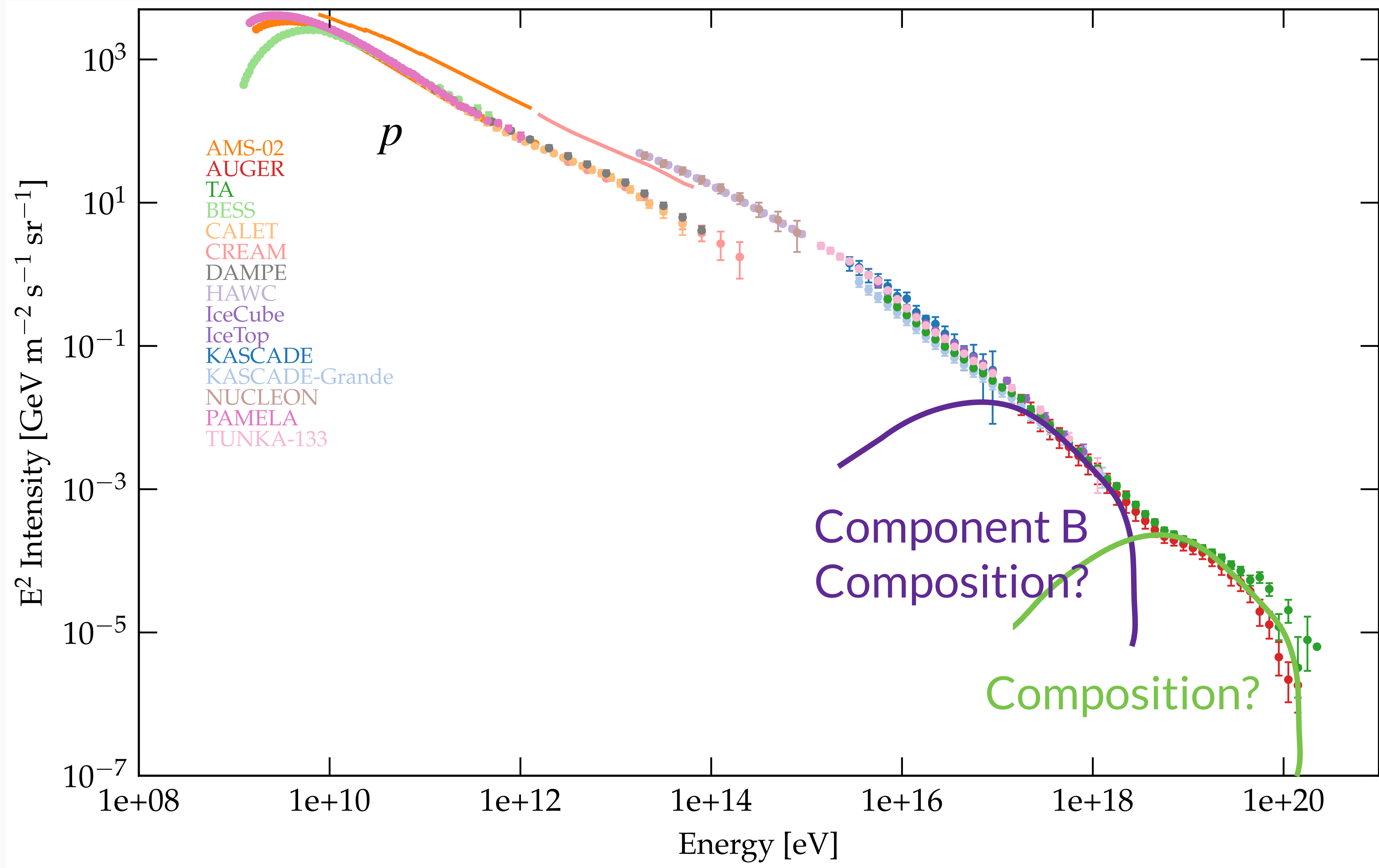




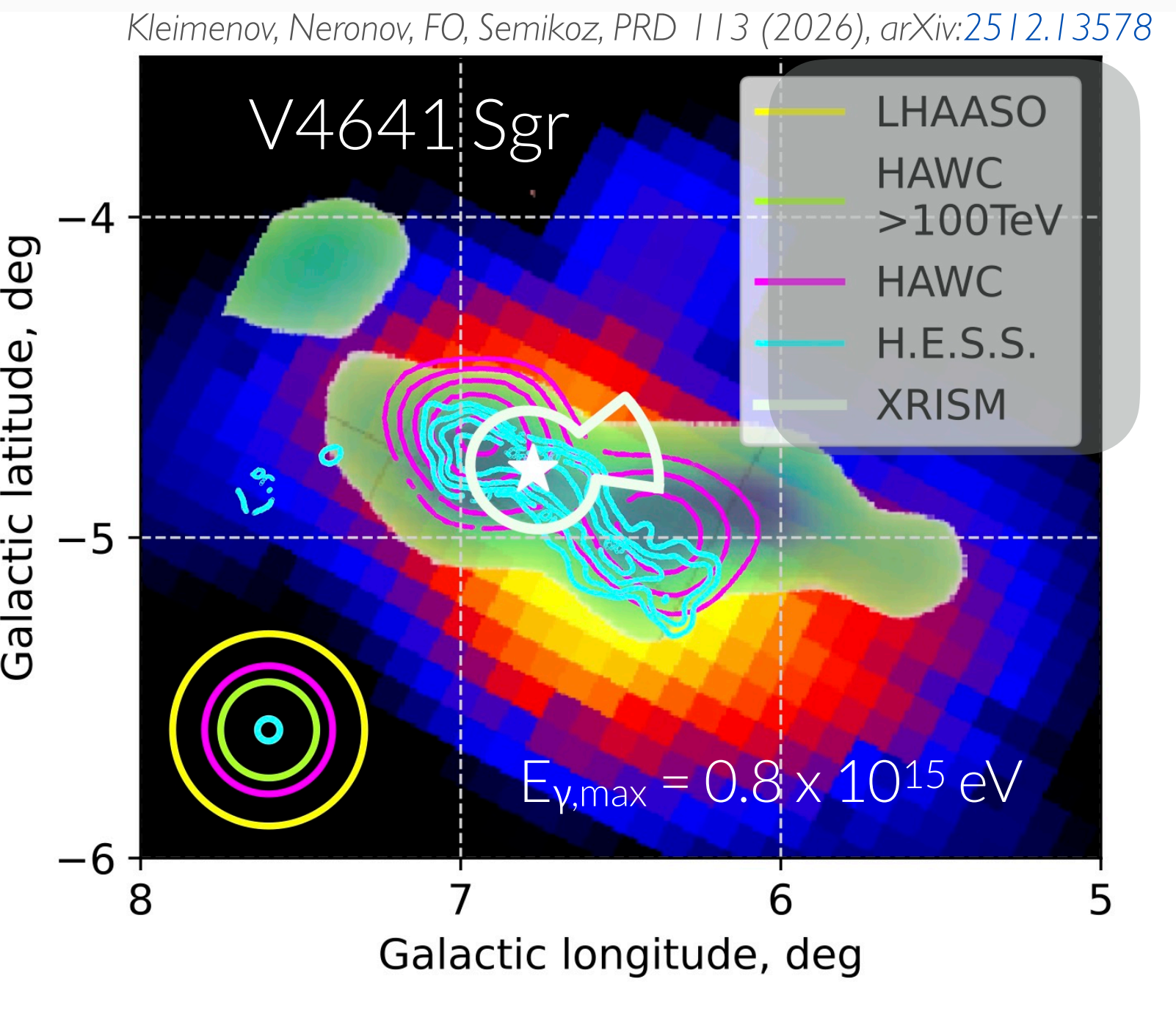
# On the metallicity of UHECRs

Foteini Oikonomou

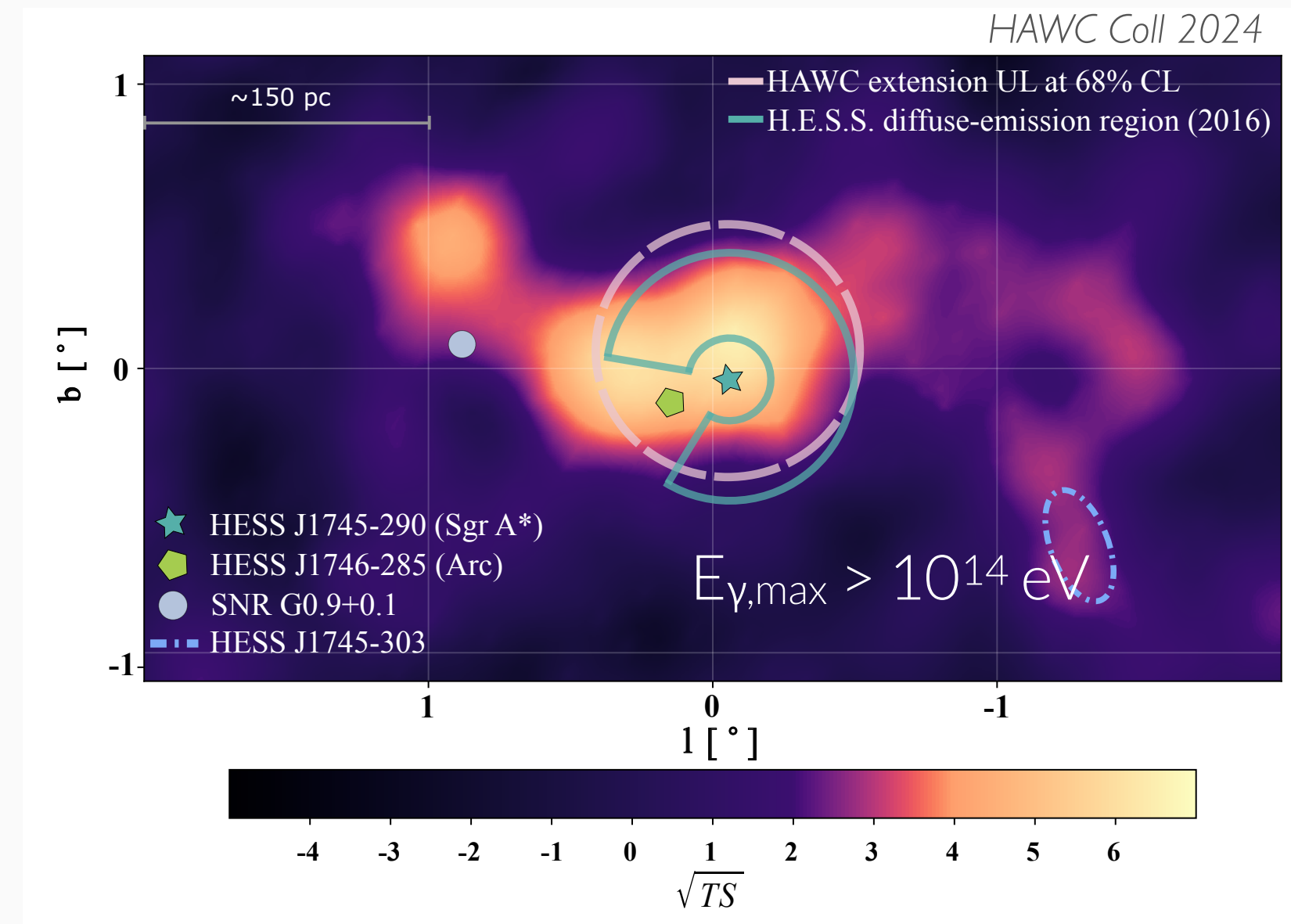




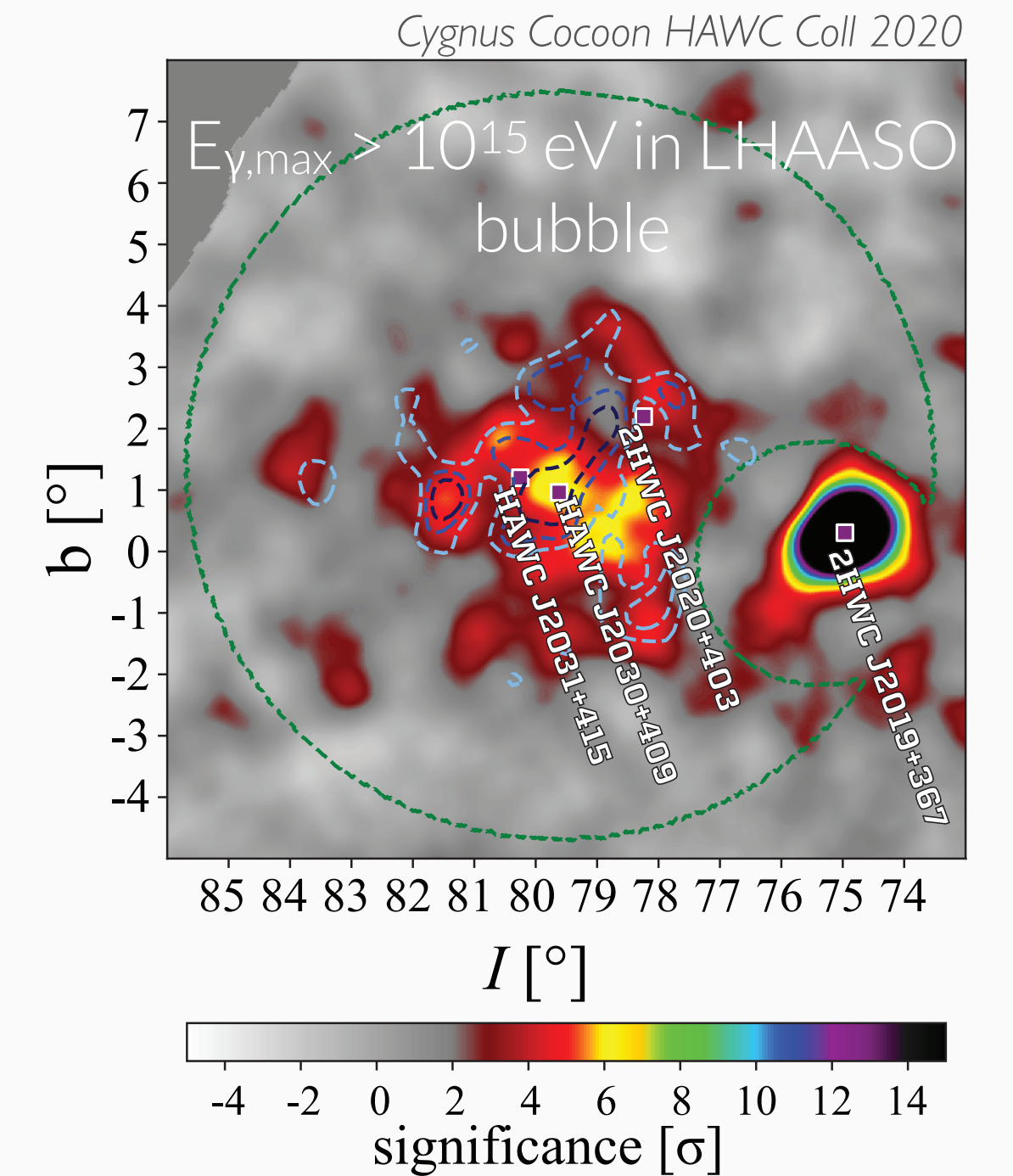
# Galactic PeVatron Accelerators as Component B candidate sources



Microquasars  
(LHAASO/HAWC/HESS)



Galactic Centre  
(HESS/HAWC)



Star Clusters  
(HESS/HAWC/LHAASO)

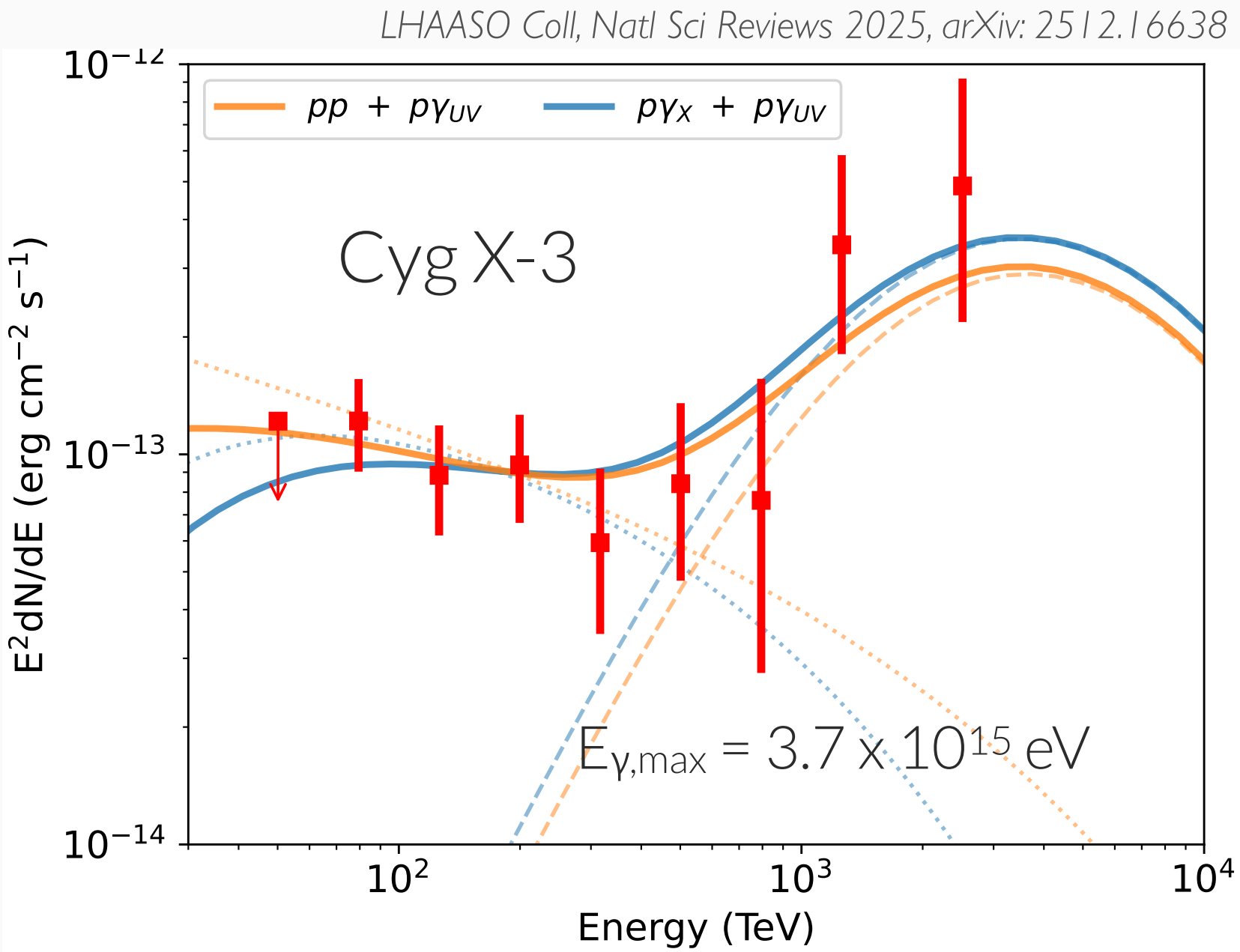
# Galactic Hadronic SuperPeVatrons as Component B candidate sources

| Source        | $L_{\gamma(>25\text{ TeV})}$<br>(erg/s) | max<br>(detected)<br>energy | site?                                     | dominant emission                             | $M_{\text{BH}}$ | persistent? |
|---------------|-----------------------------------------|-----------------------------|-------------------------------------------|-----------------------------------------------|-----------------|-------------|
| SS 433        | $2 \cdot 10^{33}$                       | ~400 TeV                    | extended <b>jet</b> lobes<br>+ nearby gas | <b>leptonic</b><br>(+ <b>hadronic</b> at UHE) | ~10 (?)         | yes         |
| Cyg X-1       | $3 \cdot 10^{31}$                       | ~80 TeV                     | consistent with <b>jet</b><br>bow shock   | ?                                             | 20              | yes         |
| MAXI<br>J1820 | $1 \cdot 10^{32}$                       | ~200 TeV                    | offset in <b>jet</b><br>direction         | likely <b>leptonic</b>                        | 8-10            | yes         |
| GRS 1915      | $4 \cdot 10^{33}$                       | ~500 TeV                    | extended, maybe <b>jet</b><br>bow shock?  | <b>hadronic?</b>                              | 10-12           | yes         |
| V4641 Sgr     | $3 \cdot 10^{34}$                       | ~800 TeV                    | elongated in <b>jet</b><br>direction      | <b>leptonic</b>                               | 7               | yes         |
| Cyg X-3       | $2 \cdot 10^{33}$<br>(>100 TeV!)        | 100-3000 TeV                | <b>jet</b> + star wind?                   | <b>hadronic</b>                               | ~2.4 (?)        | NO!         |



# Galactic Hadronic SuperPeVatrons as Component B candidate sources

| Source     | $L_{\gamma(>25\text{ TeV})}$<br>(erg/s) | max<br>(detected)<br>energy | site?                                     | dominant emission                             | $M_{\text{BH}}$ | persistent? |
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| SS 433     | $2 \cdot 10^{33}$                       | ~400 TeV                    | extended <b>jet</b> lobes<br>+ nearby gas | <b>leptonic</b><br>(+ <b>hadronic</b> at UHE) | ~10 (?)         | yes         |
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| V4641 Sgr  | $3 \cdot 10^{34}$                       | ~800 TeV                    | elongated in <b>jet</b><br>direction      | <b>leptonic</b>                               | 7               | yes         |
| Cyg X-3    | $2 \cdot 10^{33}$<br>(>100 TeV!)        | 100-3000 TeV                | <b>jet</b> + star wind?                   | <b>hadronic</b>                               | ~2.4 (?)        | NO!         |

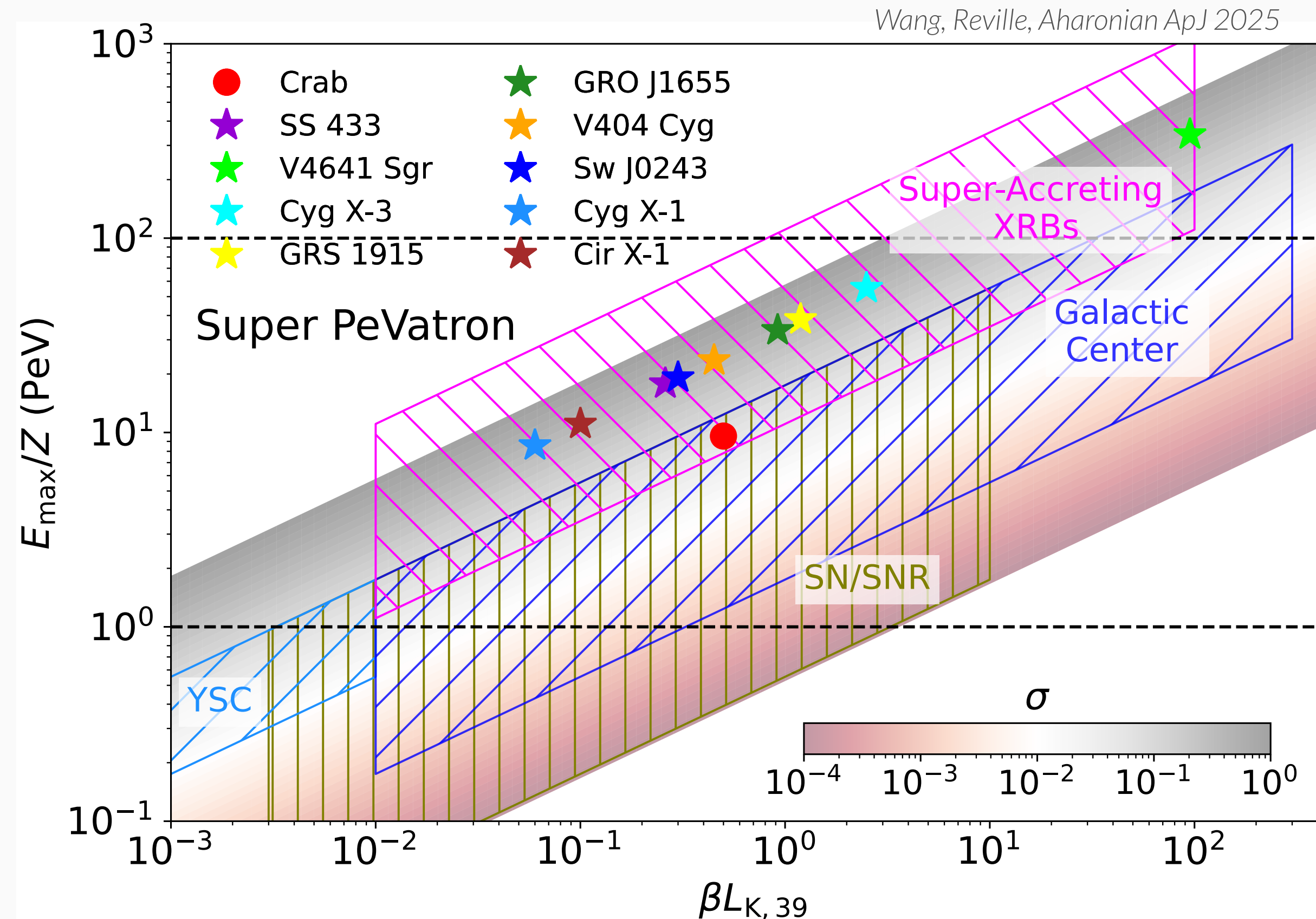


Implies:

$$E_{p,\text{max}} \approx 5 \times 10^{16} \text{ eV}$$
$$E_{N,\text{max}} \approx Z \times E_{p,\text{max}} \approx 4 \times 10^{17} \text{ eV}$$
$$E_{\text{Fe,max}} \approx 1.3 \text{ EeV}$$

(similar for Cygnus Cocoon)

# Component B Composition & Galactic Source Candidates



Past Activity of Galactic Center/Extreme Microquasars

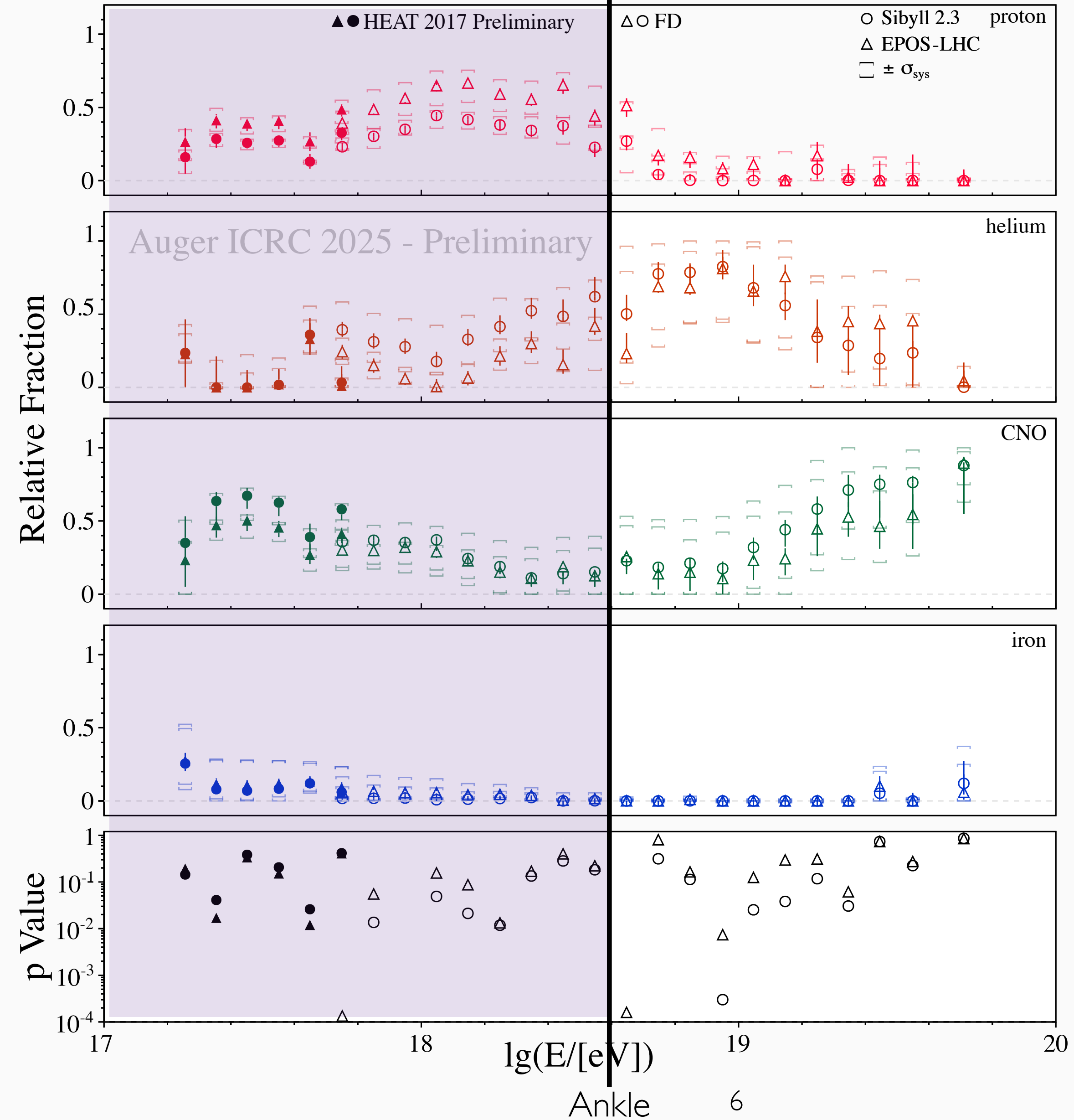
WR-Star Supernovae: Thoudam+ A&A 2016

Star Clusters: Bhadra+ ApJ 2024



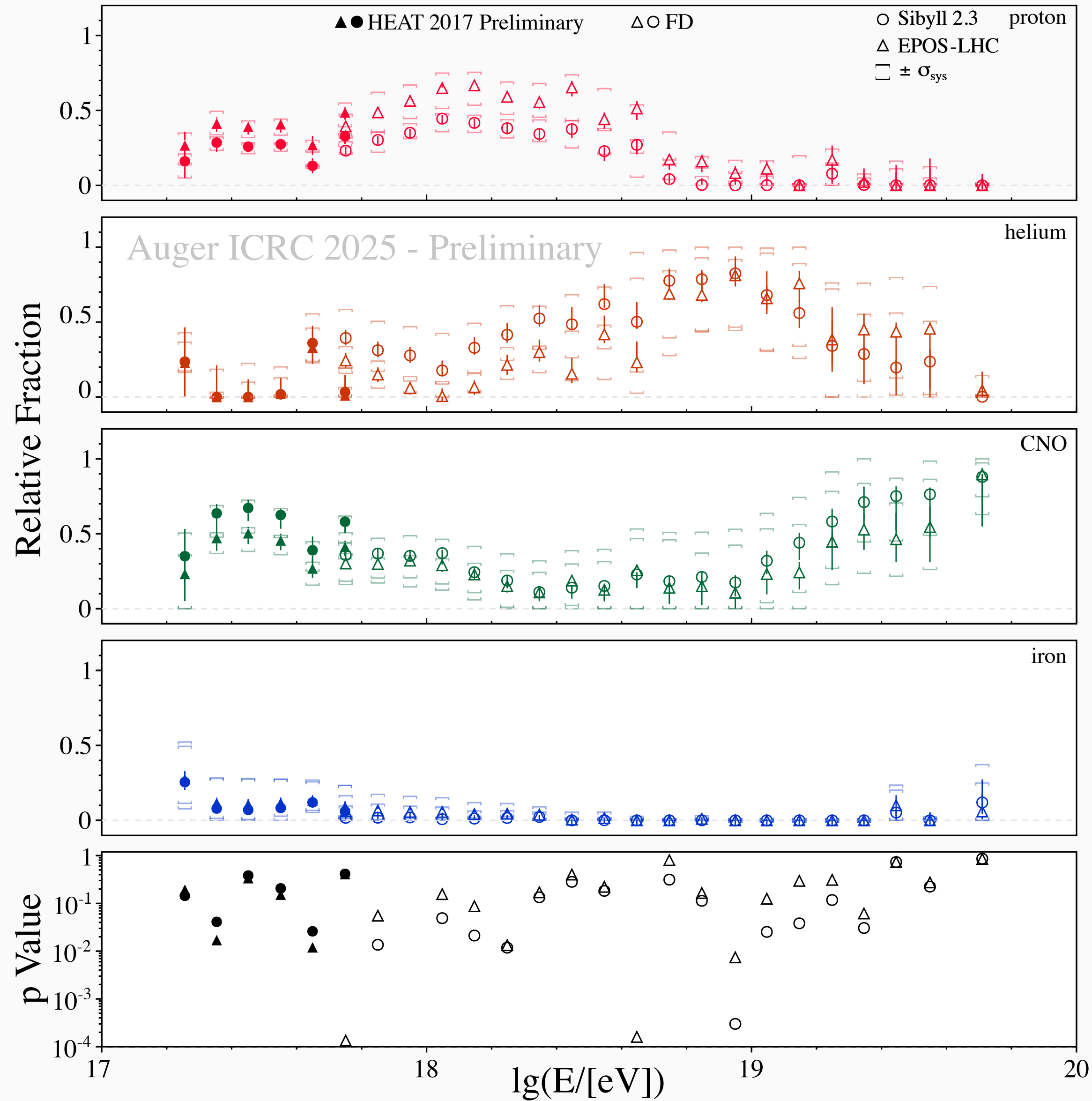
# Component B Composition

Auger Coll, Mayotte PoS 331 ICRC 2025



# Component B Composition

Auger Coll, Mayotte PoS 331 ICRC 2025

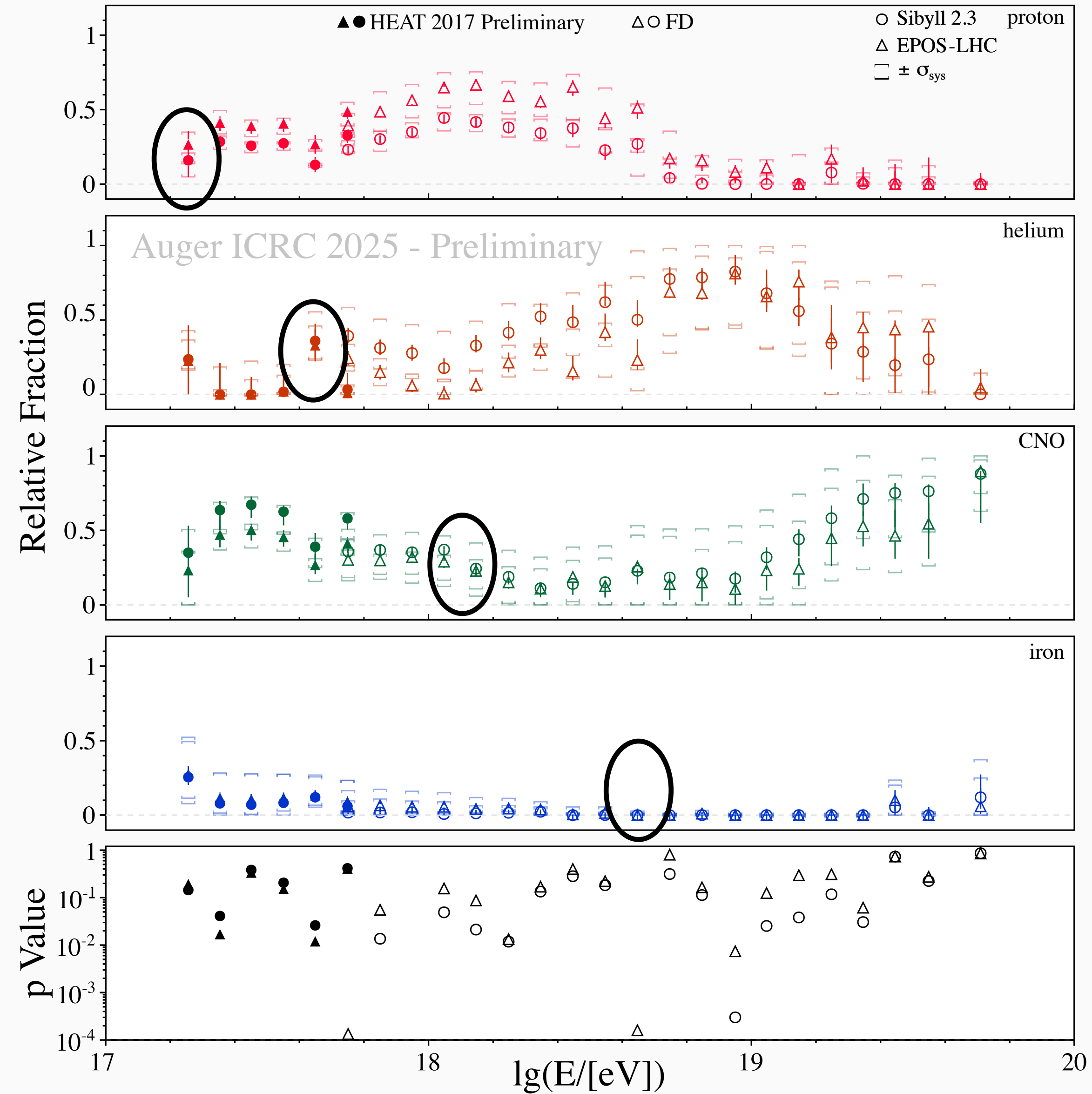




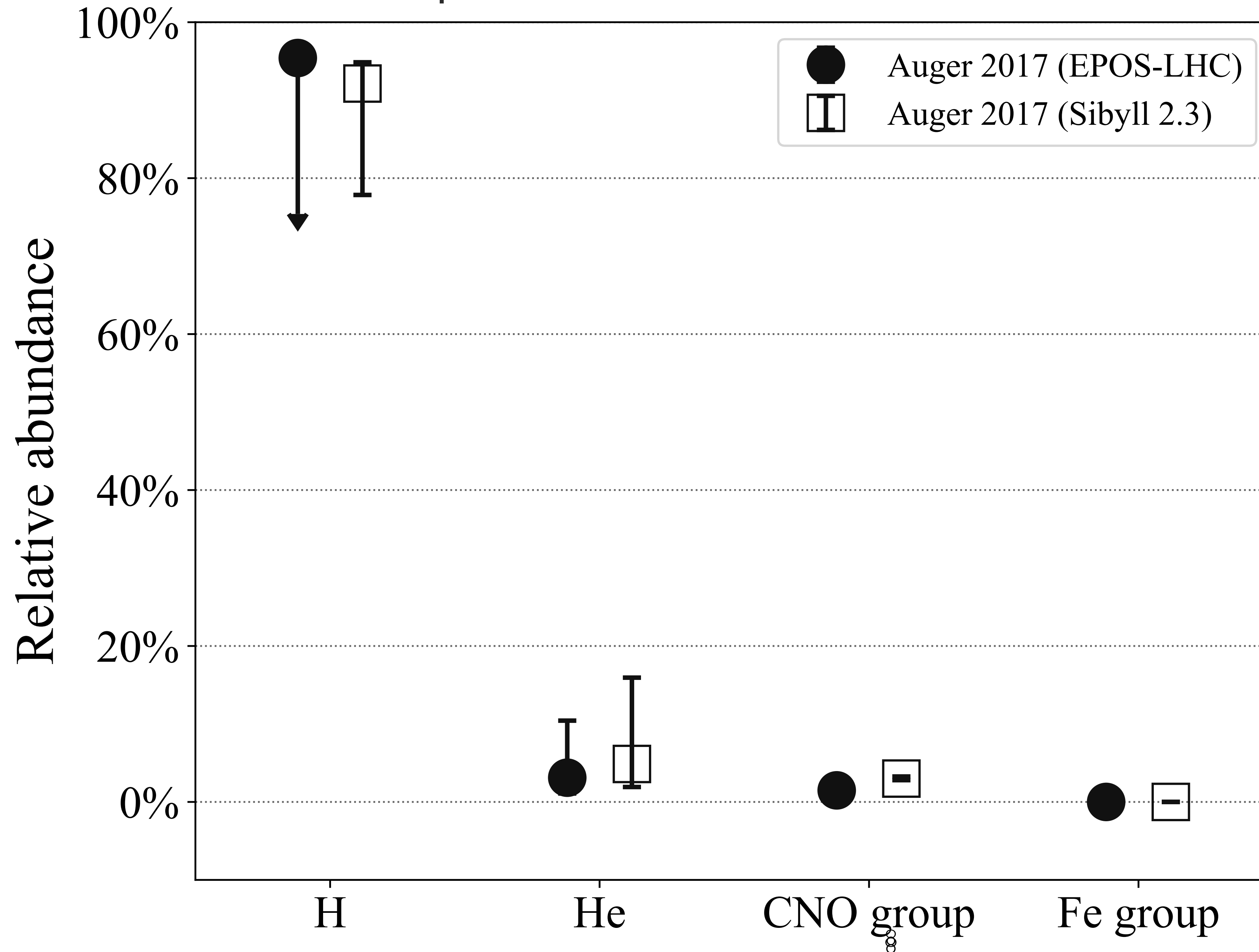
# Component B Composition

$$\log_{10} R = 17.25$$

Auger Coll, Mayotte PoS 331 ICRC 2025



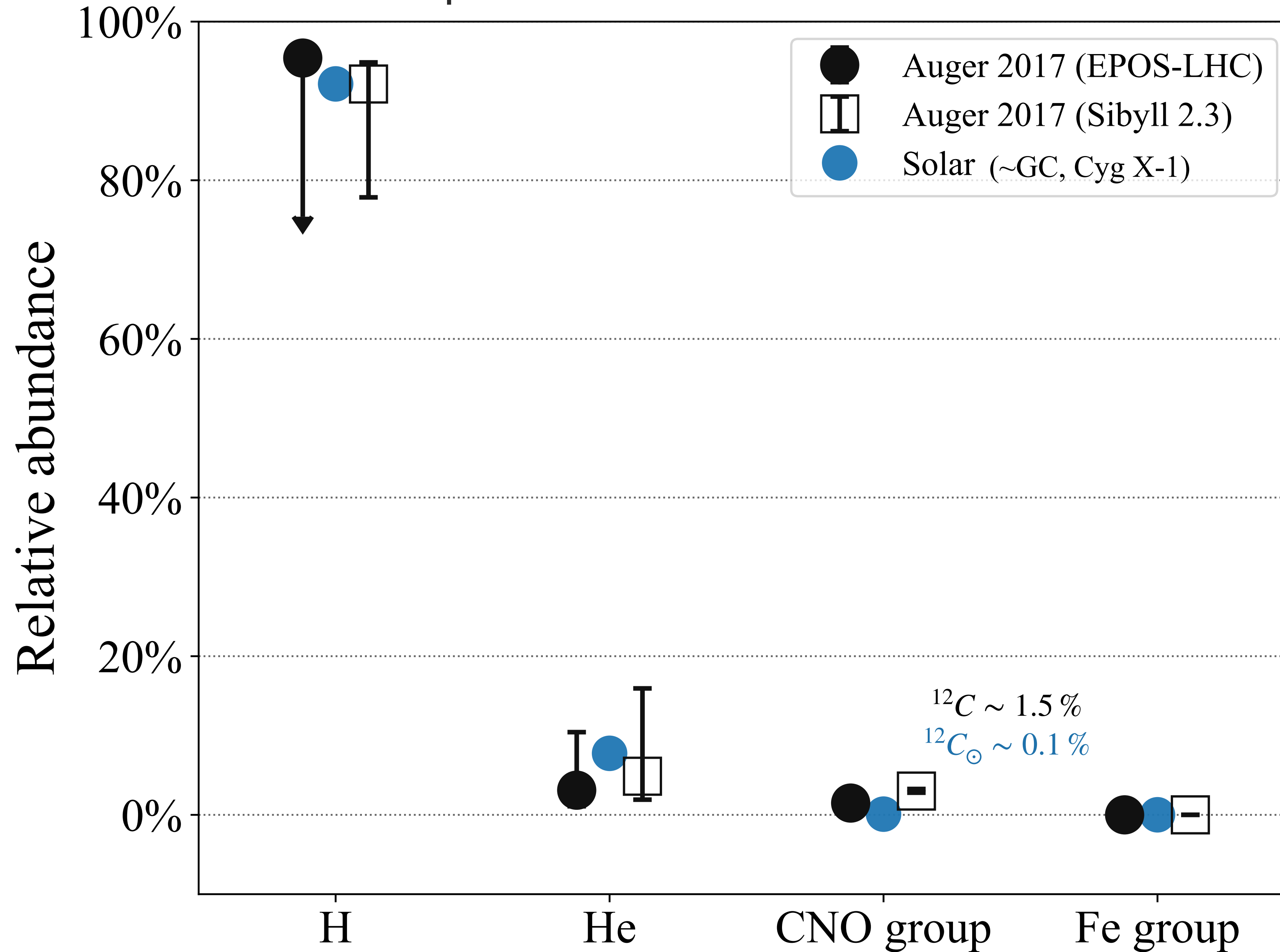
# Component B Composition



Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$

# Component B Composition

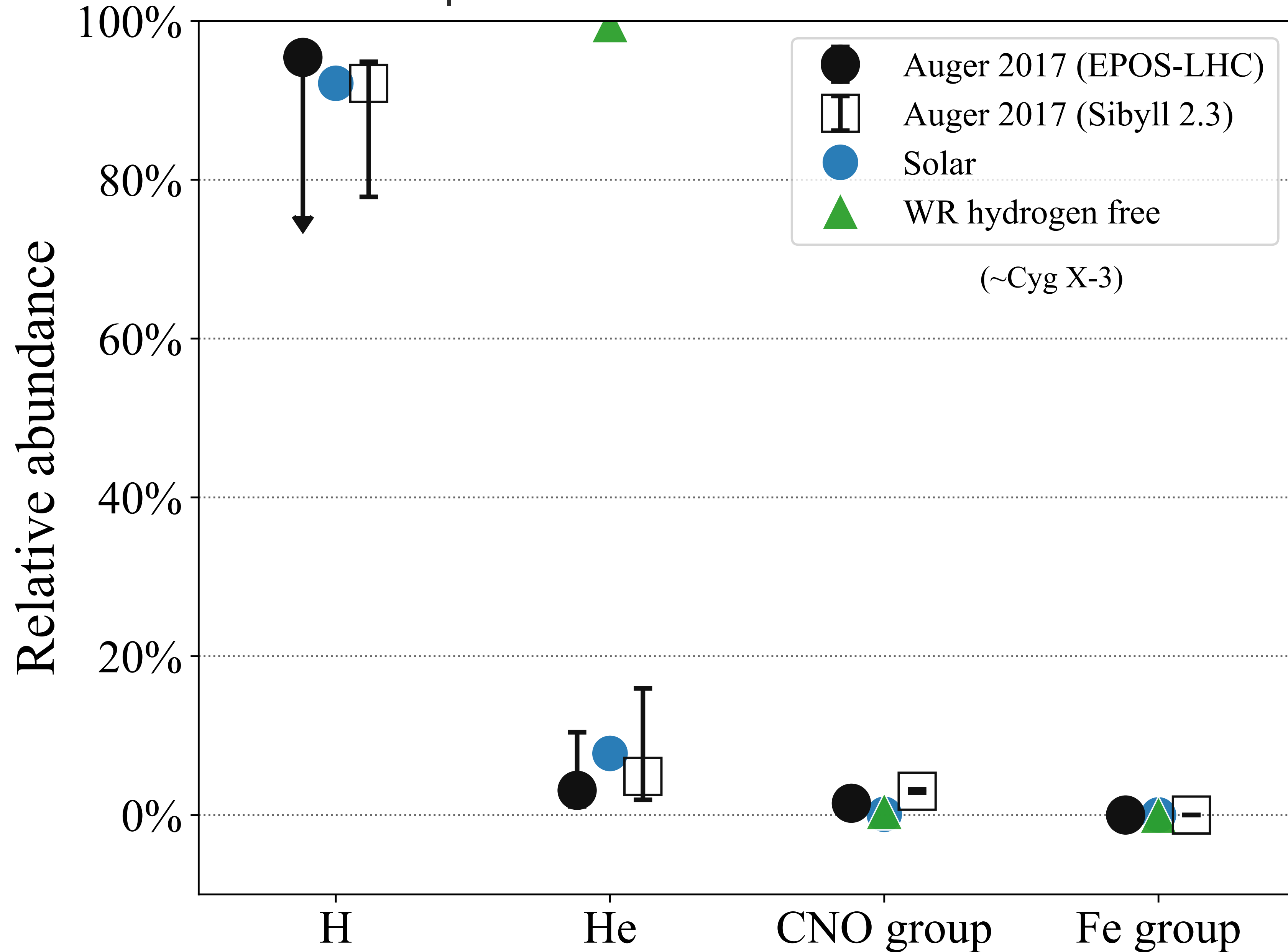


Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$



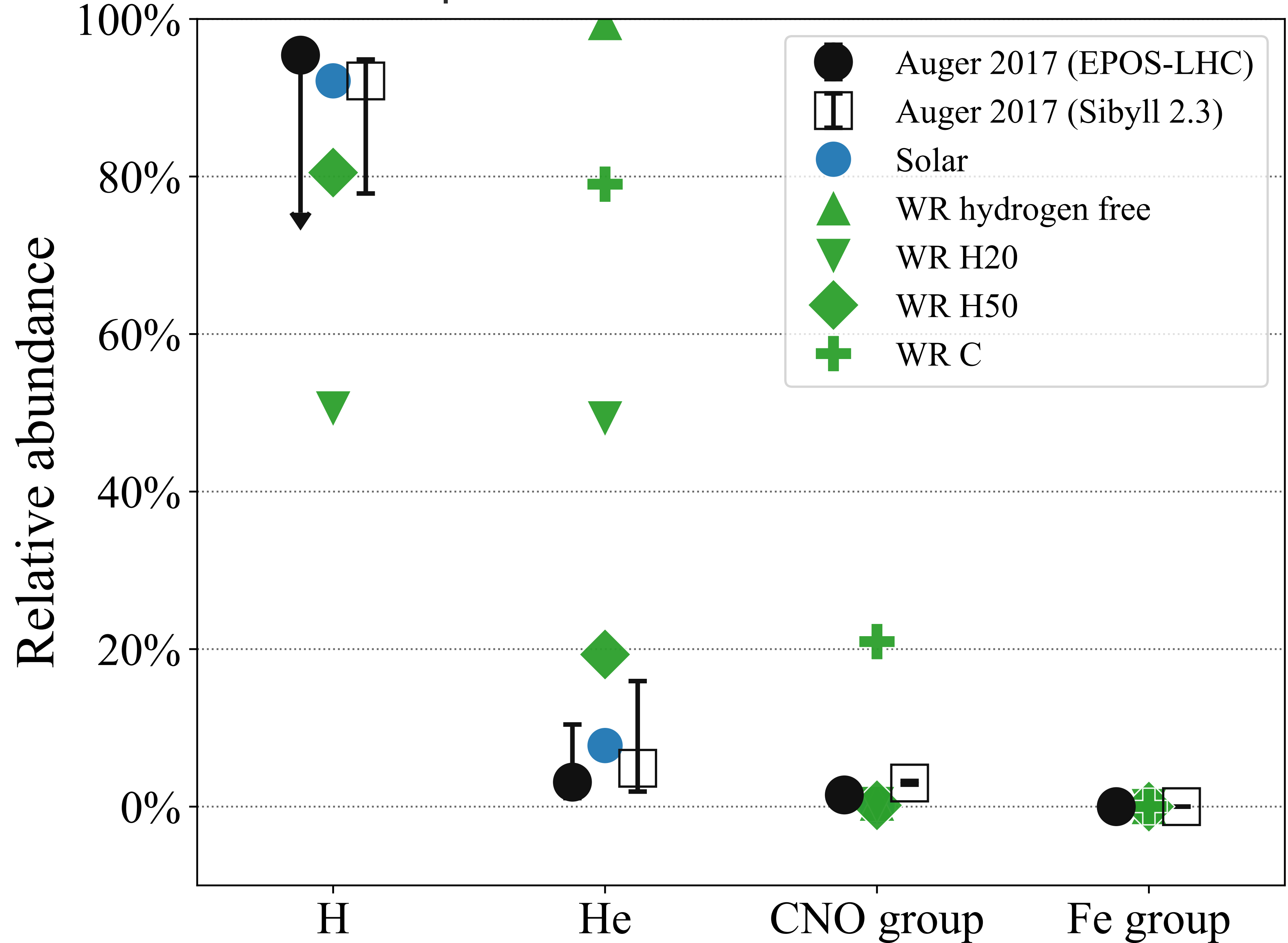
# Component B Composition



Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$

# Component B Composition

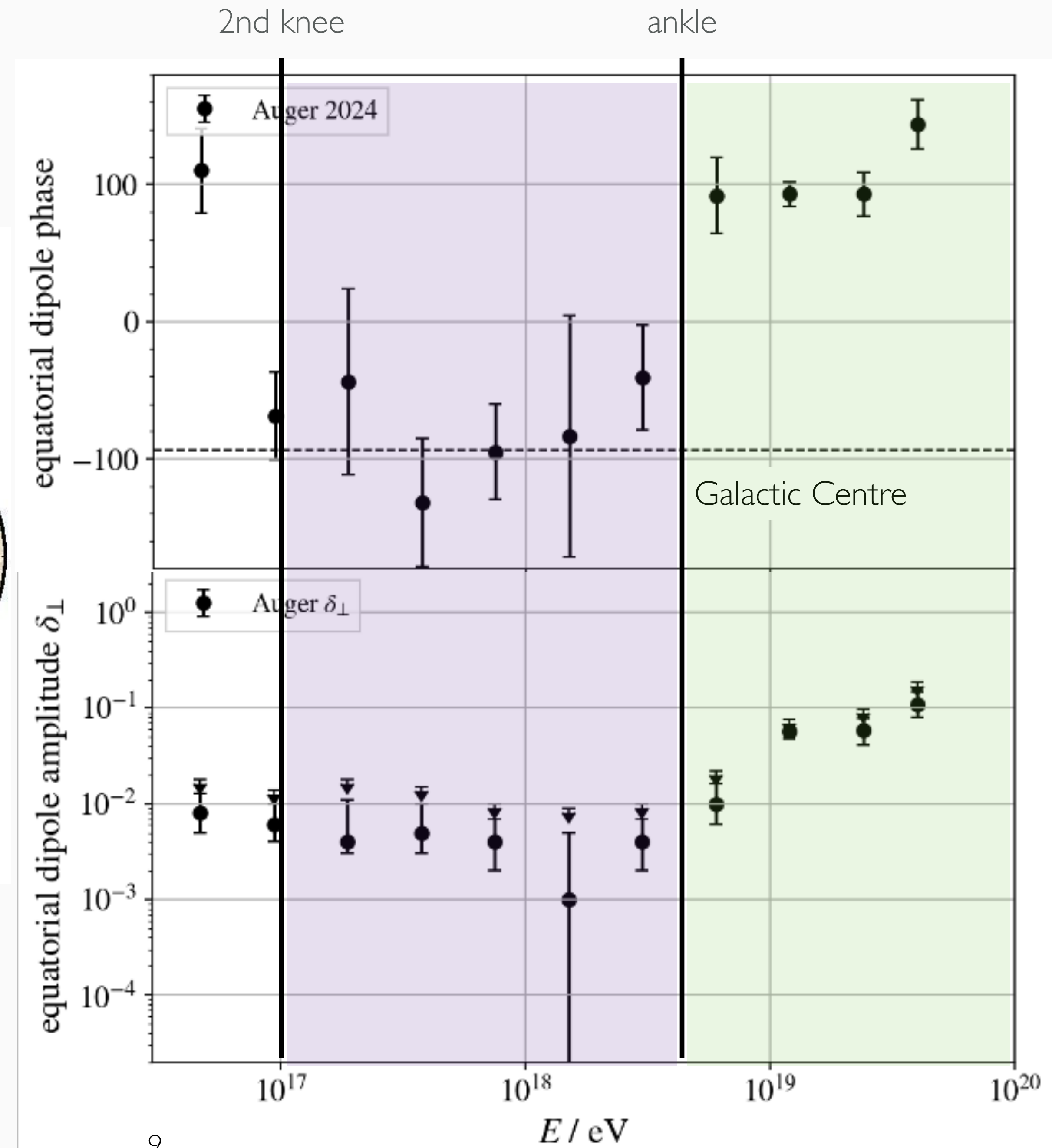
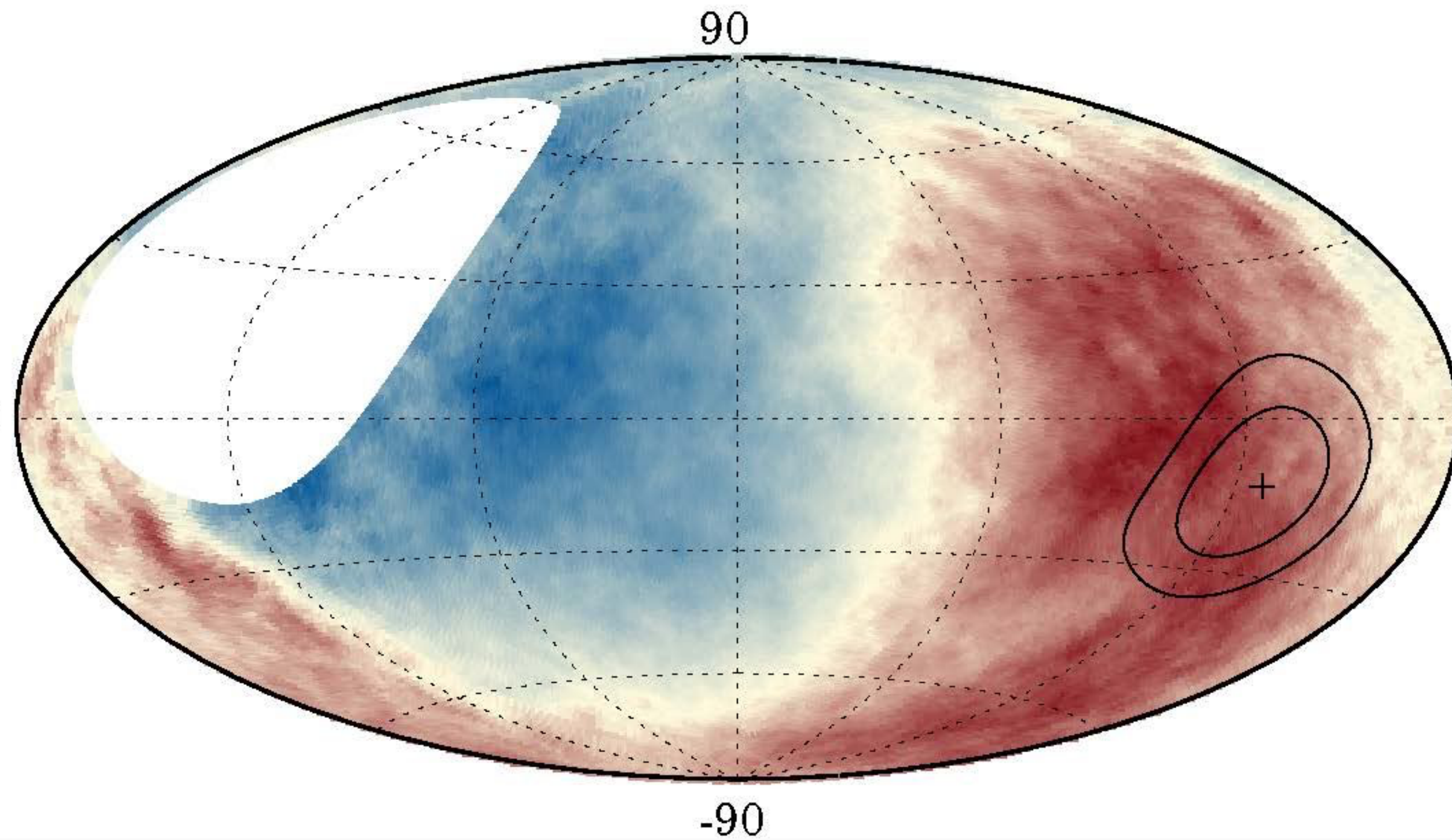


Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$

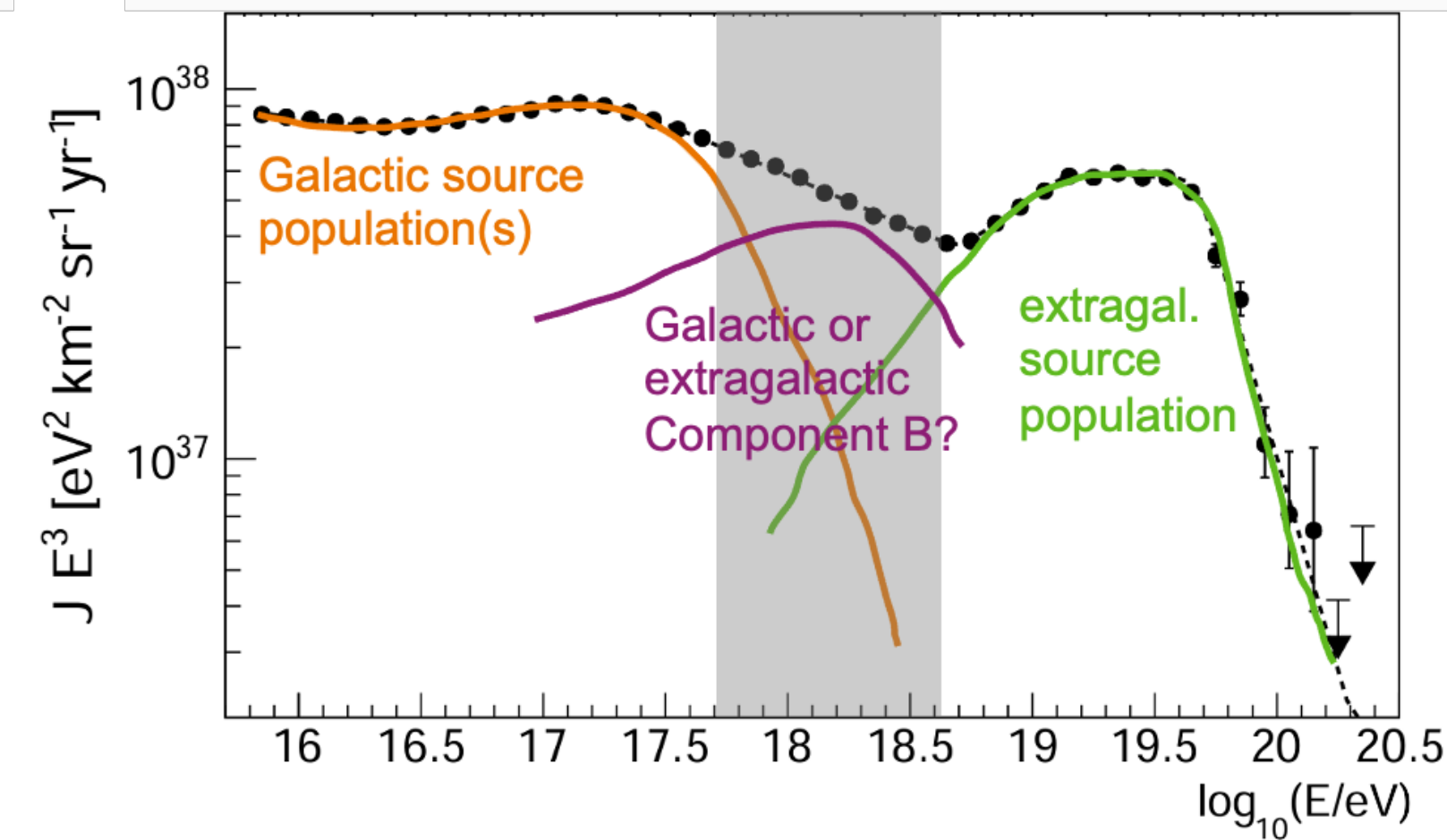
# Dipole anisotropy

Auger Coll. 2017 Science 357 6357, (updated 2024 ApJ)

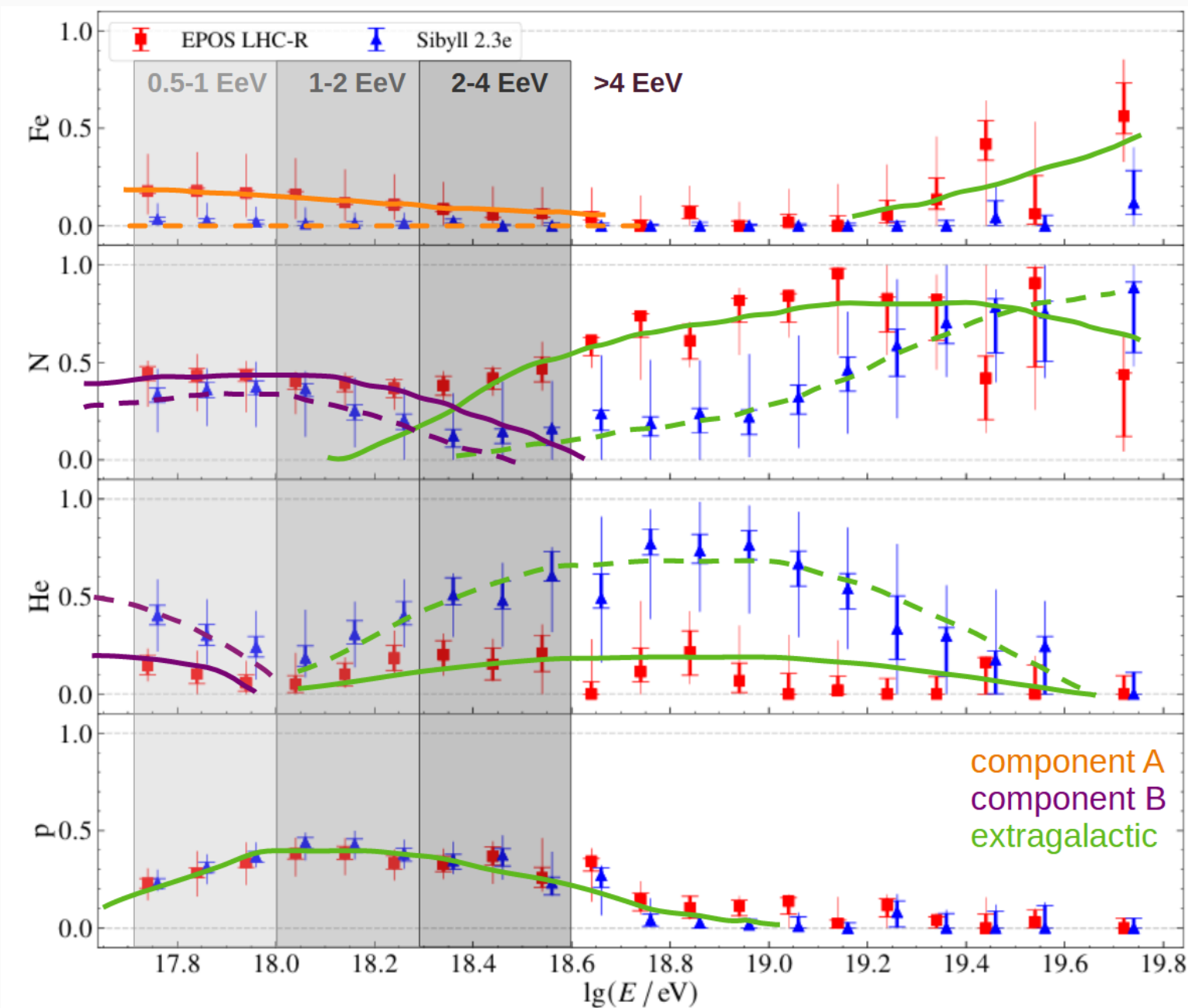
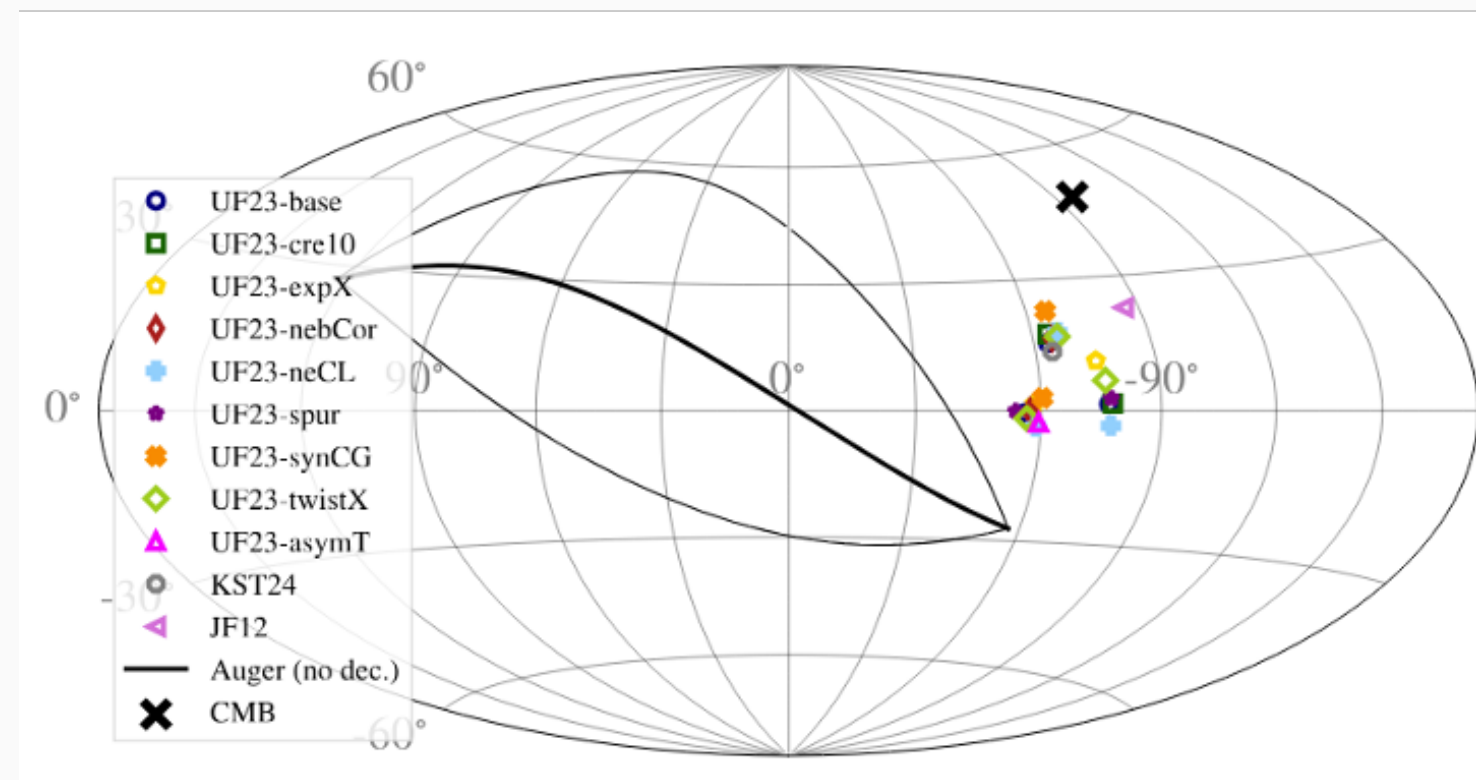




# Three-Component Model

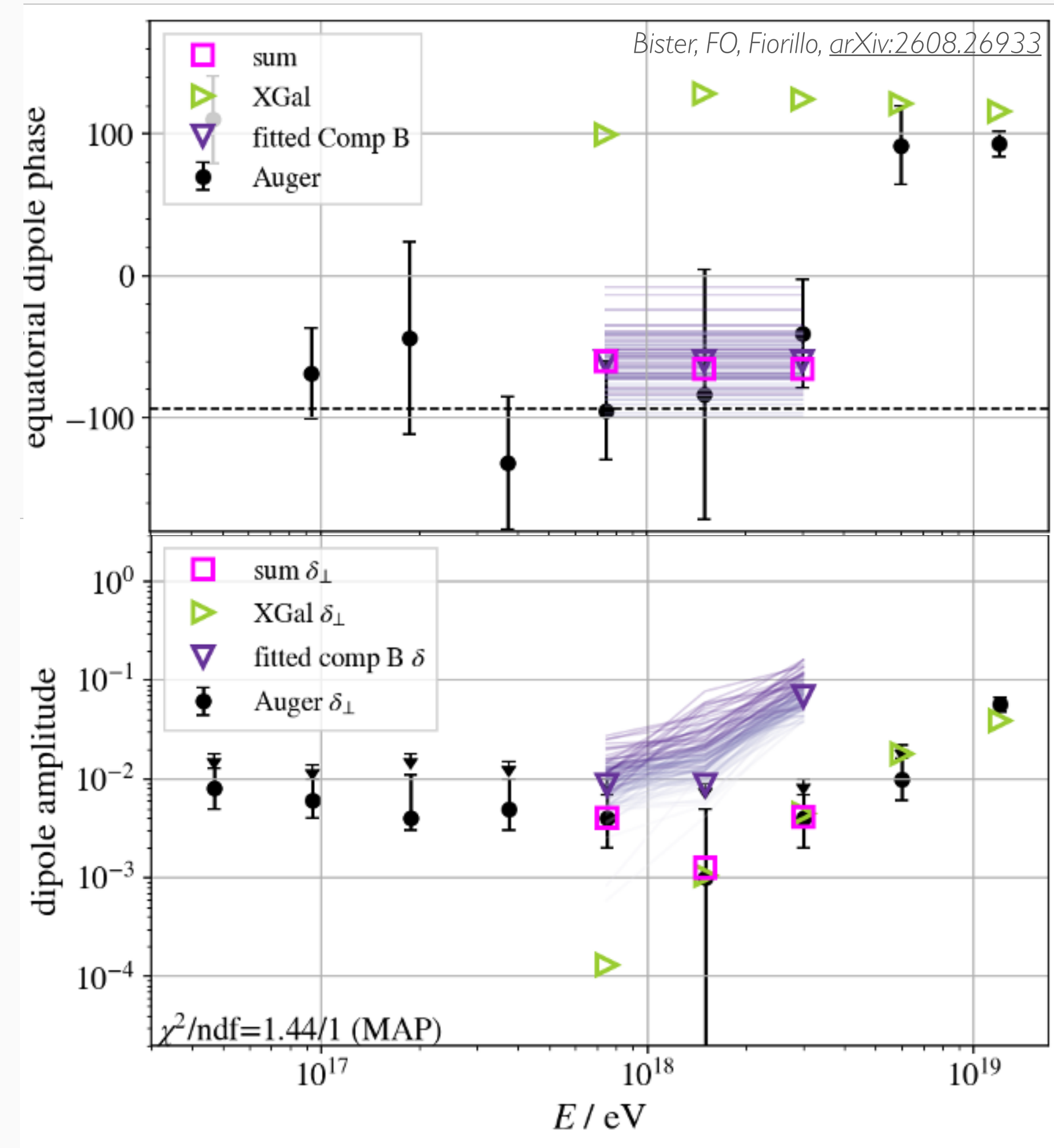


Fitted XGal dipole  
UF23+JF12Planck



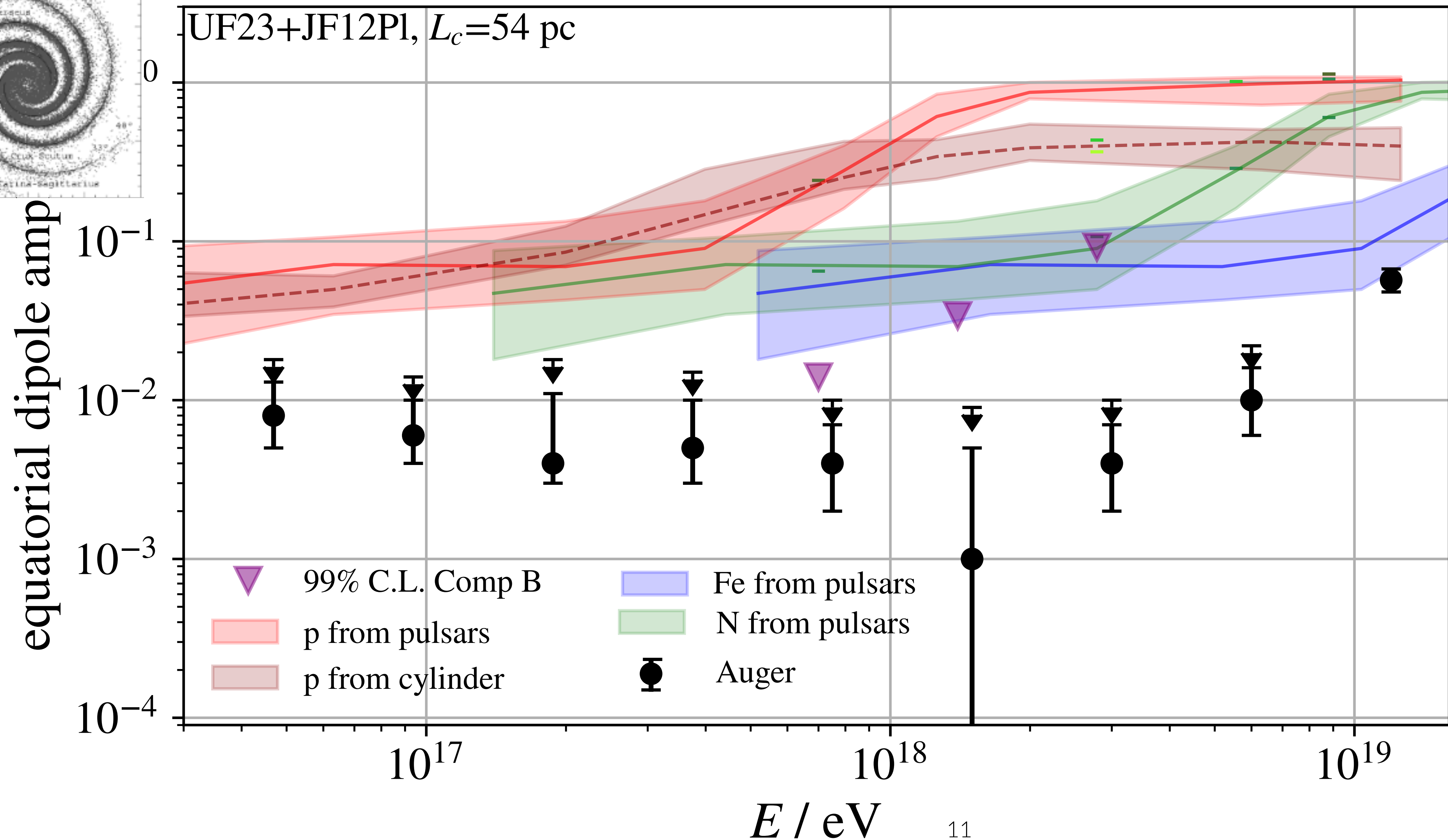
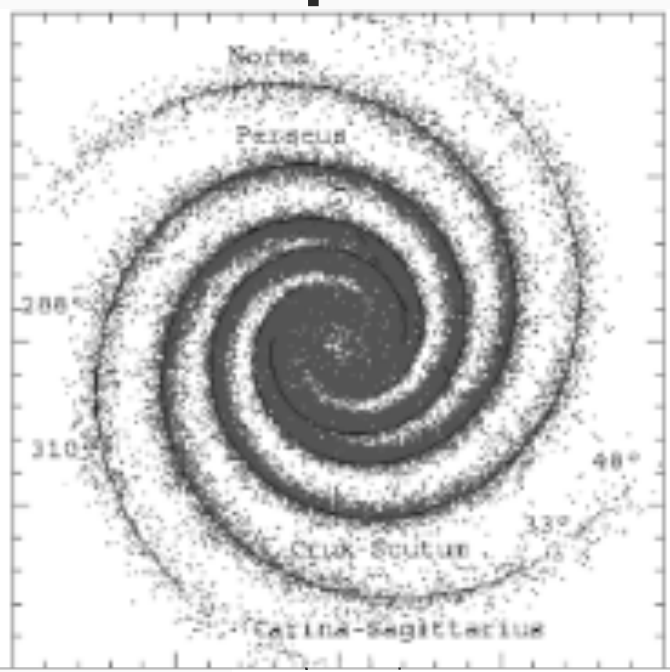
Galactic Component A - Pulsars dist'n- CRPropa  
Extragalactic - CosmicFlows4

Fitted direction and amplitude  
of Component B dipole

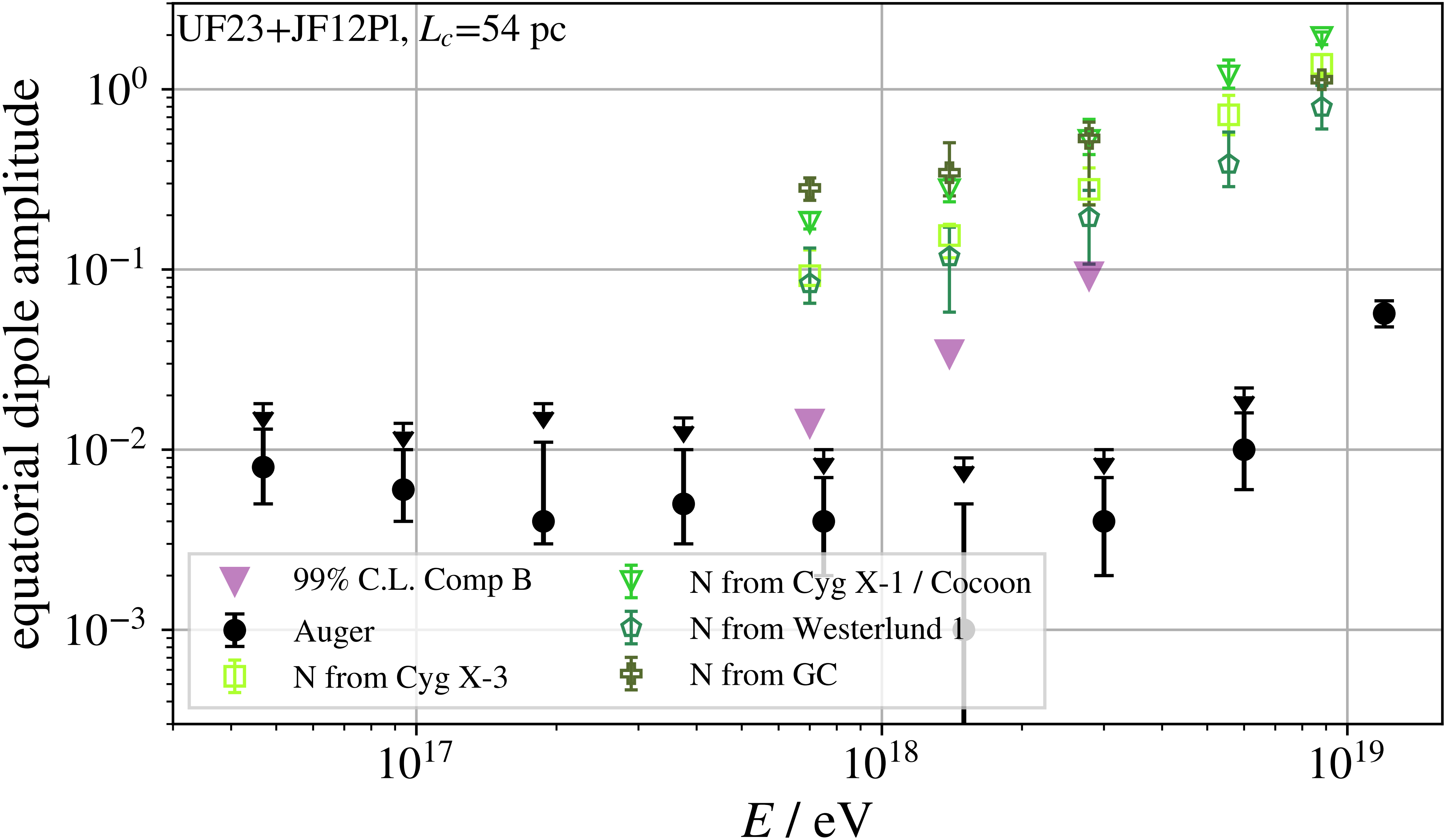


see also Giacinti+2012, Farrar PoS(ICRC 2021)488

# Dipole amplitude limits

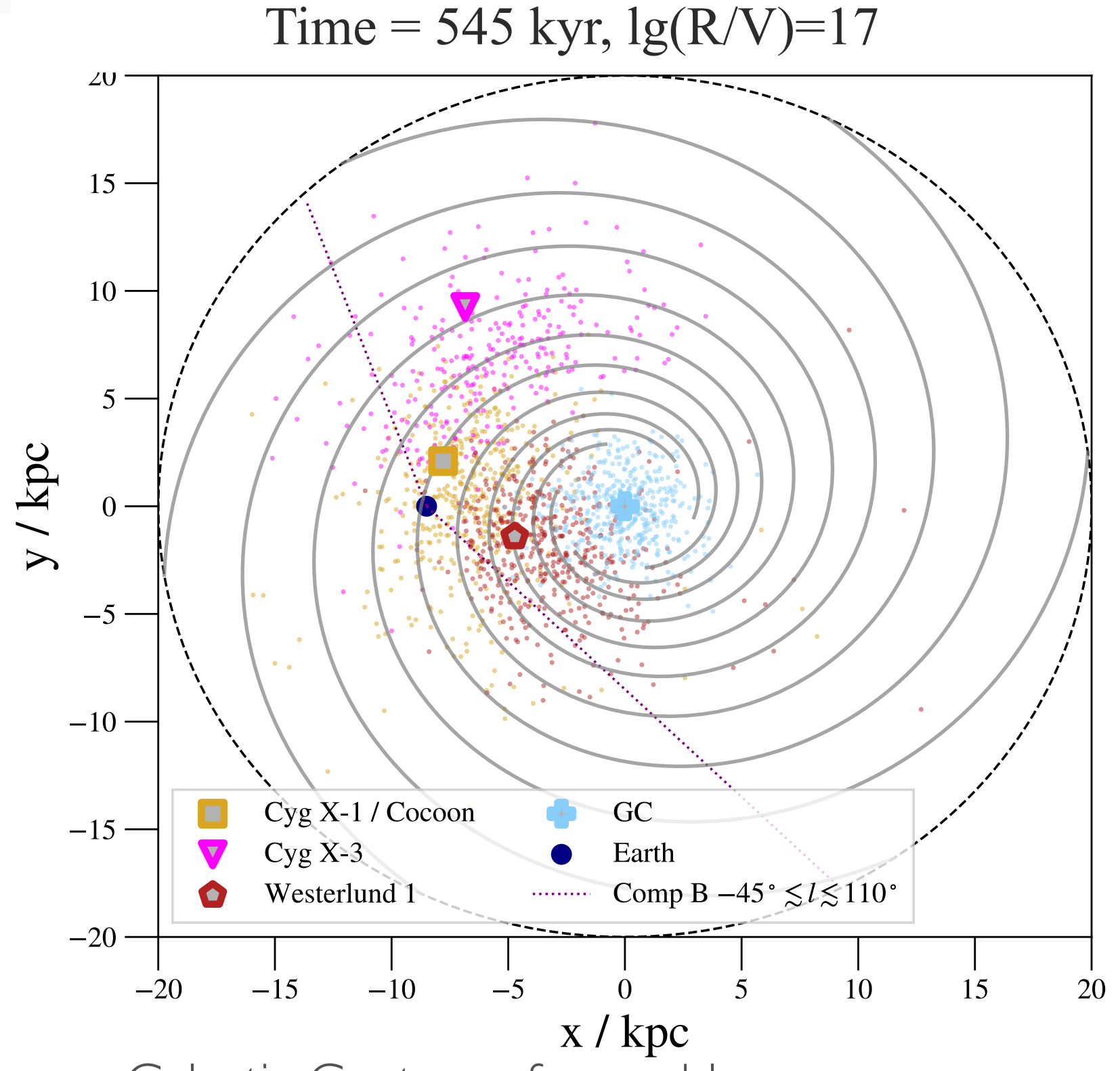


# Dipole amplitude limits

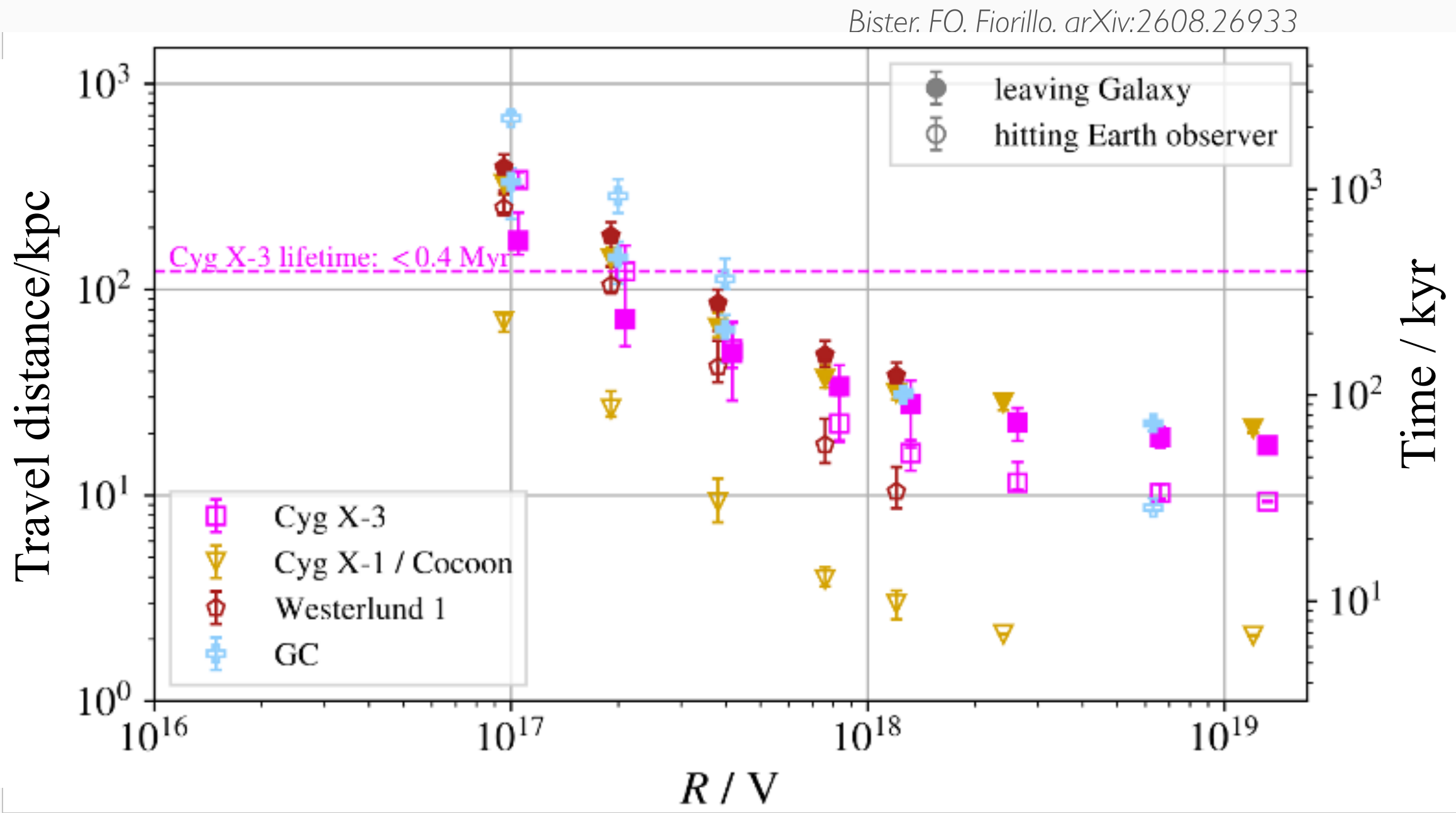




# Other issues for Galactic Sources



Galactic Centre unfavourable  
Particles transported out via X-field

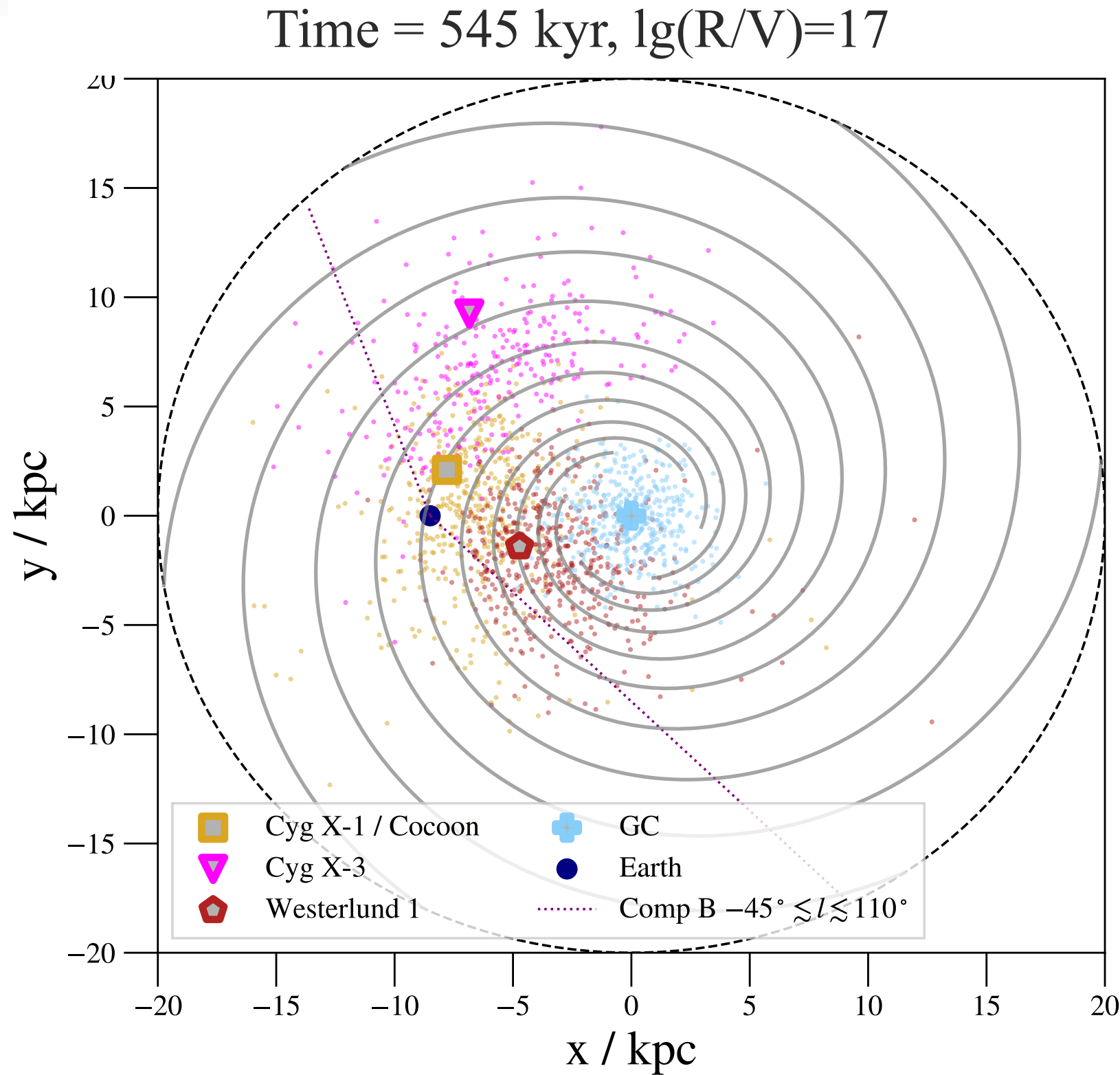


Propagation time exceeds HMXB lifetime

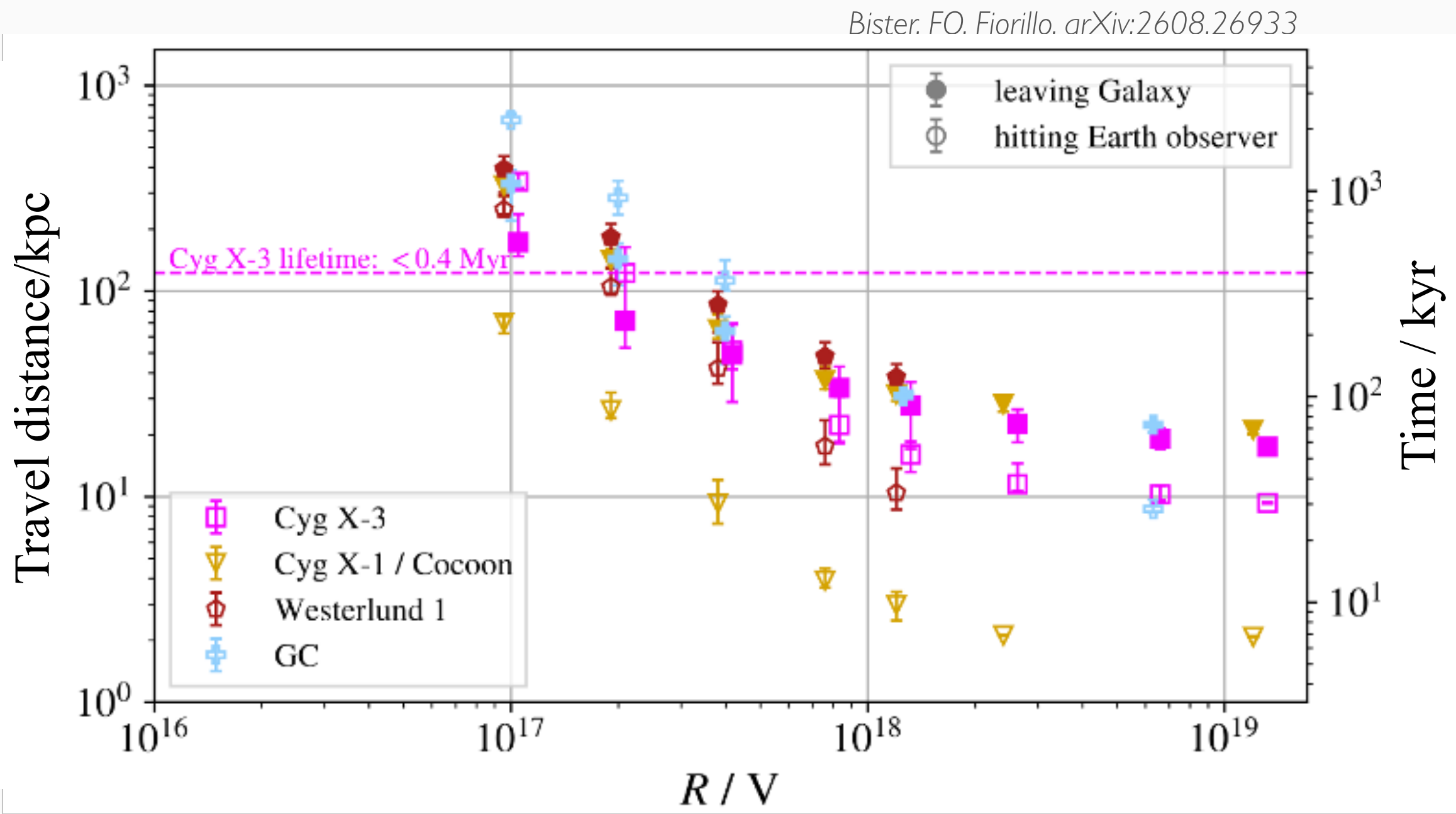
| Source              | $L_{\text{UHECR},N}^{0.5-4 \text{ EeV}}$<br>( $\text{erg s}^{-1}$ ) | $L_{\text{CR,tot}}$  | $\rho_{\text{H}}$ | $\rho_{\text{He}}$<br>mass fraction | $\rho_{\text{Fe}}$ | $\rho_N^{\text{proxy}}$ | $L_{\text{comparison}}$<br>( $\text{erg s}^{-1}$ ) | Reference                                                          |
|---------------------|---------------------------------------------------------------------|----------------------|-------------------|-------------------------------------|--------------------|-------------------------|----------------------------------------------------|--------------------------------------------------------------------|
| Cygnus X-3          | $7 \times 10^{35}$                                                  | $4.3 \times 10^{38}$ | $\simeq 0$        | 0.98                                | —                  | 0.02                    | $\lesssim 10^{39}$ (jet/outflow)                   | Todt et al. (2015); Zdziarski et al. (2013); Vilhu et al. (2021)   |
| Galactic Center     | $\sim 10^{38}$                                                      | $6 \times 10^{40}$   | 0.7231            | 0.2434                              | 0.0084             | 0.0251                  | $\lesssim 10^{41}$ (past mechanical power)         | Do et al. (2015); Asplund et al. (2009); Sarkar et al. (2017)      |
| Cygnus X-1          | $2.6 \times 10^{34}$                                                | $4.3 \times 10^{37}$ | 0.7381            | 0.2485                              | 0.0034             | 0.0101                  | $(4-14) \times 10^{36}$ (time-averaged jet power)  | Asplund et al. (2009); Russell et al. (2007)                       |
| Cygnus OB2 / Cocoon | $2.6 \times 10^{34\text{a}}$                                        | $4.3 \times 10^{37}$ | 0.7381            | 0.2485                              | 0.0034             | 0.0101                  | $(1.5-3) \times 10^{38}$ (stellar-wind power)      | Asplund et al. (2009); Menchiari et al. (2024); Vieu et al. (2024) |
| Westerlund 1        | $\sim 8.2 \times 10^{35\text{b}}$                                   | $1.4 \times 10^{39}$ | 0.7381            | 0.2485                              | 0.0034             | 0.0101                  | $(1.6-2.8) \times 10^{39}$ (stellar-wind power)    | Asplund et al. (2009); Haerer et al. (2025)                        |

Strong energetic constraints for single sources

# Other issues for Galactic Sources



Galactic Centre unfavourable  
Particles transported out via X-field

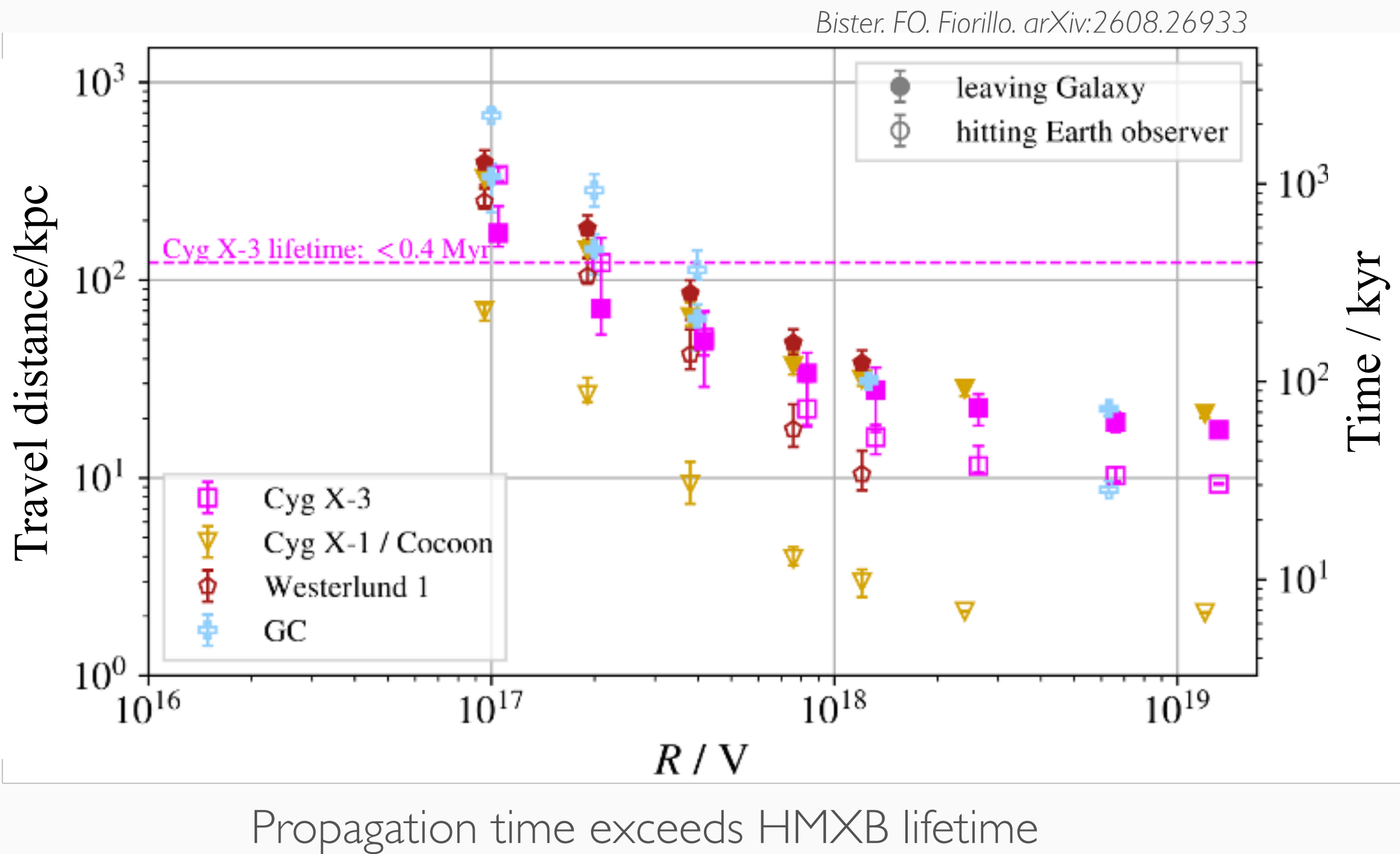
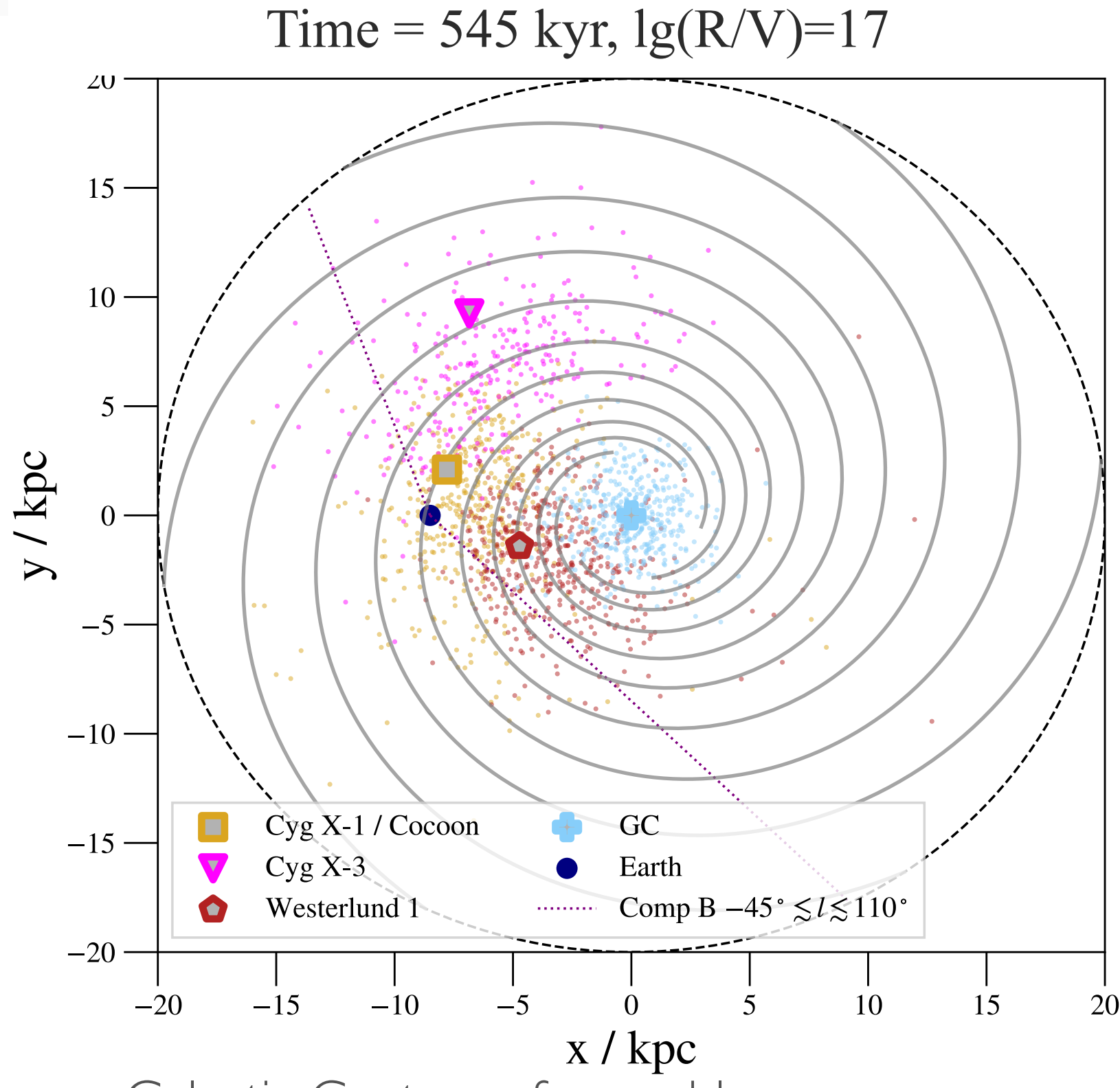


Propagation time exceeds HMXB lifetime

| Source              | $L_{\text{UHECR},N}^{0.5-4 \text{ EeV}}$<br>( $\text{erg s}^{-1}$ ) | $L_{\text{CR,tot}}$  | $L_{\text{comparison}}$<br>( $\text{erg s}^{-1}$ ) | Reference                                                          |
|---------------------|---------------------------------------------------------------------|----------------------|----------------------------------------------------|--------------------------------------------------------------------|
| Cygnus X-3          | $7 \times 10^{35}$                                                  | $4.3 \times 10^{38}$ | $\lesssim 10^{39}$ (jet/outflow)                   | Todt et al. (2015); Zdziarski et al. (2013); Vilhu et al. (2021)   |
| Galactic Center     | $\sim 10^{38}$                                                      | $6 \times 10^{40}$   | $\lesssim 10^{41}$ (past mechanical power)         | Do et al. (2015); Asplund et al. (2009); Sarkar et al. (2017)      |
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| Cygnus OB2 / Cocoon | $2.6 \times 10^{34\text{a}}$                                        | $4.3 \times 10^{37}$ | $(1.5-3) \times 10^{38}$ (stellar-wind power)      | Asplund et al. (2009); Menchiari et al. (2024); Vieu et al. (2024) |
| Westerlund 1        | $\sim 8.2 \times 10^{35\text{b}}$                                   | $1.4 \times 10^{39}$ | $(1.6-2.8) \times 10^{39}$ (stellar-wind power)    | Asplund et al. (2009); Haerer et al. (2025)                        |

Strong energetic constraints for single sources

# Other issues for Galactic Sources



Conclusion: Component B Extragalactic

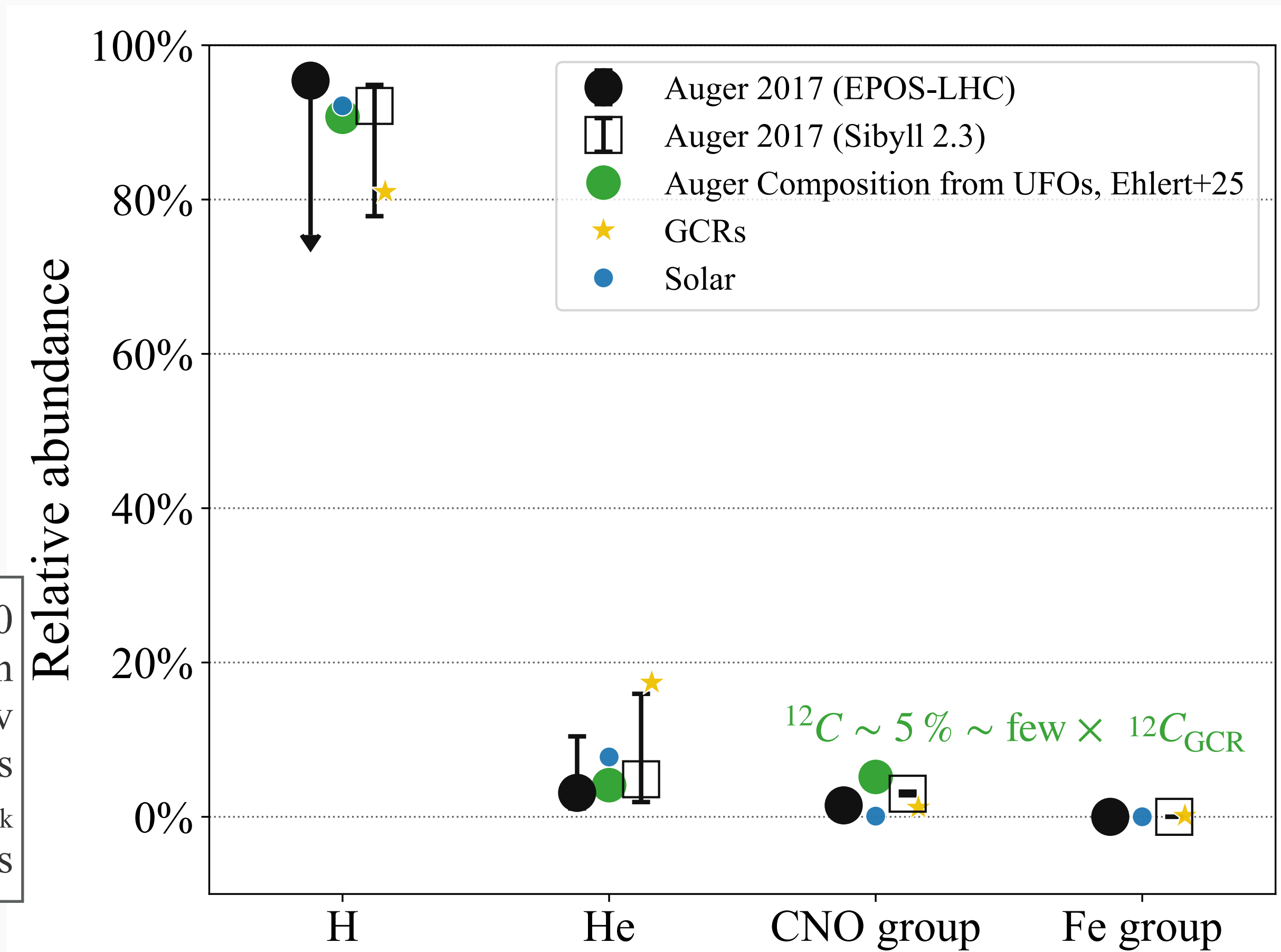
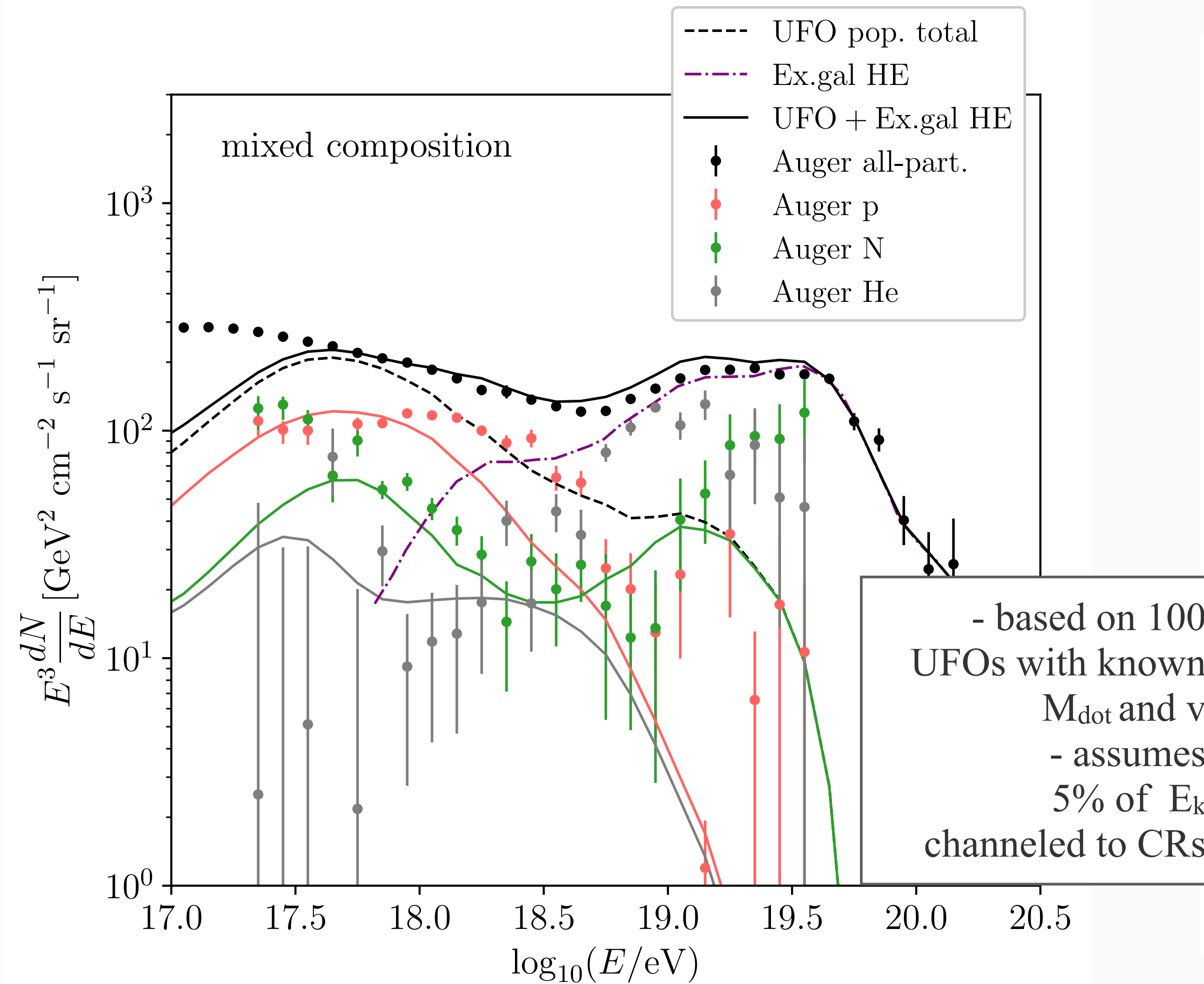
| Source              | $L_{\text{UHECR},N}^{0.5-4 \text{ EeV}}$<br>( $\text{erg s}^{-1}$ ) | $L_{\text{CR,tot}}$  | $L_{\text{comparison}}$<br>( $\text{erg s}^{-1}$ ) | Reference                                                          |
|---------------------|---------------------------------------------------------------------|----------------------|----------------------------------------------------|--------------------------------------------------------------------|
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| Cygnus OB2 / Cocoon | $2.6 \times 10^{34a}$                                               | $4.3 \times 10^{37}$ | $(1.5-3) \times 10^{38}$ (stellar-wind power)      | Asplund et al. (2009); Menchiari et al. (2024); Vieu et al. (2024) |
| Westerlund 1        | $\sim 8.2 \times 10^{35b}$                                          | $1.4 \times 10^{39}$ | $(1.6-2.8) \times 10^{39}$ (stellar-wind power)    | Asplund et al. (2009); Haerer et al. (2025)                        |

Strong energetic constraints for single sources



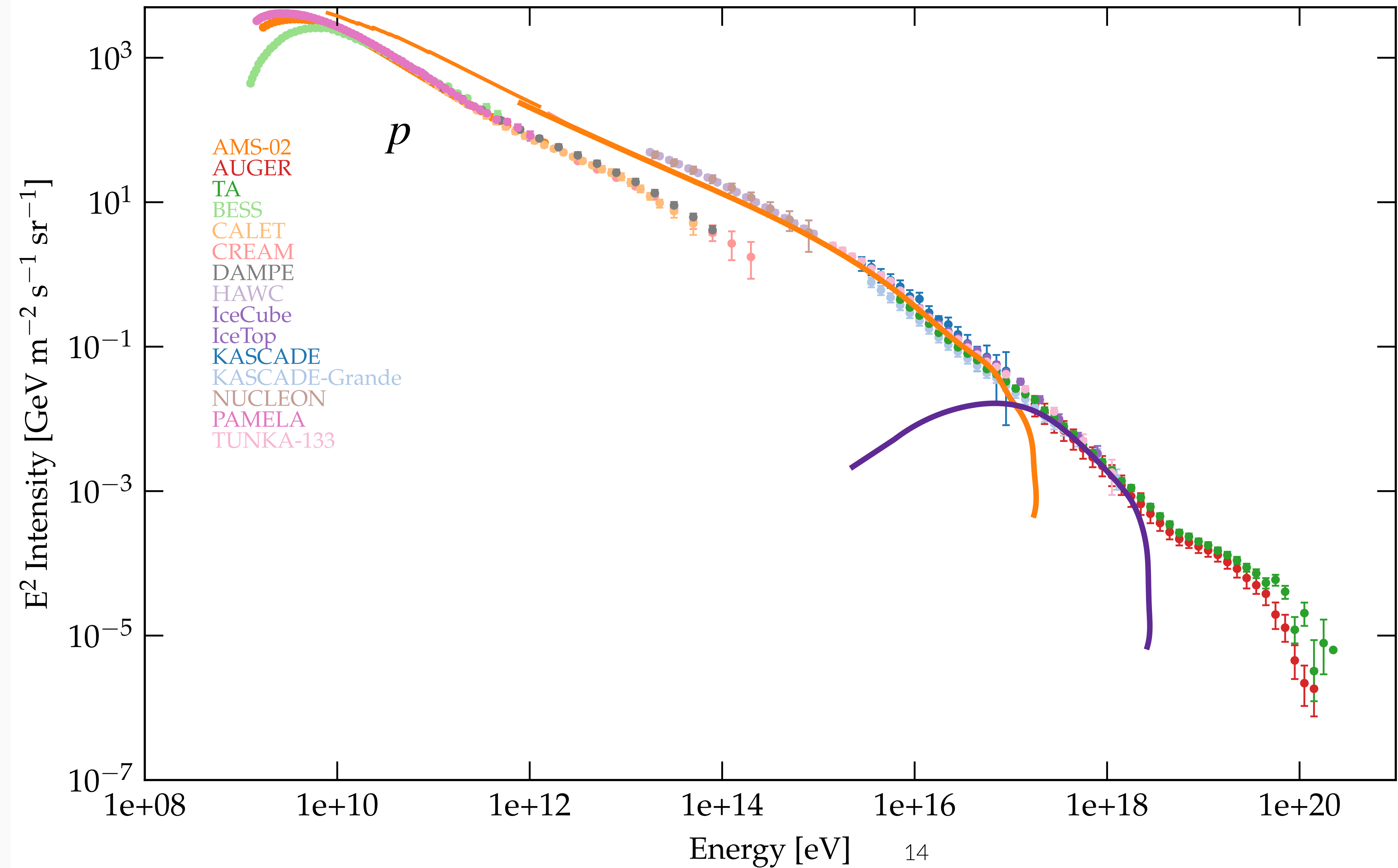
# Extragalactic Component B?

D. Ehlert, FO, E. Peretti, MNRAS, 539 (2025) 3

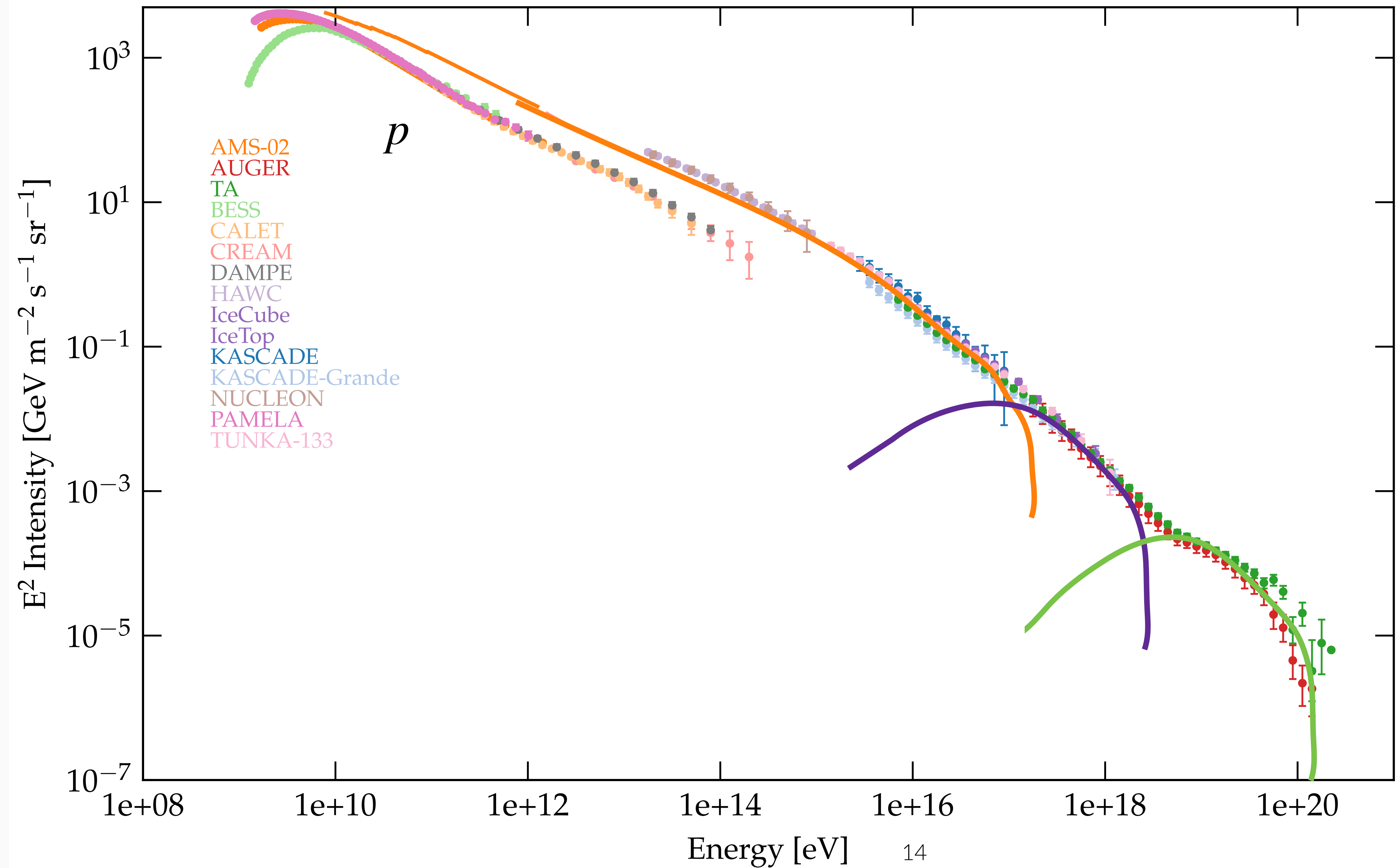


or:  
 Radio Galaxies (Matthews & Taylor 2021)  
 Galaxy Clusters (Murase et al. 2008; Fang & Murase 2018; B. T. Zhang et al. 2025)  
 Filament Accretion Shocks (P. Simeon et al. 2026)

# Ultra-high energy cosmic rays



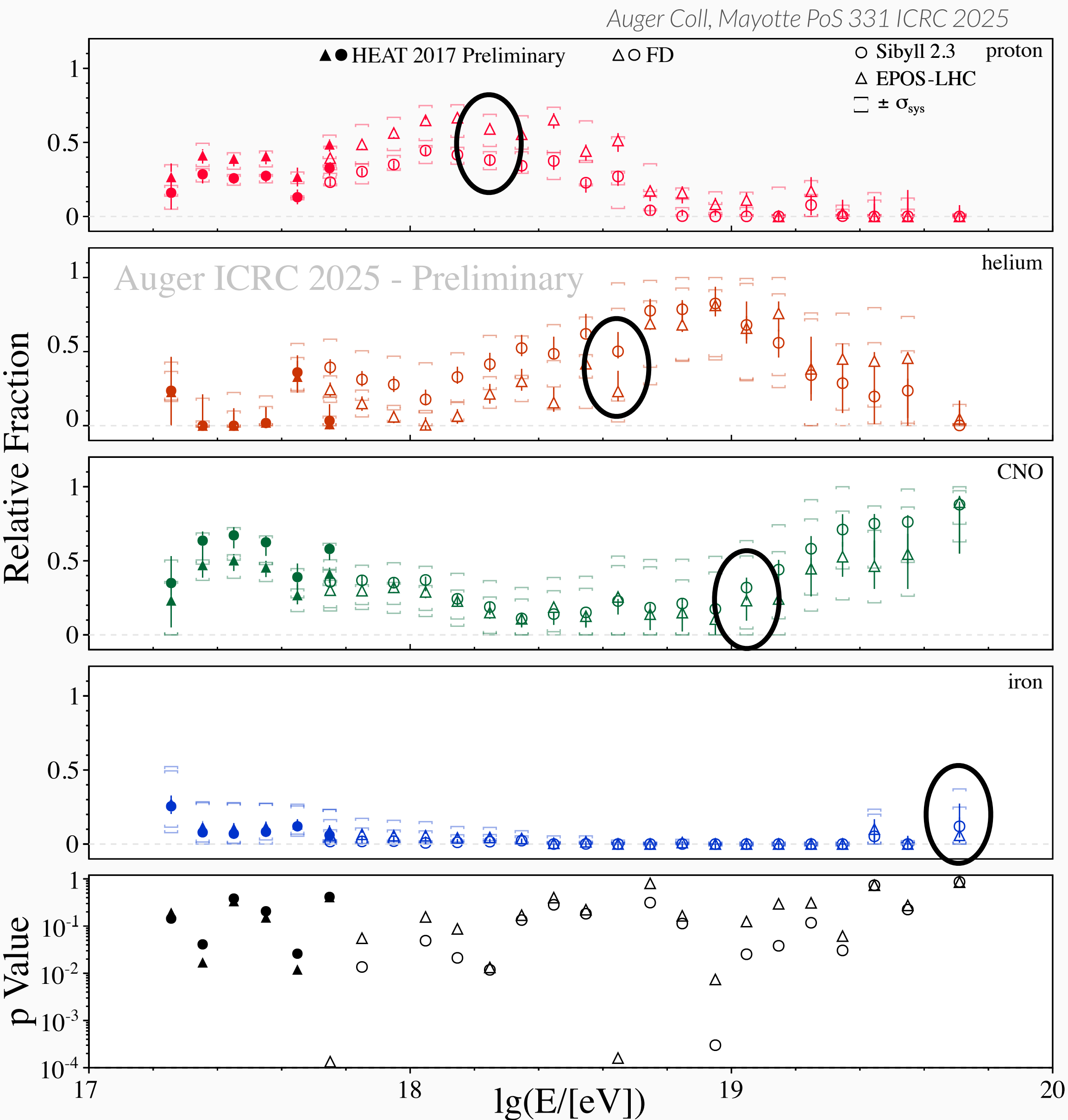
# Ultra-high energy cosmic rays





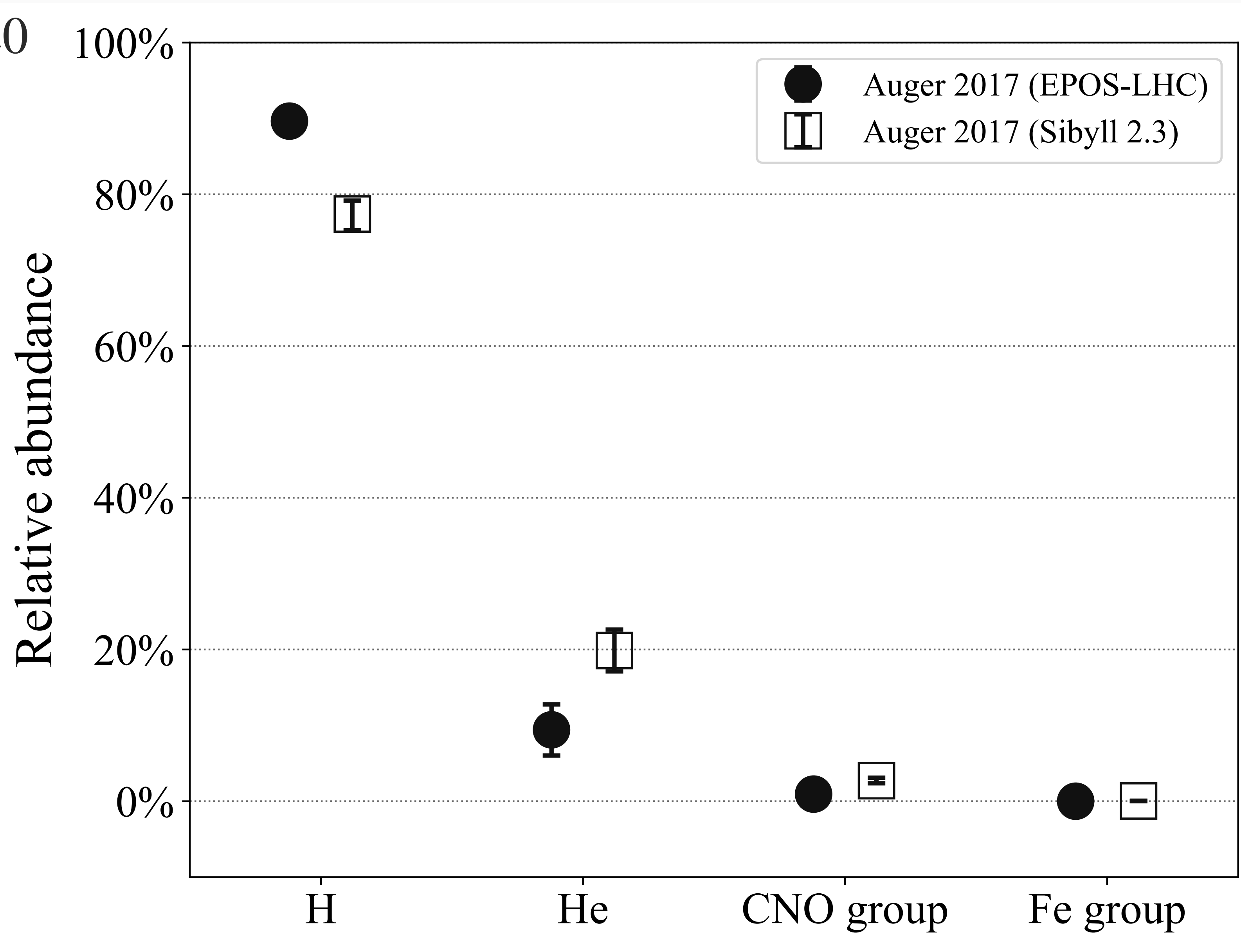
# Composition at UHE

$\log_{10} R = 18.20$



# Composition at UHE

$\log_{10} R = 18.20$



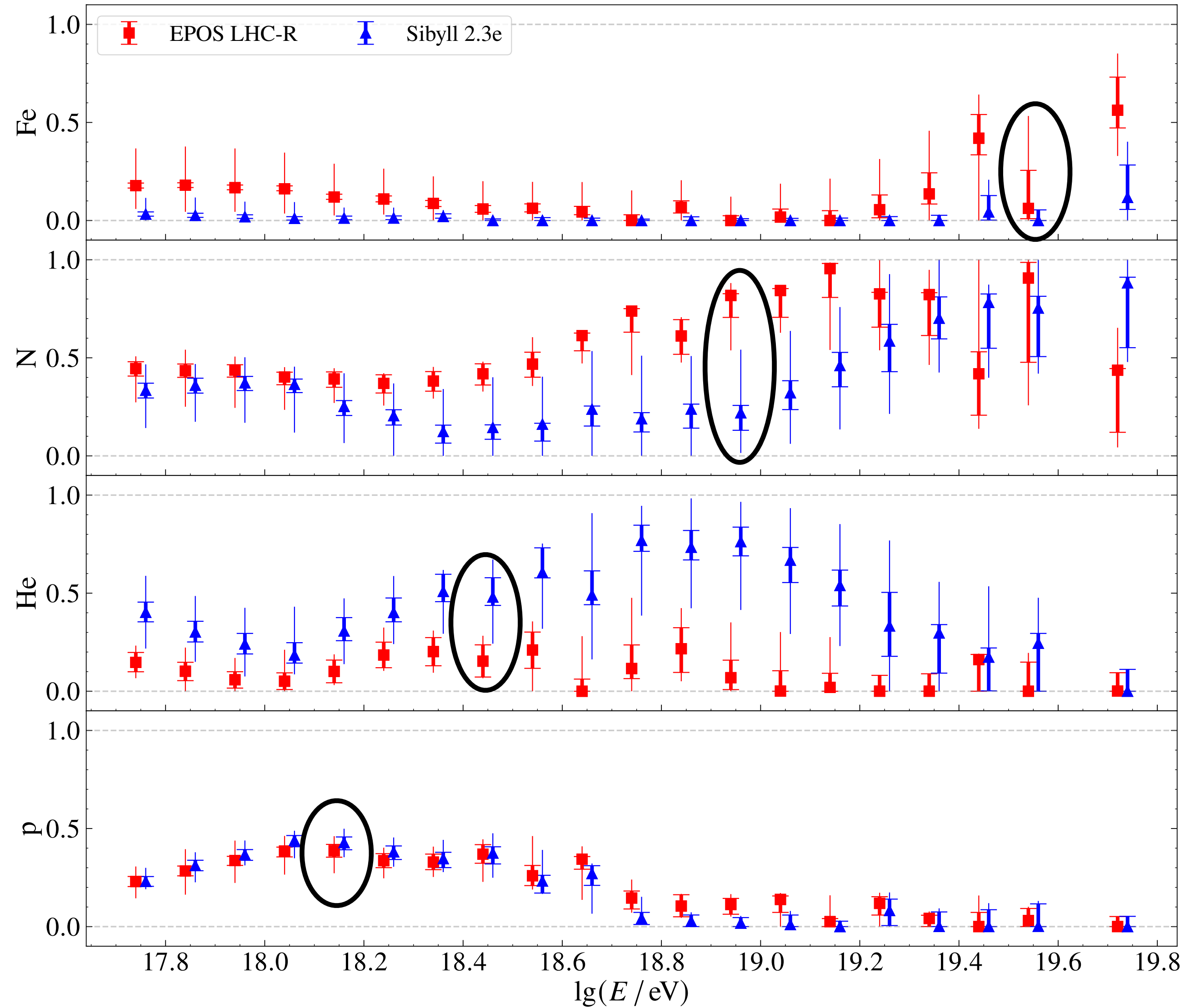
Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$

# New Auger fractions

$$\log_{10} R = 18.135$$

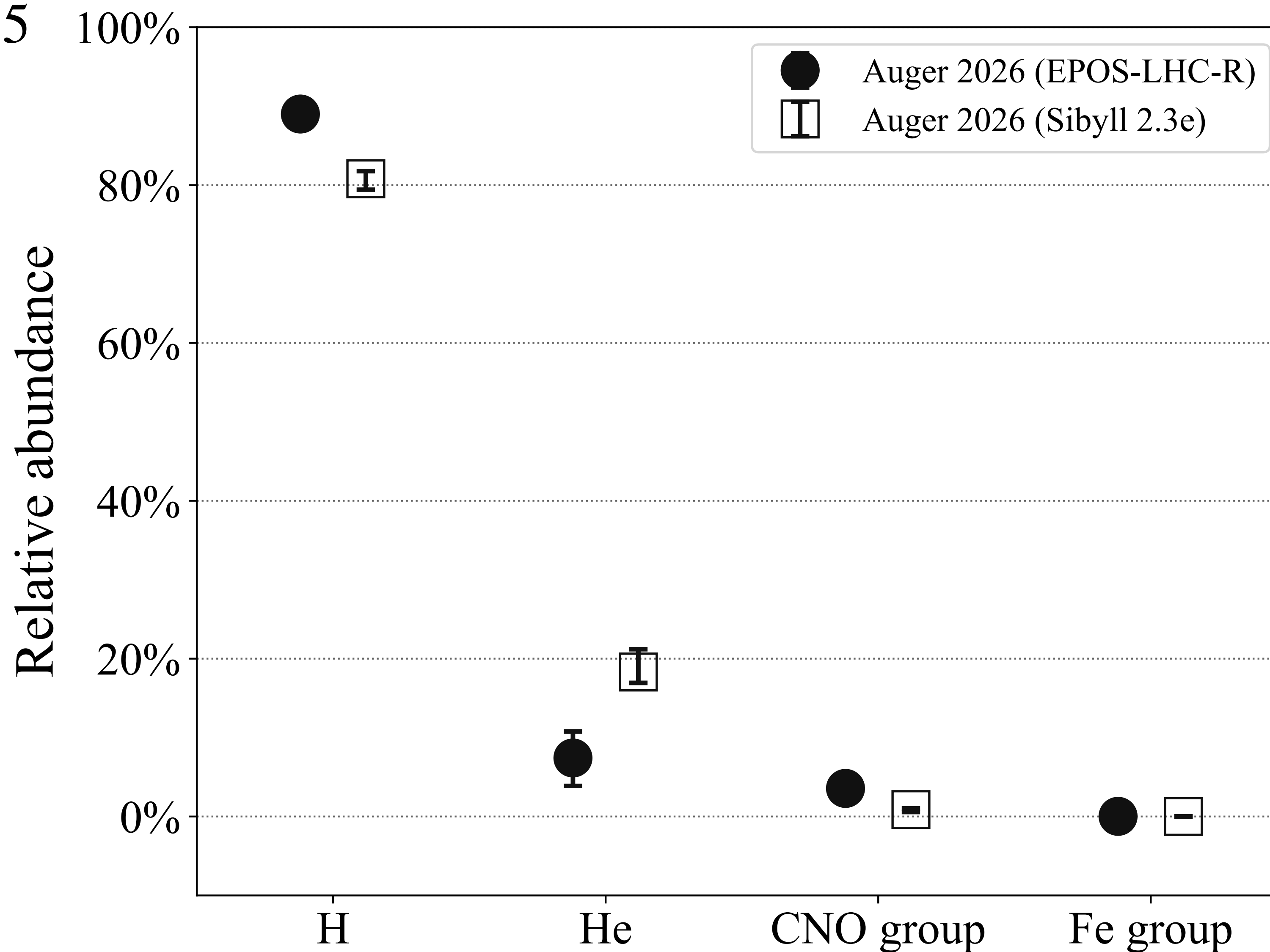
*Auger Coll, PRD 2026, arXiv:2605.12598*





# New Auger fractions

$\log_{10} R = 18.135$



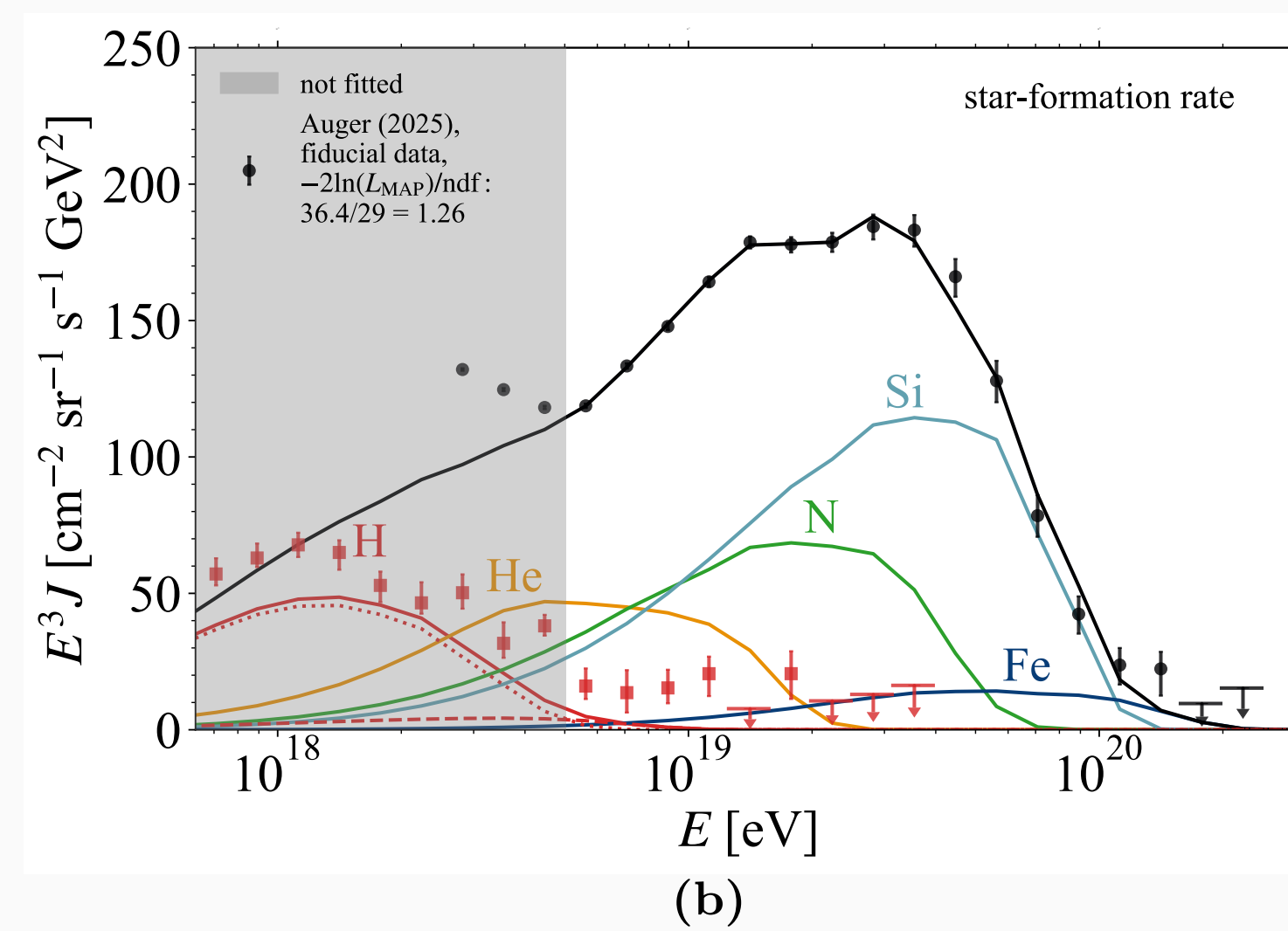
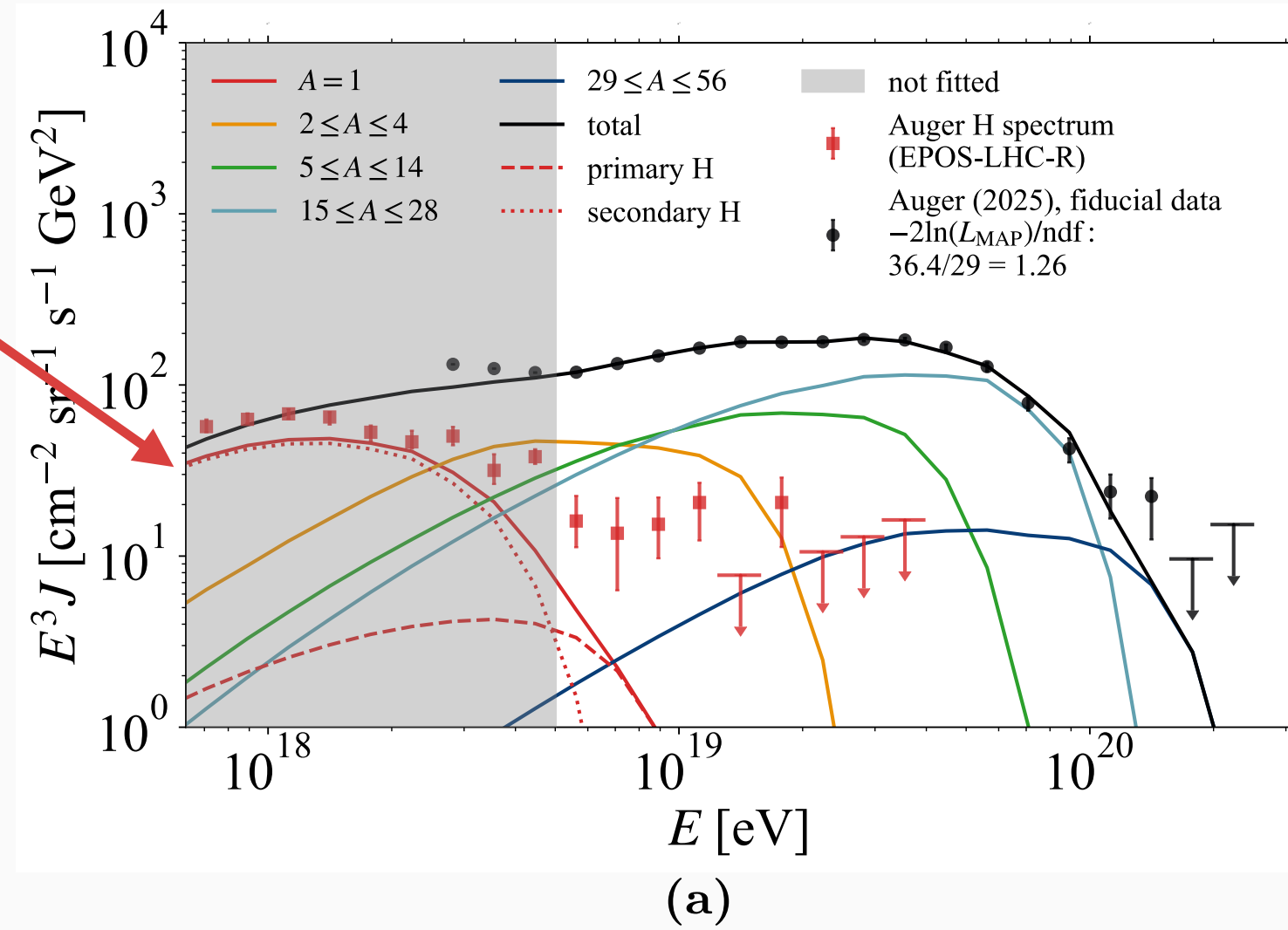
Fractions defined  
at fixed rigidity:

$$\rho_A = \frac{f_i(Z_i R_i) J_{\text{Tot}}(Z_i R_i) Z_i}{\sum_j f_j(Z_j R_j) J_{\text{Tot}}(Z_j R_j) Z_j}$$

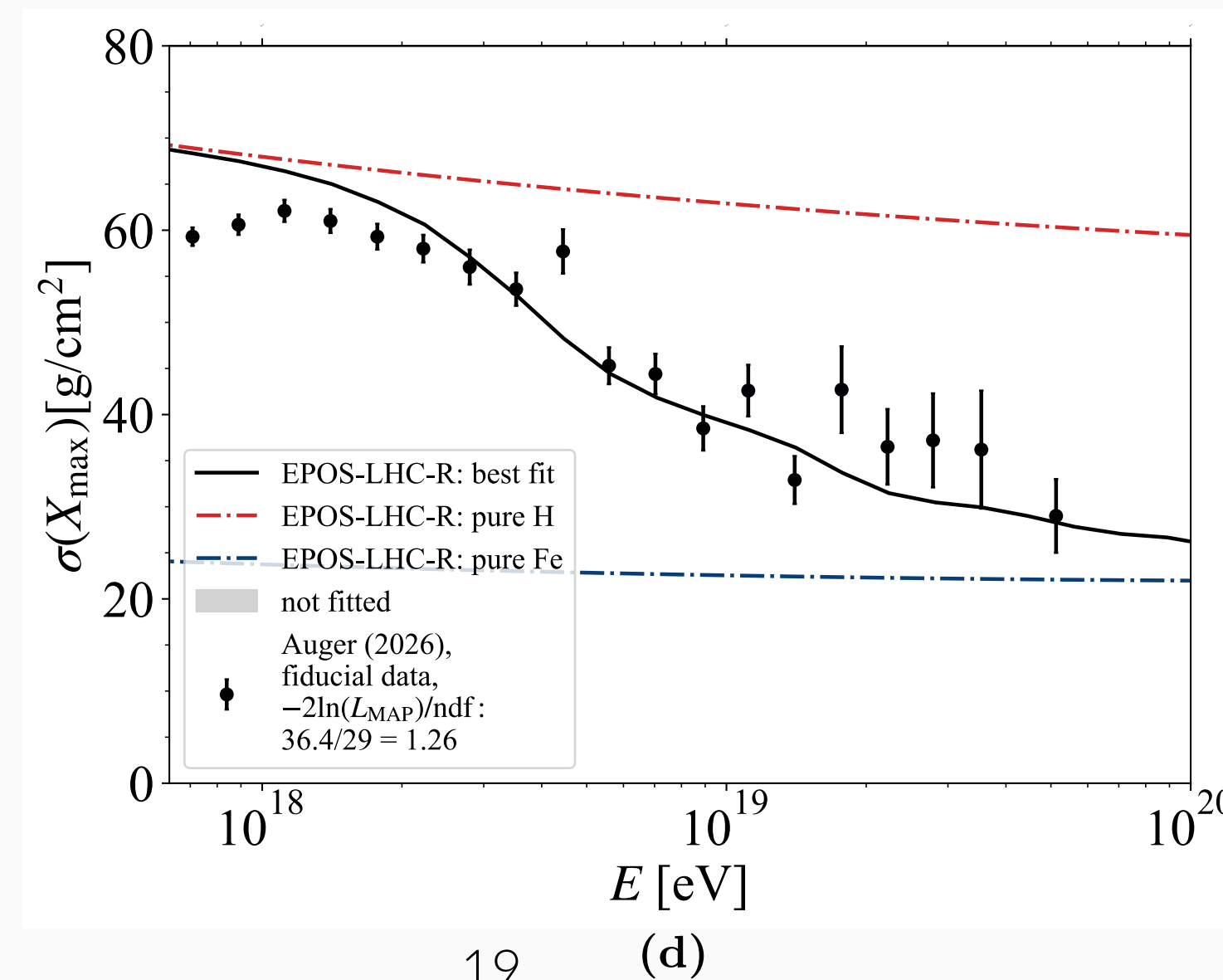
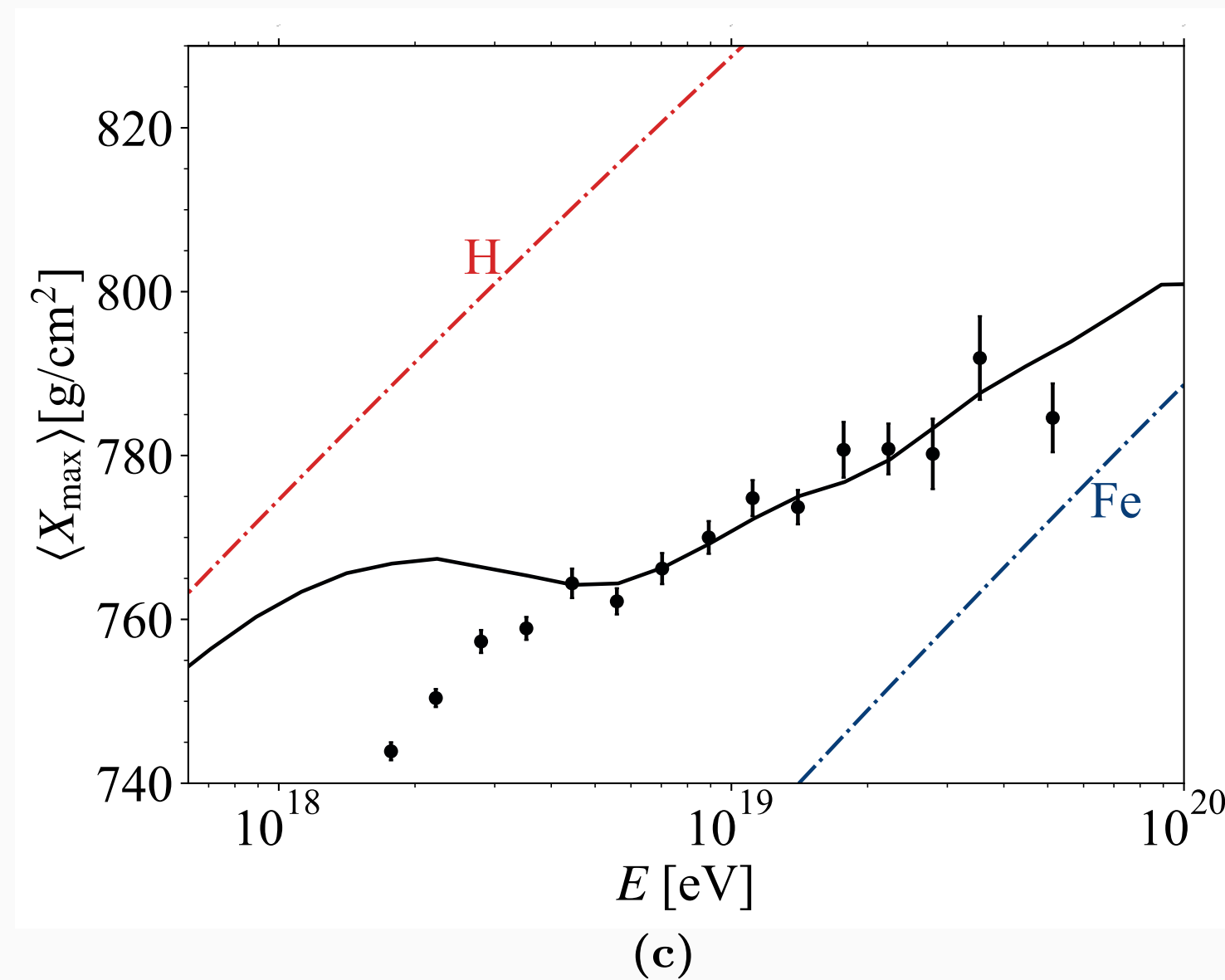
# Fit to UHE spectrum and composition

Five component model. Fiducial: SFR evolution and EPOS-LHC-R

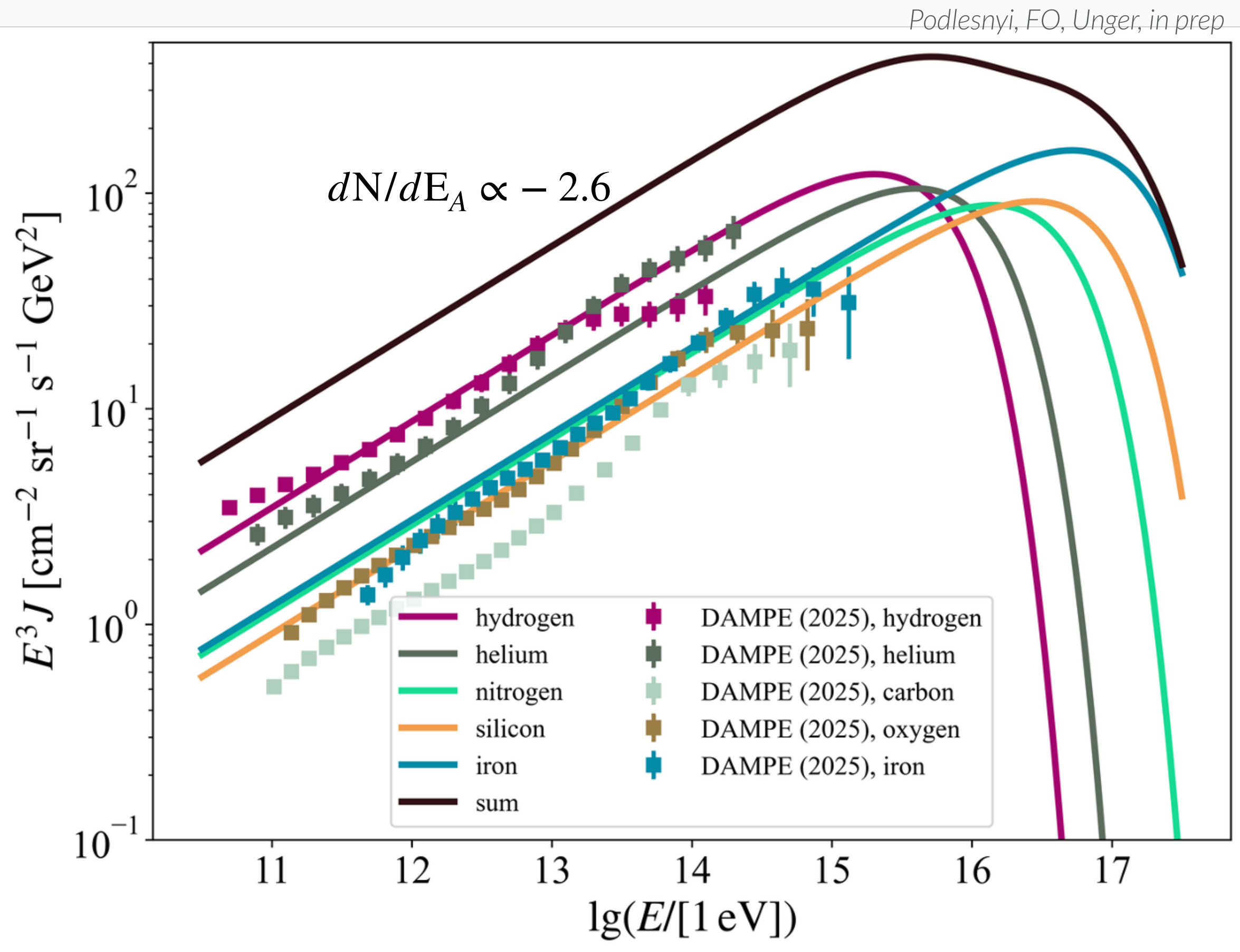
Most protons  
secondary!



Podlesnyi, FO, Unger, in prep



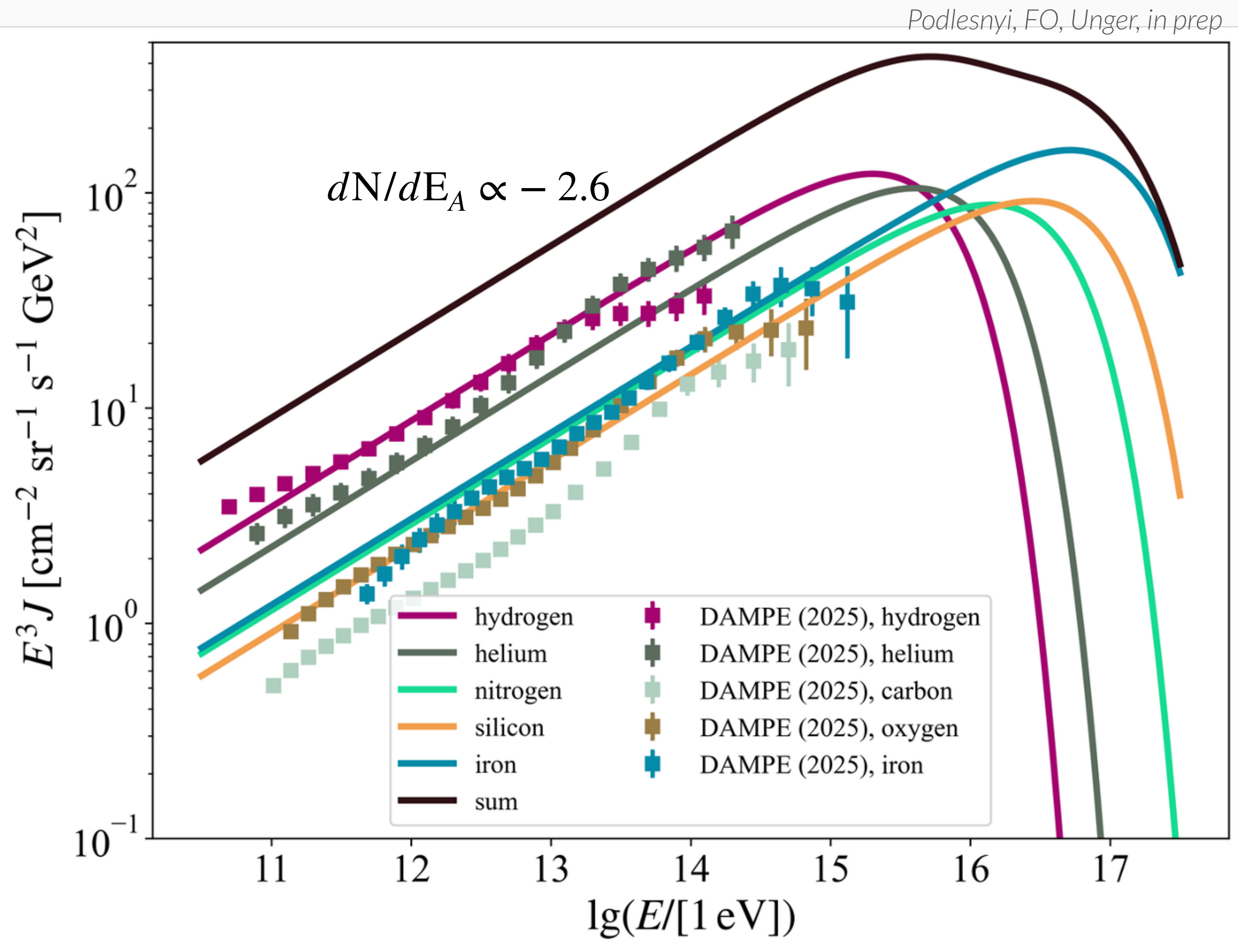
# Galactic CR Composition



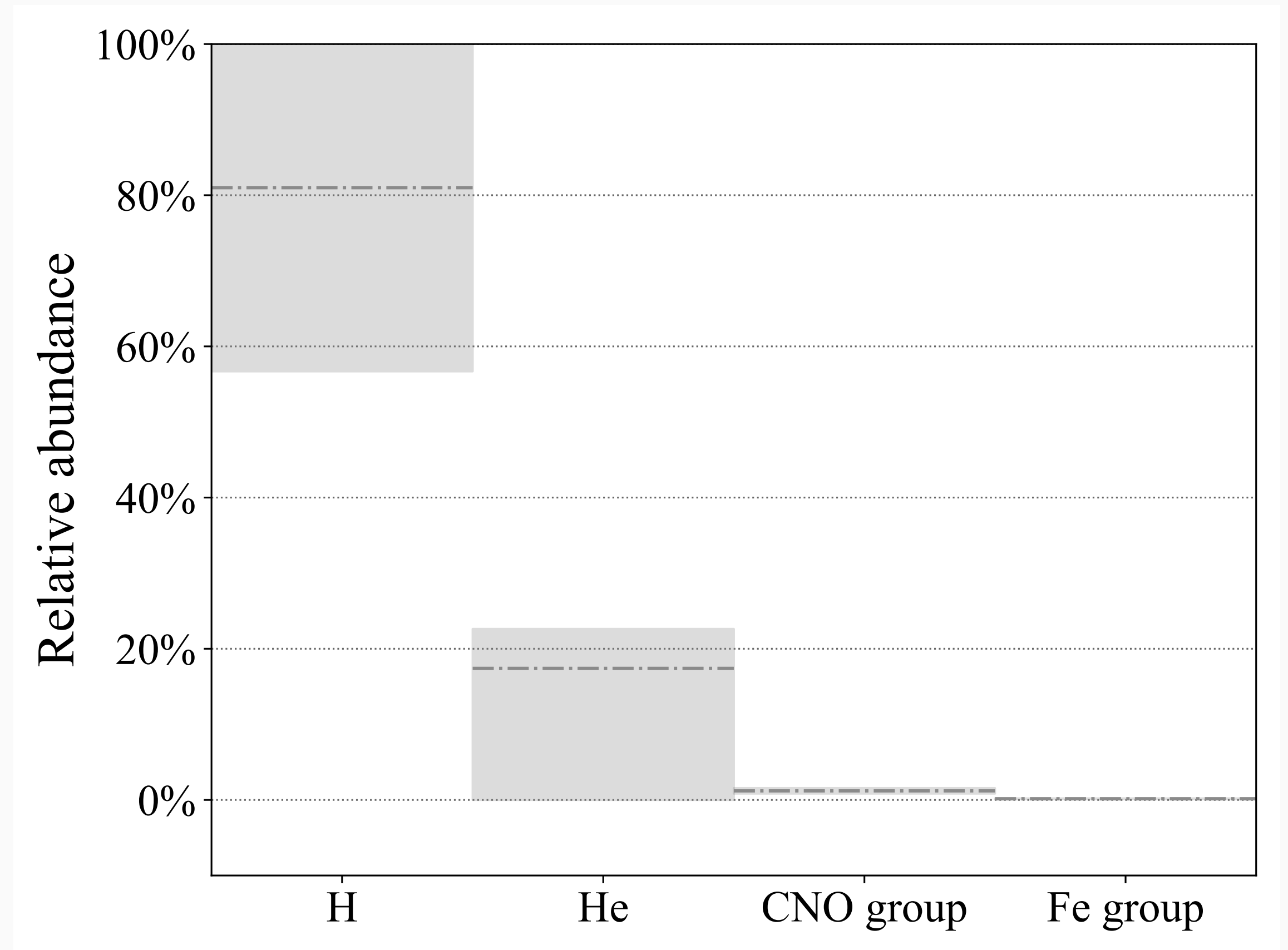
*Fractions from Hörandel, Astropart. Phys. 19, 193 (2003), at 1 TV assuming gamma = 2.6 for all species*



# Galactic CR Composition

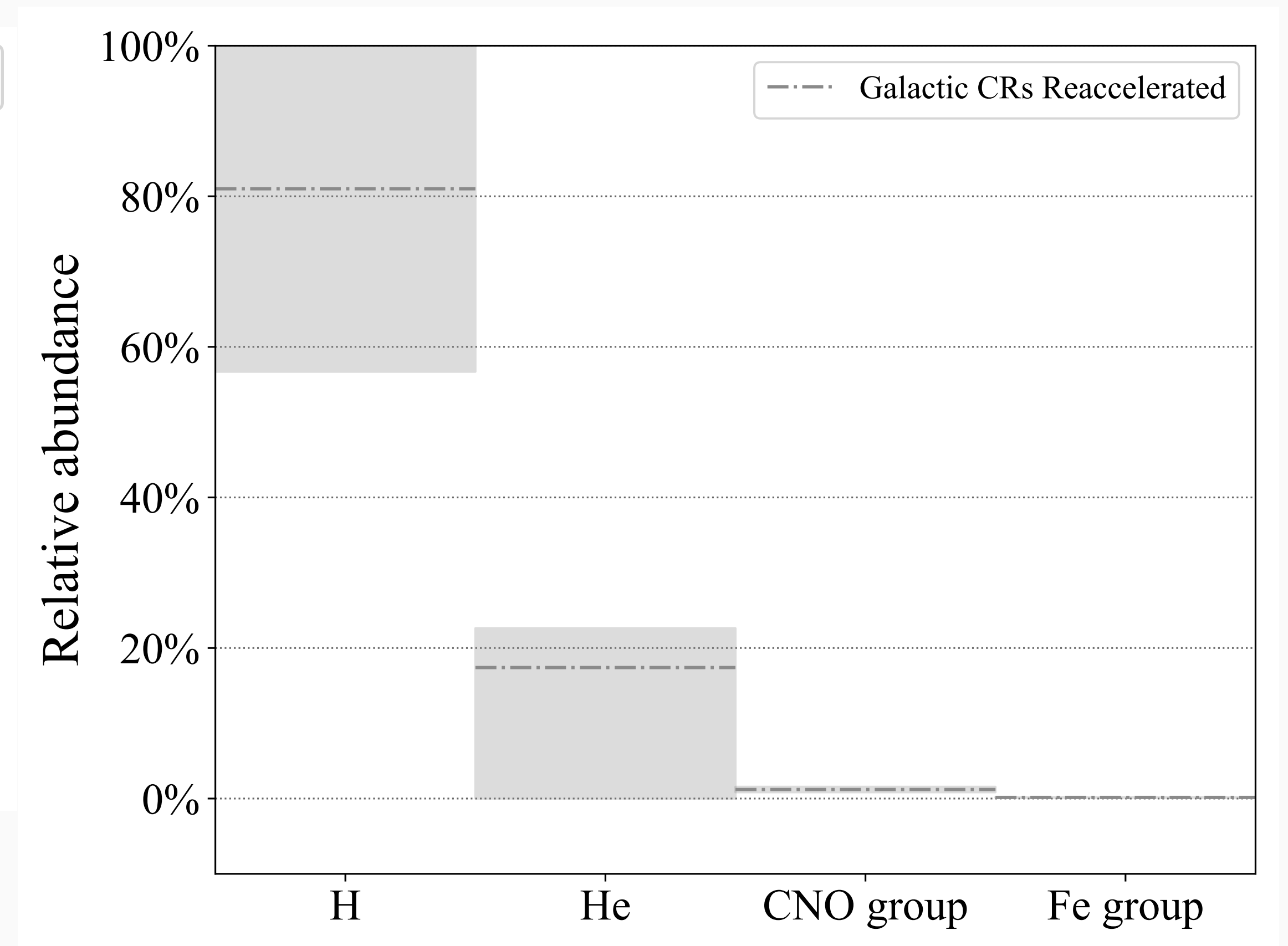
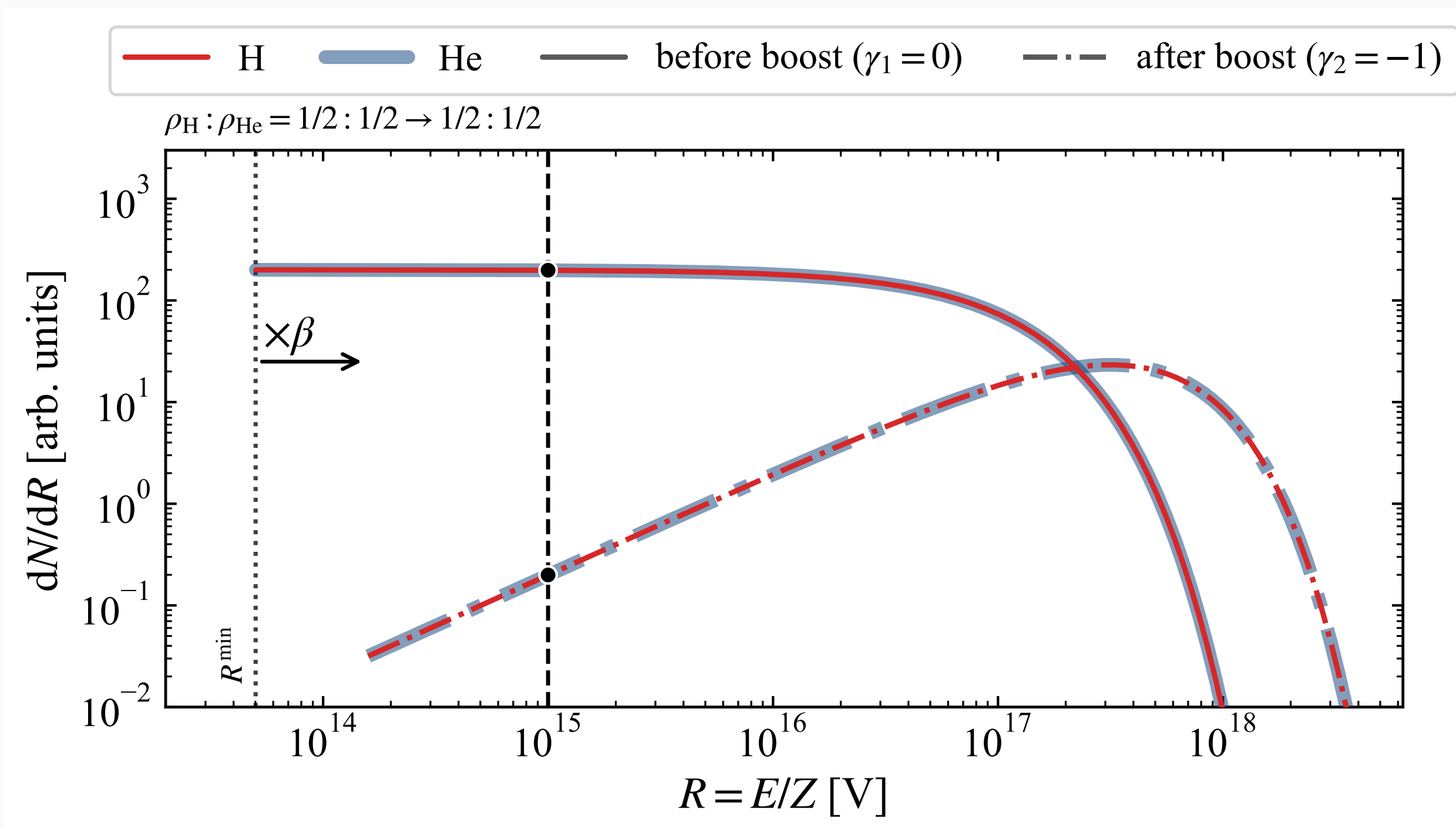


*Fractions from Hörandel, Astropart. Phys. 19, 193 (2003), at 1 TV assuming gamma = 2.6 for all species*





# Reaccelerated Galactic CRs to UHE

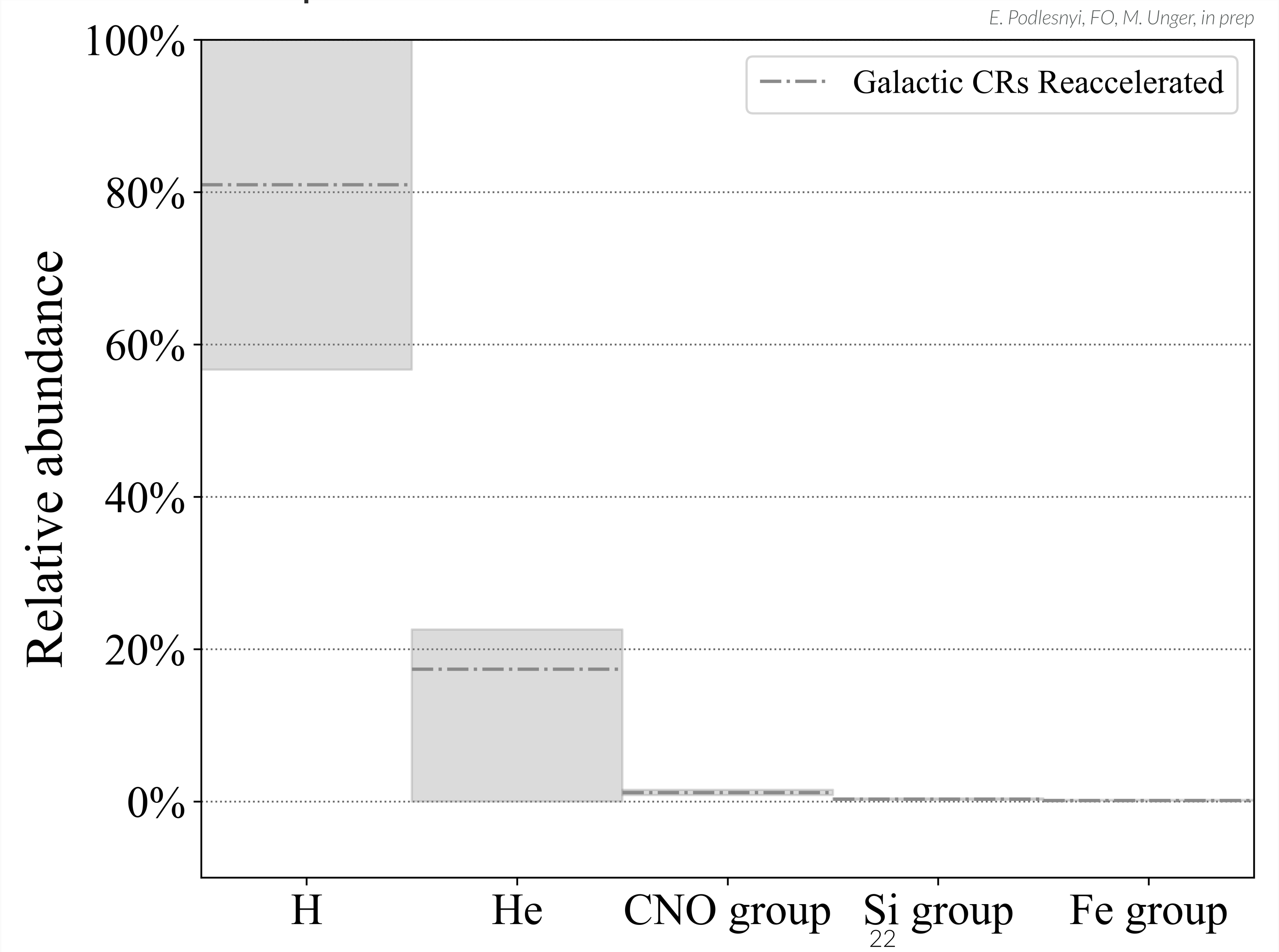


Rigidity dependent mechanisms:

Espresso (Caprioli 2015),

Shear (Rieger & Duffy 2004, 2019, Kimura, Murase, & Zhang, 2018)

# A Curious Composition

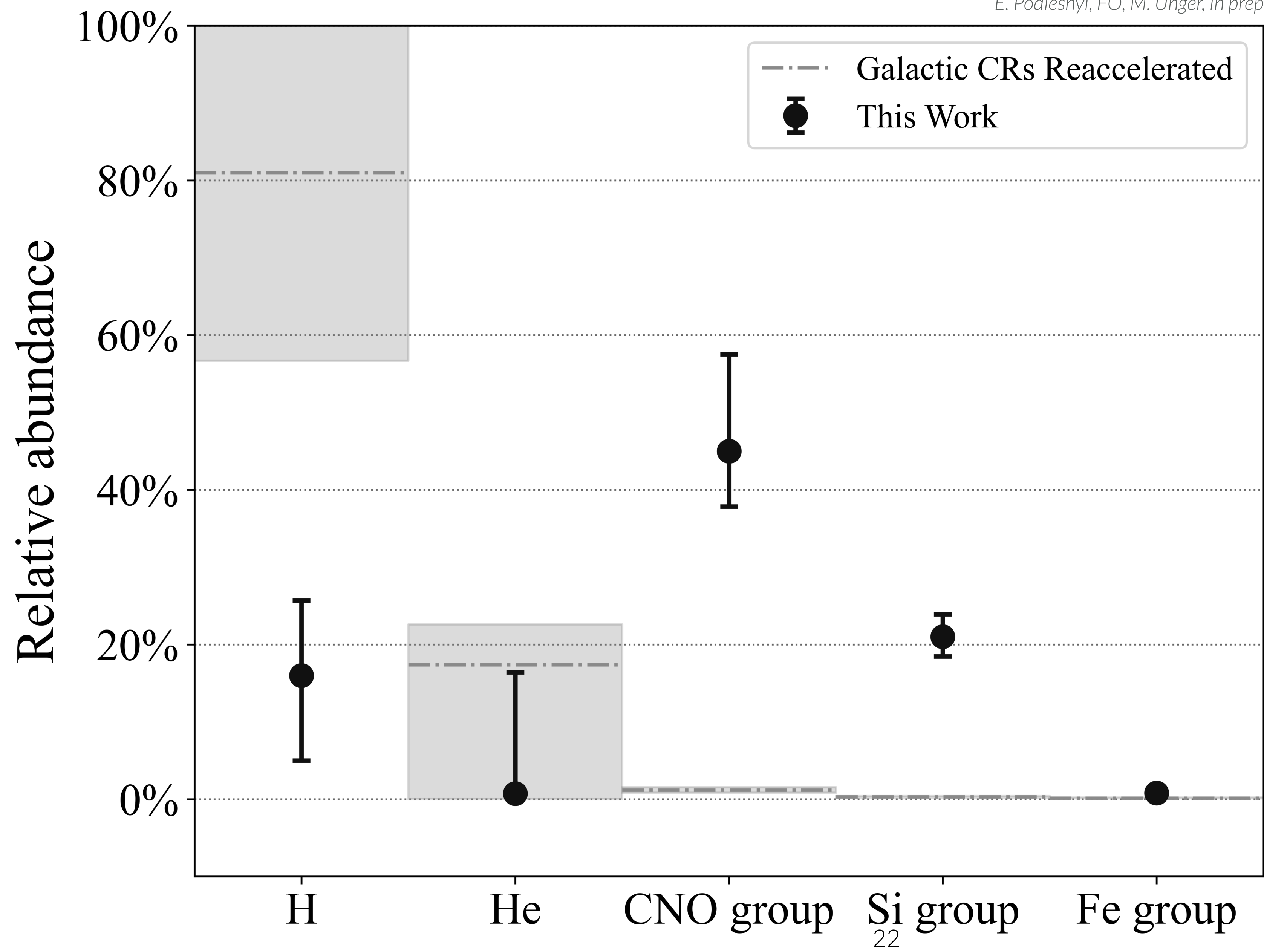


EPOS-LHC-R no shifts

UHECR models from *Kimura+2017*,  
*Zhang+2017*, *Zhang+2018*

# A Curious Composition

E. Podlesnyi, FO, M. Unger, in prep



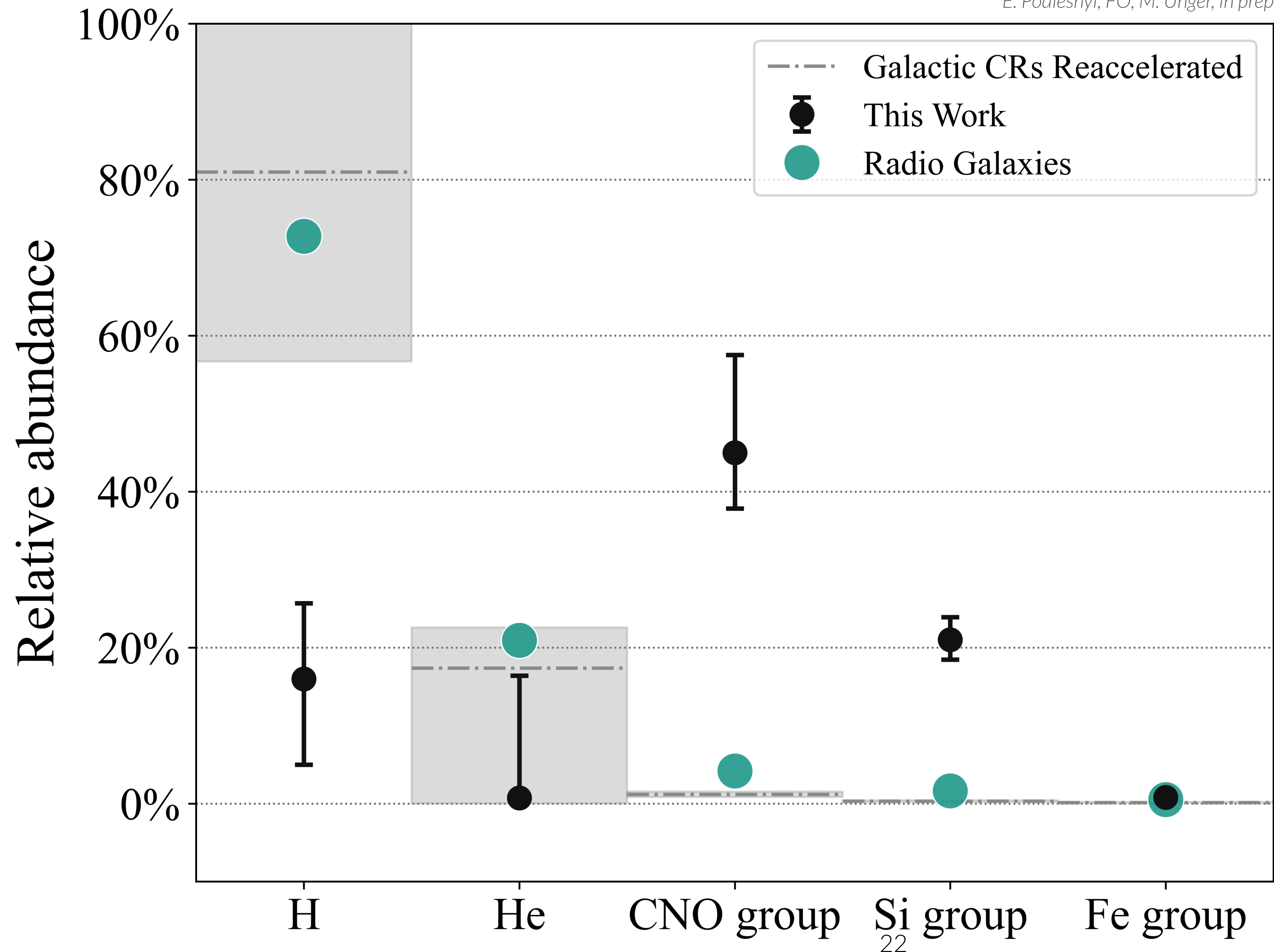
EPOS-LHC-R no shifts

UHECR models from Kimura+2017,  
Zhang+2017, Zhang+2018



# A Curious Composition

E. Podlesnyi, FO, M. Unger, in prep



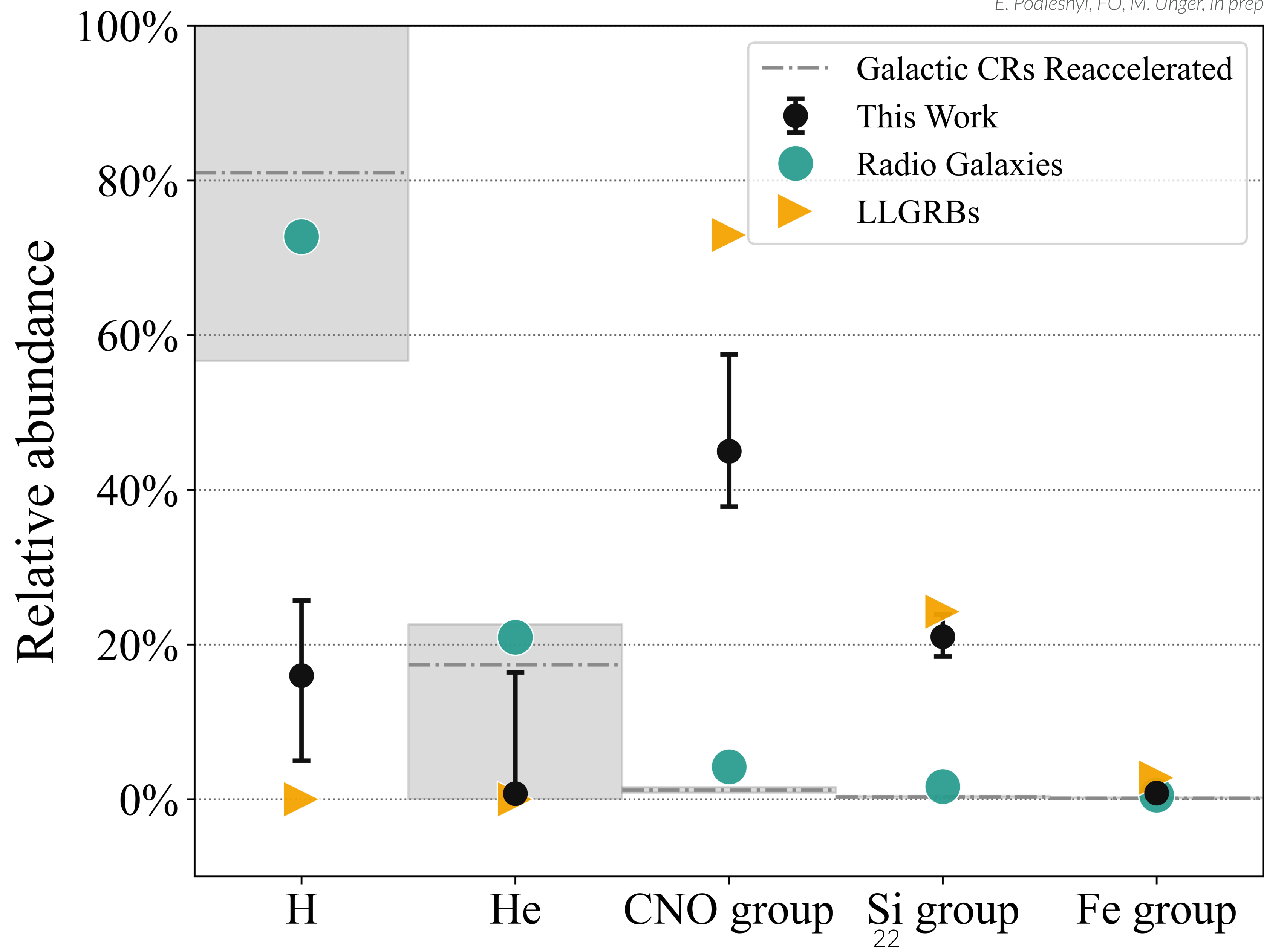
EPOS-LHC-R no shifts

UHECR models from Kimura+2017,  
Zhang+2017, Zhang+2018



# A Curious Composition

E. Podlesnyi, FO, M. Unger, in prep

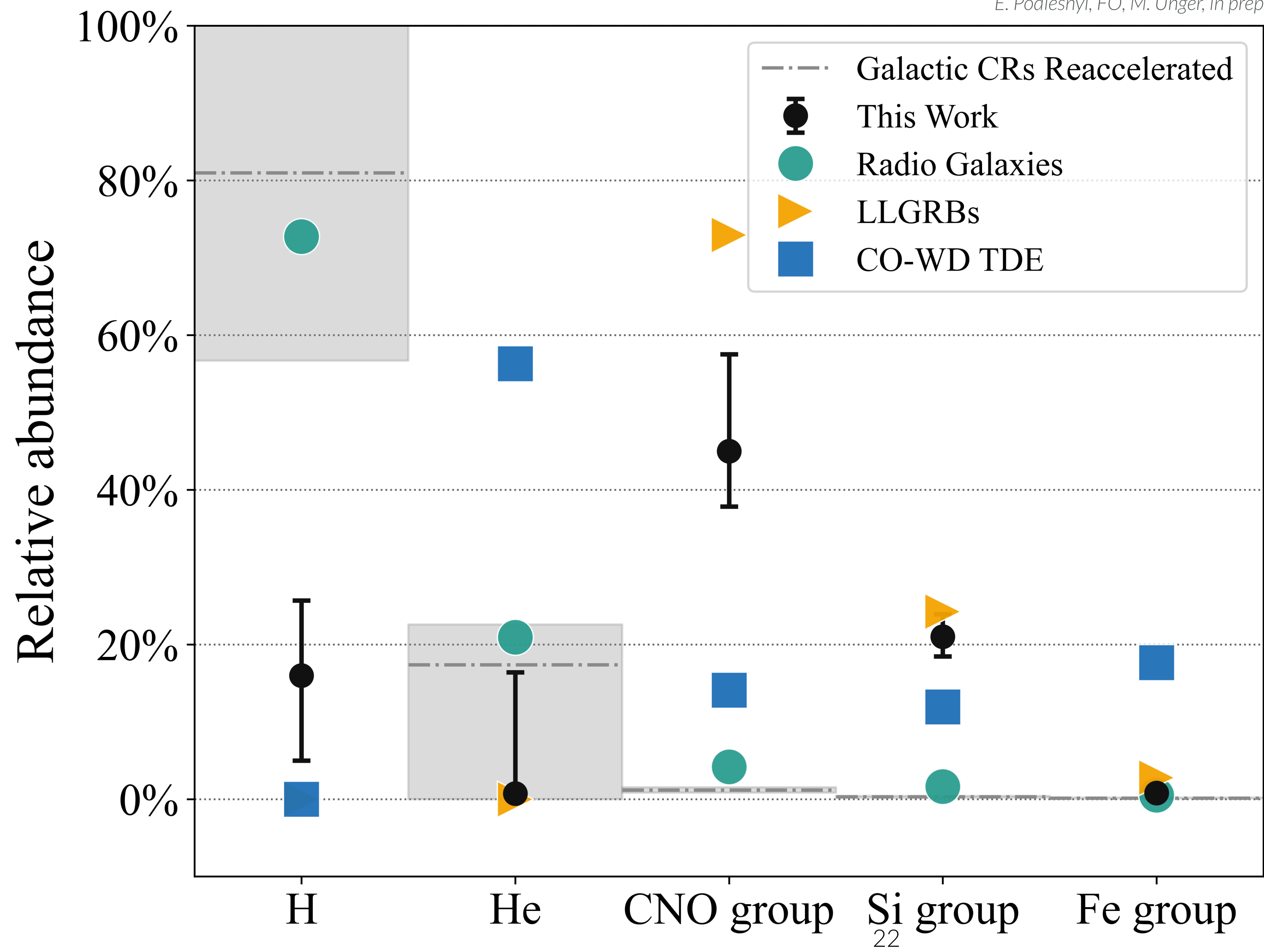


EPOS-LHC-R no shifts

UHECR models from *Kimura+2017*,  
*Zhang+2017*, *Zhang+2018*

# A Curious Composition

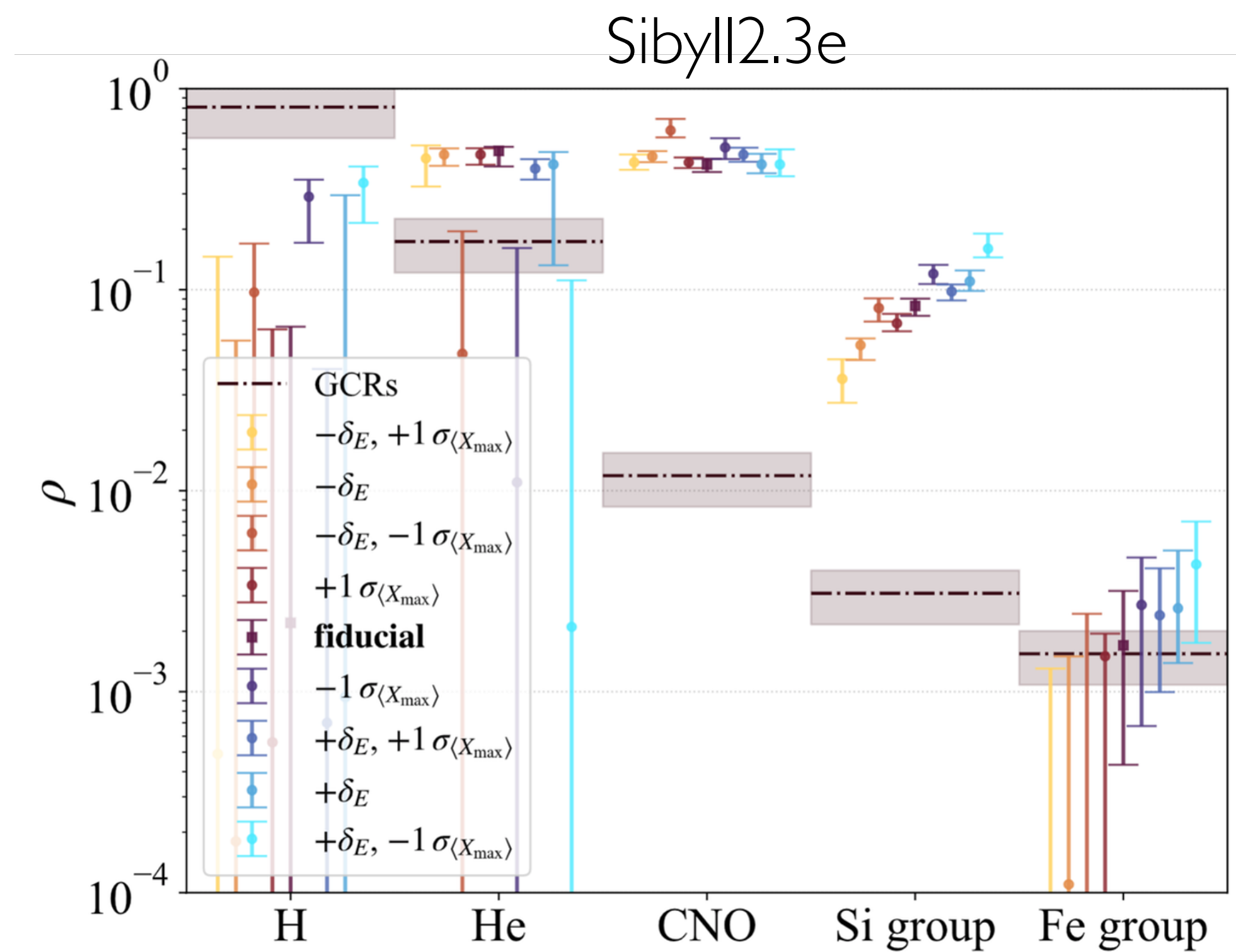
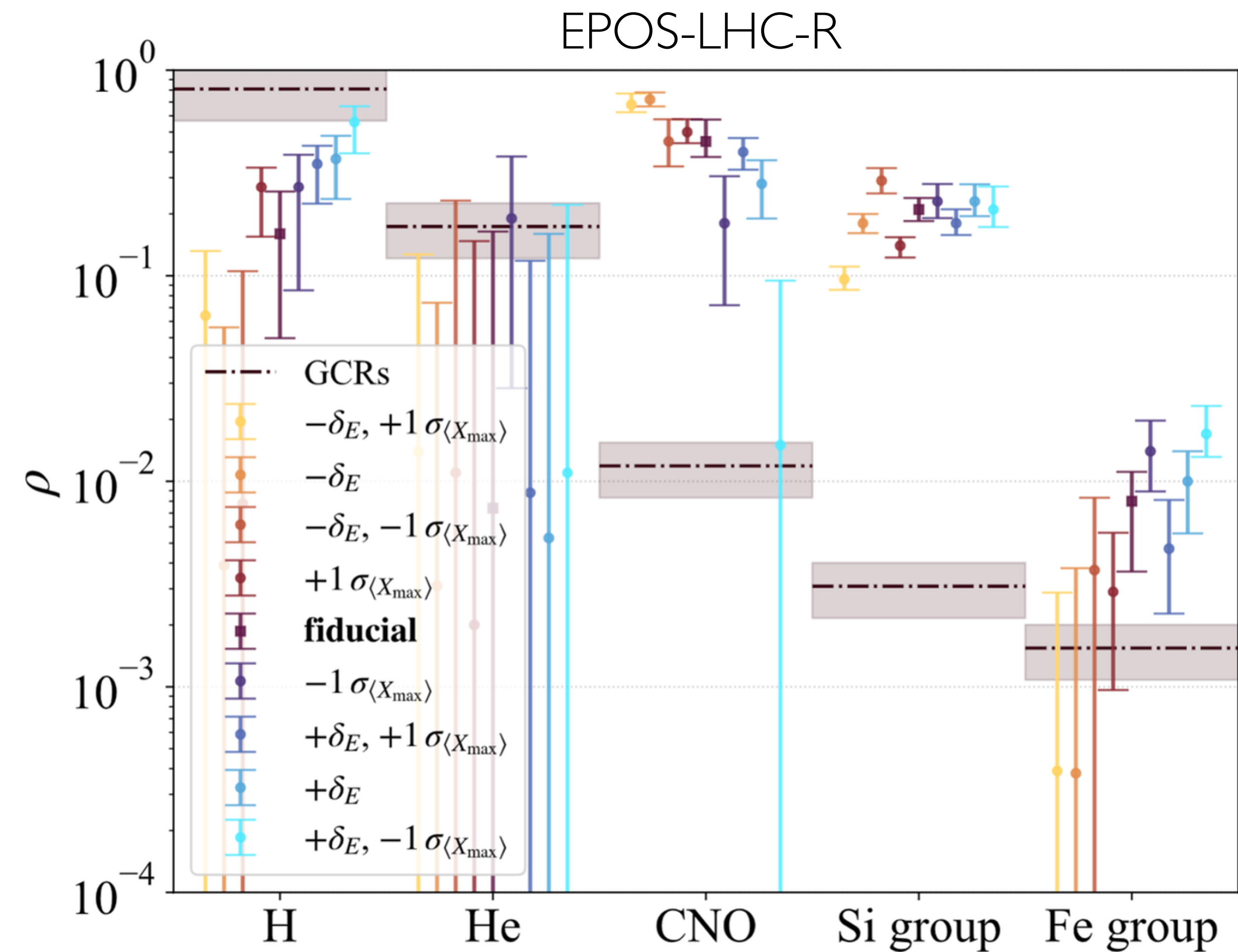
E. Podlesnyi, FO, M. Unger, in prep



EPOS-LHC-R no shifts

UHECR models from *Kimura+2017*,  
*Zhang+2017*, *Zhang+2018*

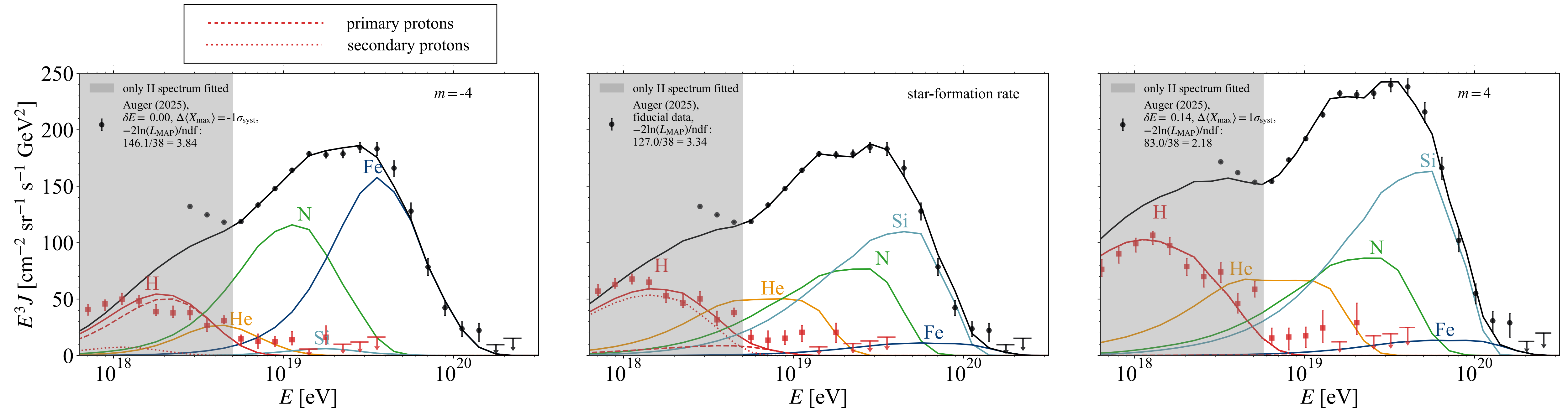
# UHECR Composition Systematics



| Parameter                          | EPOS-LHC-R                | Sibyll2.3e                   |
|------------------------------------|---------------------------|------------------------------|
| $\gamma$                           | $0.88^{+0.06}_{-0.07}$    | $-0.9^{+0.3}_{-0.4}$         |
| $R_{\text{cut}}$ [V]               | $7.4^{+0.4}_{-0.5}$       | $3.4^{+0.7}_{-0.9}$          |
| $\lambda$                          | $2.7^{+0.4}_{-0.3}$       | $1.40^{+0.16}_{-0.17}$       |
| $\rho_{\text{H}}$                  | $0.16^{+0.10}_{-0.11}$    | $0.00^{+0.06}_{-0.00}$       |
| $\rho_{\text{He}}$                 | $0.01^{+0.16}_{-0.01}$    | $0.49^{+0.02}_{-0.08}$       |
| $\rho_{\text{N}}$                  | $0.45^{+0.13}_{-0.07}$    | $0.42^{+0.03}_{-0.04}$       |
| $\rho_{\text{Si}}$                 | $0.210^{+0.029}_{-0.025}$ | $0.083^{+0.007}_{-0.009}$    |
| $\rho_{\text{Fe}}$                 | $0.008^{+0.003}_{-0.004}$ | $0.0017^{+0.0015}_{-0.0013}$ |
| $-2 \ln L_{\text{MAP}}/\text{ndf}$ | 1.25                      | 3.33                         |

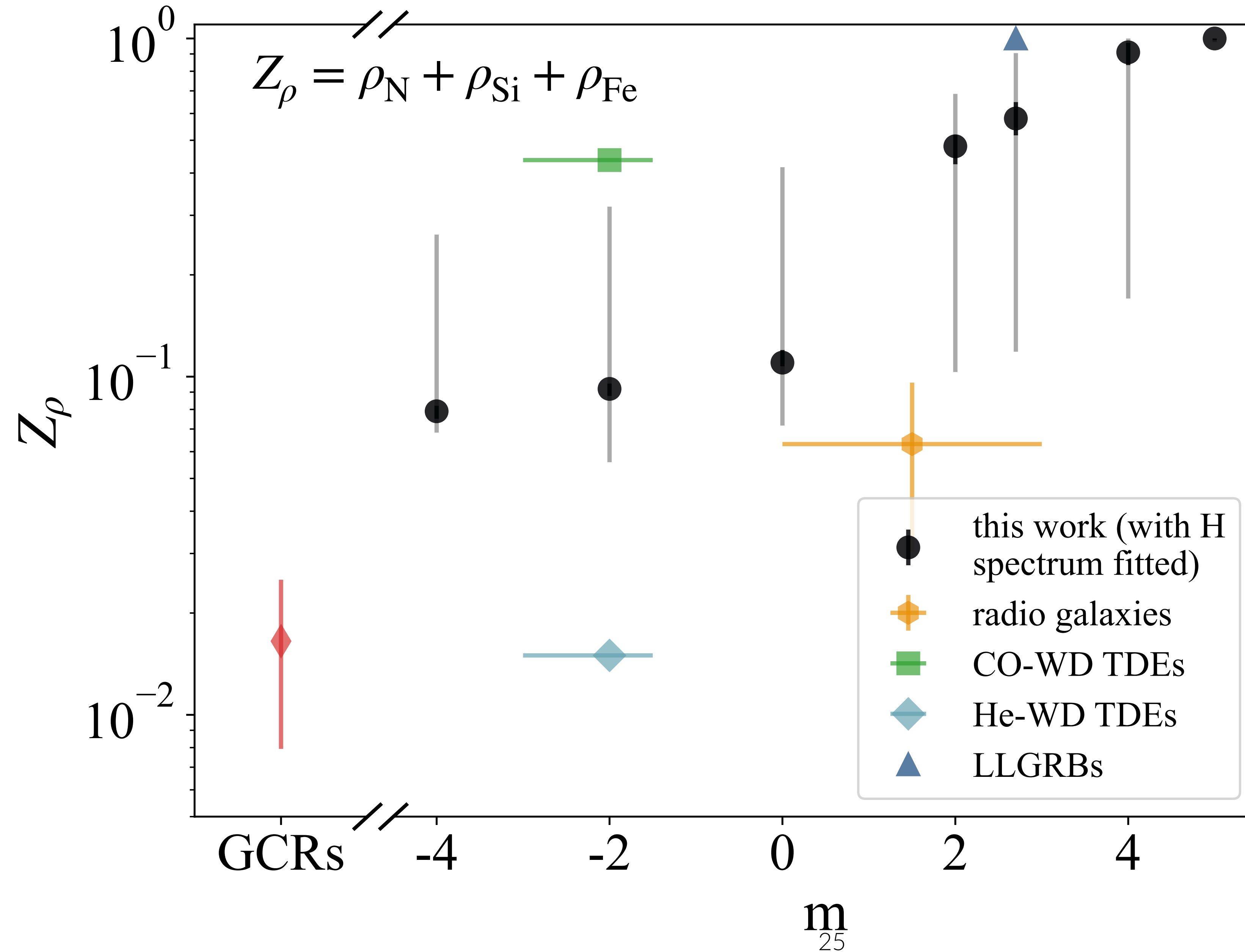


# Redshift evolution

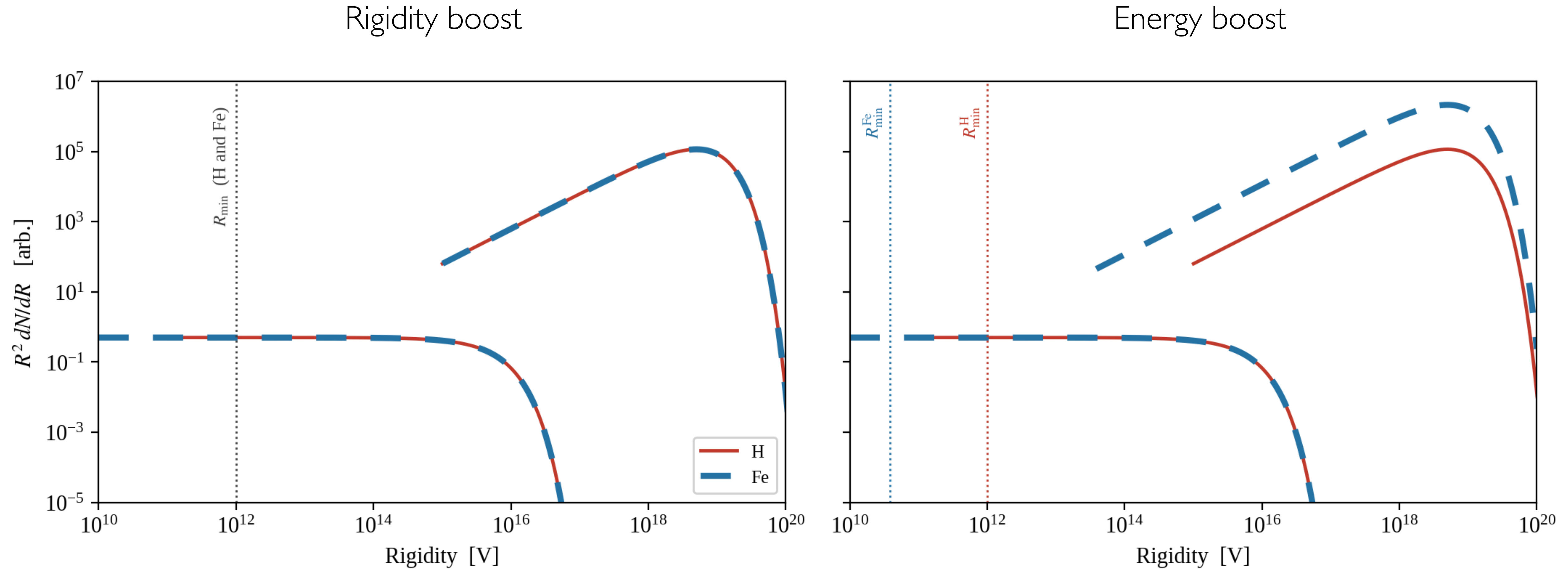




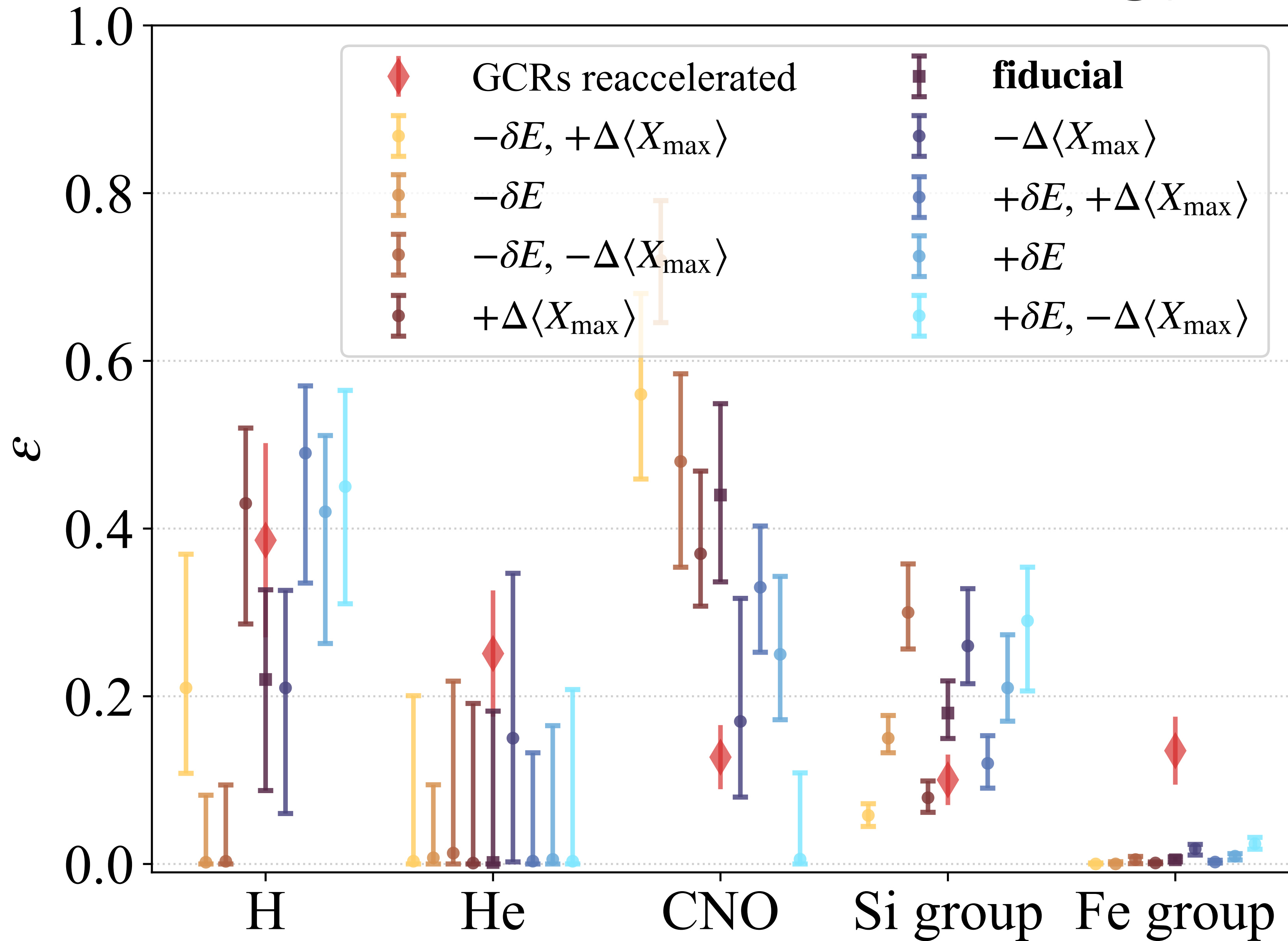
# Redshift evolution



# Acceleration from fixed minimum energy



# Acceleration from fixed minimum energy





# Summary

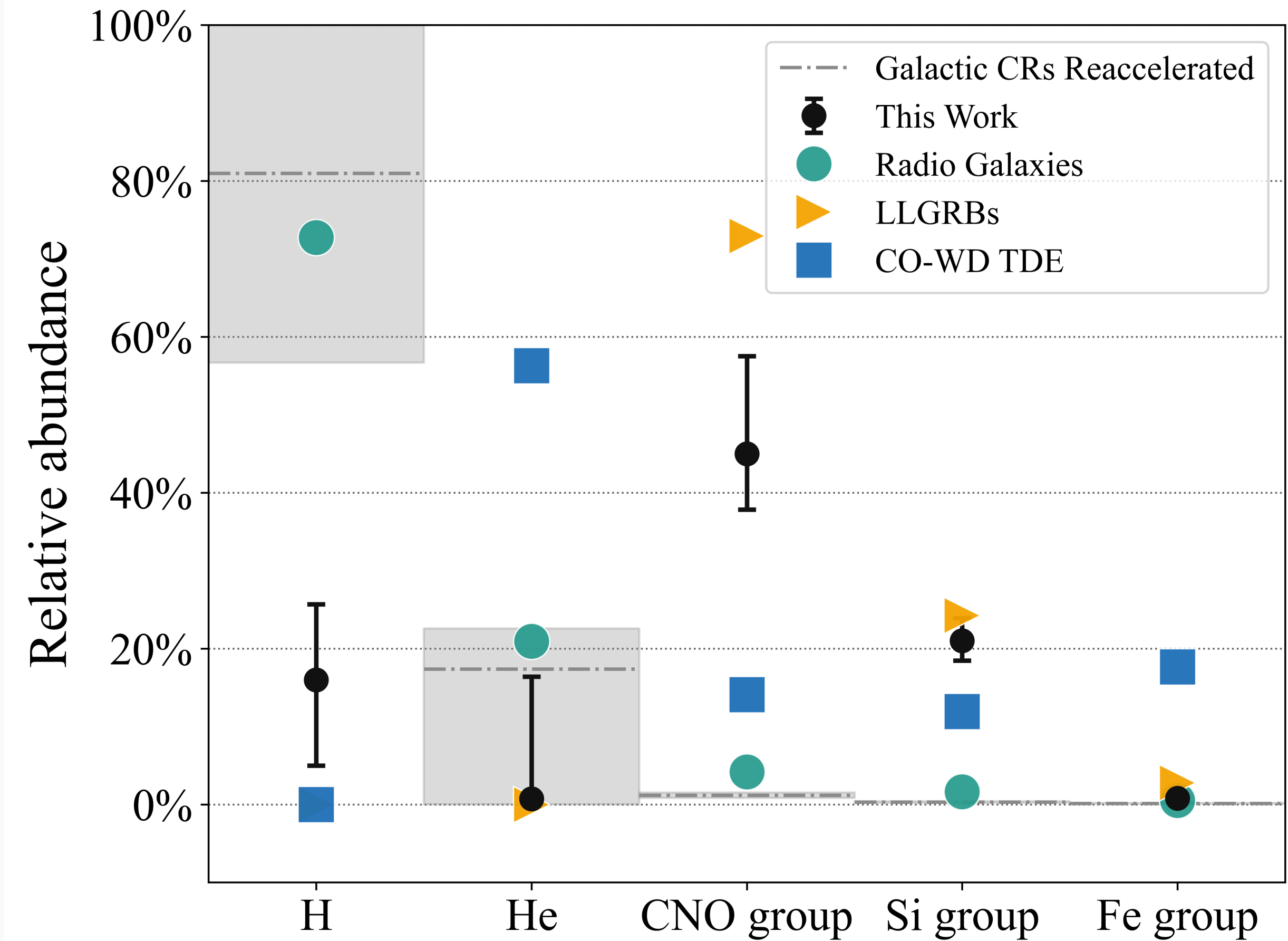
## Component B

Extragalactic Origin  
Composition ~Galactic

## Ultra-high energies

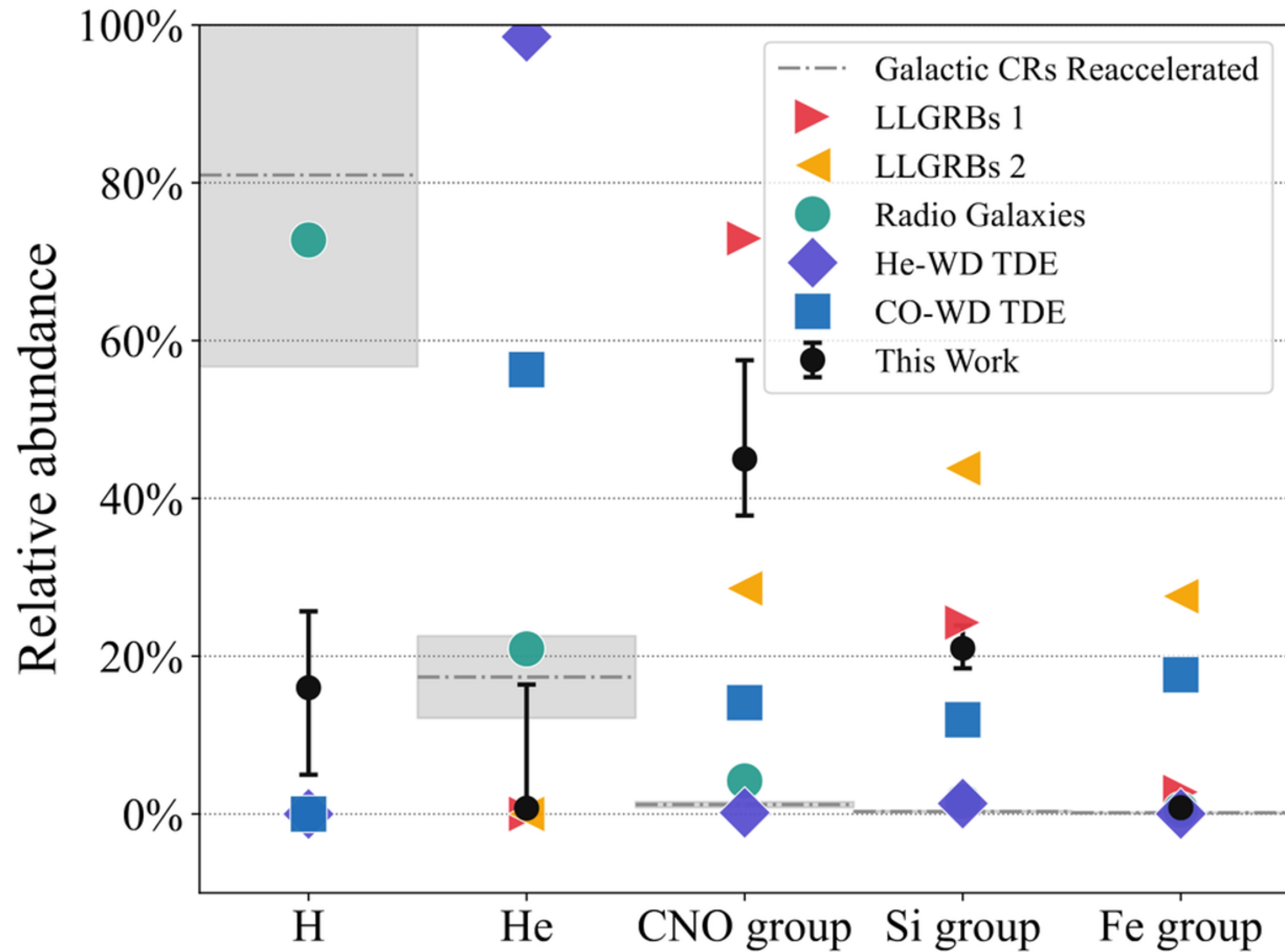
Composition differs from Galactic CR composition

Energy dependent acceleration? Local sources? In source interactions? No Hydrogen sources?

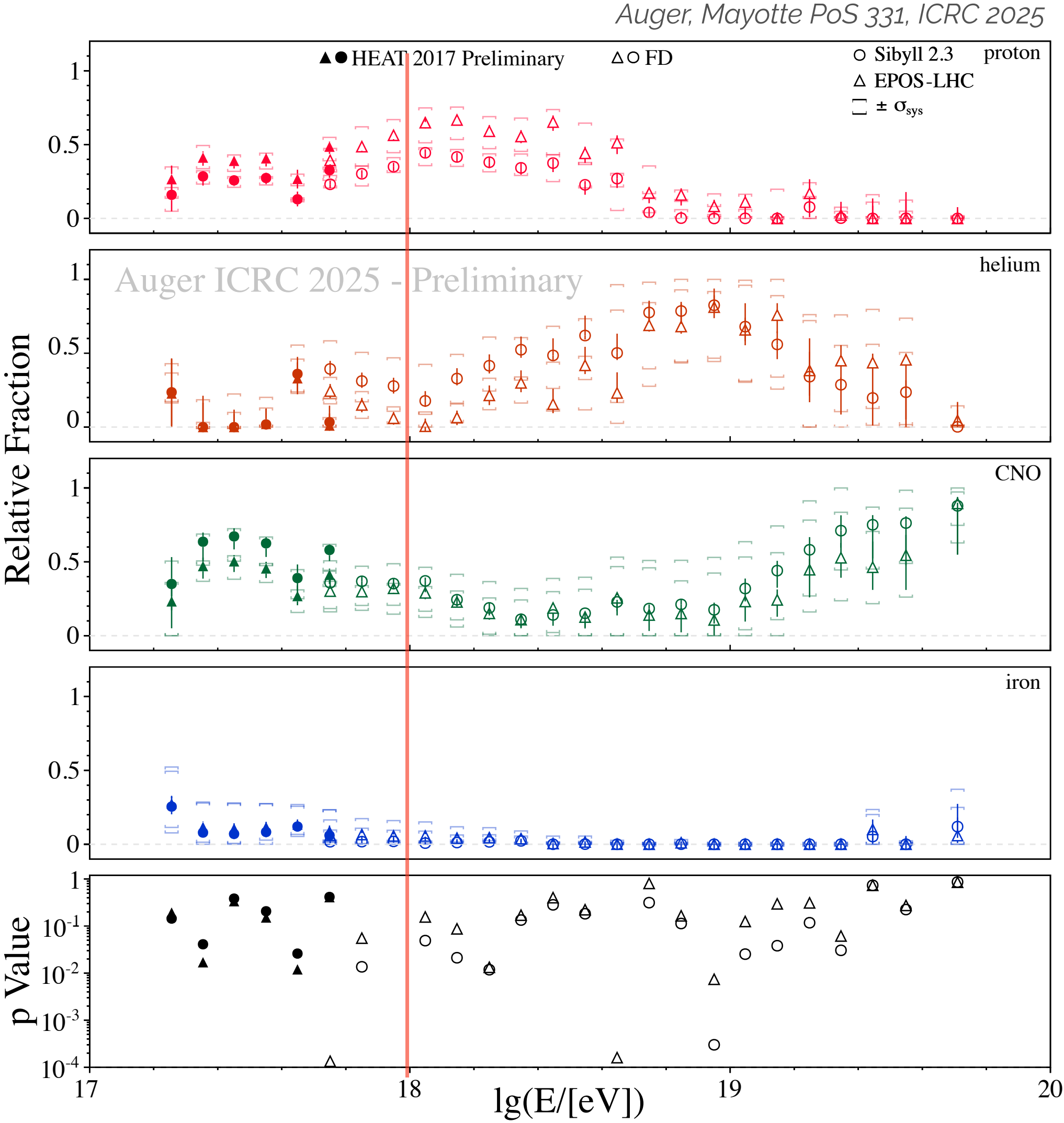
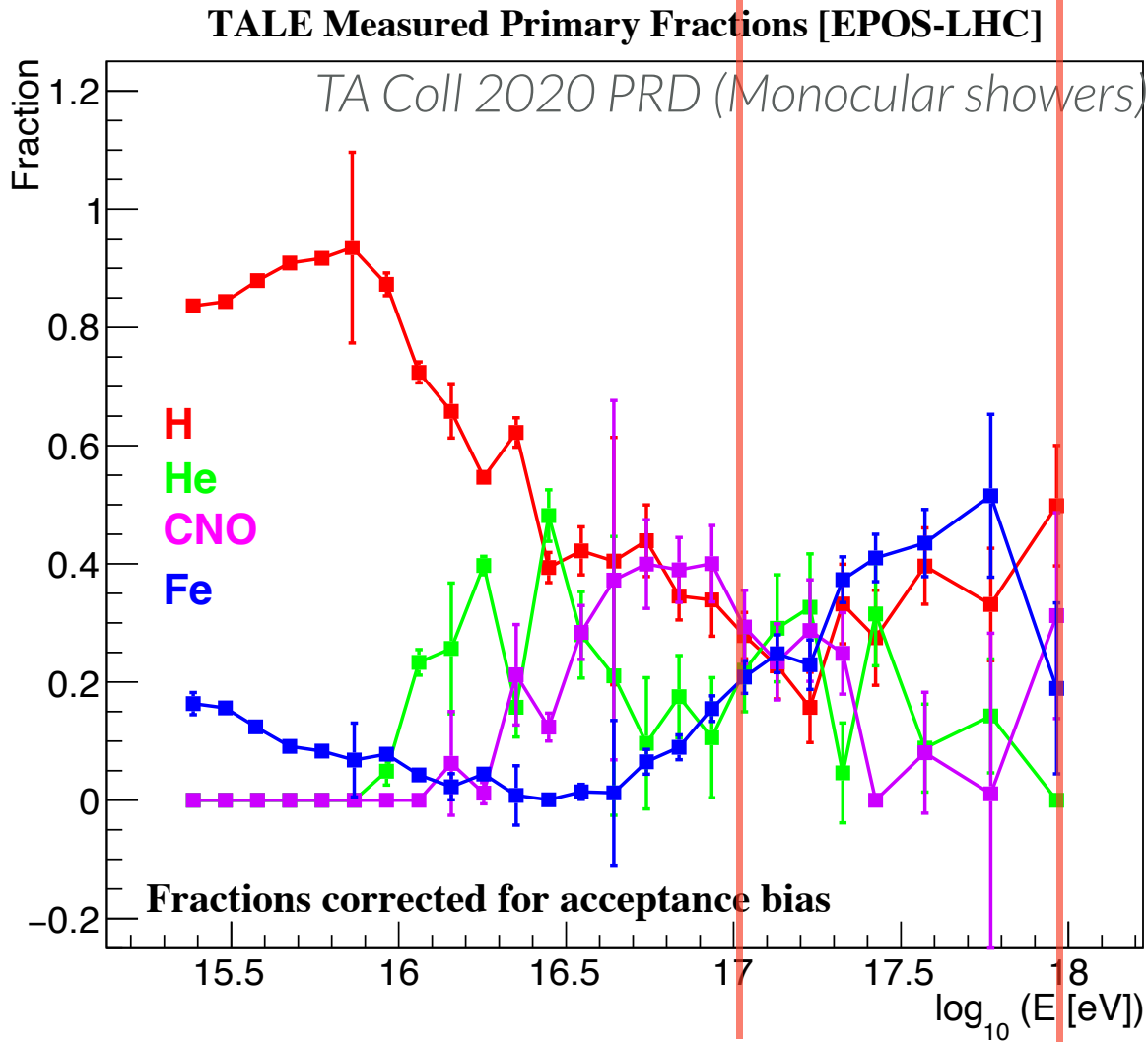
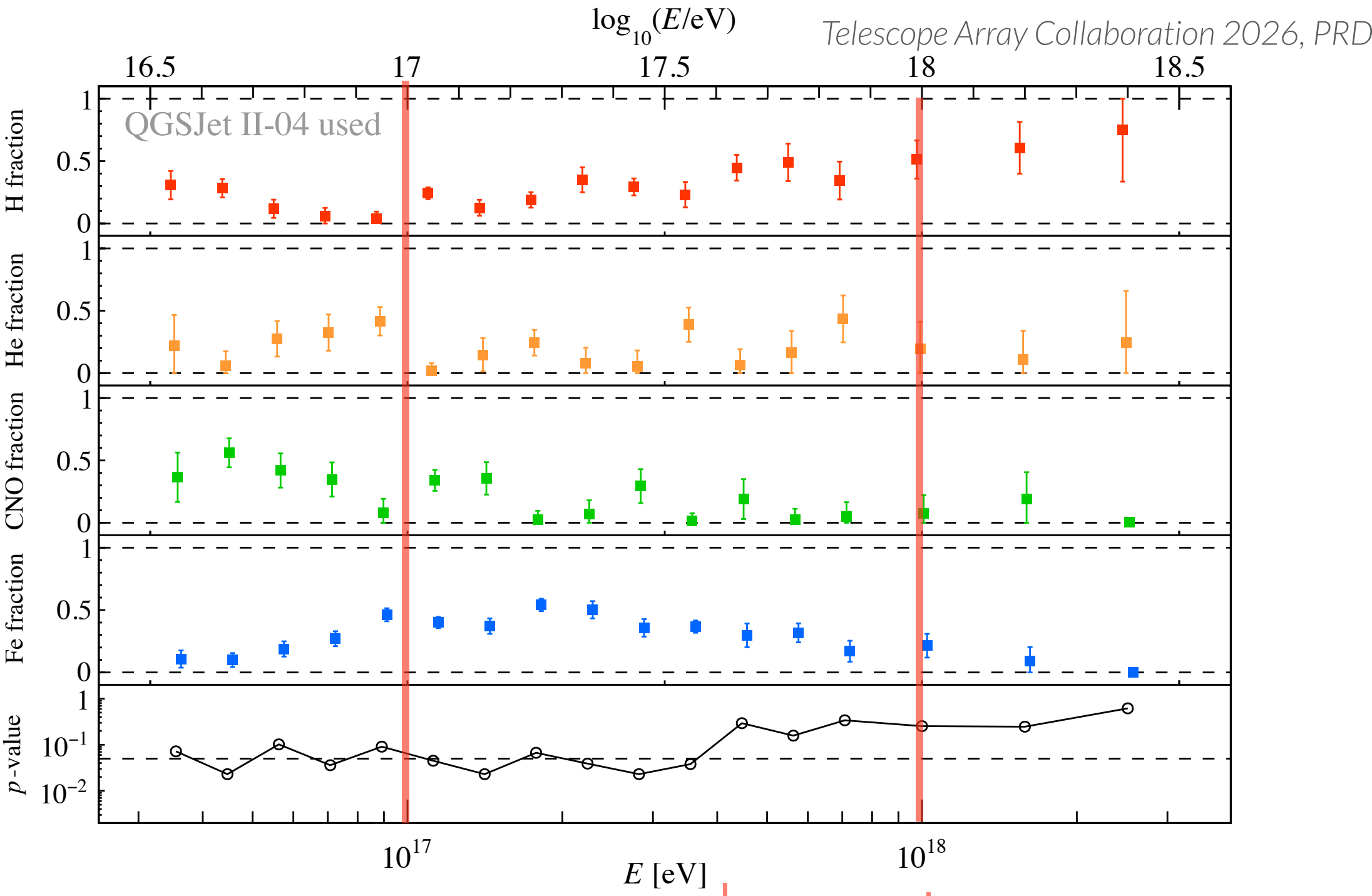




# Other models at UHE



# Component B Composition



# Component B Composition

*IceCube Coll 2019, Phys. Rev. D, 100, 082002*

