



What do we know about cosmic rays with energies from 500 PeV to 5 EeV?

on behalf of the Pierre Auger Collaboration

From Hillas... (pre Pierre Auger observatory era)

Component A

fully ionized H, He, ..., Fe

with a slope $\gamma \sim 2.7$

up to $R_A \sim 3$ PV

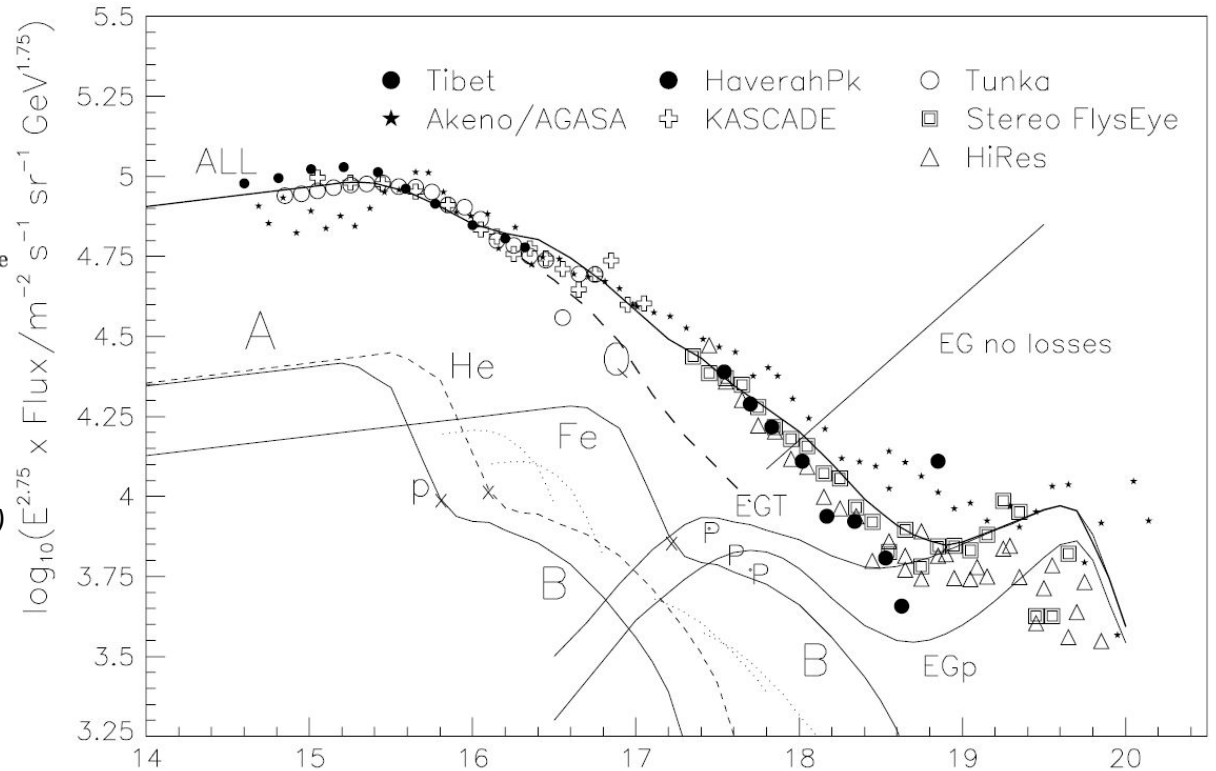
- $Z_{\text{H-He}} e R_A = 3 - 6 \text{ PeV} \equiv E_{\text{1st knee}}$
- $Z_{\text{Fe}} e R_A \approx 100 \text{ PeV} \equiv E_{\text{2nd knee}}$

Component B

Something still has to be added to the 'KASCADE' component 'A'
M. Hillas (2005)

Component C EGT = EGp + EGHe

fully ionized H and He (heavier)
with absorption features due to
extragalactic propagation



Credit: Hillas, Topical Review in J. Phys. G: Nucl. Part. Phys. 31 (2005)

$\log_{10}(E/\text{eV})$

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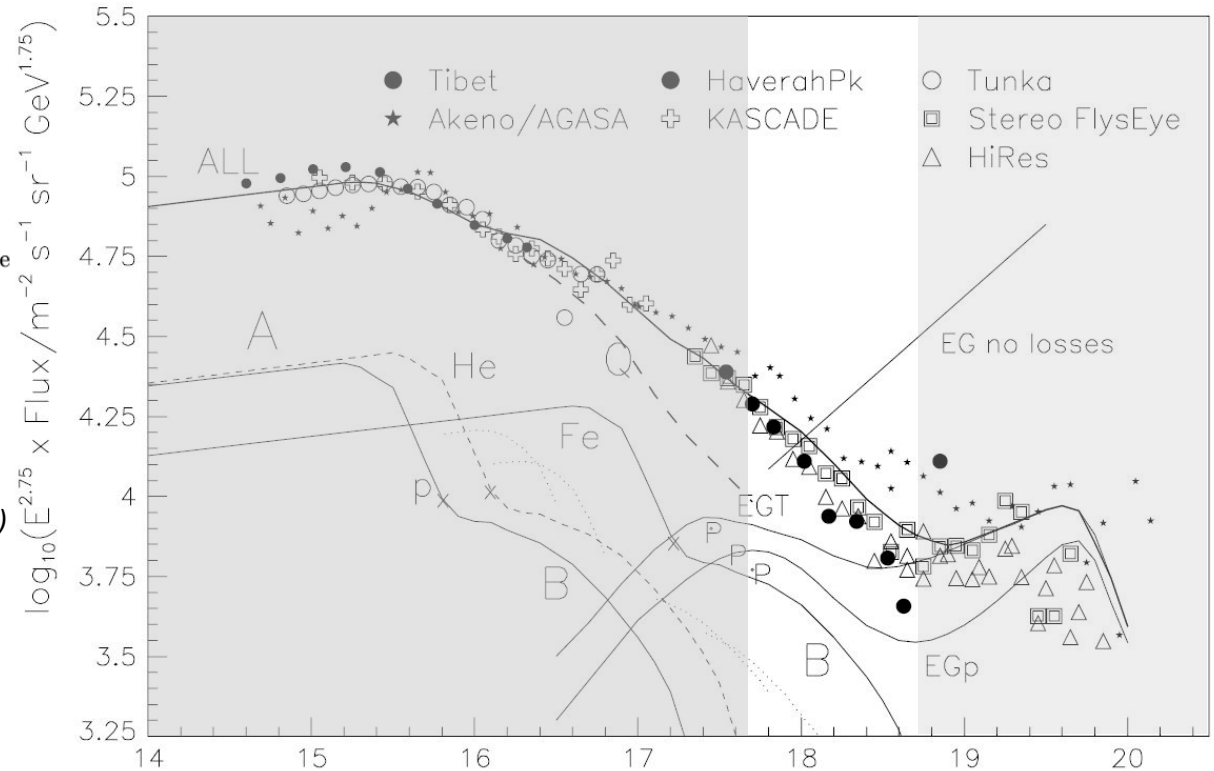
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$\log_{10}(E/\text{eV})$

From Hillas... (dawn of Pierre Auger observatory era)

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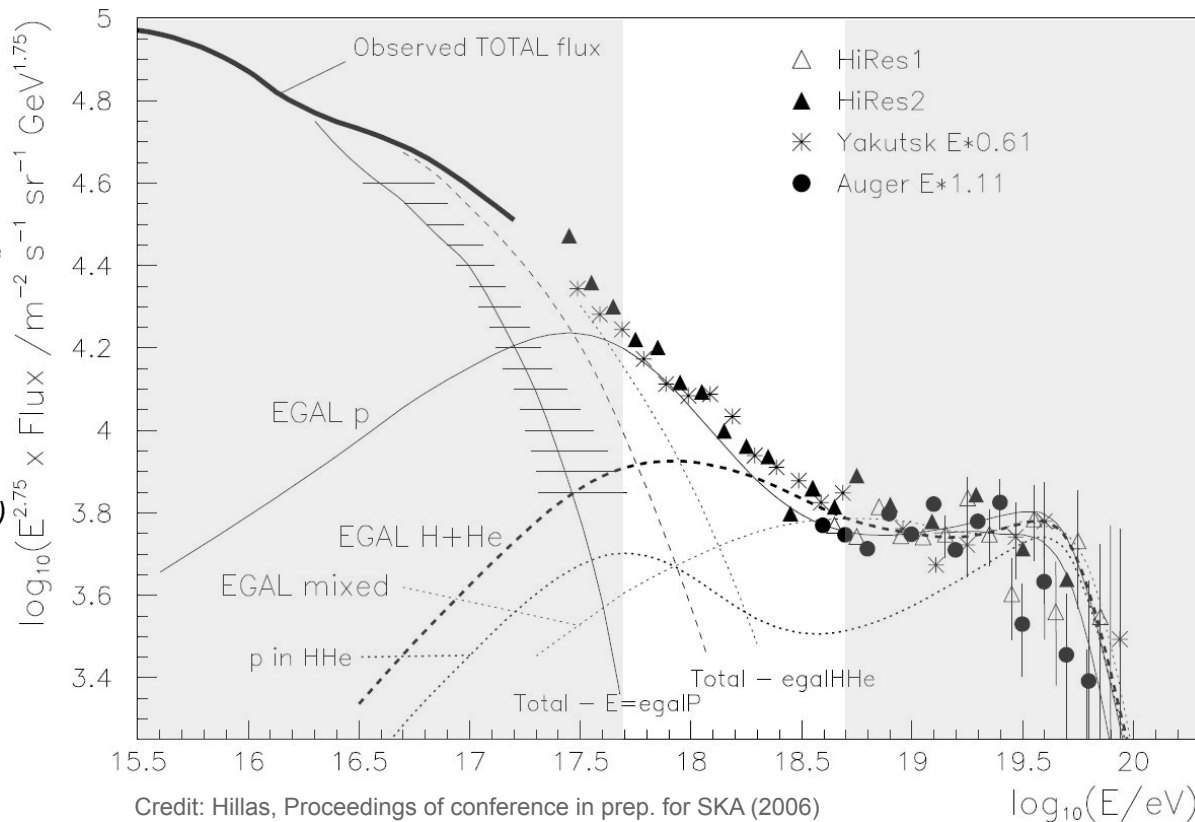
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Component C

- H only $\sim$ dip of Berezhinsky+ '04
- H and He (heavier)
- H, He, ..., Fe $\sim$ mix of Allard+ '06



Credit: Hillas, Proceedings of conference in prep. for SKA (2006)

... to Aloisio, Berezhinsky, Blasi (Pierre Auger obs. - phase I)

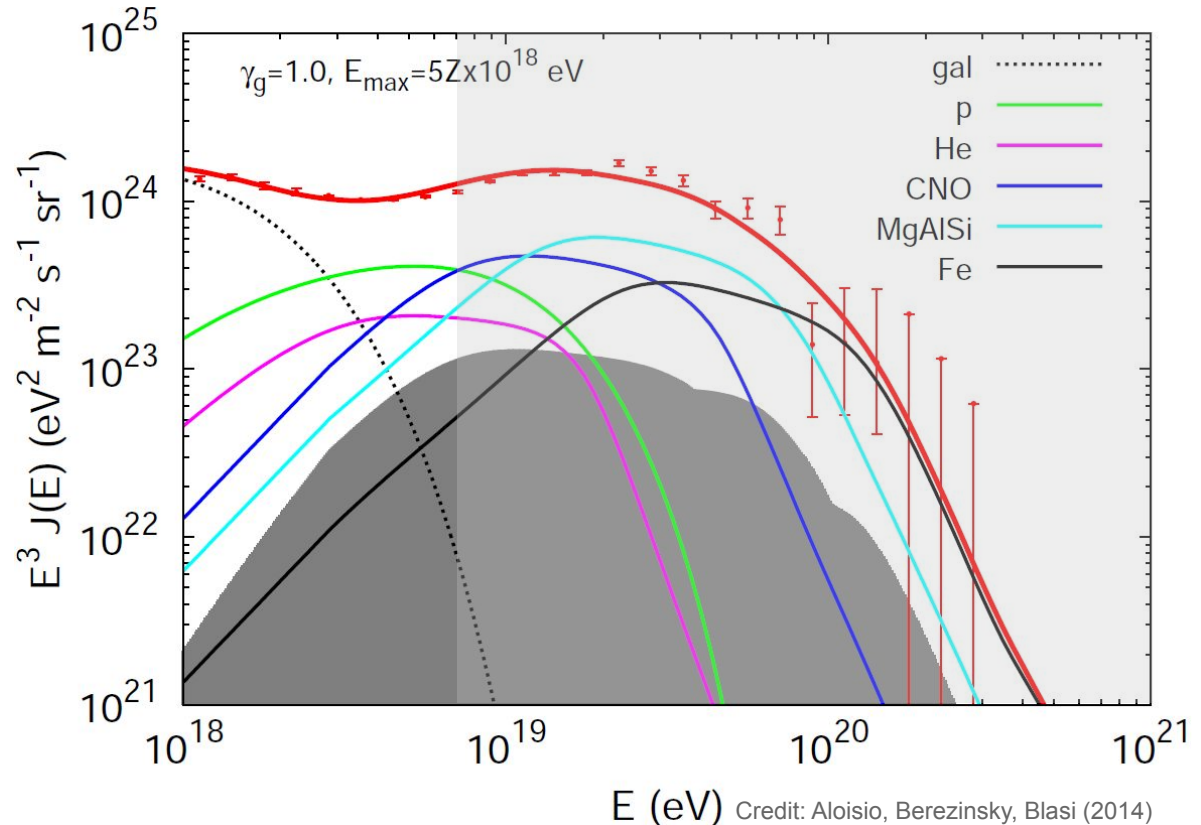
Component B

Something still has to be added to the 'KASCADE' component 'A'

M. Hillas (2005)

Component C

- H only ~ dip of Berezhinsky+ '04
- H and He (heavier)
- H, He, ..., Fe ~ mix of Allard+ '06
with a slope $\gamma \sim 1.0$ (hard injection!)
up to $R_C \sim 5$ EV
- $Z_{He} R_C = 5 \text{ EeV} \equiv E_{\text{ankle}}$
- $Z_{Fe} R_C = 130 \text{ EeV}$

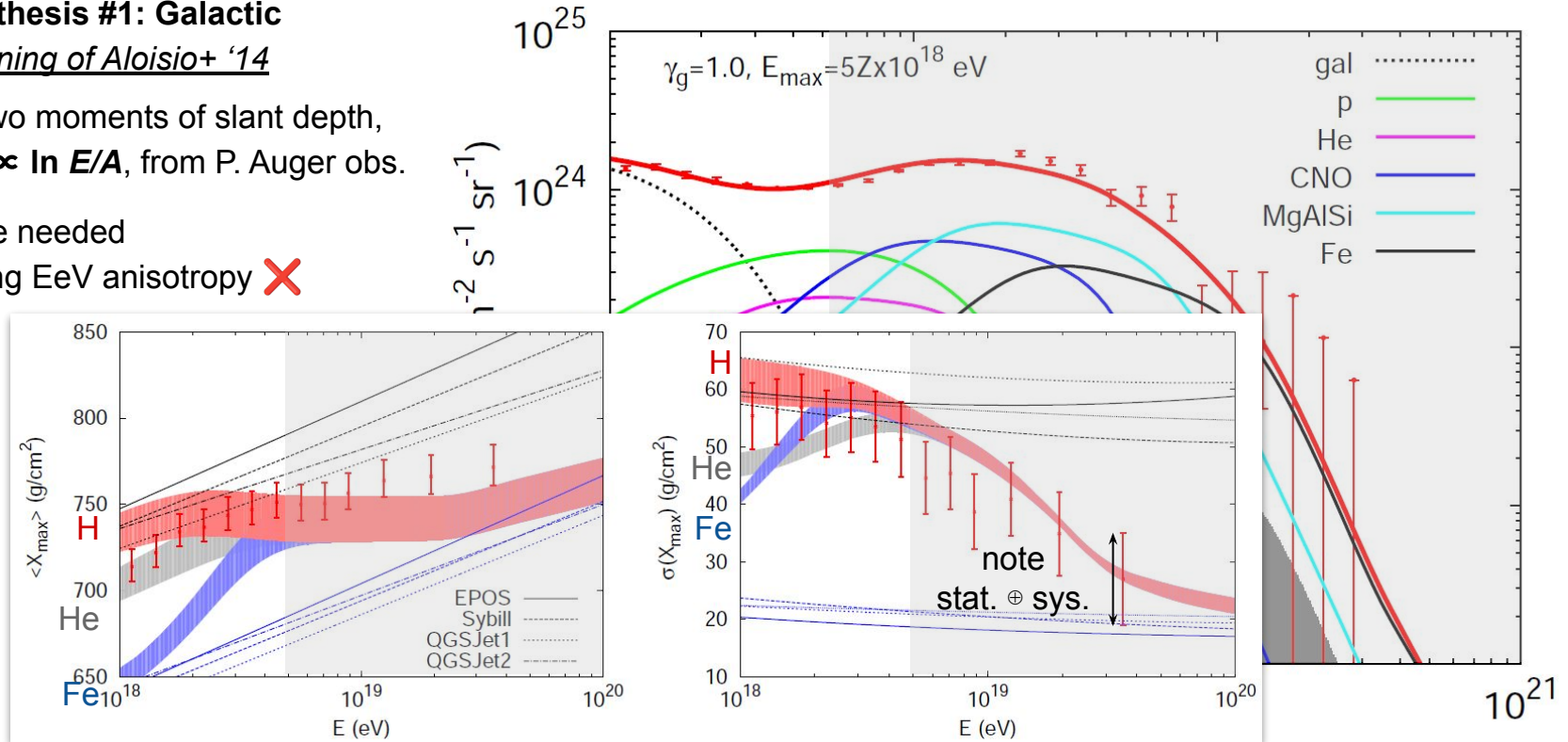


... to Aloisio, Berezhinsky, Blasi (Pierre Auger obs. - phase I)

Hypothesis #1: Galactic *reasoning of Aloisio+ '14*

first two moments of slant depth,
 $X_{\max}' \propto \ln E/A$, from P. Auger obs.

- H-He needed
- strong EeV anisotropy ✗



Credit: Aloisio, Berezhinsky, Blasi (2014)

... to Aloisio, Berezhinsky, Blasi (Pierre Auger obs. - phase I)

Hypothesis #2: Extragalactic reasoning of Aloisio+ '14

→ Two EGAL-population model

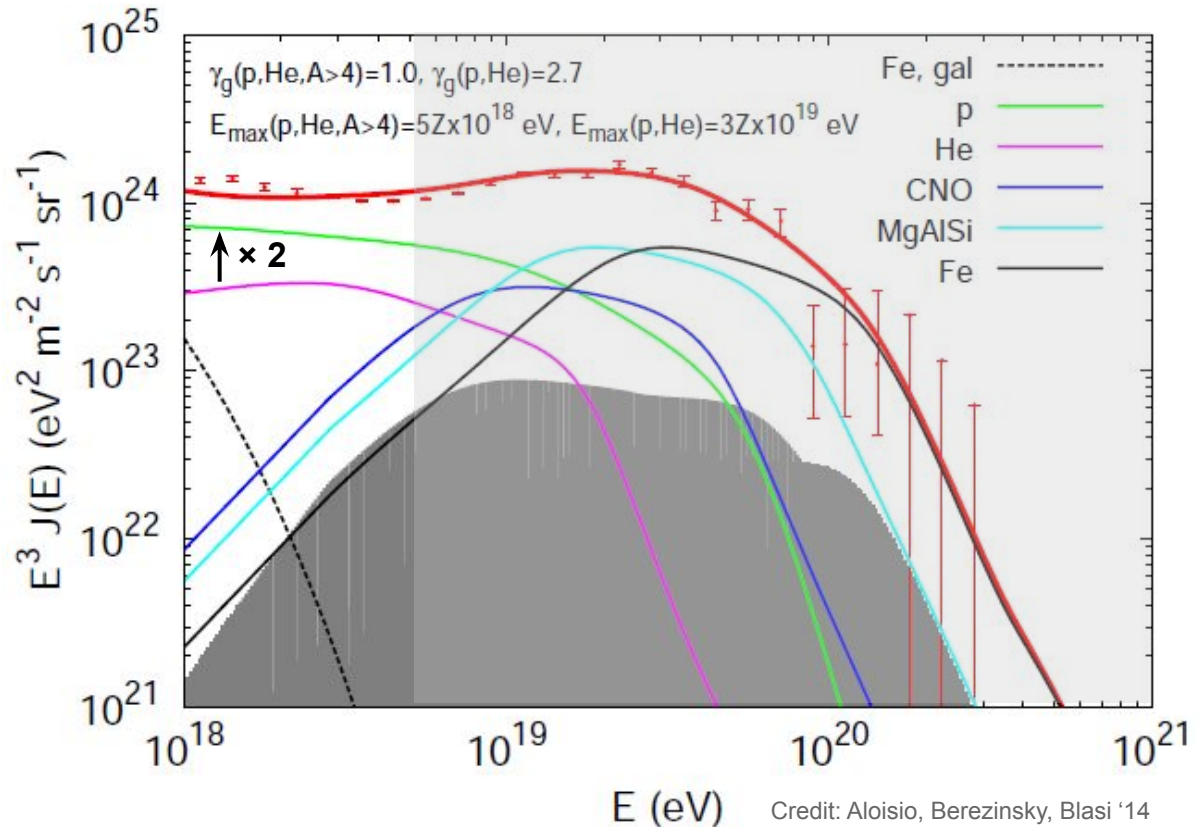
H, He, ..., Fe with a slope $\gamma \sim 1.0$
(hard injection!) up to $R_c \sim 5$ EV

+

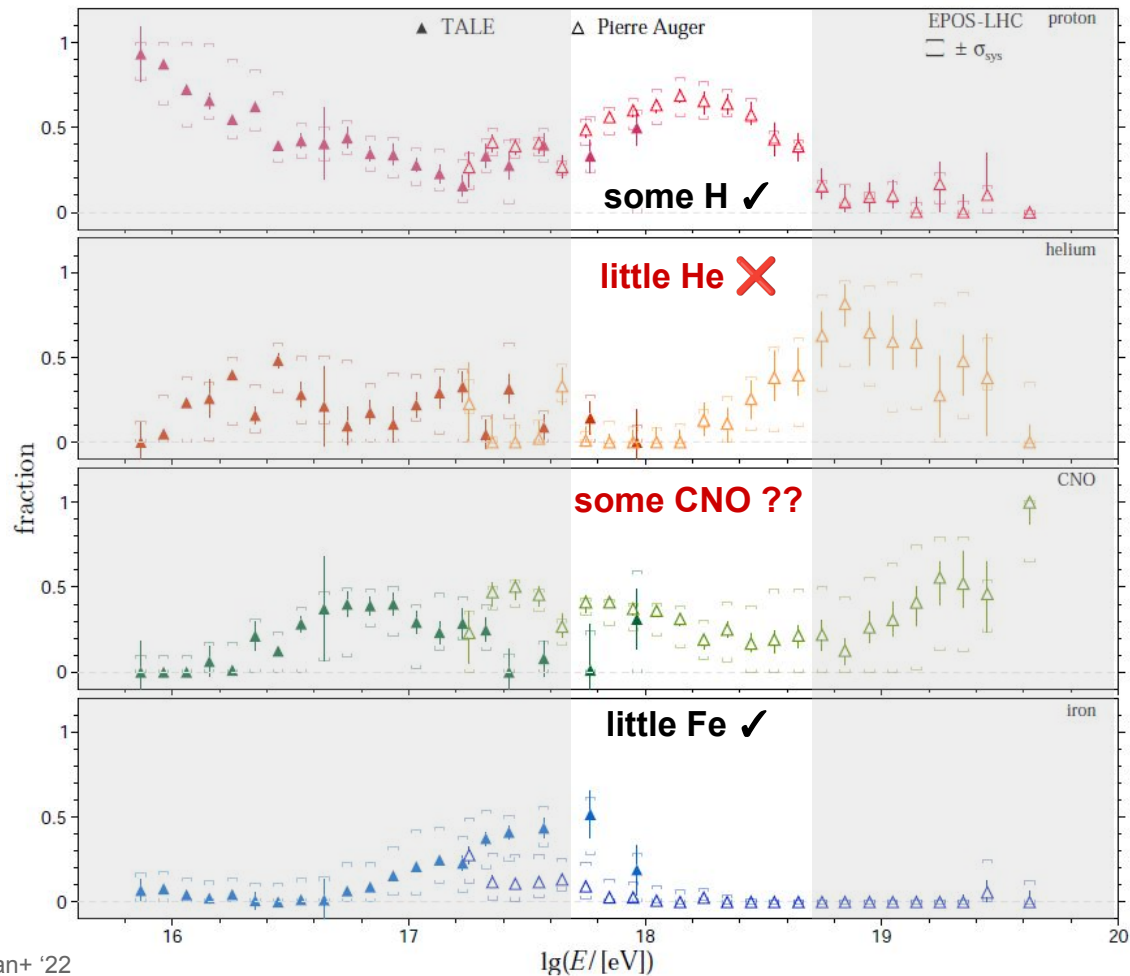
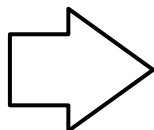
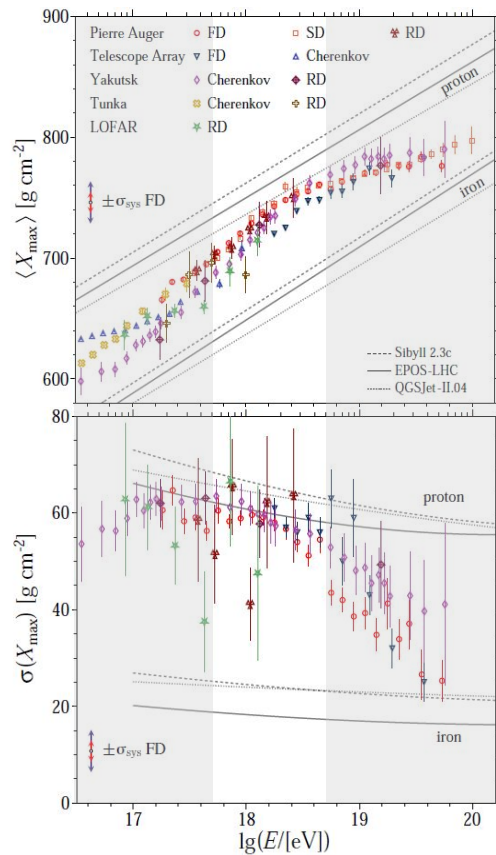
H, He (heavier) with a slope $\gamma \sim 2.7$
(soft injection) up to $R_B \sim 3$ EV

20 years after Hillas,
10 years after Aloisio+ '14

Where do we stand?



Today's picture



Credit: Coleman+ '22

Jonathan Biteau, on behalf of the Pierre Auger Collaboration

Today's picture with the Pierre Auger Observatory



Hypothesis: two extragalactic populations

H, He, ..., Fe

with a slope $\gamma < 1.0$ (very hard!)

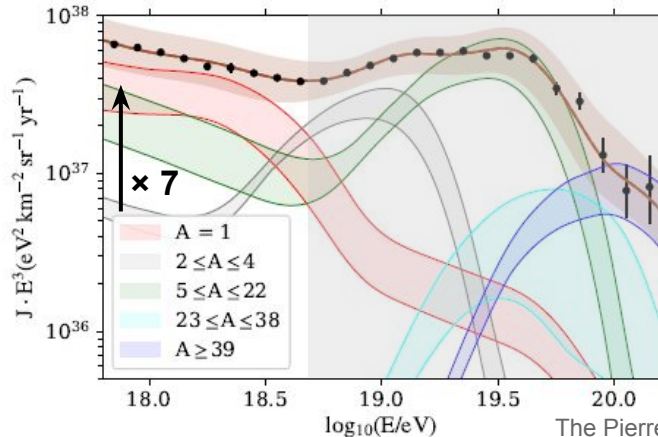
up to $R_c \sim 1\text{-}2\text{ EV}$

+

H, He, CNO (heavier) with a slope $\gamma > 3$,
underconstrained maximum rigidity

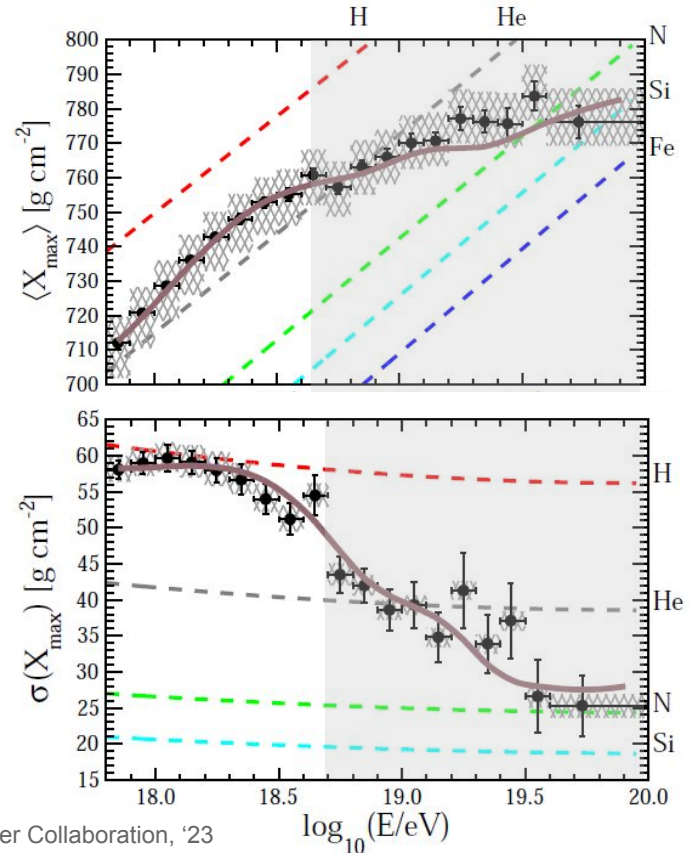
Reduced
 $\chi^2 \sim D/(N-n_{par}) \sim 1.7$

- Hard component consistent with P. Auger obs. '17
- few cosmogenic neutrinos and γ -rays



The Pierre Auger Collaboration, '23

Jonathan Biteau, on behalf of the Pierre Auger Collaboration



Today's picture with the Pierre Auger Observatory



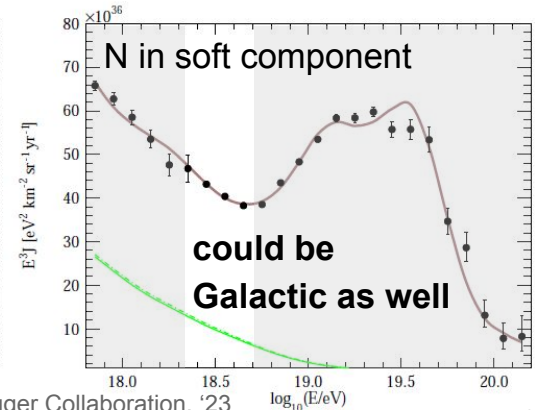
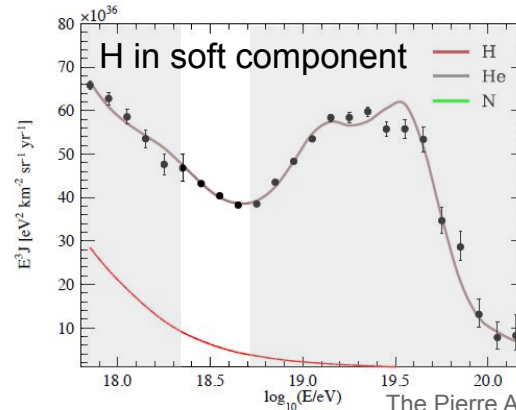
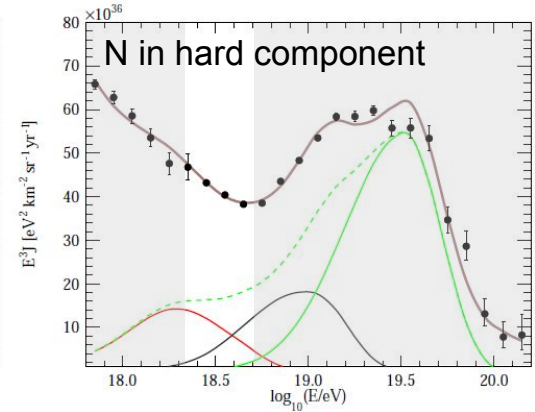
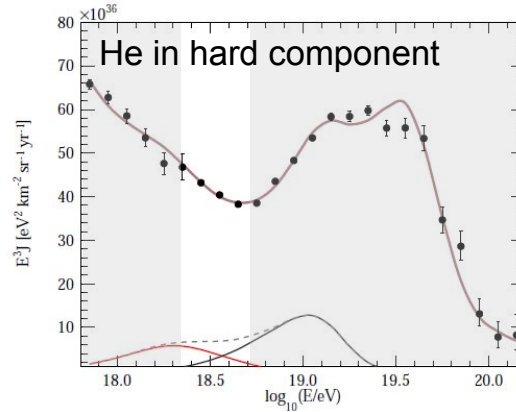
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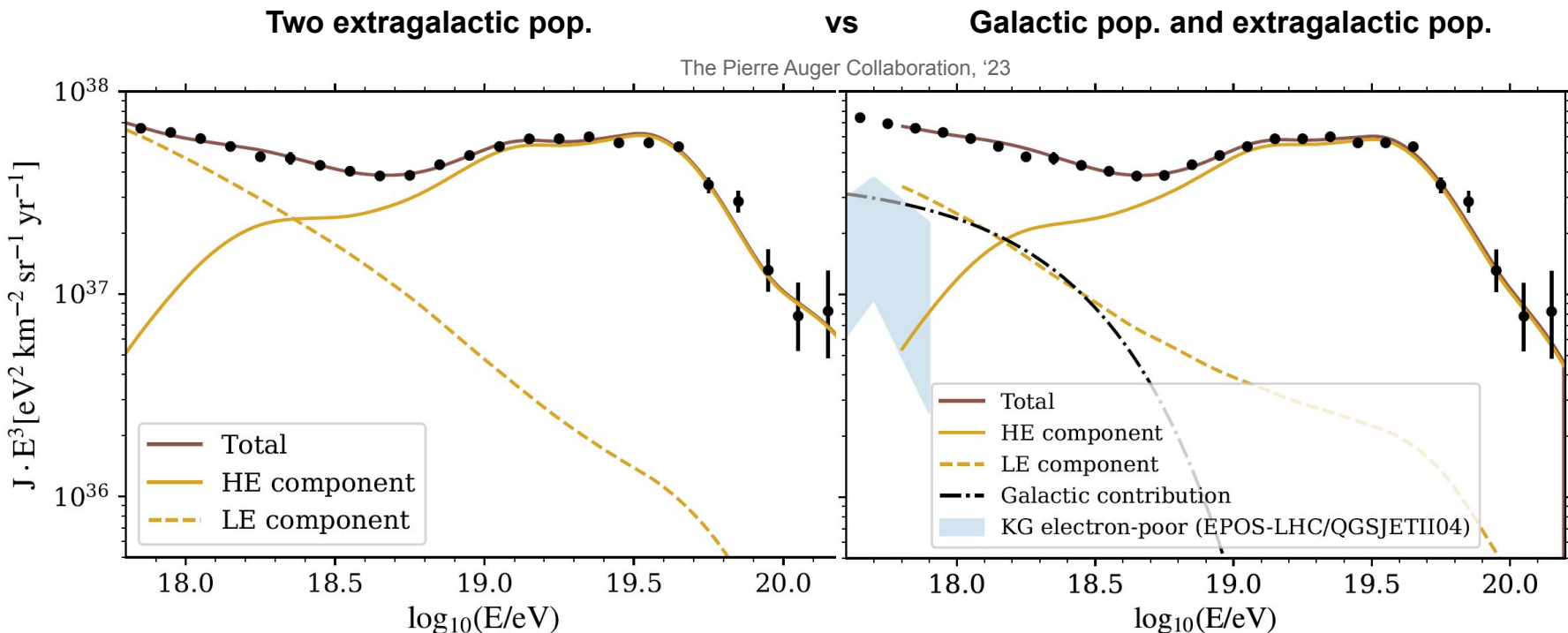
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H, He, ..., Fe
with a slope $\gamma < 1.0$ (very hard!)
up to $R_c \sim 1\text{-}2\text{ EV}$

- *Hard component consistent with P. Auger obs. '17*
- *few cosmogenic neutrinos and γ -rays*



Today's picture with the Pierre Auger Observatory



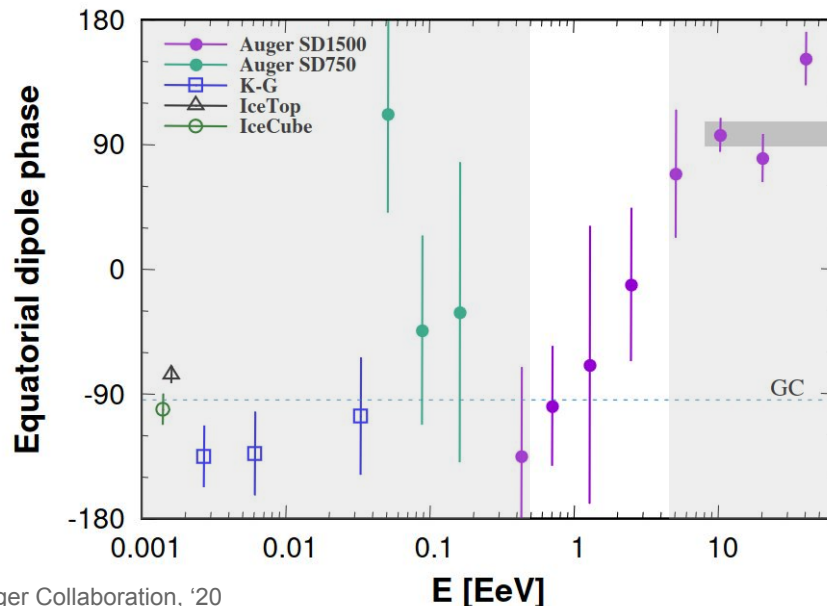
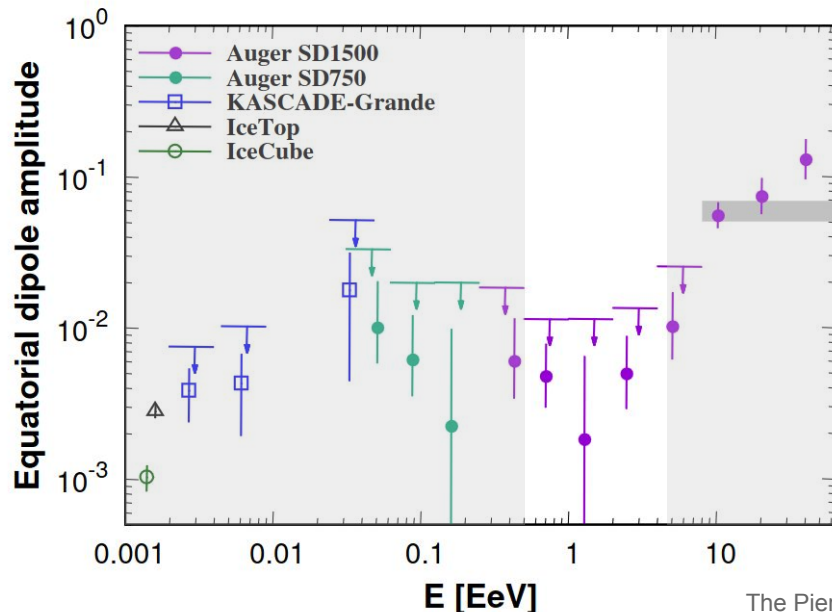
**Little difference on fit quality
as long as Galactic contribution made of CNO**

Conclusion: H + He hypothesis is natural but... wrong!



Joint fit of multi-population model to composition and spectral data $> 10^{17.8}$ eV

- Soft CNO component (**disputed origin**) + soft-proton and hard-nuclear components (**extragalactic origin**)
- Hard nuclear component above the ankle (>5 EeV) little affected by hypotheses tested for soft component
- Cannot discard a Galactic origin of soft CNO component → **key: constraints on anisotropies!**



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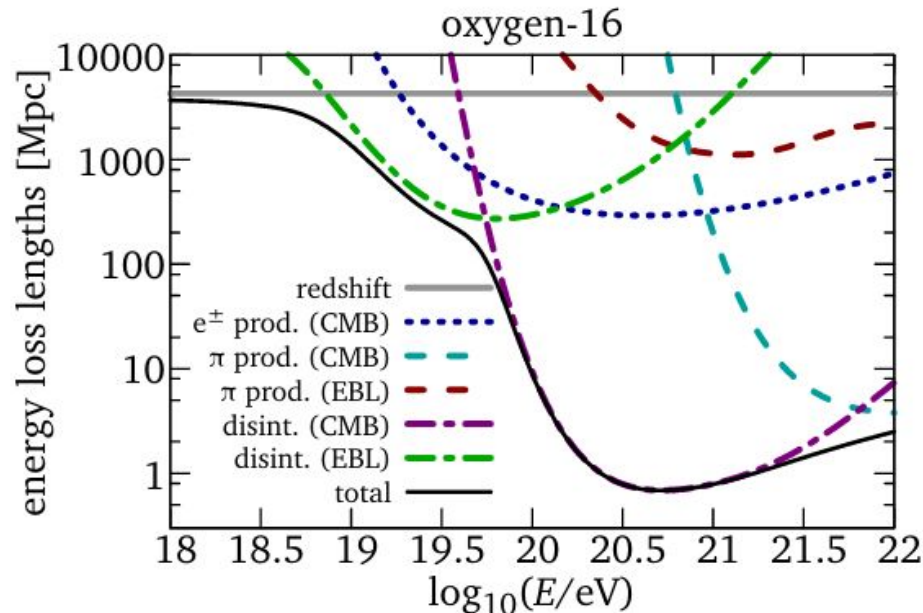
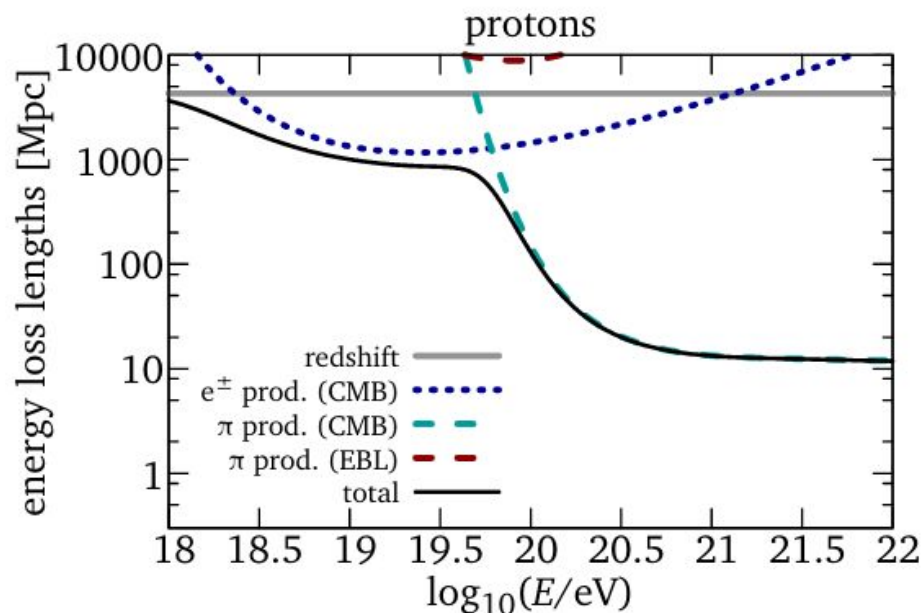
Jonathan Biteau, on behalf of the Pierre Auger Collaboration

Backup

Jonathan Biteau

Energy losses

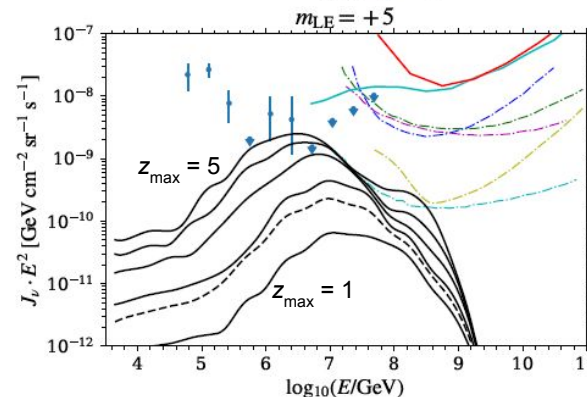
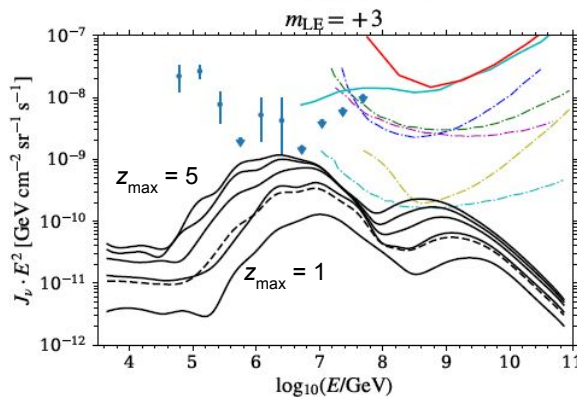
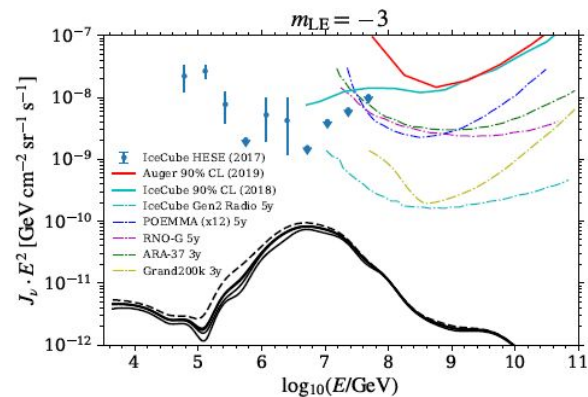
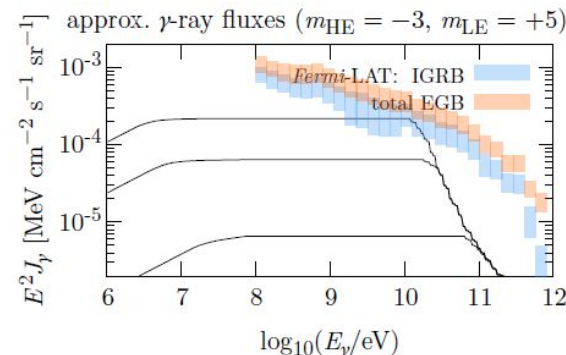
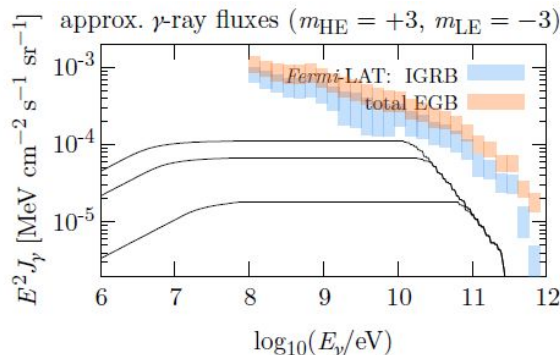
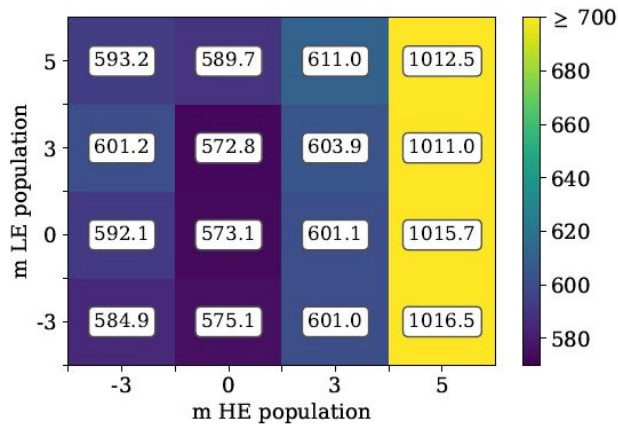
Energy loss length $\chi^{-1} = \frac{1}{E} \frac{dE}{dX}$



Cosmogenic neutrinos and gamma-rays

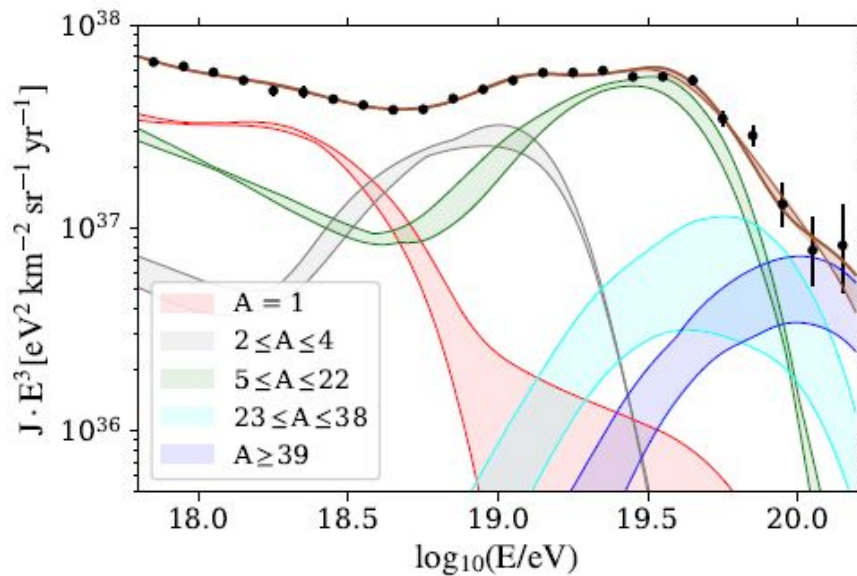
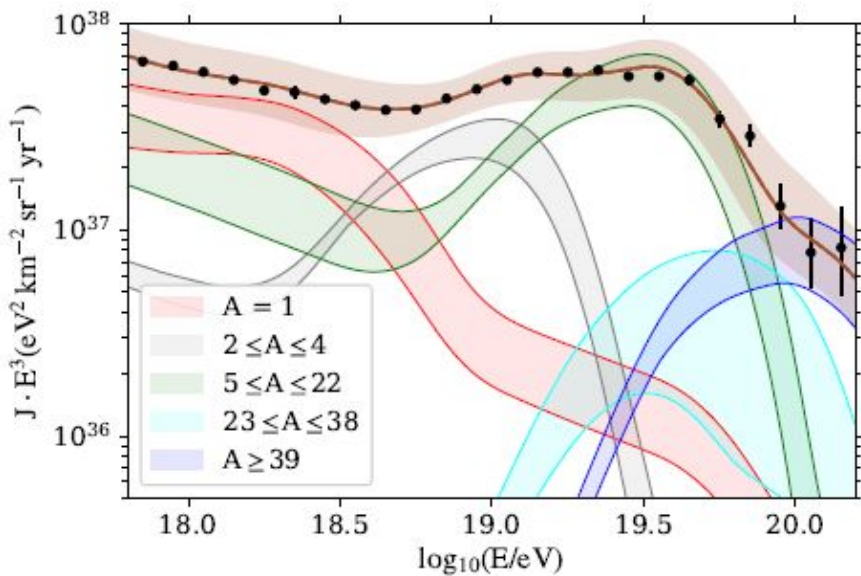


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Instrumental vs modeling uncertainties



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Today's picture with the Pierre Auger Observatory



Two extragalactic pop.

vs

Galactic pop. and extragalactic pop.

EG components (at the escape)	Galactic contribution (at Earth)		pure N	
	$J_0^{\text{Gal}} / (\text{eV}^{-1} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1})$		$(1.06 \pm 0.04) \times 10^{-13}$	
	$\log_{10}(R_{\text{cut}}^{\text{Gal}}/V)$		17.48 ± 0.02	
	LE	HE	LE	HE
$\mathcal{L}_0 / (10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1})^*$	11.35 ± 0.15	5.07 ± 0.06	6.54 ± 0.36	5.00 ± 0.35
γ	3.52 ± 0.03	-1.99 ± 0.11	3.34 ± 0.07	-1.47 ± 0.13
$\log_{10}(R_{\text{cut}}/V)$	>19.4	18.15 ± 0.01	>19.3	18.19 ± 0.02
$I_{\text{H}} (\%)$	48.7 ± 0.3	0.0 ± 0.0	100 (fixed)	0.0 ± 0.0
$I_{\text{He}} (\%)$	7.3 ± 0.4	23.6 ± 1.6	—	24.5 ± 3.0
$I_{\text{N}} (\%)$	44.0 ± 0.4	72.1 ± 3.3	—	68.1 ± 5.0
$I_{\text{Si}} (\%)$	0.0 ± 0.0	1.3 ± 1.3	—	4.9 ± 3.9
$I_{\text{Fe}} (\%)$	0.0 ± 0.0	3.1 ± 1.3	—	2.5 ± 0.2
$D_J (N_J)$	$56.6 (24)$		$48.6 (24)$	
$D_{X_{\text{max}}} (N_{X_{\text{max}}})$	$516.5 (329)$		$537.4 (329)$	
$D (N)$	$573.1 (353)$		$586.0 (353)$	

* from $E_{\text{min}} = 10^{17.8} \text{ eV}$.

Message from spectrum and composition data

No strong evidence for preference for EGAL+EGAL vs Gal.+EGAL

Note:

Reduced $\chi^2 \sim D/(N-n_{\text{par}}) \sim 1.7$

Almost half of soft component made of **CNO w/ little He!**

Note: hard component w/o H

*→ soft H goes w/ hard nuclei?
see Luce+ ApJ 936, 62 (2022)*

Modeling uncertainties



Gilmore EBL	LE	HE	Domínguez EBL	LE	HE
$\mathcal{L}_0/(10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1})^*$	11.35 ± 0.15	5.07 ± 0.06	$\mathcal{L}_0/(10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1})^*$	9.2	7.3
γ	3.52 ± 0.03	-1.99 ± 0.11	γ	3.67 ± 0.06	-0.87 ± 0.08
$\log_{10}(R_{\text{cut}}/V)$	>19.4	18.15 ± 0.01	$\log_{10}(R_{\text{cut}}/V)$	18.01 ± 0.06	18.23 ± 0.01
$I_{\text{H}} (\%)$	48.7 ± 0.3	0.0 ± 0.0	$I_{\text{H}} (\%)$	41.4	0.0
$I_{\text{He}} (\%)$	7.3 ± 0.4	23.6 ± 1.6	$I_{\text{He}} (\%)$	7.4	17.2
$I_{\text{N}} (\%)$	44.0 ± 0.4	72.1 ± 3.3	$I_{\text{N}} (\%)$	51.6	78.0
$I_{\text{Si}} (\%)$	0.0 ± 0.0	1.3 ± 1.3	$I_{\text{Si}} (\%)$	0.0	2.1
$I_{\text{Fe}} (\%)$	0.0 ± 0.0	3.1 ± 1.3	$I_{\text{Fe}} (\%)$	0.0	2.7
			δ_{HIM}	0.88 ± 0.11	
$D_J (N_J)$	56.6 (24)		$D_J (N_J)$	42.5 (24)	
$D_{X_{\text{max}}} (N_{X_{\text{max}}})$	516.5 (329)		$D_{X_{\text{max}}} (N_{X_{\text{max}}})$	561.6 (329)	
$D (N)$	573.1 (353)		$D (N)$	604.2 (353)	

* from $E_{\text{min}} = 10^{17.8} \text{ eV}$.

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Soft proton component

