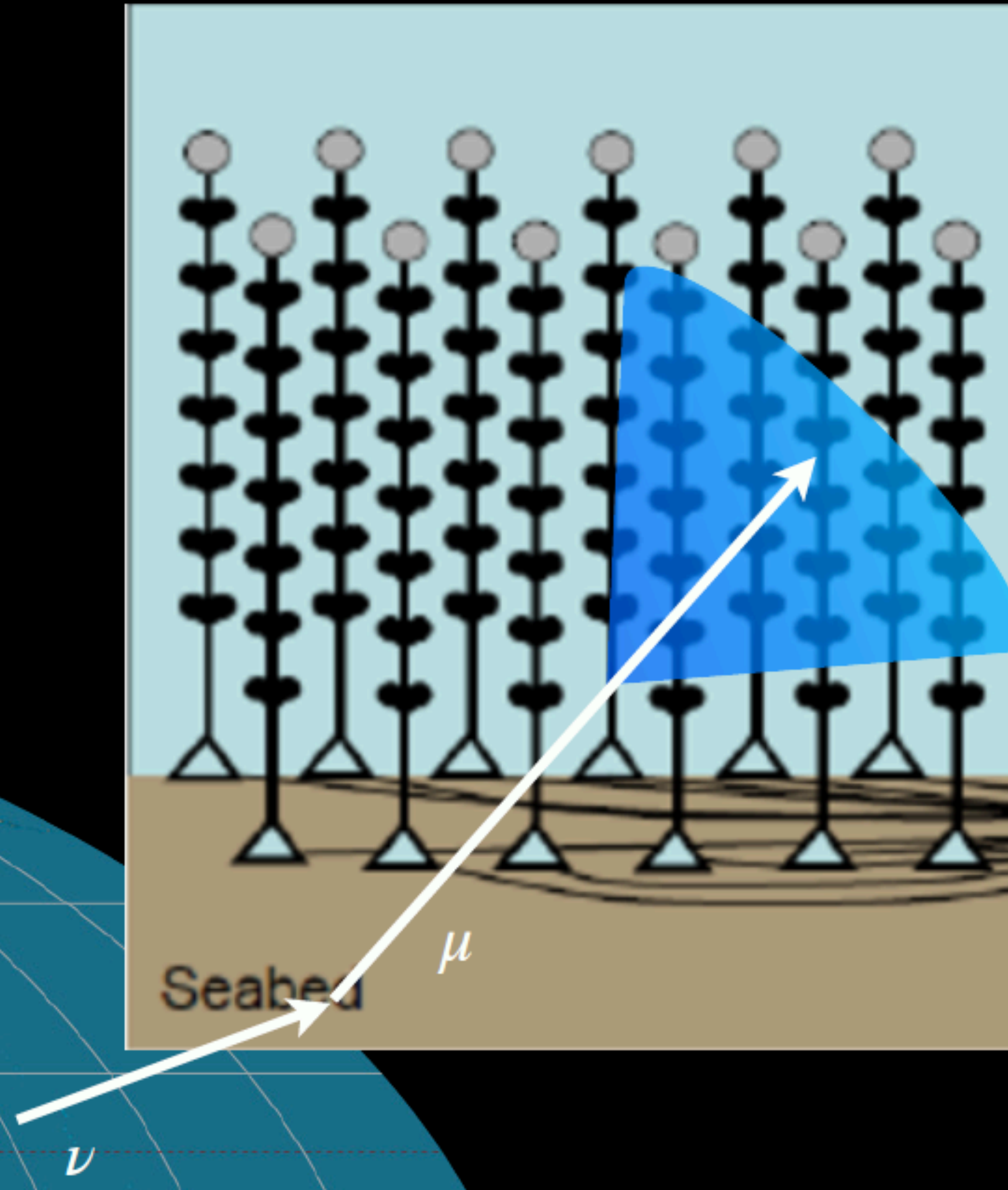
Cosmic rays

Protons, other nuclei, up to ~10^{20} eV
Deflected by magnetic fields
→ **Unknown origin!**

High-energy neutrino telescopes

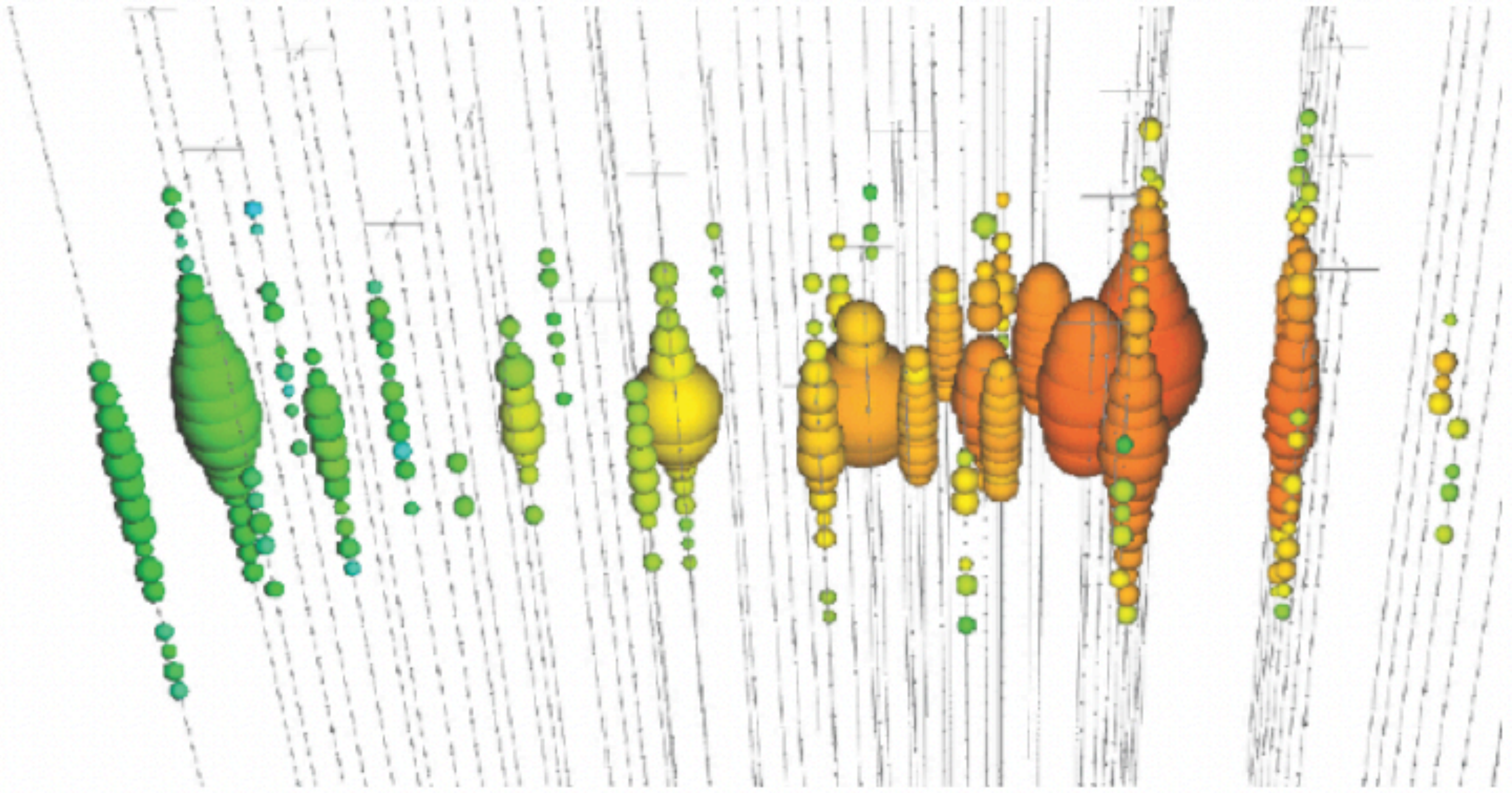
Current status





Event topologies

Tracks



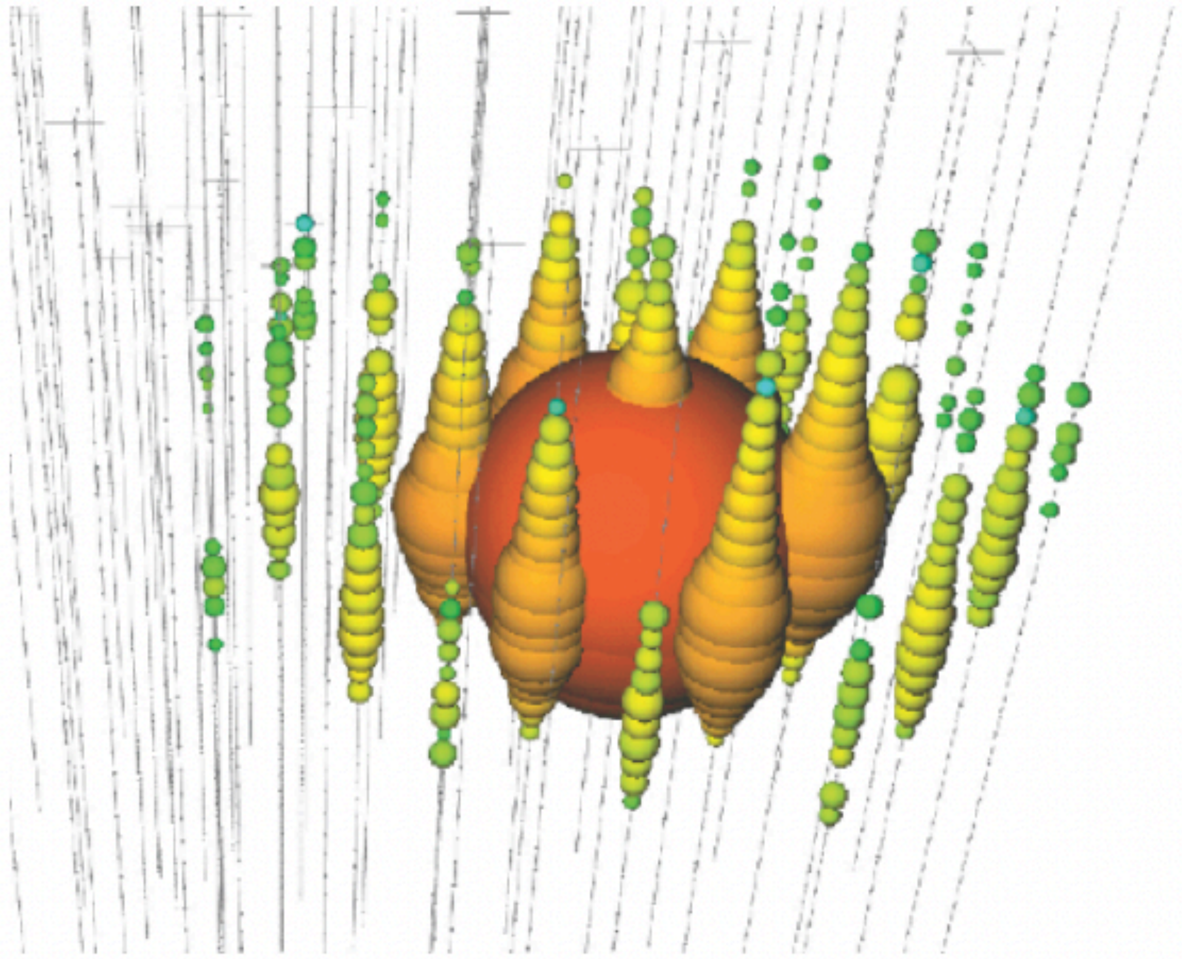
ν_μ CC Interaction

Angular resolution < 1°

Energy resolution ~ 29%

→ Ideal to look for CR sources

Cascades



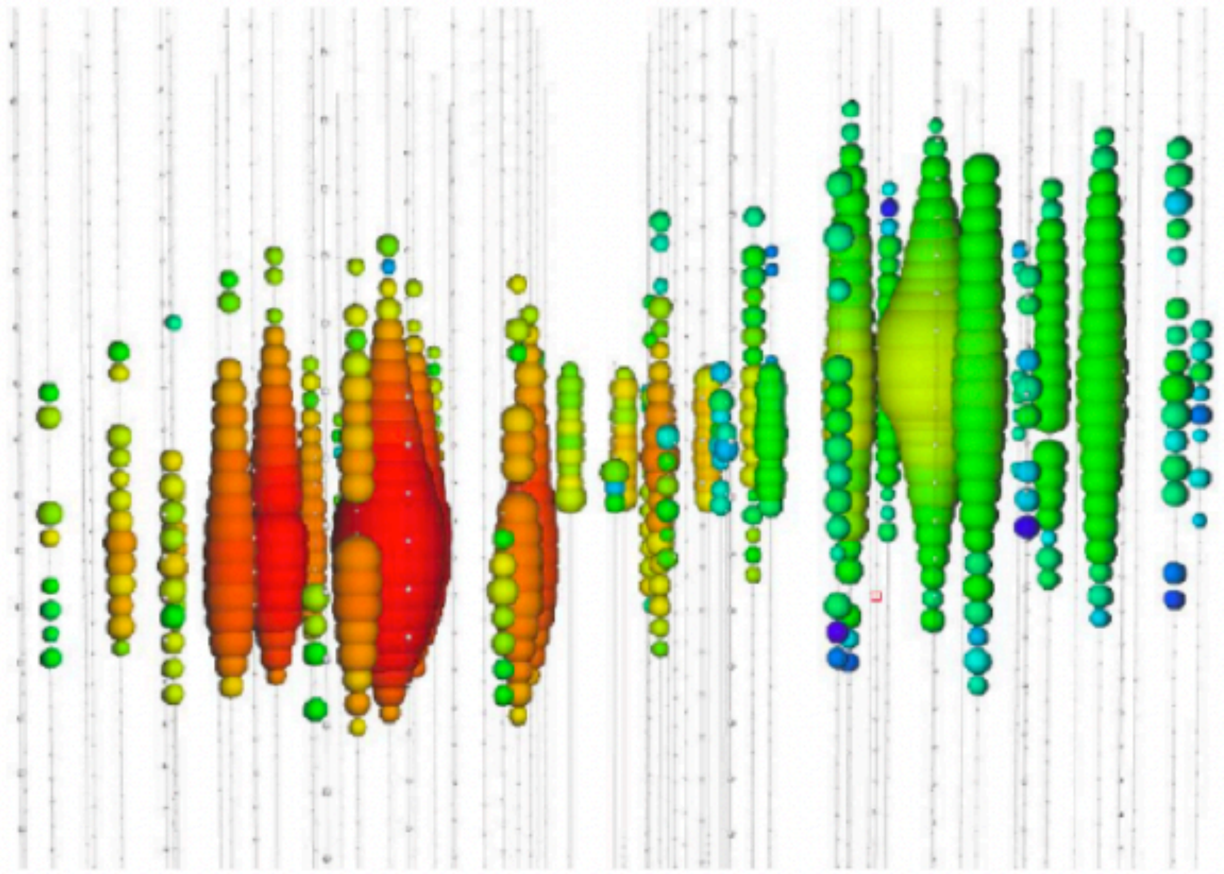
ν_{all} NC, ν_e/ν_τ CC Interaction

Angular resolution : 15 to 20°

Energy resolution ~15%

→ Good for diffuse flux searches

Double cascades



ν_τ CC Interaction

$\nu_\tau + N \rightarrow \tau + X$

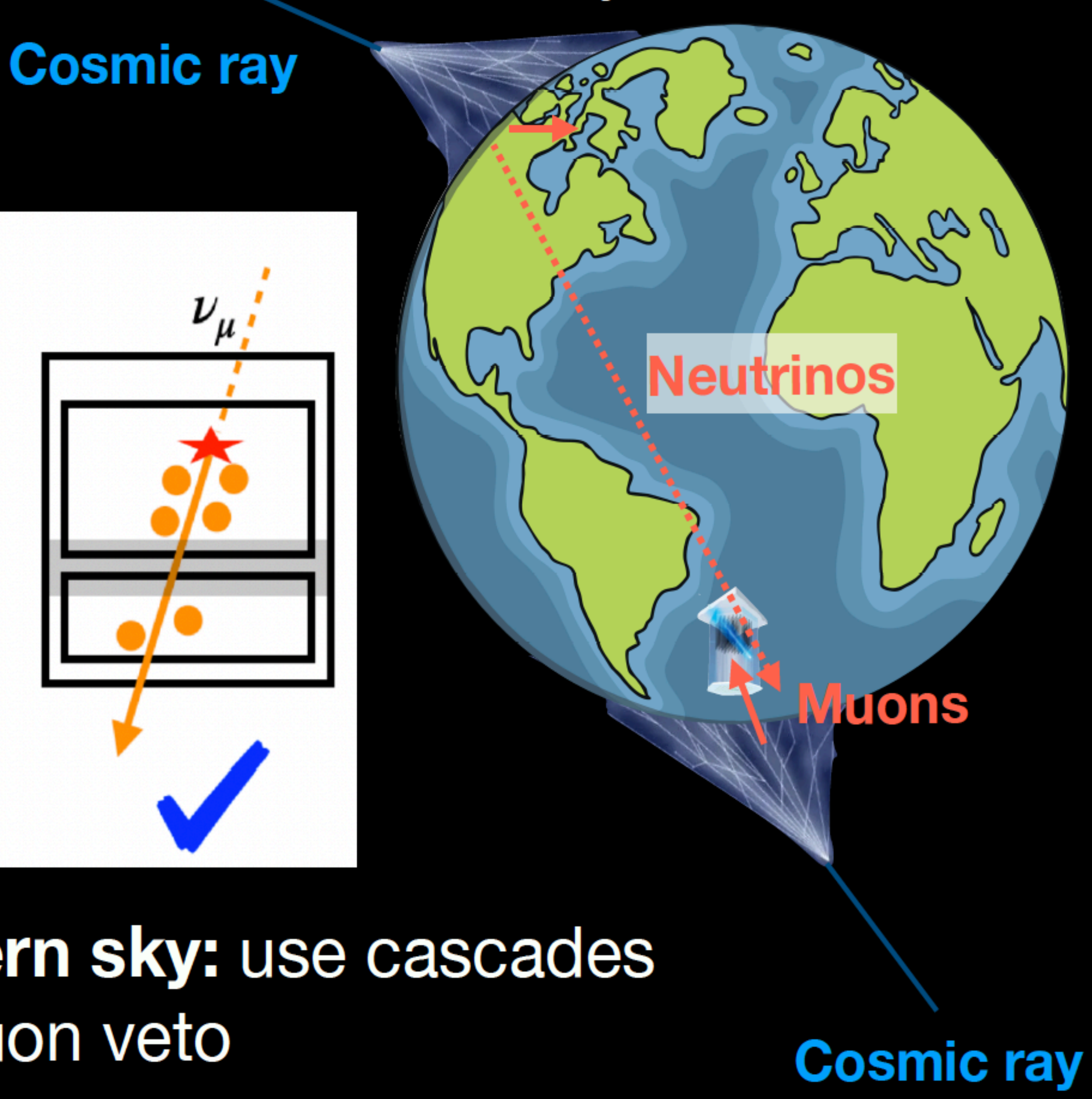
$\tau \rightarrow X$ or e

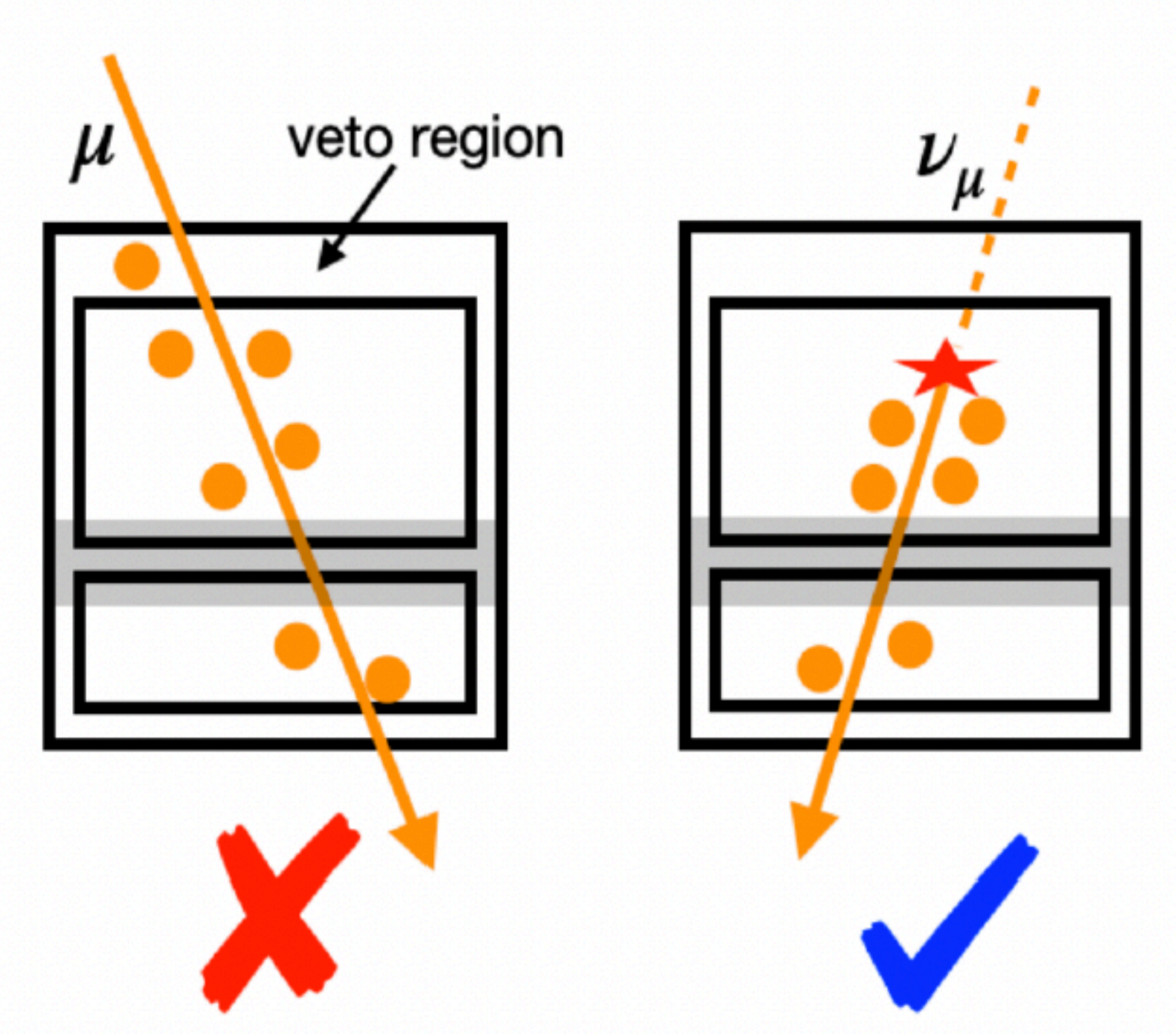
→ Very high energies
Probe flavor conversions

Background reduction

Atmospheric muons

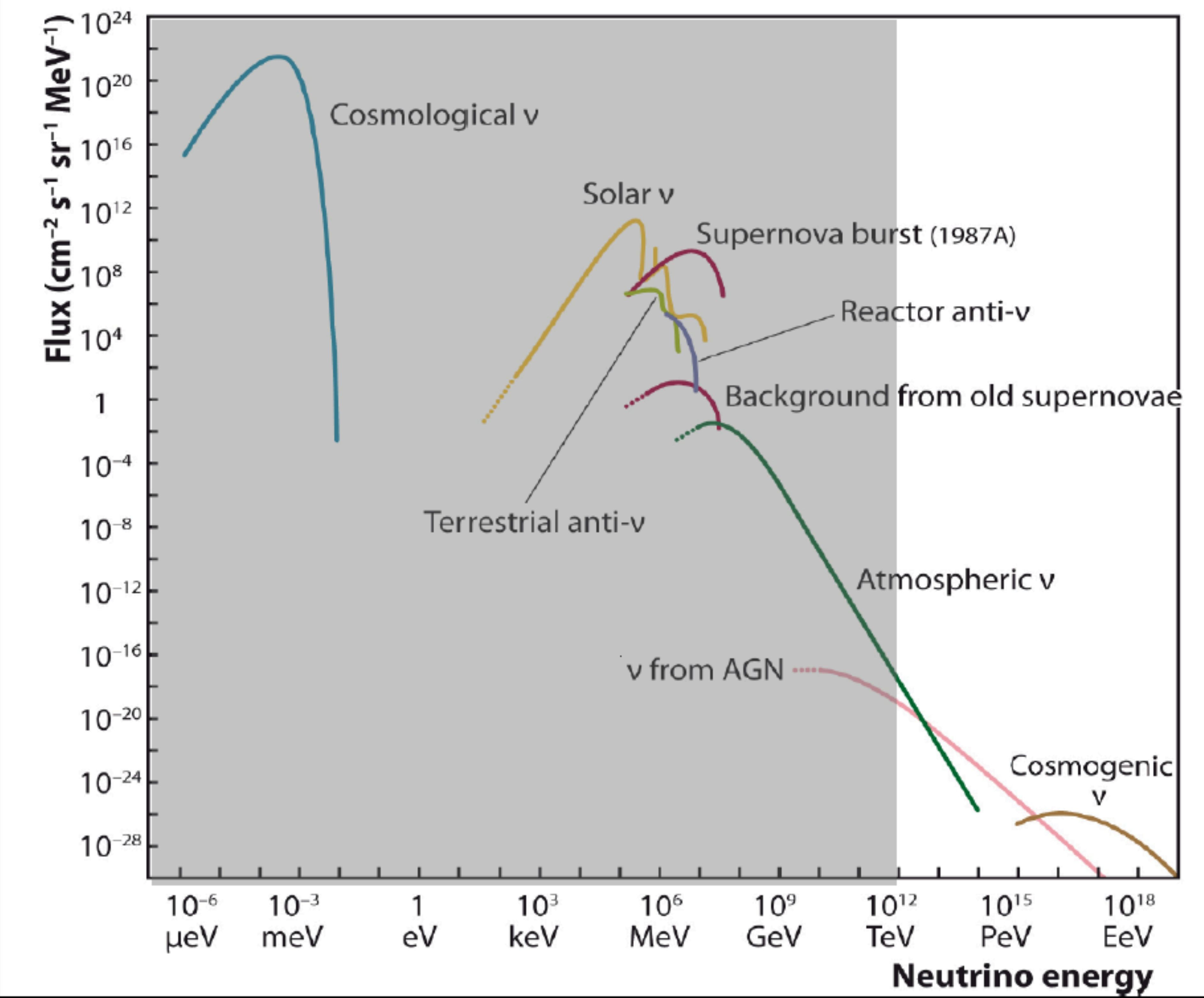
Northern Sky: better sensitivity and resolution





Southern sky: use cascades or a muon veto

Atmospheric neutrinos



3 levers:

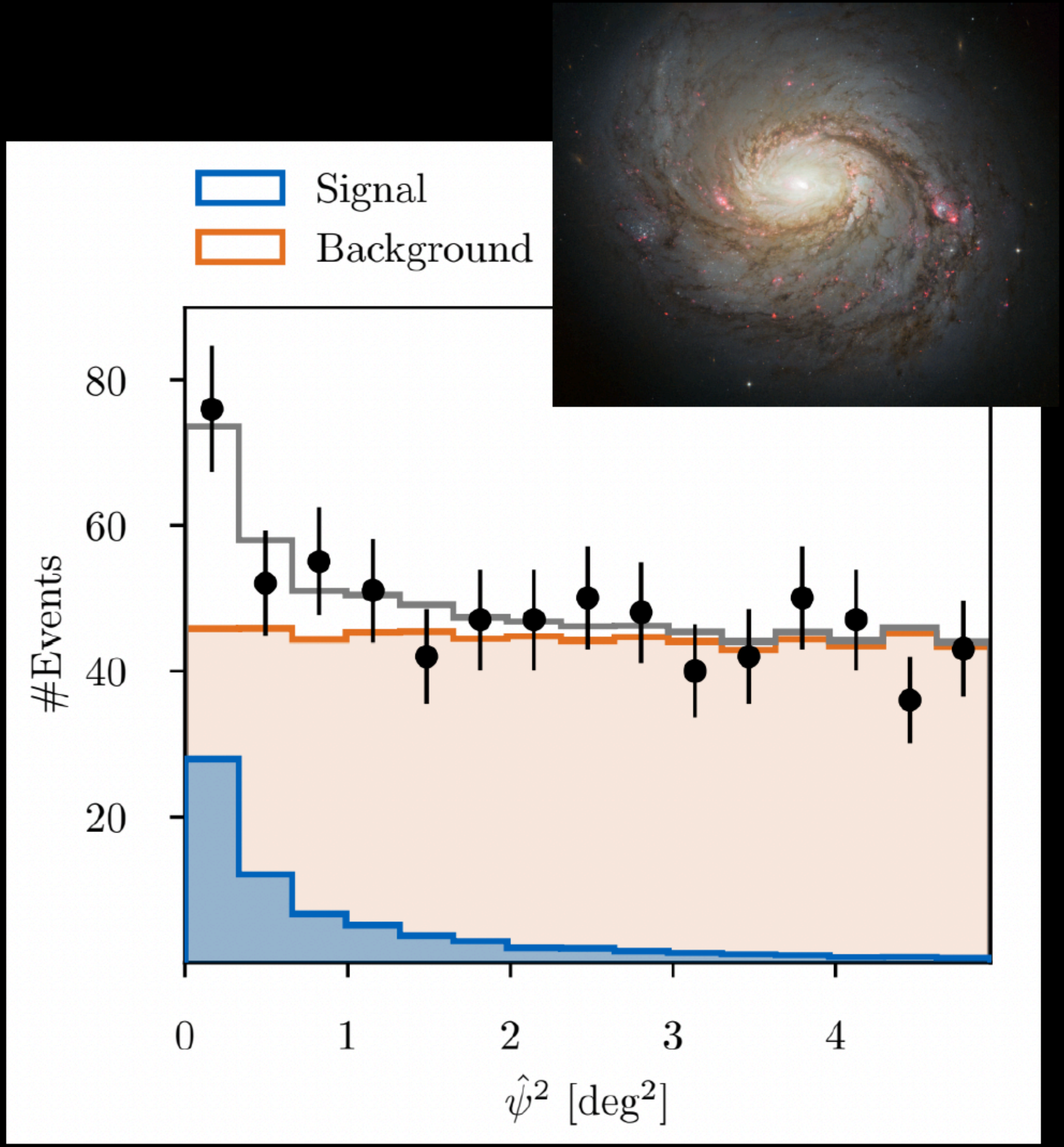
- Event energy (> TeV)
- Event localization
- Event time

→ **Coincidences with catalogs**

IceCube
South Pole Neutrino Observatory
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

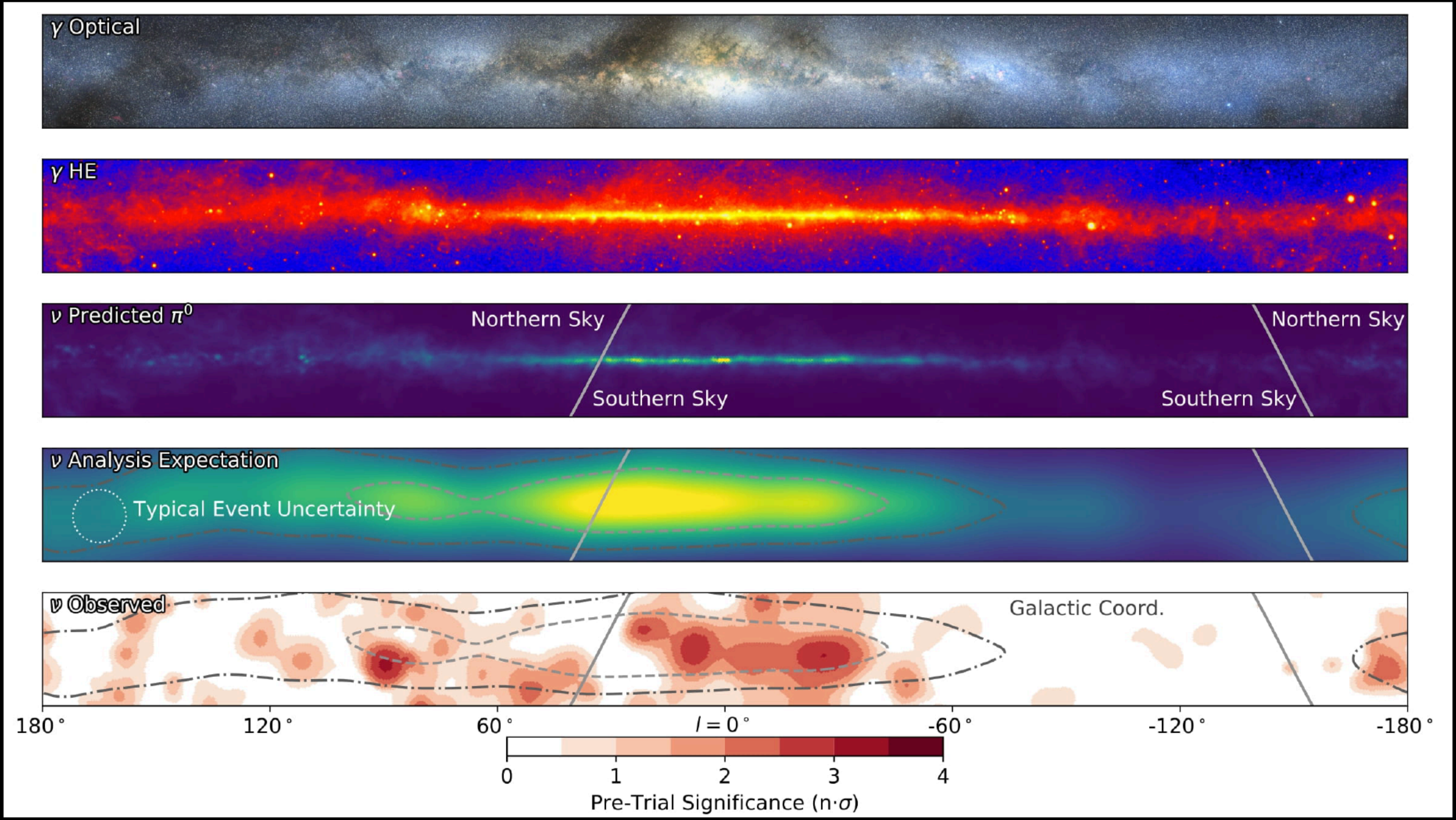
Neutrinos from the NGC1068 galaxy - 2022

- 670,000 upgoing tracks, 3186 days
  0.4° resolution @ 100 TeV
- Search for coincidences with FERMI-LAT catalog: 110 sources
- Improvements: calibration + direction reconstruction (graph neural networks)
- Models favor neutrino production close to the black hole, in opaque regions
  $\Rightarrow$ use X-ray emission in addition to γs



IceCube Collaboration, *Science* 378 (2022) 6619, 538-543

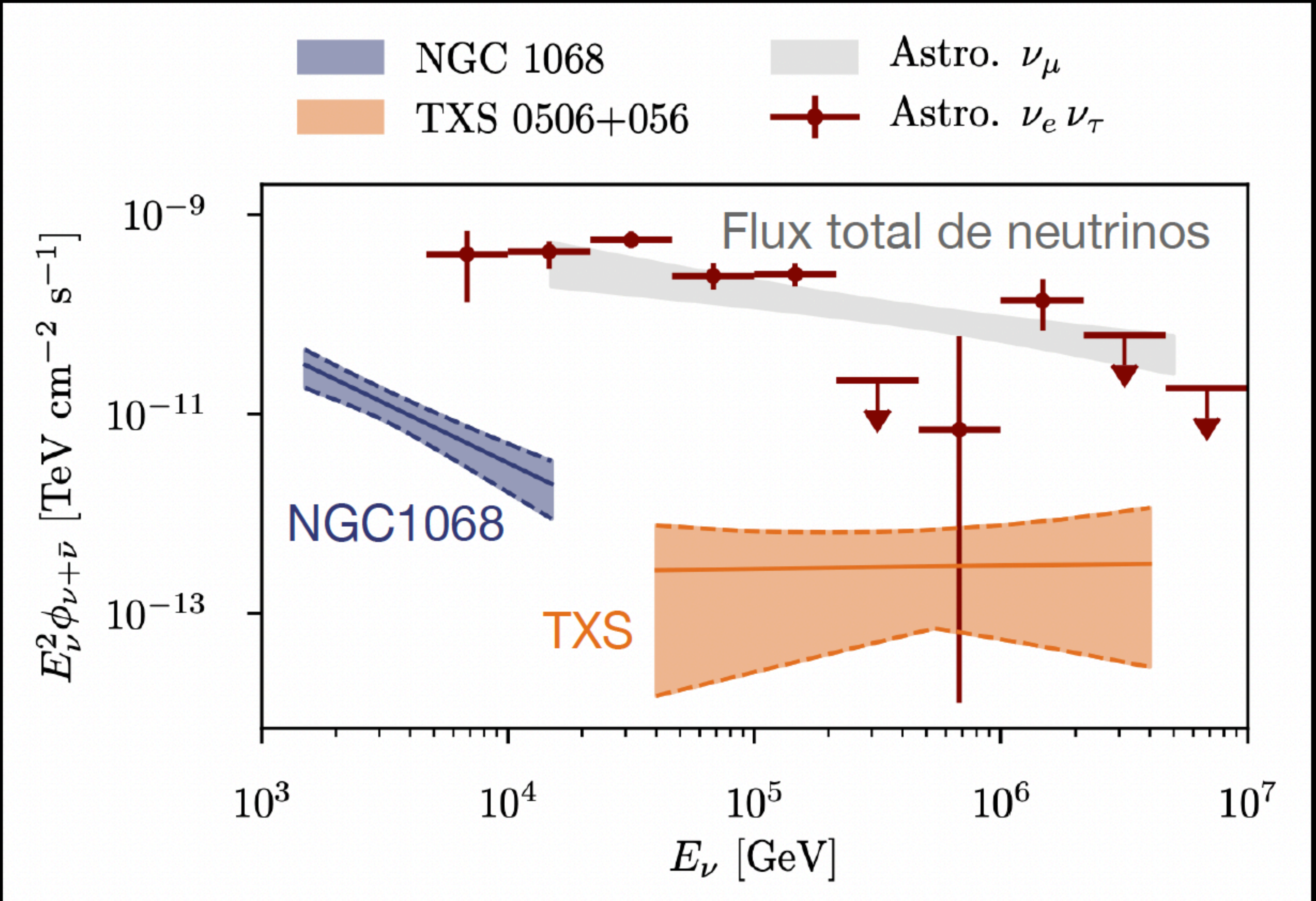
Neutrinos from the Milky Way Plane — 2023



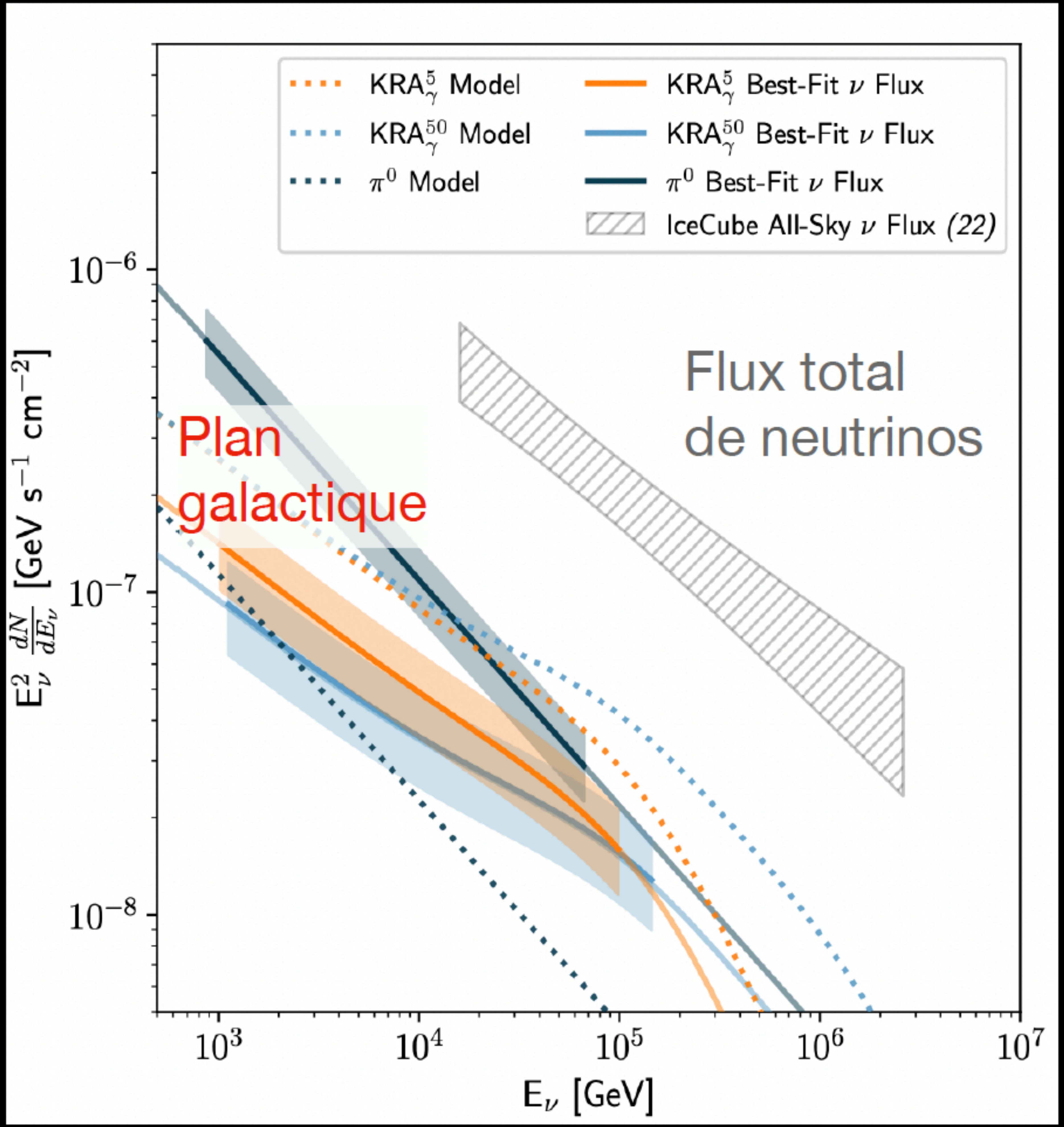
IceCube Collaboration, *Science* 380 (2023) 6652

Still many sources yet to discover..

Most of the astrophysical neutrino flux remains unidentified

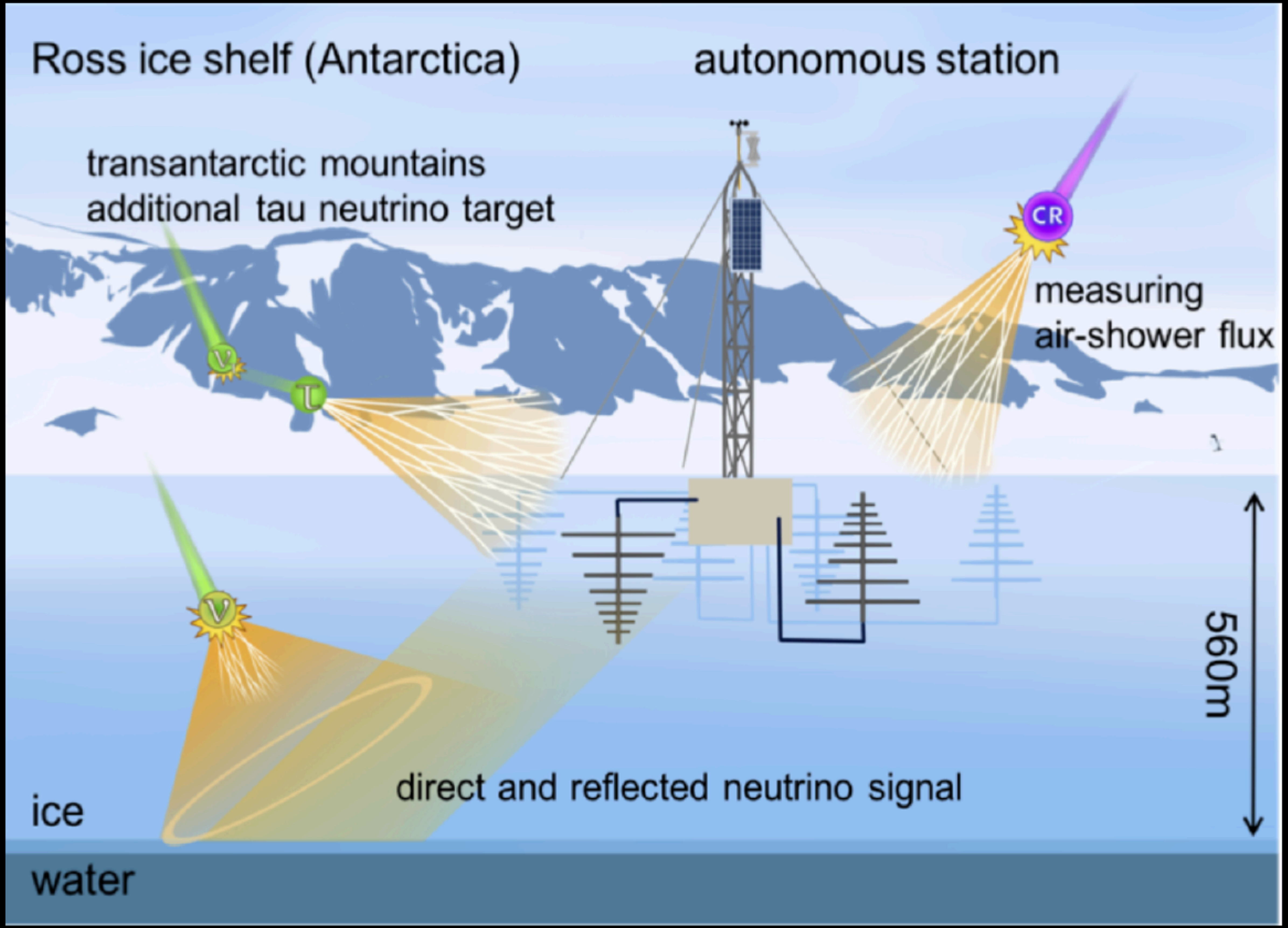


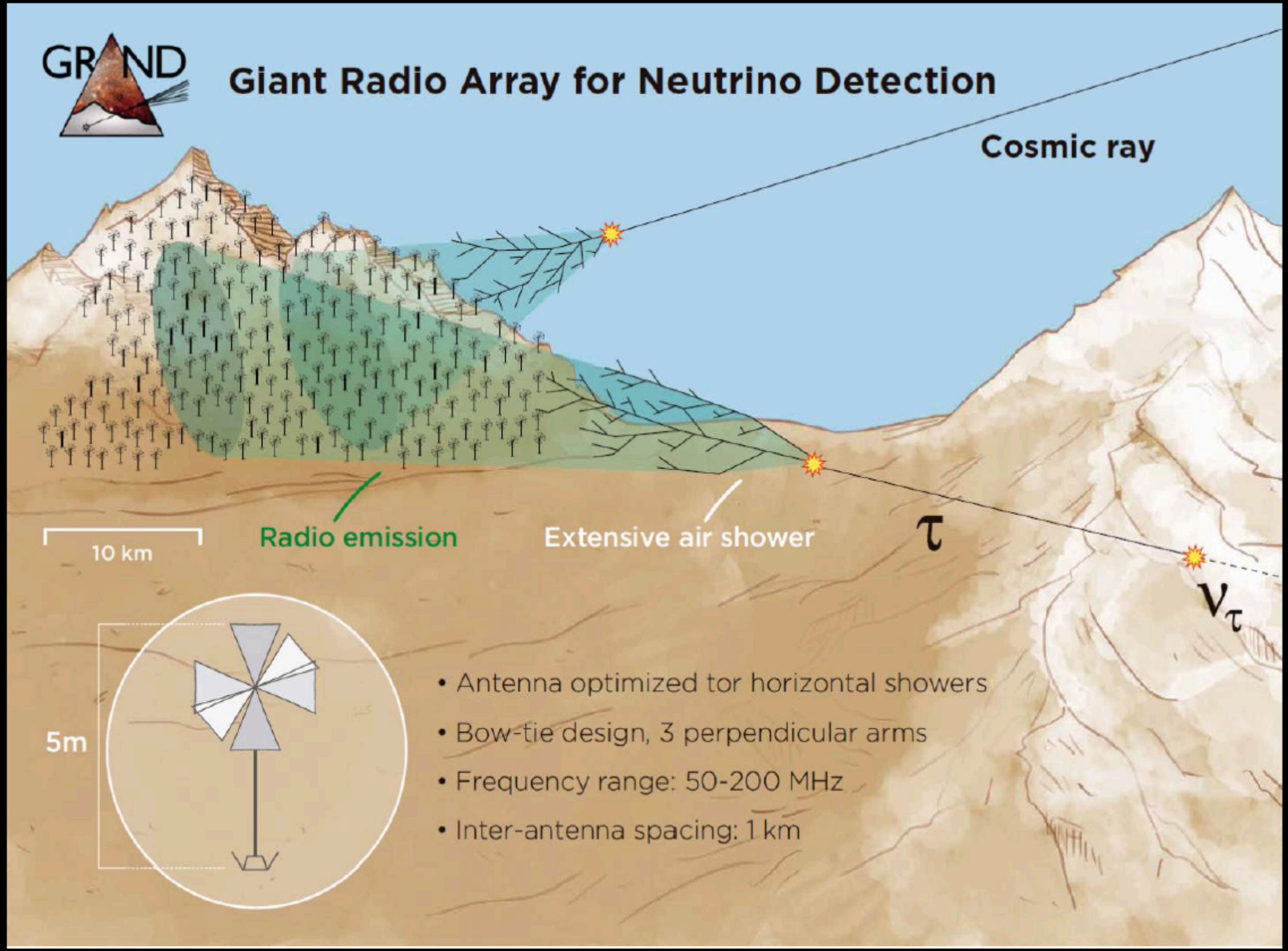
IceCube Collaboration, *Science* 378 (2022) 6619, 538-543



IceCube Collaboration, *Science* 380 (2023) 6652

Radiodetection in ice and air





ARIANNA, ARA, ANITA (balloon) @ South Pole

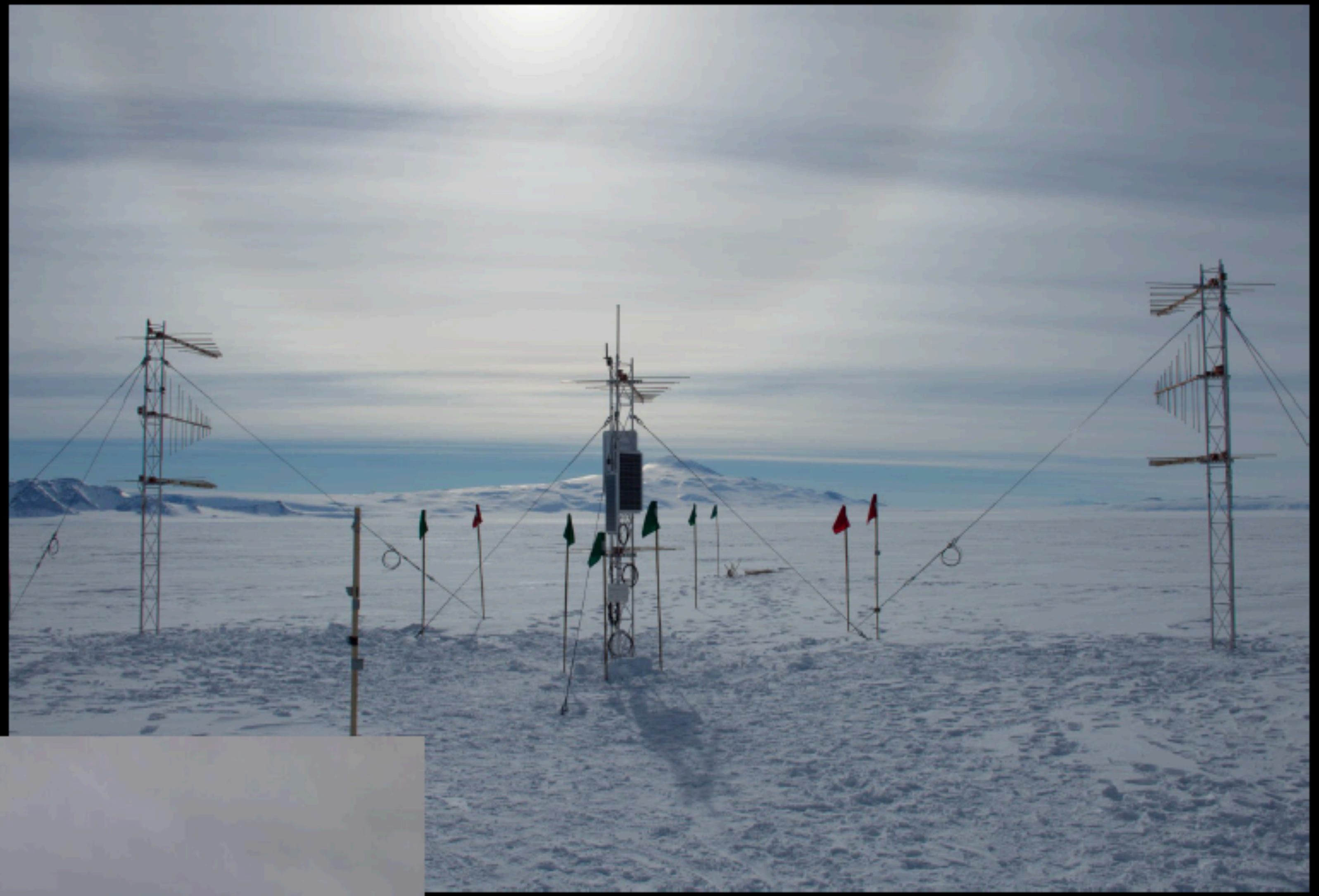
Future: RNO-G (Groenland), IceCube-Gen2

Future: GRAND, POEMMA (space-based)

Chasing the neutrino spectrum tail

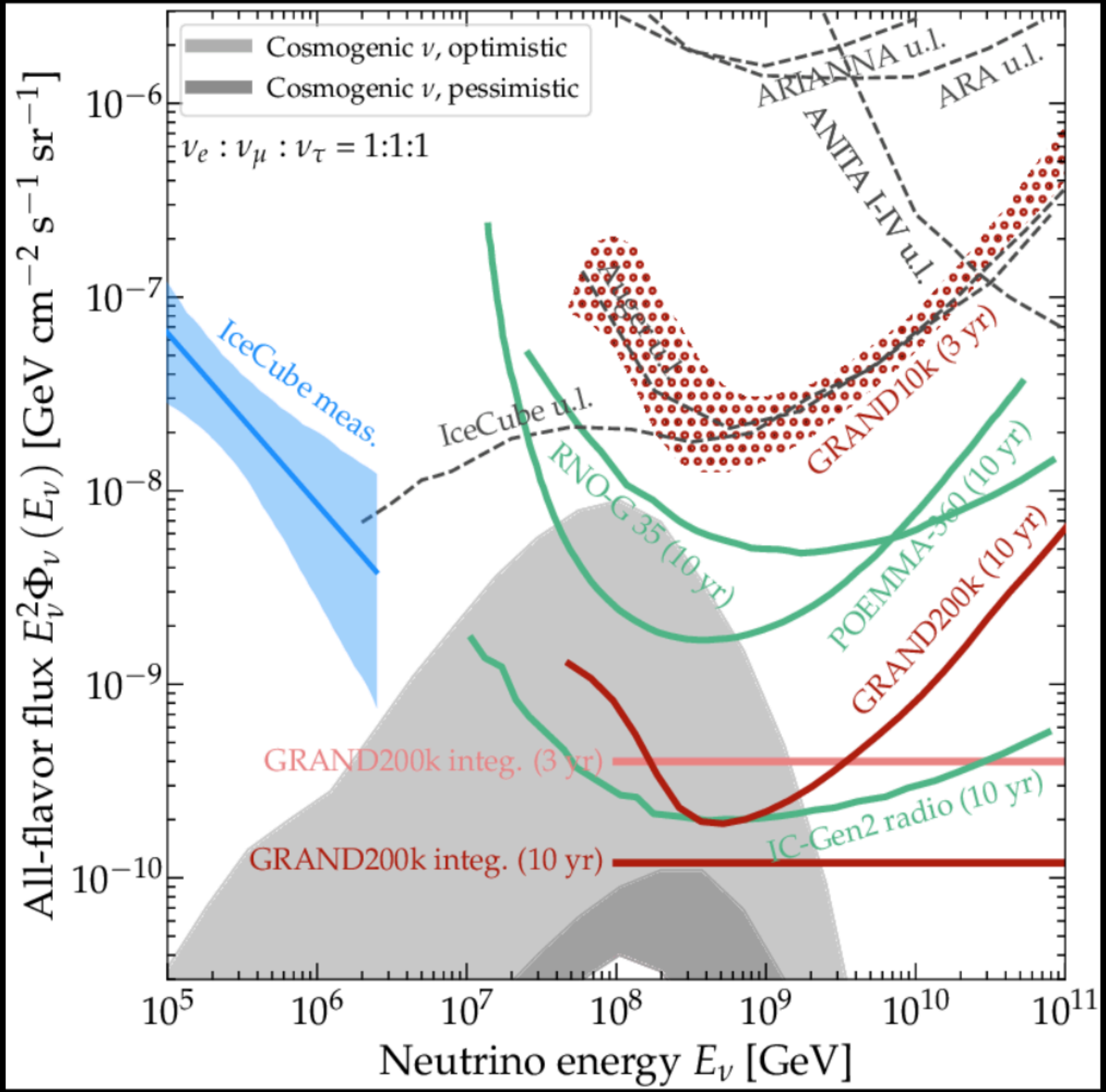
Landscape of experiments — Prospects

ANITA



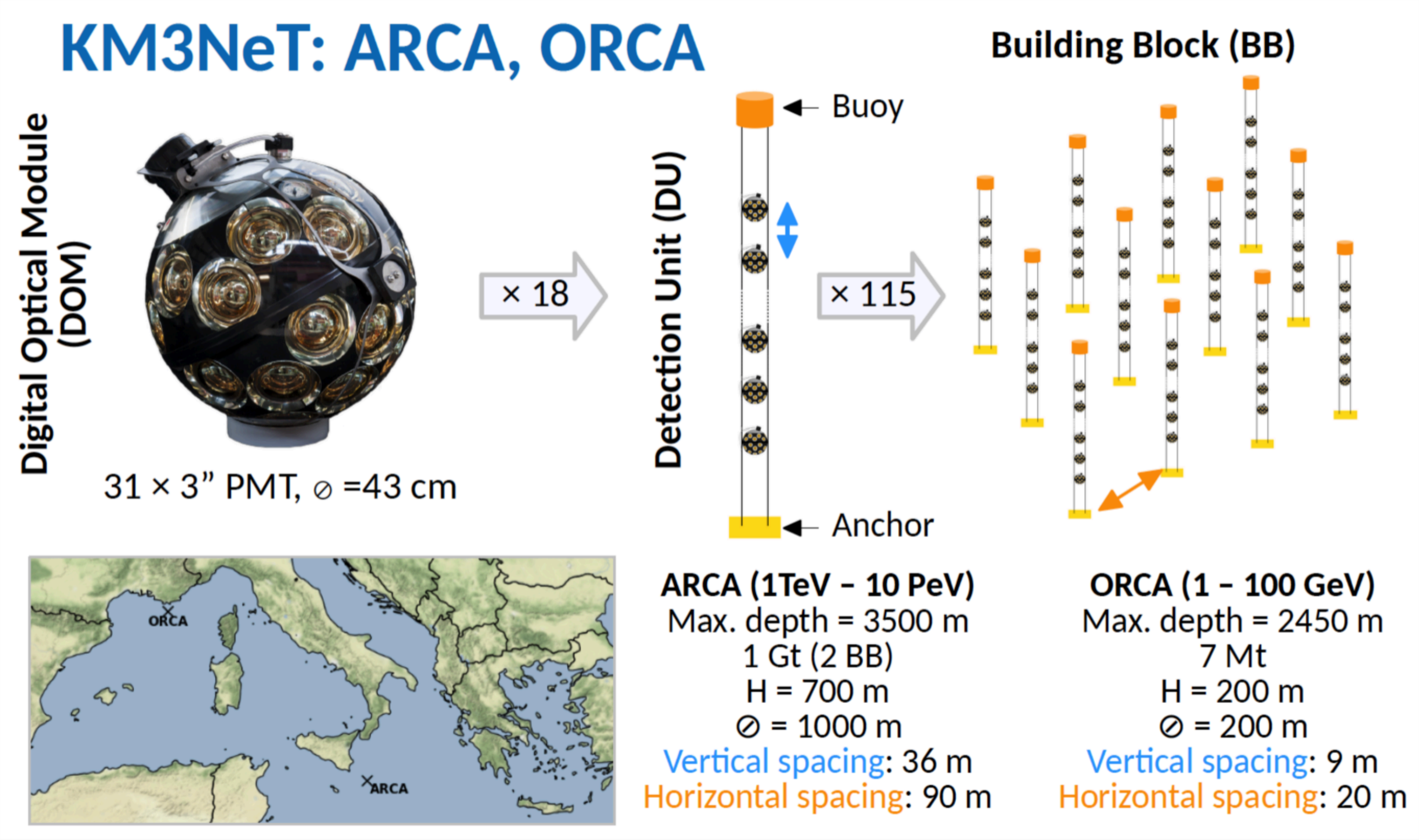
ARIANNA

GRAND antenna



Ackermann et al, *JHEAp* 36 (2022) 55-110

Introduction to KM3NeT

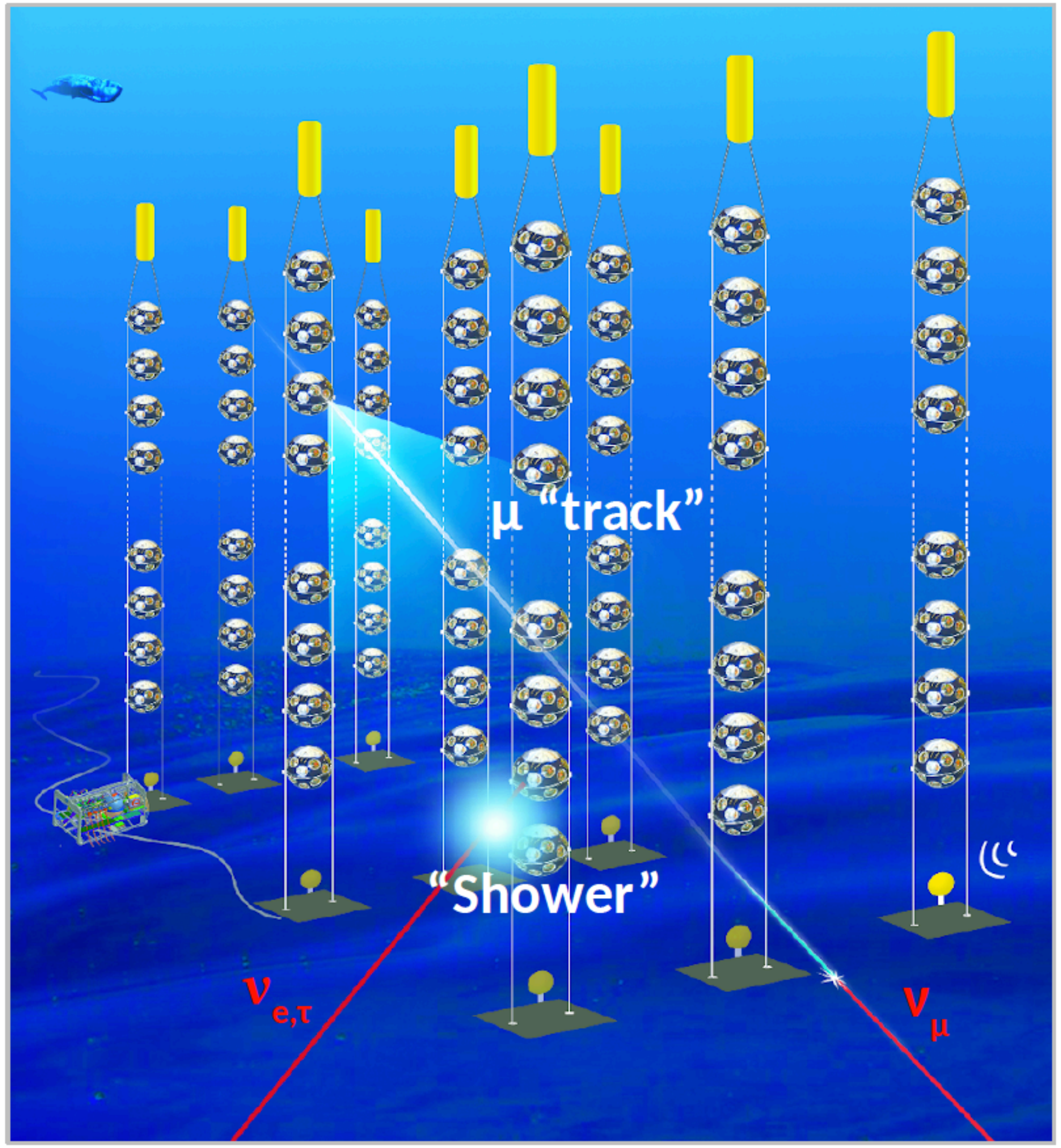


KM3NeT goals

Detect atmospheric and astrophysical neutrinos through Cherenkov effect of the produced
leptons propagating in sea-water.

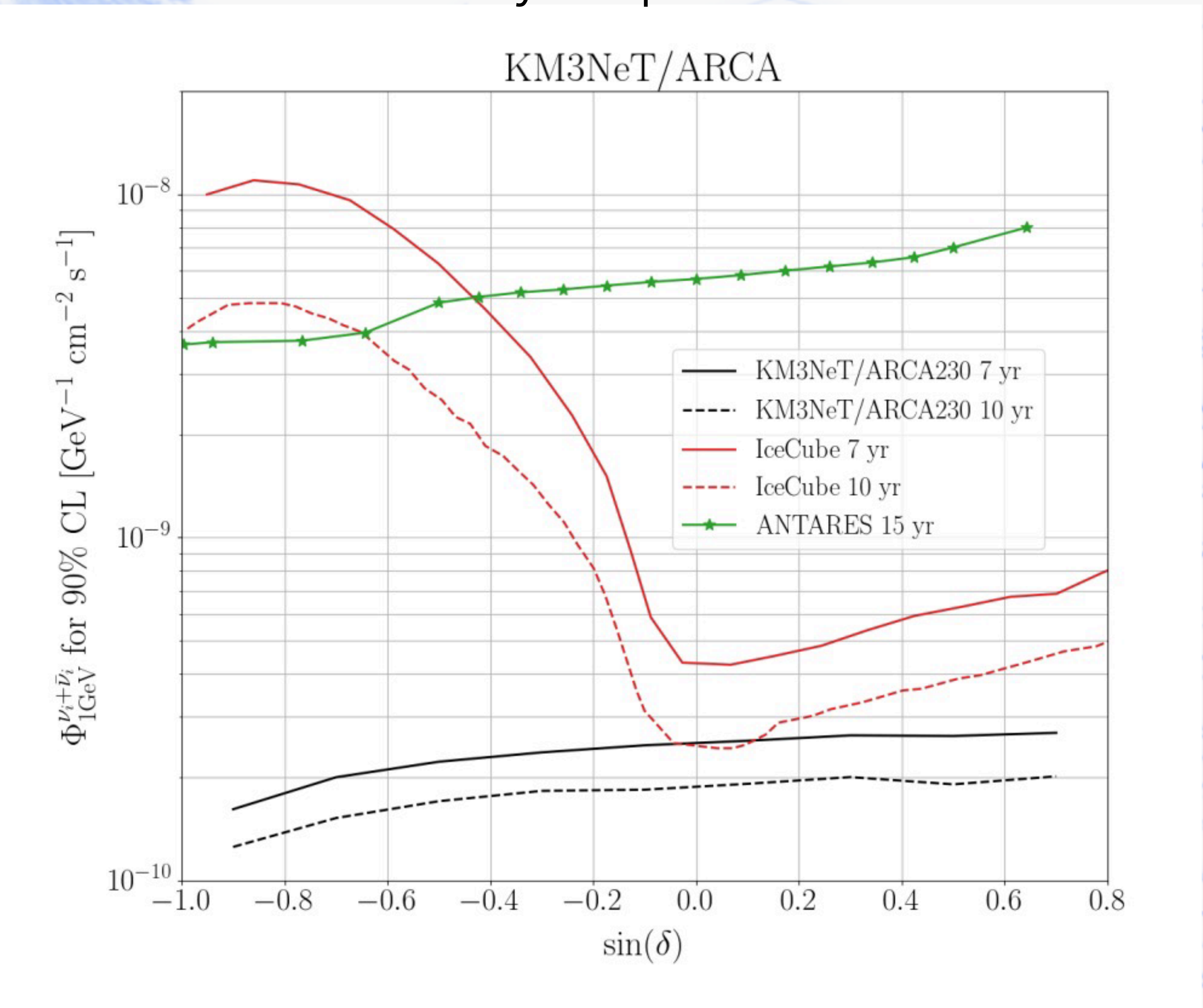
Two main physics goals:

- Oscillations: Neutrino Mass Ordering;
- Astronomy: Astrophysical ν sources;



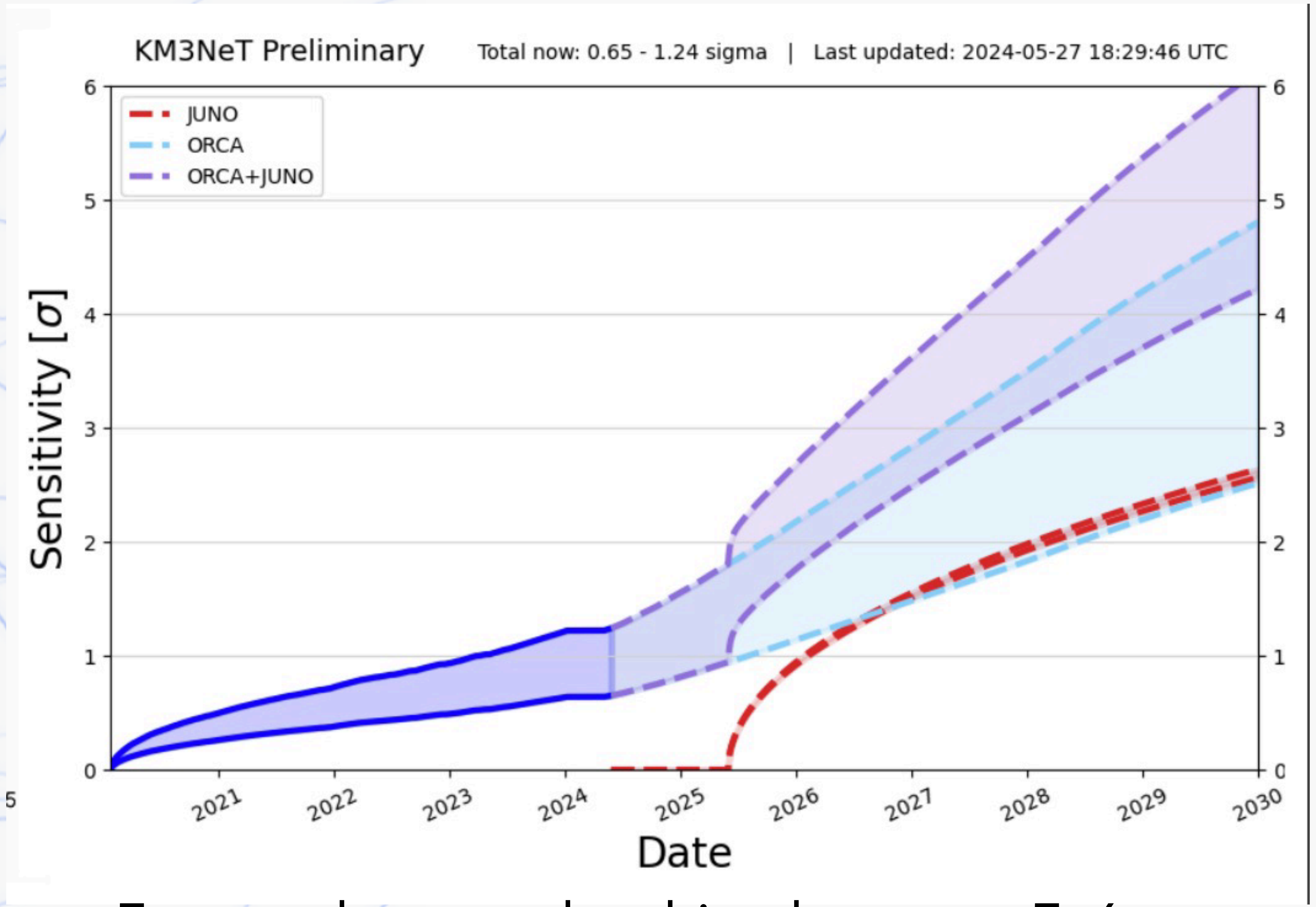
KM3NeT perspectives

ARCA - Sensitivity for point-like searches



Best sensitivity in the Southern Sky

ORCA - Neutrino mass ordering



5σ can be reached in the next 5-6 years if combined with Juno

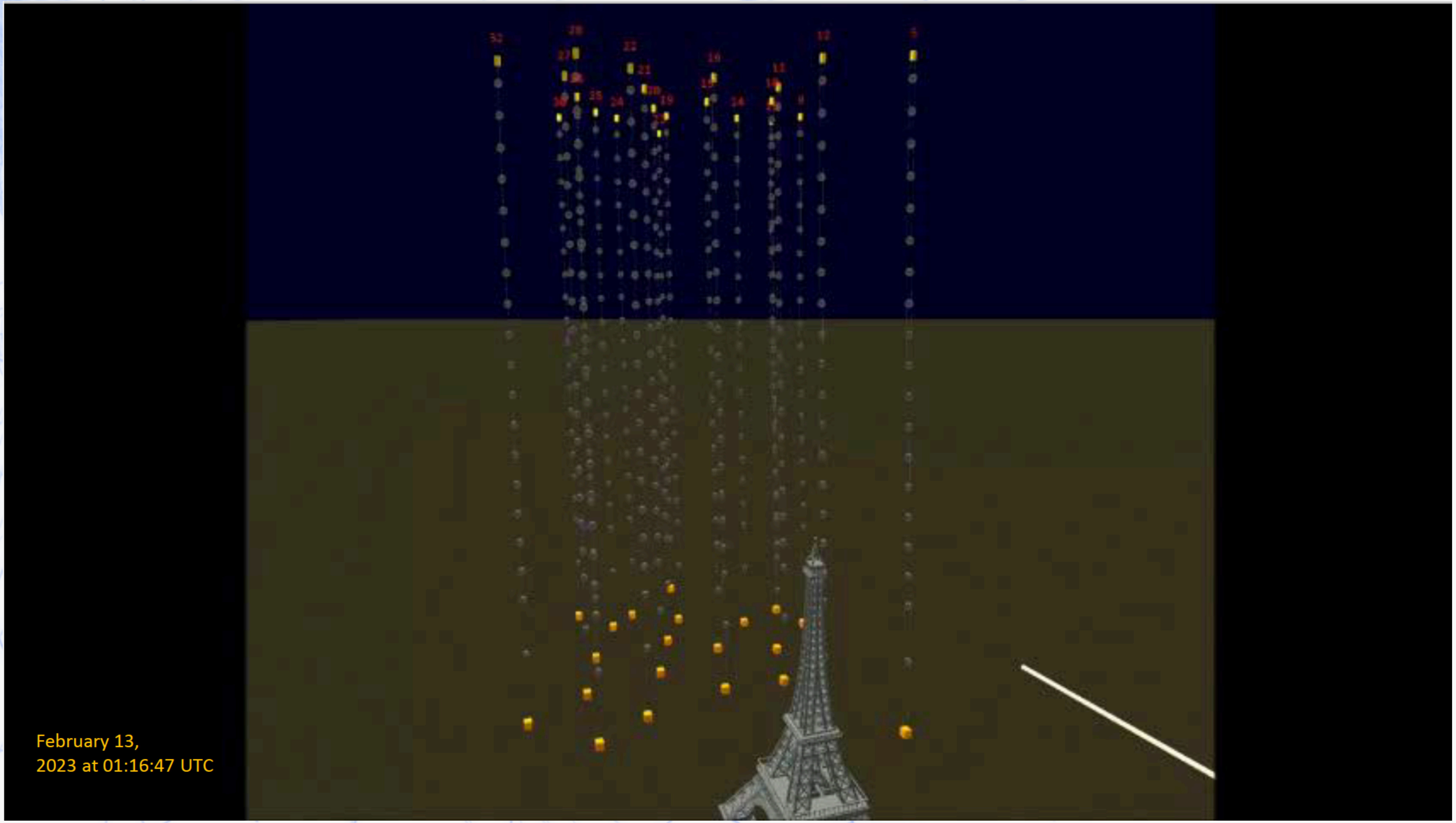
ANTARES decommissioning

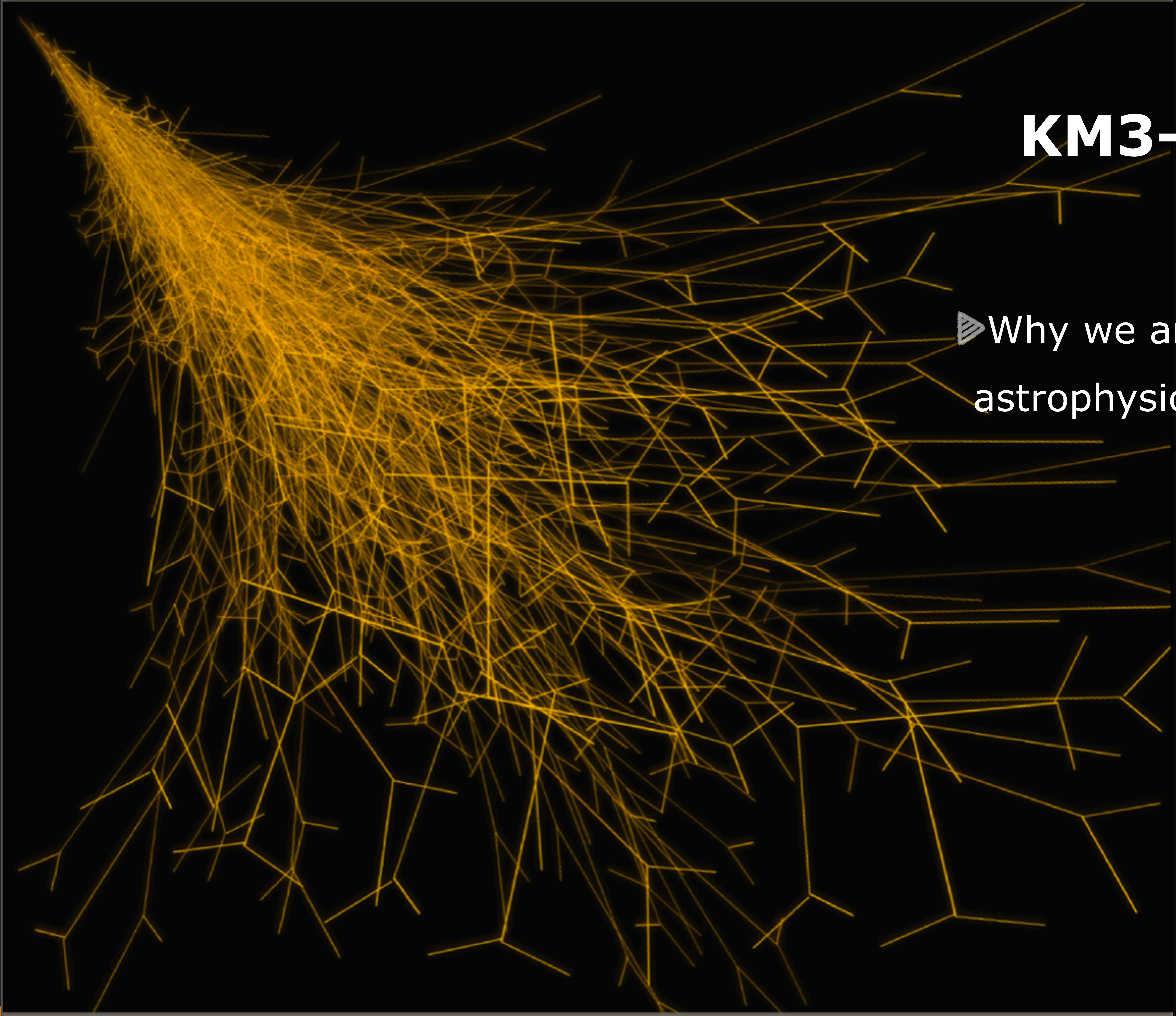
ORCA ARCA completions

The KM3NeT collaboration, https://arxiv.org/abs/2402.08363

J. Brunner @ Neutrino2024

Let's watch the video!



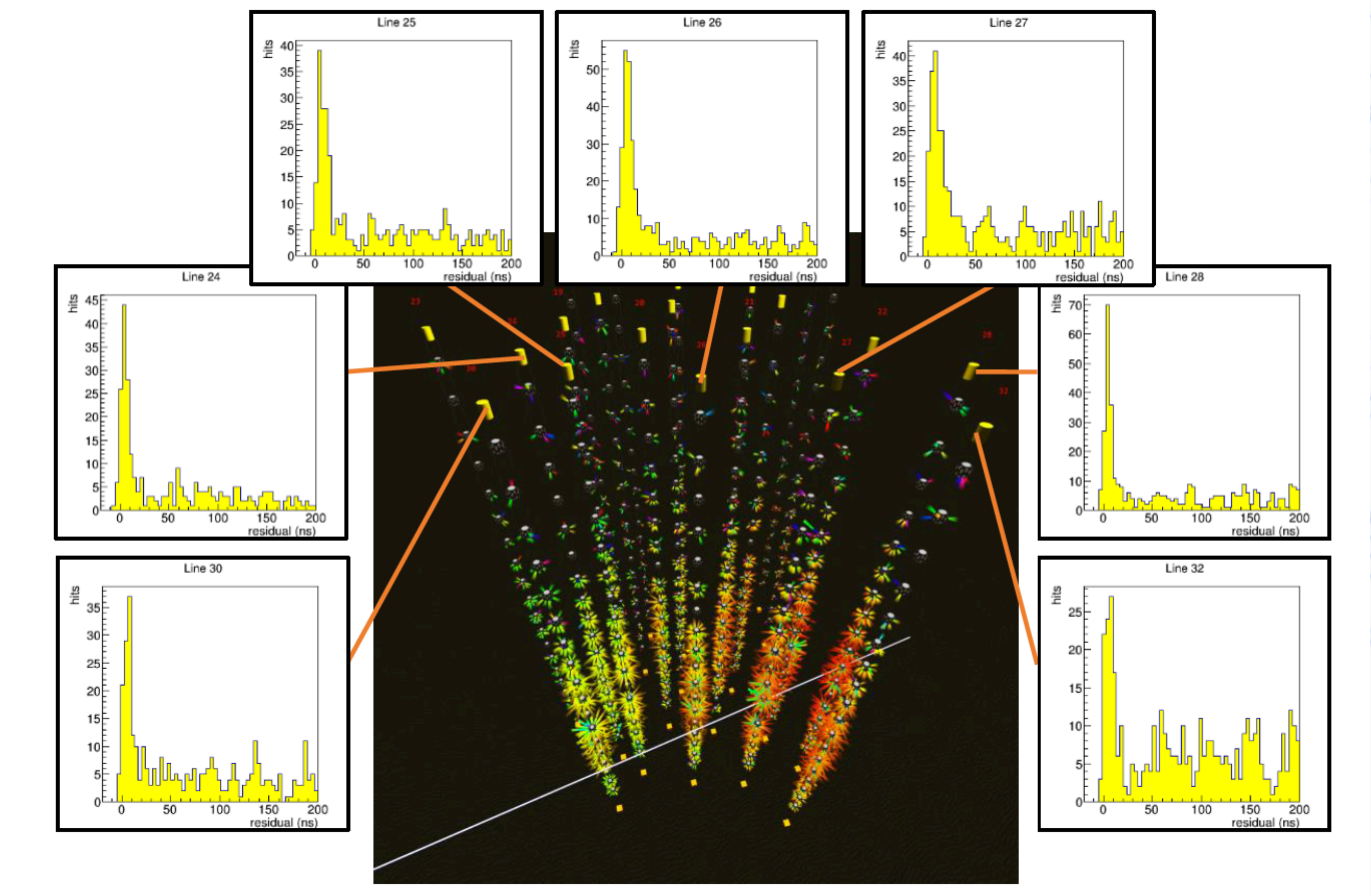


KM3-230213A

- Why we are so sure that this is an astrophysical neutrino?

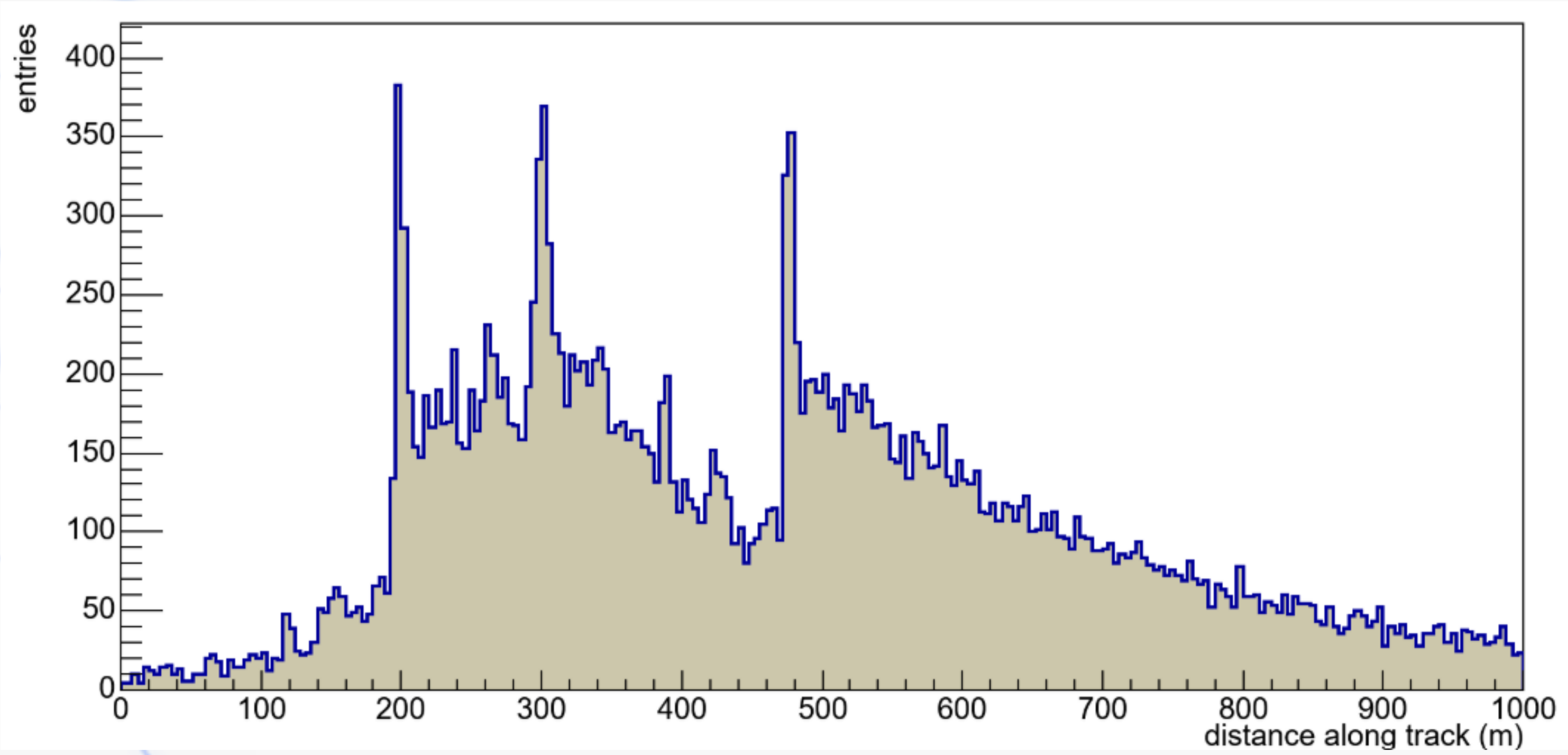
Did not you see a whale?

- Extremely high-quality reconstructed track



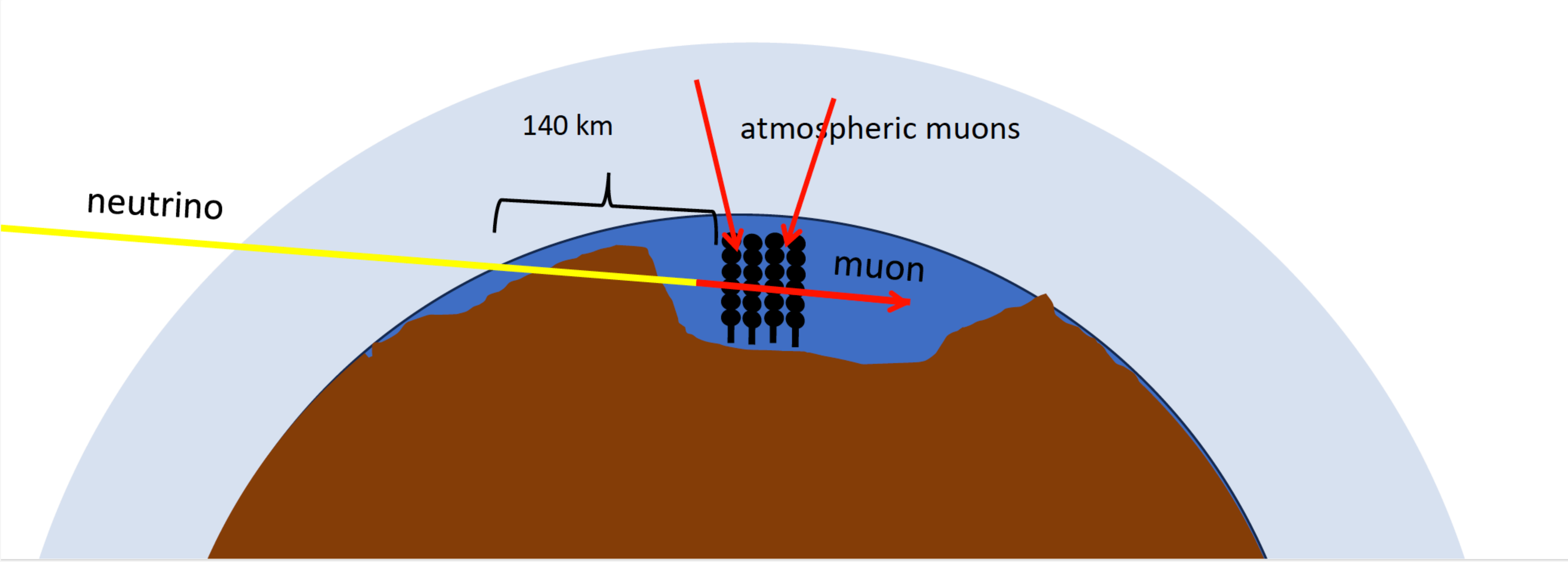
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons

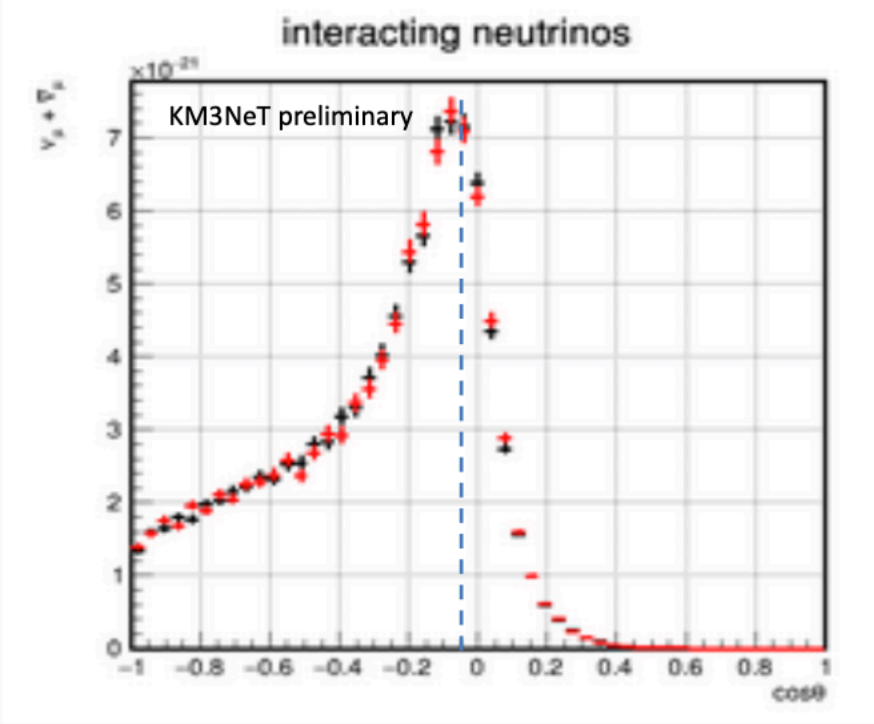
Position of light emission along track consistent with hit time assuming direct light

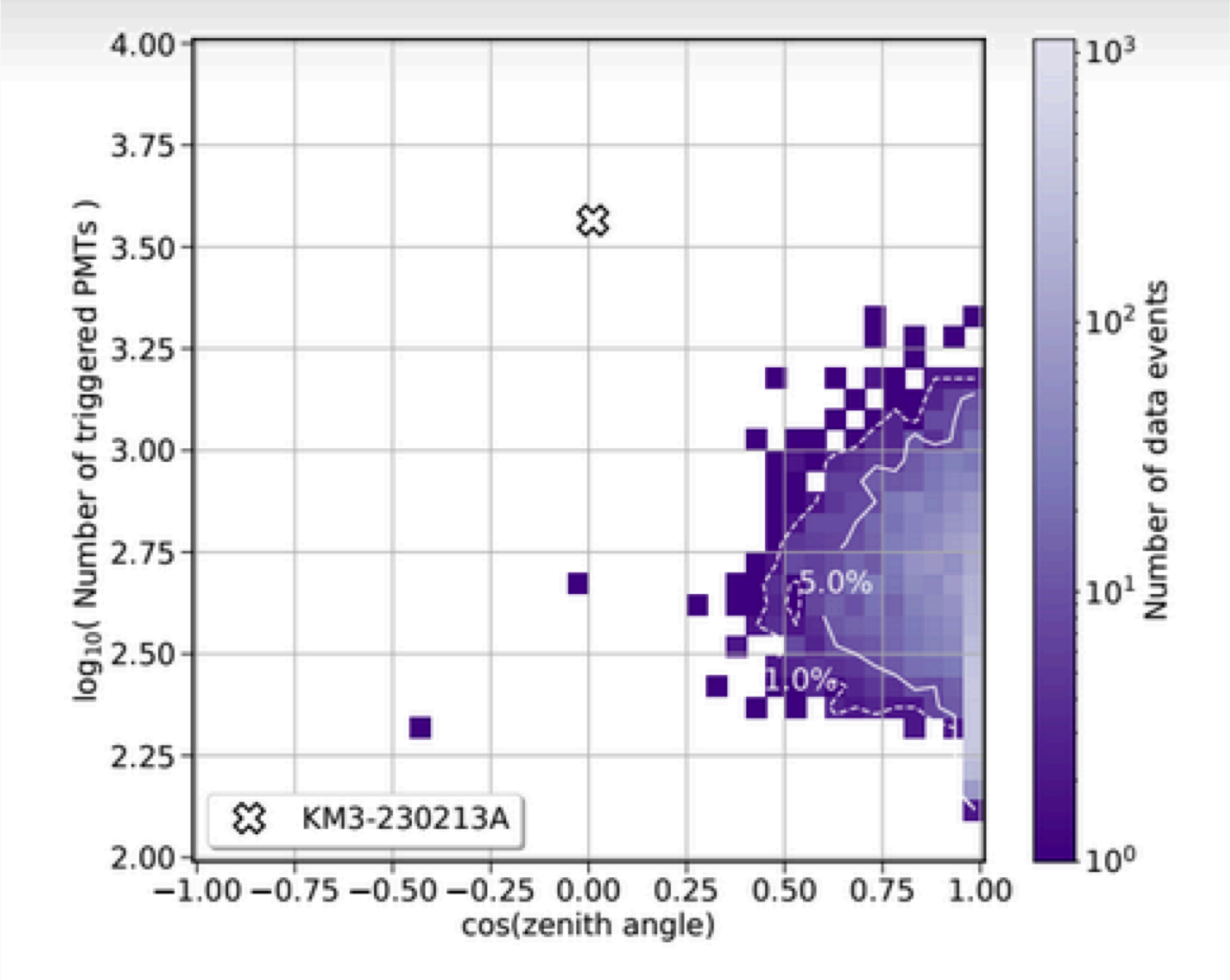


Why it cannot be a muon bundle?

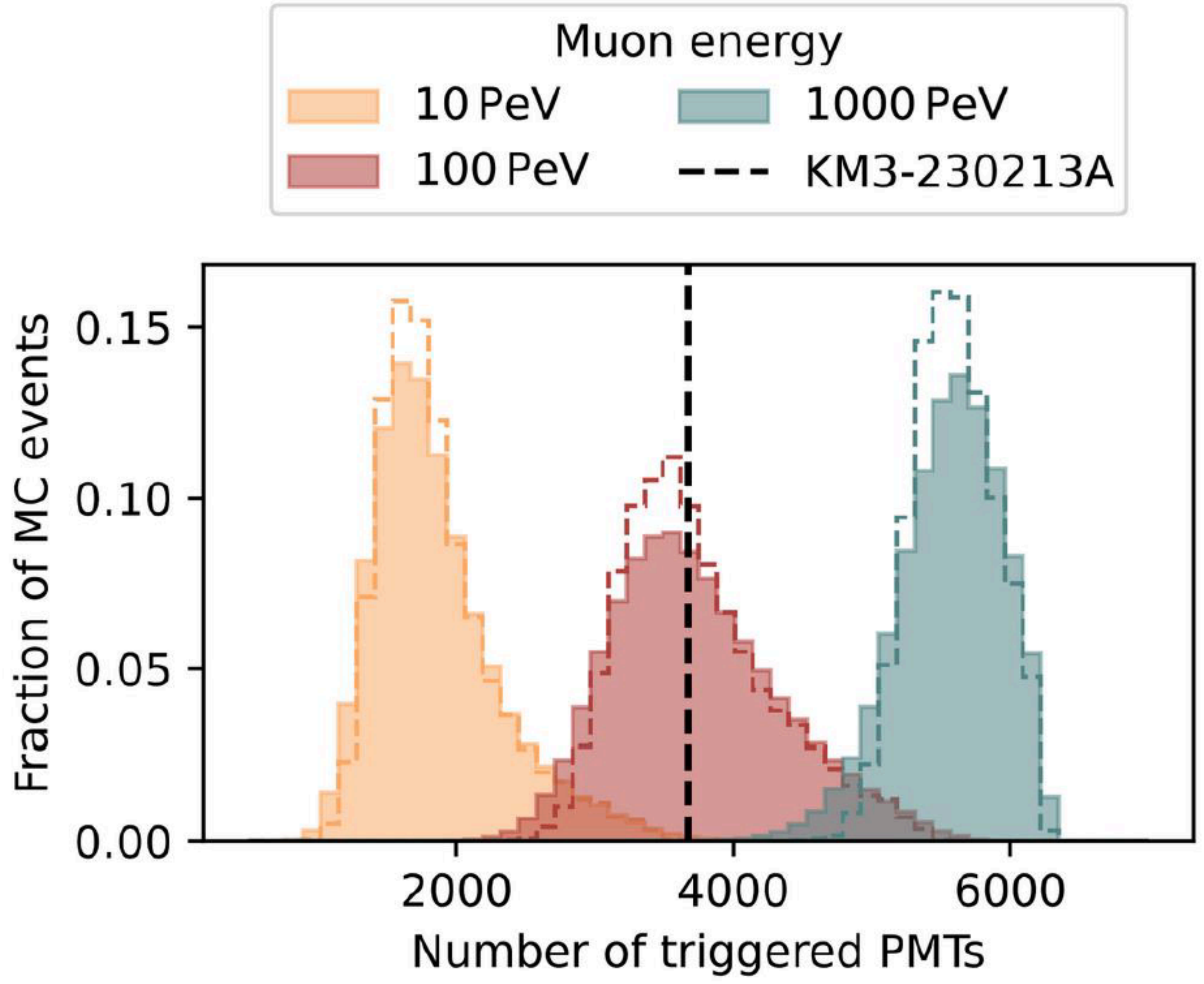
- Very horizontal –> atmospheric muons cannot travel that long







Energy and direction of the event



- Energy is measured from the amount of light:

$$E_\mu = 120^{+110}_{-60} \text{ PeV}$$

(10000 times the energy of the LHC)

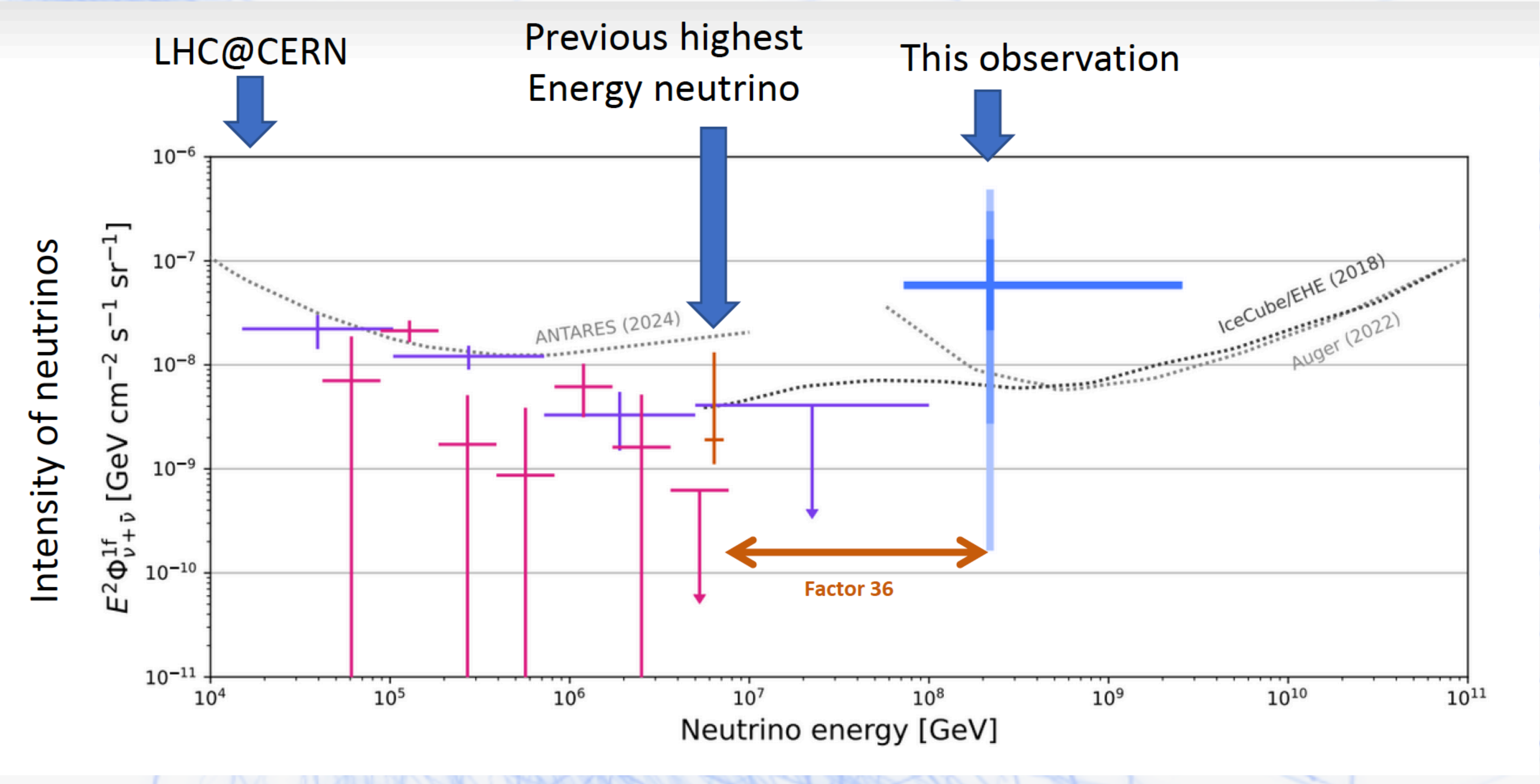
- The neutrino Energy is higher

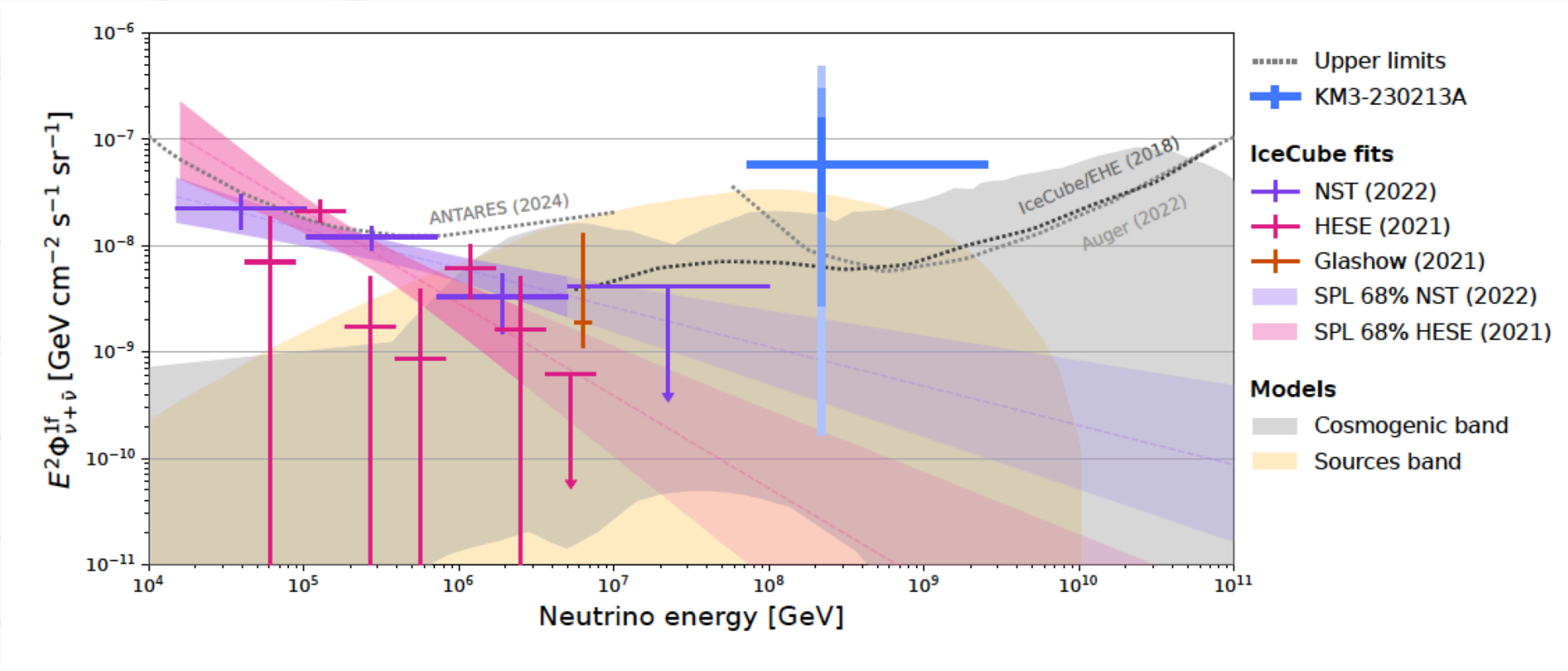
$$E_\nu = 220^{+570}_{-100} \text{ PeV}$$

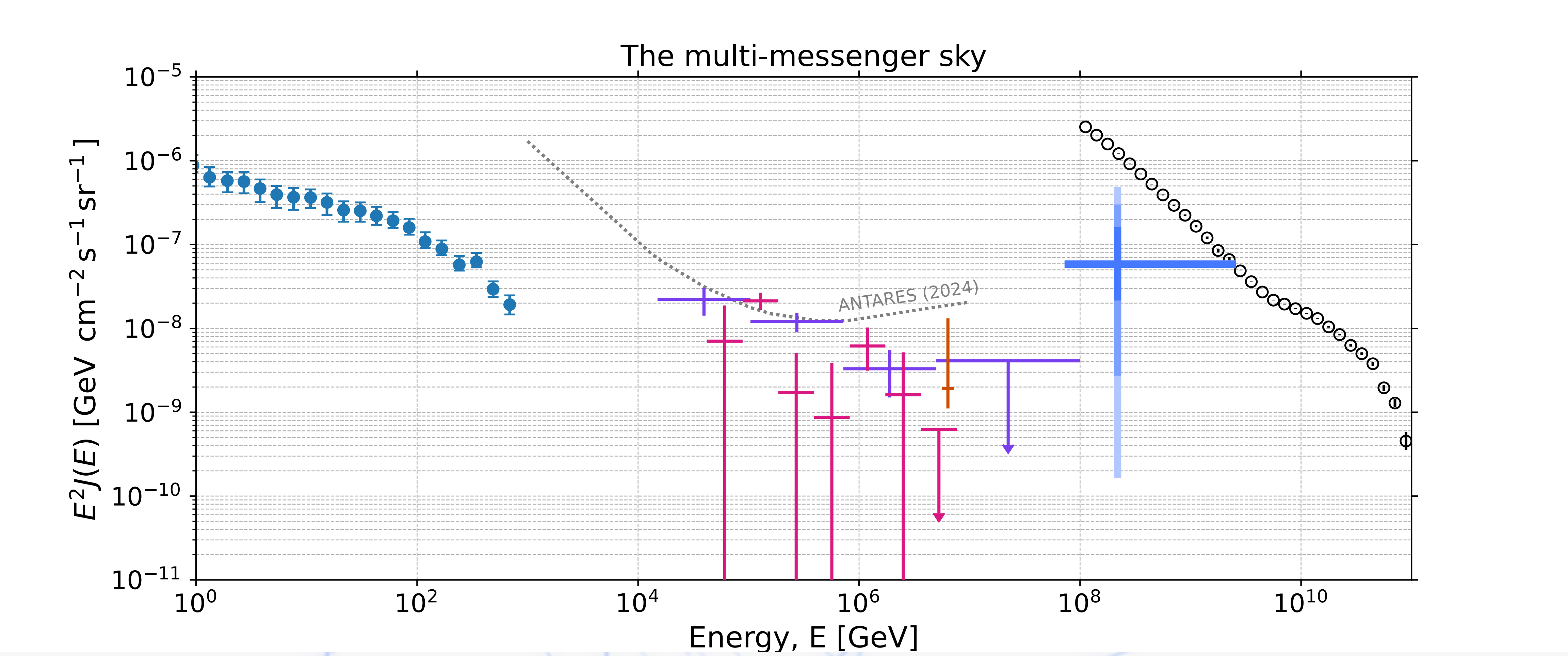
(assuming an E^{-2} source spectrum)

- Approximate celestial Origin: RA = 94.3∘, Dec= −7.8∘ with 1.5 ∘ error circle

Multi-messenger astronomy







Conclusions and final remarks

The UHECRs phenomenology is a mess!

Particles of unknown chemical composition are accelerated through unknown mechanisms by astrophysical objects of uncertain nature with uncertain spatial distribution and temporal evolution, achieving an unknown injection energy spectrum; then they travel through intergalactic space, interacting with photon backgrounds with poorly known energy density at certain wave-lengths, in processes with unknown cross sections for certain channels, and may be deflected by poorly known intergalactic and galactic magnetic fields; then they reach Earth and generate particle cascades in the atmosphere through nuclear interactions whose behaviour is uncertain; finally they are detected by apparatuses with partly uncertain characteristics.

Conclusions and final remarks

In spite of all this, thanks to years of study by hundreds of scientists, there are a few solid results:

- UHECRs are atomic nuclei and most of them are protons or light nuclei except possibly at the highest energies.
- The UHECR energy spectrum is approximately a power law except for an ankle feature at 5 EeV and a cutoff above 40 EeV (with a new feature to be studied).
- Their arrival directions are distributed nearly isotropically, except for a dipole moment.

  Need for a clear-cut understanding of the dynamics inside EG sources: in-source backgrounds and UHECR interactions.

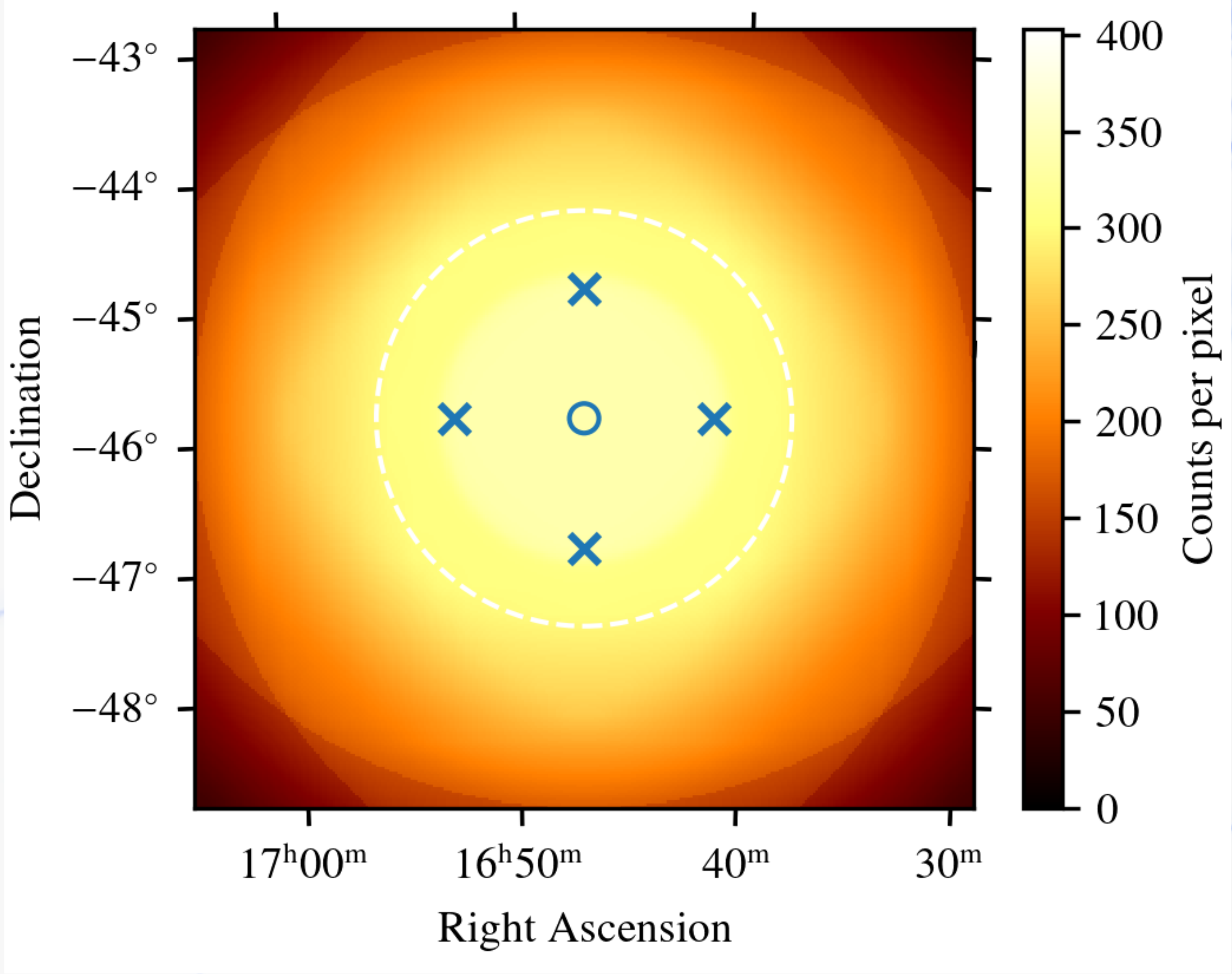
Combining different information is the key to infer something about the astrophysical sources.

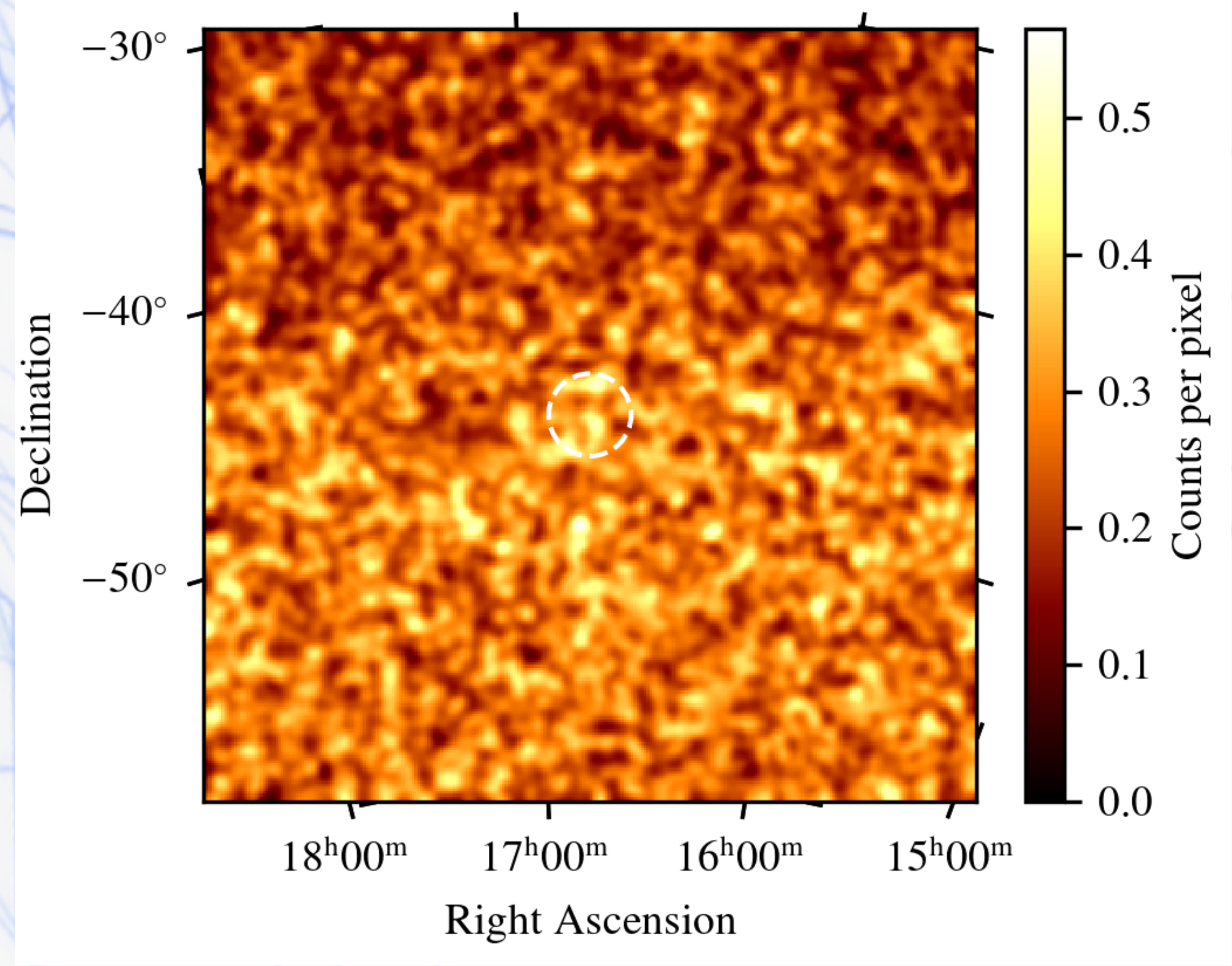
Conclusions and final remarks

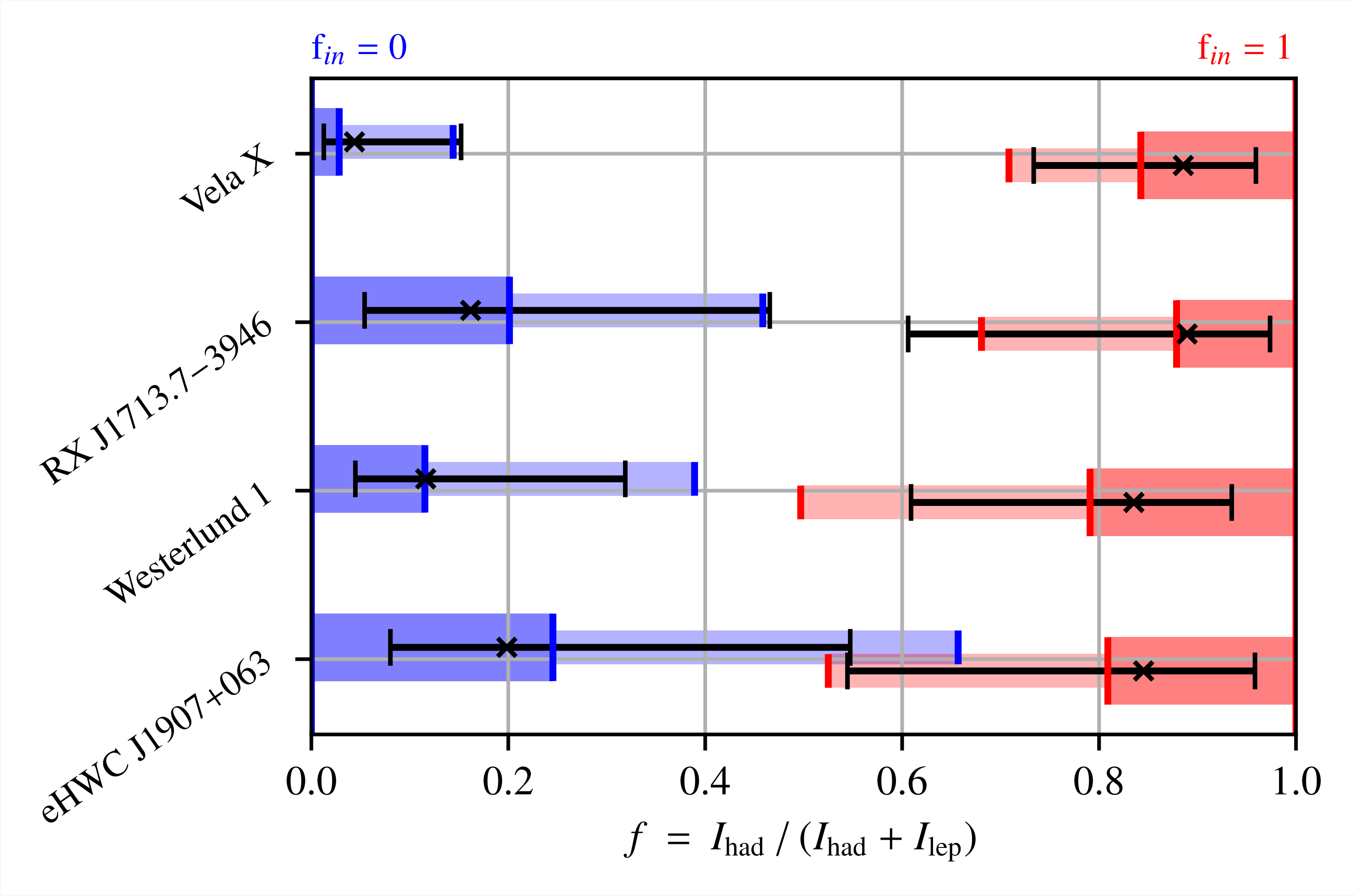
The UHE neutrinos observed by KM3NeT:

- Smoking gun of a UHE accelerator? Maybe transient source?
- Diffuse flux: let's wait to see if the tension with IceCube is real or not!
- In preparation: search for other events in ARCA/ORCA?
- In preparation: differential sensitivity of ARCA21 at the highest energies.

Multi-messenger is the key!



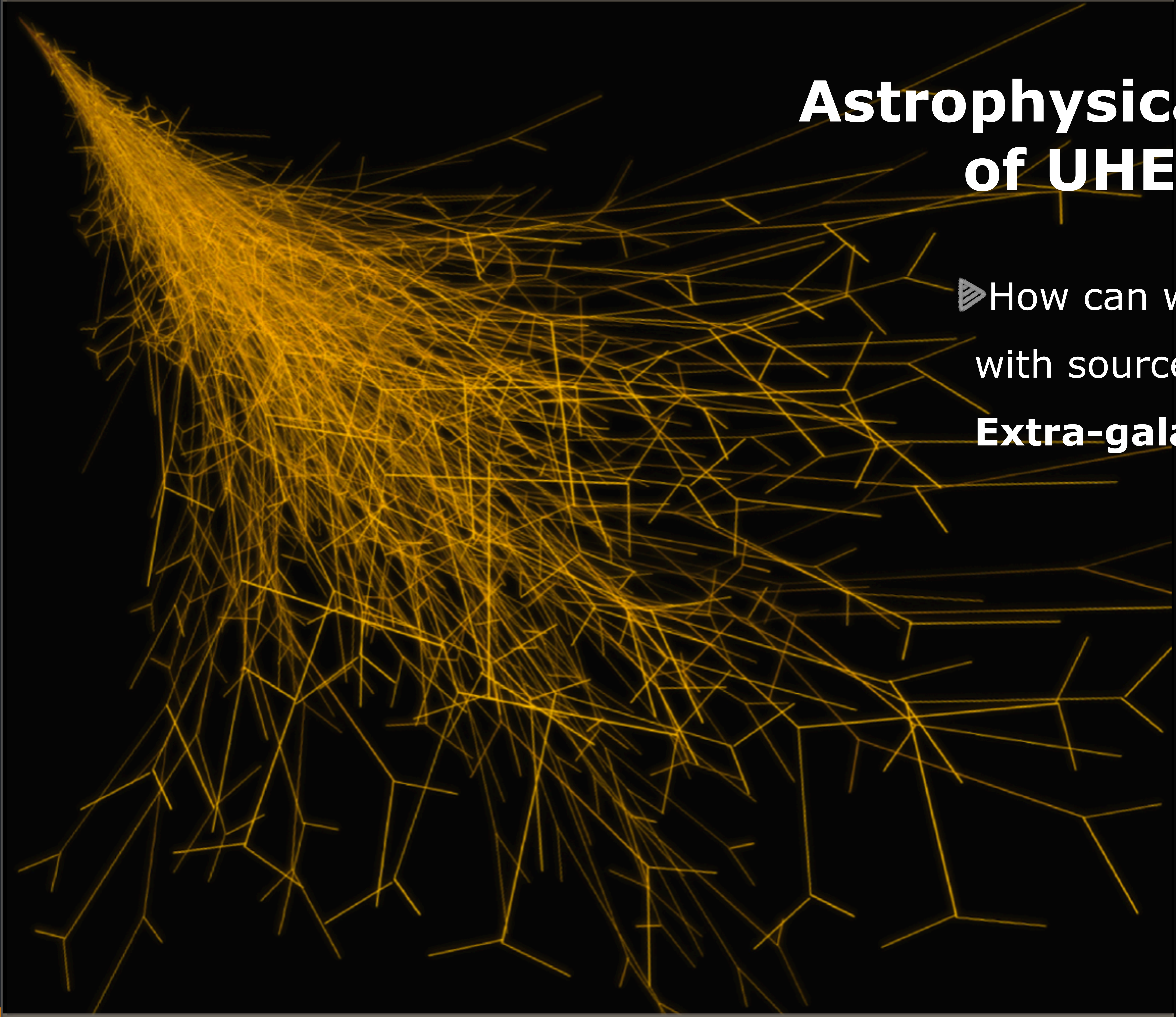




Conclusions and final remarks

Thanks for your attention!


Source
Universe
Earth
p
ν



Astrophysical interpretation of UHECR sources

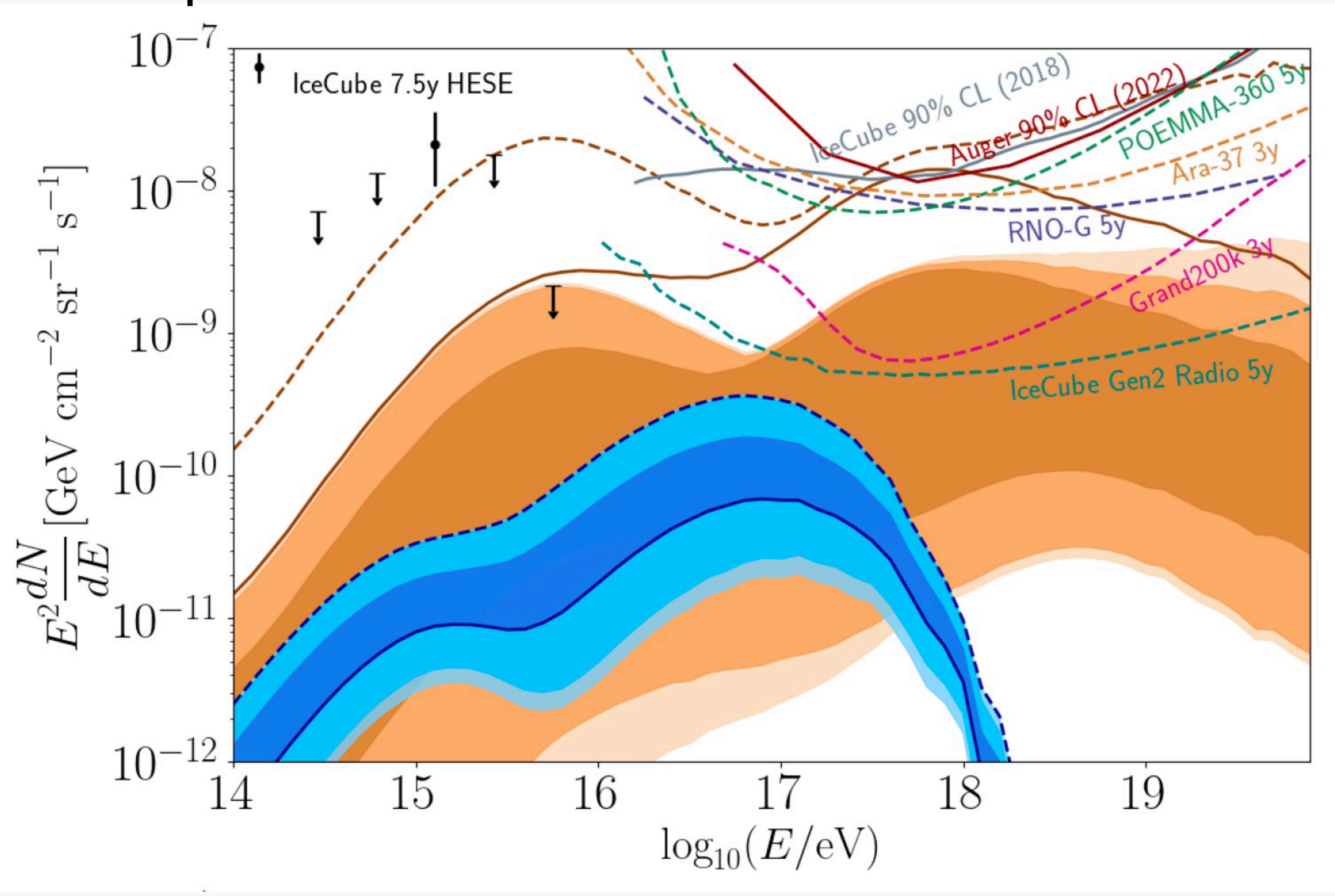
- How can we connect features at Earth with source parameters?

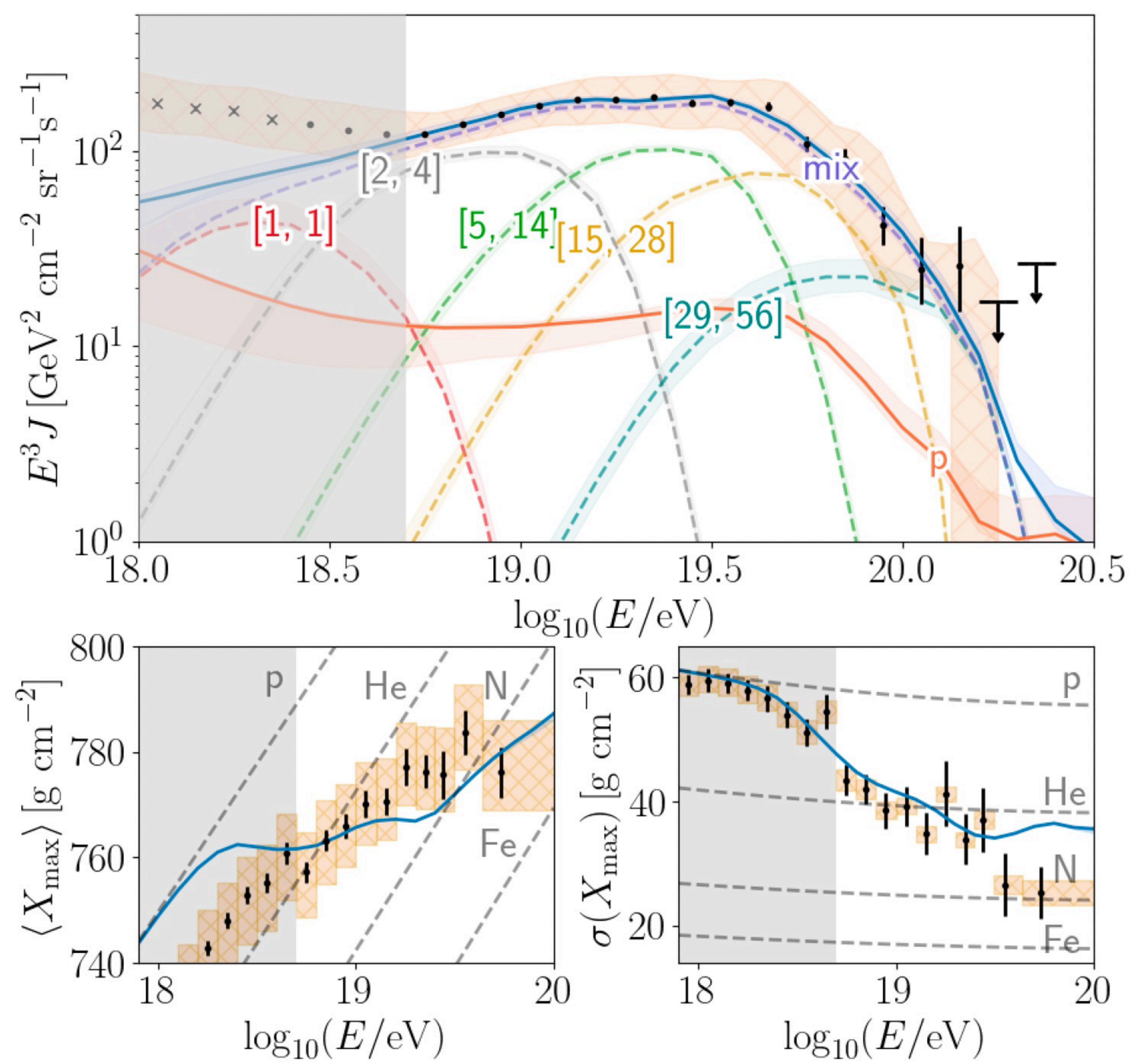
Extra-galactic Propagation

Cosmogenic neutrinos

Cosmogenic neutrino prediction from fit to UHECR flux

- Depends on extrapolation for z>1 (UHECRs not sensitive there!)
- No cosmogenic neutrinos in minimal scenario;
- Strong evolution and proton component –> boost in neutrino production!





Ehlert, van Vliet, Oikonomou, Winter, JCAP 02 (2024) 022;

ntify a charge particle?

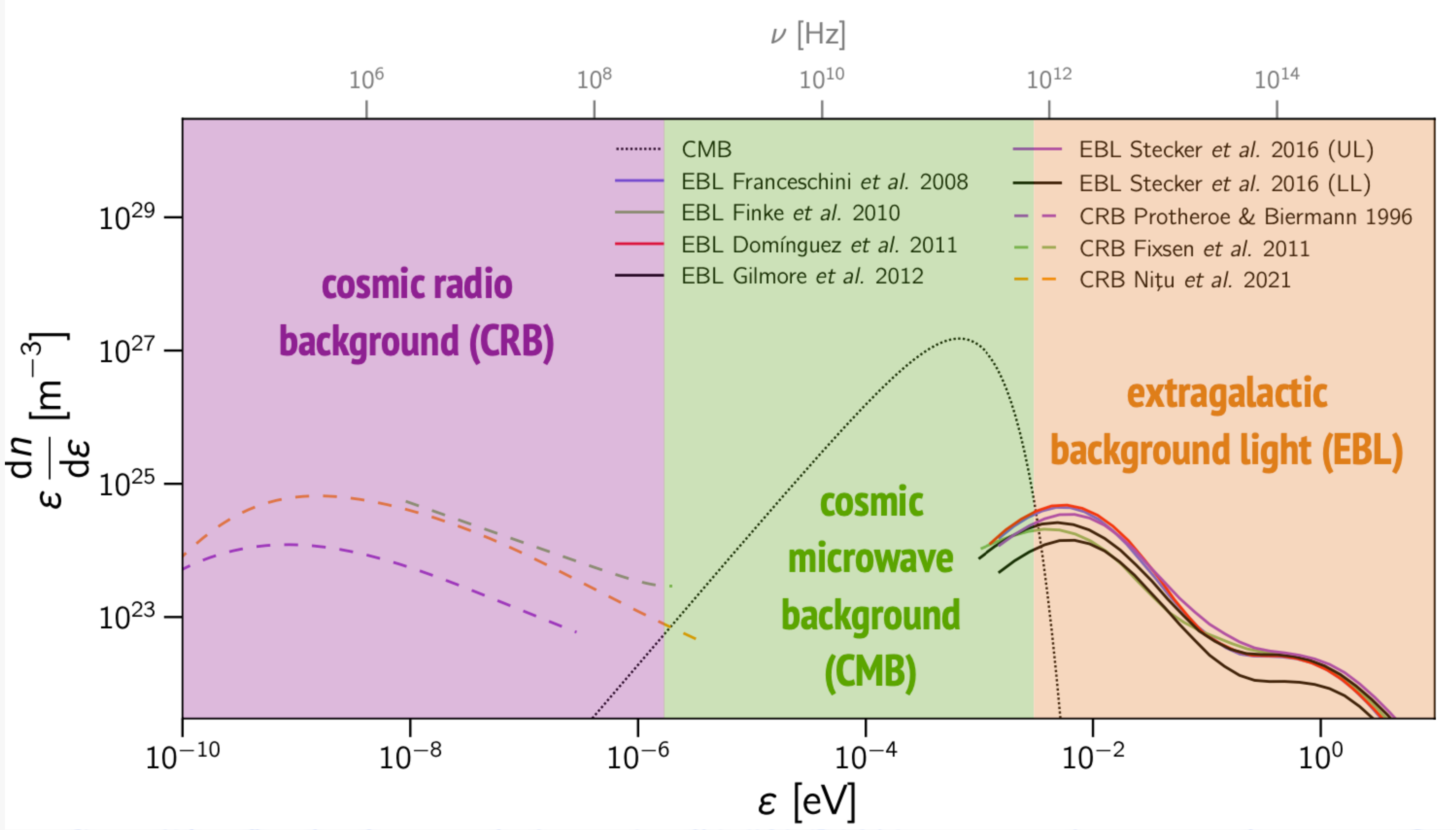
- Where:
  - z: Charge of the incident particle (in units of elementary charge e).
  - e: Elementary charge.
  - n: Number density of electrons in the material.
  - m: Mass of the electron.
  - v: Velocity of the incident particle.
  - B: Factor accounting for material properties (related to ionization potential and density).
  - Z: Atomic number of the medium.
  - I: Mean excitation potential of the medium.
  - $\beta = v/c$: Relativistic beta.

Simplification: Neglecting the dependence of B on E (the energy of the incident particle), we can see a simplified proportionality:

dxdE ∝v2Z2 ∝EZ2A dx

- **Key Implication:** For a fixed thickness dx, the energy loss dE depends directly on Z2 (the square of the particle's charge) and A (the mass number of the medium), and inversely on its ener

UHECR interactions



Extra-galactic photon fields:

$\varepsilon_{CMB} \simeq$ 0.1 meV

$\varepsilon_{IR} \simeq$ 10 meV

$\varepsilon_{OPT} \simeq$ 1 eV

Background photons can trigger interactions with the very high energy cosmic rays !

UHECR interactions

Reference frame of the photon field

$$E_{CR} \sim 1\,\mathrm{EeV}, \quad \epsilon \sim 1\,\mathrm{meV}$$

→ Lorentz boost

Reference frame of the CR

$$E'_{CR} \sim m_p$$

$$\epsilon' \sim \Gamma\epsilon(1 - \cos\theta) < 2\Gamma\epsilon$$

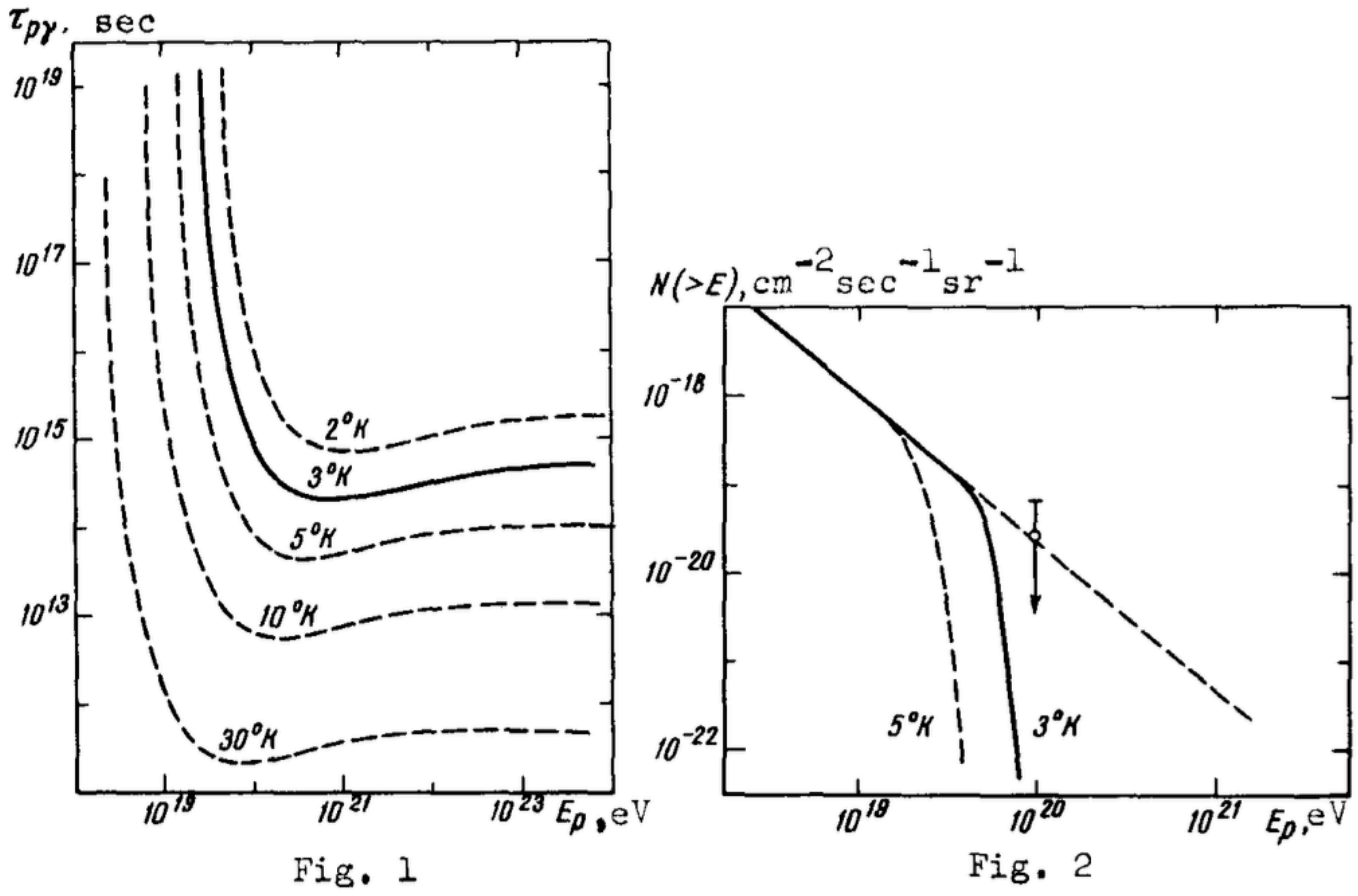
Because of the Lorentz boost a low energy photon appears as a high energy gamma ray

Interaction rate

$$\tau^{-1}(\Gamma) = \frac{c}{2\Gamma^2}\int_{\epsilon'_{\mathrm{th}}}^{\infty} \epsilon'\sigma(\epsilon')\int_{\epsilon'/2\Gamma}^{\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon\, d\epsilon'$$

Primed quantities in the reference frame of the CR, unprimed quantities in the reference frame of the photon field

GZK effect



K. Greisen. Phys. Rev. Lett. 16 (1966)
G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4 (1966)

Pion production in photohadronic interactions with CMB photons

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

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

Proton energy:

$$E_p = \frac{(m_\pi + m_p)^2 - m_p^2}{2\epsilon(1 - \cos\theta)}$$

Threshold:

$$E_p^{\text{th}} = \frac{2m_\pi m_p + m_\pi^2}{4k_B T} \sim 7 \cdot 10^{19}\,\text{eV}$$

UHECR interactions

- Pair production

$$p + \gamma \rightarrow p + e^+ + e^-$$

$$E_p^{\mathrm{th}} \sim 2.5 \cdot 10^{18}\,\mathrm{eV}$$

- Photodisintegration

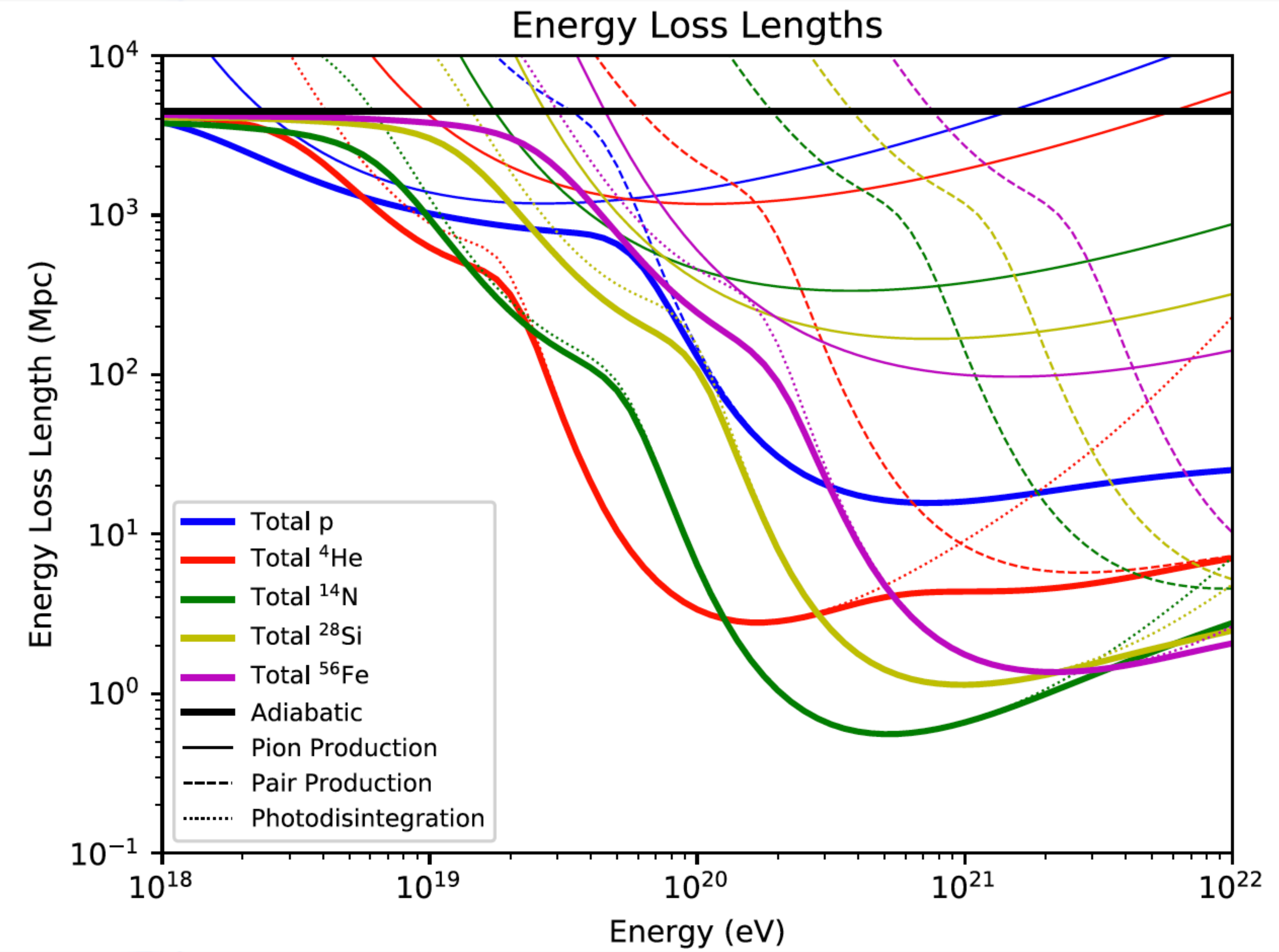
$$(A, Z) + \gamma \rightarrow (A - n, Z - m) + nN$$

- Adiabatic

$$-\frac{1}{E}\frac{dE}{dt} = H_0$$

- Nuclear decay

$$\tau = \Gamma \tau_0$$



UHECR interactions

UHECRs propagate over cosmological distances Background photon fields are not static, but evolve with redshift

Cosmological expansion:

$$n_\gamma(\epsilon, z) = (1+z)^2 n_\gamma\left(\frac{\epsilon}{1+z}\right) \quad \longrightarrow \quad \tau^{-1}(\Gamma, z) = (1+z)^3 \tau^{-1}((1+z)\Gamma)$$

Astrophysical feedback:

$$n_\gamma(\epsilon, z) = (1+z)^2 n_\gamma\left(\frac{\epsilon}{1+z}, z\right) \quad \longrightarrow \quad \text{Numerical integration}$$

Extra-galactic magnetic field

UHECRs are charged particles and they are deflected by magnetic fields.
The extra-galactic magnetic field is purely known in both strength and structure

Statistically uniform field:

The magnetic field has the same statistical properties everywhere and it can be characterised by two parameters *Brms* , *λcoh*

Structured field:

The magnetic field has been obtained with constrained cosmological simulations of the evolution of the local Universe The strength and the structure of the field depend on the simulation parameters

UHECR interactions

Energy loss equation:

$$-\frac{1}{E}\frac{dE}{dt} = \frac{c}{2\Gamma^2}\int_{\epsilon'_{\rm th}}^{\infty} \epsilon'\nu(\epsilon')\sigma(\epsilon')\int_{\epsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\epsilon)}{\epsilon^2}d\epsilon\, d\epsilon' = \beta(E)$$

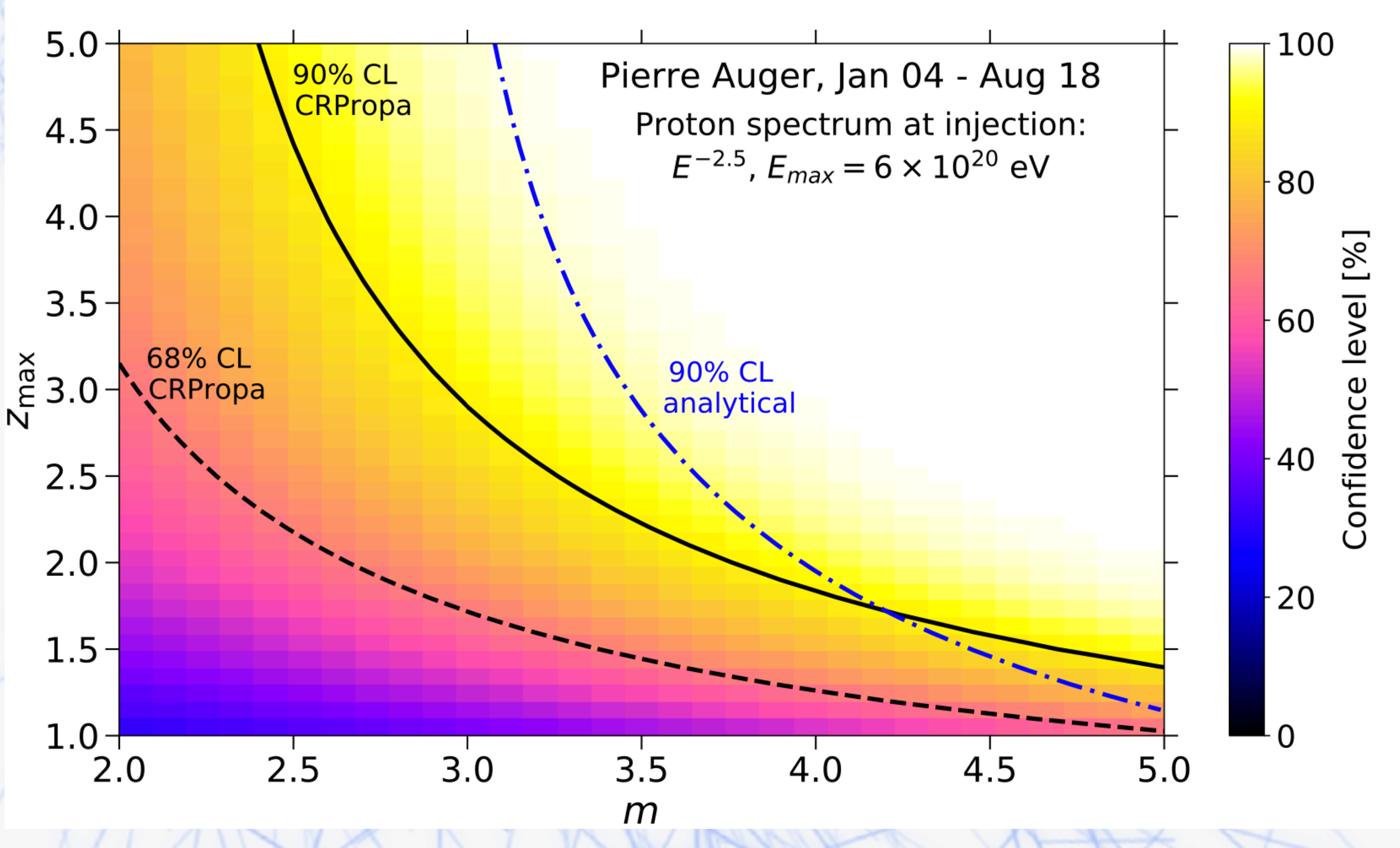
Adiabatic expansion:

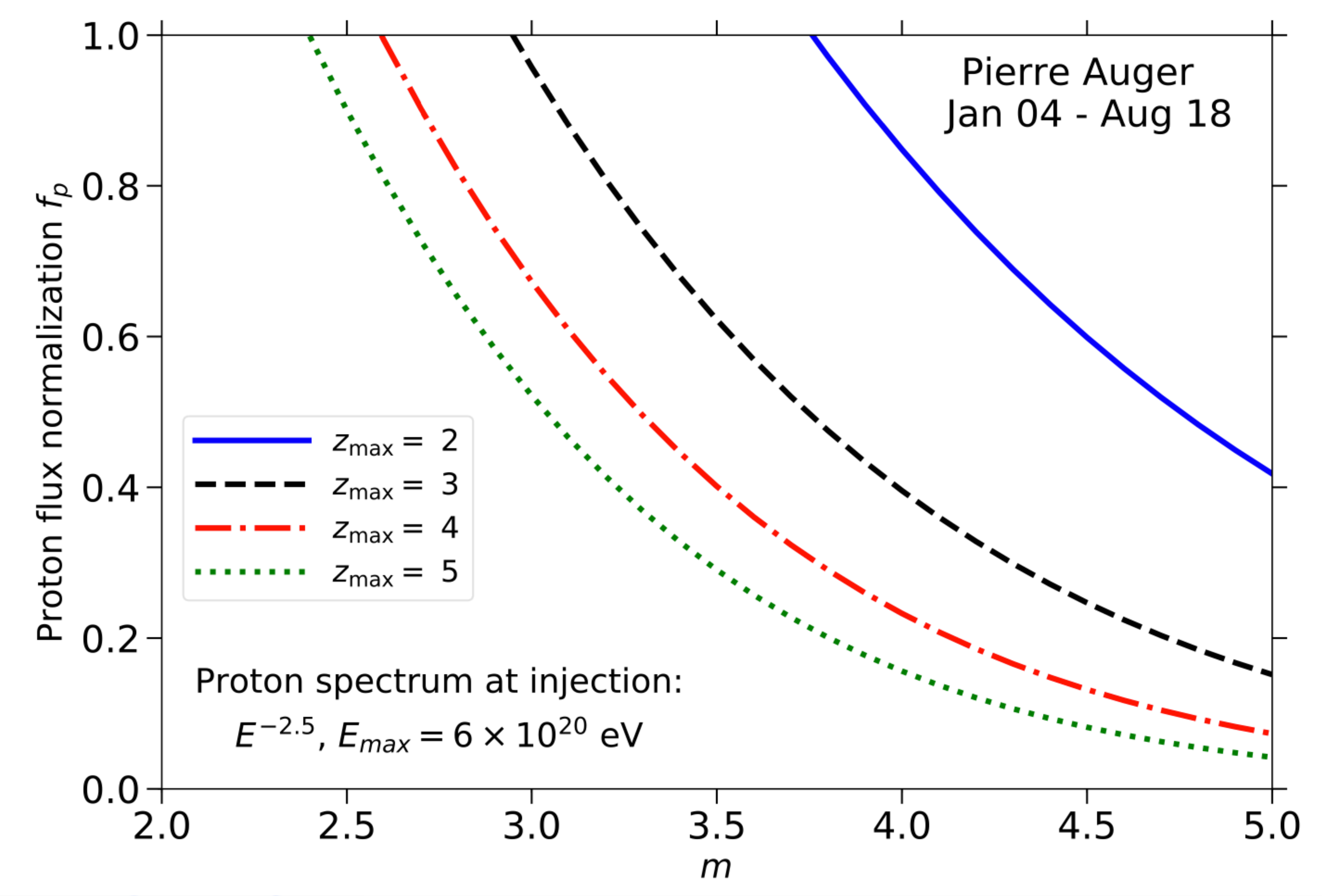
$$\frac{1}{E}\frac{dE}{dt} = \beta(E,t) + H(t), \quad \beta(E,t) = \sum_{\rm int}\beta_i(E,t)$$

Redshift evolution:

$$\left(\frac{dt}{dz}\right)^{-1} = -(1+z)H(z), \quad H(z) = H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

UHECR interactions



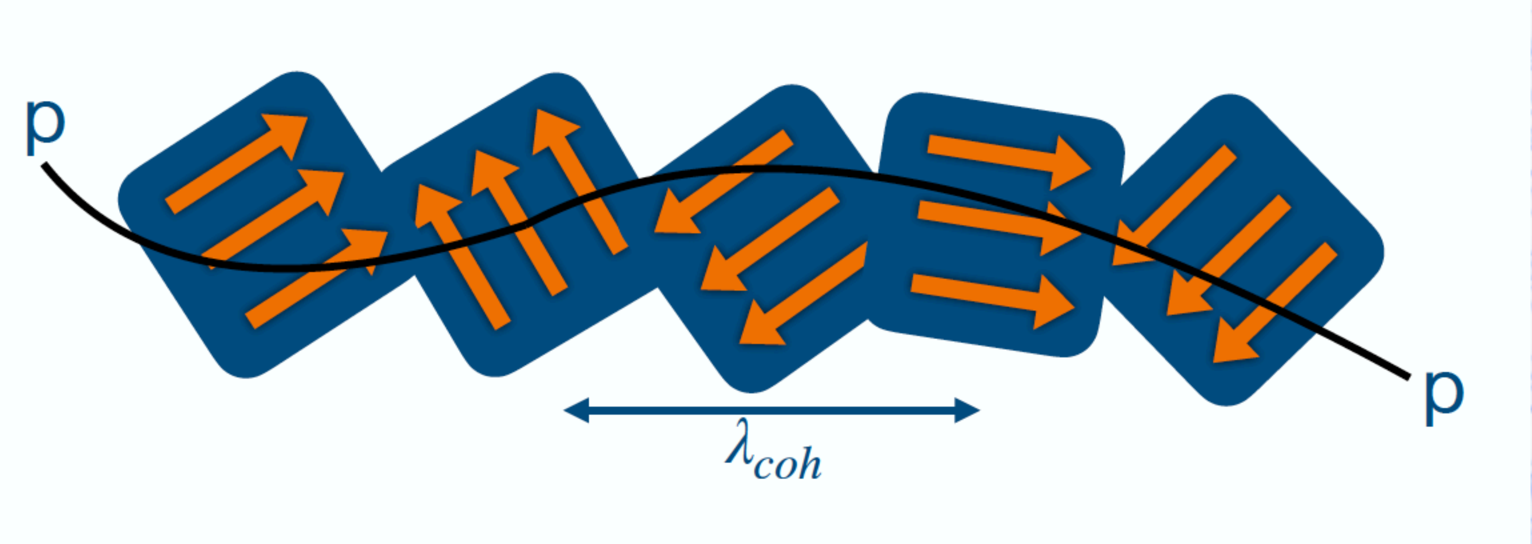


Energy spectrum, mass composition and neutrinos can constrain **source evolution** and **proton fraction**!

A. Condorelli, The Pierre Auger Collaboration, Winter, JCAP 10 (2019) 022

Extra-galactic magnetic field

UHECRs are charged particles and they are deflected by magnetic fields.
The extra-galactic magnetic field is purely known in both strength and structure



The average deflection angle can be obtained by modelling the magnetic field as a series of regions with the same magnetic field strength, but different orientation

Larmor radius

$$r_L(E) = \frac{E}{q\ B} \sim 100 \left(\frac{E/Z}{10^{20}\,eV}\right)\left(\frac{1\,\mu G}{B}\right) kpc$$

Deflection angle

$$\alpha_{\lambda_{coh}} \sim \frac{\lambda_{coh}}{r_L}$$

Total deflection angle

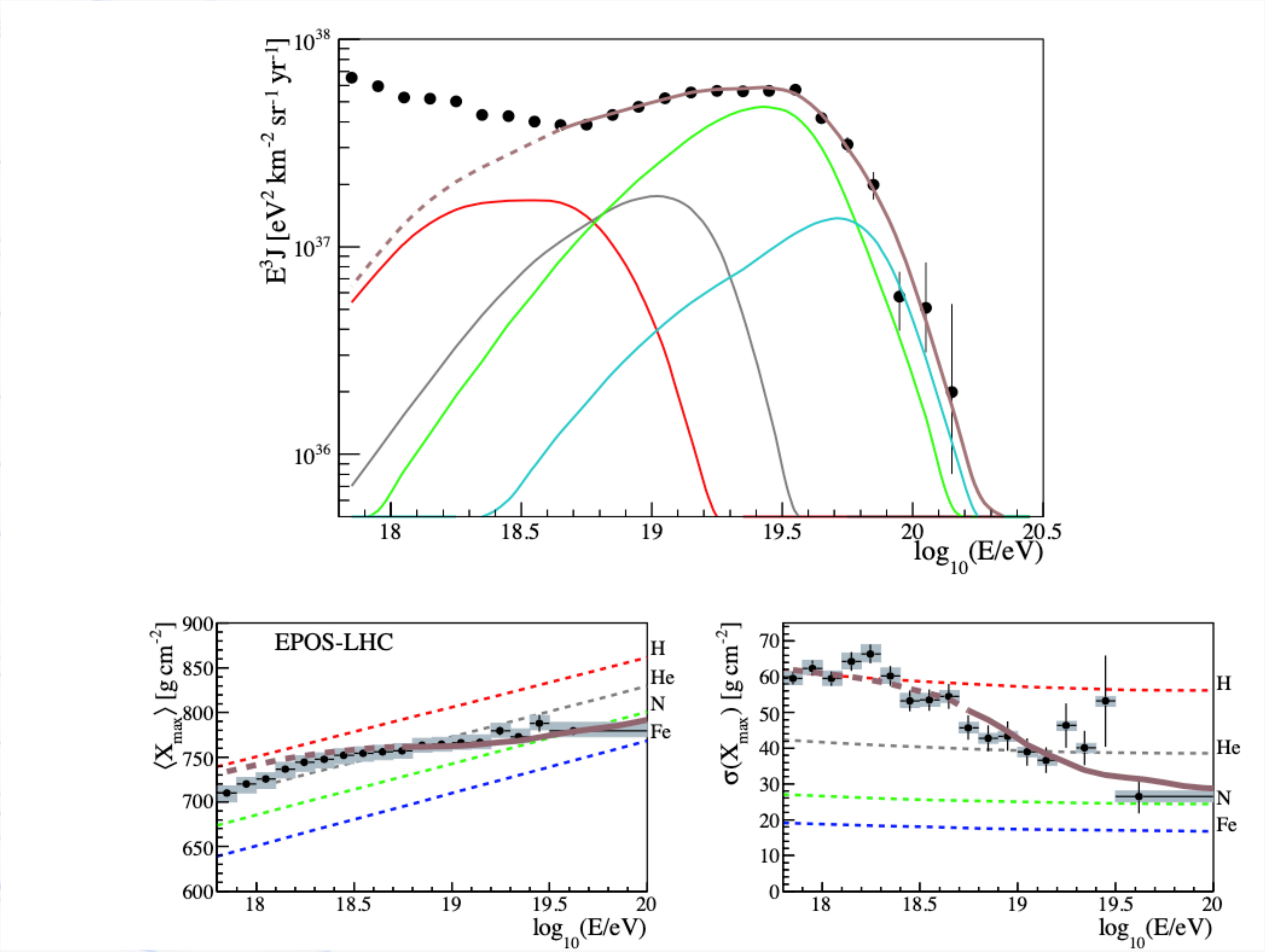
$$\langle \alpha^2 \rangle \sim \frac{d}{\lambda_{coh}} \alpha^2_{\lambda_{coh}} = \frac{d\lambda_{coh}}{r_L^2} = d\lambda_{coh} \left(\frac{eB}{E/Z}\right)^2$$

$$\theta \sim 0.8^\circ Z \left(\frac{E}{10^{20}\,eV}\right)^{-1} \left(\frac{d}{10\,Mpc}\right)^{1/2} \left(\frac{\lambda_{coh}}{1\,Mpc}\right)^{1/2} \left(\frac{B}{1\,nG}\right)$$

Astrophysical interpretation of UHECR data

Minimal cosmological model, by assuming identical and point-like sources as standard candles emitting with a power law and rigidity cutoff;

- Nuclei are accelerated at the sources.
- A hard injection spectrum at the sources is required.
- Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accommodate.



A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038