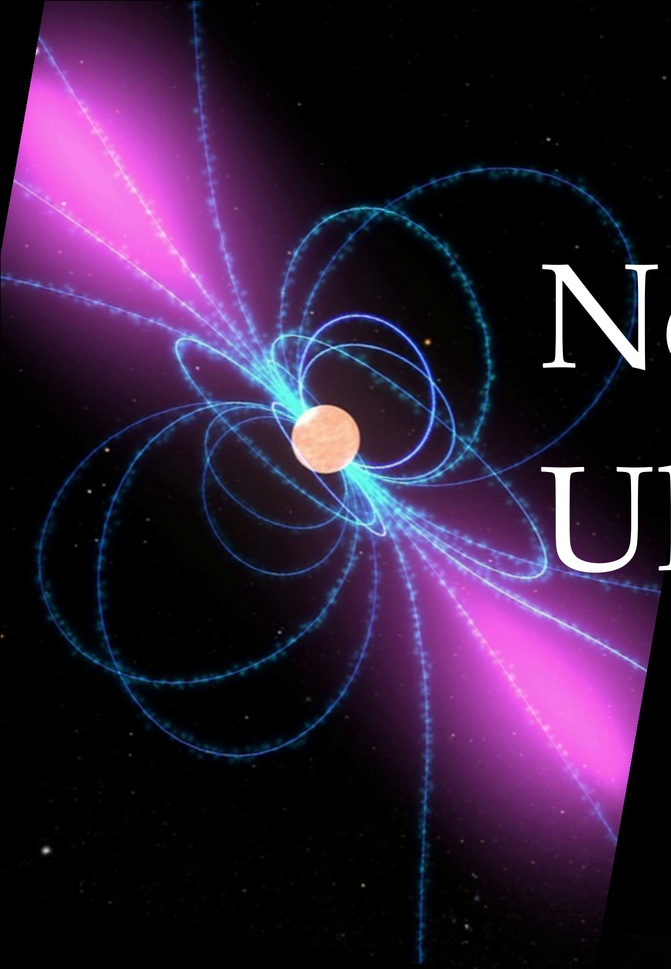
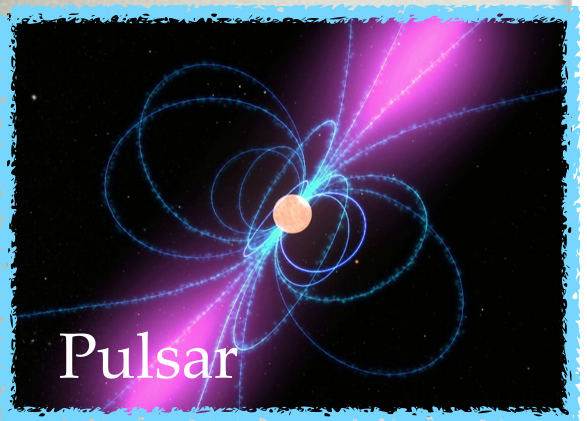
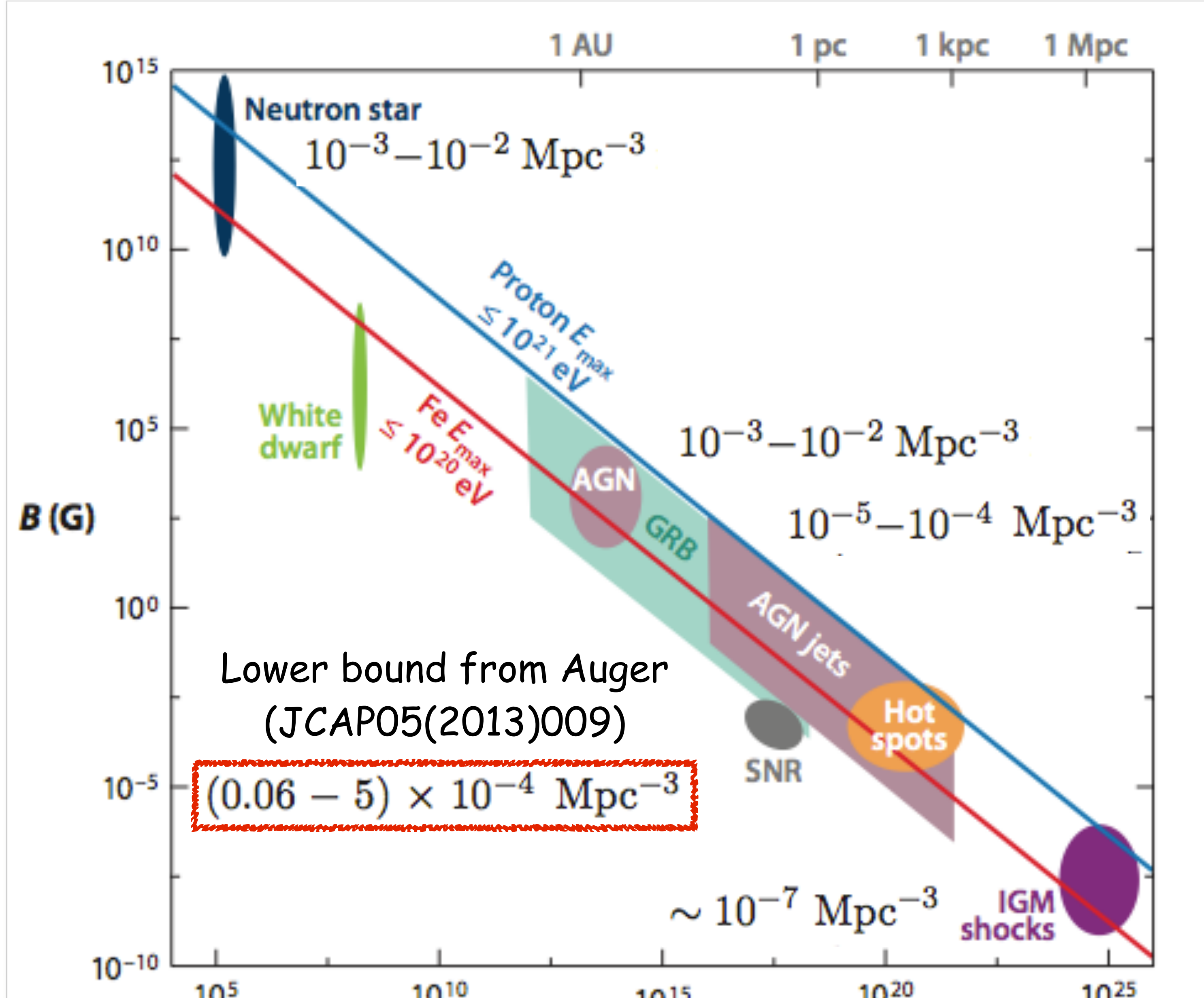


Newborn Pulsars as Sources of Ultrahigh Energy Cosmic Rays

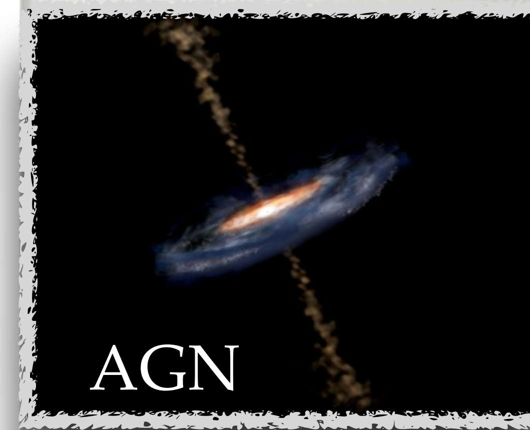
Ke Fang
University of Chicago
MACROS
Nov 27, 2013

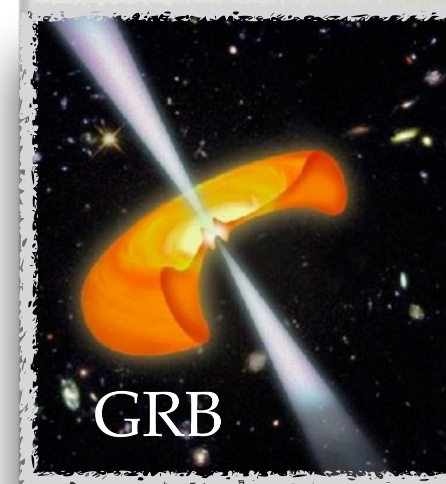
Possible Candidates of UHECR Sources



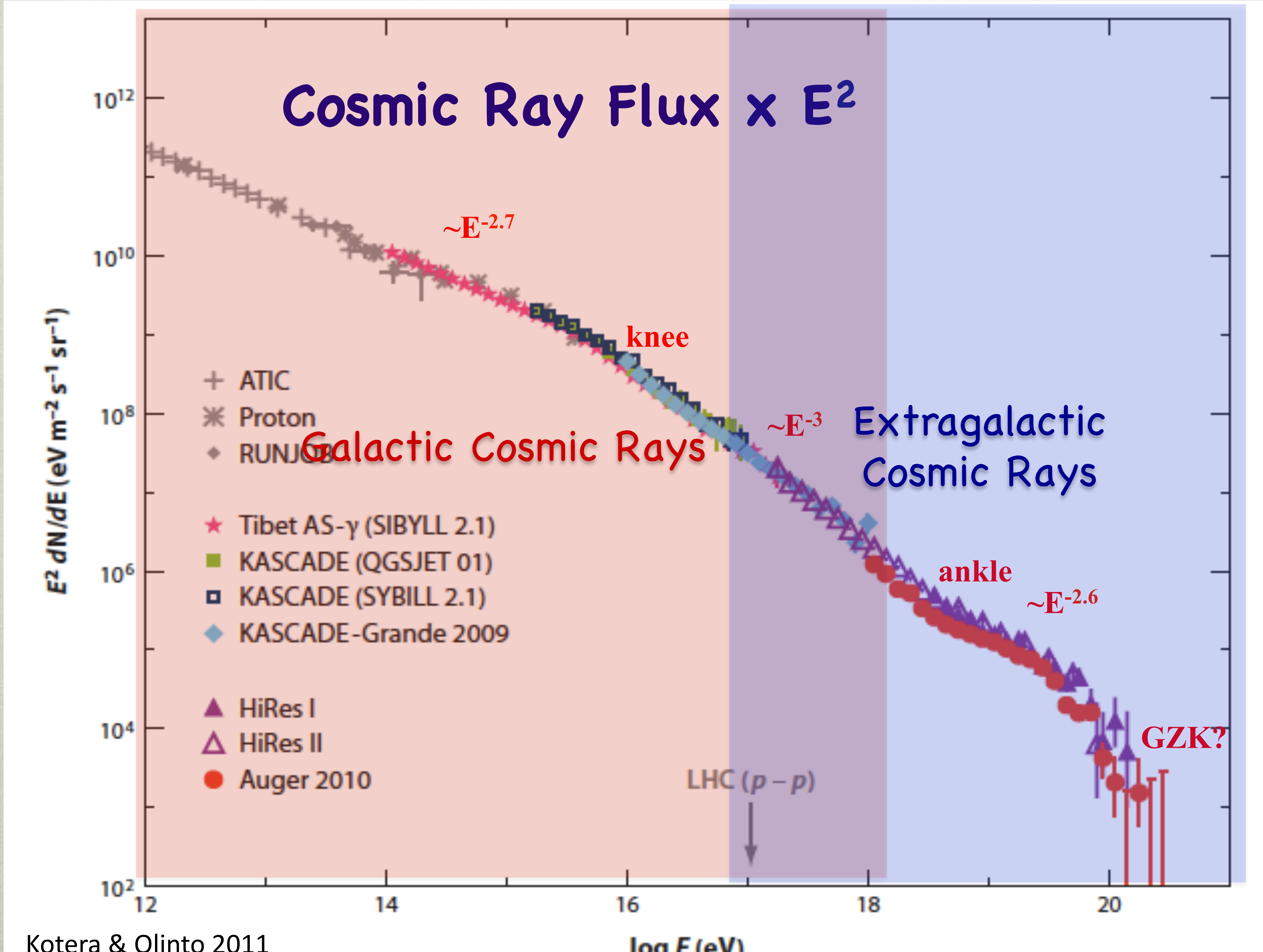


Hillas Diagram (1984)
updated Kotera & Olinto, 2011



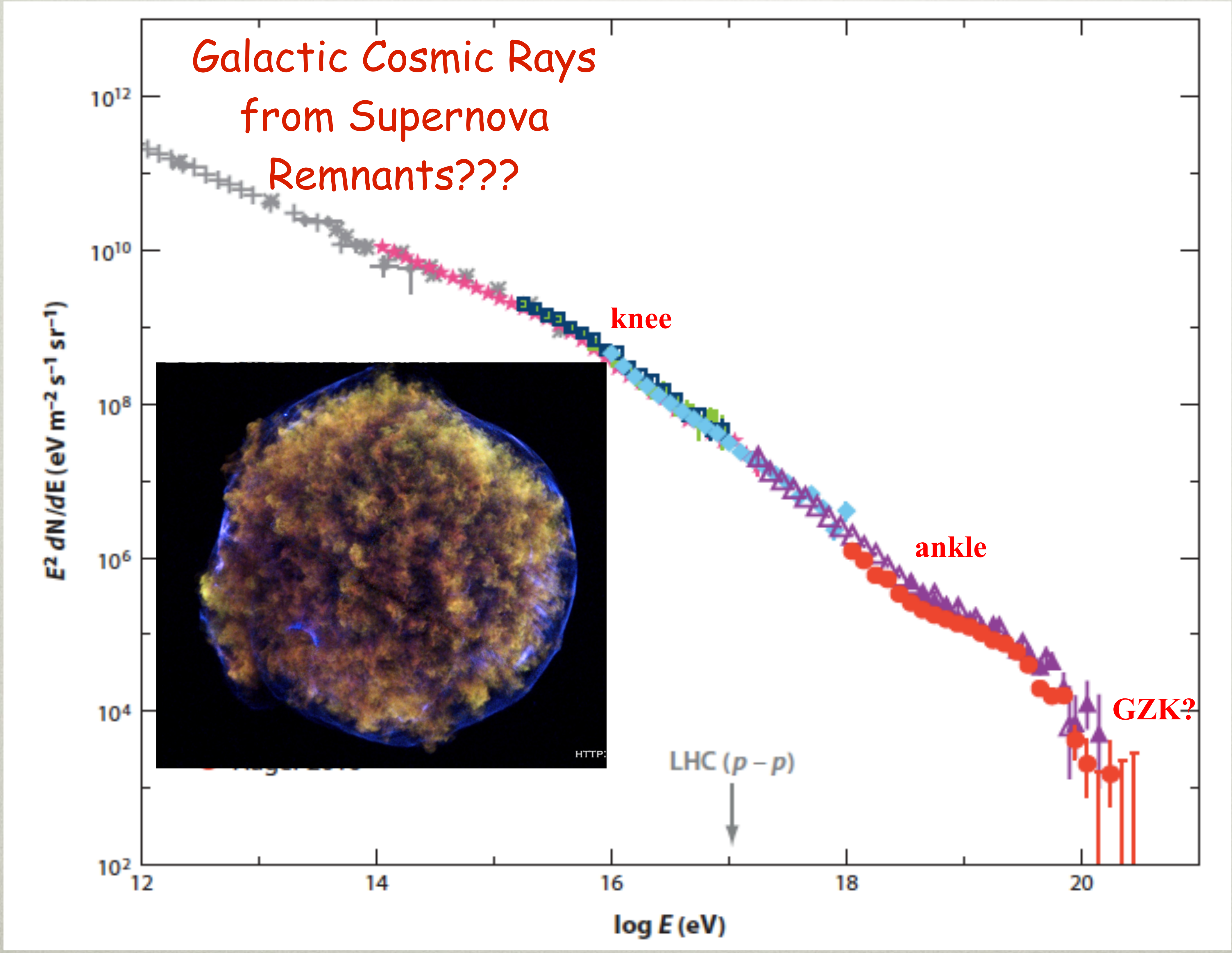


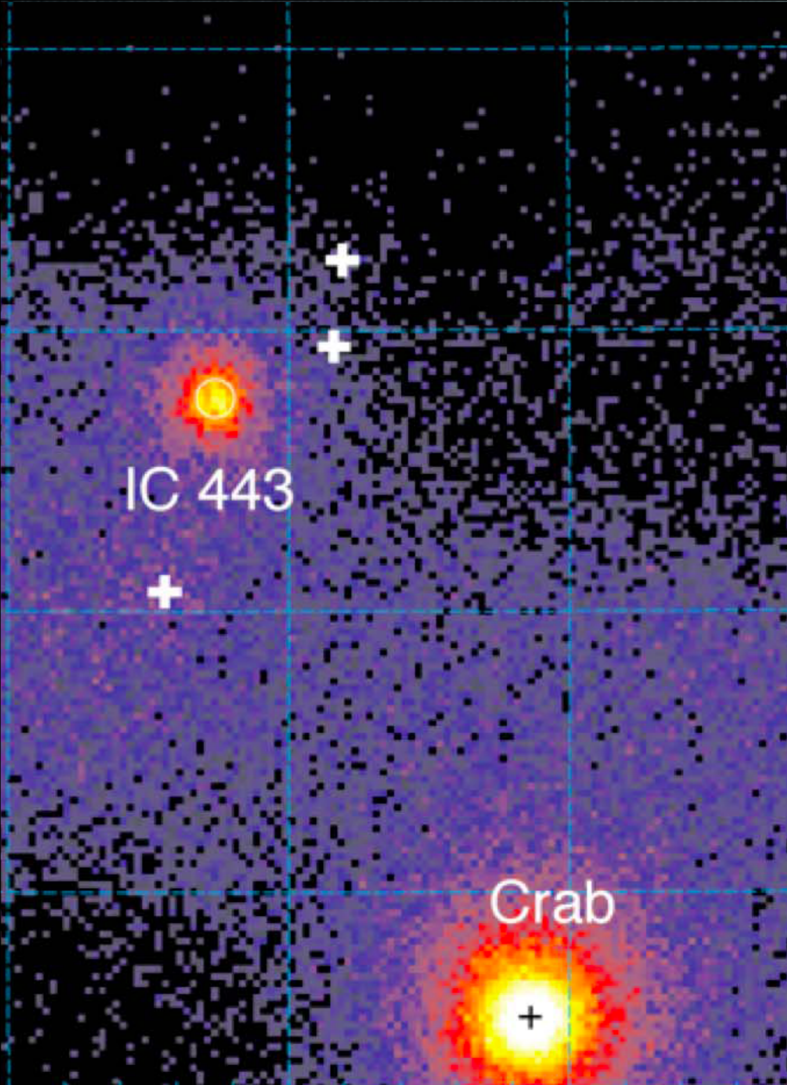
What have we learnt in 100 years?



Kotera & Olinto 2011

What remains unknown?

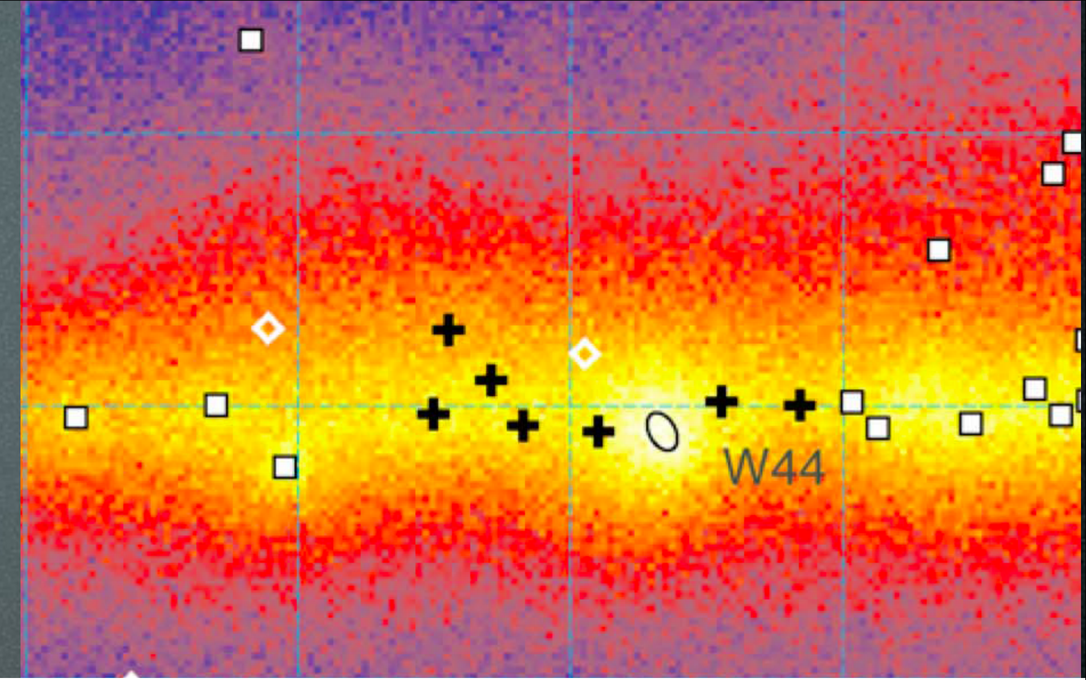


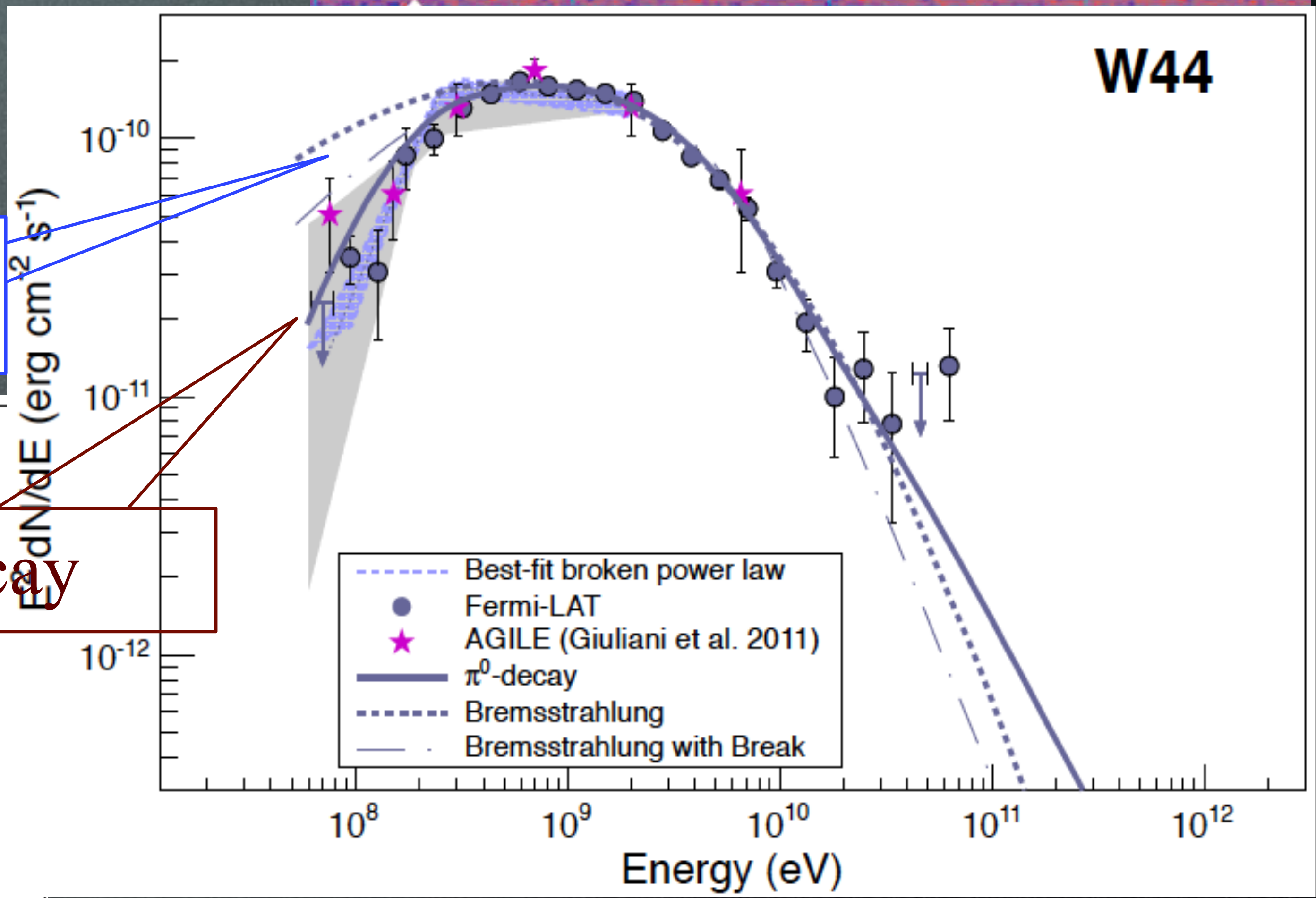


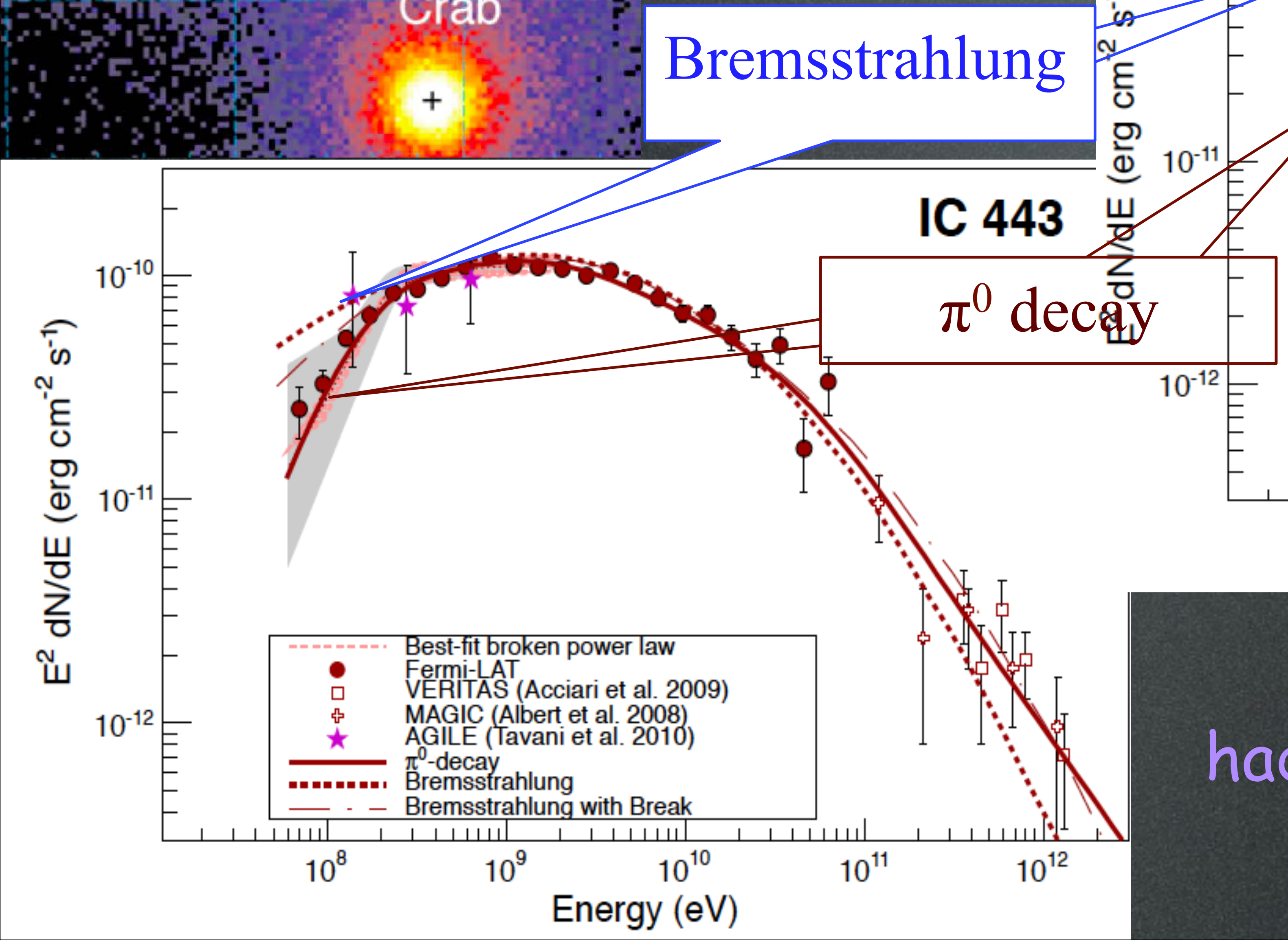
π^0 decay!

IC 443 & W44

Fermi & AGILE



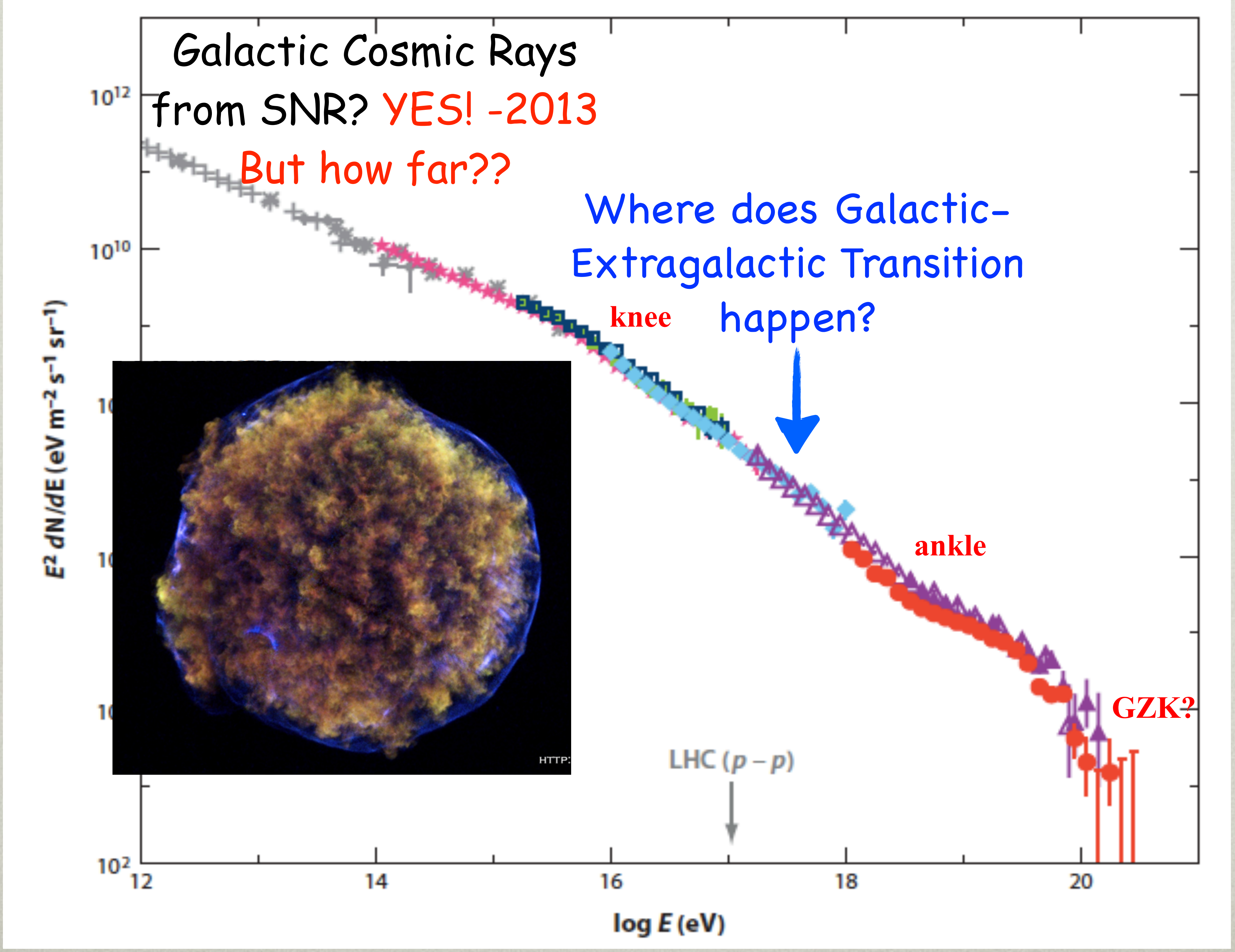




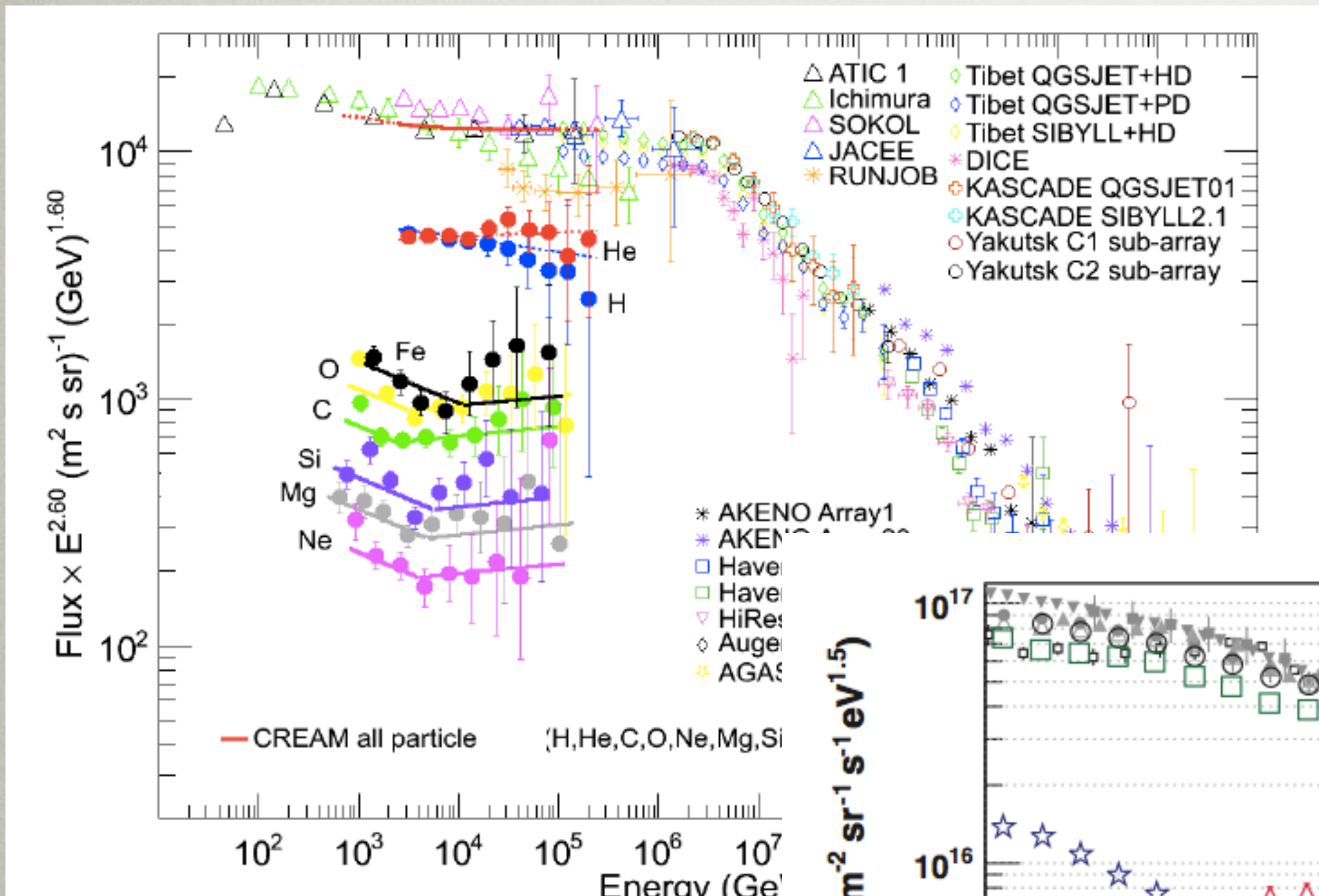
hadrons are accelerated in SNR

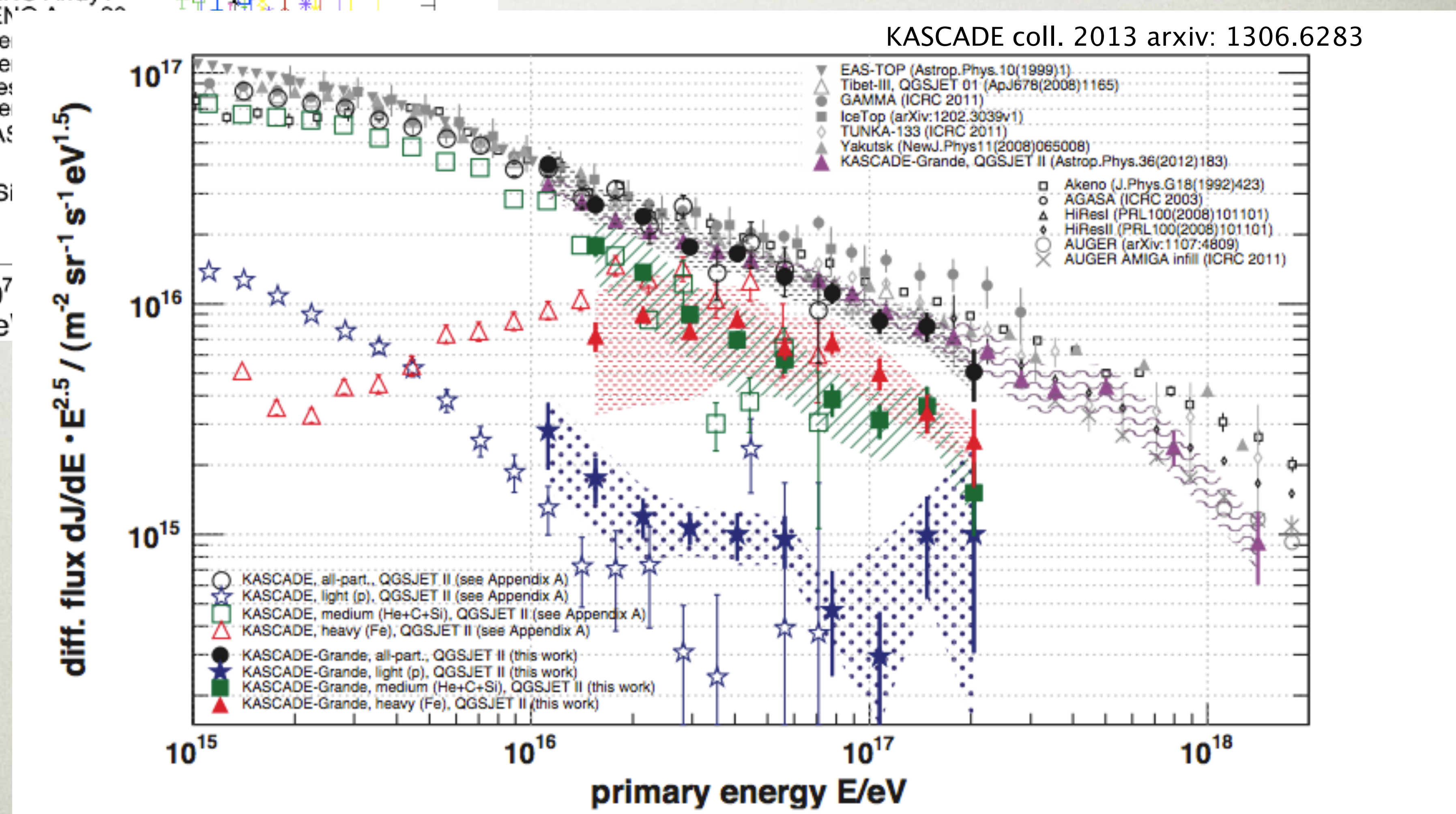
Ackermann et al (Fermi Collab) '13

What remains unknown?



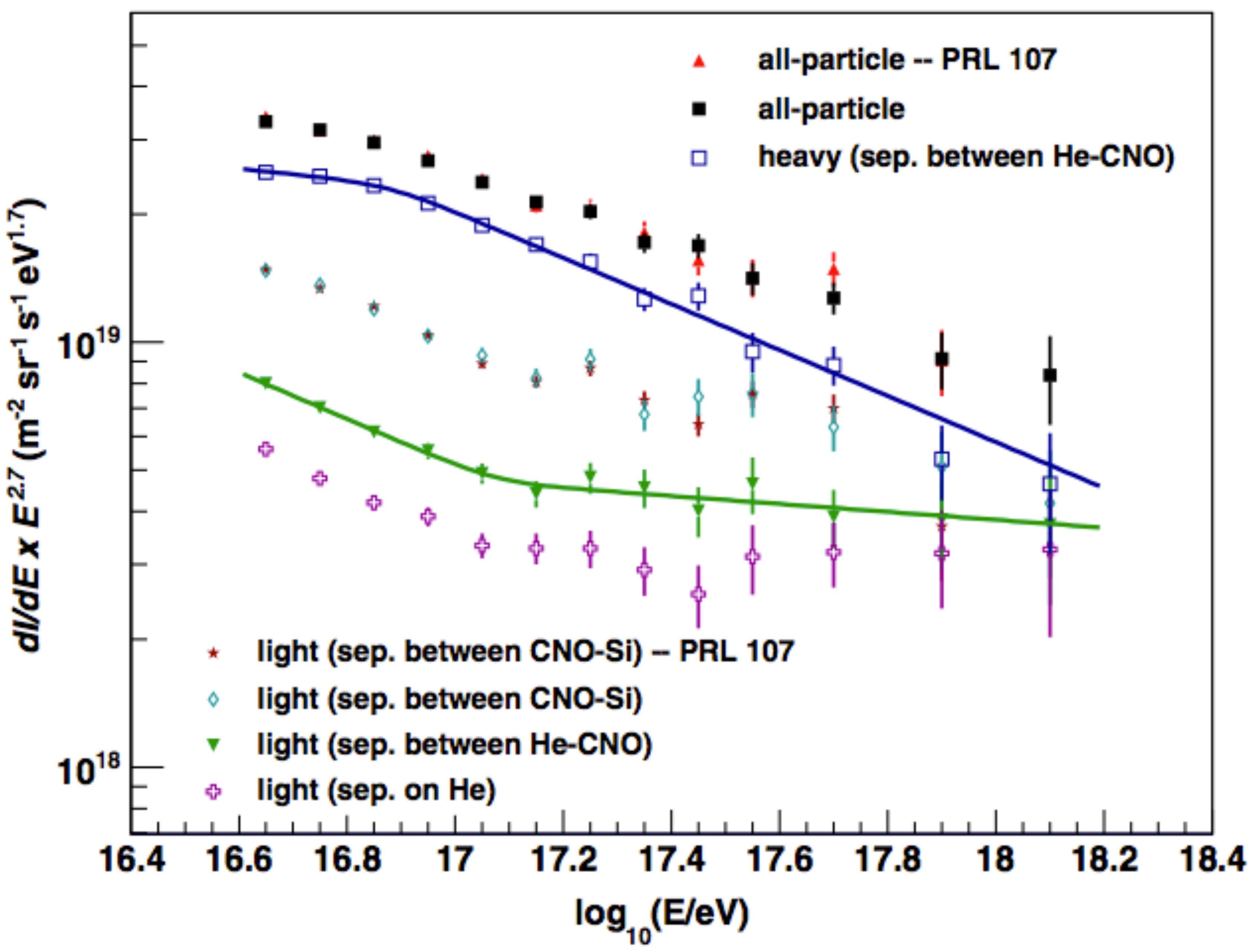
Galactic - Extragalactic Transition





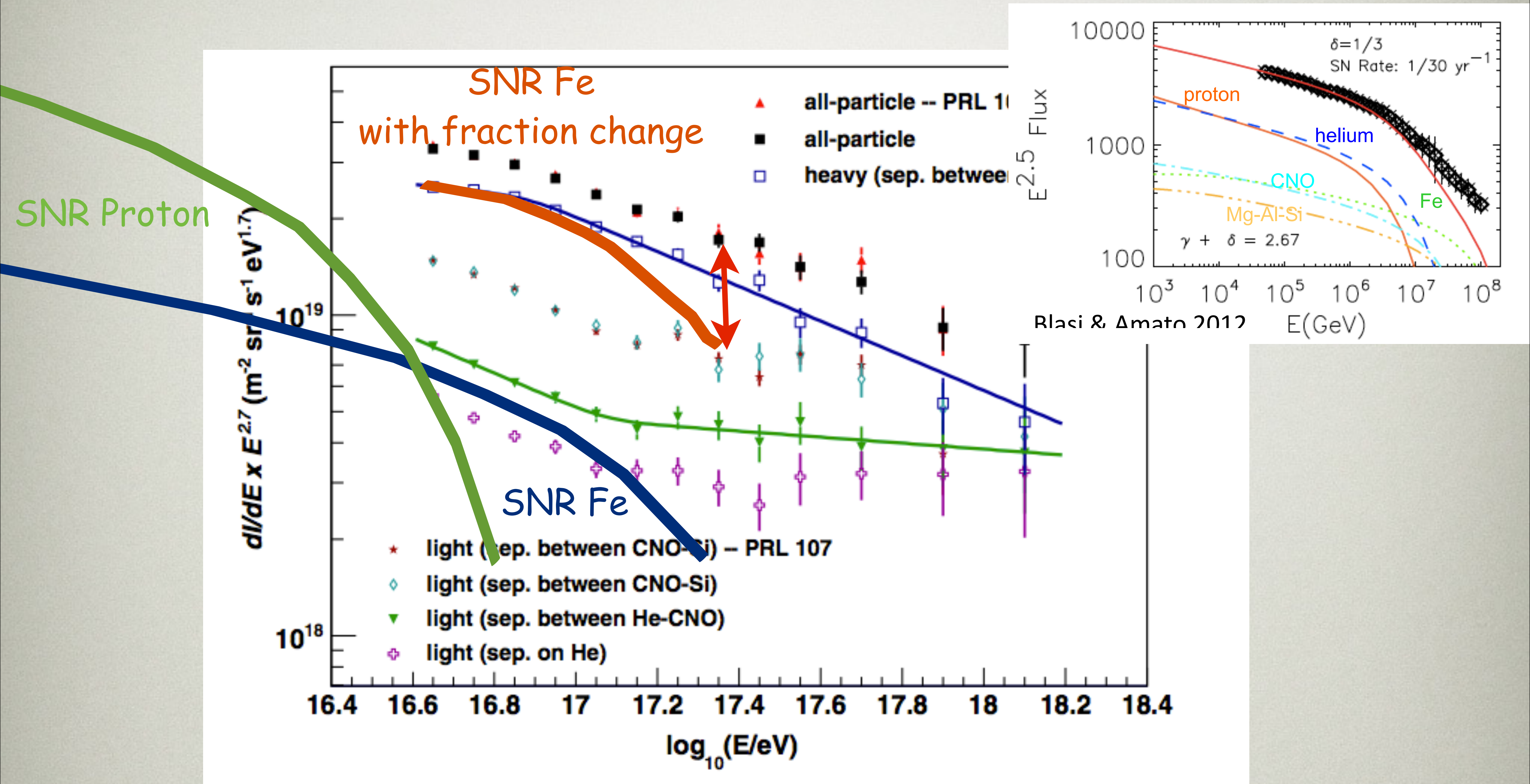
Composition Change

Galactic - Extragalactic Transition



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

Galactic - Extragalactic Transition



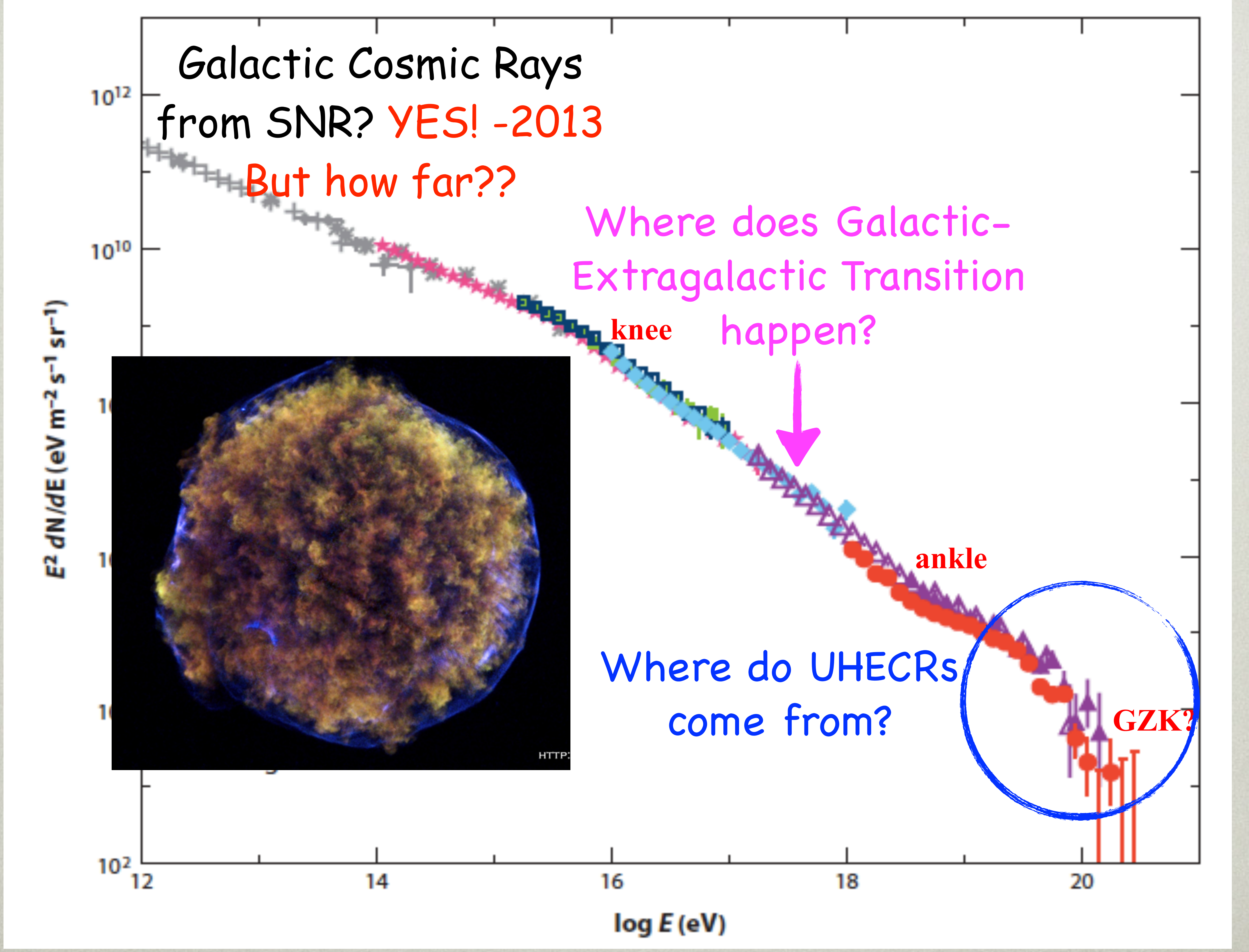
KASCADE coll. PHYSICAL REVIEW D 87, 081101(R) (2013)

SNR Fe with 'normal' fraction ✗

100% SNR Fe at 'second knee' ✗

Mind the gap in both composition and spectrum!

What remains unknown?

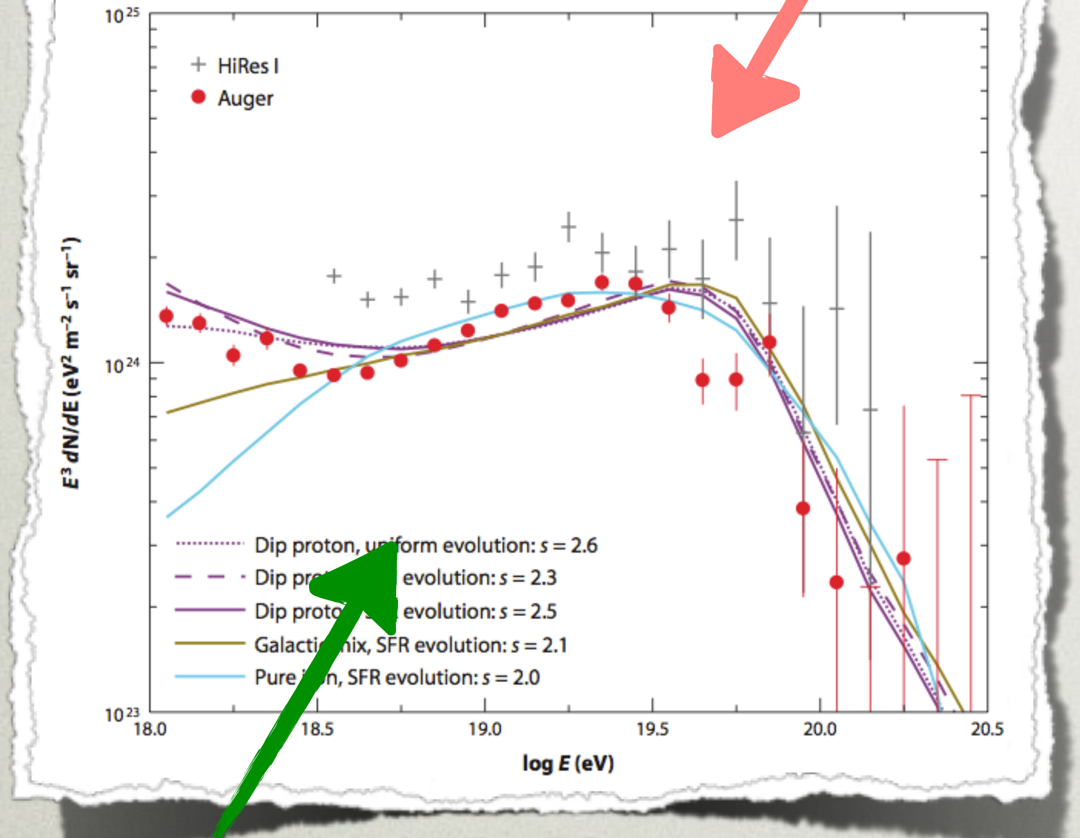


UHECR observables - 1. Spectrum

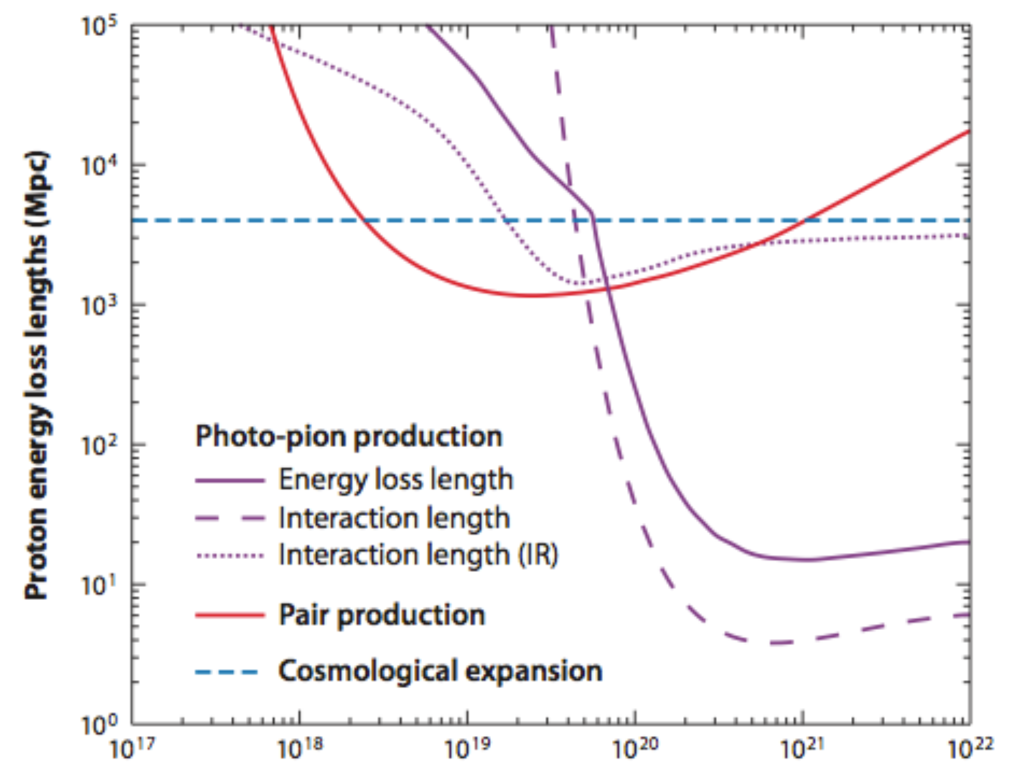
GZK cutoff and/or end of Emax

GZK Cutoff
Greisen, Zatsepin, Kuzmin 1966

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



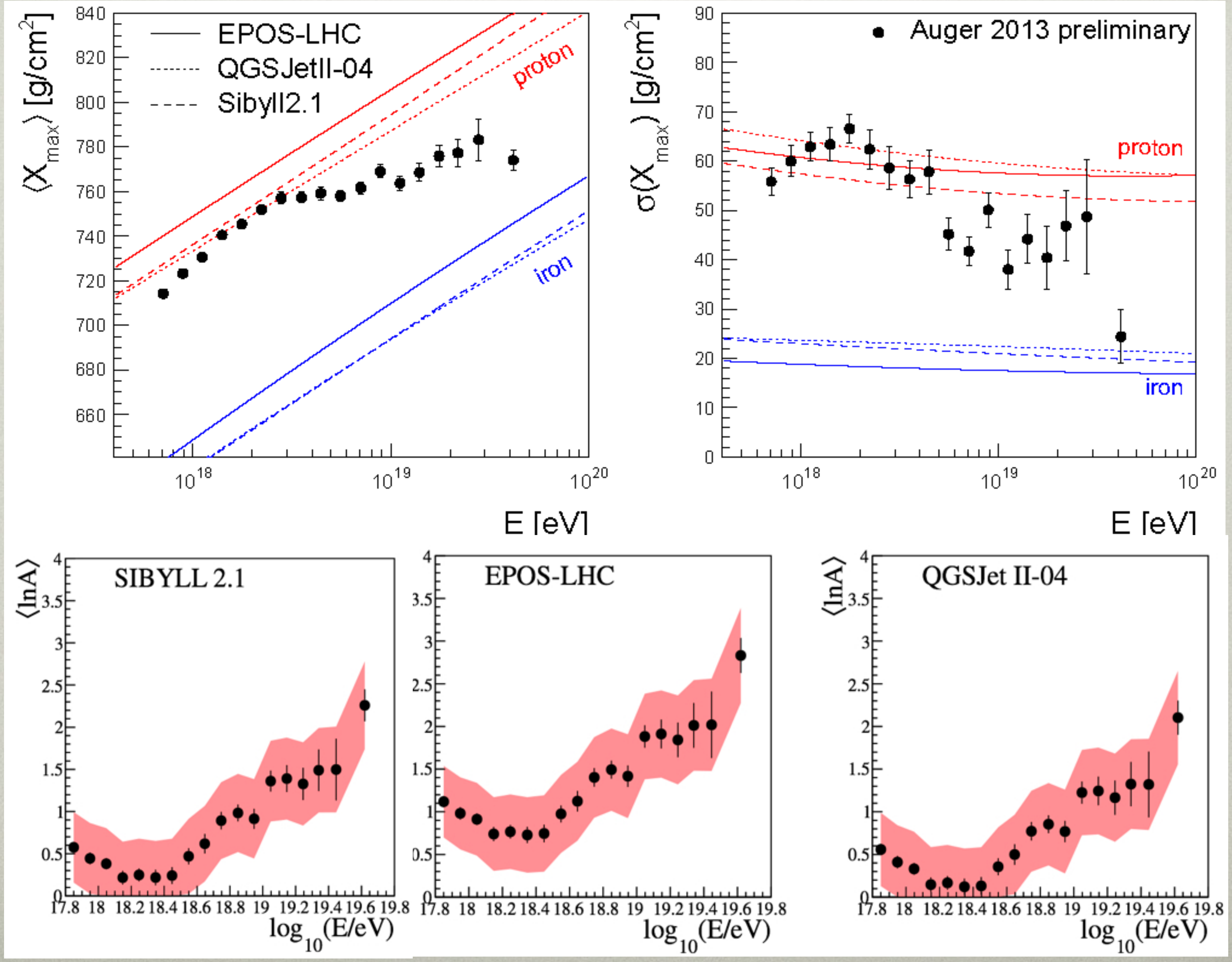
intrinsic index ~ 2



Abraham et al. 2010b, Kotera & Olinto 2011

Kotera & Olinto 2011

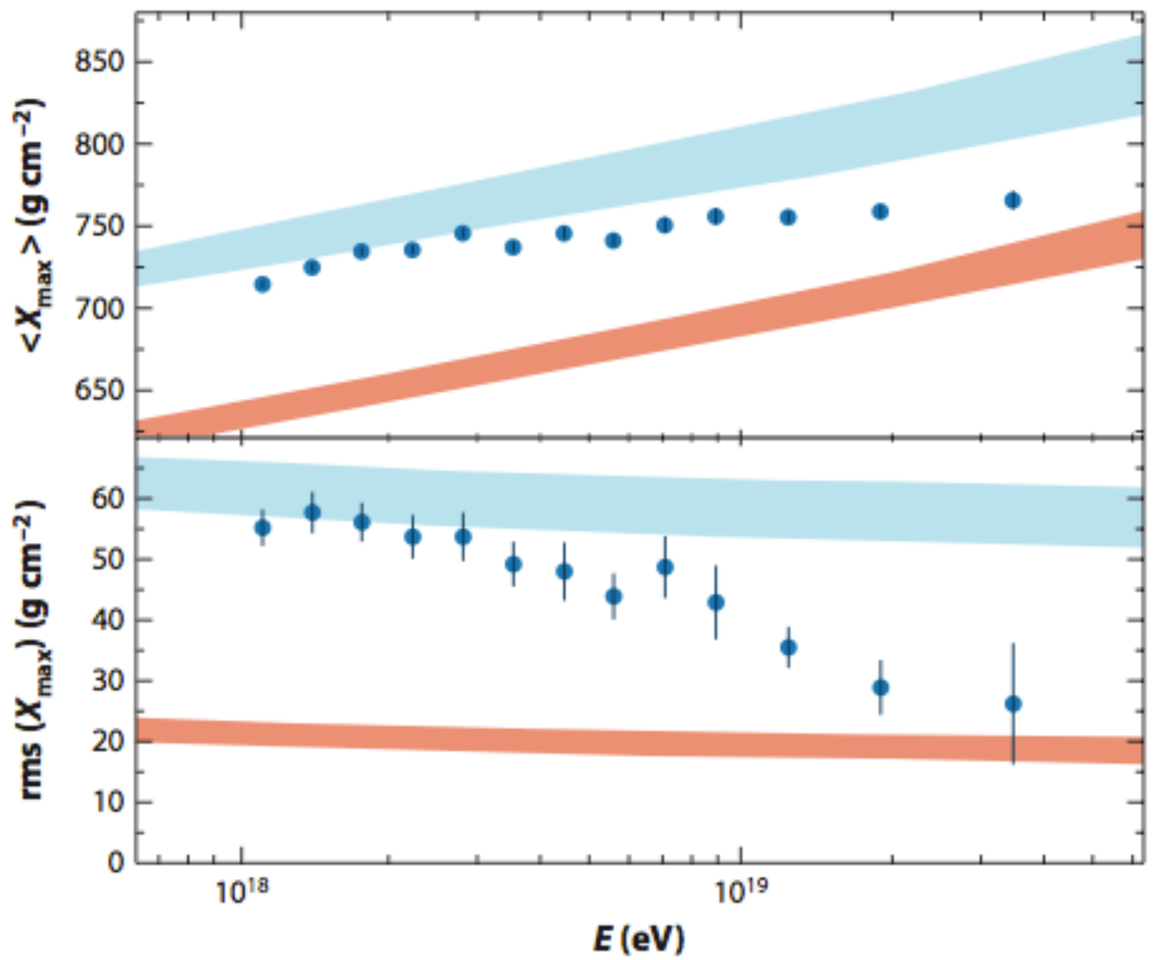
UHECR observables - **2. Chemical Composition**

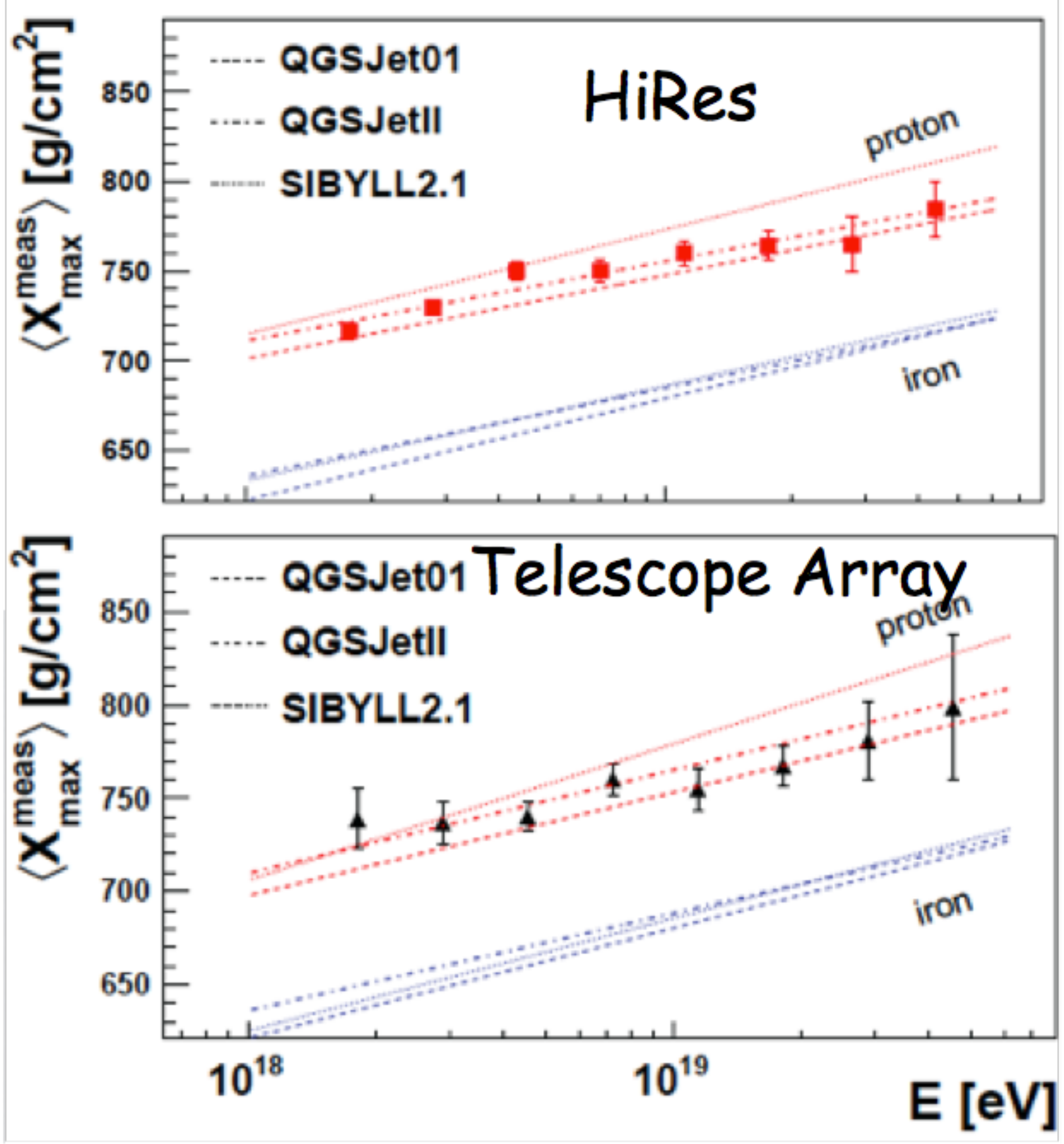


Auger: Light to Heavy Transition

Not confirmed by North Hemisphere telescopes

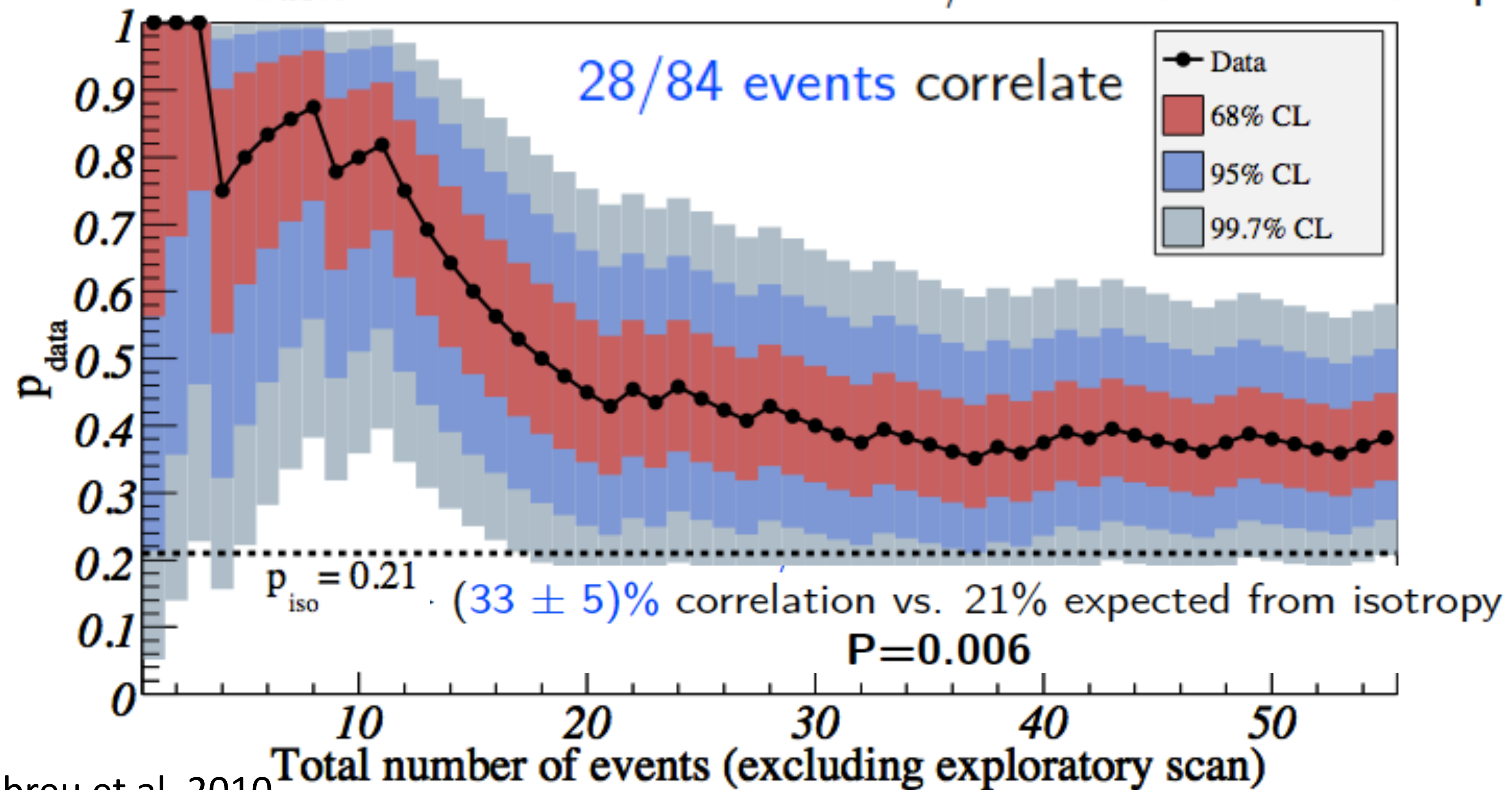
Auger Collaboration, PRL 104 (2010) 091101, ICRC 2011, arXiv:1107.4804



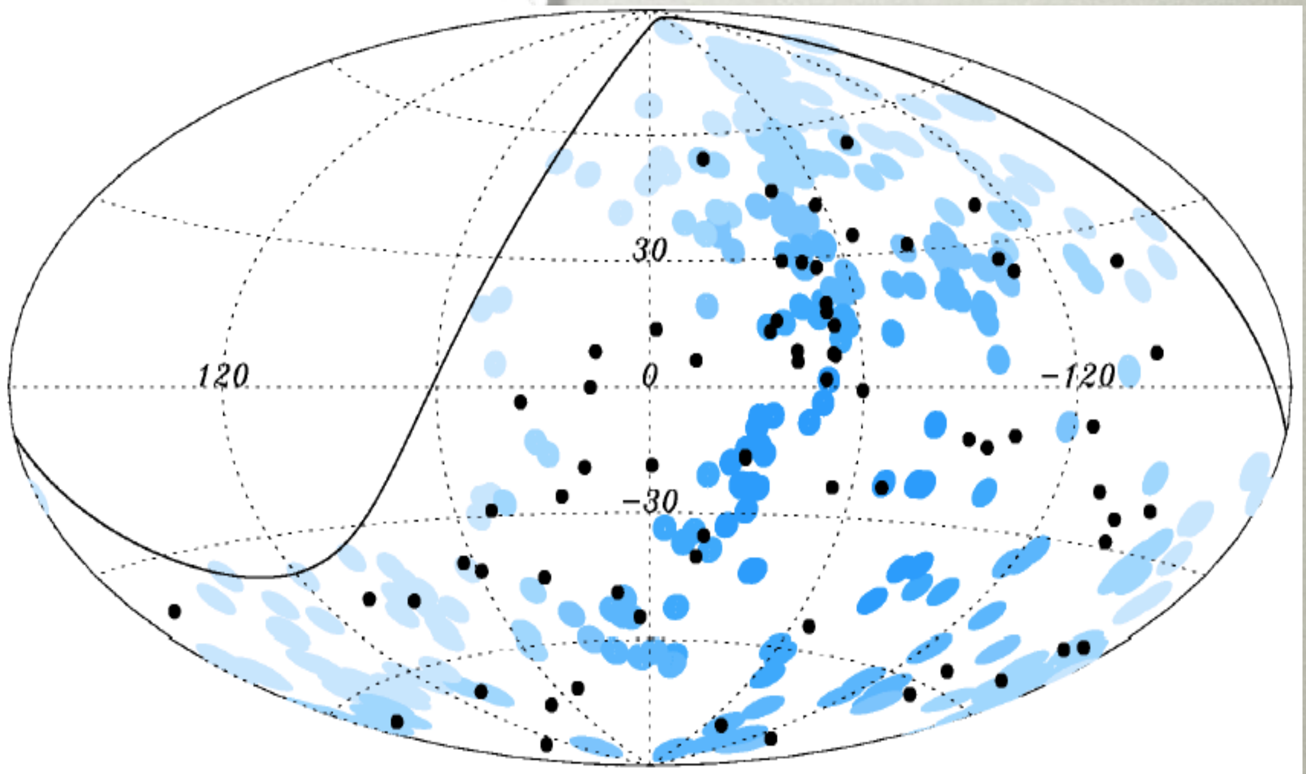


UHECR observables - **3. Anisotropy**

TELESCOPE ARRAY: 8/20 - 40% with 24% expected from isotropy

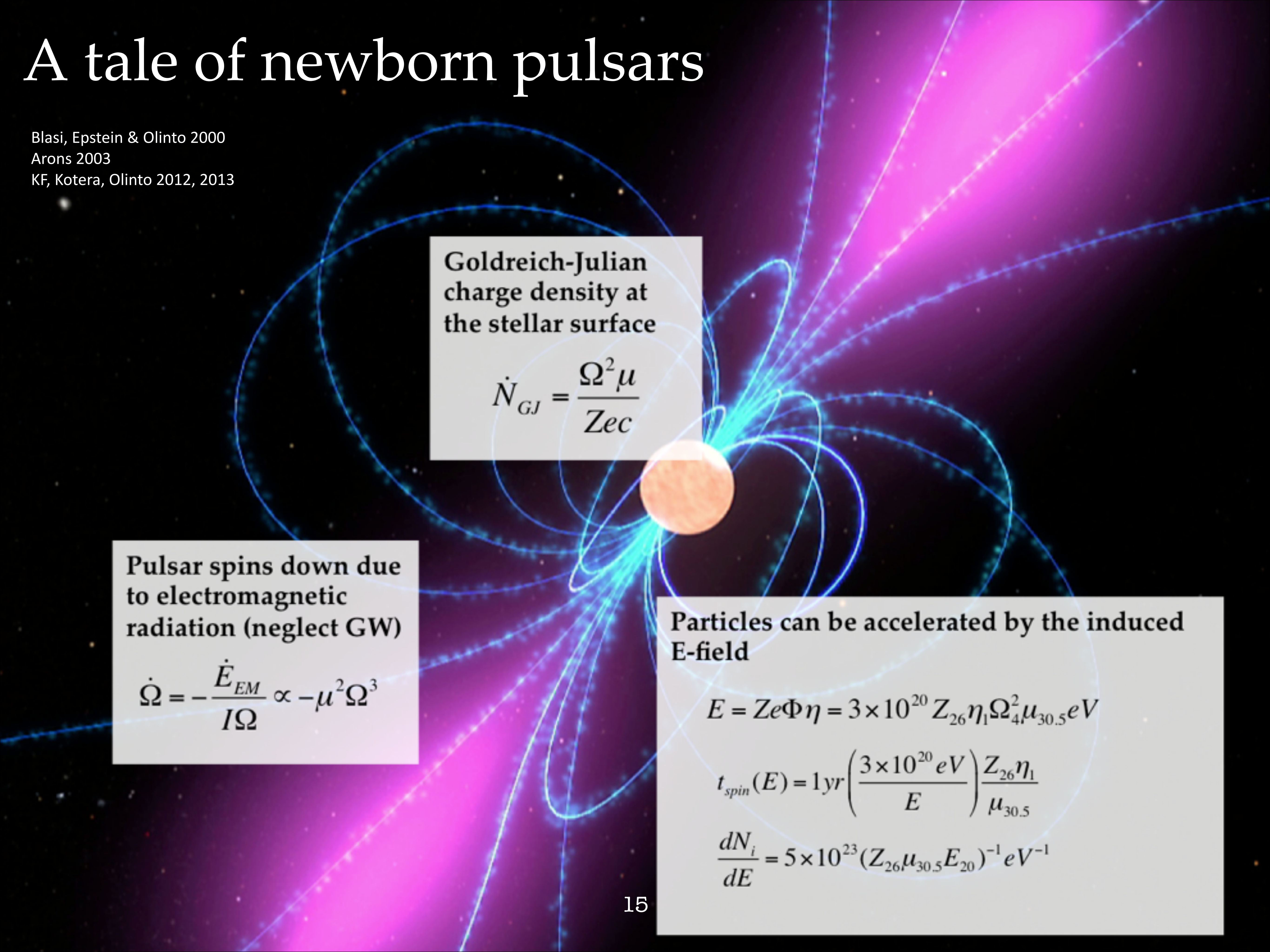


Abreu et al. 2010



No derivation from isotropy in large scale

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)

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

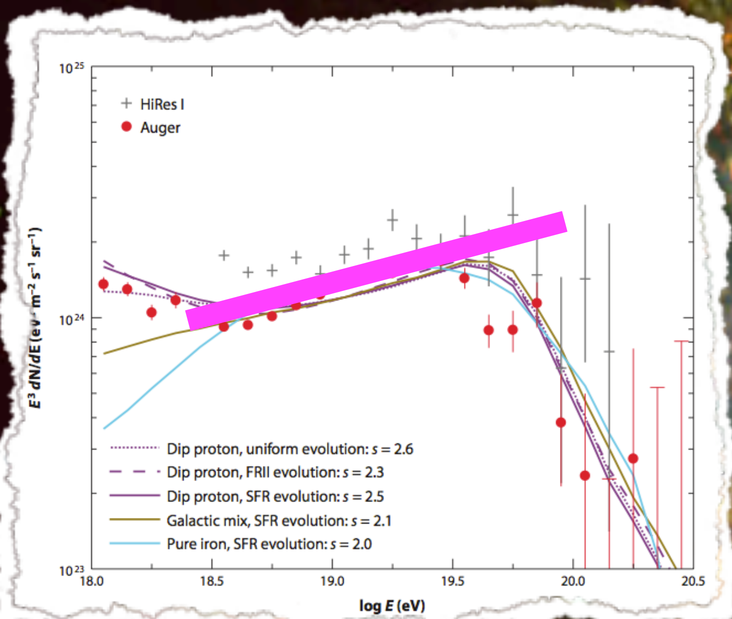
Particles can be accelerated by the induced E-field

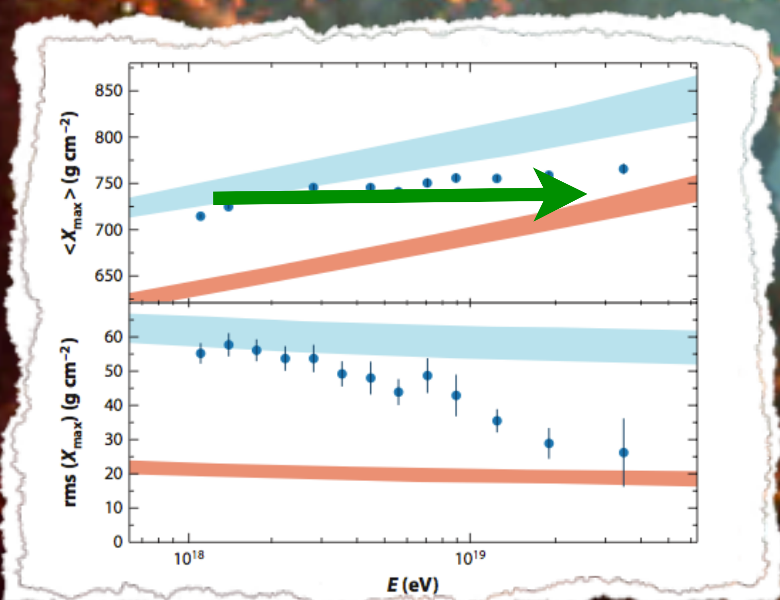
$$E = Ze\Phi\eta = 3\times 10^{20}\, Z_{26}\eta_1 \Omega_4^2 \mu_{30.5} eV$$

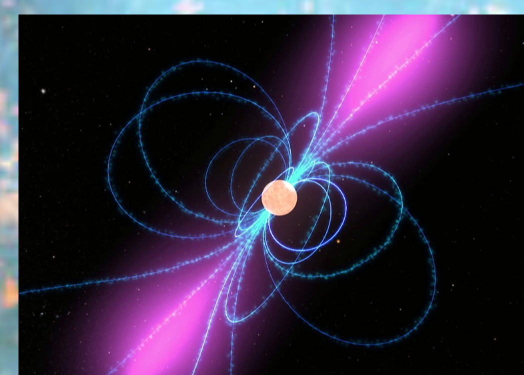
$$t_{spin}(E) = 1 yr \left(\frac{3\times 10^{20} eV}{E} \right) \frac{Z_{26}\eta_1}{\mu_{30.5}}$$

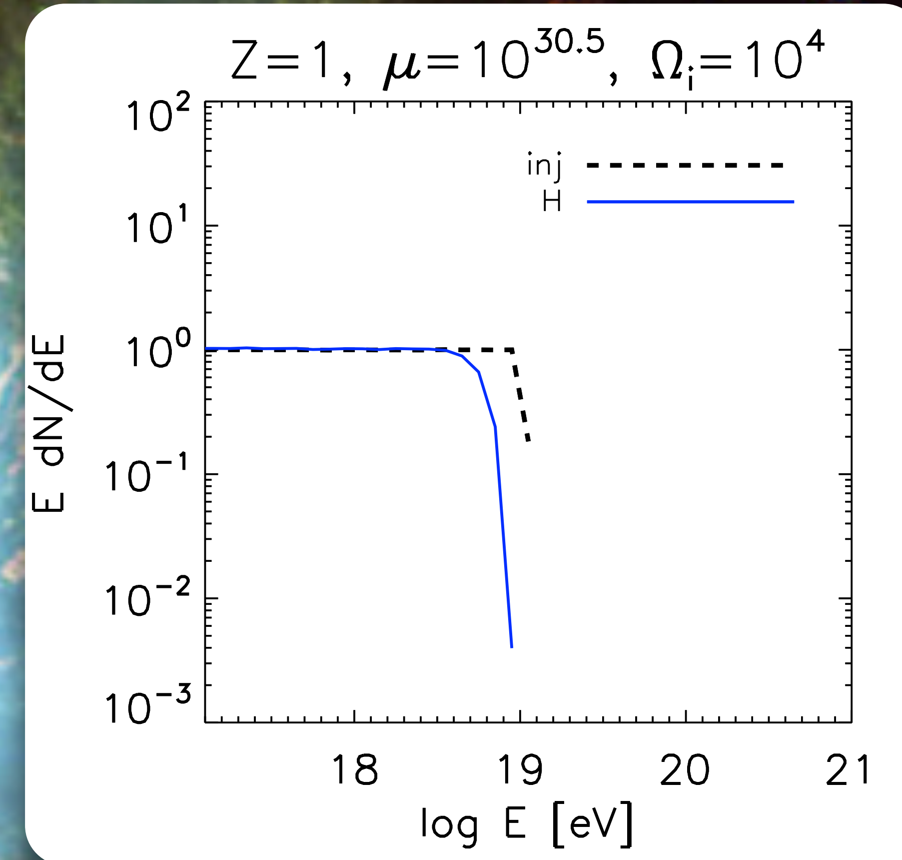
$$\frac{dN_i}{dE} = 5\times 10^{23} (Z_{26}\mu_{30.5}E_{20})^{-1} eV^{-1}$$

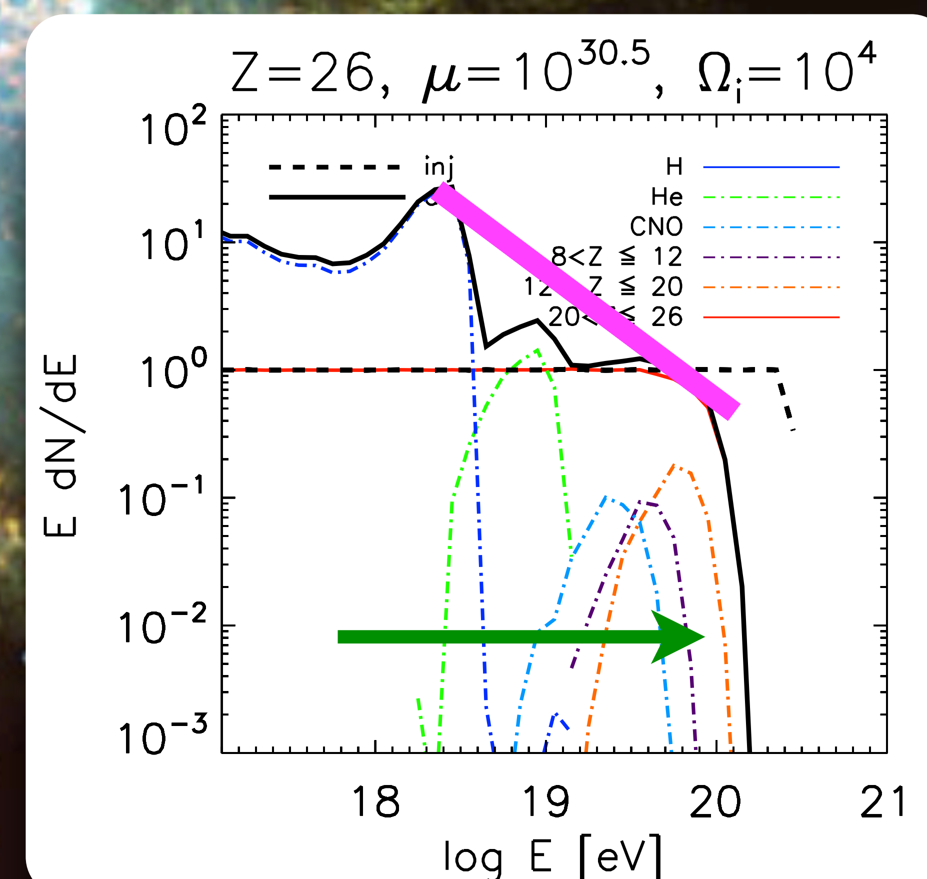
Monte-Carlo propagation
hadron interactions simulated
with EPOS + CONEX





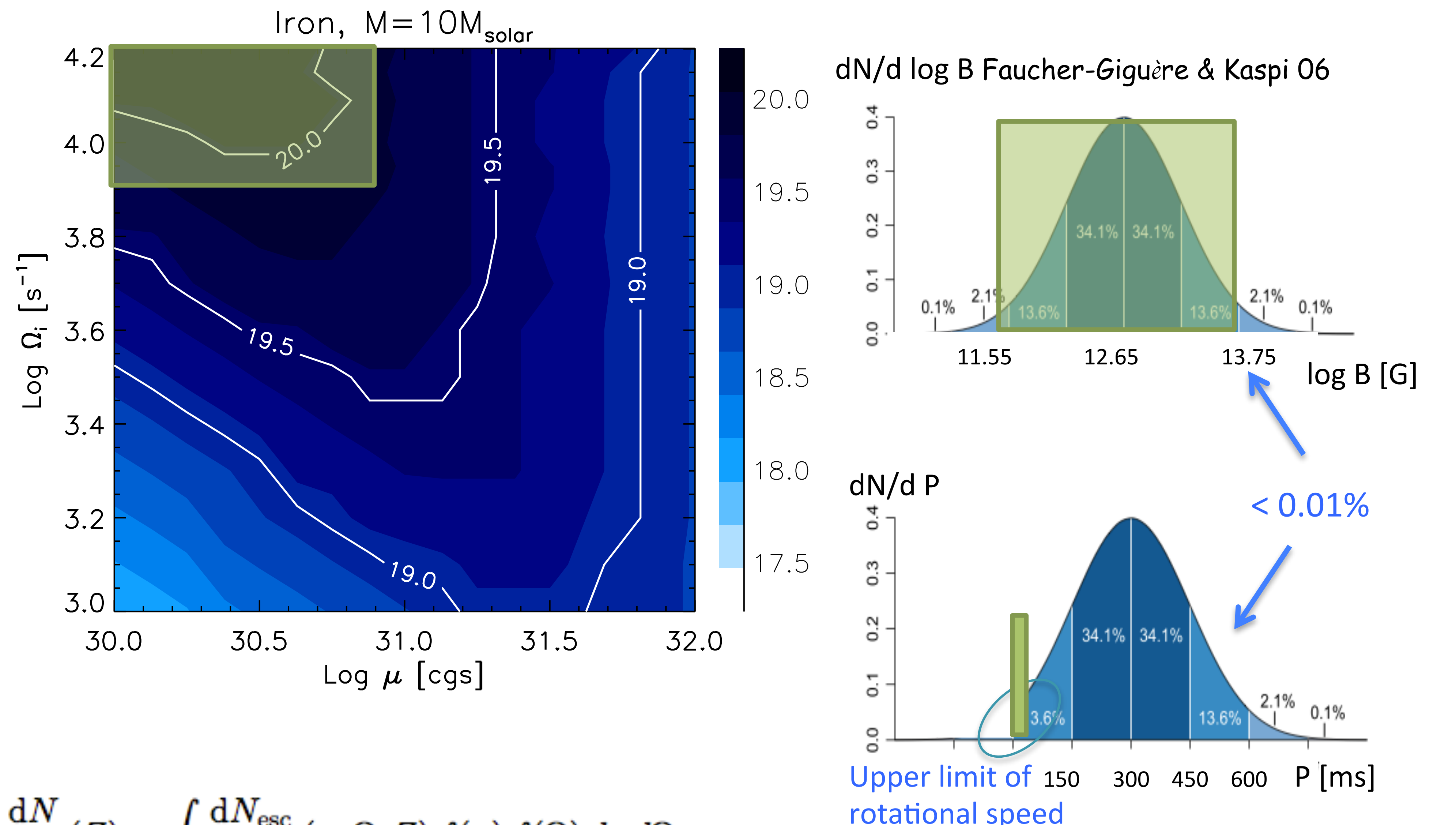






KF, Kotera & Olinto, ApJ, 750:118, 2012

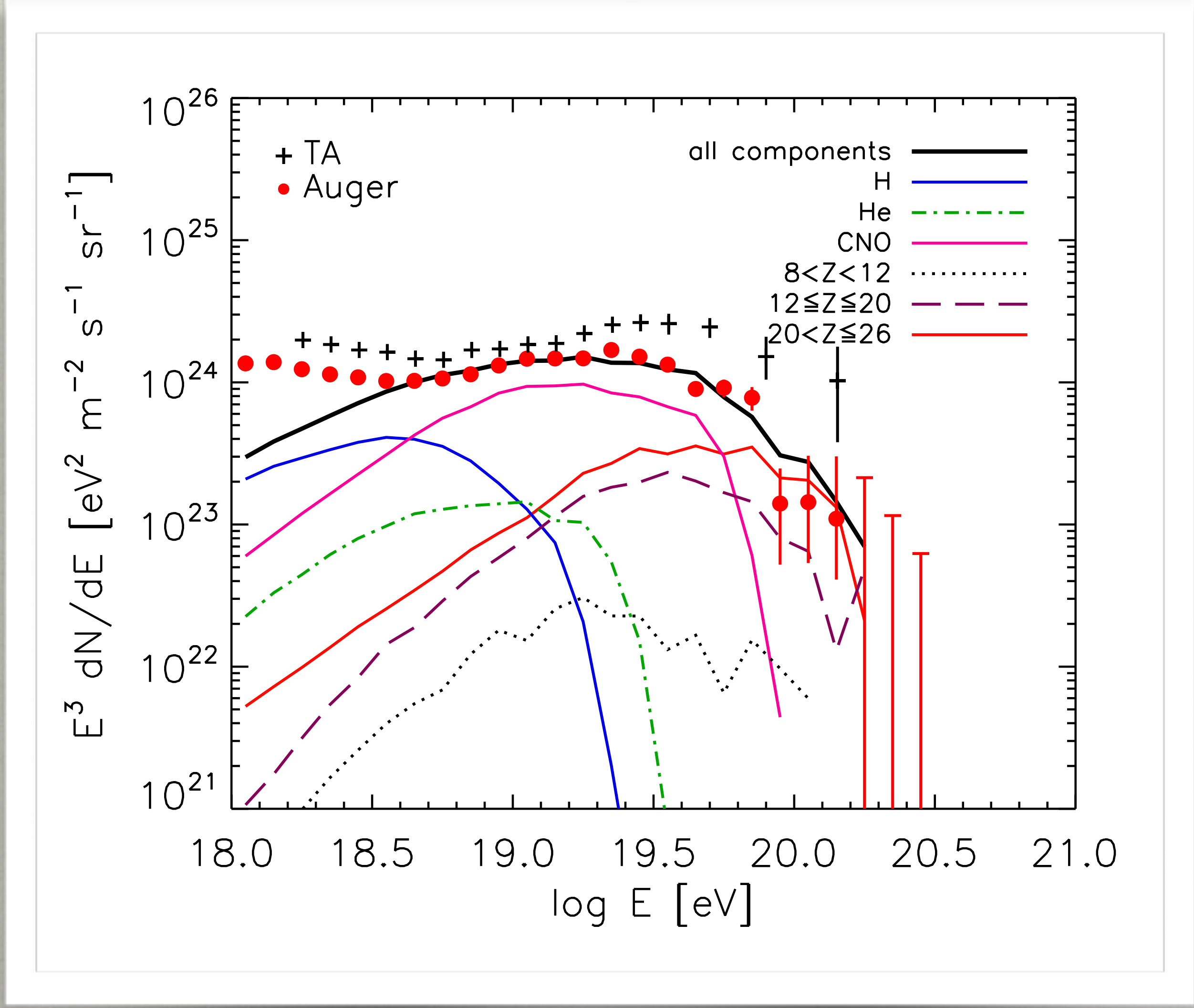
Pulsar Distribution in a Galaxy

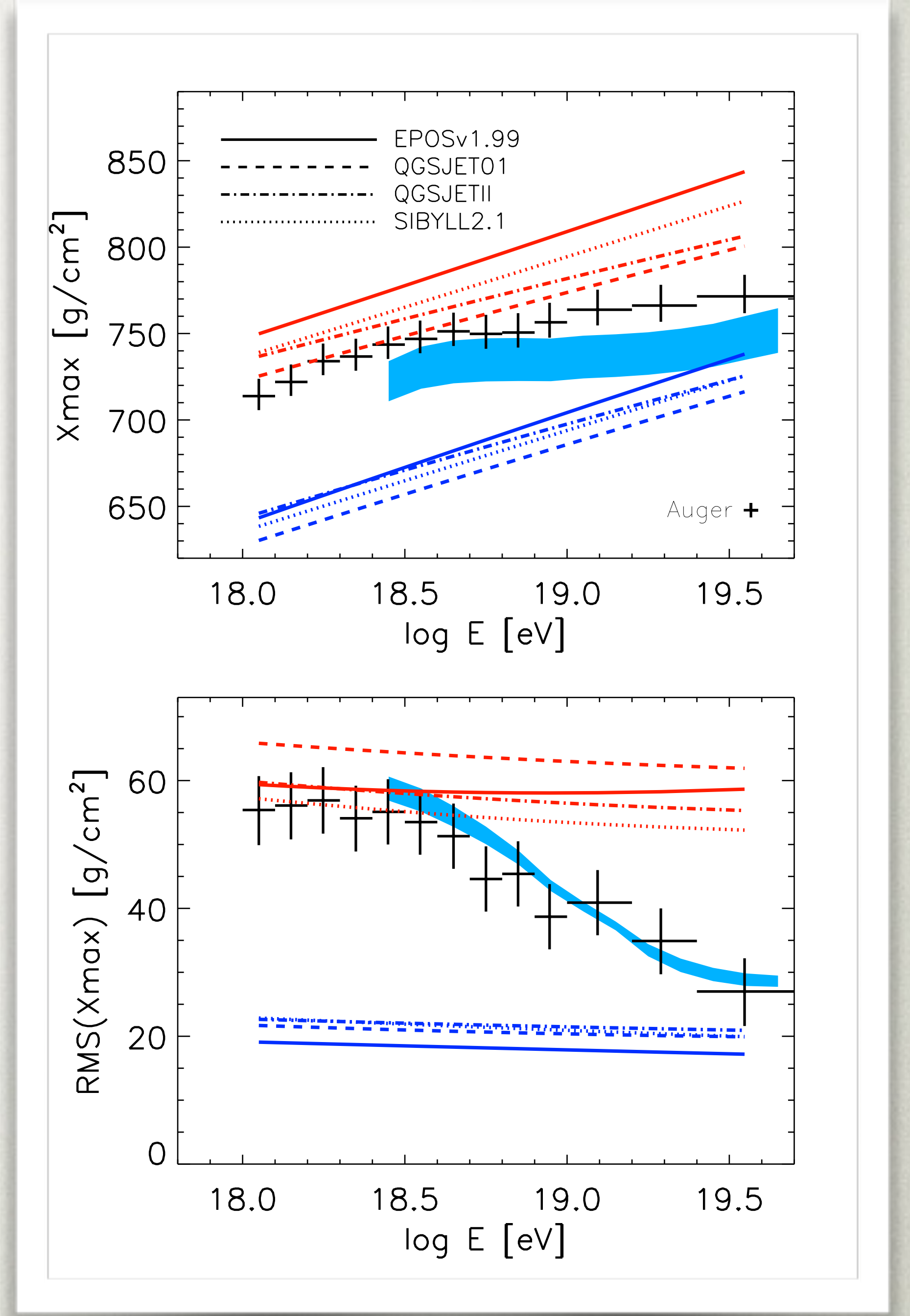


$$\frac{\mathrm{d}N}{\mathrm{d}E}(Z) = \int \frac{\mathrm{d}N_{\mathrm{esc}}}{\mathrm{d}E}(\mu, \Omega, Z)\, f(\mu)\, f(\Omega)\, d\mu\, d\Omega$$

- 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





Newborn pulsars can be successful UHECR accelerators

KF, Kotera & Olinto 2013

Anisotropy Check

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

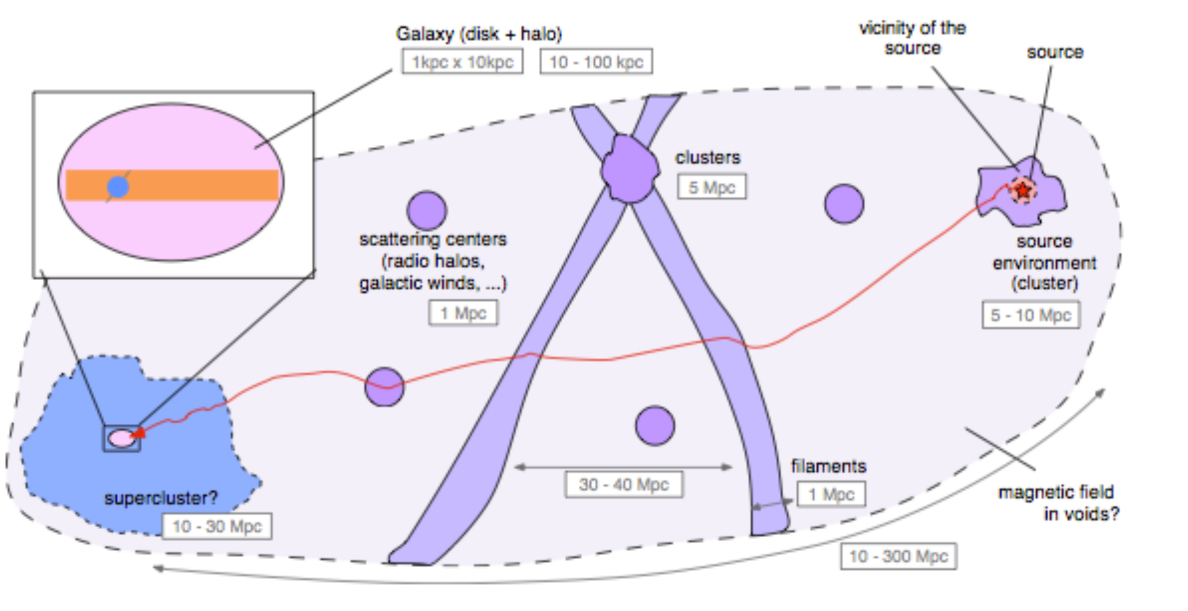
$$\lambda \approx 10-100\,kpc << r_L \Rightarrow small \quad deflections$$

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

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

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

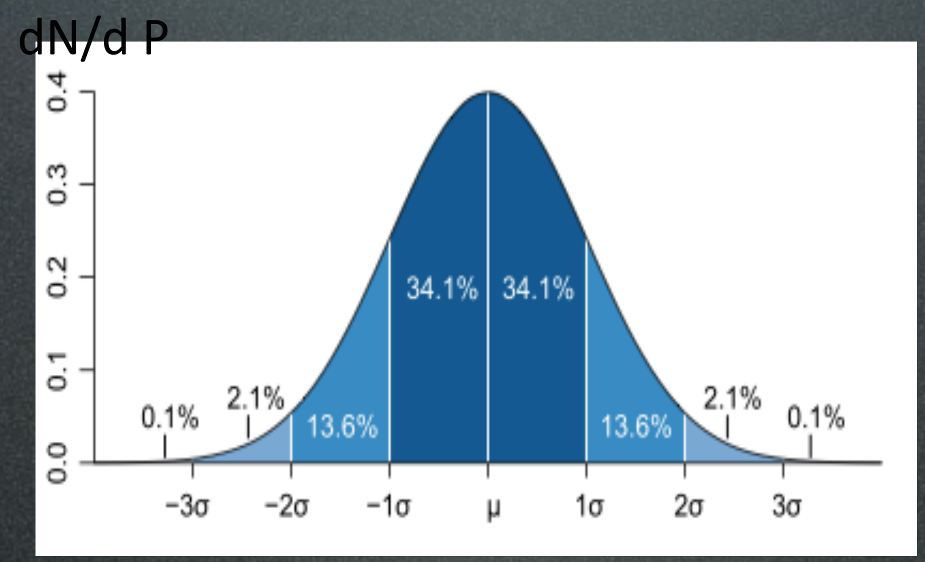
$>>$

Time the source was lighted

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

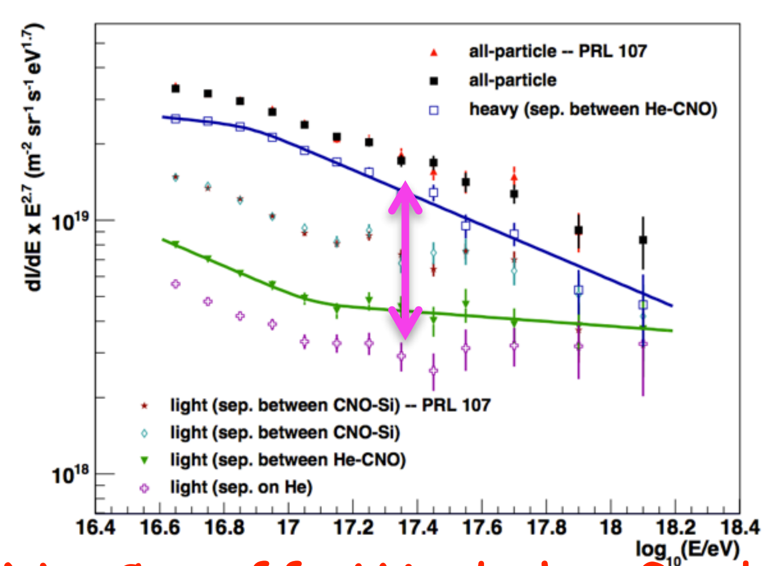
=> Transients, no source- arrival direction correlation

What about their Galactic Counterparts?

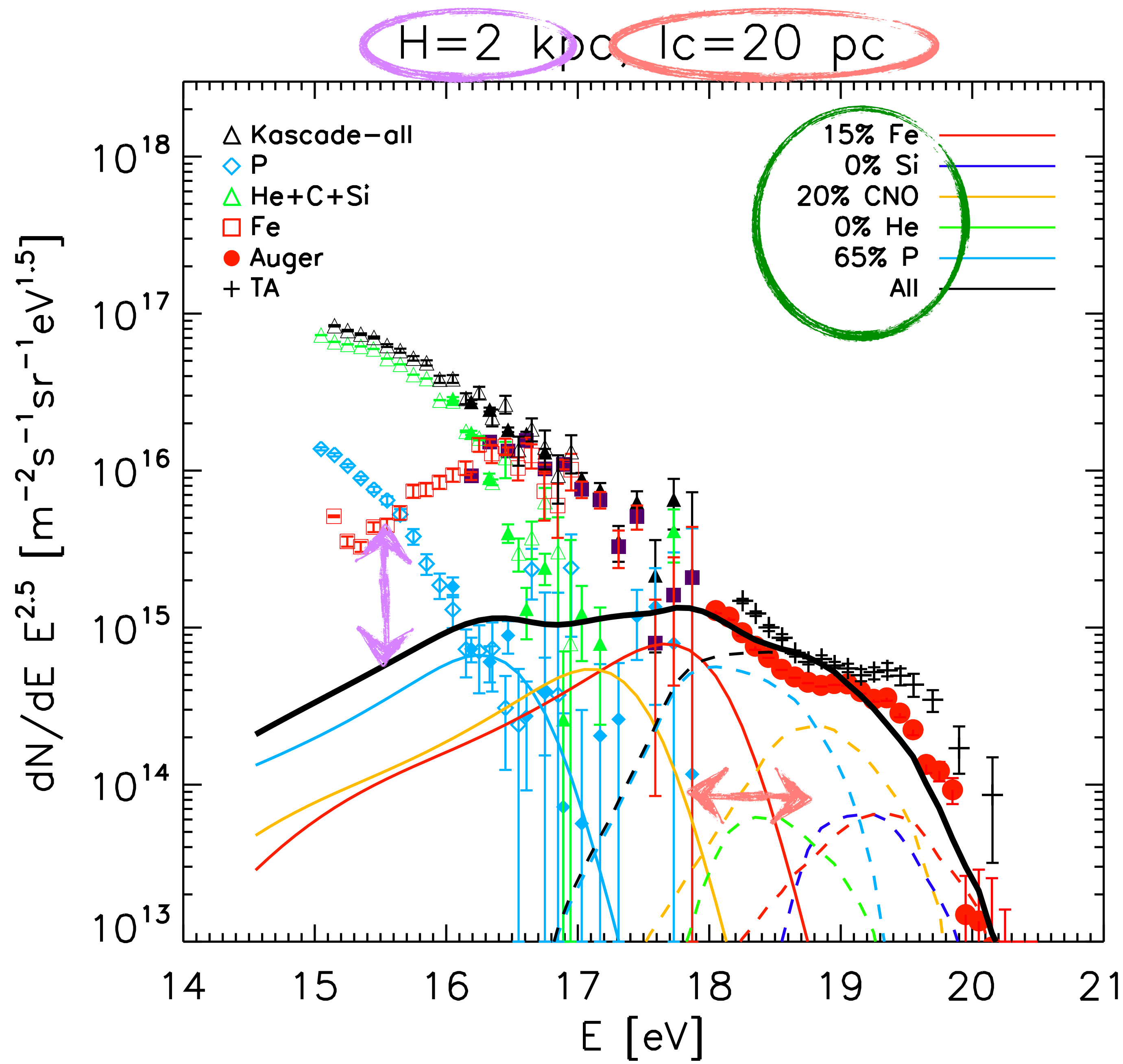


Contribution from Galactic pulsars

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

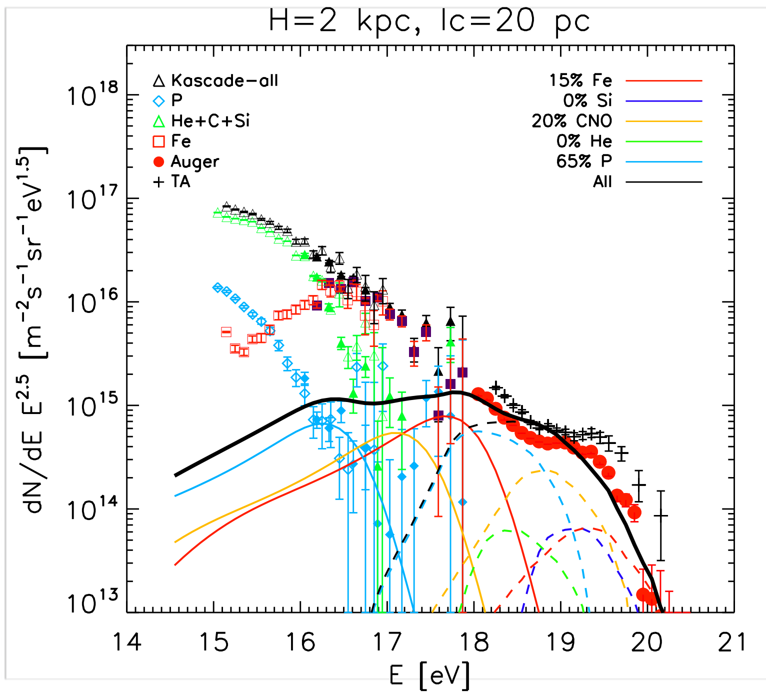


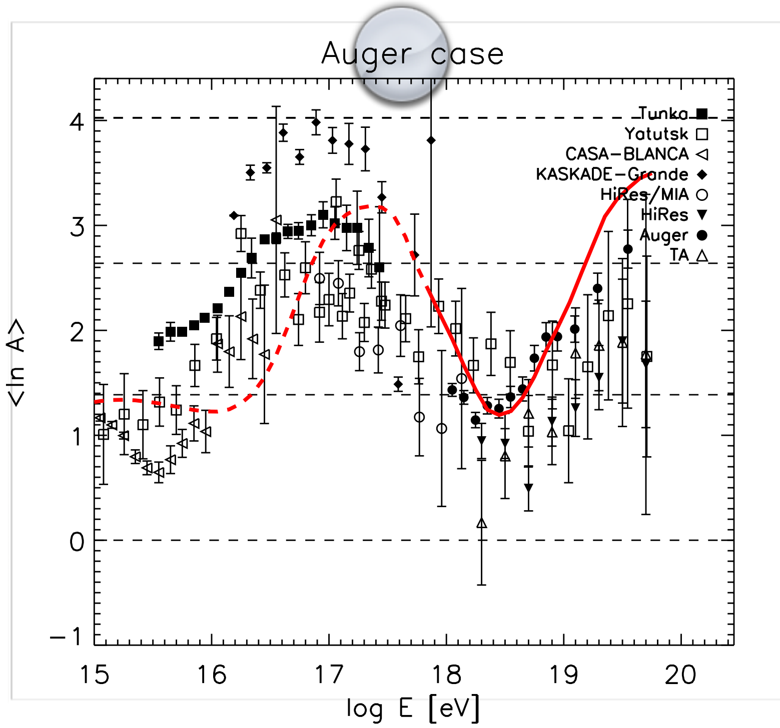
No Cutoff, Mind the Gap!

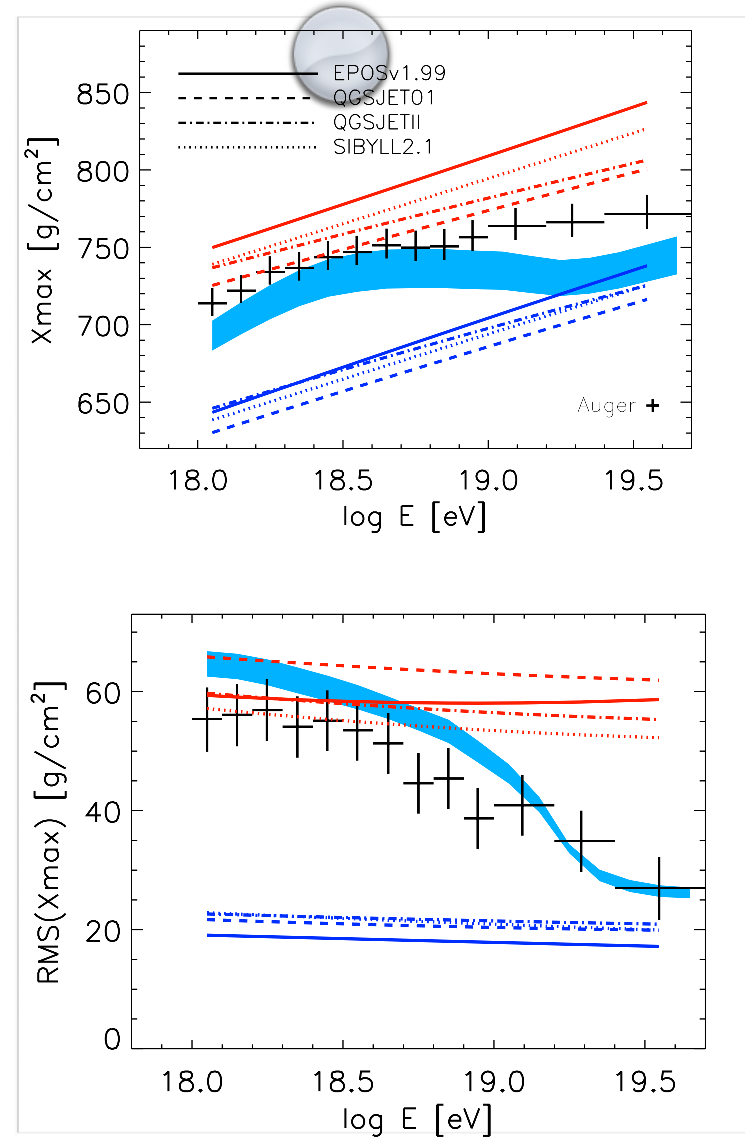


Galactic pulsars can fill the gap

Composition



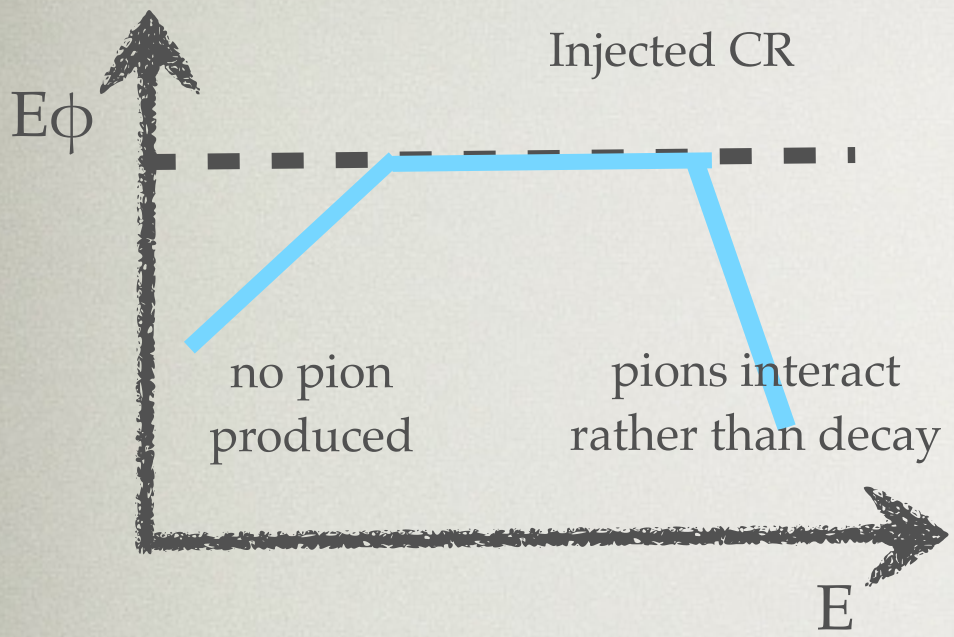




KF, Kotera & Olinto, JCAP, 010: 03, (2013)

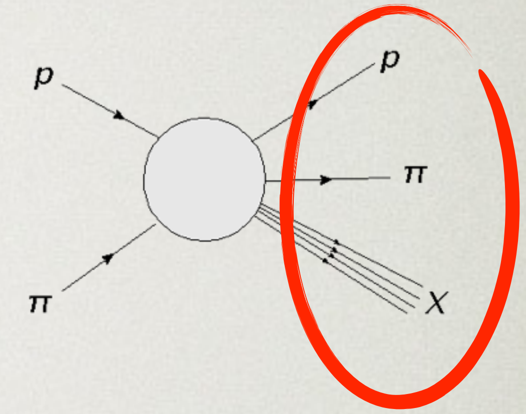
Testable Scenario?

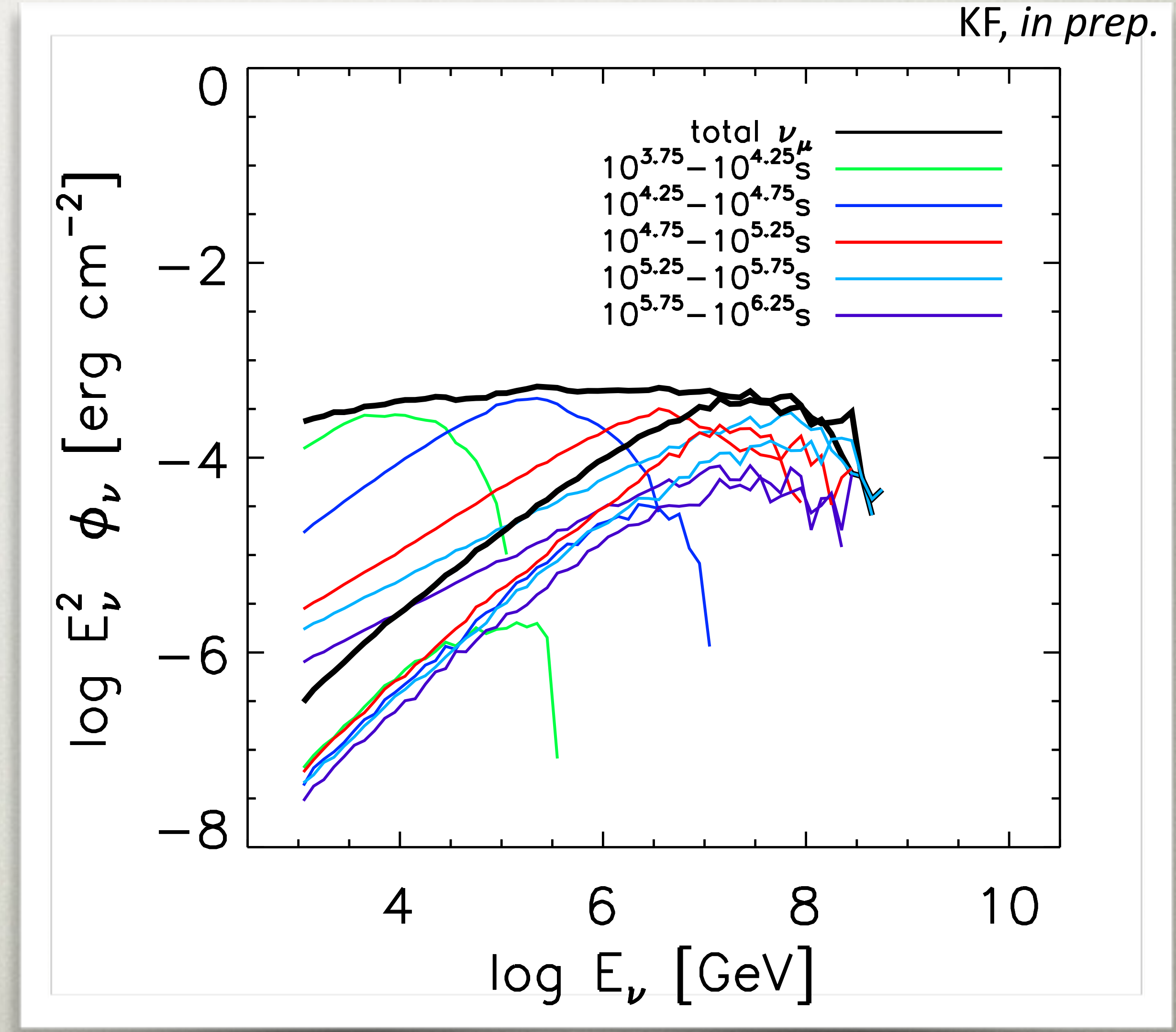
Neutrino as a smoking gun?



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

Not really!





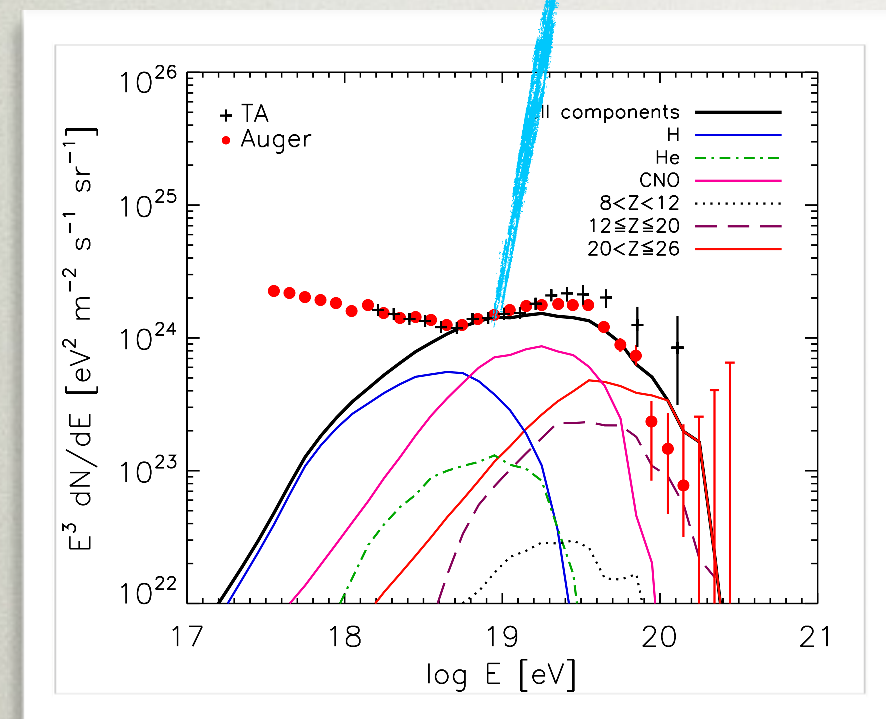
Conclusion III

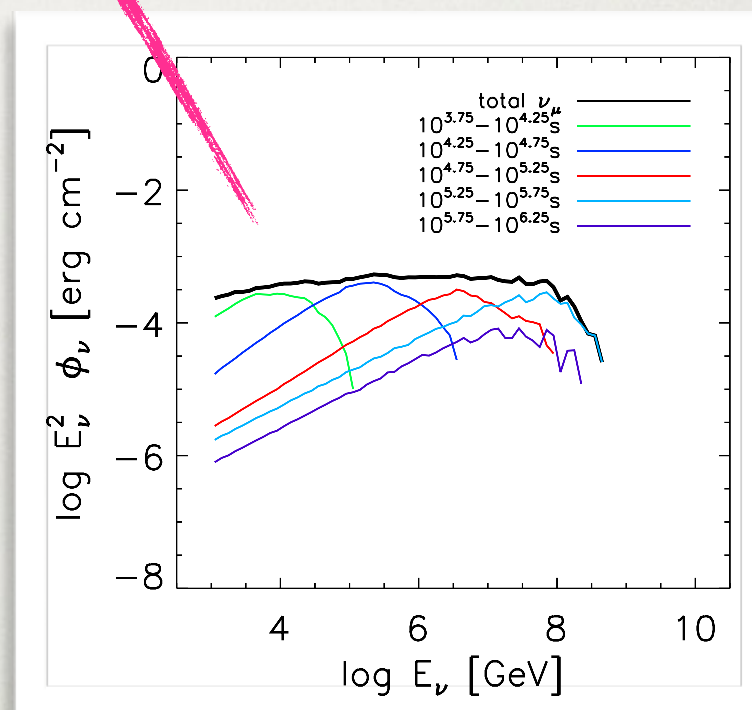
Secondaries flatten the spectrum.
A magnetar produces E-2 spectrum!

Neutrinos from Integrated Pulsar Sources

$$\Phi_\nu = \frac{f_s}{4\pi}\int_0^{z_H}\int_0^{t_\nu}\frac{\mathrm{d}N_\nu}{\mathrm{d}t'\,\mathrm{d}E_\nu\,4\pi D^2}\,\mathrm{d}t'\,\Re(z)\,4\pi D^2\,\frac{\mathrm{d}D}{\mathrm{d}z}\,\mathrm{d}z$$

$$\Re(0) \approx 3.3\times10^{-4}\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}$$



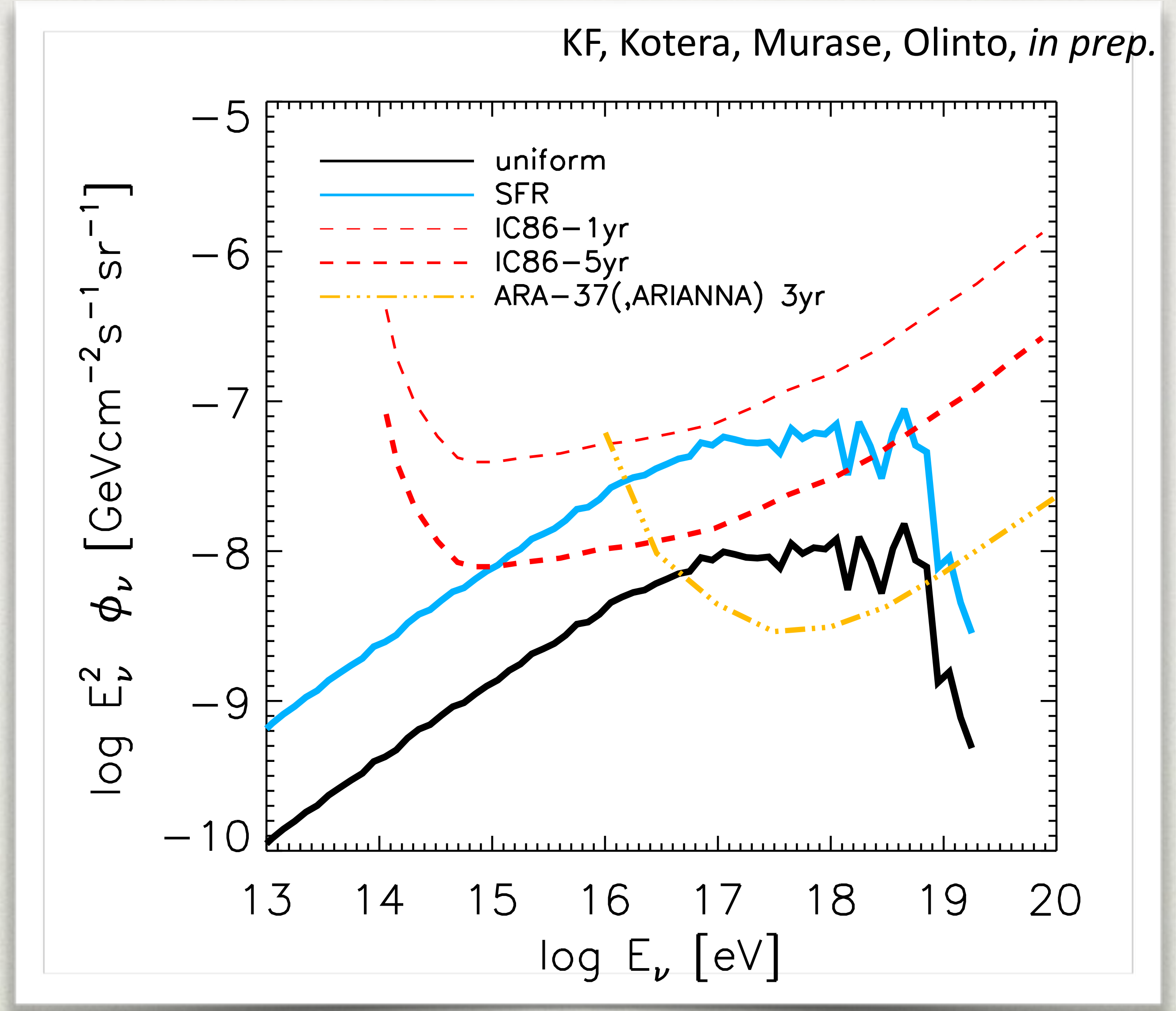


Insensible to injection composition:
Fe~56P/26
CNO~28P/14

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

Measured UHECR flux → $f_s \approx 0.05$

Neutrinos from Integrated Pulsar Sources



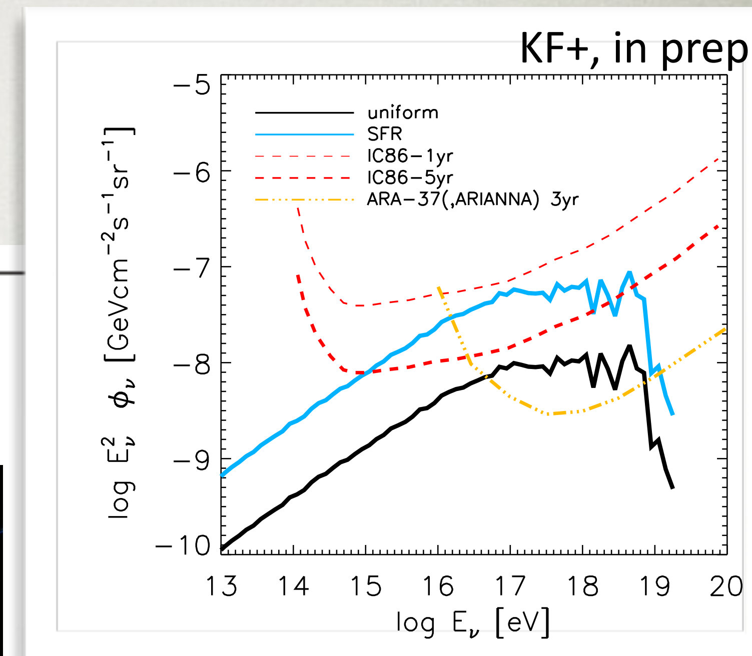
Conclusion III

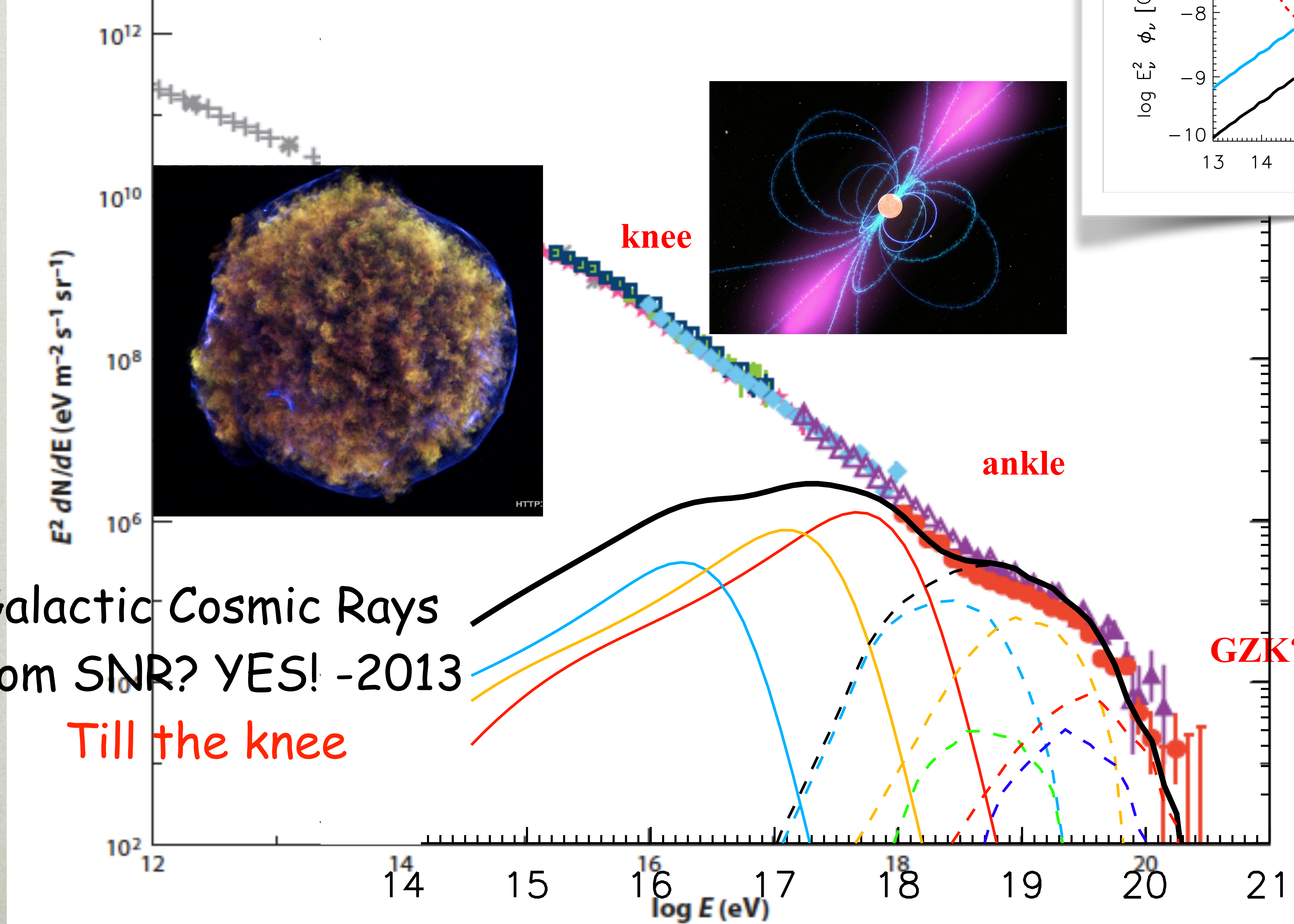
Consistent with current detection upper limits;

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

Summary

Newborn pulsars contribute above
the knee and the ankle,
testable with cumulative neutrinos





Galactic Cosmic Rays
from SNR? YES! -2013
Till the knee

Backups

Conclusions

Below the knee: hadron acceleration in SNR proved

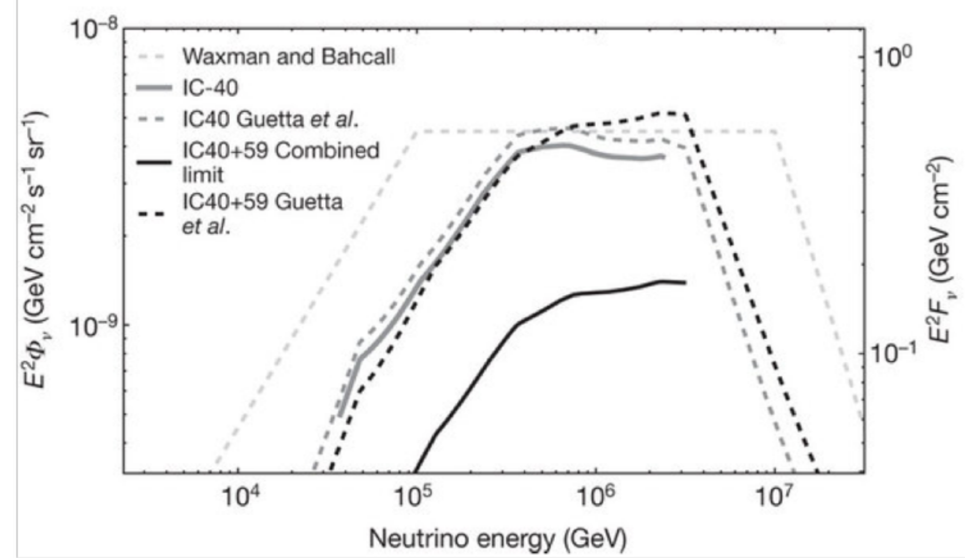
Transition: additional components may be needed

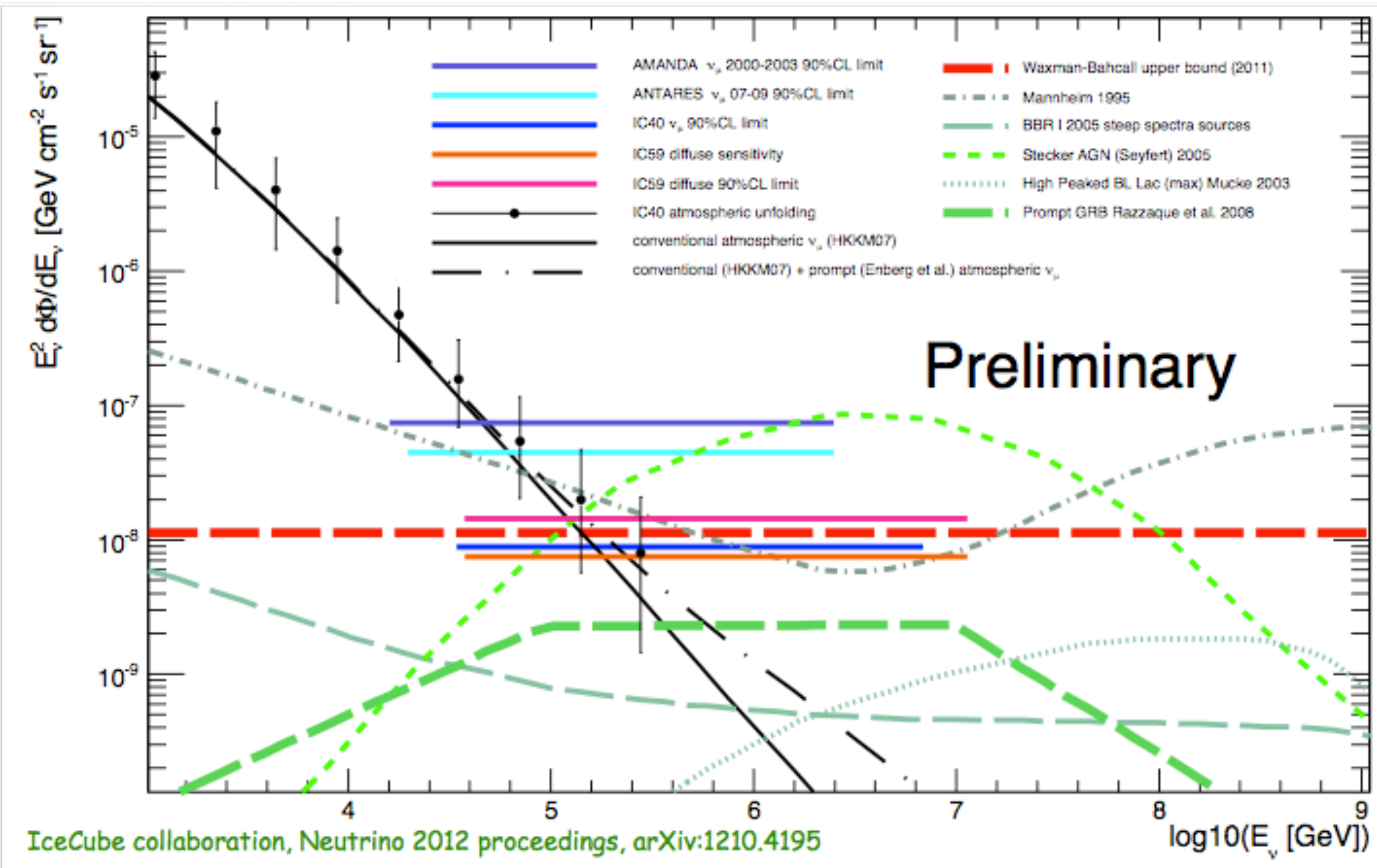
Above the ankle:
Leading Observatories:
  Pierre Auger Observatory: 3,000 km^2 Argentina
  Telescope Array: 700 km^2 Utah, USA
Agreement on the shape of the spectrum
Composition: controversial
Anisotropies: hints above 60 EeV – no >3σ signal

Newborn pulsars - can significantly contribute above the knee. Testable in 3-4 years.

Multimessenger Approach - ν from GRBs

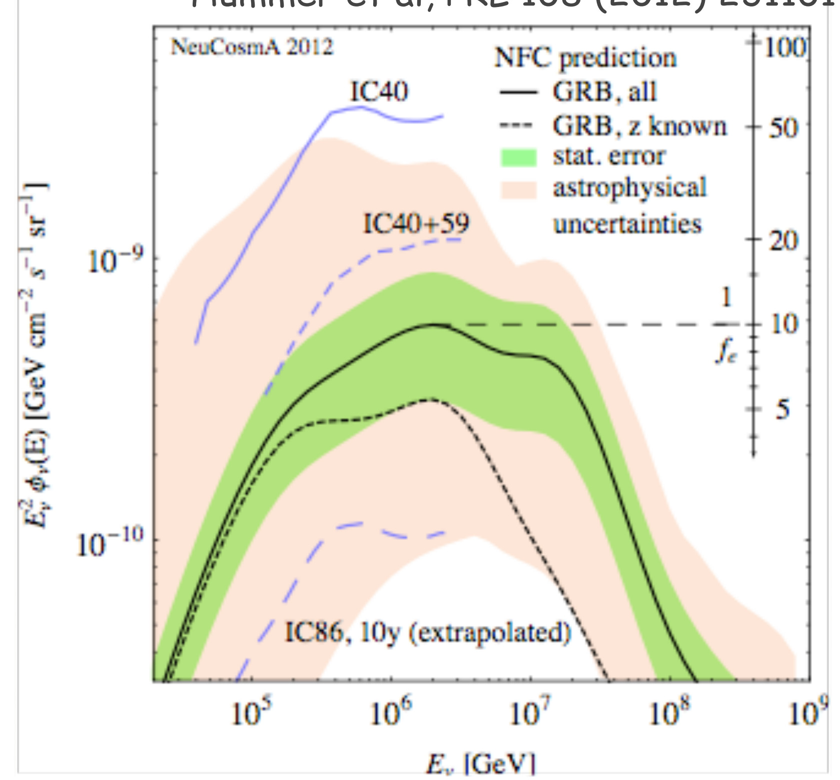
IceCube collaboration, Nature 484 (2012) 351





Absence of ν from GRBs

Hümmer et al, PRL 108 (2012) 231101

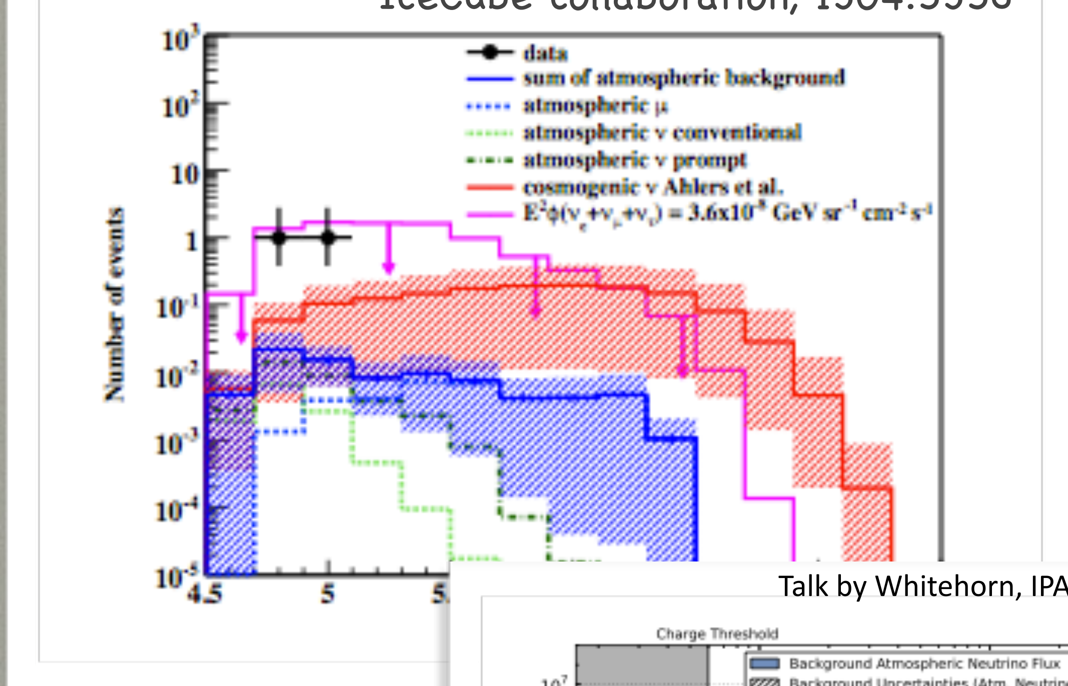


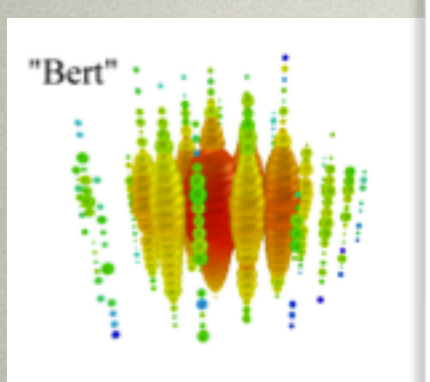
Re-evaluation of diffusive ν background -> 10 times smaller

Multimessenger Approach - PeV ν events

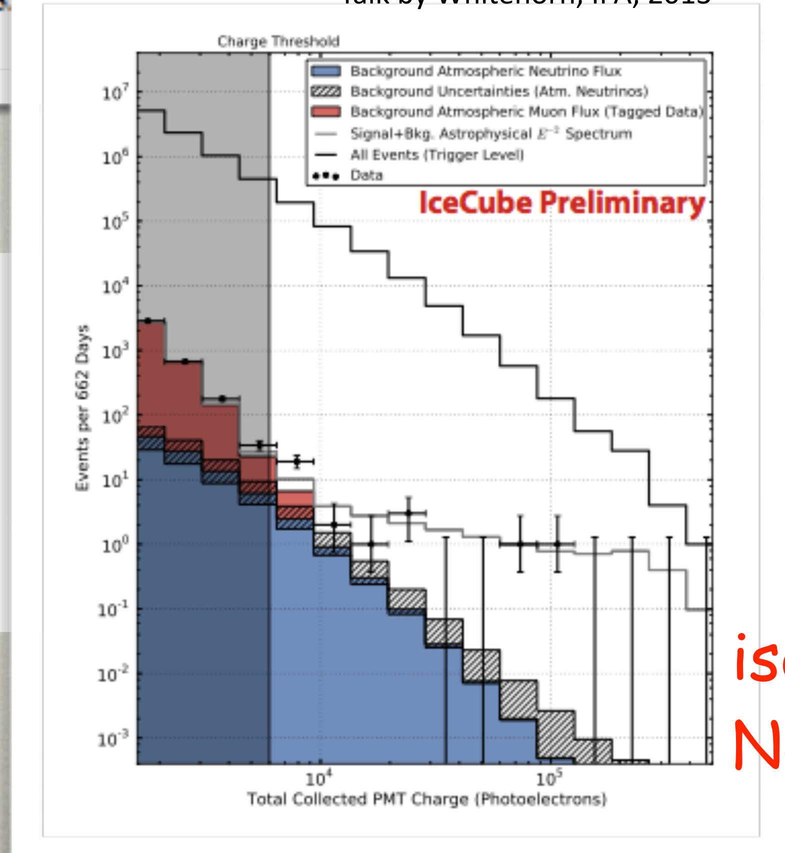
2 PeV energy neutrino detected by IceCube

IceCube collaboration, 1304.5356

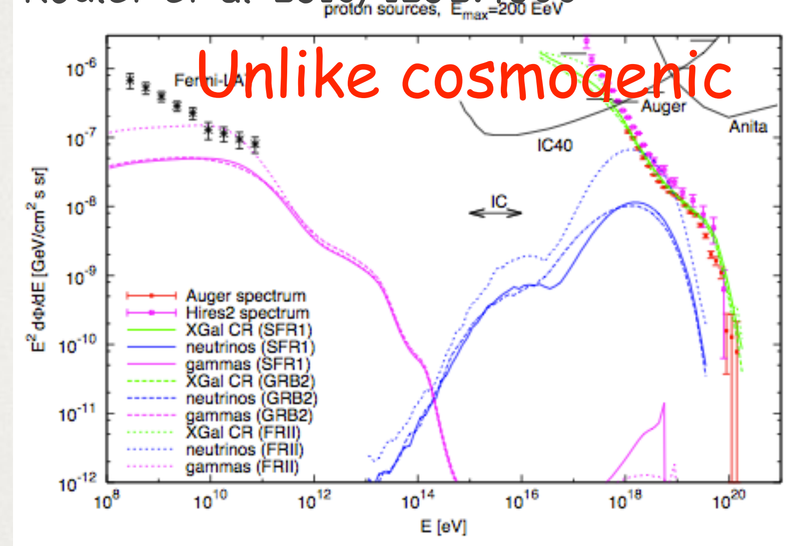




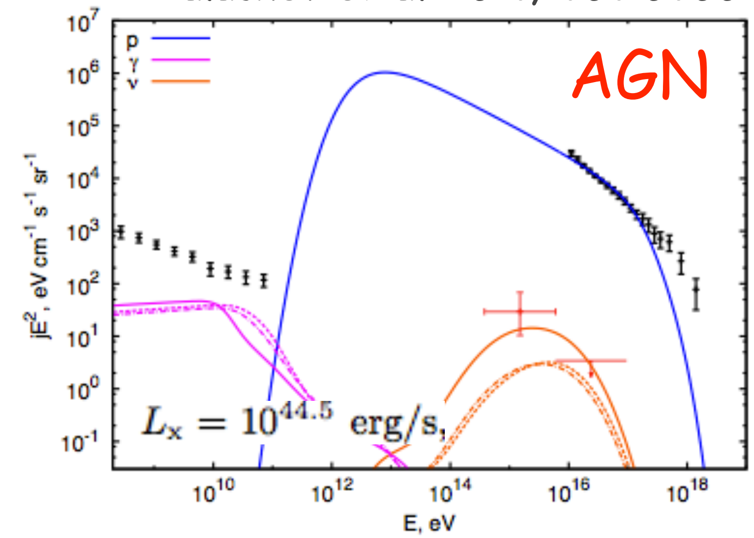
Talk by Whitehorn, IPA, 2013

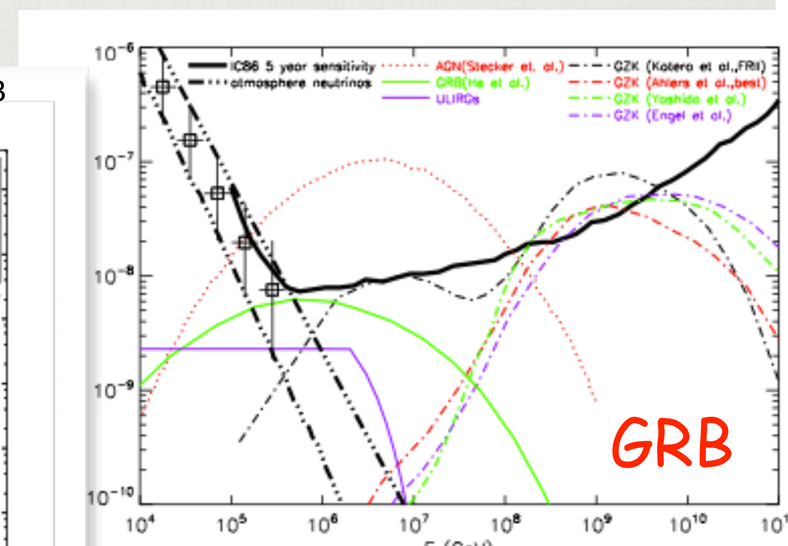


Roulet et al 2013, 1202.4033



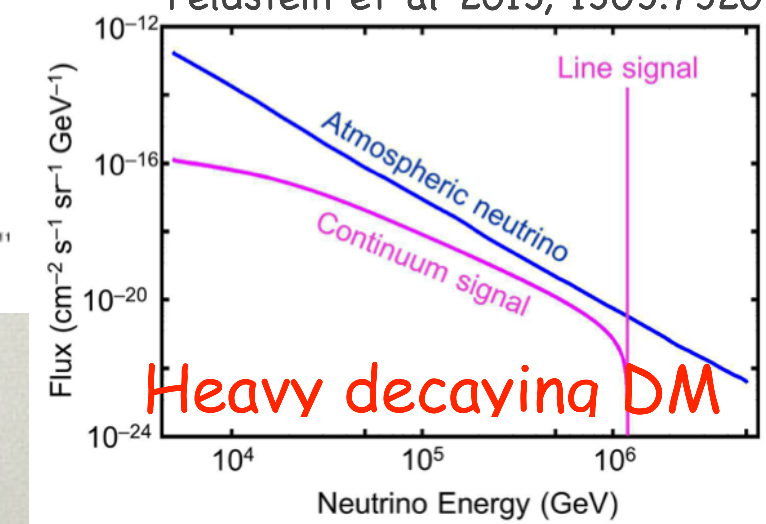
Kalashev et al 2013,1303.0300





He et al 2013,1303.1253

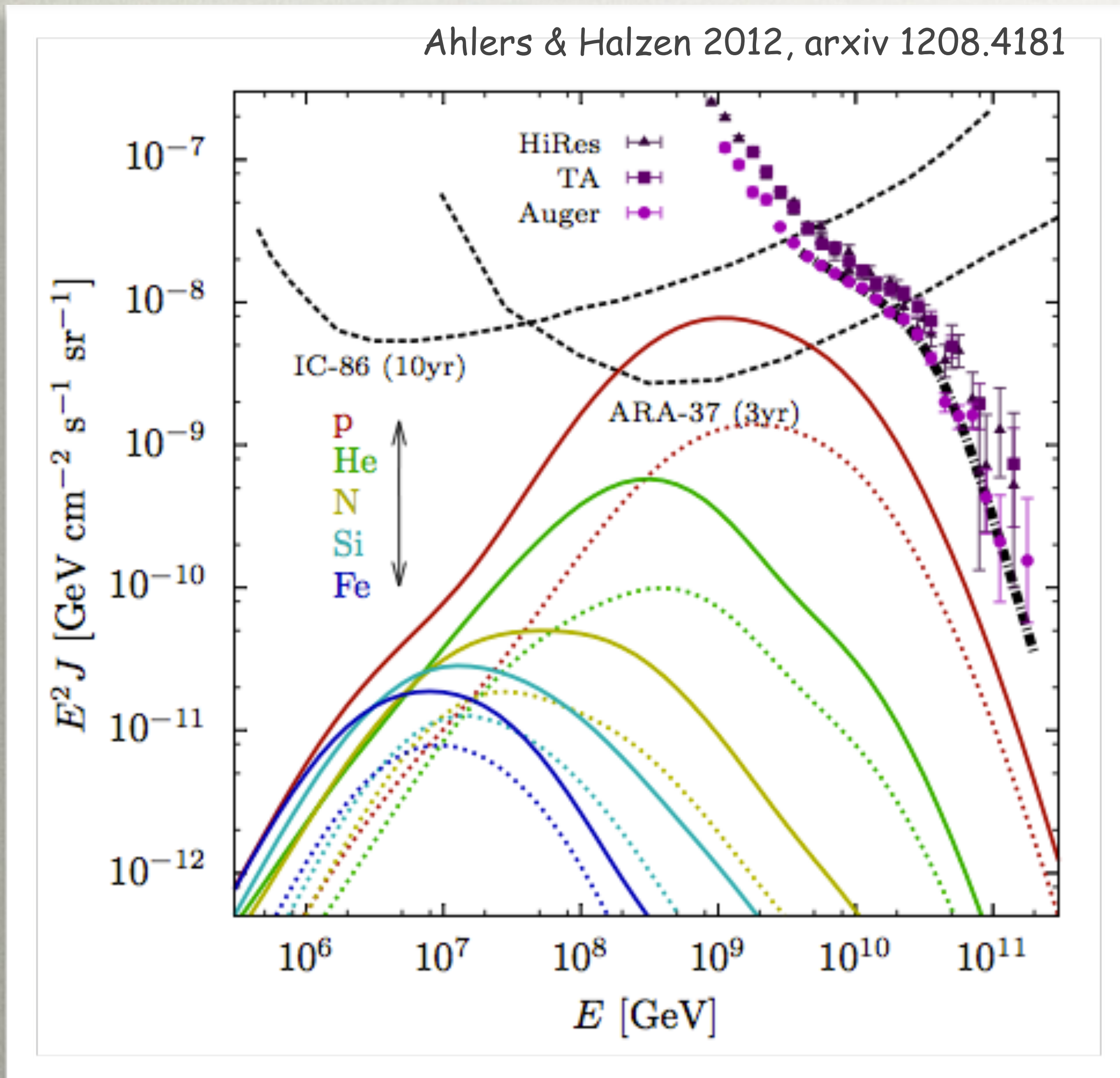
Feldstein et al 2013, 1303.7320

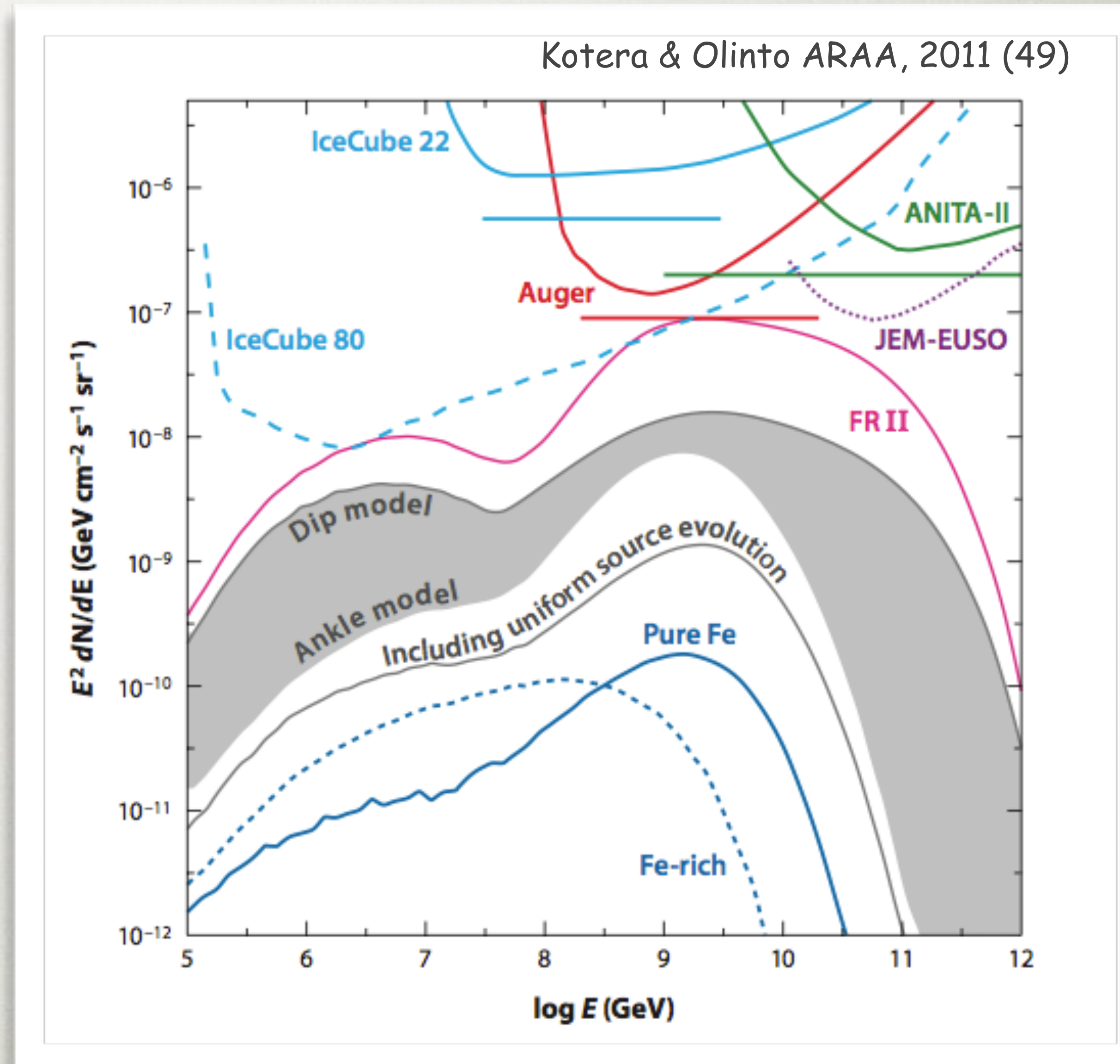


isotropic

No events above PeV

Multimessenger Approach - Cosmogenic ν





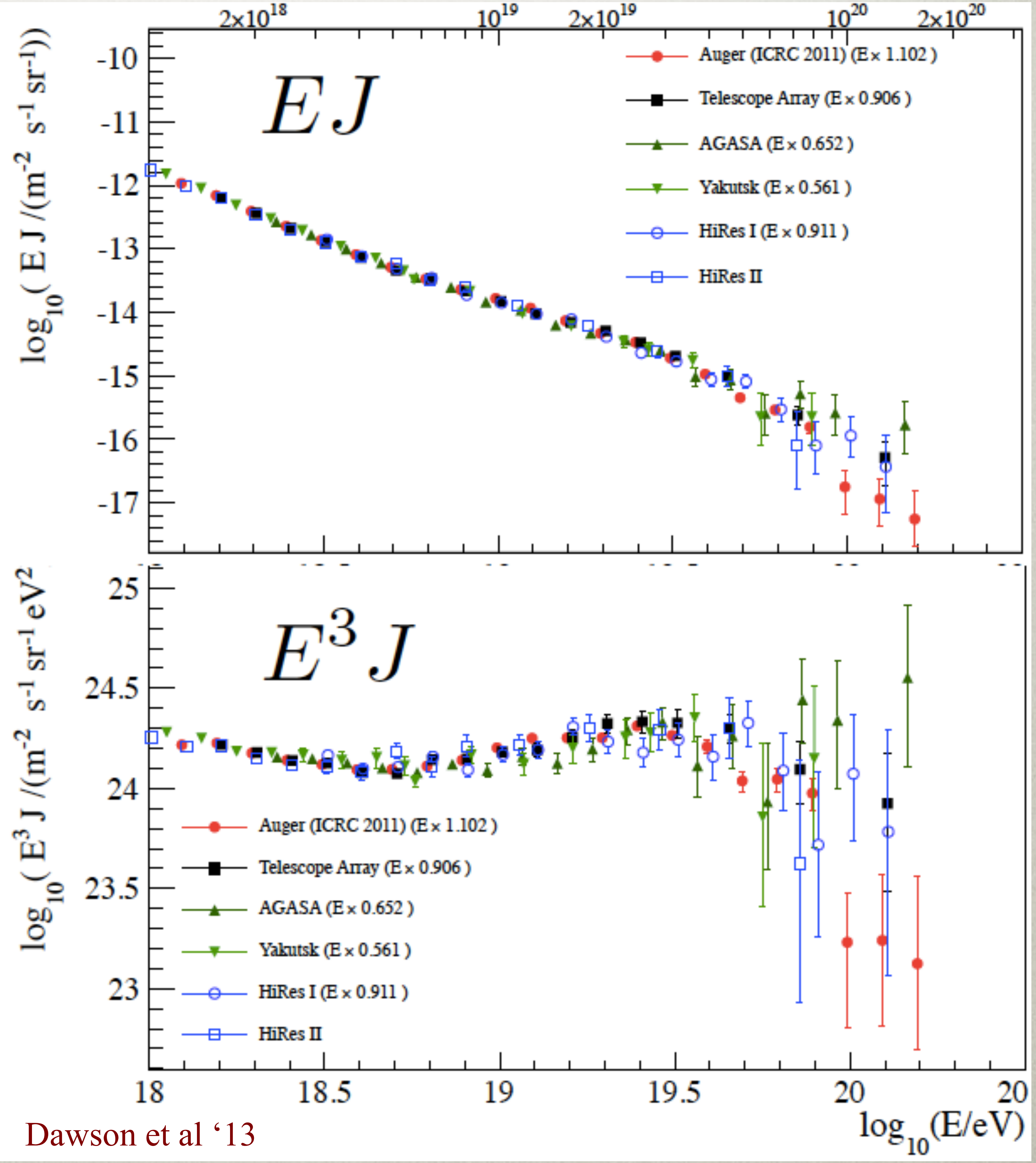
Detectability of cosmogenic neutrino dependent on source composition, evolution

1. spectrum

2012 CERN working group

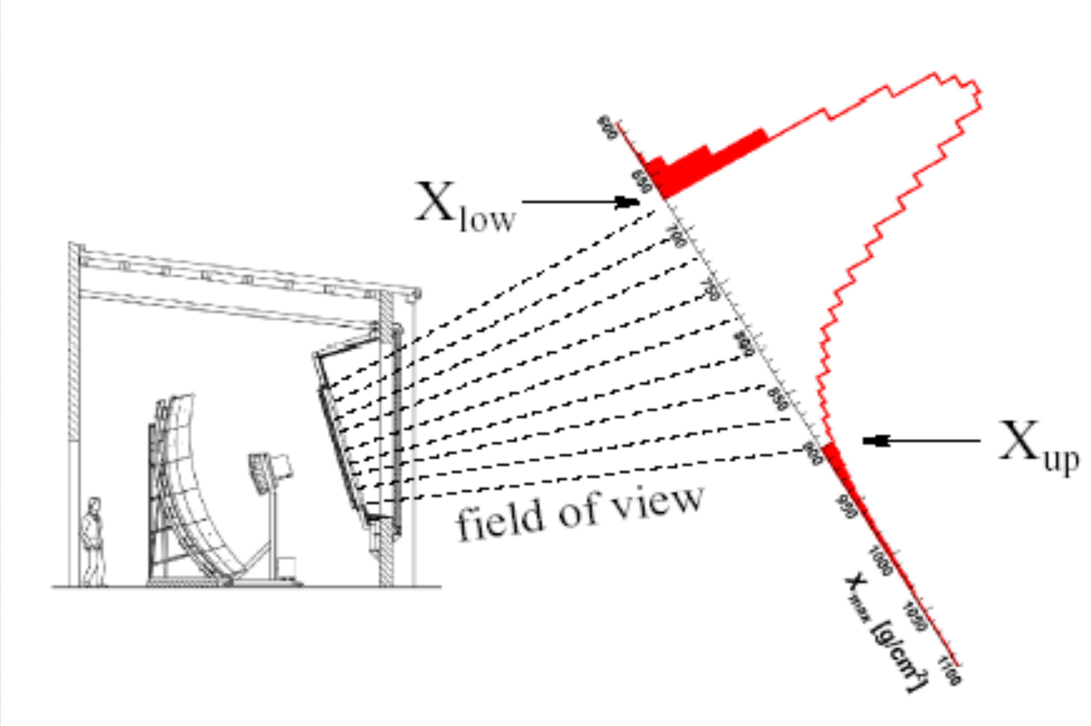
unified spectrum

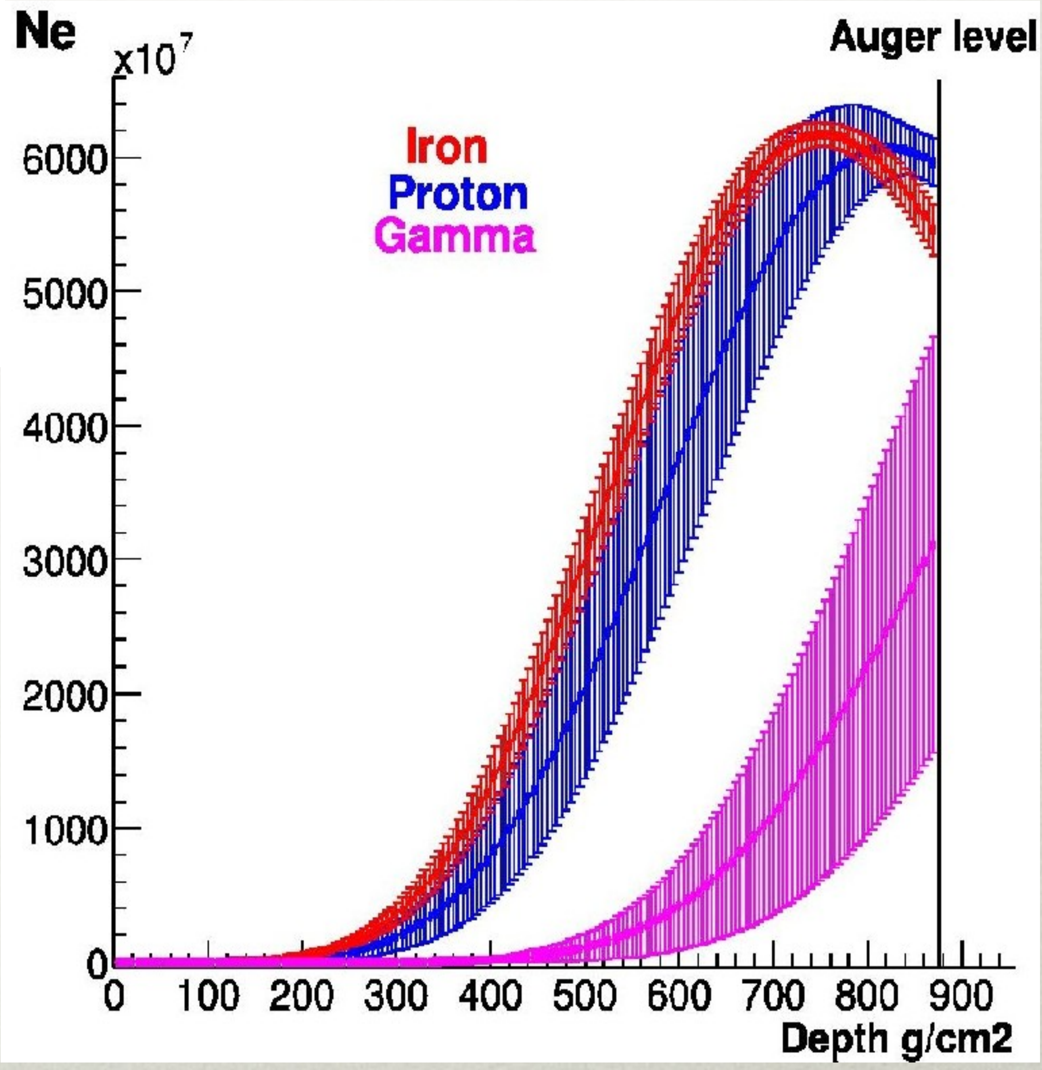
energy recaled



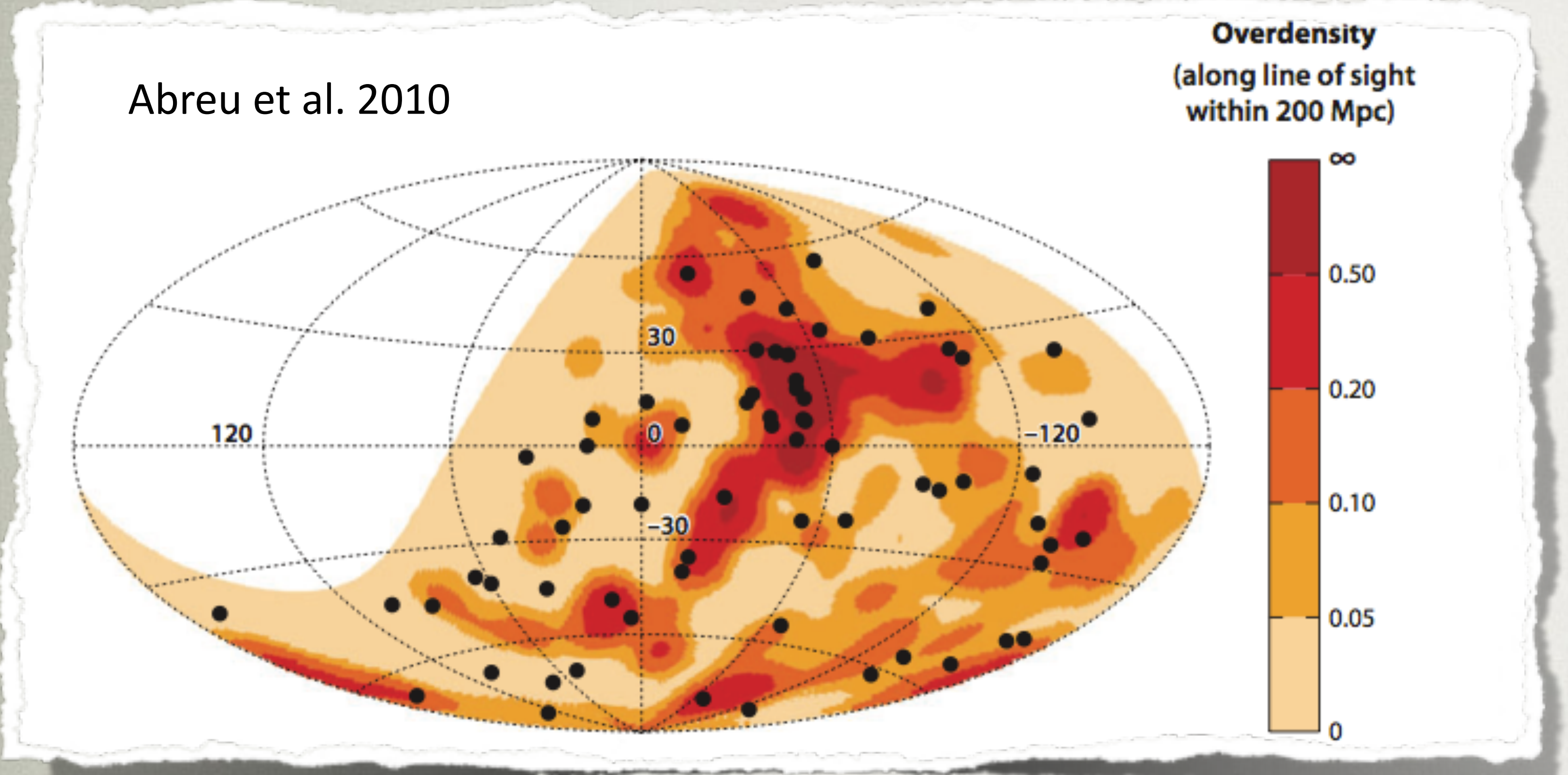
2. Chemical Composition

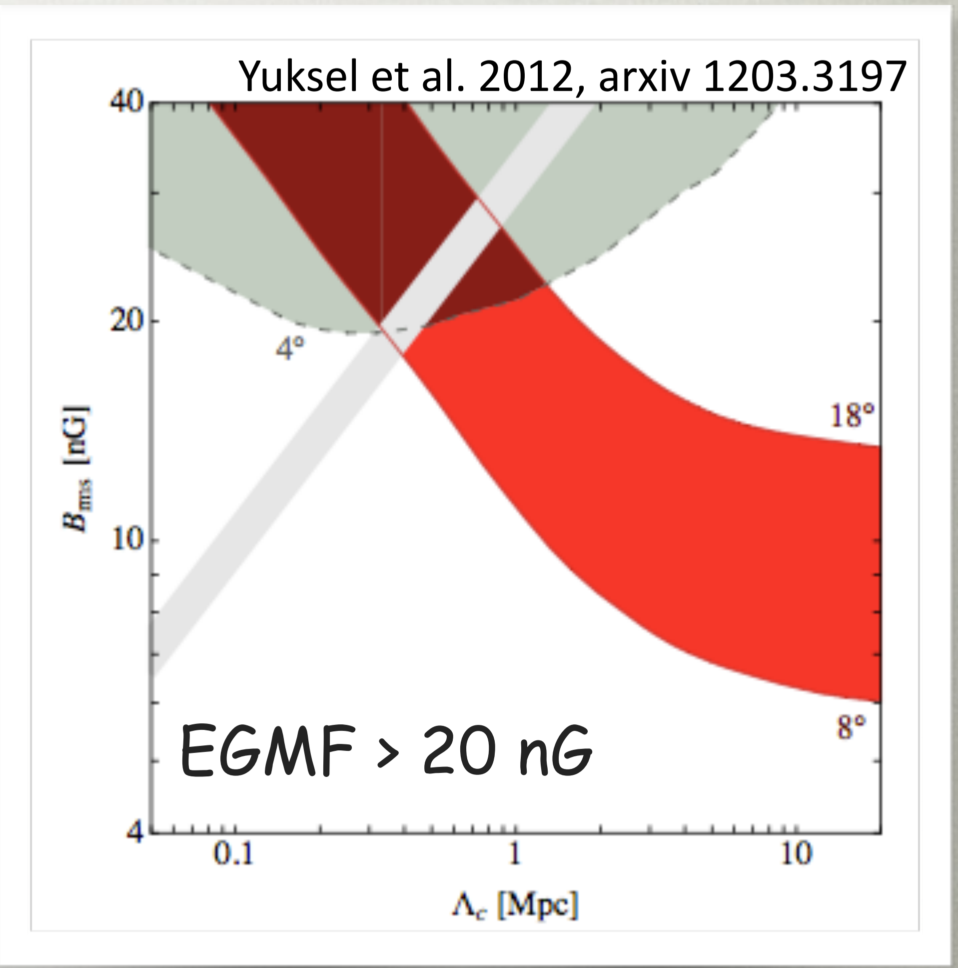
Composition Observable: Shower Maximum





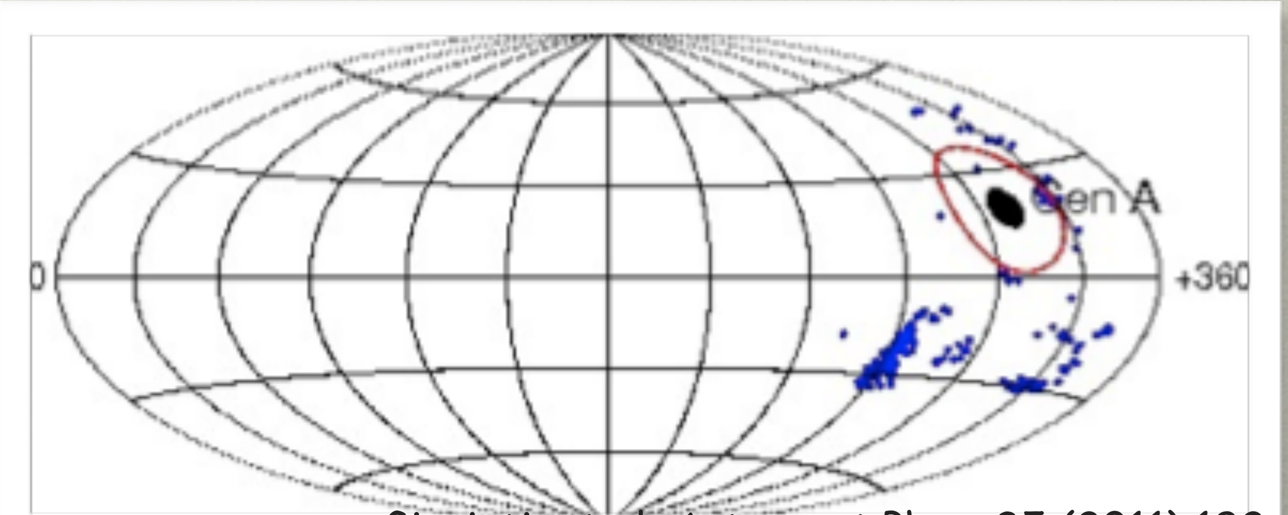
Anisotropy - hot spot around Cen A





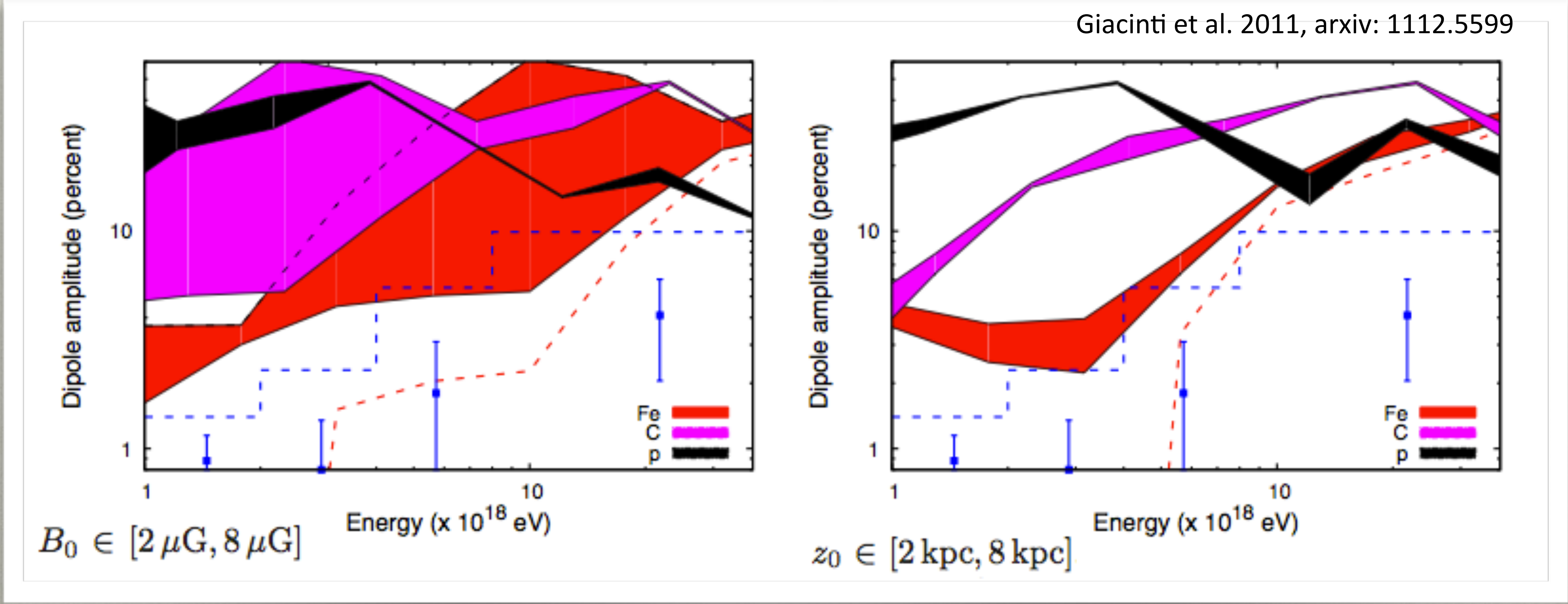
Pierre Auger sees an excess
in the direction of Centaurus A above 55 EeV

even for iron primaries
Centaurus A can not be
the only UHECR source



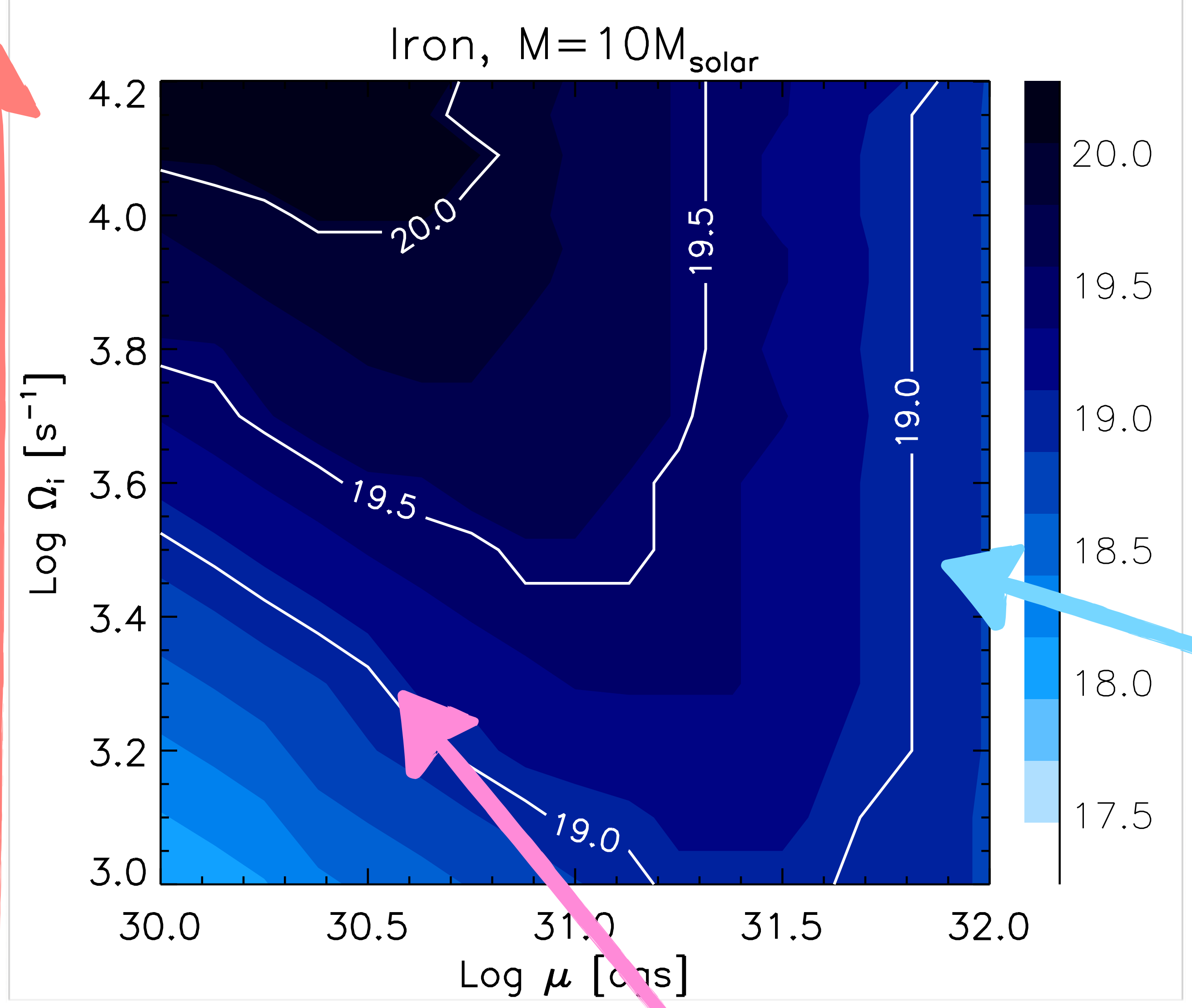
Giacinti, et al, Astropart.Phys. 35 (2011) 192

Extragalactic??
-Yes, particles point at highest energy



rule out Galactic P-CNO
as dominant cosmic ray component at E>1EeV
Fe at E>20 EeV

UHE-allowed Pulsars



Two competing timescales:

Time to escape $t_{dyn} = \frac{R_{SN}}{c} \sim t_{spin}$

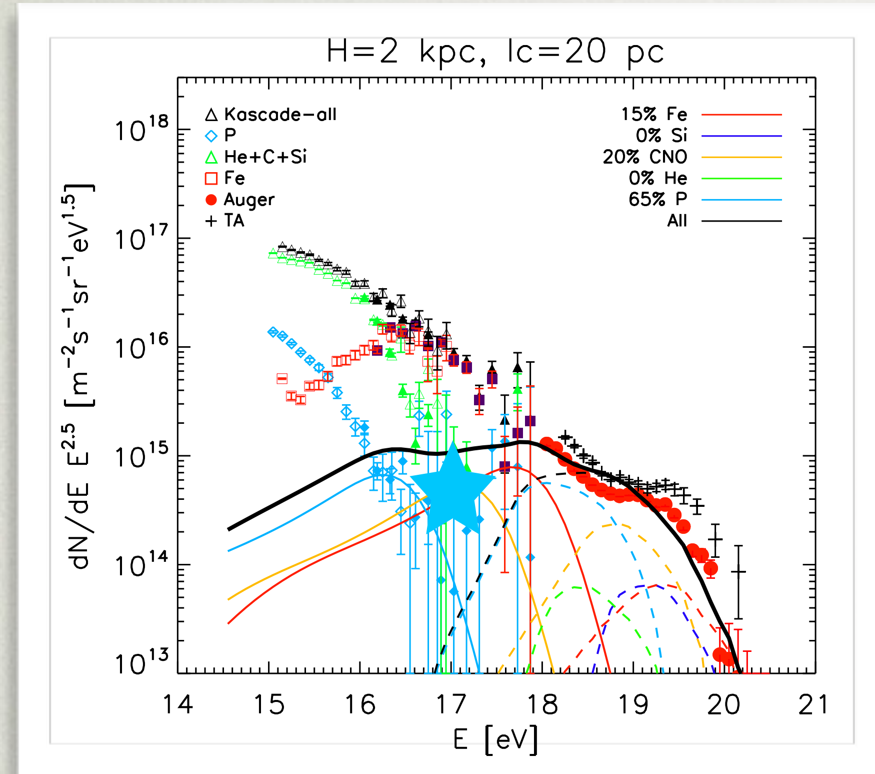
CR Life time $t_{had} = (n_{SN}\sigma\kappa c)^{-1} \sim t_{spin}^3$

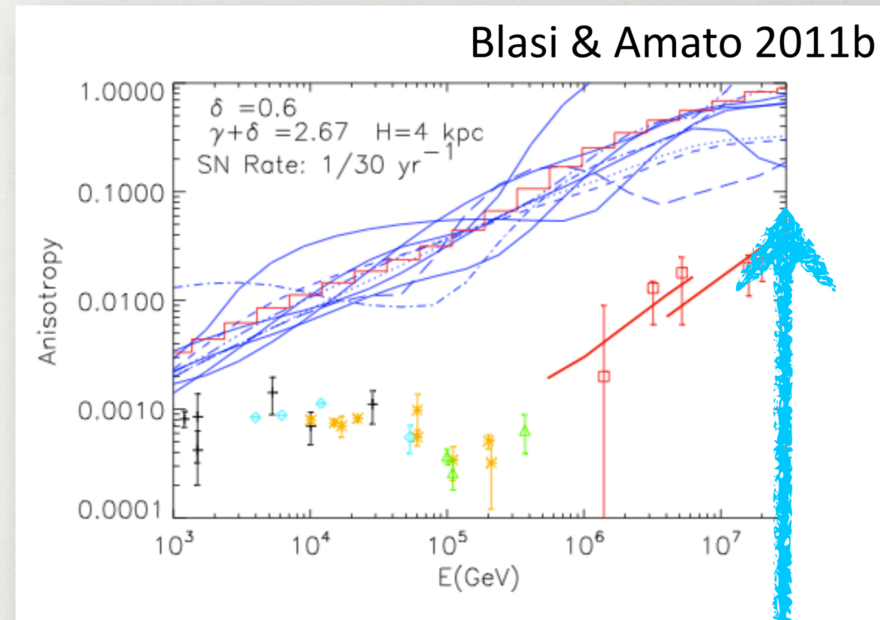
To successfully escape: $t_{dyn} \leq t_{had}$

Strong B-field $t_{dyn} = t_{had}$,
$E = E_{cut} \sim \mu^{-1}\,\Omega^0$

Weak B-field $t_{had} >> t_{dyn}$,
$E = E_{max} \sim \mu^1\,\Omega^2$

Estimation on Anisotropy

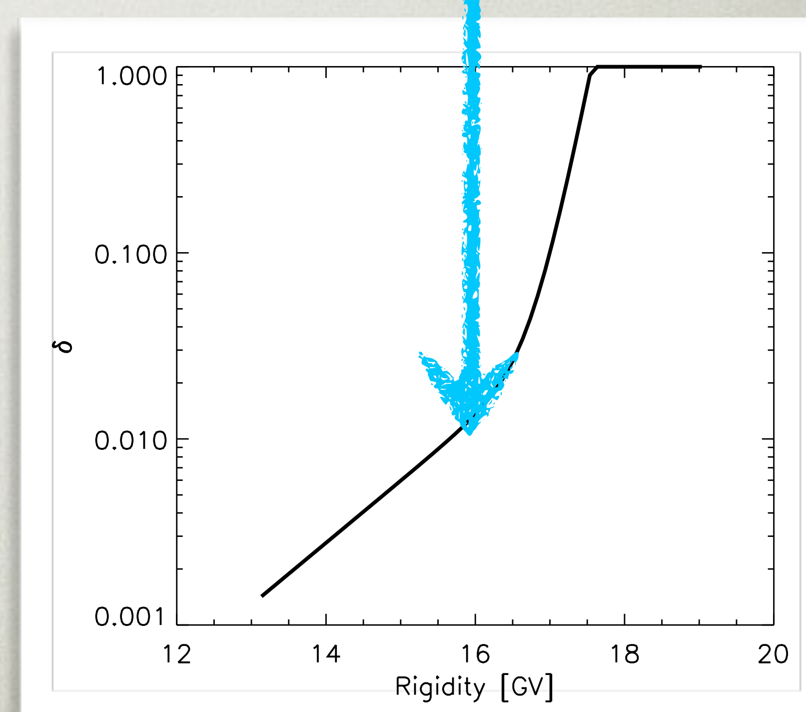




Heavy composition reduces anisotropy levels

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!