Cosmic ray acceleration and propagation in the Galaxy: some open problems

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Slide zero

Acceleration and propagation of (Galactic) cosmic rays are two intimately connected problems: the cosmic ray spectrum that we observe locally is the result of:

1) the acceleration of cosmic rays at their sources
2) the escape of cosmic rays from their sources
3) the escape of cosmic rays from the Galaxy

All of the above depends on COSMIC RAY TRANSPORT

I will adopt here a phenomenological approach.

Overview

- ☑ The supernova remnant paradigm for the origin of CRs: the 3 pillars of orthodoxy
- ☑ Cosmic ray spectral anomalies challenge the standard scenario
- ☑ An (intendedly provocative) exercise for undergraduates
- ☑ Superbubbles or isolate supernova remnants?
- ☑ Is the "Lagage & Cesarsky" problem solved? [hint: no]
- ☑ Can the Galactic centre contribute to observed CRs?
- ☑ What about stellar clusters?
- ☑ Conclusions (?)

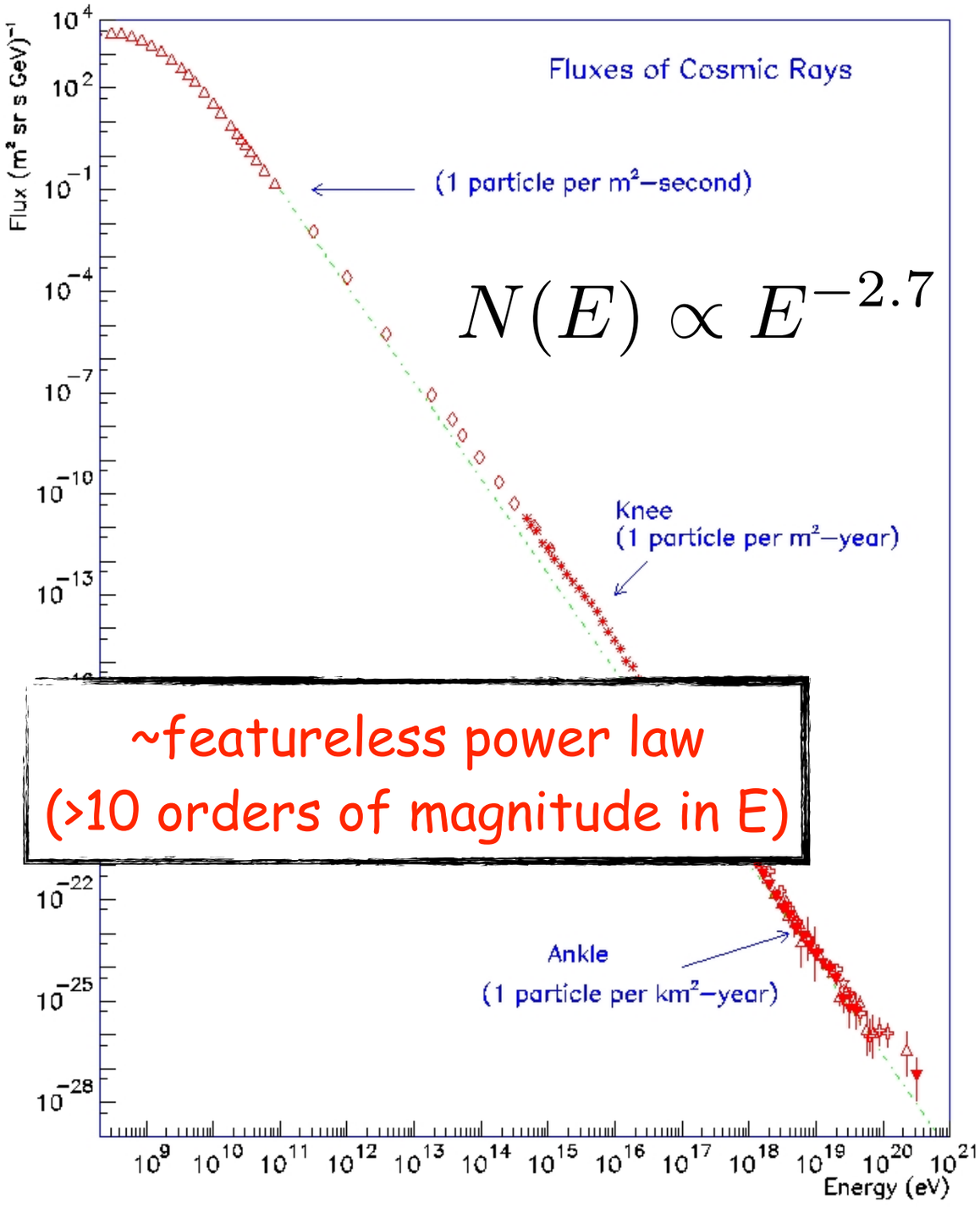
The three pillars of "orthodoxy"

With "orthodoxy" I refer here to the ideas and assumptions which are most commonly invoked to interpret the observations of cosmic rays.

These ideas and assumptions constitute a standard framework for cosmic ray studies which is broadly (though not unanimously!) accepted.

Surprisingly (?), the basic ideas did not change much from the renown monograph: "The origin of cosmic rays" by Ginzburg and Syrovatskii, which dates bak to 1964!

I-The bulk of the energy of CRs originates from Galactic supernova explosions



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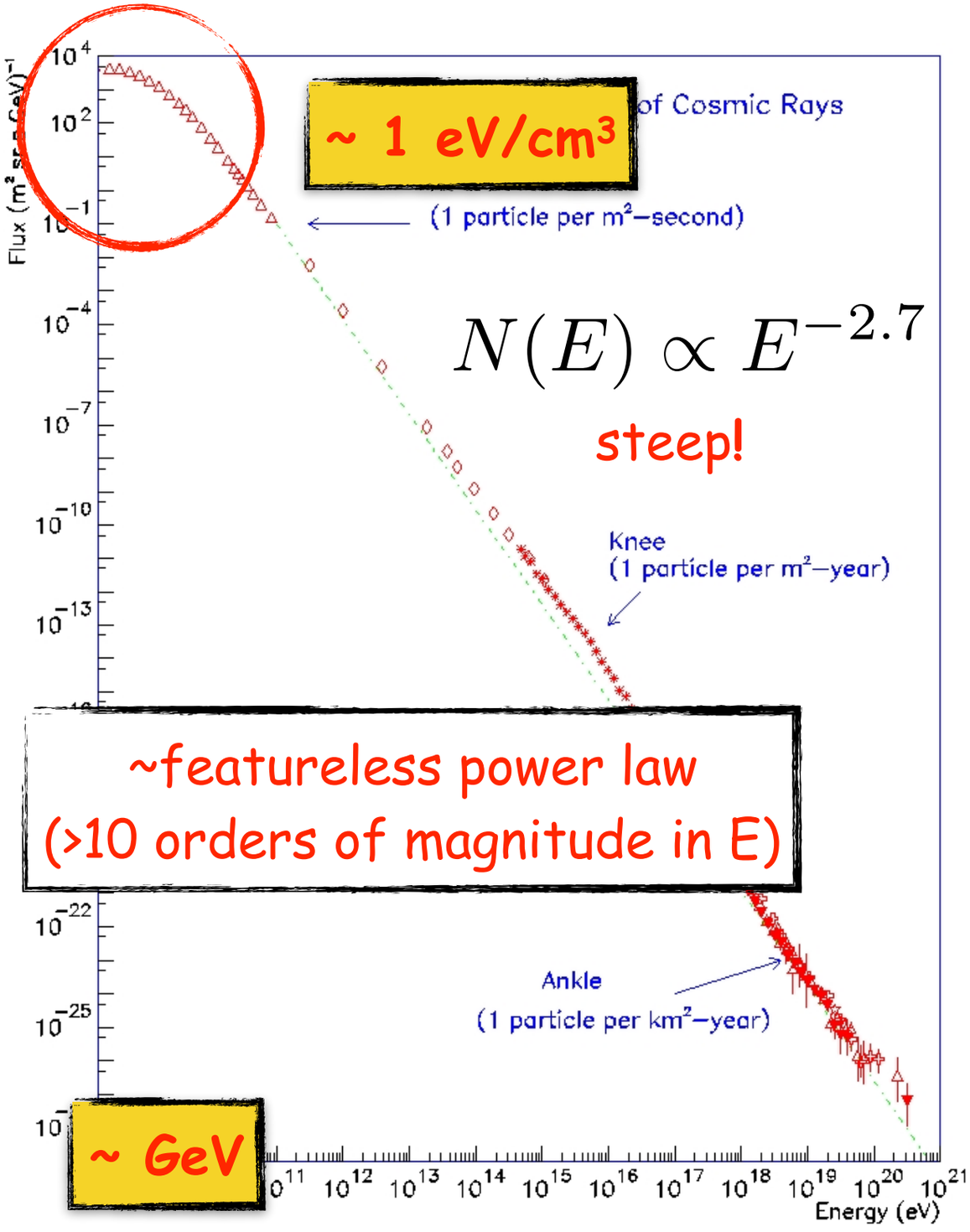

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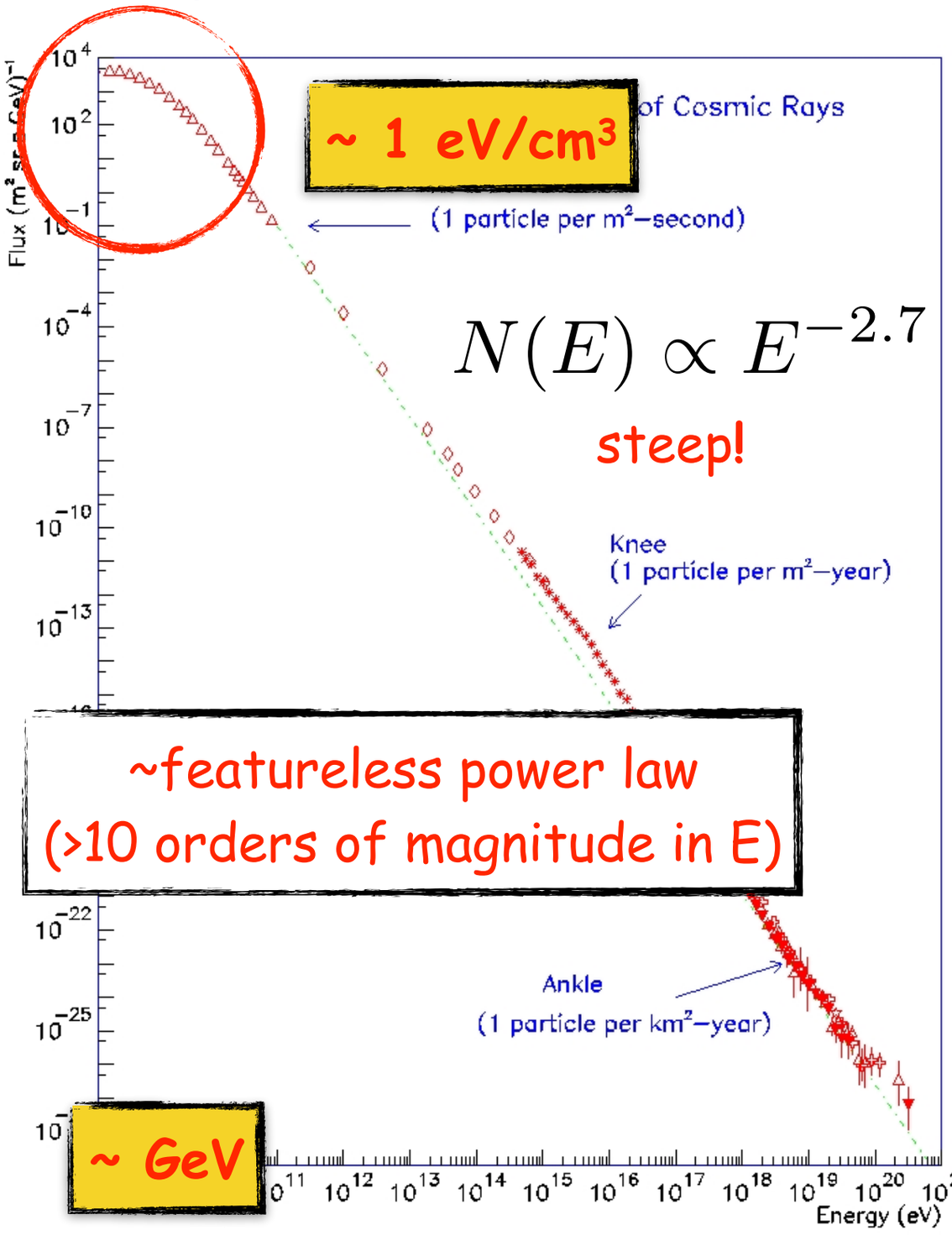

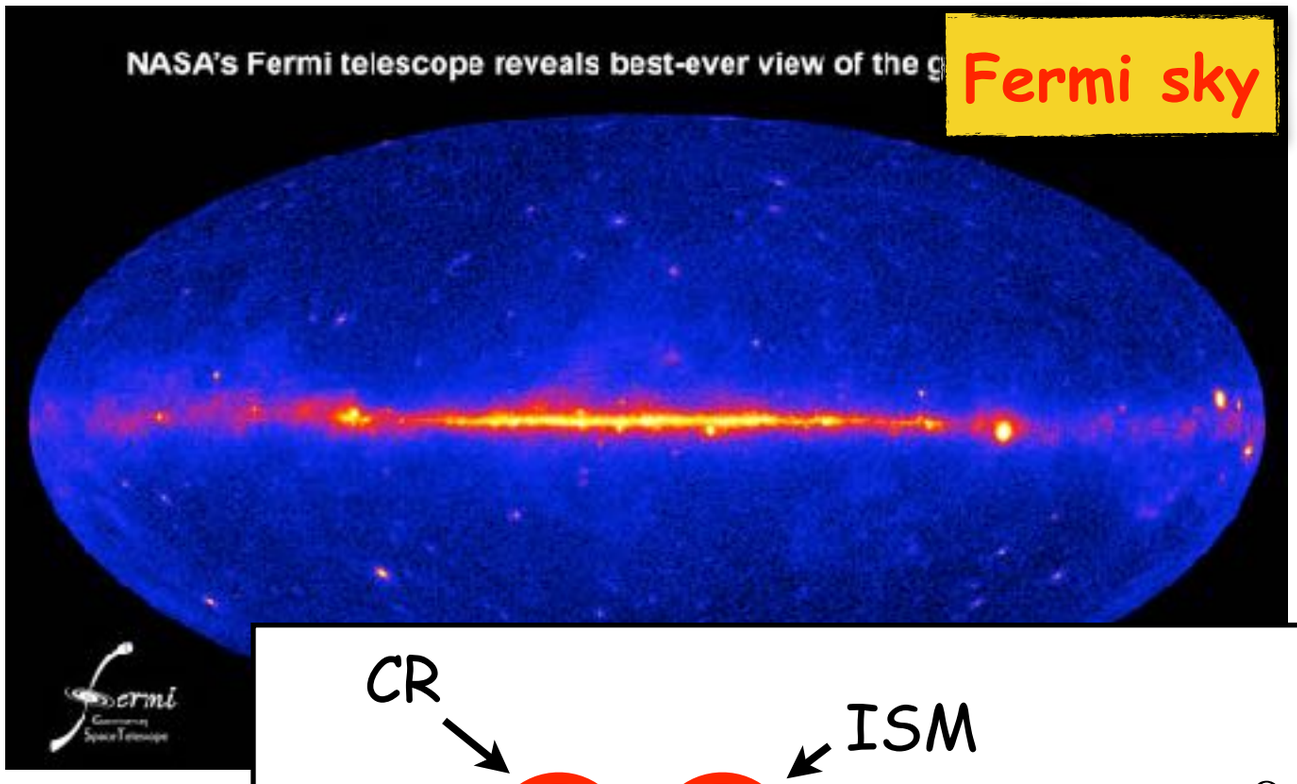

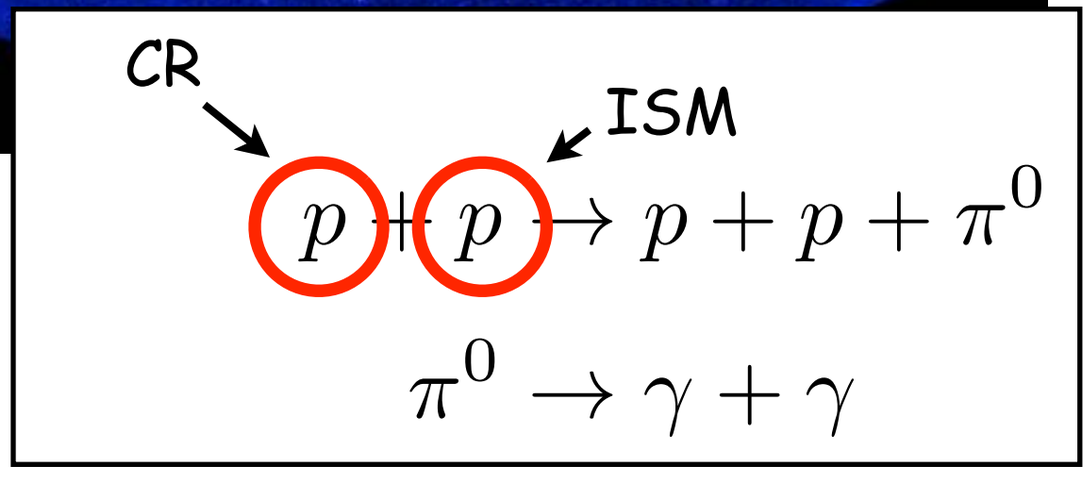

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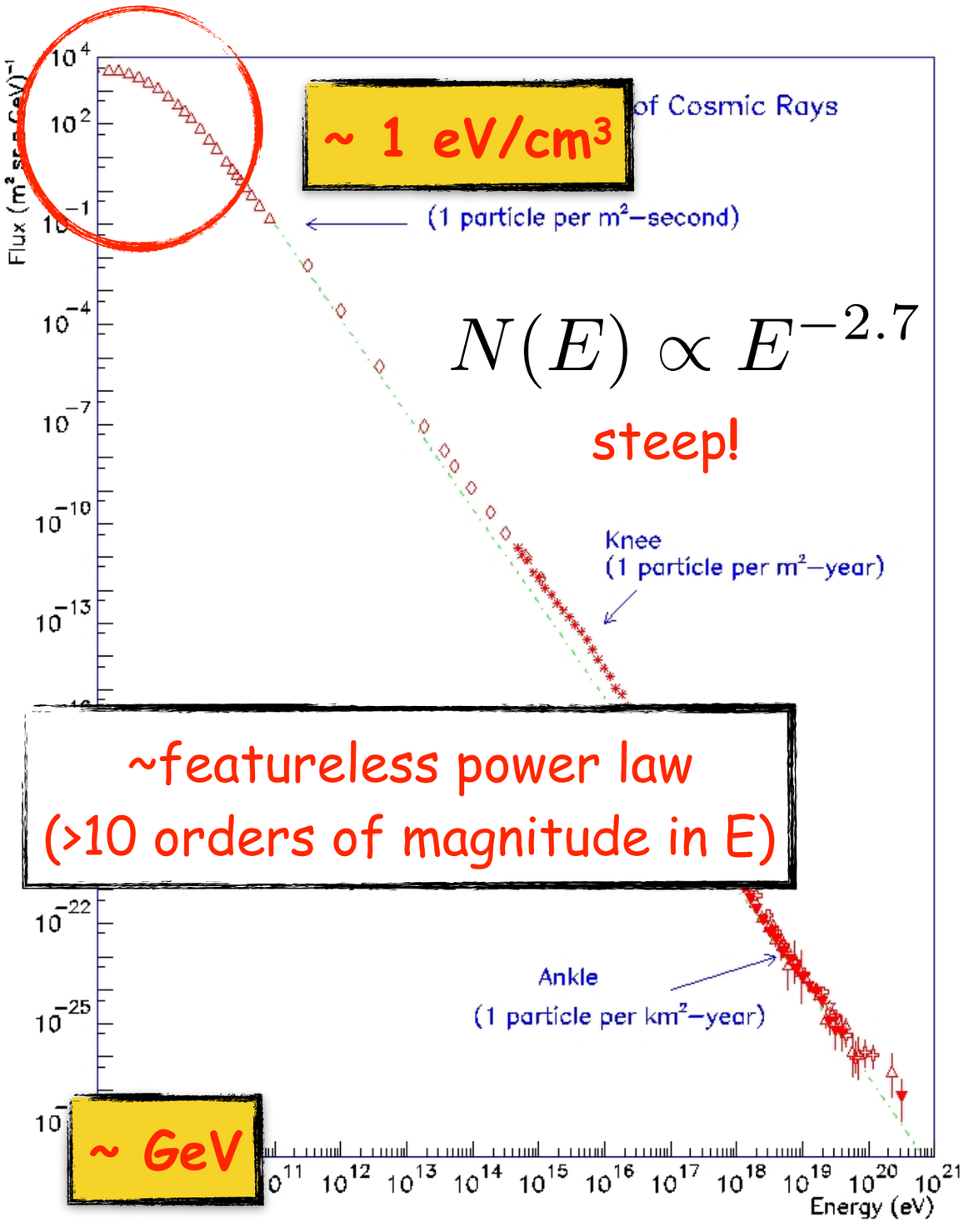

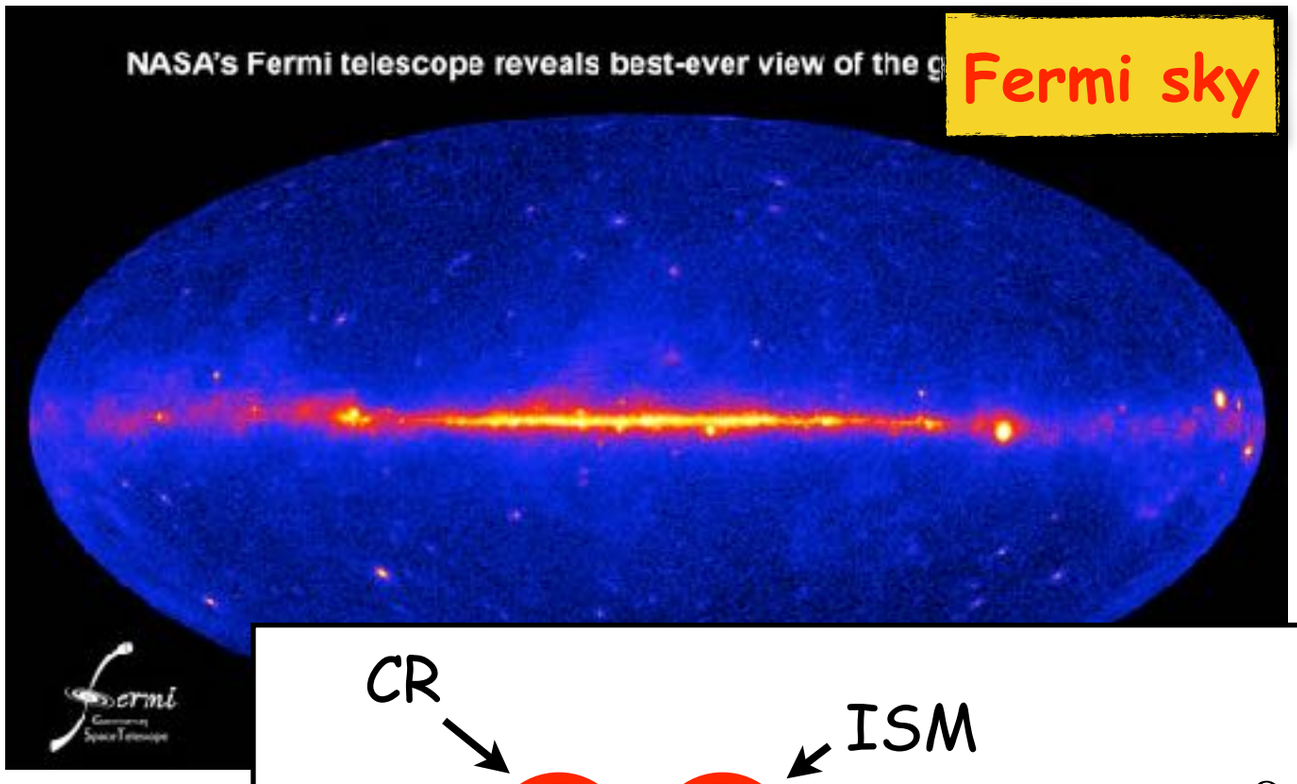

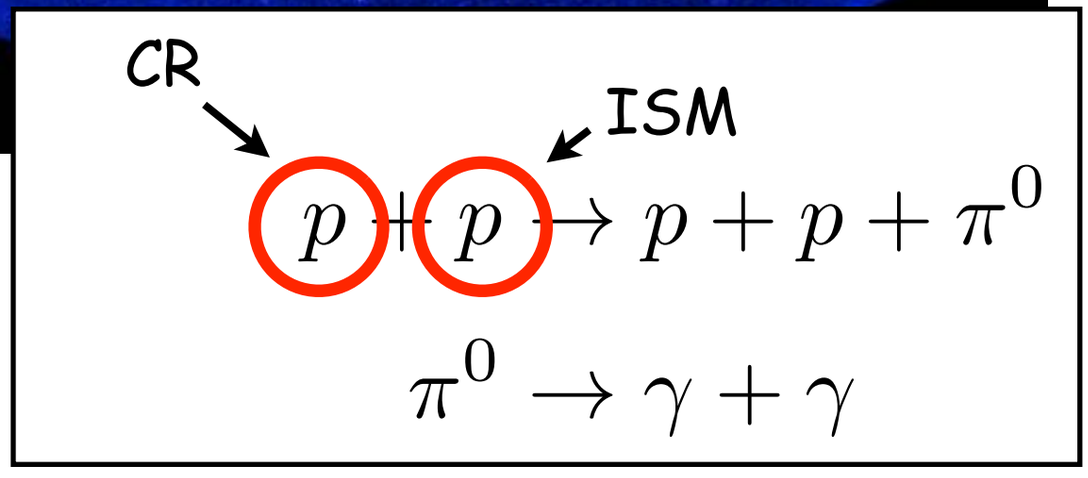

CR "roughly" homogeneous in the disk
-> $W_{CR} \sim 10^{55}$ erg

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Baade & Zwicky 1934, ter Haar 1950

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(E_{SN}: 10^{51} erg; ν_{SN}: 3/century)

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Supernovae can provide the energy needed to explain CRs is ~10% of their explosion energy is somehow converted into CRs

Baade & Zwicky 1934, ter Haar 1950

II-CRs are diffusively confined within an extended and magnetized Galactic halo

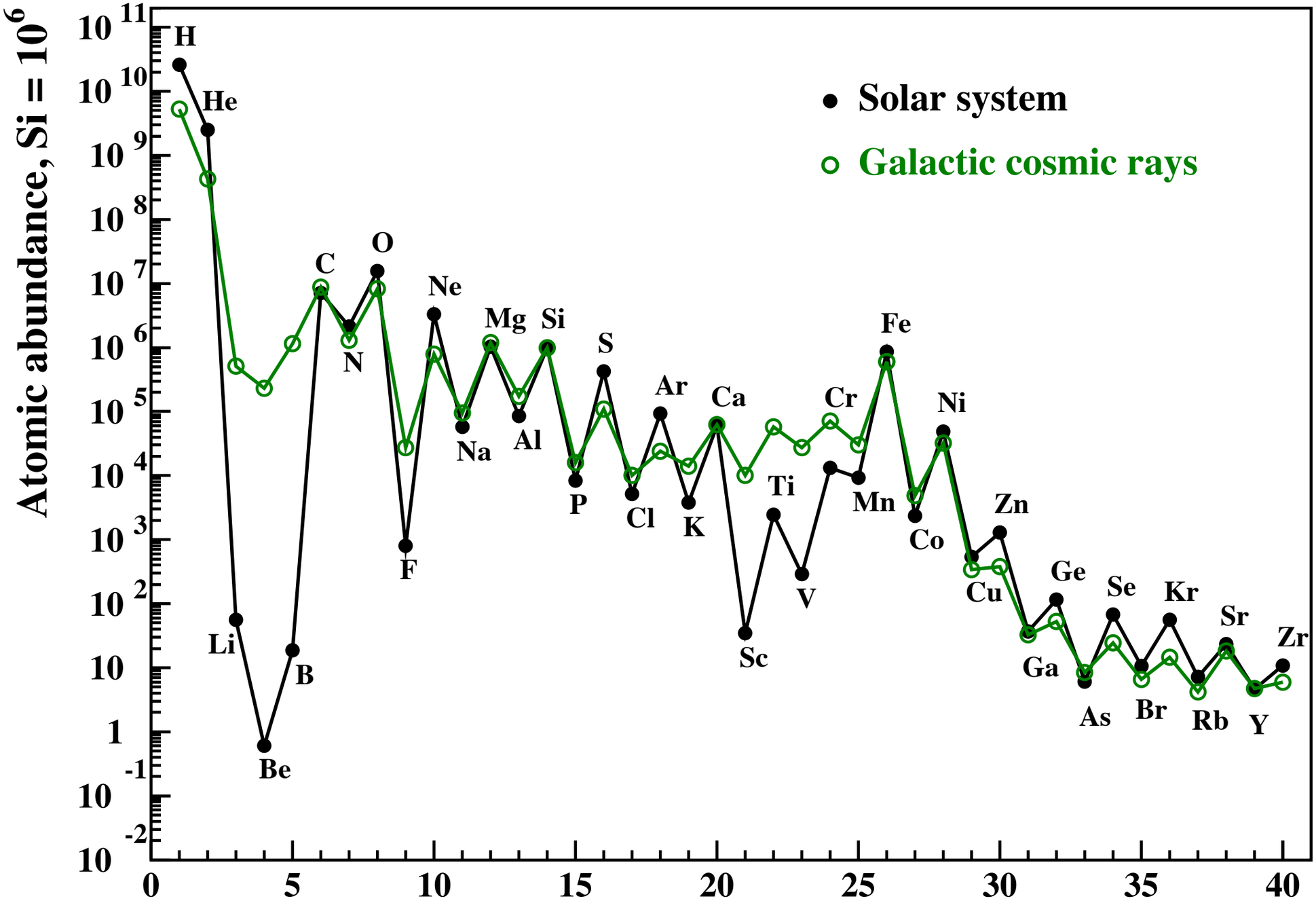

figure from Tatischeff & Gabici (ARNPS, 2018)

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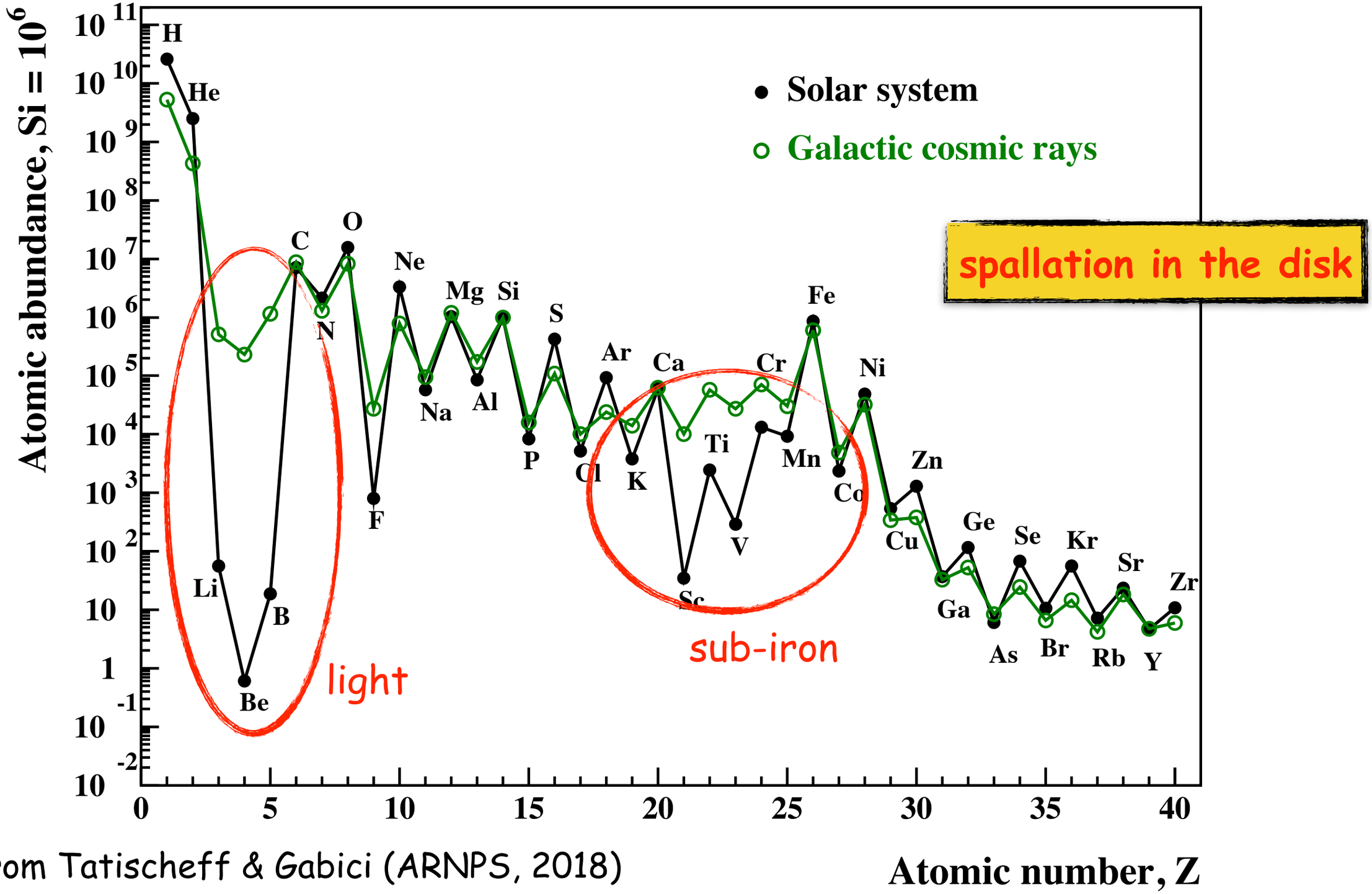

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grammage

$$\Lambda_g = \mu m_p \; n_{ISM} \; \tau_{disk} \longrightarrow \boxed{\frac{n_B}{n_C} \sim \frac{\sigma_s}{\mu m_p} \Lambda_g}$$

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$n_{disk} \sim 0.1\text{-}1\ \mathrm{cm}^{-3}$

$$\Lambda_g \sim 10\ \mathrm{g/cm}^2 \longrightarrow l_{disk} \sim 1\ \mathrm{Mpc} \longrightarrow \tau_{disk} \sim 3\ \mathrm{Myr}$$

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diffusive, rather than ballistic transport of CRs

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How much time do CRs spend in the Galactic halo?

escape time from the Galaxy (disk+halo) τ_{esc}

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$$\frac{n(^{10}Be)}{n(Be)} \sim \frac{\tau(^{10}Be)}{\tau_{esc}} \frac{q(^{10}Be)}{q(Be)} \longrightarrow \tau_{esc} \sim 10 - 20 \text{ Myr} > \tau_{disk}$$

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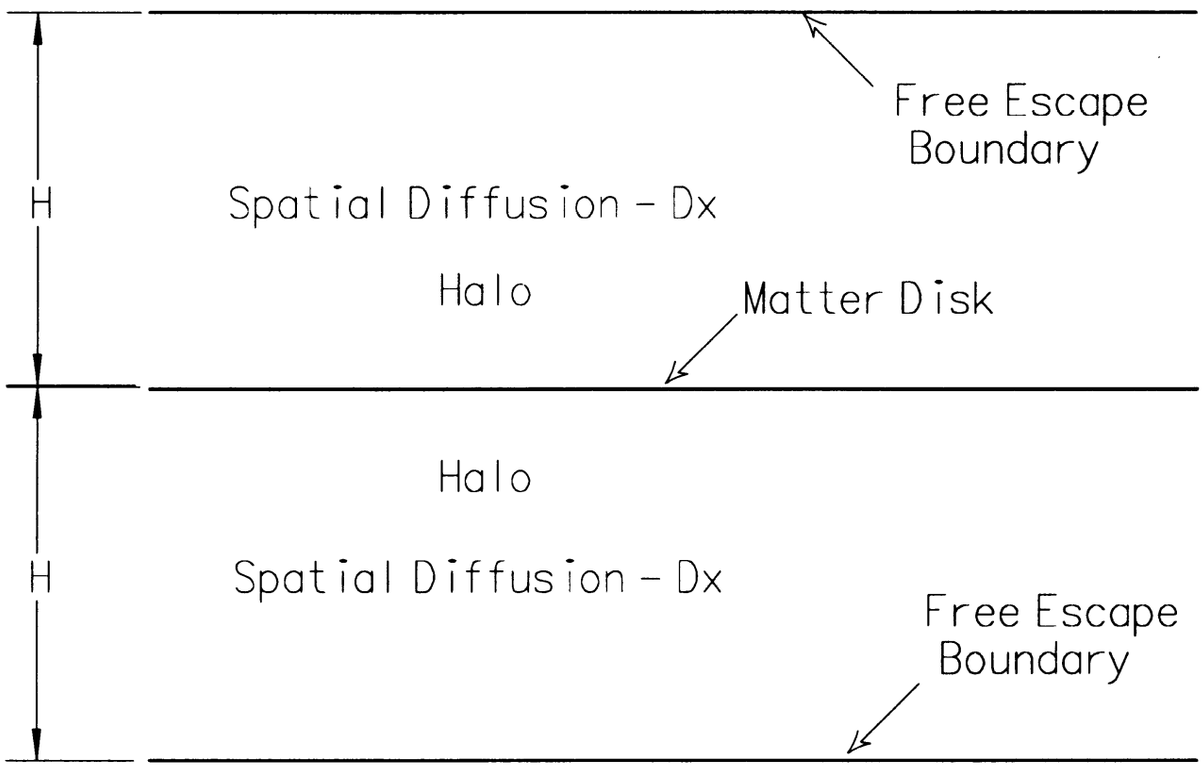
infinitely thin disk + extended halo



Jones+ (2001)

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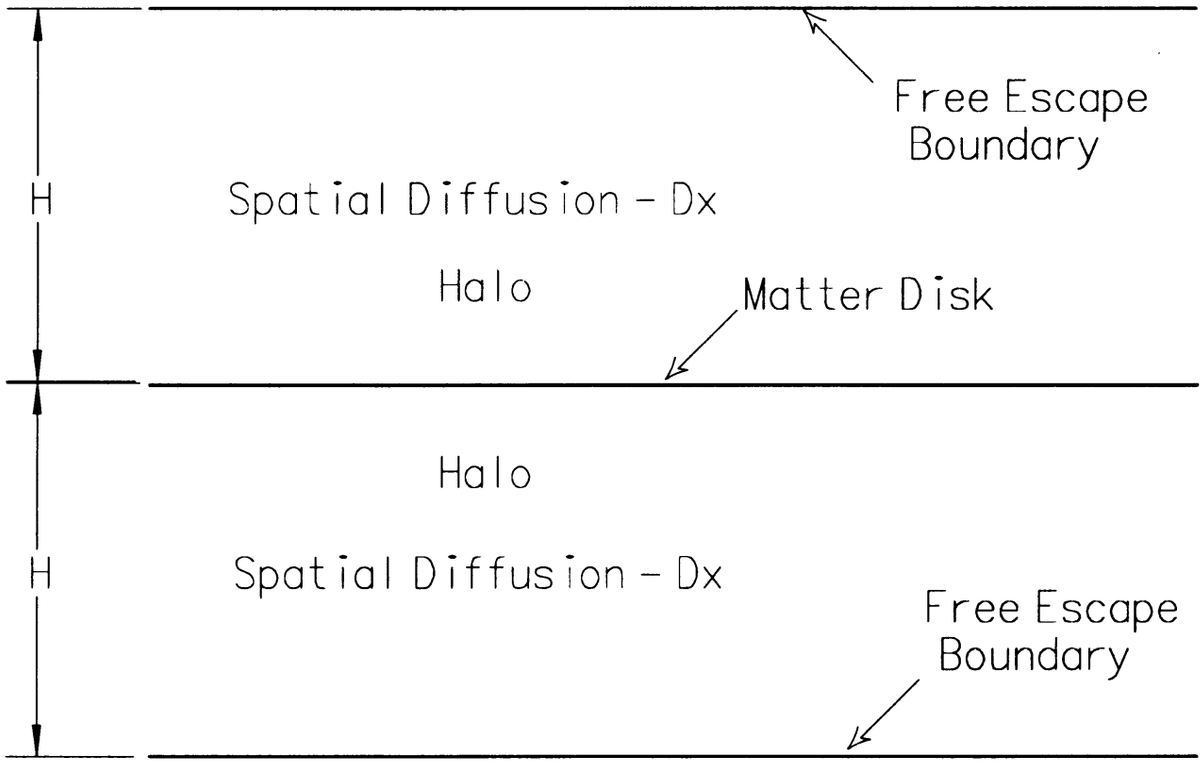

diffusion coefficient (halo)

surface mass density of the disk

height of the halo

$$D = \frac{\Sigma \; c \; H}{2 \; \Lambda_g}$$

grammage

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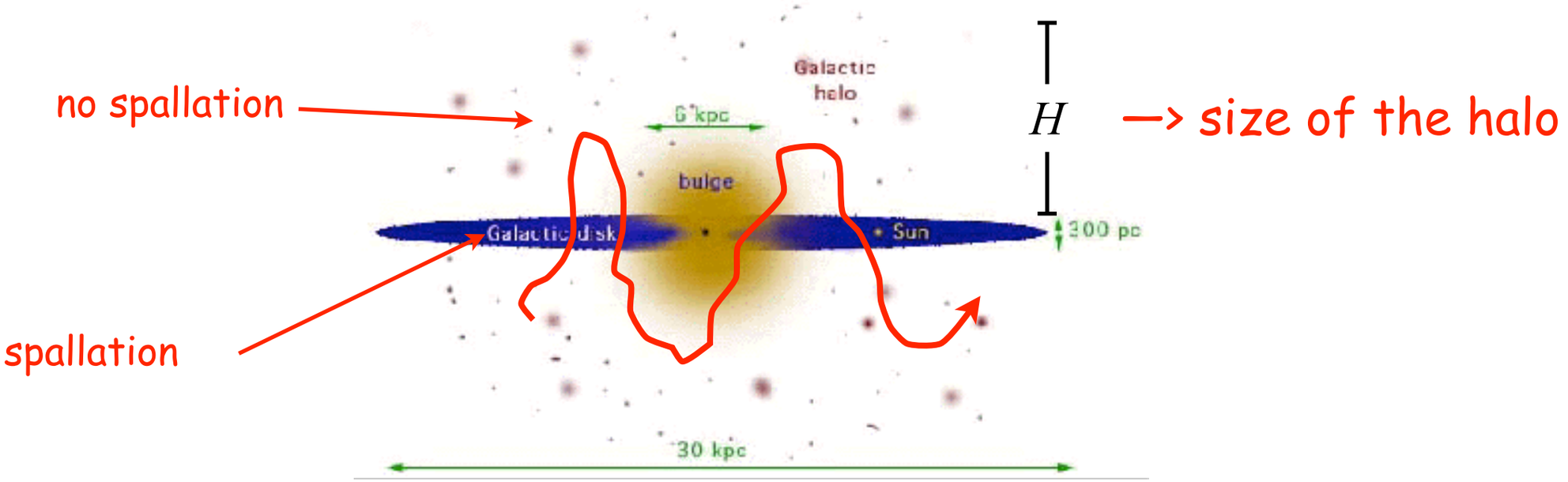

typical diffusion coefficient

$$D \sim 10^{29} \left(\frac{H}{3 \text{ kph}} \right) \text{cm}^2/\text{s}$$

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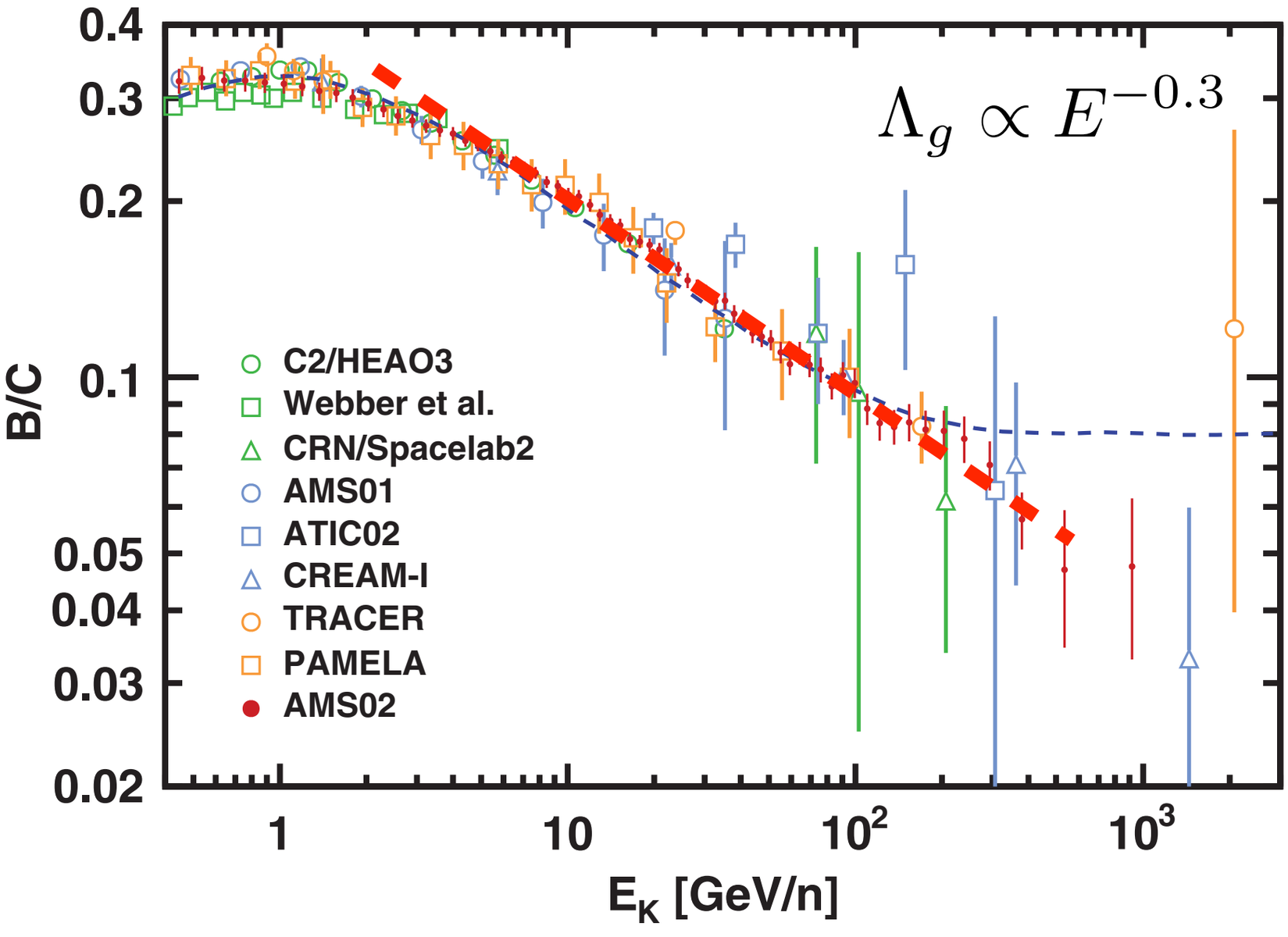

Aguilar+ (2016)

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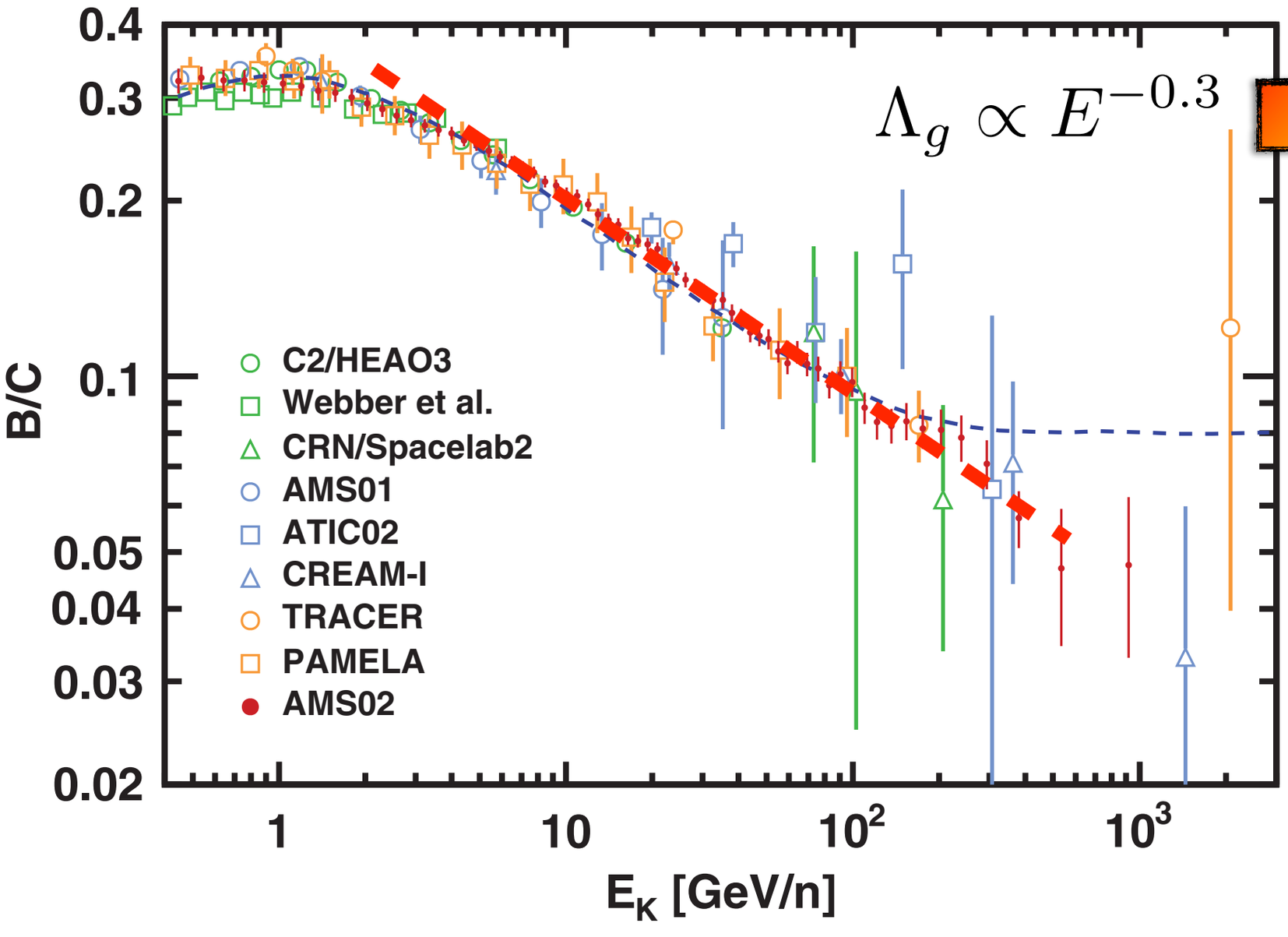

Aguilar+ (2016)

$$D \propto E^{0.3}$$

People are happy about this because it matches the prediction from quasi-linear theory in a Kolmogorov turbulence.
In fact, **predictions from realistic models of turbulence might be different.**

III-CRs are accelerated out of the (dusty) ISM through diffusive shock acceleration operating at supernova remnants

observed spectrum ->

$$n_p \propto E^{-2.7}$$

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escape time ->

$$\tau_{esc} \sim H^2/D \propto E^{-0.3}$$

$$n_p(E) \sim q_p(E) \times \tau esc \longrightarrow q_p \propto E^{-2.4}$$

quite close to the predictions of diffusive shock acceleration ->

$$\propto E^{-2}$$

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Quite close???

A large number of theoretical papers aimed at explained why SNRs inject in the ISM CRs with spectrum ~$E^{-2.4}$ instead of the canonical E^{-2} (Ptuskin&Zirakashvili, Schure&Bell, Caprioli, …)

Most of them are focussed on the non-linearity of diffusive shock acceleration

CR pressure —> shock structure —> modified acceleration

CR-driven instability —> magnetic field amplification —> modified acceleration

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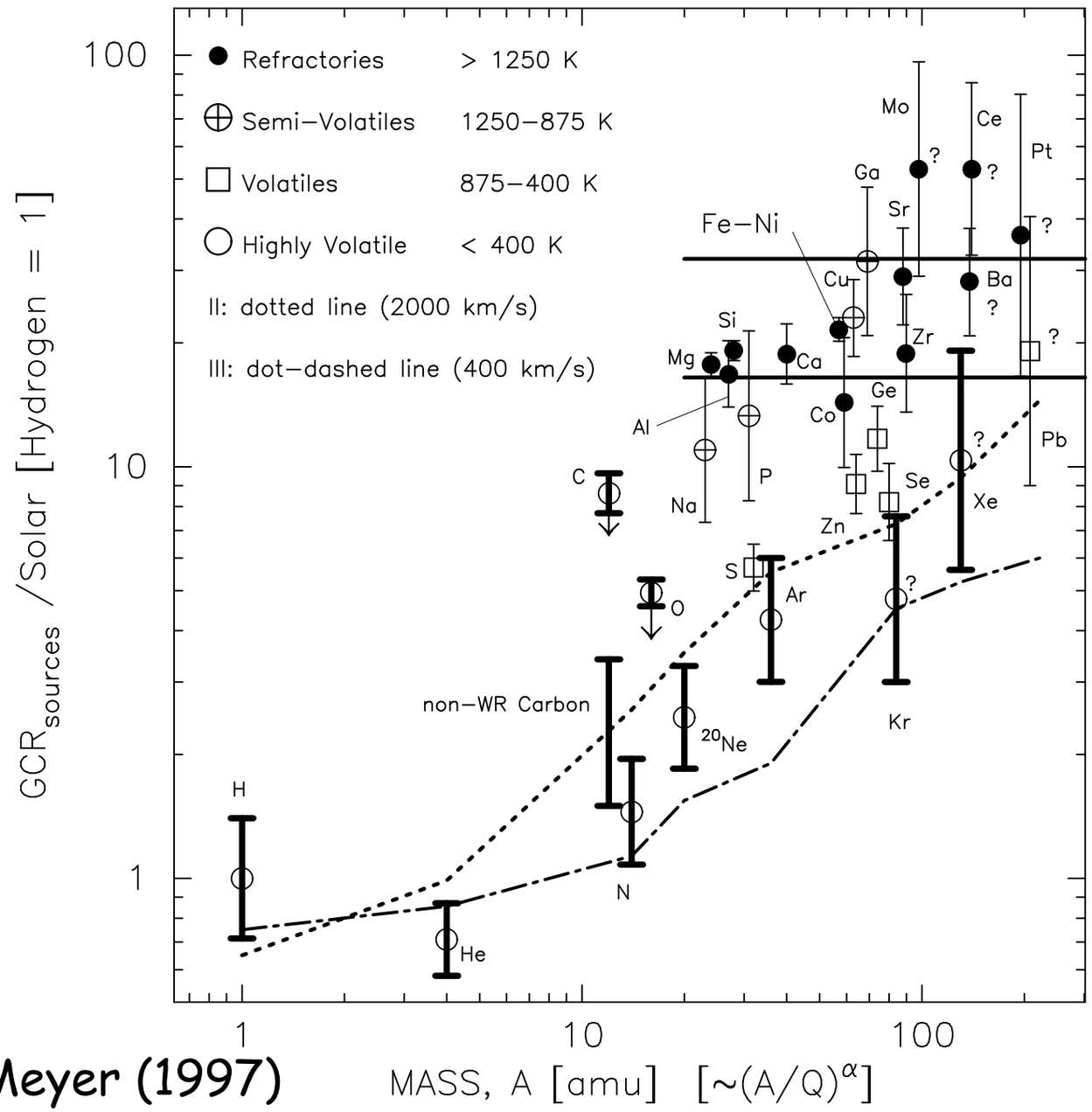

Ellison, Drury, Meyer (1997)

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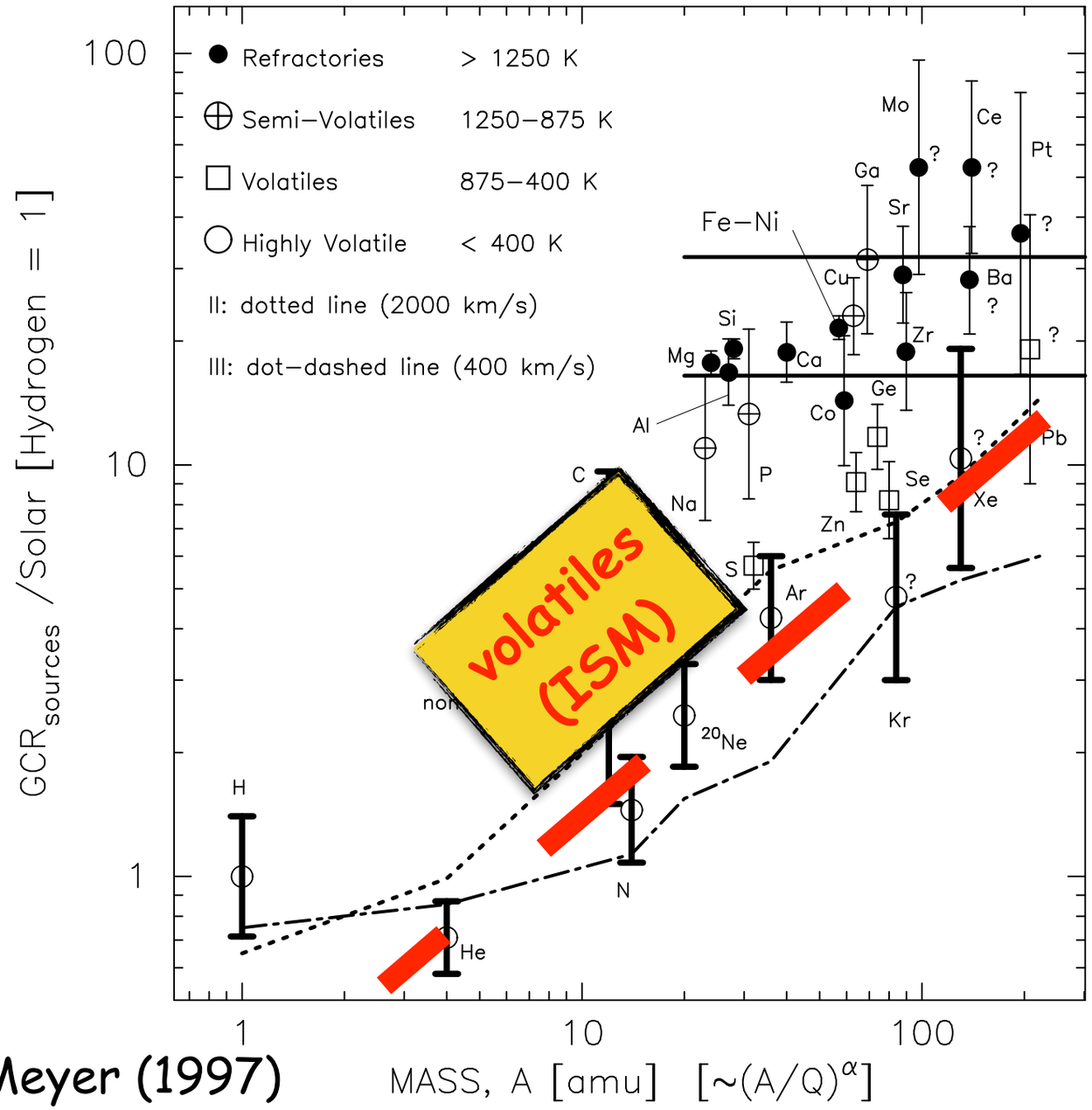

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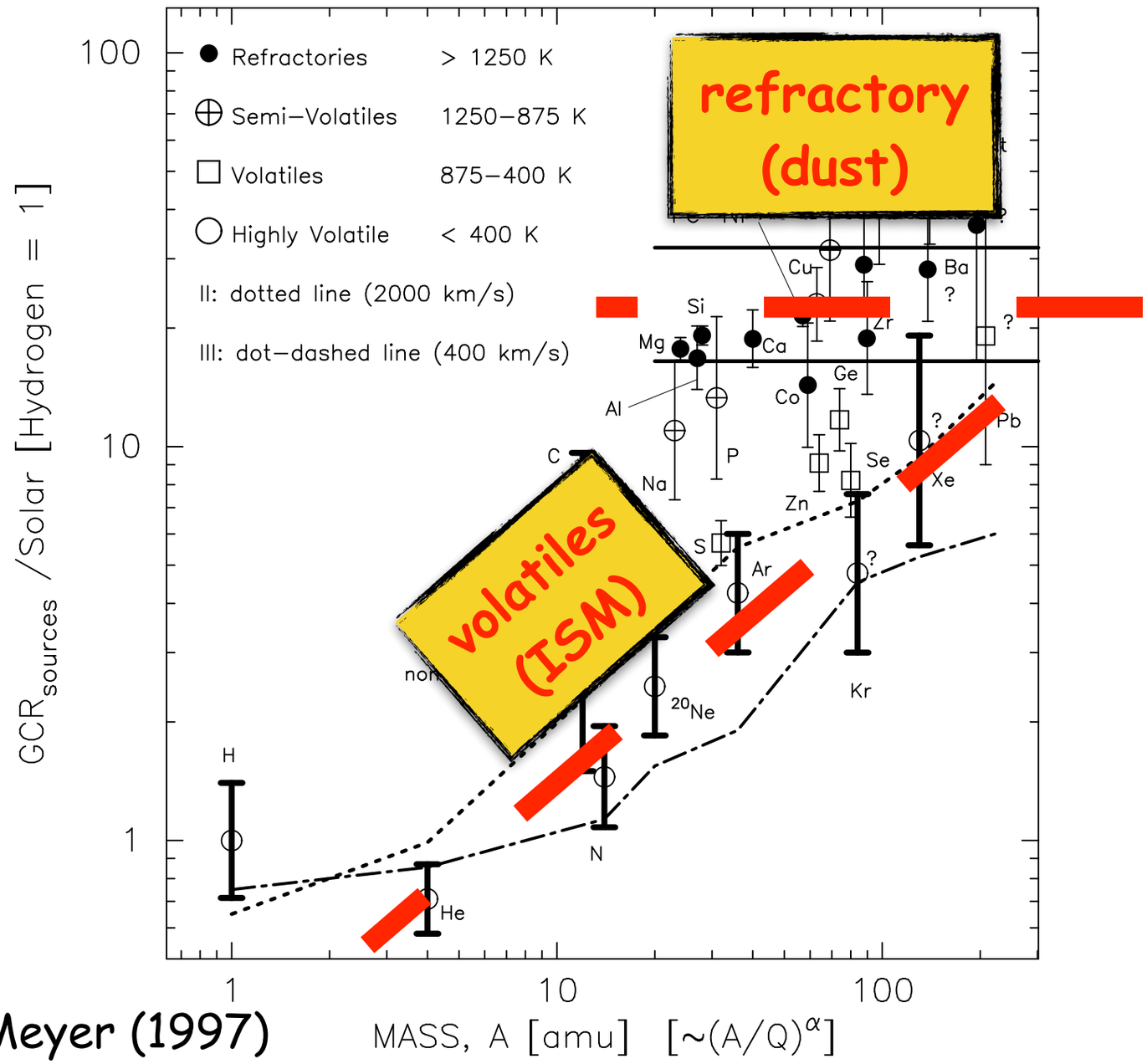

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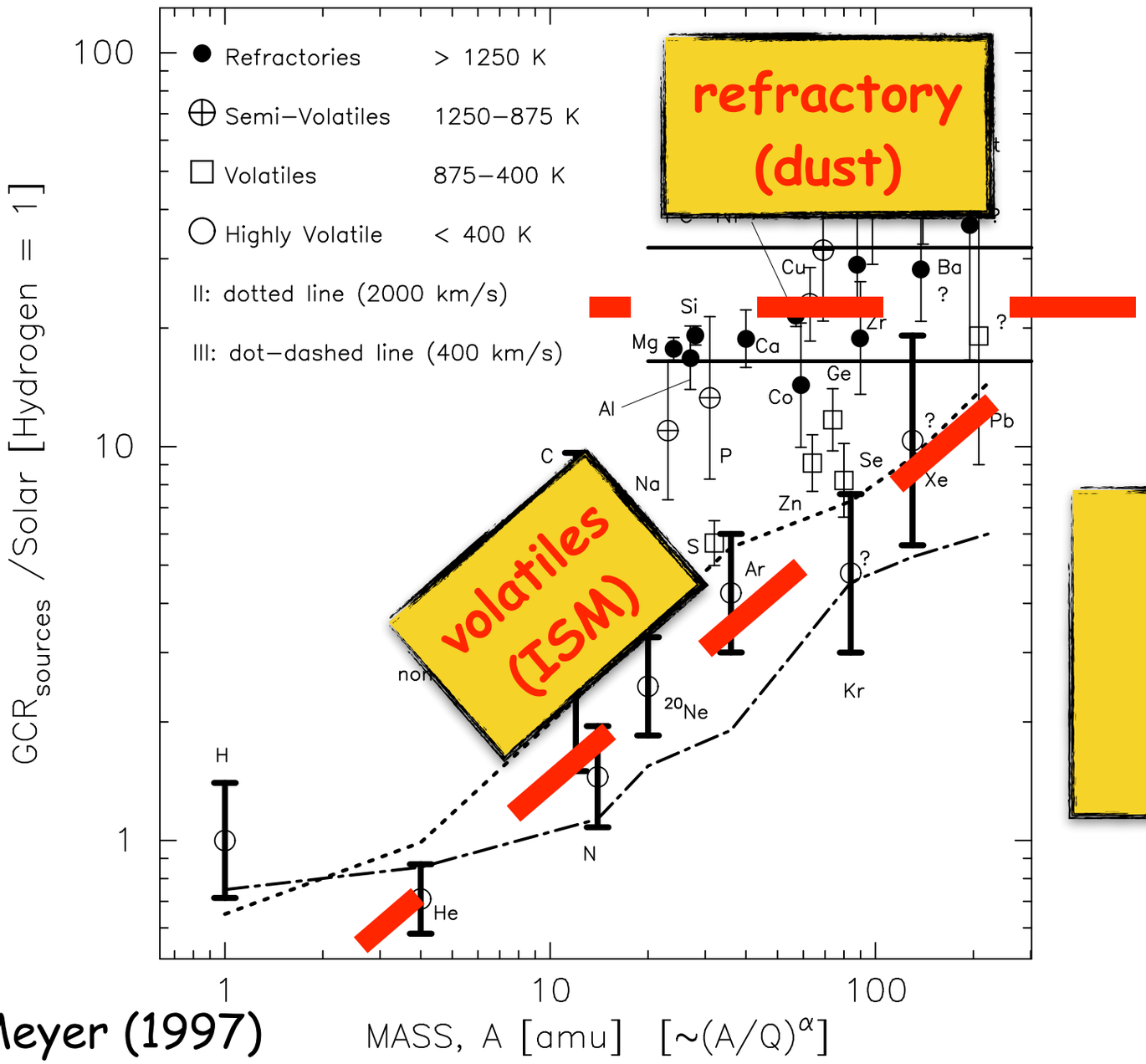
Data are best explained if refractory CRs are injected at shocks through sputtering of pre-accelerated dust grains



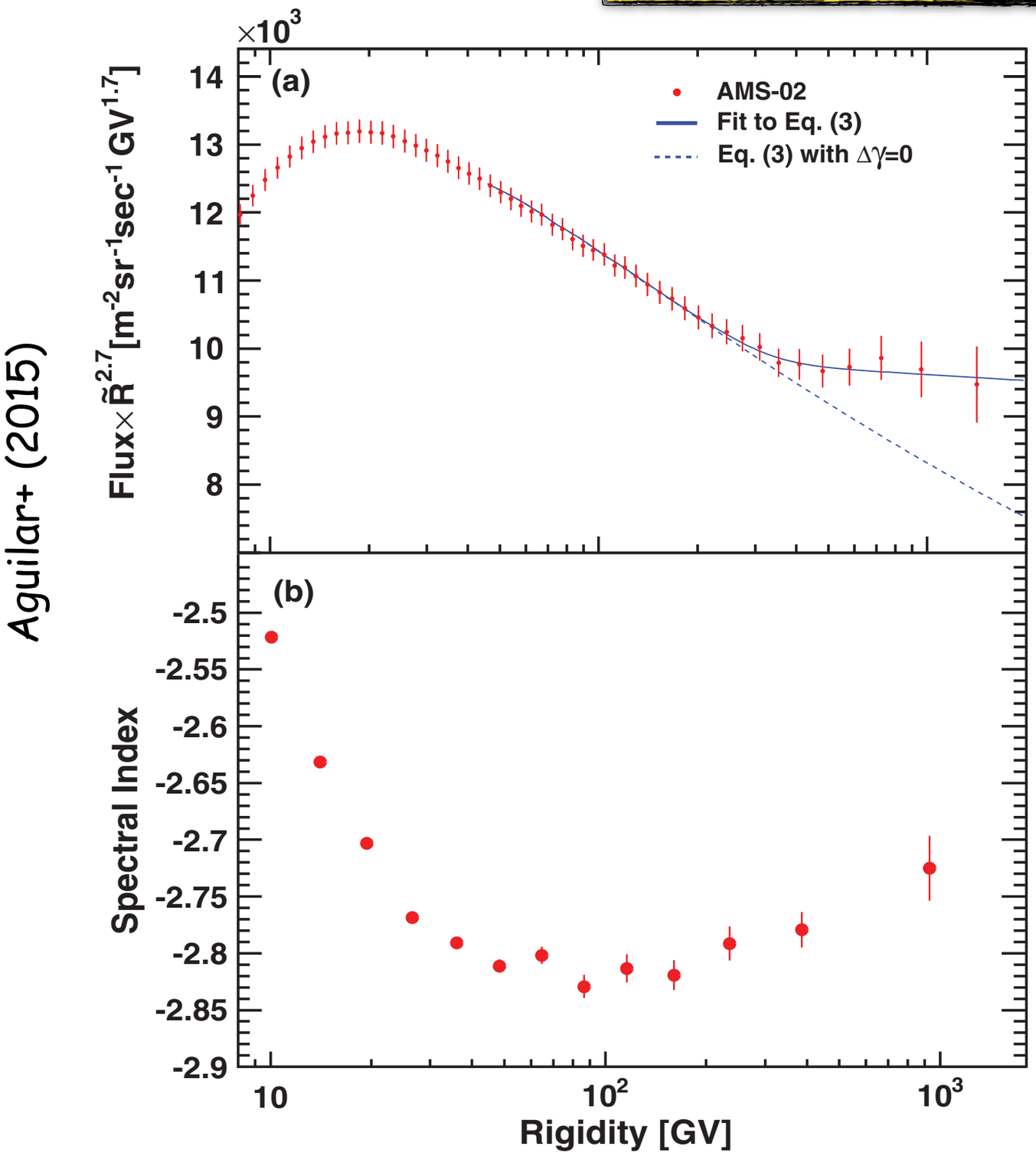
MESSAGE
CR composition deserves more attention

Ellison, Drury, Meyer (1997)

Spectral anomaly: spectral breaks

discovered by PAMELA

Aguilar+ (2017)



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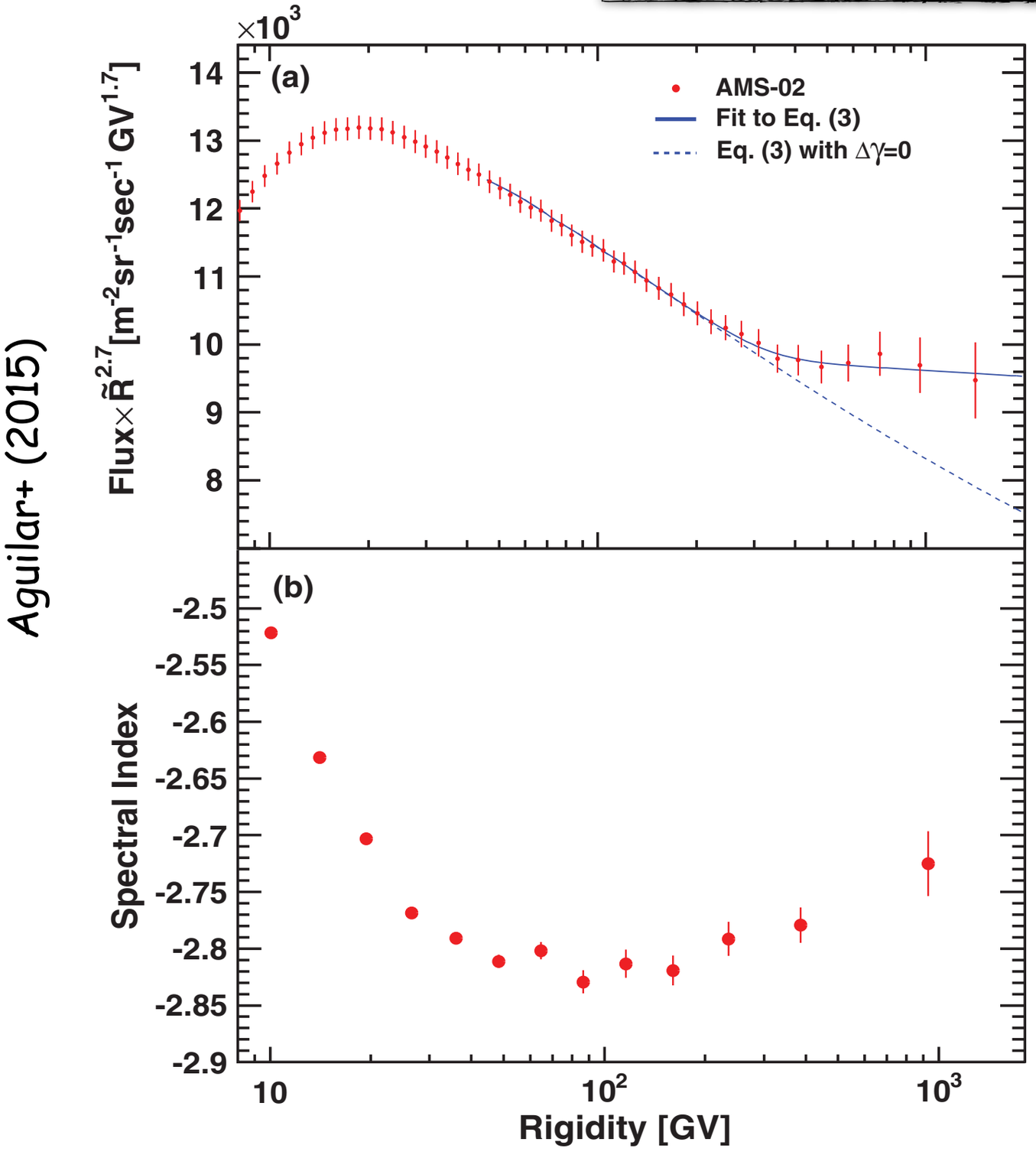
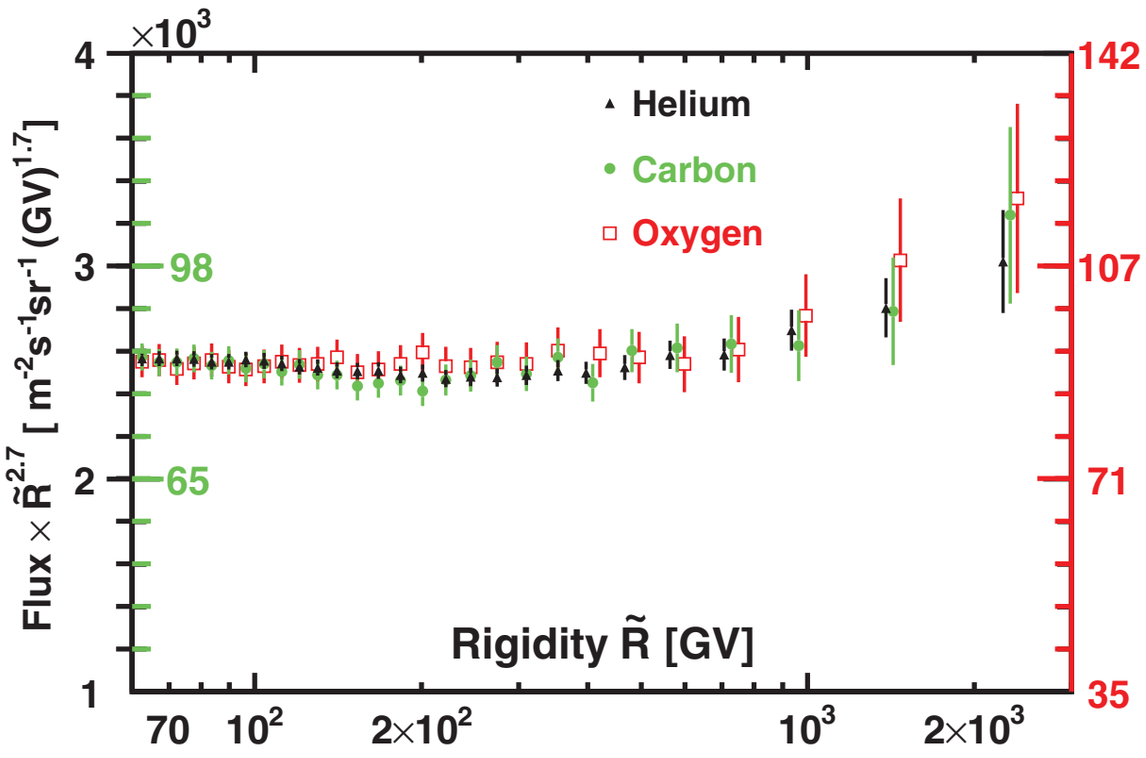


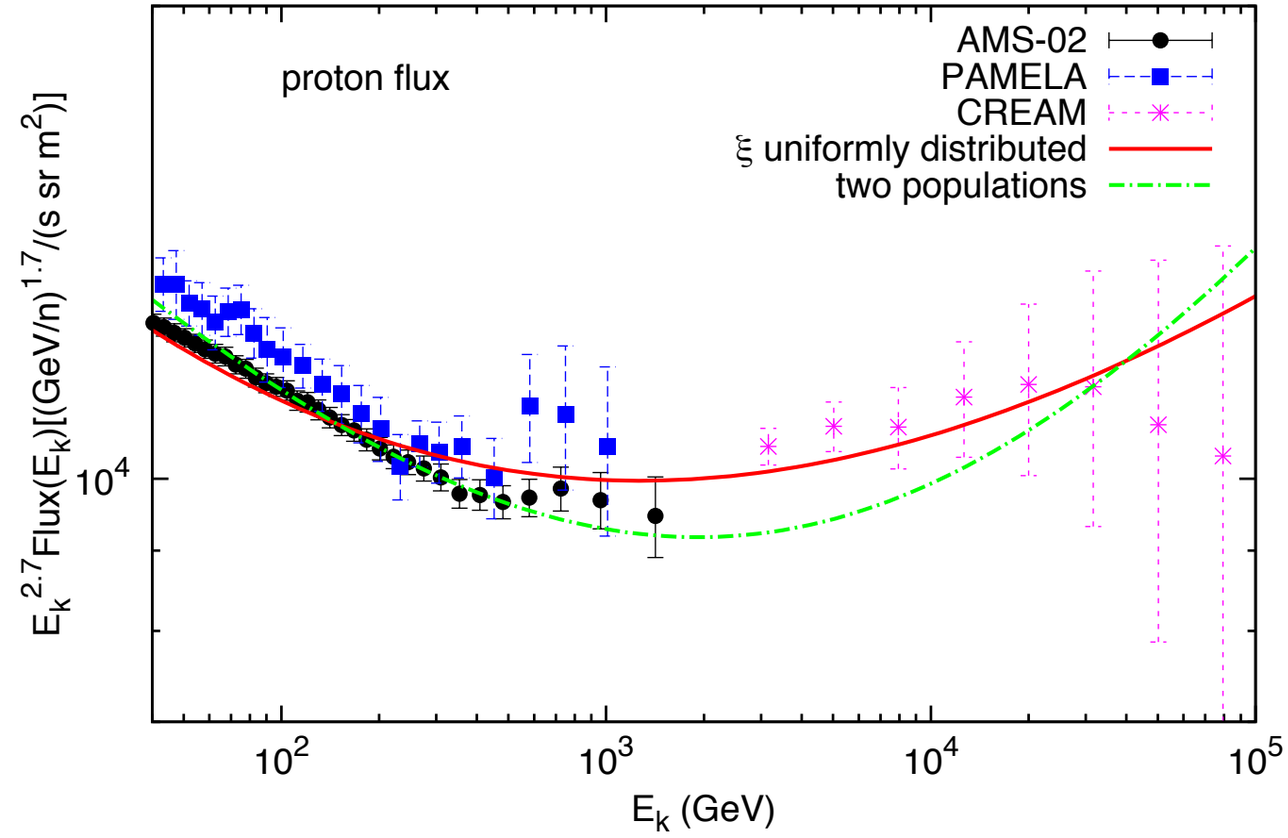


hardening break at rigidity ~ few 100 GV

Sources or propagation?

Many many many references…….

source spectra w. break
power law diffusion



Recchia & Gabici (2018)

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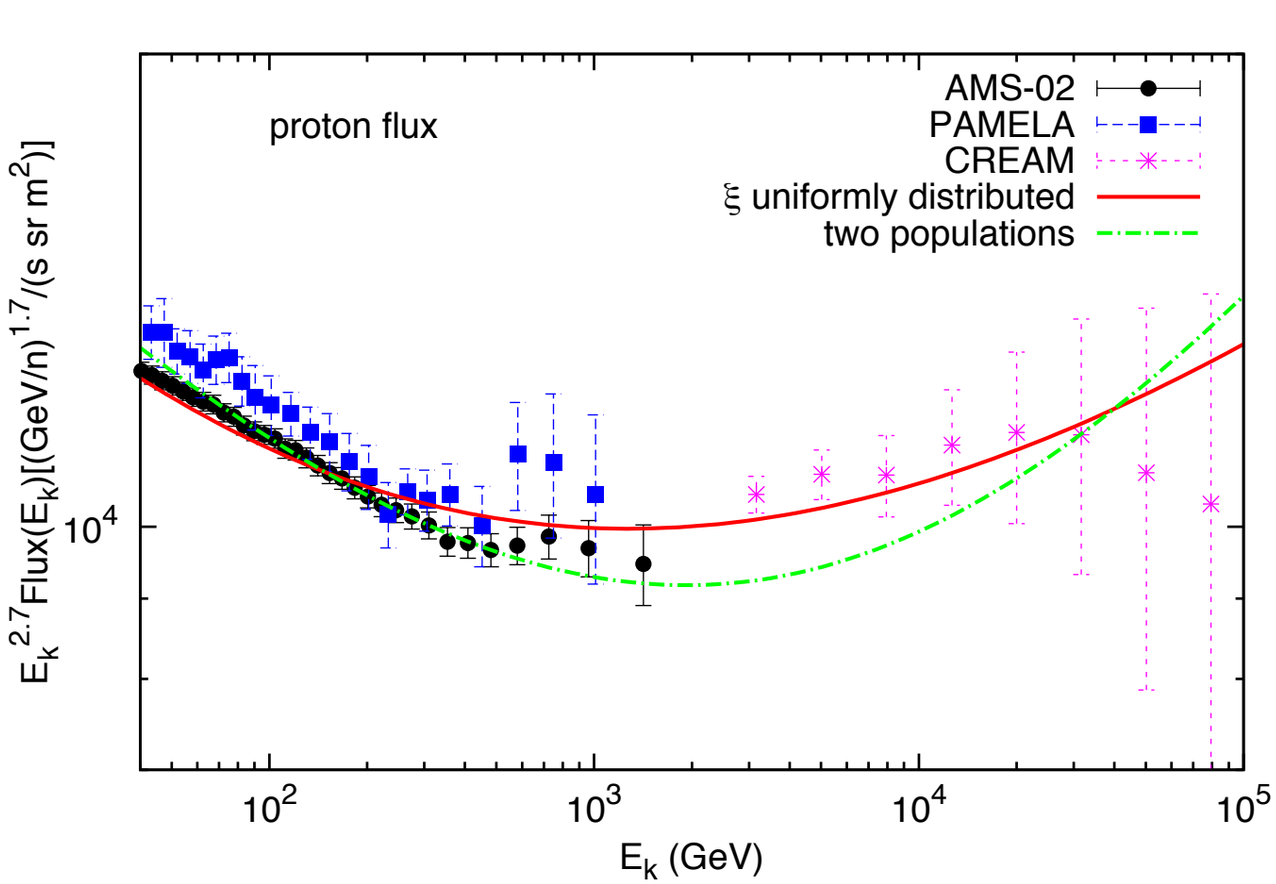
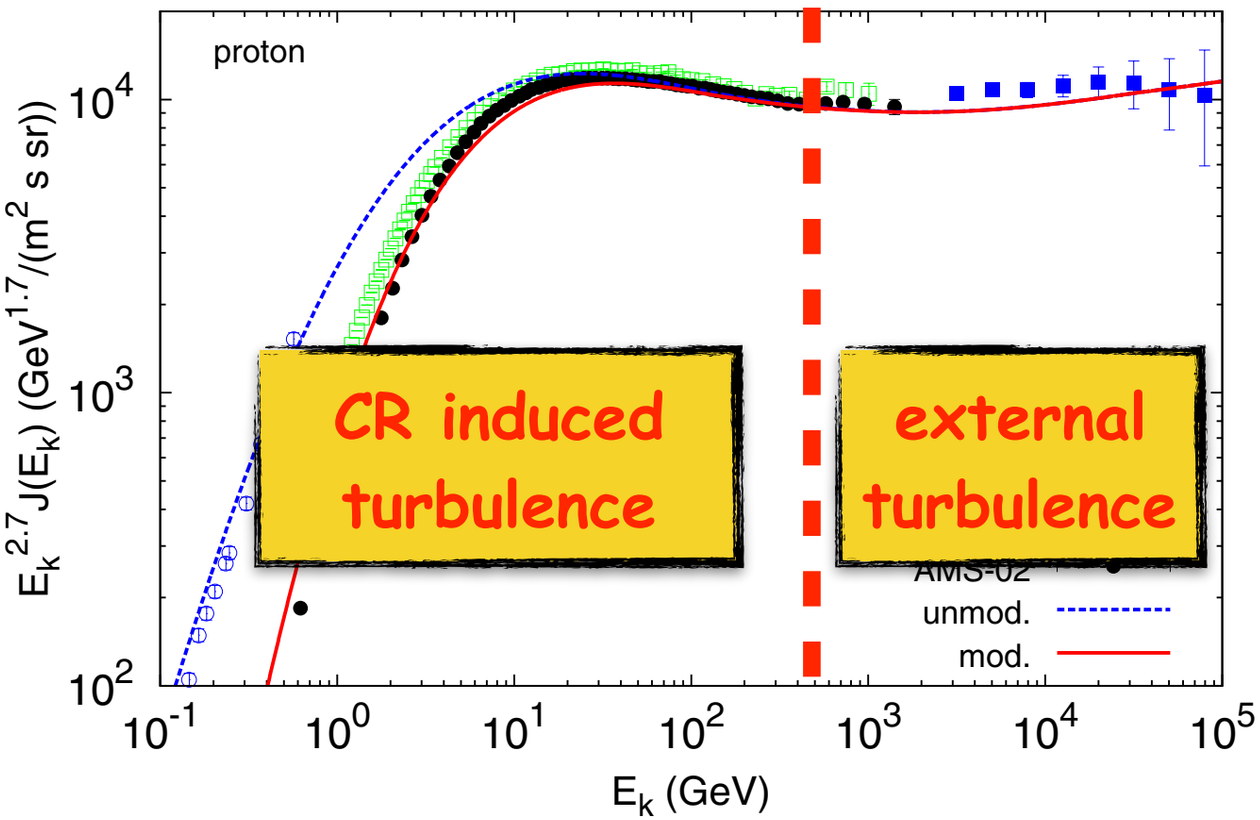


Recchia & Gabici (2018)

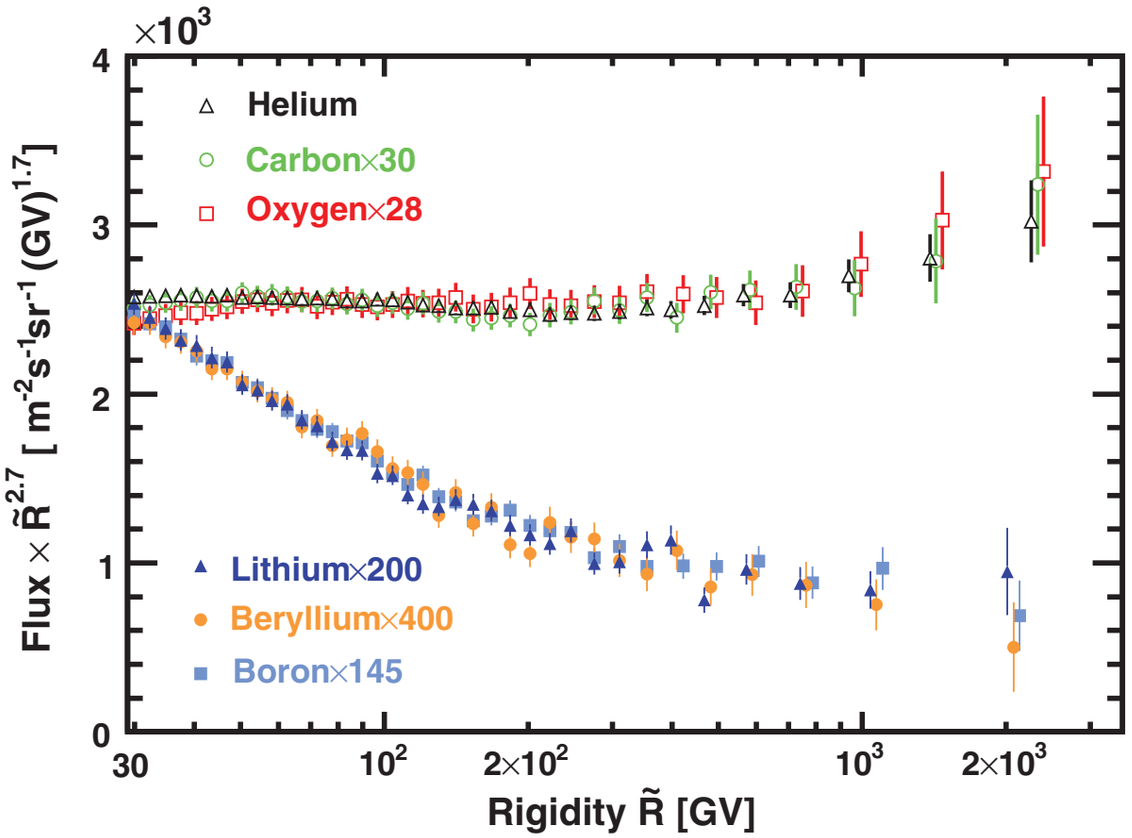
Aloisio, Blasi & Serpico (2015)



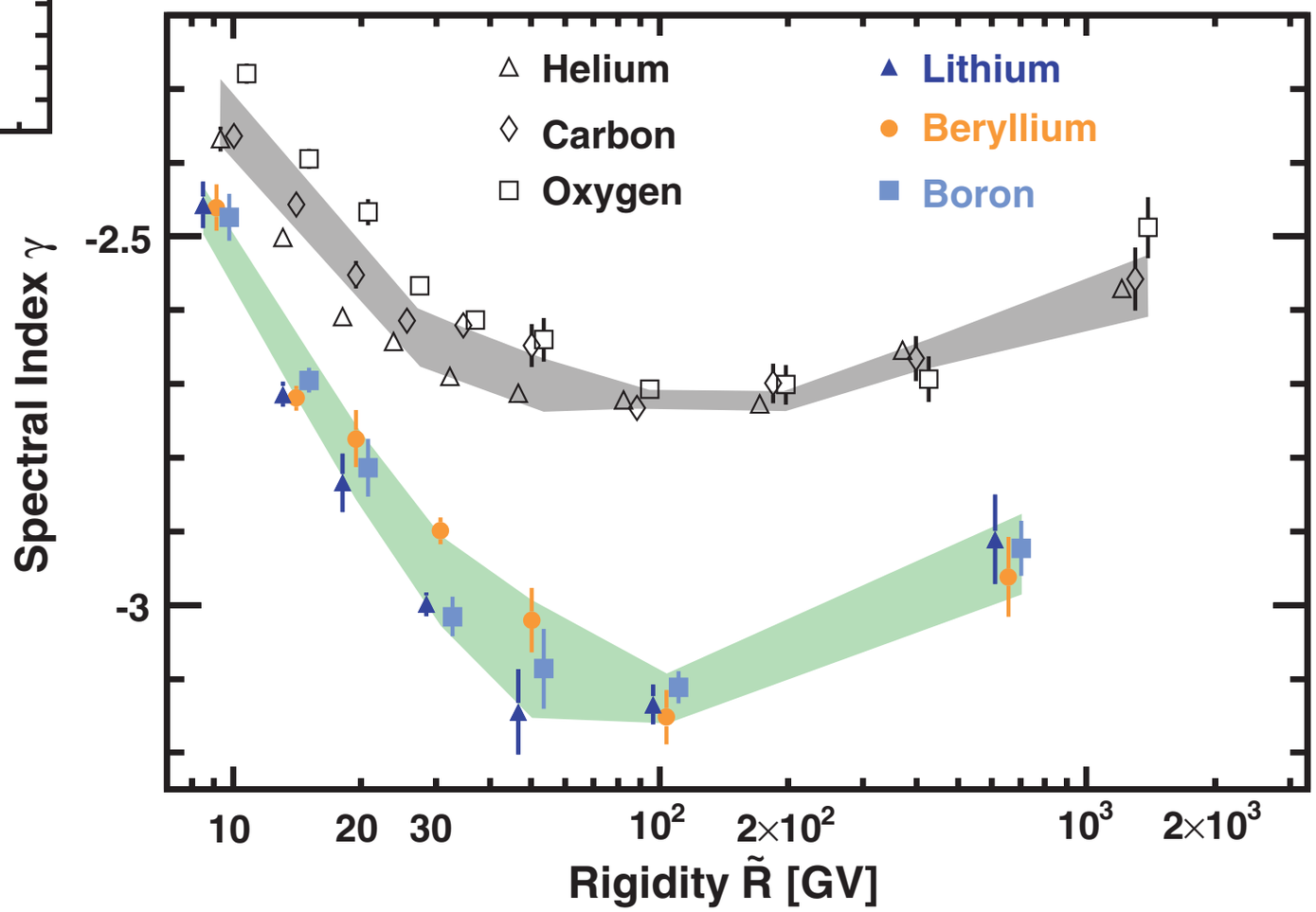
source spectra power law
diffusion w. break

see the incredibly ahead of time paper
by Farmer & Goldreich (2004)

Most likely propagation



break for secondaries is TWICE more pronounced

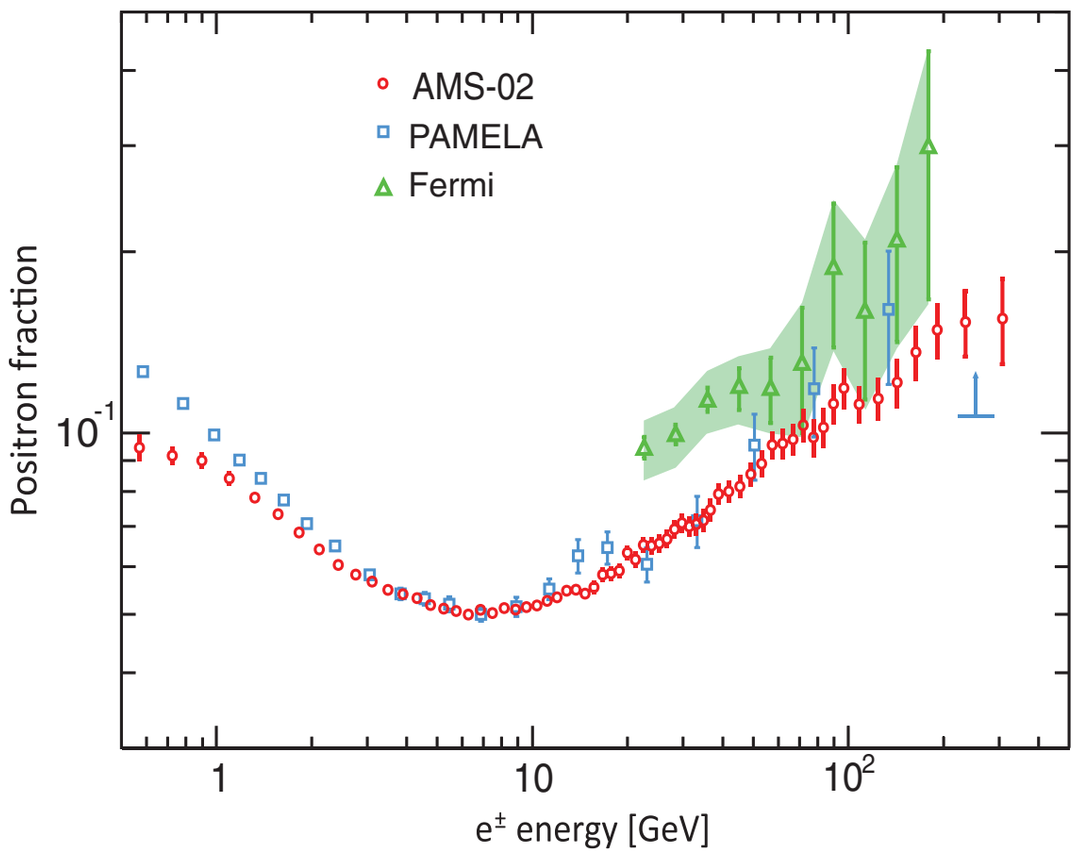


Consider all uncertainties (e.g. cross sections…) before making a conclusive claim

Aguilar+ (2018)

Positron anomaly (?)

Aguilar+ (2013)



Dark matter?

Positron anomaly (?)

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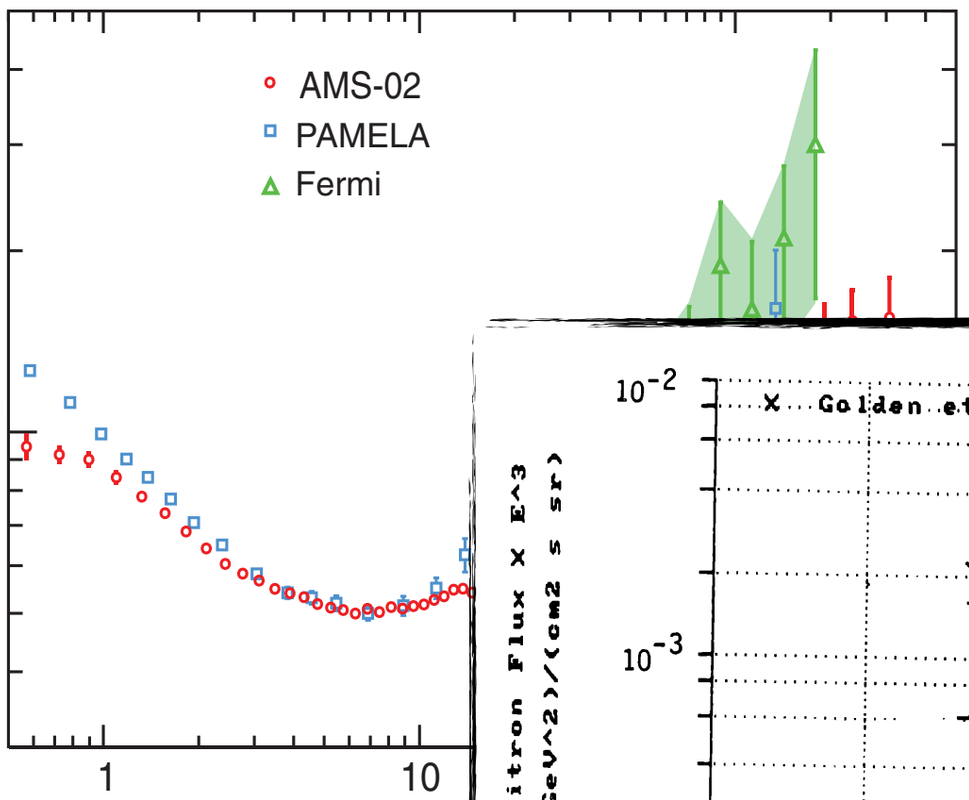
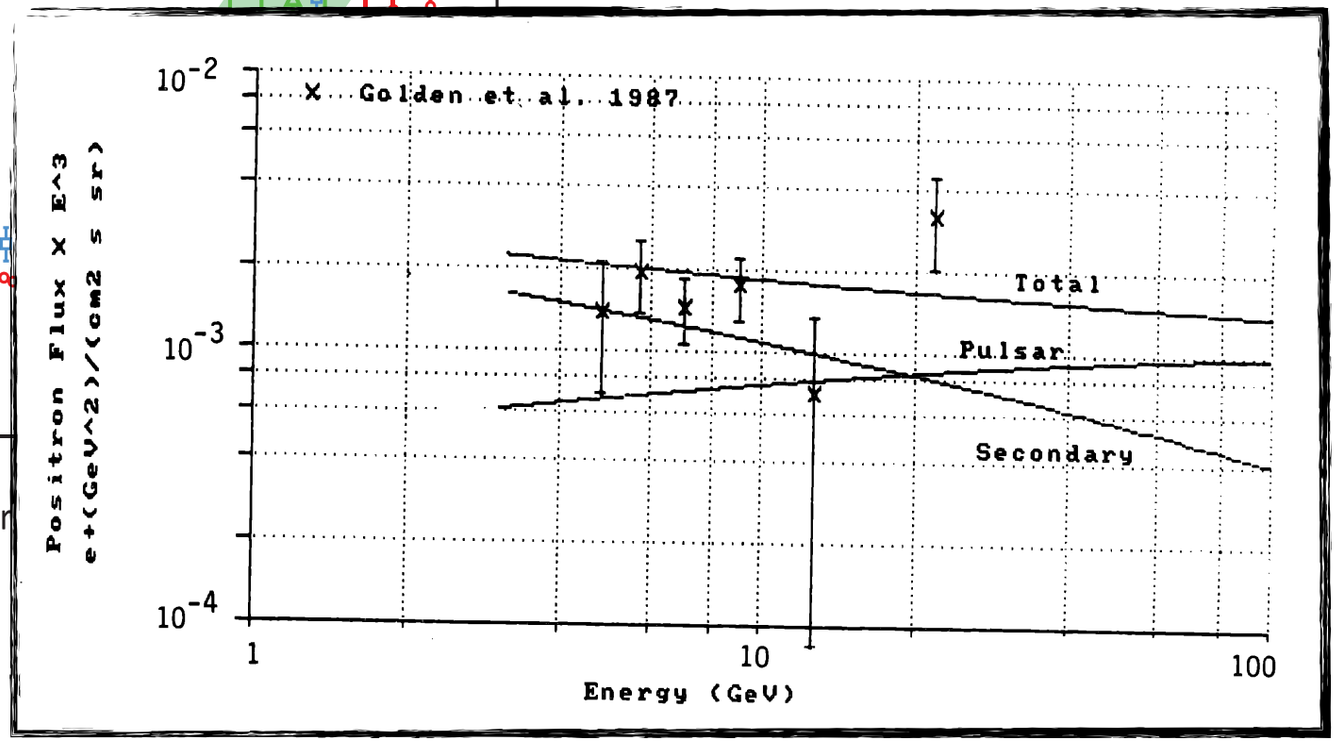


Harding & Ramaty (1987)



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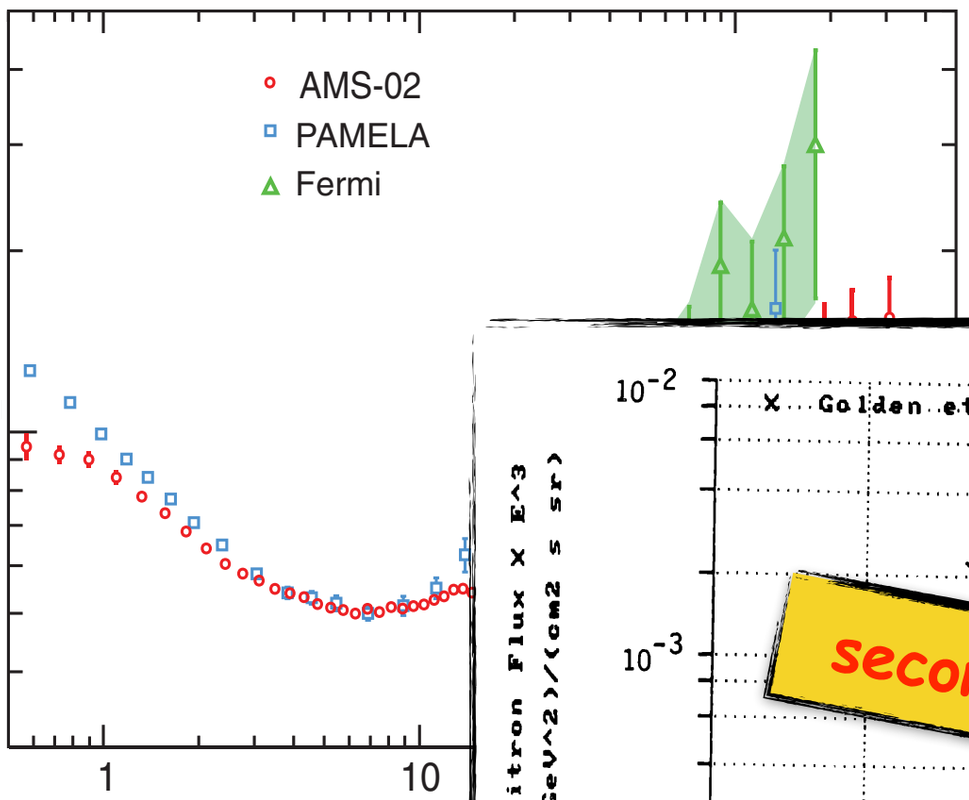

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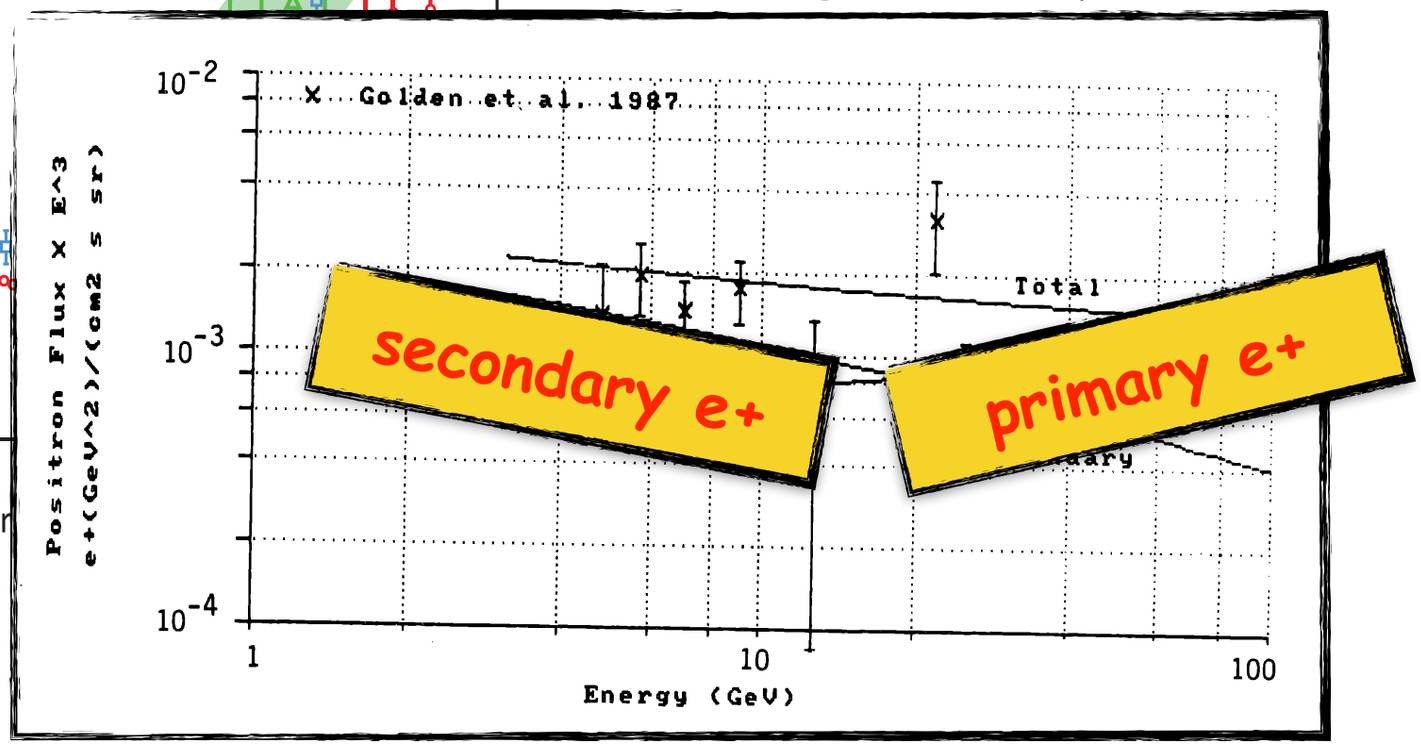

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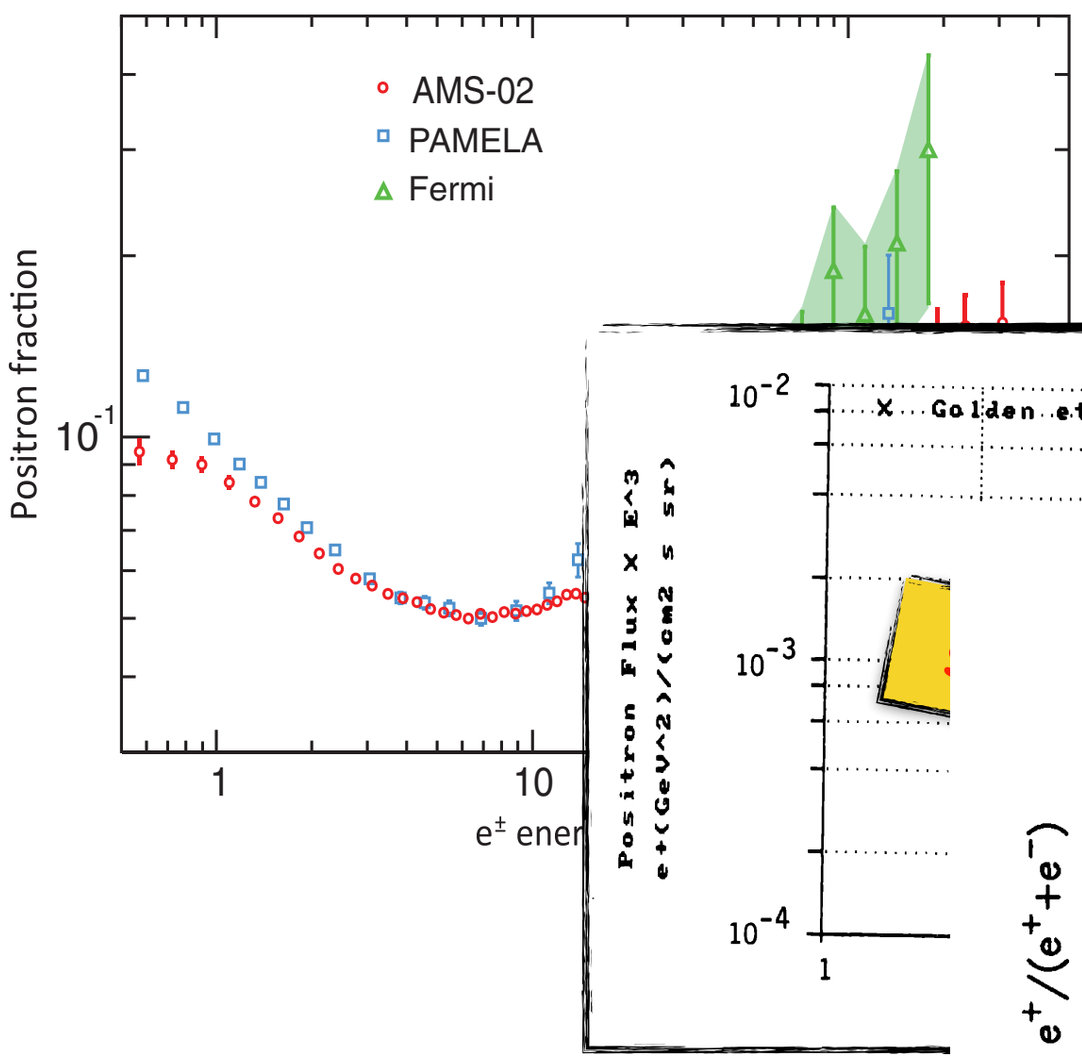

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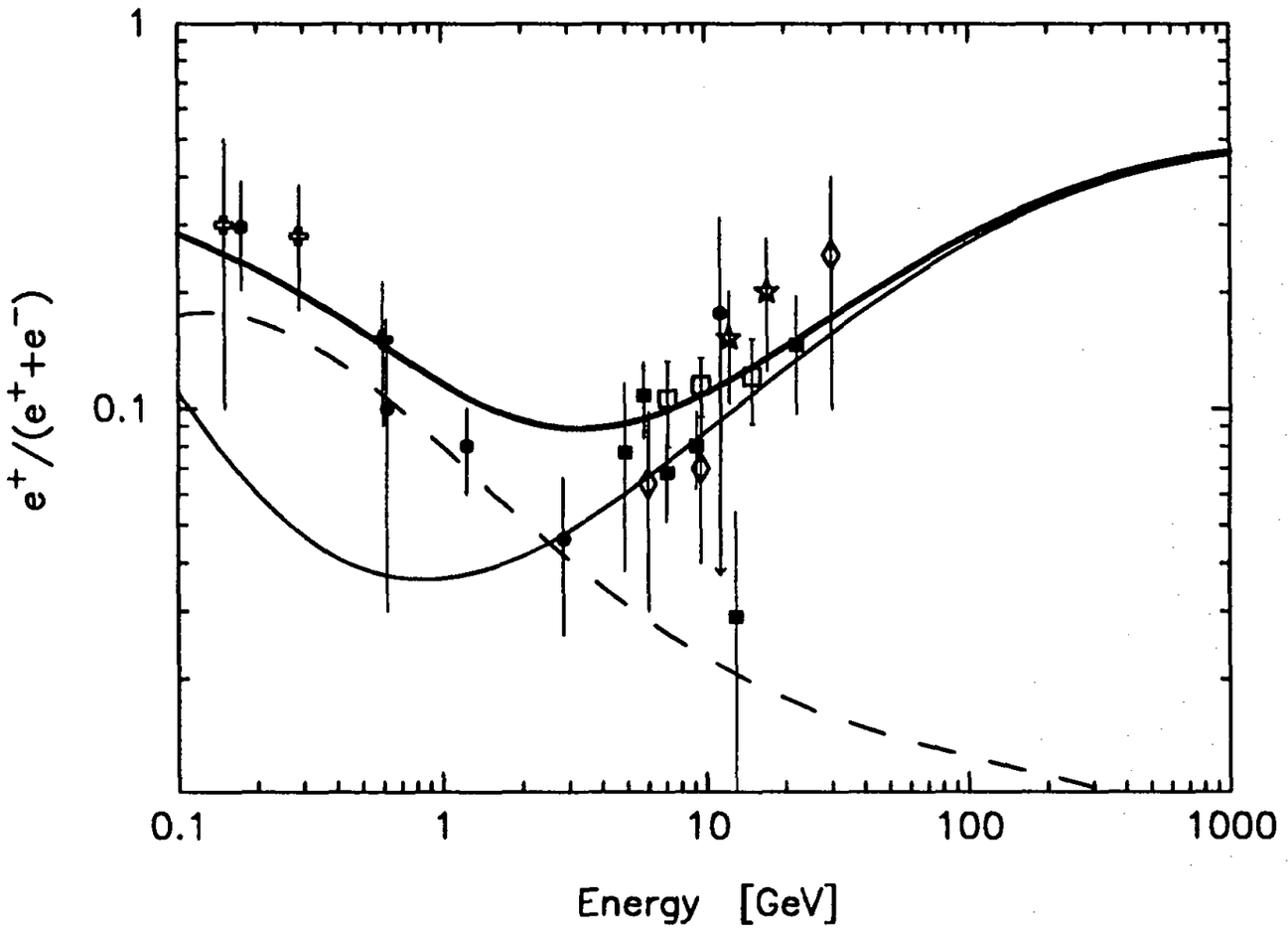
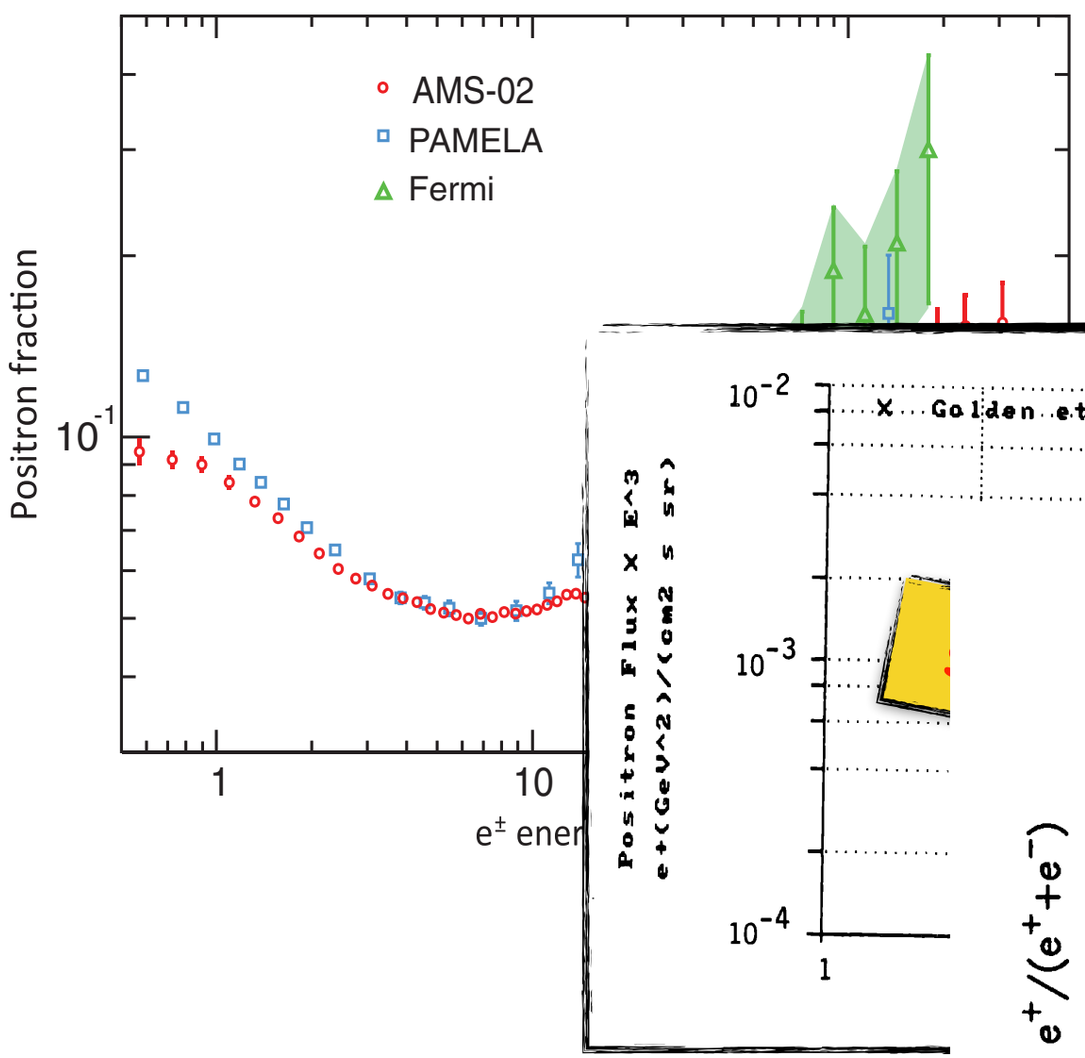


Aharonian+ (1995)

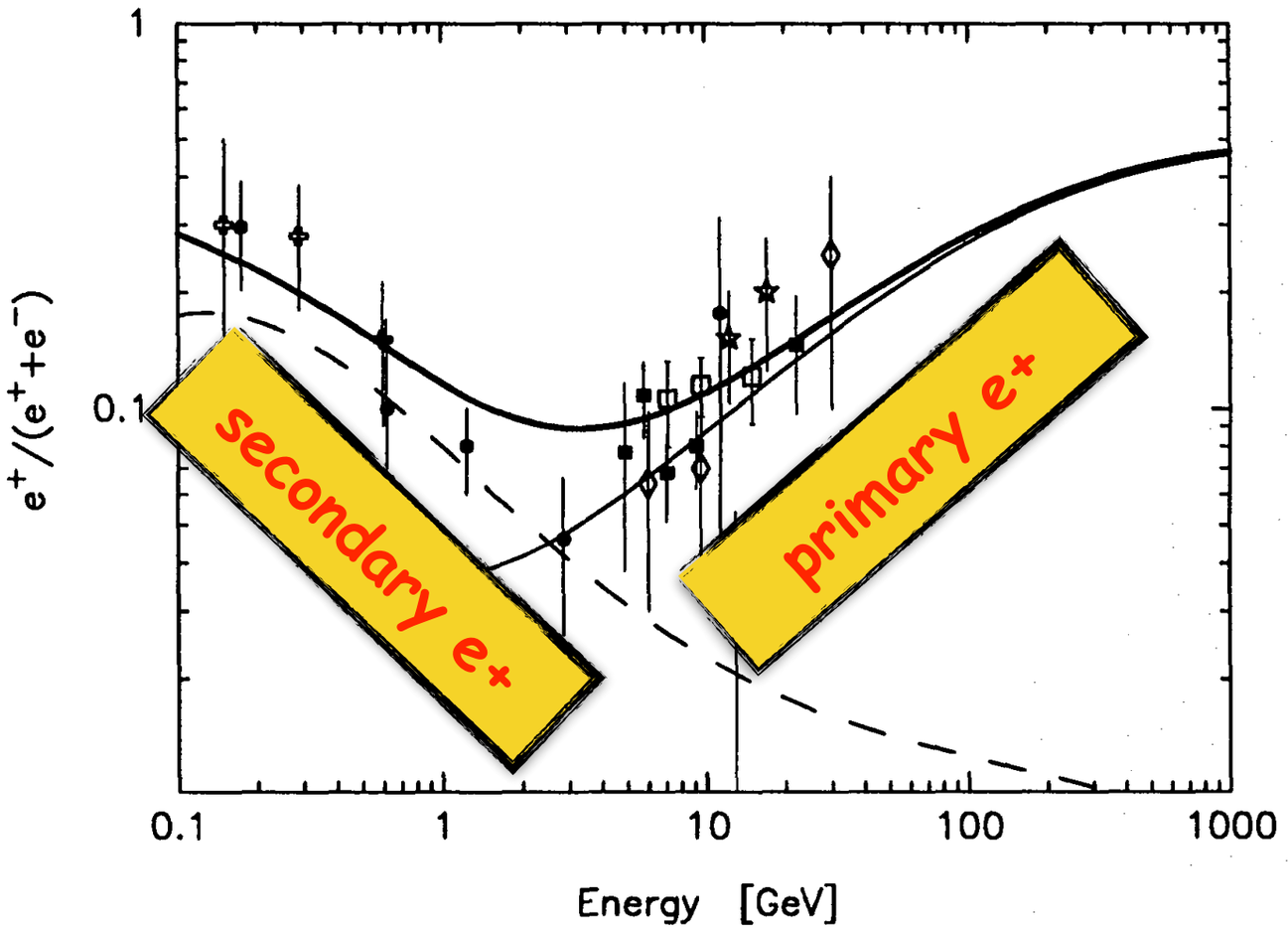
Positron anomaly (?)

Aguilar+ (2013)



Dark matter?

Harding & Ramaty (1987)



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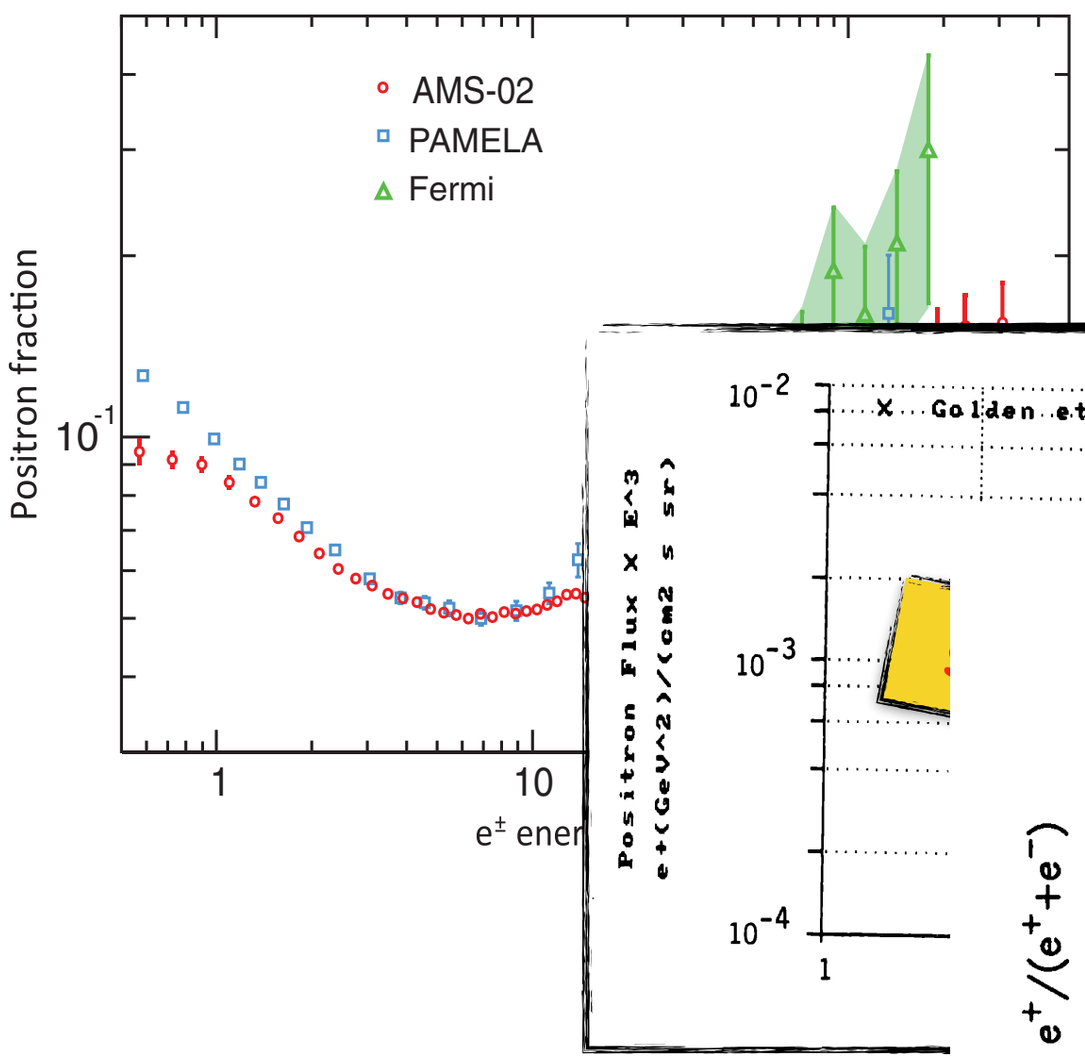

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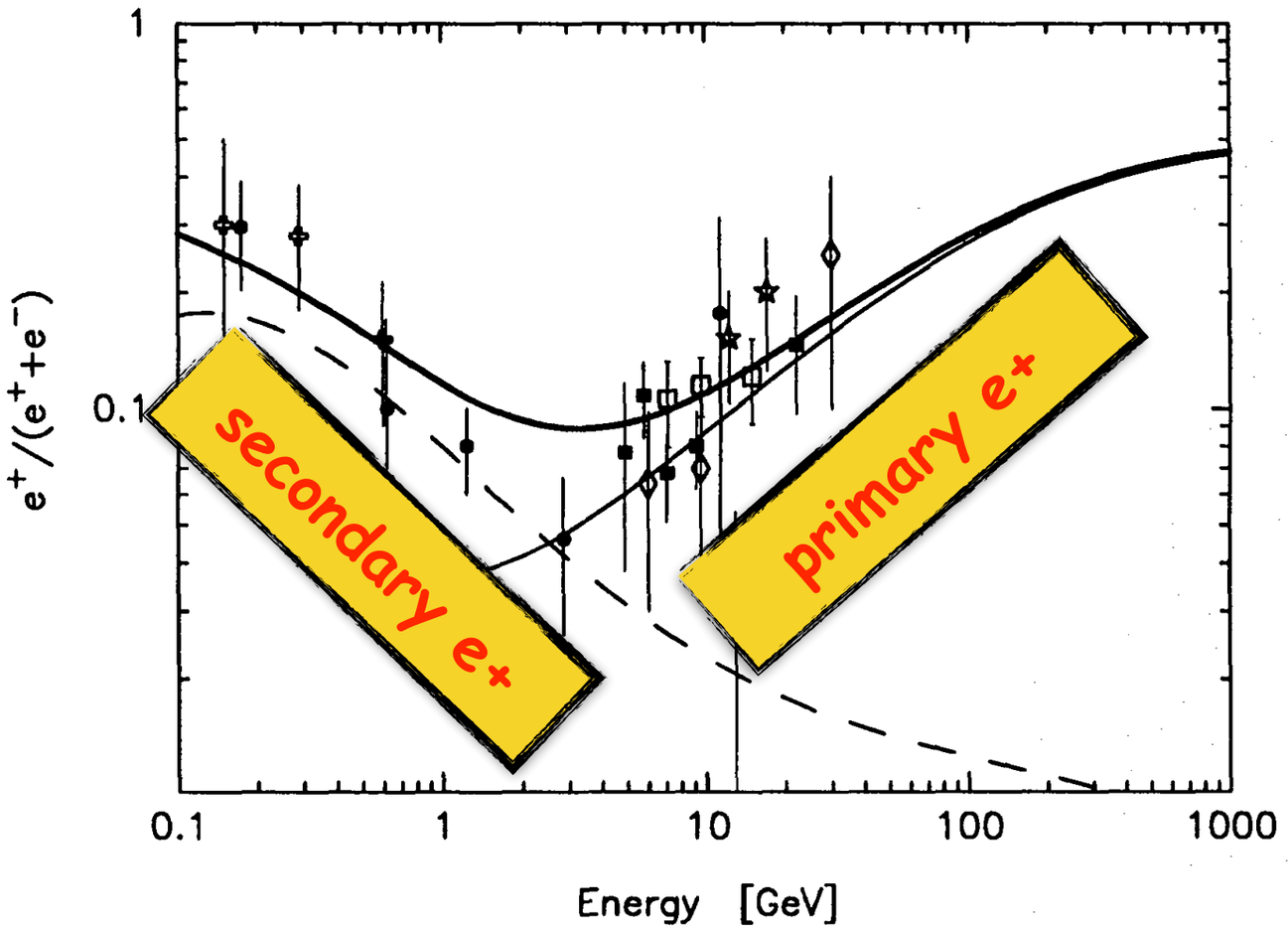
Dark matter?

Positron excess can be explained within a standard, solid, and cheap astrophysical framework -> a nearby pulsar



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Exercise for undergrads: compute spectra of secondary p̄ and e^+

protons

injection spectrum —> $q_p \propto E^{-2.4}$

escape time—> $\tau_{esc} \propto E^{-0.3}$

$$n_p \sim q_p \times \tau_{esc} \propto E^{-2.7}$$

Exercise for undergrads: compute spectra of secondary p̄ and e⁺

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anti-protons

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Exercise for undergrads: compute spectra of secondary p̄ and e^+

positrons

injection spectrum —> $q_{e+} \propto n_p \propto q_p \times \tau_{esc}$

Exercise for undergrads: compute spectra of secondary p̄ and e^+

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equilibrium spectrum (cooled)

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Exercise for undergrads: compute spectra of secondary p̄ and e^+

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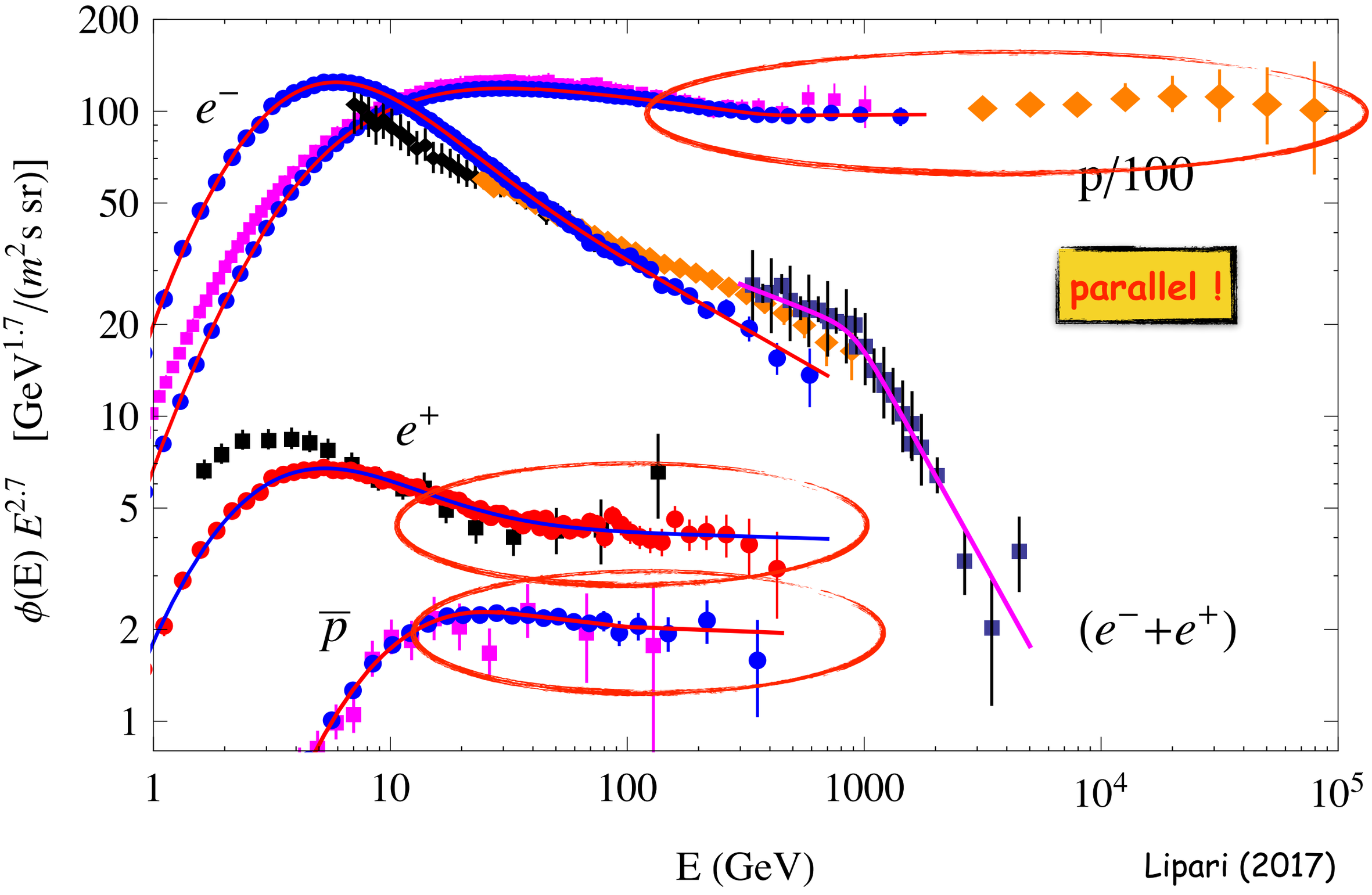
SUMMARY

protons -> $E^{-2.7}$ antiprotons -> E^{-3} positrons -> E^{-3} or $E^{-3.7}$

Exercise for undergrads: compute spectra of secondary p̄ and e⁺



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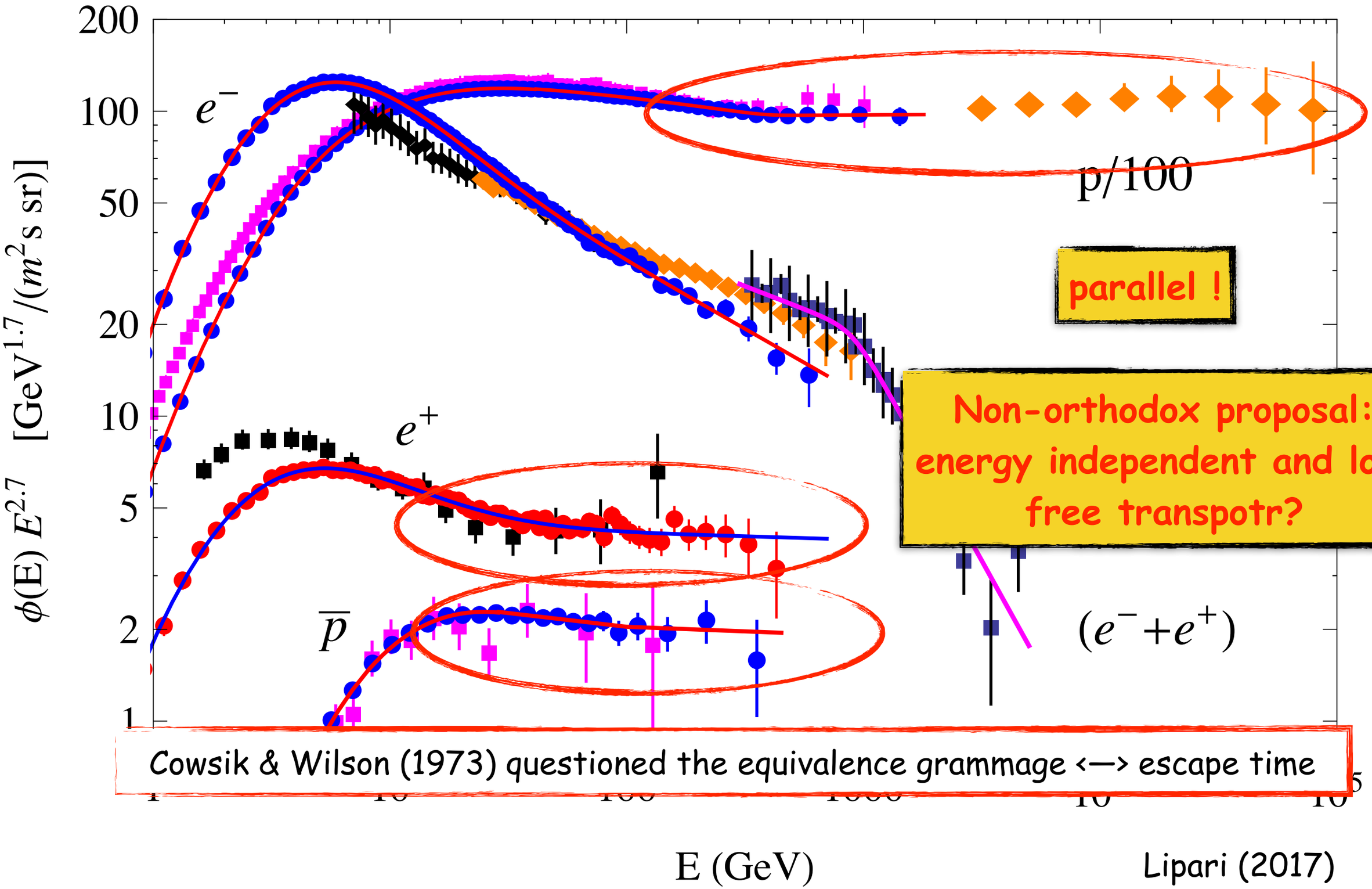
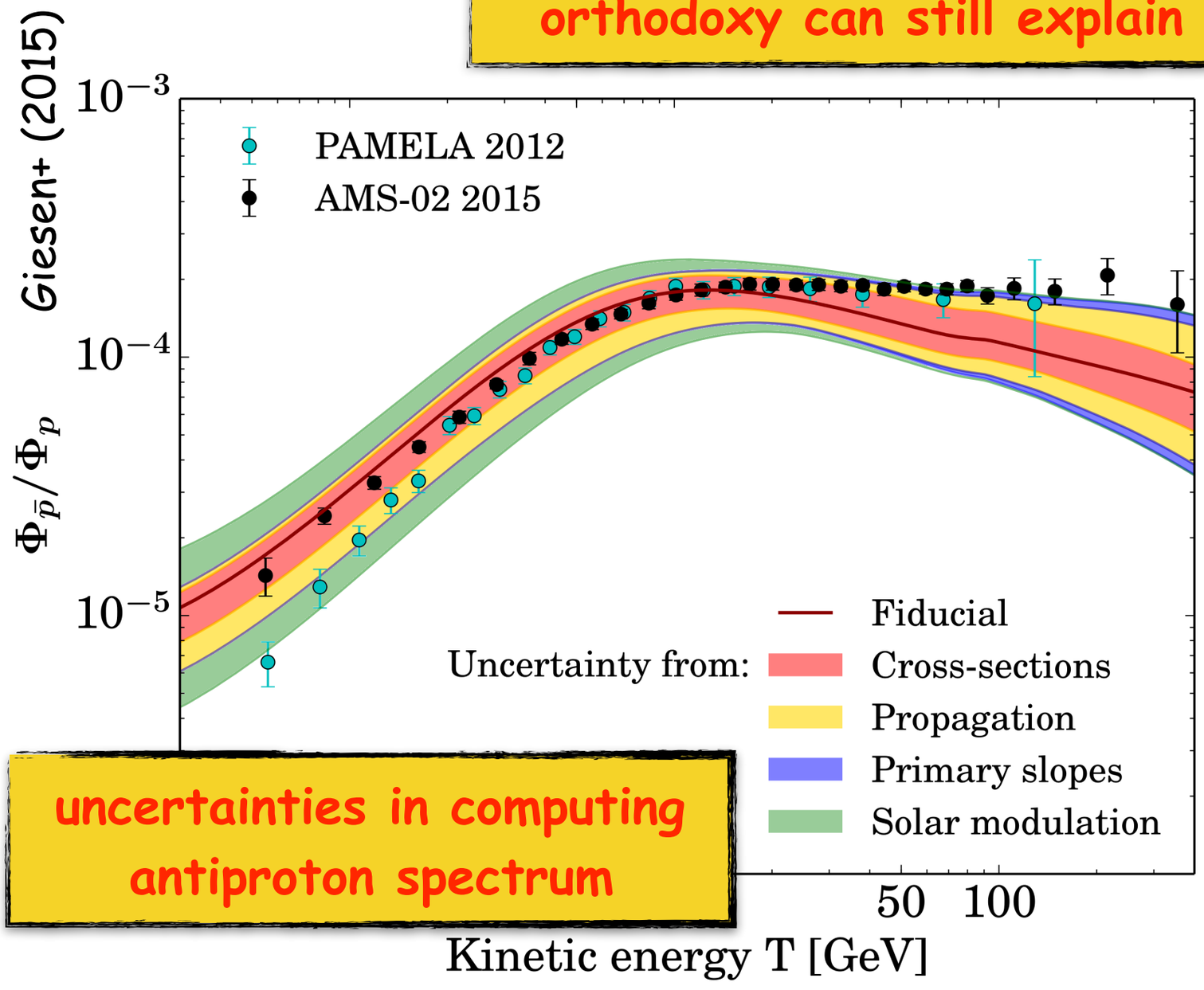


Cowsik & Wilson (1973) questioned the equivalence grammage <—> escape time

Lipari (2017)

Exercise for undergrads: compute spectra of secondary p̄ and e⁺

orthodoxy can still explain observations



uncertainties in computing antiproton spectrum

Exercise for undergrads: compute spectra of secondary p̄ and e^+

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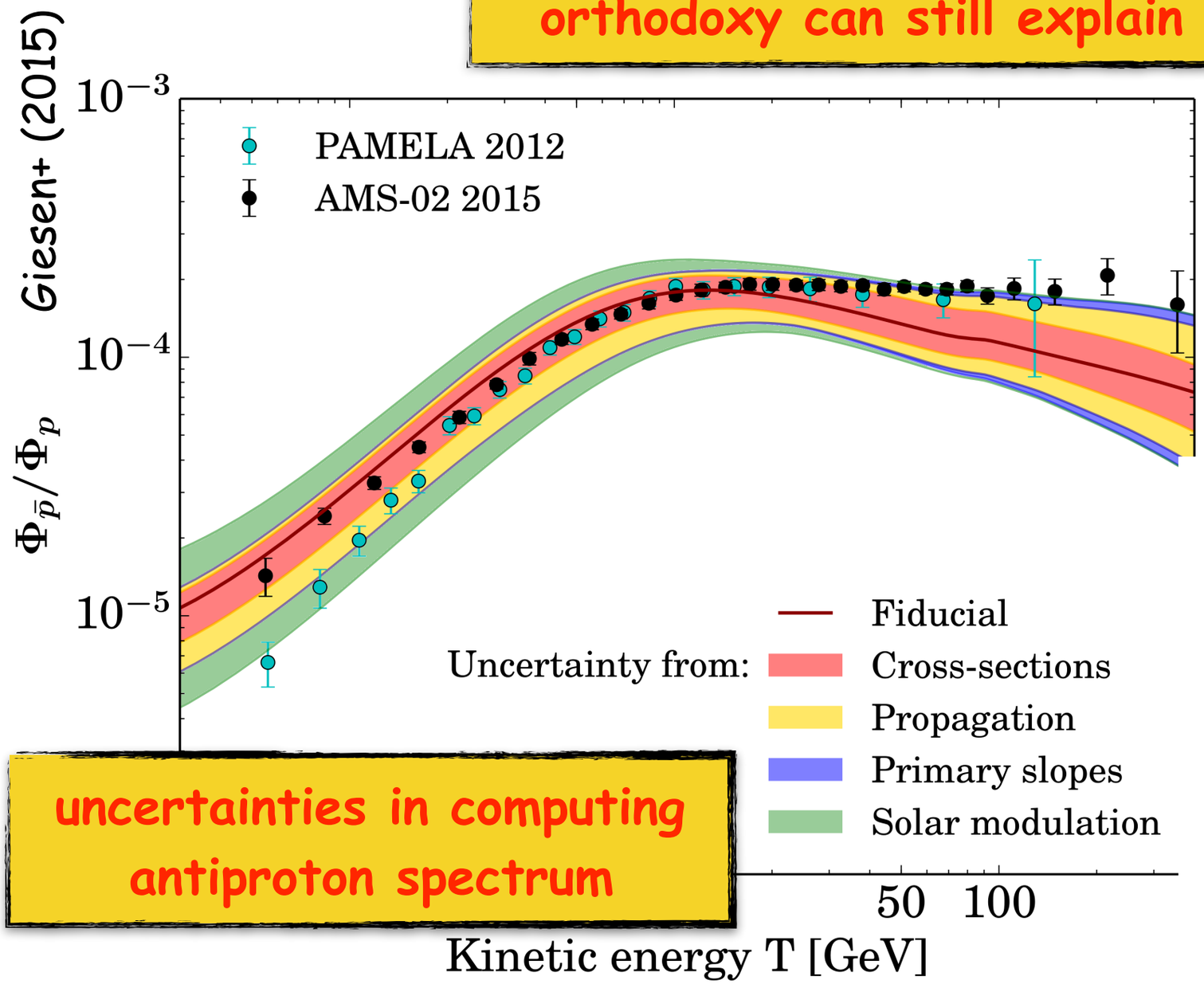
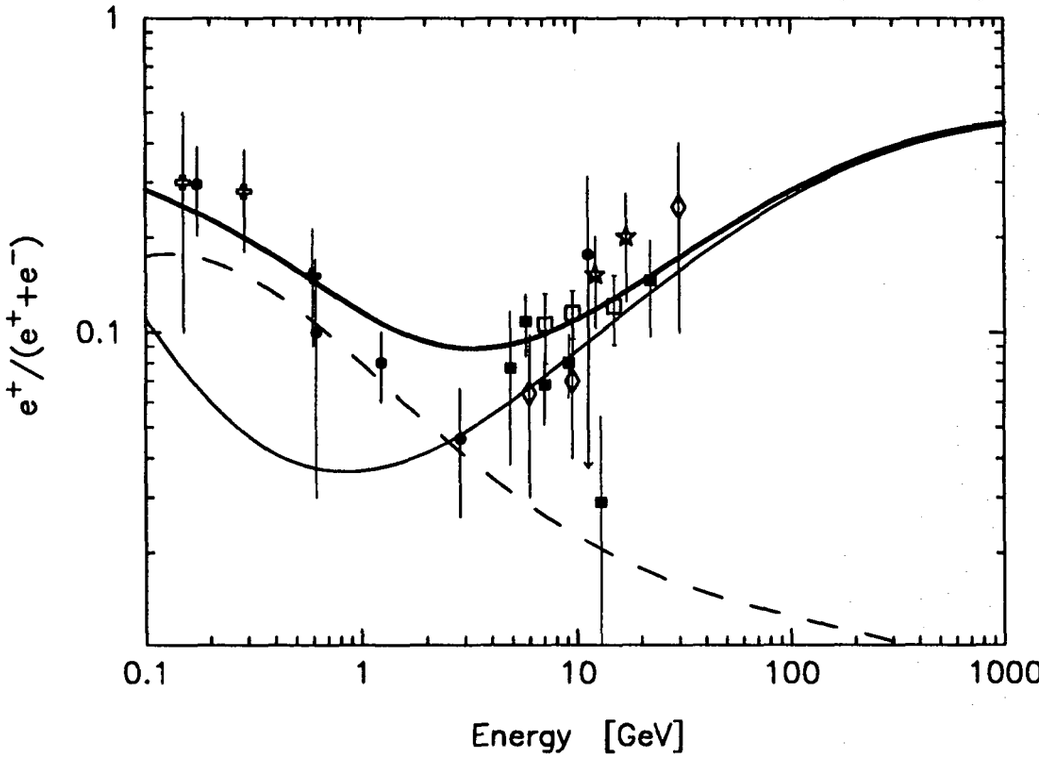


uncertainties in computing antiproton spectrum

local source of primary positrons

Aharonian+ (1995)



Exercise for undergrads: compute spectra of secondary p̄ and e^+

Disclaimer

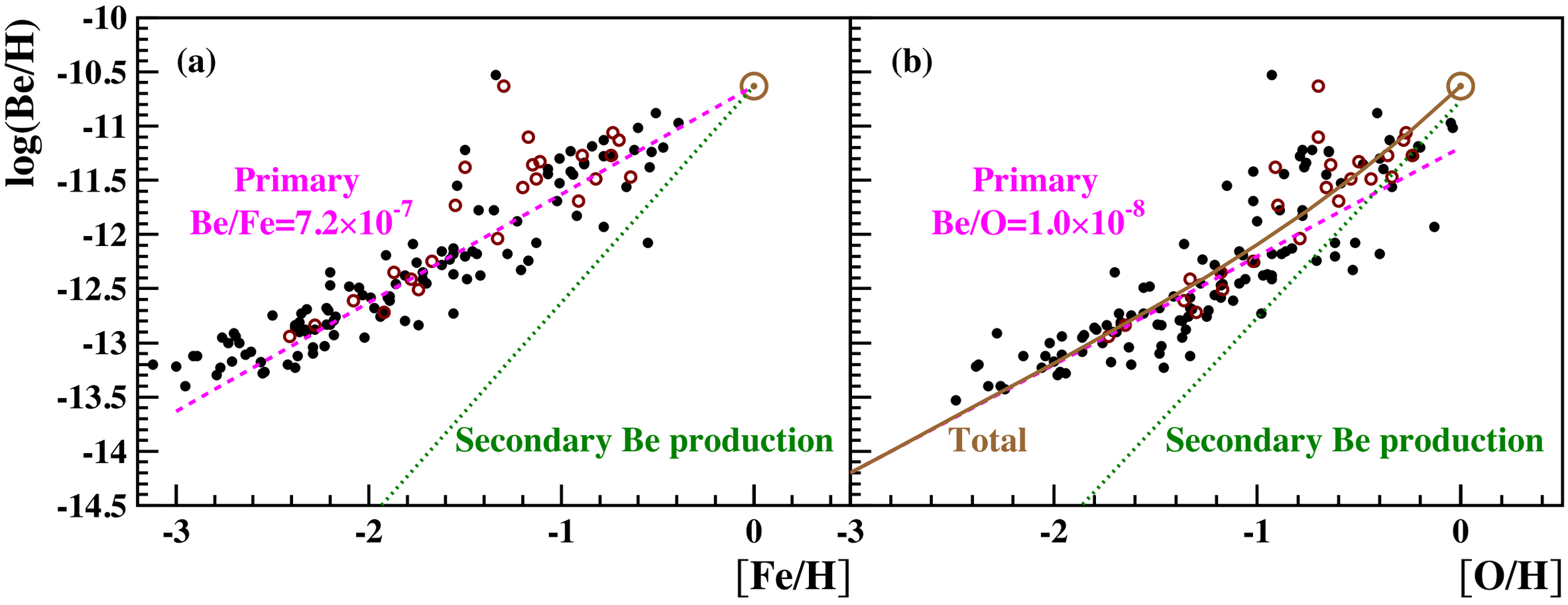
☑ I am aware that the "exercise for undergrads" is a brutal and probably over-simplifyied description of the processes of injection and transport of particles in the Galaxy

☑ The "exercise" was also (intendedly) provocative

☑ The goal was to show that, even though the "orthodoxy" certainly constitutes a solid and non-falsified-yet paradigma for CR origin, **radically different scenarios are allowed by data and should be investigated!**

Superbubbles or isolated SNRs?

spallogenic nucleosynthesis of LiBeB Reeves (1994), Vangioni-Flam, Casse, Audouze (2000)



e.g. Parizot 2000, for a recent review see Tatischeff&Gabici 2018

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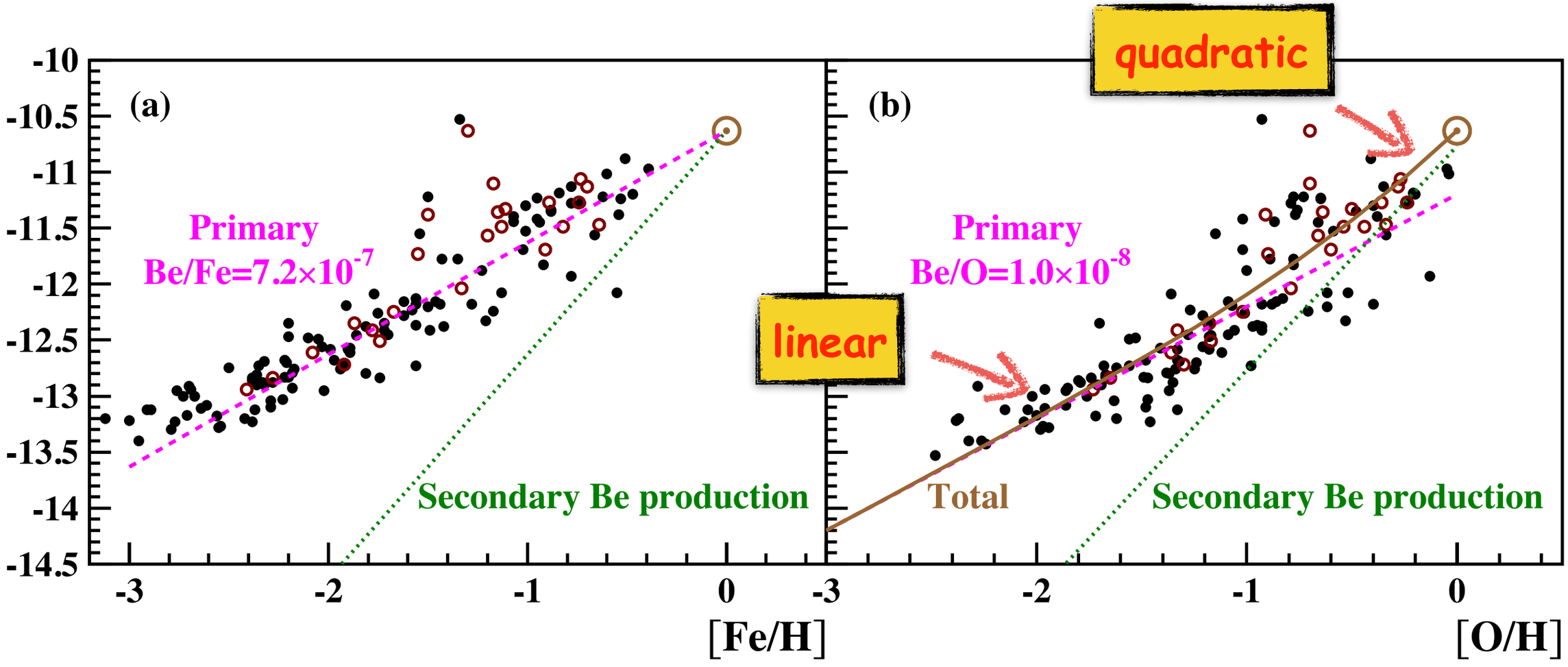

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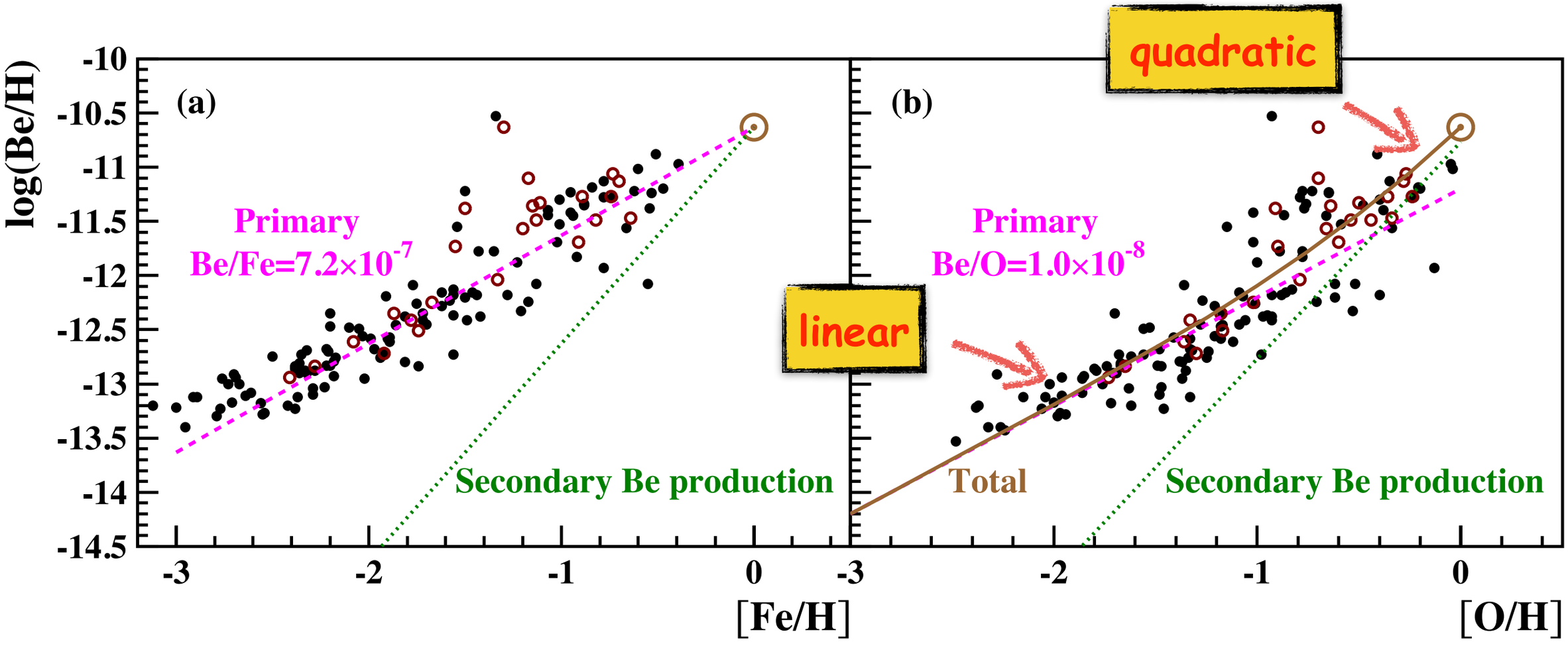


superbubbles -> CRs are accelerated from an enriched ISM (X_{CR} closer to constant rather than X_{ISM})

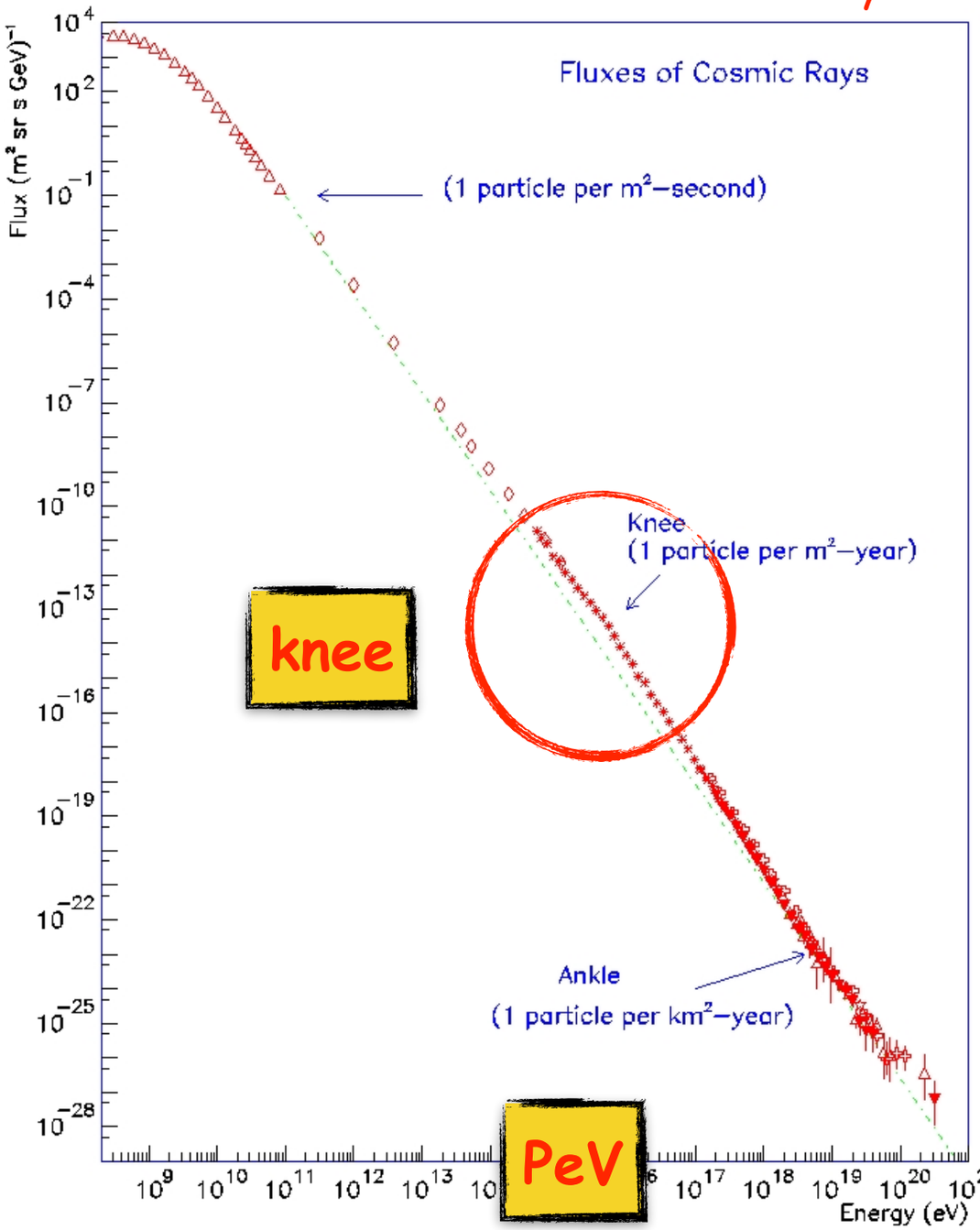
e.g. Parizot 2000, for a recent review see Tatischeff&Gabici 2018

Is Lagage&Cesarsky problem solved yet?

Hillas criterium

$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right) \left(\frac{R}{\mathrm{pc}}\right) \left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{TeV}$$

velocity — size — magnetic field



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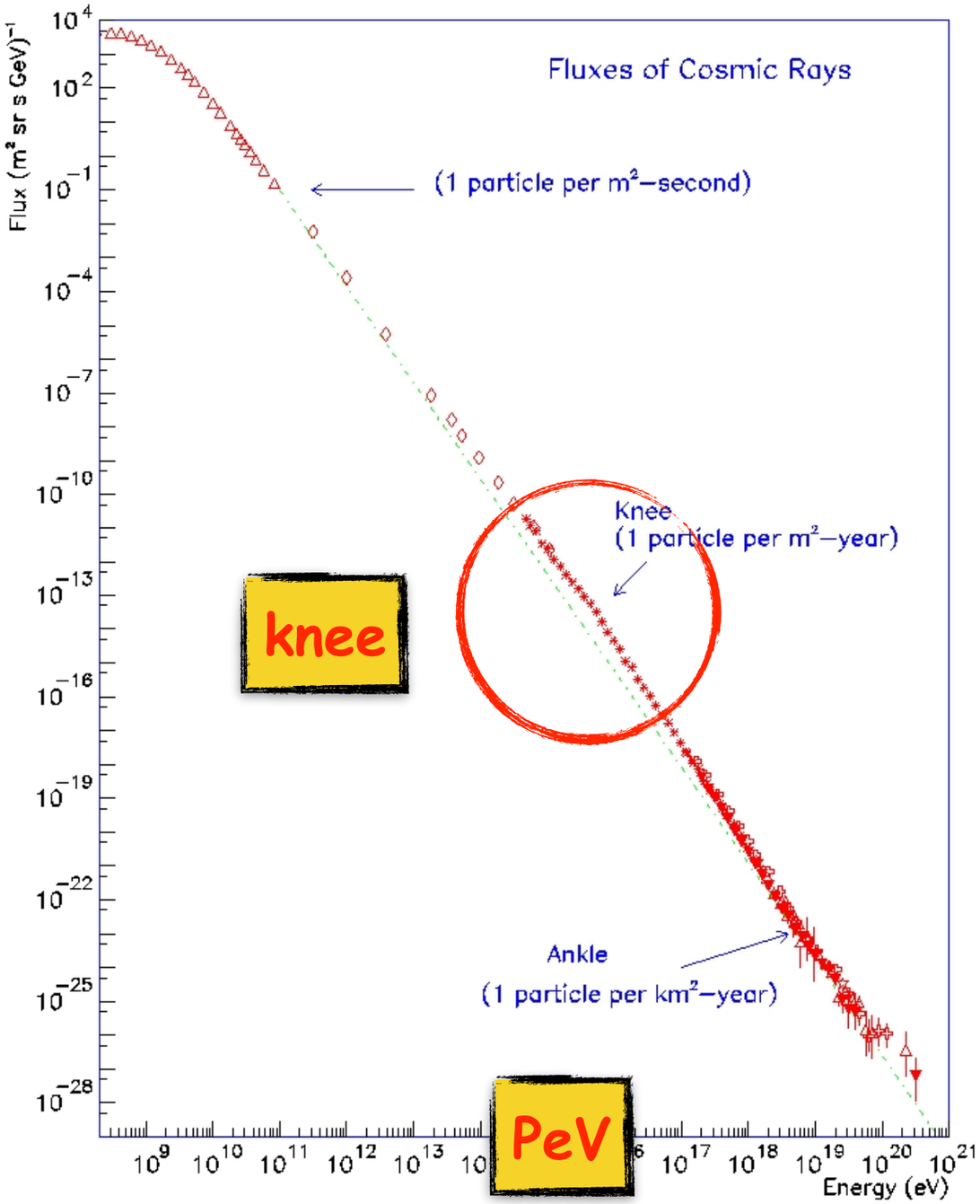
~10 ~3 ~3



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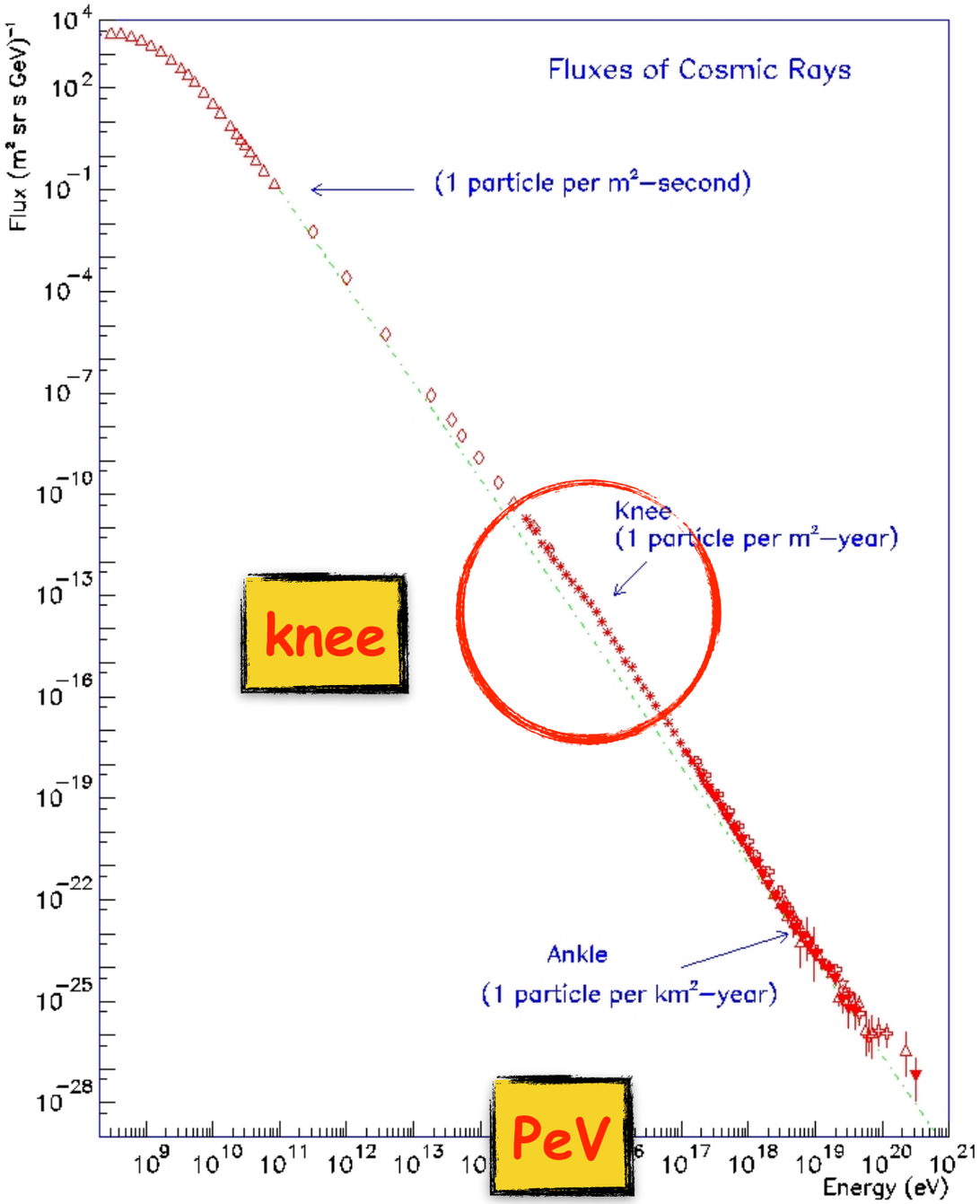

Bell (2004) -> CR driven instability at shocks can amplify B well above the ISM value!

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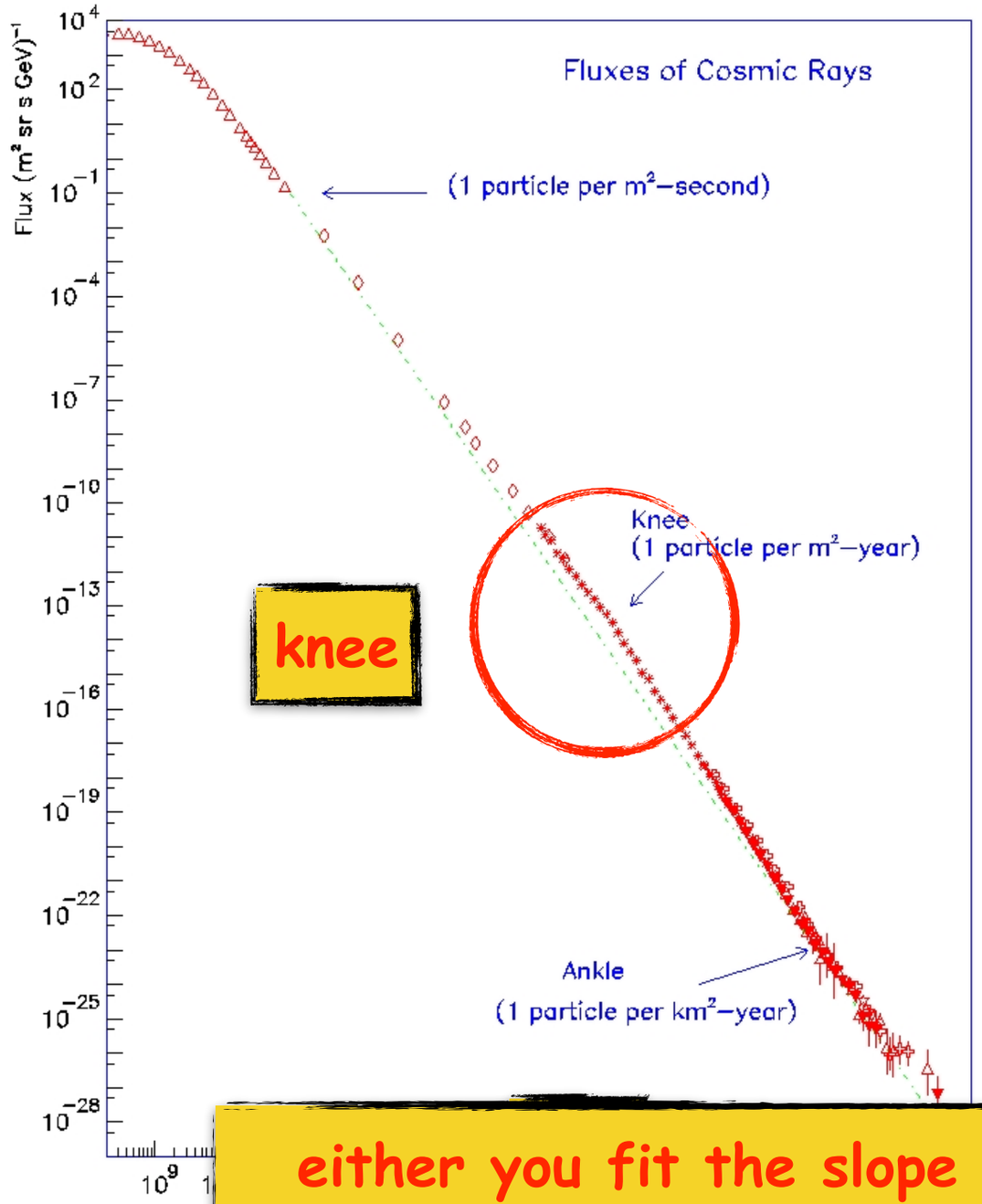

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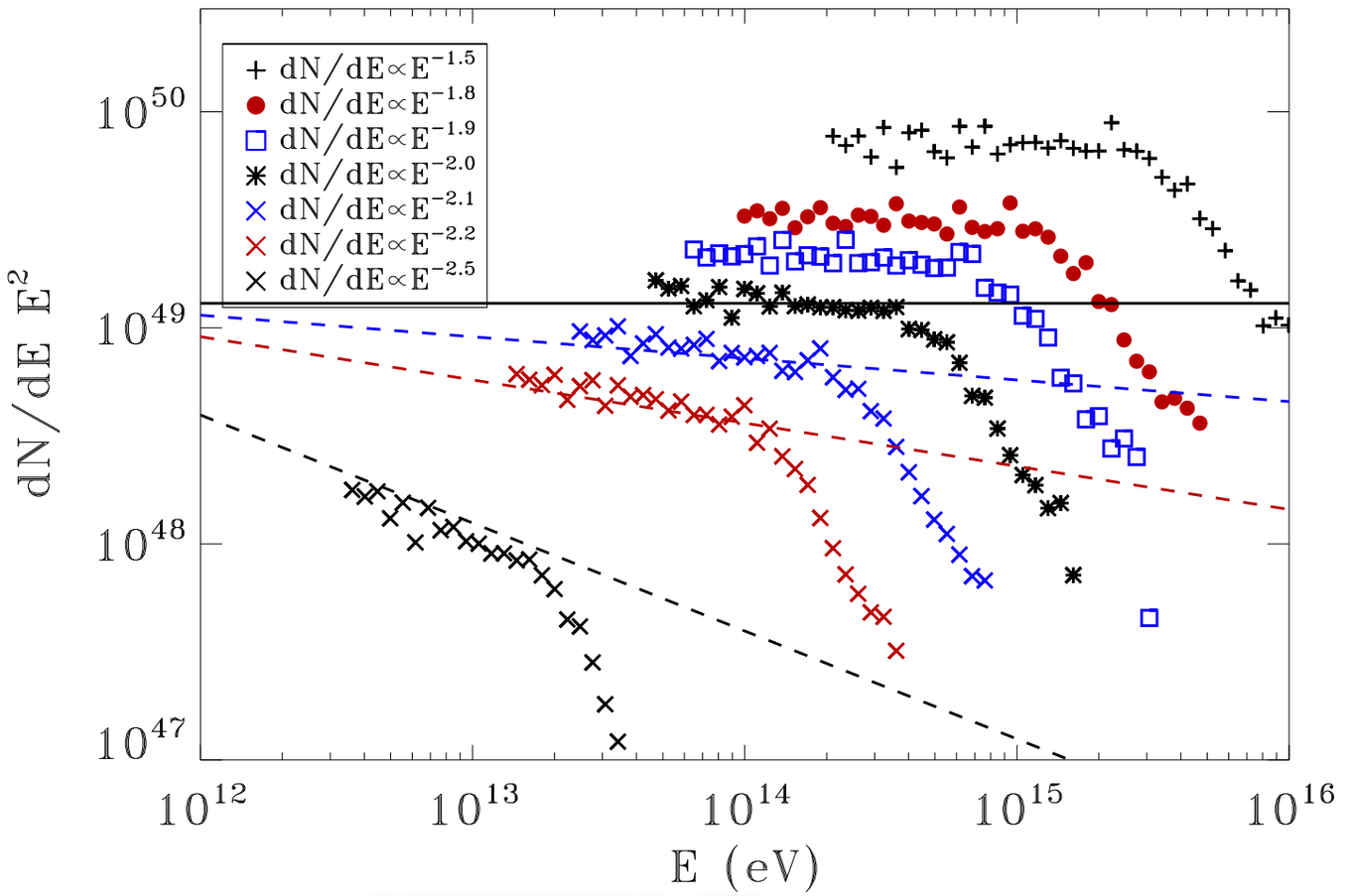
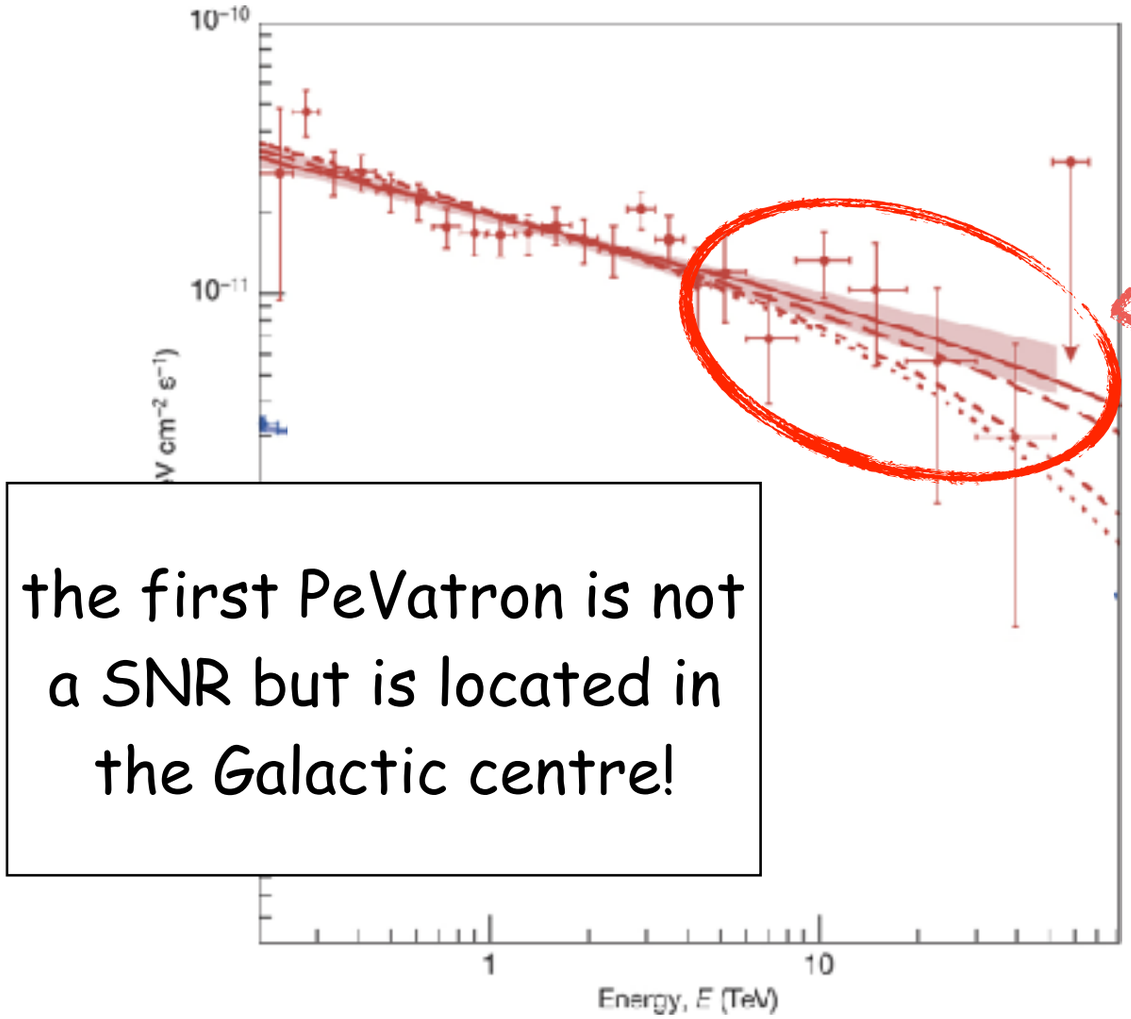


either you fit the slope or the knee, not both!

Schure&Bell 2014

Galactic centre as a CR PeVatron

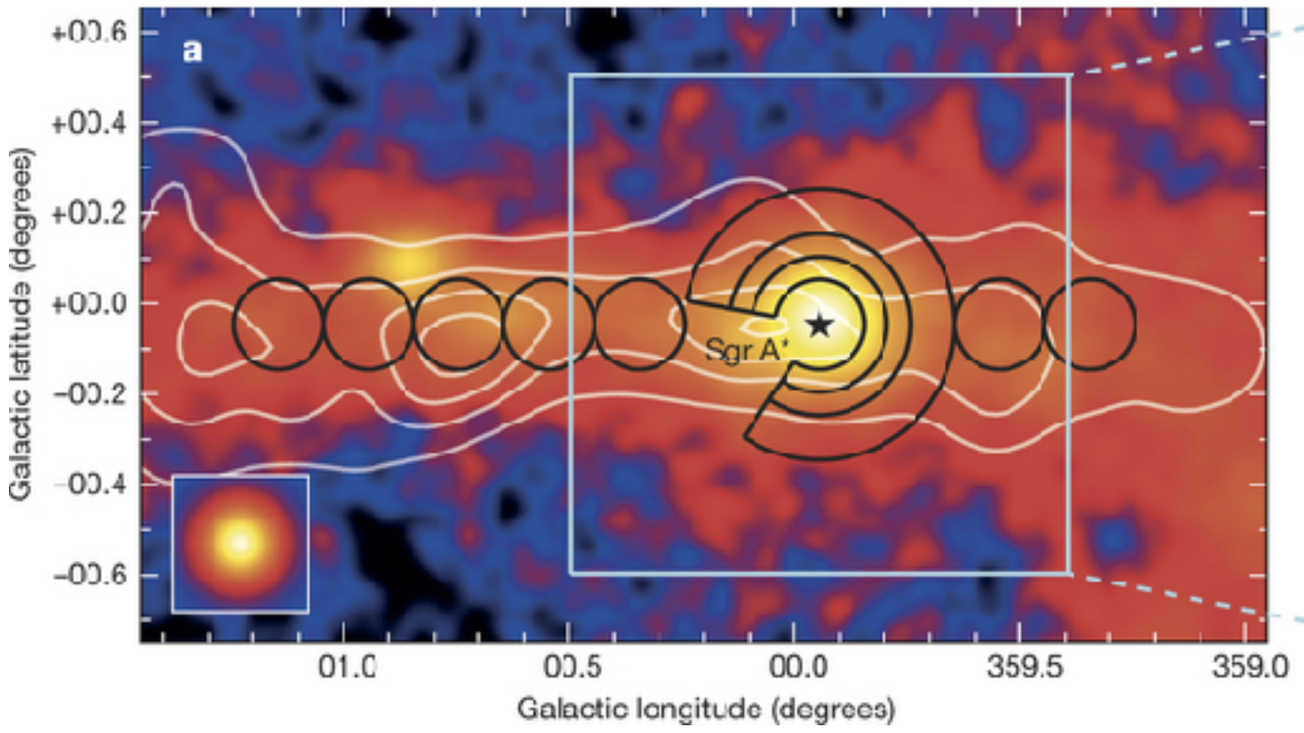


the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

no cutoff!

H.E.S.S. Coll. 2016



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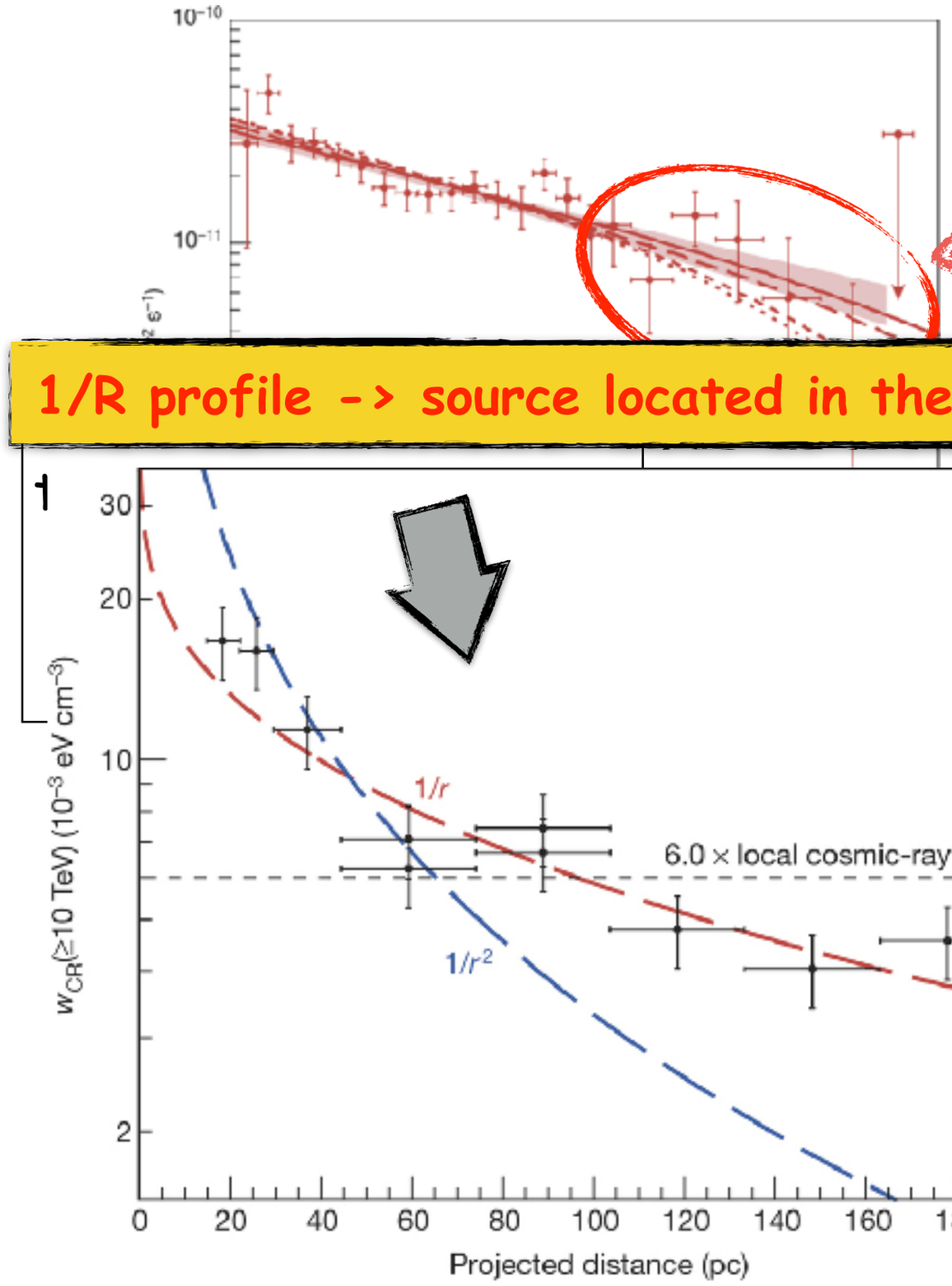

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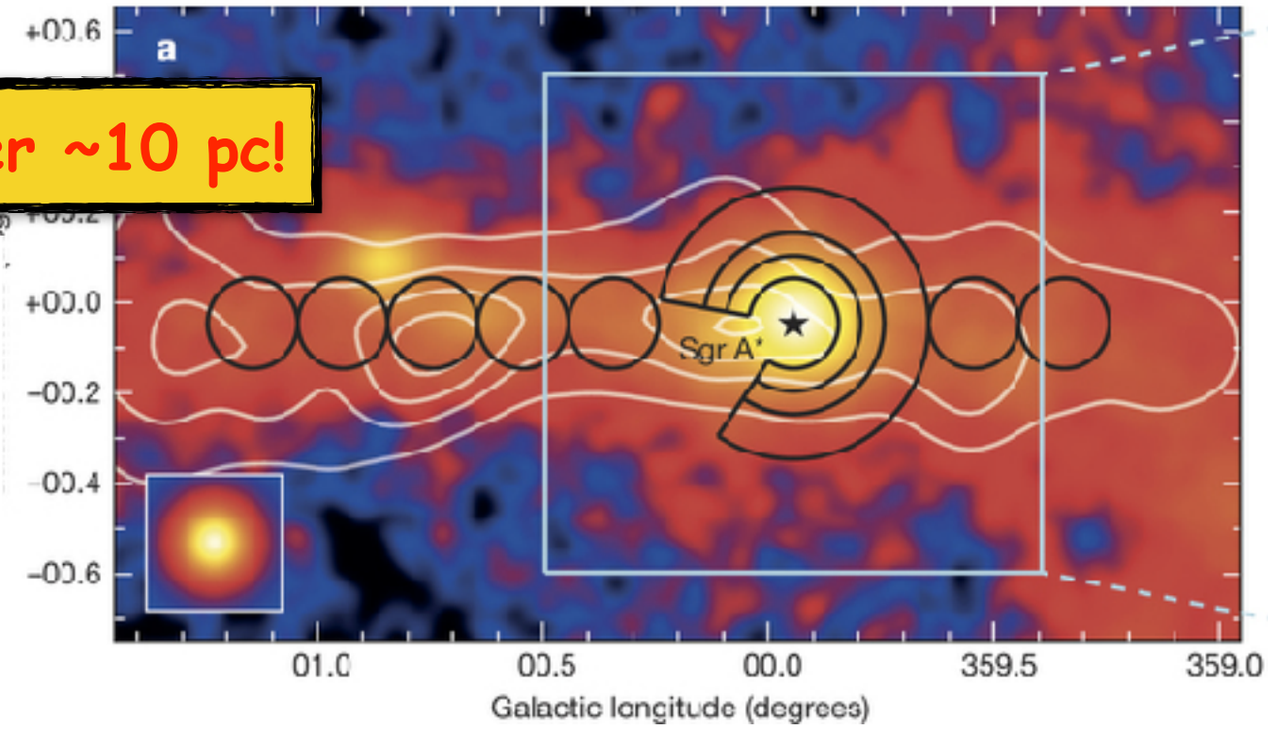
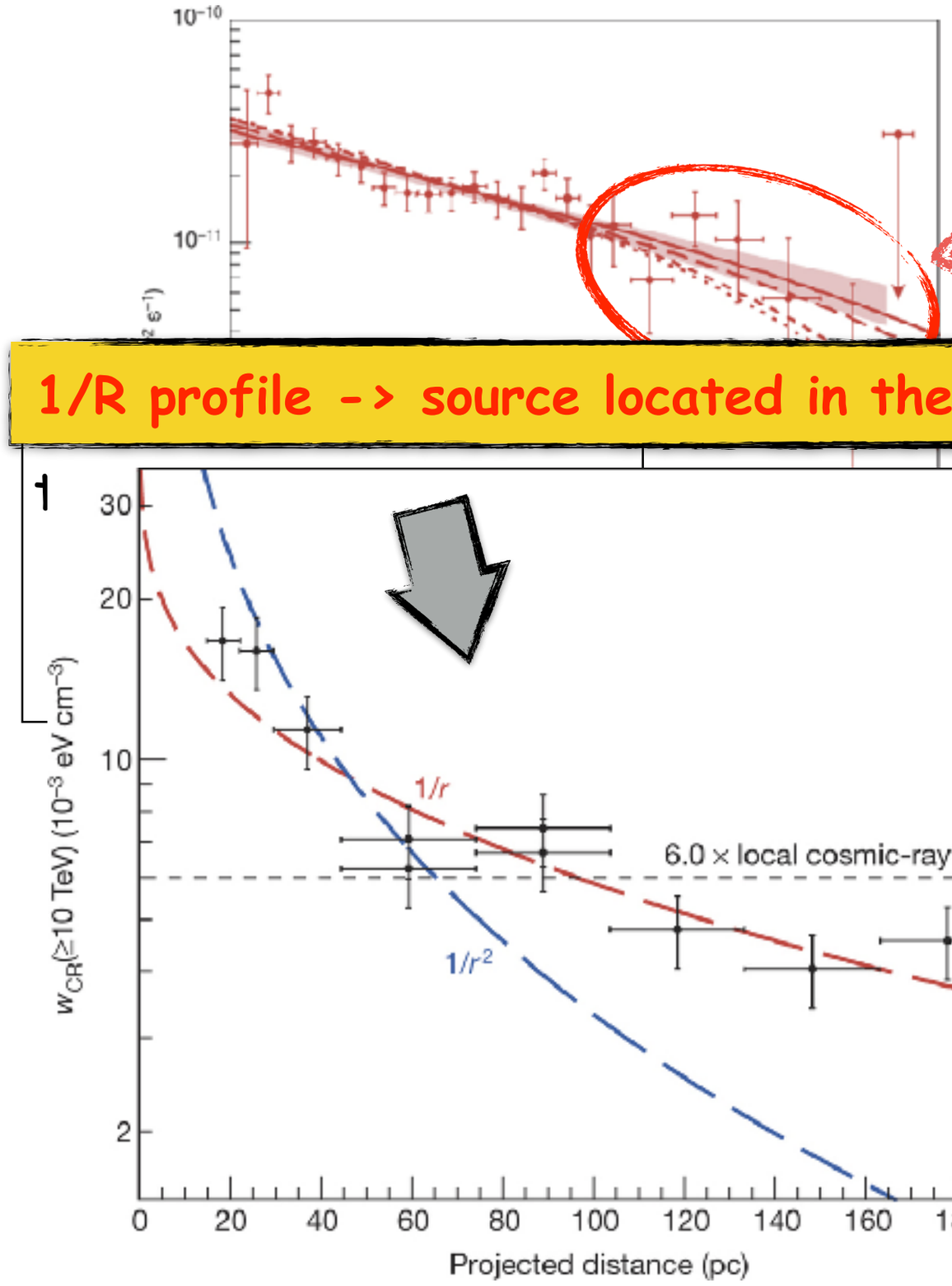


1/R profile -> source located in the inner ~10 pc!

Galactic centre as a CR PeVatron



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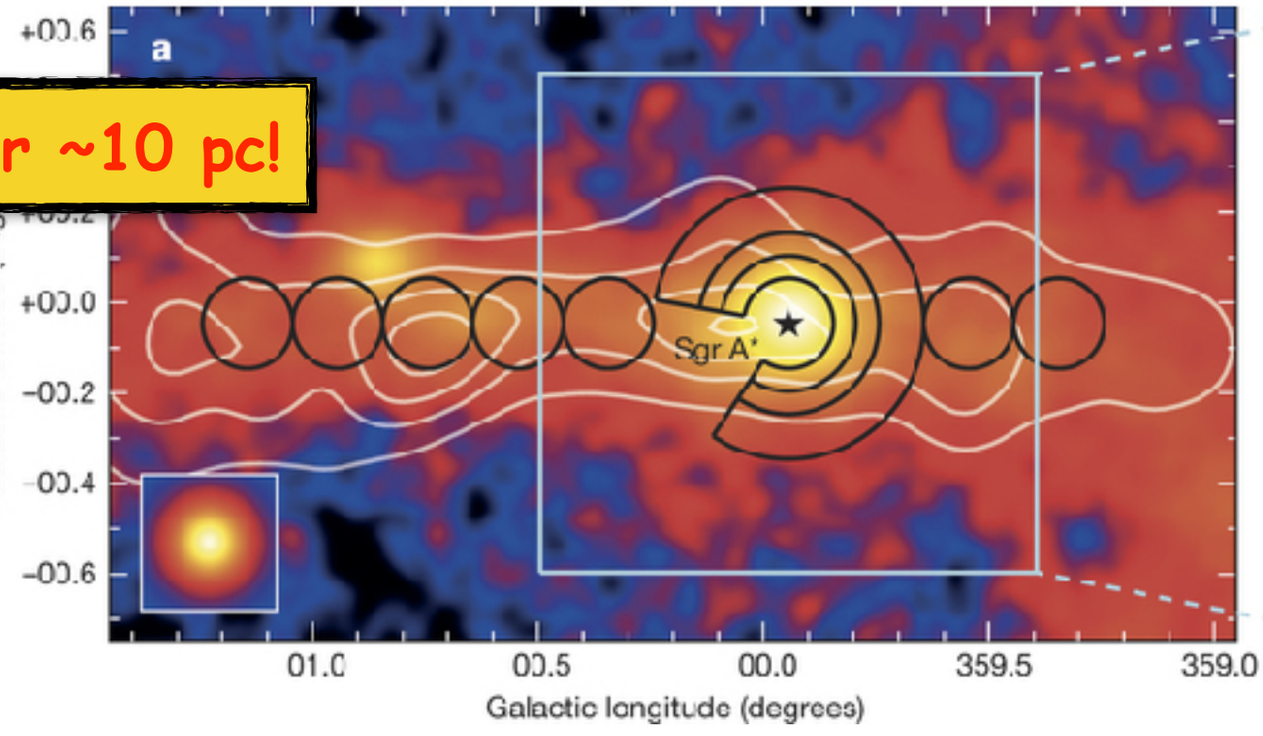

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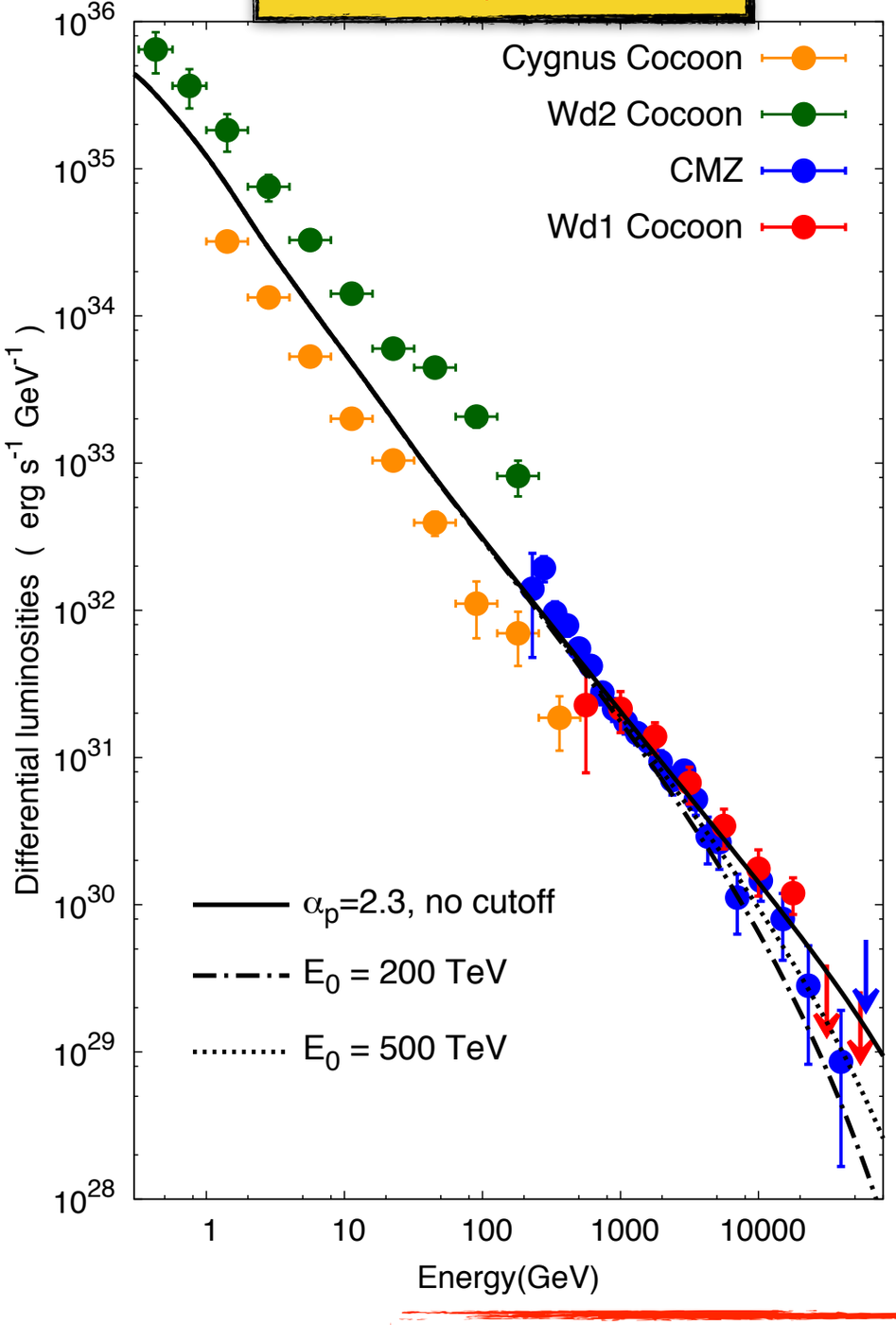
GC contributes to CRs? Not if steadily active at its present rate. Past activity?
—> see Etienne's talk!

What about stellar winds?

$E^{-2.3}$ spectrum



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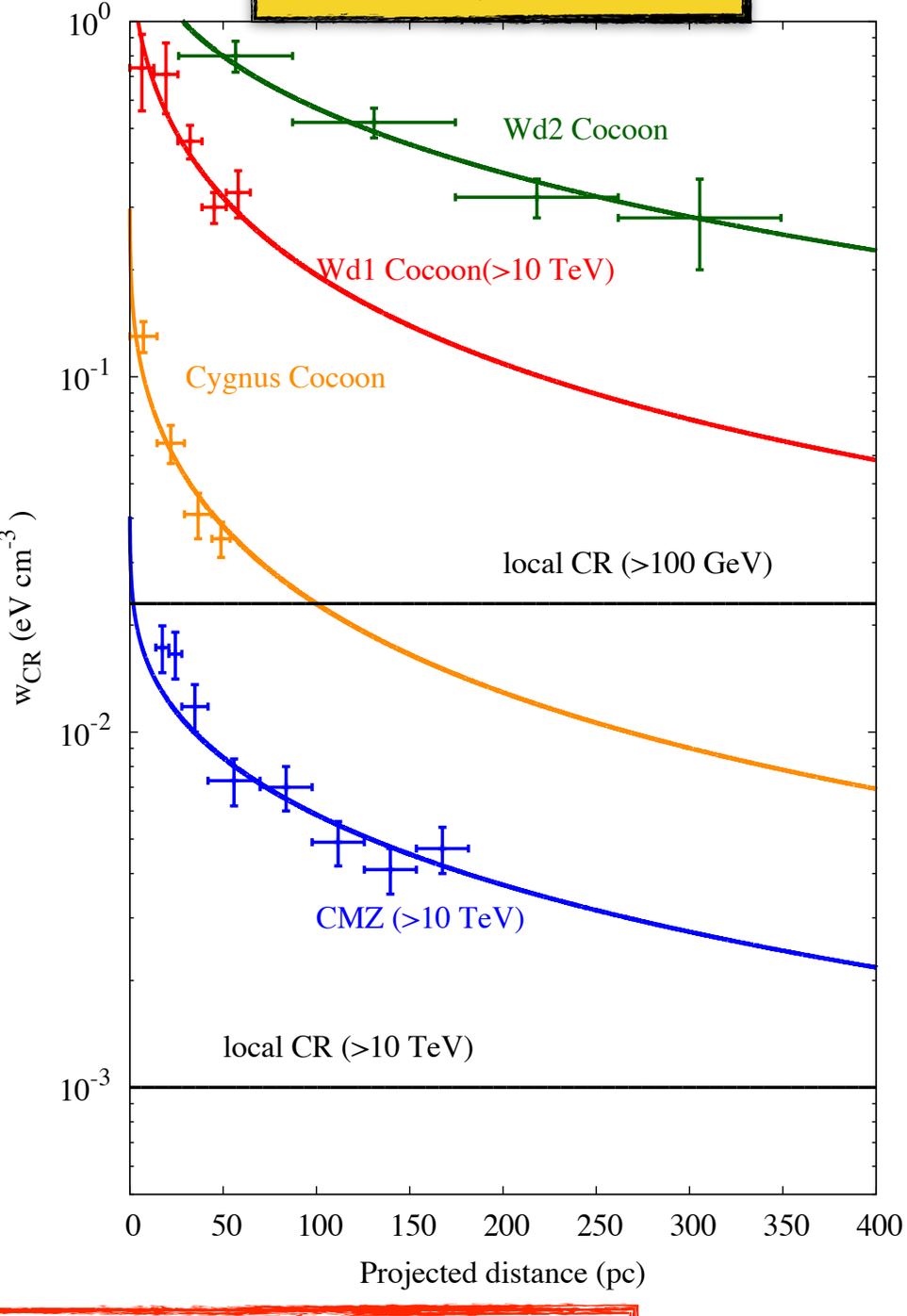

this revives the old idea by Casse & Paul (1982)

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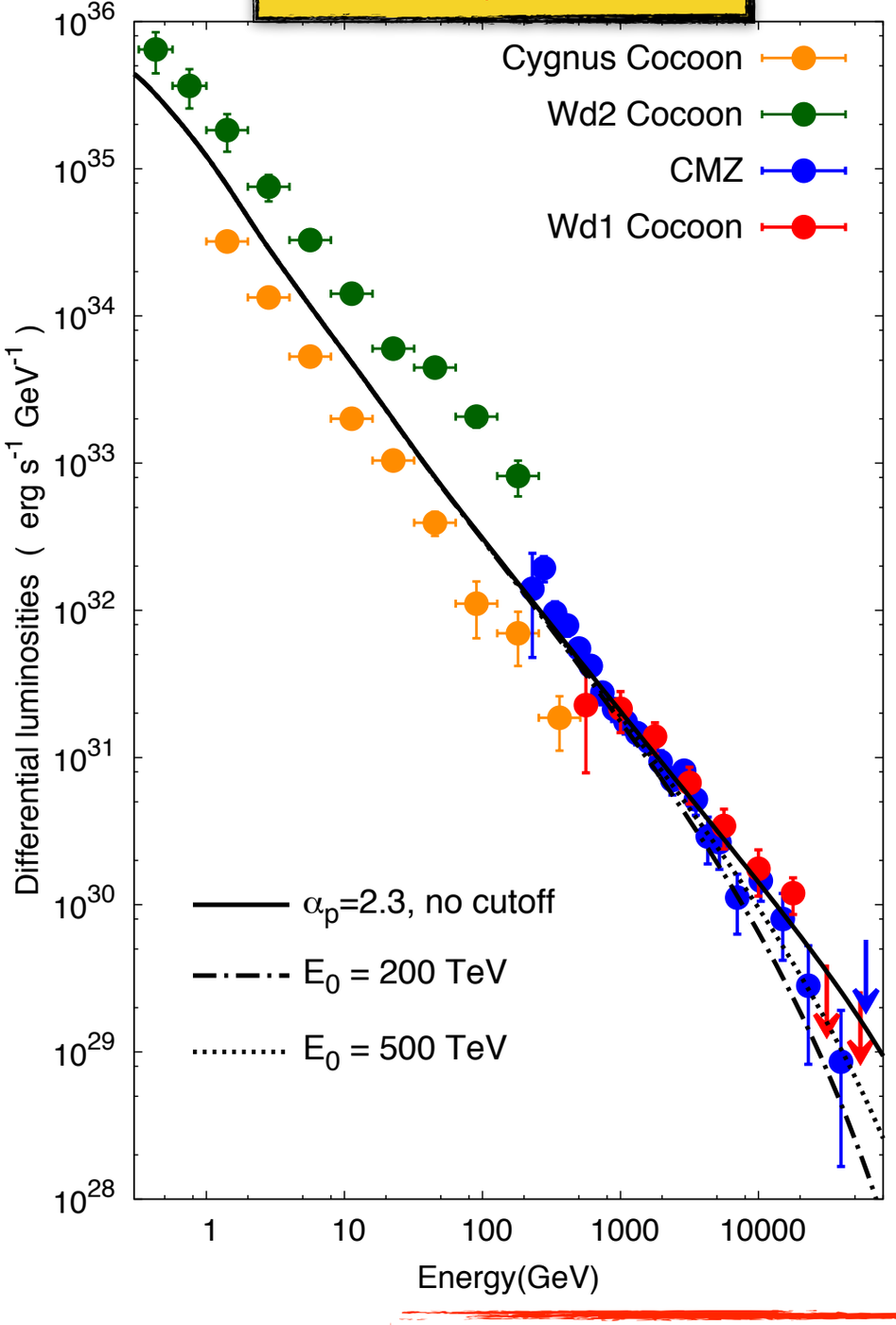

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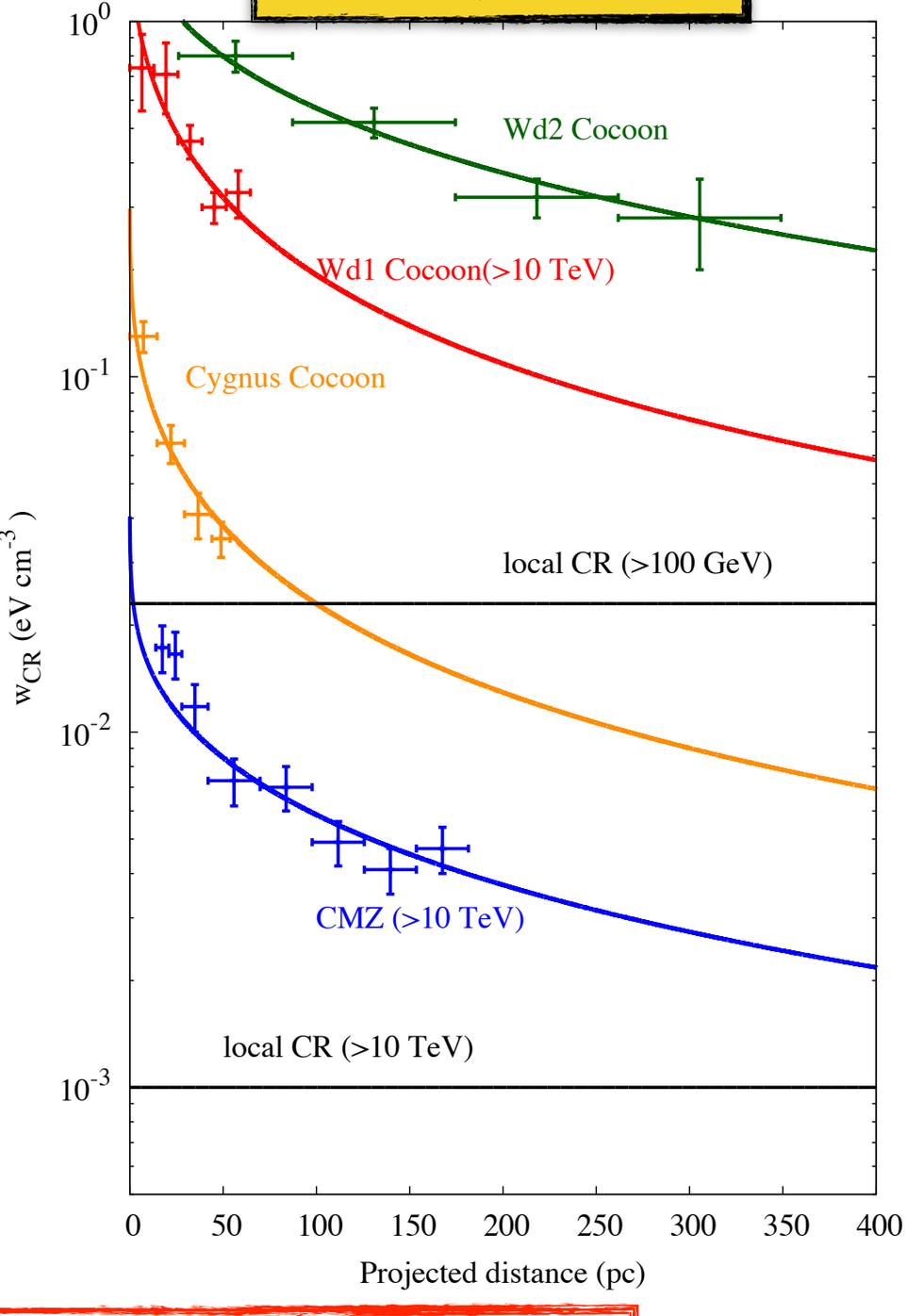

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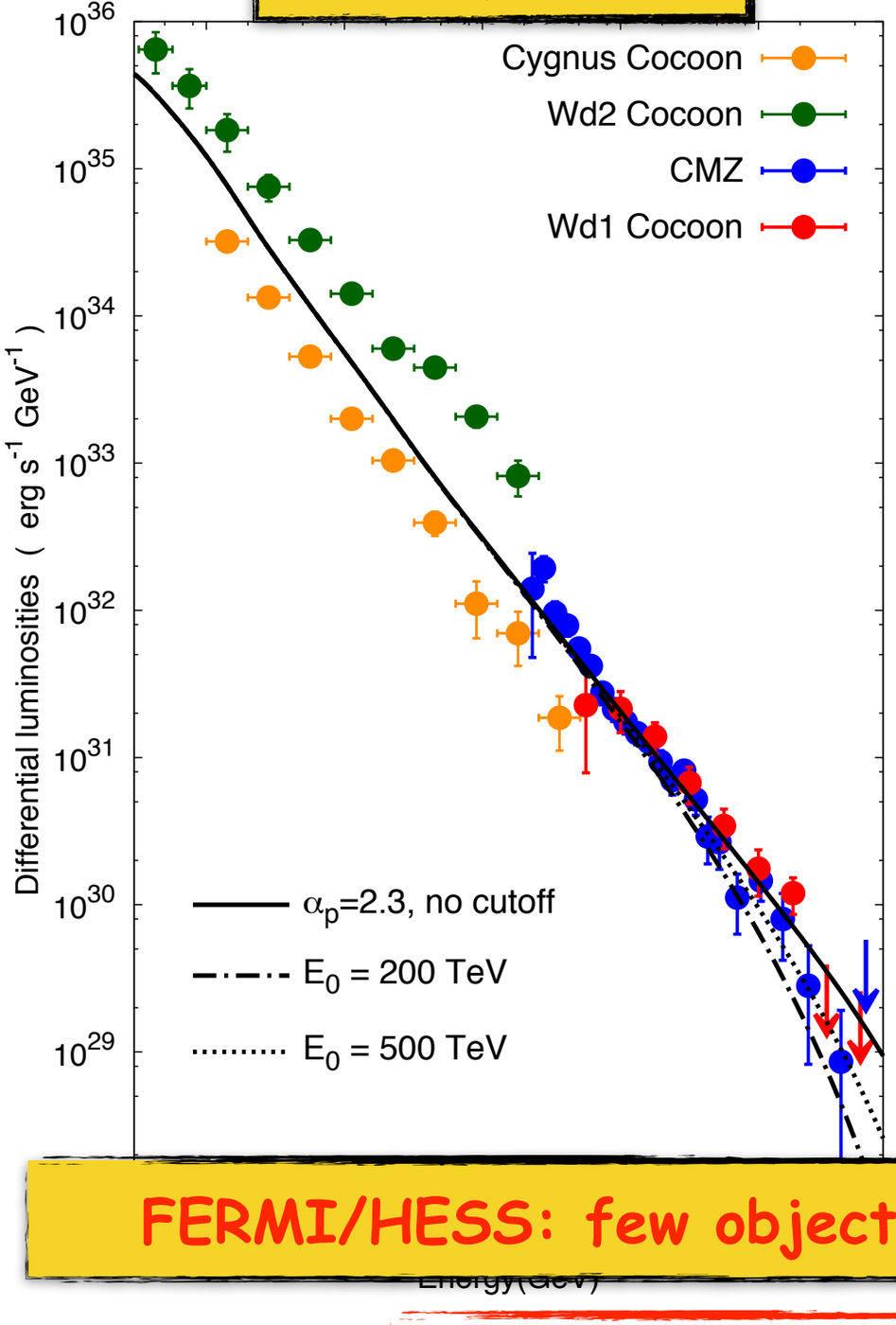

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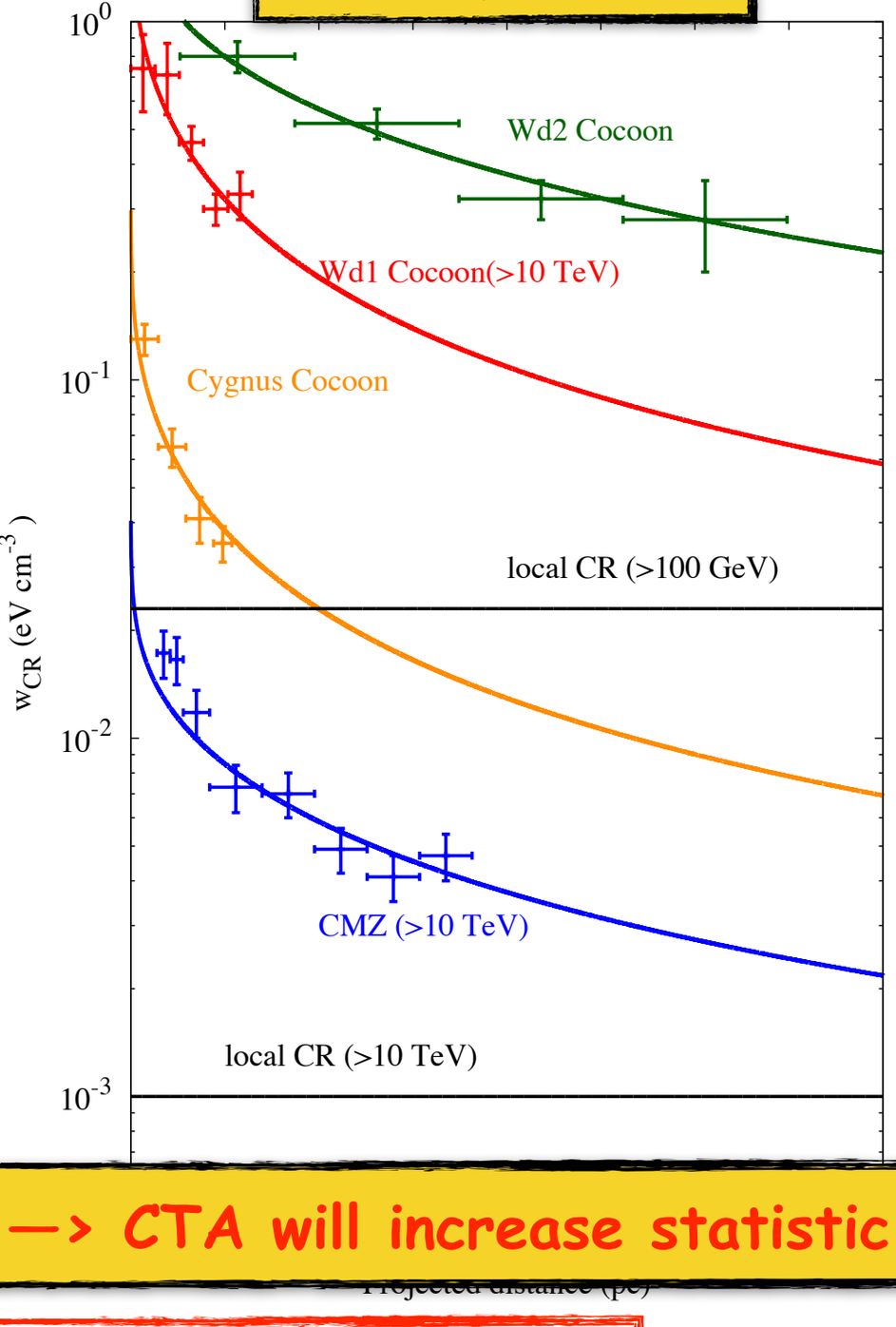

FERMI/HESS: few objects —> CTA will increase statistic

this revives the old idea by Casse & Paul (1982)

Aharonian, Yang, de Oña Wilhelmi 2018

Conclusions

Let's be brave and fight orthodoxy !