Propagation mechanisms of cosmic rays

Yutaka Ohira (The University of Tokyo)

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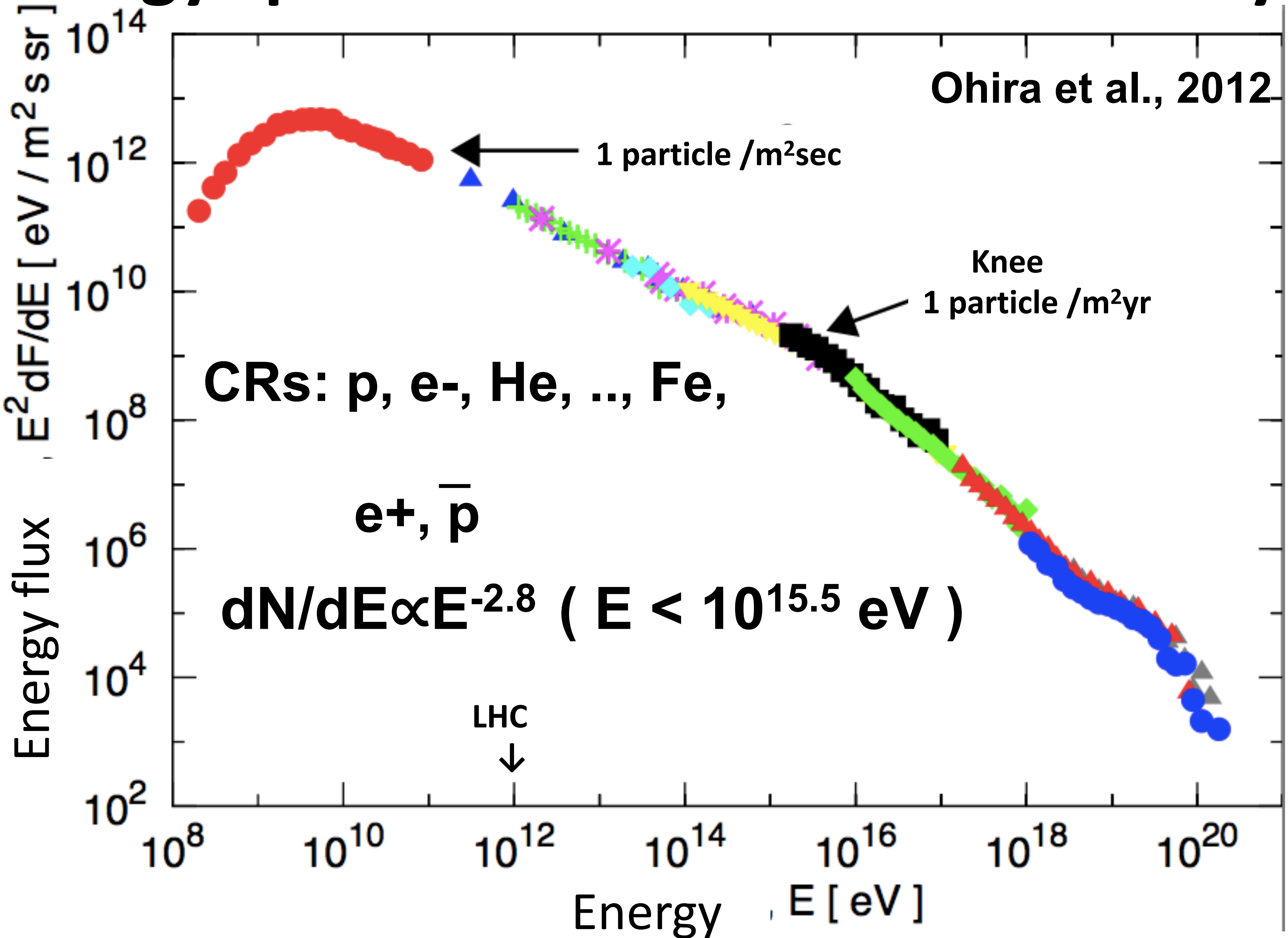
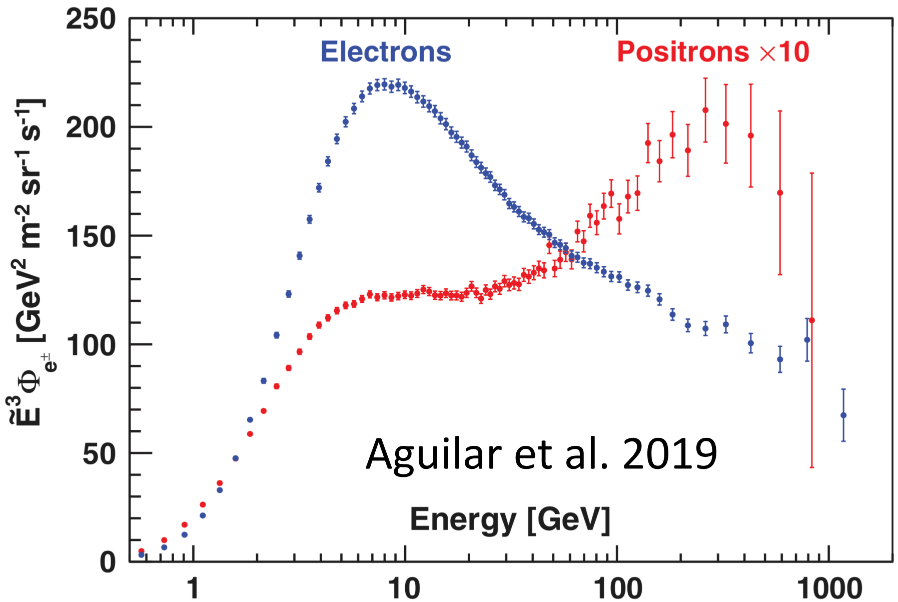
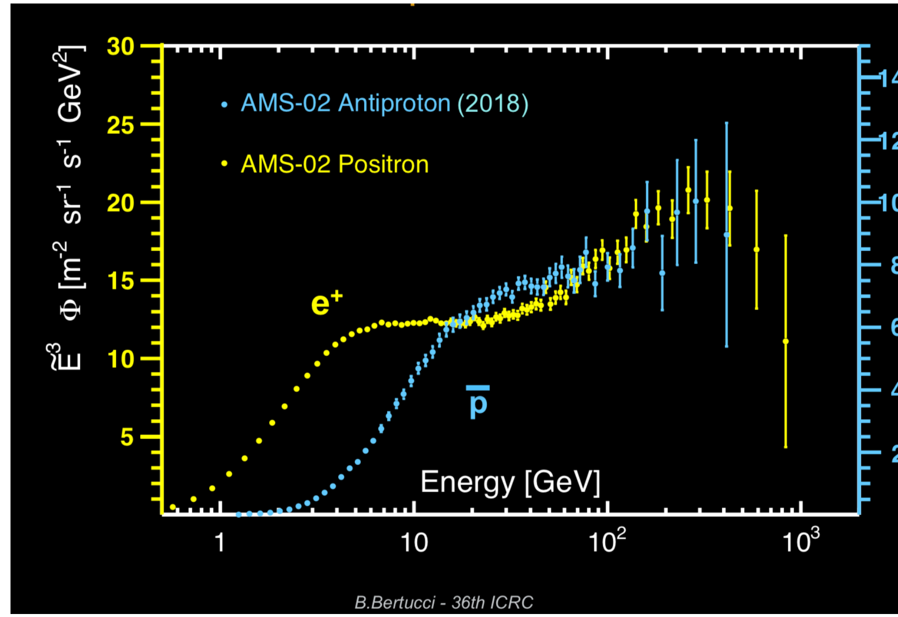
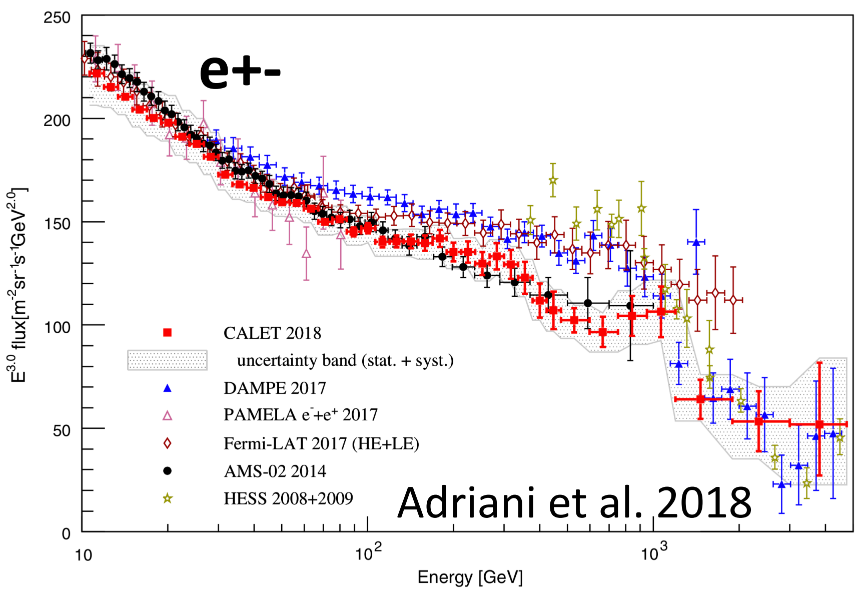
Energy spectrum of hadronic cosmic rays



Energy spectra of CR e^-, e^+, $\bar{p}$







What is the origins of CR e^+ and $\bar{p}$?

Dark matter origin?

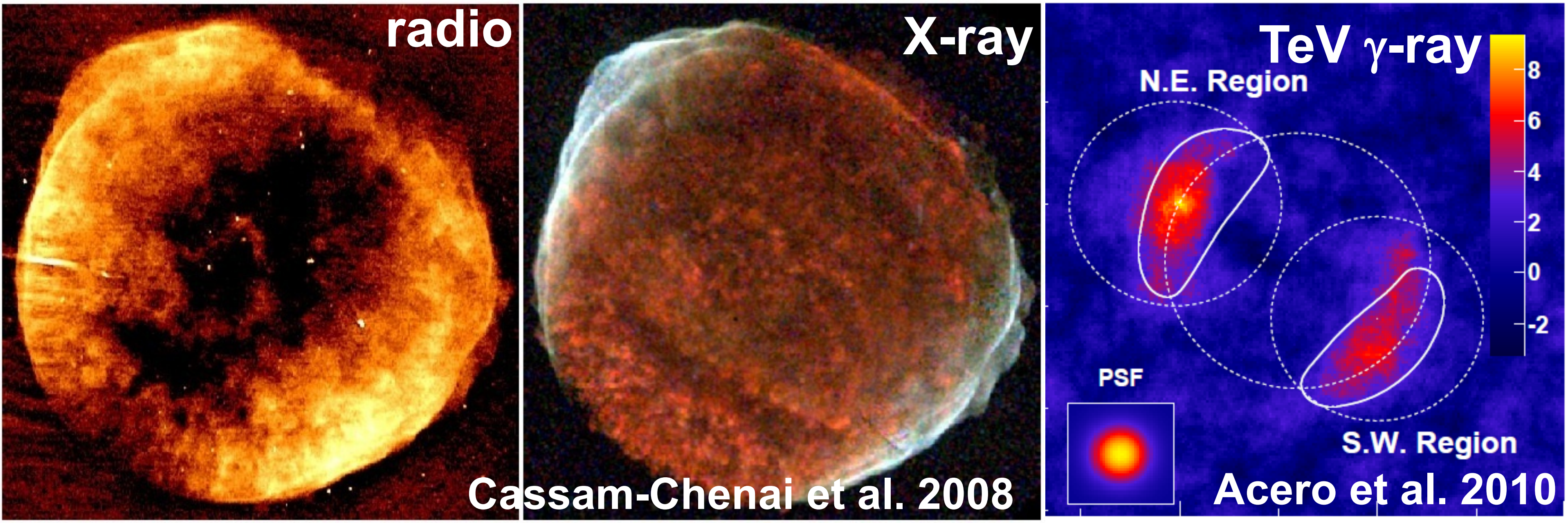
Astrophysical origins?

Pulsar wind nebulae?

Supernova remnants?

SuperNova Remnant (SNR)

SNRs are remnants of explosions of a star. E_{SN}~10^{51}erg, rate ~ 1/30yr



Size

R ~ 10^{18} – 10^{20} cm

Expansion velocity

v/c ~ 10^{-2} – 10^{-3}

Radio synchrotron ~ 300 SNRs

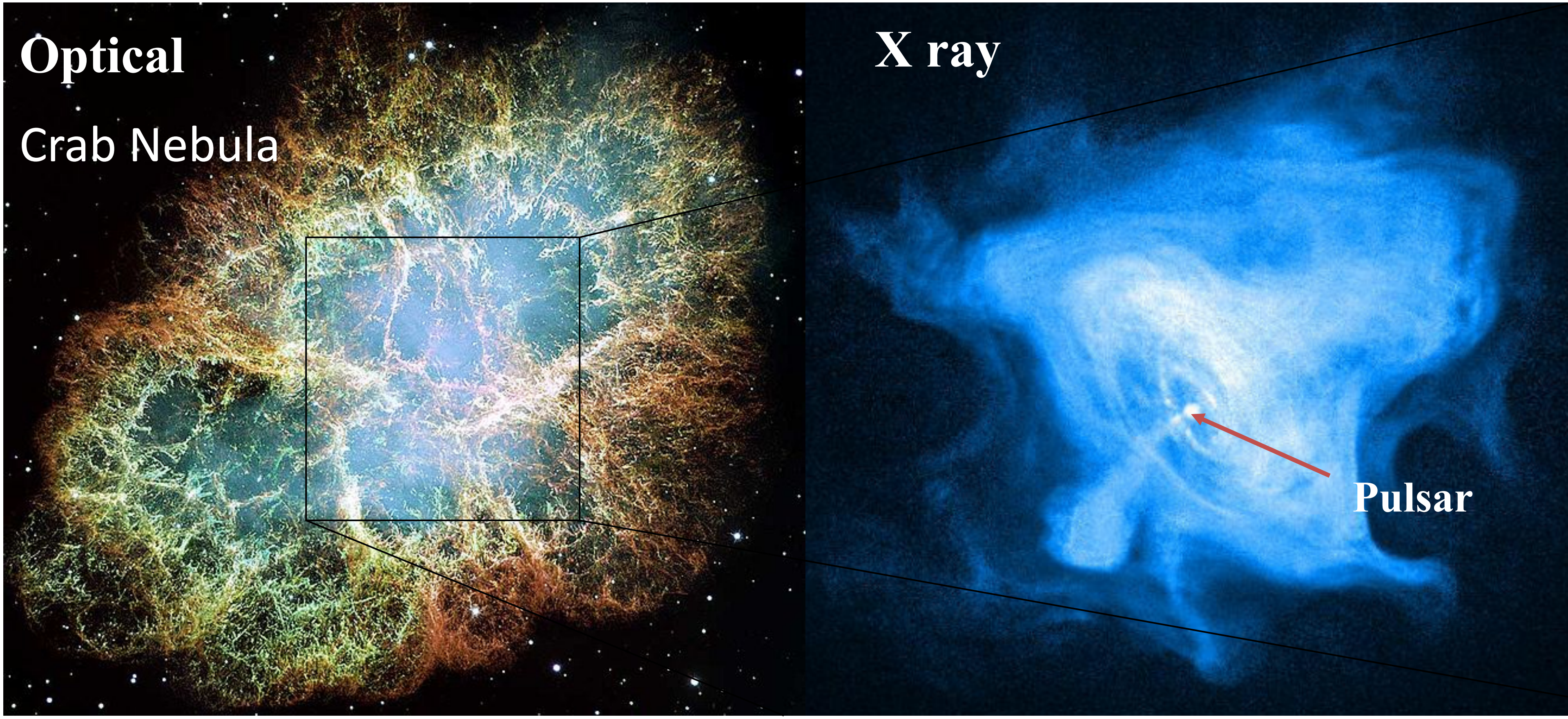
X ray synchrotron ~ 10 SNRs

GeV γ ray ~ 30 SNRs

TeV γ ray ~ 10 SNRs

SNRs can make high energy e^+ thanks to decay of π^+, ^{56}Ni, ^{44}Ti, …

Pulsar Wind Nebula (PWN)



$2pc \sim 6\times10^{18}$ cm

Spinning magnetized neutron stars generate high energy e+- plasmas.

Most core-collapse SNRs are expected to have a PWN (Watters & Romani 2012)

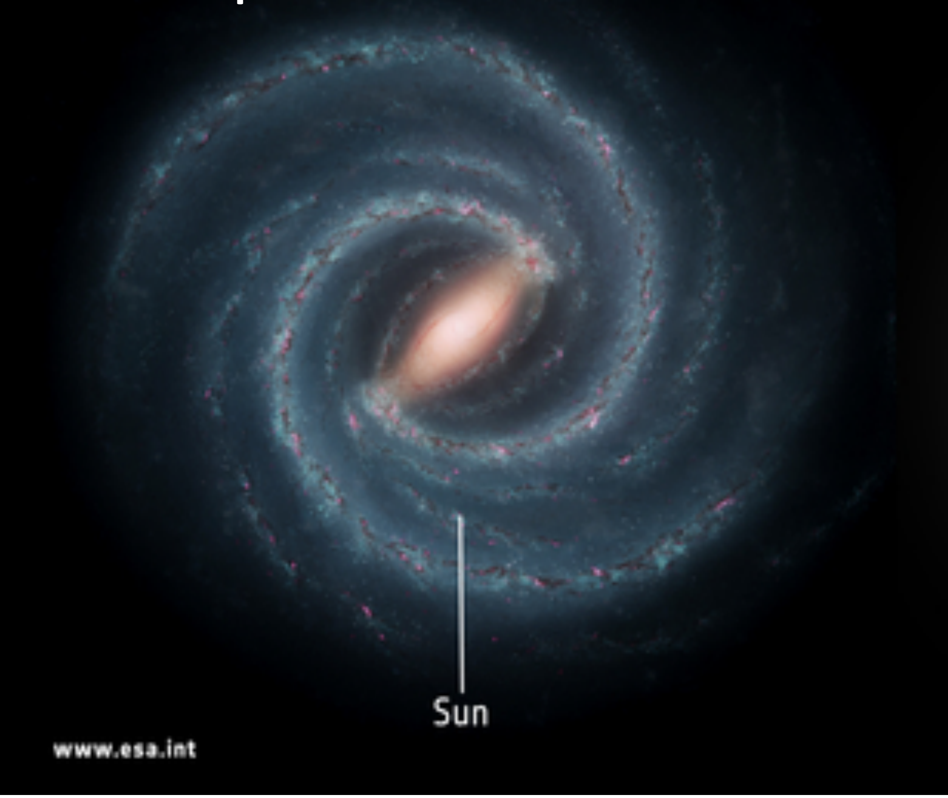
CR propagation in our Galaxy

Mass ~ 10^{12} M_{sun} ~ 10^{45} g (M_{DM} : M_{gas} : M_{star} ~ 84 : 12 : 4)

Radius ~ 20 kpc ~ 6 x 10^{22} cm   Thickness of gas ~ 0.2 kpc << Radius

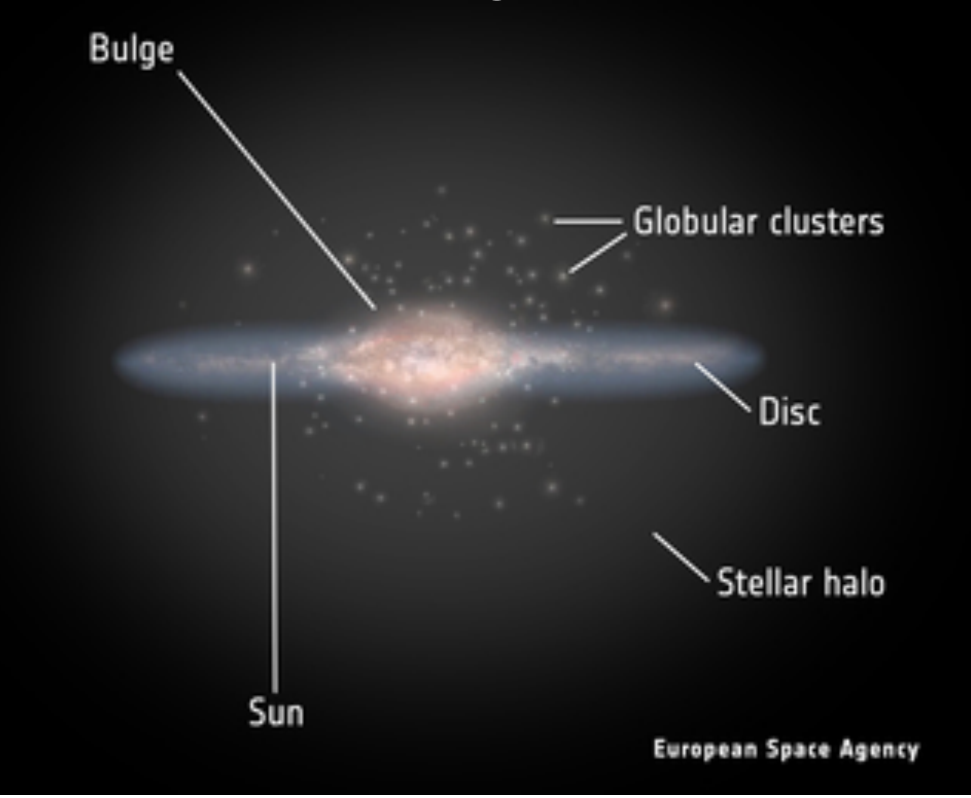
Face-on view of the Milky way

Spiral structure + a bar



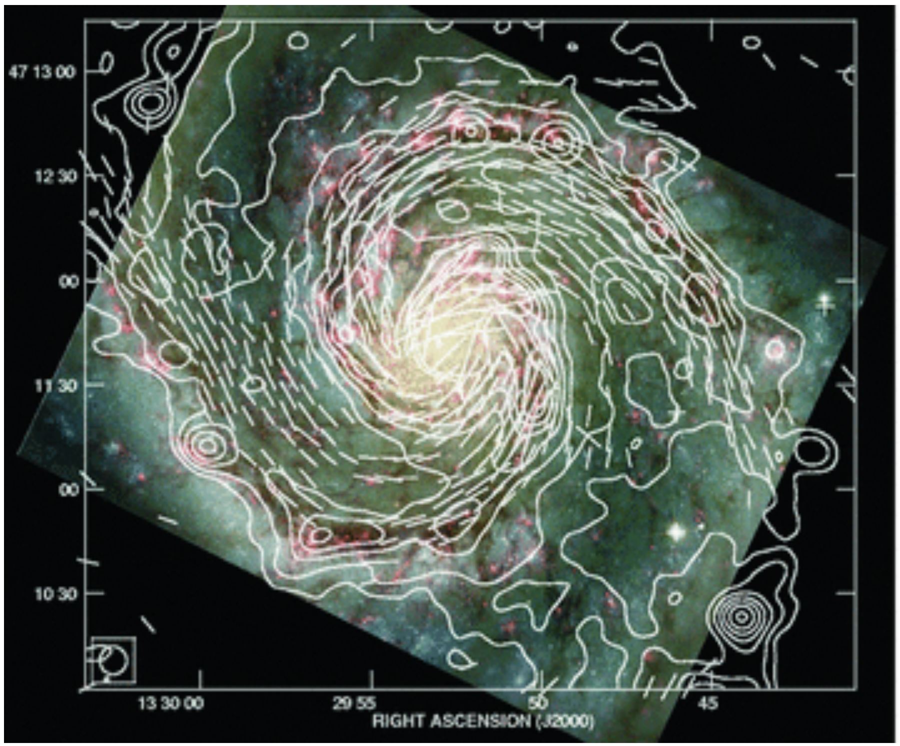
Edge-on view of the Milky way

Disc + bulge + halo



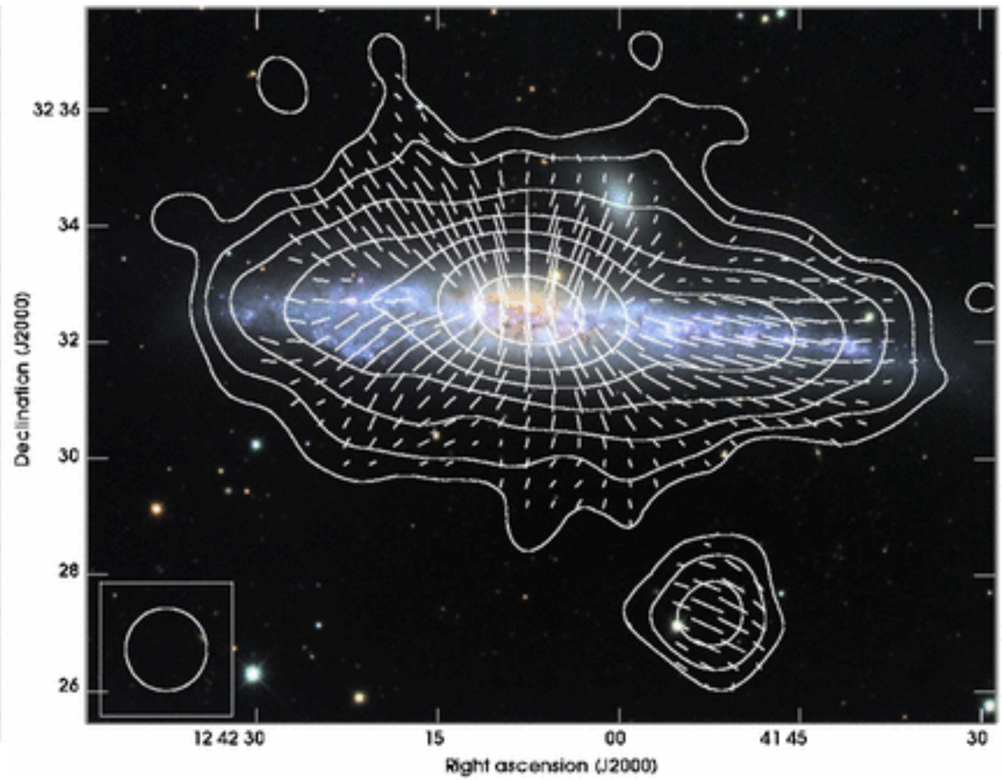
Magnetic field in galaxies

M51 (face-on view)



Fletcher et al. 2011

NGC 4631 (edge-on view)



Mora & Krause 2013

The lines show magnetic field orientation integrated over a line of sight.

Motion of CRs in our Galaxy

Uniform B field → spiral orbit → CRs are bounded in a magnetic field line.

Turbulent B field → complex orbit

→ For $L \gg l_{mfp}$, CR motions are diffusive.

$\langle(\Delta x)^2\rangle \sim D_{xx}\, t$, $D_{xx} \sim v l_{mfp}/3$, $l_{mfp} = (B_0/\delta B_{\lambda=rg})^2\, r_g$

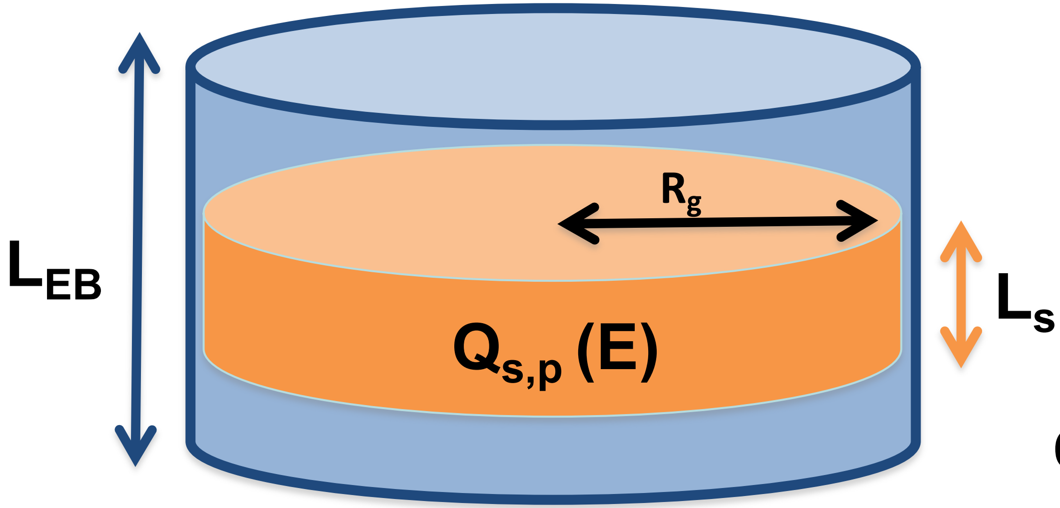
$r_g = cP/eB \propto E$, $\delta B_{\lambda=rg} = \delta B_{\lambda=rg}(E)$ → $D_{xx} \propto E^{\delta}$ $(\delta>0)$

Diffusion time, $t_{diff} \sim L^2/D_{xx} \propto E^{-\delta}$

Diffusion length, $R_{diff} \sim (D_{xx} t)^{0.5} \propto E^{0.5\delta}$

Galactic diffusion of primary CR nuclei

After escaping from SNRs, CRs propagate into our Galaxy.



L_s: size of the source region

L_{EB}: size of the diffusion region

R_g: radius of our galaxy

$Q_{s,p}$: injection rate density of primary CRs

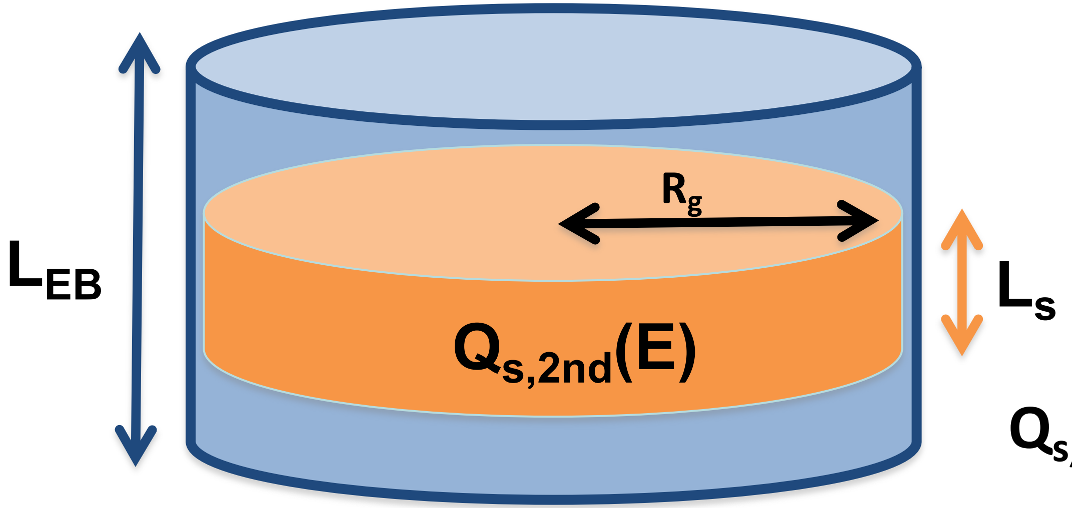
Once CRs reach the escape boundary, the CRs never go back.

$$t_{esc}(E) = L_{EB}^2 / D_{xx}(E) \qquad D_{xx}(E) \propto E^{\delta},\ Q_{s,p}(E) \propto E^{-s}$$

$$\frac{dn_{p,CRn}}{dE} = \frac{\text{Total Number}(E)}{\text{Volume}} = \frac{t_{esc}(E)\, Q_{s,p}(E)\, L_s\, \pi R_{galaxy}^2}{L_{EB}\, \pi R_{galaxy}^2} \propto E^{-(s+\delta)}$$

Galactic diffusion of secondary CRs nuclei

During propagation, primary CRs generate secondary CRs.



L_s: size of the source region

L_{EB}: size of the diffusion region

R_g: radius of our galaxy

$Q_{s,2nd}$: injection rate density of secondary CRs

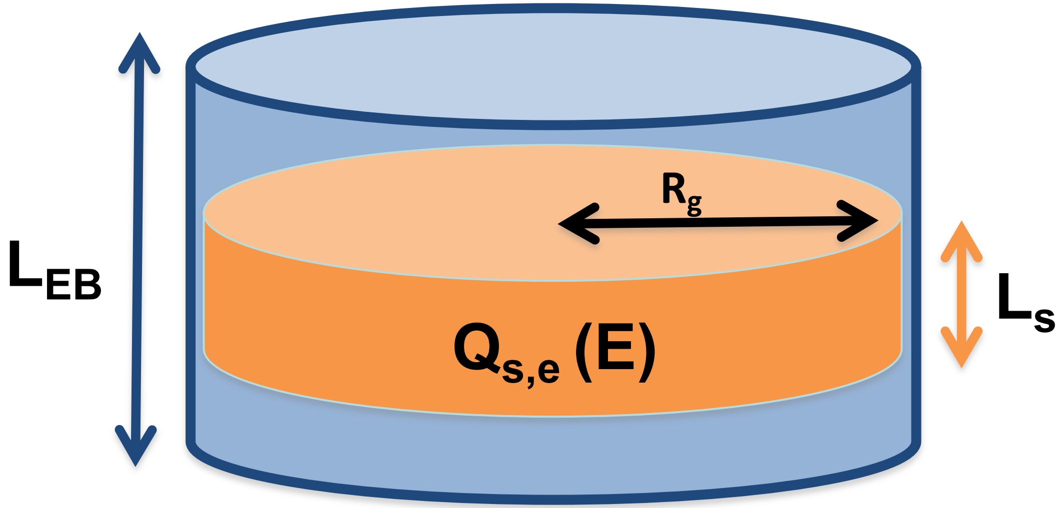
The source spectrum of secondary CRs is proportional to $dn_{p,CRn}/dE$.

$t_{esc}(E) = L_{EB}^2 / D_{xx}(E)$, $D_{xx}(E) \propto E^{\delta}$, $Q_{s,2nd}(E) \propto dn_{p,CRn}/dE \propto E^{-(s+\delta)}$

$$\frac{dn_{2nd,CRn}}{dE} = \frac{\text{Total Number}(E)}{\text{Volume}} = \frac{t_{esc}(E)\, Q_{s,2nd}(E)\, L_s\, \pi R_{galaxy}^2}{L_{esc}\, \pi R_{galaxy}^2} \propto E^{-(s+2\delta)}$$

Galactic diffusion of primary CR e-

CR e- lose their energy before escaping from our galaxy.



L_s: size of the source region

L_{EB}: size of the diffusion region

R_g: radius of our galaxy

$Q_{s,e}$: injection rate density of primary CRs e^-

$\lambda_{d,cool}$:propagation length during the cooling time

$$\lambda_{d,cool}(E) = (4D_{xx}t_{cool})^{1/2} \propto E^{(\delta-1)/2} \quad , \; t_{cool}(E) = 6\text{x}10^5 \text{ yr } (E/1\text{TeV})^{-1}$$

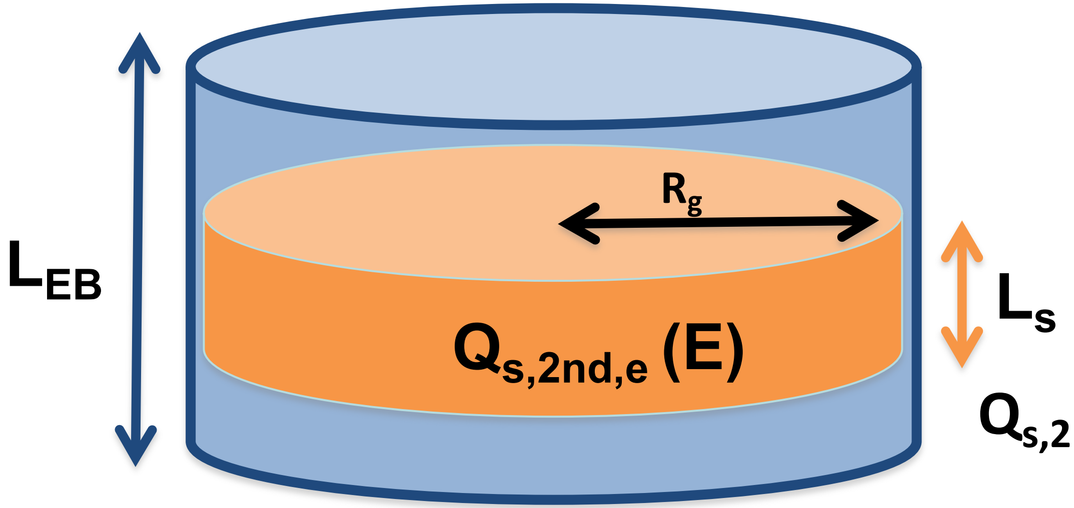
$D_{xx}(E) \propto E^{\delta}$, $Q_{s,e}(E) \propto E^{-s}$

For CR e- (1GeV<E<10TeV), $L_s < \lambda_{d,cool} < L_{EB}$,

$$\frac{dn_{p,CRe}}{dE} = \frac{\text{Total Number(E)}}{\text{Volume(E)}} = \frac{t_{cool}(E)\, Q_{s,e}(E)\, L_s\, \pi R_{galaxy}^2}{\lambda_{d,cool}(E)\, \pi R_{galaxy}^2} \propto E^{-\{s+(1+\delta)/2\}}$$

Galactic diffusion of secondary CR e-

CR e- loses their energy before escaping from our galaxy.



L_s: size of the source region

L_{EB}: size of the diffusion region

R_g: radius of our galaxy

$Q_{s,2nd,e}$: injection rate density of secondary CRs e^-

$\lambda_{d,cool}$:propagation length during the cooling time

$$\lambda_{d,cool}(E) = (4D_{xx}t_{cool})^{1/2} \propto E^{(\delta-1)/2}\,,\ t_{cool}(E) = 6\mathrm{x}10^5\ \mathrm{yr}\ (E/1\mathrm{TeV})^{-1}$$

$$D_{xx}(E) \propto E^{\delta},\ Q_{s,2nd,e}(E) \propto E^{-(s+\delta)}$$

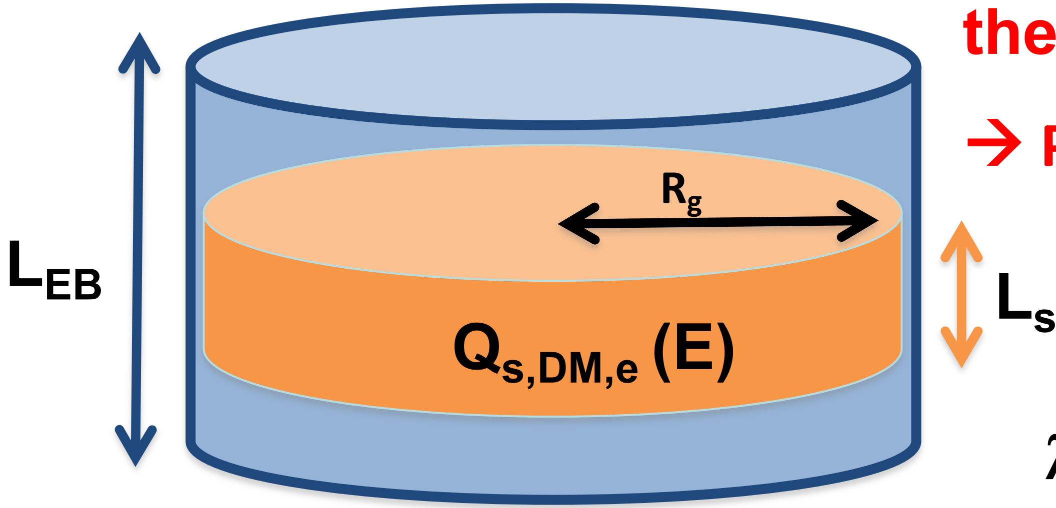
For CR e- (1GeV<E<10TeV), $L_s < \lambda_{d,cool} < L_{EB}$,

$$\frac{dn_{2nd,CRe}}{dE} = \frac{\mathrm{Total\ Number}(E)}{\mathrm{Volume}(E)} = \frac{t_{cool}(E)\,Q_{s,2nd,e}(E)\,L_s\,\pi R_{galaxy}^2}{\lambda_{d,cool}(E)\,\pi R_{galaxy}^2} \propto E^{-\{s+(1+3\delta)/2\}}$$

Galactic diffusion of e+- from DM

e+- from DM loses their energy before escaping from the source region ($L_s > \lambda_{d,cool}$).

→ Propagation is not important.



L_s: size of the source region

$Q_{s,DM,e}$: source of e+- from DM

$\lambda_{d,cool}$:propagation length during the cooling time

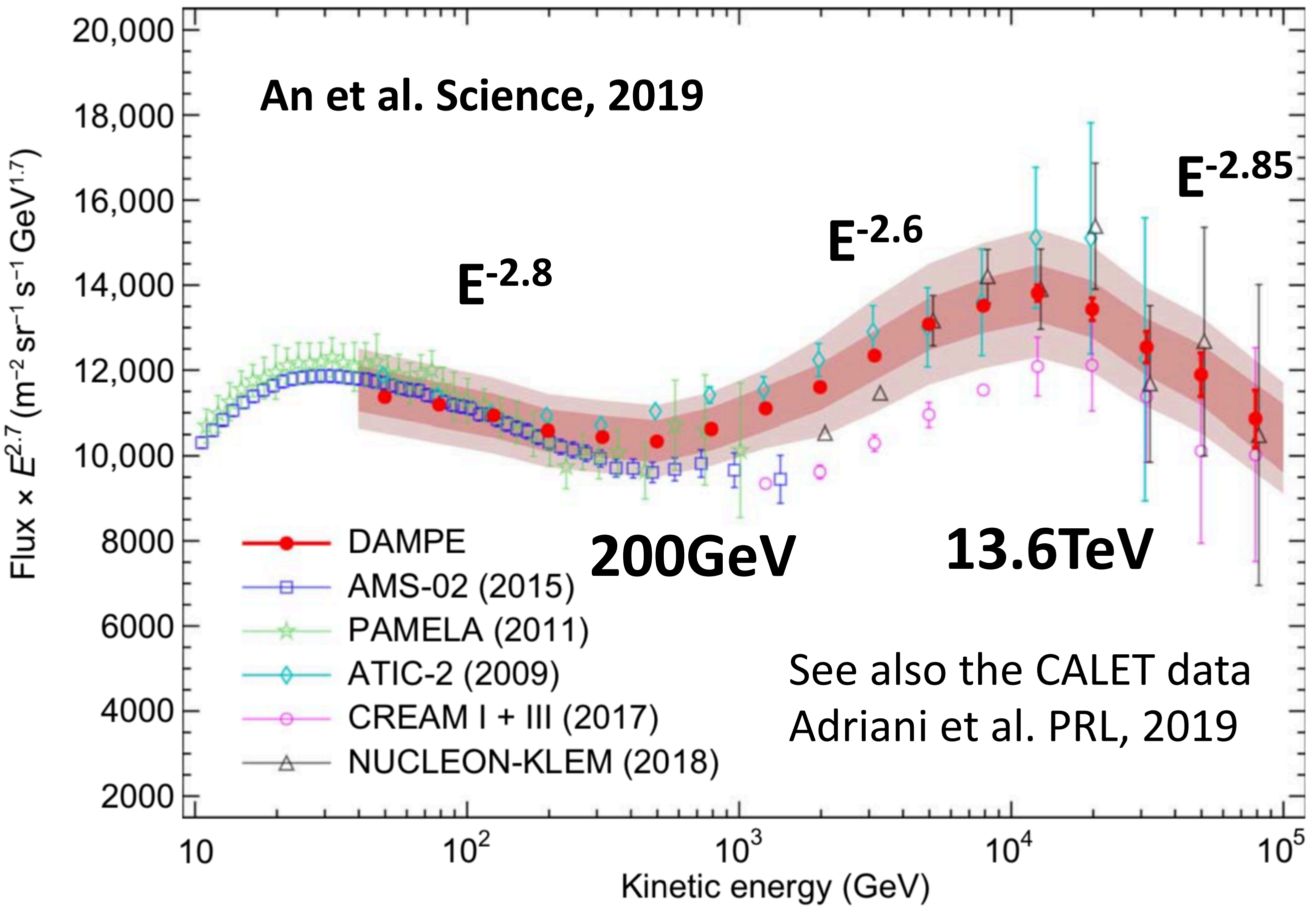
If $Q_{s,DM,e}(E)$ is a continuum spectrum,

$$\frac{dn_{DM,CRe}}{dE} = \frac{\text{Total Number}(E)}{\text{Volume}} = \frac{t_{cool}(E)\, Q_{s,DM,e}(E)\, L_s\, \pi R_{galaxy}^2}{L_s\, \pi R_{galaxy}^2} \propto Q_{s,DM,e}(E) E^{-1}$$

If $Q_{s,DM,e}(E)$ has a low energy cutoff, E_c, the e- spectrum below E_c is

$$\frac{d}{dE}\left(\frac{E}{t_{cool}(E)} n_{DM,CRe}\right) = 0 \rightarrow \frac{dn_{DM,CRe}}{dE} \propto E^{-2}$$

Primary CR spectrum (Proton)



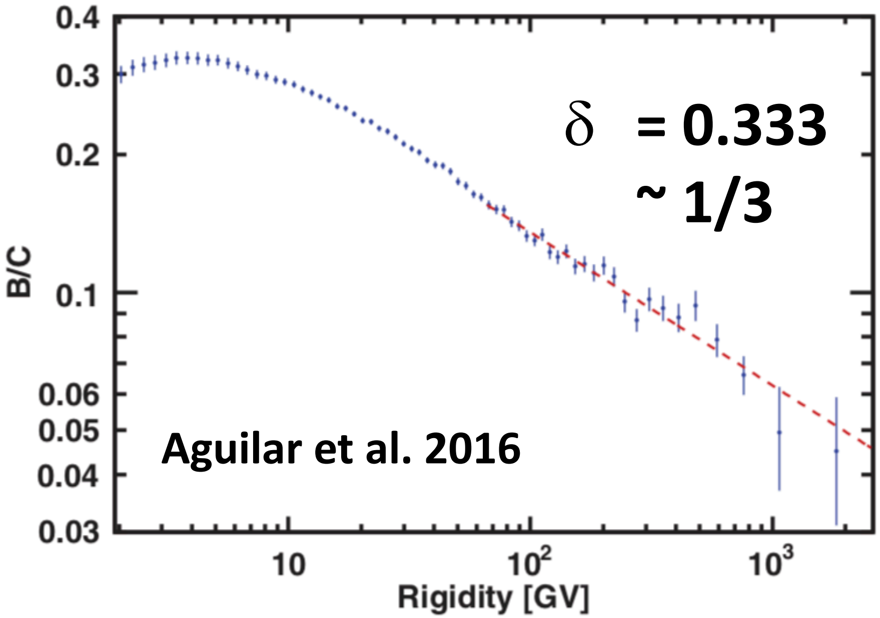
$$\frac{dn_{p,CRn}}{dE} \propto E^{-(s+\delta)}$$

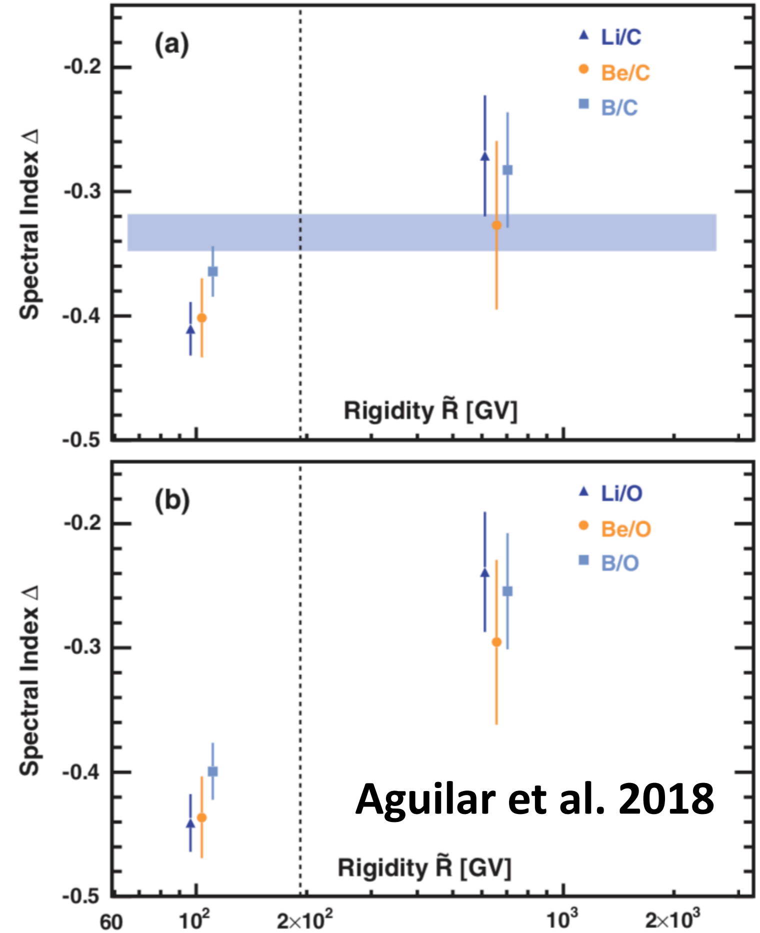
The observed spectrum is not a single power law.

The spectrum has two breaks above 100GeV.

The data show $D_{xx}(E)$ or $Q_{s,p}(E)$ or both are not single power law forms.

Secondary/Primary ratio





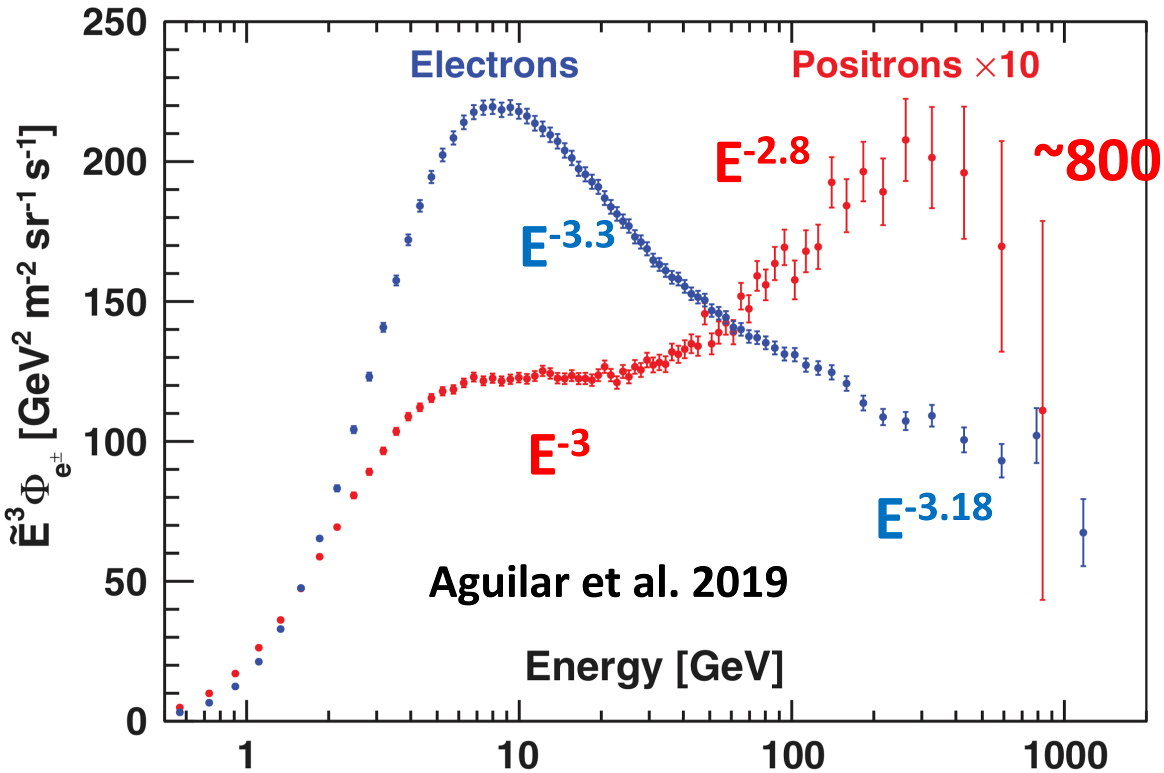
$$\frac{dn_{2nd,CRn}}{dE} \Big/ \frac{dn_{p,CRn}}{dE} \propto E^{-\delta}$$

$\delta = 0.333 \rightarrow s = 2.4 - 2.5$

$D_{xx}(E)$ breaks at several 100 GV.

The spectral hardening on the primary CR spectra at 200GV would be due to D_{xx}.

Primary e- and secondary e+



~800GeV

$$\frac{dn_{p,CRe}}{dE} \propto E^{-\{s+(1+\delta)/2\}}$$

δ=0.333,s=2.45 → $E^{-3.1}$

$$\frac{dn_{2nd,CRe}}{dE} \propto E^{-\{s+(1+3\delta)/2\}}$$

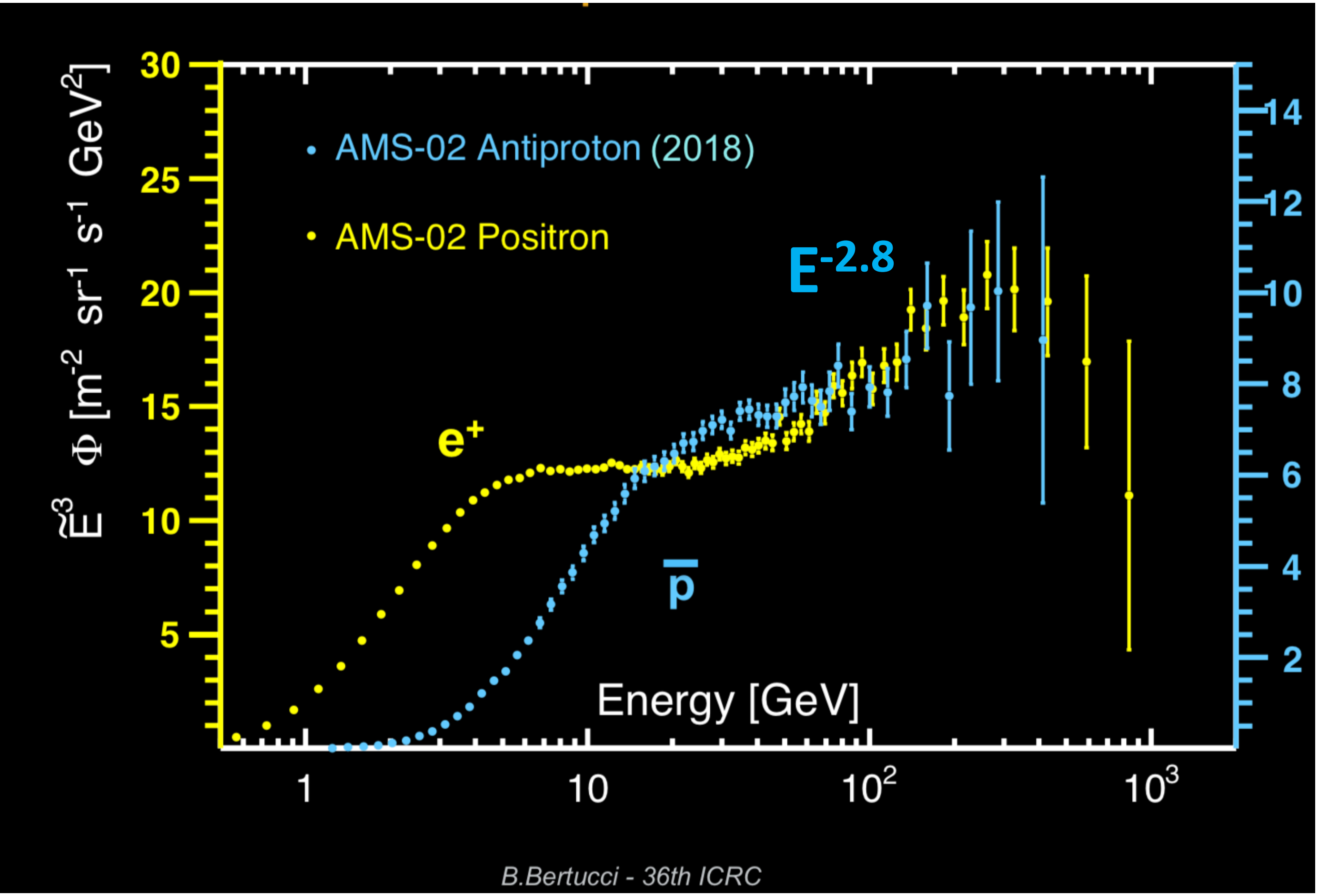
δ=0.333,s=2.45 → $E^{-3.45}$

The standard model predicts s_{e+} =3.45 , but the data show s_{e+} <= 3.

$f_{e+,max}$ <~ 0.2, $E_{c,e+}$ ~ 800GeV, and s_{e+} ~ 2.8 ~ s_{pbar} ~ s_{proton}.

Both e^- and e^+ spectra harden at E ~ 20 - 40 GeV.

Spectrum of CR $\bar{p}$



The standard theory predicts

$$\frac{dn_{2nd,CRn}}{dE} \propto E^{-(s+2\delta)}$$

$\delta = 0.333$, $s = 2.45$

$\rightarrow s_{pbar} \sim 3.1$

Data show $s_{pbar} \sim 2.8 \sim s_{e+} \sim s_{proton}$. Is this a coincidence?

Pulsar cannot provide CR $\bar{p}$.

Any models need a fine tuning?

Supernova remnants as the source of e^+ and $\bar{p}$

In the standard model, e^+ and p are generated only during propagation in our Galaxy.

However, CRs accelerating in SNRs can produce e^+ and $\bar{p}$.
These secondary CRs can be accelerated further by SNRs.
The source spectra of the secondary CRs have harder spectra.

(Berezhko et al. 2003, Berezhko & Ksenofontov 2013, 2014, Blasi 2009, Fujita et al. 2009, Mertisch & Sarker 2009, Kohri et al. 2016)

To explain $s_{e+} \sim s_p \sim s_{pbar}$, the energy loss of secondary e^+ below 800 GeV must be negligible.

→ The origin of CR e^+ must be a local source and not so old.
D <~ 0.5-1kpc, t<~ 10^6yer

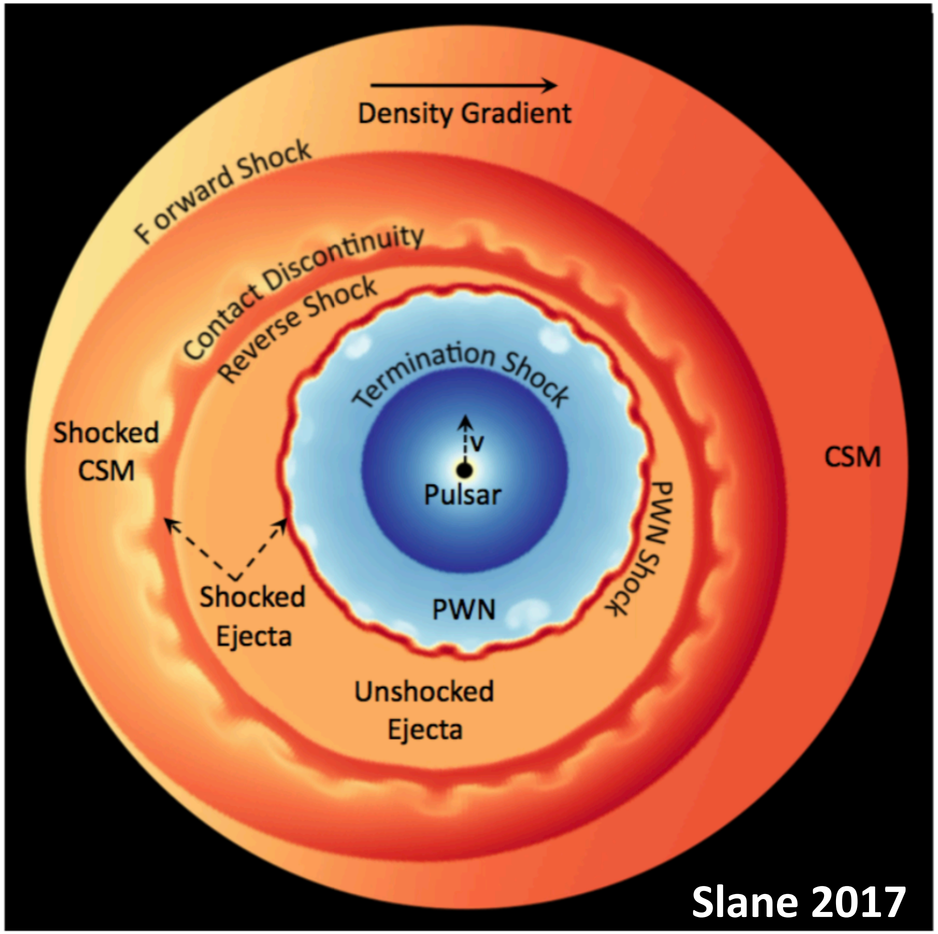
We do not know the local diffusion coefficient and B-field structure.

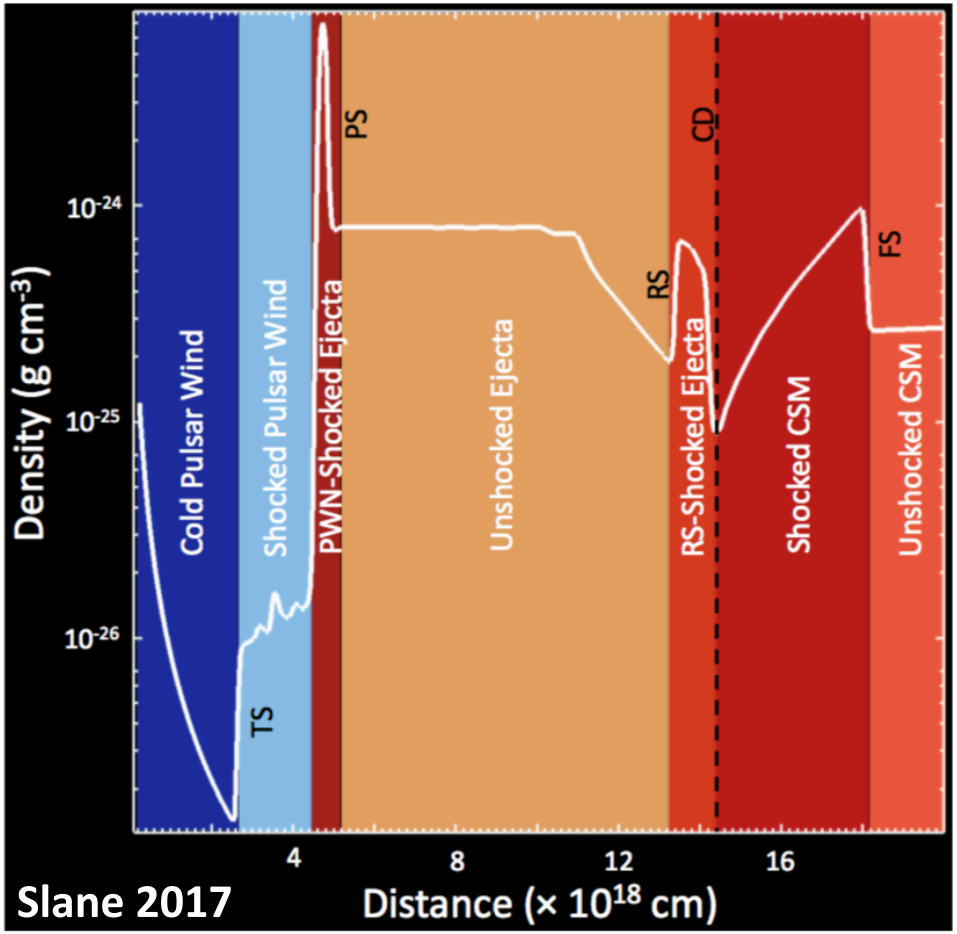
These model did not consider an escape process from SNRs.

High energy CRs escape faster than low energy CRs. (Ohira et al. 2010)

Pulsar wind nebula as the source of e^+

Most core-collapse SNRs are expected to have a PWN (Watters & Romani 2012)





PWN and SNR generate CR e^+, but PWN-SNR systems have very complicated structures.

We do not know how CR e^{+-} escape from the PWN-SNR system.

→ We do not know source spectra of e^{+-} from PWNe, so we cannot rule out PWN models.

s_{pbar} ~ 2.8 ~ s_{e+} ~ s_{proton} is a coincidence?

Summary

After escaping from accelerators of CRs, CRs propagate in our Galaxy.

Then, CR spectra at the Earth becomes steeper than source spectra.

Degrees of the steepening depend on CR particles. Primary or secondary, nuclei or electrons.

Predictions of the standard model are inconsistent with observed data.

Dark matter?
Pulsar wind nebula?
Local SNR?

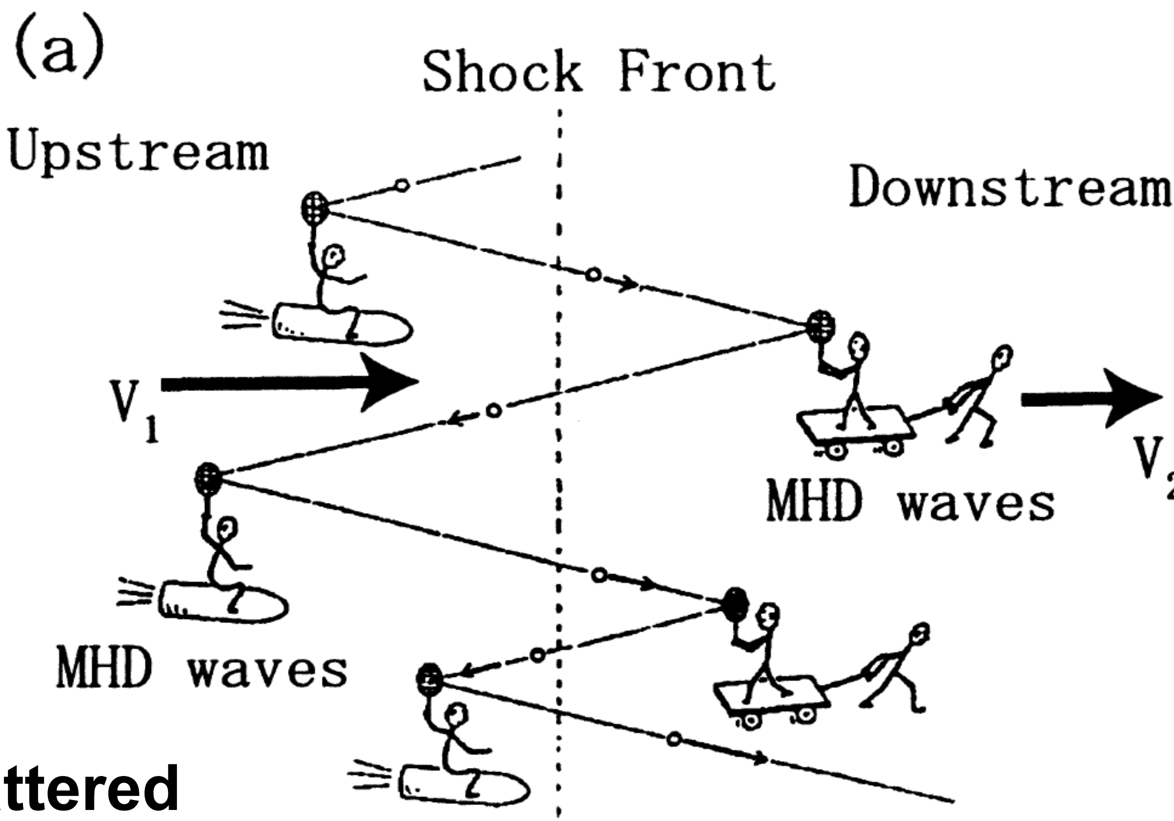
or

More realistic diffusion model?

- **Spiral arm structures for gas and B**
- **Non-isotropic and non-uniform diffusion coefficient**
- **Self confinement by CRs**
- **Galactic wind**

Shaviv et al. 2009, Blasi et al. 2012, Cowsik et al. 2014, Gaggero et al. 2013, Evoli et al. 2017, Jóhannesson et al. 2018

Diffusive Shock Acceleration(DSA)



Scholer

CRs are scattered by MHD waves.

CRs excite the MHD waves.

($u_1/u_2 \rightarrow 4$)

$dN/dE \propto E^{-s}$

Single power law

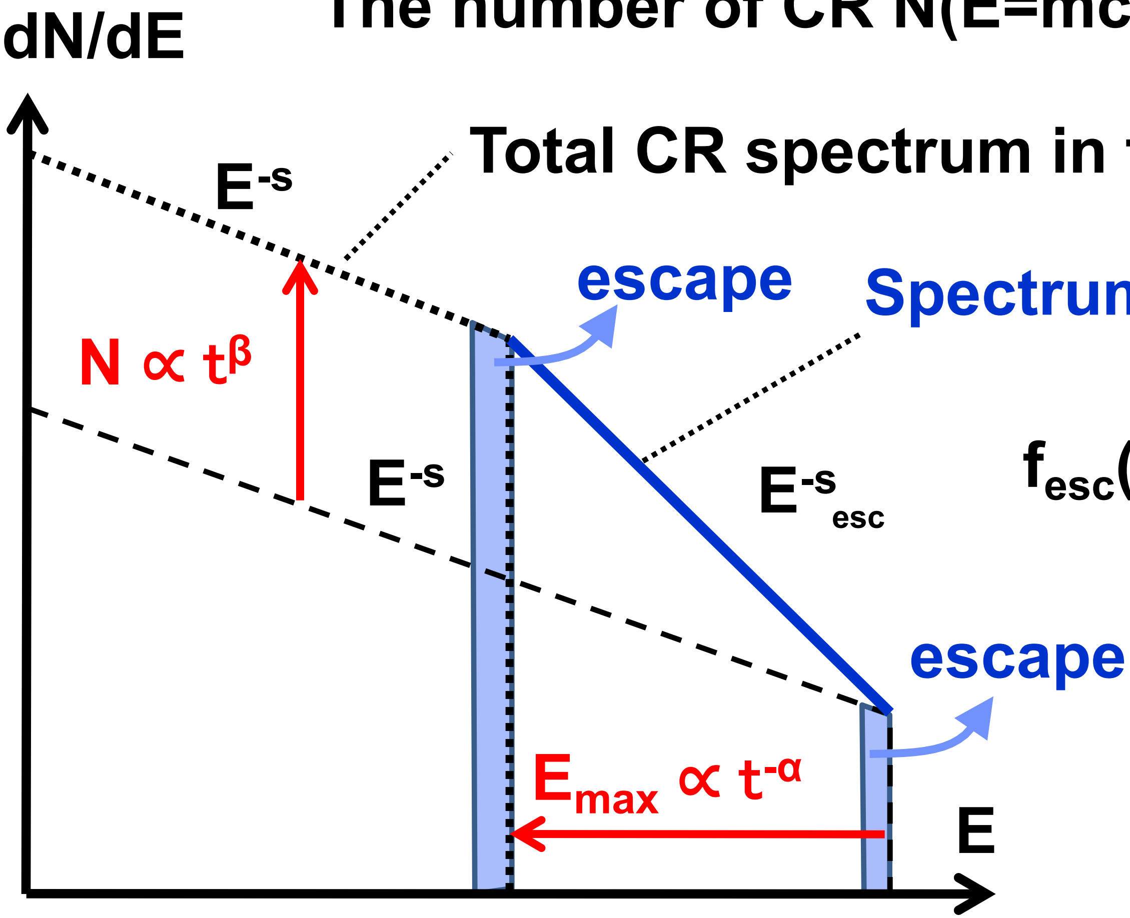
$$s = \frac{u_1/u_2 + 2}{u_1/u_2 - 1} = 2$$

Axford 1977, Krymsky 1977, Blandford&Ostriker 1978, Bell 1978

Spectrum of escaping CRs

Maximum energy $E_{max} \propto t^{-\alpha}$, $\alpha > 0$

The number of CR $N(E=mc^2) \propto t^{\beta}$, $\beta > 0$



$$f_{esc}(E)\, dE = f_{SNR} \frac{dE_{max}}{dt} dt$$

$$f_{esc} \propto E^{-s_{esc}}$$

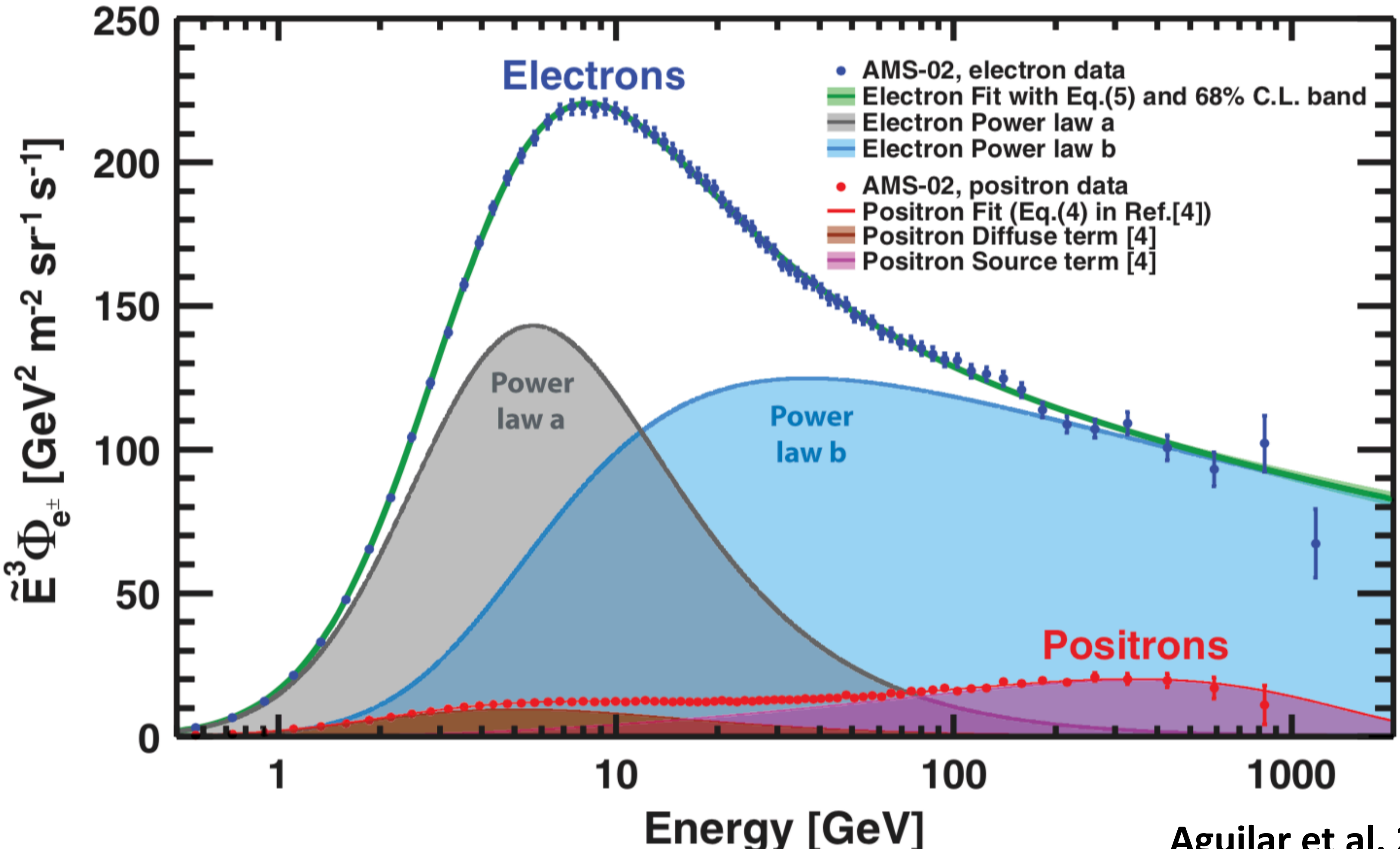
$$s_{esc} = s + \frac{\beta}{\alpha}$$

$s \neq s_{esc}$

Y. Ohira, K. Murase, R. Yamazaki, 2010, A&A, 513, A17

Y. Ohira, K. Ioka, 2011, ApJL, Y. Ohira et al. 2015

Primary e- and secondary e+



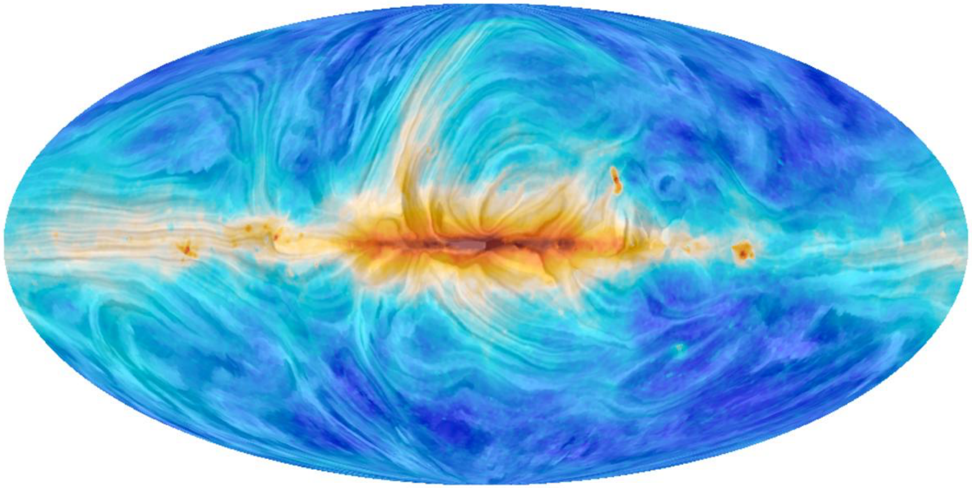
Aguilar et al. 2019

The positron source cannot explain the spectral hardening of CR e-.

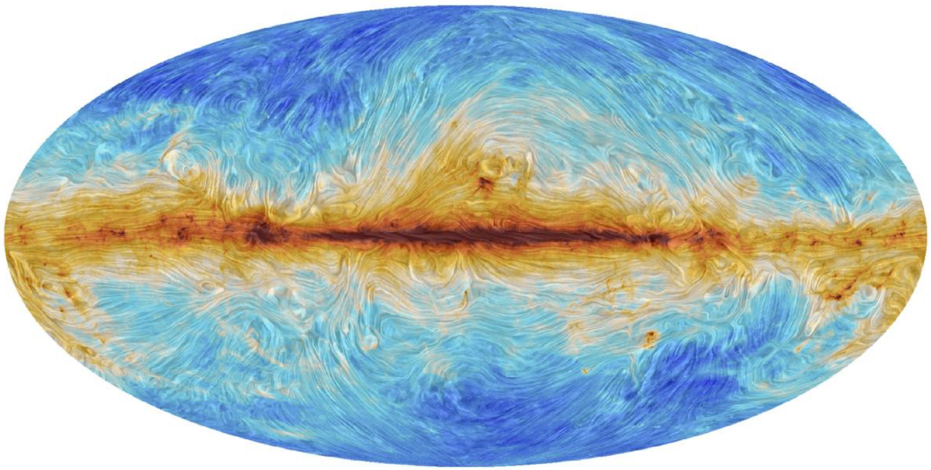
Both e^- and e^+ spectra harden at E ~ 20 - 40 GeV. Is this a coincidence?

Magnetic field (Milky way Galaxy)

Planck Collaboration, A&A, 594, 1(2016)



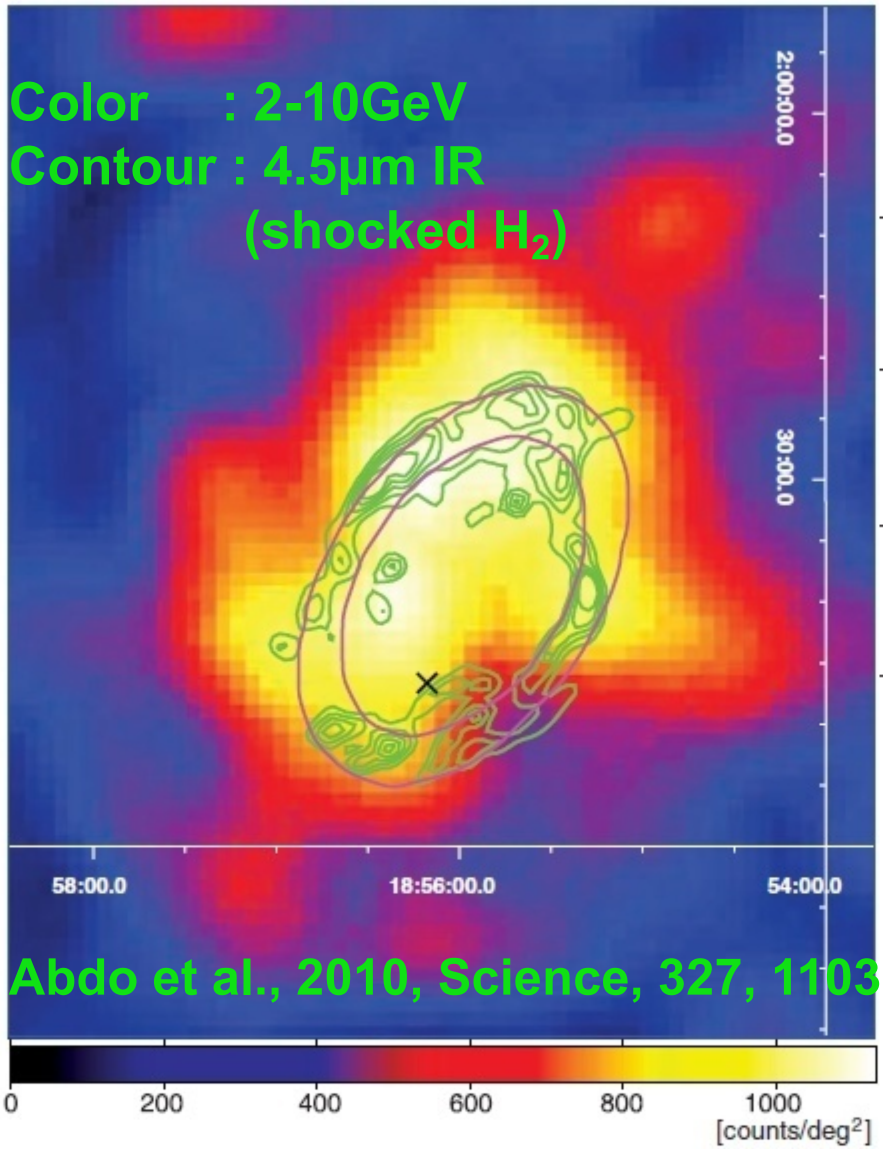
From synchrotron radiation of CR e- @30Ghz

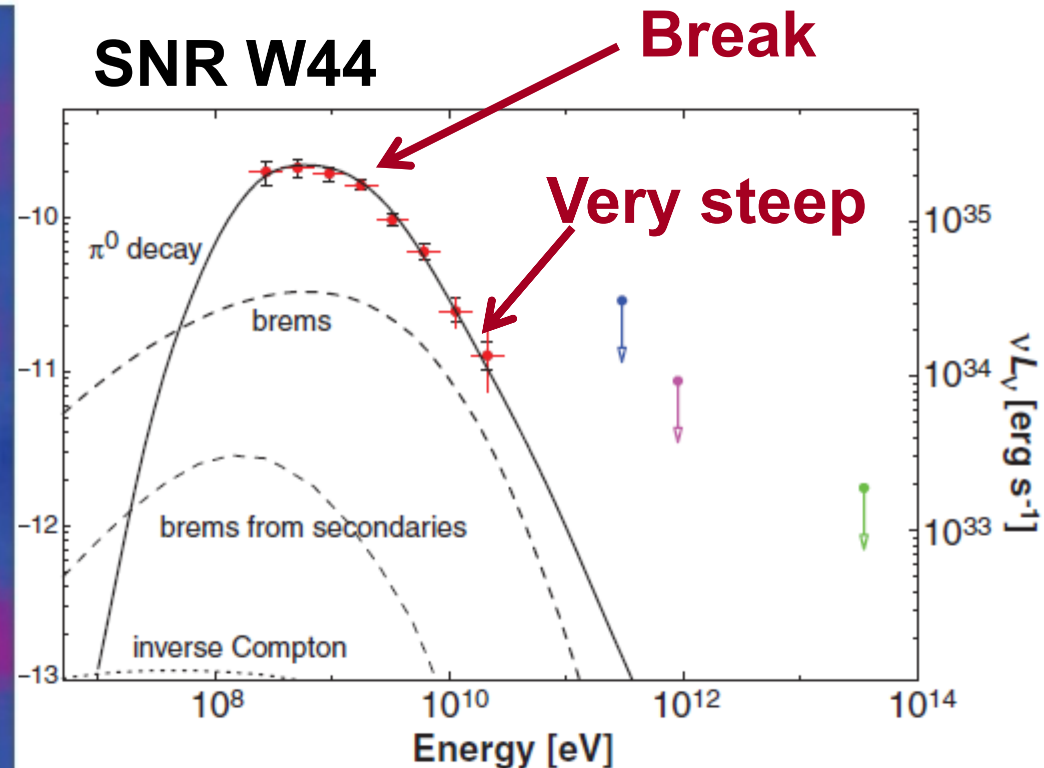


From dust emission @353 Ghz

The stripe patterns show magnetic field orientation integrated over a line of sight.

γ-ray spectra of Middle-aged SNRs





Broken power law

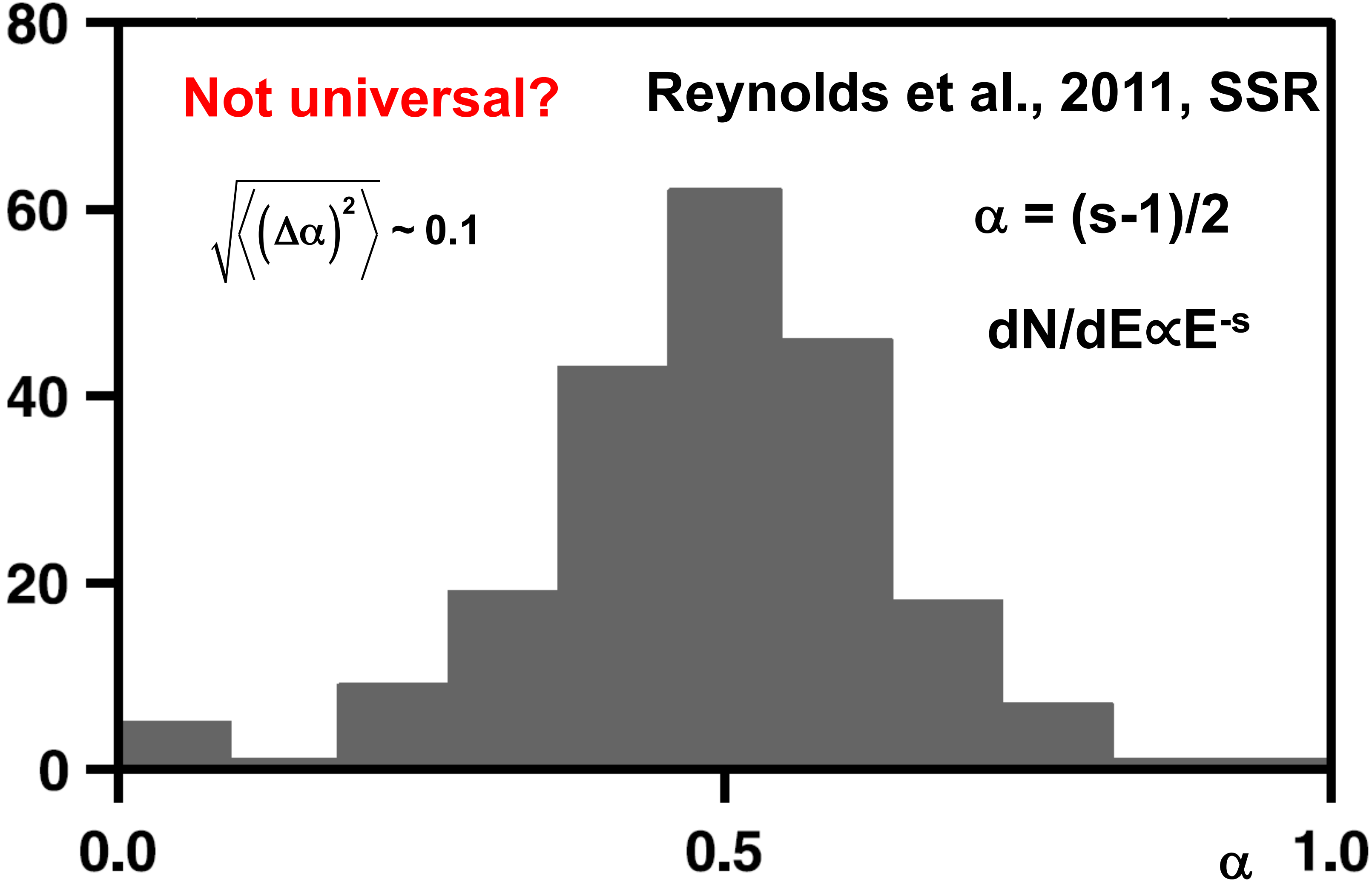
Very steep spectrum ($dN/dE \propto E^{-3}$)

DSA ($dN/dE \propto E^{-2}$)

CR obs. ($dN/dE \propto E^{-2.1-2.4}$)

The SNR is interacting with MC.

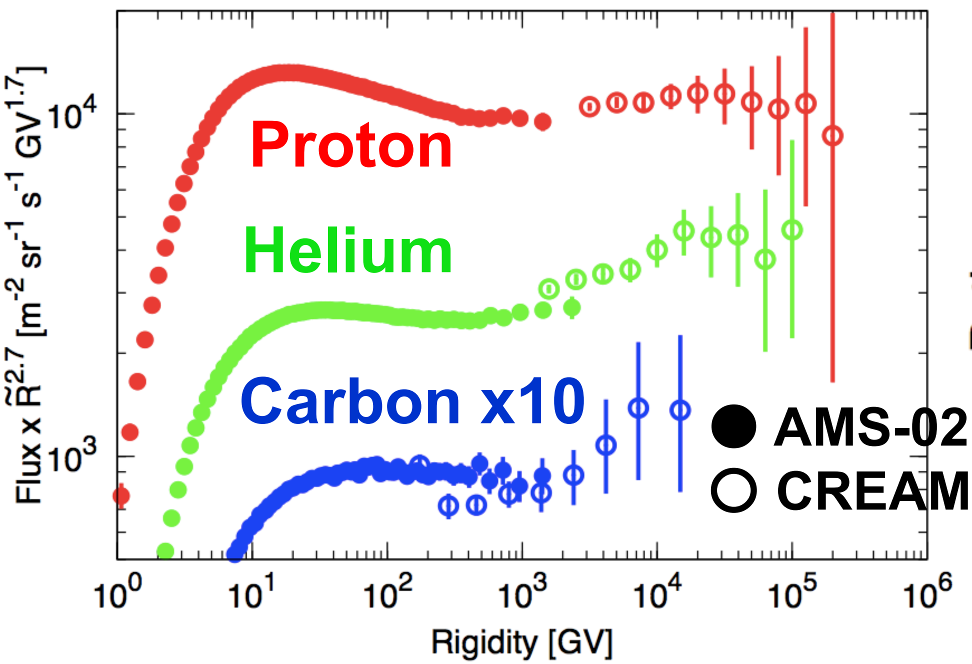
Spectral index of radio synchrotron flux, $f_\nu \propto \nu^{-\alpha}$

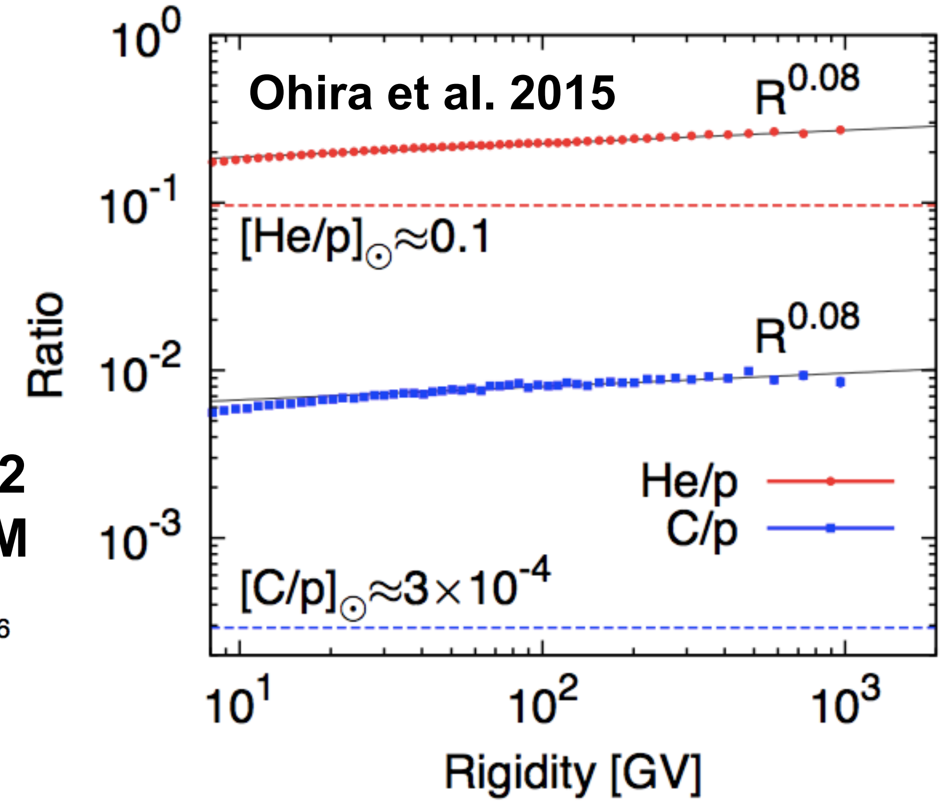


The standard DSA predicts $s = 2$ $(\alpha = 0.5)$

CR observations require $s_{source} \sim 2.4$ $(\alpha \sim 0.7)$

CR hardening





Spectra of CR p and He (and C) break at R~300GV.

Spectra of CR He and C are harder than that of CR p.

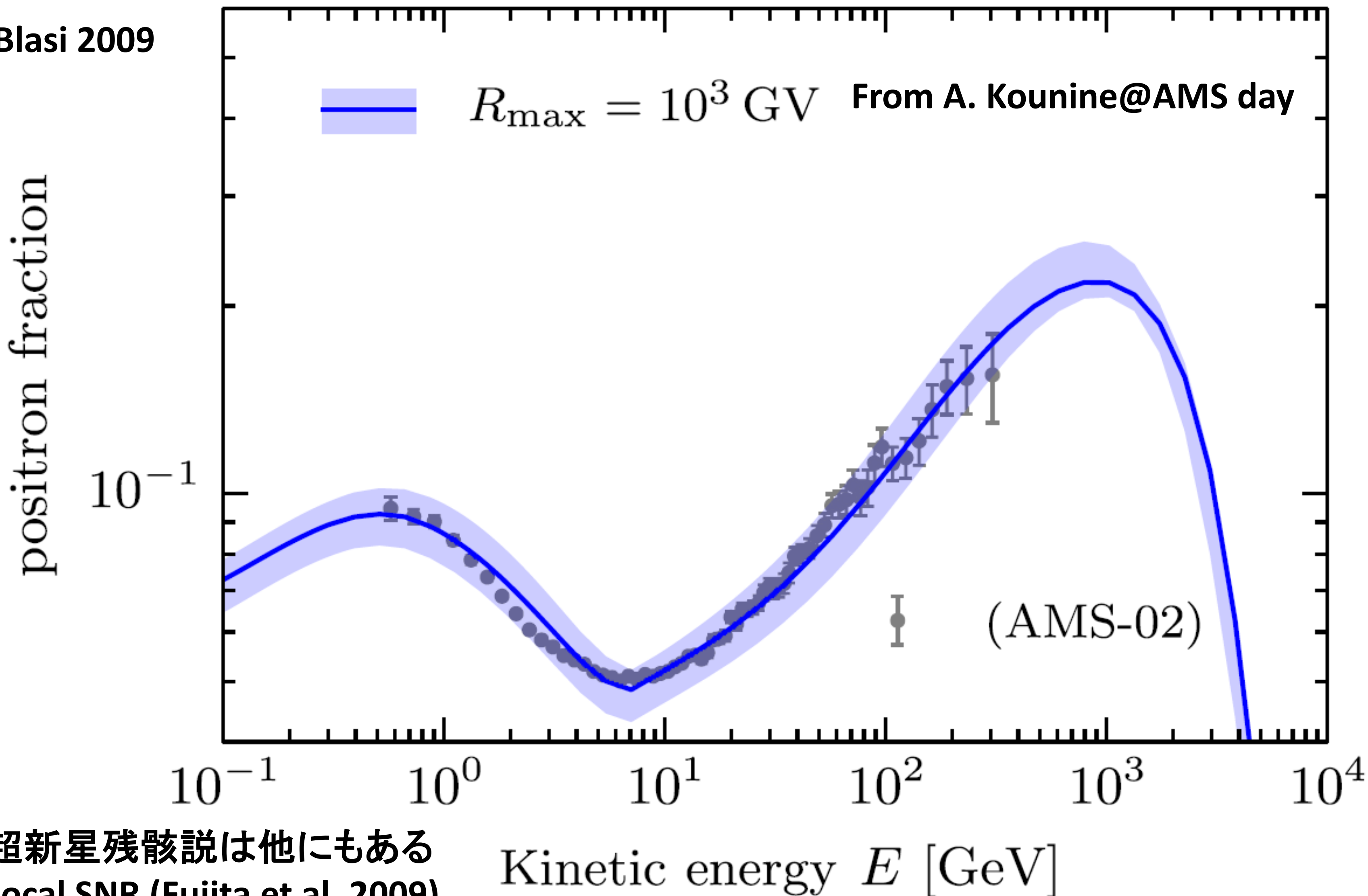
The standard model predicts that all primary CRs have the same spectral index.

→ The standard model needs any other physics.

Acceleration in SNRs

P. Mertsch and S. Sarkar, Phys.Rev. D 90 (2014) 061301(R)

Blasi 2009



超新星残骸説は他にもある

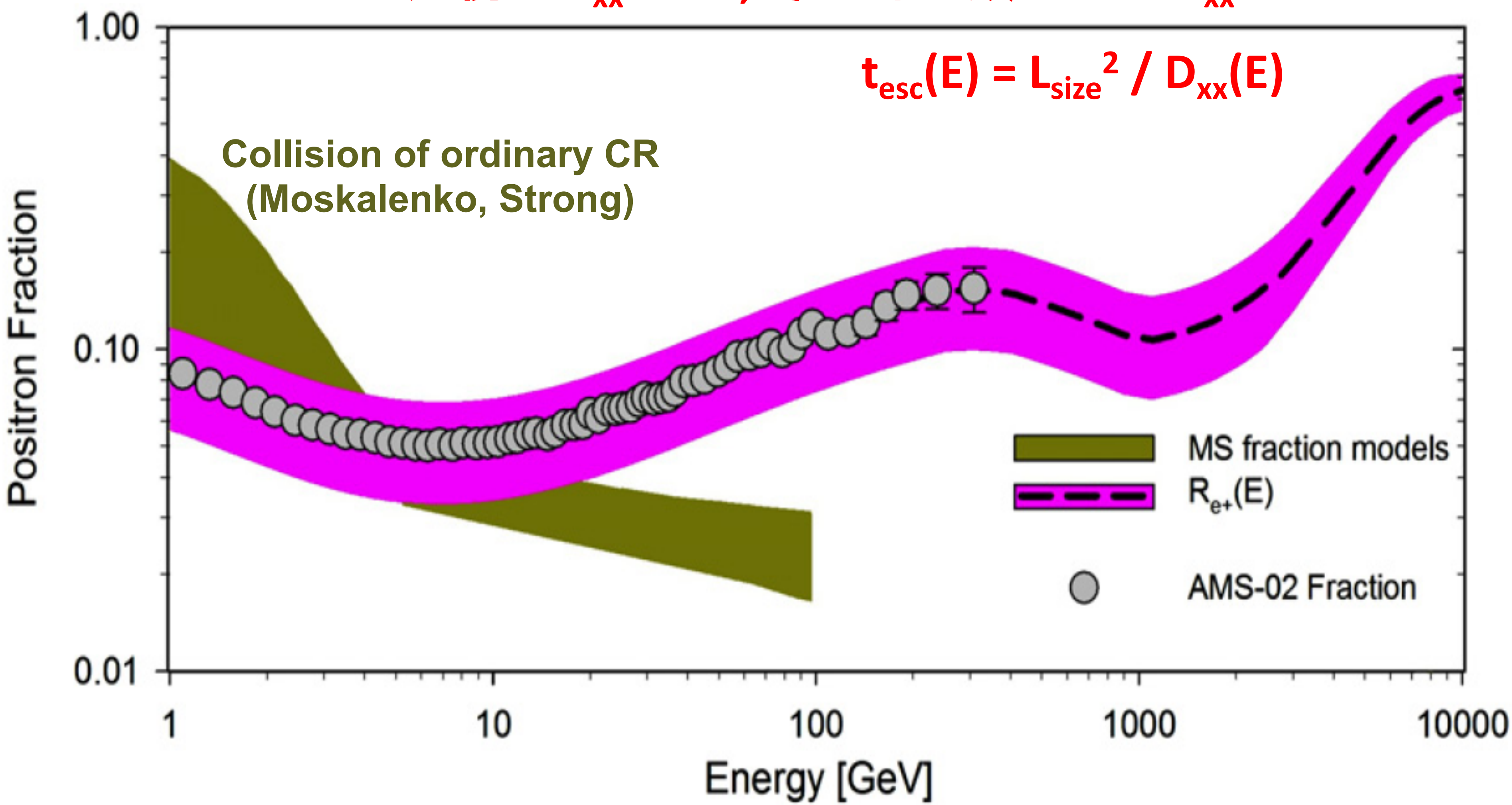
Local SNR (Fujita et al. 2009)

S. Sarkar talk on April 16

Propagation of secondaries

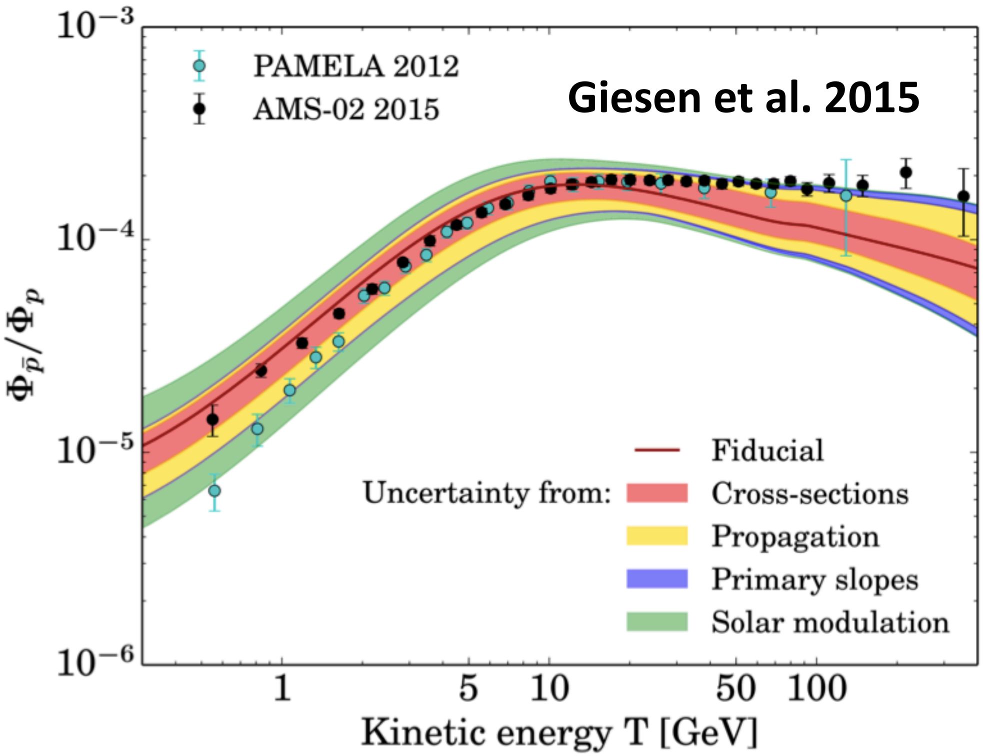
R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124

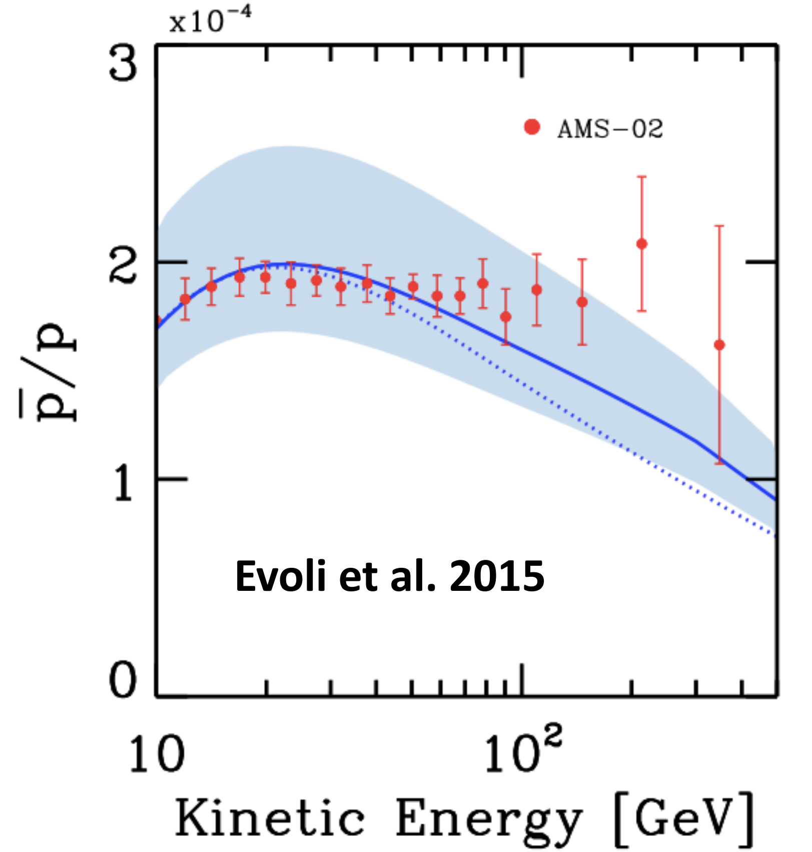
CR source 近傍は$D_{xx} \propto E^{0.6}$, その外の銀河内は$D_{xx} \propto E^{0}$



From A. Kounine@AMS day

Giesen et al. 2015, Evoli et al. 2015





標準伝搬モデルの不定性や散乱断面積の不定性などを考慮すると、最新の pbar/p は、宇宙線の標準モデルで説明可能