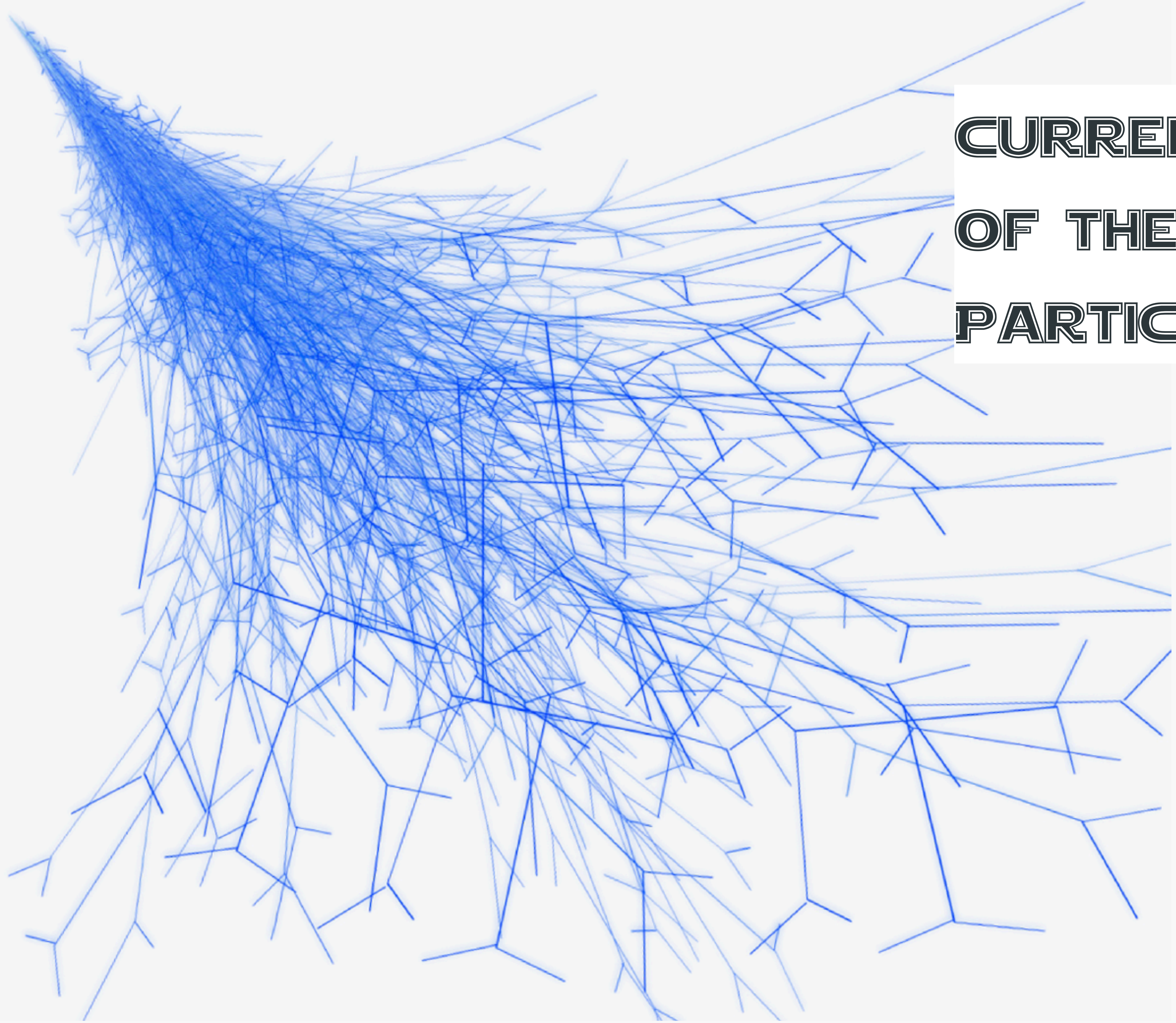


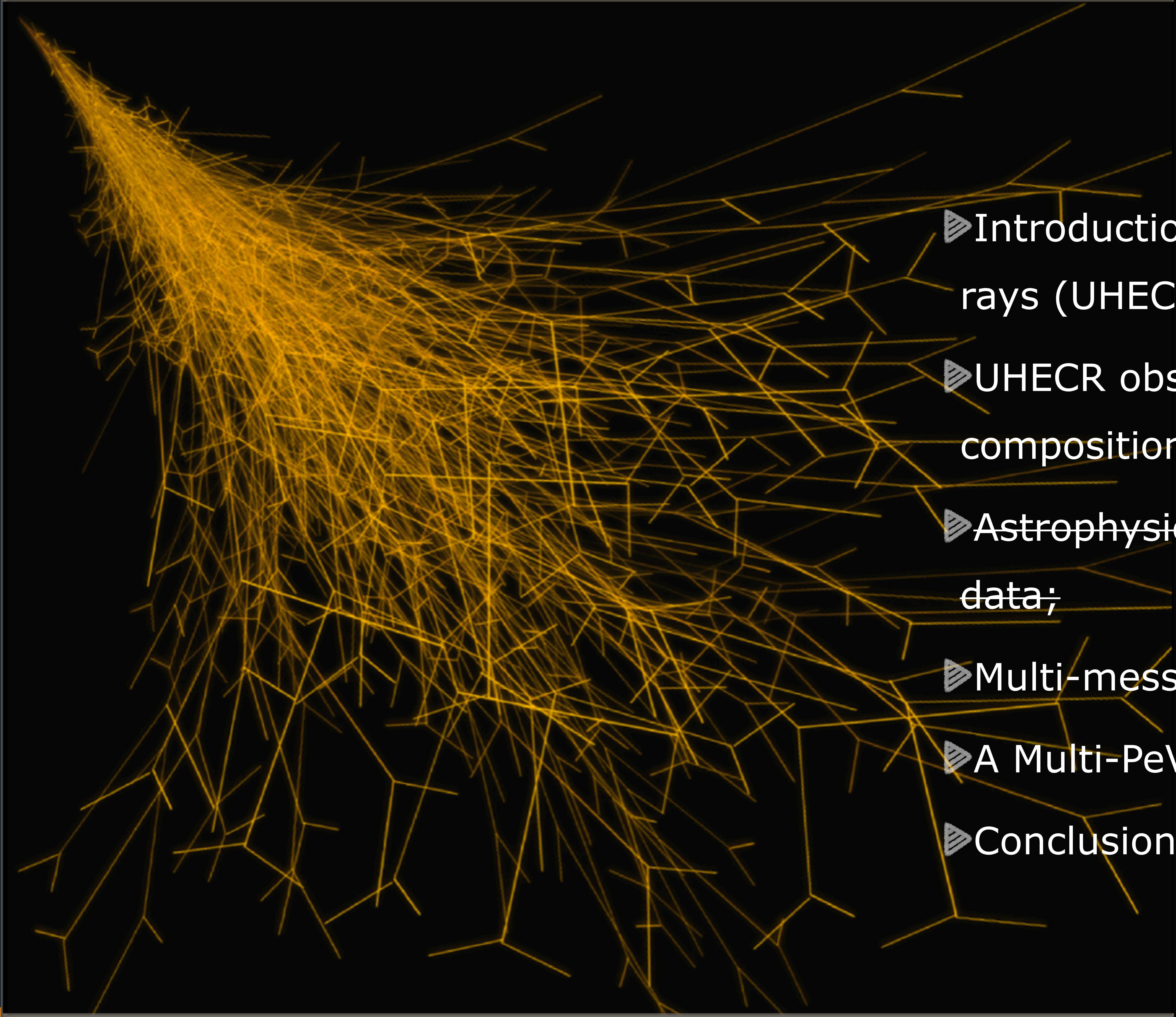
CURRENT UNDERSTANDING OF THE HIGHEST-ENERGY PARTICLES IN NATURE

@ LPNHE,
07/04/2025

Antonio Condorelli

KM3NeT

APC, CNRS, FRANCE



Outline

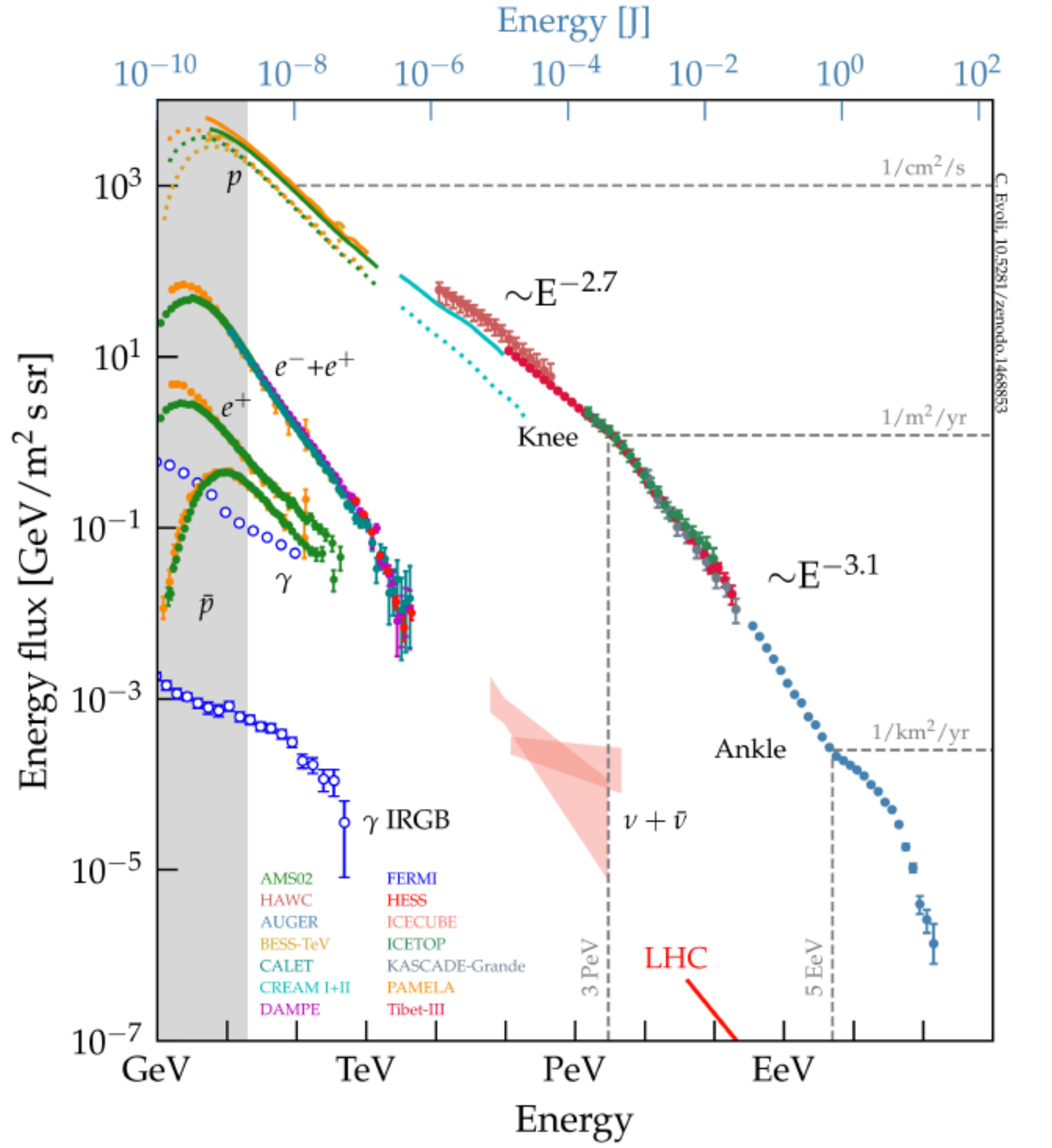
- Introduction: Ultra-high-energy cosmic rays (UHECRs);
- UHECR observables: spectrum, mass composition and arrival direction;
- ~~Astrophysical interpretation of UHECR data;~~
- Multi-messenger constraints;
- A Multi-PeV neutrino
- Conclusions and future perspectives.

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.

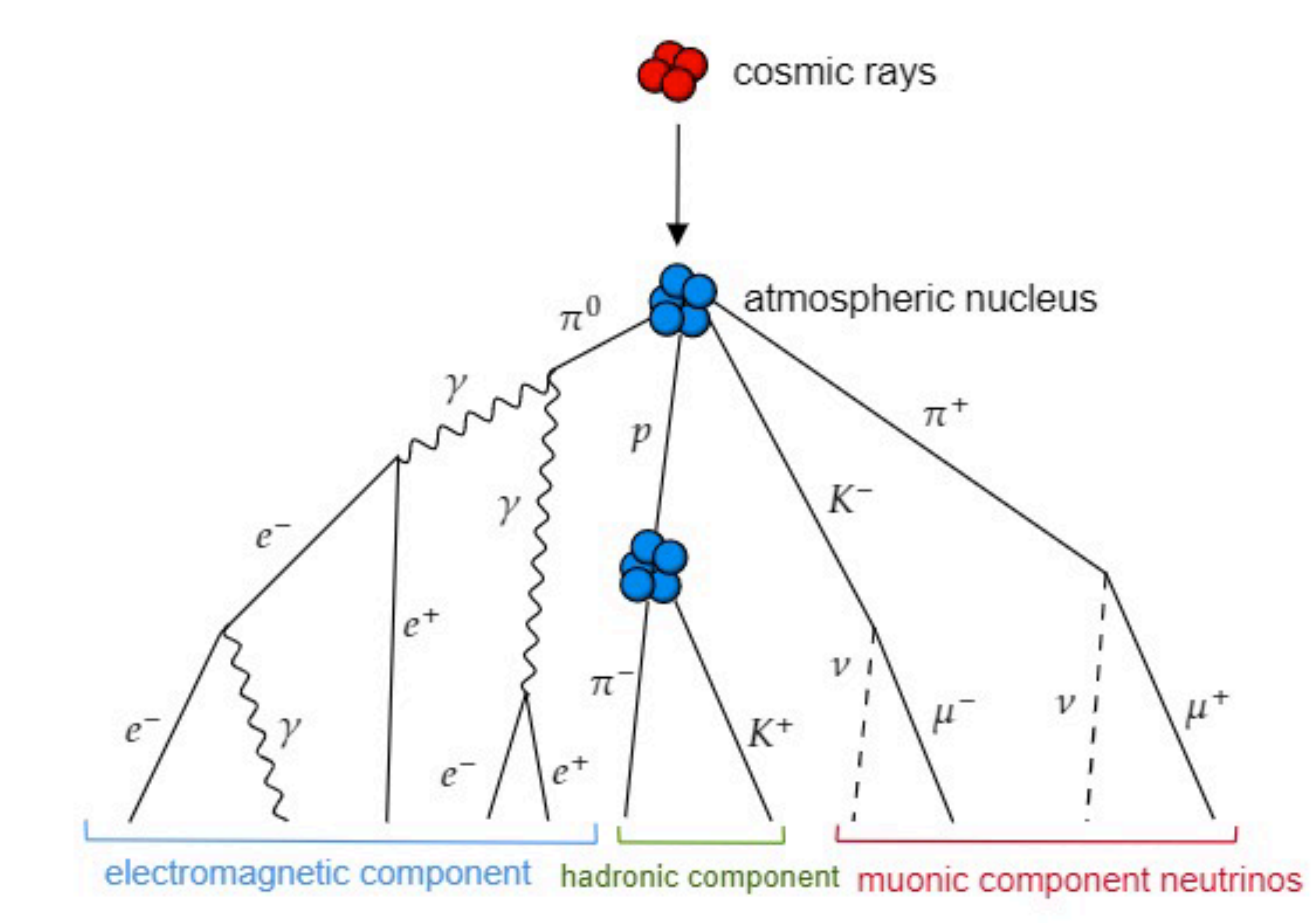


Indirect detection: Extensive Air Shower (EAS)

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)

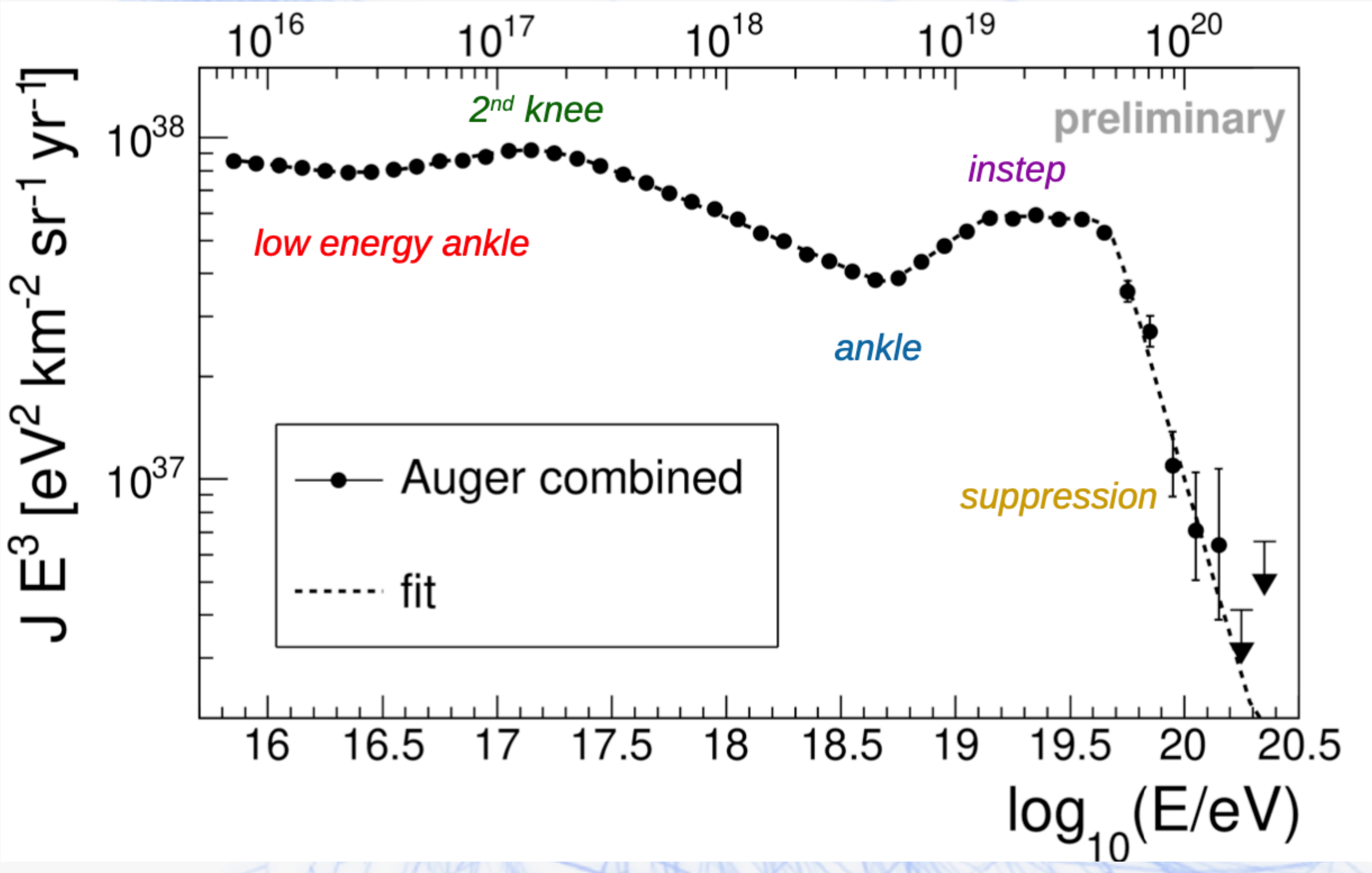


A key information to infer about properties of the primary particle is the depth of the shower maximum

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

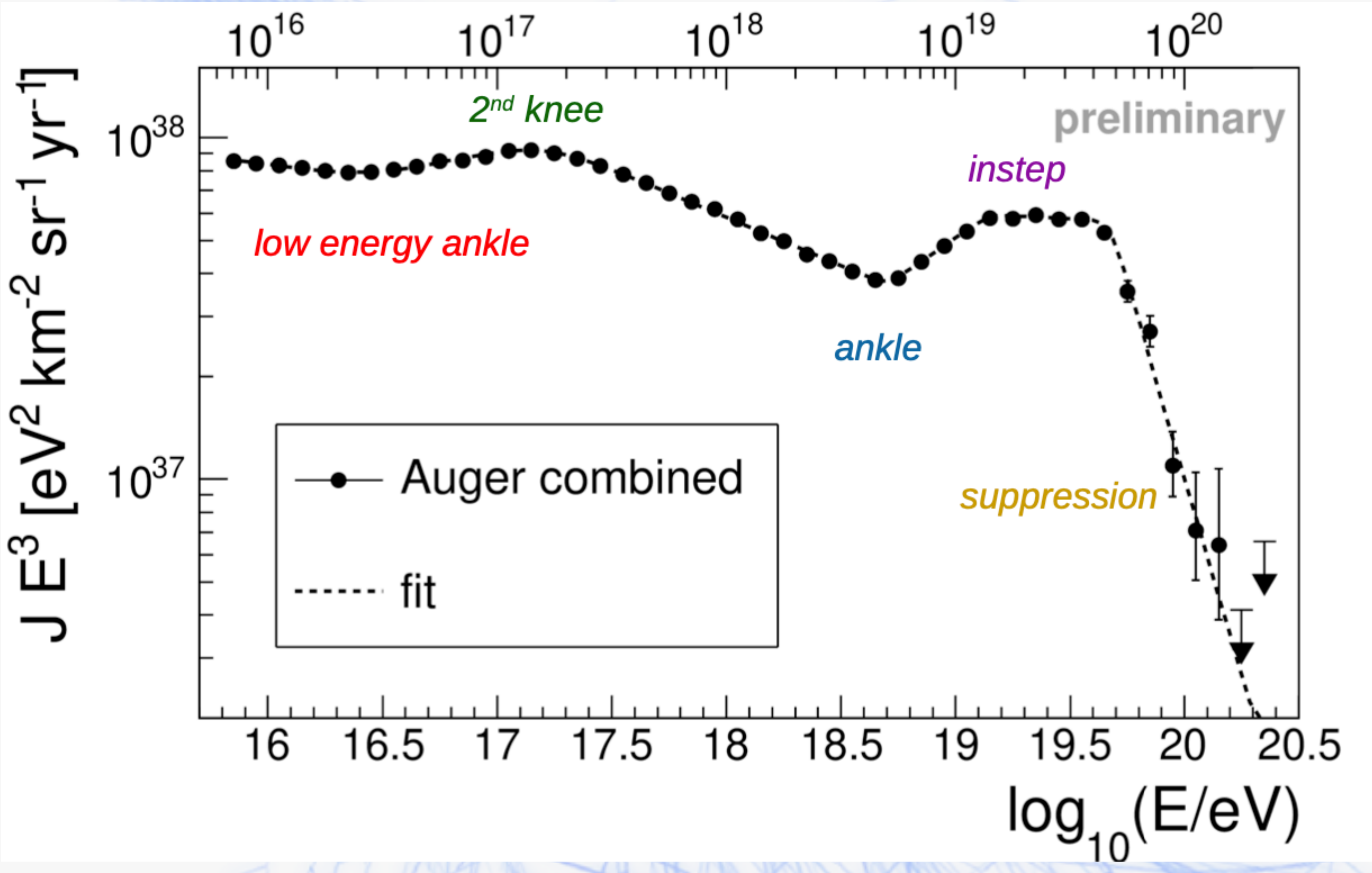
UHECR observables

Energy spectrum

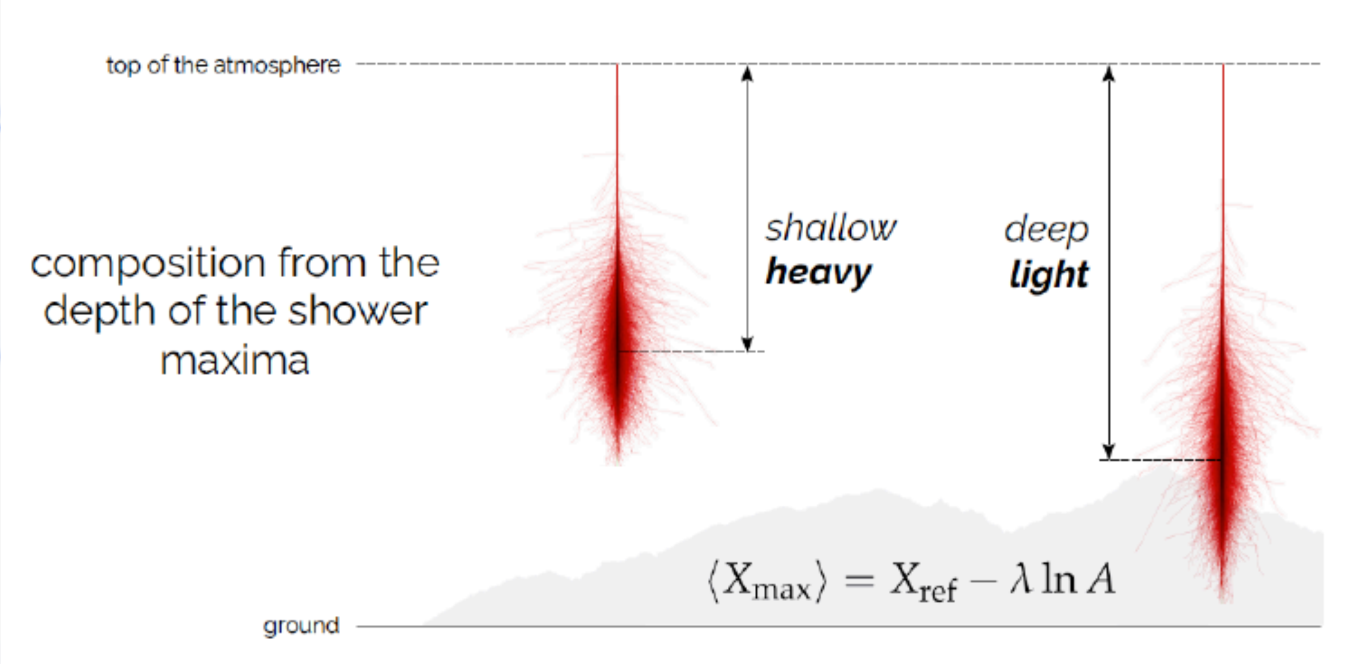


UHECR observables

Energy spectrum

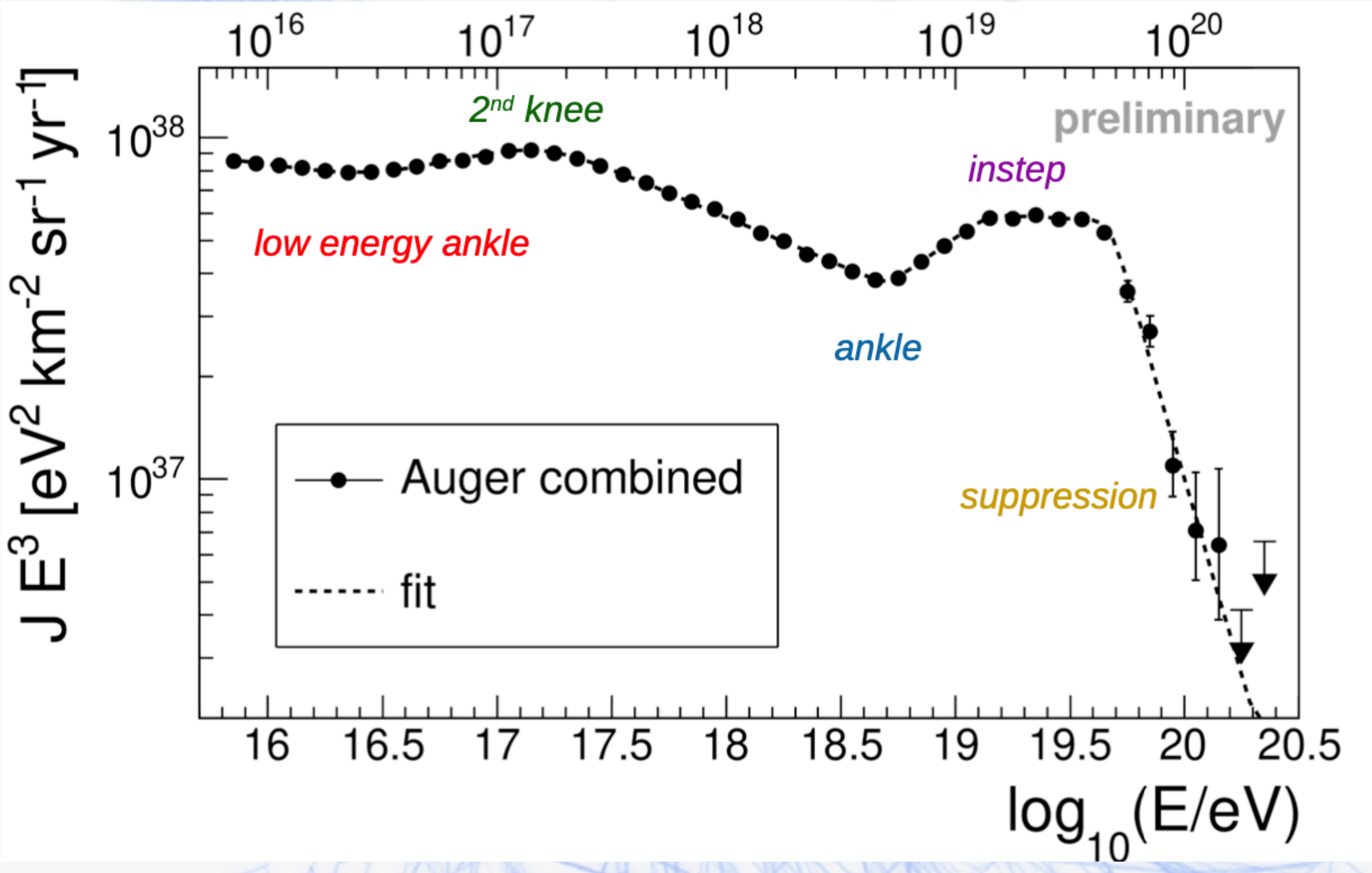


Mass Composition

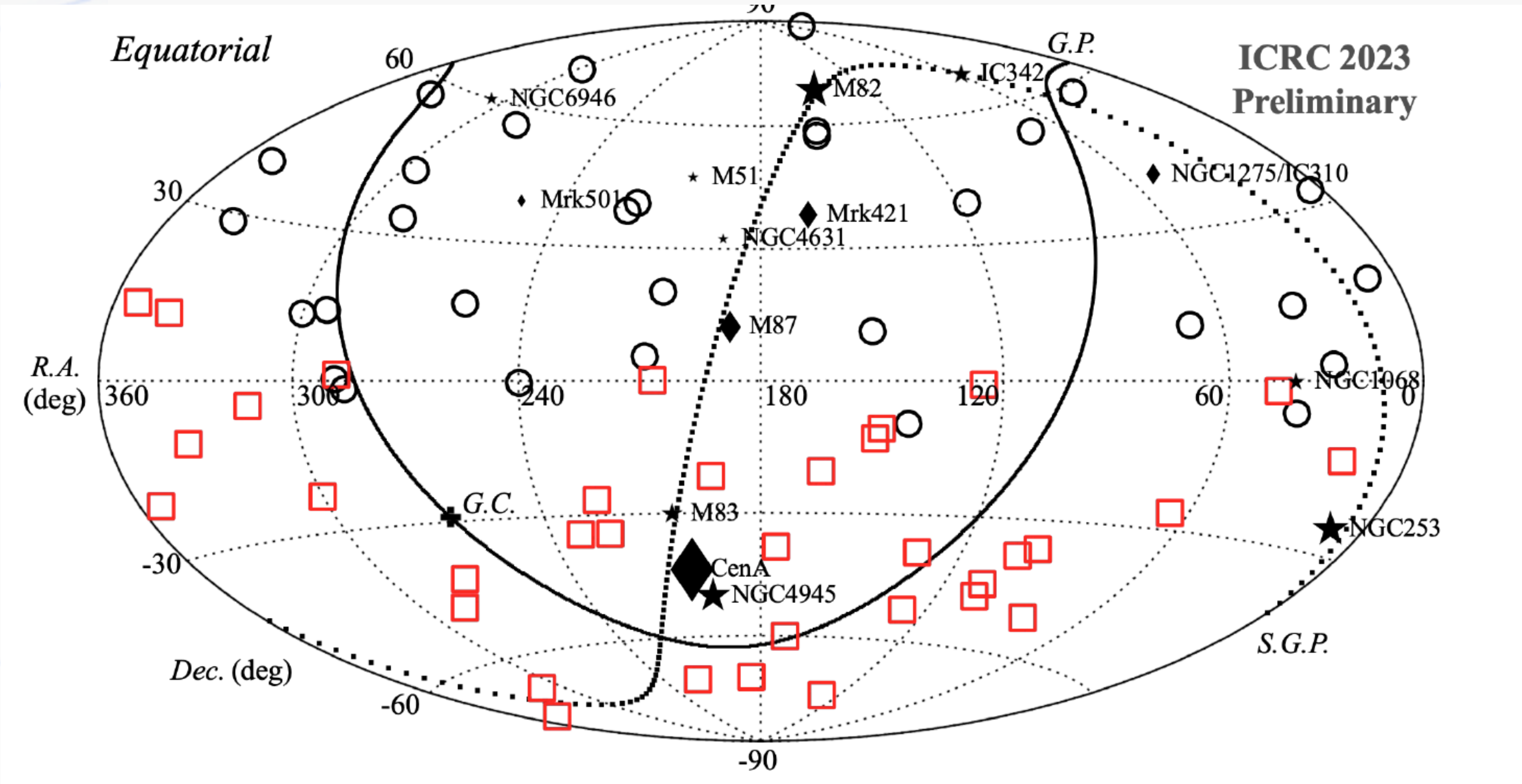


UHECR observables

Energy spectrum

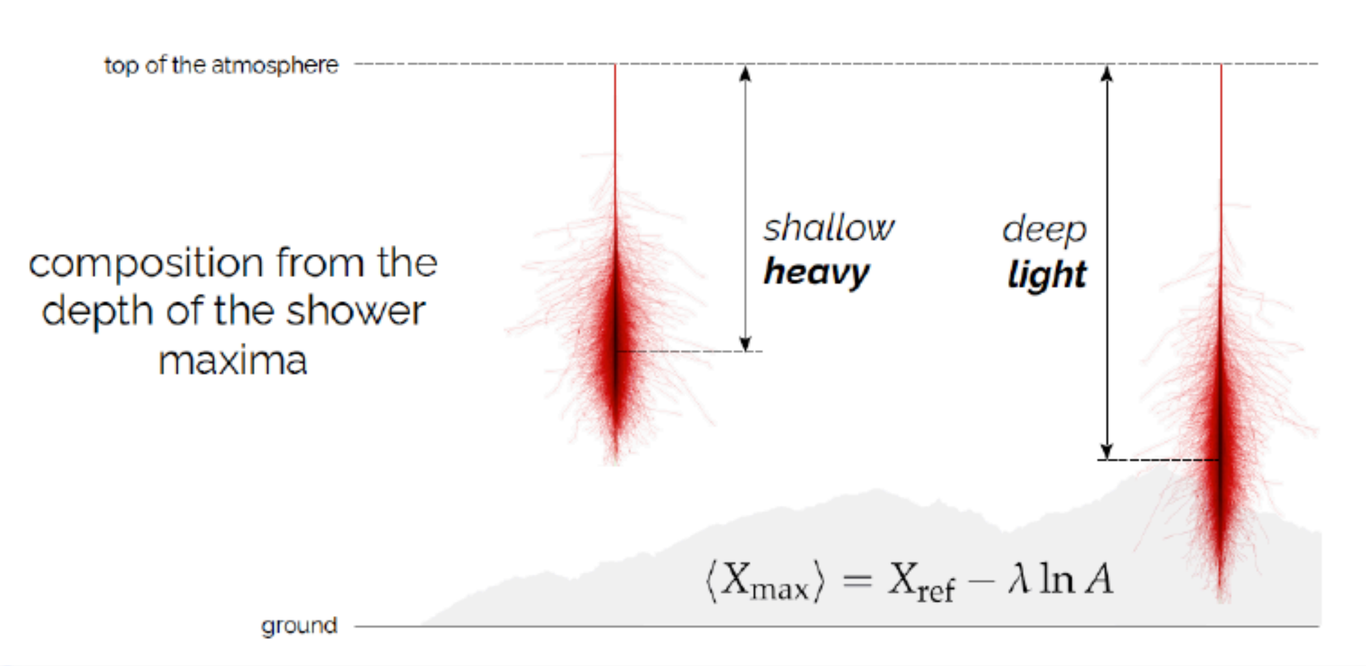


Arrival direction



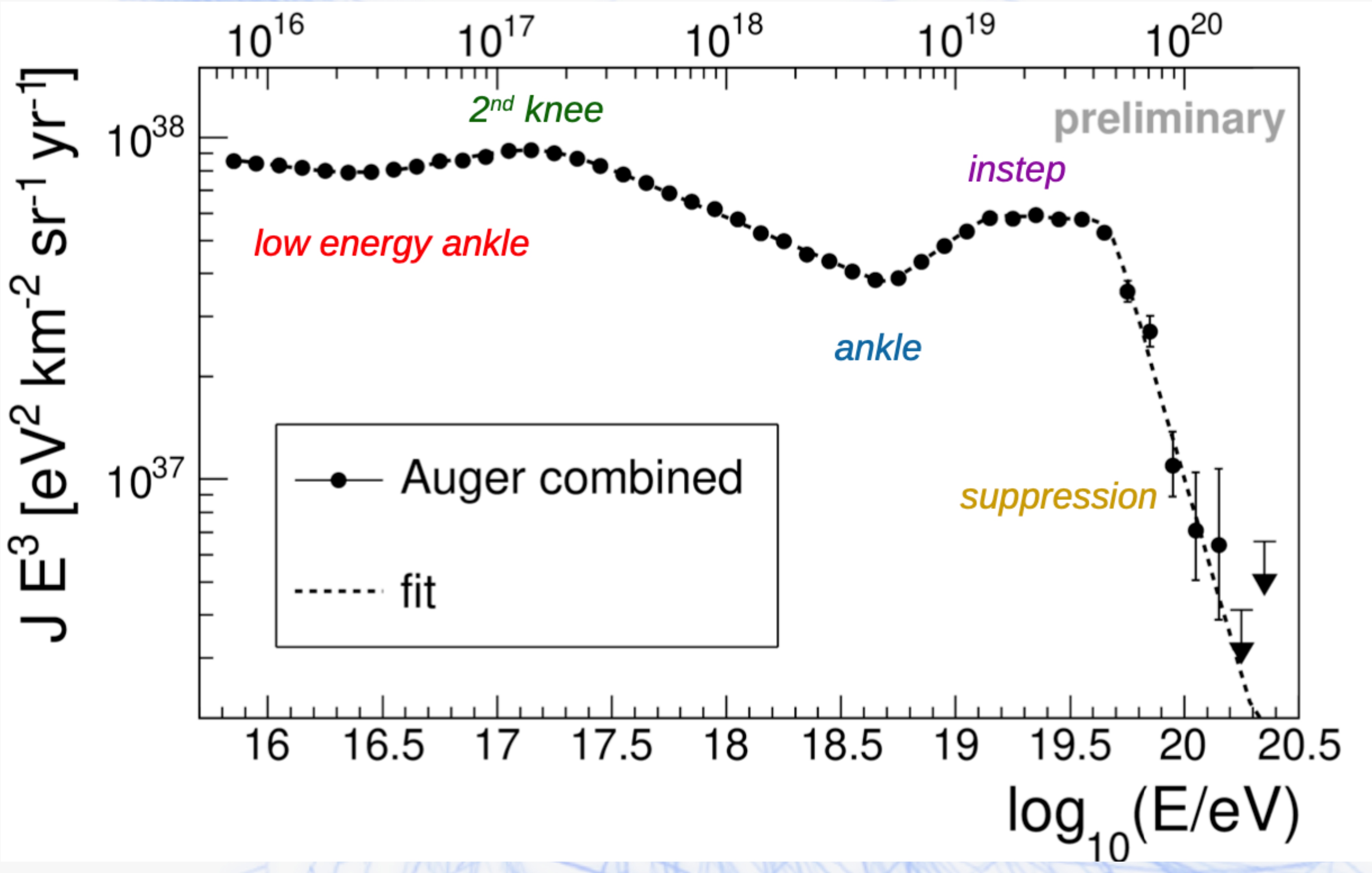
TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

Mass Composition

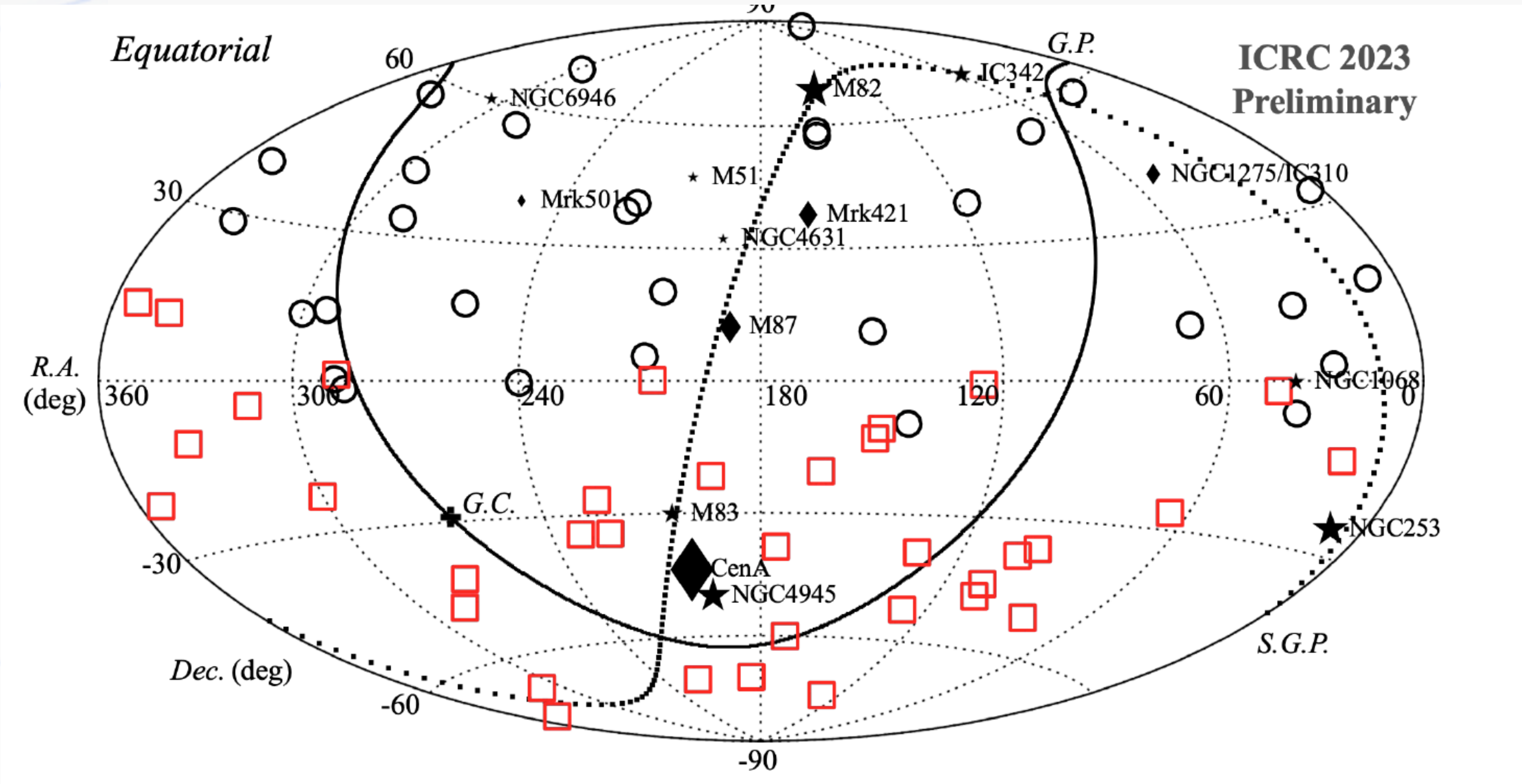


UHECR observables

Energy spectrum



Arrival direction



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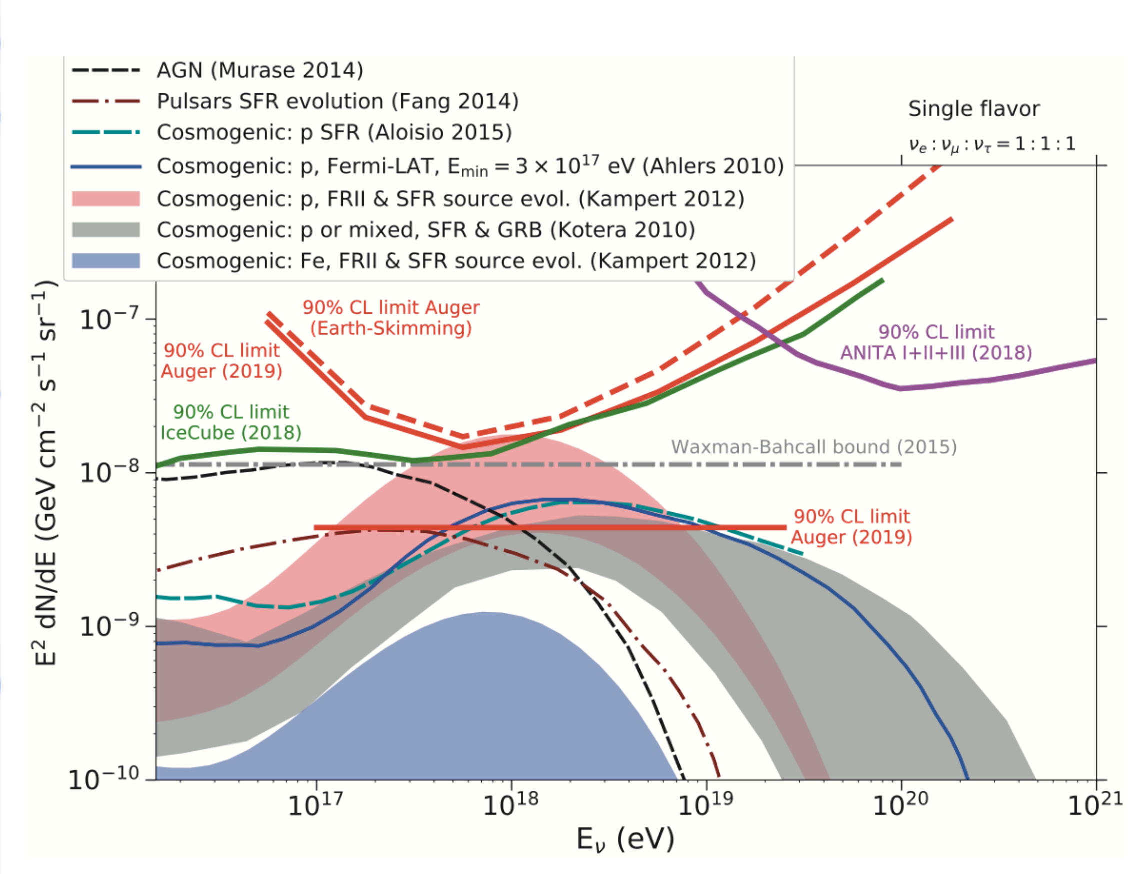
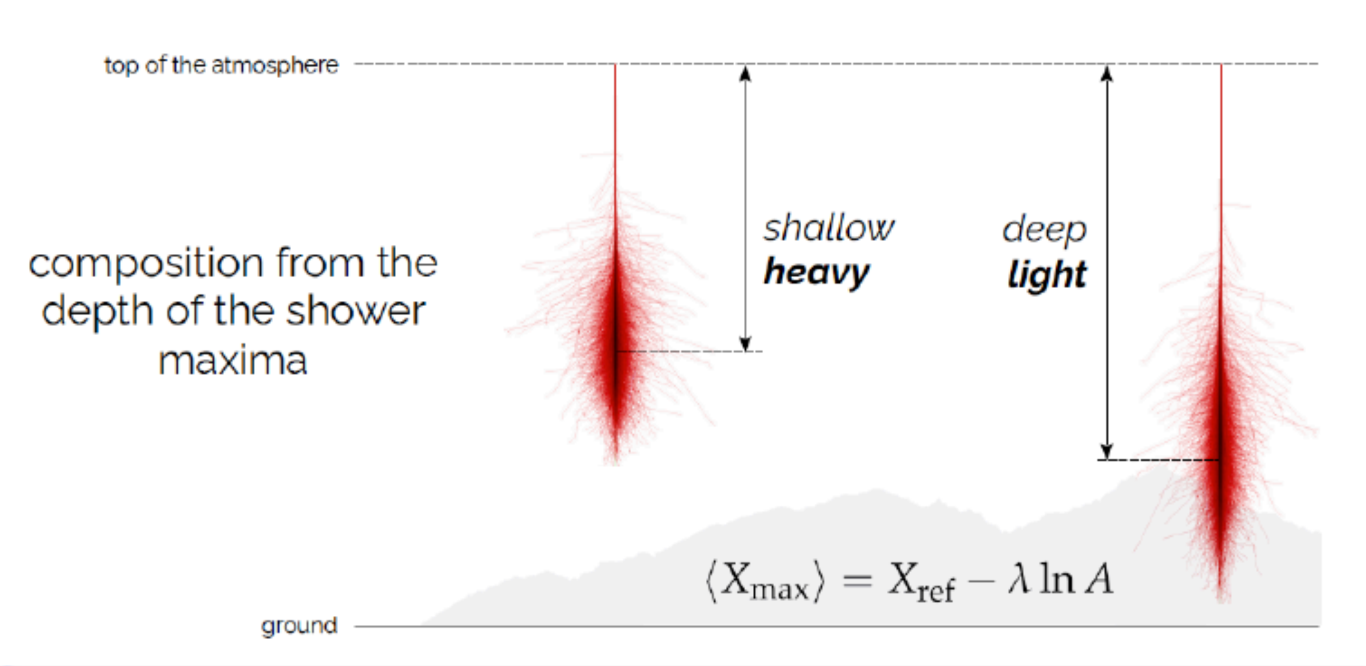
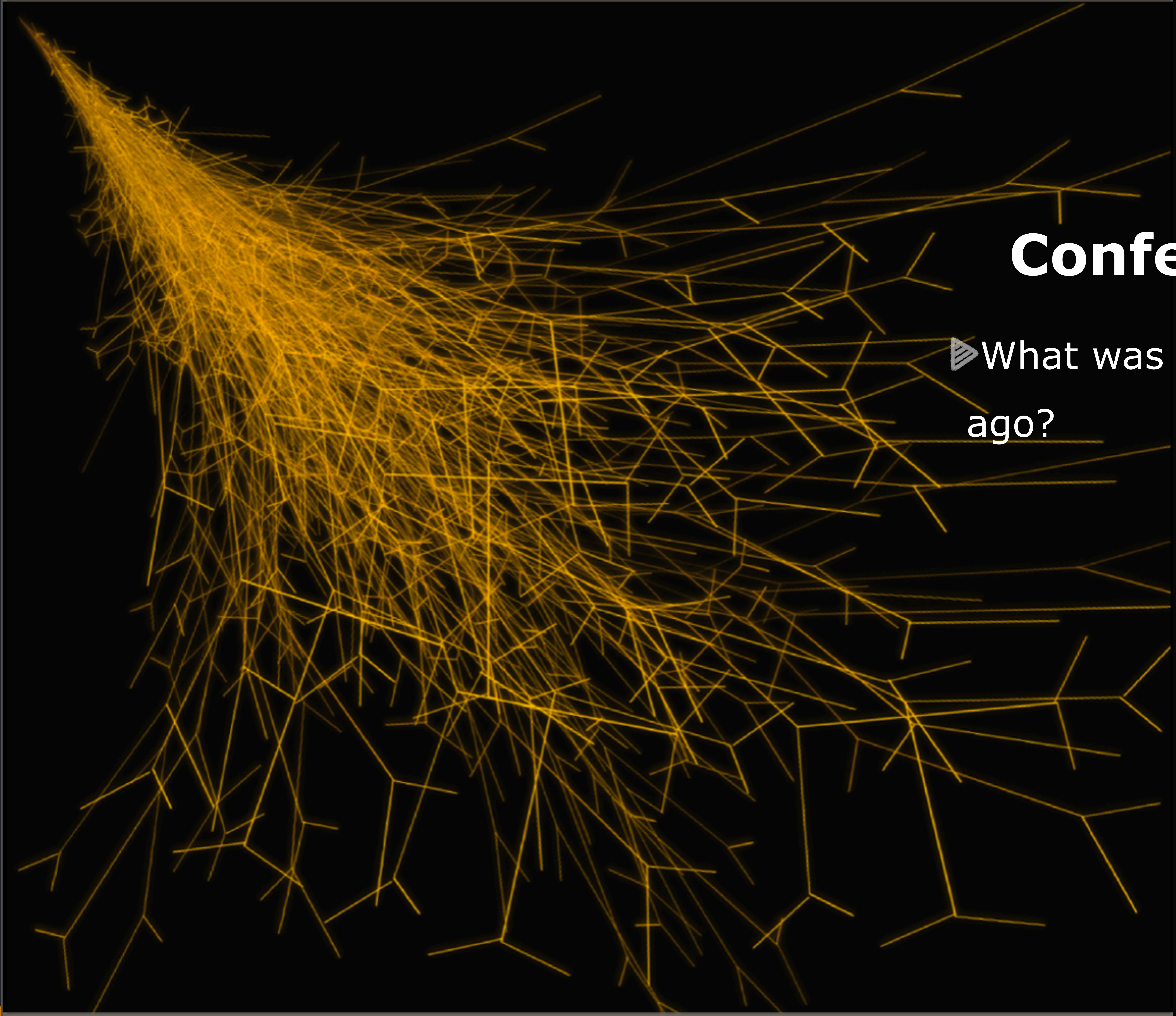
Secondary fluxes



Mass Composition





Back in International Comics Ray Conference (ICRC) 2003

- What was the status of the art 20 years ago?

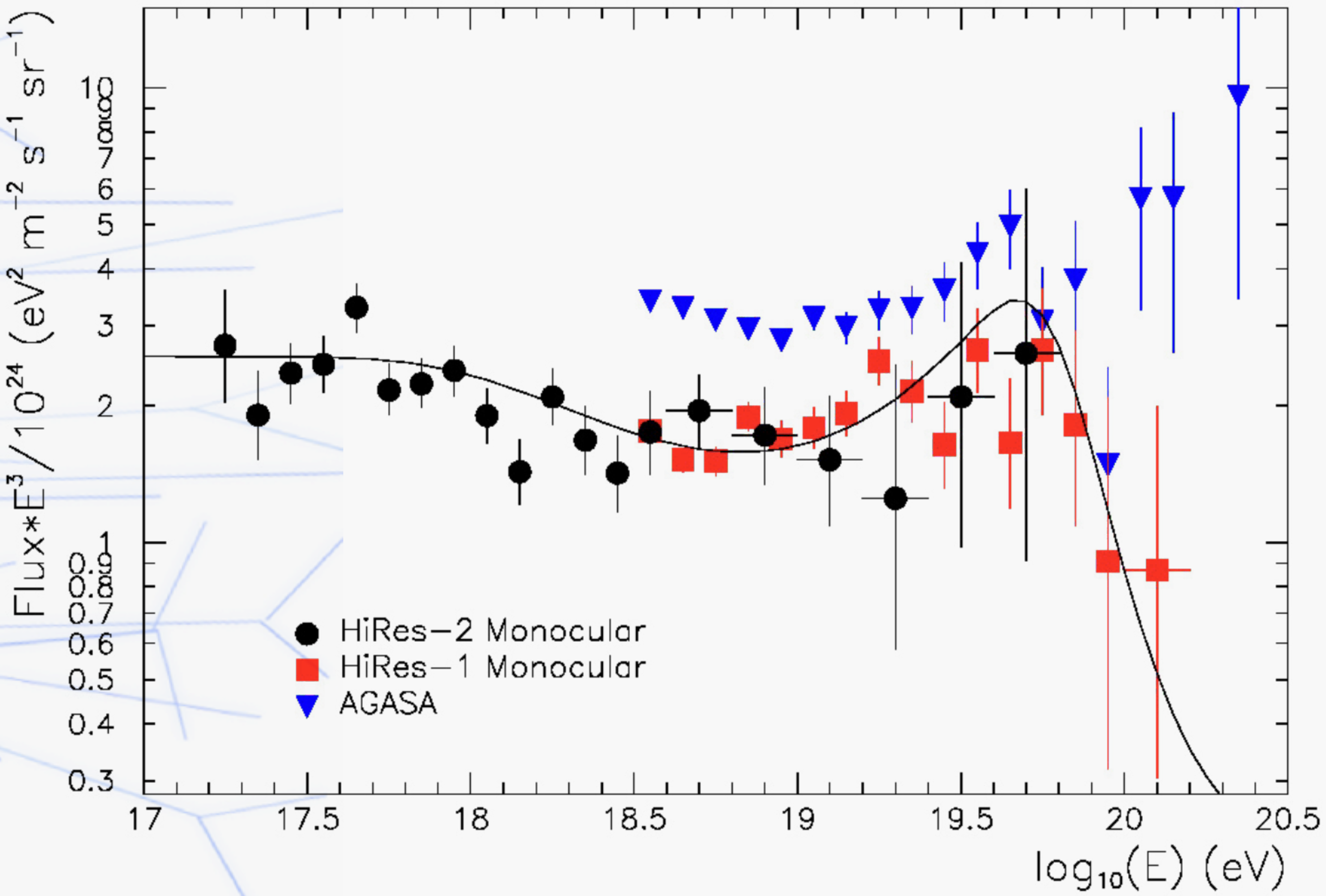
UHECR Spectrum Picture ICRC 2003 ➜Uncertain

Ankle is visible! Lots of speculation about Spectrum @ 50EeV:

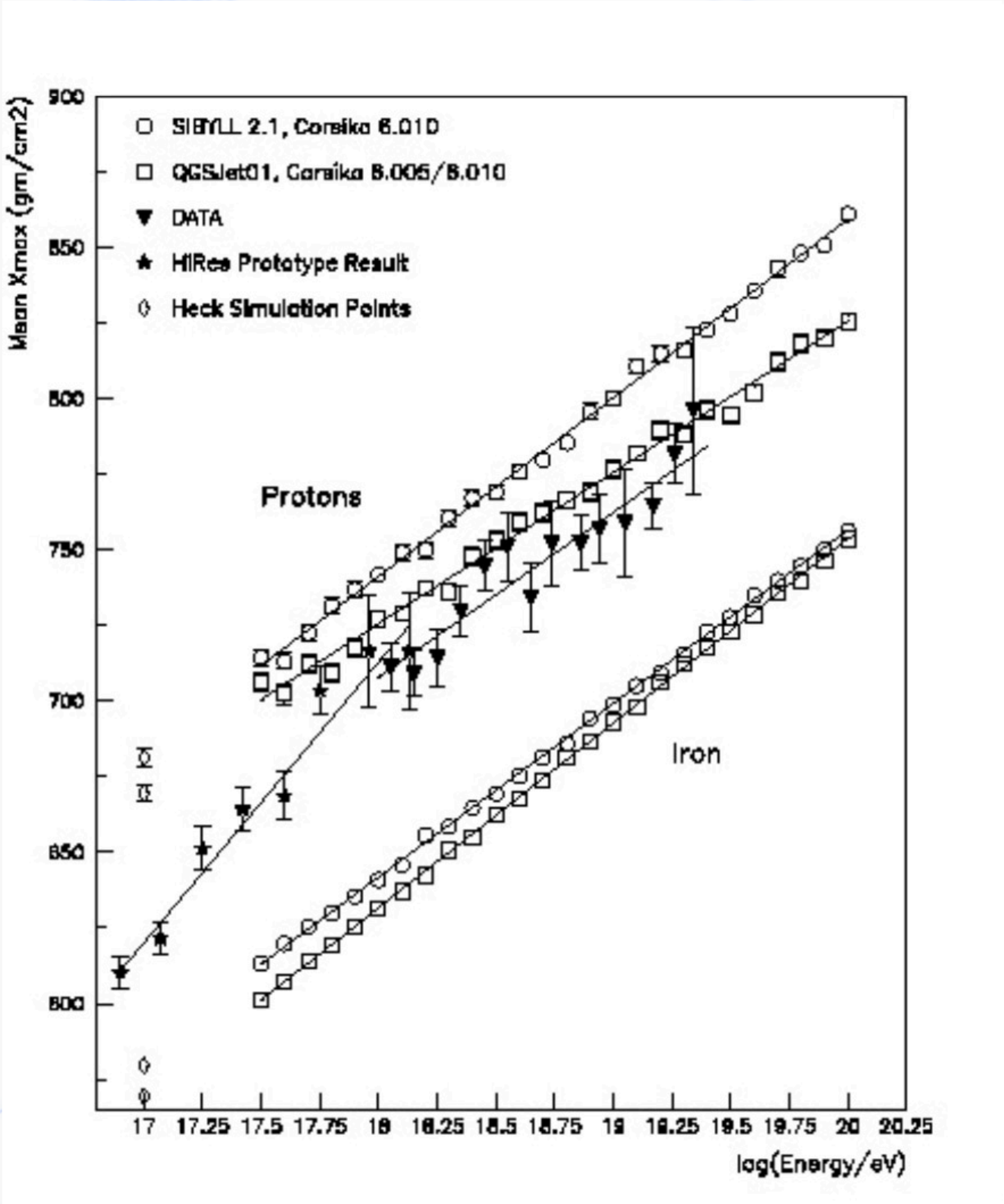
➢ Is the HiRes suppression correct and is it the GZK?

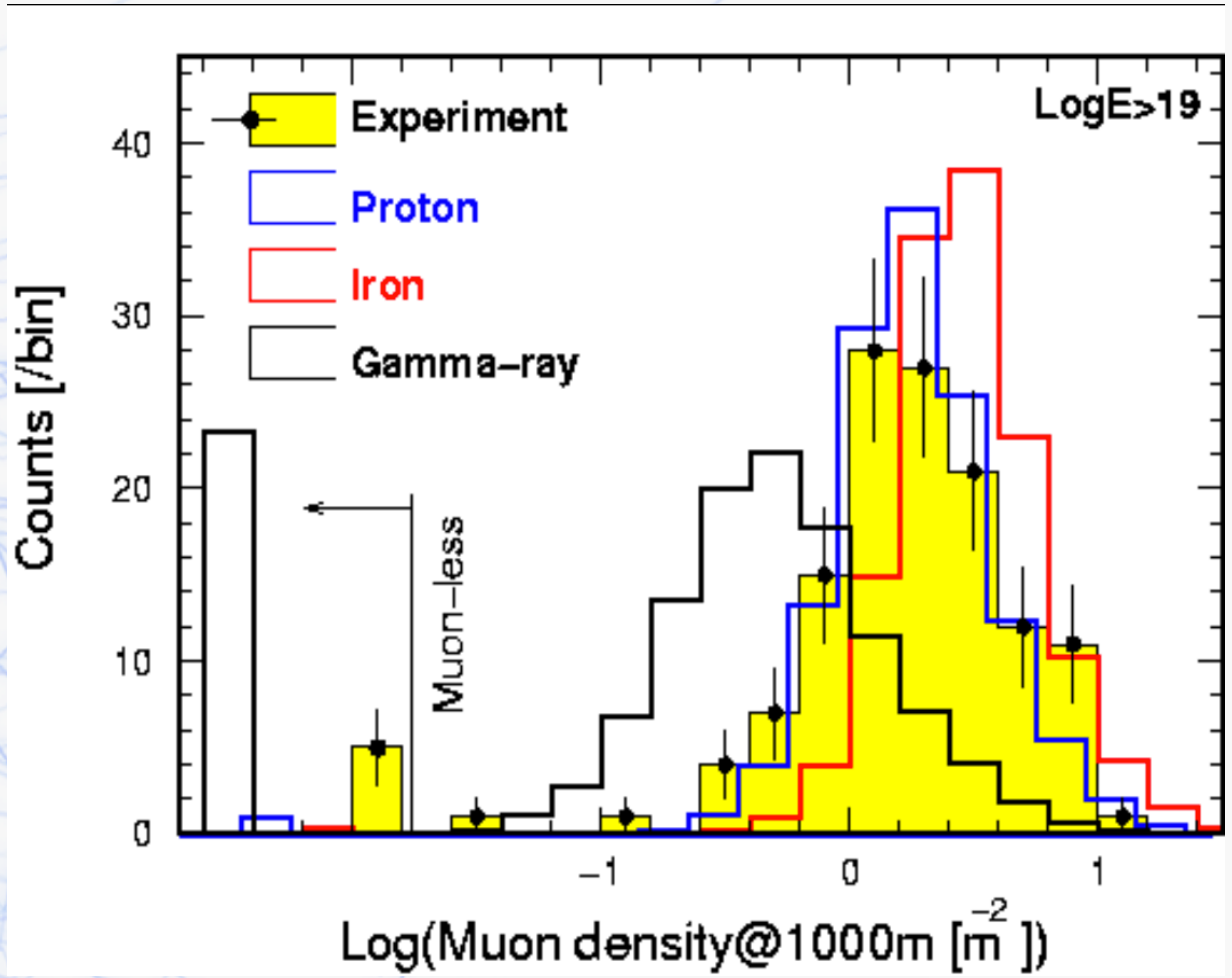
➢ How far will the spectrum go if AGASA is correct?

Plans to study many super-GZK cosmic rays and identify their origin.



UHECR Spectrum Picture ICRC 2003 ➜Uncertain





HiRes

- Heavy composition @10^{17}eV
- Shift to light by 10^{18} eV
- “Constant” up to ~$10^{19.4}$eV

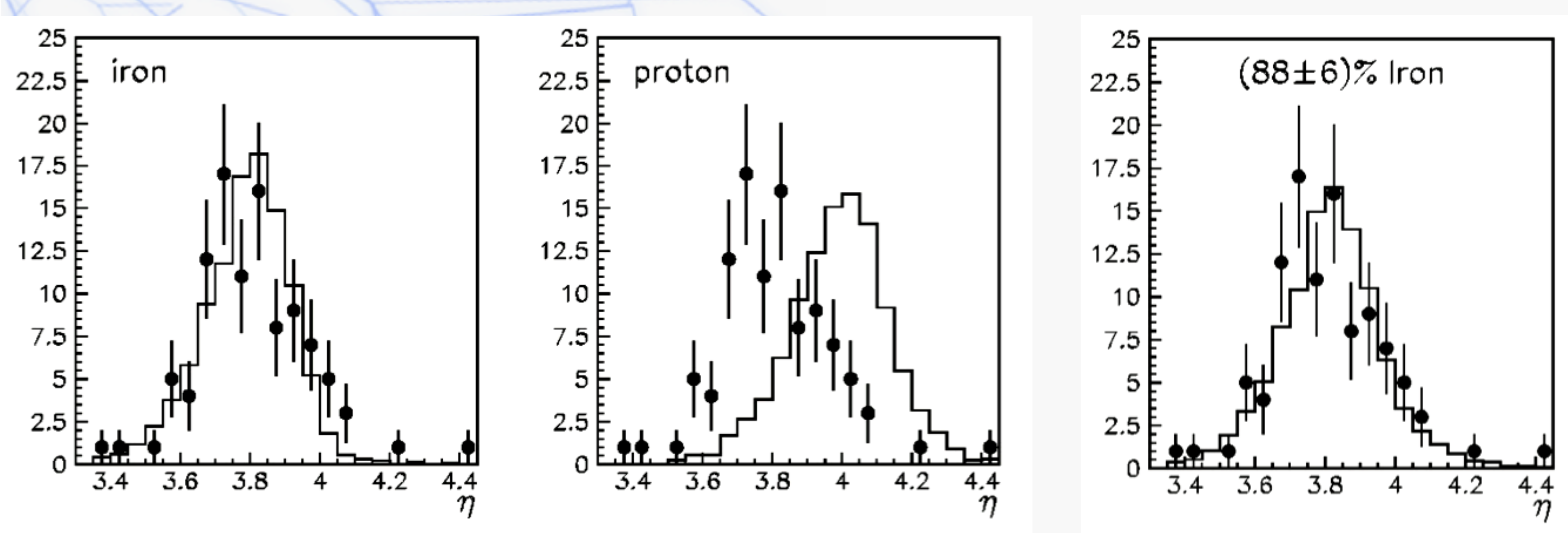
AGASA

- 14% Iron for E>10^{19} eV
- 30% Iron for E>$10^{19.25}$eV
- < 66% Iron for E> $10^{19.5}$ eV

Volcano Ranch

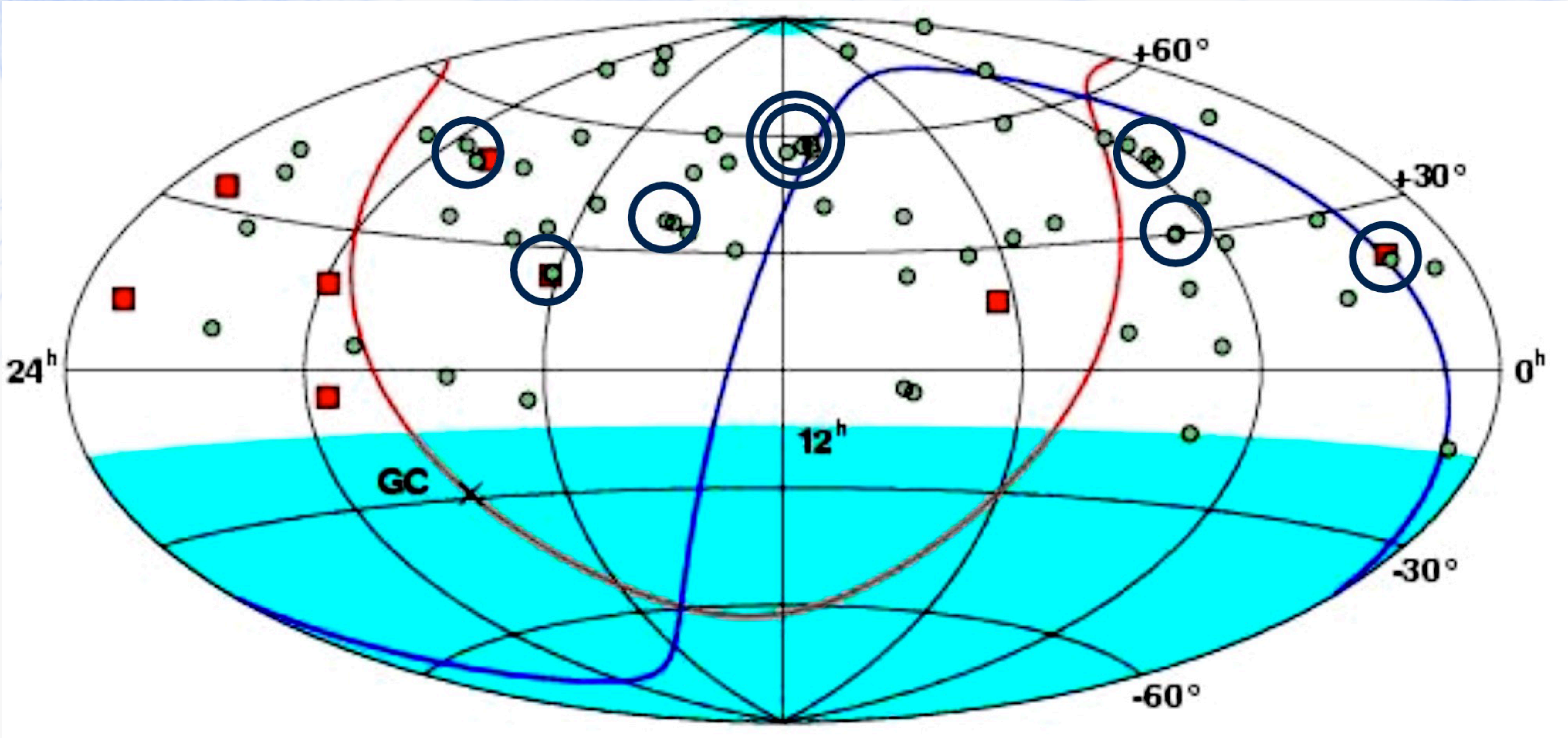
- 88% Iron for ⟨E⟩ = 10^{18}eV

Volcano Ranch



UHECR Spectrum Picture ICRC 2003 ➜Uncertain

AGASA

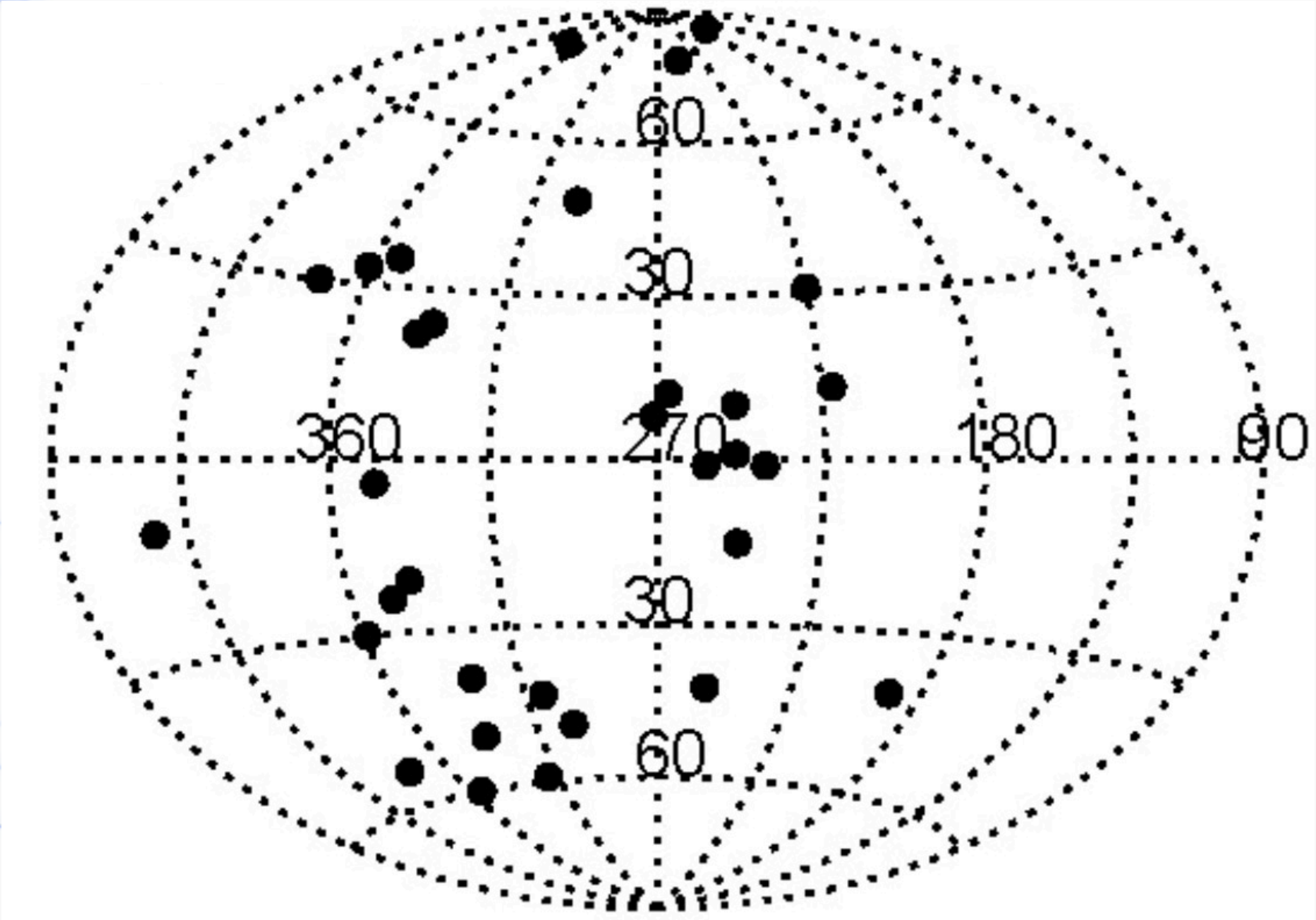


6 “Doublets” and a “Triplet” $\Delta\theta$< 2.5 ° observed

2 doublets Expected given statistics

➜ 3.2 σ excess

SUGAR



Strong Isotropy in SUGAR data

The era of the giant arrays

Pierre Auger and Telescope Array *circa* 2003

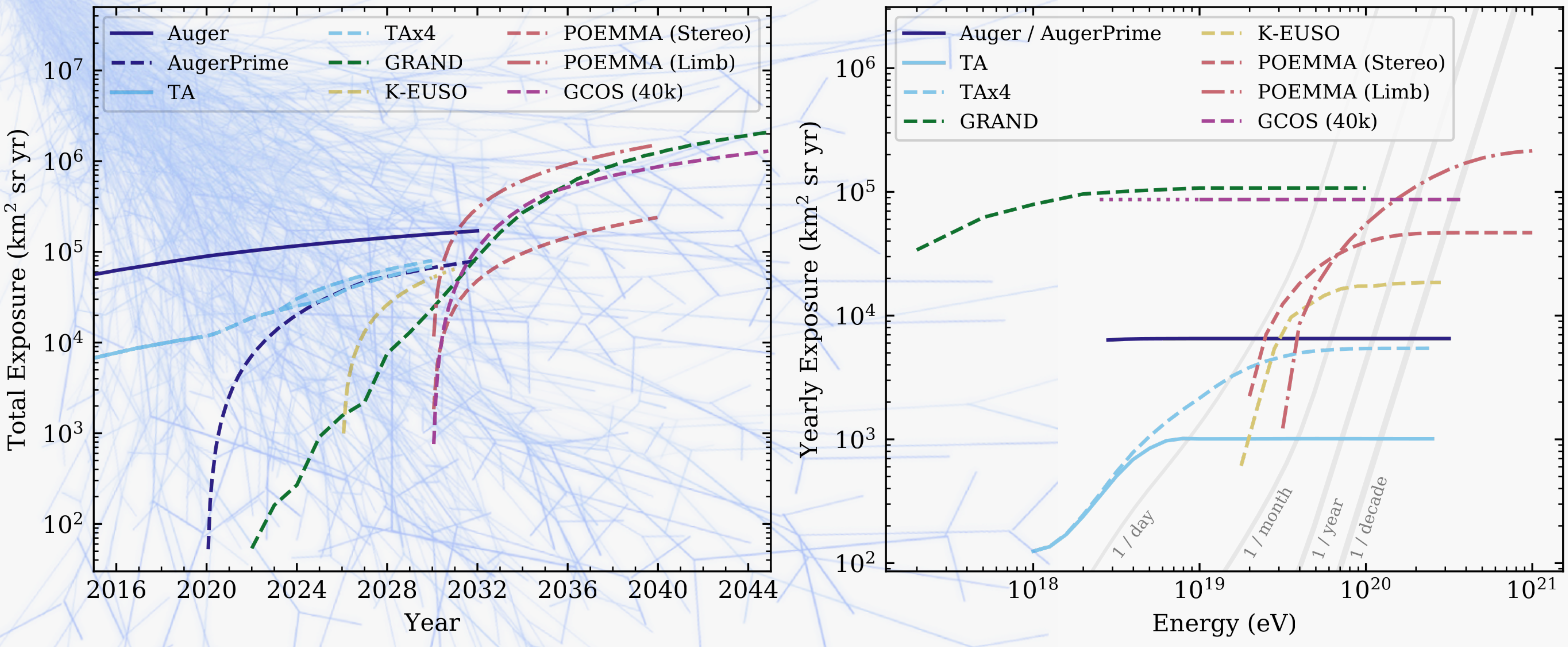
- The **Auger Array** was under construction
- A partial array was taking data
- An initial search (to begin Aug. 2003) for the AGASA doublets and triplet as well as other selected targets had been defined
- Full array data from 2008

PIERRE AUGER OBSERVATORY

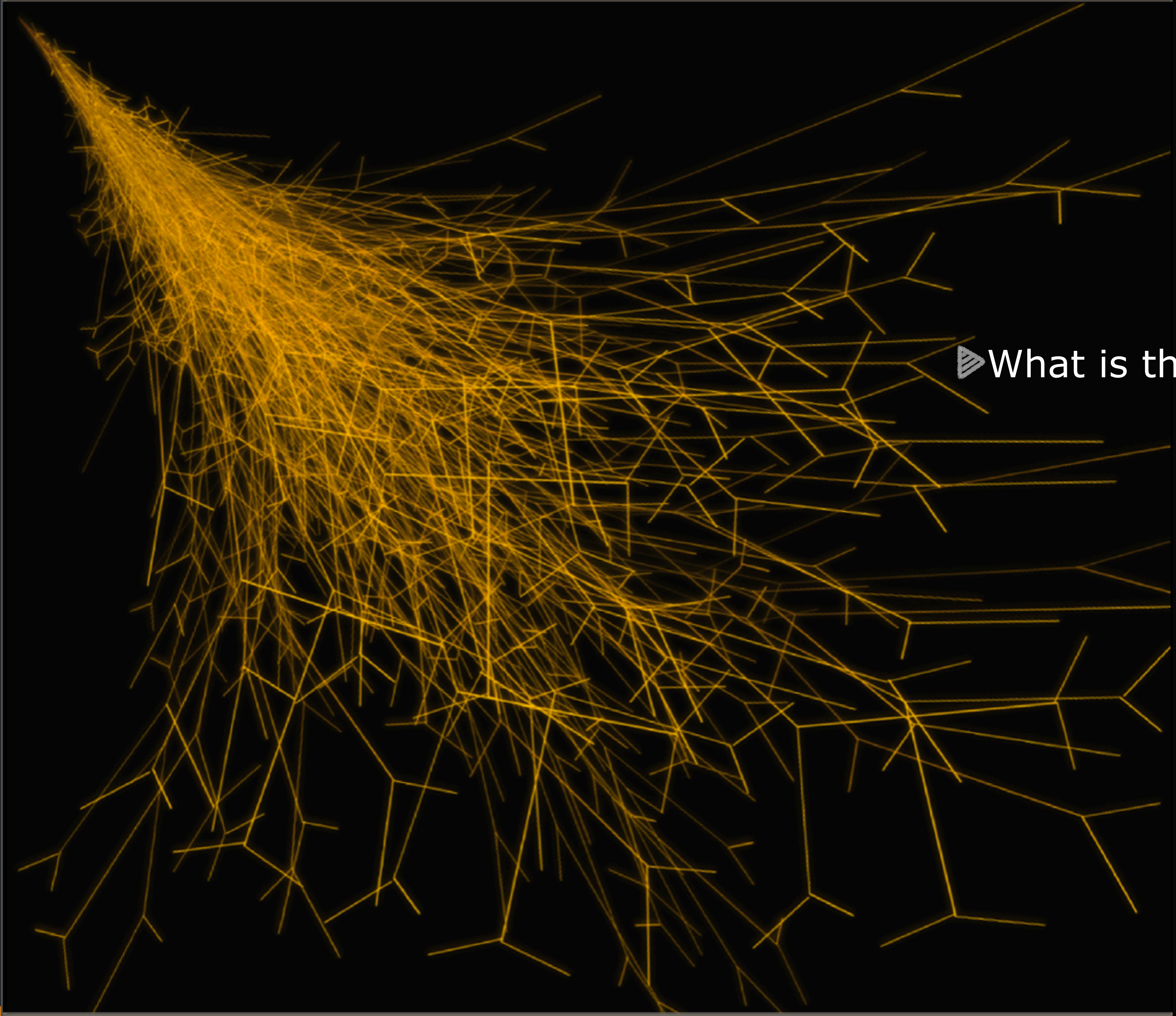
- **Telescope Array** had just been approved and details were being ironed out
- Engineering array of 18 SD deployed in 2004
- Full operation began in 2008

TELESCOPE ARRAY PROJECT

The era of the giant arrays



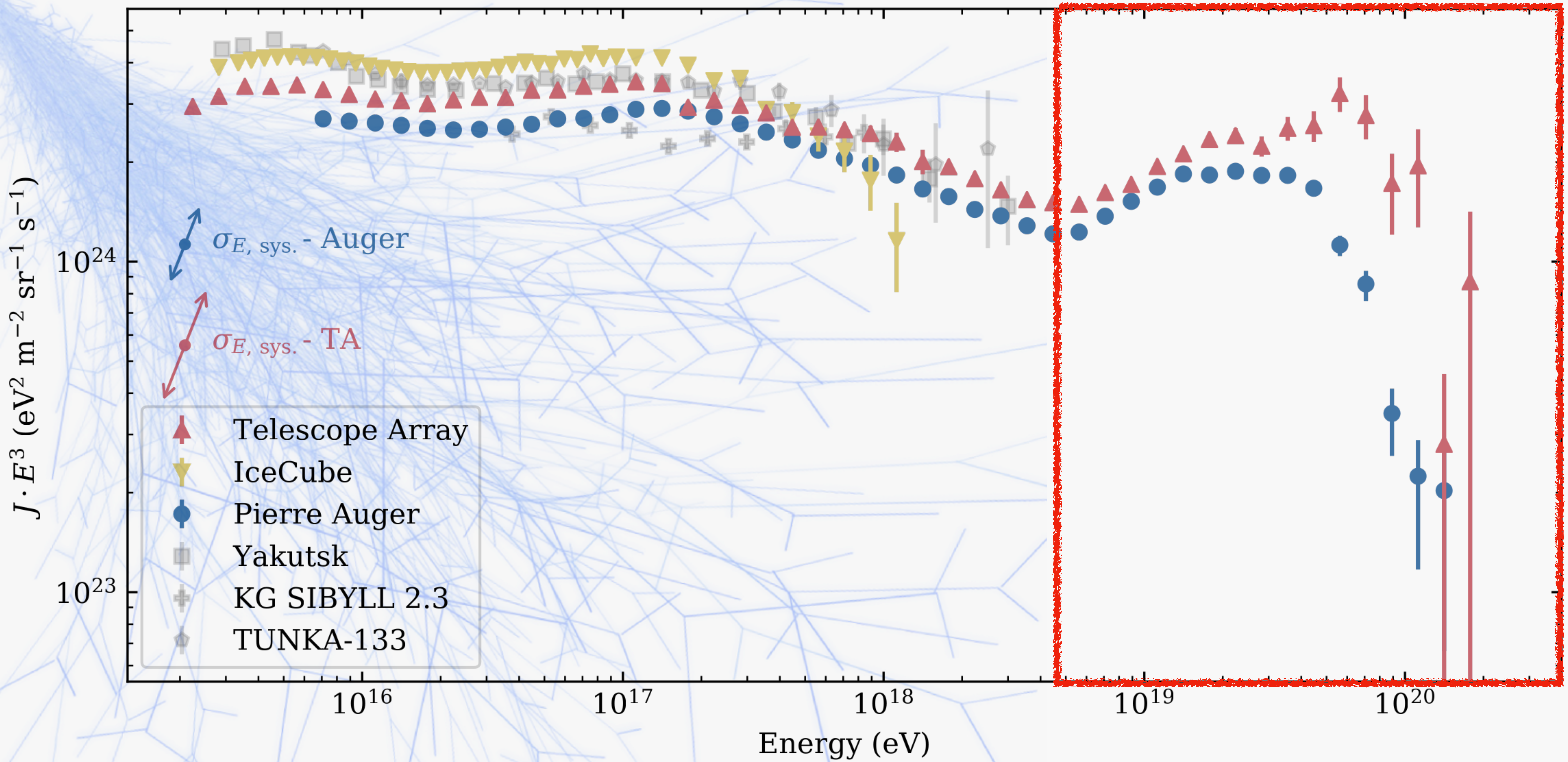
Great exposure –> high statistics (despite the energy spectrum)



Now, in 2025

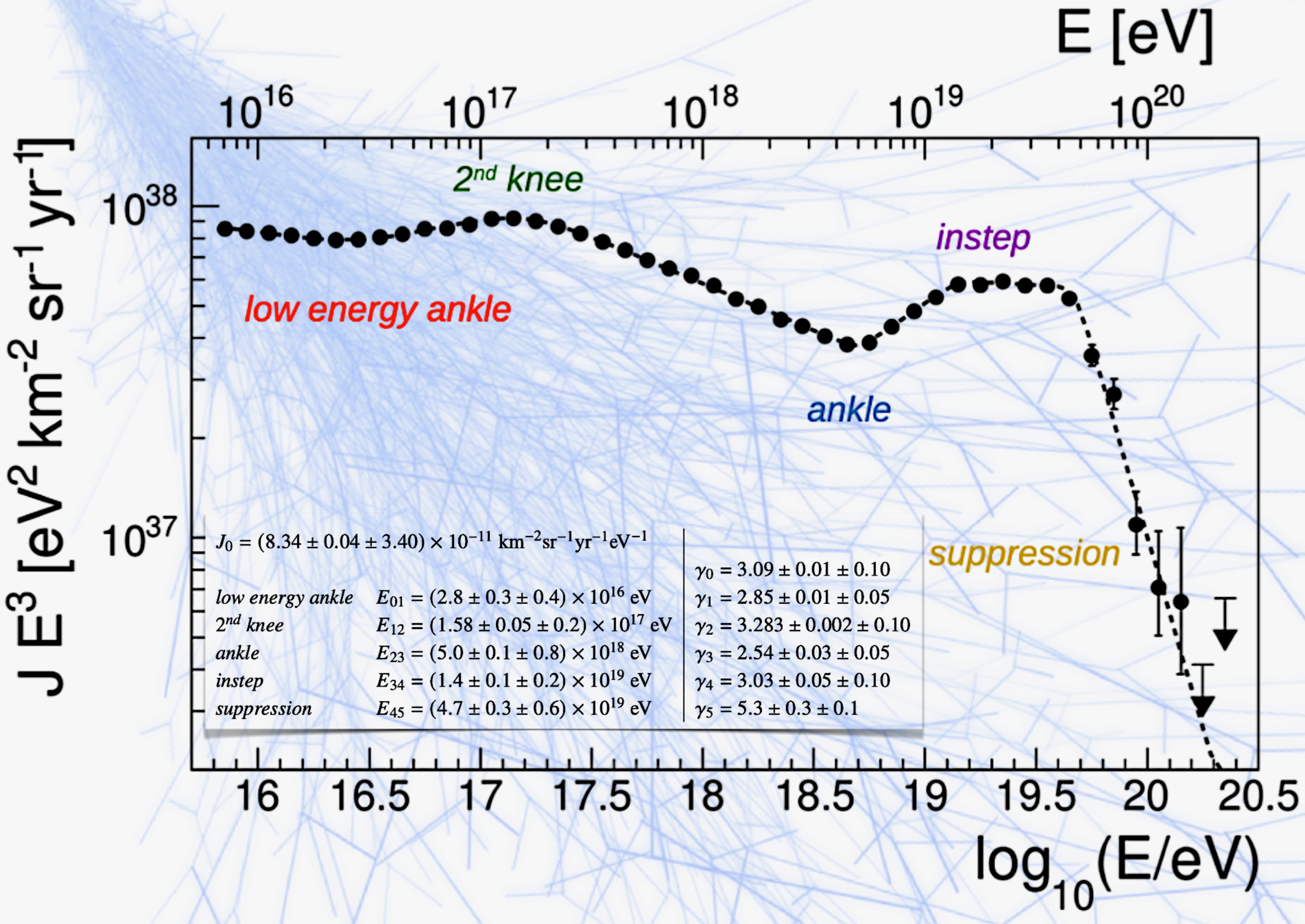
- What is the status of the art **today**?

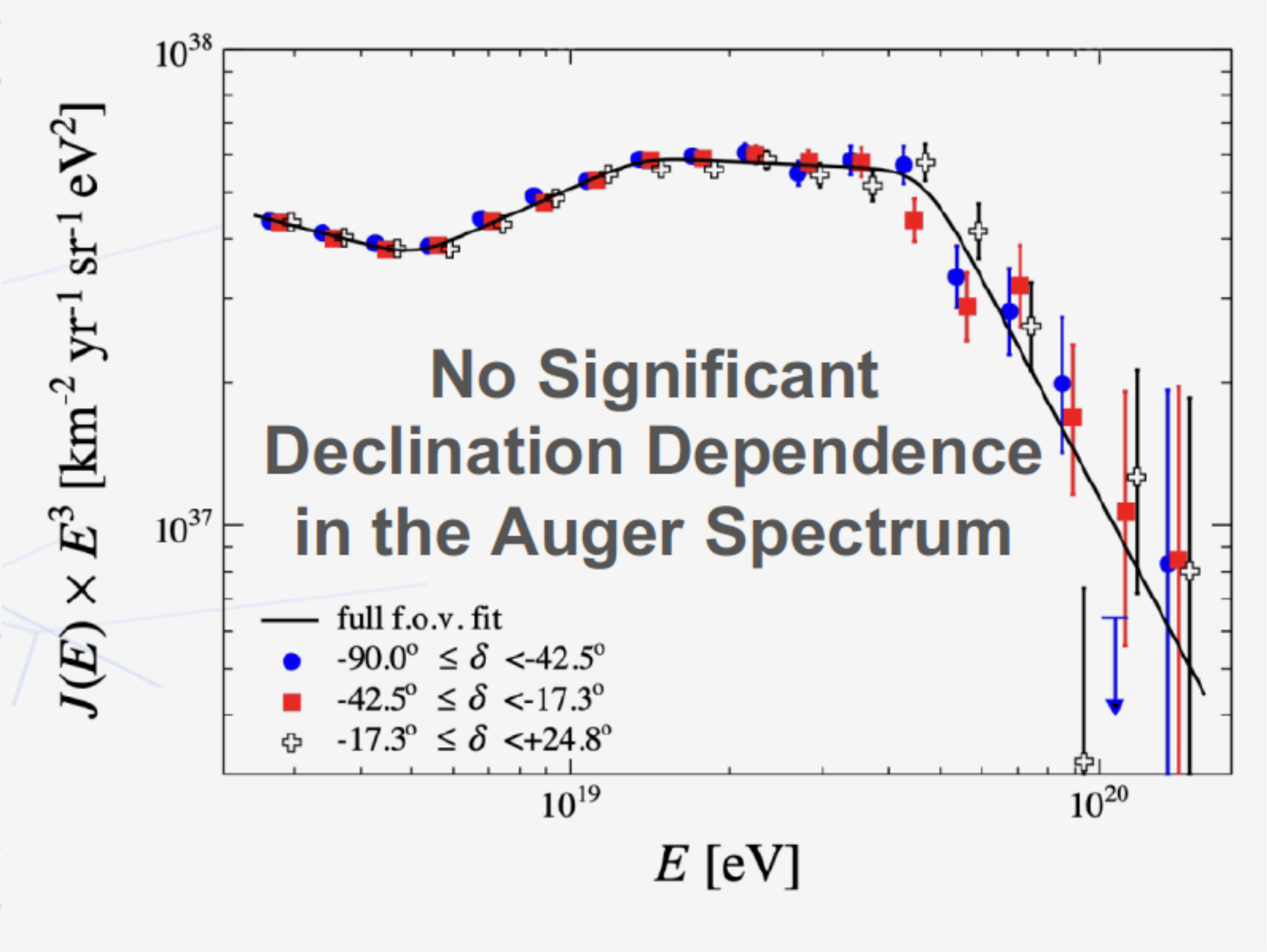
Current UHECR Picture: Energy Spectrum

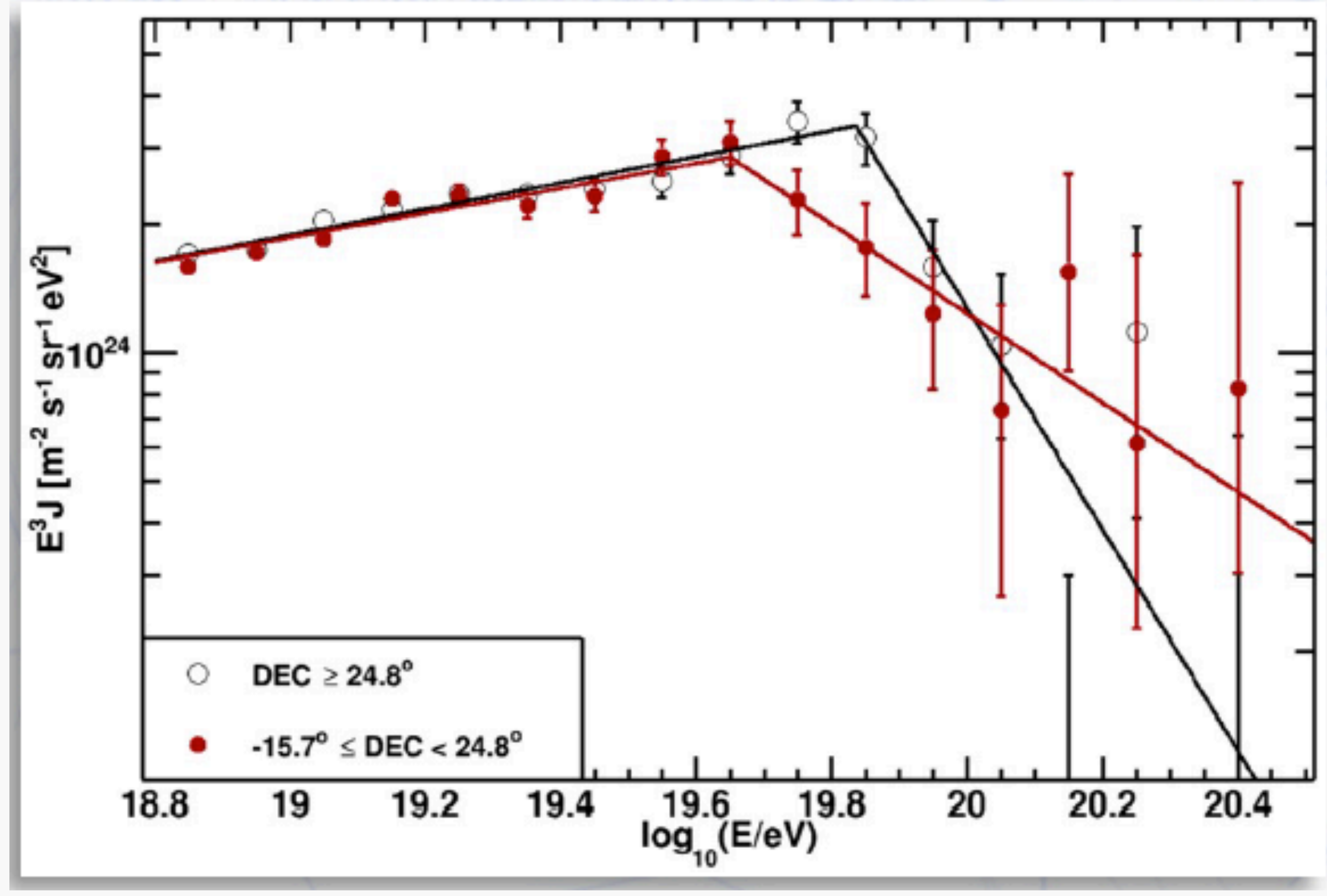


Differences in the UHECR spectra as measured as two experiments!

Current UHECR Picture: Energy Spectrum

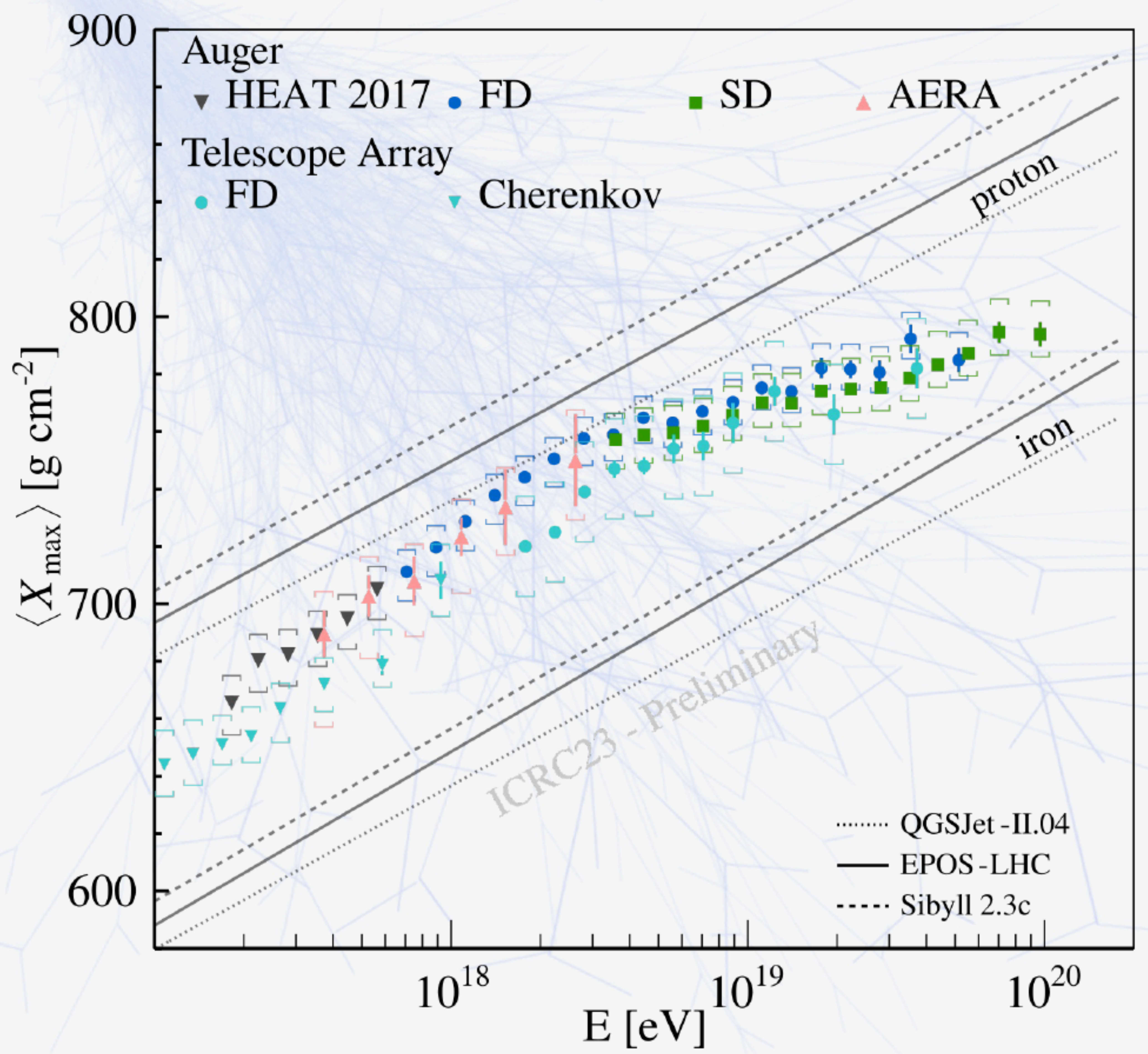


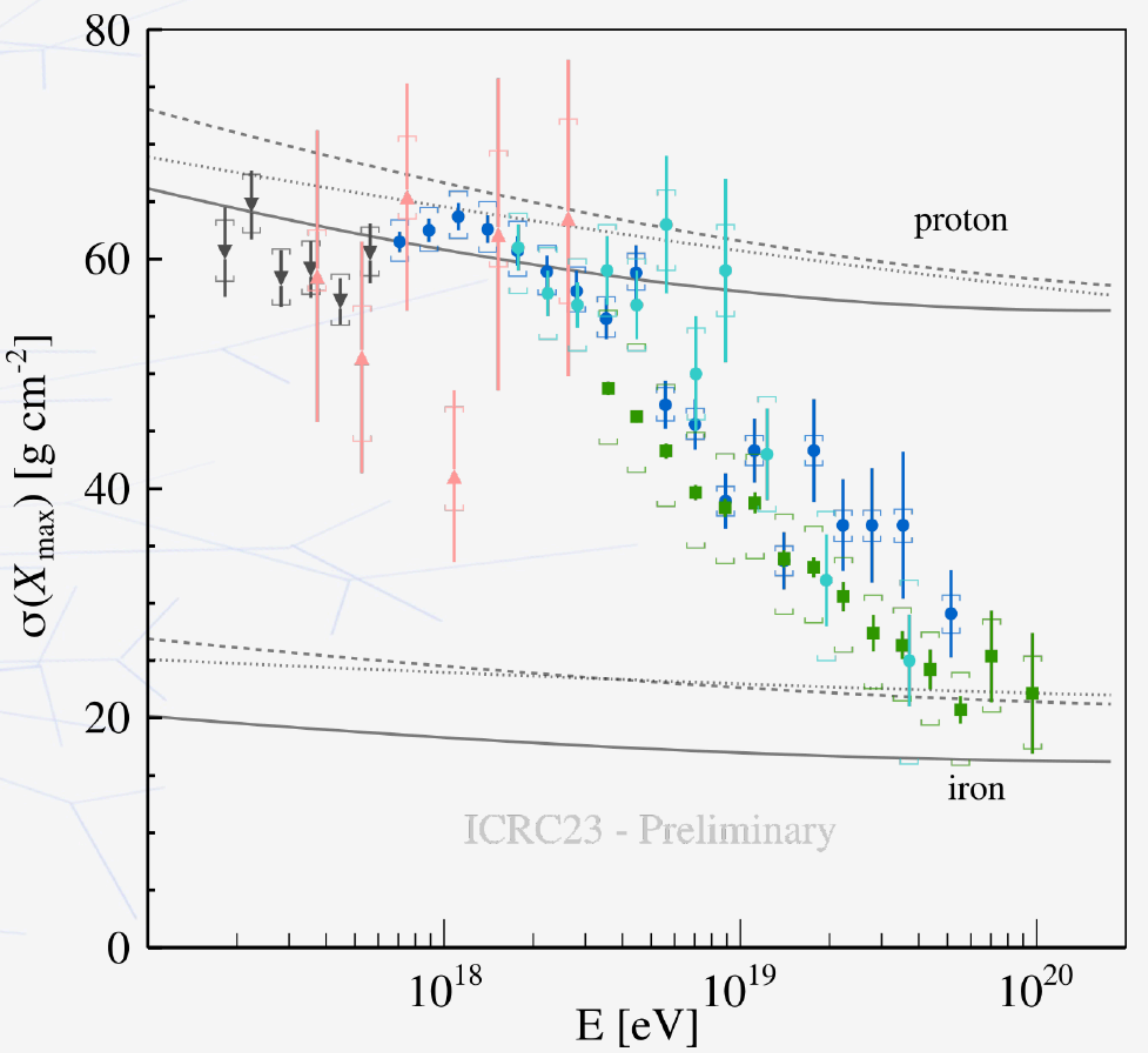




Differences in fluorescence yield, invisible energy, etc…
Possible astrophysical explanation?

Current UHECR Picture: Mass composition





Auger and TA measurements are in agreement!

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

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

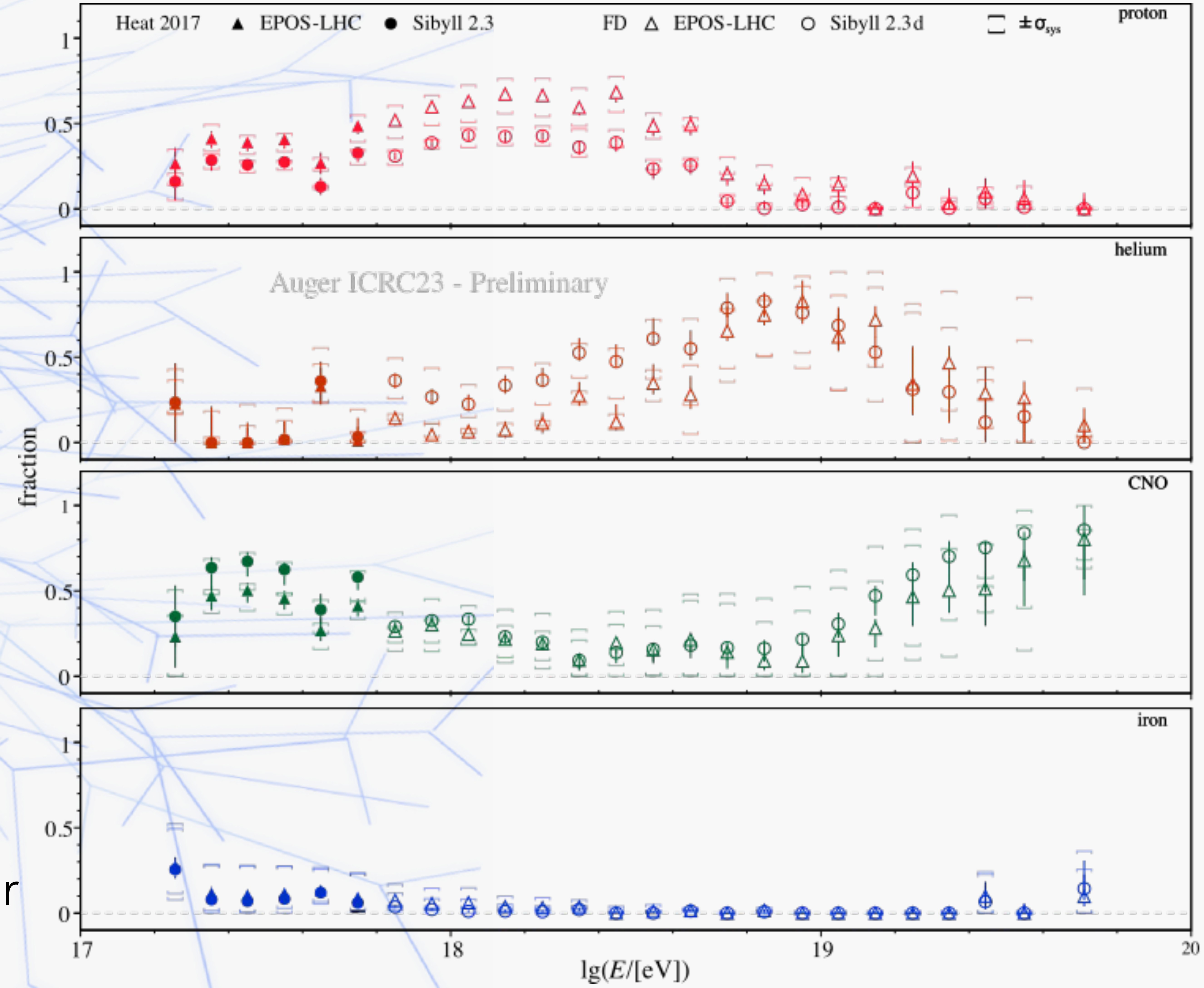
Current UHECR Picture: Mass composition

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

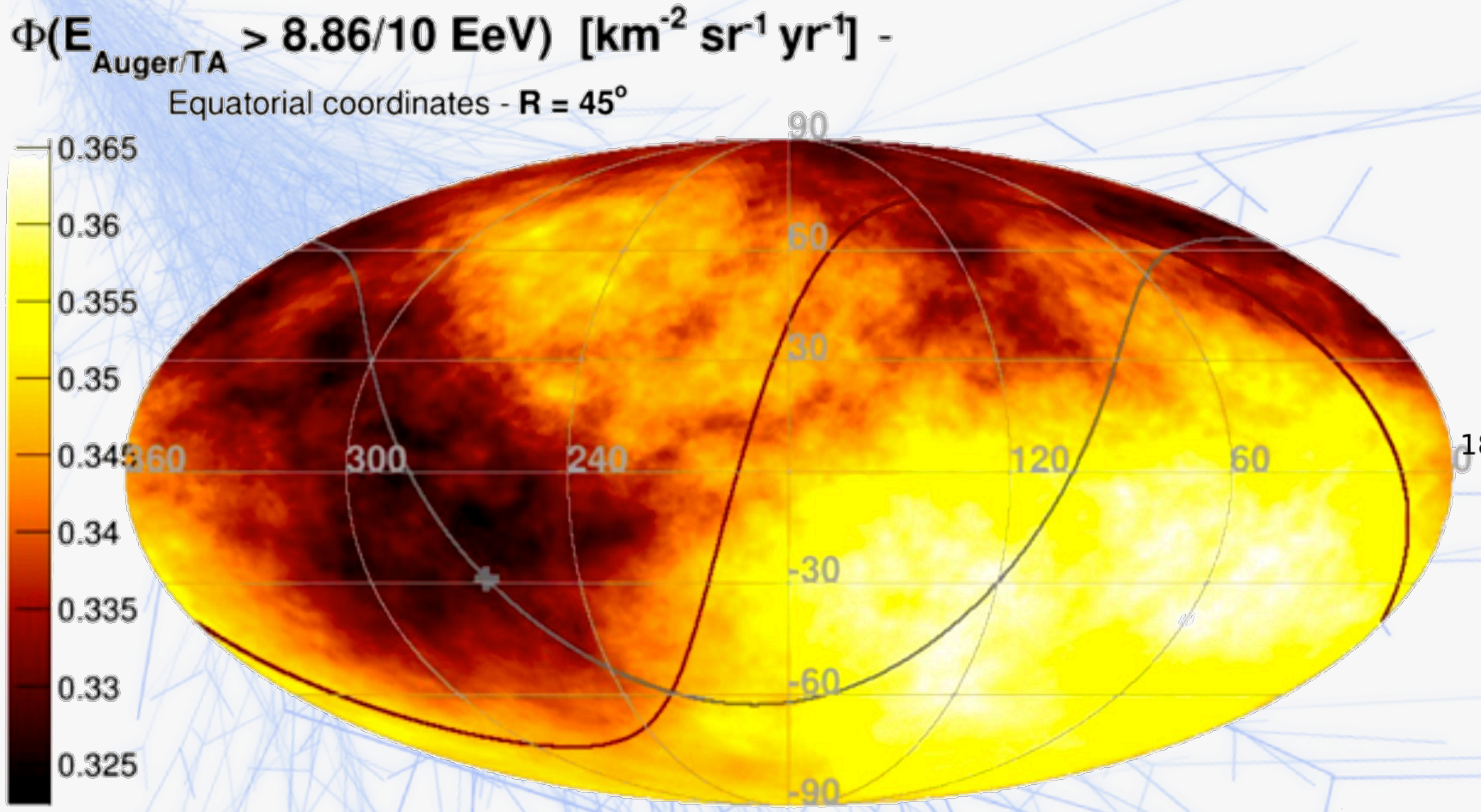
Helium: peaks at ~ 8 EeV
→ roughly ~ 4 times higher energy than protons

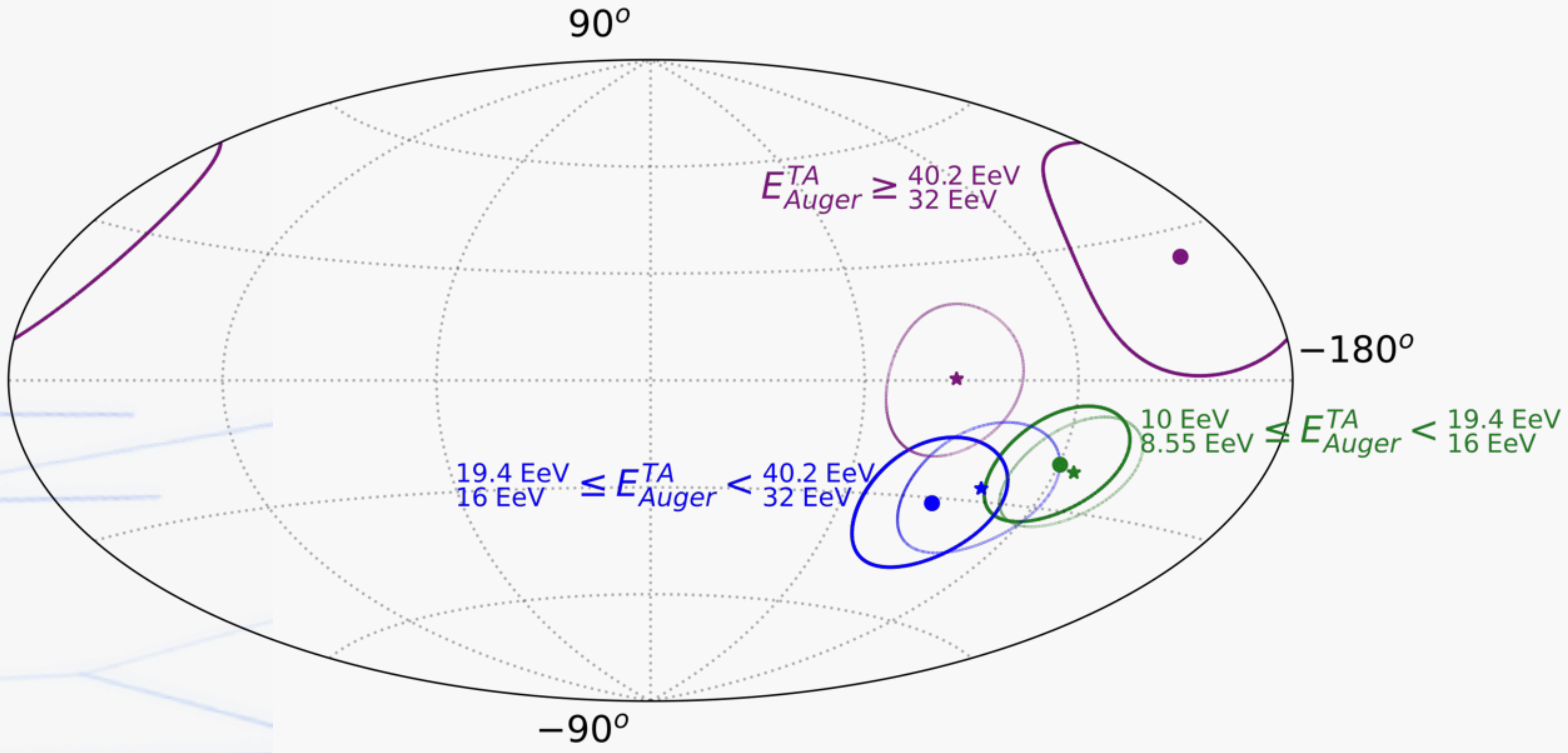
CNO: fraction continues to climb up to ~ 50 EeV
and may continue beyond

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

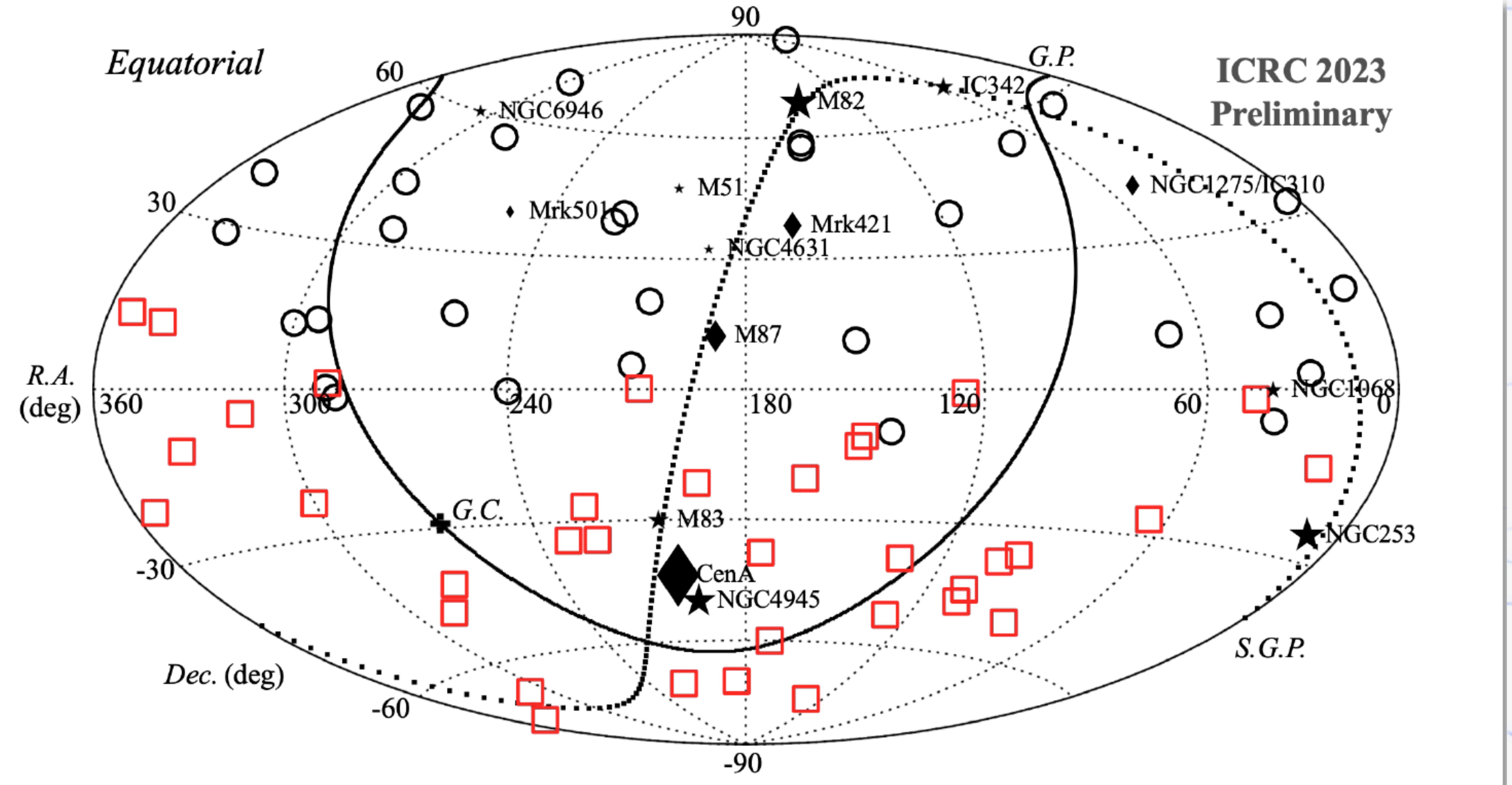
➢ equal sensitivity anywhere in the sky

➢ 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

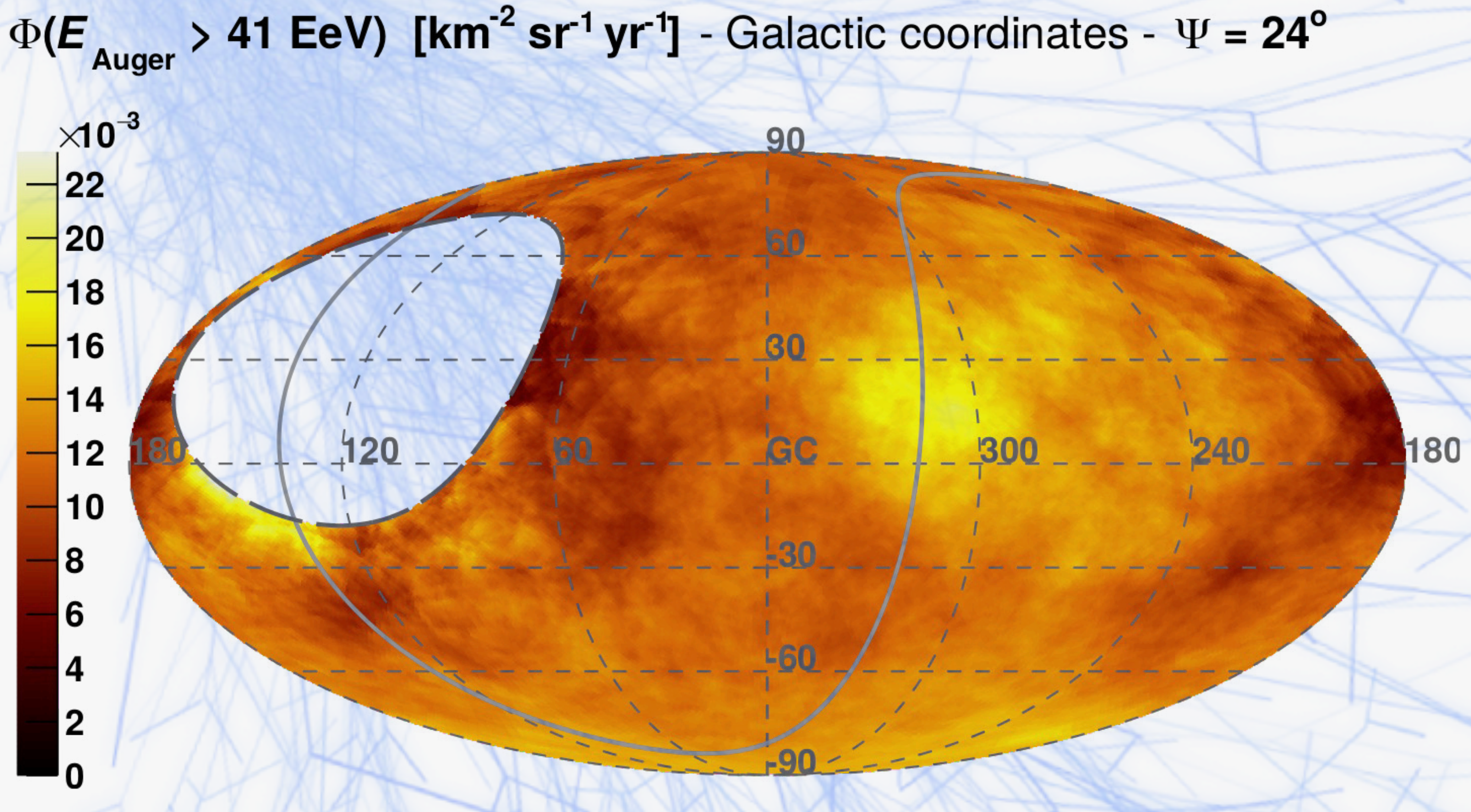
Current UHECR Picture: Arrival direction



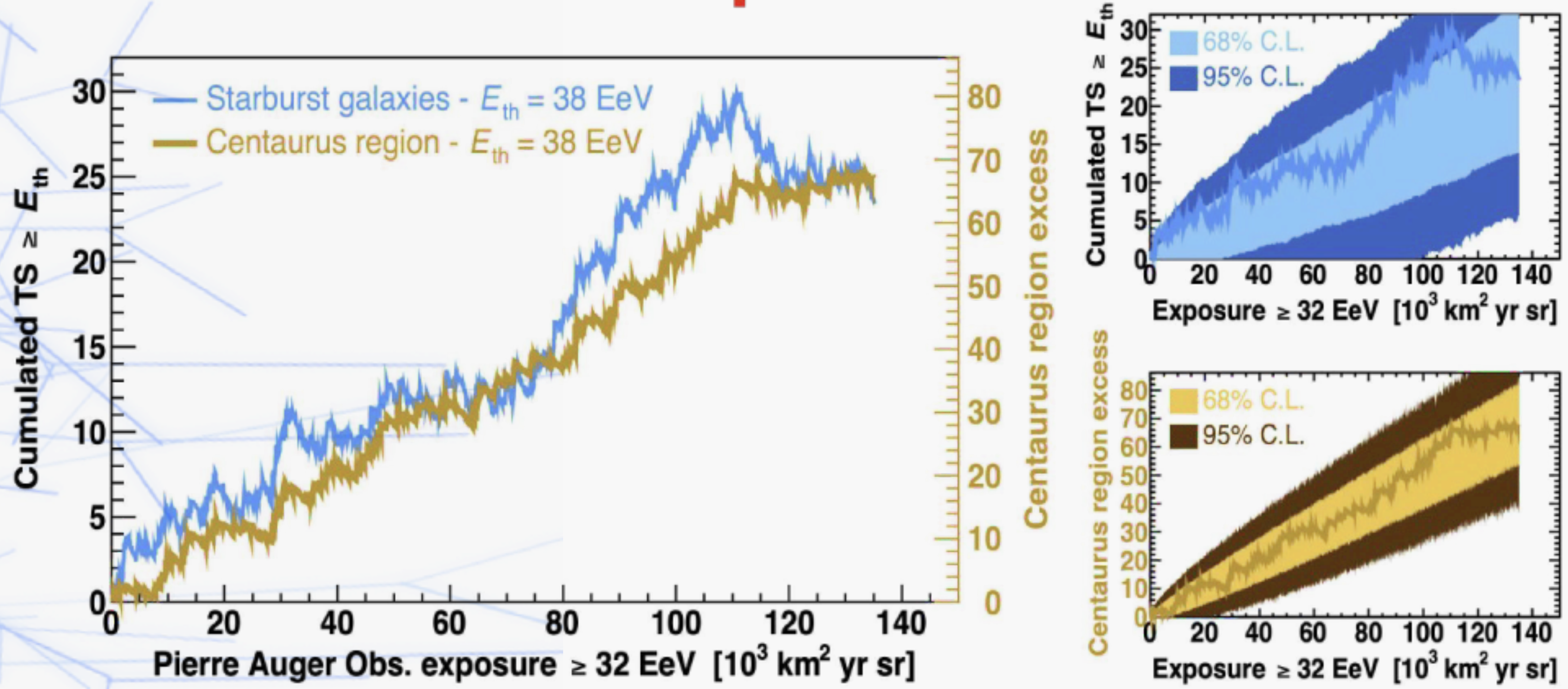
TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

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



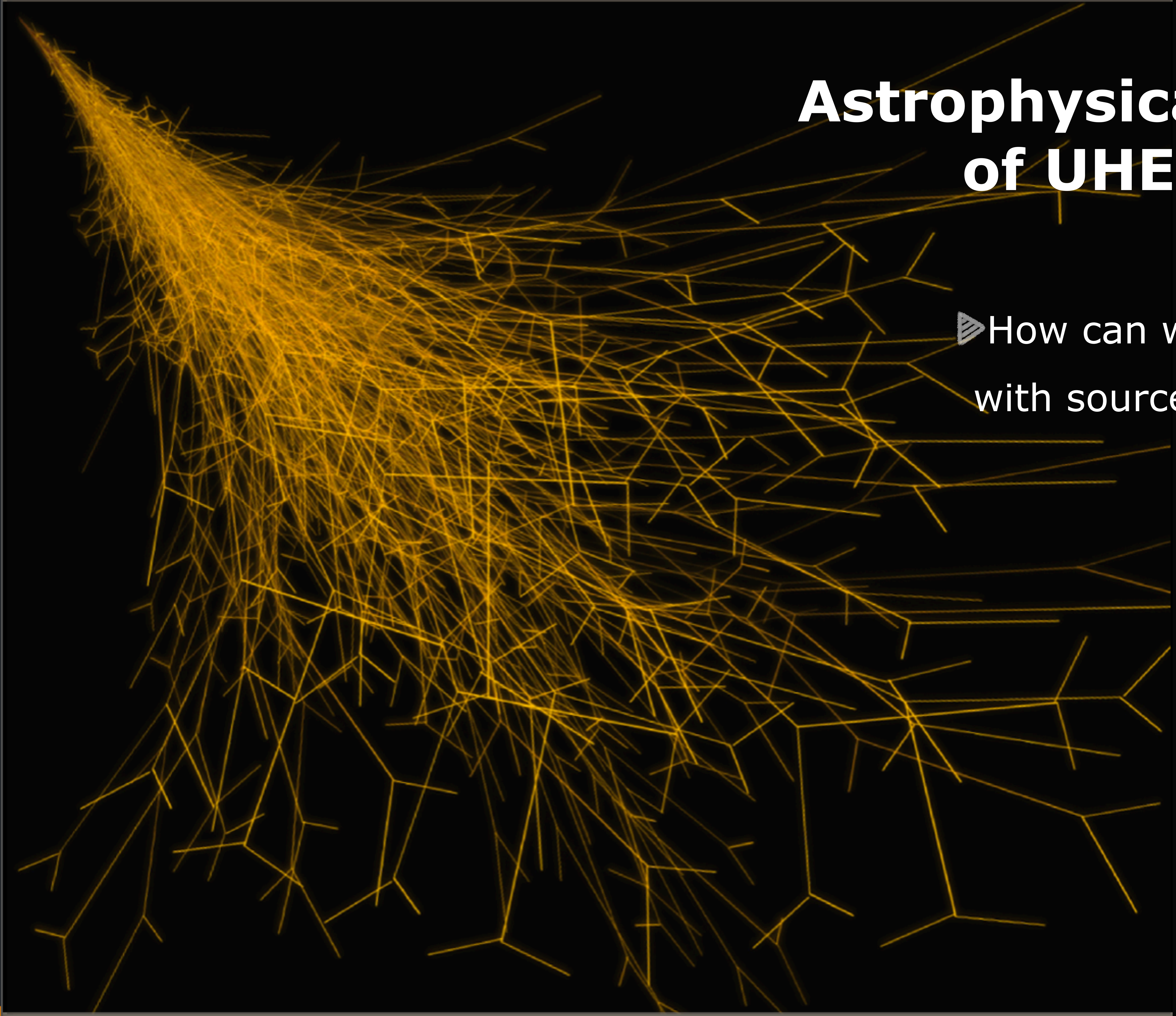
~90% isotropic distribution



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?



Astrophysical interpretation of UHECR sources

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

Narrowing down Source Candidates In Southern Sky

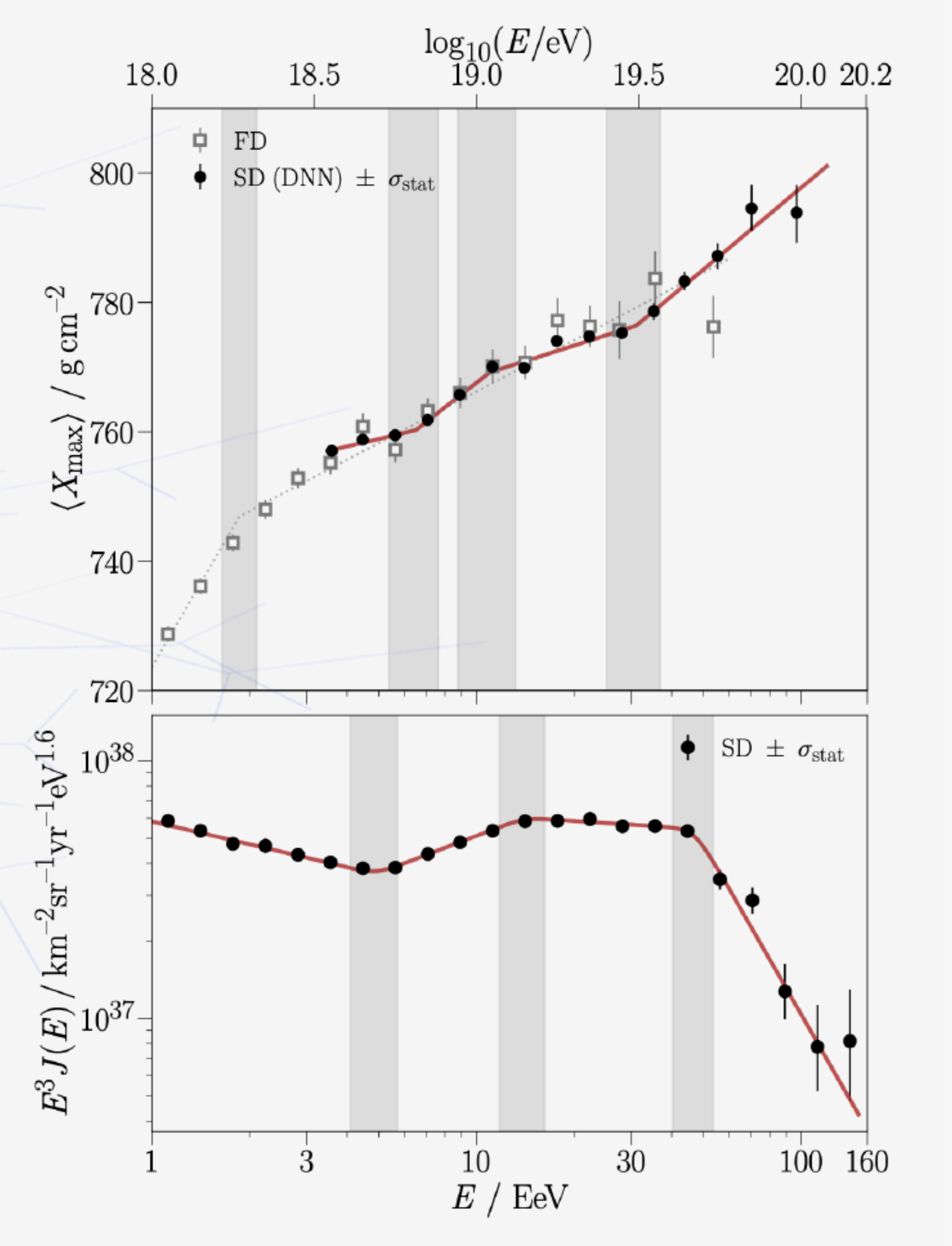
Features in spectrum and composition do not coincide –> why?
It is possible to link features in the UHECRs to astrophysical processes?

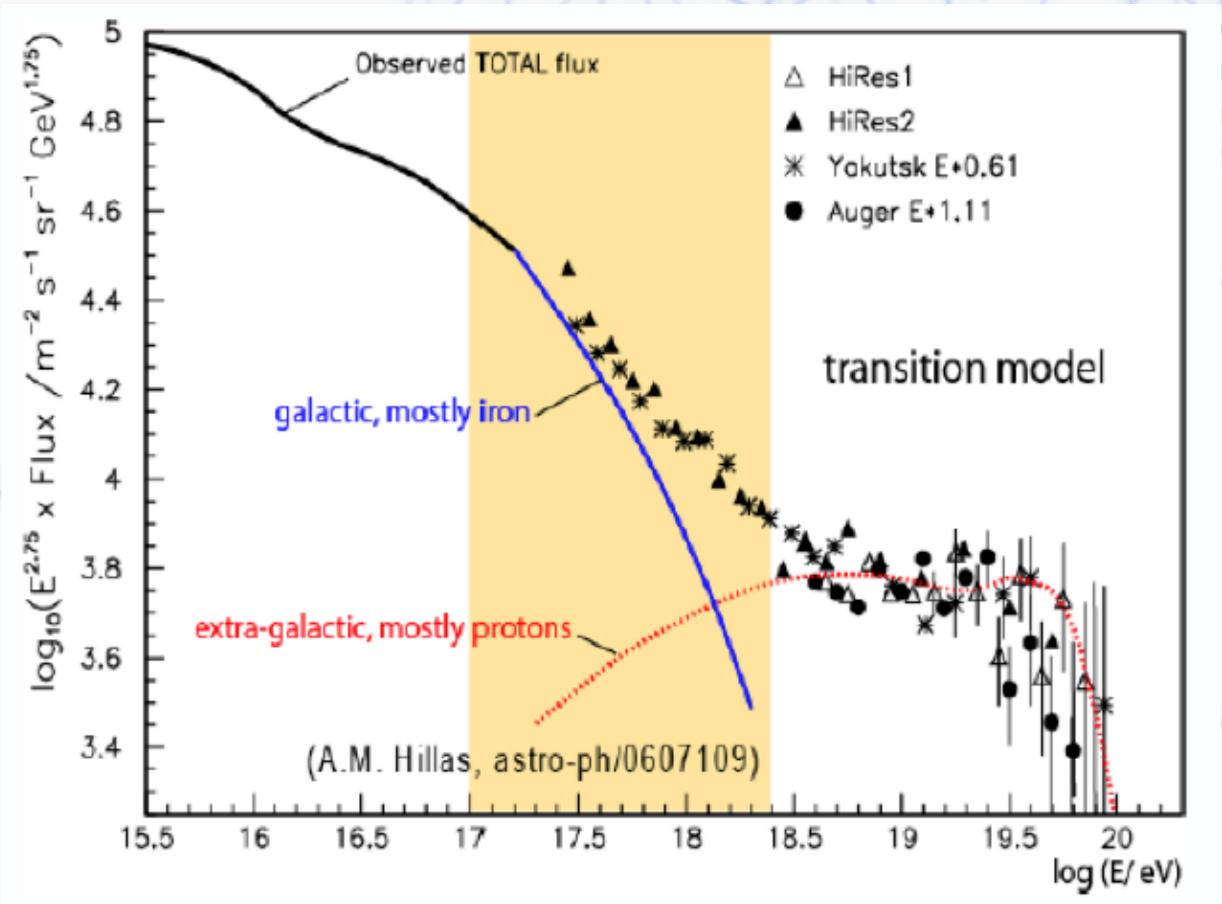
Several possible explanations:

- Transition model;
- Pure proton scenario;
- Mixed composition scenario;

How to disentangle this?

Transition model





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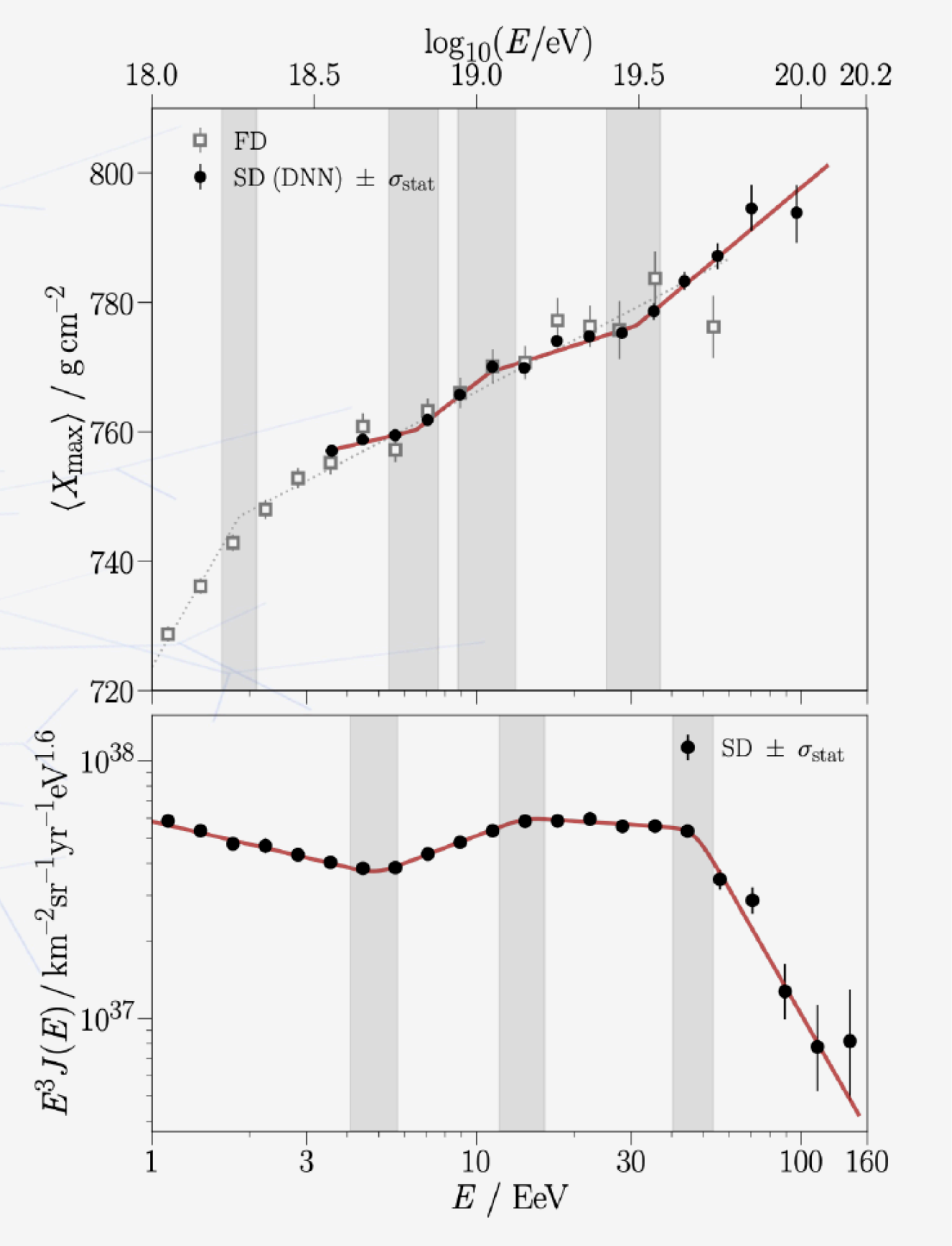
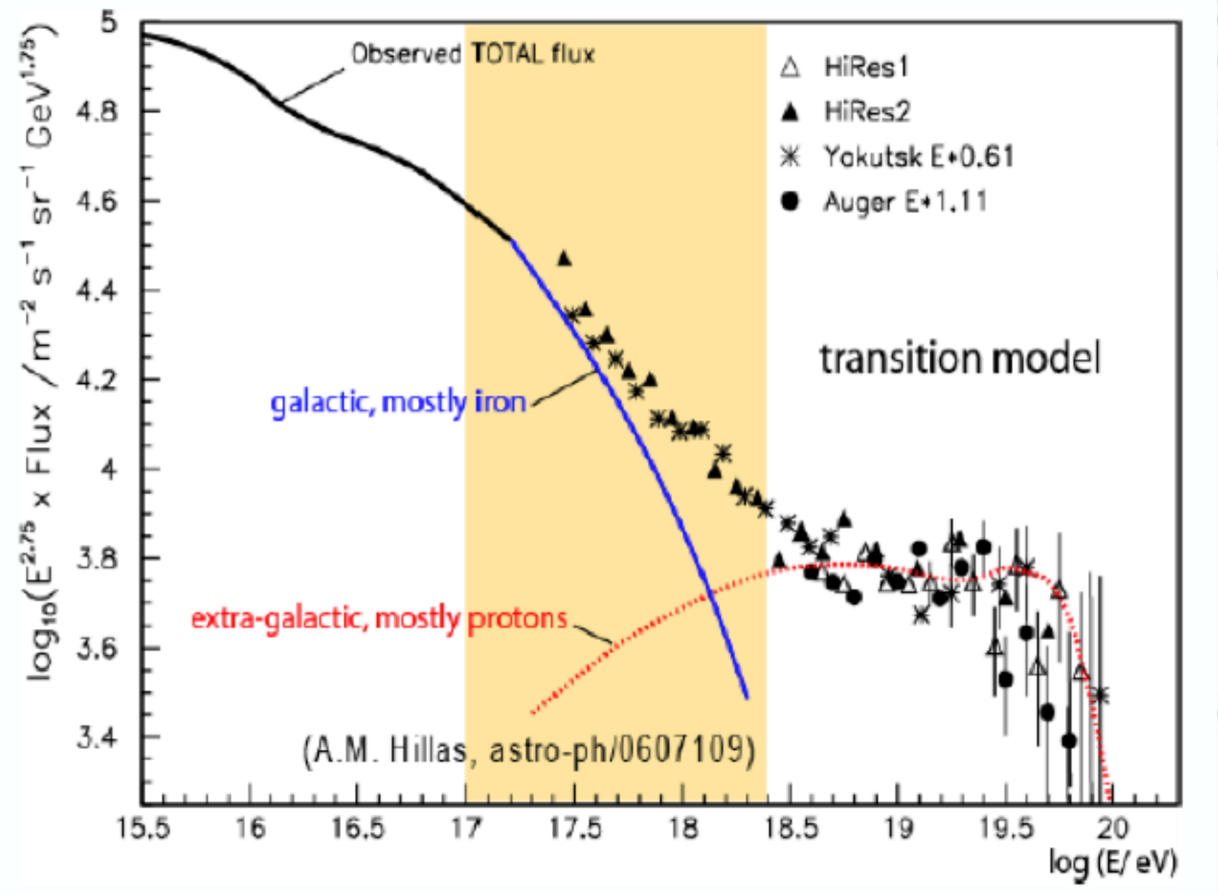
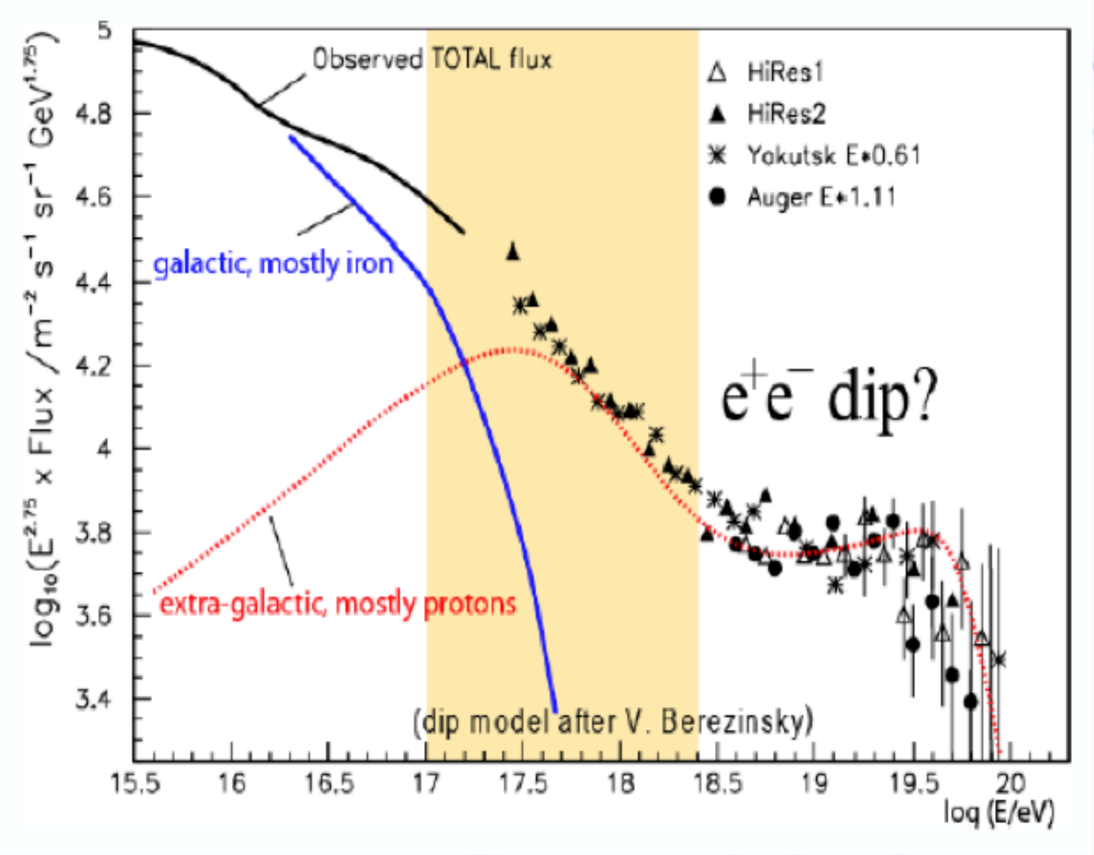


How to disentangle this?

Transition model



Pure proton scenario



Narrowing down Source Candidates In Southern Sky

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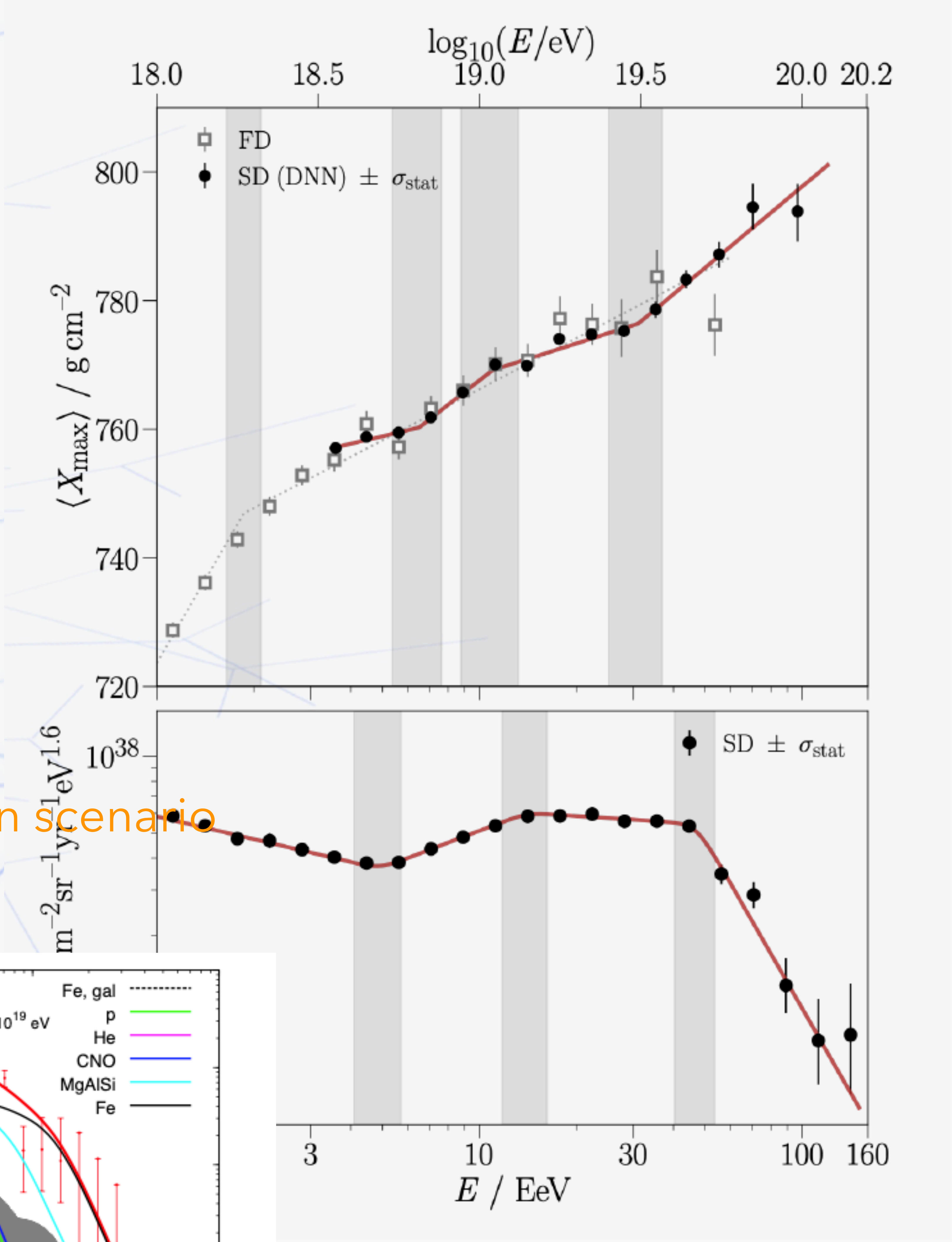
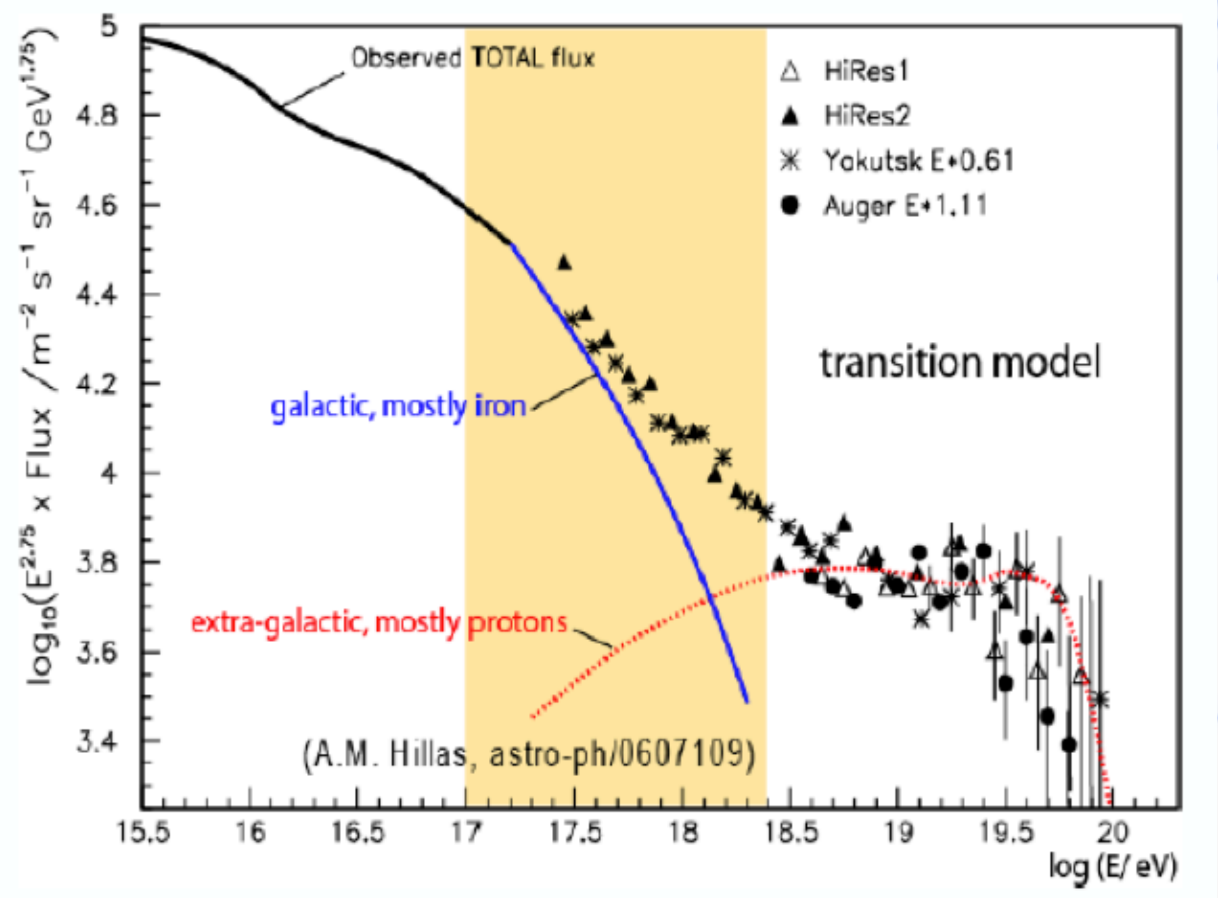


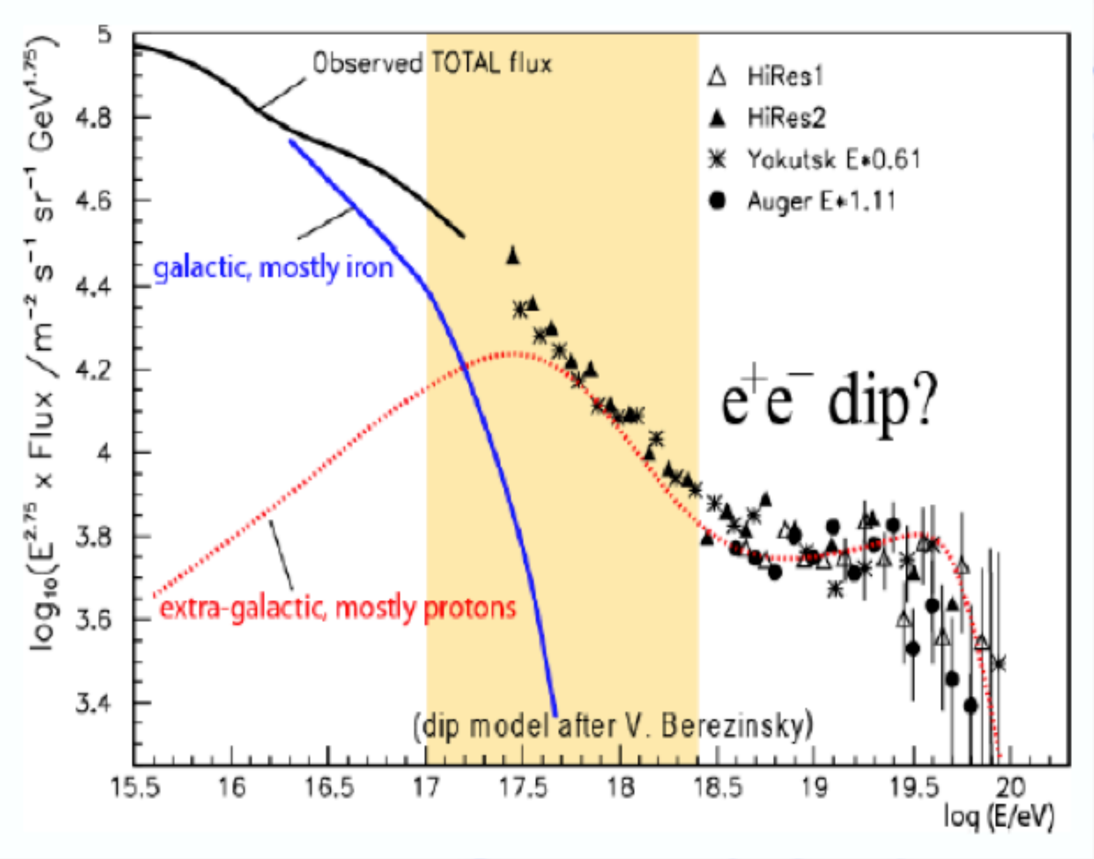
How to disentangle this?

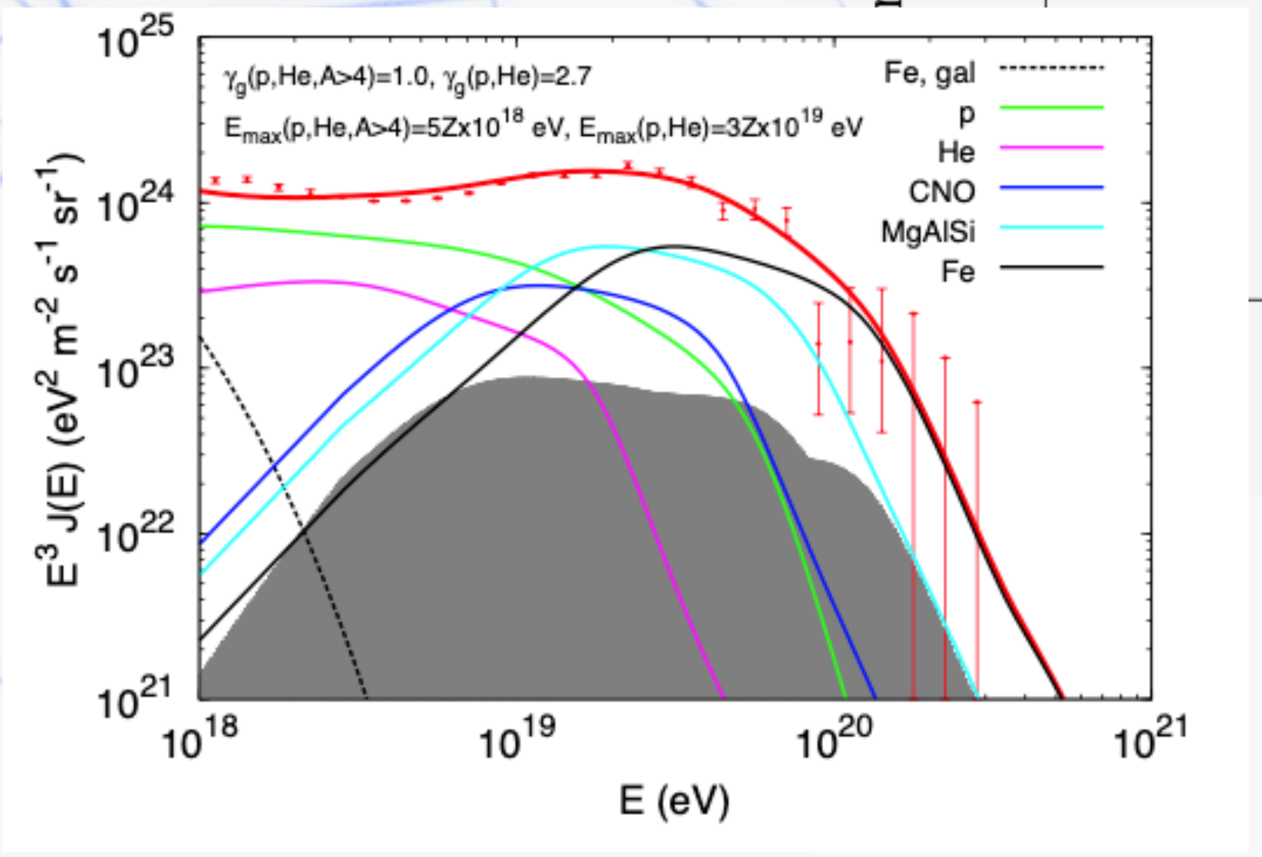
Transition model

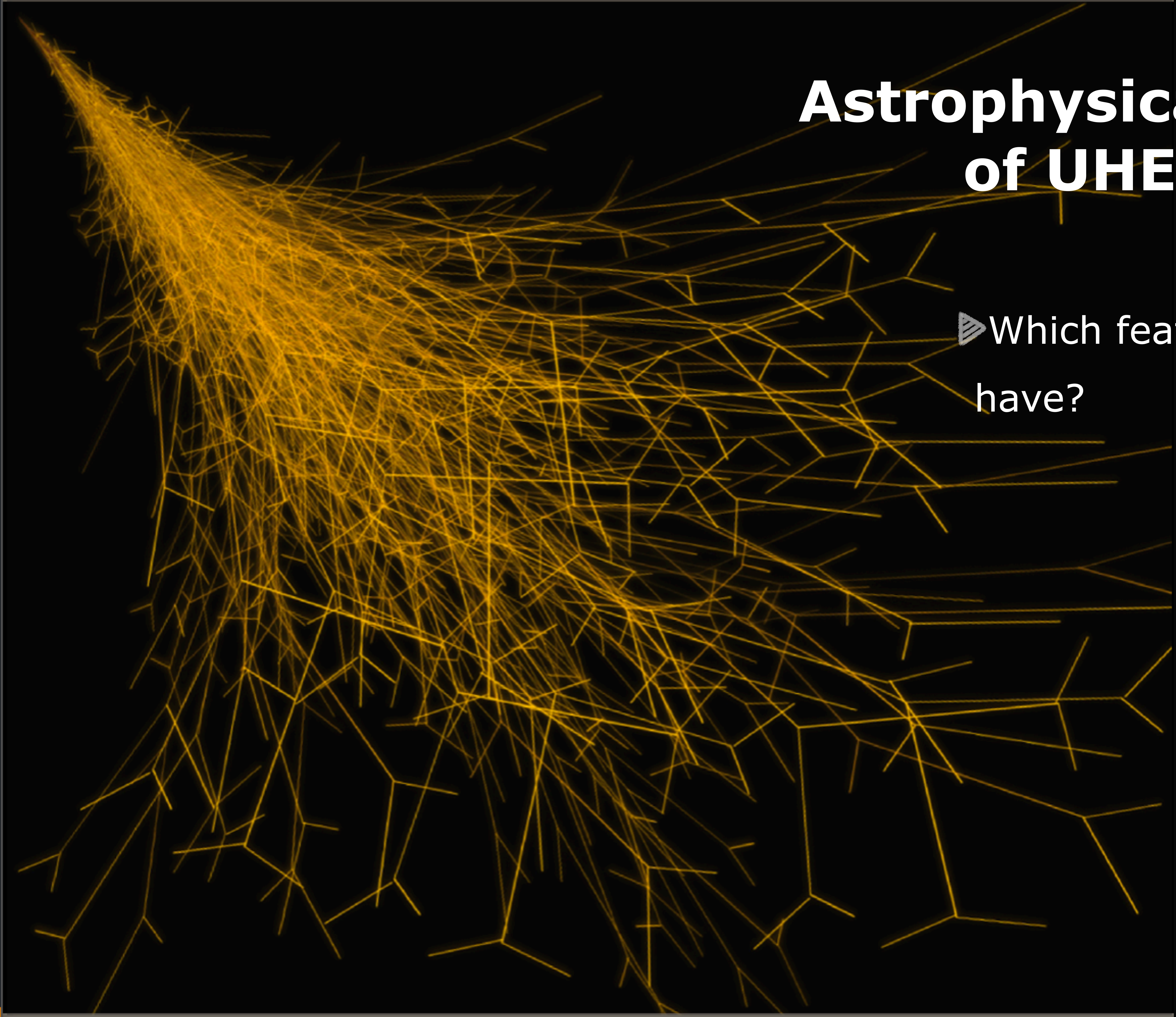
Pure proton scenario

Mixed composition scenario



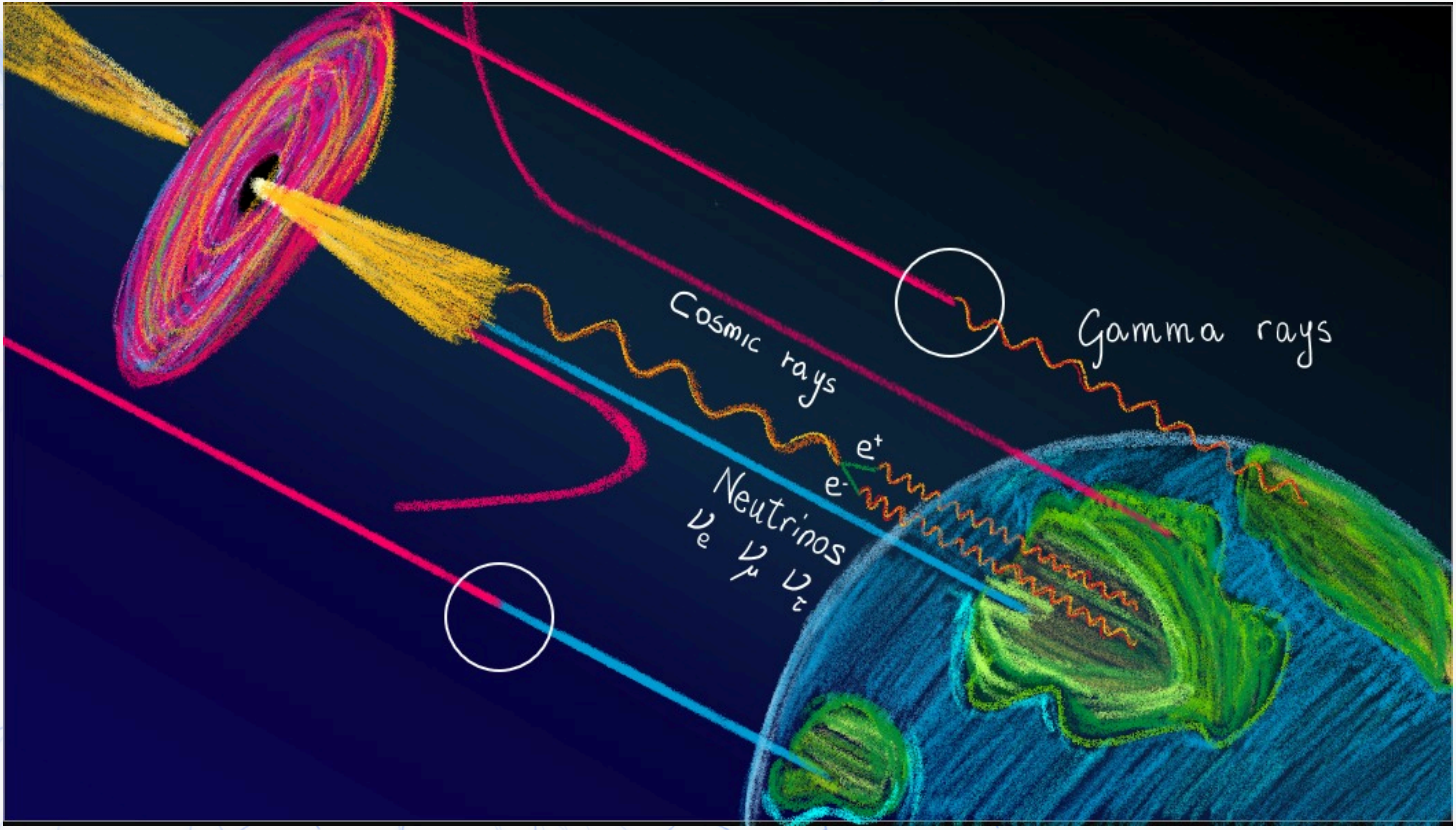






Astrophysical interpretation of UHECR sources

- Which features UHECR sources should have?

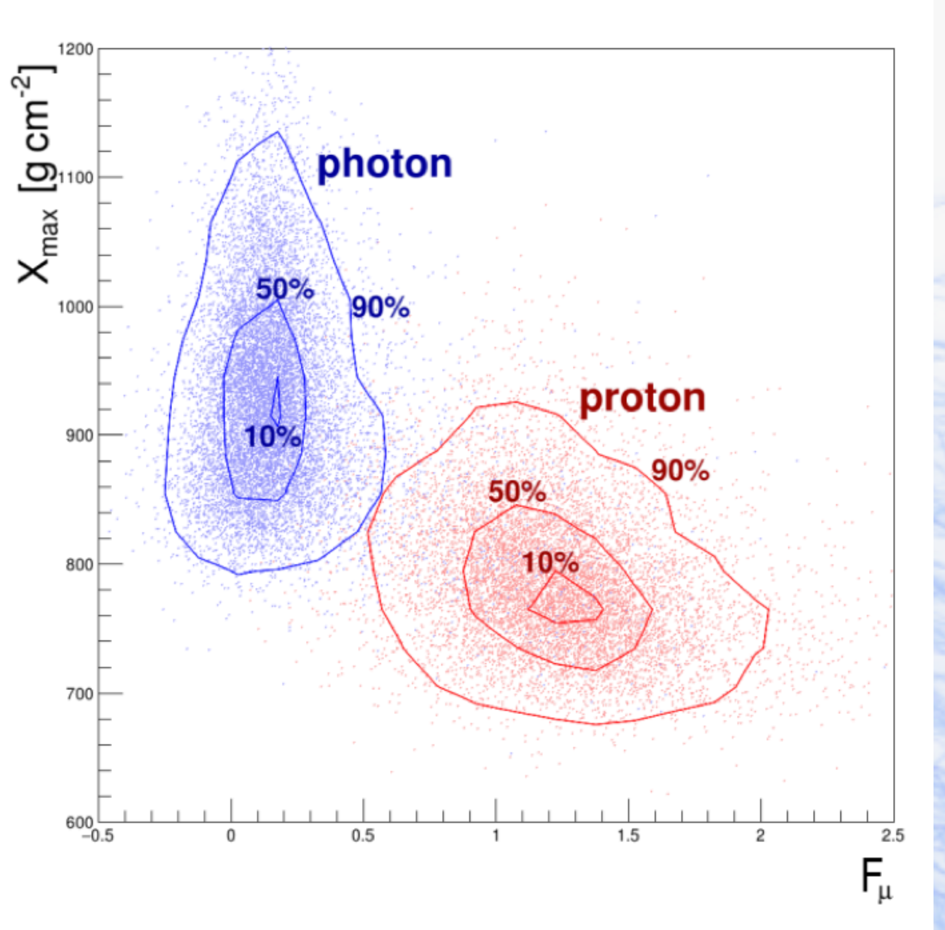

Cosmic rays
Gamma rays
e^+
e^-
Neutrinos
ν_e ν_μ ν_τ

Astrophysical interpretation of UHECR data

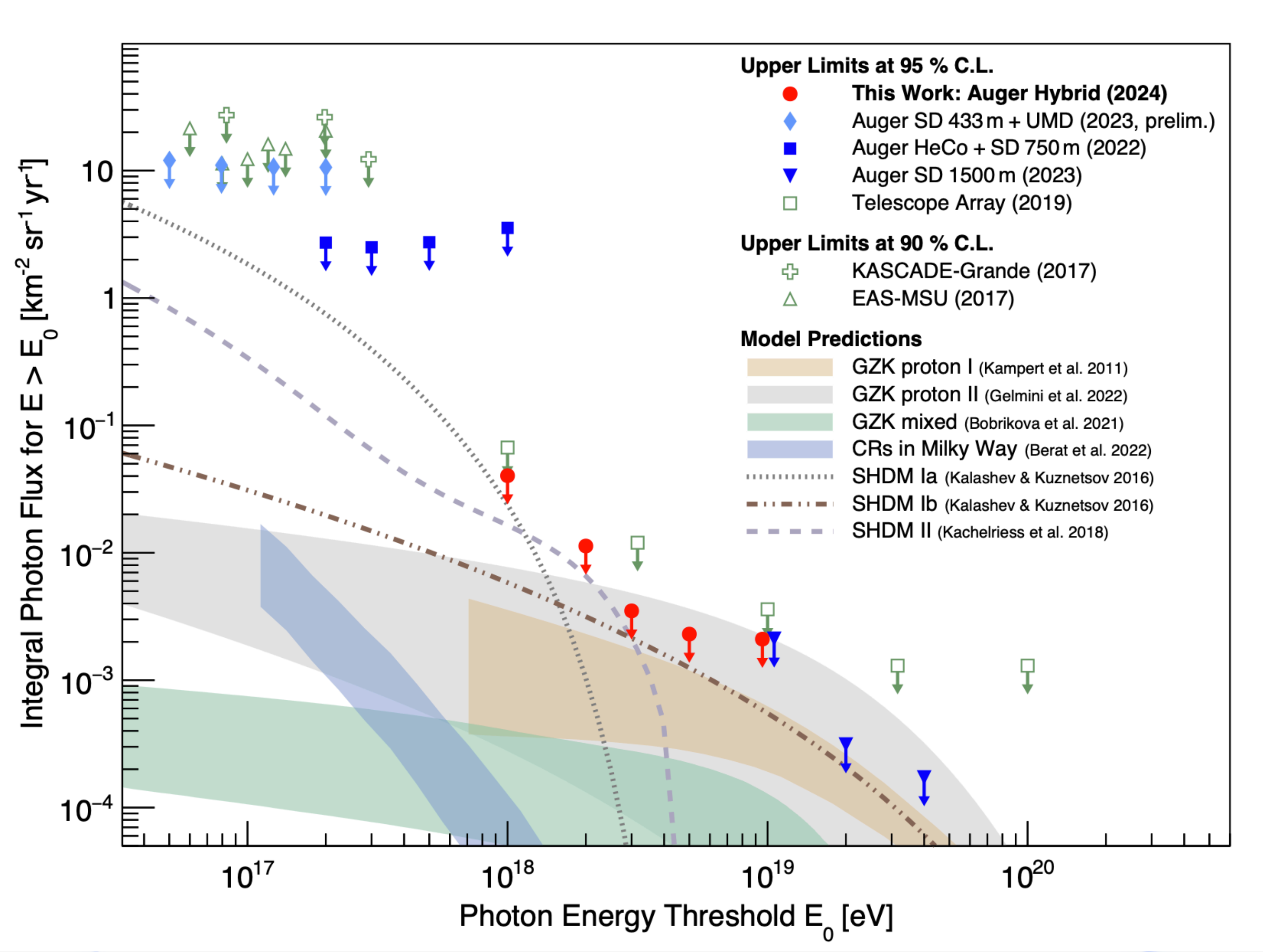
Minimal cosmological model, by assuming identical and point-like sources as standard candles emitting with a power law and rigidity cutoff;

- Minimal scenario above the ankle (arXiv:1612.07155);
- Minimal scenario above the ankle+ fit of proton fraction below the ankle (arXiv:2207.08092v1);
- Fit below the ankle with two independent components (arXiv:2211.02857);
- Fit below the ankle with a single component produced in starburst environment (arXiv:2209.08593v1);
- Fit above the ankle + including arrival direction (arXiv:2305.16693);
- Fit below the ankle + EG magnetic field (arXiv:2404.03533);
- Fit above the ankle + including arrival direction+ transient hypothesis (arXiv:2405.17179);

Multi-messenger observation



Photons interact deeper and with less muons



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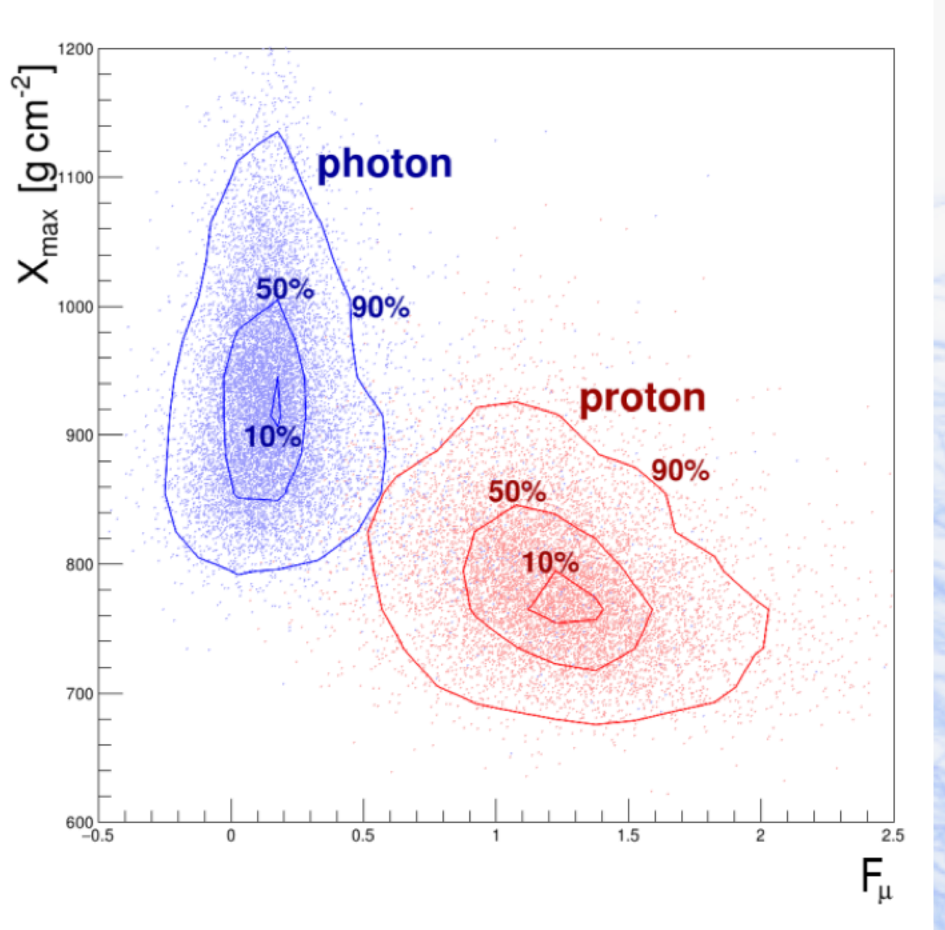

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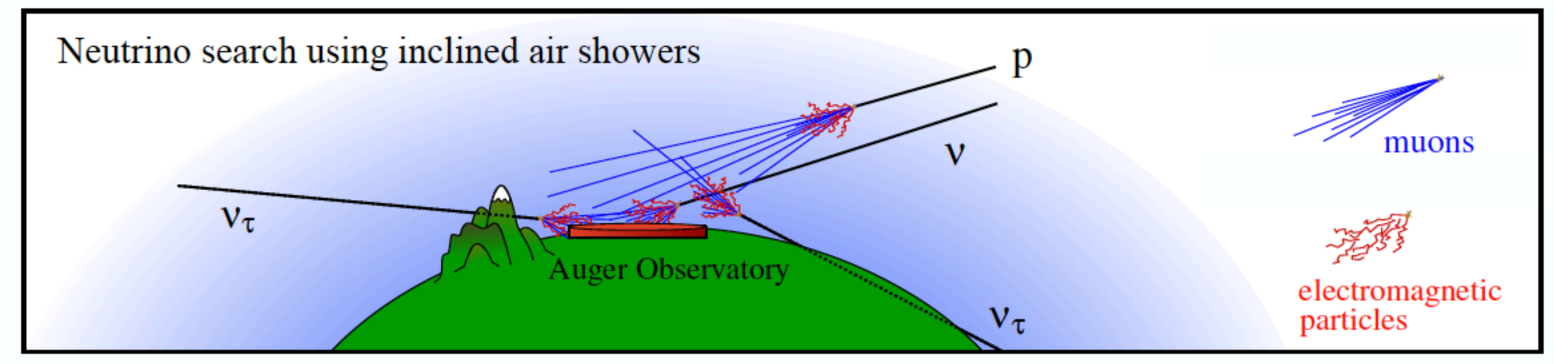
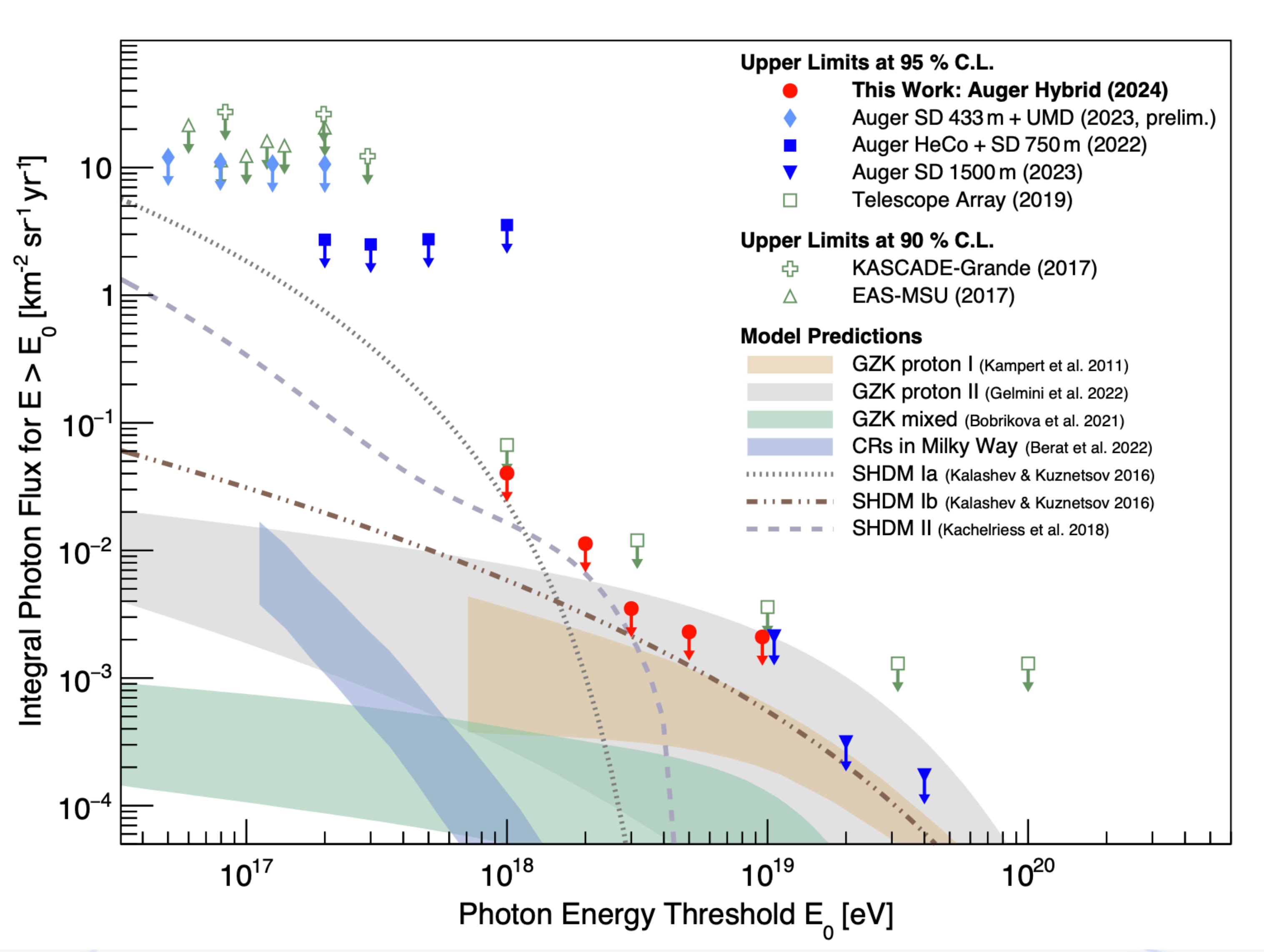
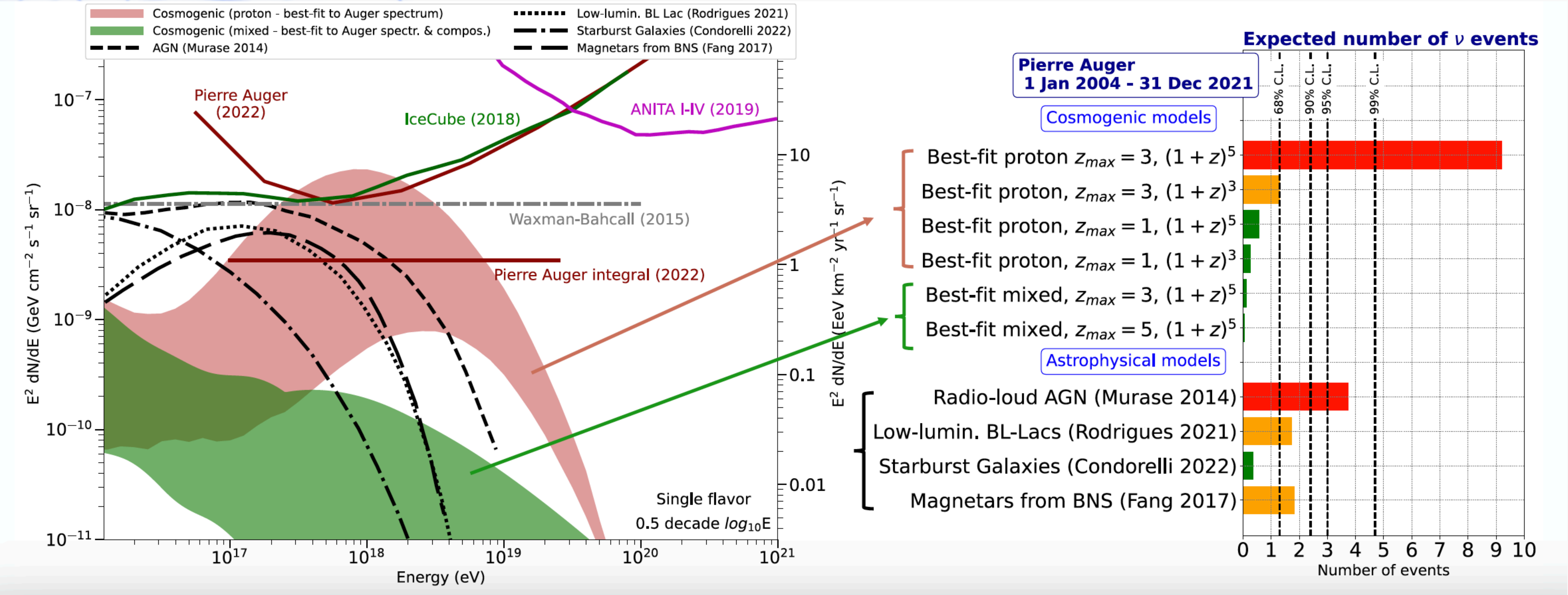


Aperture comparable to IceCube at highest energies Limits constrain astrophysical neutrino models

The high-energy Universe in photons and neutrinos is quite…





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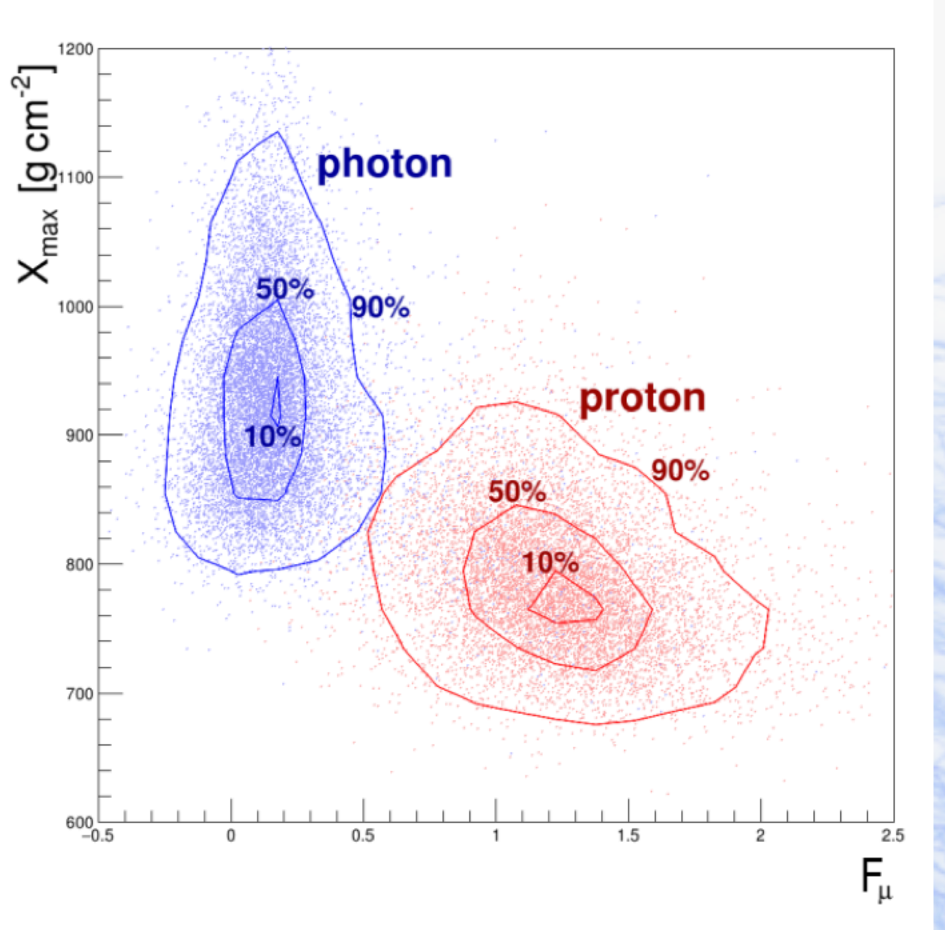

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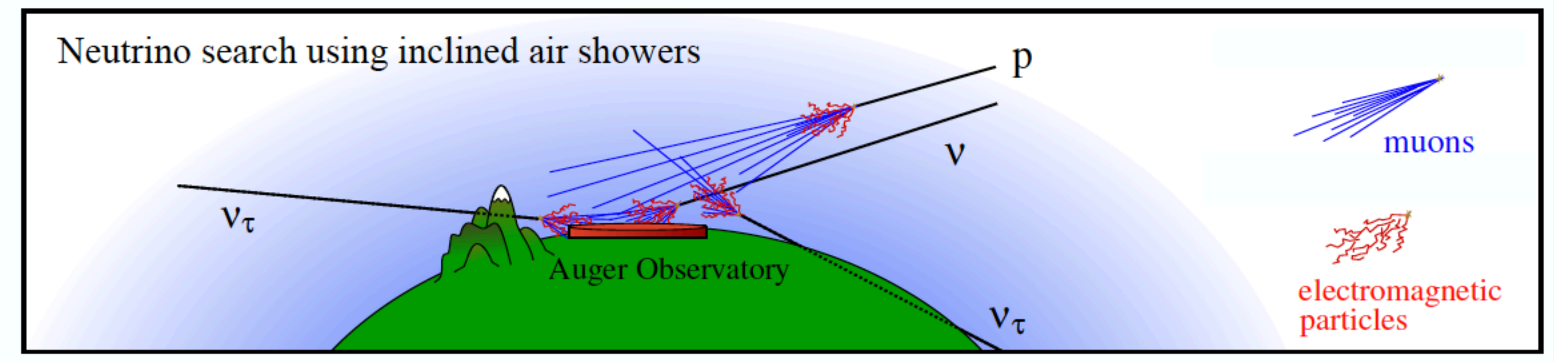
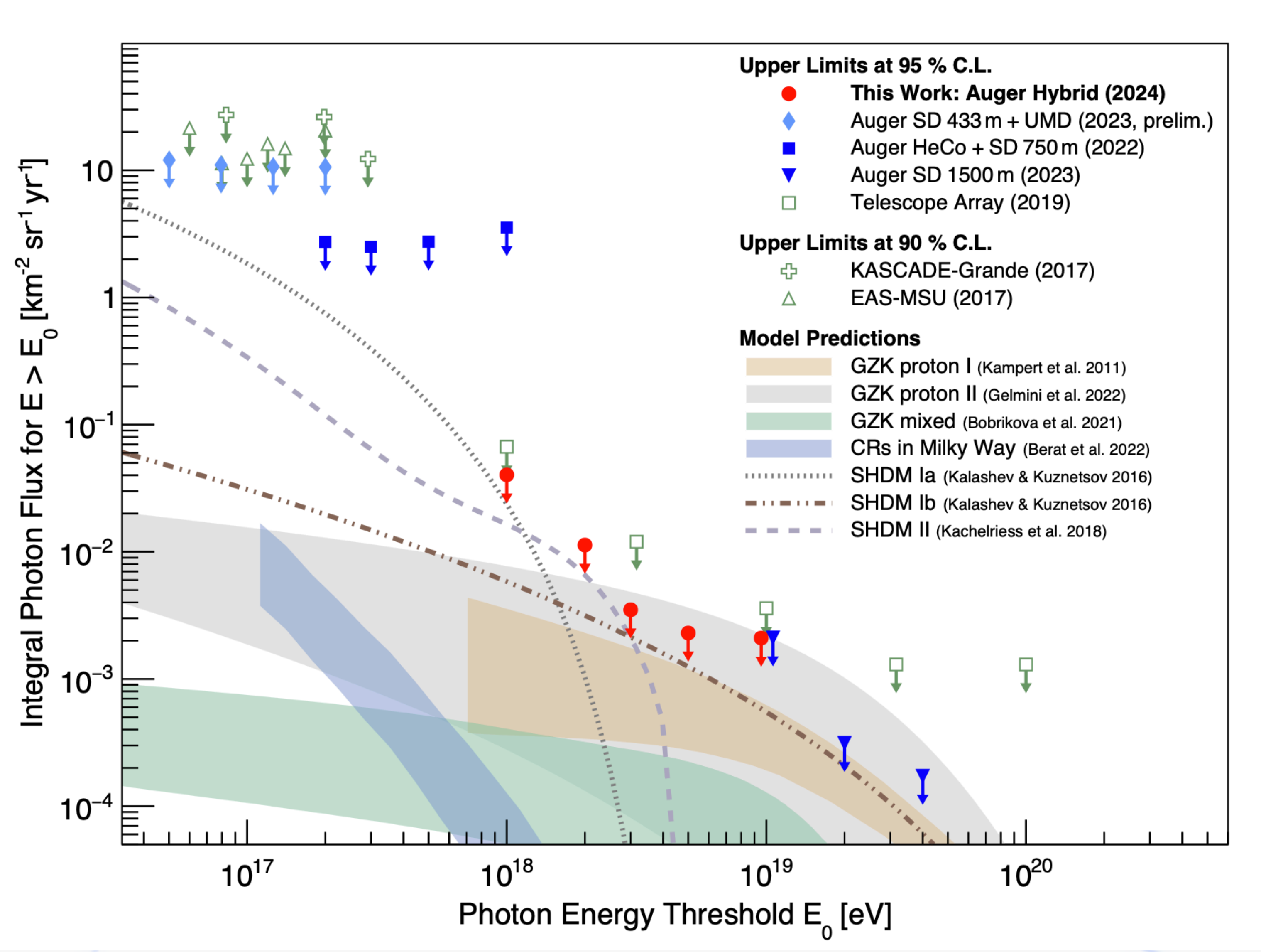
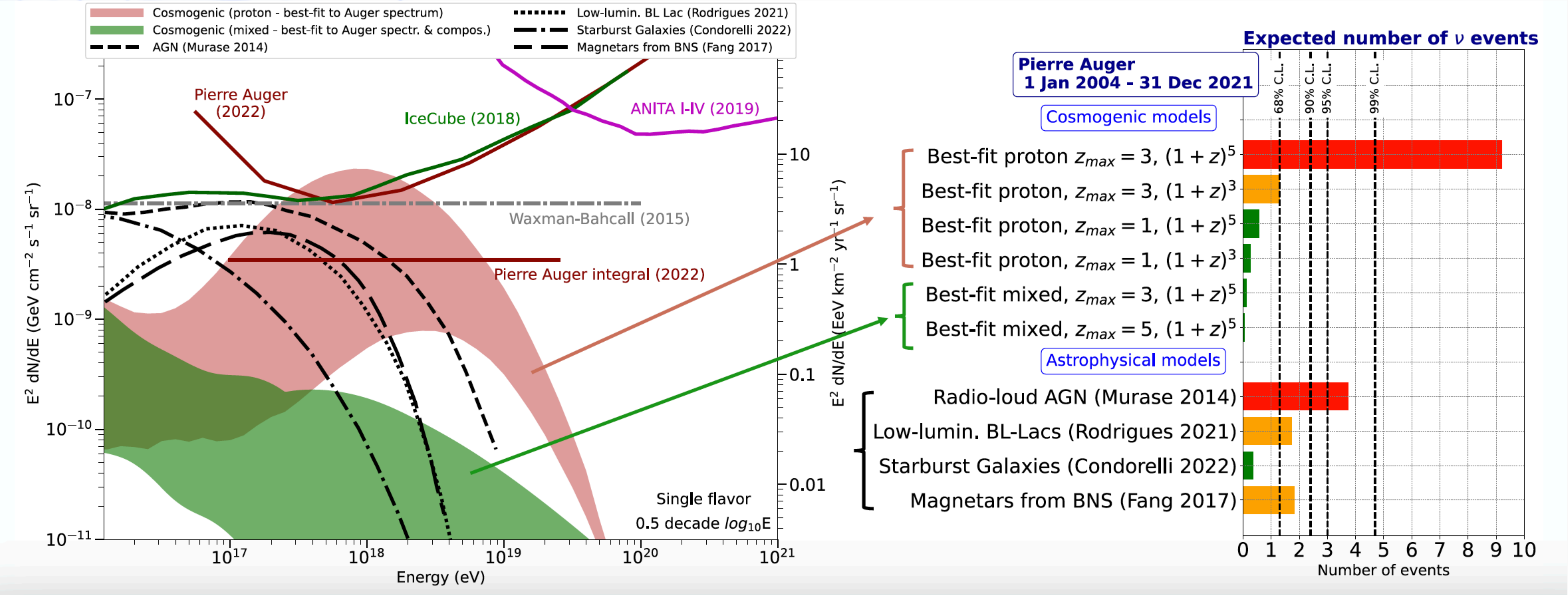
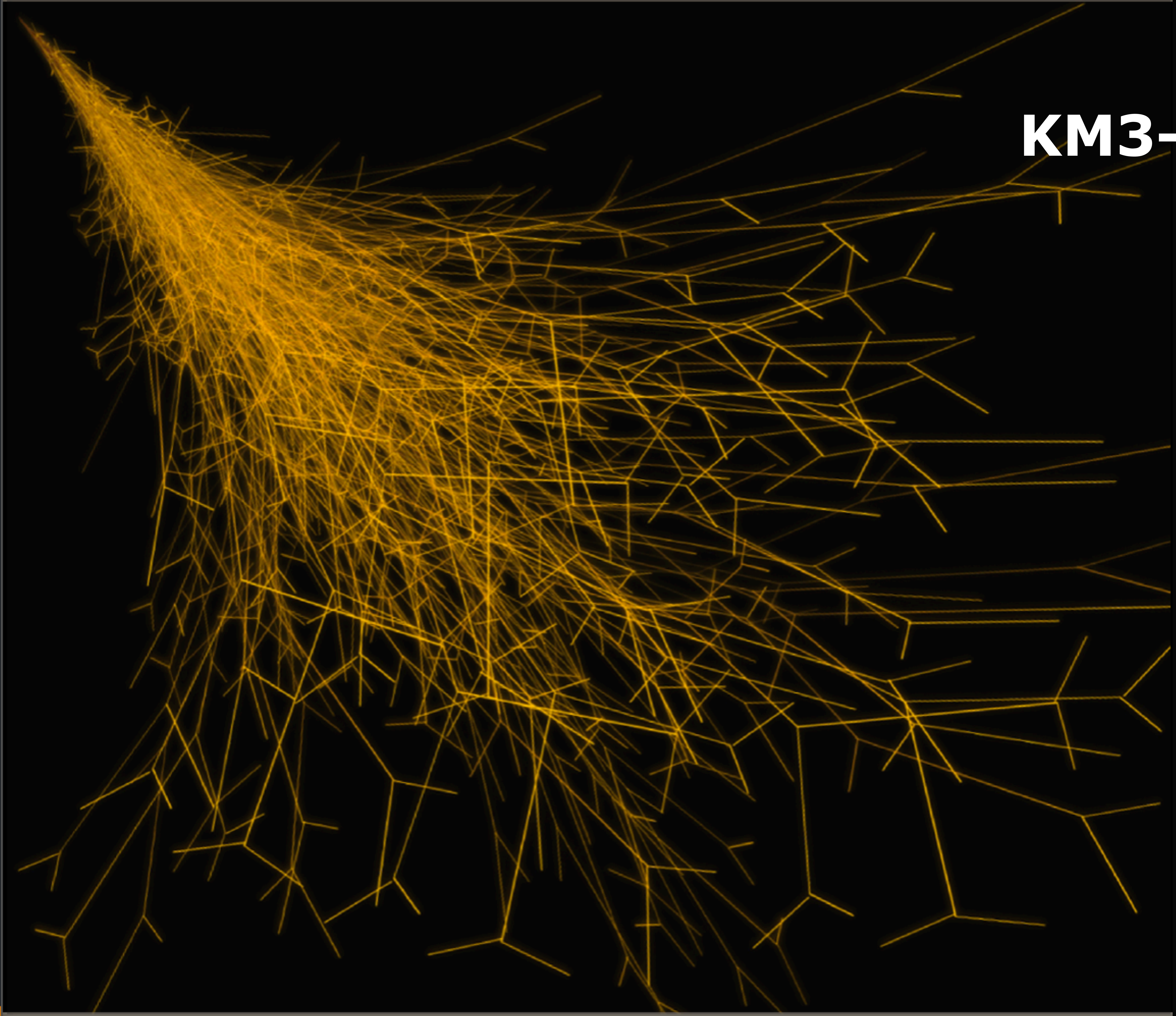


Aperture comparable to IceCube at highest energies Limits constrain astrophysical neutrino models

The high-energy Universe in photons and neutrinos is quite… usually!

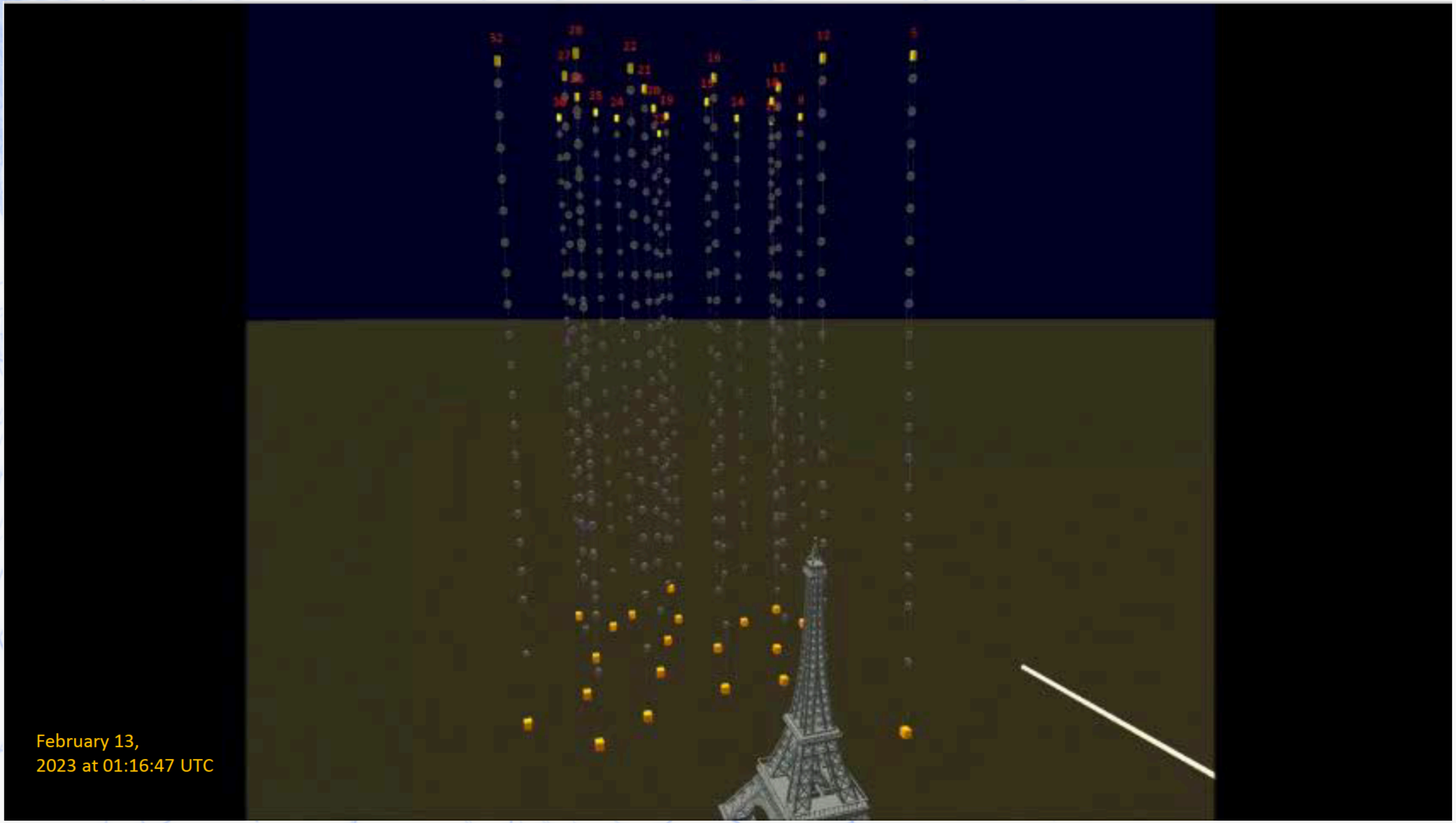




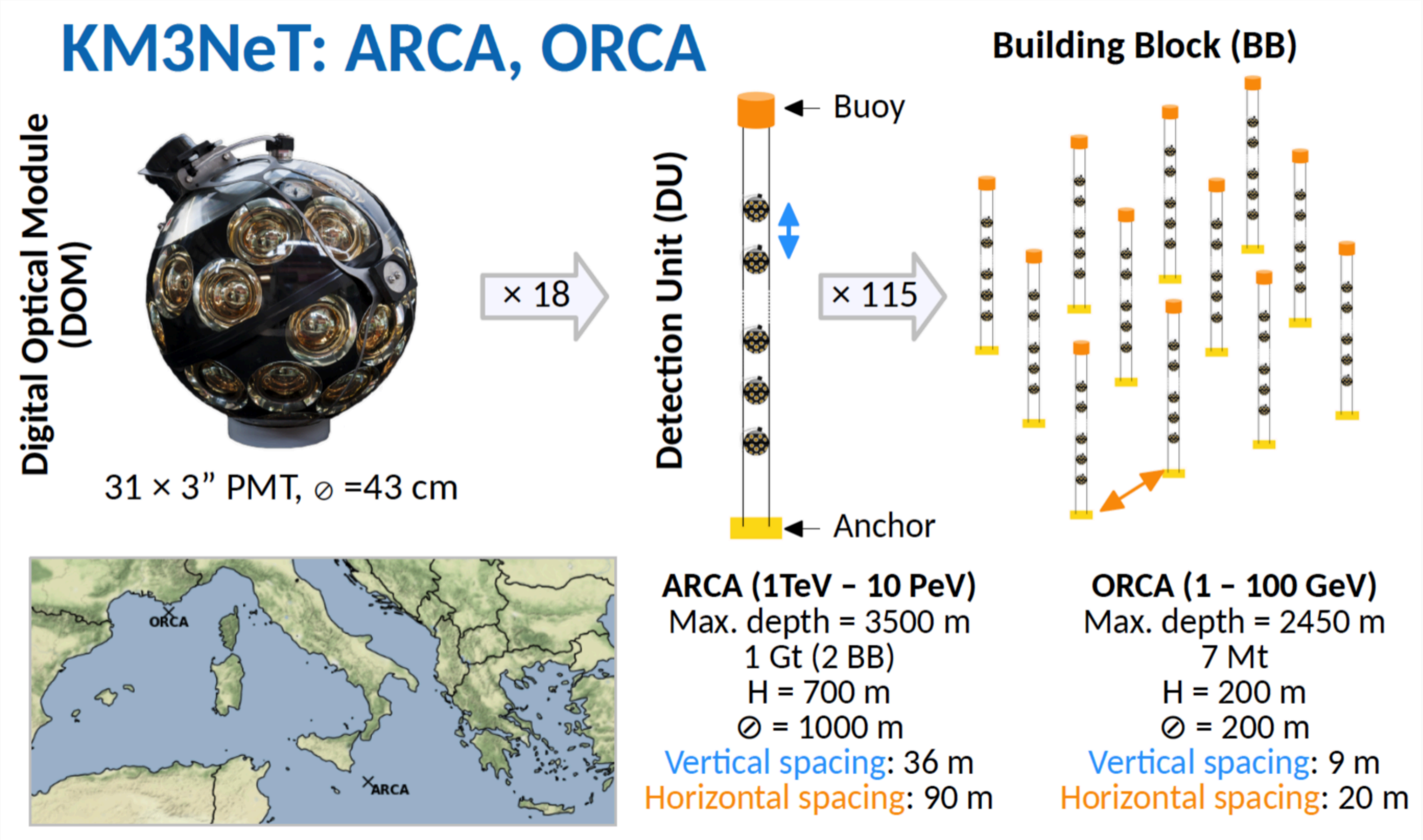


KM3-230213A

Let's watch the video!



Introduction to KM3NeT

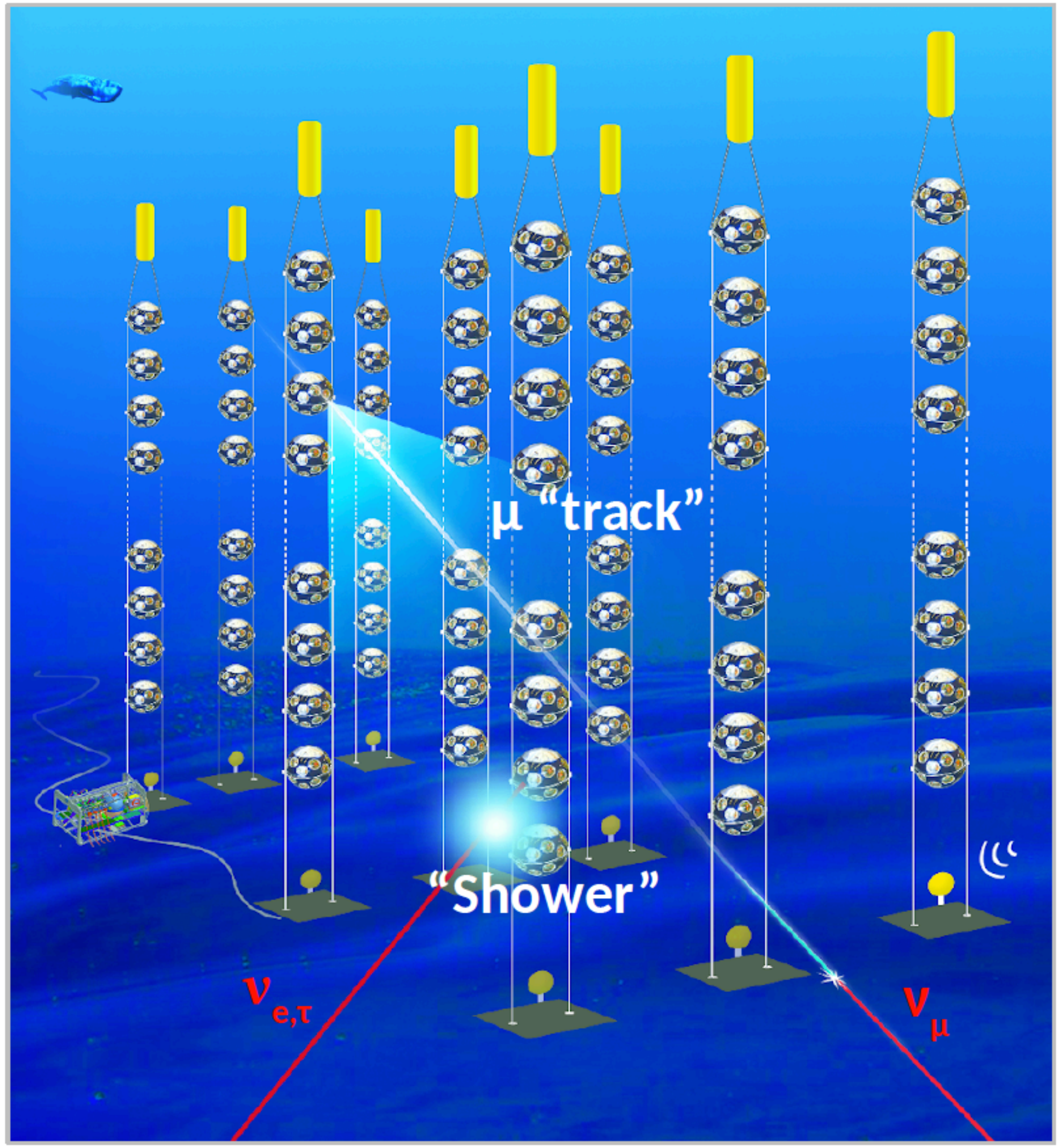


KM3NeT goals

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;



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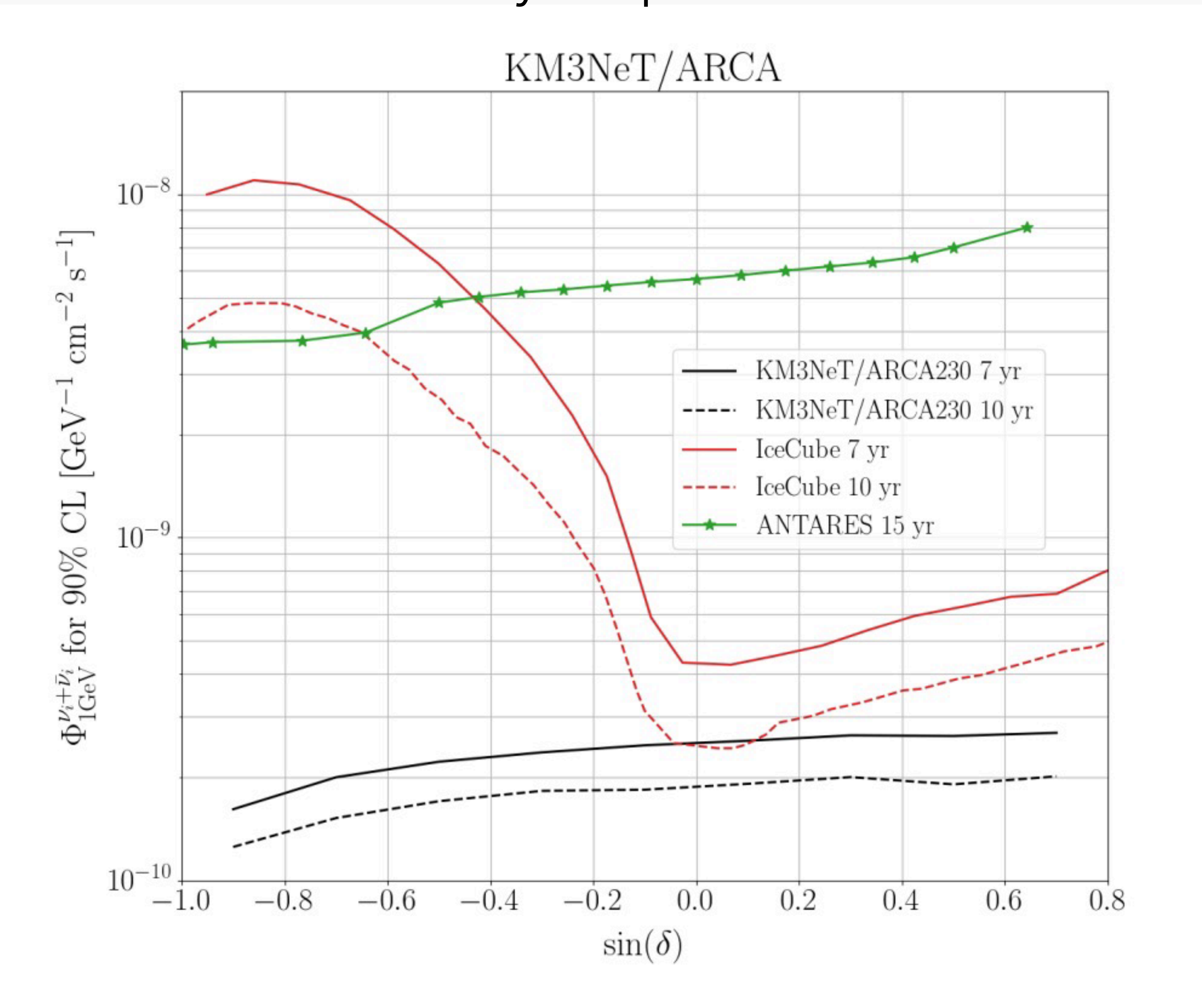
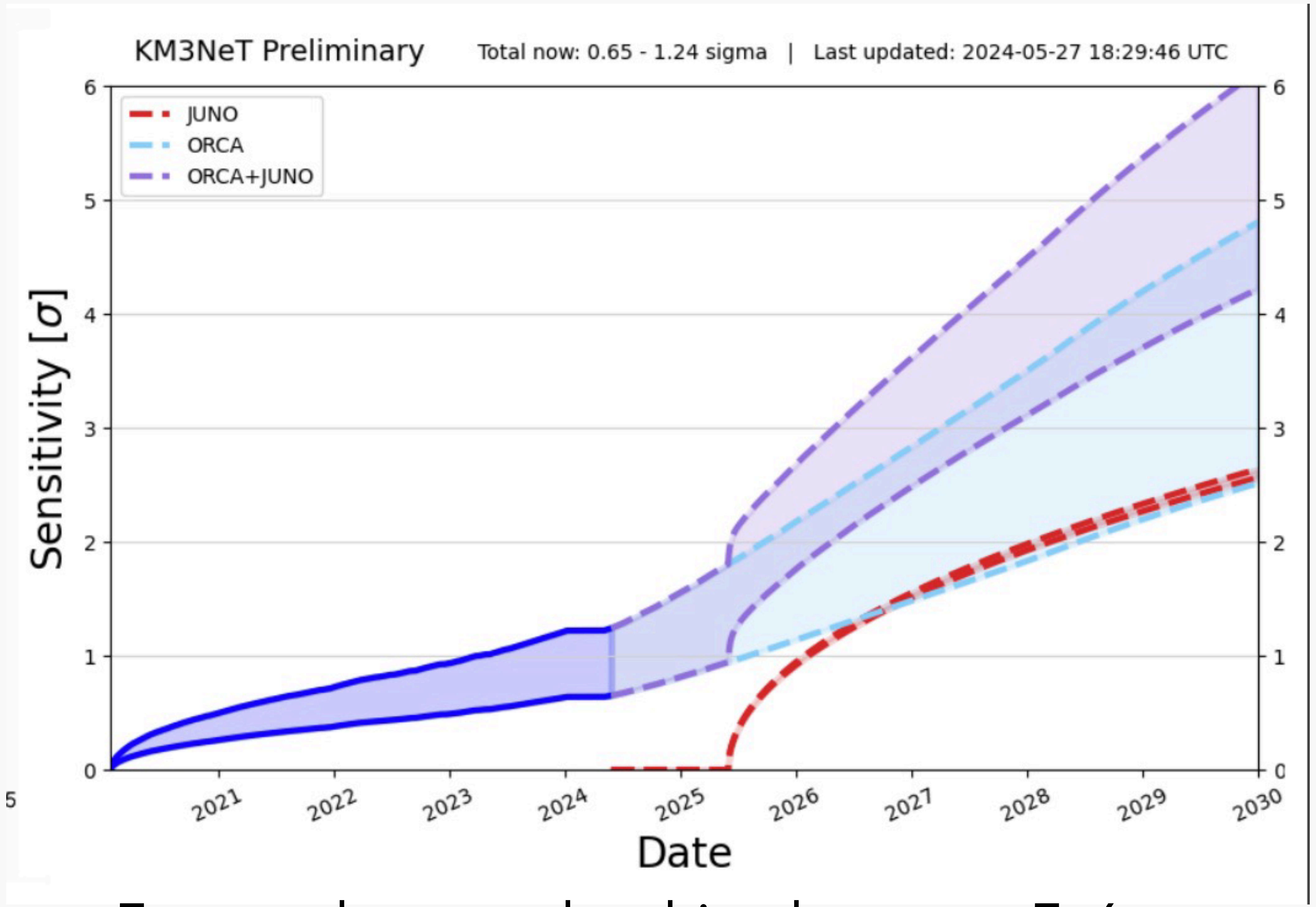
KM3NeT perspectives

ARCA - Sensitivity for point-like searches



Best sensitivity in the Southern Sky

ORCA - Neutrino mass ordering



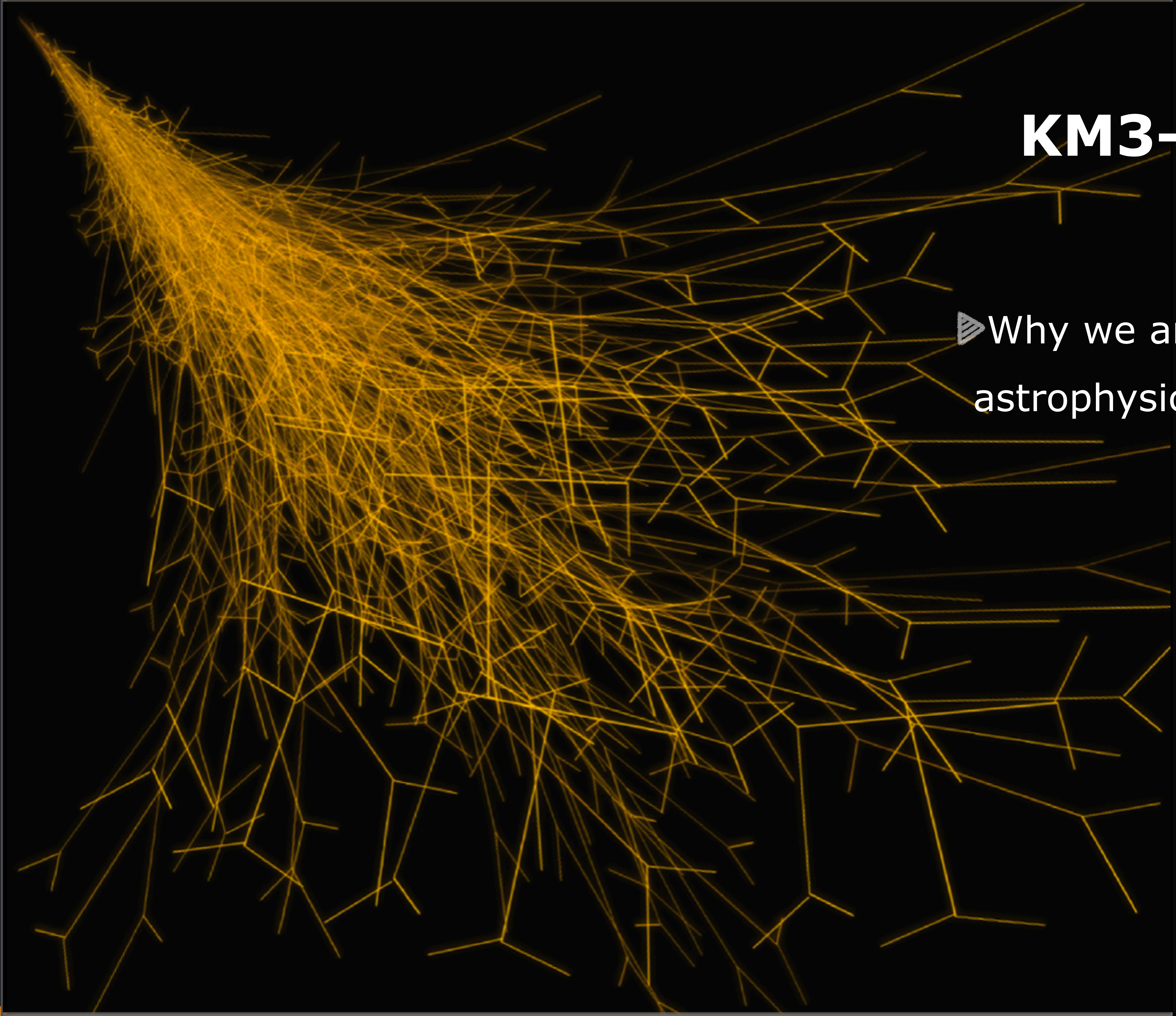
5σ can be reached in the next 5-6 years if combined with Juno

ANTARES decommissioning

ORCA ARCA completions

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

J. Brunner @ Neutrino2024

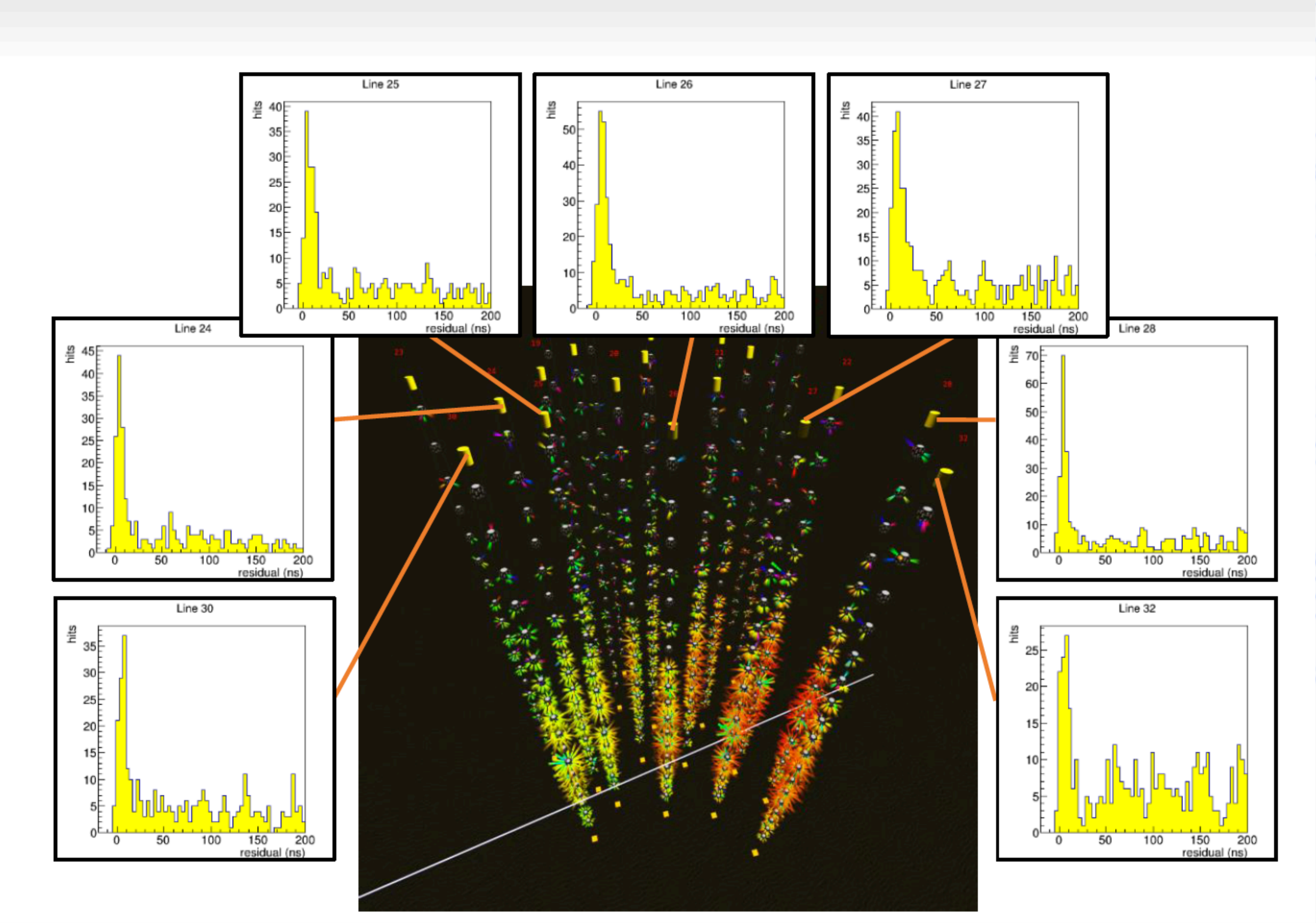


KM3-230213A

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

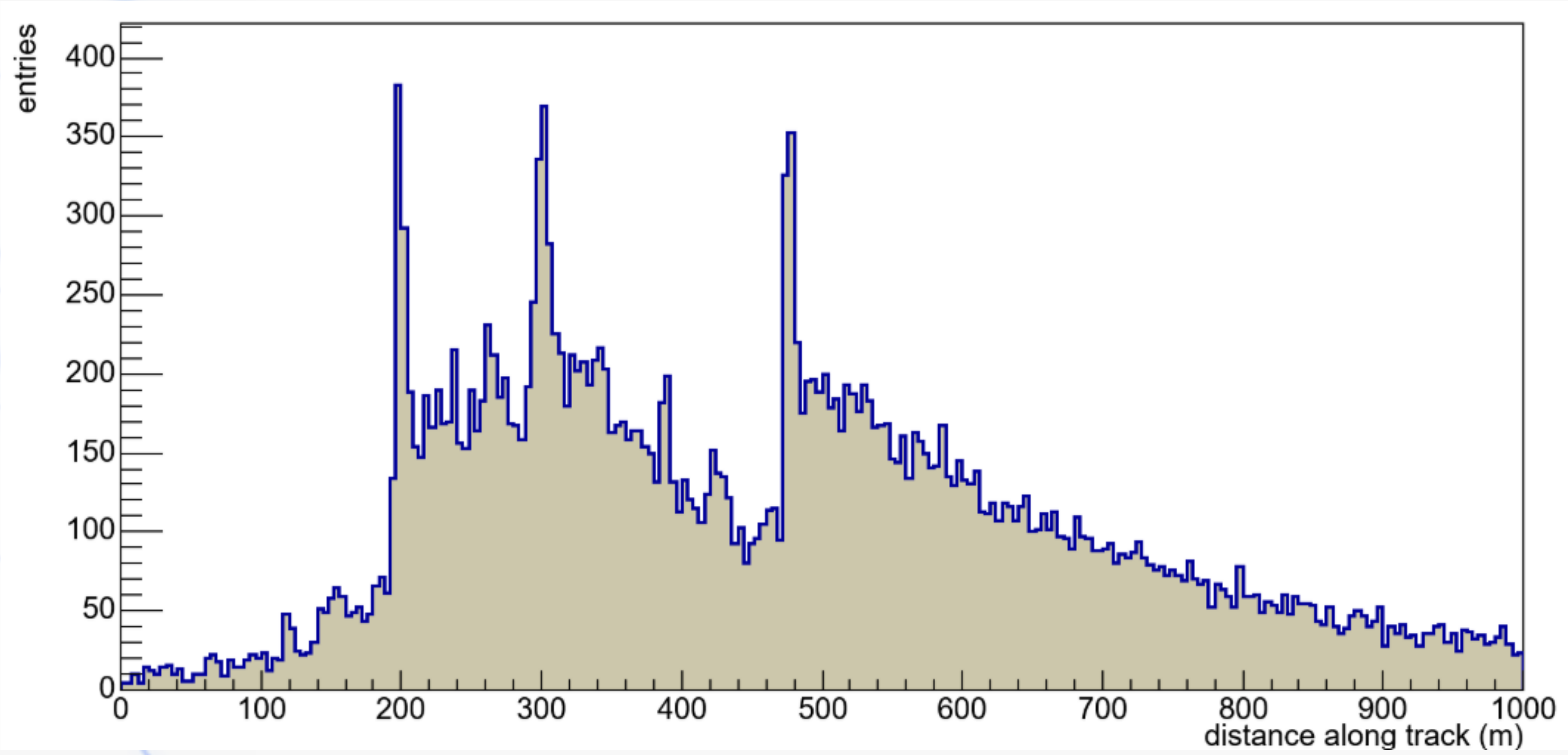
Did not you see a whale?

Extremely high-quality reconstructed track



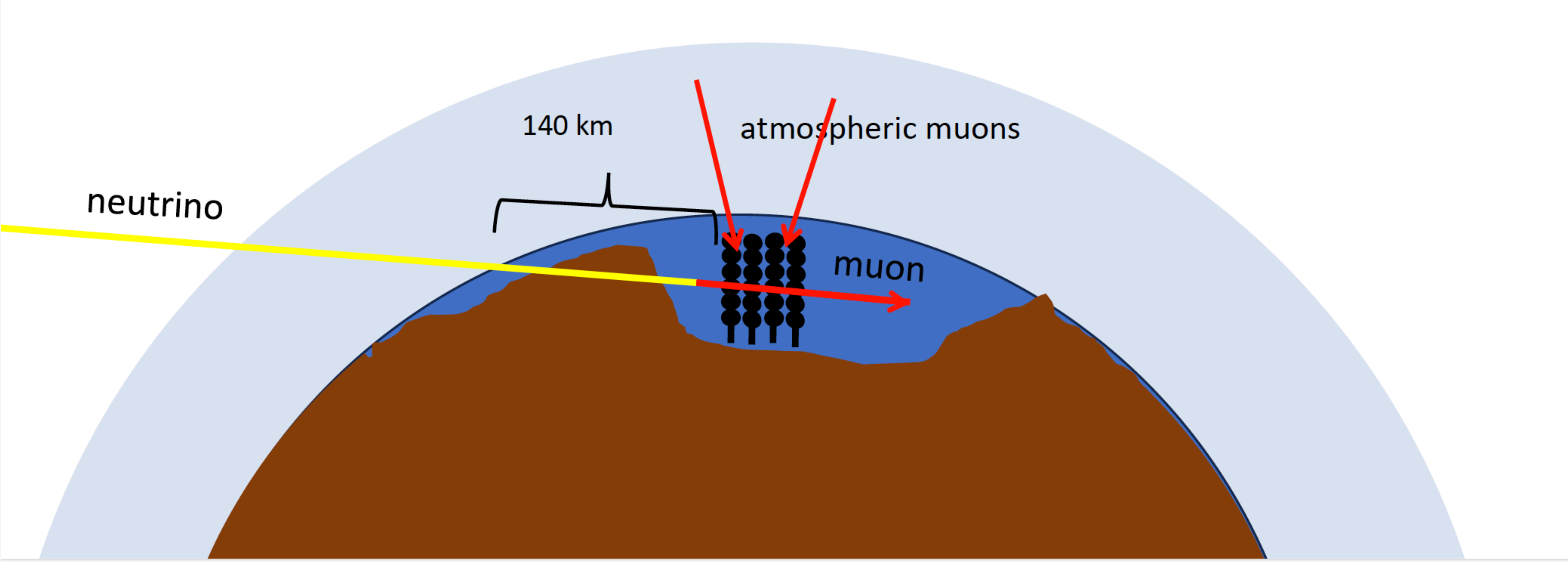
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons

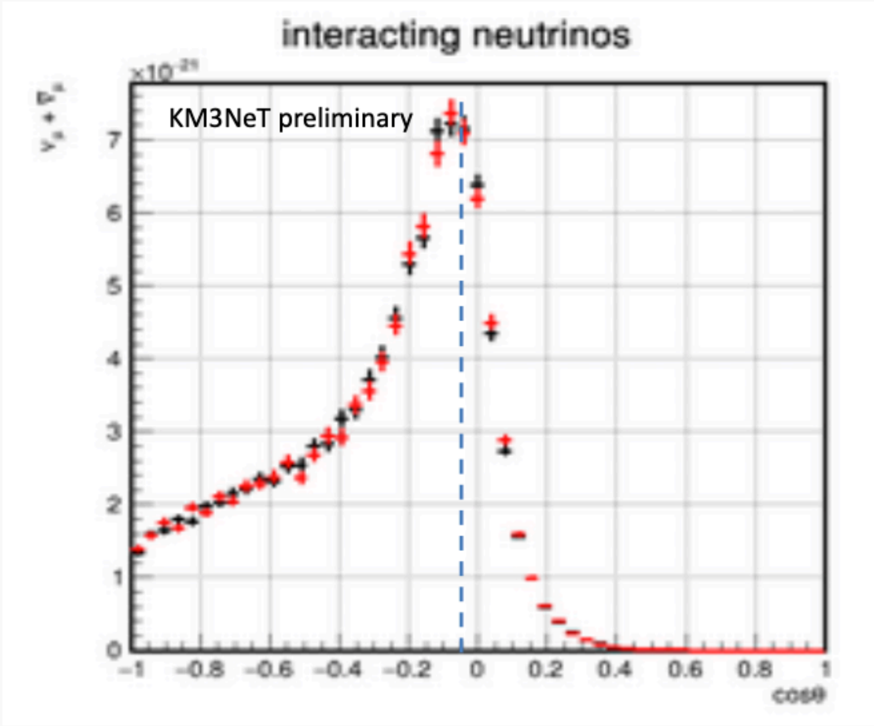
Position of light emission along track consistent with hit time assuming direct light

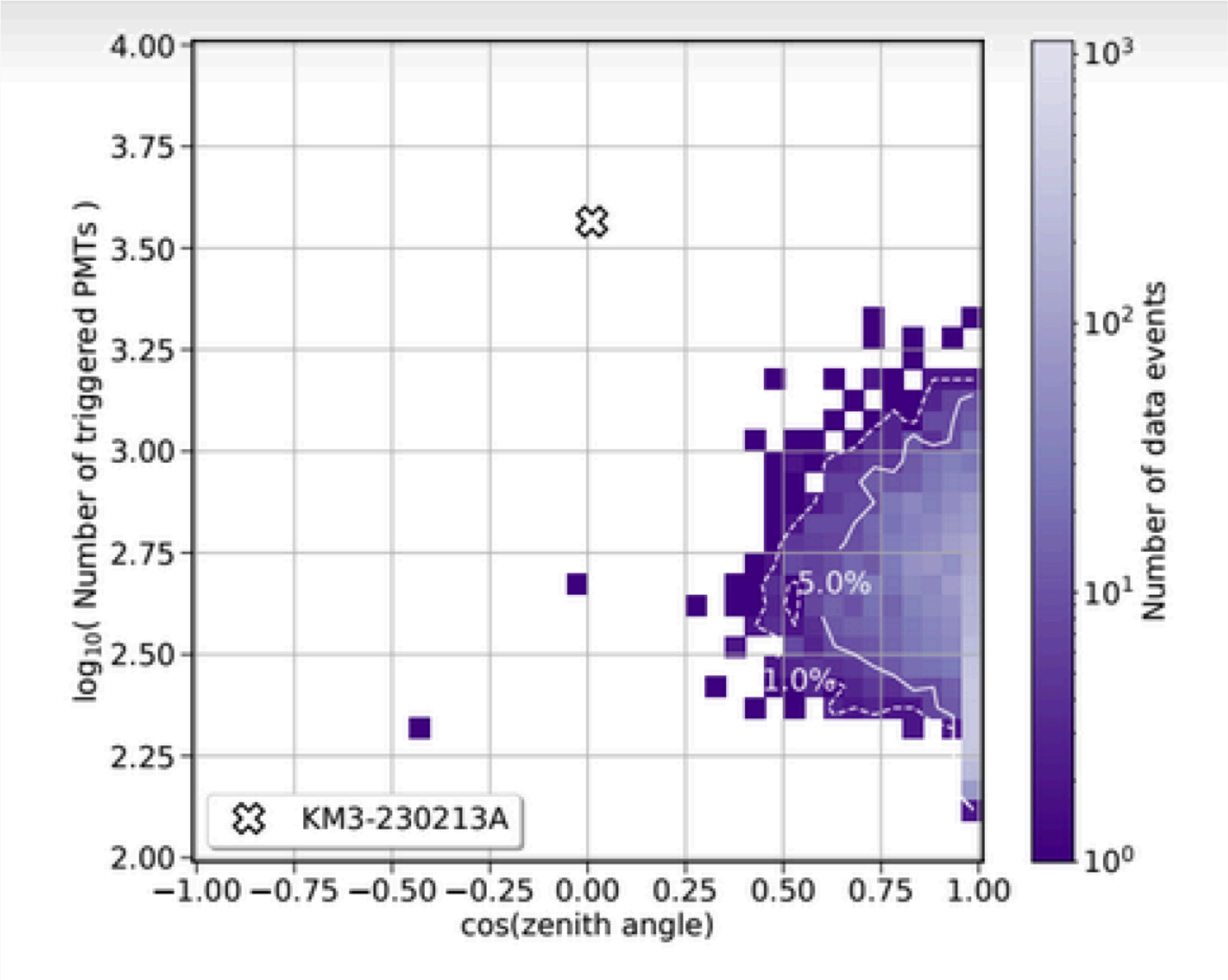


Why it cannot be a muon bundle?

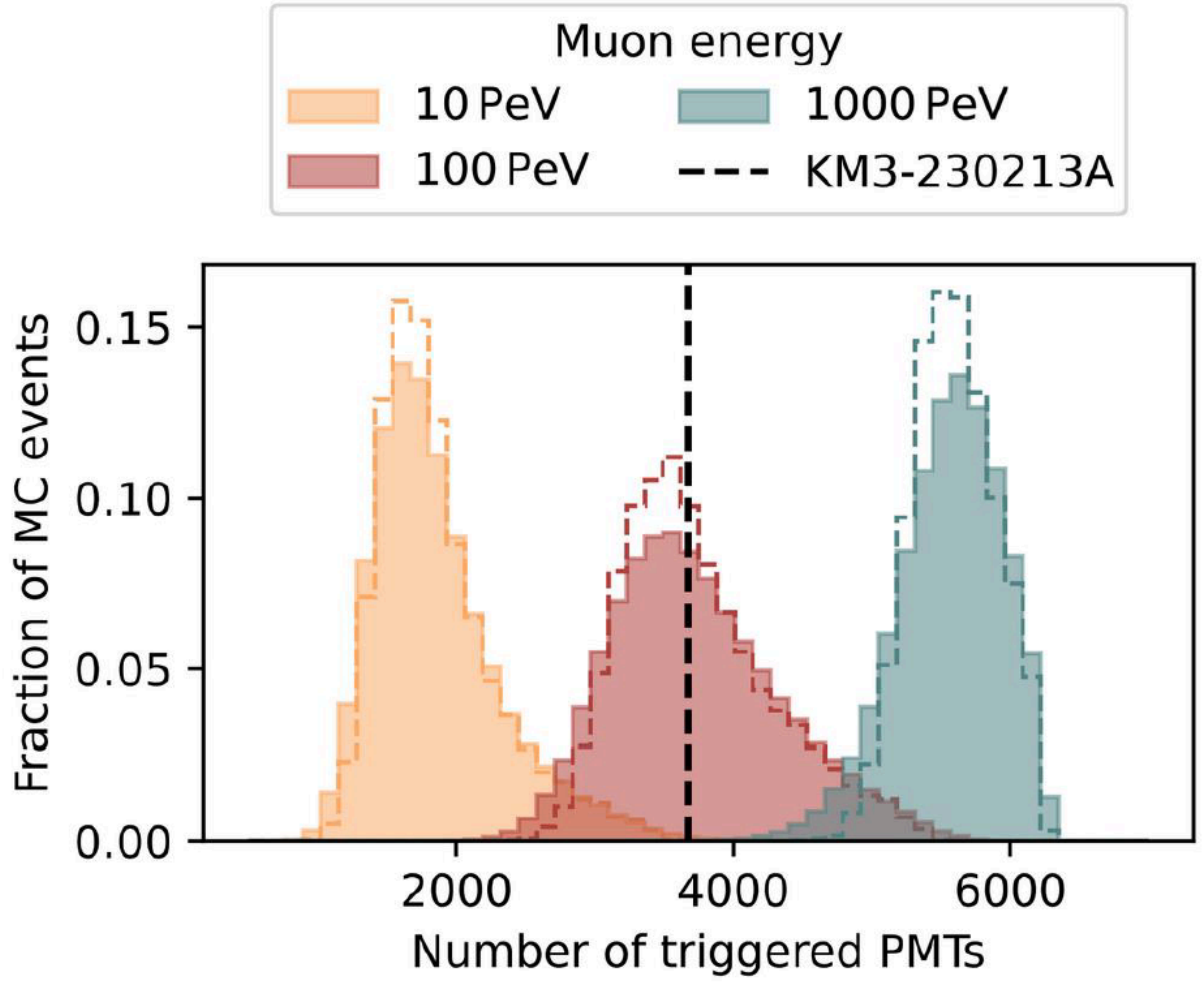
- Very horizontal –> atmospheric muons cannot travel that long







Energy and direction of the event



- Energy is measured from the amount of light:

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

(10000 times the energy of the LHC)

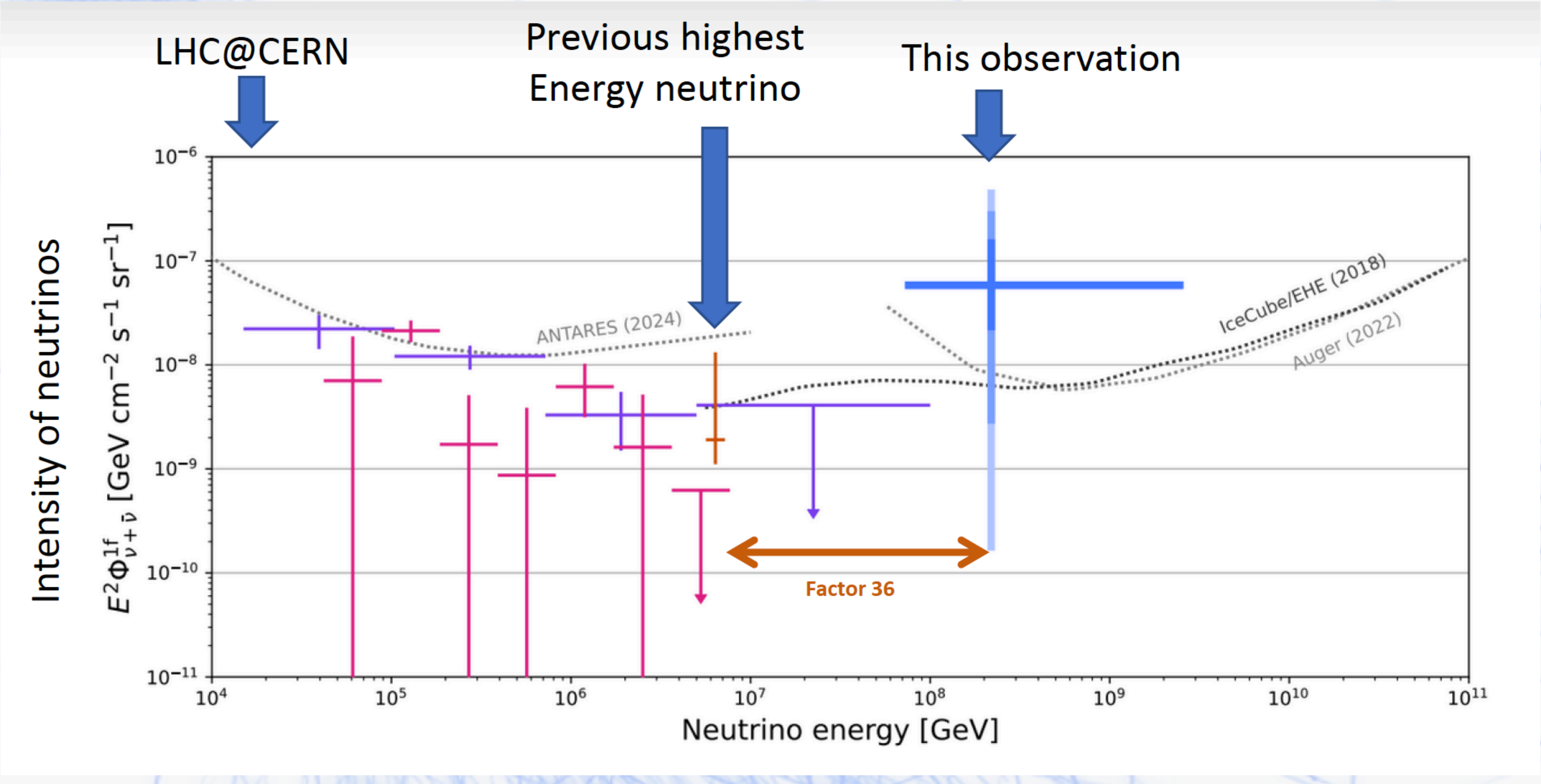
- The neutrino Energy is higher

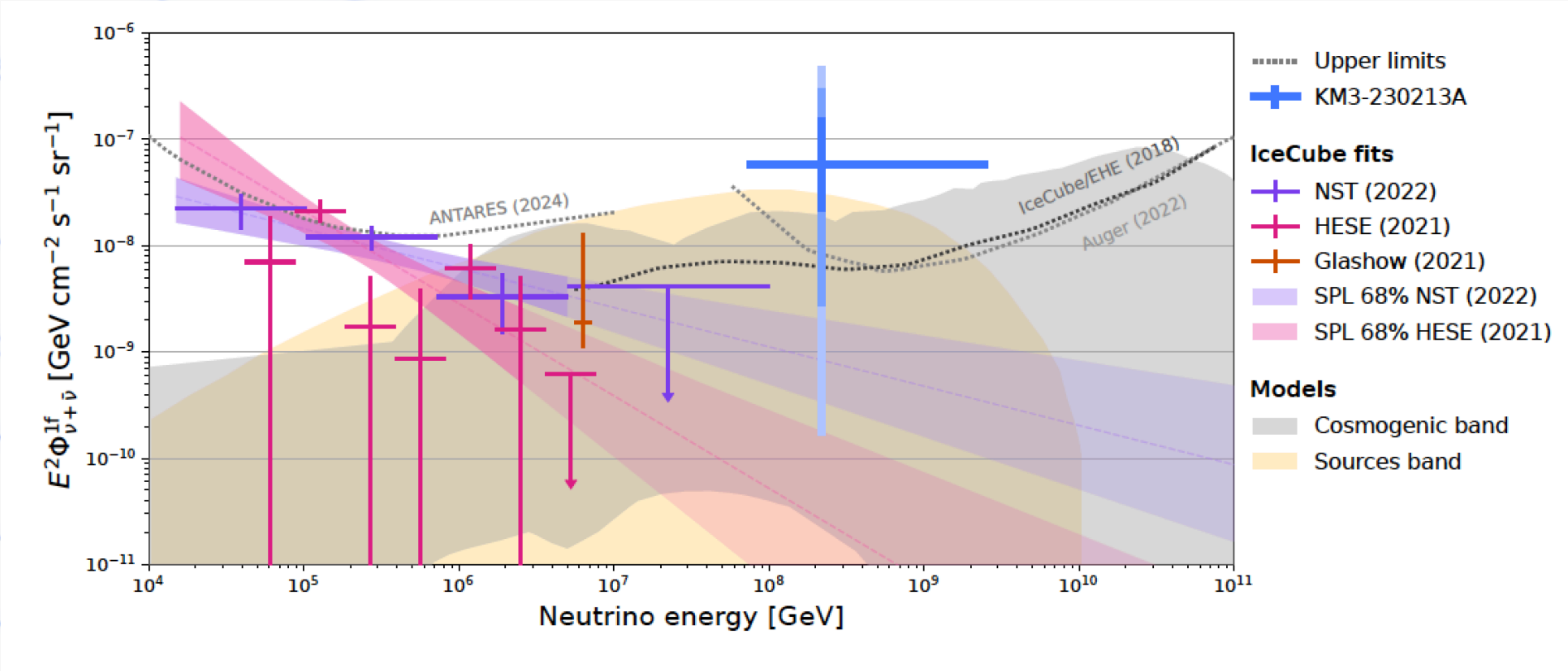
$$E_\nu = 220^{+570}_{-100}\ \mathrm{PeV}$$

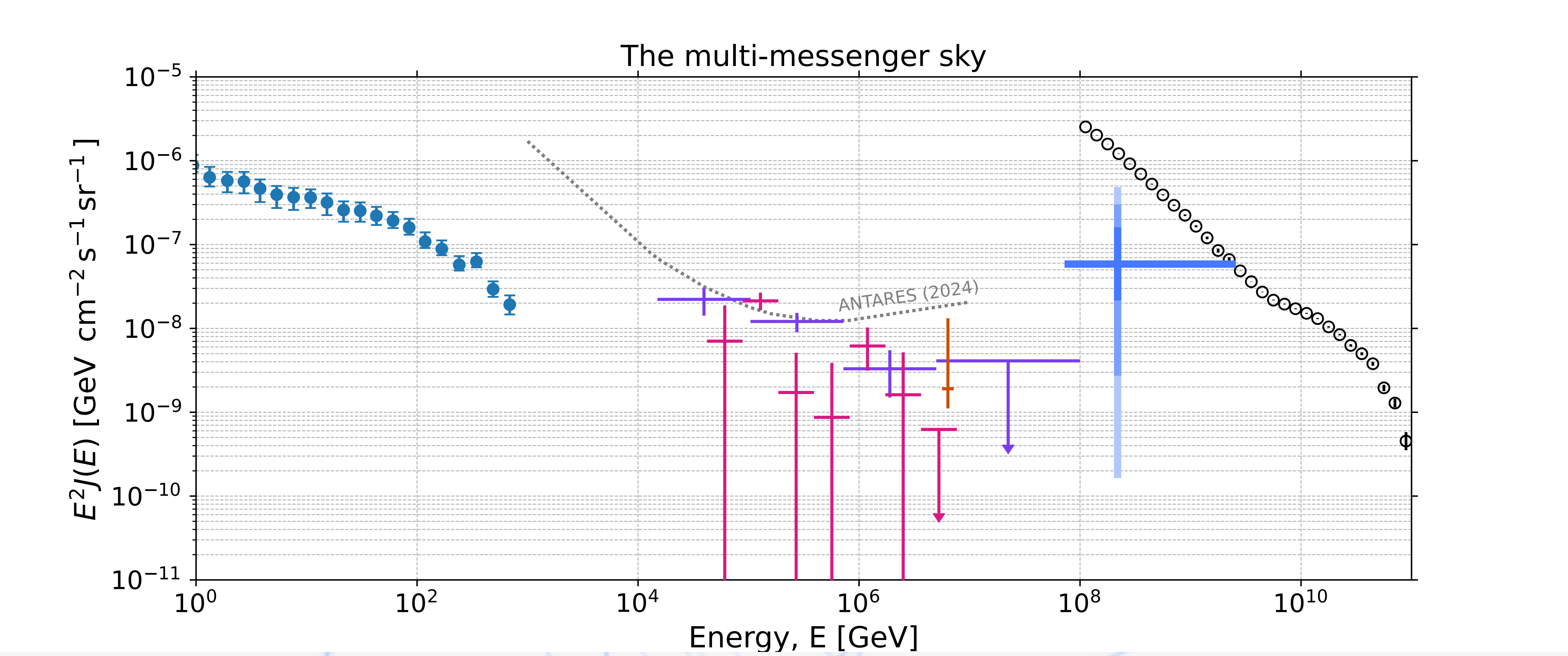
(assuming an E^{-2} source spectrum)

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

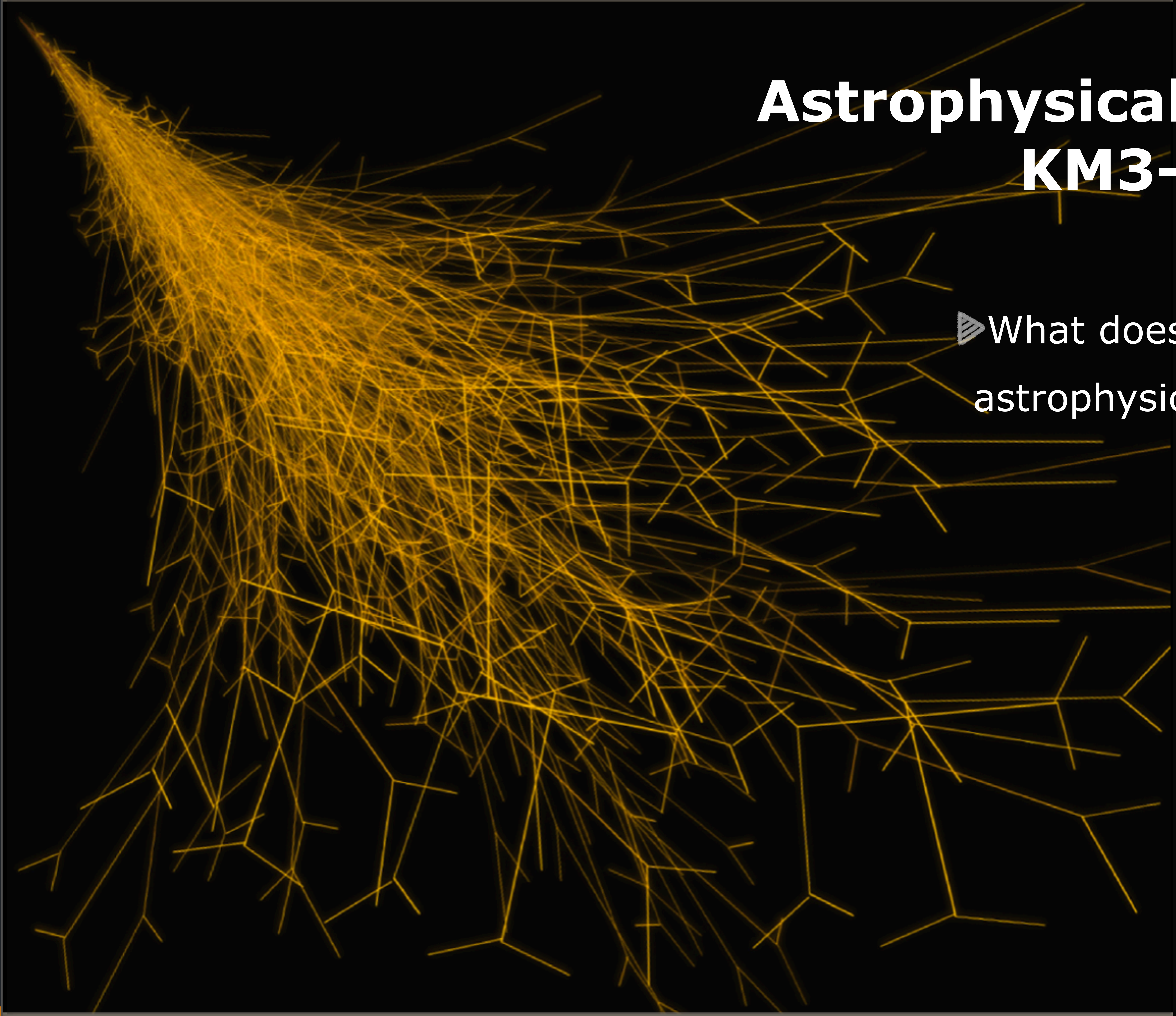
Multi-messenger astronomy





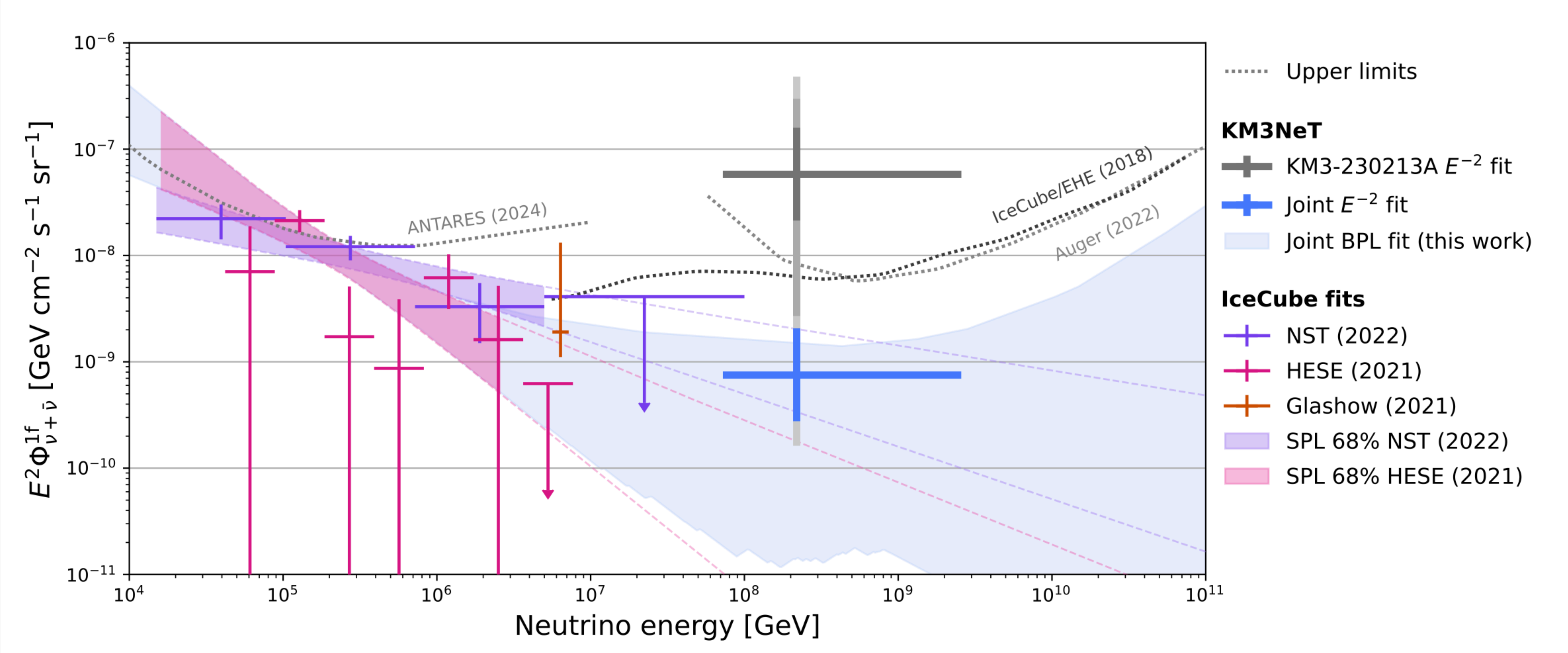


Astrophysical interpretation of KM3-230213A



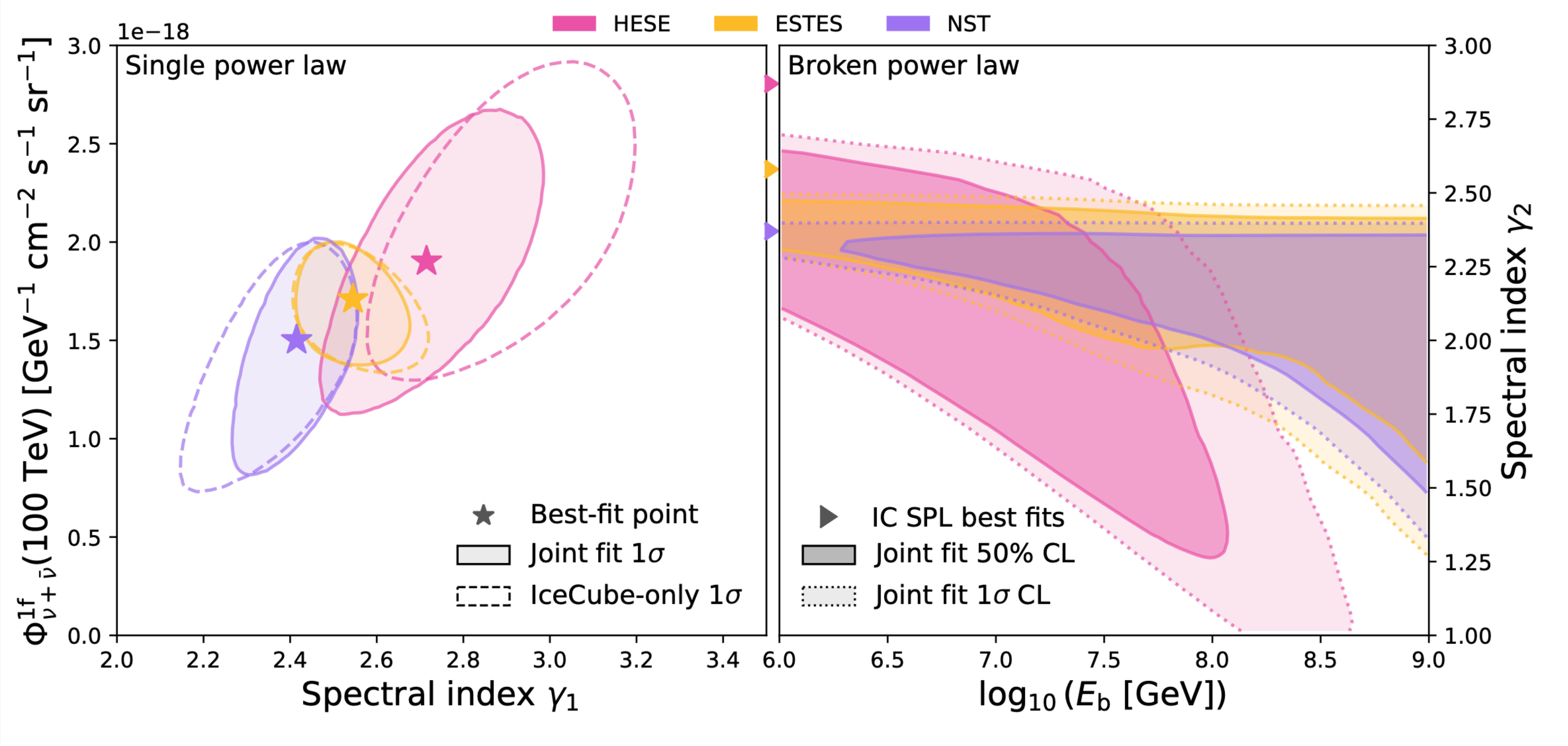
- What does it mean in terms of plausible astrophysical sources?

The ultra-high-energy event KM3-230213A within the global neutrino landscape



Include Icecube & Auger effective area –> no tension!

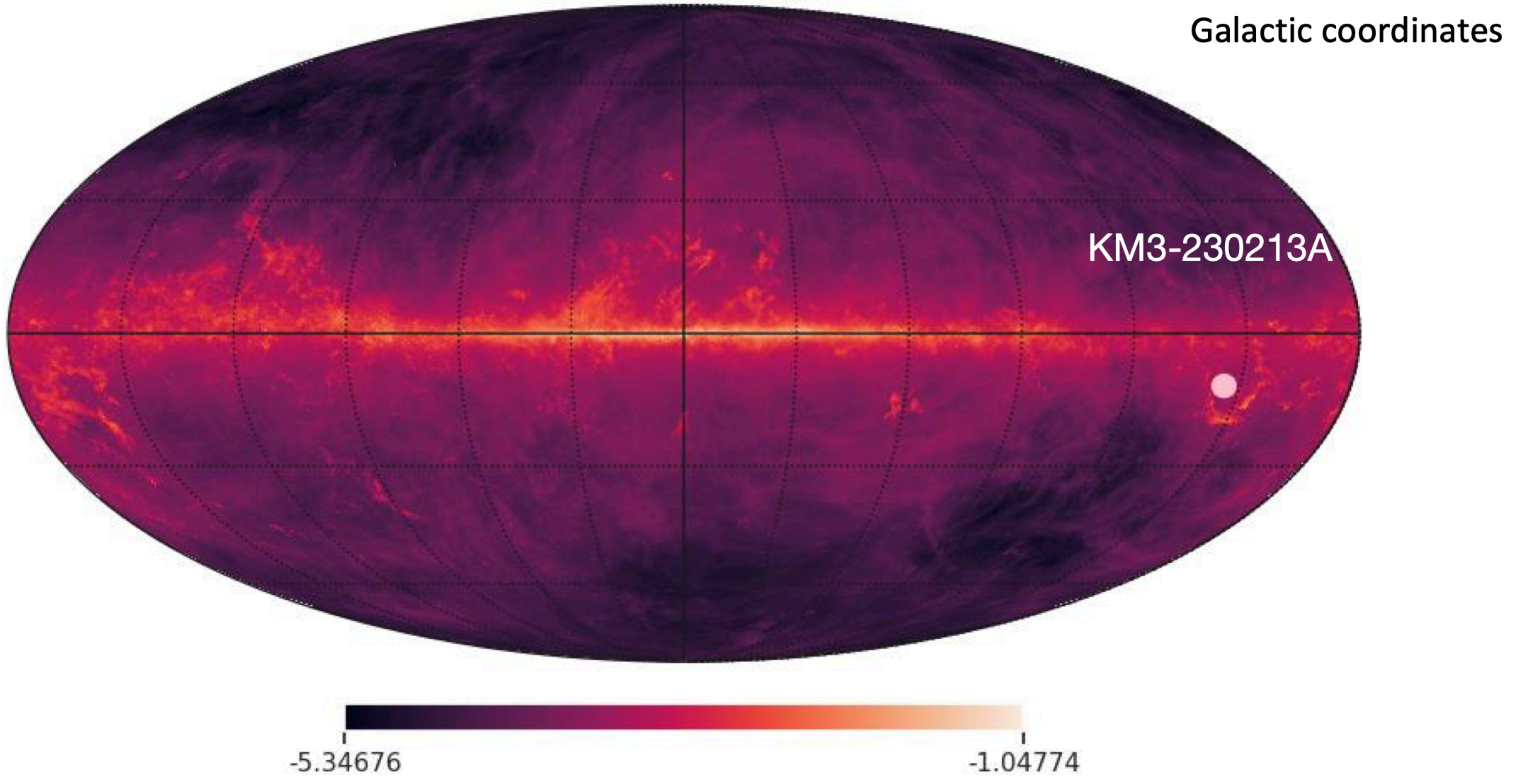
Study of a break in IceCube extrapolation

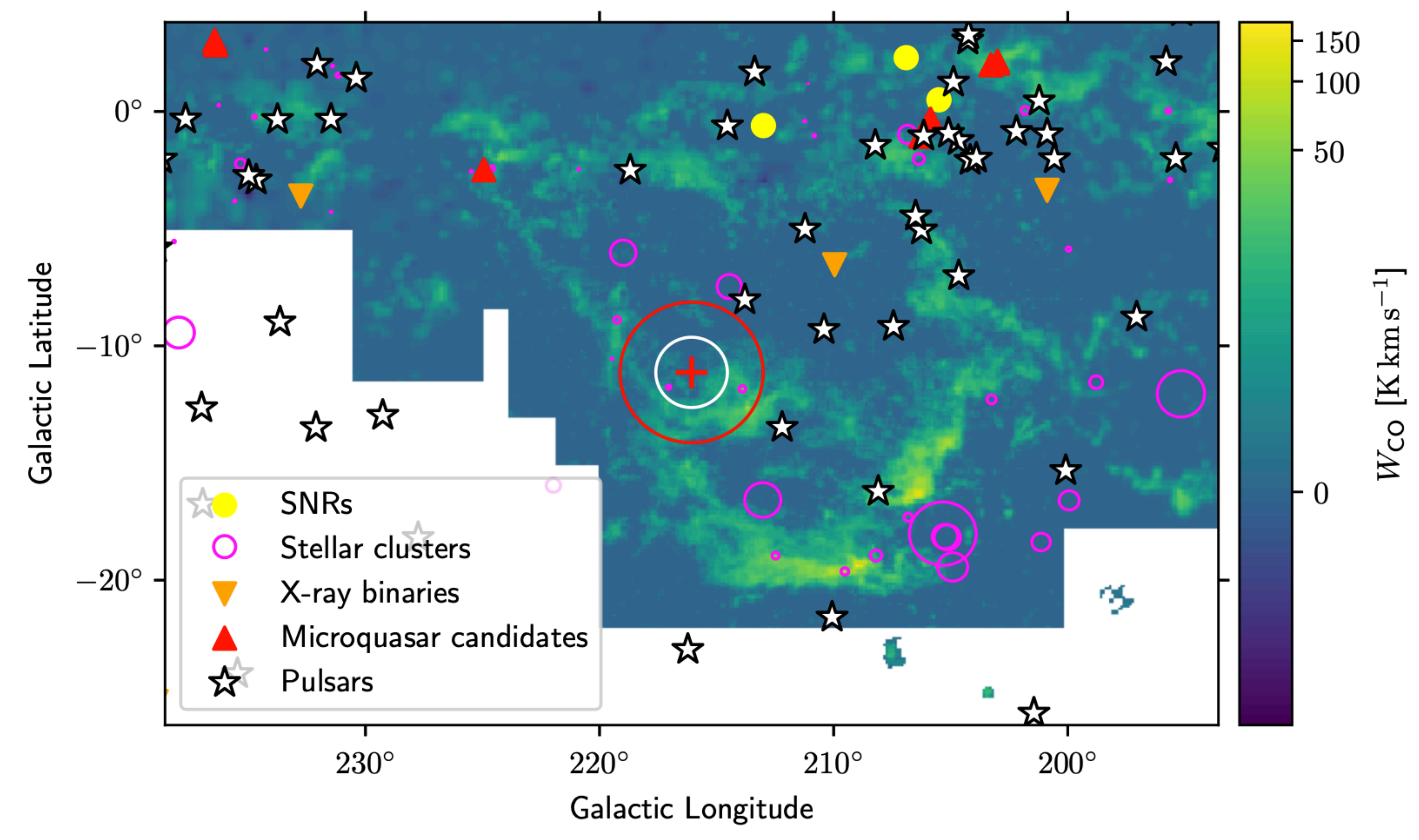


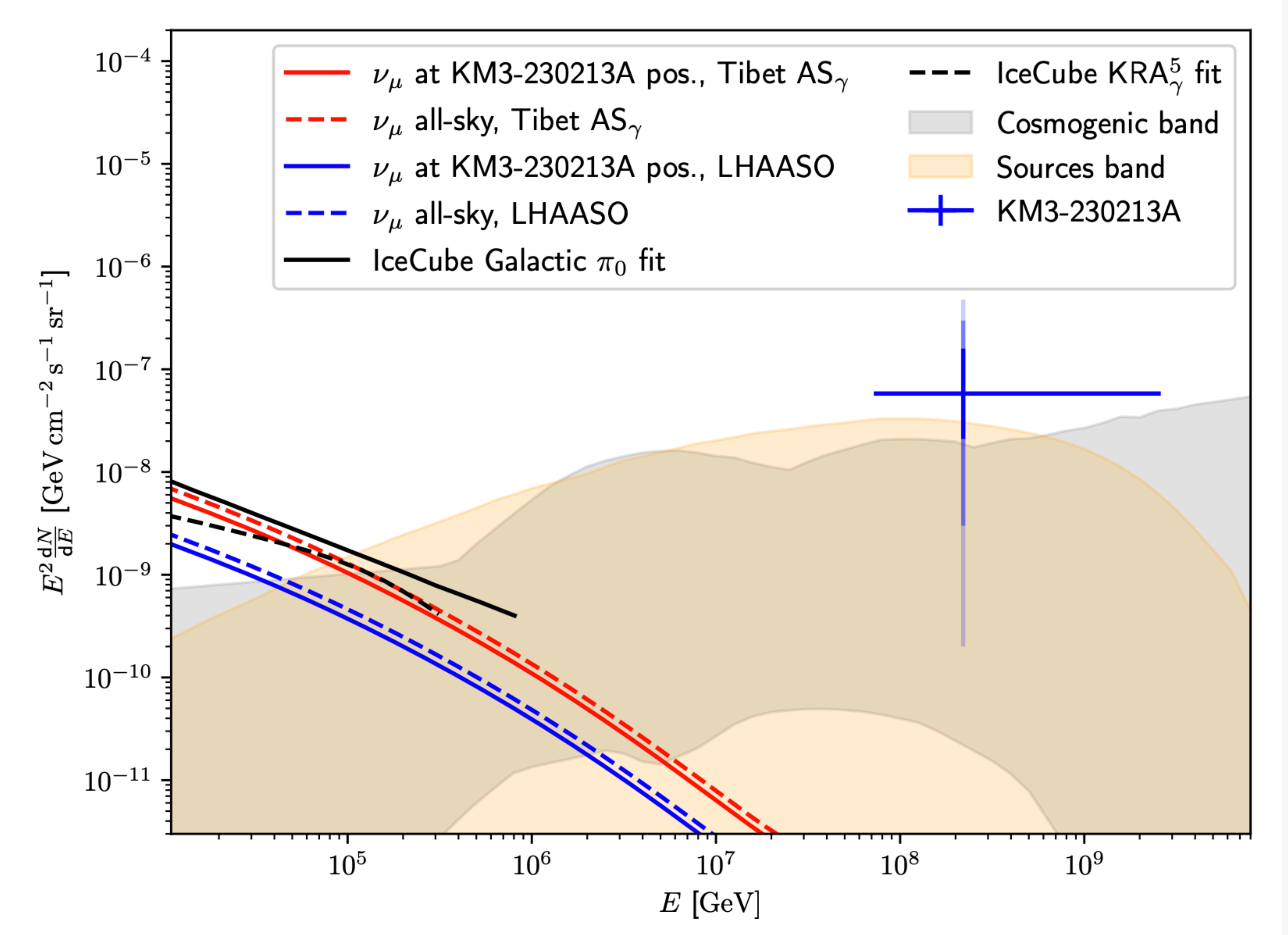
arXiv:2502.08173

Galactic hypothesis

Diffuse neutrino sky map (Kra-gamma Model)

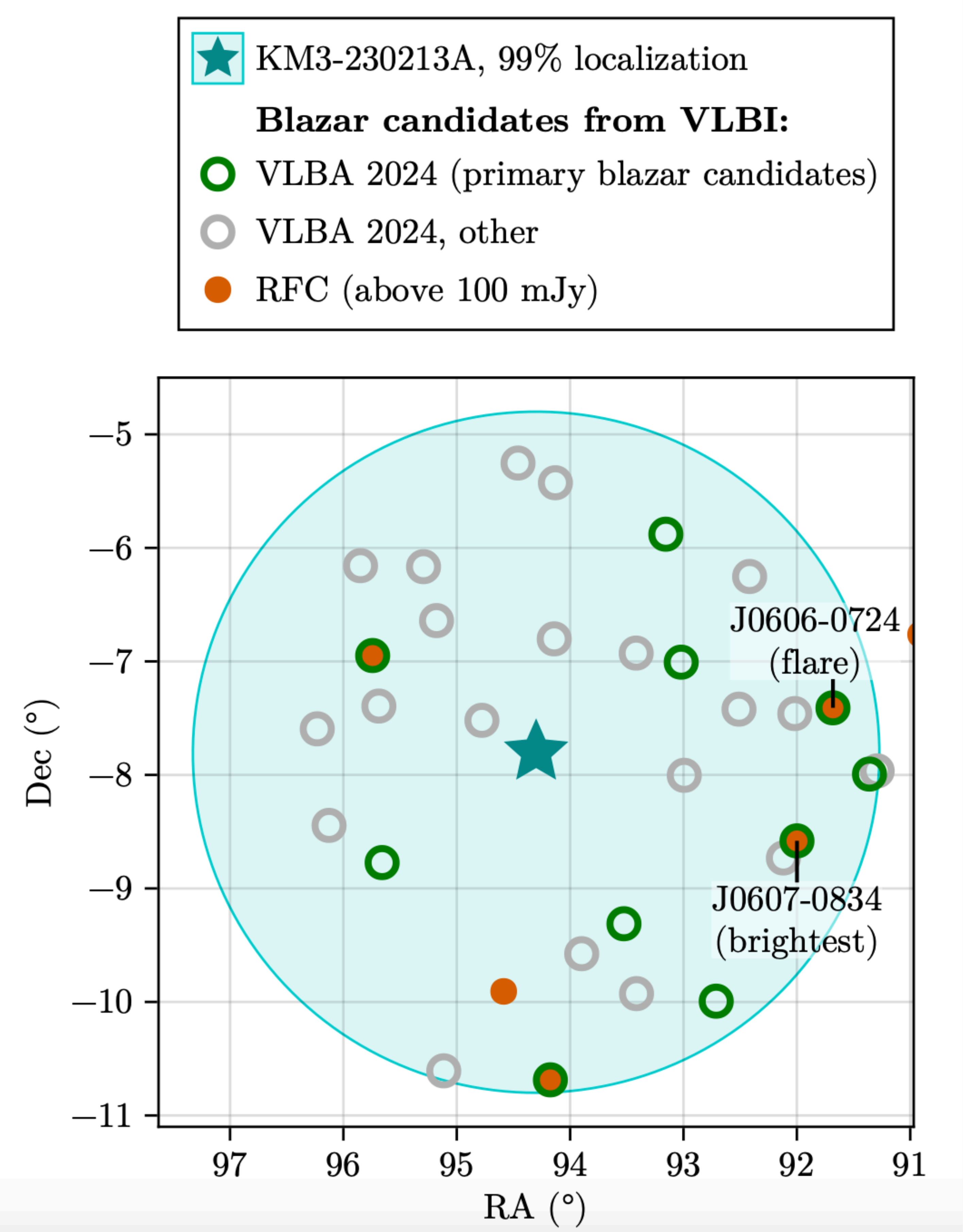






arXiv:2502.08387

Search for counterpart



A. Foisseau,[15] A. Coleiro,[15] F. Cangemi,[15] D. Dornic,[7] C. Lachaud,[15] P. Maggi,[75] D. Gotz,[76] L. Xin,[77]
B. Cordier,[76] O. Godet,[78] A. Goldwurm,[79] H. Goto,[76] X. Han,[77] N. Leroy,[80] C. Plasse,[76] Y. Qiu,[77]
J. Rodriguez,[76] J. Wang,[77] J. Wei,[77]
SVOM Collaboration

Table 2. Properties of sources observed with VLBA within 3° from the KM3-230213A position.

Blaz (1)	Name (J2000) (2)	Position J2000 RA and Dec. (3)	Sep (°) (4)	z (5)	S_{VLASS} 2-4 GHz (mJy) (6)	Hist 8 GHz (mJy) (7)	S_{VLBA} 5 GHz (mJy) (8)	8 GHz (mJy) (9)	α_{VLBA} 5-8 GHz (10)	Core T_b 5 GHz (K) (11)	8 GHz (K) (12)
x	J0607−0834	06:07:59.699 −08:34:49.978 *	2.4	0.87	3100	2067	2176 ± 220	2240 ± 226	0.05 ± 0.26	$10^{11.9\pm0.1}$	$10^{11.3\pm0.1}$
x	J0606−0724	06:06:43.546 −07:24:30.231 *	2.6	1.227	461	309	379 ± 38	306 ± 31	-0.38 ± 0.26	$> 10^{12.0}$	$10^{10.4\pm0.1}$
x	J0616−1041	06:16:41.808 −10:41:08.456 *	2.9		197	185	215 ± 22	248 ± 25	0.26 ± 0.26	$> 10^{10.4}$	$> 10^{12.1}$
x	J0622−0656	06:22:58.046 −06:56:51.971 *	1.7		101	103	111 ± 11	87 ± 9	-0.42 ± 0.26	$> 10^{12.1}$	$> 10^{10.9}$
x	J0610−0959	06:10:50.711 −09:59:33.958 *	2.7		97	78	100 ± 10	94 ± 10	-0.11 ± 0.26	$> 10^{12.1}$	$> 10^{11.4}$
x	J0622−0846	06:22:37.999 −08:46:18.263 *	1.7		61	74	93 ± 10	109 ± 12	0.28 ± 0.27	$> 10^{12.2}$	$> 10^{12.0}$
x	J0605−0759	06:05:26.187 −07:59:31.786 *	2.9		149	74	76 ± 8	67 ± 7	-0.24 ± 0.27	$10^{9.9\pm0.1}$	$10^{10.2\pm0.1}$
x	J0614−0918	06:14:06.042 −09:18:37.911 *	1.7		95	63	72 ± 7	55 ± 6	-0.46 ± 0.27	$10^{10.5\pm0.2}$	$> 10^{9.8}$
x	J0612−0700	06:12:04.843 −07:00:22.853	1.5		63		54 ± 6	62 ± 7	0.24 ± 0.27	$10^{10.2\pm0.1}$	$> 10^{11.0}$
x	J0612−0552	06:12:37.360 −05:52:44.418 *	2.2		65	62	53 ± 6	45 ± 5	-0.29 ± 0.27	$10^{10.5\pm0.3}$	$> 10^{10.0}$

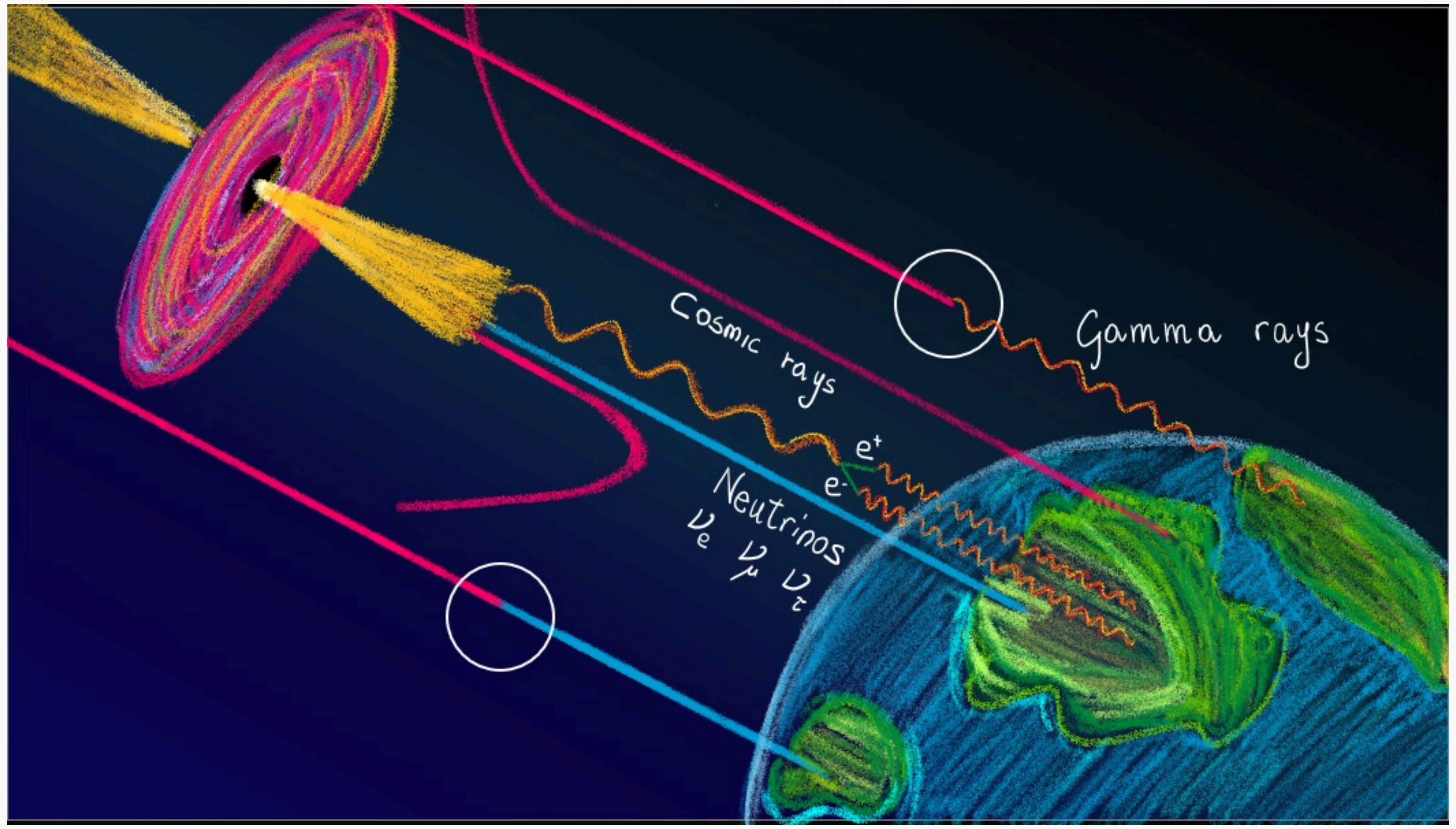
arXiv:2502.08484

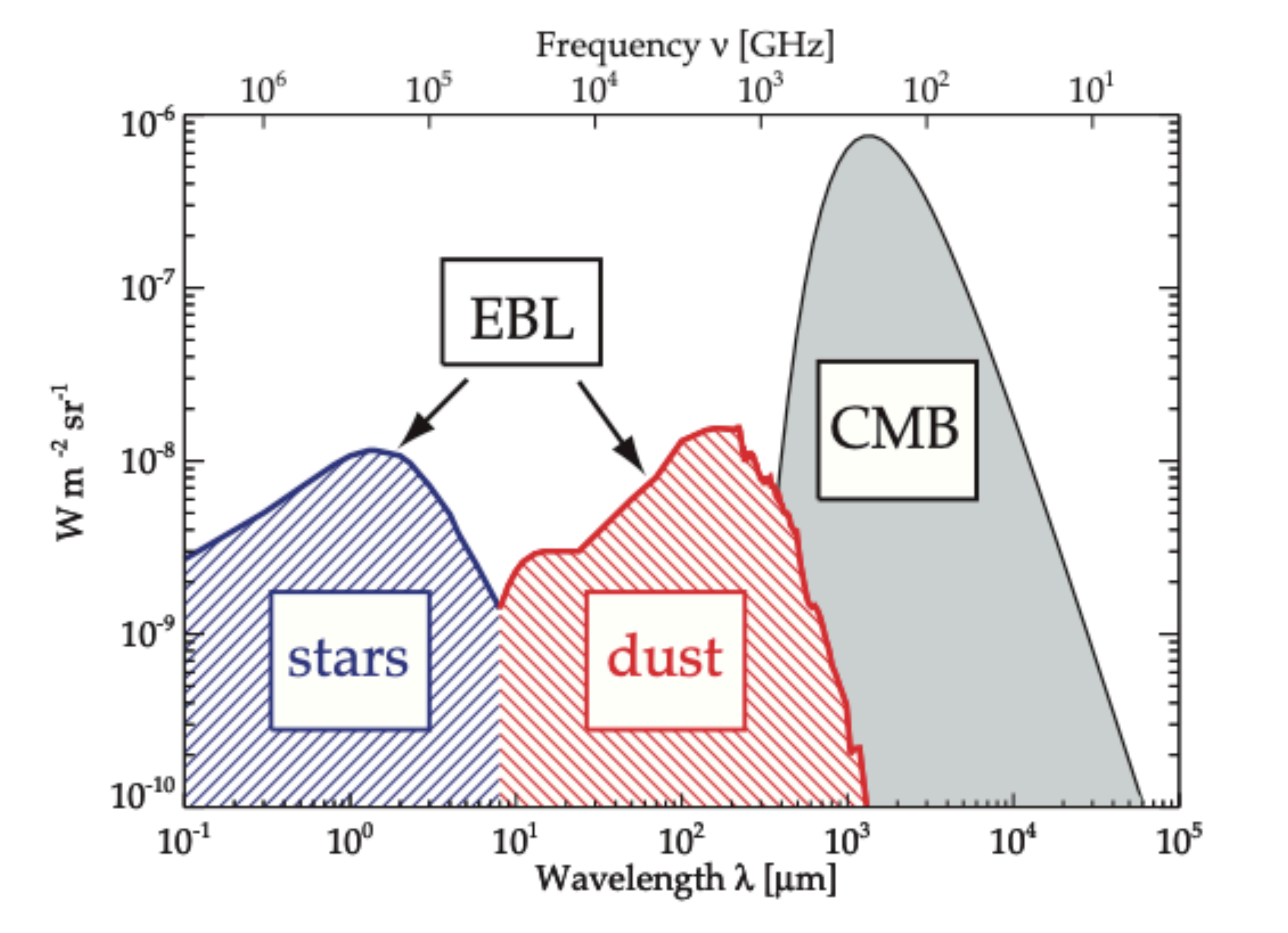
Cosmogenic neutrinos

We want to investigated the probability that KM3-230213A has a cosmogenic origin, i.e. it has been produced due to CR interaction with extra-galactic photons.

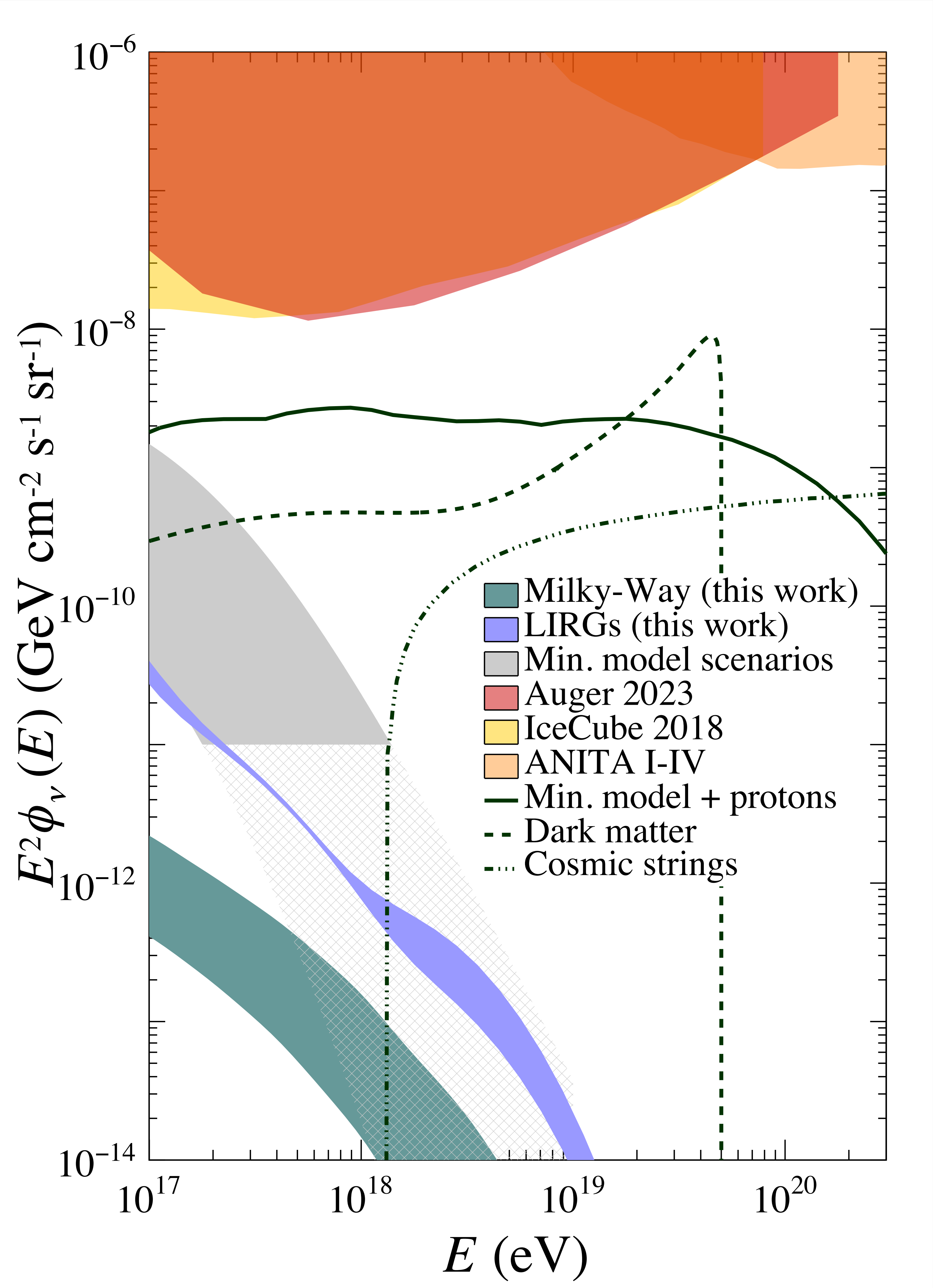
$$p + \gamma \longrightarrow n + \pi^{+},\ \pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu_{\mu}}),\ \mu^{\pm} \longrightarrow e^{\pm} + \nu_{e}(\bar{\nu_{e}}) + \bar{\nu_{\mu}}(\nu_{\mu})$$

$$n \longrightarrow p + e^{-} + \bar{\nu_{e}}, (A, Z) \longrightarrow (A, Z \pm 1) + e^{\mp} + \bar{\nu_{e}}(\nu_{e})$$

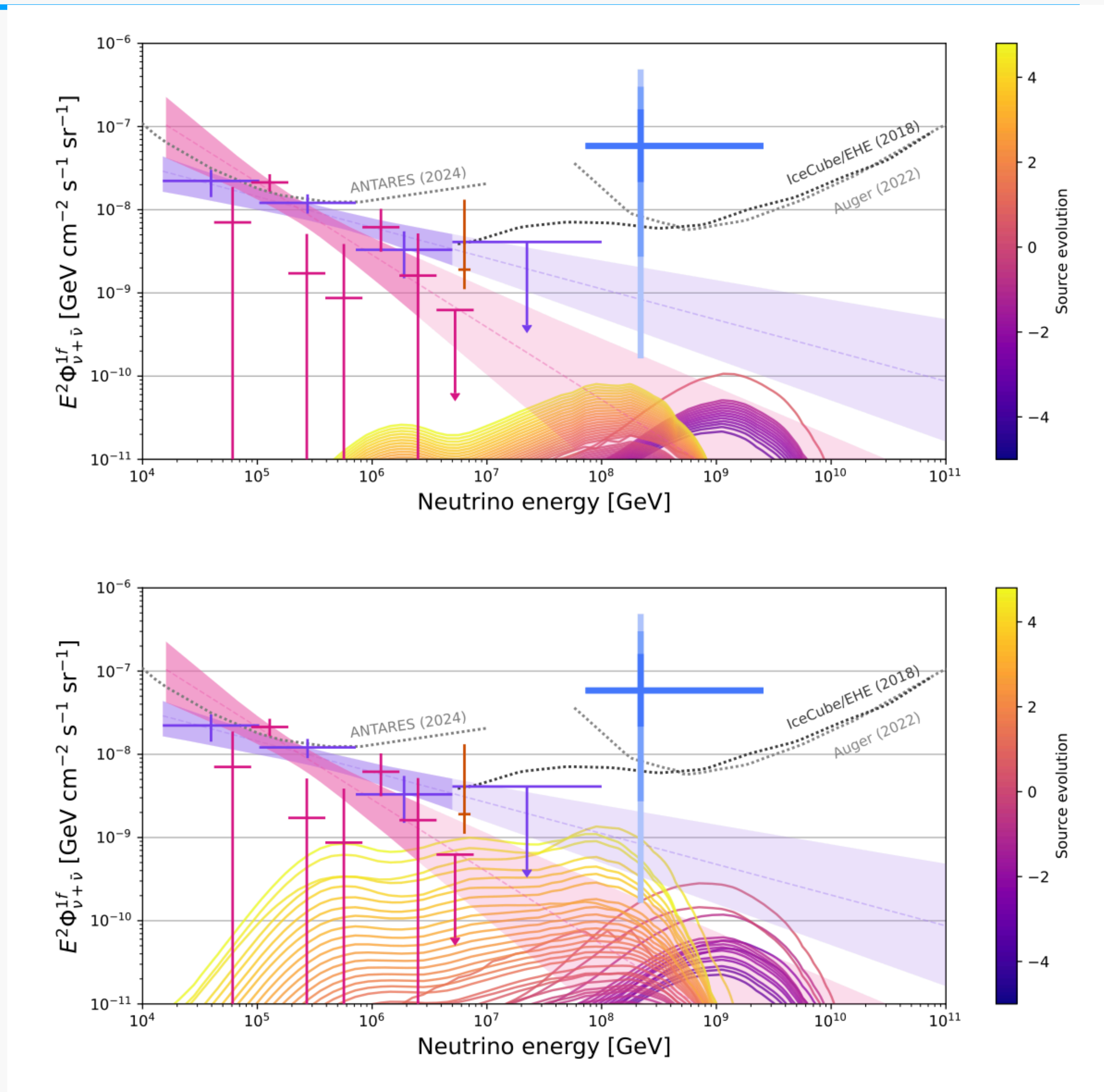




Cosmogenic hypothesis



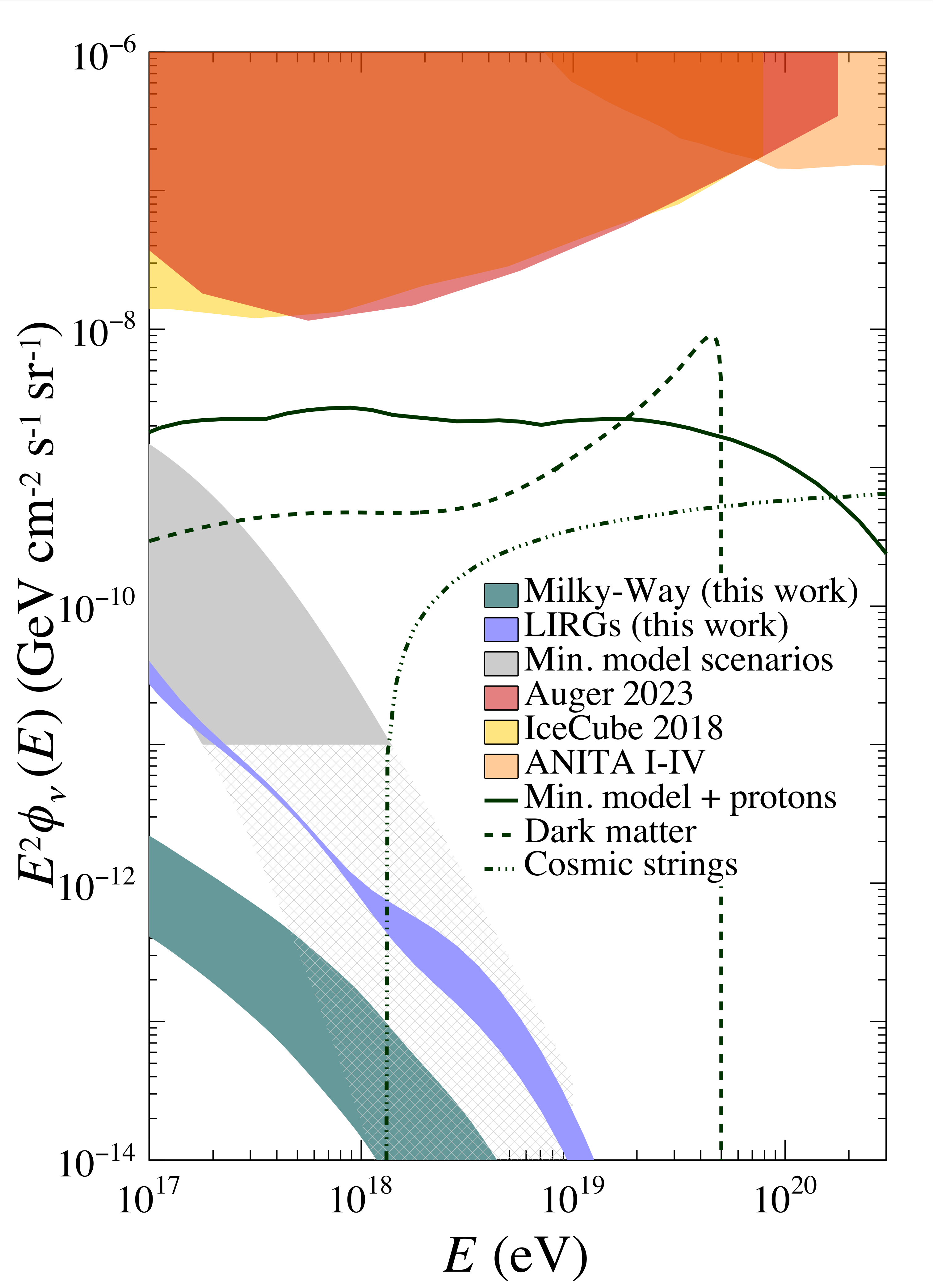
- The neutrino flux associated to the minimal scenario is very low.



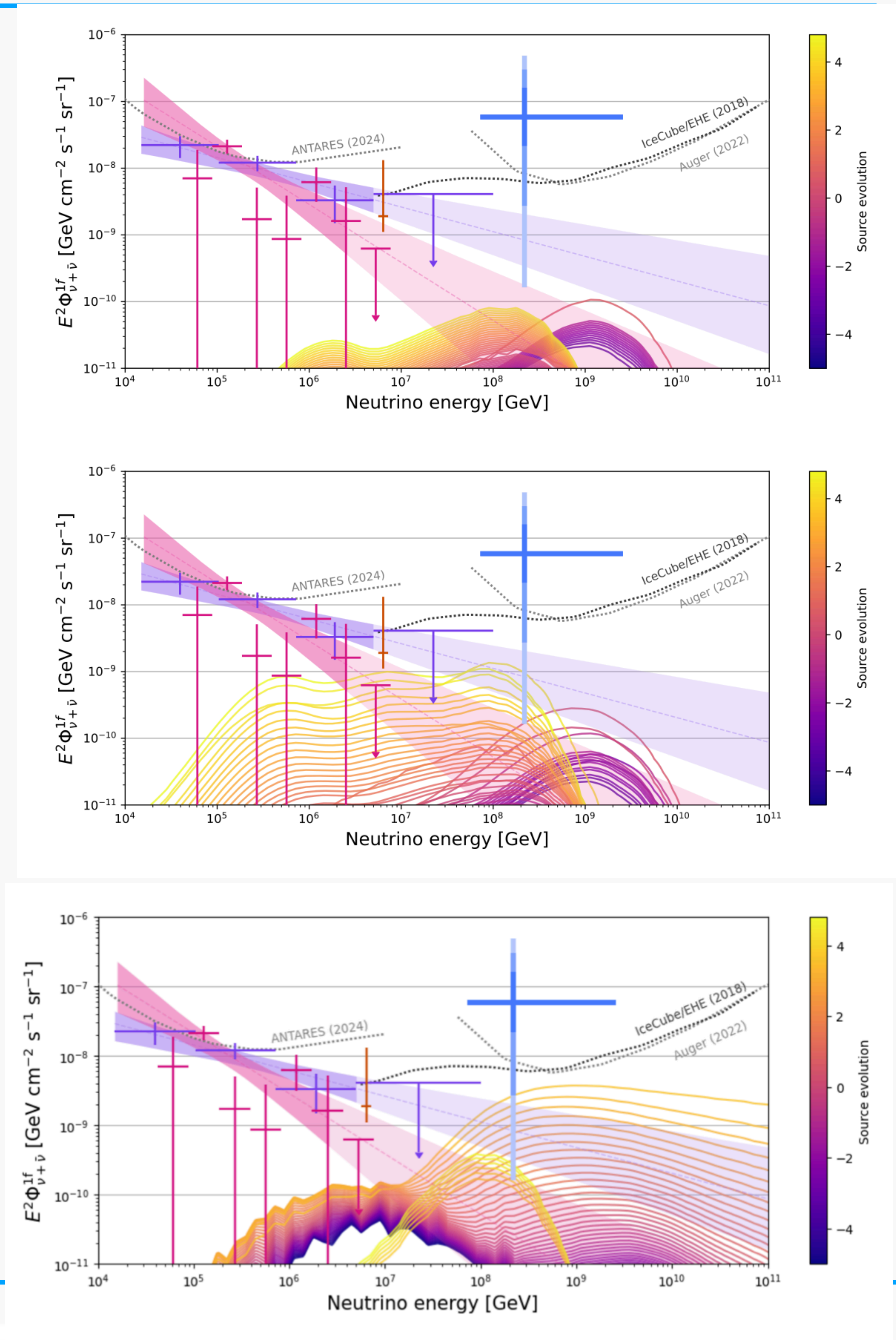
Berat, Condorelli et al., 2024 *ApJ* **966** 186

arXiv:2502.08508

Cosmogenic hypothesis



- The neutrino flux associated to the minimal scenario is very low.
- Important parameters for the neutrino flux: proton fraction & source evolution;
- If cosmogenic –> Strong evolution & non-negligible proton fraction at the highest energies.



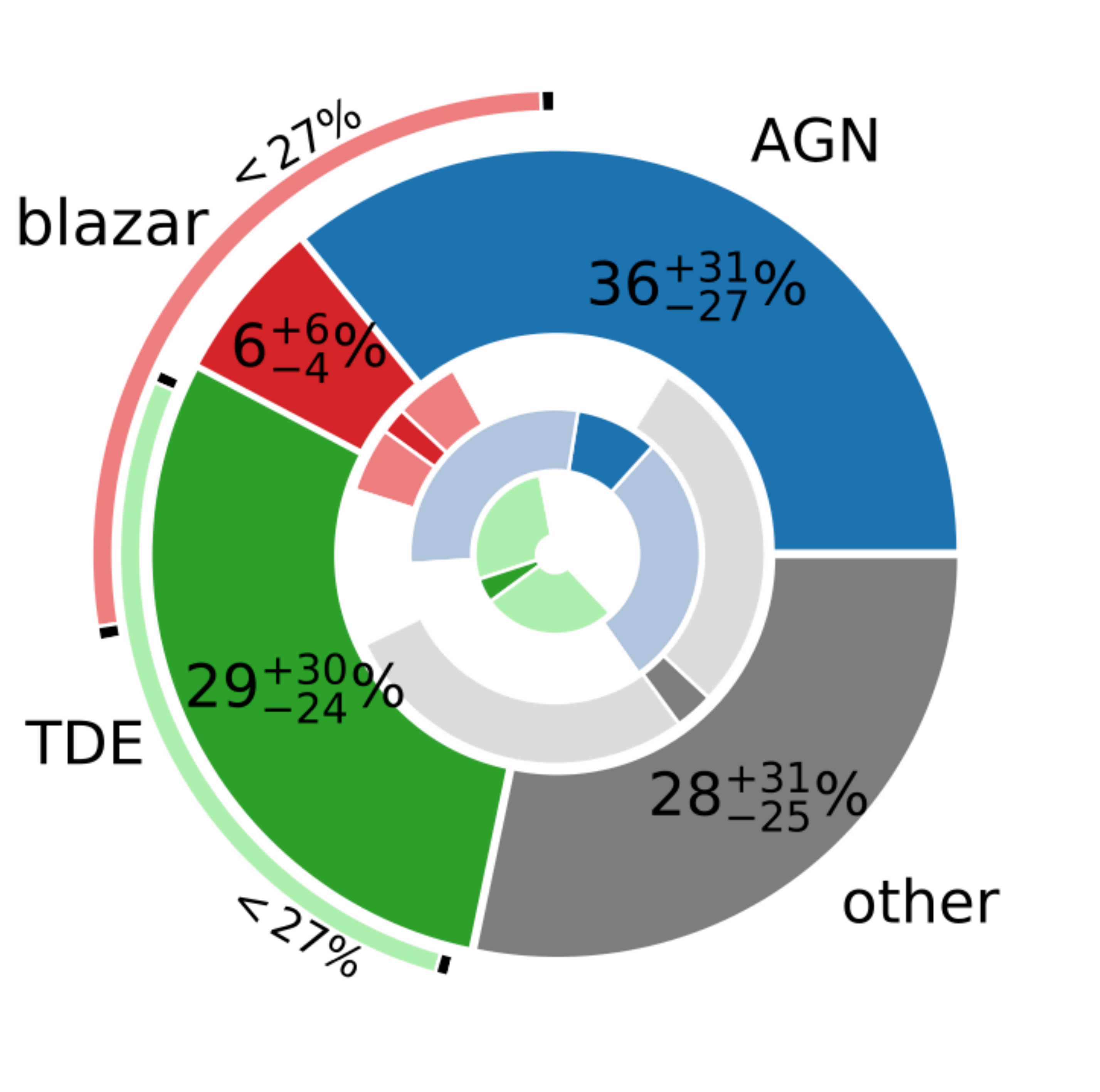
Berat, Condorelli et al., 2024 *ApJ* **966** 186

arXiv:2502.08508

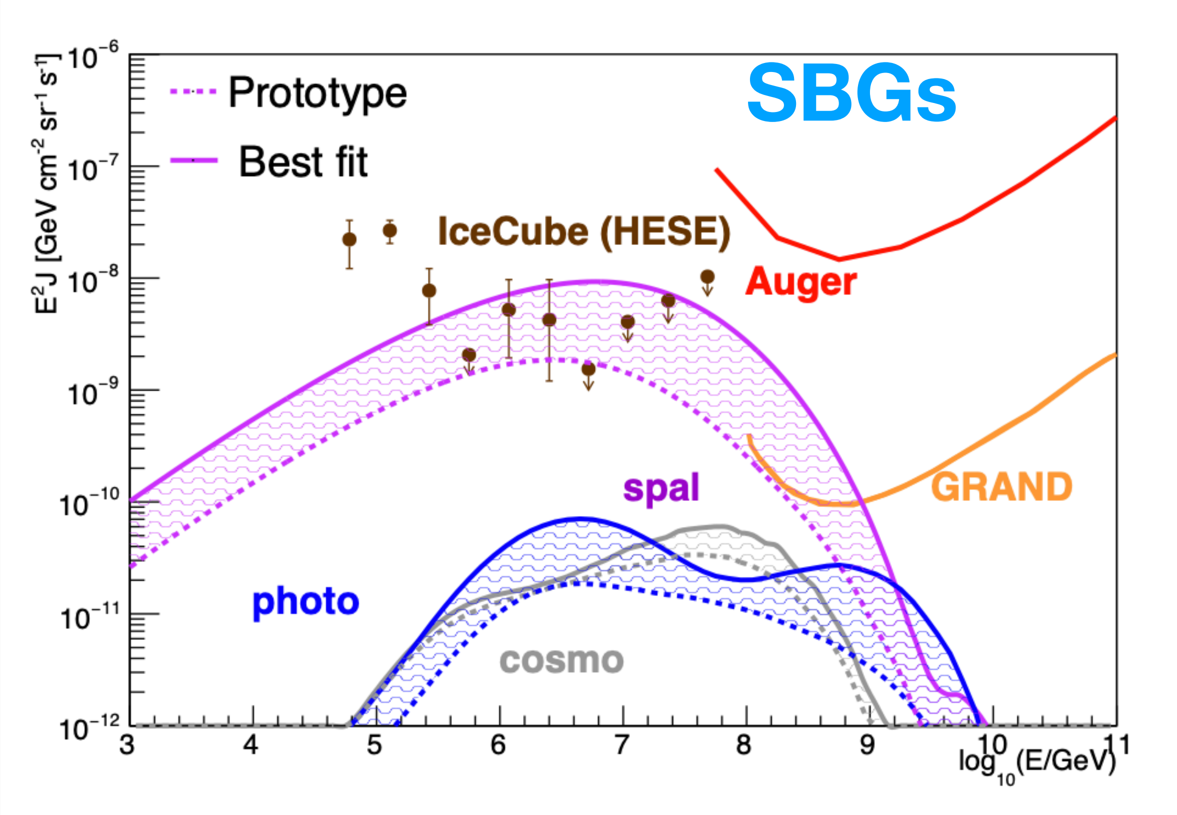
Other papers in preparation

Evidence for multiple individual neutrino source populations emerging

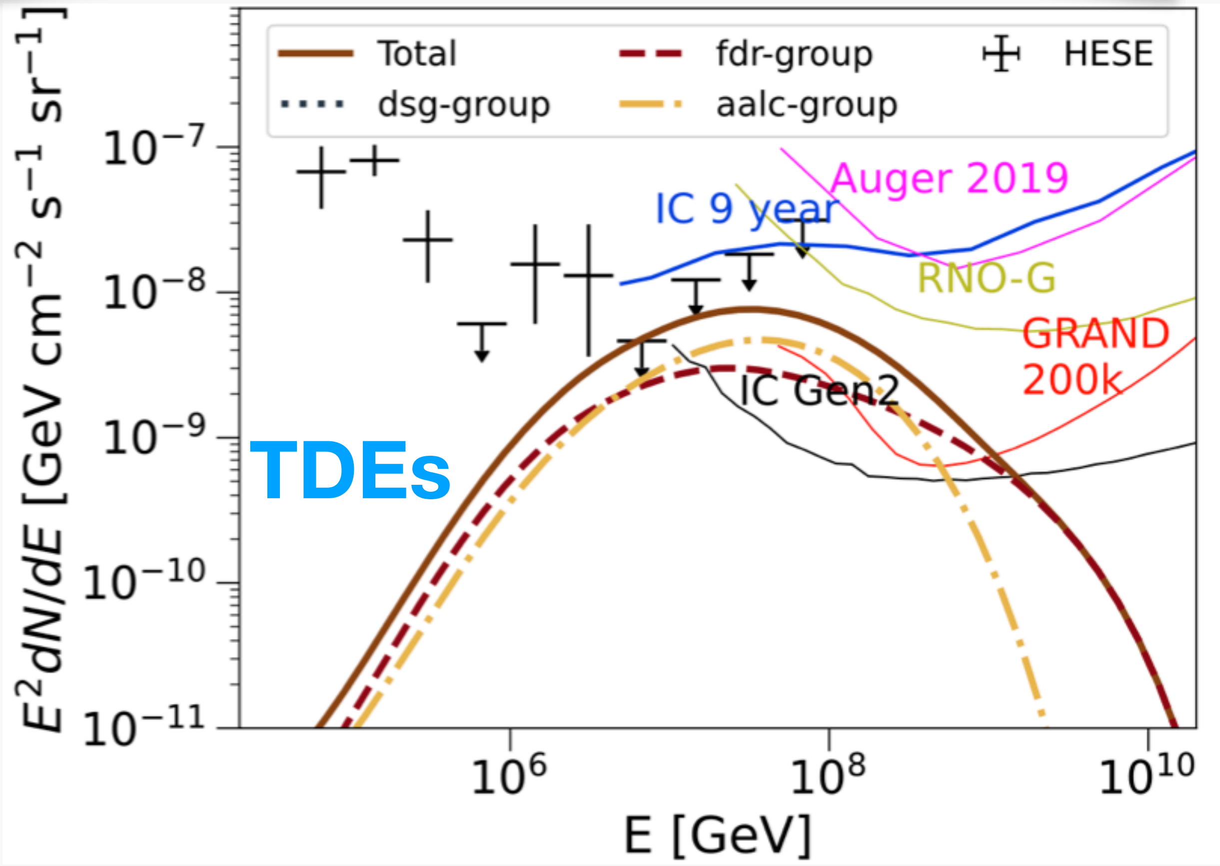
- AGN blazars
- AGN cores
- Galactic
- TDE?



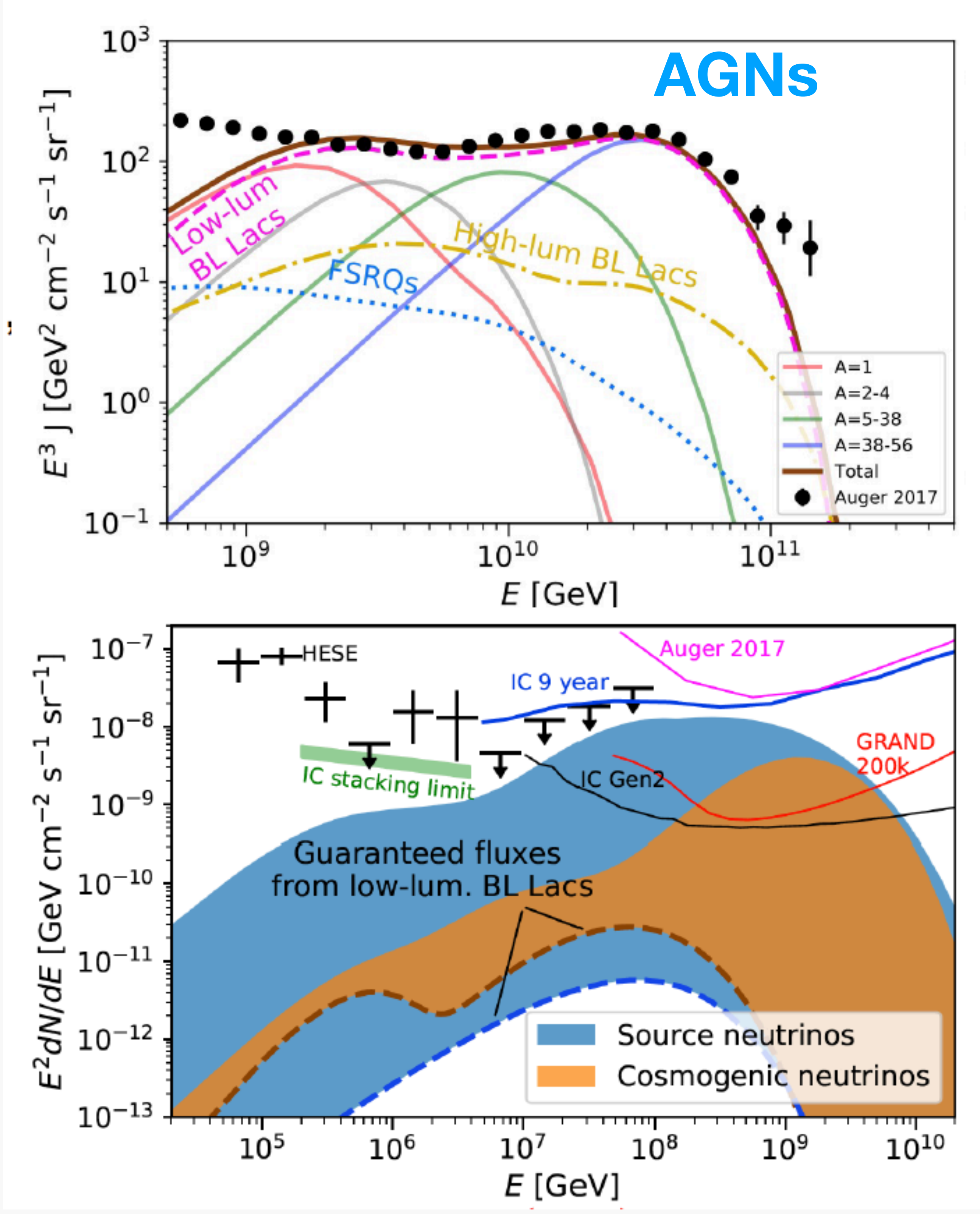
Bartos et al, arXiv:2105.03792



Condorelli et al., , Phys. Rev. D 107 (8), p. 083009

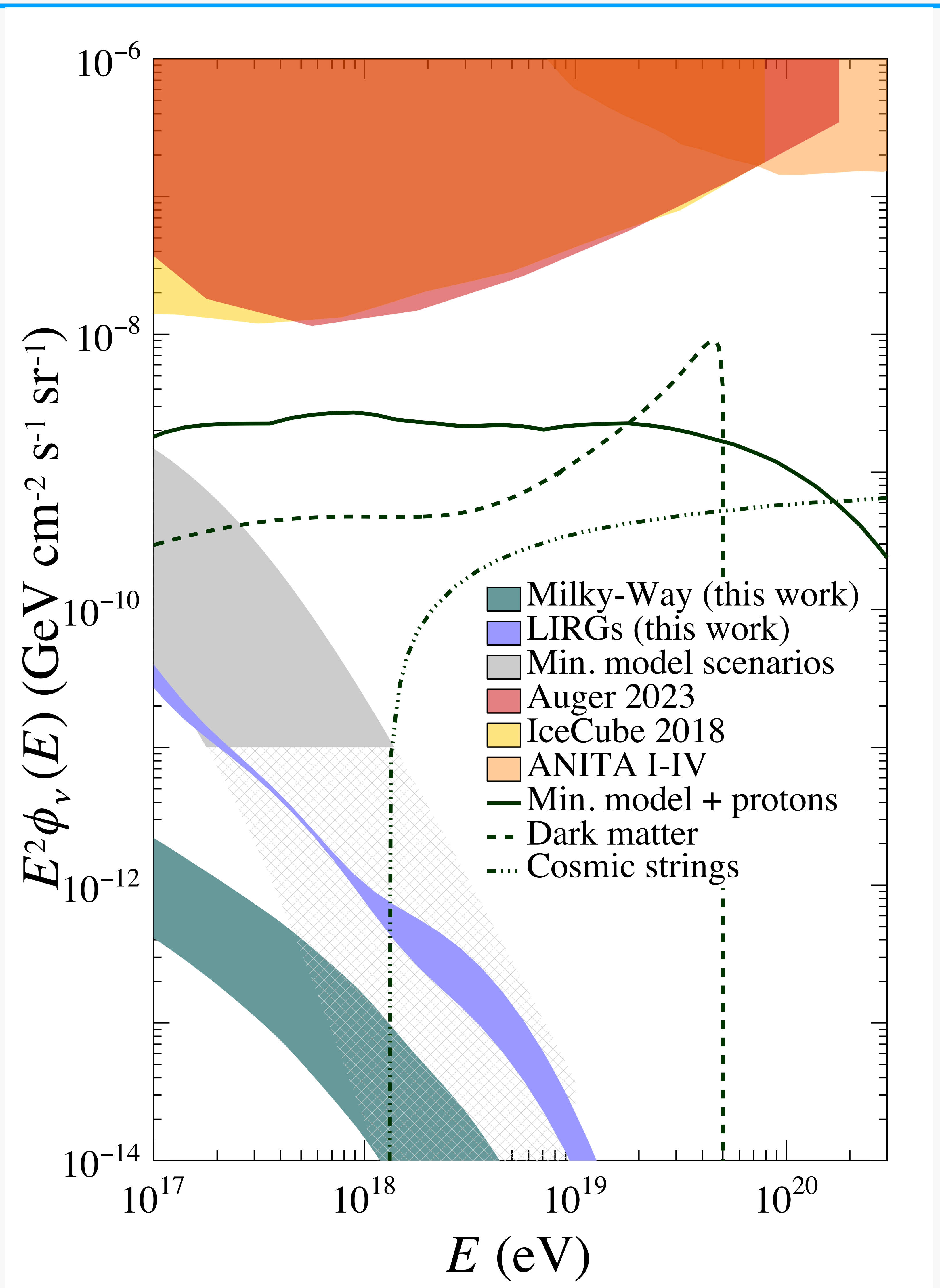


Plotko et al, in preparation



Rodrigues, et al., PRL 126 (2021) 191101

Other papers in preparation



- The neutrino flux associated to the minimal scenario is very low, –>room for detecting rare events:
- Super Heavy Dark Matter Decay: searching for byproduct of decay in VHE neutrinos.
- Cosmic strings: hypothetical 1-dimensional topological defects which may have formed during a symmetry-breaking phase transition in the early universe (top-down scenario).

Berat, Condorelli et al., 2024 *ApJ* **966** 186

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

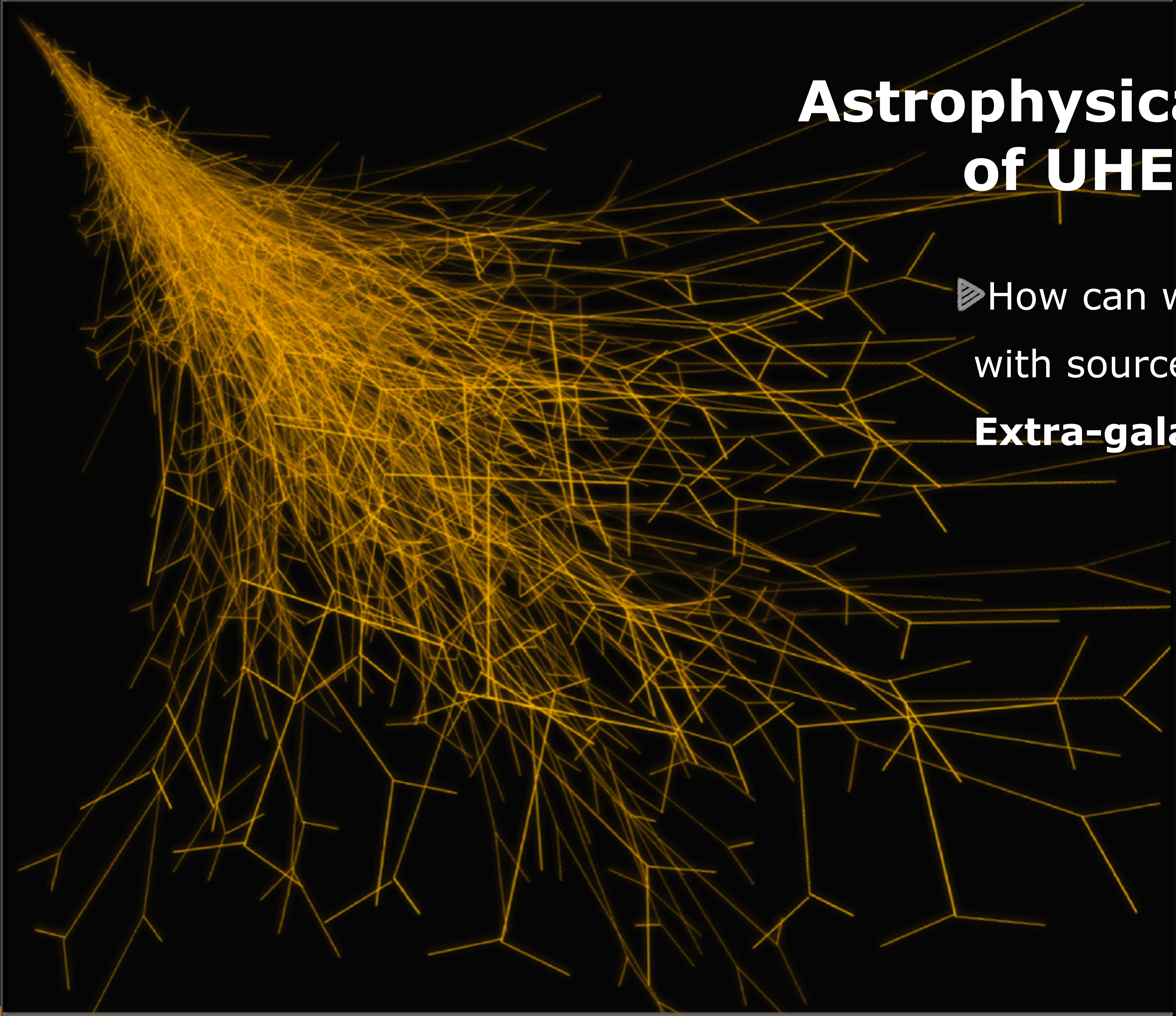
The UHE neutrinos observed by KM3NeT:

- 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.

Conclusions and final remarks

Thanks for your attention!


Source
Universe
Earth
p
ν



Astrophysical interpretation of UHECR sources

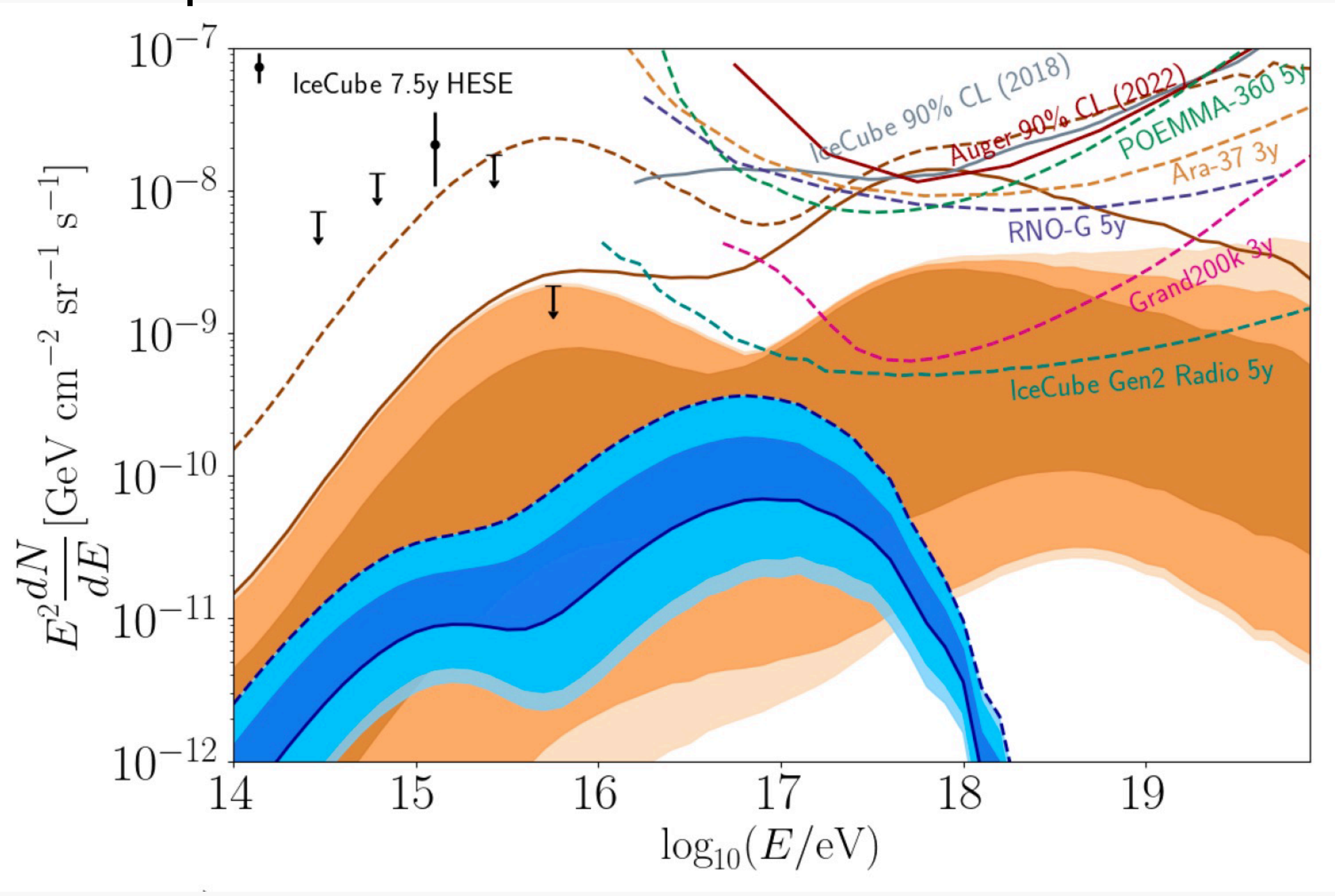
- How can we connect features at Earth with source parameters?

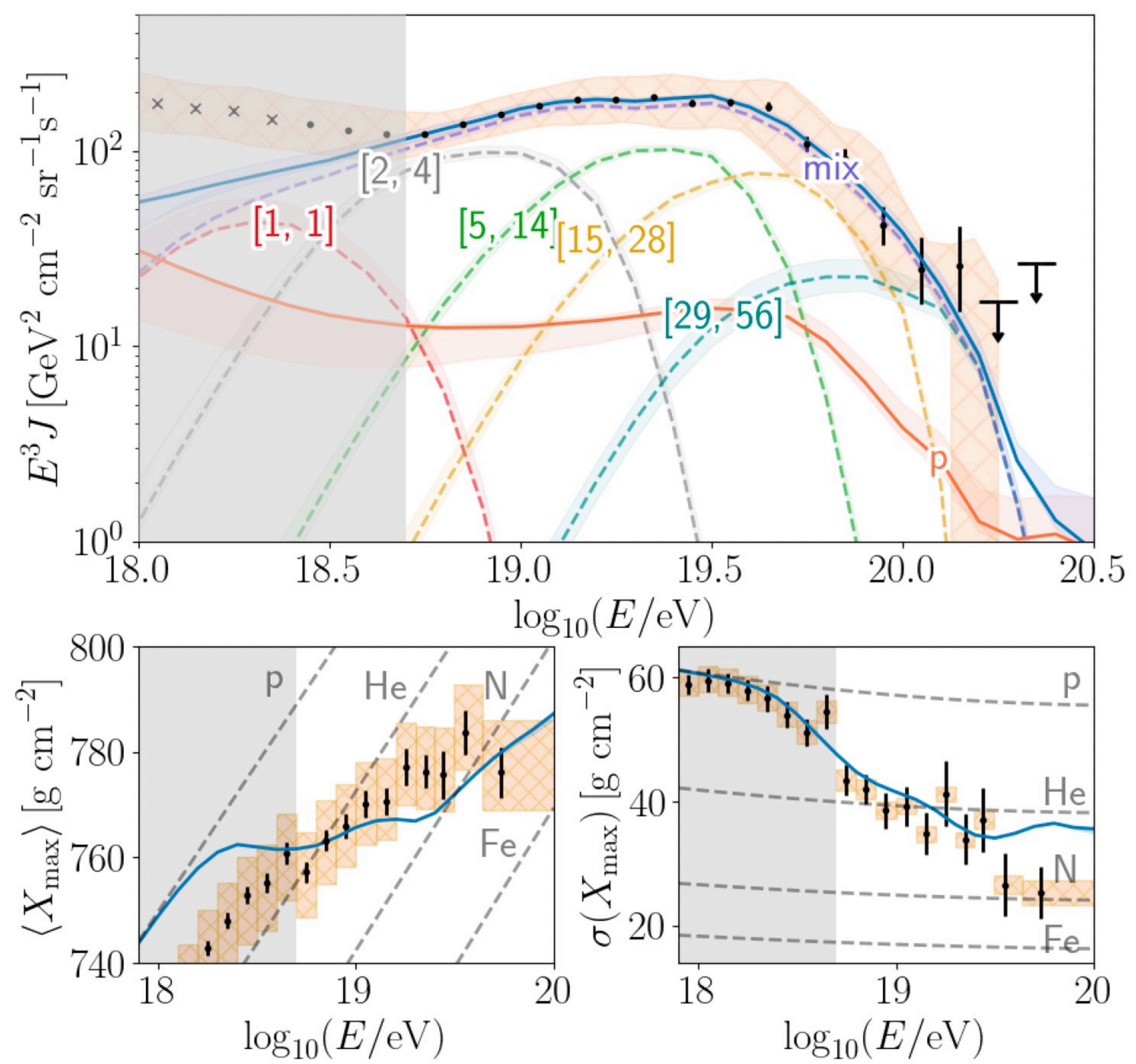
Extra-galactic Propagation

Cosmogenic neutrinos

Cosmogenic neutrino prediction from fit to UHECR flux

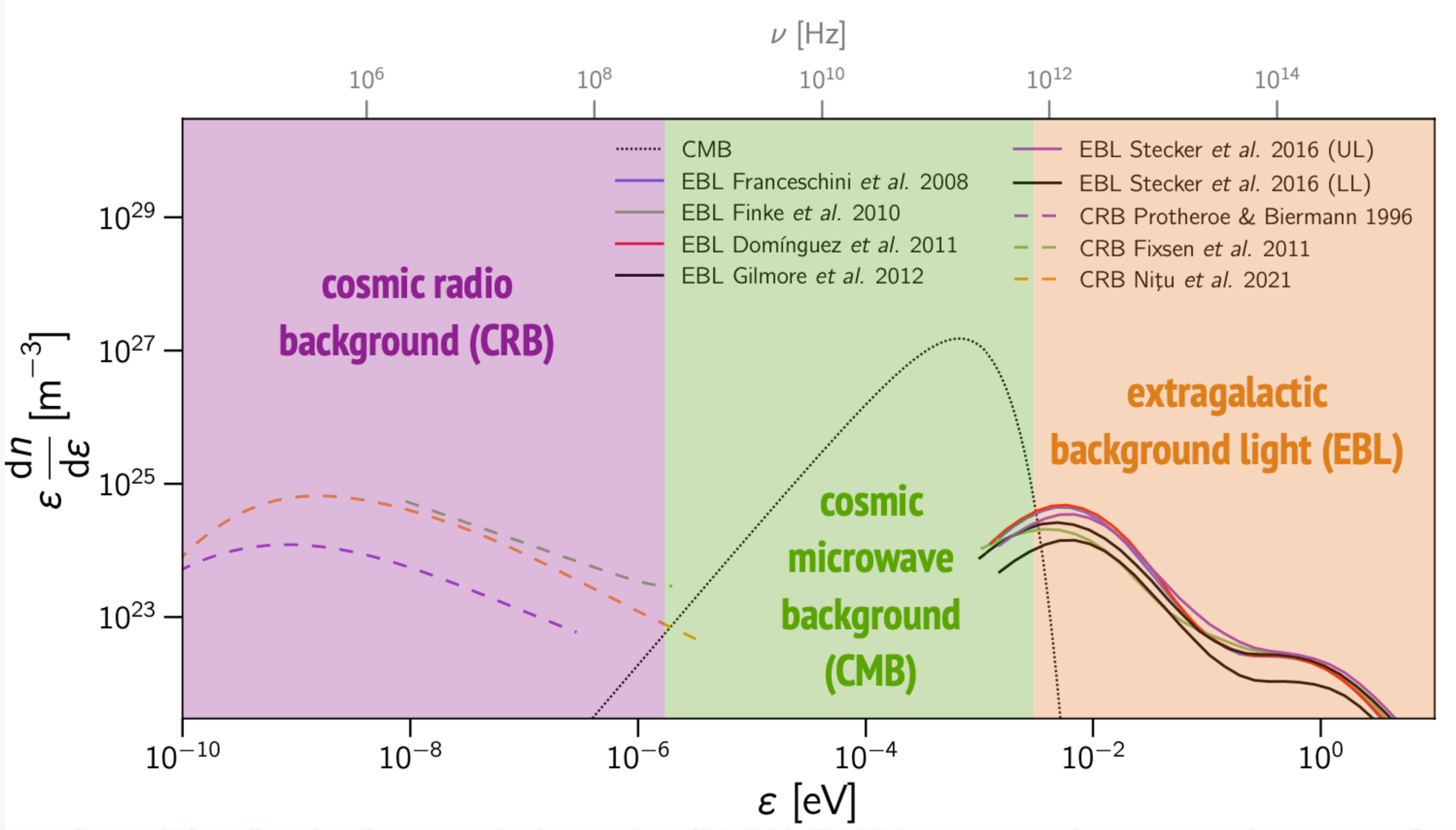
- Depends on extrapolation for z>1 (UHECRs not sensitive there!)
- No cosmogenic neutrinos in minimal scenario;
- Strong evolution and proton component –> boost in neutrino production!





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

UHECR interactions



Extra-galactic photon fields:

$\varepsilon_{CMB} \simeq\ 0.1\ \text{meV}$

$\varepsilon_{IR} \simeq\ 10\ \text{meV}$

$\varepsilon_{OPT} \simeq\ 1\ \text{eV}$

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

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

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

GZK effect

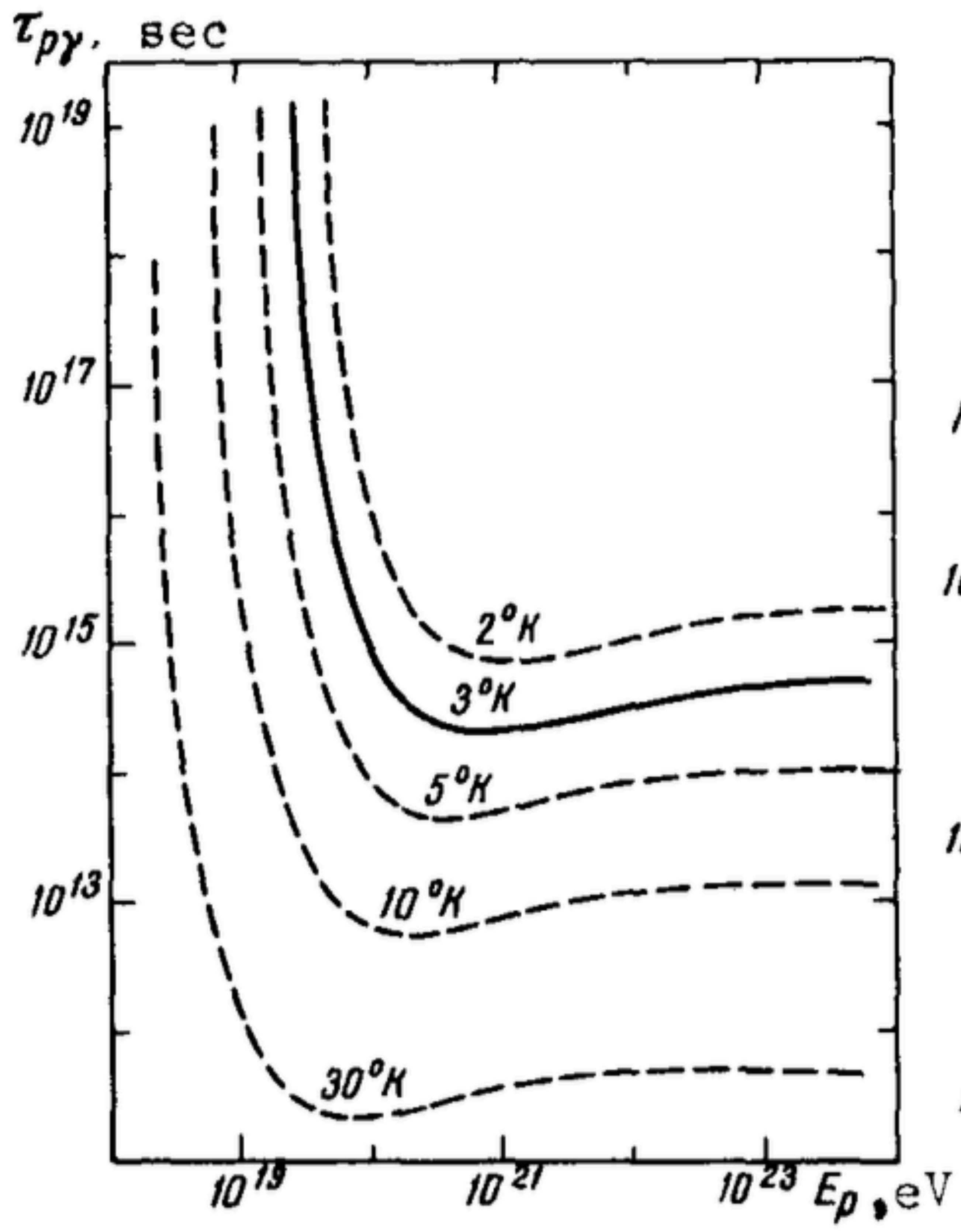


Fig. 1

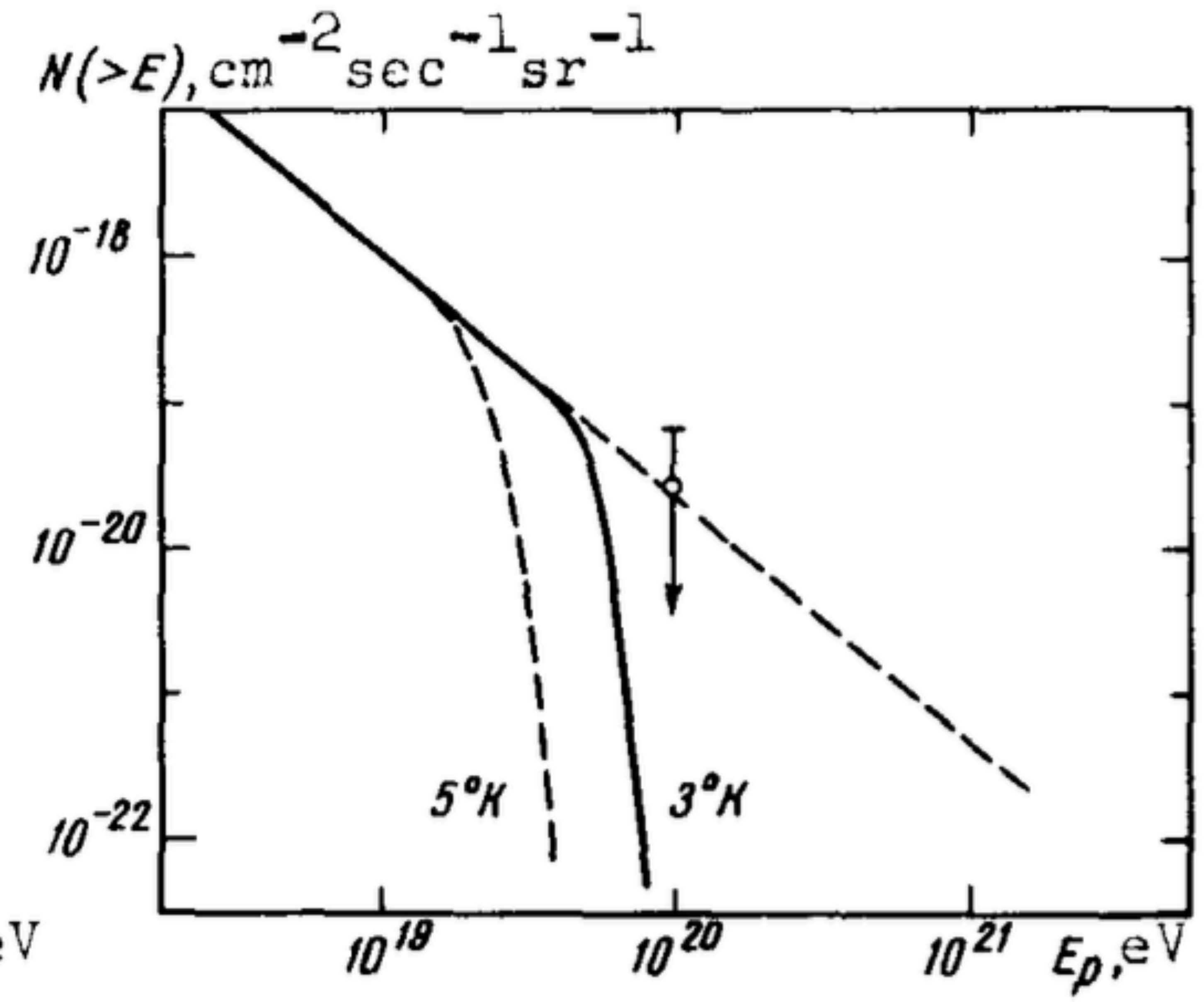


Fig. 2

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

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

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

Proton energy:

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

Threshold:

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

UHECR interactions

- Pair production

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

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

- Photodisintegration

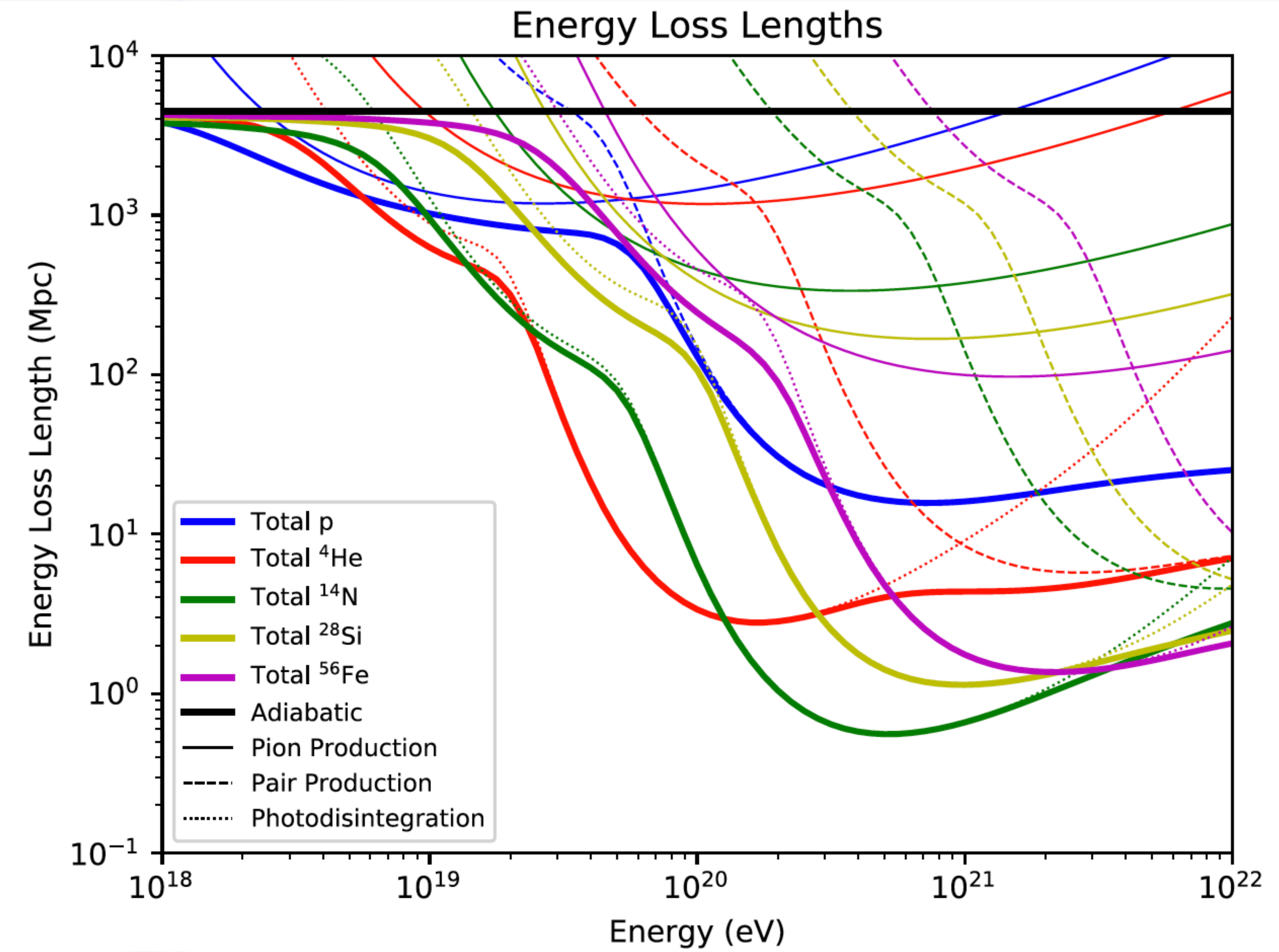
$$(A, Z) + \gamma \rightarrow (A - n, Z - m) + nN$$

- 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:

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

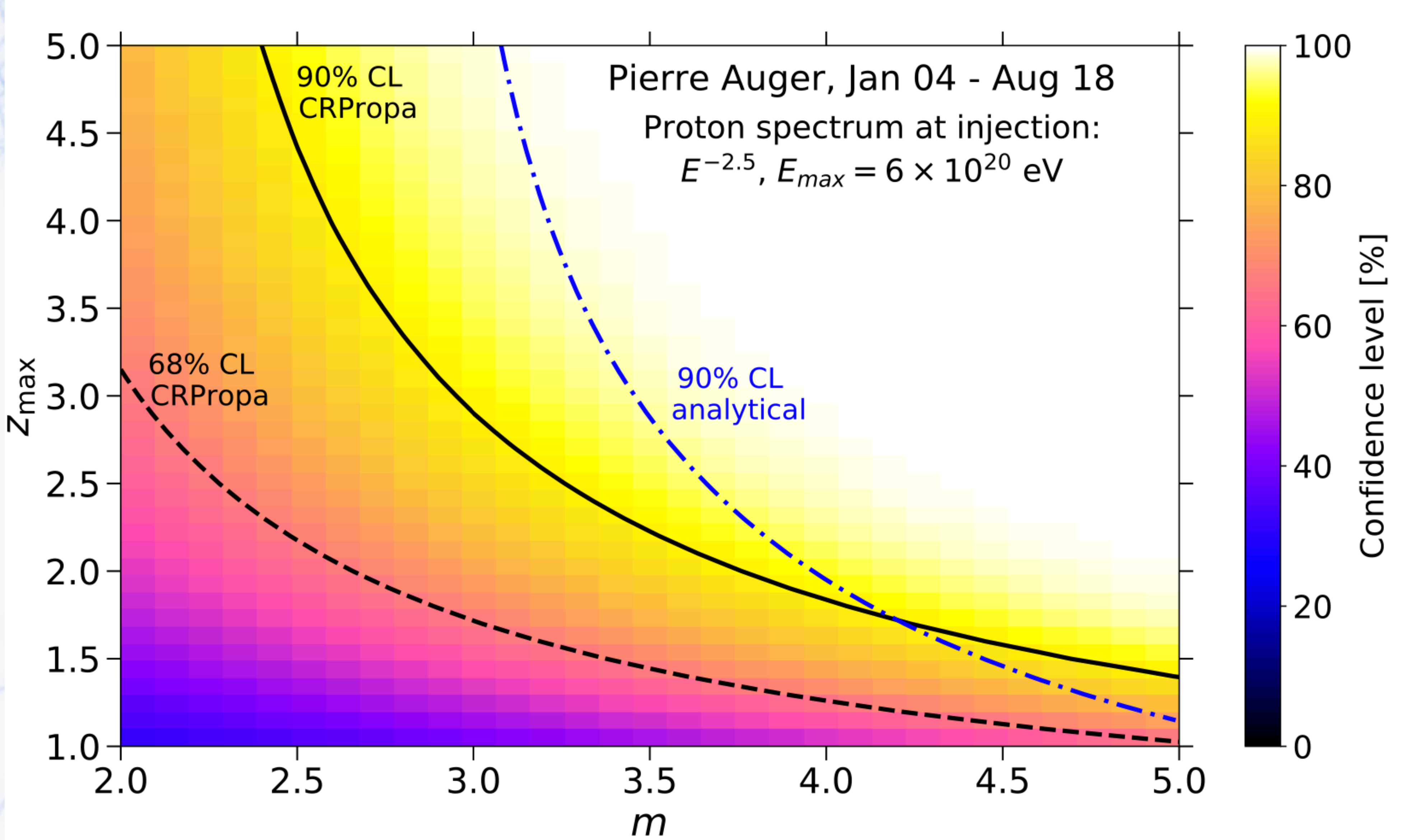
Adiabatic expansion:

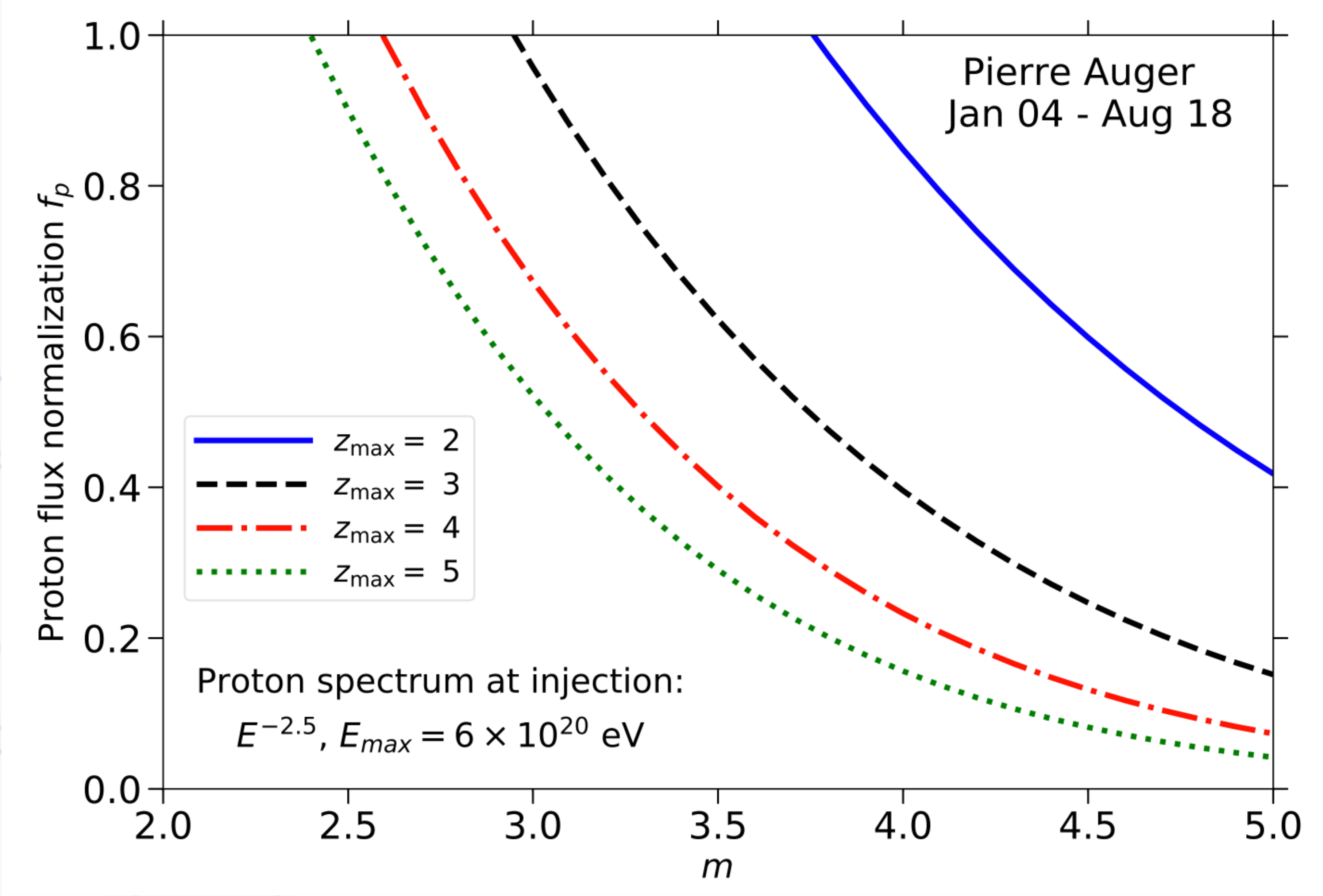
$$\frac{1}{E}\frac{dE}{dt} = \beta(E,t) + H(t), \quad \beta(E,t) = \sum_{\rm int}\beta_i(E,t)$$

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



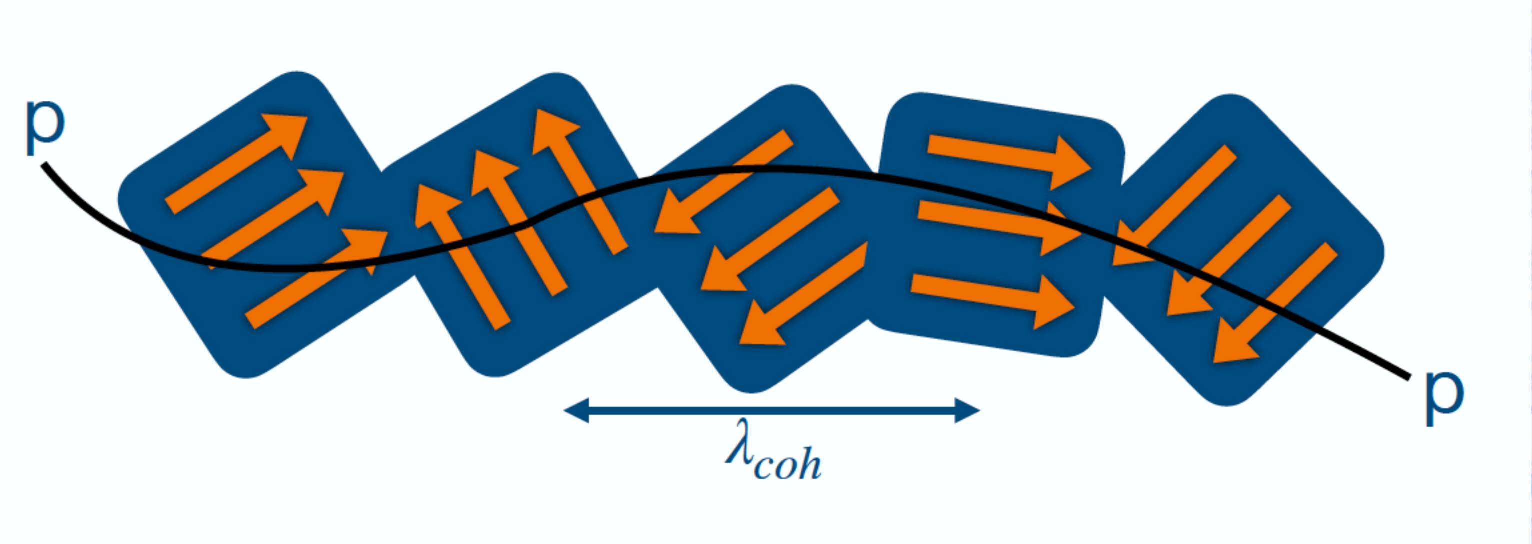


Energy spectrum, mass composition and neutrinos can constrain **source evolution** and **proton fraction**!

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

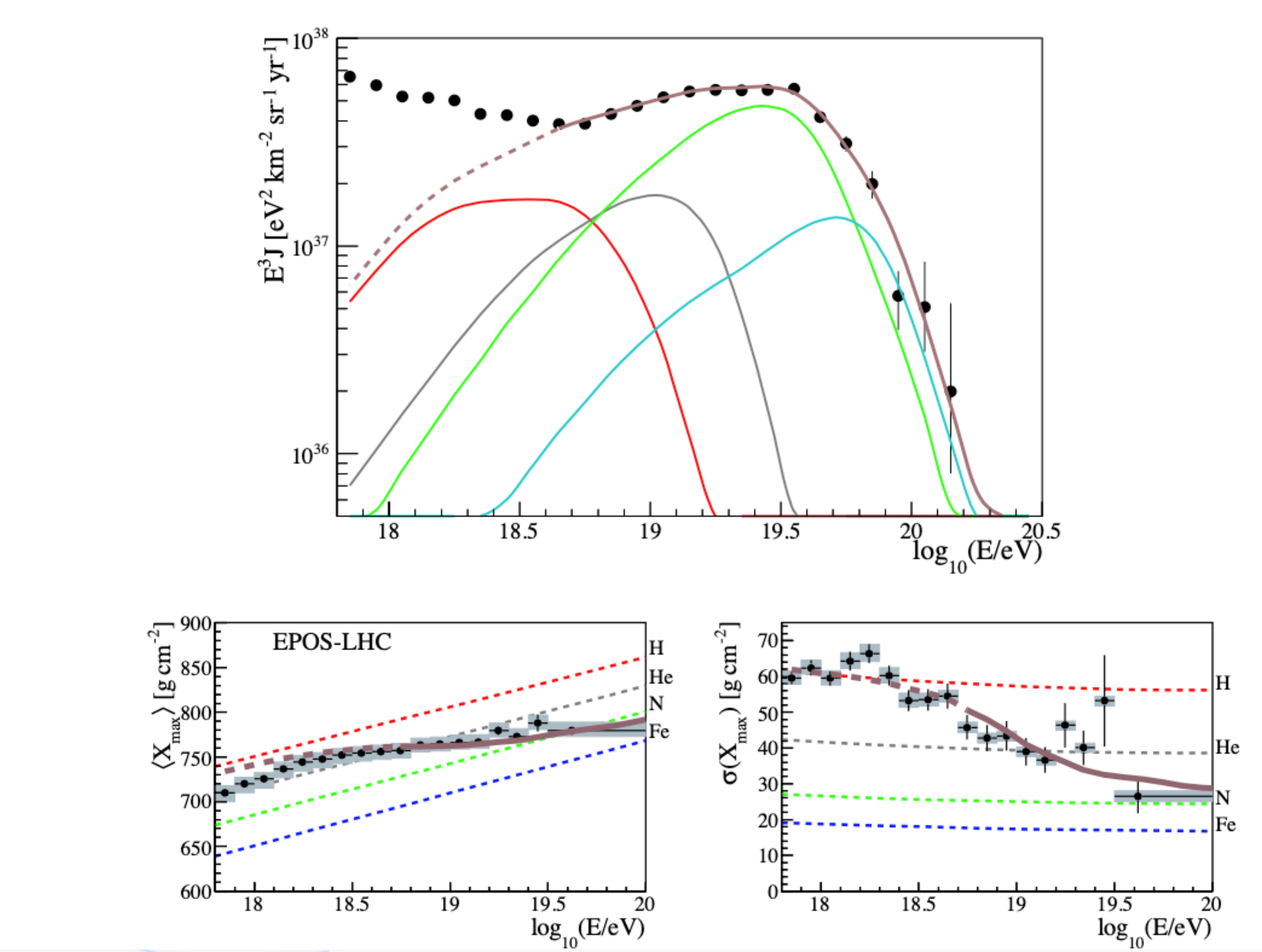
$$\langle \alpha^2 \rangle \sim \frac{d}{\lambda_{coh}}\alpha^2_{\lambda_{coh}} = \frac{d\lambda_{coh}}{r_L^2} = d\lambda_{coh}\left(\frac{eB}{E/Z}\right)^2$$

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

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;

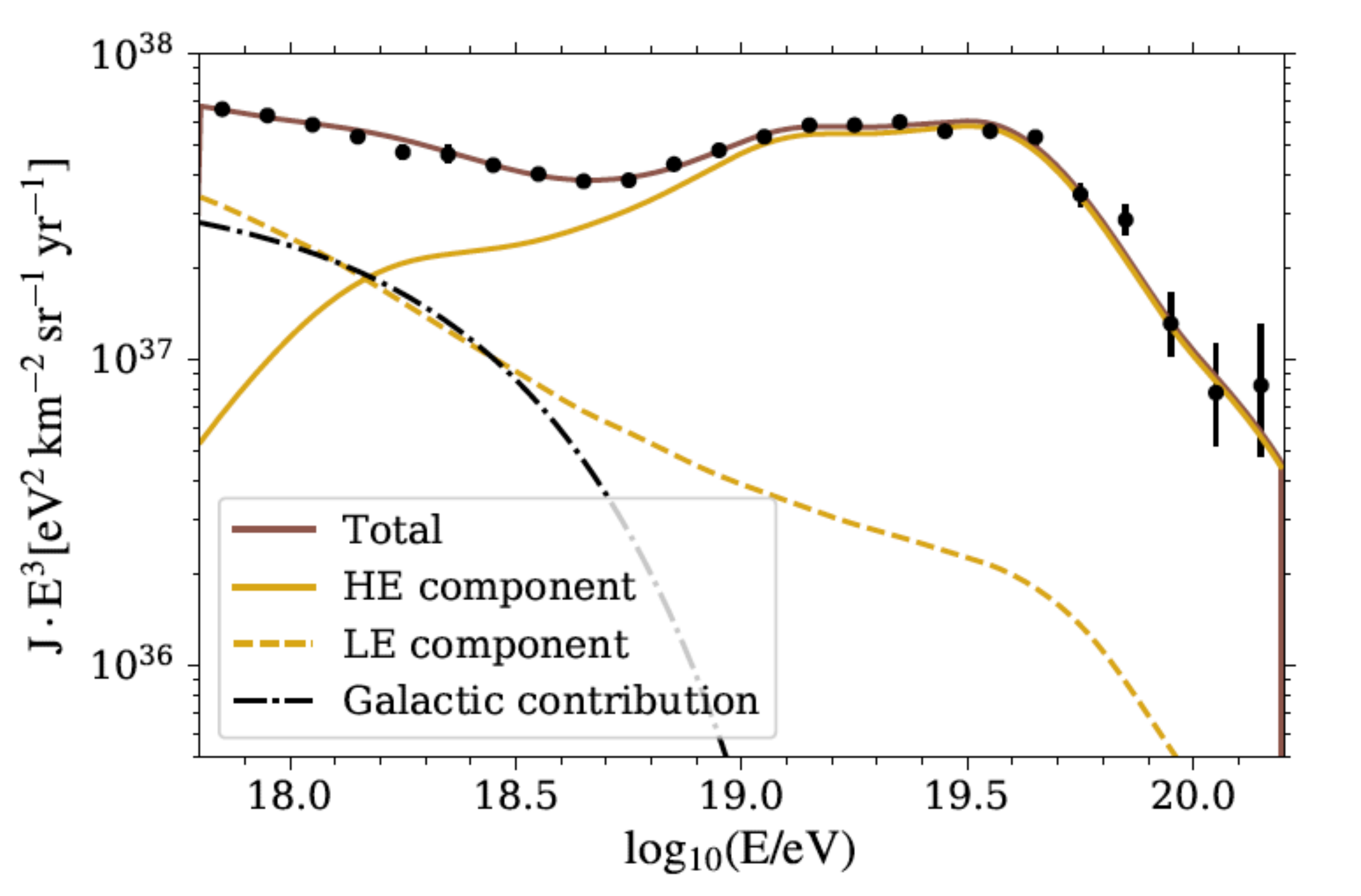
- Nuclei are accelerated at the sources.
- A hard injection spectrum at the sources is required.
- Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accommodate.



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

UHECR interactions

Additional component

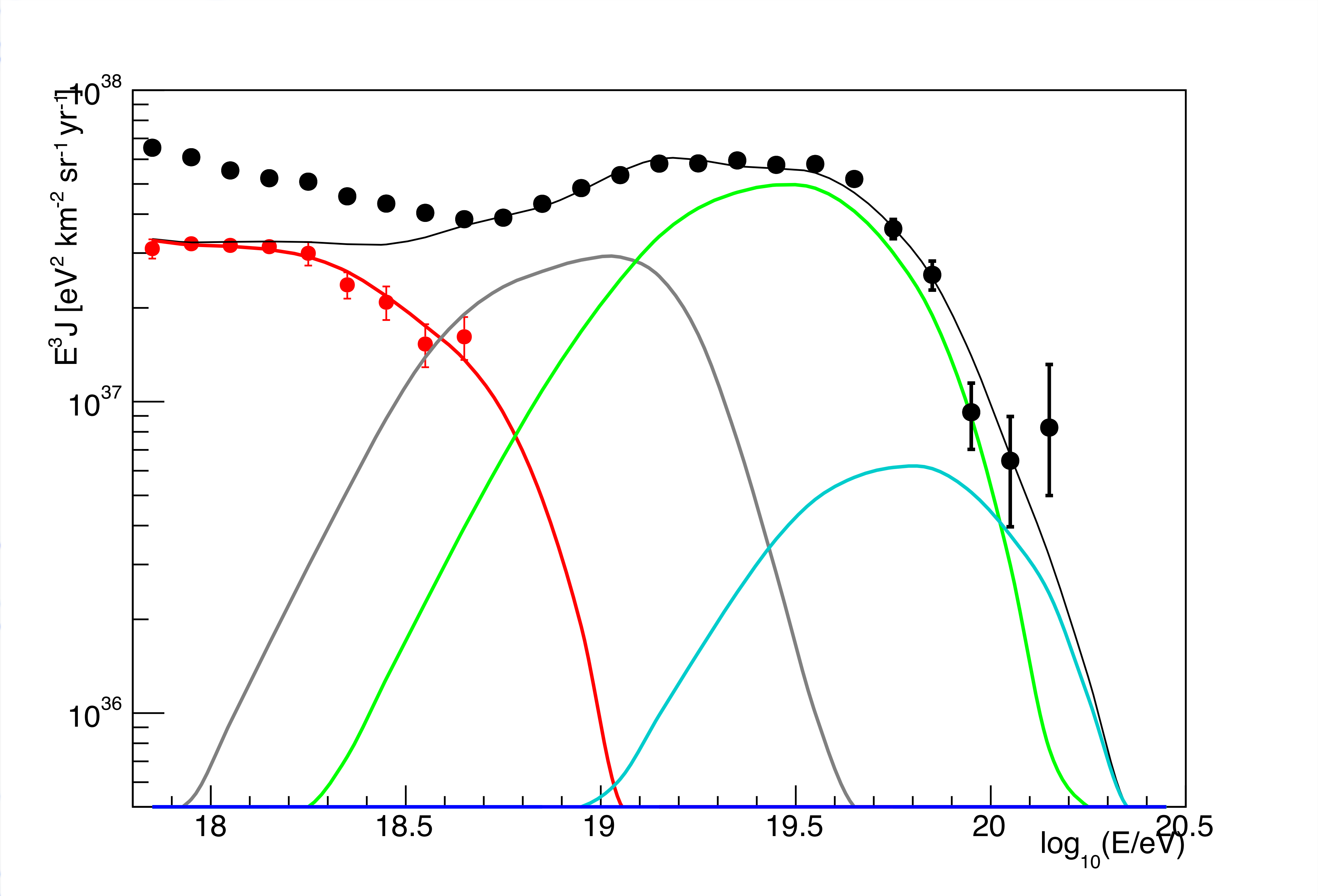


▶Impossibility to distinguish between a galactic and an extra-galactic contribution at low energies.

▶Iron Galactic flux is strongly disfavoured.

The Pierre Auger Collaboration, JCAP05(2023)024

Source interactions



▶Accelerated particles confined in the environment surrounding the source;

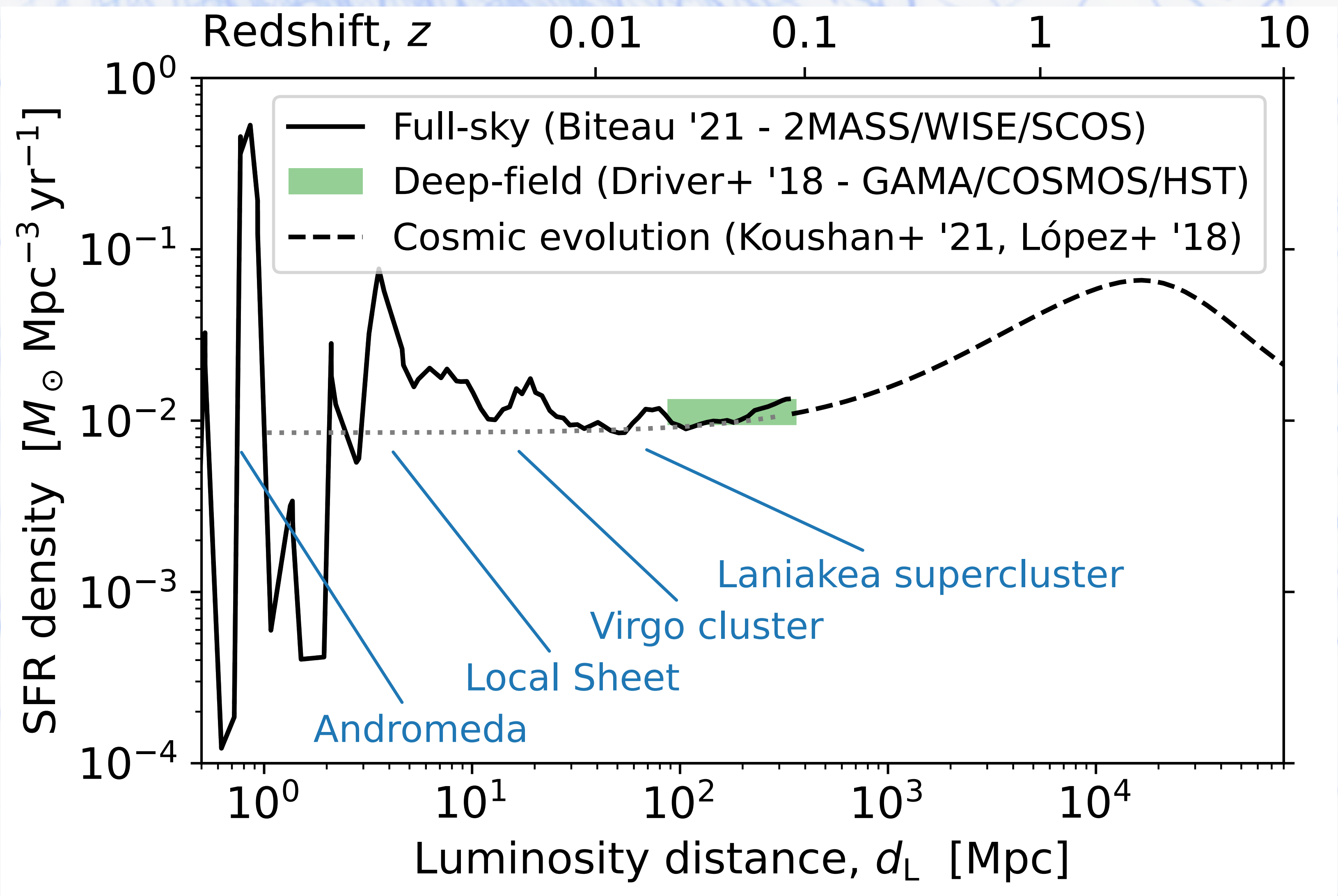
▶Low energy particles –> Pile-up of nucleons at lower energies.

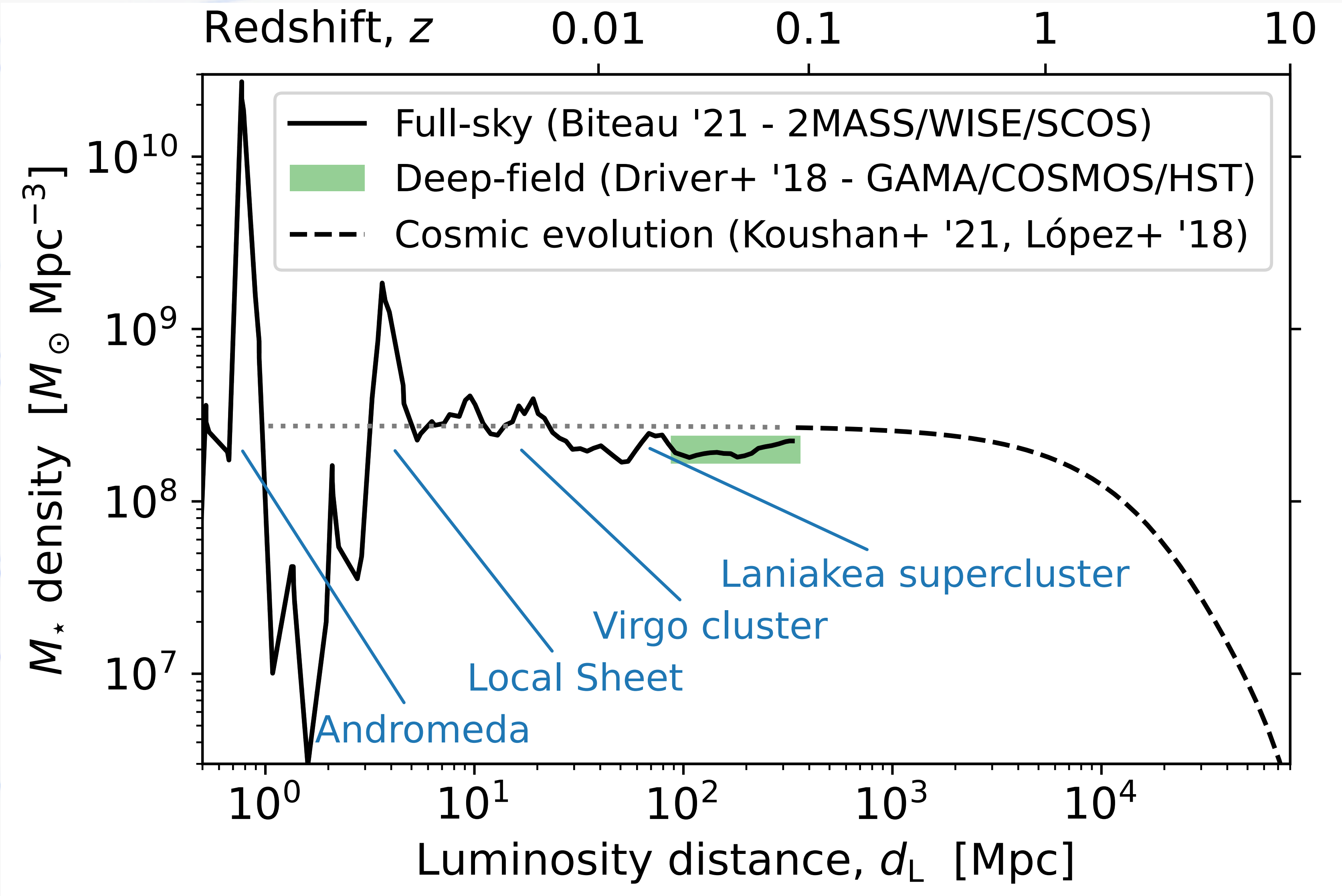
A. Condorelli et al., Phys. Rev. D **107**, 083009

Transient scenario

Studying the plausible UHECR sources in the nearby Universe in a transient scenario.

- Catalogue of ~400,000 galaxies in the nearby Universe (< 350 Mpc).
- Assuming that UHECR production rate follows a tracer (SFRD or Stellar mass density)





A. Condorelli et al., 2023 *ApJ* **957** 80

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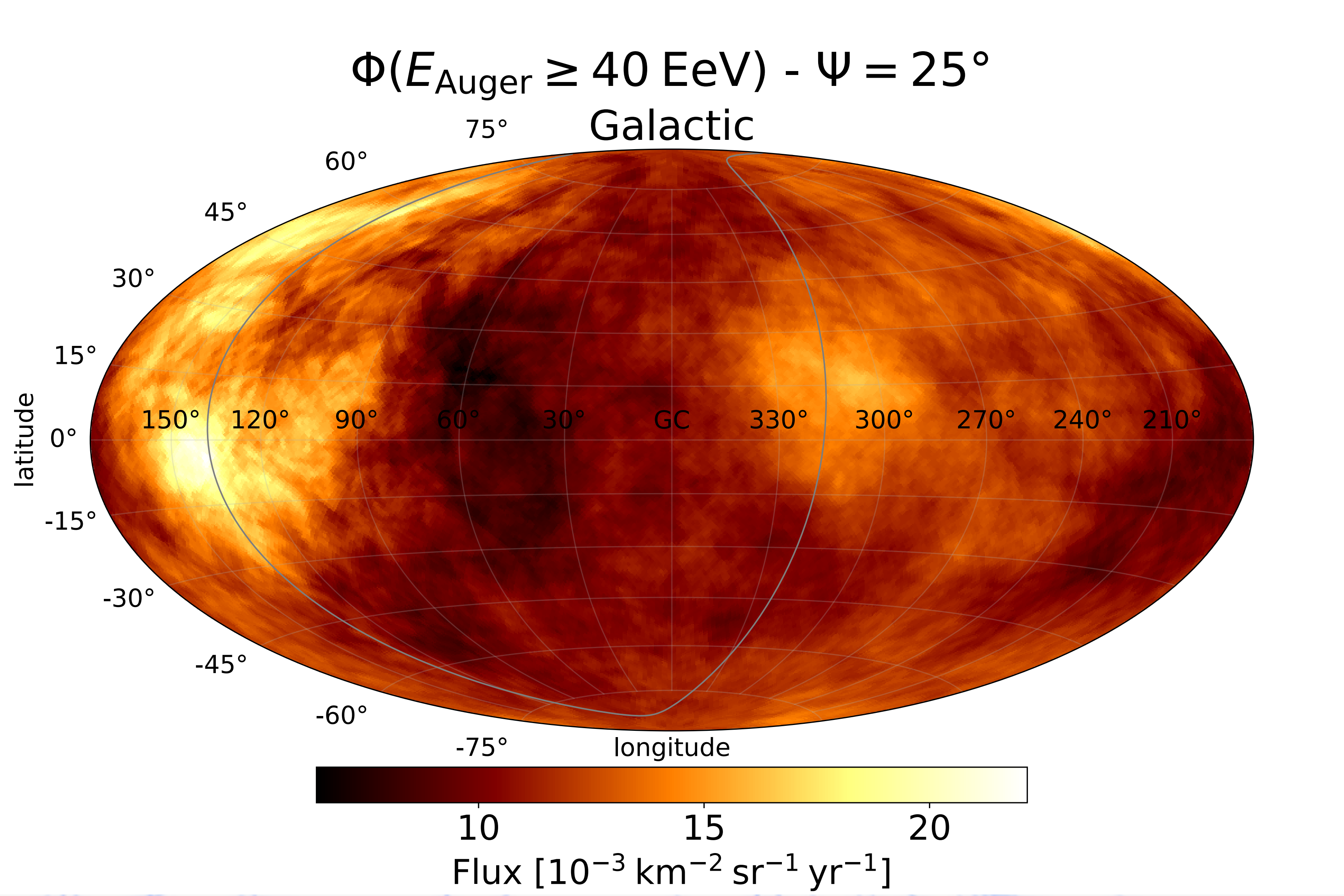
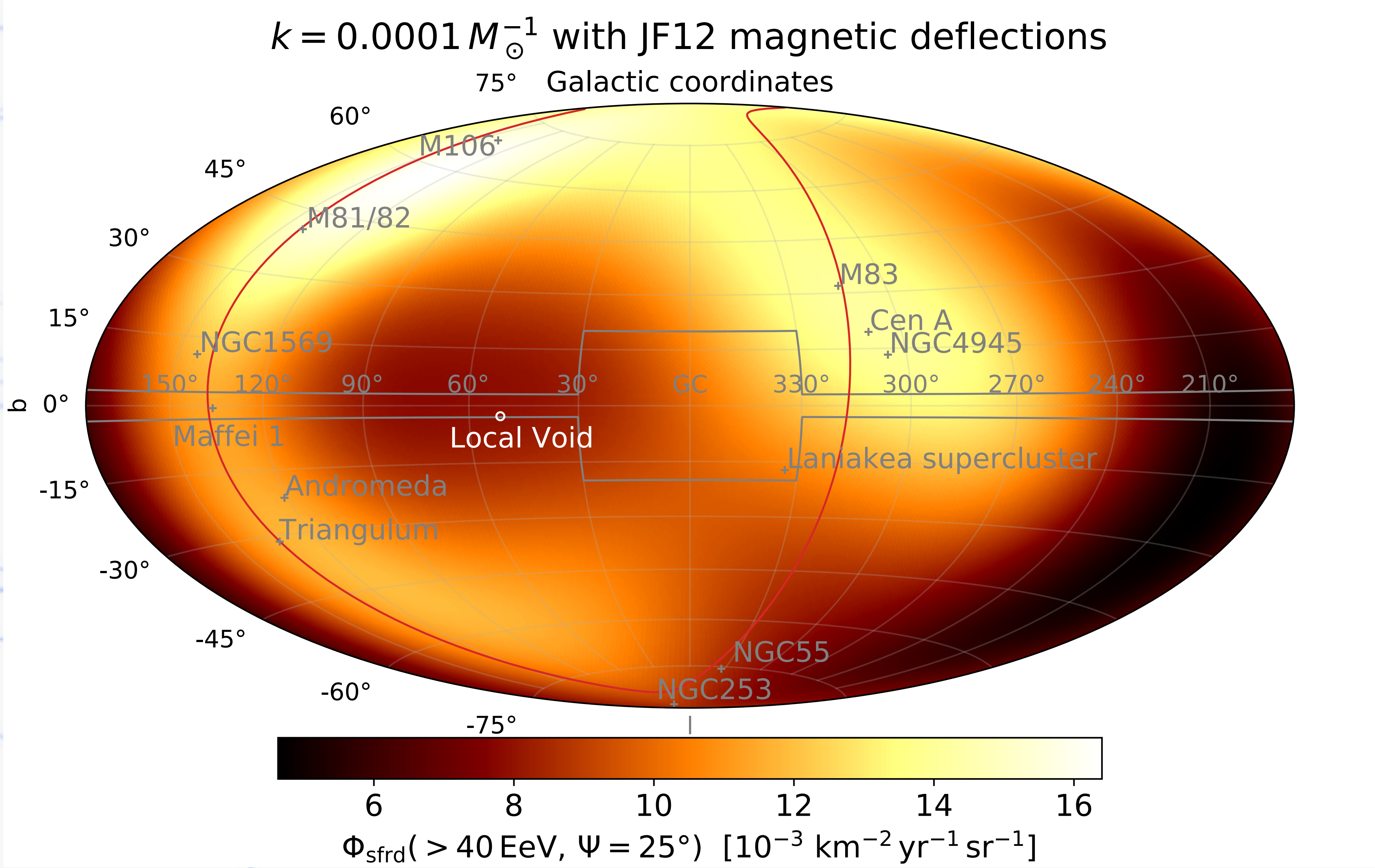




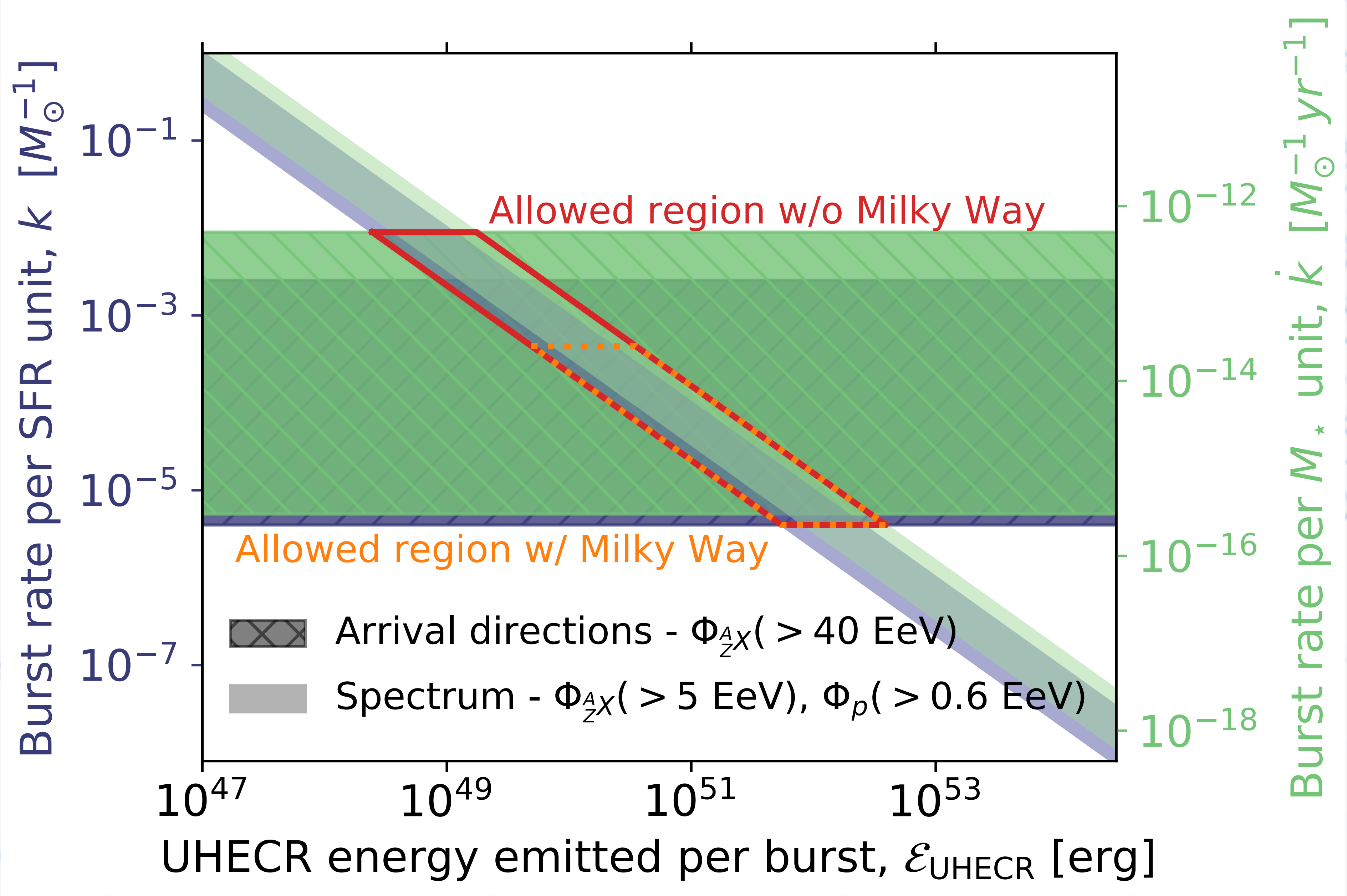
- Arrival direction –> constraint on the burst rate!

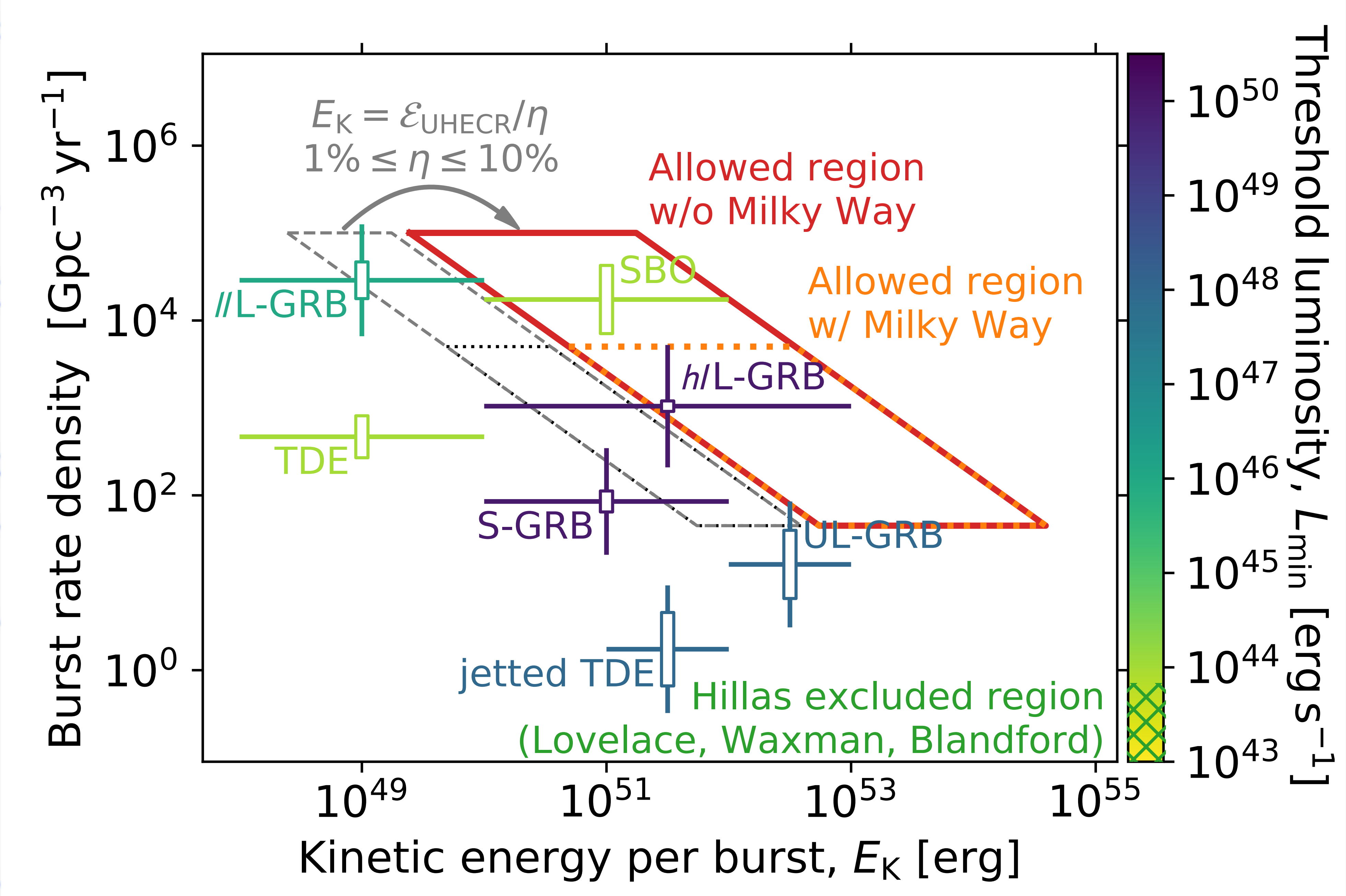
A. Condorelli et al., 2023 *ApJ* **957** 80

Transient scenario

- The experimental skymaps constrains the burst rate.
- Spectrum and composition constrain the energetic budget.

- Long gamma ray burst are the only stellar-size suitable candidate UHECR sources in a transient scenario.





A. Condorelli et al., 2023 *ApJ* **957** 80