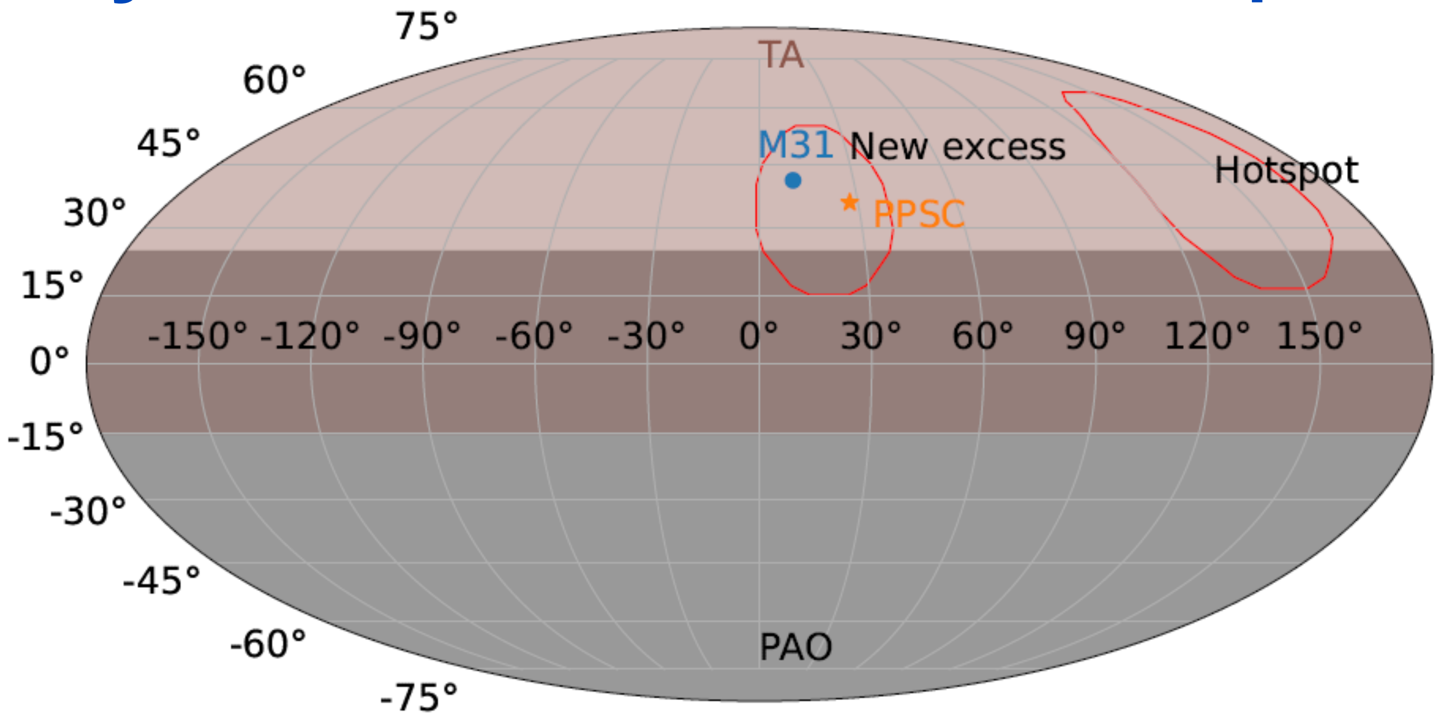
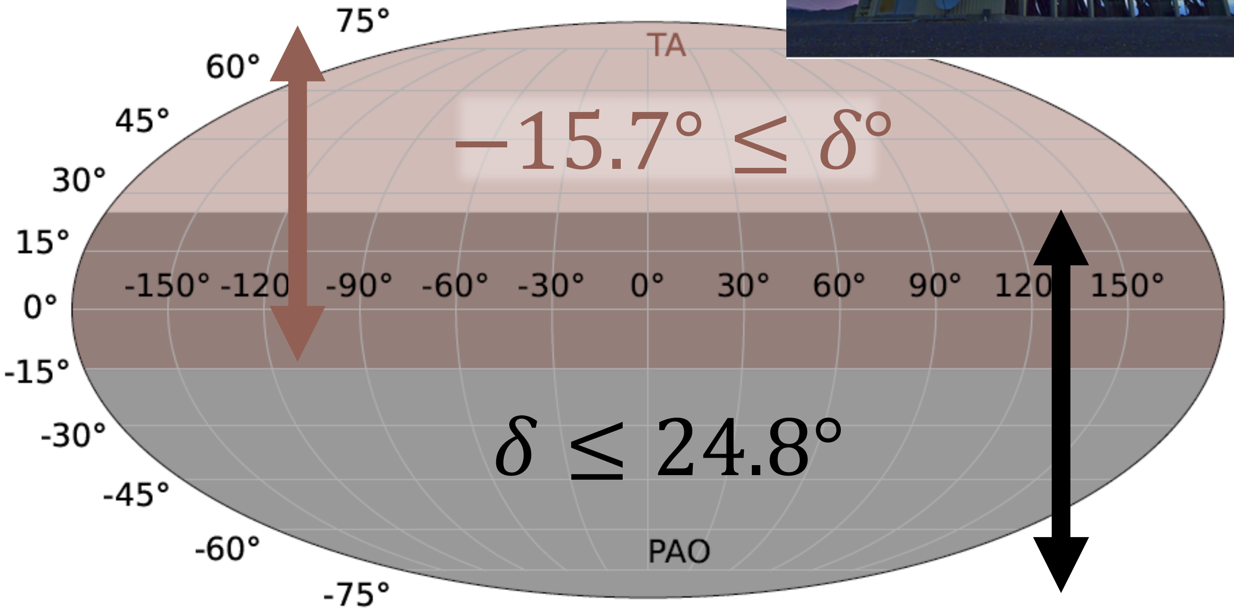
Indication for a Local Source of Ultra-High-Energy Cosmic Rays in the Northern Hemisphere



ARJEN VAN VLIET
PAVLO PLOTKO, XAVIER RODRIGUES, WALTER WINTER
ECRS, 27 JULY 2022

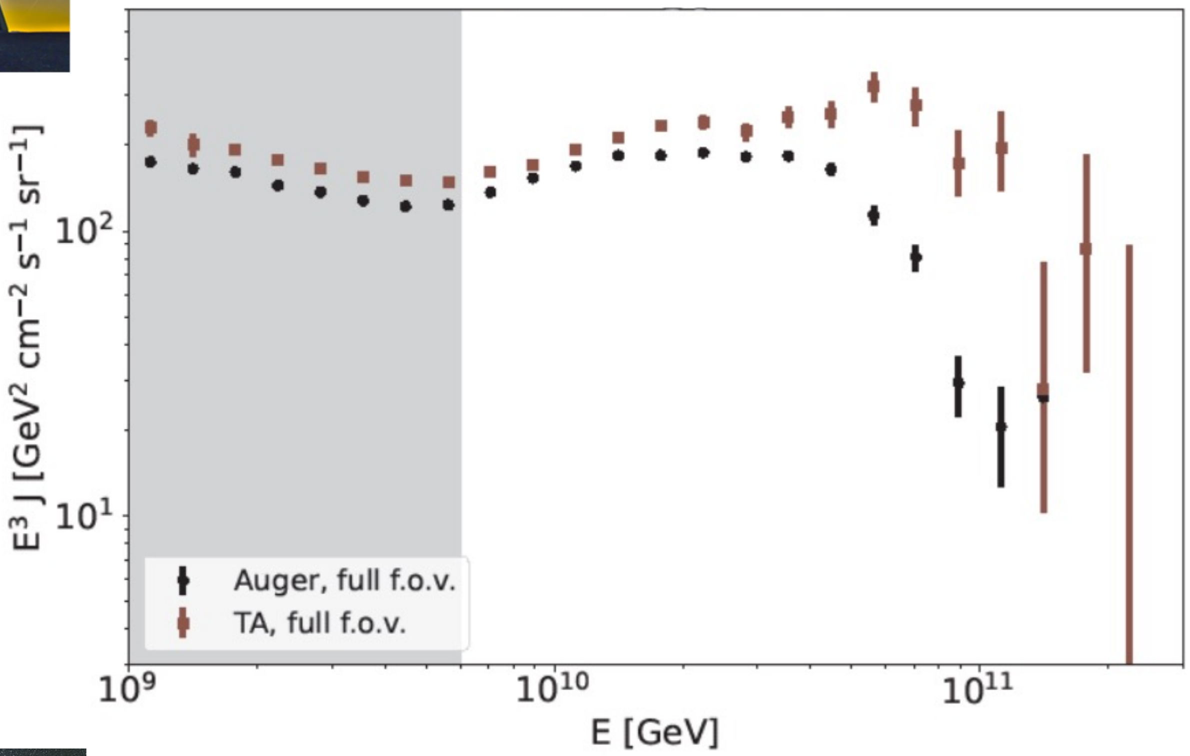
UHECR detectors: TA vs PAO

Telescope Array (TA), USA

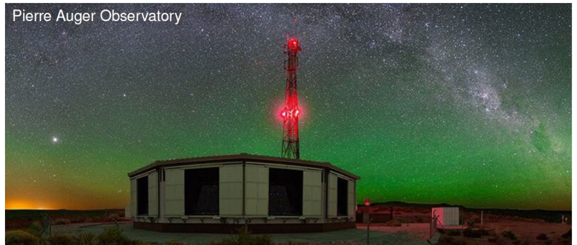


Energy systematic uncertainties:

14%   21%

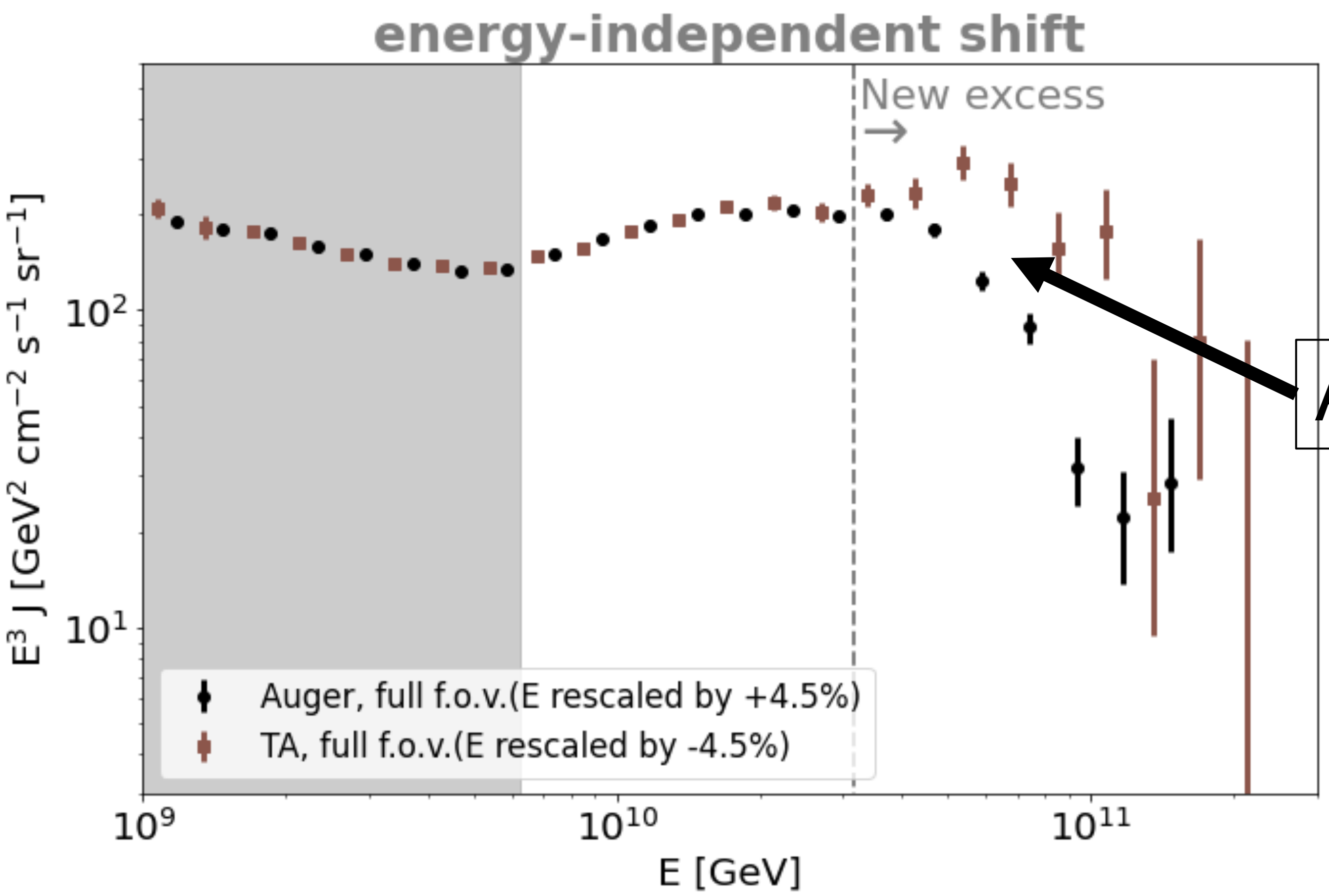


Pierre Auger Observatory (PAO) , Argentina



Why are there differences?

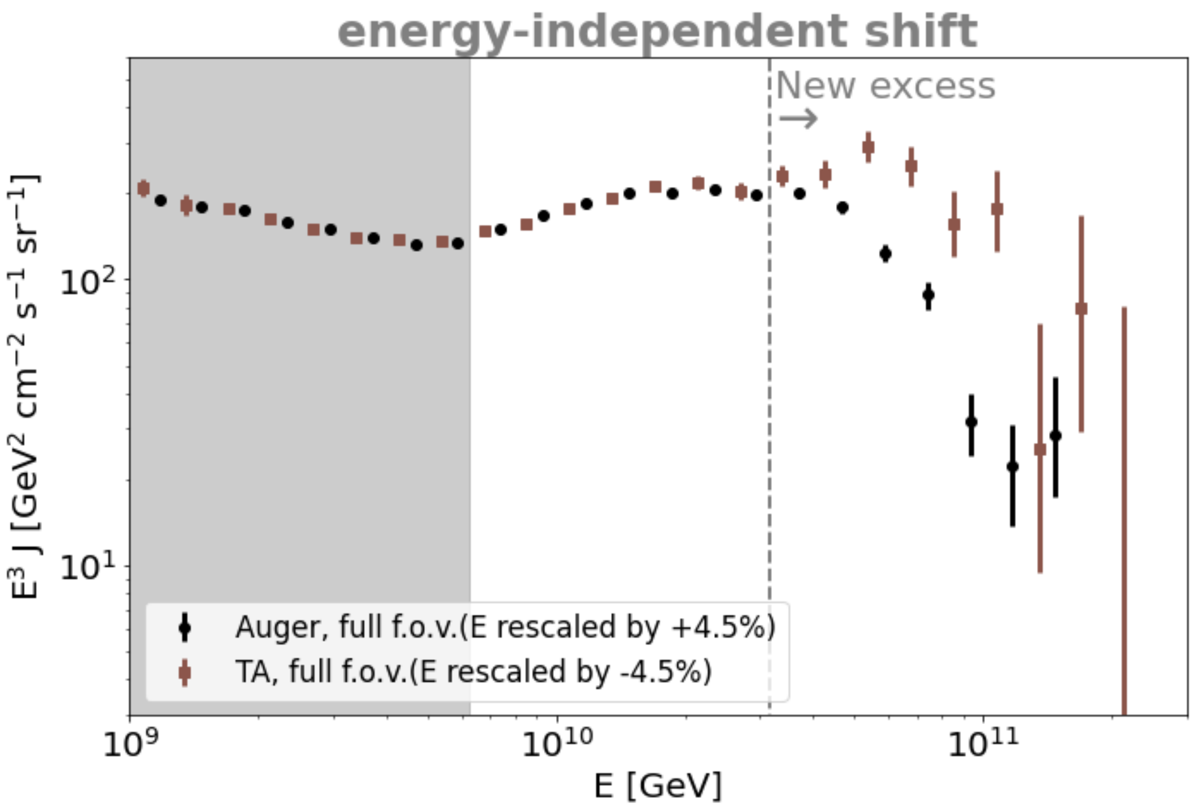
Differences in spectrum after rescaling within uncertainties



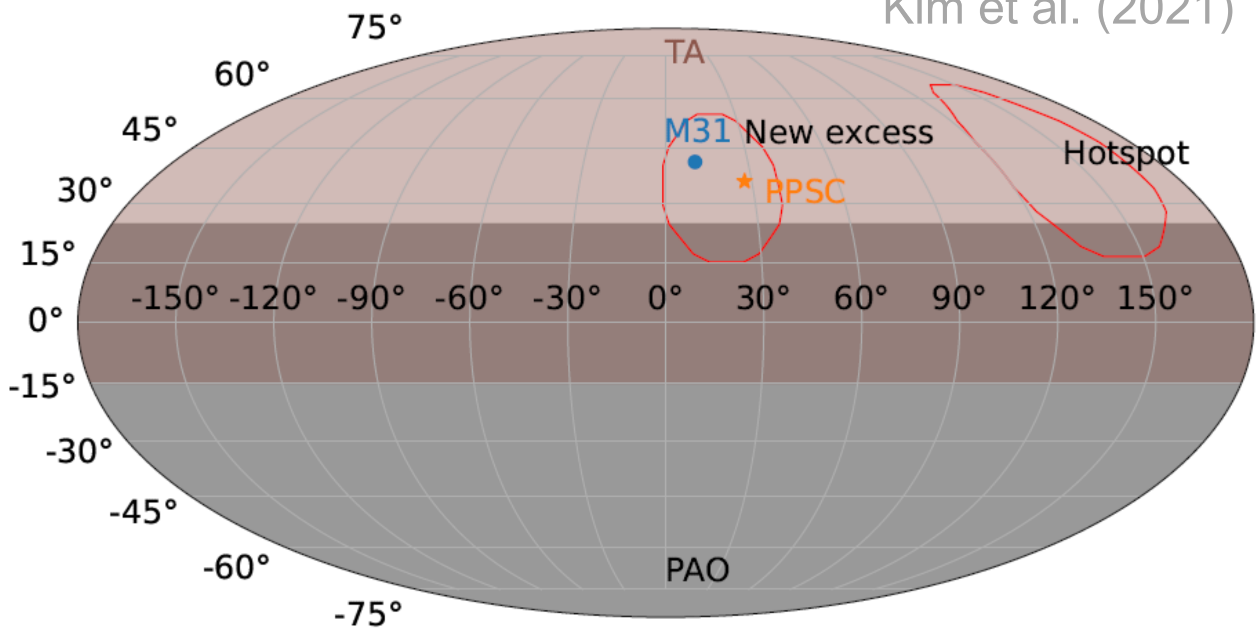
Astrophysical origin?


PAO
Our
Goal
TA
Pierre Auger Observatory
Telescope Array

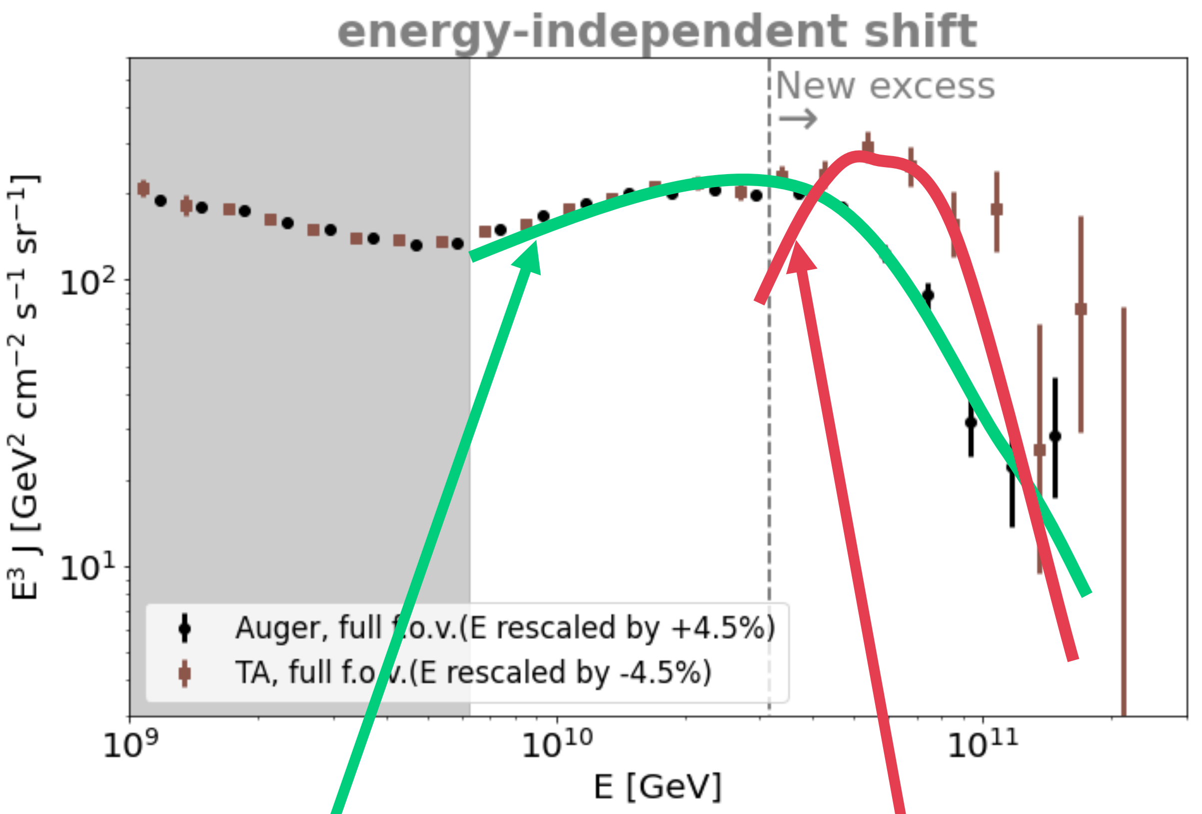
The idea: explain differences with a local source in the North

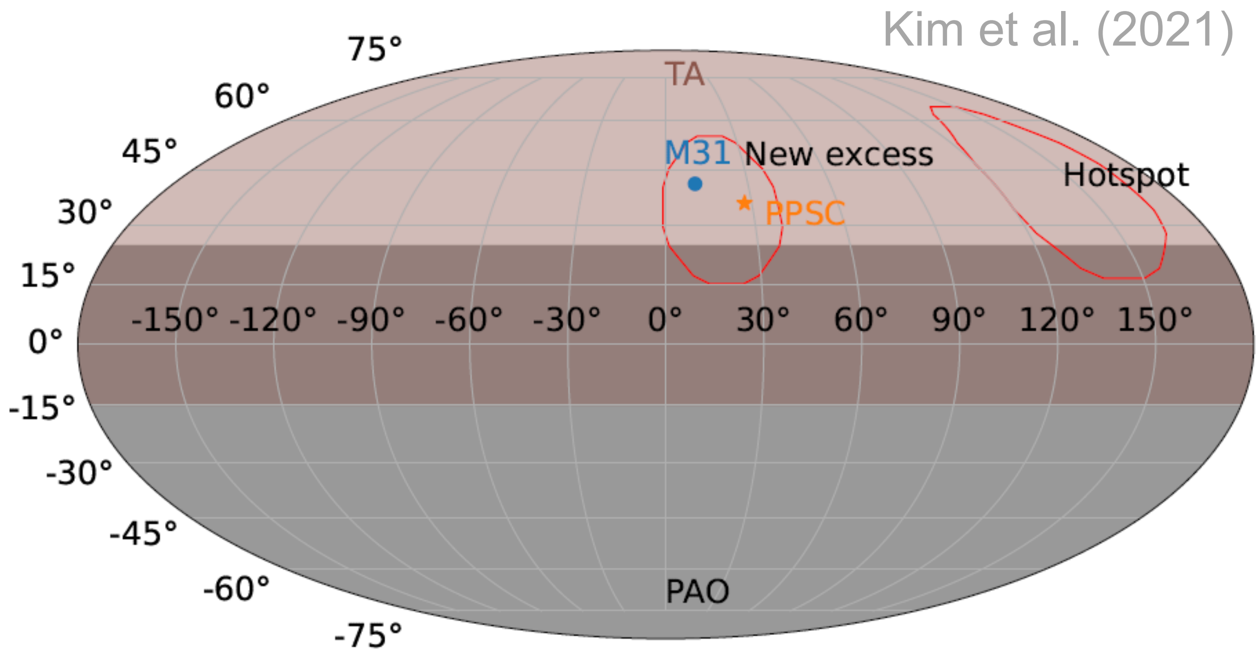


Kim et al. (2021)



The idea: explain differences with a local source in the North

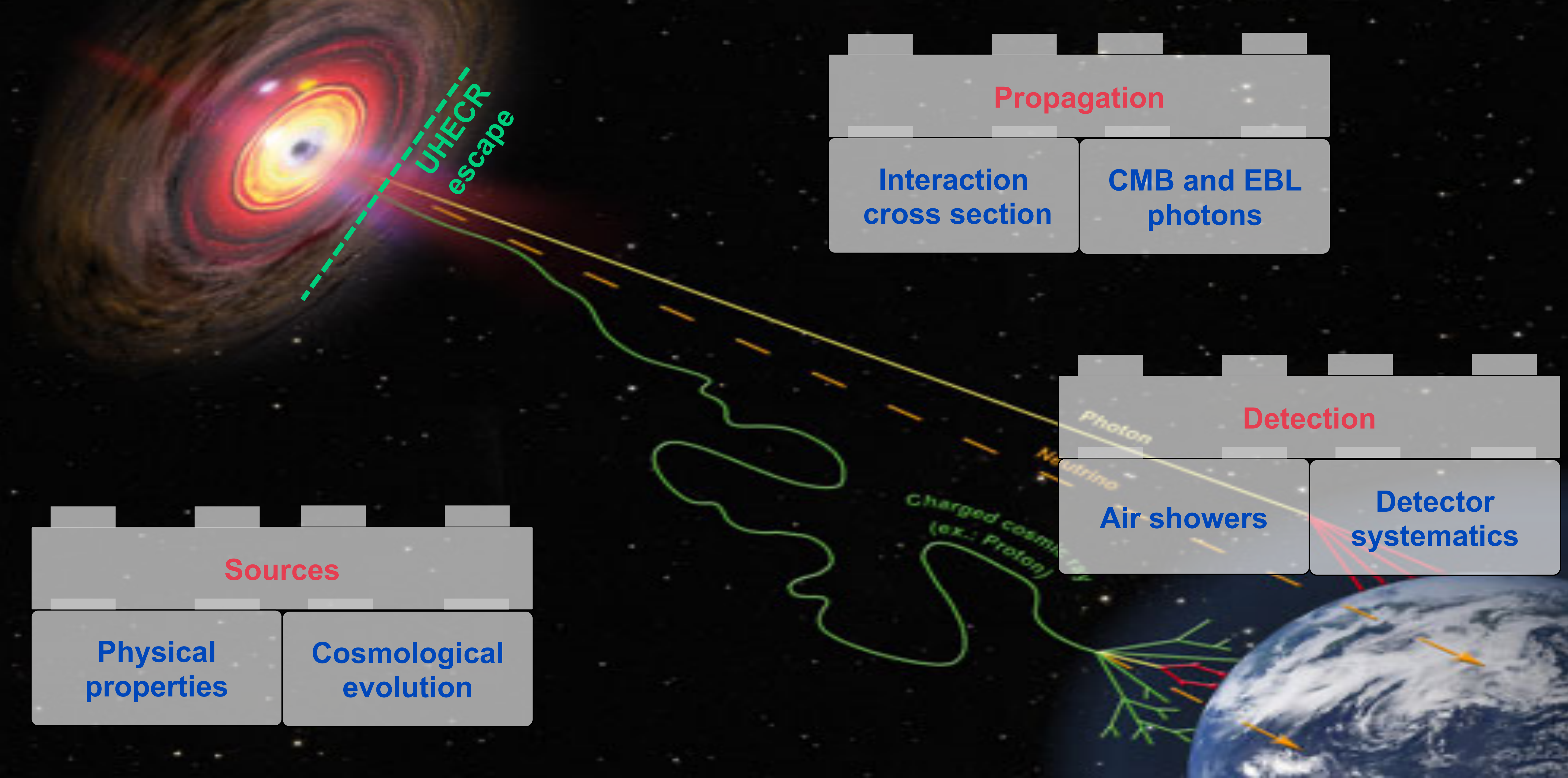




1. Isotropic source distribution – TA and PAO
2. Local source in Northern hemisphere – TA only

Heinze et al. (2019)

Propagation including Nuclear Cascade



UHECR source assumptions

Plotko et al. in prep.

Choices following Auger Combined Fit (and many other papers):
Simple power-law with rigidity dependent cut-off

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

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

Source evolution locally as

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

Five injected elements:
H, He, N, Si, Fe

See also presentation by Antonio Condorelli
And PAO 2017, Alves Batista et al. 2019, Heinze et al. 2019

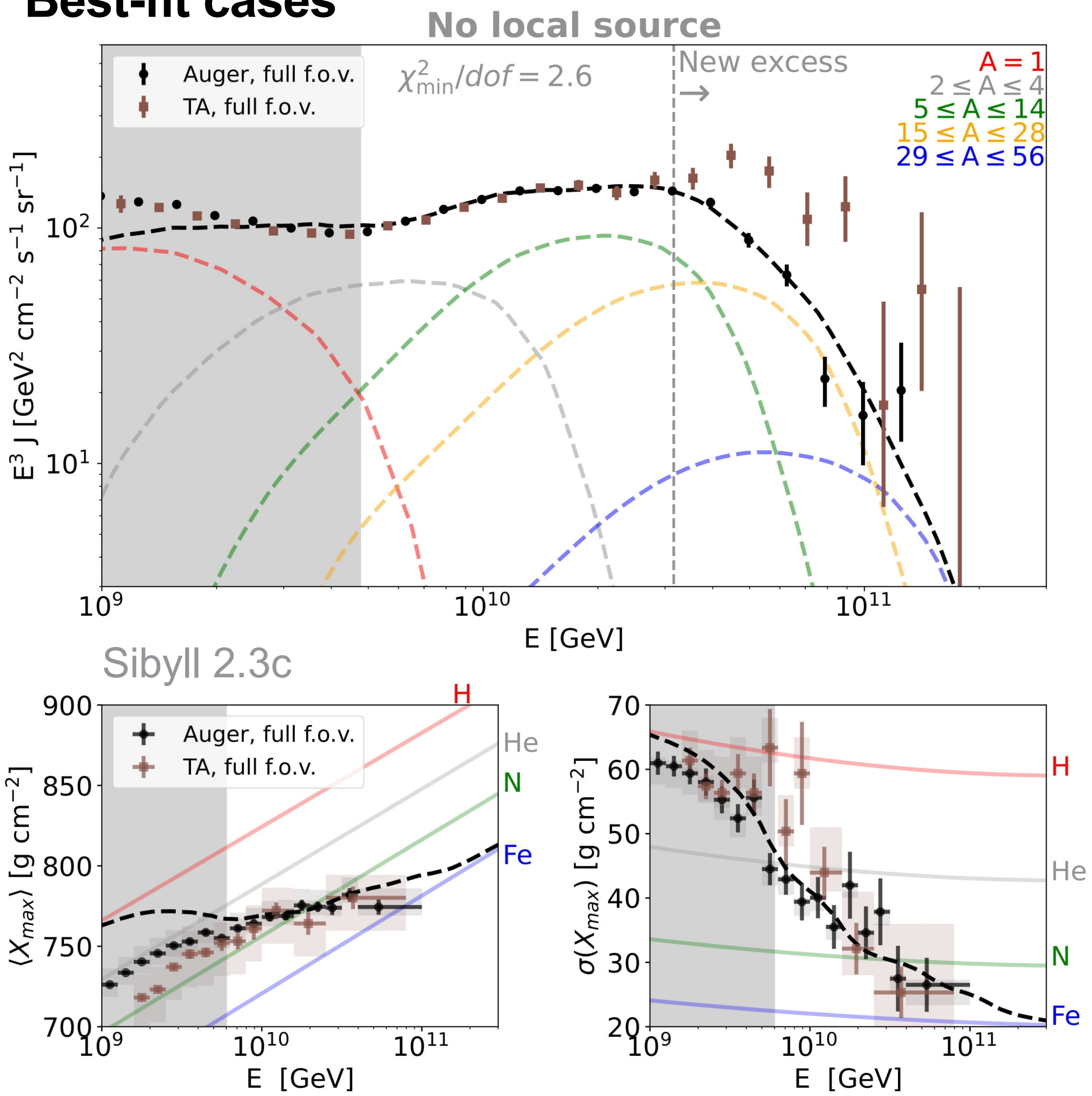
Main parameters:
m, *γ*, R_{max}, elemental fractions

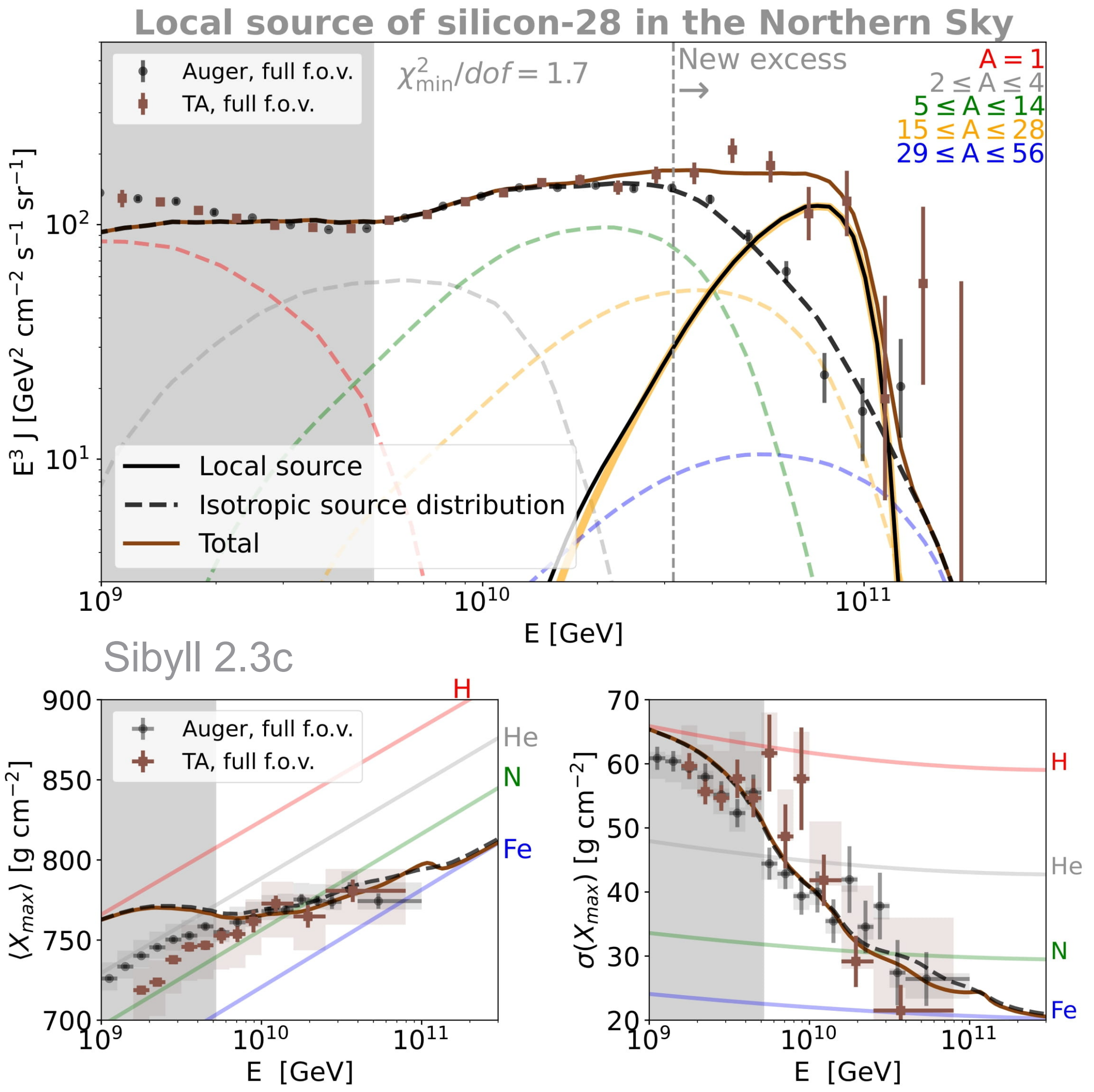
Hadronic interaction models:
Sibyll 2.3c, Epos-LHC, QGSJET-II-04

Without and with a local source

Plotko et al. in prep.

Best-fit cases





Local source

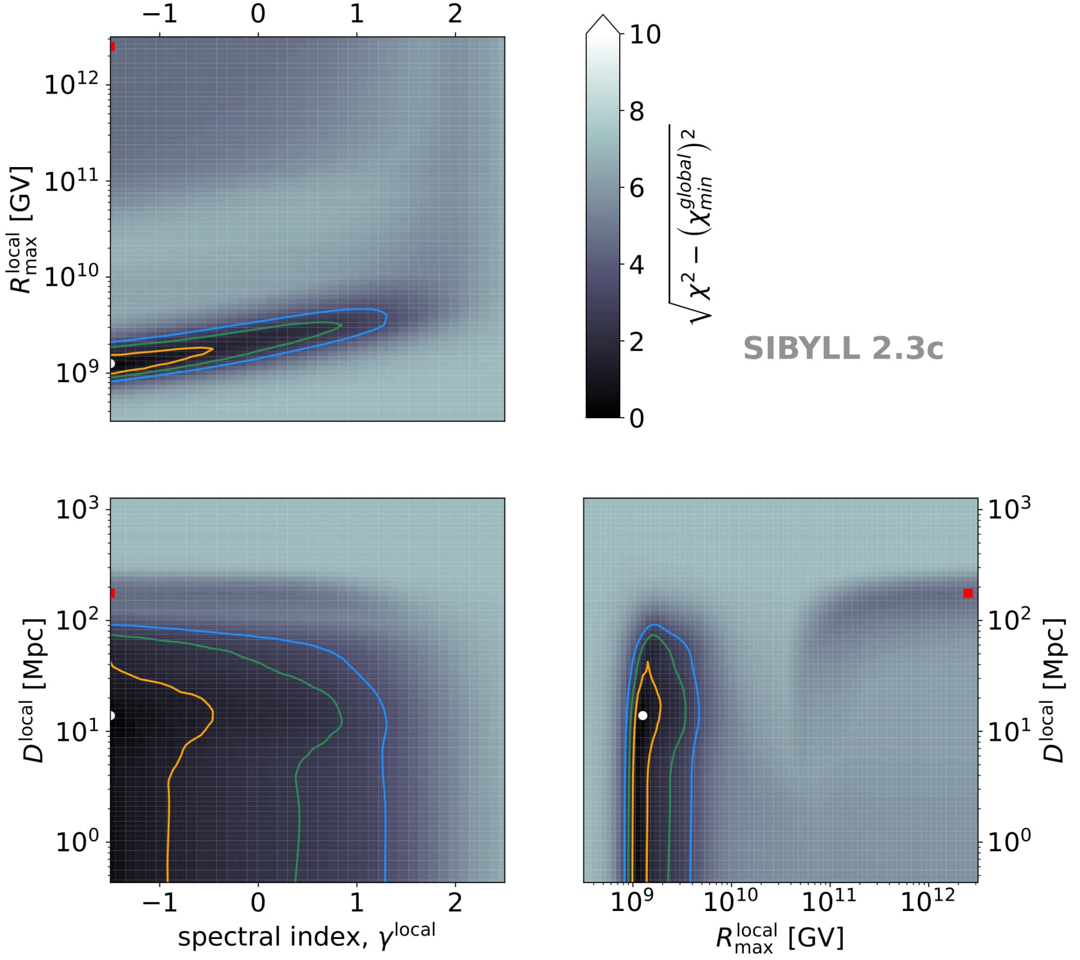
Plotko et al. in prep.

Composition assumption for local source: dominated by one elemental group where it dominates the spectrum

Best-fit case:

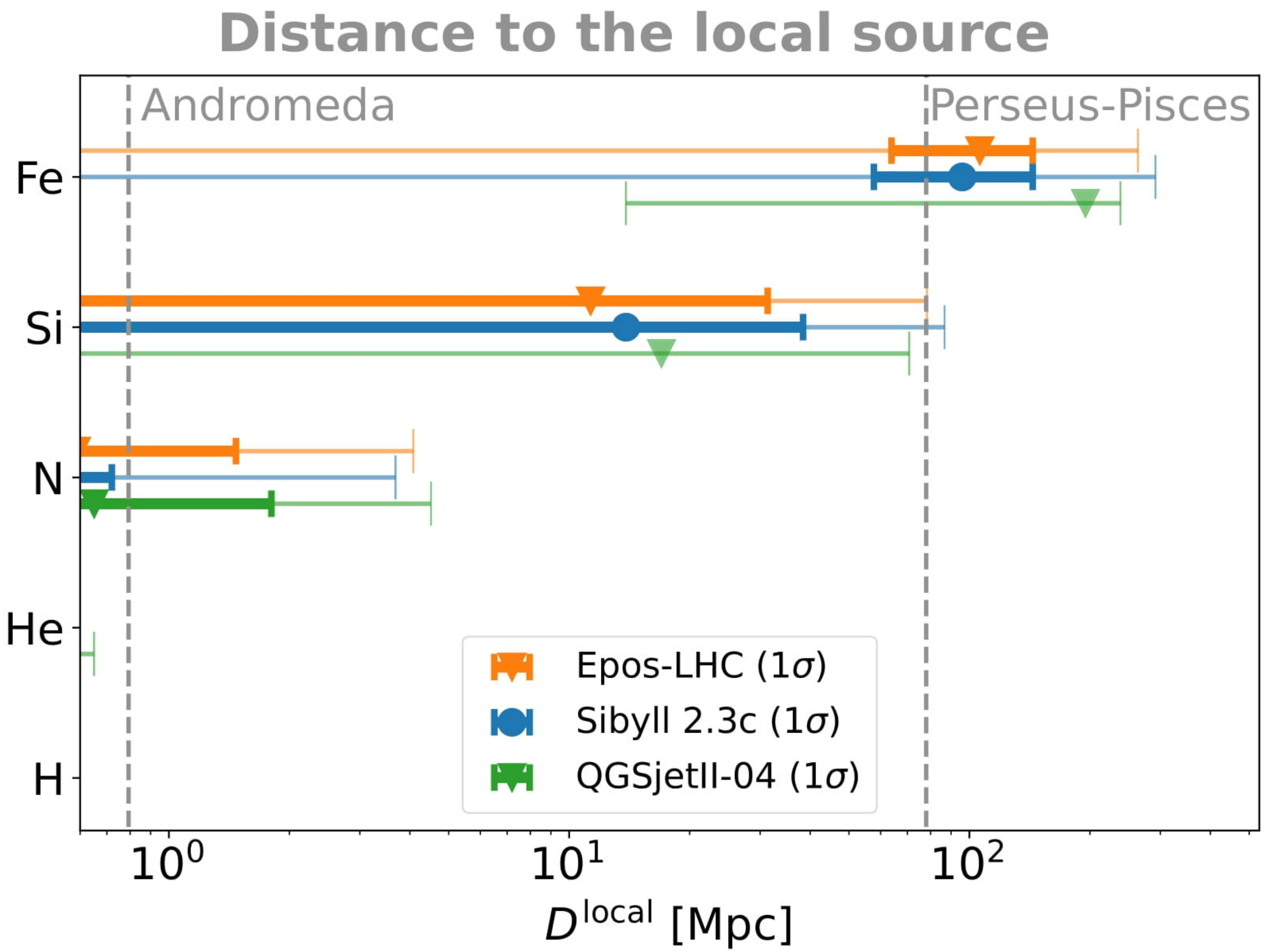
- Dominant elemental group: Si
- Distance $13.9^{+9.2}_{-13.9}$ Mpc
- Luminosity $1.1^{+2.0}_{-1.1} \cdot 10^{42}\,{}^{\mathrm{erg}}/_{\mathrm{s}}$
- The maximum rigidity $1.3^{+0.2}_{-0.1} \cdot 10^{9}$ GV

Local source of silicon-28 in the Northern Sky



Local source

Plotko et al. in prep.

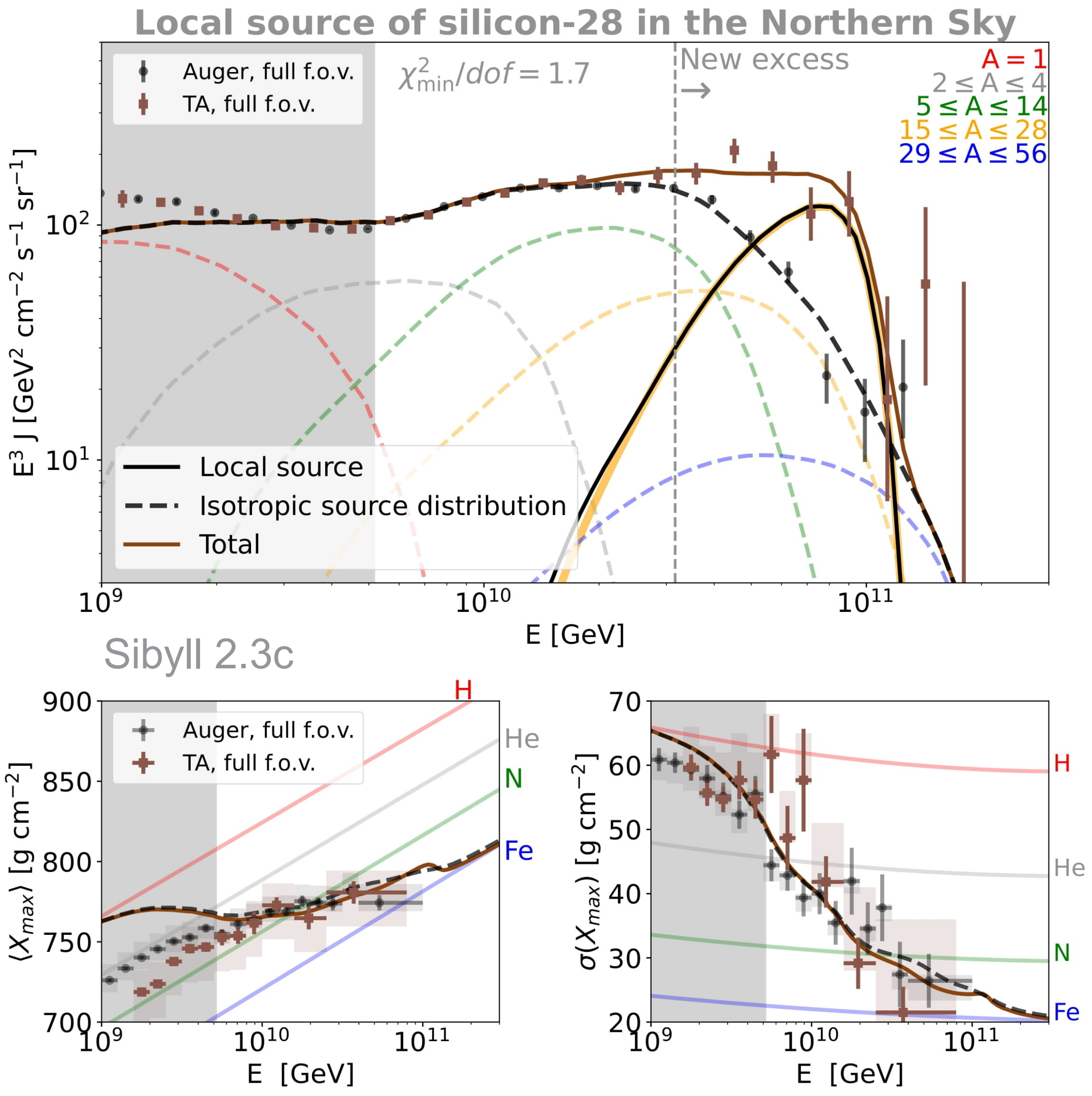


1. Intermediate to heavy elements preferred.
2. He and H disfavored.
3. Distance depends on the type of composition.

Conclusions

Plotko et al. in prep.

- Differences in the UHECR spectrum between PAO and TA can be explained by a dominant local source in the northern hemisphere.
- The presence of that local source is favored at the 5.6σ level compared to the scenario where both experiments observe the same isotropic UHECR flux.
- The best-fit case for the local source:
    - Source at < 23 Mpc
    - Emitting predominantly Si-group nuclei



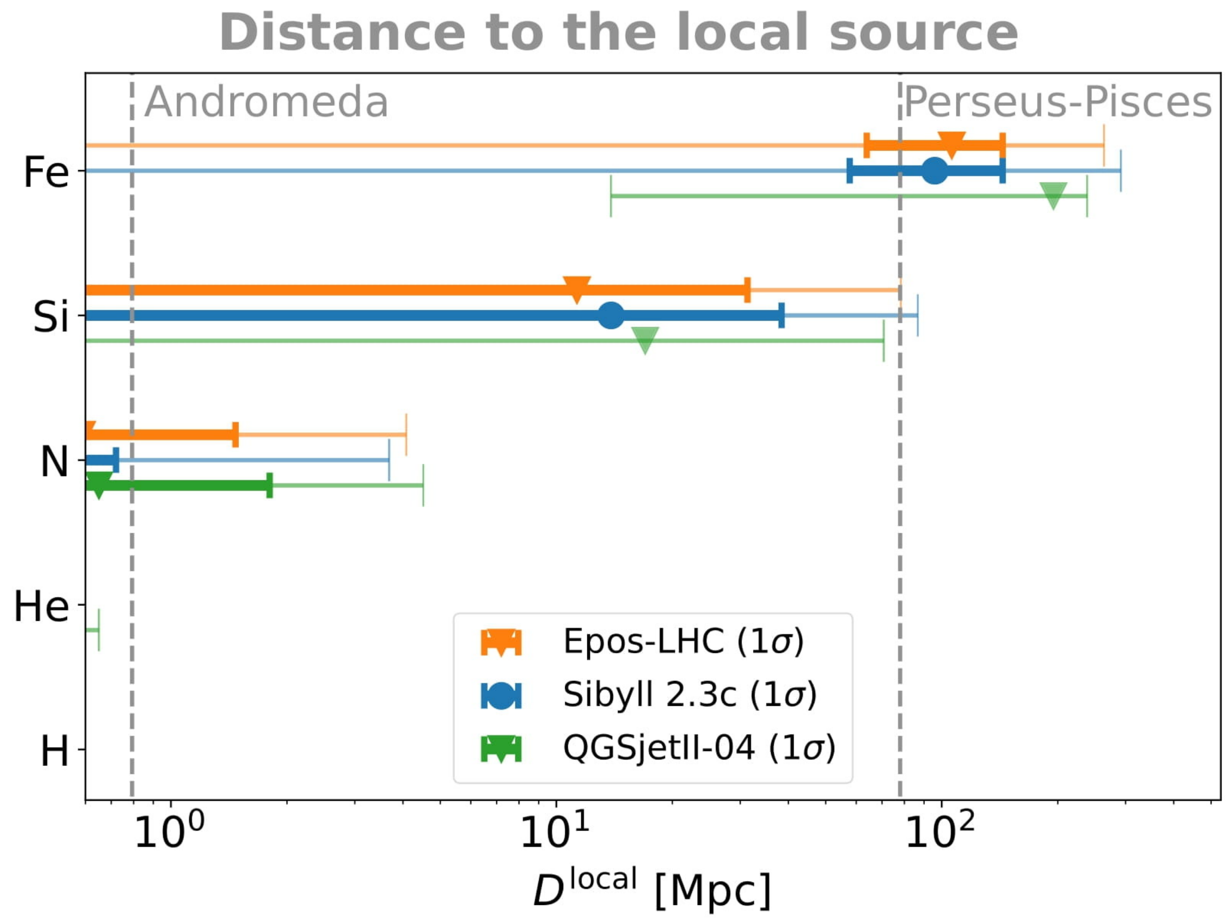
Backup Slides

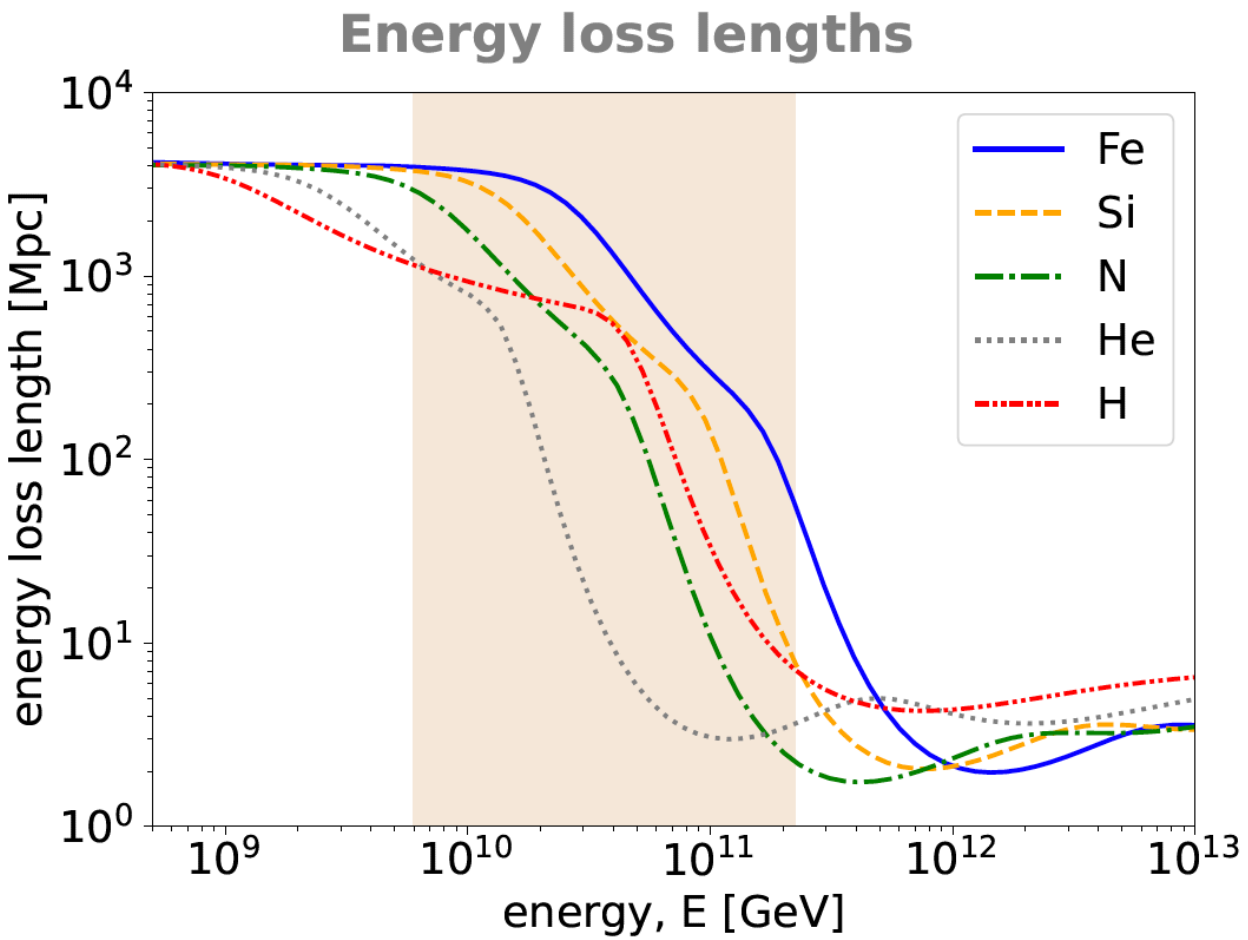
		Isotropic source distribution only			Isotropic source distribution + local source		
		SIBYLL 2.3C	EPOS-LHC	QGSJET-II-04	SIBYLL 2.3C	EPOS-LHC	QGSJET-II-04
Isotropic source distrib.	$\gamma^{\rm iso}$	$-0.75^{+0.15}_{-0.15}$	$0.10^{+0.05}_{-0.1}$	$-0.60^{+0.03}_{-0.05}$	$-0.75^{+0.15}_{-0.45}$	$-0.85^{+0.05}_{-0.05}$	$-0.65^{+0.05}_{-0.03}$
	$R^{\rm iso}_{\rm max}$ (GV)	$1.8^{+0.2}_{-0.2}\times10^9$	$2.5^{+0.2}_{-0.2}\times10^9$	$2.5^{+0.2}_{-0.2}\times10^9$.	$1.8^{+0.2}_{-0.2}\times10^9$	$2.0^{+0.2}_{-0.2}\times10^9$	$2.5^{+0.2}_{-0.2}\times10^9$
	$m^{\rm iso}$	$3.6^{+0.6}_{-0.6}$	<-4.8	<-5.8	$3.8^{+0.6}_{-0.6}$	$0.6^{+0.6}_{-0.6}$?	<-5.8
	f_A(%)						
	H	$0.00^{+100.0}_{-0.00}$	$0.00^{+86.76}_{-0.00}$	$0.00^{+99.94}_{-0.00}$	$0.00^{+99.93}_{-0.0}$	$0.00^{+99.88}_{-0.00}$	$0.00^{+99.91}_{-0.00}$
	He	$86.01^{+1.99}_{-2.26}$	$88.80^{+0.33}_{-0.34}$	$92.98^{+0.26}_{-0.27}$	$80.50^{+4.15}_{-4.95}$	$92.13^{+0.49}_{-0.51}$	$92.72^{+0.25}_{-0.26}$
	N	$13.32^{+0.73}_{-0.70}$	$10.59^{+0.41}_{-0.40}$	$6.87^{+0.27}_{-0.26}$	$18.80^{+0.94}_{-0.90}$	$7.74^{+0.31}_{-0.30}$	$7.15^{+0.20}_{-0.19}$
	Si	$0.57^{+0.11}_{-0.09}$	$0.61^{+0.11}_{-0.09}$	$0.14^{+0.03}_{-0.03}$	$0.68^{+0.27}_{-0.19}$	$0.13^{+0.05}_{-0.03}$	$0.13^{+0.03}_{-0.03}$
	Fe	$0.010^{+0.008}_{-0.004}$	$0.015^{+0.017}_{-0.008}$	$0.005^{+0.002}_{-0.002}$	$0.012^{+0.012}_{-0.006}$	$0.003^{+0.003}_{-0.002}$	$0.005^{+0.002}_{-0.002}$
Loc. source	isotope				silicon-28	silicon-28	nitrogen-14
	$\gamma^{\rm local}$				<-1.0	<-1.1	<-1.1
	$R^{\rm local}_{\rm max}$ (GV)				$1.3^{+0.2}_{-0.1}\times10^8$	$2.3^{+0.3}_{-0.1}\times10^8$	$2.5^{+0.3}_{-0.3}\times10^9$
	$L^{\rm local}_{\rm CR}$ (erg s^{-1})				$1.1^{+2.0}_{-1.1}\times10^{42}$	$7.3^{+18.0}_{-7.3}\times10^{41}$	$<1.0\times10^{40}$
	$D^{\rm local}$ (Mpc)				$13.9^{+9.2}_{-13.9}$	$11.3^{+9.5}_{-11.3}$	$<+1.4$
Systematics	$\delta^{\rm PAO}_E$(%)	$-11.6^{+2.1}_{-0.5}$	$-8.97^{+1.1}_{-0.5}$	$10.8^{+0.0}_{-0.3}$	$-11.7^{+0.8}_{-1.5}$	$-9.5^{+0.5}_{-0.6}$	$10.9^{+0.9}_{-0.0}$
	$\delta^{\rm TA}_E$(%)	$-20.5^{+1.9}_{-0.5}$	$-18.3^{+1.0}_{-0.4}$	$10.8^{+0.0}_{-0.3}$	$-19.7^{+0.7}_{-1.3}$	$-17.6^{+0.5}_{-0.6}$	$1.1^{+0.8}_{-0.00}$
	$\delta^{\rm PAO}_{\langle X_{\rm max}\rangle}$(%)	-25^{+25}_{-27}	-100.0^{+0}_{-0}	-100^{+0}_{-0}	-26^{+26}_{-23}	-100^{+0}_{-0}	-100^{+0}_{-0}
	$\delta^{\rm TA}_{\langle X_{\rm max}\rangle}$(%)	18^{+12}_{-12}	-18^{+5}_{-3}	-47^{+2}_{-0}	22^{+13}_{-11}	-12^{+4}_{-5}	-31^{+0}_{-2}
	$\delta^{\rm PAO}_{\sigma(X_{\rm max})}$(%)	50^{+26}_{-30}	-59^{+15}_{-9}	100^{+0}_{-0}	56^{+27}_{-24}	-73^{+11}_{-11}	100^{+0}_{-0}
	$\delta^{\rm TA}_{\sigma(X_{\rm max})}$(%)	-41^{+7}_{-9}	-90^{+4}_{-2}	3^{+3}_{-0}	-83^{+10}_{-9}	-100^{+0}_{-0}	-9^{+0}_{-3}
	χ^2/d.o.f.	109.1/44	130.4/44	269.6/44	67.6/40	87.8/40	239.6/40
	Favored vis-a-vis isotropic-only				5.6σ	5.7σ	4.6σ

Plotko et al. in prep.

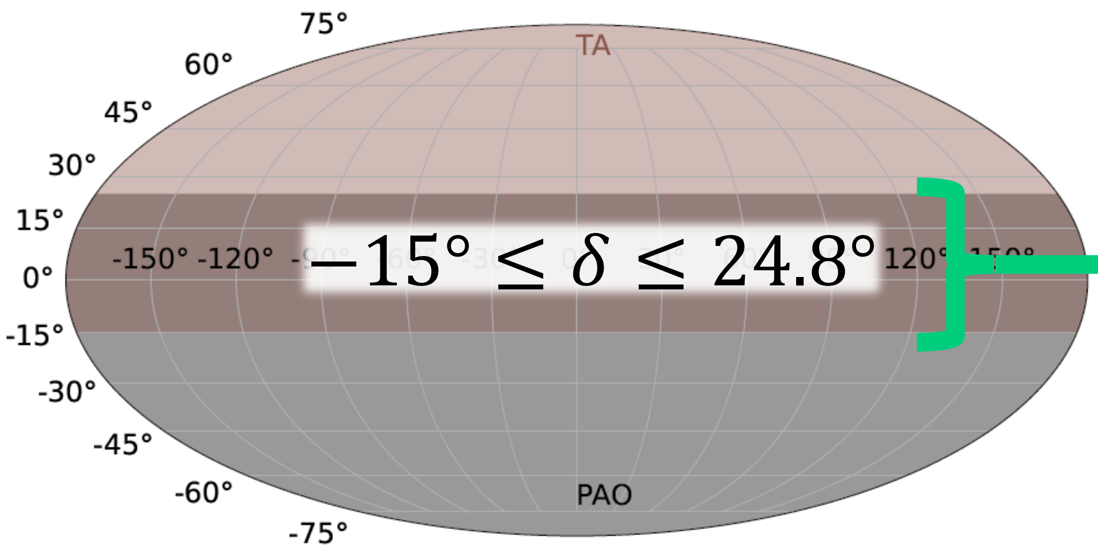
Local source

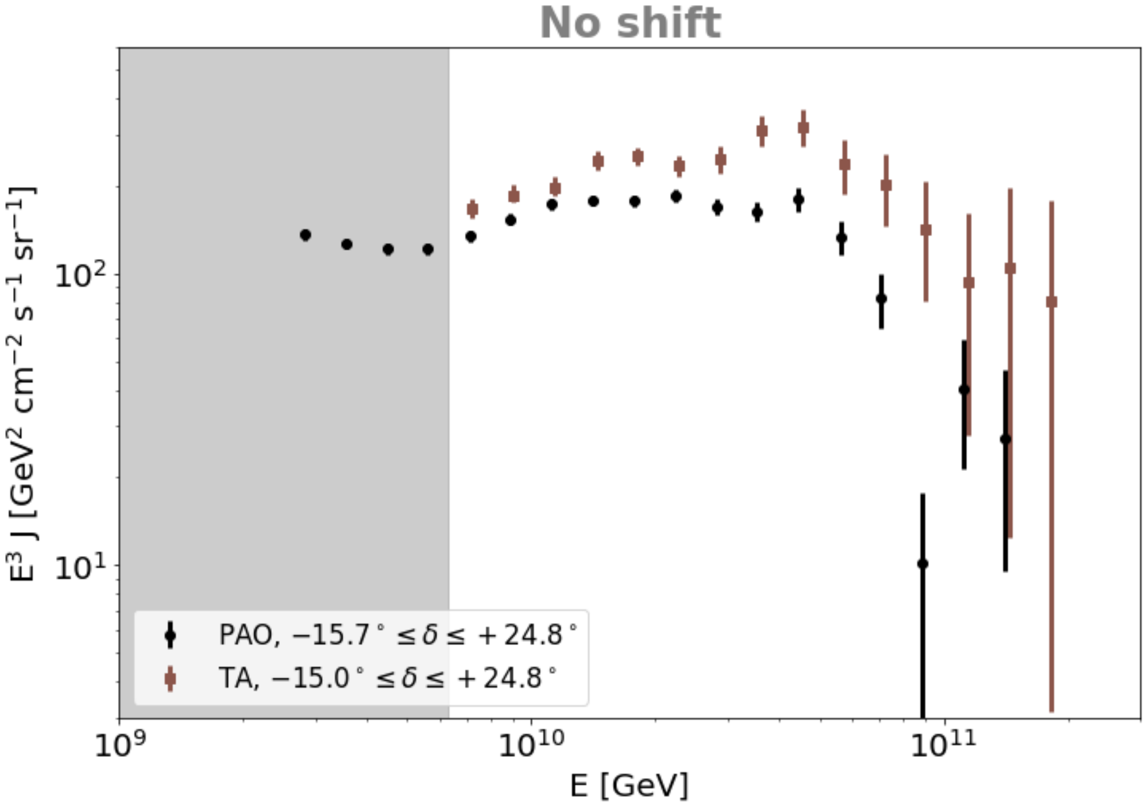
Plotko et al. in prep.





Joint TA/PAO group for UHECR spectrum





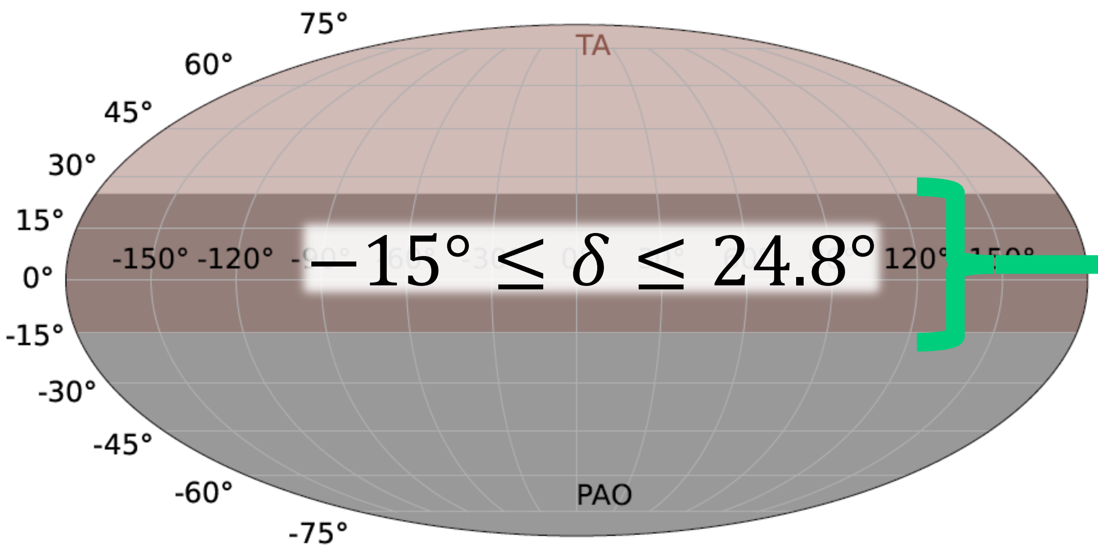
PAO and TA see the same part of the sky

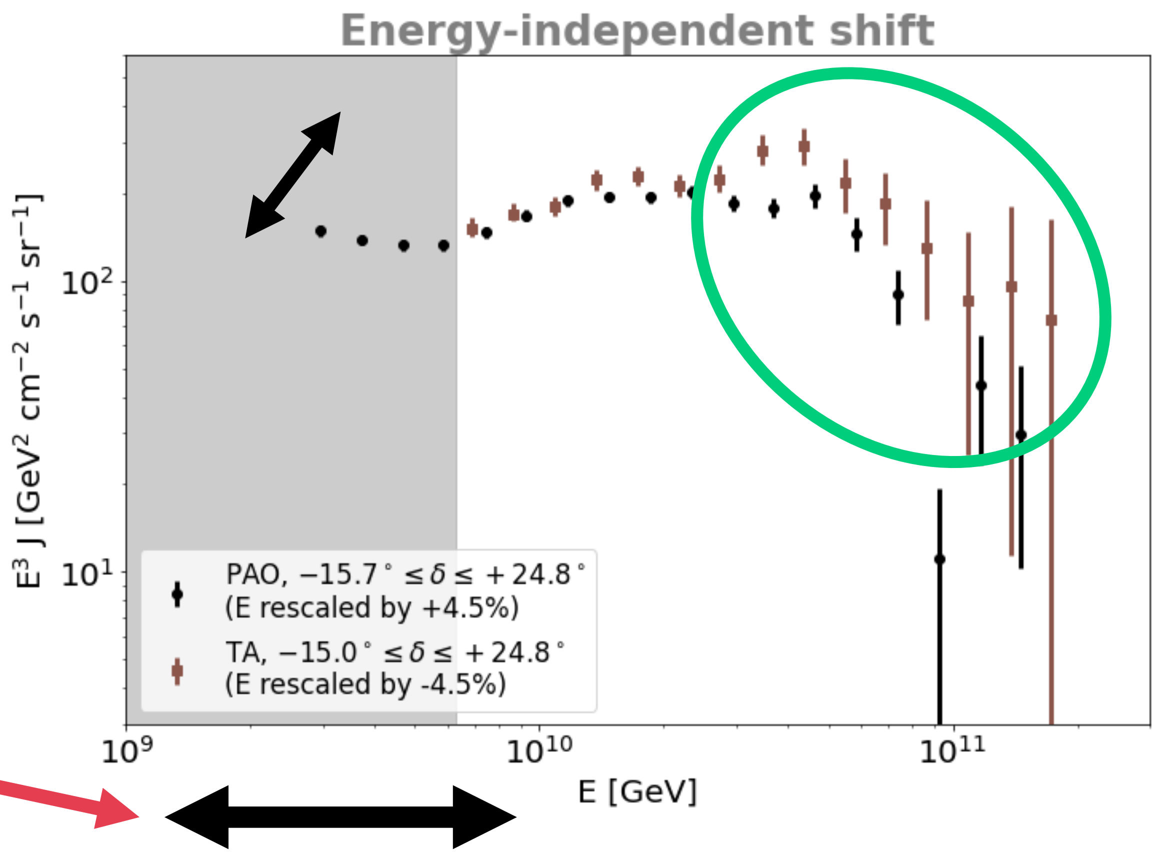
⇩

PAO and TA should observe the same spectrum?

Joint spectrum group
(ICRC 2017, 2019 and 2021)

Joint TA/PAO group for UHECR spectrum

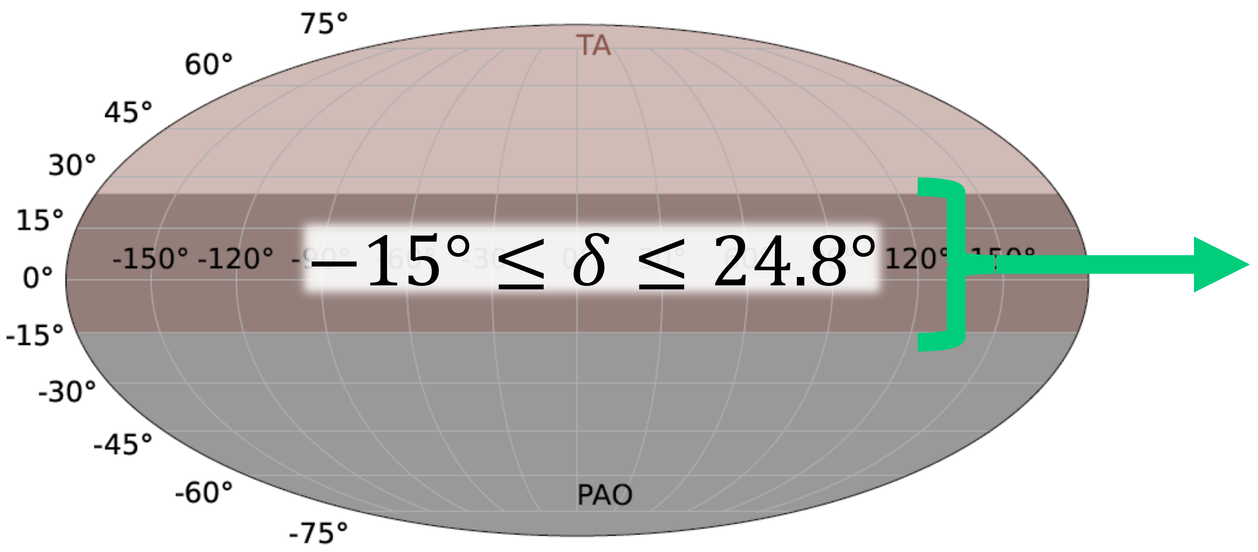


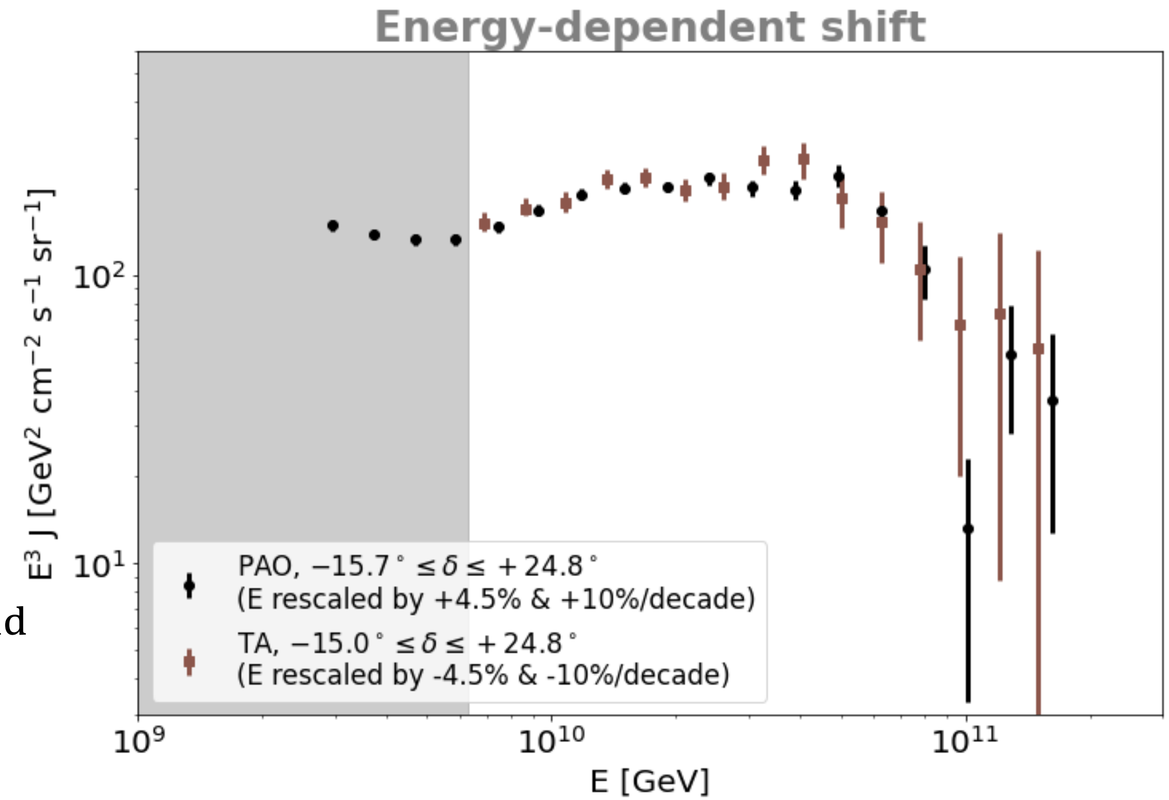


Energy-independent shift:

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

Joint TA/PAO group for UHECR spectrum

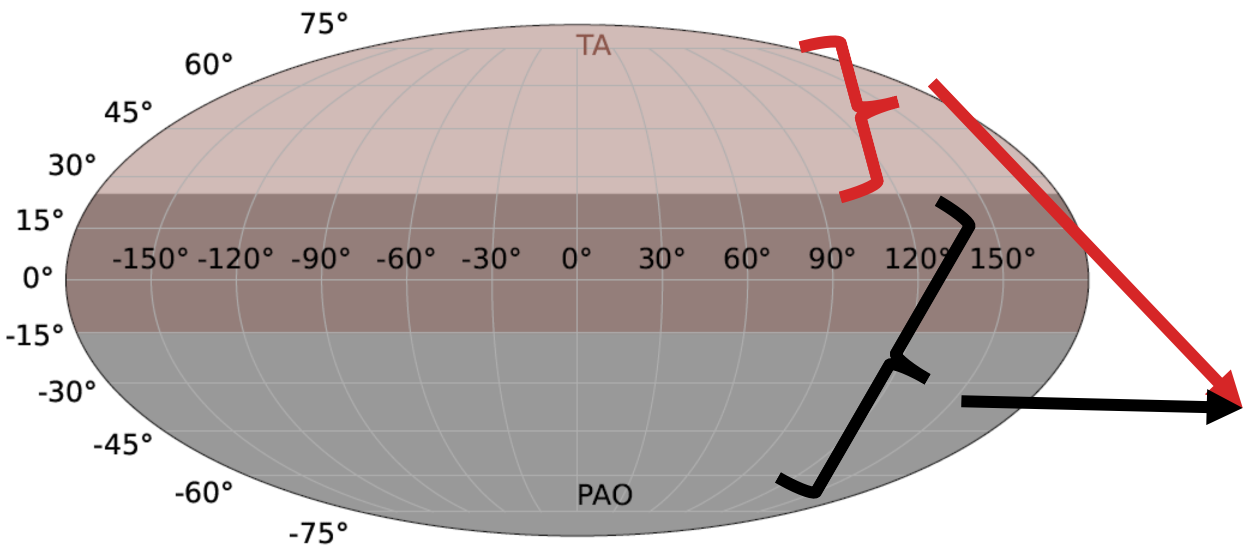


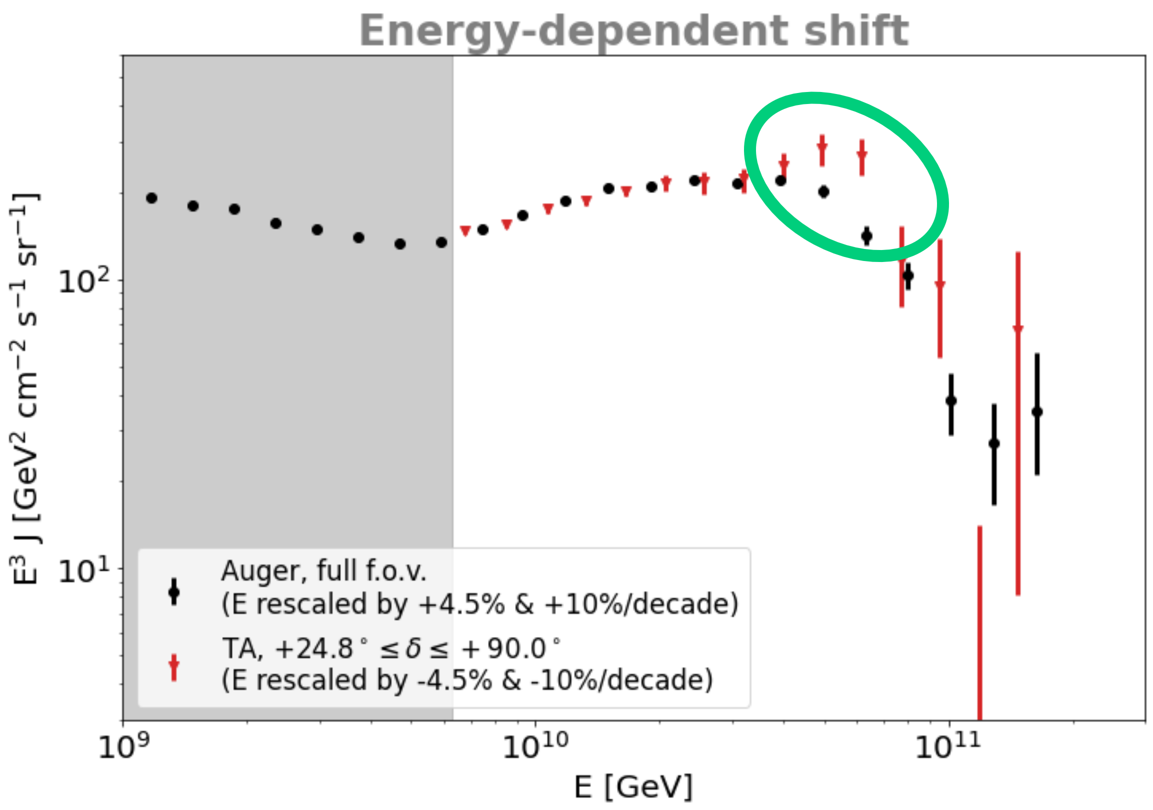


$$E_{\mathrm{new}} = \left(1 \pm 4.5\% \pm 10\% \cdot \log_{10}\left(\frac{E_{\mathrm{old}}}{10^{10}\ \mathrm{GeV}}\right)\right) E_{\mathrm{old}}$$

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

Joint TA/PAO group for UHECR spectrum

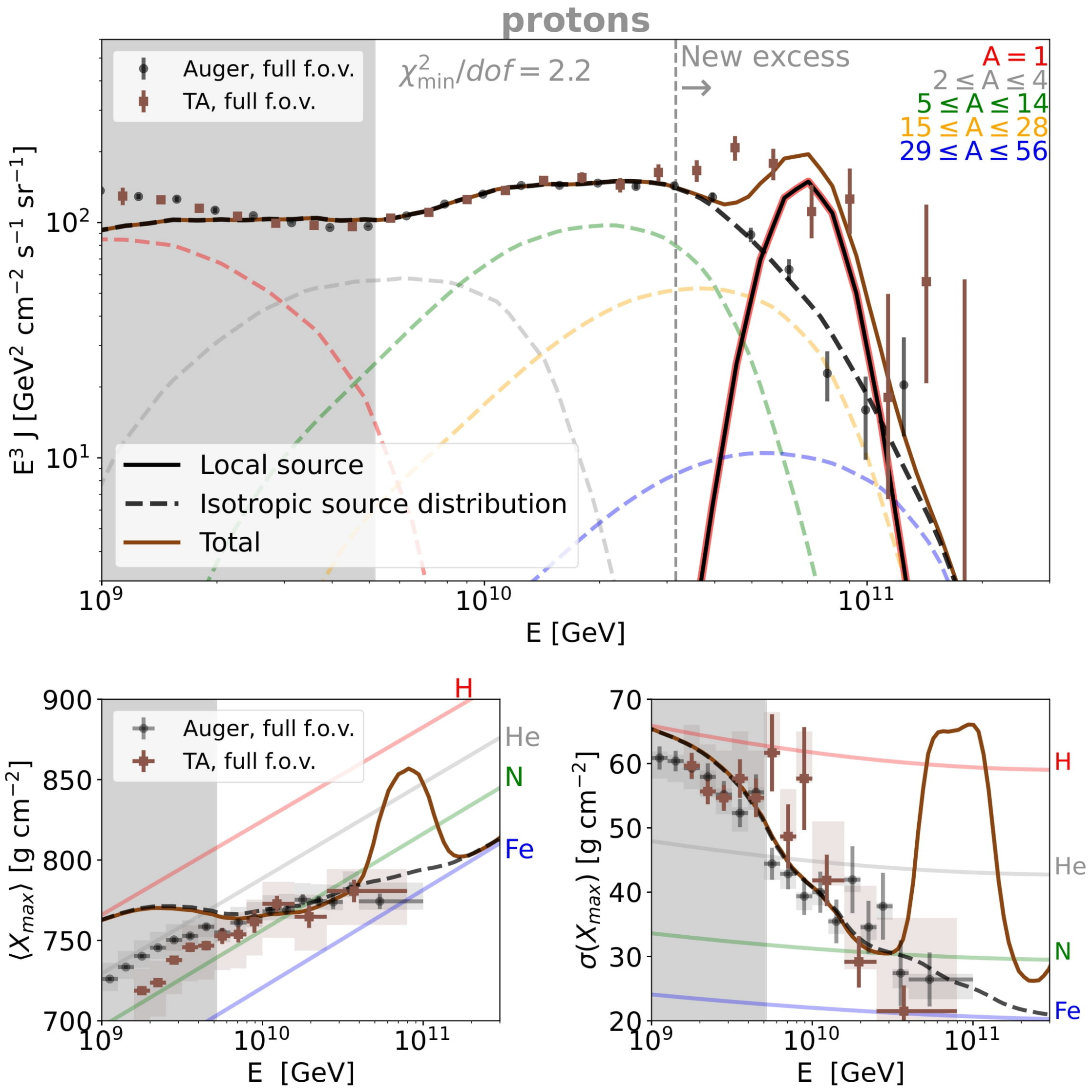


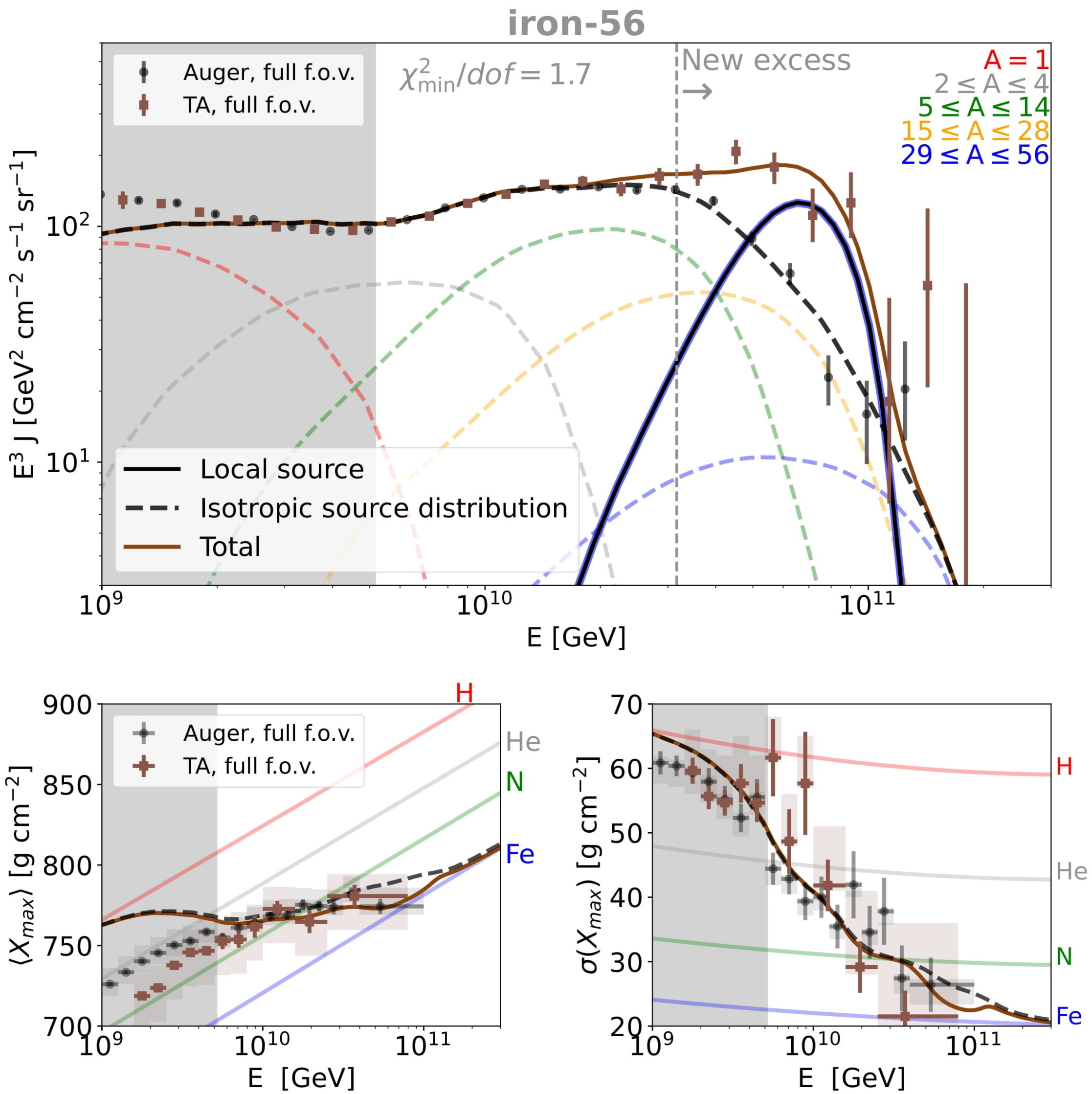


Declination-dependent shift?
→ Physics behind the shift?

Local source, proton and iron elemental groups

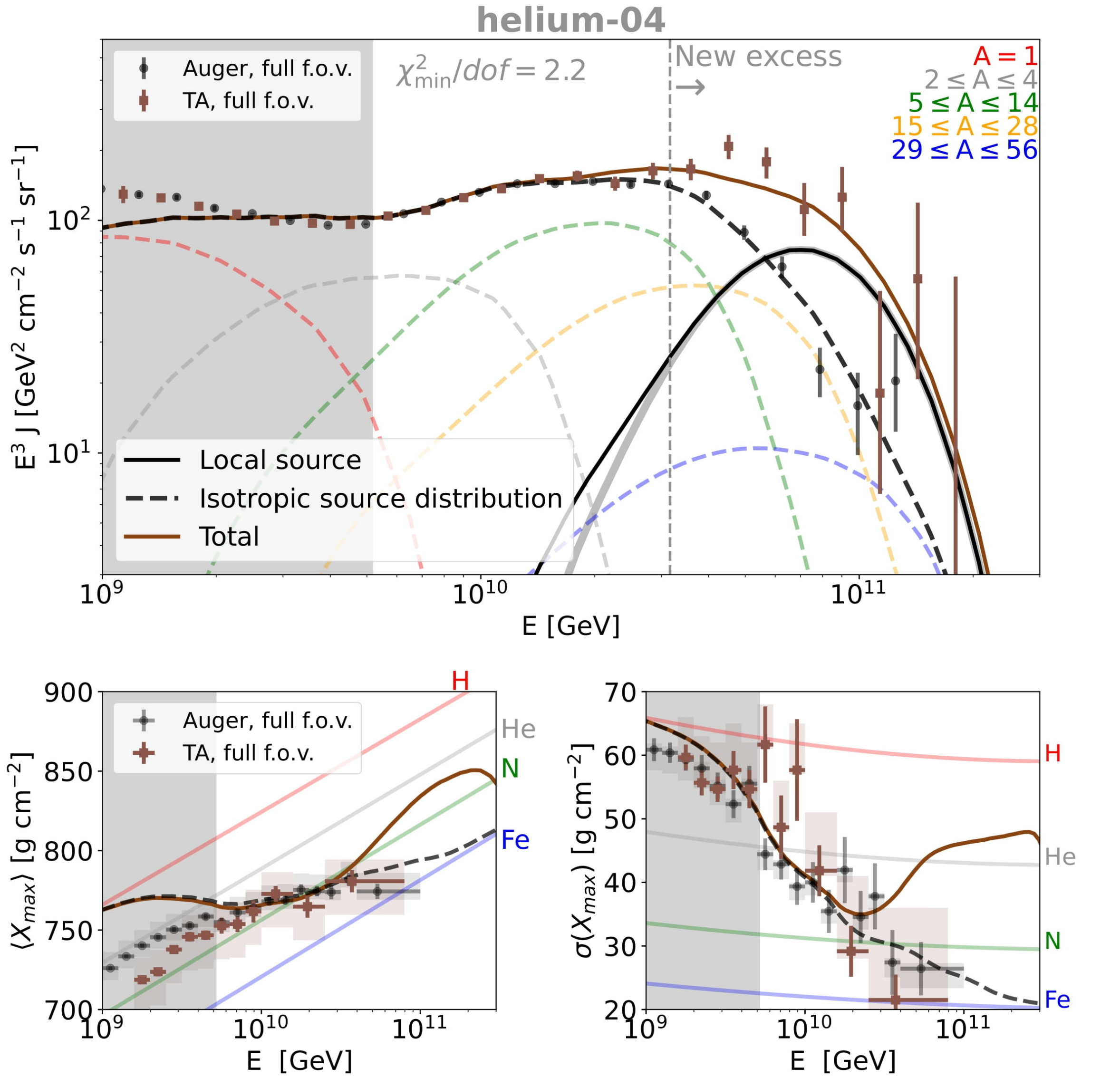
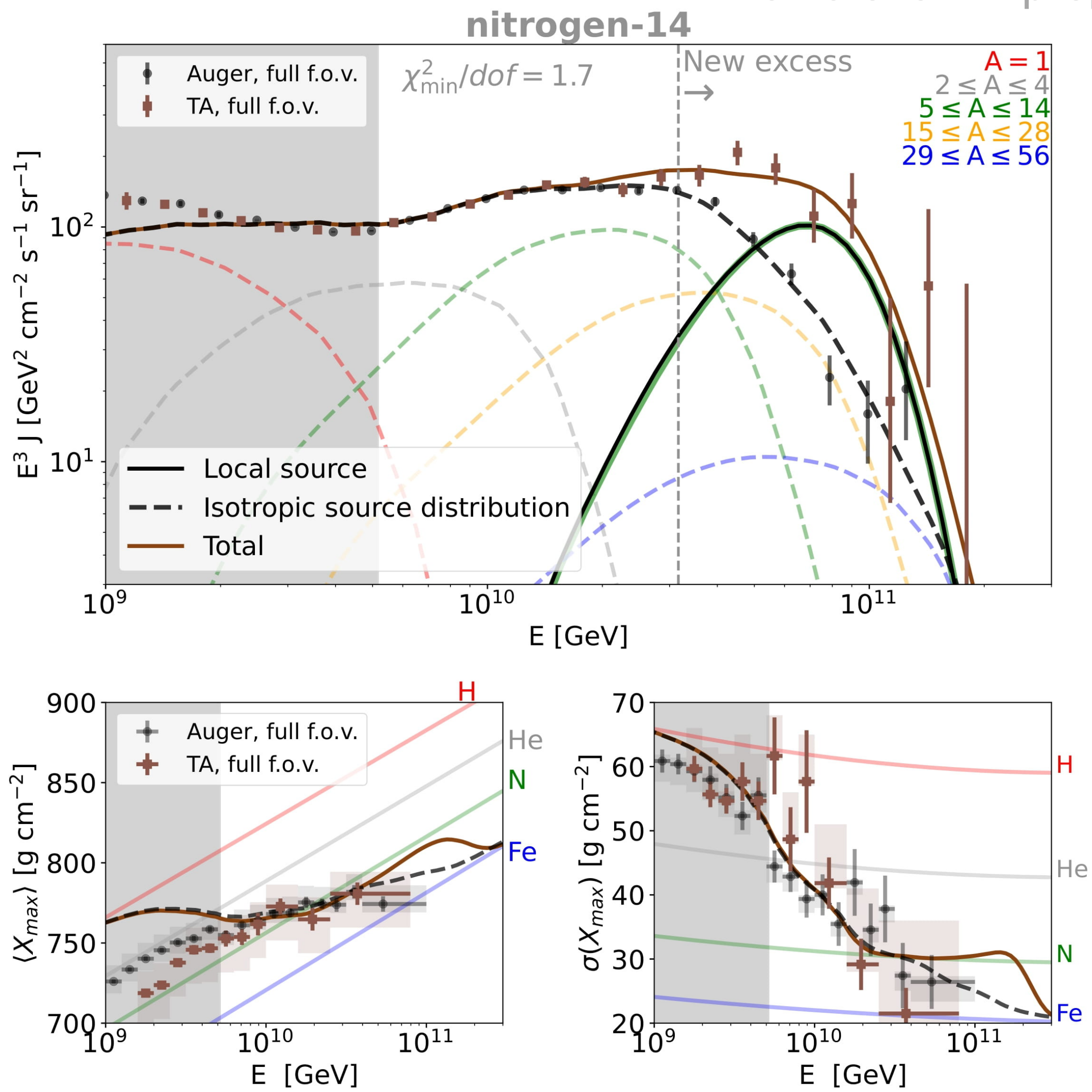
Plotko et al. in prep.





Local source, helium and nitrogen elemental groups

Plotko et al. in prep.

Method

Parameters:

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

$$\boldsymbol{\lambda}^{\text{local}} = \left(\gamma^{\text{local}}, R_{\text{max}}^{\text{local}}, D^{\text{local}}, L^{\text{local}}, A^{\text{local}}\right).$$

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

χ^2test:

$$\chi^2_{\text{PAO}} = \chi^2_{\text{PAO}}(\boldsymbol{\lambda}^{\text{iso}}, \delta_E^{\text{PAO}}, \delta_{\langle X_{\text{max}}\rangle}^{\text{PAO}}, \delta_{\sigma(X_{\text{max}})}^{\text{PAO}}).$$

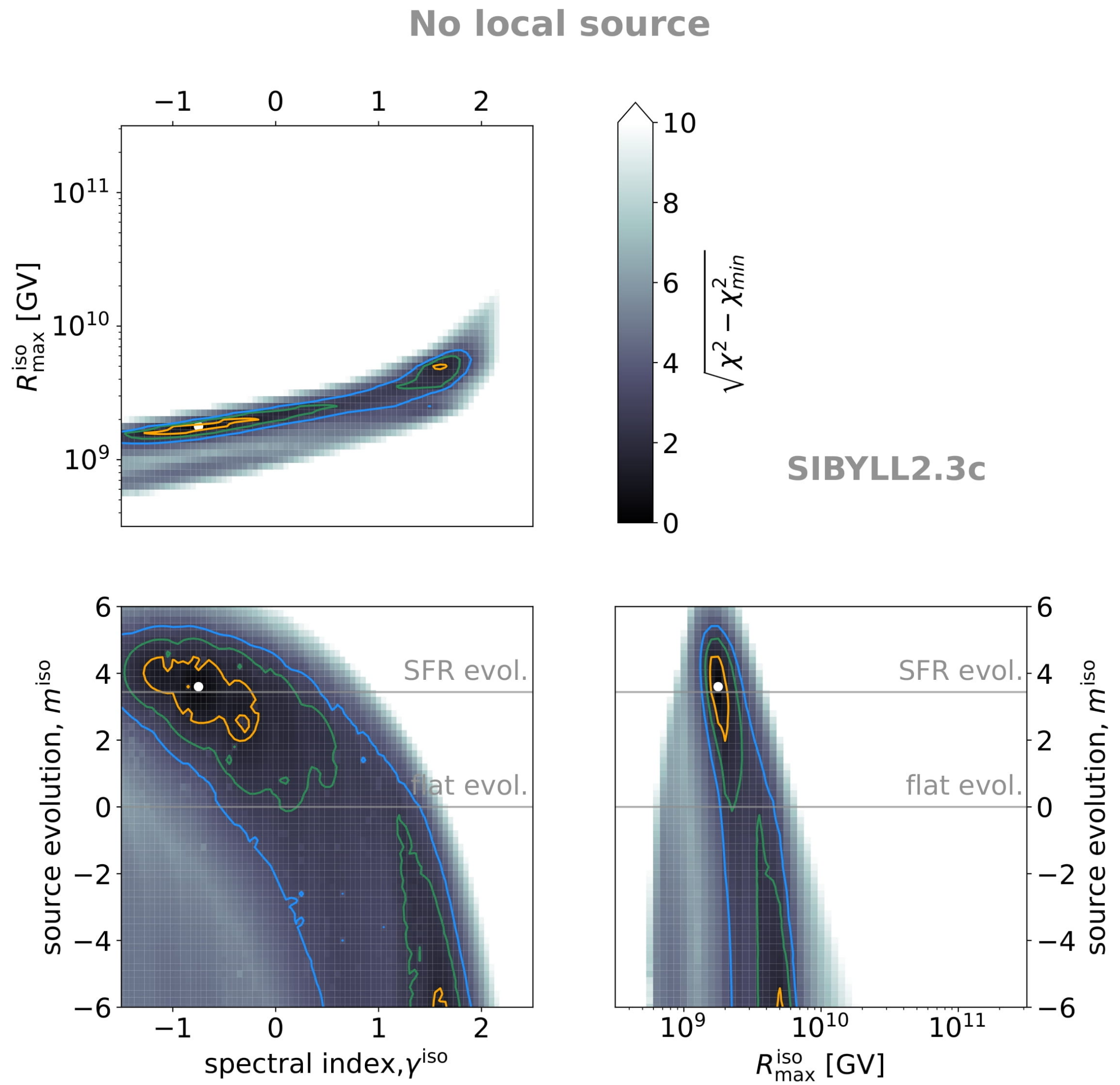
$$\chi^2_{\text{TA}} = \chi^2_{\text{TA}}(\boldsymbol{\lambda}^{\text{iso}}, \boldsymbol{\lambda}^{\text{local}}, \delta_E^{\text{TA}}, \delta_{\langle X_{\text{max}}\rangle}^{\text{TA}}, \delta_{\sigma(X_{\text{max}})}^{\text{TA}})$$

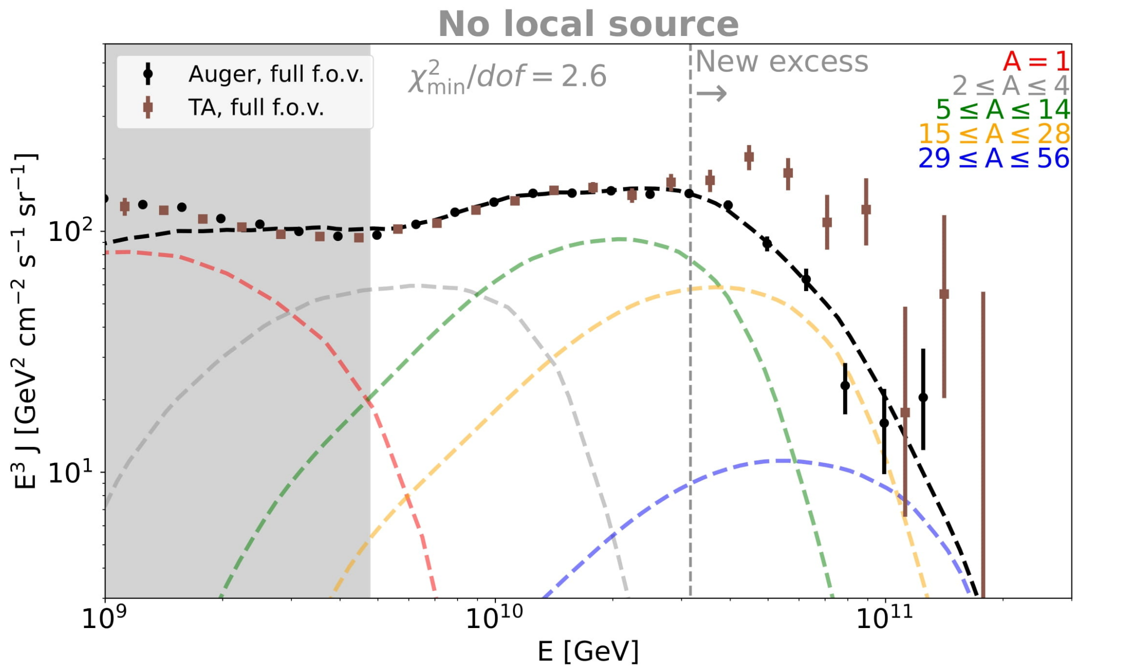
$$\chi^2_{\text{global}}(\boldsymbol{\lambda}^{\text{iso}}, \boldsymbol{\lambda}^{\text{local}}, \boldsymbol{\delta}) = \chi^2_{\text{PAO}} + \left(\frac{\delta_E^{\text{PAO}}}{\sigma_{\text{E}}^{\text{PAO}}}\right)^2 + \left(\frac{\delta_{\langle X_{\text{max}}\rangle}^{\text{PAO}}}{100\%}\right)^2 + \left(\frac{\delta_{\sigma(X_{\text{max}})}^{\text{PAO}}}{100\%}\right)^2 + \chi^2_{\text{TA}} + \left(\frac{\delta_E^{\text{TA}}}{\sigma_{\text{E}}^{\text{TA}}}\right)^2 + \left(\frac{\delta_{\langle X_{\text{max}}\rangle}^{\text{TA}}}{100\%}\right)^2 + \left(\frac{\delta_{\sigma(X_{\text{max}})}^{\text{TA}}}{100\%}\right)^2.$$

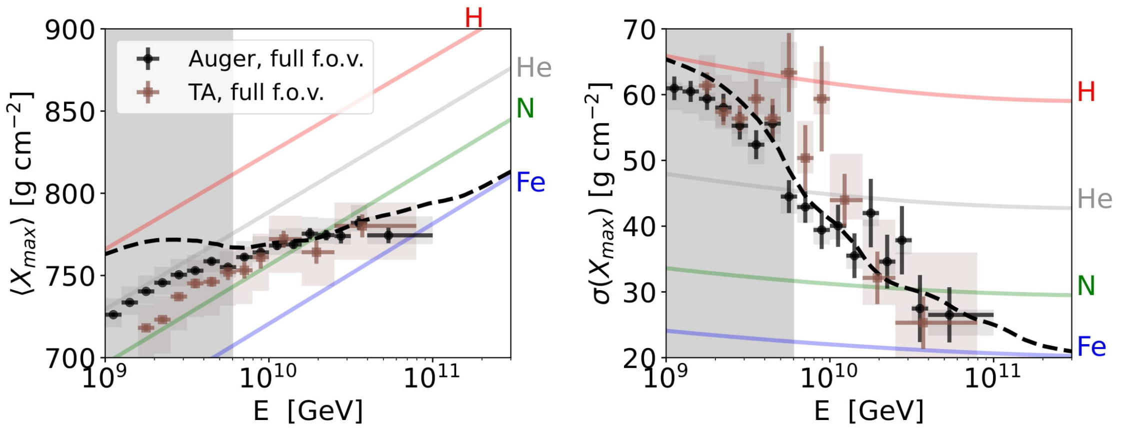
Energy-independent shift

Plotko et al. in prep.

- **No Local source**

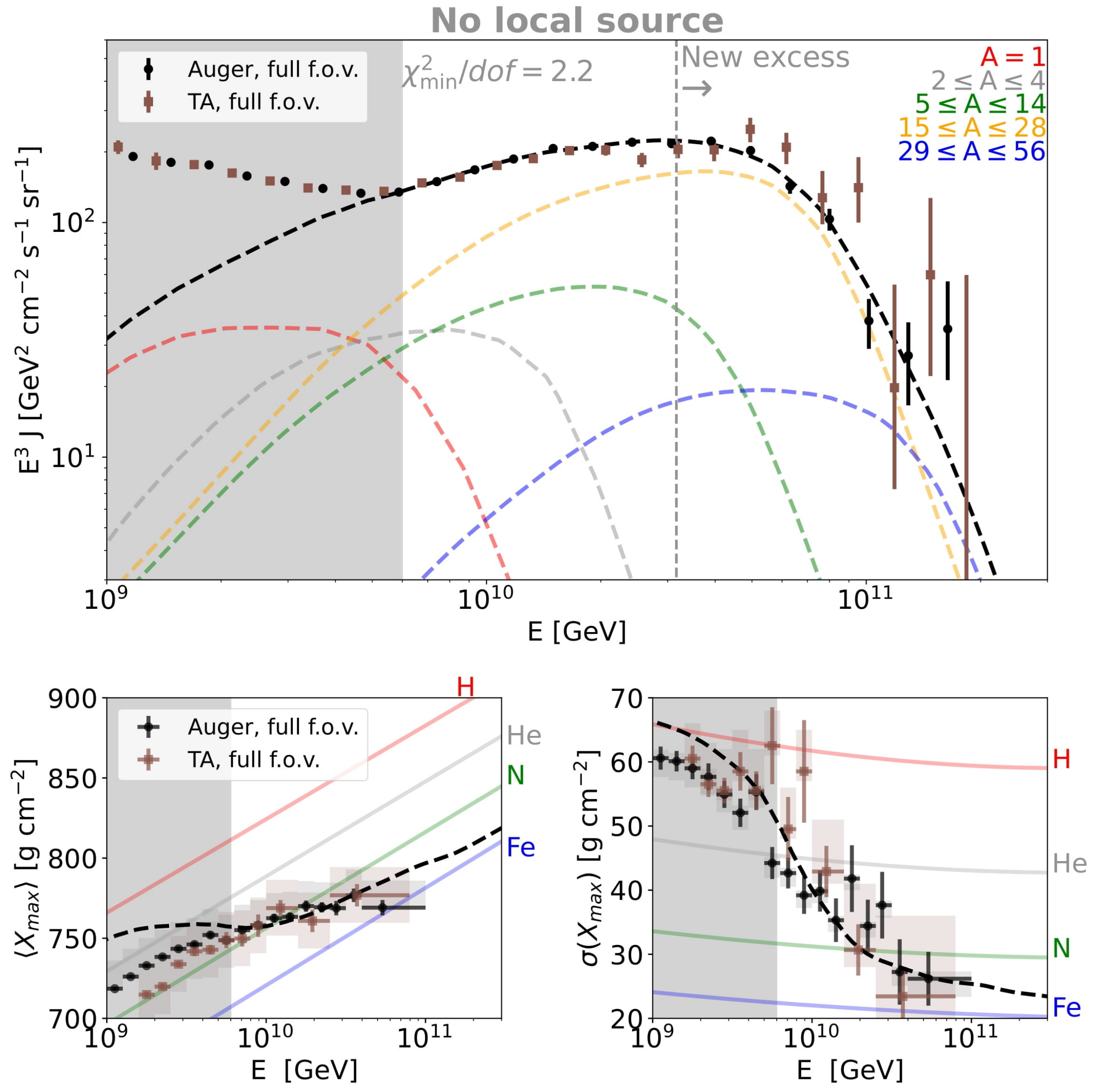


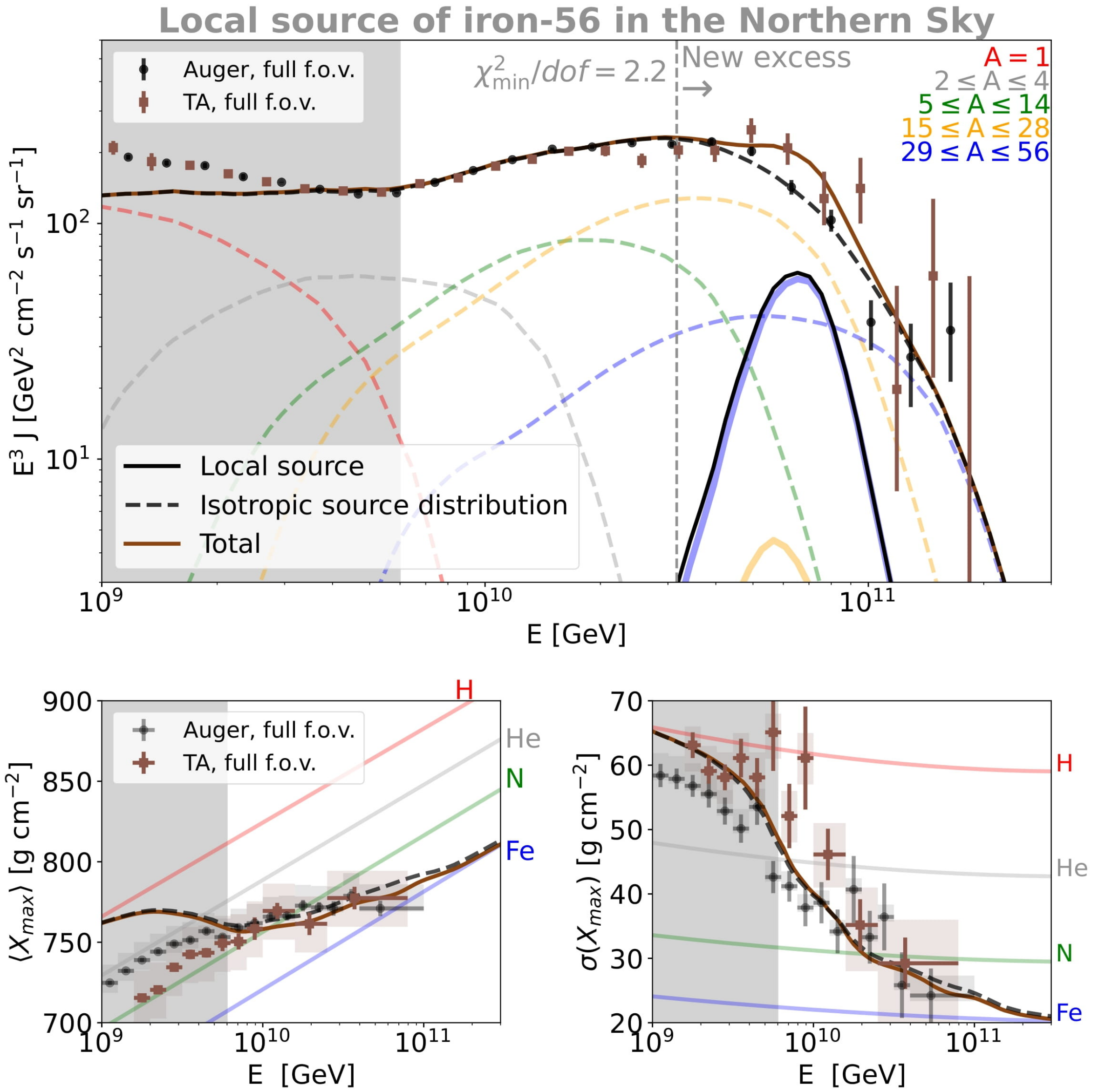




Energy-dependent shift

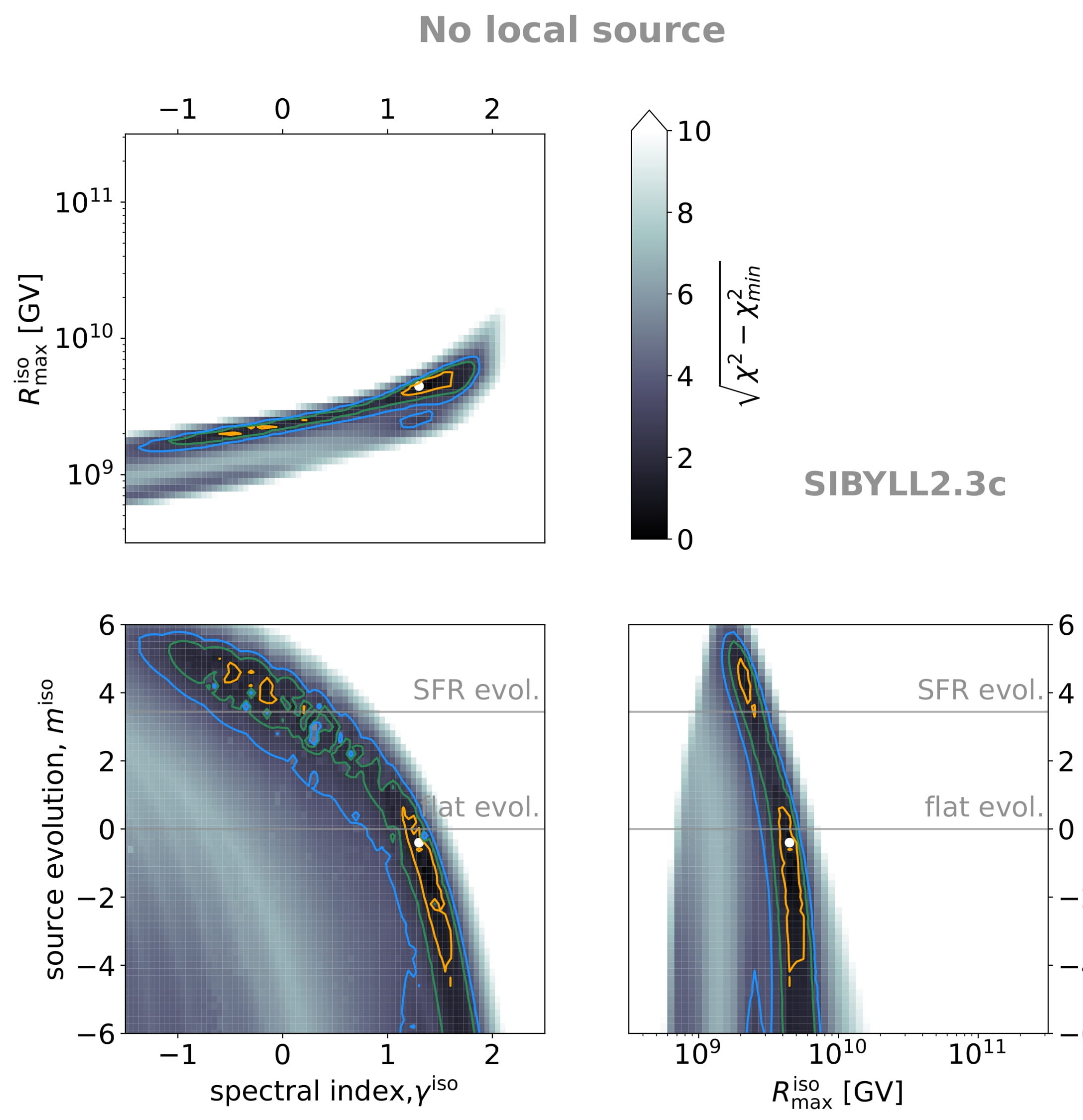
Plotko et al. in prep.

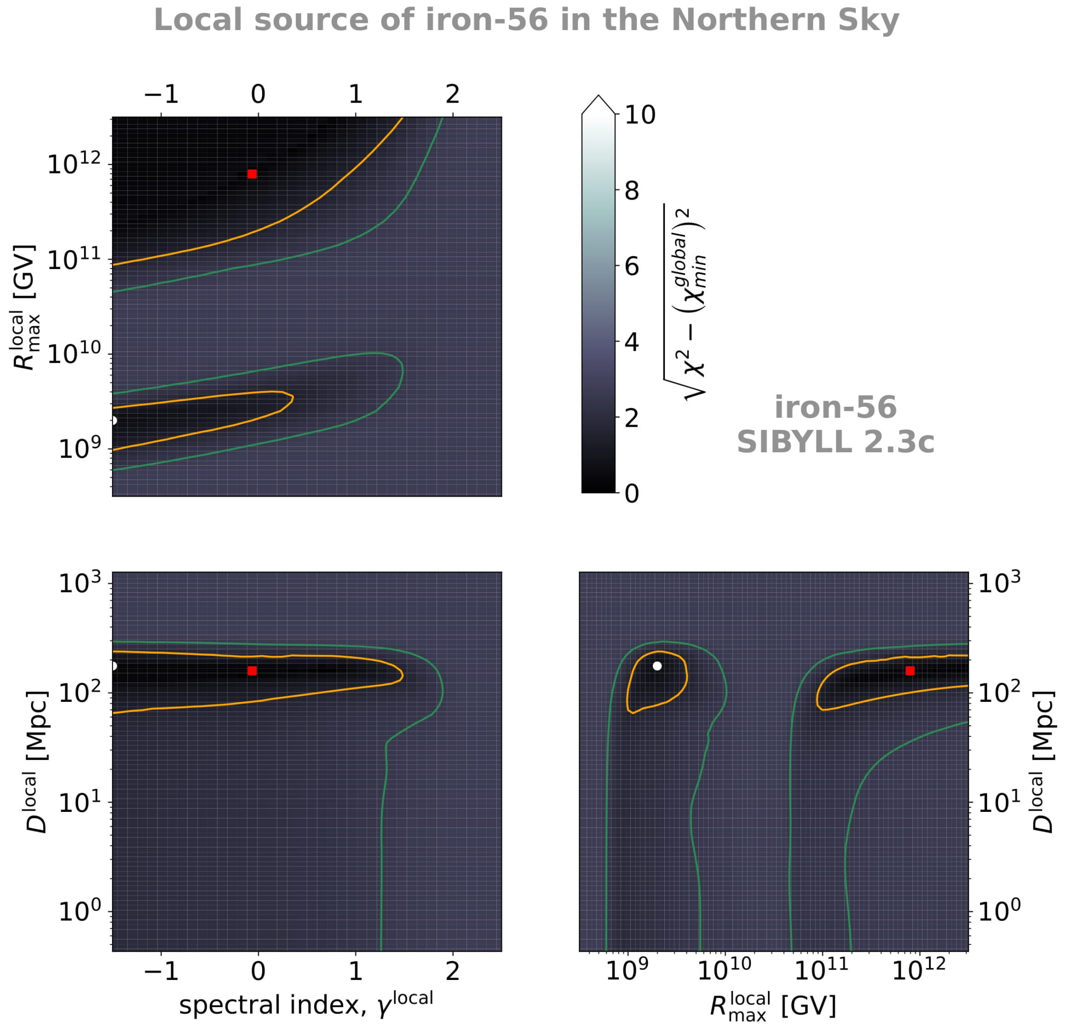




Energy-dependent shift

Plotko et al. in prep.



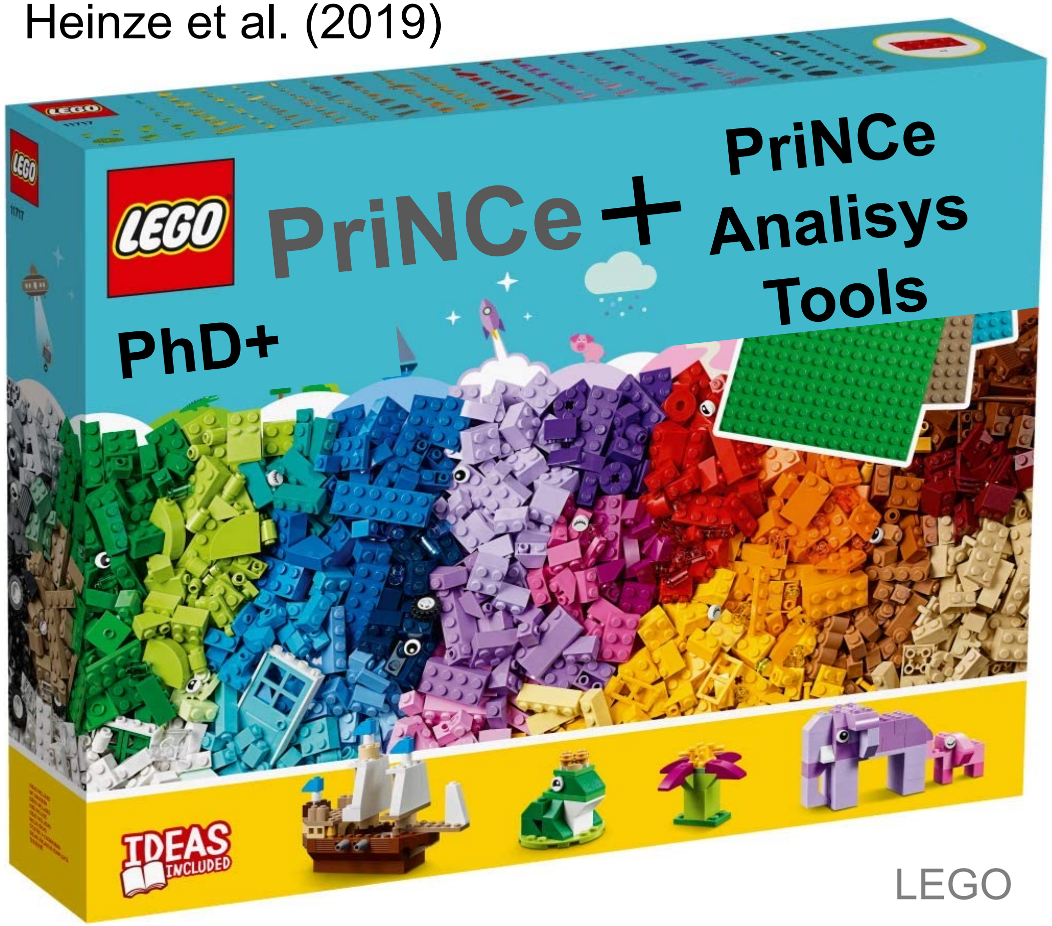


PriNCe

Propagation including Nuclear Cascade

- Written in pure Python using Numpy and Scipy
- Directly solve the transport equation
- Large speed boost from sparse matrix algorithms
- Public available Analysis tools for parameters scan (https://github.com/joheinze/PriNCe)
- Developed at DESY

Heinze et al. (2019)



LEGO

>28 models → >200 different scenarios