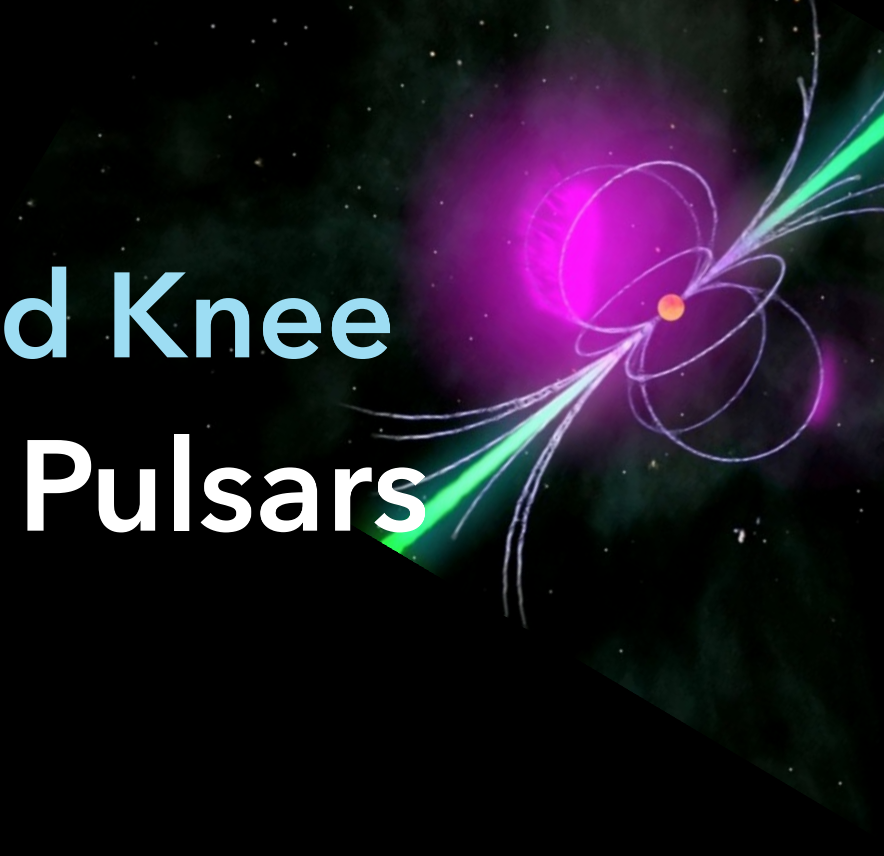


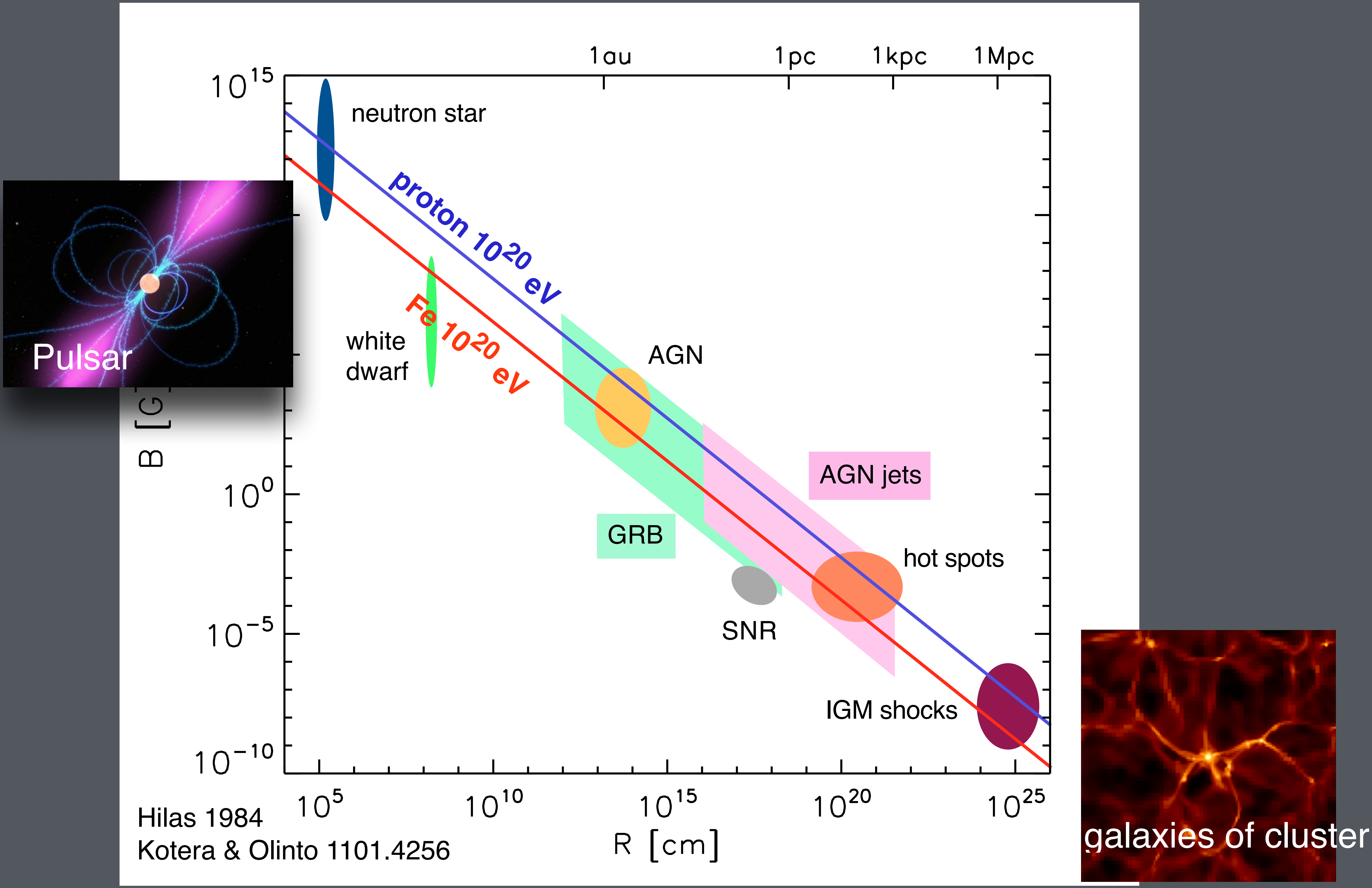
Accelerators for > Second Knee

Fast-spinning Newborn Pulsars
+
Galaxy Clusters

Ke Fang

JSI Fellow
University of Maryland
MARCROS Workshop, Jun 21, 2016

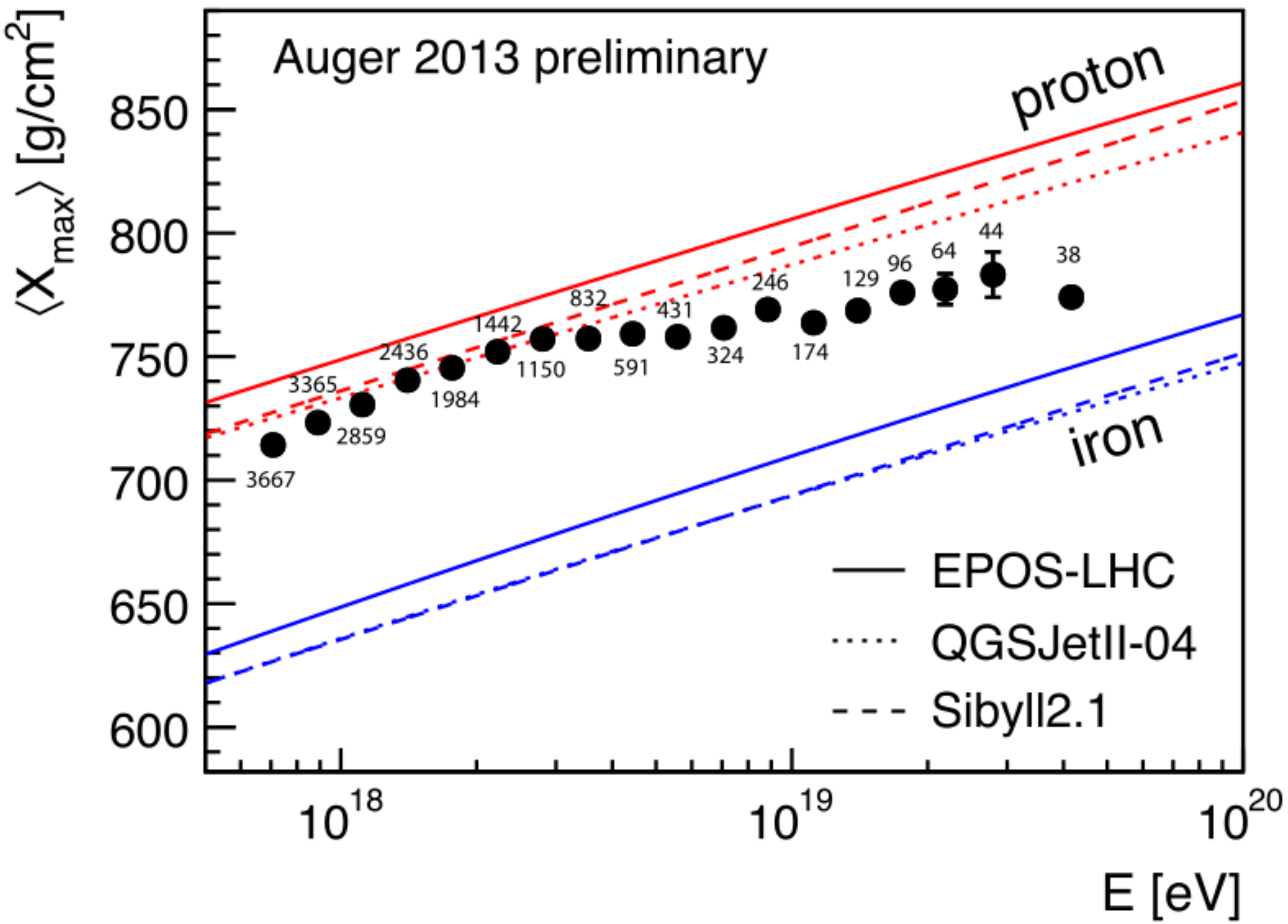
Possible Extreme Accelerators



Hilas 1984
Kotera & Olinto 1101.4256

Fast-spinning pulsars

Hint of Heavy Composition



Neutron stars are favorable sites for heavy nuclei injection

Pulsars: Cosmic Ray Acceleration

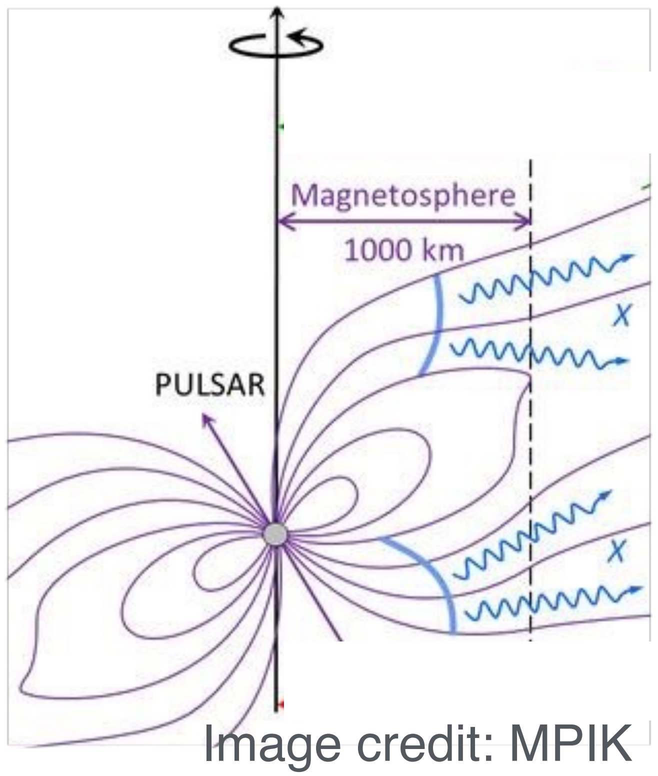


Image credit: MPIK

Particle injection spectrum

$$\frac{dN}{dE} \propto E^{-1}$$

initial spin period

Magnetic Field

Wind efficiency

Multiplicity

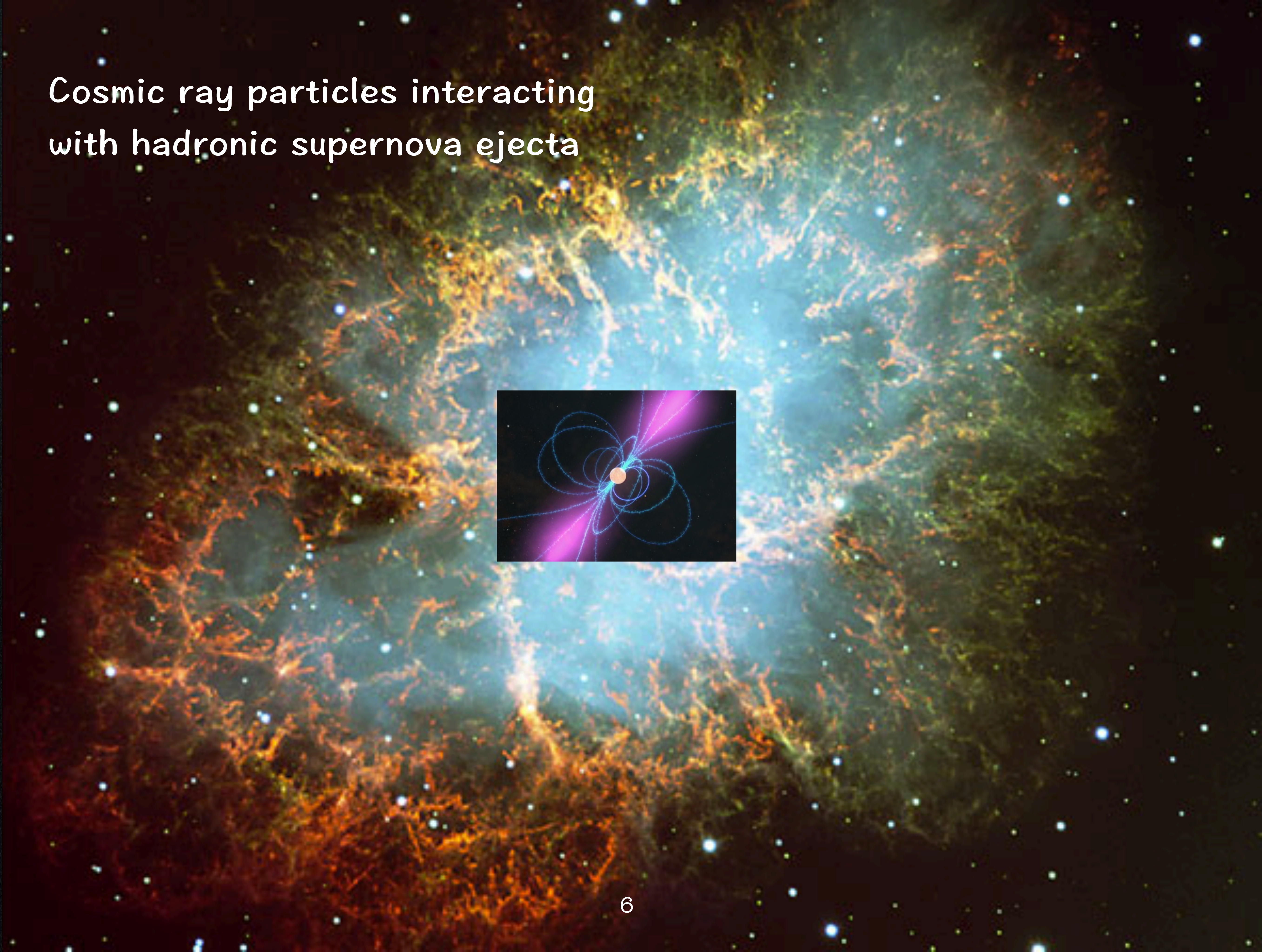
$$E_{\rm CR} = 10^{18}\, A \left(\frac{B}{10^{13}\,{\rm G}}\right) \left(\frac{P_i}{1\,{\rm ms}}\right)^{-2} \left(\frac{\eta}{0.3}\right) \left(\frac{\kappa}{10^4}\right)^{-1} \left(1 + \frac{t}{\tau_{\rm sd}}\right)^{-1} {\rm eV}$$

t ↑ E ↓

$$\tau_{\rm sd} = 1 B_{13}^{-2} P_{i,1{\rm ms}}^2\, {\rm yr}$$

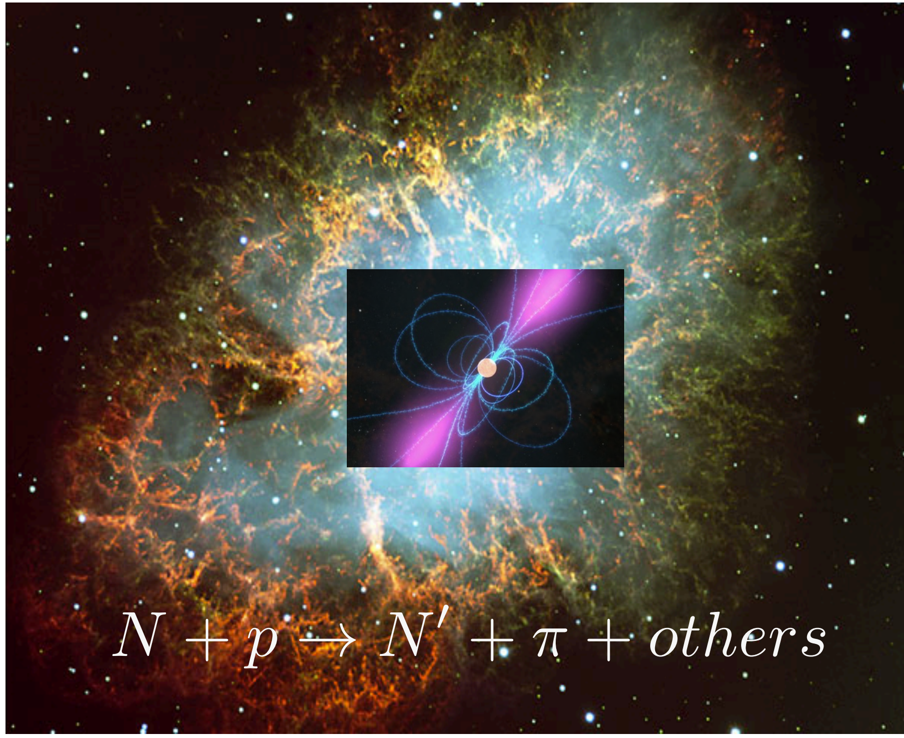
Blasi, Epstein & Olinto ApJ 533 (2000)
Arons, ApJ 589 (2003)
Lemoine, Kotera & Petri 1409.0159

Cosmic ray particles interacting with hadronic supernova ejecta



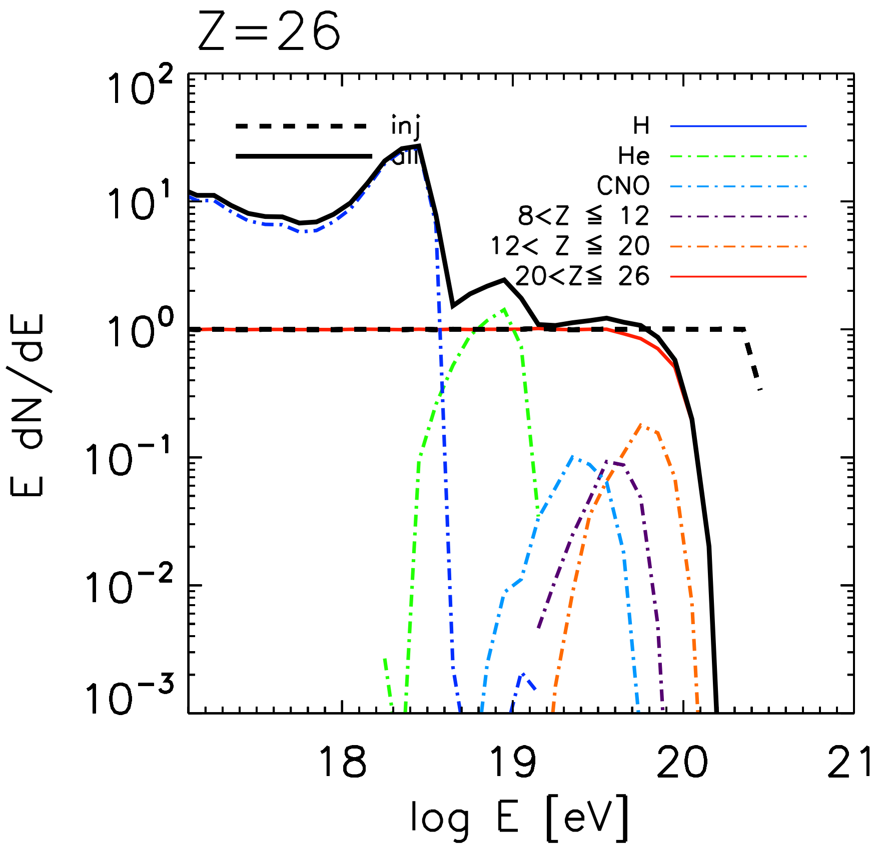
Interaction with Ejecta

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

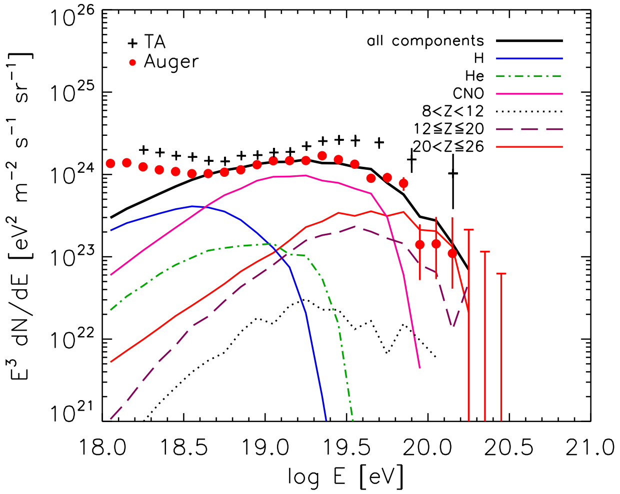


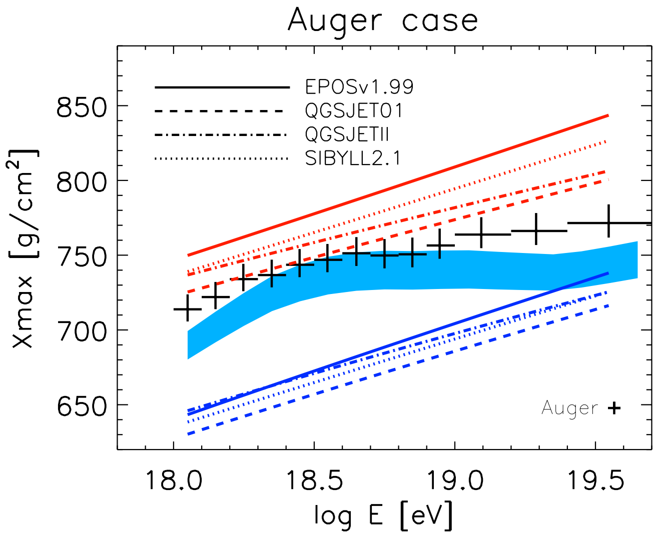
$N + p \to N' + \pi + others$

Monte Carlo simulation tracking particle propagation



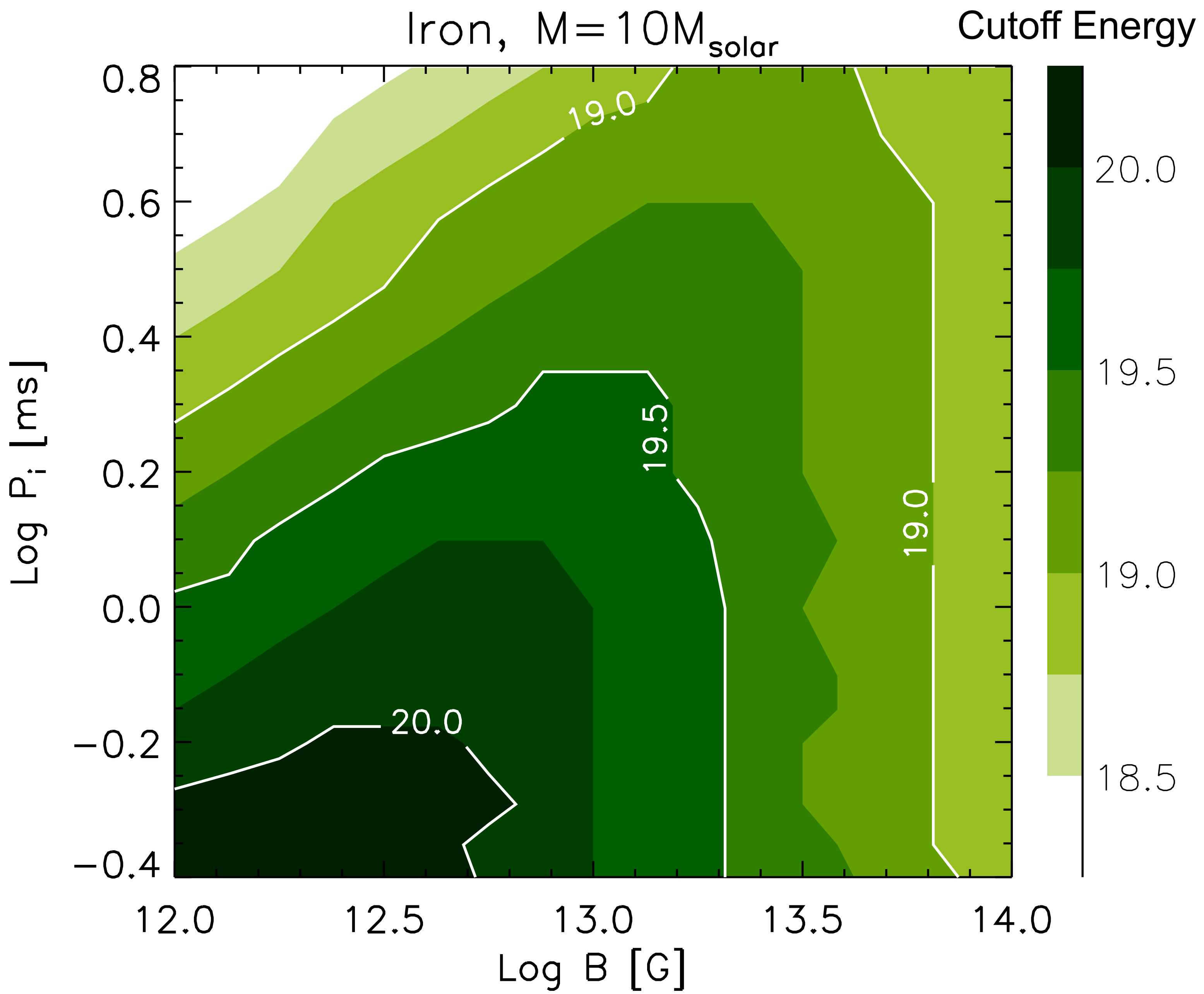
$$B = 10^{13}\,{\rm G}, {\rm P_i} = 0.6\,{\rm ms}$$

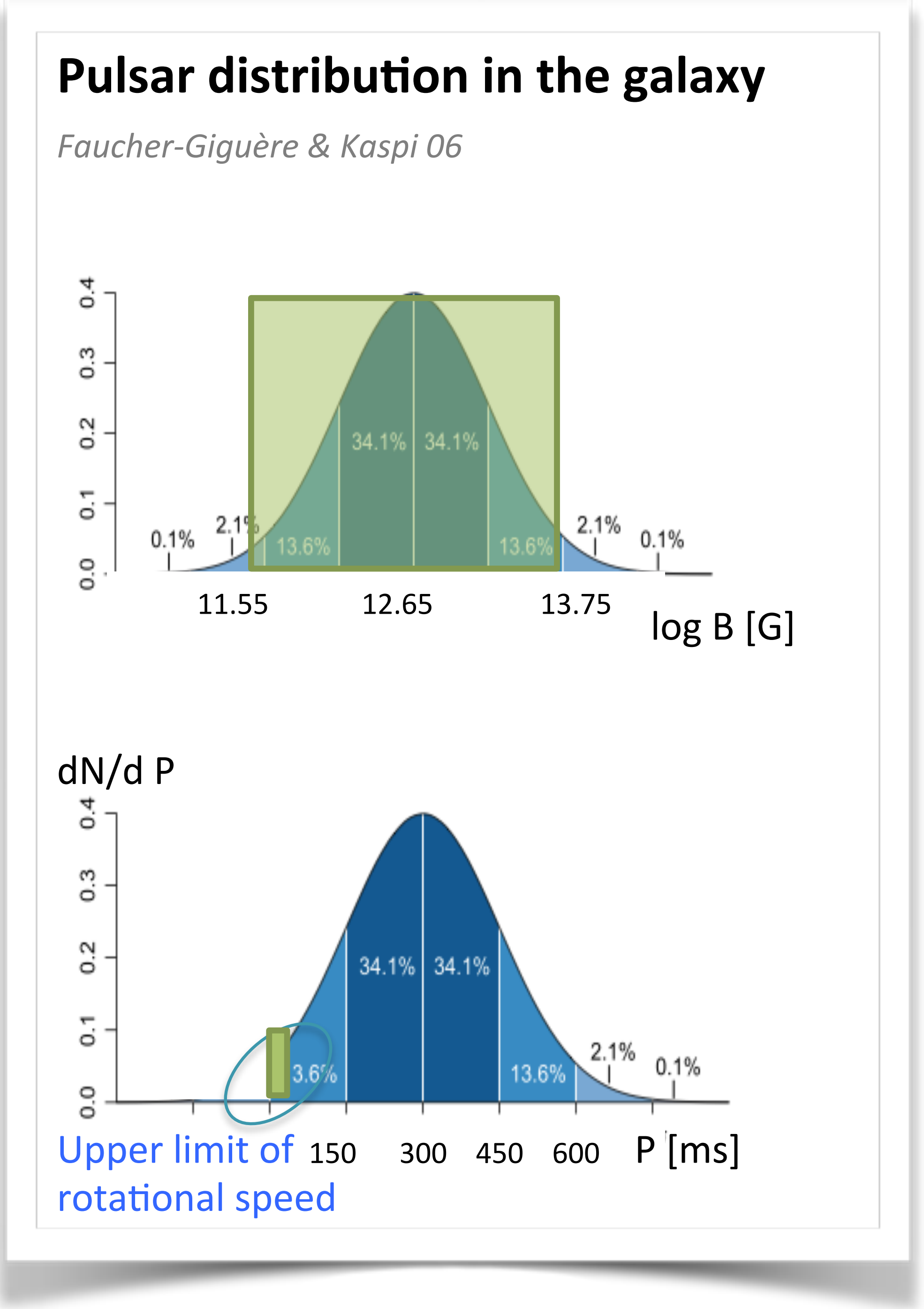




KF, Kotera & Olinto, ApJ, 750, 118, 2012

UHE-allowed Pulsars





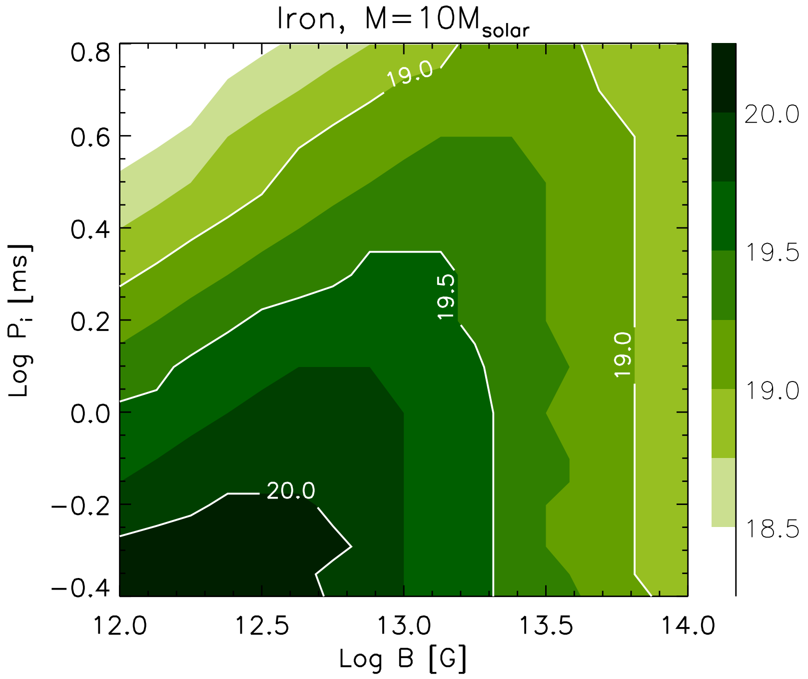
Pulsar distribution in the galaxy

Faucher-Giguère & Kaspi 06

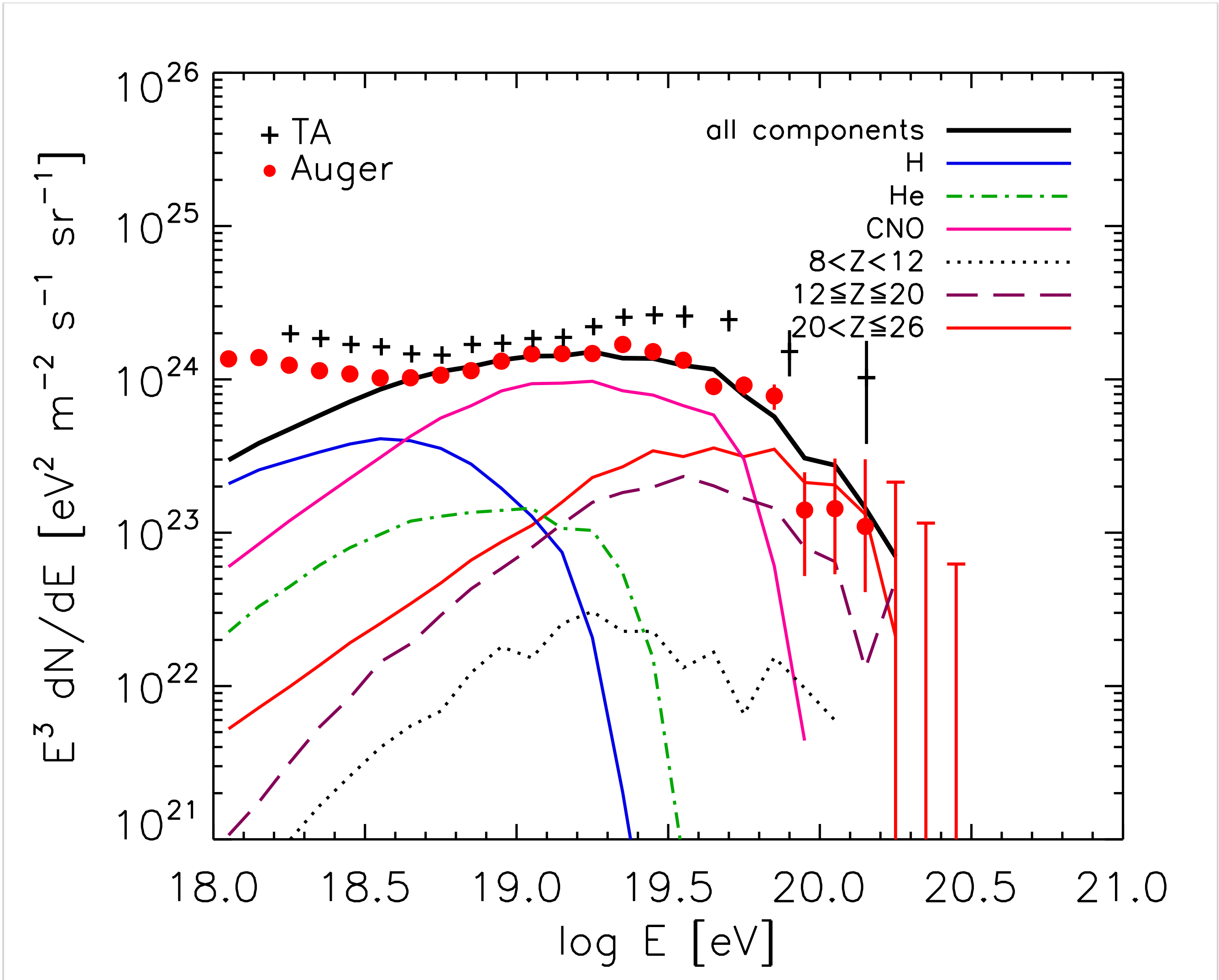
Upper limit of rotational speed

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

Integrated Extragalactic Pulsars



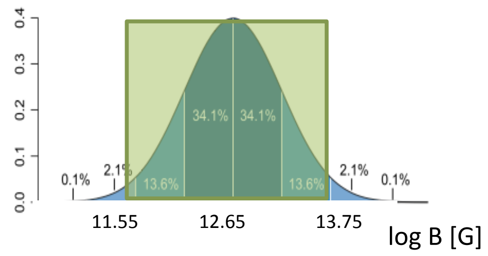
$$\langle\frac{dN}{dE}\rangle = \int \frac{dN}{dE}(B,P_i)f(B,P_i)dBdP_i$$

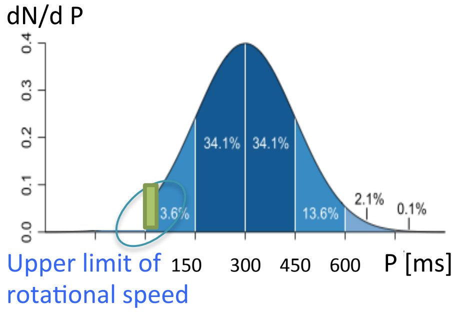


$$f_s \approx 0.05$$

Pulsar distribution in the galaxy

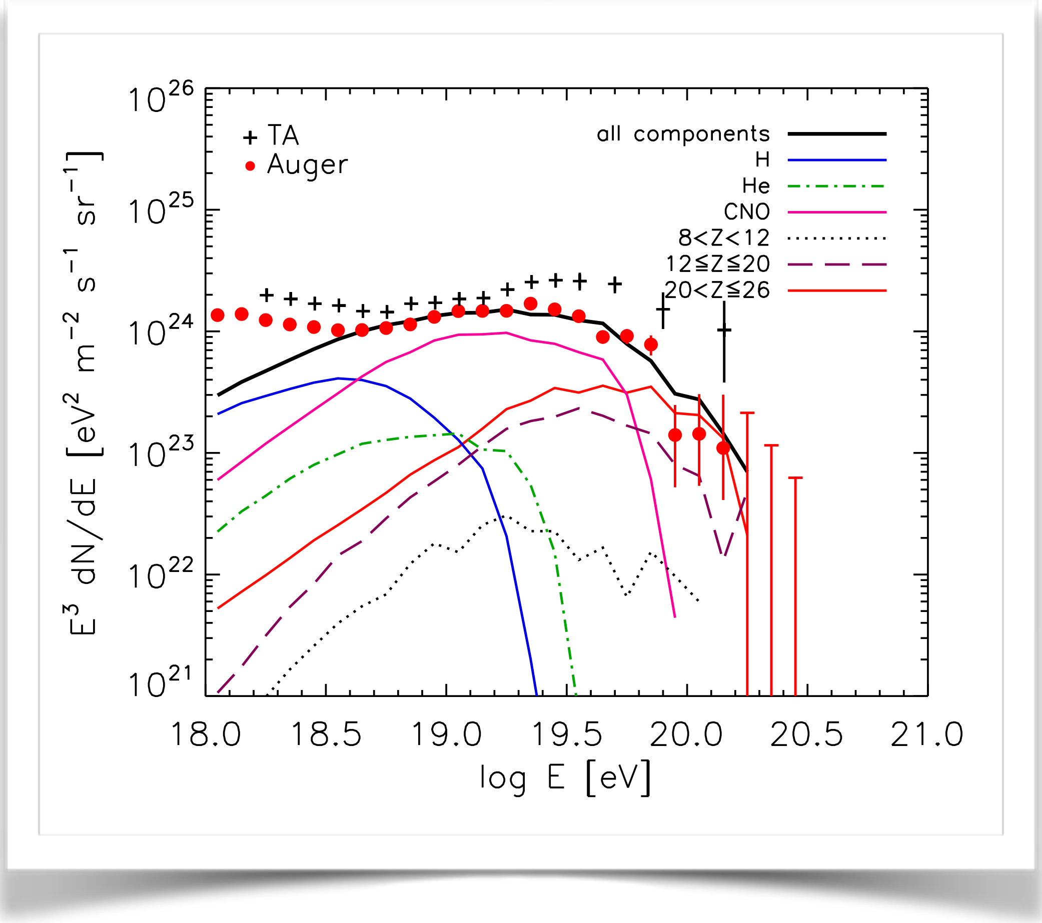
Faucher-Giguère & Kaspi 06

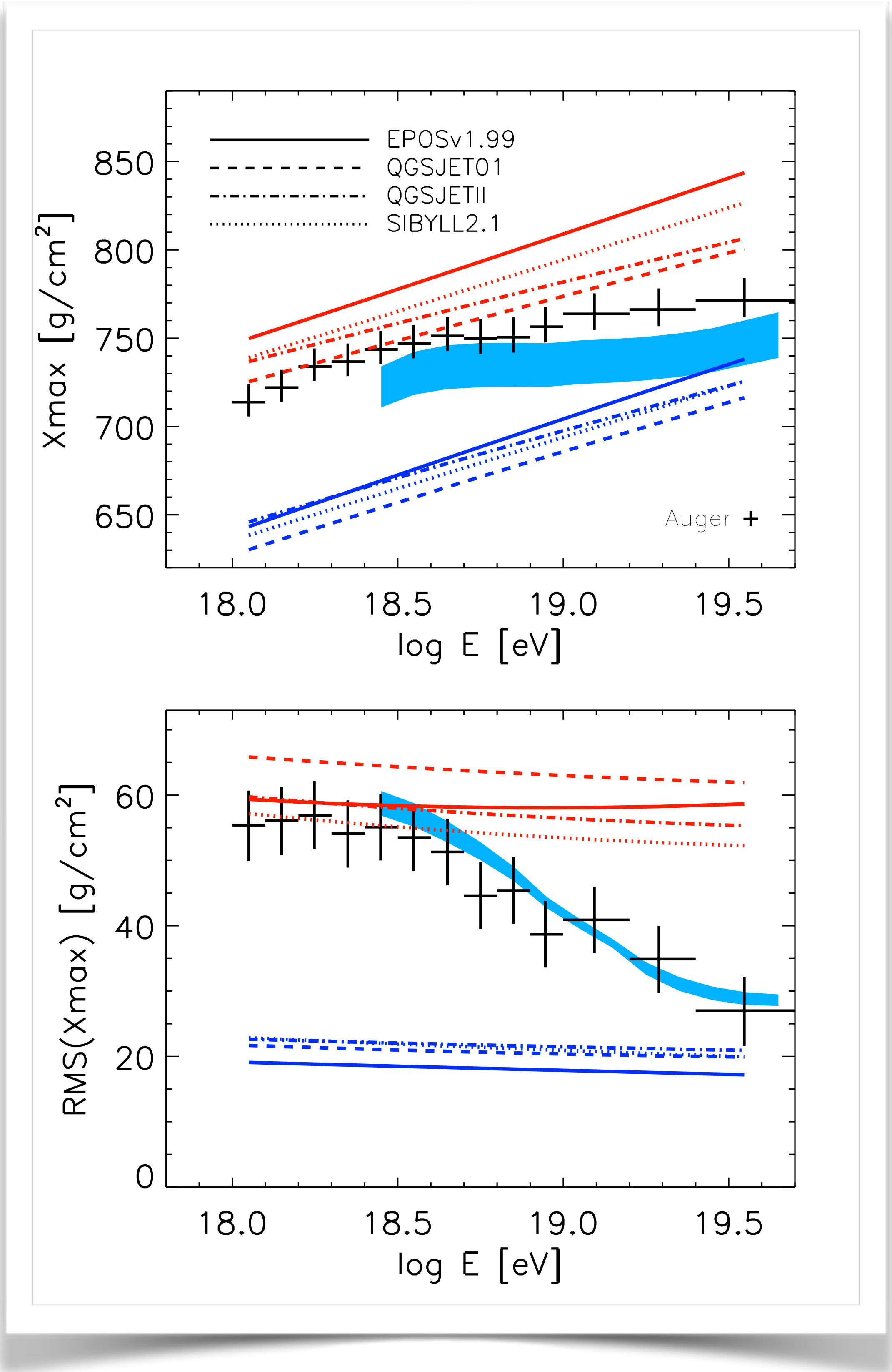




KF, Kotera & Olinto, ApJ, 750, 118, 201
KF, Kotera & Olinto, JCAP 03(2013)01

Integrated Extragalactic Pulsars

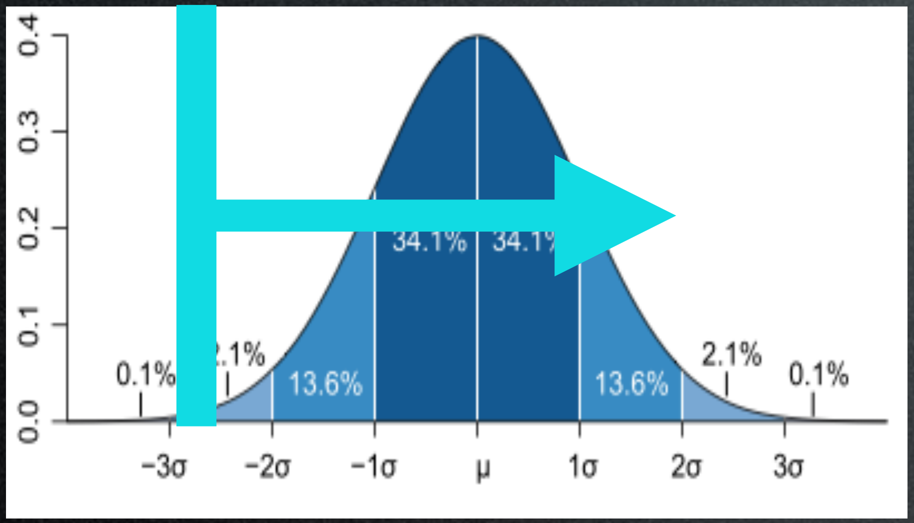


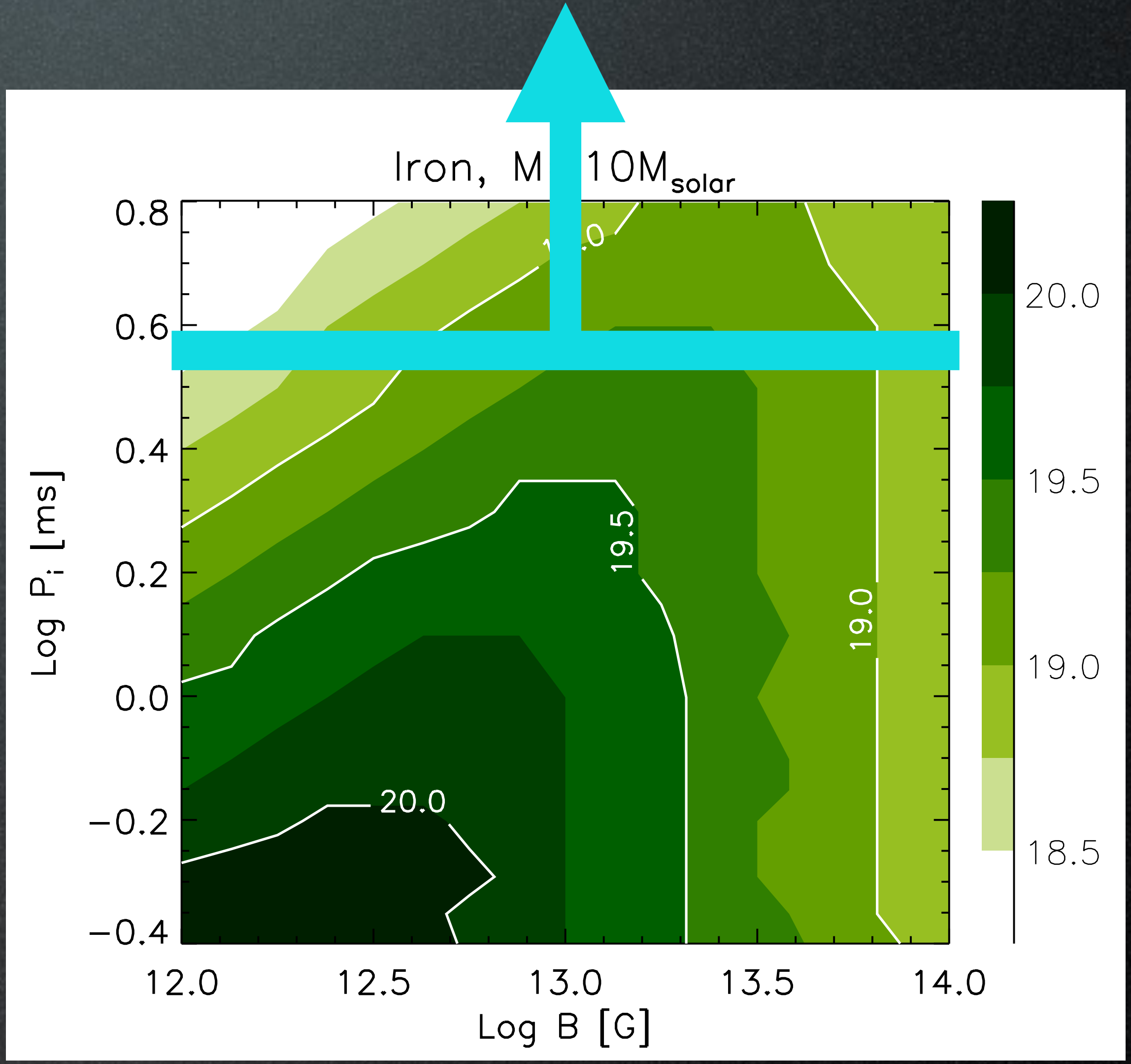


Newborn pulsars can be successful UHECR accelerators!

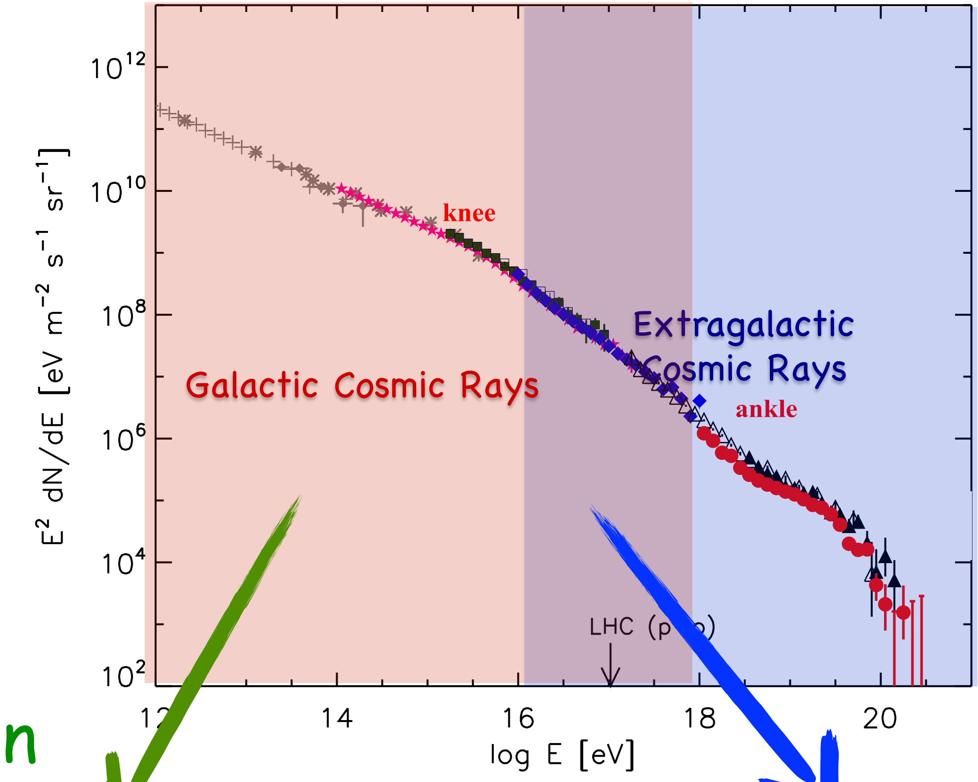
KF, Kotera & Olinto, ApJ, 750, 118, 2012
KF, Kotera & Olinto, JCAP 03(2013)010

What about their Galactic Counterparts?



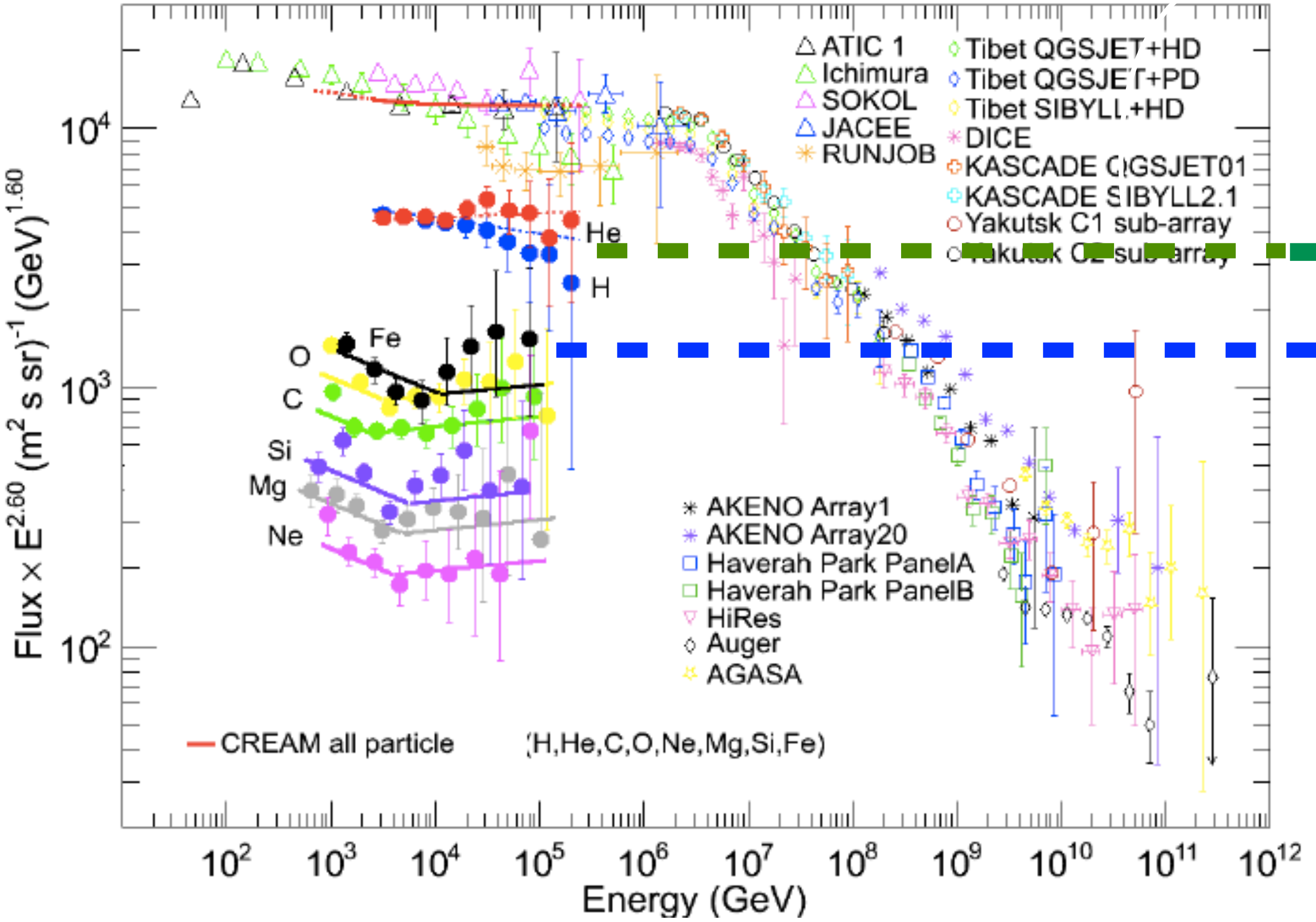


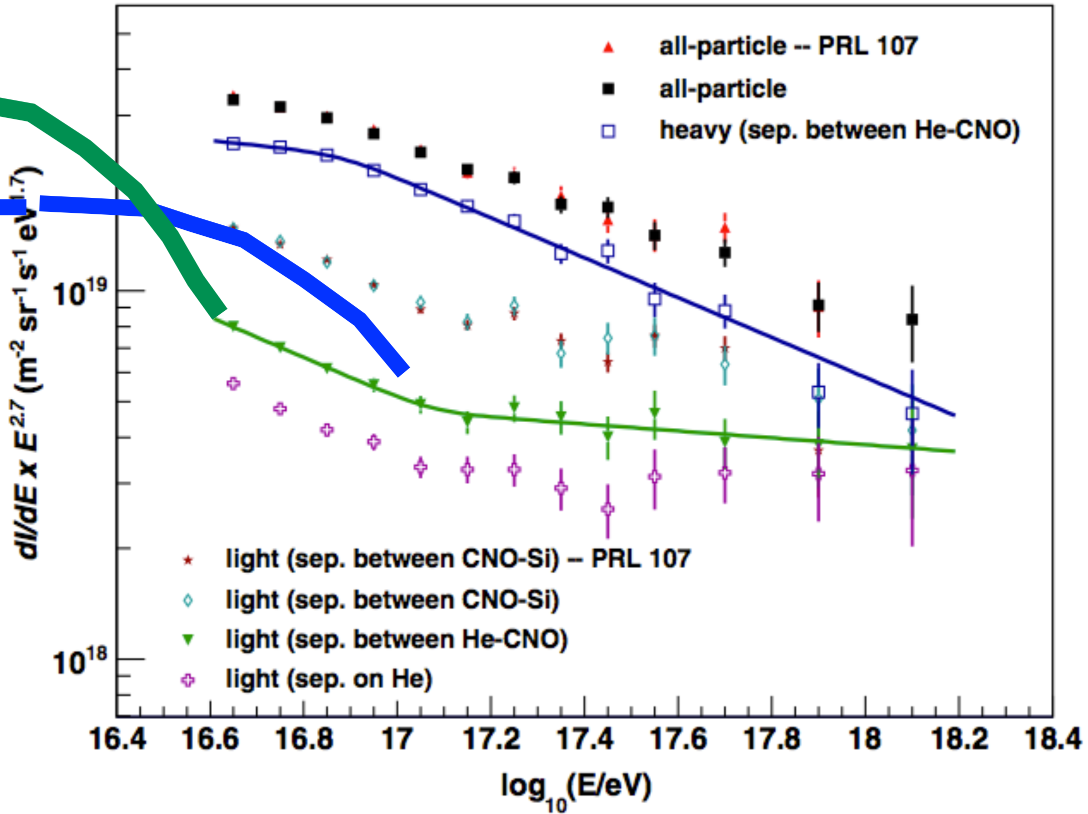
Galactic - Extragalactic Transition



Mostly light composition below the knee

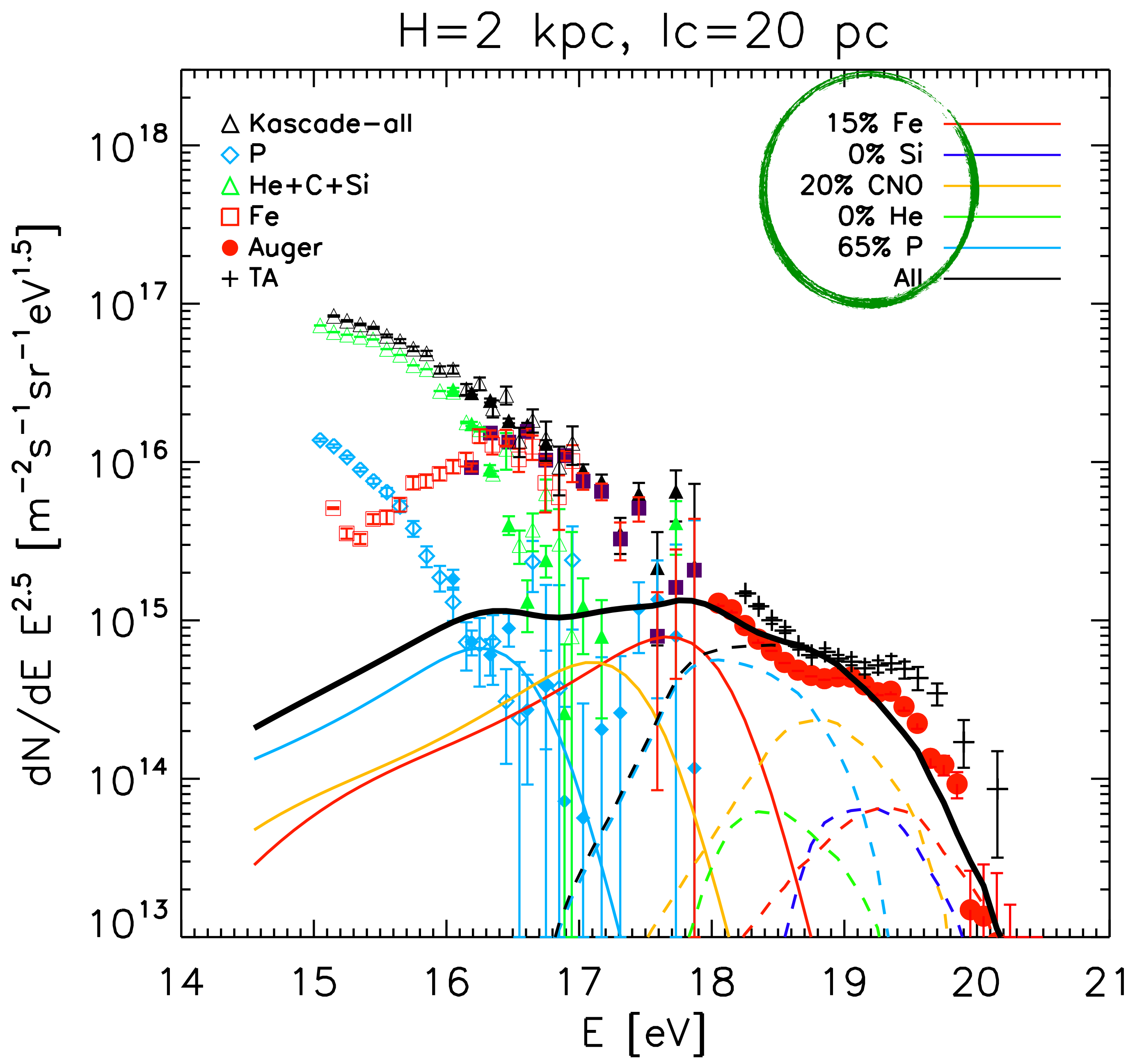
But changed to heavy dominated at the transition regime





KASCADE, 1306.6283

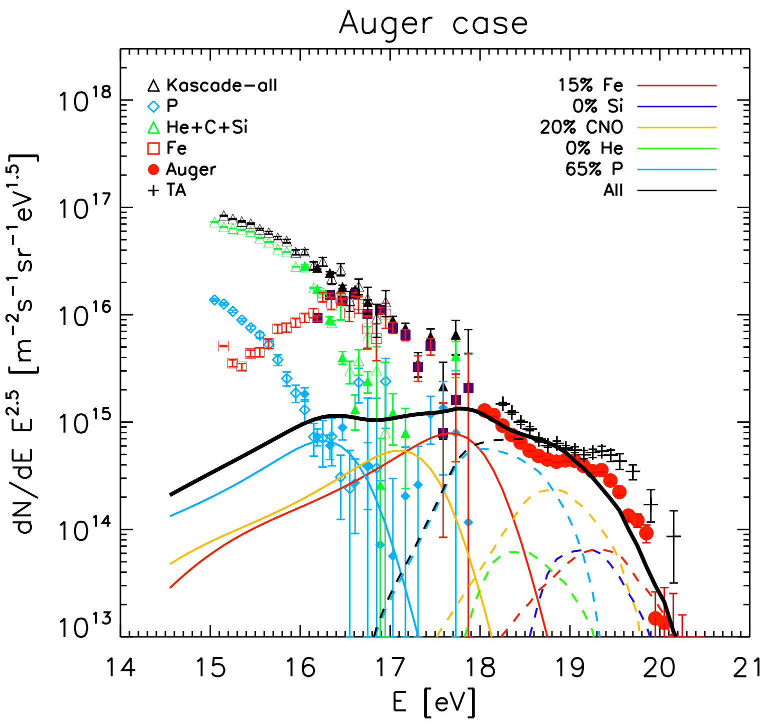
Contribution from Galactic pulsars - Spectrum

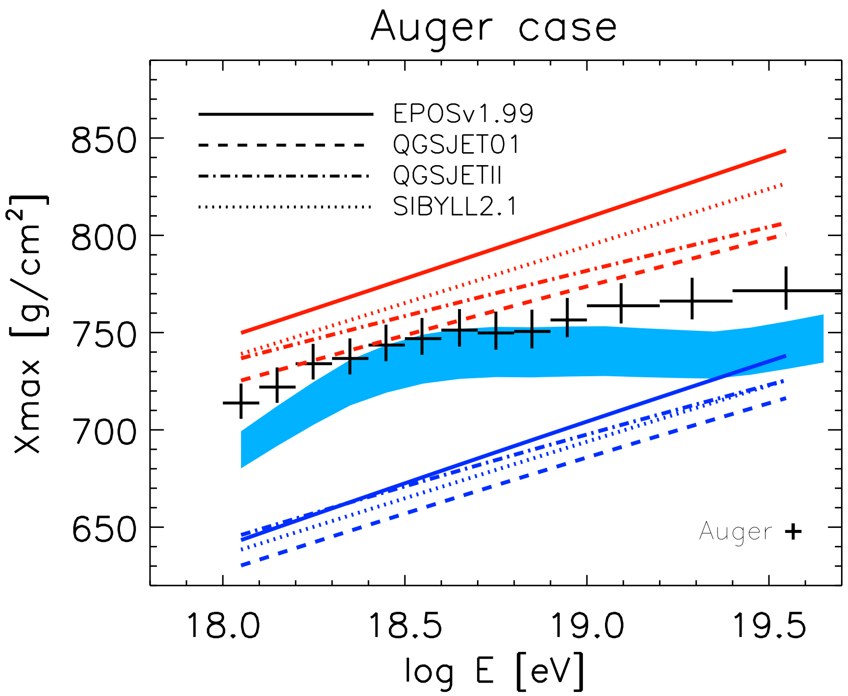


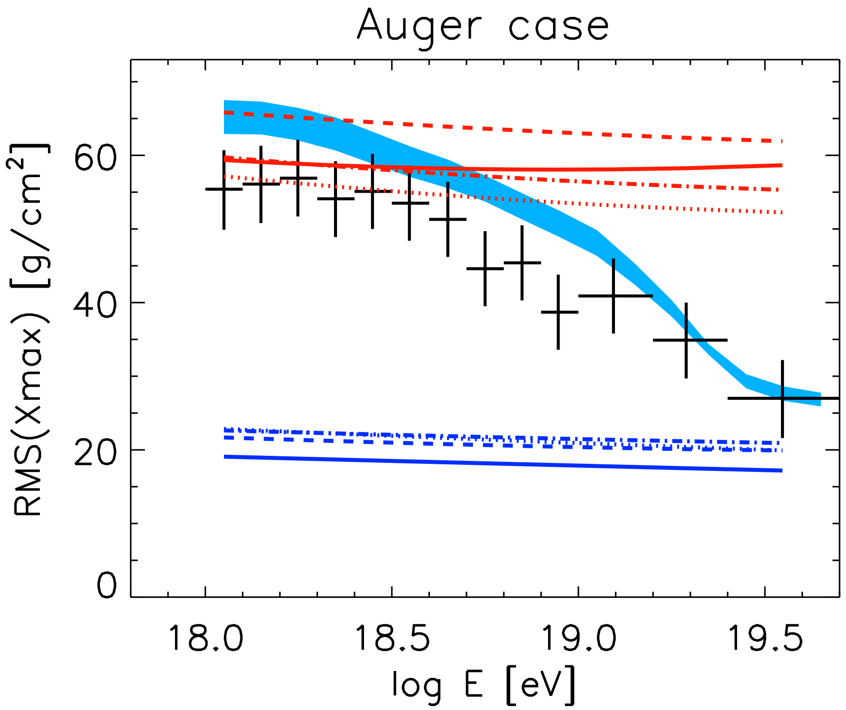
Galactic pulsars can fill the gap

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

Contribution from Galactic pulsars - Composition







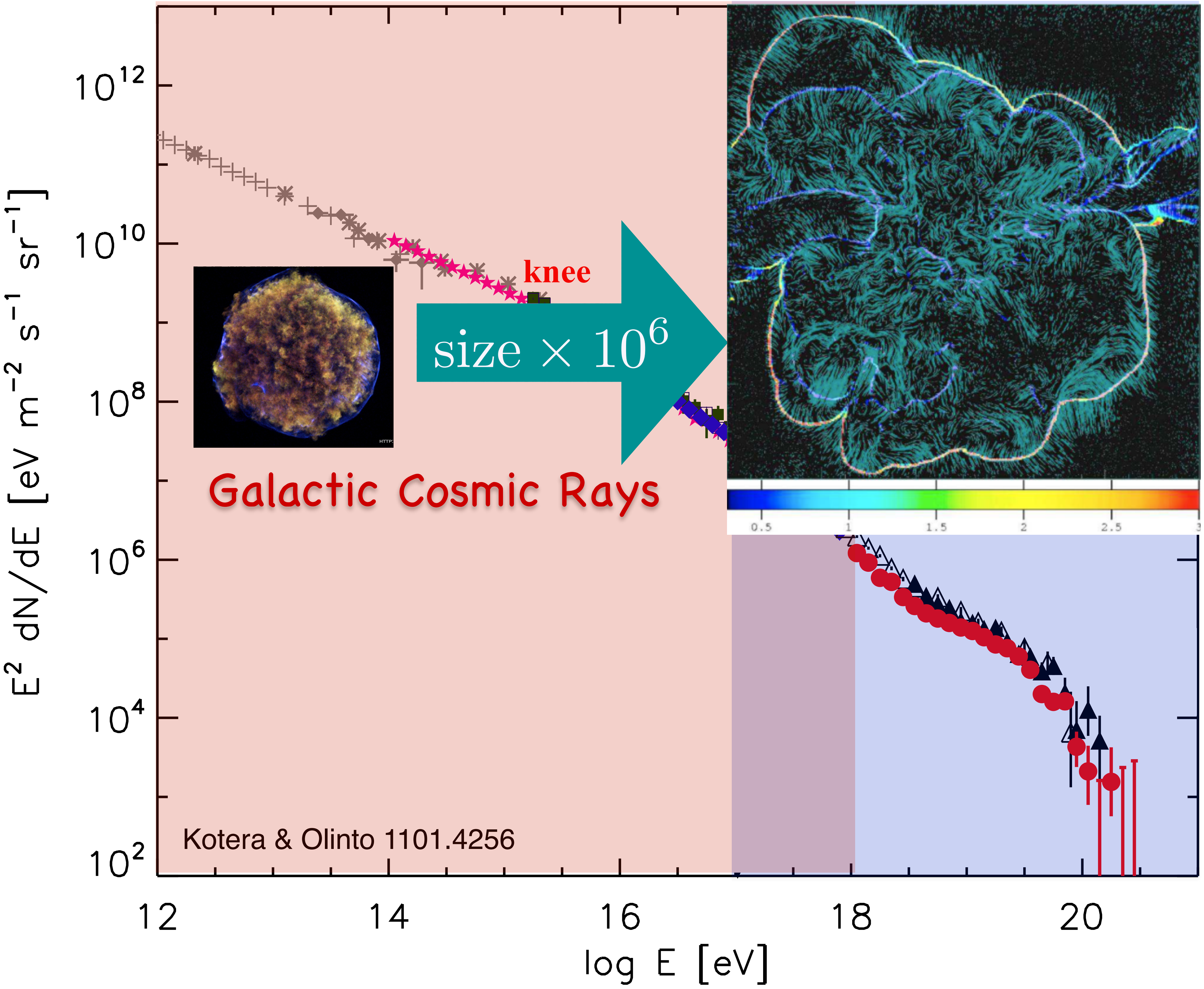
Galactic pulsars can contribute between the knee and the ankle!

- Unger, Farrar & Anchordoqui, 1505.02153
- Tilav, UHECR 2014, “Global View of Cosmic Ray Data”

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

galaxies of clusters

A Simple Scale-Up?



size × 10^6

Galactic Cosmic Rays

Kotera & Olinto 1101.4256

Cosmic Ray Acceleration

Keshet, Waxman, Loeb+ 2003
Inoue & Aharonian 2005
Murase, Inoue & Nagataki 2008
Kotera, Allard, Murase+ 2009

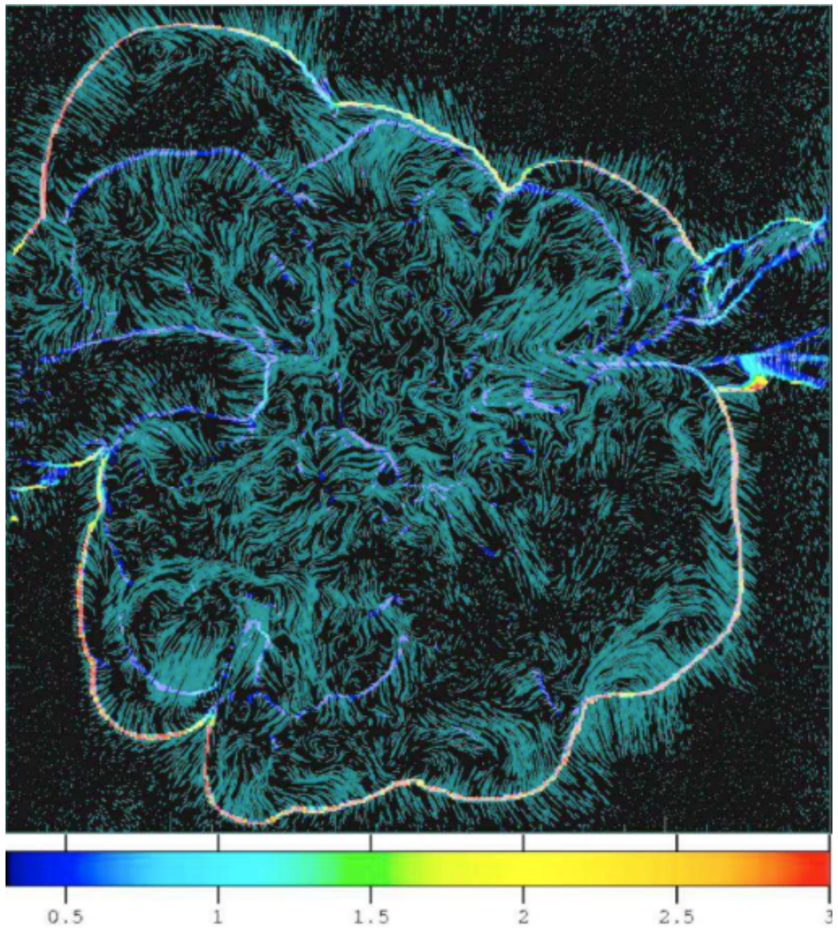
Diffusive Shock Acceleration

$$r_{\rm sh} \sim r_{\rm vir} = 3{\rm Mpc}\left(\frac{M}{10^{15}M_\odot}\right)^{1/3}$$

Cluster mass

$$E_{\rm max} = 3\times 10^{18}\, M_{15}^{2/3} Z \left(\frac{B}{1\mu{\rm G}}\right) {\rm eV}$$

Magnetic Field



Energy Budget

$$L_{\rm CR} = f_b f_{\rm CR} \frac{GM\dot{M}}{r_{\rm sh}} = 2\times 10^{44} M_{15}^{2} f_{{\rm CR},-2}\, {\rm erg\,s^{-1}}$$

channel fraction

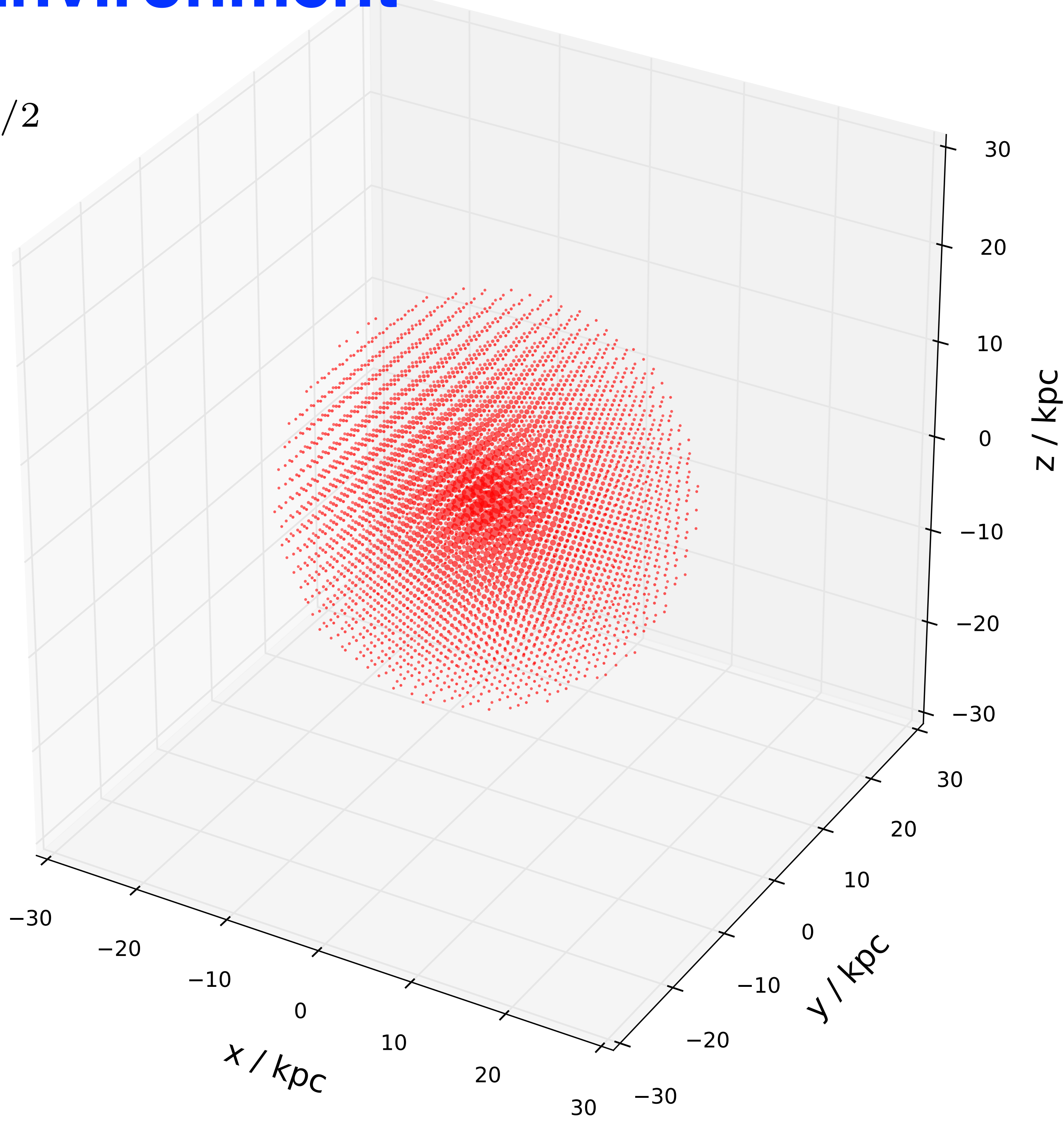
Cosmic ray injection spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-\alpha} \qquad \alpha \sim 2-2.5$$

Cluster Environment

$$n_{\mathrm{ICM}}(r) = n_{\mathrm{ICM},0}\,\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

$$B(M,r) \propto n(M,r)^{\eta}$$



Particle Larmor Radius

$$r_L = 1\,E_{18}\,B_{-6}^{-1}\,Z^{-1}\,\mathrm{kpc}$$

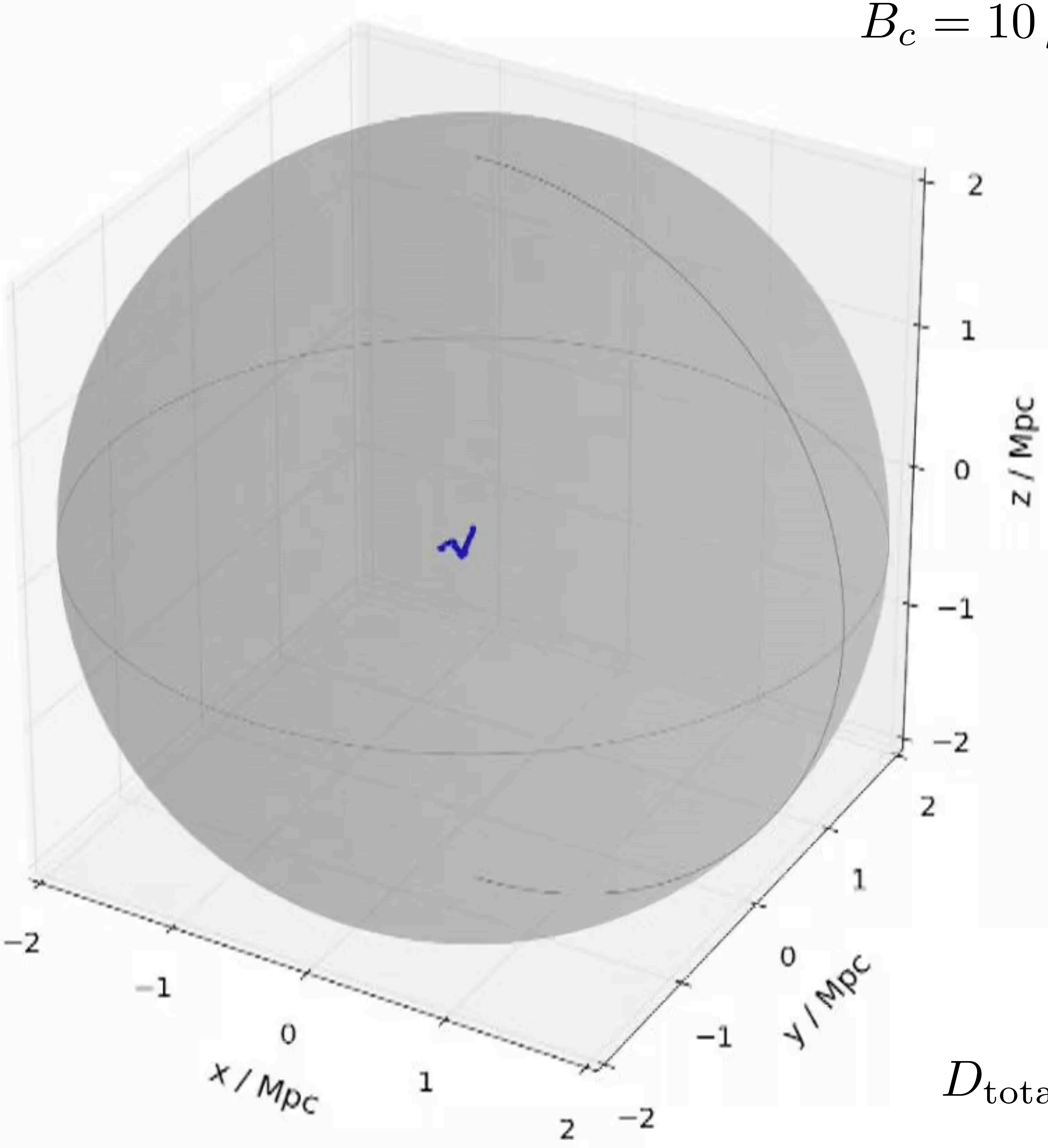
Coherence Length of B fields

$$l_0 \sim 0.1\,\mathrm{Mpc}$$

Cavaliere & Fusco-Femiano, A&A 49, 137 (1976)

Particle Trajectory - 10 EeV

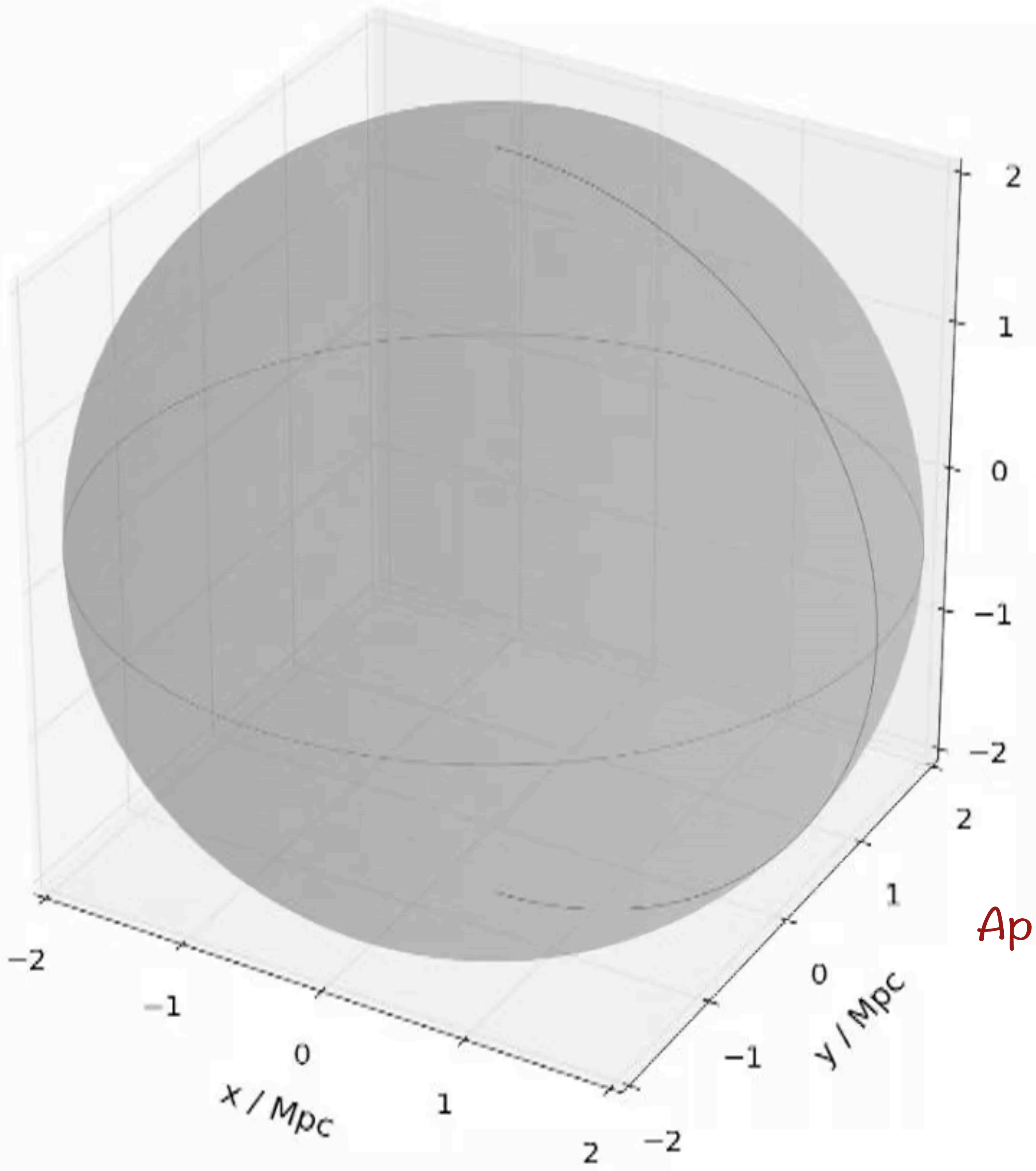
$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$

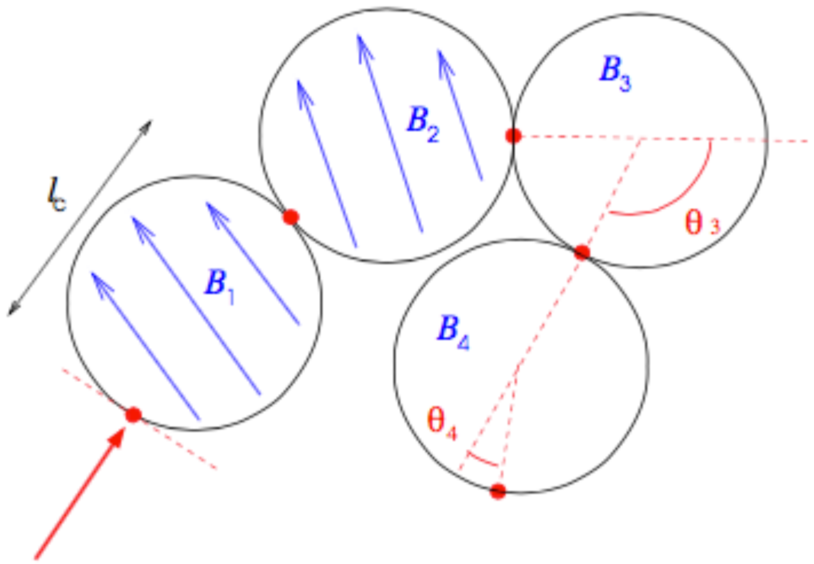


$D_{\rm total} = 46\,{\rm Mpc}$

Particle Trajectory - 0.1 EeV

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$





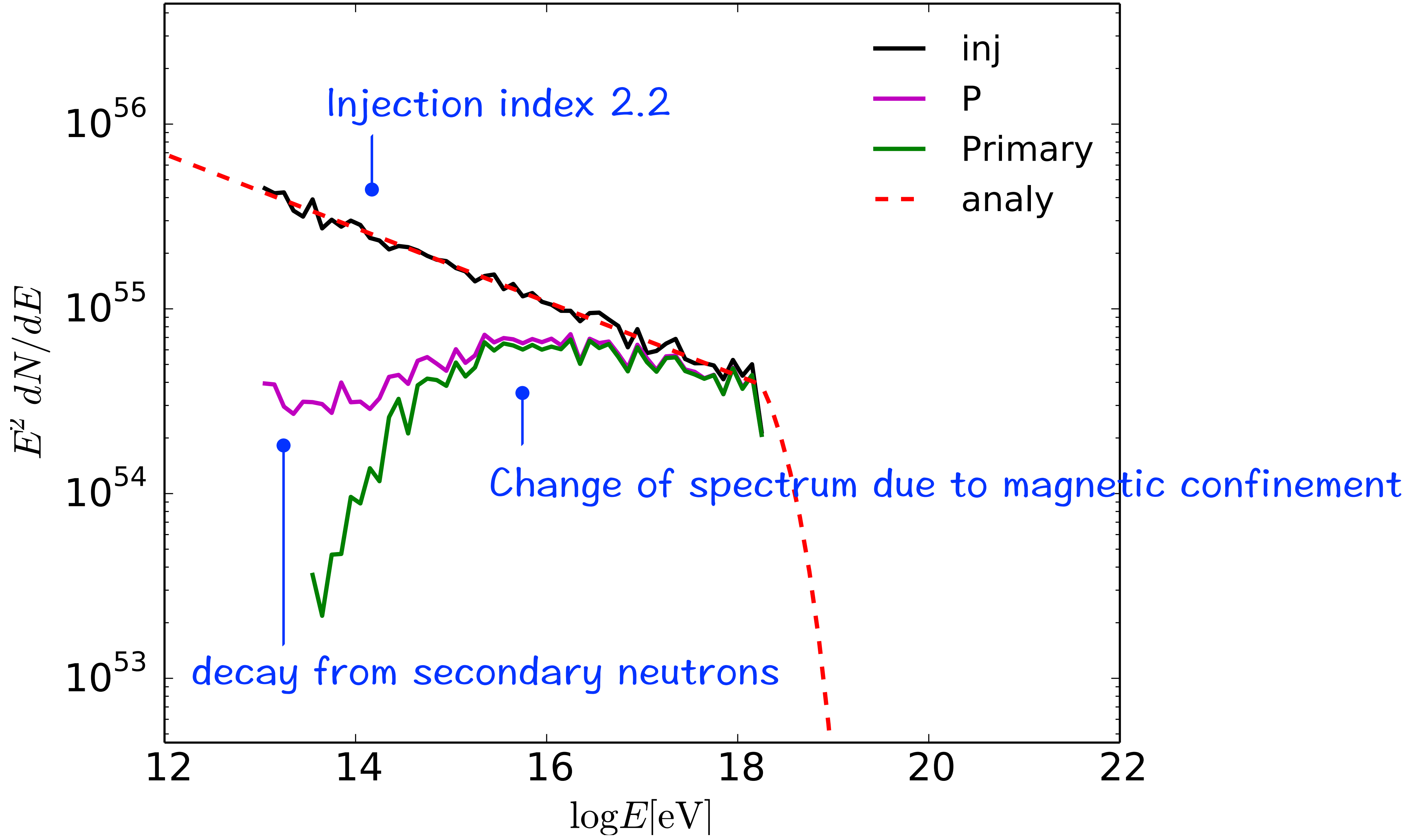
Kotera & Lemoine 0706.1891

Approximation for diffusion computation

$$D_{\text{total}} \sim t_{\text{Hubble}}$$

Cosmic Ray Flux from One Single Cluster

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$



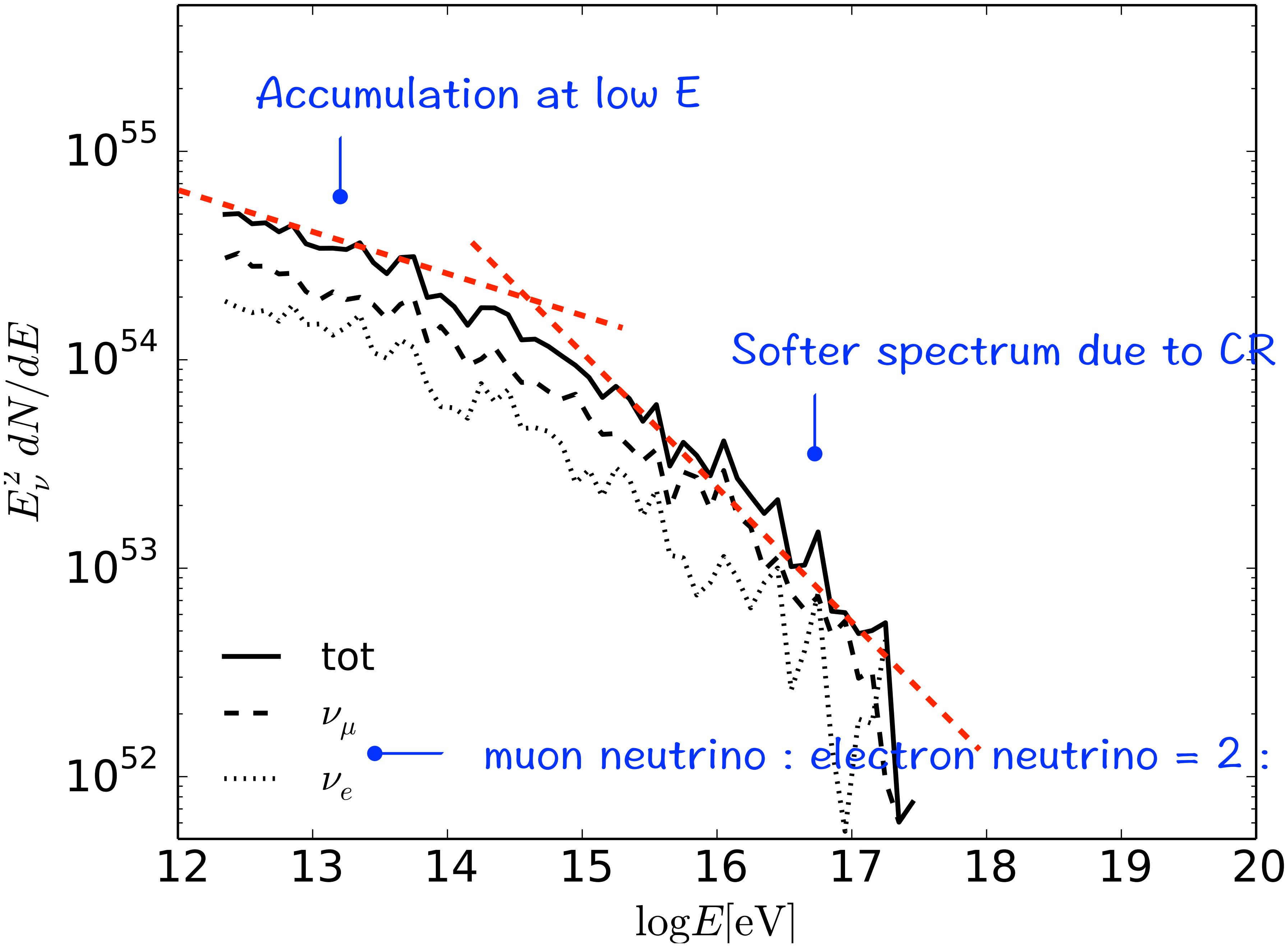
Injection index 2.2

Change of spectrum due to magnetic confinement

decay from secondary neutrons

Neutrino Flux from One Single Cluster

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$



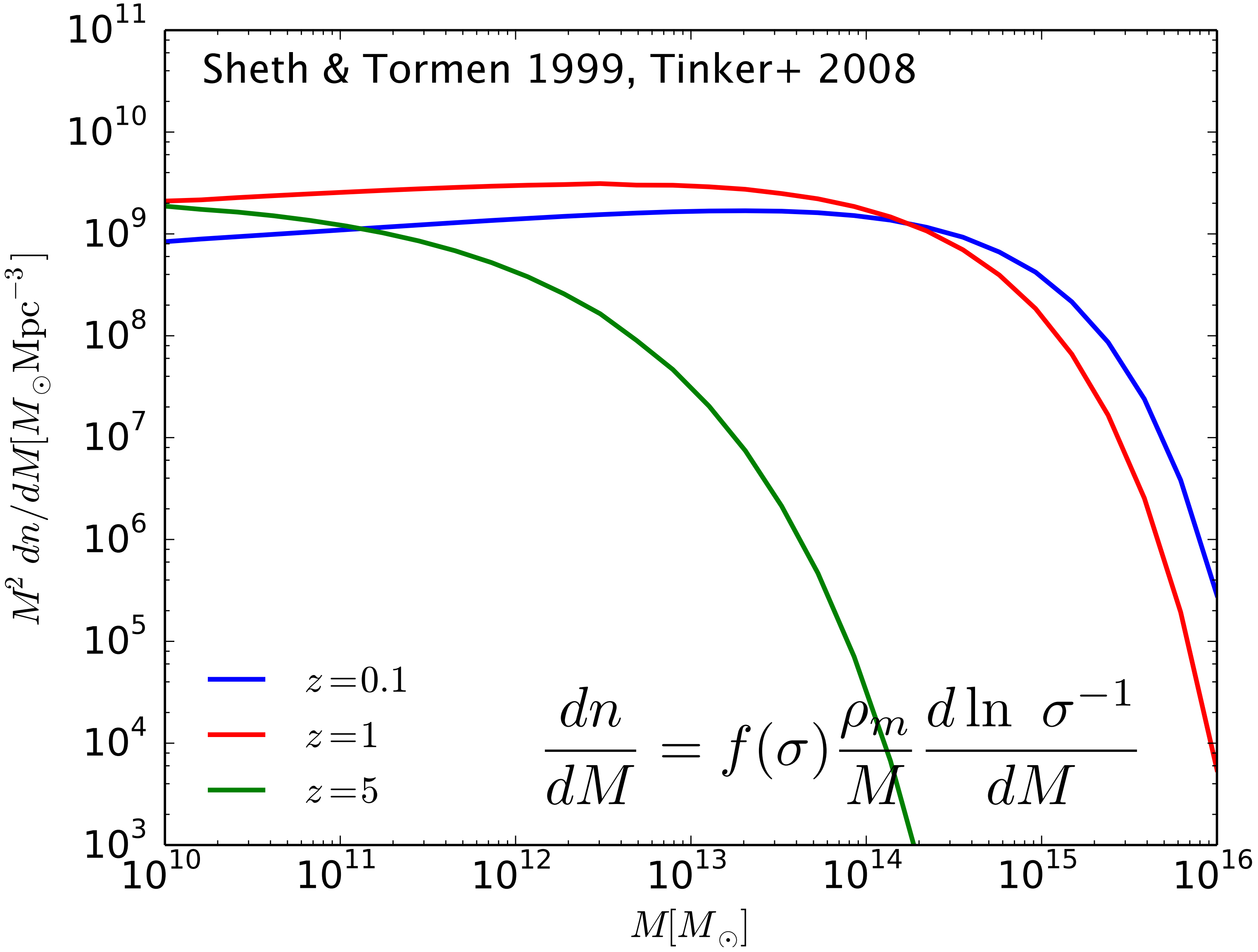
Accumulation at low E

Softer spectrum due to CR escape

muon neutrino : electron neutrino = 2 : 1

Integrated Cluster Contribution

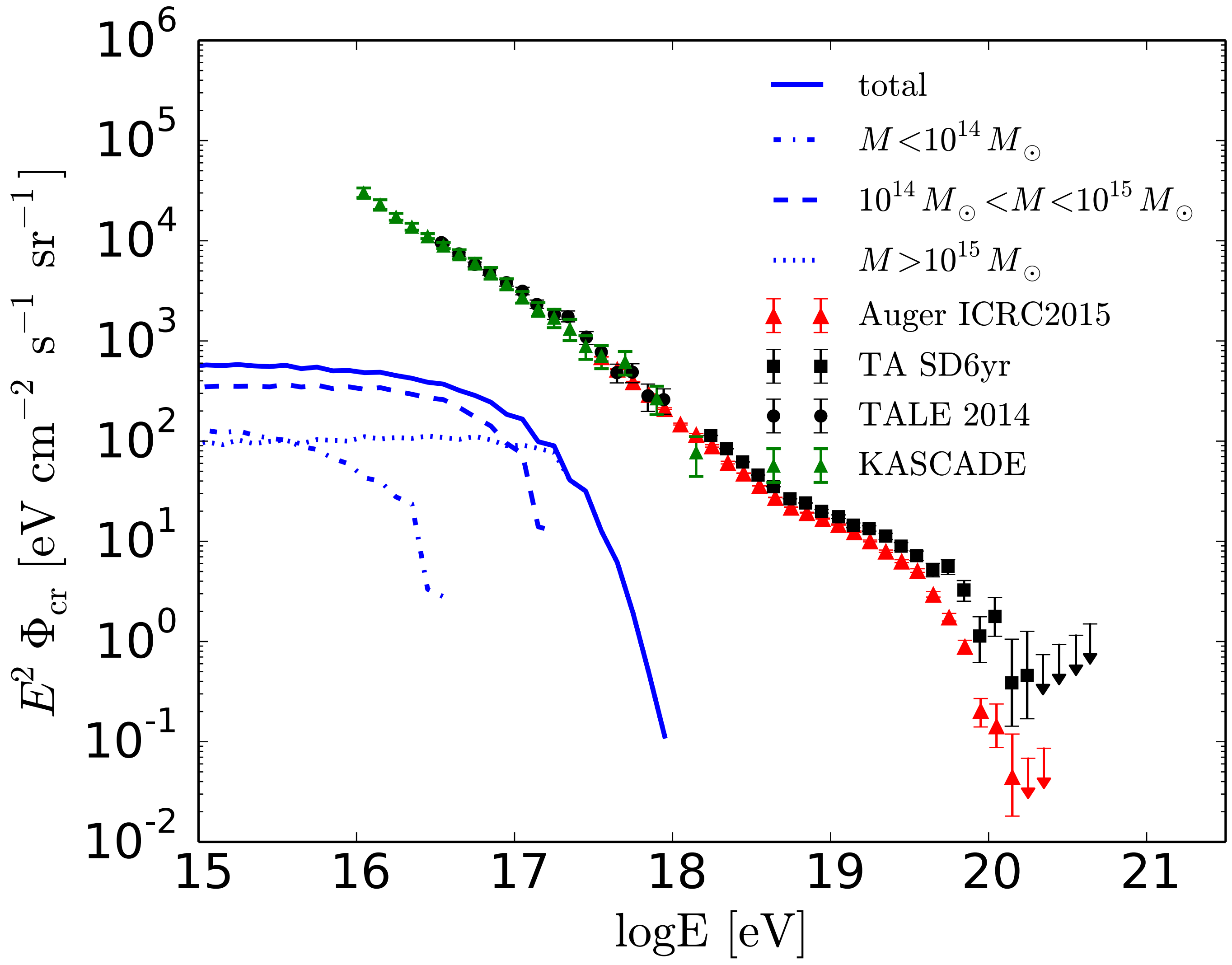
$$E_\nu^2 \Phi_\nu(E_\nu) = \int dM \, \frac{dn}{dM} \, \frac{(1+z)^2 L_\nu(M,z)}{4\pi d_L^2}$$



$$\frac{dn}{dM} = f(\sigma) \frac{\rho_m}{M} \frac{d \ln\ \sigma^{-1}}{dM}$$

The Integrated Cosmic Ray Flux from Clusters

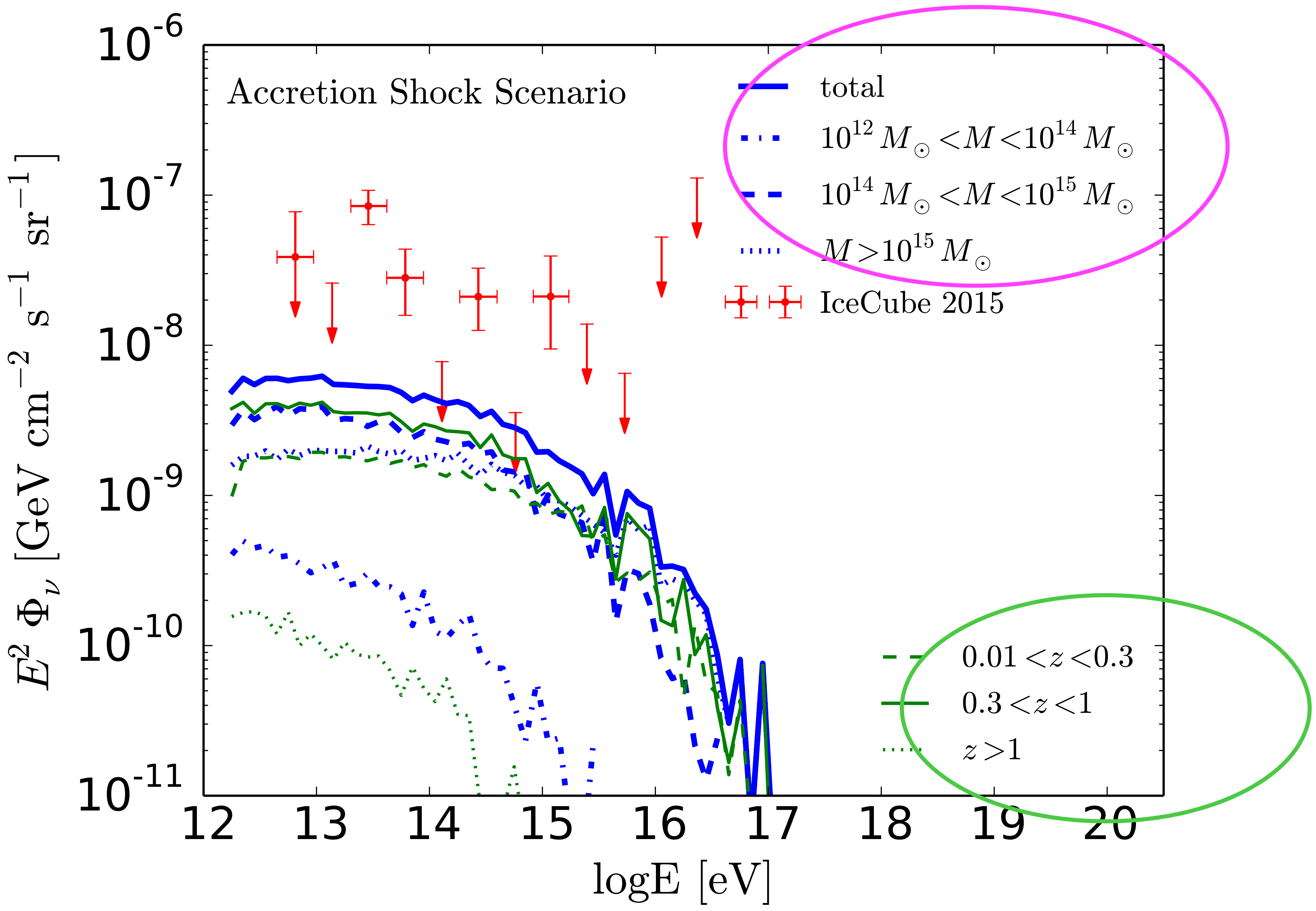
$B_c = 3\,\mu G, f_{\rm CR} = 1\%$



Flux of cosmic ray protons from cluster shocks can partially contribute to second knee

Neutrinos from Accretion Shocks

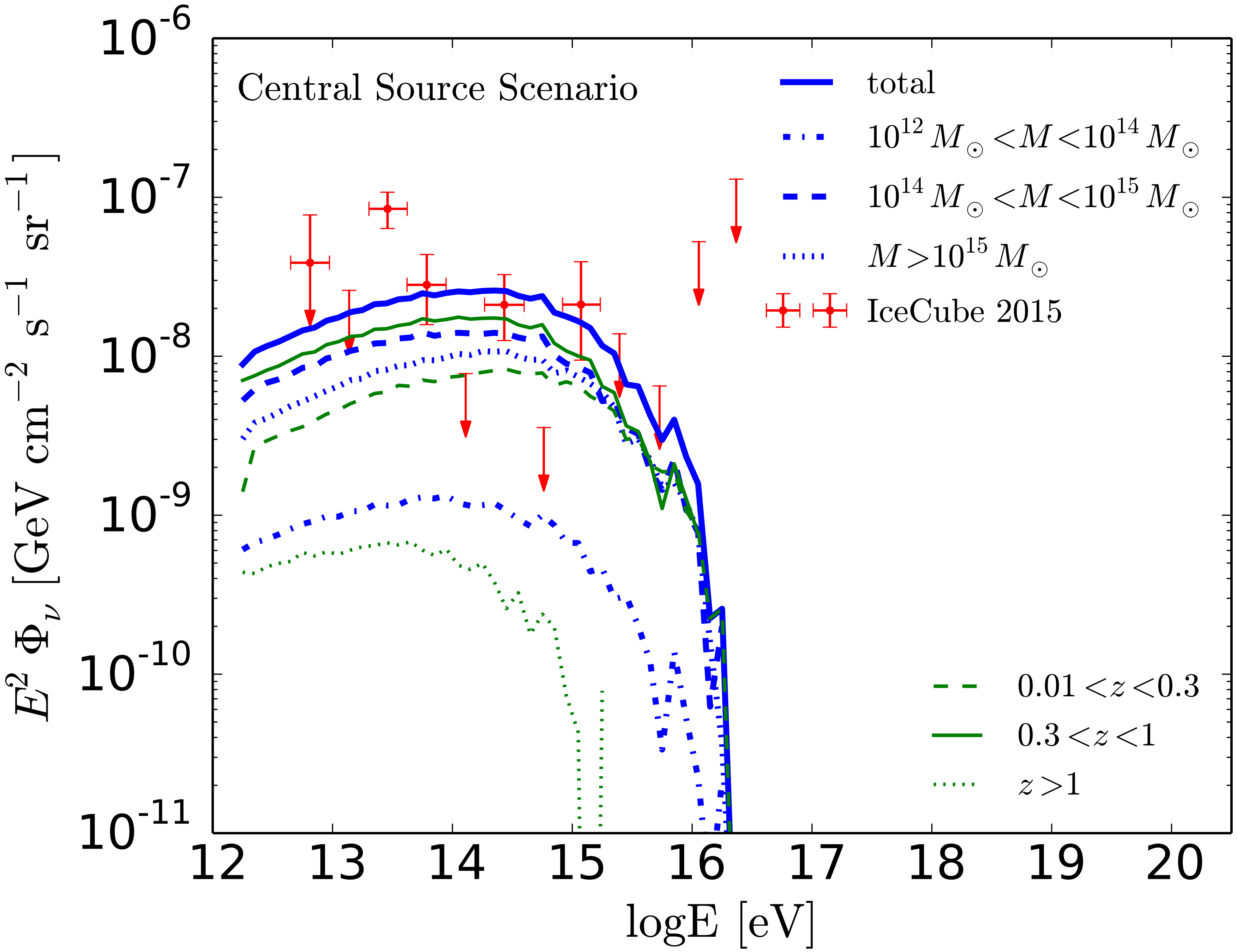
$B_c = 3\,\mu G, f_{\rm CR} = 1\%$



Cluster accretion shocks can contribution <20% IceCube flux

Neutrinos from Sources Inside Clusters

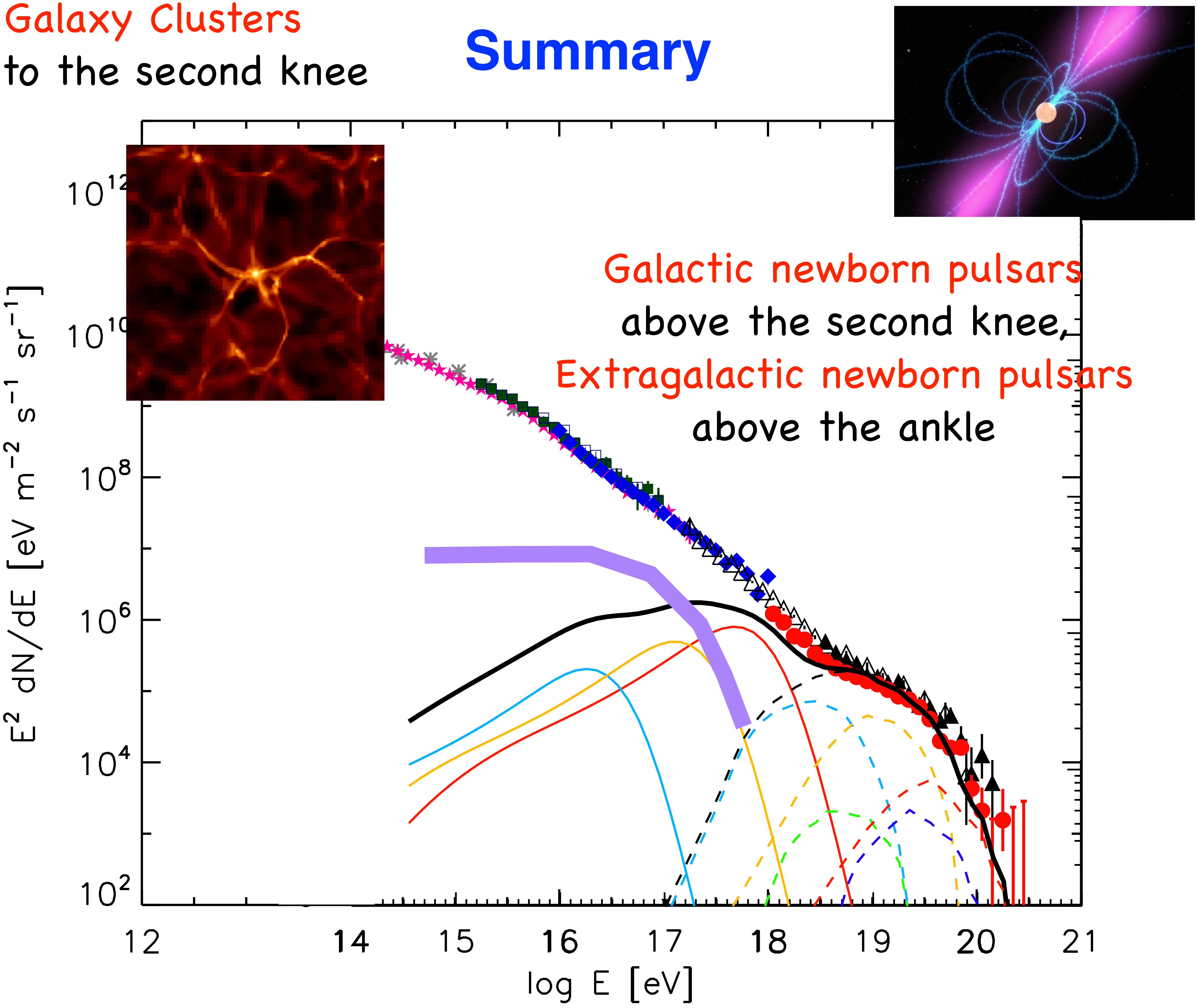
$B_c = 3\,\mu G, f_{\rm CR} = 1\%$



Assuming a hard injection (<2), the neutrino flux from the sources hosted by clusters can explain IceCube data above 30 TeV.

Summary

Galaxy Clusters
up to the second knee



Galactic newborn pulsars
above the second knee,
Extragalactic newborn pulsars
above the ankle