Galactic cosmic rays

Stefano Gabici
APC, Paris

Plan of the talk

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

[2] The **cosmic ray knee**: before and after LHAASO

[3] Can **the SNR paradigm** explain the knee (and beyond)?

[4] The role of **winds of massive stars** —> mixed scenarios?

[5] Explaining the knee is a problem also for stellar winds

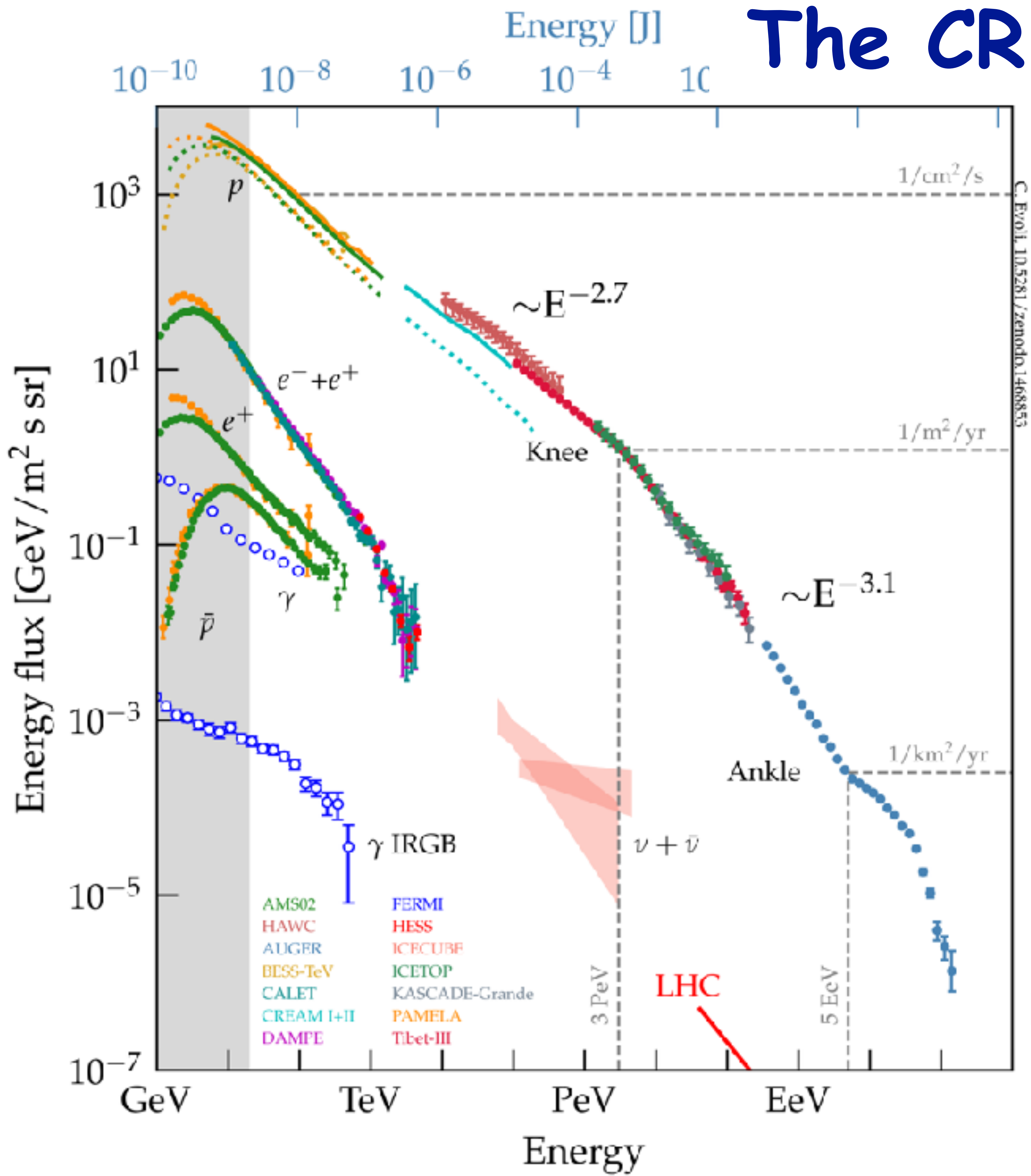
[6] **Cosmic rays from star clusters**: observational evidences

[7] Conclusions

[8] 1 future perspective and 1 puzzle

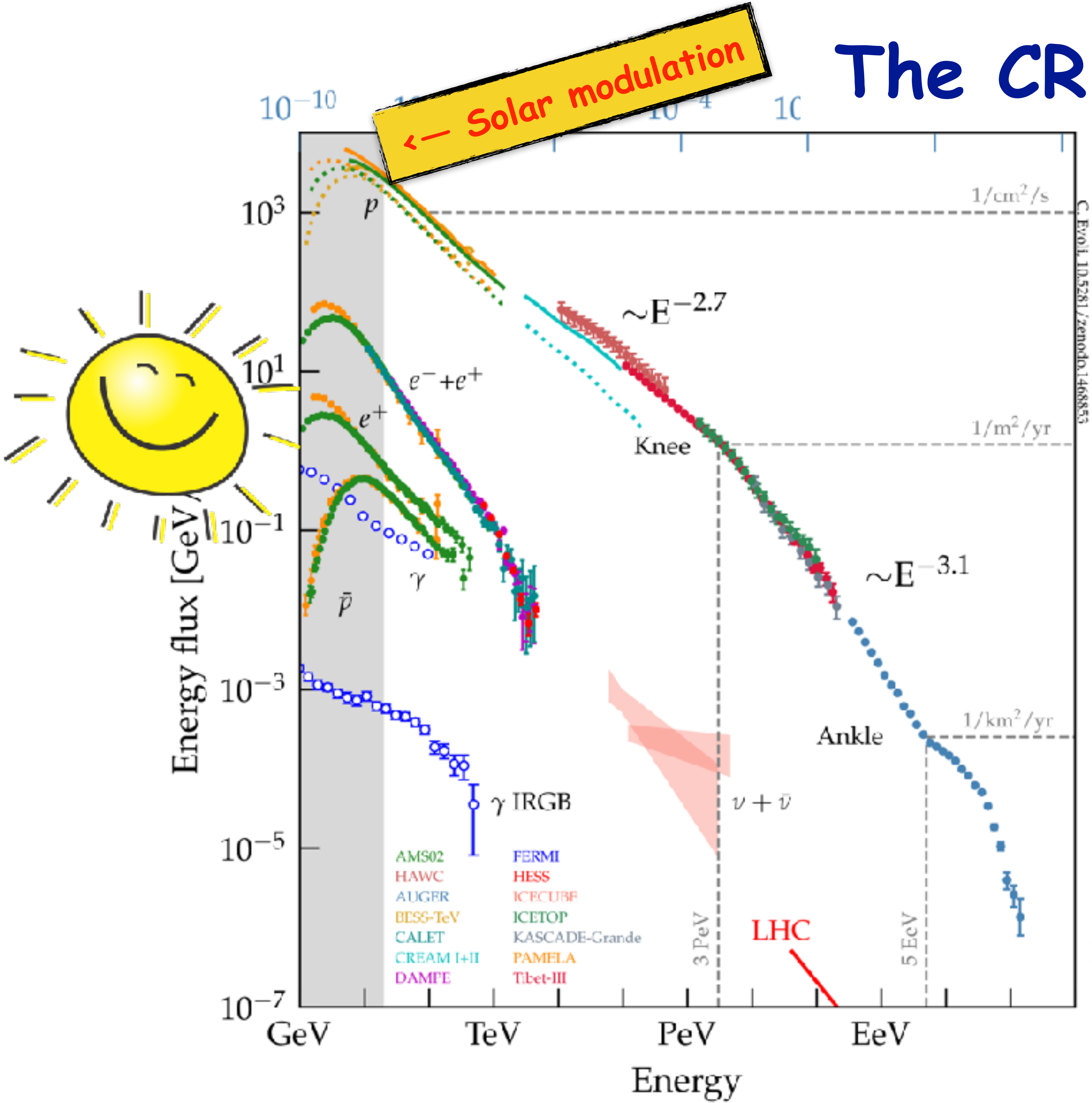
[1] What are cosmic rays and why we study them

The CR spectrum



Evoli's compilation

The CR spectrum



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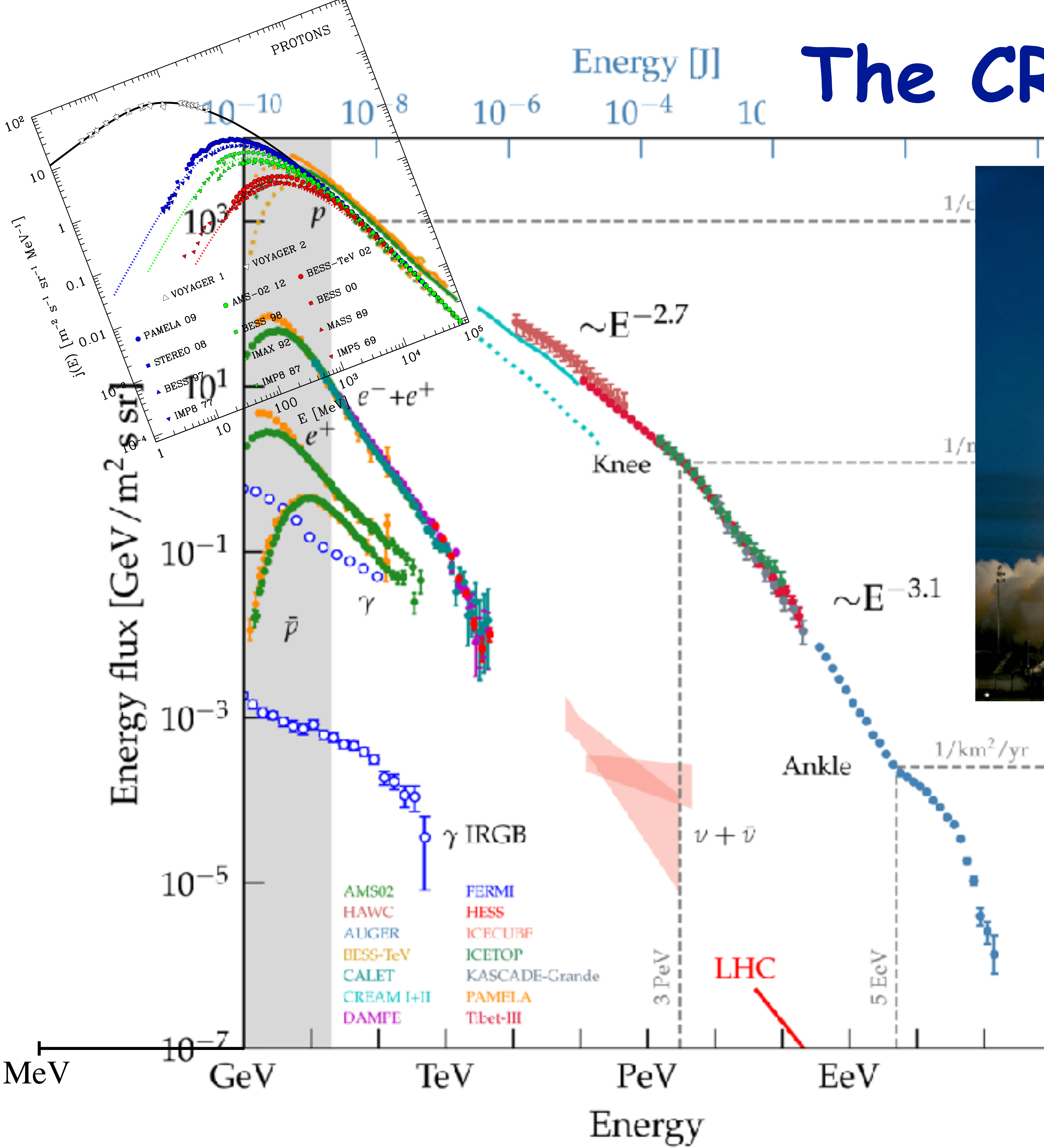

Voyager(s)

Evoli's compilation

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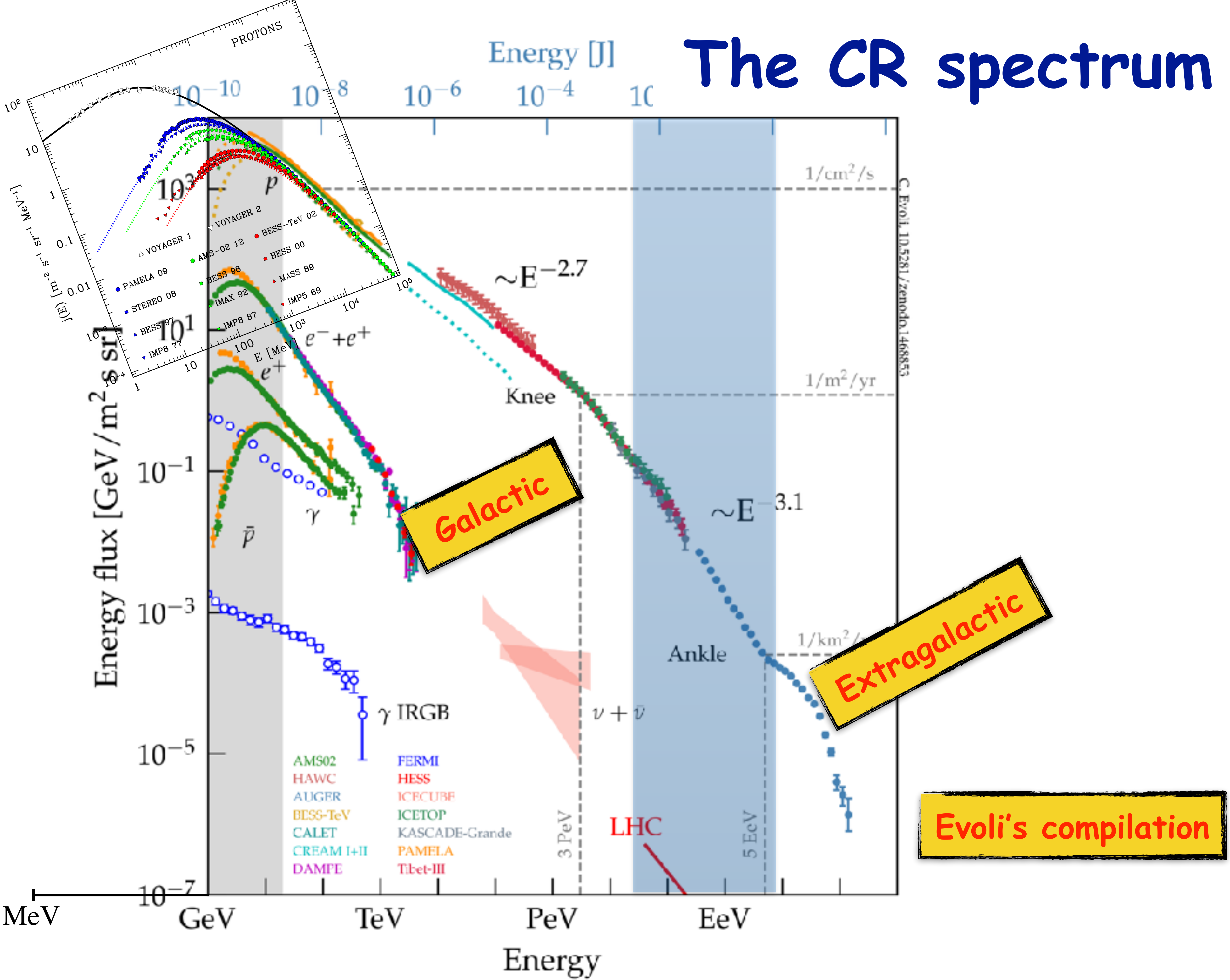

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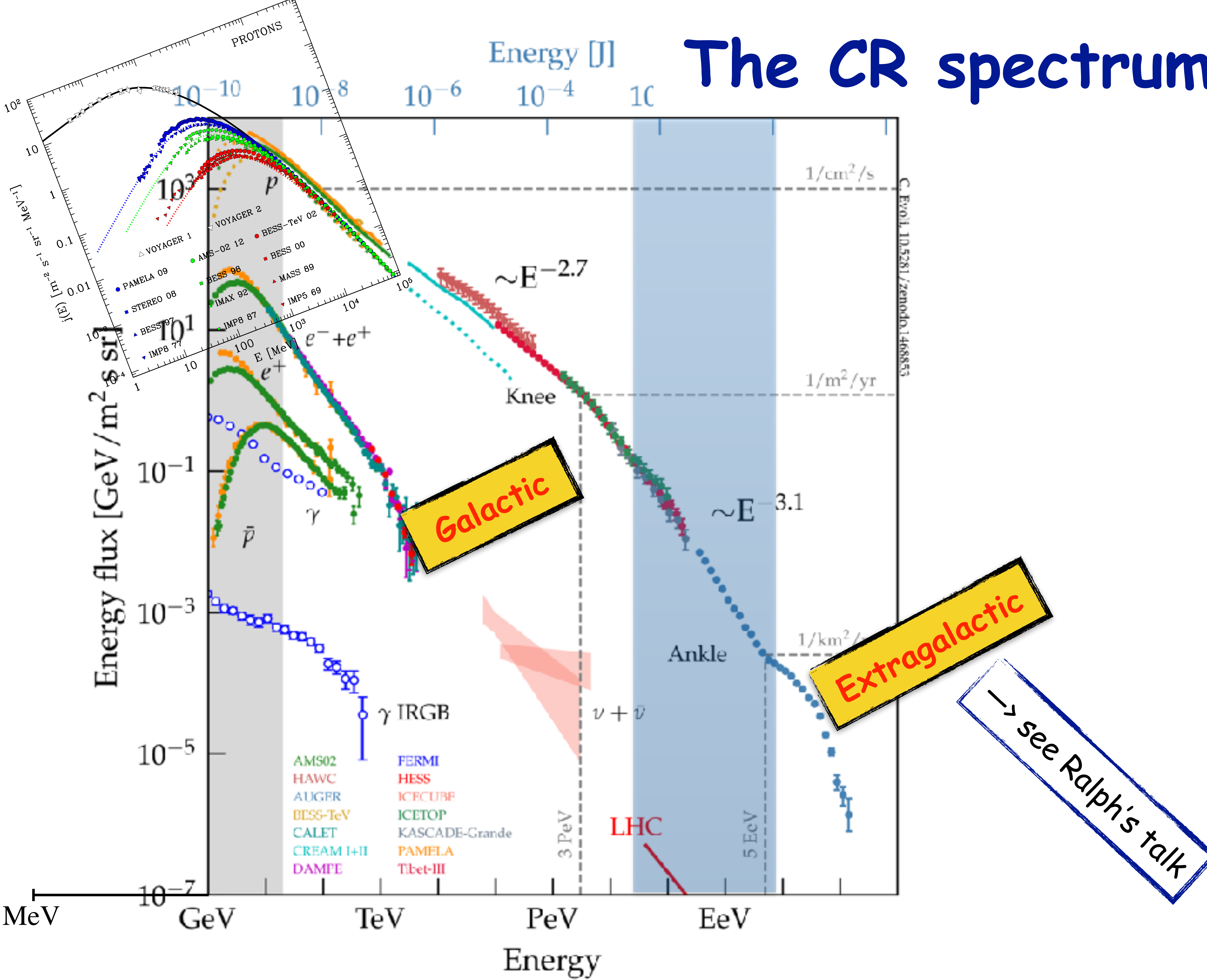

Luke's questions

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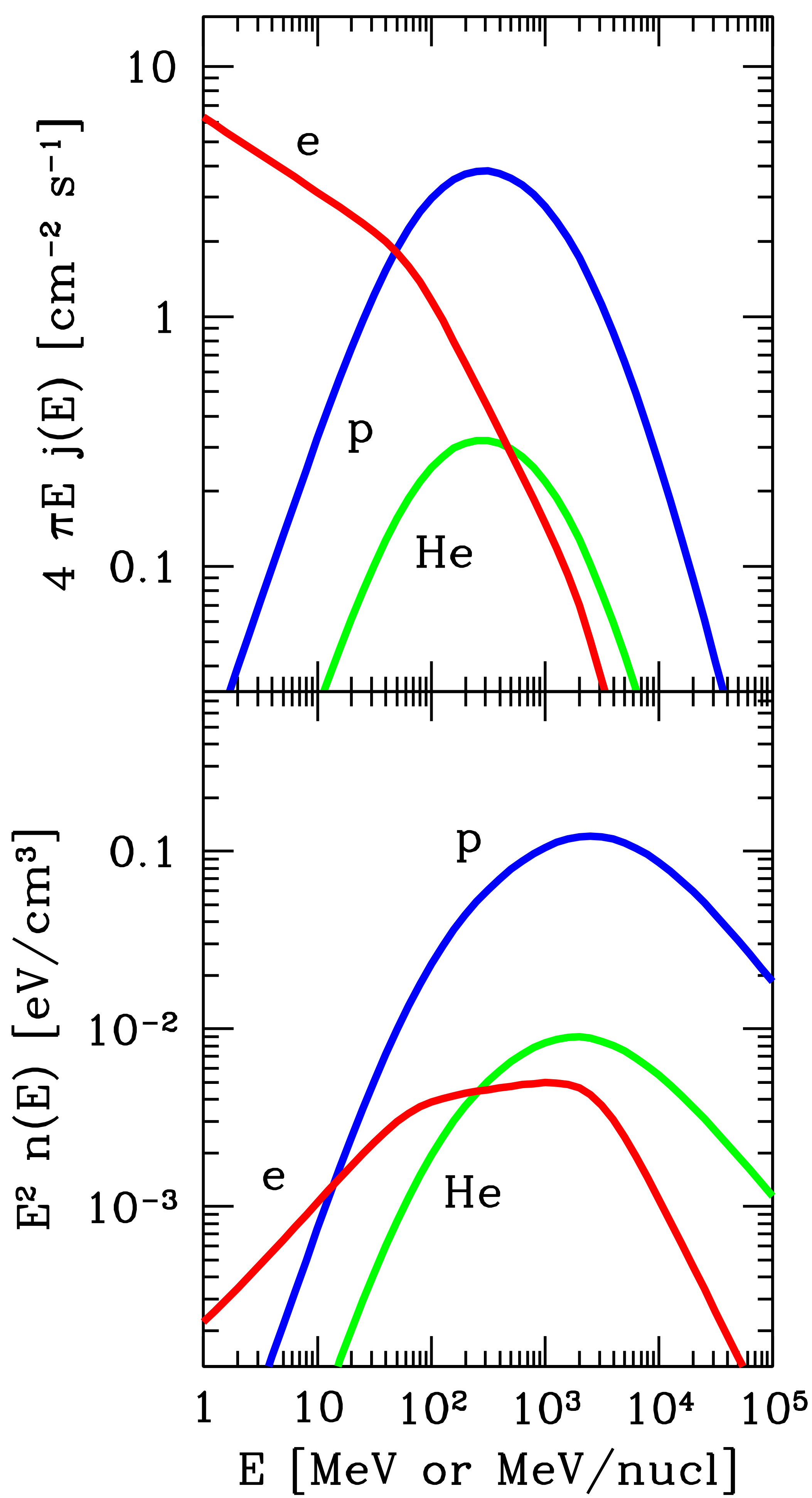
These are actually three different questions which require different solution methods and answers, and some of the confusion in the field has been due to people not carefully distinguishing these concepts.

We study cosmic rays because…



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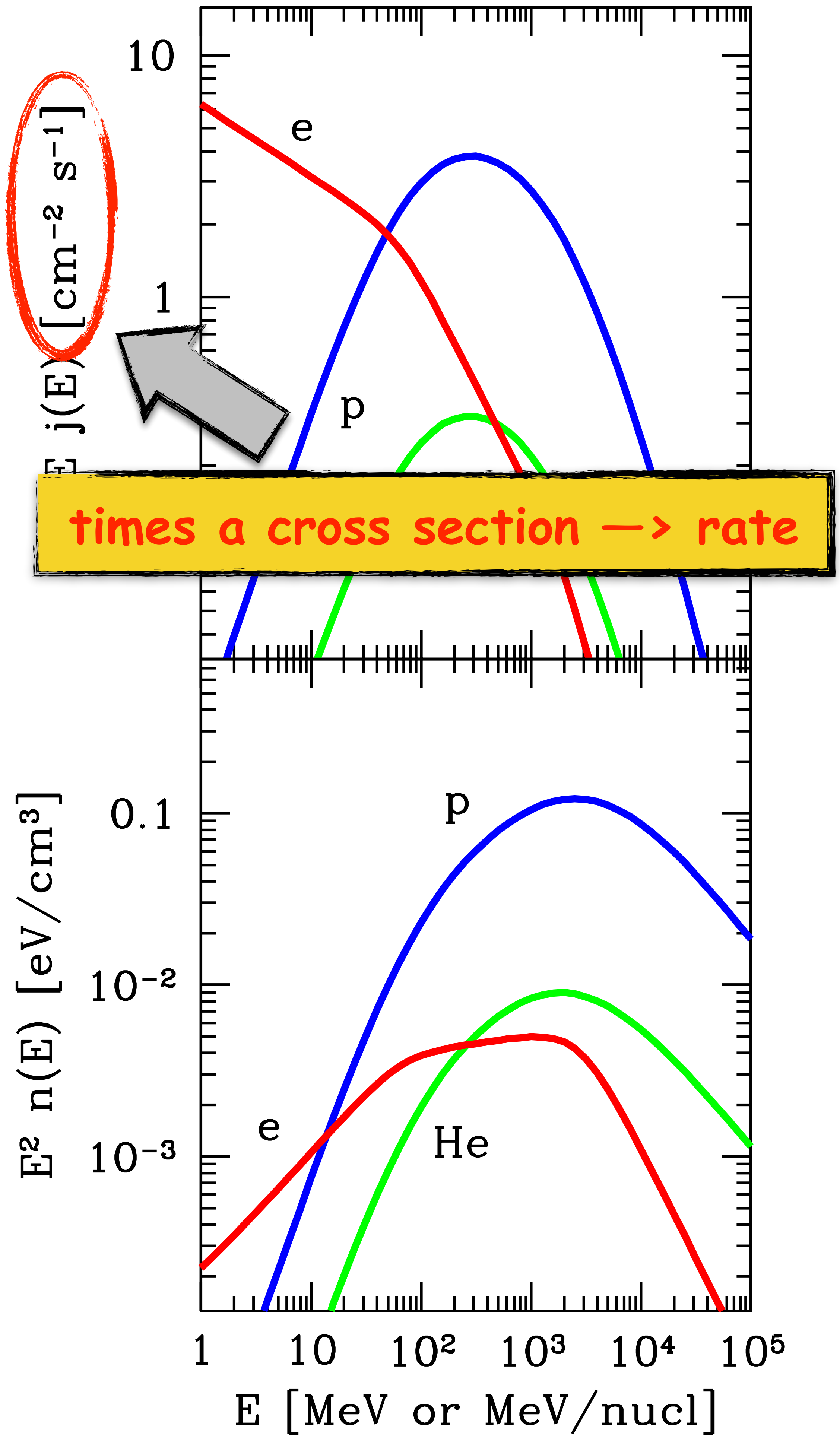

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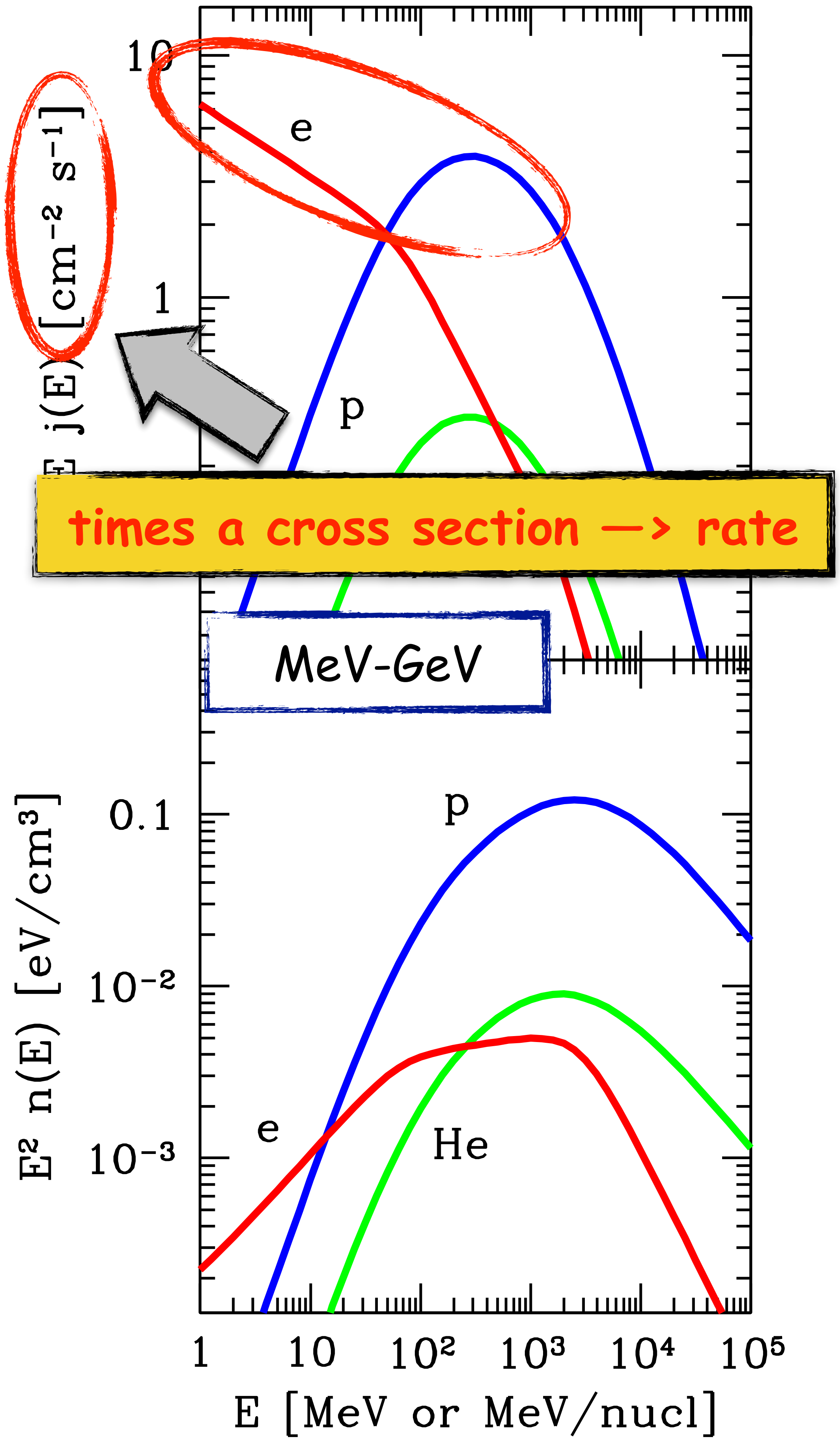
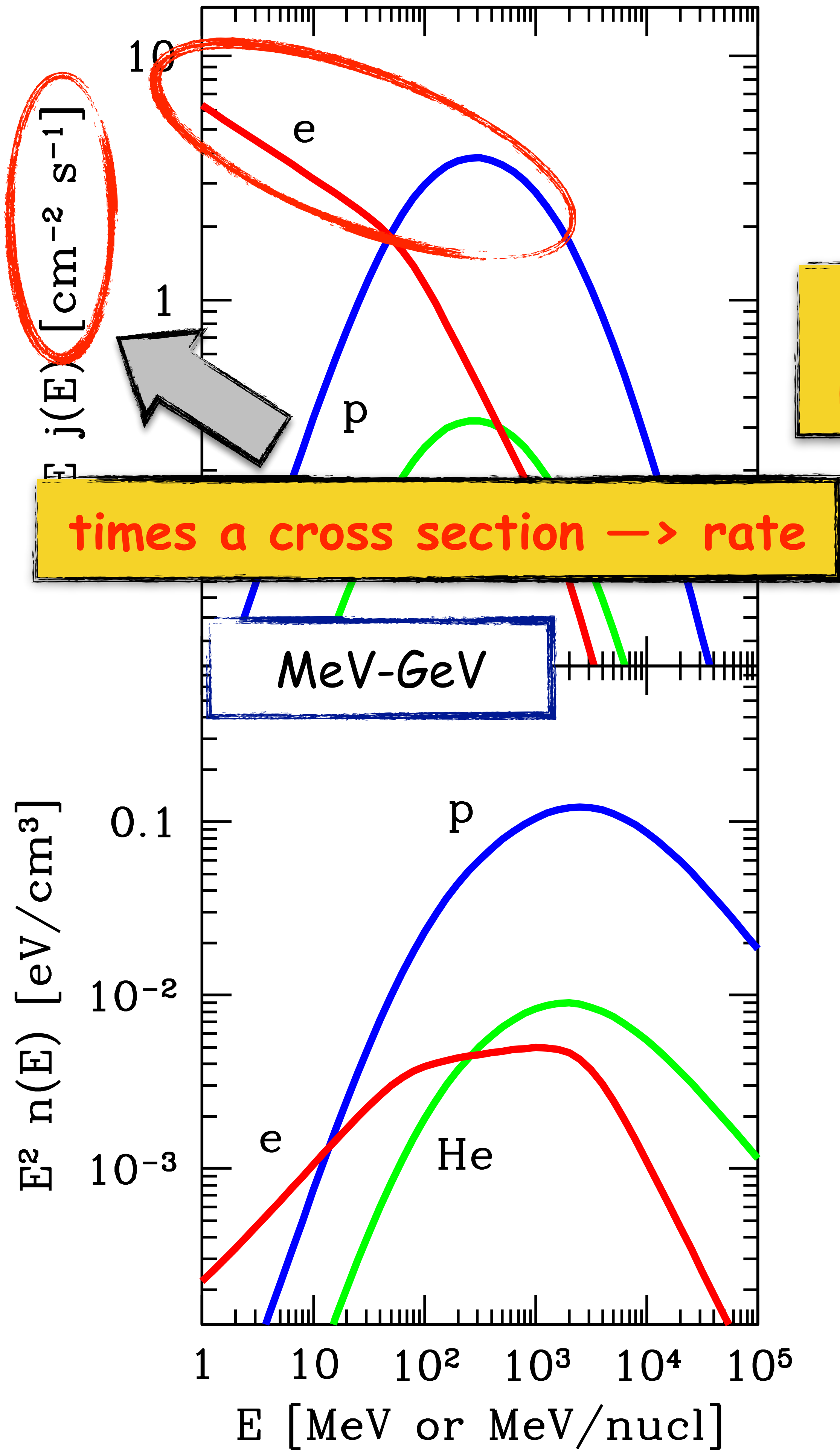


We study cosmic rays because…

impact on ISM and star formation: ionisation, heating, astrochemistry…



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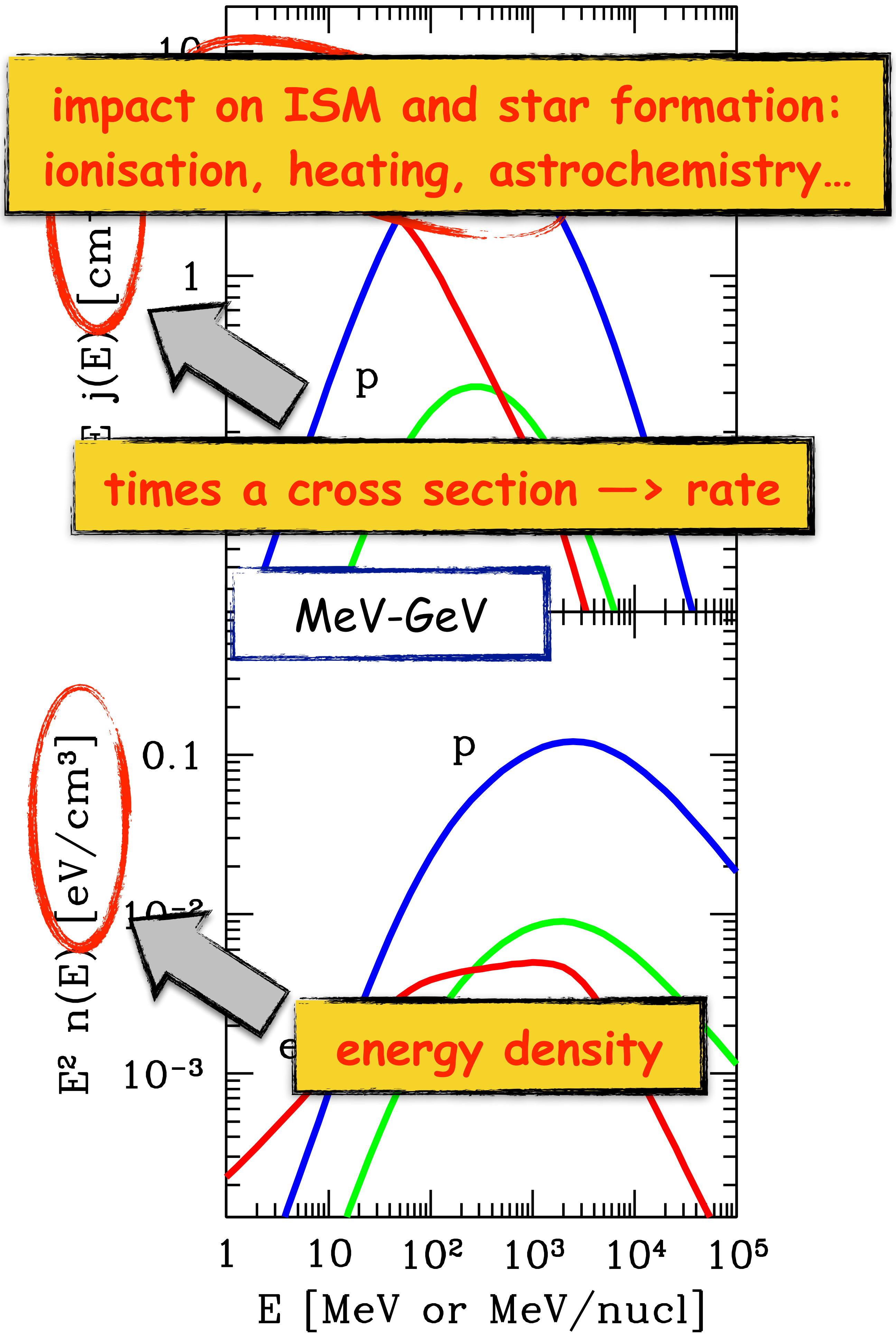

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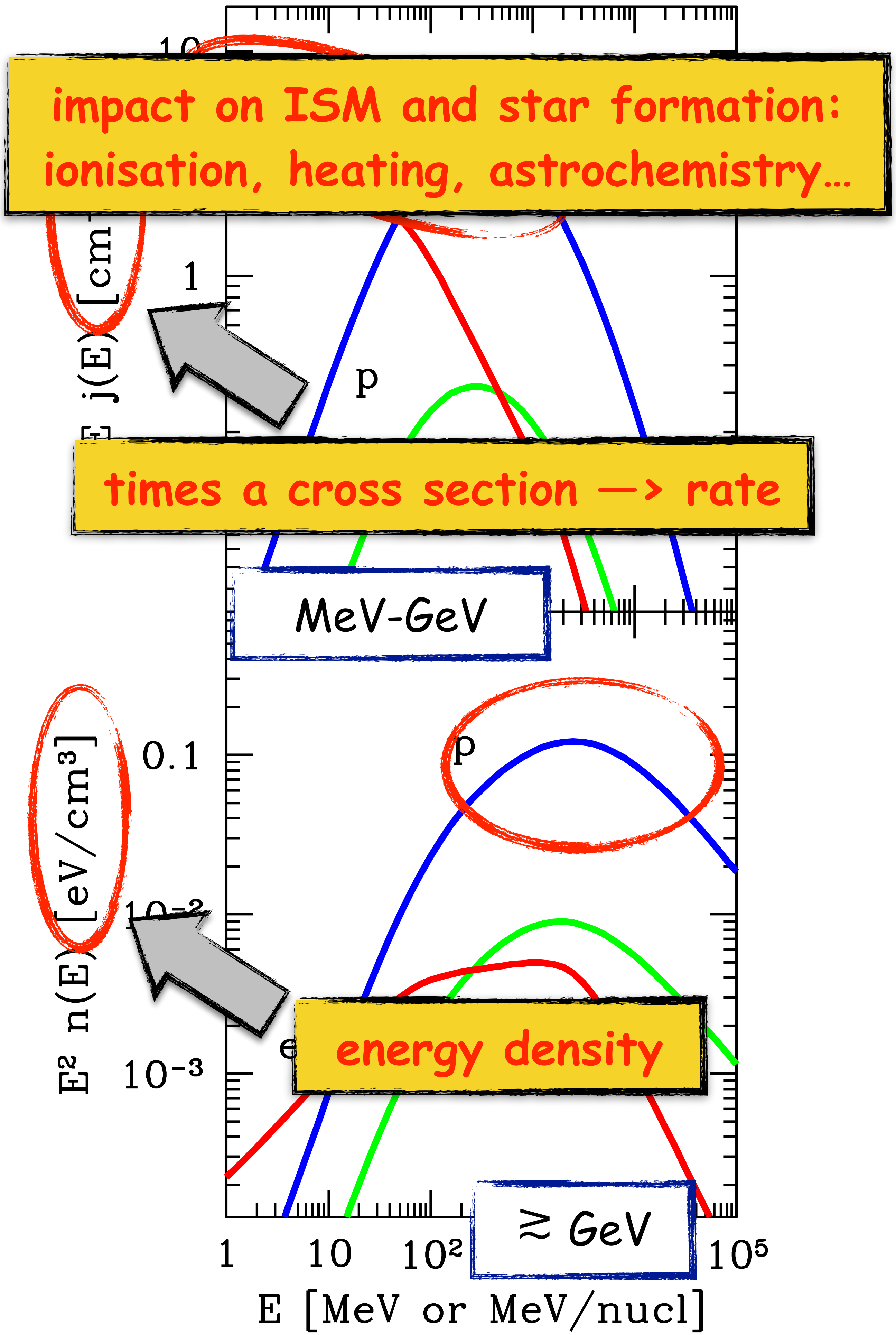

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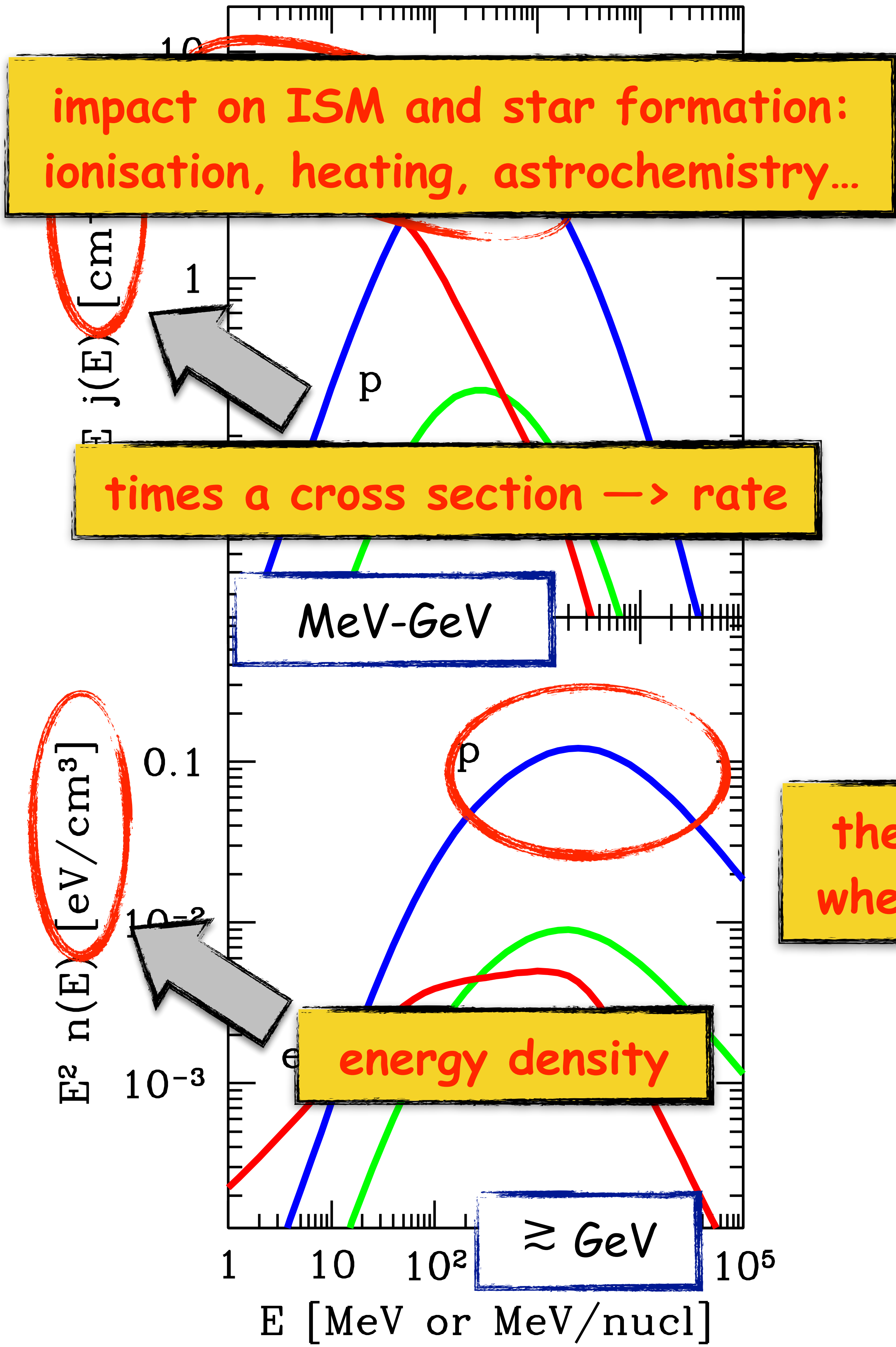
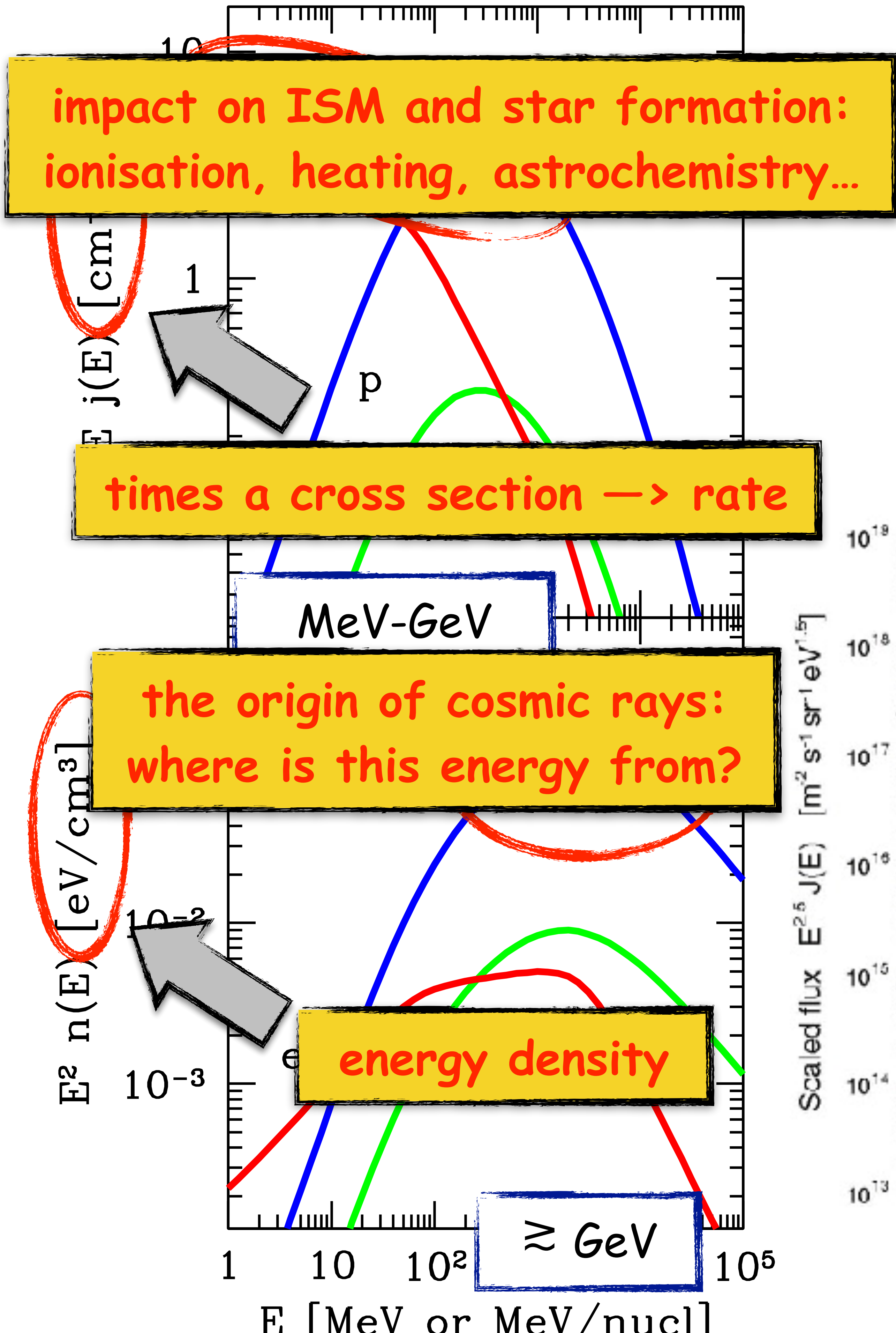
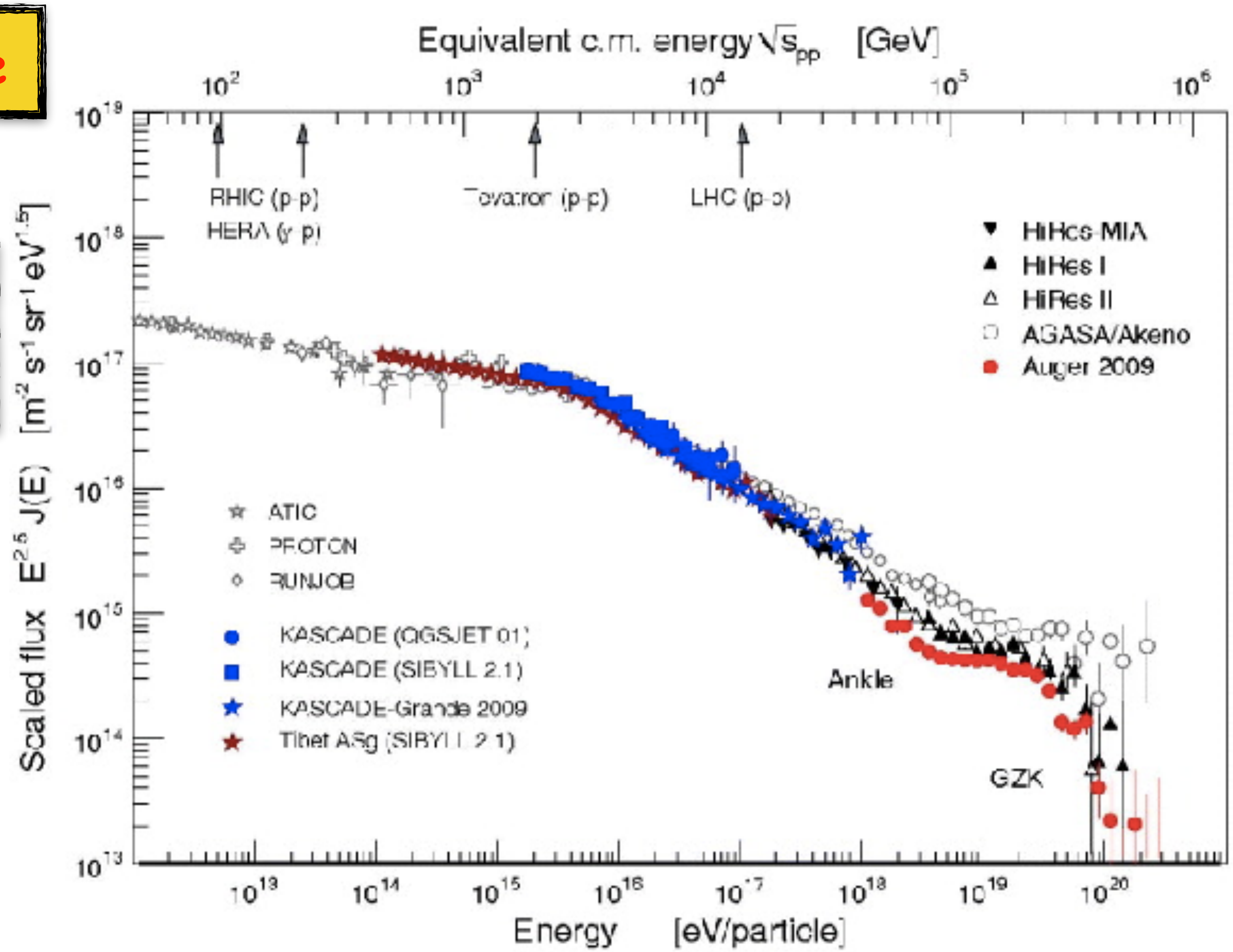


the origin of cosmic rays:
where is this energy from?

We study cosmic rays because…





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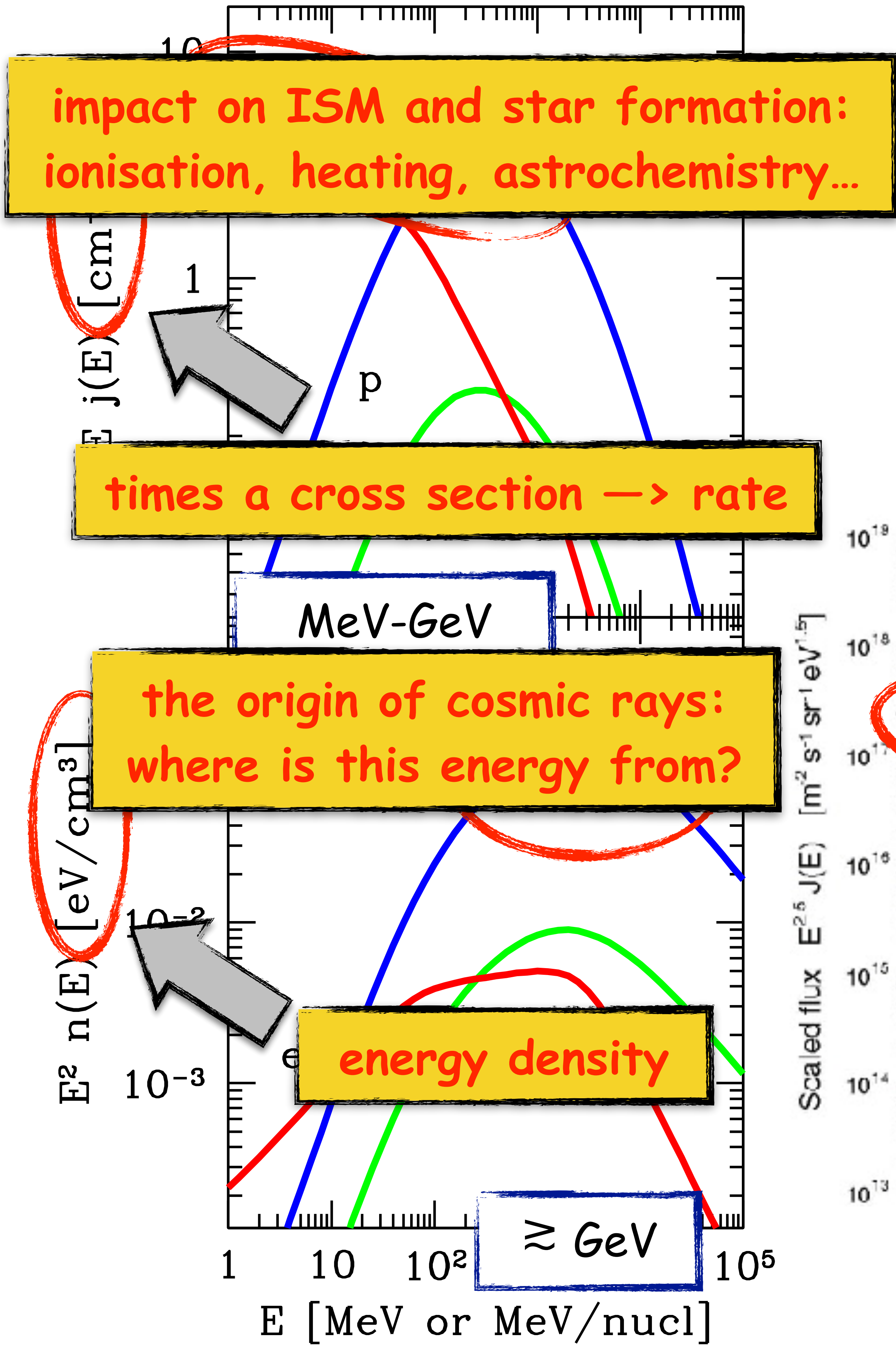

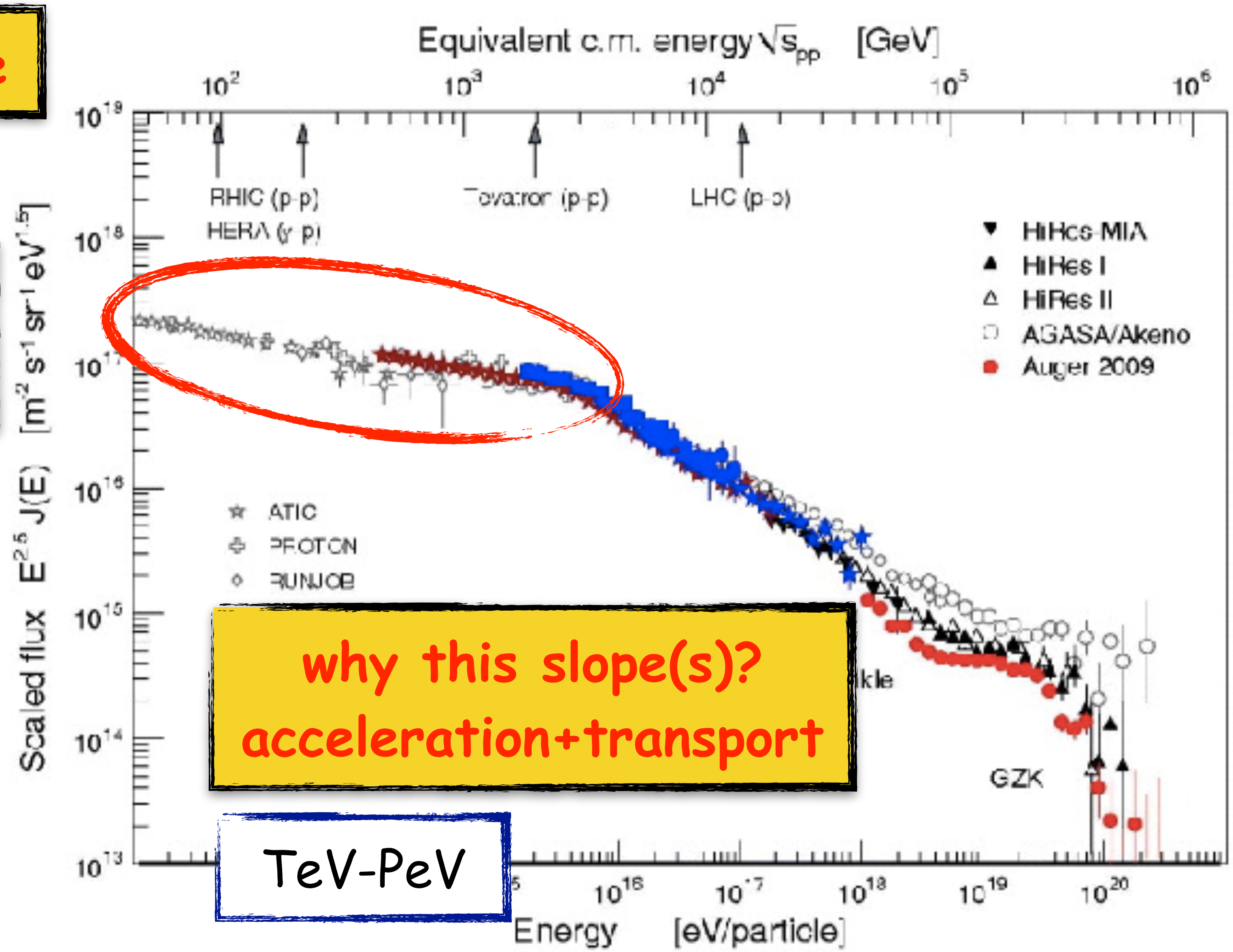

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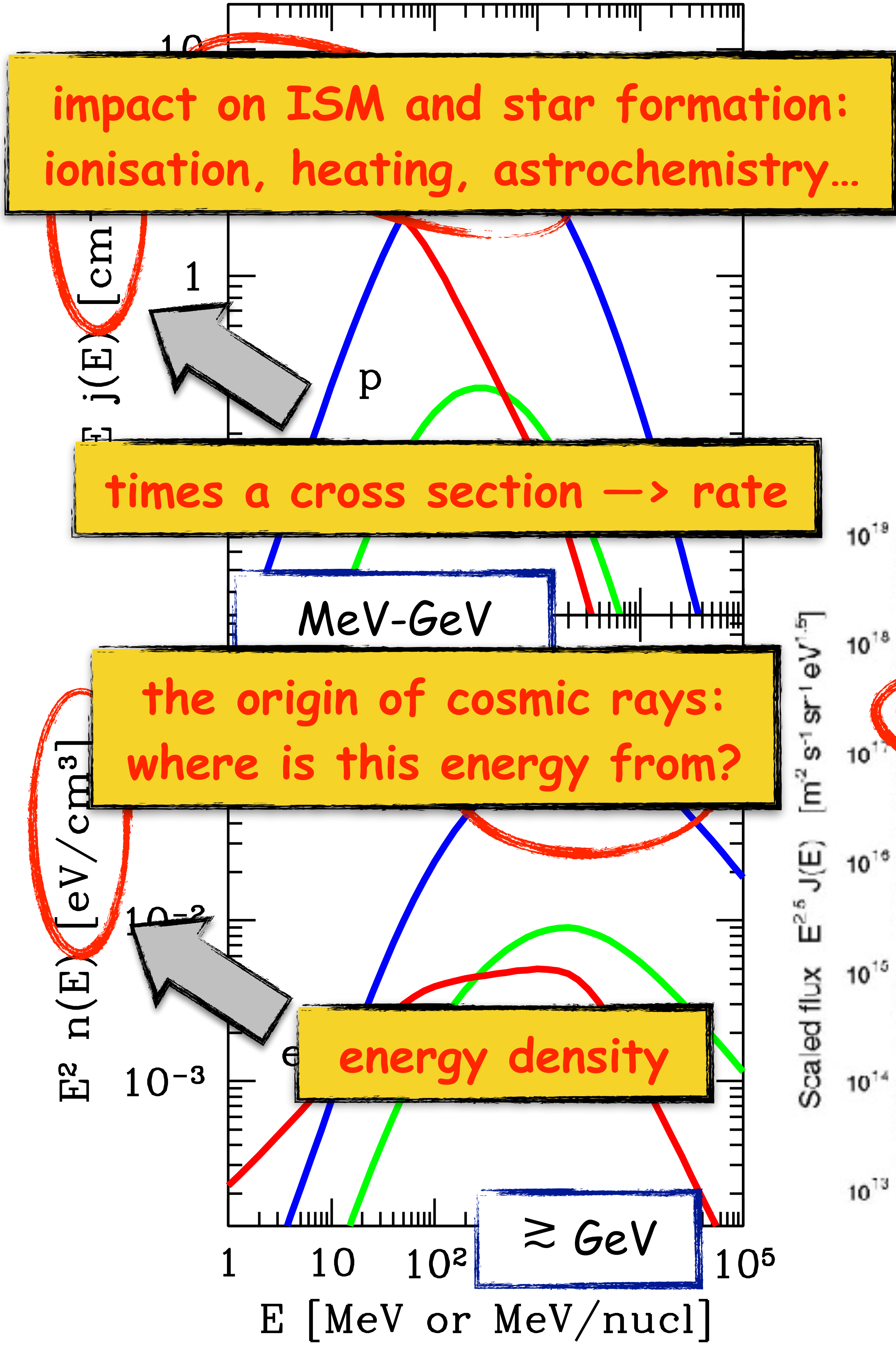

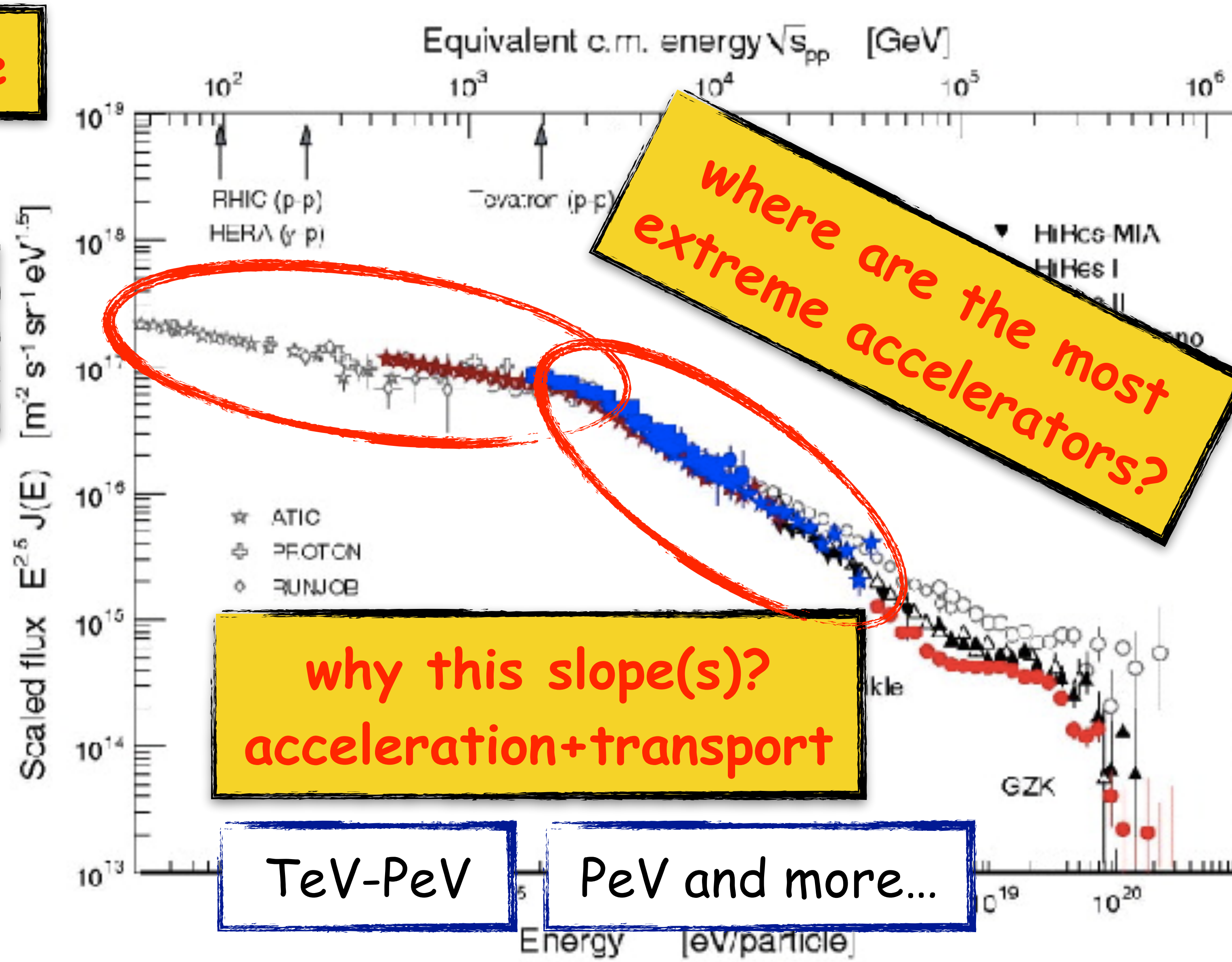

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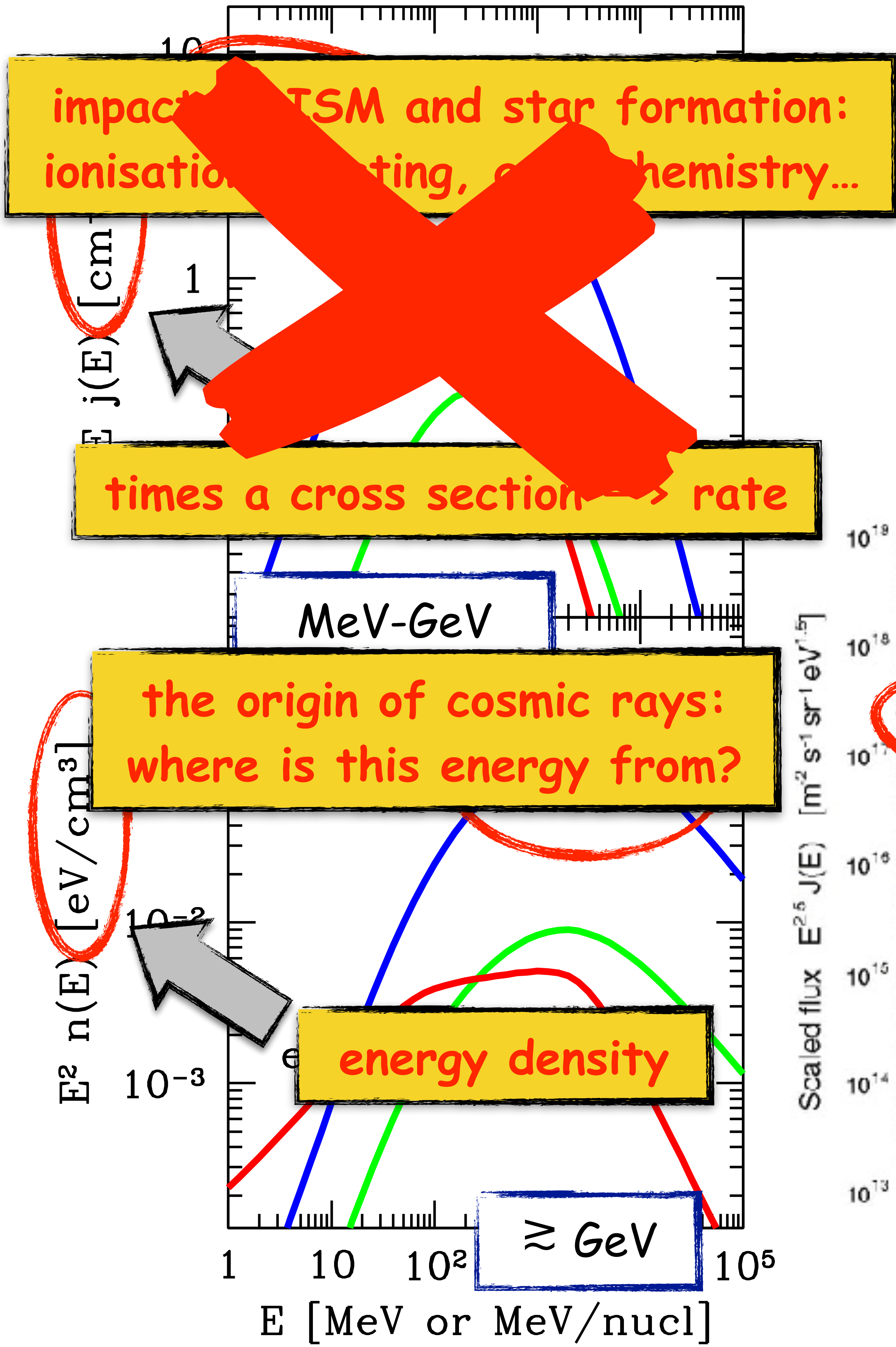

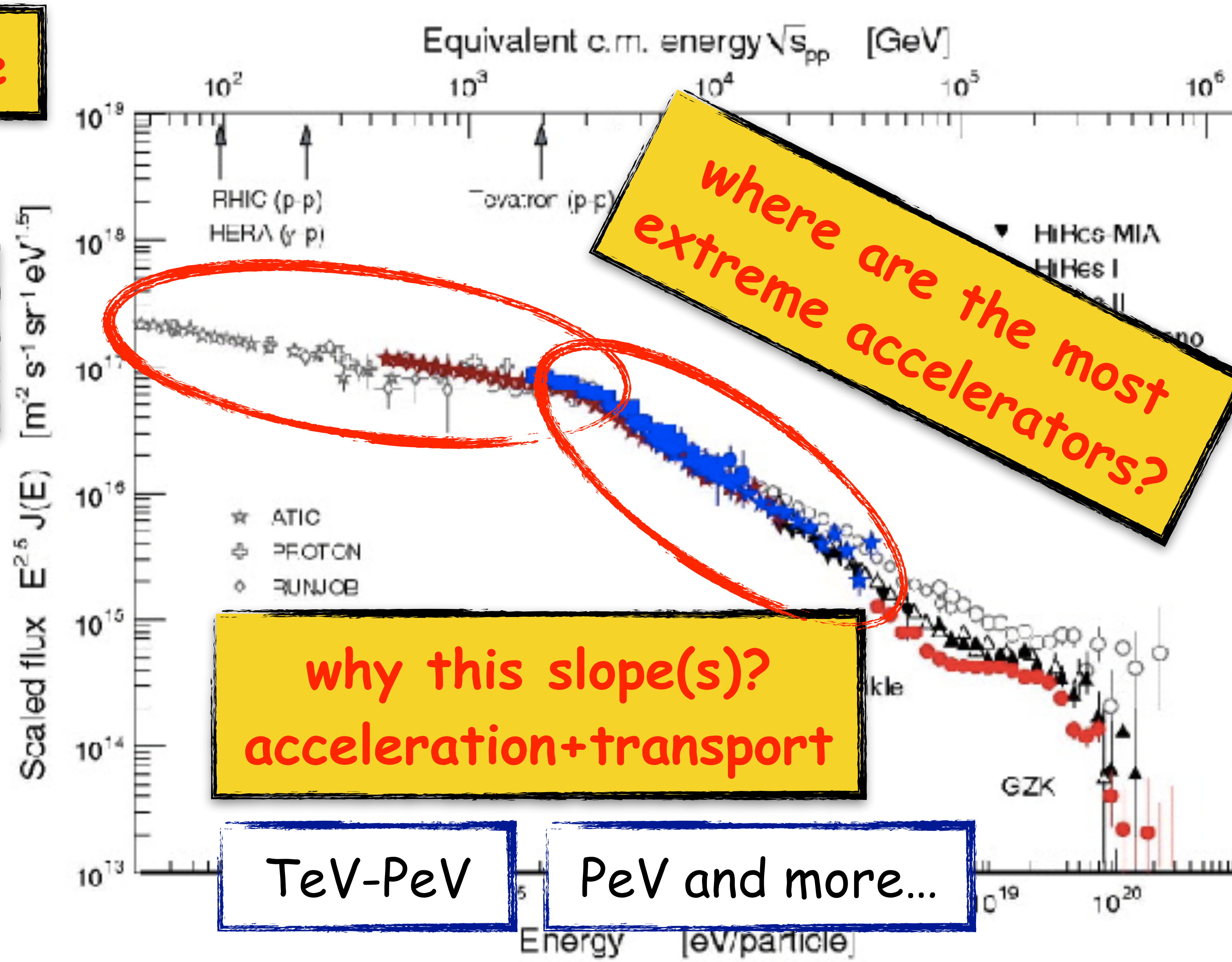

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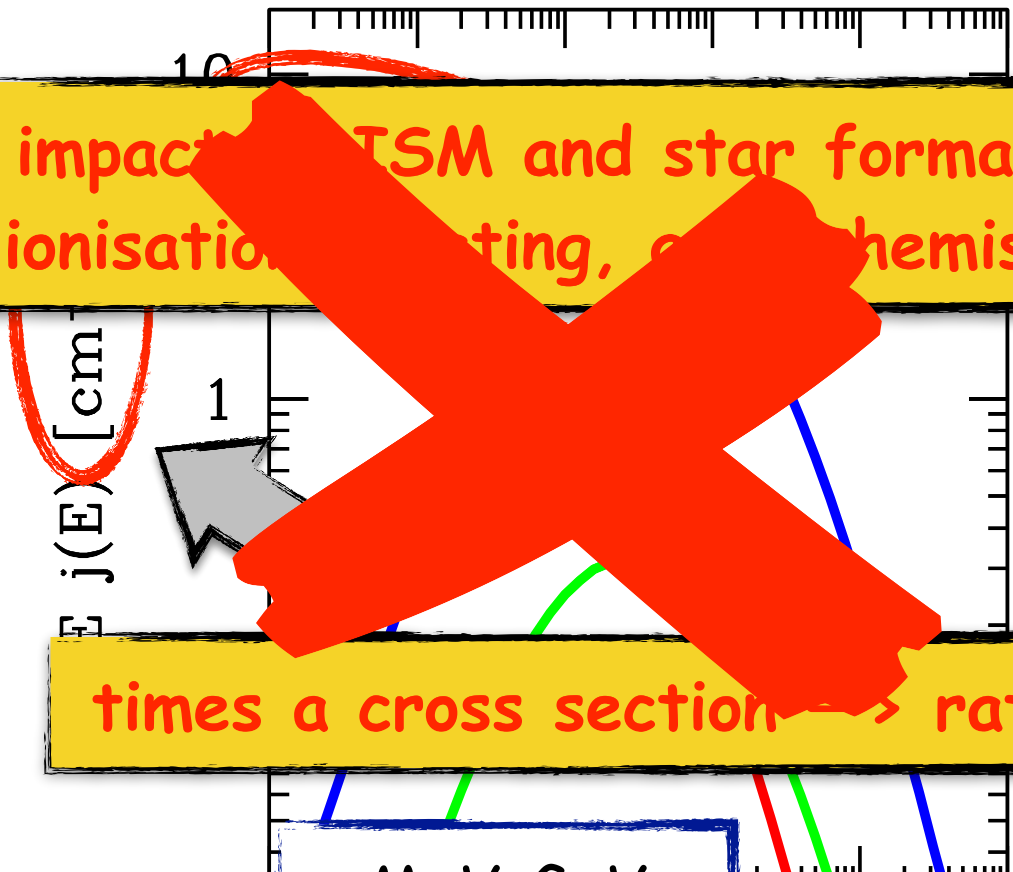
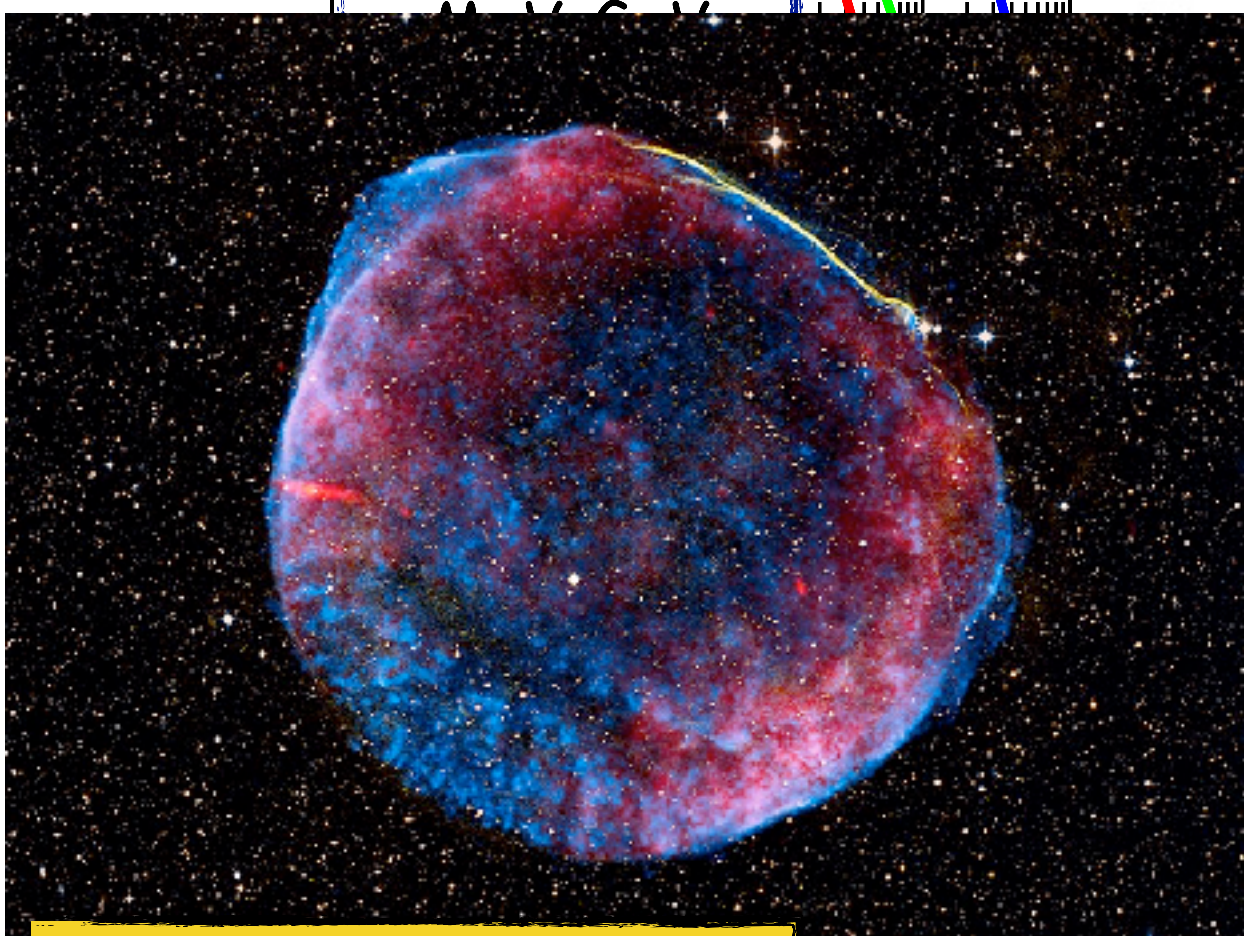
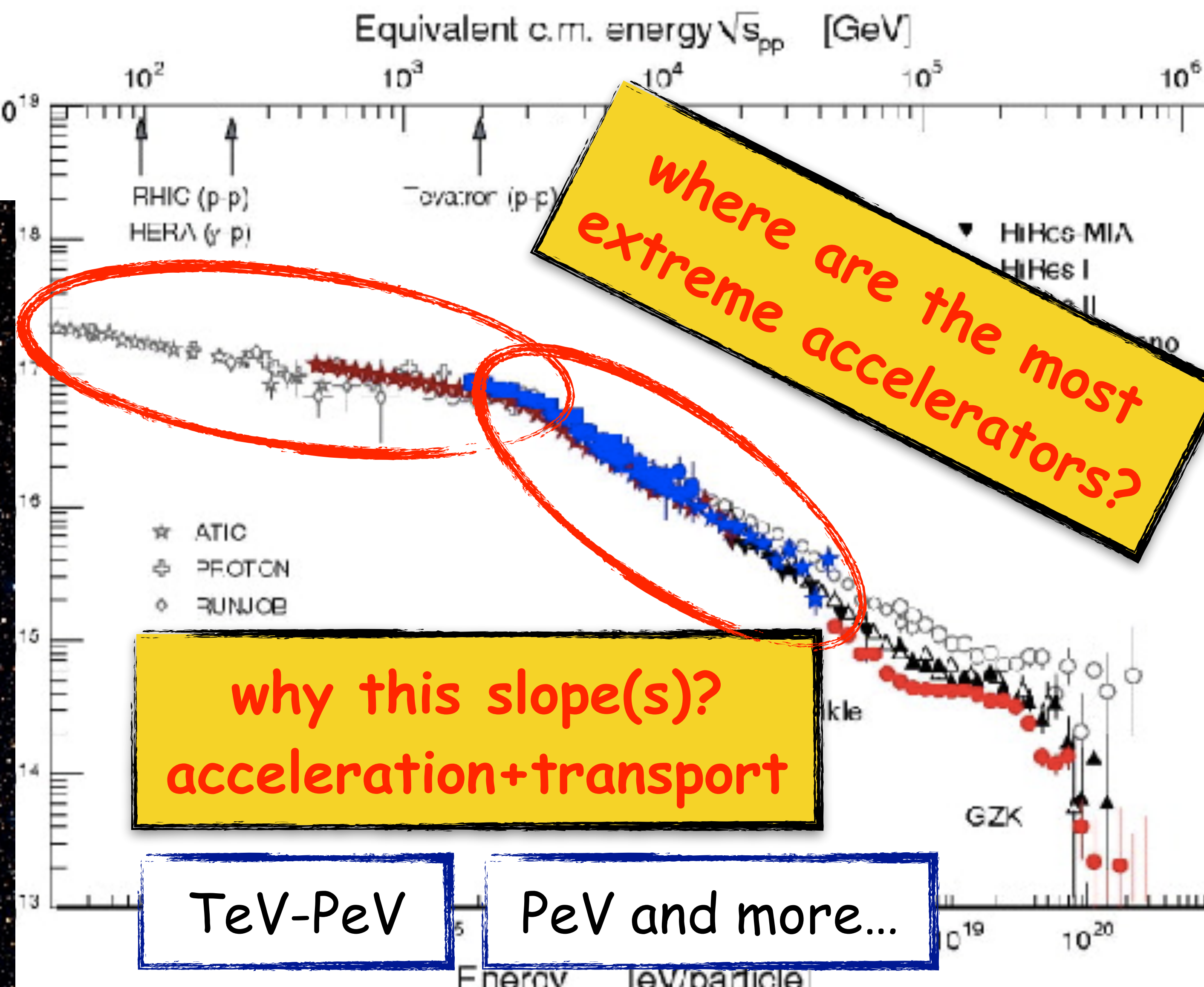


impac ISM and star formation:
ionisatio ting, c hemistry…

times a cross section rate



the SNR origin of CRs



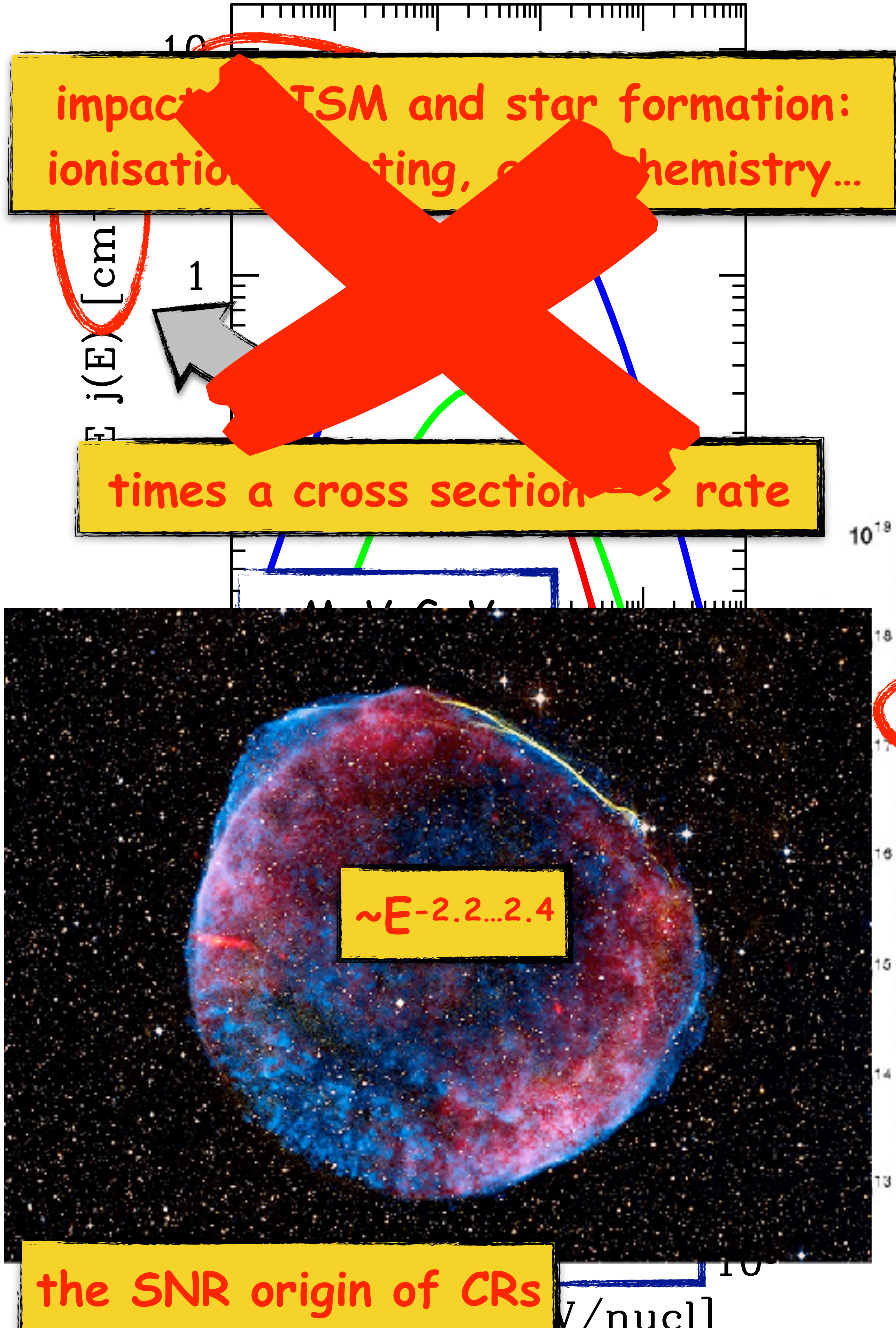
where are the most extreme accelerators?

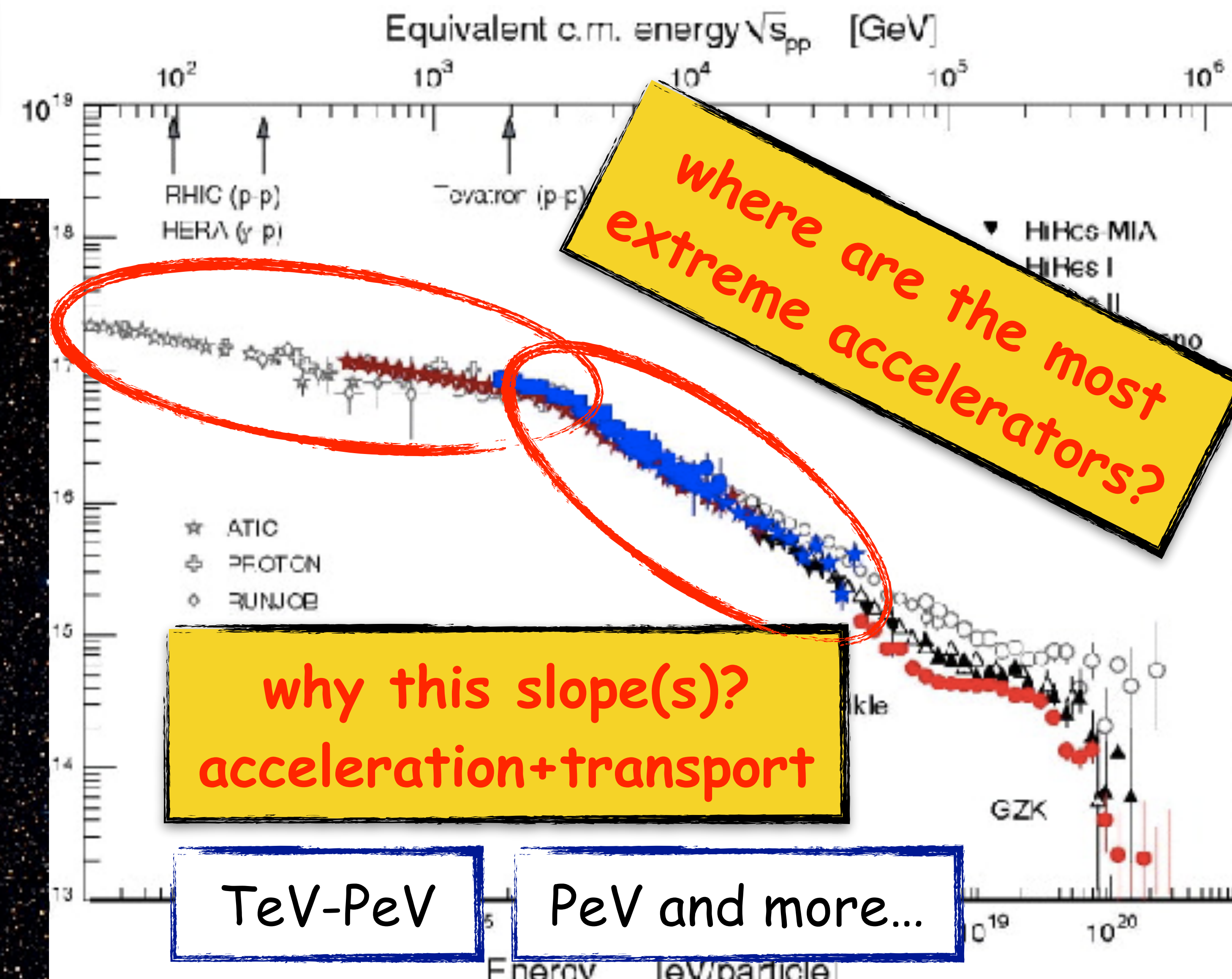
why this slope(s)?
acceleration+transport

TeV-PeV

PeV and more…

We study cosmic rays because…





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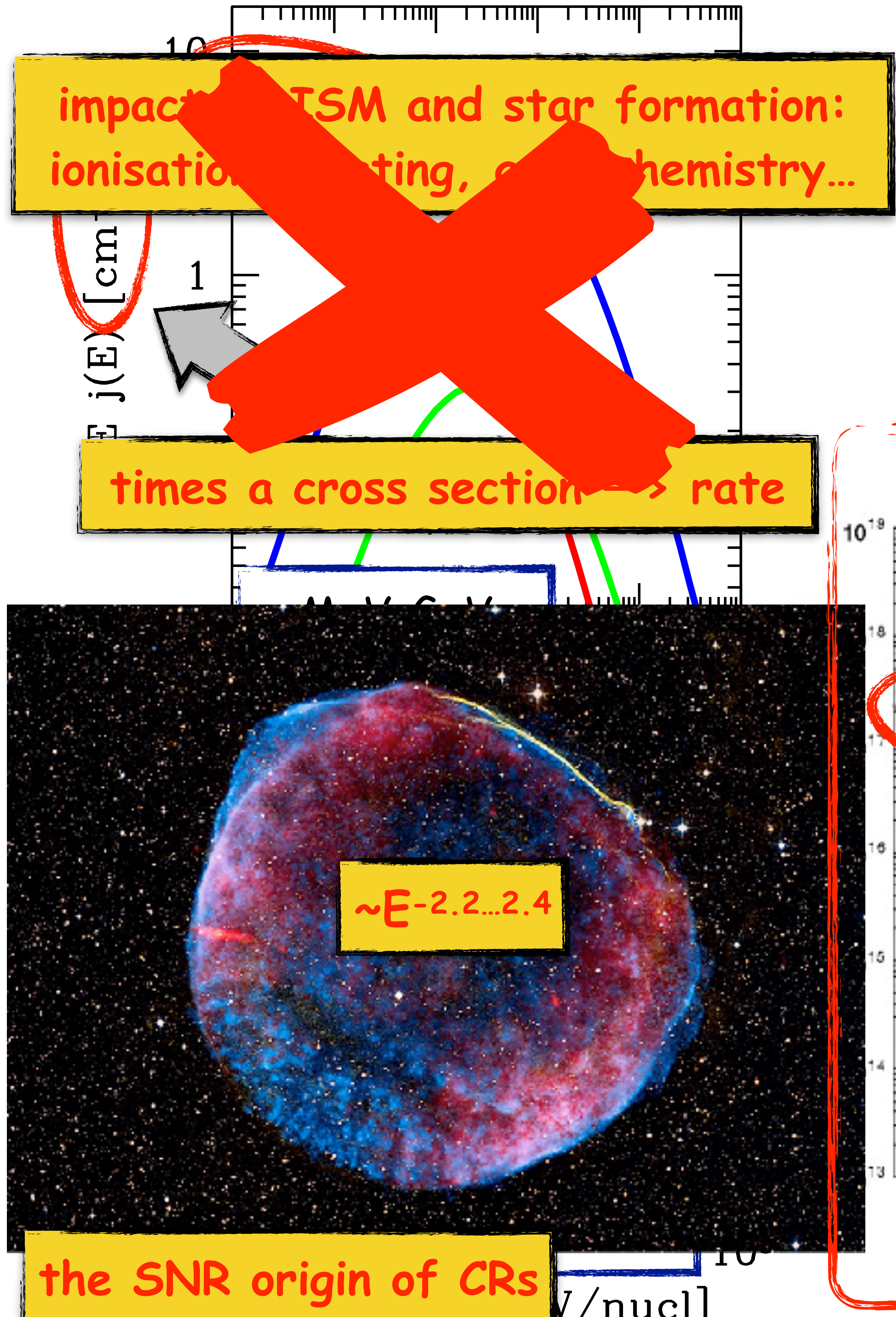
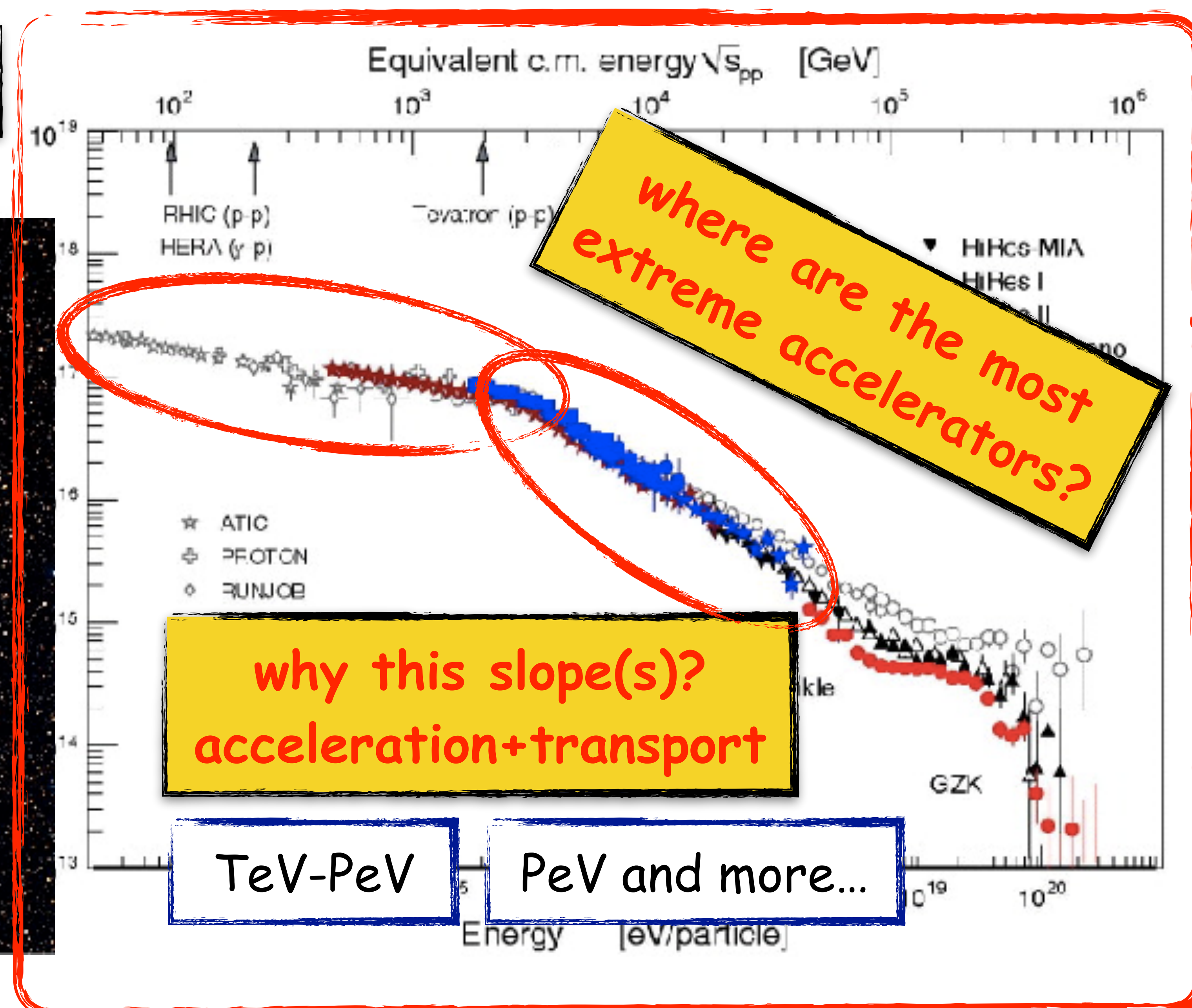
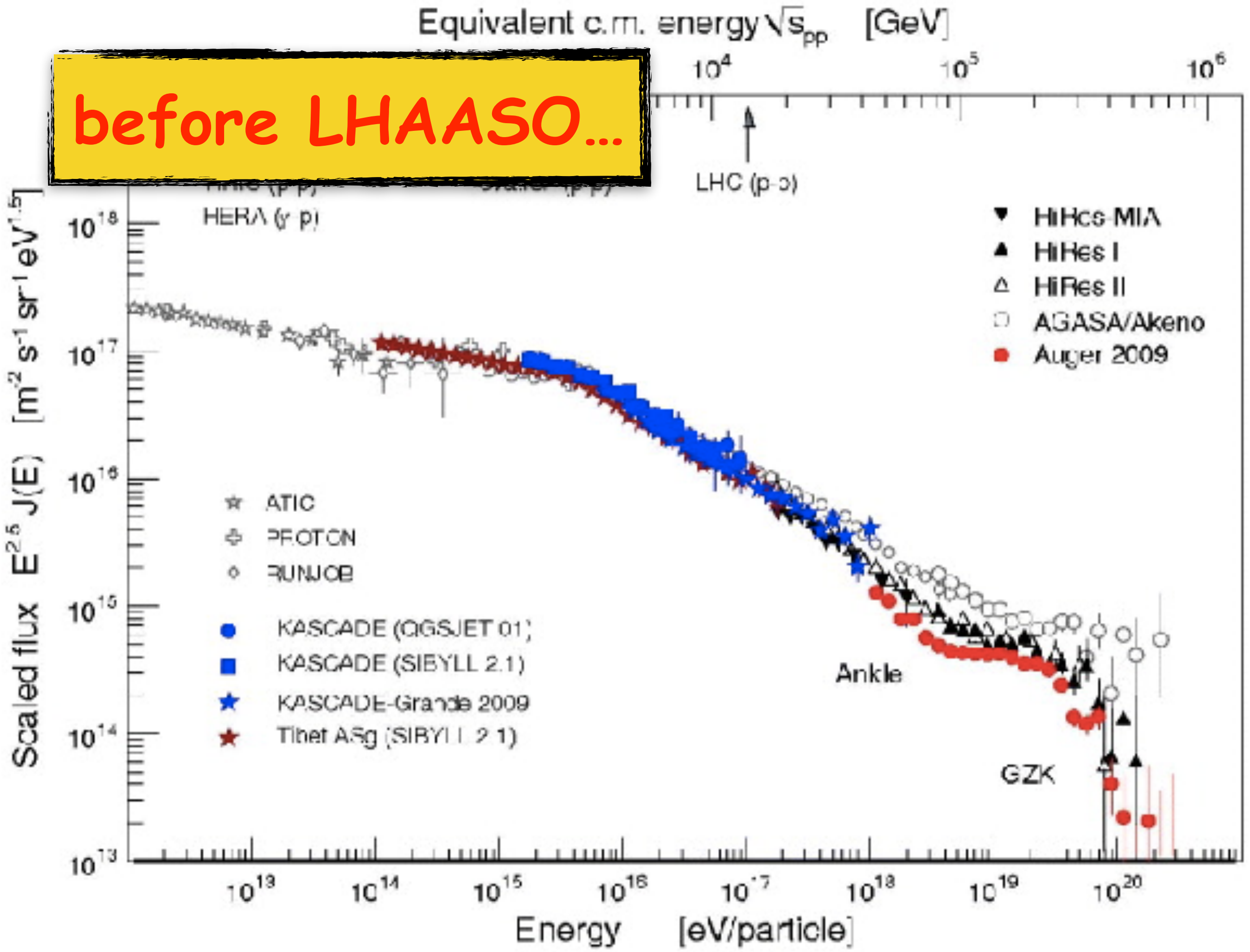




[2] The knee:
before and after LHAASO

The knee in the CR spectrum



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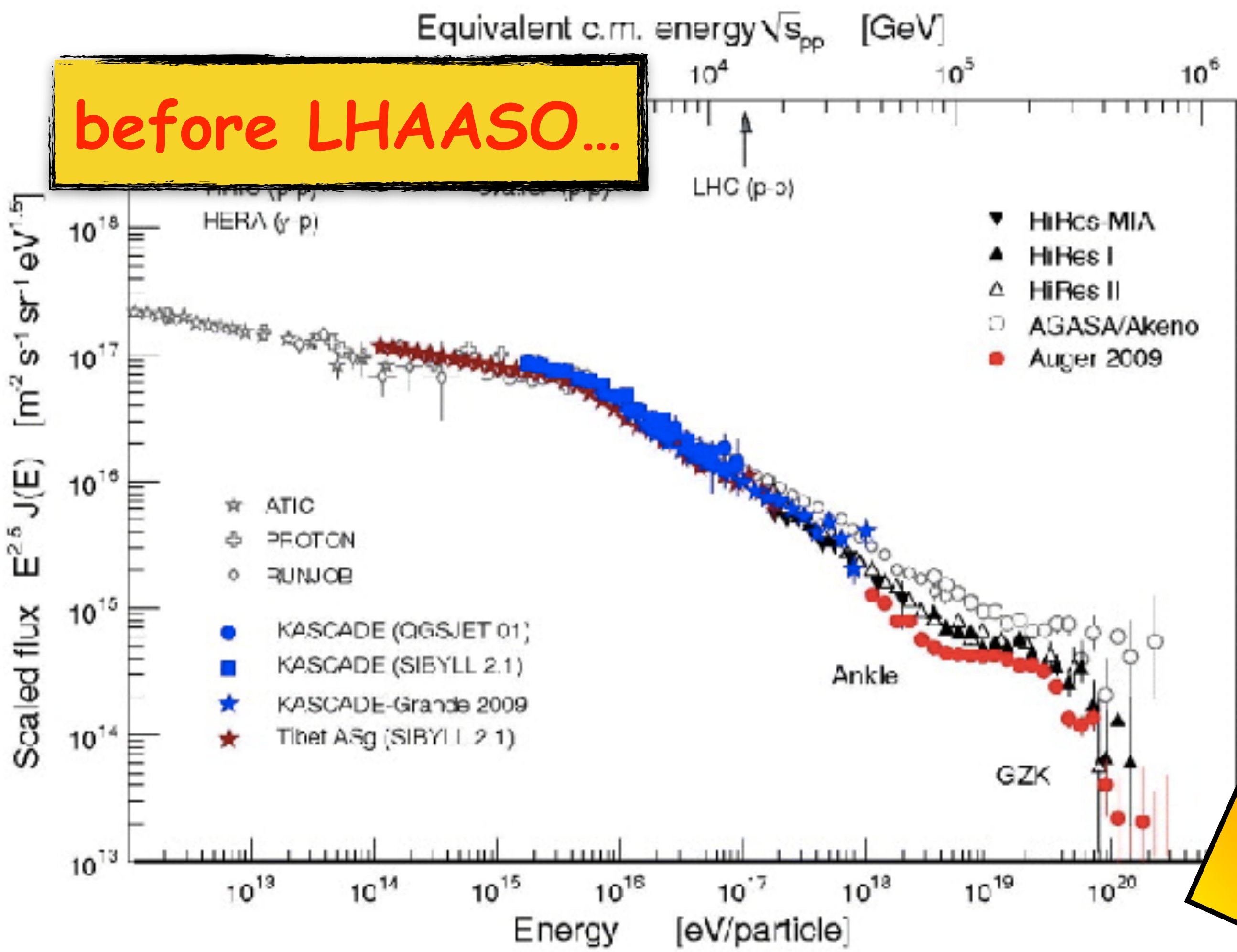

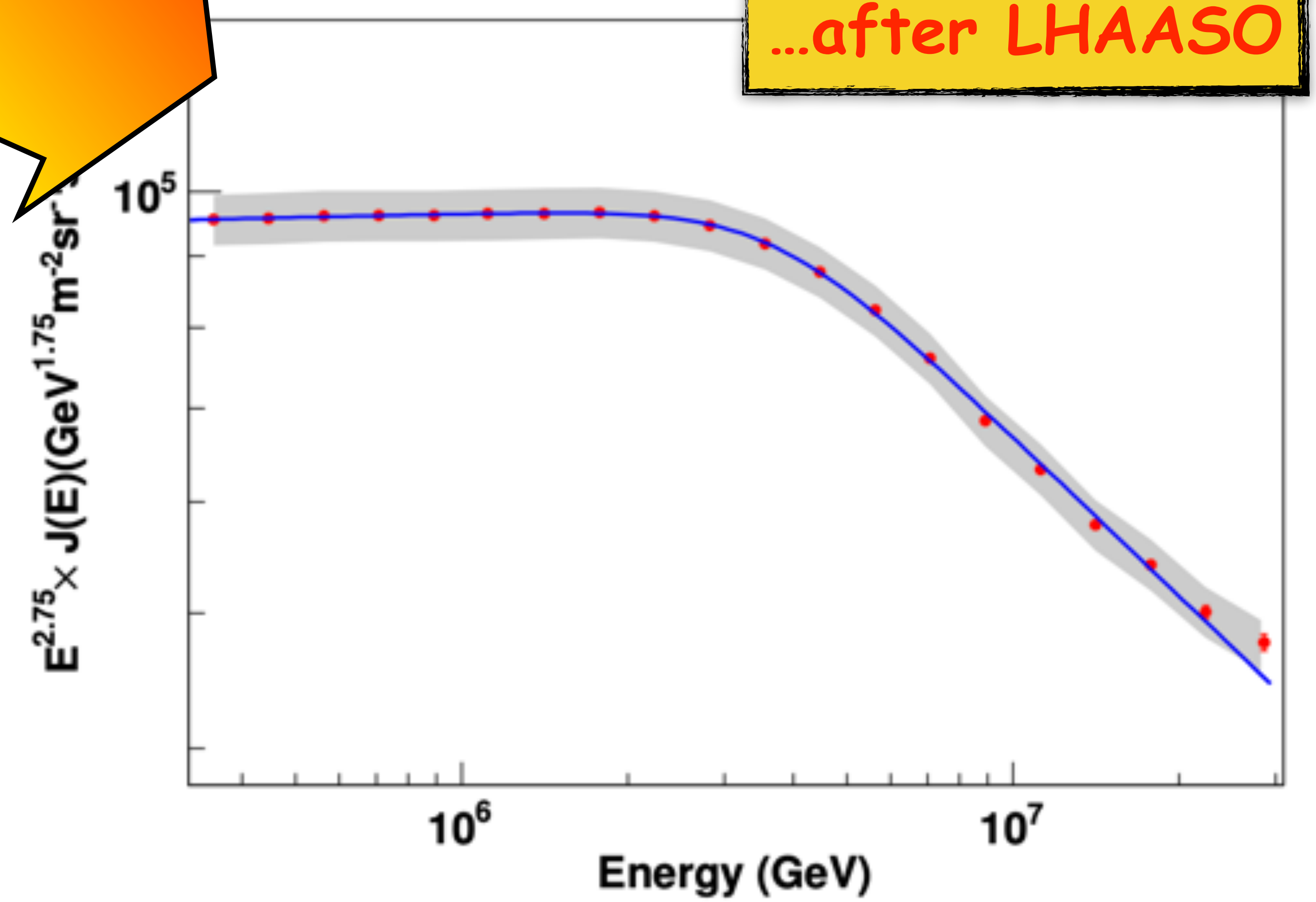

The knee in the CR spectrum/element

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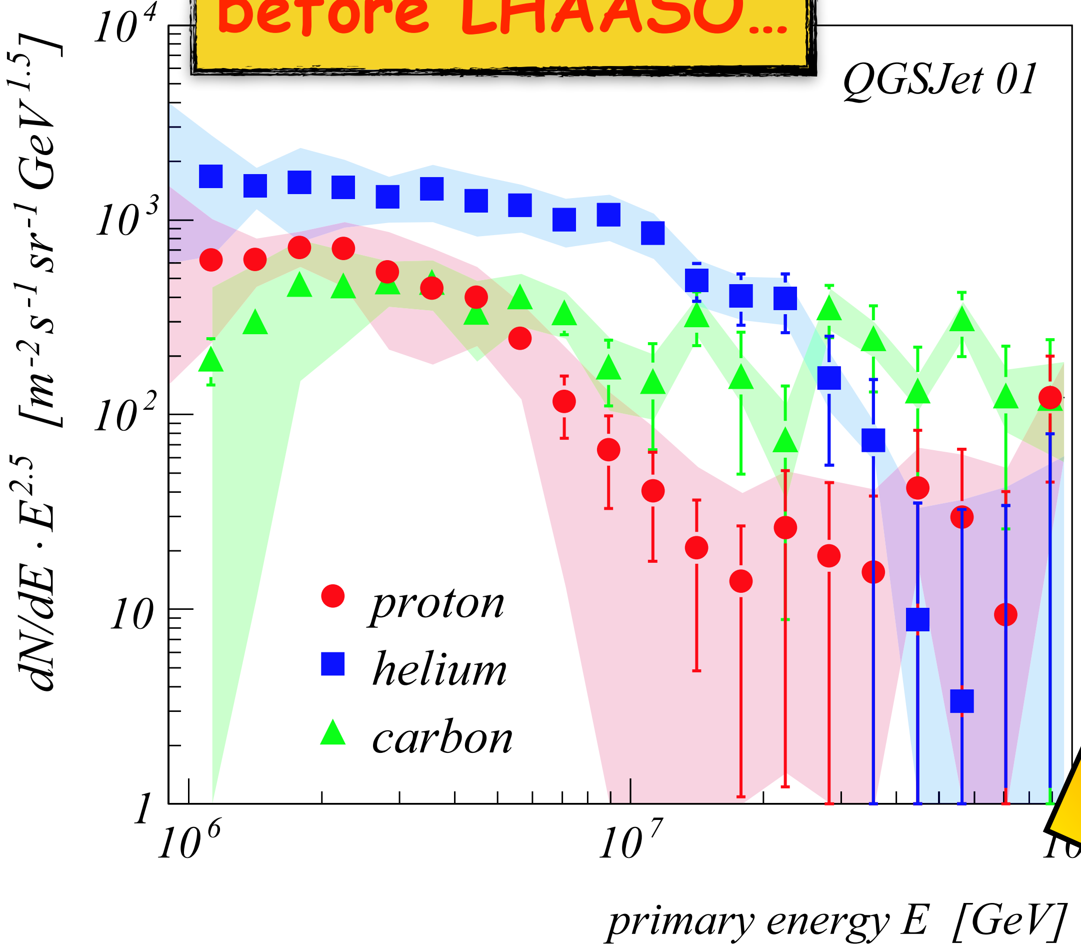
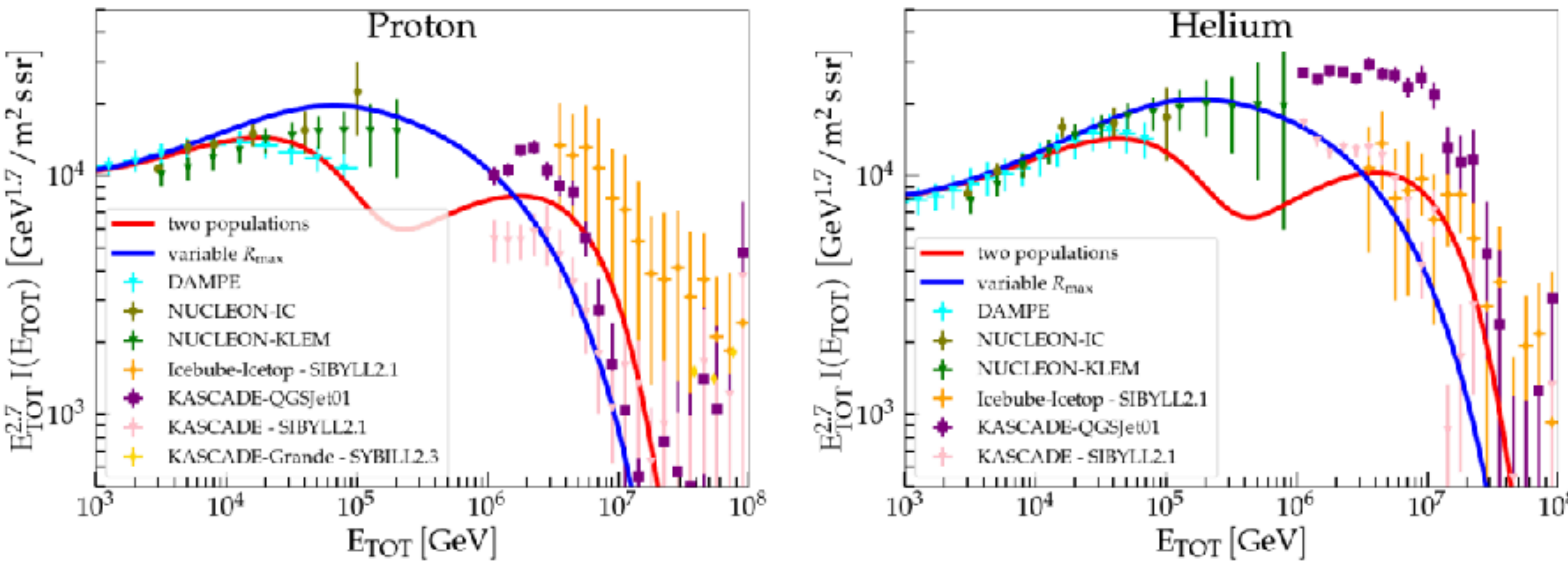
before LHAASO…

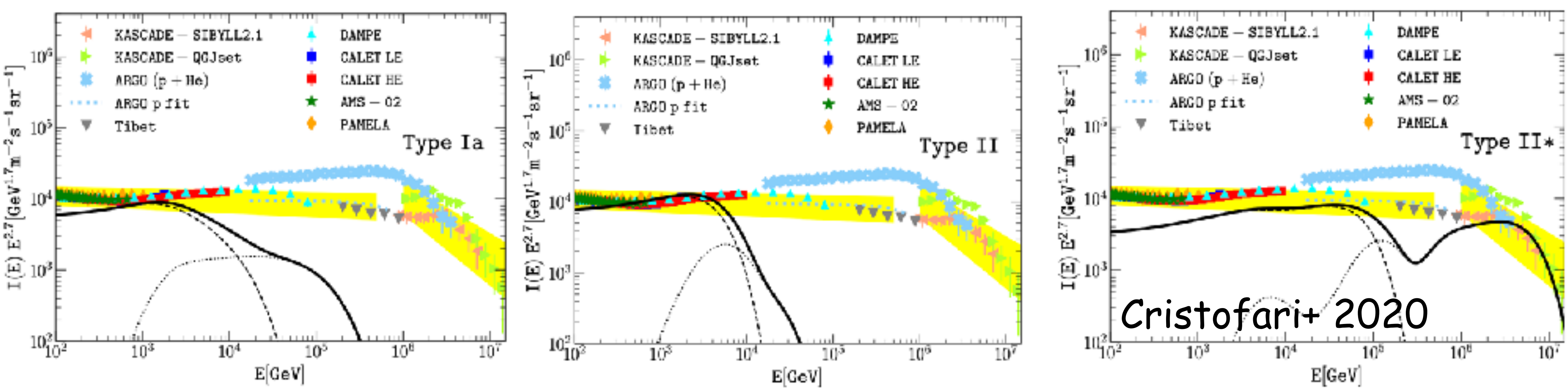


…after LHAASO

Interpreting the knee

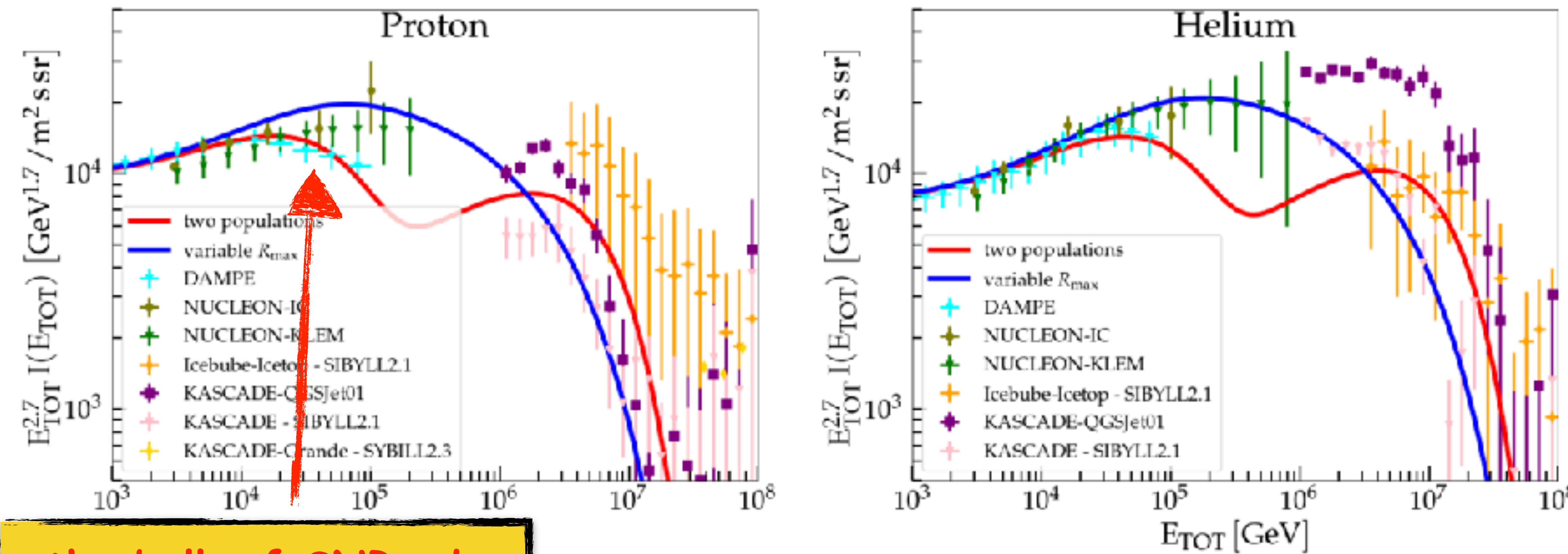
Recchia & SG 2024



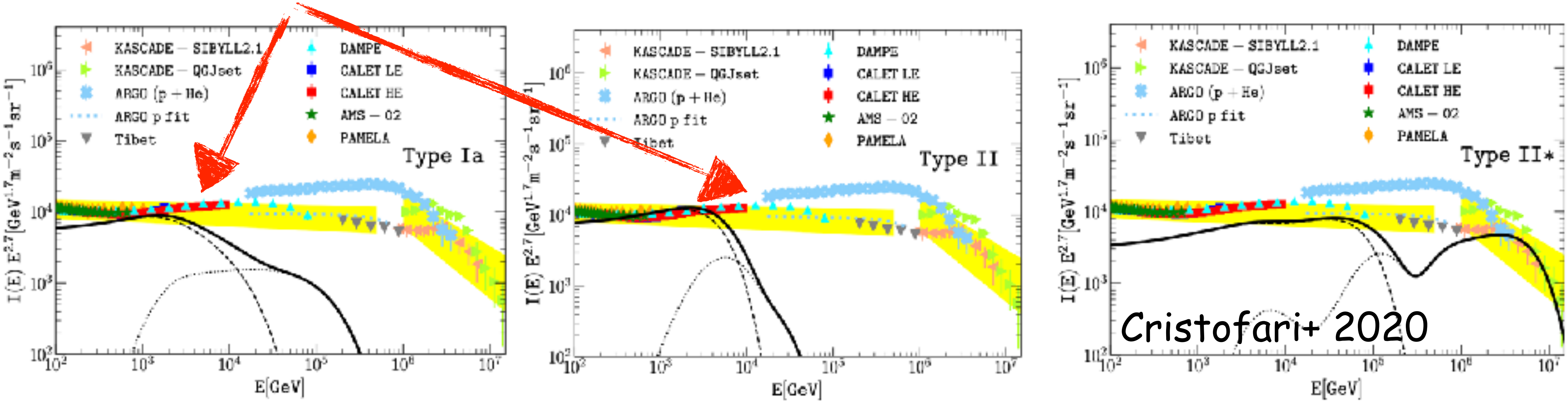


Interpreting the knee

Recchia & SG 2024



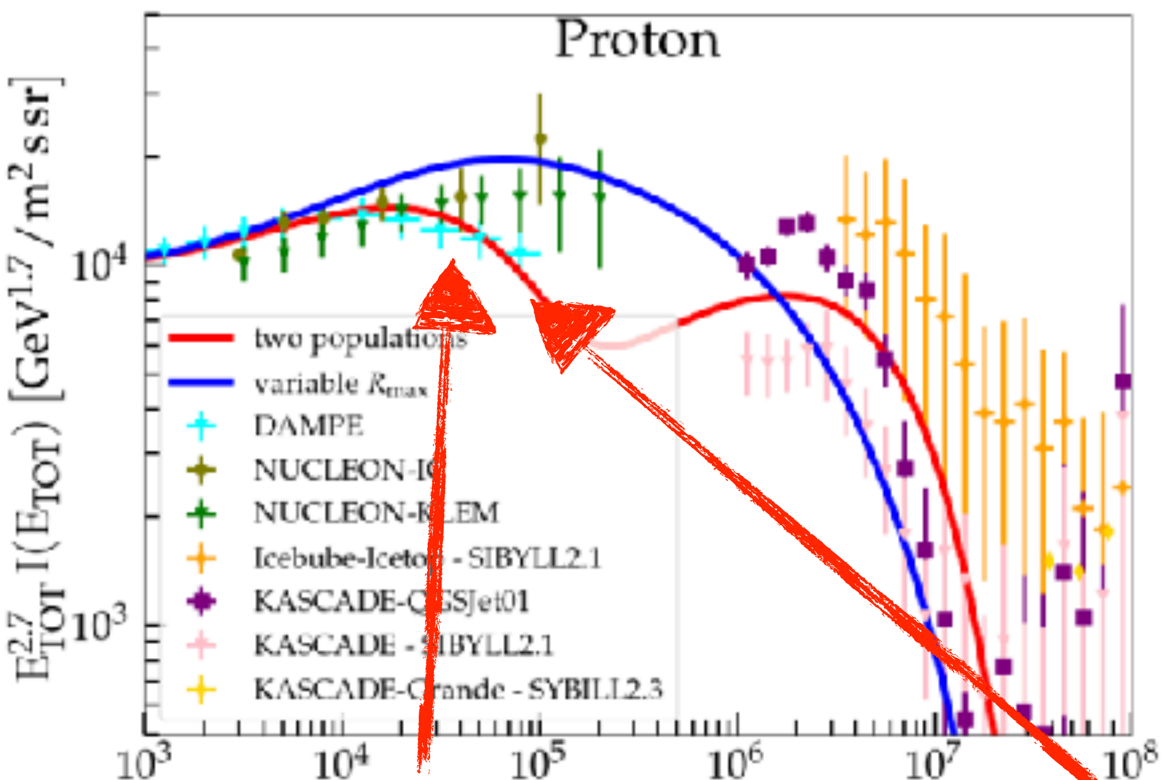
the bulk of SNRs do NOT go to the knee

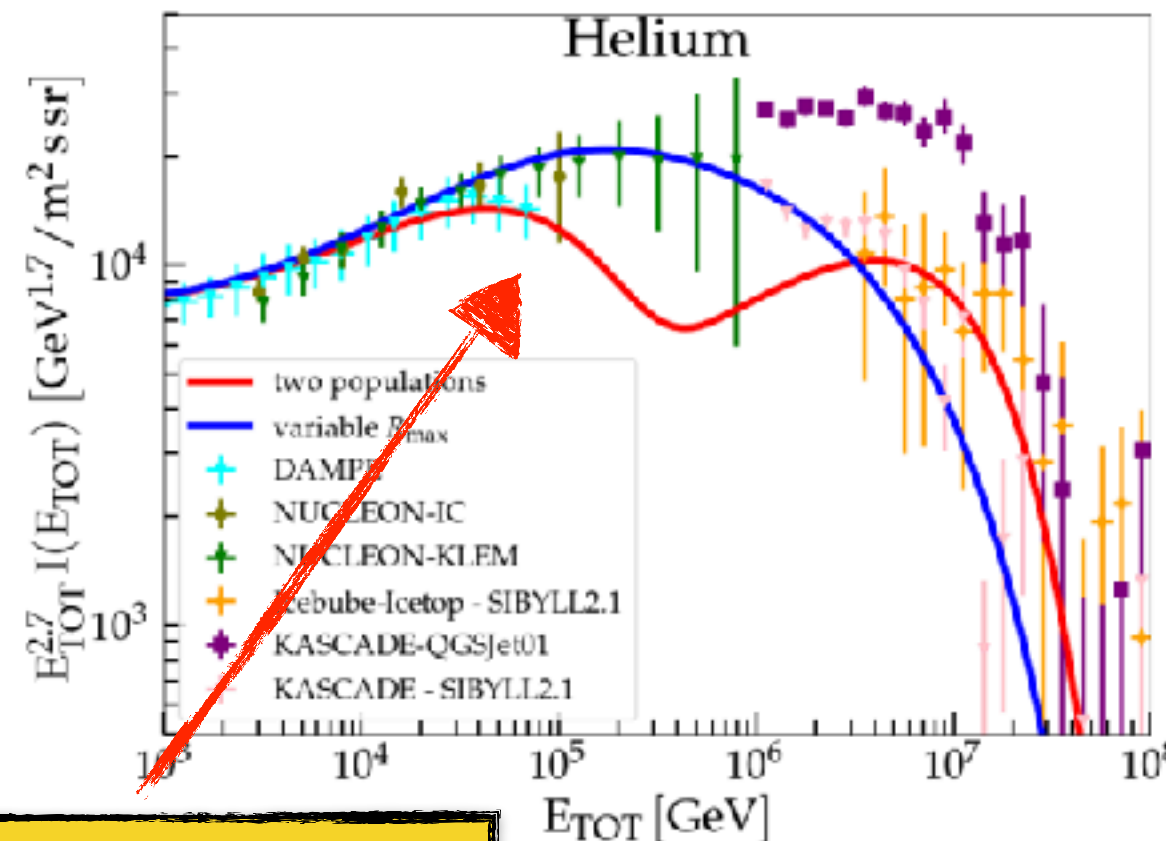


Cristofari+ 2020

Interpreting the knee

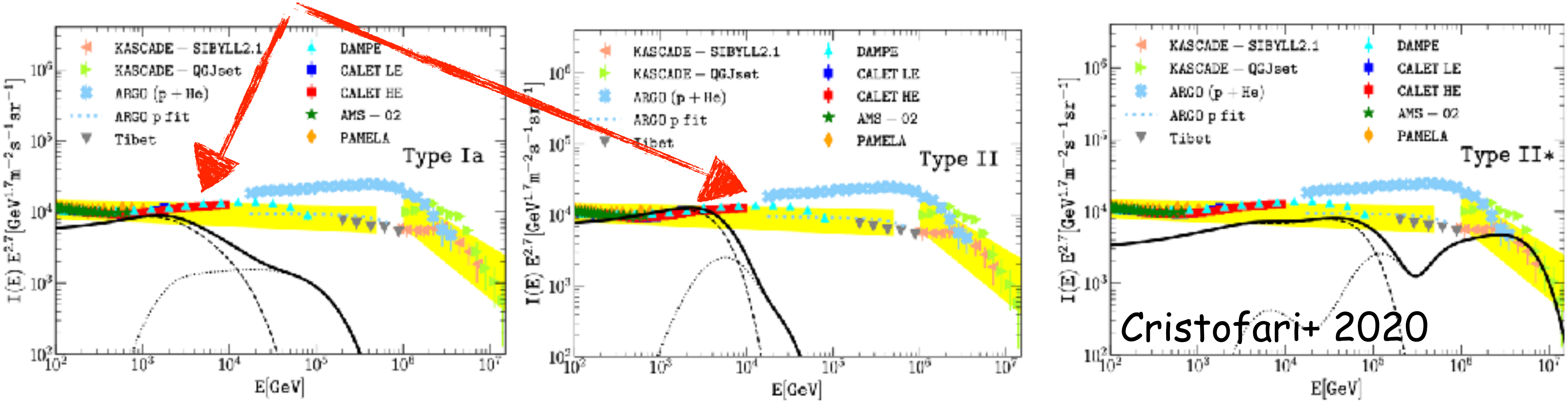
Recchia & SG 2024





the bulk of SNRs do NOT go to the knee

DAMPE steepening?



Cristofari+ 2020

Interpreting the knee

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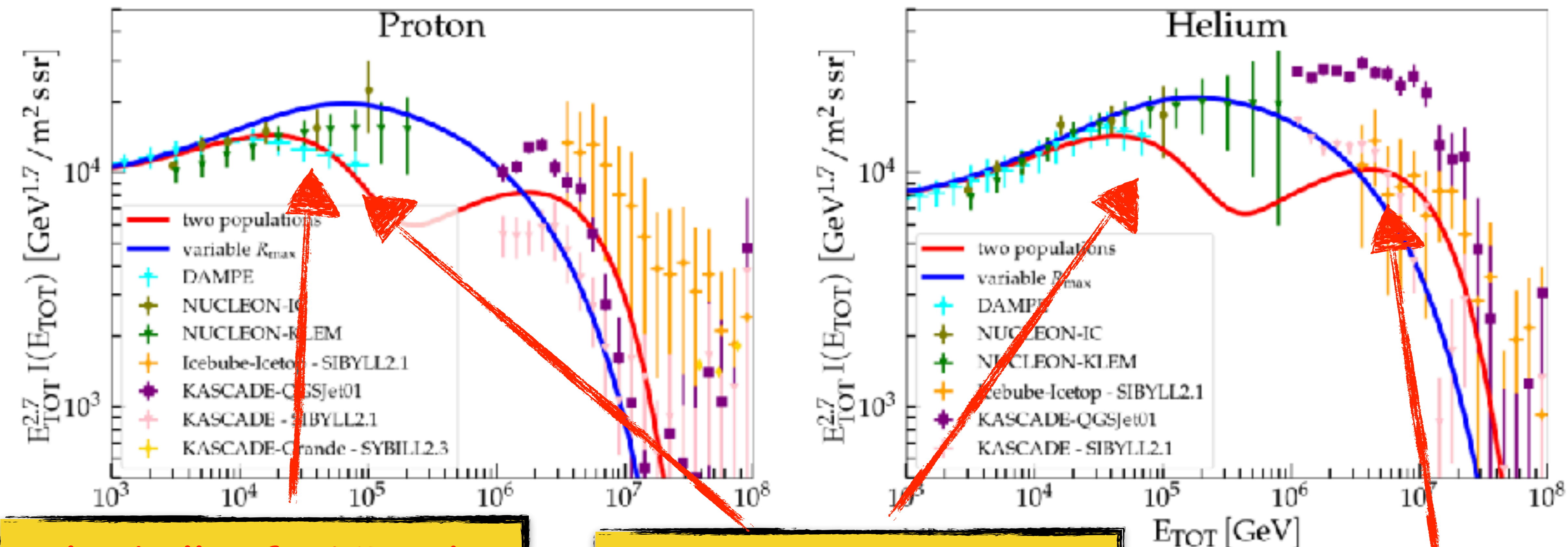
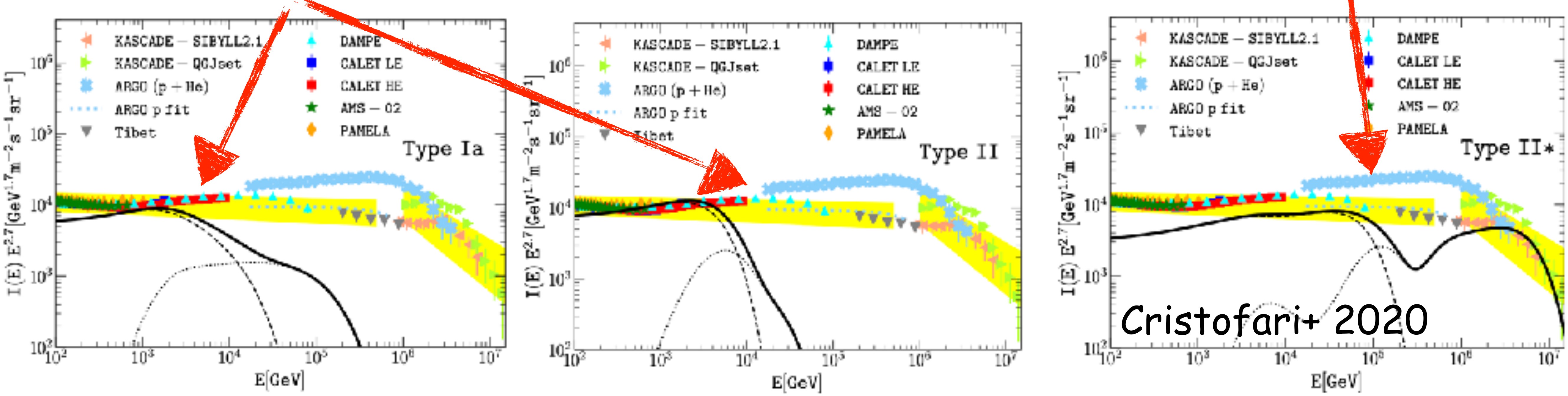


the bulk of SNRs do NOT go to the knee

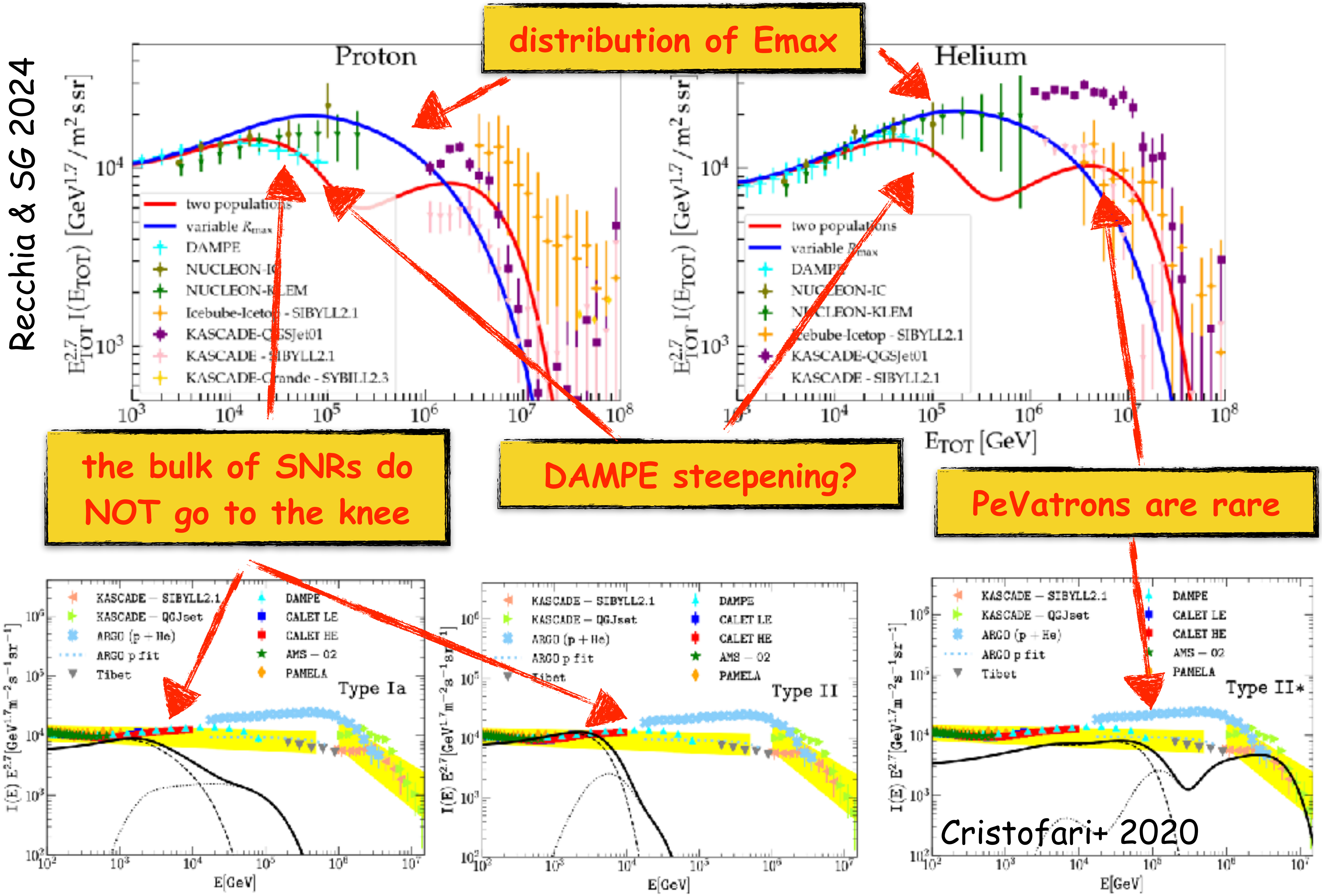
DAMPE steepening?

PeVatrons are rare

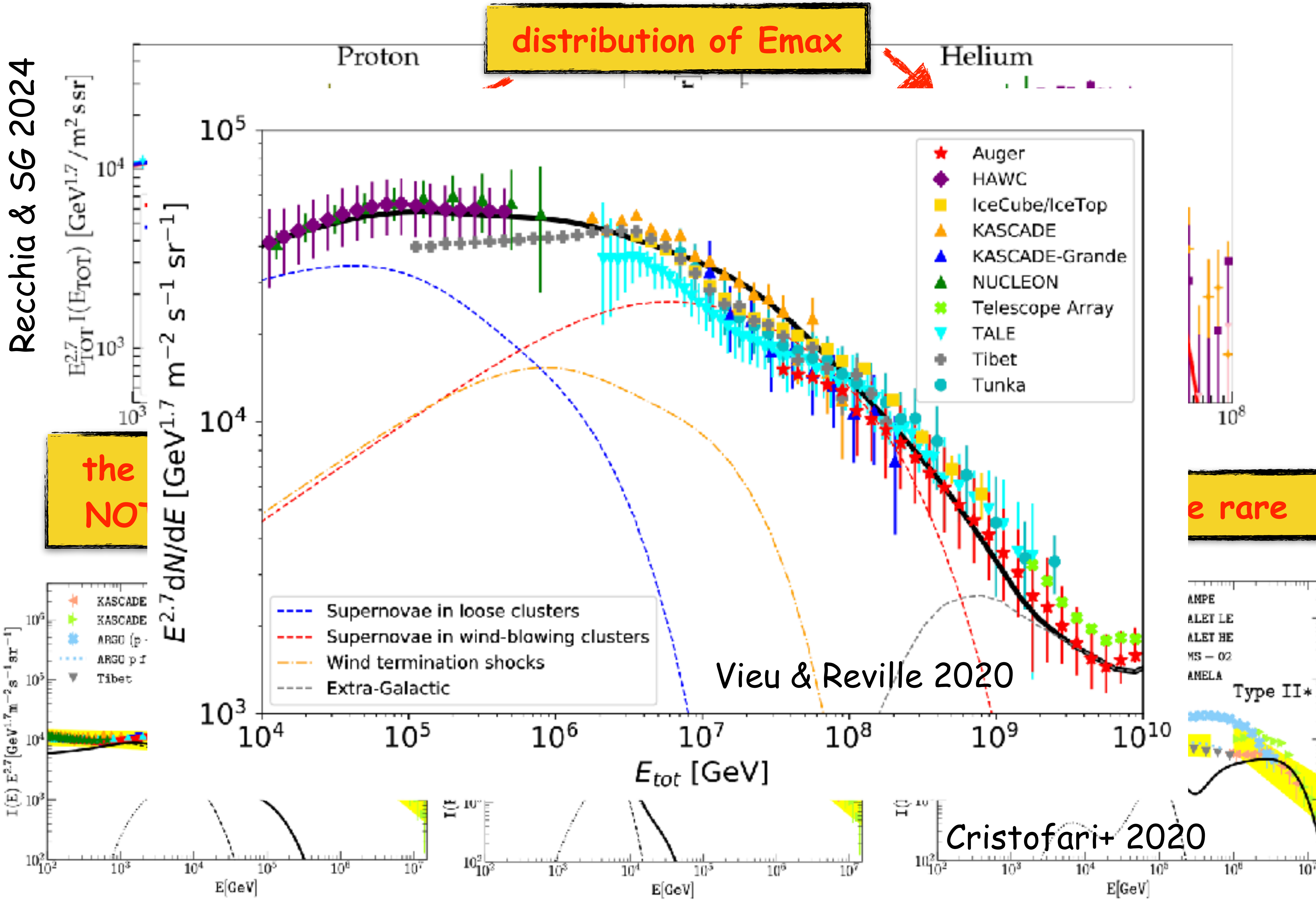


Cristofari+ 2020

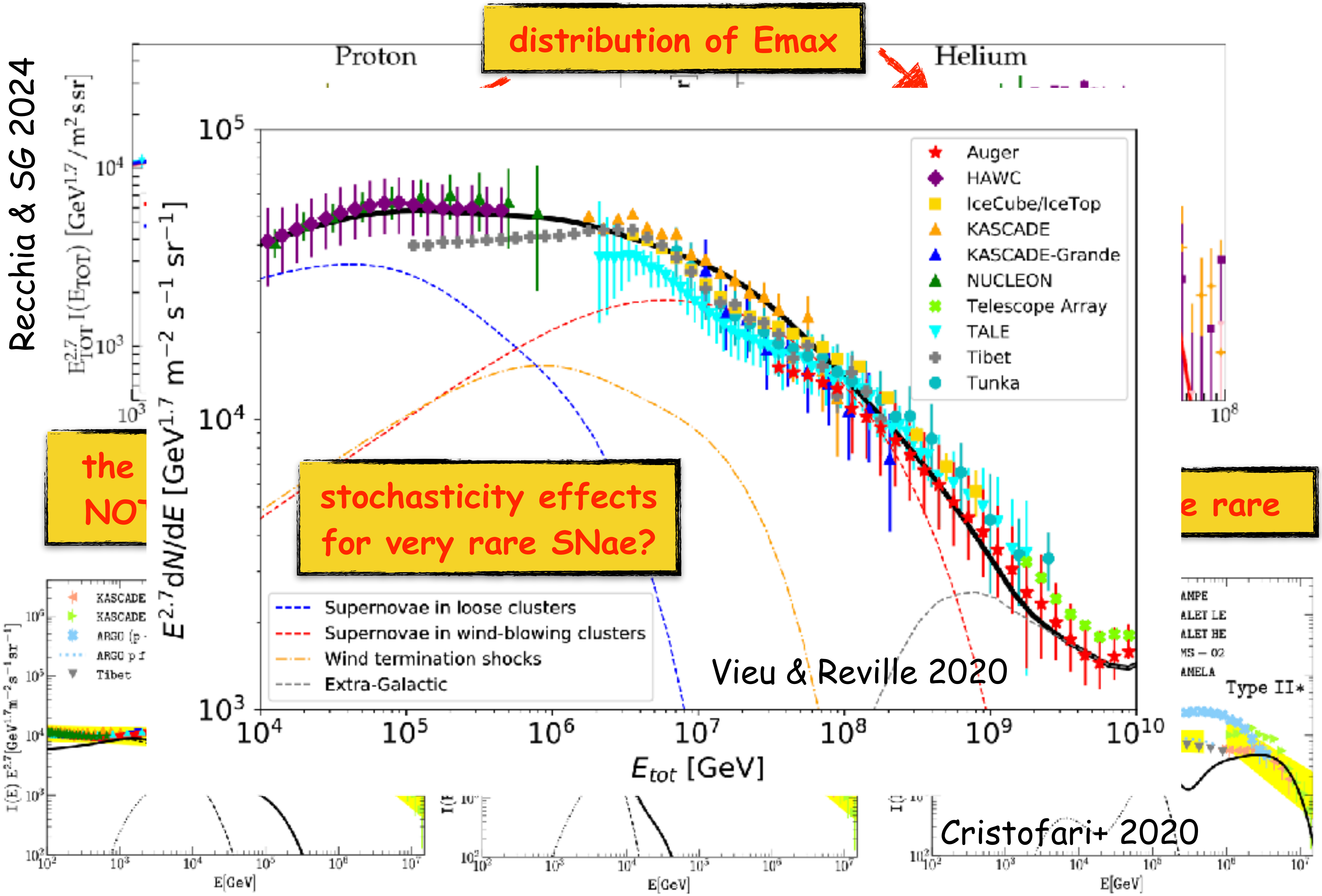
Interpreting the knee



Interpreting the knee

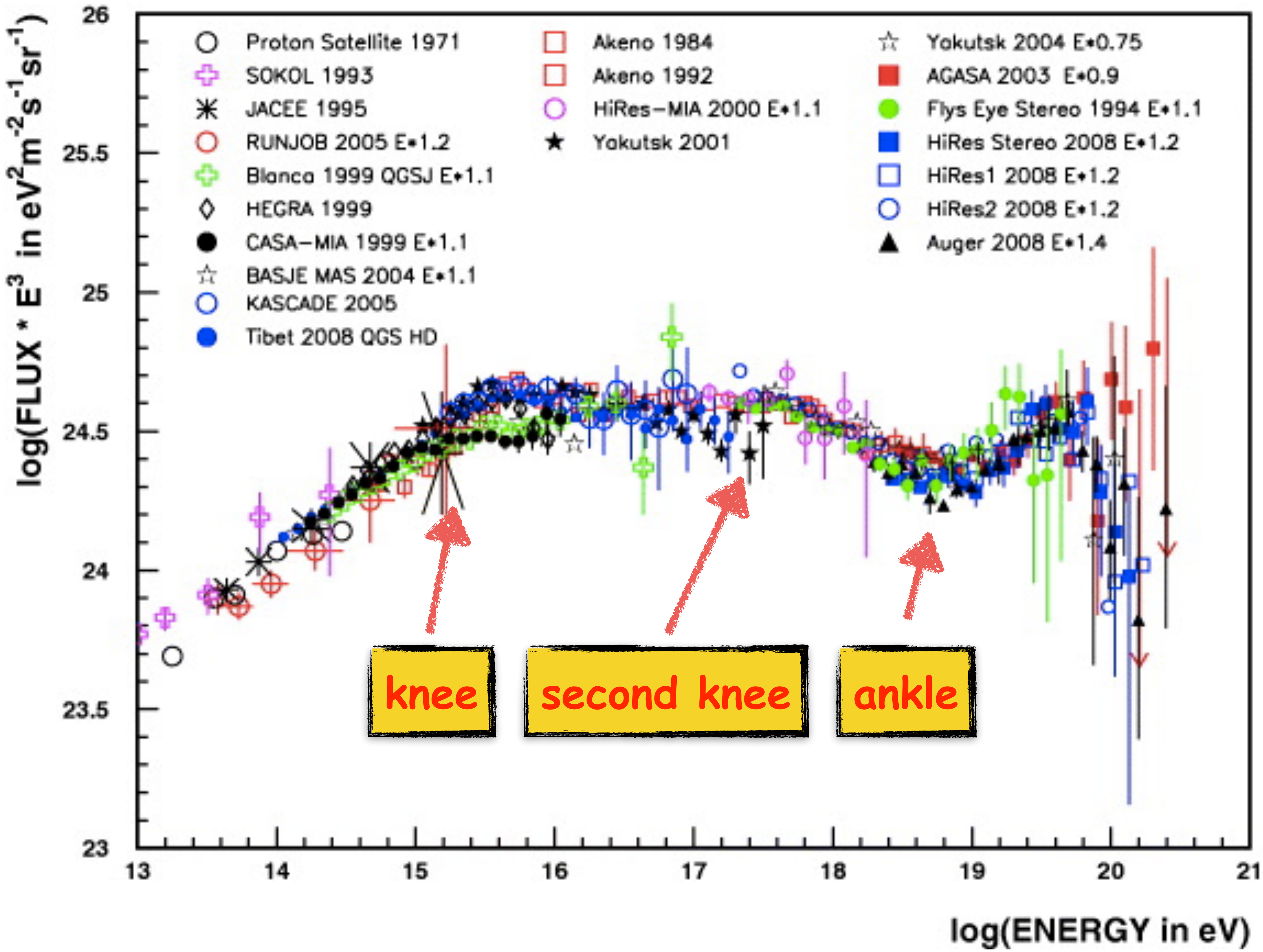


Interpreting the knee



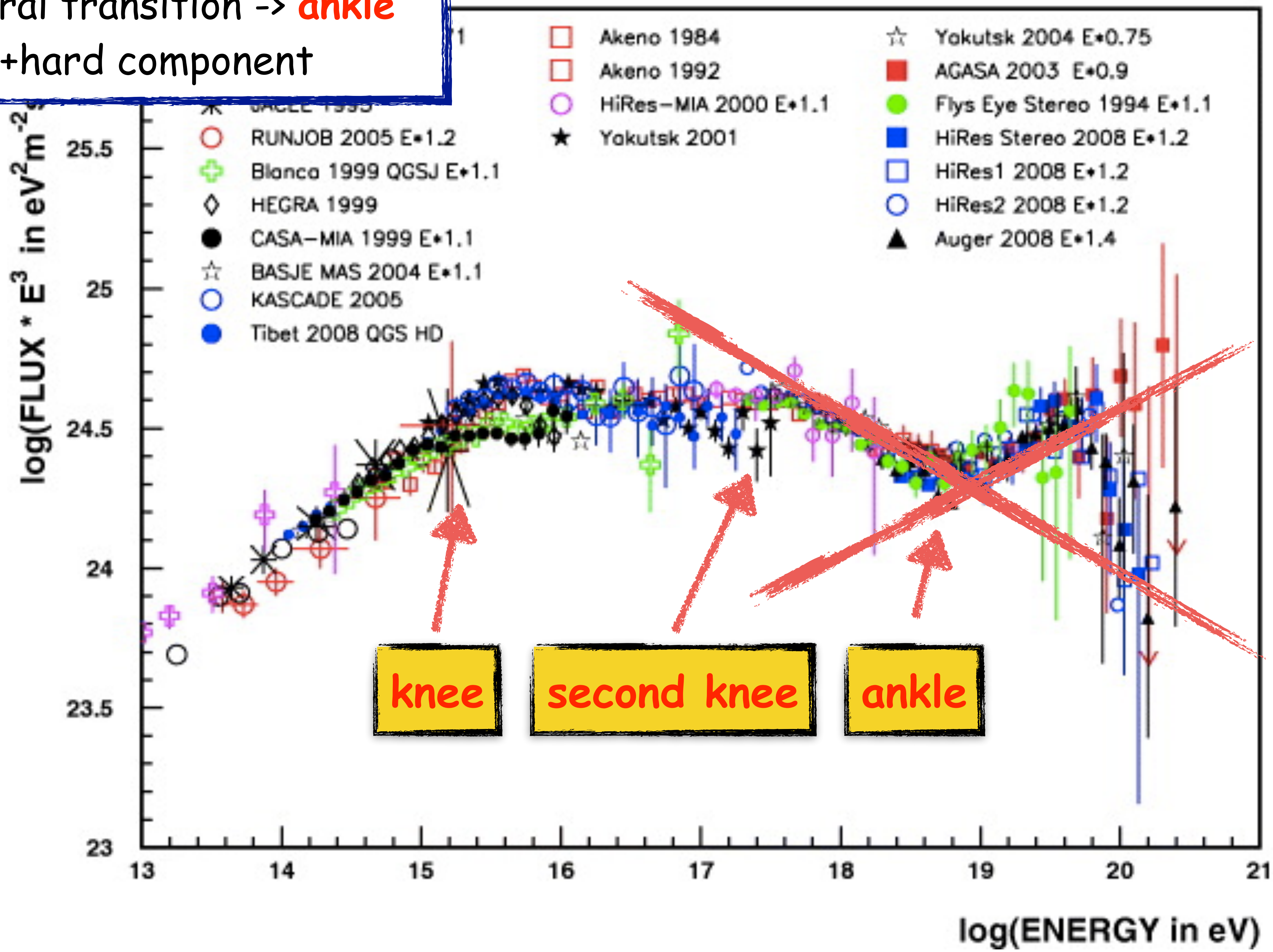
[3] Problems with the SNR paradigm

Transition from galactic to extra-galactic CRs



Transition from galactic to extra-galactic CRs

most natural transition -> ankle
steep+hard component



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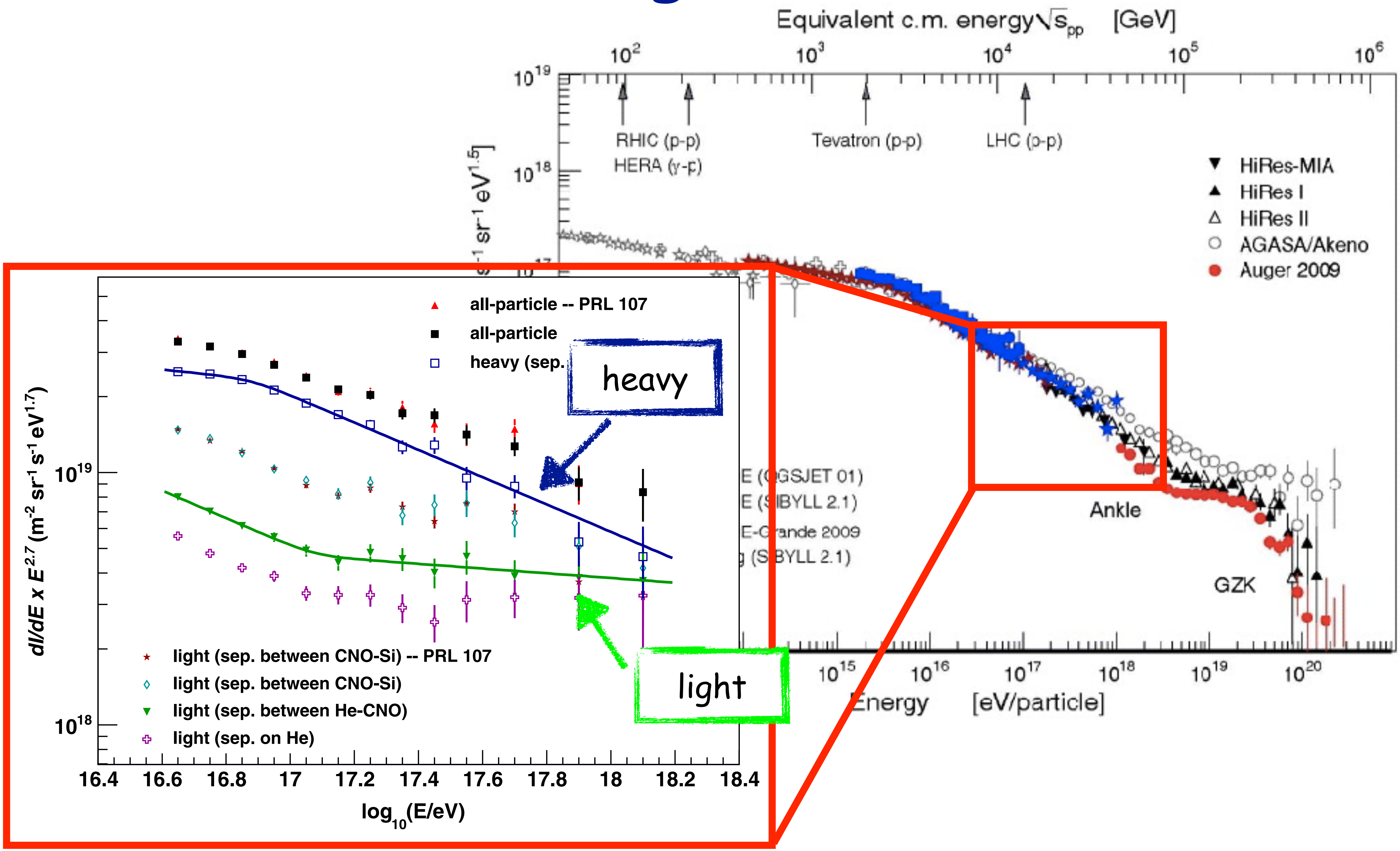

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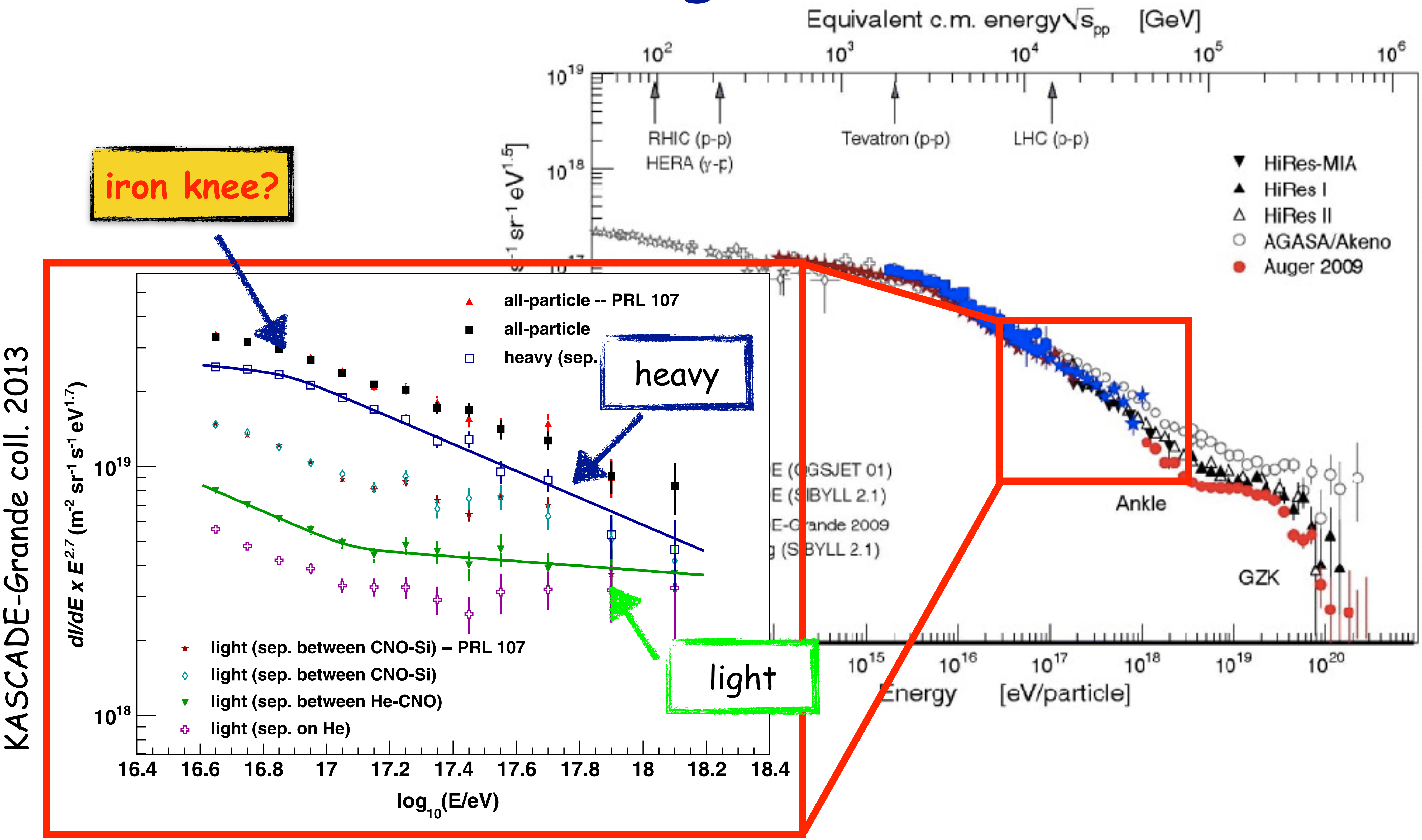
Transition from galactic to extra-galactic CRs



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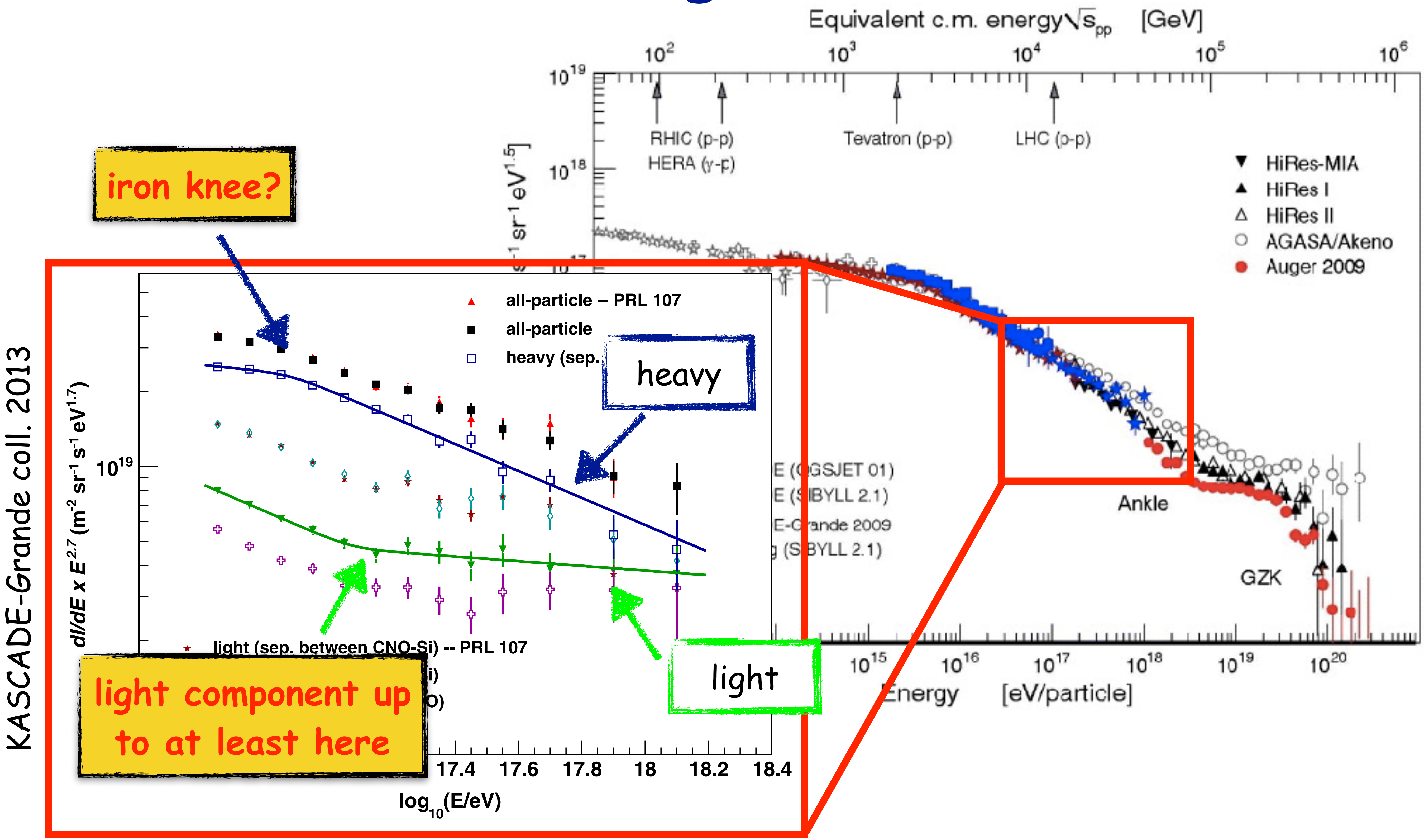

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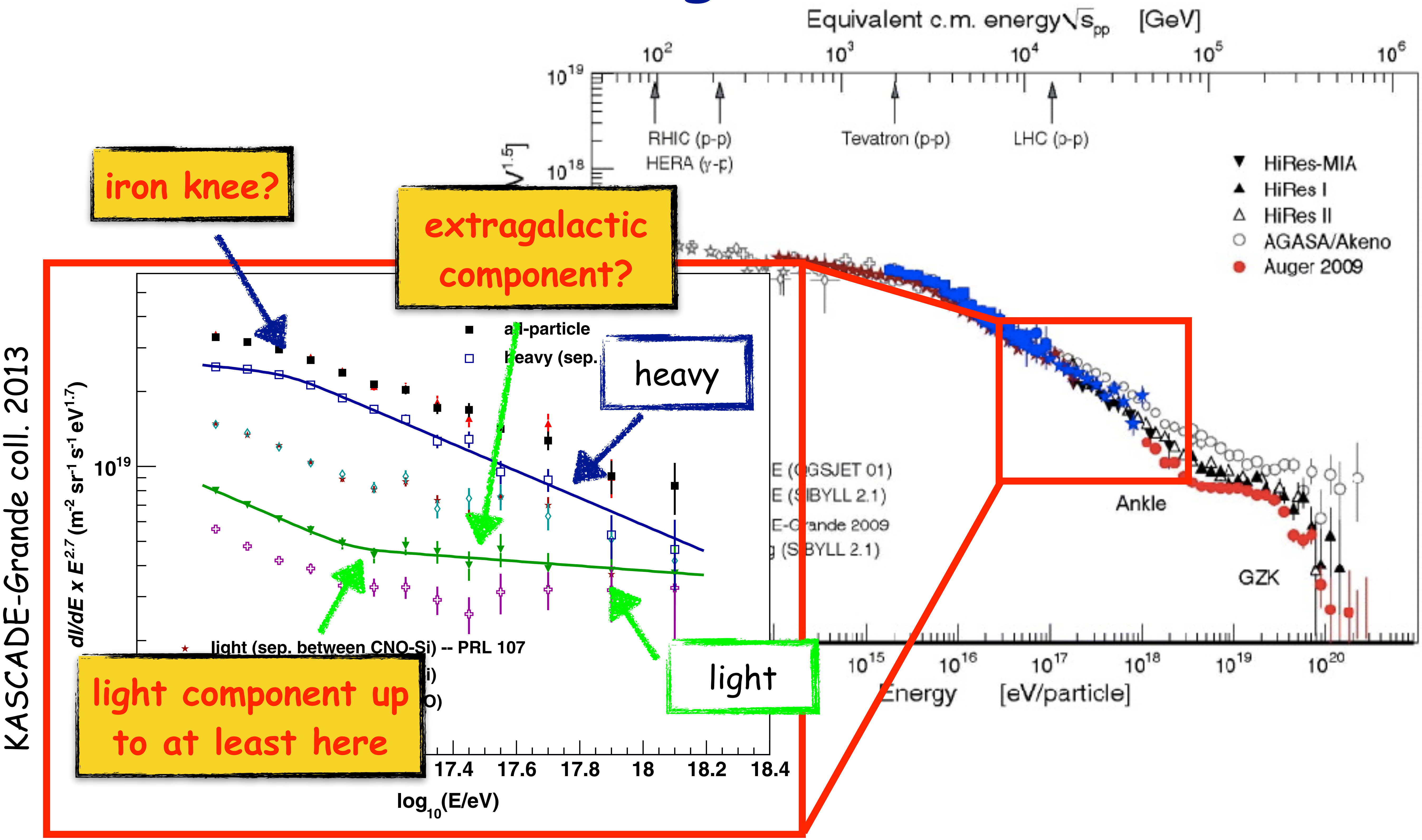

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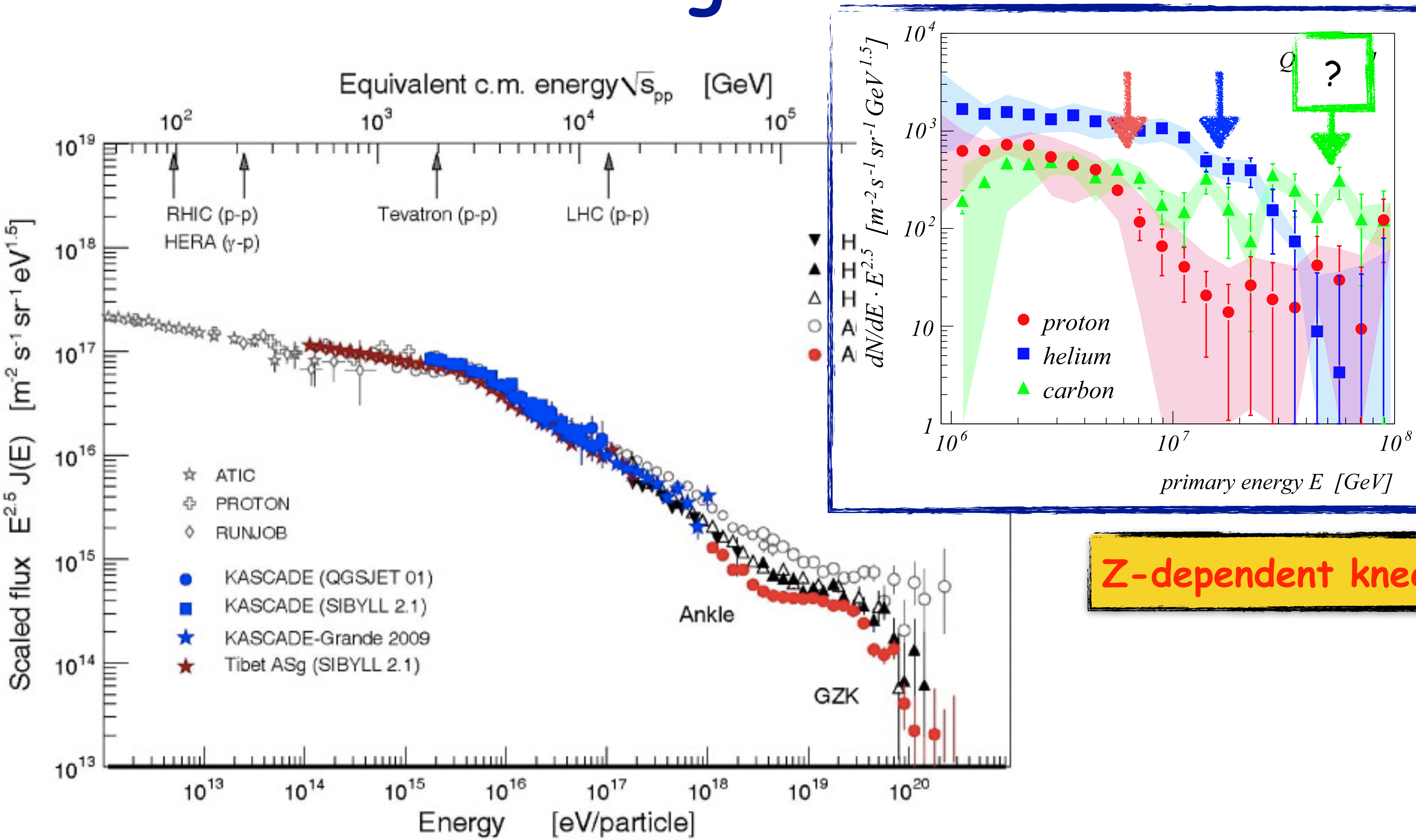

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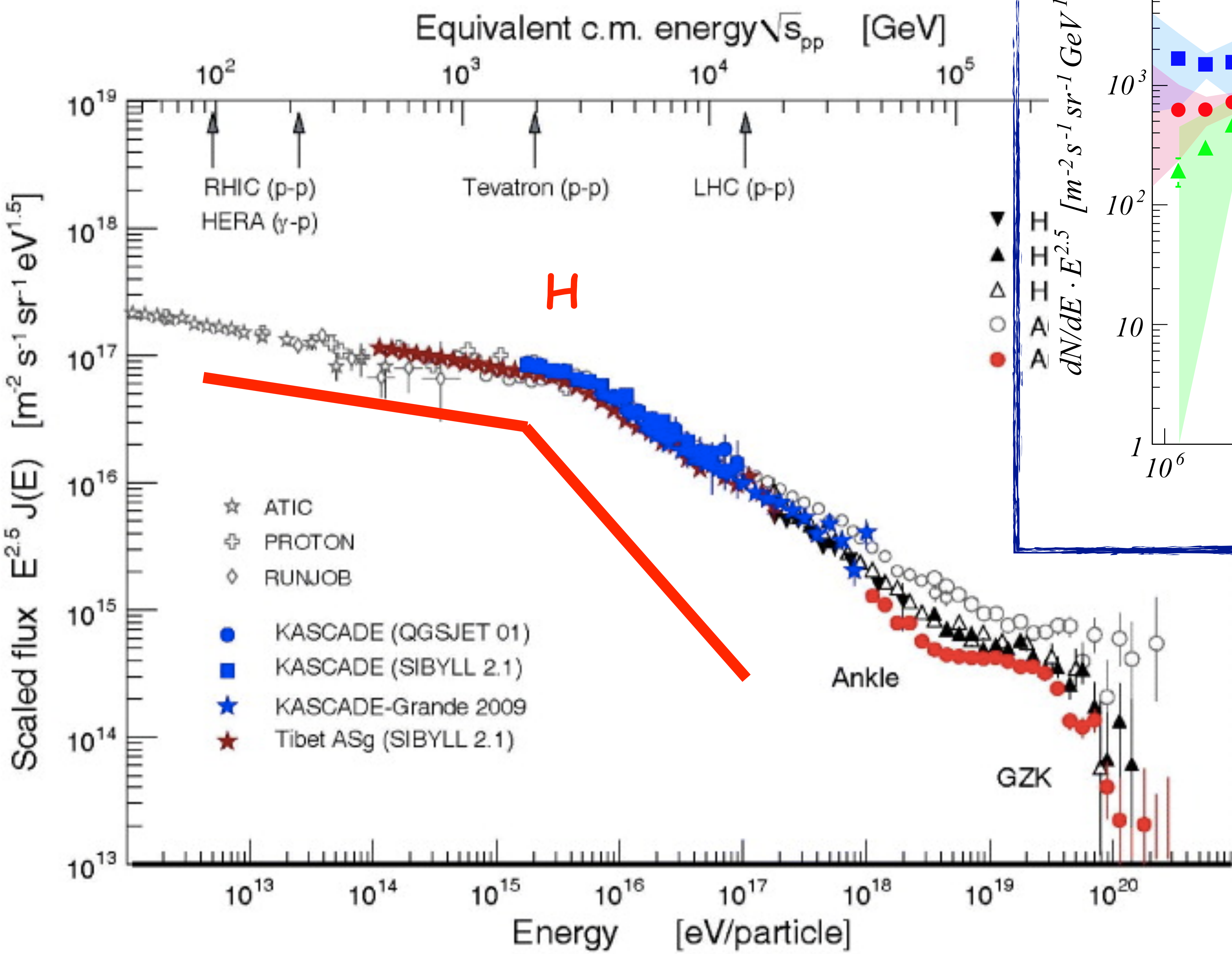
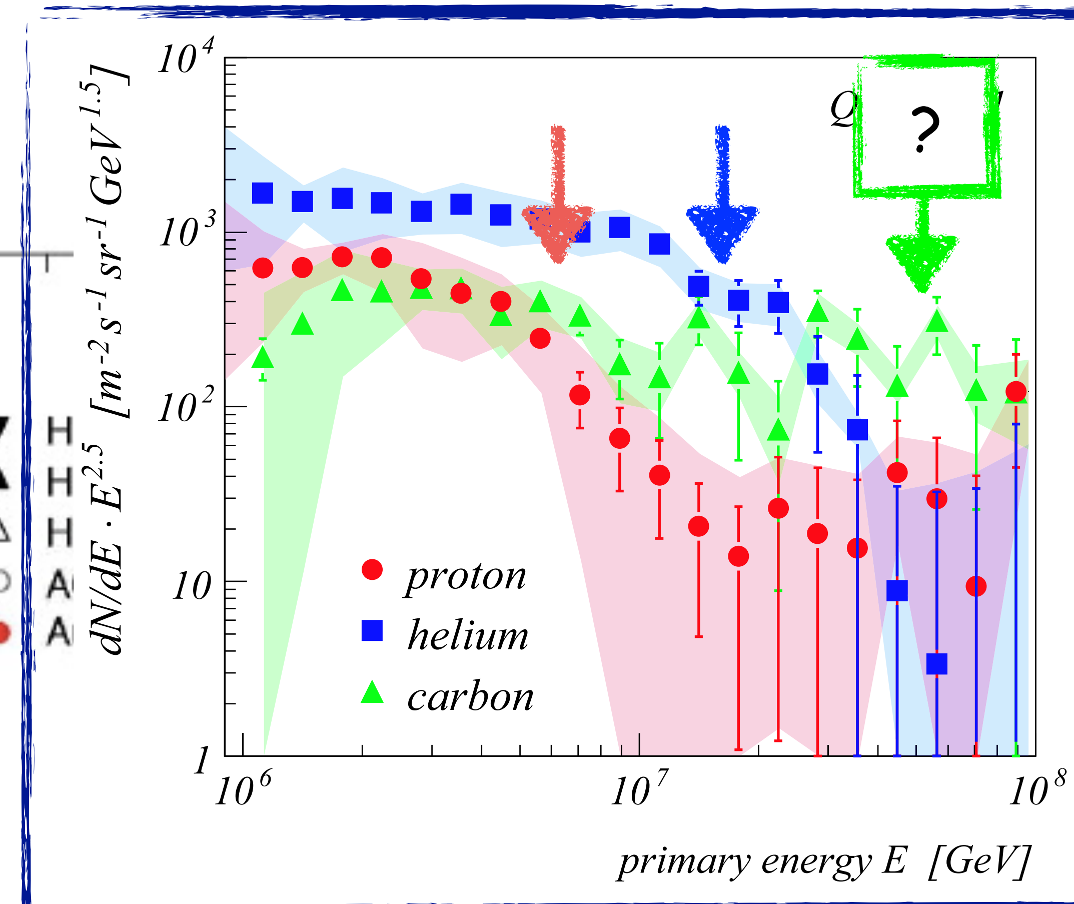
Z-dependent knee

Transition from galactic to extra-galactic CRs

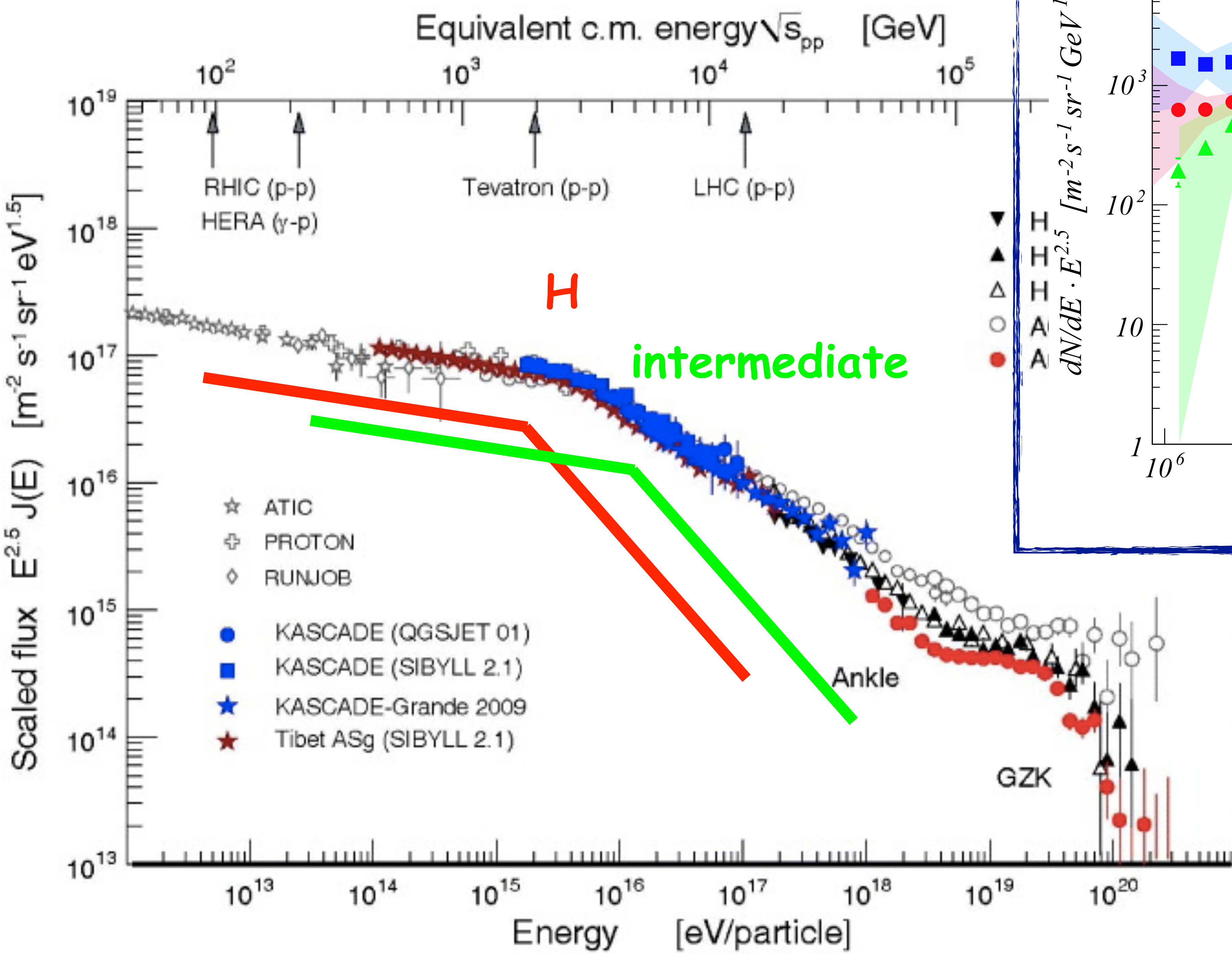


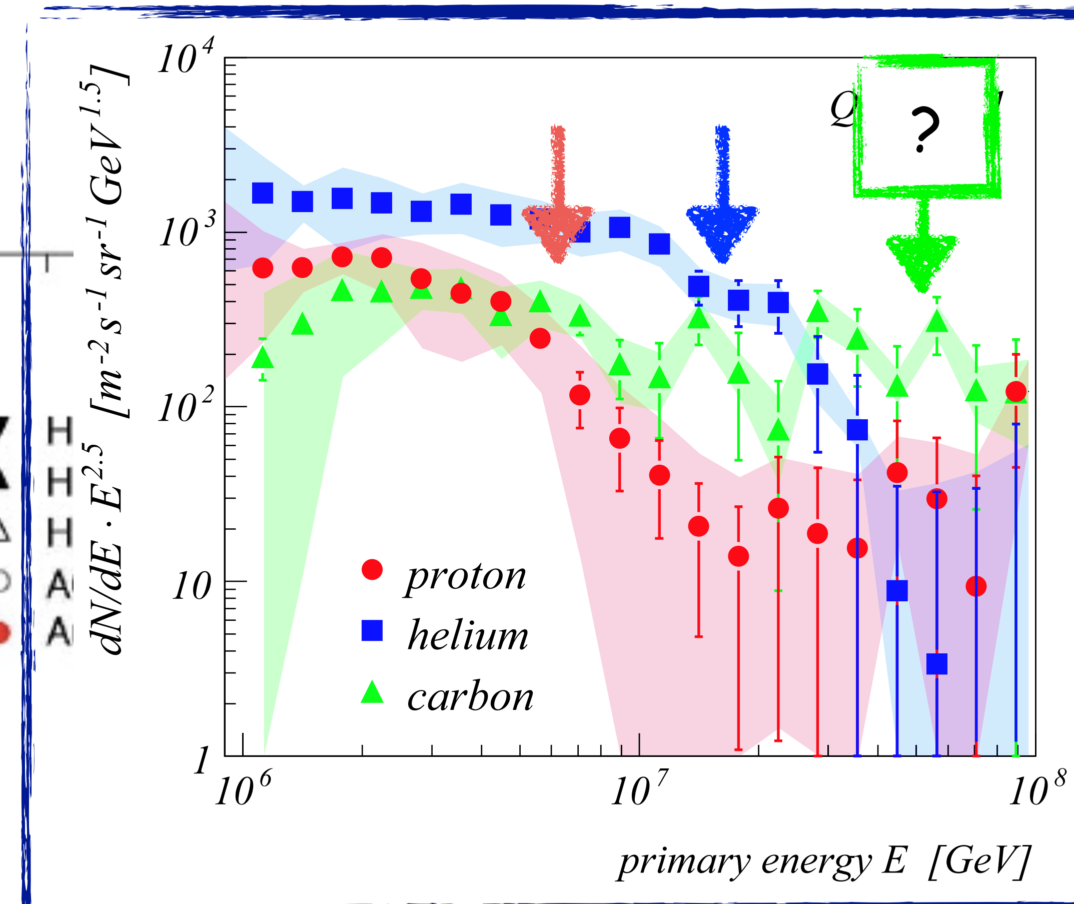


KASCADE coll. 2005

Z-dependent knee

Transition from galactic to extra-galactic CRs





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Z-dependent knee

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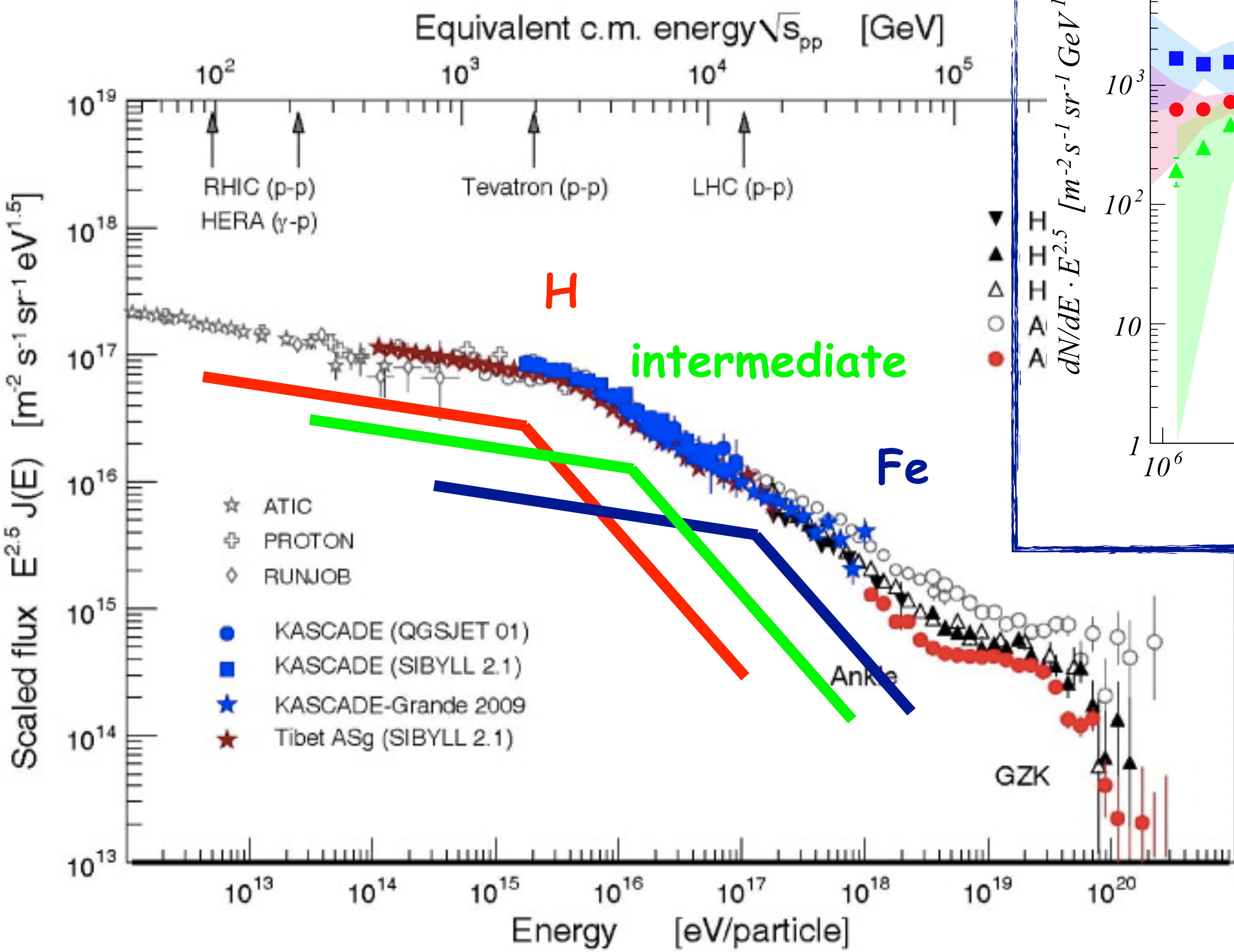

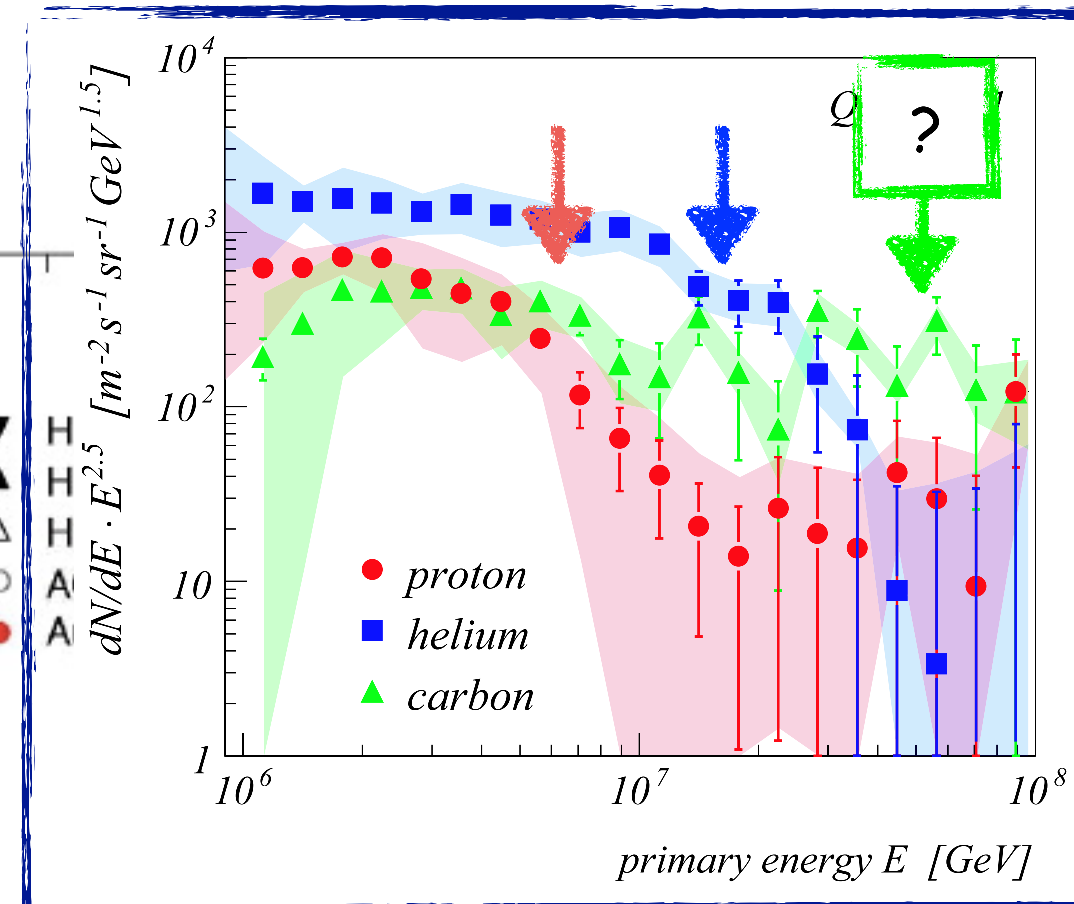

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Z-dependent knee

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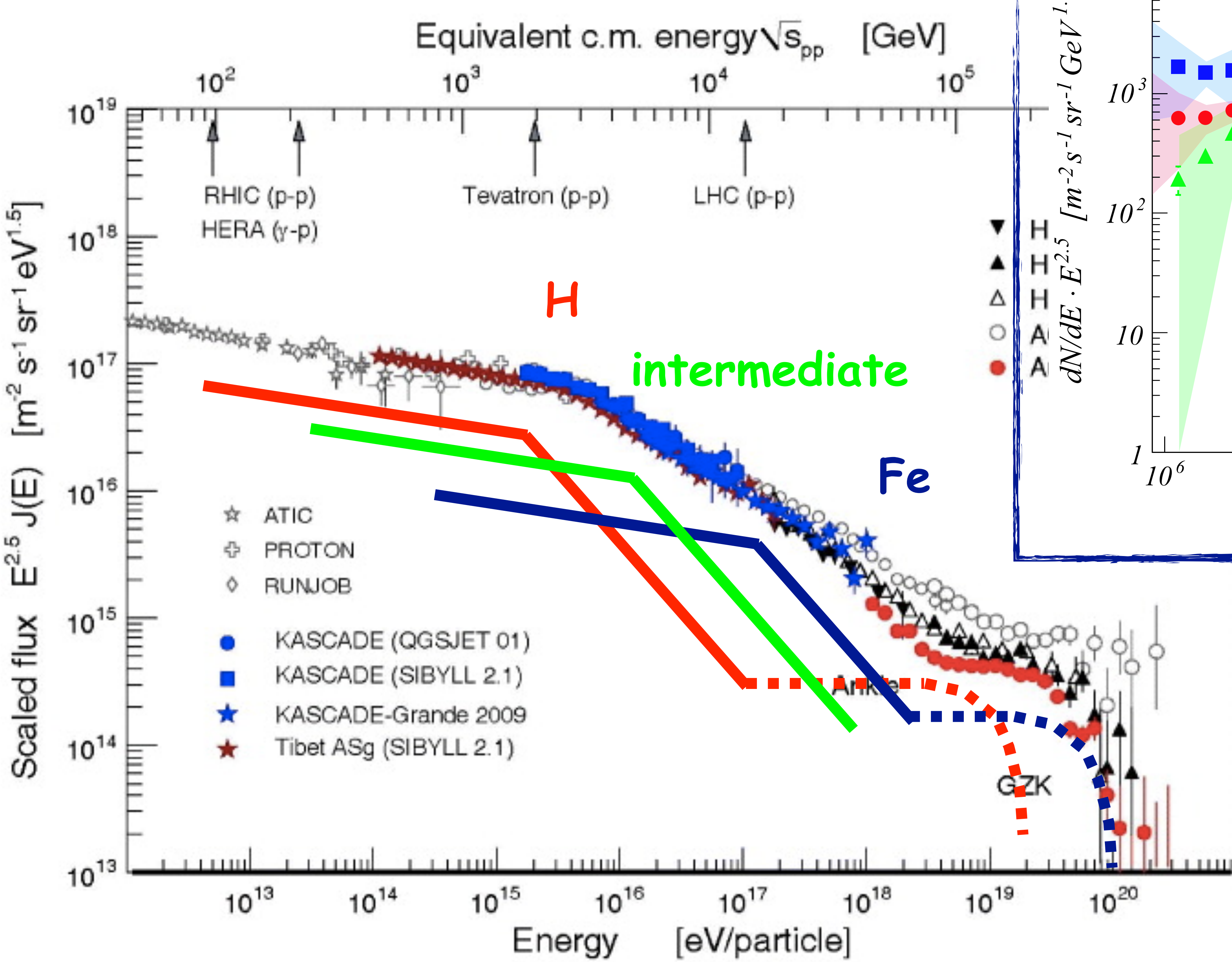

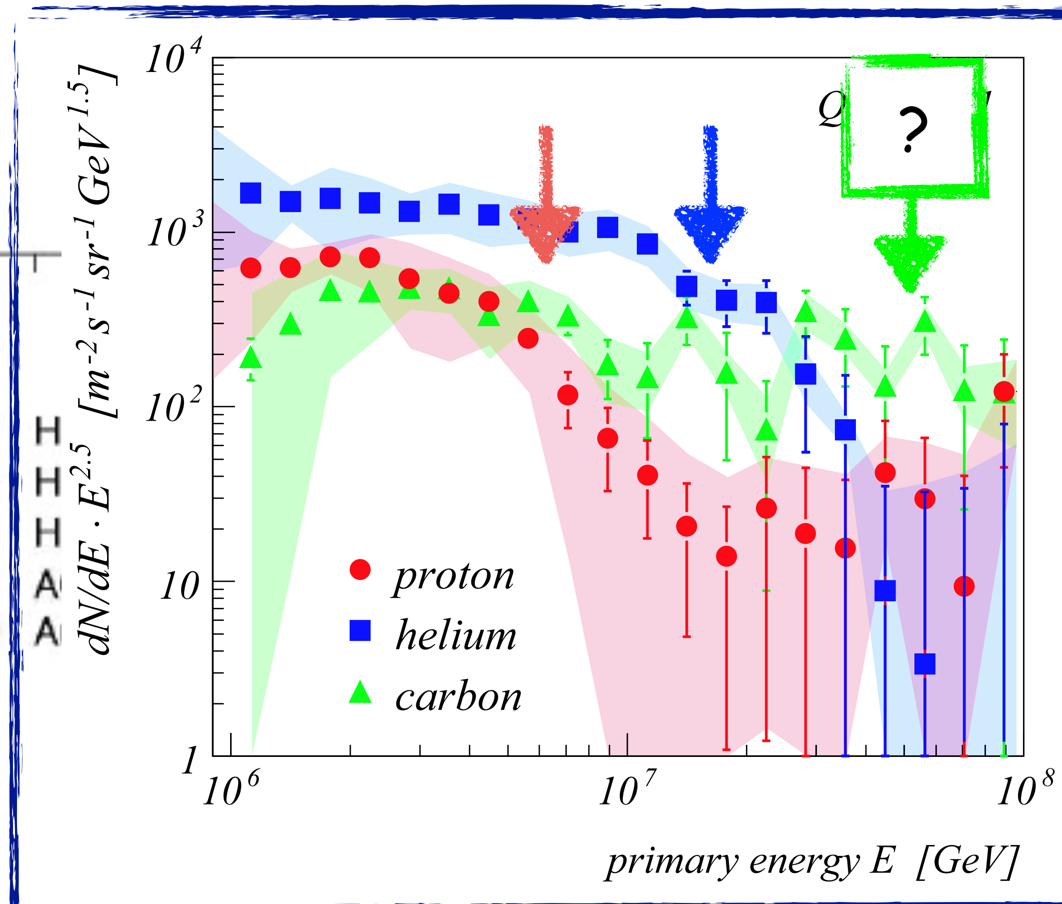

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Z-dependent knee

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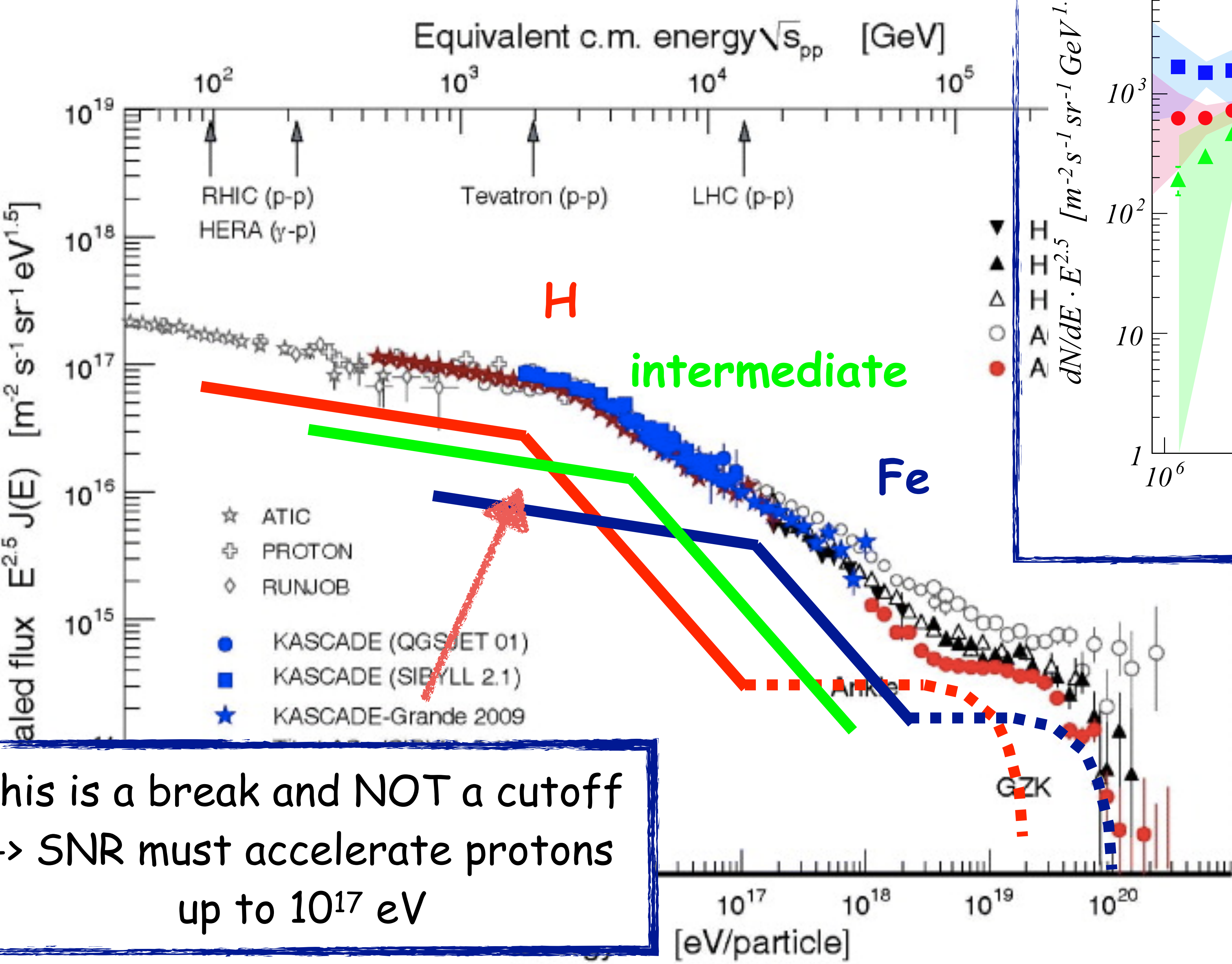

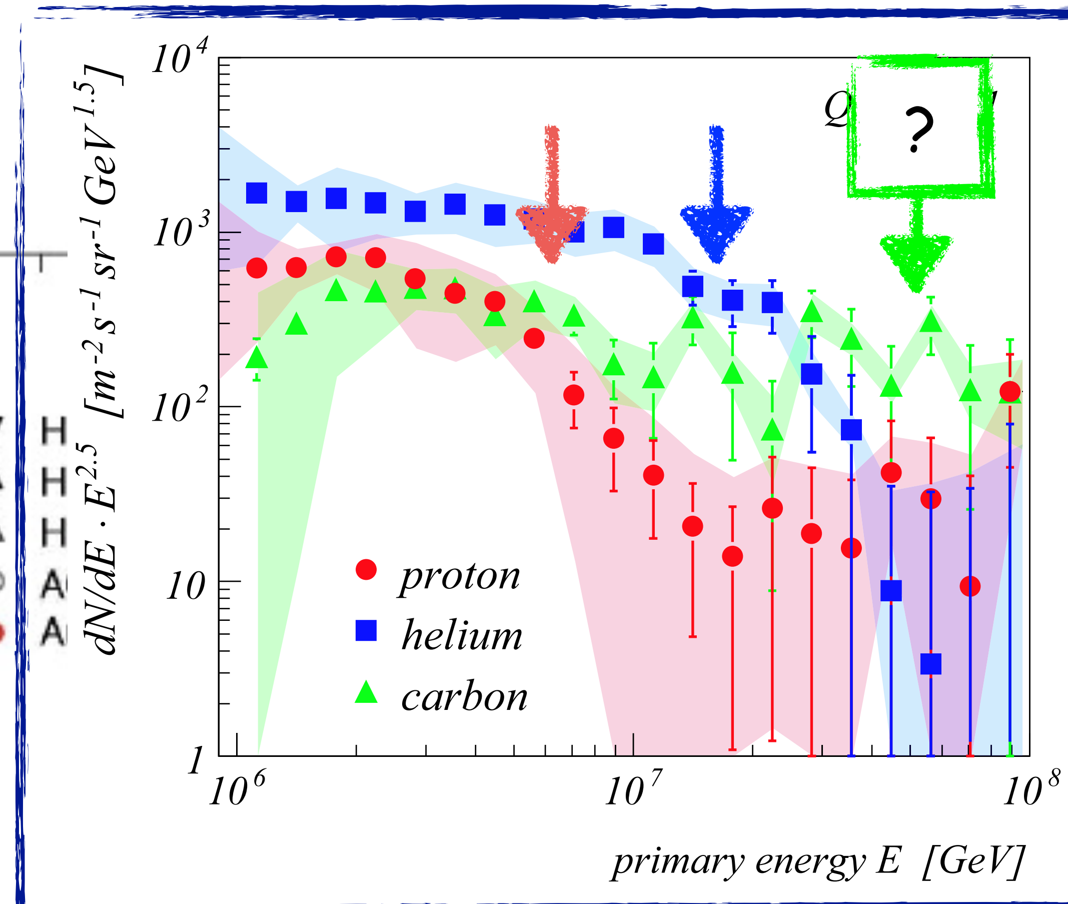

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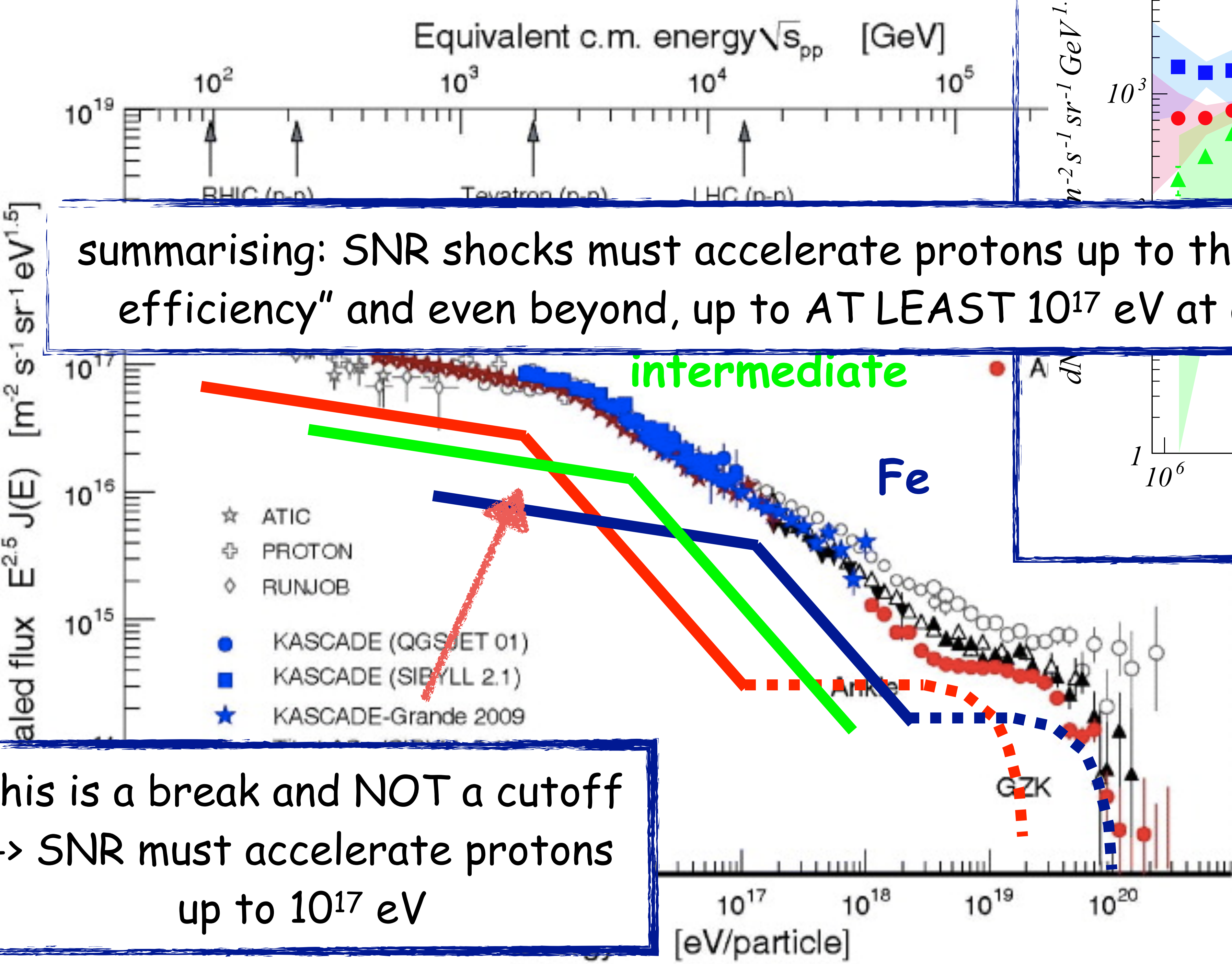
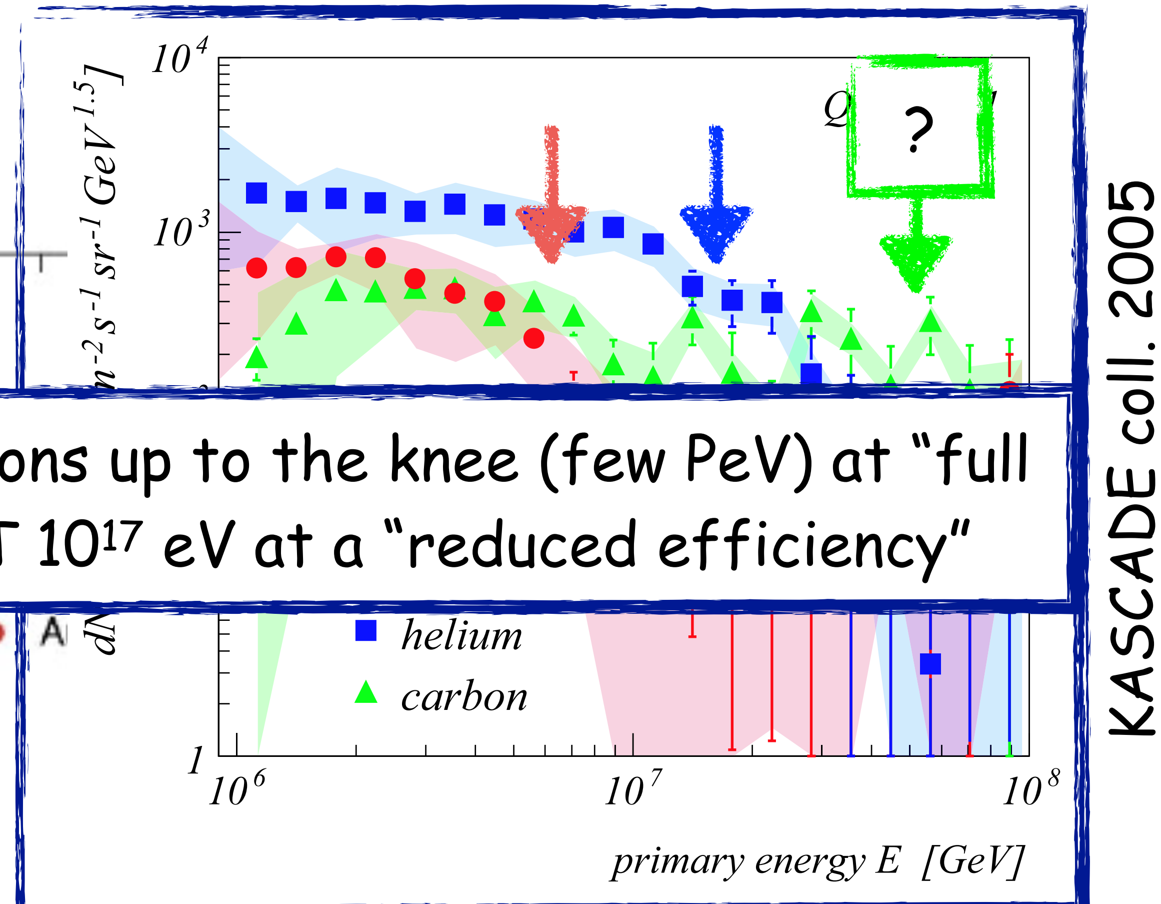
Z-dependent knee

this is a break and NOT a cutoff
-> SNR must accelerate protons
up to 10^{17} eV

Transition from galactic to extra-galactic CRs





summarising: SNR shocks must accelerate protons up to the knee (few PeV) at "full efficiency" and even beyond, up to AT LEAST 10^{17} eV at a "reduced efficiency"

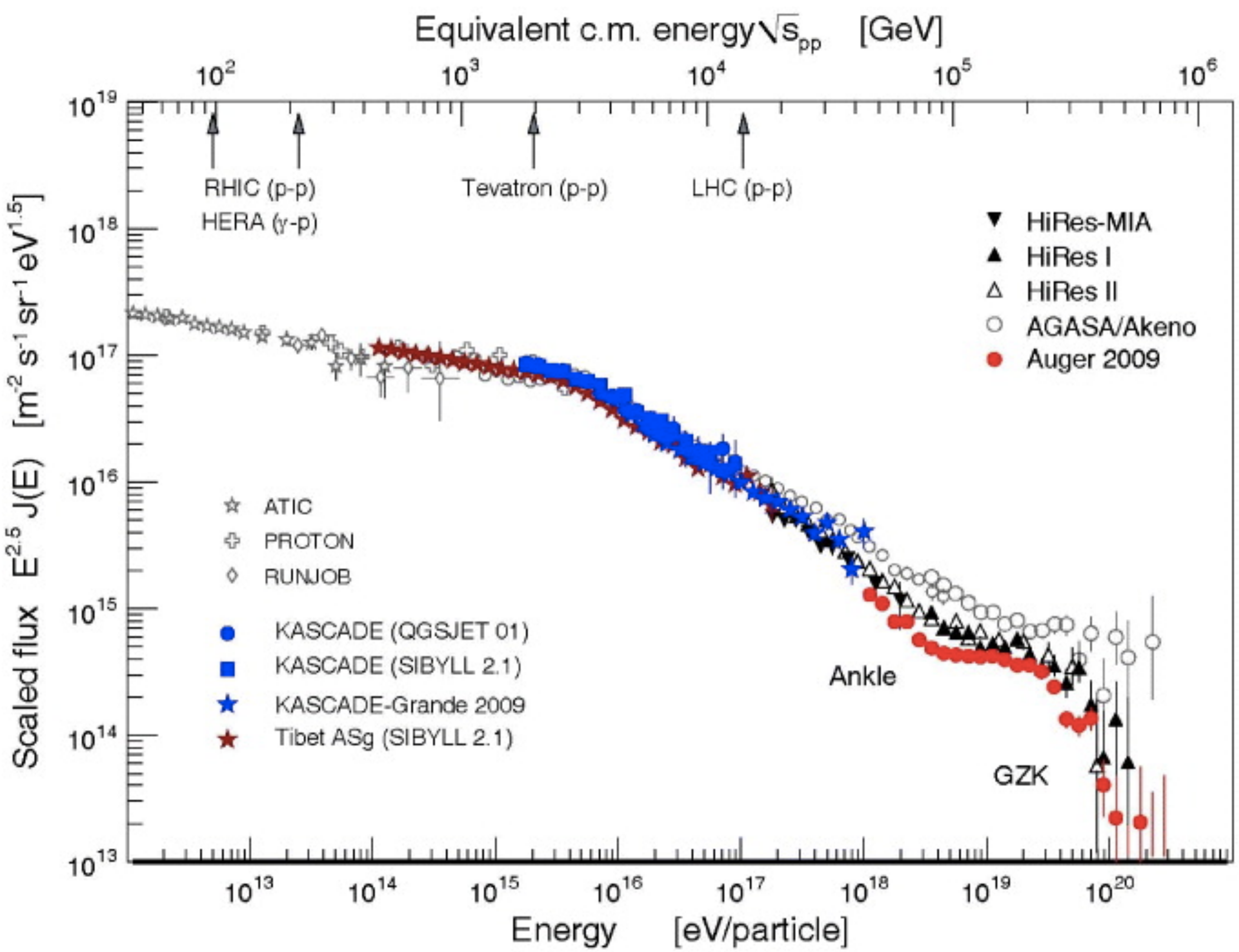
Z-dependent knee

this is a break and NOT a cutoff -> SNR must accelerate protons up to 10^{17} eV

Can SNRs explain this?

—> see Pasquale's talk

Hillas criterion —> B-field MUST be amplified in order to reach the knee



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↖ ↘

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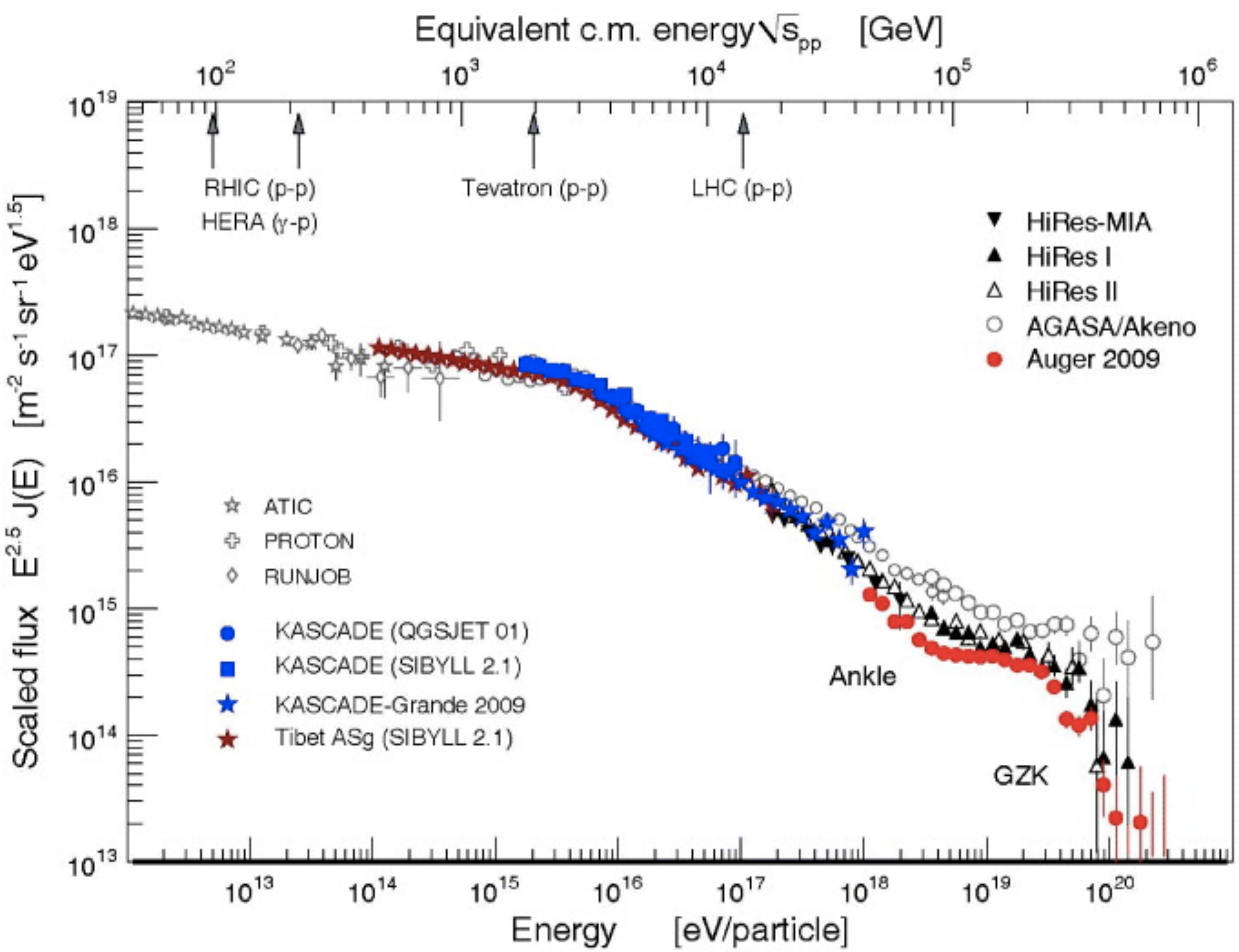

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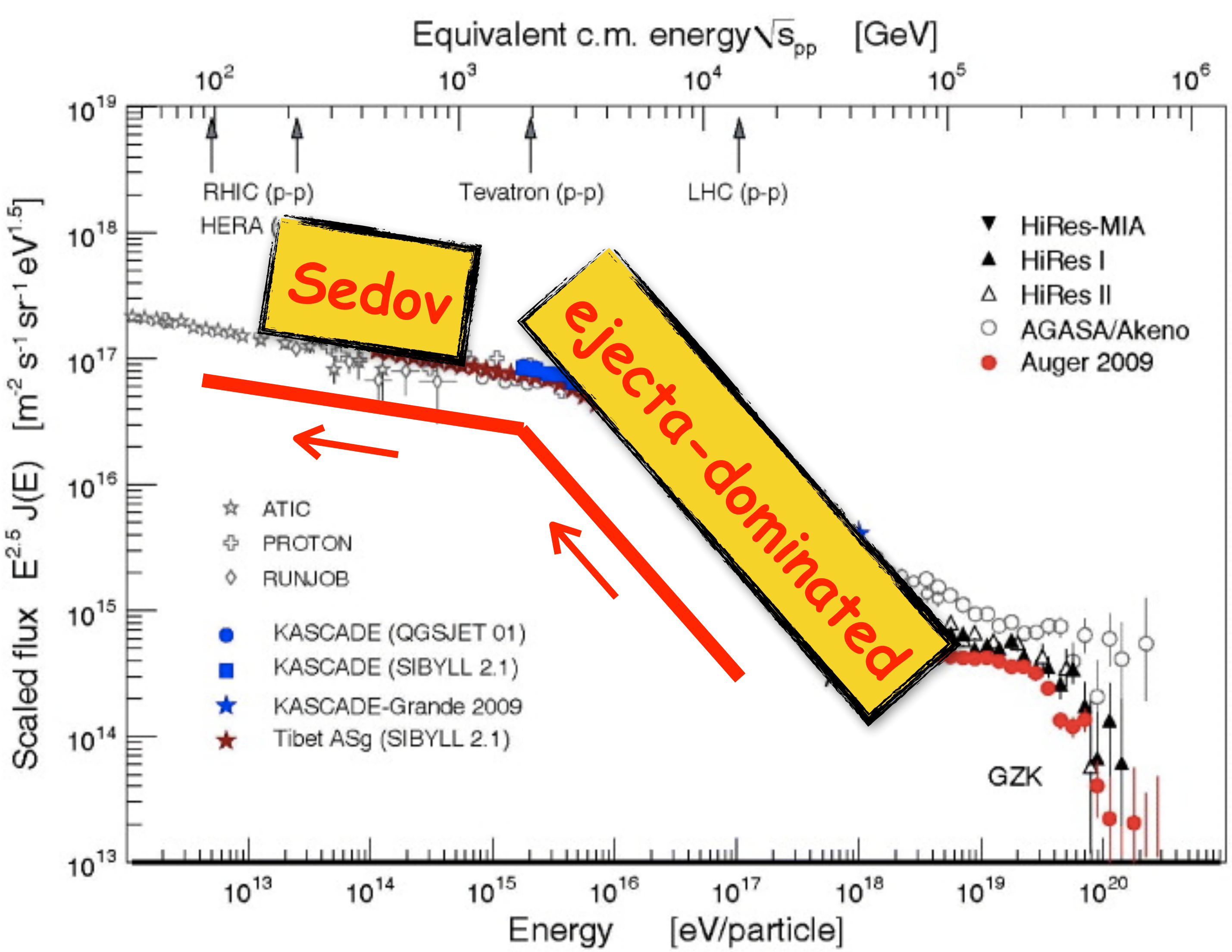

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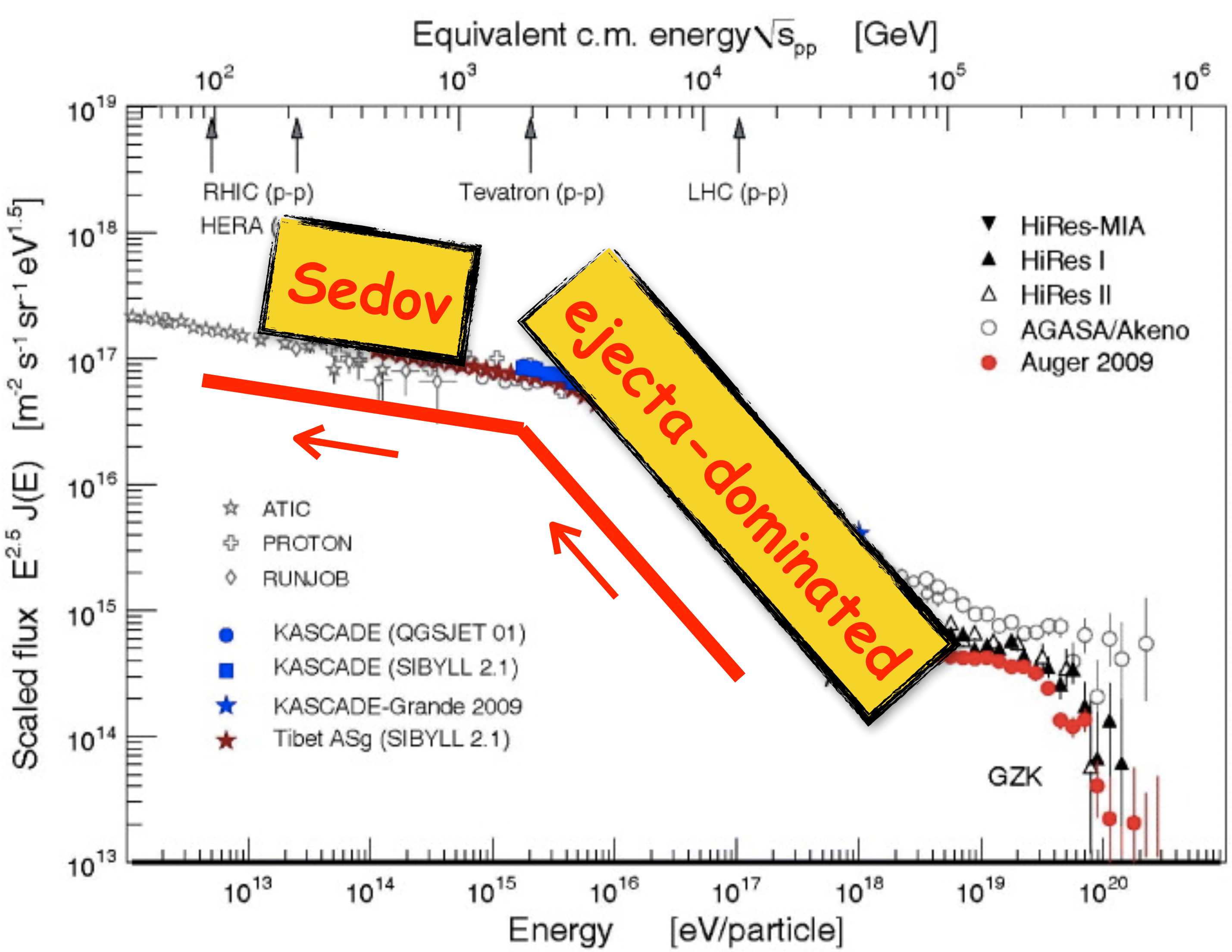

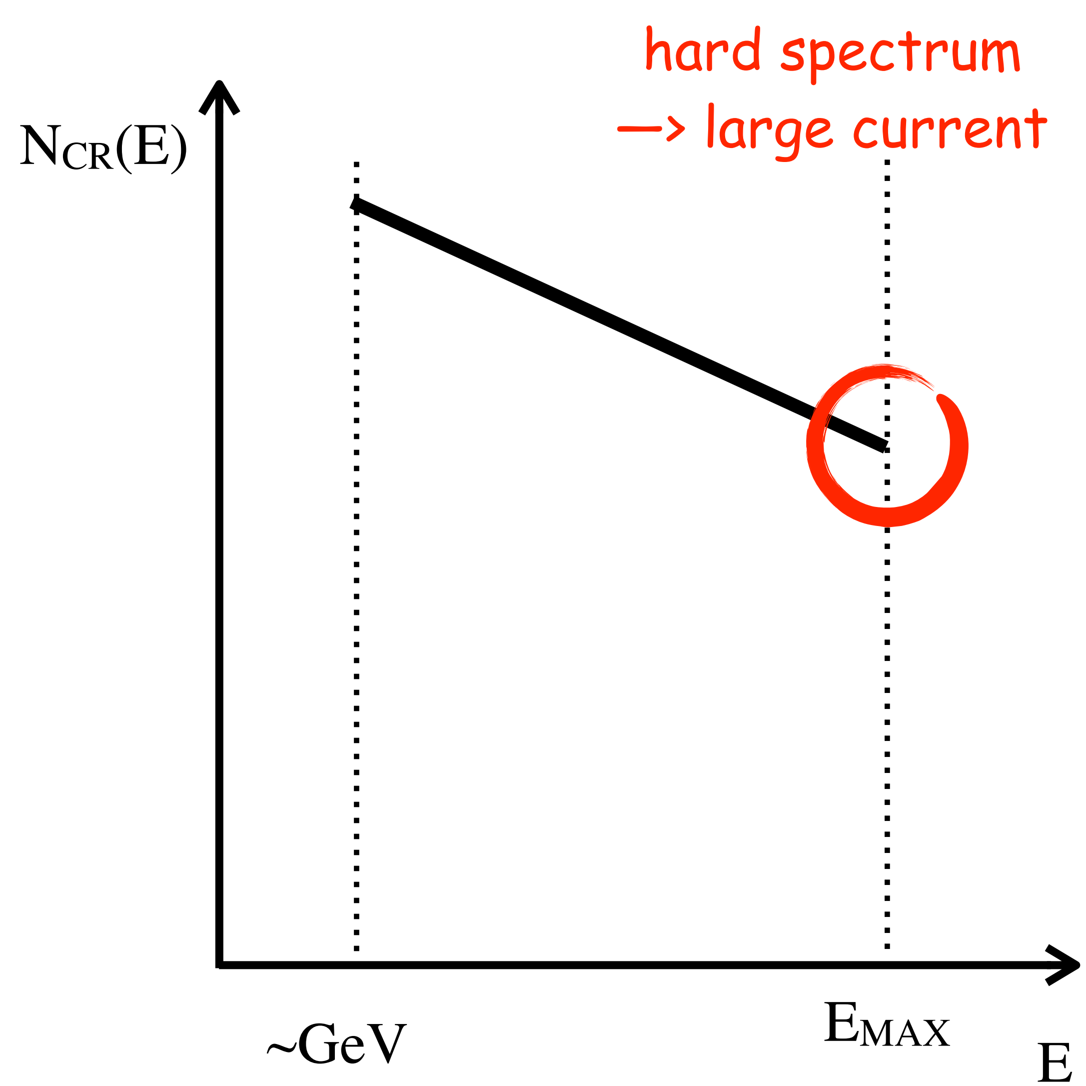

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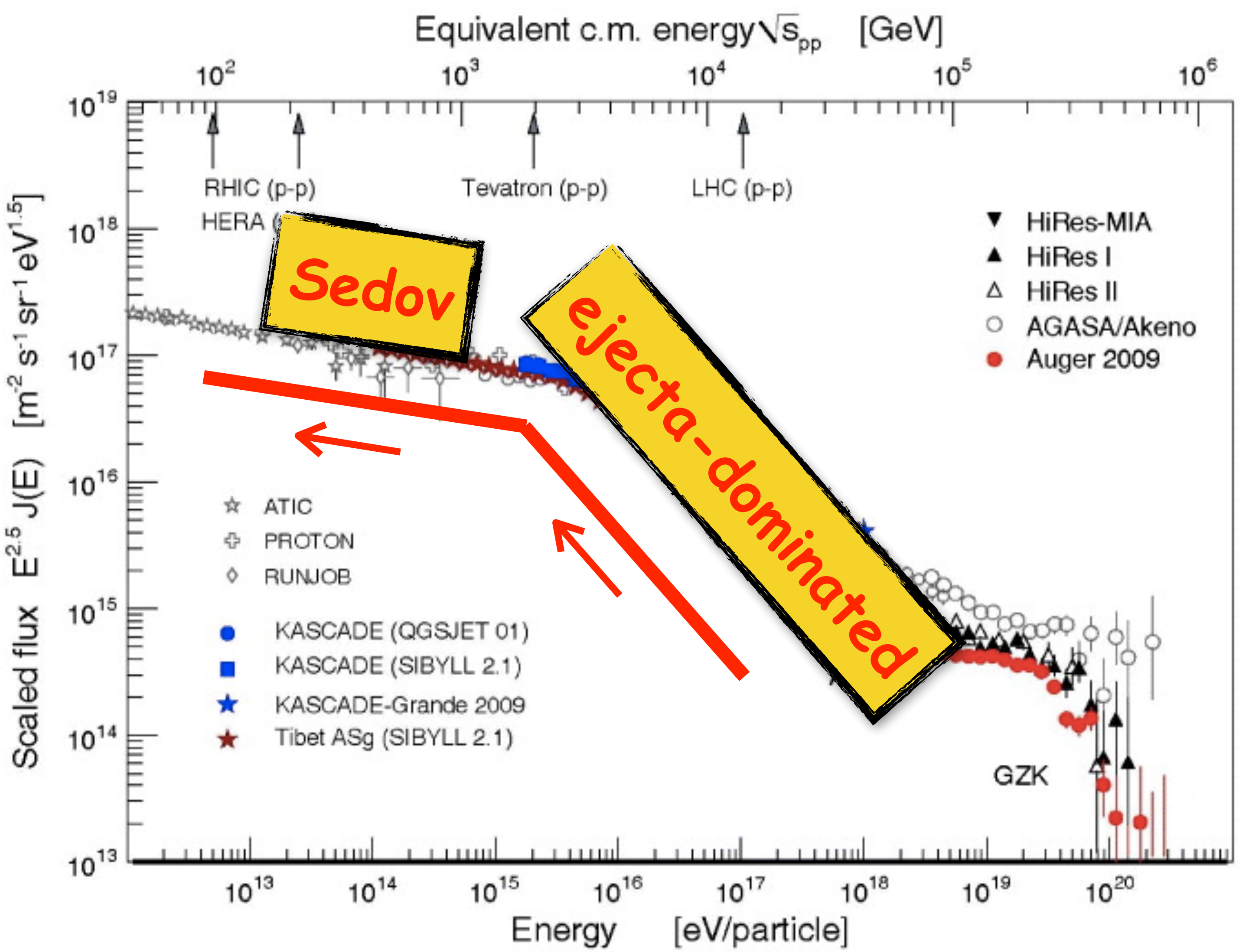
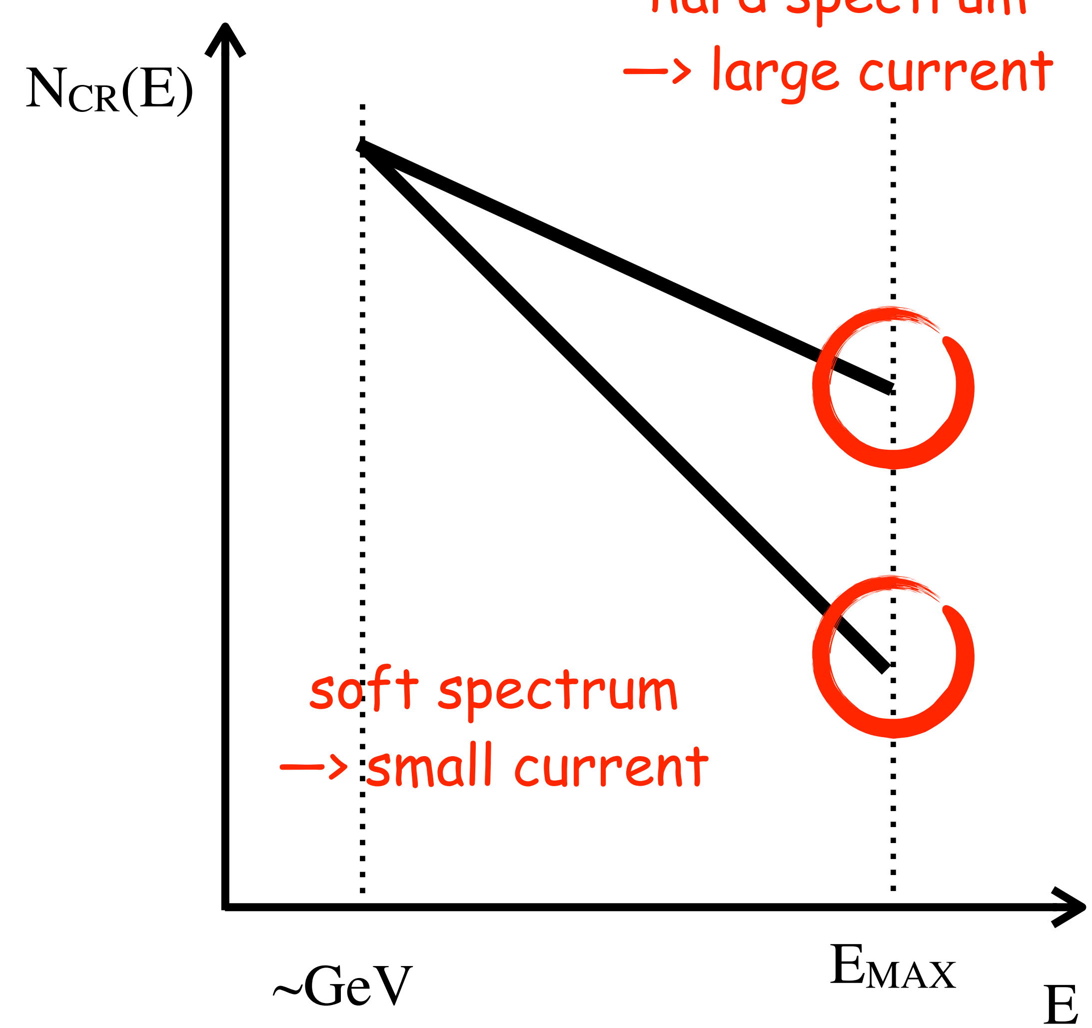
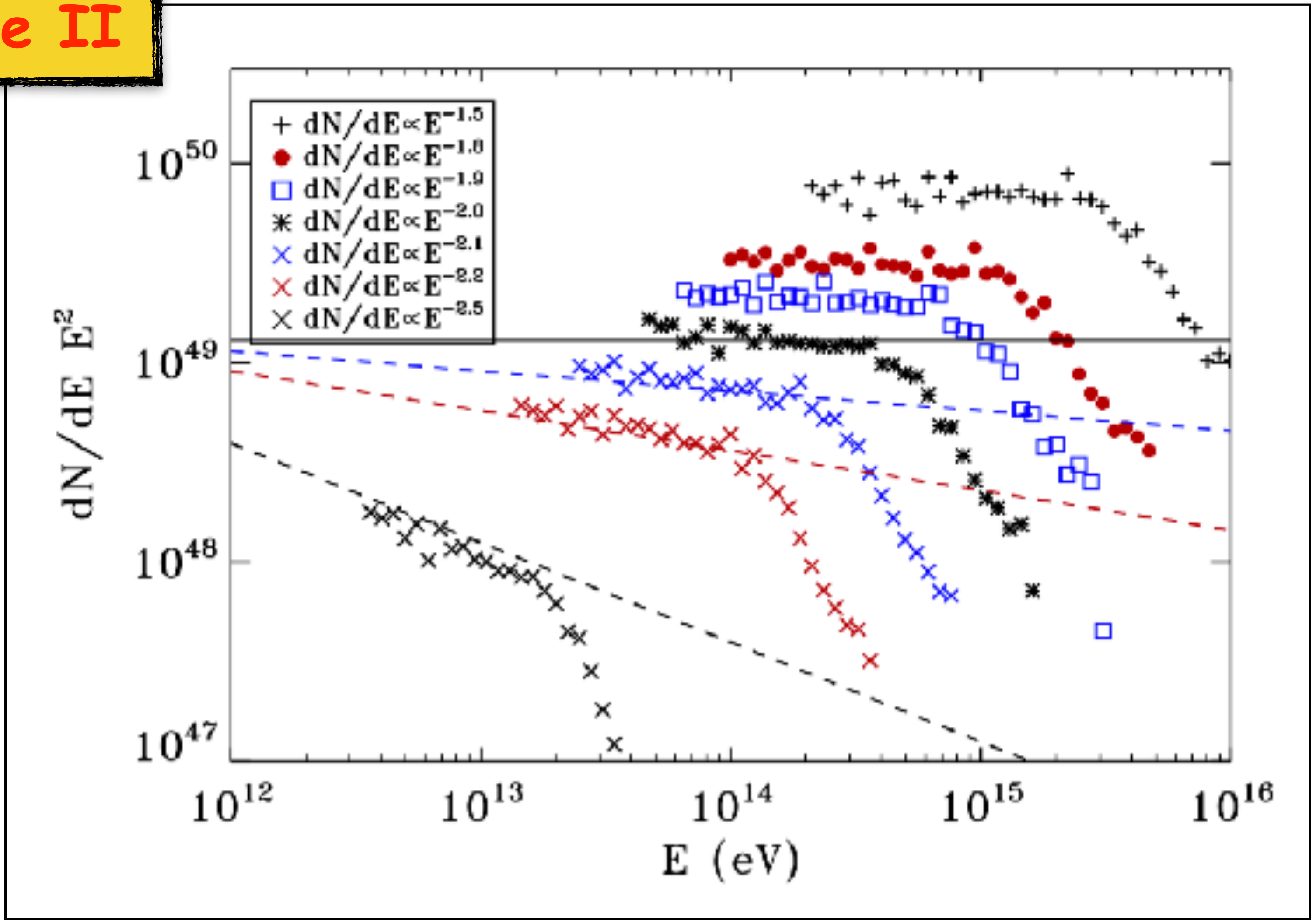




One can't have everything…

spectrum of CRs released in the ISM during the entire SNR life

type II



Schure & Bell 2014

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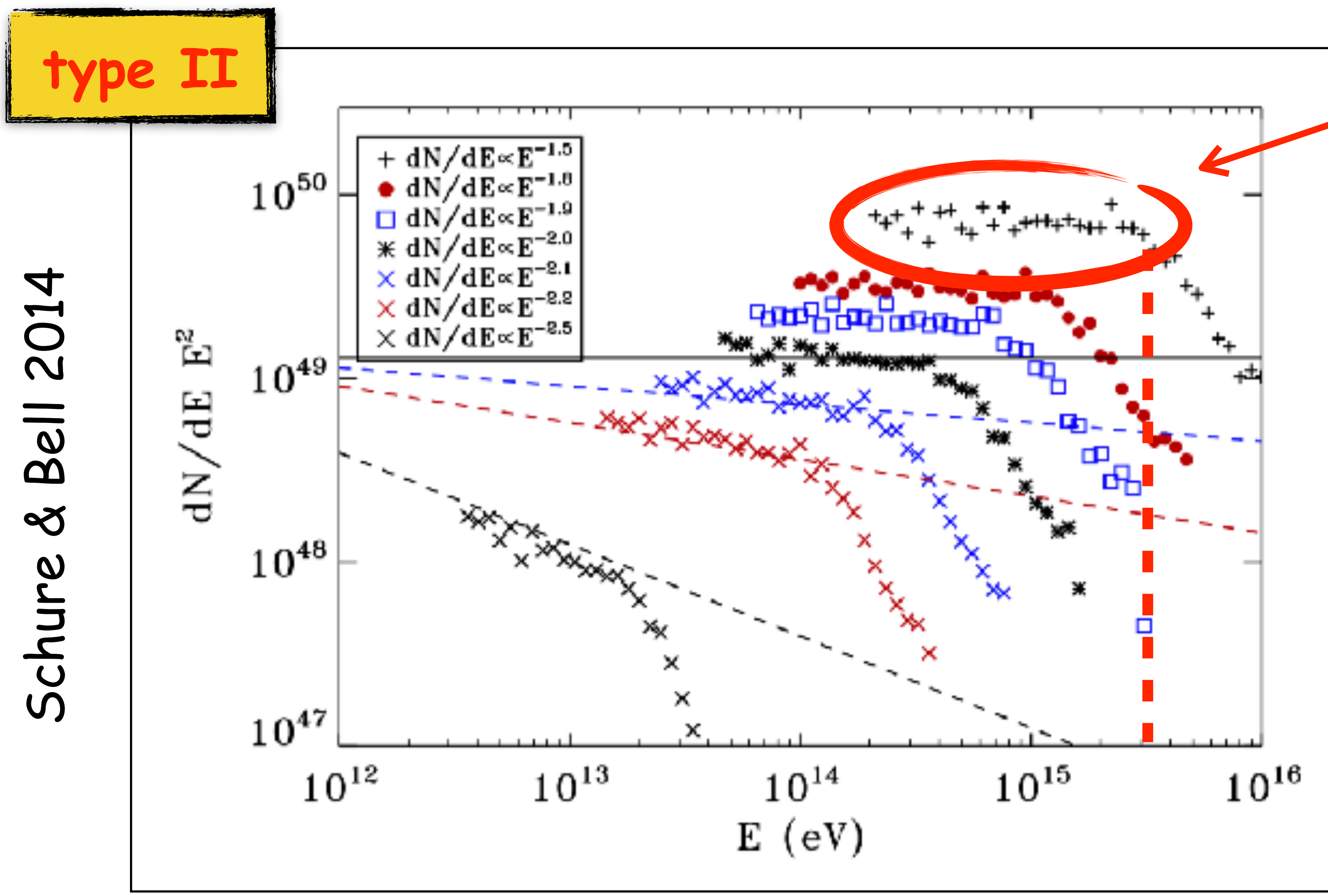

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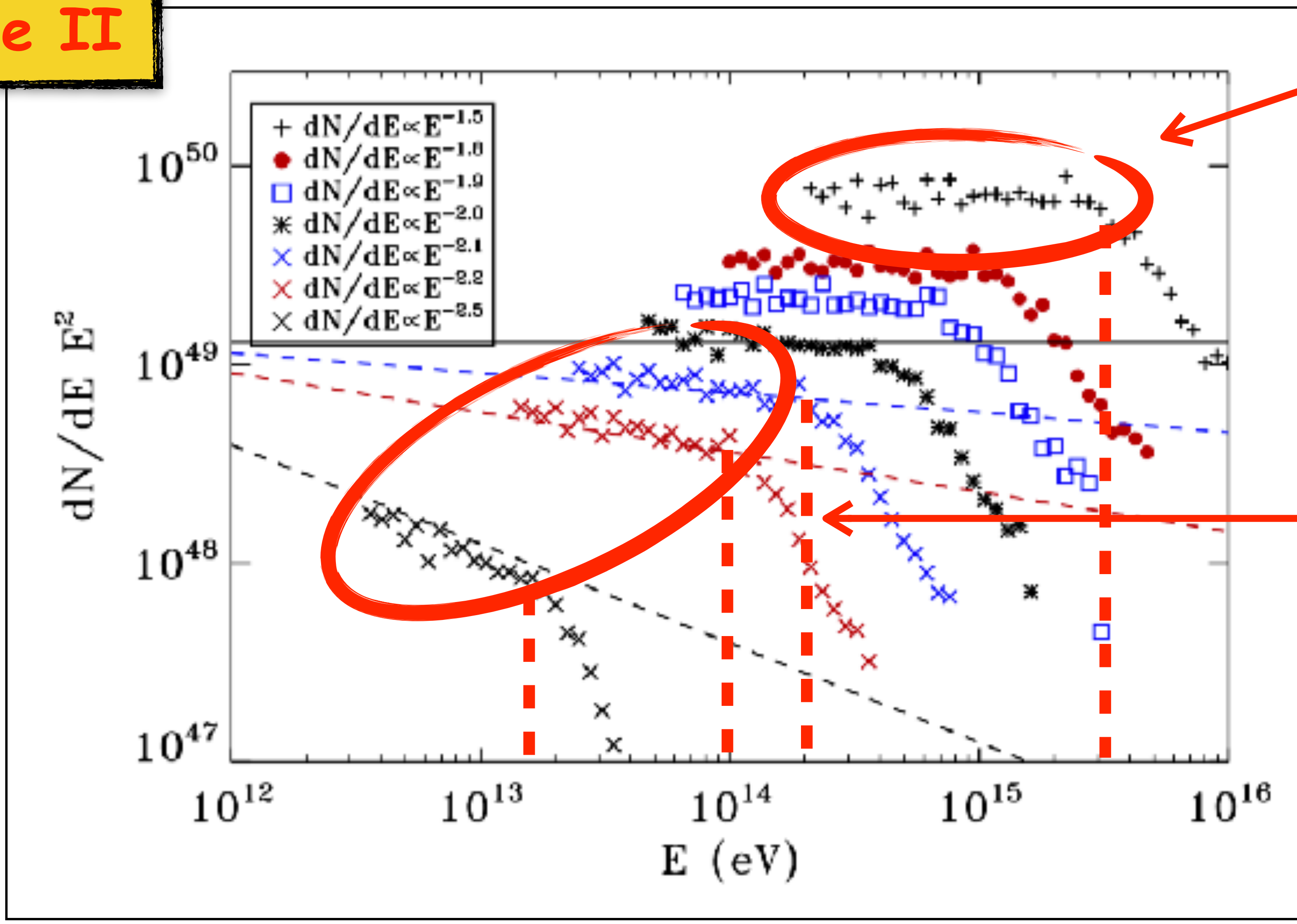

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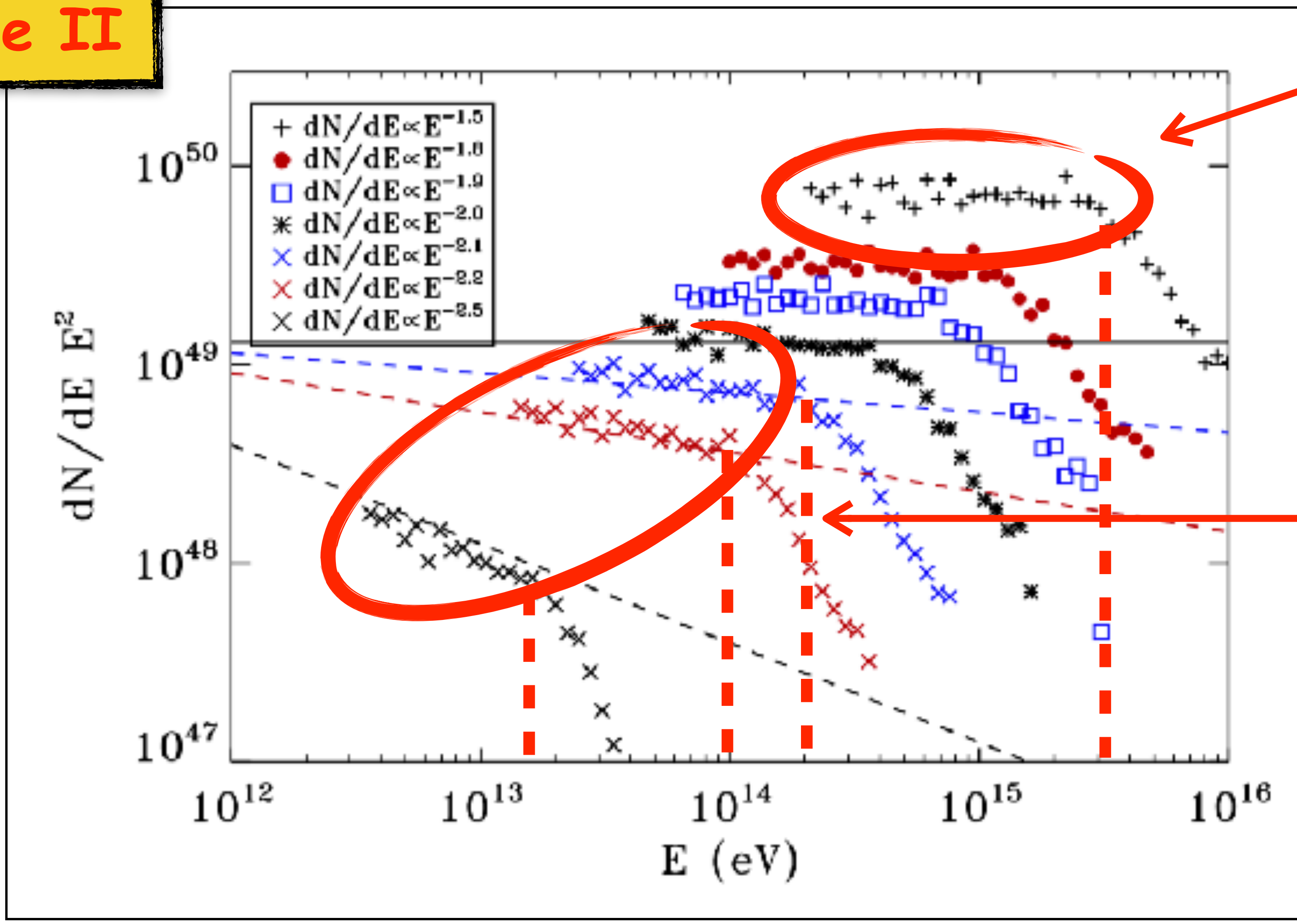

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(Cristofari+ 2020)

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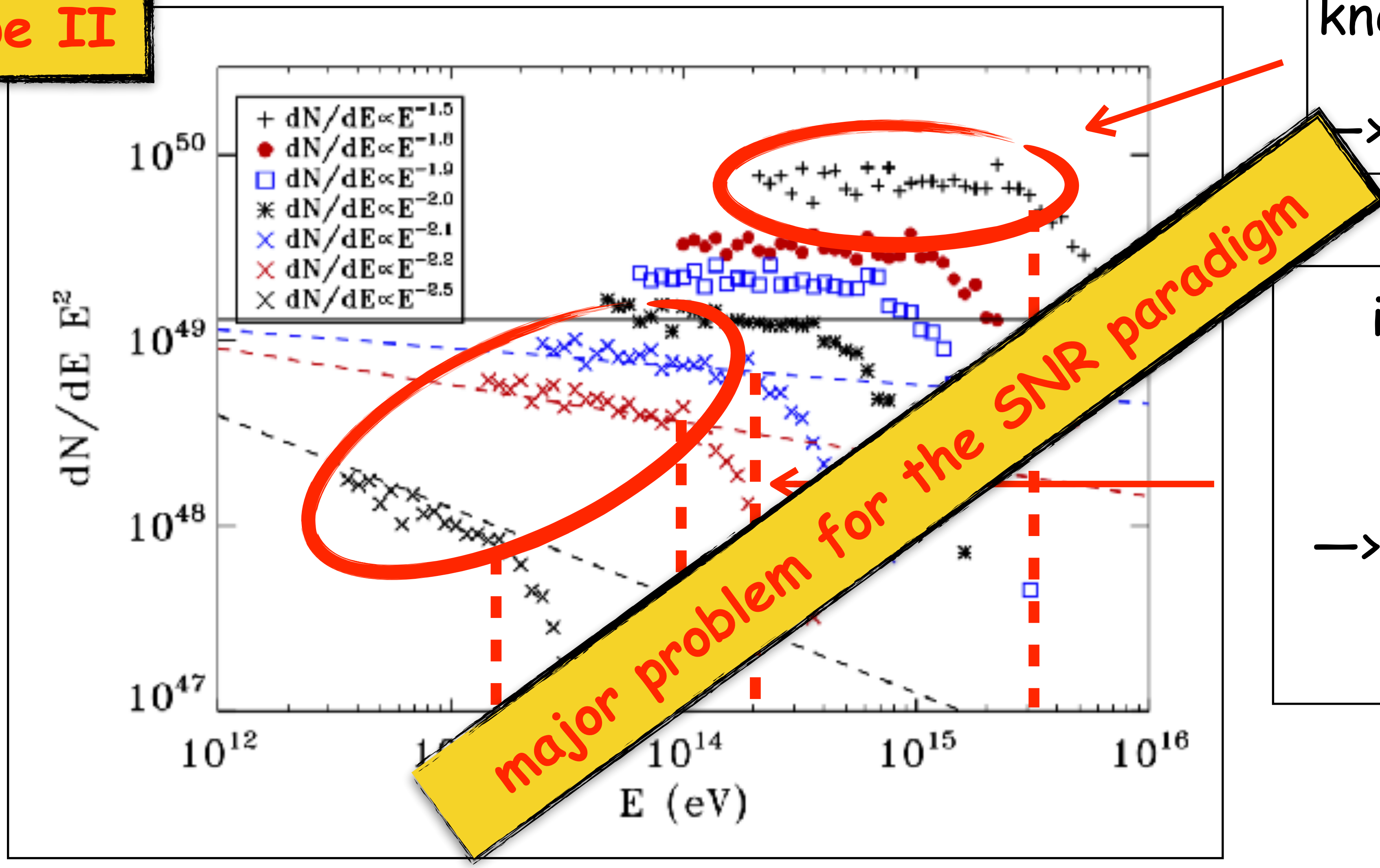

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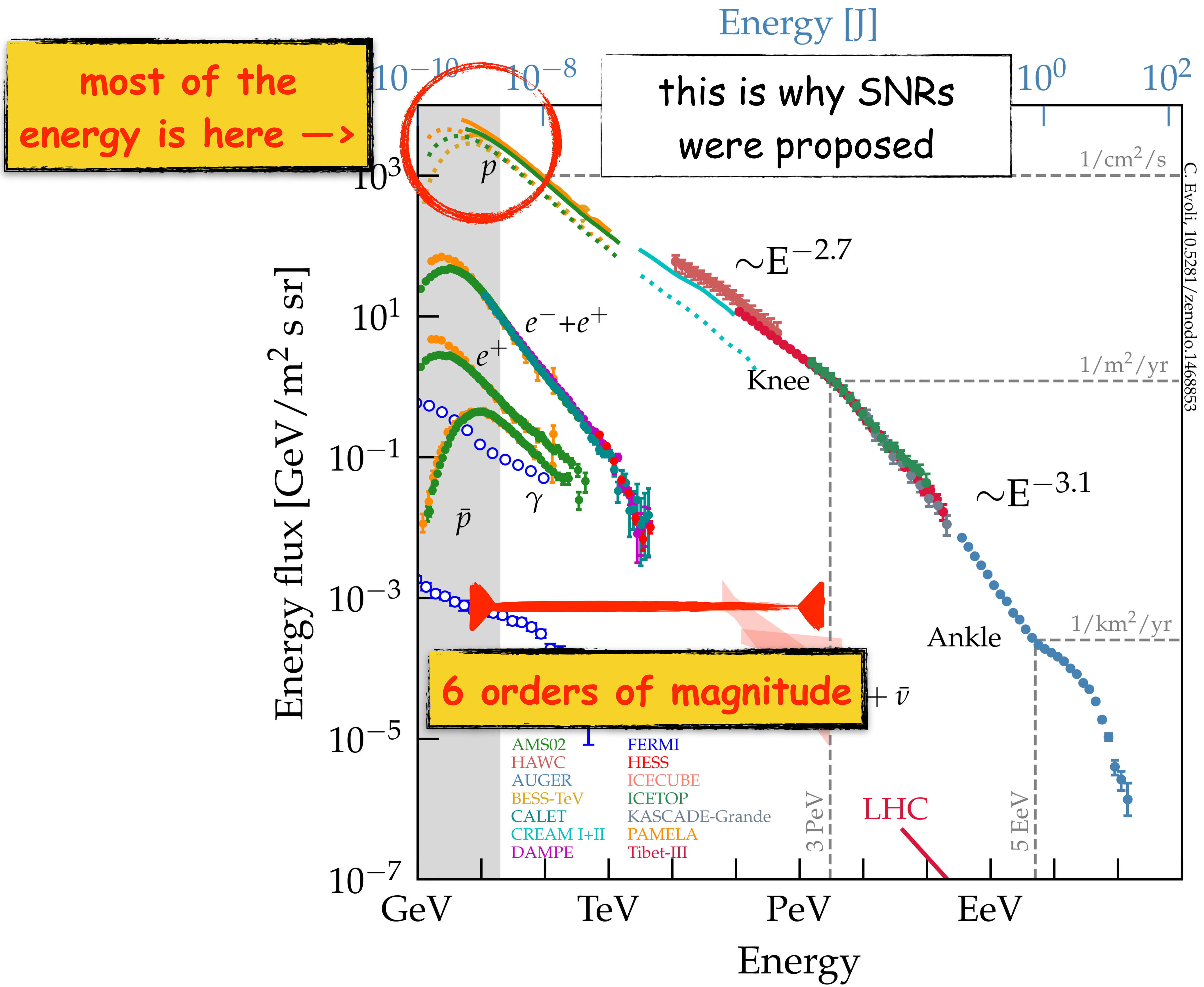
[4] The role of stellar wind termination shocks

—> see Giovanni's talk

Note on energetic



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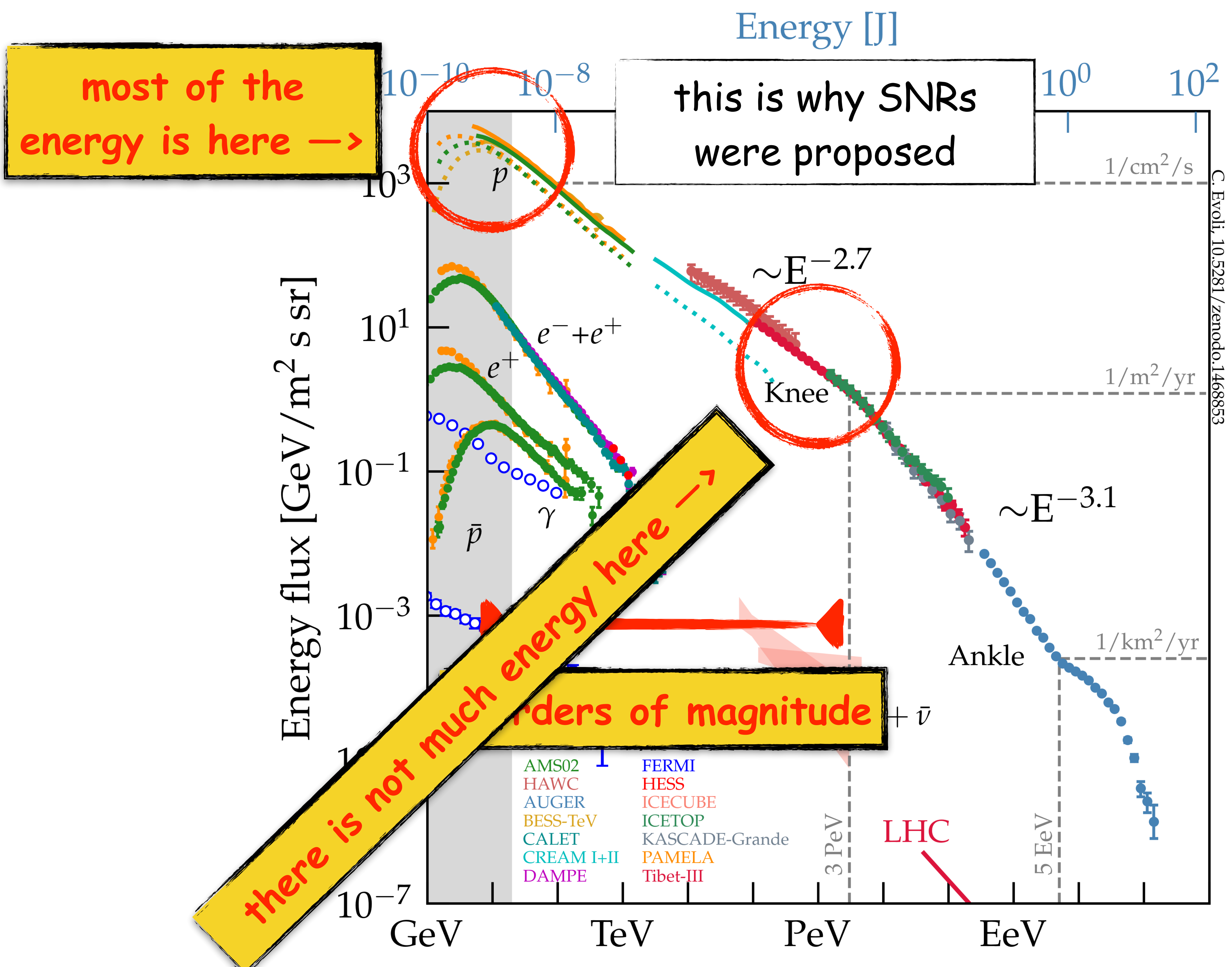

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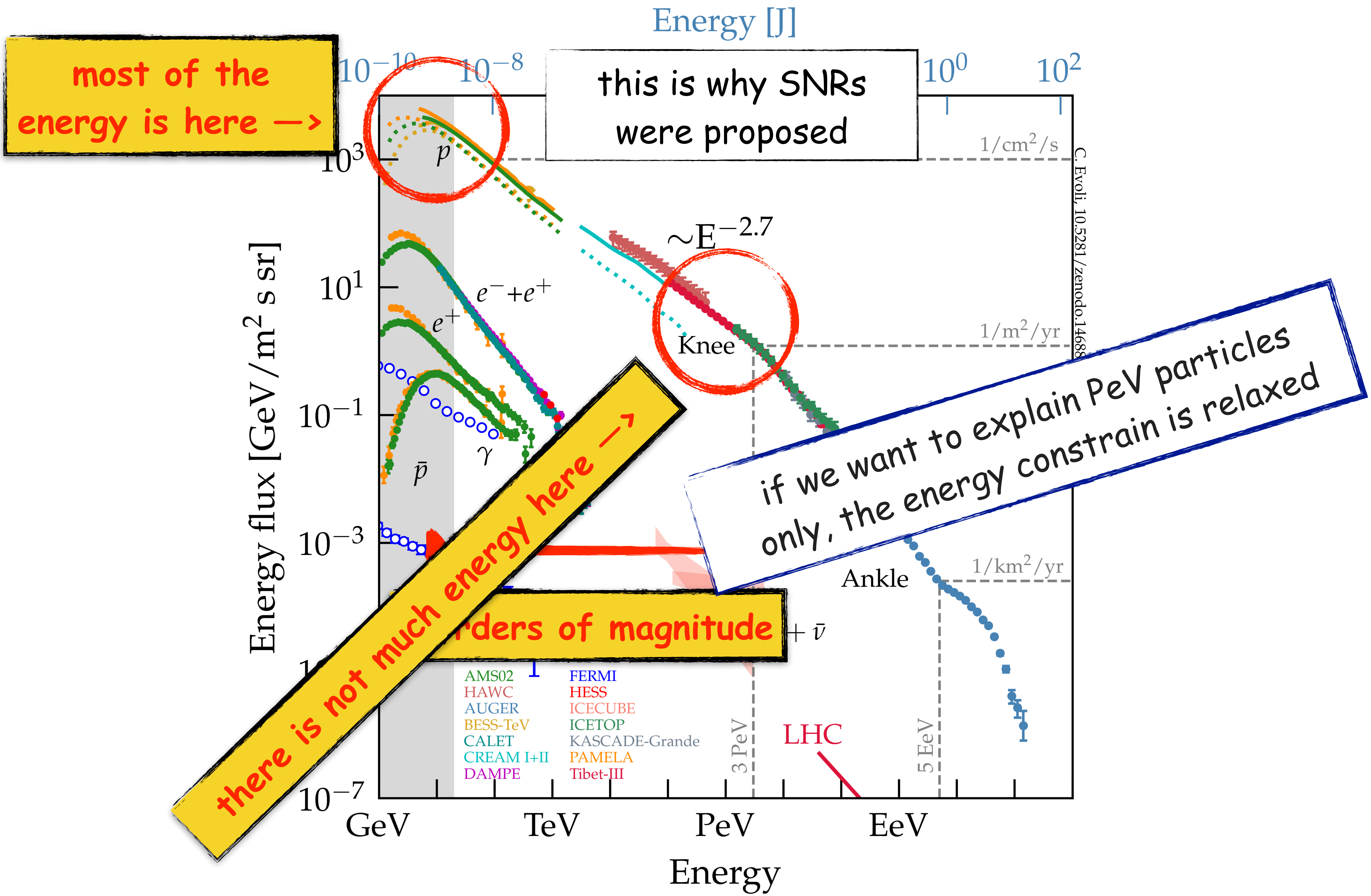
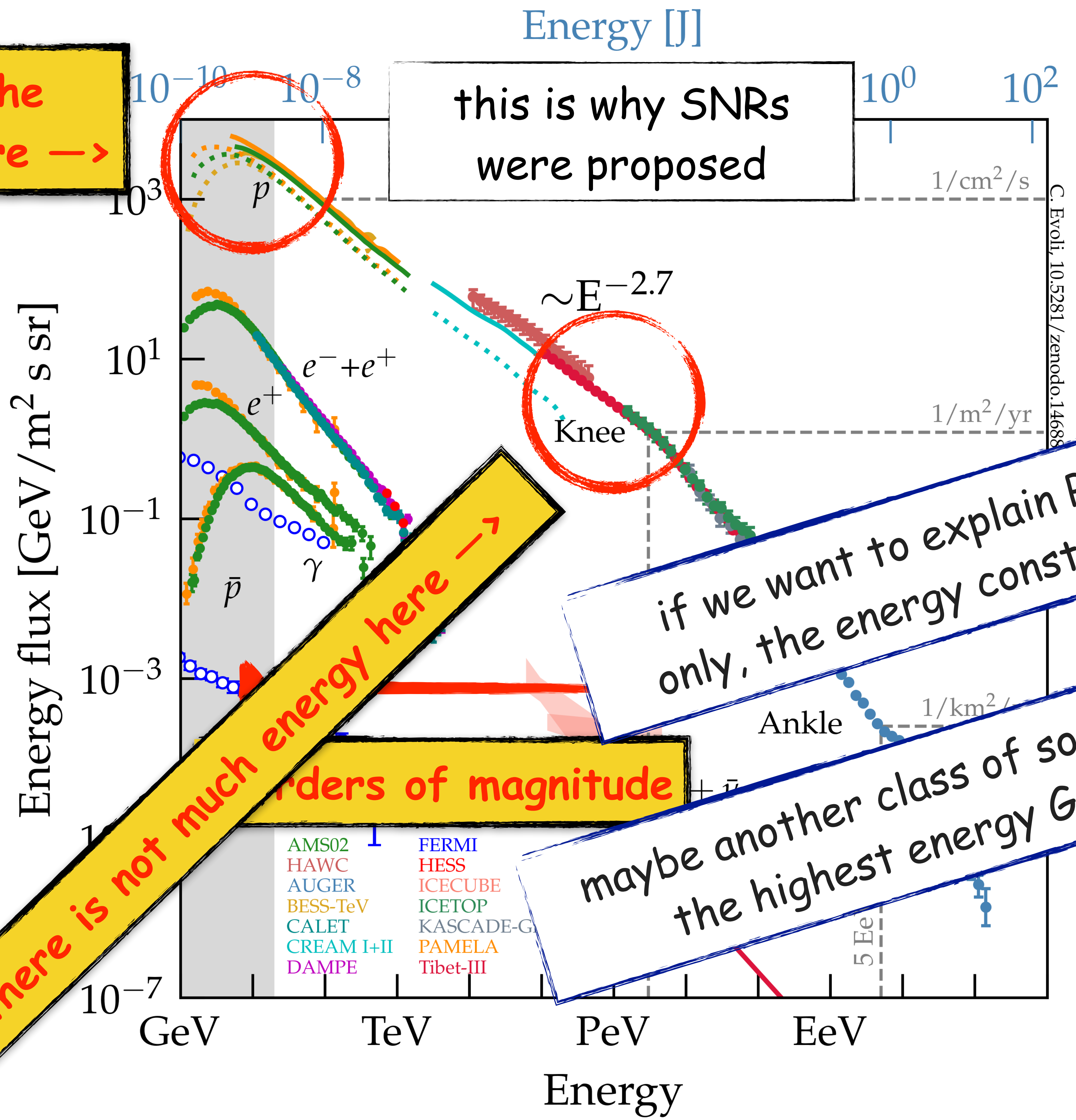


Note on energetic

most of the energy is here —>

this is why SNRs were proposed



there is not much energy here —>

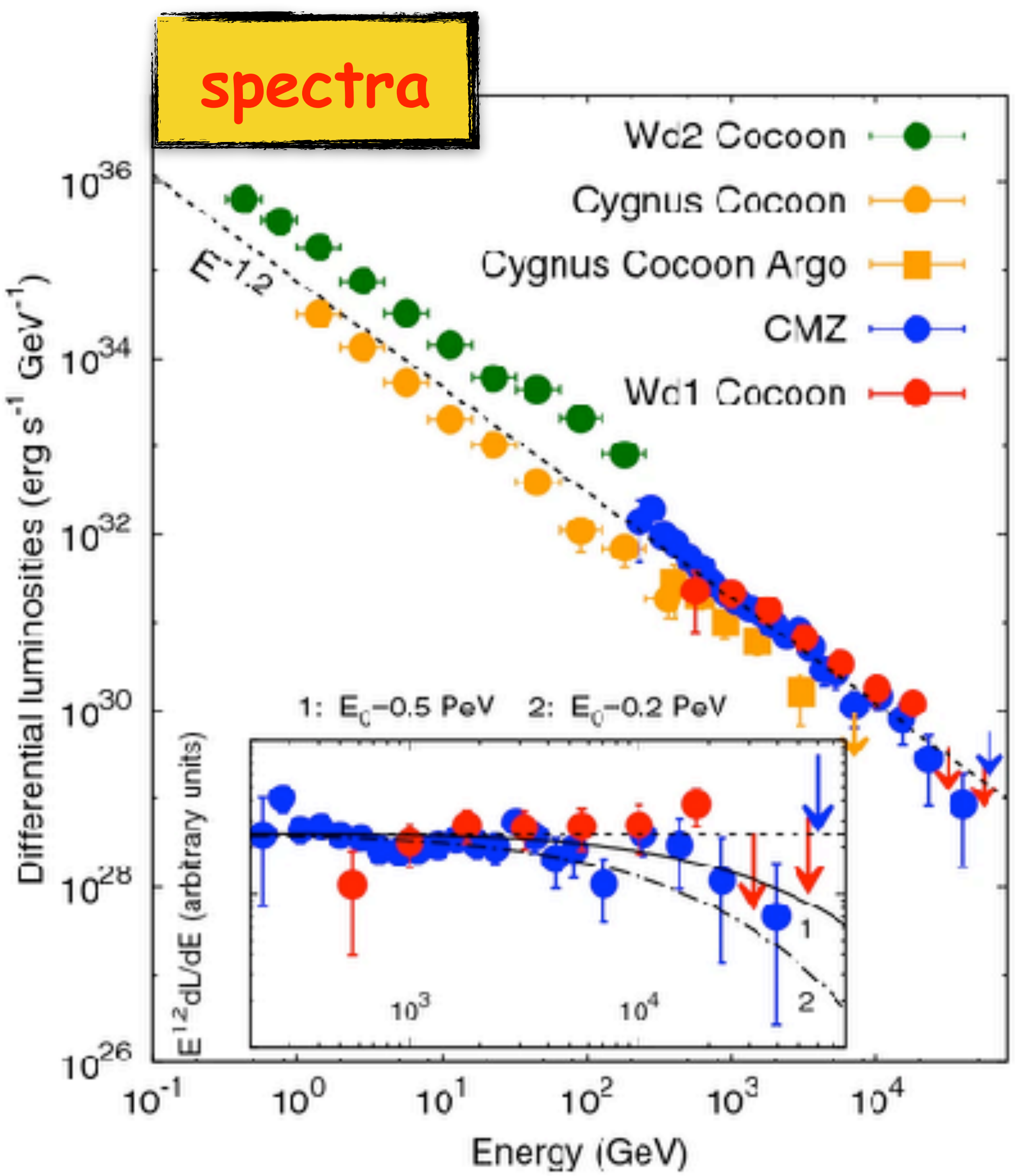
...rders of magnitude

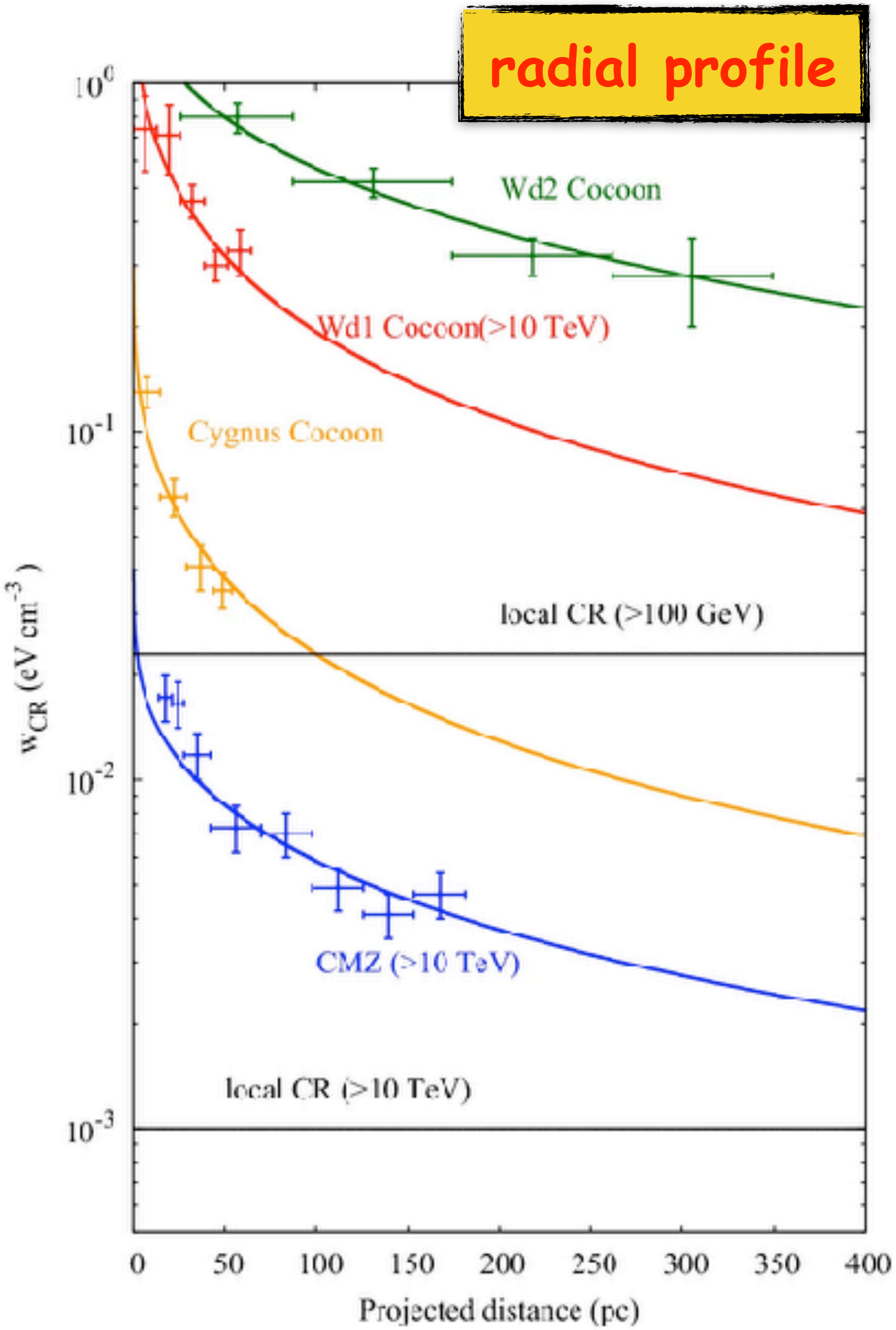
if we want to explain PeV particles only, the energy constrain is relaxed

maybe another class of sources produces the highest energy Galactic CRs?

Stars or star clusters? Gamma rays…

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





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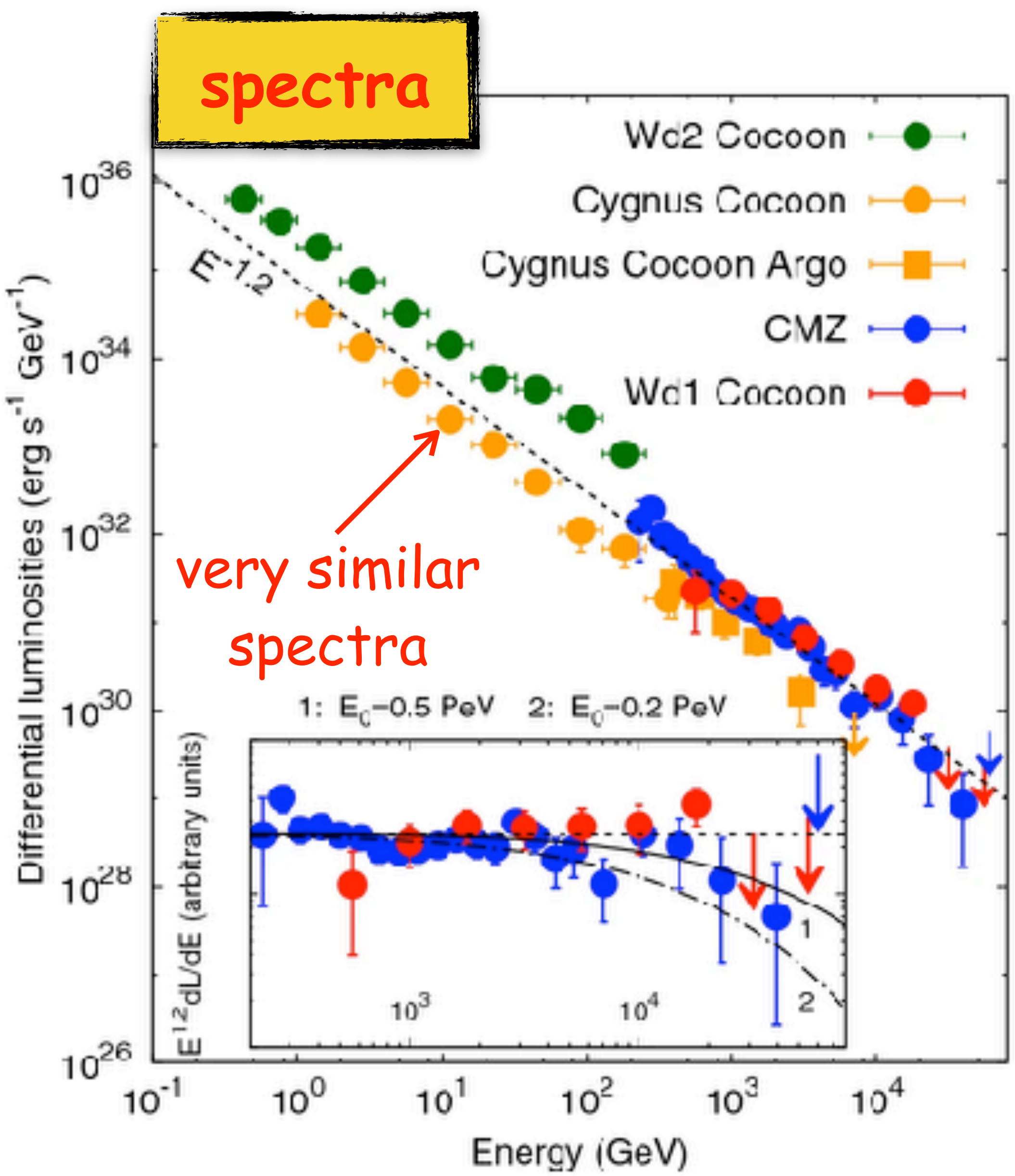

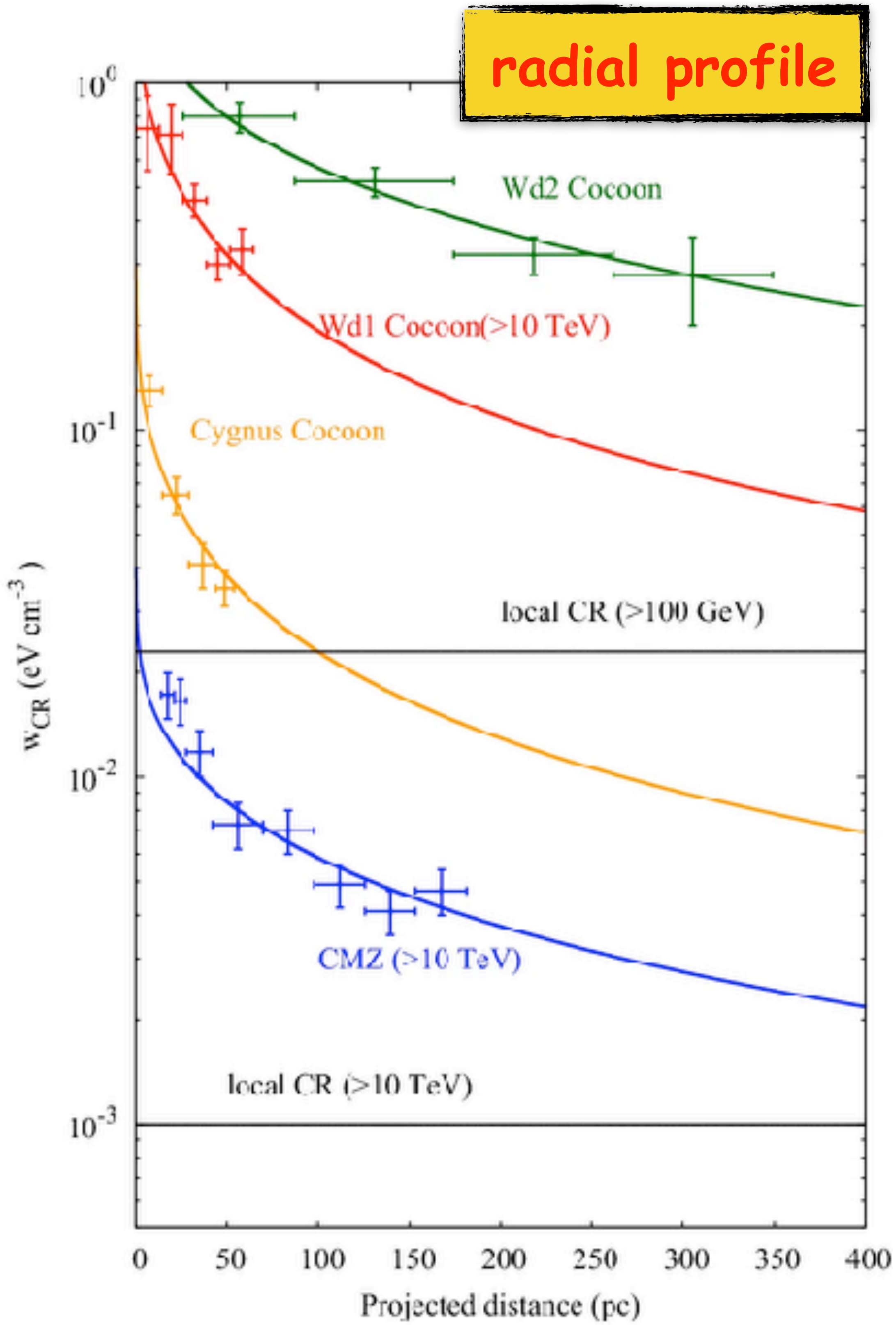

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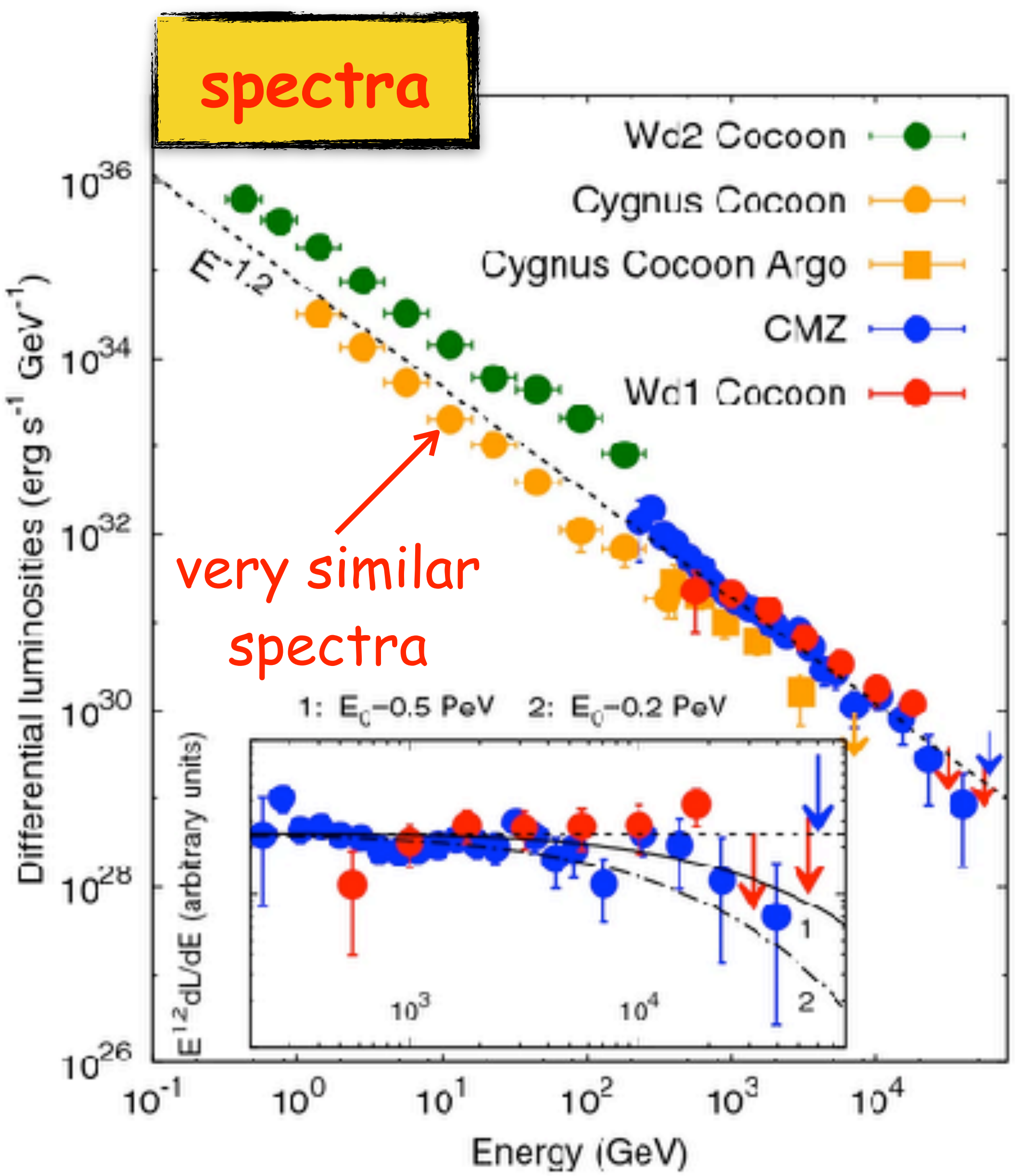

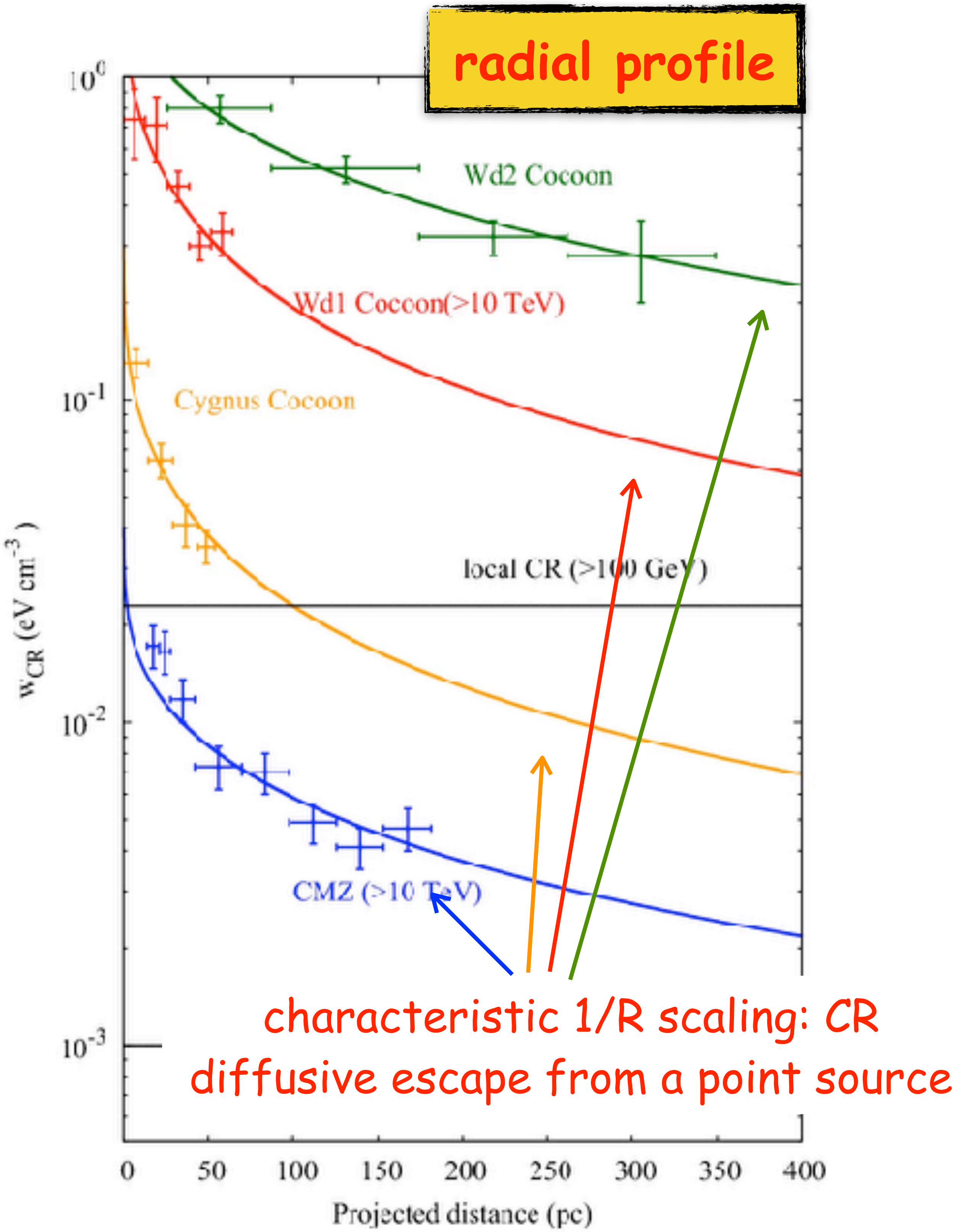

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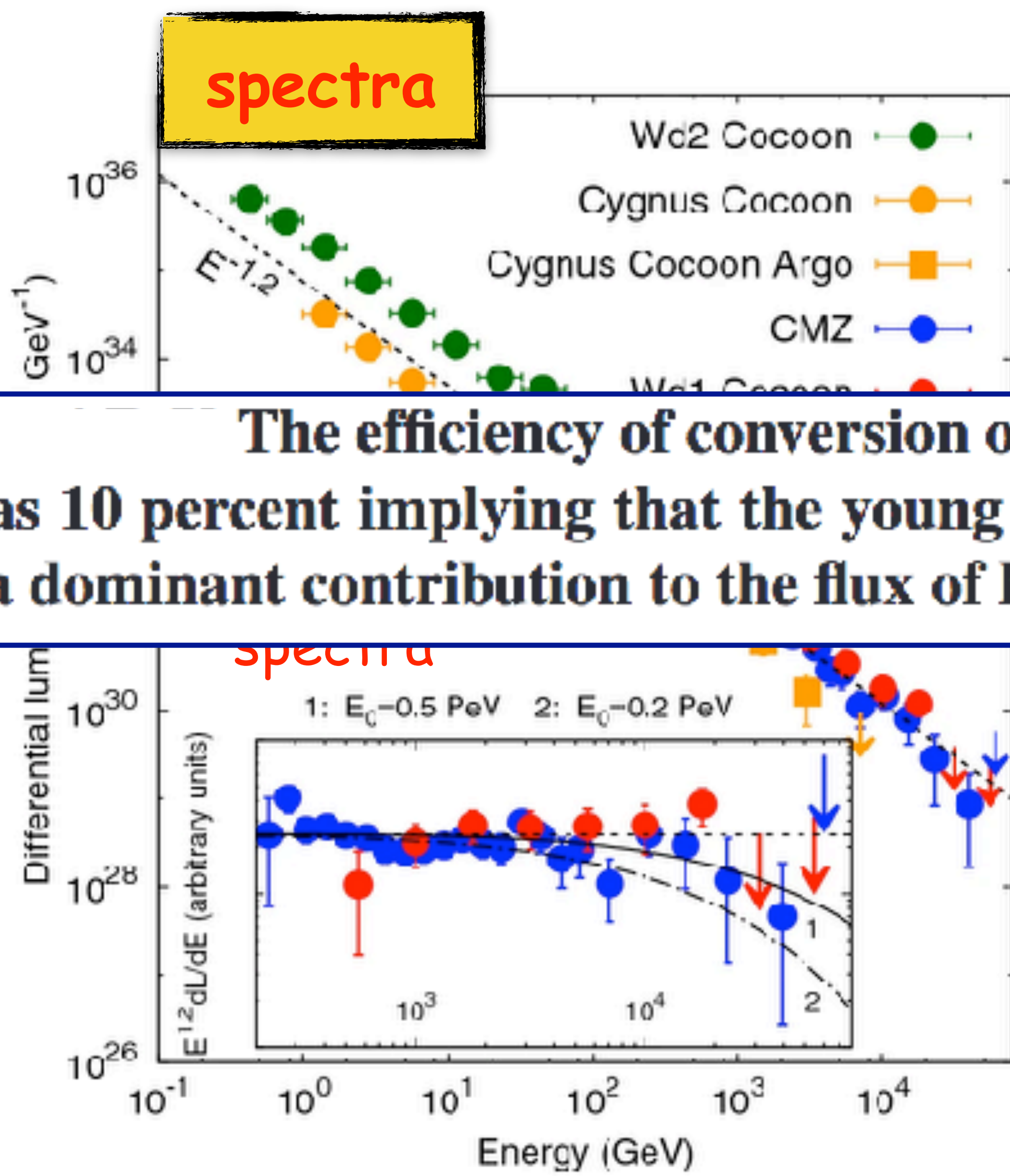

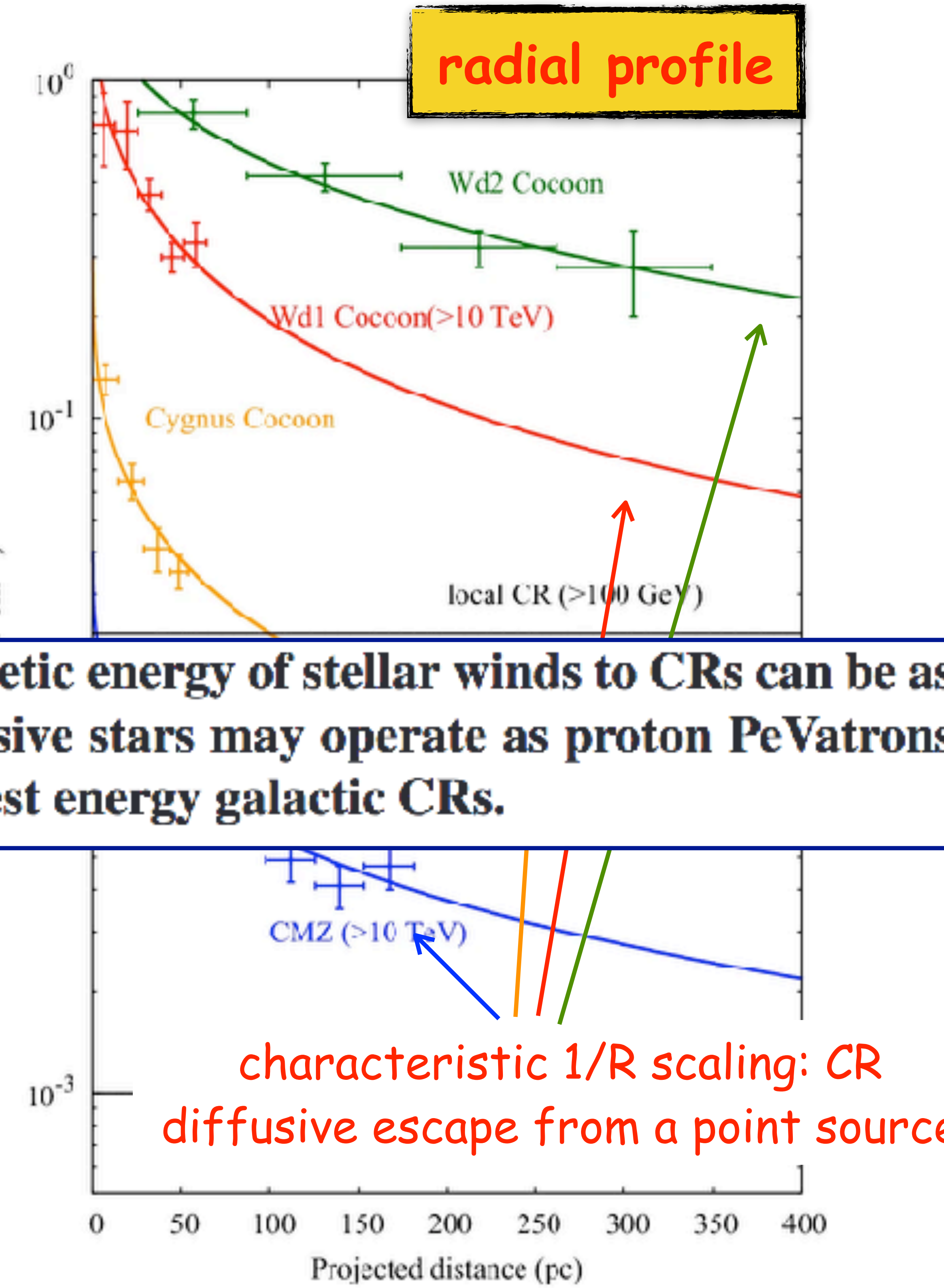

The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

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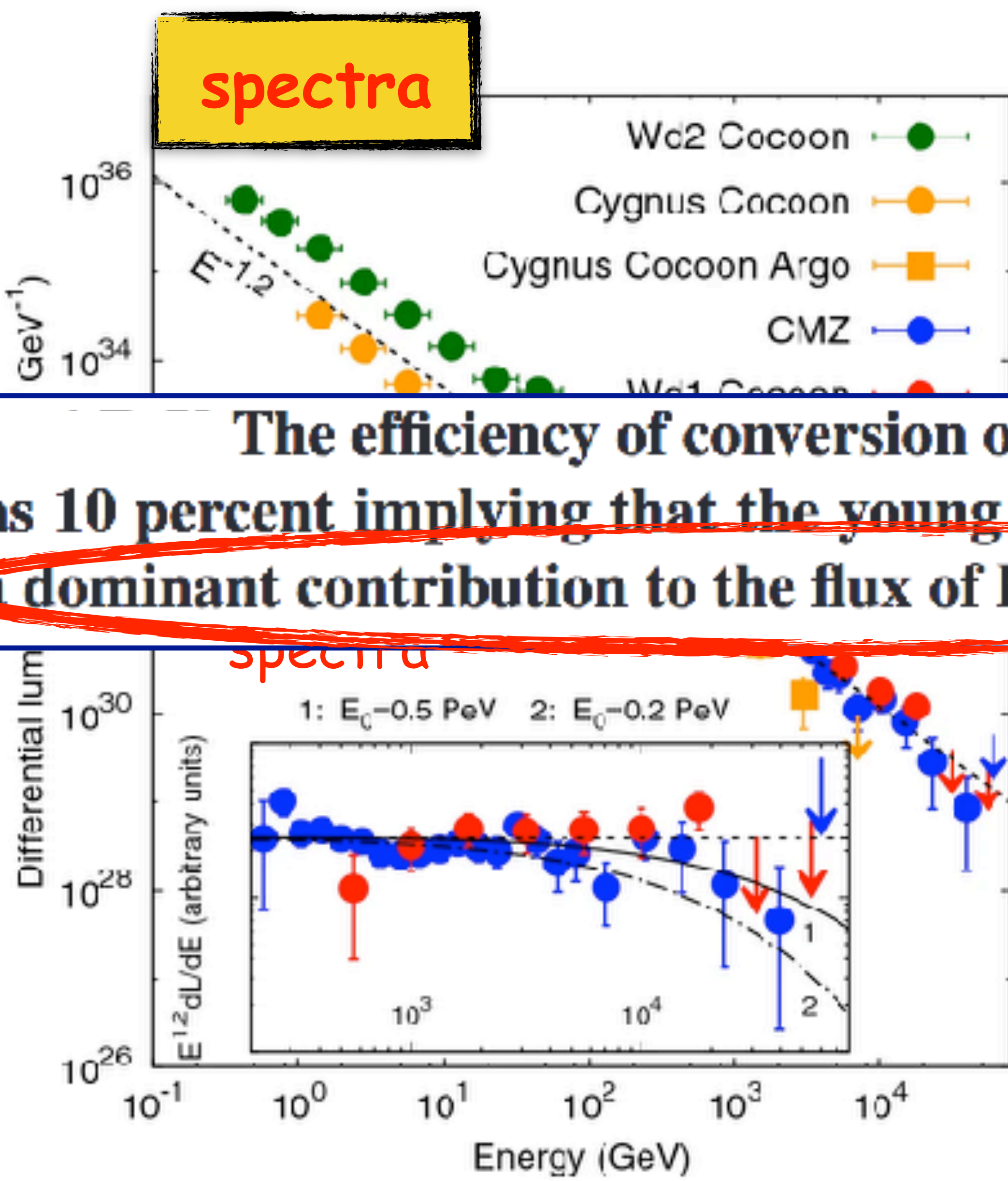

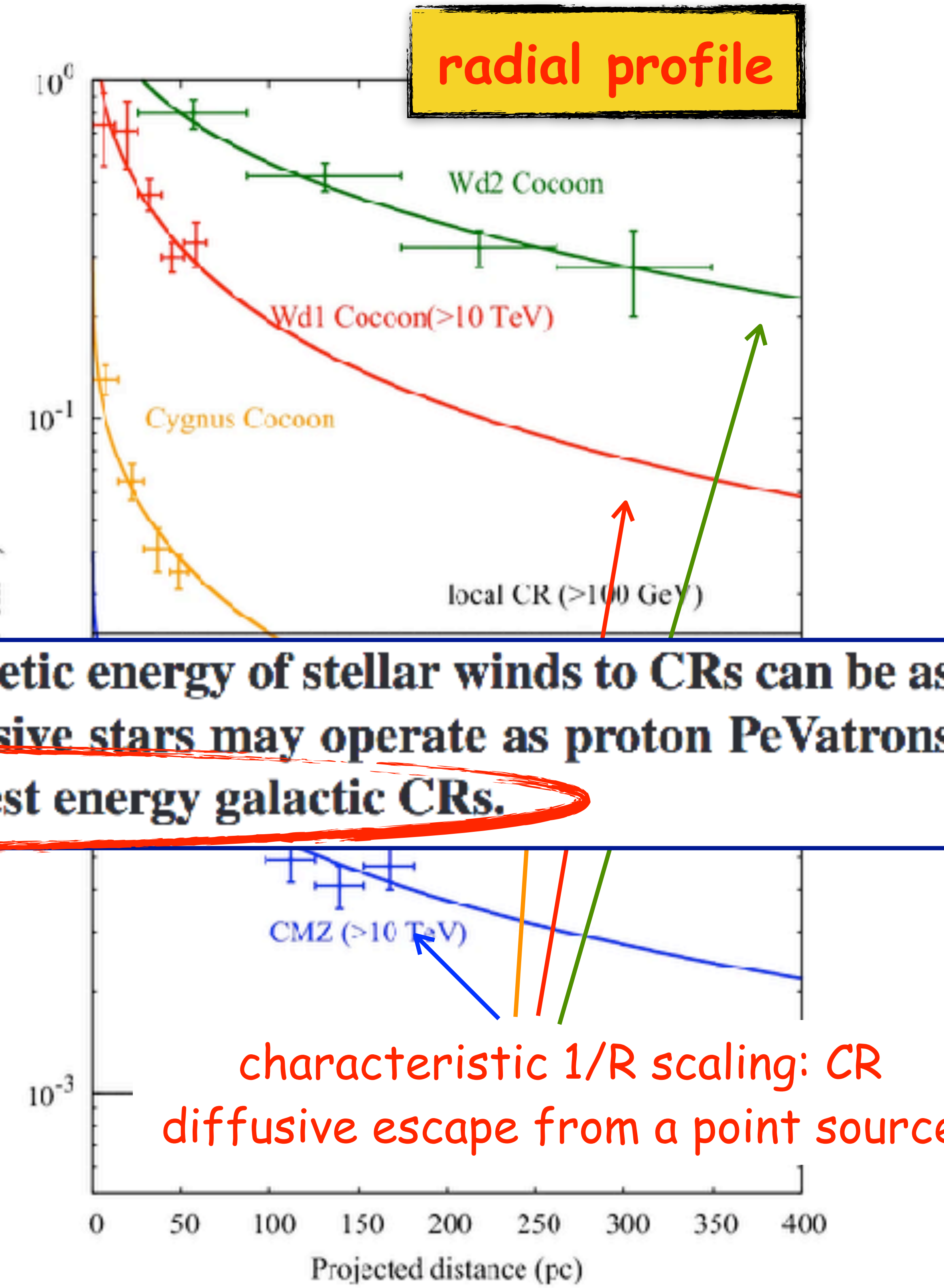

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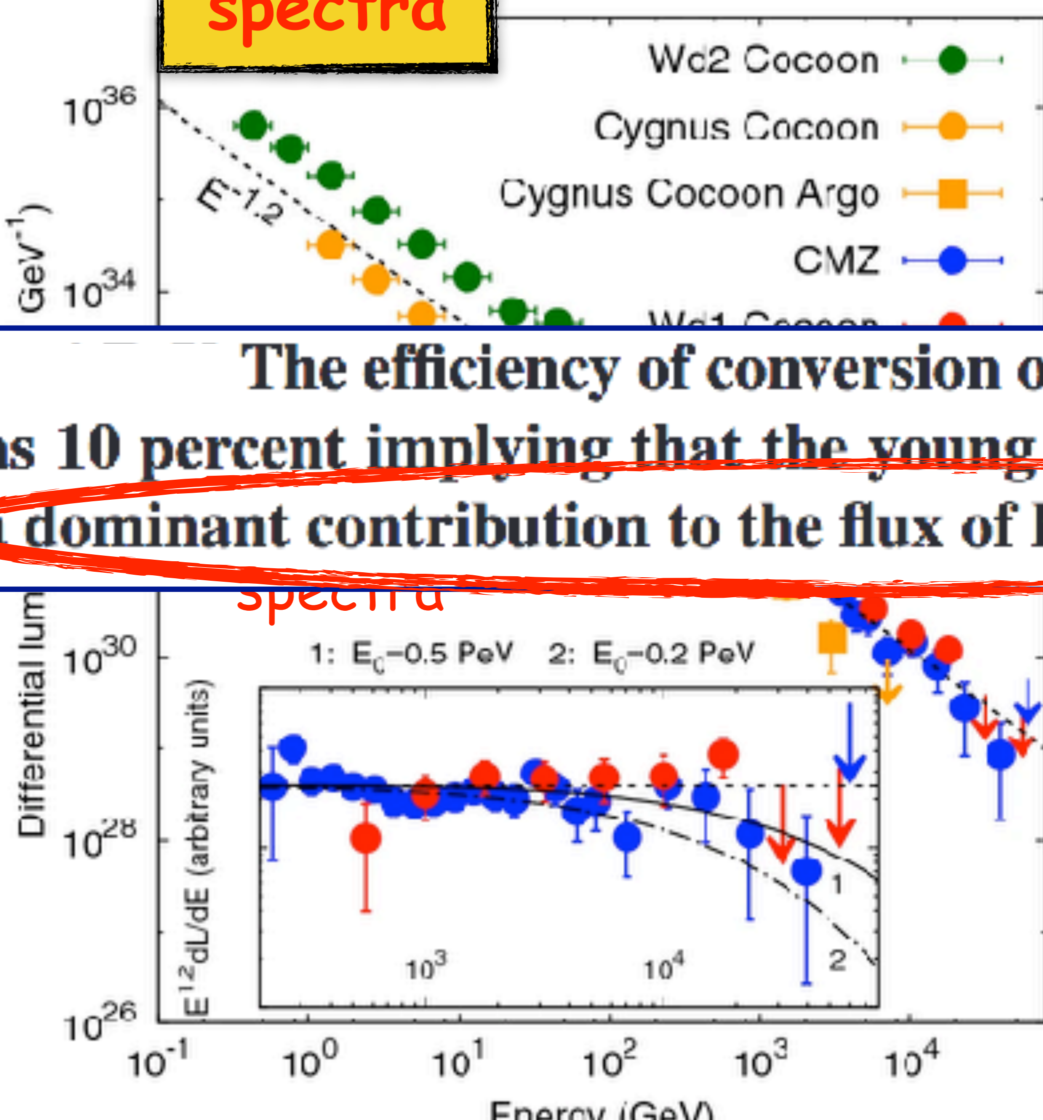
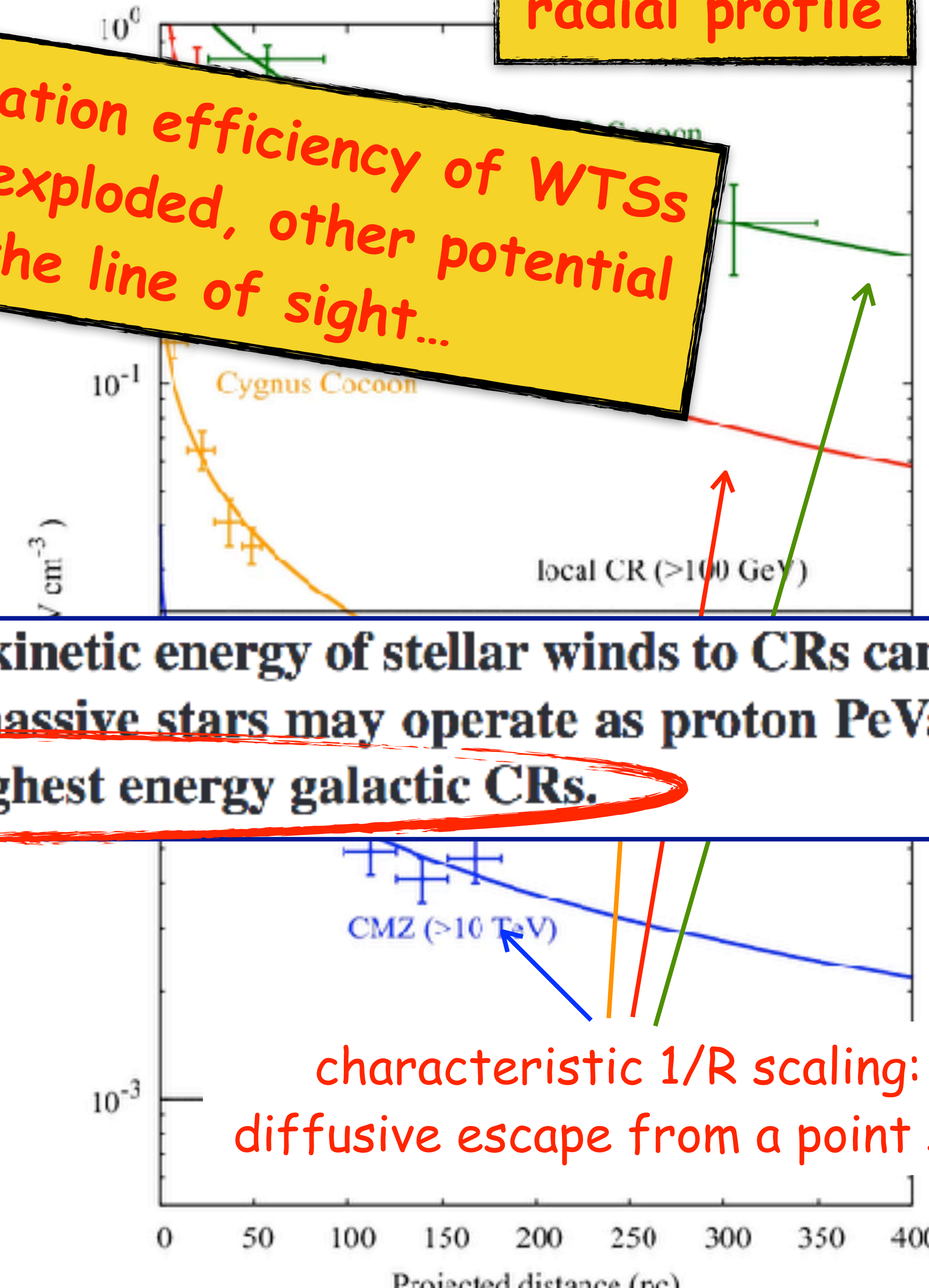
cannot constrain acceleration efficiency of WTSs —> some SNae already exploded, other potential CR source along the line of sight…

spectra



radial profile



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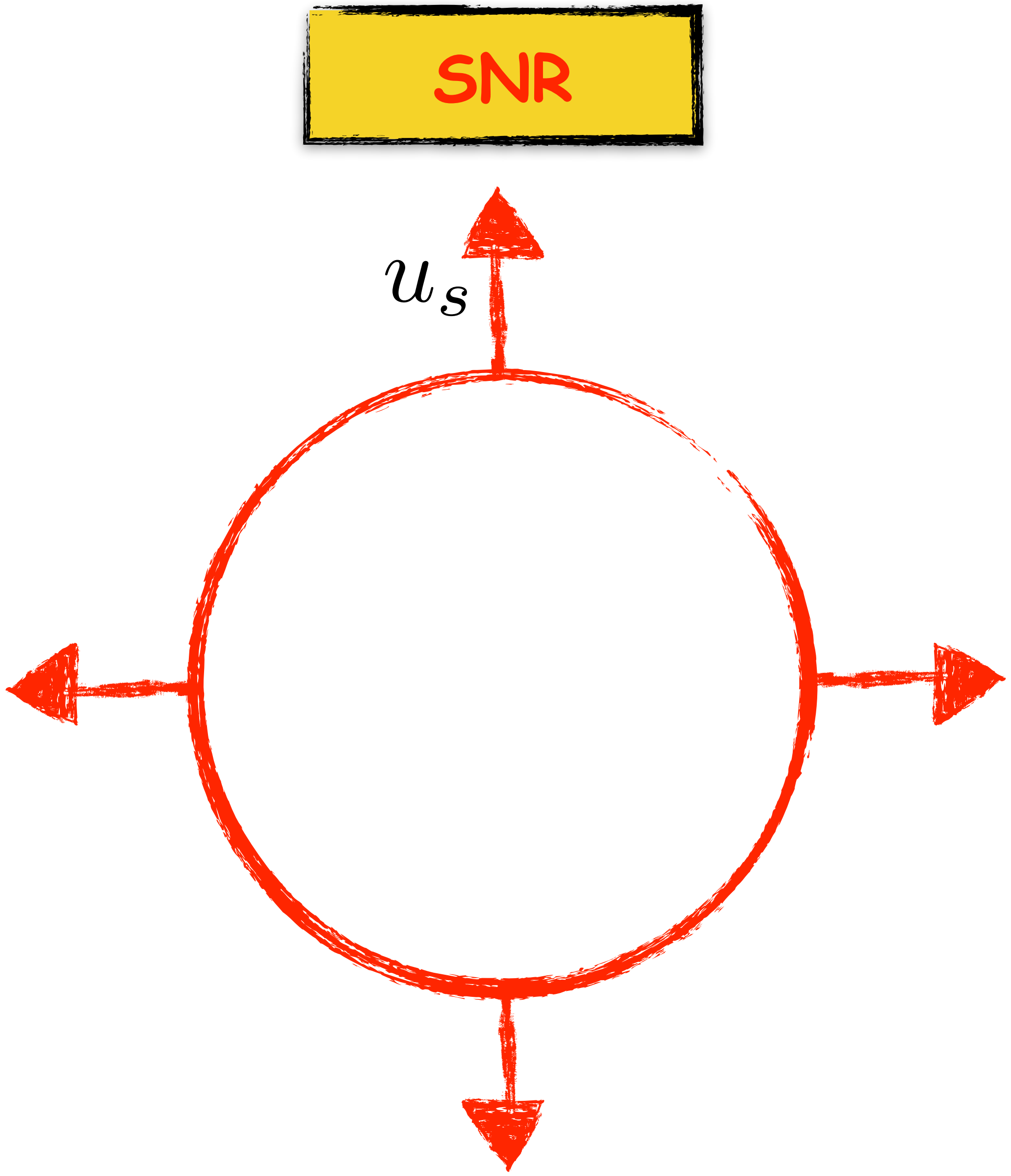
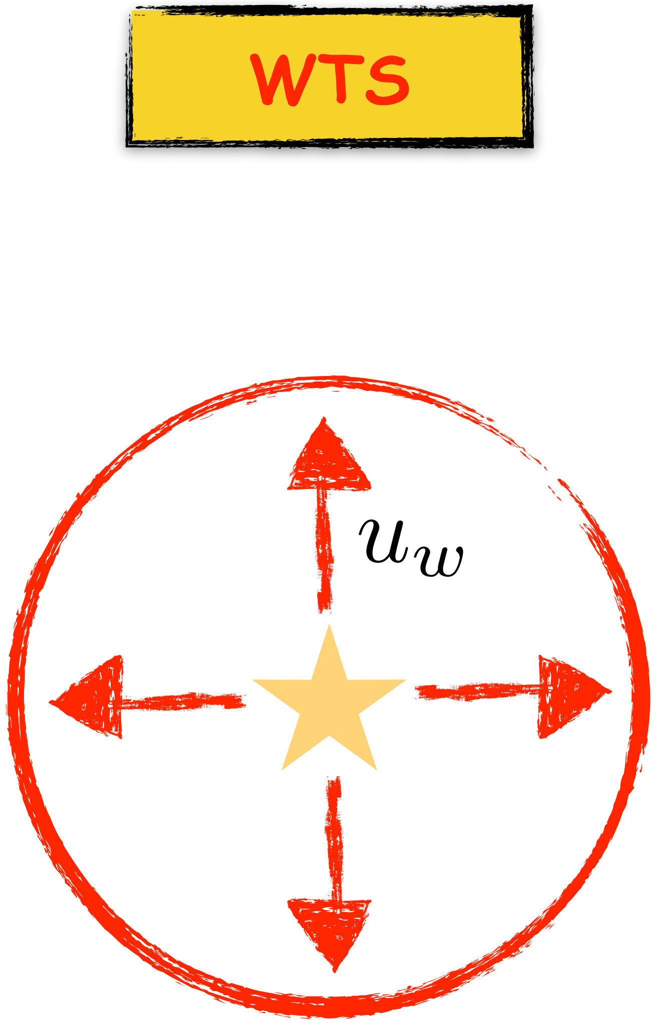
characteristic 1/R scaling: CR diffusive escape from a point source

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983





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

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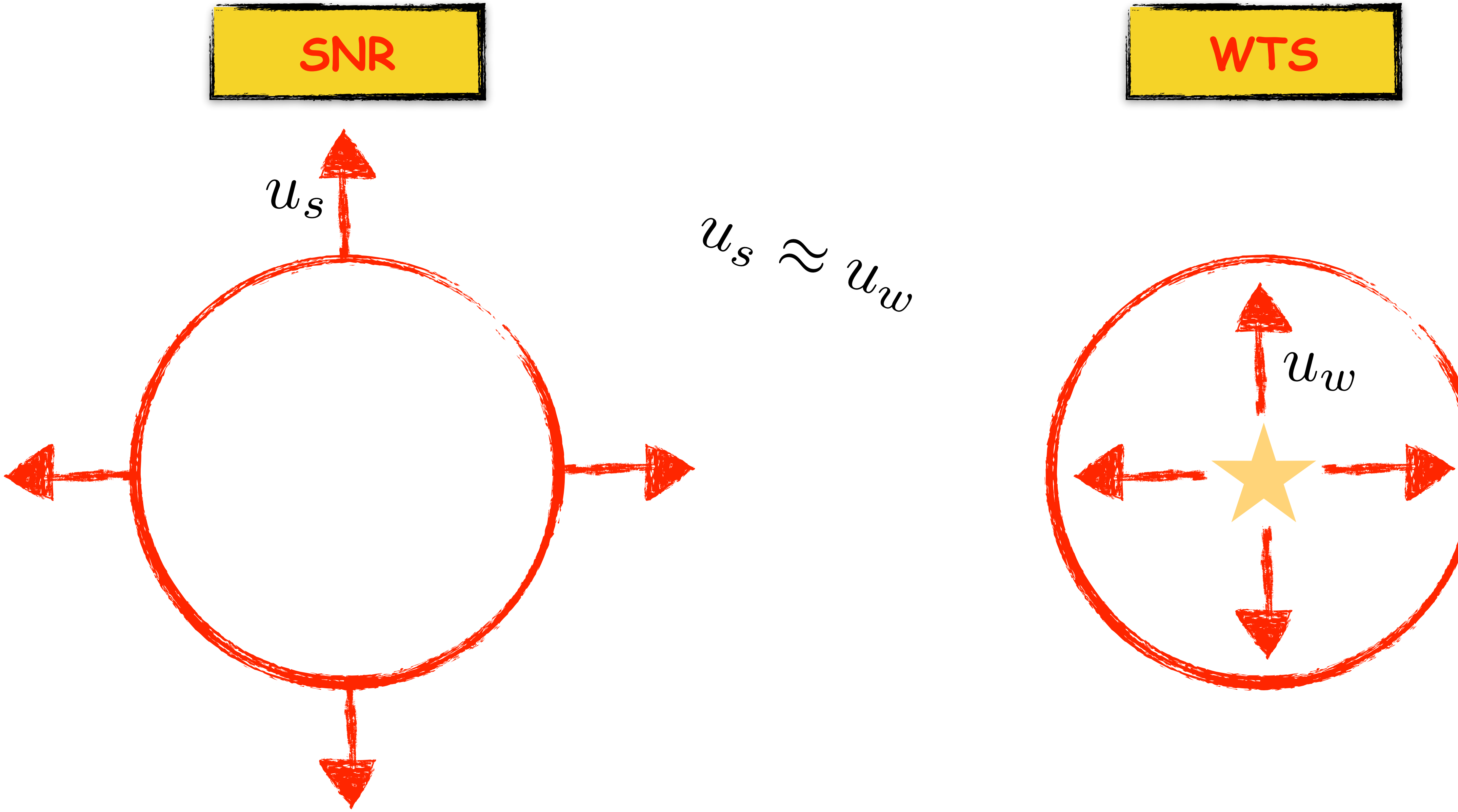

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Originally proposed for completely different reasons!

[1] explain LOCAL cosmic rays only (and their related GeV gamma-ray emission)

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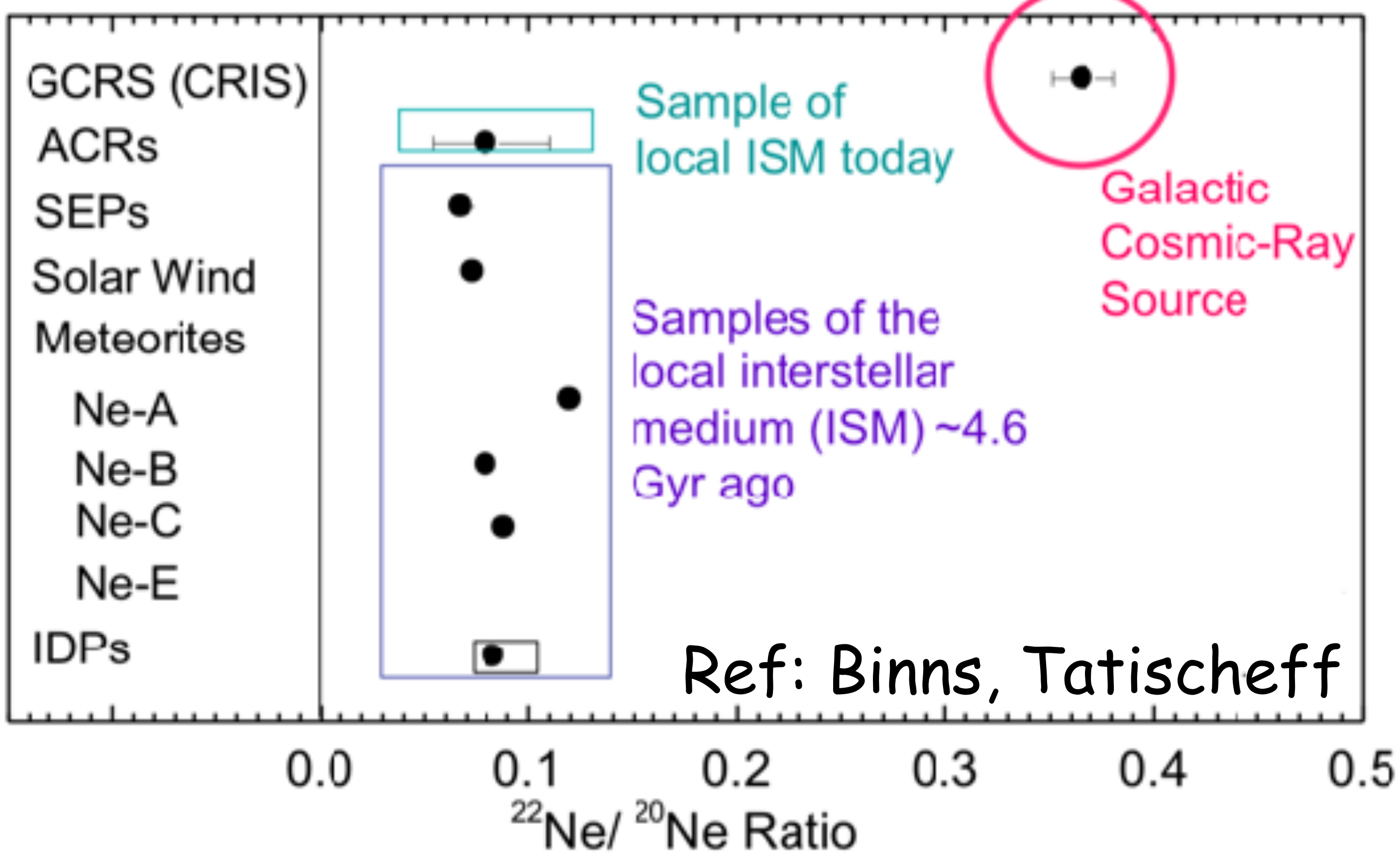

[2] explain the anomalous excess of the $^{22}Ne/^{20}Ne$ ratio in cosmic rays

Wolf-Rayet wind material enriched in ^{22}Ne —> need DILUTION!

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

Energy problem

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total wind power dominated by the most massive stars

very steep mass-luminosity scaling

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

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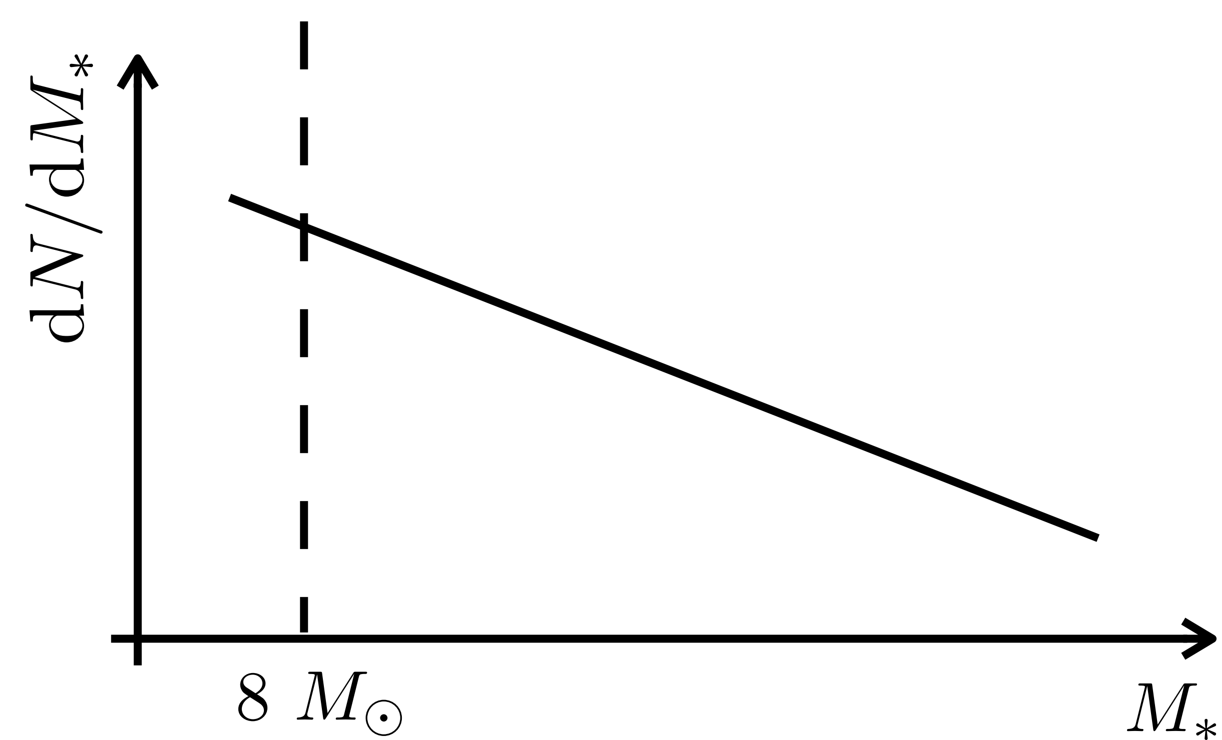

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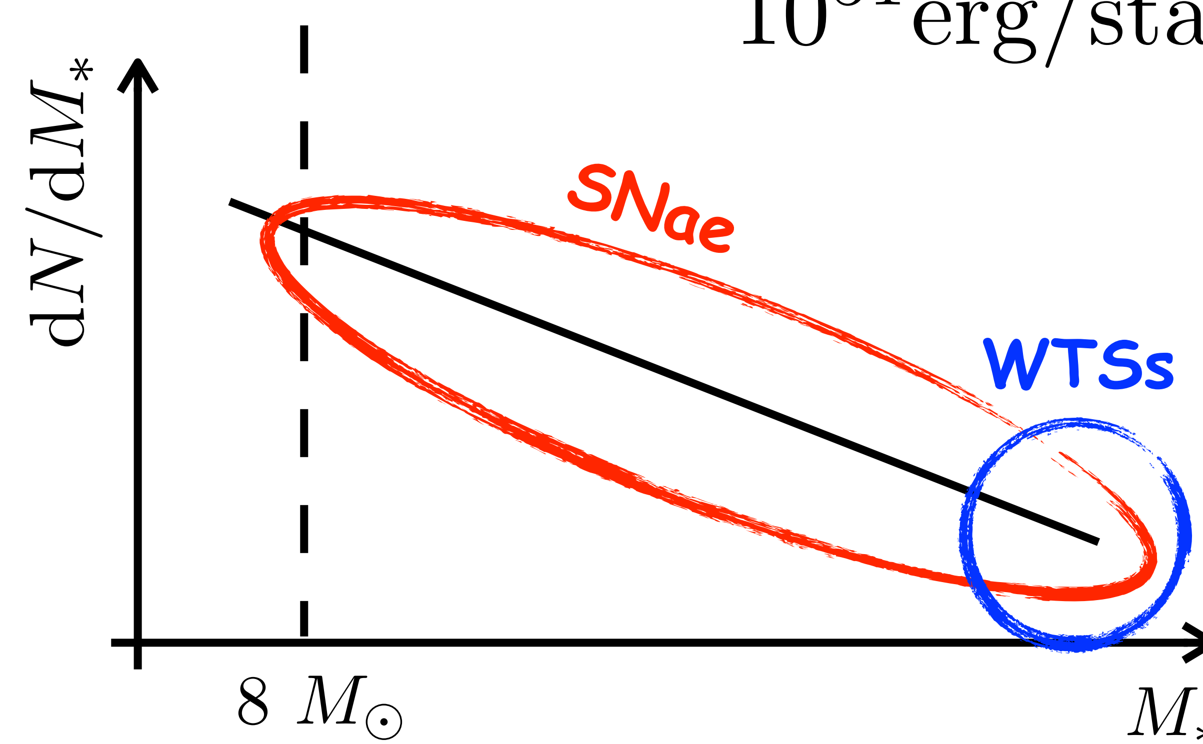

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momentum ca... by stell...

total ... stars

very steep mass-luminos... sc...

$\approx M_*^3$

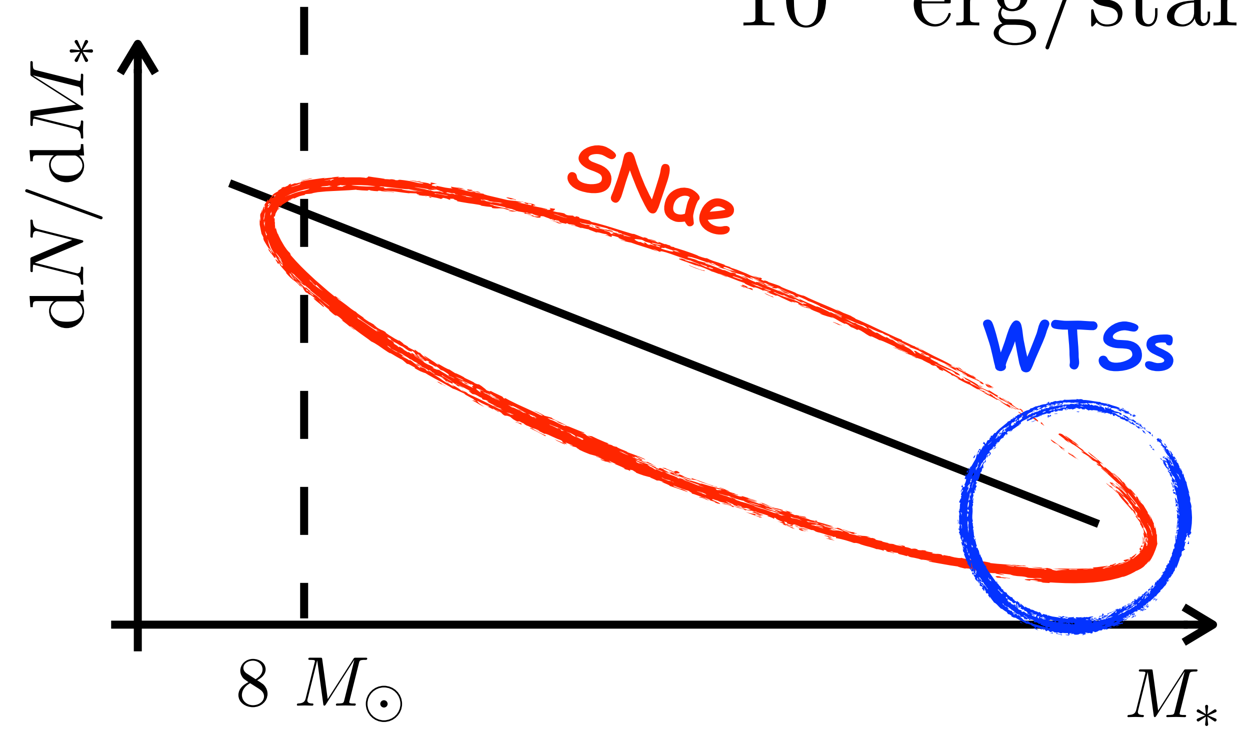
$10^{51}\mathrm{erg/star}$

--> supernovae win by about a factor of several

--> WTS could explain a fraction of CRs only

...ssive stars:

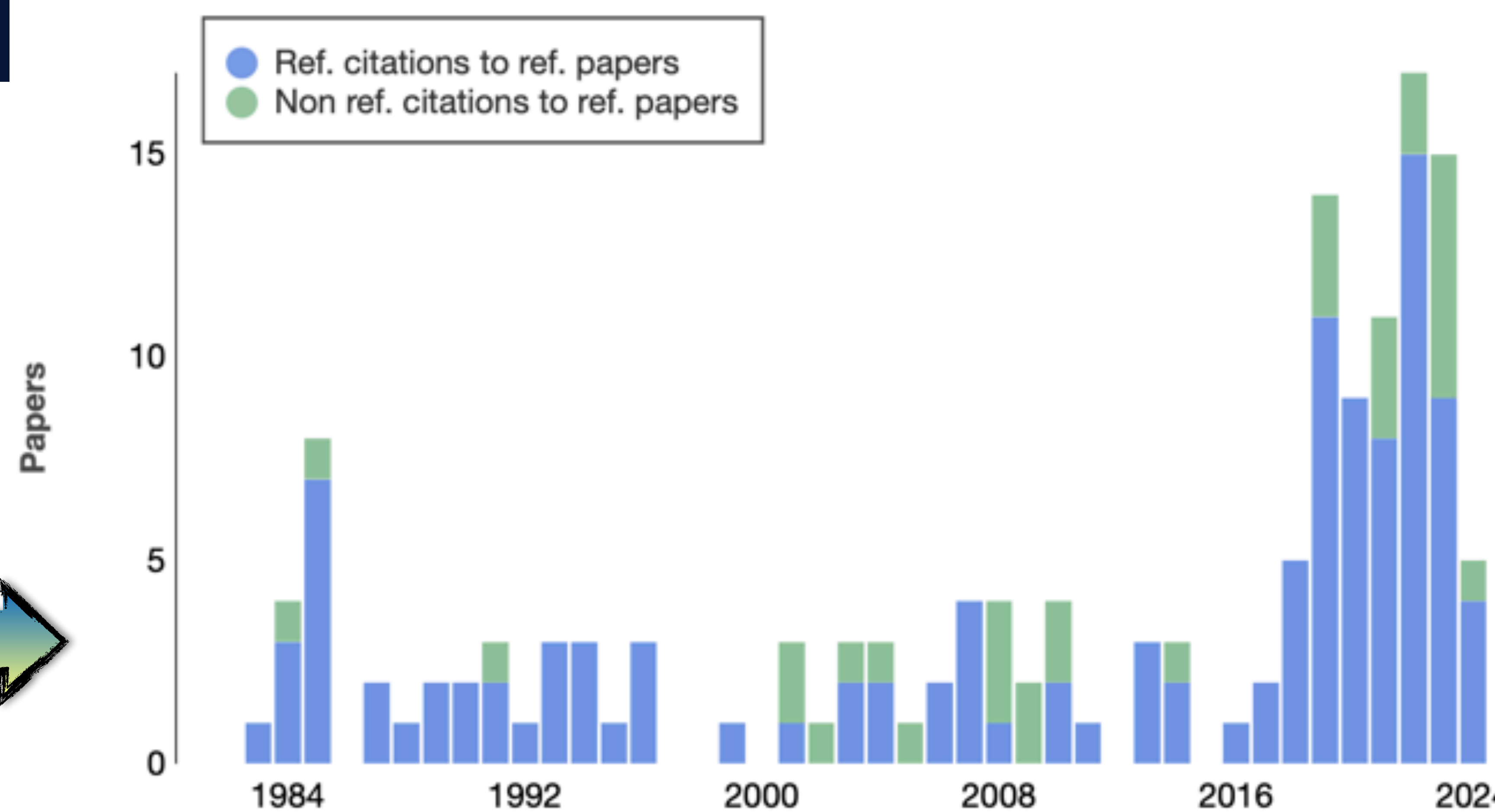
$$\ldots t \; P_w \approx 10^{51}\mathrm{erg} \sim \mathrm{E_{SN}}$$



Then nobody cared for few decades...

CR physicists thinking about star clusters winds between 1983 and 2019

citation counts for Cesarsky & Montmerle review



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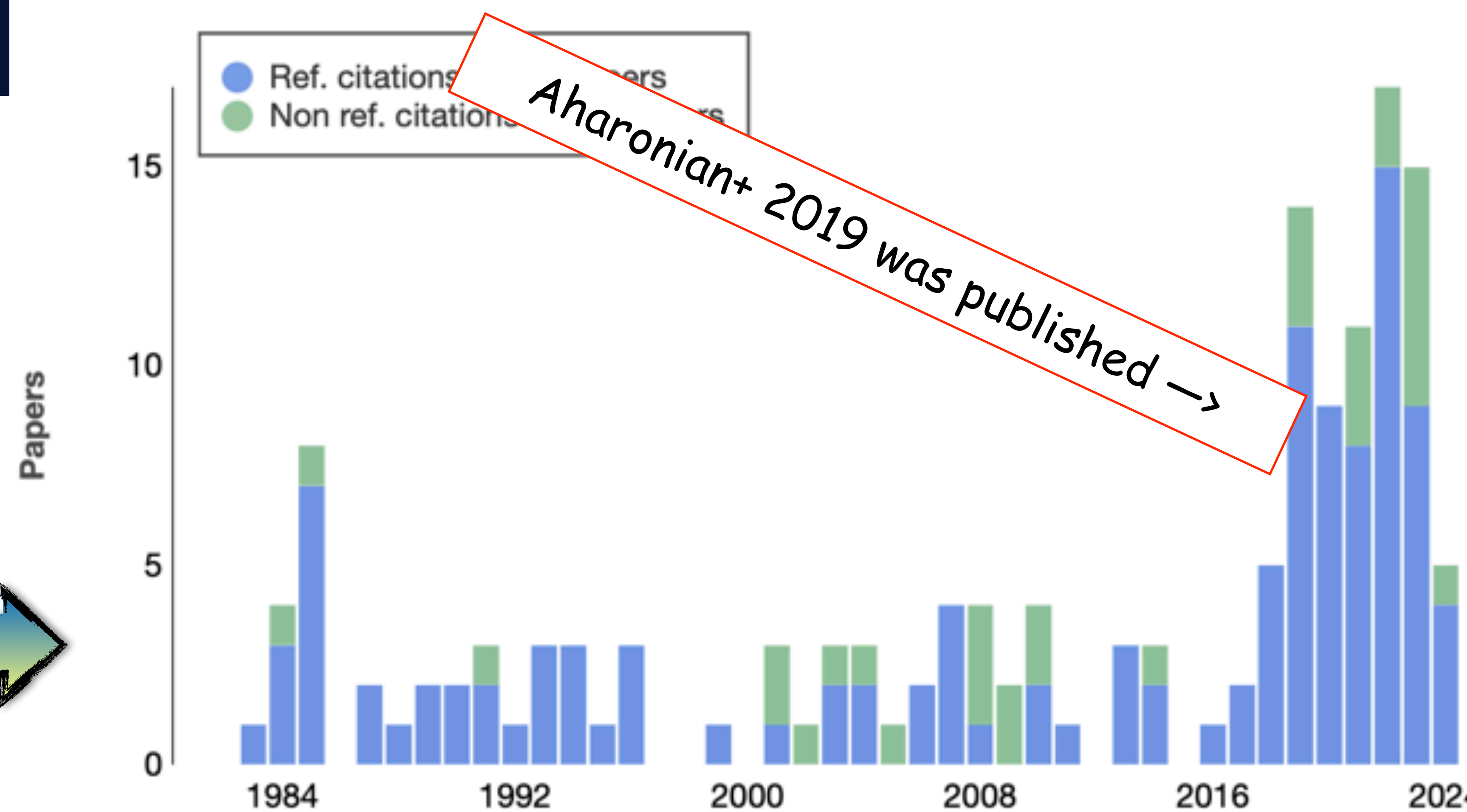

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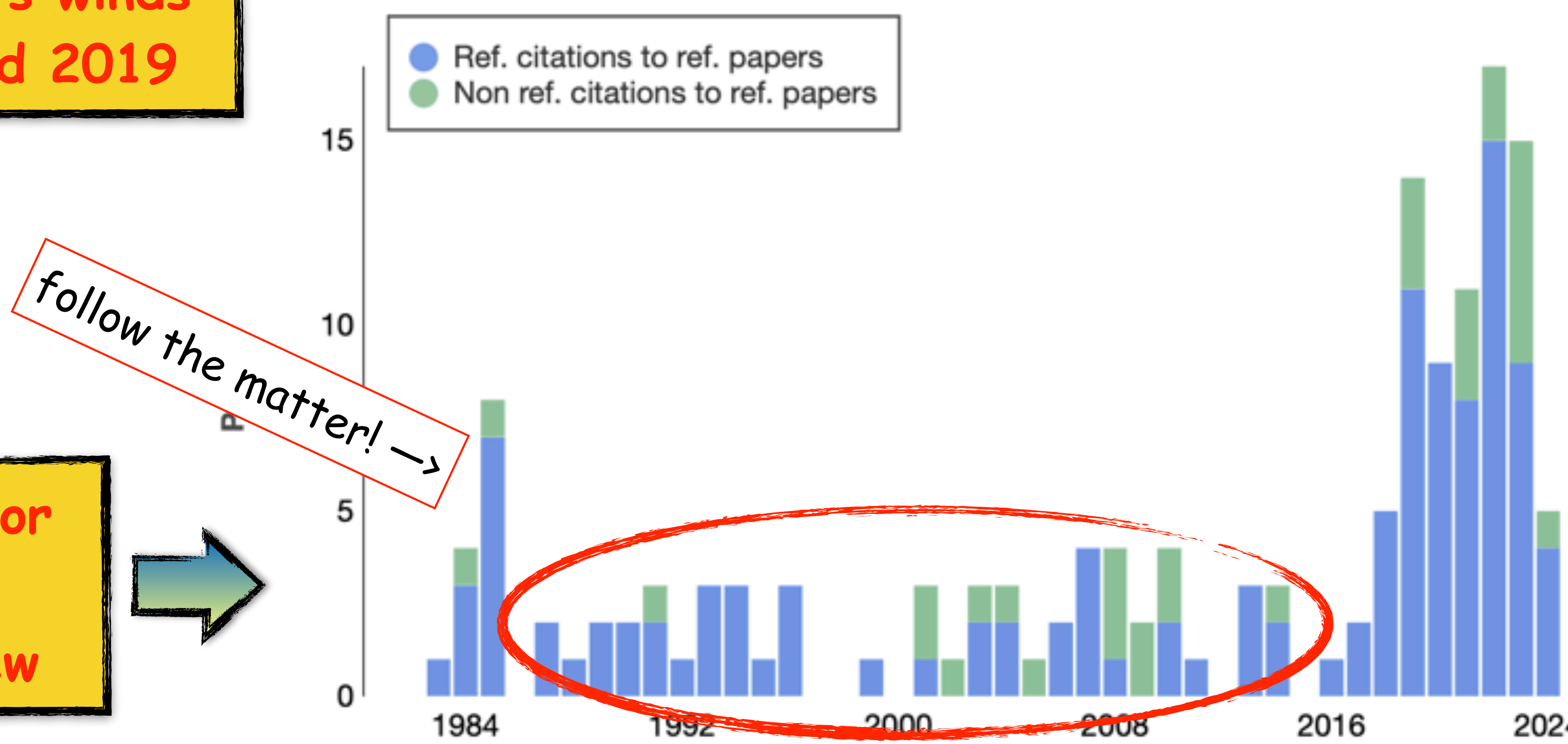

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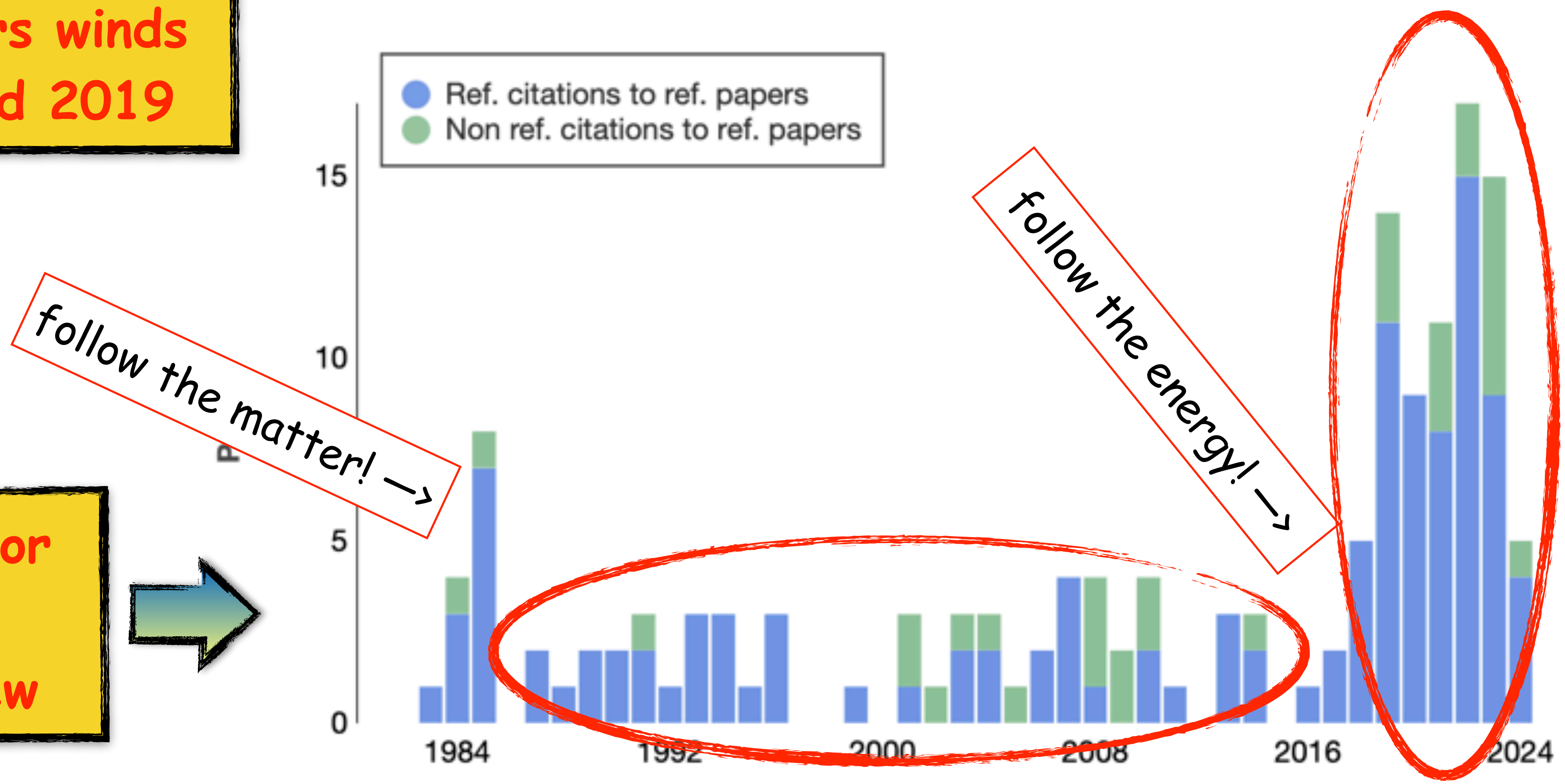

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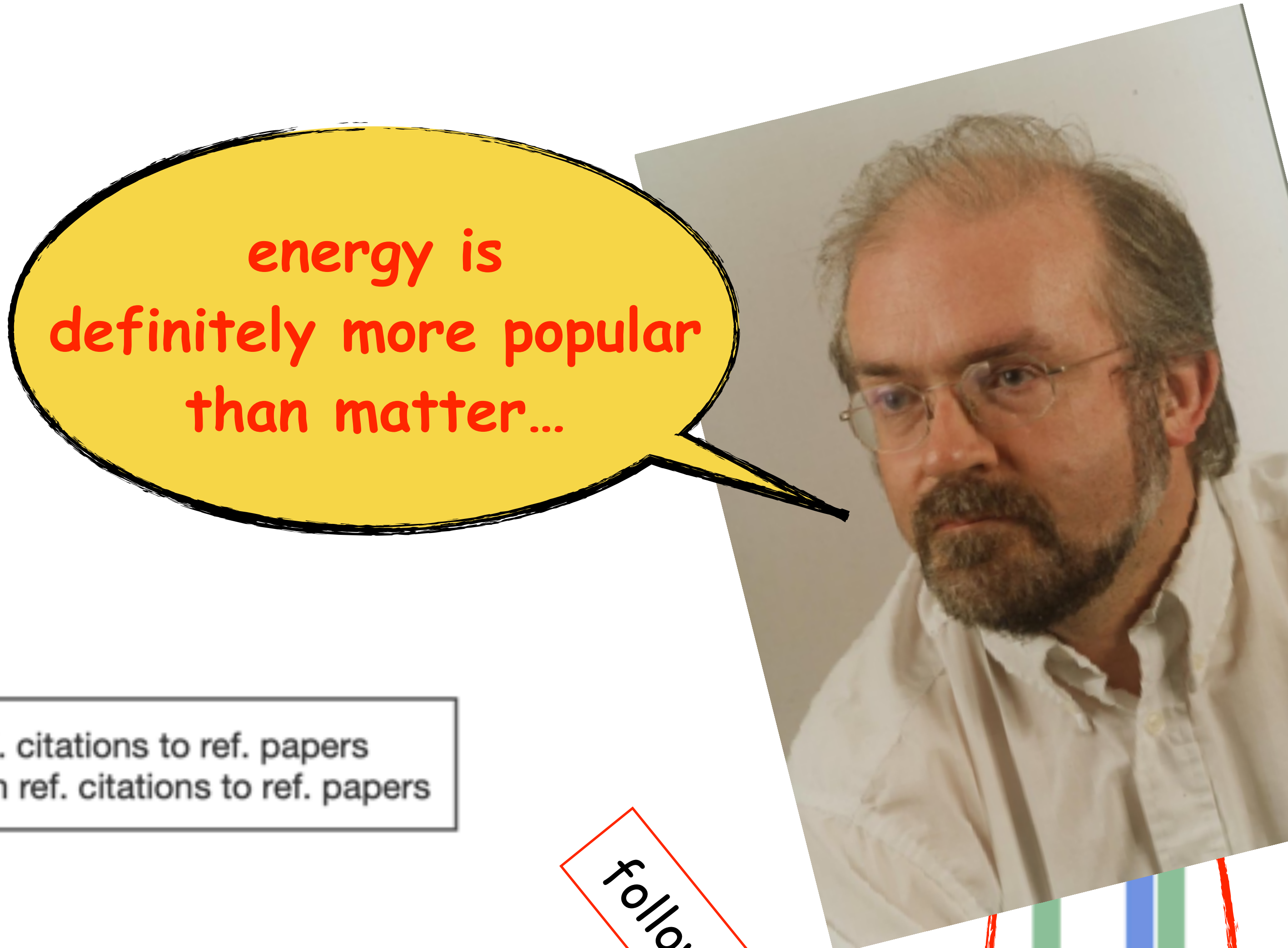

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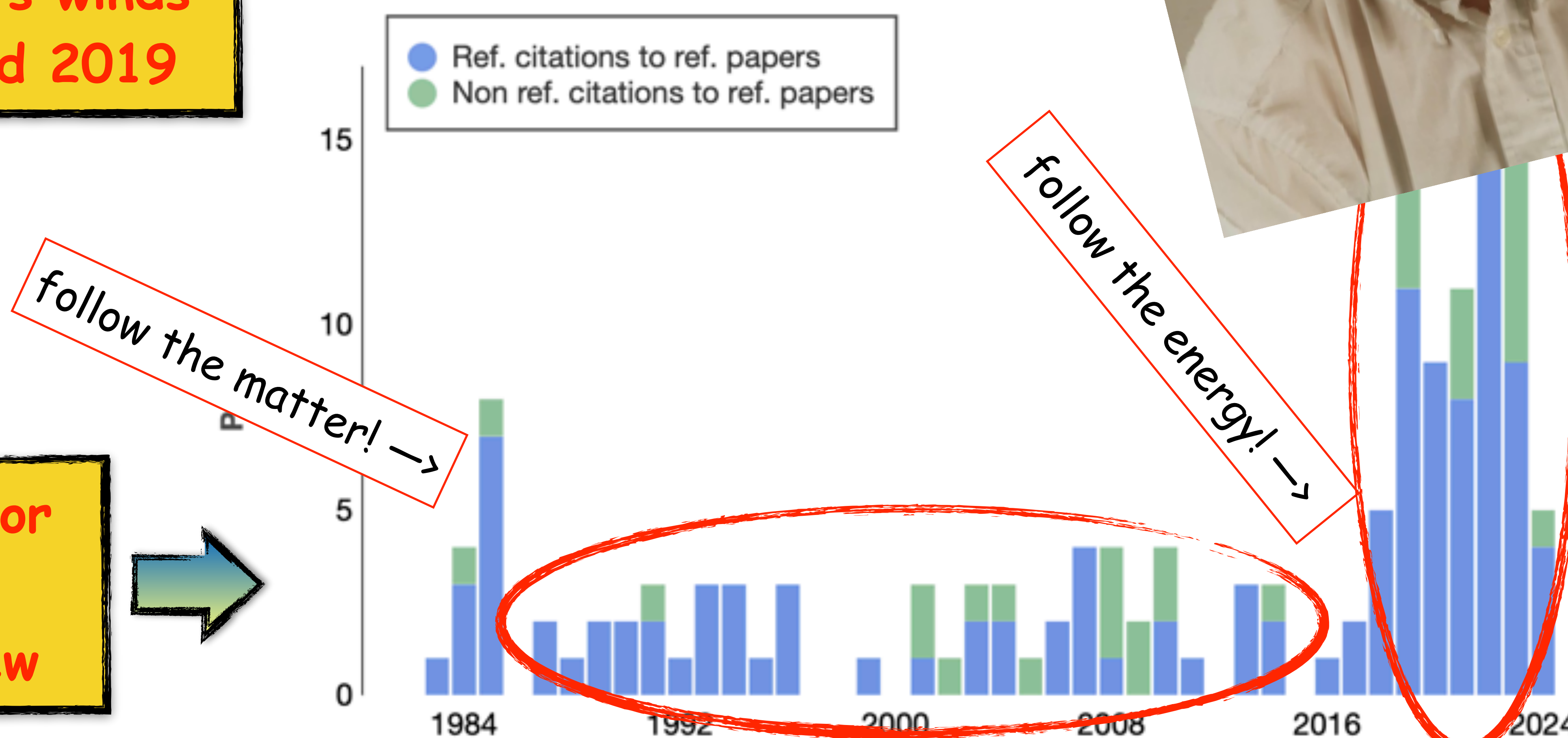
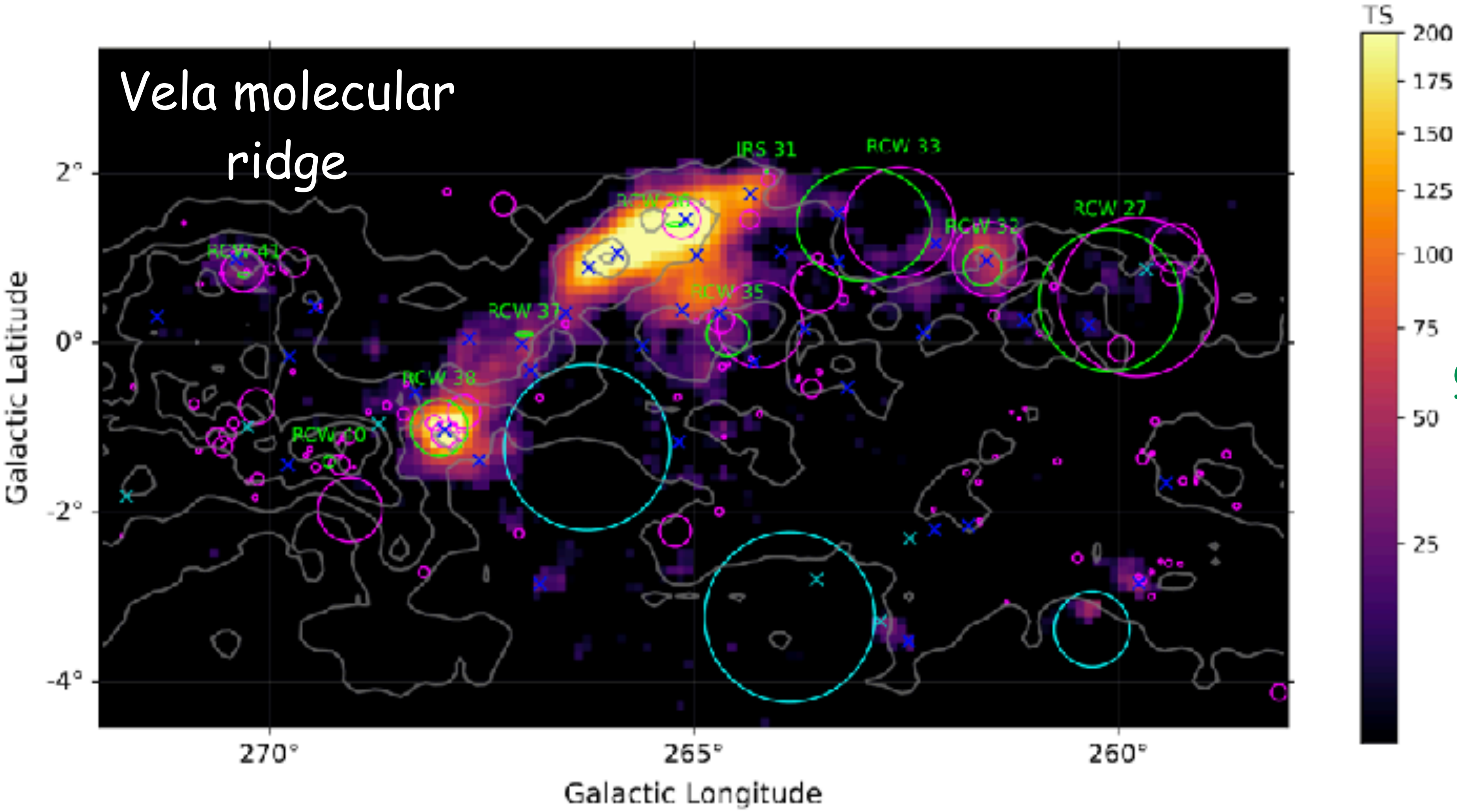


Yes, wind termination shocks do accelerate cosmic rays



grey —> gas

color —> gamma

green/purple —> HII regions

Peron+, 2024a

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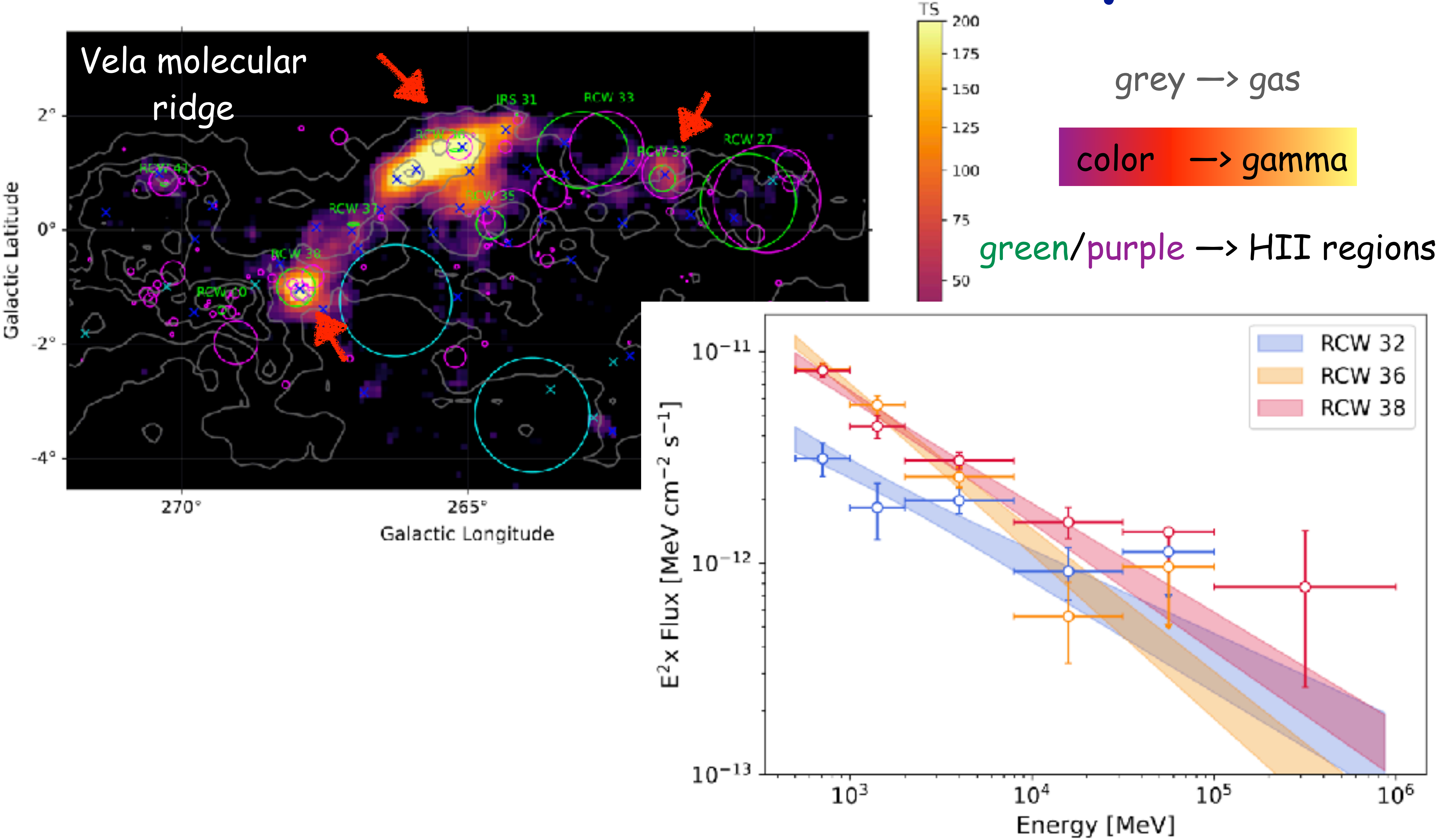

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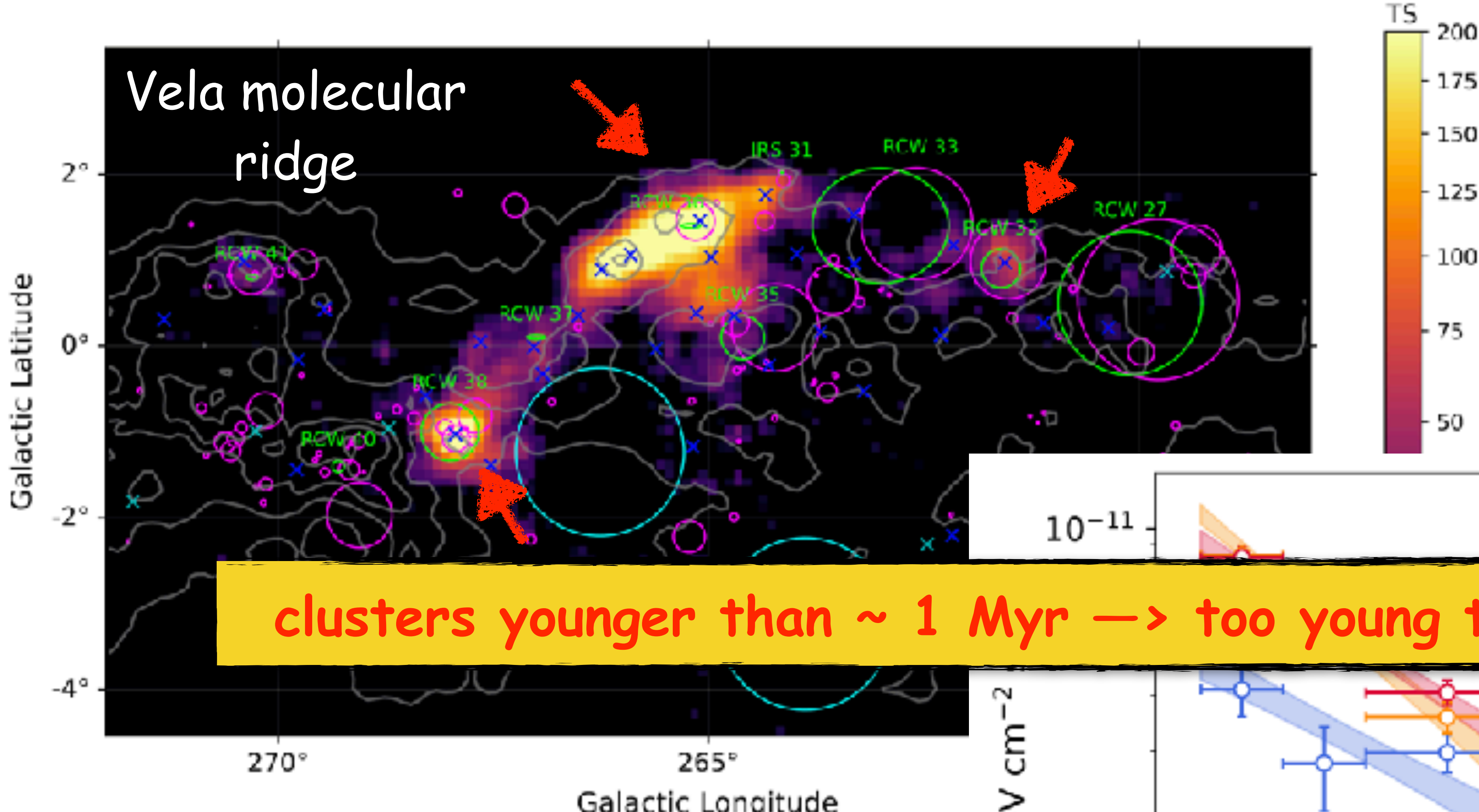

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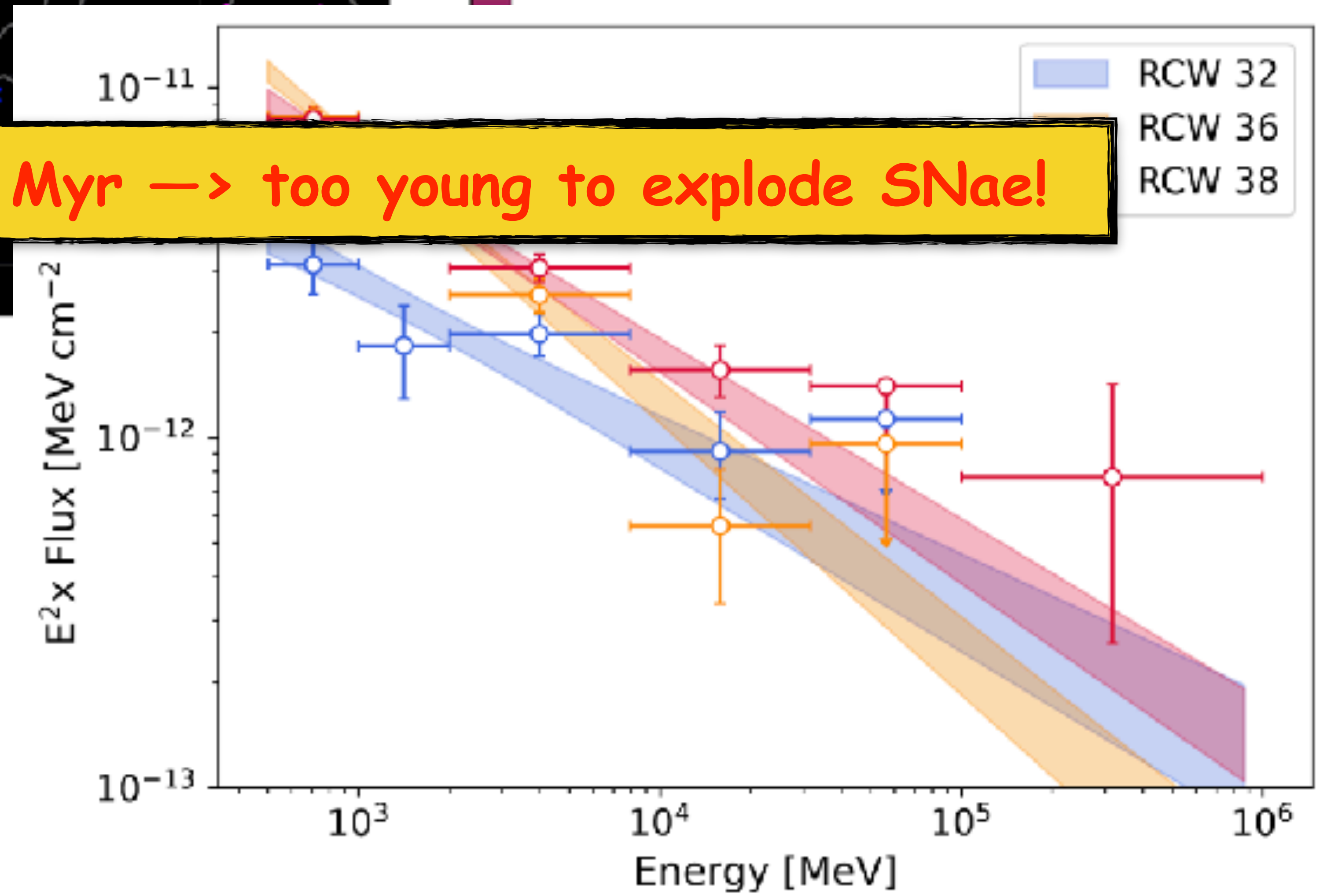

clusters younger than ~ 1 Myr —> too young to explode SNae!

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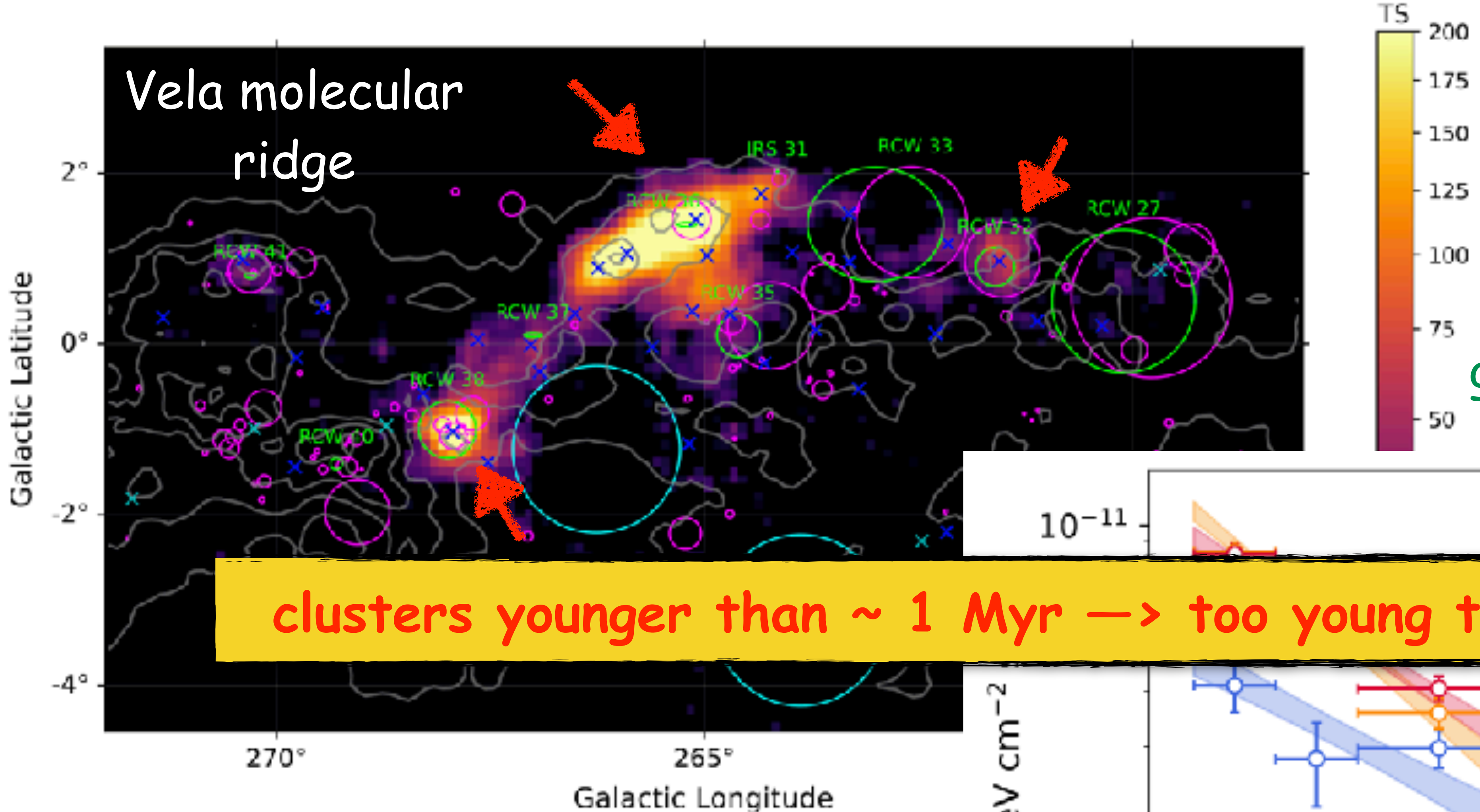

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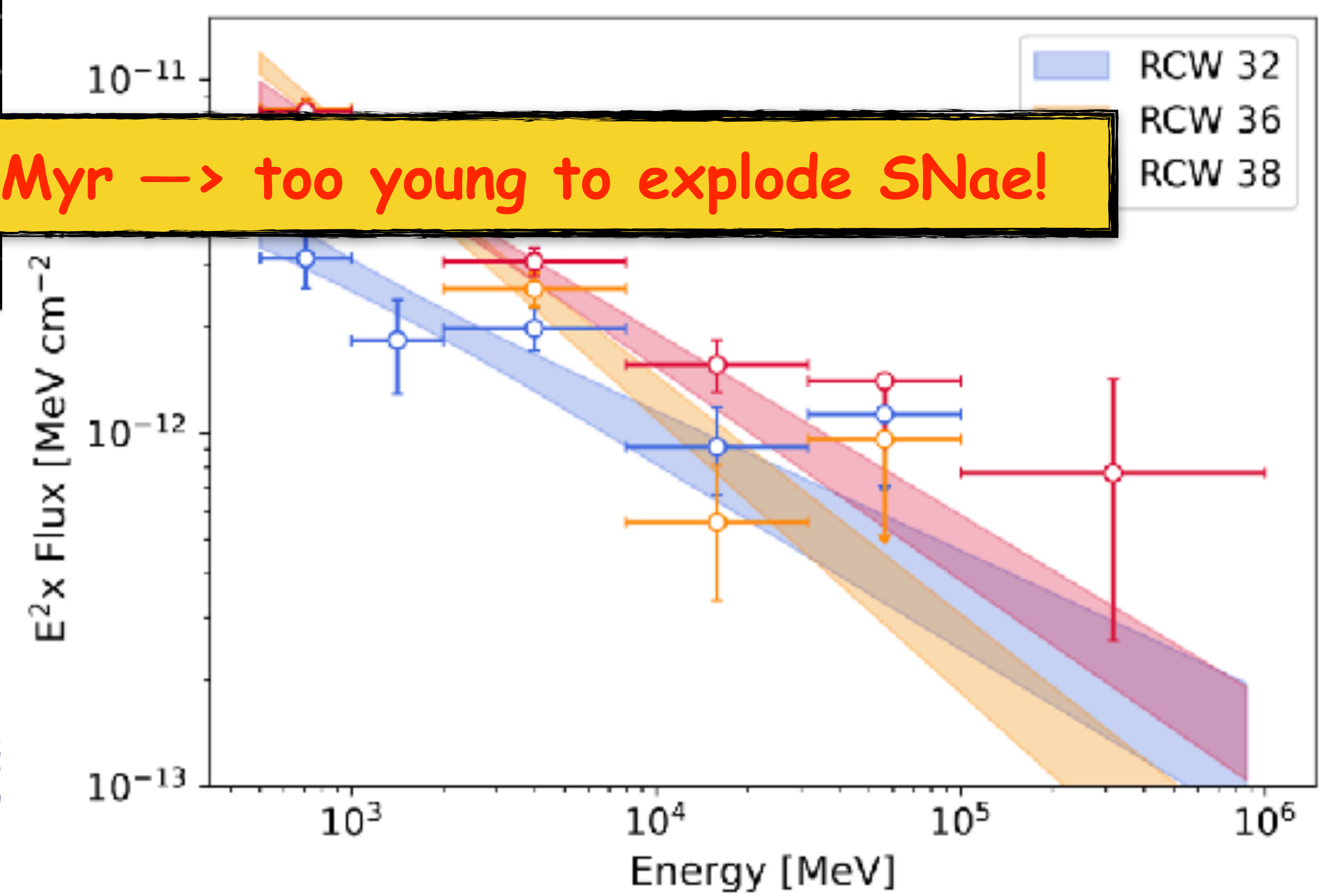

Peron+, 2024a

strict lower bound on the CR acceleration efficiency (energy)

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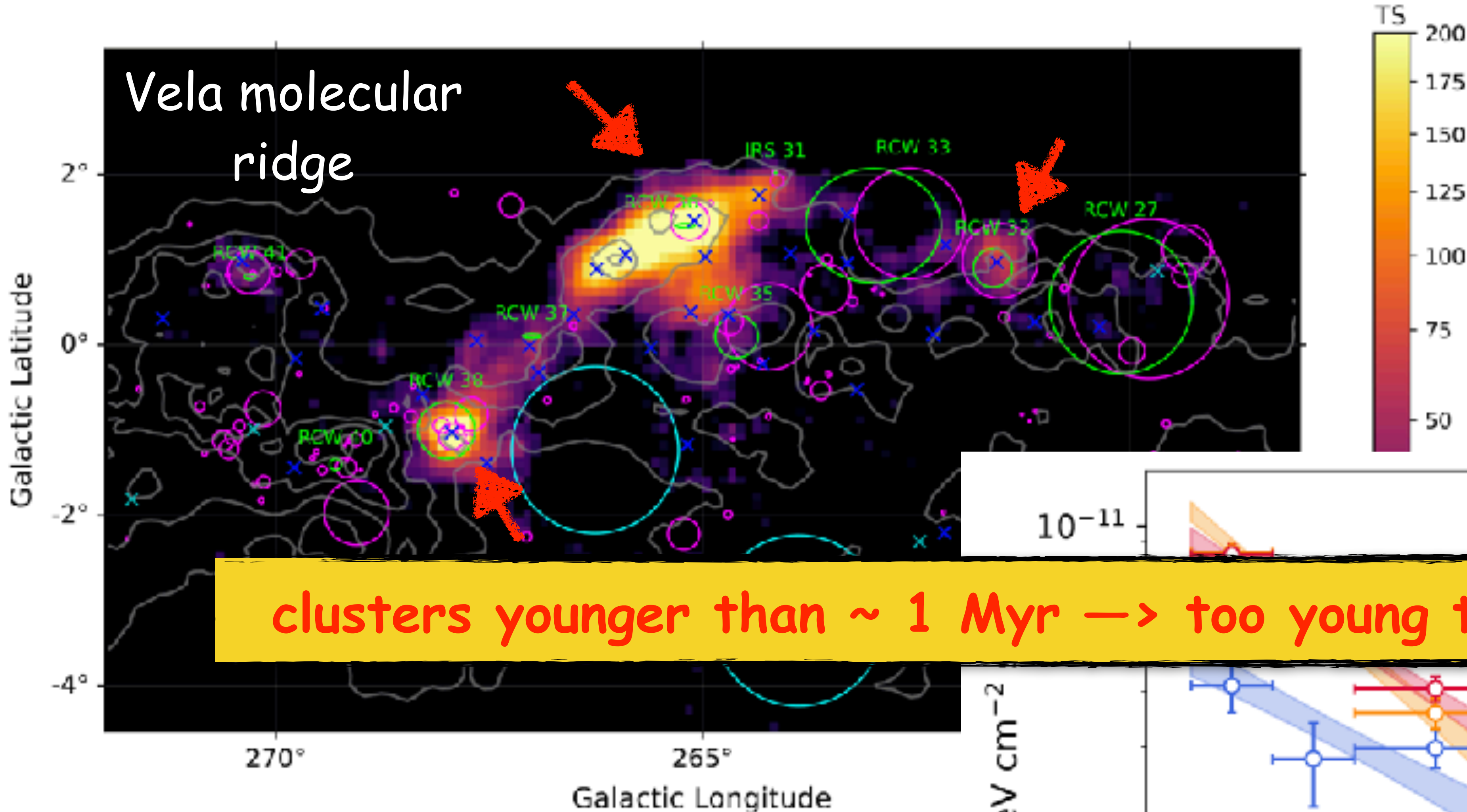

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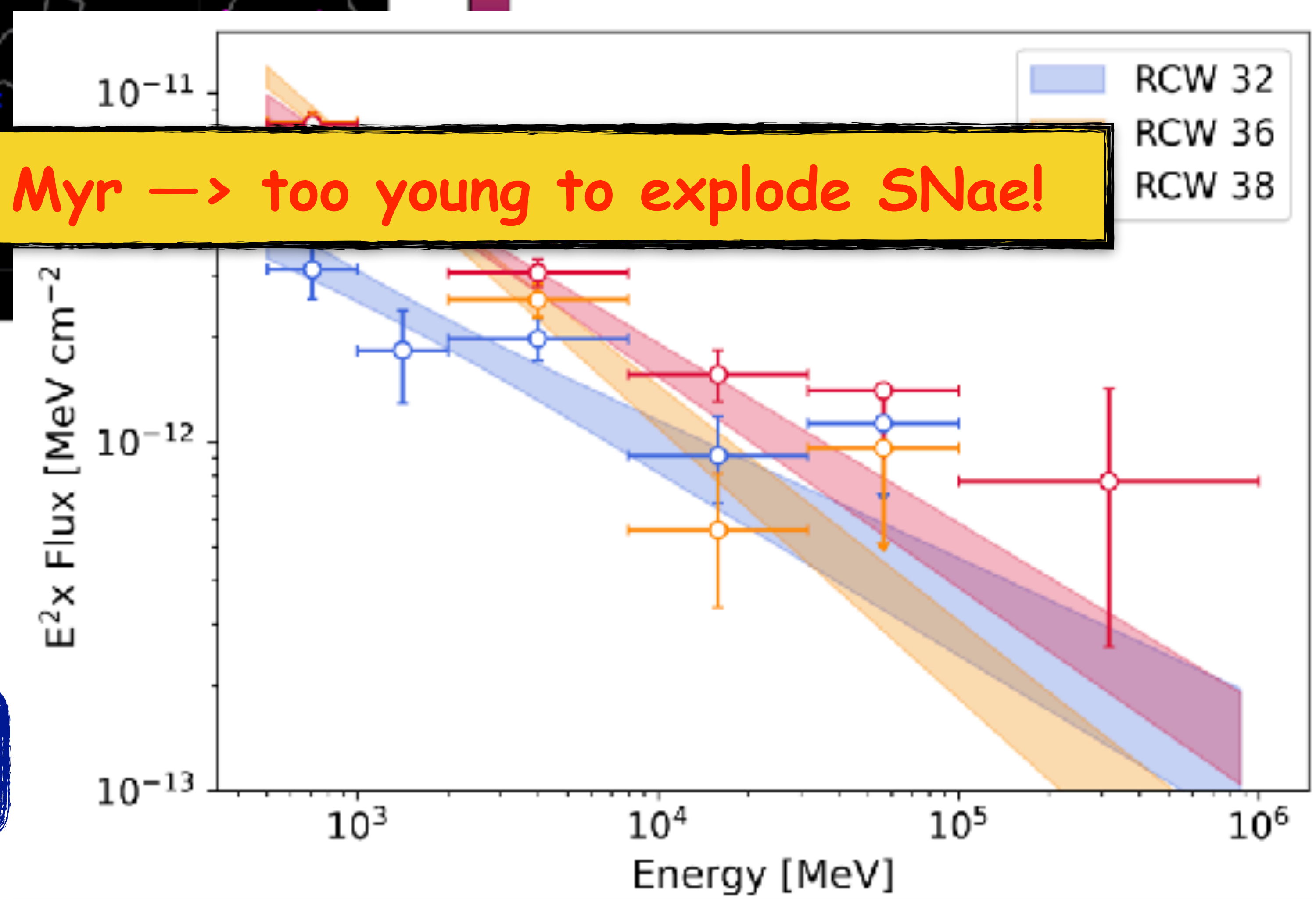

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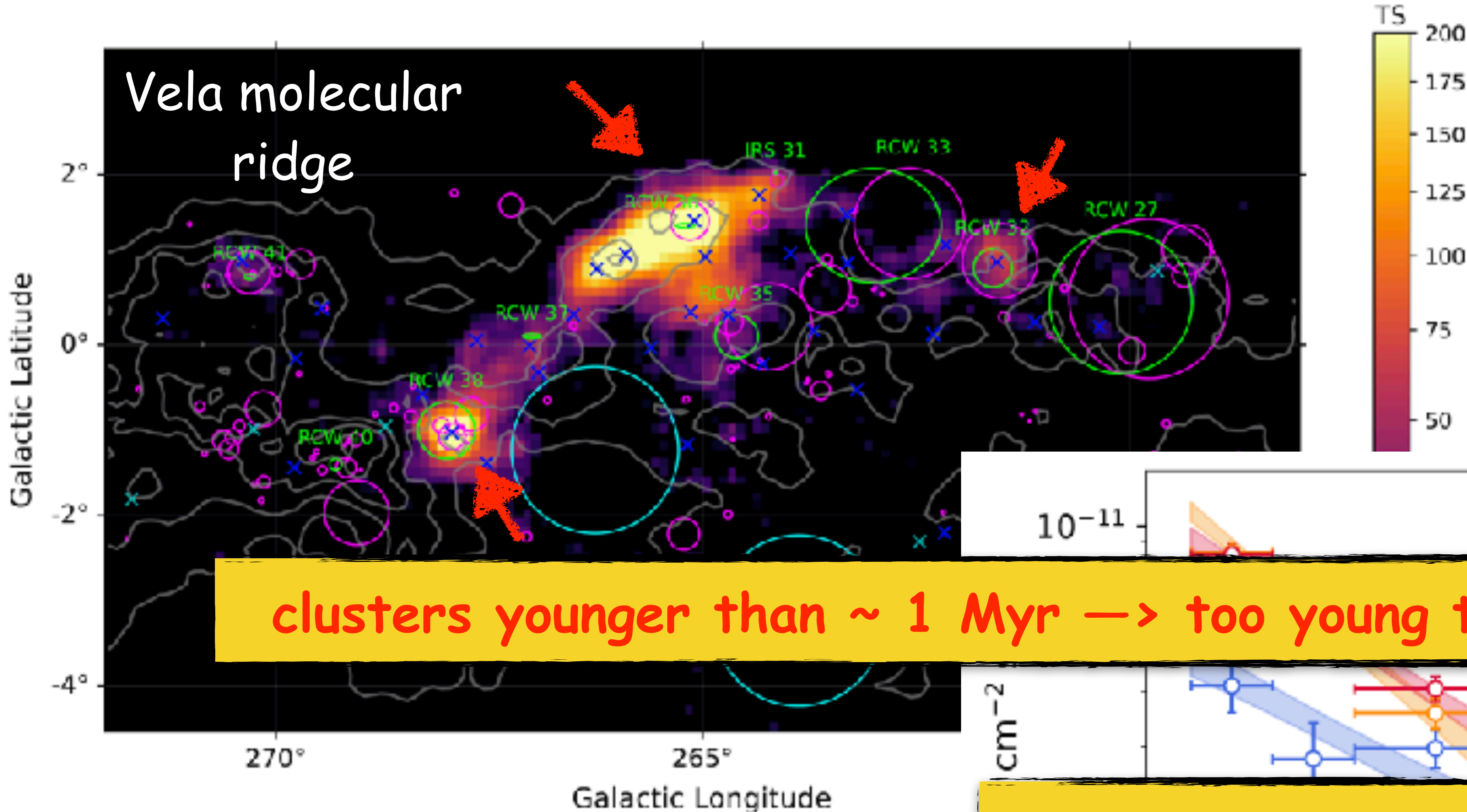
fraction of CRs coming from stellar winds

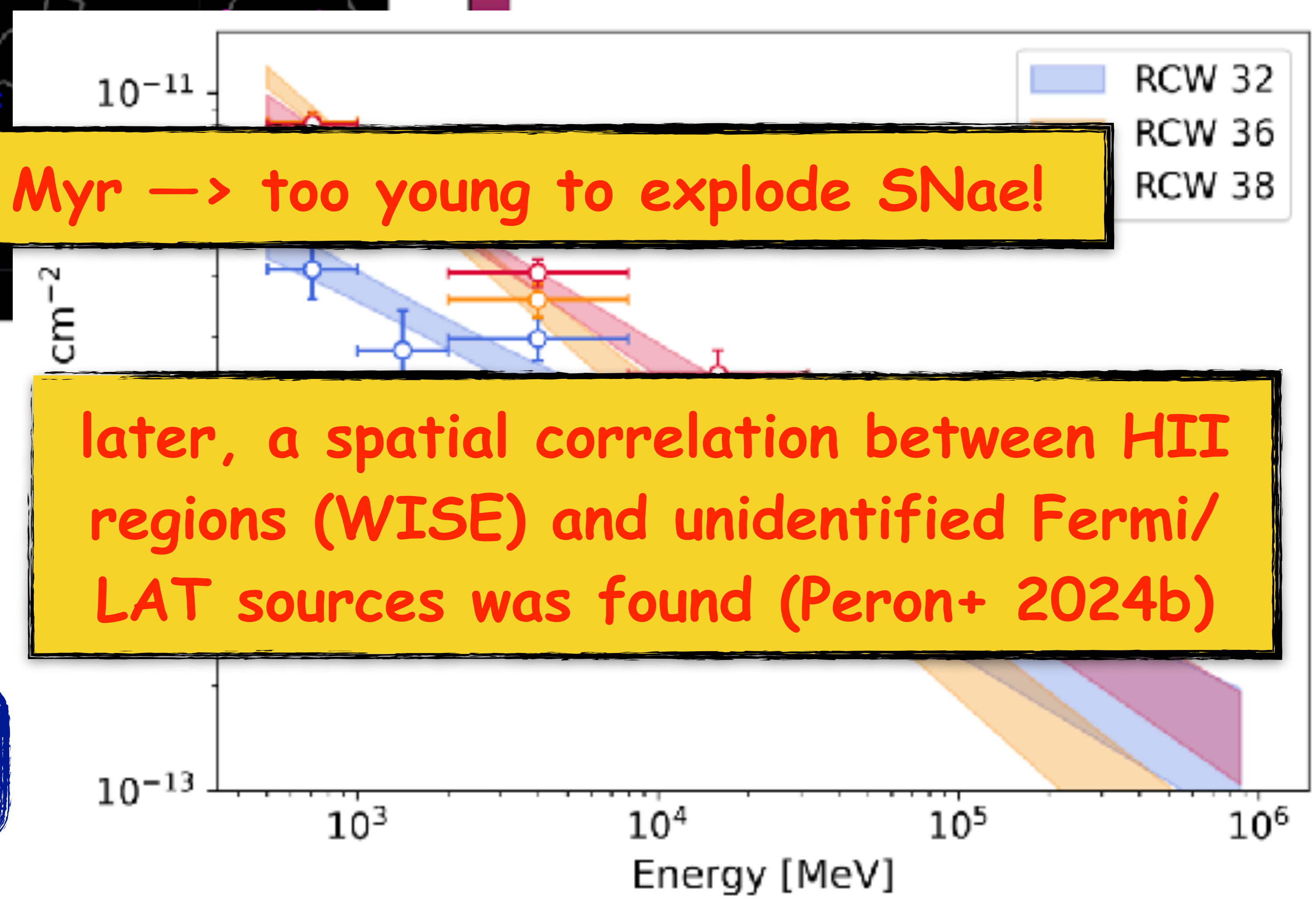
Yes, wind termination shocks do accelerate cosmic rays



grey —> gas

color —> gamma

green/purple —> HII regions



Peron+, 2024a

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

later, a spatial correlation between HII regions (WISE) and unidentified Fermi/LAT sources was found (Peron+ 2024b)

strict lower bound on the CR acceleration efficiency (energy)

fraction of CRs coming from stellar winds

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

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

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isotopic rati…
in C…

…o in winds

Solar/interstellar
isotopic ratio

In other words: if WTS contribute >1% to Galactic CRs then an excess in the ^{22}Ne/^{20}Ne ratio is predicted !

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

[5] Problems with the wind termination shock model

Can we go to the knee?

wind power: $P = \frac{1}{2}\dot{M}u^2$

wind density profile: $\varrho = \frac{\dot{M}}{4\pi u R^2}$

I stole this argument from T. Vieu's talk at TOSCA, Italy (2024)

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$$E_{max} \sim \frac{q}{c}uBR$$

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Hillas criterion

$$E_{max} \sim \frac{q}{c} uBR \ll 6 \left(\frac{P}{10^{38}\mathrm{erg/s}}\right)^{1/2} \left(\frac{u}{3000\ \mathrm{km/s}}\right)^{1/2} \mathrm{PeV}$$

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Hillas criterion

$E_{max} \sim \frac{q}{c} \left(\ldots \right)^{1/2} \left(\ldots \right)^{1/2}$ PeV

who accelerates PeV and multi PeV particles?

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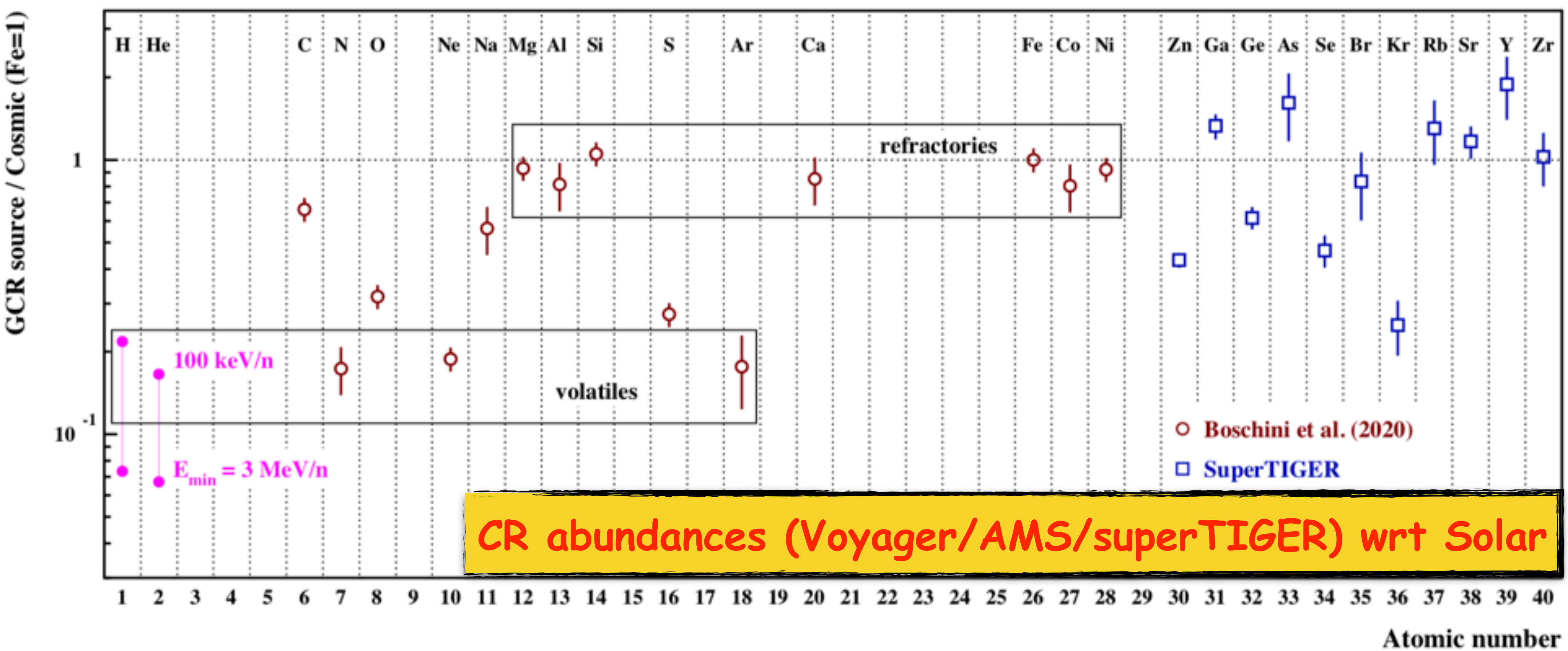
[6] CRs from star clusters: observational evidences (obtained following matter)

CR composition points towards the hot phase of the ISM (super bubbles)

Tatischeff+ 2021



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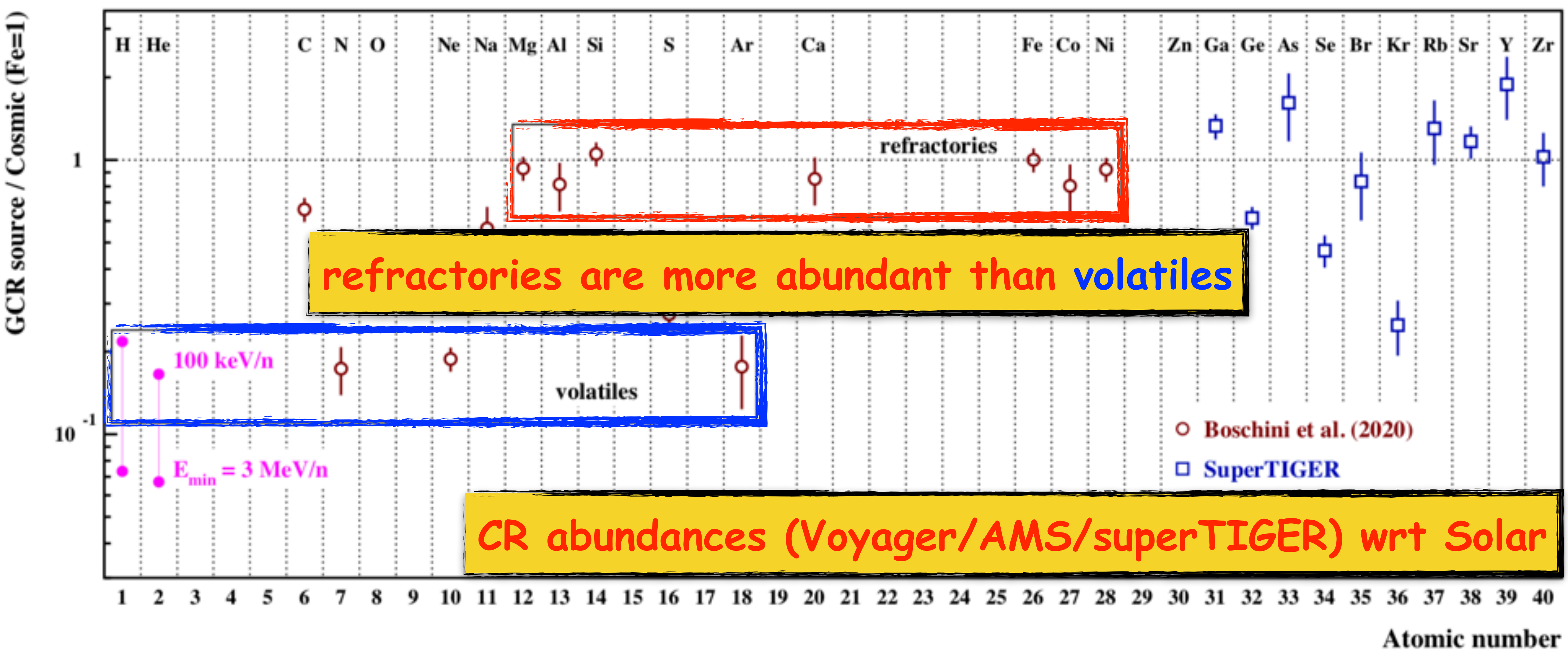

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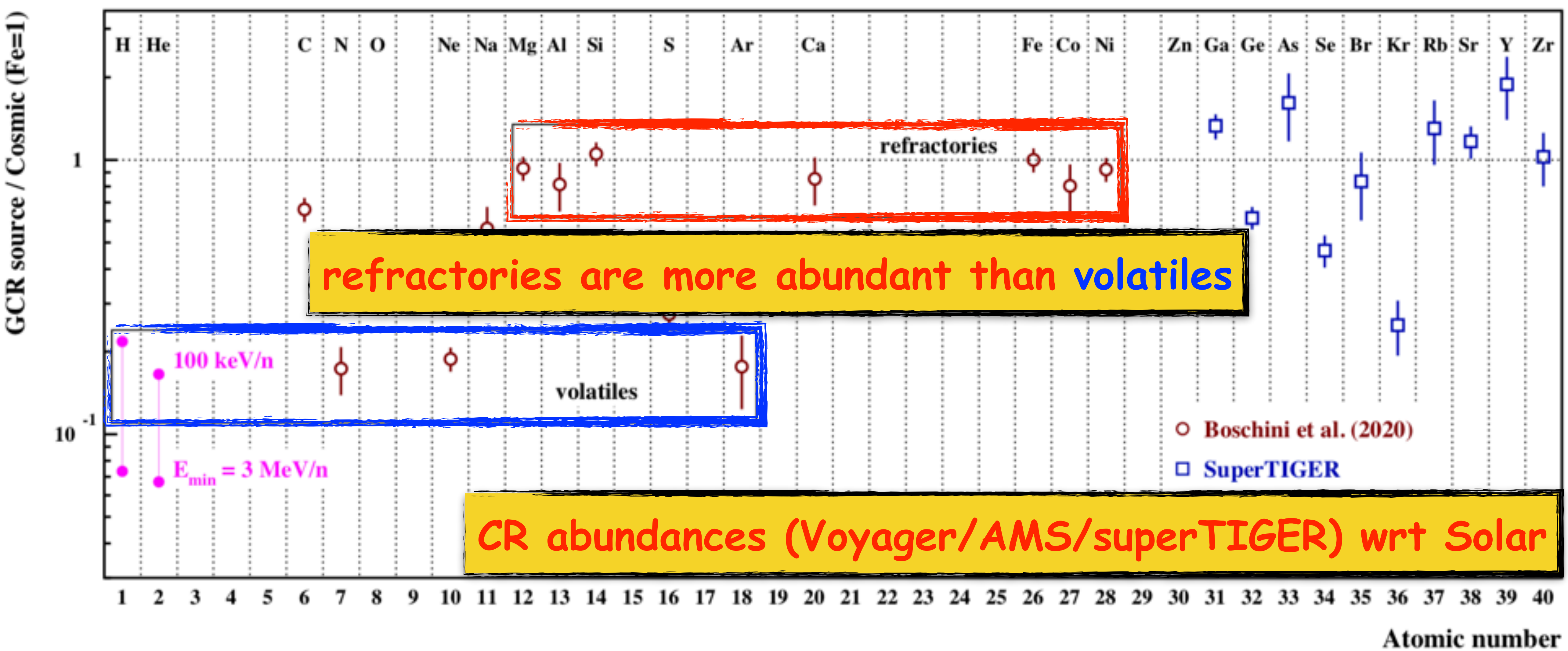

DUST must play a role in CR acceleration, and this is known since Meyer, Drury, Ellison 1998

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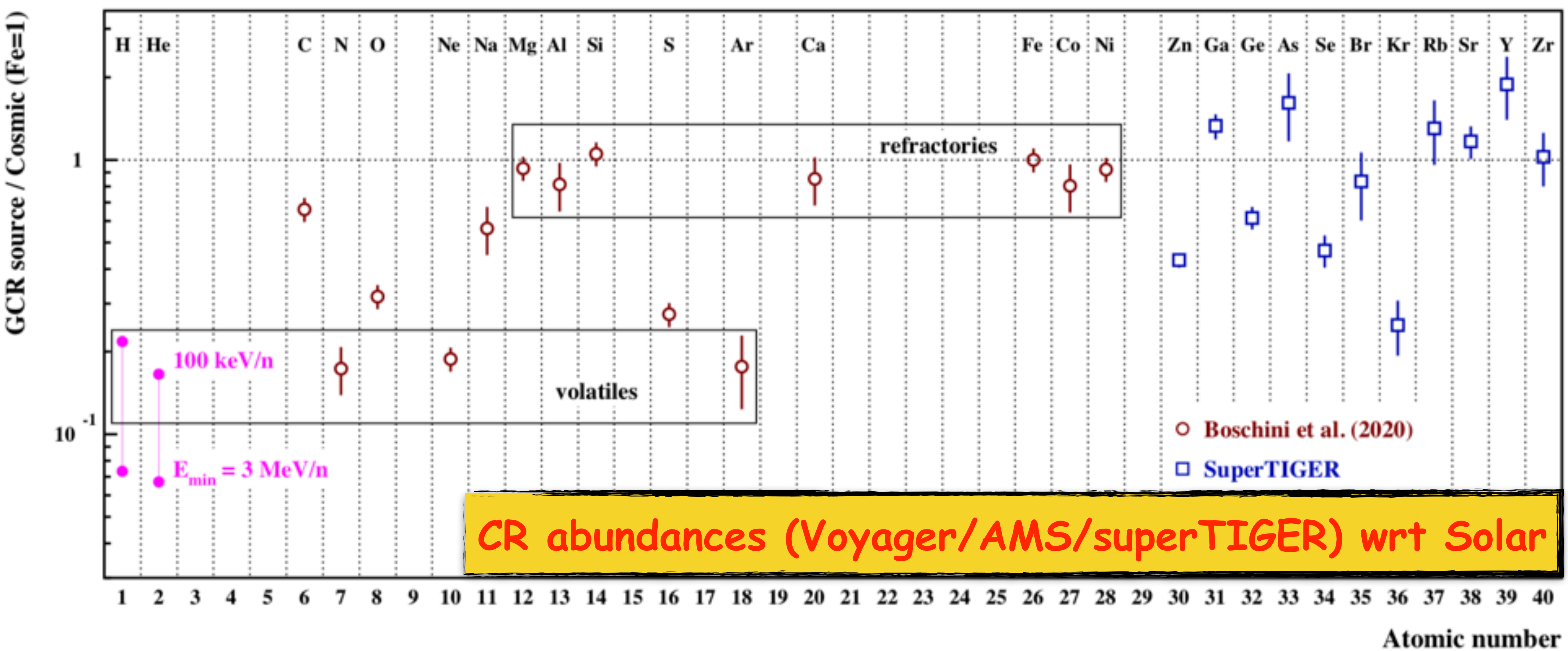
Tatischeff+ 2021



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DSA —> preferential injection of high A/Q ions (Meyer, Drury, Ellison 1998)

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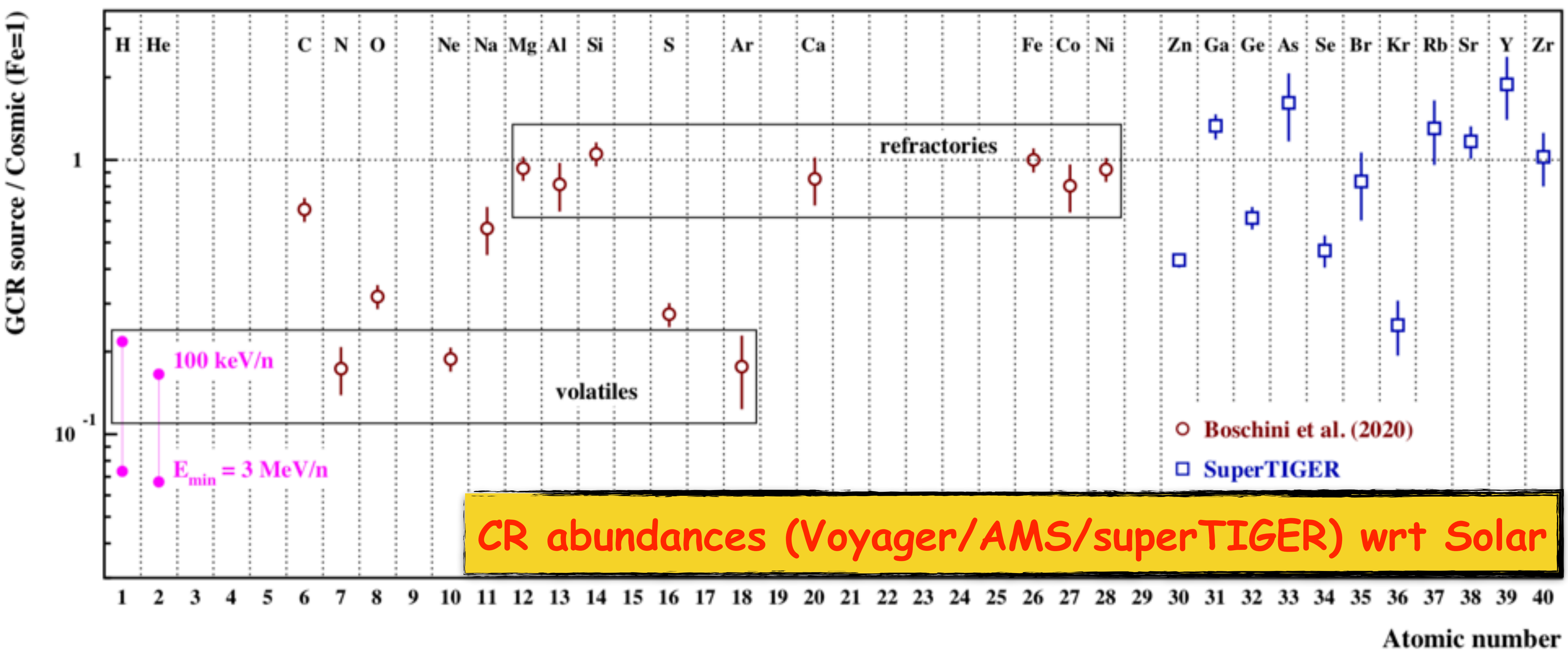

CR abundances (Voyager/AMS/superTIGER) wrt Solar

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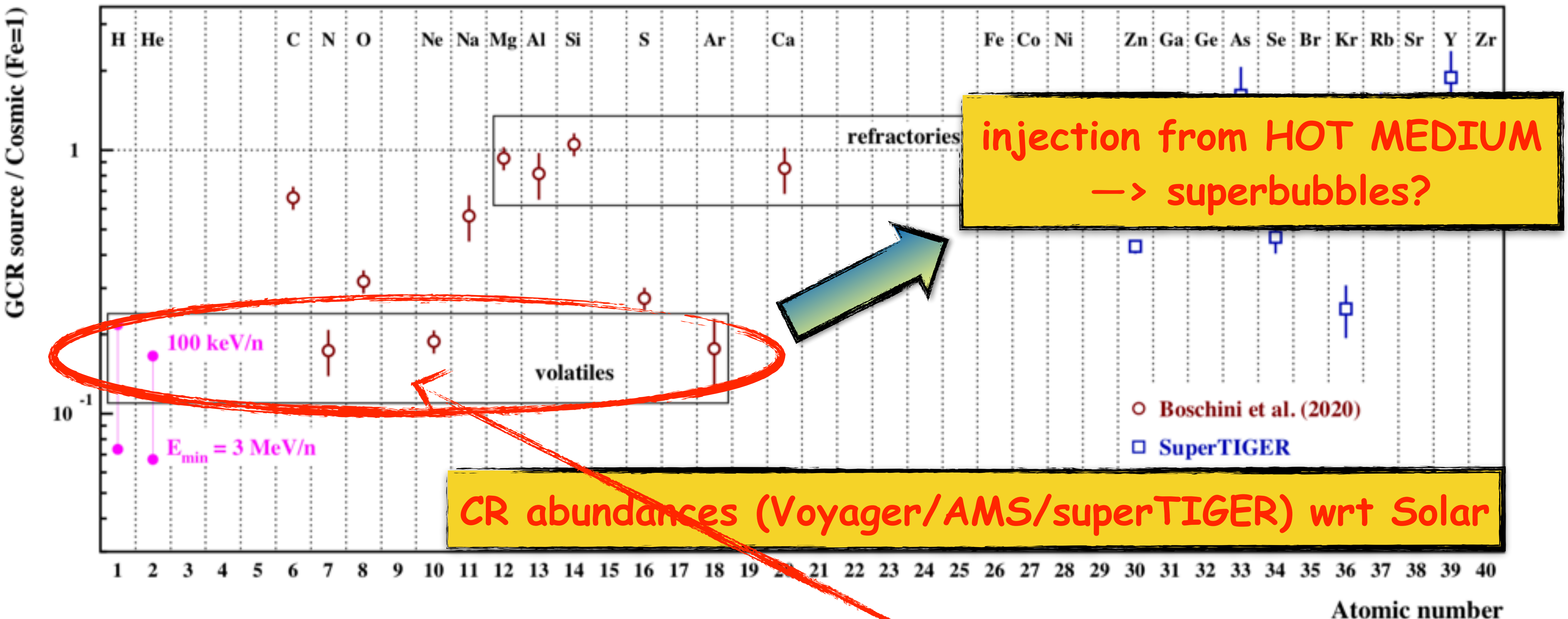

SBs are hot —> A/Q ~2 for all elements —> **flat abundance/solar ratio**

^{60}Fe in CRs —> local accelerators

ACE detected 15 ^{60}Fe nuclei in CRs (Binns+ 2016)

—> need for at least 2 SNae (one to produce ^{60}Fe, one to accelerate it)

—> star clusters!

de Séréville+ 2024

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lifetime of ^{60}Fe ~ 3.8 Myr

$$l_{max} = \sqrt{6\ D\ \gamma\ \tau_{decay}}$$

CR diffusion coefficient

Lorentz factor

decay time

de Séréville+ 2024

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decay time → τ_{decay}

$$l_{max} \sim 2 \text{ kpc}$$

de Séréville+ 2024

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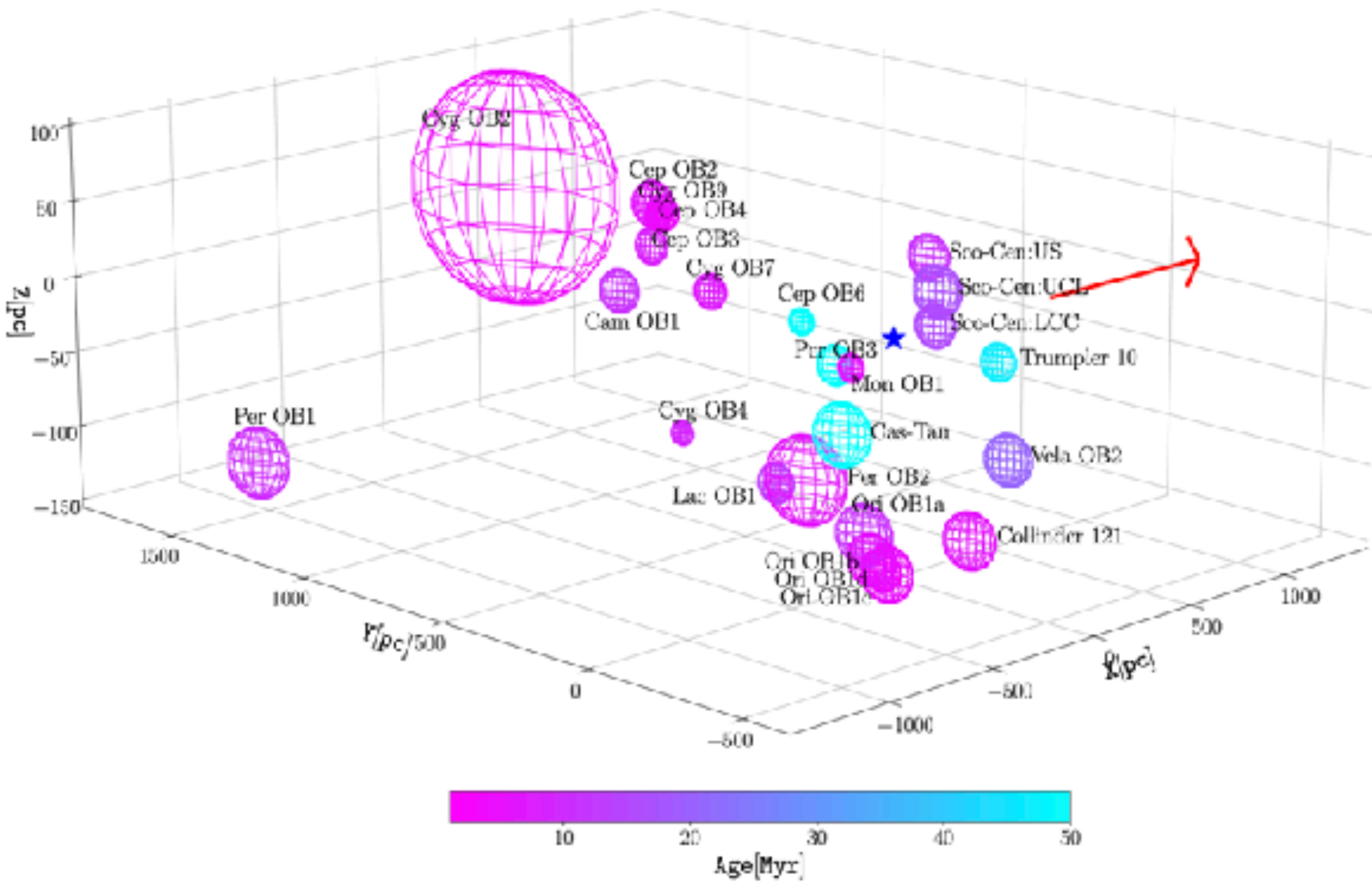

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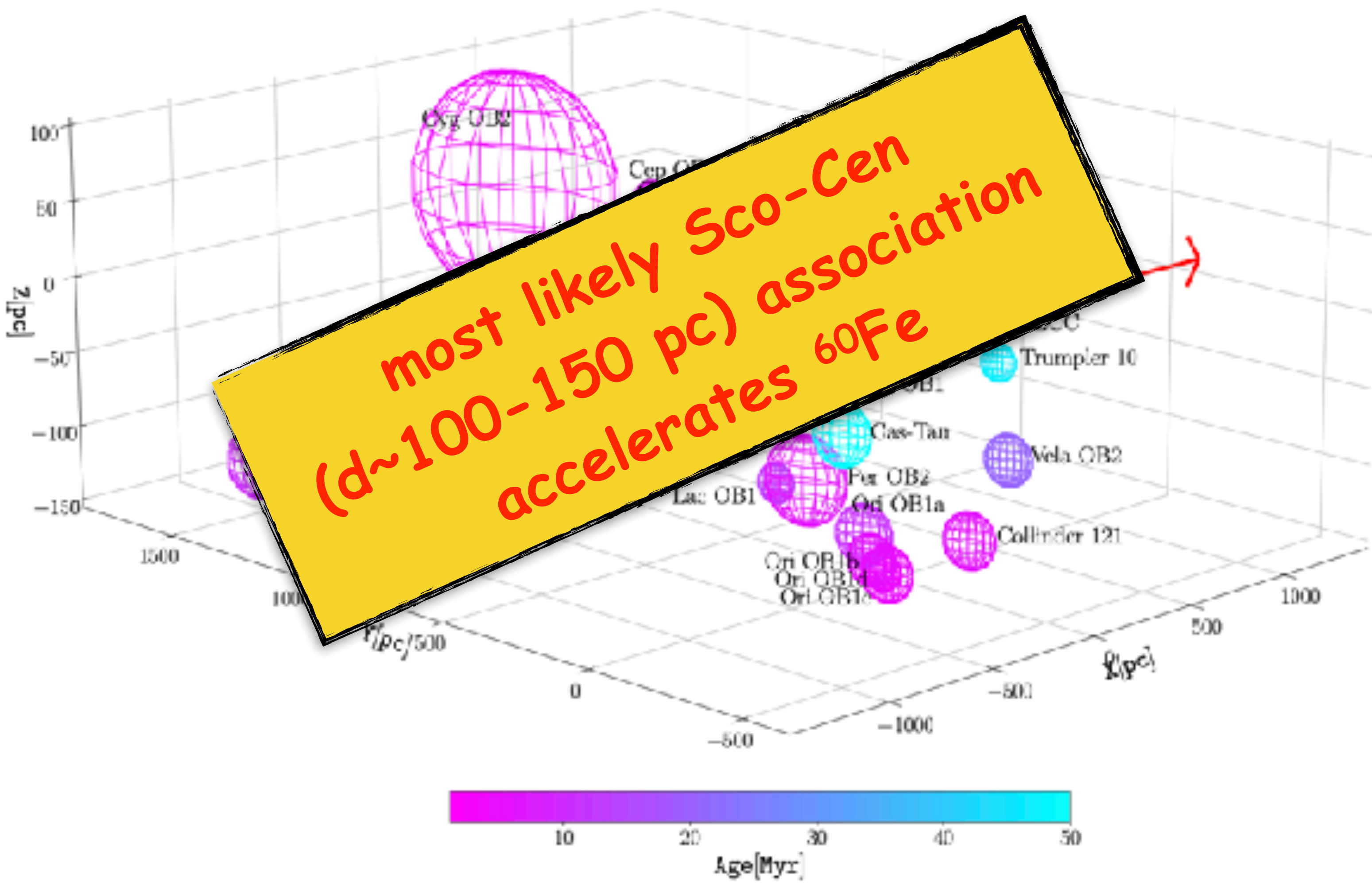

most likely Sco-Cen (d~100-150 pc) association accelerates ^{60}Fe

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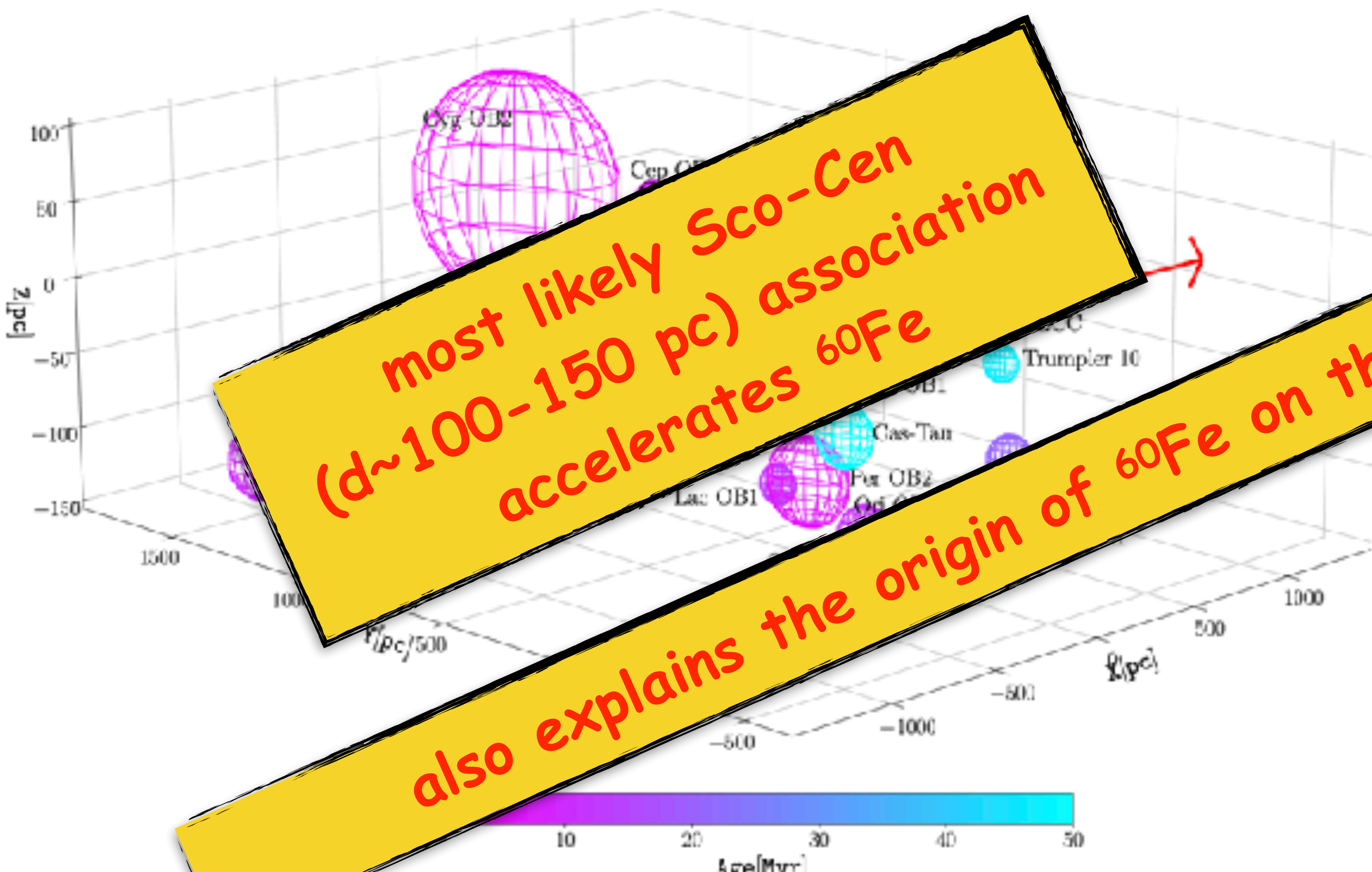

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also explains the origin of ^{60}Fe on the bottom of the ocean!

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Conclusions (+perspective +puzzle)

- Explaining the knee (and beyond!) is still a problem
- LHAASO provides and will provide an unprecedented view on the CR knee

  AND on gamma ray signatures of PeV Cos

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- Overabundance refractories —> dust must play a role
- Volatiles.vs.(A/Z) —> probably from hot ISM (superbubbles)
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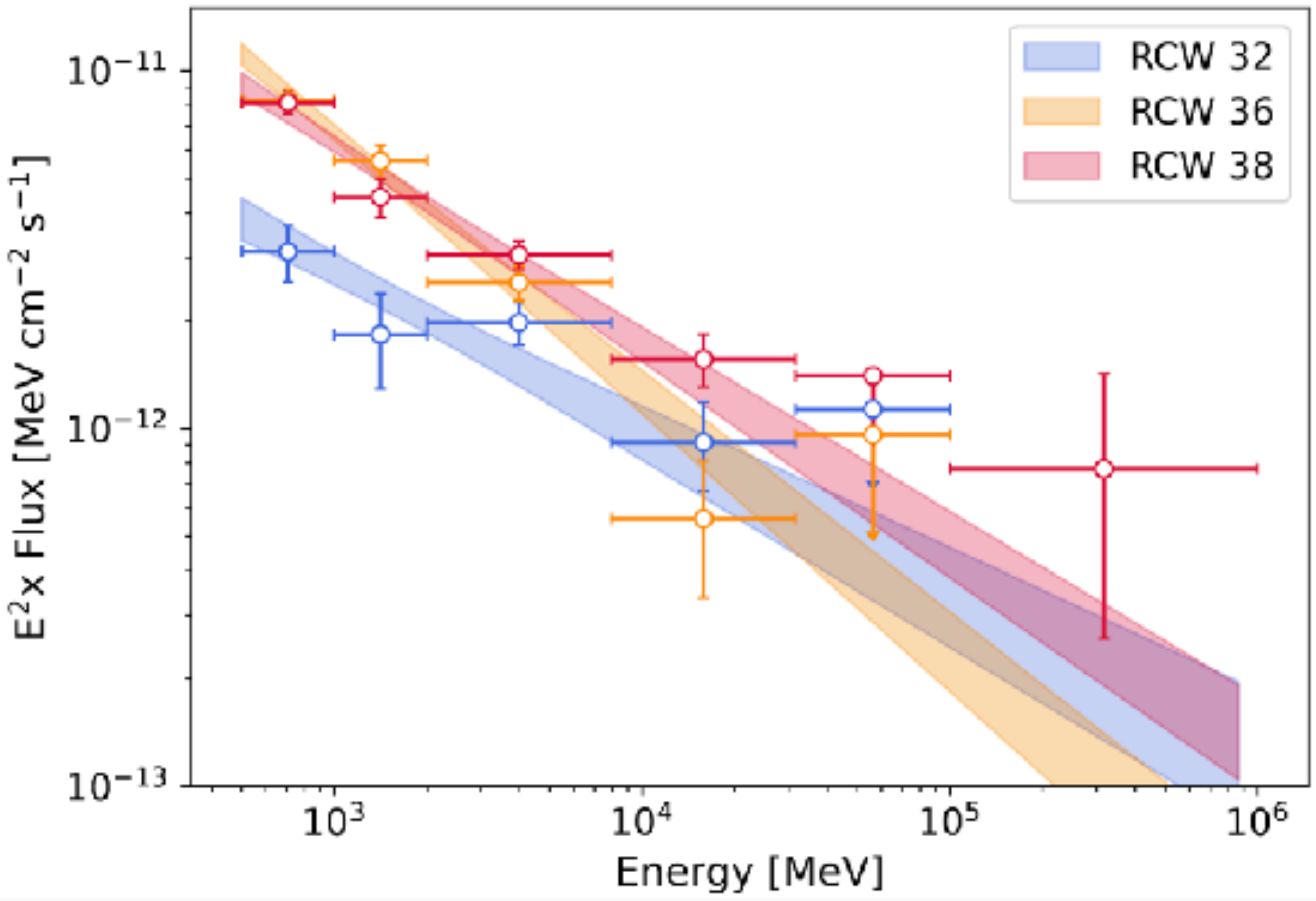
We still don't know who accelerates PeV and multi-PeV cosmic rays! —> physics

Perspective: PeV CRs from stellar WTS?

Peron+, 2024a



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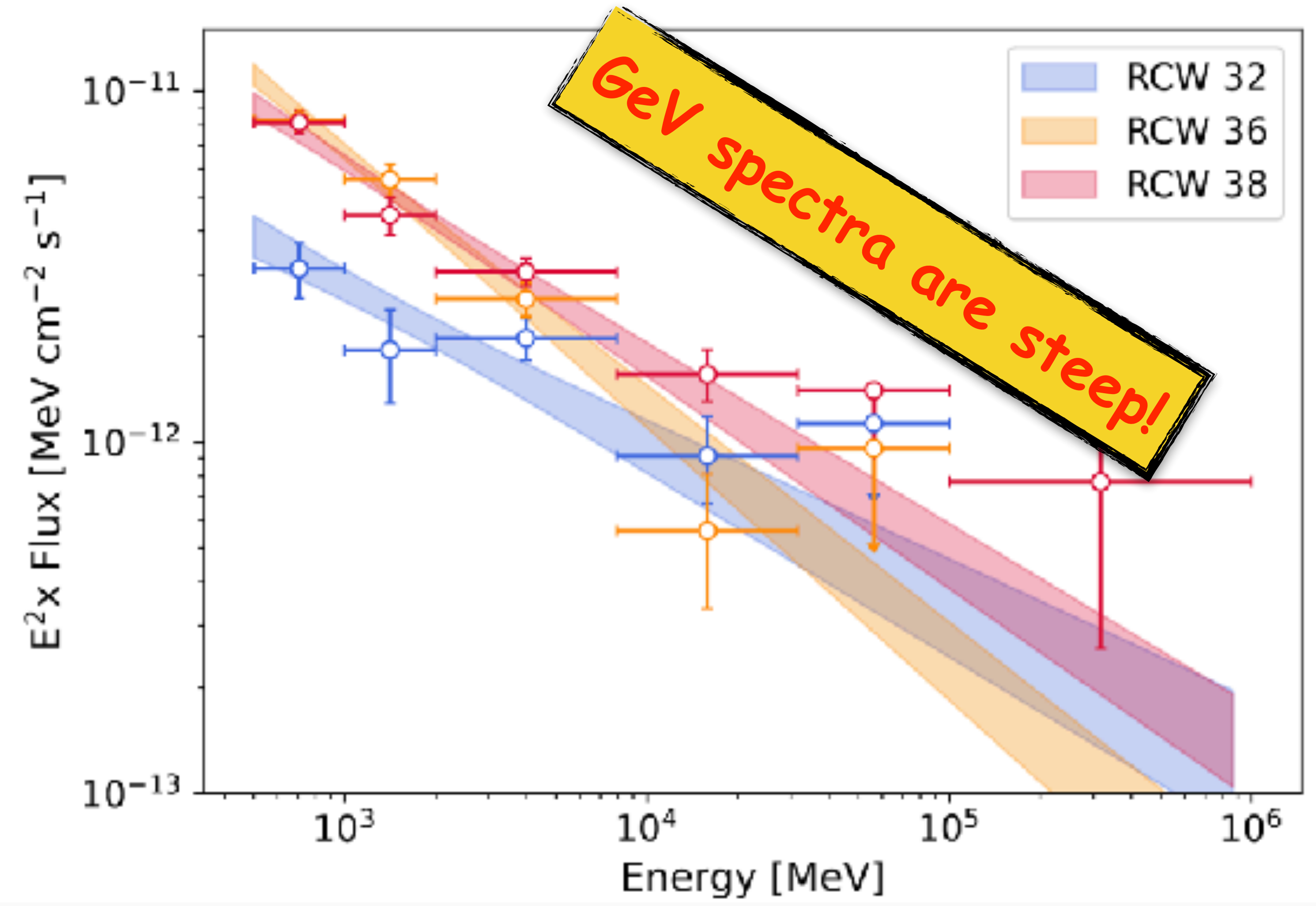
Peron+, 2024a



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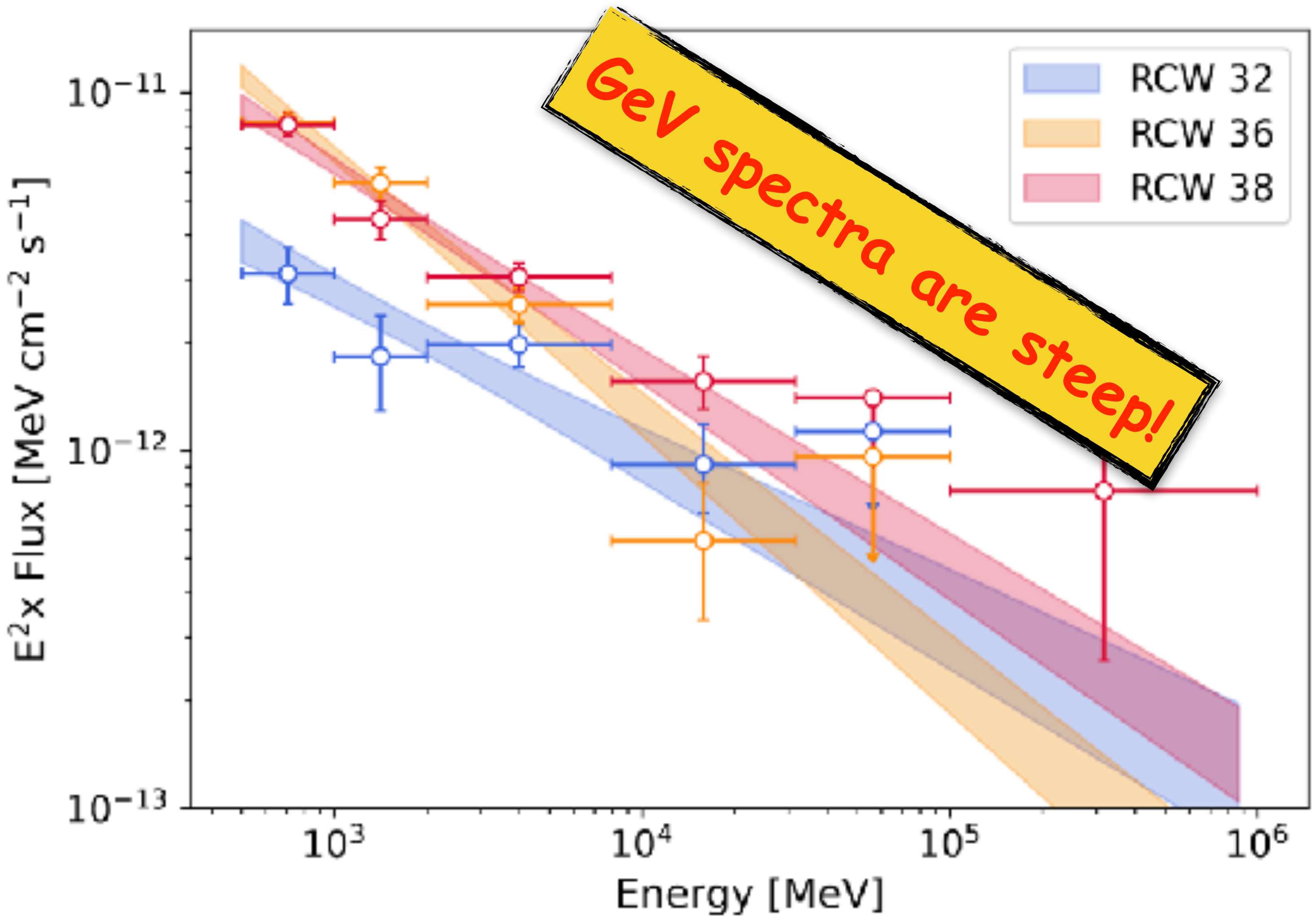
intrinsically steep —> bad PeVatrons (even if the accelerate to the PeV domain)

Peron+, 2024a



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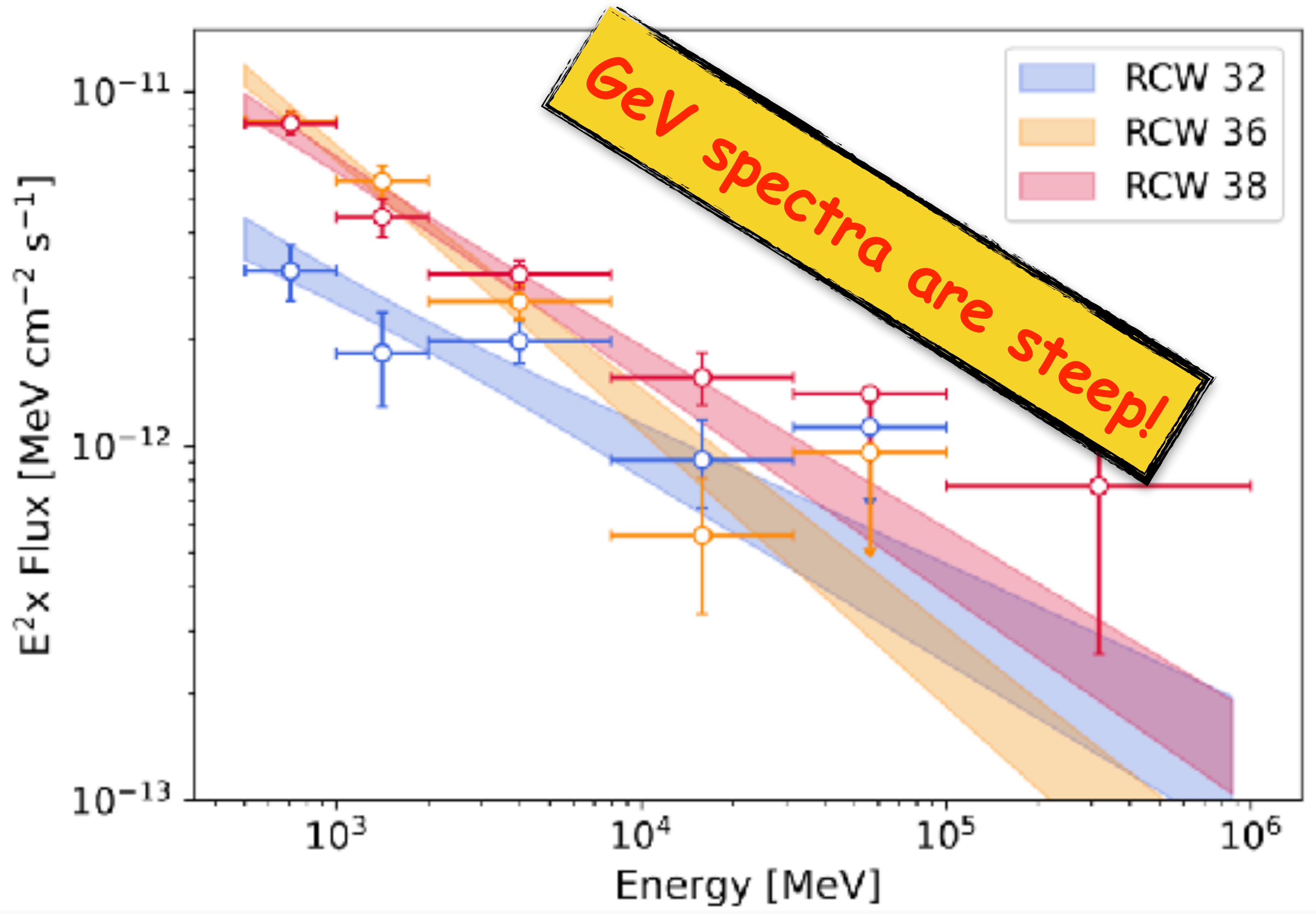

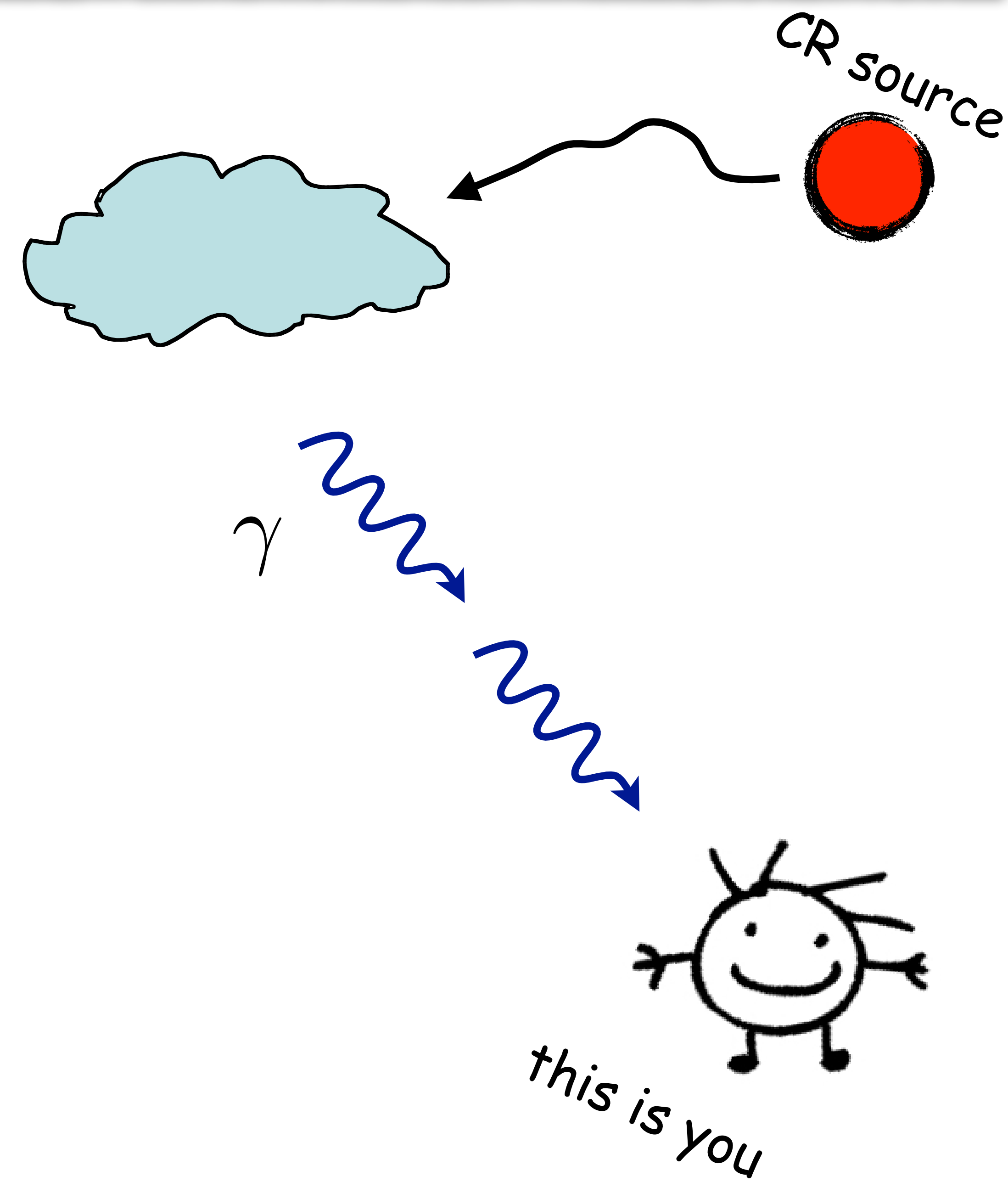

steep because of CR escape —> search for multi-TeV signal from runaway CRs!

Puzzle: the SN rate in the Galaxy

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **538**, 1367–1383 (2025) https://doi.org/10.1093/mnras/staf083
Advance Access publication 2025 March 18

A census of OB stars within 1 kpc and the star formation and core collapse supernova rates of the Milky Way

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ABSTRACT

OB stars are crucial for our understanding of Galactic structure, star formation, stellar feedback and multiplicity. In this paper we have compiled a census of all OB stars within 1 kpc of the Sun. We performed evolutionary and atmospheric model fits to observed SEDs compiled from astro-photometric survey data. We have characterized and mapped 24,706 O- and B-type stars ($T_{\rm eff} > 10,000$ K) within 1 kpc of the Sun, whose overdensities correspond to well-studied OB associations and massive star-forming regions such as Sco-Cen, Orion OB1, Vela OB2, Cepheus and Circinus. We have assessed the quality of our catalogue by comparing it with spectroscopic samples and similar catalogues of OB(A) stars, as well as catalogues of OB associations, star-forming regions and young open clusters. Finally, we have also exploited our list of OB stars to estimate their scale height (76 ± 1 pc), a local star formation rate of 2896^{+417}_{-1} M$_\odot$ Myr^{-1} and a local core-collapse supernova rate of ~15–30 per Myr. We extrapolate these rates to the entire Milky Way to derive a Galactic SFR of $0.67^{+0.09}_{-0.01}$ M$_\odot$ yr^{-1} and a core-collapse supernova rate of 0.4–0.5 per century. These are slightly lower than previous estimates, which we attribute to improvements in our census of OB stars and changes to evolutionary models. We calculate a near-Earth core collapse supernova rate of ~2.5 per Gyr that supports the view that nearby supernova explosions could have caused one or more of the recorded mass extinction events on Earth.