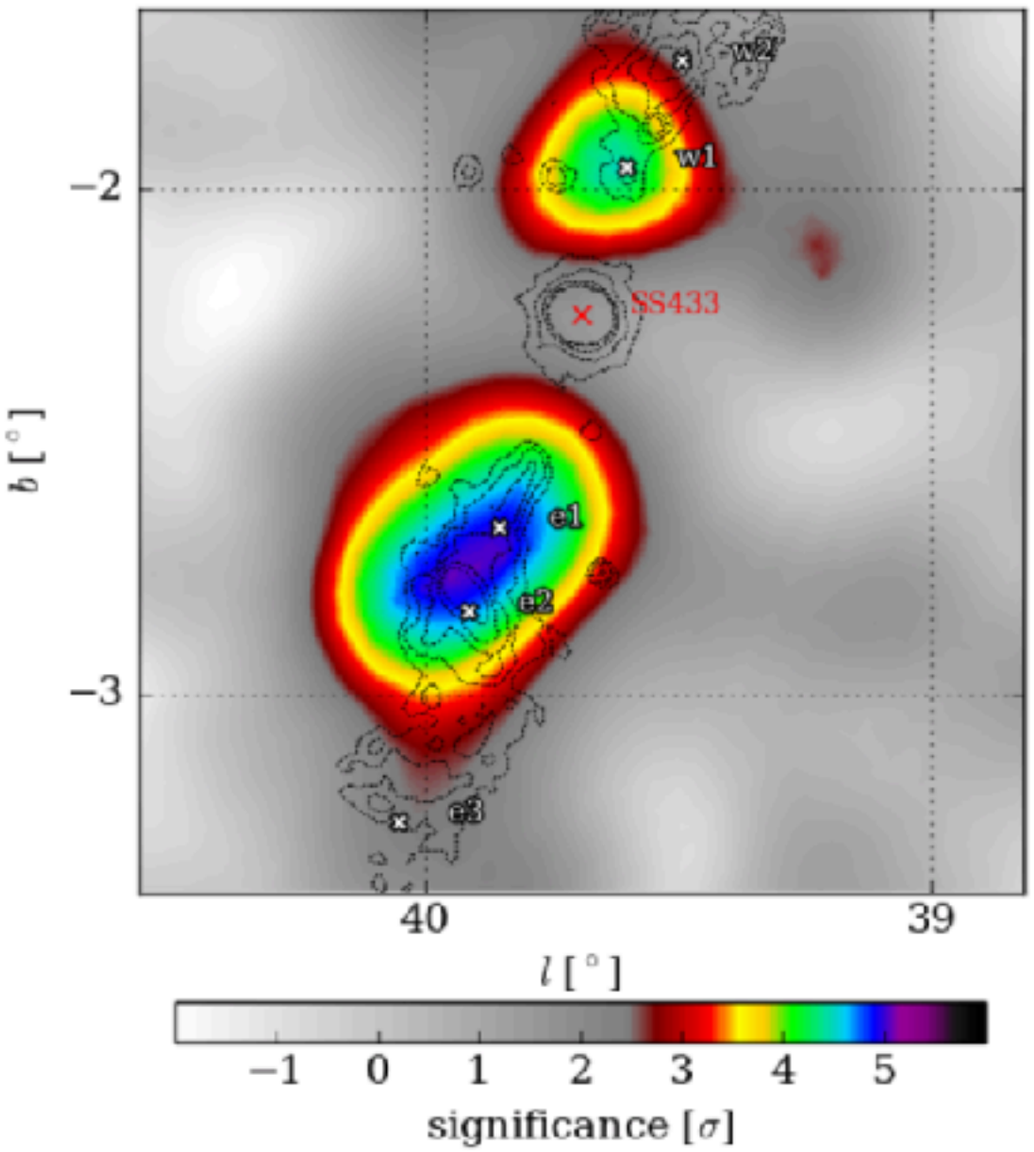
Cosmic Ray Anisotropy and the Galactic-Extragalactic Transition Regime

Ke Fang
Einstein Fellow, Stanford University

GRAND Collaboration Meeting, Dunhuang, China
Apr 25, 2019

Very-high-energy Gamma-ray Sources could be nearby



HAWC Collaboration, Nature (2018)
Main authors: BenZvi, Brenda, KF, Rho, Zhang, Zhou

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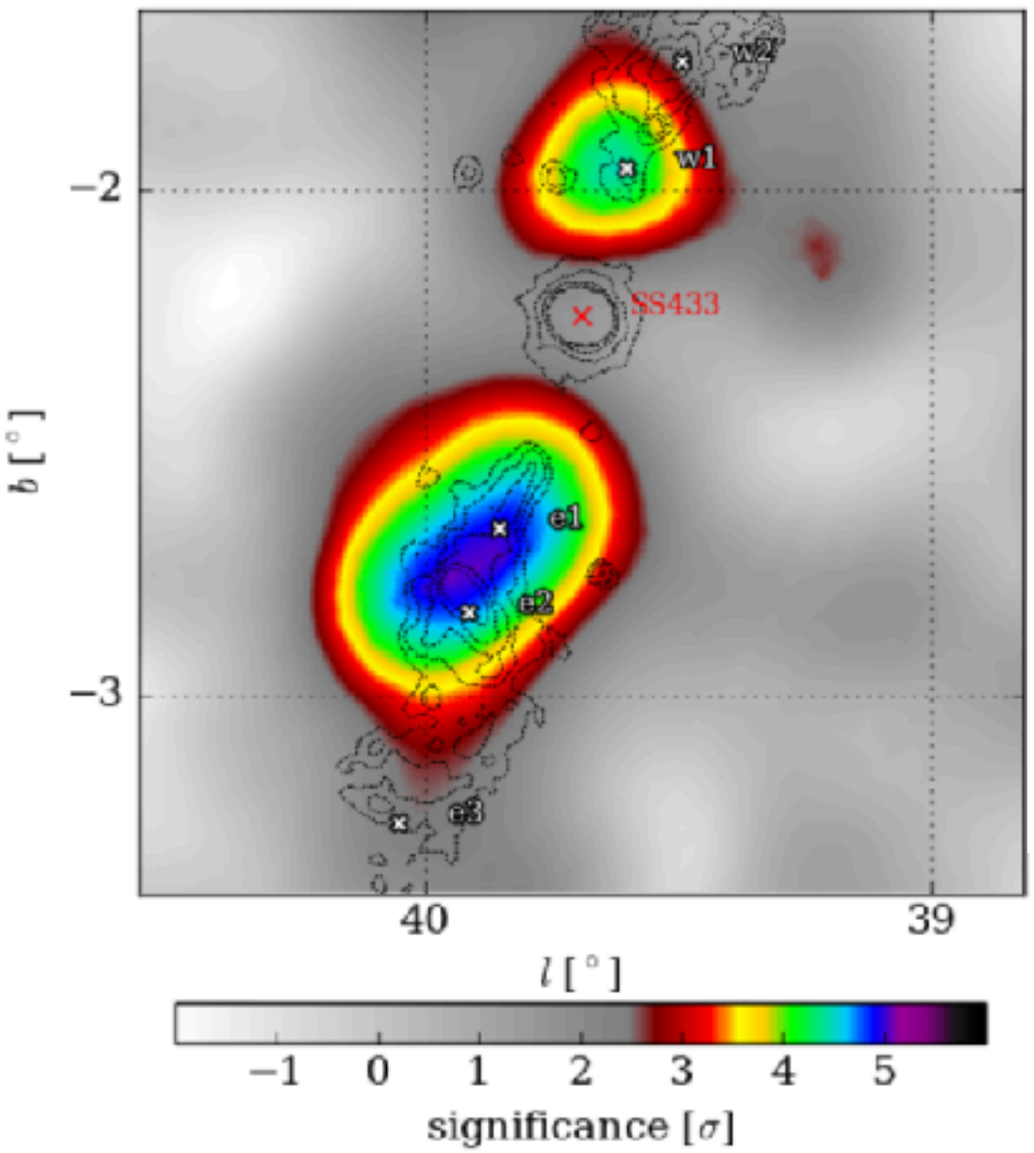

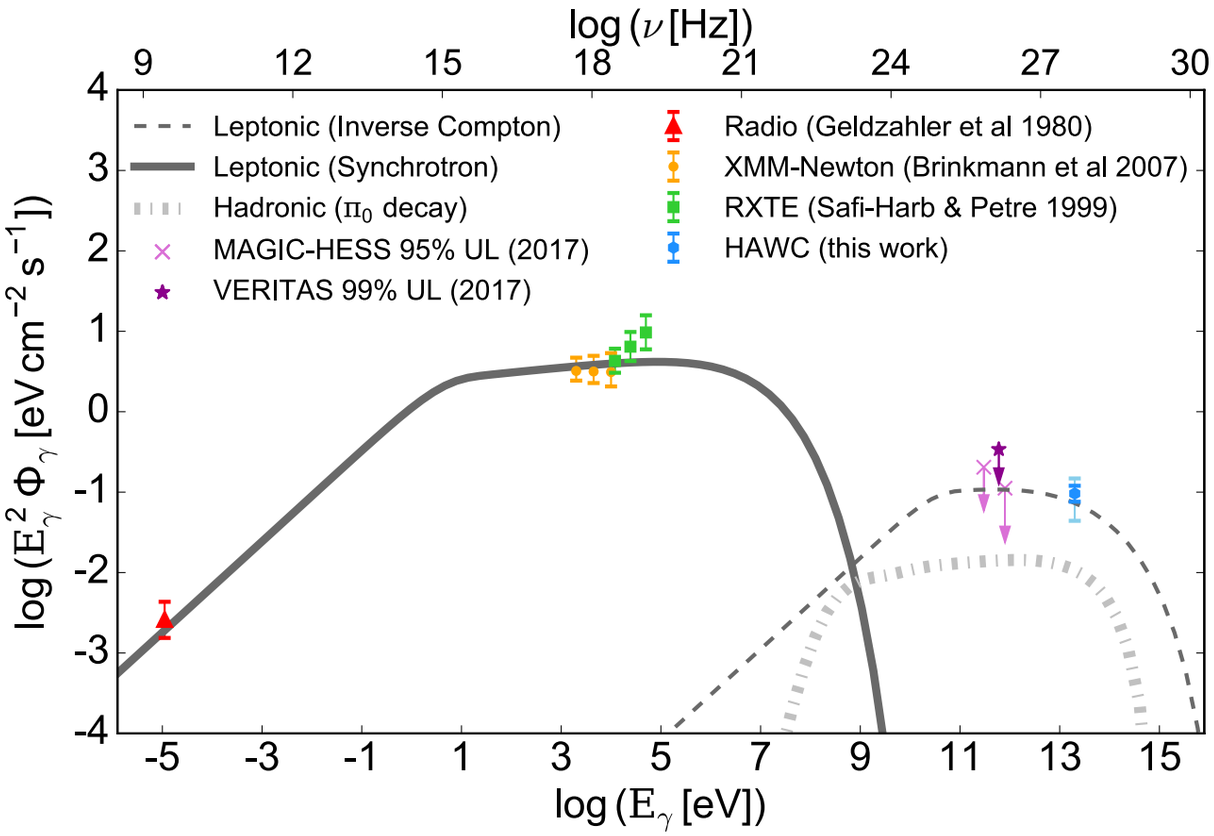

Very-high-energy gamma rays are observed from the lobes of SS 433. Such objects could be promising gamma-ray sources for GRAND

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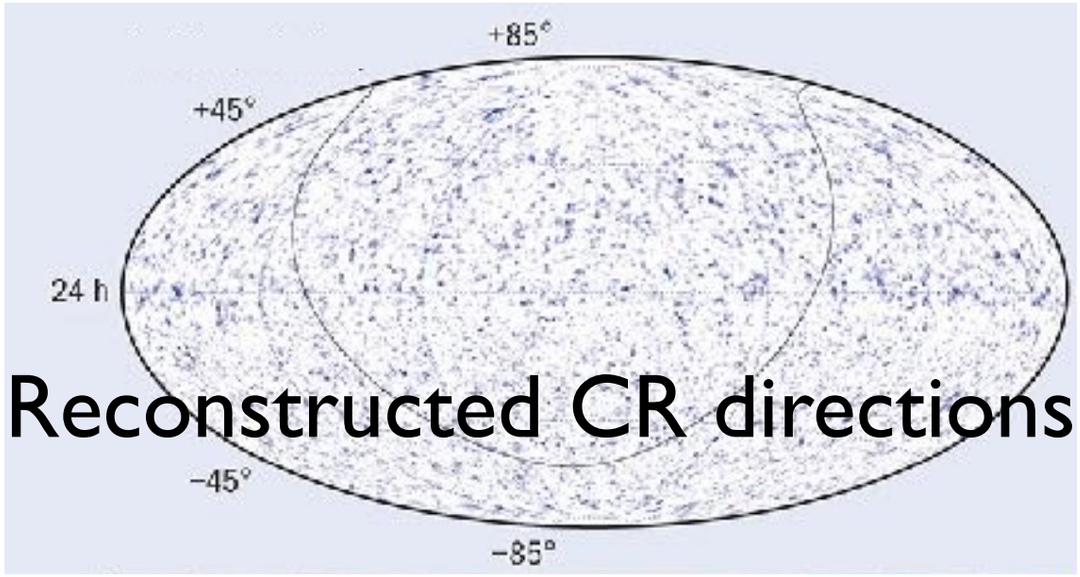
Cosmic Ray Anisotropy



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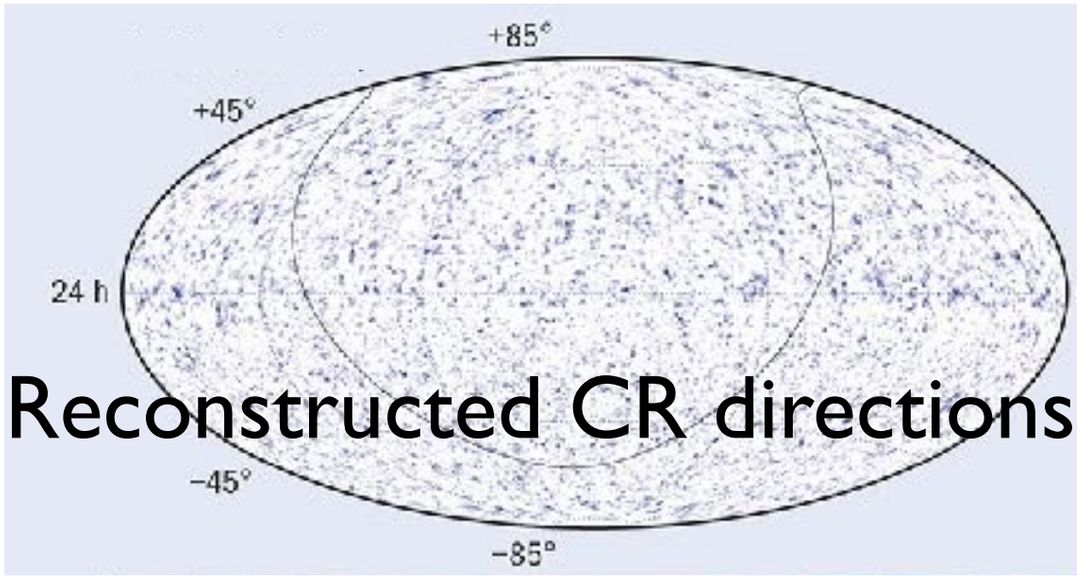
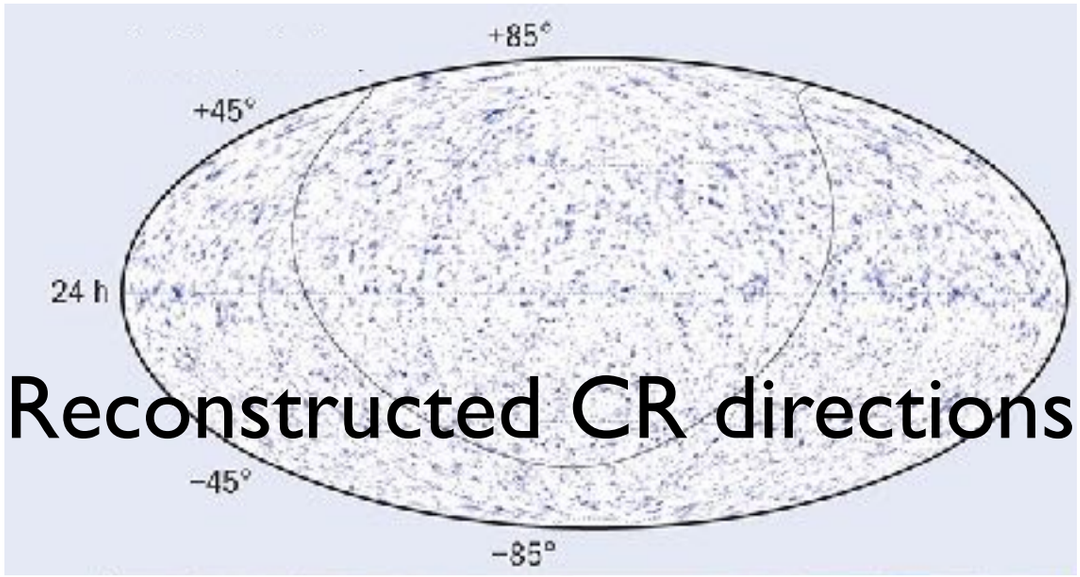


Reconstructed CR directions

Remove the isotropic term to obtain relative intensity distribution

Cosmic Ray Anisotropy



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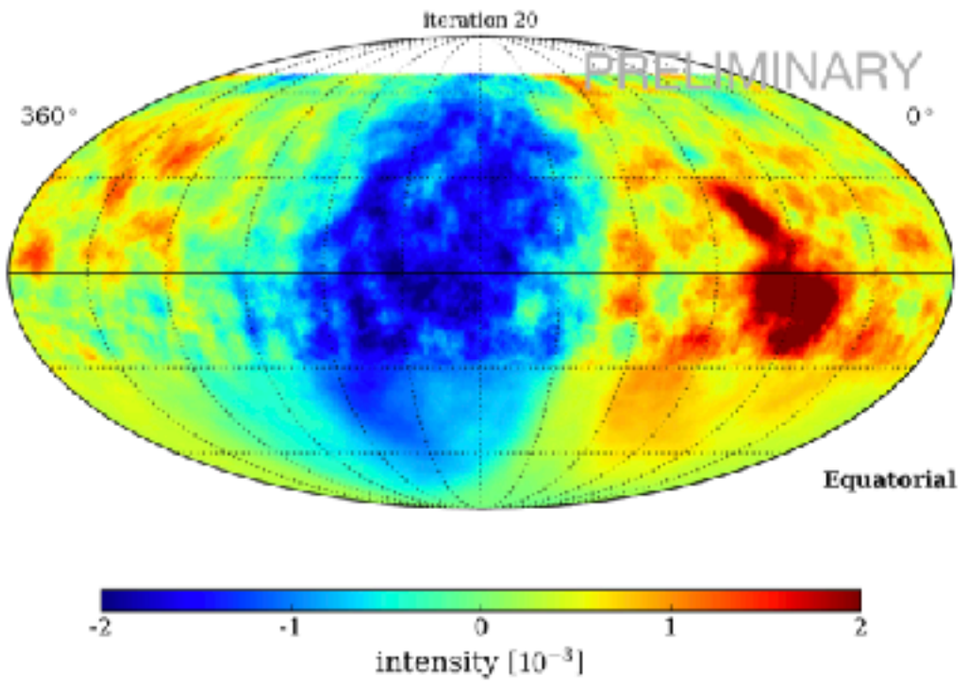
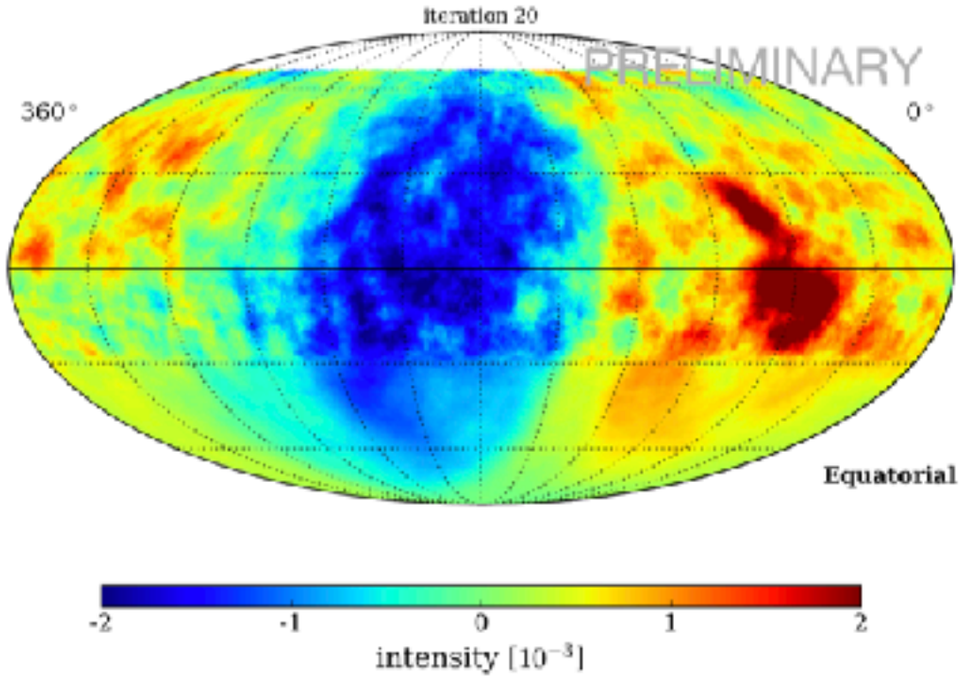
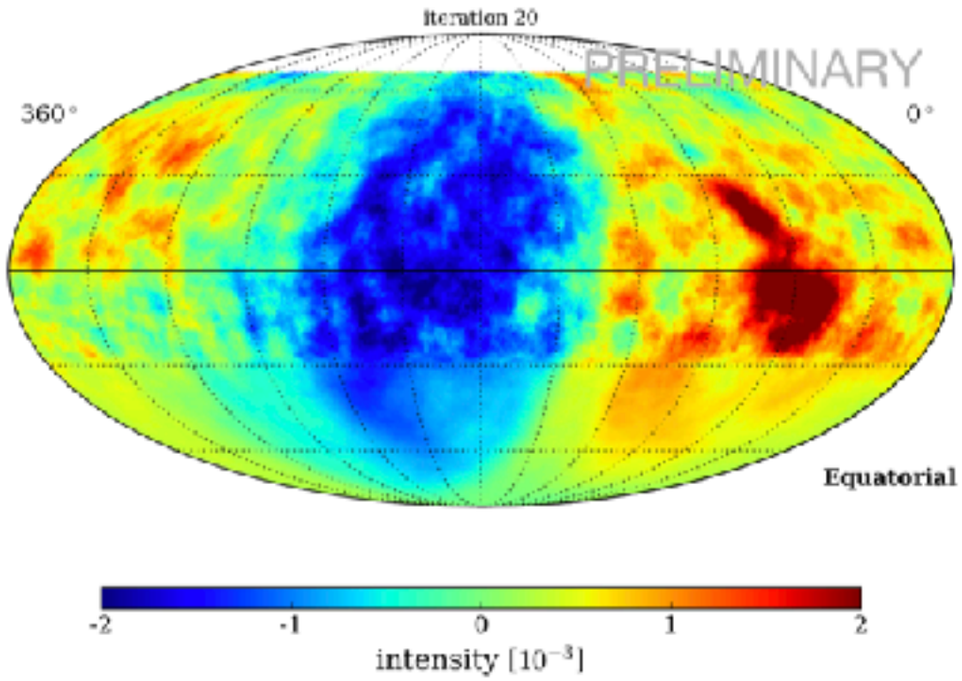


Large and Small-Scale Anisotropies



- Flux

Large and Small-Scale Anisotropies



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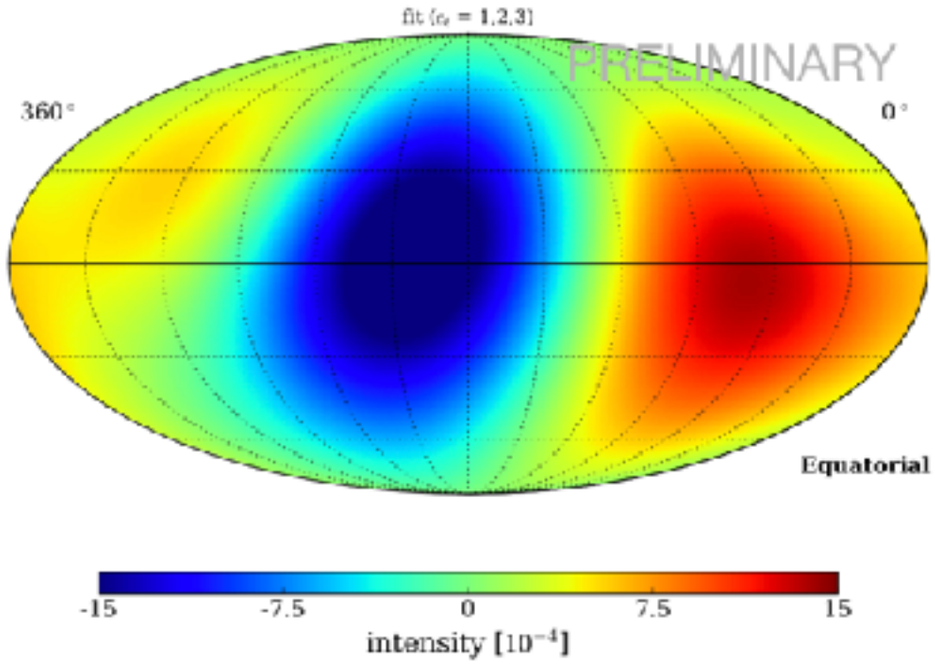

l=1, 2, 3 model

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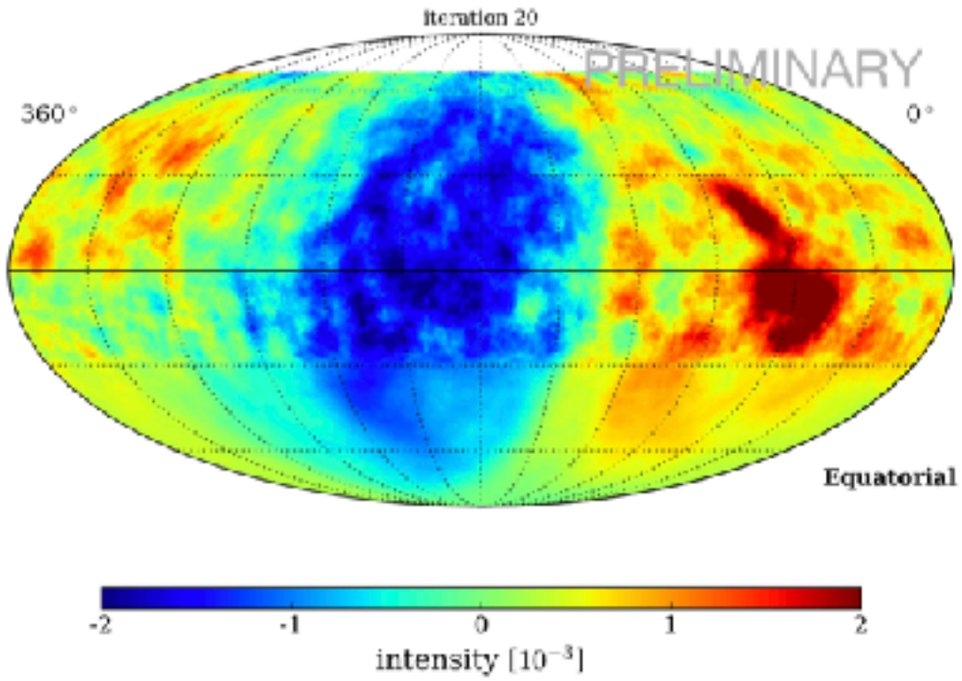

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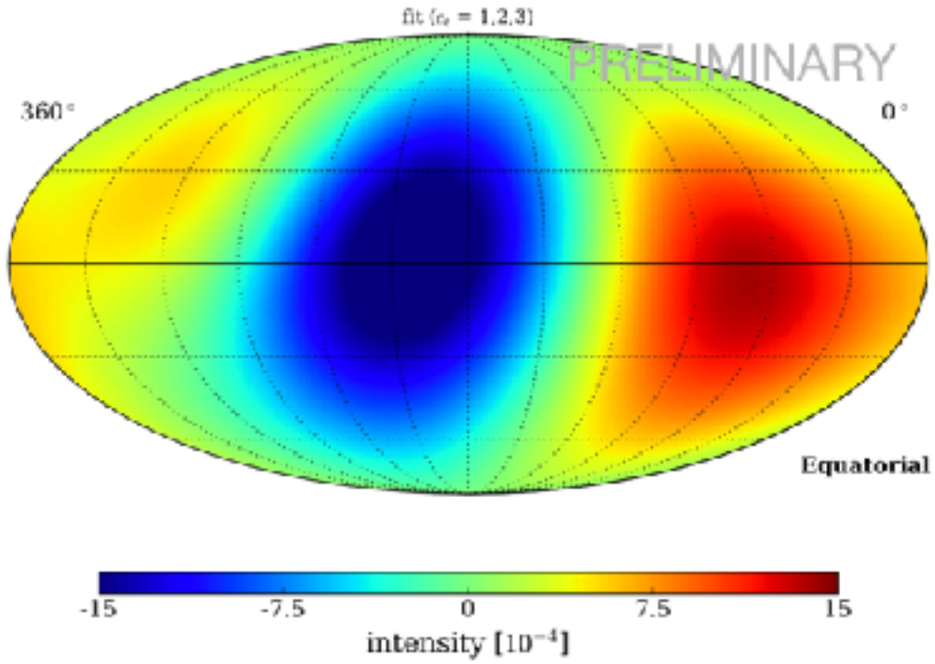

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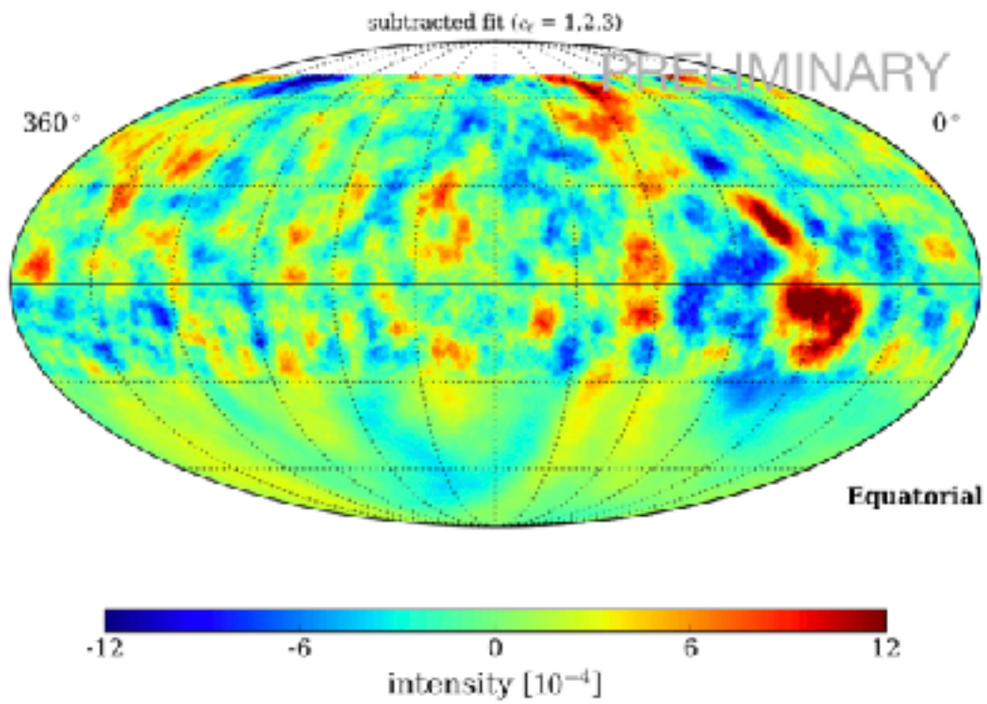

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Assume that flux in given direction can be written as an isotropic flux times a relative factor

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HAWC & IceCube, ICRC 1708.03005

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Maximize this likelihood with respect to the null hypothesis (I = 1) gives the best-fit relative intensity and isotropic flux

$$\lambda = \frac{\mathscr{L}(n|I,\mathscr{N},\mathscr{A})}{\mathscr{L}(n|I^{(0)},\mathscr{N}^{(0)},\mathscr{A}^{(0)})}$$

HAWC & IceCube, ICRC 1708.03005

Cosmic Ray Anisotropy at Tens of TeVs - large scale

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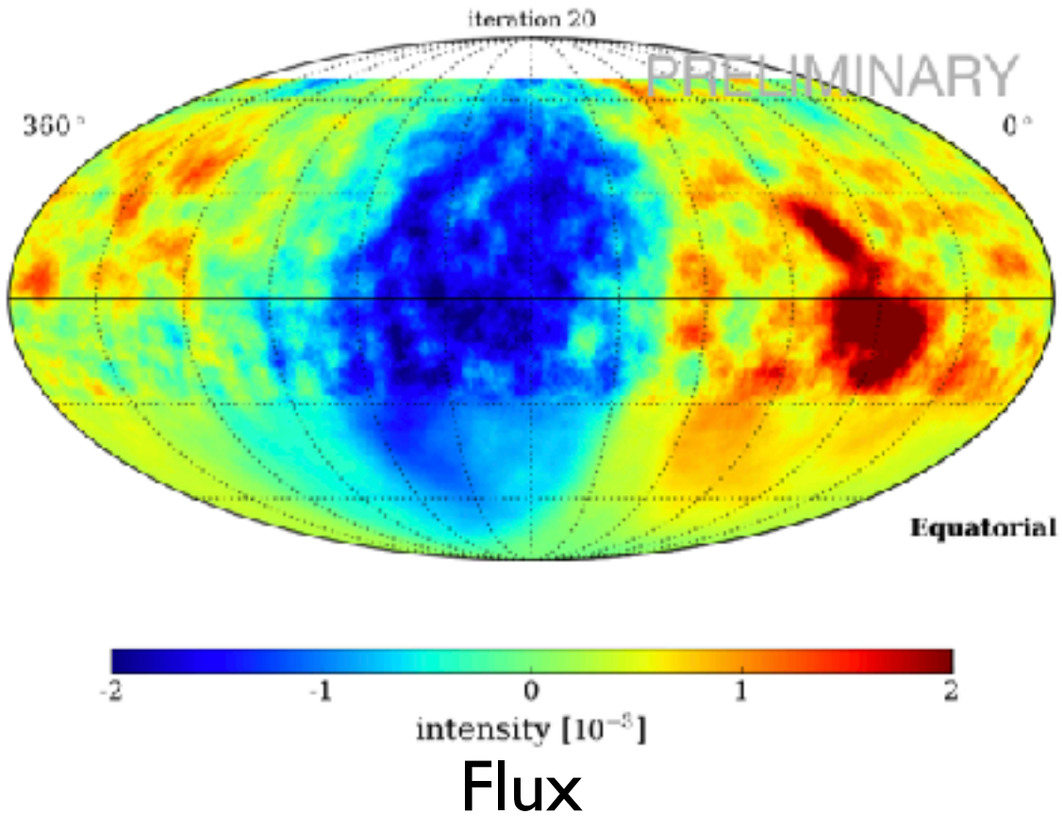

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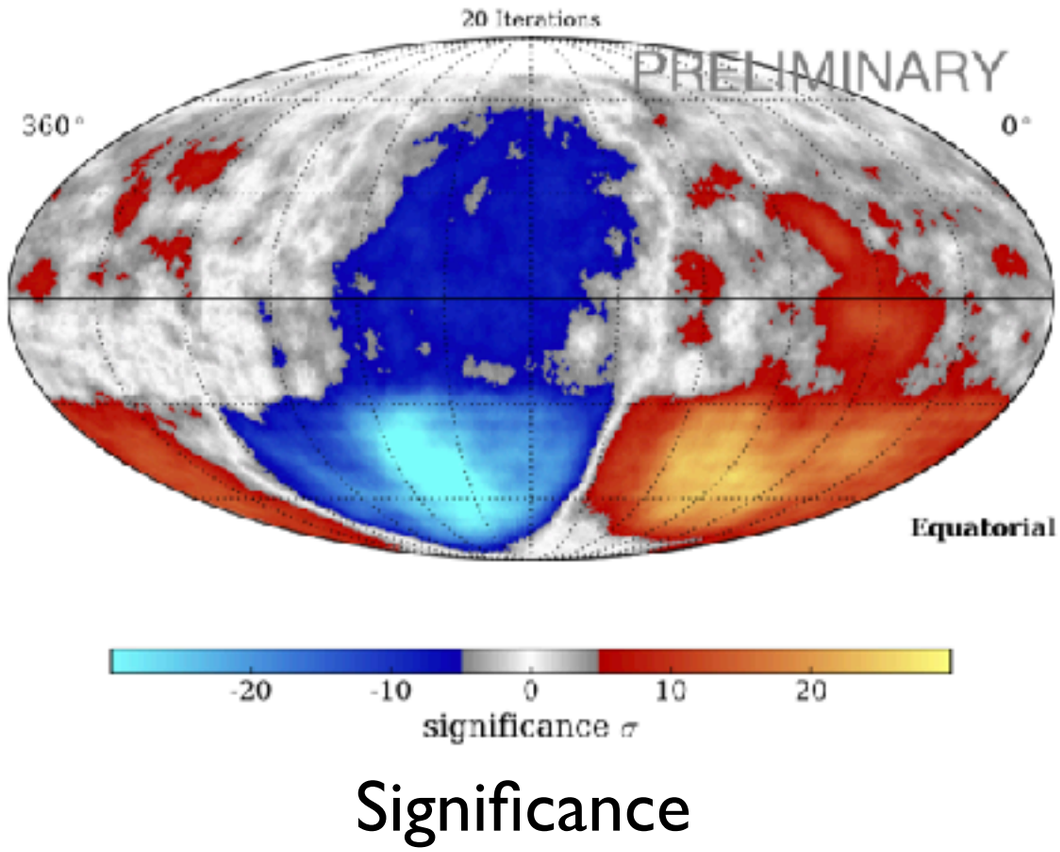

Significance

Large-scale anisotropy is at the level of 10^-3 at ~10 TeV

HAWC & IceCube, ICRC 1708.03005

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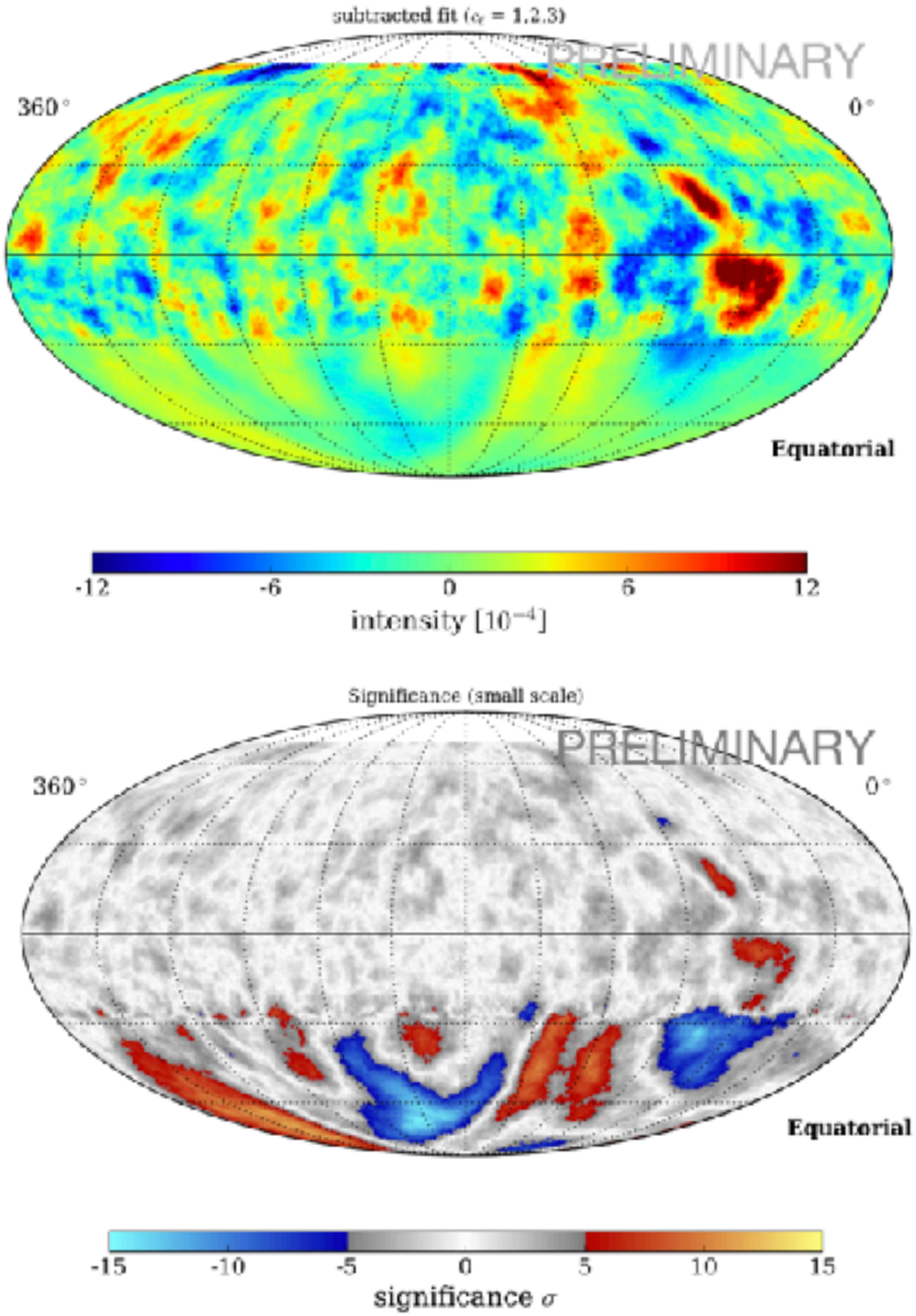

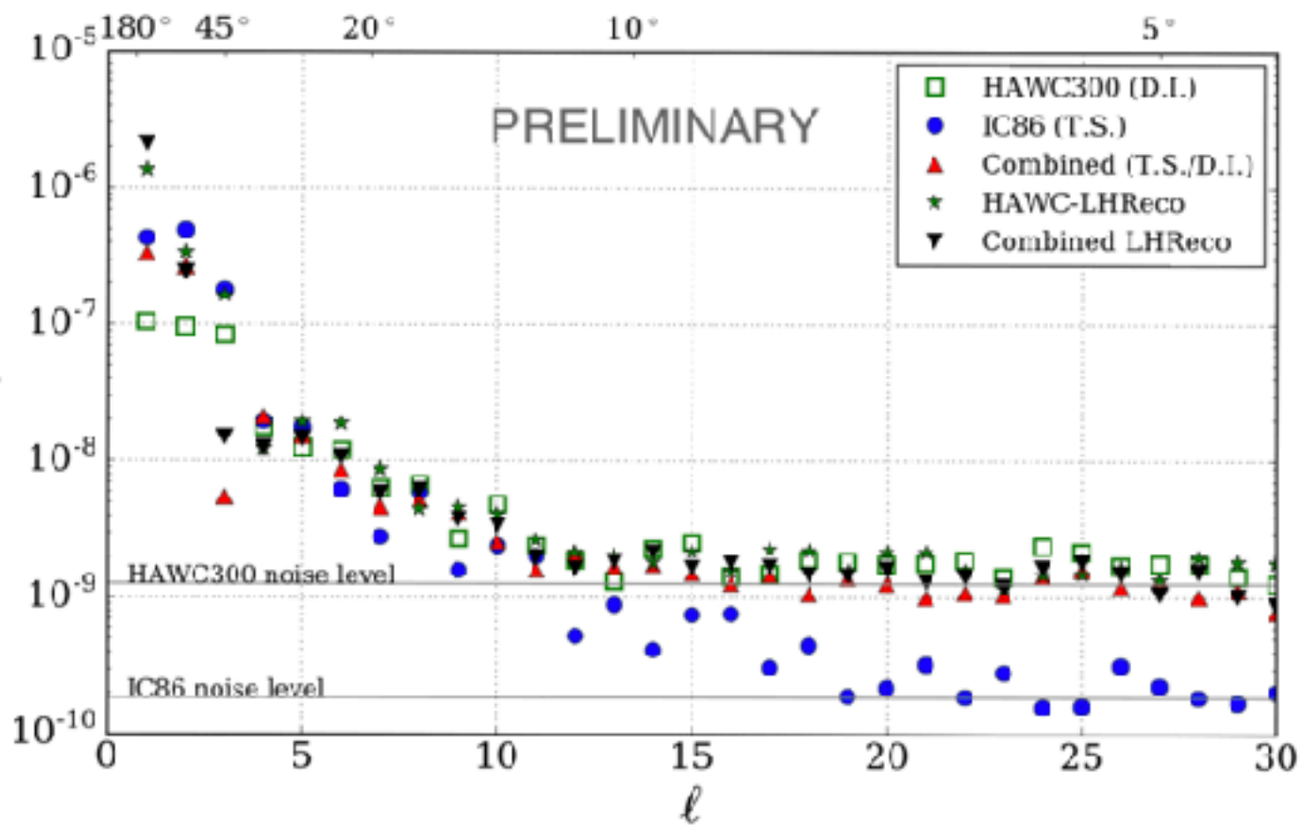

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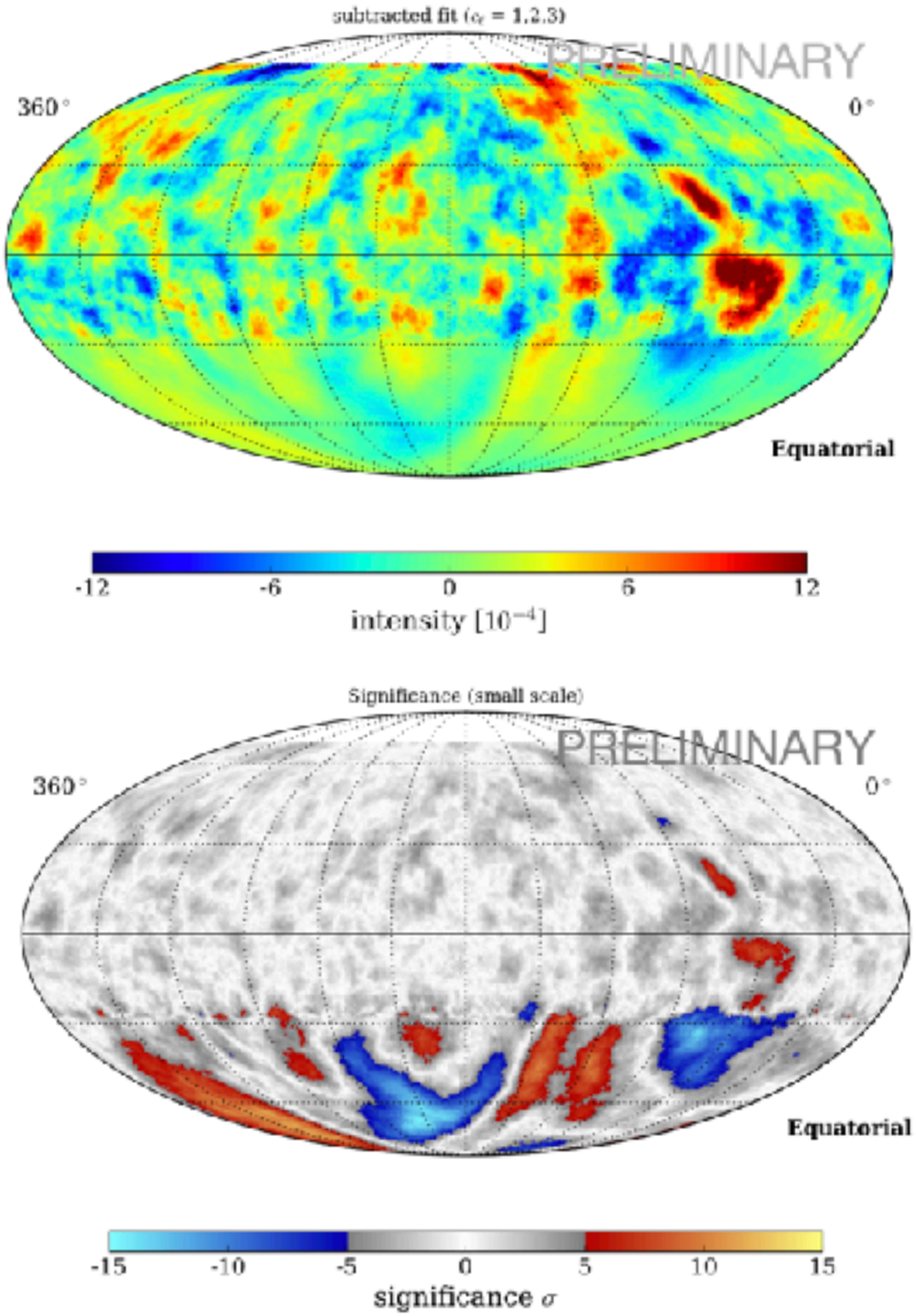

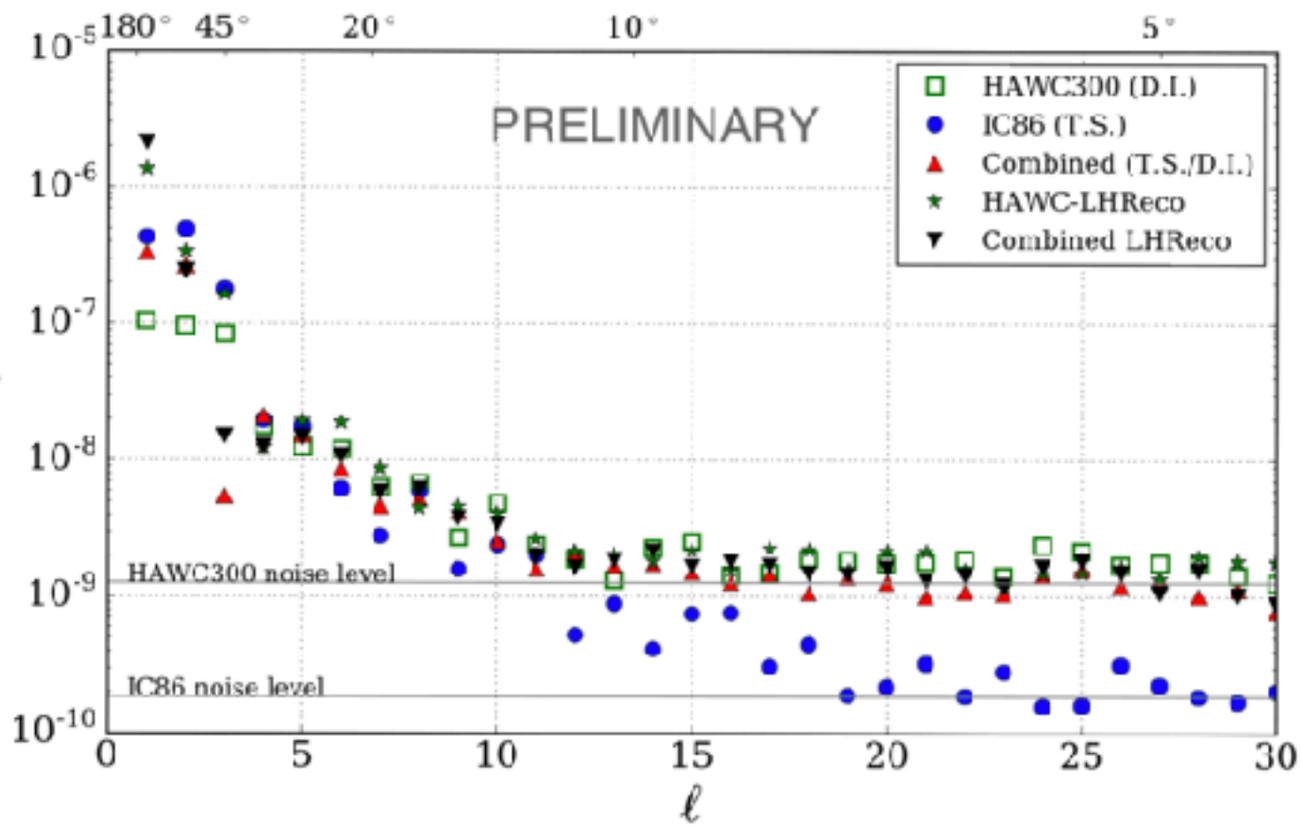

Combined analysis of the HAWC-1yr and IceCube-5yr data finds significant level of anisotropy up to l~10

HAWC & IceCube, ICRC 1708.03005

Cosmic Ray Anisotropy at > EeV

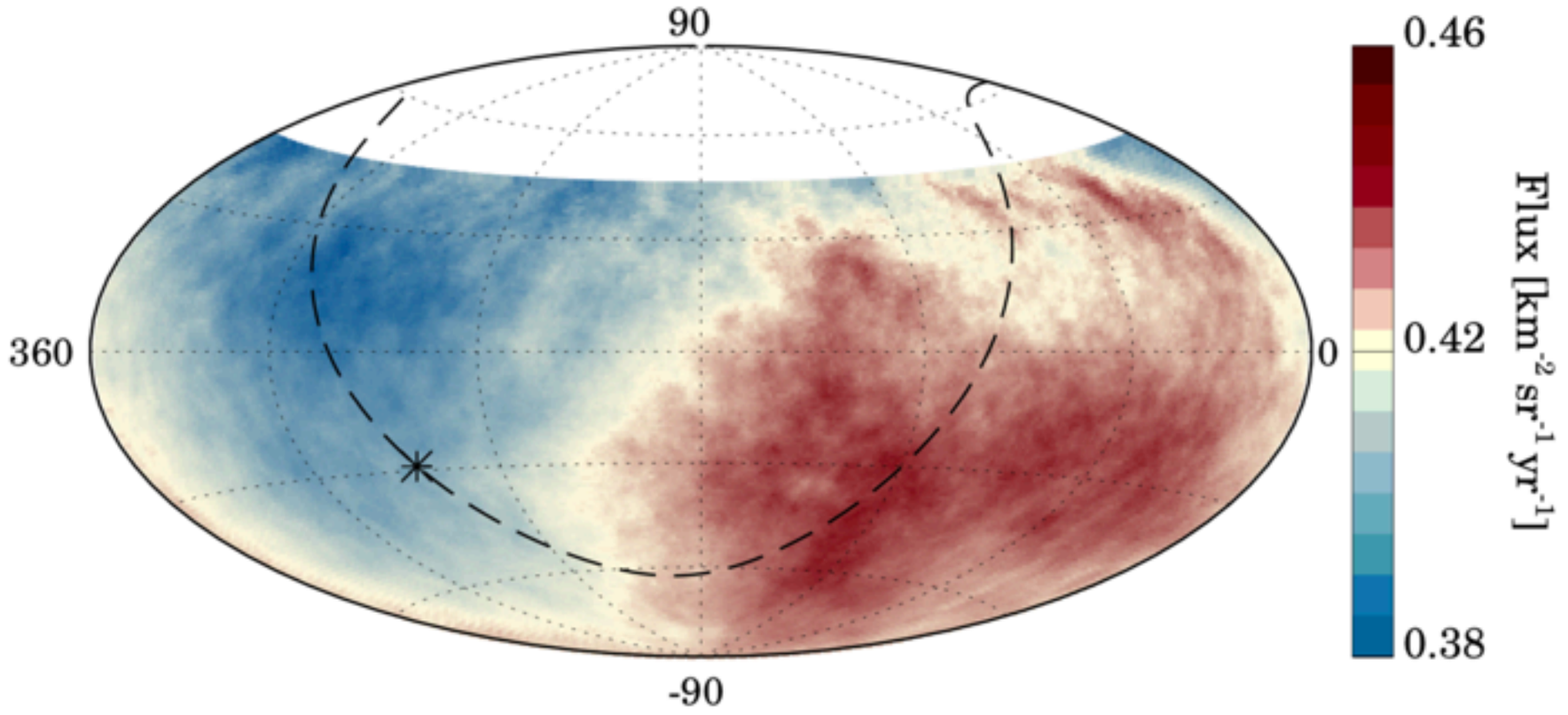

Table 3. Results of the first-harmonic analysis in right ascension in the three bins above 8 EeV.

Energy [EeV]	events	a_1^α	b_1^α	r_1^α	φ_1^α [°]	$P(\geq r_1^\alpha)$
8 - 16	24,070	-0.011 ± 0.009	0.044 ± 0.009	0.046	104 ± 11	3.7×10^{-6}
16 - 32	6,604	0.007 ± 0.017	0.050 ± 0.017	0.051	82 ± 20	0.014
≥ 32	1,513	-0.03 ± 0.04	0.05 ± 0.04	0.06	115 ± 35	0.26

Auger Collaboration, Science (2017), ApJ (2018)

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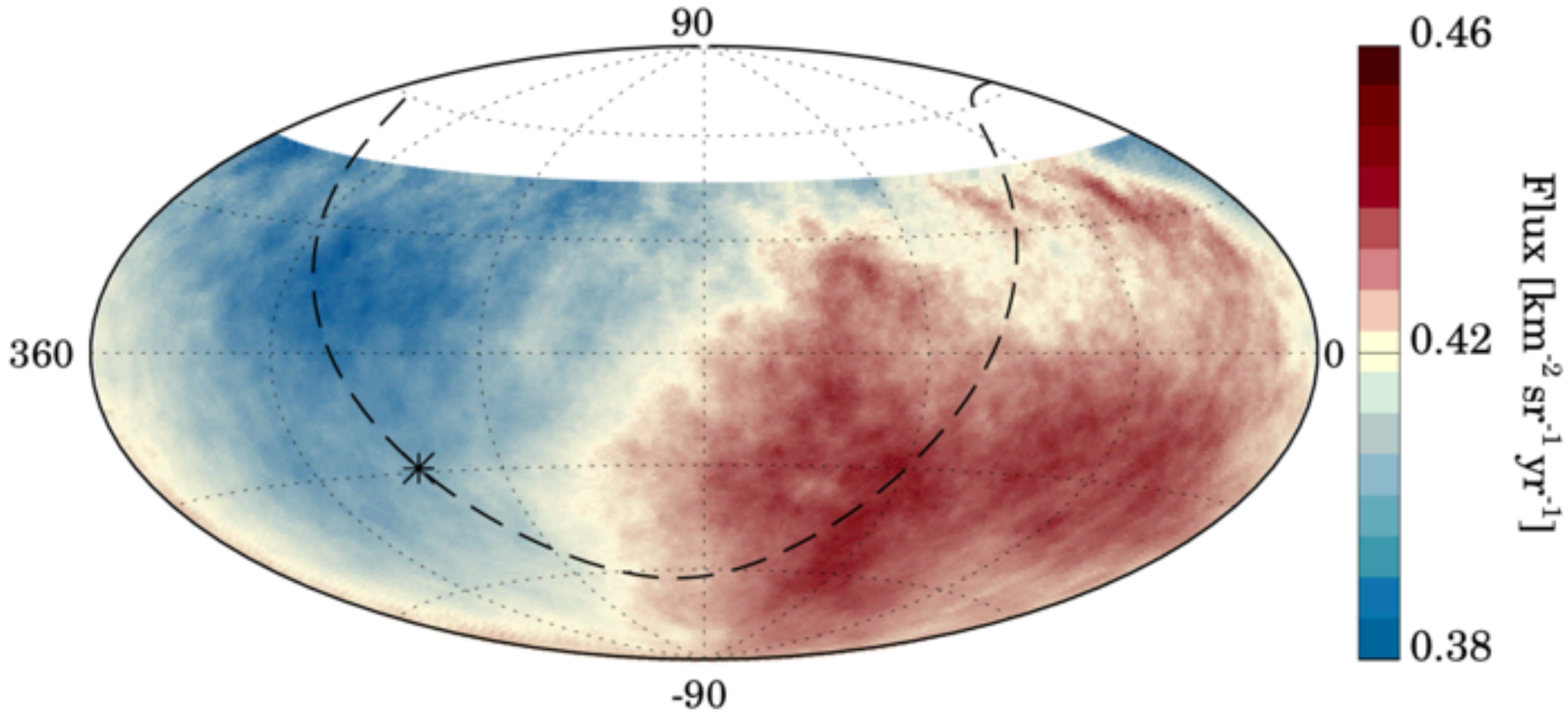

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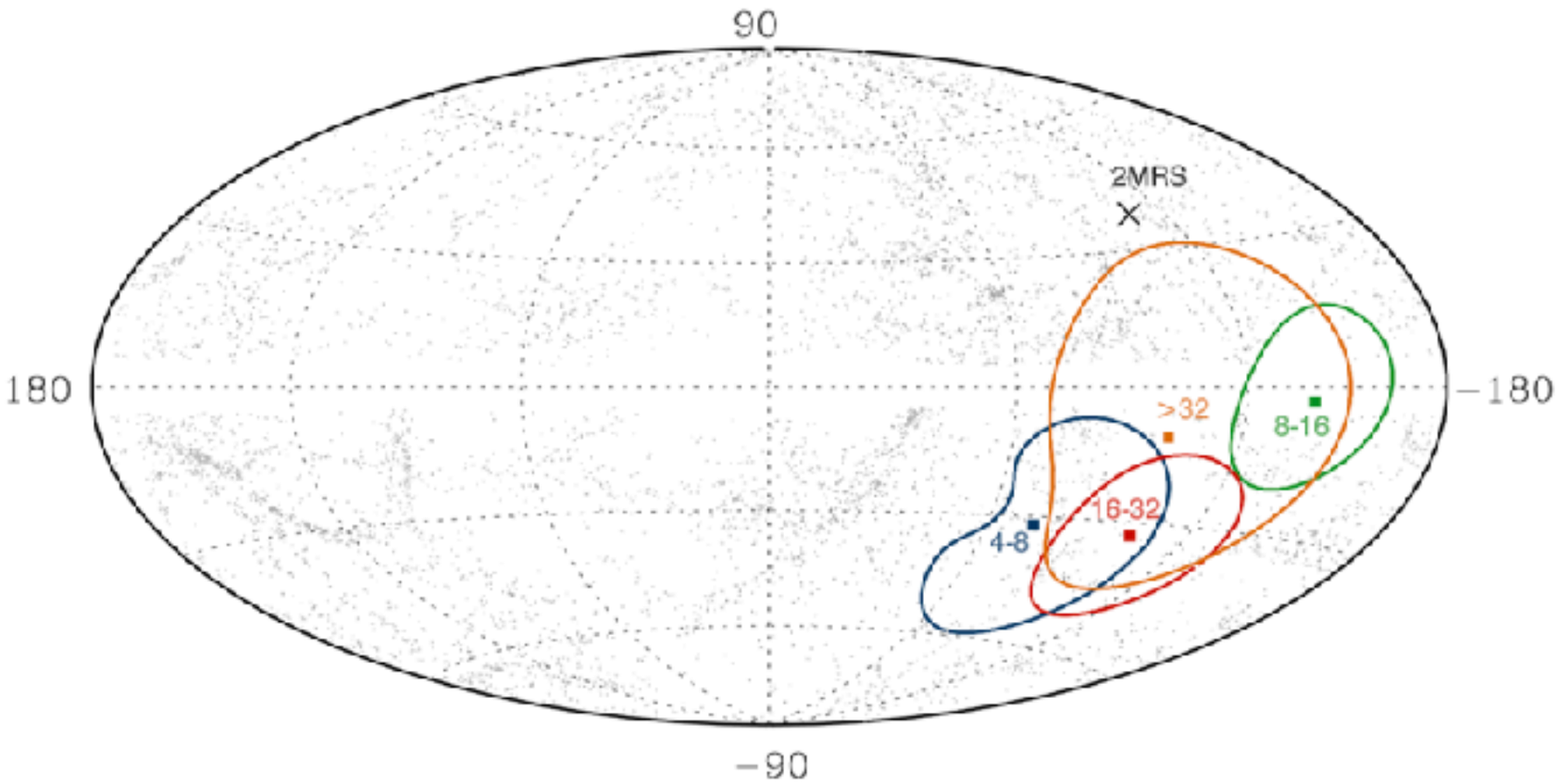
>5 sigma Dipole found above 8 EeV

Auger Collaboration, Science (2017), ApJ (2018)

Hints to Cosmic Ray Origins



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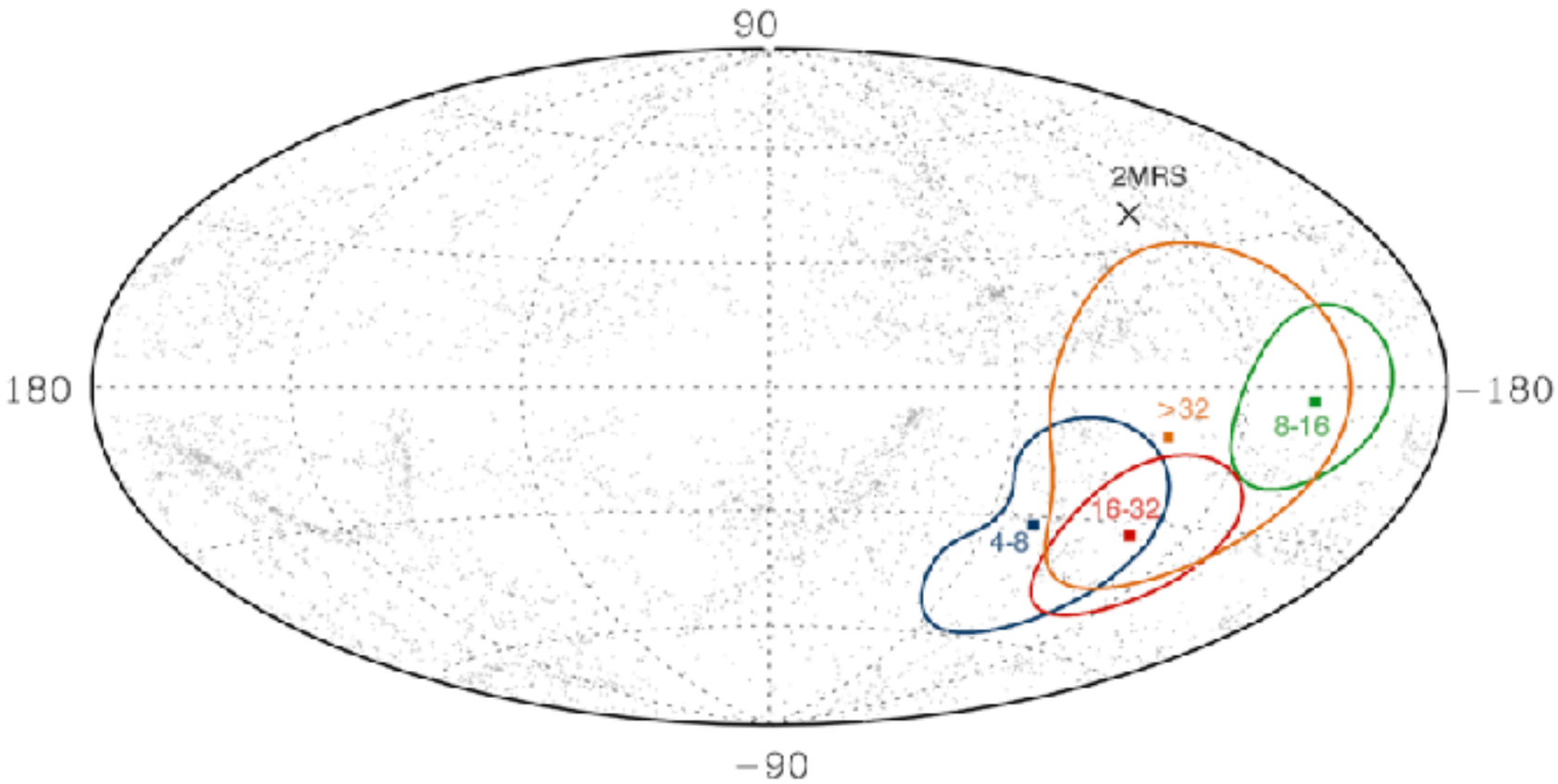
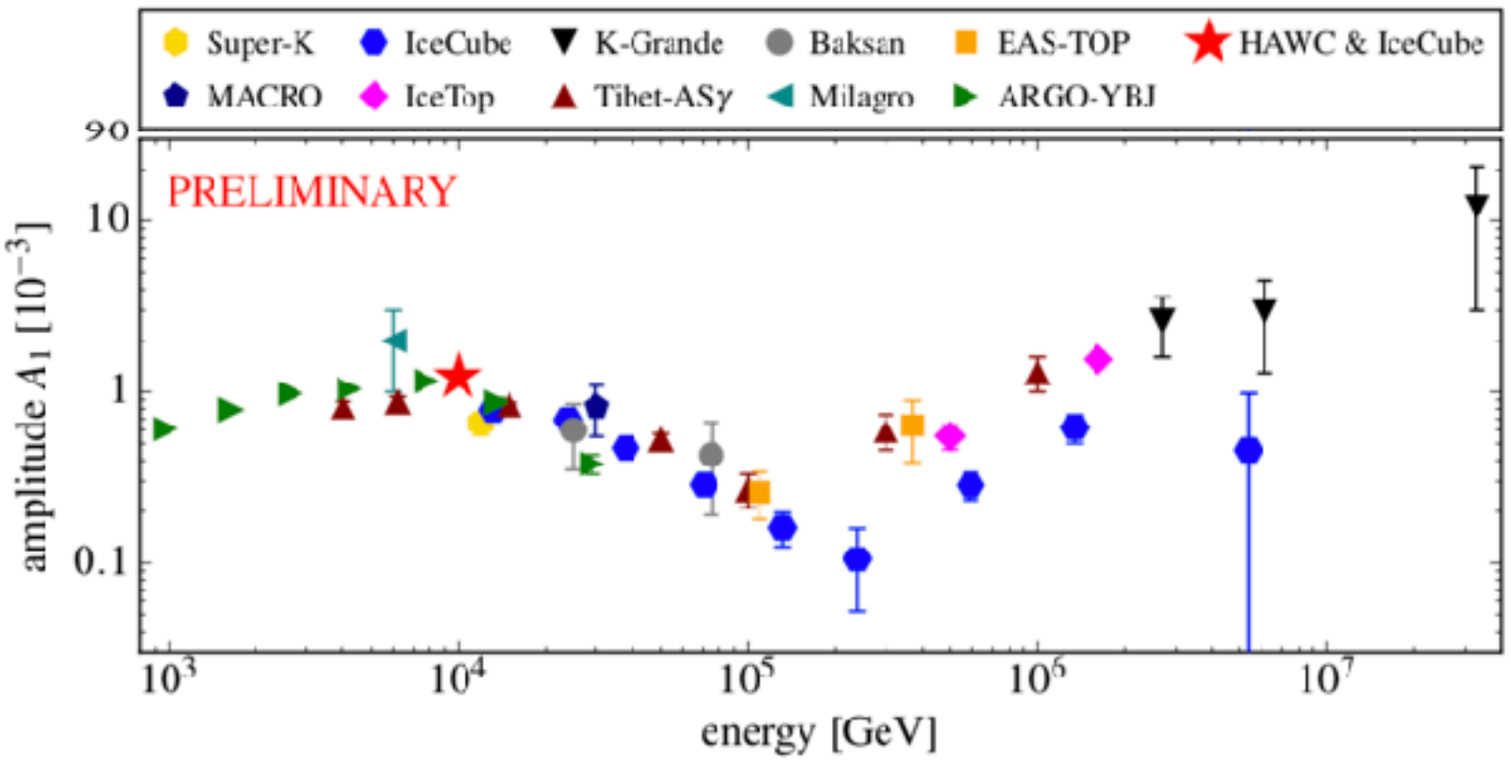
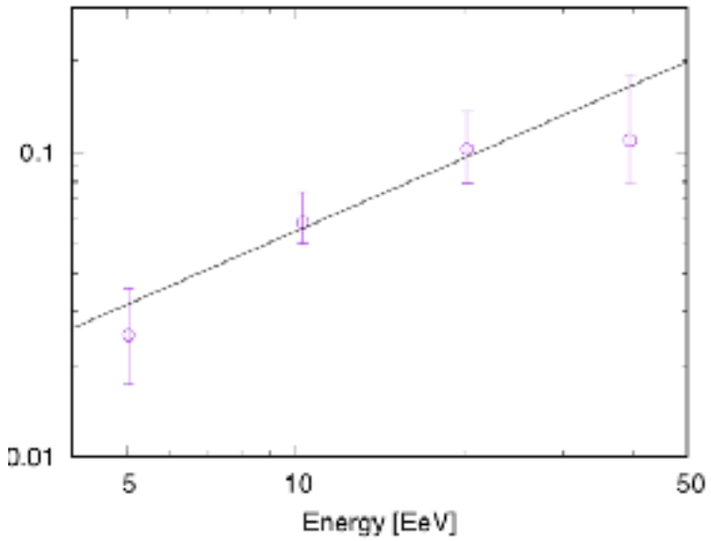


Dipole directions as function of energy, comparing with that from galaxies in the 2MRS catalog

Auger Collaboration ApJ (2018)

Dipole Amplitude Over Energy





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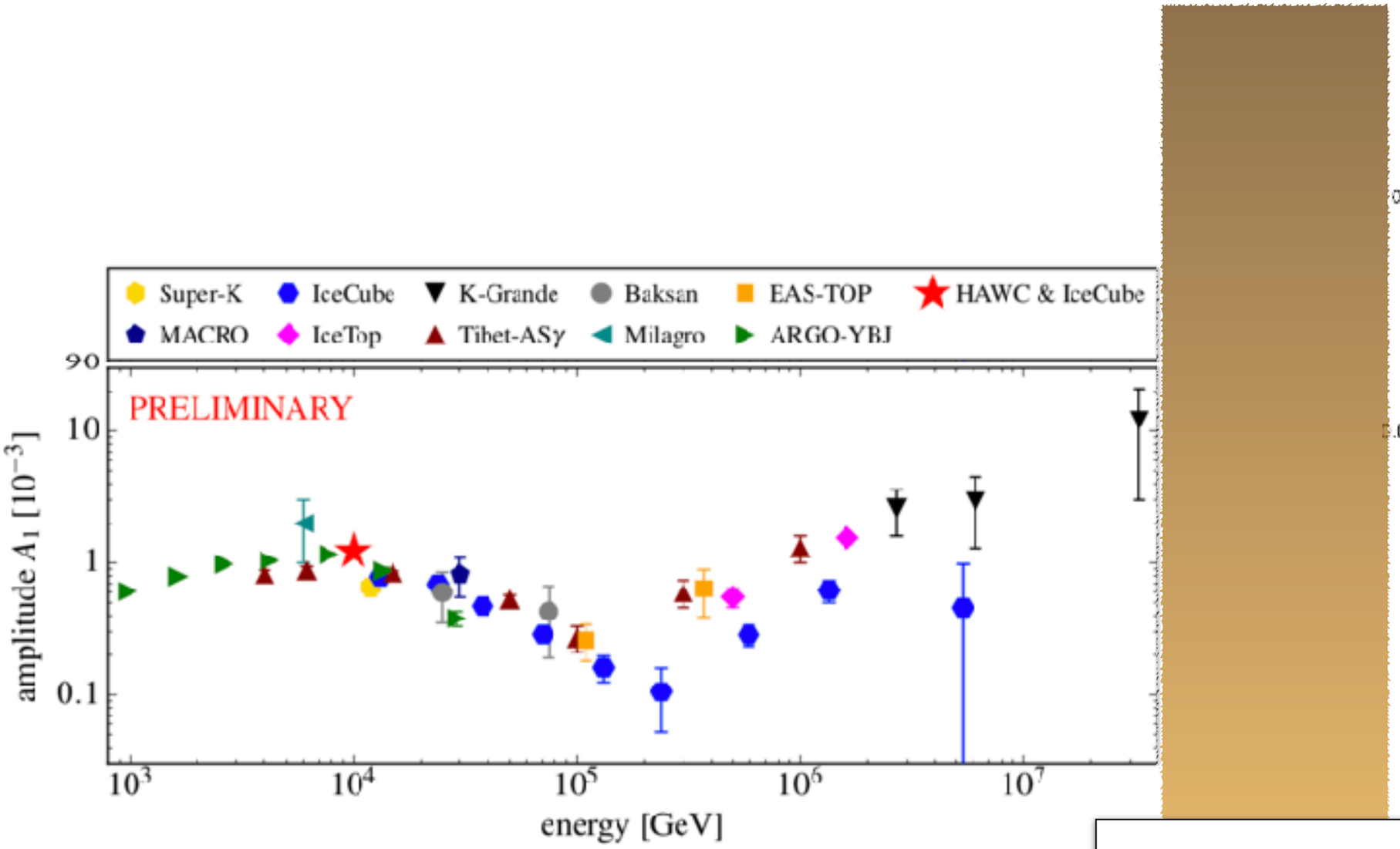

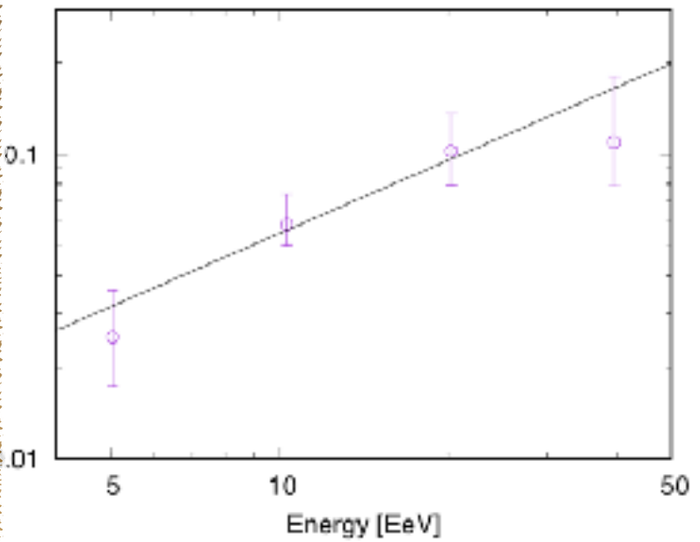

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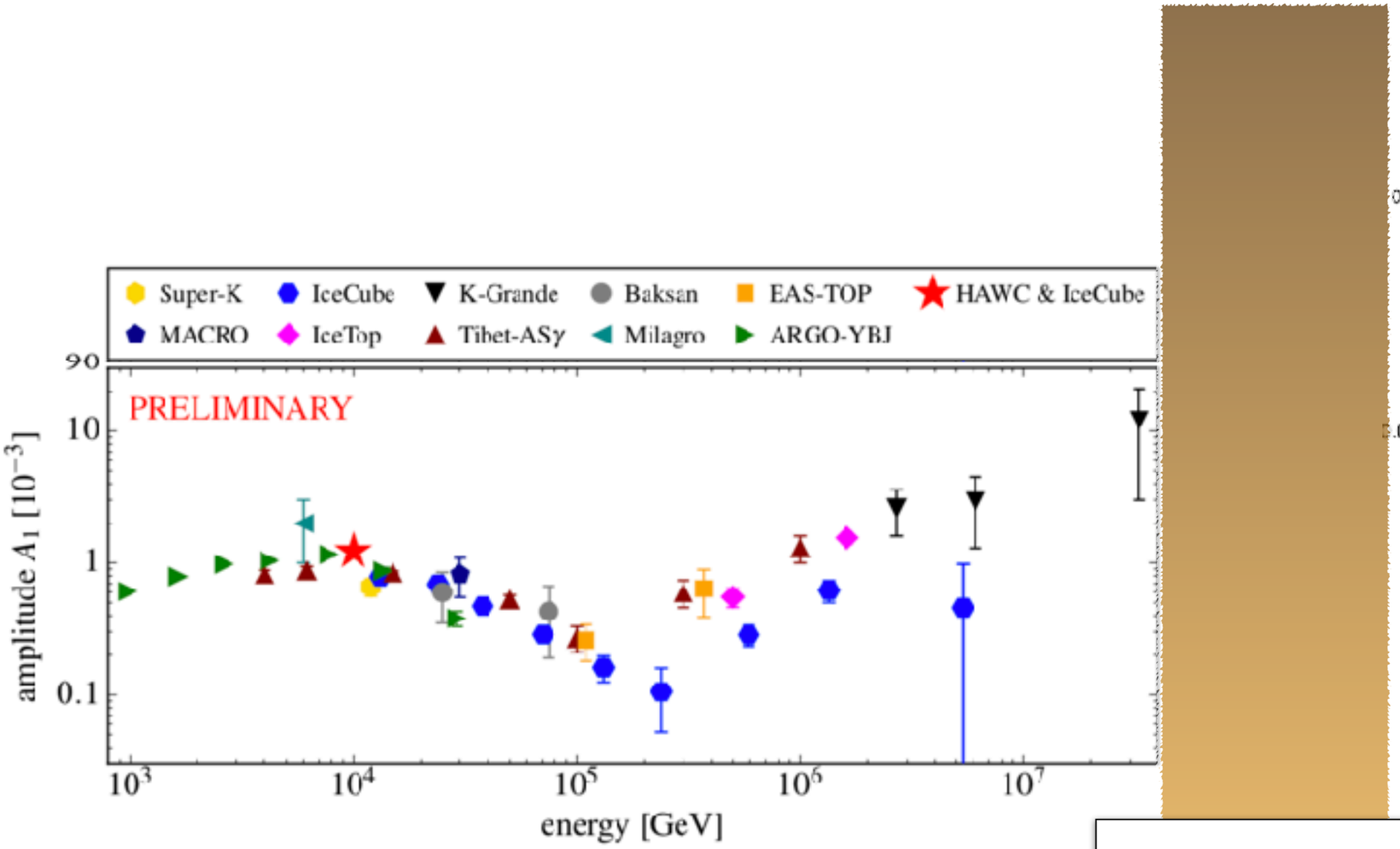
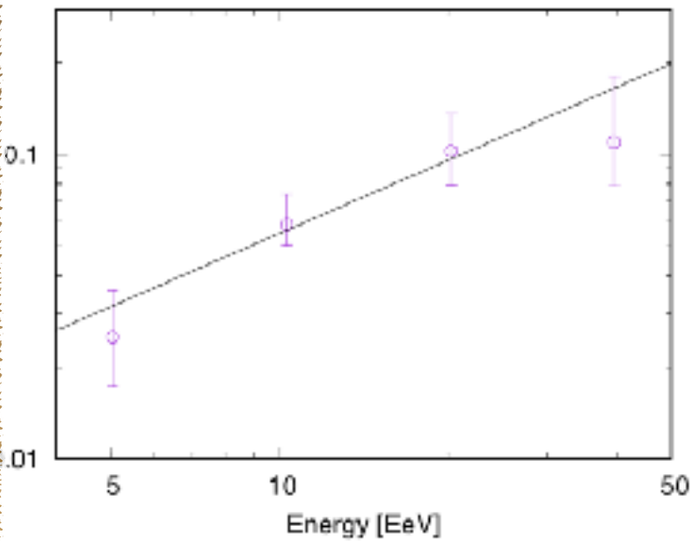
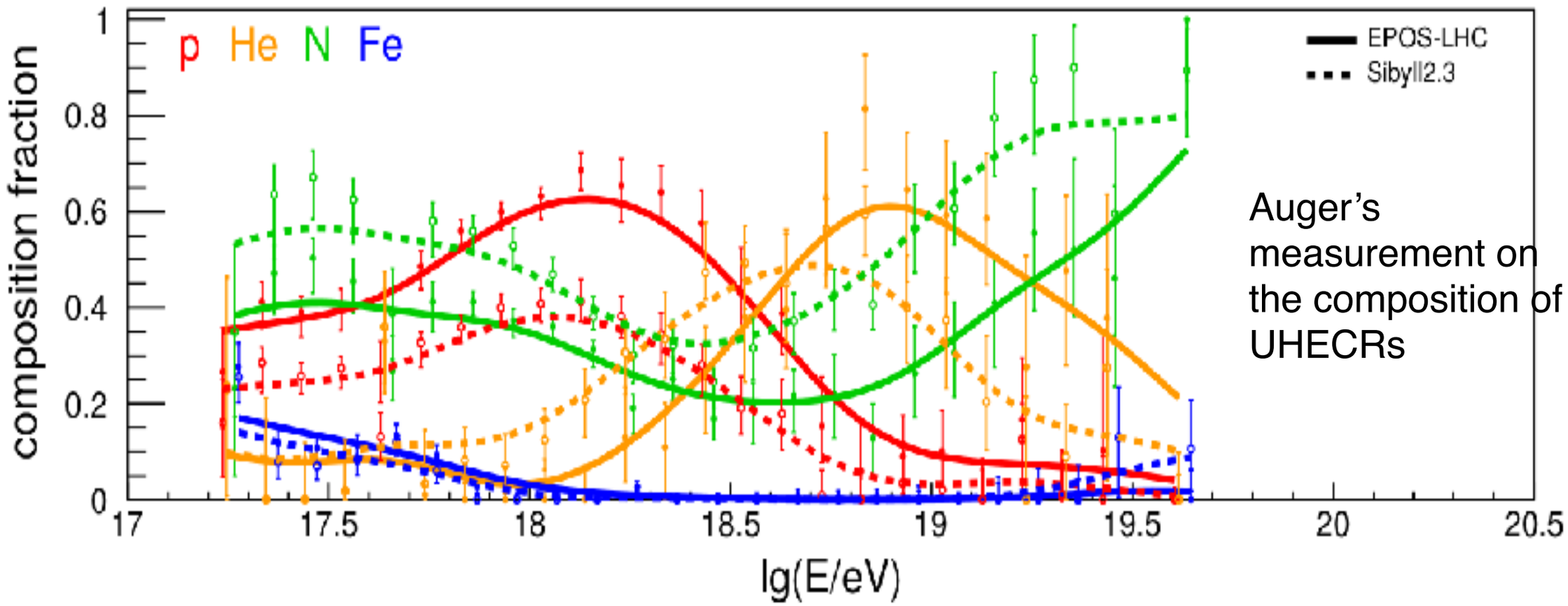




$N \sim 10^5$

$\delta \sim 5 \times 10^{-3}$

Ahlers & Mertsch, PPNP (2017)
Auger Collaboration ApJ (2018)

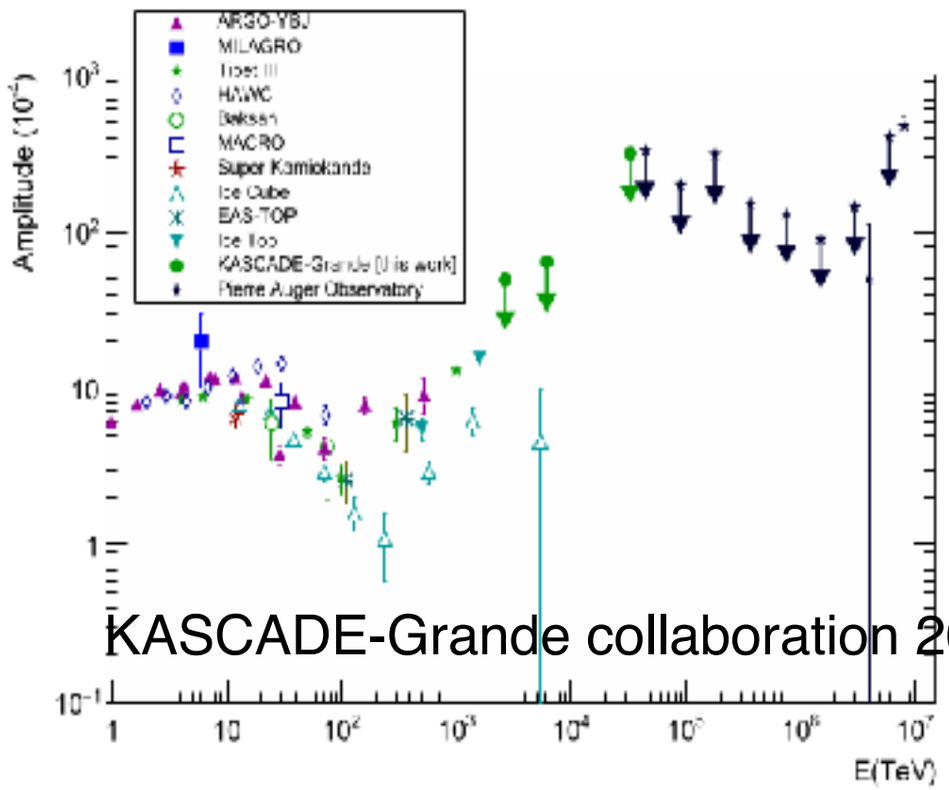


Auger's measurement on the composition of UHECRs

Large-scale anisotropy:
Dipolar component

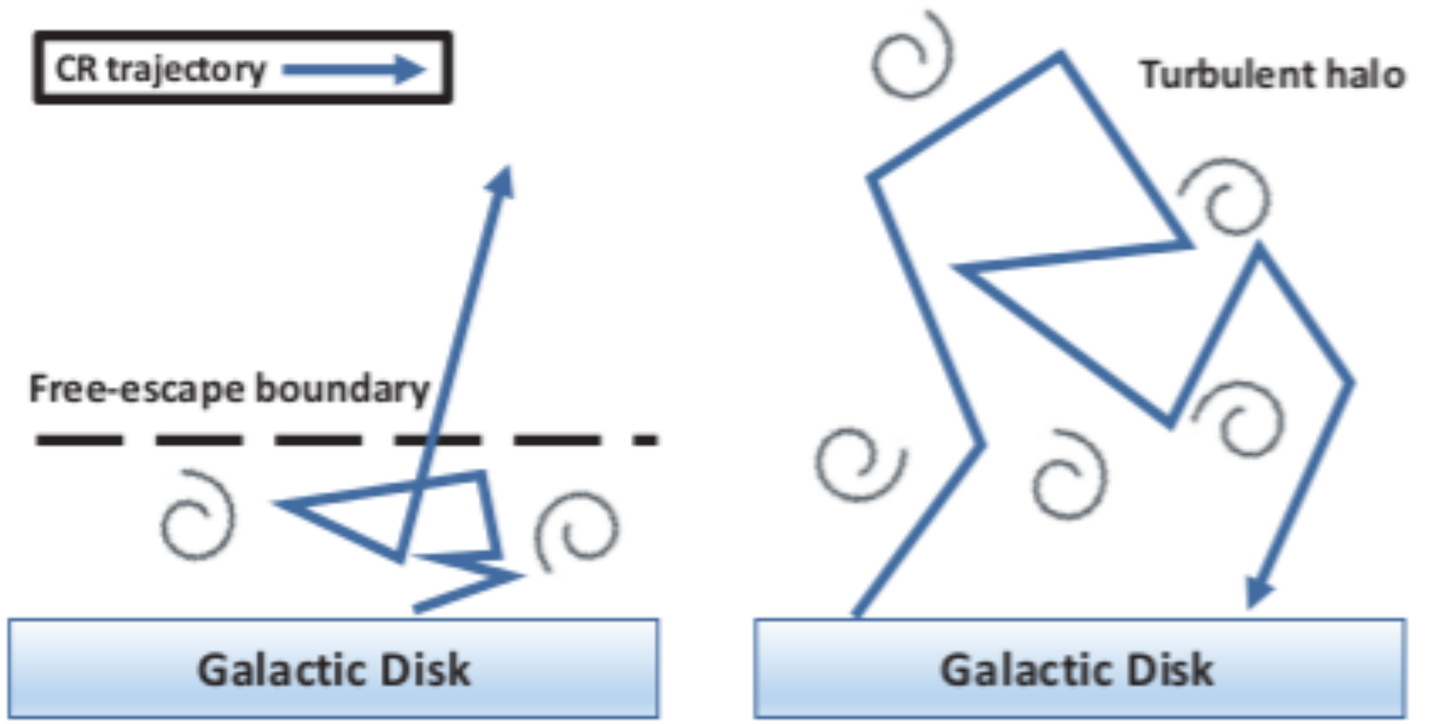
$$\vec{\Delta} = 3D\frac{\vec{\nabla} n}{n}$$

Possible contribution from GP300：
origin of intermediate-mass nuclei at sub-ankle
Constraint on the properties of local magnetic field (D)



KASCADE-Grande collaboration 2019

Galactic CRs



Liu et al. 2019

Ex-Galactic CRs

$$D_{\rm diff}(E<E_*) \sim \left(\frac{c\ell_{\rm coh}}{H_0}\right)^{1/2}\left(\frac{E}{E_*}\right)^{1/2}$$

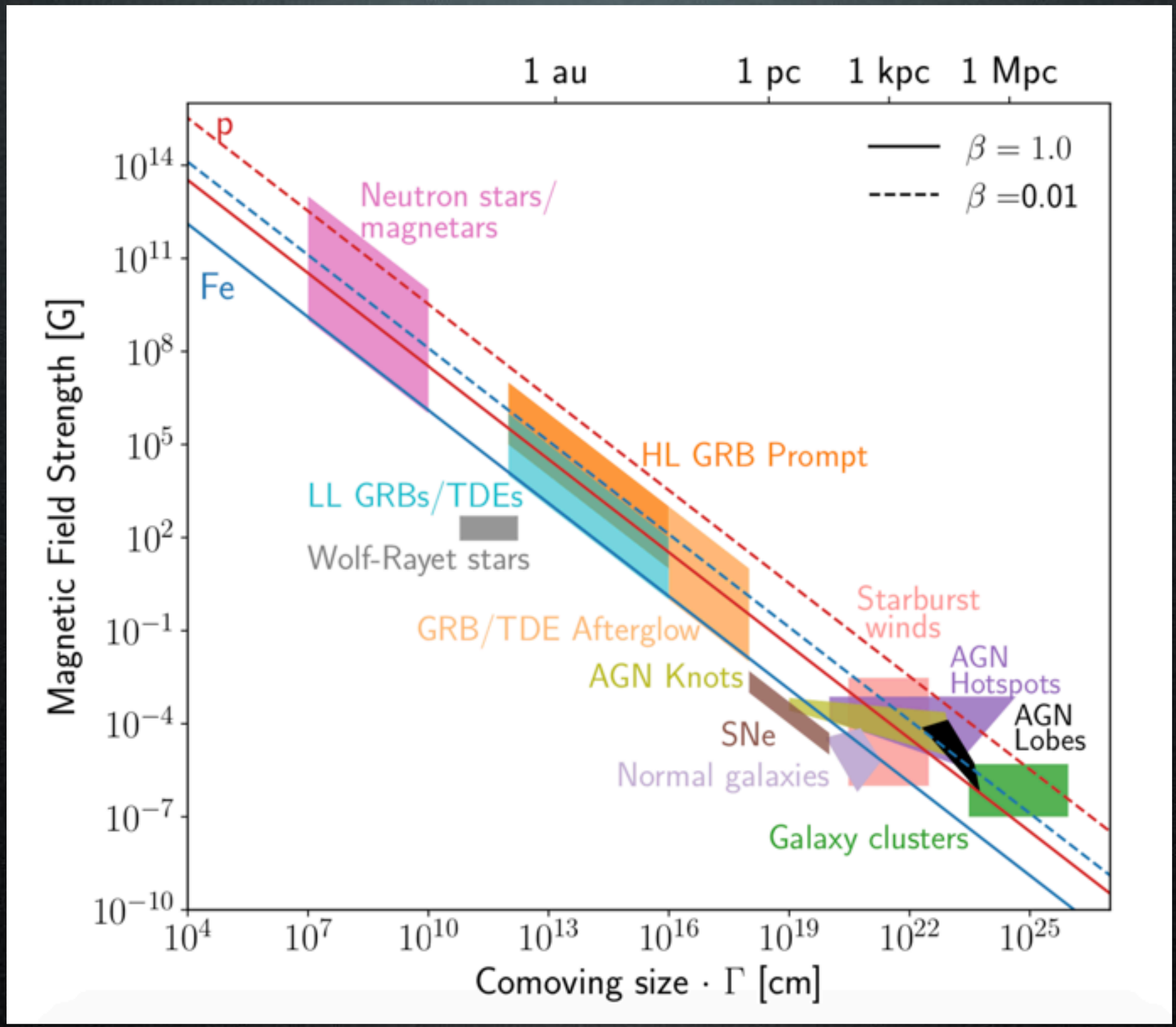
$$\simeq 55\,\ell_0^{1/2}h^{-1/2}\left(\frac{E}{E_*}\right)^{1/2}\ {\rm Mpc}$$

Magnetic horizon for E<E*
(Crs trapped by intergalactic magnetic field
Diffuse slow and cannot reach Earth within the age of the Universe)

$$\ell_0=\ell_{\rm coh}/(1\ {\rm Mpc}) \qquad E_*\equiv ZeB_{\rm r}\,\ell_{\rm coh}\simeq 9.2\times10^{17}ZB_{-9}\ell_0\ {\rm eV}$$

Achterberg et al. 1999

Pulsars as Sources of UHECRs



Hilas 1984
Kotera & Olinto 1101.4256
Alves Batista, Biteau, Bustamante et al, 1903.06714

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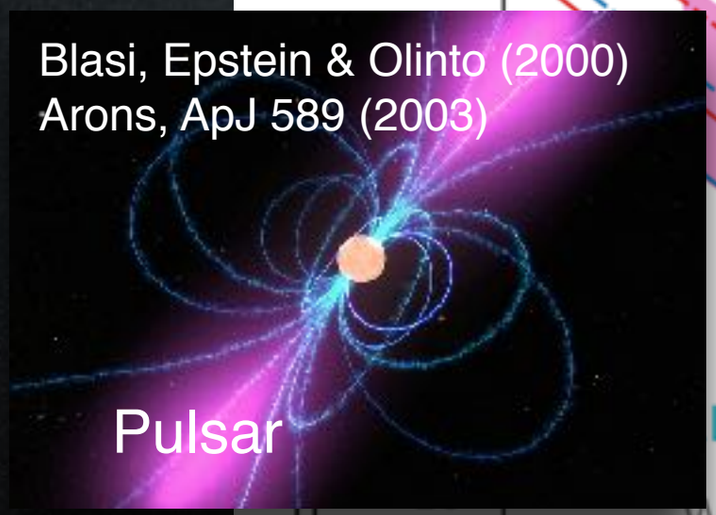

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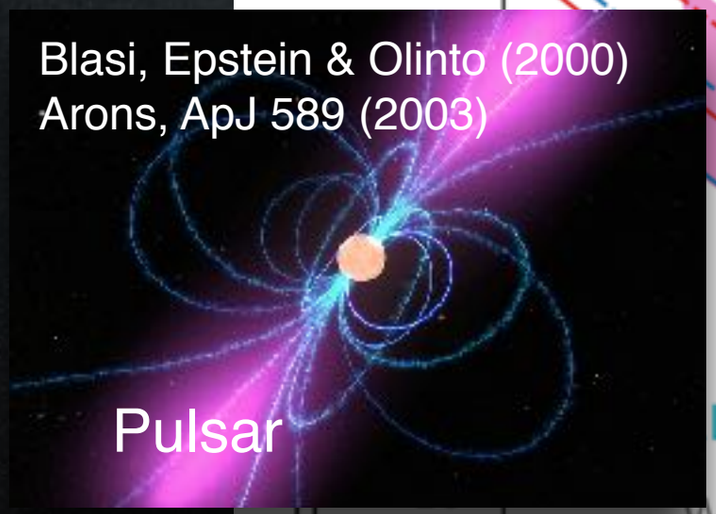

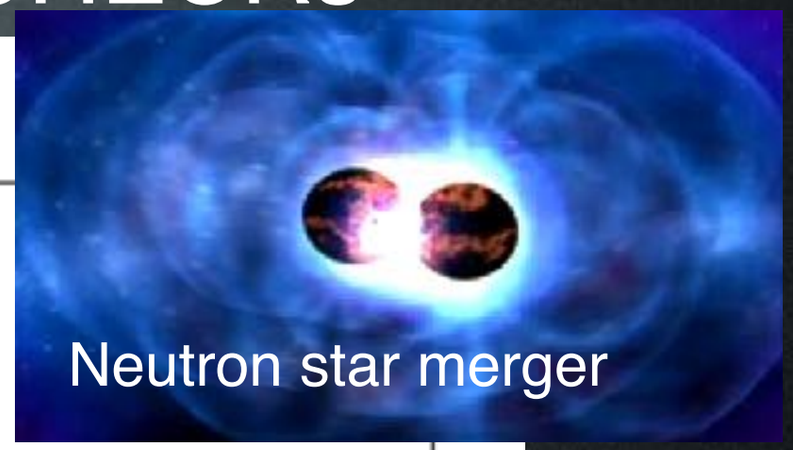

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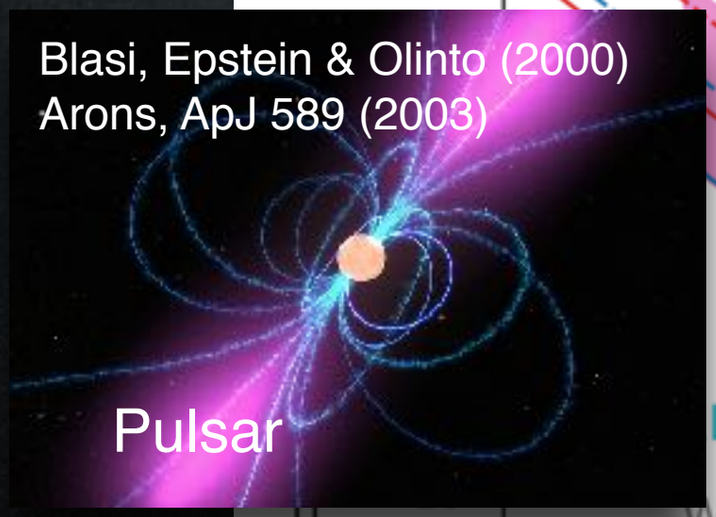

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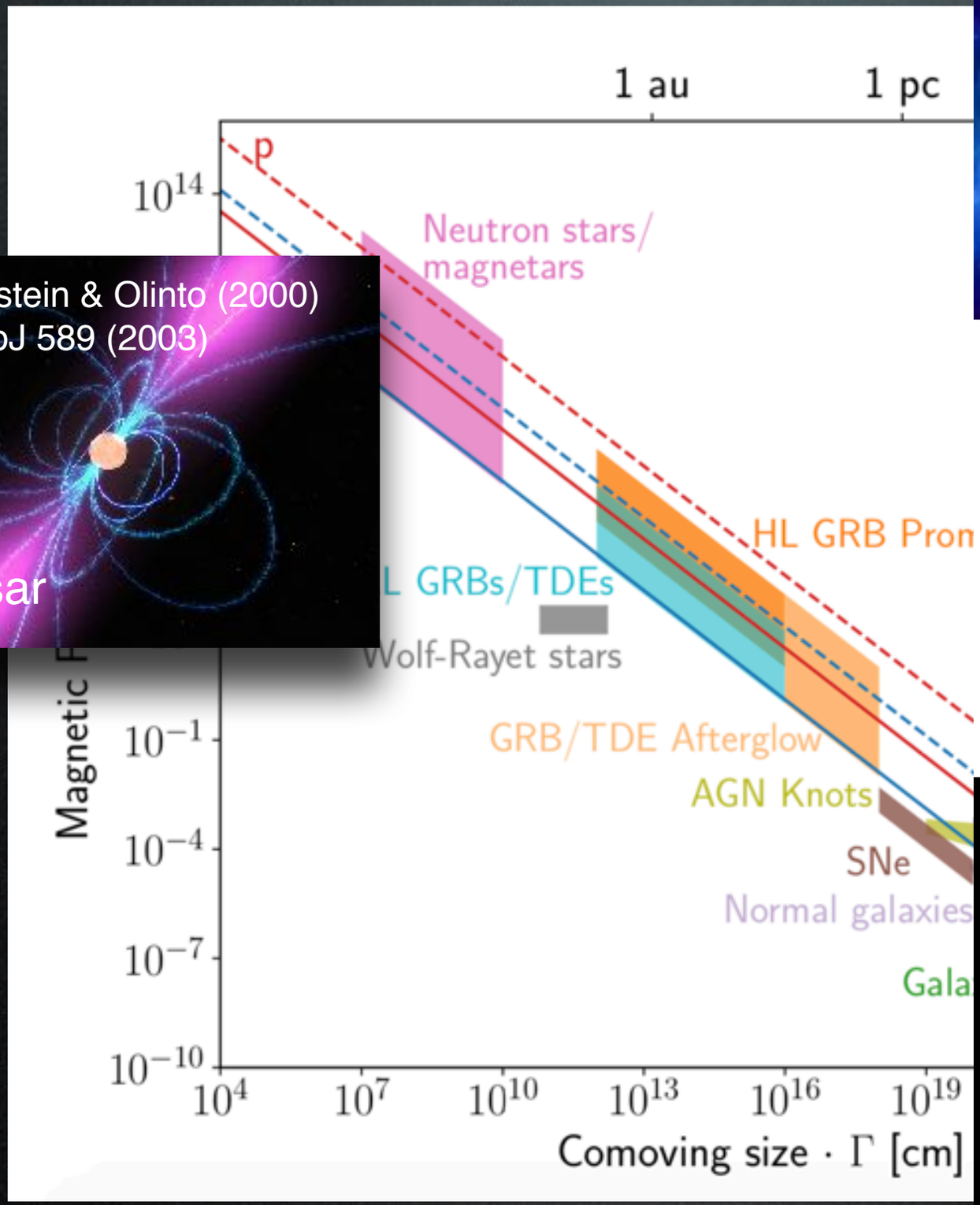

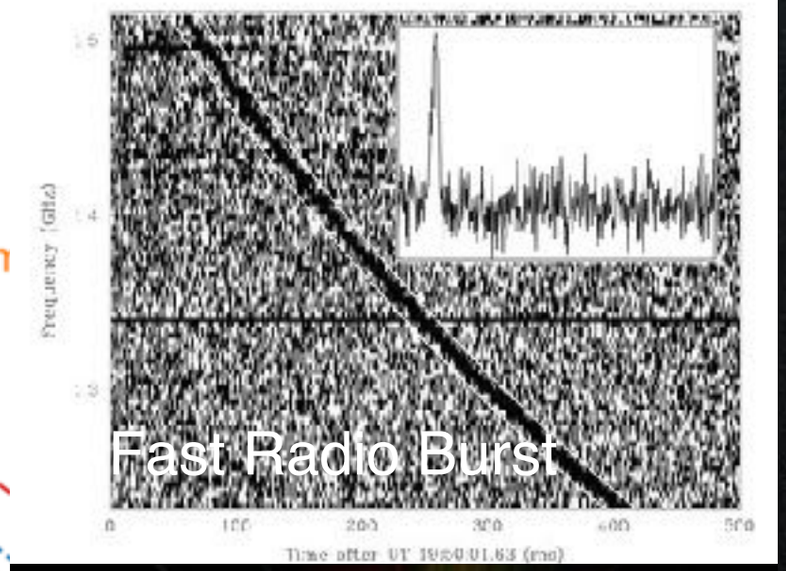

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Cosmic Ray Acceleration

e.g.
Kirk & Lyubarsky (2001)
Arons, ApJ 589 (2003)

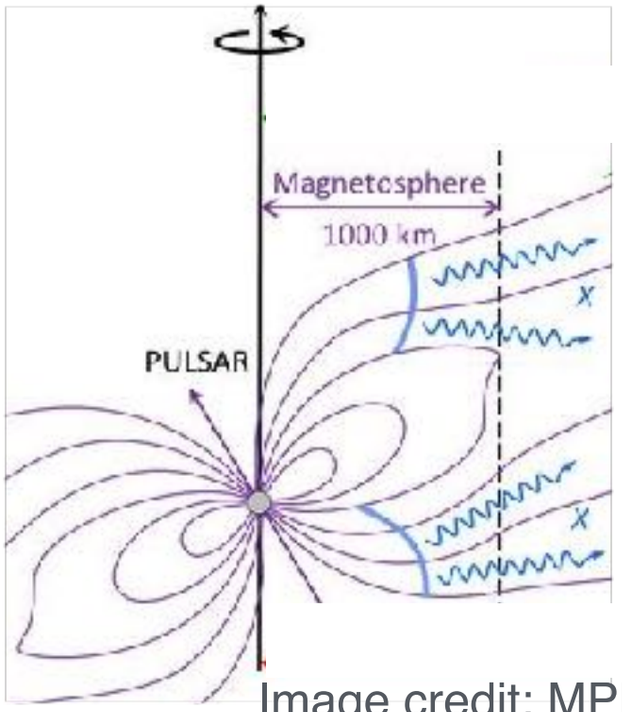

Image credit: MPIK

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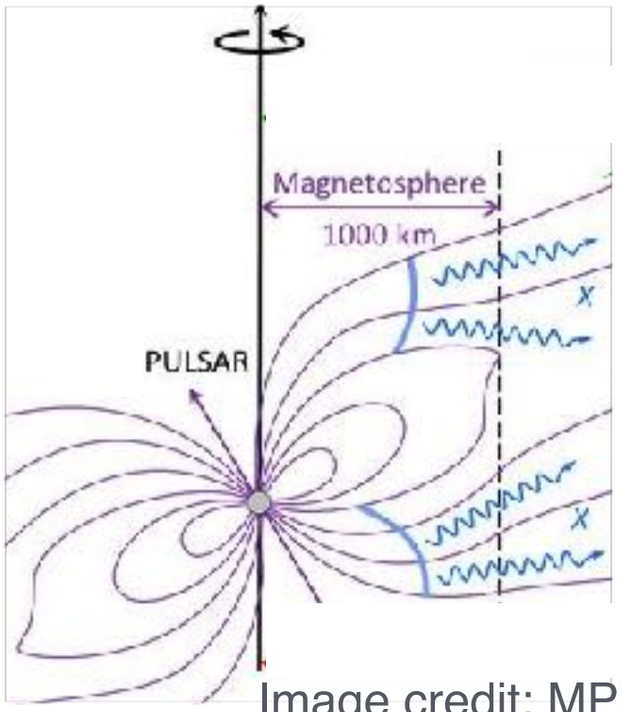

Image credit: MPIK

Particle energy

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

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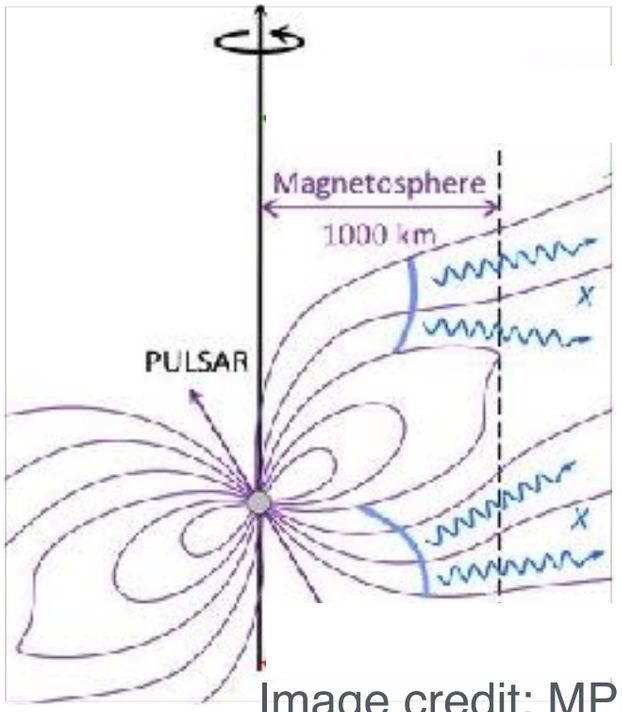

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Particle energy

Magnetic Field

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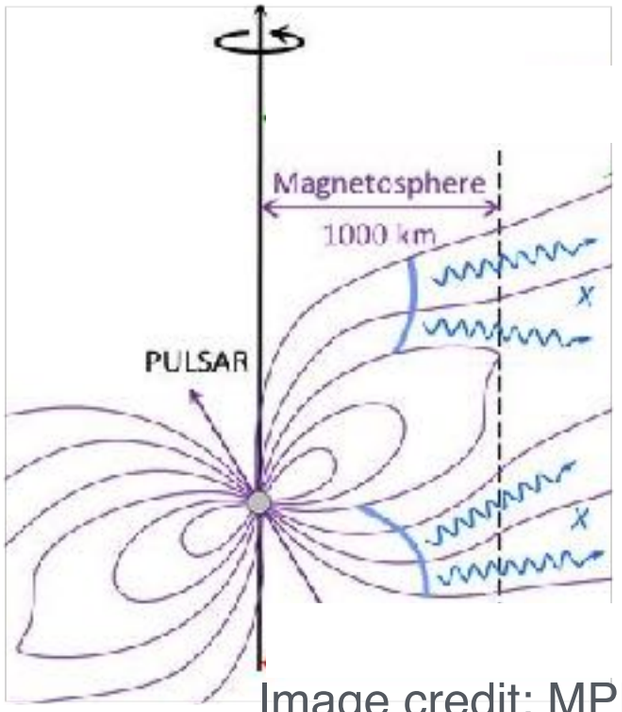

Image credit: MPIK

Particle energy

Magnetic Field

initial spin period

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

Cosmic Ray Acceleration

e.g.
Kirk & Lyubarsky (2001)
Arons, ApJ 589 (2003)

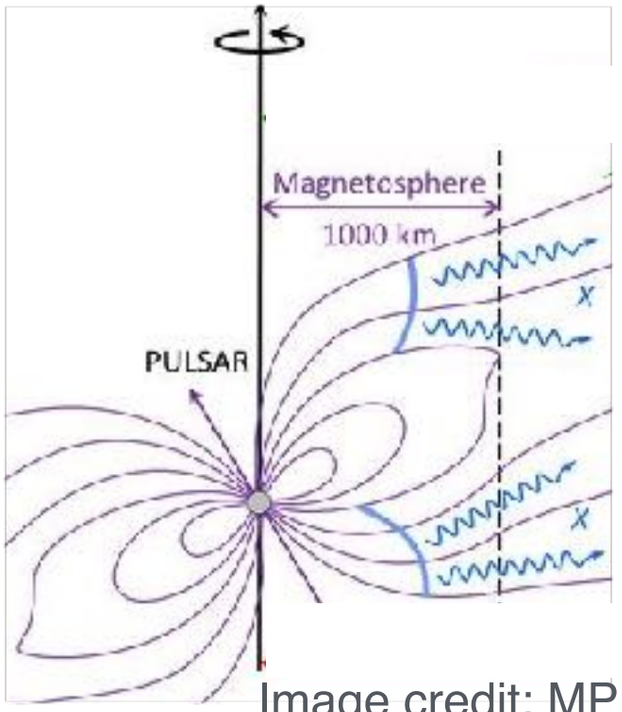

Image credit: MPIK

Particle energy

Magnetic Field

initial spin period

Wind efficiency

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

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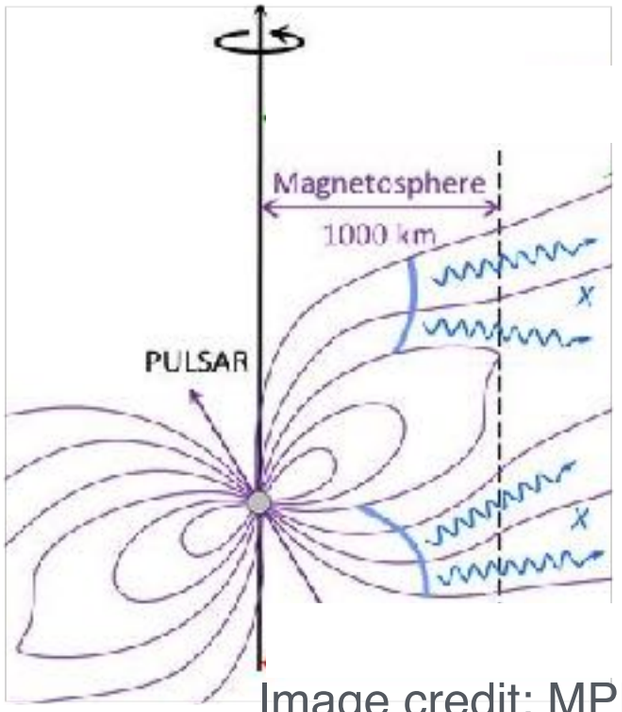

Image credit: MPIK

Particle energy

Magnetic Field

initial spin period

Wind efficiency

Multiplicity

$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1+\frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

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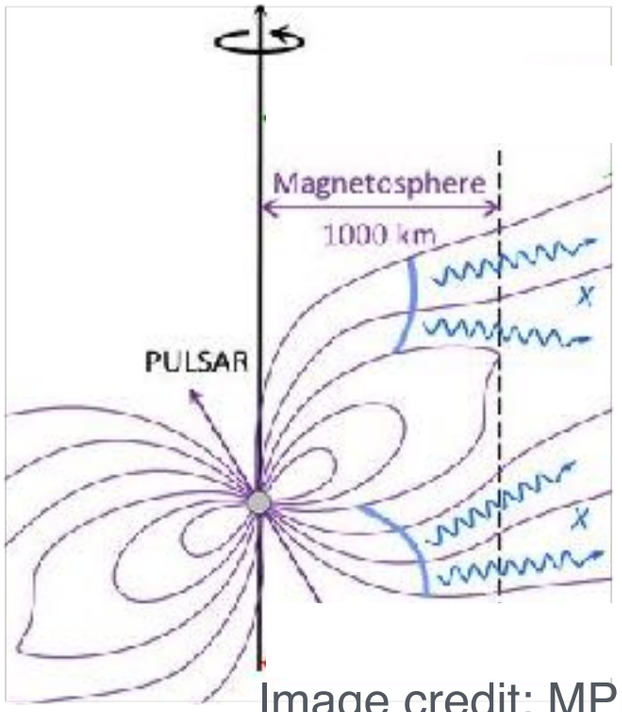

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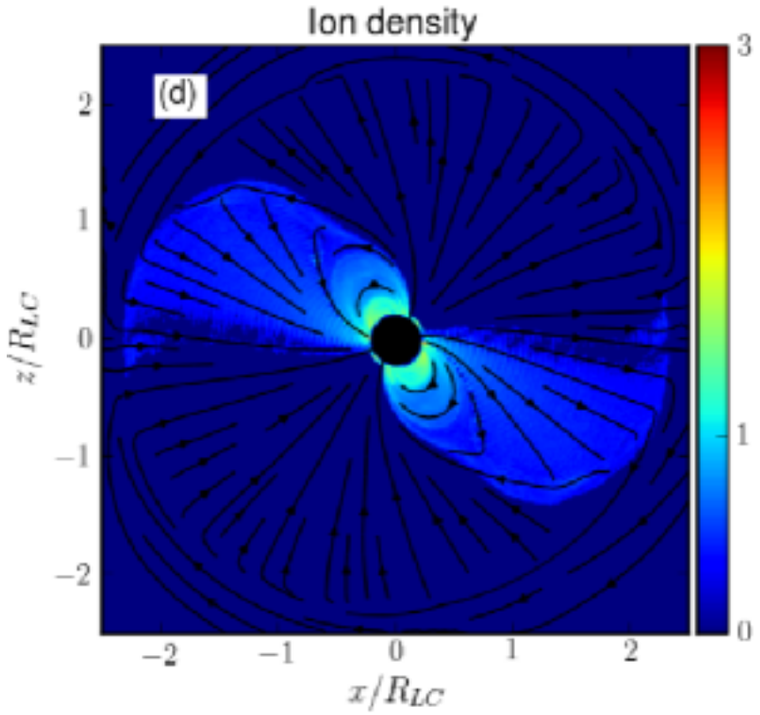
Cosmic ray injection spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-1}$$

Cosmic Ray Acceleration



Philippov & Spitkovsky 1707.04323

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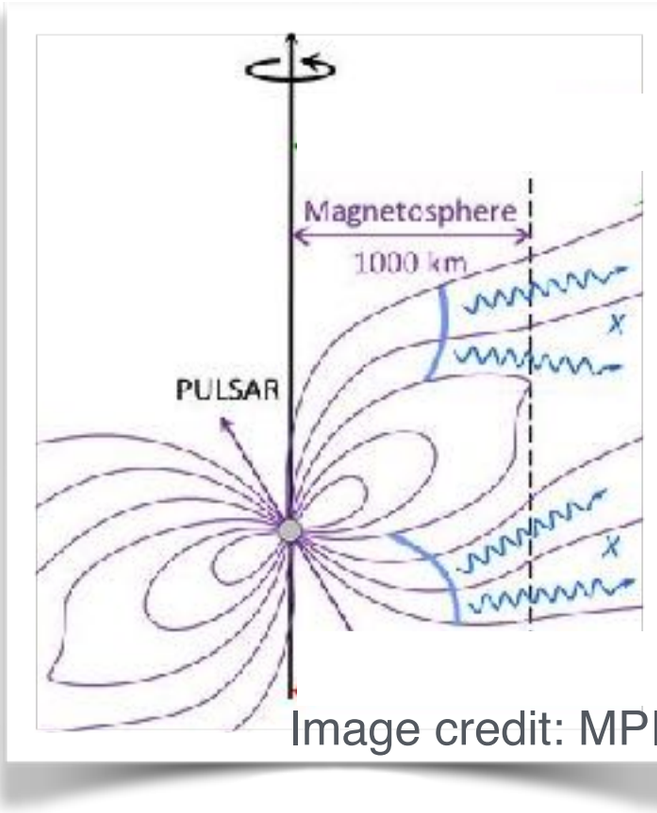

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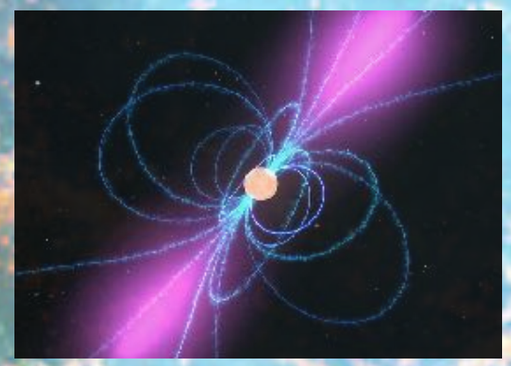
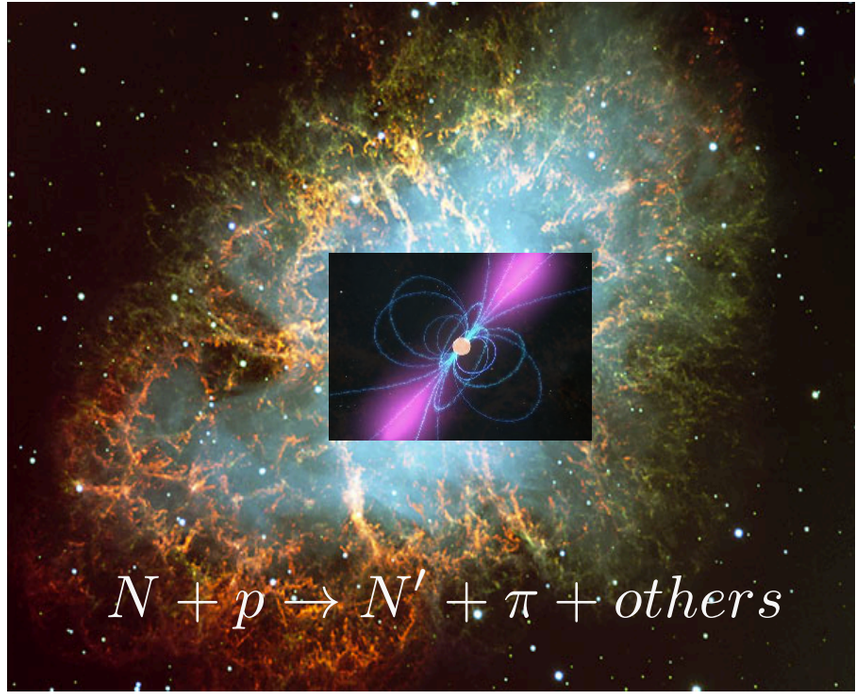
Cosmic ray particles interacting
with hadronic supernova ejecta



Interaction with Ejecta

$$\tau_{pp} = 0.2 \left(\frac{M_{\rm ej}}{10 M_\odot} \right) \left(\frac{v_{\rm ej}}{10^4 {\rm km/s}} \right)^{-2} \left(\frac{t}{1 {\rm yr}} \right)^{-2}$$



KF, Kotera & Olinto (2012)

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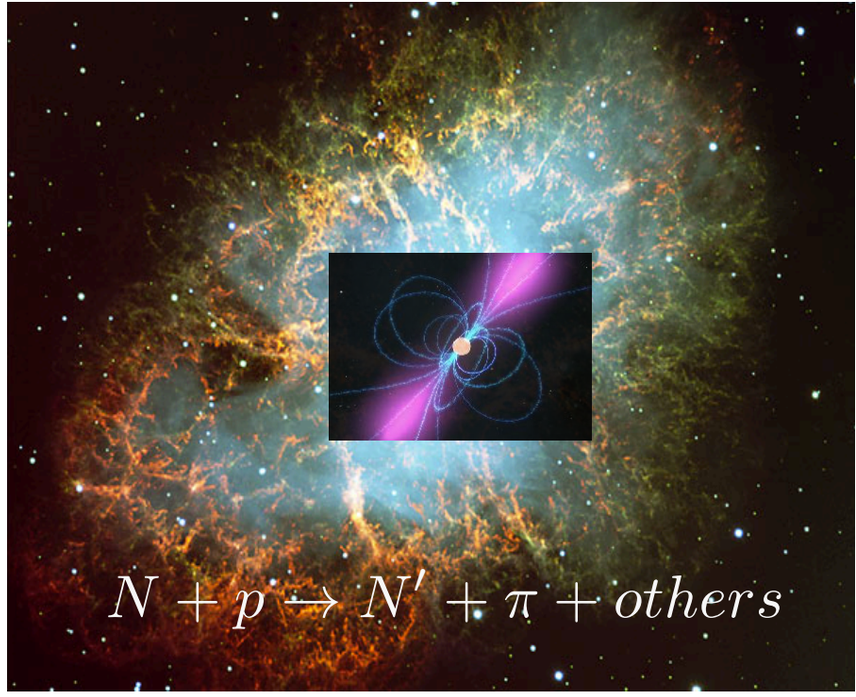
t ↑



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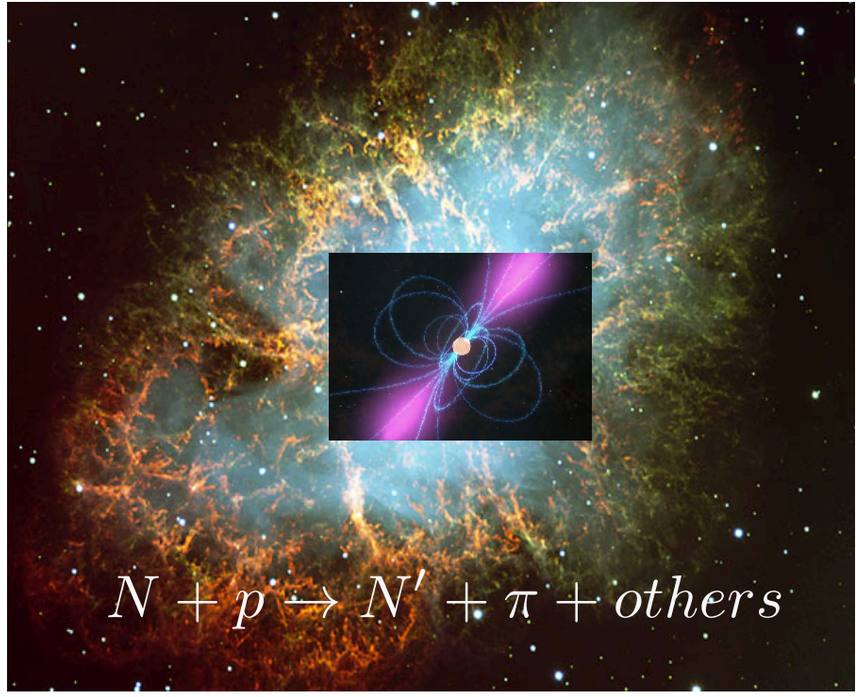
t ↑ $E_{\rm CR}$ ↓



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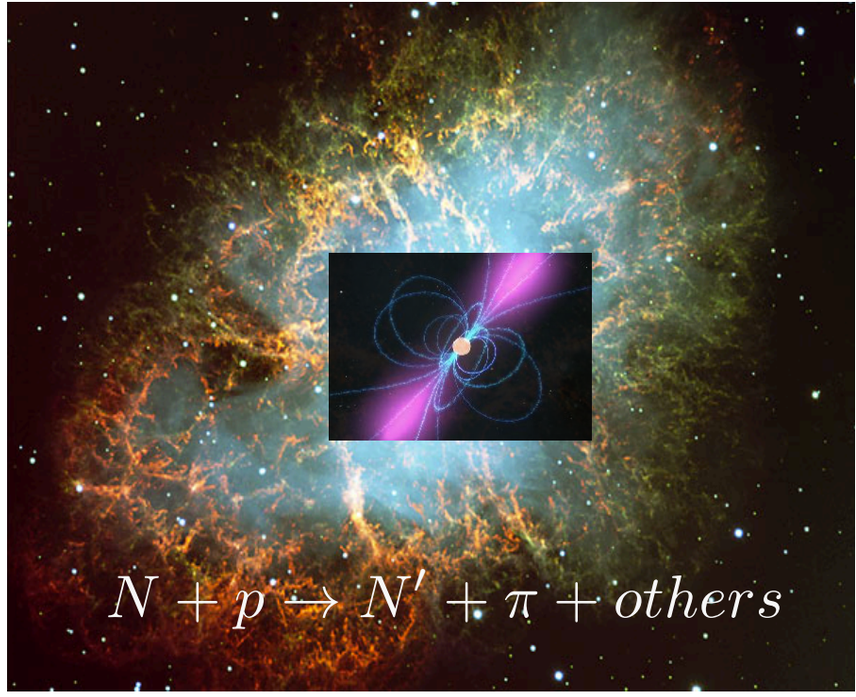

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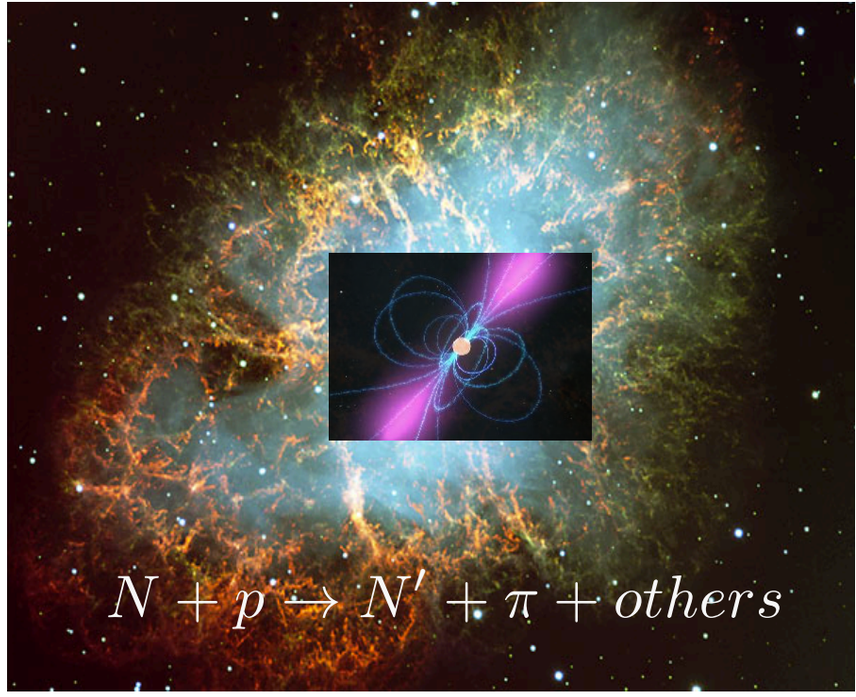
Monte Carlo simulation tracking particle propagation



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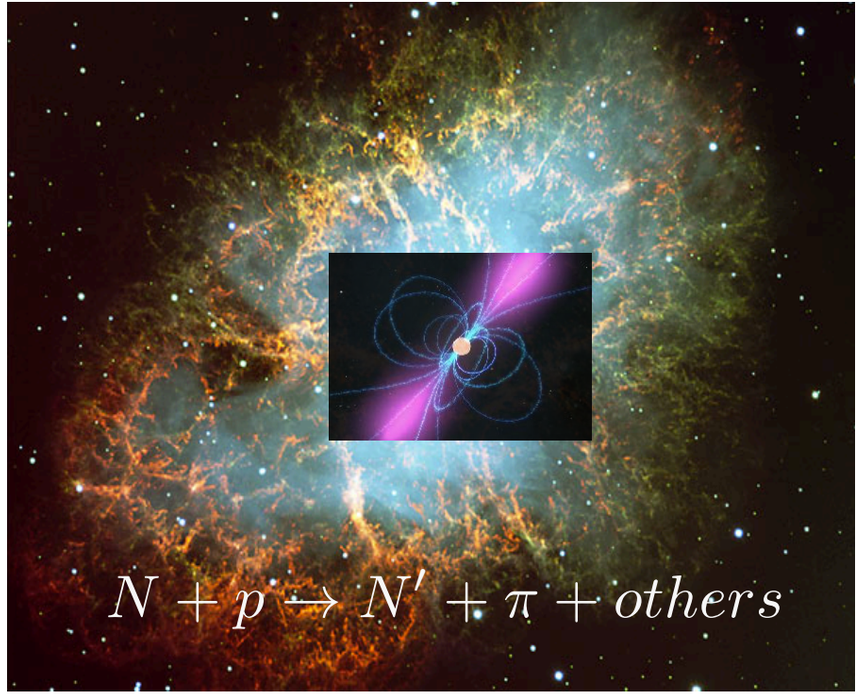

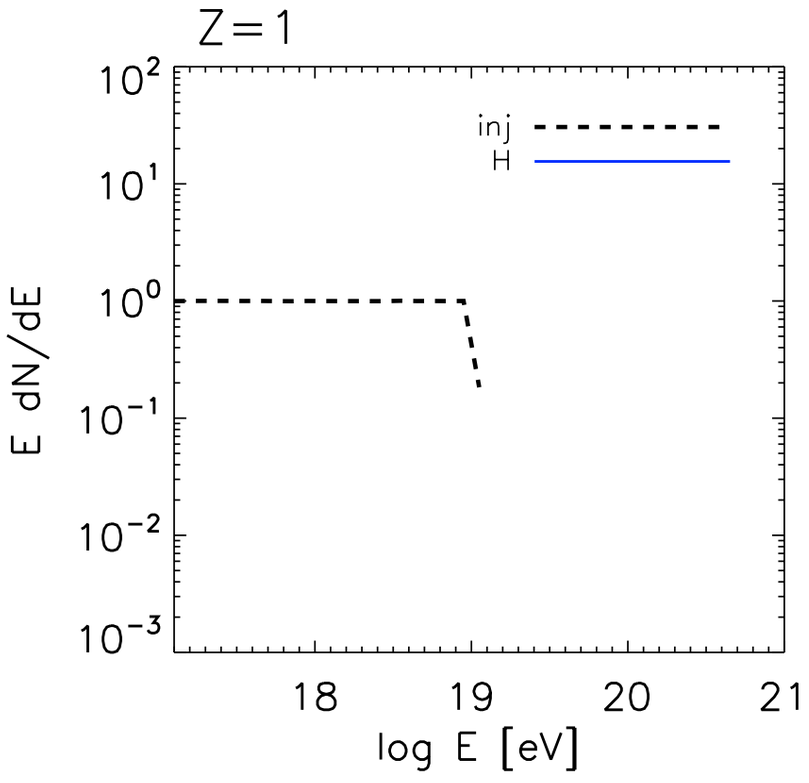

$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

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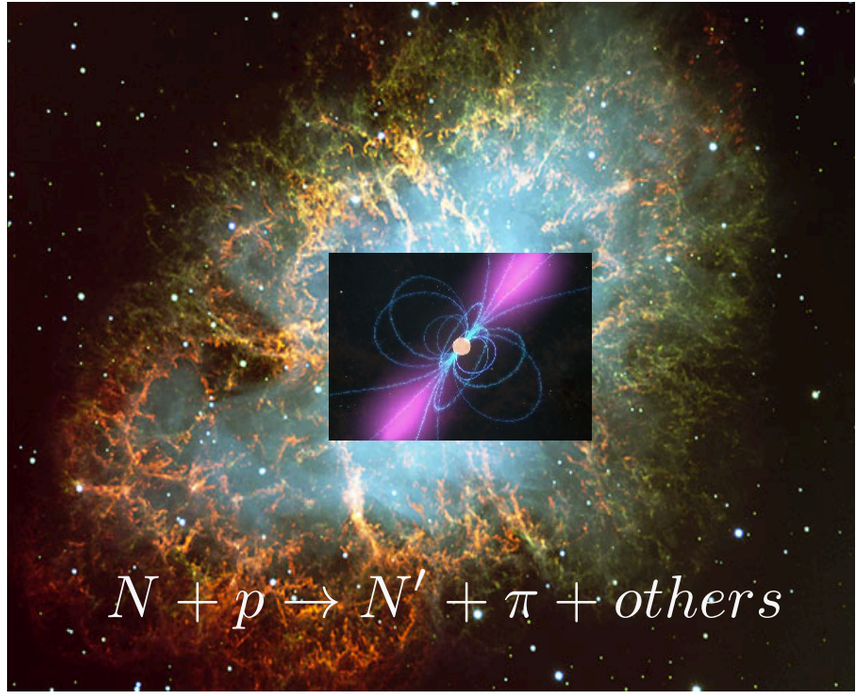

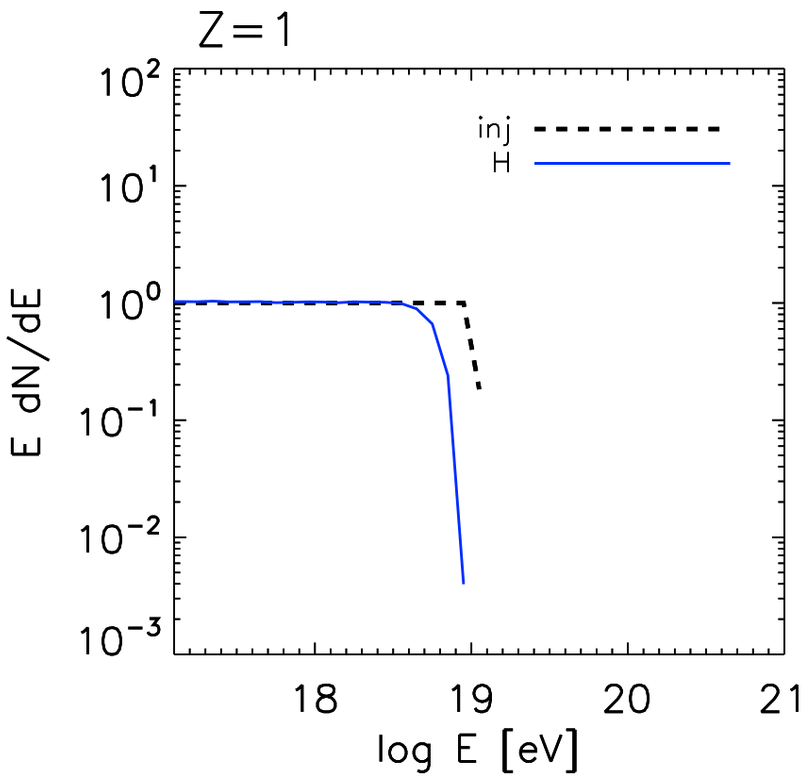

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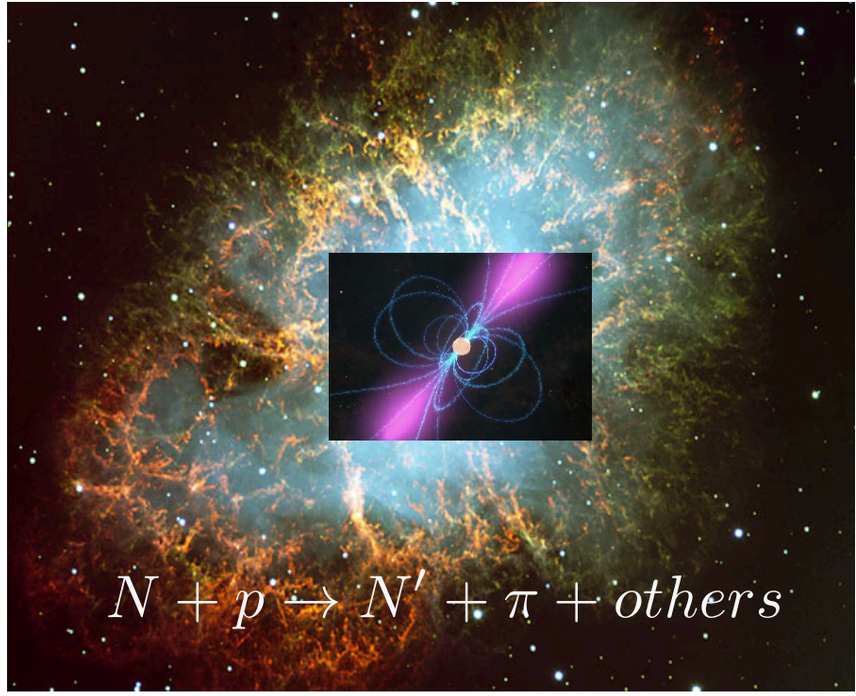

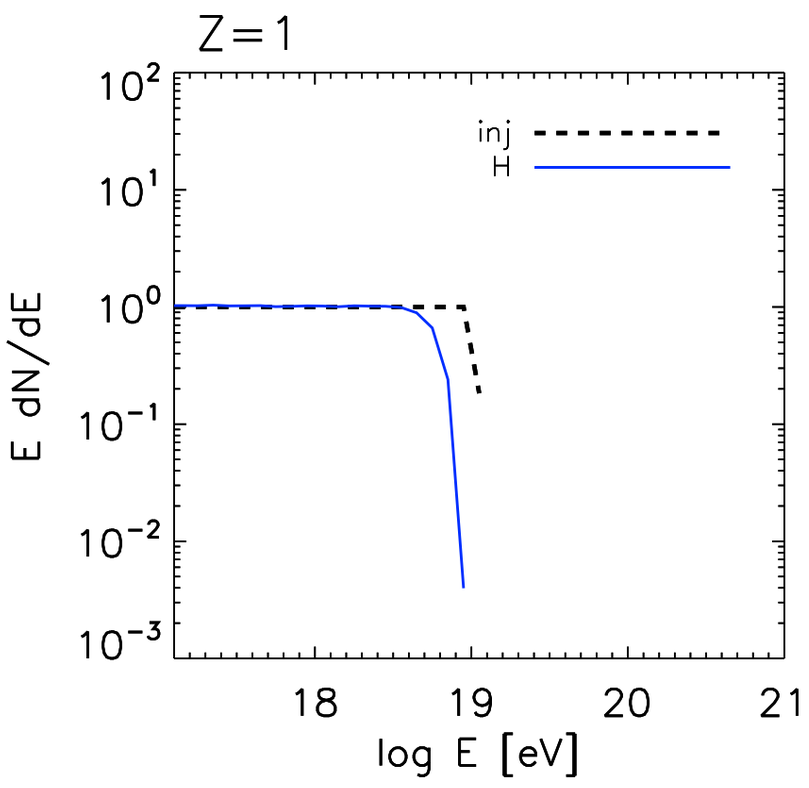

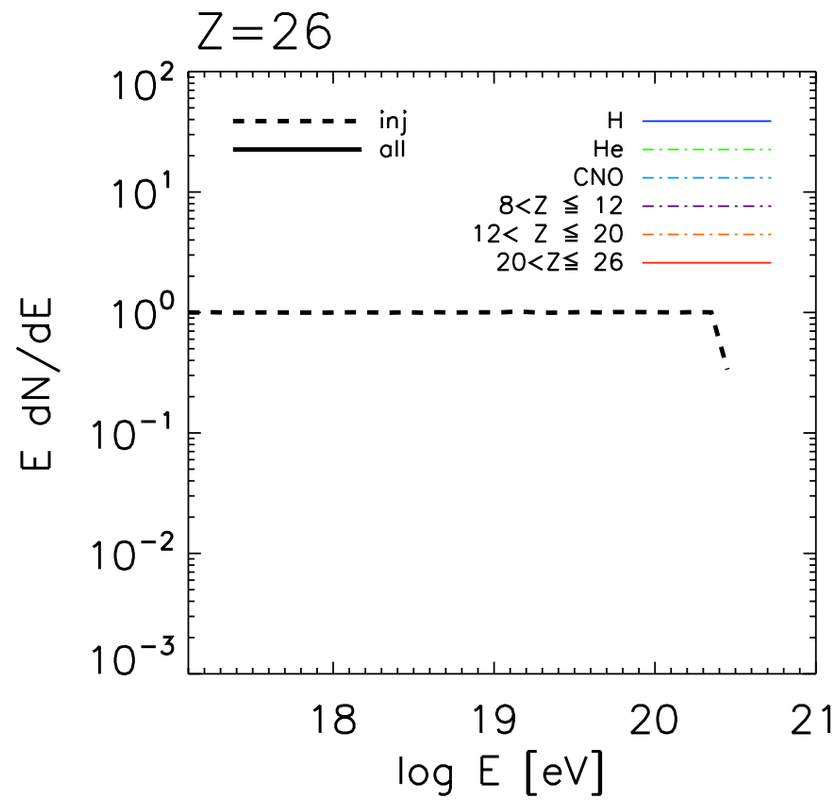

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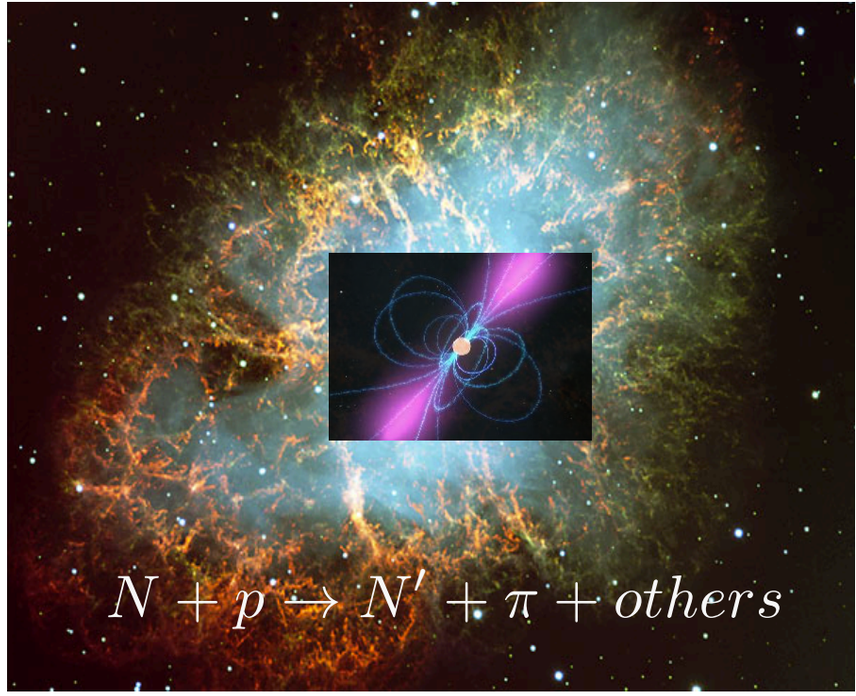

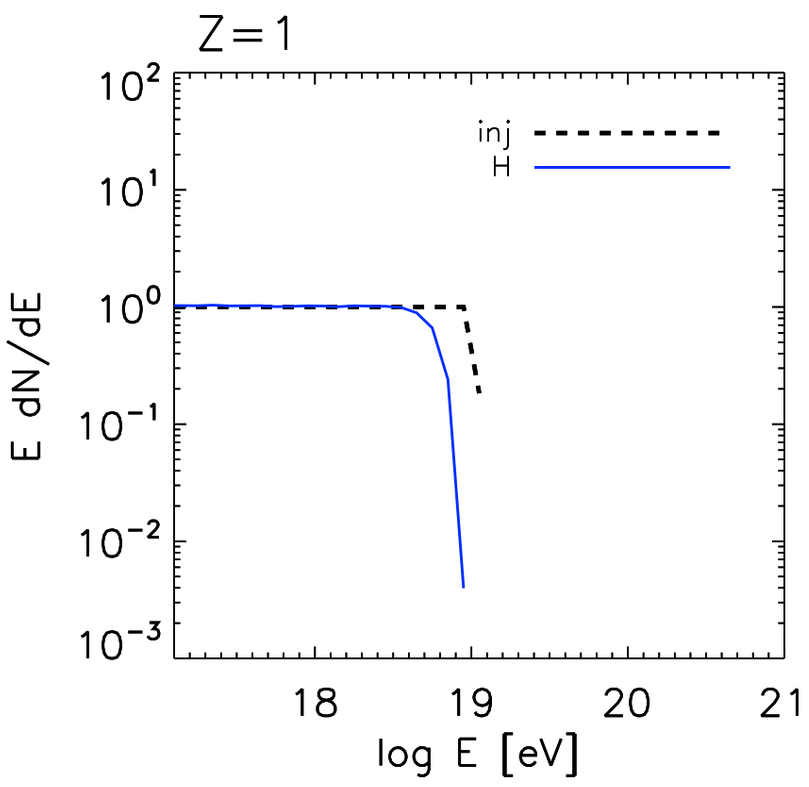

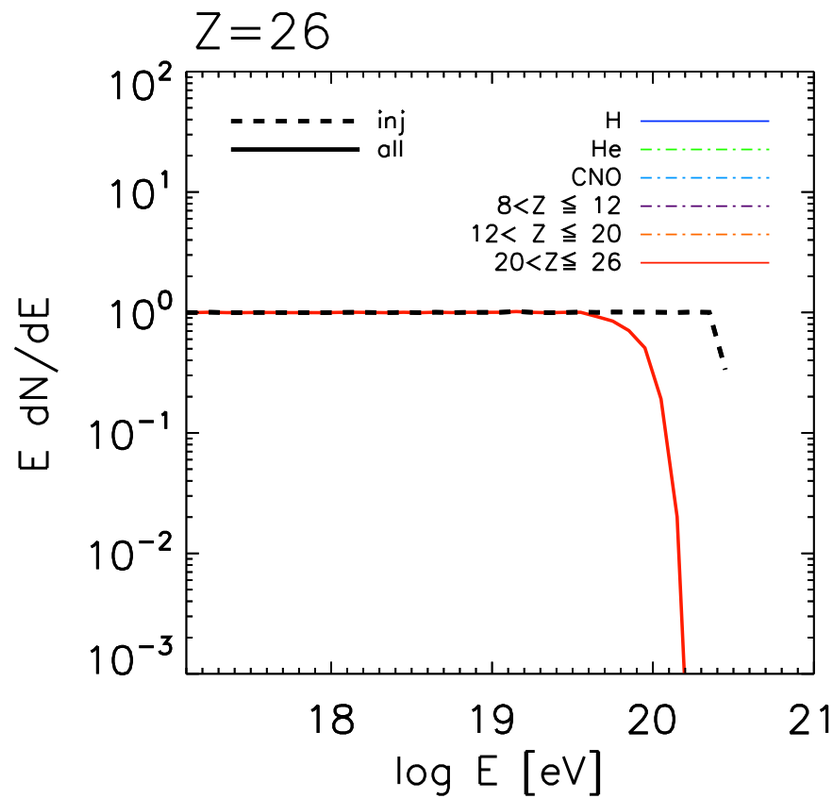

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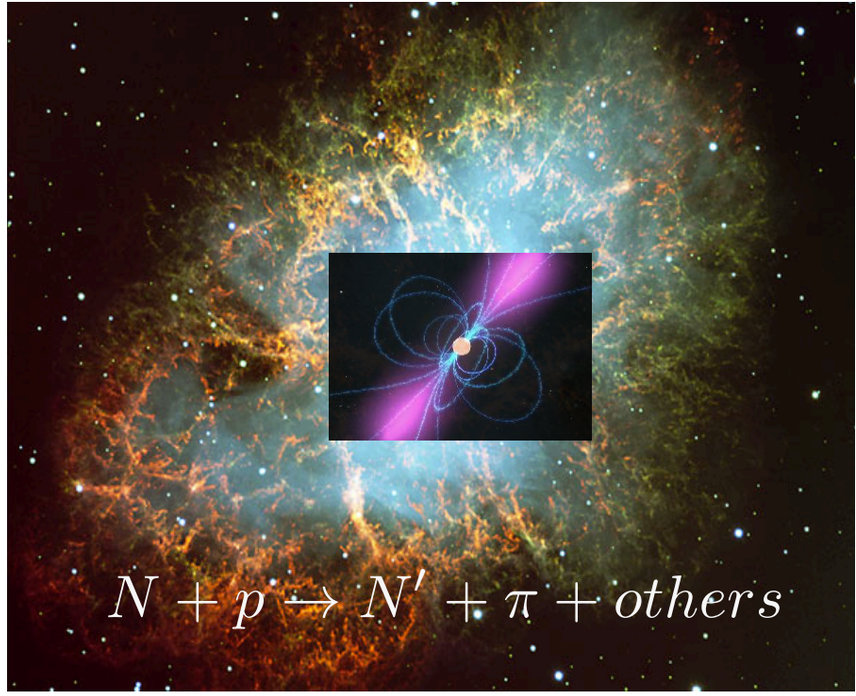

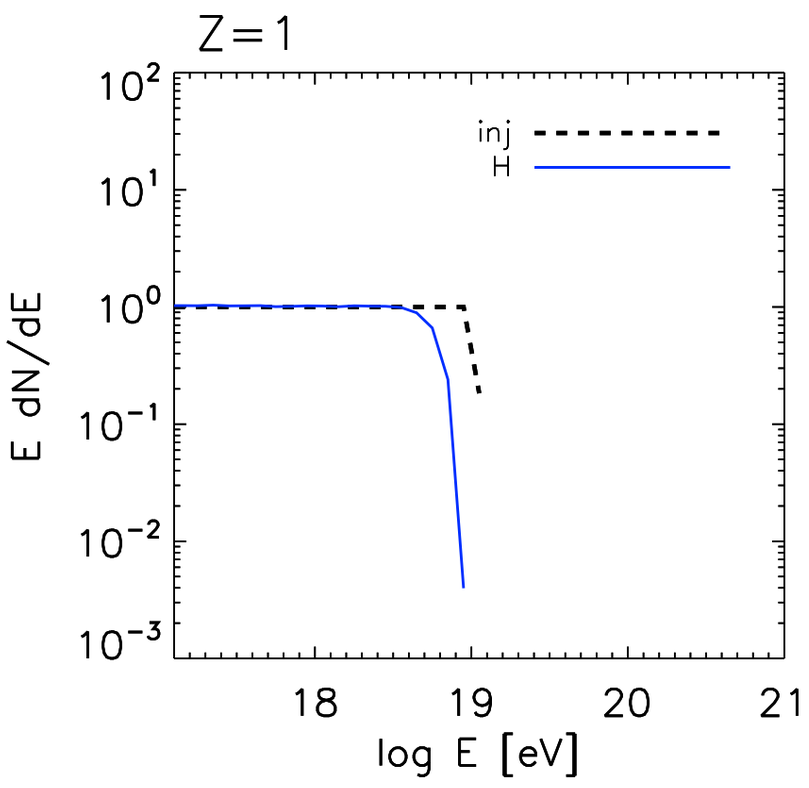

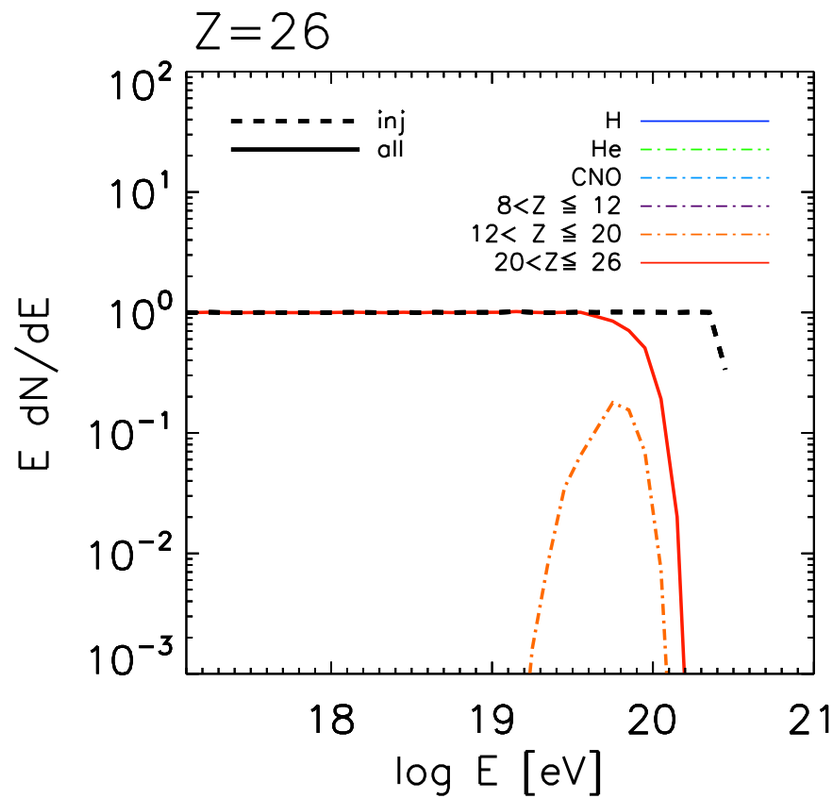

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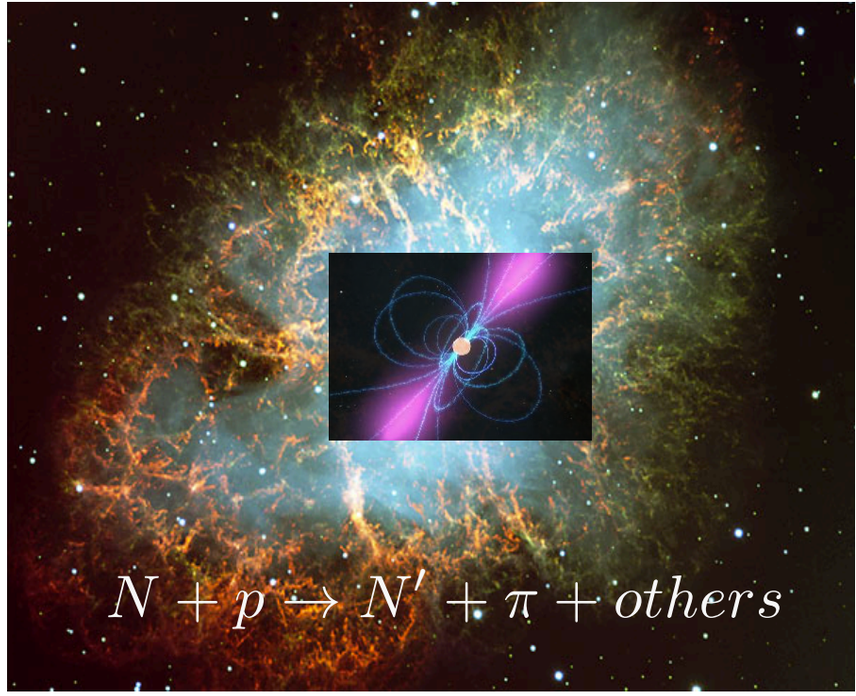

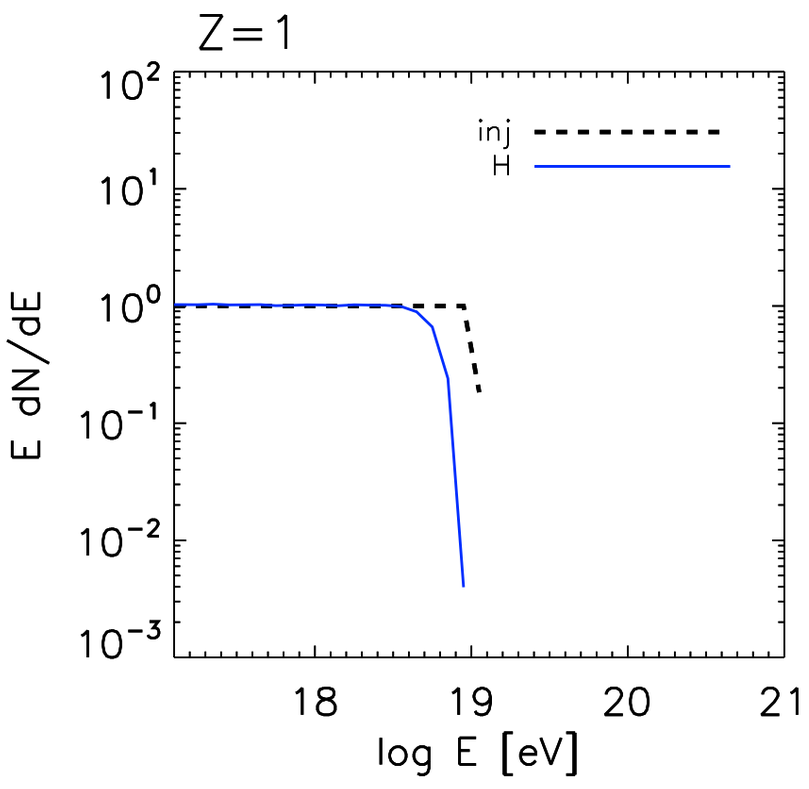

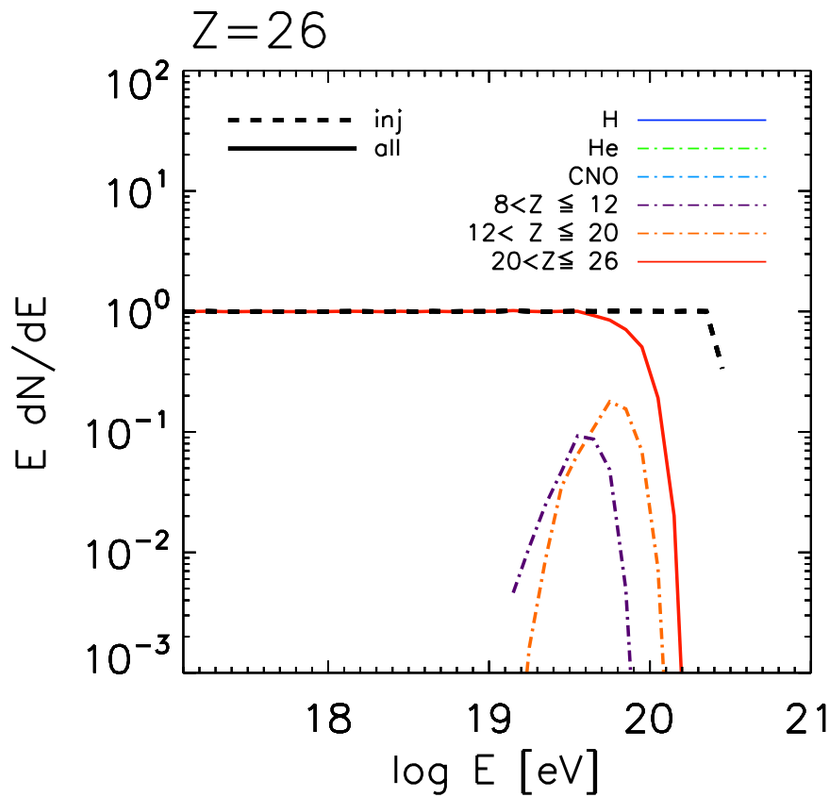

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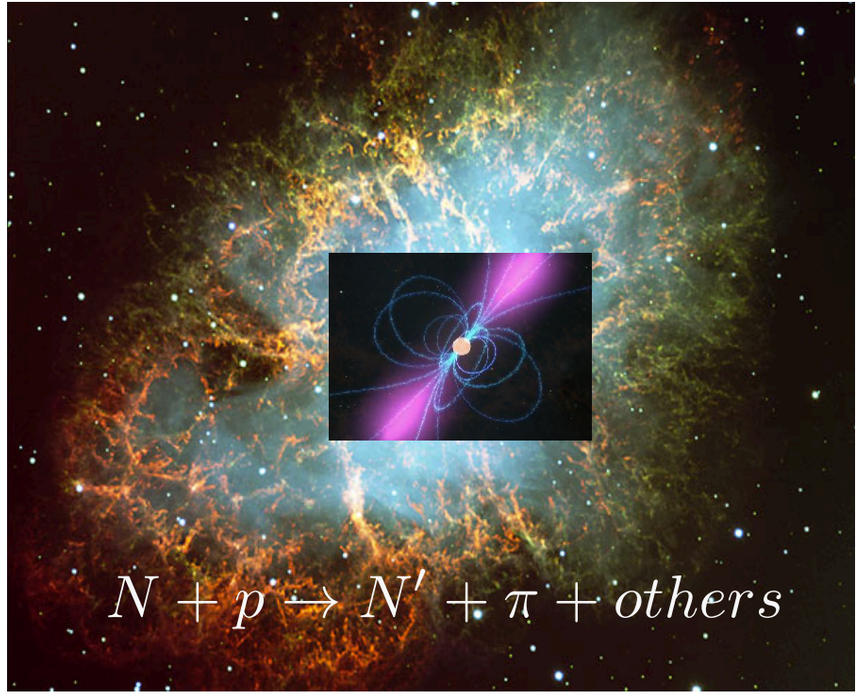

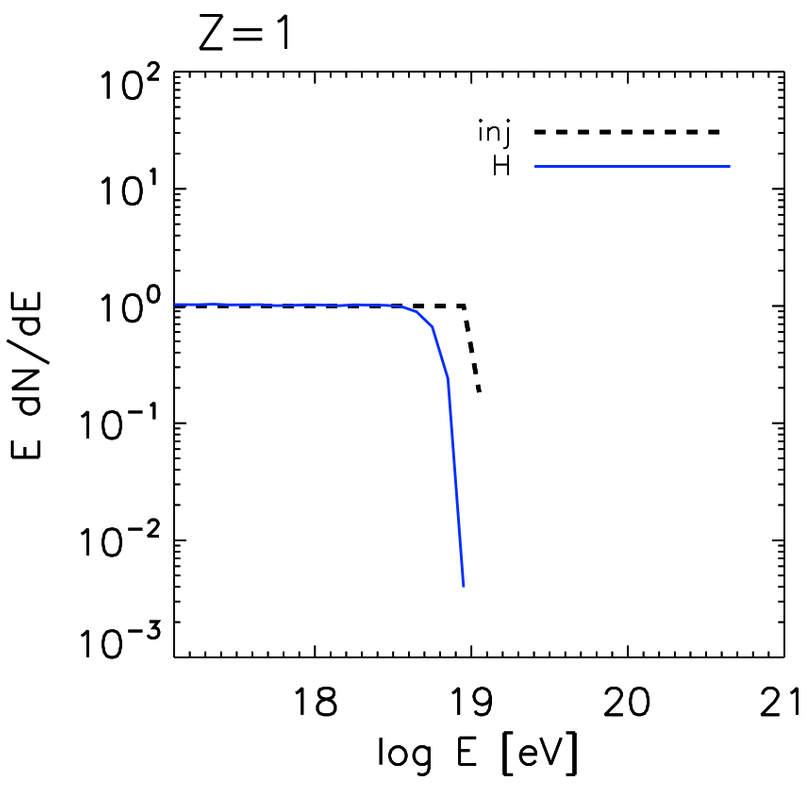

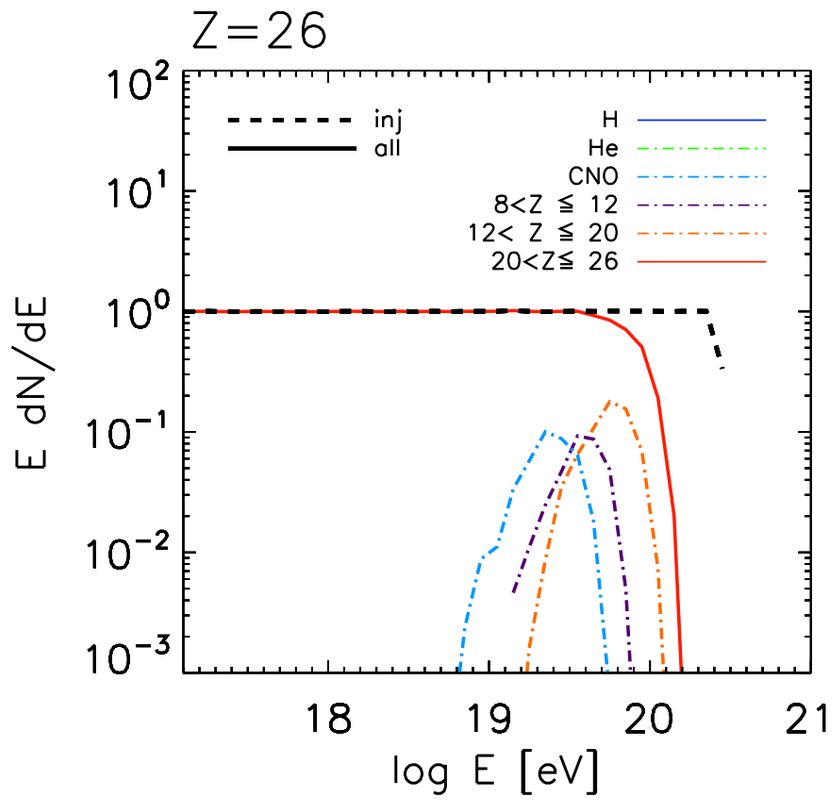

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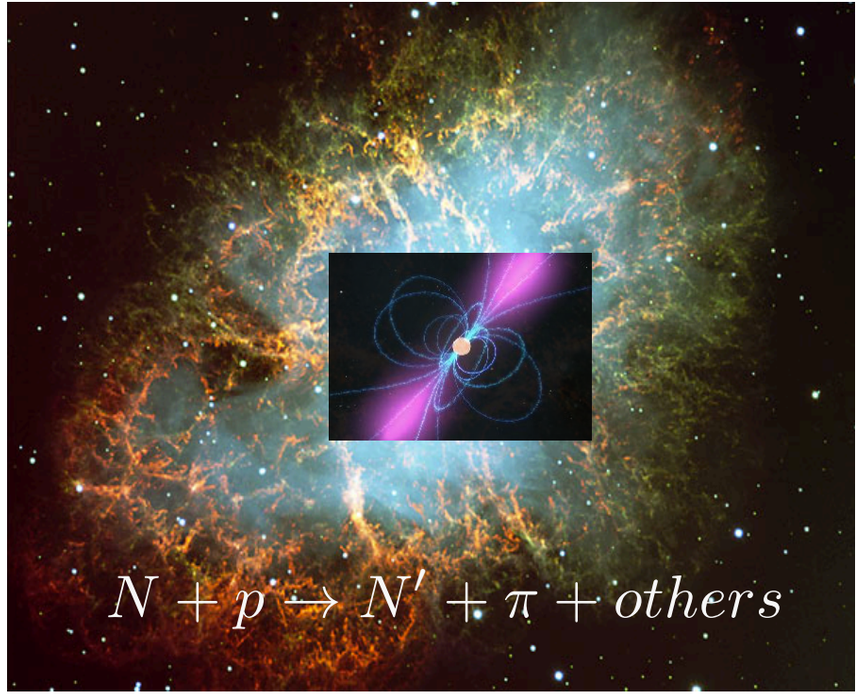

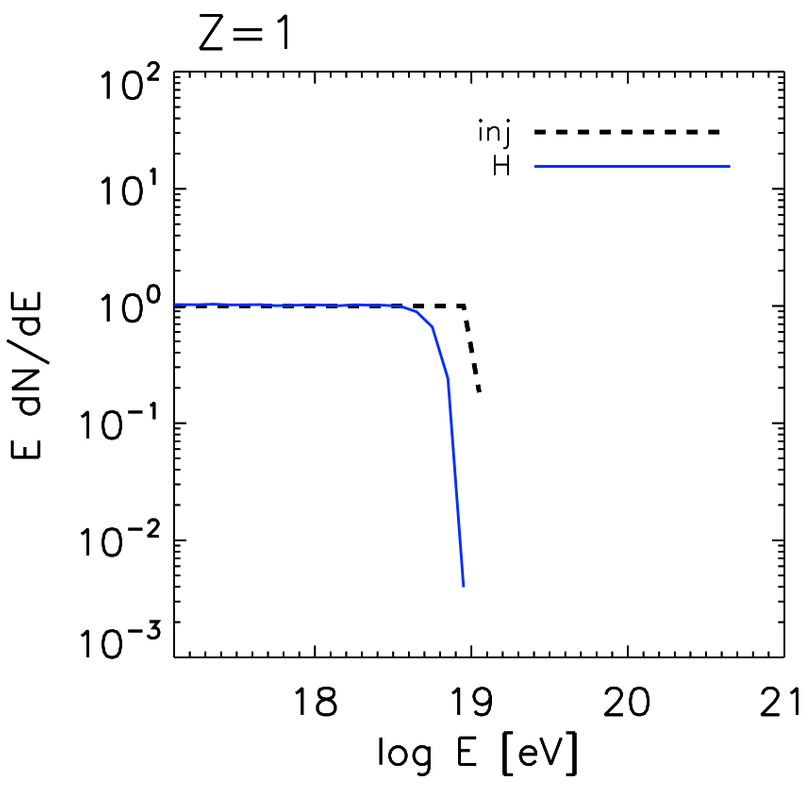

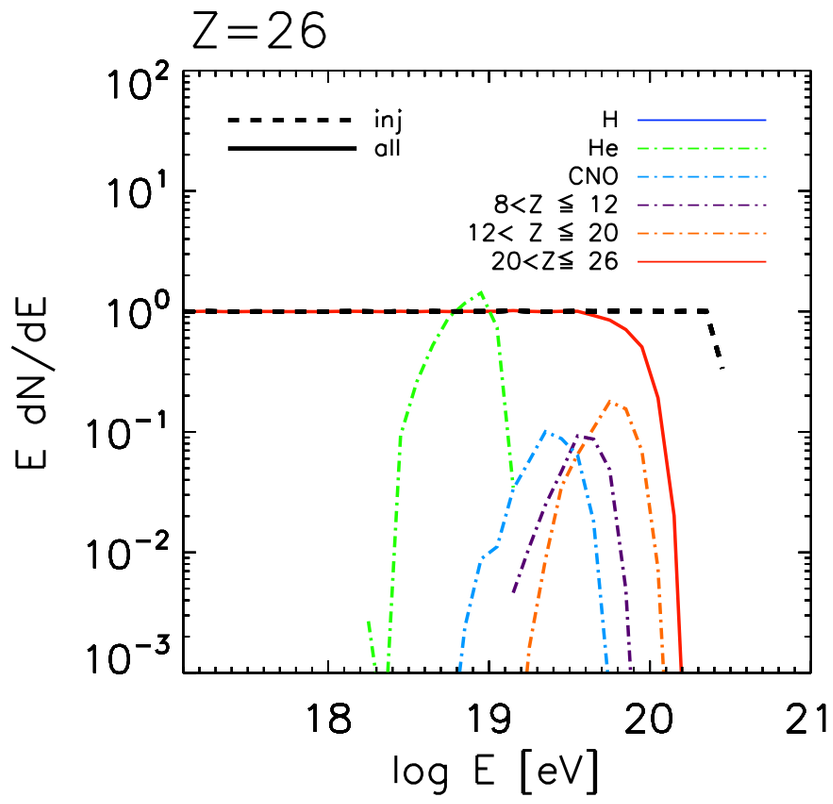

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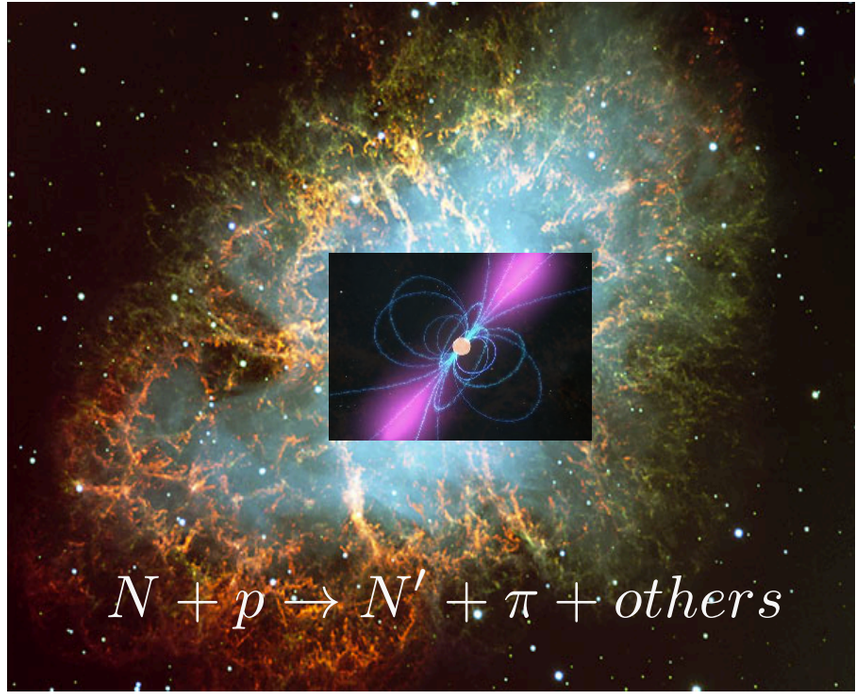

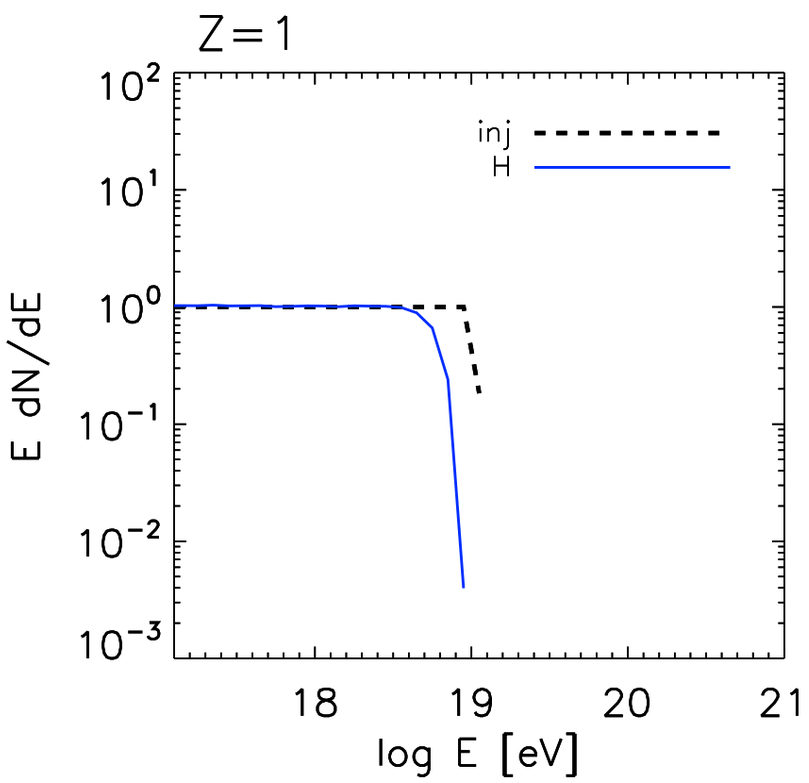

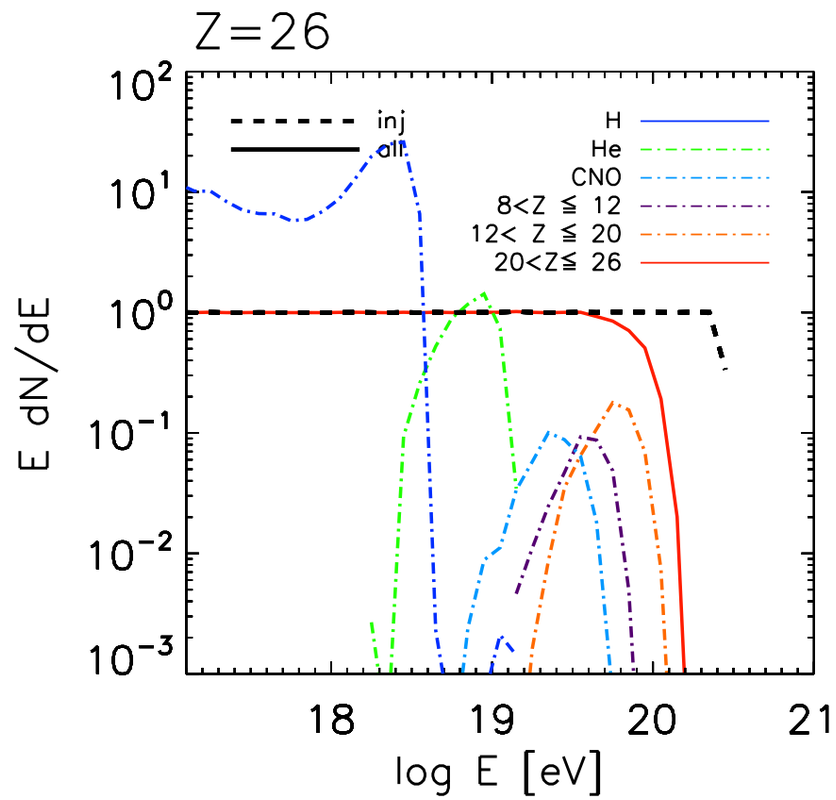

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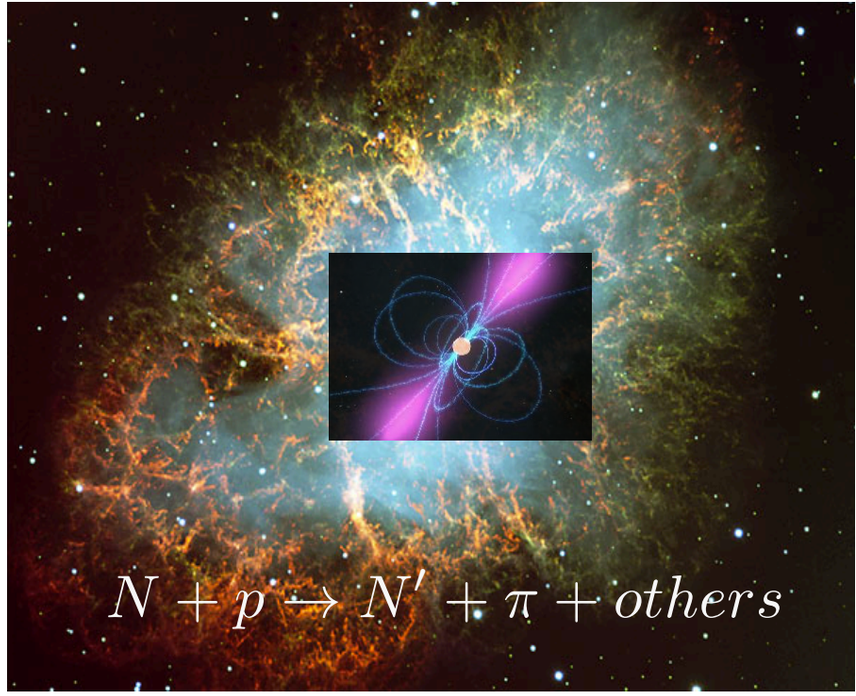

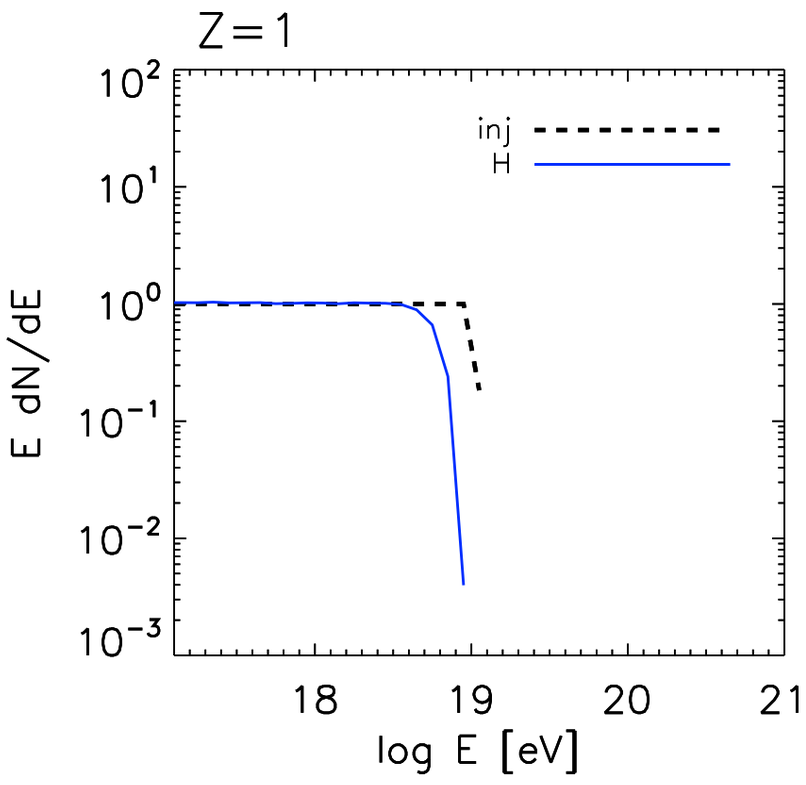

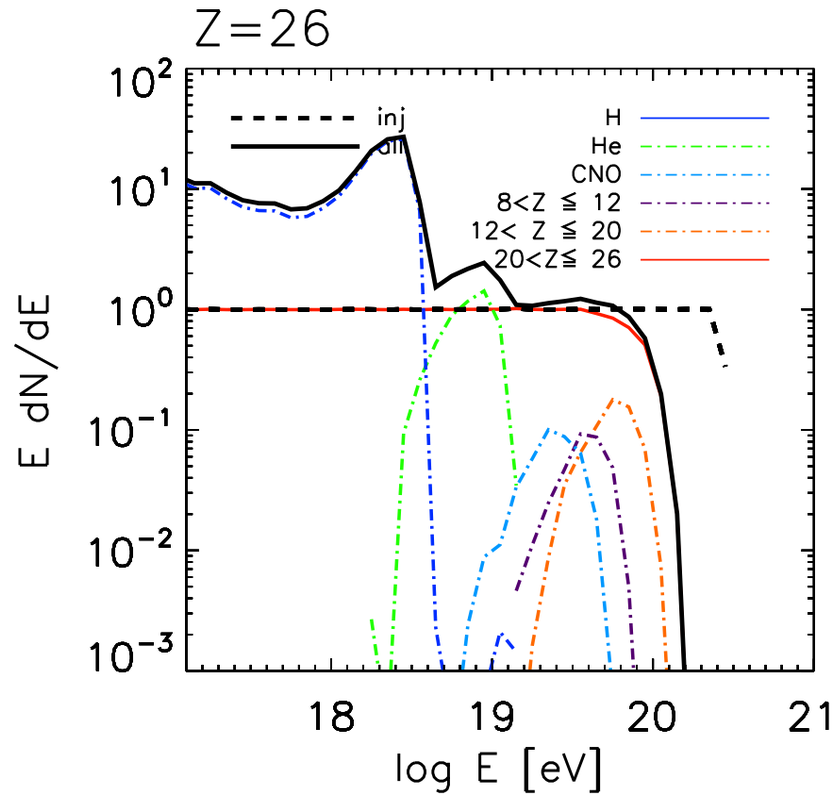

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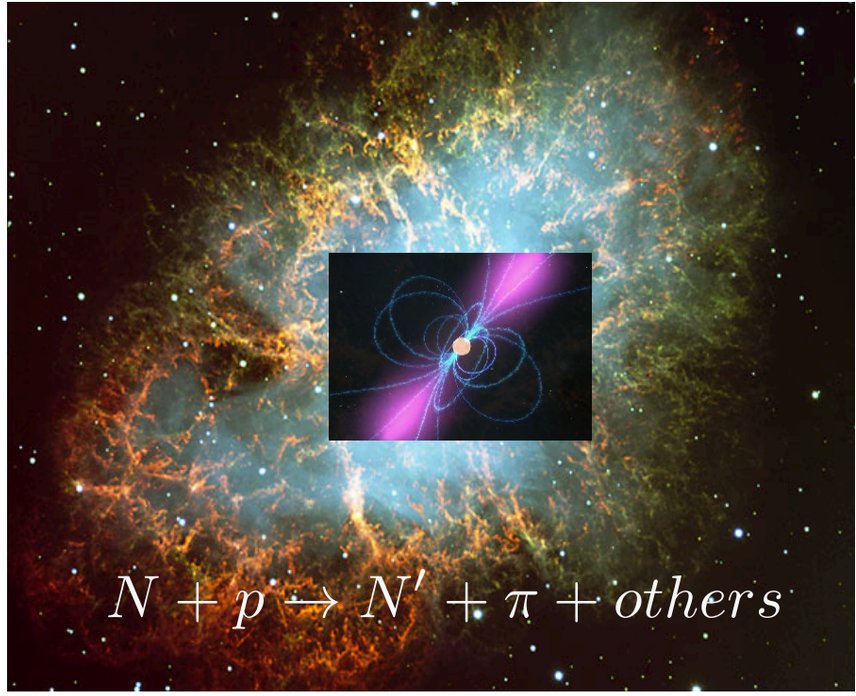
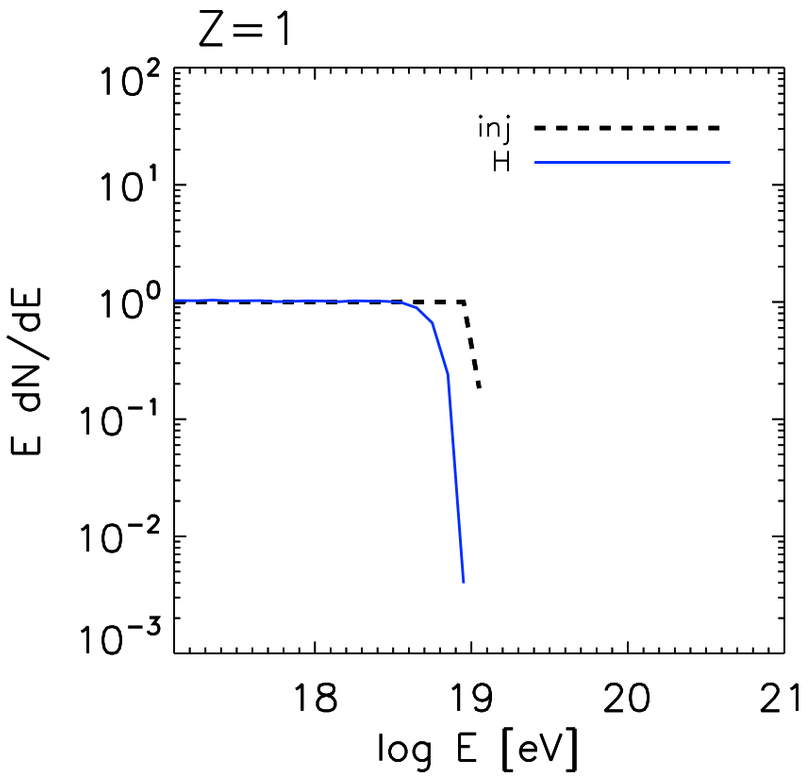
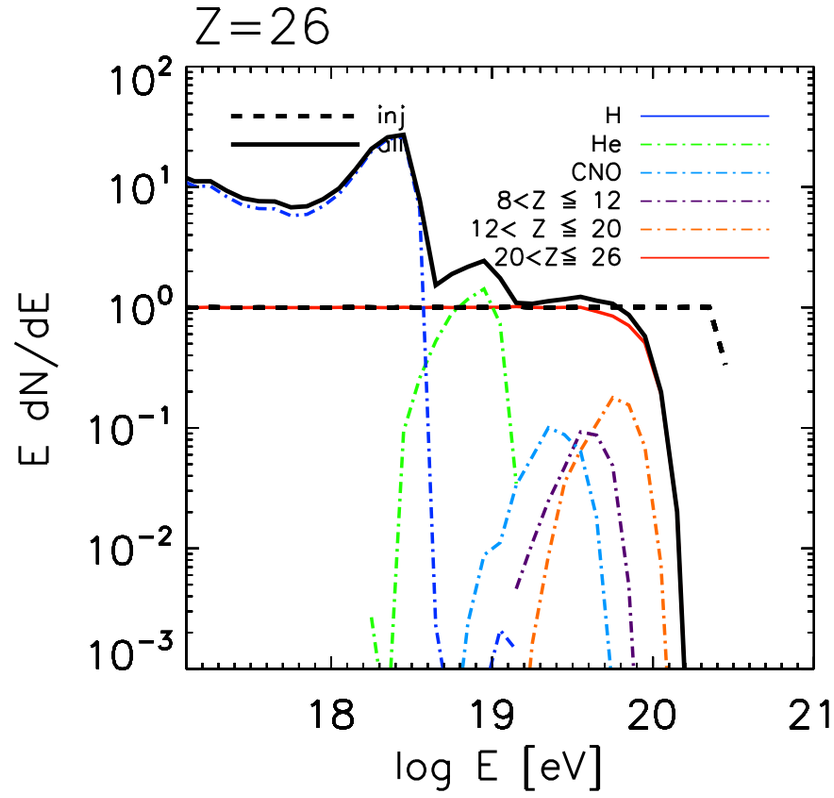
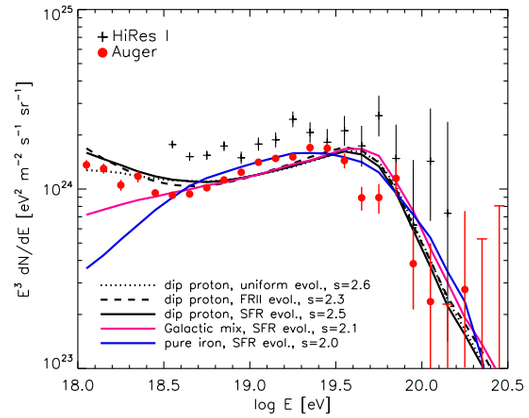
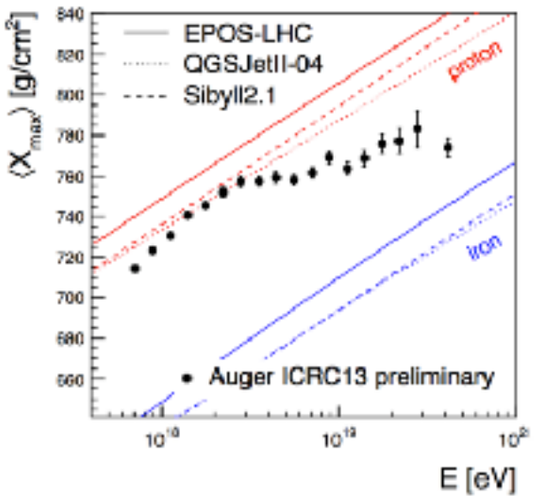
Monte Carlo simulation tracking particle propagation







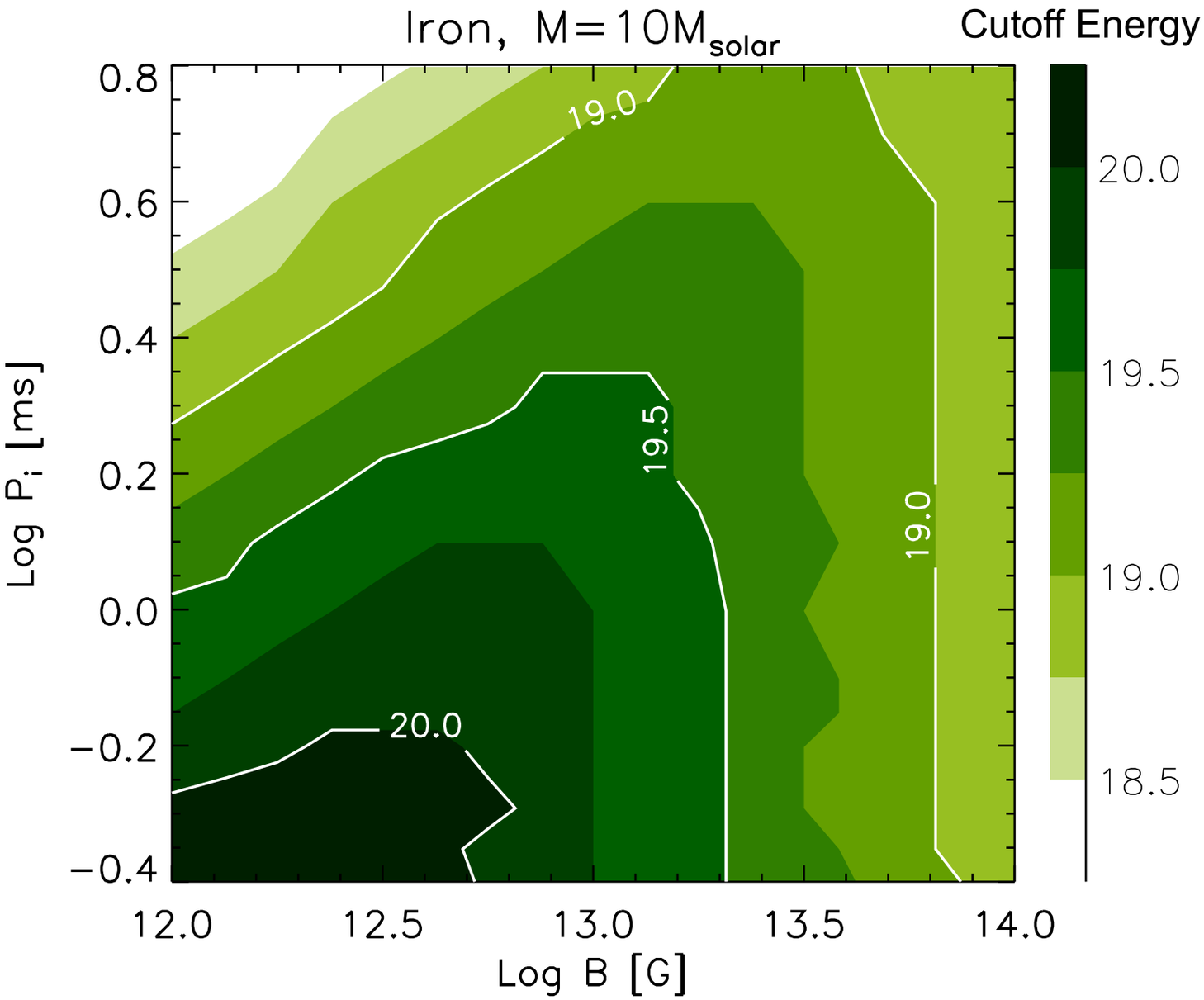




$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$

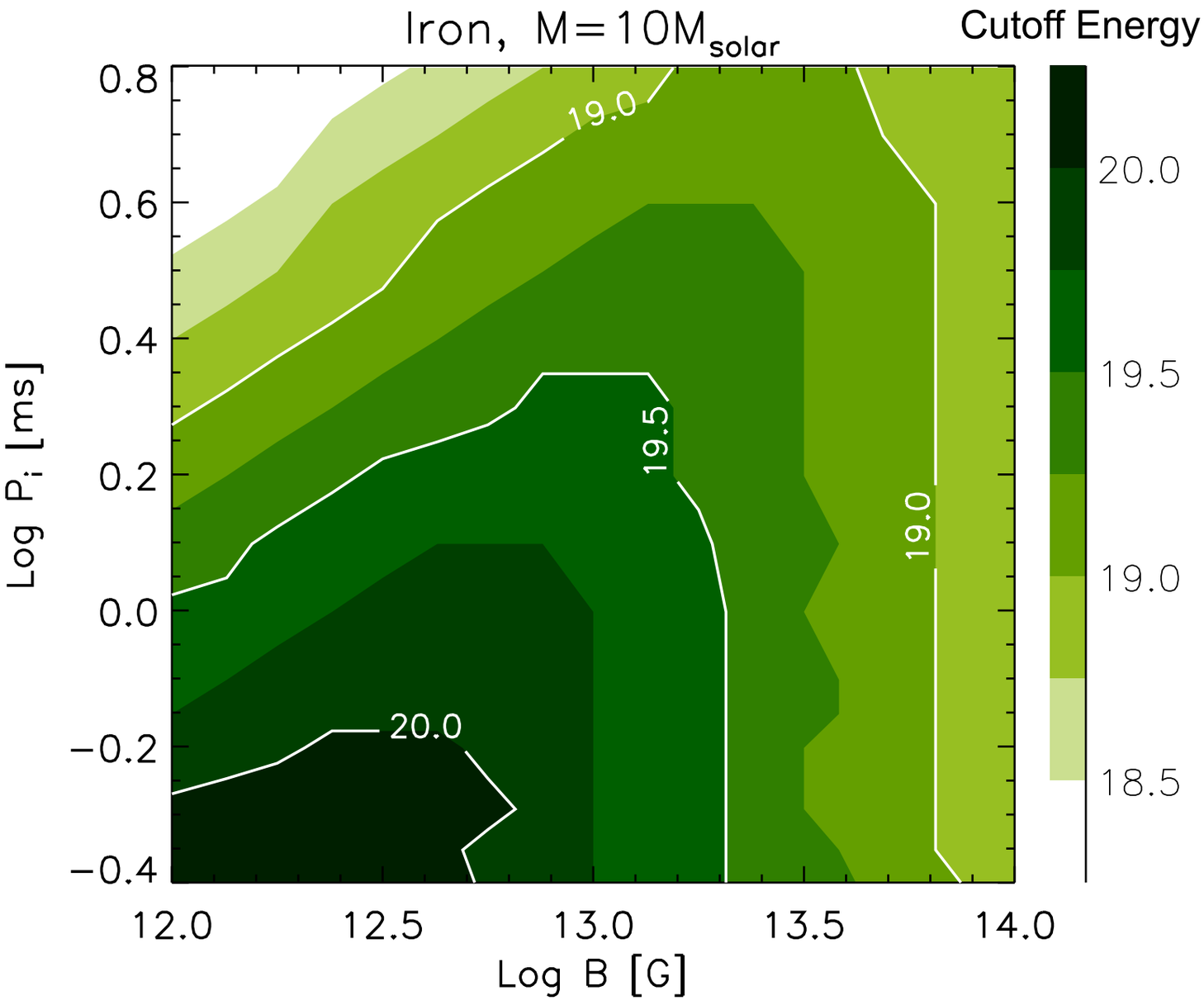
KF, Kotera & Olinto (2012)

UHE-allowed Pulsars



KF, Kotera & Olinto (2012)

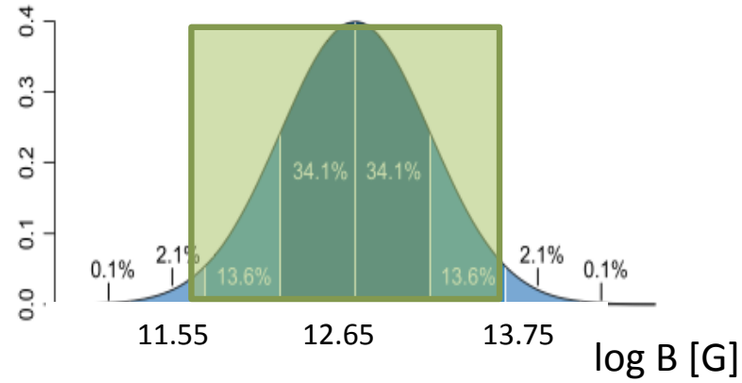
UHE-allowed Pulsars

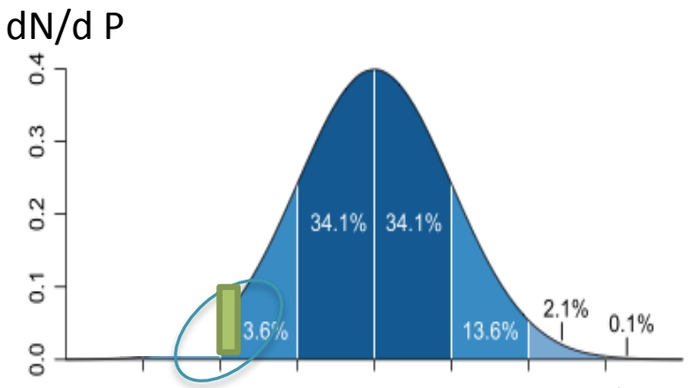


KF, Kotera & Olinto (2012)

Pulsar distribution in the galaxy

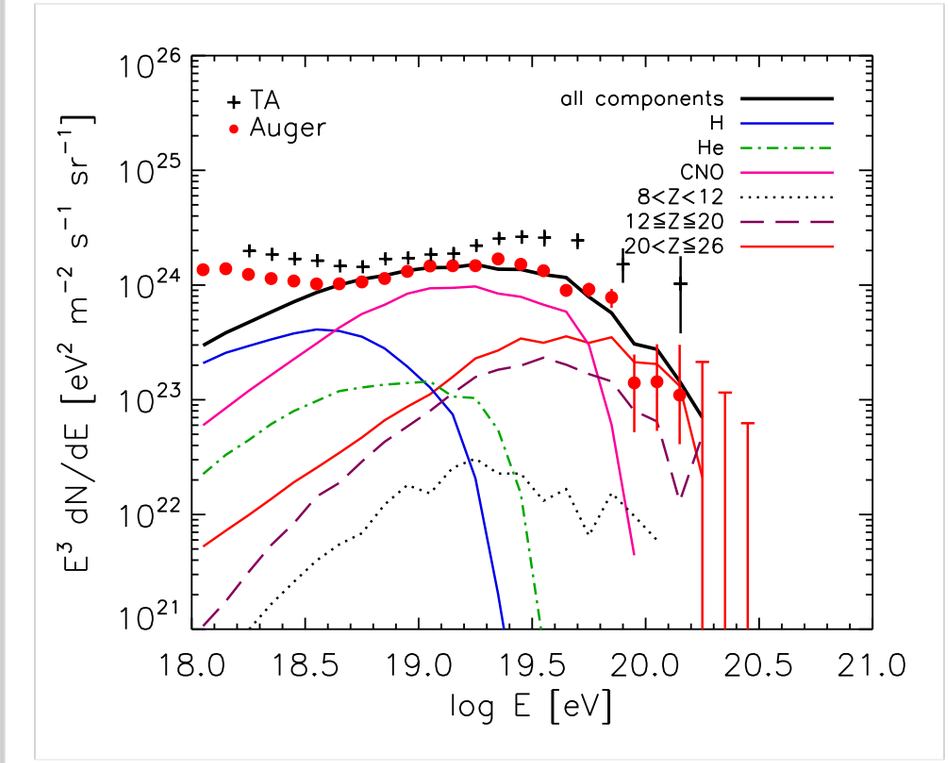
Faucher-Giguère & Kaspi 06





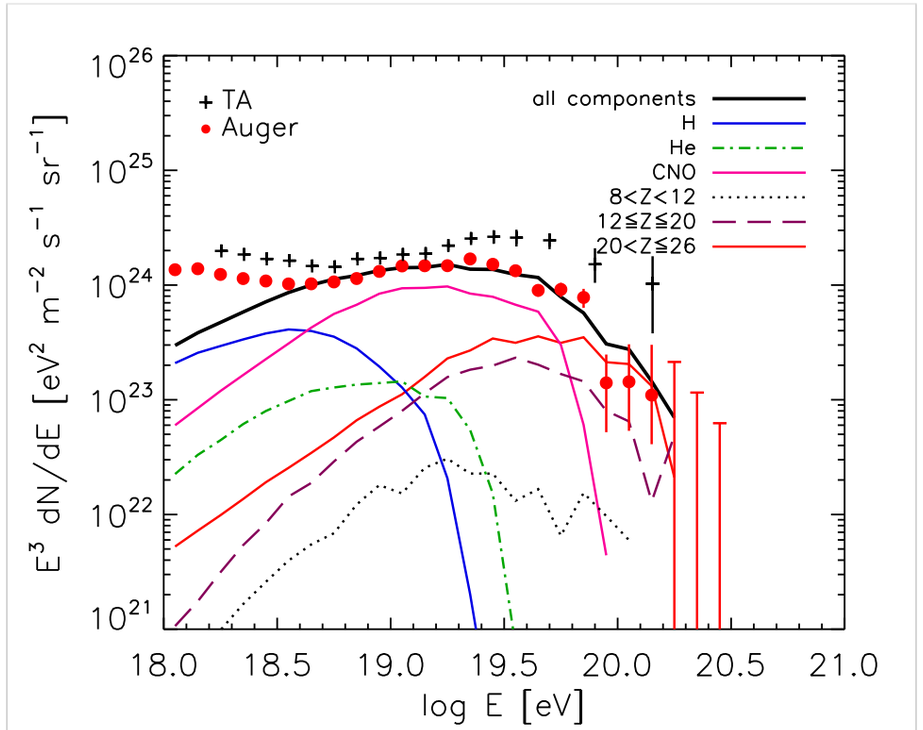
Upper limit of rotational speed

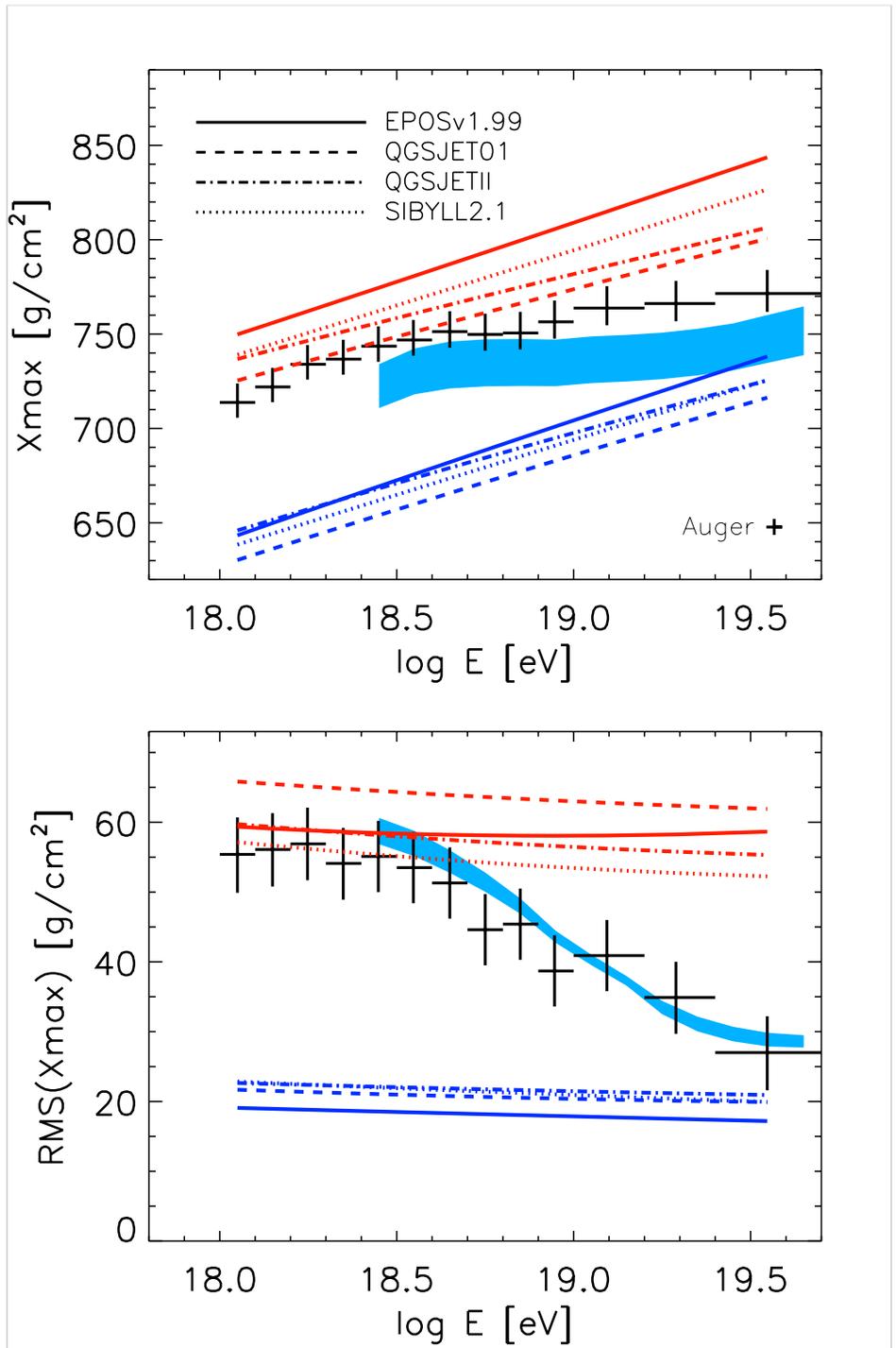
Integrated Extragalactic Pulsars



KF, Kotera & Olinto (2012, 2013)

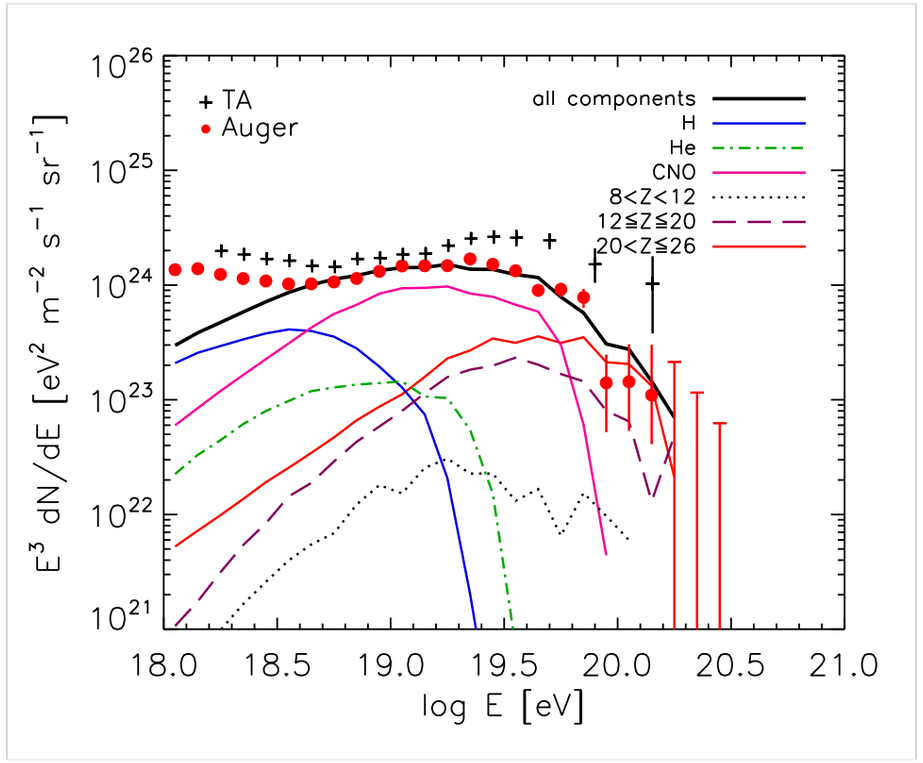
Integrated Extragalactic Pulsars

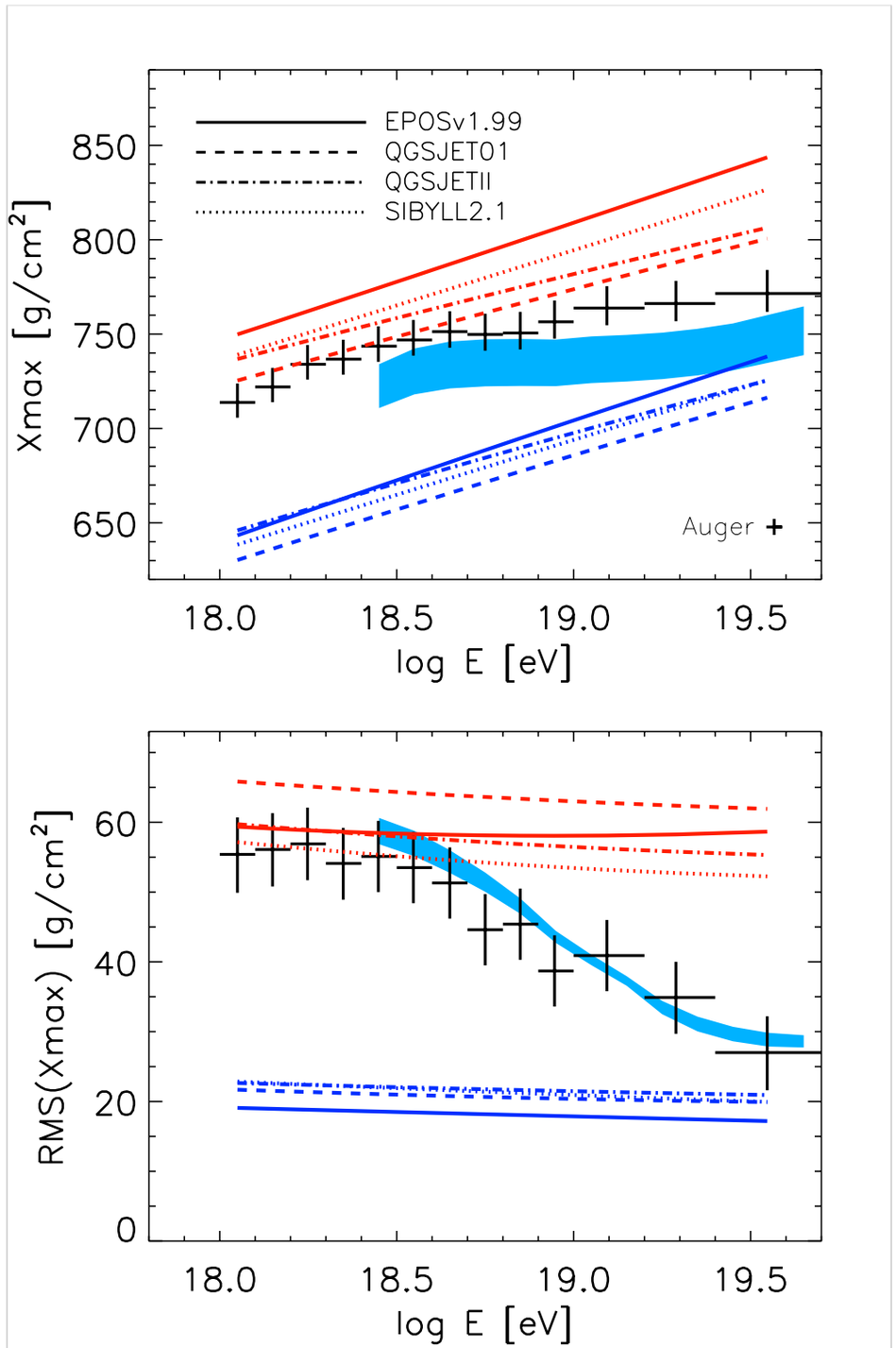




KF, Kotera & Olinto (2012, 2013)

Integrated Extragalactic Pulsars

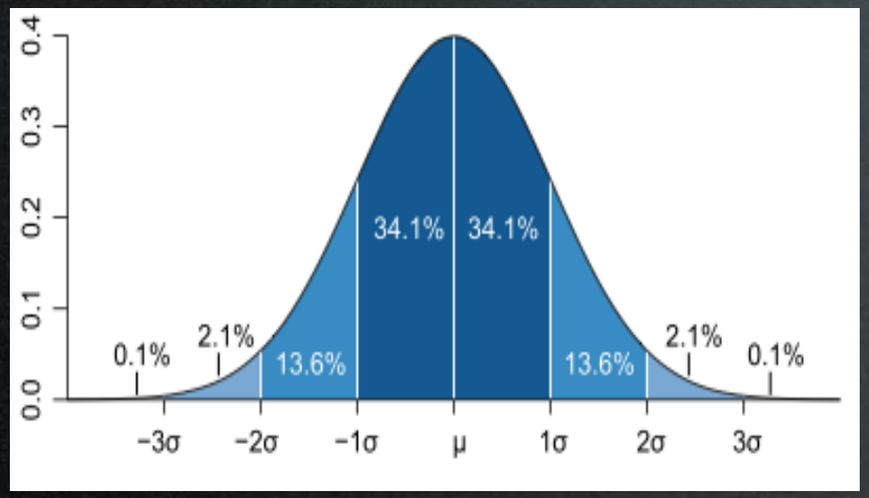


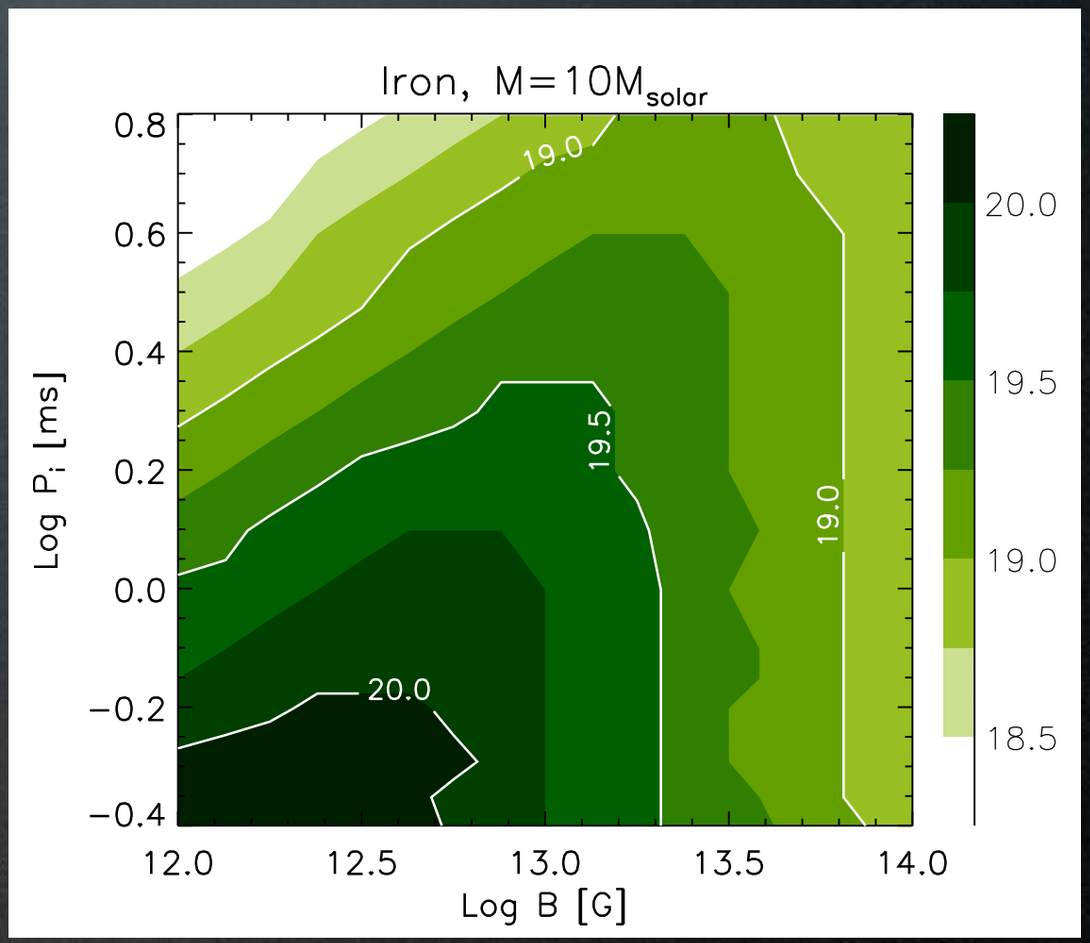


Newborn pulsars can be successful UHECR accelerators

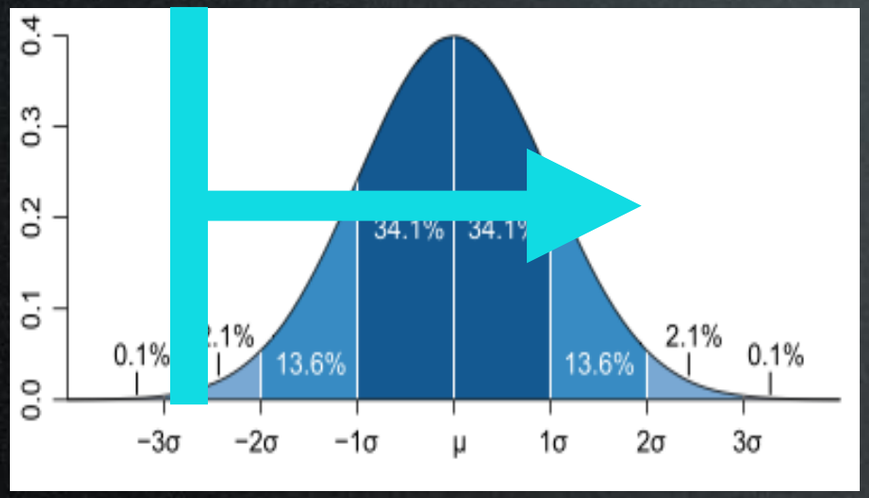
KF, Kotera & Olinto (2012, 2013)

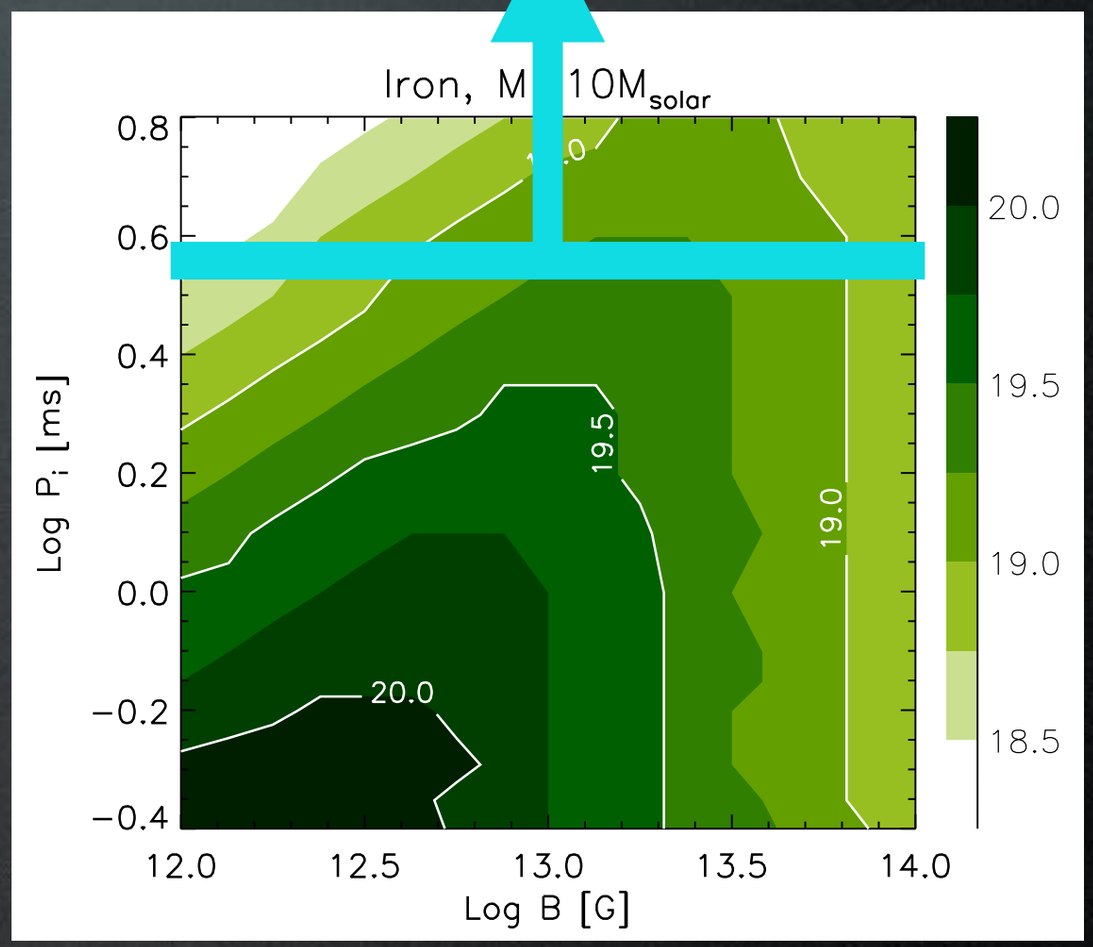
What about their Galactic Counterparts?



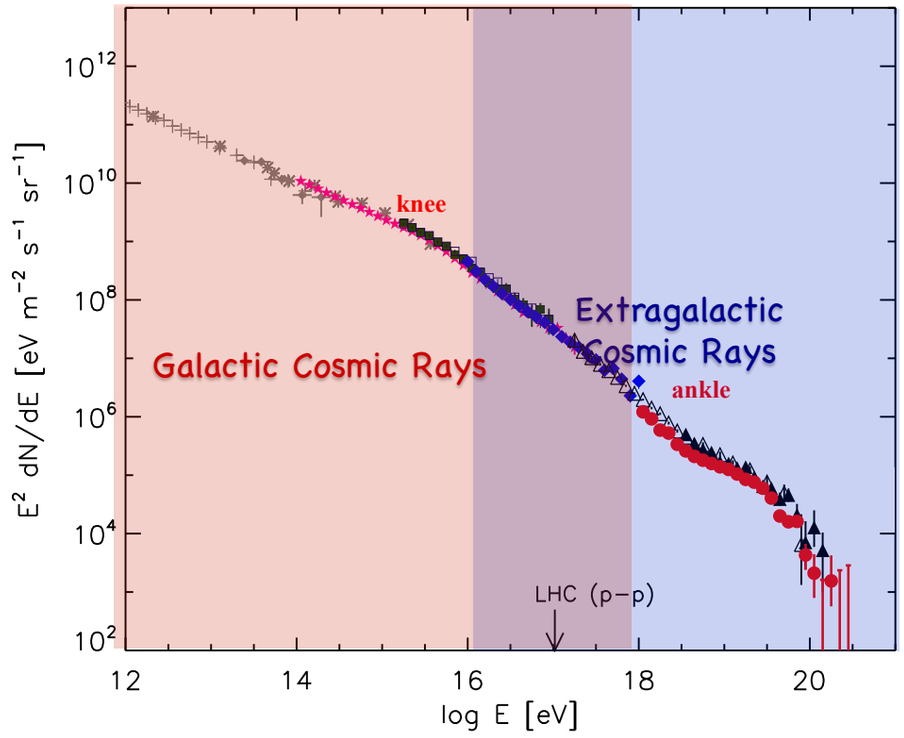


What about their Galactic Counterparts?

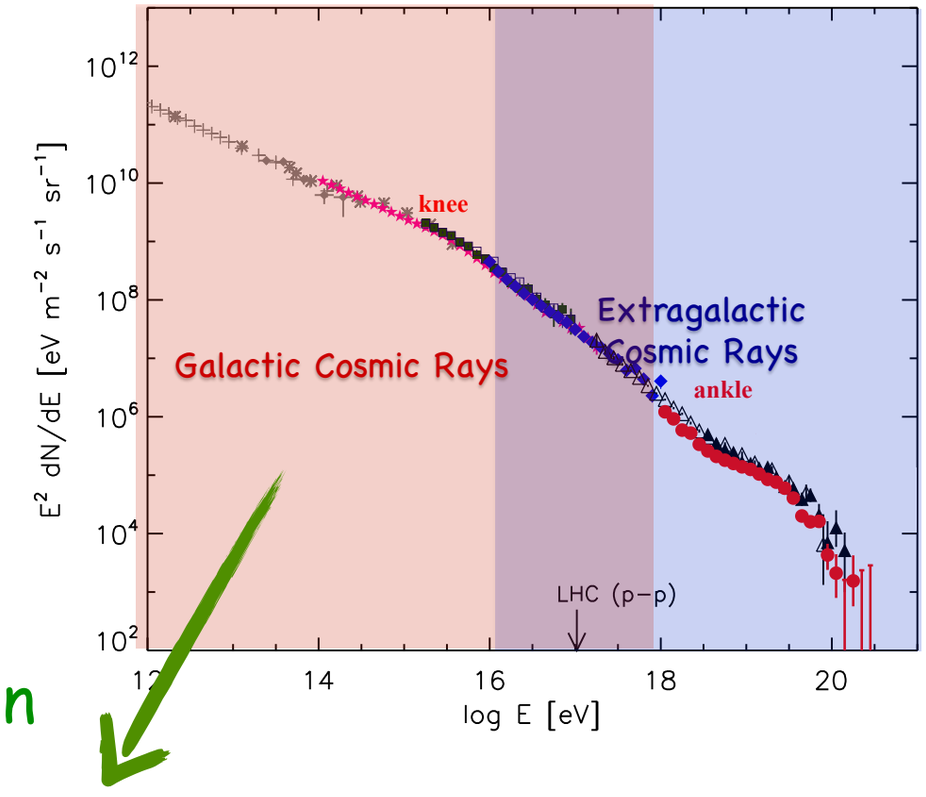




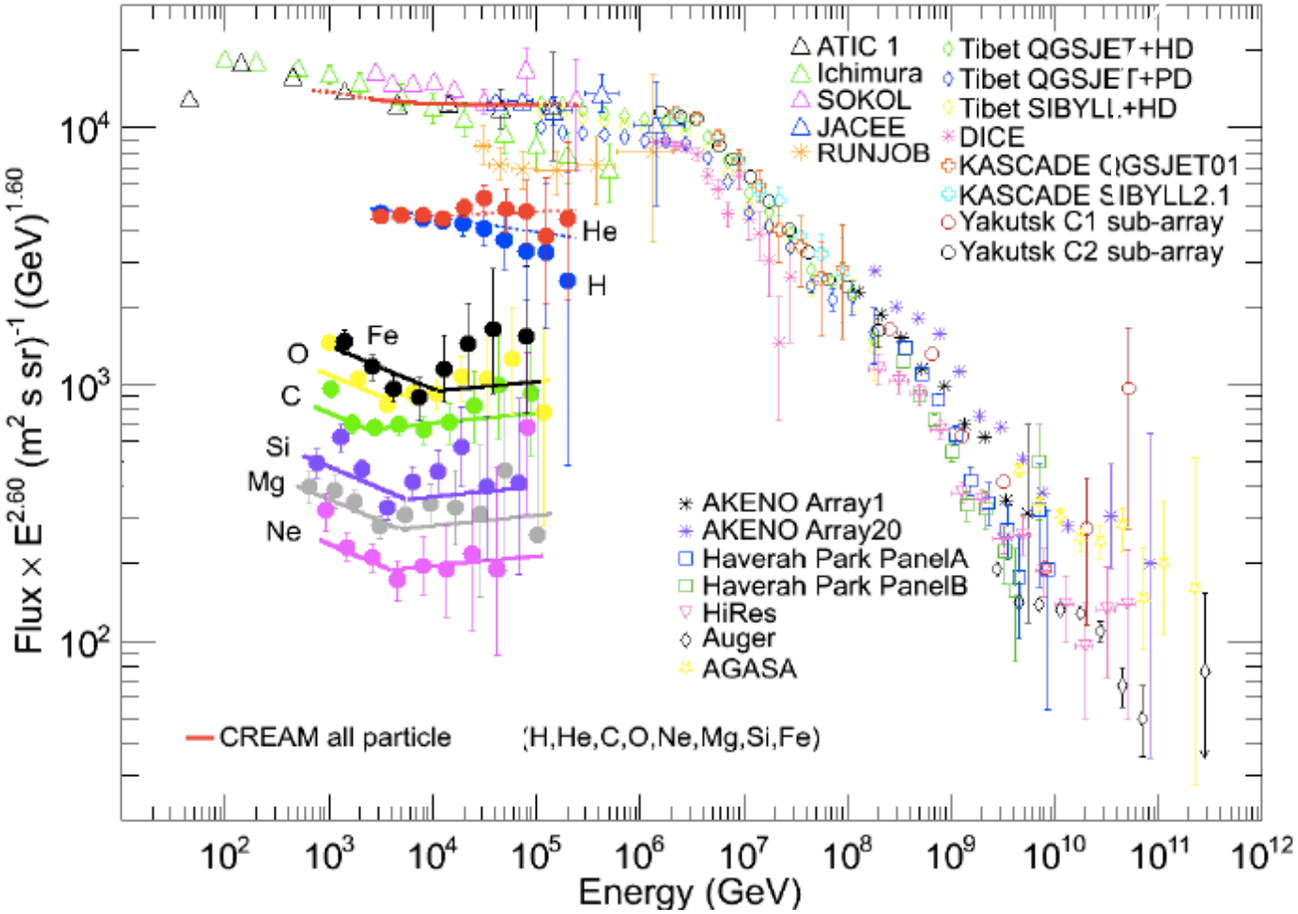
Galactic - Extragalactic Transition



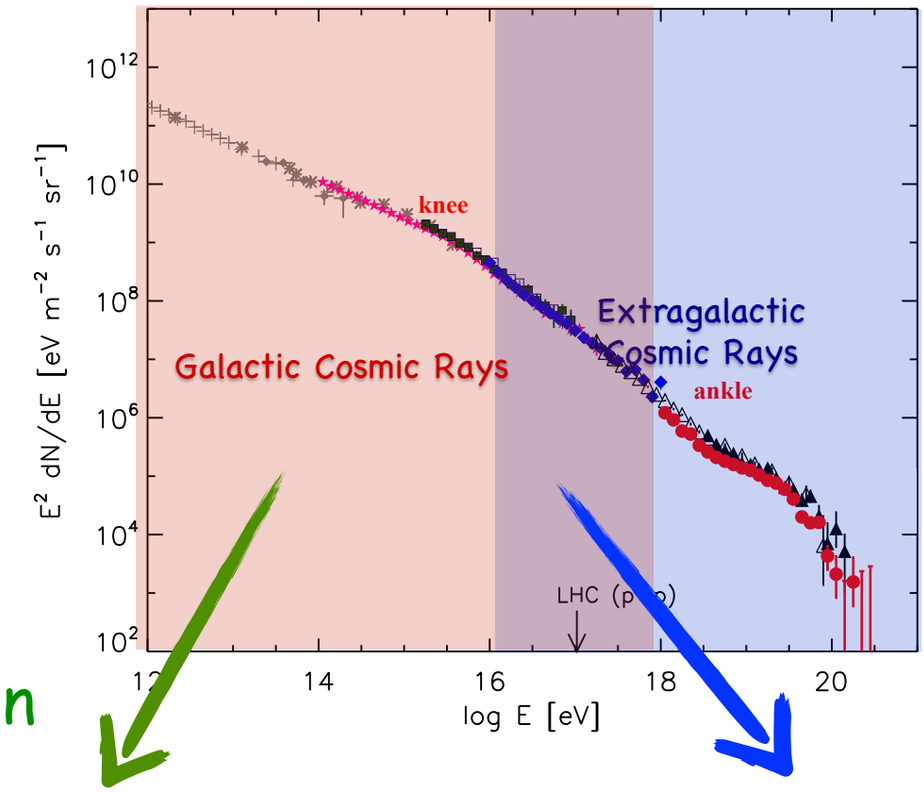
Galactic - Extragalactic Transition



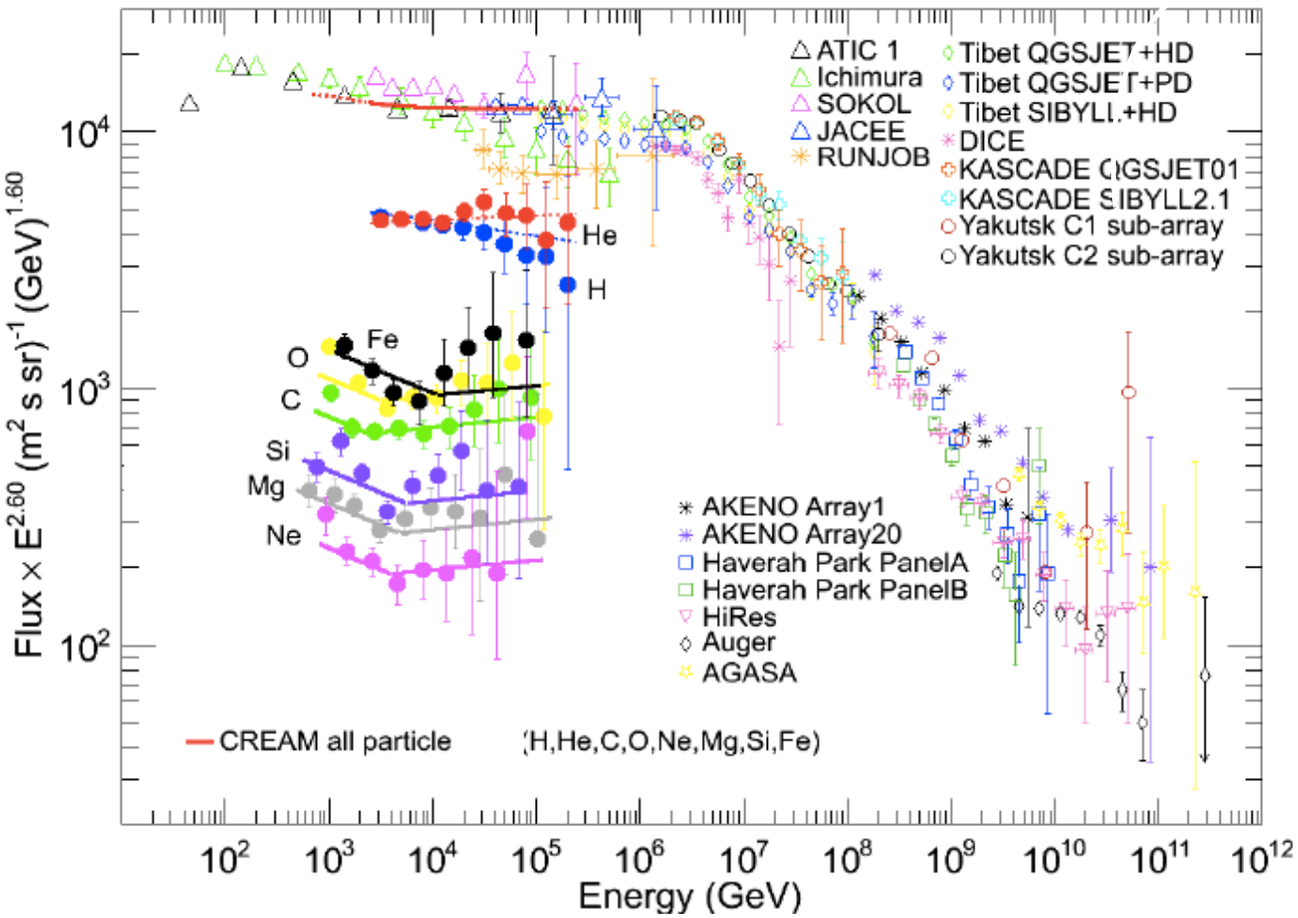
Mostly light composition below the knee



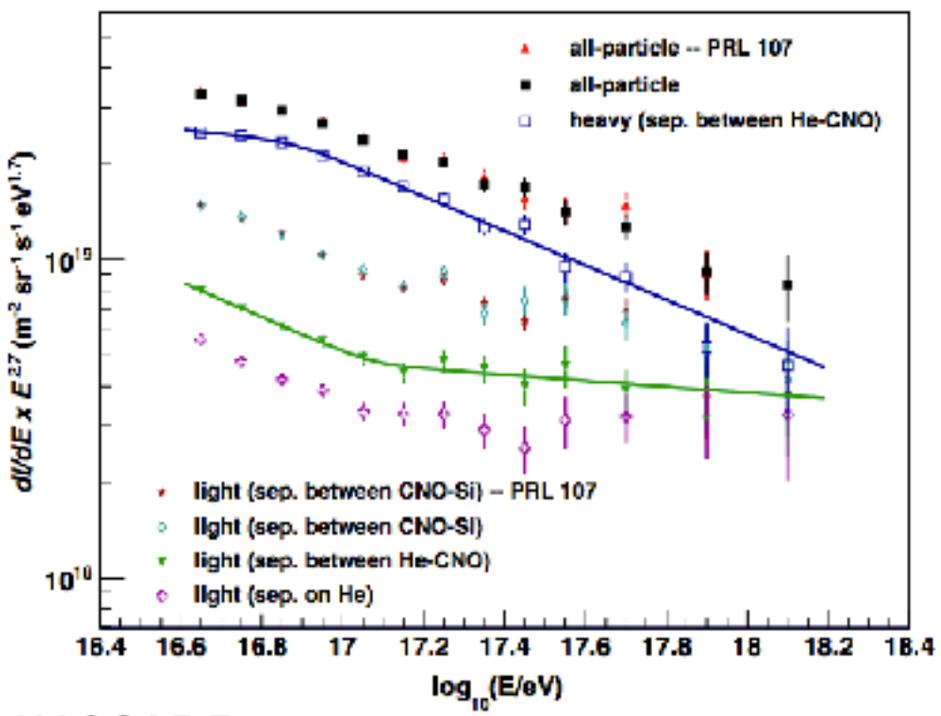
Galactic - Extragalactic Transition



Mostly light composition below the knee

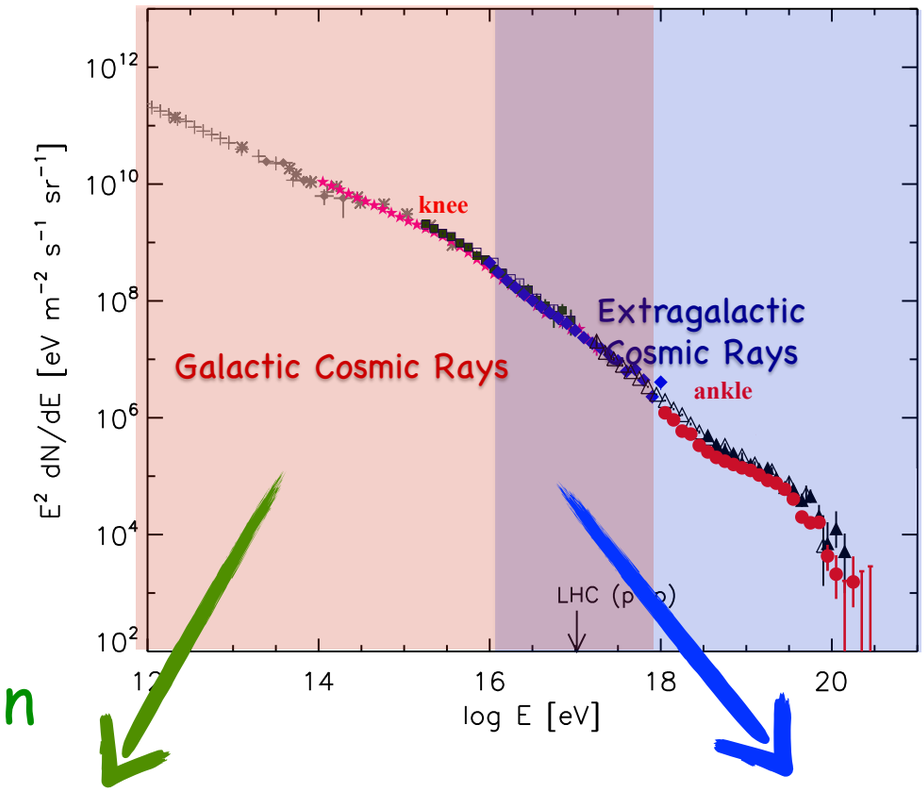


But changed to heavy dominated at the transition regime

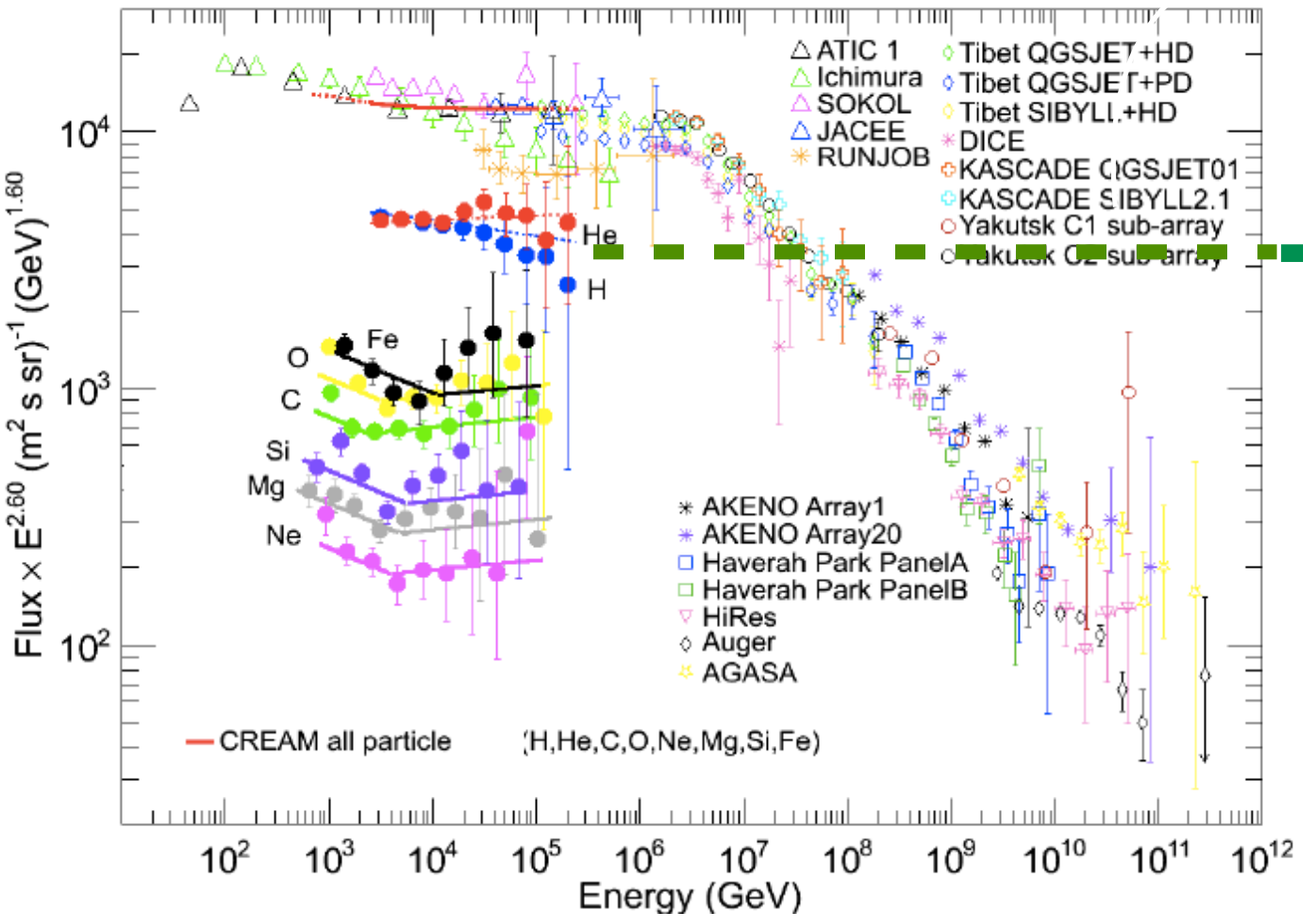


KASCADE,

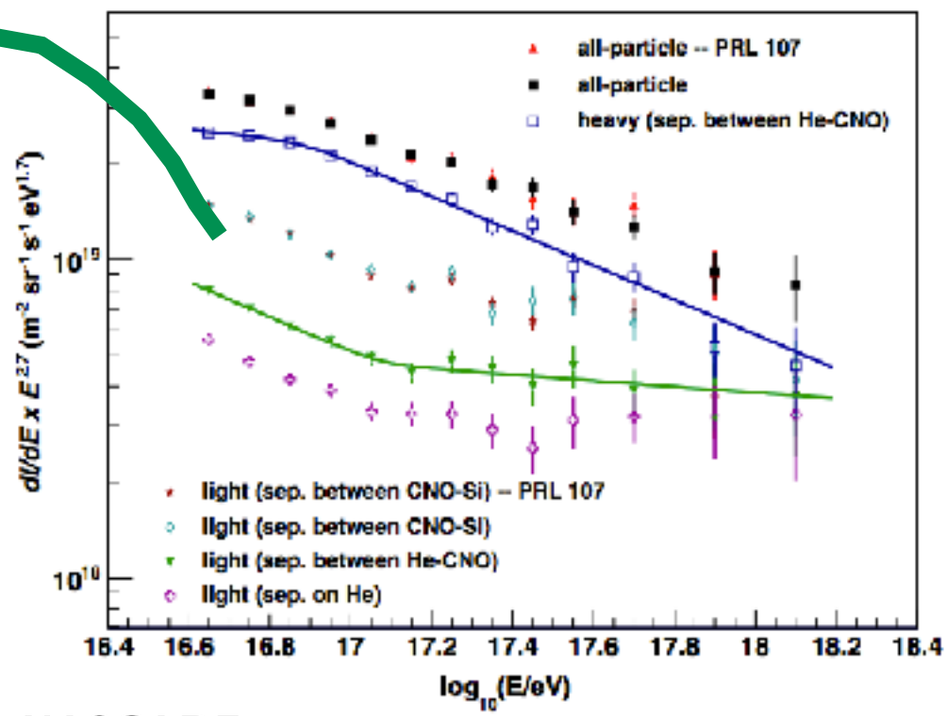
Galactic - Extragalactic Transition



Mostly light composition below the knee

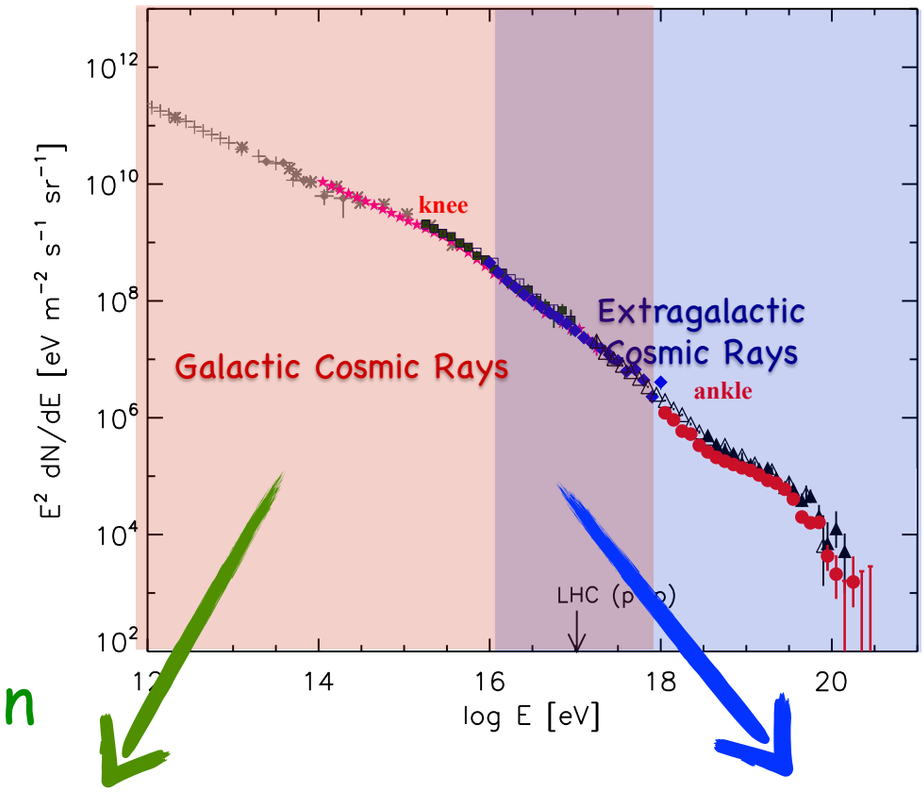


But changed to heavy dominated at the transition regime

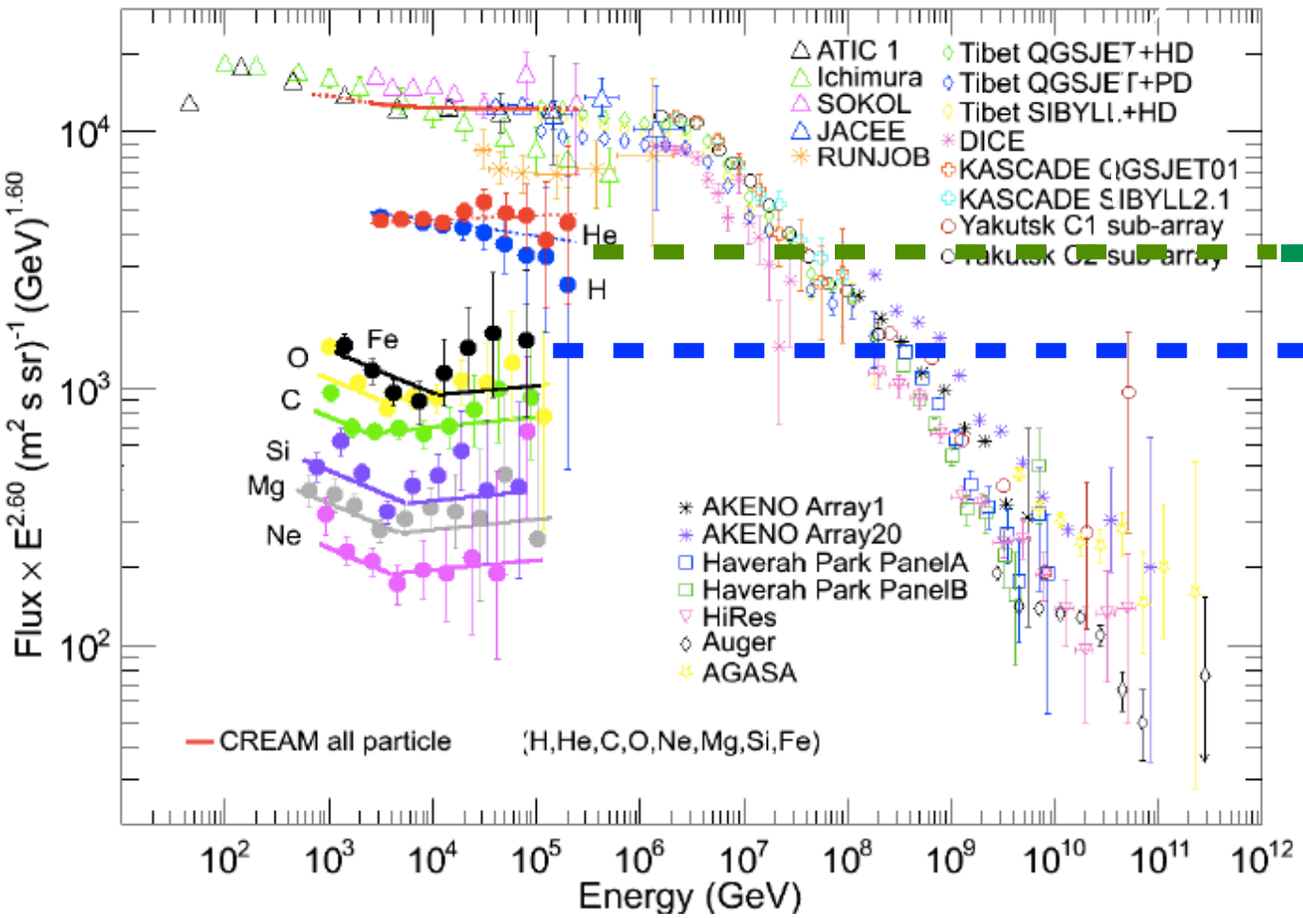


KASCADE,

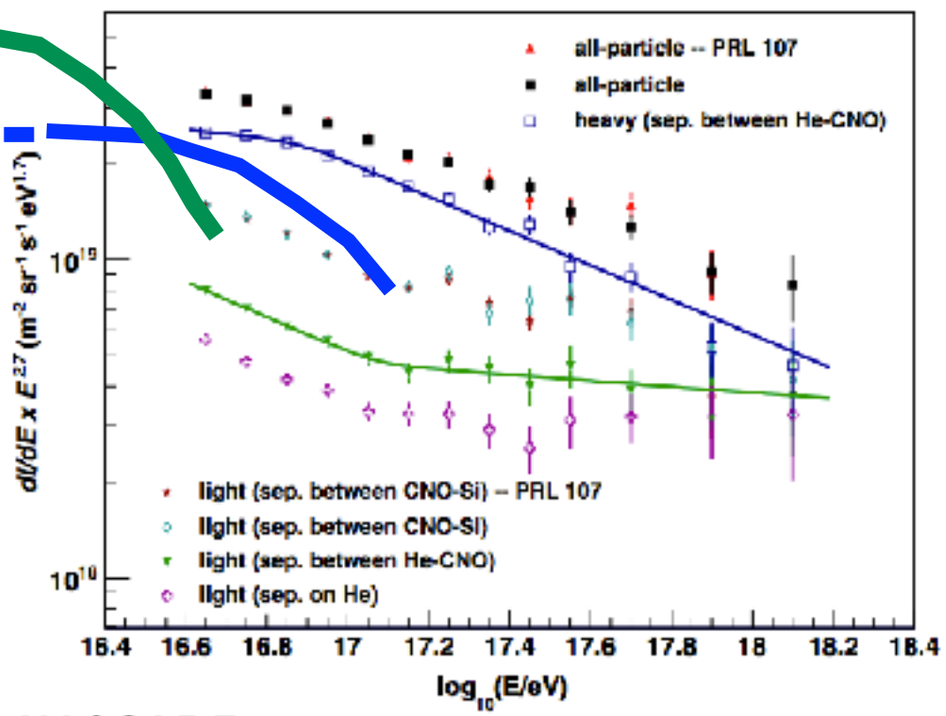
Galactic - Extragalactic Transition



Mostly light composition below the knee



But changed to heavy dominated at the transition regime



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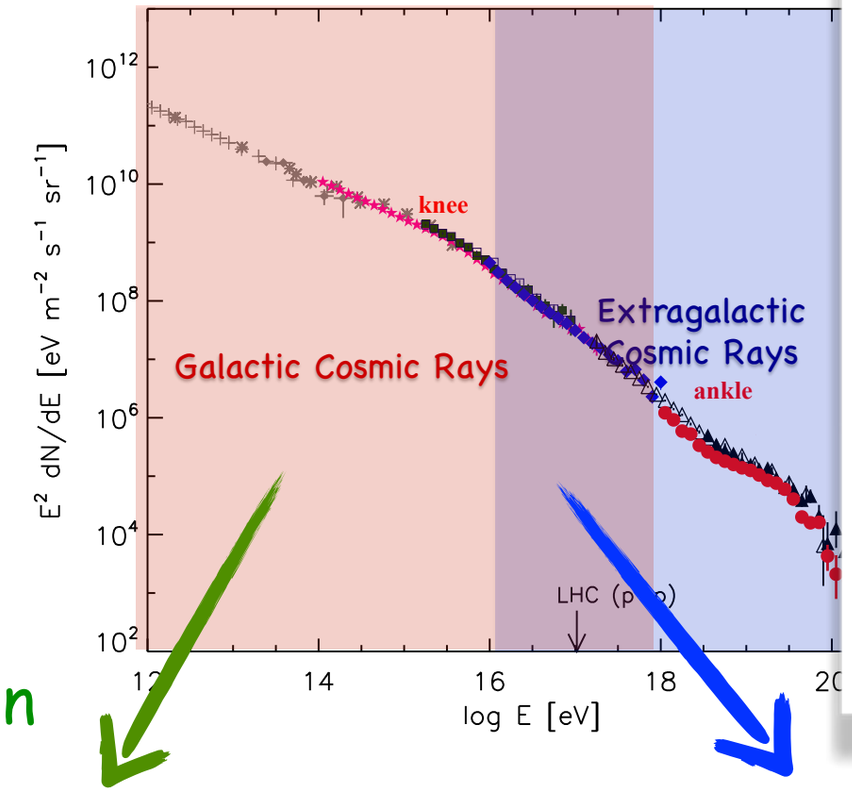
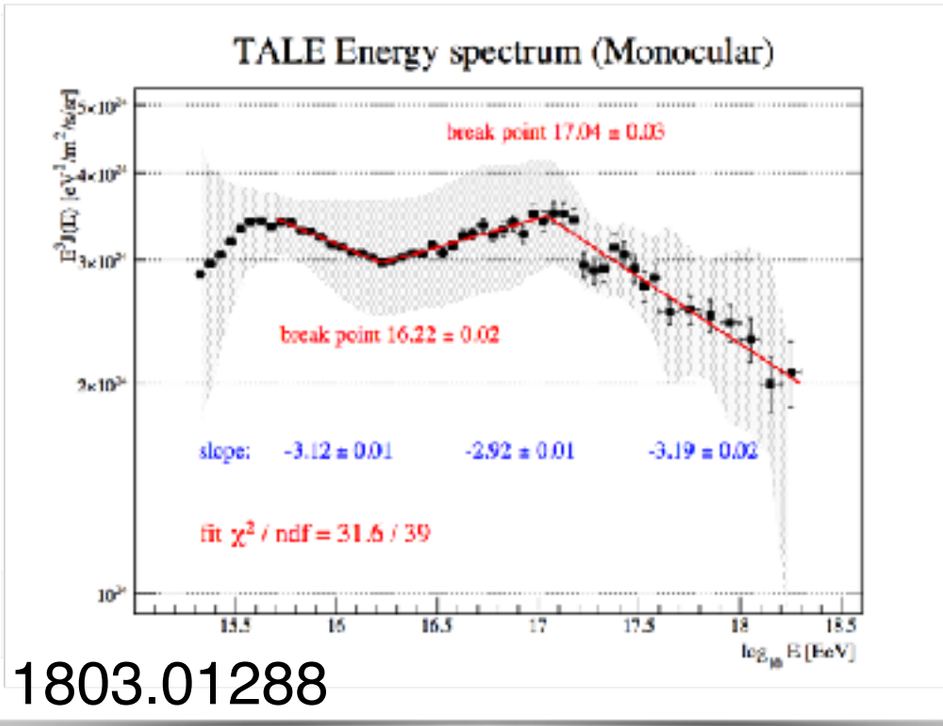
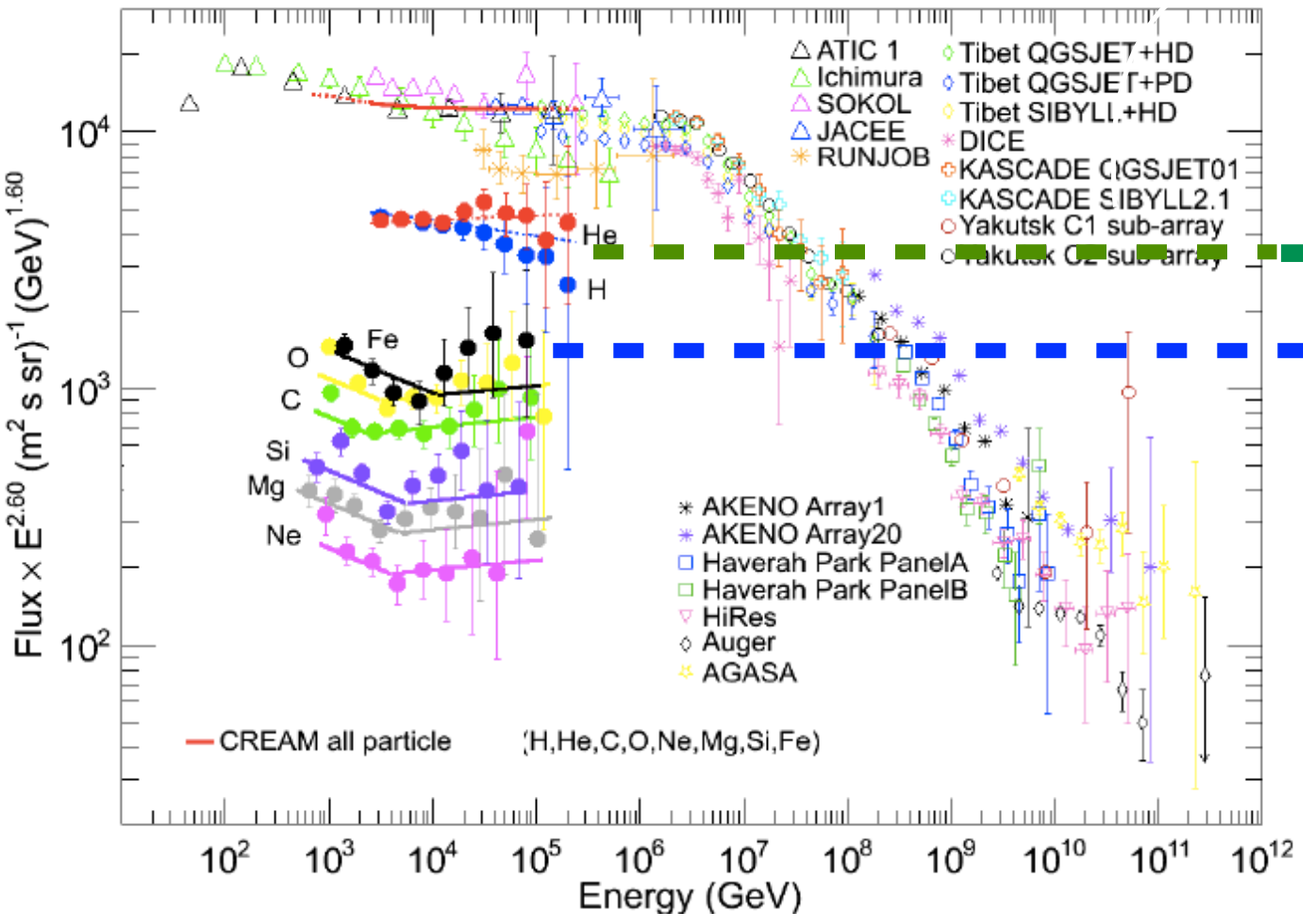
Galactic - Extragalactic Transition





1803.01288

Mostly light composition below the knee



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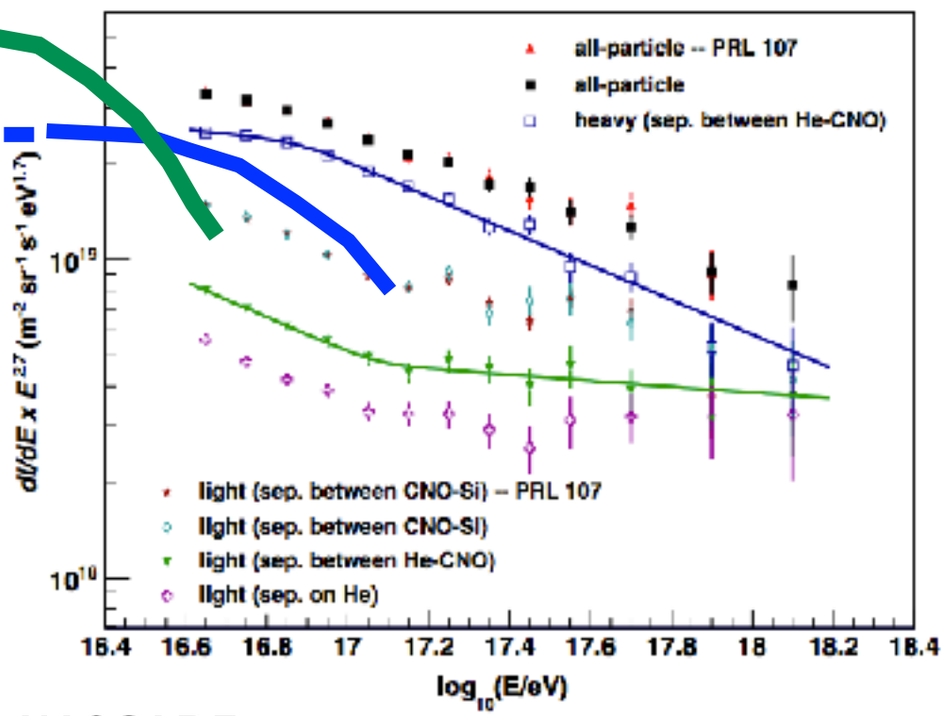

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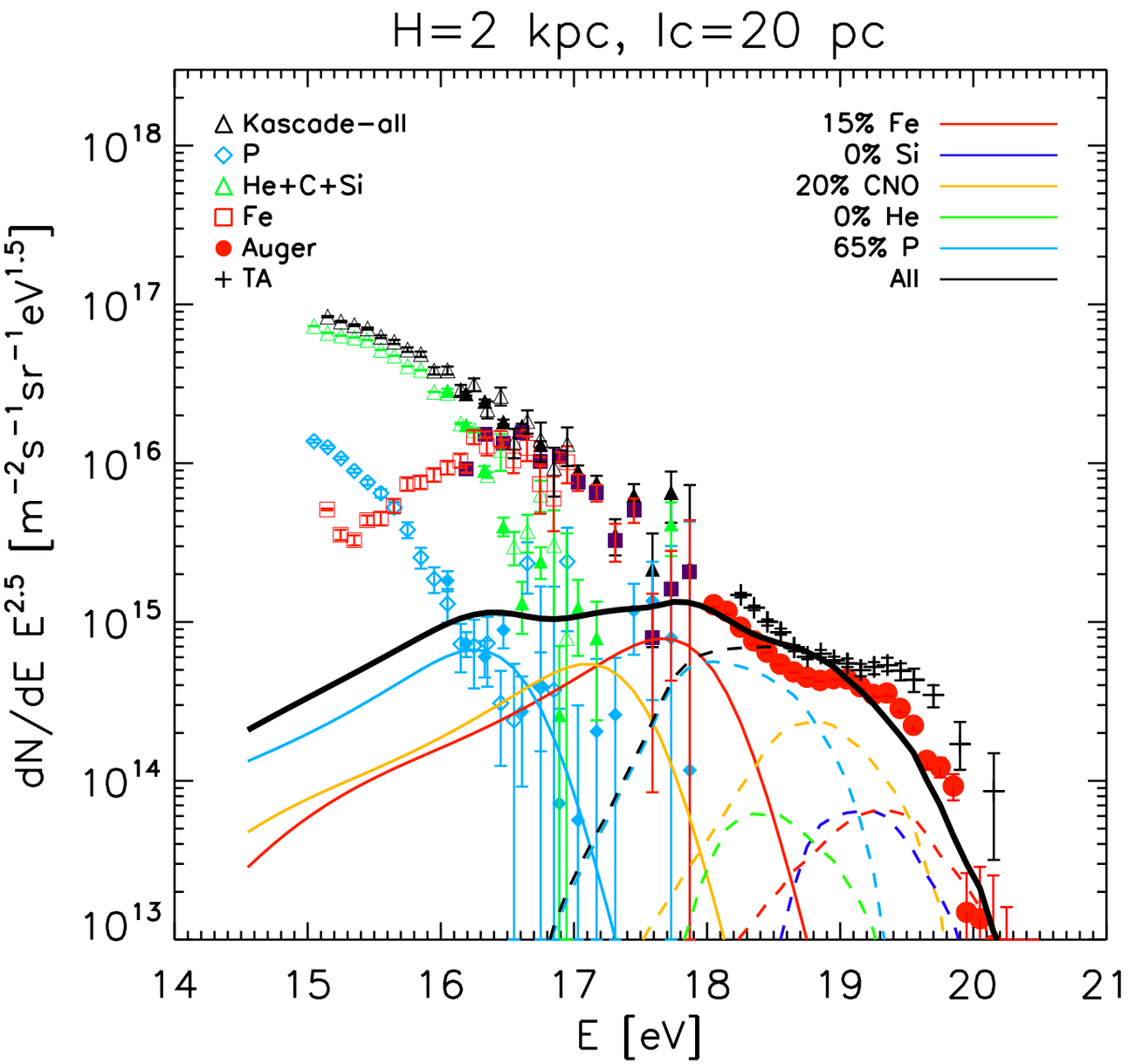
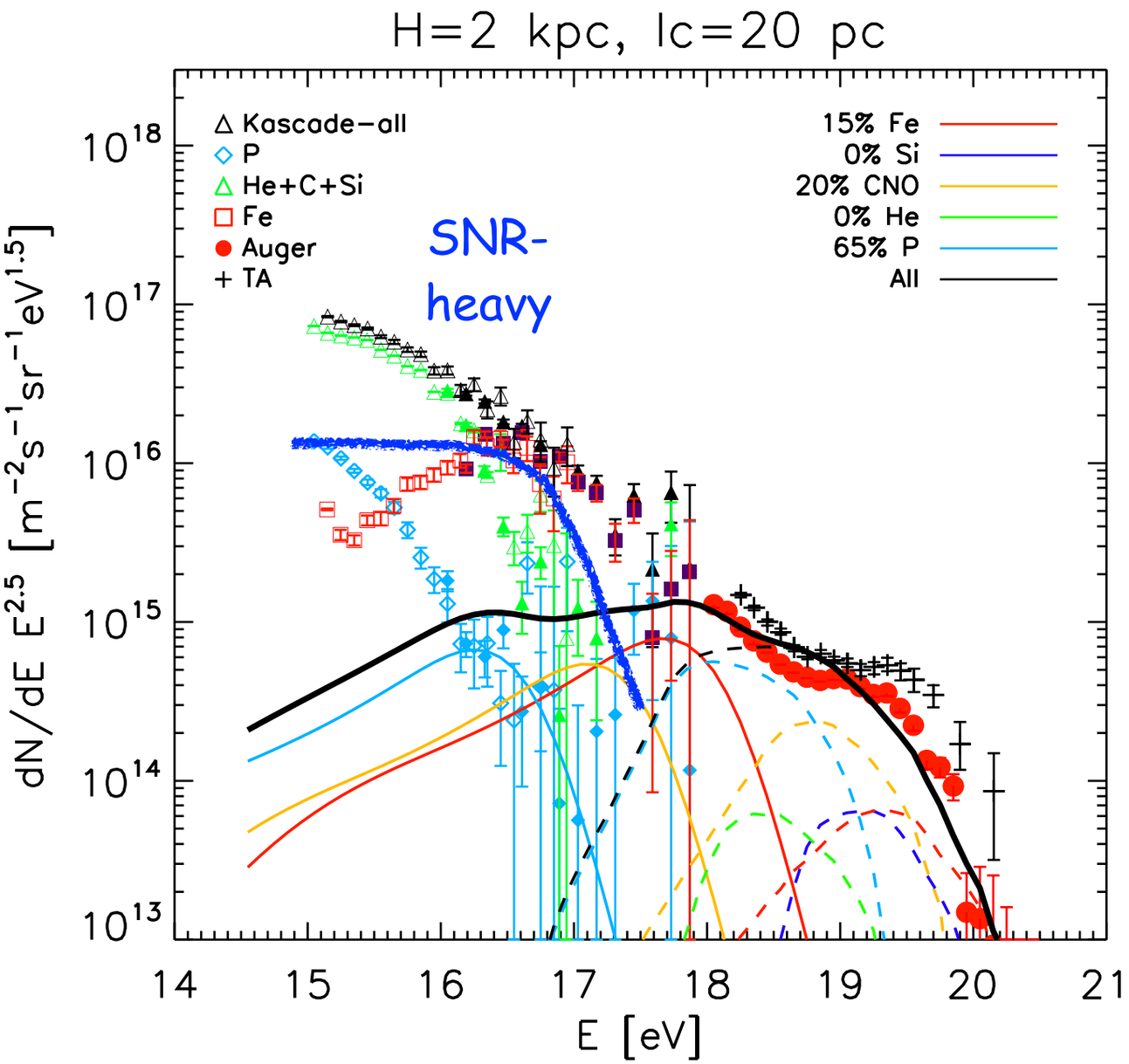
Contribution from Galactic pulsars - Spectrum



Galactic pulsars can fill the gap

KF, Kotera & Olinto JCAP (2013)

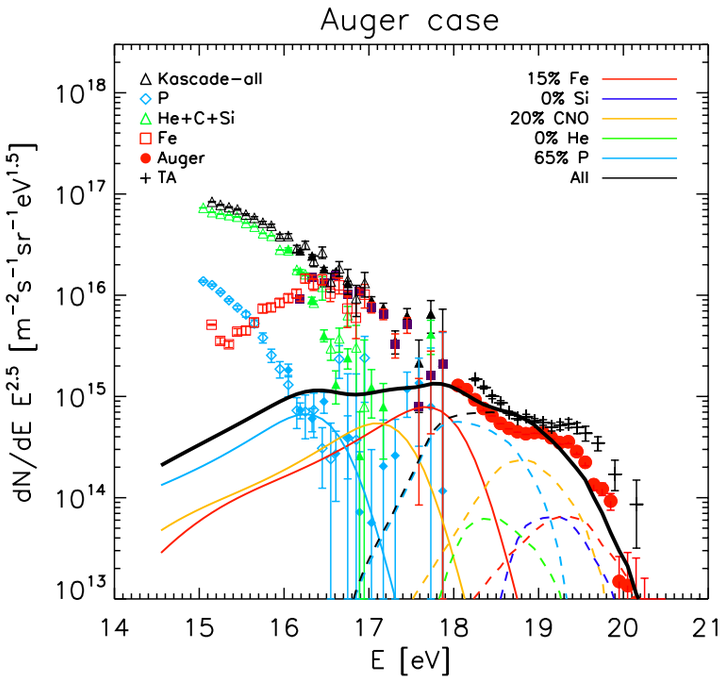
Contribution from Galactic pulsars - Spectrum

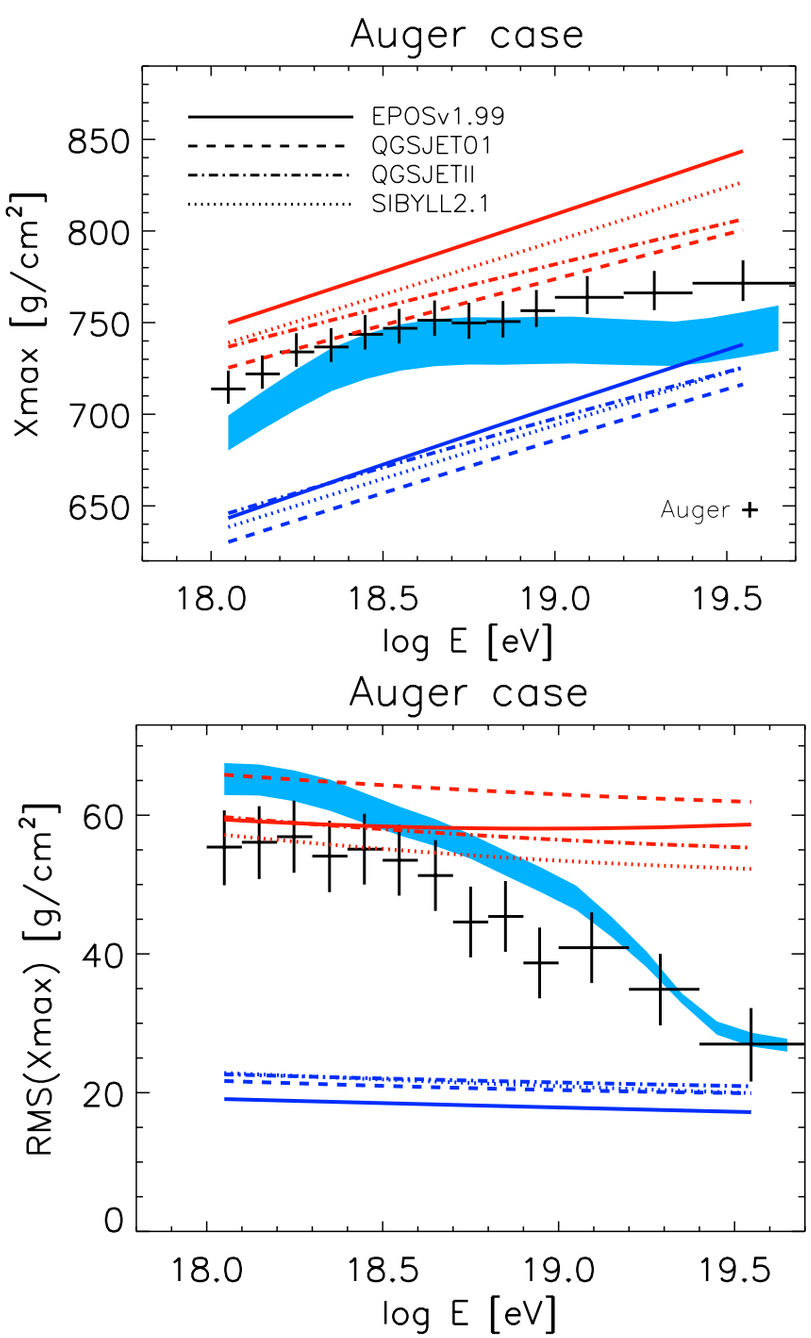


Galactic pulsars can fill the gap

KF, Kotera & Olinto JCAP (2013)

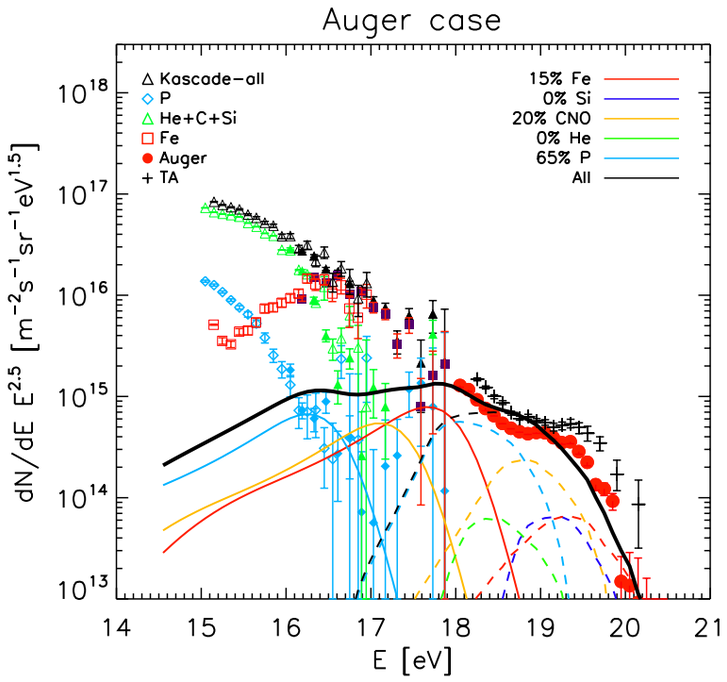
Contribution from Galactic pulsars - Composition

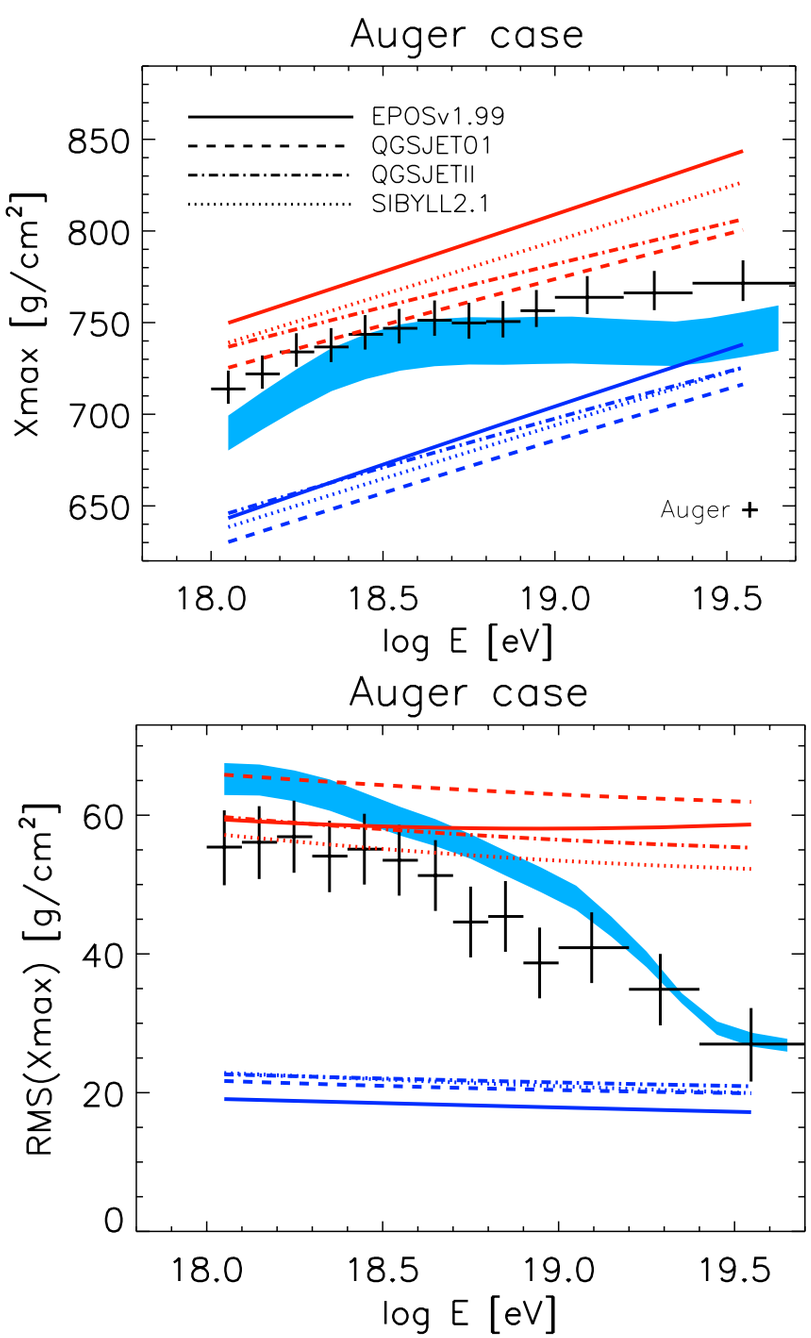




KF, Kotera & Olinto JCAP (2013)

Contribution from Galactic pulsars - Composition





Galactic pulsars can contribute between the knee and the ankle.

GRAND can diagnose the Galactic-extragalactic transition by accurately measuring features in cosmic rays spectrum and composition.

KF, Kotera & Olinto JCAP (2013)