Indication of a Local Source of Ultra-High-Energy Cosmic Rays in the Northern Hemisphere

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

Pavlo Plotko

UHECR 2022, L'Aquila, 06.10.2022

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HELMHOLTZ

DESY.


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WHICH ONE
IS BETTER ?
VS


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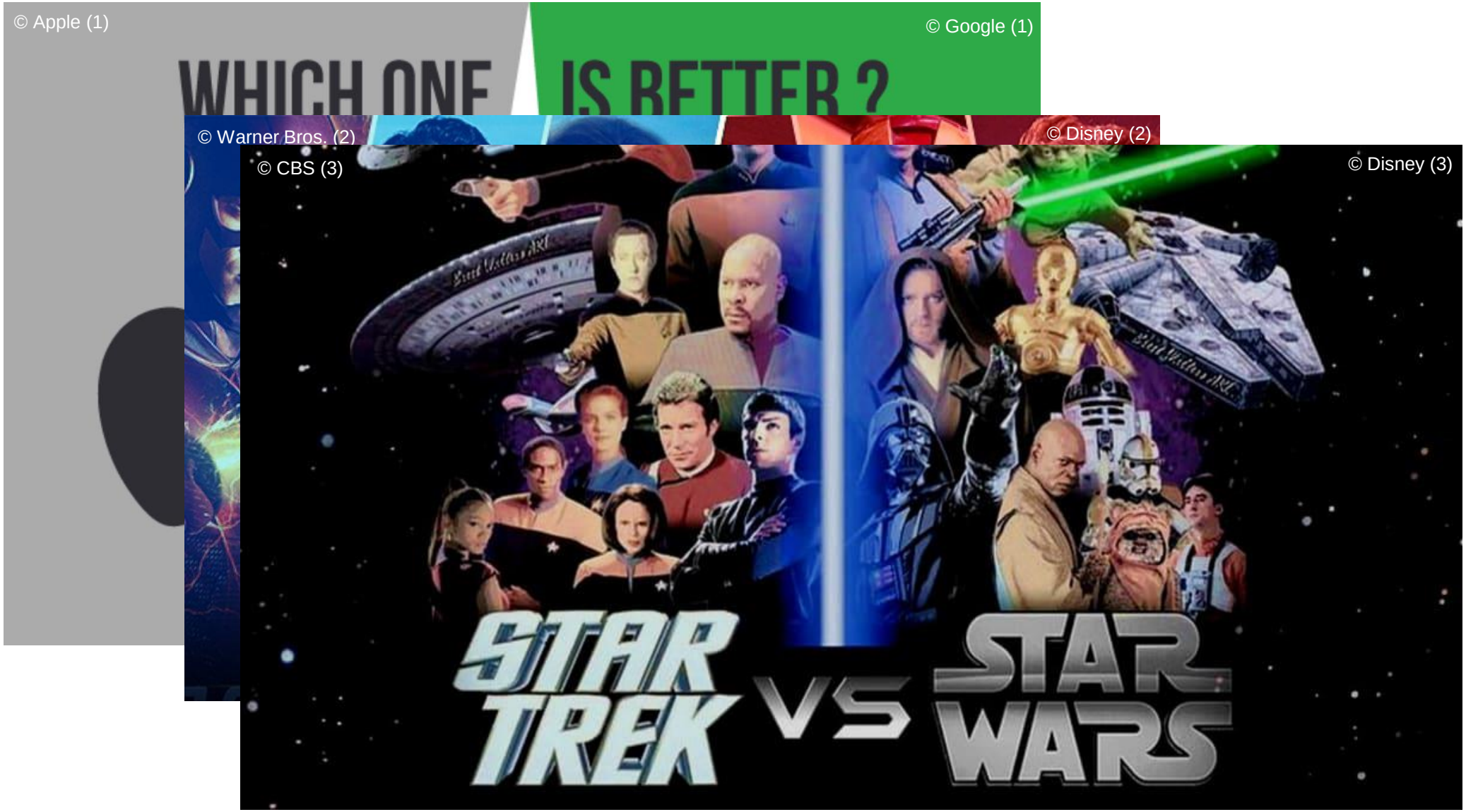
WHICH ONE
IS BETTER ?
© Warner Bros. (2)
© Disney (2)
© Sony (2)
DC
VS
MARVEL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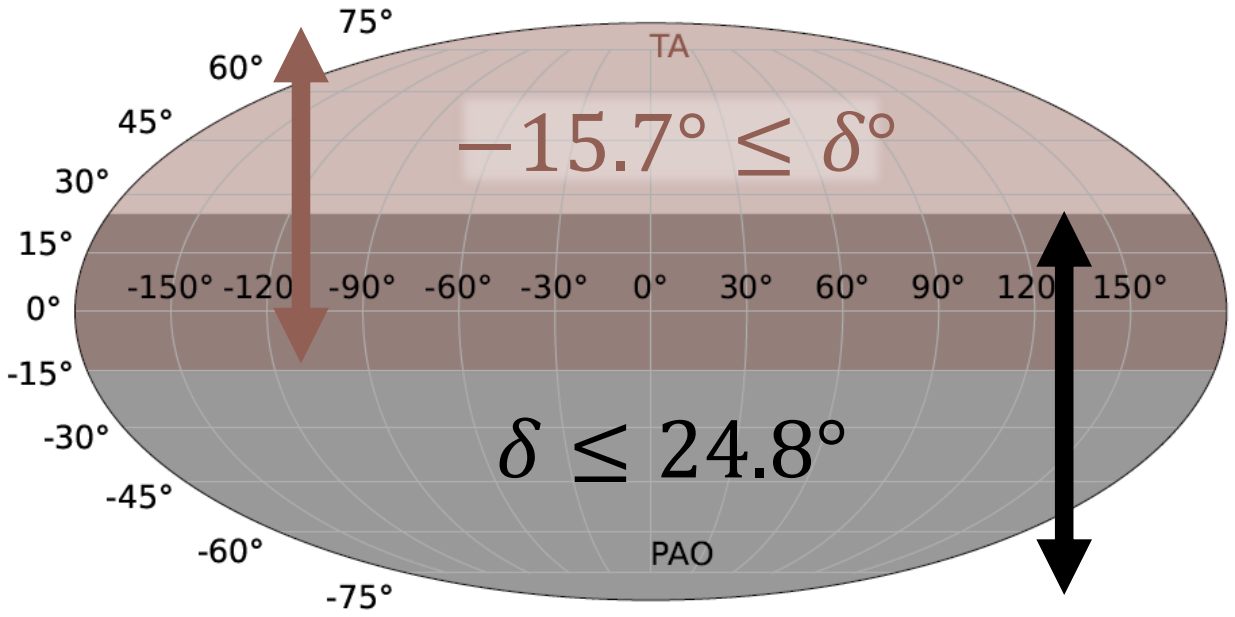
STAR TREK
VS
STAR WARS

Prof. Alan Watson UHECR2022


Pierre Auger Observatory
VS
Telescope Array

UHECR detectors: TA vs PAO

Telescope Array (TA), USA

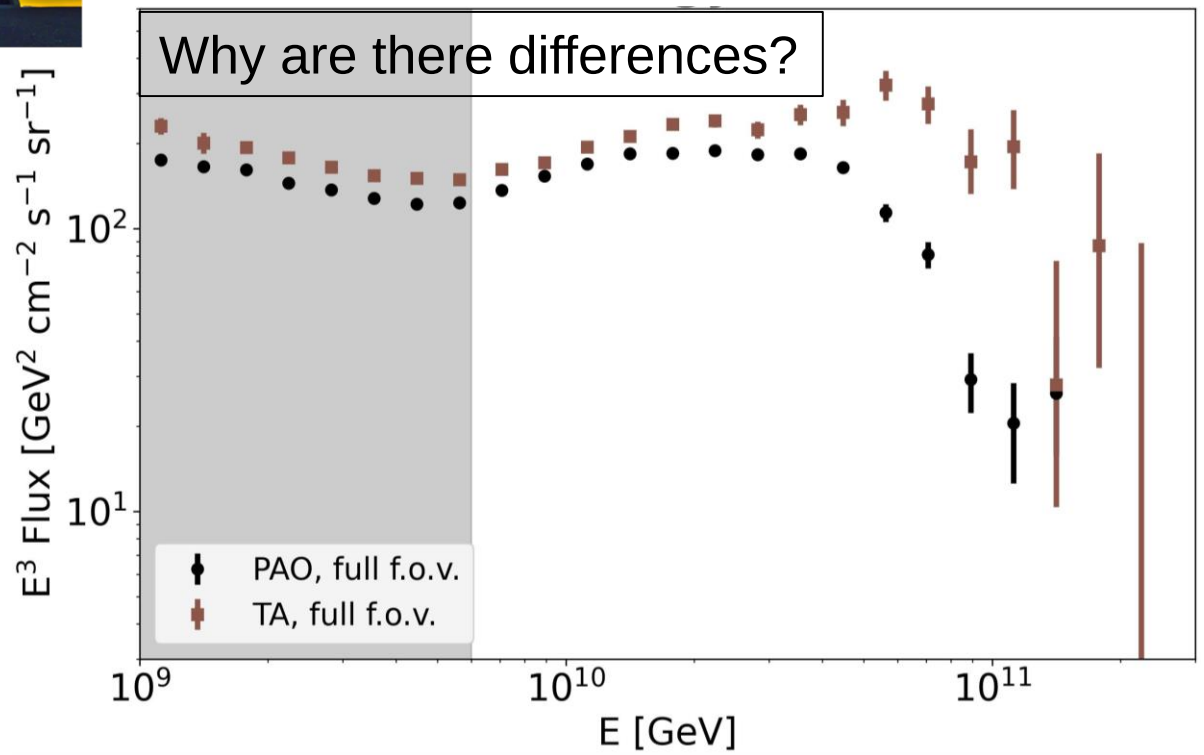


Pierre Auger Observatory (PAO), Argentina

Energy systematic uncertainties:

14% **21%**

Why are there differences?



Check presentations:
Dr Valerio Verzi, Dr Jihyun Kim, Douglas Bergman
Quentin Luce, Prof. Shoichi Ogio, Federico Urban

UHECR spectrum

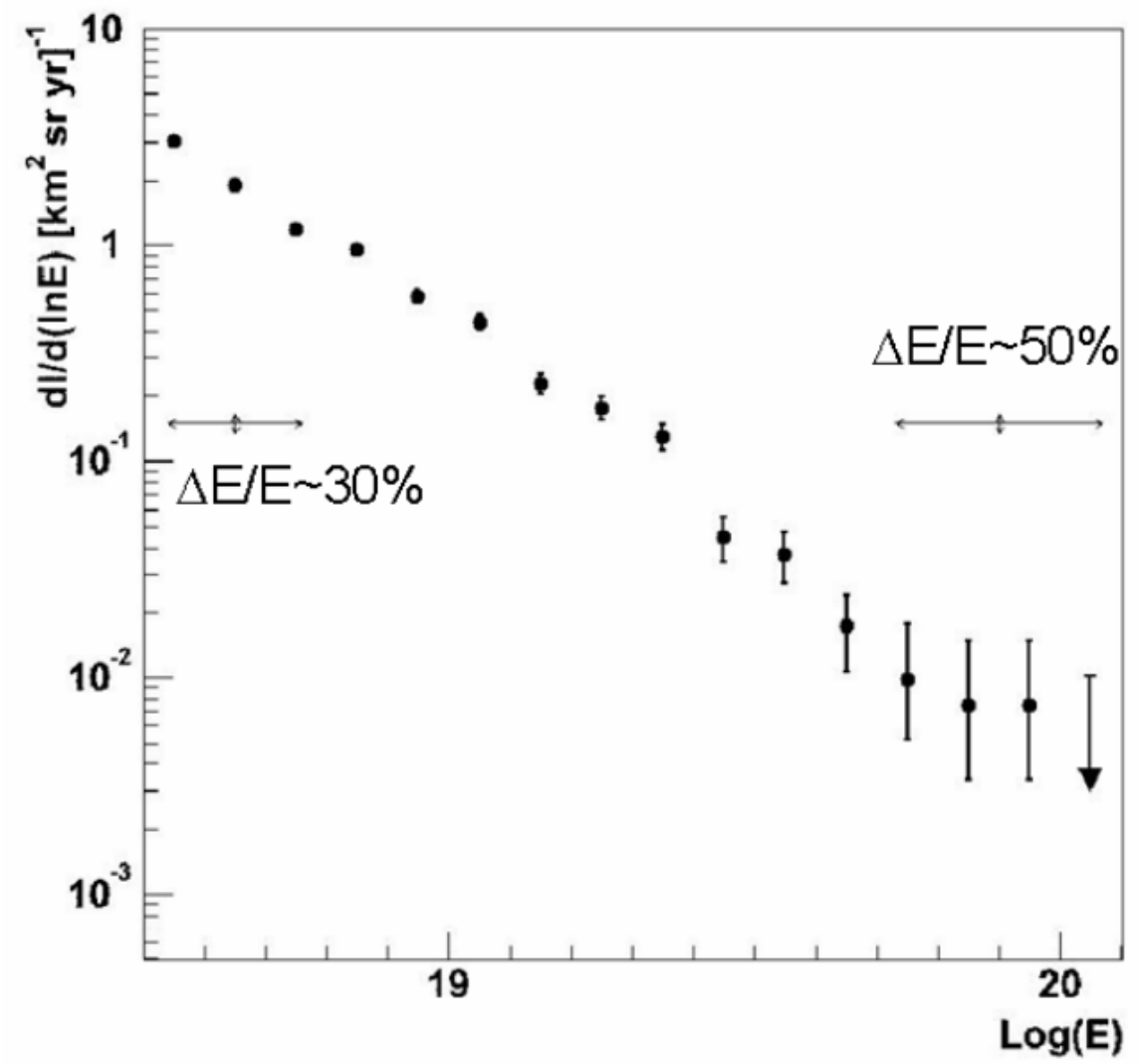
Motivation

UHECR time line

PAO

first results

2004



Mantsch et al. (2006)

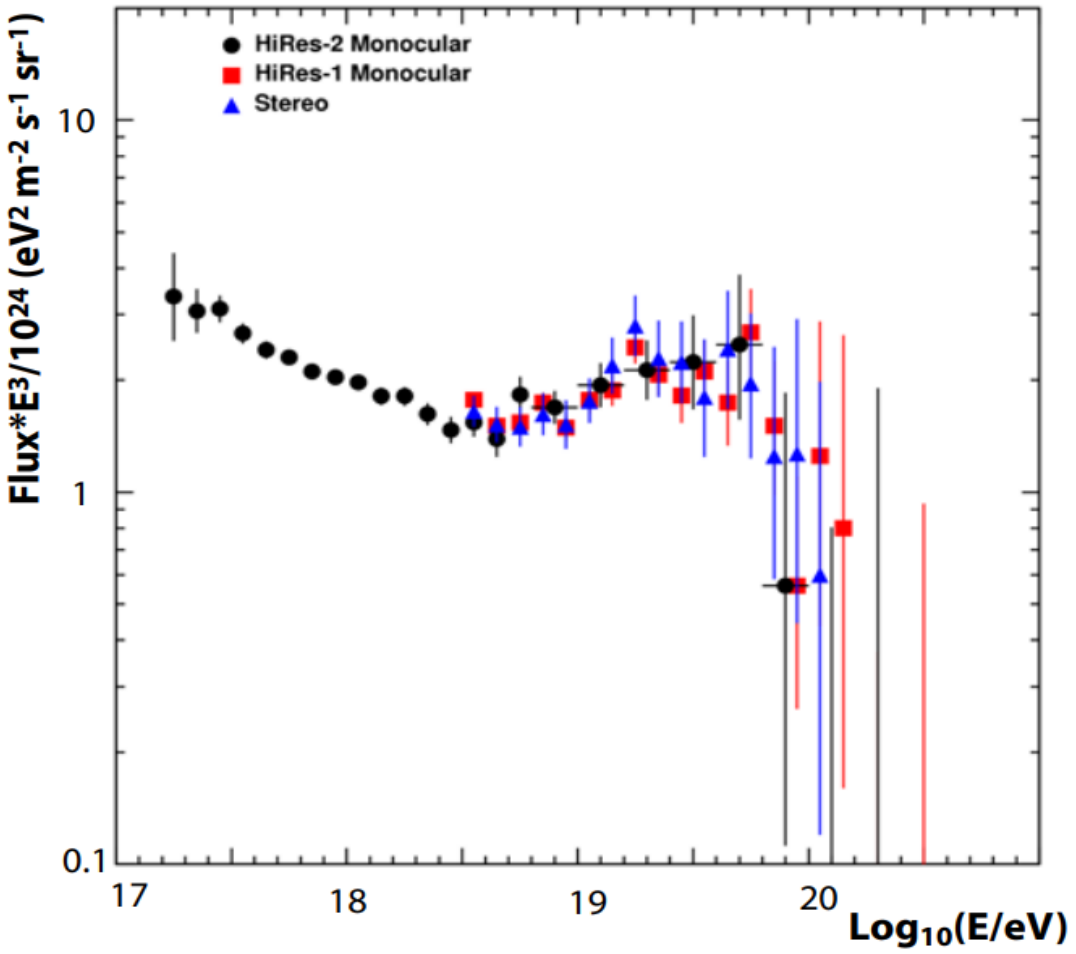
UHECR time line

PAO

first results
2004

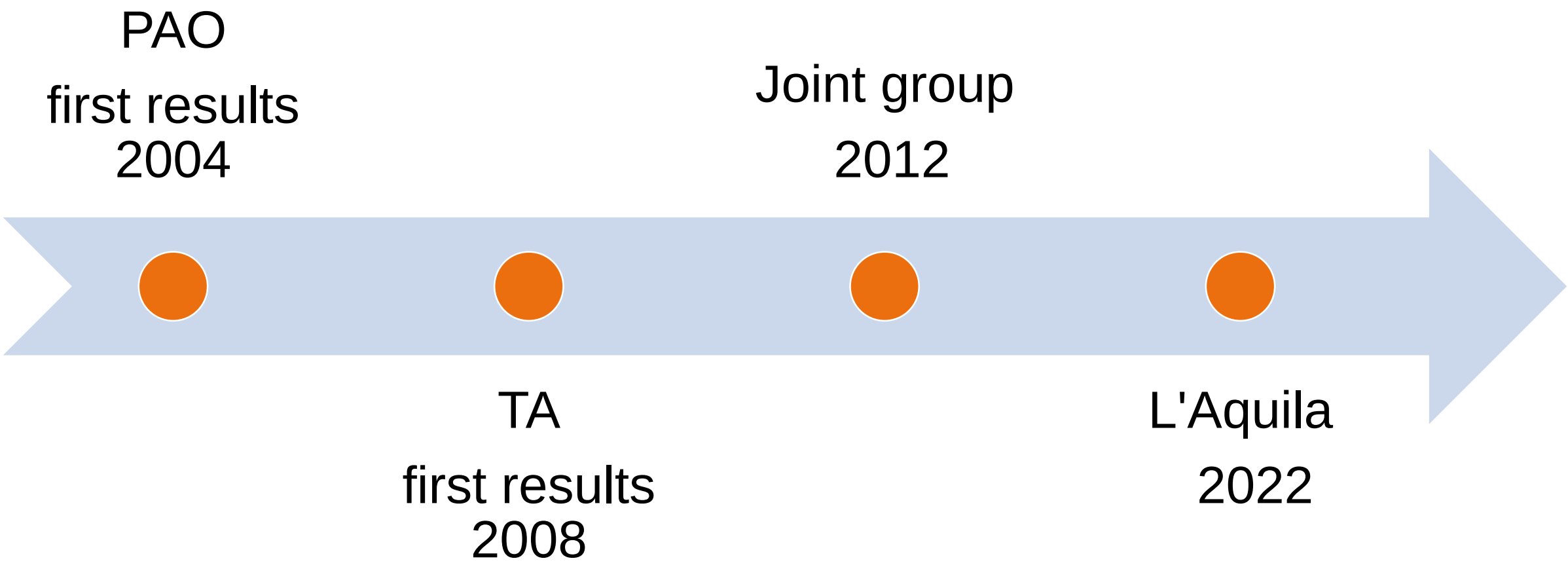
TA

first results
2008

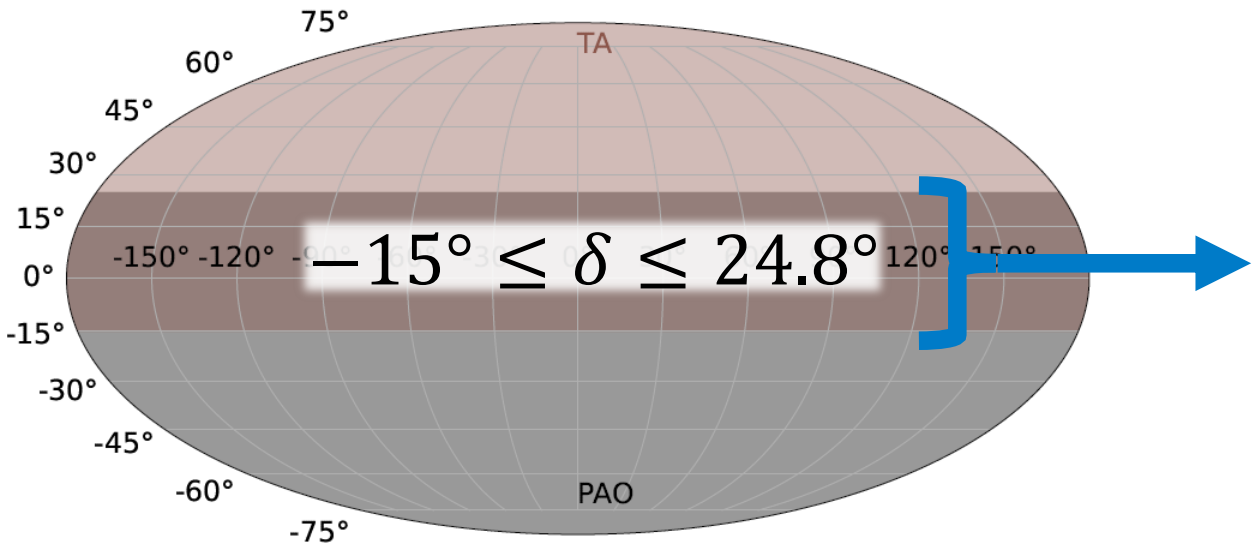


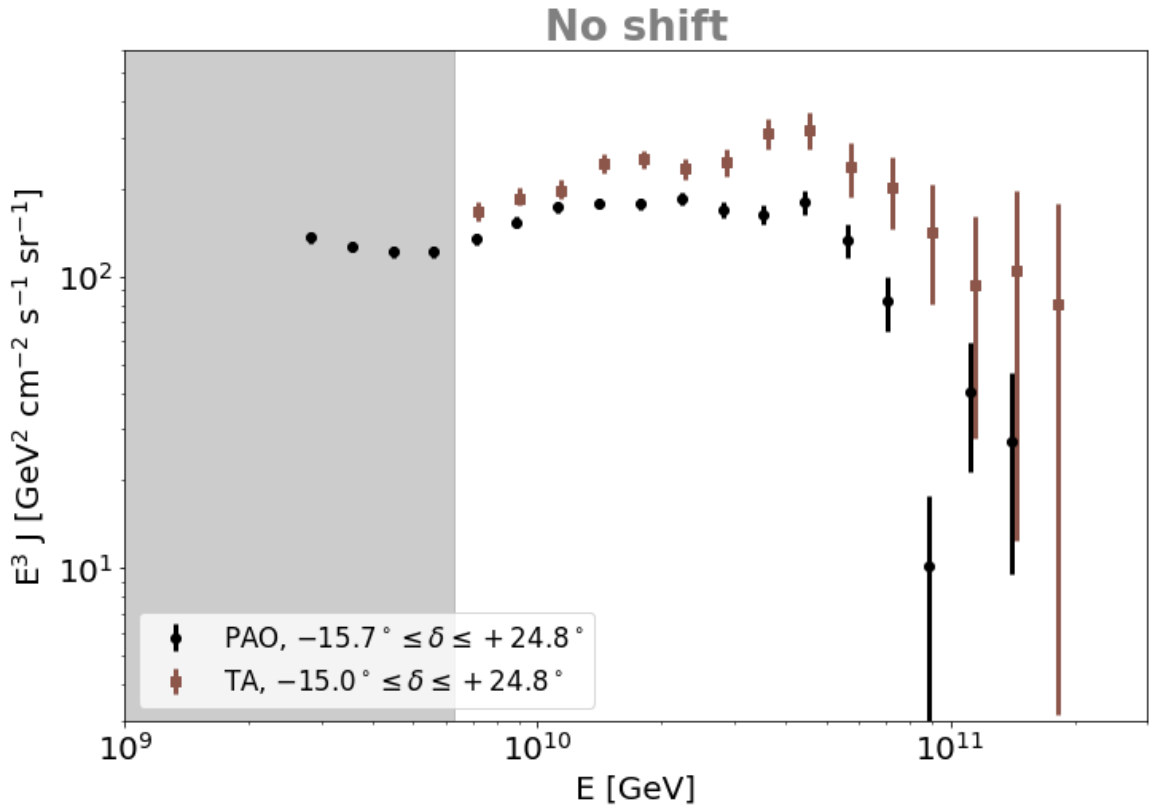
Sokolsky et al. (2008)

UHECR time line



Joint group for UHECR spectrum





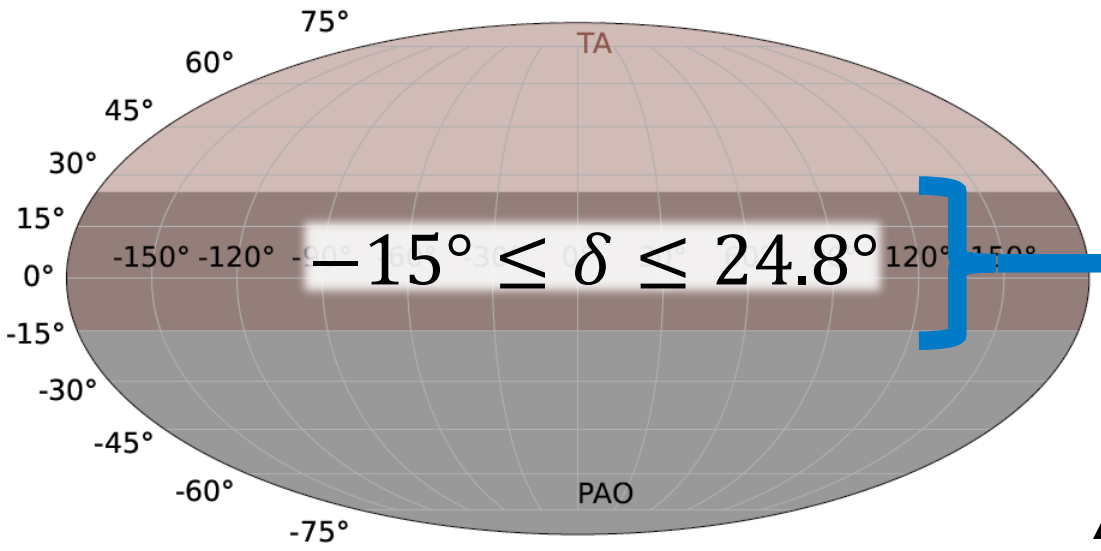
PAO and TA see the same part of the sky

PAO and TA should observe the same spectrum?

Joint spectrum group
(ICRC 2017, 2019 and 2021)

Joint group for UHECR spectrum

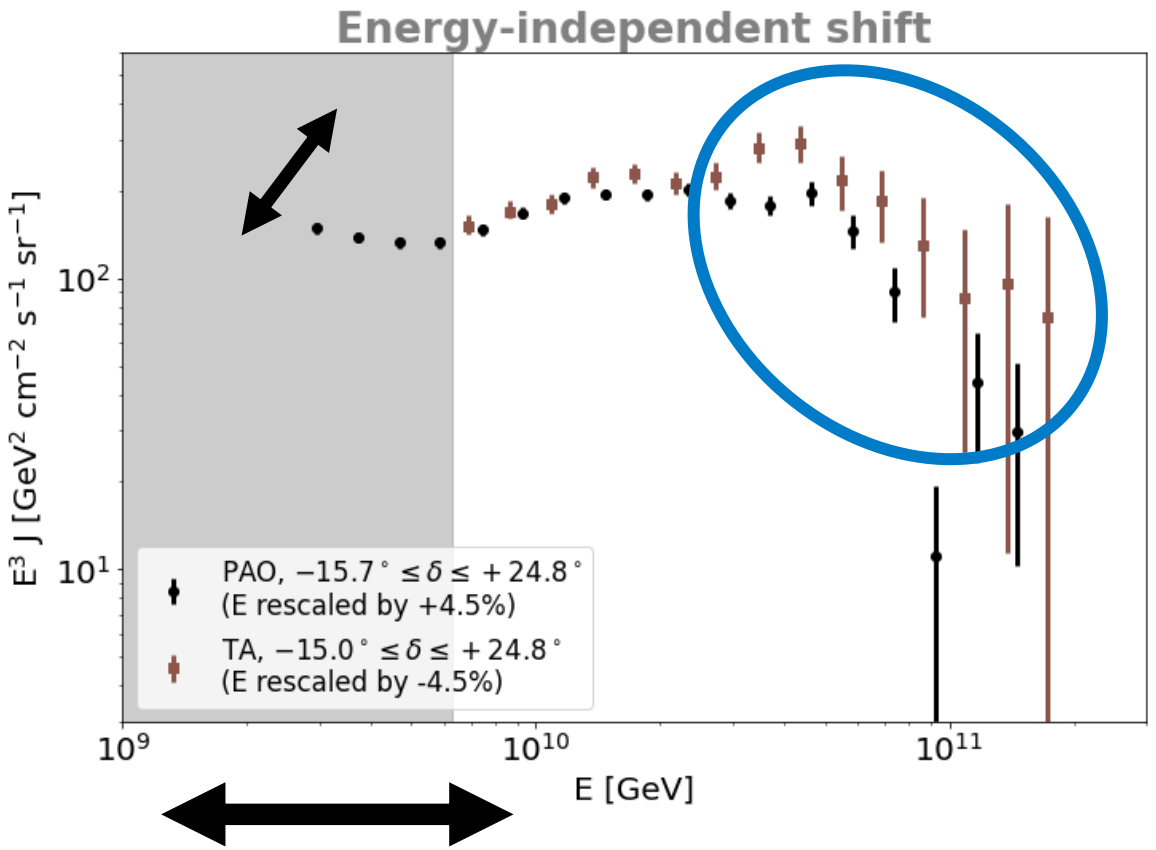
Simple shift



Energy-independent shift:

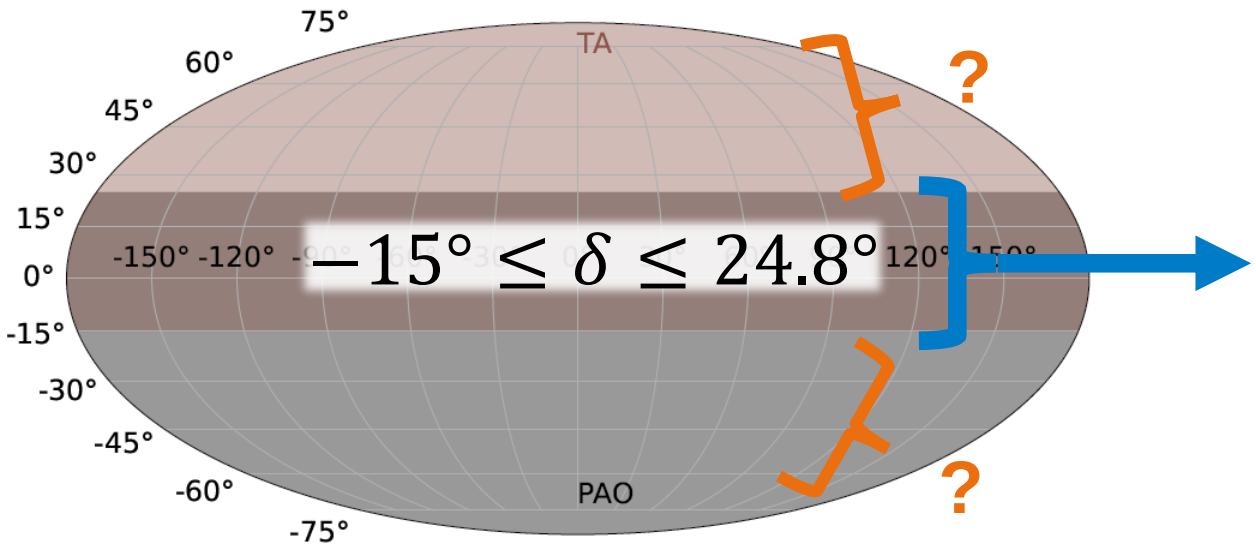
$$E_{\text{new}} = (1 \pm 4.5\%) E_{\text{old}}$$

$$E^3_{\text{new}} \cdot J_{\text{new}} = (1 \pm 4.5\%)^2 E^3_{\text{old}} \cdot J_{\text{old}}$$



Joint group for UHECR spectrum

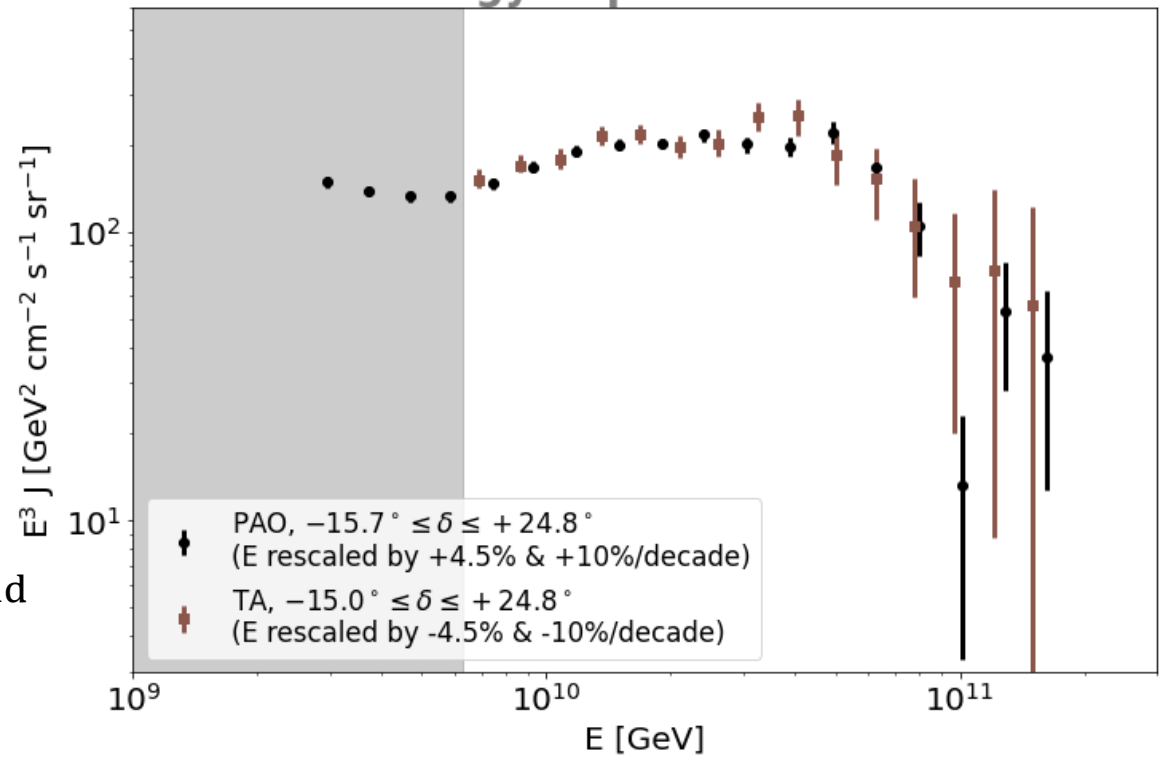
Complex shift



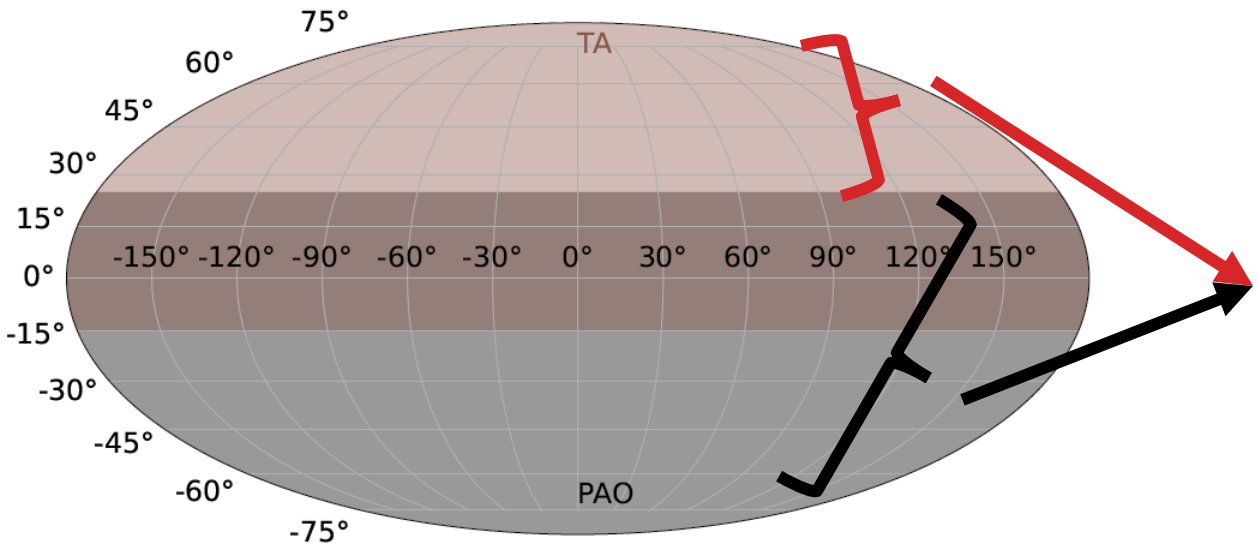
$$E_{\text{new}} = \left(1 \pm 4.5\% \pm 10\% \cdot \log_{10}\left(\frac{E_{\text{old}}}{10^{10}\ \text{GeV}}\right)\right) E_{\text{old}}$$

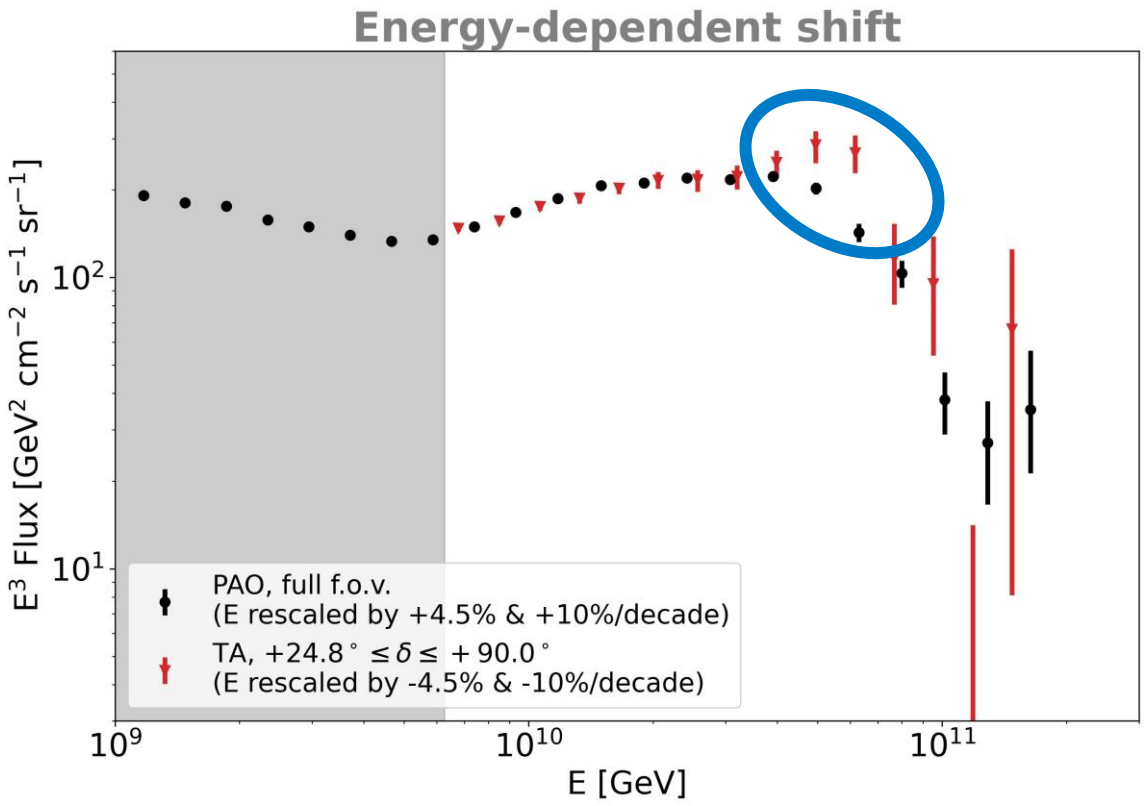
$$E^3_{\text{new}} \cdot J_{\text{new}} = \left(1 \pm 4.5\% \pm 10\% \cdot \log_{10}\left(\frac{E_{\text{old}}}{10^{10}\ \text{GeV}}\right)\right)^2 E^3_{\text{old}} \cdot J_{\text{old}}$$

Energy-dependent shift



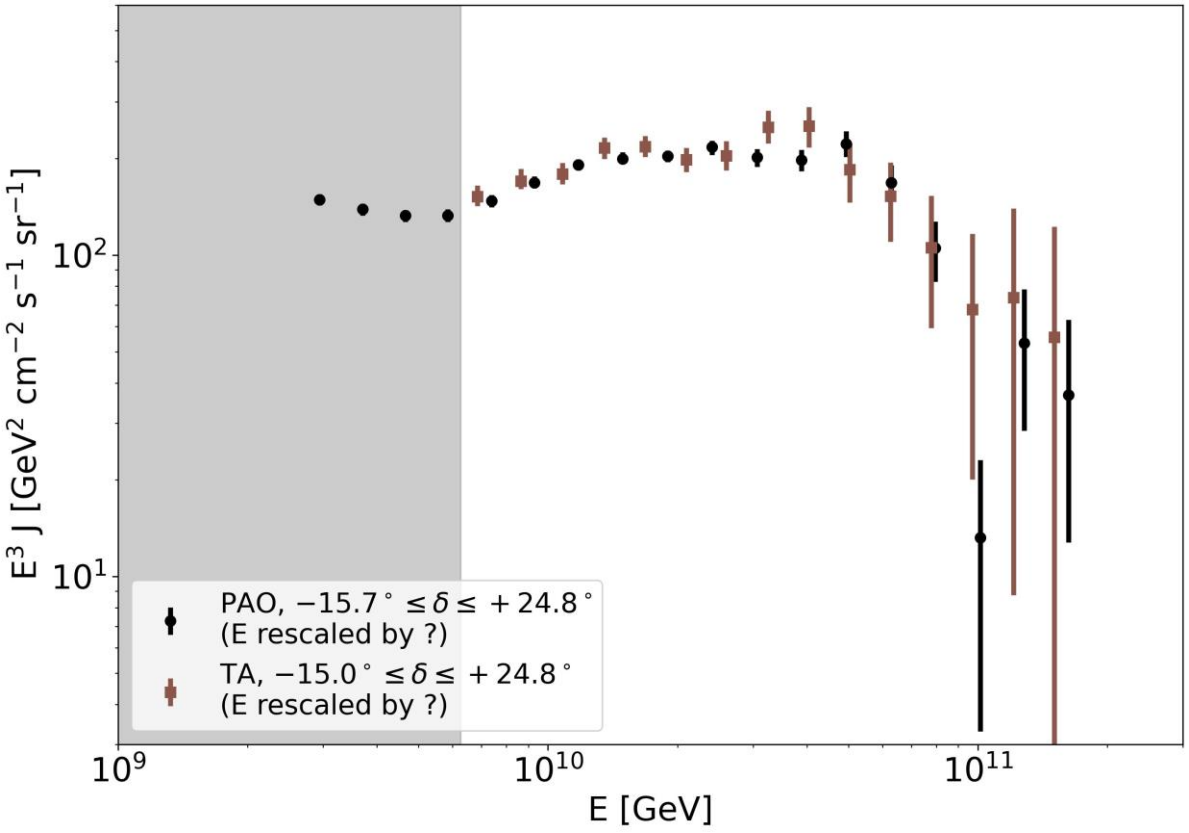
Joint group for UHECR spectrum

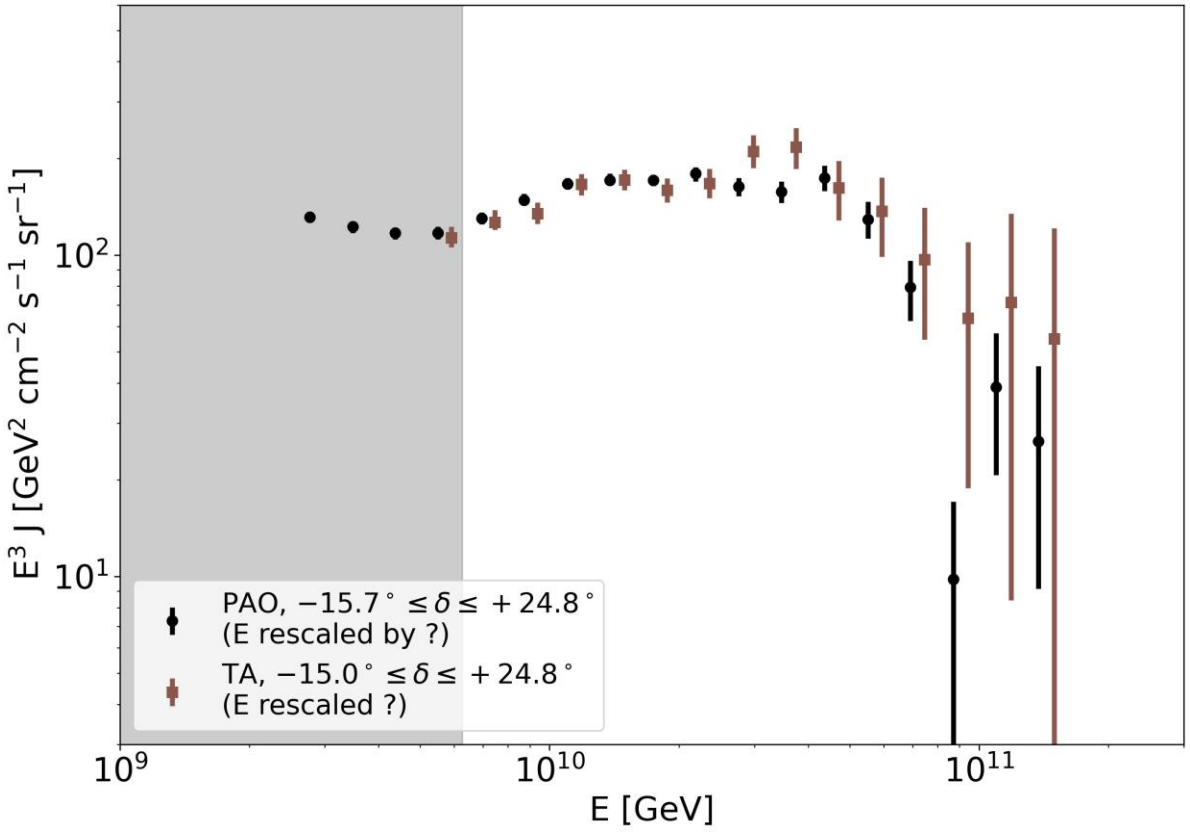




Declination-dependent shift?
→ Physics behind the shift?

Energy shifts in common declination band



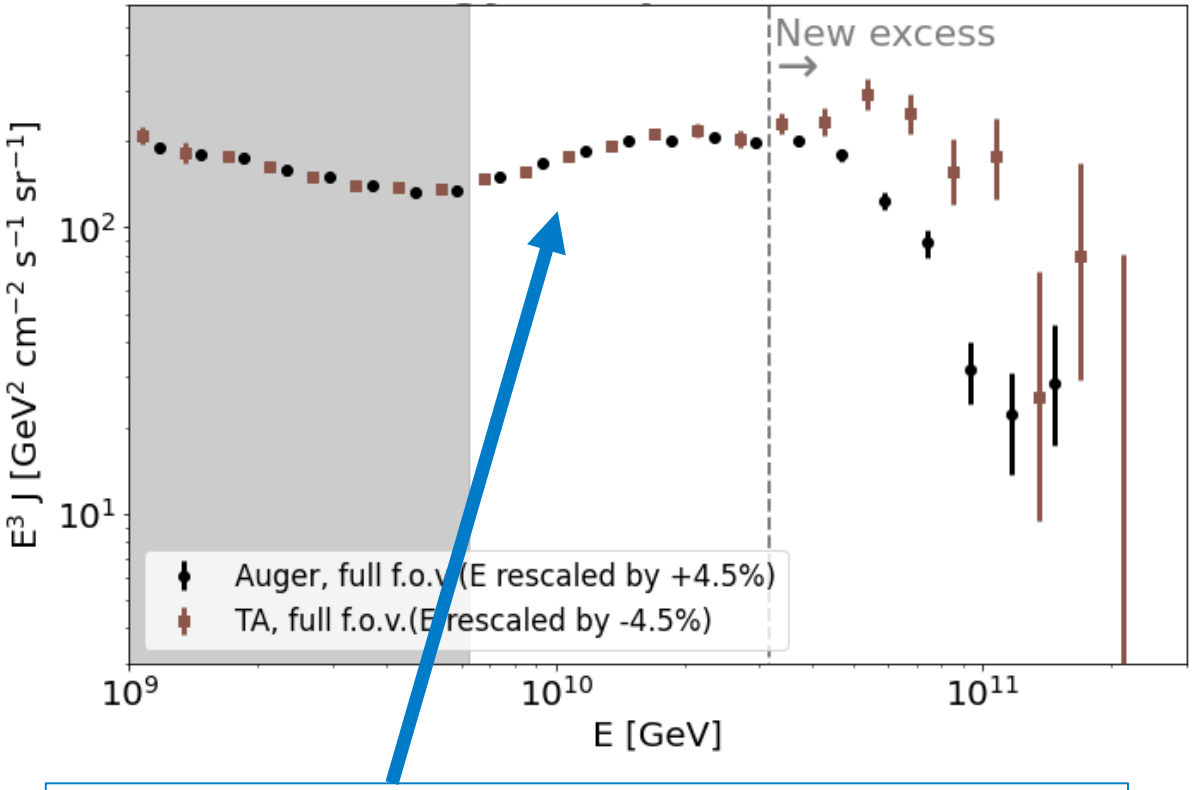


The simple and complex shifts are compatible within the uncertainties

Energy shifts in common declination band

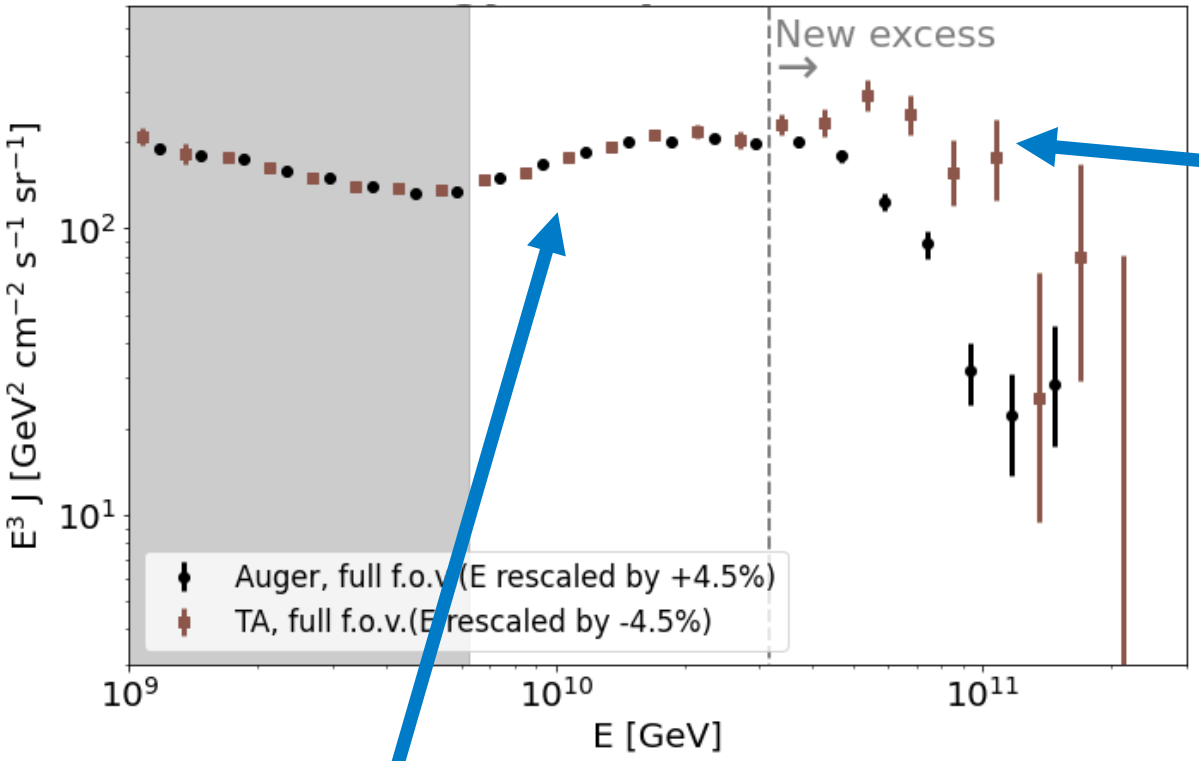
Tables for spectrum in different declination bands are not public! :(

Our proposal



Can be explained by simple shift

Our proposal

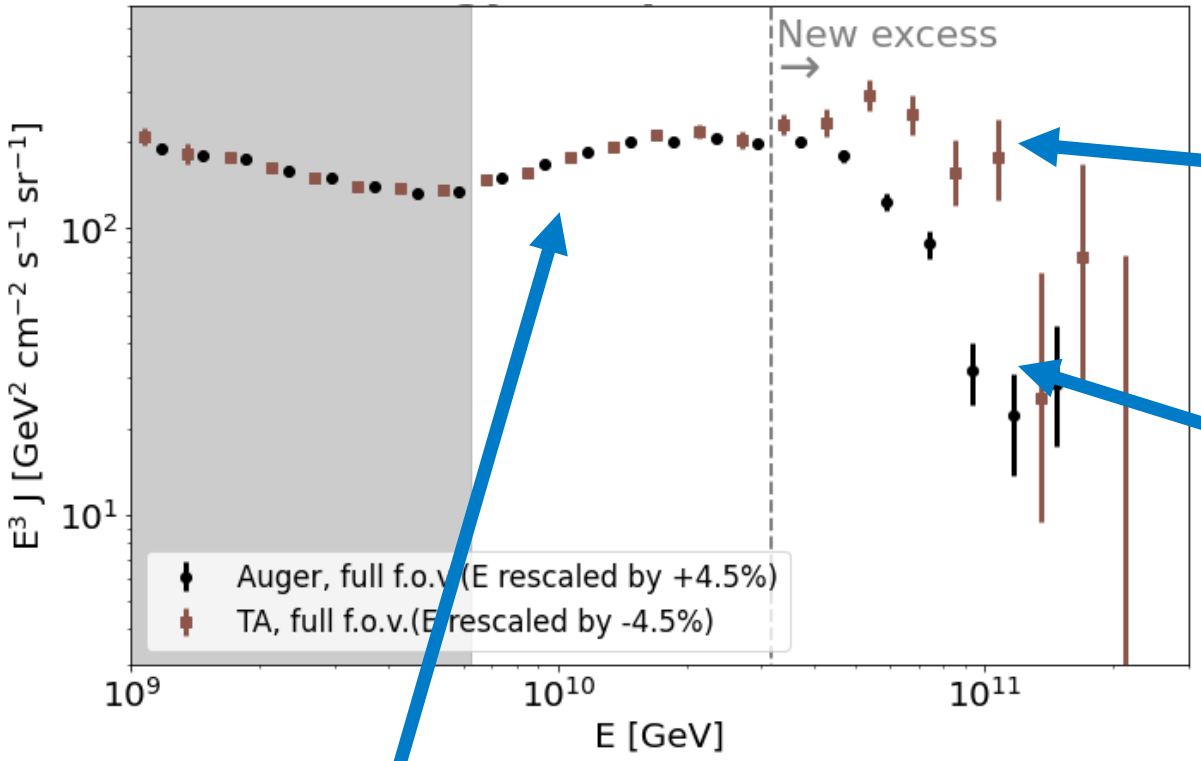


Systematics?

Can be explained by simple shift

Our proposal

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274



Systematics?

Astrophysical origin?

Can be explained by simple shift

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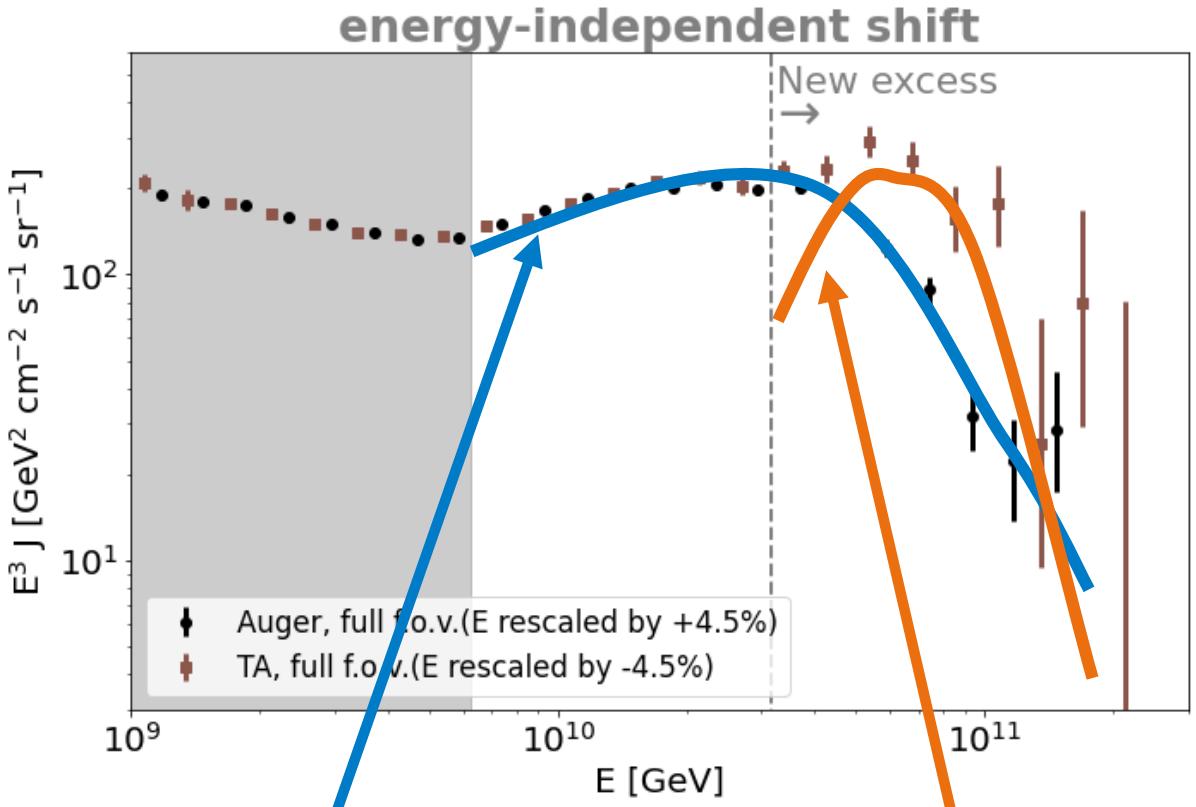
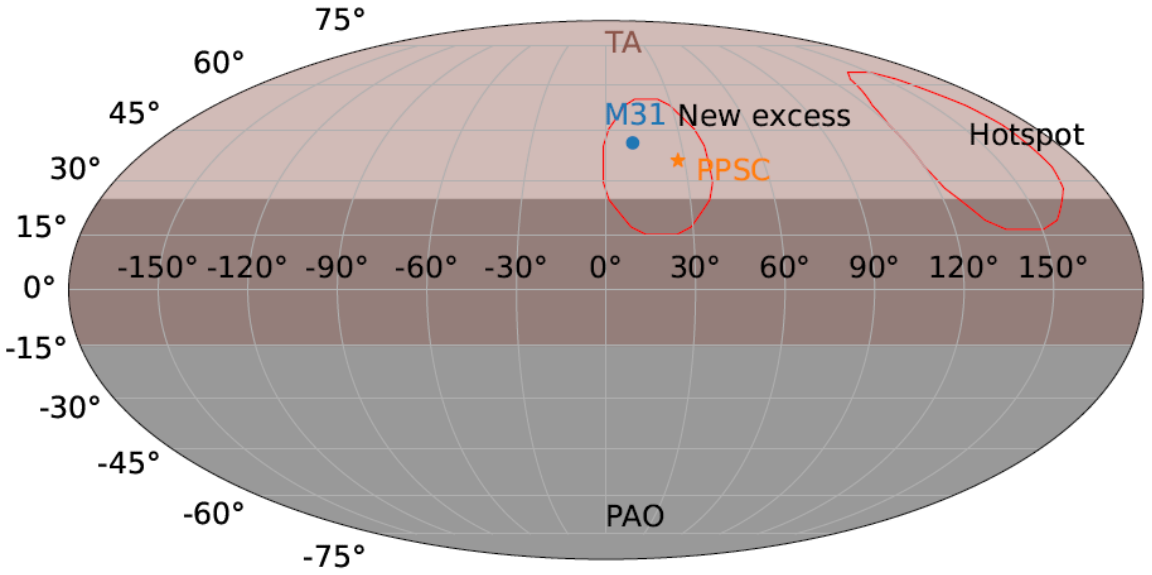




1. Cosmological source distribution – TA and PAO
2. Local source in Northern hemisphere – TA only

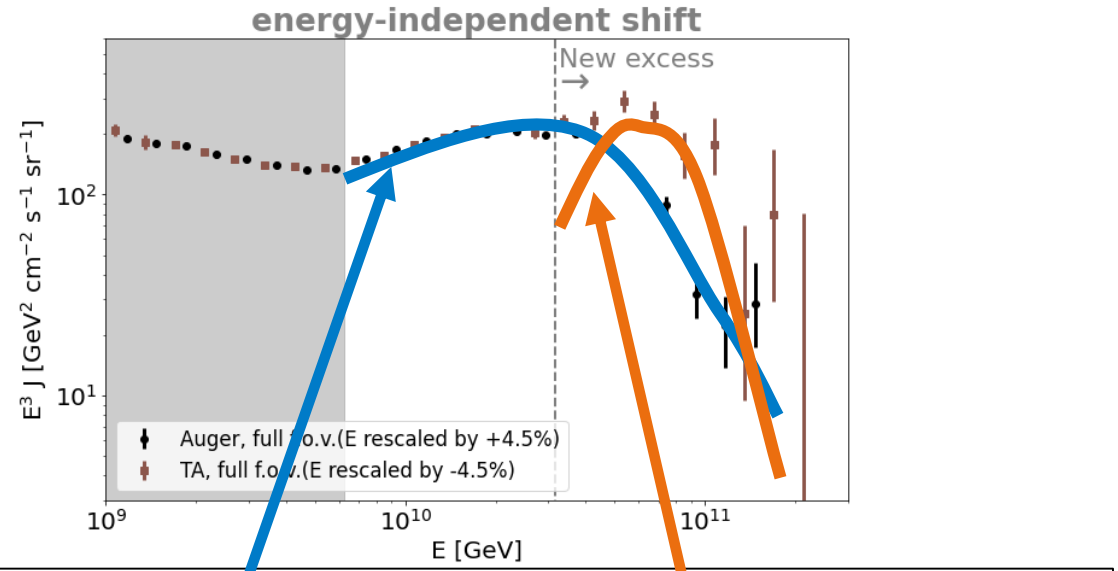
Kim et al. (2021)

Method

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

Parameters:

- $\boldsymbol{\lambda}_{\text{cosmo}} = (\gamma^{\text{cosmo}}, R_{\text{max}}^{\text{cosmo}}, m^{\text{cosmo}}, \mathcal{L}_{\text{CR}}^{\text{cosmo}}, \boldsymbol{f}_{\text{A}}^{\text{cosmo}})$
- $\boldsymbol{\lambda}_{local} = \left(\gamma^{\text{local}}, R_{\text{max}}^{\text{local}}, D^{\text{local}}, L^{\text{local}}, A^{\text{local}}\right)$



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Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
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Parameters:

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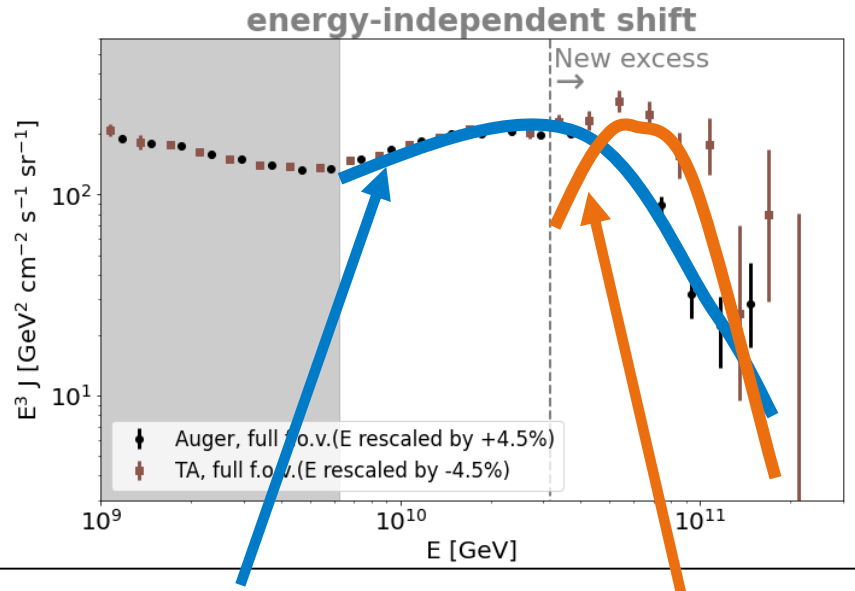
- $\boldsymbol{\lambda}_{local} = (\gamma^{\text{local}}, R_{\text{max}}^{\text{local}}, D^{\text{local}}, L^{\text{local}}, A^{\text{local}})$

χ^2test (Combined fit):

- $\chi^2_{\text{PAO}} = \chi^2_{\text{PAO}}(\boldsymbol{\lambda}_{\text{cosmo}}, \delta_{\text{E}}^{\text{PAO}}, \delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{PAO}}, \delta_{\sigma(\text{X}_{\text{max}})}^{\text{PAO}})$
- $\chi^2_{\text{TA}} = \chi^2_{TA}(\boldsymbol{\lambda}_{\text{cosmo}}, \boldsymbol{\lambda}_{local}, \delta_{\text{E}}^{\text{TA}}, \delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{TA}}, \delta_{\sigma(\text{X}_{\text{max}})}^{\text{TA}})$



1. Cosmological source distribution – TA and PAO
2. Local source in Northern hemisphere – TA only

$\boldsymbol{\delta}$ represent the systematic uncertainties

Method

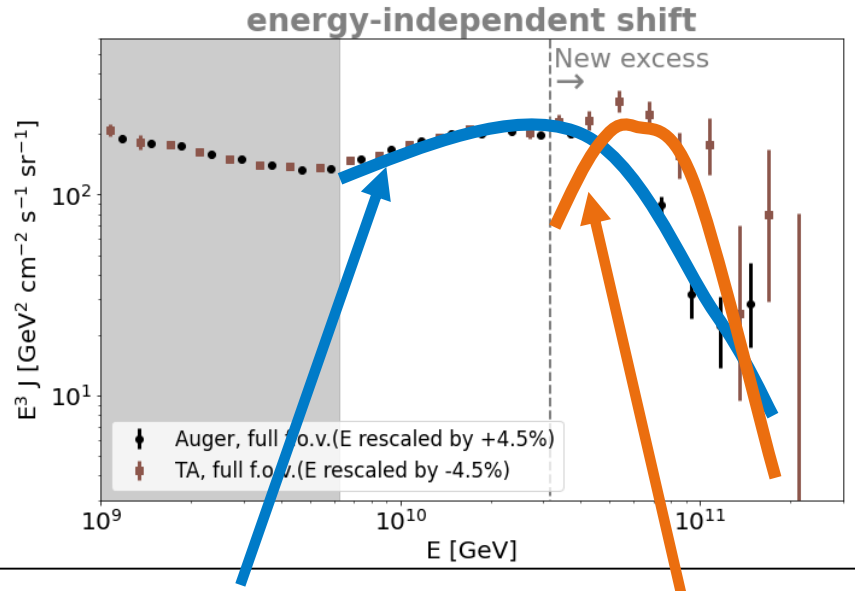
Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

Parameters:

- $\boldsymbol{\lambda}_{\text{cosmo}} = (\gamma^{\text{cosmo}}, R_{\text{max}}^{\text{cosmo}}, m^{\text{cosmo}}, \mathcal{L}_{\text{CR}}^{\text{cosmo}}, \boldsymbol{f}_{\text{A}}^{\text{cosmo}})$
- $\boldsymbol{\lambda}_{local} = (\gamma^{\text{local}}, R_{\text{max}}^{\text{local}}, D^{\text{local}}, L^{\text{local}}, A^{\text{local}})$

χ^2test (Combined fit):

- $\chi^2_{\text{PAO}} = \chi^2_{\text{PAO}}(\boldsymbol{\lambda}_{\text{cosmo}}, \delta_{\text{E}}^{\text{PAO}}, \delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{PAO}}, \delta_{\sigma(\text{X}_{\text{max}})}^{\text{PAO}})$
- $\chi^2_{\text{TA}} = \chi^2_{TA}(\boldsymbol{\lambda}_{\text{cosmo}}, \boldsymbol{\lambda}_{local}, \delta_{\text{E}}^{\text{TA}}, \delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{TA}}, \delta_{\sigma(\text{X}_{\text{max}})}^{\text{TA}})$



Joint fit:

$$\chi^2_{\text{global}}(\boldsymbol{\lambda}^{\text{cosmo}}, \boldsymbol{\lambda}^{local}, \boldsymbol{\delta}) = \chi^2_{\text{PAO}} + \chi^2_{\text{TA}} + \left(\frac{\delta_{\text{E}}^{\text{PAO}}}{\sigma_{\text{E}}^{\text{PAO}}}\right)^2 + \left(\frac{\delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{PAO}}}{\sigma_{\langle \text{X}_{\text{max}} \rangle}^{\text{PAO}}}\right)^2 + \left(\frac{\delta_{\sigma(\text{X}_{\text{max}})}^{\text{PAO}}}{\sigma_{\sigma(\text{X}_{\text{max}})}^{\text{PAO}}}\right)^2 + \left(\frac{\delta_{\text{E}}^{\text{TA}}}{\sigma_{\text{E}}^{\text{TA}}}\right)^2 + \left(\frac{\delta_{\langle \text{X}_{\text{max}} \rangle}^{\text{TA}}}{\sigma_{\langle \text{X}_{\text{max}} \rangle}^{\text{TA}}}\right)^2 + \left(\frac{\delta_{\sigma(\text{X}_{\text{max}})}^{\text{TA}}}{\sigma_{\sigma(\text{X}_{\text{max}})}^{\text{TA}}}\right)^2$$

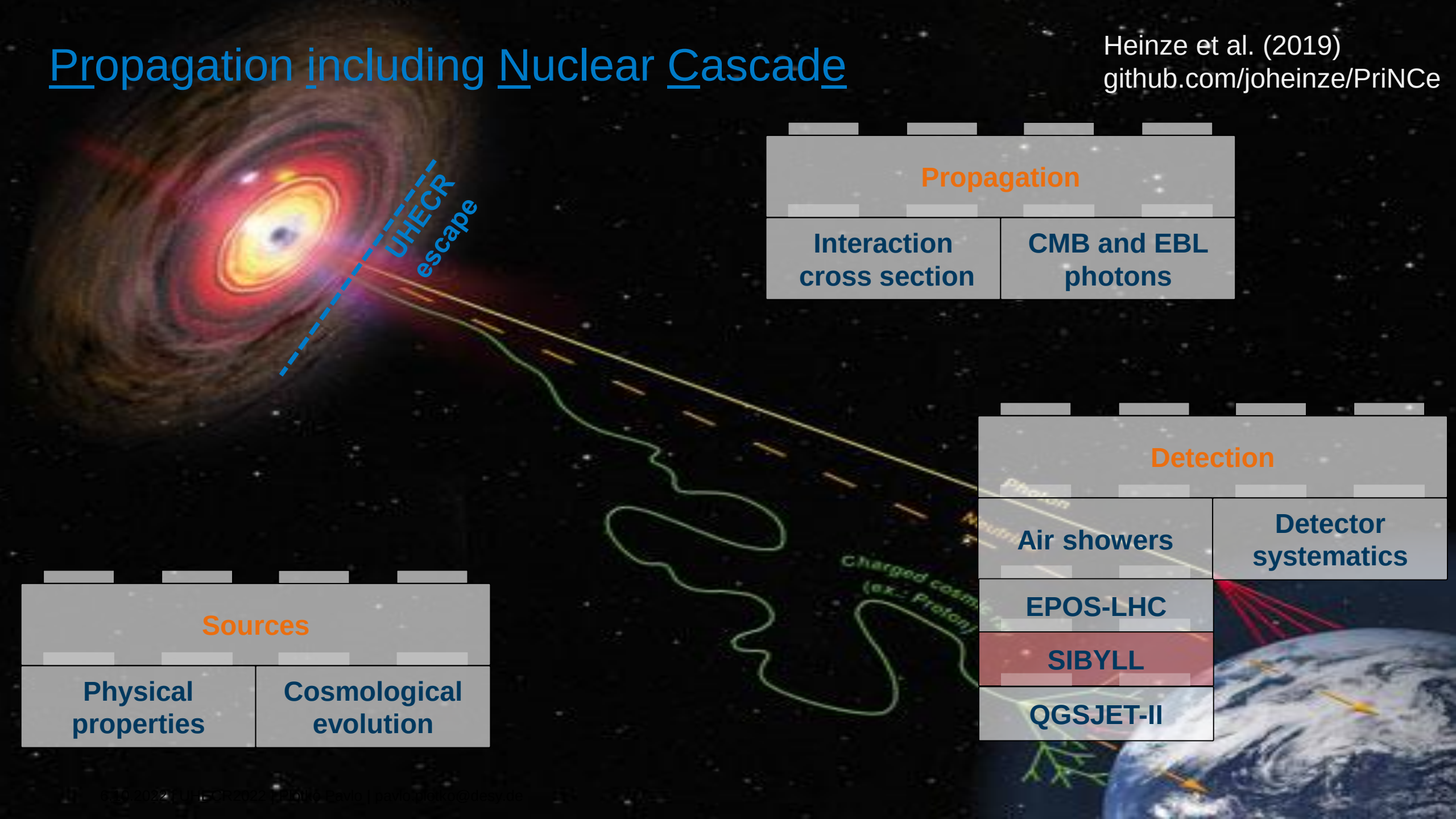
1. Cosmological source distribution – TA and PAO
2. Local source in Northern hemisphere – TA only

$\boldsymbol{\delta}$ represent the systematic uncertainties

~ 20 CPU years to reproduce results

Propagation including Nuclear Cascade

Heinze et al. (2019)
github.com/joheinze/PriNCe



Propagation

Interaction cross section	CMB and EBL photons

Detection

Air showers	Detector systematics

- EPOS-LHC
- SIBYLL
- QGSJET-II

Sources

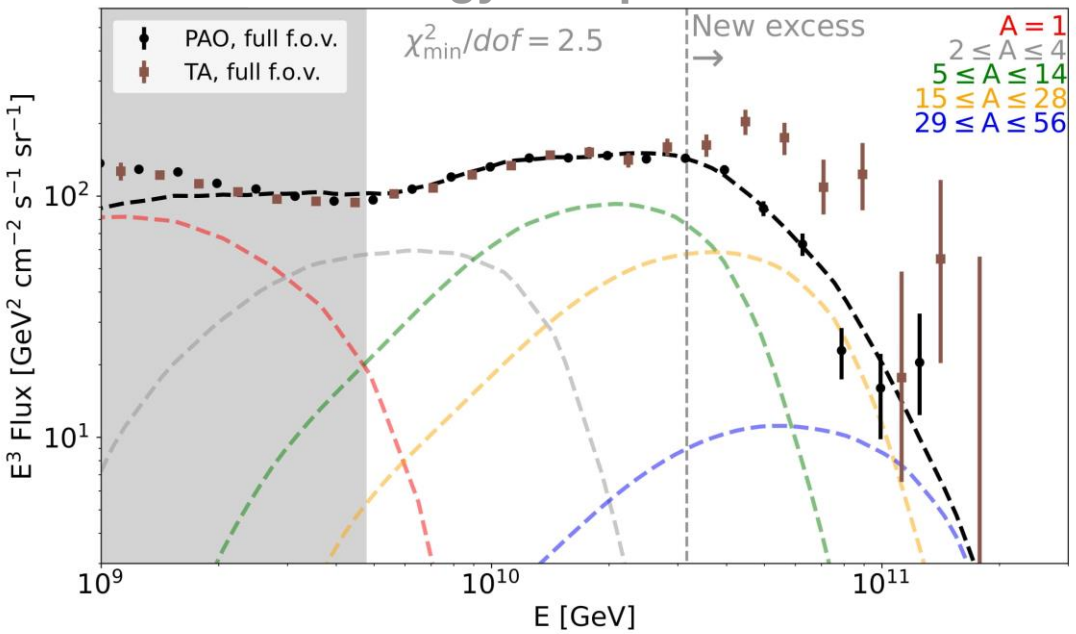
Physical properties	Cosmological evolution

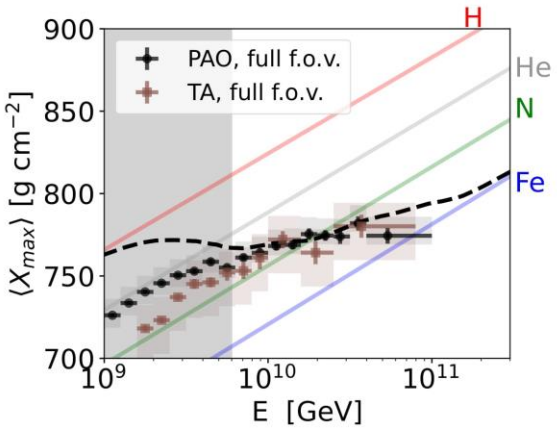
Results

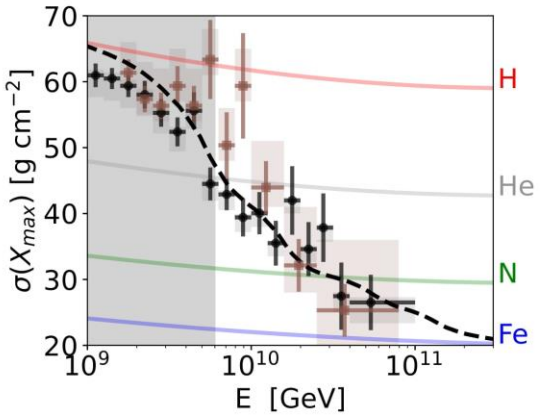
Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

Systematics

Energy-independent shift







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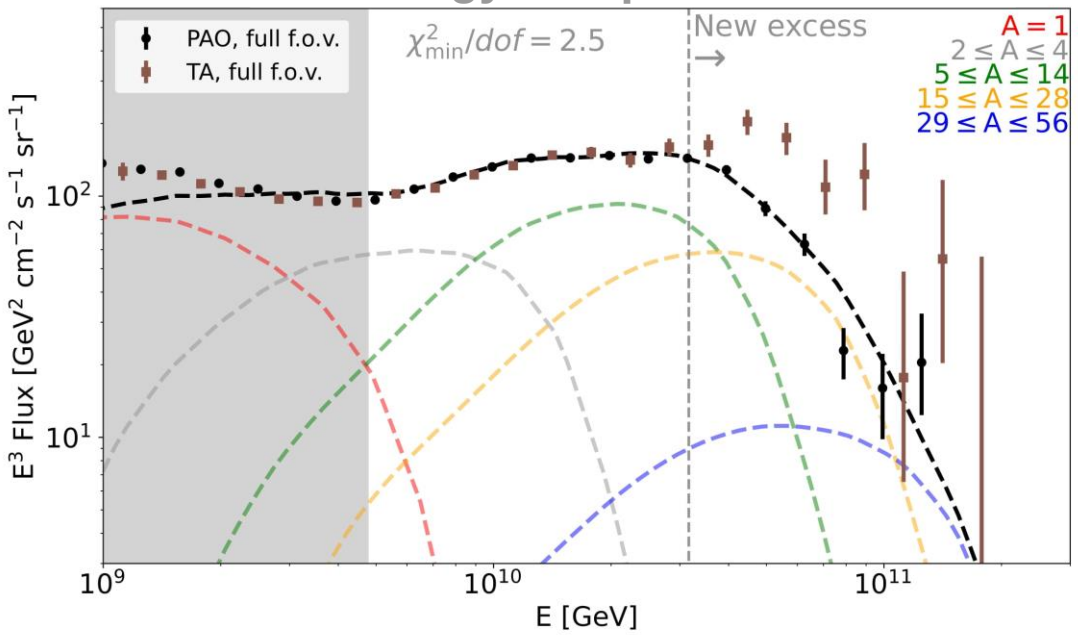
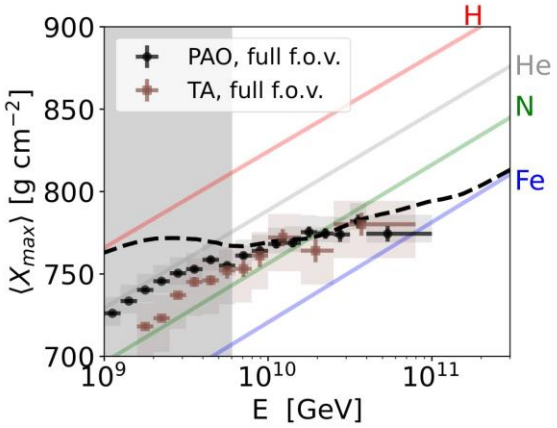
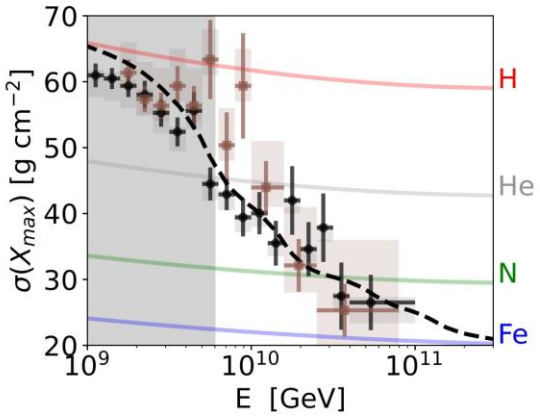
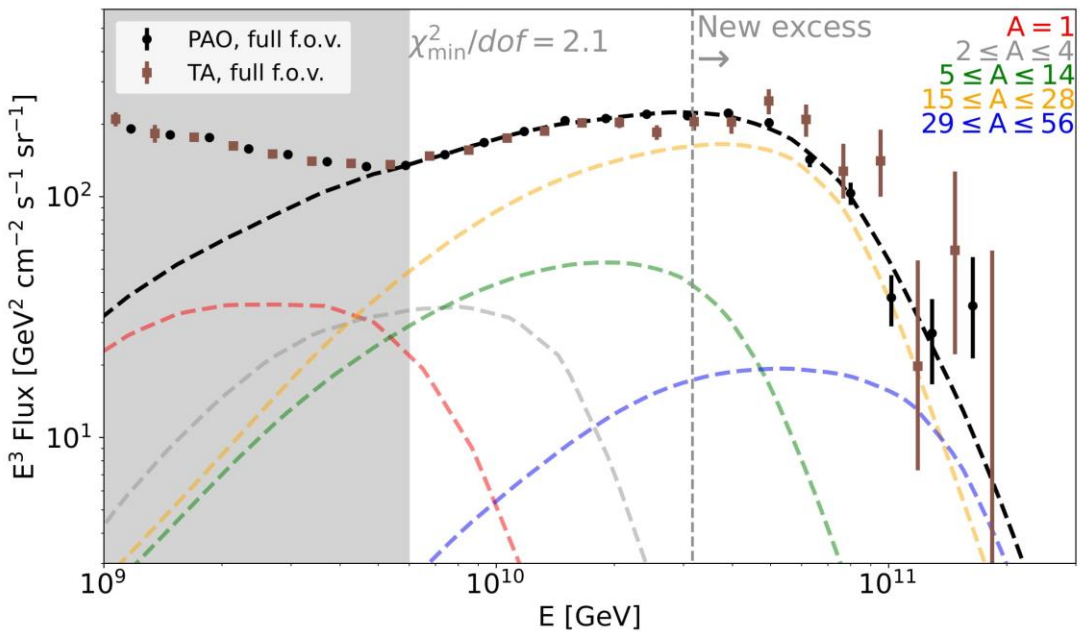
Energy-independent shift

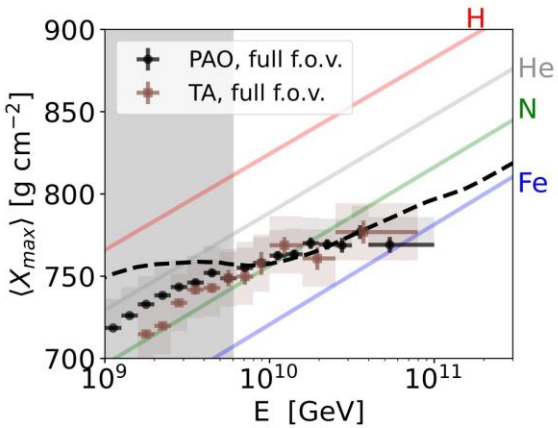


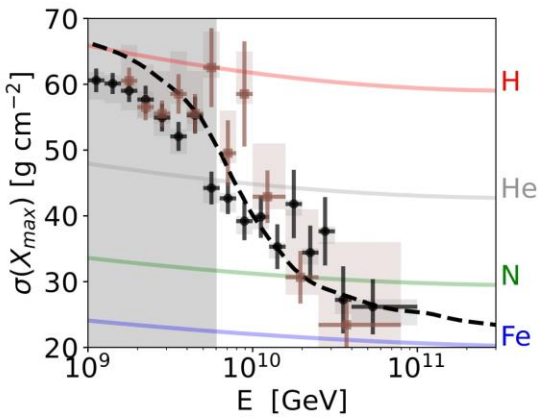




Energy-dependent shift







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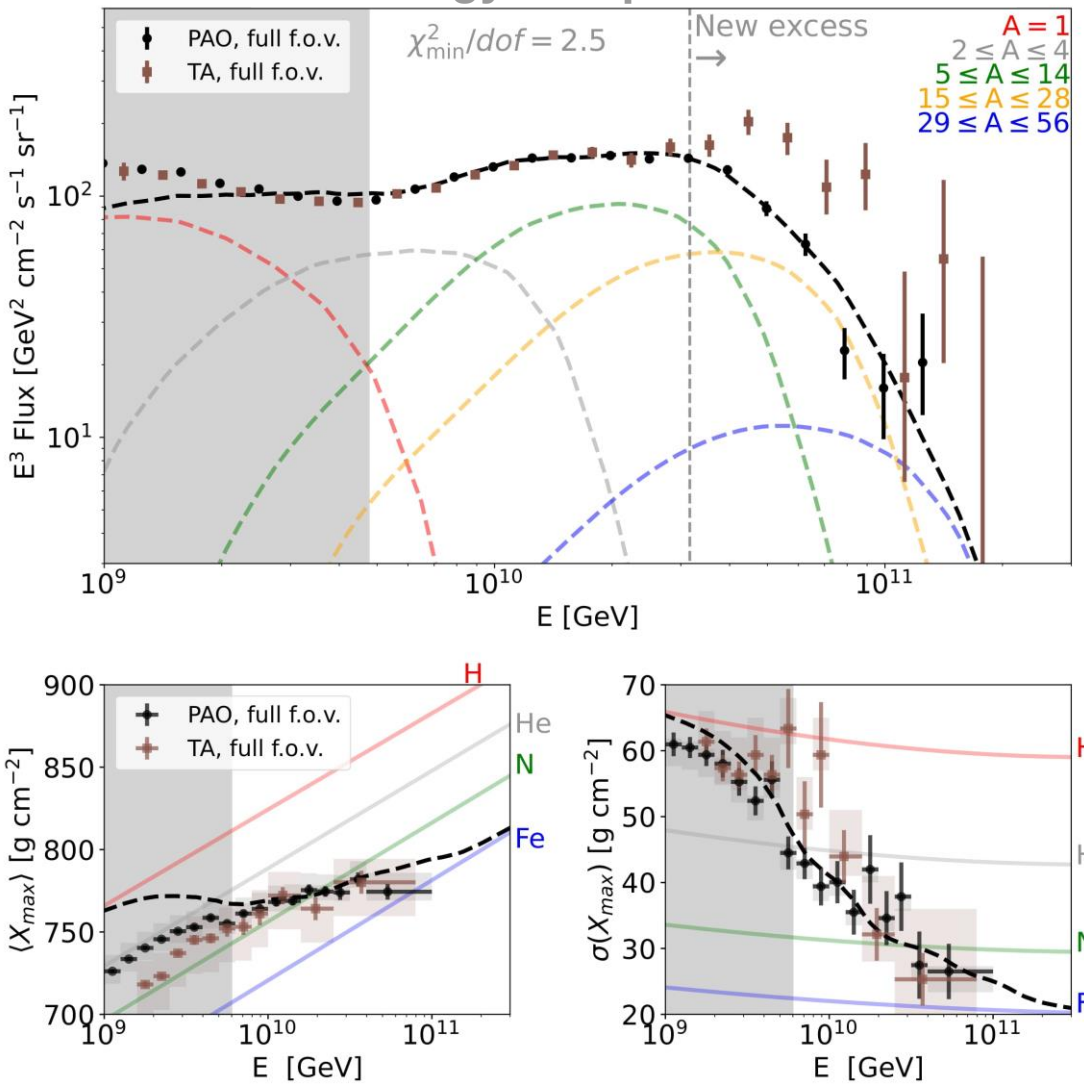
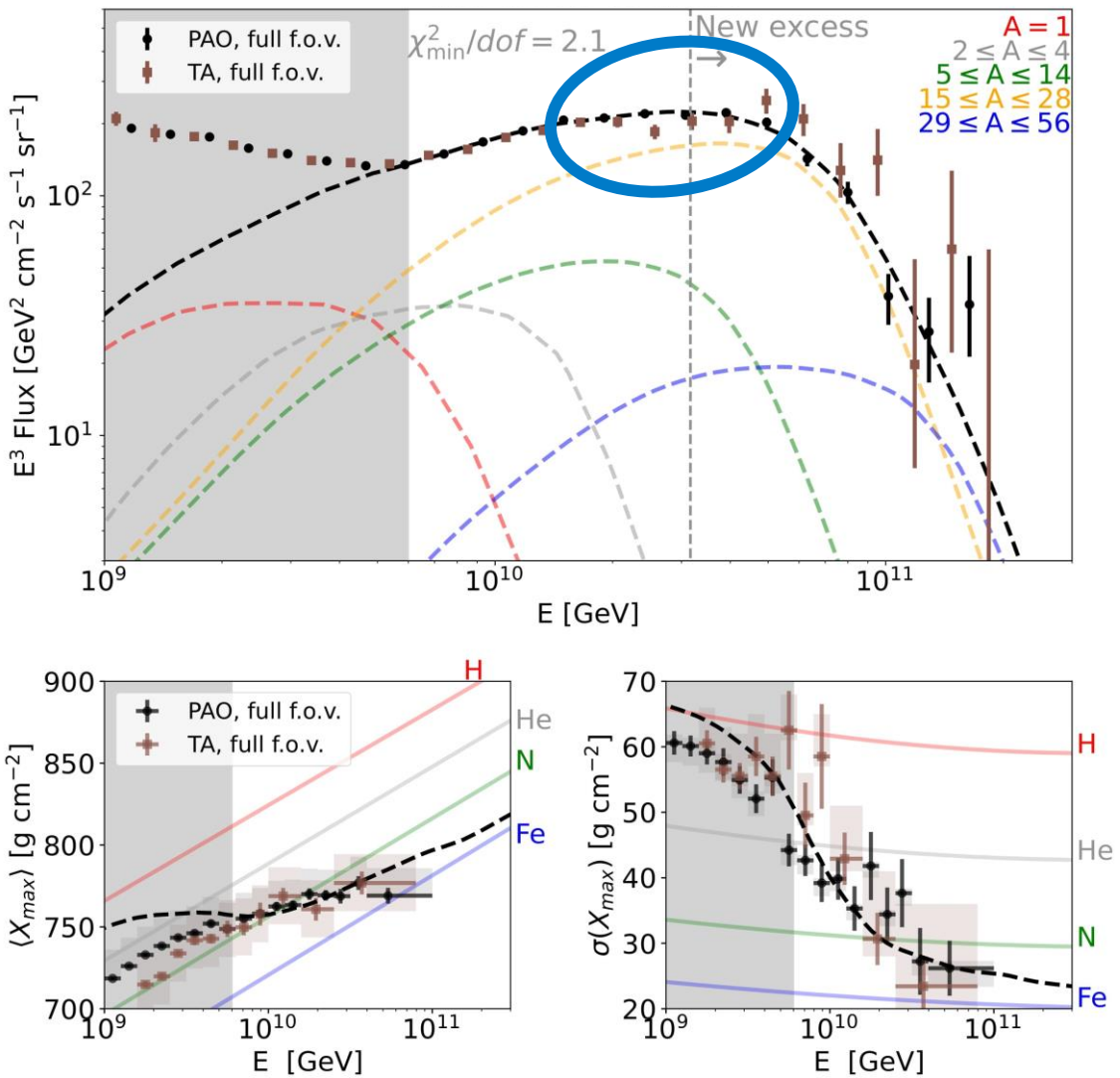
Energy-independent shift



Energy-dependent shift



Results

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
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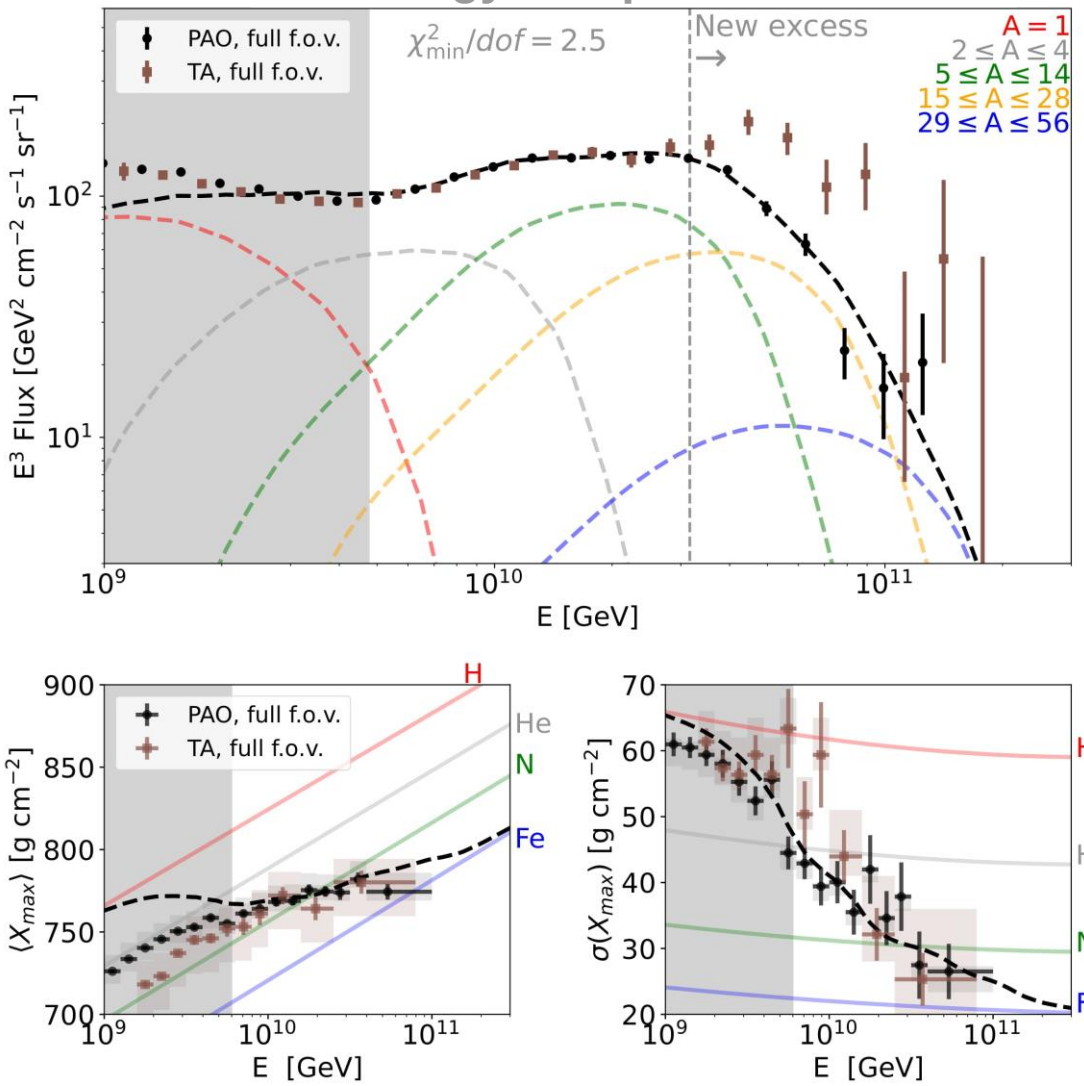
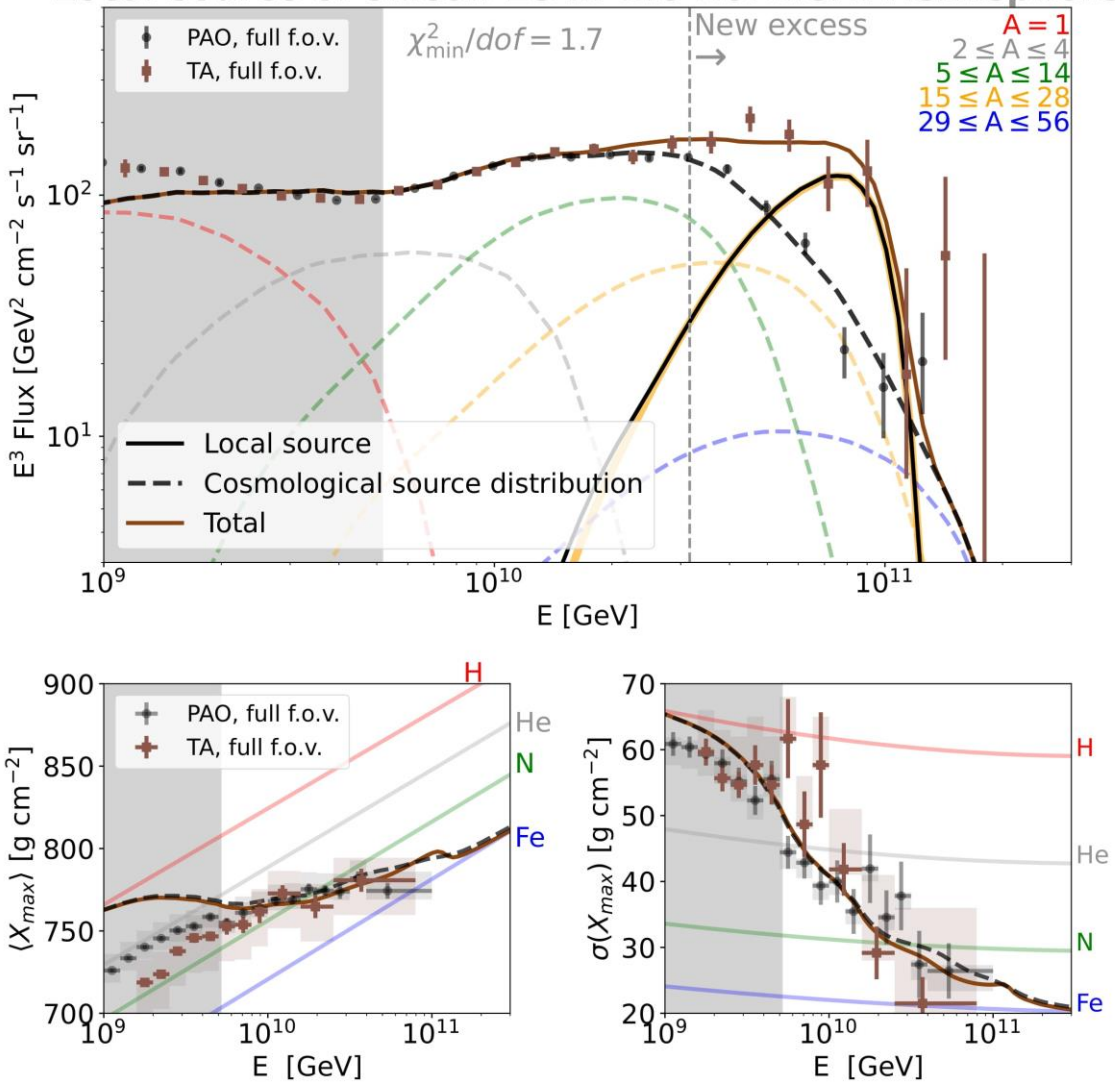
Astrophysical origin

Energy-independent shift

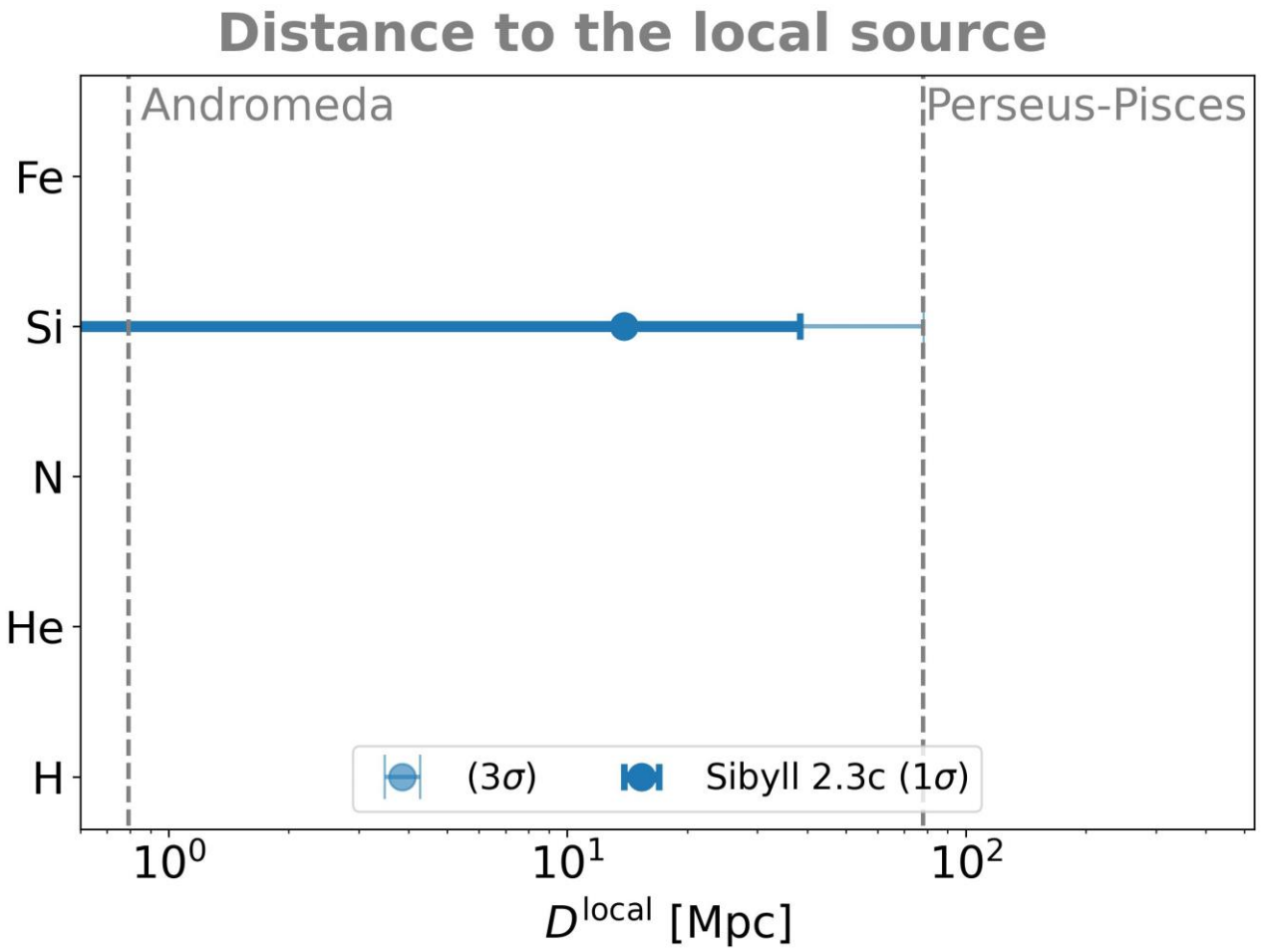


Local source of silicon-28 in the Northern Hemisphere



Local source

Distance



A local source emits only one isotope (silicon-28)

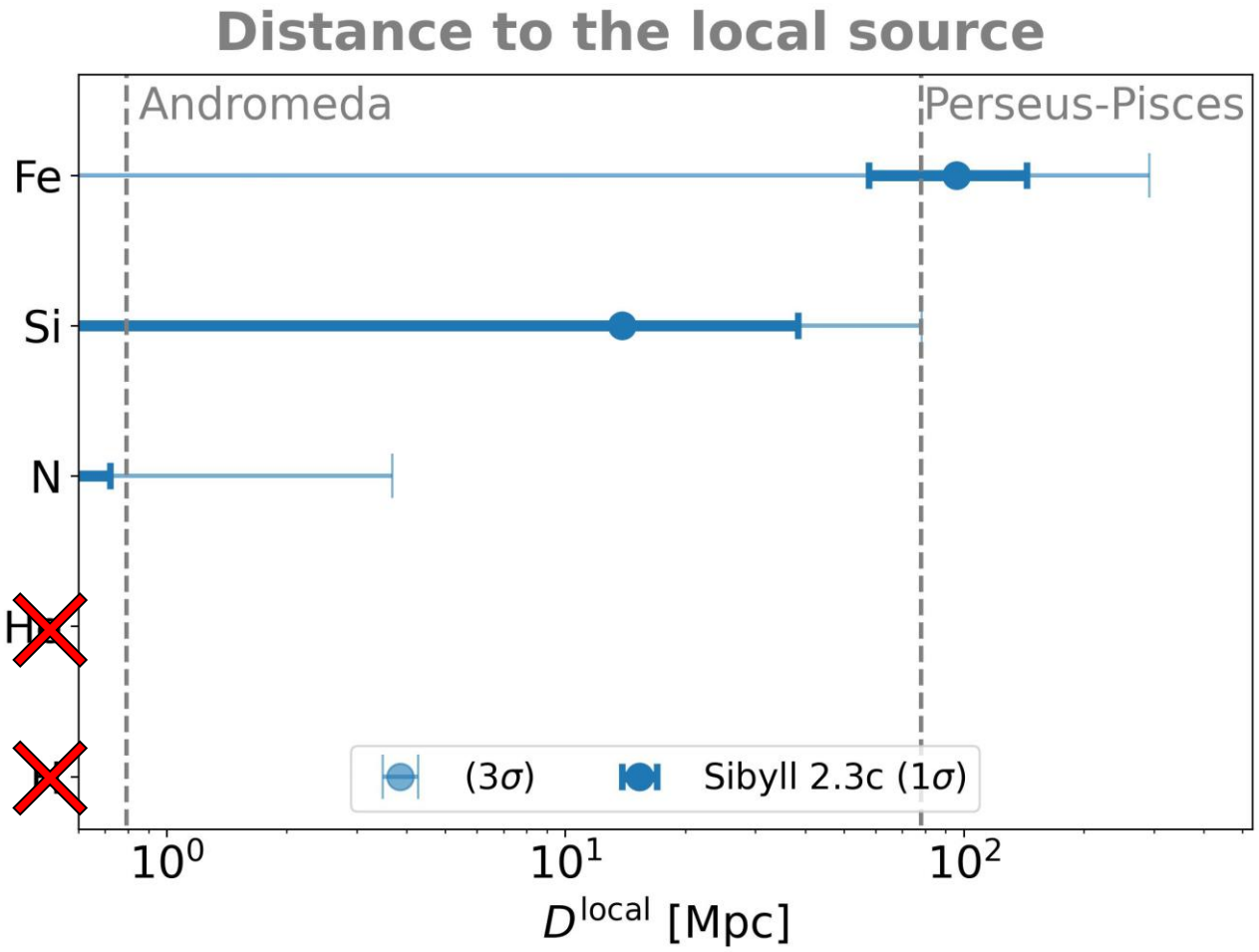
Distance $13.9^{+9.2}_{-13.9}$ Mpc

Luminosity $7.3^{+18.0}_{-7.3} \cdot 10^{41\ \mathrm{erg}/s}$

The maximum rigidity $1.3^{+0.2}_{-0.1} \cdot 10^{9}$GV

Local source

Distance

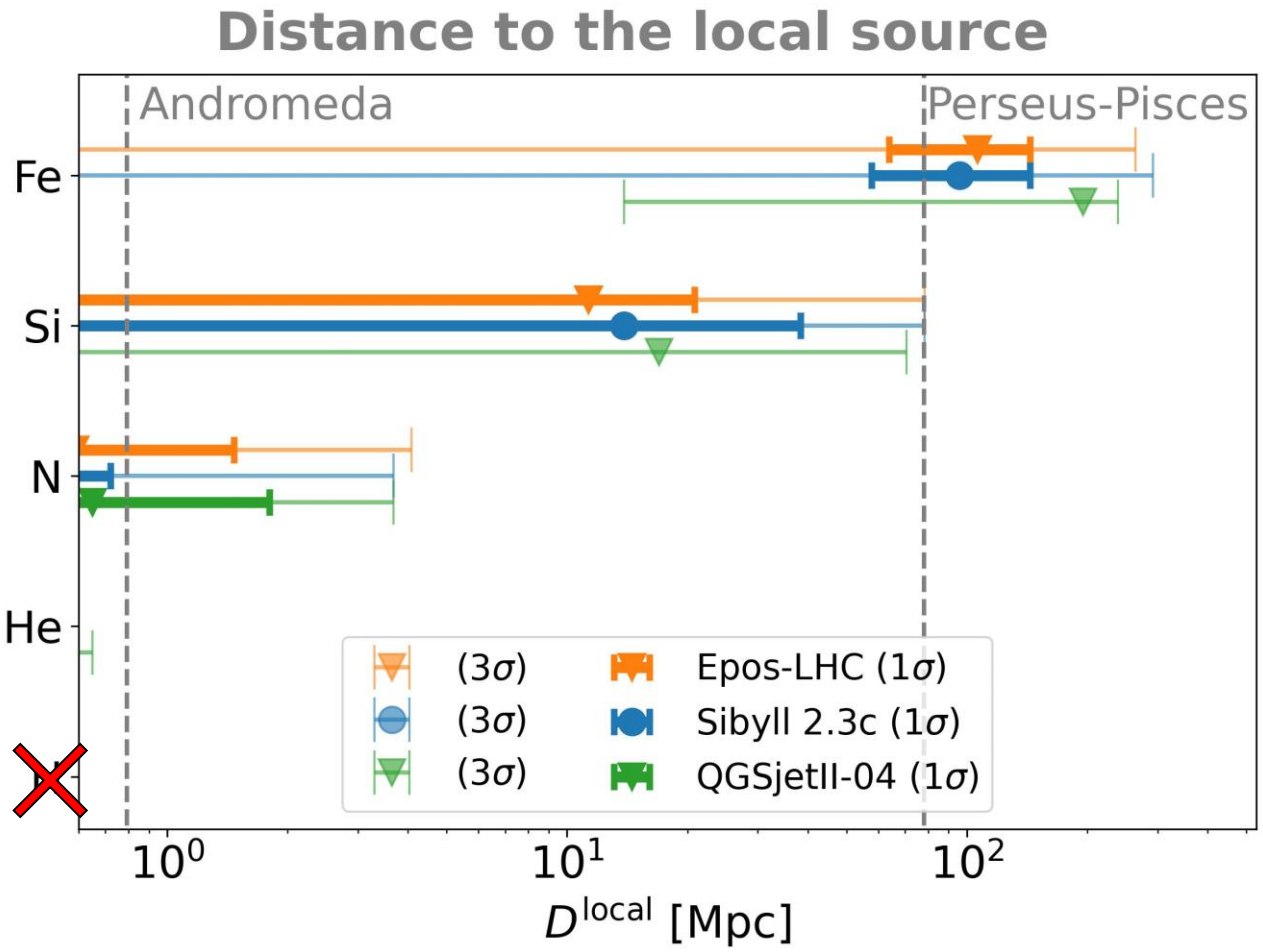


1. Intermediate-mass elements are preferred.
2. He (almost) and H are excluded in 3 sigma.
3. Distance depends on the type of isotope.

Local source

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

Distance



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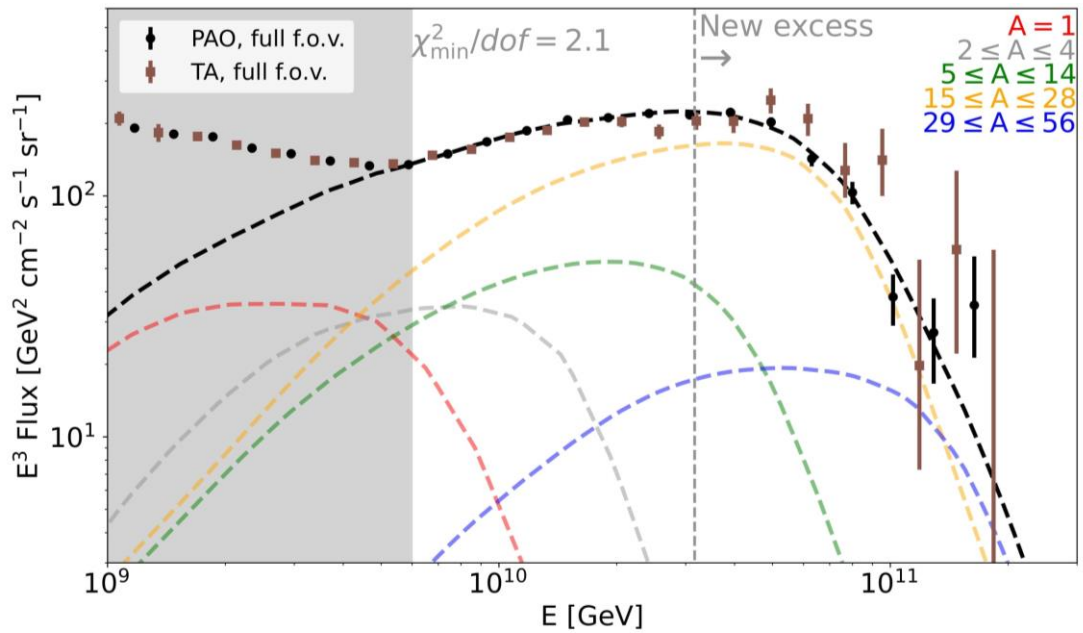
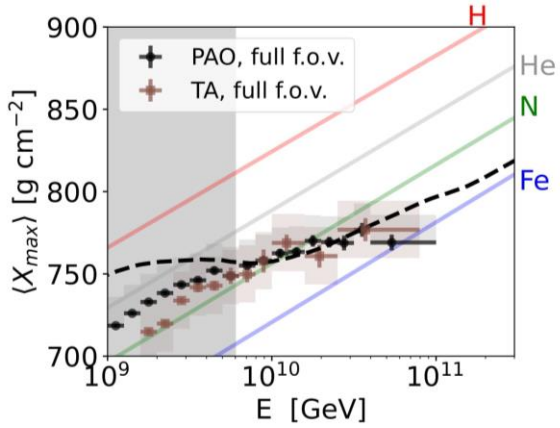
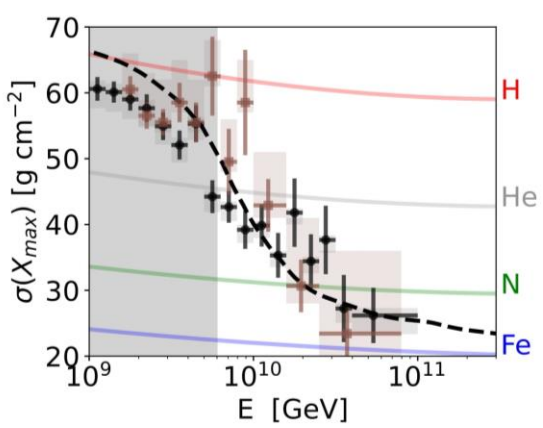
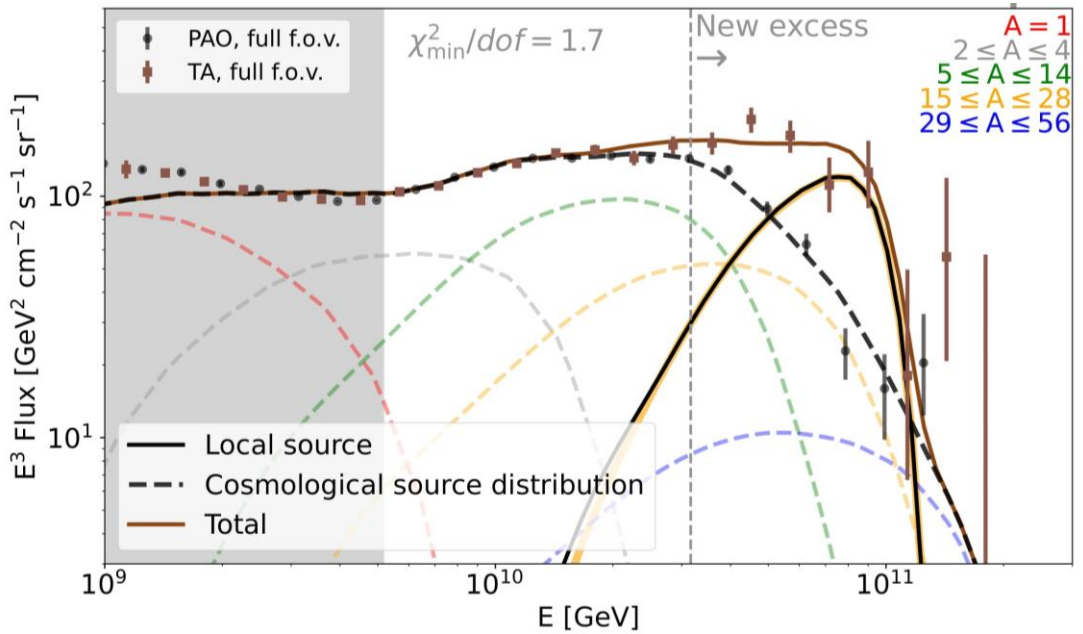
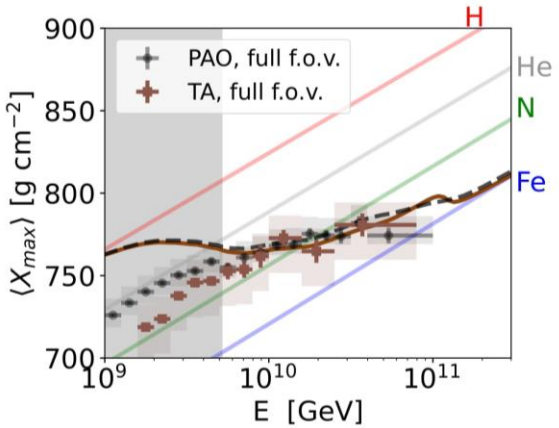
Systematics vs Astrophysical origin

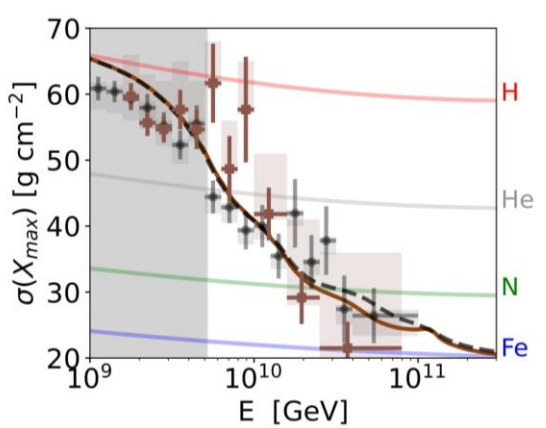












Take-home messages

Both scenarios could explain the differences

Systematics:

1. What about the different declination bands?
2. Physics behind the shift?

Astrophysical:

1. What is the local source?
2. Is there a probability to observe it?

Are there any differences between the simple and complex shifts in the common declination band?

More publicly available data for theory :)

Credits for imagines

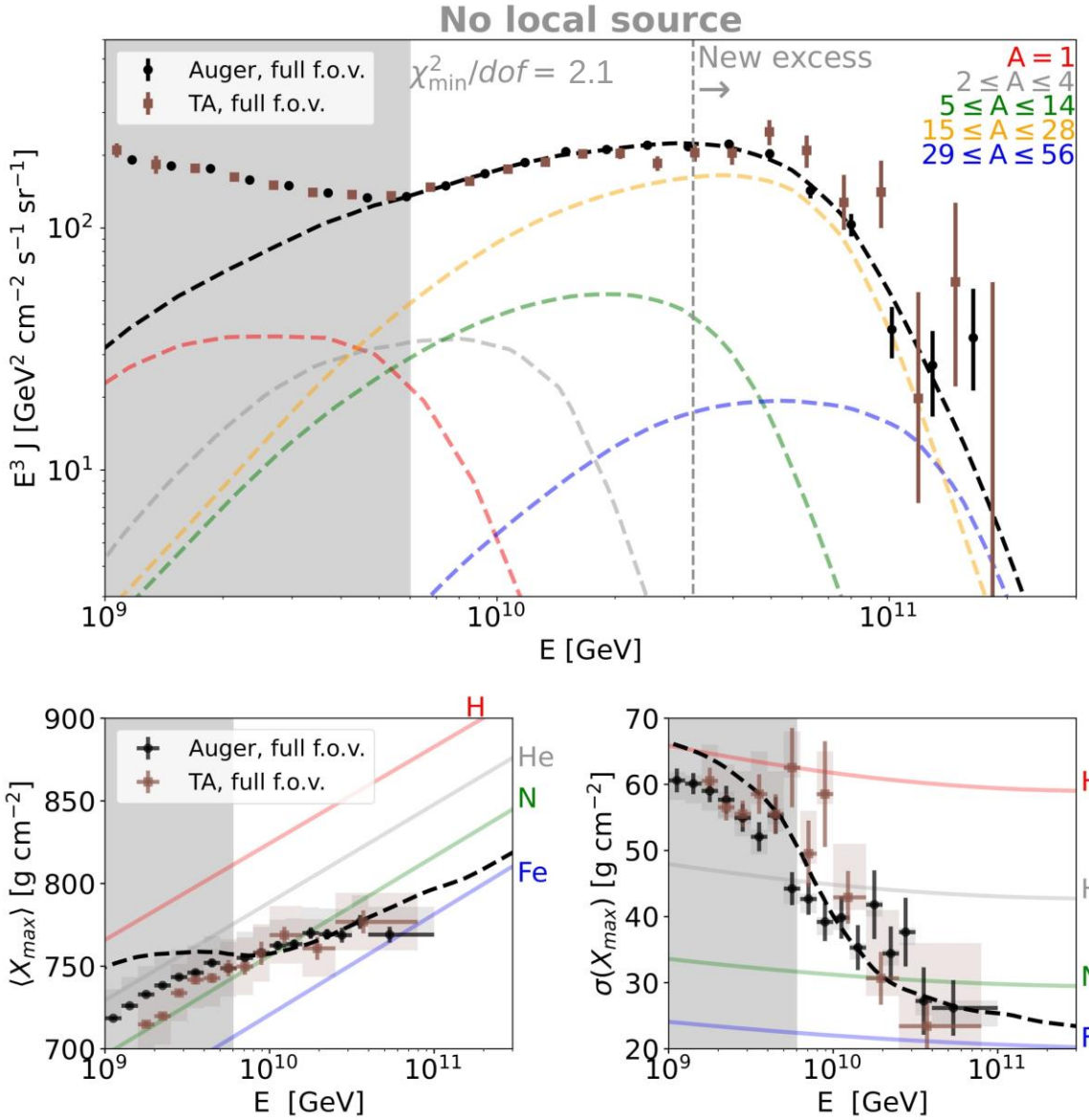
1. “Which Is Better To Launch Your First Mobile App: Android Or iOS?” by Abhijeet Nirmal (https://www.volumetree.com/which-is-better-for-your-first-mobile-app-to-launch-on-android-or-ios/)
2. “DC VS. MARVEL: WHO HAS THE HIGHER TOMATOMETER?“ by Mark Hofmeyer ("https://editorial.rottentomatoes.com/article/dc-vs-marvel-who-has-the-higher-tomatometer/)
3. “Star Wars vs. Star Trek” by Otis Adams (https://vocal.media/geeks/star-wars-vs-star-trek)
4. “Spider-Man” 2022 by Sony Pictures Releasing
5. https://thechoiceisyours.whatisthematrix.com by WARNER BROS
6. “Shrek” 2001 by DreamWorks Pictures

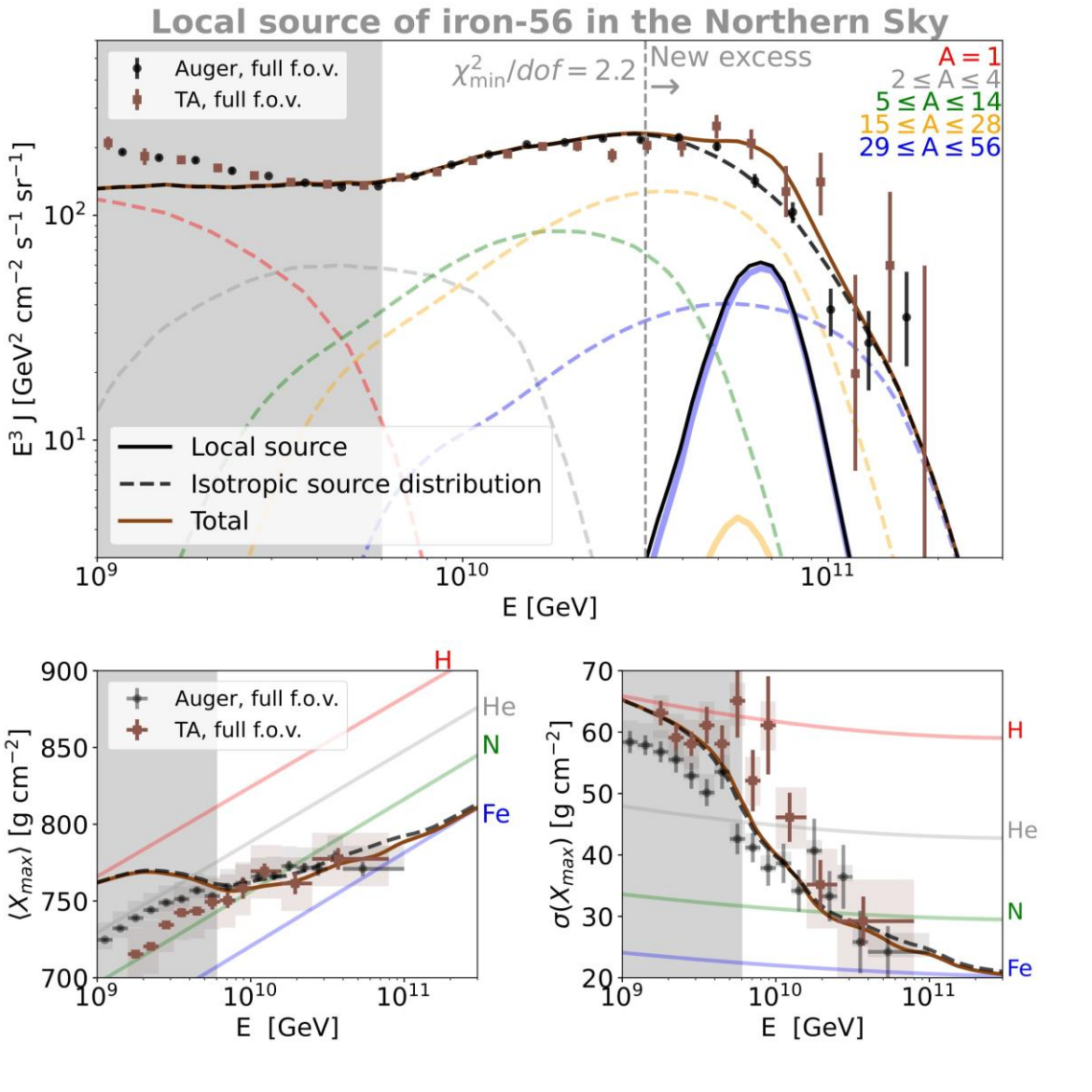
All images are used for non-profit and educational reasons

Backup slides

Energy-dependent shift

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274





Local source

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

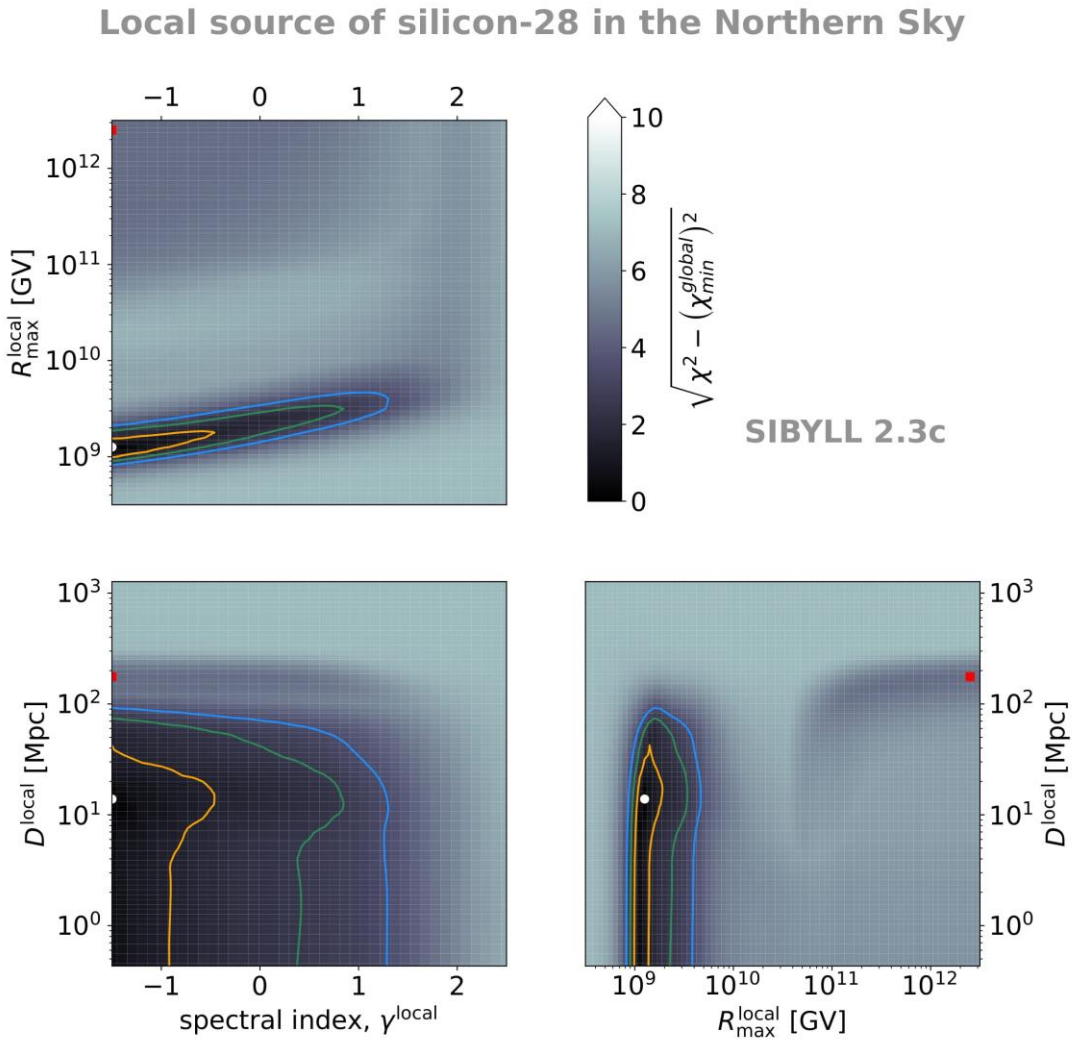
Best fit case

A local source emits only one isotope (silicon-28)

Distance $13.9^{+9.2}_{-13.9}$ Mpc

Luminosity $7.3^{+18.0}_{-7.3} \cdot 10^{41}\ {}^{\mathrm{erg}}/_{s}$

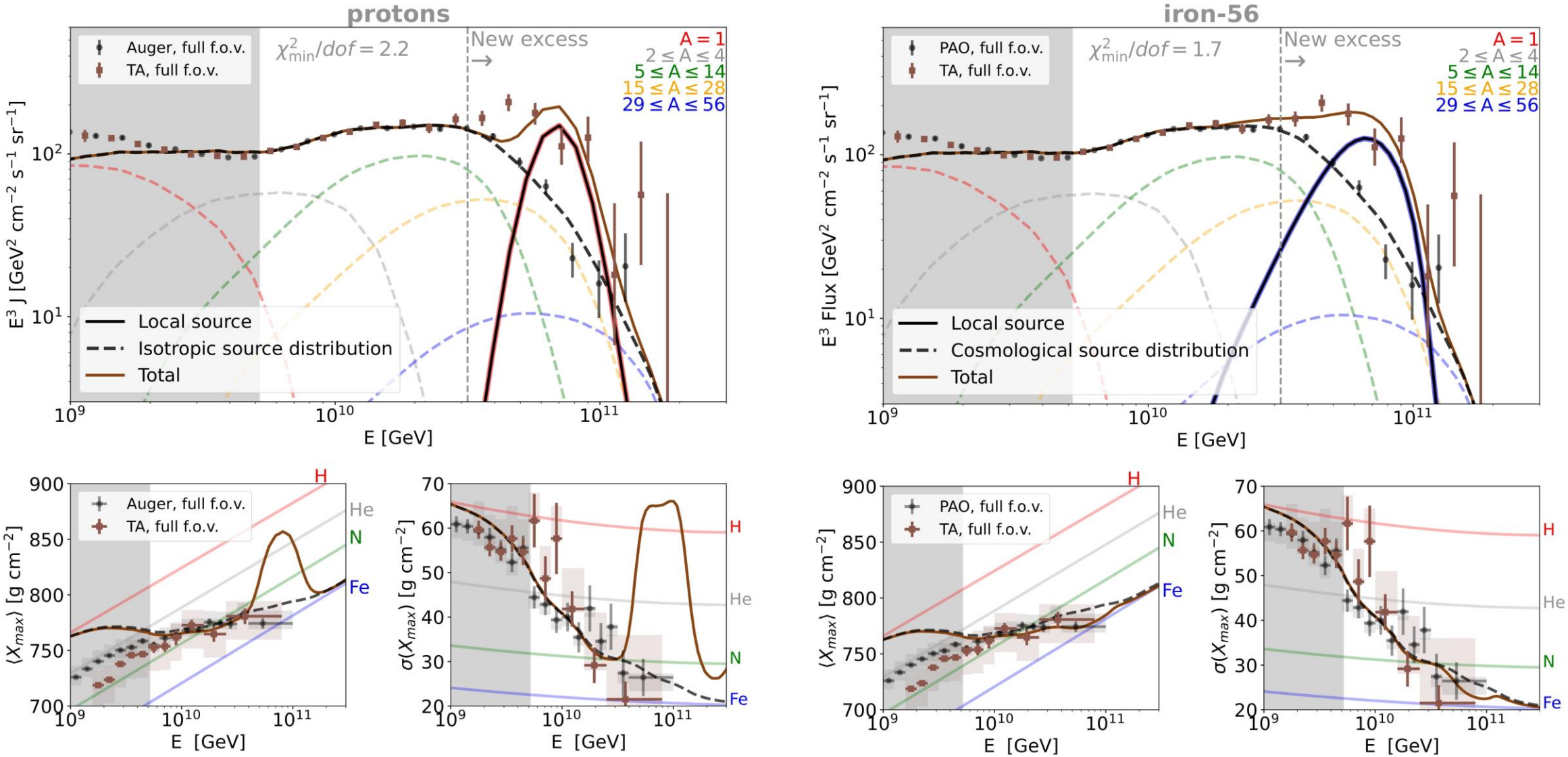
The maximum rigidity $1.3^{+0.2}_{-0.1} \cdot 10^{9}$GV



Results

Pavlo Plotko, Arjen van Vliet, Xavier Rodrigues and Walter Winter
arXiv:2208.12274

Astrophysical origin



Results

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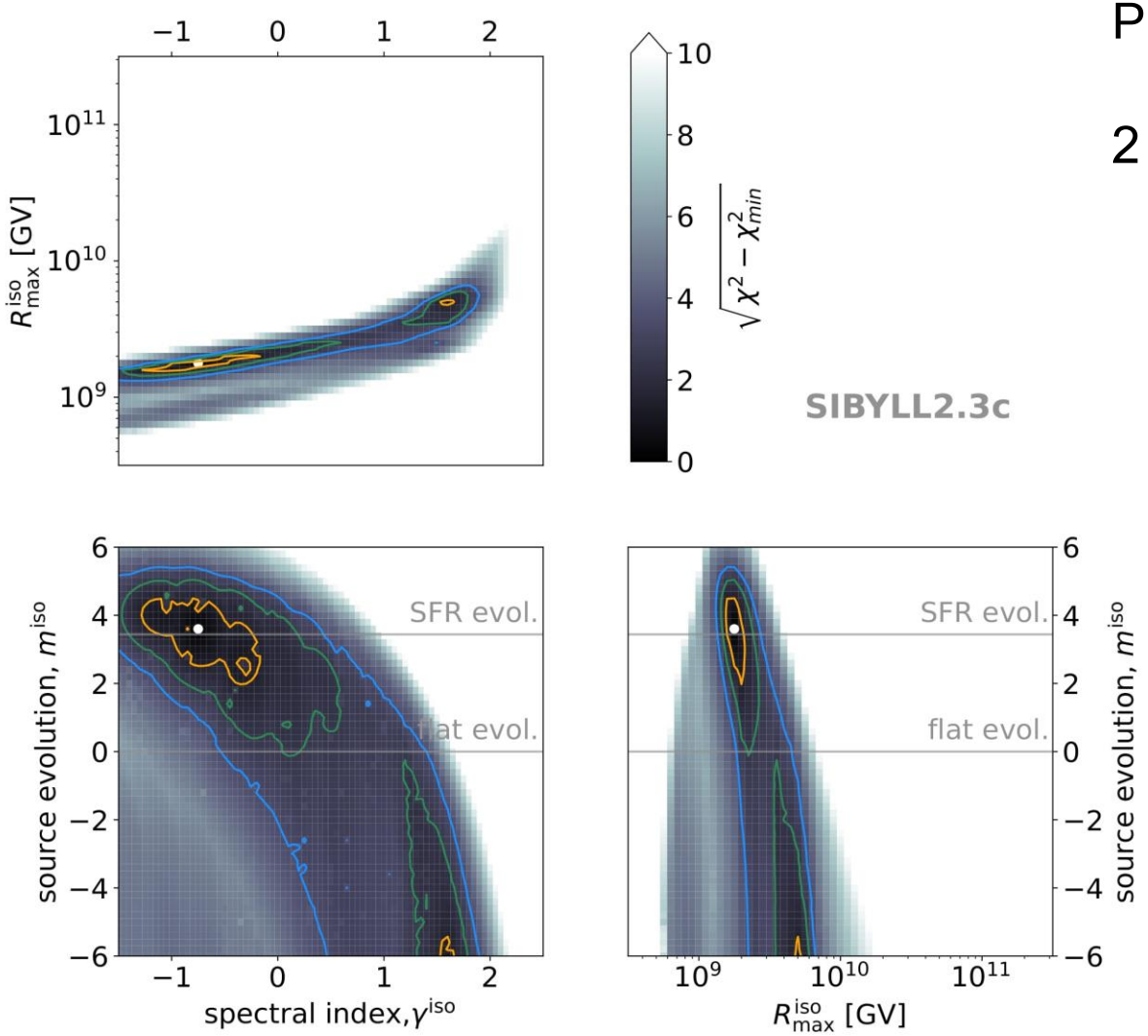
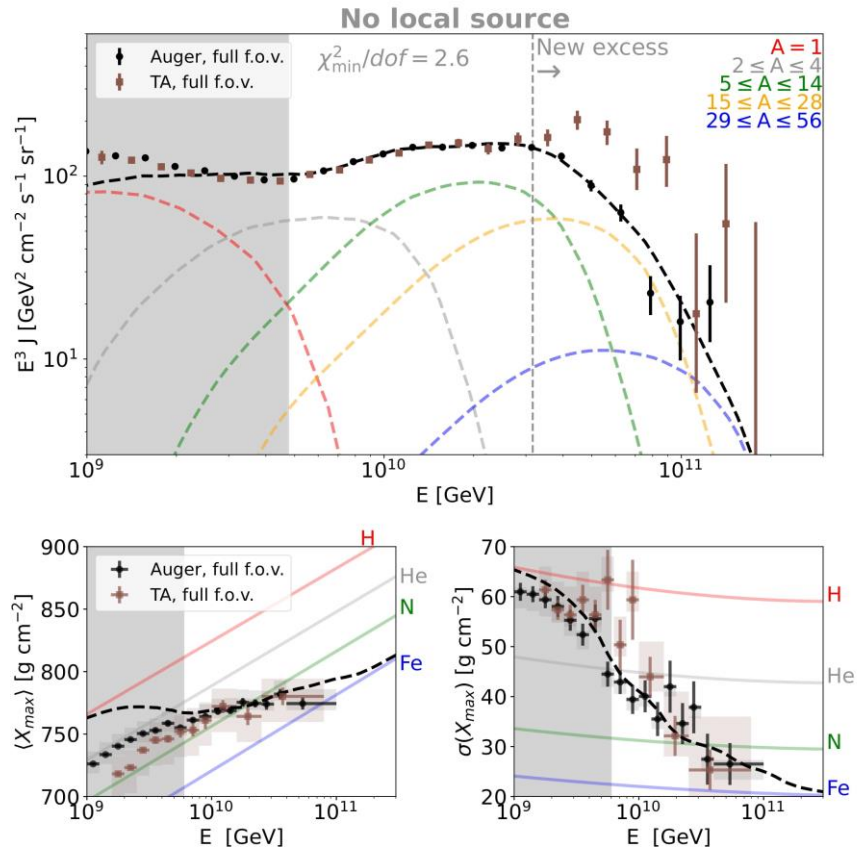
No Local source

Energy-independent shift



Parameters are similar for all cases

2 local minimum: “PAO” and “TA”



Results

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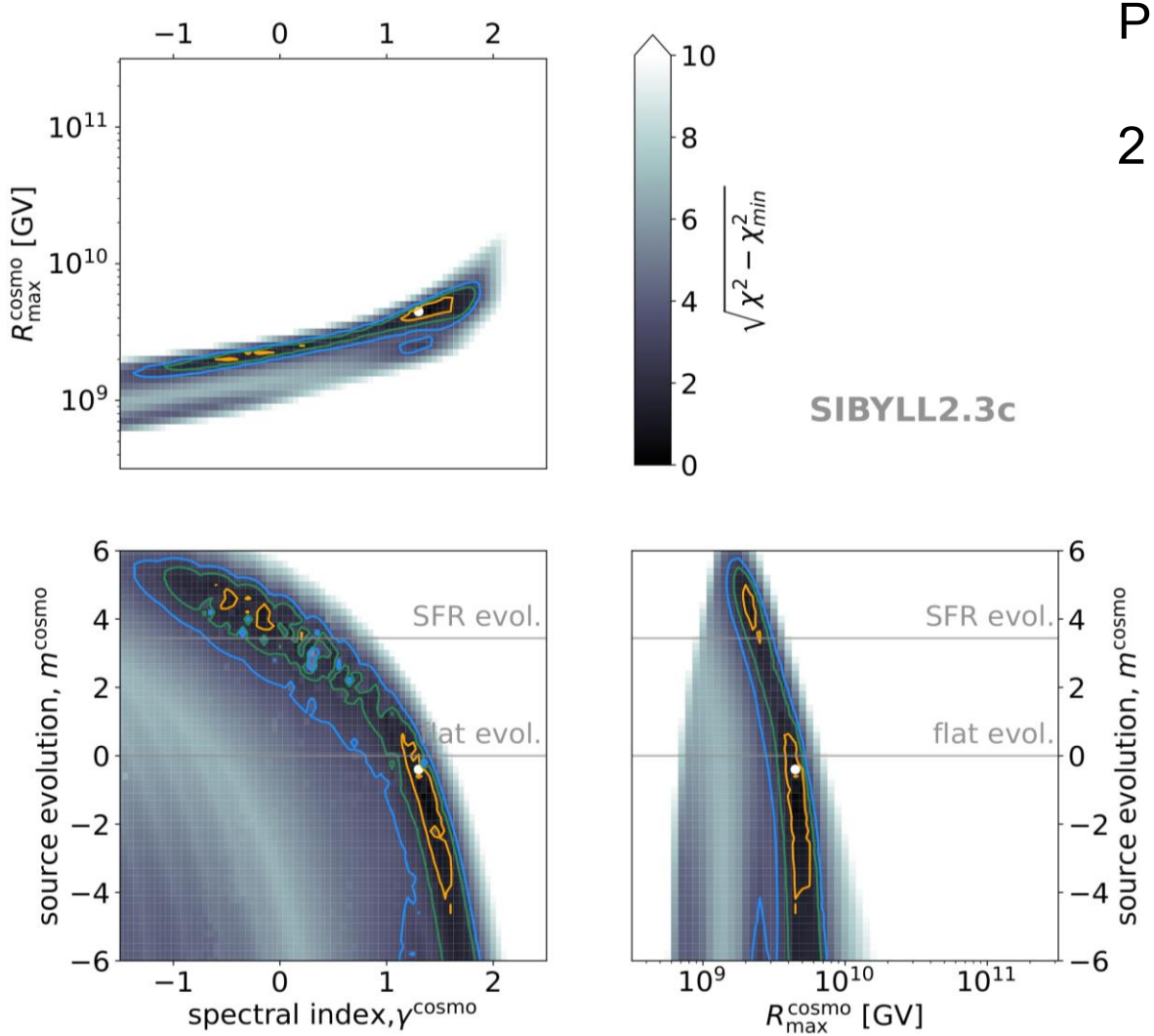
Systematics

Energy-dependent shift



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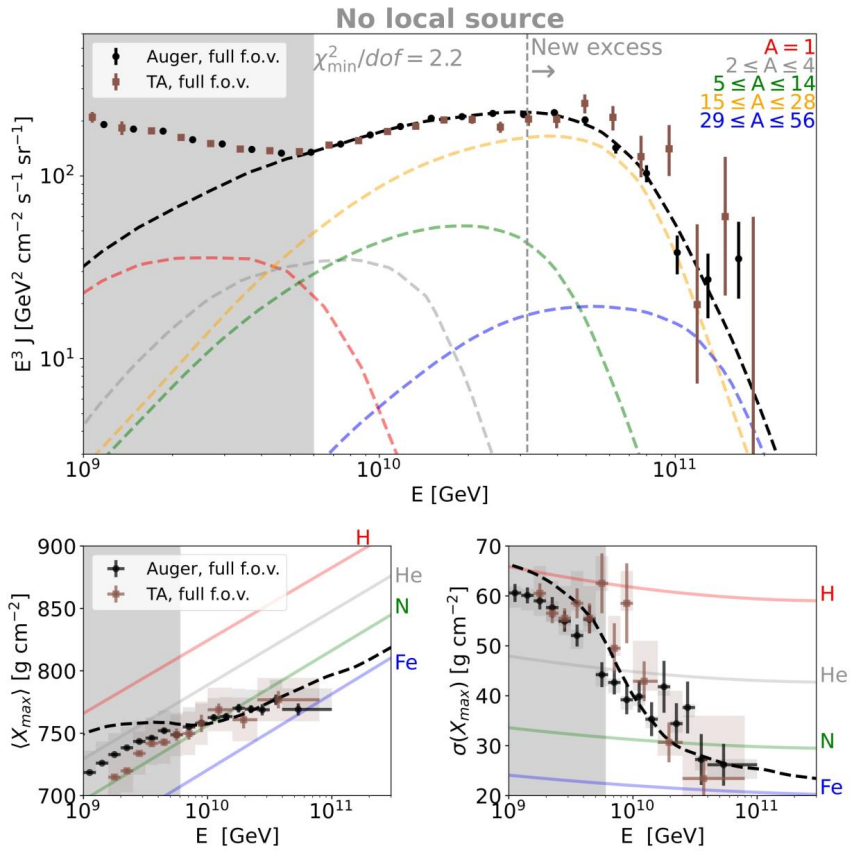


Sources

Spectrum of injected CR

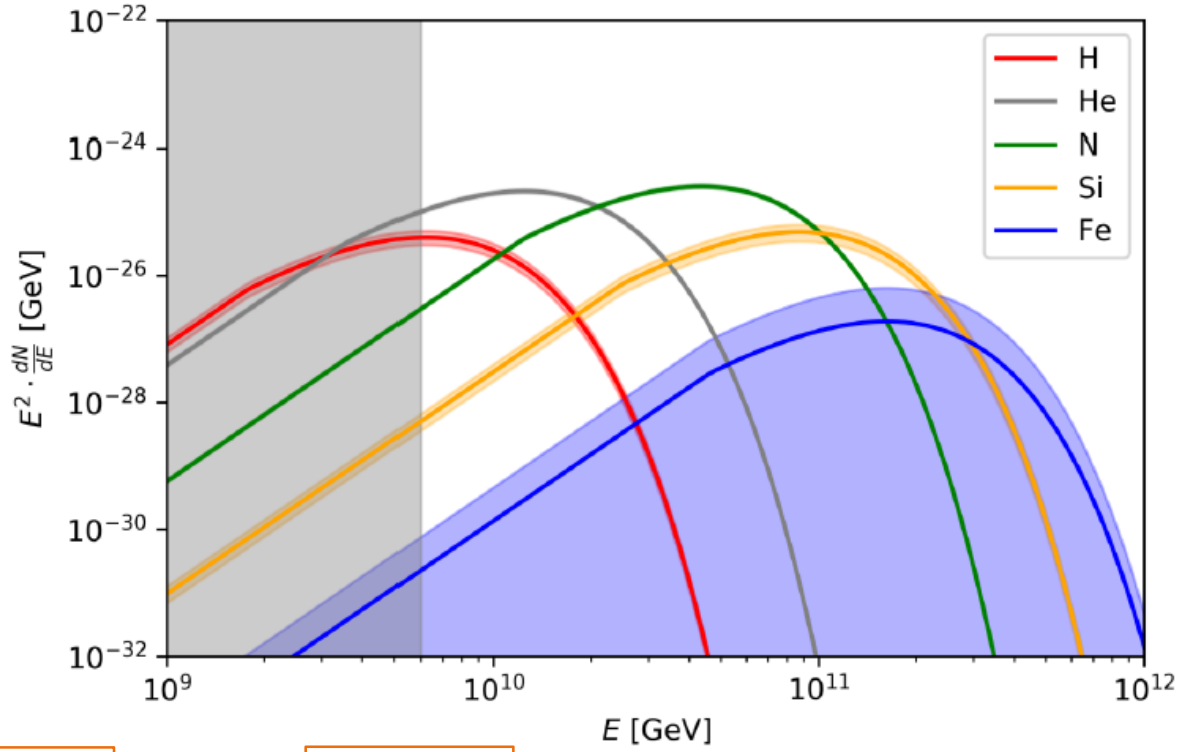
Choices following *Auger Combined Fit*:
Simple *Power-law* with *rigidity-dependent* cut-off

$$J_{source\_A}(E) = \mathcal{J}_A f_{\text{cut}}(E, Z_A, R_{\text{max}}) \left(\frac{E}{10^9 \text{GeV}}\right)^{-\gamma}$$

$$f_{\text{cut}}(E) = \begin{cases} 1 & , E < Z_A R_{\text{max}} \\ \exp\left(1 - \frac{E}{Z_A R_{\text{max}}}\right) & , E > Z_A R_{\text{max}} \end{cases}$$

Source evolution locally as

$$n_{\text{evol}}(z) = (1+z)^m$$
$$z < 1$$
$$n_{\text{evol}}(z) = \delta(z)$$



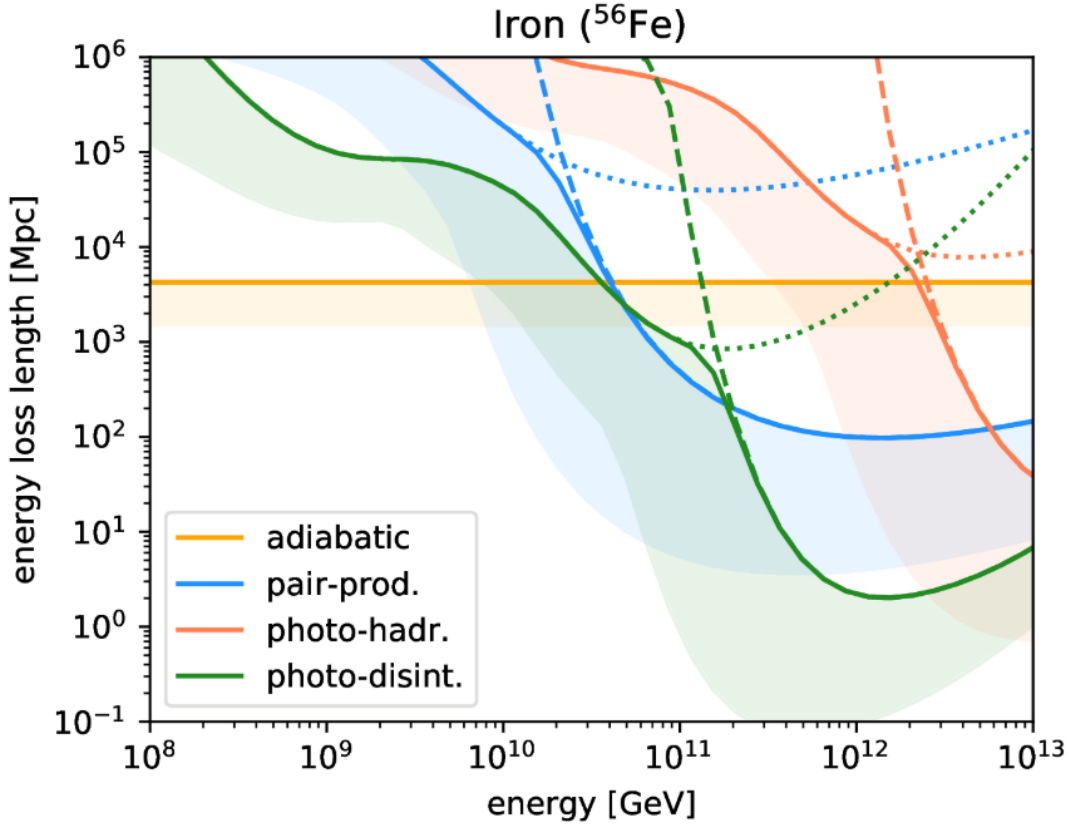
Only *five injection elements:*
H, He, N, Si, Fe

3 main parameters:
m (z), gamma, R

Propagation

Transport equation

- About 50 coupled differential equations
- Speed: **20s – 120s** for single spectrum (depending on number of system species)



$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

adiabatic cooling | pair - production | photo-hadronic / Photo-disintegration | Injection

Jonas Heinze at TeVPA 2018;