Cosmic ray physics

Stefano Gabici
APC, Paris

Disclaimer

This will be a very incomplete overview on cosmic rays (40 min is too short!)

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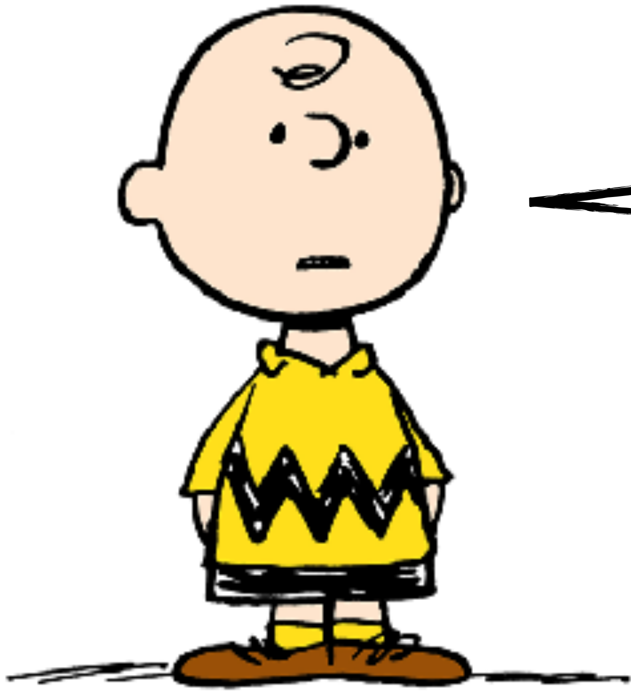

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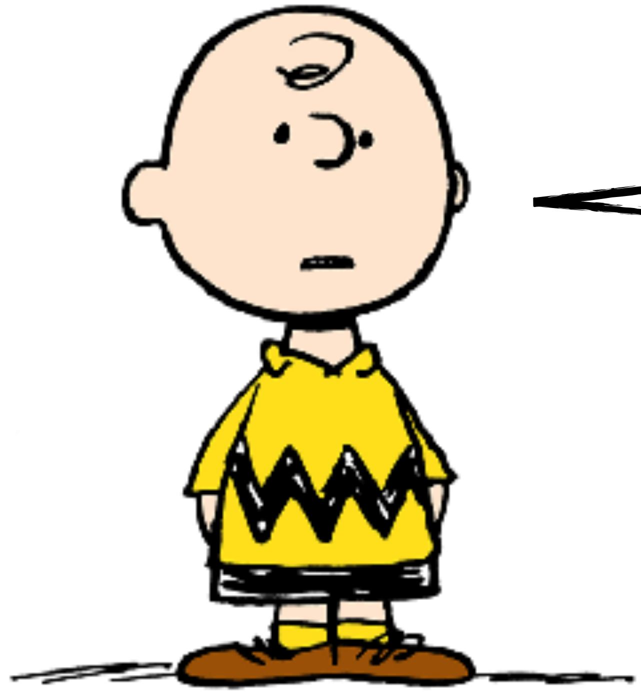
I will focus on one problem only, summarised by this question:

Do supernova remnants accelerate ALL Galactic cosmic rays?



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Do supernova remnants accelerate ALL Galactic cosmic rays?

List of classic reviews (from 2000 on):

[1] Strong, Moskalenko, Ptuskin, Cosmic-Ray Propagation and Interactions in the Galaxy, ARNPS, 57, 285 (2007)

[2] Helder+, Observational Signatures of Particle Acceleration in Supernova Remnants, Space Sci Rev, 173, 369 (2012)

[3] Schure+, Diffusive Shock Acceleration and Magnetic Field Amplification, Space Sci Rev, 173, 91 (2012)

[4] Zweibel, The microphysics and macrophysics of cosmic rays, Phys Plasmas, 20, 055501 (2013)

[5] Blasi, The origin of galactic cosmic rays, A&A Rev, 21, 70 (2013)

[6] Amato, The origin of galactic cosmic rays, IJMPD, 23, 1430013 (2014)

[7] Adriani+, The PAMELA Mission: Heralding a new era in precision cosmic ray physics, Phys Rep, 544, 323 (2014)

[8] Grenier, Black, Strong, The Nine Lives of Cosmic Rays in Galaxies, ARA&A, 53, 199 (2015)

[9] Amato, Blasi, Cosmic ray transport in the Galaxy: A review, Adv Space Res, 62, 2731 (2018)

[10] Aguilar+, The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II - Results from the first seven years, Phys Rep, 894, 1 (2021)

updated set of references —> Gabici, ICRC2023, Rapporteur talk CRD (PoS)

Plan of the talk

[1] What are **cosmic rays** and why and how we study them

[2] The "orthodoxy" —> the **supernova remnant paradigm**

[3] Follow the **energy** —> supernova explosions

—> is there room left for other sources?

[4] Follow the **physics** —> where does acceleration end?

—> the Hillas criterion —> troubles with SNRs?

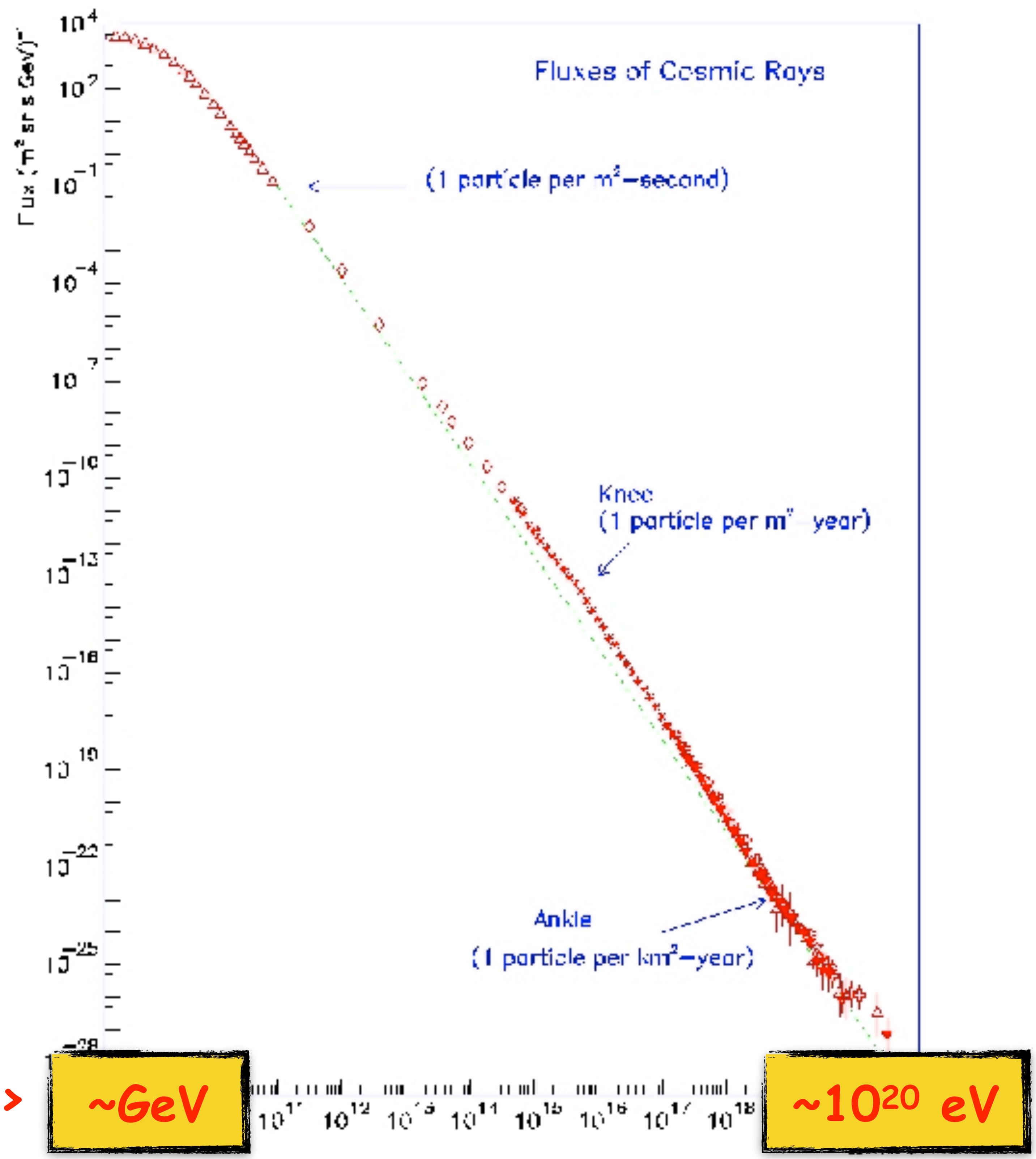
[5] Follow the **mass** —> isotopic anomalies

—> the role of stellar winds: polluters or accelerators?

[6] Conclusions —> do we need **mixed scenarios?**

[1] What are cosmic rays (and how and why to study them)

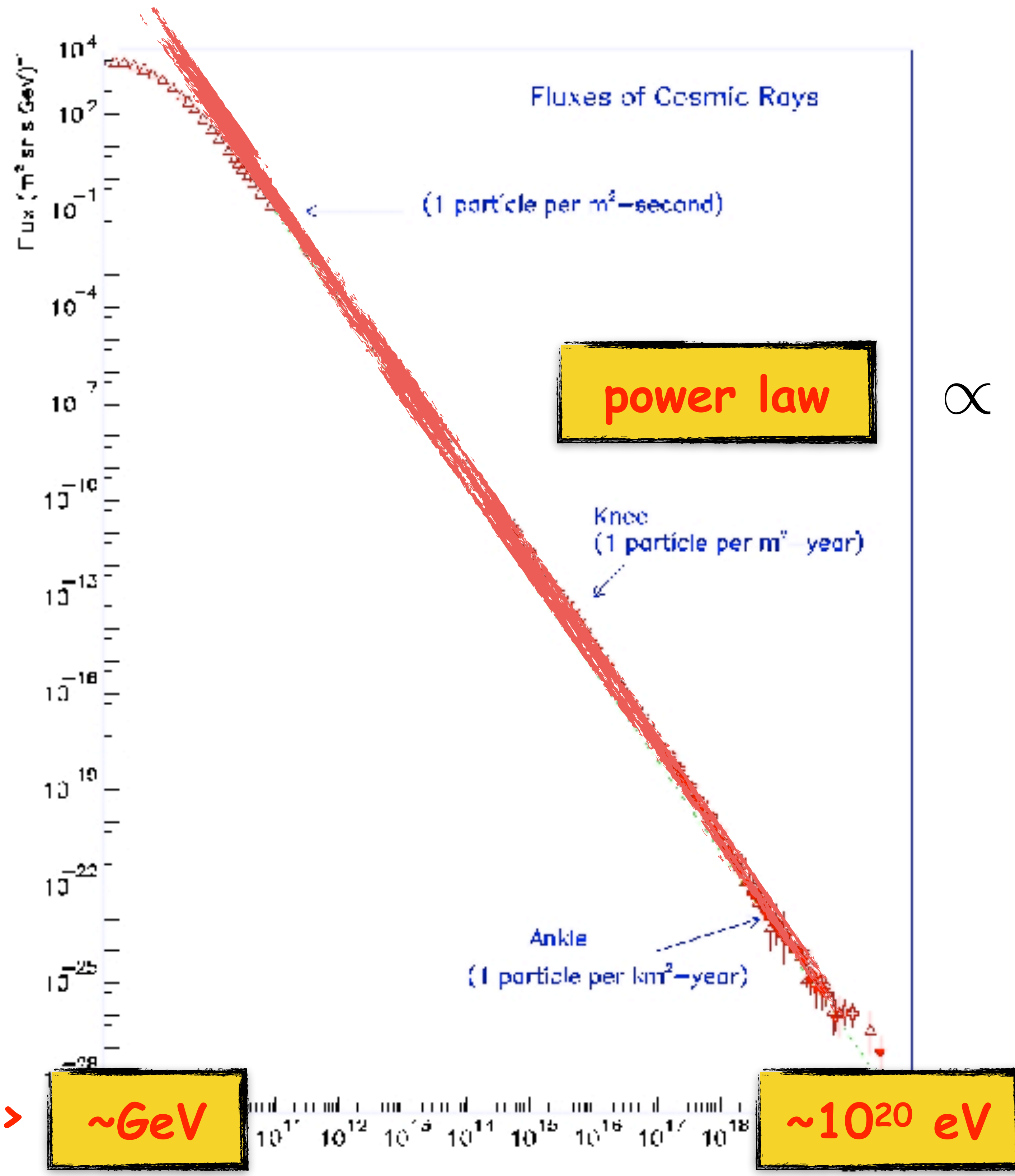
The (local) Cosmic Ray spectrum



mean energy ->

<- maximum energy

The (local) Cosmic Ray spectrum

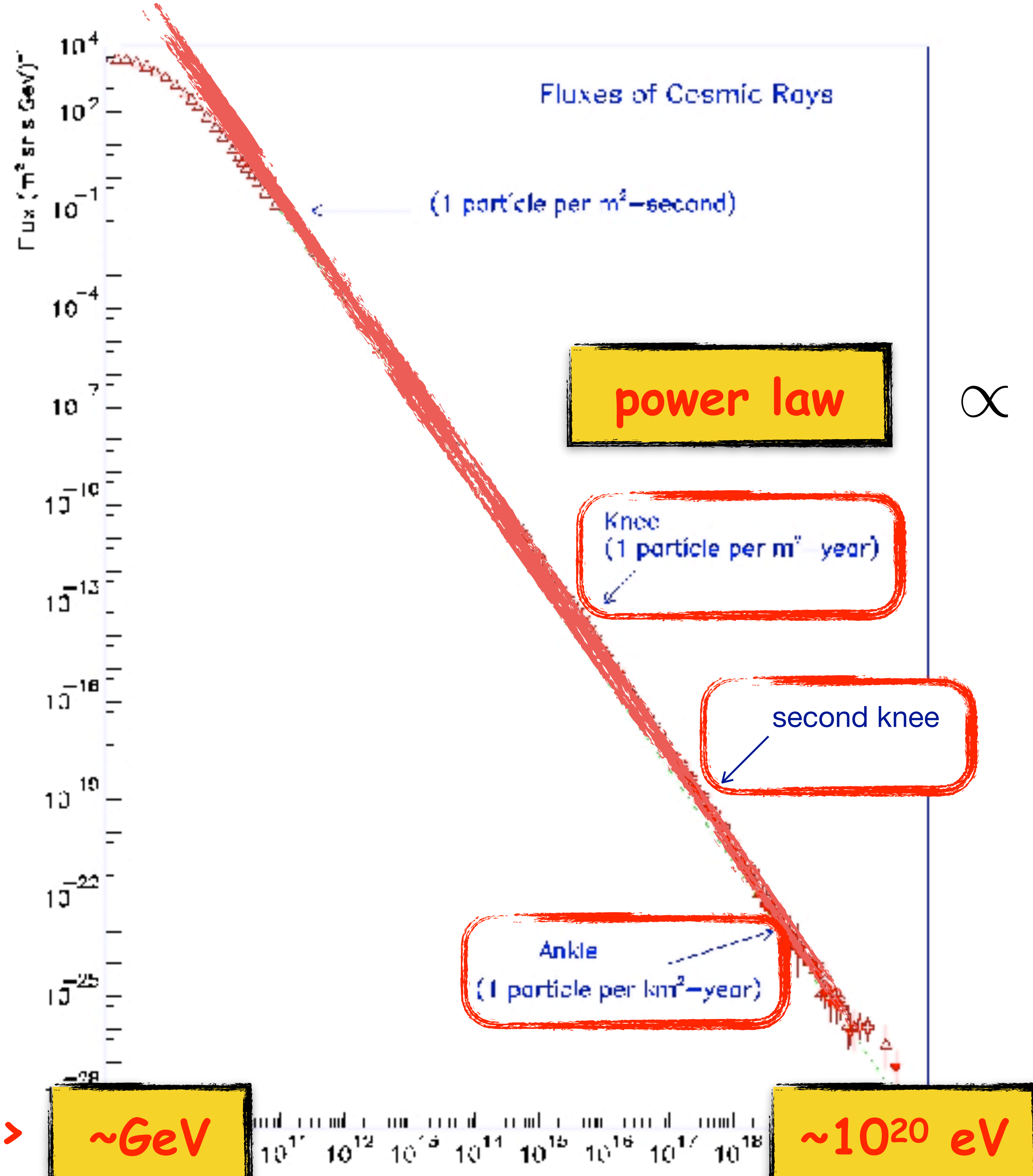


$\propto E^{-2.7} - E^{-3}$

mean energy ->

<- maximum energy

The (local) Cosmic Ray spectrum



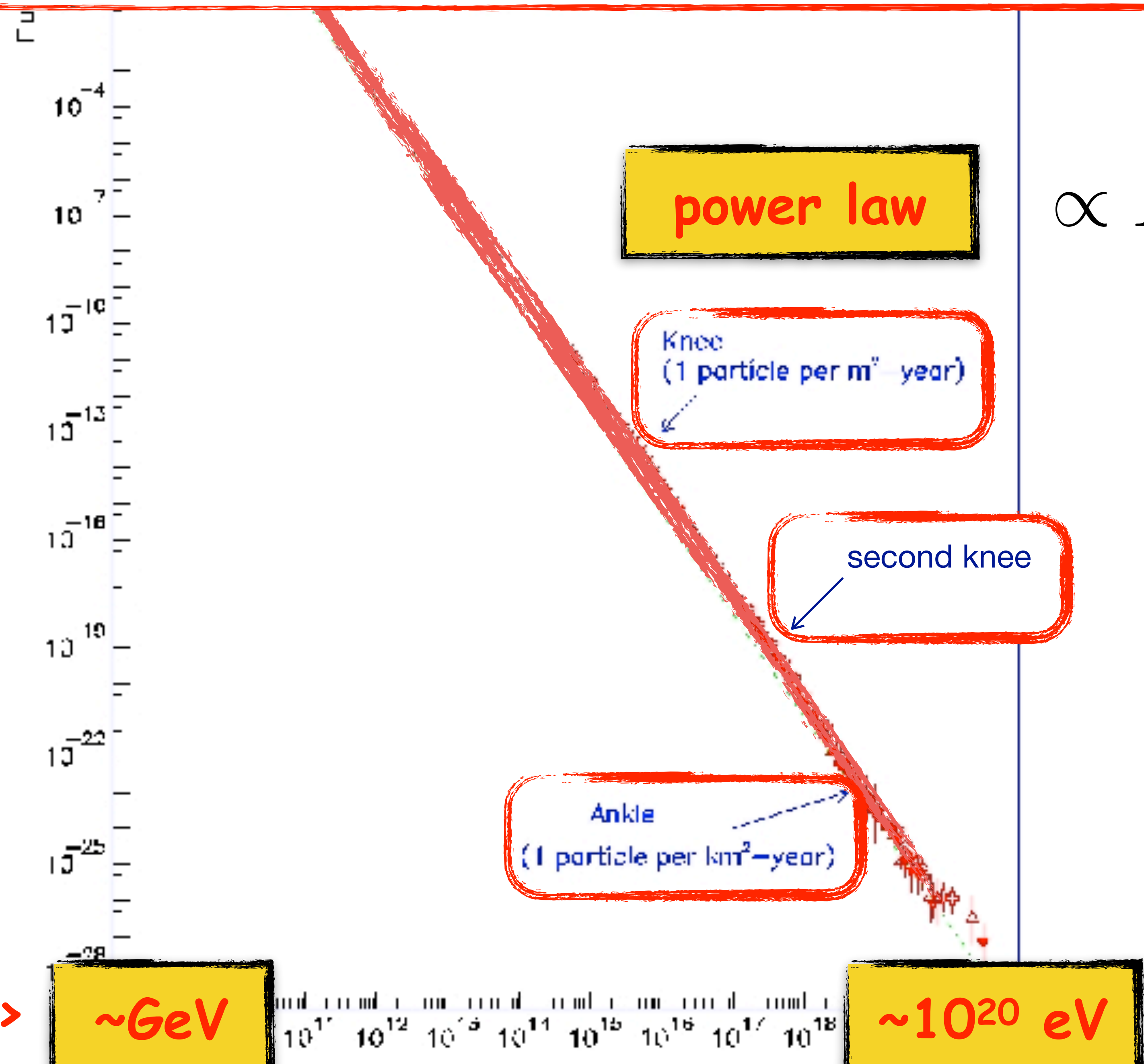
$$\propto E^{-2.7} - E^{-3}$$

mean energy -> ~GeV

~10^{20} eV <- maximum energy

The (local) Cosmic Ray spectrum

…a single component of cosmic rays appears to extend from below 10^{10} eV to at least 10^{16} eV in proton energy. To a good approximation a uniform spectrum in rigidity, $R^{-2.69}$ […] is quite acceptable… (Hillas 2005)



$$\propto E^{-2.7} - E^{-3}$$

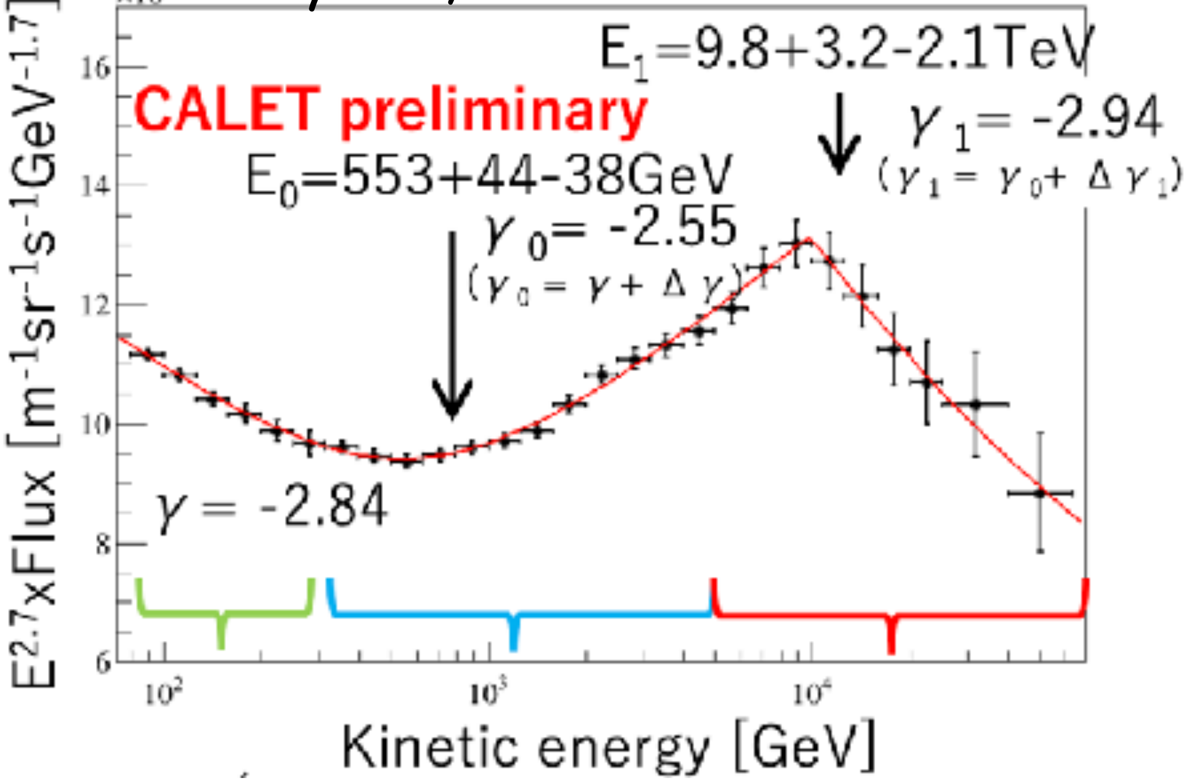
mean energy ->

<- maximum energy

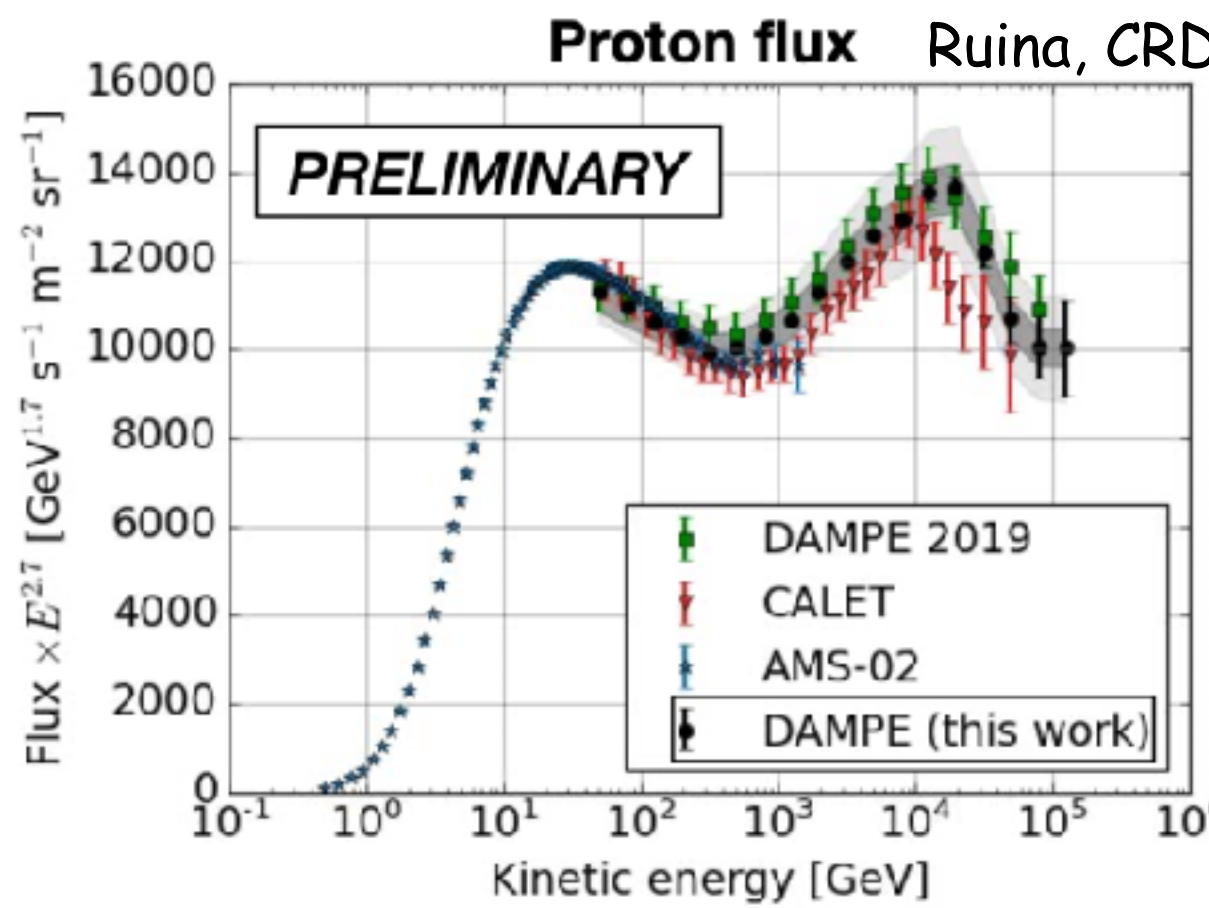
…and then, new data were taken

Give me a break! (CR protons)

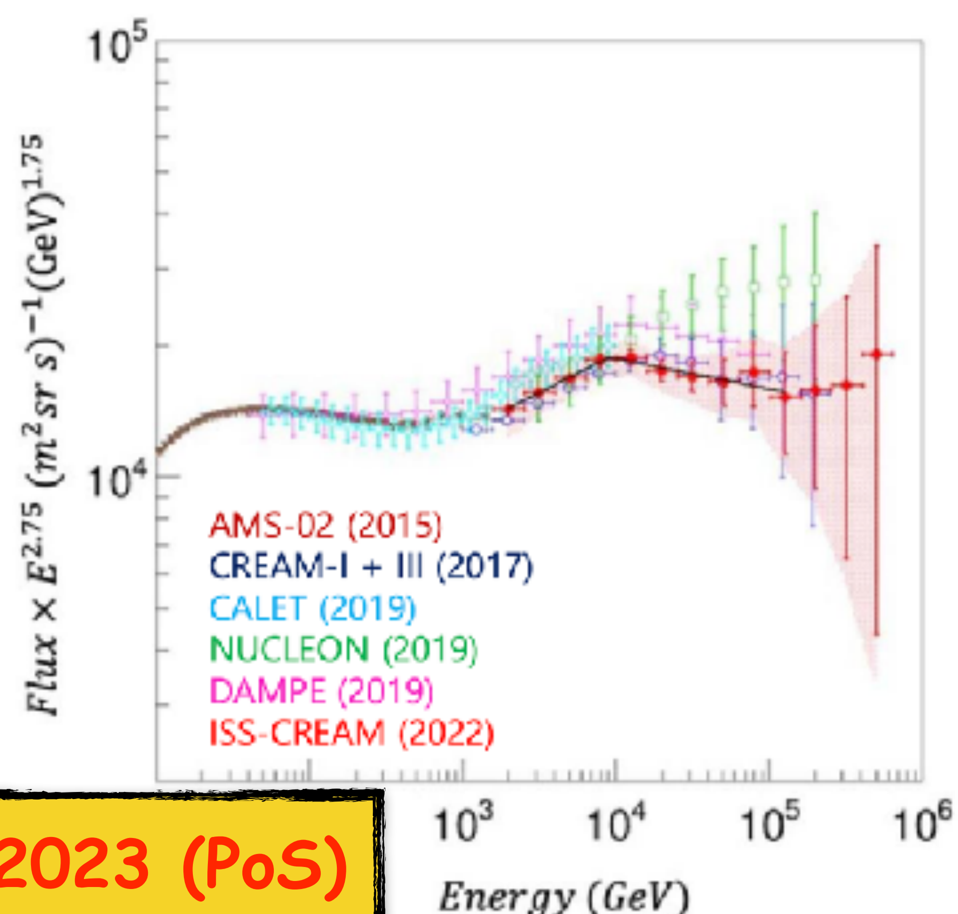
Kobayashi, CRD1



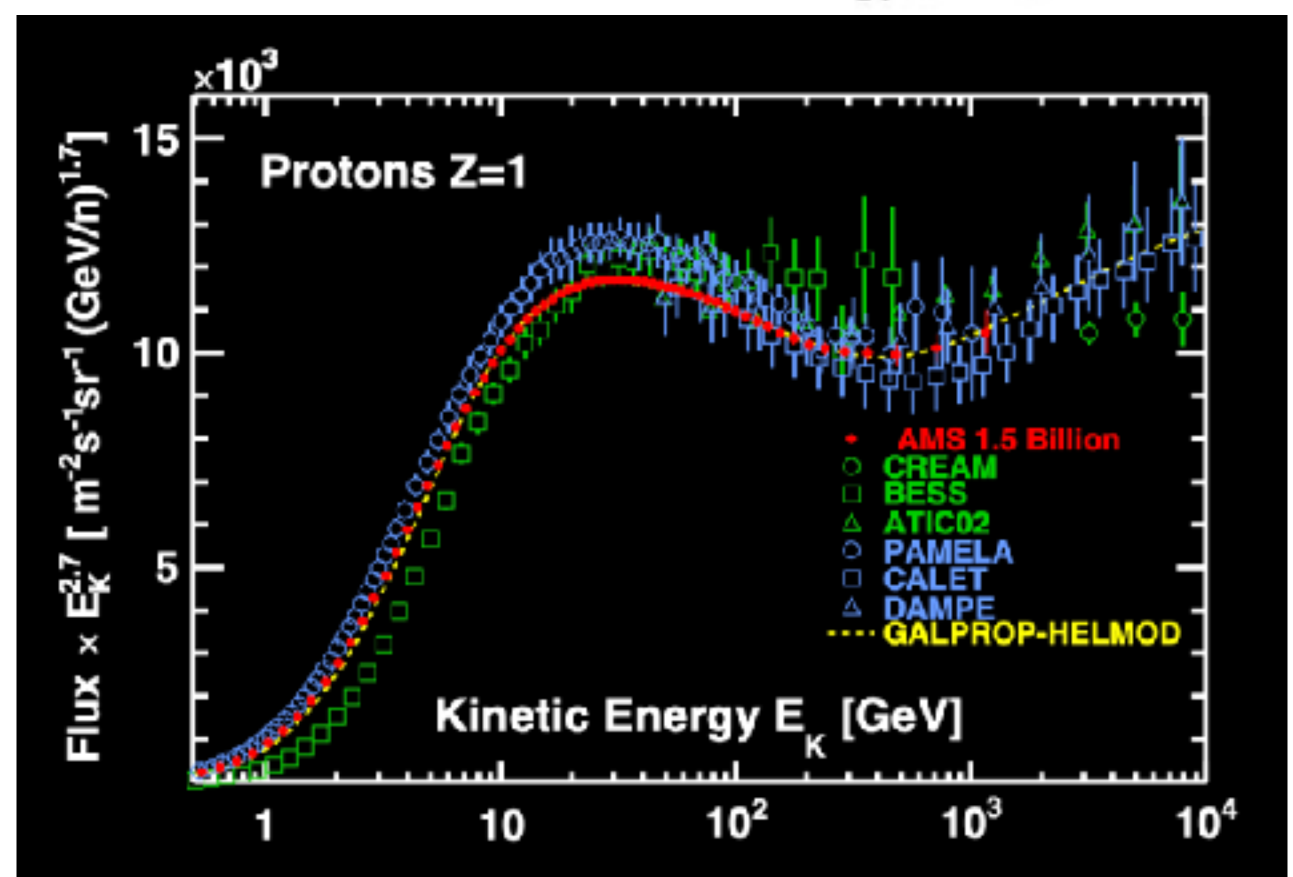
Ruina, CRD1



Choi, CRD1



Oliva, CRD2



ICRC2023 (PoS)

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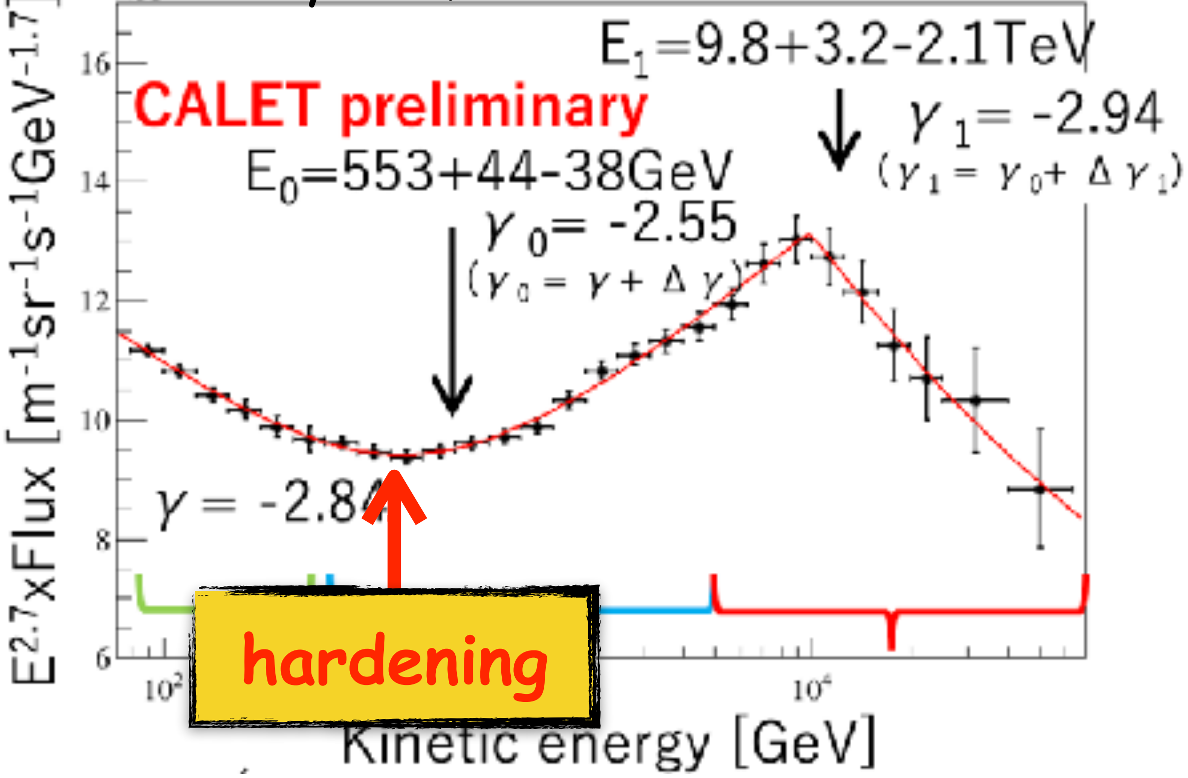

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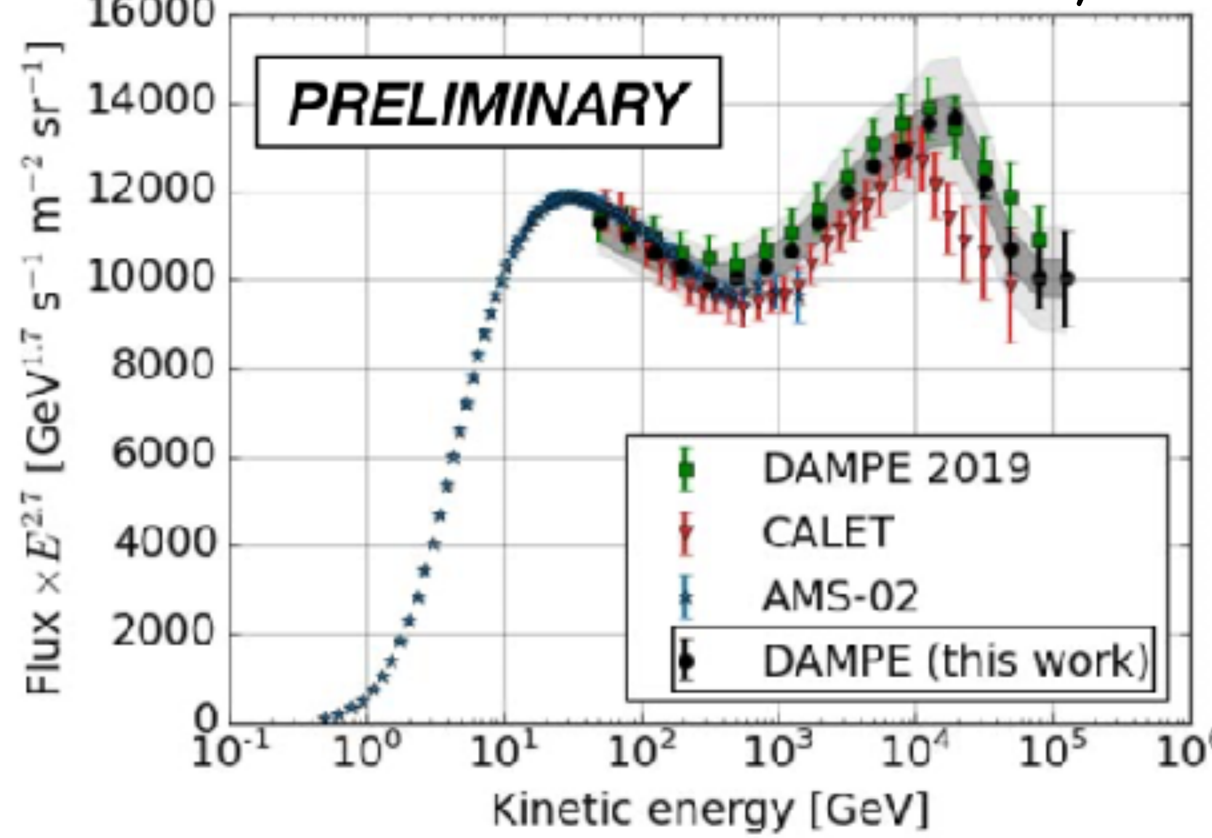

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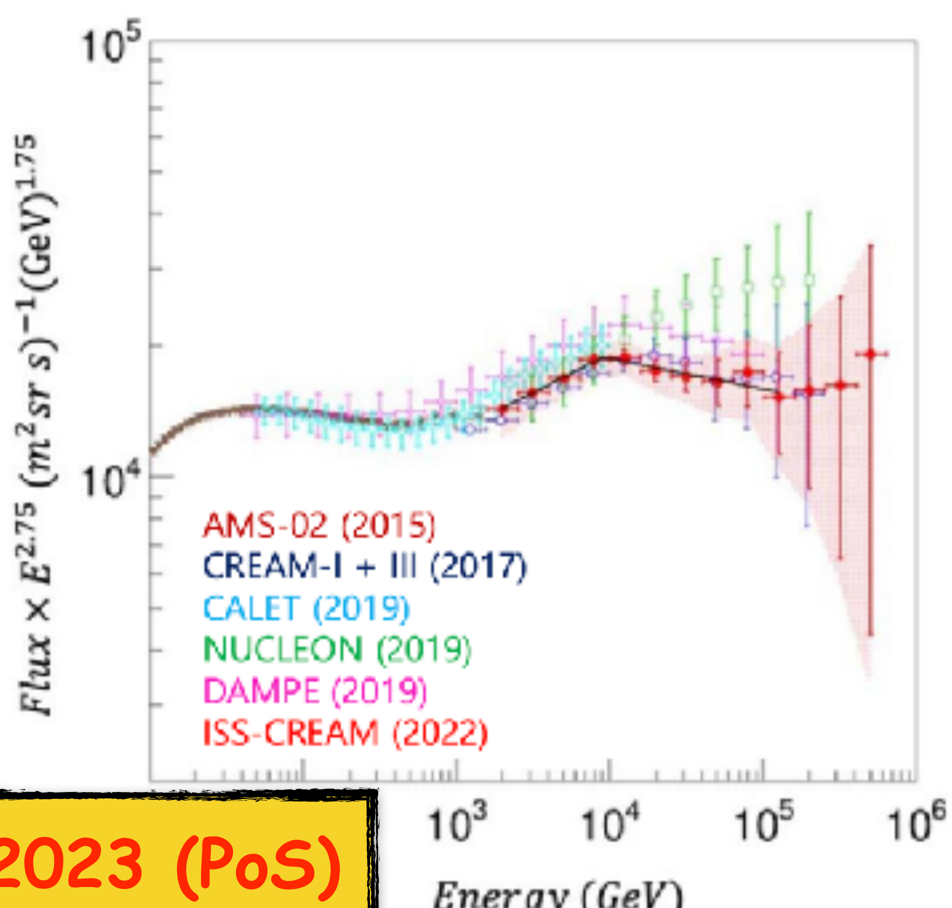

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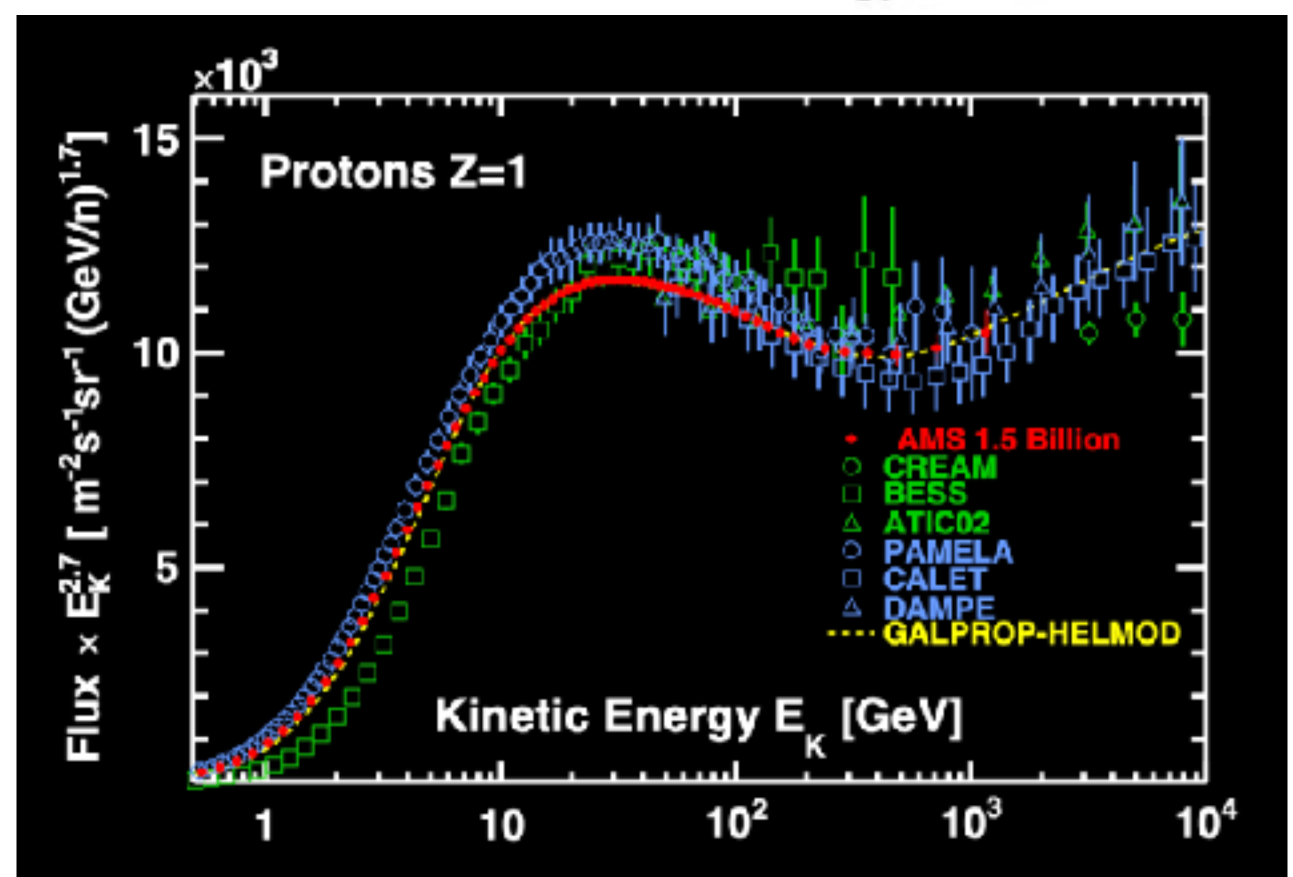

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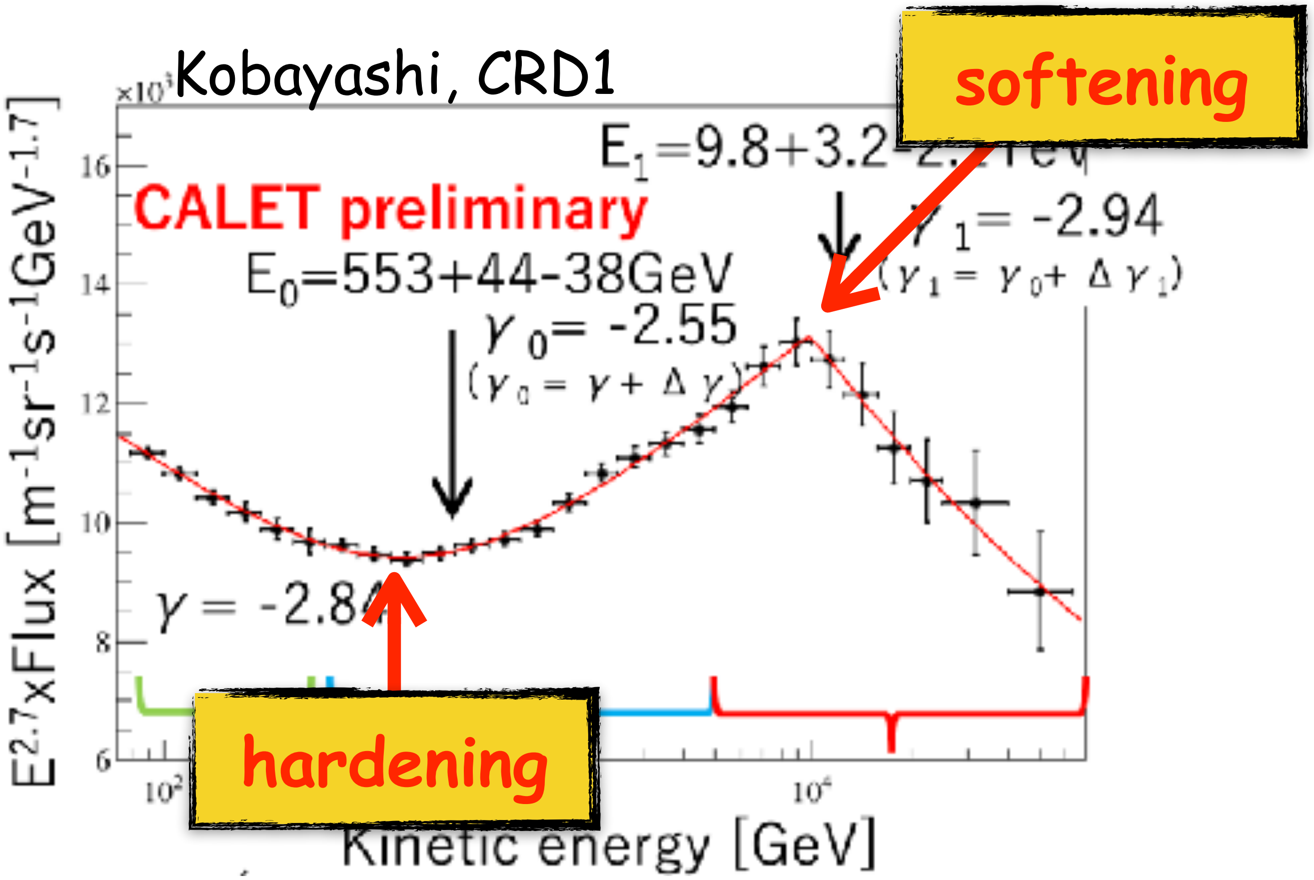

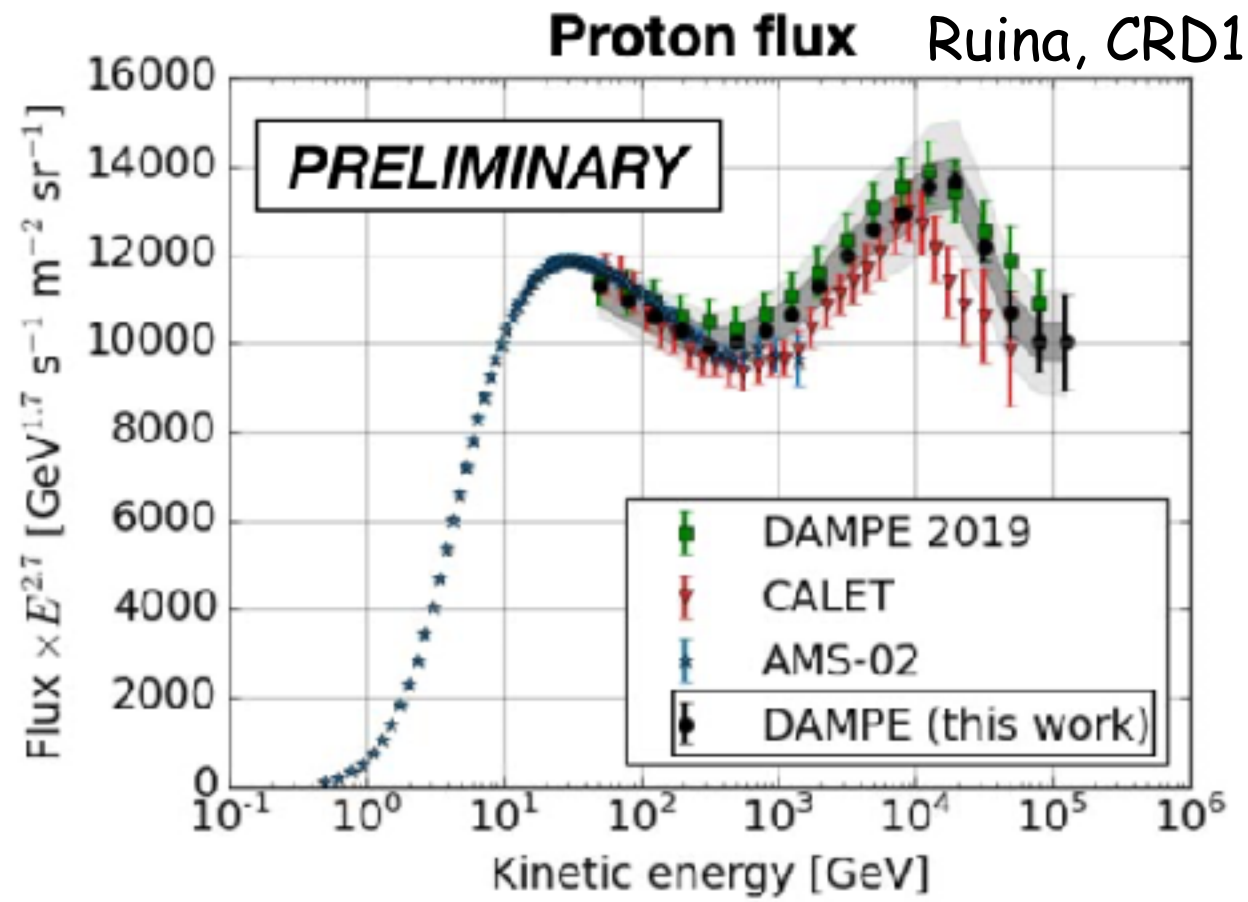

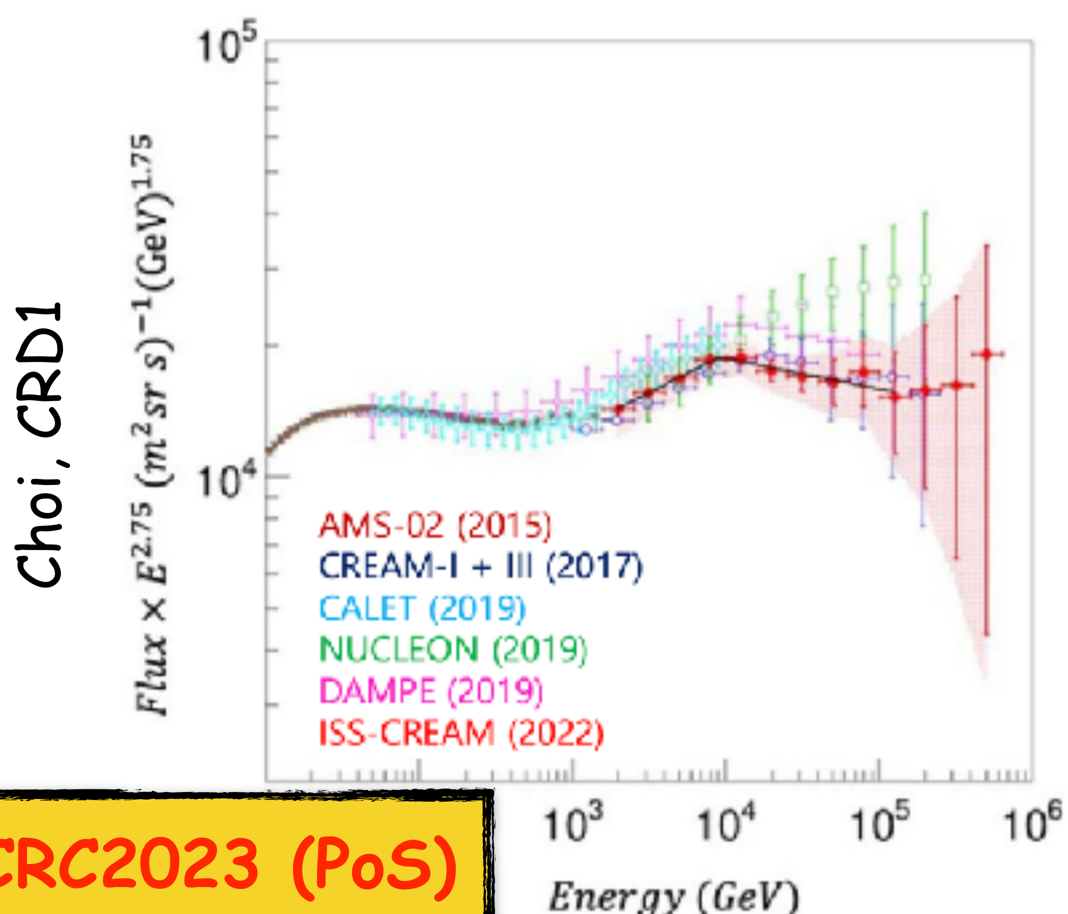

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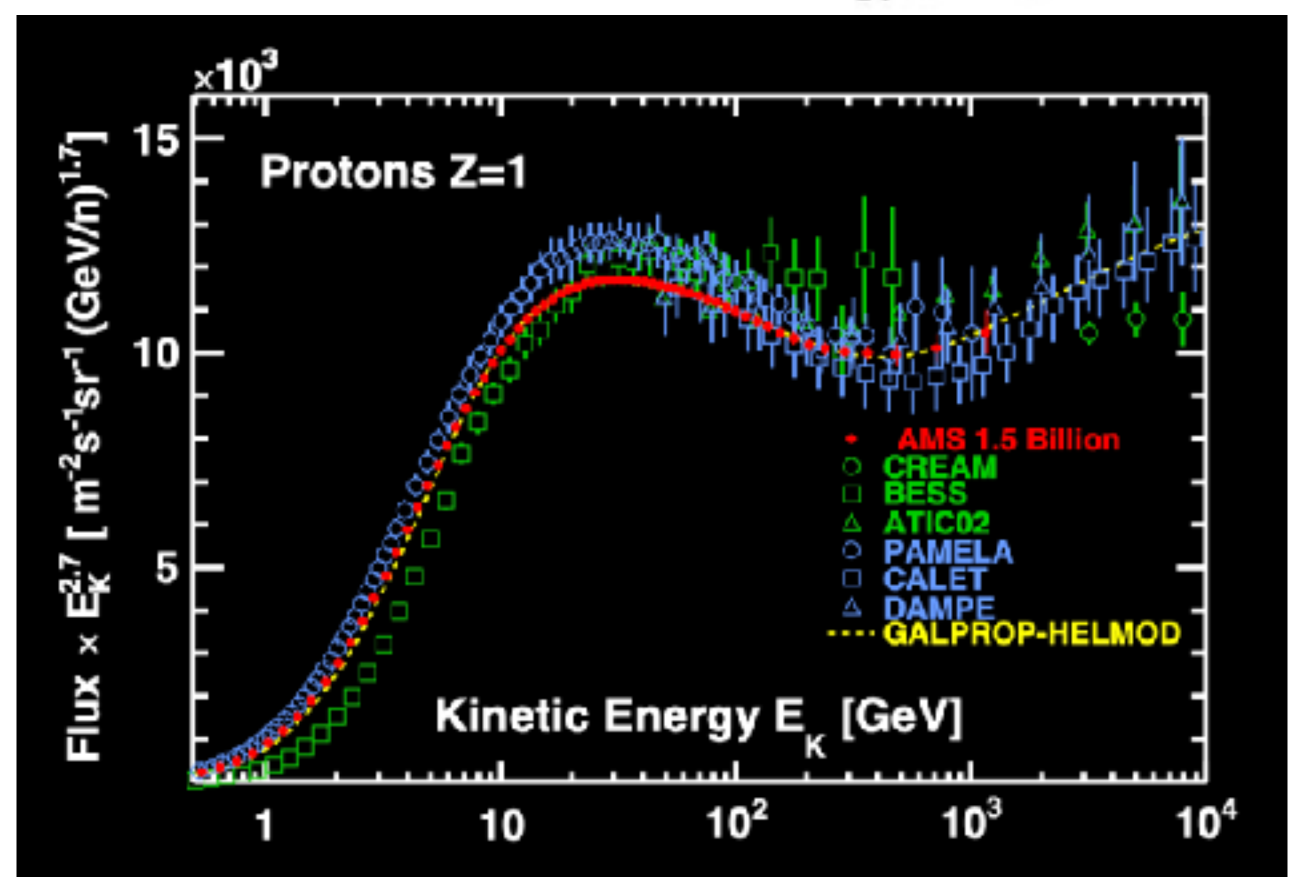
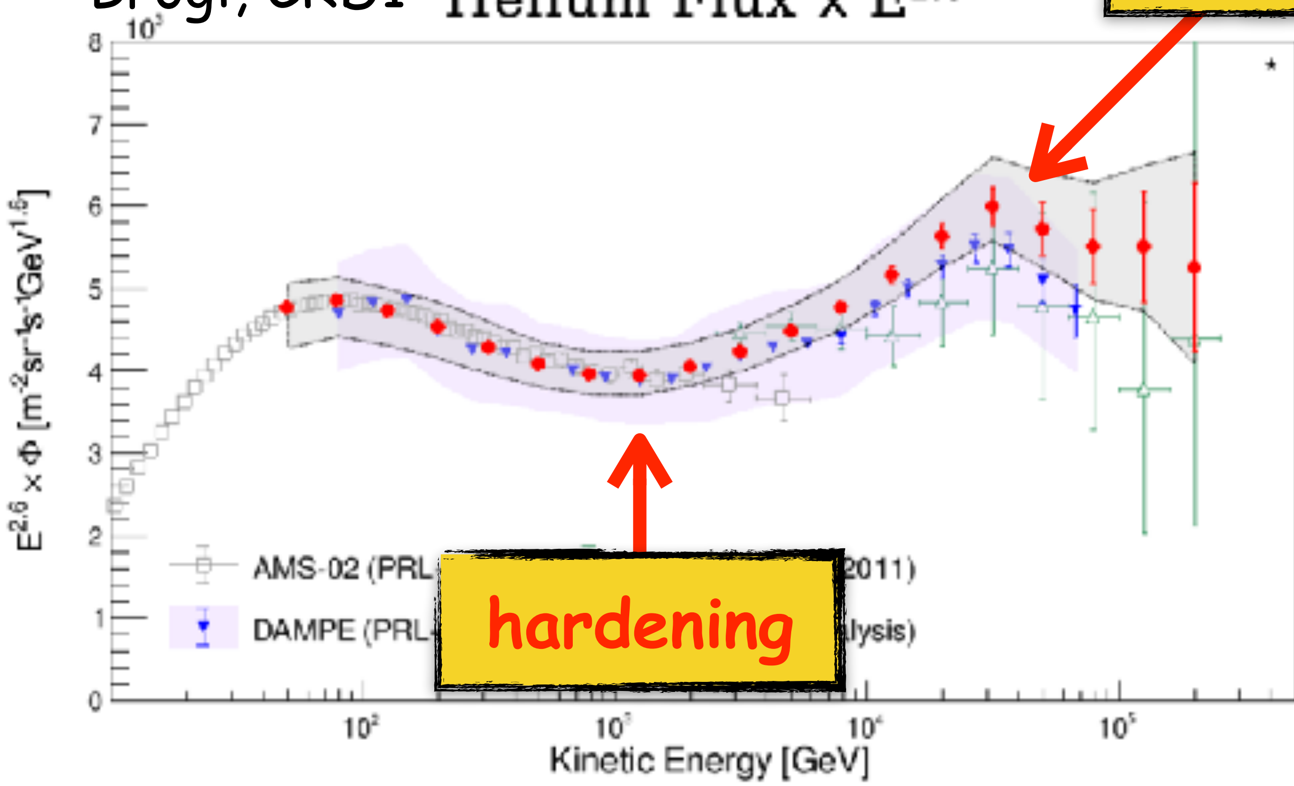
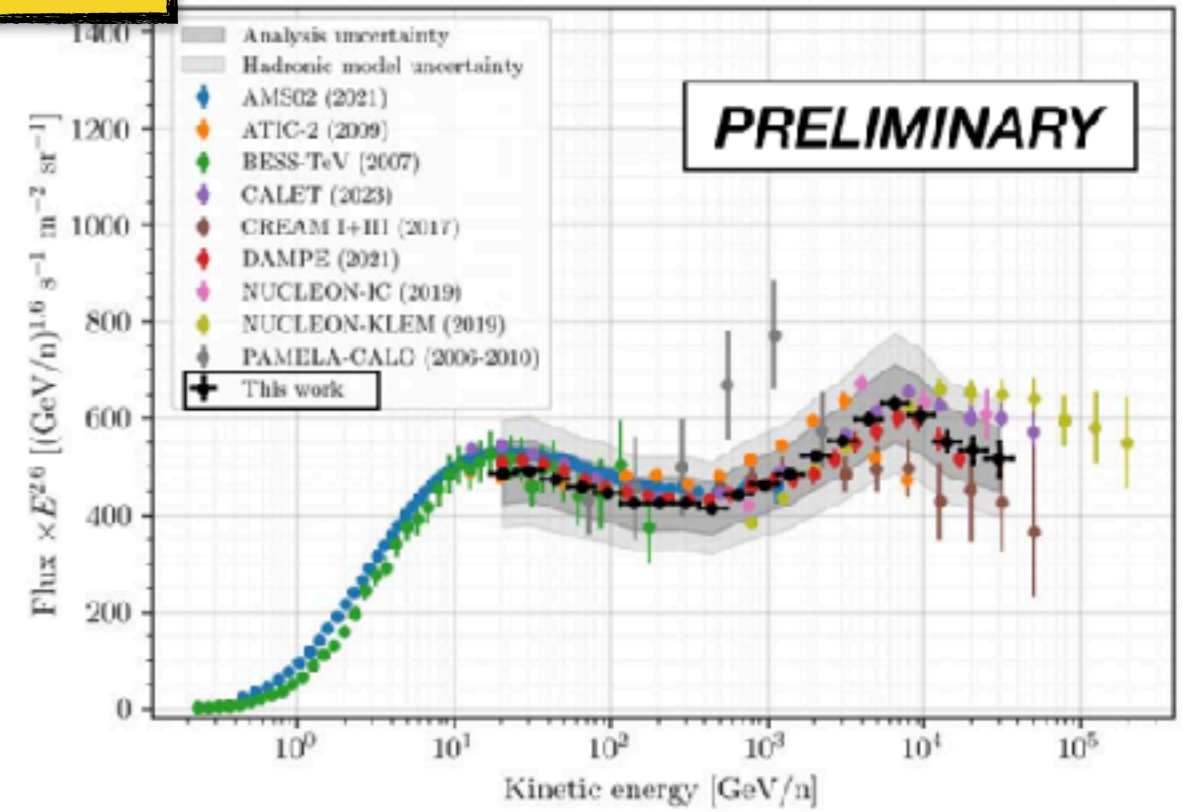


Give me a break! (CR Helium)

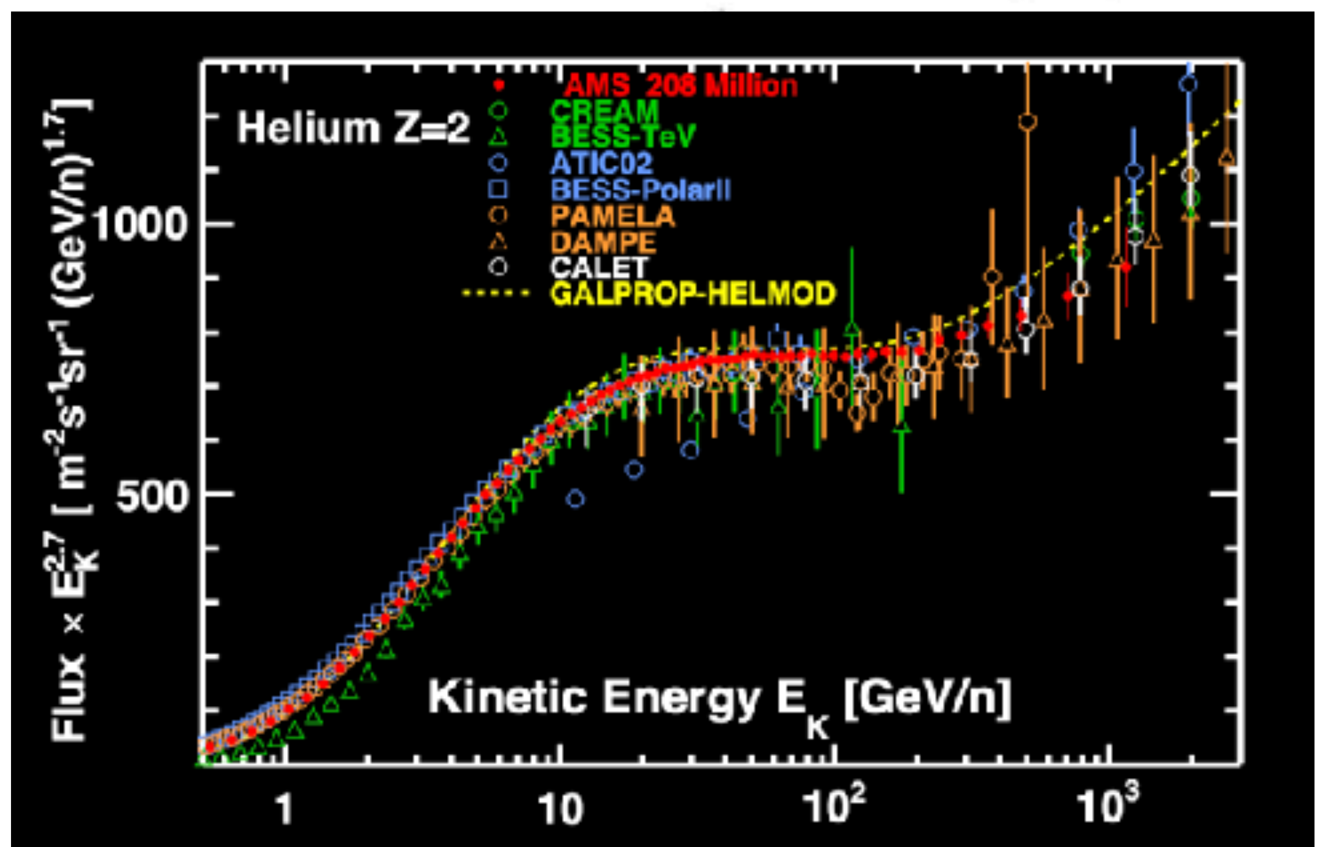
Brogi, CRD1



Ruina, CRD1



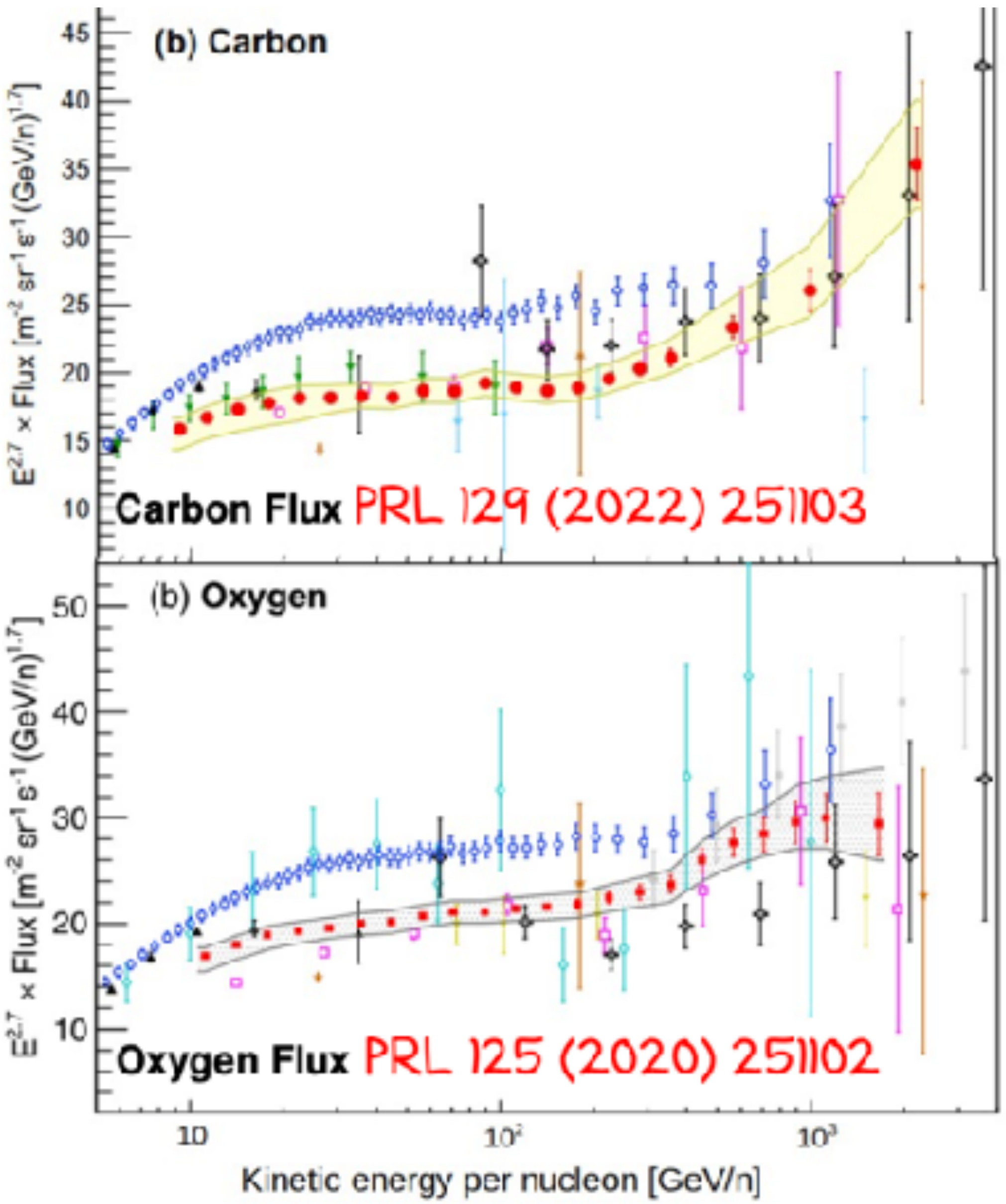
He spectrum follows the same pattern as the proton one

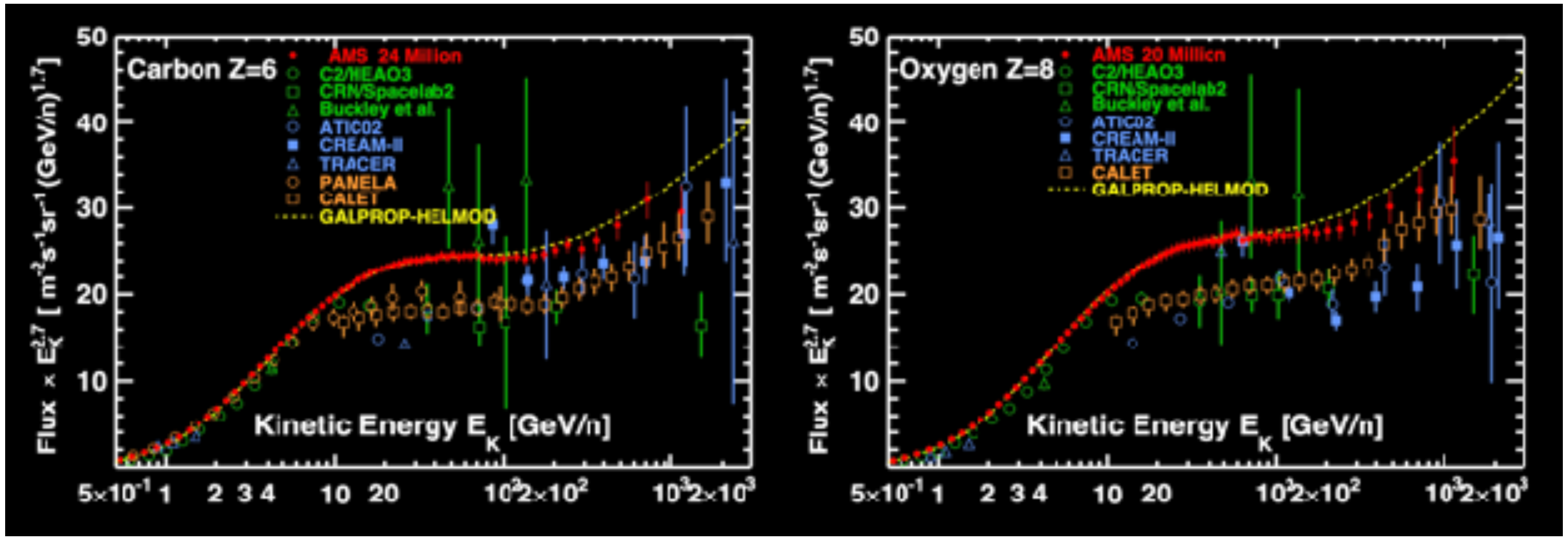


Oliva, CRD2

ICRC2023 (PoS)

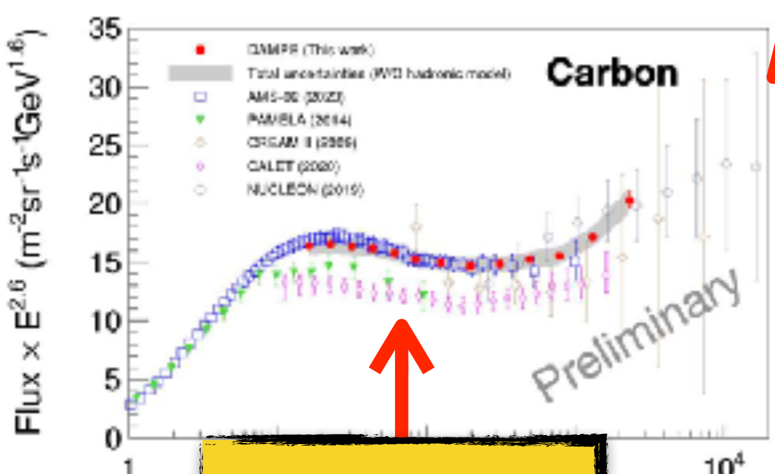
Give me a break! (C and O)

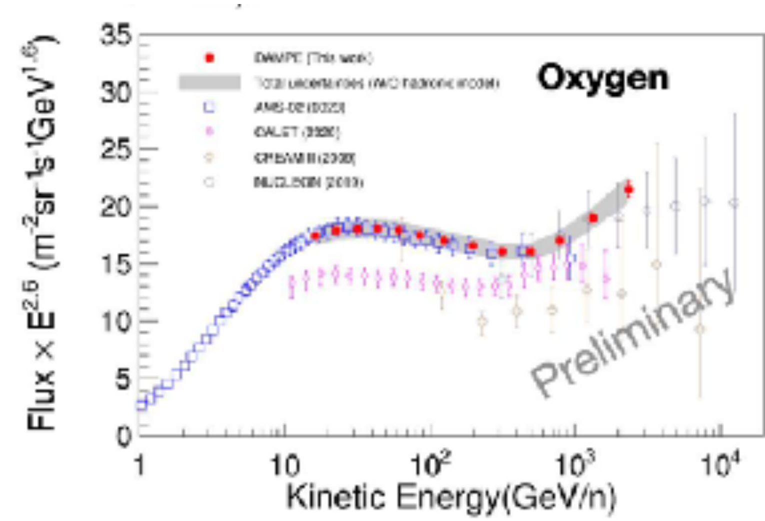




Oliv

softening?





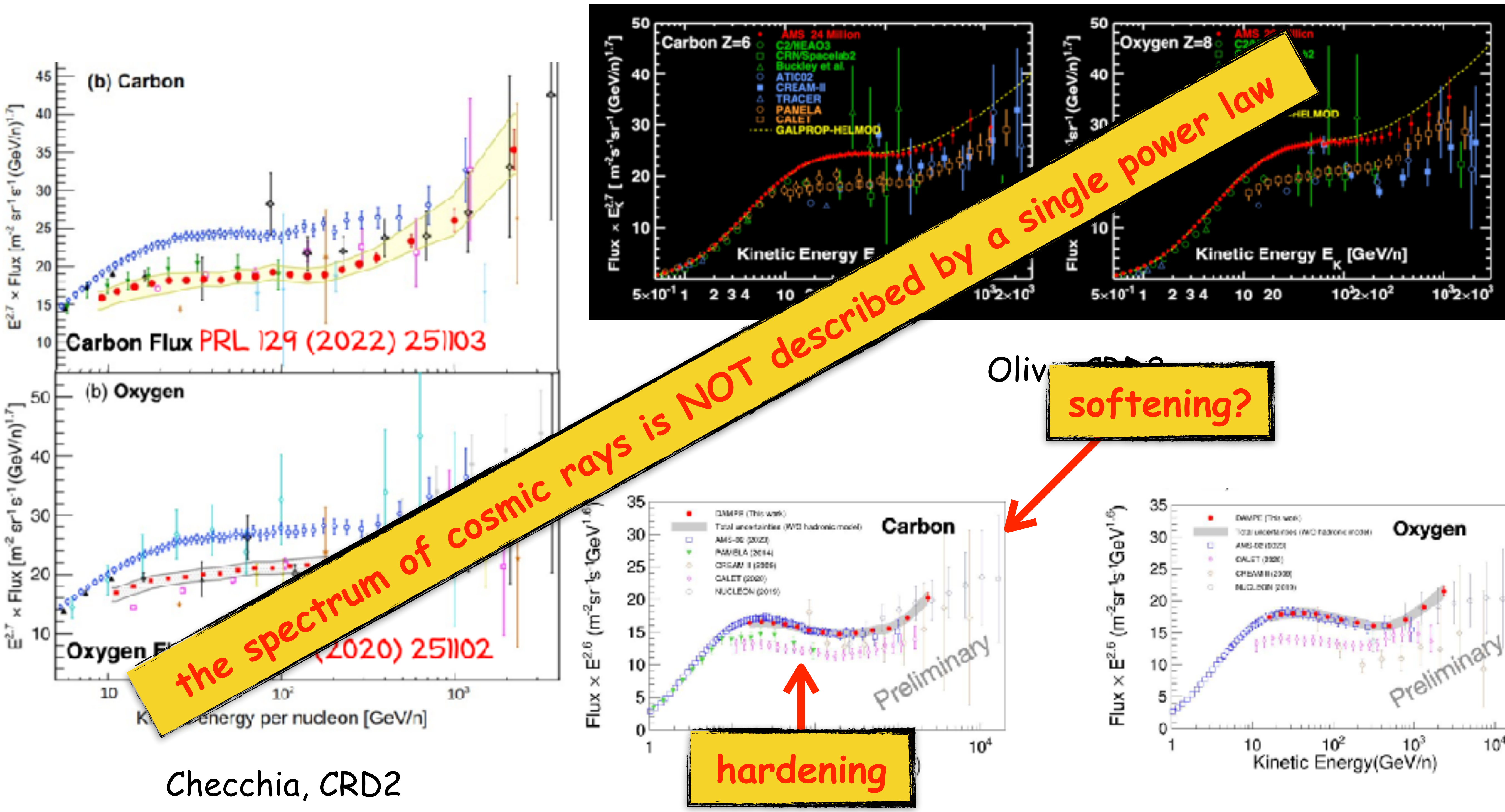
hardening

Checchia, CRD2

Wei, CRD2

ICRC2023 (PoS)

Give me a break! (C and O)



Checchia, CRD2

Olivа, CRD2

Wei, CRD2

ICRC2023 (PoS)

So what?

…as the observed spectrum of cosmic rays is shaped by:
[1] acceleration at sources;
[2] escape from sources;
[3] transport in the interstellar magnetic field;
the presence of breaks means that AT LEAST one of such physical processes cannot be described by a pure power law.
…on the other hand this opens up new possibilities because deviations from pure power laws imply:
[1] modified transport (that explains the break at 200 GV!)
<u>and/or</u>
[2] non-universality of injection (sources do not inject pure power laws or sources are not all the same)
<u>and/or</u>
[3] more than one class of sources contributing to the cosmic ray population…

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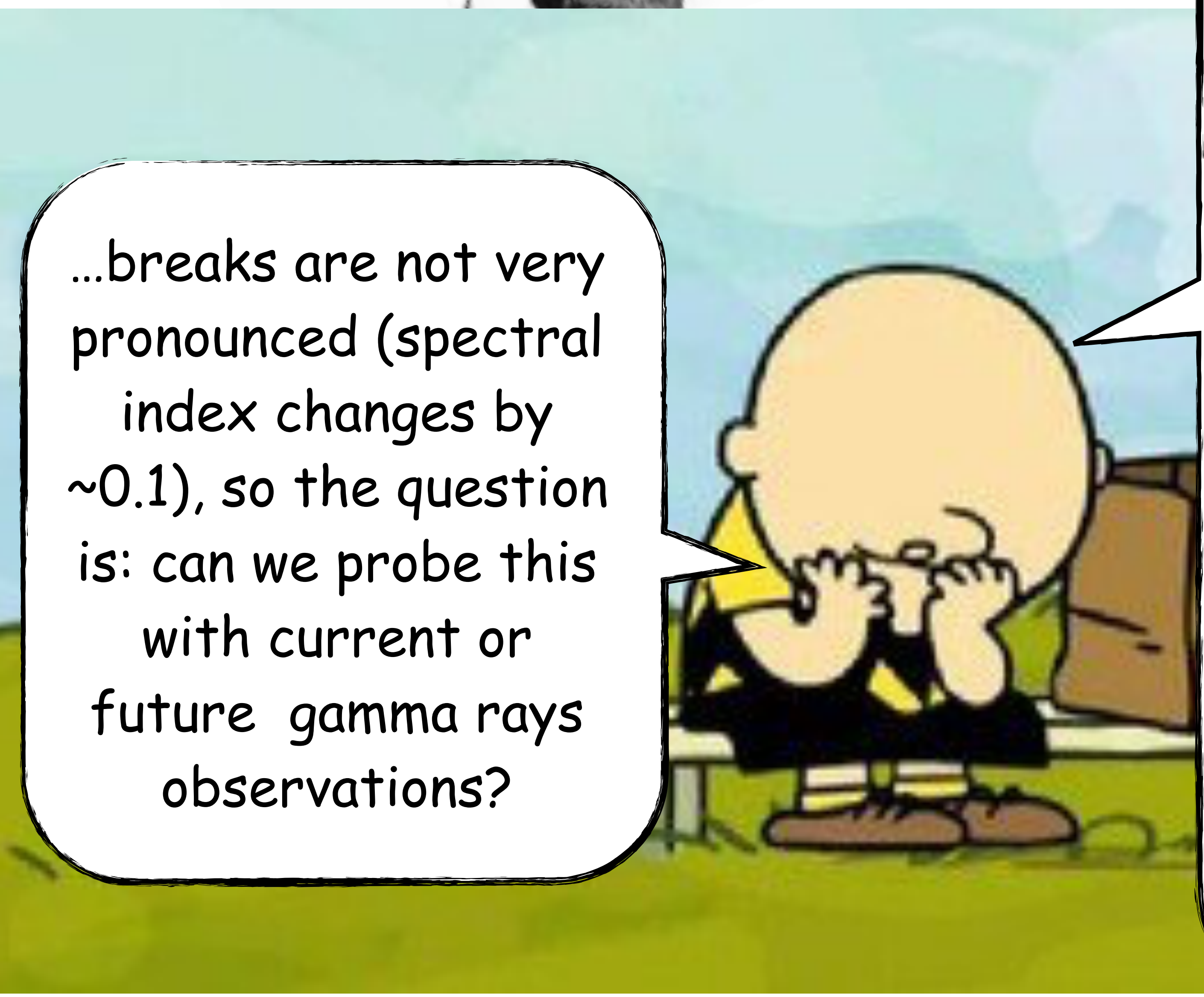

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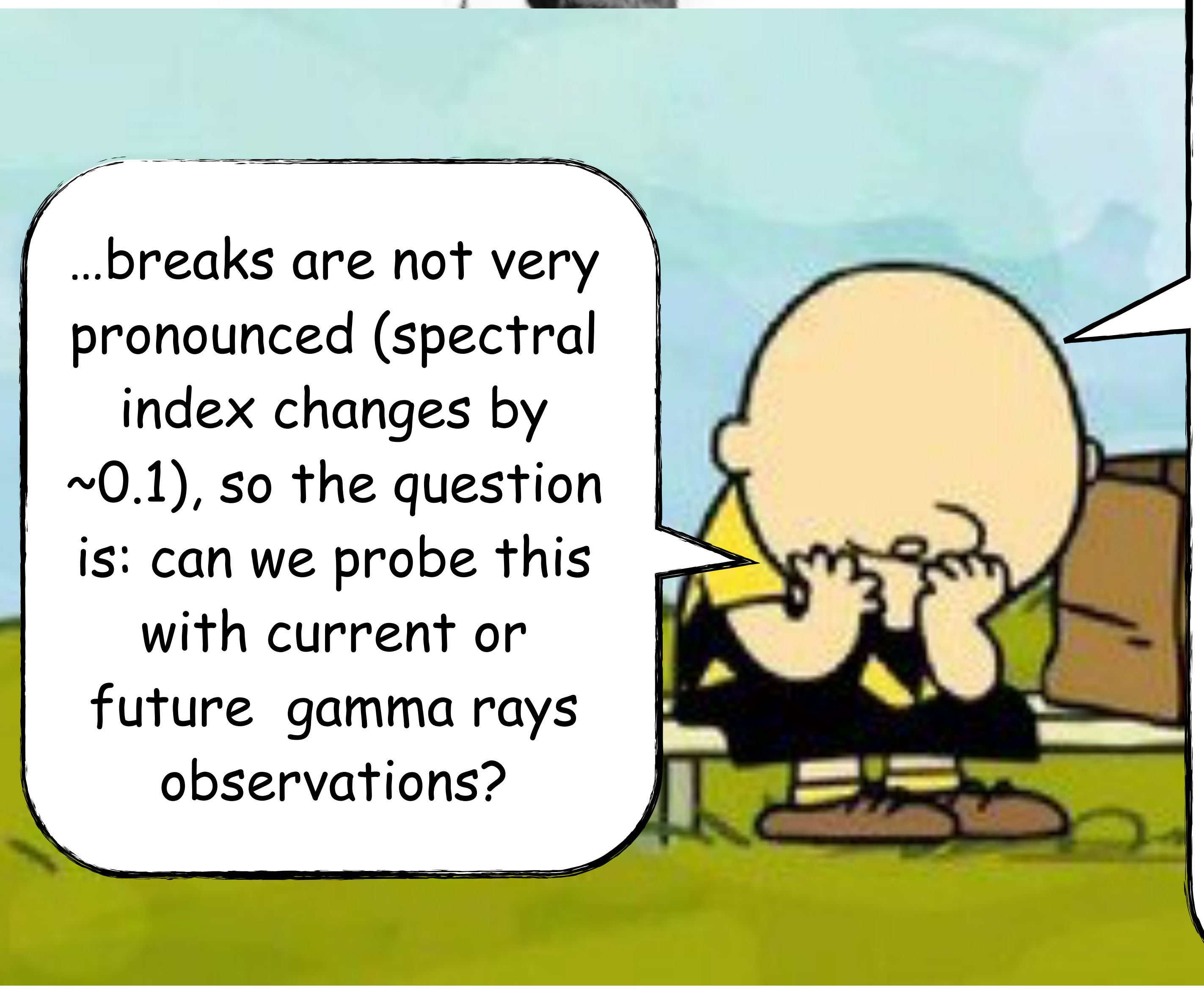
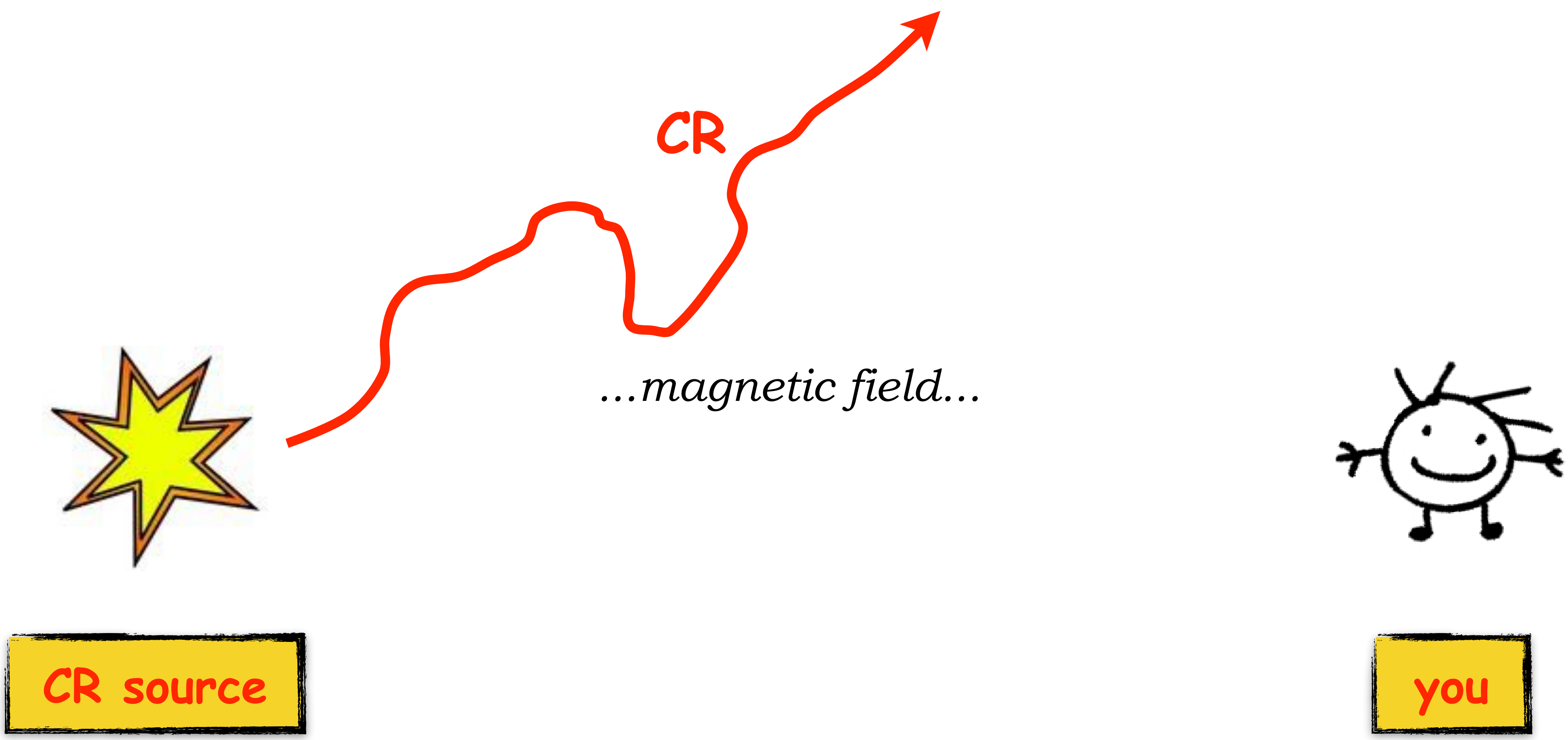


Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy

Need for indirect identification of CR sources

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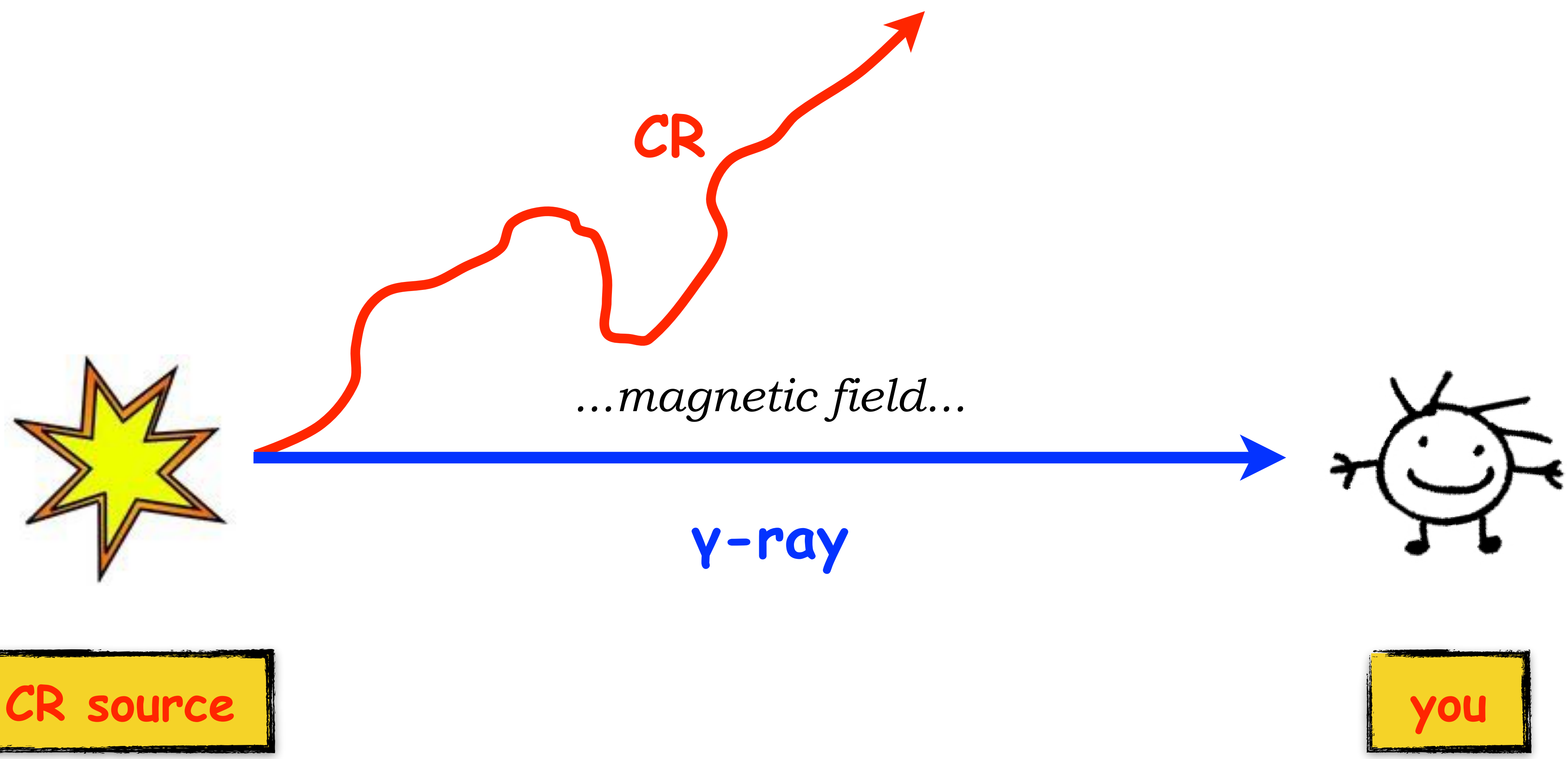
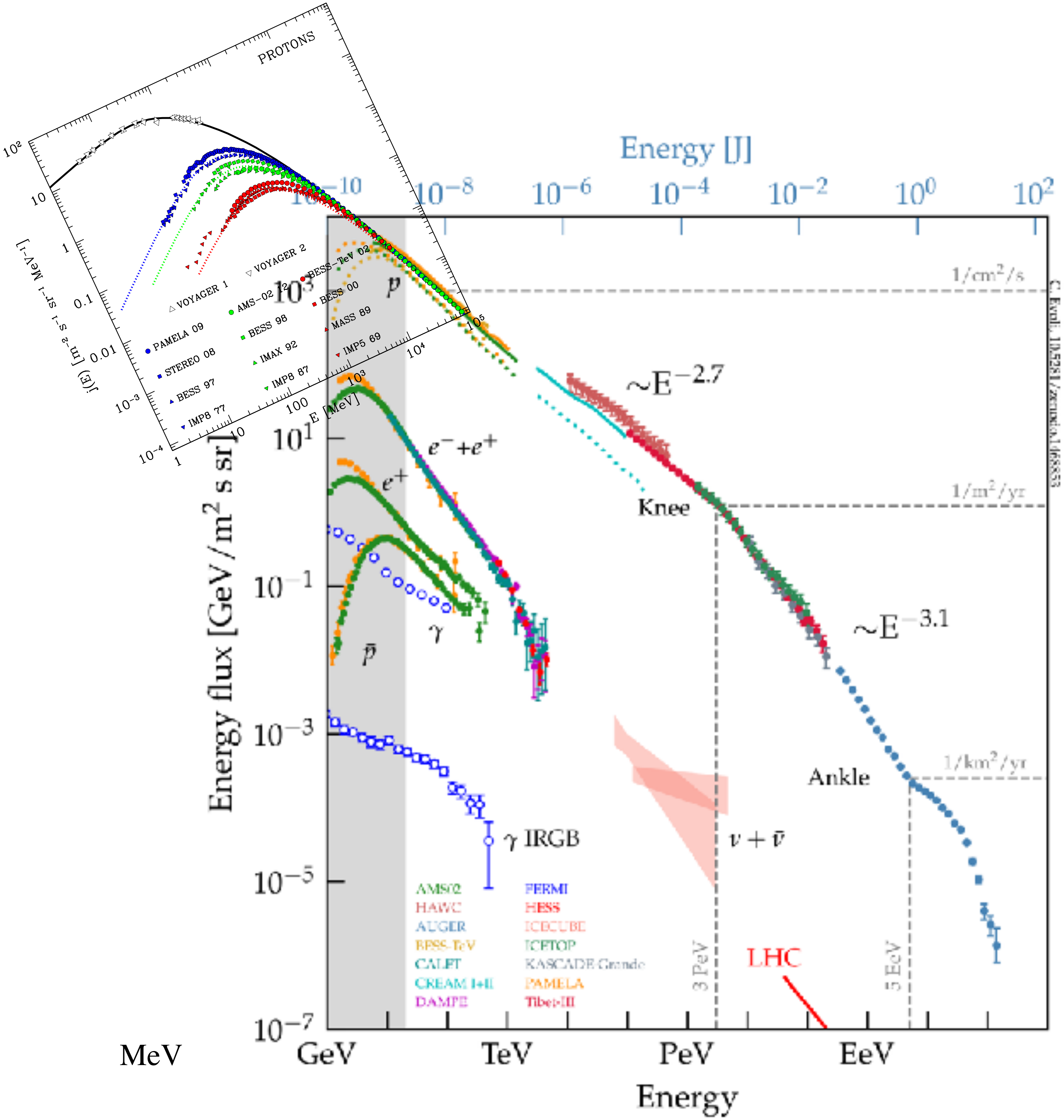


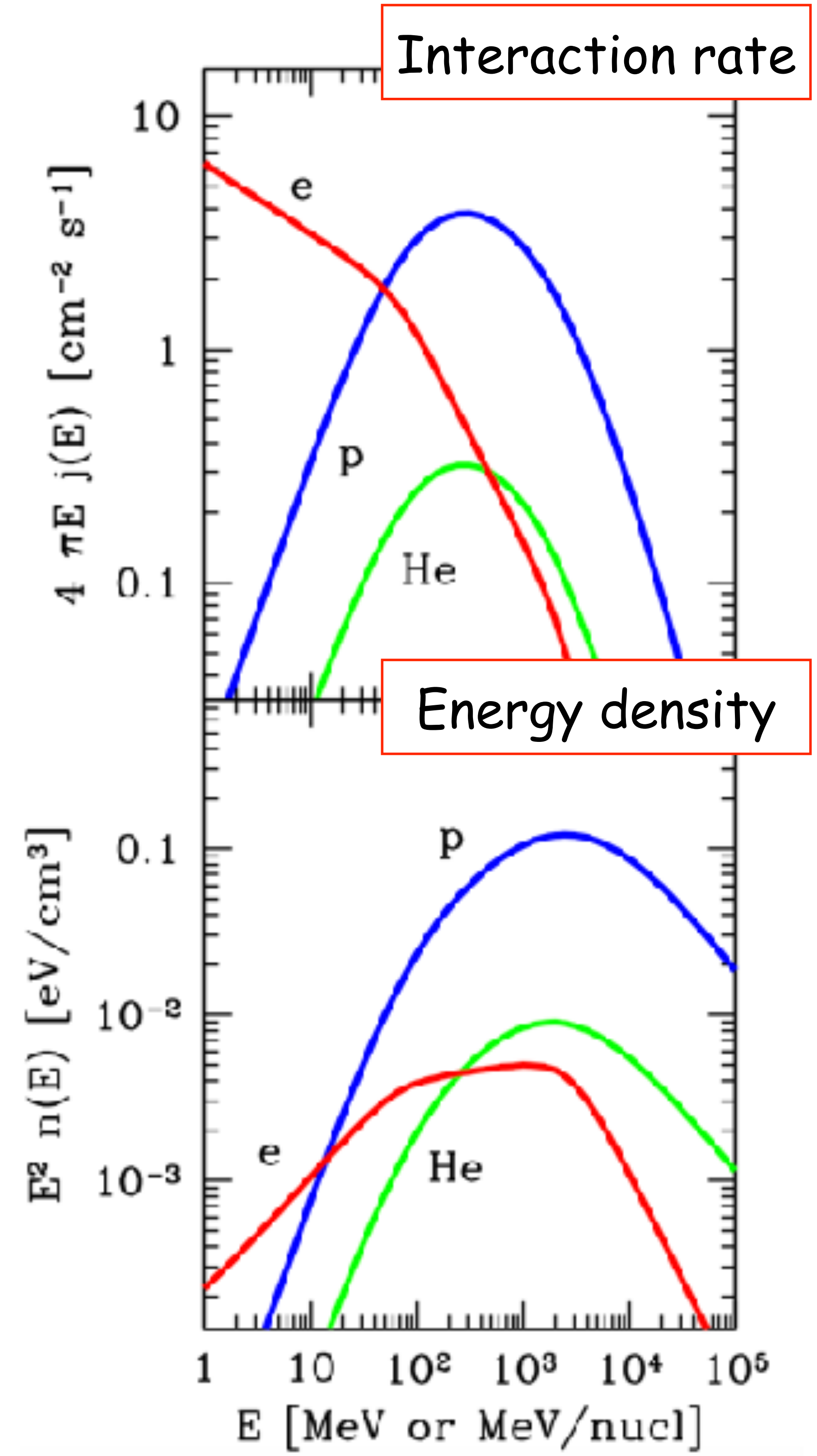
We cannot do CR Astronomy

Need for indirect identification of CR sources

—> γ-ray astronomy!

One question every 3 (energy) decades…





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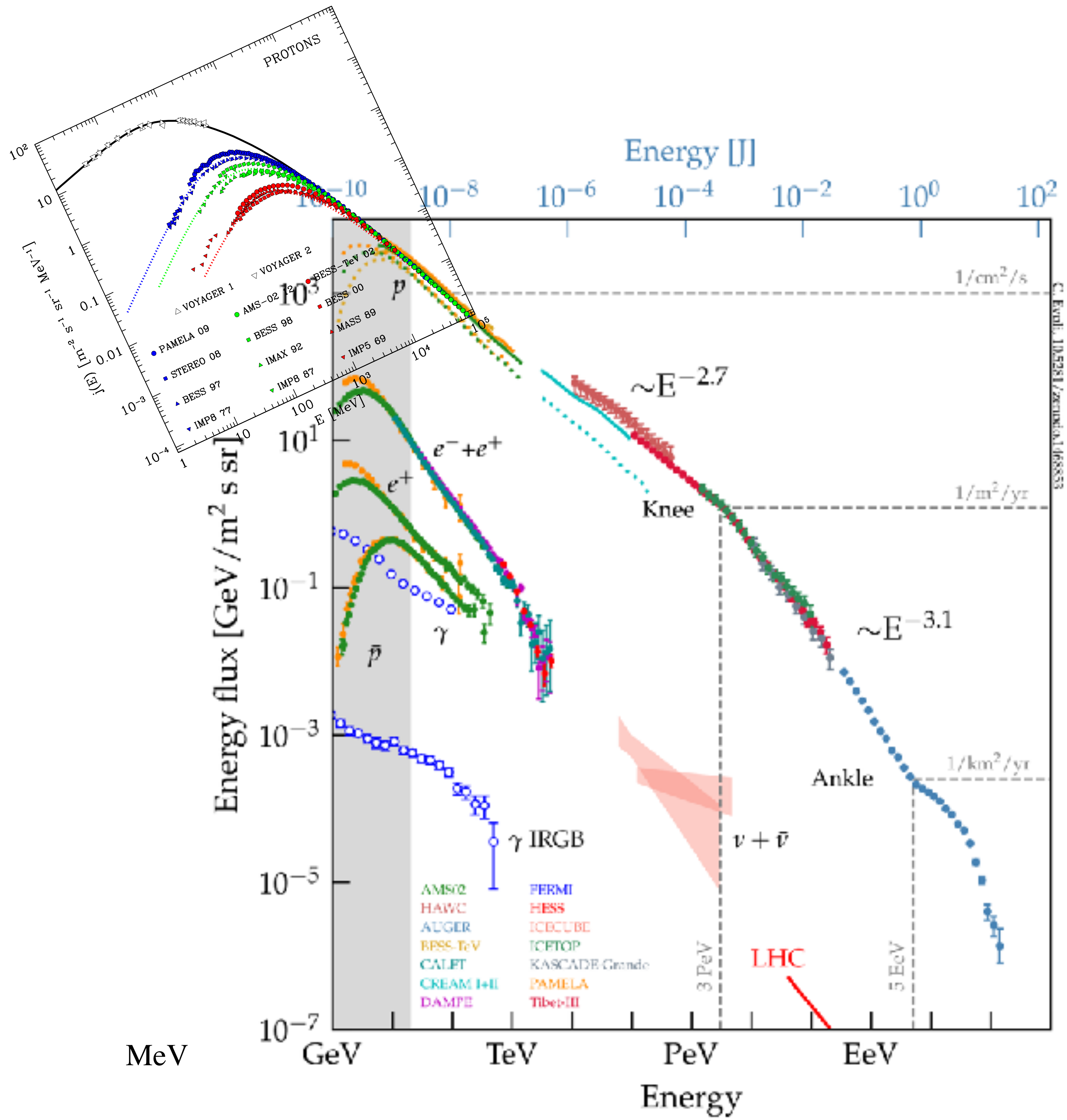

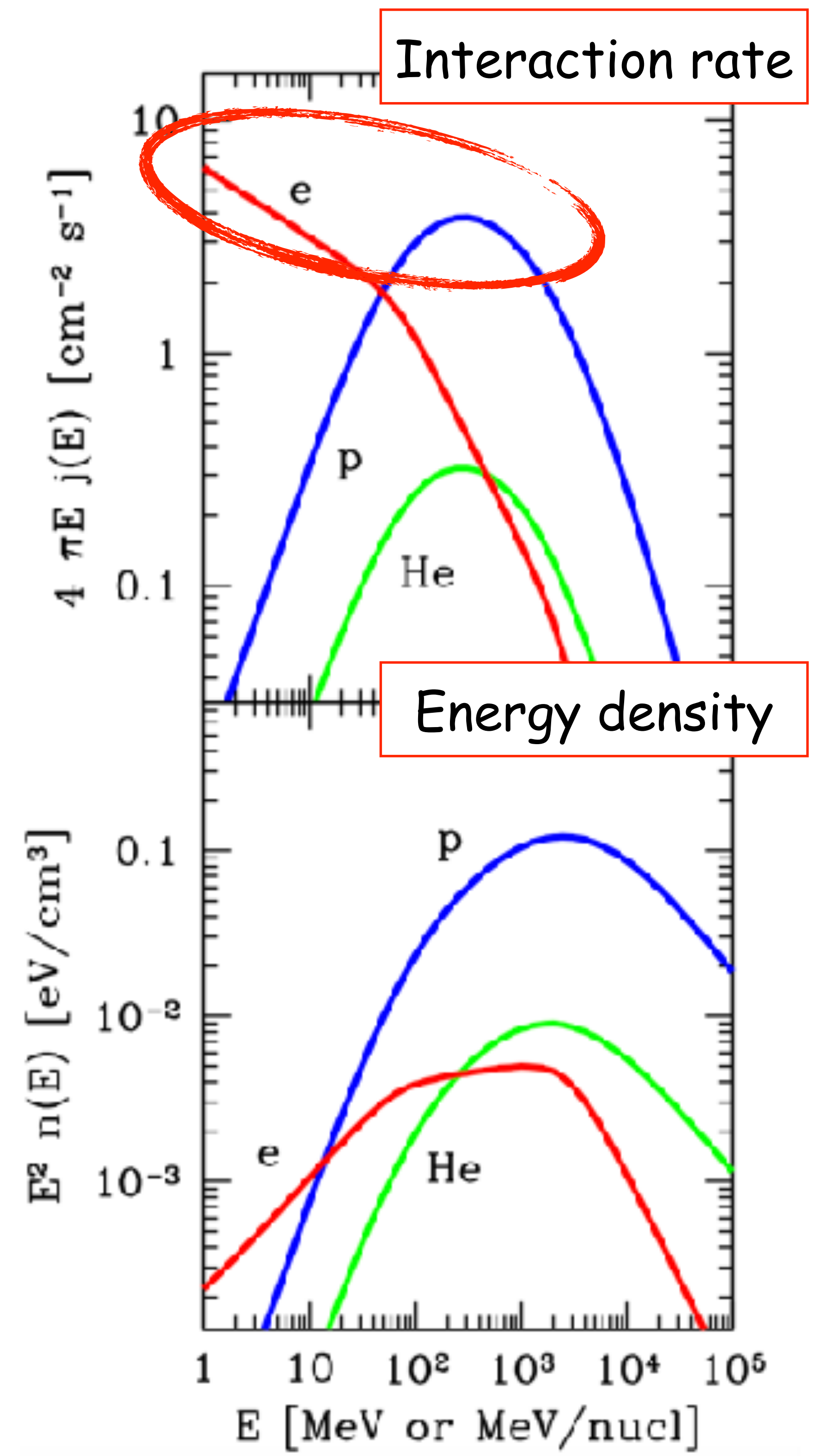

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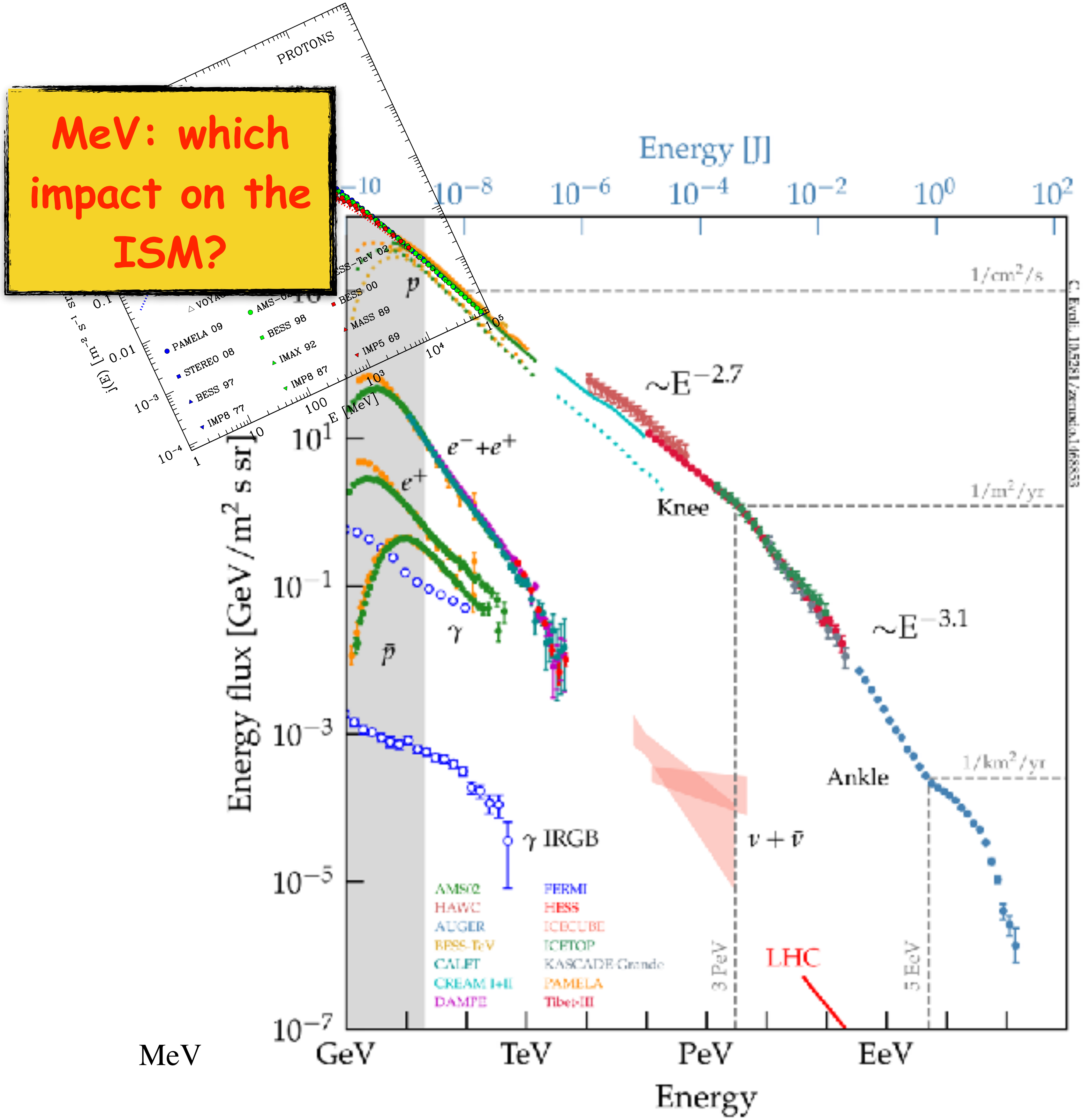

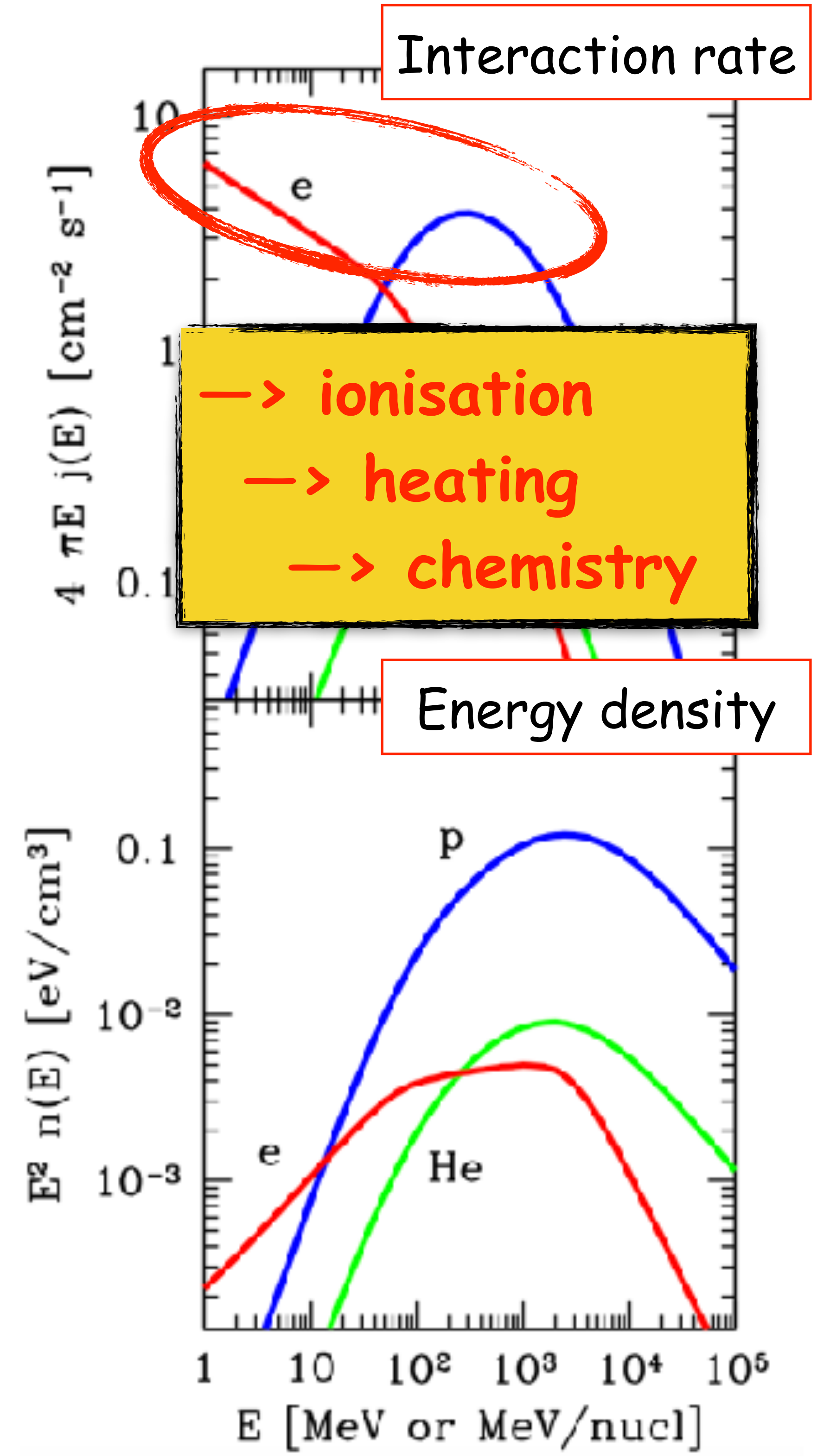

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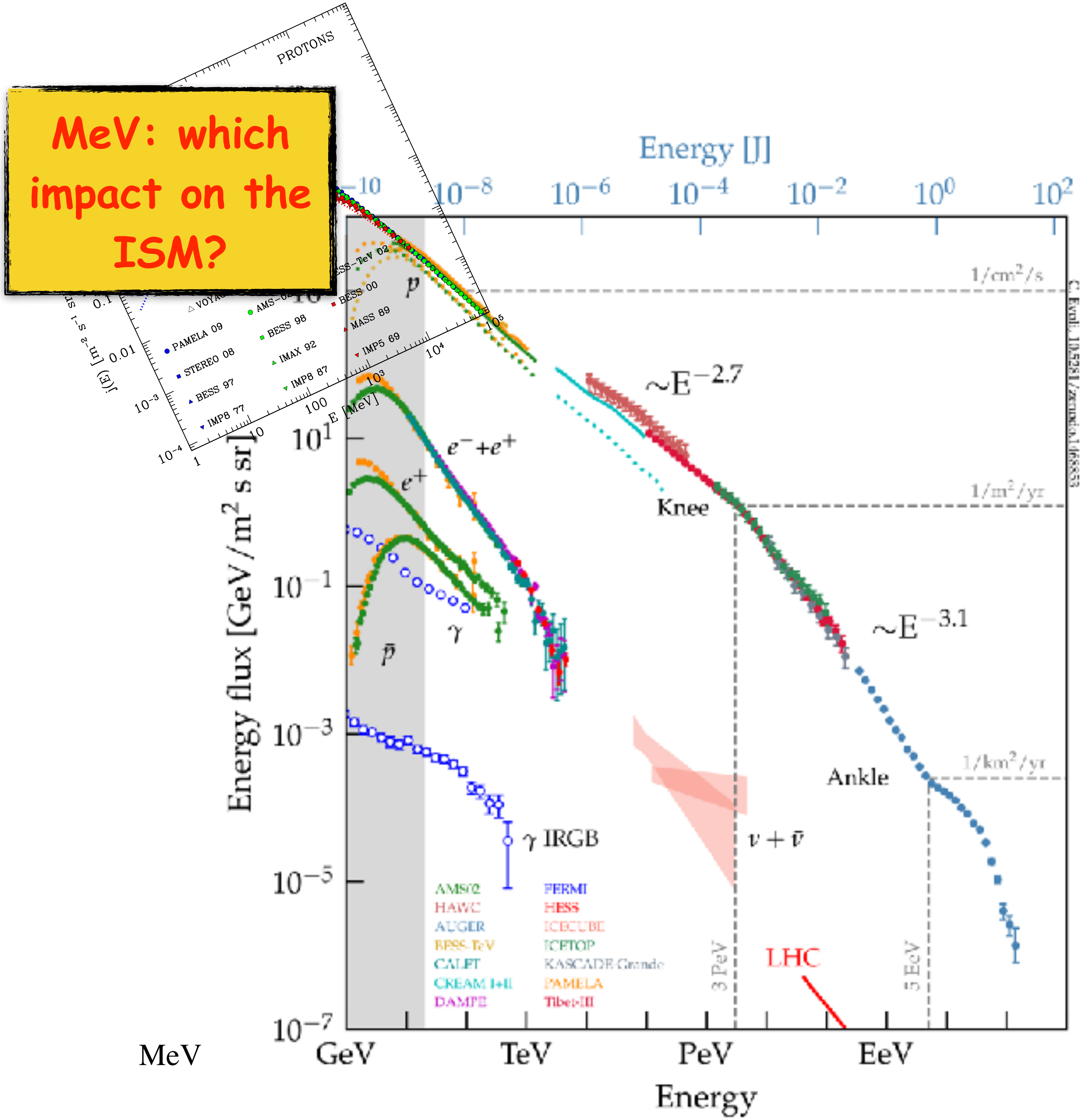

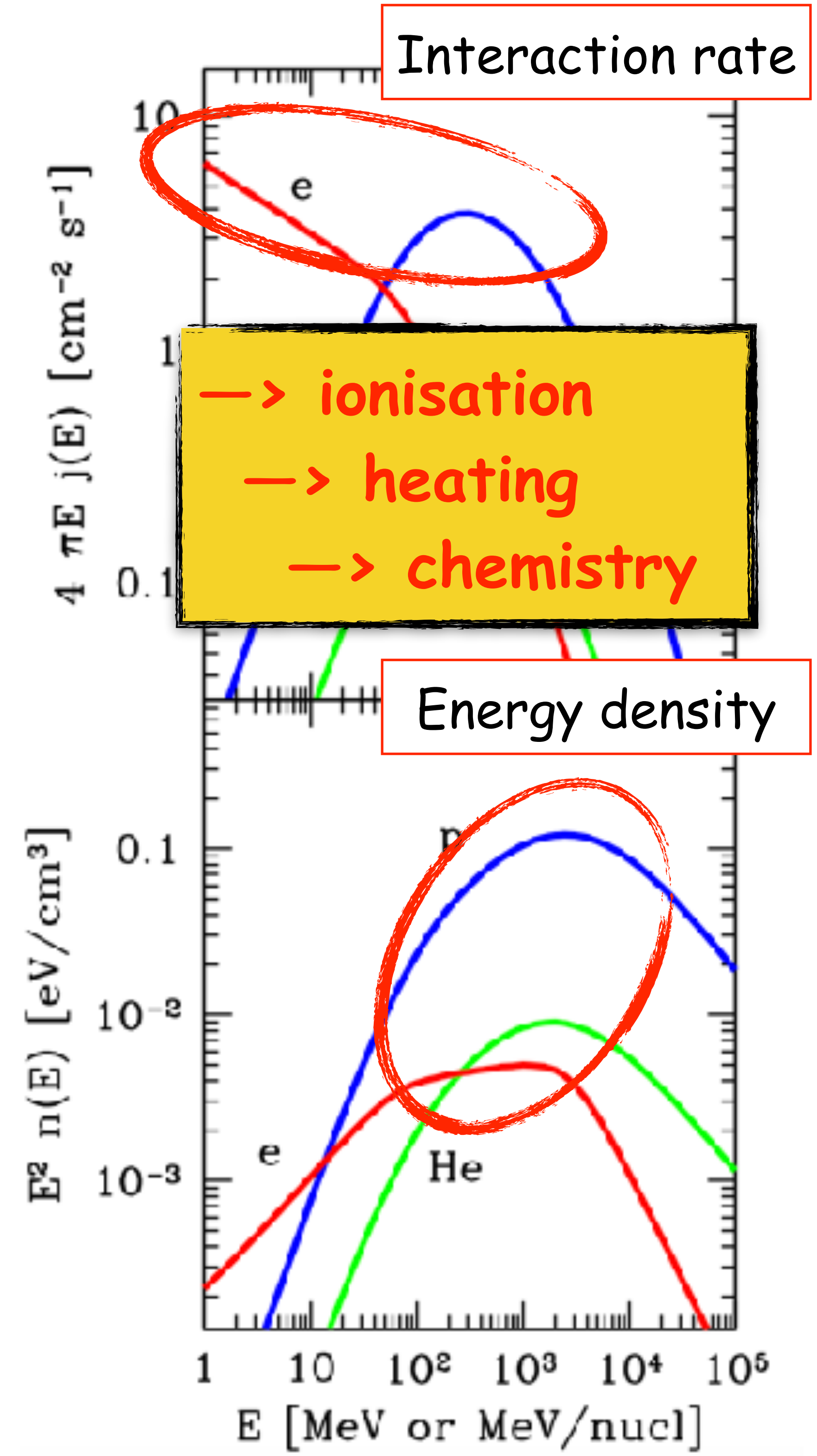

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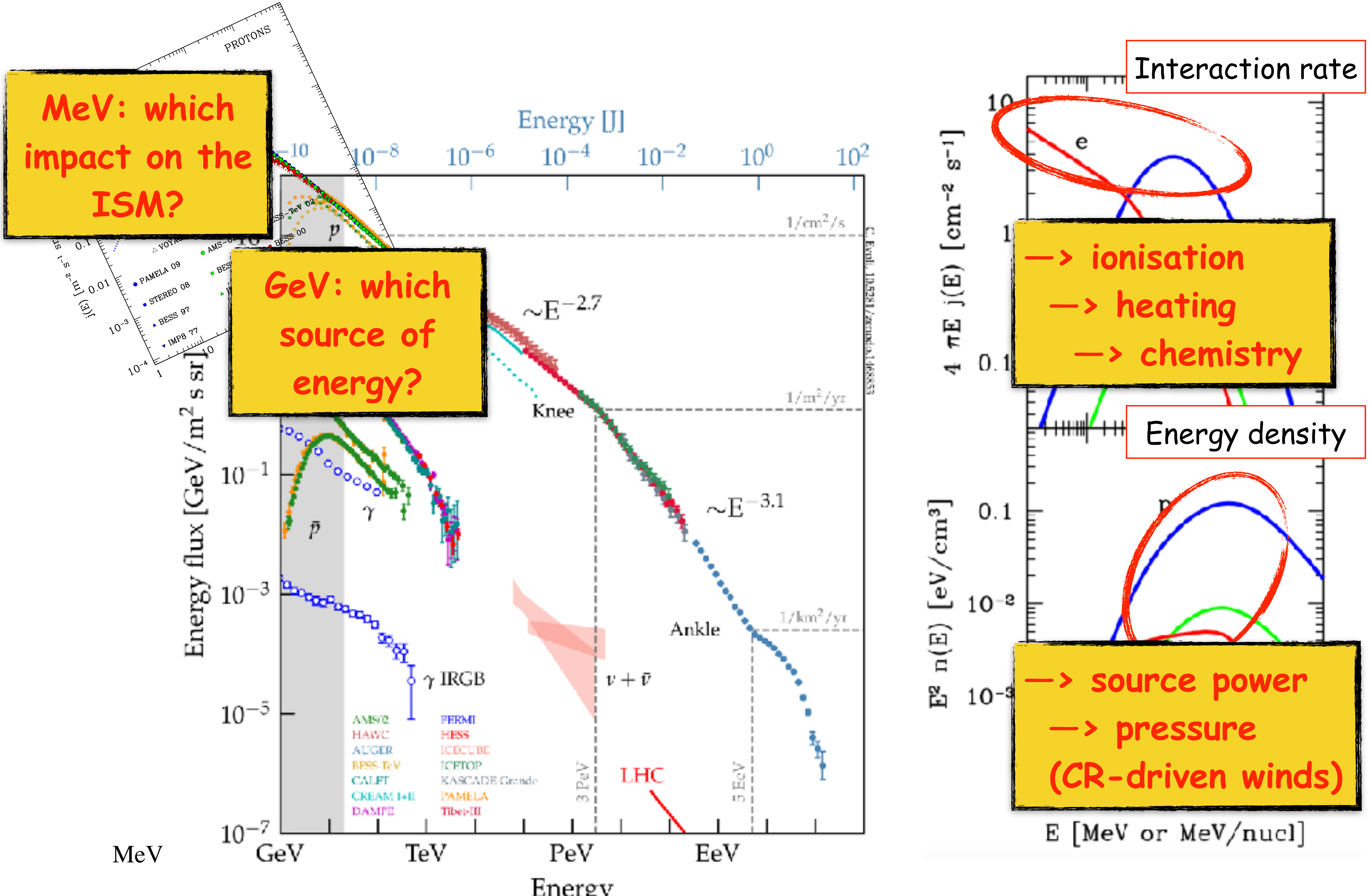

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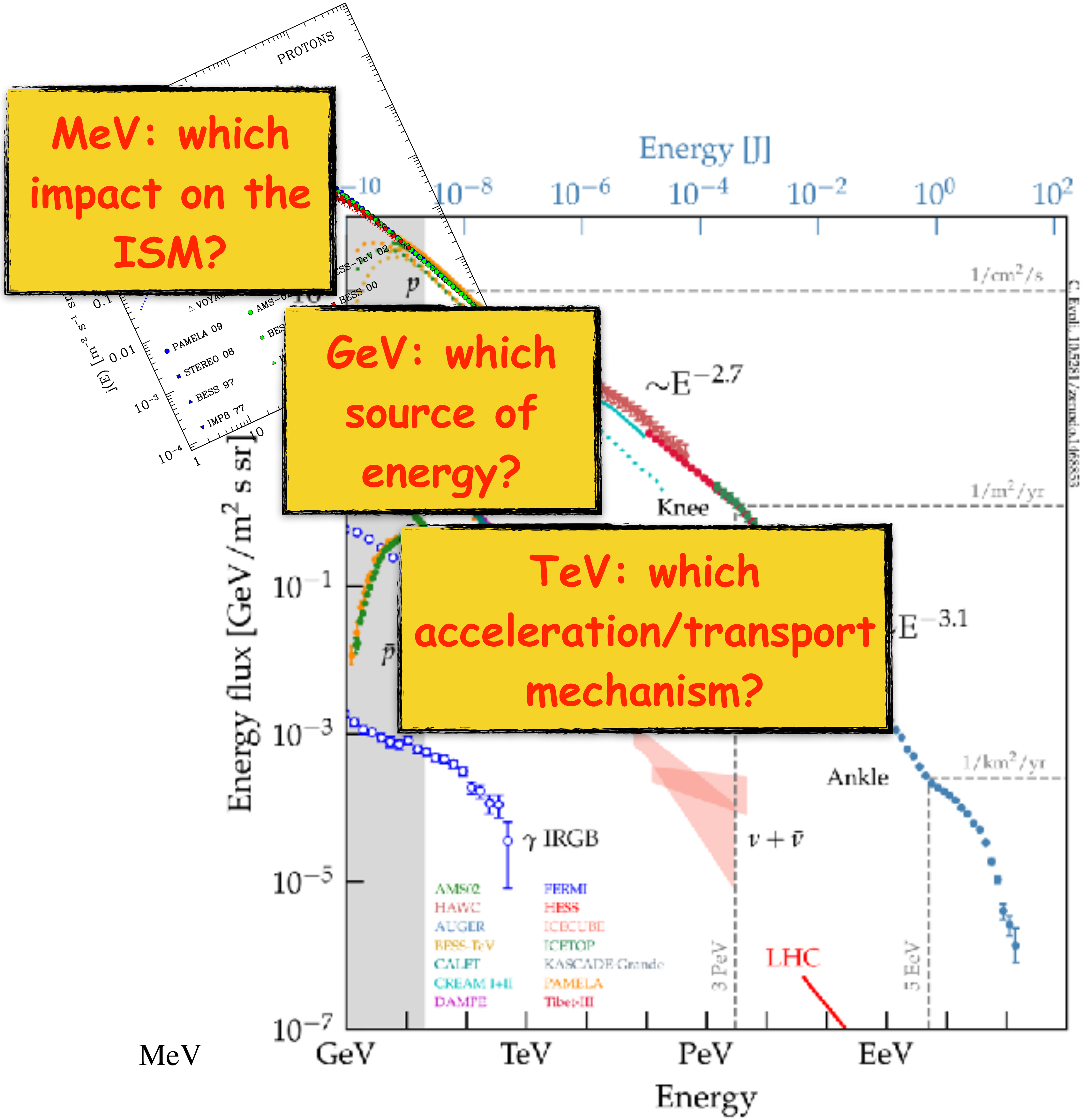

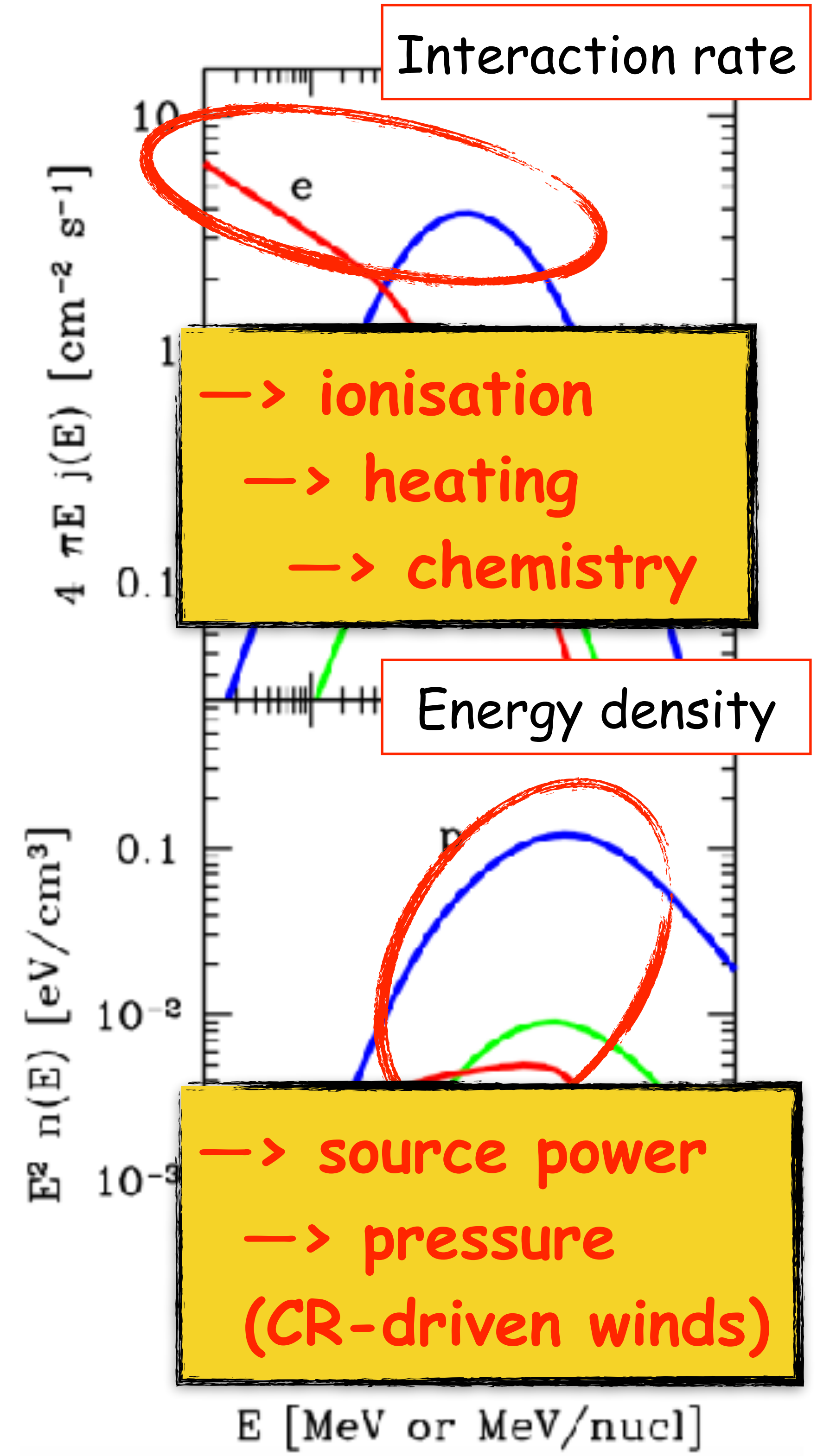

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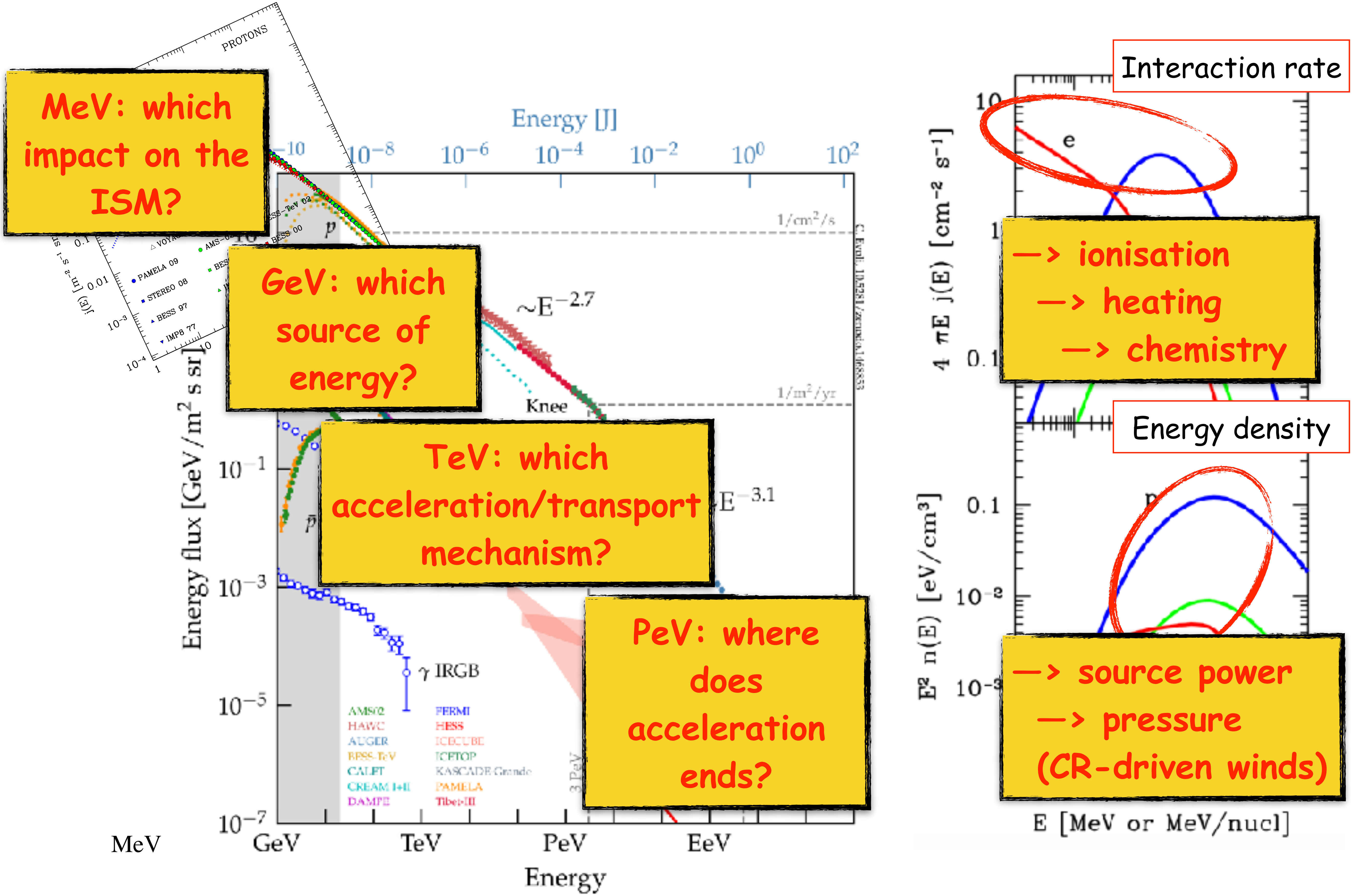
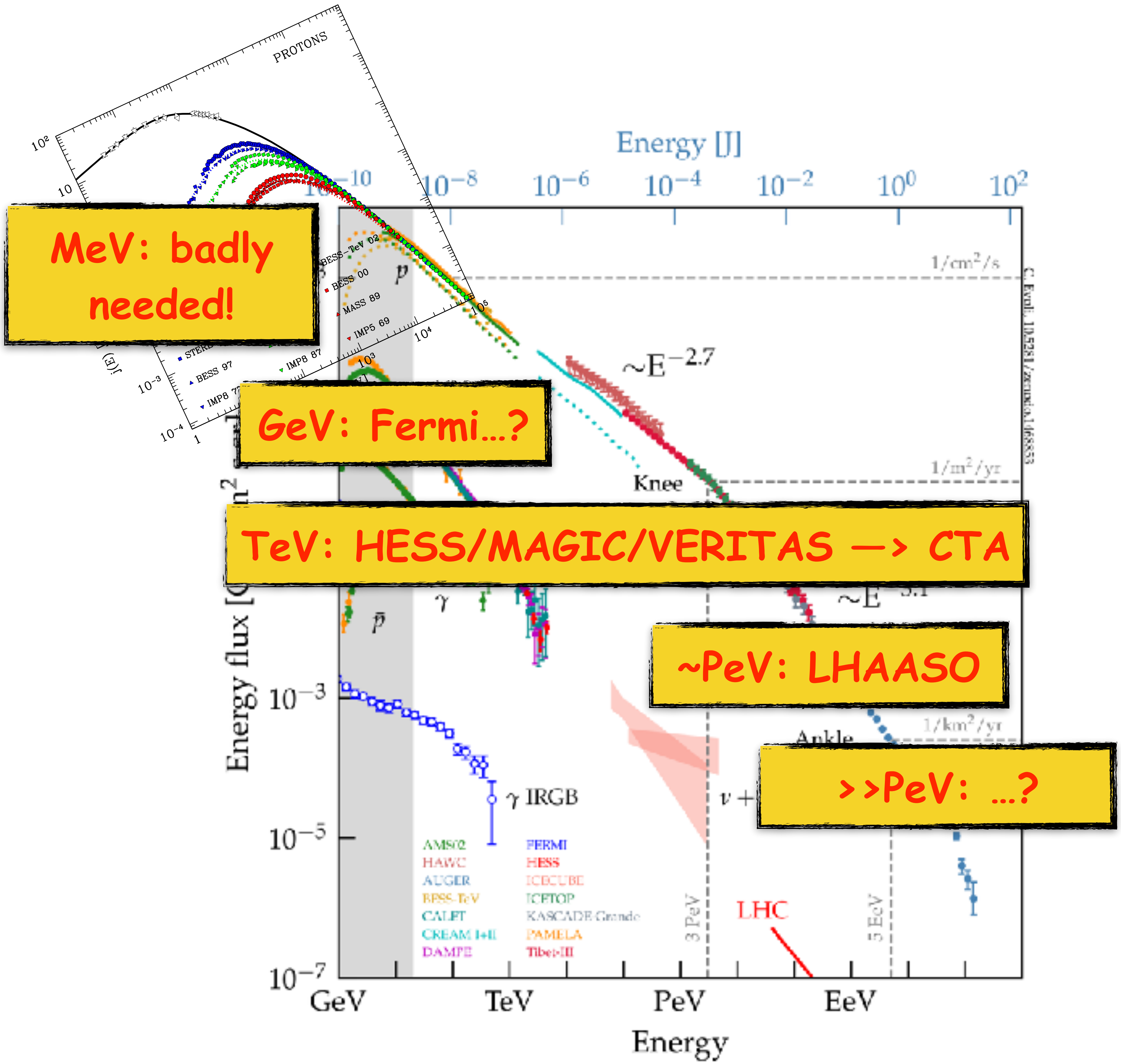


Which gamma rays?



[2] The "orthodoxy" *

*according to Google: authorised or generally accepted theory, doctrine, or practice

Luke's questions

Luke Drury's brief (and very nice) review (2018)

1. The first is the question of where the energy comes from which powers the acceleration of the cosmic rays? In other words, what drives the accelerator?
2. The second is the question of where do the atoms come from which end up being accelerated? In other words, what is the source of the matter that gets fed into the accelerator?
3. And the third and final sense is the question of where exactly the accelerator is located and how does it work? In other words, what is the physics?

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These are actually three different questions which require different solution methods and answers, and some of the confusion in the field has been due to people not carefully distinguishing these concepts.

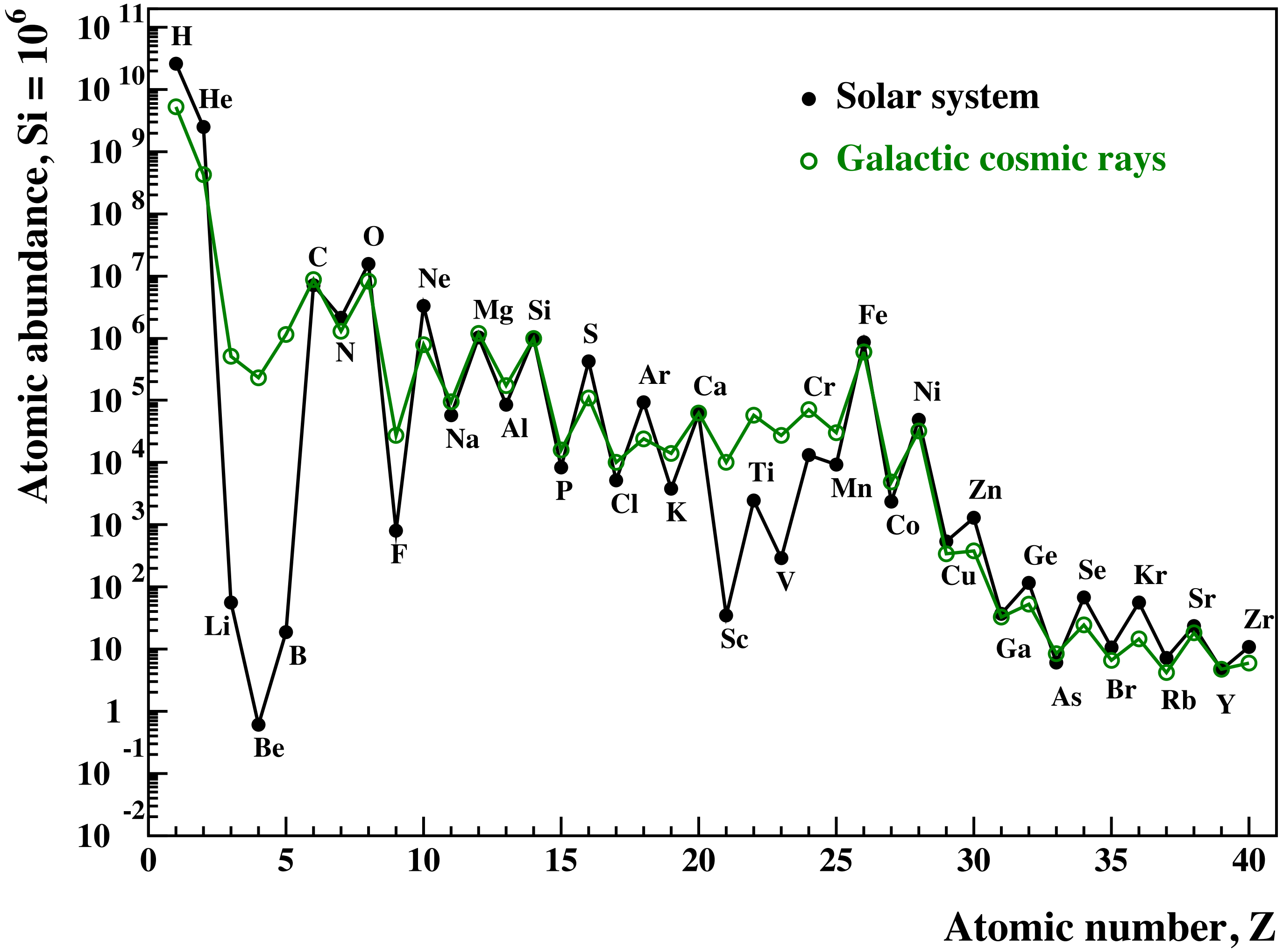
The orthodoxy (1)

- The bulk of the energy of cosmic rays originates from supernova explosions in the Galactic disk

The orthodoxy (1)

The bulk of the energy of CRs originates from SN explosions in the Galactic disk

Tatischeff & SG 2018



for a review see e.g. Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

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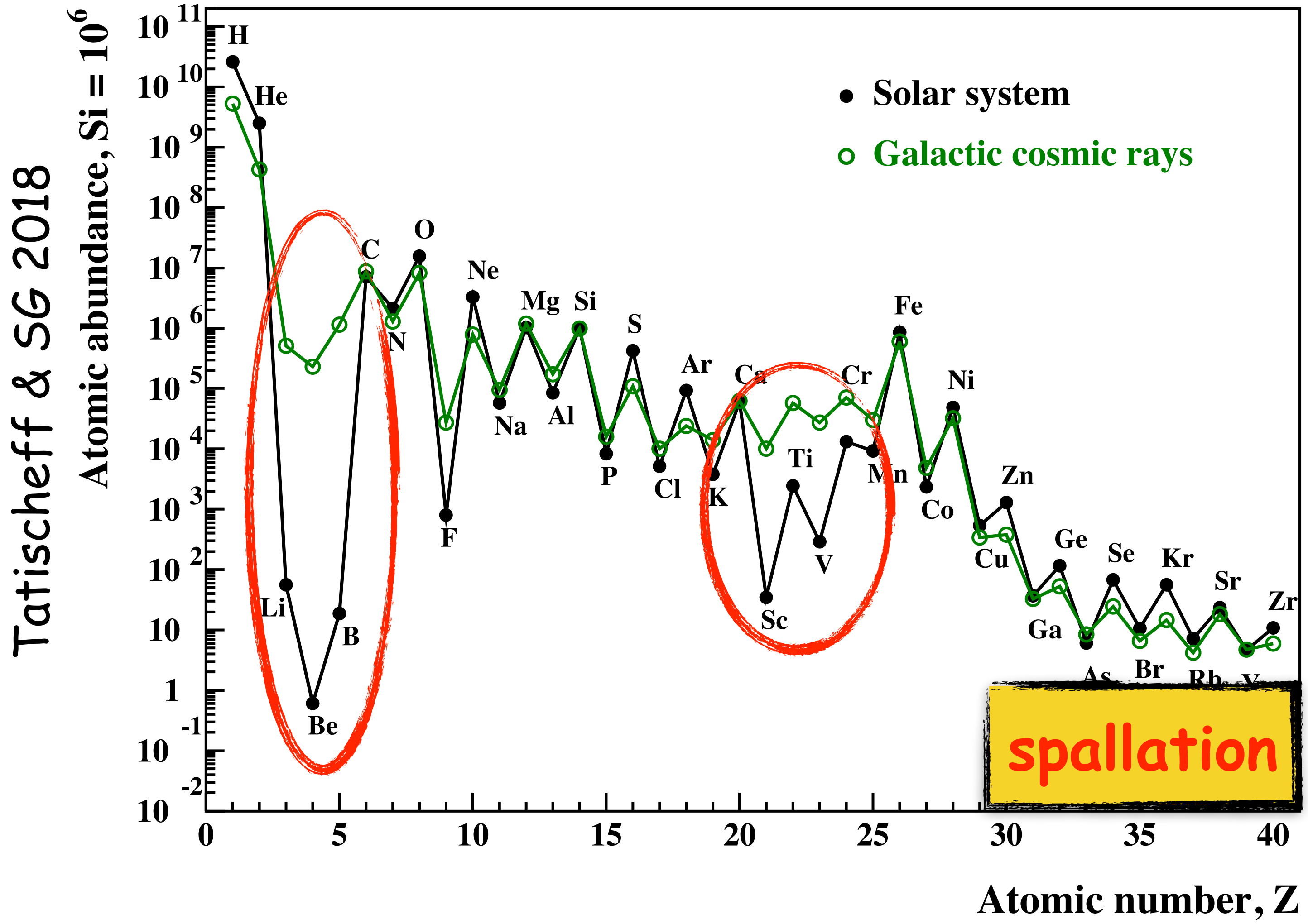

- energy/nucleon is conserved in spallation reactions
- Boron (secondary) is produced mainly in spallation reactions involving Carbon (primary)

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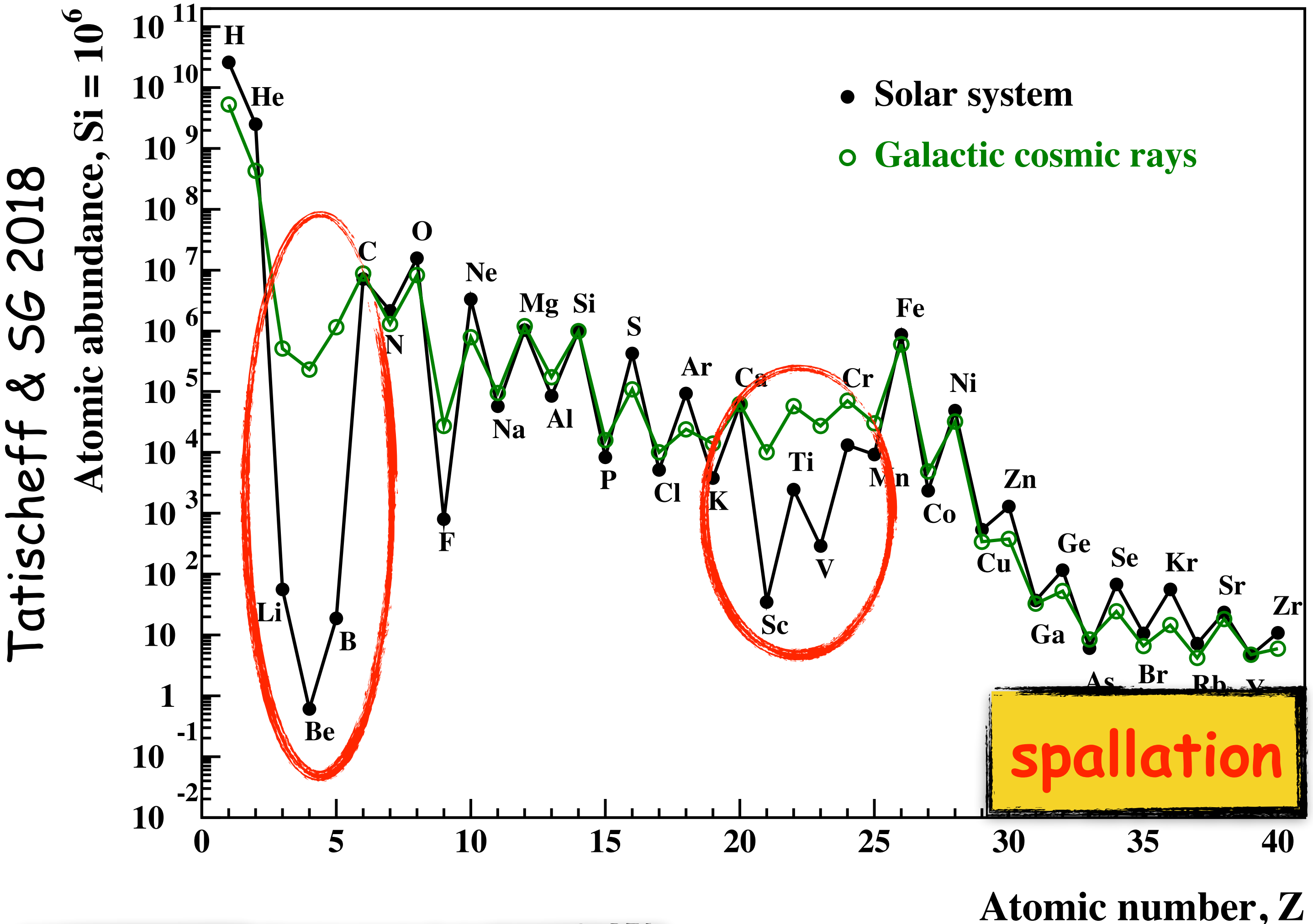

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production rate of B

$$q_B \sim n_C \; \sigma_s \; n_{ISM} \; c$$

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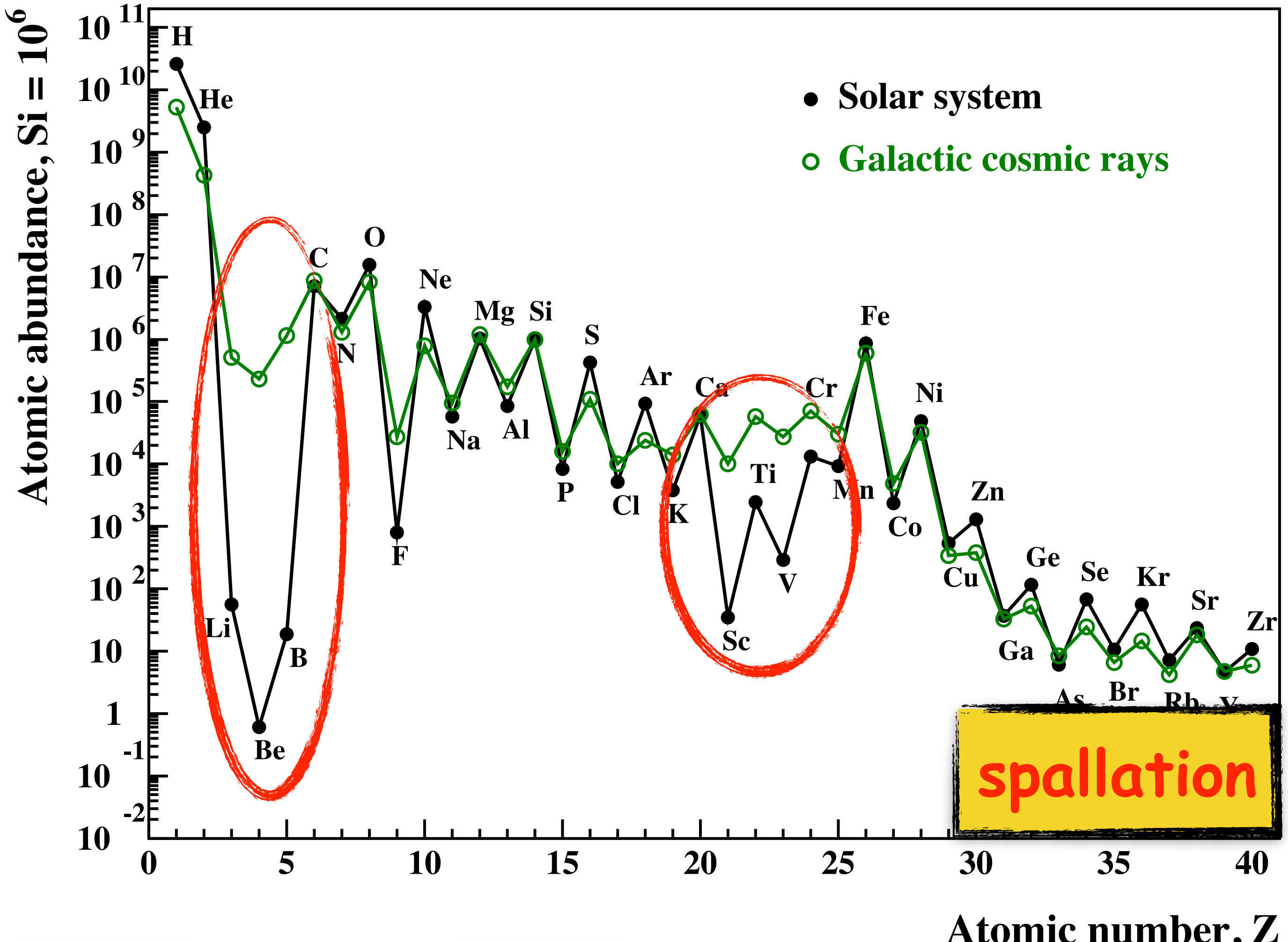

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production rate of B $q_B \sim n_C \, \sigma_s \, n_{ISM} \, c$

equilibrium density of B $n_B \sim q_B \, \tau_{disk}$

for a review see e.g. Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

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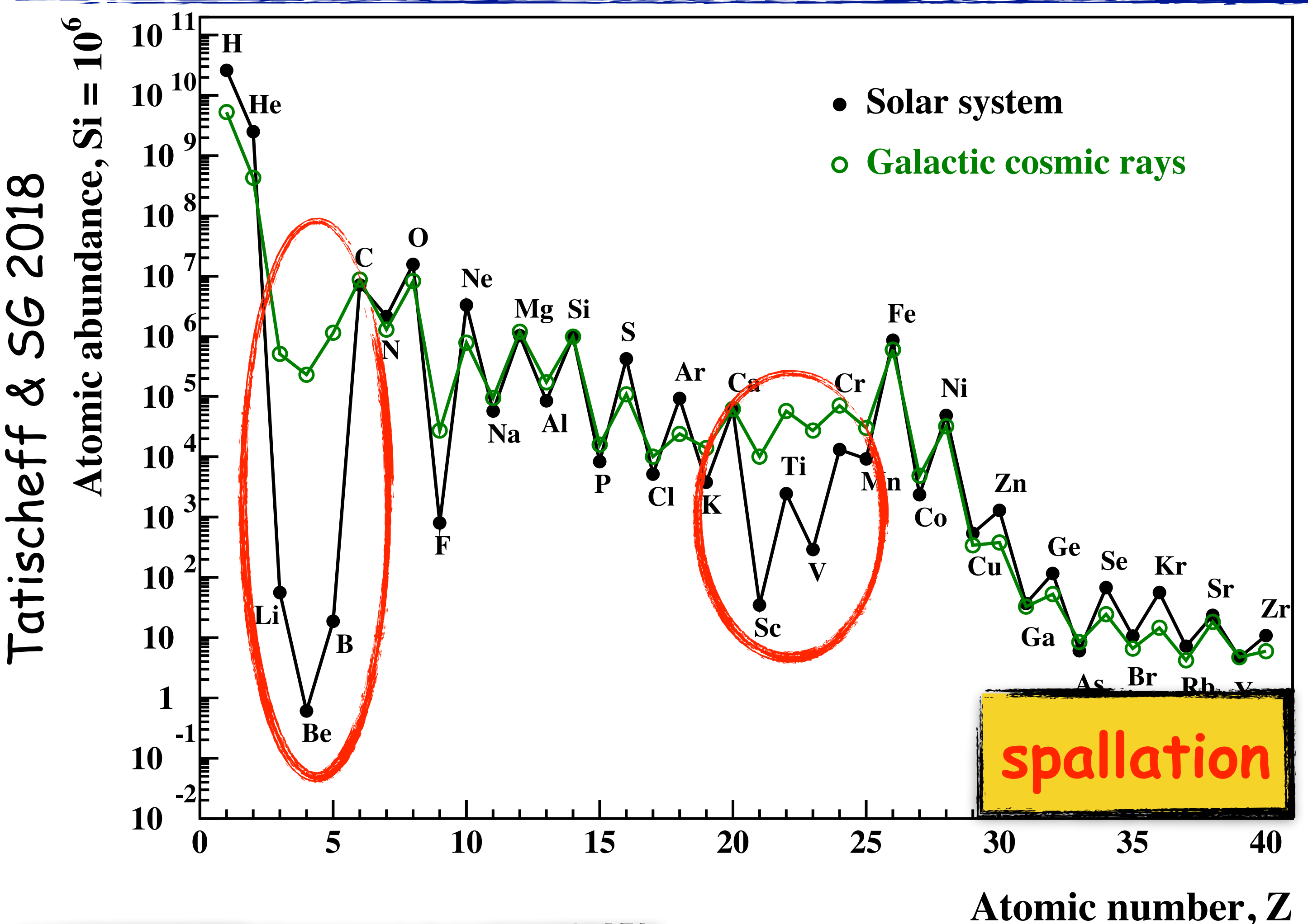

- energy/nucleon is conserved in spallation reactions
- Boron (secondary) is produced mainly in spallation reactions involving Carbon (primary)

production rate of B $q_B \sim n_C \, \sigma_s \, n_{ISM} \, c$

equilibrium density of B $n_B \sim q_B \, \tau_{disk}$

$$\frac{n_B}{n_C} \sim \sigma_s \, n_{ISM} c \, \tau_{disk}$$

for a review see e.g. Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

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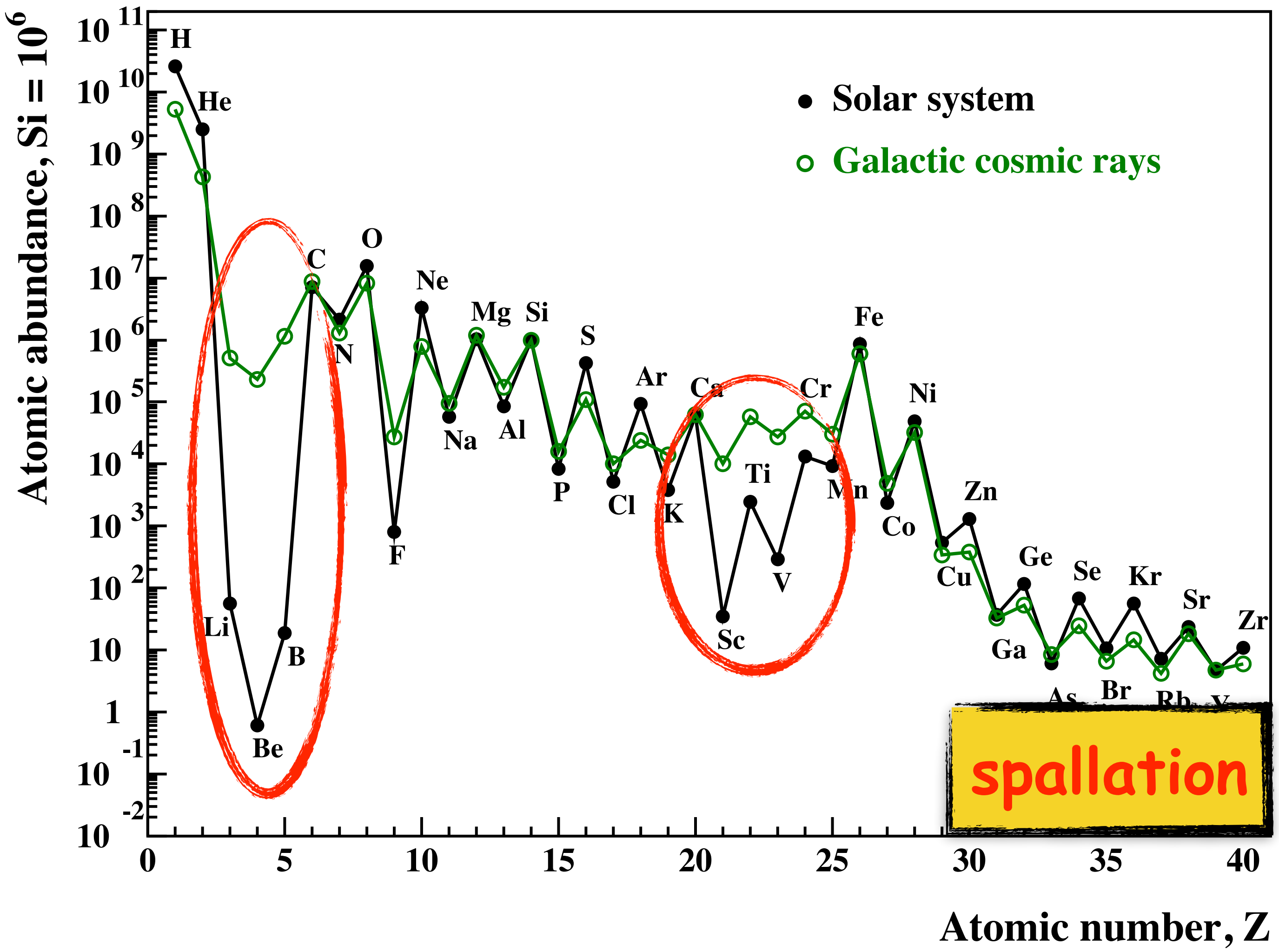
Tatischeff & SG 2018



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grammage

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

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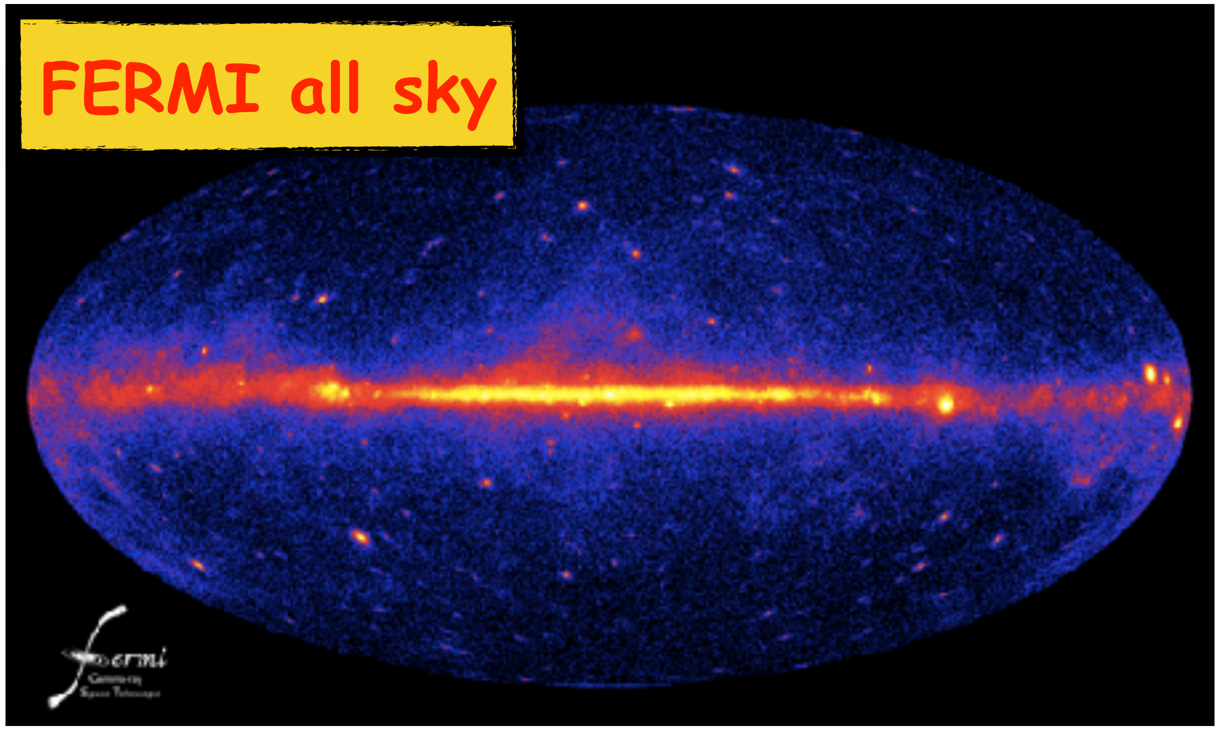
CR energy density — total CR energy in the disk — MW disk volume

$$w_{CR} \sim 1 \text{ eV/cm}^3 \longrightarrow \mathcal{E}_{CR} = w_{CR} V_{disk}$$

Small spatial gradient



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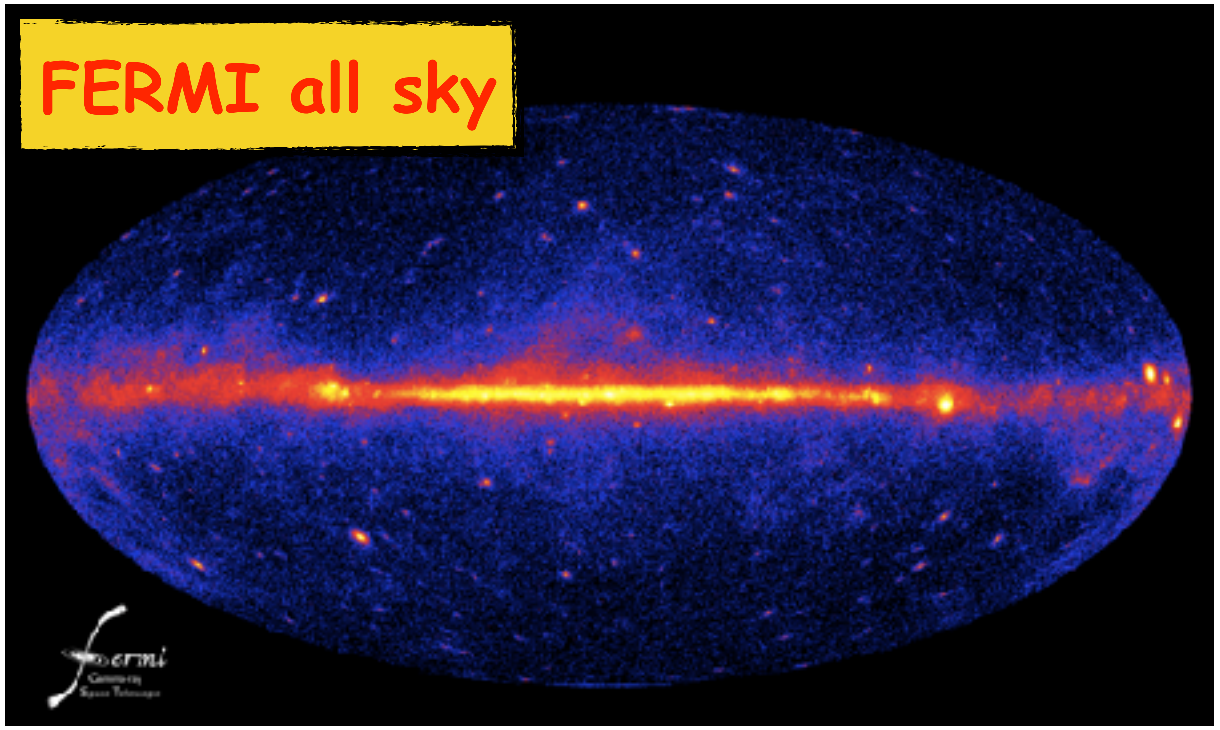
Small spatial gradient

Power of CR sources in the disk

$$L_{CR} = W_{CR}/\tau_{disk} \sim 10^{41} \text{erg/s}$$

FERMI all sky



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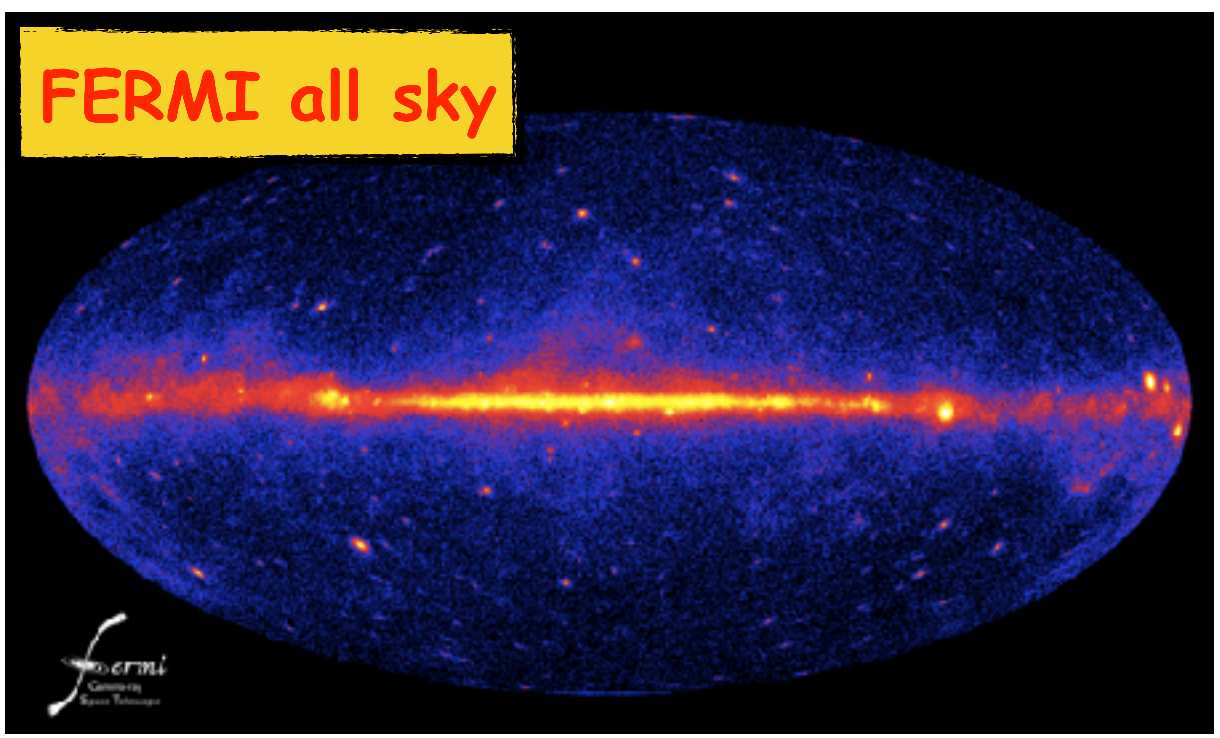


Power of CR sources in the disk

$$L_{CR} = W_{CR}/\tau_{disk} \sim 10^{41}\mathrm{erg/s}$$

Power of Galactic SN explosions

10^{51} erg

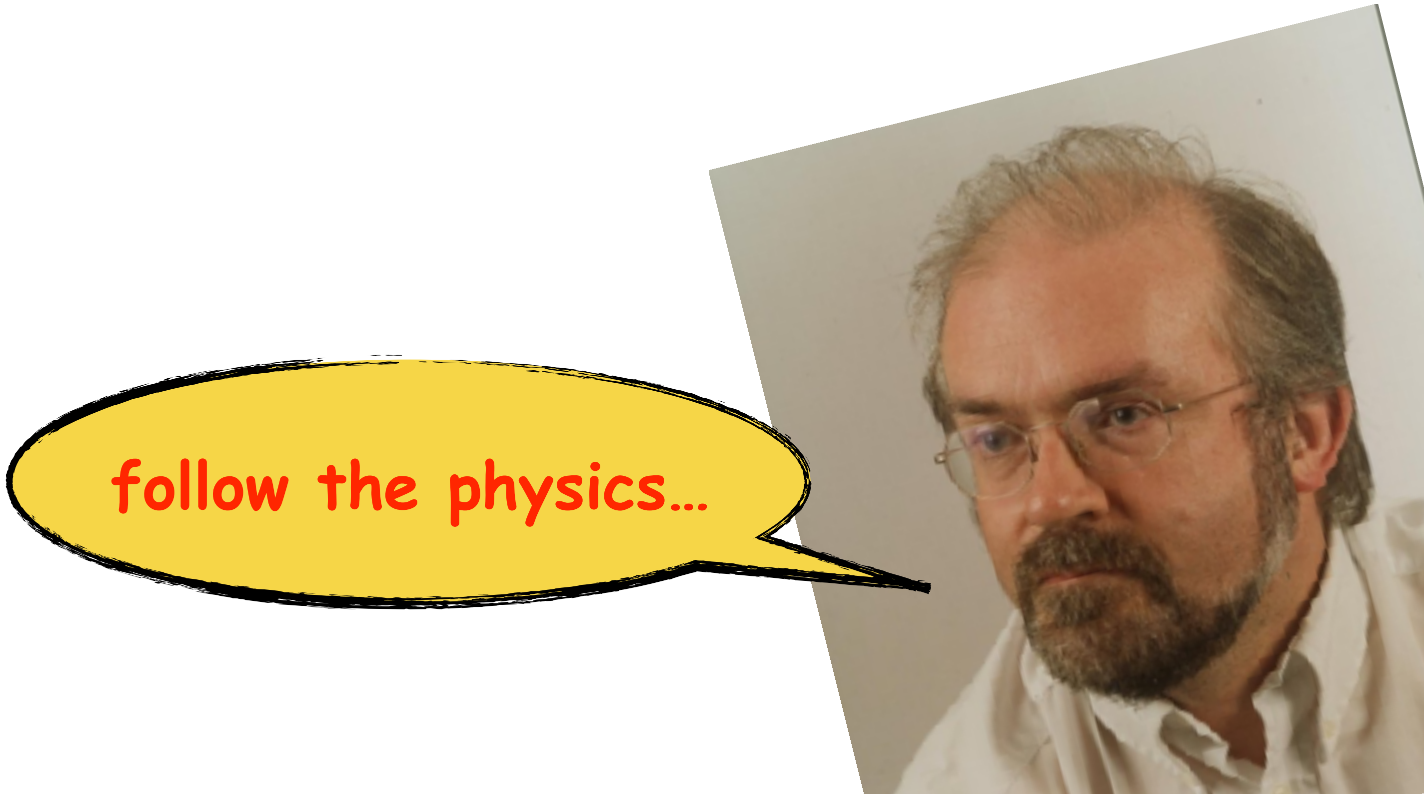
3/century

$$L_{SN} = E_{SN}\nu_{SN} \sim 10^{42}\mathrm{erg/s}$$

for a review see e.g. Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

The orthodoxy (2)

- Cosmic rays are diffusively confined within an extended and magnetised Galactic halo



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unstable secondaries

$$\tau(^{10}\text{Be}) \sim 1.4 \text{ Myr}$$

$$\frac{^{10}\text{Be}}{\text{Be}} \sim \frac{\tau(^{10}\text{Be})}{\tau_{esc}} \frac{q(^{10}\text{Be})}{q(\text{Be})}$$

$$\tau_{esc} \approx 10 - 20 \text{ Myr}$$

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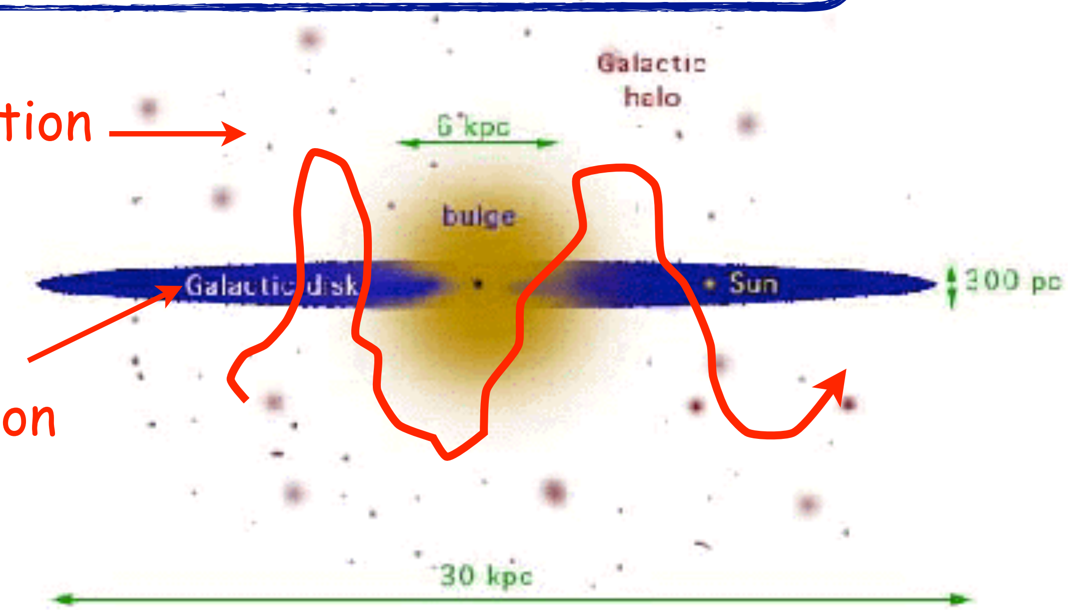
no spallation

spallation



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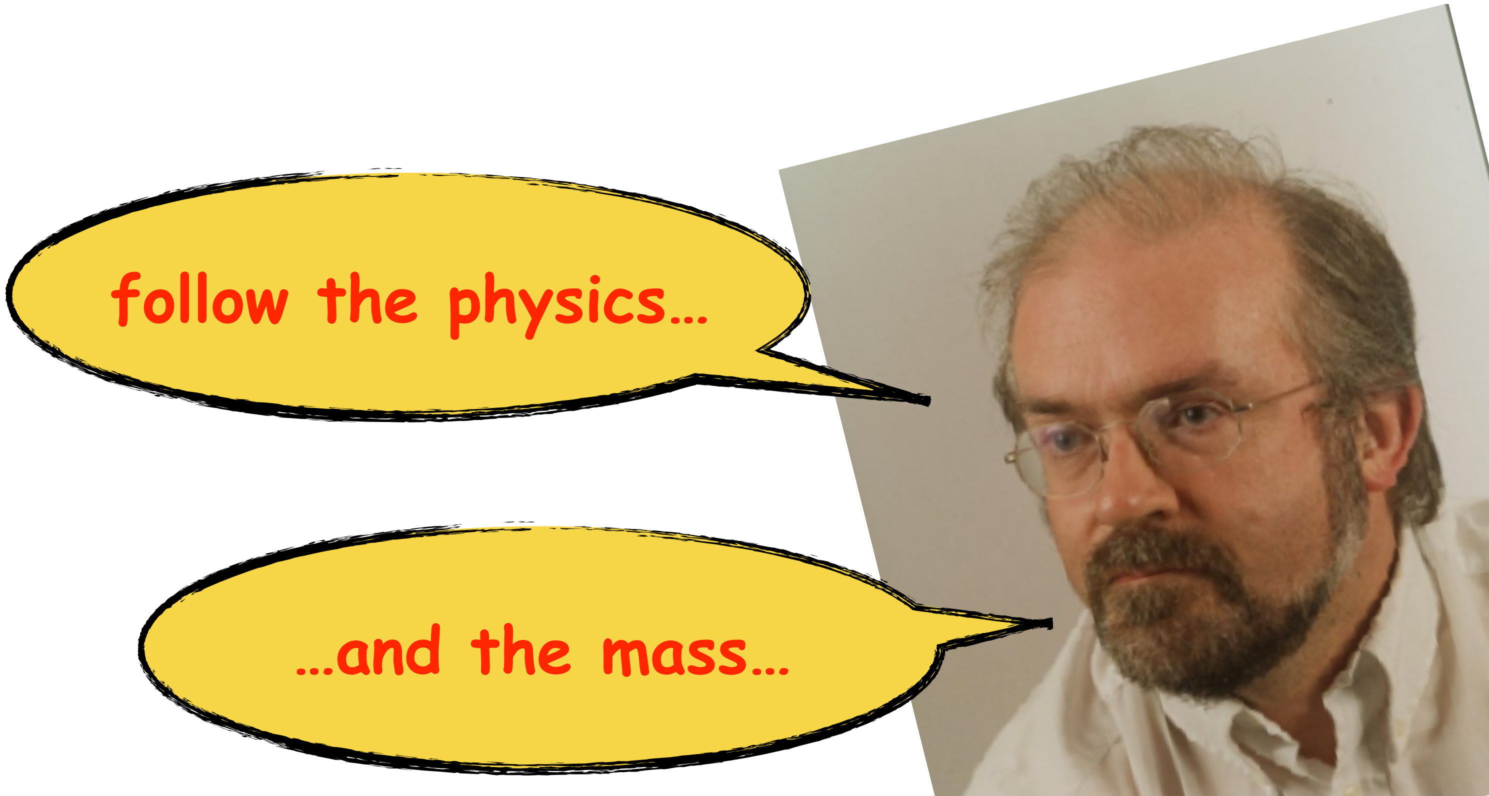
The orthodoxy (3)

- Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants



The orthodoxy (3)

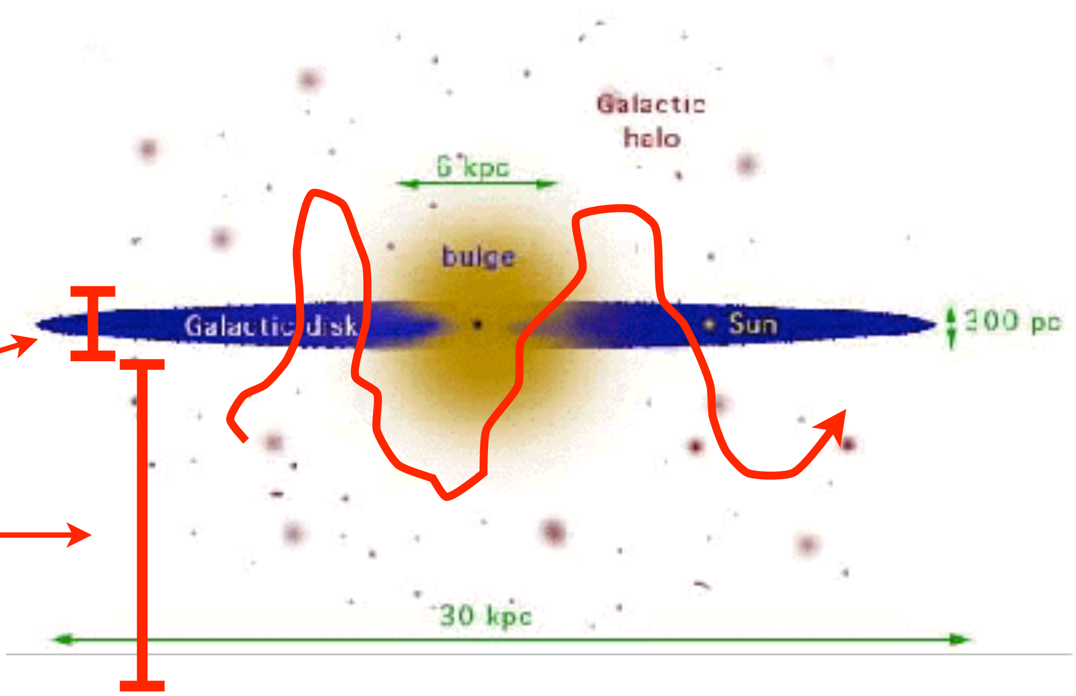
CRs are accelerated out of the (dusty) ISM through DSA in SNRs

effective grammage

$$\Lambda_g \sim \bar{\varrho}\, \tau_{esc}\, c$$

mean density

$$\bar{\varrho} = \mu m_p n_{ISM} \left(\frac{h}{H} \right)$$



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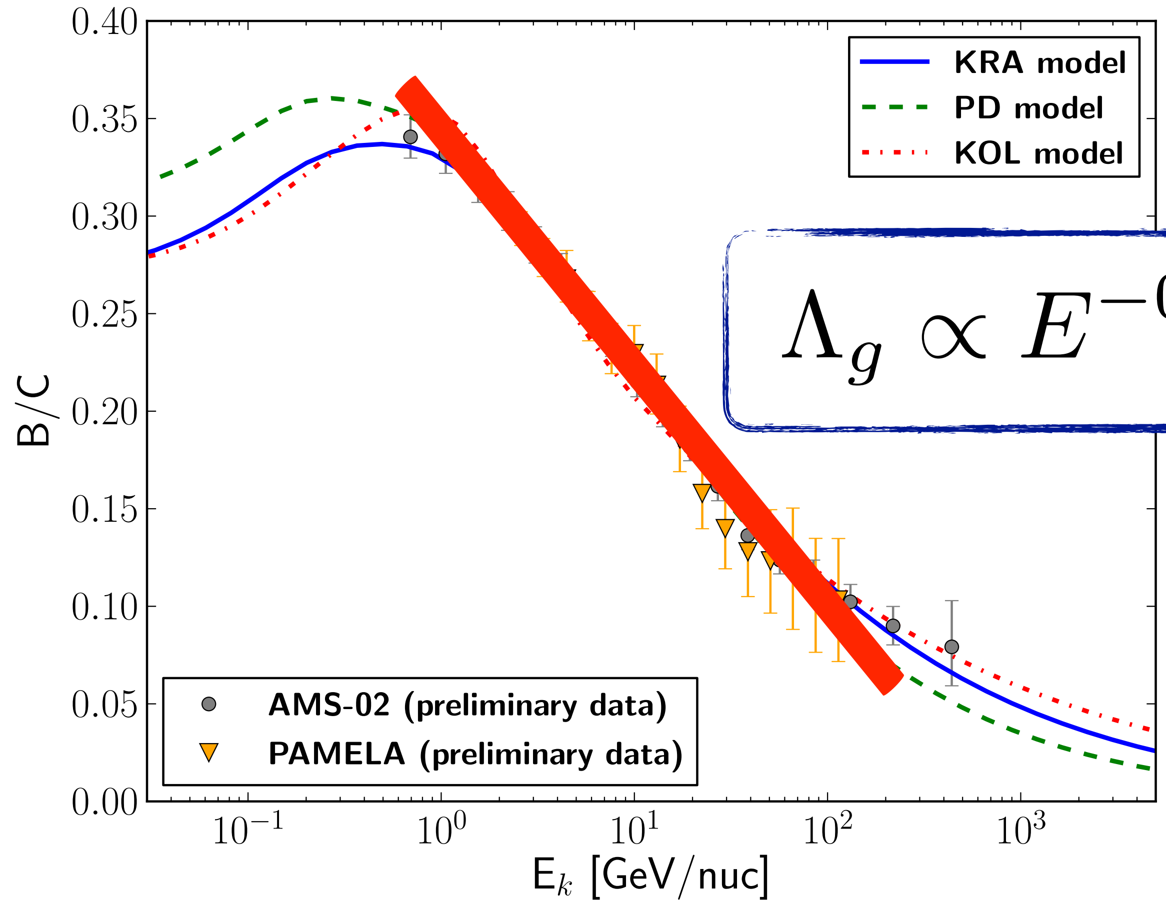
Gaggero et al (2014)



$$\Lambda_g \propto E^{-0.3}*$$

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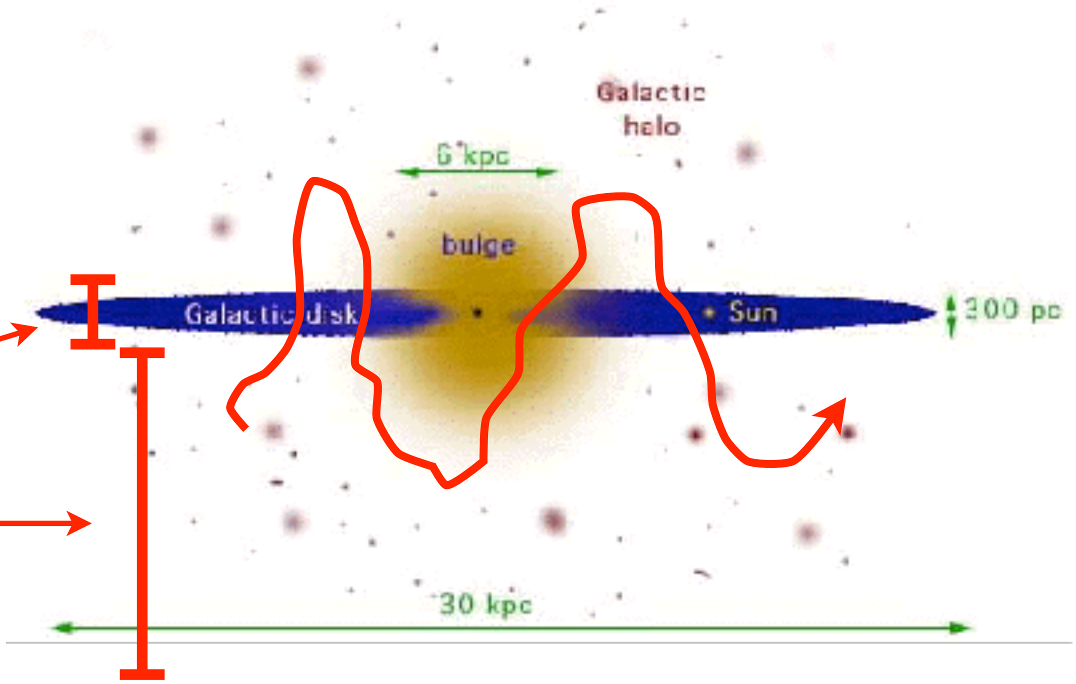

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* this is not true! but "almost" true...

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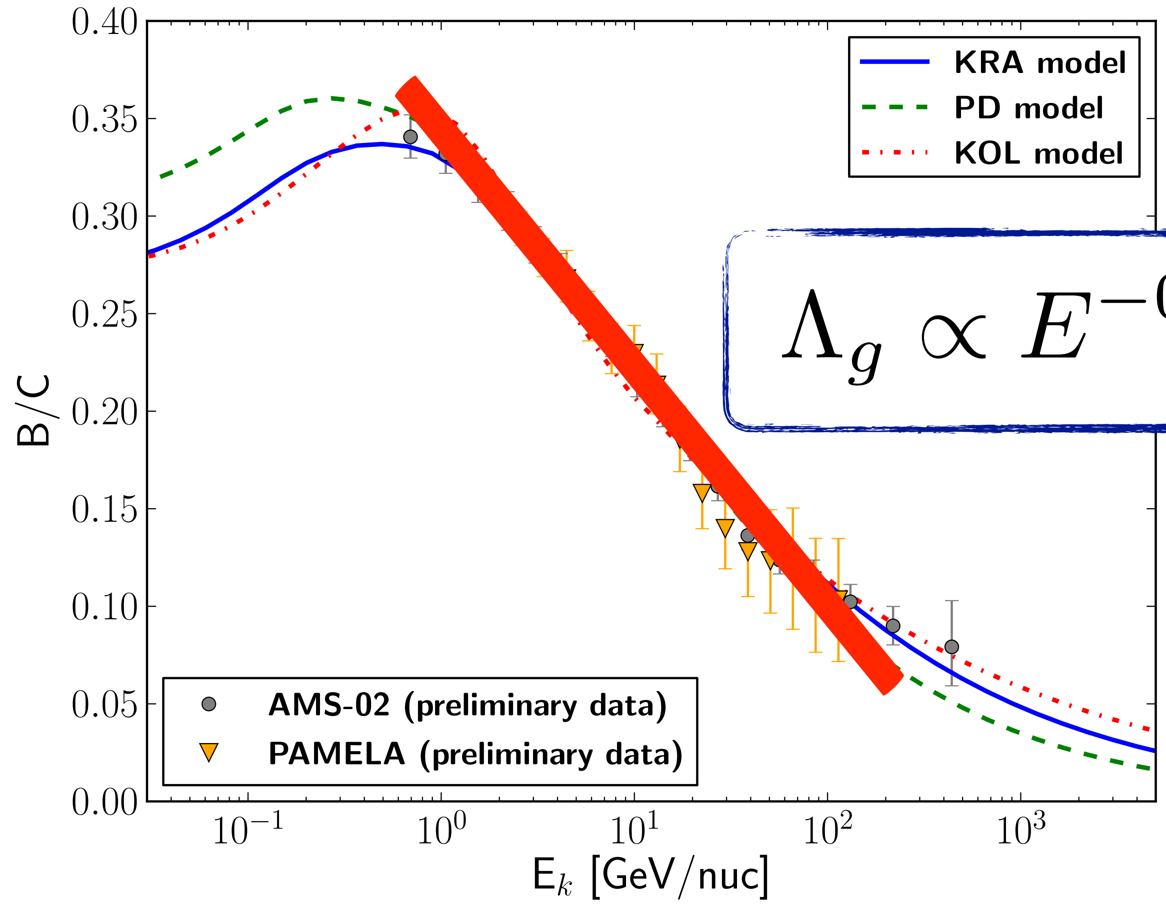

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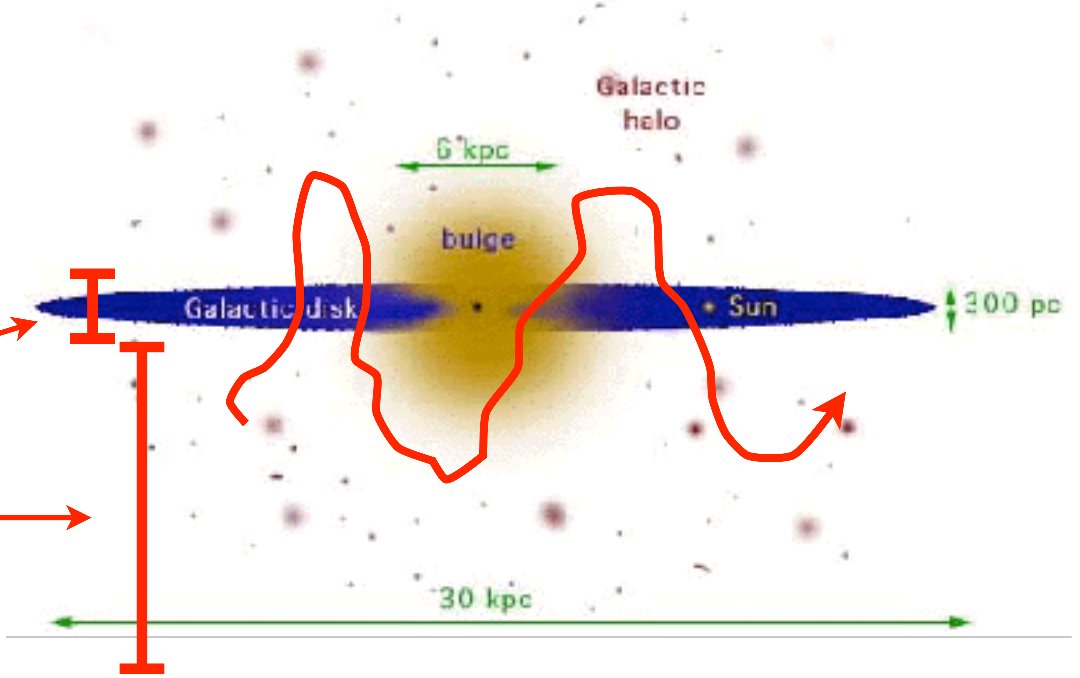

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observed spectrum -> $n_p \propto E^{-2.7}$

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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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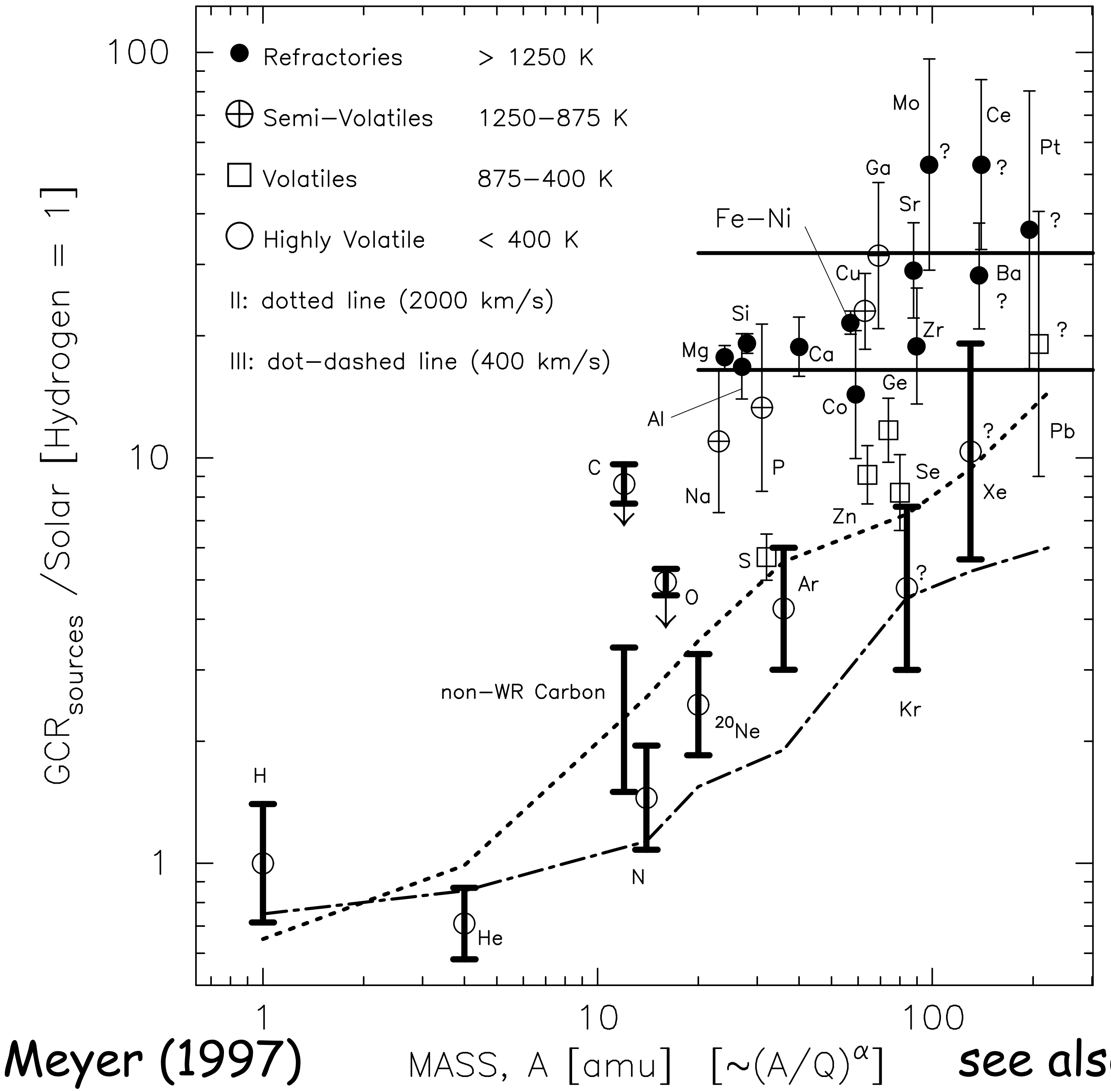

why dusty?

Ellison, Drury, Meyer (1997)

see also Caprioli+ 17, Tatischeff+ 21

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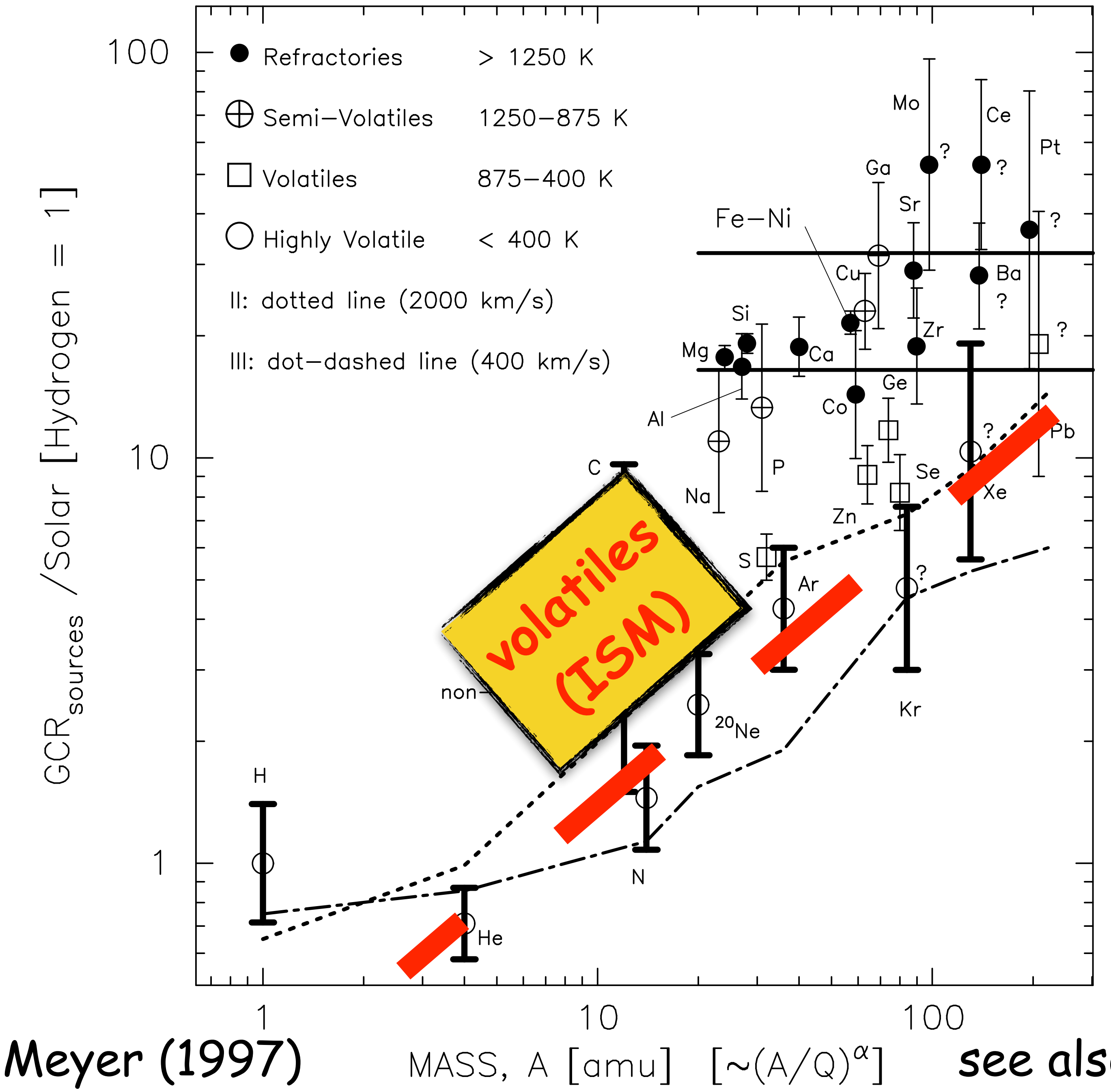

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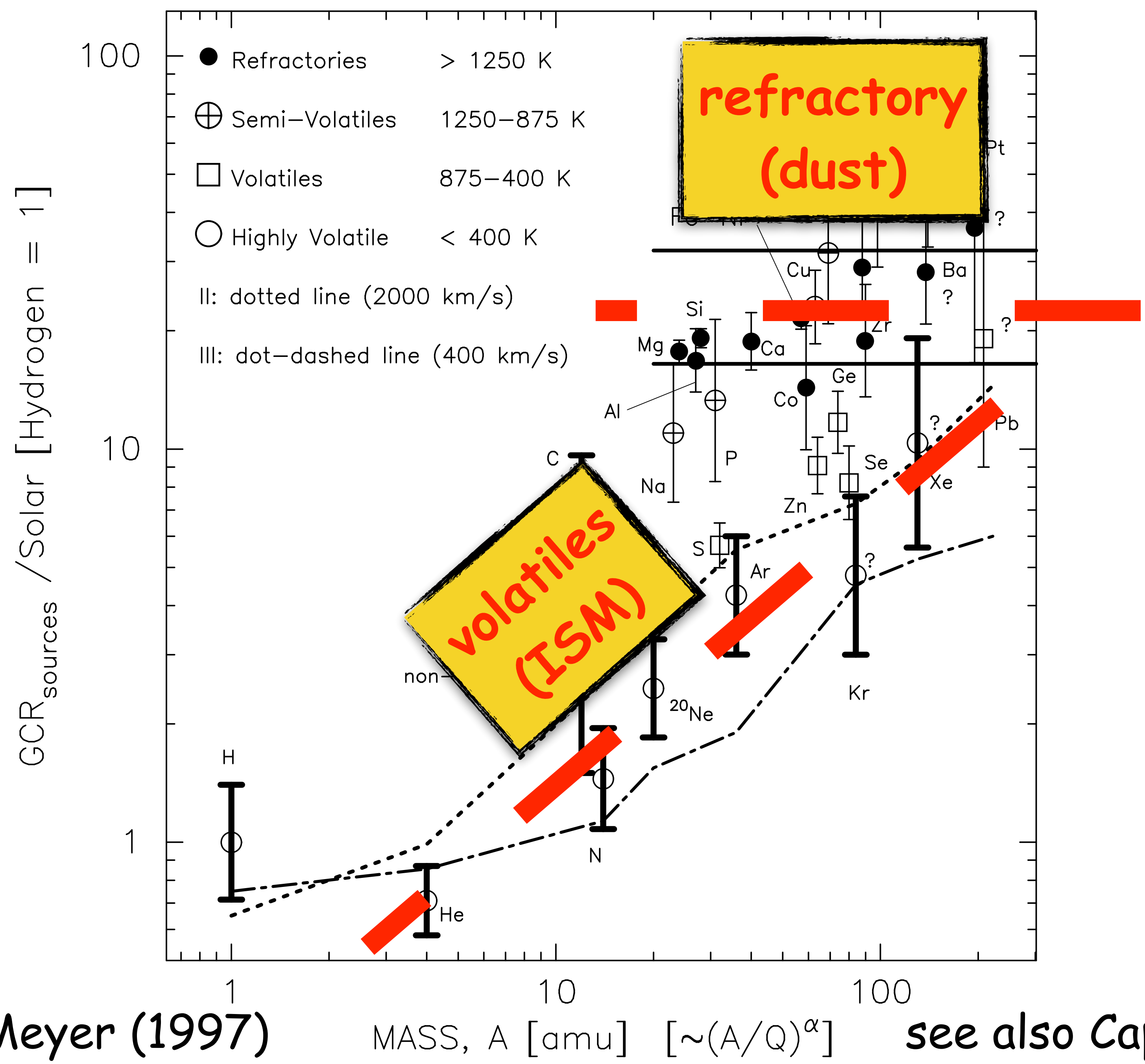

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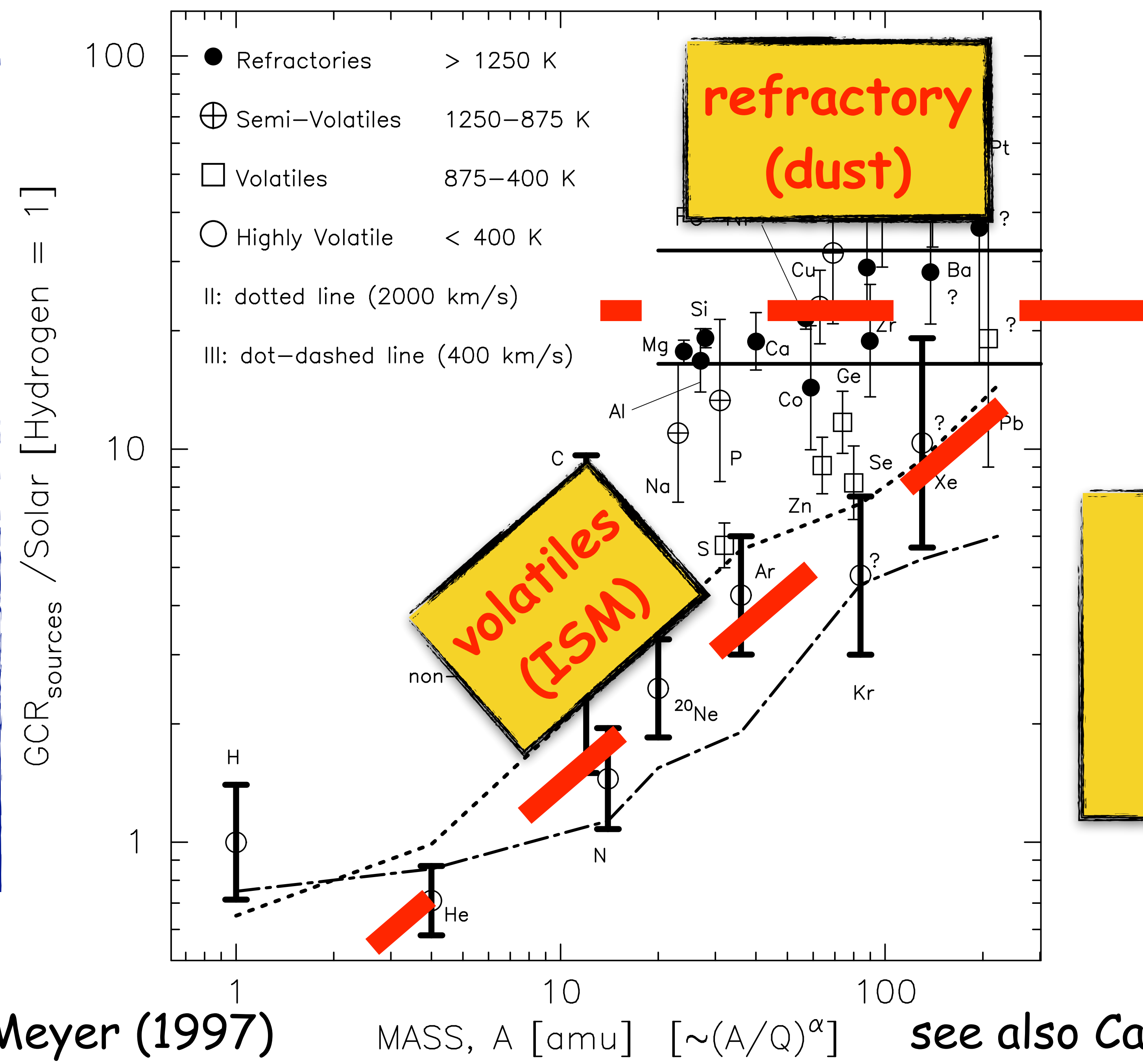
Data are best explained if refractory CRs are injected at shocks through sputtering of pre-accelerated dust grains



why dusty?

MESSAGE
CR composition deserves more attention

Ellison, Drury, Meyer (1997)

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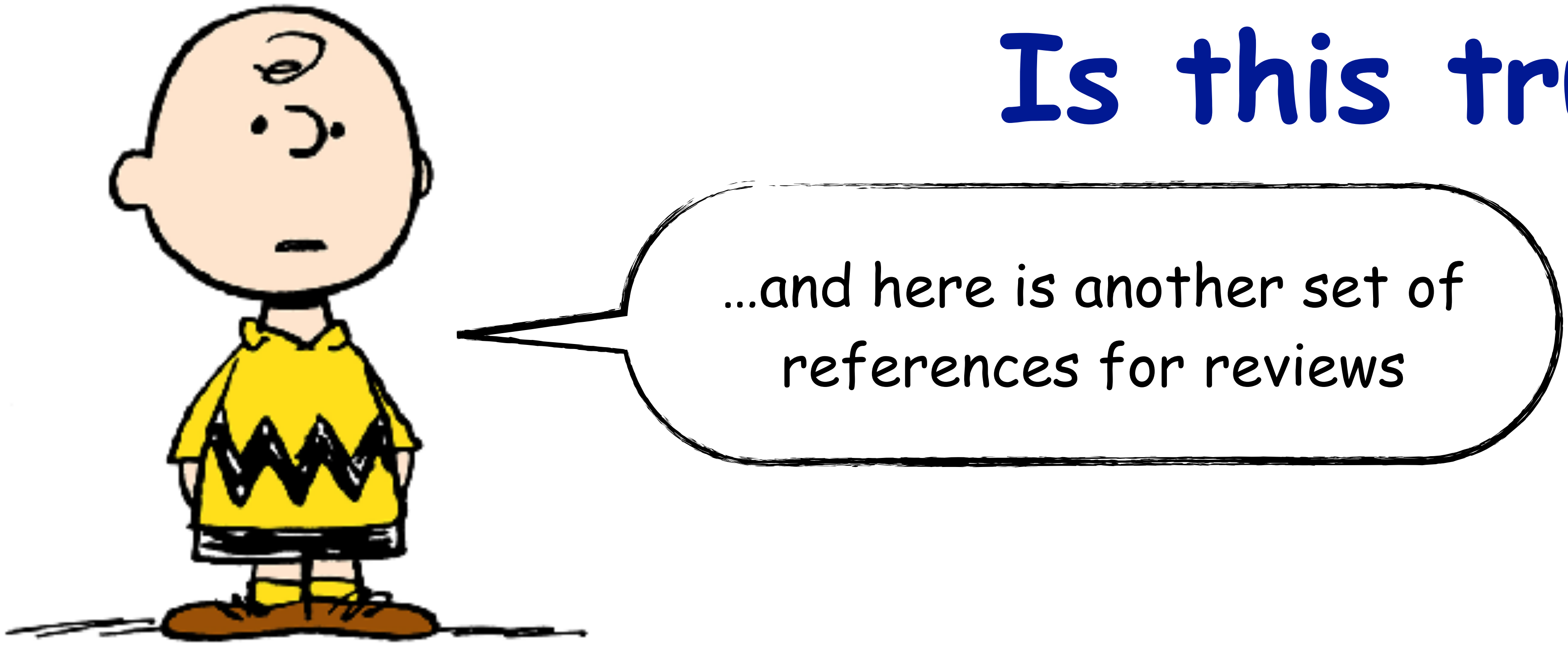
Is this true?



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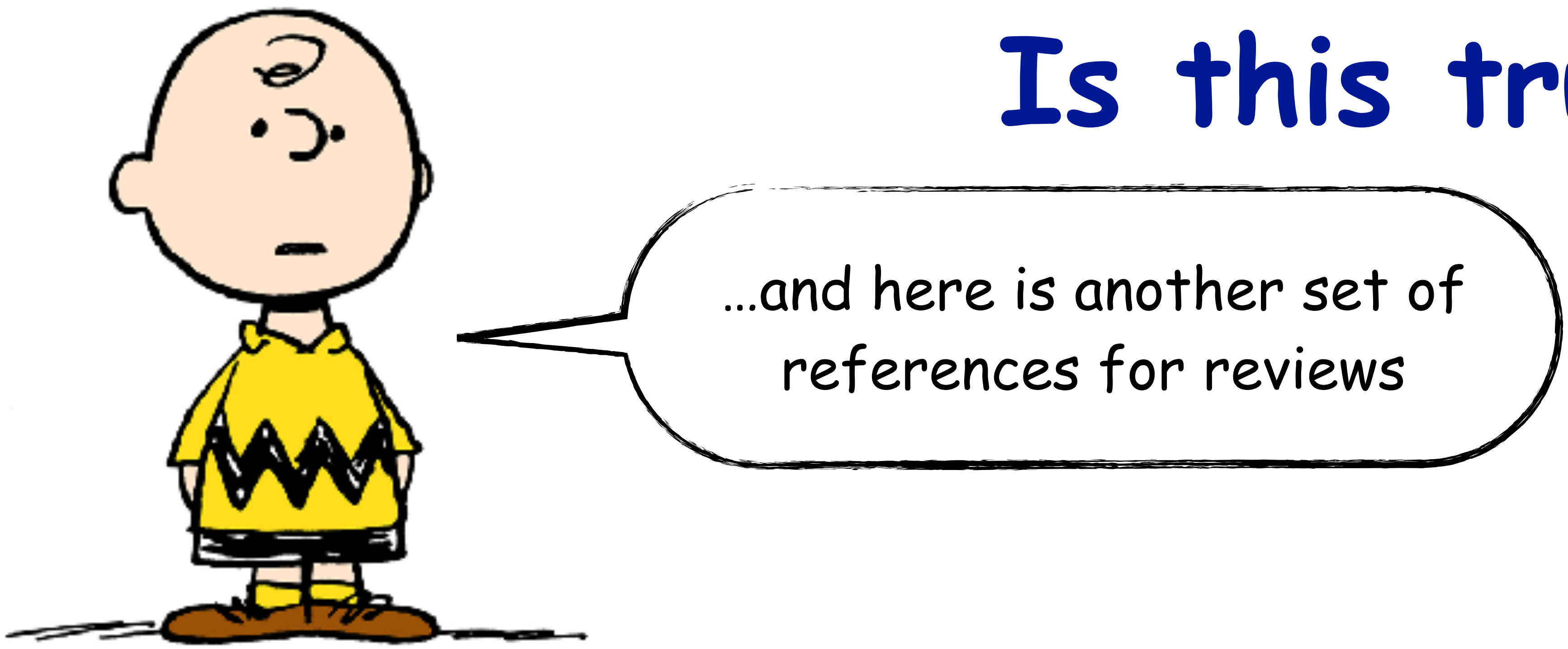


List of critical ("unorthodox"?) reviews (questioning SNR origin and/or discussing other sources):

[1] Hillas, Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays?, J Phys G: Nucl Part Phys, 31, R95 (2005)

[2] Parizot, Cosmic Ray Origin: Lessons from Ultra-High-Energy Cosmic Rays and the Galactic/ Extragalactic Transition, Nucl Phys B (Proc Suppl), 256, 197 (2014)

[3] Bykov, Nonthermal particles and photons in starburst regions and superbubbles, A&A Rev, 22, 77 (2014)

[4] Lingenfelter, Cosmic rays from supernova remnants and superbubbles, Adv Space Res, 62, 2750 (2018)

[5] Strong, Truths universally acknowledged? Reflections on some common notions in cosmic rays, Nucl Part Phys Proc, 297, 165 (2018)

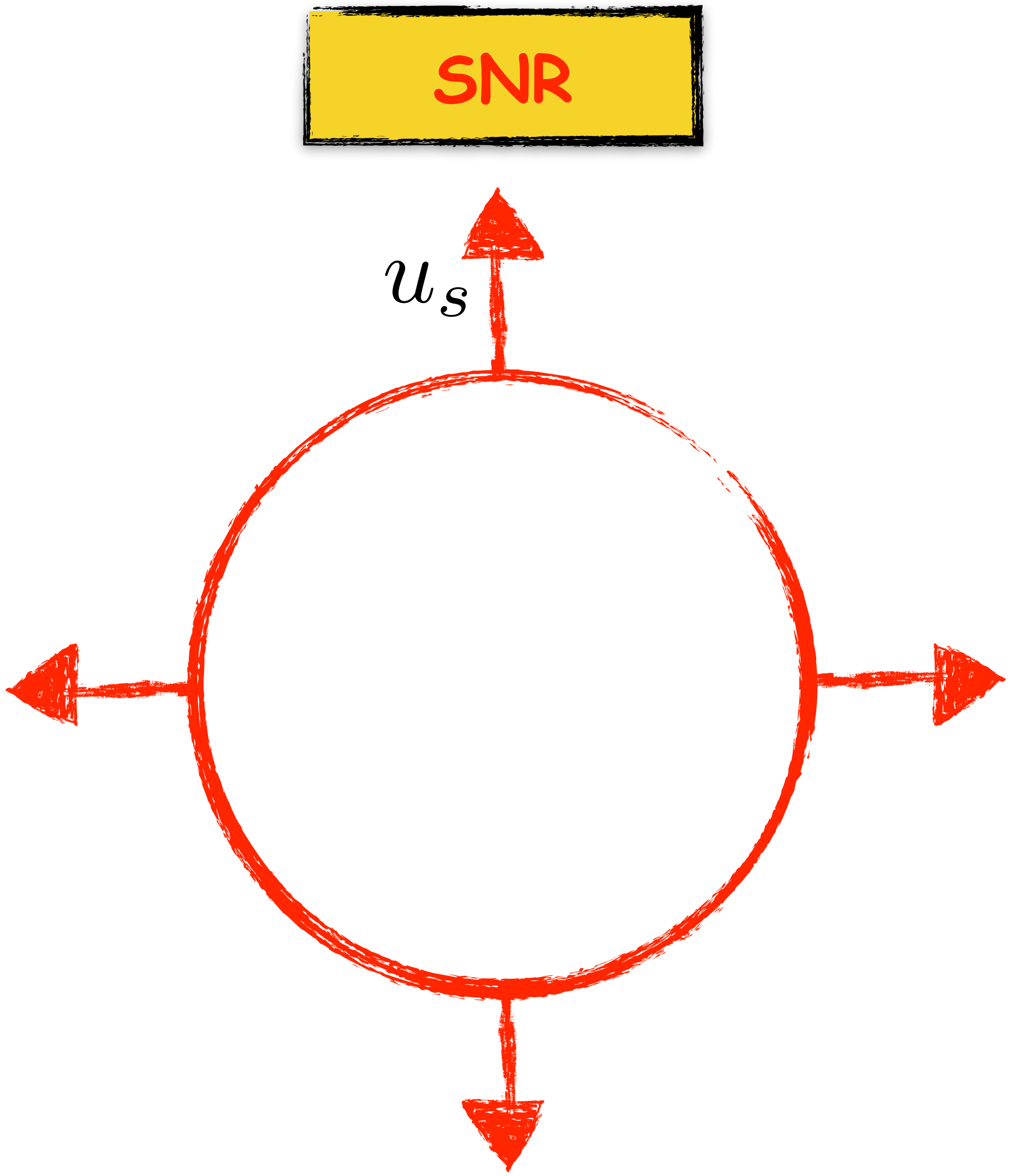
[6] Tatischeff, Gabici, Particle Acceleration by Supernova Shocks and Spallogenic Nucleosynthesis of Light Elements, ARNPS, 68, 377 (2018)

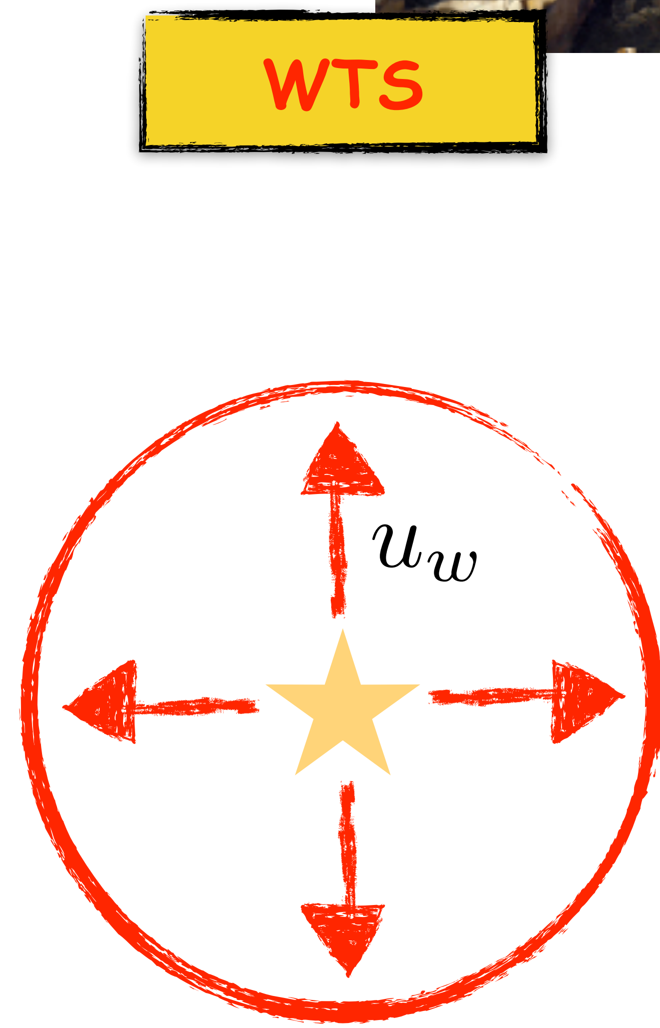
[7] Gabici et al., The origin of Galactic cosmic rays: Challenges to the standard paradigm, IJMPD, 28, 1930022-339 (2019)

[3] Follow the energy
Is there space left
for other sources?

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983





analogy with solar WTS (Parker, Jokipii…) + DSA (BOBALSKy…)

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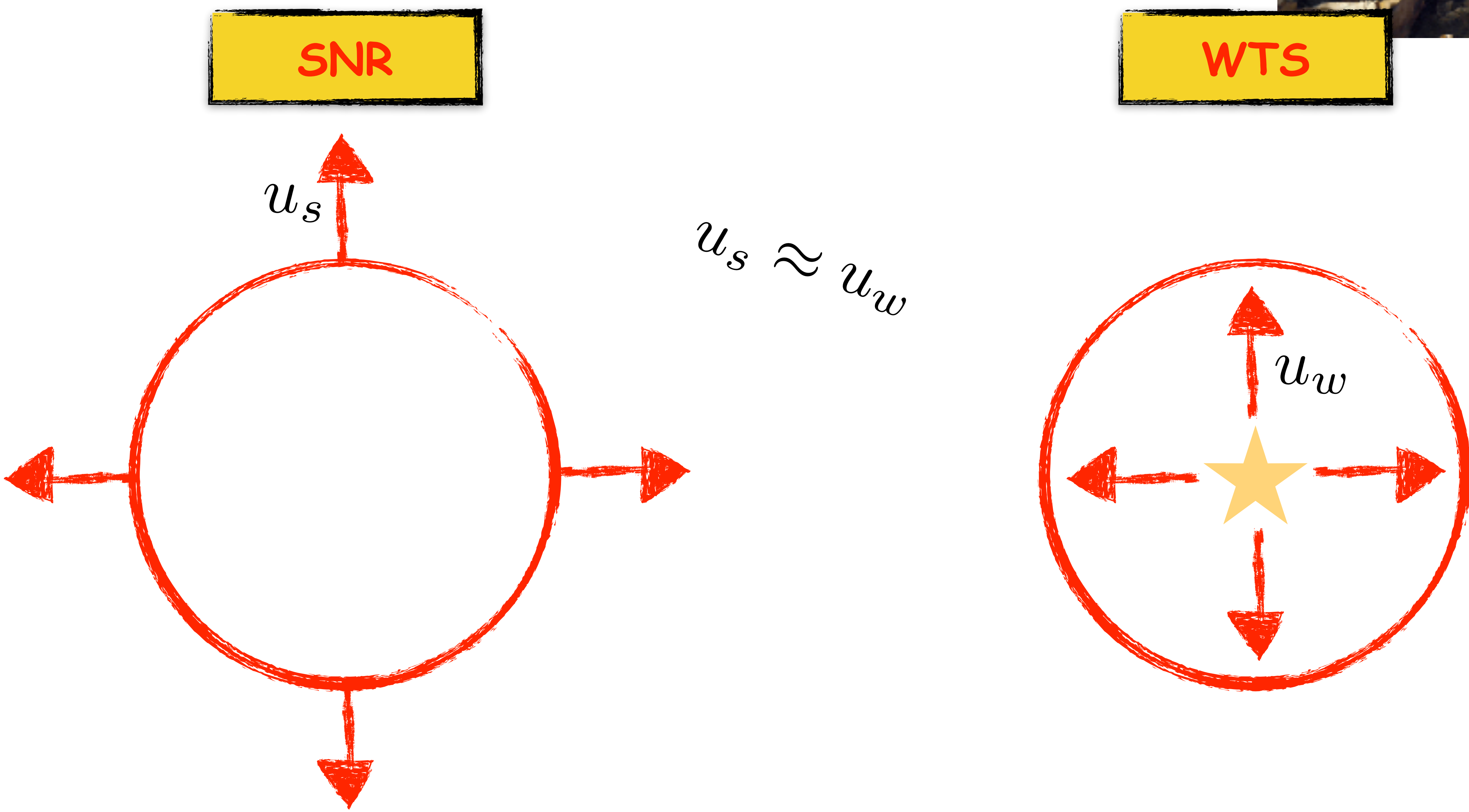

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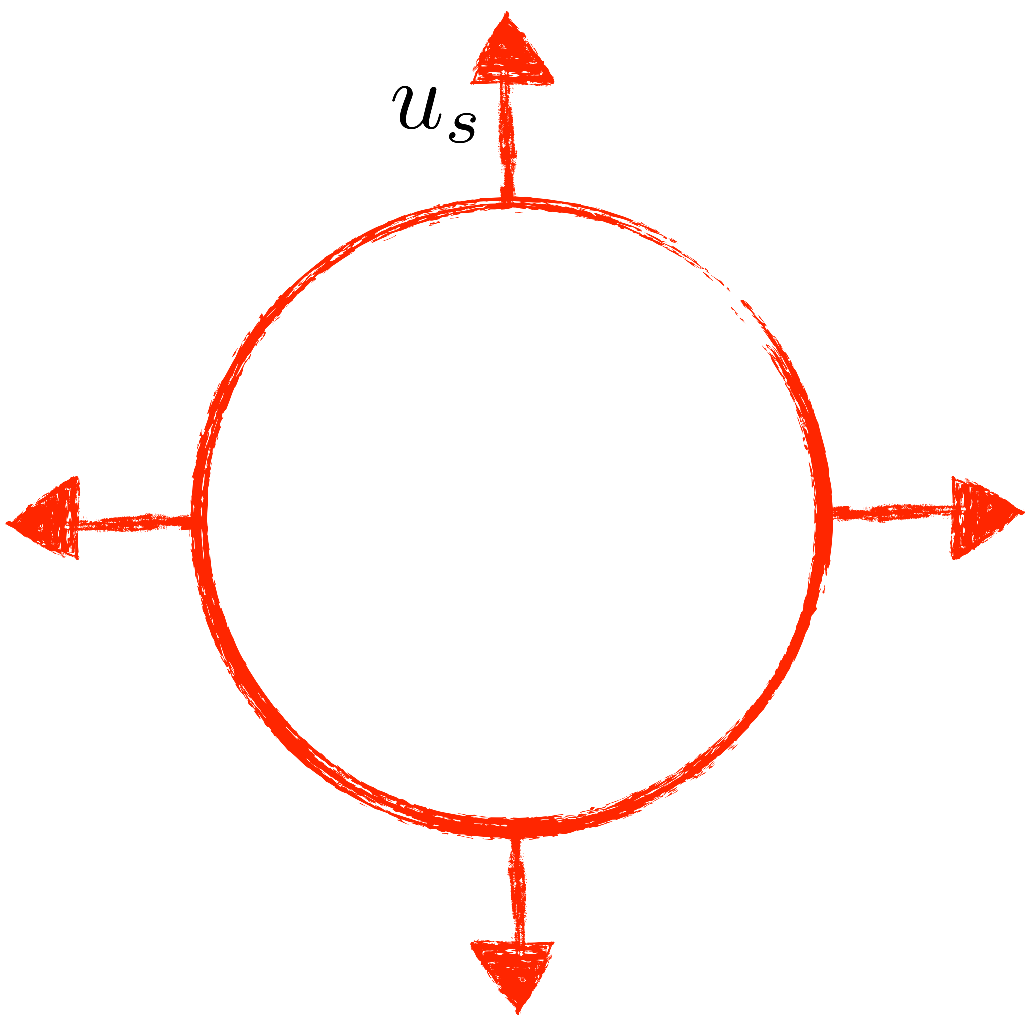
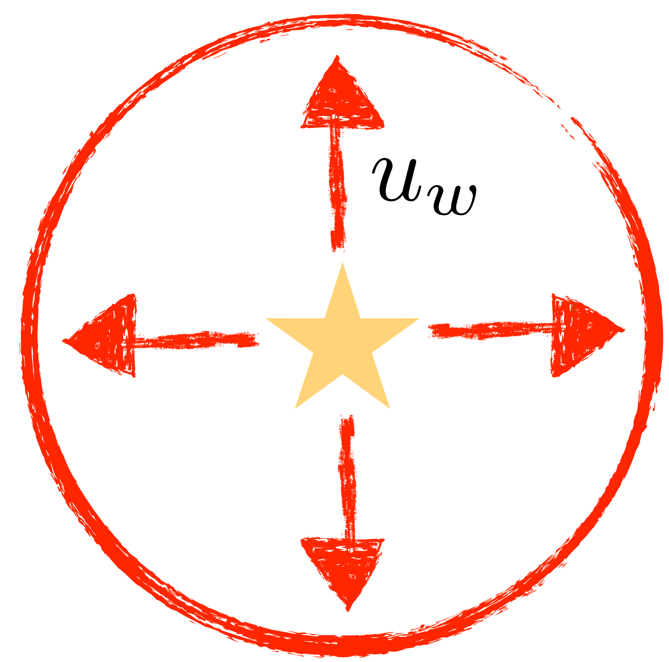


$u_s \approx u_w$

WTS



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Bonus: Wolf-Rayet wind material enriched in ^{22}Ne —> composition (with dilution)

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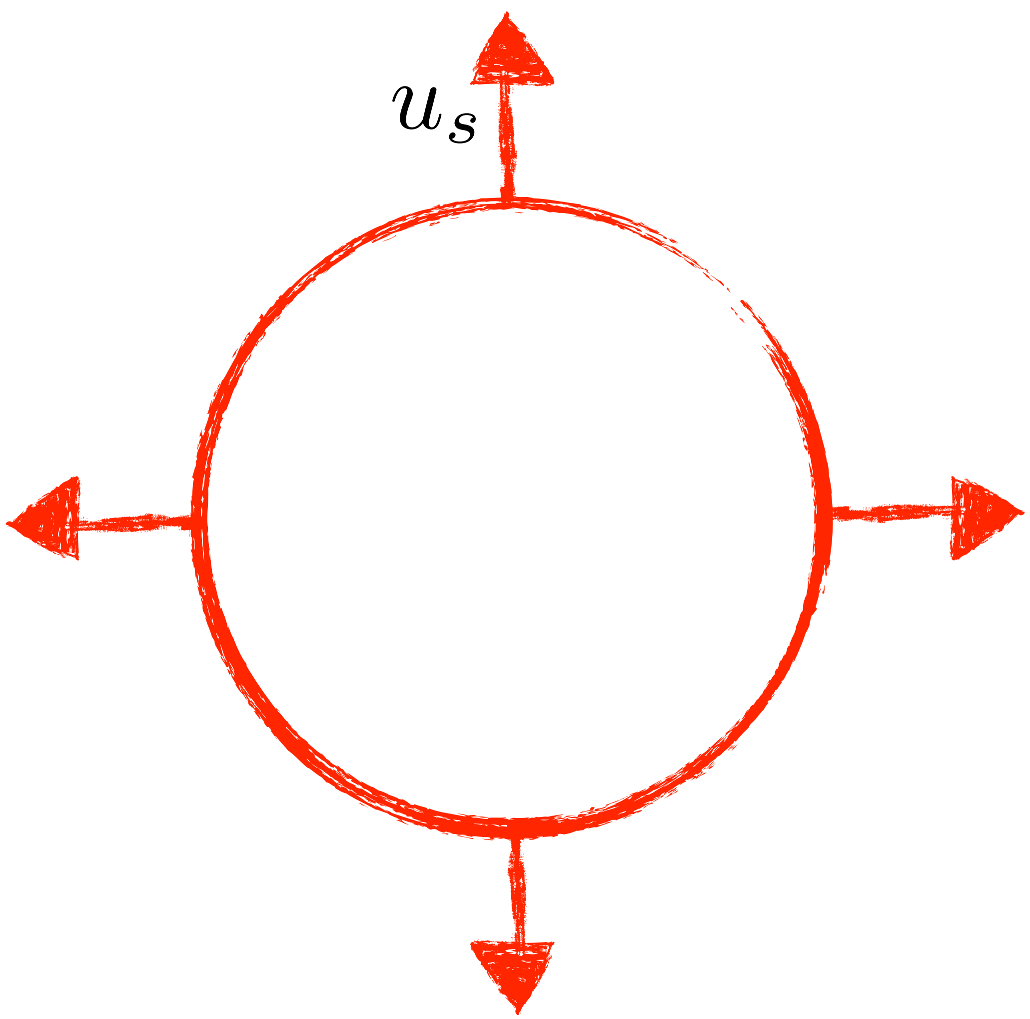

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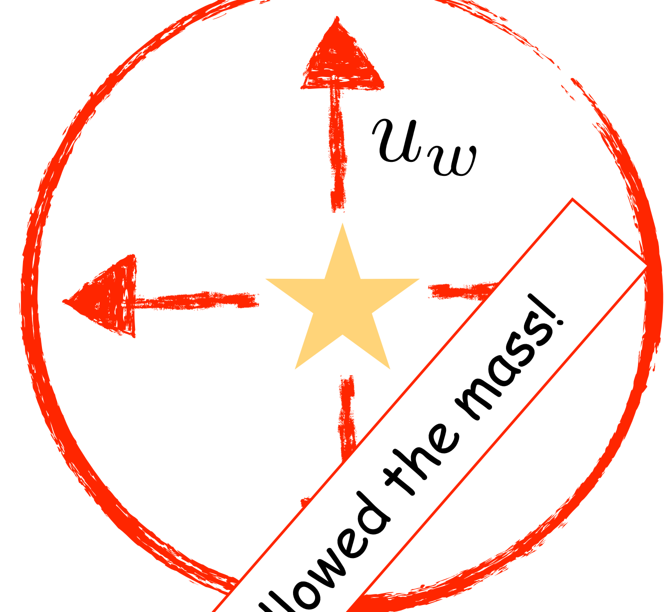

<— These guys followed the mass!

analogy with solar WTS (Parker, Jokipii...) ...SA (BOBALSKy...)

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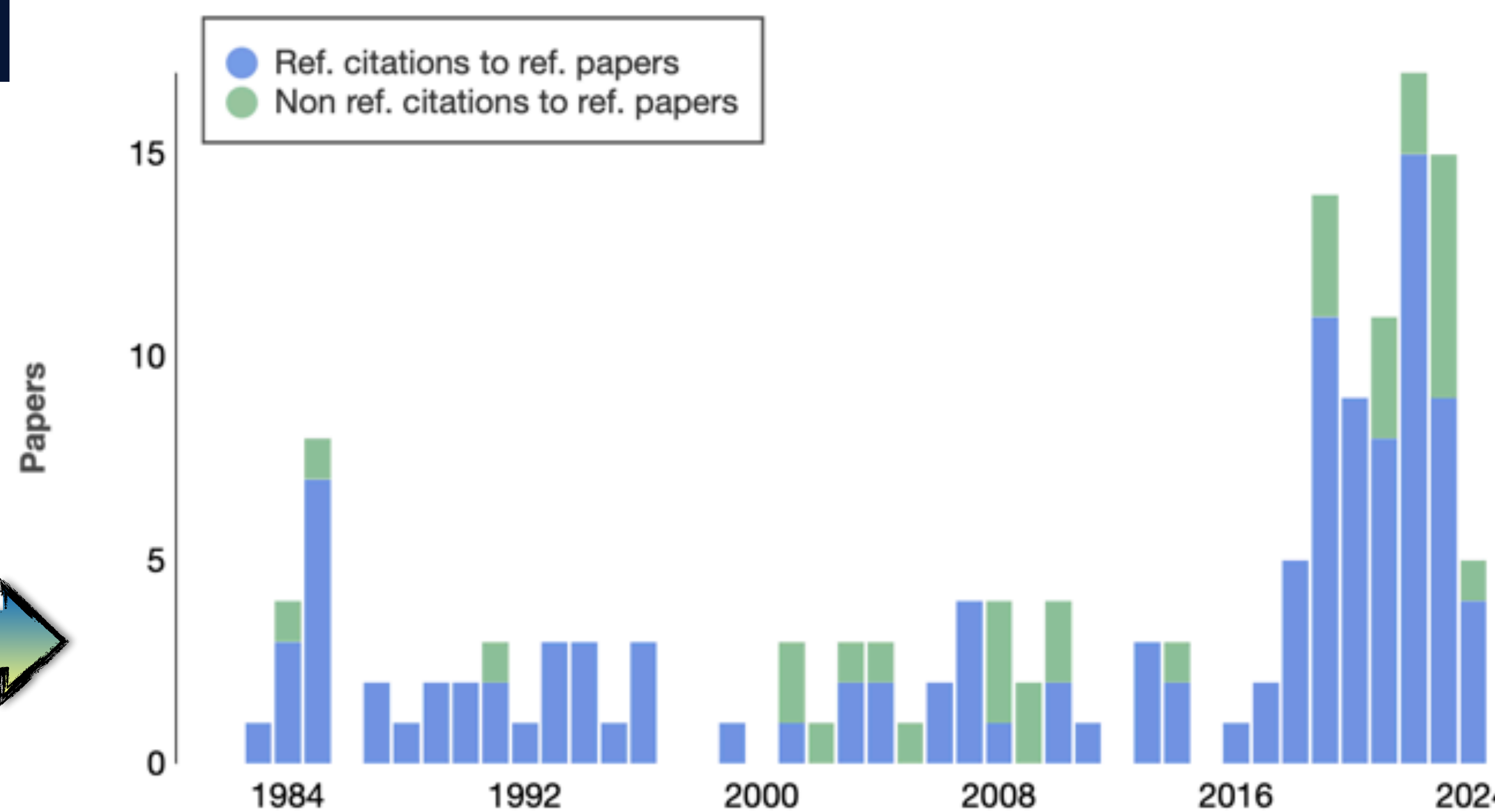
Then nobody cared for few decades…

CR physicists thinking about stellar winds between 1983 and 2019

citation counts for Cesarsky & Montmerle review



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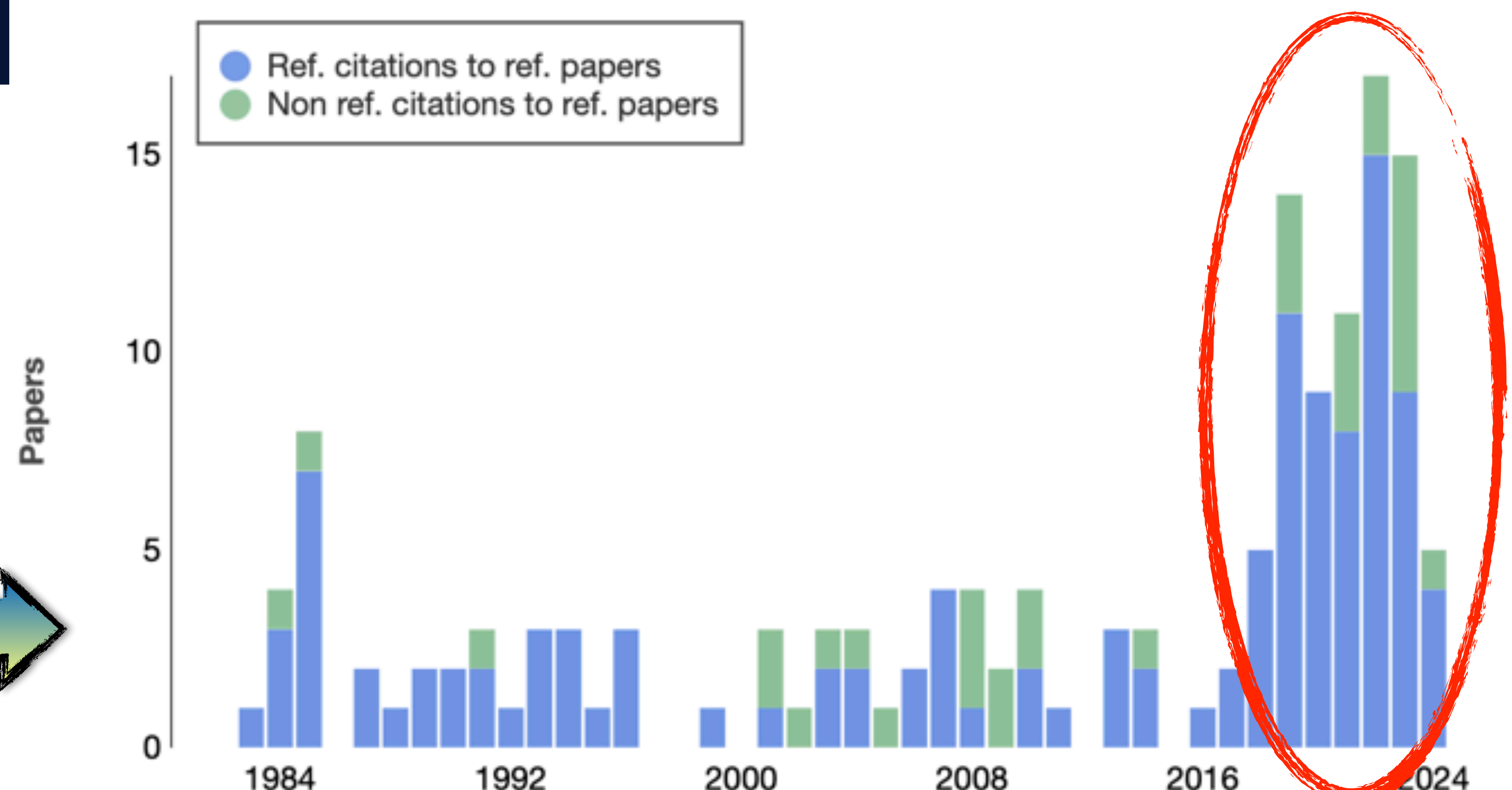

Energy problem

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

stellar winds are radiation driven

$$\dot{M}_w u_w \approx \eta \frac{L_*}{c}$$

momentum carried by the wind

momentum carried by stellar photons

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$$\dot{M}_w u_w \approx \eta \frac{L_*}{c} \propto M_*^3$$

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momentum carried by stellar photons

total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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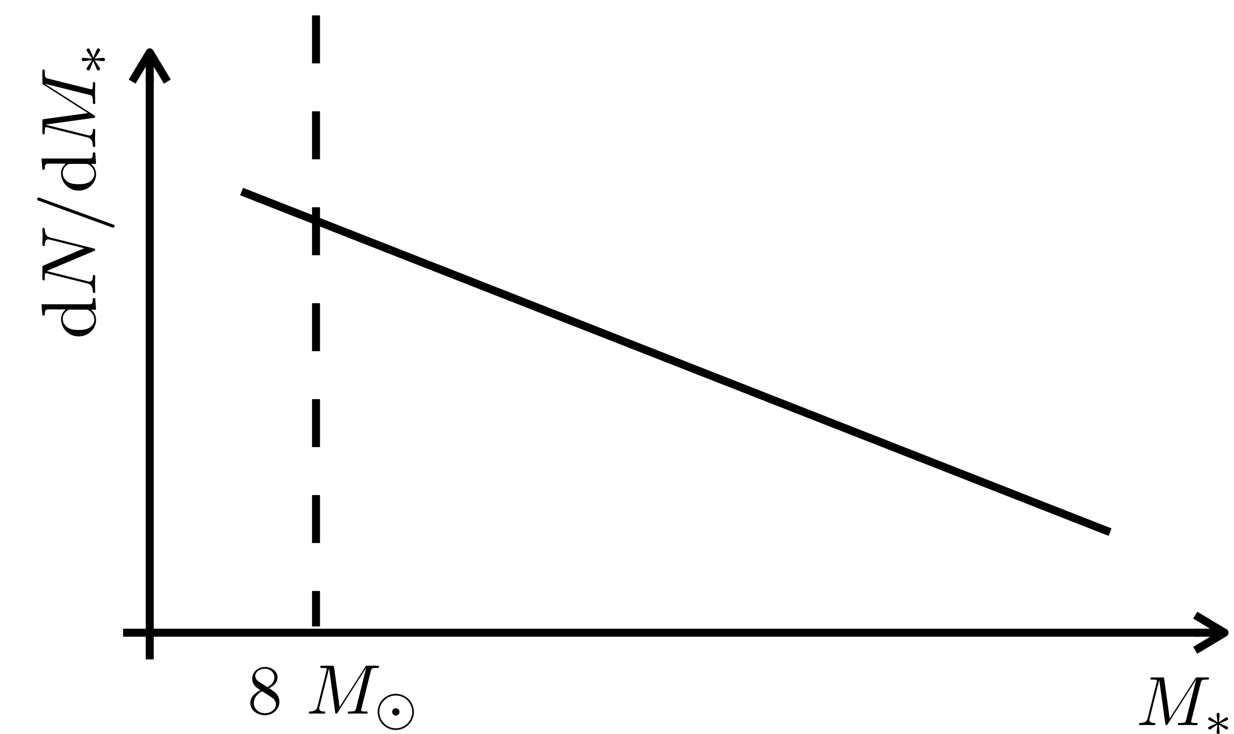

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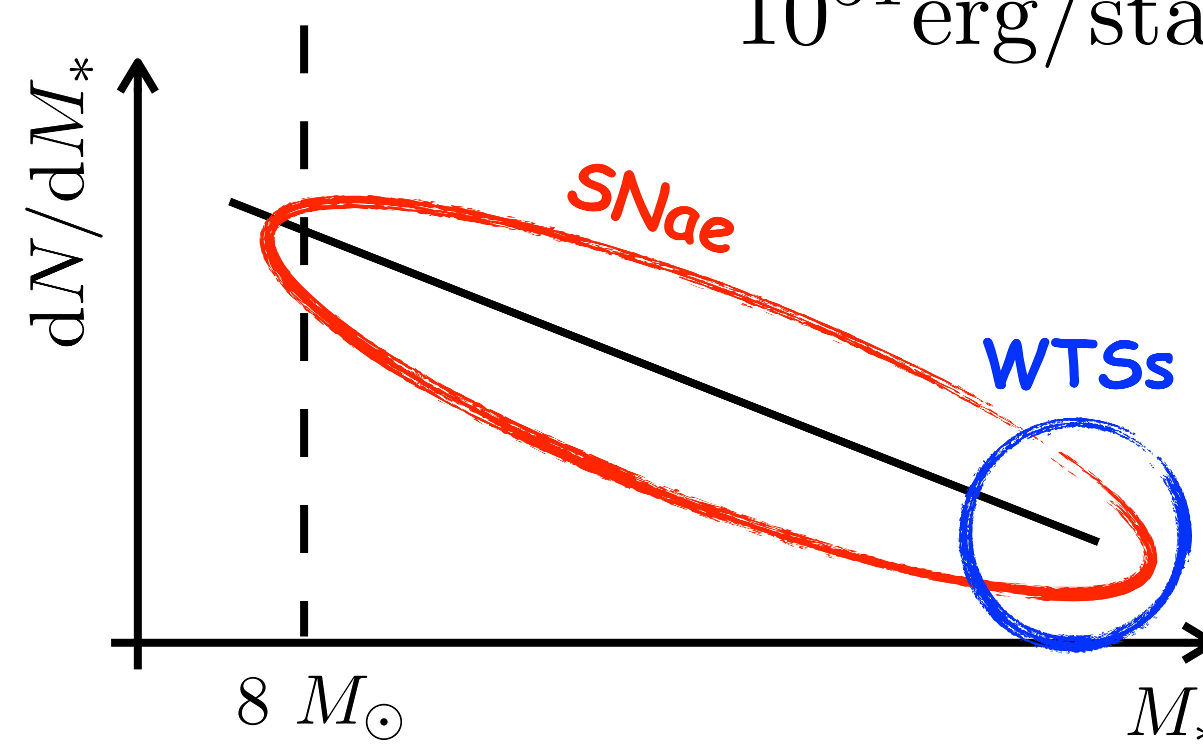

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momentum carried by the wind

momentum ... by st...

to... ...er ... ...ne ...ive stars

very steep mass-lumi...

$L_* \approx M_*^3$

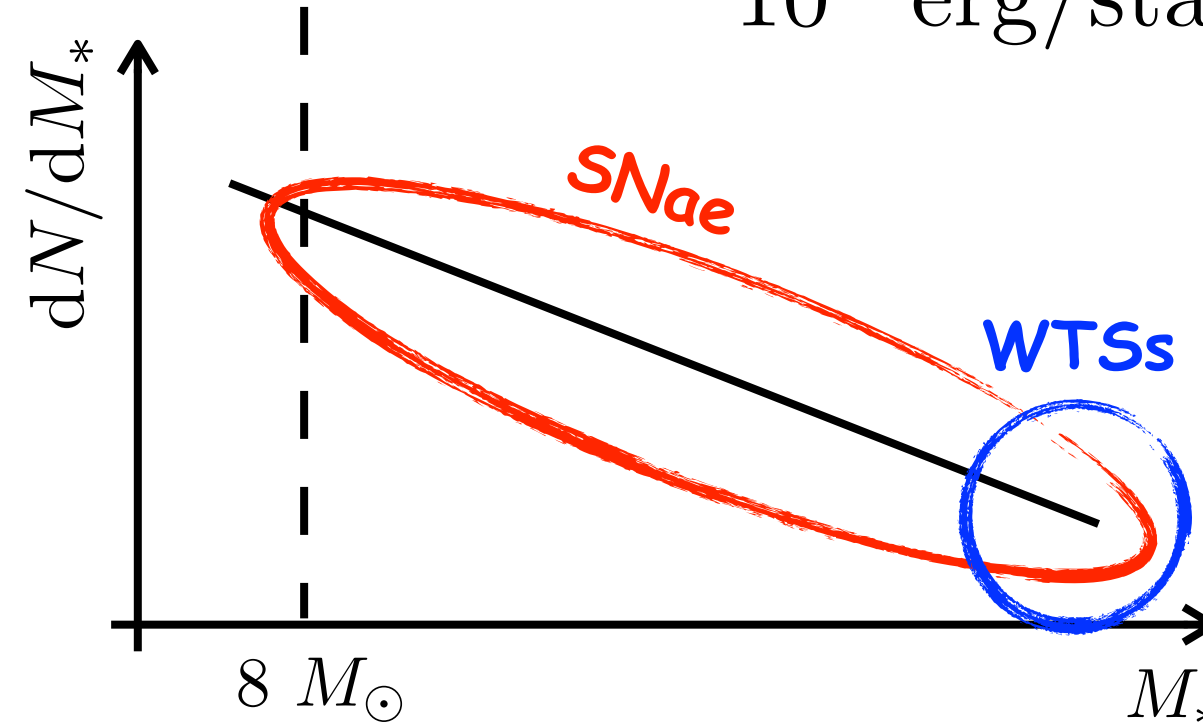
—> supernovae win by about a factor of several

—> WTS might explain a (sizeable) fraction of CRs

for ... massive stars:

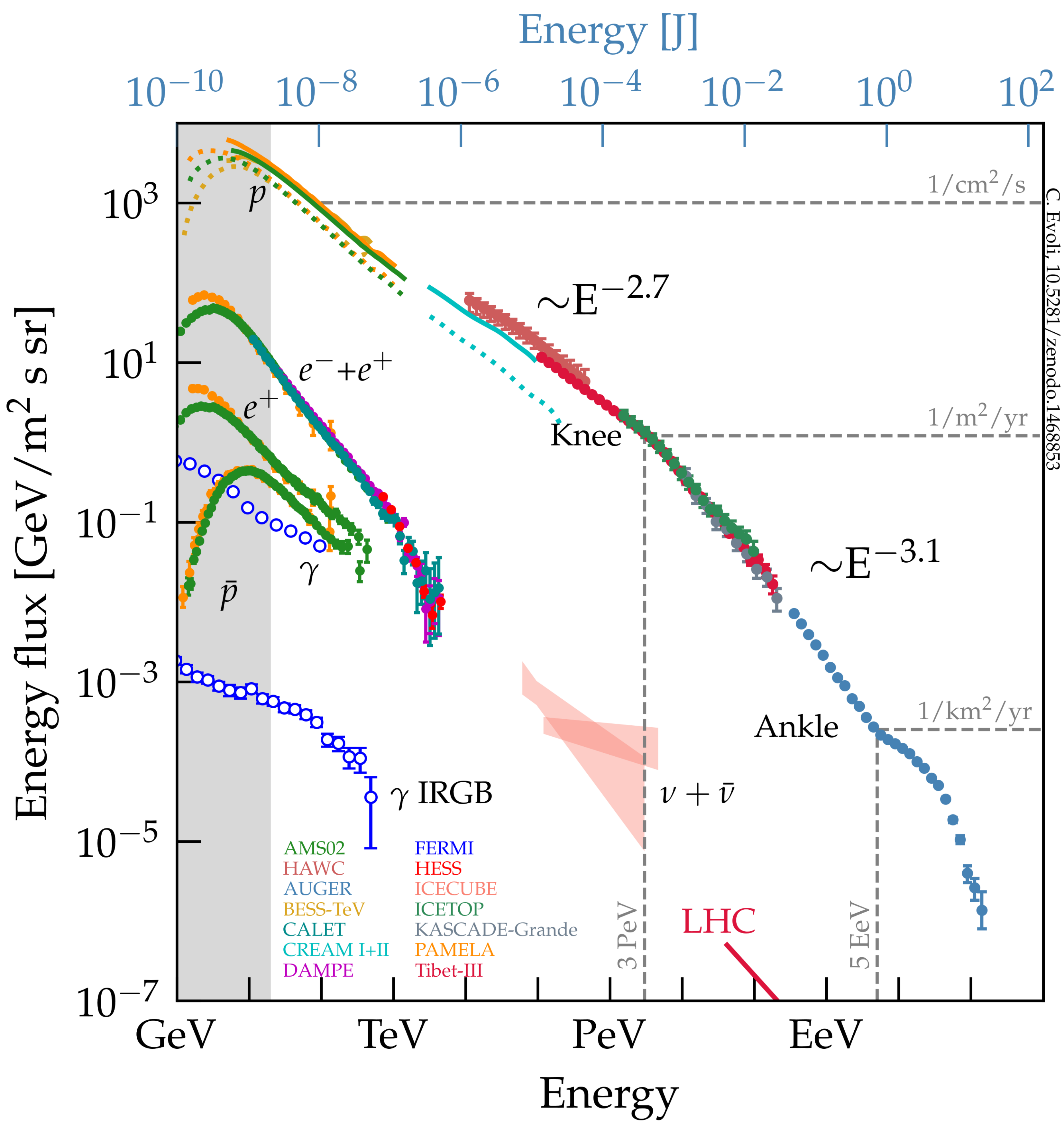
$$\int \mathrm{d}t \; P_w \approx 10^{51} \mathrm{erg} \sim \mathrm{E_{SN}}$$

$10^{51}\mathrm{erg/star}$



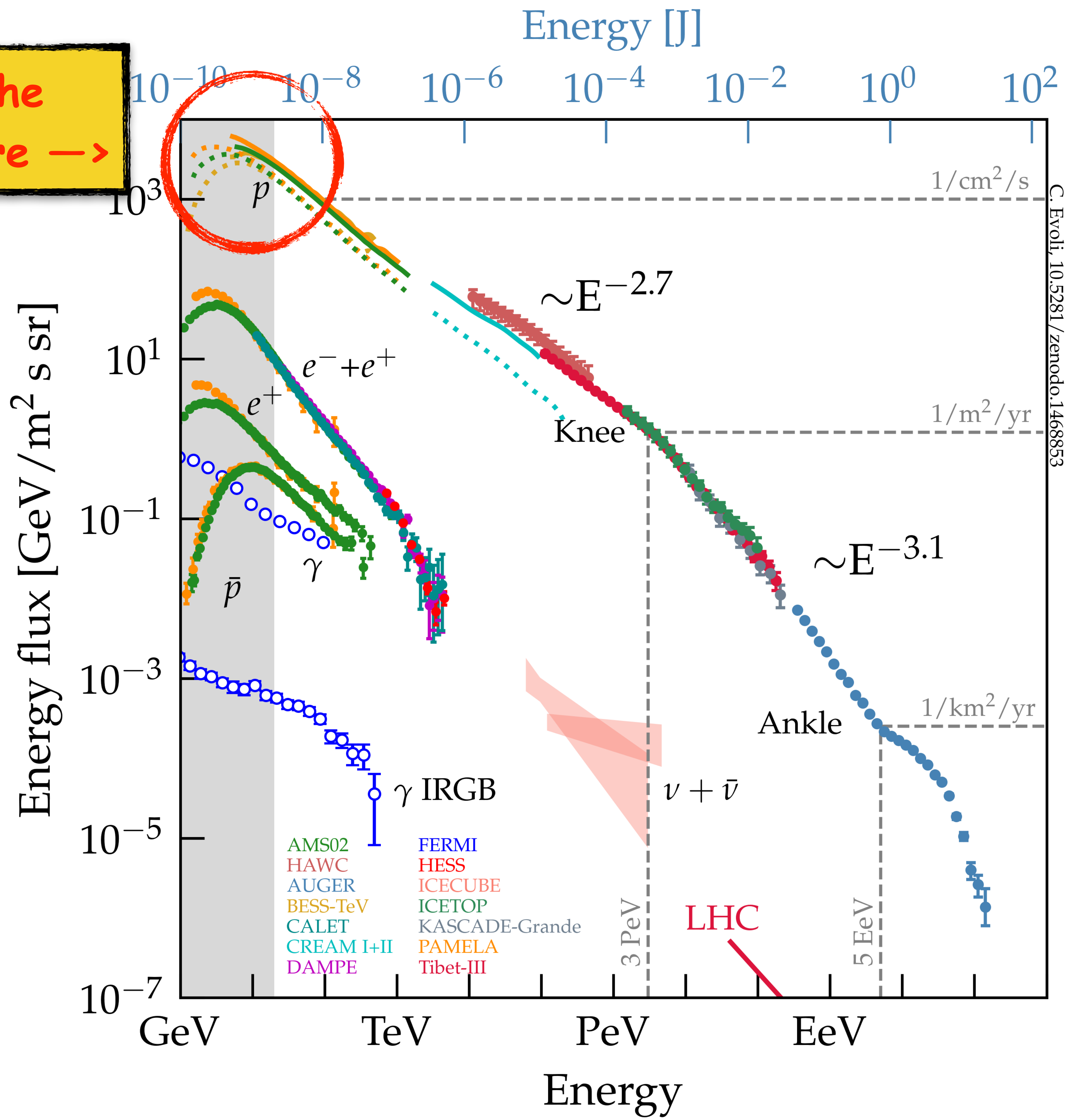
[4] Follow the physics
Where does acceleration end?
The Hillas criterion

Energy, energy, energy…



Energy, energy, energy…

most of the energy is here —>



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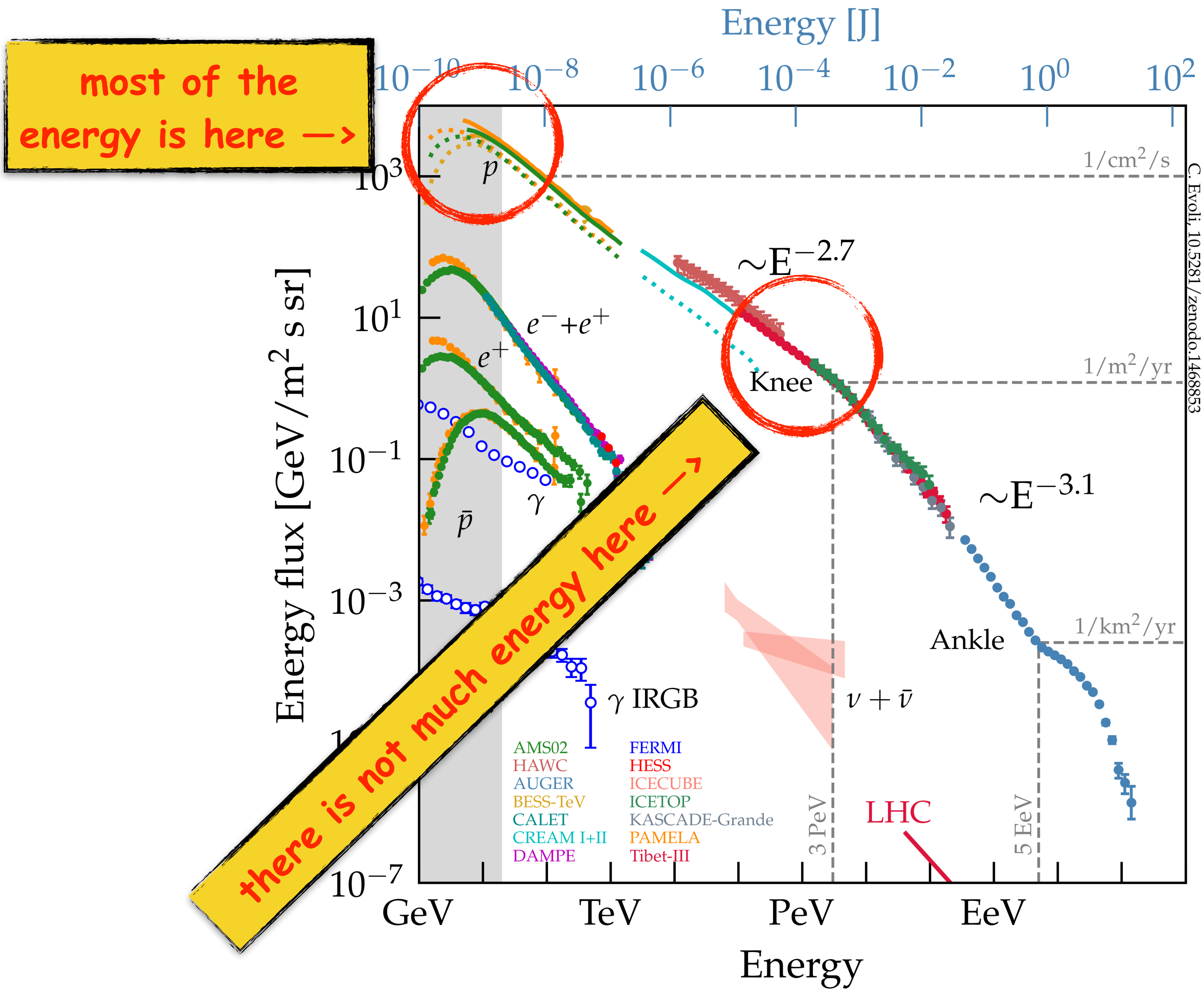

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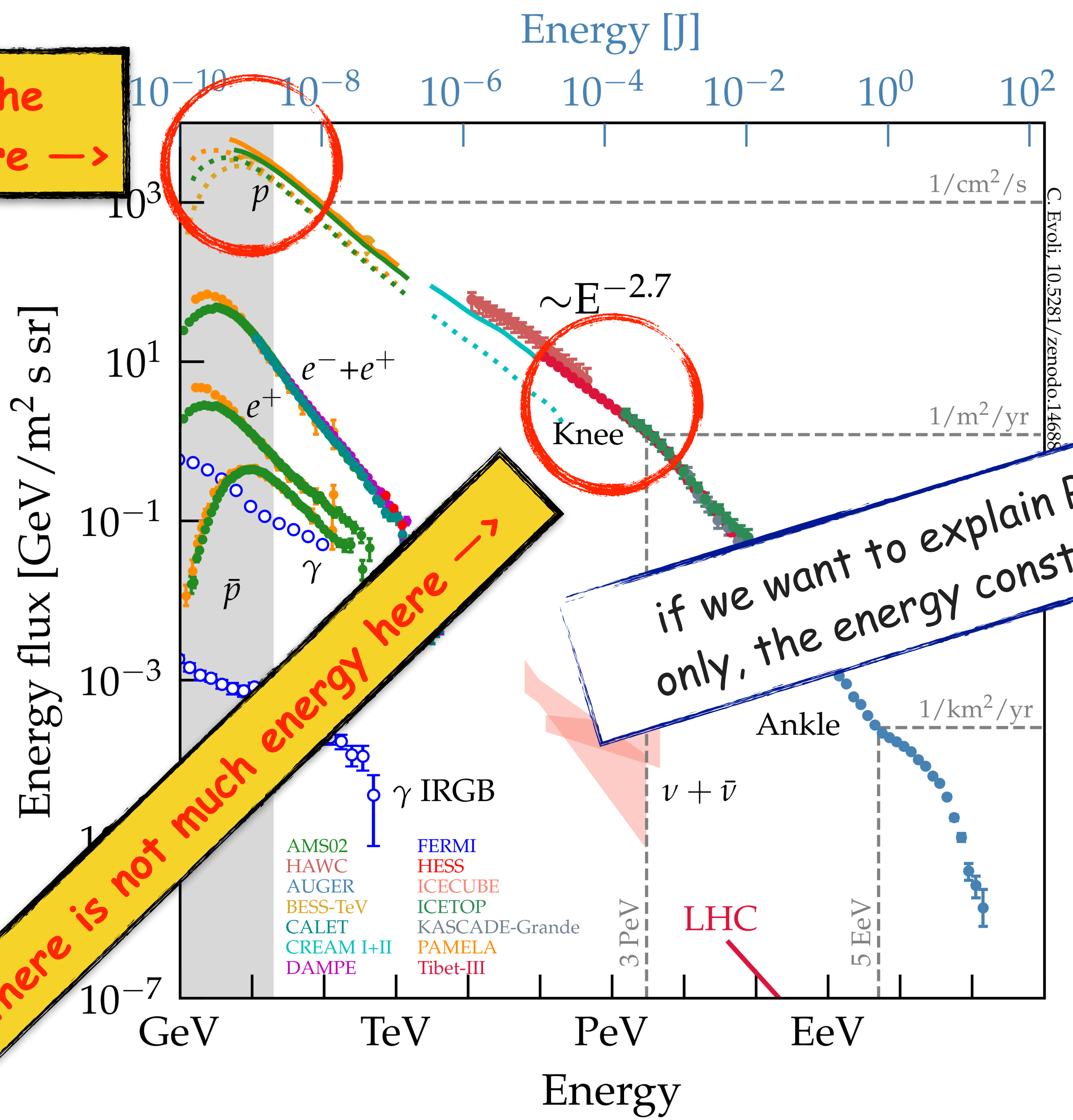
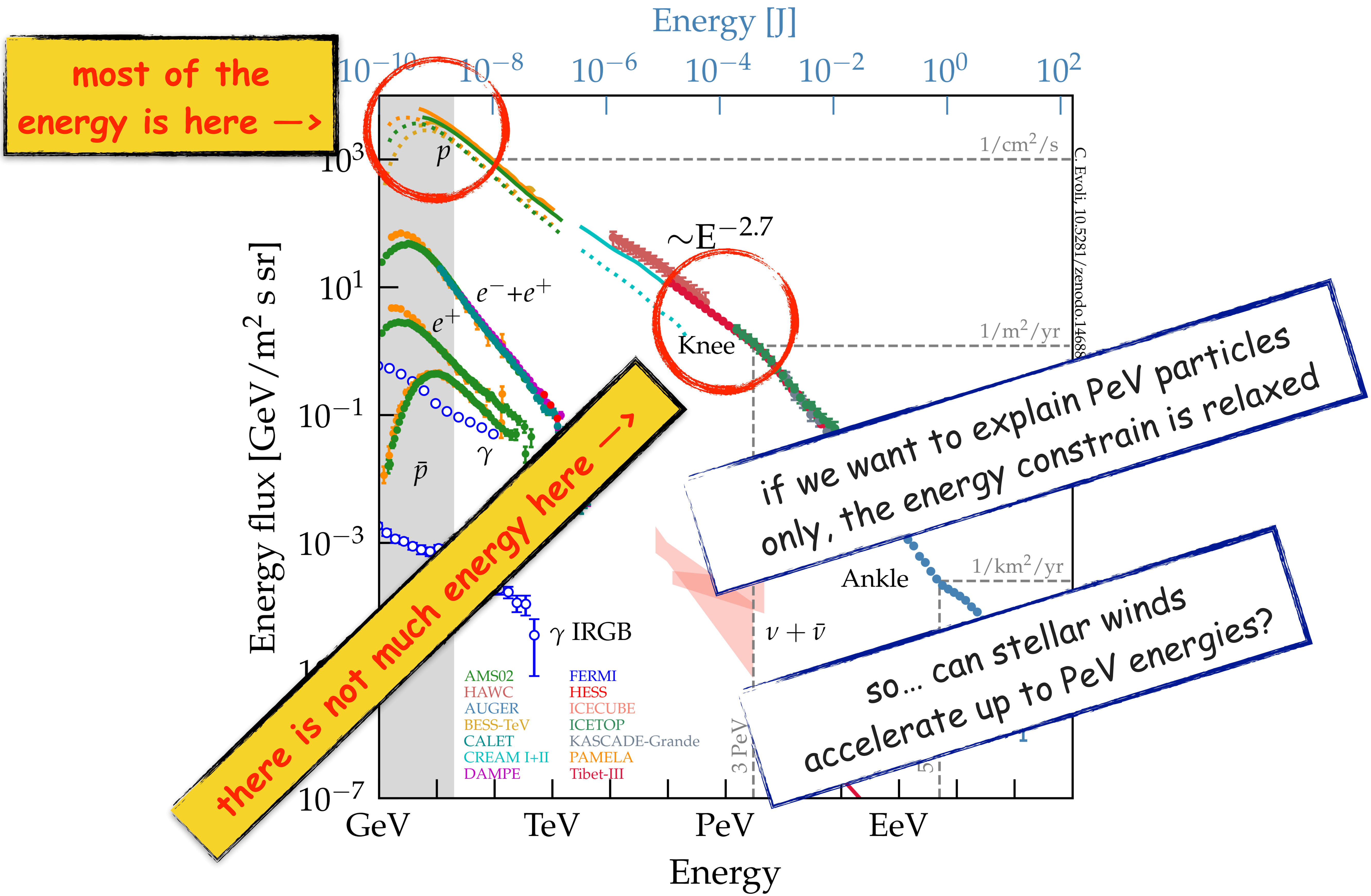


there is not much energy here —>

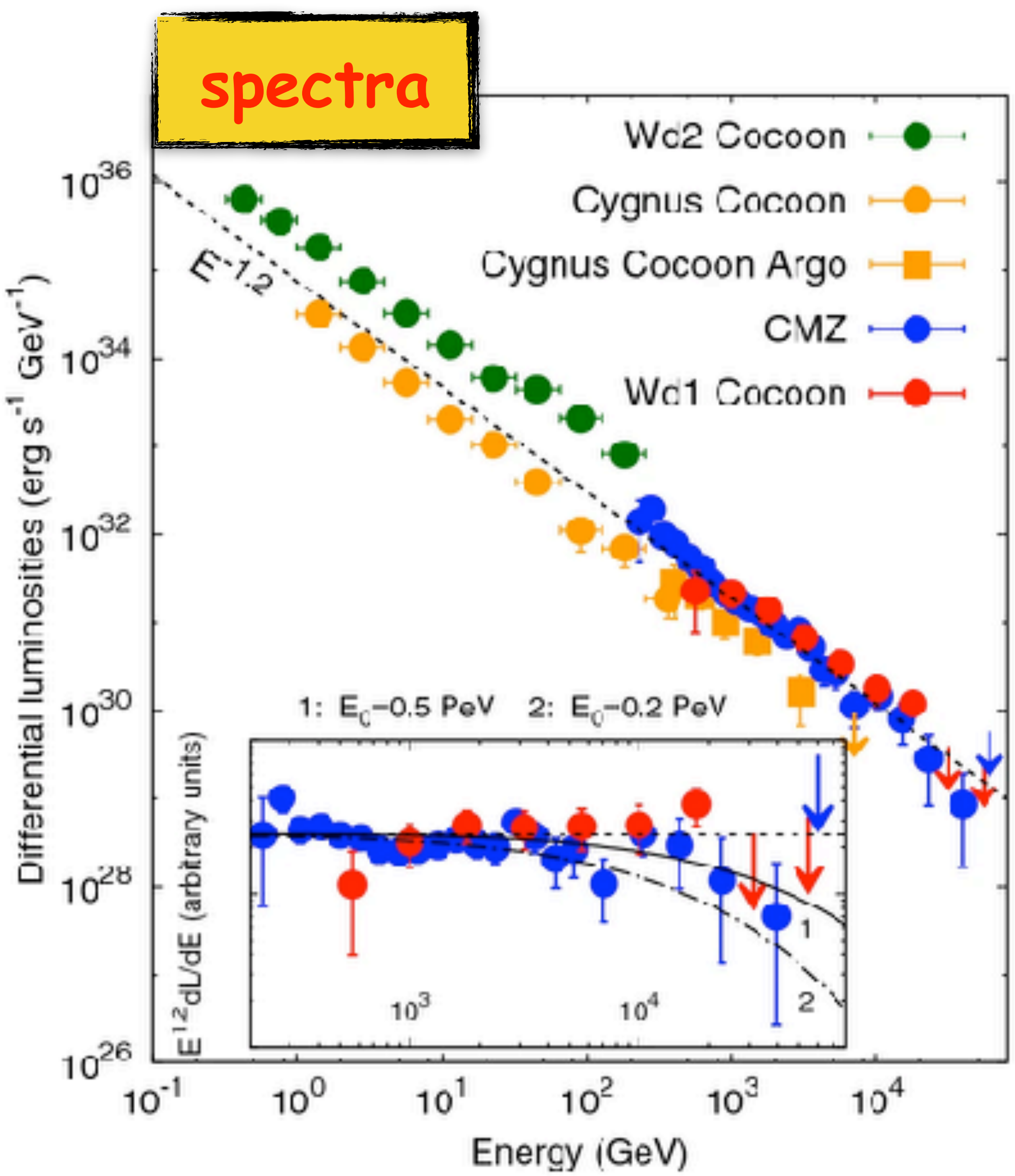
if we want to explain PeV particles only, the energy constrain is relaxed

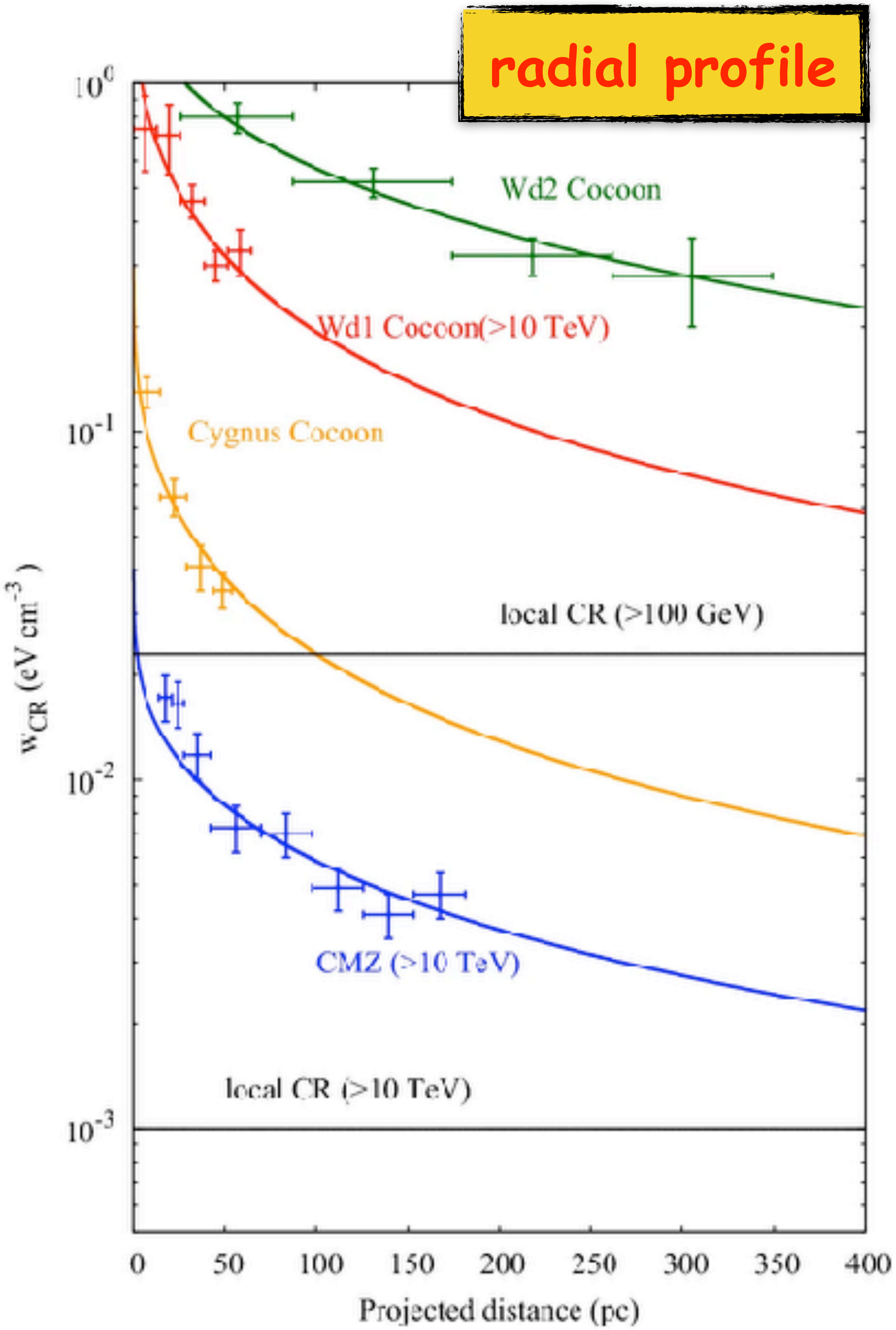
Energy, energy, energy...



Stars or star clusters? Gamma rays…

Aharonian+ 2019, plus several papers especially by Yang and collaborators





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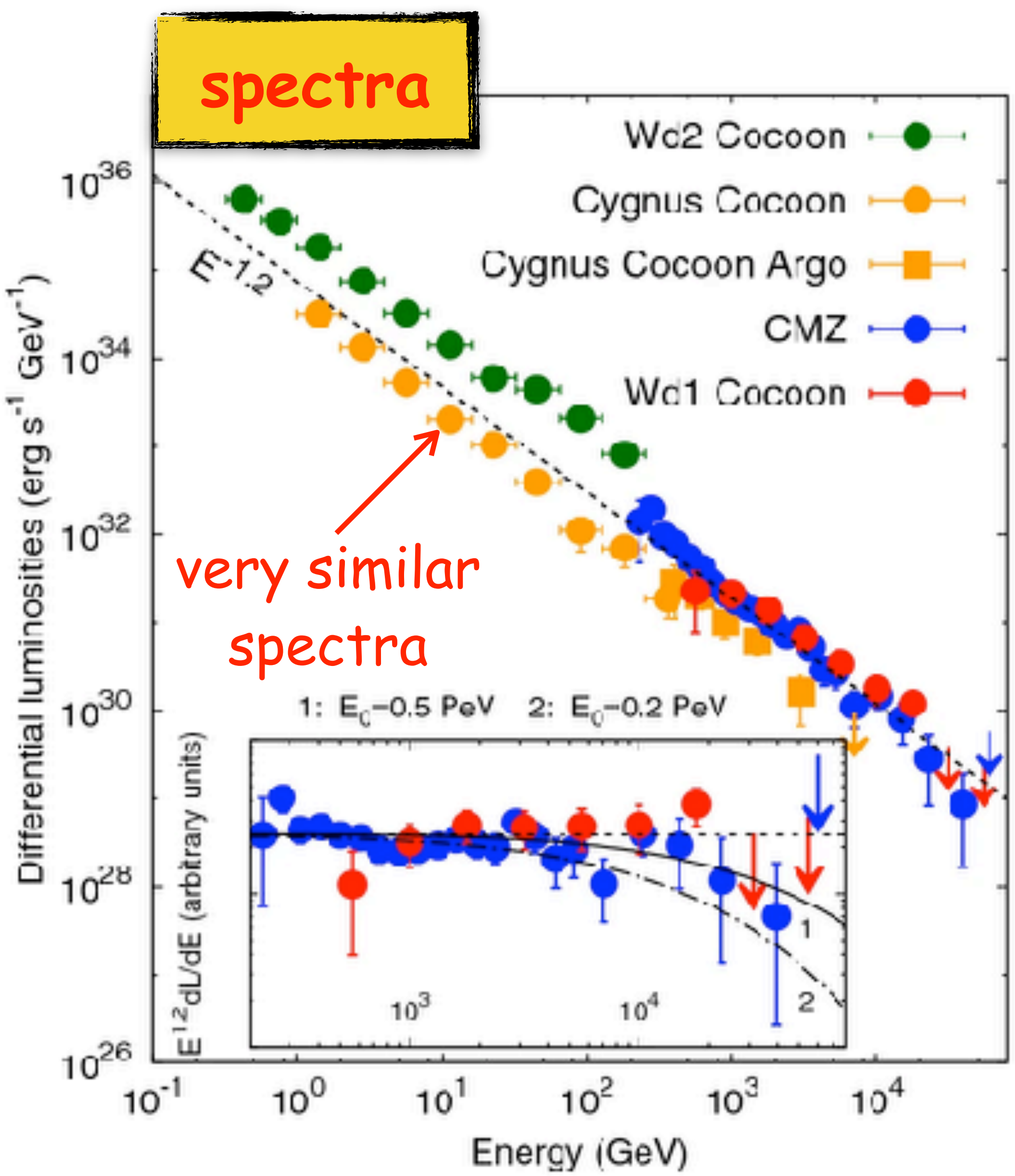

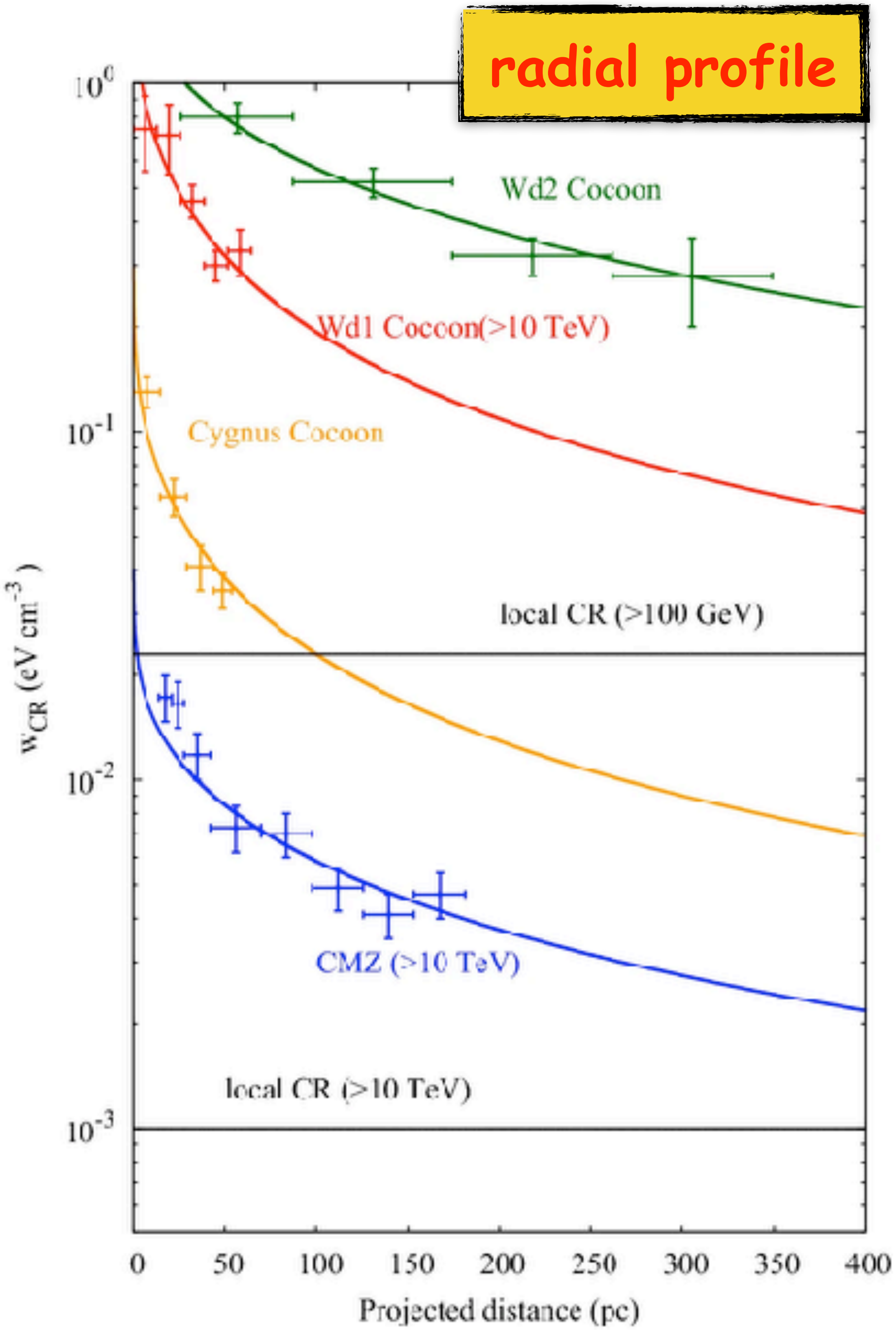

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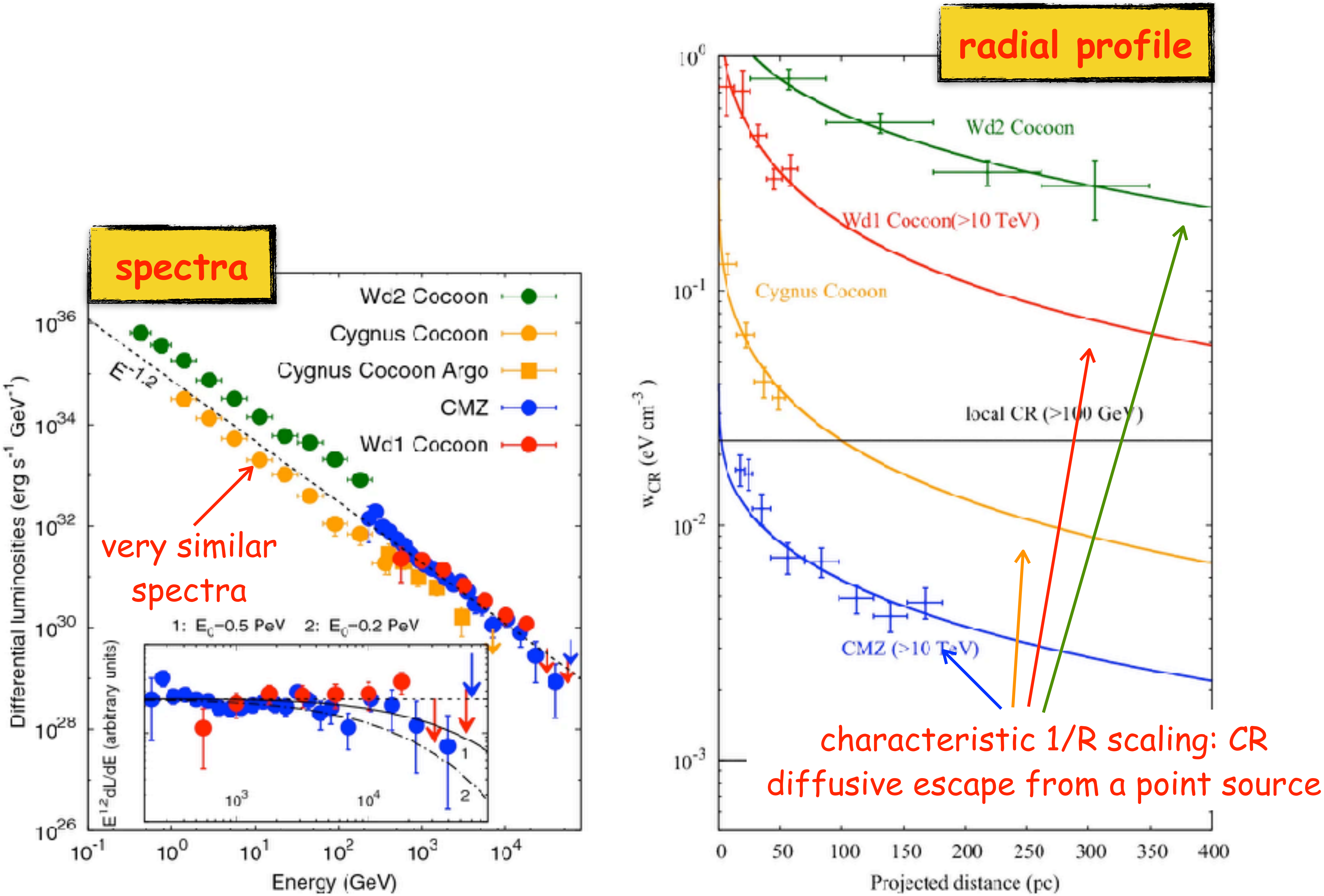

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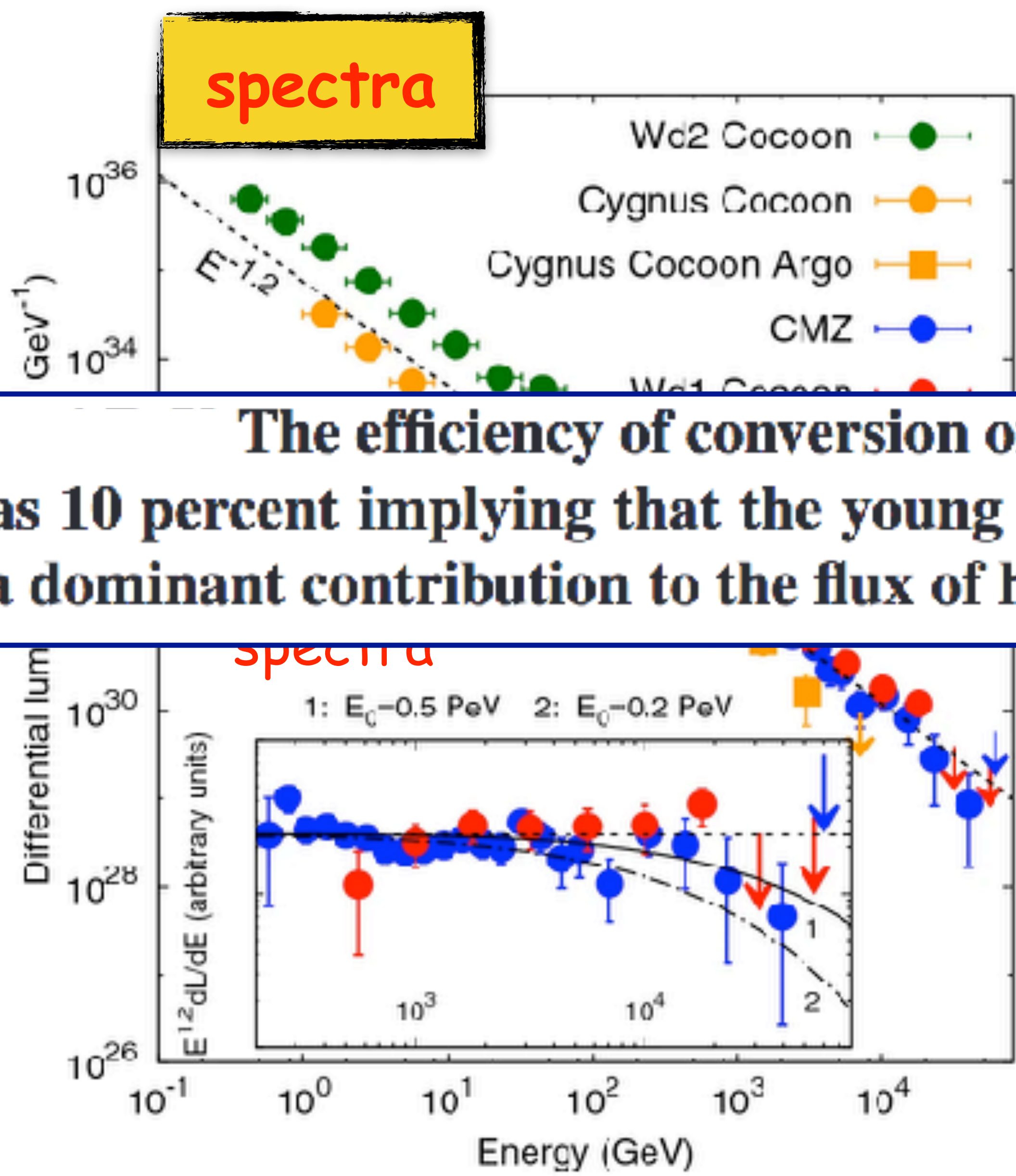

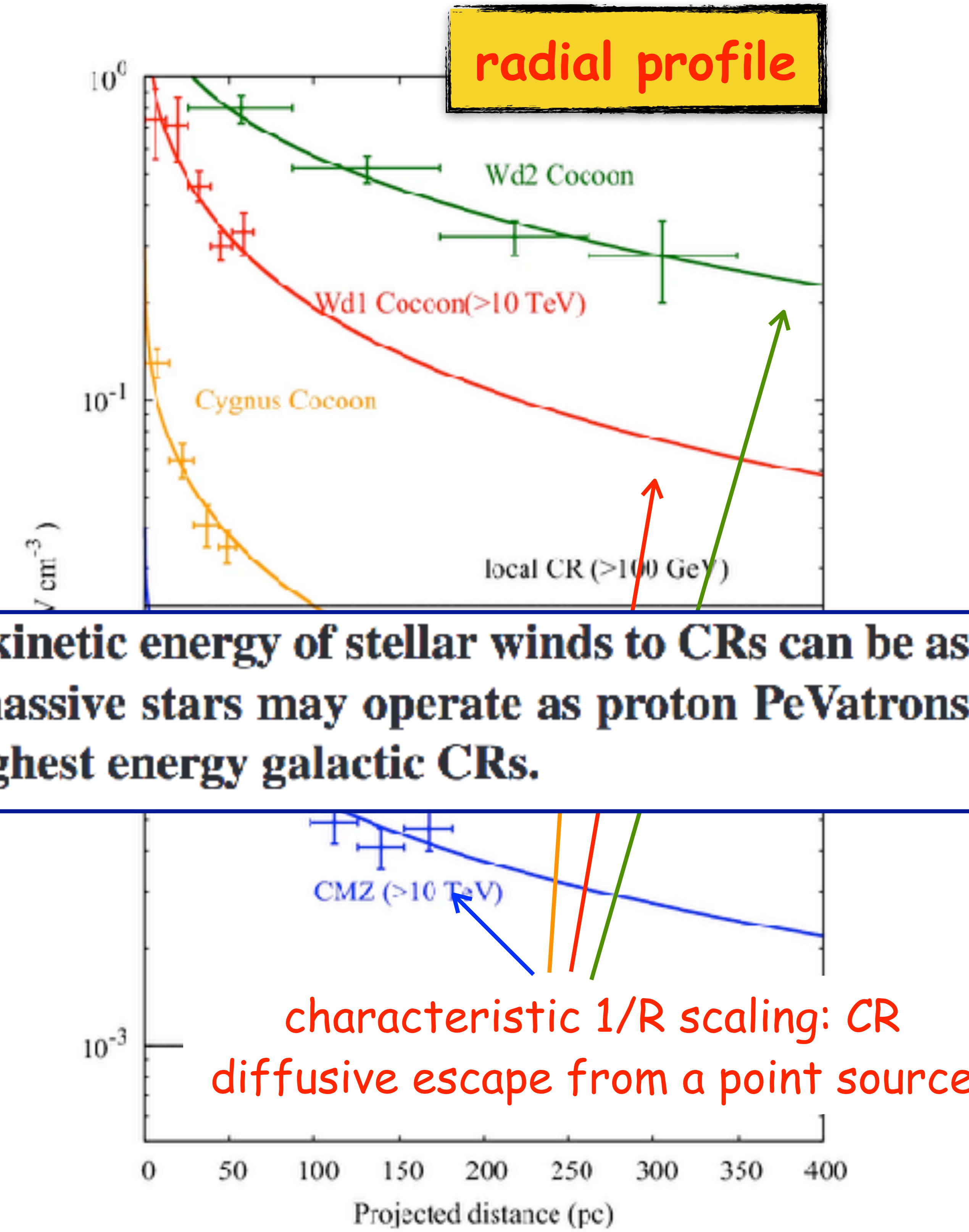

The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

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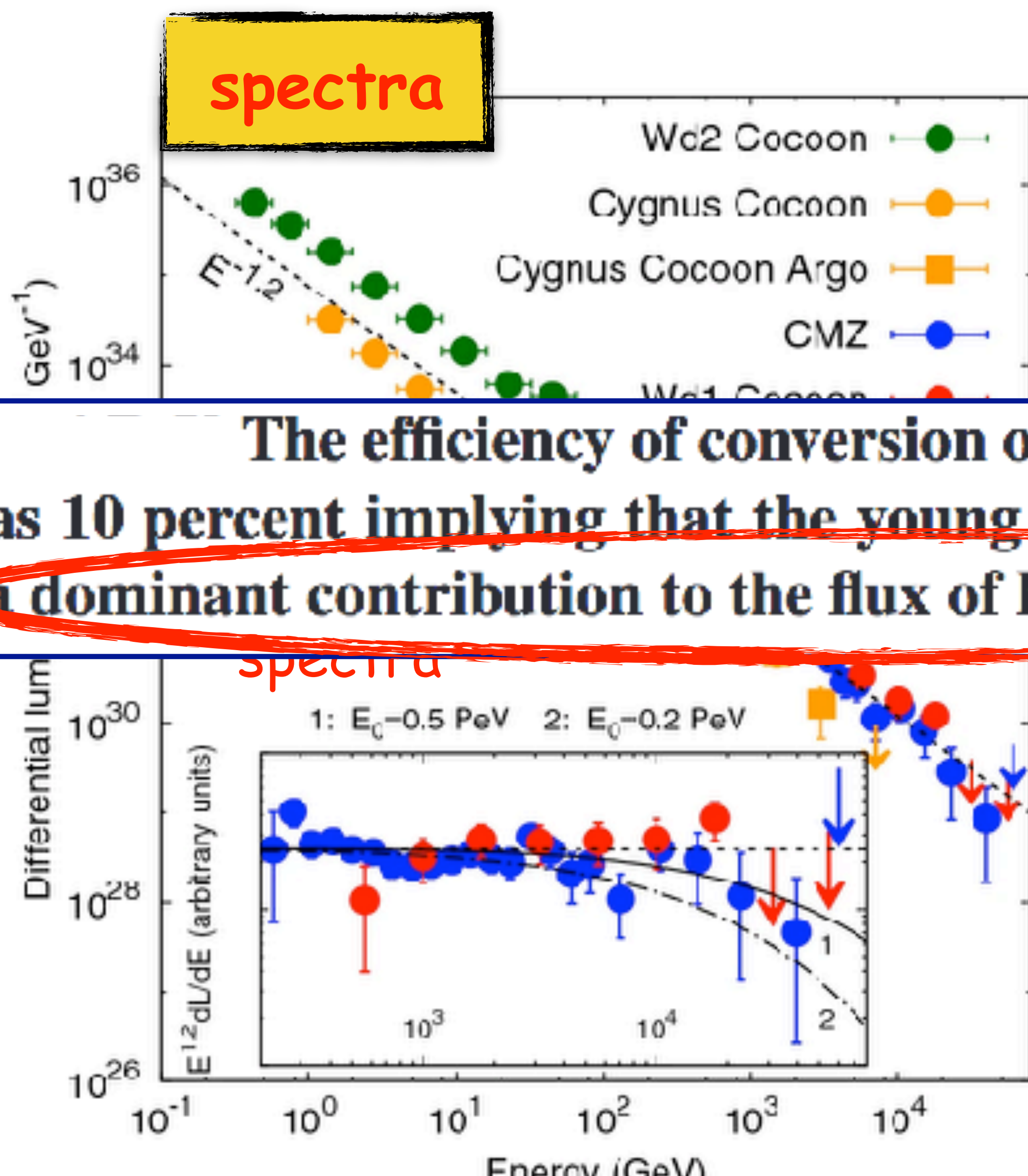

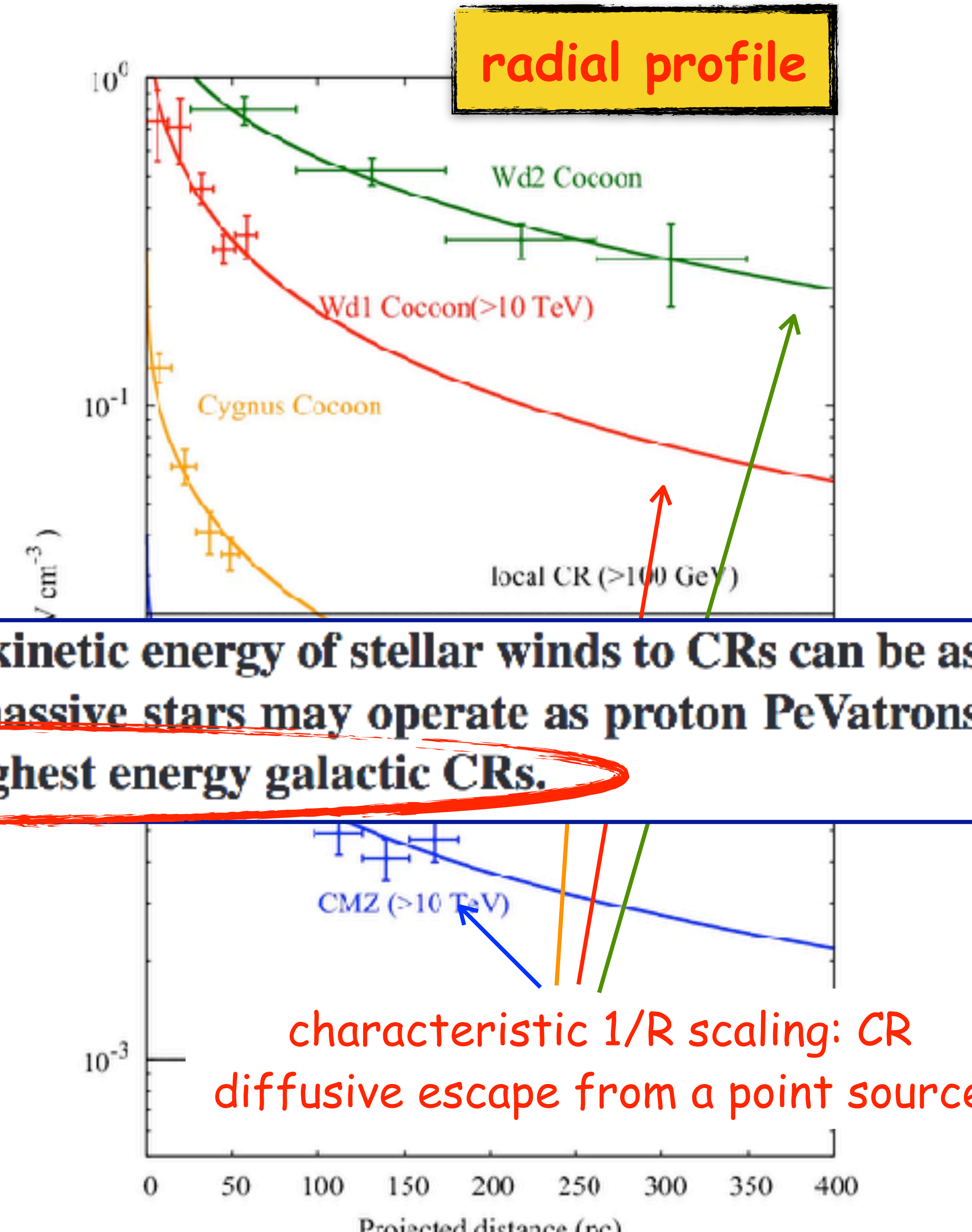

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Stars or star clusters? Gamma rays…

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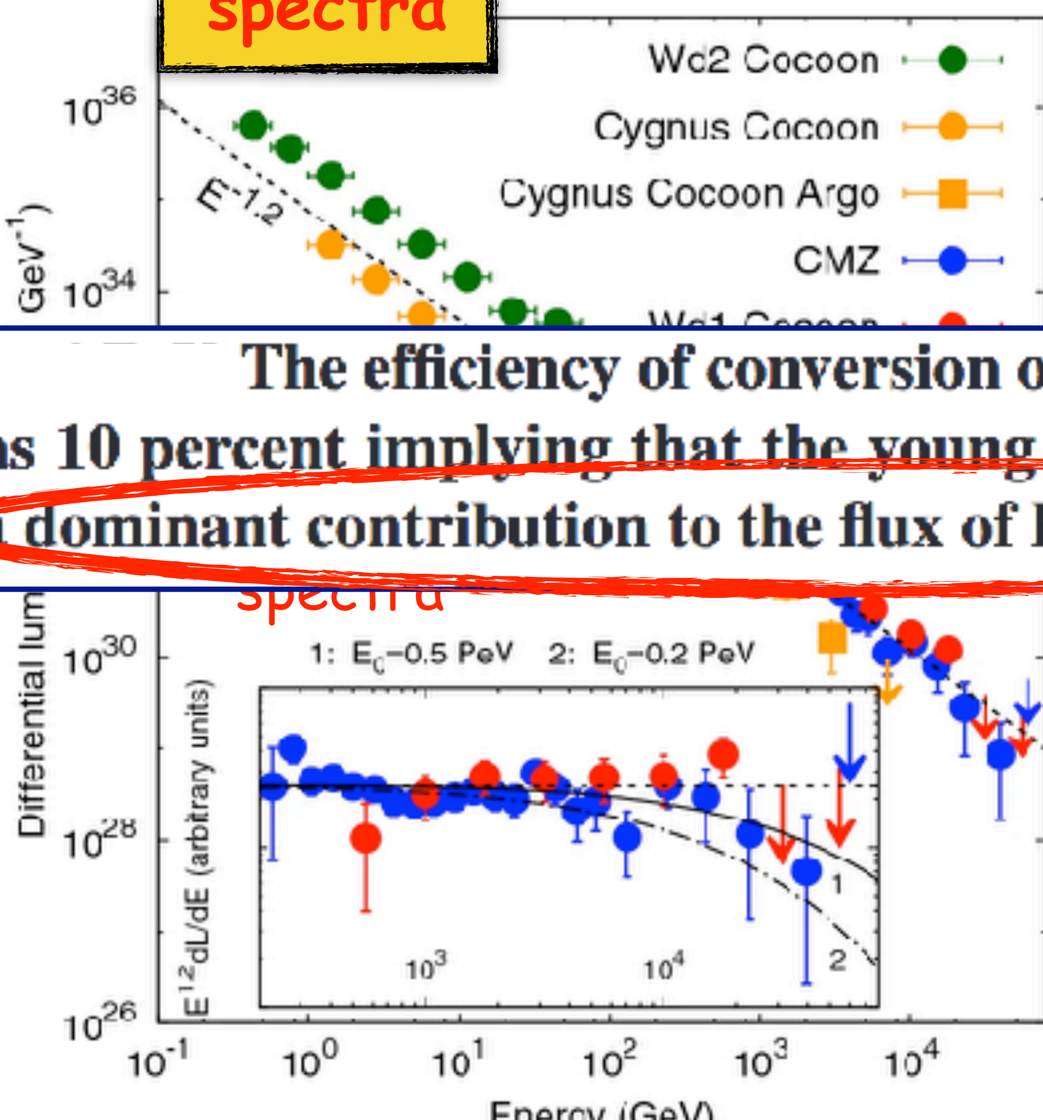
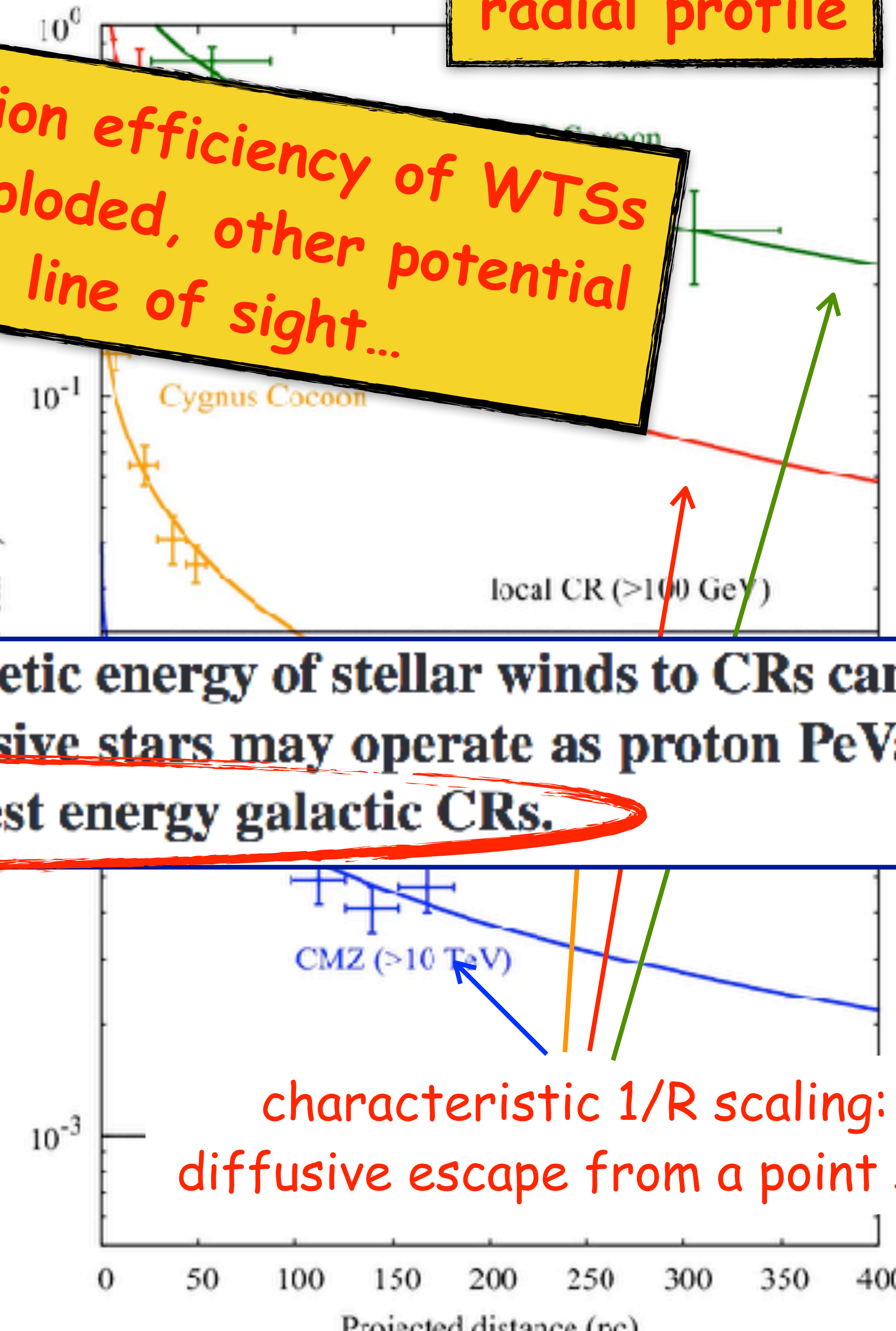
cannot constrain acceleration efficiency of WTSs
—> some SNae already exploded, other potential CR source along the line of sight…

spectra



radial profile



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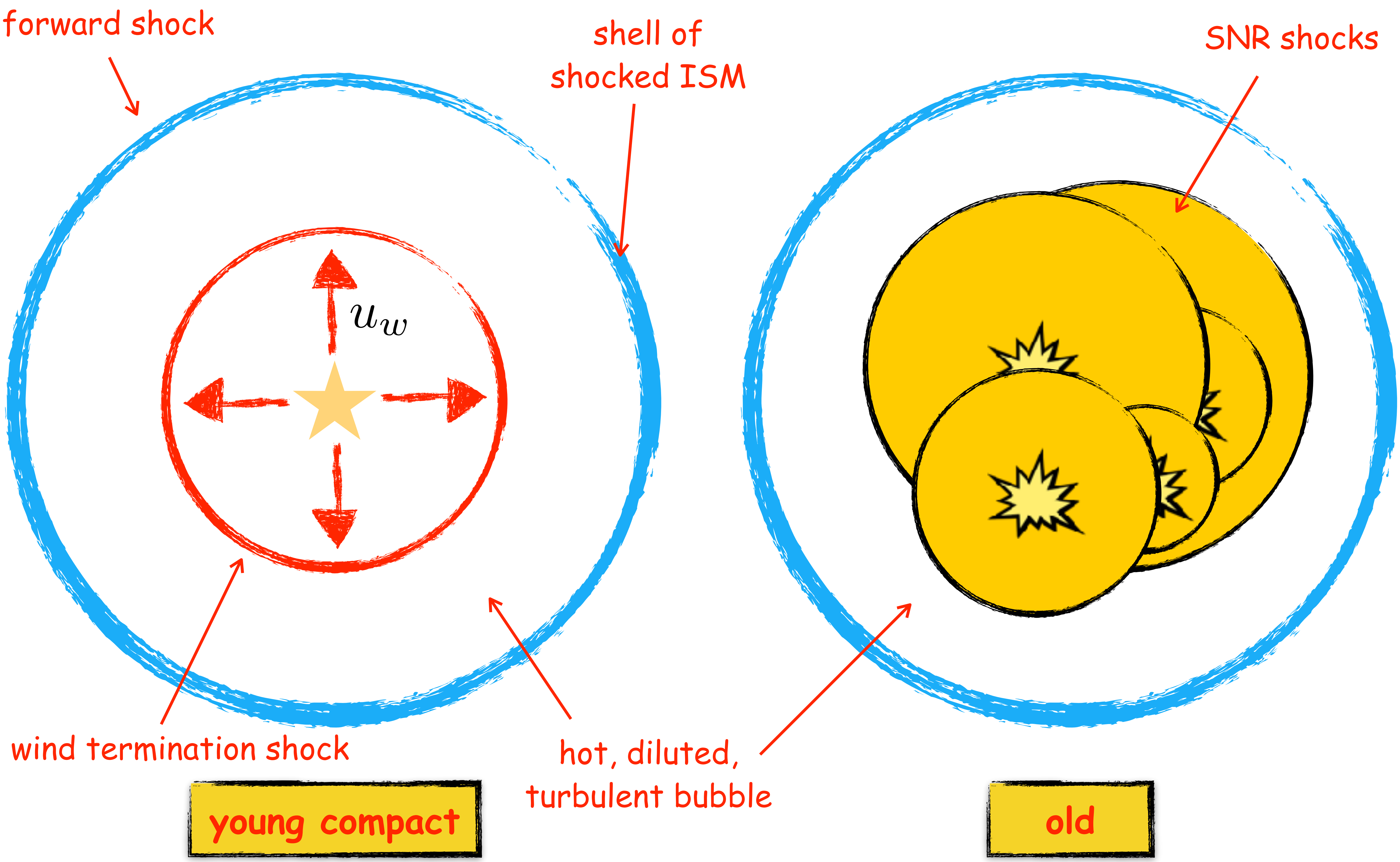
characteristic 1/R scaling: CR diffusive escape from a point source

Interstellar bubbles around star clusters

Castor+ 75, Weaver+ 77, McCray&Kafatos 87, Mac Low&McCray 88, Koo&McKee 92...



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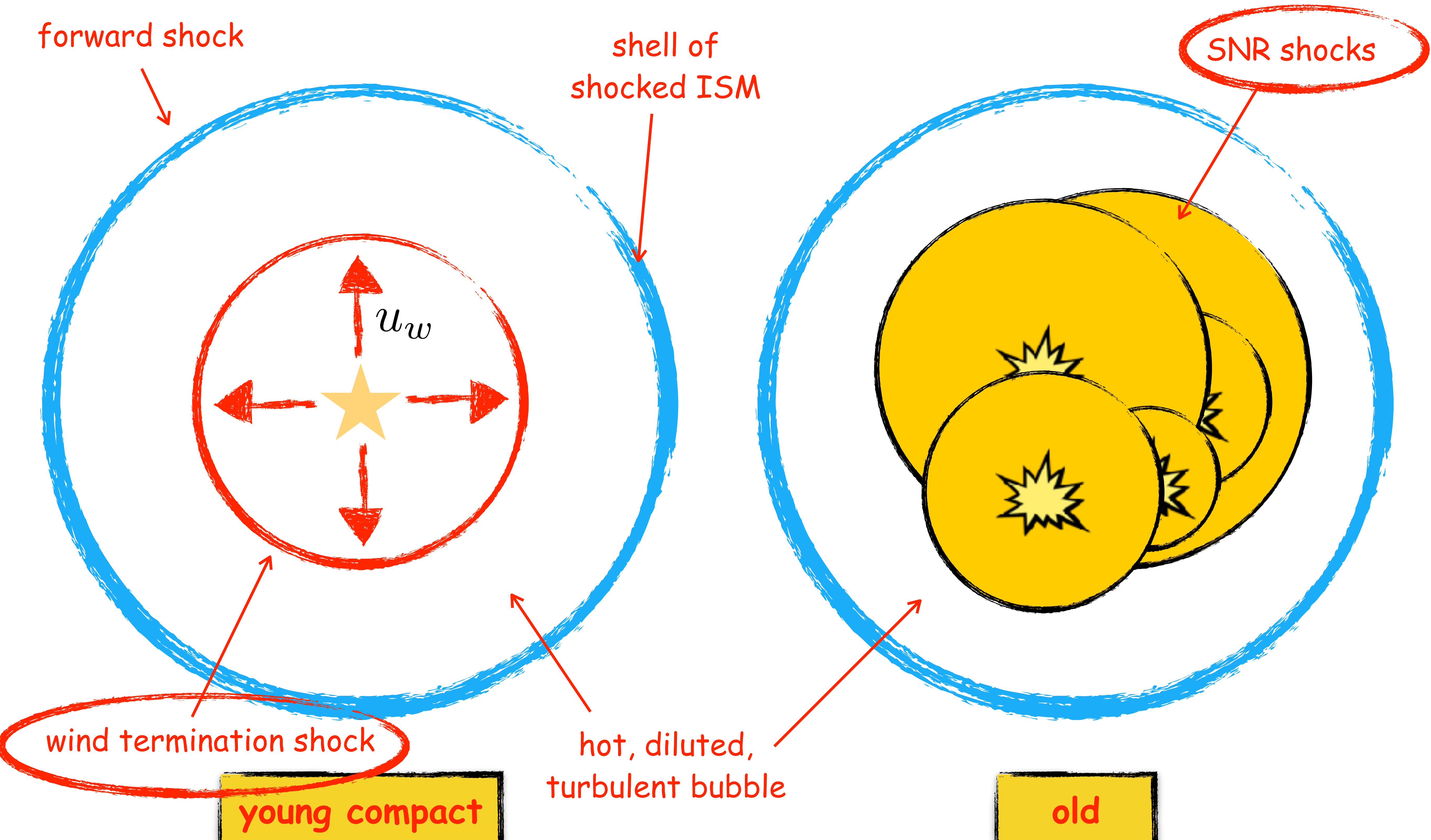

Particle acceleration at WTSs: E_{max}

Hillas criterium —> $$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

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Morlino+ 2021

$$L_w = 3 \times 10^{38} \mathrm{erg/s}$$

$$u_w = 3000 \ \mathrm{km/s}$$

$$n_{ISM} = 1 \ \mathrm{cm}^{-3}$$

$$\eta_B = 0.1$$

$$E_{max} \approx 2 - 3 \ \mathrm{PeV}$$

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possible for powerful clusters?

multiple shocks in star cluster cores cannot accelerate to PeV —> Vieu+, arXiv, yesterday

[5] Follow the mass
Isotopic anomalies
Stellar winds: polluters or accelerators?

Isotopic anomalies: the $^{22}Ne/^{20}Ne$ ratio

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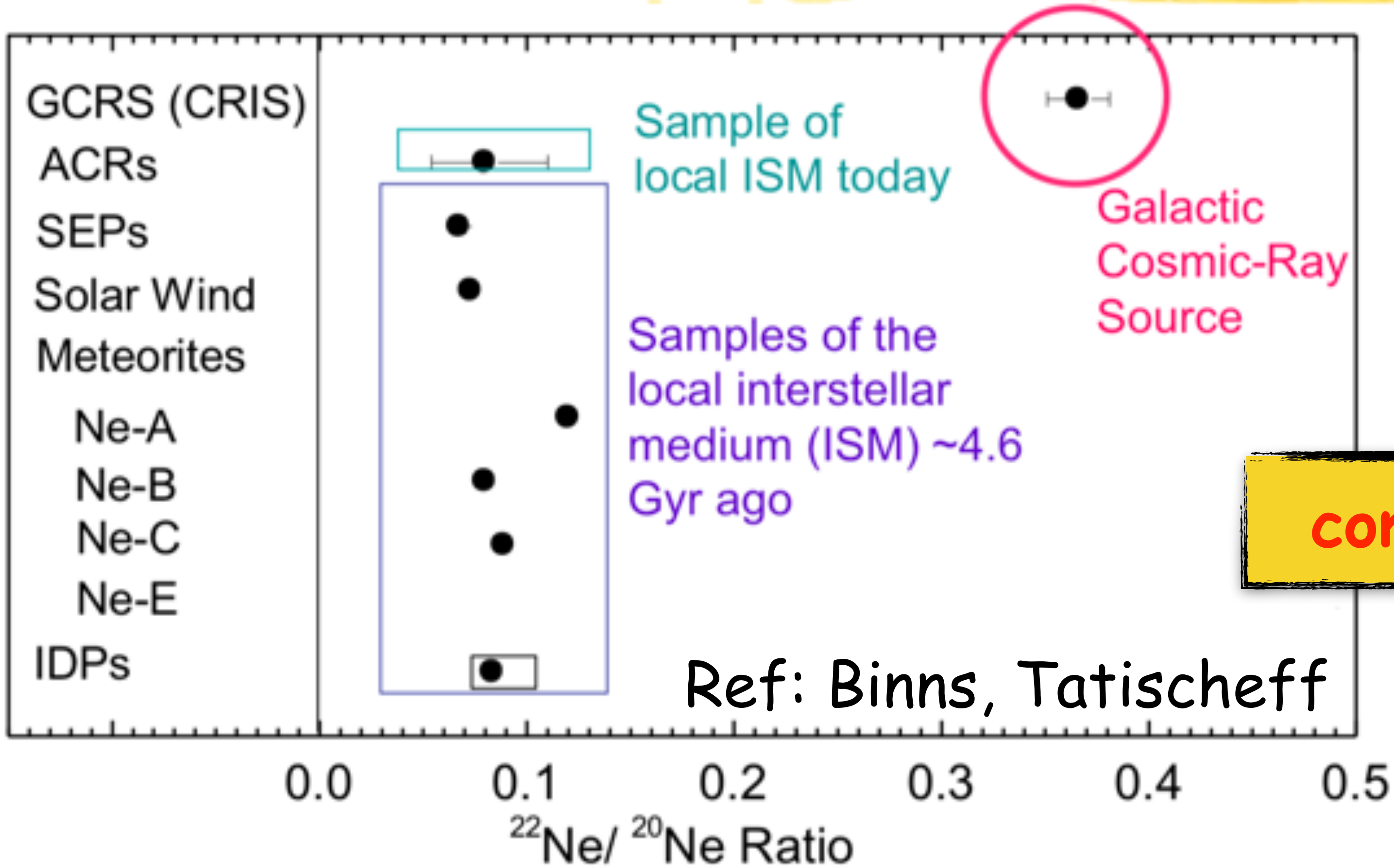
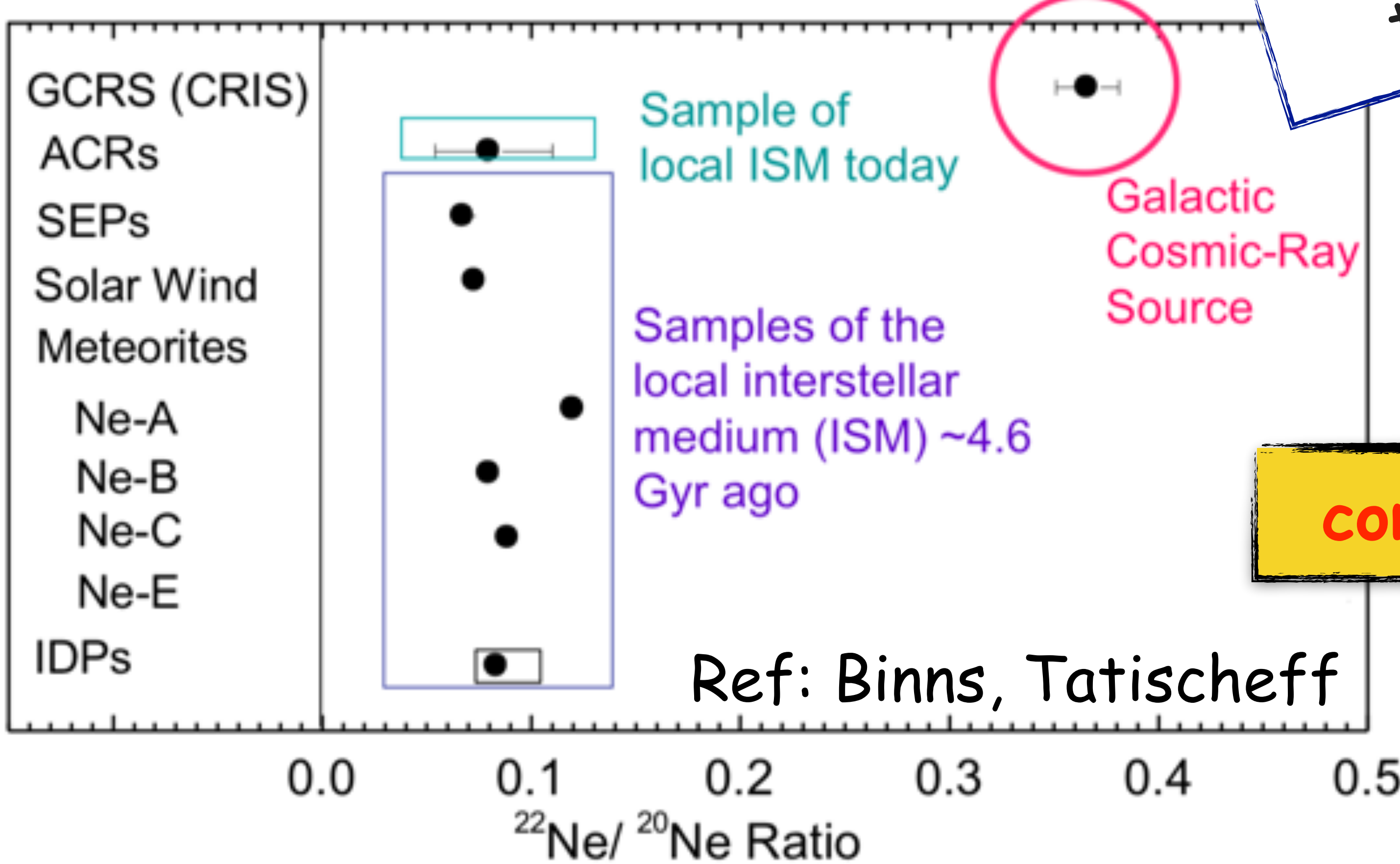


composition

Isotopic anomalies: the $^{22}Ne/^{20}Ne$ ratio

...a factor of ~4 larger in cosmic rays than in solar/interstellar matter...



composition

Can supernova remnants explain all CRs?

YES! —> WR stars pollute of ^{22}Ne the interior of the bubble —> mixing with ambient ISM —> supernovae explode —> supernova remnants accelerate the polluted/mixed material (see papers by Lingenfelter+, Parizot+ …)

NO! —> WTSs of WR stars accelerate wind material enriched in ^{22}Ne (Tatischeff+ 2021)

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Questions:

- Do WTSs accelerate CRs?
- If so, how many of them?
- Can star clusters (WTS plus SNR inside superbubbles) explain all CRs?

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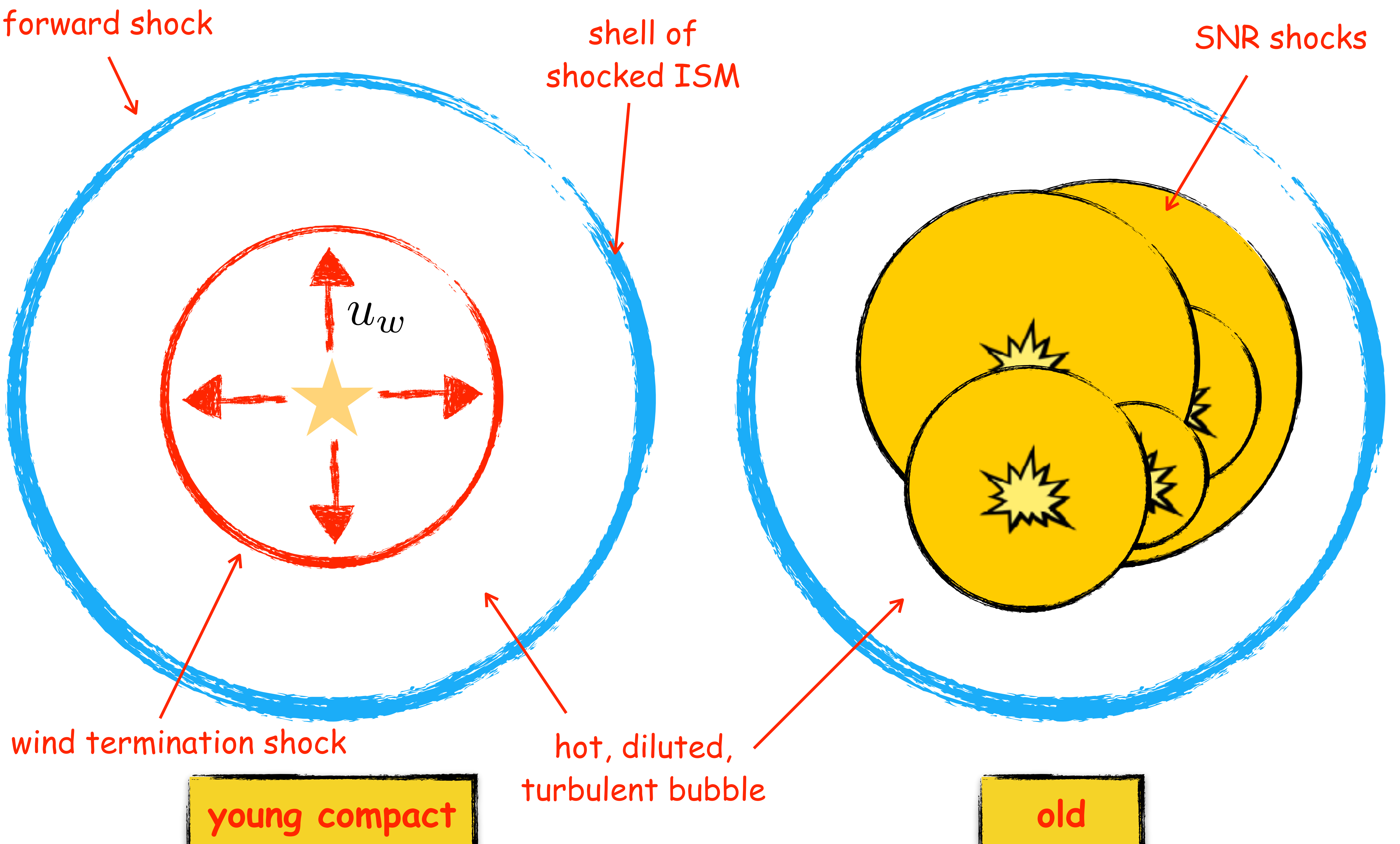

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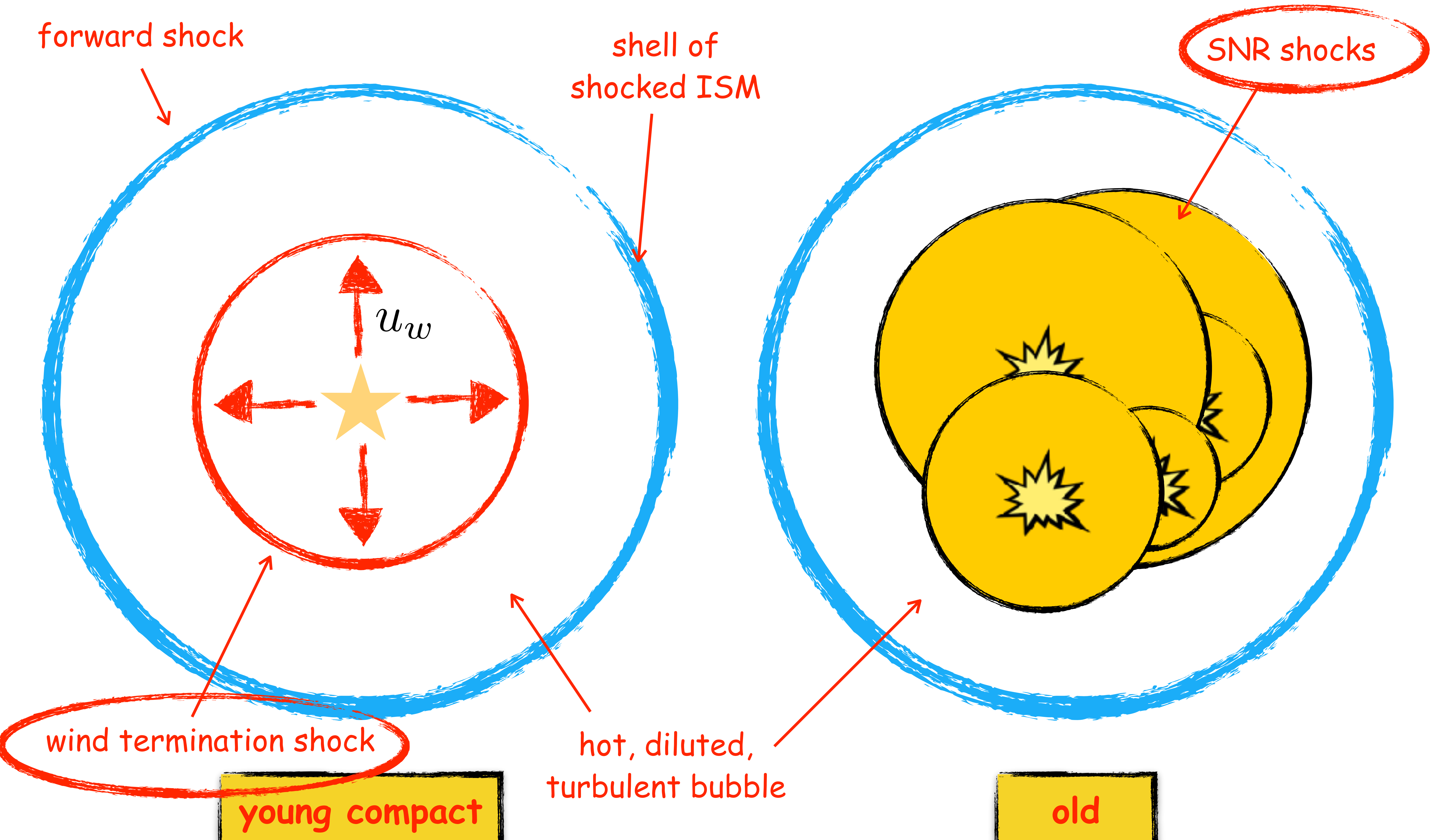

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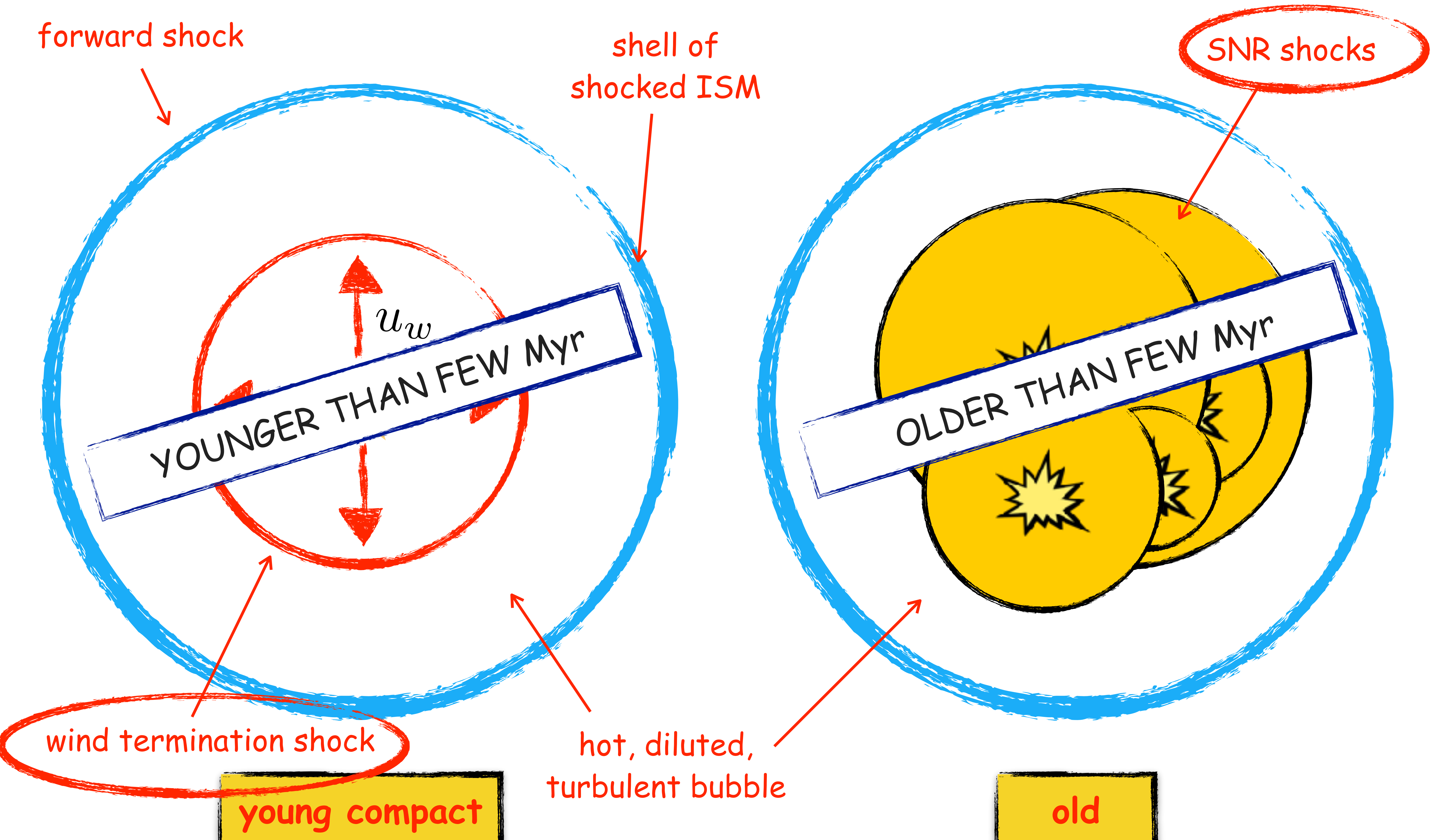
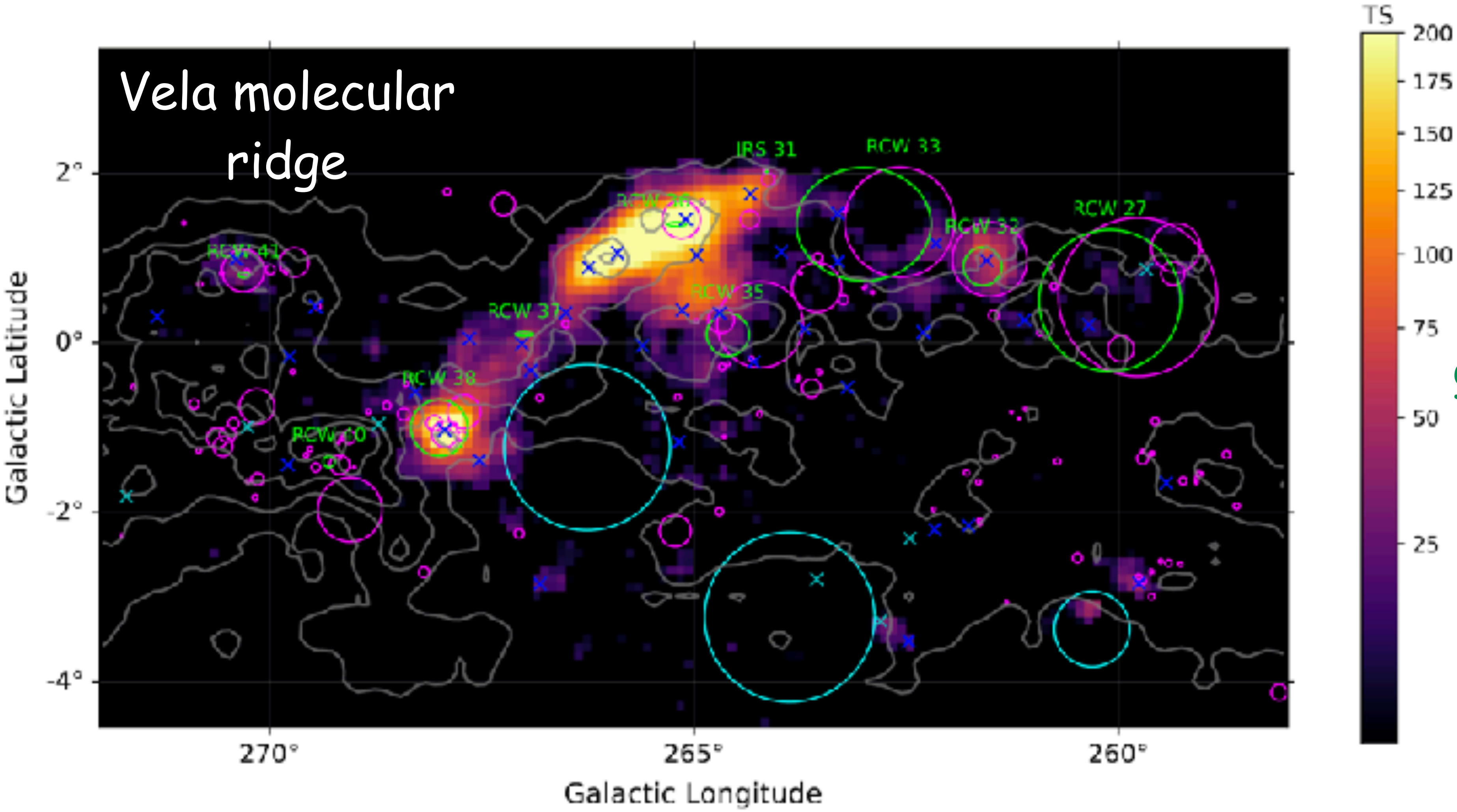


Yes, wind termination shocks do accelerate cosmic rays

see talk by Peron, this afternoon



grey —> gas

color —> gamma

green/purple —> HII regions

Peron+, Nature Astronomy, 2024

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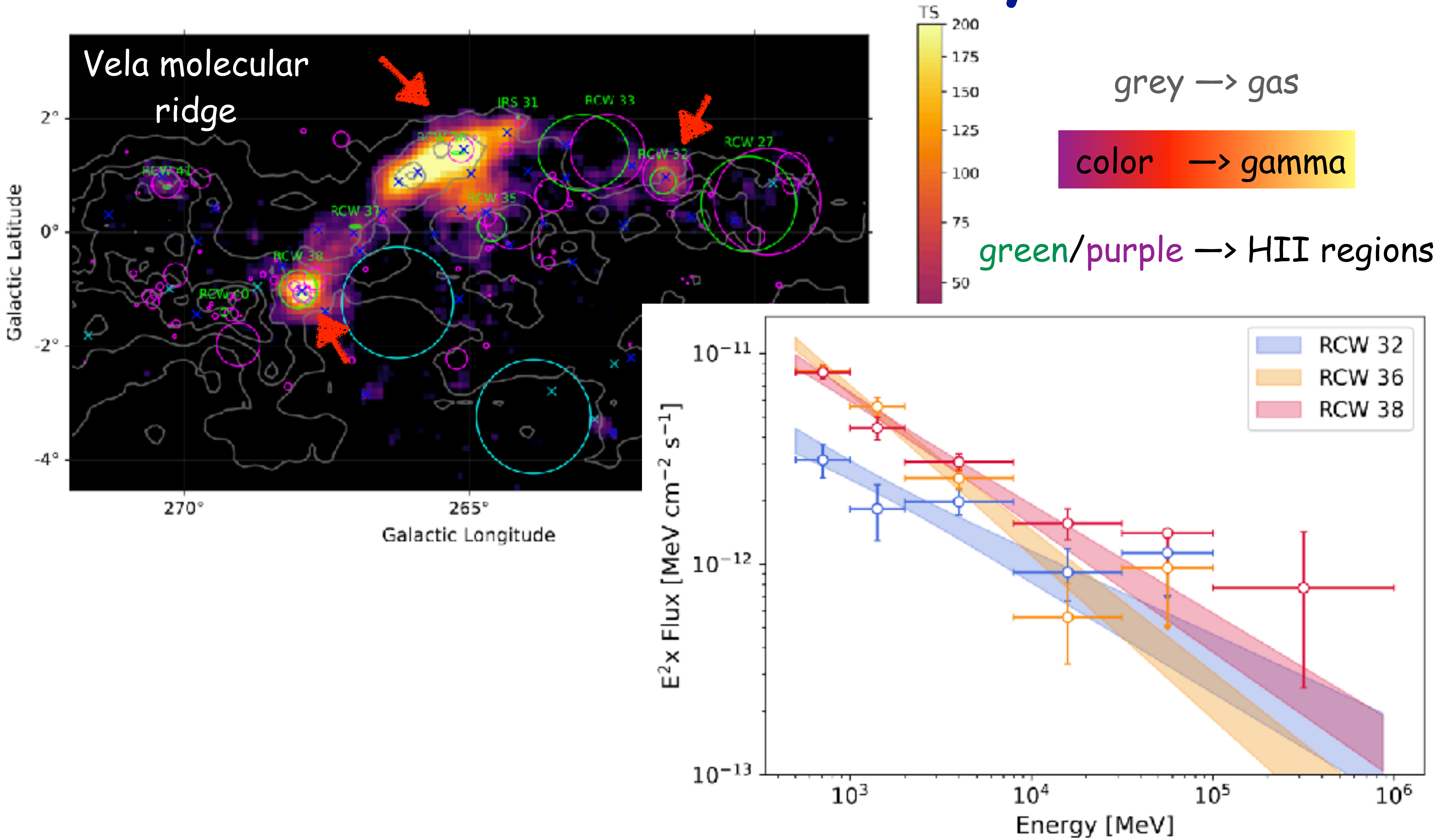

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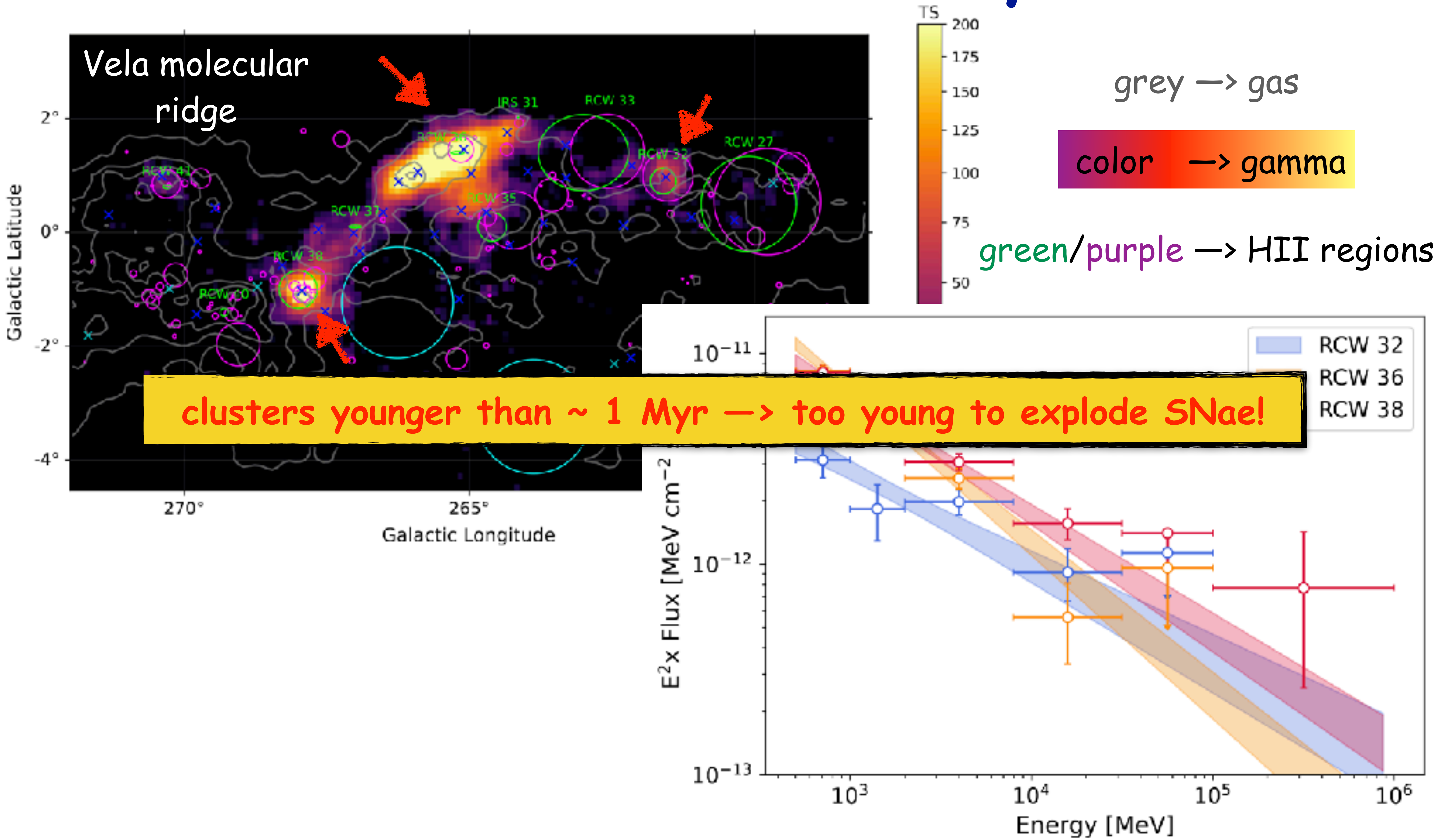

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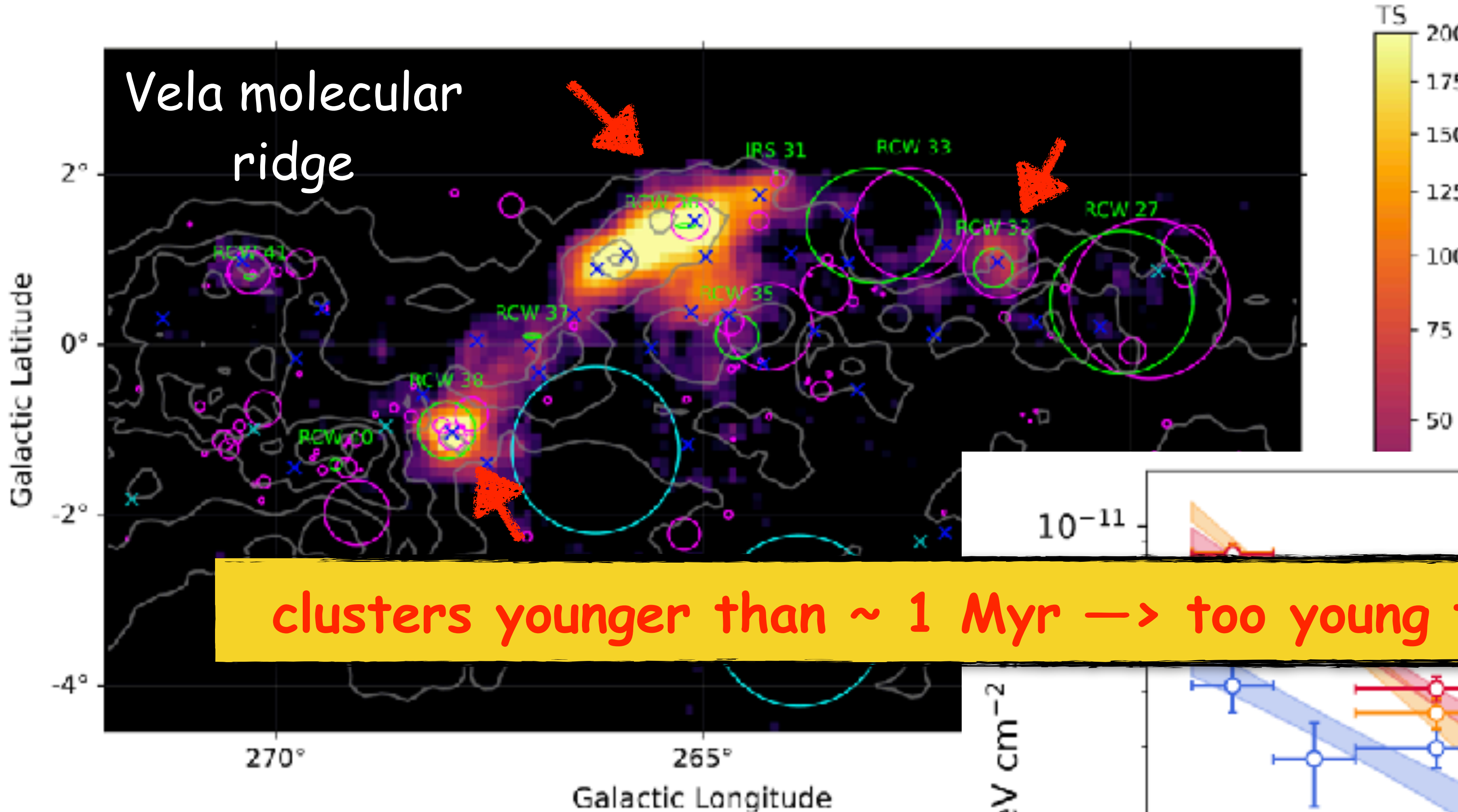

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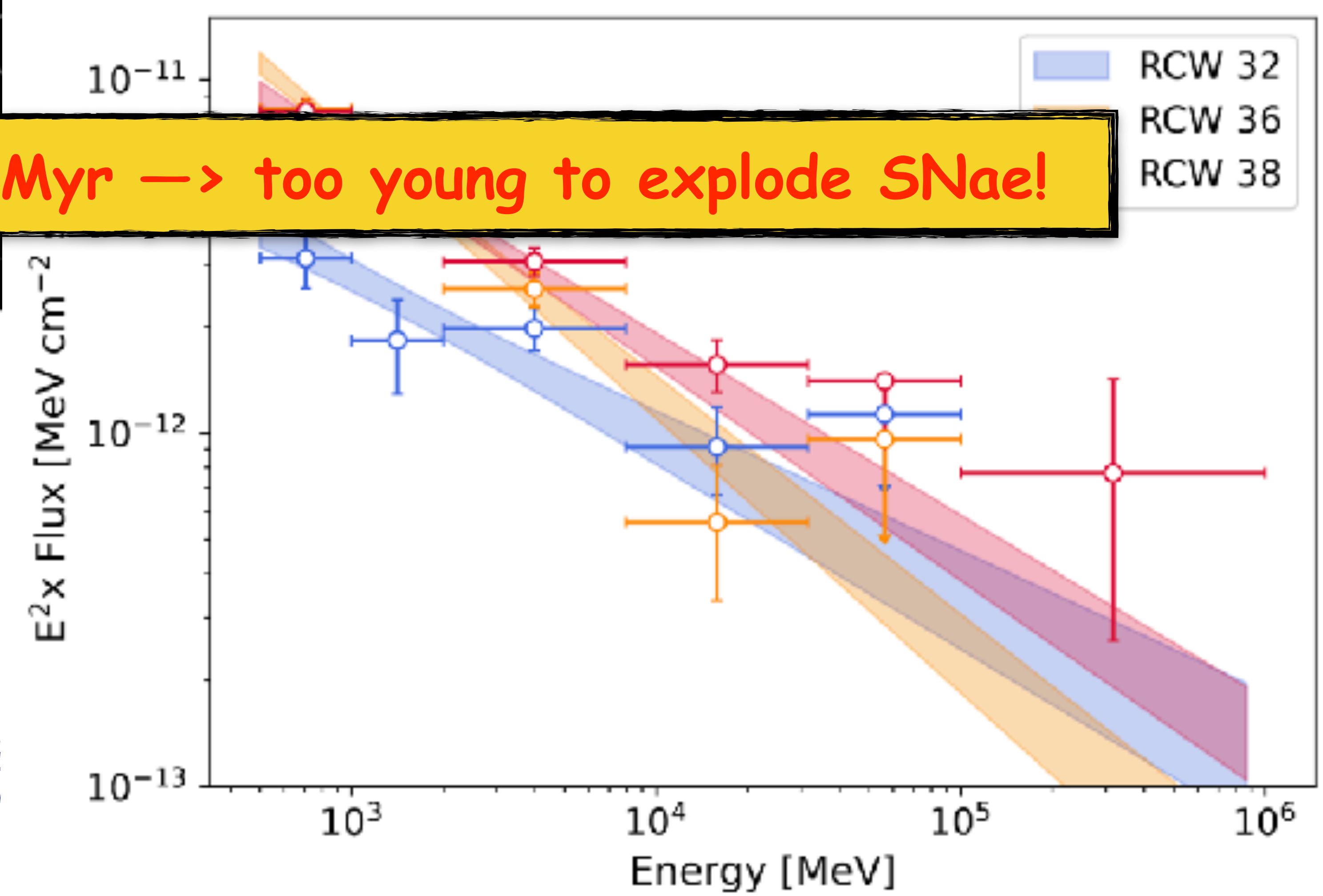
clusters younger than ~ 1 Myr —> too young to explode SNae!



strict lower bound on the CR acceleration efficiency (energy)

$$\eta_{CR} > 1\%$$

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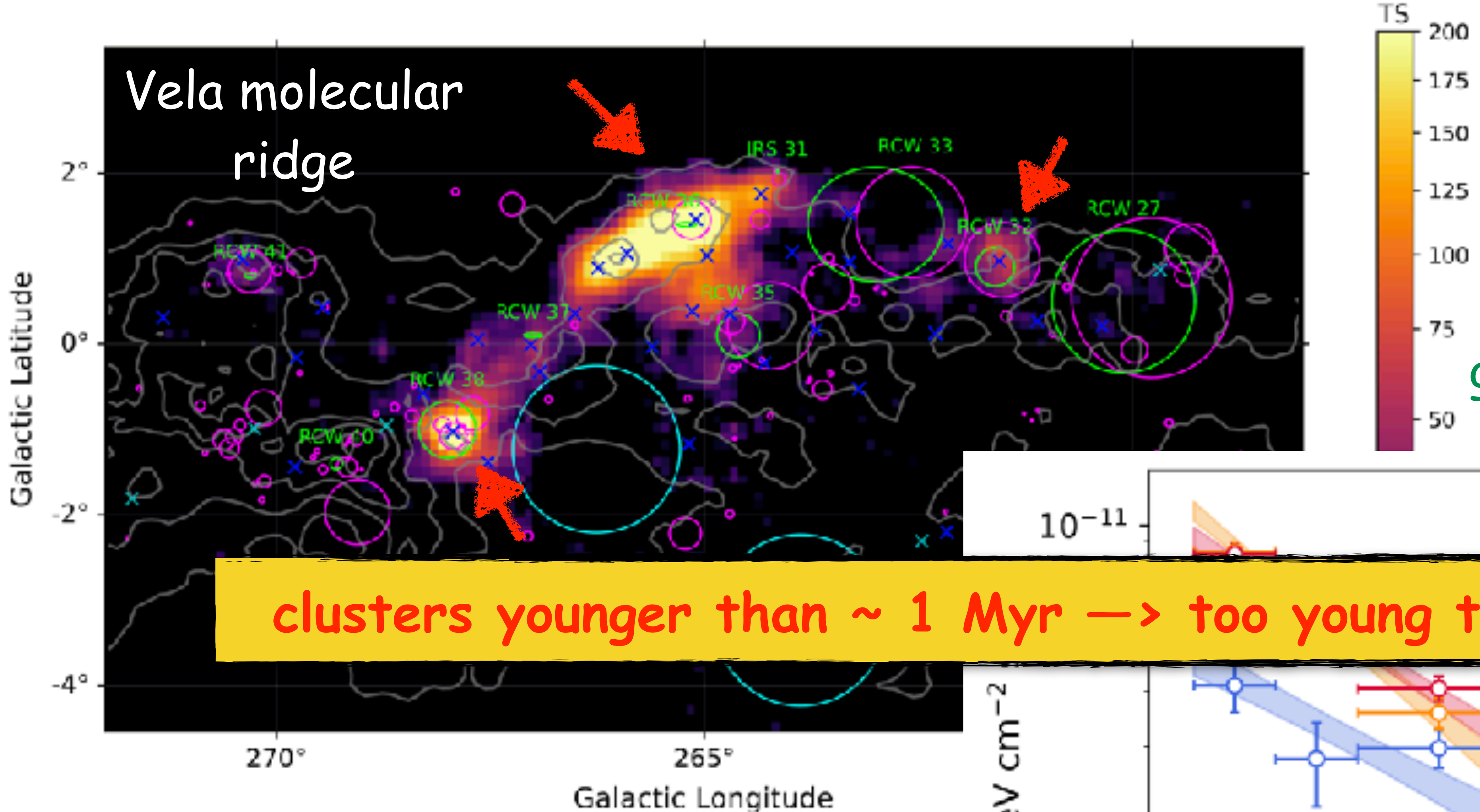

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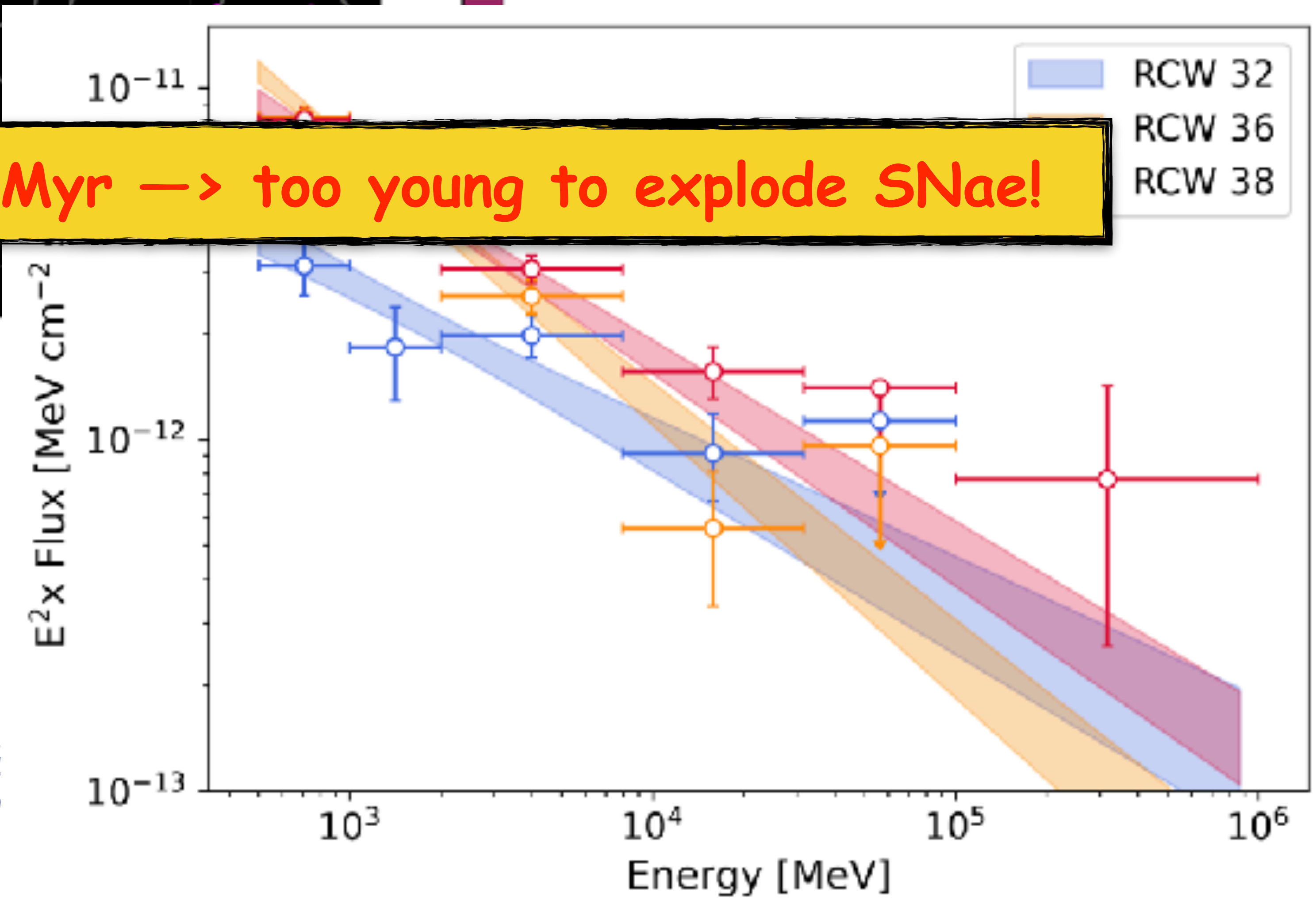

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fraction of CRs coming from stellar winds

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Peron+, Nature Astronomy, 2024

The X = $^{22}Ne/^{20}Ne$ ratio can be explained!

$$X_{CR} \sim \eta_w X_w + (1-\eta_w) X_S \sim 0.09 > X_S$$

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isotopic ratio
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Solar/interstellar isotopic ratio

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isotopic ratio in CRs

isotopic ratio in winds (corrected for CR efficiency)

Solar/interstellar isotopic ratio

accurate analysis of CR abundances (Tatischeff+ 2021) —> ~6%

Conclusions: mixed origin for CRs?

- Supernova remnants may still provide most CRs —> **follow the energy!**
- Star clusters accelerate CRs (we see gamma rays!)
- YOUNG star clusters accelerate CRs —> gammas from WTSs!
- Stellar winds must play a role (^{22}Ne) —> **follow the mass!**
- Passive (polluters) and/or active (accelerators) role?
- All CRs from star clusters? —> **follow the physics!**
  - Most of them from SNR inside super bubbles (abundance of CR volatiles)
  - Provided dust grains are present inside super bubbles (CR refractories)
  - Some of them from WTSs (^{22}Ne)