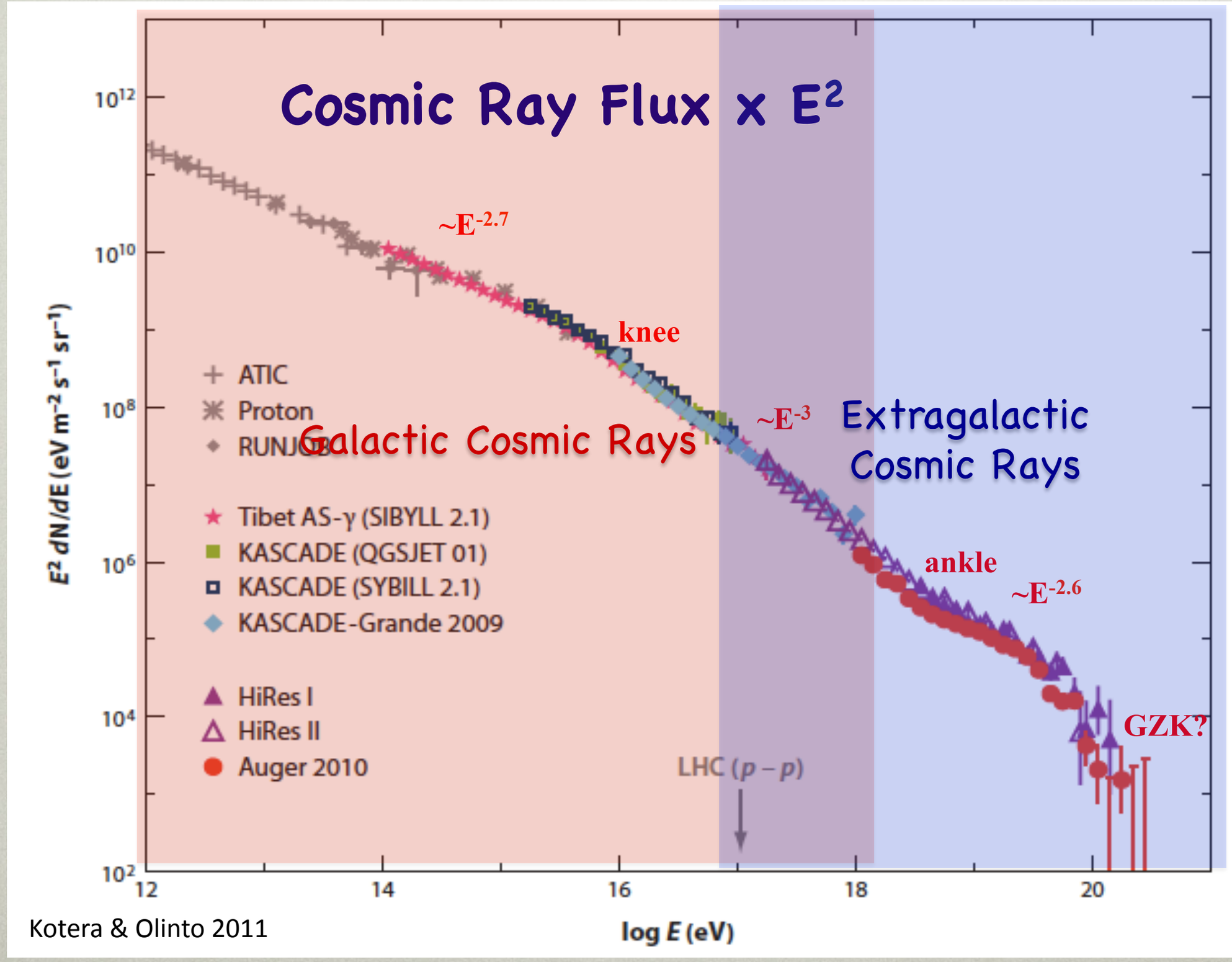
Newborn Pulsars as Sources of Ultrahigh Energy Cosmic Rays

Ke Fang

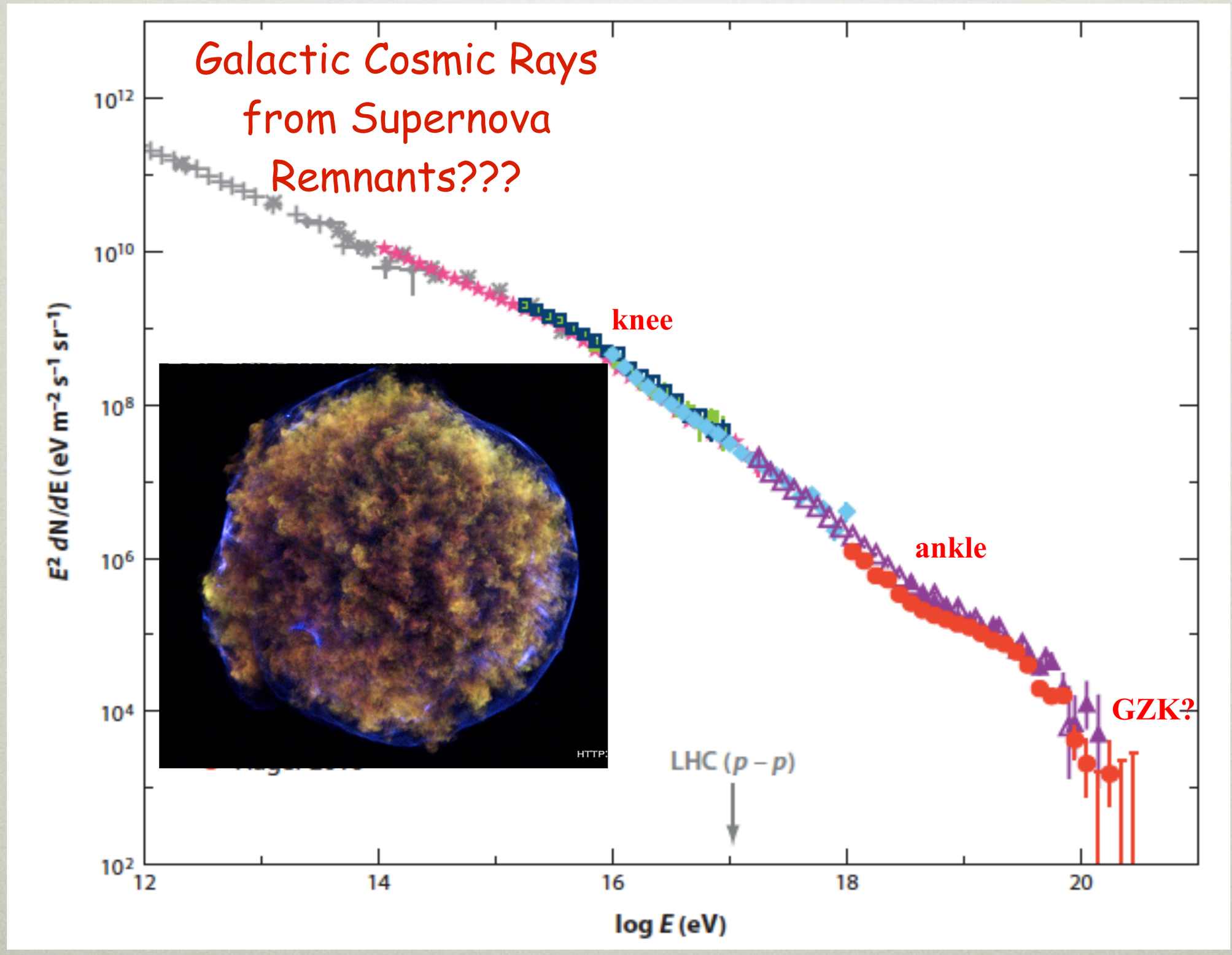
UHECR2014, Springdale, Utah
Oct 13 2014

What have we learnt in 100 years of efforts?



Kotera & Olinto 2011

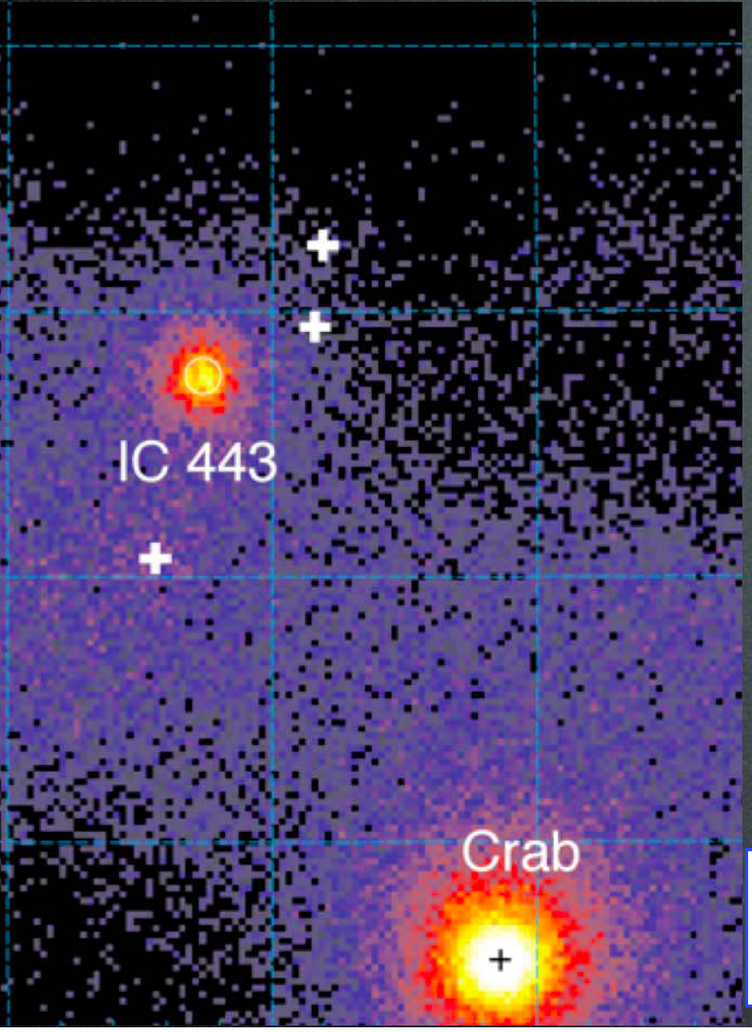
What remains unknown?

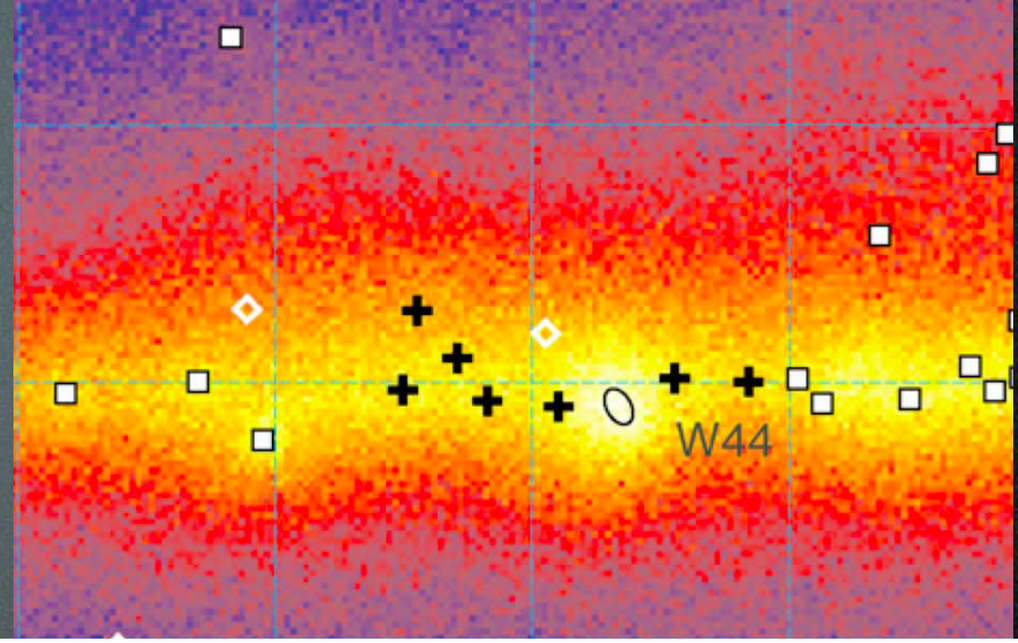


π^0 decay!

IC 443 & W44

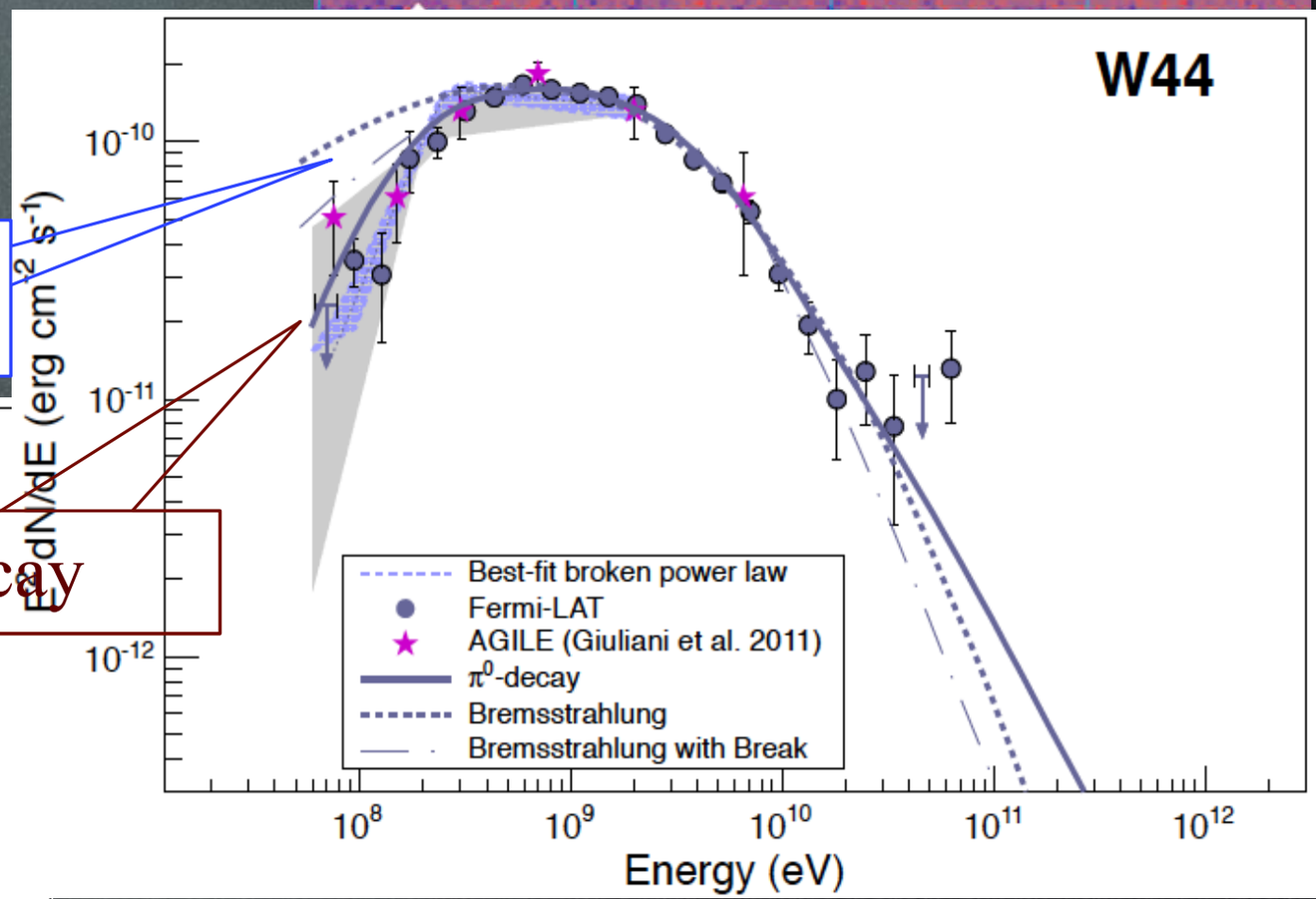
Fermi & AGILE

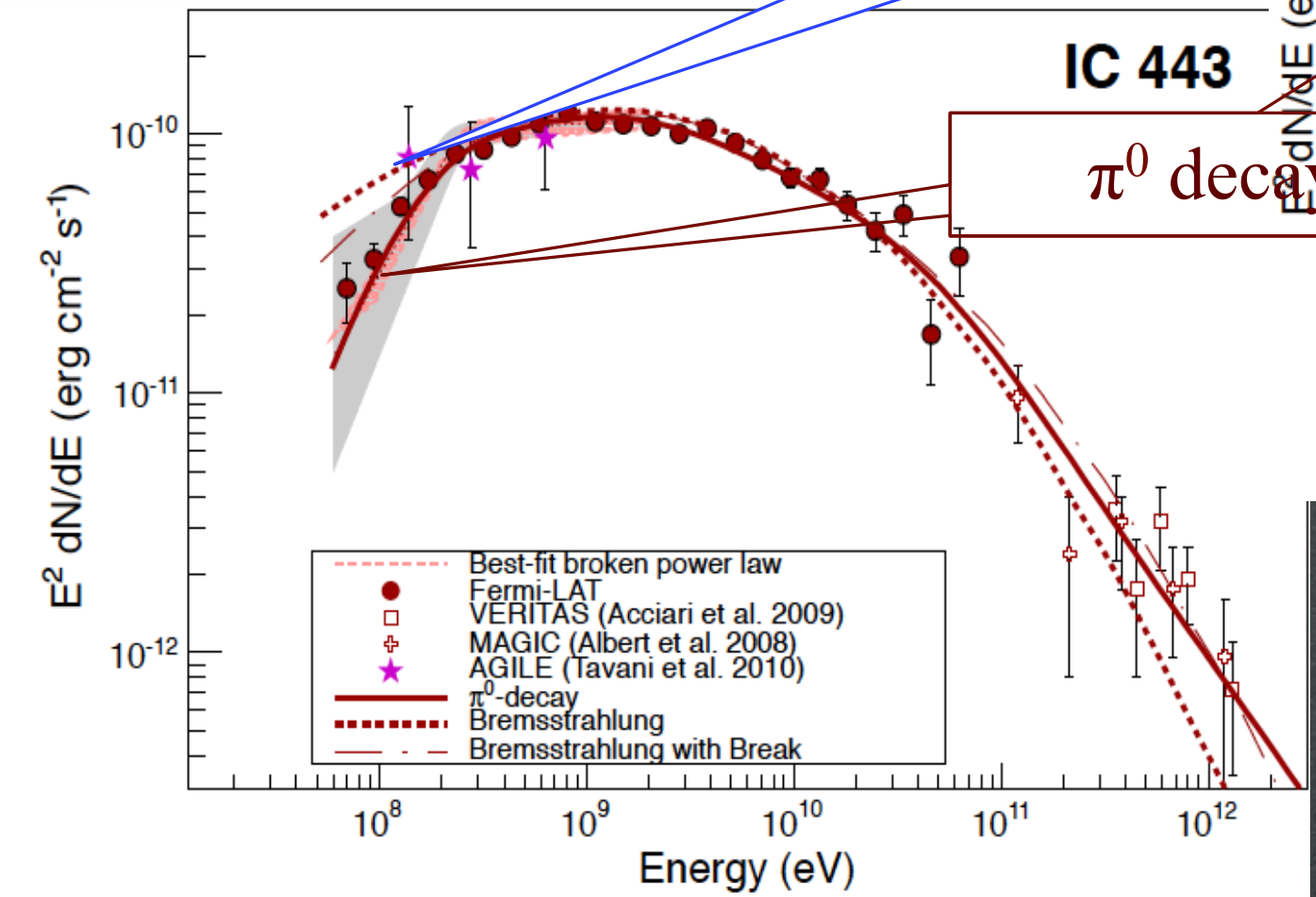




Bremsstrahlung

π^0 decay

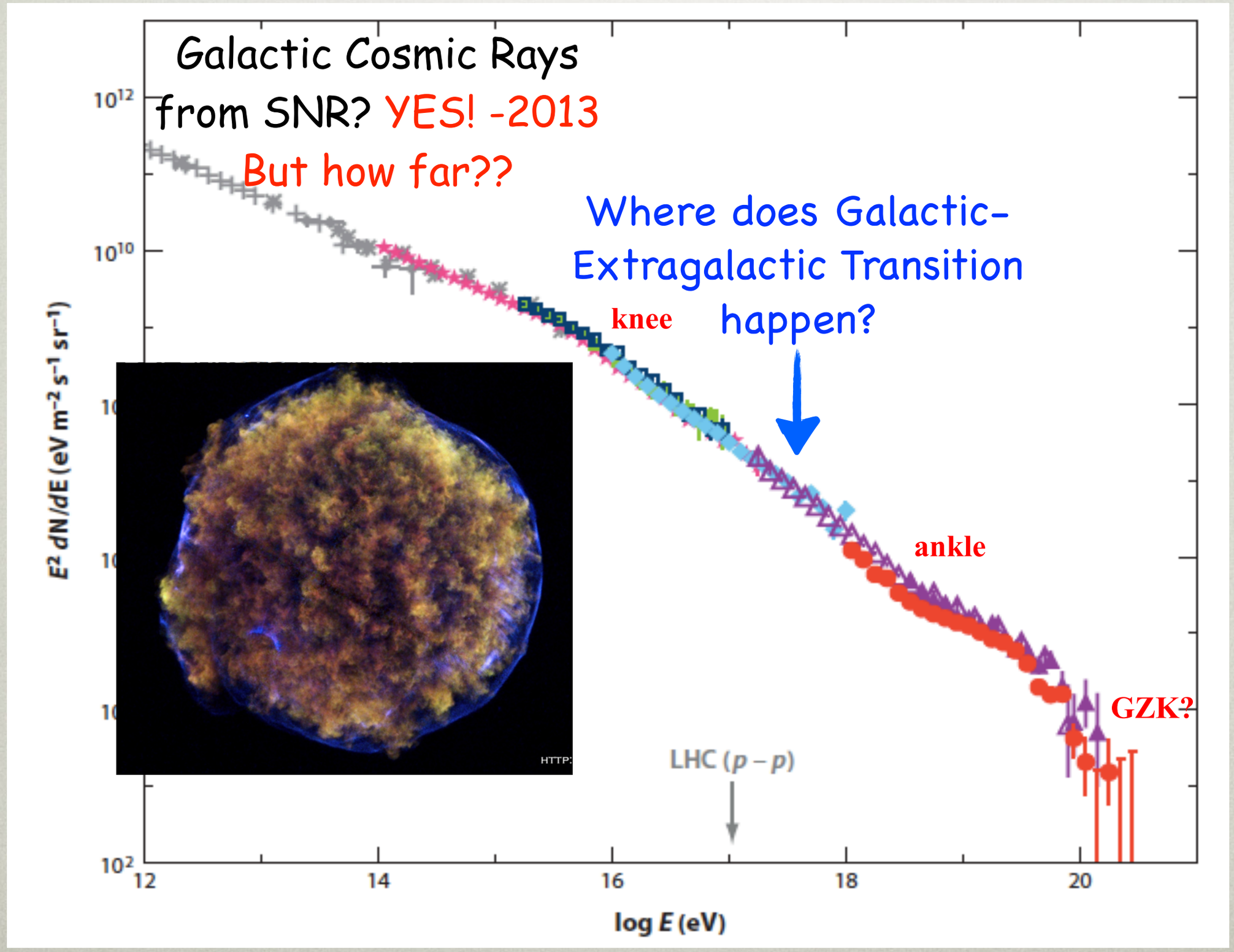




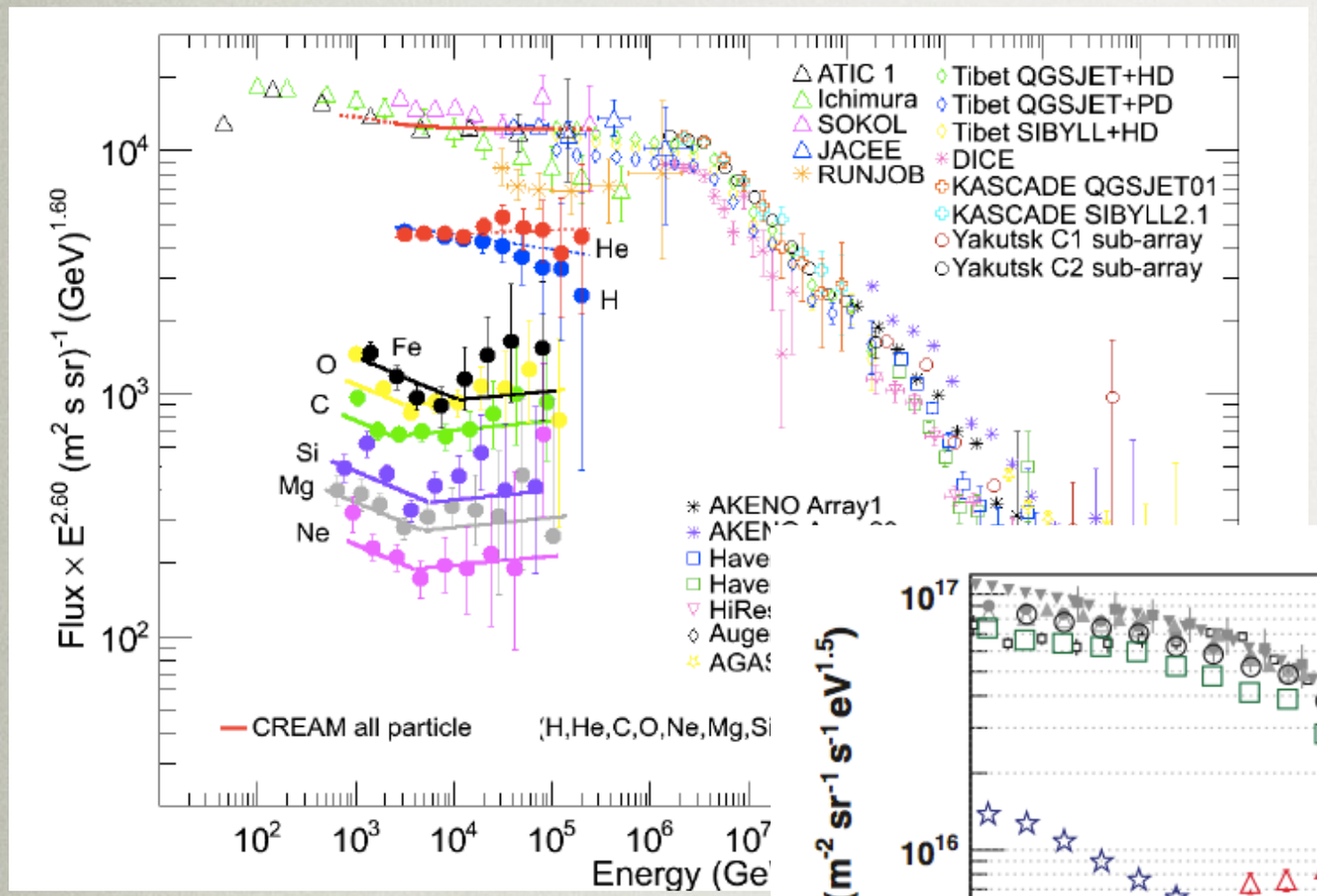
hadrons are accelerated in SNR

Ackermann et al (Fermi Collab) ‘13

What remains unknown?

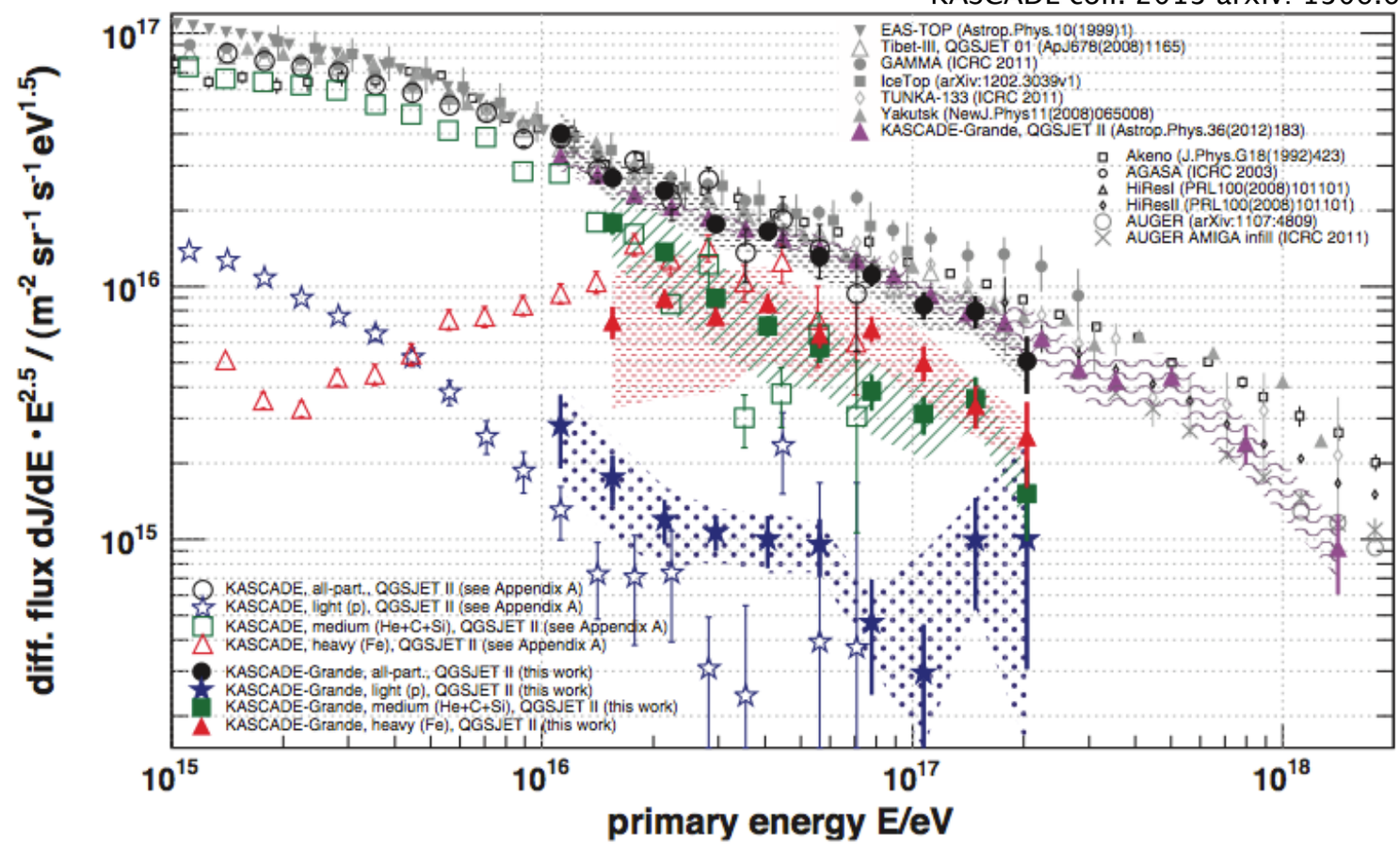


Galactic - Extragalactic Transition

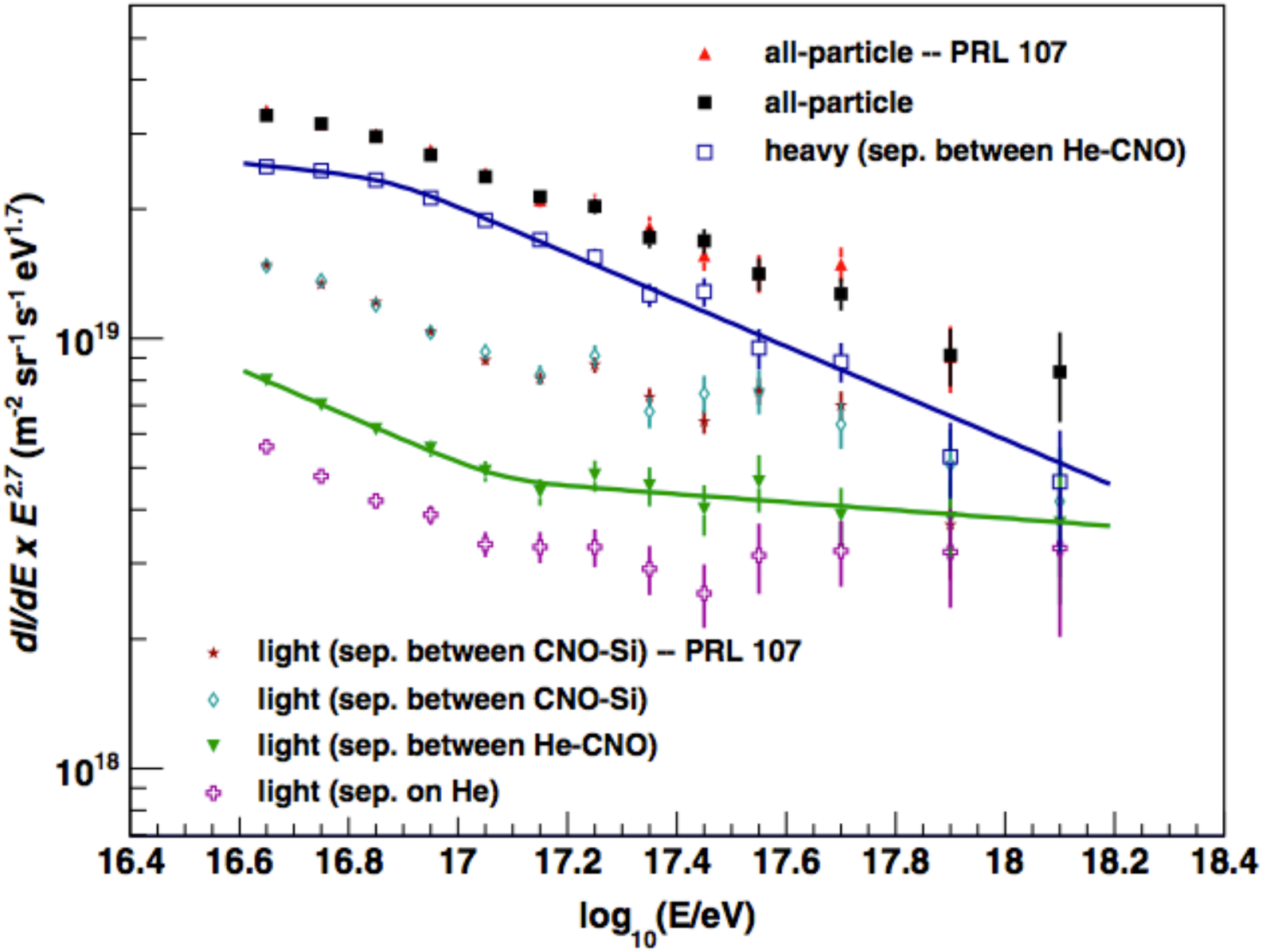


Composition Change

KASCADE coll. 2013 arxiv: 1306.6283

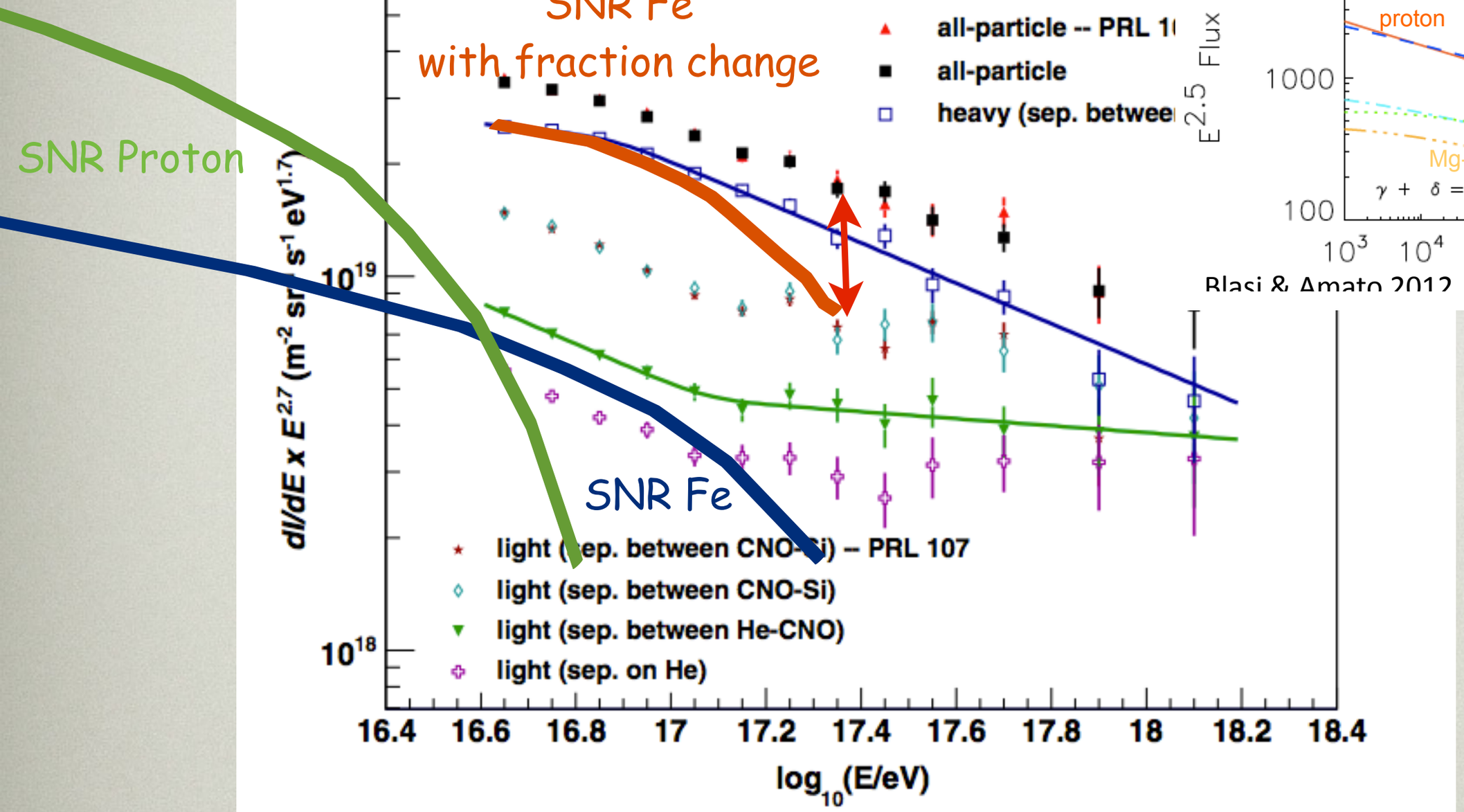


Galactic - Extragalactic Transition

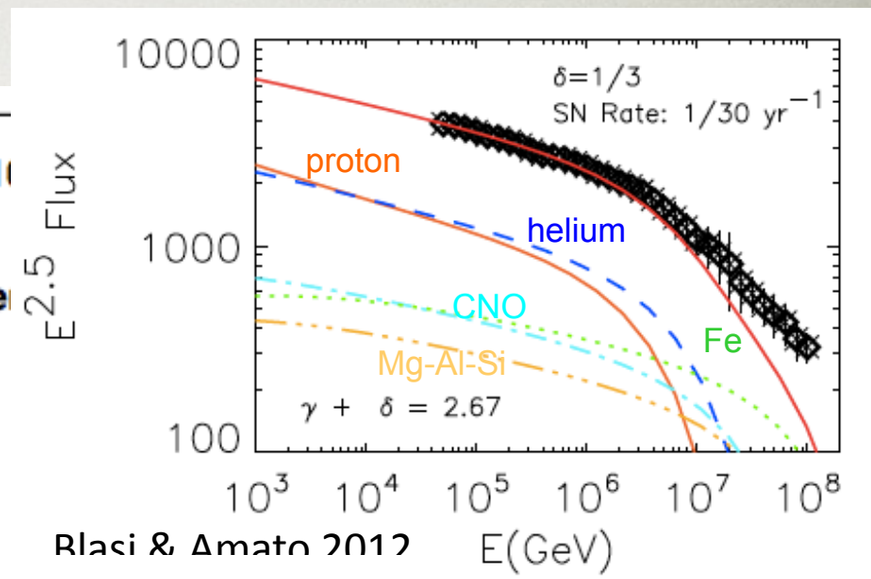


KASCADE coll. PHYSICAL REVIEW D 87, 081101(R) (2013)

Galactic - Extragalactic Transition



KASCADE coll. PHYSICAL REVIEW D 87, 081101(R) (2013)



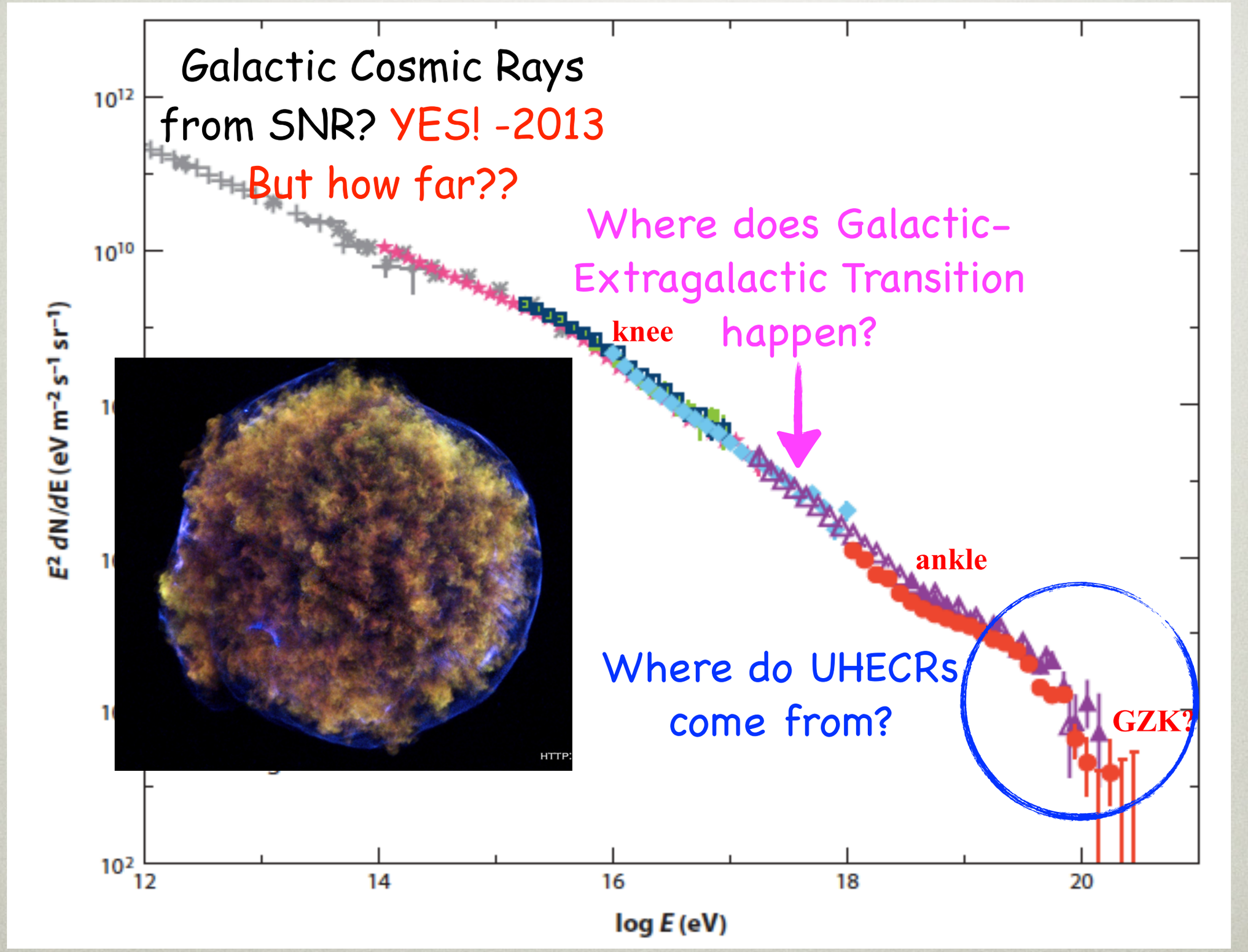
Blasi & Amato 2012

SNR Fe with 'normal' fraction ✗

100% SNR Fe at 'second knee' ✗

Mind the gap in both composition and spectrum!

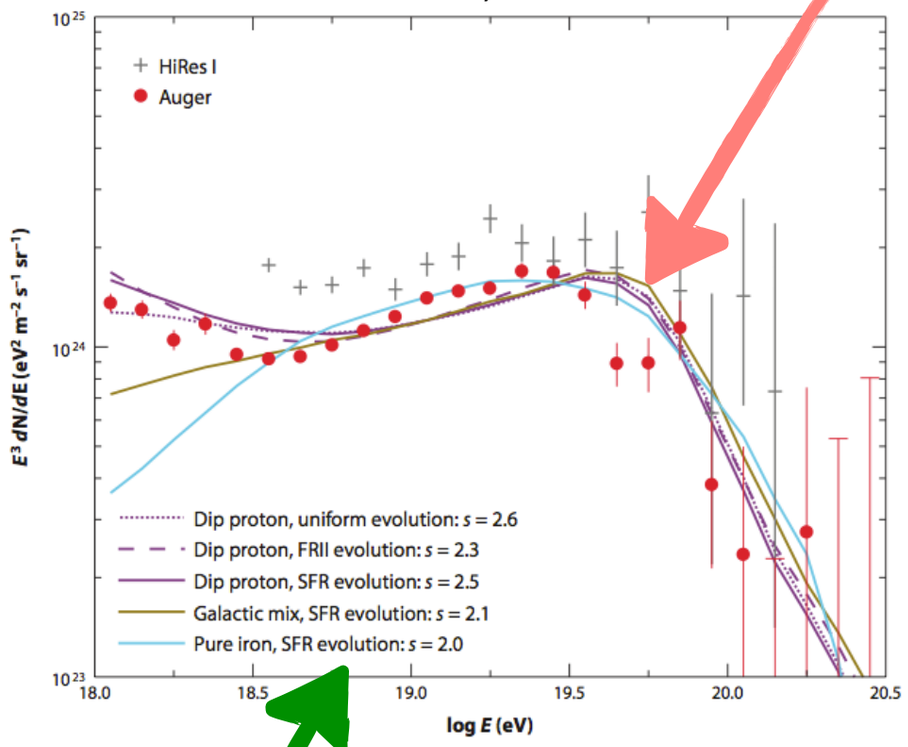
What remains unknown?



UHECR measurements -1. Spectrum

GZK cutoff and/or end of Emax

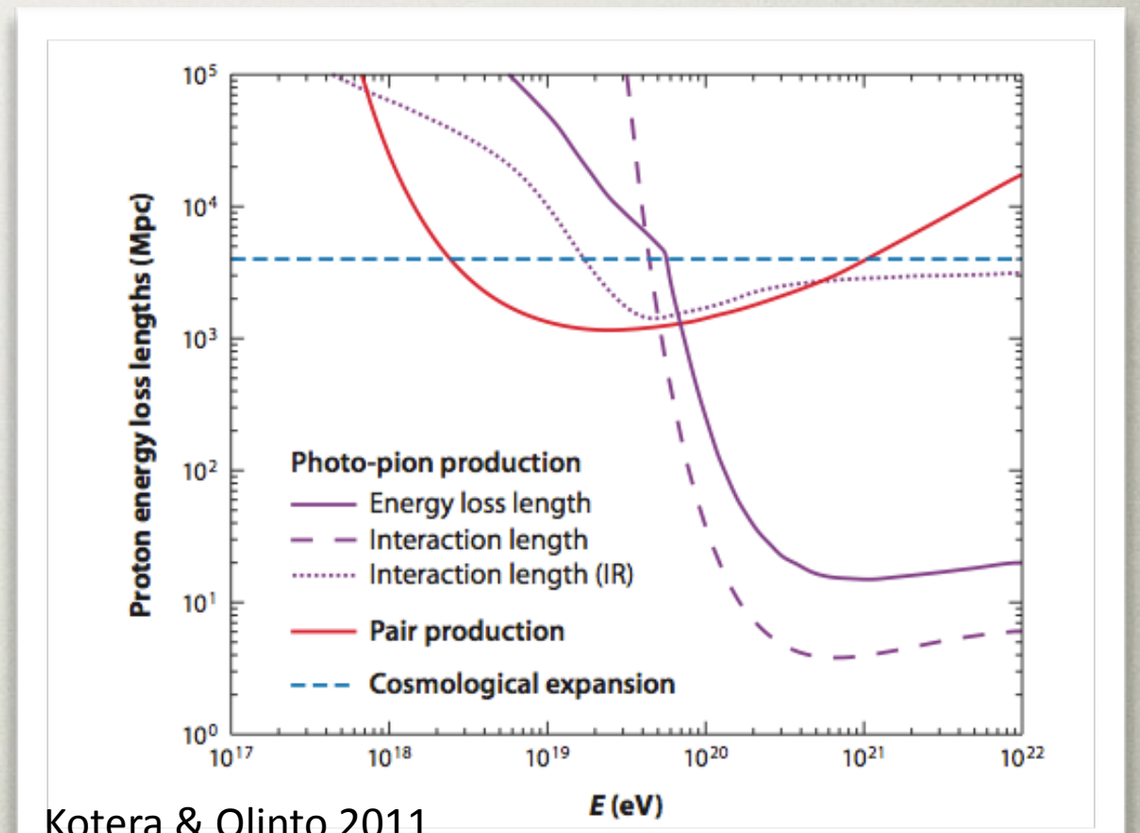
Abraham et al. 2010b, Kotera & Olinto 2011



intrinsic index ~ 2

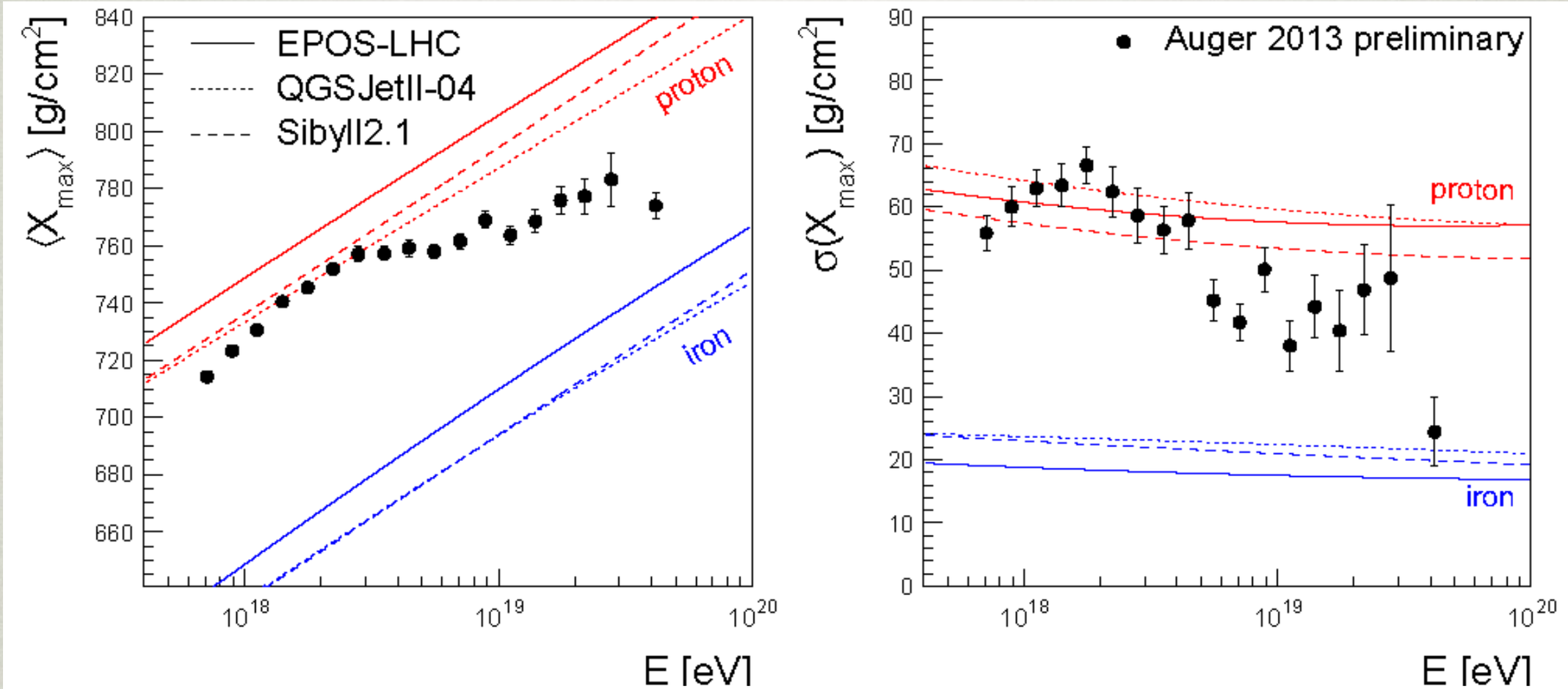
GZK Cutoff
Greisen, Zatsepin, Kuzmin 1966

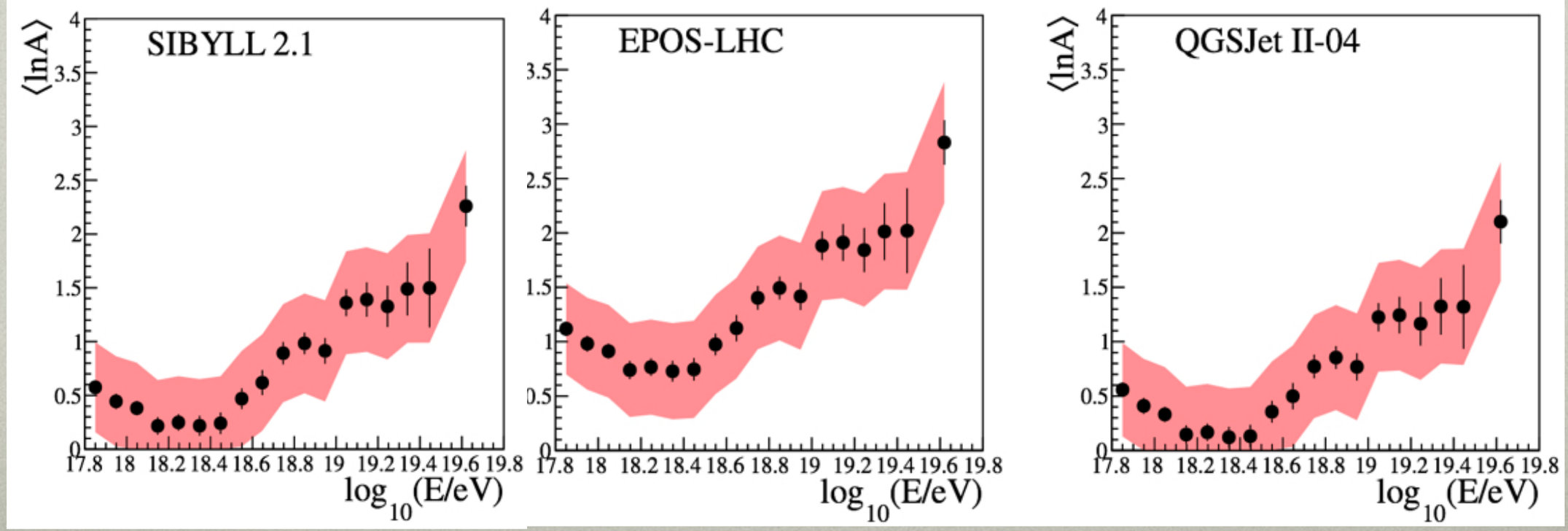
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



Kotera & Olinto 2011

UHECR measurements - **2. Chemical Composition**



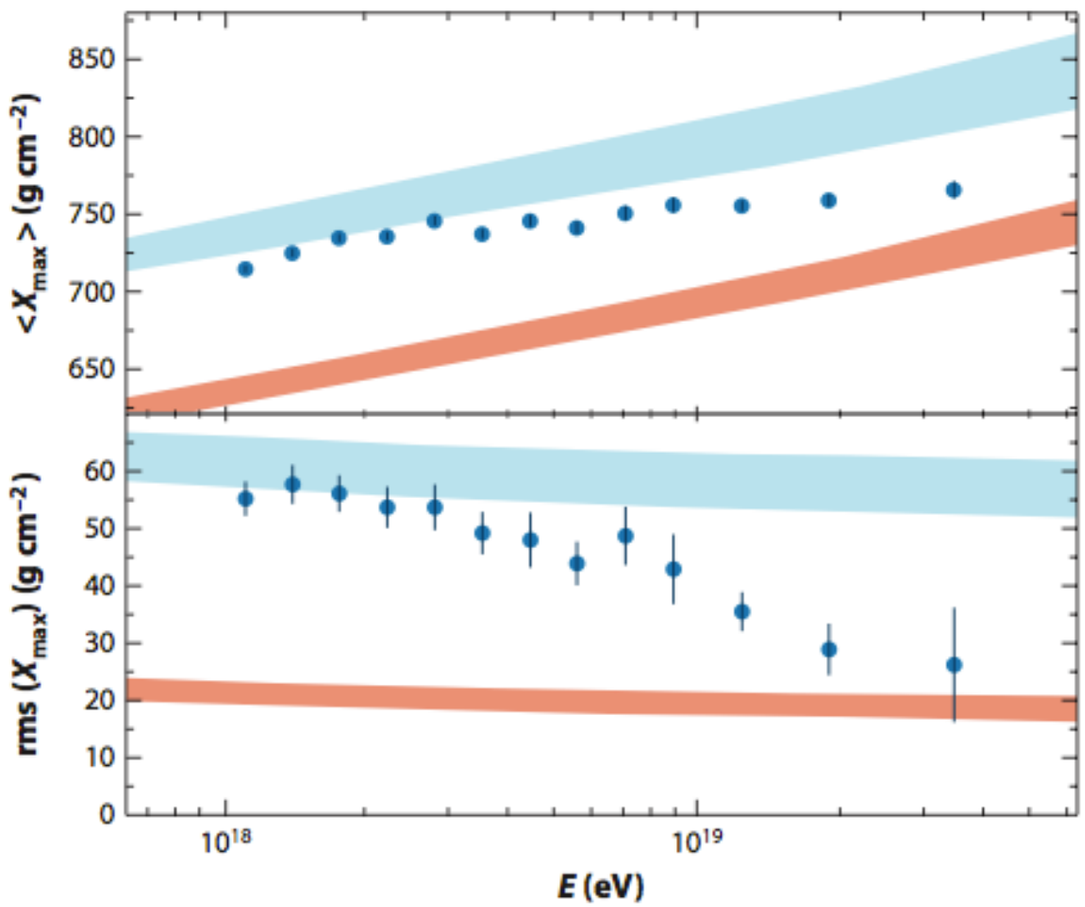


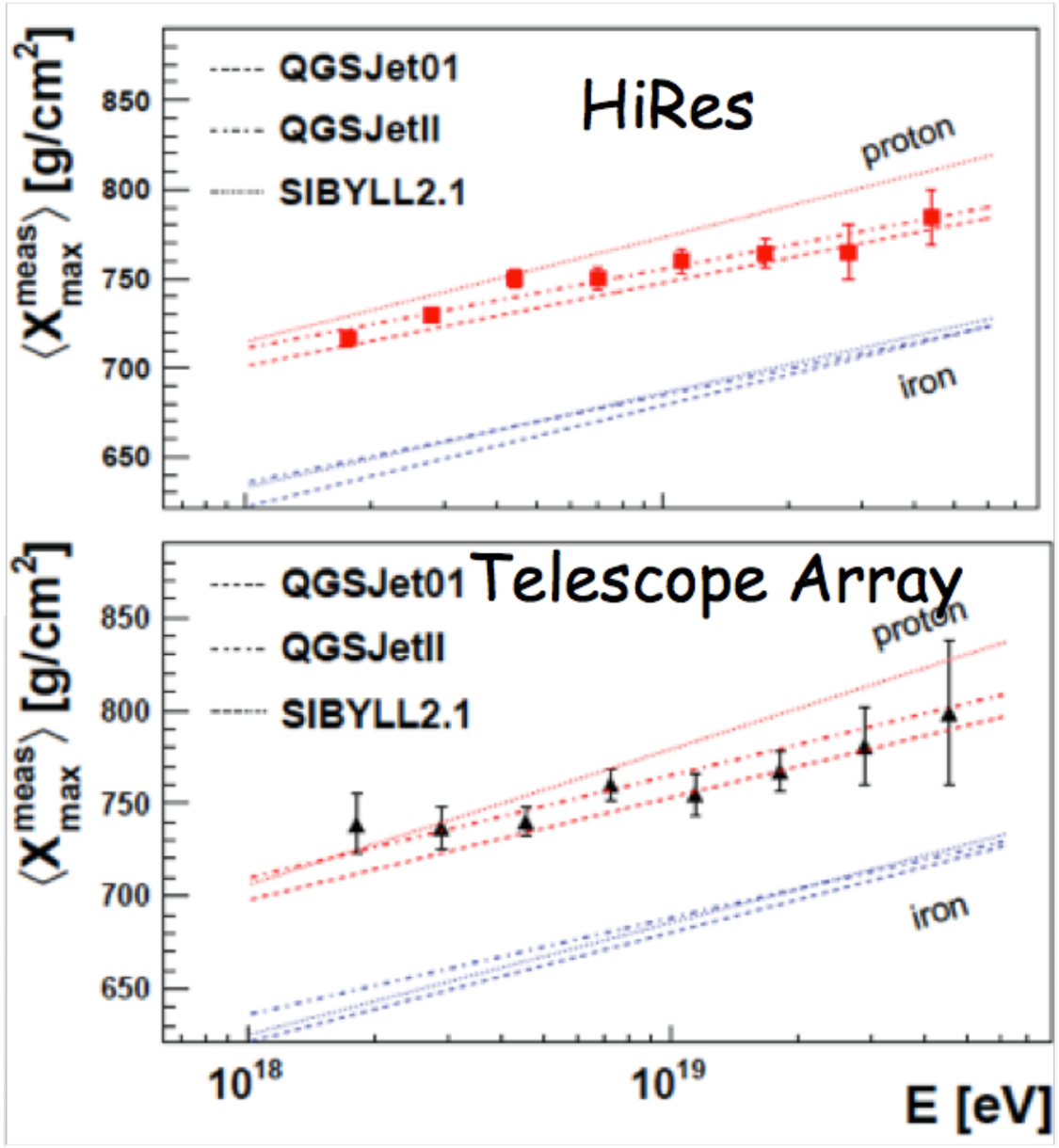
UHECR measurements - **2. Chemical Composition**

Auger: Light to Heavy Transition

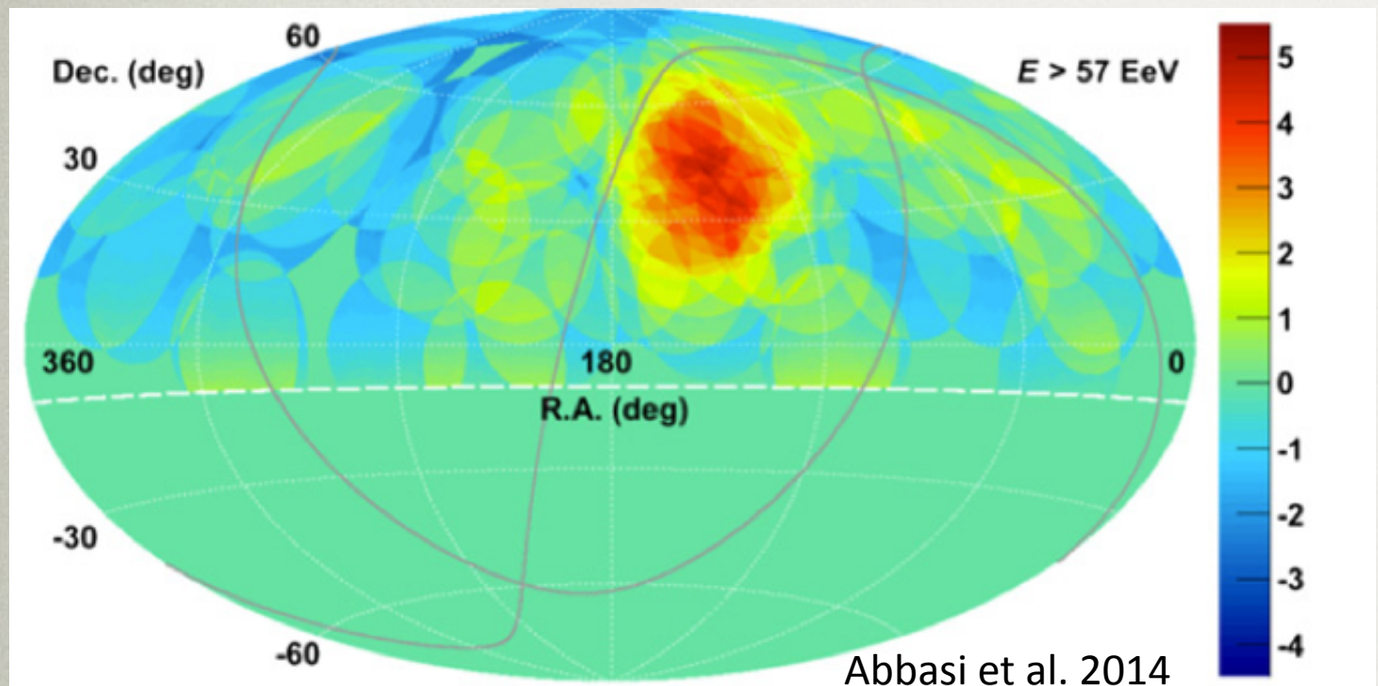
Not confirmed by North Hemisphere telescopes

Auger Collaboration, PRL 104 (2010) 091101, ICRC 2011, arXiv:1107.4804





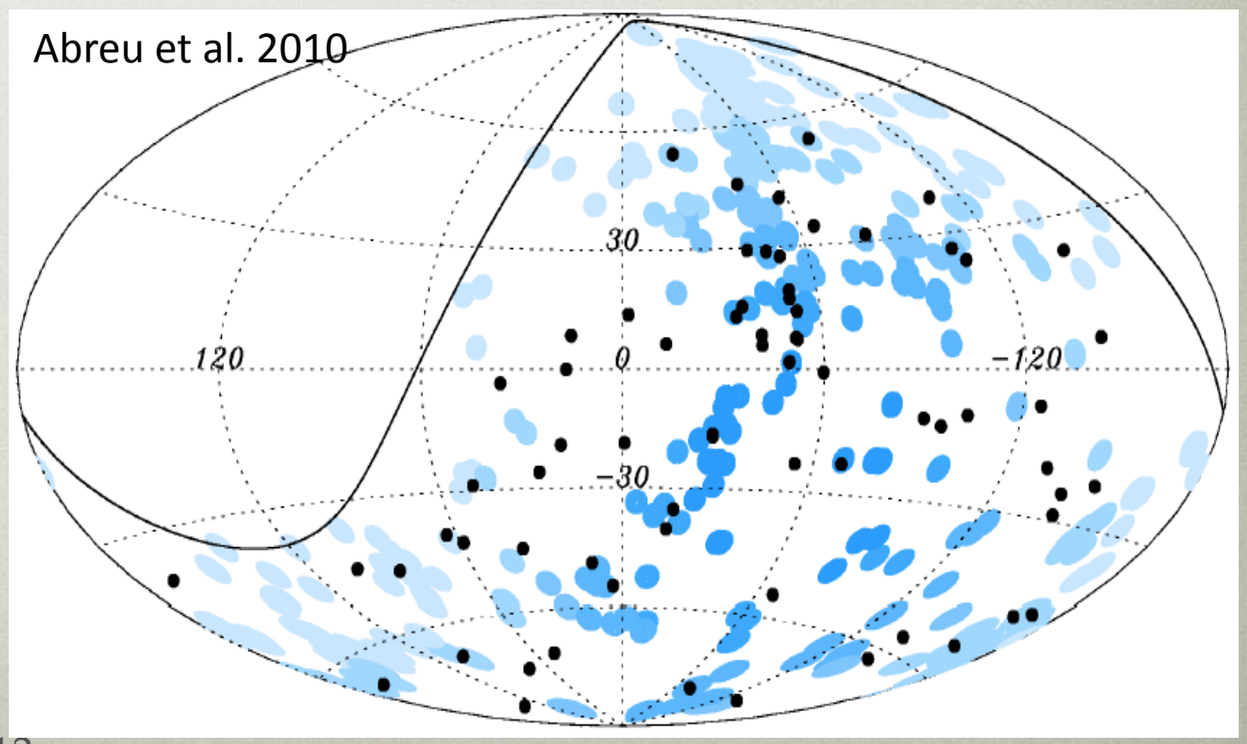
UHECR measurements - **3. Anisotropy**



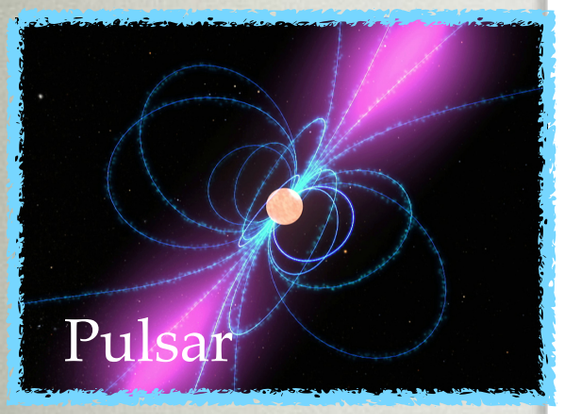
Abbasi et al. 2014

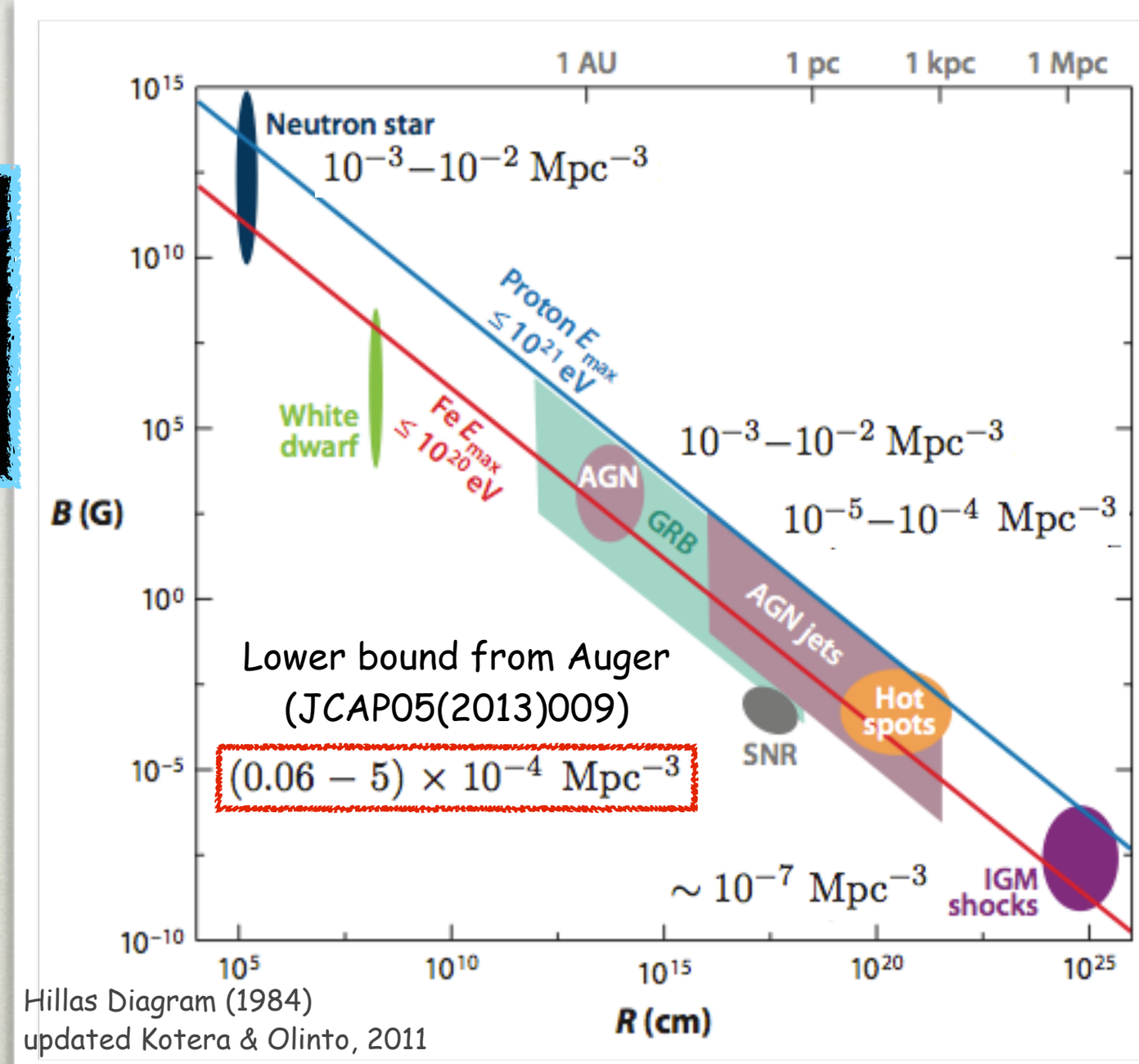
Indications of Intermediate-scale anisotropy

No derivation from isotropy in large scale

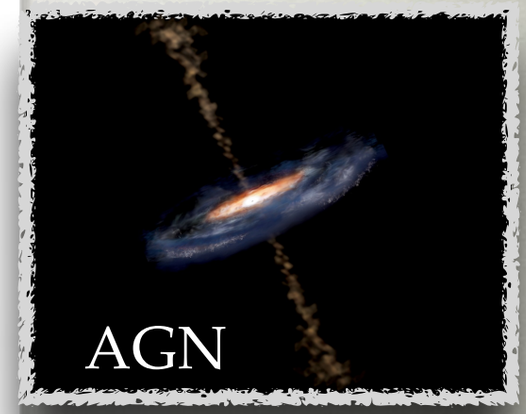


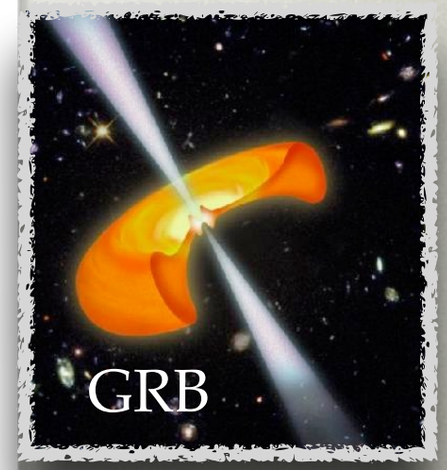
Possible Candidates of UHECR Sources

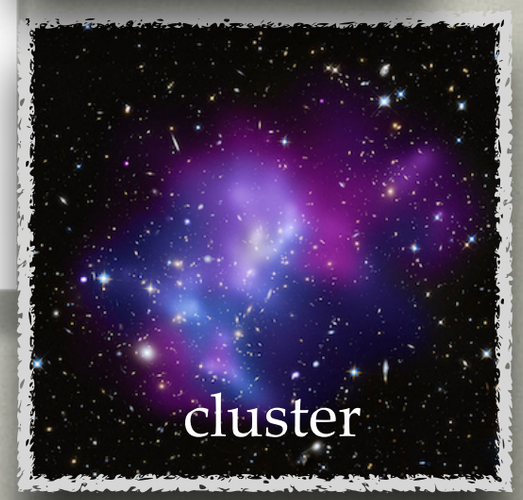




Hillas Diagram (1984)
updated Kotera & Olinto, 2011







A tale of newborn pulsars

Blasi, Epstein & Olinto 2000
Arons 2003
KF, Kotera, Olinto 2012, 2013

Goldreich-Julian charge density at the stellar surface

$$\dot{N}_{GJ} = \frac{\Omega^2 \mu}{Zec}$$

Pulsar spins down due to electromagnetic radiation (neglect GW)

$$\dot{\Omega} = -\frac{\dot{E}_{EM}}{I\Omega} \propto -\mu^2 \Omega^3$$

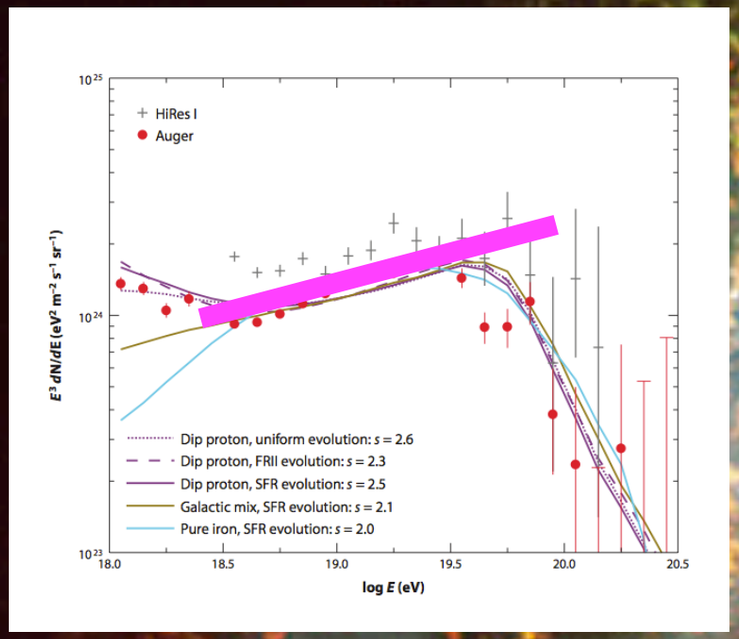
Particles can be accelerated by the induced E-field

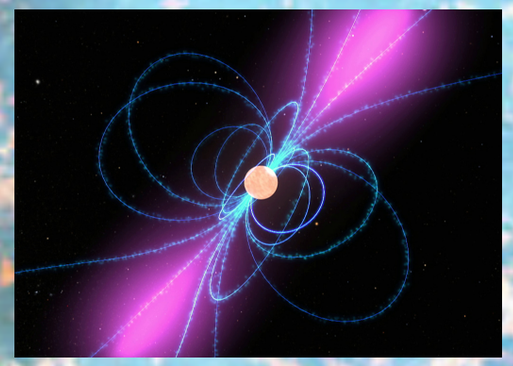
$$E = Ze\Phi\eta = 3\times10^{20} Z_{26}\eta_1 \Omega_4^2 \mu_{30.5} eV$$

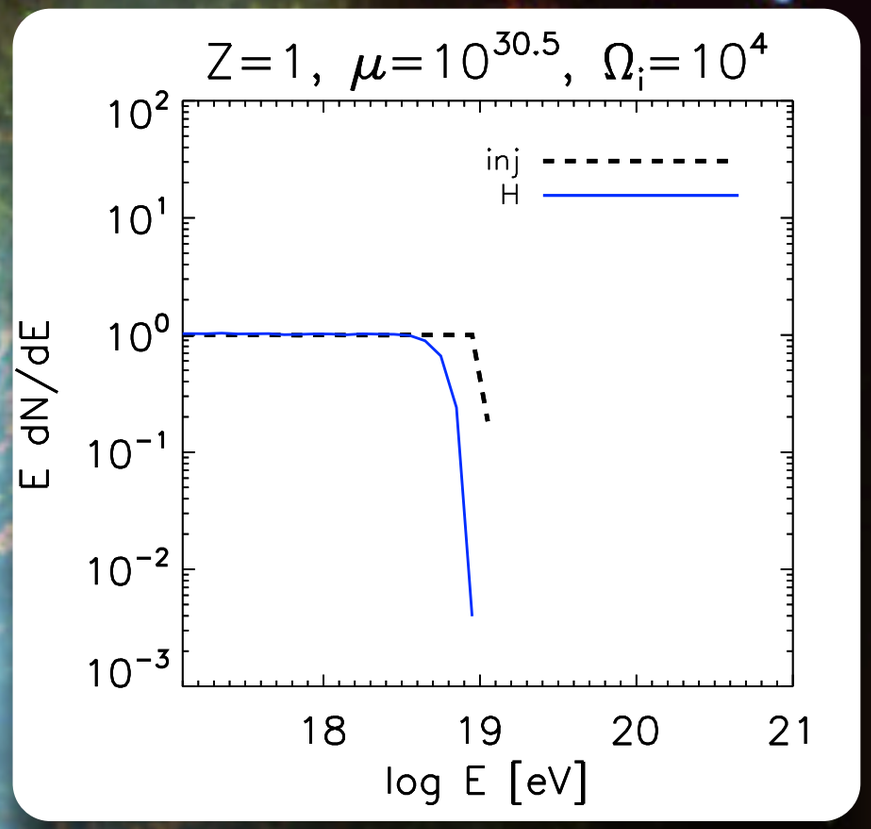
$$t_{spin}(E) = 1yr\left(\frac{3\times10^{20} eV}{E}\right)\frac{Z_{26}\eta_1}{\mu_{30.5}}$$

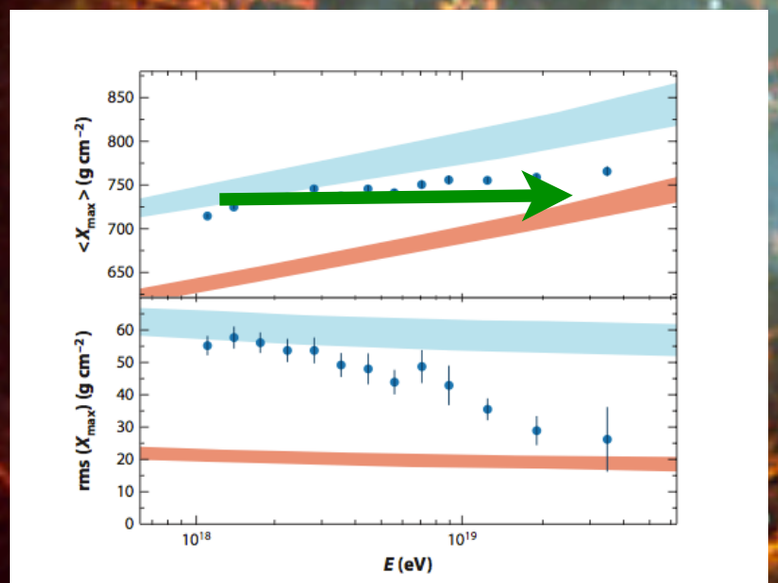
$$\frac{dN_i}{dE} = 5\times10^{23}(Z_{26}\mu_{30.5}E_{20})^{-1} eV^{-1}$$

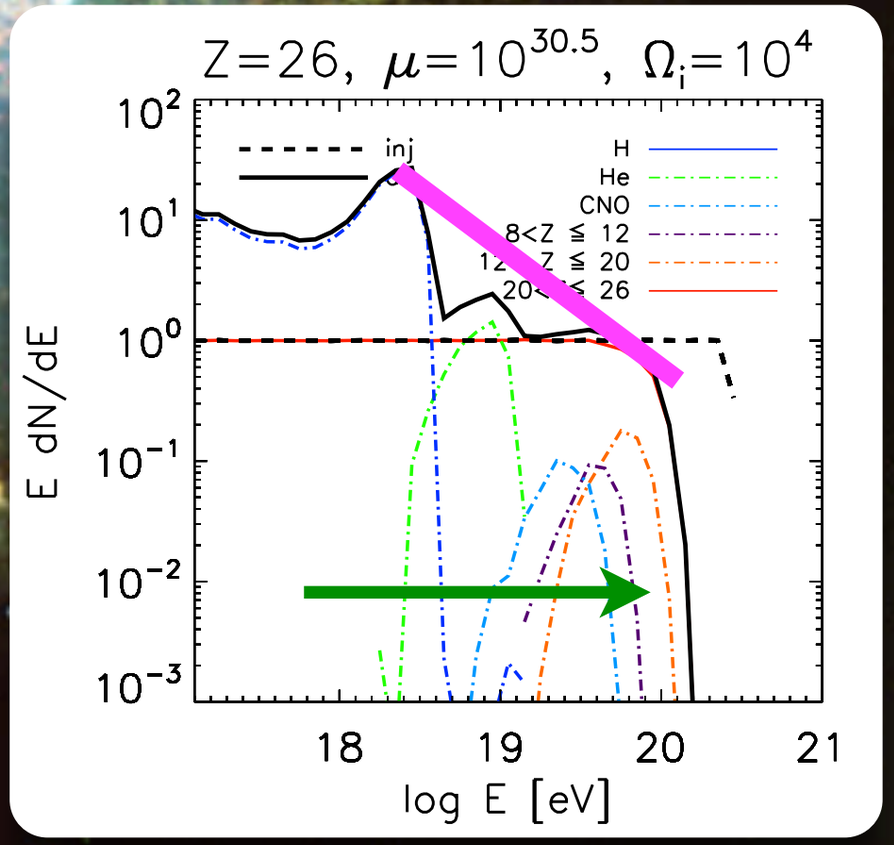
Monte-Carlo propagation
hadron interactions simulated
with EPOS + CONEX





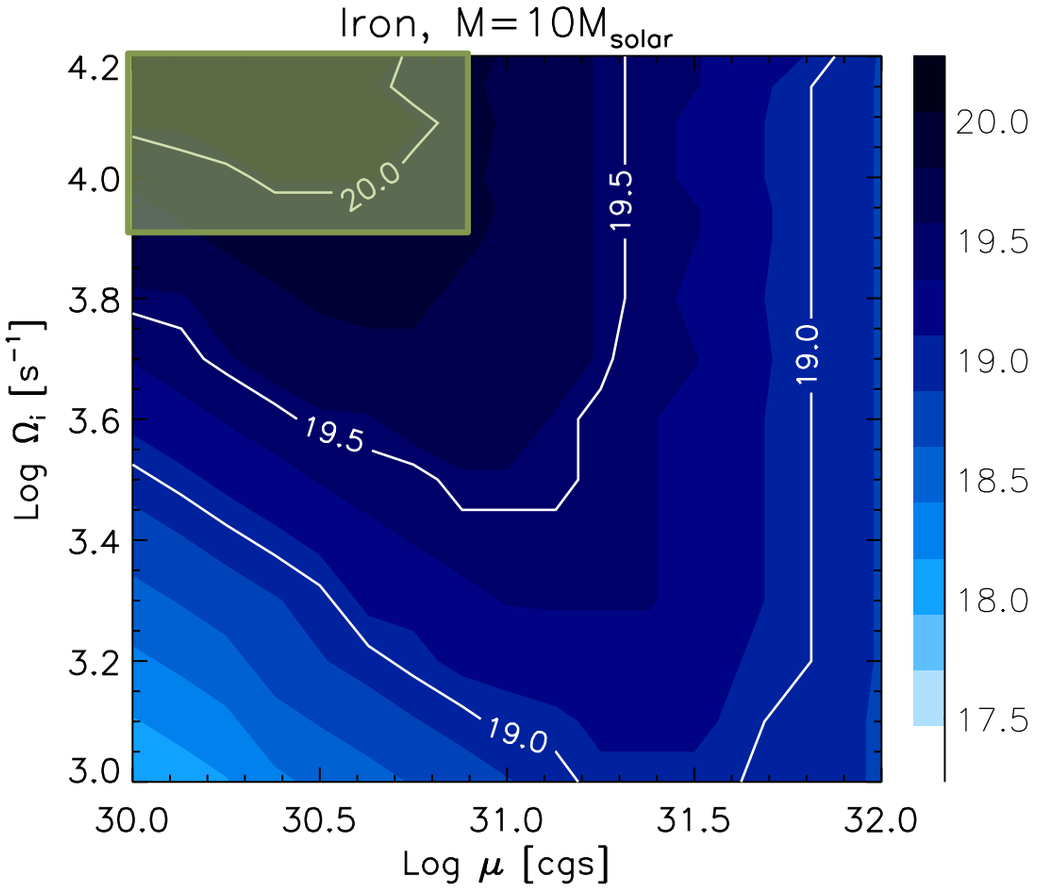


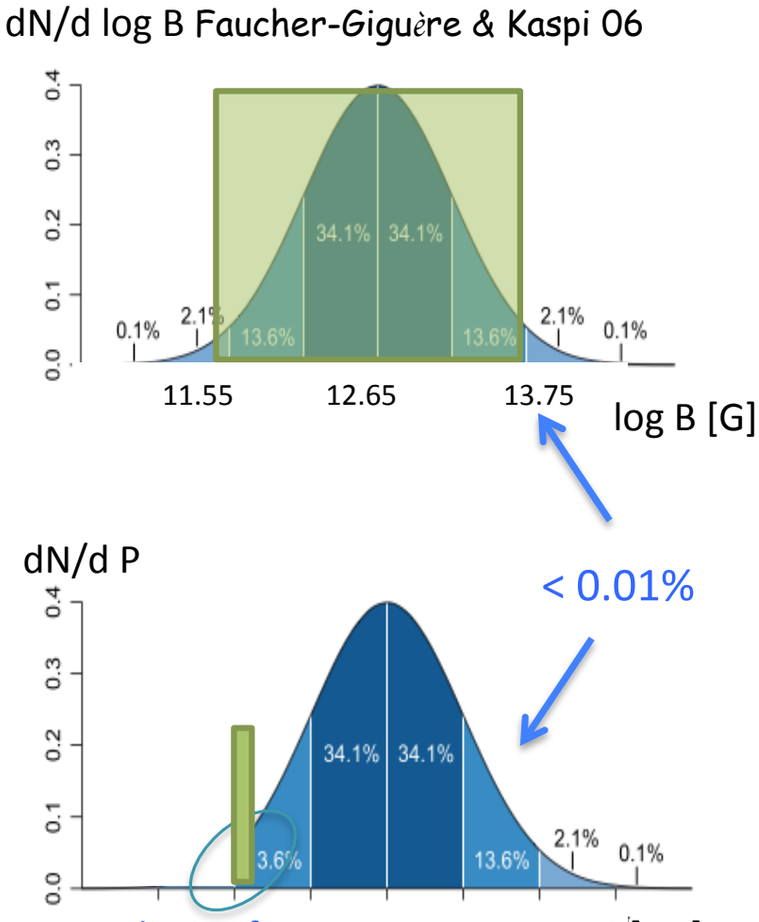




KF, Kotera & Olinto, ApJ, 750:118, 2012

Pulsar Distribution in a Galaxy

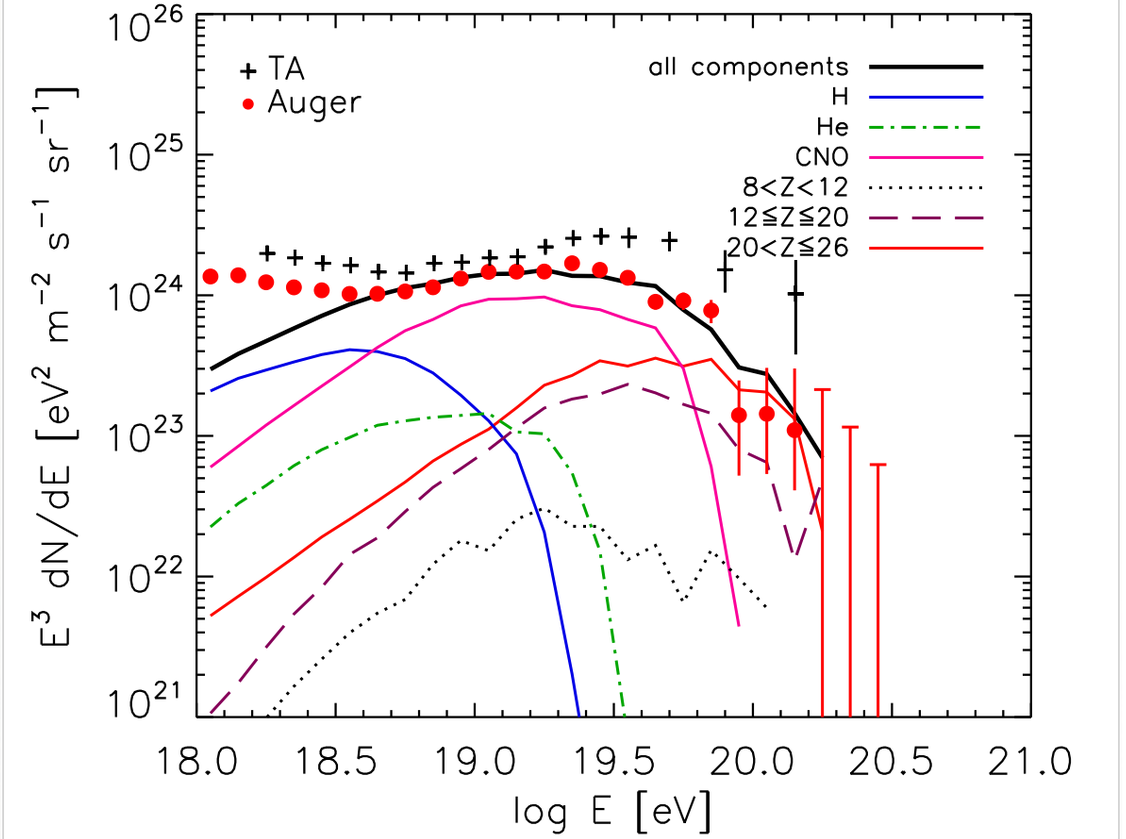


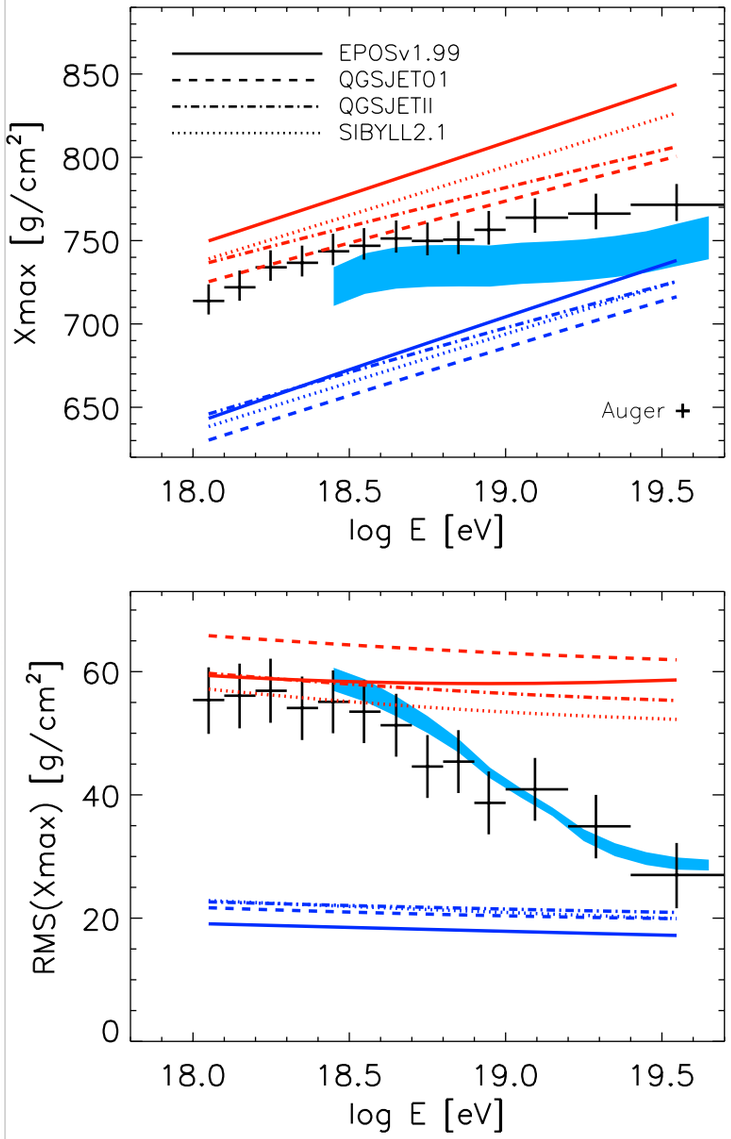


$$\frac{dN}{dE}(Z) = \int \frac{dN_{esc}}{dE}(\mu, \Omega, Z)\, f(\mu)\, f(\Omega)\, d\mu\, d\Omega$$

- log-normally on B <log B> = 12.65 G, σ= 0.55 G
- normally on P <P> = 300 ms, σ= 150 ms
- pulsar burst rate 1 per 60 yr per galaxy

Integrated Extragalactic Pulsars



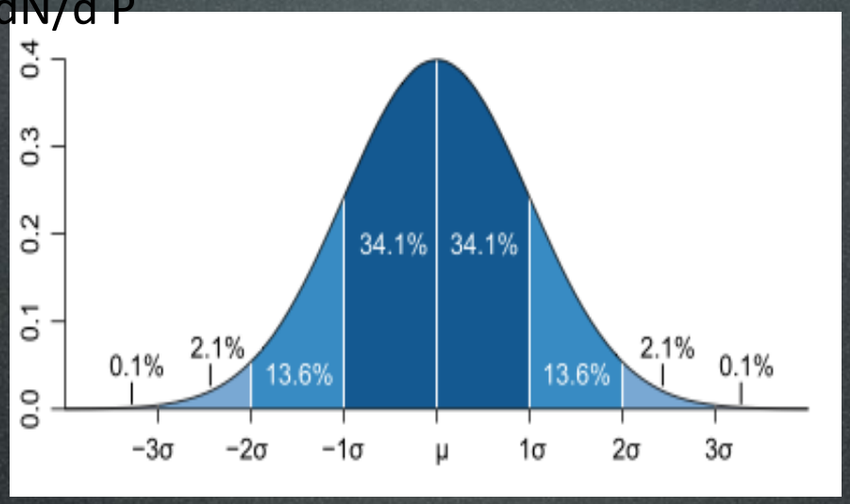


Conclusion I

Newborn pulsars can be successful UHECR accelerators

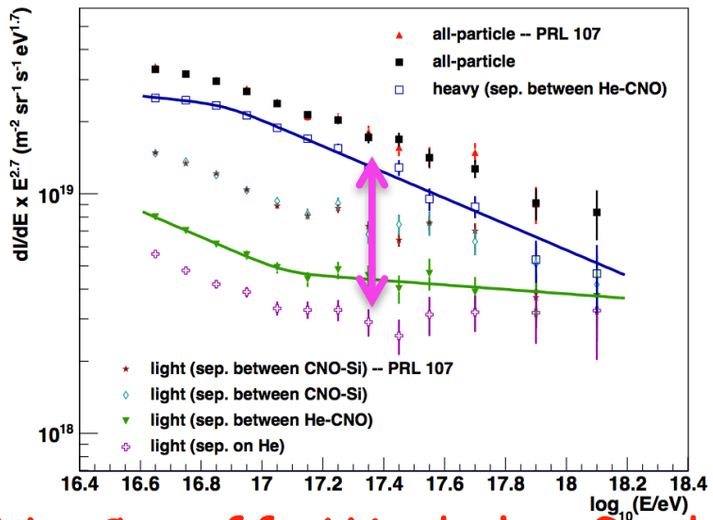
KF, Kotera & Olinto 2013

What about their Galactic Counterparts?

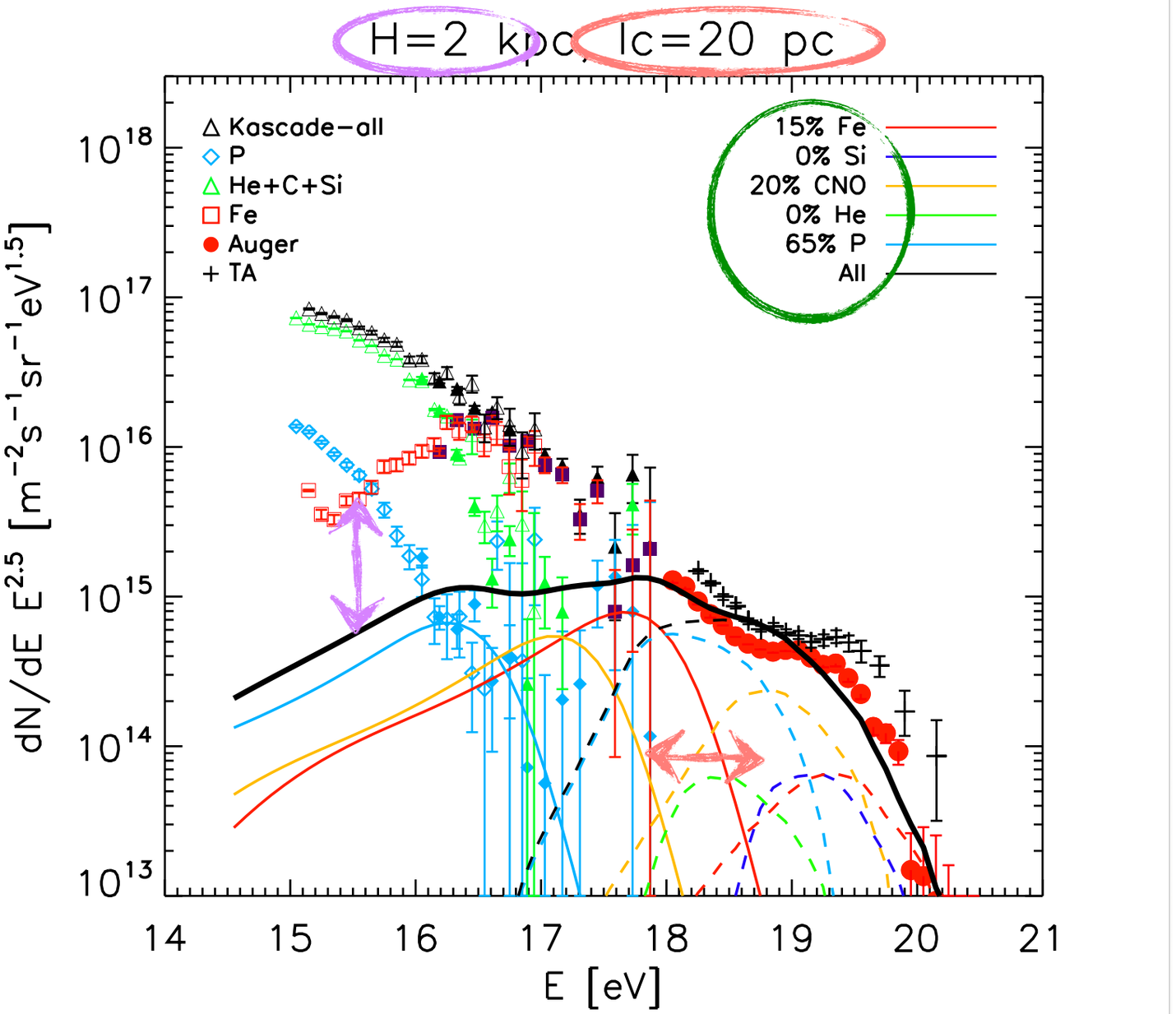


Contribution from Galactic pulsars

KASCADE coll. PRD 87, 081101(R) (2013)

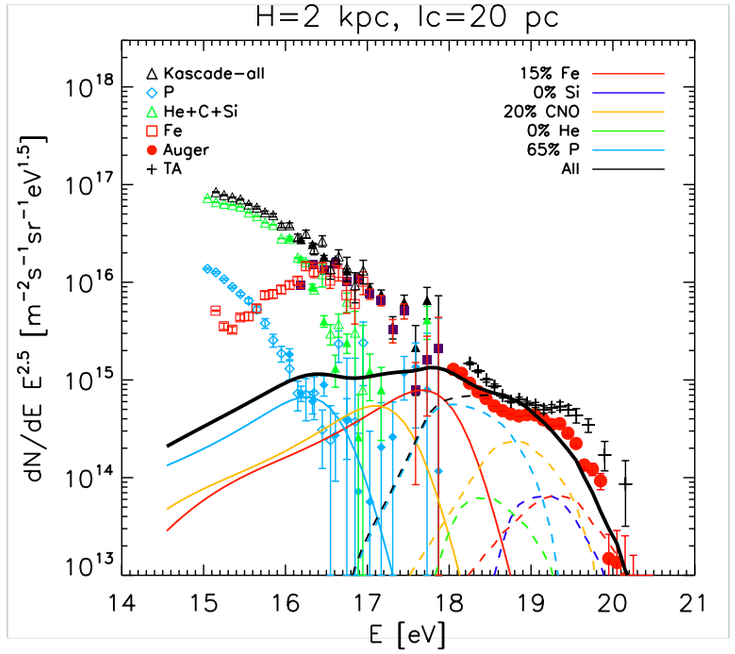


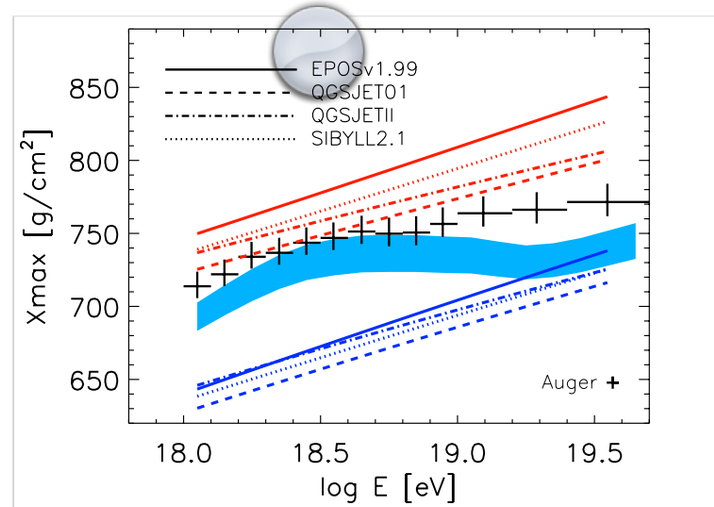
No Cutoff, Mind the Gap!

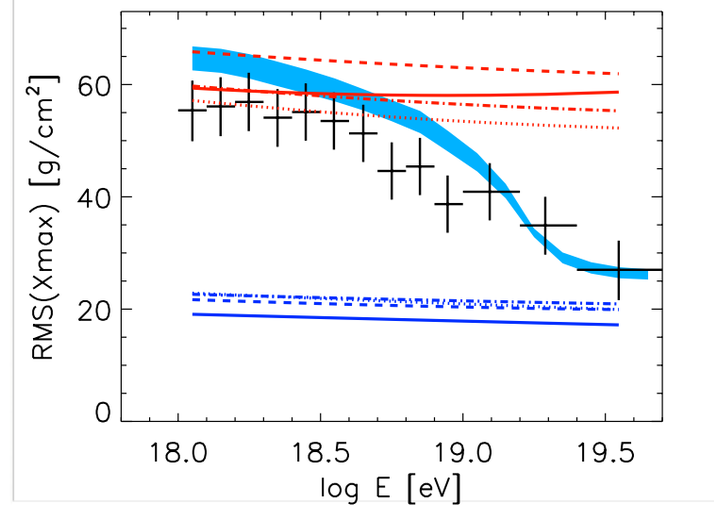


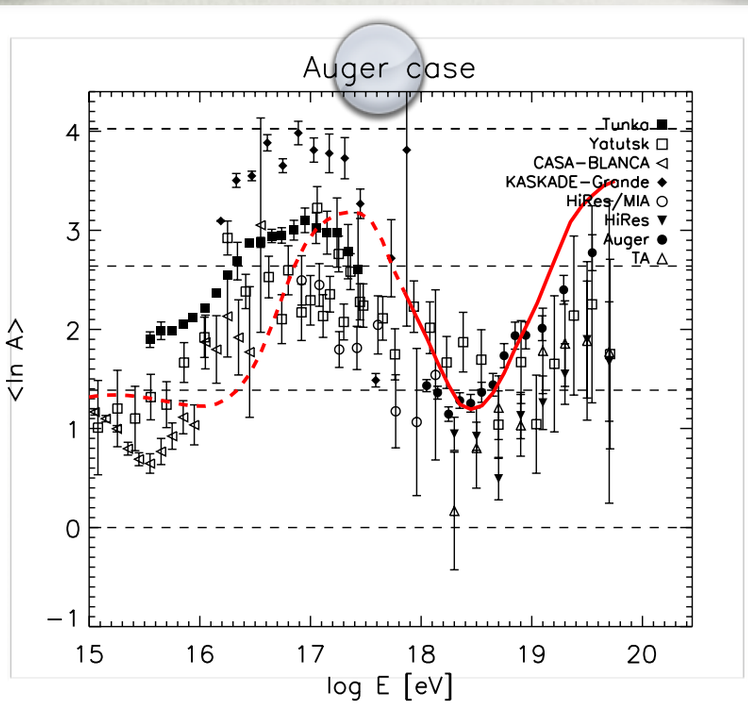
Galactic pulsars can fill the gap

Composition









Conclusion II

Galactic newborn pulsars can bridge the transition region

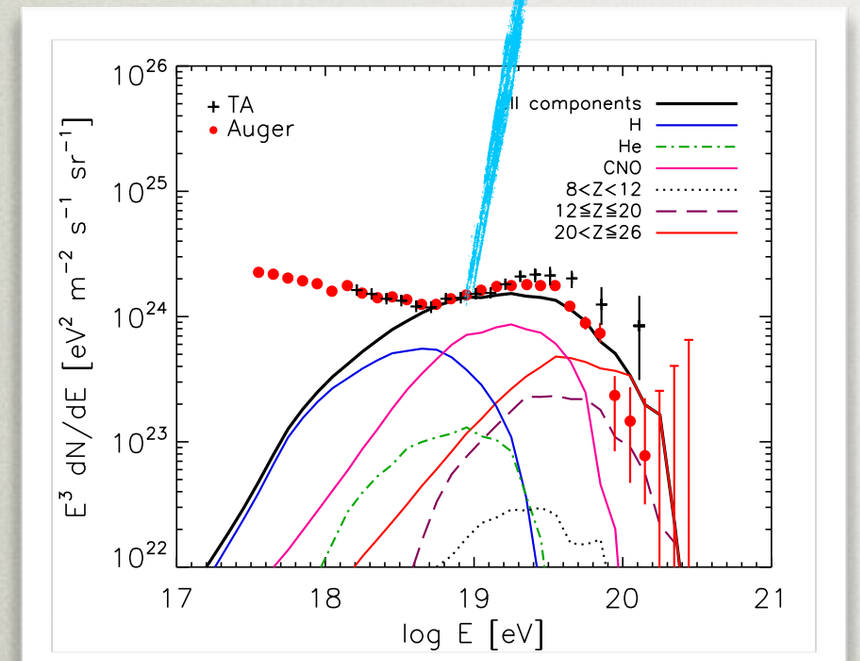
KF, Kotera & Olinto, JCAP, 010: 03, (2013)

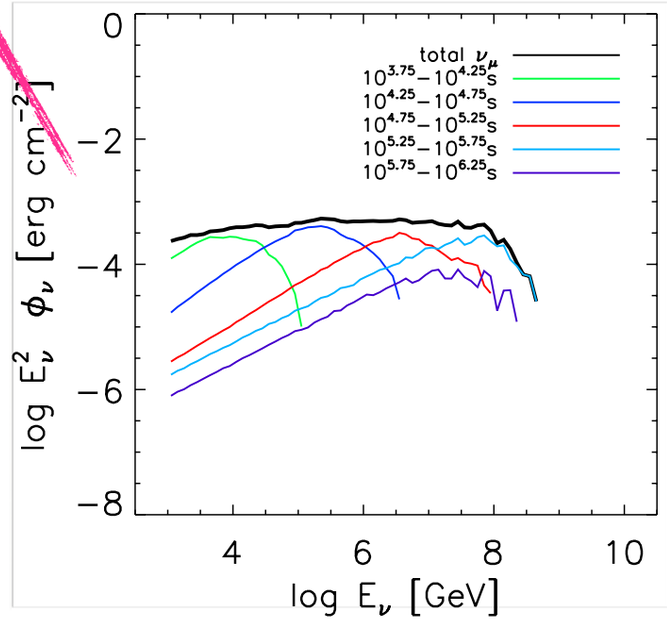
Testable Scenario?

Neutrinos from Integrated Pulsar Sources

$$\Phi_\nu = \frac{f_s}{4\pi} \int_0^{z_H} \int_0^{t_\nu} \frac{dN_\nu}{dt'\, dE_\nu\, 4\pi D^2}\, dt'\, \Re(z)\, 4\pi D^2\, \frac{dD}{dz}\, dz$$

$$\Re(0) \approx 3.3 \times 10^{-4}\, \mathrm{yr}^{-1}\, \mathrm{Mpc}^{-3}$$





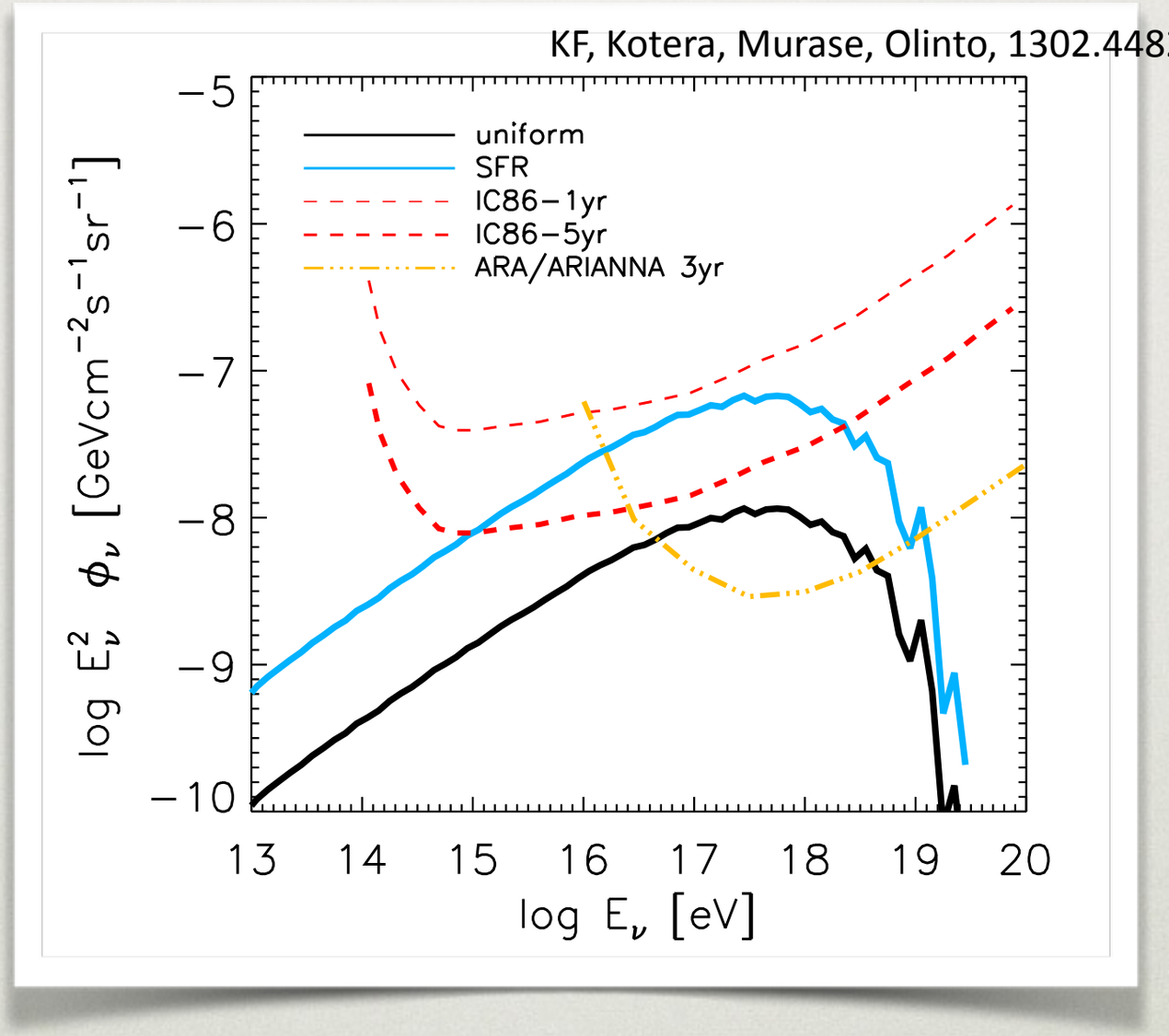
$$\dot{N} = c\left(\frac{\Omega B_{*,\mathrm{dipole}}}{2\pi c}\right)(2\pi A_{\mathrm{cap}})$$

× Neutrino-loud lifetime

Measured UHECR flux

→ $f_s \approx 0.05$

Neutrinos from Integrated Pulsar Sources

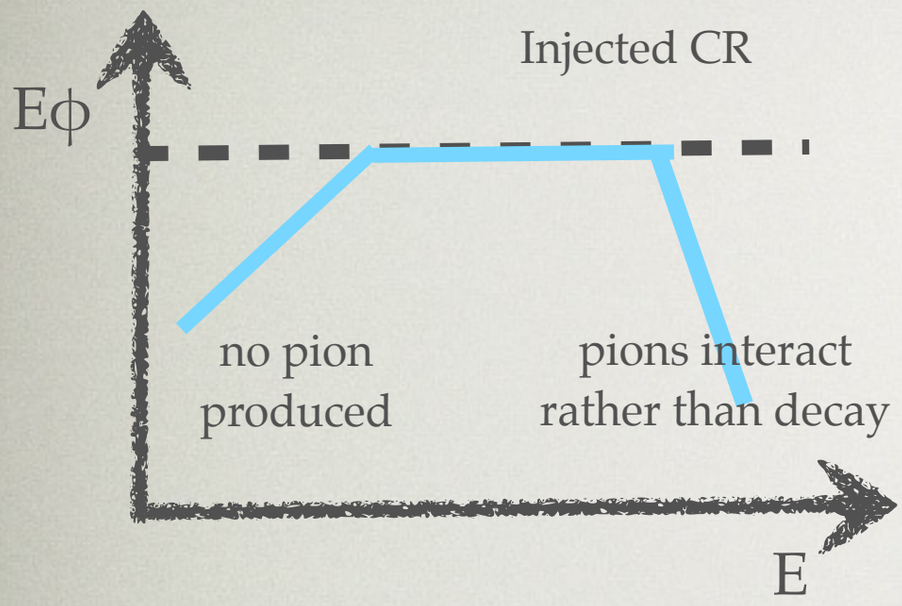


Conclusion III

Consistent with current detection upper limits;

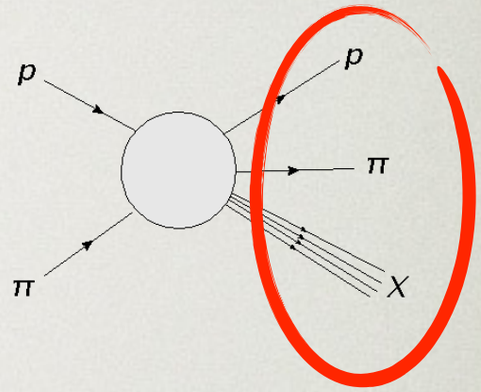
Robustly tested with IC86-5 year and projected ARA-37 3 year operations.

Neutrino as a smoking gun?



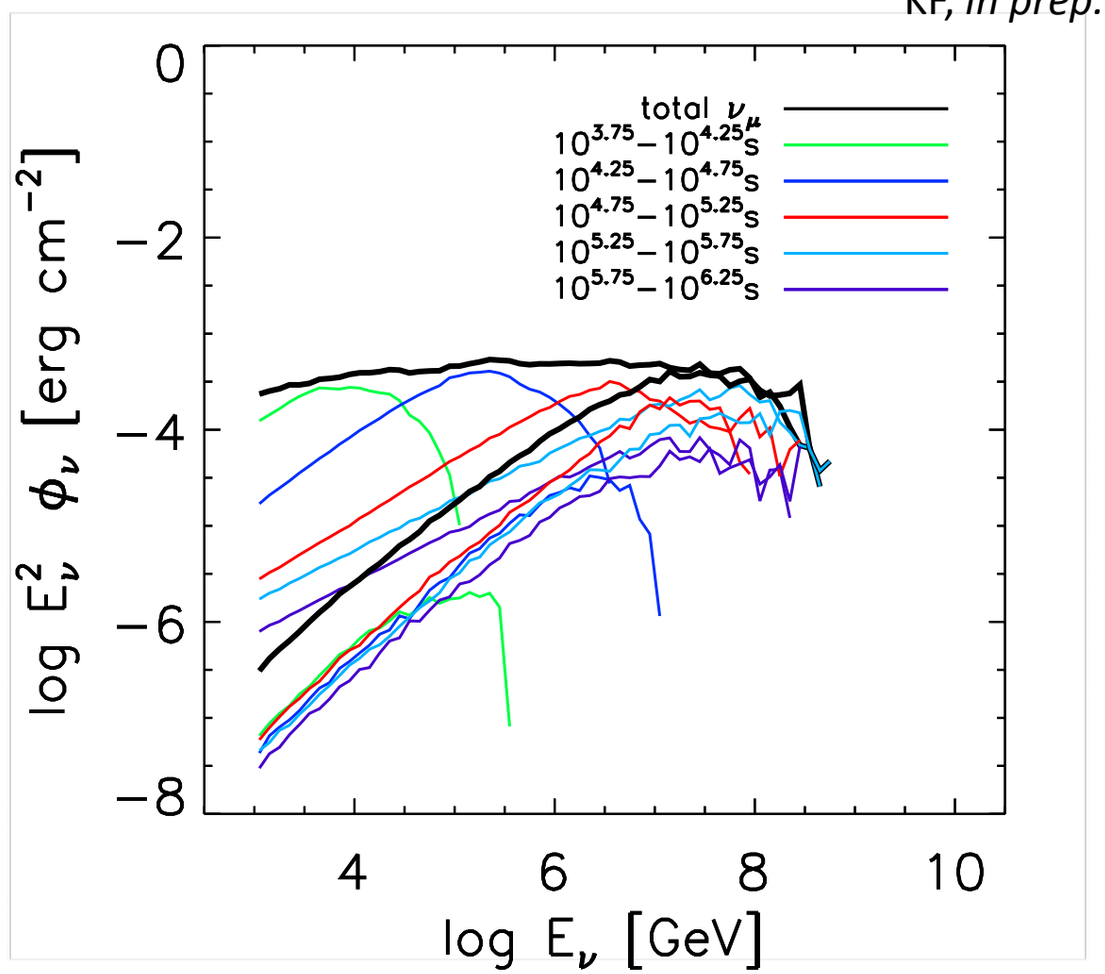
$\phi \sim E^{-1}$?

Not really!

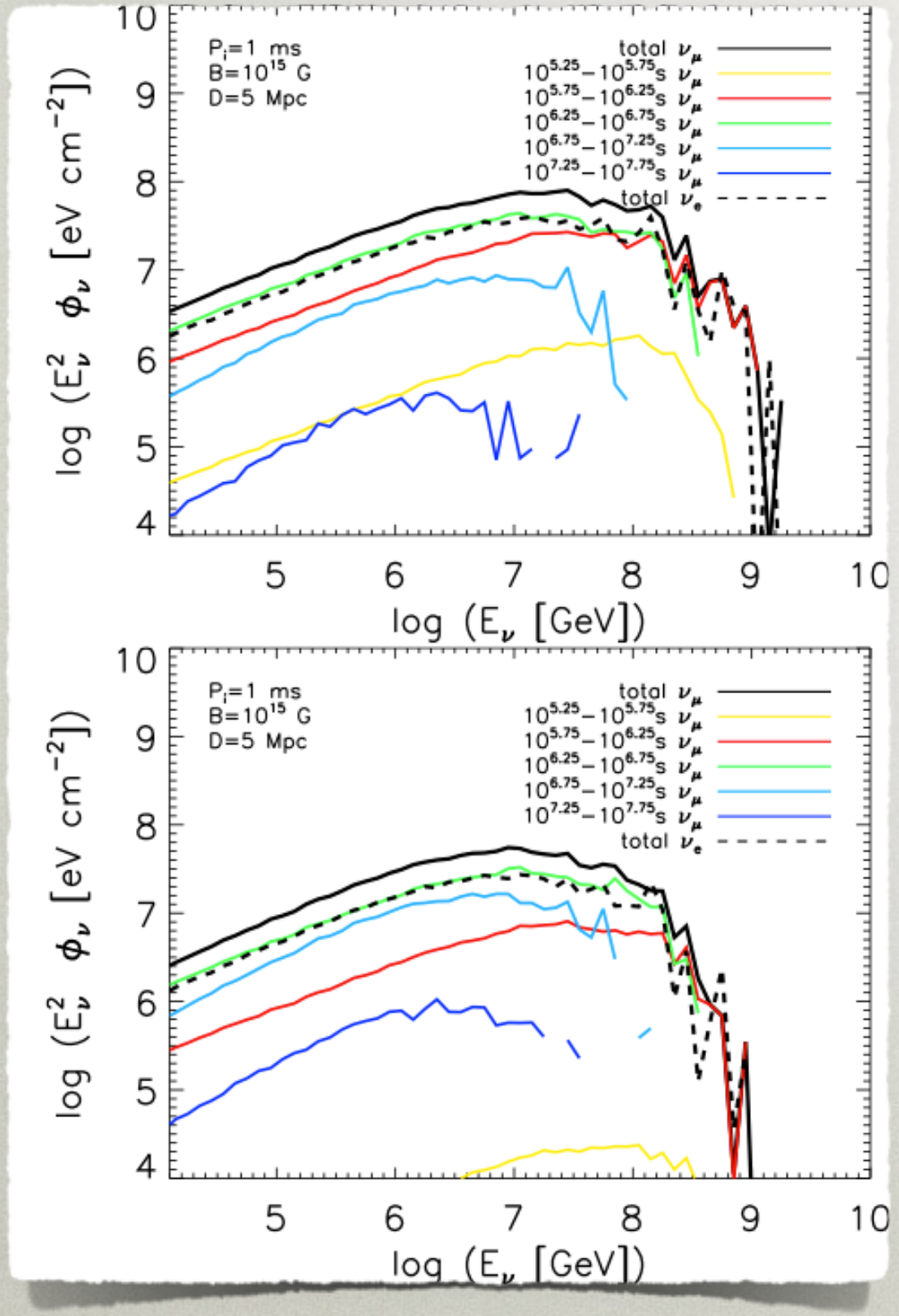


Secondaries flatten the spectrum.
A magnetar produces E-2 spectrum!

KF, *in prep.*



Neutrino from a local newborn pulsar

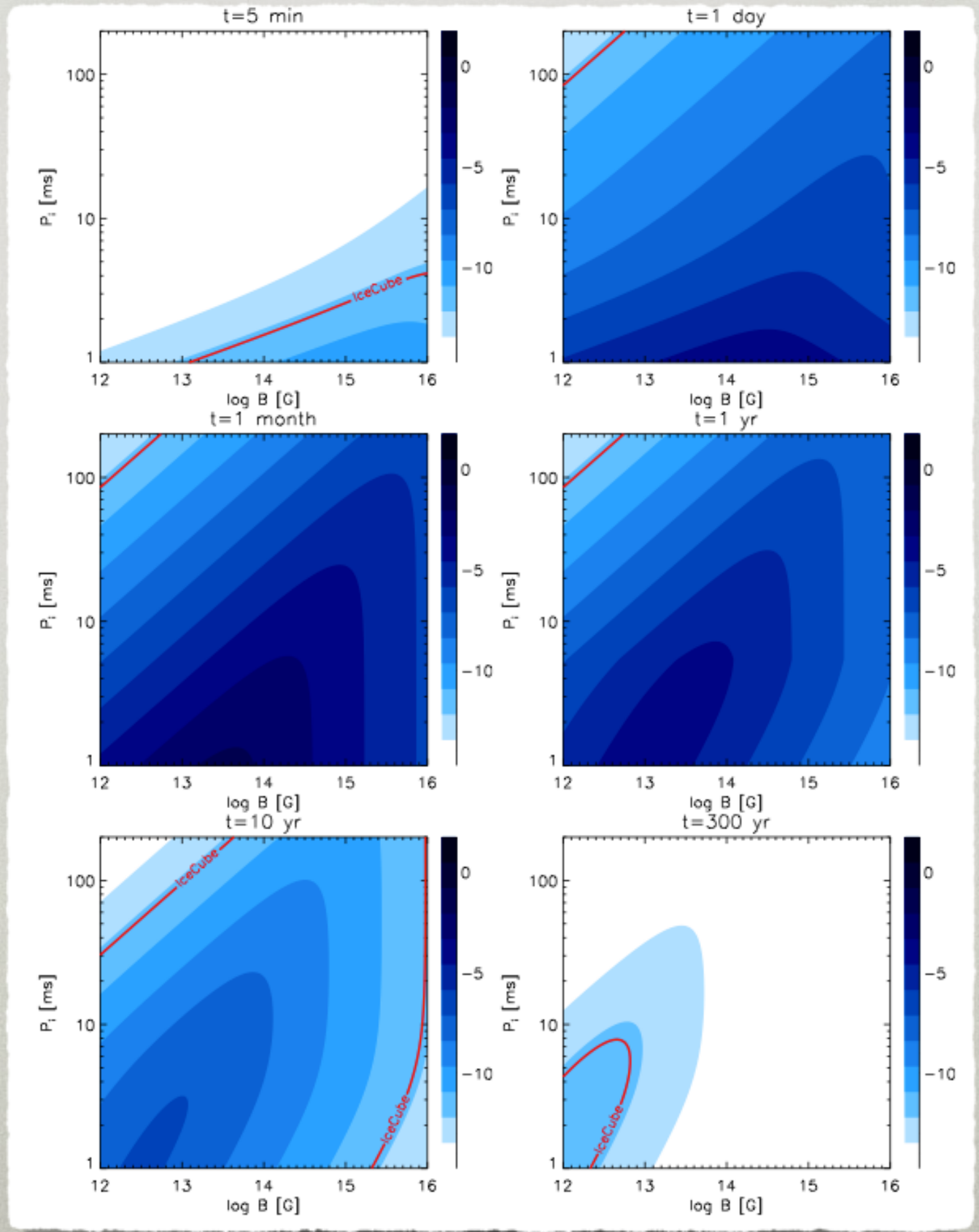


Pure Proton injection

Pure Fe injection

Insensible to injection composition:
Fe~56P/26
CNO~28P/14

Neutrino from a local newborn pulsar



detectability

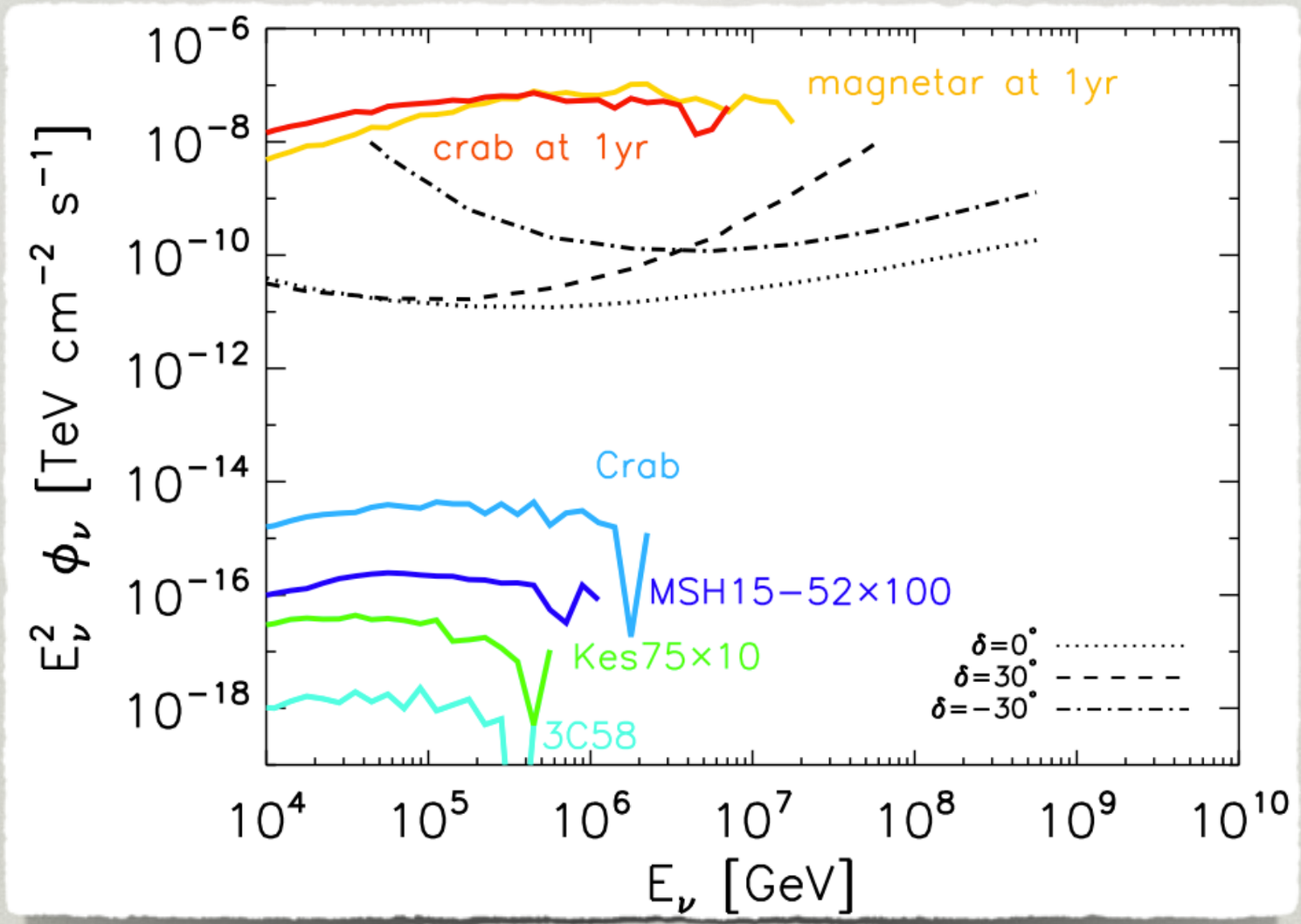


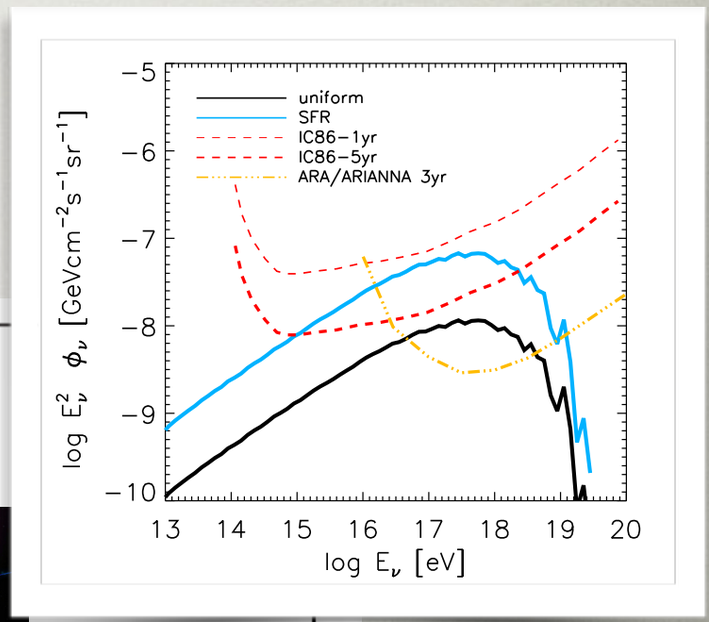
Table 2. Properties of Pulsars

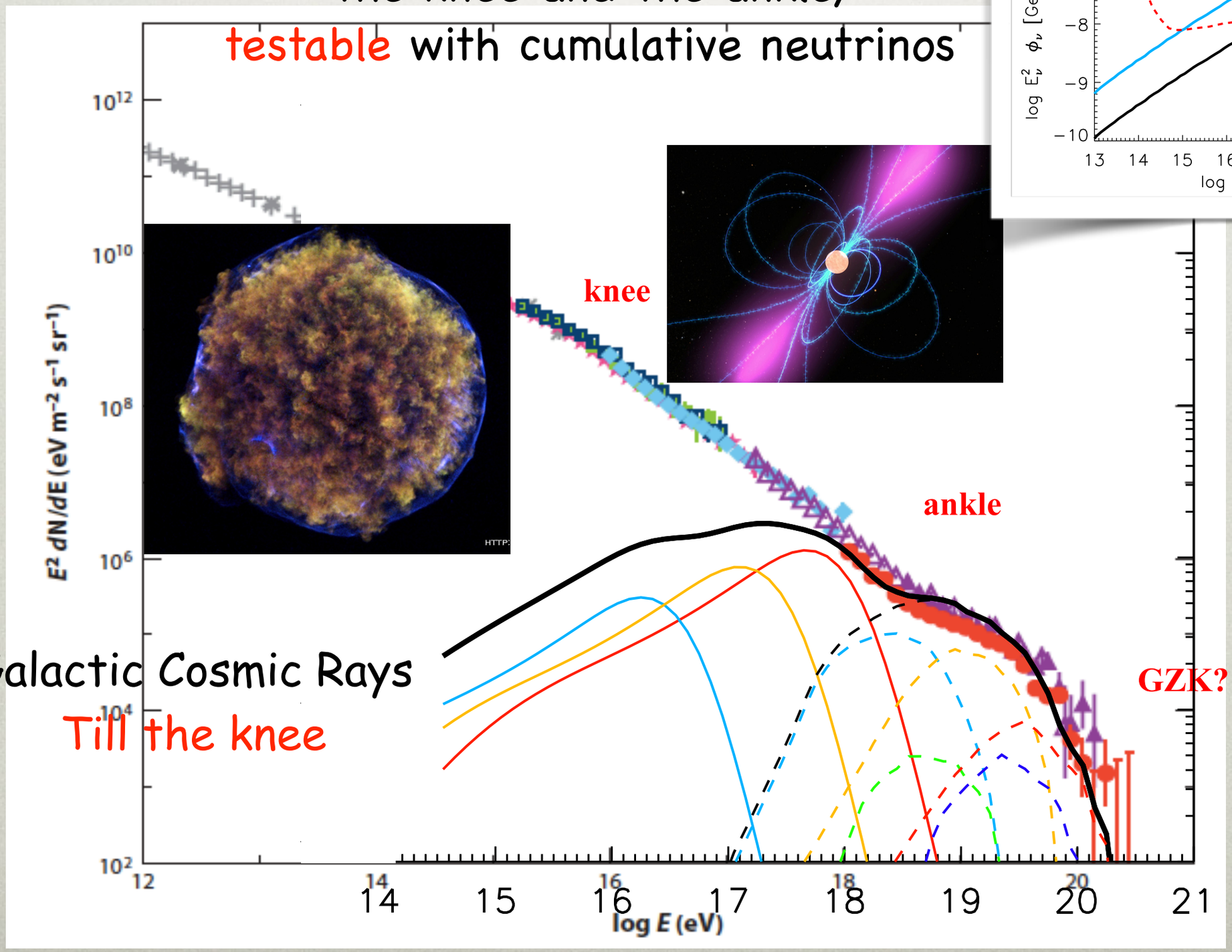
PSR	SNR	Supernova Type	D (kpc)	P_i (ms)	B (10^{12} G)	Age (yr)	$E_{\rm exp}$ (10^{51} erg)	$M_{\rm ej}$ ($M_\odot$)
B0531+21	Crab	IIP	2	20	4	950	1	9.5
J0205+64	3C 58	IIP	3.2	50	4	2400	1	3.2
J1846-03	Kes 75	Ib/c	19	30	48	1000	2.1	16.4
B1509-58	MSH 15-52	Ib/c	5.2	10	14	1700	7	4

Summary

Newborn pulsars contribute above the knee and the ankle,

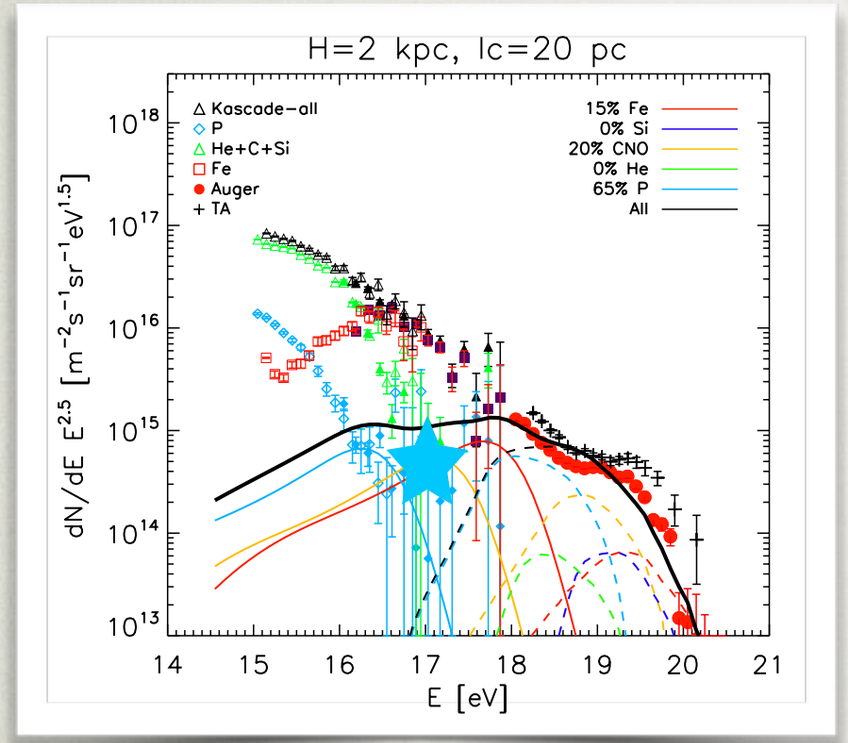
testable with cumulative neutrinos

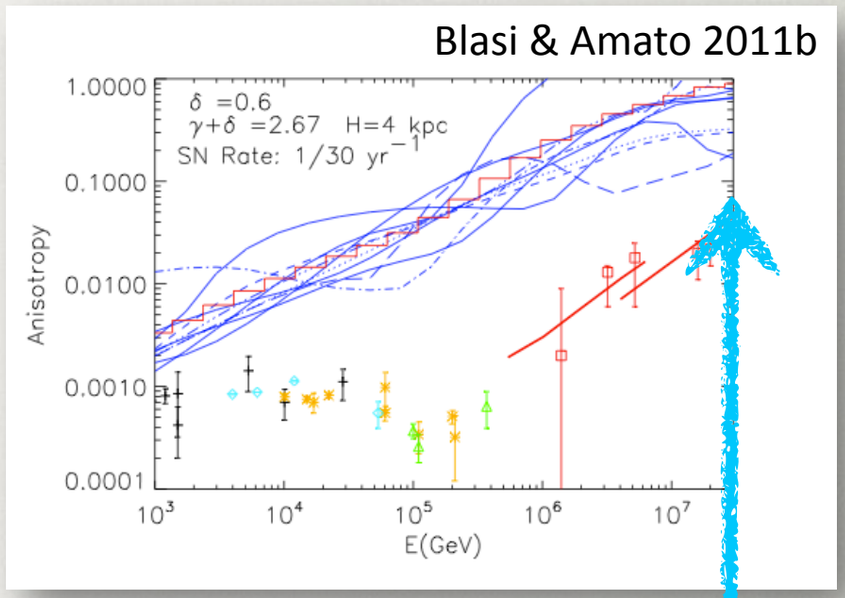




Backups

Estimation on Anisotropy

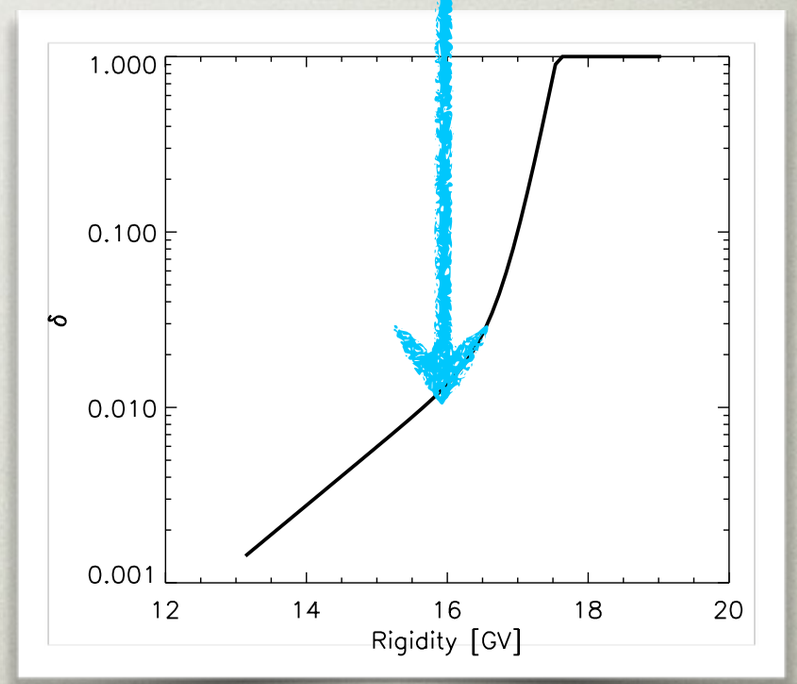




Heavy composition reduces anisotropy levels

Assume sources homogeneously distributed in the disc, small scale anisotropy can be estimated as (Blasi & Amato 2011b)

$$\delta = \frac{3}{2^{3/2}\,\pi^{1/2}}\,\frac{D(E)}{Hc}$$



Conclusion II

Galactic pulsars can contribute between the knee and the ankle!

Anisotropy

$$r_L = 10 Mpc \frac{1}{Z} \frac{E}{10^{20} eV} \left(\frac{B}{10^{-8} G} \right)^{-1}$$

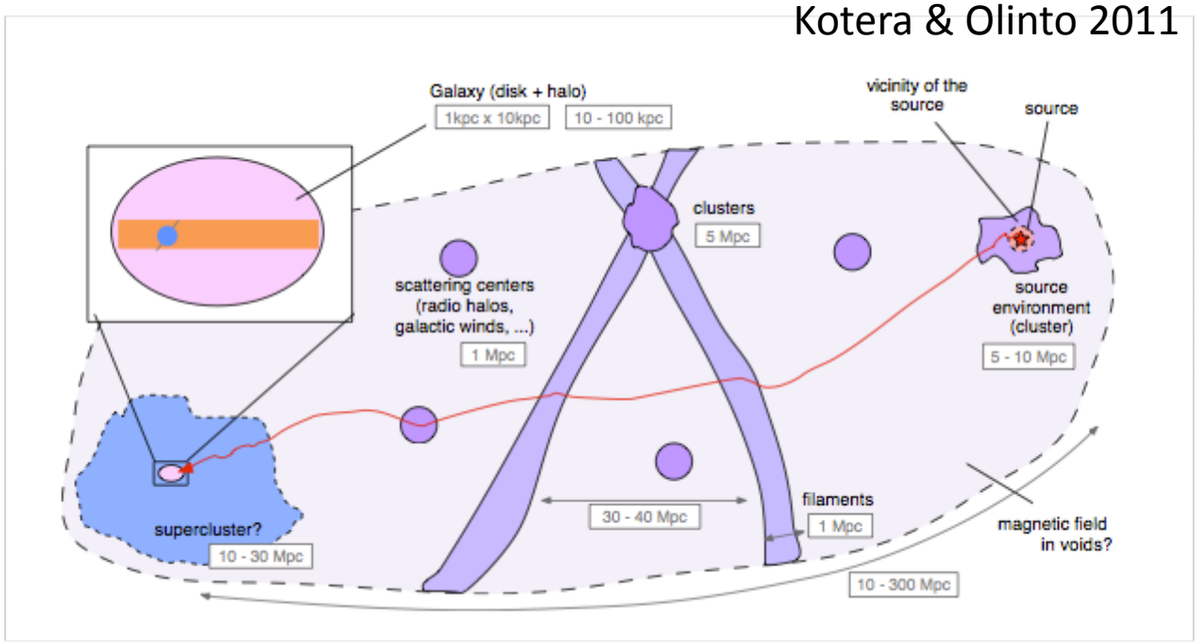
$$\lambda \approx 10 - 100 kpc << r_L \Rightarrow small \quad deflections$$

$$\delta\theta^2 \approx \frac{r_{structure}}{r_L^2 / l_c}$$

$$\delta\theta_i \simeq 1.7^\circ \left(\frac{\bar{r}_i}{2\,\mathrm{Mpc}} \right)^{1/2} \left(\frac{B_i}{10^{-8}\,\mathrm{G}} \right) \times \left(\frac{\lambda_i}{0.1\,\mathrm{Mpc}} \right)^{1/2} \left(\frac{E}{10^{20}\,\mathrm{eV}} \right)^{-1} .$$

Kotera et al 2009

Kotera & Olinto 2011



Time delay after the deflections

$$\delta t_i \simeq 0.93 \times 10^3\,\mathrm{yr} \left(\frac{\bar{r}_i}{2\,\mathrm{Mpc}} \right)^2 \left(\frac{B_i}{10^{-8}\,\mathrm{G}} \right)^2 \times \left(\frac{\lambda_i}{0.1\,\mathrm{Mpc}} \right) \left(\frac{E}{10^{20}\,\mathrm{eV}} \right)^{-2} .$$

Kotera et al 2009

>>

Time the source was lighted

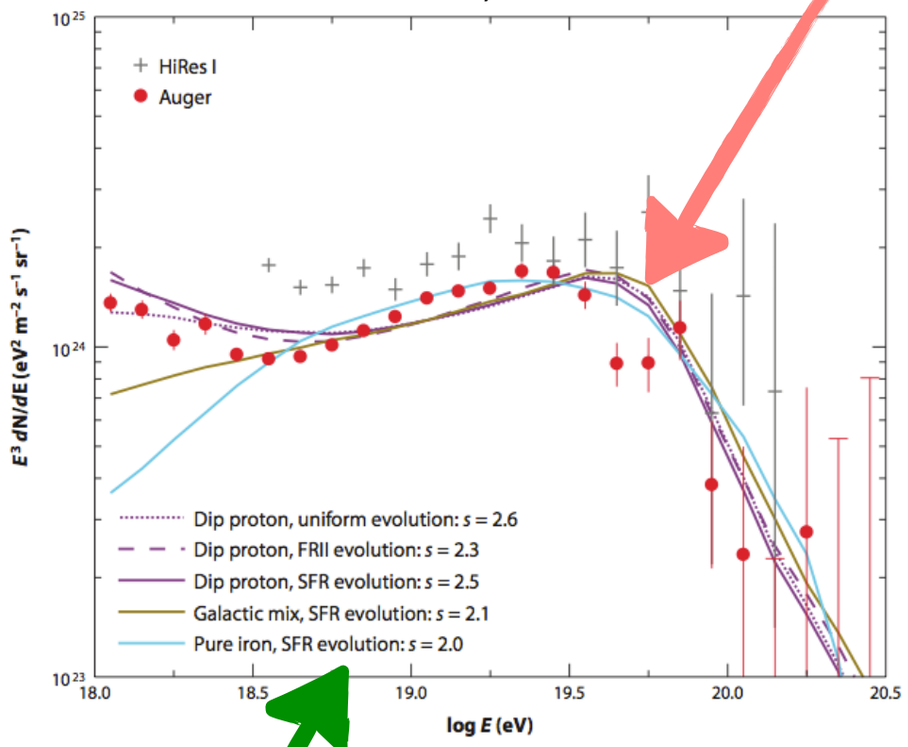
$$t_{spin} = 3yr \left(\frac{10^{20} eV}{E} \right) \frac{Z_{26} \eta_1}{\mu_{30.5}}$$

=> Transients, no source- arrival direction correlation

UHECR measurements -1. Spectrum

GZK cutoff and/or end of Emax

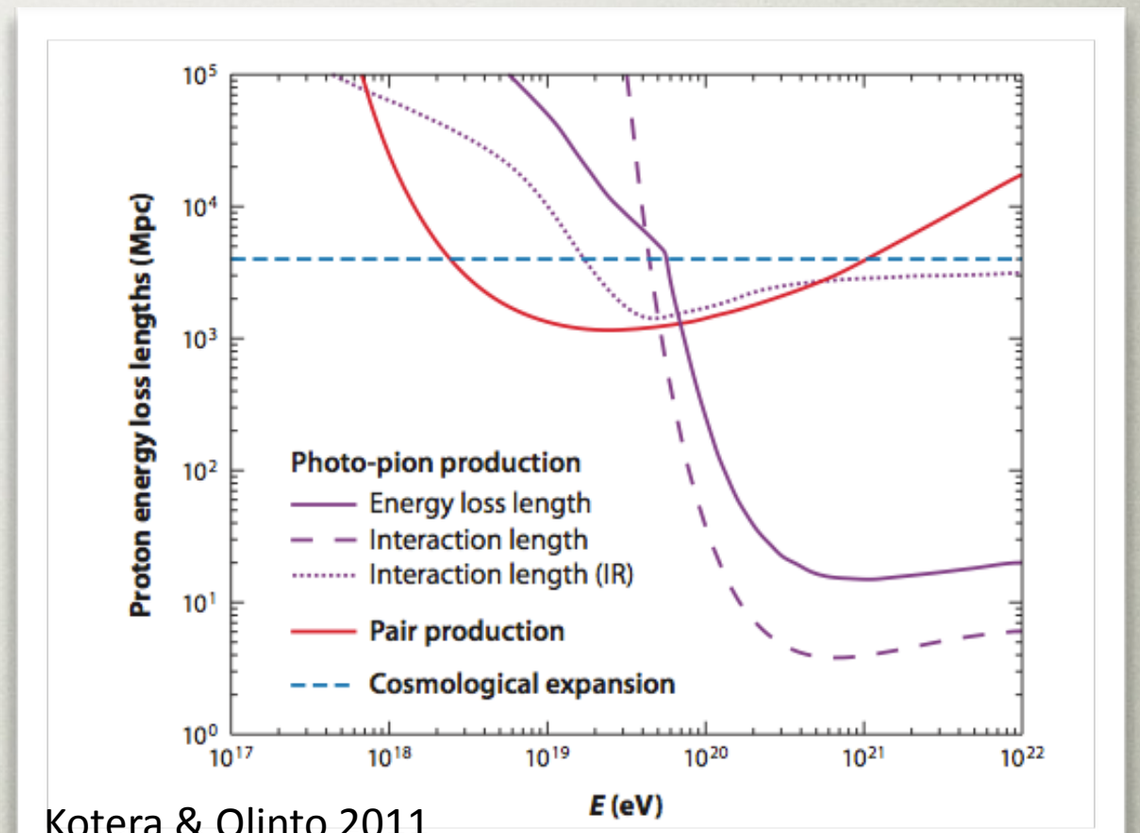
Abraham et al. 2010b, Kotera & Olinto 2011



intrinsic index ~ 2

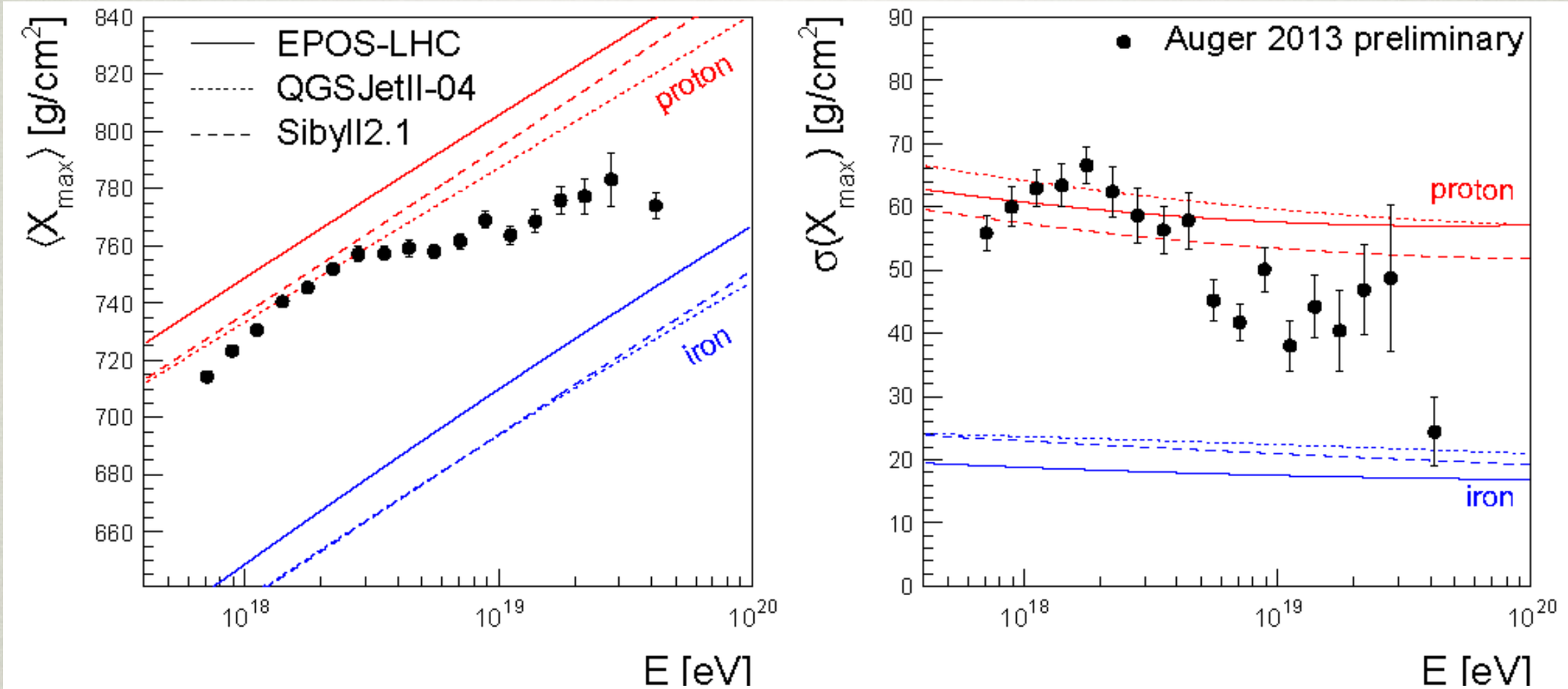
GZK Cutoff
Greisen, Zatsepin, Kuzmin 1966

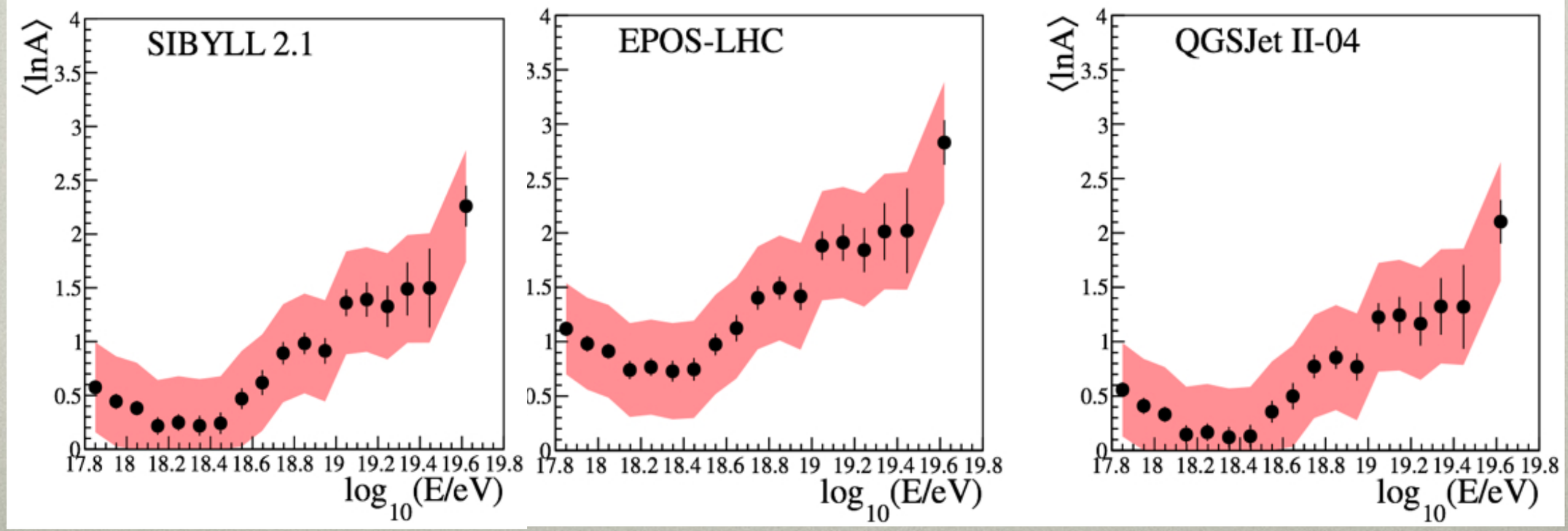
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



Kotera & Olinto 2011

UHECR measurements - **2. Chemical Composition**





UHECR measurements - **2. Chemical Composition**

Auger: Light to Heavy Transition

Not confirmed by North Hemisphere telescopes

Auger Collaboration, PRL 104 (2010) 091101, ICRC 2011, arXiv:1107.4804