Ultra-heavy nuclei and ultra-high-energy cosmic rays

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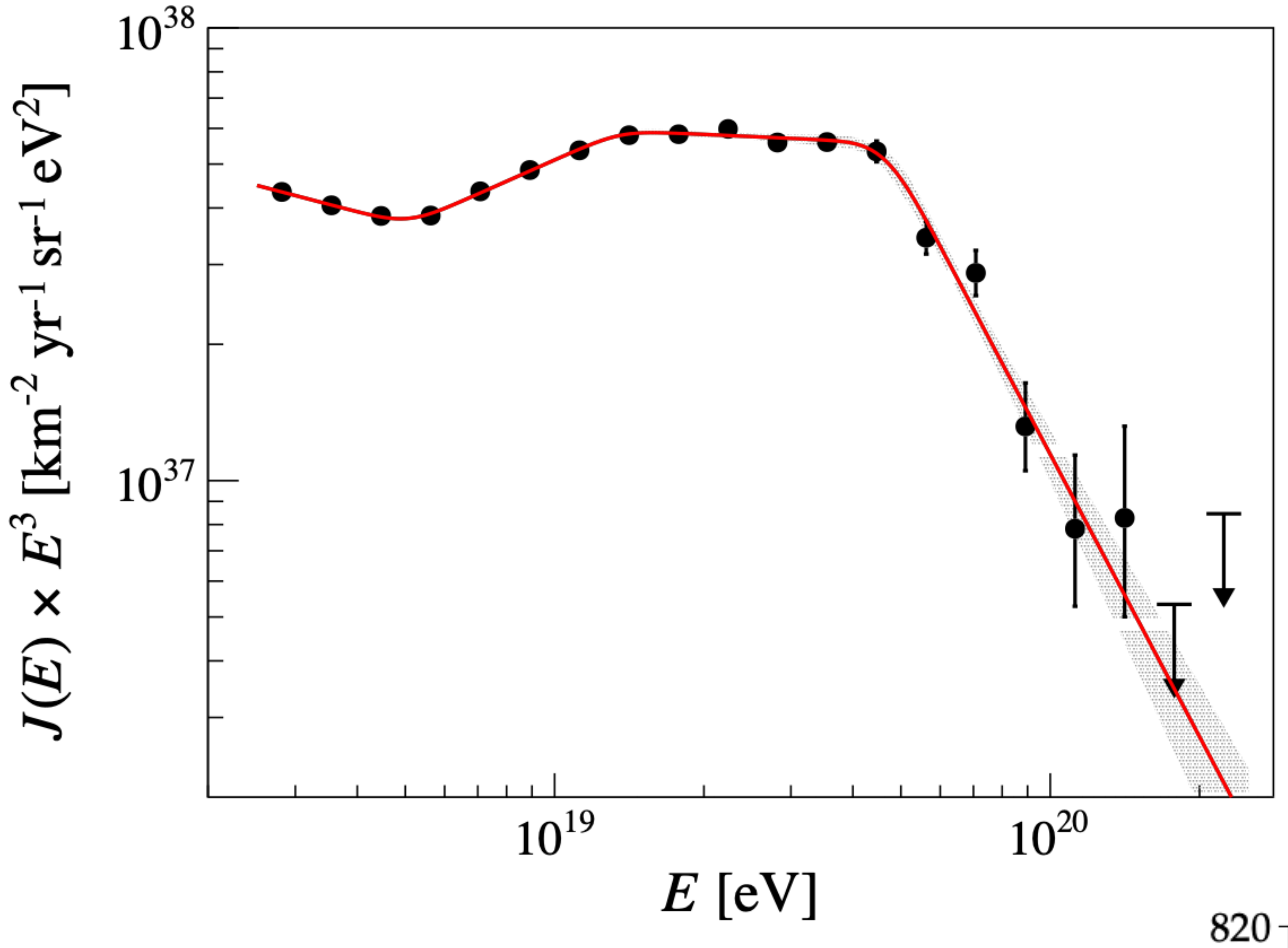
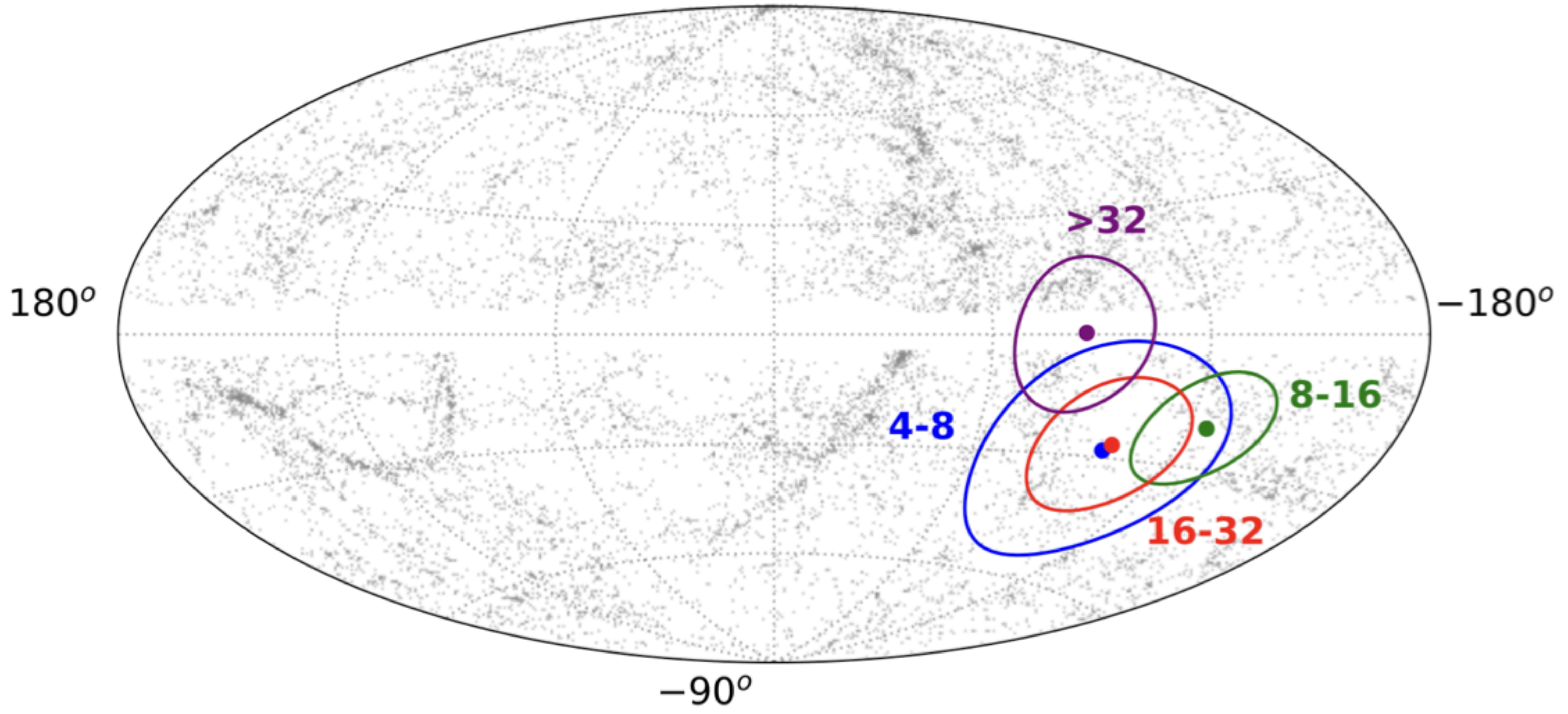
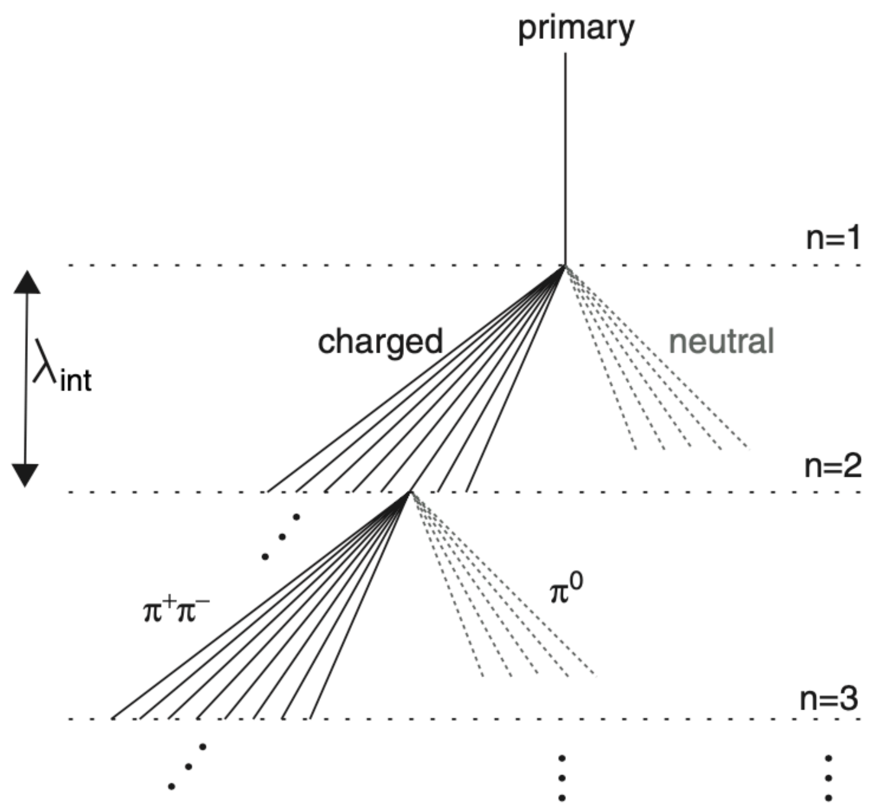
WHY ARE WE INTERESTED IN NUCLEAR REACTIONS IN THE CONTEXT OF UHECRS?

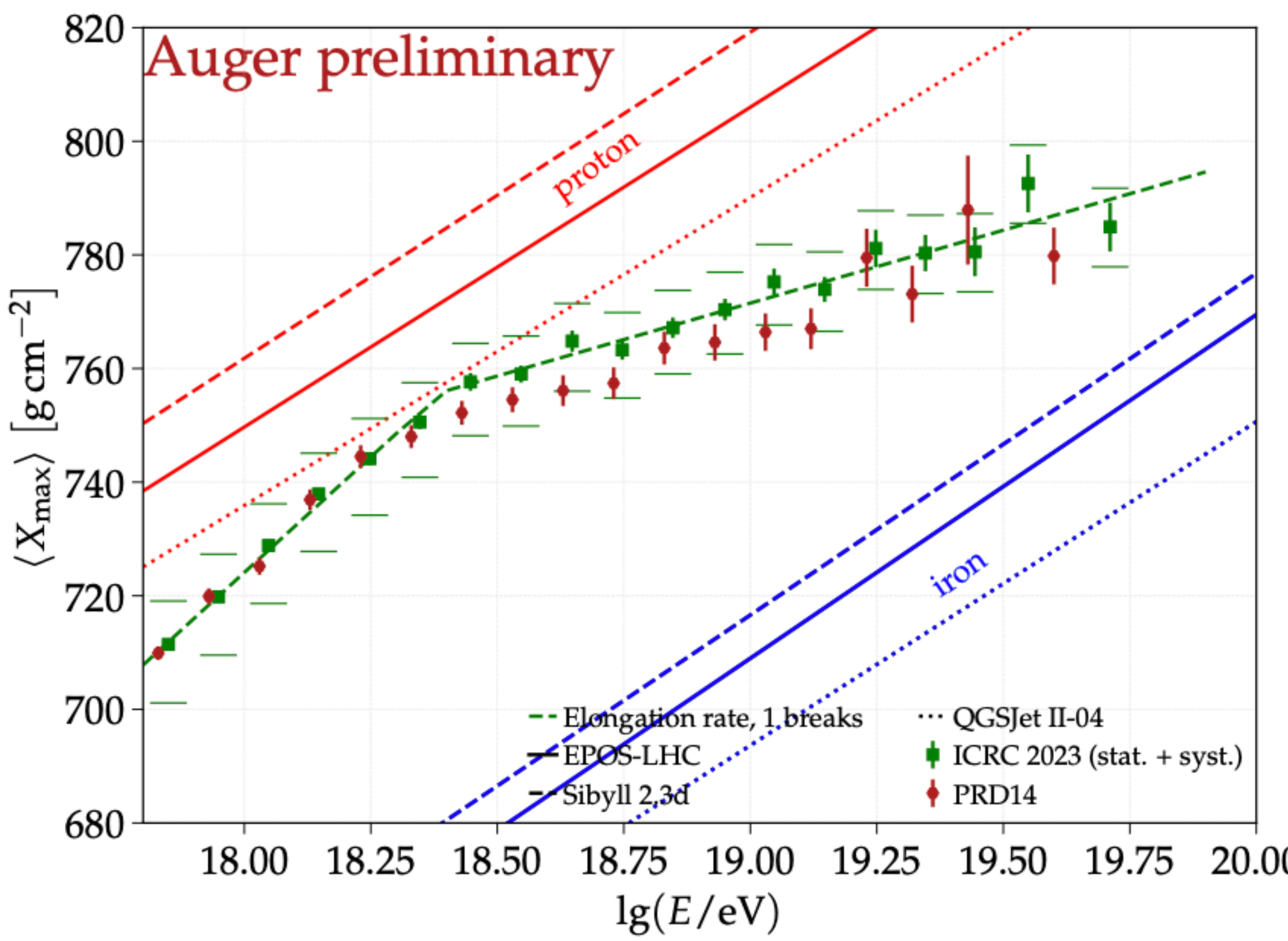
The Pierre Auger Collab. PRD&PRL 2020

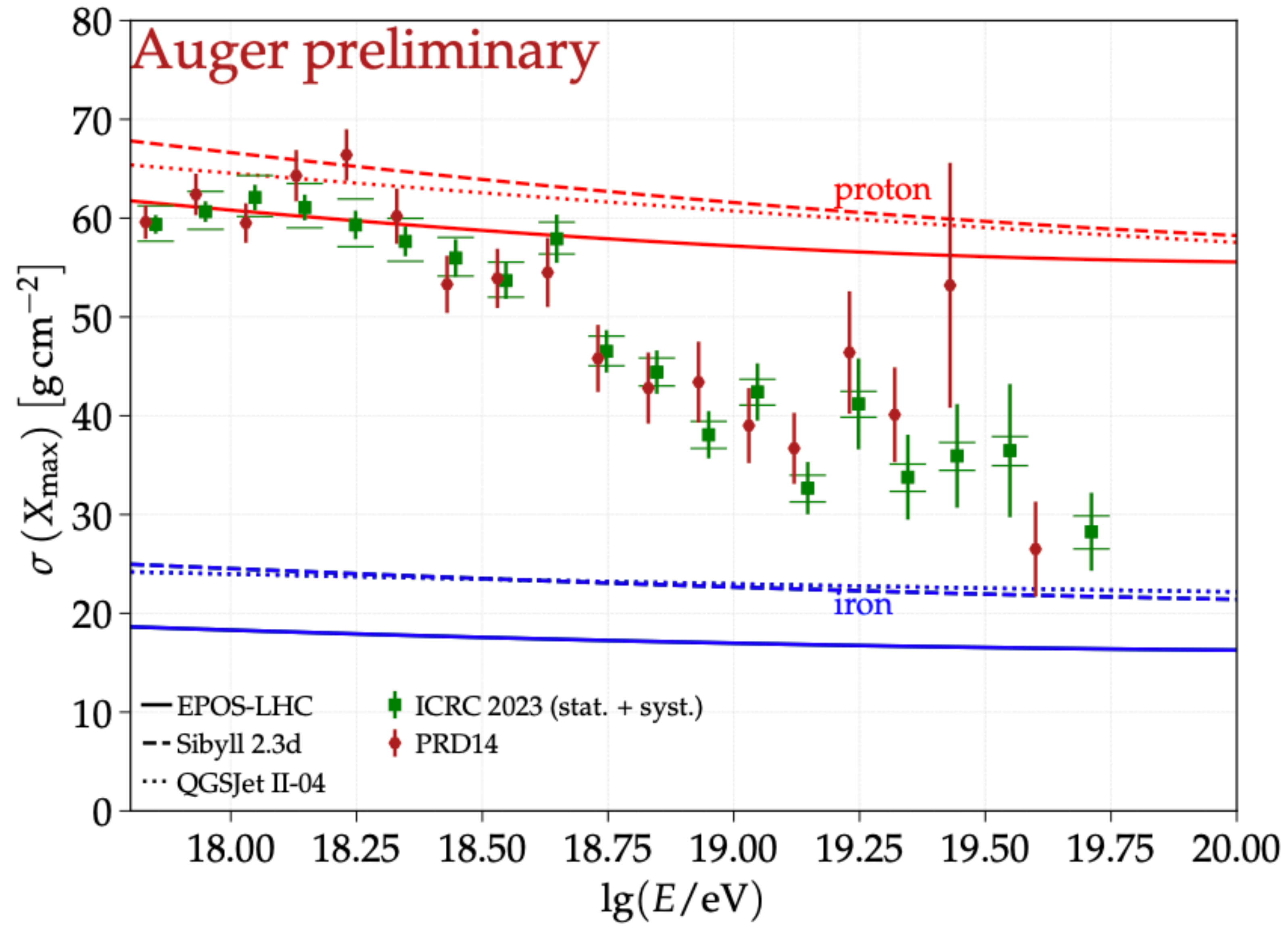


The Pierre Auger Collab. arxiv:2408.05292



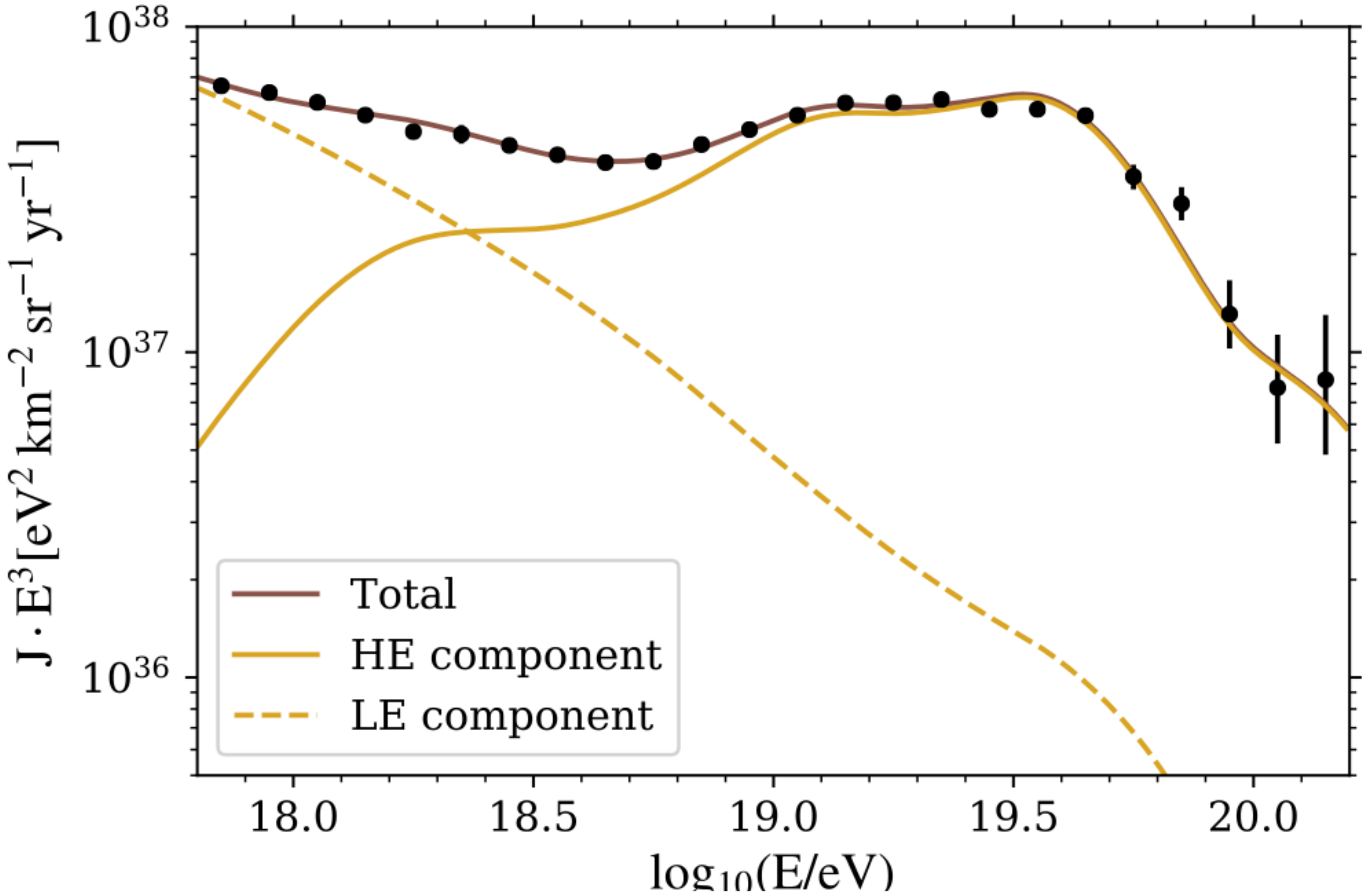


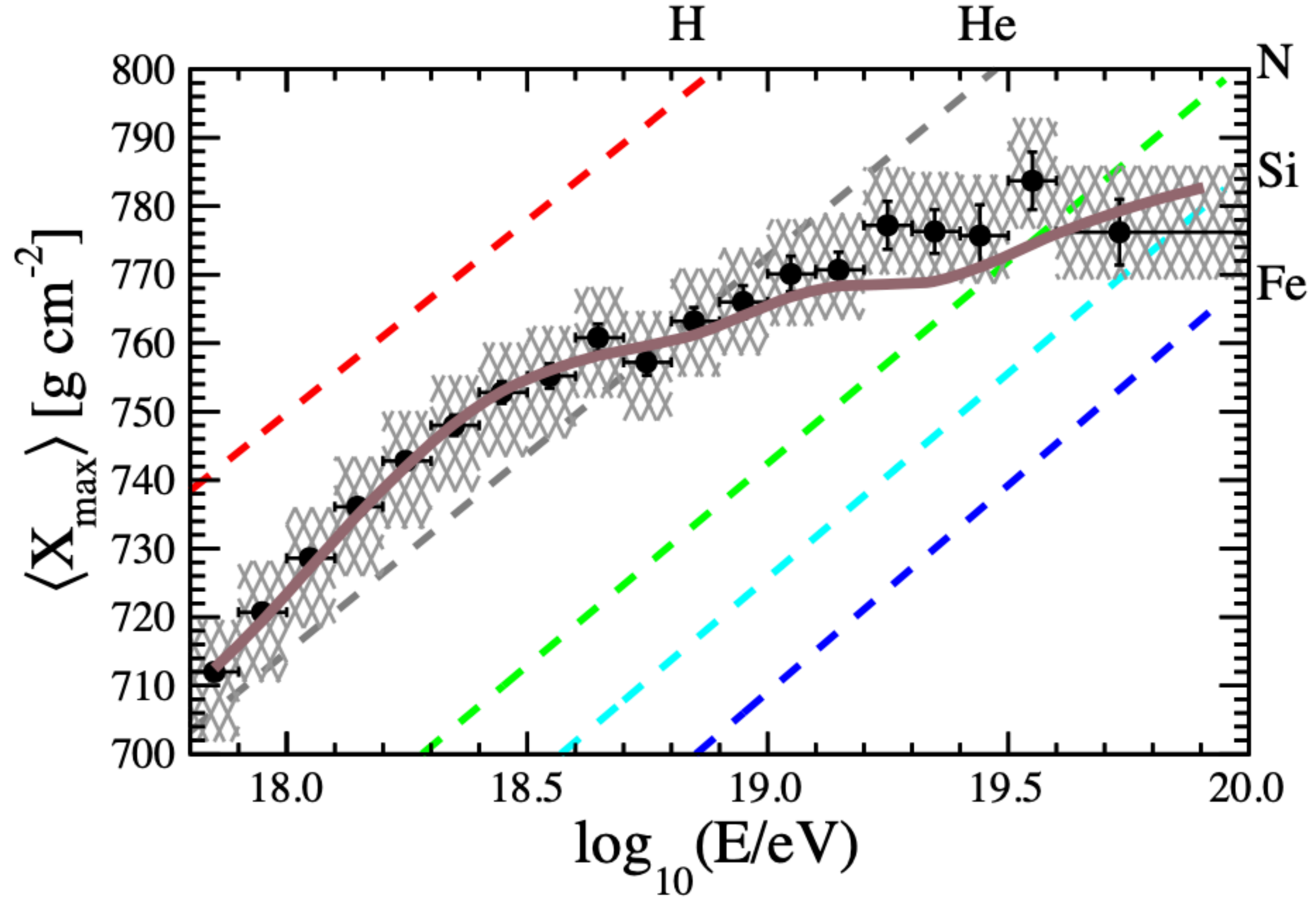


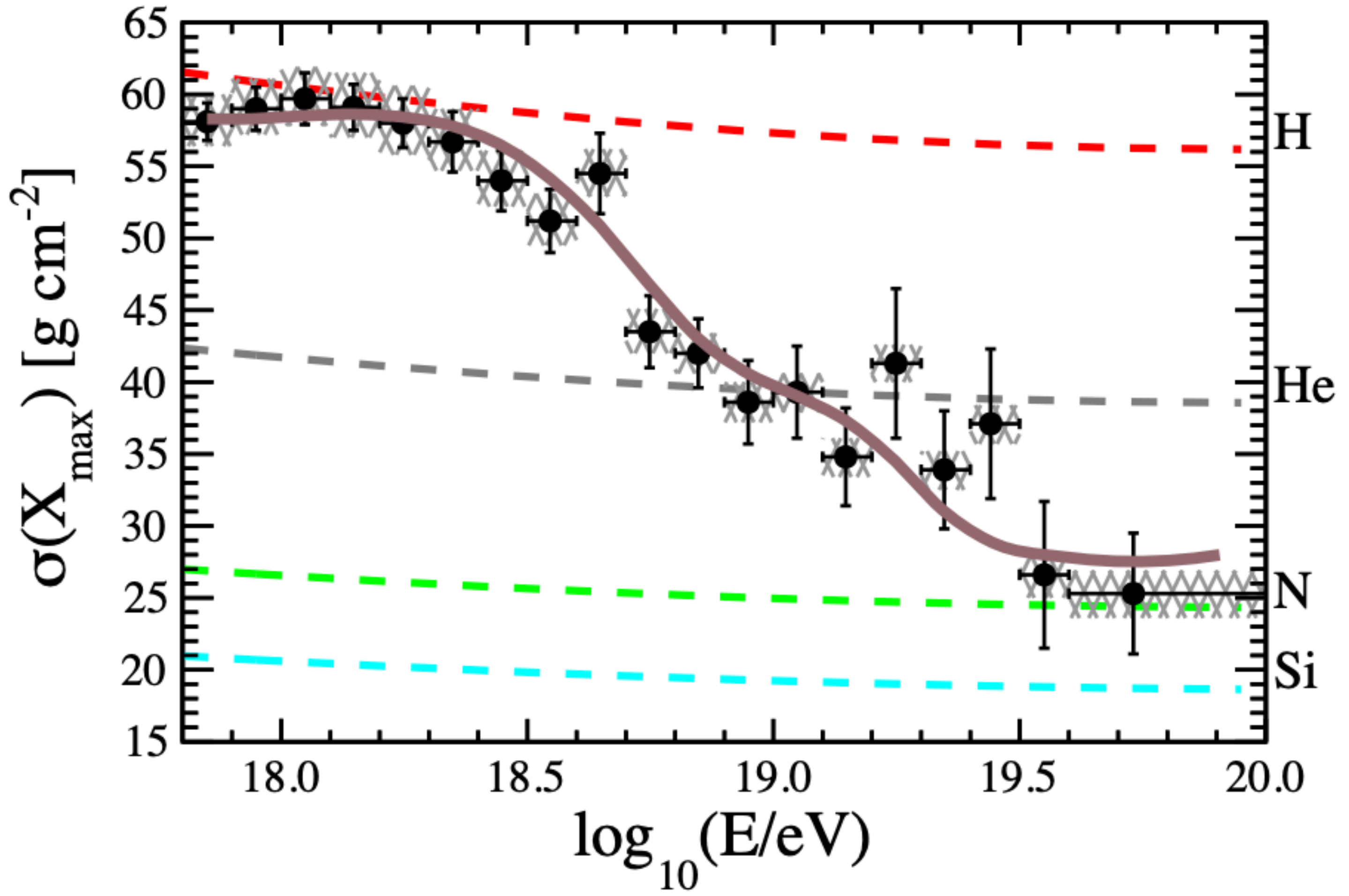


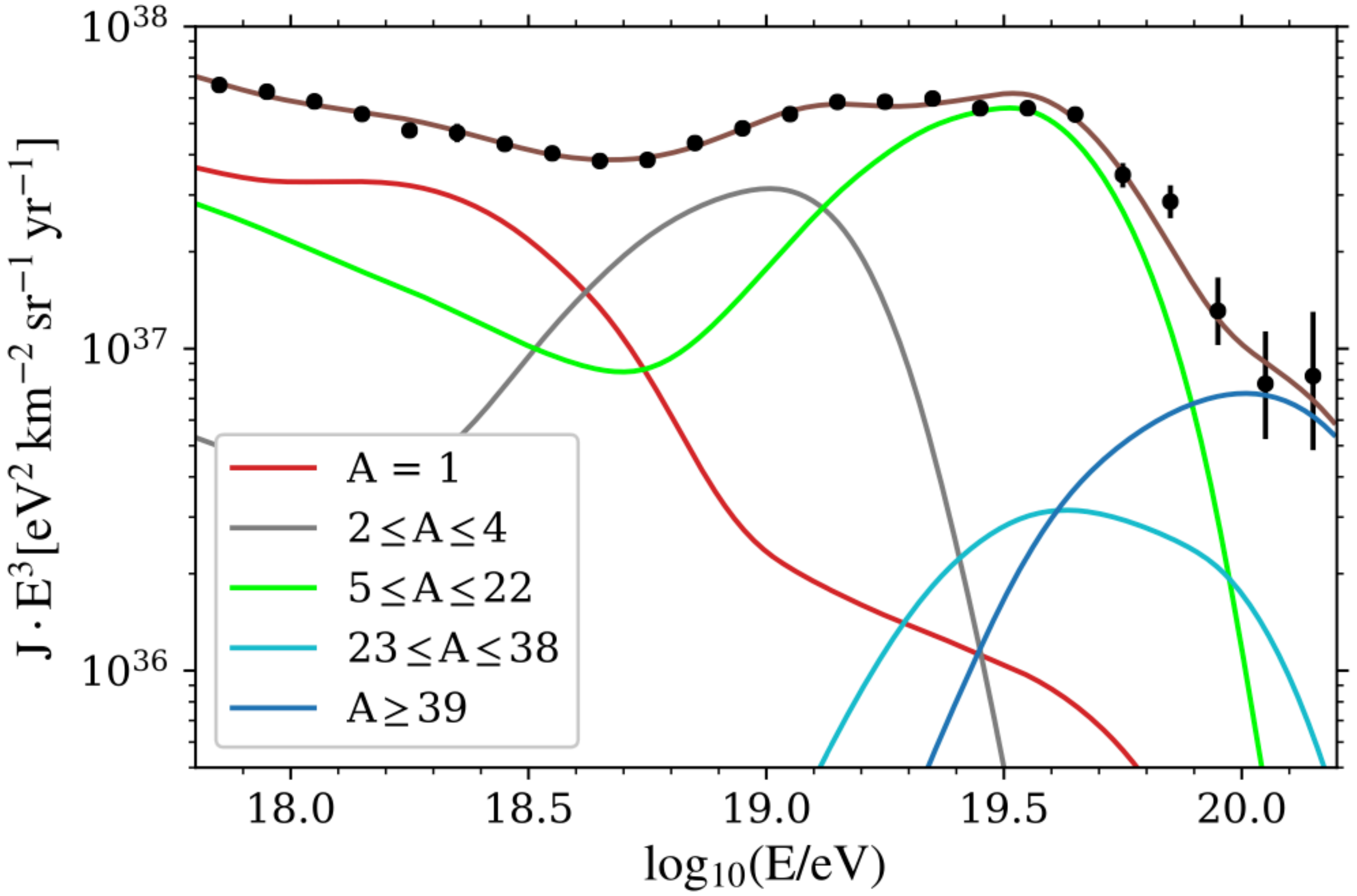
The Pierre Auger Collab. ICRC23

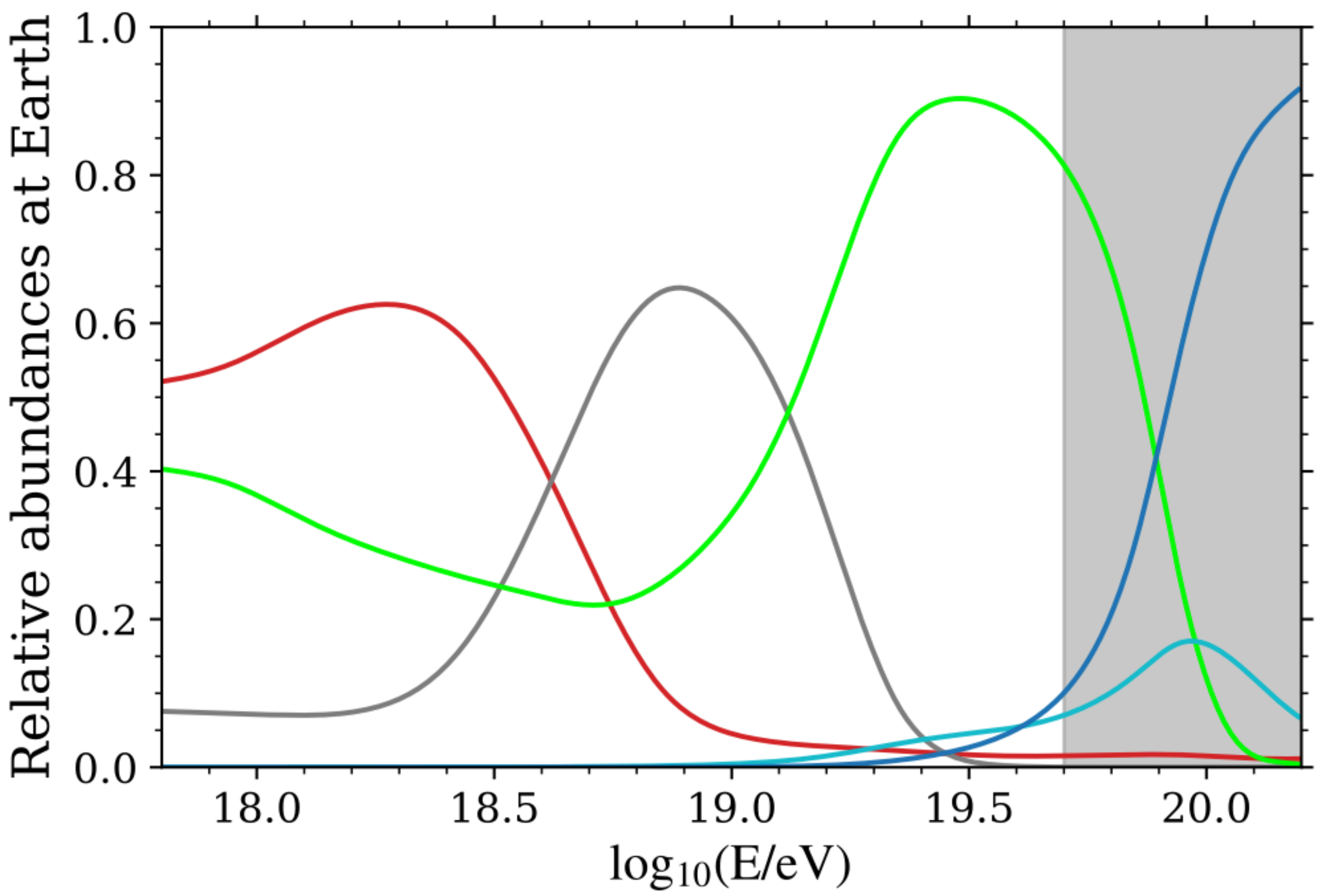
ASTROPHYSICAL SCENARIOS EXPLAINING UHECR DATA





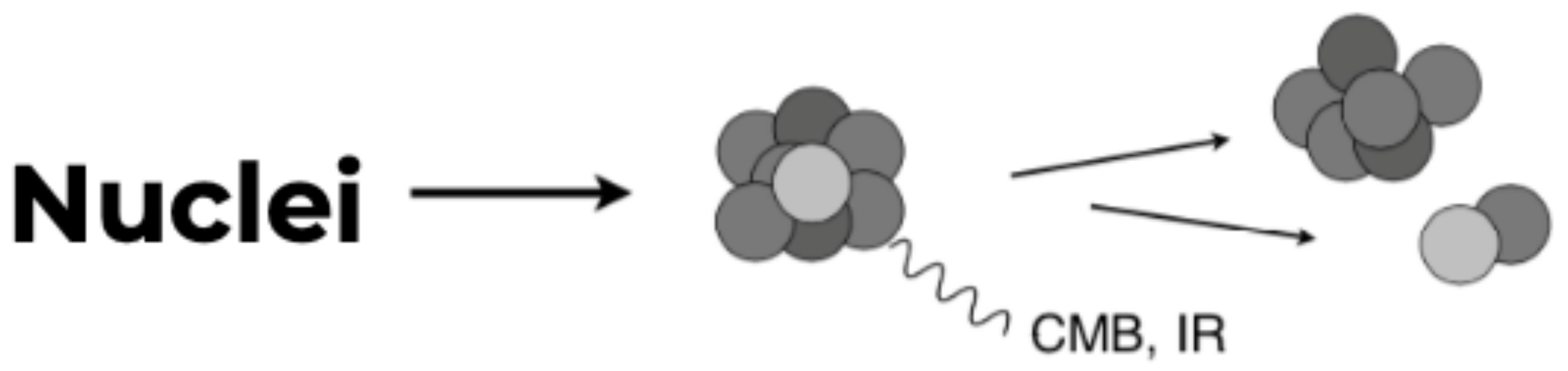


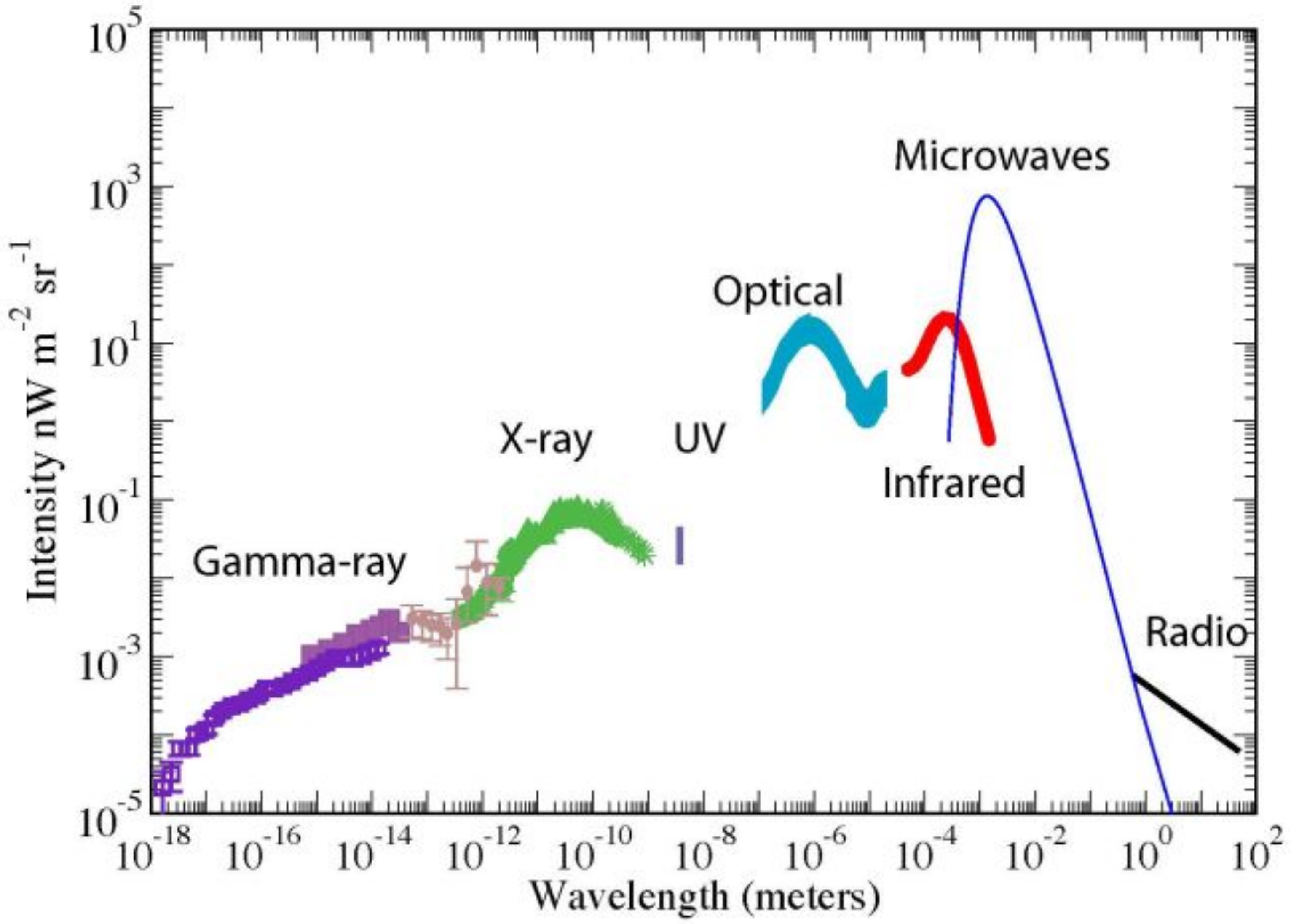




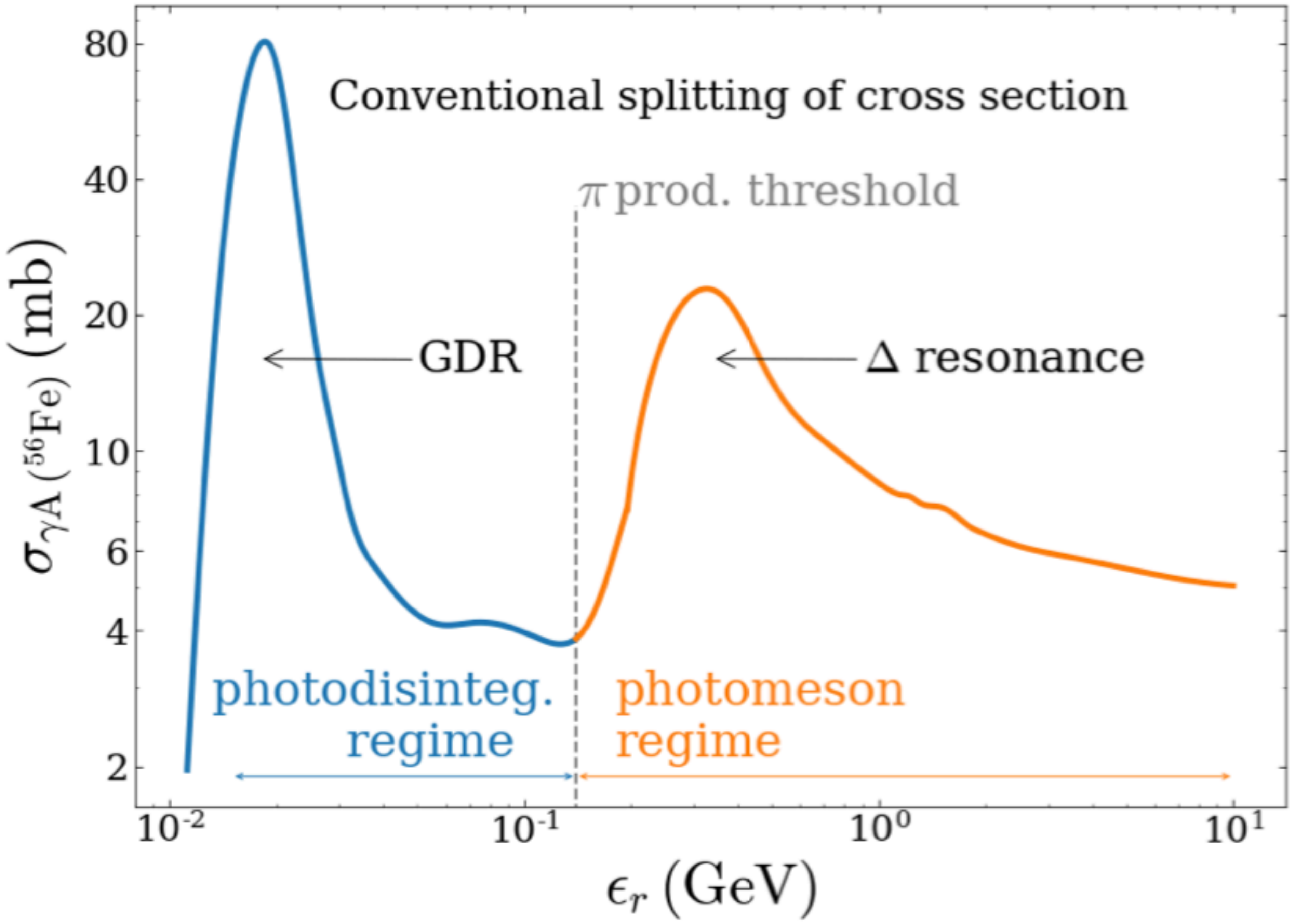
Aloisio, Berezinsky & Blasi JCAP 2014; Mollerach & Roulet PRD 2020; Das et al, Eur.Phys.J. 2021; Luce et al, ApJ 2022; **The Auger Collab. JCAP 2023**

PHOTO-DISINTEGRATION OF NUCLEI IN EXTRAGALACTIC SPACE





Morejon, Fedynitch, DB, Biehl & Winter JCAP 2019



- Regimes of photo-disintegration reactions
  - Giant Dipole Resonance (GDR): protons and neutrons can be considered as penetrating fluids; absorption of photons determines vibrations; ejection of one/two nucleons is dominant
  - Quasi-Deuteron (QD), 20-150 MeV: the photon wavelength becomes comparable with the nuclear dimensions; photon interacts with nucleon pair; ejection of pair + possibly other nucleons
- Conservation of Lorentz factor

Photodisintegration implemented in several UHECR propagation codes, such as

CRPropa (Alves Batista et al, JCAP 2022), SimProp (Aloisio, DB, di Matteo, Grillo, Petrera, Salamida JCAP 2017), Prince (Fedynitch & Heinze)…

MOTIVATIONS TO LOOK AT **HEAVIER NUCLEI**

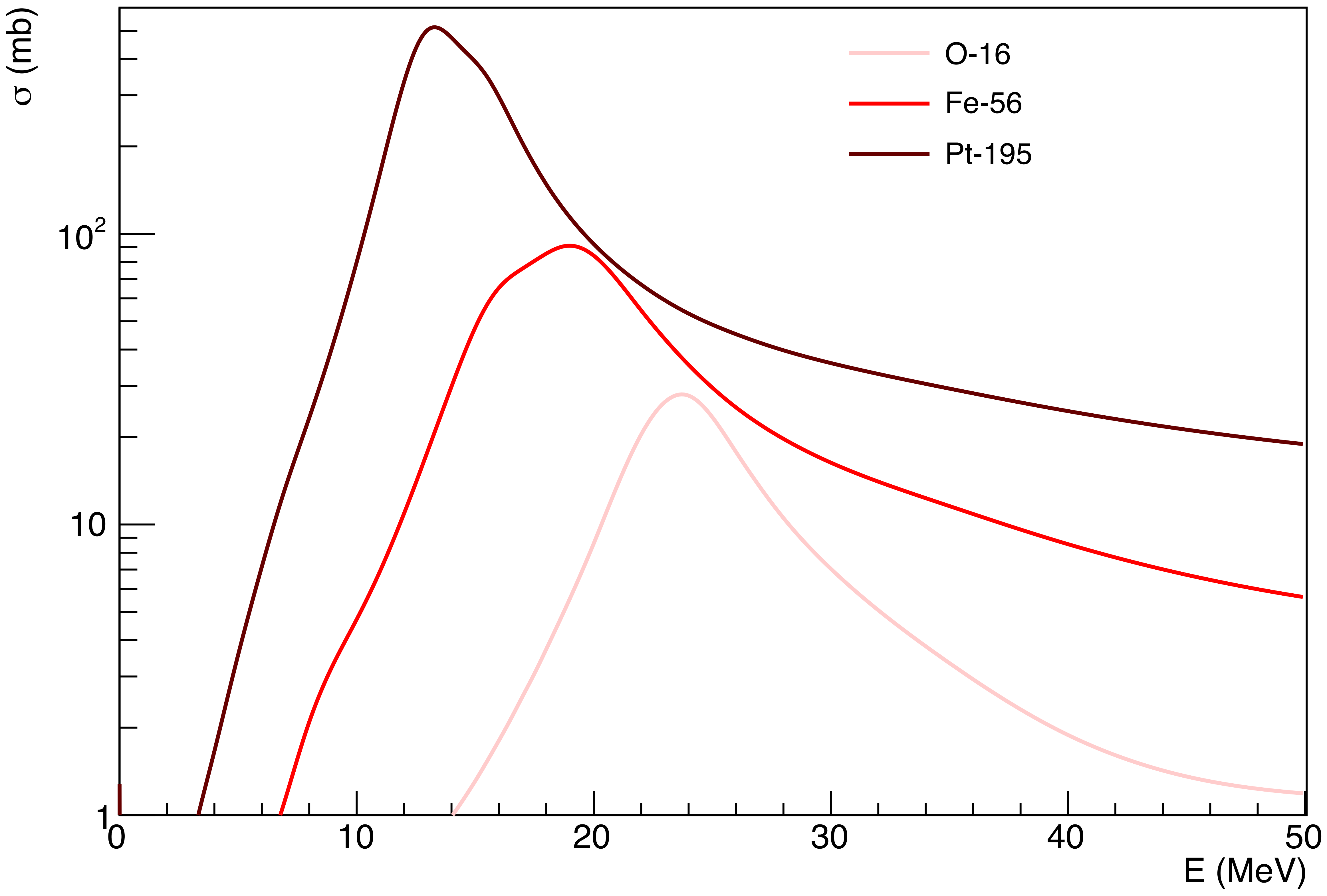
- Def: a ultra-heavy nucleus has A>56
- Heavy nuclei are synthesised due to the r-processes inside neutron-rich environments (compact binary mergers, including binary neutron star and neutron-star–black-hole mergers; collapsars)

  -> see Farrar arxiv:2405.12004 for motivations, and Decoene et al JCAP 2020; Rossoni, DB & Sigl arxiv:2407.19957 for computations of CR interactions in the photon fields of a BNS merger (a thermal photon field is produced due to the nuclear decay of the unstable species synthesised in the ejecta by the merger) -> energetics inspired from the electromagnetic counterpart of GW170817

- To be considered as UHECRs they have to:
  - Be accelerated (advantage: large Z)
  - Escape from the acceleration environment
  - Propagate through the extragalactic space

- Only nuclei up to A=56 are considered for the interpretation of UHECR data
  - Could heavier nuclei account for the observed trend of the mass composition at the highest energies? See Zhang et al arxiv:2405.17409

CROSS SECTIONS



Note that if one-nucleon emission is taken into account, the threshold does not depend on the nuclear mass:

$$E_{\rm th} \approx \frac{m_p A \Delta B}{2\varepsilon} \qquad \Gamma_{\rm th} = \frac{\Delta B}{2\varepsilon}$$

Total inelastic photo-absorption cross section

-> from **TENDL-2021** (nuclear data library which provides the output of the **TALYS** nuclear model)

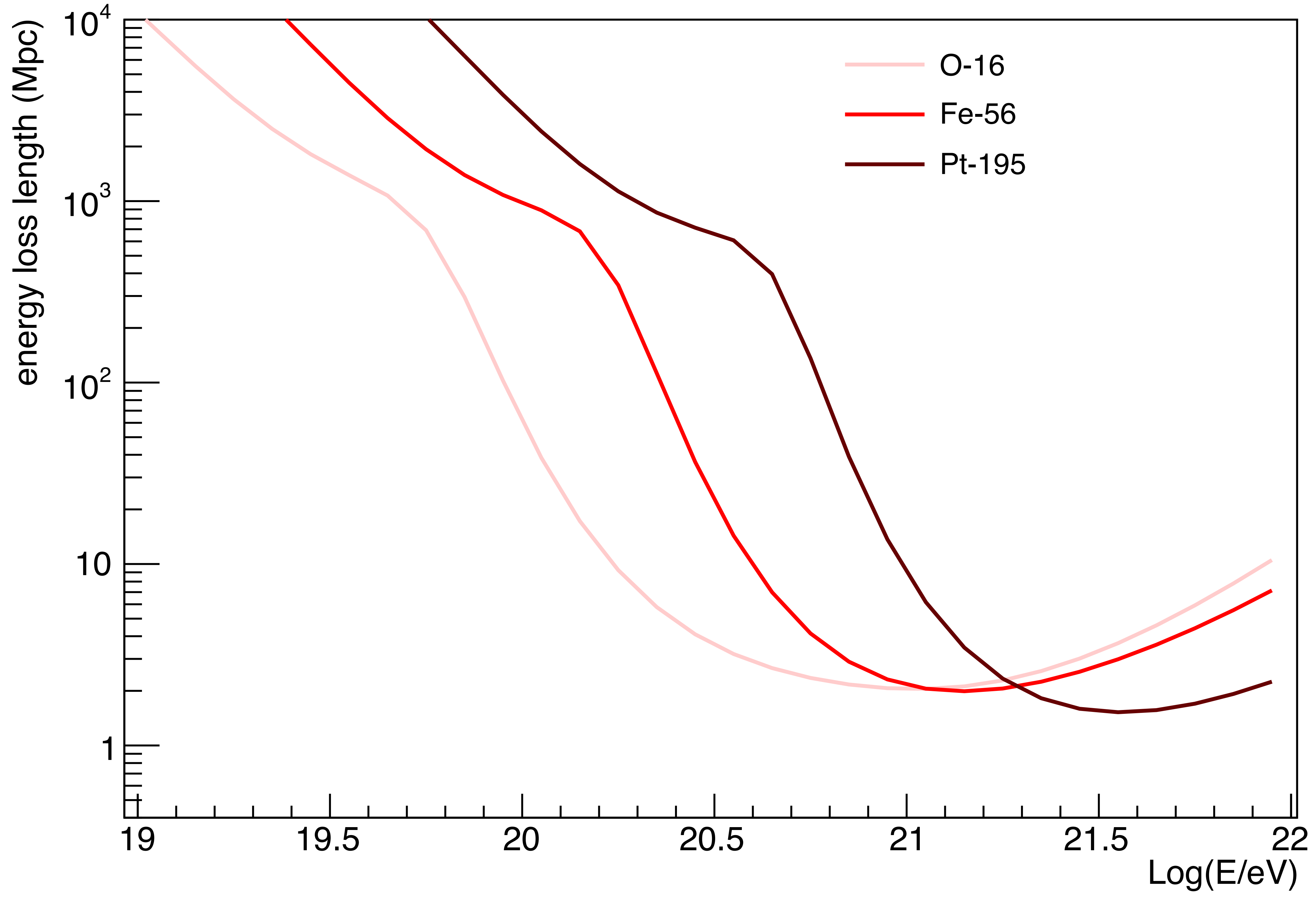
-> **TALYS** (nuclear reaction program for simulations of nuclear reactions up to energies of 200 MeV)

- The heavier is the nucleus
  - the peak of the cross section is shifting to lower energies
  - the cross section at the peak becomes larger

- **SimProp v2r4**, several cross section models implemented
  - Puget, Stecker & Bredekamp, ApJ 1976, PSB model (single, double and multiple nucleon ejection with tabulated branching ratios)
  - Fit of TALYS cross sections for single, double and multiple nucleon ejection with PSB branching ratios
  - Fit of TALYS cross sections for one-nucleon + alpha particle ejection
  - Interpolation of TENDL cross sections, from an extended list of nuclei (beyond A=56)

ENERGY LOSS LENGTH

$$\mathrm{ELL} \approx A\left(\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\mathrm{th}}}^{\infty}\varepsilon'\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'\right)^{-1}$$

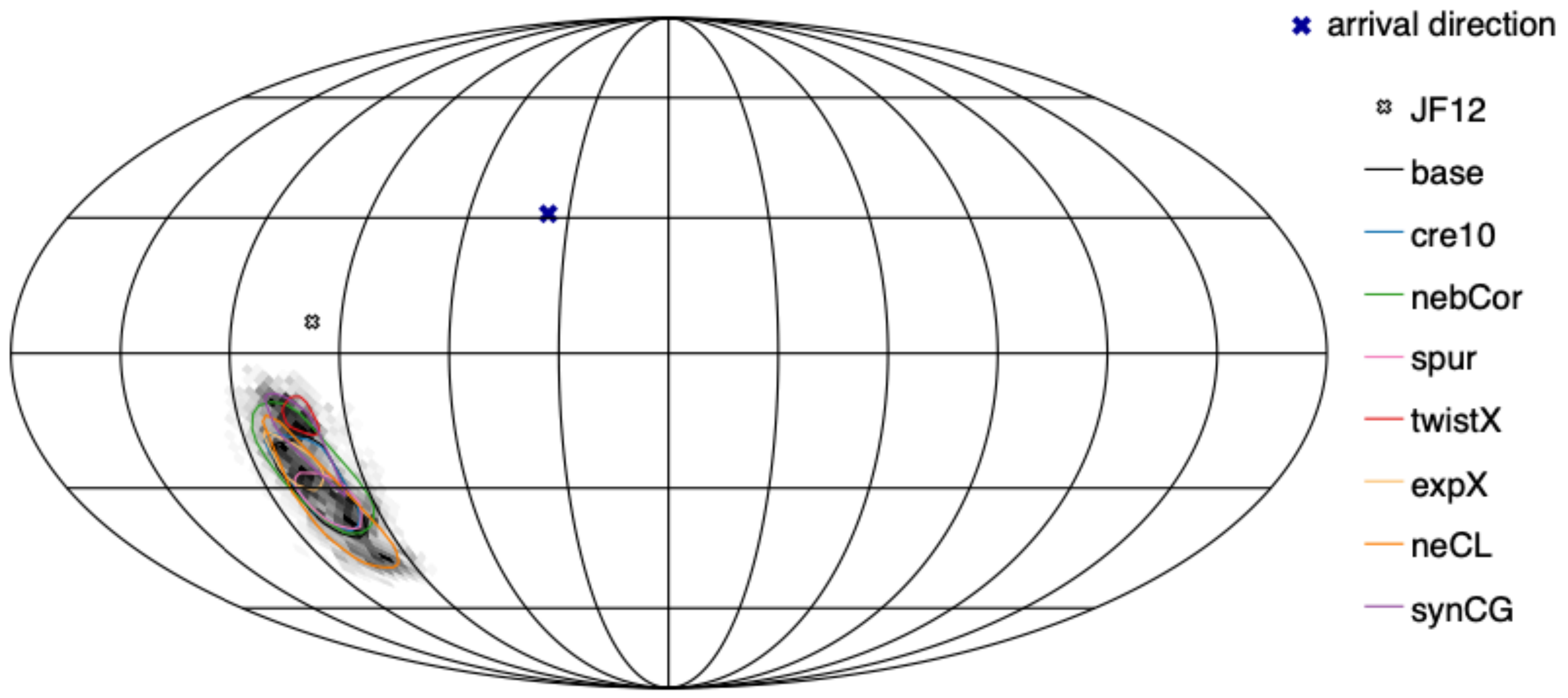


- At the minimum, the ELL are similar to each other
    - The increase in the maximum of the cross section is roughly compensated by the multiplicity
- If the ELL as a function of the Lorentz factor is taken into account,
    - The rapid decrease of the ELL has similar behaviour for each nucleus

- At a fixed energy, the ELL increases with A
    - A larger portion of the Universe is available if nuclei with large A are considered

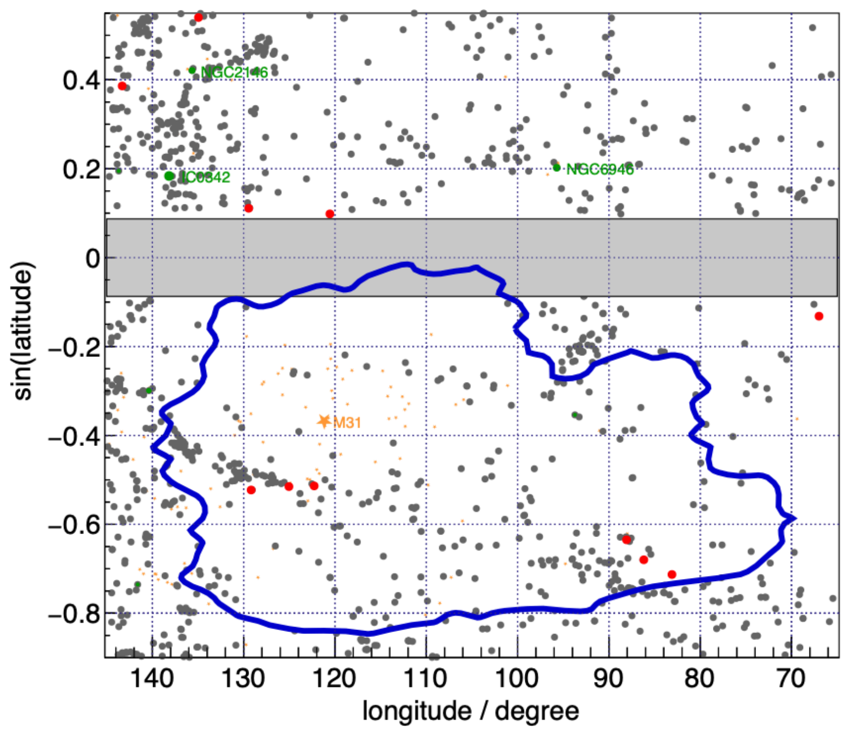
What can we learn from the highest energy CRs?

Unger & Farrar ApJL 2024

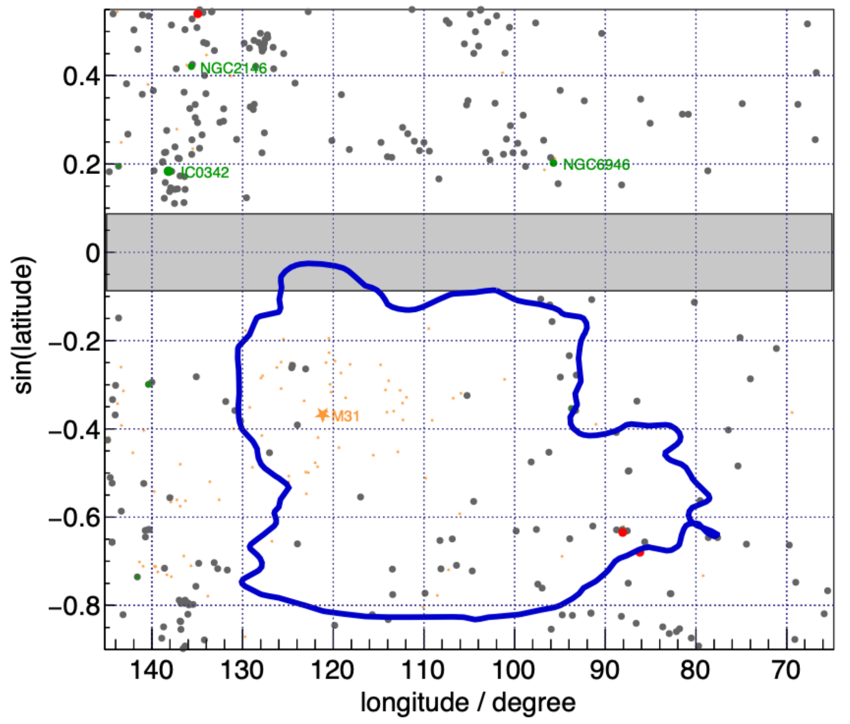


(b) $\lg(\mathcal{R}/\mathrm{V}) = 18.83$, $B\&b$, $n_b = 1$

- **How to gain insights about UHECR sources with extremely energetic events?**
  - By assuming a nuclear species for the event, it is possible to
    - Determine the area of the sky from which the CR is coming, taking into account the Galactic magnetic field models
    - Compute the maximum distance from which the CR is coming, taking into account the interactions in the extragalactic fields



(b) $E_{\mathrm{low}} - 2\,\sigma$, $D_{0.1} = 72$ Mpc



(c) $E_{\mathrm{low}} - 1\,\sigma$, $D_{0.1} = 42$ Mpc

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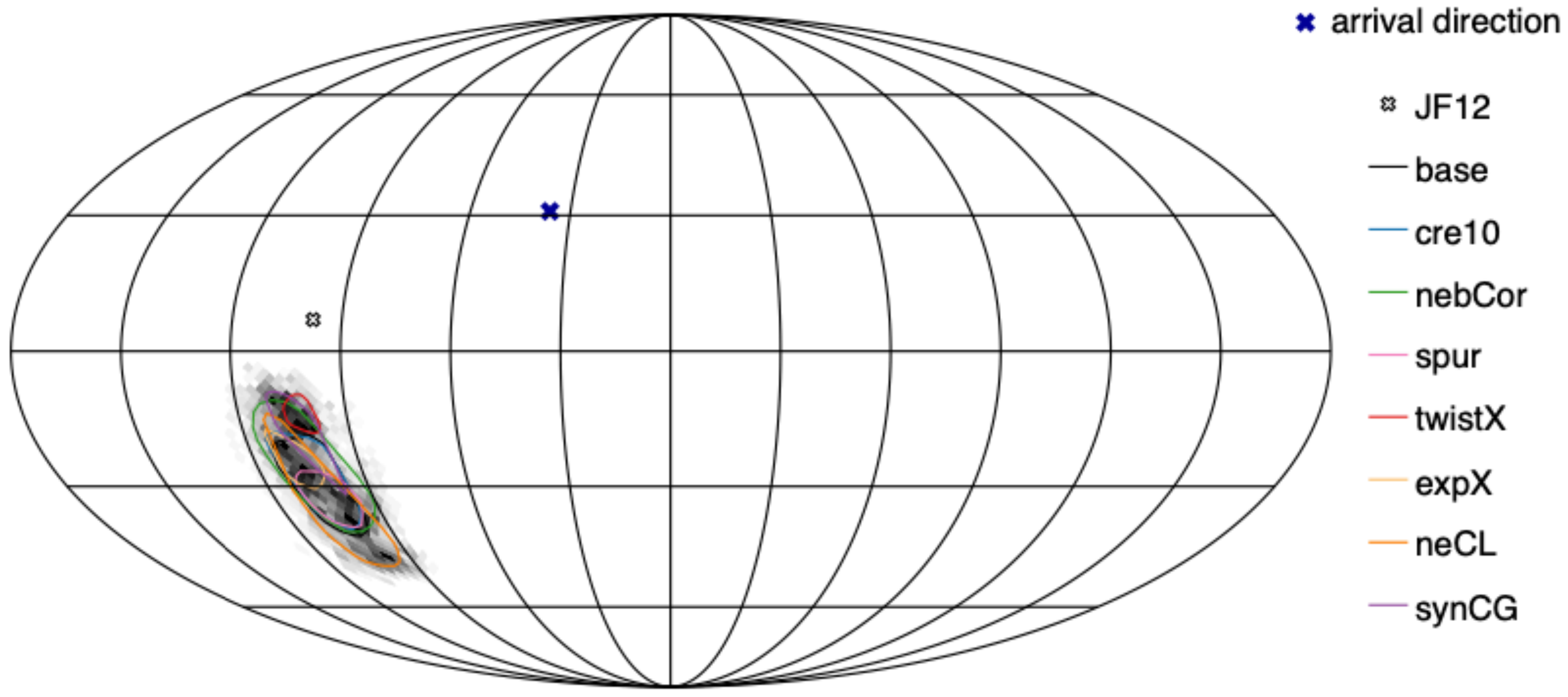

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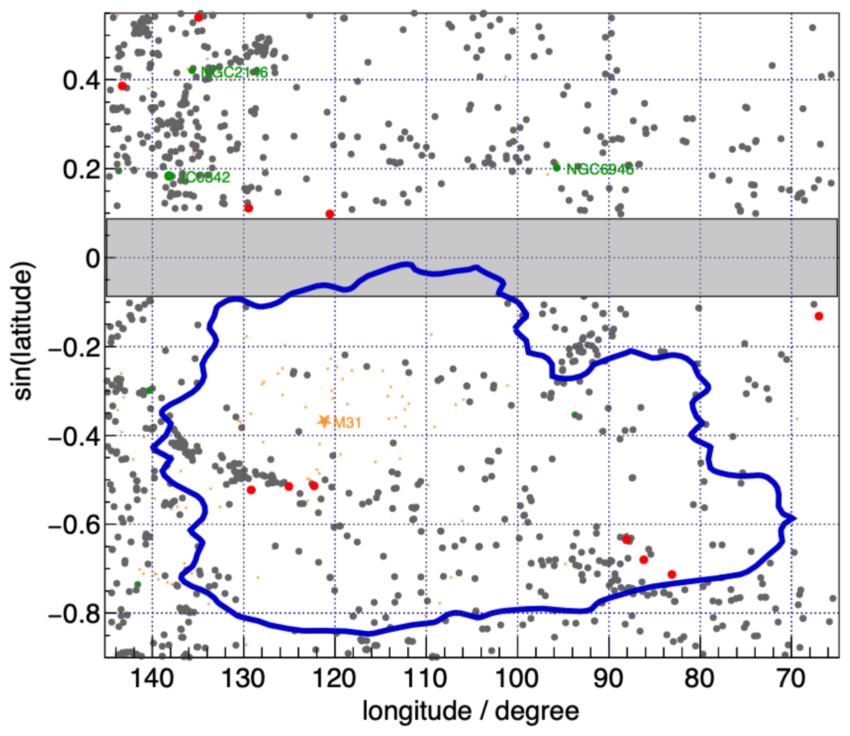

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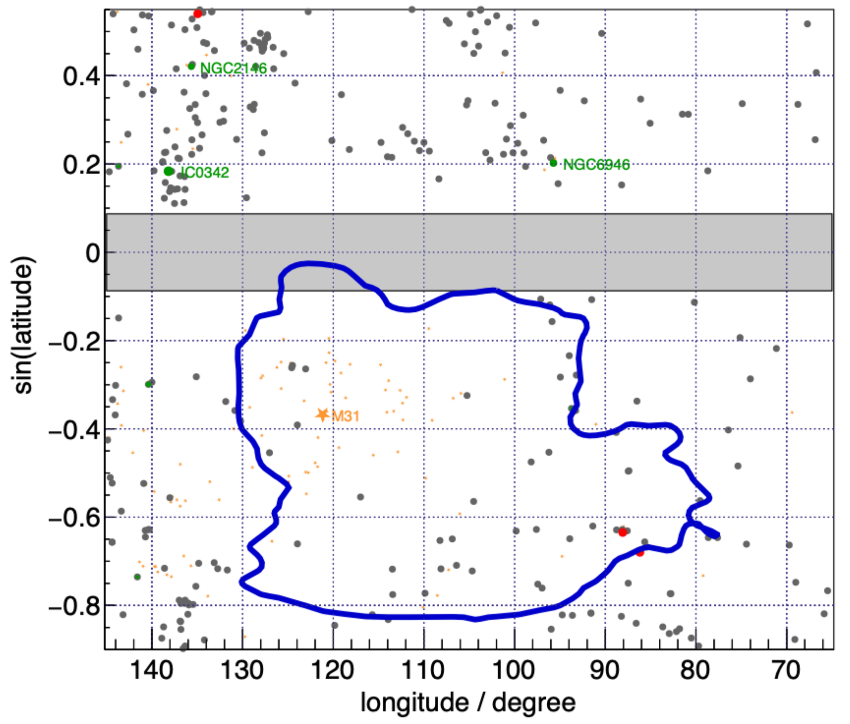

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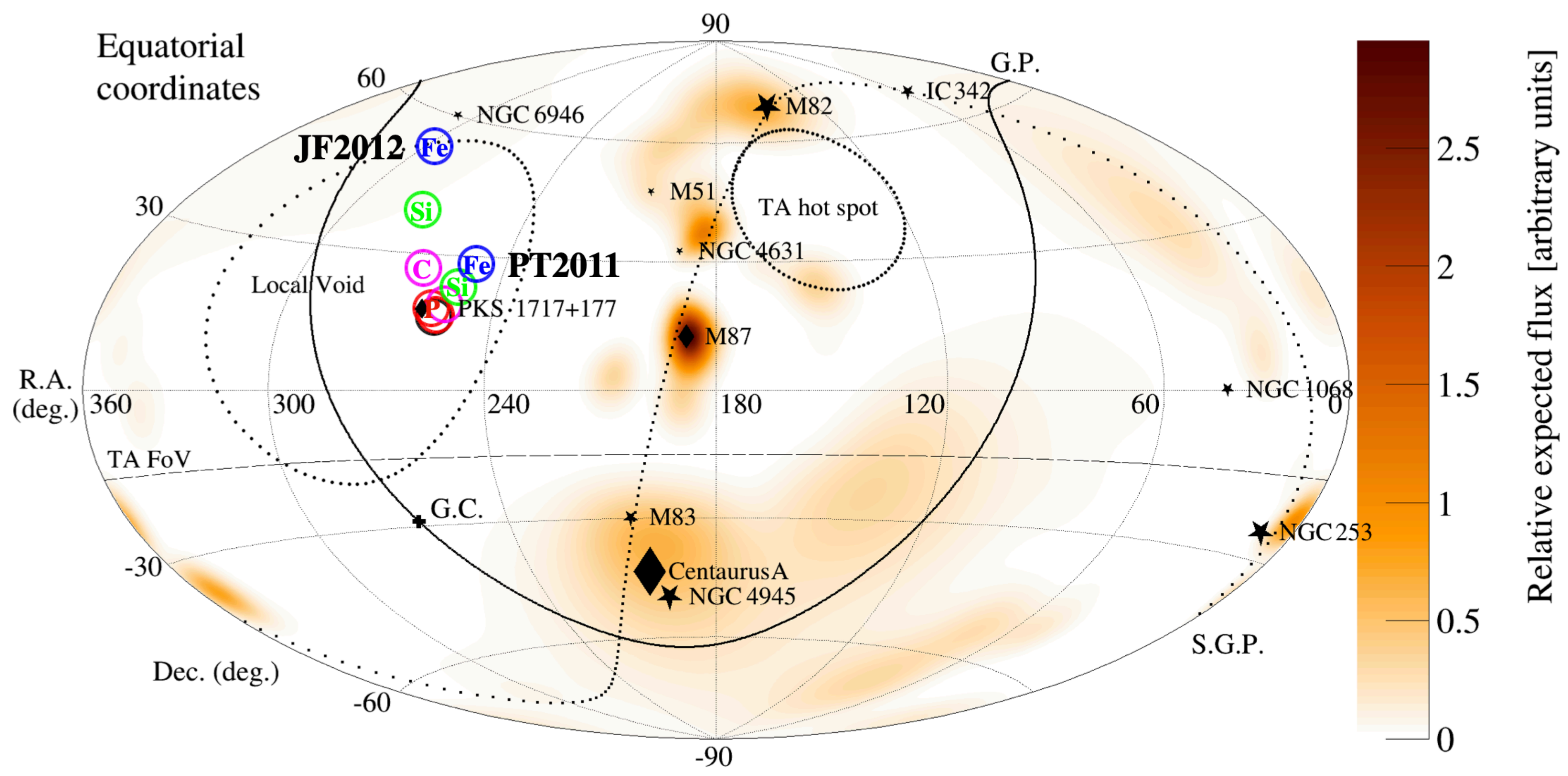
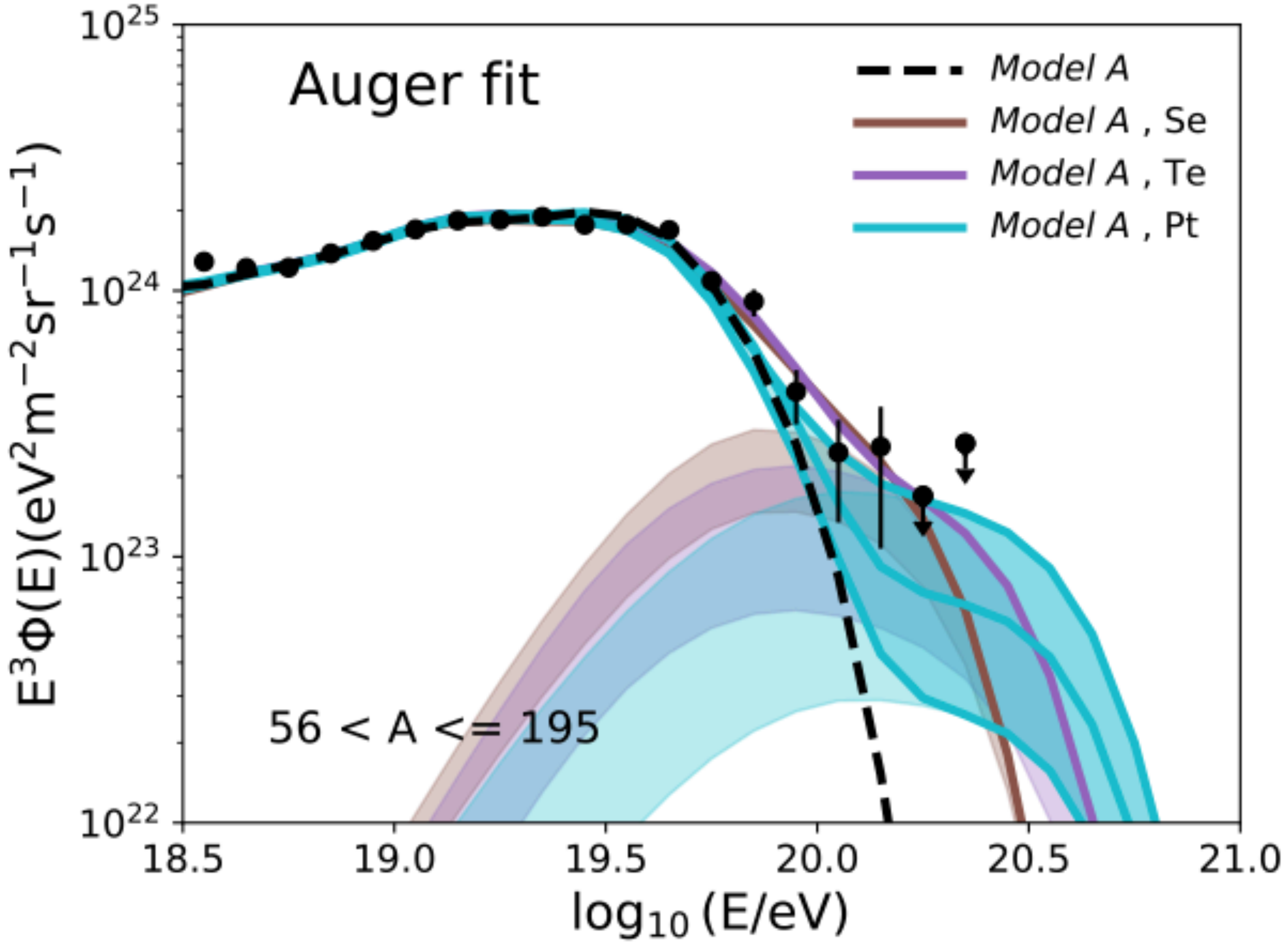


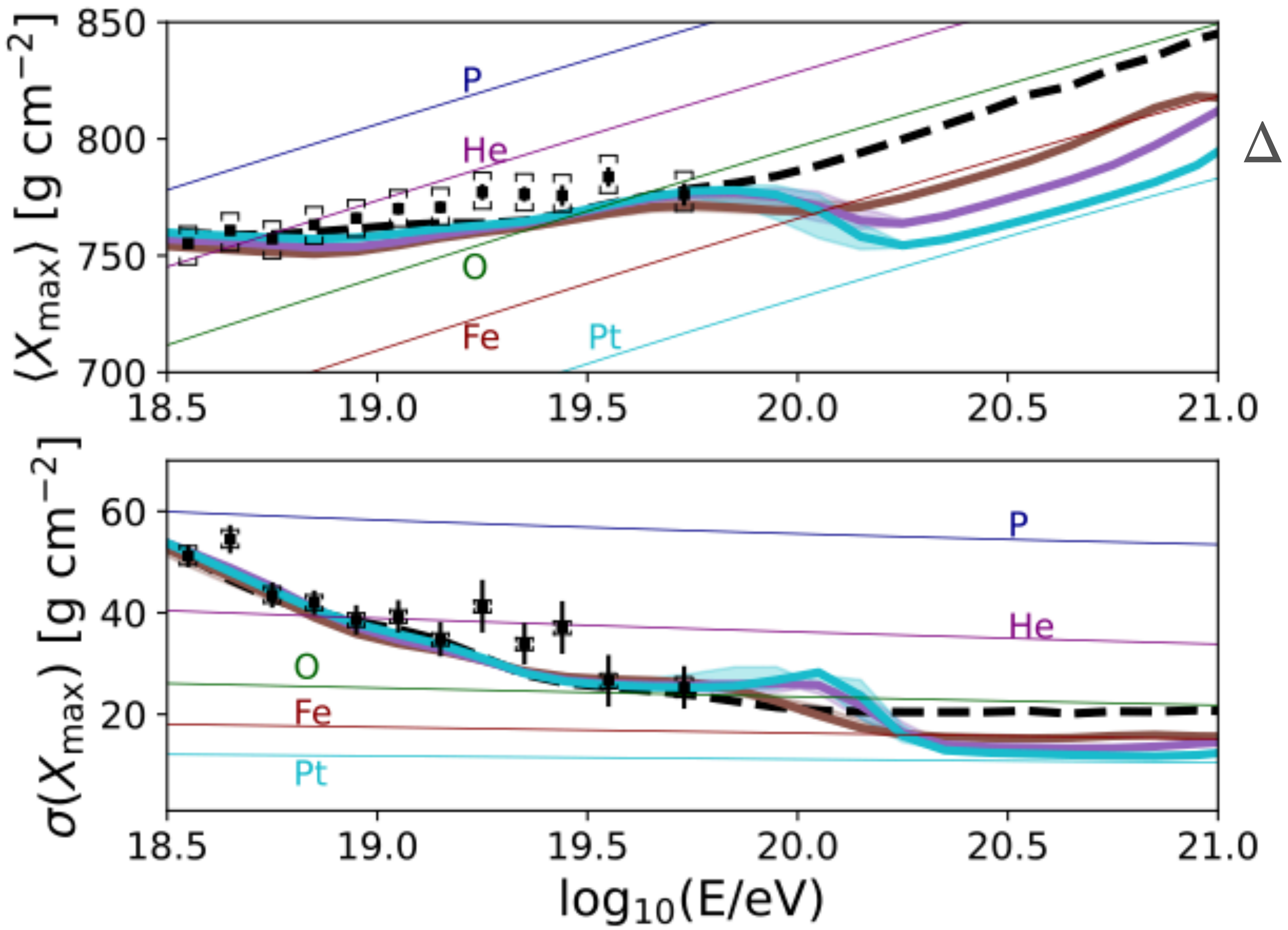
- Amaterasu event, 244 EeV -> coming from a local void?
- Lack of a nearby source for Amaterasu
  - larger magnetic deflections than predicted by the GMF models?
  - Primary particle heavier than the ones considered?

Telescope Array Collab, Science 2023

What can we learn from the highest energy CRs?

Zhang et al arxiv:2405.17409





$\Delta \ln A \approx 1.2$

- Combination of nuclear species up to A=56 + ultra-heavy nuclei
- Ultra-heavy nuclei
  - can reach larger energies with the same rigidity at the sources, compared to heavy nuclei
  - can be used to test the trend of the mass observables at the highest energies

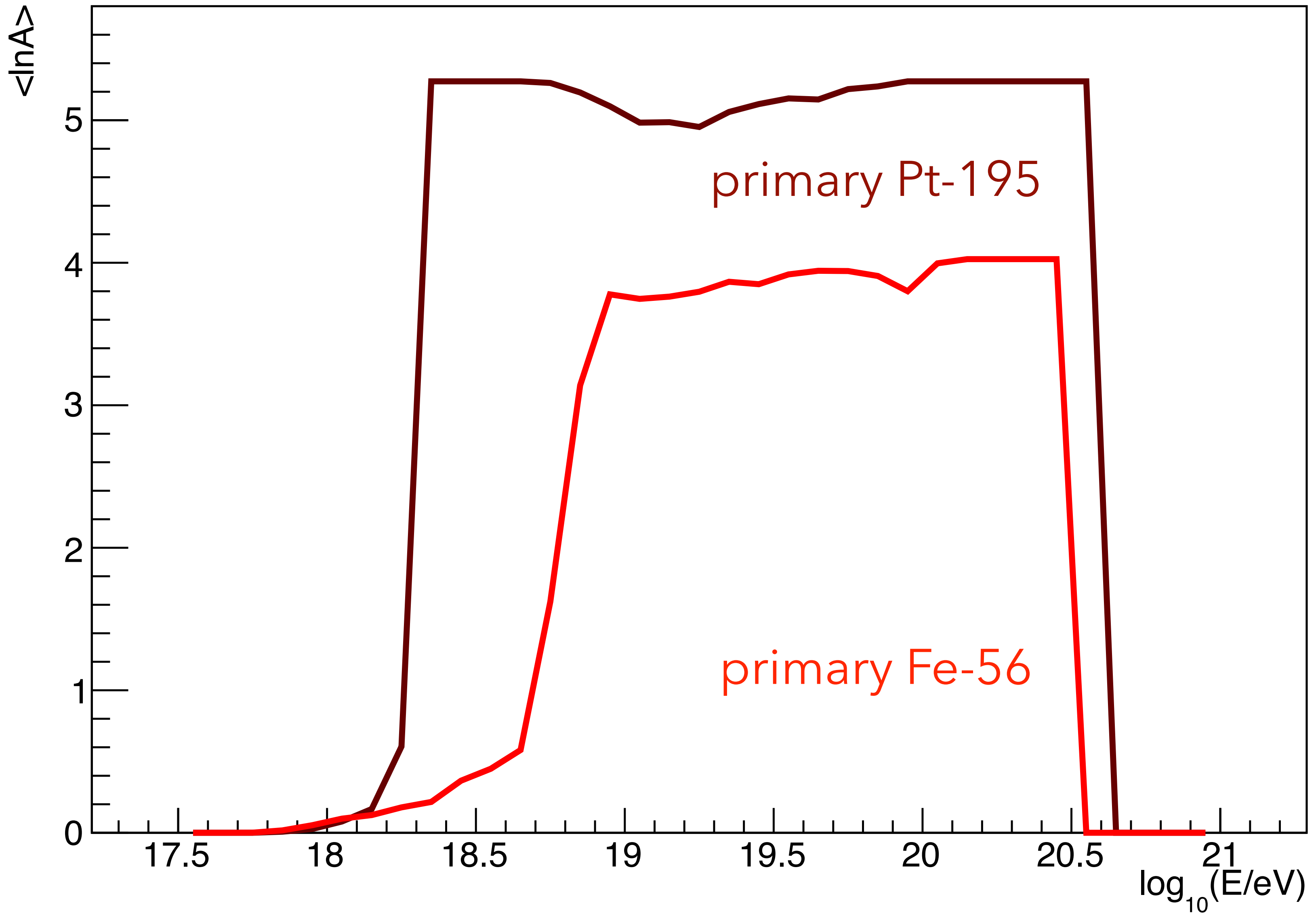
WORK IN PROGRESS IN SIMPROP

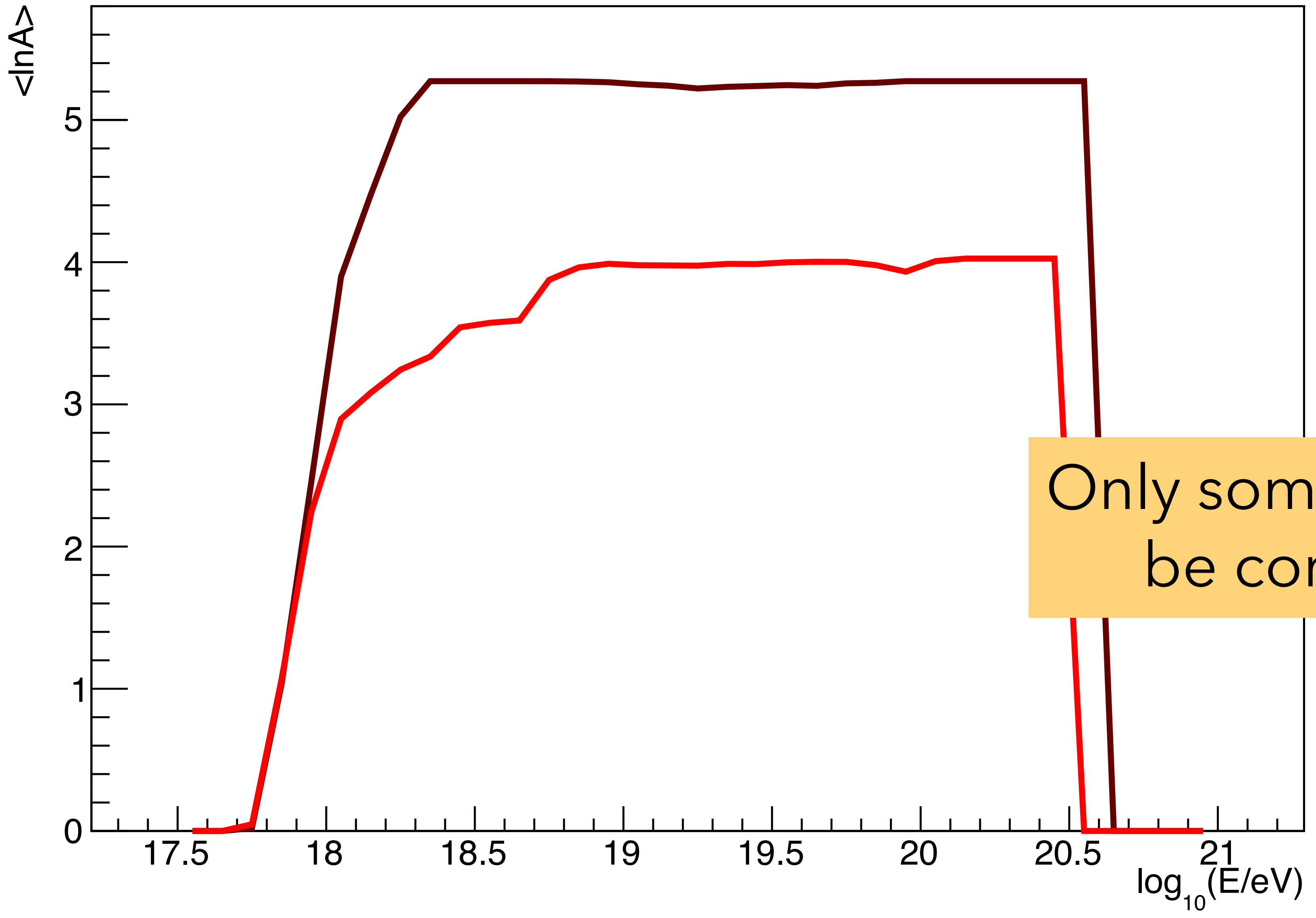
- Increased list of stable nuclei (from A=56 to A=195)
- TENDL2021 cross sections (TALYS) with one-nucleon emission

- Work in progress: only 6000 simulated events
  - Effects in <lnA> as a function of the energy, for different spectral index at the source (only one primary, not mixed composition at source)

$$< \ln A > = \sum^{A_{max}} \ln A_i \frac{J_{A_i}}{J}$$

Hard spectrum





Soft spectrum

Only some examples, not to be compared to data

- In addition, successfully produced interactions of Pt-195 on N for 1 EeV/nucleon with **EPOS-LHC**

SUMMARY

See discussion "Roadmap about cross section and models" tomorrow

- Several aspects of nuclear physics are relevant in the context of UHECRs
  - Uncertainties affect the interpretation of UHECR data

- Nuclear species up to A=56 are usually taken into account in UHECRs
- Among UHECR candidate sources, there can be conditions to have nuclei heavier than A=56
- At the highest energies, UHECR mass composition observables indicate that the mass composition is heavy… **how heavy?**
- The universe accessible with UHECRs depends on the nuclear species
- Among the open issues in UHECR physics: **how are they accelerated?** Example of acceleration of iron nuclei in young fast-rotating pulsars, see Blasi et al ApJL 2000; Kotera et al JCAP 2015. Can this be extended to heavier nuclei?

- SimProp, work in progress:
  - Increased list of stable nuclei (from A=56 to A=195)
  - TENDL2021 cross sections (TALYS) with one-nucleon emission
- Cross section models for heavy nuclei less affected by uncertainties with respect to lighter ones (?) -> example: the E1 function (electric dipole excitation mainly responsible for the giant dipole resonance) has been studied for the mass region above A=90, where nuclei exhibit lesser dependence on the shell structure
- Input from air-shower simulations needed to design a science case