Antonio Condorelli

Particle Propagation and the Multi-Messenger View of the Highest-Energy Particles in Nature

High Energy Astrophysics Seminair, DESY

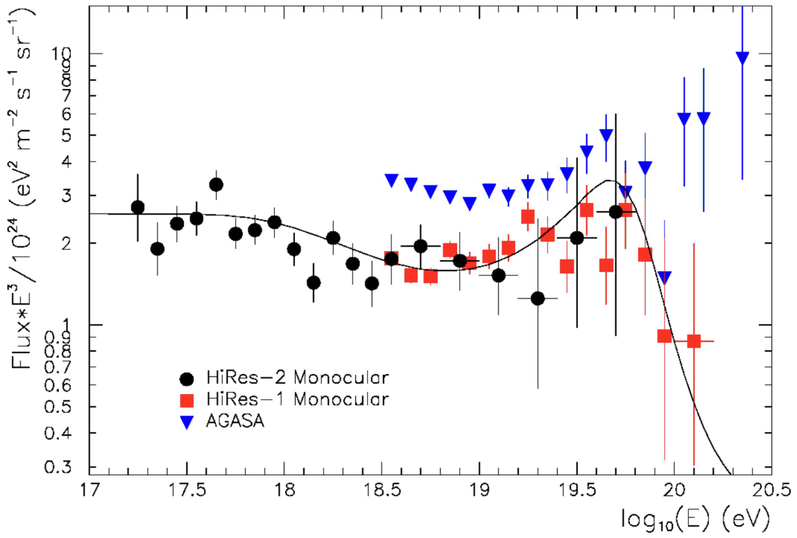
17/10/2025

My goal

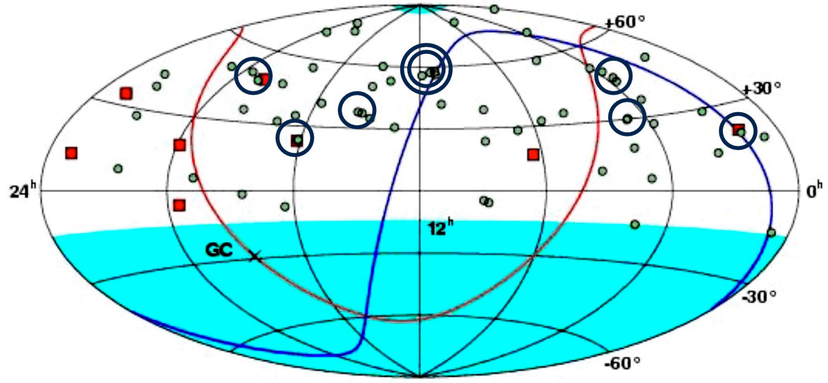
Goal: Finding the highest energies sources.

Complicated to say something 20 years ago..

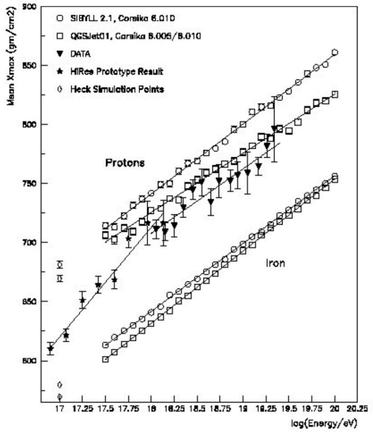
Energy spectrum



Arrival direction



Mass Composition

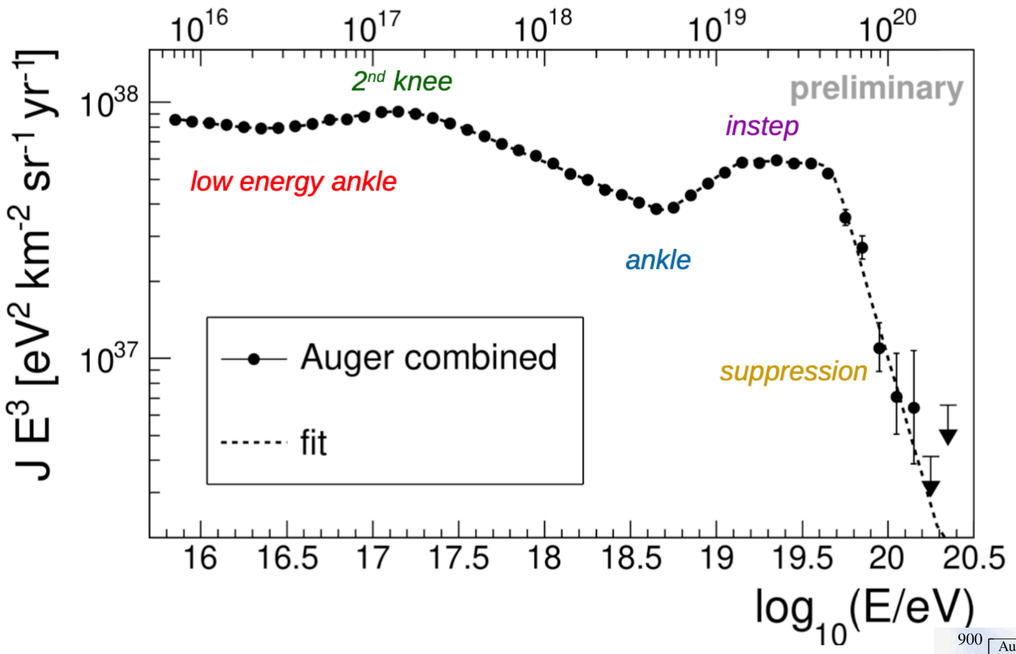


My goal

Goal: Finding the highest energies sources.

High-quality data, still not easy to point back at sources

Energy spectrum



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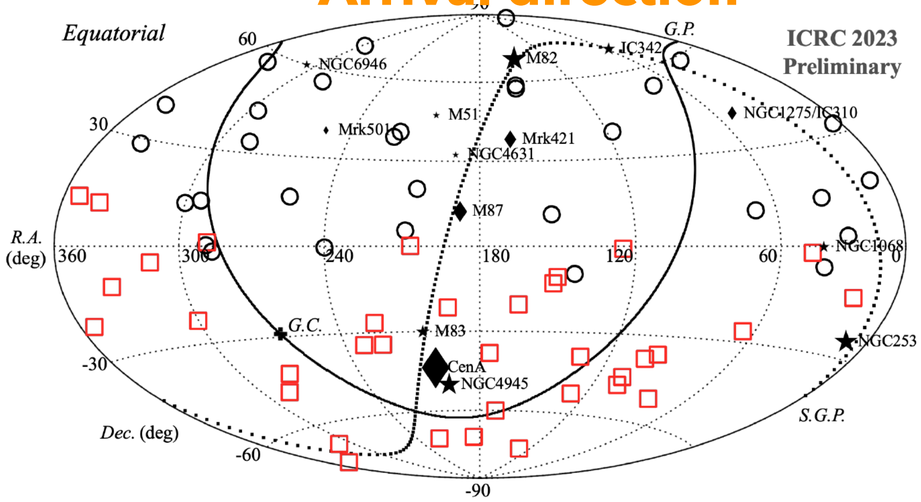
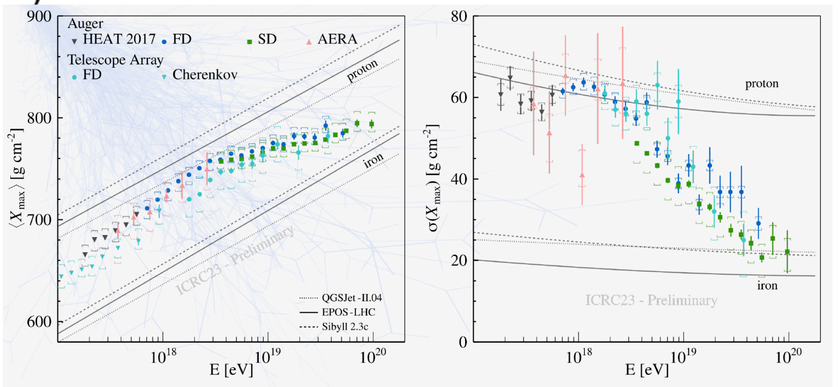


TA 15-years (ICRC2023 Preliminary), Auger 17-years (ApJ 935 170 (2022))

Mass Composition

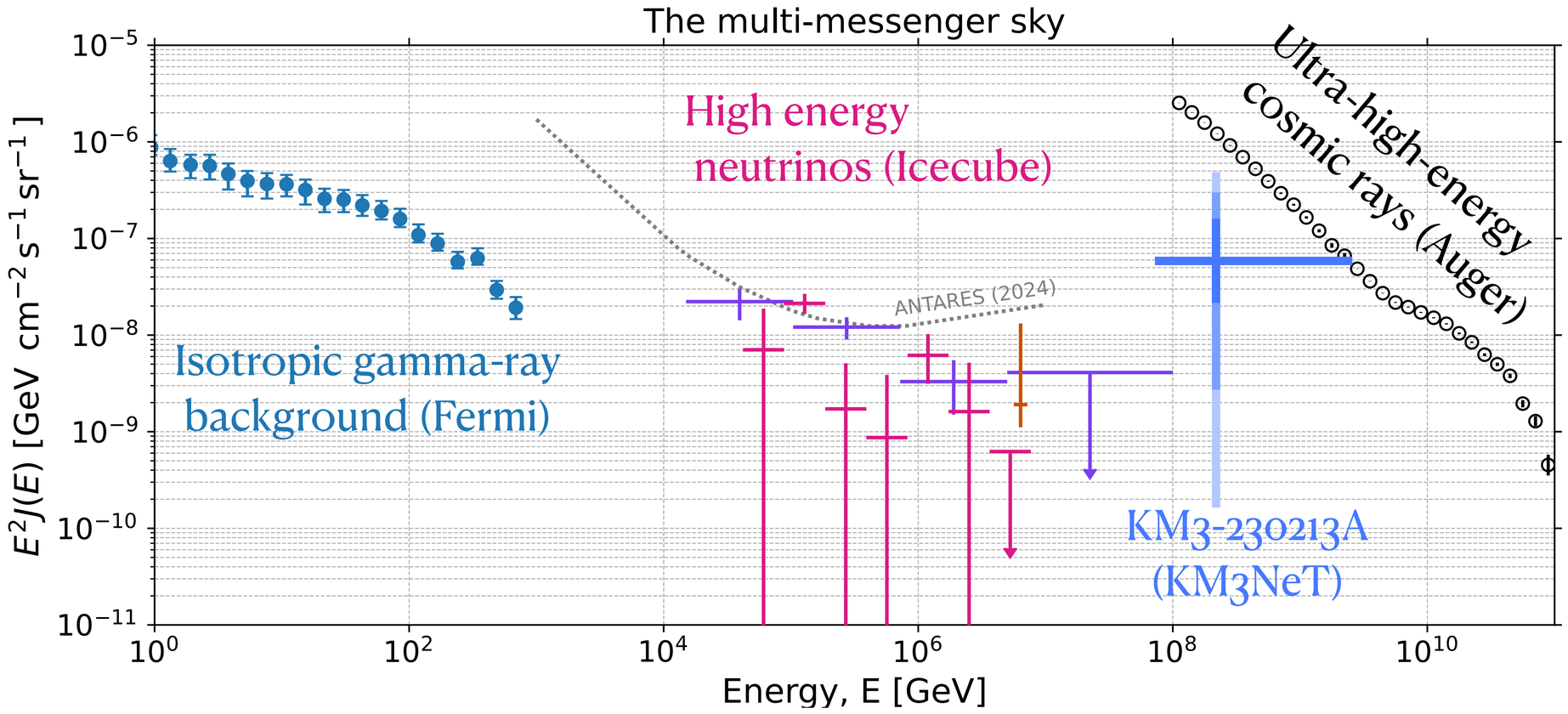


My goal

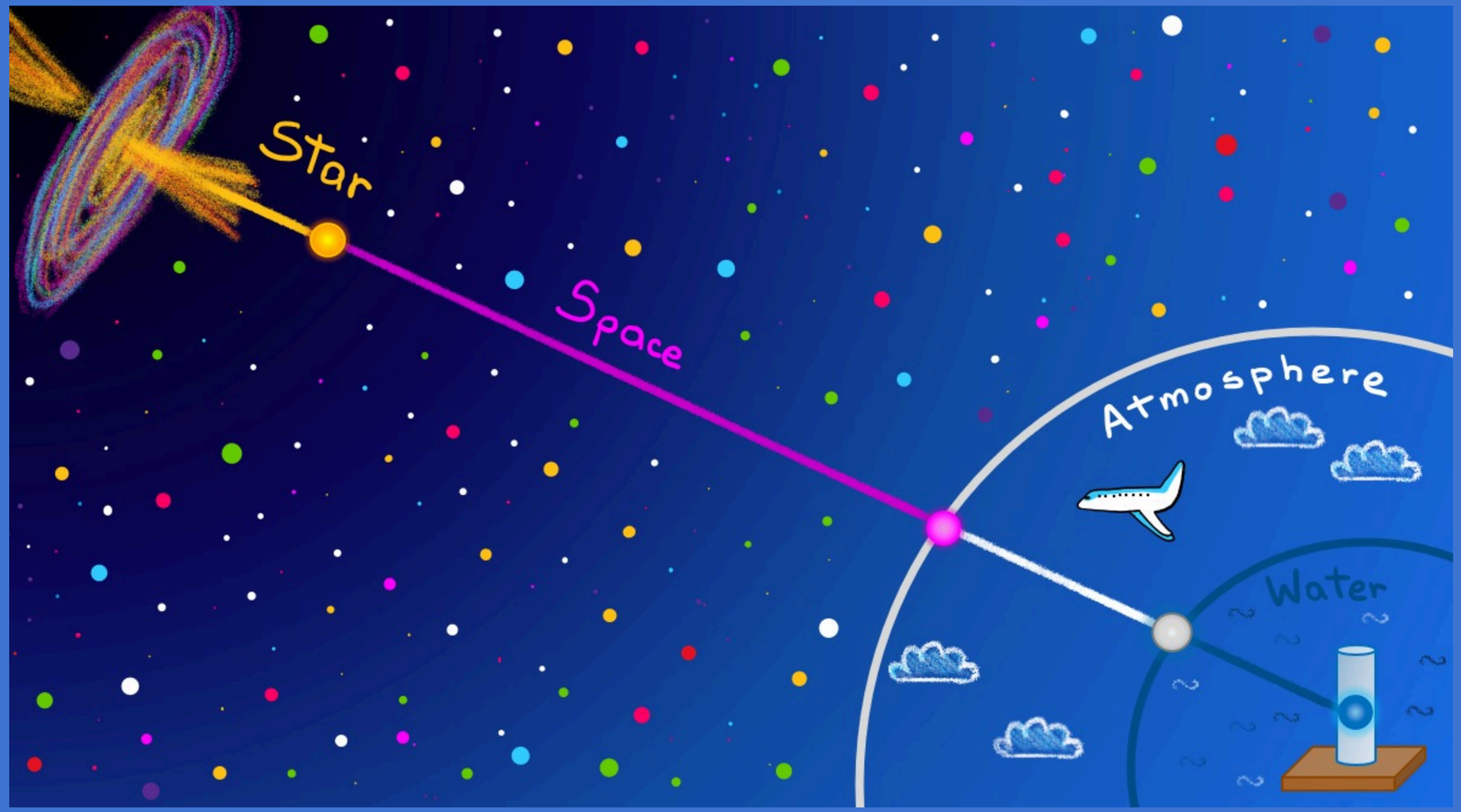
Goal: Finding the highest energies sources.

How: Multi-messenger astrophysics.

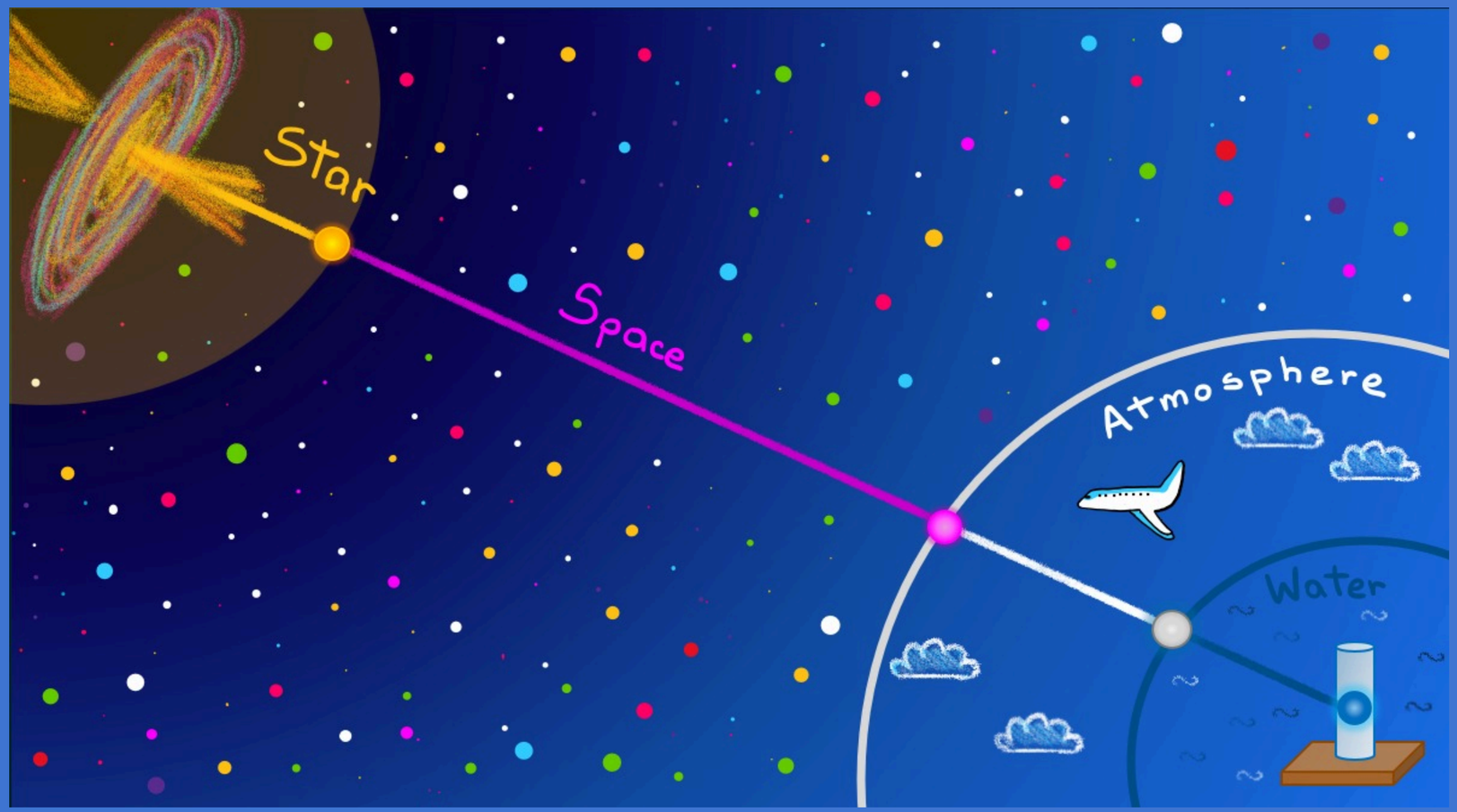
Requirement: High quality data to understand astrophysical environment.



Particle propagation



Propagation in astrophysical environment



Multi-messenger study of starburst galaxies

Motivation: Acceleration & Correlation.

Leaky box model: computation of interaction and escape times.

G. E. Romero, A. L. Müller and M. Roth, Astron. Astrophys. 616 (2018), A57
L. A. Anchordoqui, Phys. Rev. D **97** (2018) no.6, 063010

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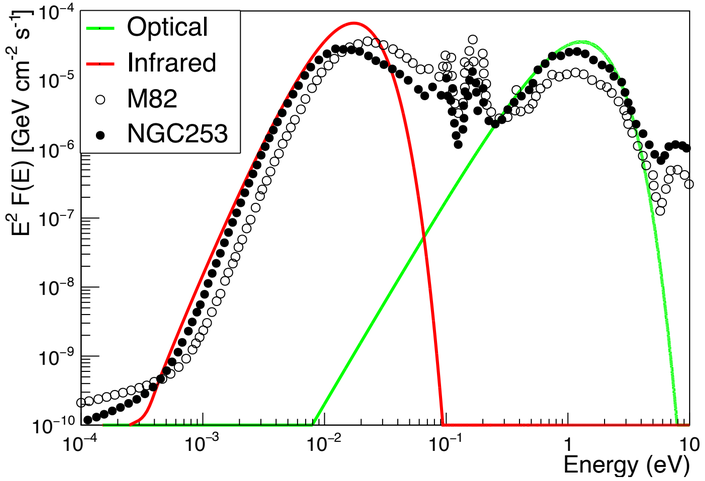

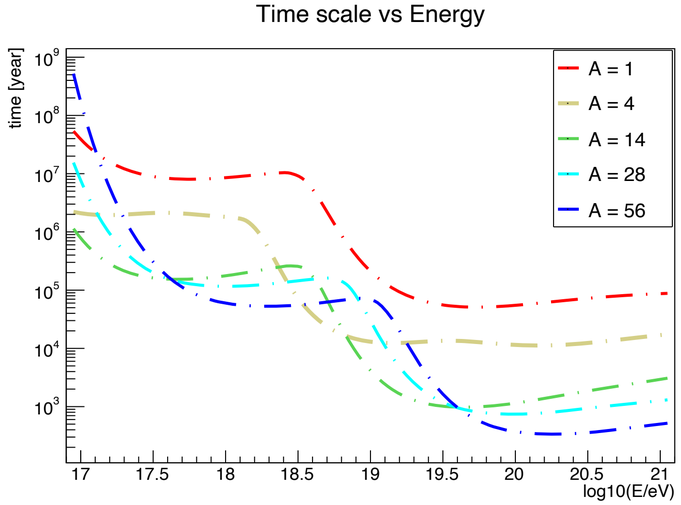

Adapting SimProp (software for UHECRs propagation in extra-galactic space):

Implementation of the photon field in the source;

$$\frac{dN}{dt} = \frac{c}{2\Gamma}\int_{\epsilon'_{th}}^{\infty}\sigma_{A\gamma}(\epsilon')\epsilon'\int_{\epsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\epsilon)}{\epsilon^2}\,d\epsilon\,d\epsilon'$$

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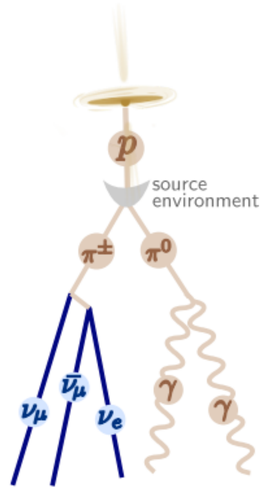

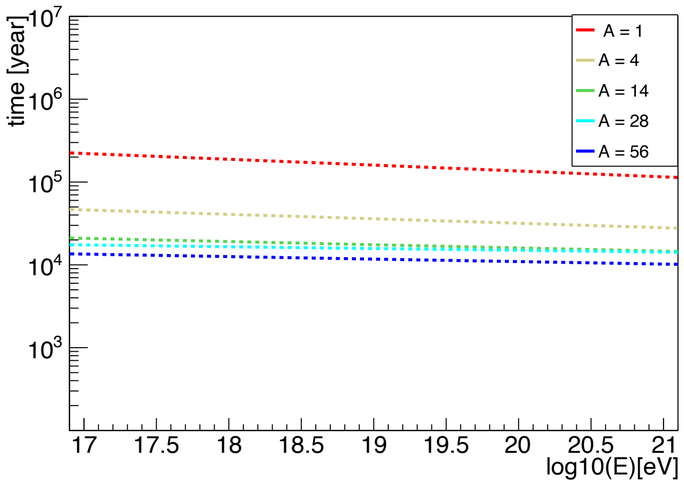

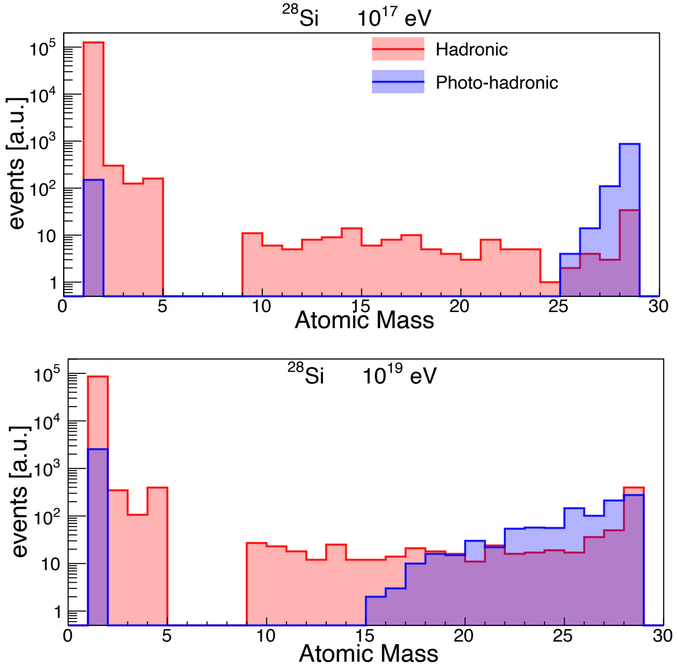

Adapting SimProp (software for UHECRs propagation in extra-galactic space):

Implementation of the photon field in the source;

Implementation of the spallation process;

G. E. Romero, A. L. Müller and M. Roth, Astron. Astrophys. 616 (2018), A57
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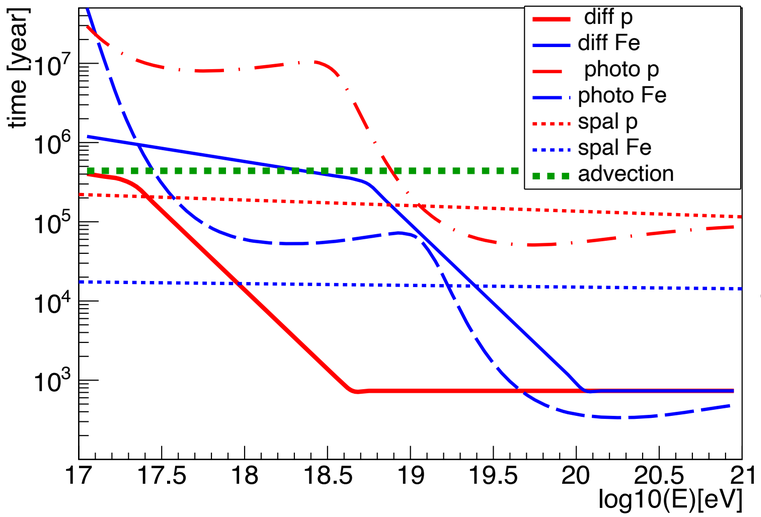
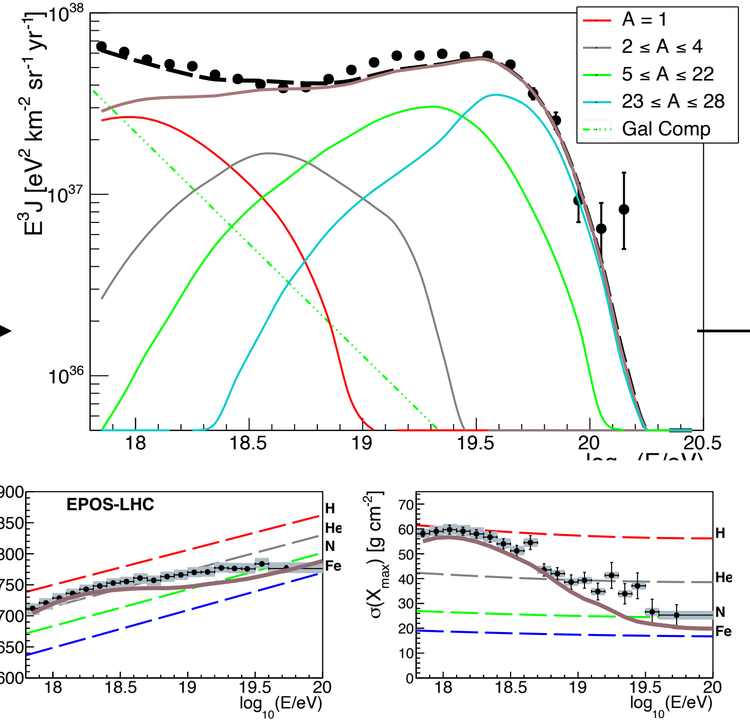
Multi-messenger study of starburst galaxies

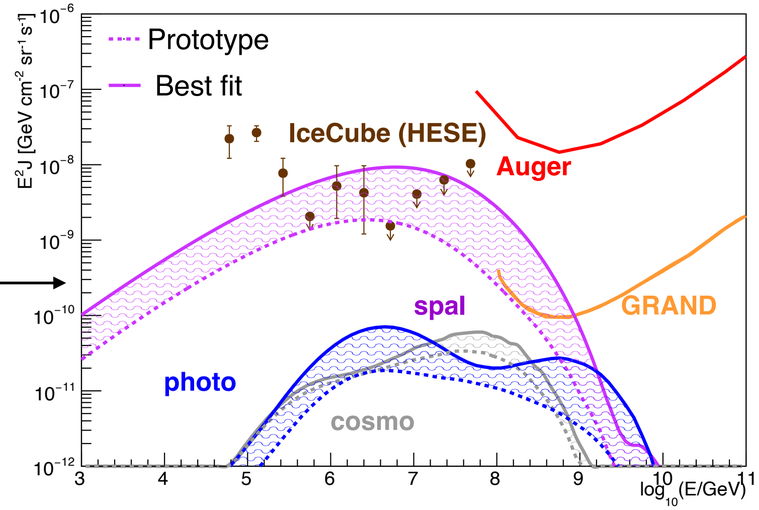
Timescale



CR observables



Neutrino flux



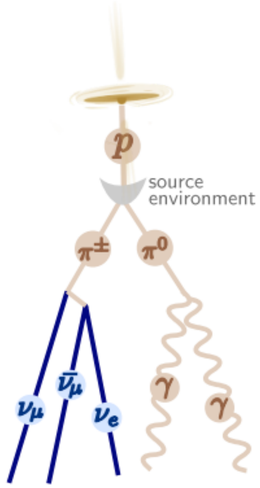
Hadronic interactions —> major contributor to the expected neutrino flux —> can be used to constrain plausible scenarios that describe the UHECR data.

Multi-messenger study of starburst galaxies

Starburst galaxy environment

+

Interactions



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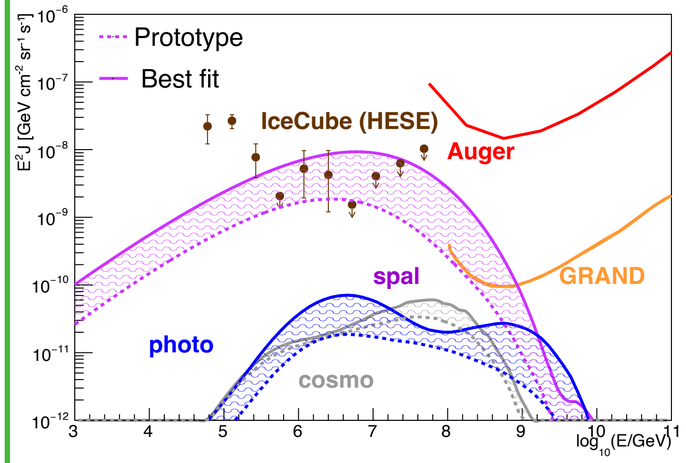
Multi-messenger expectations



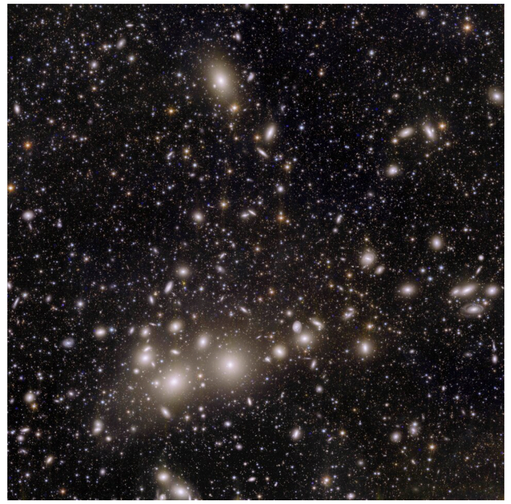
Take home message: Starburst Galaxies are significant contributors to the diffuse multi-messenger sky.

Public code available to compute interactions in astrophysical environment.

A. Condorelli et al., Phys. Rev. D 107 (8), p. 083009 (2023) (promoted as Editor's suggestion).11

A. Condorelli, Astroparticle Physics, 165, 103047 (2024)

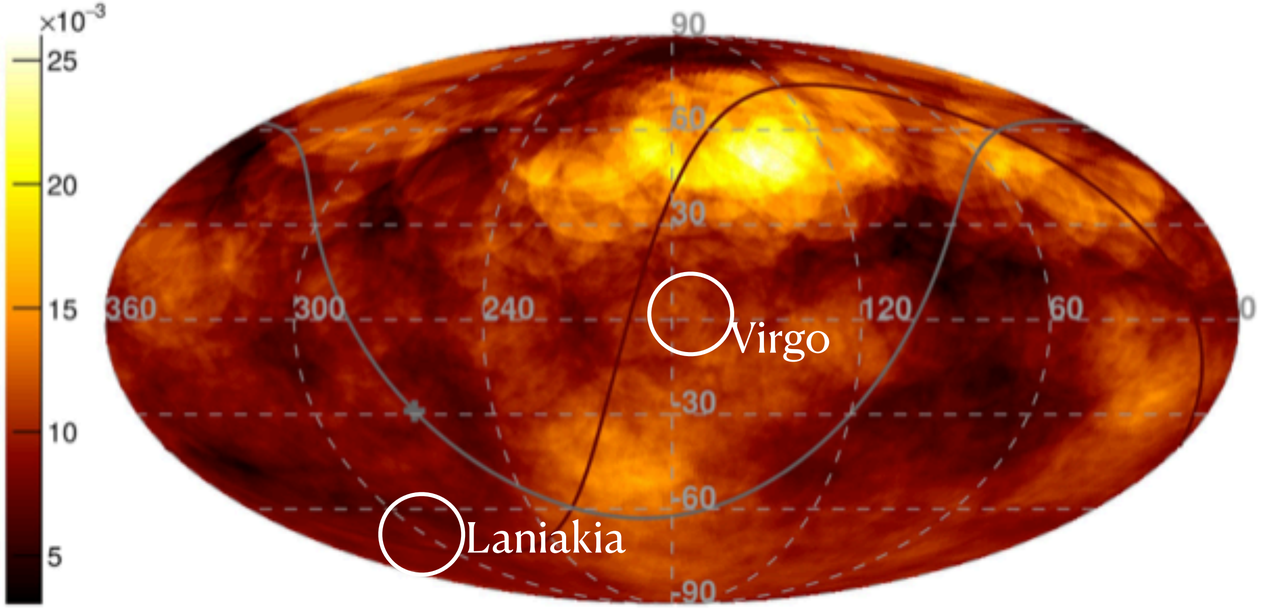
Why we do not see Galaxy clusters in the cosmic-ray sky?



Largest object in the Universe held together by gravity.

Dark region for cosmic rays at the highest energies: why?

Cosmic-ray flux above 40 EeV



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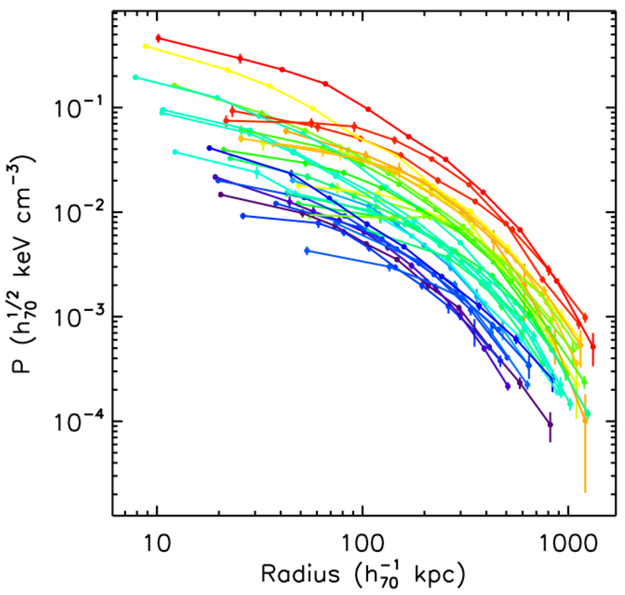

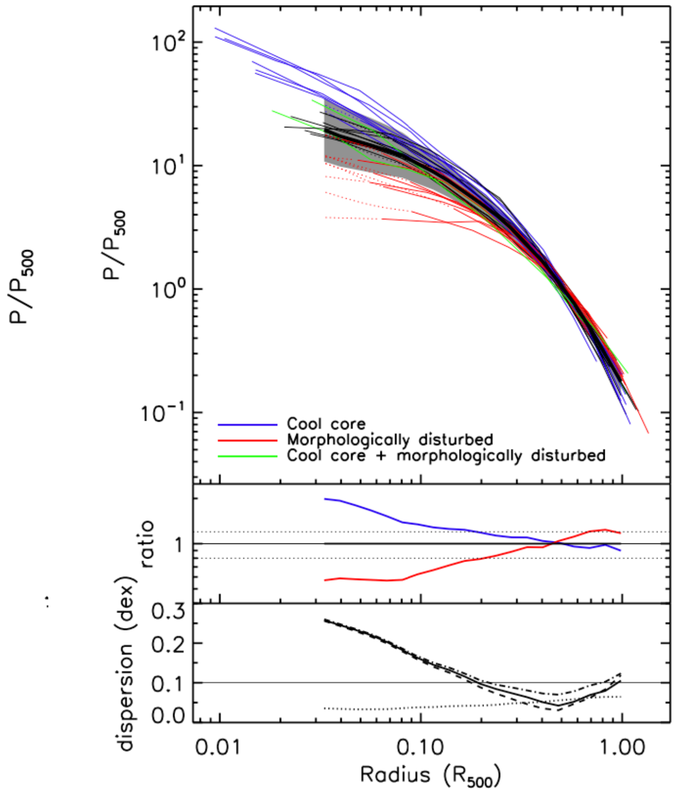

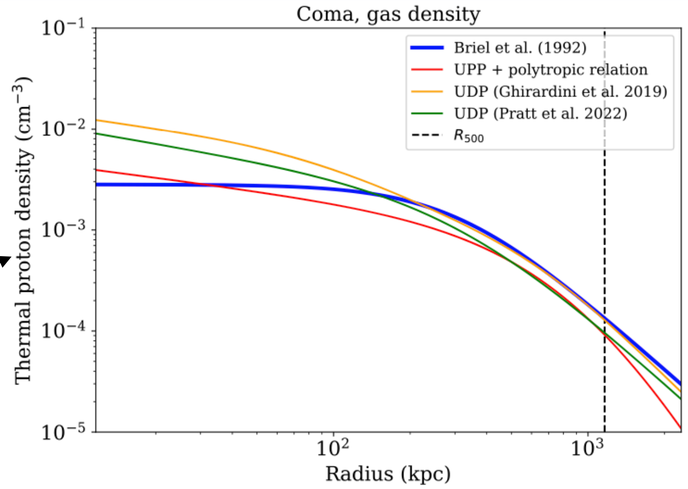

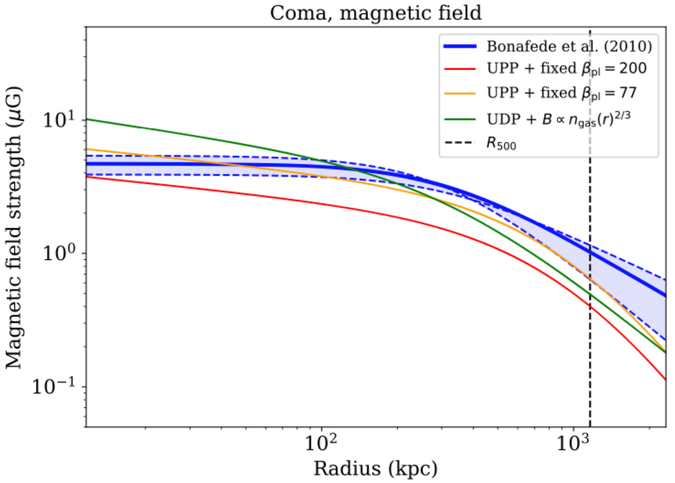

Self-similarity: approximation all their properties depend only on mass and redshift;

(M, z) —> pressure profile for any cluster.

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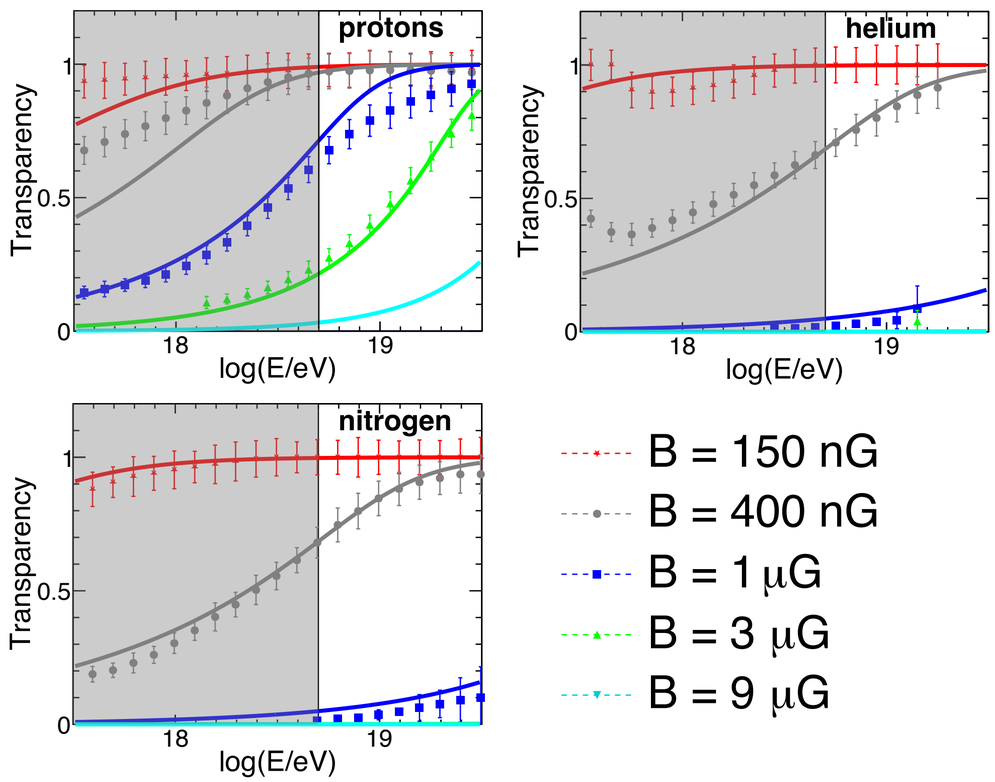
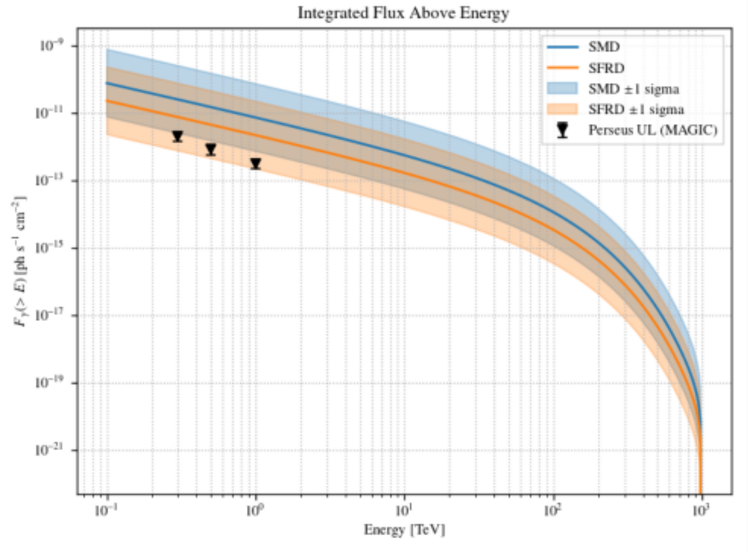


Simulations in the environment with hadronic processes and magnetic confinement implemented;

From the simulations —>universal parametrization of the cluster transparency;

Take-home message: Galaxy clusters are opaque environment for UHECR nuclei.

Secondaries (gamma & neutrinos) can help us constrain maximal energies!



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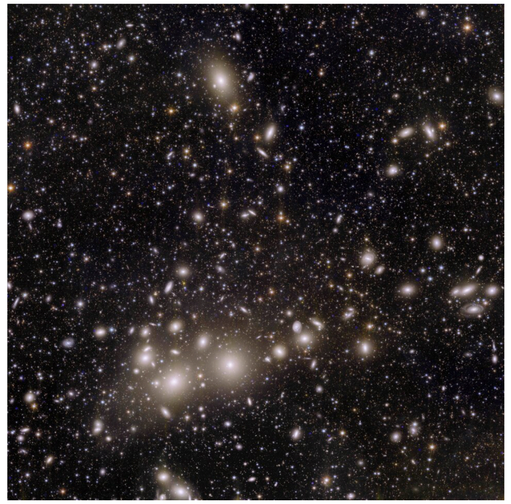


Largest object in the Universe held together by gravity.

Dark region for cosmic rays at the highest energies: why?

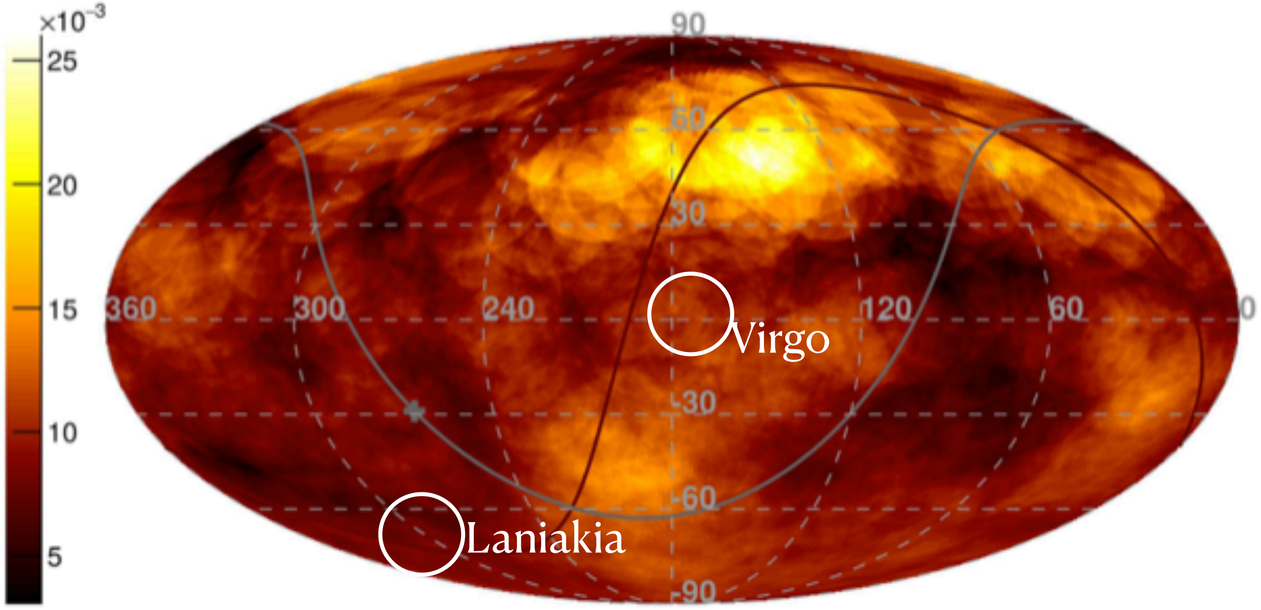
Propagation in the environment ⟶

Galaxy clusters are opaque environment for UHECR nuclei.

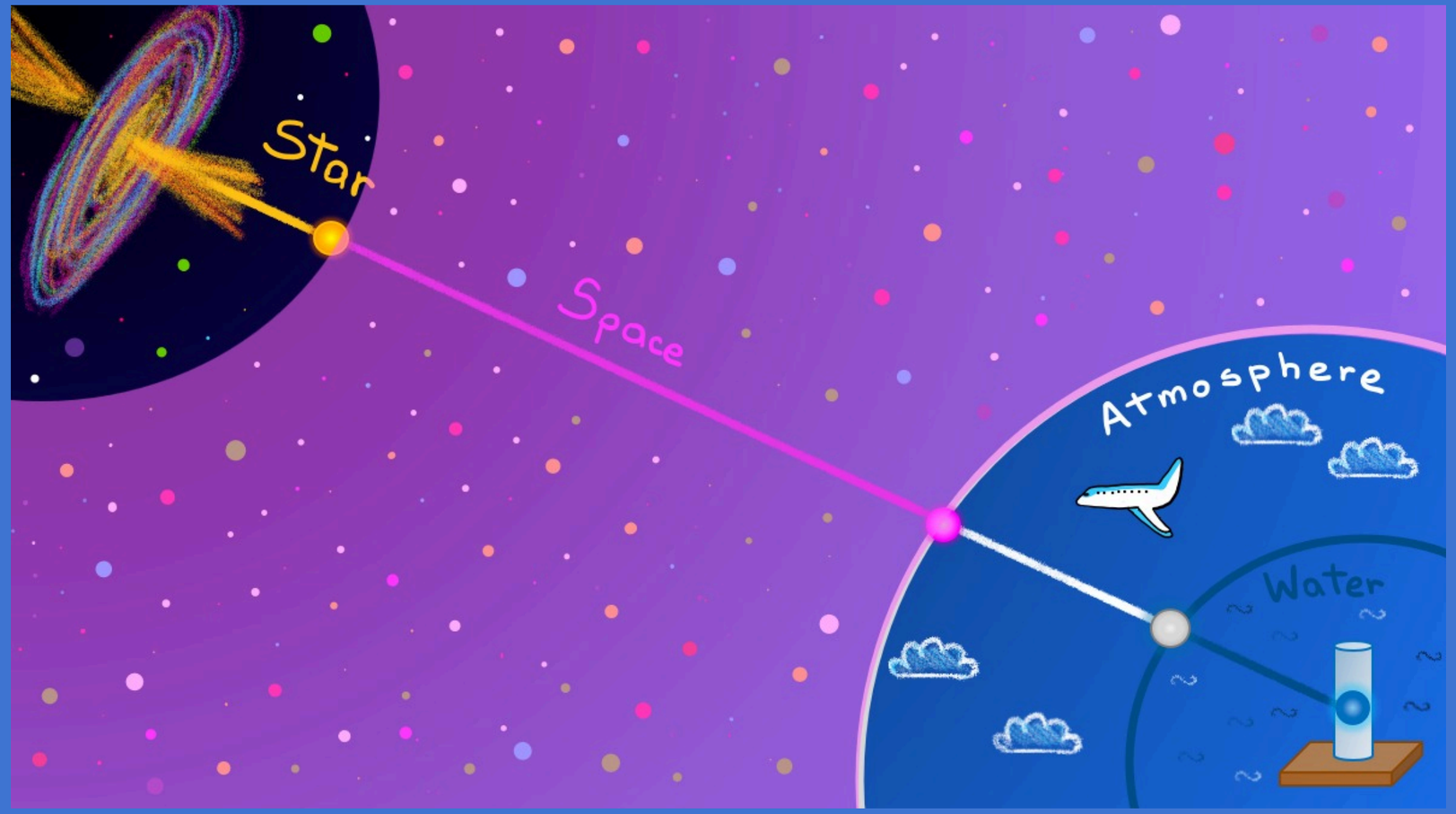
⟶ bright in secondaries (gamma & neutrinos).

Explained for non-experts in the YouTube channel of AAS.

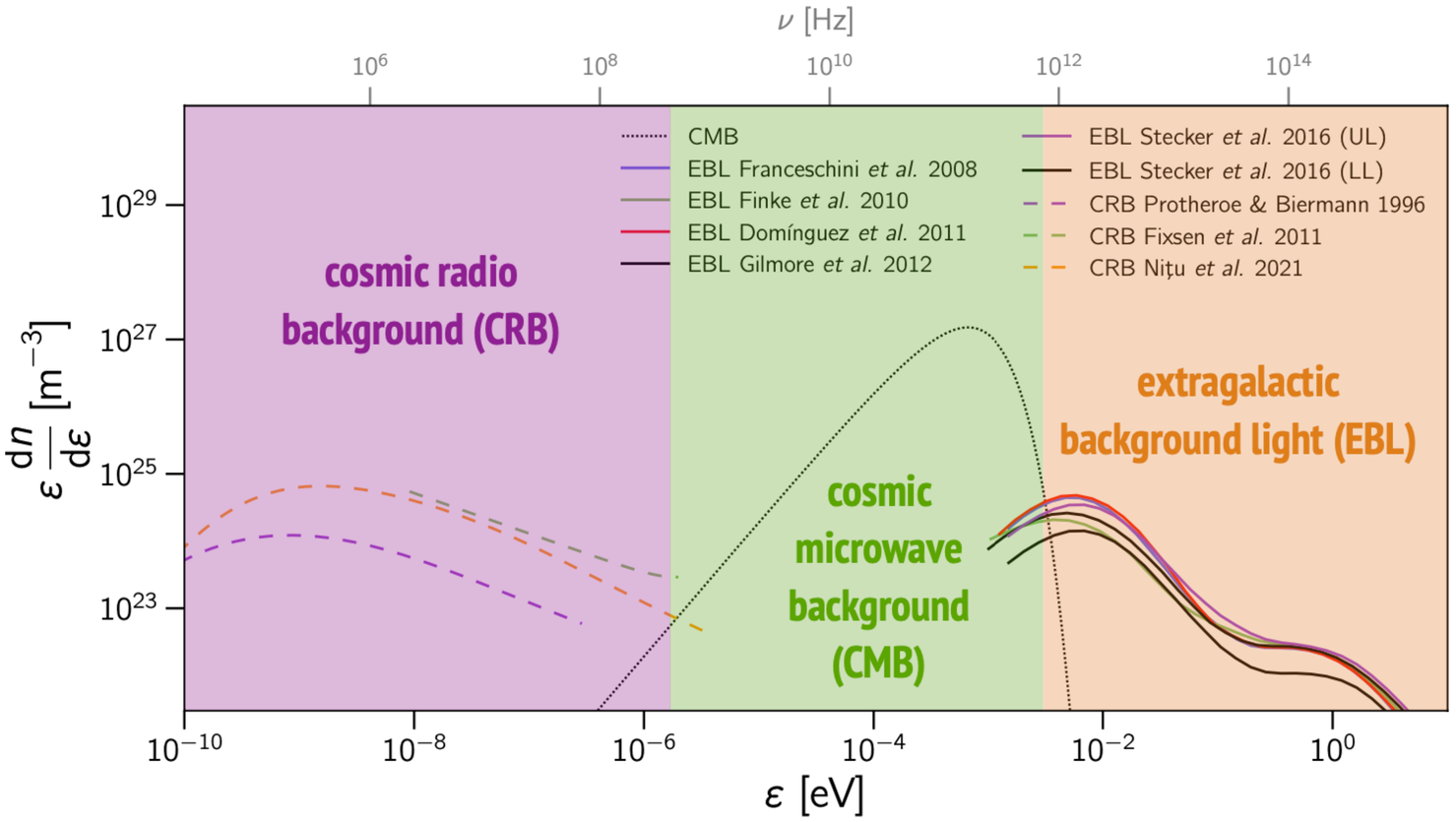
Cosmic-ray flux above 40 EeV



Propagation in the extra-galactic space



Which are the sources of UHECRs?



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 !

Which are the sources of UHECRs?

- Pair production

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

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

- Photodisintegration

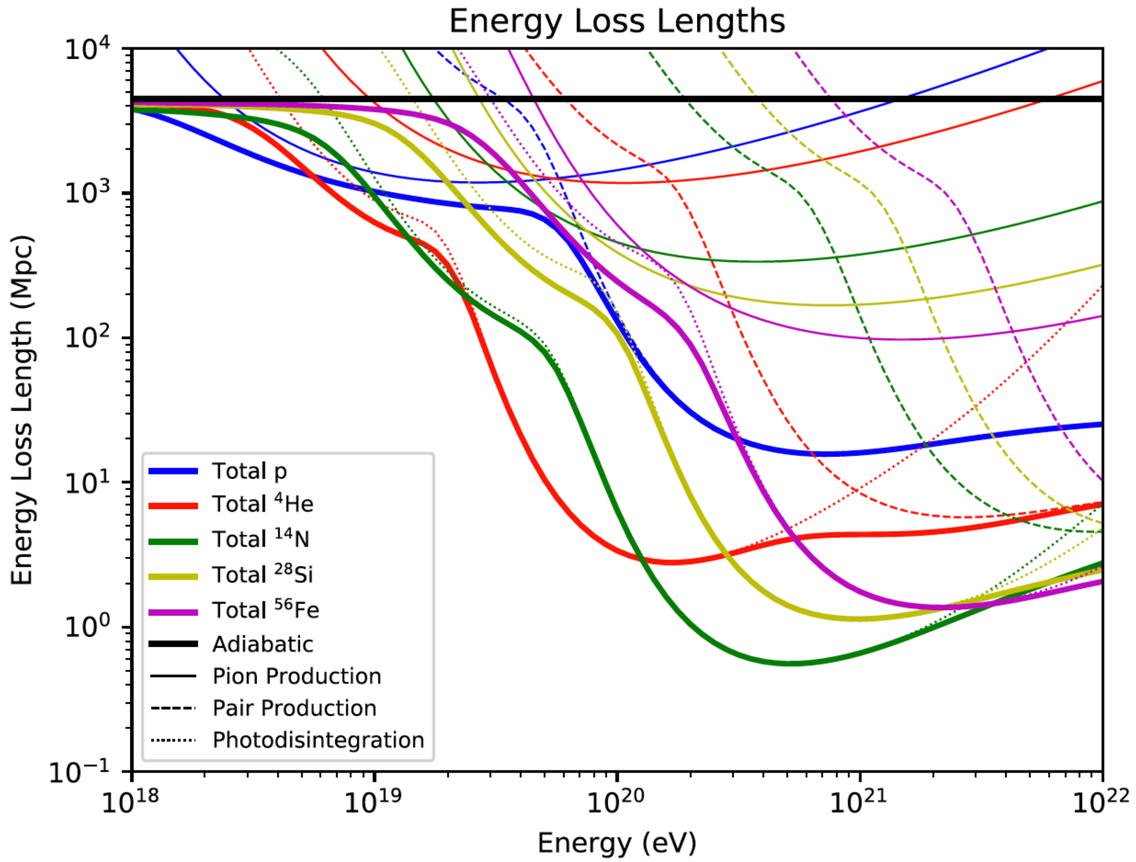
$$(A, Z) + \gamma \rightarrow (A - n, Z - m) + nN$$

- Adiabatic

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

- Nuclear decay

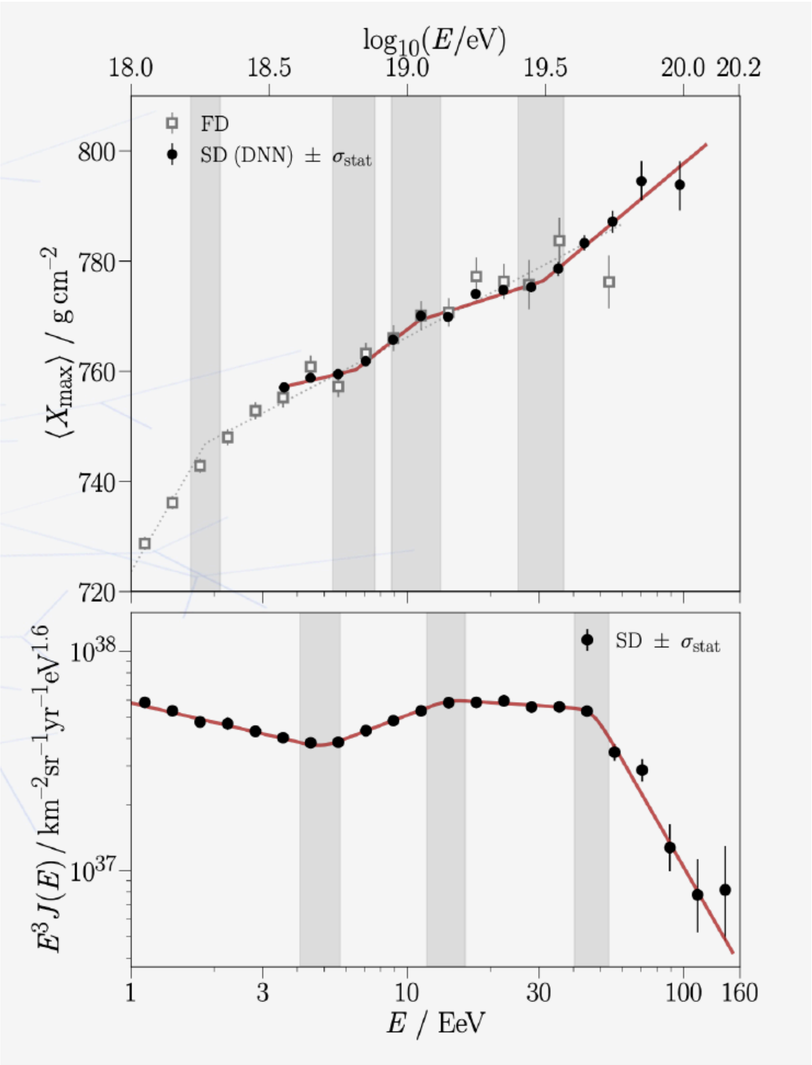
$$\tau = \Gamma \tau_0$$



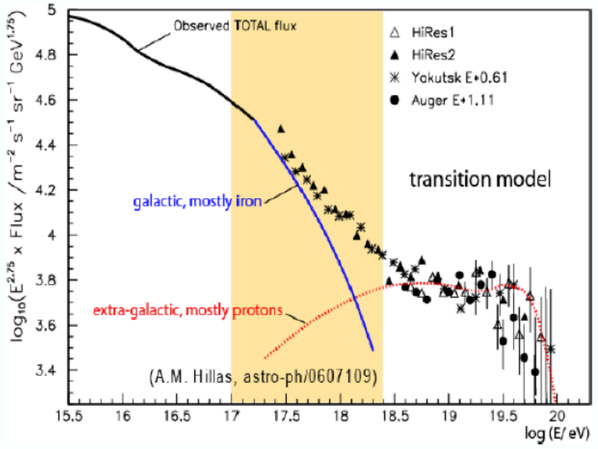
Which are the sources of UHECRs?

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

How to disentangle this?



Transition model



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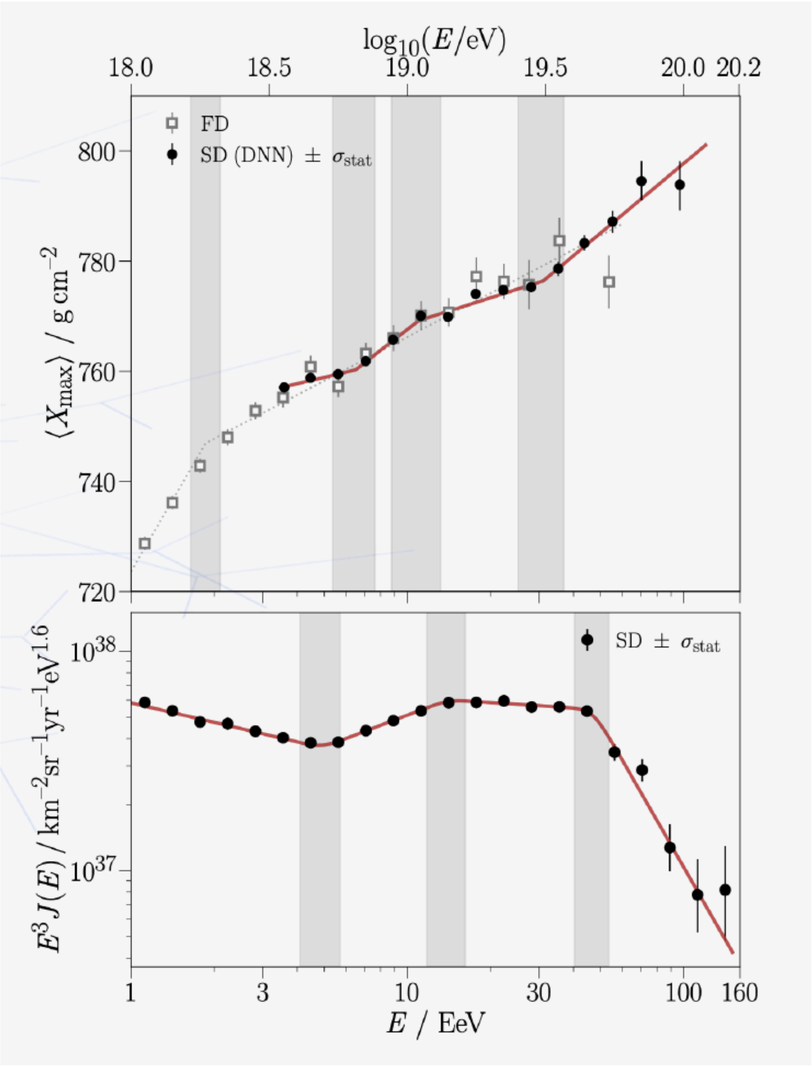

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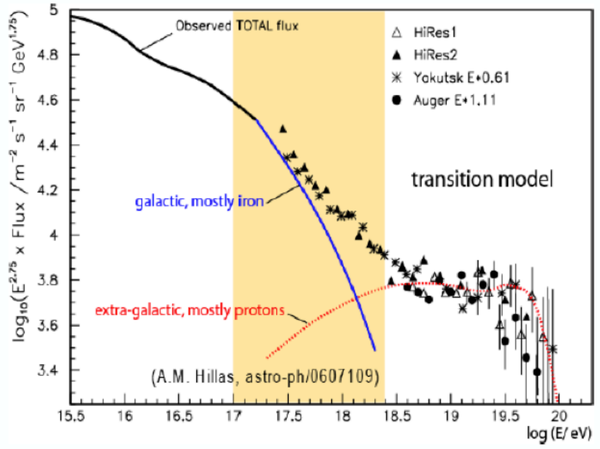
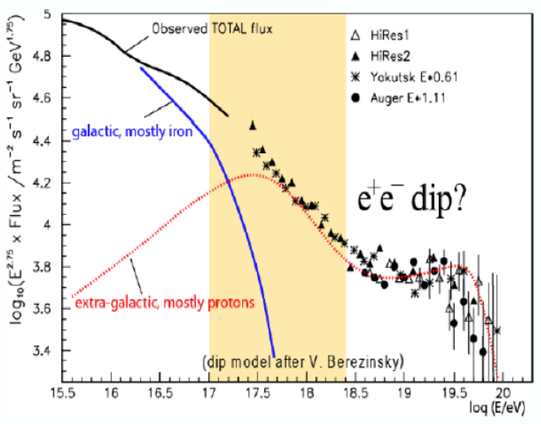


Pure proton scenario



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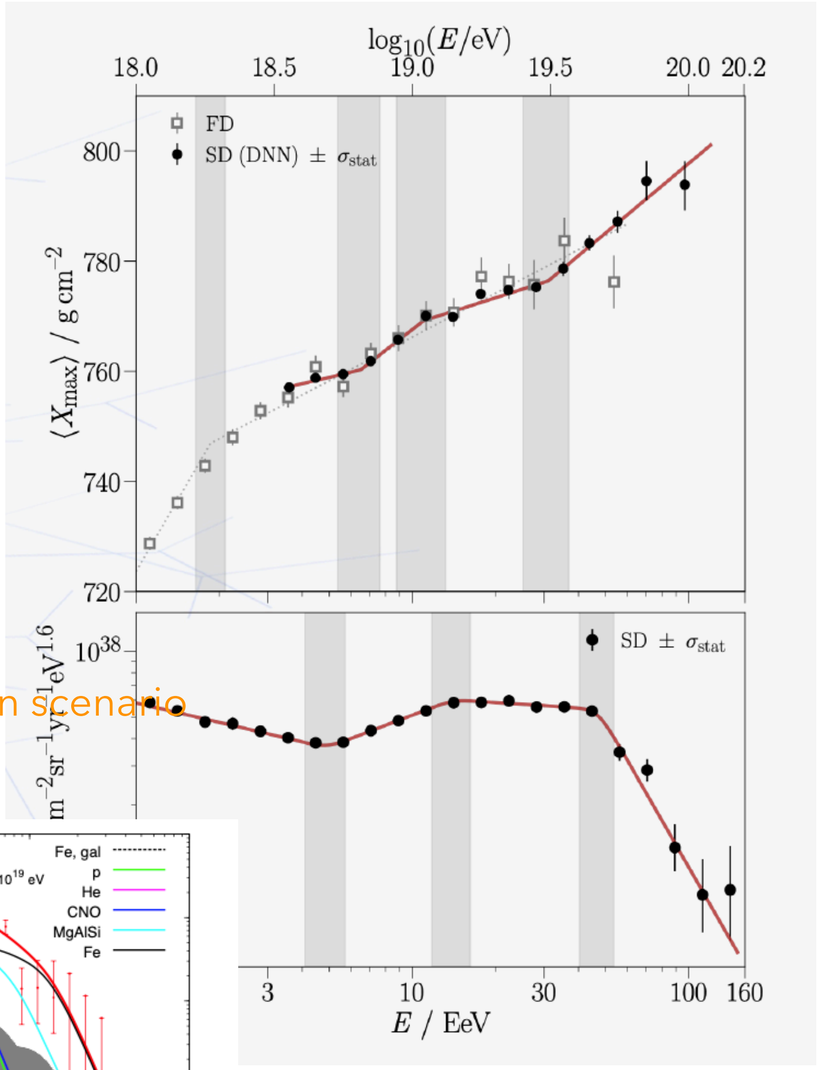

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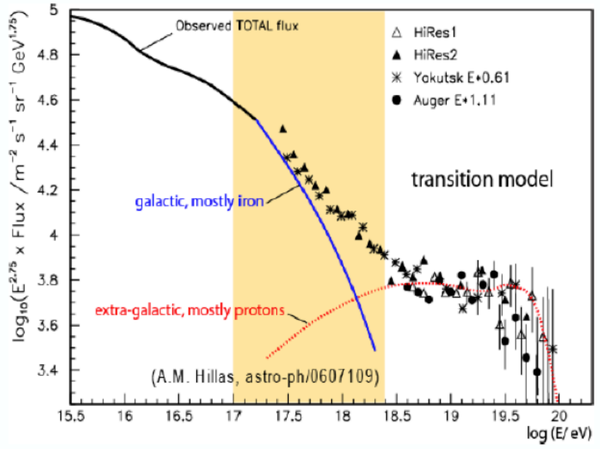

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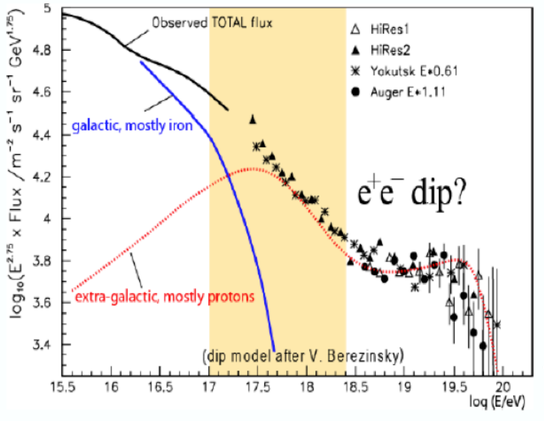
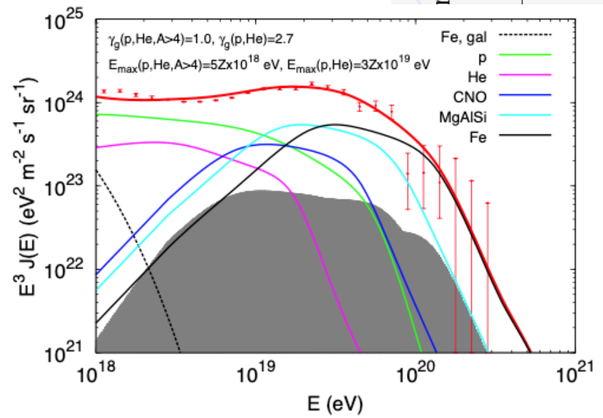


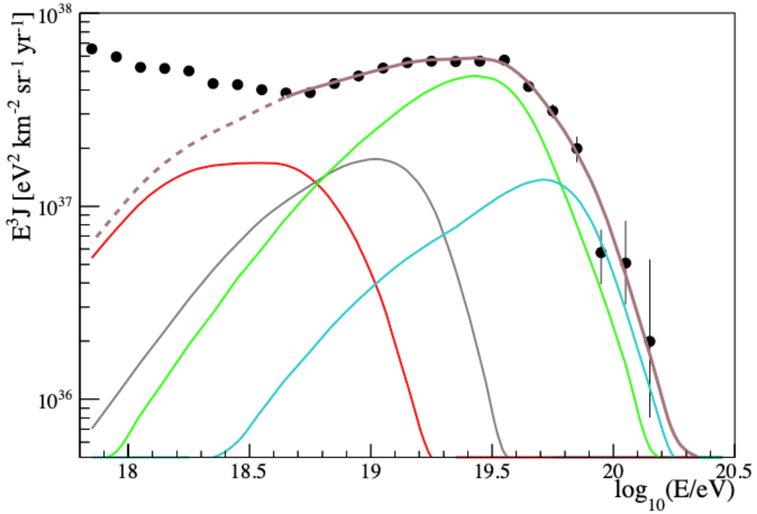
Mixed composition scenario

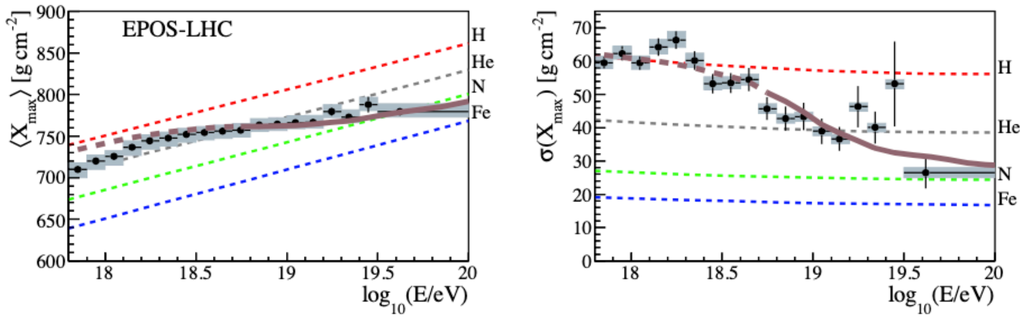


Which are the sources of UHECRs?

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.

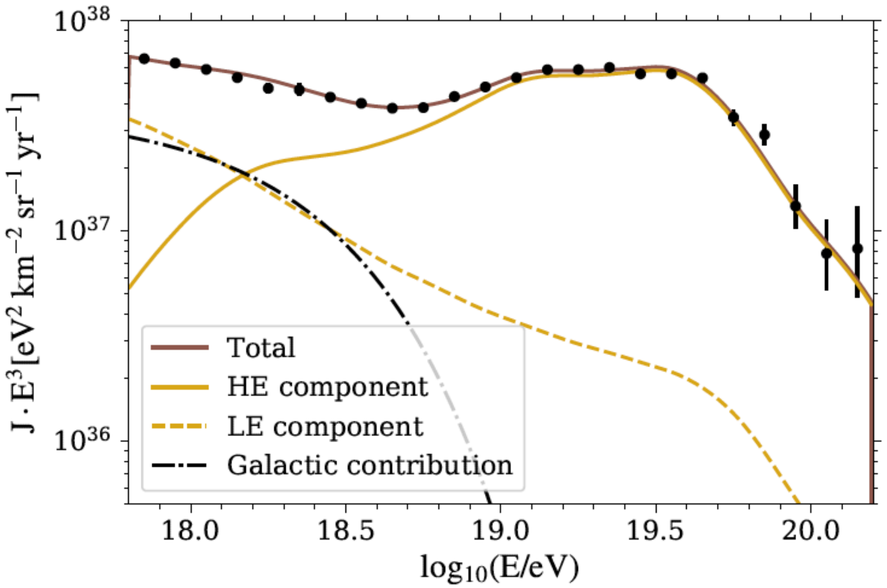




A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038

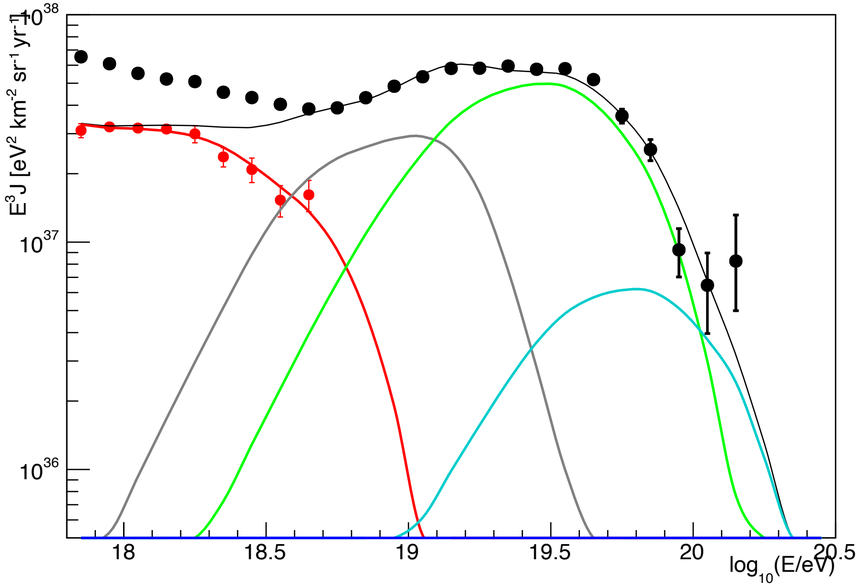
Which are the sources of UHECRs?

Additional component



- Impossibility to distinguish between a galactic and an extra-galactic contribution at low energies.
- Iron Galactic flux is strongly disfavoured.

Source interactions

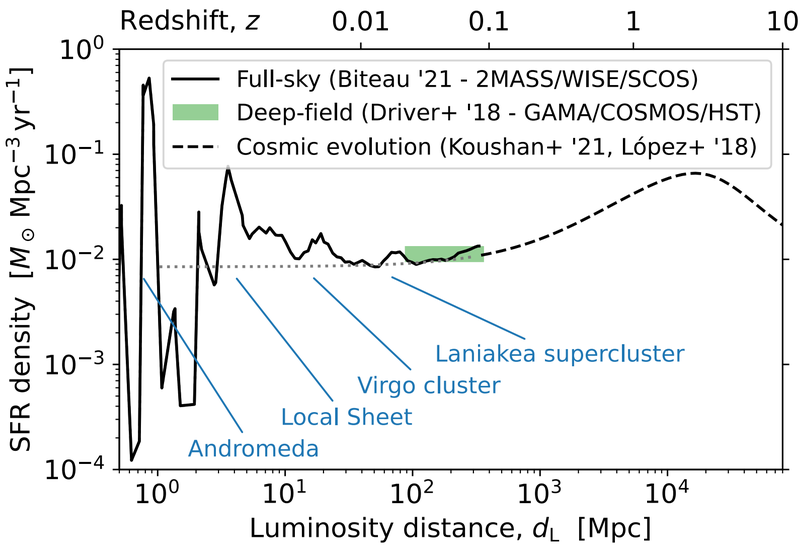


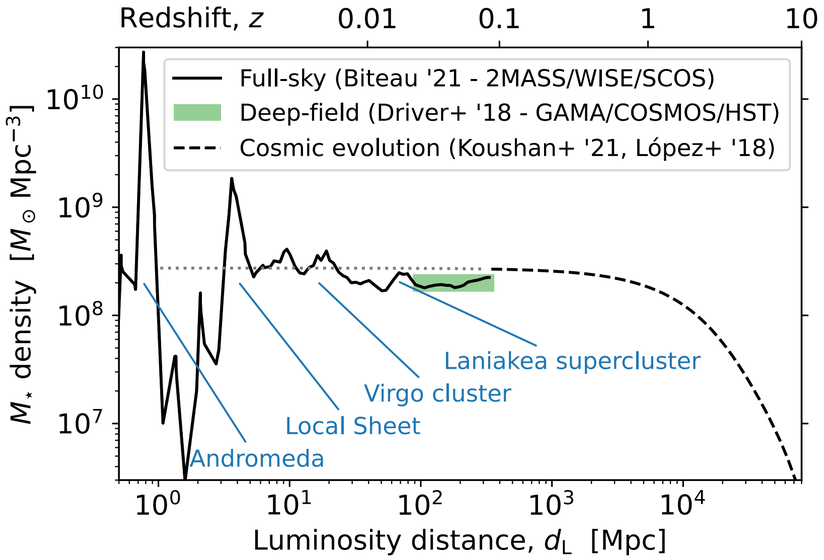
- Accelerated particles confined in the environment surrounding the source;
- Low energy particles —> Pile-up of nucleons at lower energies.

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)





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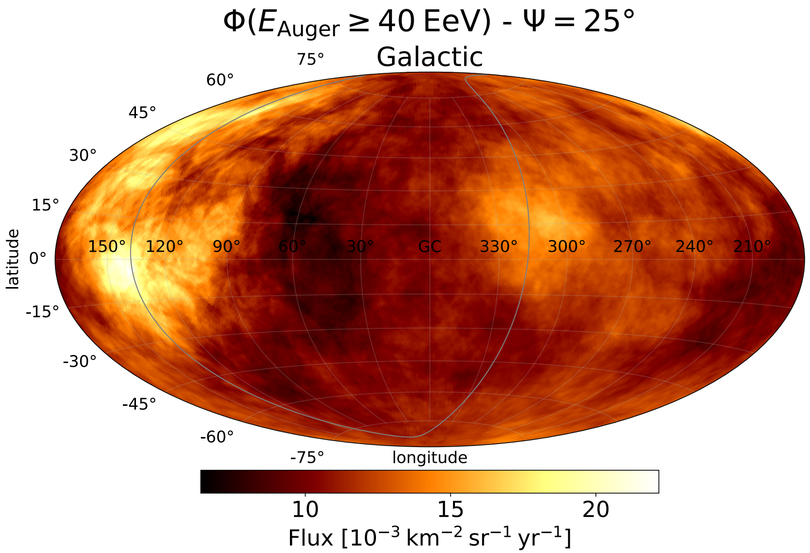
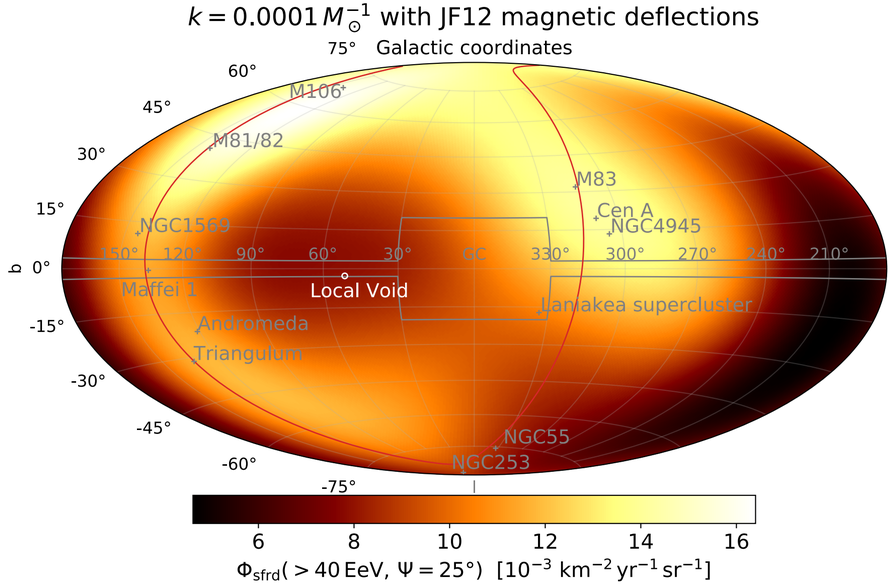
- Assuming that UHECR production rate follows a tracer (SFRD or Stellar mass density)



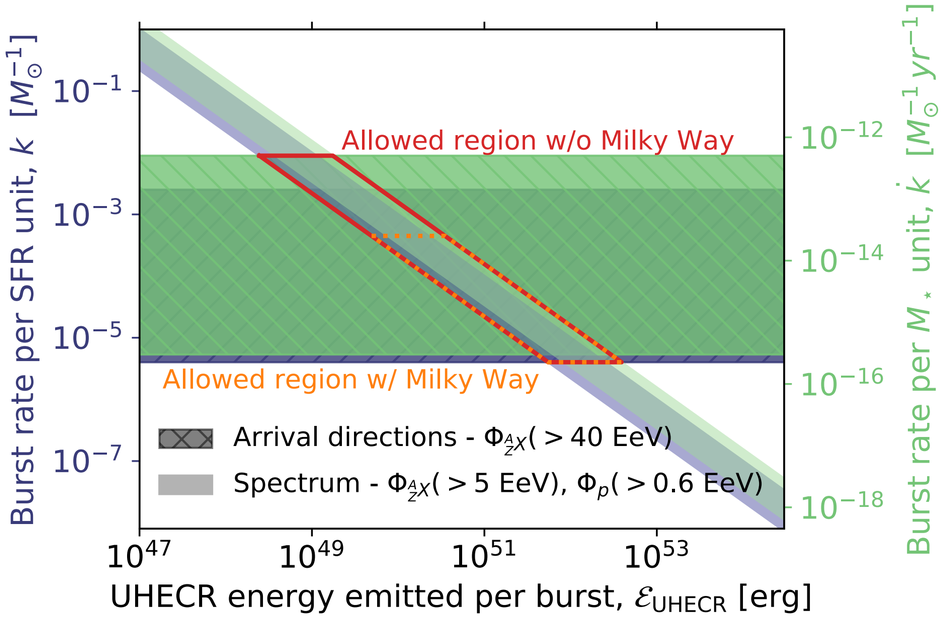


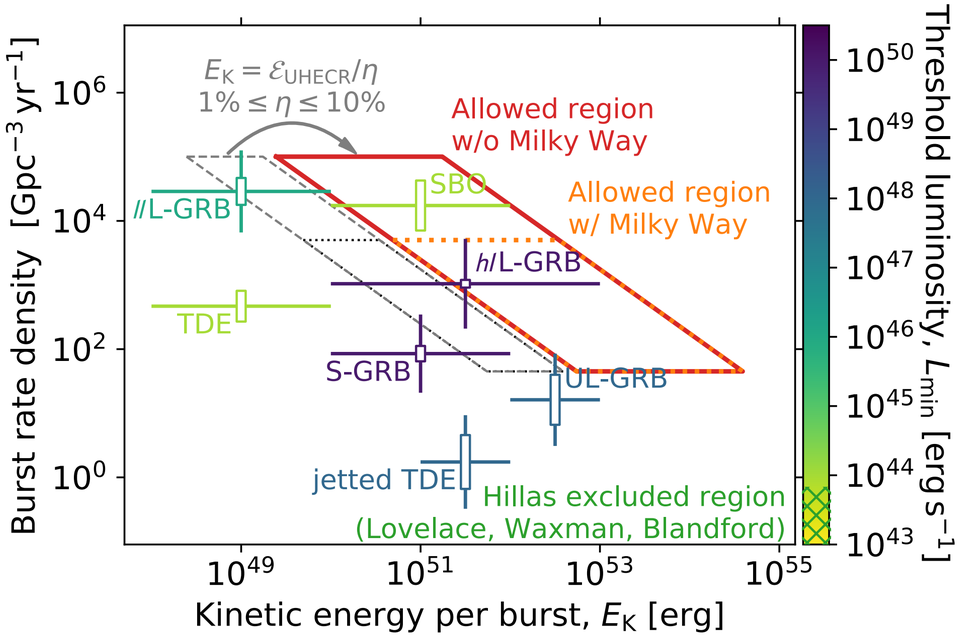
- Arrival direction –> constraint on the burst rate!

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.



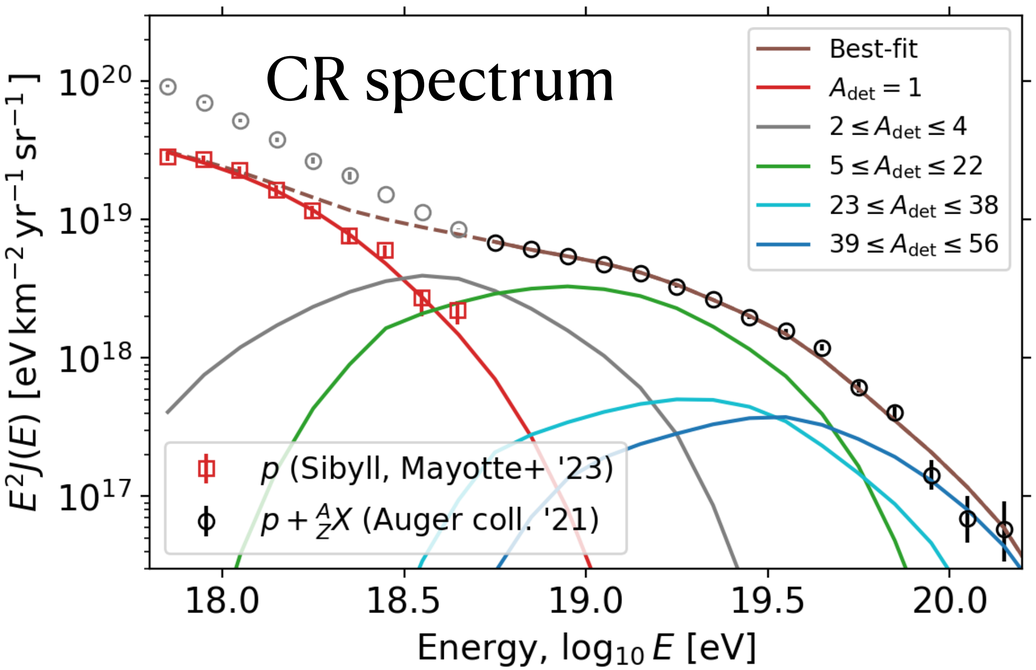


Summary

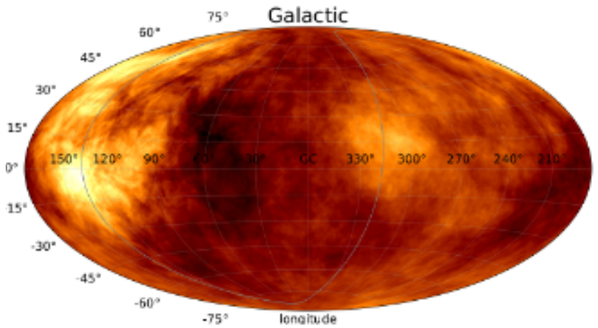
Extra-galactic propagation connects astrophysical features and high-quality data at Earth.

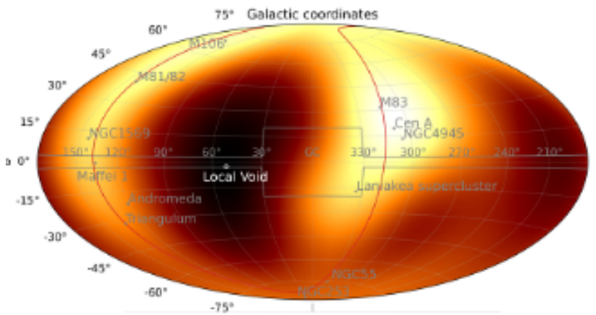
Using energy spectrum, mass composition and arrival directions to constrain plausible sources at the highest energies.

Only long GRBs can describe energy spectrum, mass composition and arrival directions.



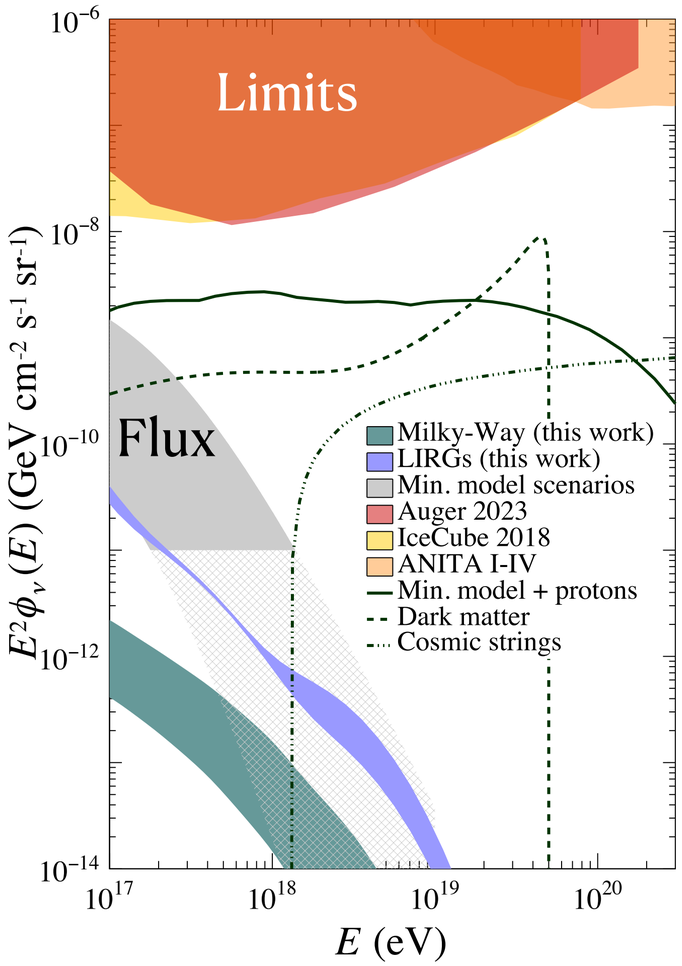
CR arrival directions

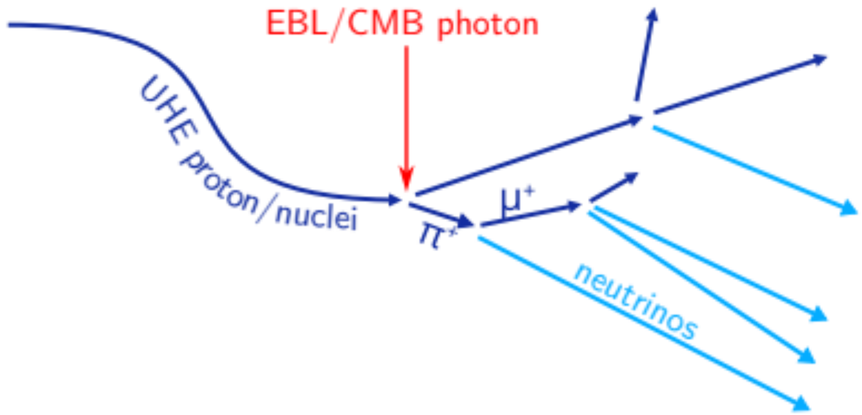




A. Condorelli et al. In: ApJ 972 4 (2024) **A. Condorelli**, et al., ApJ 936 62(2022) **The Pierre Auger Collaboration** et al., JCAP05(2023)024

What is the neutrino flux associated to the UHECR flux?





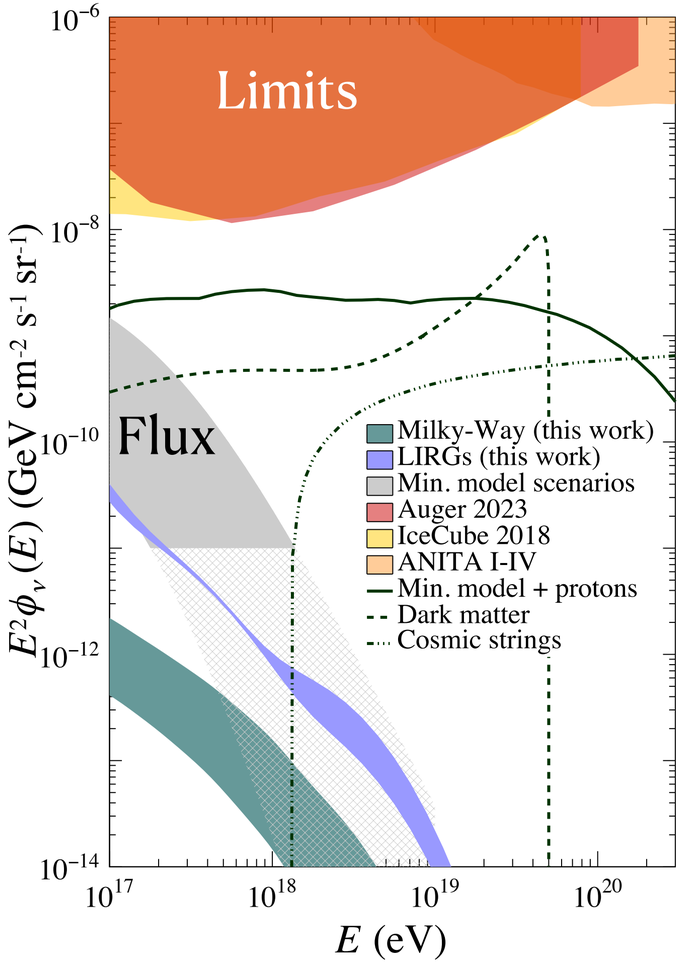
What is the minimal neutrino flux associated to the UHECR flux?

Galactic contribution: computing the interaction of UHECRs within our Galaxy;

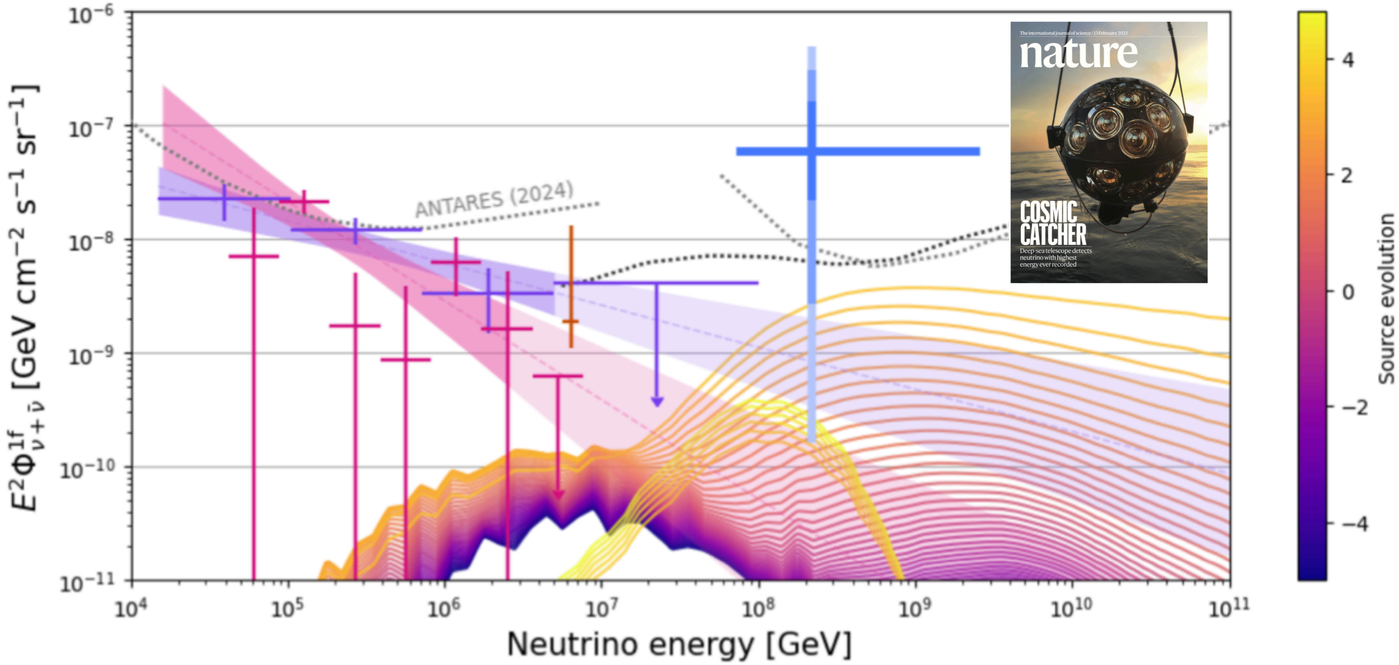
Extra-galactic contribution: assuming a generic source as standard candle for UHECR acceleration and computing neutrino in source environment and in extra-galactic propagation.

Take-home message: the neutrino flux associated to the minimal model is very low, room for detecting UHE protons and/or dark matter decay.

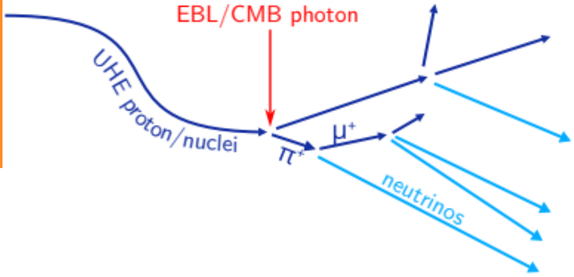
What is the neutrino flux associated to the UHECR flux?

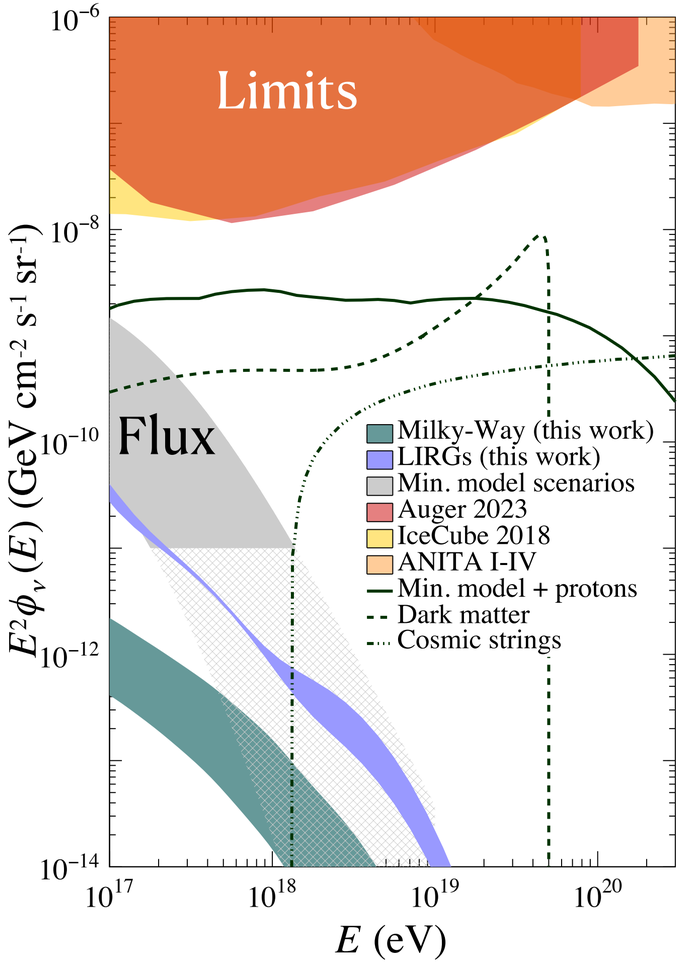


- Important parameters for the neutrino flux: proton fraction & source evolution;
- If cosmogenic —> Strong evolution & non-negligible proton fraction at the highest energies.



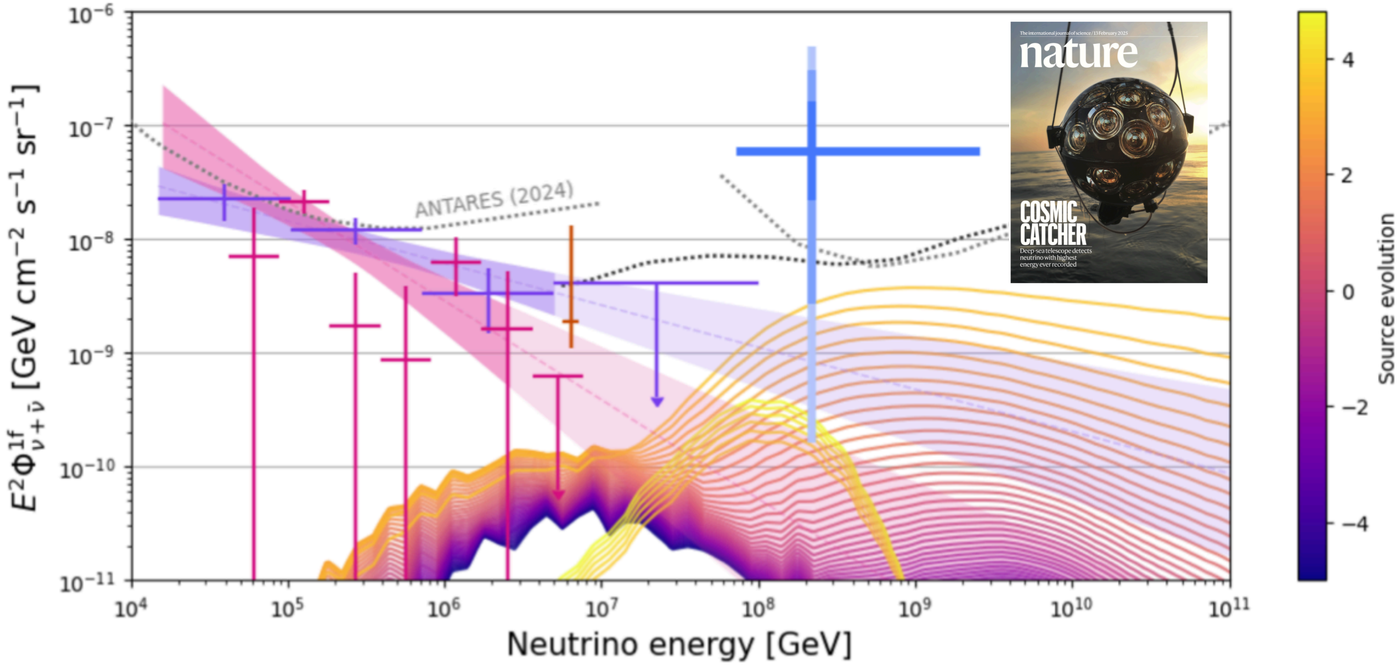
Summary



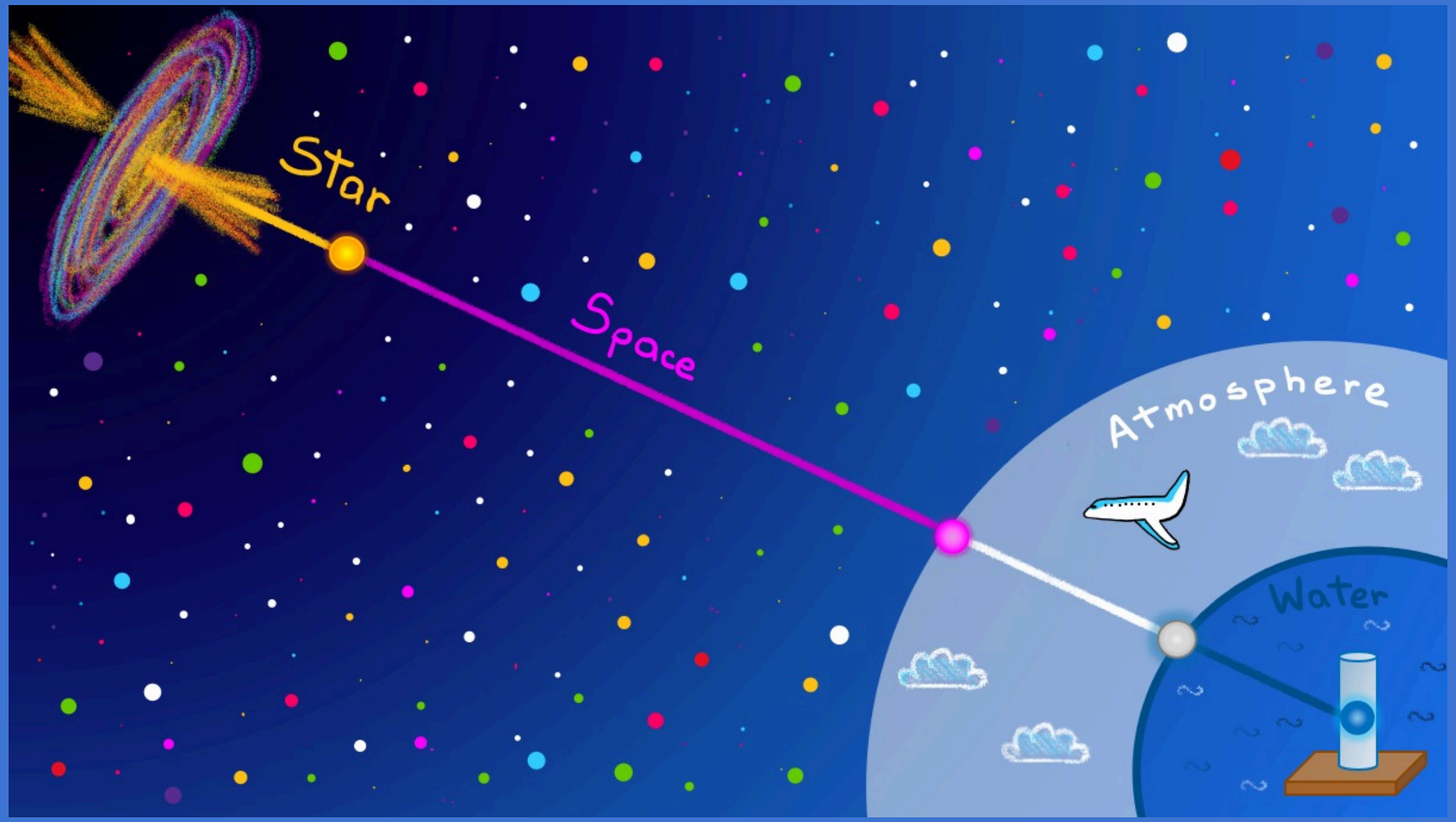


The cosmogenic neutrino flux associated to the minimal model is very low.

Source evolution & proton fraction ⟶ crucial parameters to boost the flux.

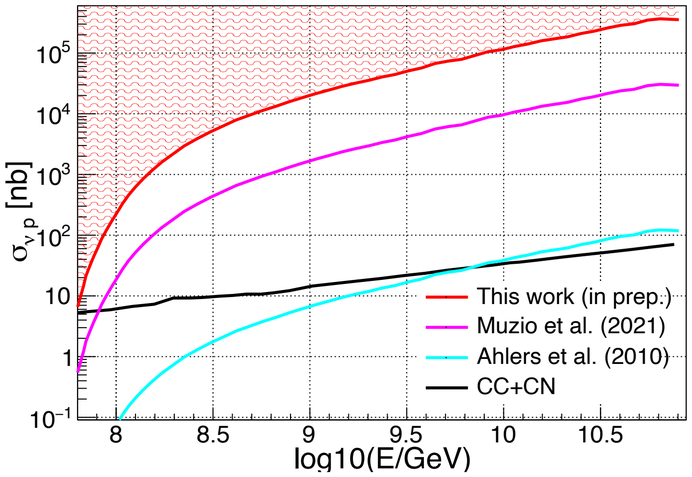


Propagation in the atmosphere

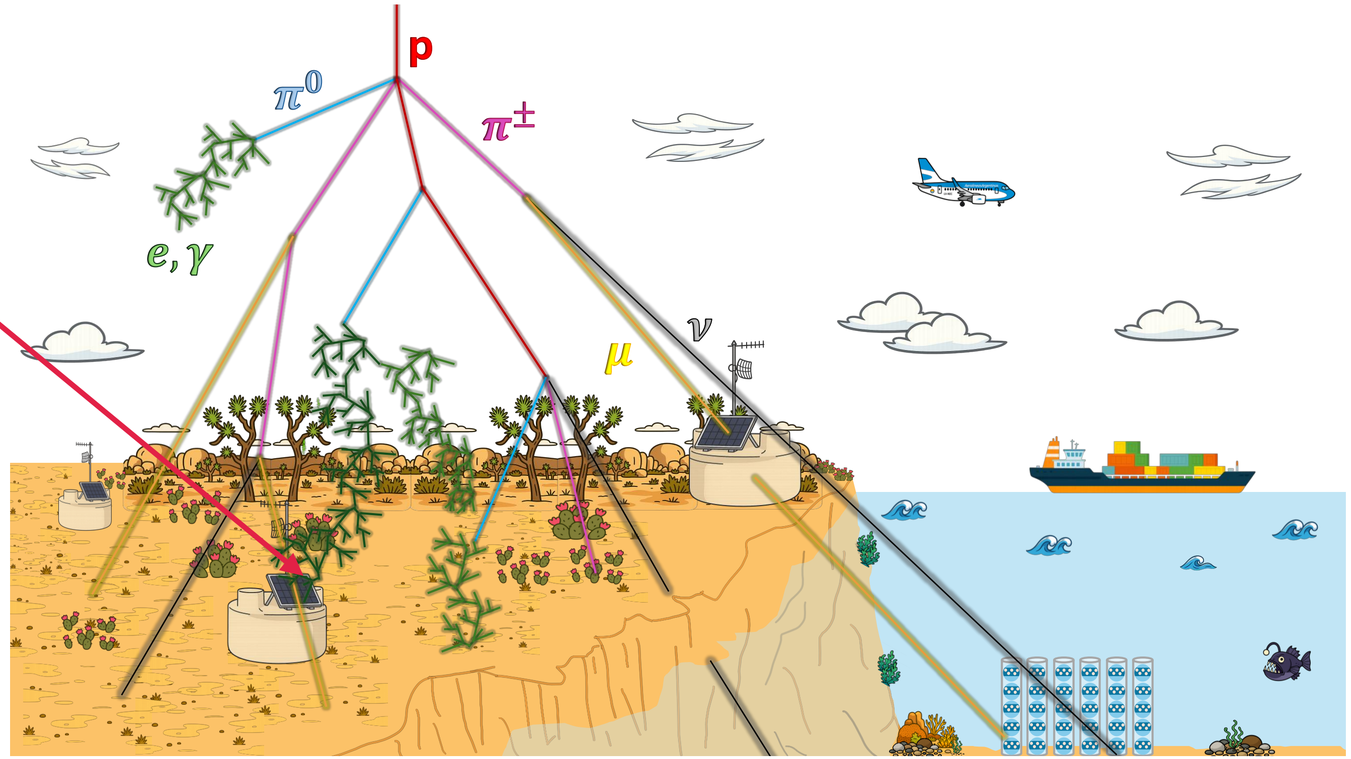


Particles from Extensive air shower: signal or background?

Cosmic-ray physics



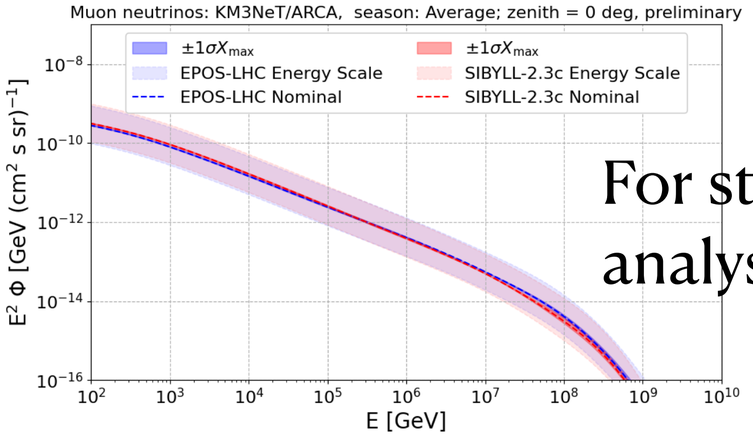
$$\mathscr{E}_{\nu}^{\mathrm{DG}}(E,\delta) = \iiiint dX d\mathbf{x} dt d\Omega \cos\theta \epsilon(E,\theta,\varphi,X,\mathbf{x}) \sigma_c m_{\mathrm{p}}^{-1},$$



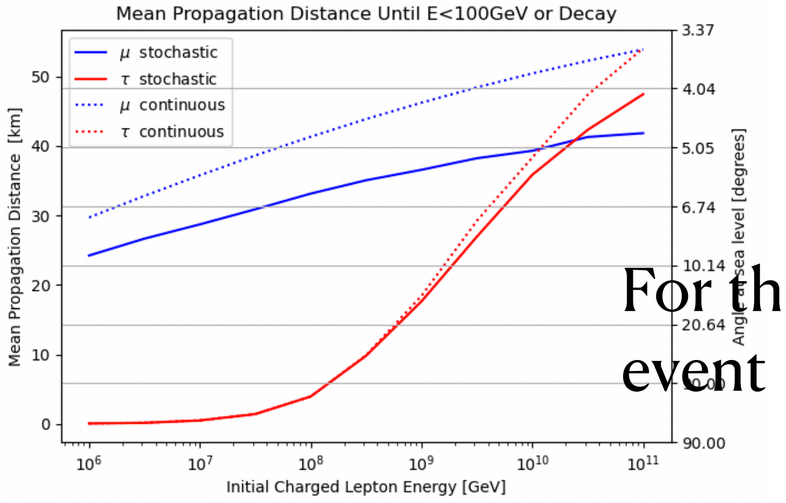
- Pierre Auger Observatory —>sensitive to neutrinos developing deeply in the atmosphere.
- Increase of neutrino-nucleon cross section for rare events (Non-perturbative SM enhancements, BSM physics) which lead to a larger multiplicities in the final state.
- Currently quantifying the exposure of the Observatory to such changes of cross sections through Montecarlo simulations to constrain neutrino-nucleon cross section.

Particles from Extensive air shower: signal or background?

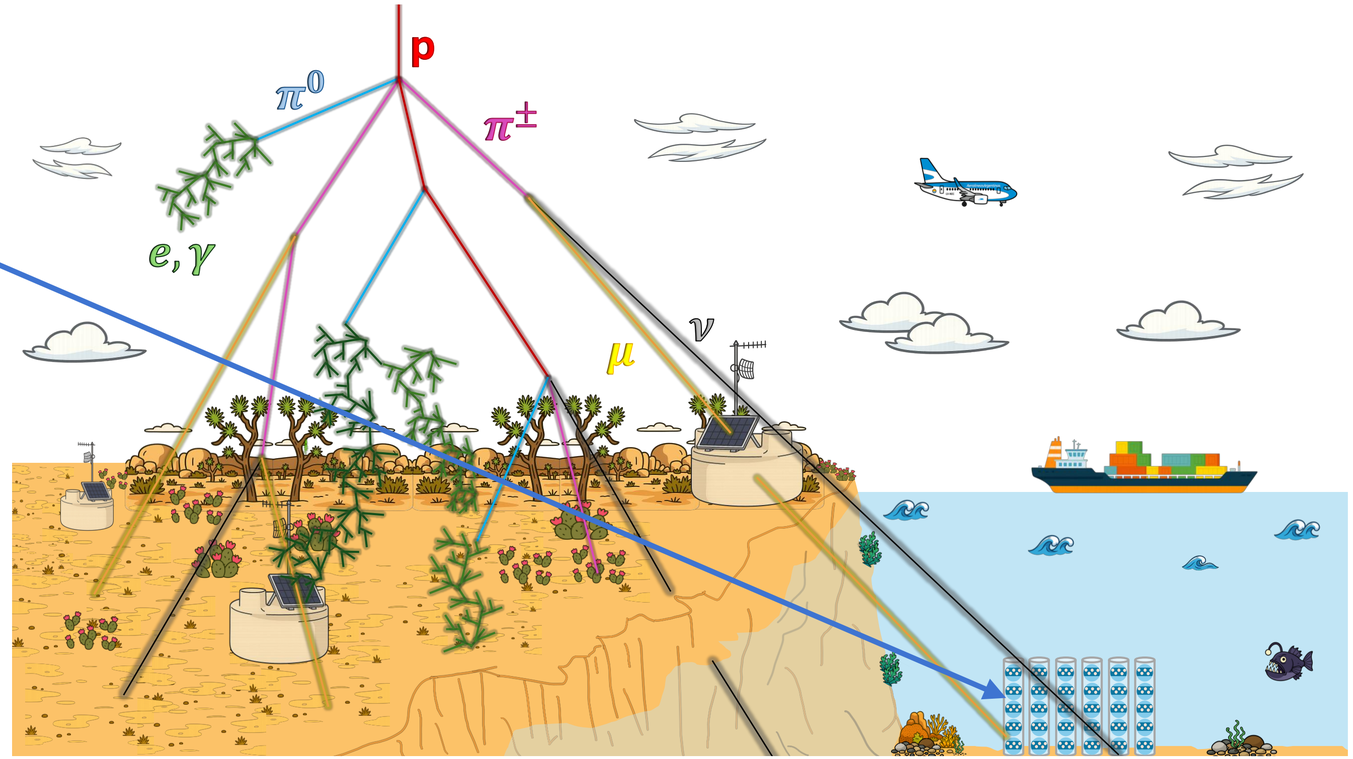
Neutrino physics



For standand analysis



For the UHE event



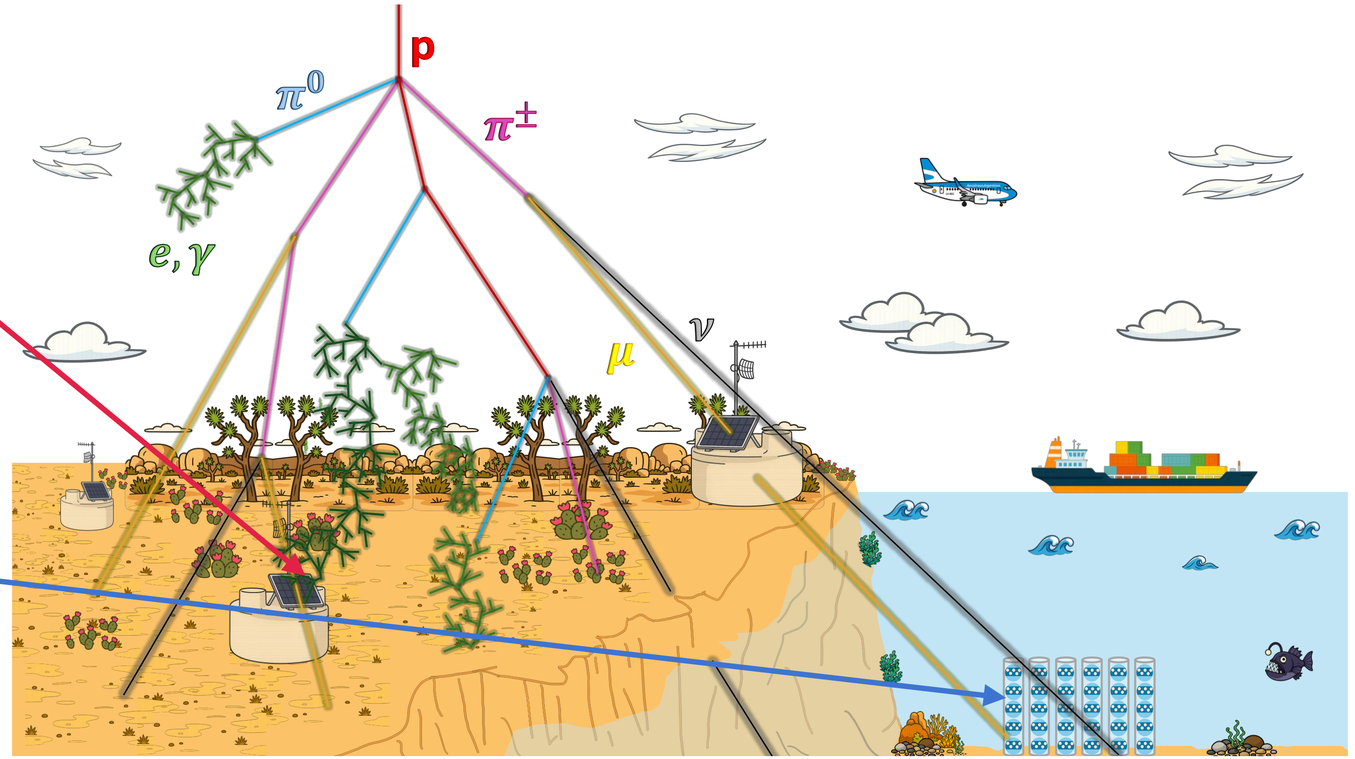
Particles from Extensive air shower: signal or background?

Cosmic-ray physics

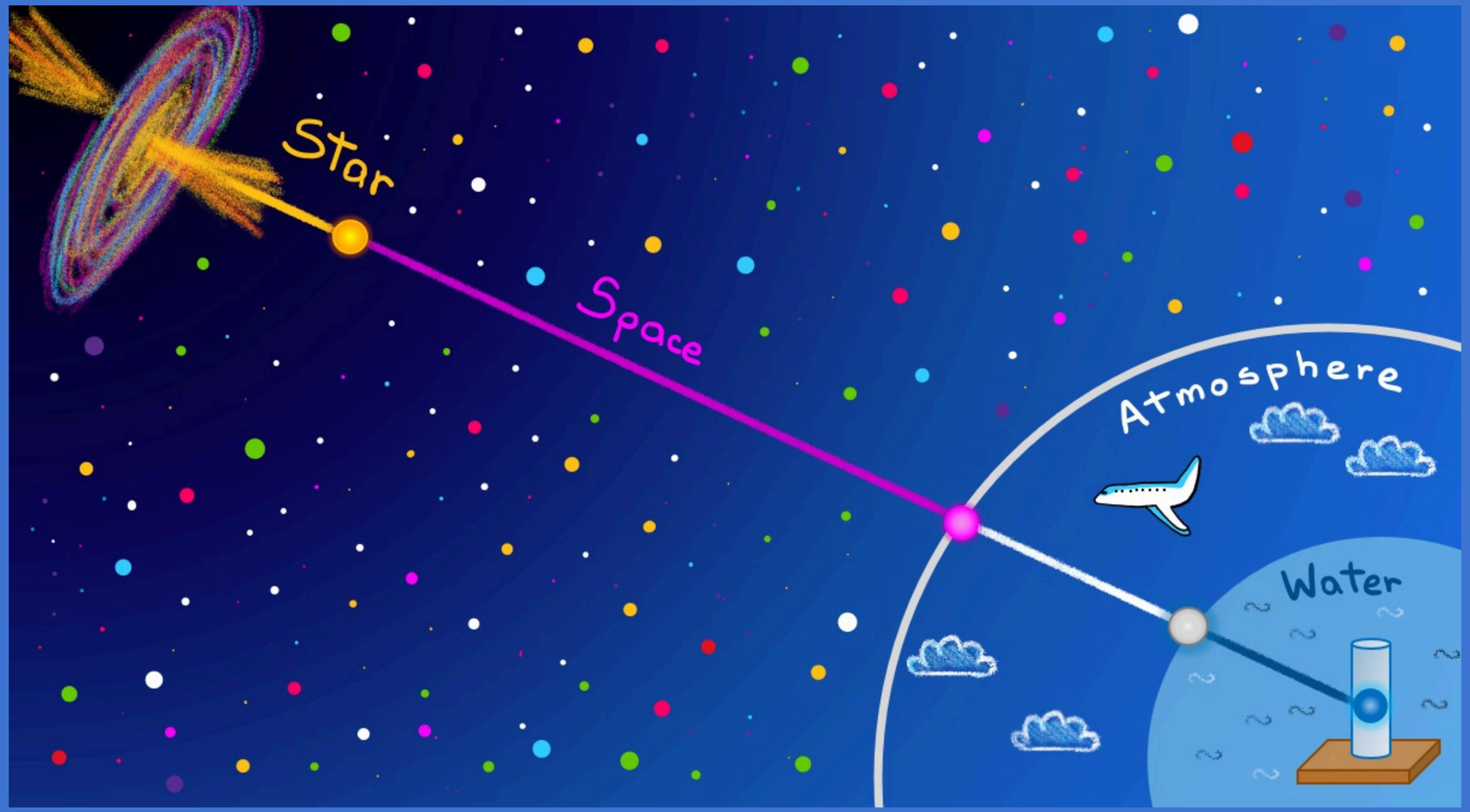
- Extensive air shower simulations to test SM suppressed mechanisms (CORSIKA).

Neutrino physics

- Production and validation of CORSIKA simulations to estimate atmospheric background.
- Estimation of possible background in the direction of the UHE event.
- Cosmic-ray properties using high-energy muons.



Propagation in water



Calibration of the detector

KM3NeT: ARCA, ORCA

Digital Optical Module (DOM)

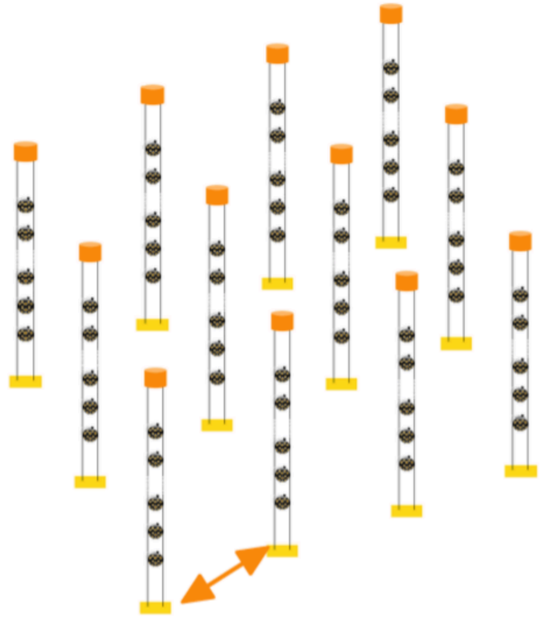
31 × 3” PMT, ⊘ =43 cm

× 18

Detection Unit (DU)

× 115

Building Block (BB)



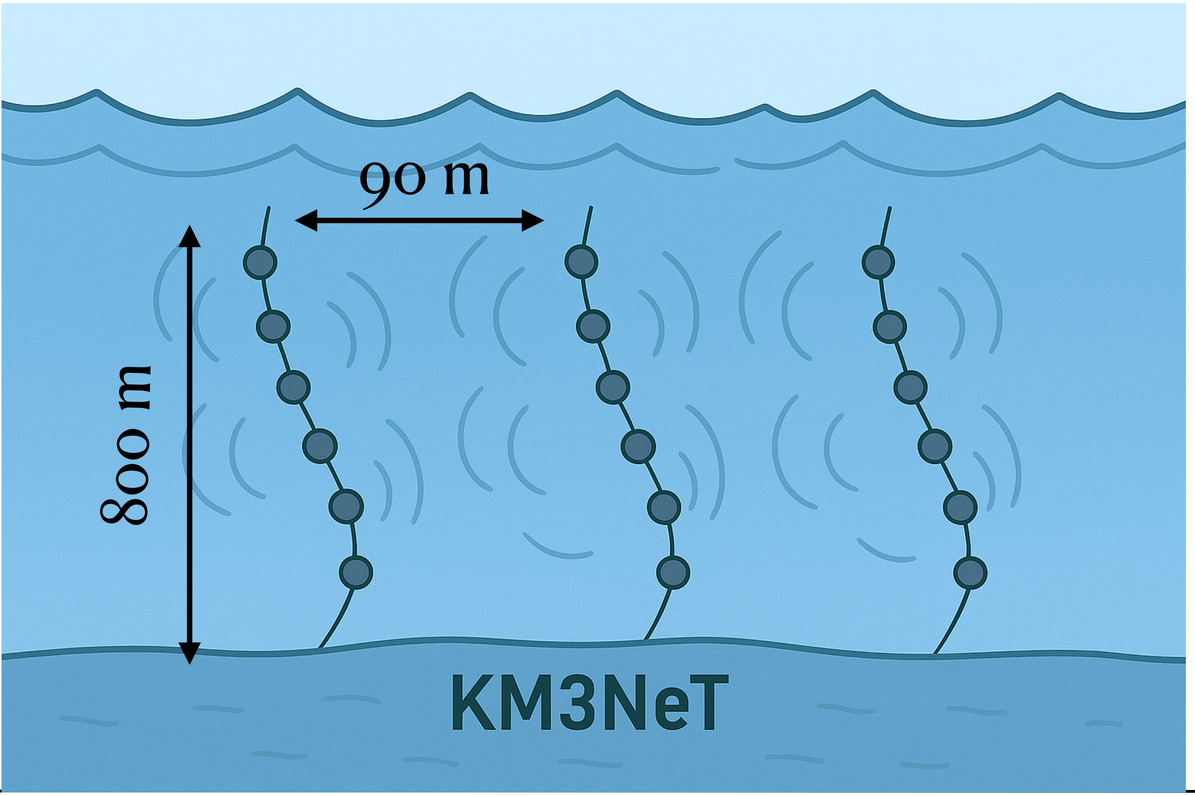
ARCA (1TeV – 10 PeV)
Max. depth = 3500 m
1 Gt (2 BB)
H = 700 m
⊘ = 1000 m
Vertical spacing: 36 m
Horizontal spacing: 90 m

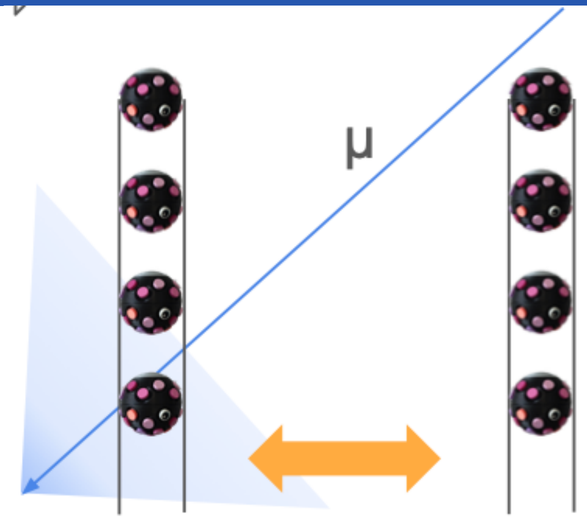
ORCA (1 – 100 GeV)
Max. depth = 2450 m
7 Mt
H = 200 m
⊘ = 200 m
Vertical spacing: 9 m
Horizontal spacing: 20 m

Calibration of the detector

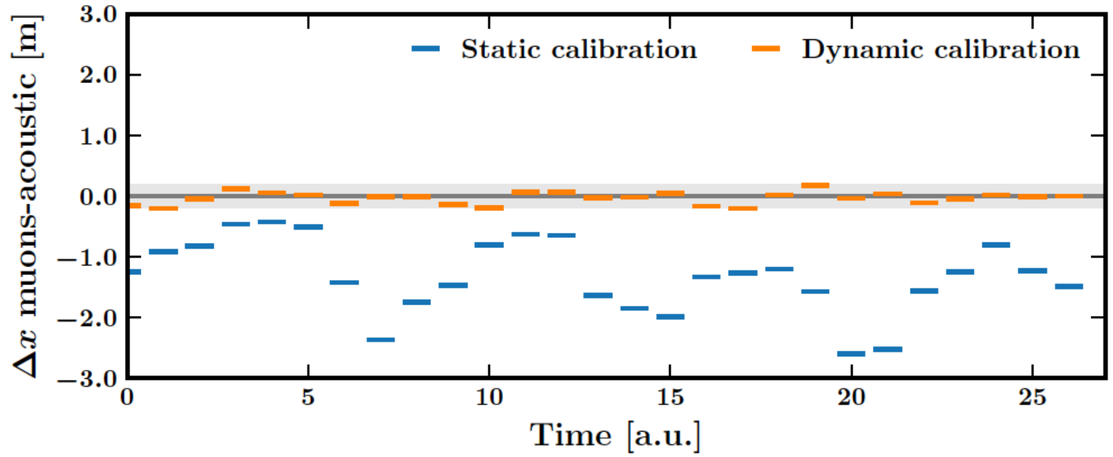
DOM positions within 20 cm,
DOM orientations within 3°,
sub-nanosecond synchronisation
of all the PMTs.

⟶ Angular resolution 0.1 degree.





Atmospheric muons ⟶ crucial for detector calibrations.



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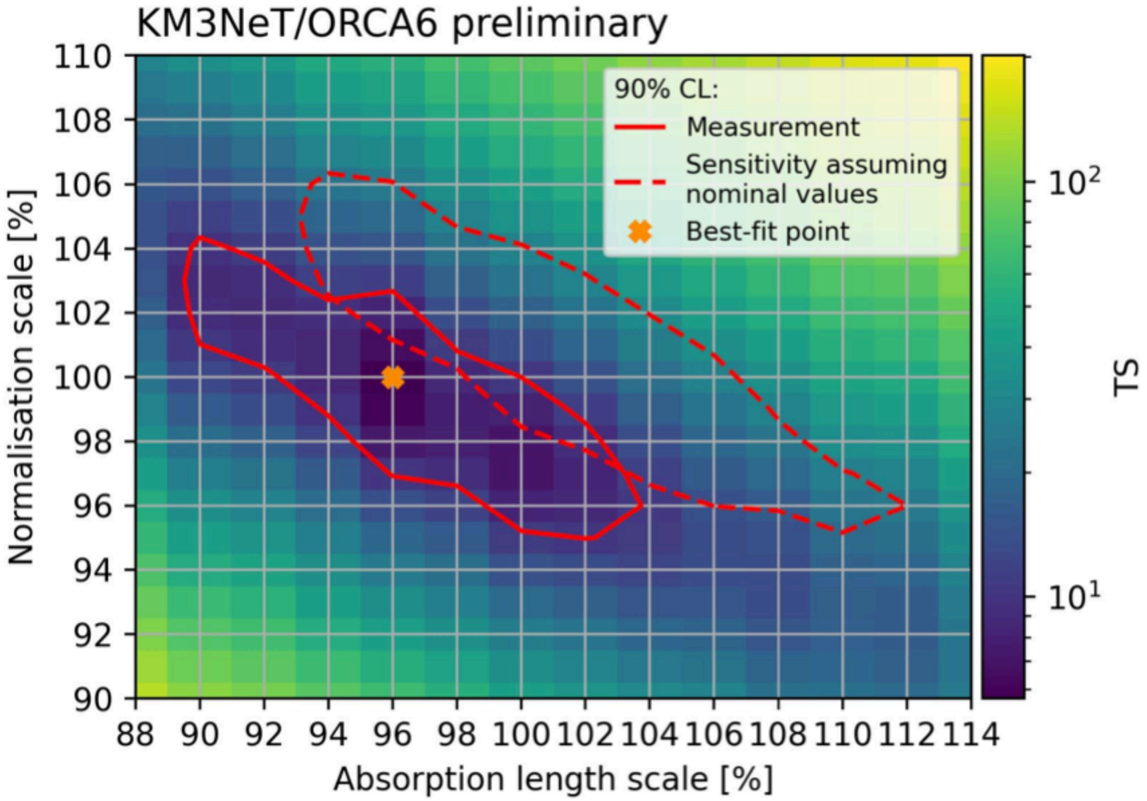
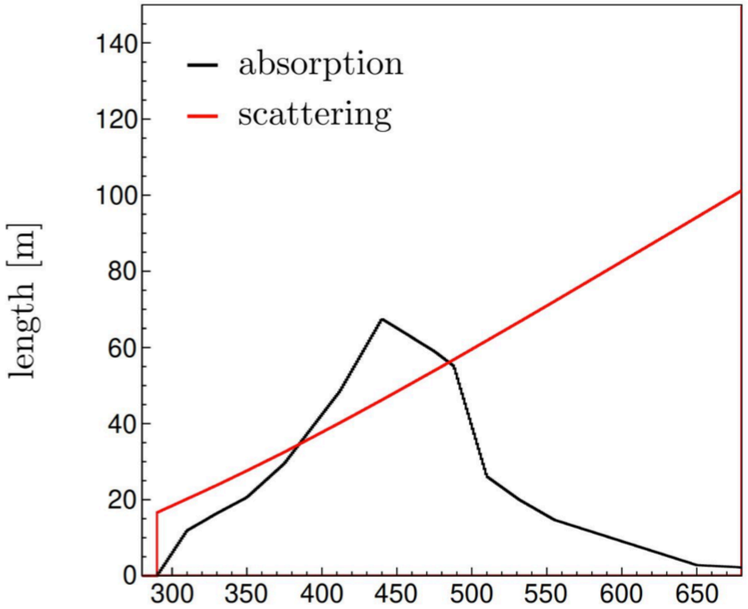
Calibration of the detector





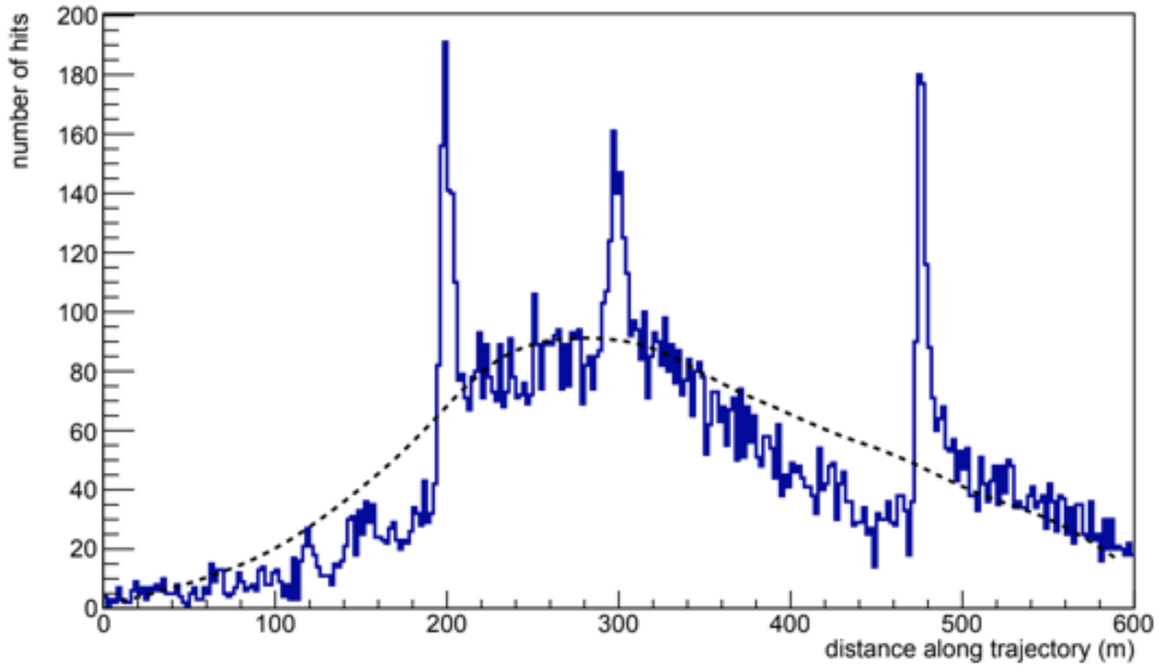
Atmospheric muons ⟶ crucial for detector performance.

Selecting stopping muons —> MIP particles —> crucial for water properties!

Muon or tau?

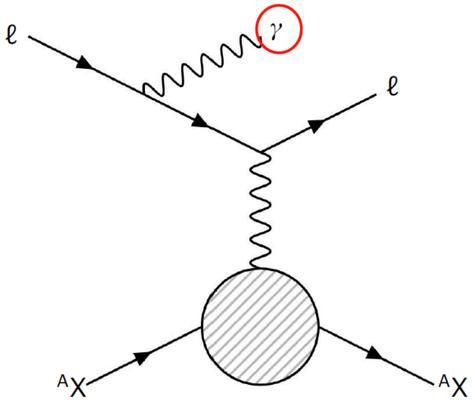
Light profile consistent with at least 3 large energy depositions along the lepton track.

Ongoing investigation on particle identification



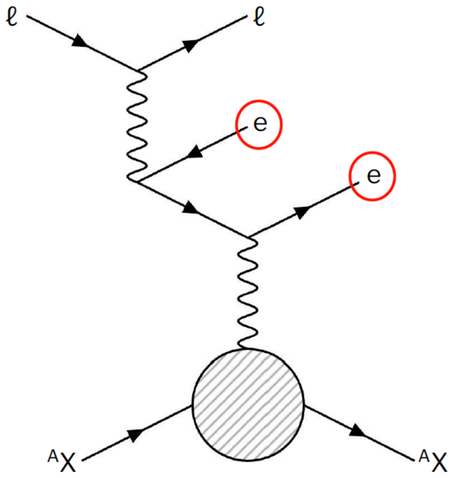
Muon or tau?

Bremsstrahlung



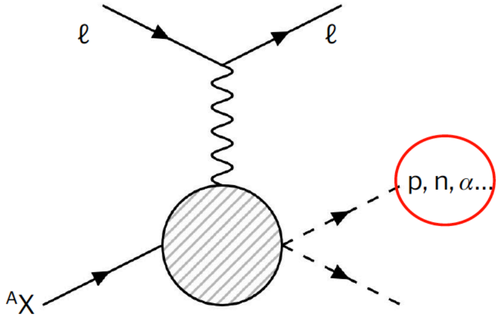
High energy γ

Pair Production

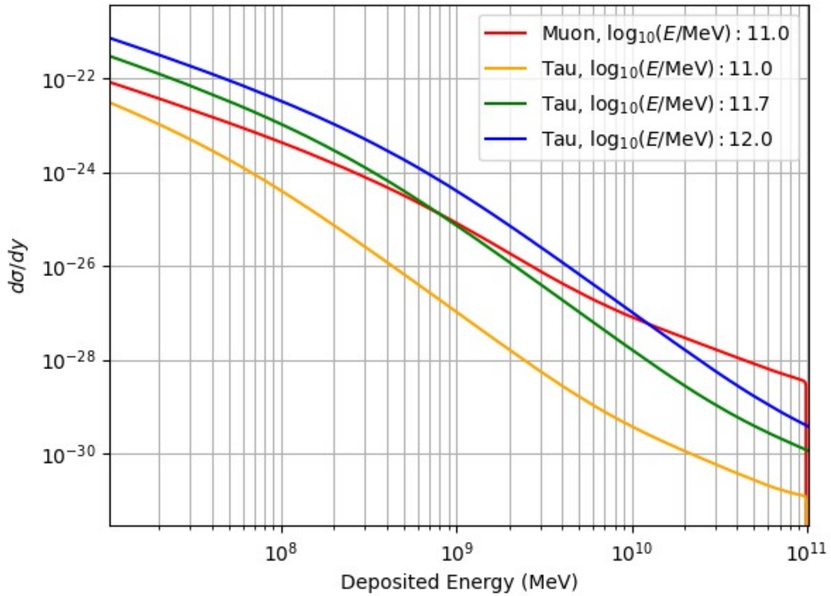


High energy $e^{\pm}$

Photonuclear



High energy nuclei

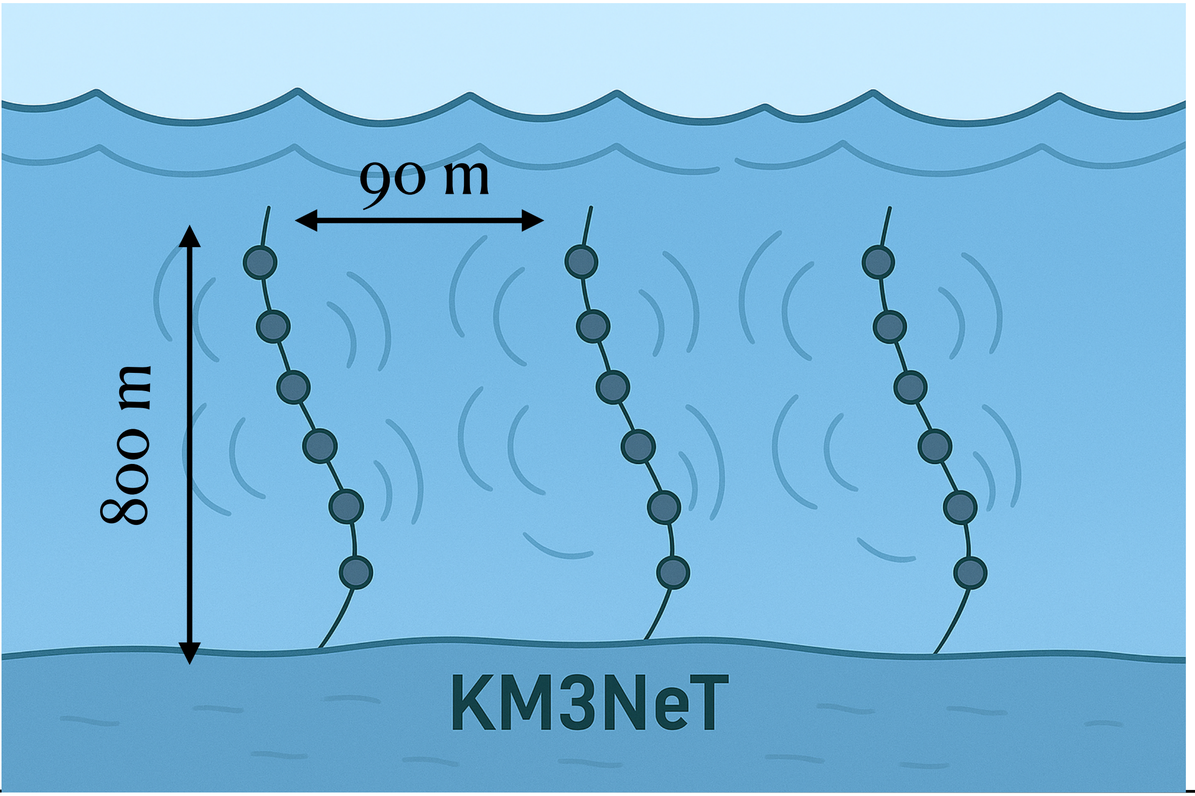


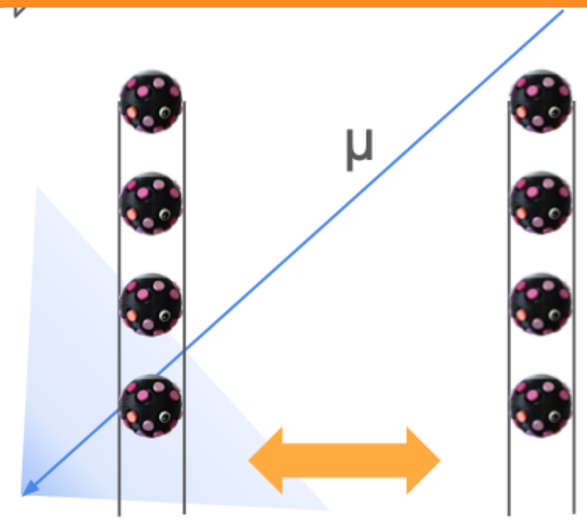
- Production via neutrino-nucleon interactions.
- Propagation: ionization, bremsstrahlung, pair production, photonuclear.
- Decay: muon and tau decay channels included.

Summary

DOM positions within 20 cm,
DOM orientations within 3°,
sub-nanosecond synchronisation
of all the PMTs.

⟶ Angular resolution 0.1 degree.





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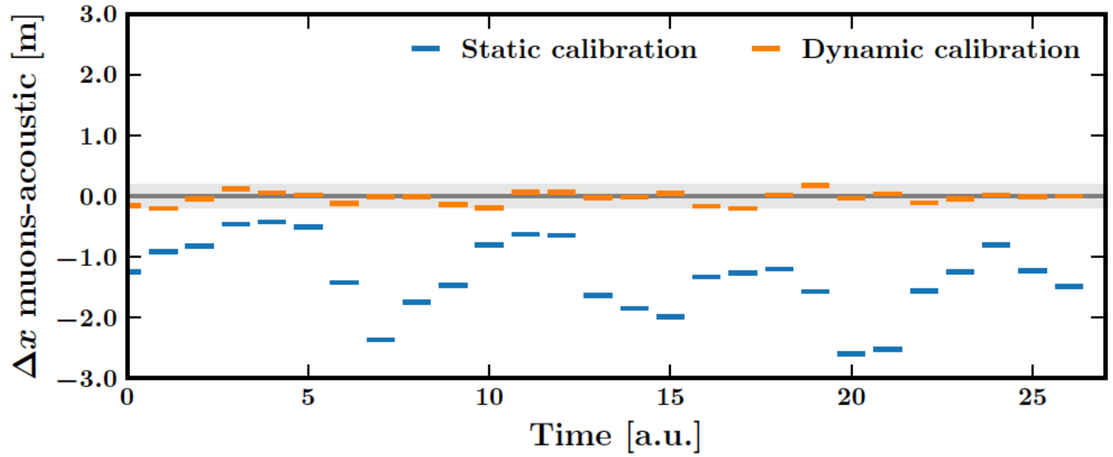

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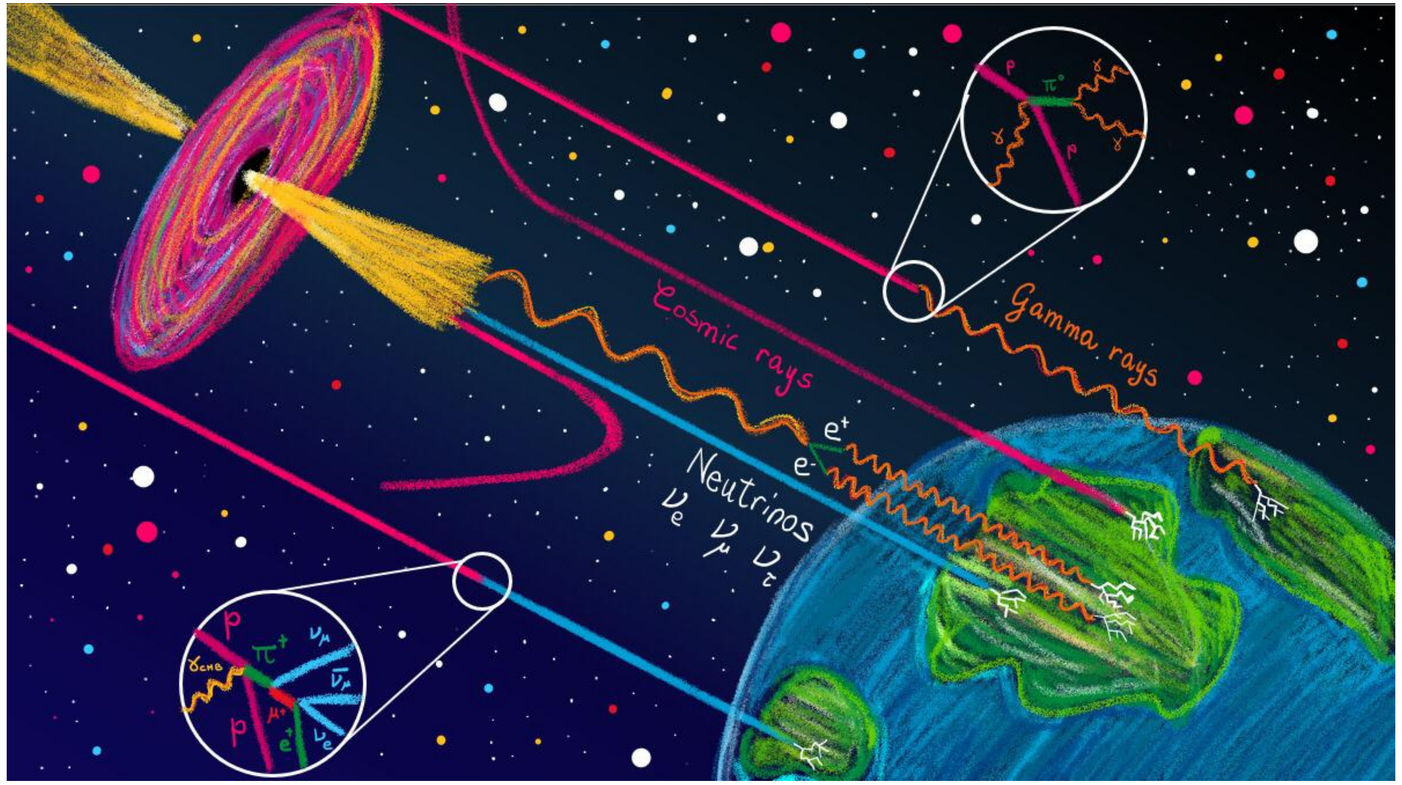
Summary of the summaries

- Understanding how particles behaves in a given environment —> crucial for Multi-messenger astrophysics.
- Combining different information is the key to infer something about the astrophysical sources.
- Need for a clear-cut understanding of the dynamics inside EG sources: in-source backgrounds and cosmic-ray interactions.
- New high-quality data —> acceleration processes in astrophysical environment.

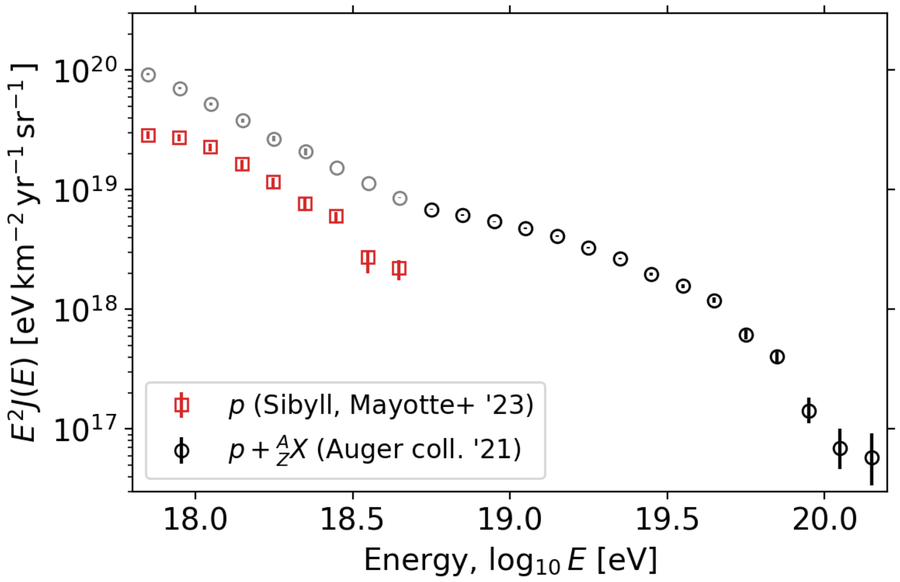


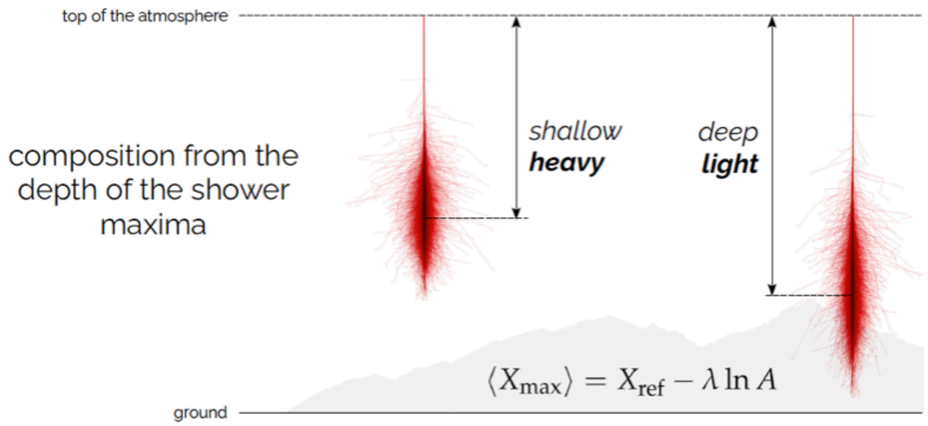
Thanks a lot for your attention!

Back-up

UHECRs : What do we know?

- Ultra-high-energy cosmic rays (UHECR) spectrum —> power law broken in some features;
- First moment of $X_{\max}$ distribution is sensitive to primary mass; from light to heavy and then from heavy to light.
- It is possible to link features in the UHECRs to astrophysical processes?





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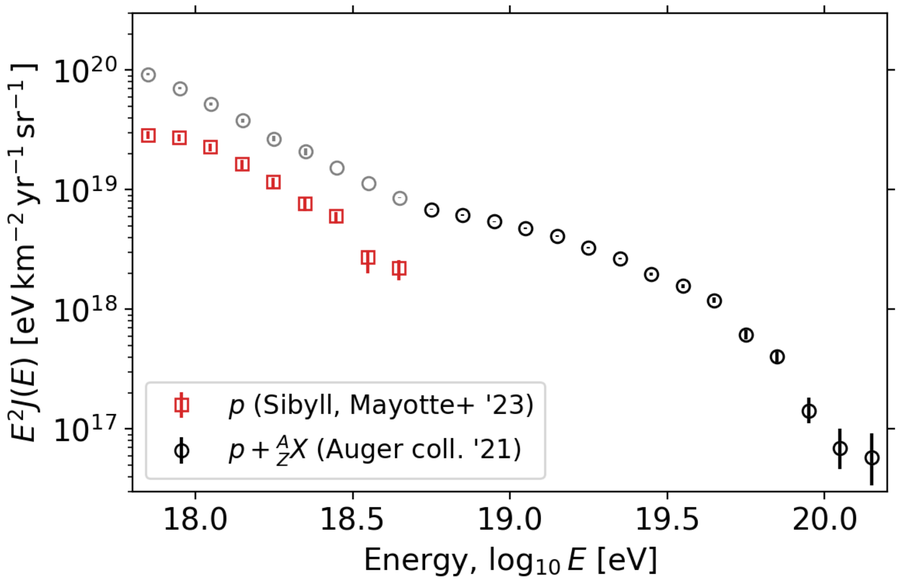

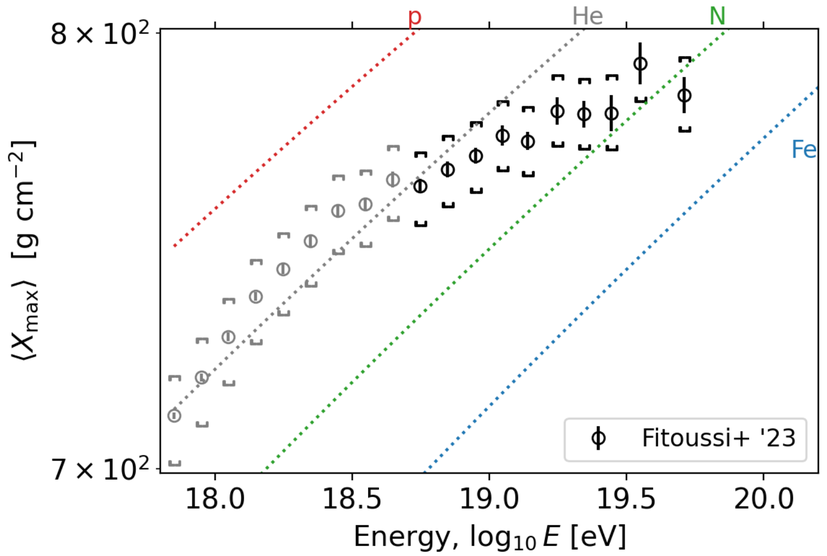

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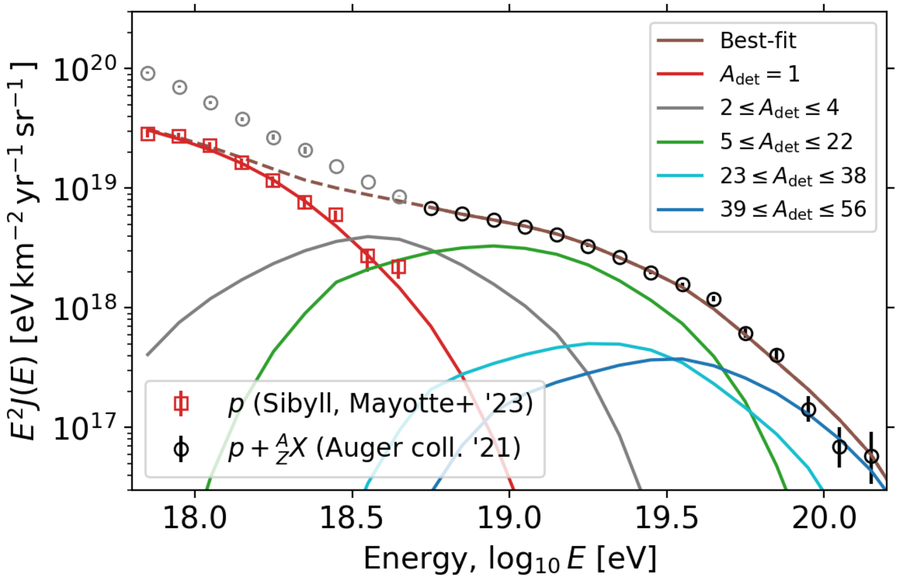
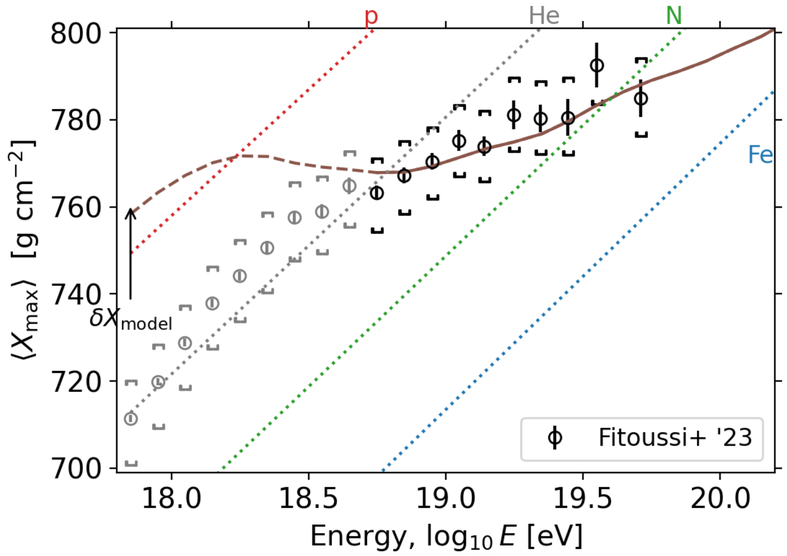
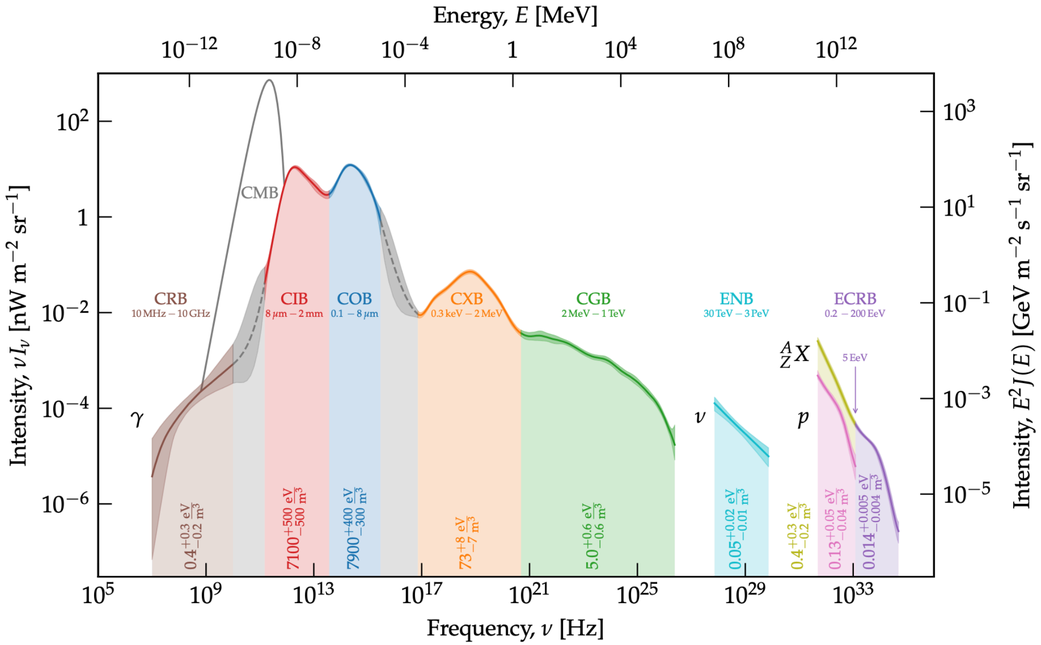




Current constrain on transient sources

Table 1
Instrumental Parameters

Detectors (Instrument)	Operation Time (T) yrs	Field of View (Ω) sr	Sensitivity (erg cm^{-2} s^{-1}) ($F_{\rm th}$)
CGRO (BATSE)	10	π	3.0×10^{-8}
HETE-II (WXM)	7	0.8	8.0×10^{-9}
INTEGRAL(IBIS)	12	0.26	9.1×10^{-9}
Swift (XRT)	10	5×10^{-5}	10^{-12} (1000 s)
ROSAT(PSPC)	8	10^{-3}	3.0×10^{-13} (500 s)
XMM-Newton (EPIC)	15	2×10^{-4}	2.0×10^{-14} (10^3 s)
Chandra(ACIS)	14	6×10^{-4}	4.0×10^{-15} (10^5 s)
Swift (BAT)	10	1.33	3×10^{-8} for HL-LGRBs and rate-triggered LL-GRBs
Swift (BAT)	10	1.33	10^{-7} for SGRBs
Swift (BAT)	10	1.33	$2.8(3.1) \times 10^{-9}$ for LL-LGRB 060218/100316D
Swift (BAT)	10	1.33	10^{-8} for Sw J1644+57
Swift (BAT)	10	1.33	4.3×10^{-11} for Sw J2058+05



UHECR arrival direction to constrain plausible sources