Efficient UHECR simulations with PrINCE
and what they taught us so far

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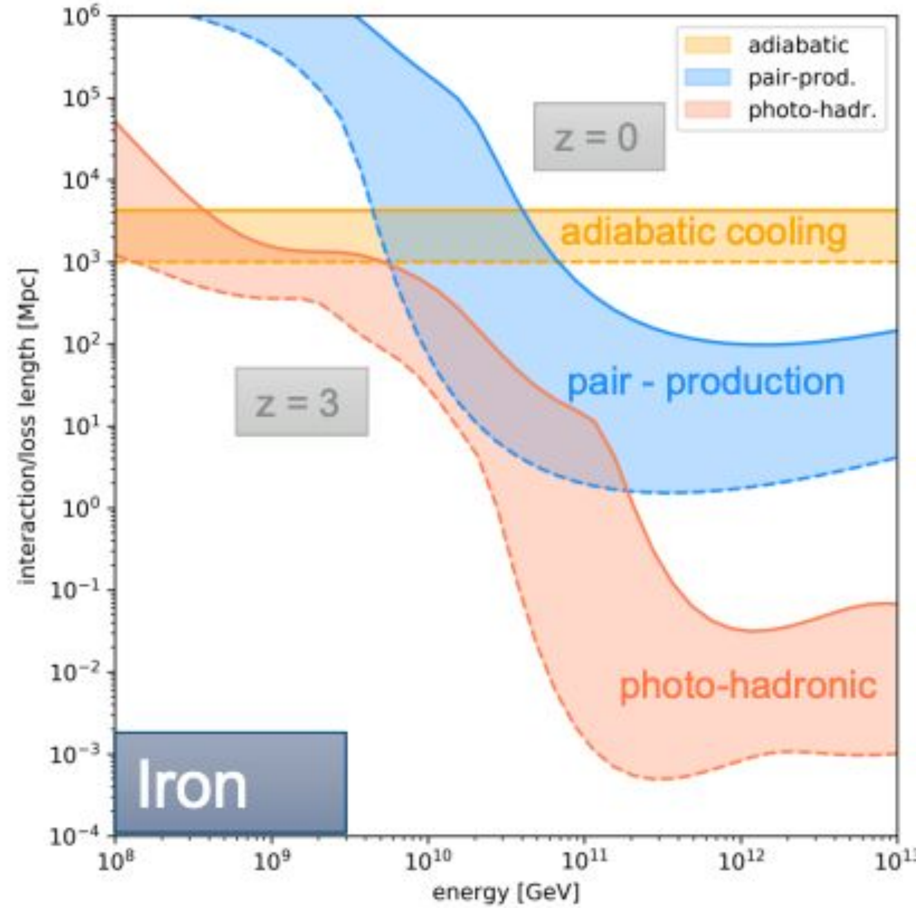
Ruhr-University Bochum

CRPropa Workshop
Madrid, Sep 14 2022

1. The novel PriNCe framework
2. Combined source-propagation models
3. Two recent applications

UHECR Transport Equation



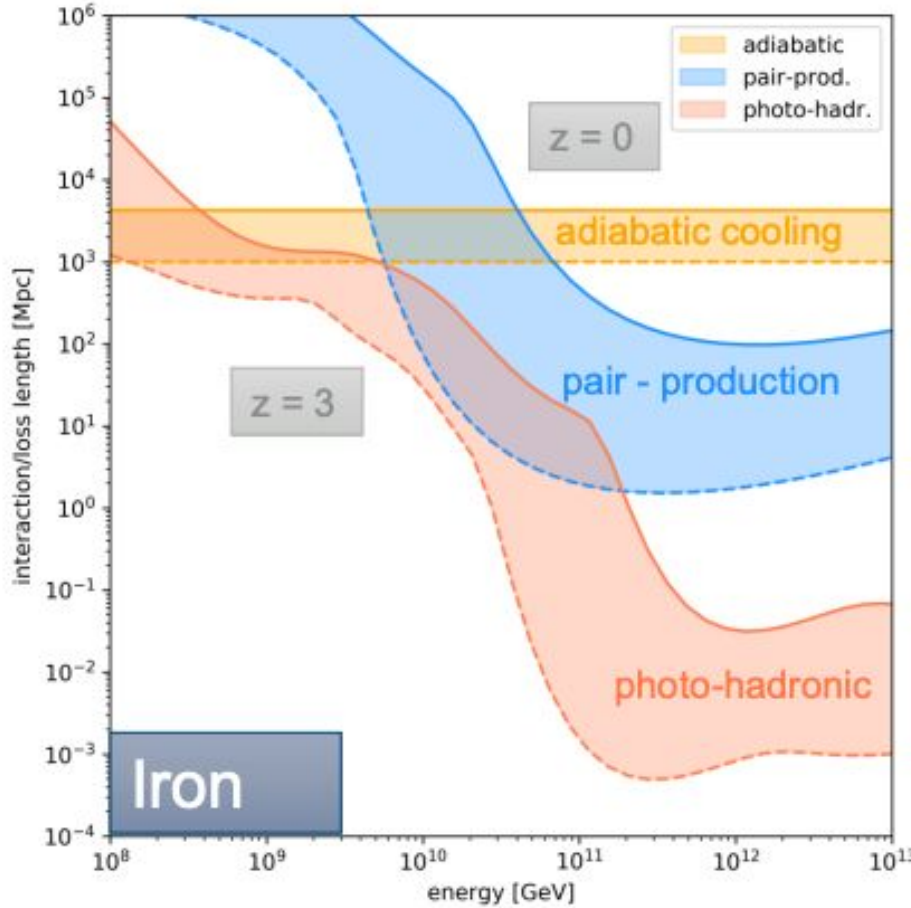
$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

adiabatic cooling — pair - production — photo-hadronic — Injection

UHECR Transport Equation

- About 50 × number of E-bins coupled differential equations
- All coefficients time and energy dependent

- Fast computation times needed to study cross-section / photon-field uncertainties



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adiabatic cooling — pair - production — photo-hadronic — Injection

Propagation Code - PriNCe

https://github.com/joheinze/PriNCe

Propagation including Nuclear Cascade equations

Primary (interacting) nucleus

- Written in pure Python using Numpy and Scipy

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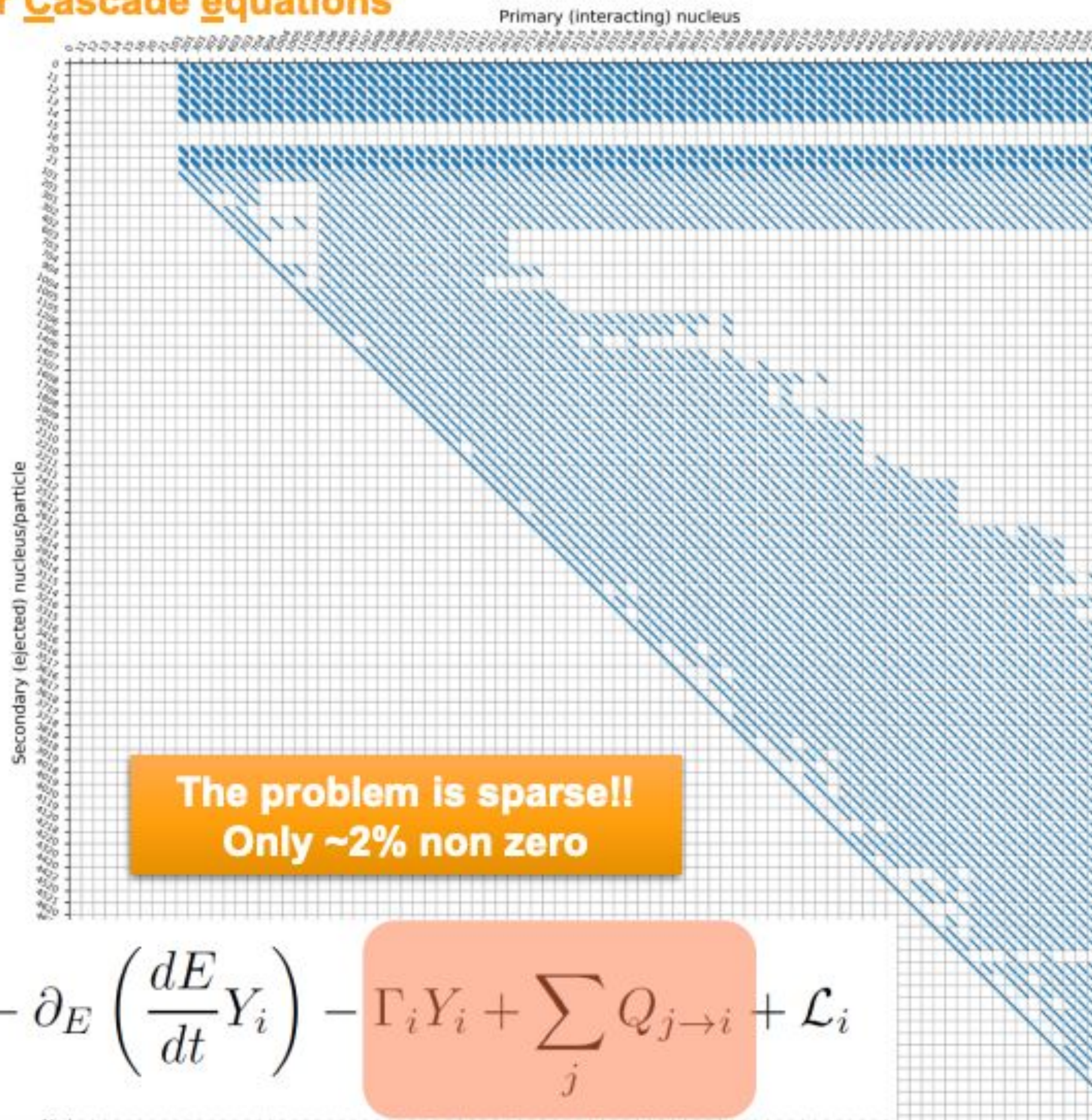
Propagation including Nuclear Cascade equations

- Written in pure Python using Numpy and Scipy
- Specifically makes use of sparse matrix structure



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Propagation Code - PriNCe

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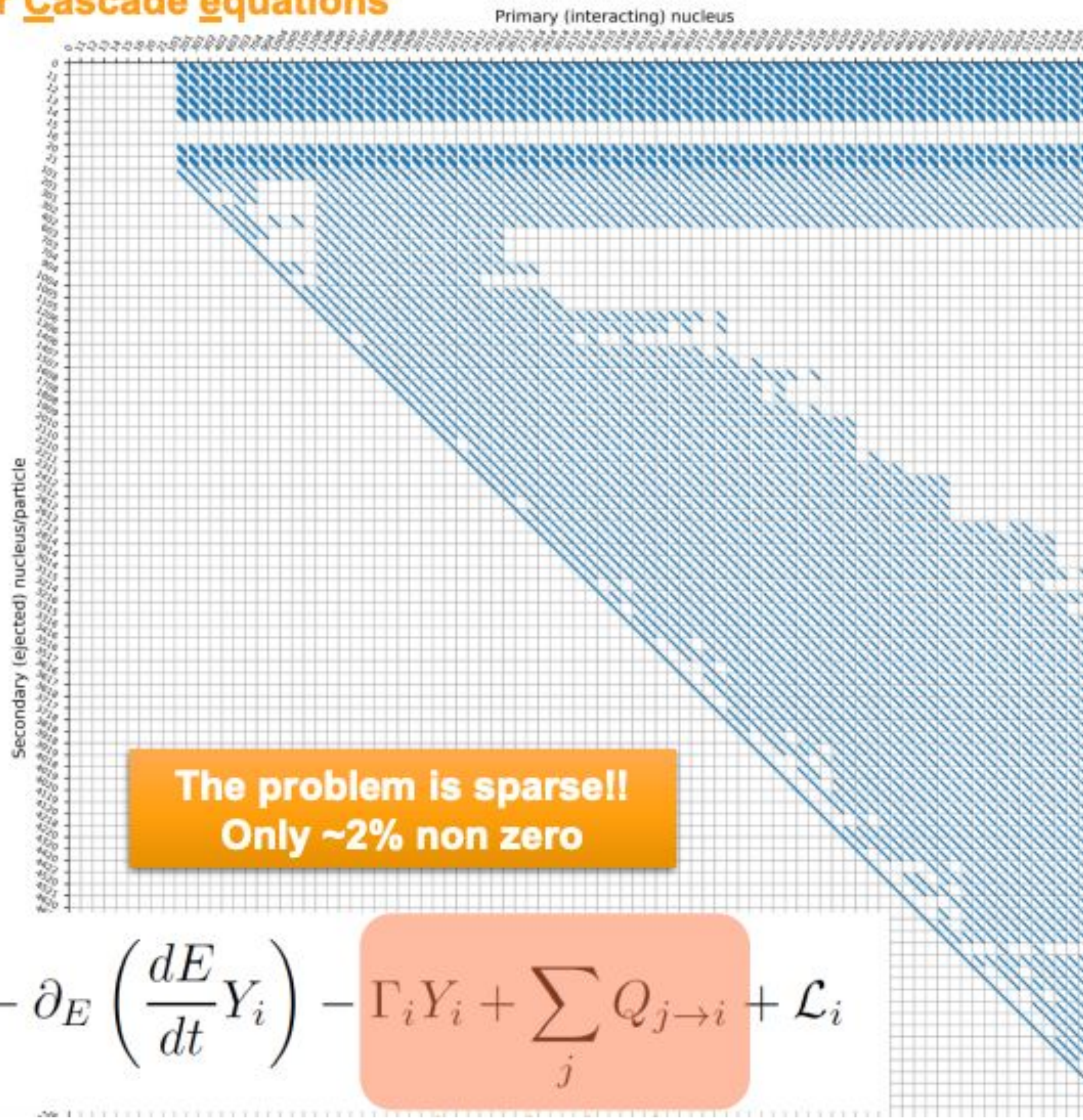
Propagation including Nuclear Cascade equations

- Written in pure Python using Numpy and Scipy
- Specifically makes use of sparse matrix structure

- **20s – 40s** for single spectrum (depending on number of system species)

- More efficient to study model uncertainties than Monte-Carlo (cross-section, photon fields etc.)



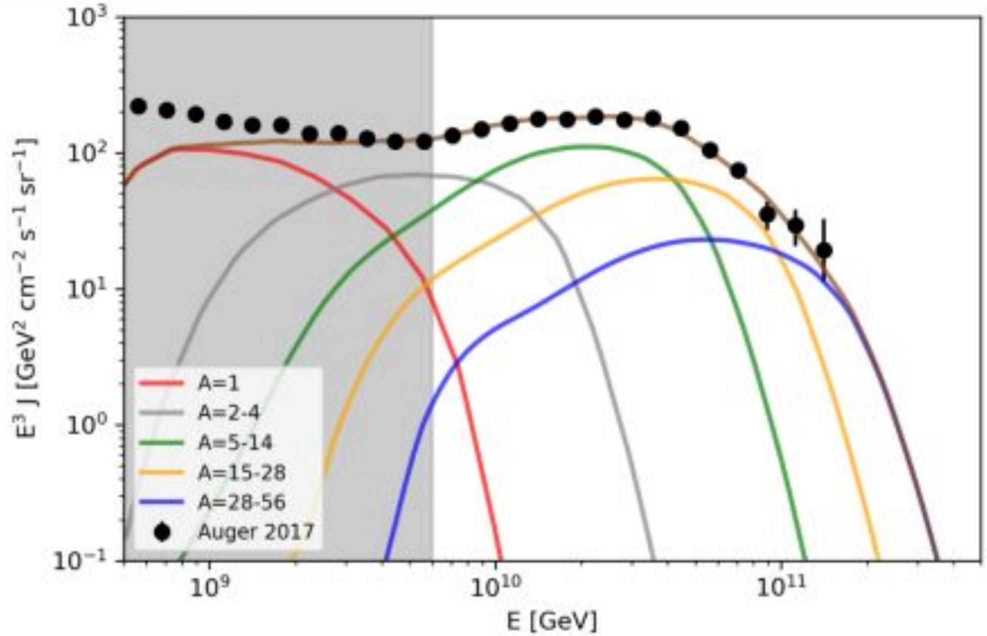
The problem is sparse!!
Only ~2% non zero

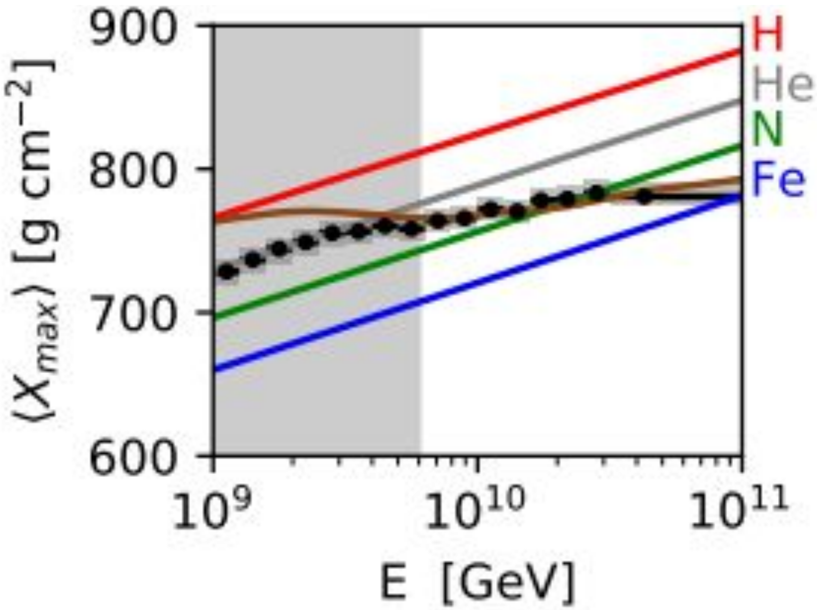
$$\partial_t Y_i(E,z) = +\,\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

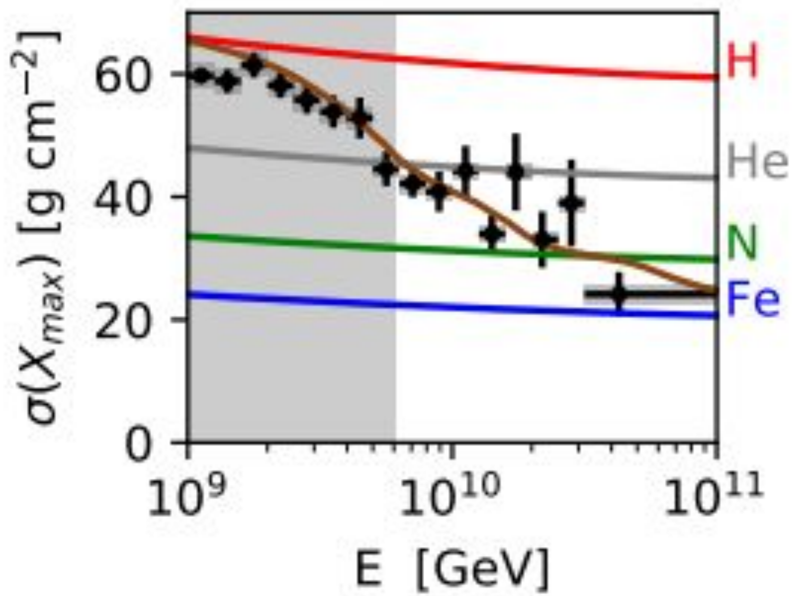
First results (Heinze et al 2019, ApJ 873)

For combination Talys – Sibyll 2.3

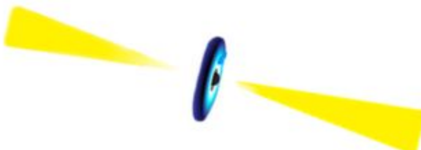
- Fit mainly sensitive to envelope of cutoffs
- Fit-range insensitive above z = 1!
- Composition below ankle proton dominated (by construction) …



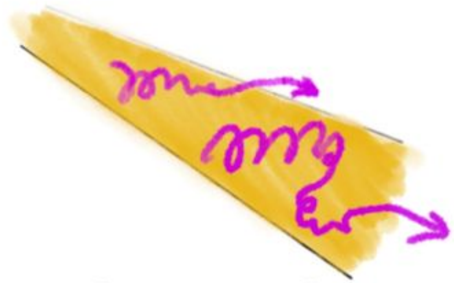




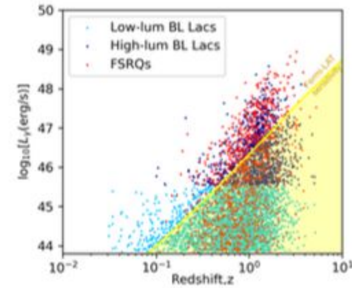
Blueprint of a source-propagation model



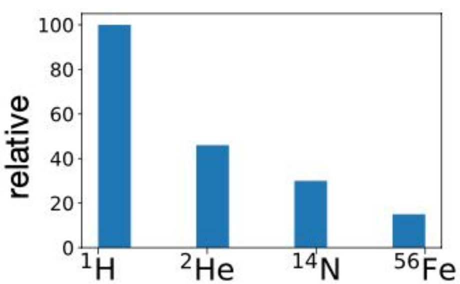
Assume AGN jets accelerate UHECRs to an E^{-2} spectrum



Assume cosmic rays escape diffusively



Assume cosmological source distribution



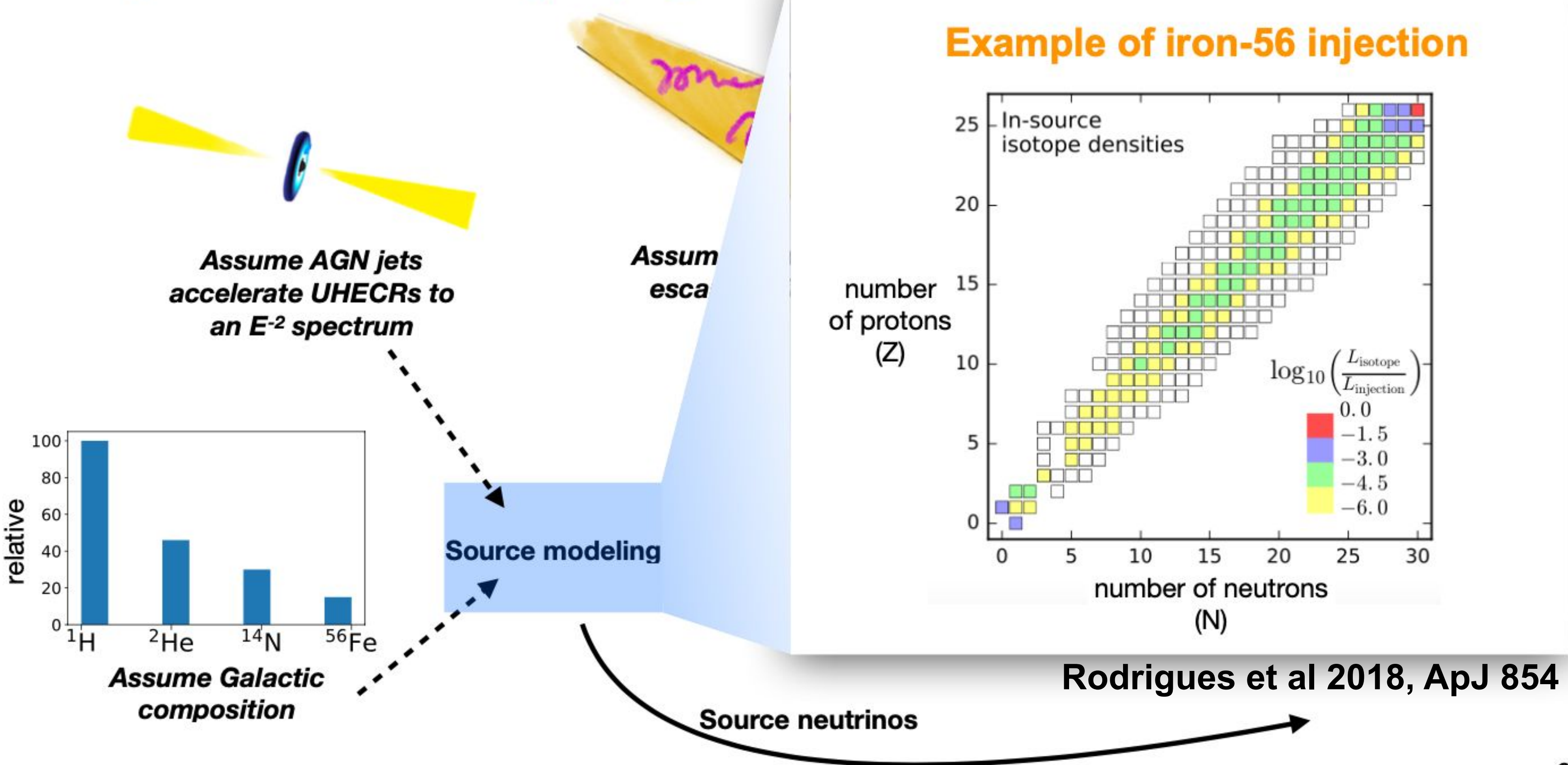
Assume Galactic composition

Source modeling

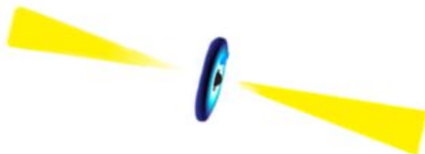
Ejected cosmic-ray nuclei

Source neutrinos

Blueprint of a source-propagation model

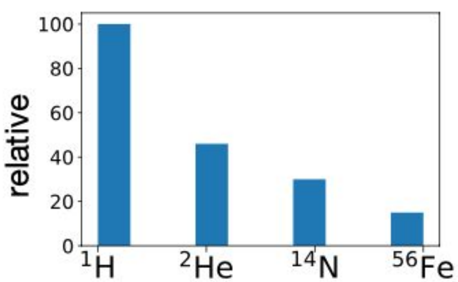


Blueprint of a source-propagation model



Assume AGN jets accelerate UHECRs to an E^{-2} spectrum

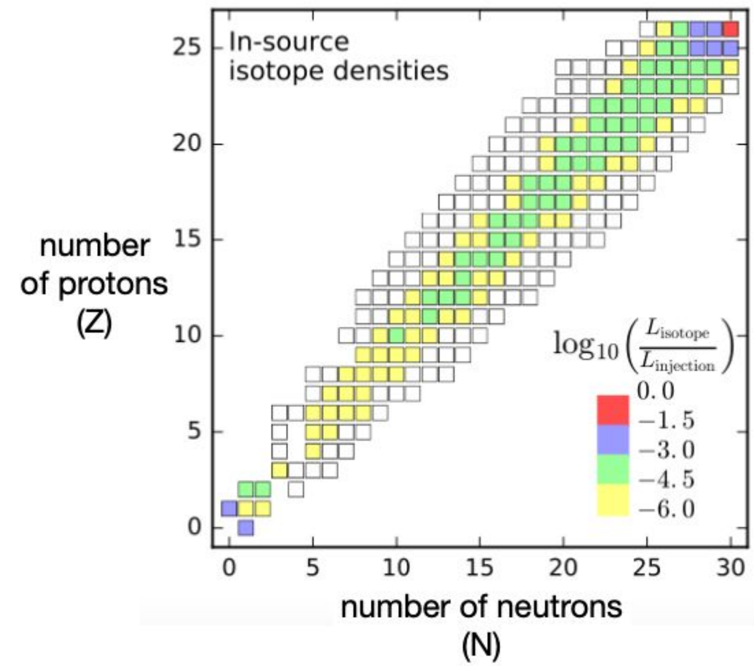
Assum
esca



Assume Galactic composition

Source modeling

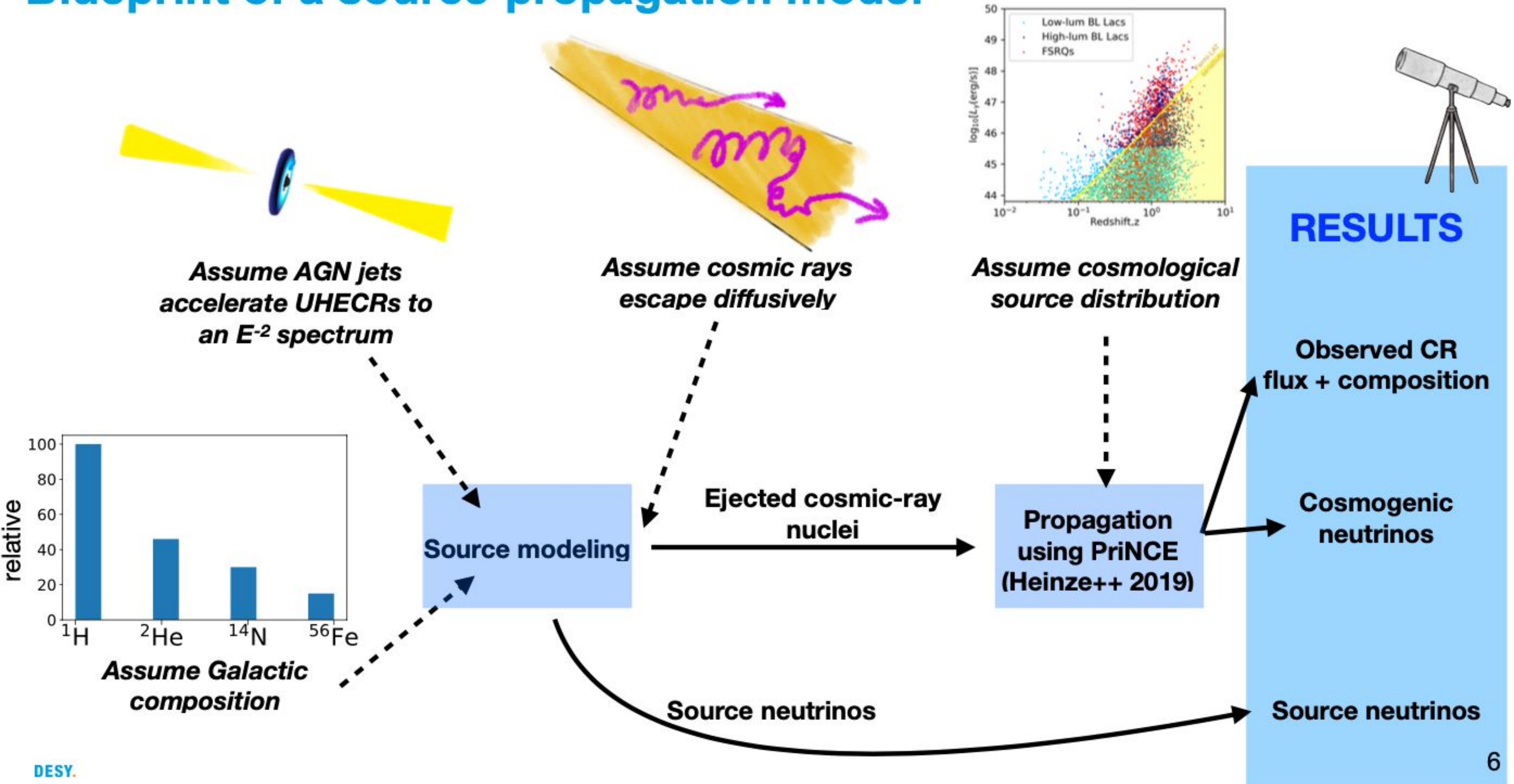
Example of iron-56 injection



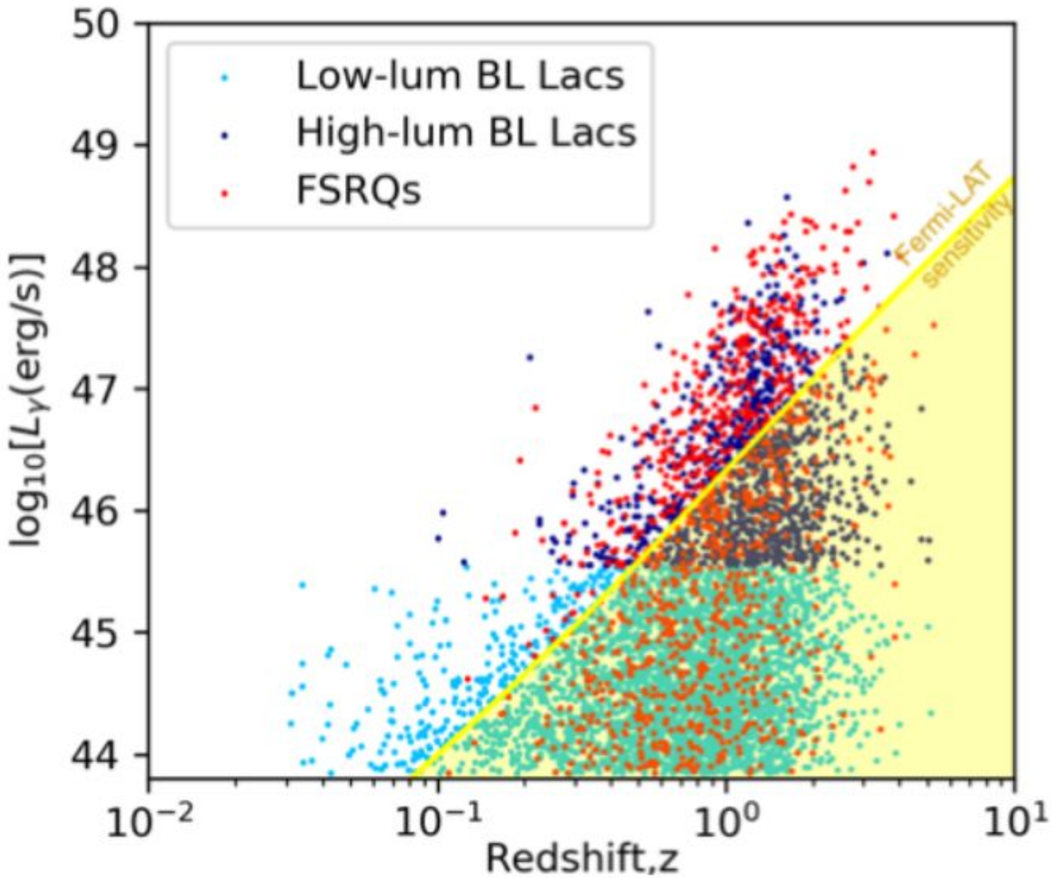
Rodrigues et al 2018, ApJ 854

Source neutrinos

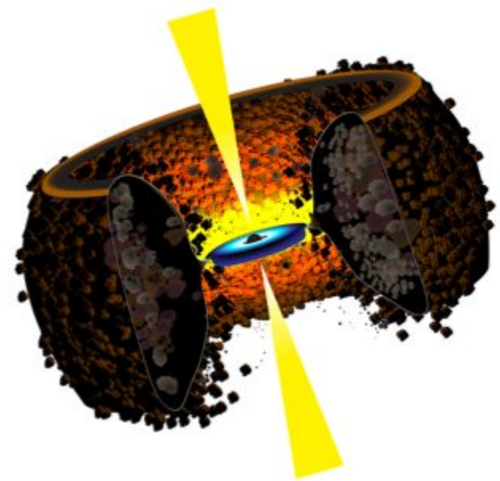
Blueprint of a source-propagation model



Application 1: testing AGN as UHECR accelerators



FSRQ



BL Lac

Rodrigues, Heinze, Palladino, van Vliet and Winter, PRL 126 (2021)

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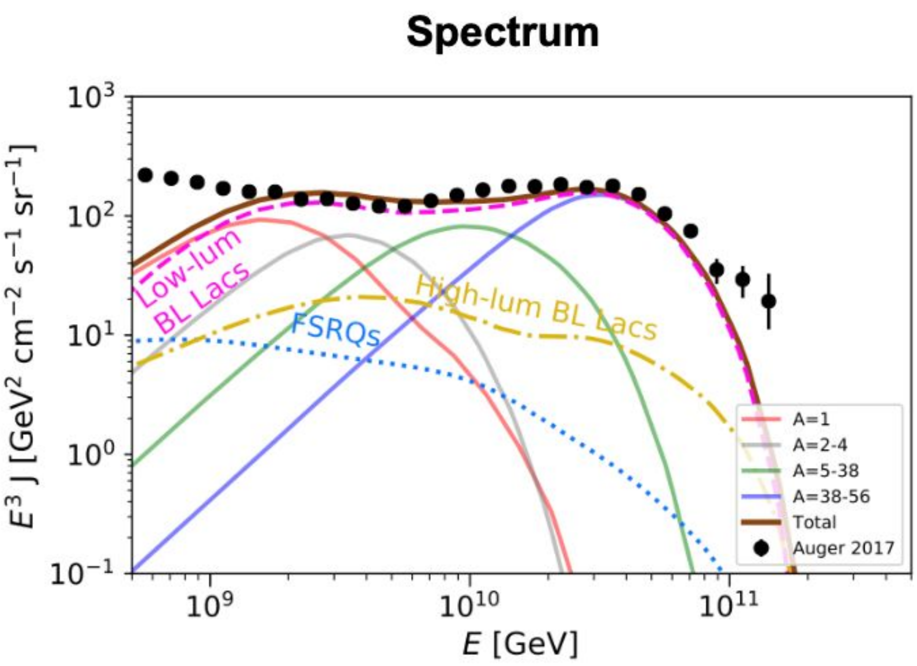

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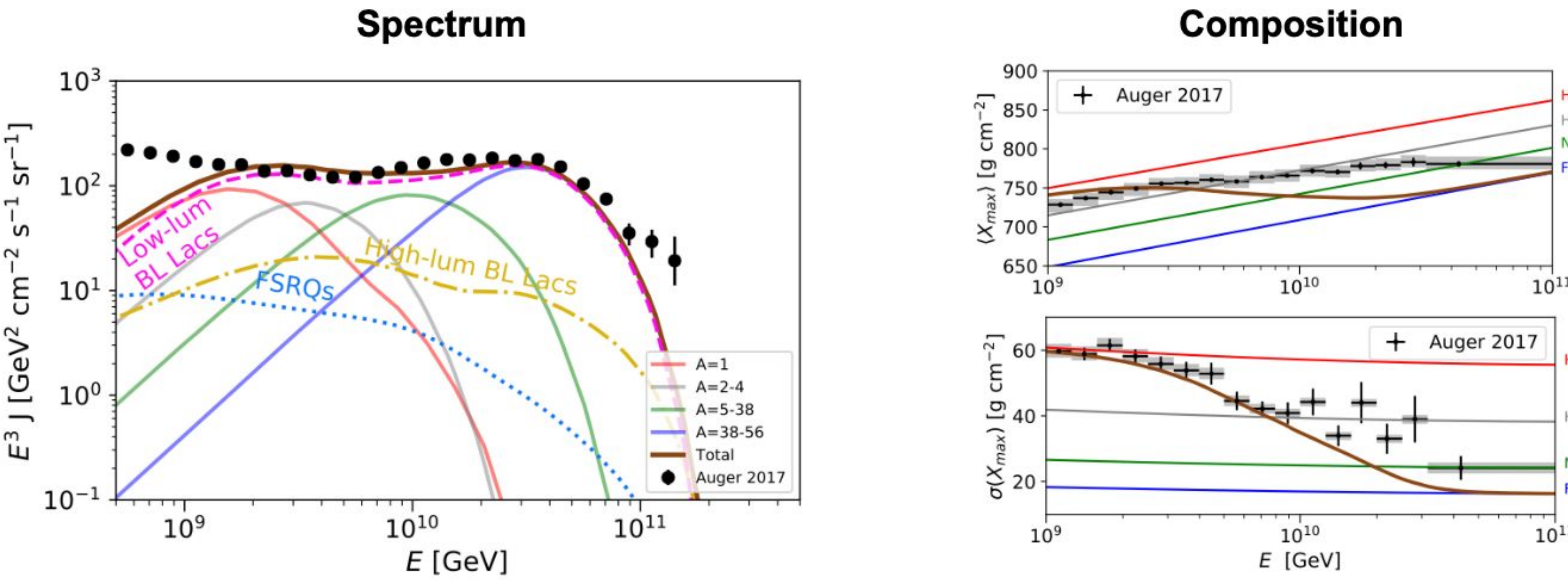

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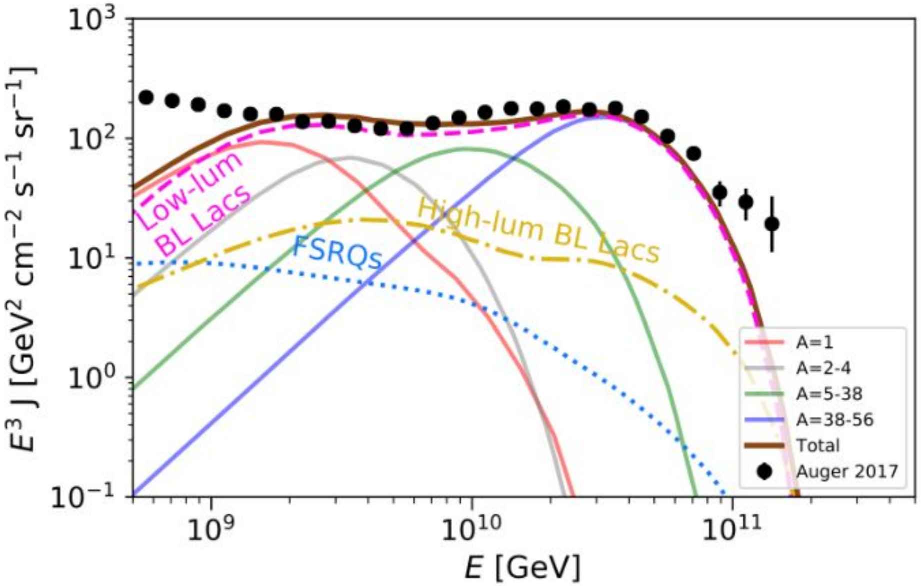
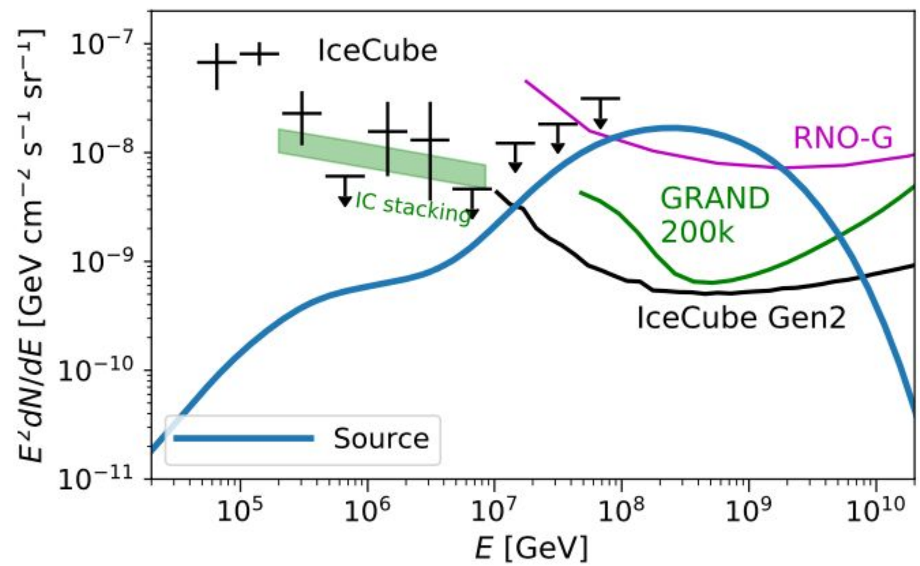
Spectrum



Neutrinos



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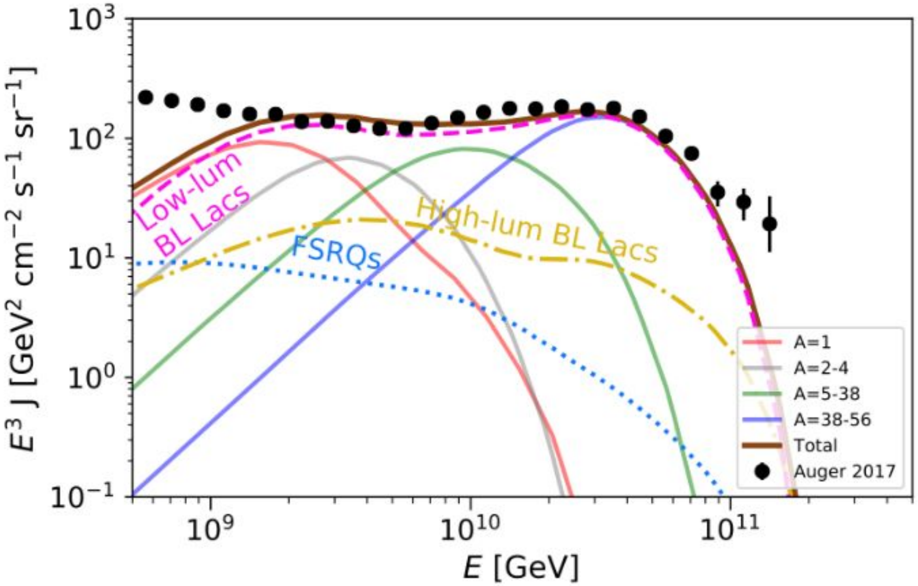
DESY.

Application 1: testing AGN as UHECR accelerators

Spectrum



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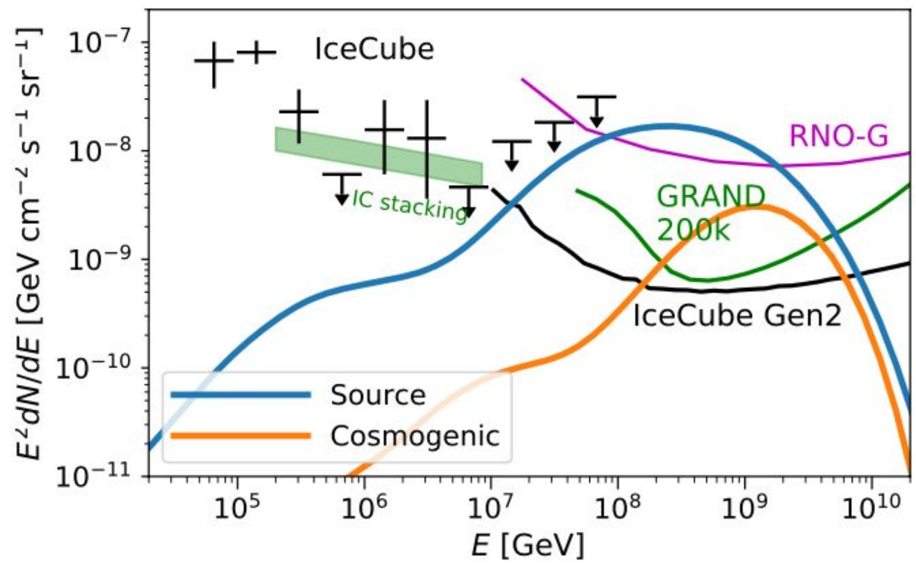

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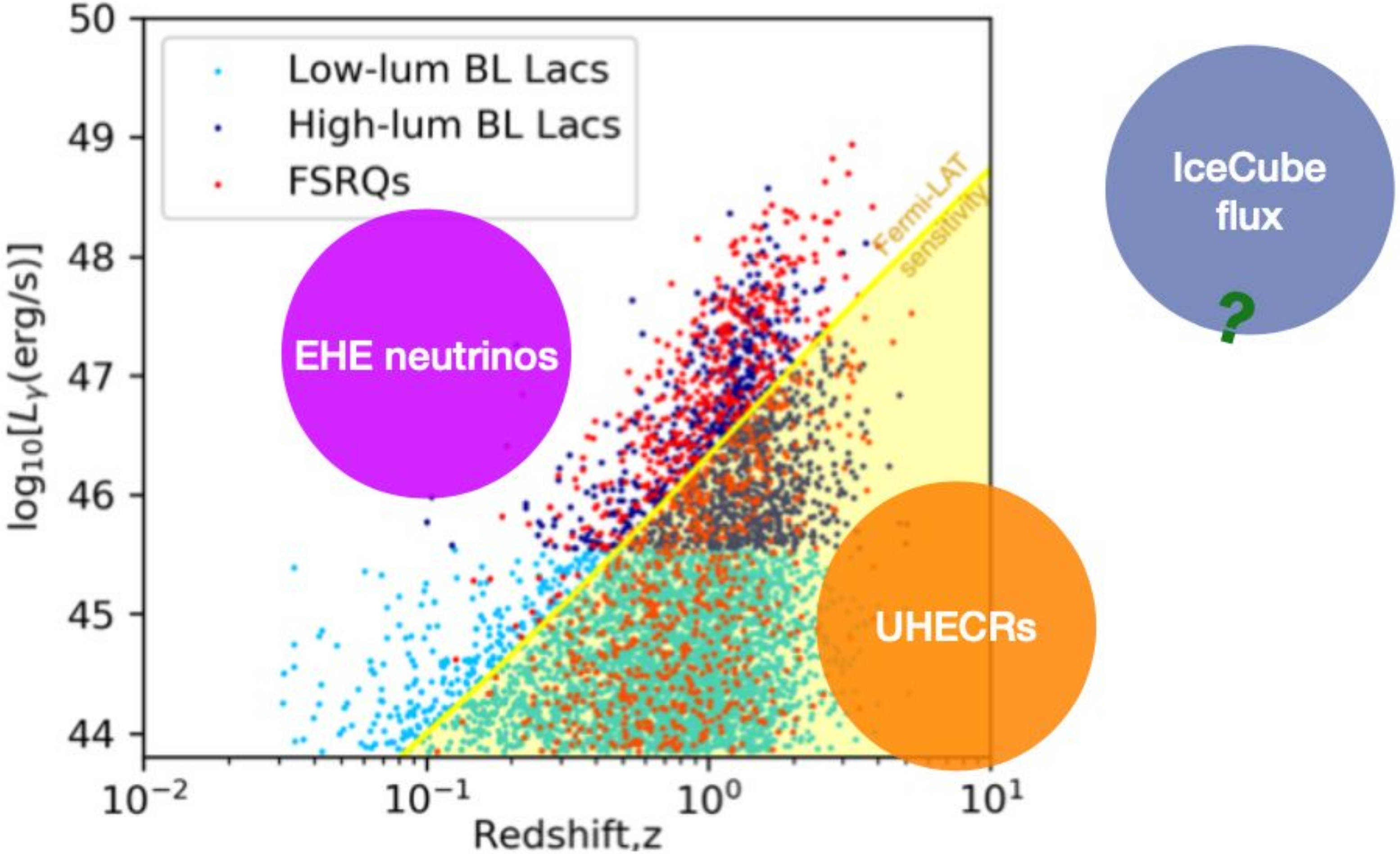
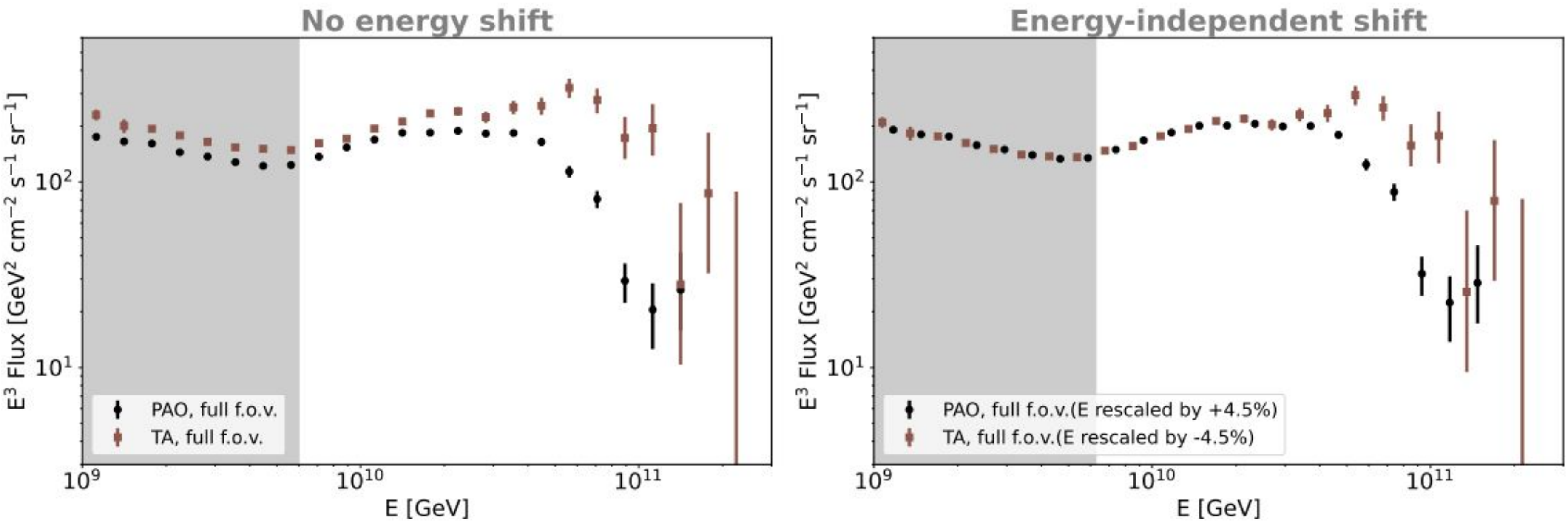


Application 2: testing astrophysics vs systematics



PAVLO PLOTKO [1] ARJEN VAN VLIET [1,2] XAVIER RODRIGUES [1,3] AND WALTER WINTER [1]

arXiv:2208.12274

Application 2: testing astrophysics vs systematics

$$\boldsymbol{\lambda}_{\mathrm{cosmo}} = (\gamma_{\mathrm{cosmo}}, R^{\mathrm{max}}_{\mathrm{cosmo}}, m_{\mathrm{cosmo}}, \mathcal{L}^{\mathrm{CR}}_{\mathrm{cosmo}}, \boldsymbol{f}^{\mathrm{cosmo}}_{\mathrm{A}}),$$
$$\boldsymbol{\lambda}_{\mathrm{local}} = (\gamma_{\mathrm{local}}, R^{\mathrm{max}}_{\mathrm{local}}, D_{\mathrm{local}}, L^{\mathrm{CR}}_{\mathrm{local}}, A_{\mathrm{local}}).$$

Pavlo Plotko [1], Arjen van Vliet [1,2] Xavier Rodrigues [1,3] and Walter Winter [1]

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$$\boldsymbol{\lambda}_{\text{local}} = (\gamma_{\text{local}}, R^{\text{max}}_{\text{local}}, D_{\text{local}}, L^{\text{CR}}_{\text{local}}, A_{\text{local}}).$$

$$\chi^2_{\text{PAO}} = \chi^2_{\text{PAO}}(\boldsymbol{\lambda}_{\text{cosmo}}, \delta^{\text{PAO}}_{E}, \delta^{\text{PAO}}_{\langle X_{\text{max}}\rangle}, \delta^{\text{PAO}}_{\sigma(X_{\text{max}})}).$$

$$\chi^2_{\text{TA}} = \chi^2_{\text{TA}}(\boldsymbol{\lambda}_{\text{cosmo}}, \boldsymbol{\lambda}_{\text{local}}, \delta^{\text{TA}}_{E}, \delta^{\text{TA}}_{\langle X_{\text{max}}\rangle}, \delta^{\text{TA}}_{\sigma(X_{\text{max}})}),$$

astrophysics

systematics

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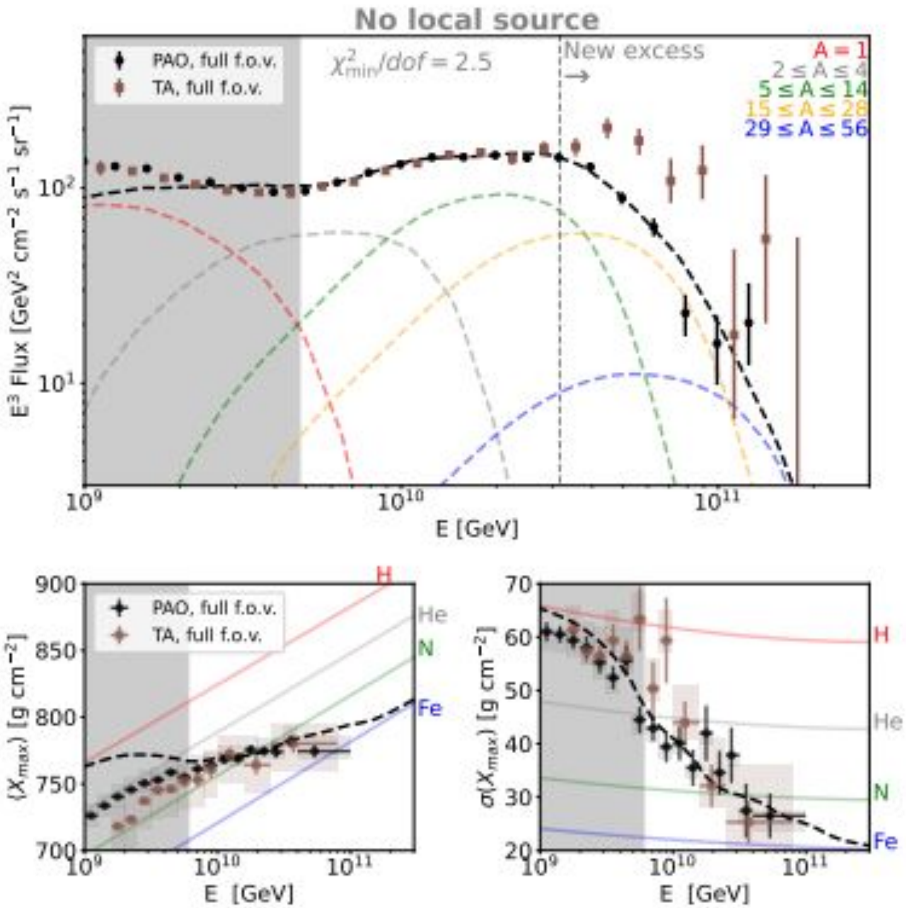

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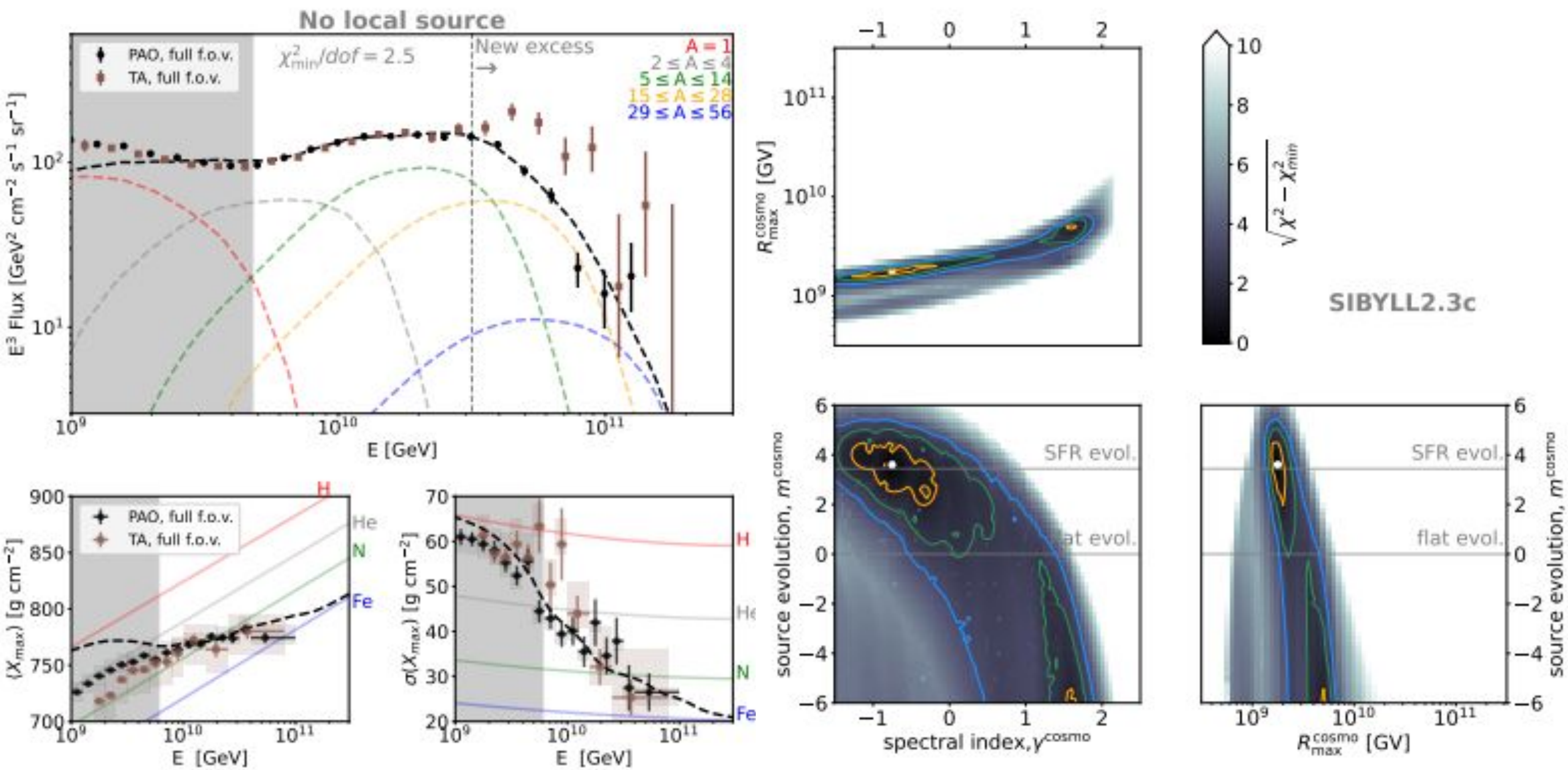

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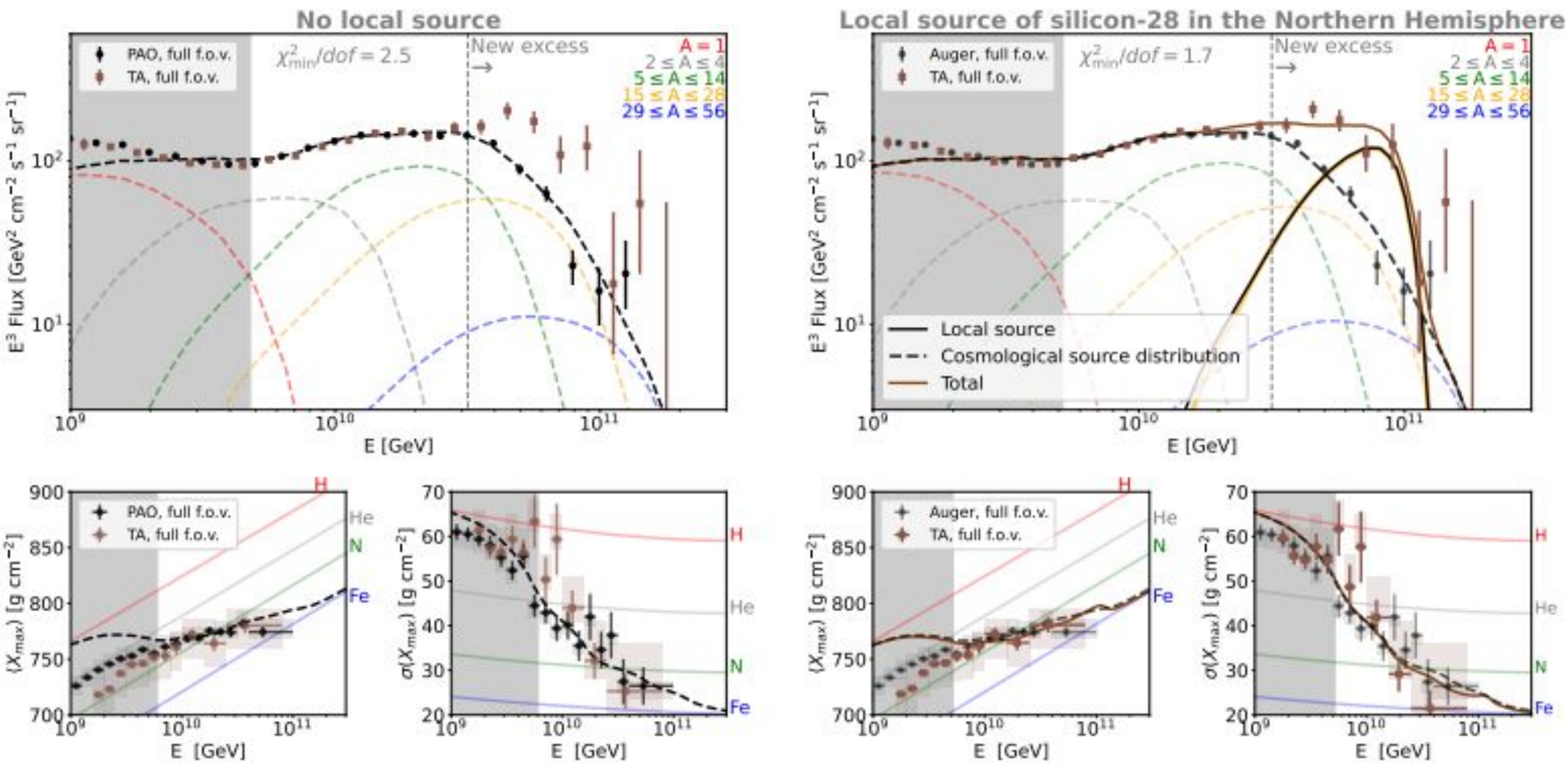

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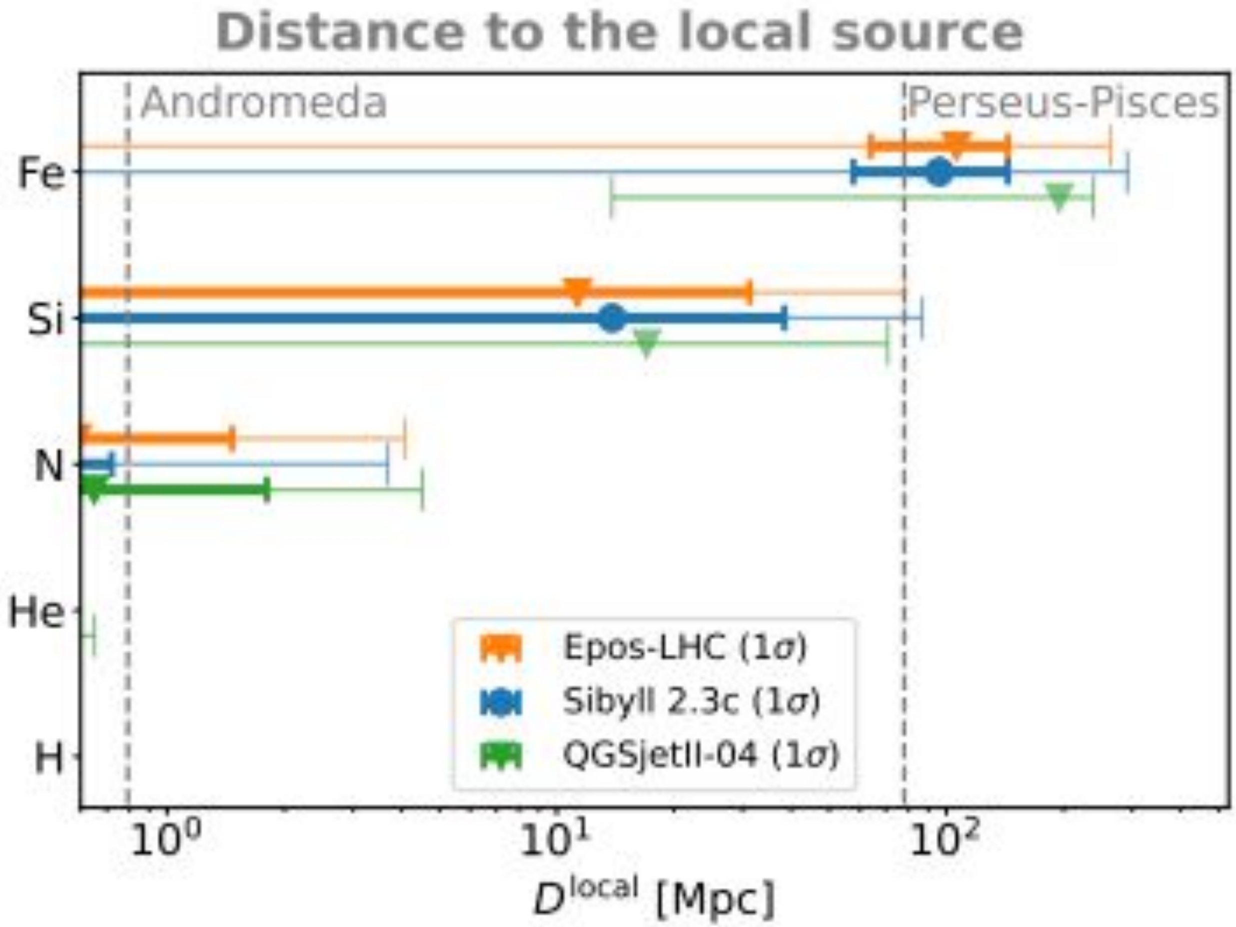

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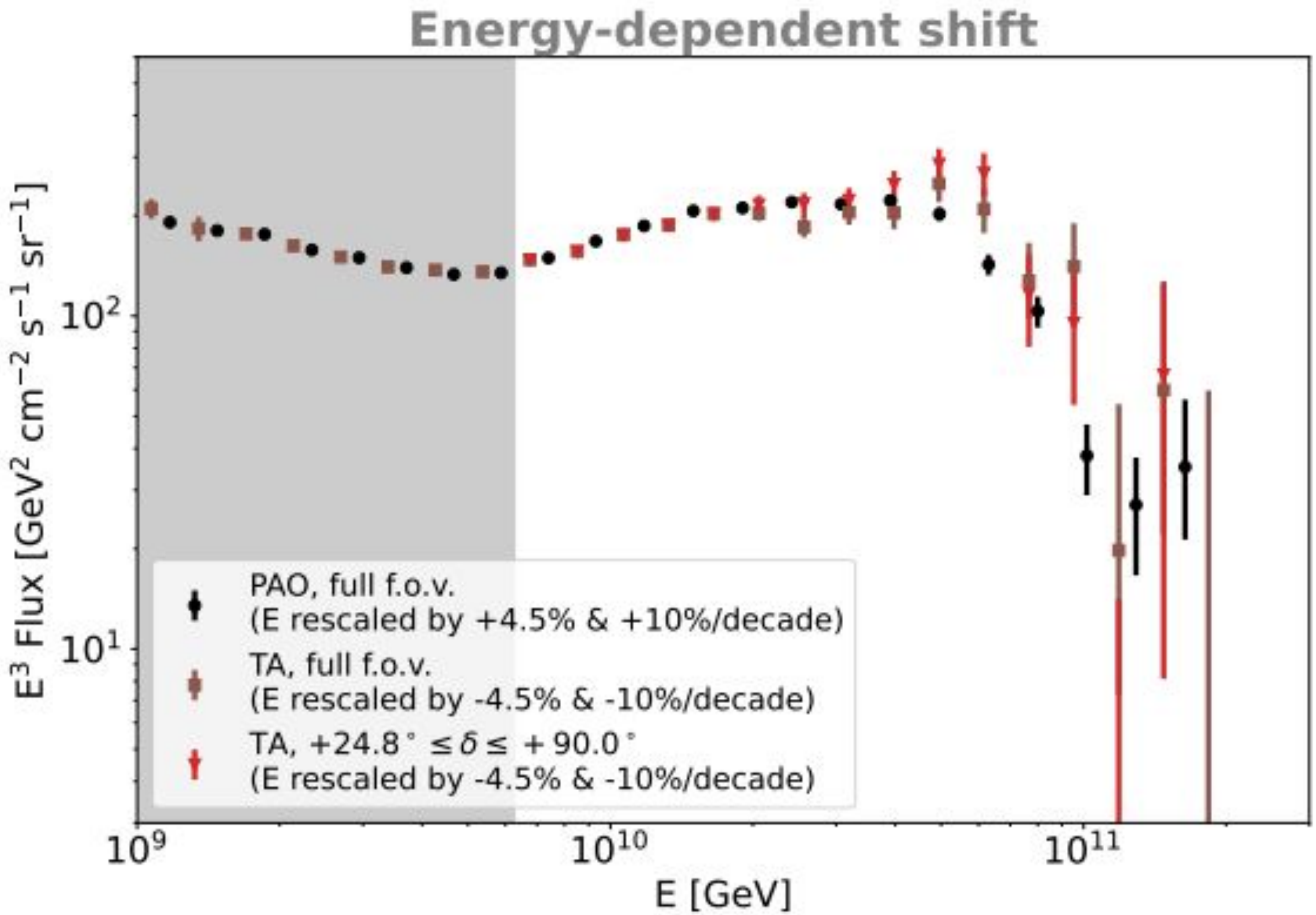

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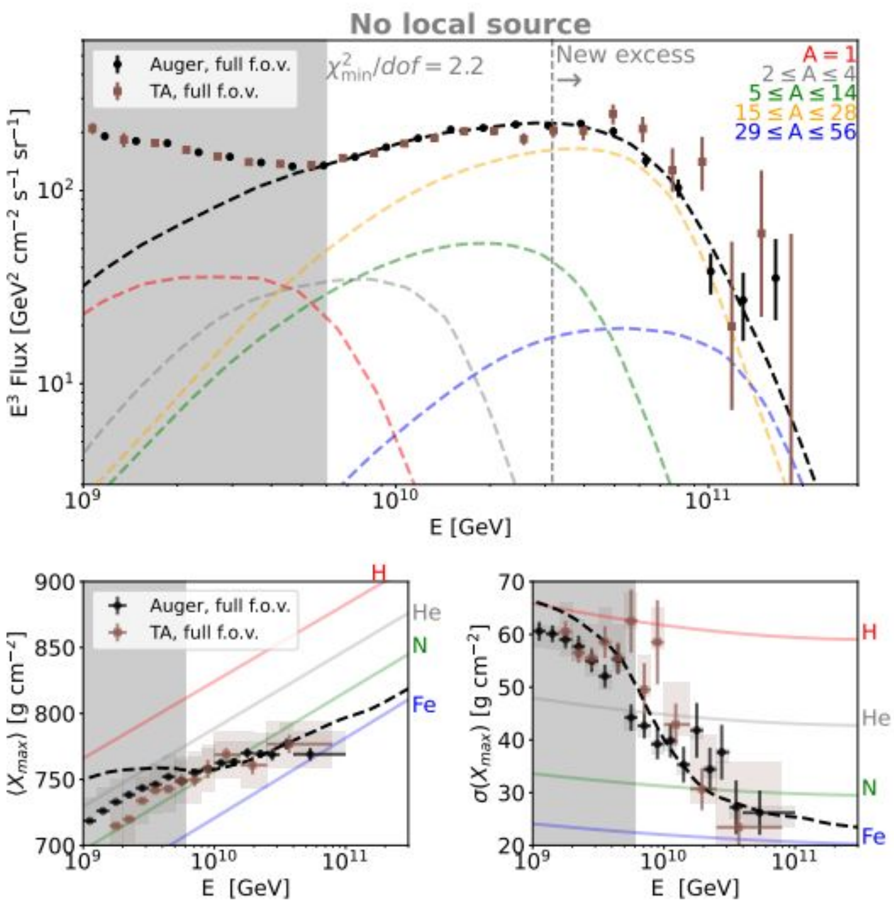

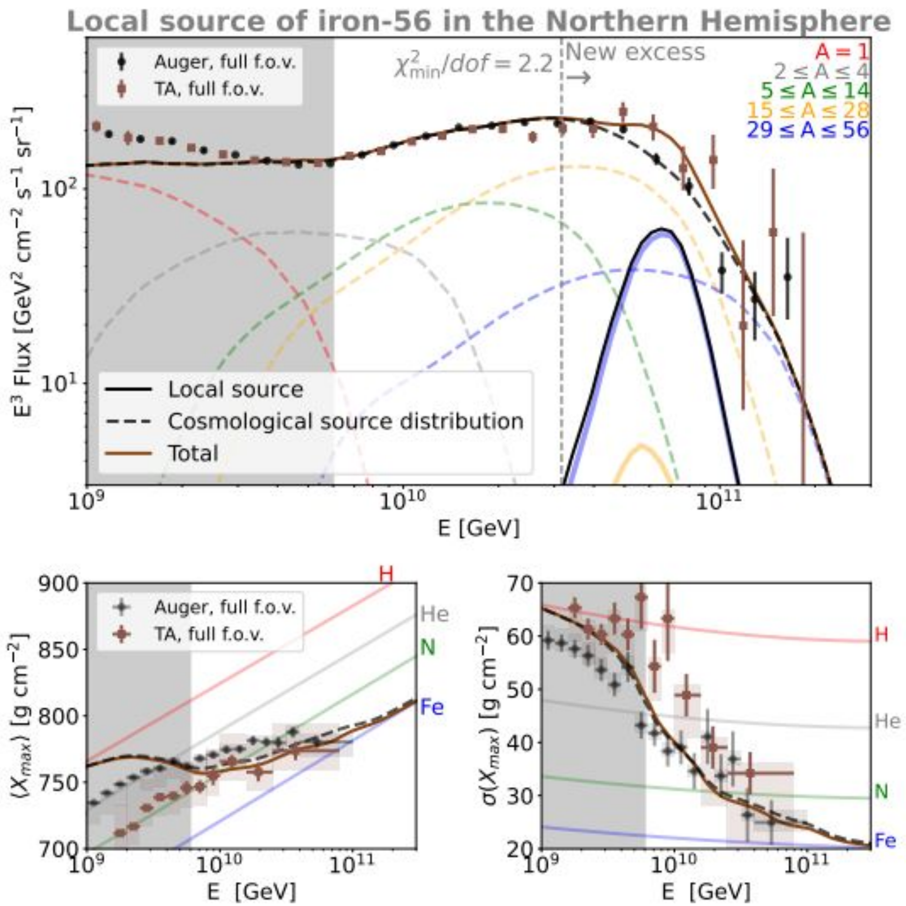

Pavlo Plotko [1], Arjen van Vliet [1,2], Xavier Rodrigues [1,3] and Walter Winter [1]

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What we need: better tools for joint treatment of composition data from both experiments (starting with more information on the acceptance and resolution for TA Xmax analysis)

What we can do while we wait: combine the spectrum/composition constraints from the PrINCe approach with directional capabilities of the CRPropa approach

Backup

Table 1. Best-fit parameters corresponding to the results of the joint fit to PAO and TA. The 1σ uncertainty region is given for 1 d.o.f.

		cosmological source distribution only			cosmological source distribution + local source		
		Sibyll 2.3c	Epos-LHC	QGSJET-II-04	Sibyll 2.3c	Epos-LHC	QGSJET-II-04
cosmological source distrib.	$\gamma_{\rm cosmo}$	$-0.75^{+0.15}_{-0.15}$	$0.10^{+0.05}_{-0.1}$	$-0.60^{+0.03}_{-0.05}$	$-0.75^{+0.15}_{-0.45}$	$-0.85^{+0.05}_{-0.05}$	$-0.65^{+0.05}_{-0.03}$
	$R^{\rm max}_{\rm cosmo}$ (GV)	$1.8^{+0.2}_{-0.2}\times 10^9$	$2.5^{+0.2}_{-0.2}\times 10^9$	$2.5^{+0.2}_{-0.2}\times 10^9$.	$1.8^{+0.2}_{-0.2}\times 10^9$	$2.0^{+0.2}_{-0.2}\times 10^9$	$2.5^{+0.2}_{-0.2}\times 10^9$
	$m_{\rm cosmo}$	$3.6^{+0.6}_{-0.6}$	< -4.8	< -5.8	$3.8^{+0.6}_{-0.6}$	$0.6^{+0.6}_{-0.6}$?	< -5.8
	$f_A(\%)$						
	H	$0.004^{+99.996}_{-0.004}$	$0.000^{+86.756}_{-0.000}$	$0.002^{+99.881}_{-0.002}$	$0.004^{+99.928}_{-0.004}$	$0.001^{+99.879}_{-0.001}$	$0.000^{+84.659}_{-0.000}$
	He	$86.096^{+1.986}_{-2.256}$	$88.799^{+0.329}_{-0.338}$	$92.588^{+0.258}_{-0.266}$	$80.504^{+4.150}_{-4.948}$	$92.125^{+0.485}_{-0.514}$	$92.471^{+0.261}_{-0.270}$
	N	$13.324^{+0.728}_{-0.696}$	$10.578^{+0.414}_{-0.400}$	$7.222^{+0.291}_{-0.281}$	$18.803^{+0.936}_{-0.901}$	$7.738^{+0.308}_{-0.298}$	$7.375^{+0.207}_{-0.202}$
	Si	$0.567^{+0.113}_{-0.094}$	$0.609^{+0.110}_{-0.093}$	$0.181^{+0.034}_{-0.028}$	$0.676^{+0.266}_{-0.192}$	$0.133^{+0.045}_{-0.034}$	$0.147^{+0.033}_{-0.027}$
	Fe	$0.010^{+0.008}_{-0.004}$	$0.015^{+0.017}_{-0.008}$	$0.007^{+0.003}_{-0.002}$	$0.012^{+0.012}_{-0.006}$	$0.003^{+0.003}_{-0.002}$	$0.005^{+0.002}_{-0.002}$
Loc. source	isotope				silicon-28	silicon-28	nitrogen-14
	$\gamma_{\rm local}$				< -1.0	< -1.1	< -1.1
	$R^{\rm max}_{\rm local}$ (GV)				$1.3^{+0.2}_{-0.1}\times 10^9$	$2.3^{+0.3}_{-0.1}\times 10^9$	$2.5^{+0.3}_{-0.3}\times 10^9$
	$L^{\rm CR}_{\rm local}$ (erg s^{-1})				$1.1^{+2.0}_{-1.1}\times 10^{42}$	$7.3^{+18.0}_{-7.3}\times 10^{41}$	$< 1.0\times 10^{40}$
	$D_{\rm local}$ (Mpc)				$13.9^{+9.2}_{-13.9}$	$11.3^{+9.5}_{-11.3}$	$< +1.4$
Systematics	$\delta_E^{\rm PAO}(\%)$	$-11.6^{+2.1}_{-0.5}$	$-8.97^{+1.1}_{-0.5}$	$10.8^{+0.0}_{-0.3}$	$-11.7^{+0.8}_{-1.5}$	$-9.5^{+0.5}_{-0.6}$	$10.9^{+0.9}_{-0.0}$
	$\delta_E^{\rm TA}(\%)$	$-20.5^{+1.9}_{-0.5}$	$-18.3^{+1.0}_{-0.4}$	$10.8^{+0.0}_{-0.3}$	$-19.7^{+0.7}_{-1.3}$	$-17.6^{+0.5}_{-0.6}$	$1.1^{+0.8}_{-0.00}$
	$\delta^{\rm PAO}_{\langle X_{\rm max}\rangle}(\%)$	-25^{+25}_{-27}	-100^{+0}_{-0}	-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 no local source				5.6σ	5.7σ	4.6σ

Pavlo Plotko [1], Arjen van Vliet [1,2], Xavier Rodrigues [1,3] and Walter Winter [1]

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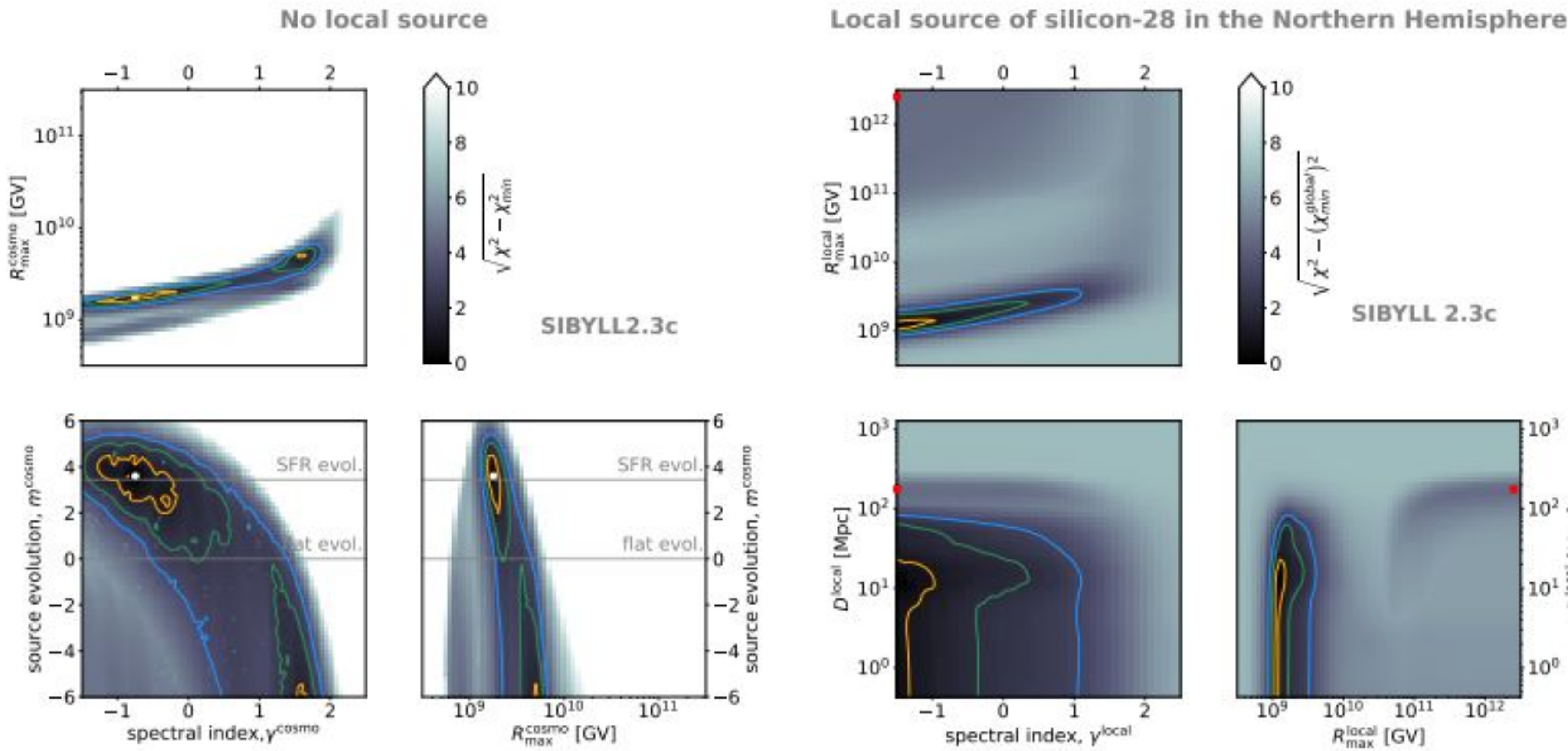
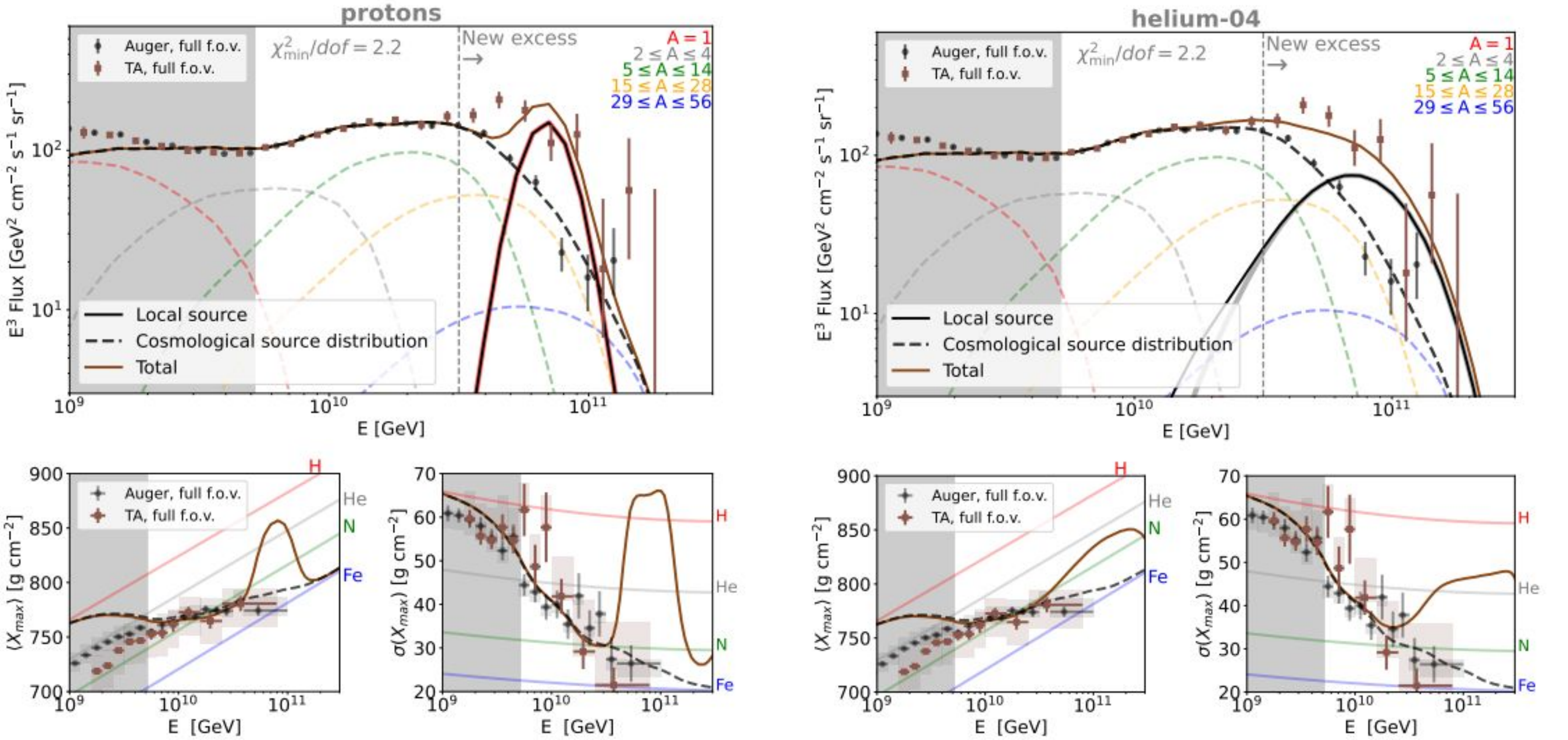
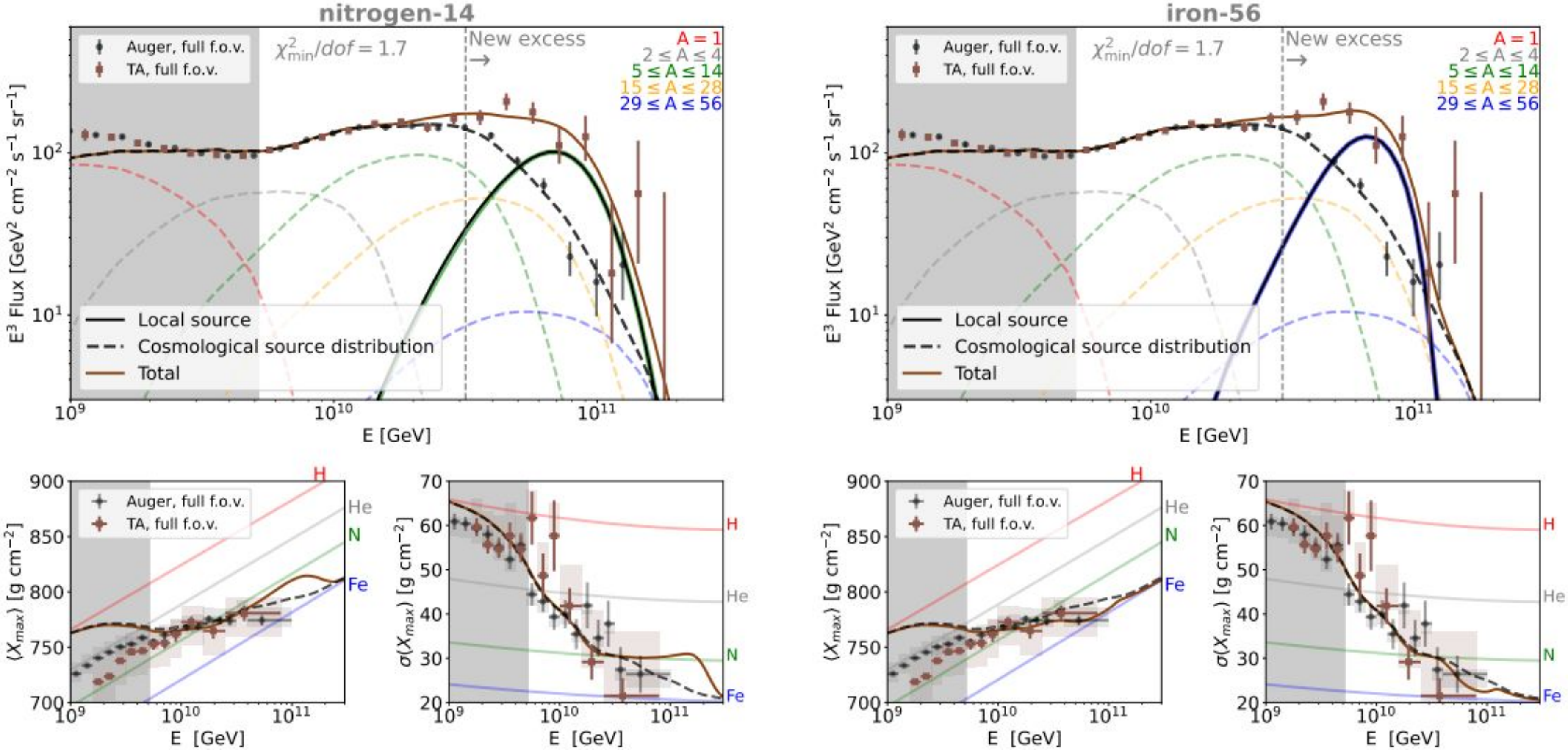


No local source
Local source of silicon-28 in the Northern Hemisphere
SIBYLL2.3c
SIBYLL 2.3c
R_{max}^{cosmo} [GV]
$\sqrt{\chi^2 - \chi^2_{min}}$
R_{max}^{local} [GV]
$\sqrt{\chi^2 - (\chi^{global}_{min})^2}$
SFR evol.
flat evol.
source evolution, m^{cosmo}
spectral index, γ^{cosmo}
D^{local} [Mpc]
spectral index, γ^{local}

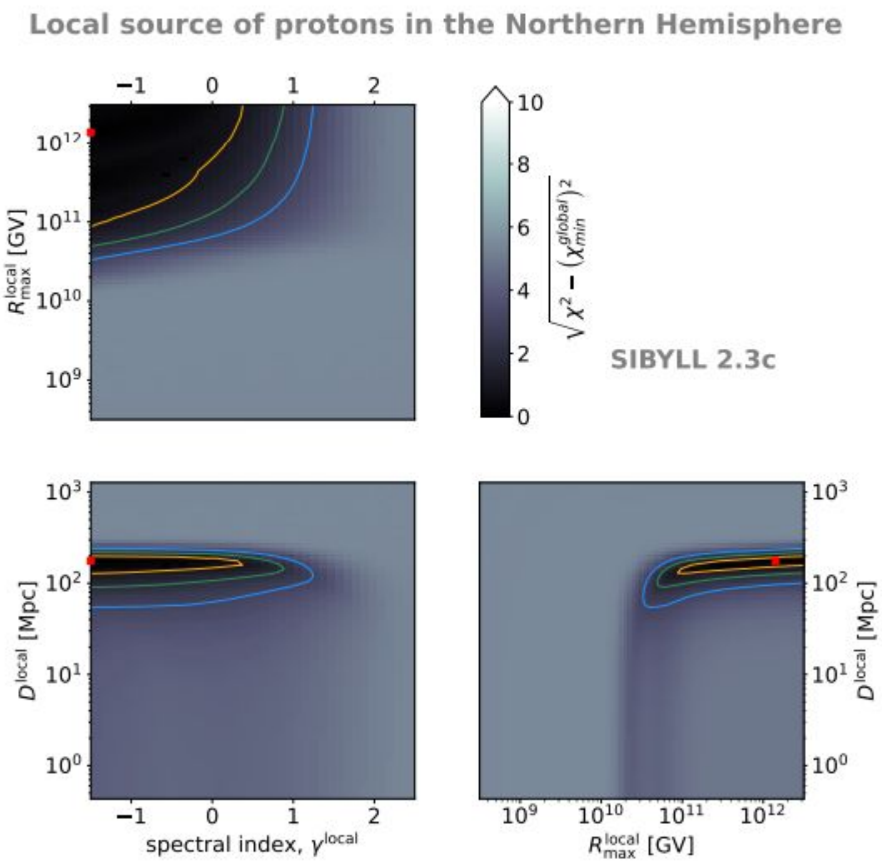


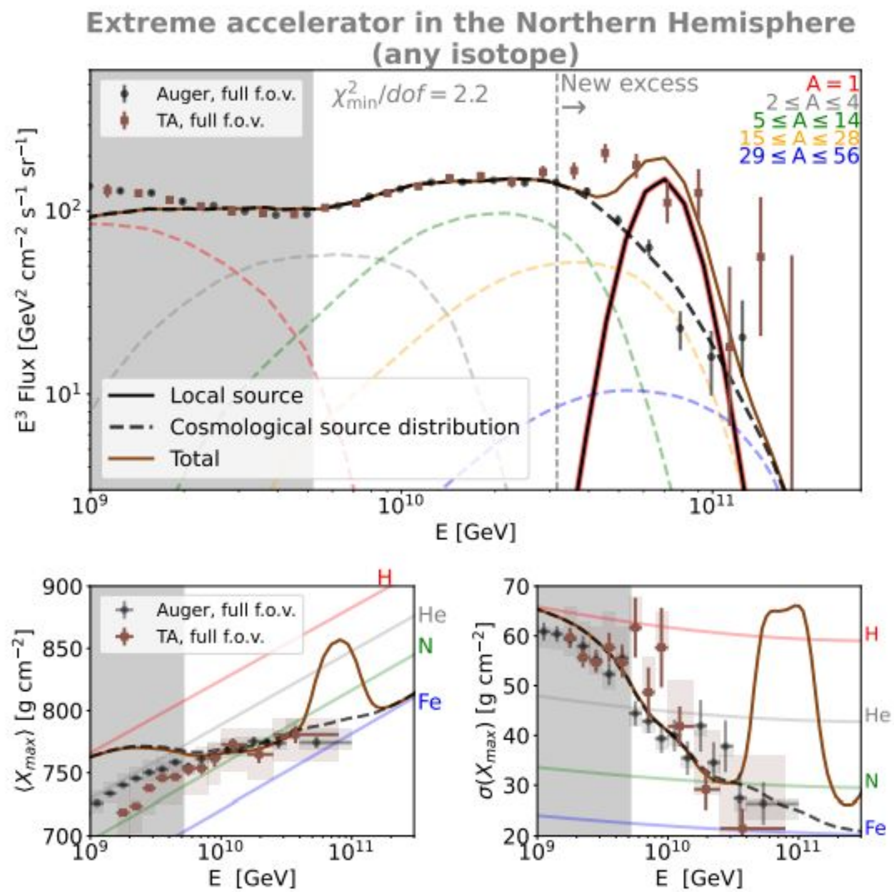
protons
helium-04
Auger, full f.o.v.
TA, full f.o.v.
$\chi^2_{\rm min}/dof = 2.2$
New excess →
A = 1
2 ≤ A ≤ 4
5 ≤ A ≤ 14
15 ≤ A ≤ 28
29 ≤ A ≤ 56
Local source
Cosmological source distribution
Total
E³ Flux [GeV² cm⁻² s⁻¹ sr⁻¹]
E [GeV]
⟨X_max⟩ [g cm⁻²]
σ(X_max) [g cm⁻²]
H
He
N
Fe



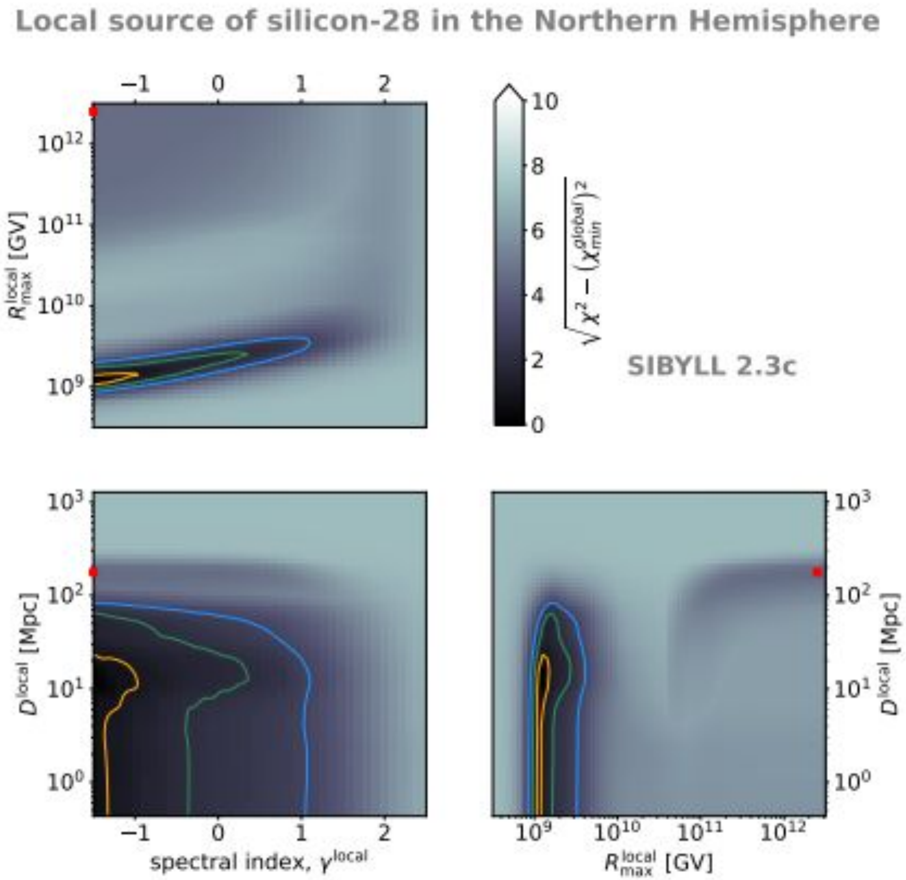
nitrogen-14
iron-56
Auger, full f.o.v.
TA, full f.o.v.
$\chi^2_{\rm min}/dof = 1.7$
New excess
→
A = 1
2 ≤ A ≤ 4
5 ≤ A ≤ 14
15 ≤ A ≤ 28
29 ≤ A ≤ 56
Local source
Cosmological source distribution
Total
E³ Flux [GeV² cm⁻² s⁻¹ sr⁻¹]
E [GeV]
⟨X_max⟩ [g cm⁻²]
σ(X_max) [g cm⁻²]
H
He
N
Fe

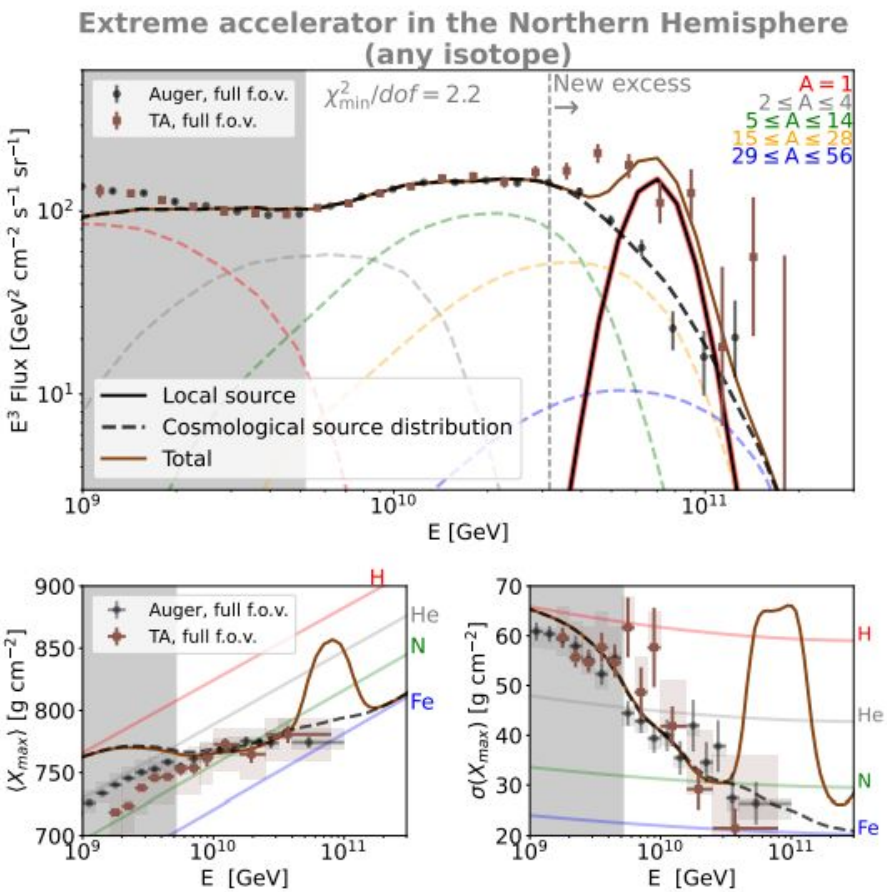
Extreme accelerator in the Northern sky



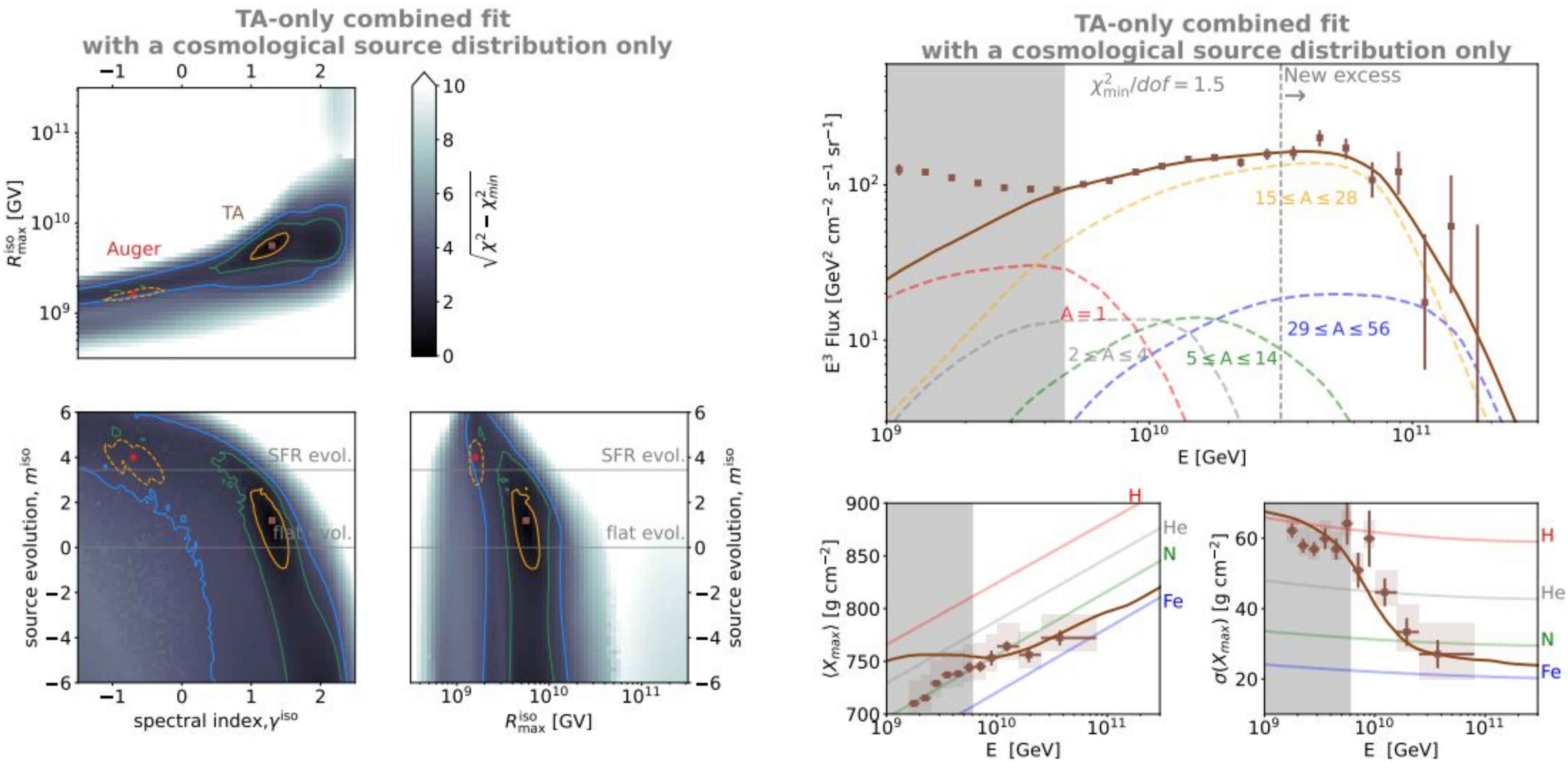


Extreme accelerator in the Northern sky

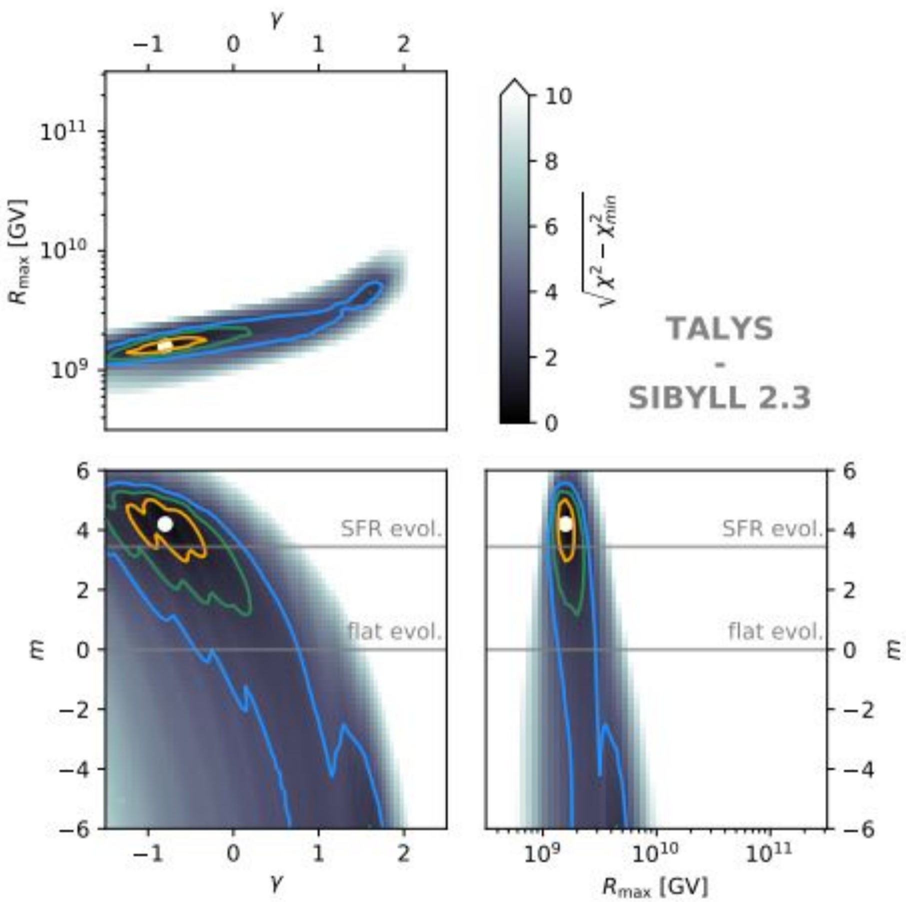


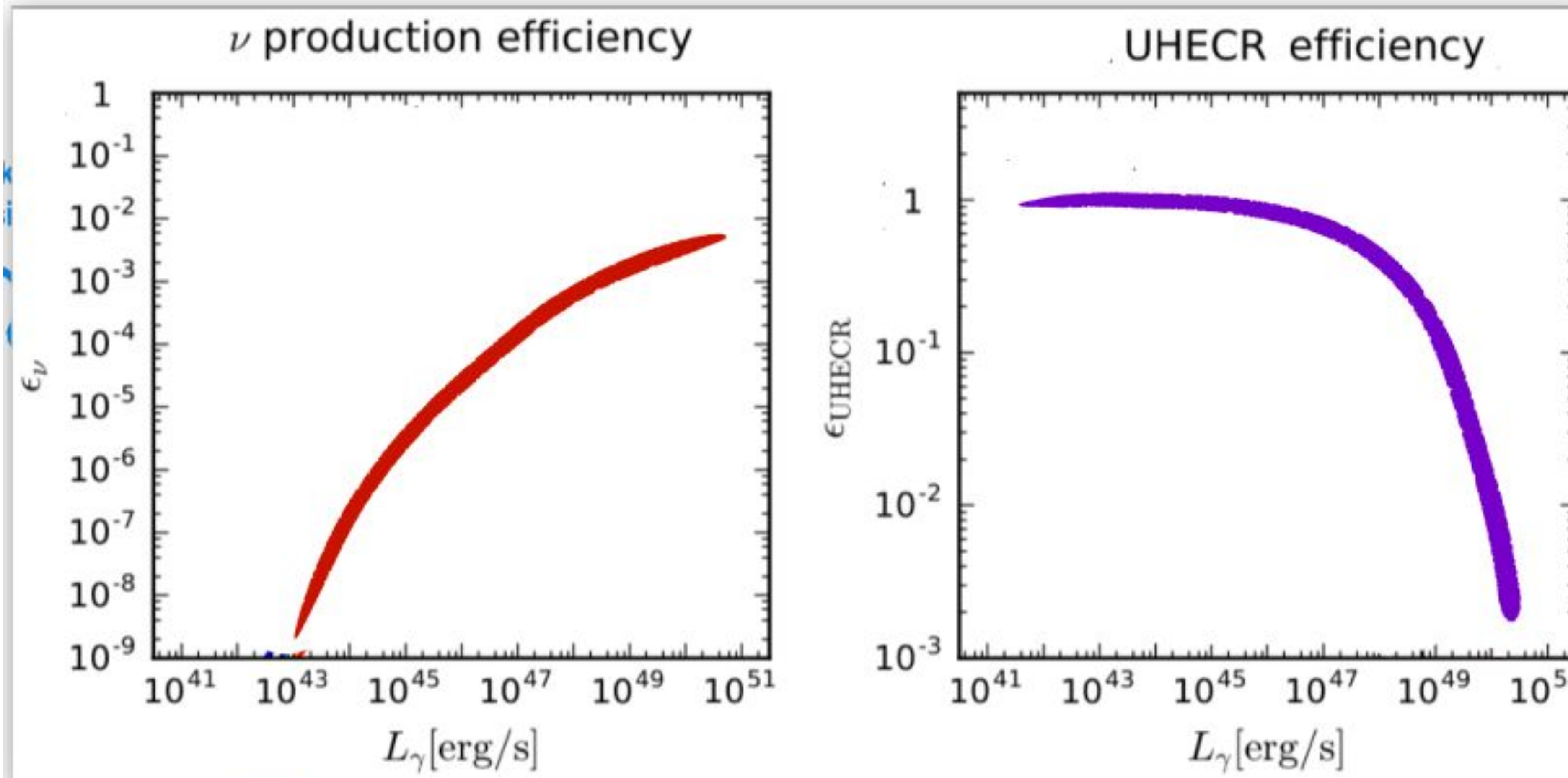


Direct comparison of TA and Auger fits



First results (Heinze et al 2019, ApJ 873)





XR, Fedynitch, Gao, Boncioli, Winter, ApJ 854 (2018)