Galactic cosmic rays

Stefano Gabici
APC, Paris

Disclaimer


This will be a very incomplete overview on cosmic rays (1h is too short!)

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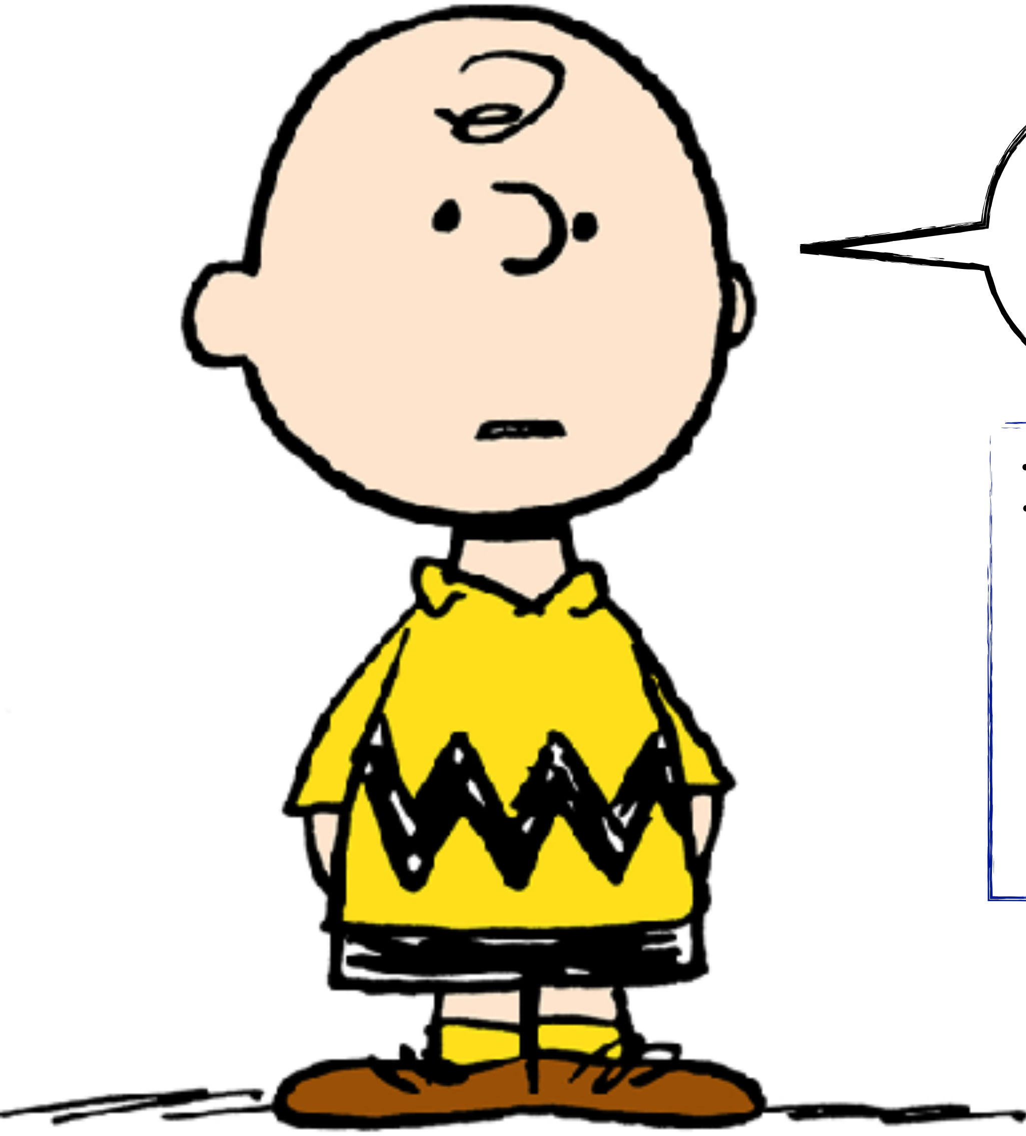

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Do supernova remnants accelerate ALL Galactic cosmic rays? (and will focus on stellar winds)

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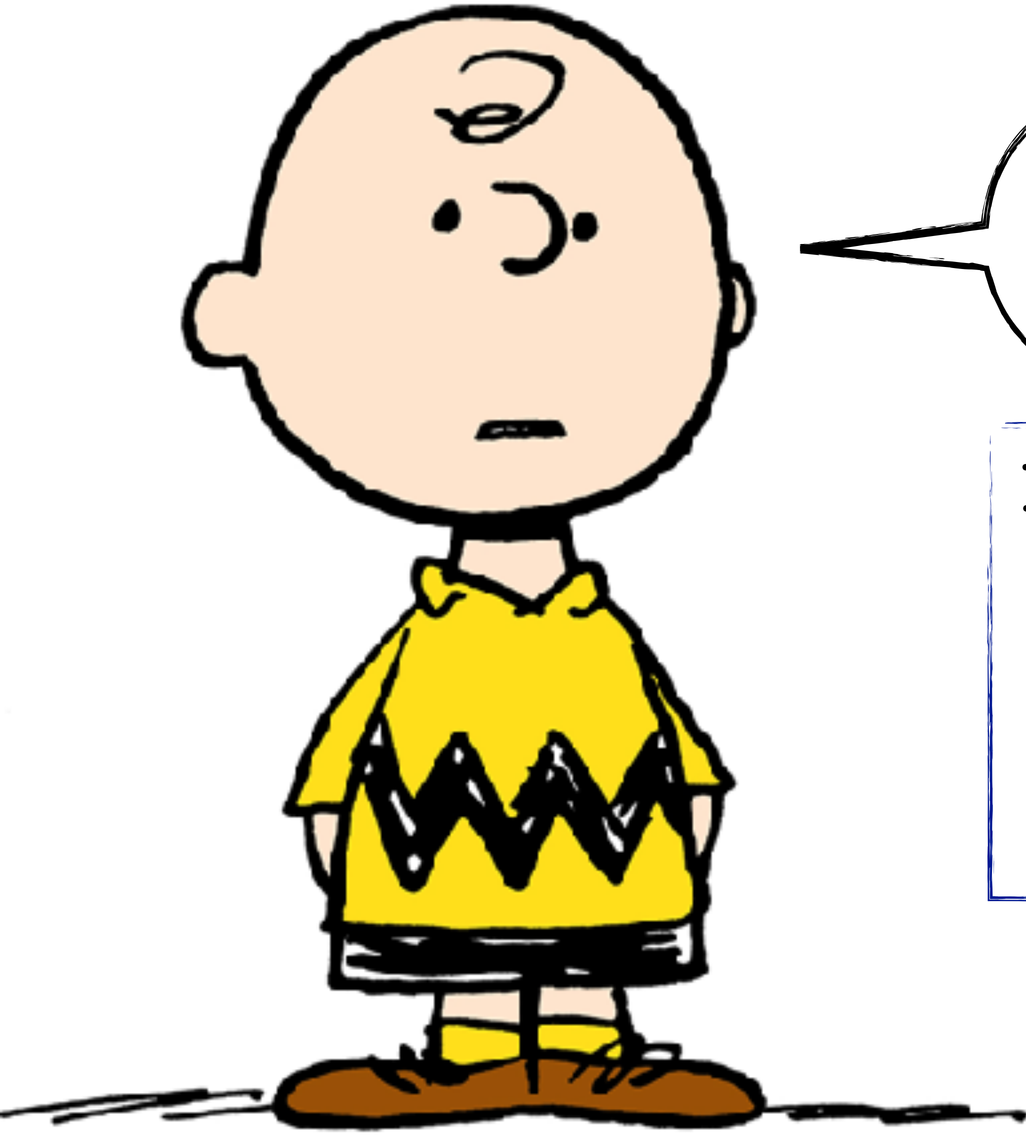

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For an updated set of references to recent results
—> Gabici, ICRC2023, Rapporteur talk CRD (PoS)

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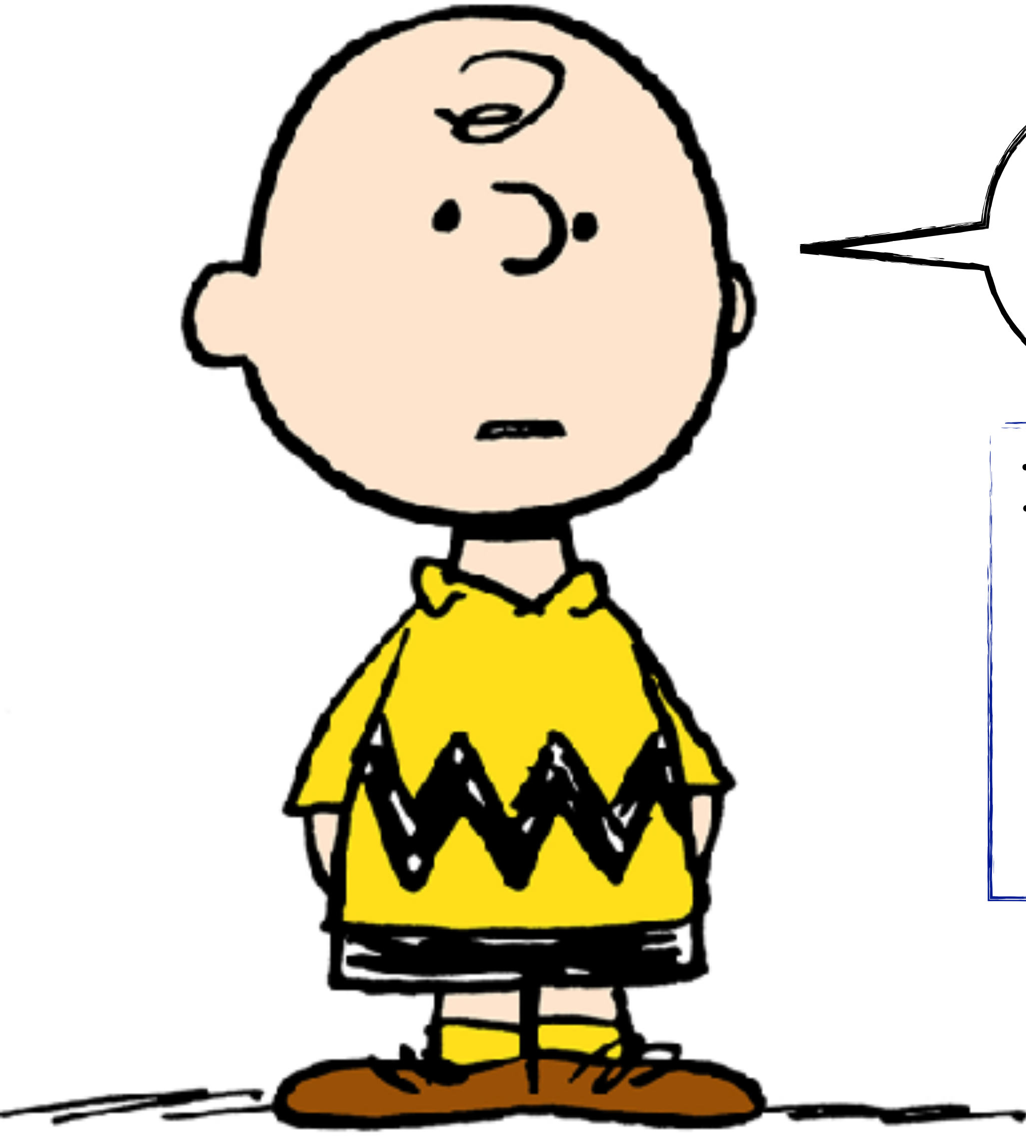

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List of critical ("unorthodox"?) reviews:

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

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

Plan of the talk

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

[2] **The "sizes" of cosmic rays** —> from low to extreme energies

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

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

—> is there room left for other sources?

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

—> the Hillas criterion

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

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

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

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

What are cosmic rays?

1.1 What are cosmic rays?

Cosmic ray particles hit the Earth's atmosphere at the rate of about 1000 per square meter per second. They are ionized nuclei – about 90% protons, 9% alpha particles and the rest heavier nuclei – and they are distinguished by their high energies. Most cosmic rays are relativistic, having energies comparable to or somewhat greater than their masses. A small but very interesting fraction of them have ultra-relativistic energies extending up to 10^{20} eV (about 20 joules), eleven orders of magnitude greater than the equivalent rest mass energy of a proton. The fundamental question of cosmic ray physics is, "Where do they come from?" and, in particular, "How are they accelerated to such high energies?"

The answer to the question of the origin of cosmic rays is not yet fully known. It is clear, however, that nearly all of them come from outside the solar system, but from within the Galaxy. The relatively few particles of solar origin are characterized by temporal association with violent events on the Sun and consequently by a rapid variability. In contrast, the bulk of cosmic rays show an anti-correlation with solar activity, being more effectively excluded from the solar neighborhood during periods when the expanding, magnetized plasma from the Sun – the solar wind – is most intense. The very highest energy cosmic rays have gyroradii in typical galactic magnetic fields that are larger than the size of the Galaxy. These may be of extragalactic origin.

Gaisser, Engel, Resconi "Cosmic Rays and Particle Physics" (2016)

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Solar metallicity?

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energetic

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$\langle E \rangle \sim$ GeV

what cosmic ray physicists would like to know

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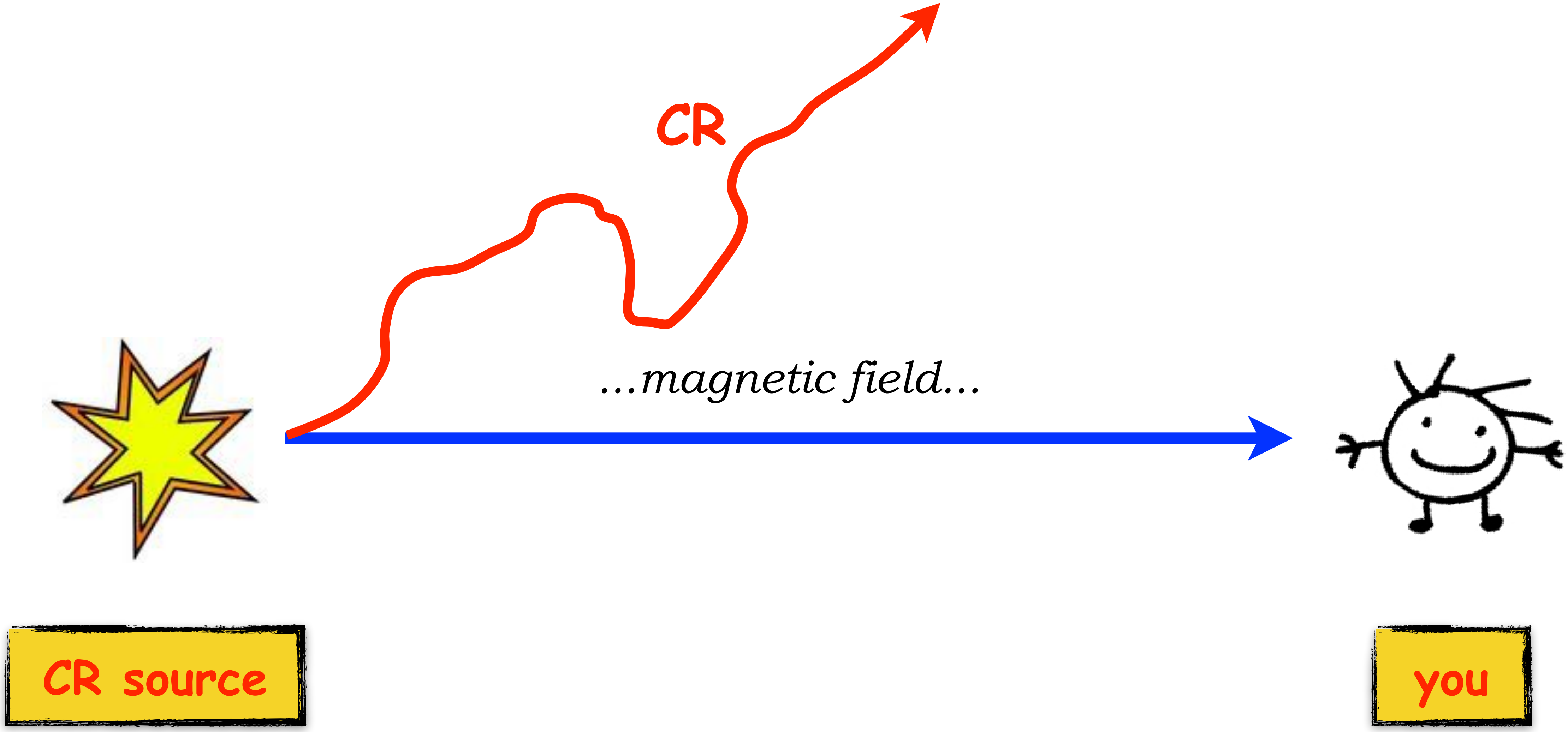
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

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the Sun is a problem

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Solar metallicity?

energetic

<E> ~ GeV

what cosmic ray physicists would like to know

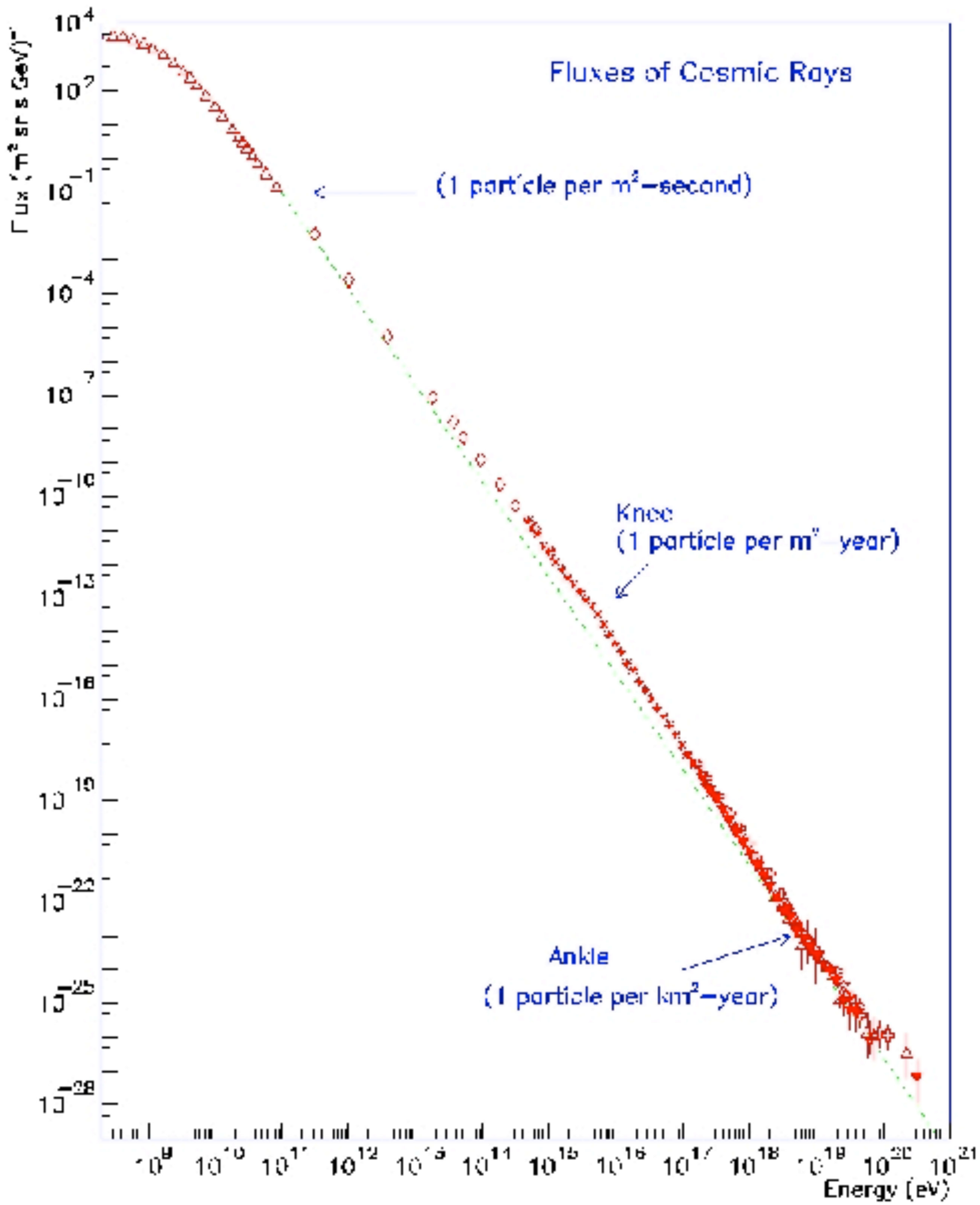
Galactic

the Sun is a problem

very few extragalactic particles?

Gaisser, Engel, Resconi "Cosmic Rays and Particle Physics" (2016)

The (local) Cosmic Ray spectrum



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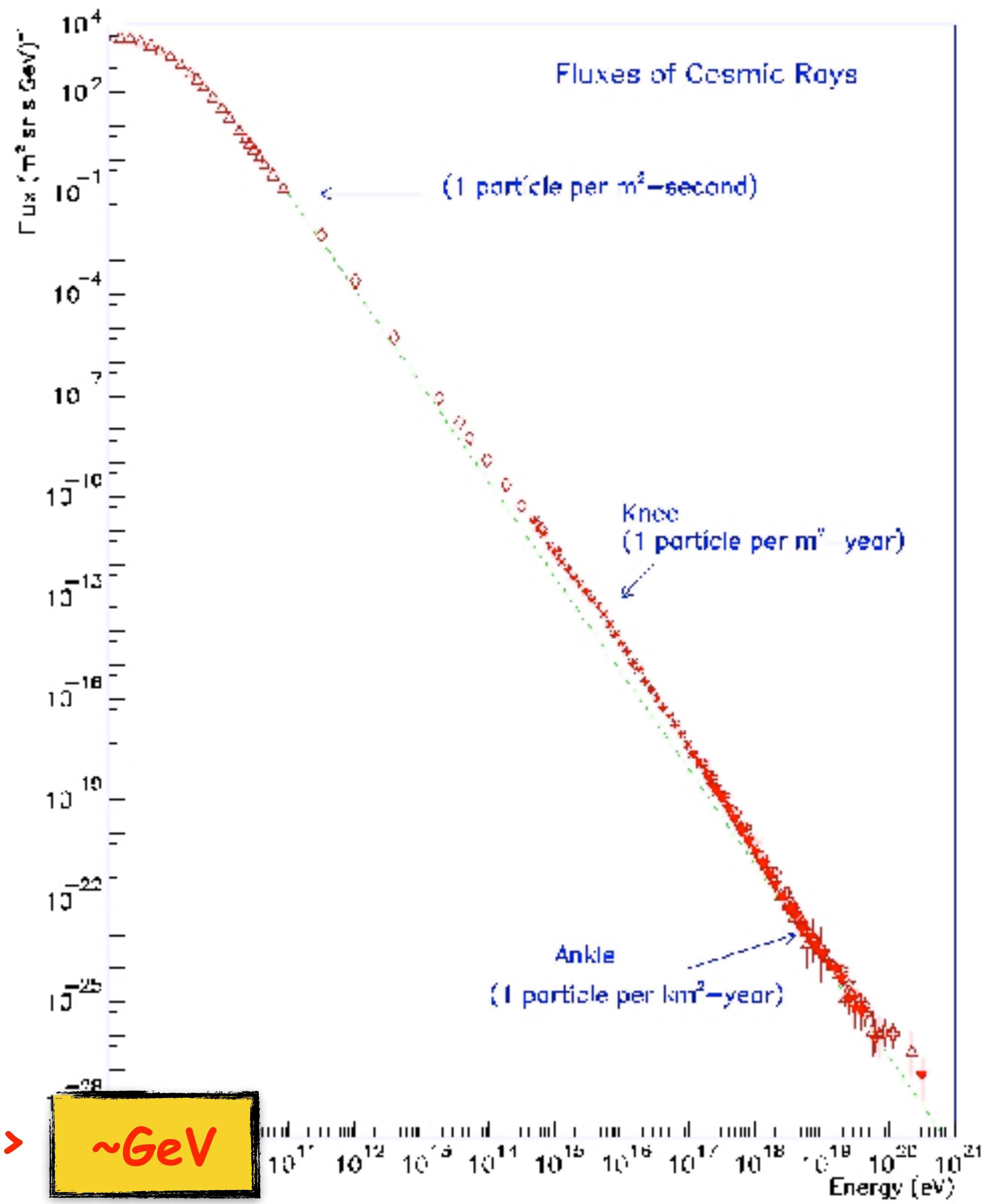

mean energy -> ~GeV

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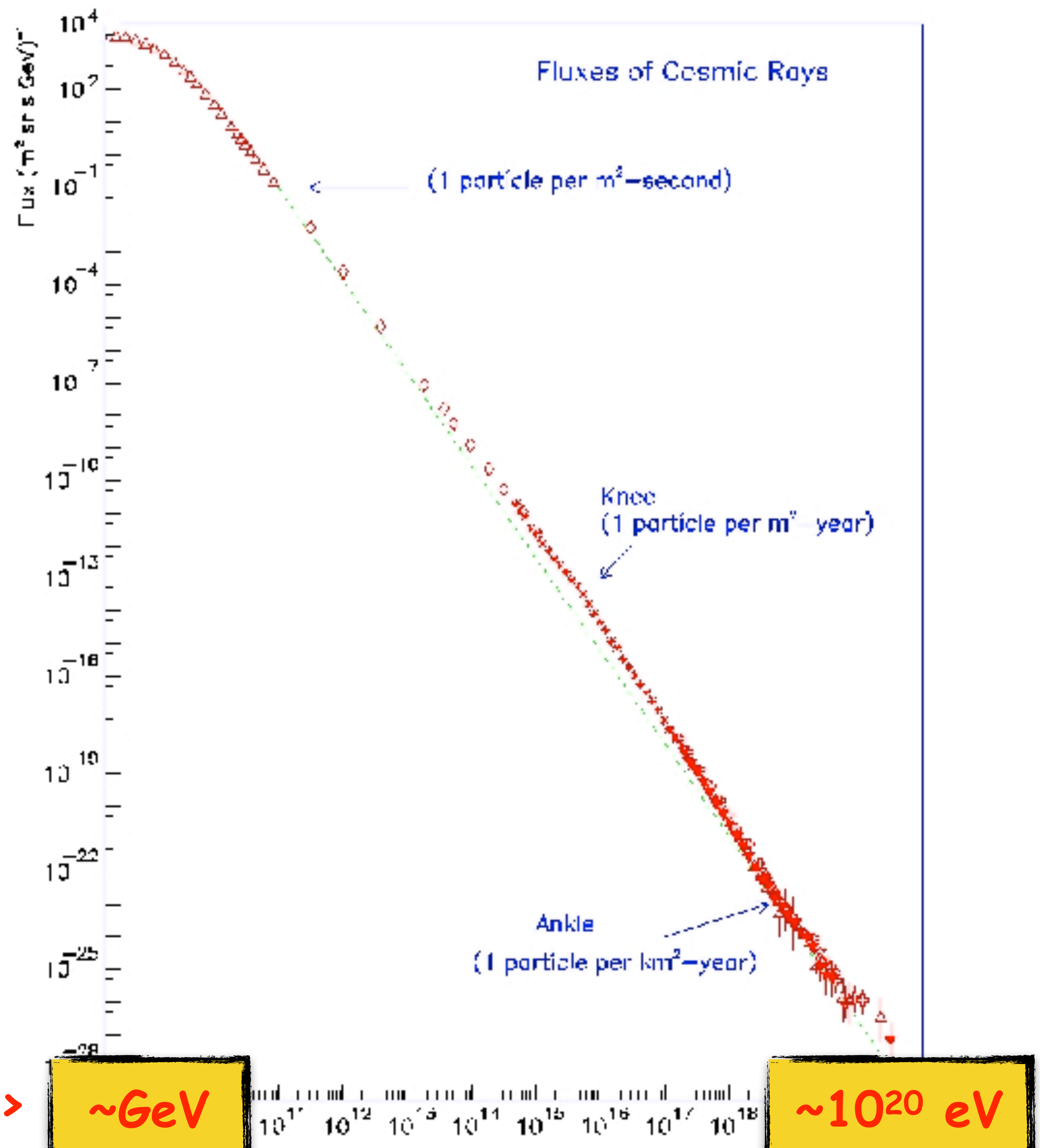

mean energy -> ... <- maximum energy

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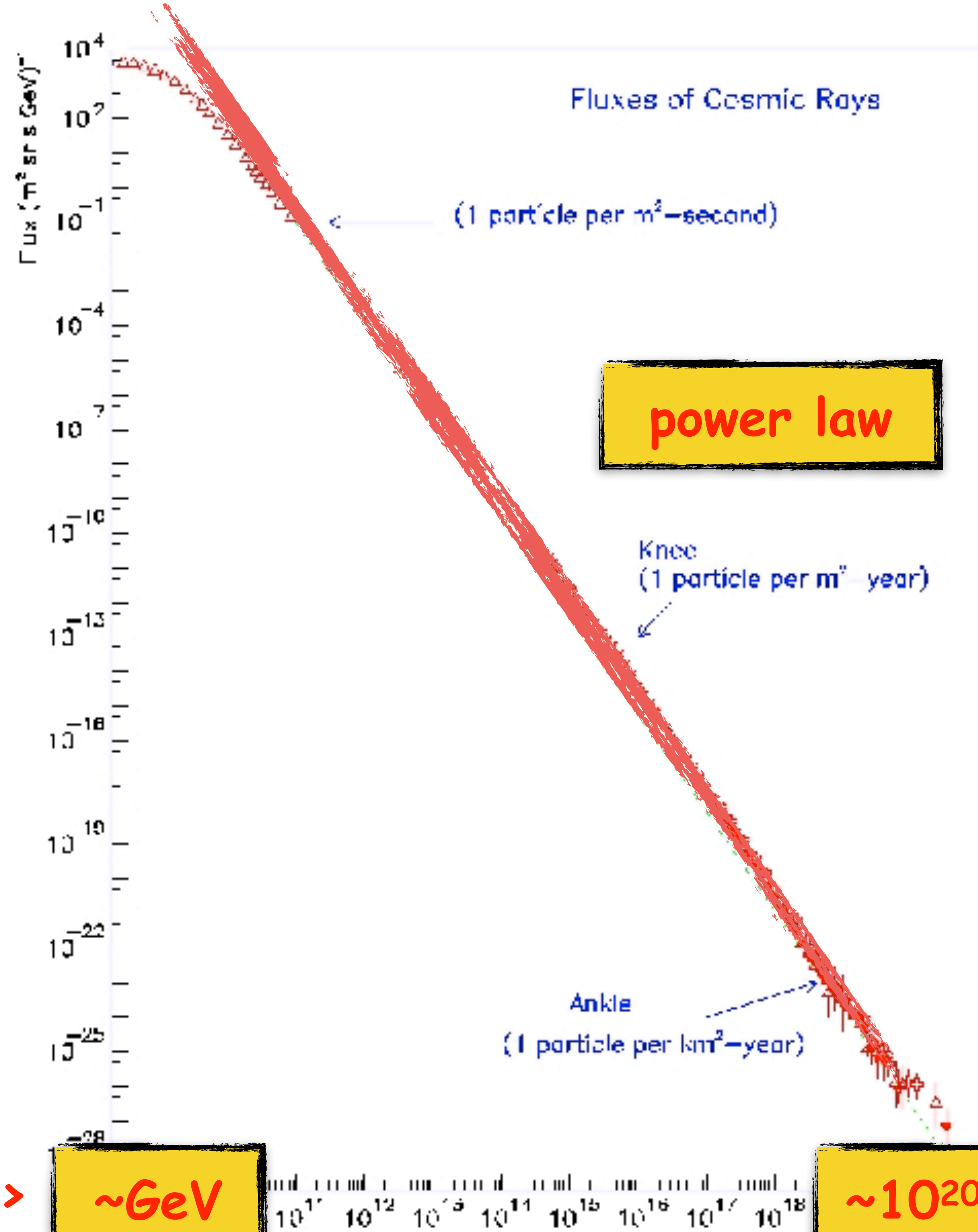

$$\propto E^{-2.7} - E^{-3}$$

mean energy -> ~GeV

~10^{20} eV <- maximum energy

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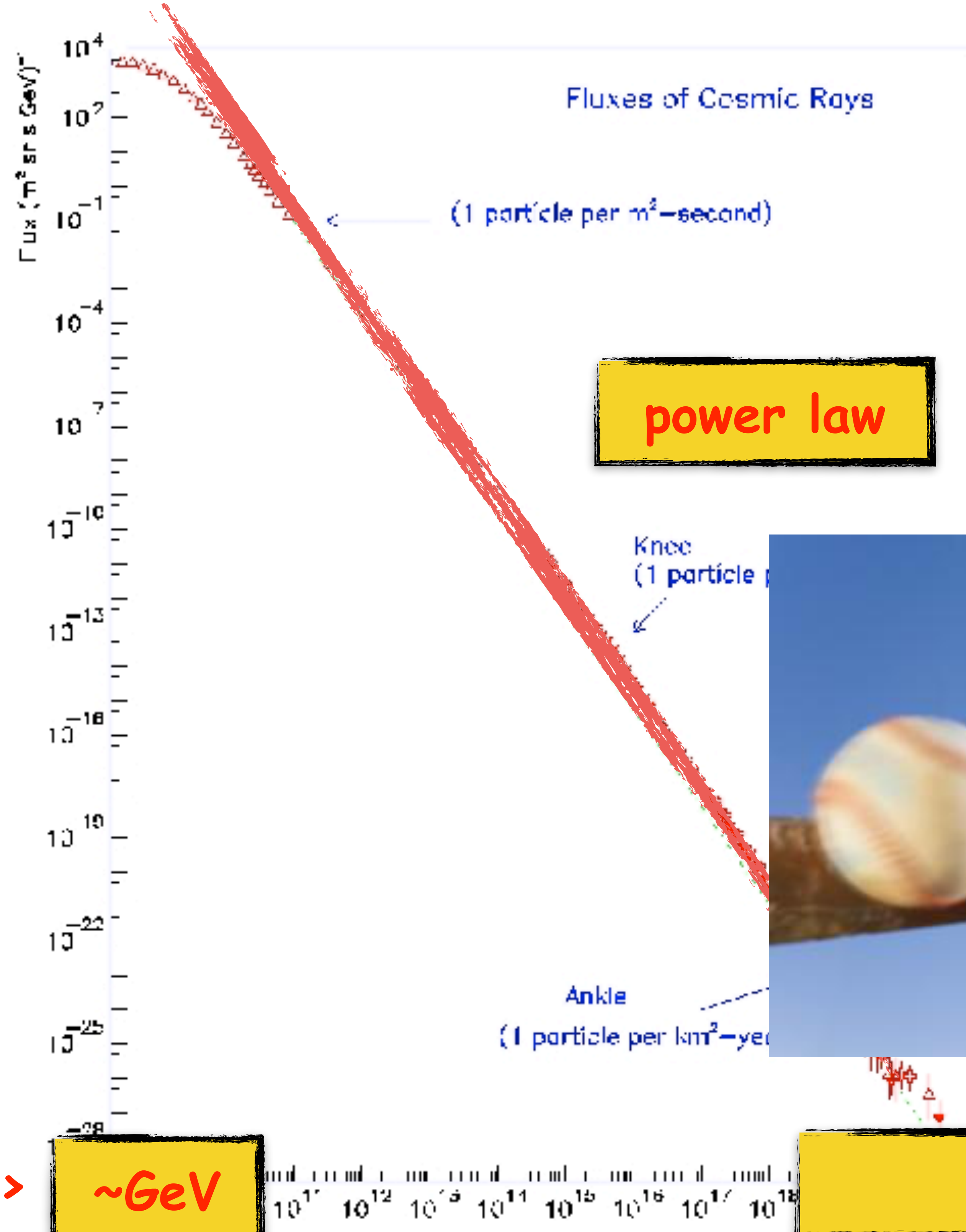


power law

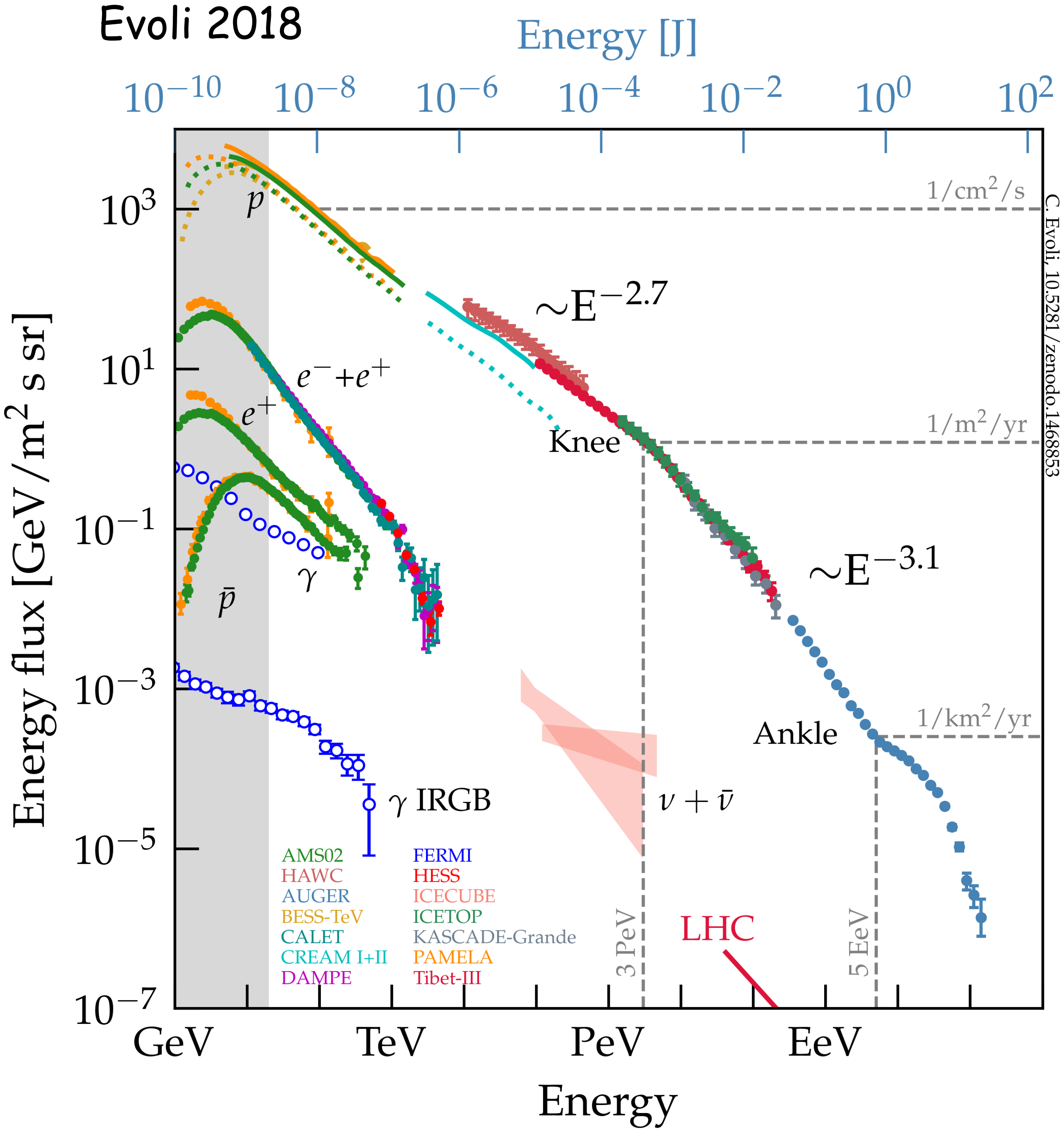
$$\propto E^{-2.7} - E^{-3}$$

mean energy -> ~GeV

tens of Joules!

The cosmic ray spectrum

Evoli 2018



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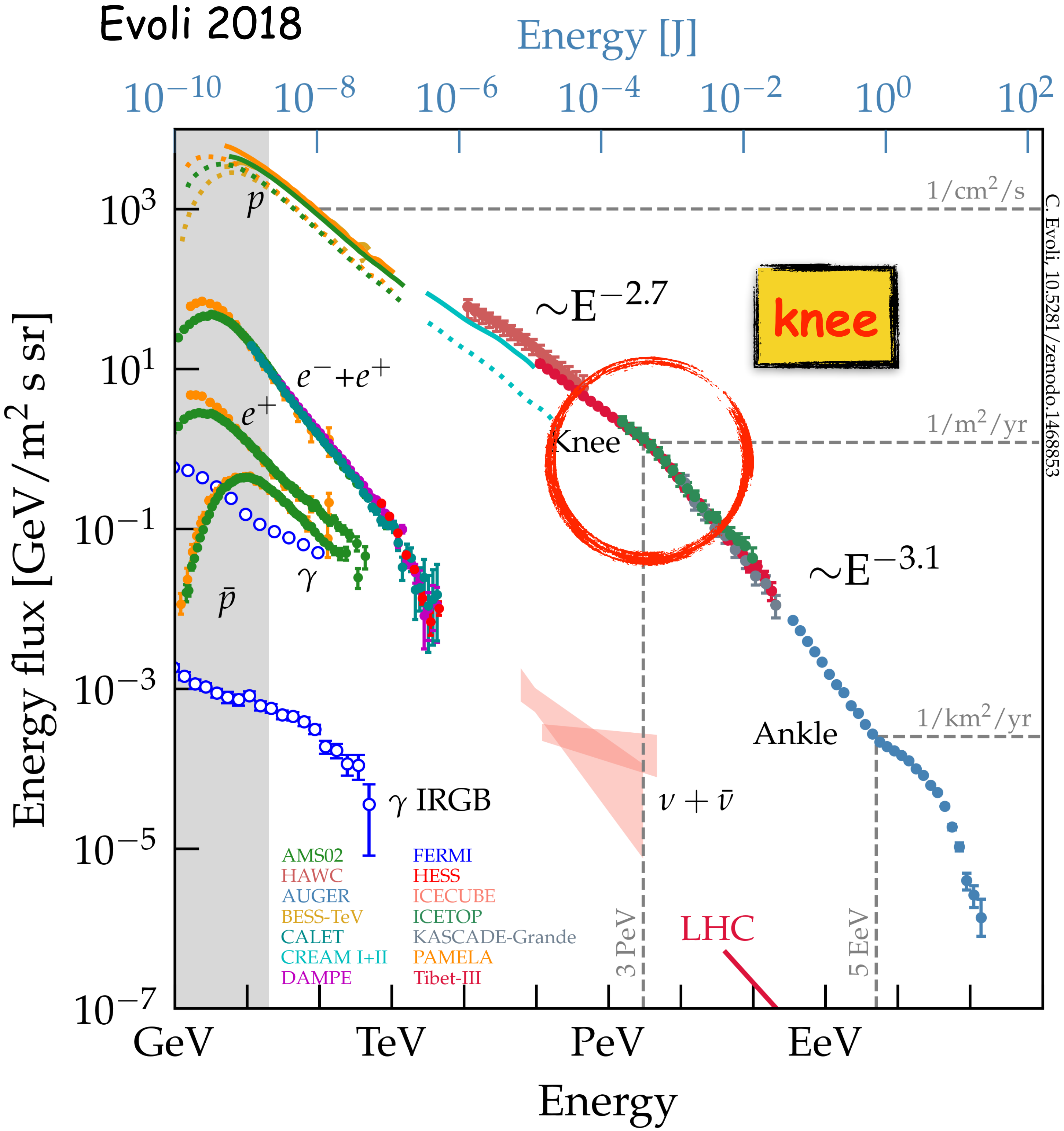

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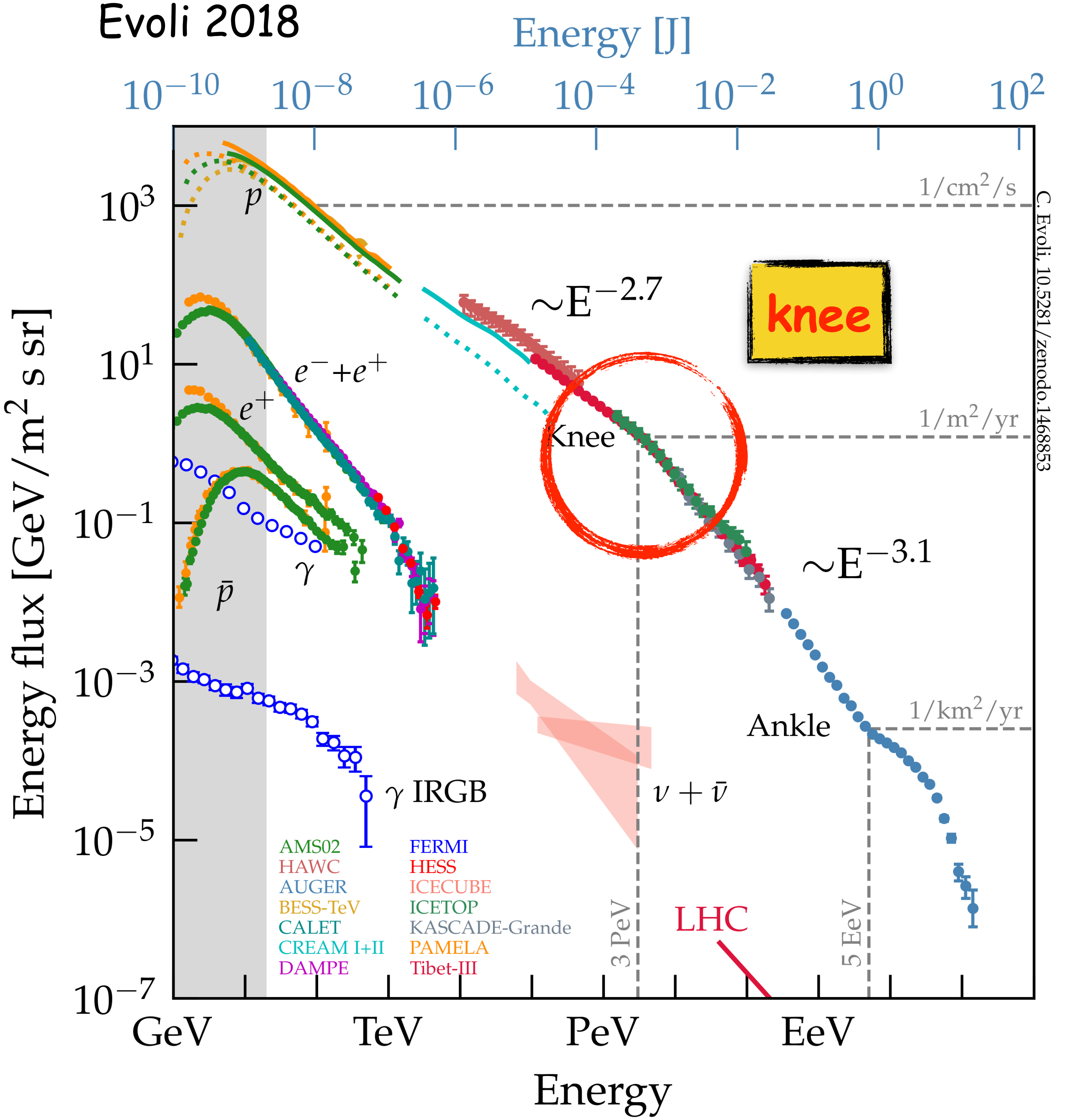
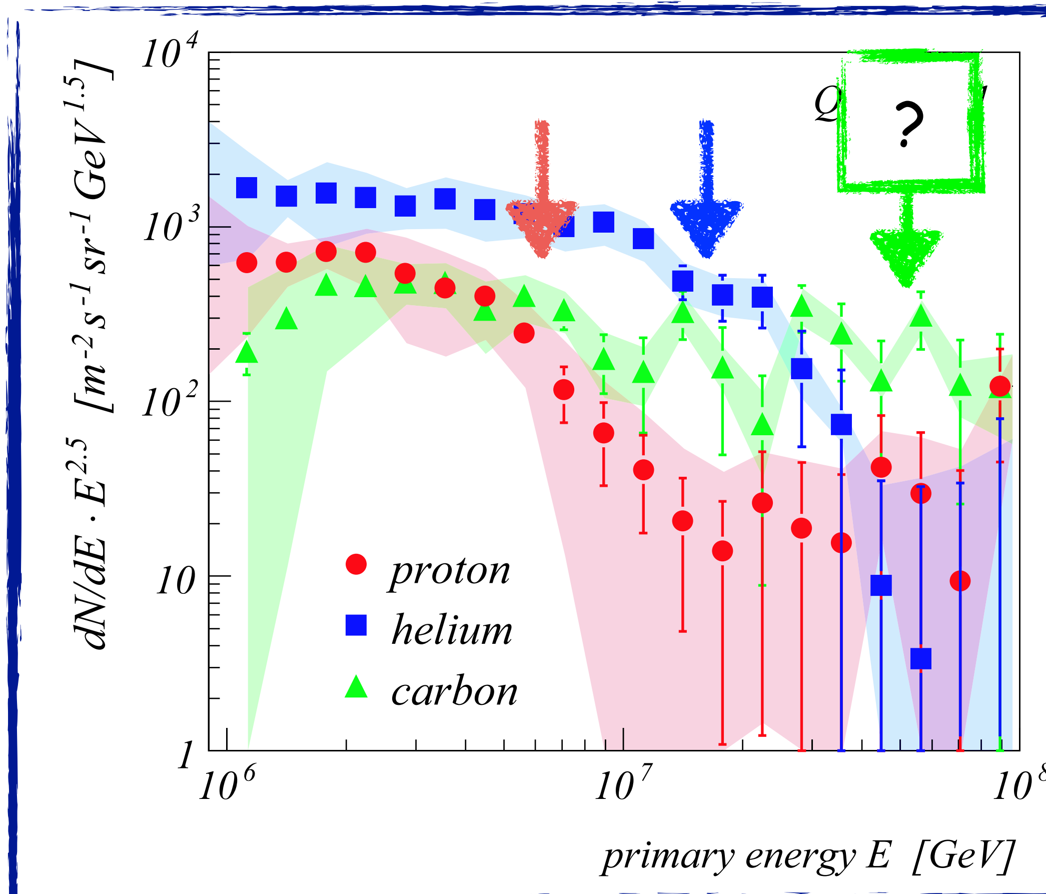
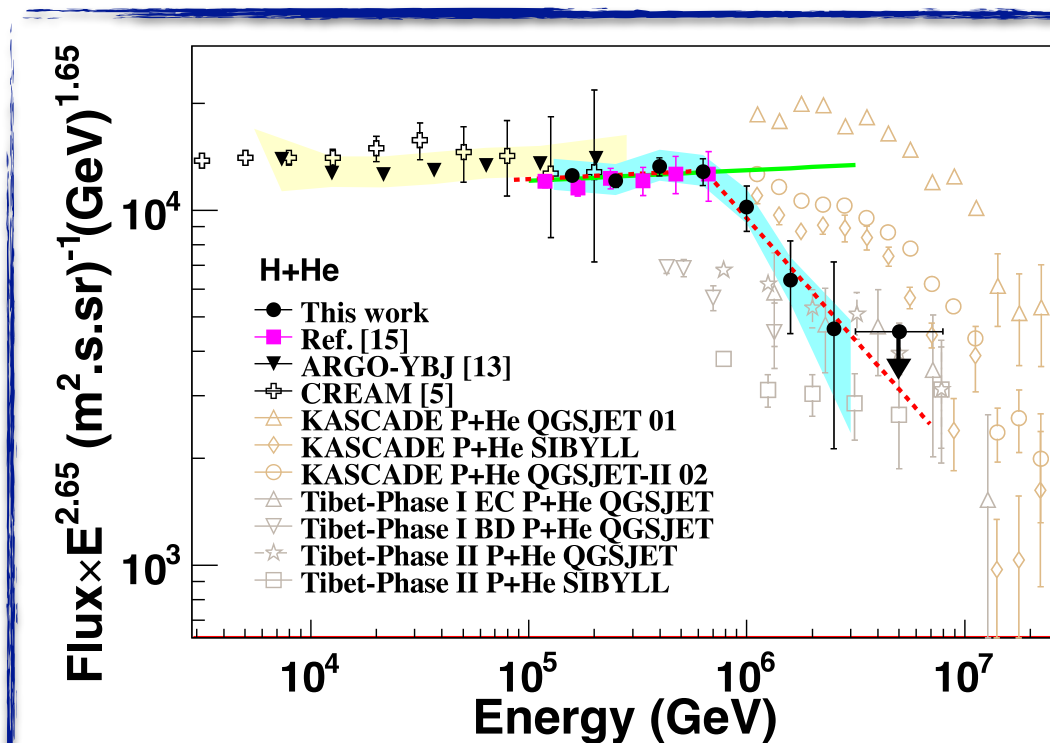




KASCADE coll. 2005



ARGO coll. 2015

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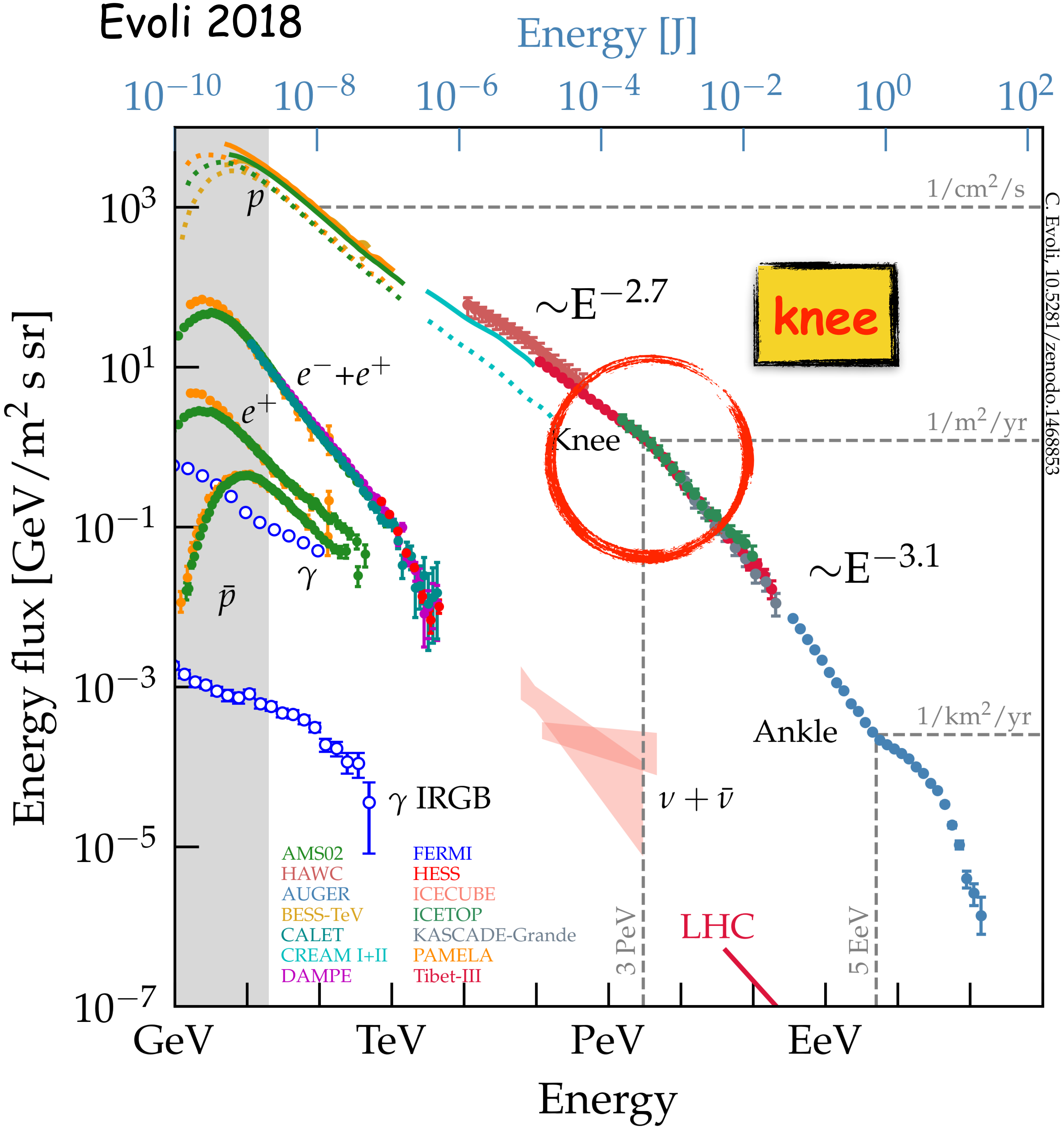

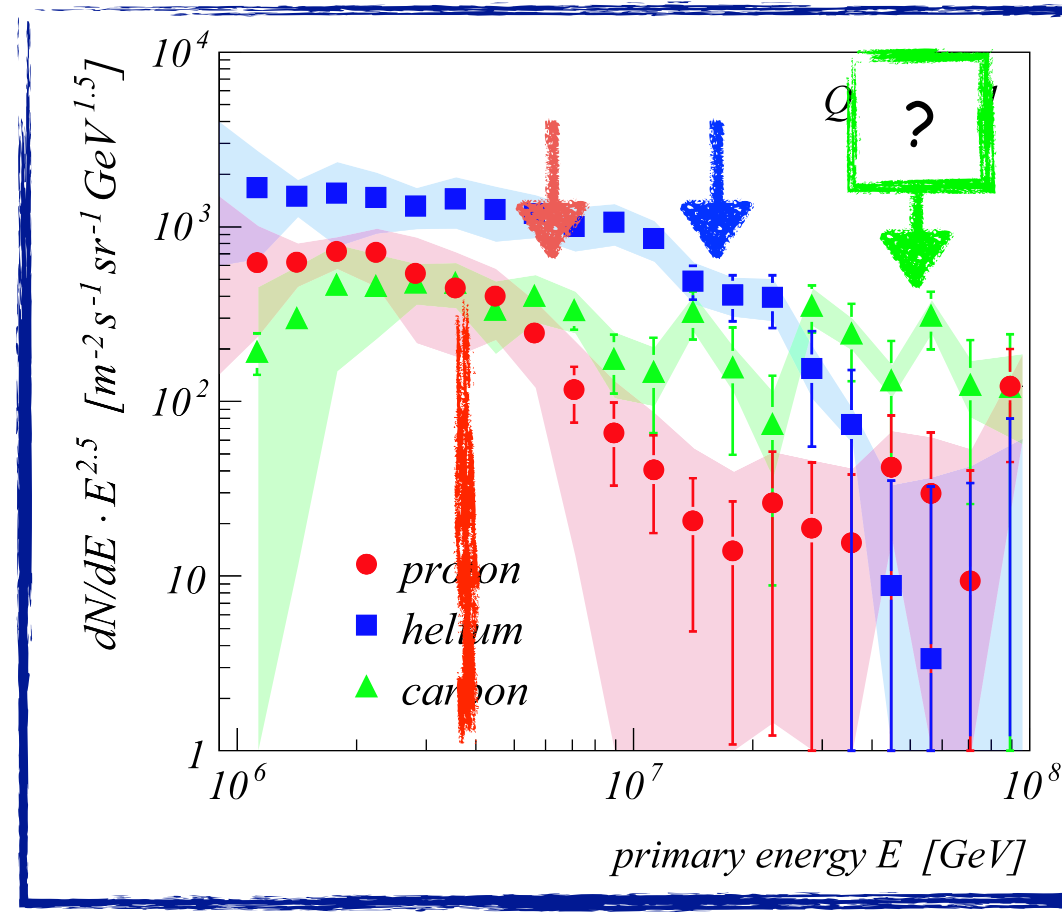

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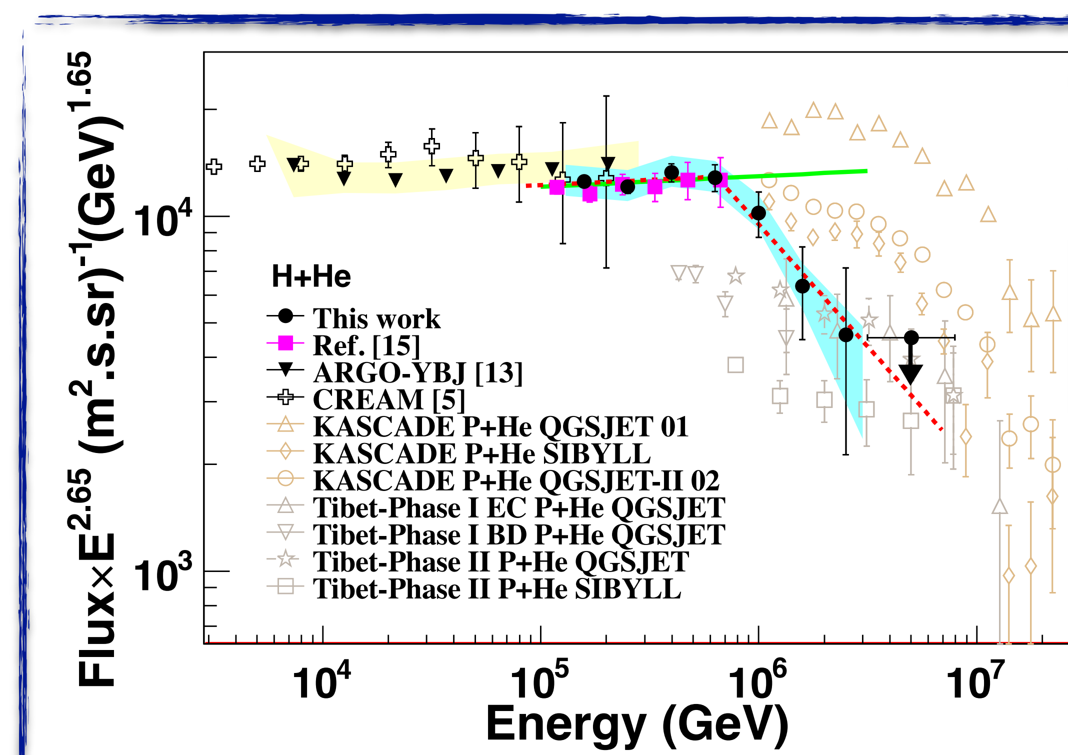

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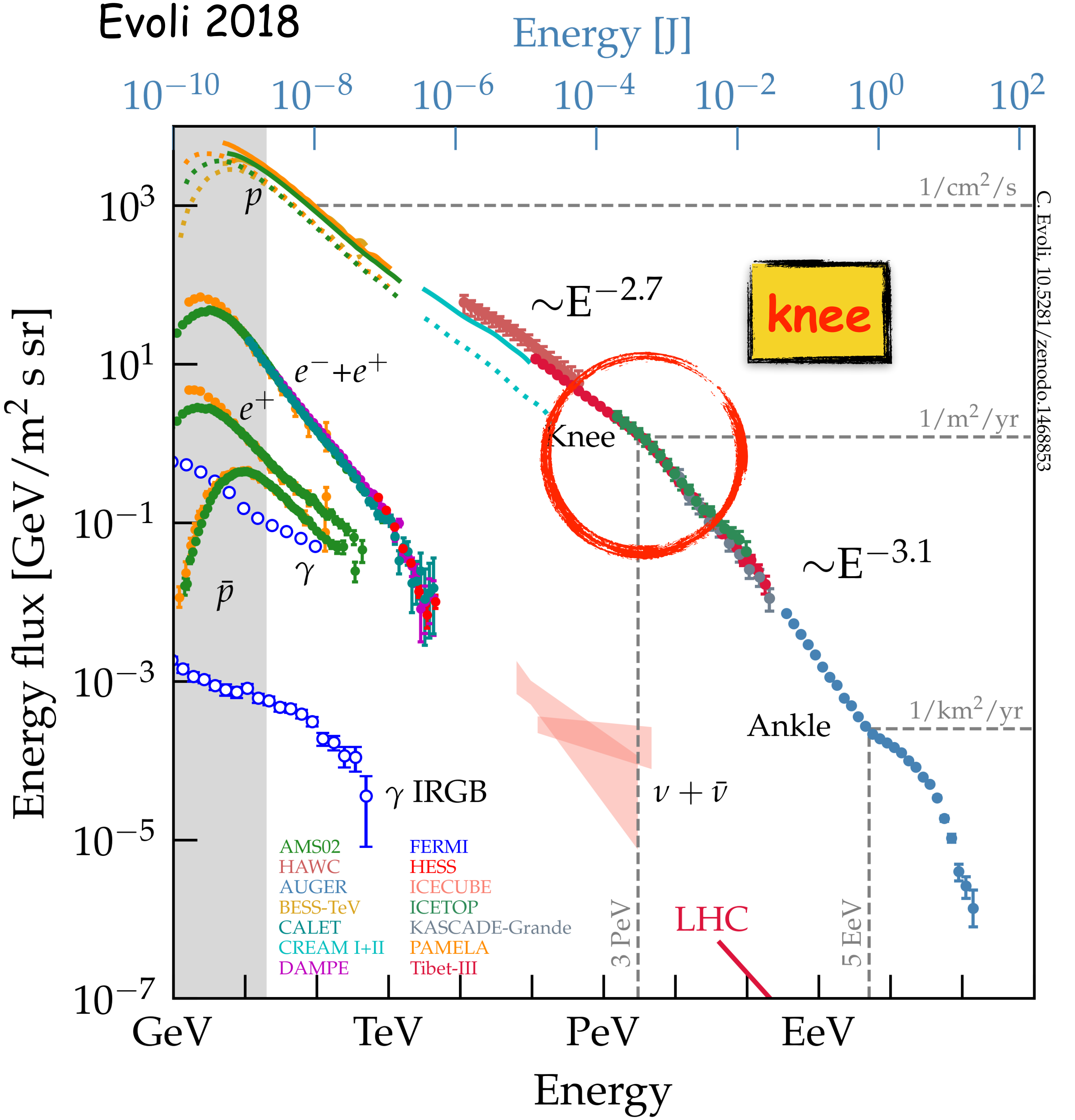

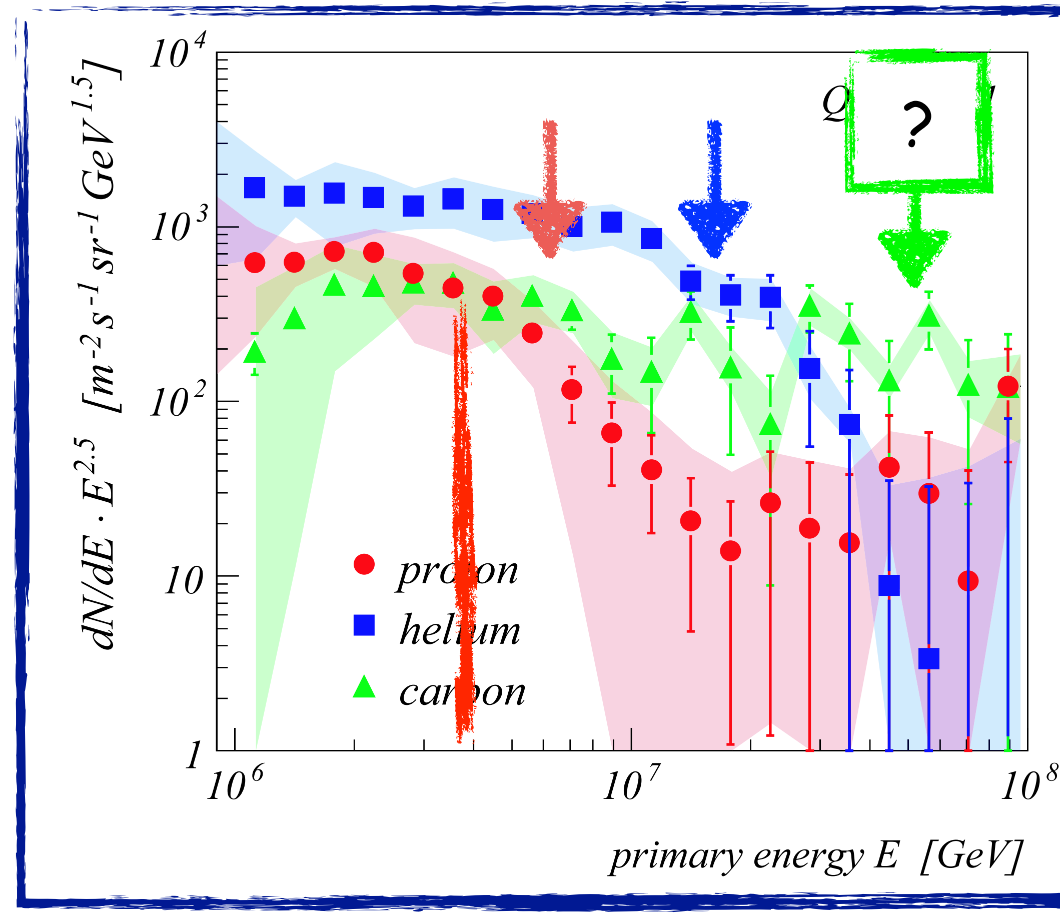

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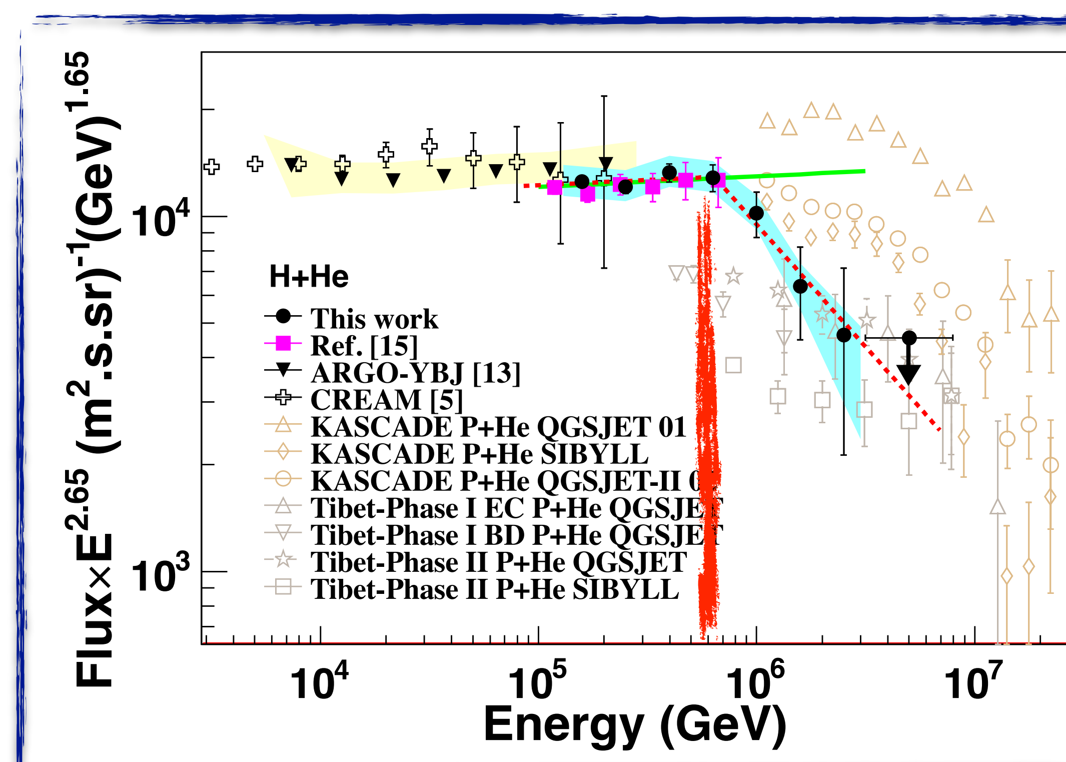

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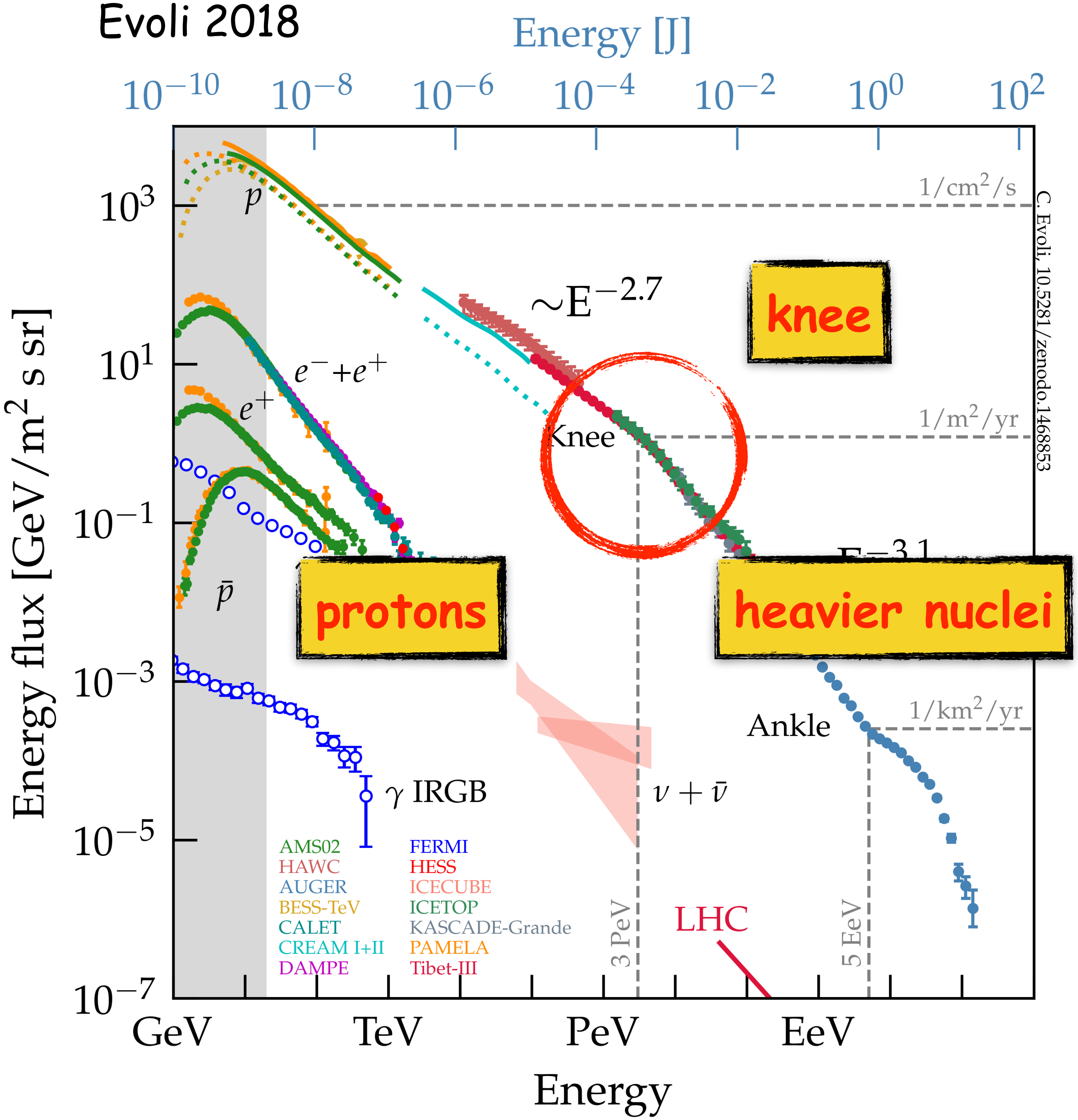

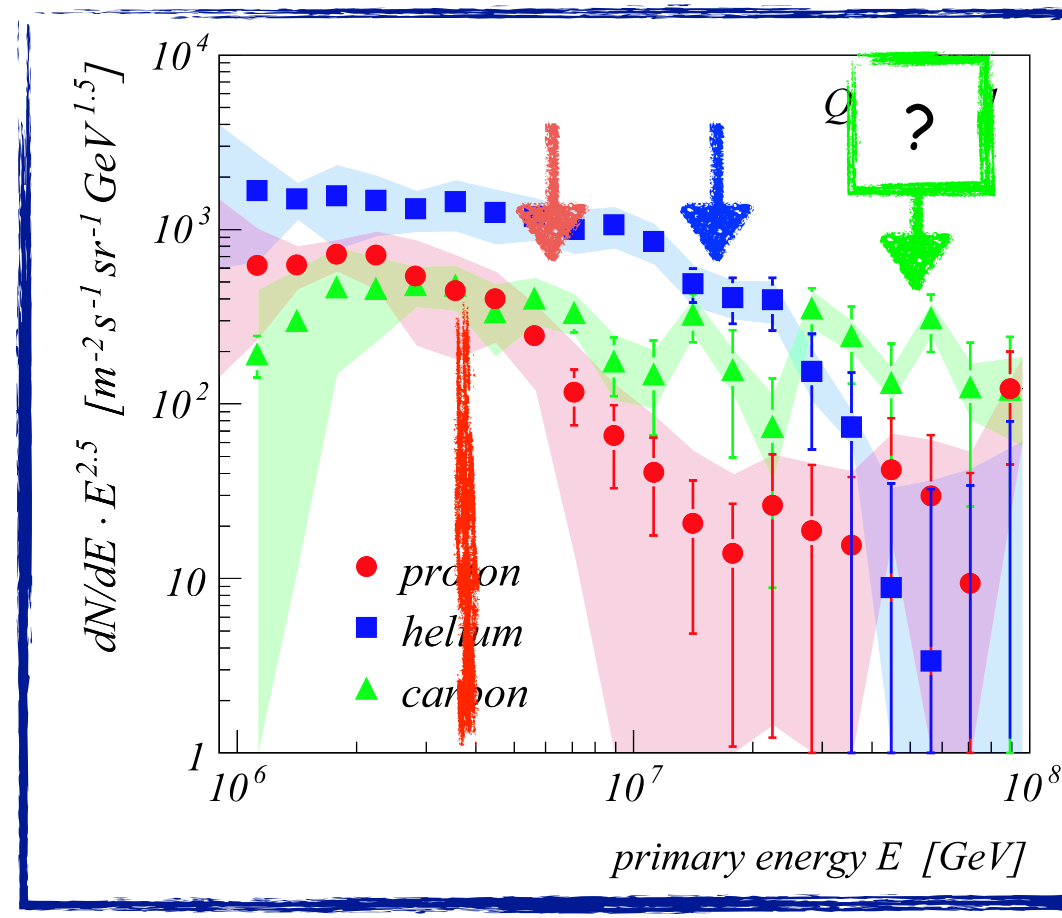

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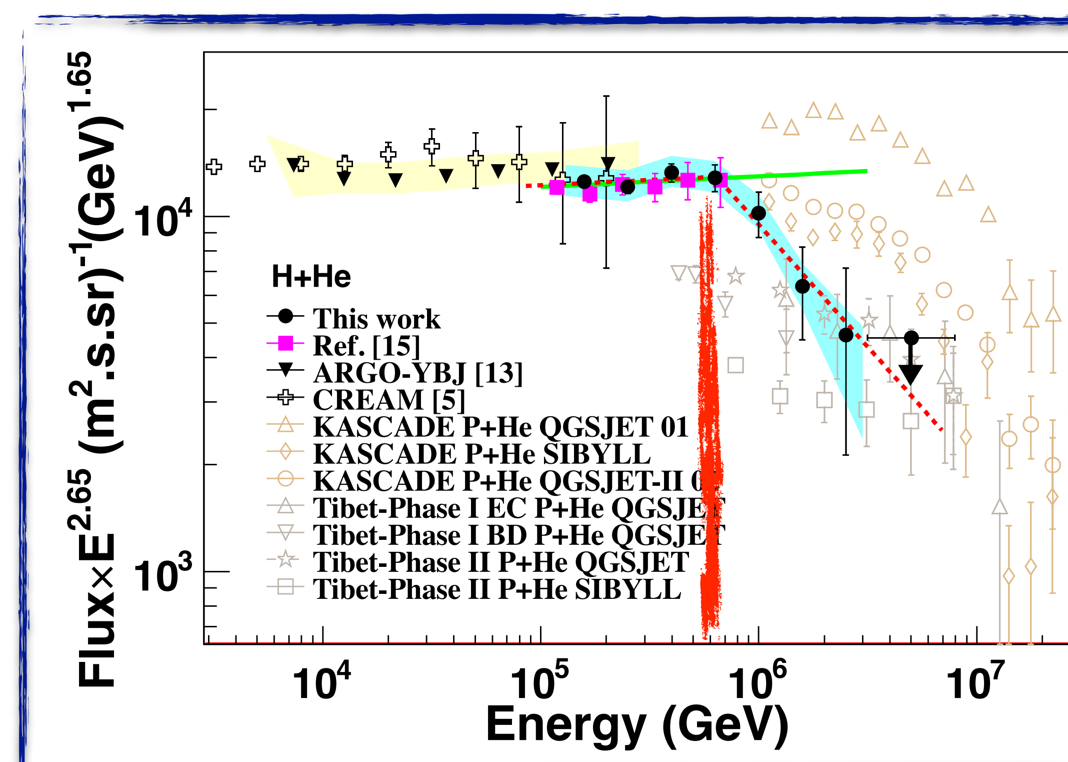

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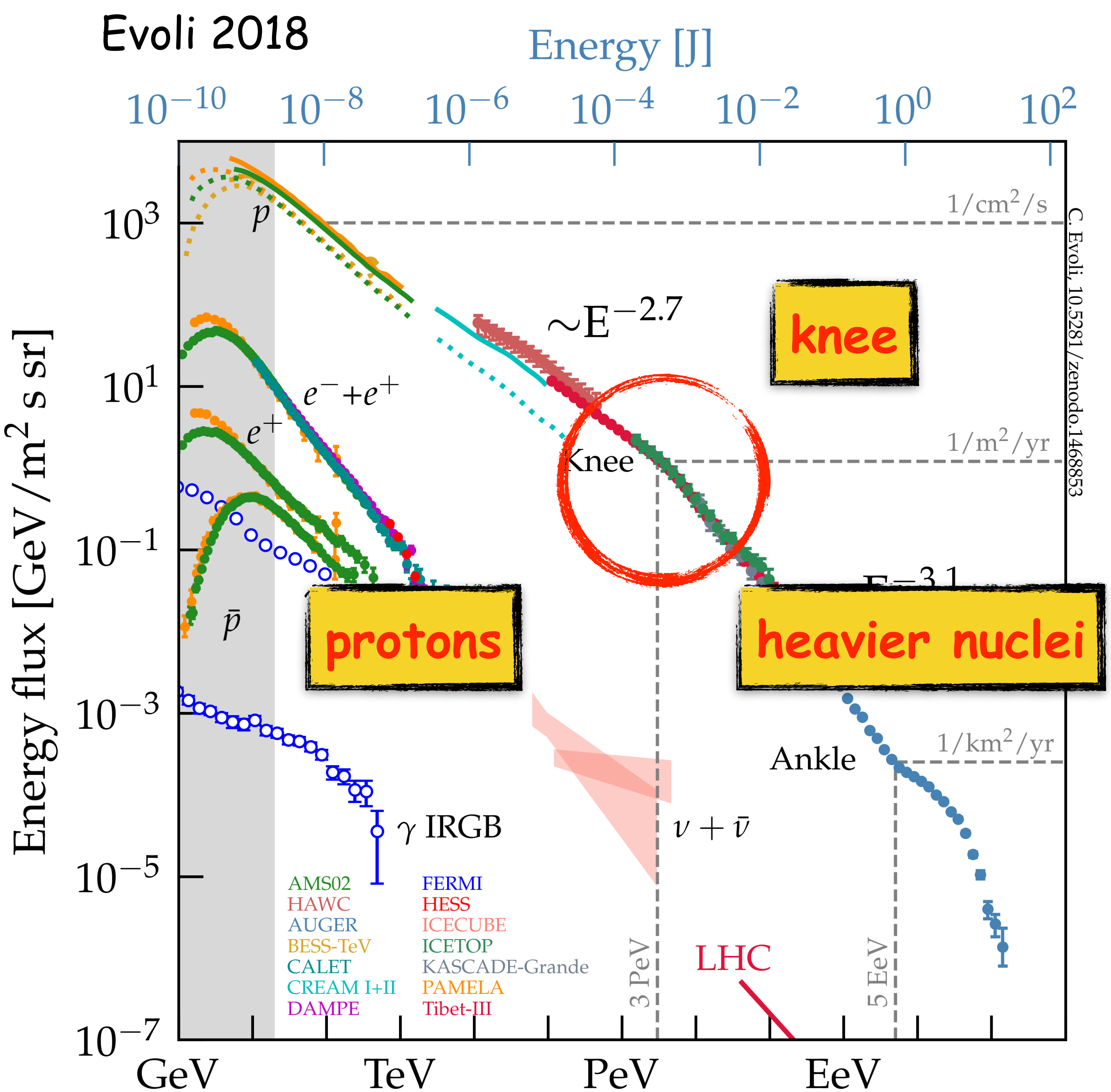
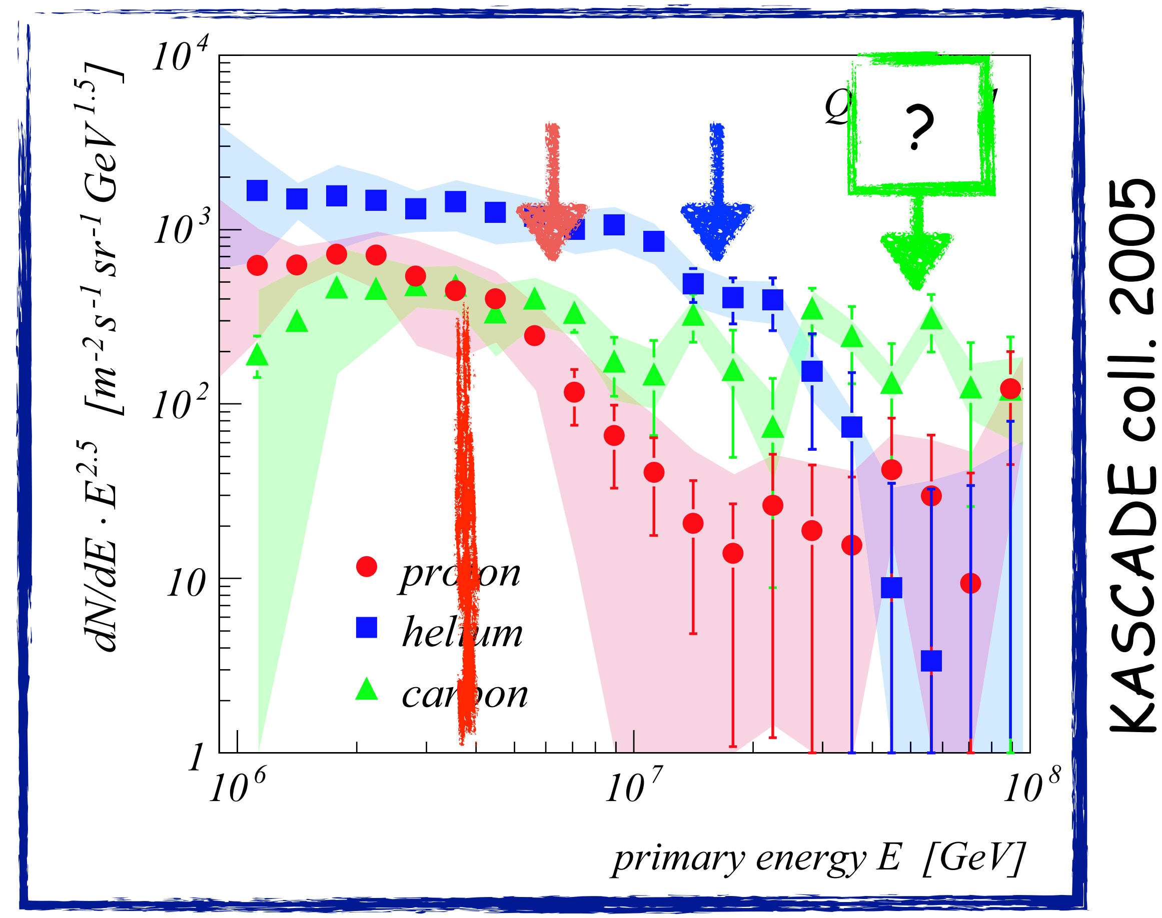
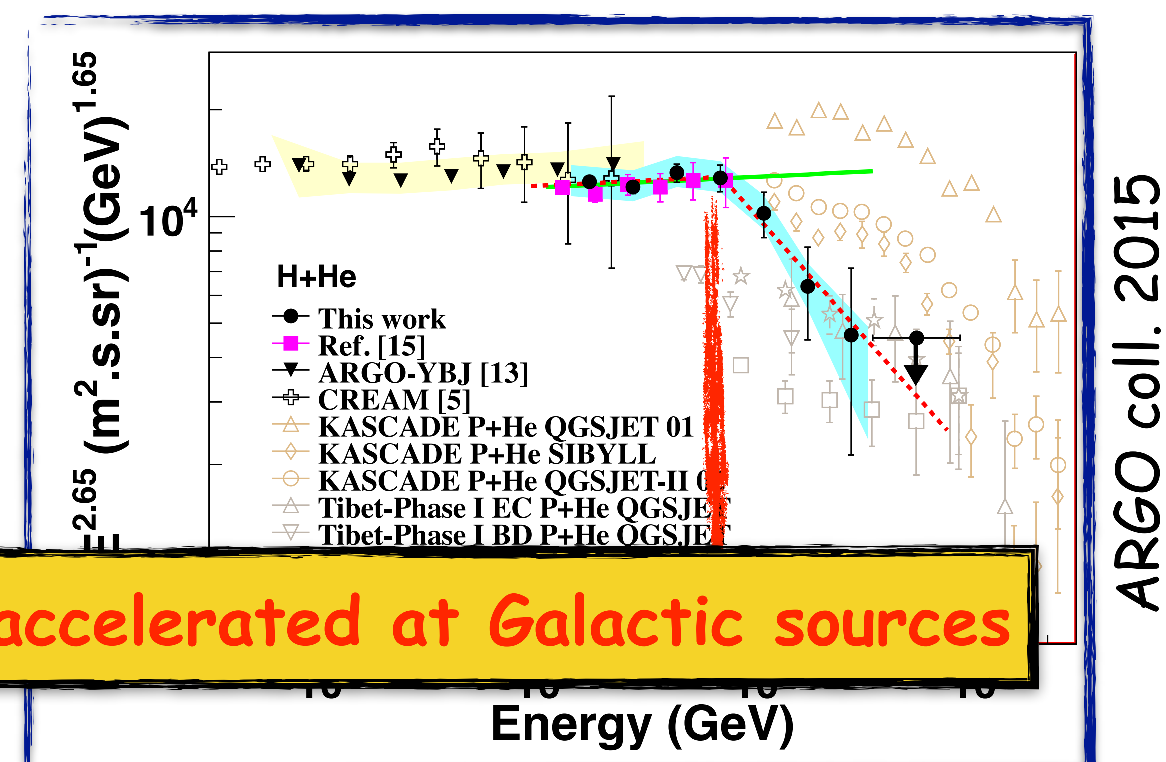
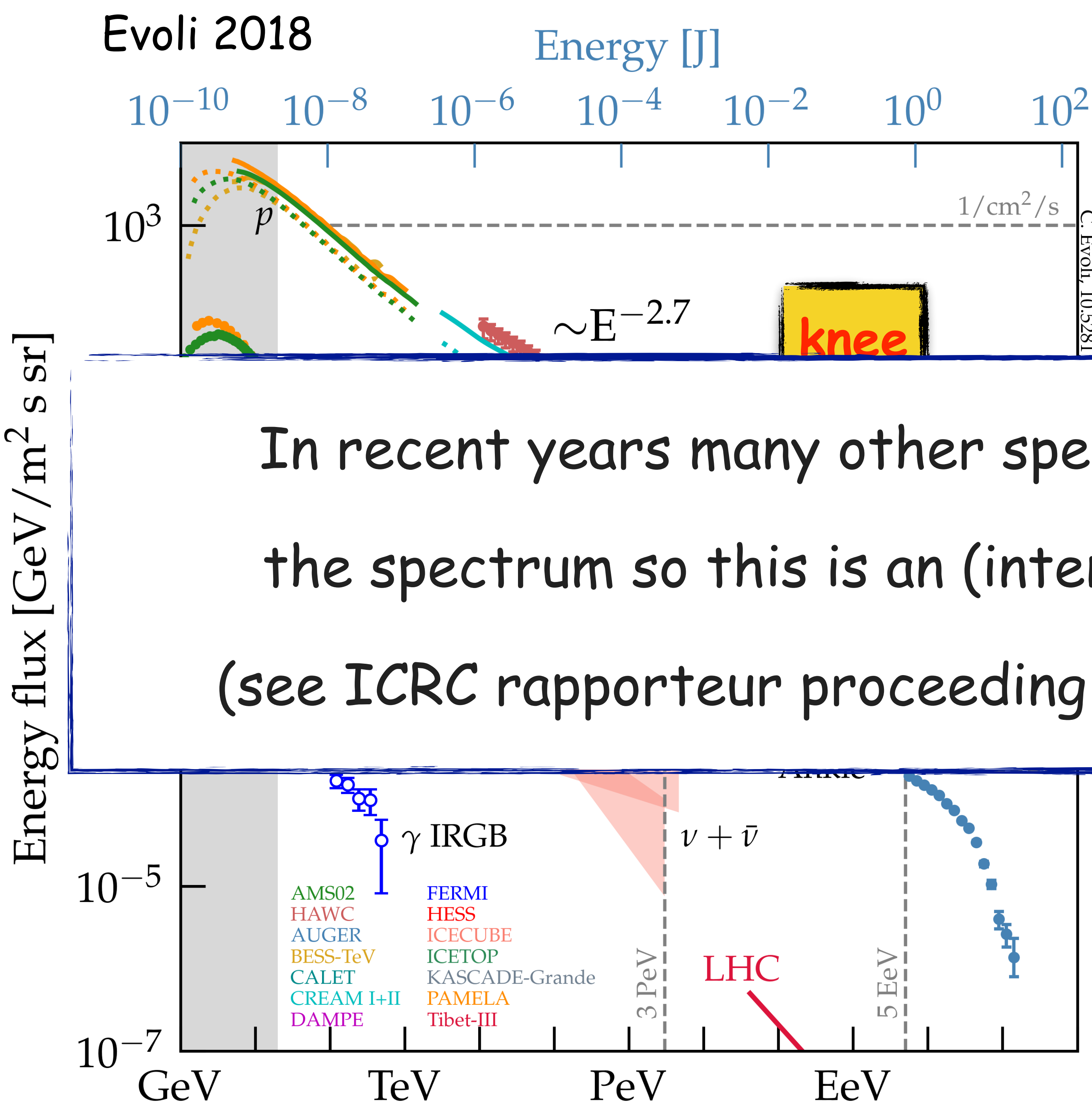


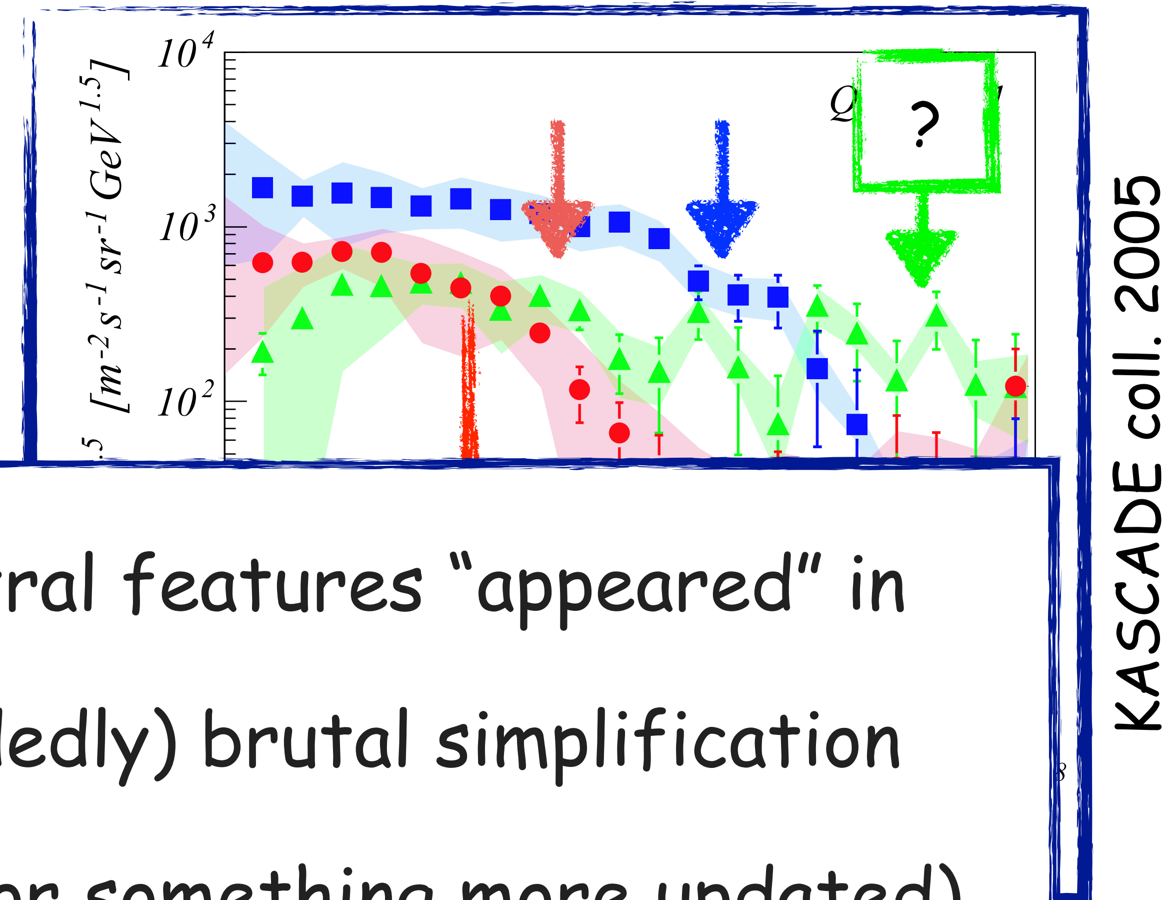




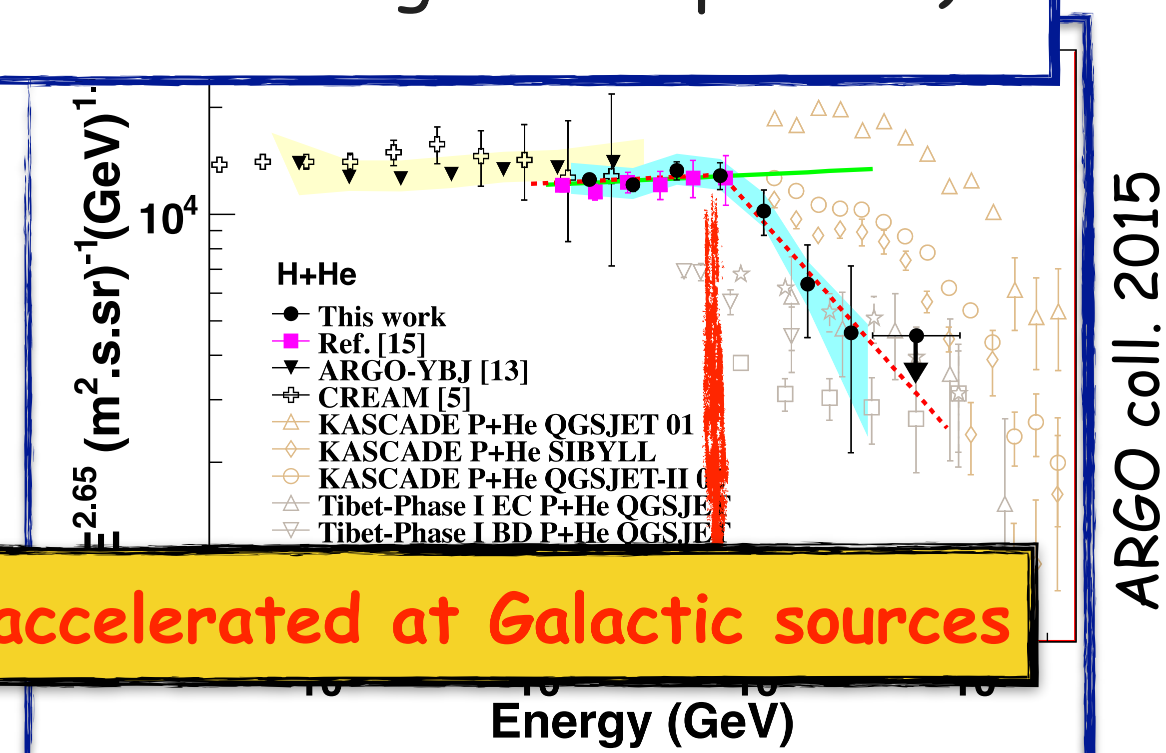
the knee —> maximum energy of protons accelerated at Galactic sources

The cosmic ray spectrum





In recent years many other spectral features “appeared” in the spectrum so this is an (intendedly) brutal simplification (see ICRC rapporteur proceeding for something more updated)



the knee —> maximum energy of protons accelerated at Galactic sources

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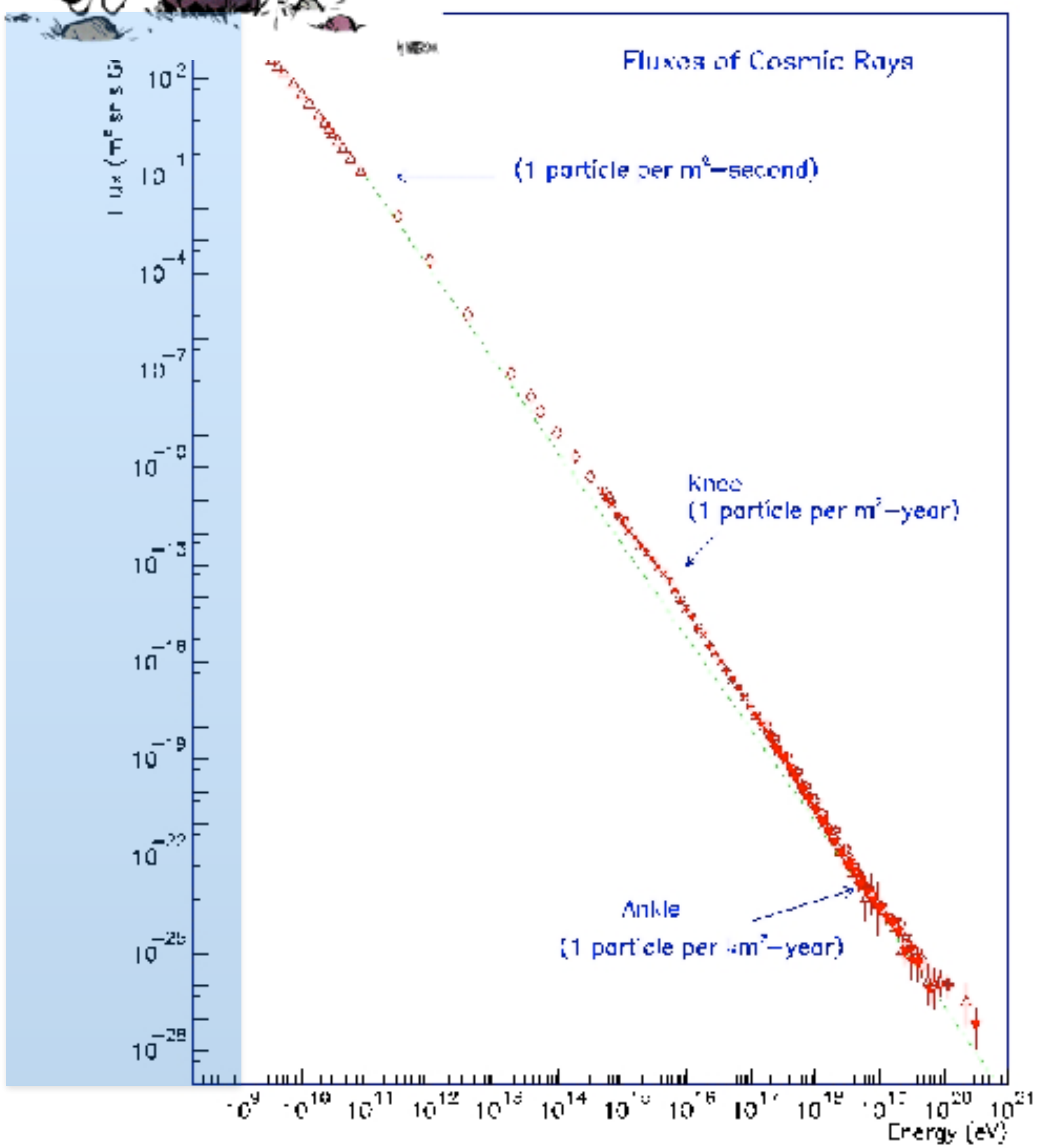
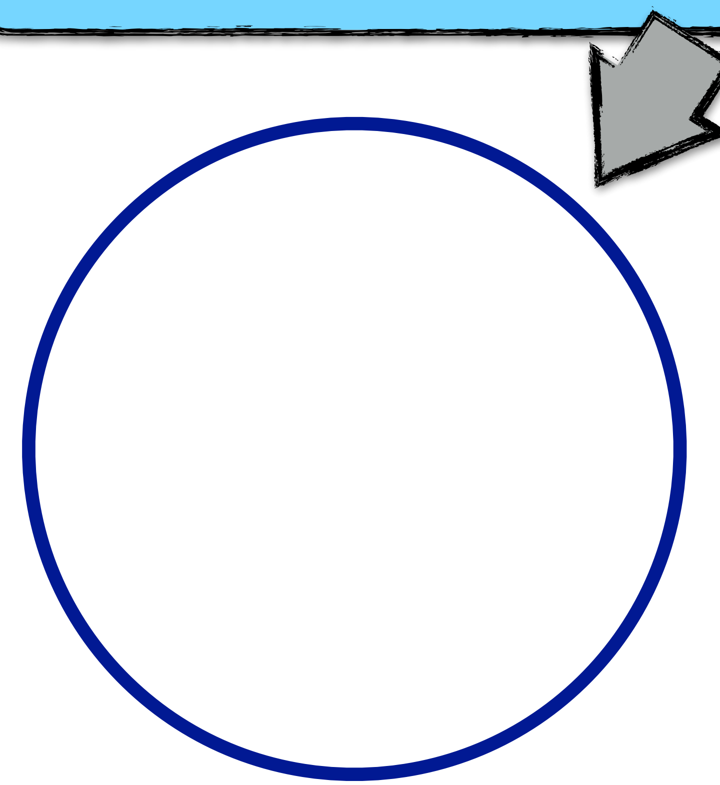
These are actually three different questions which require different solution methods and answers, and some of the confusion in the field has been due to people not carefully distinguishing these concepts.

[2] The “sizes” of cosmic rays

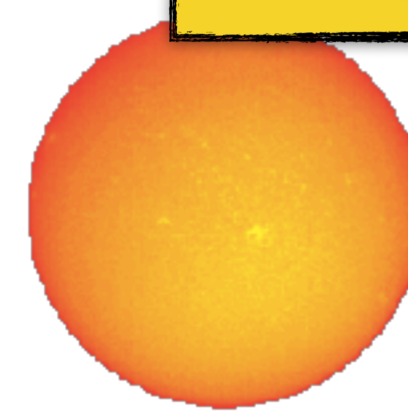
The MeV domain



$R_L(100\ \mathrm{MeV}) \sim 10^{11}\ \mathrm{cm}$



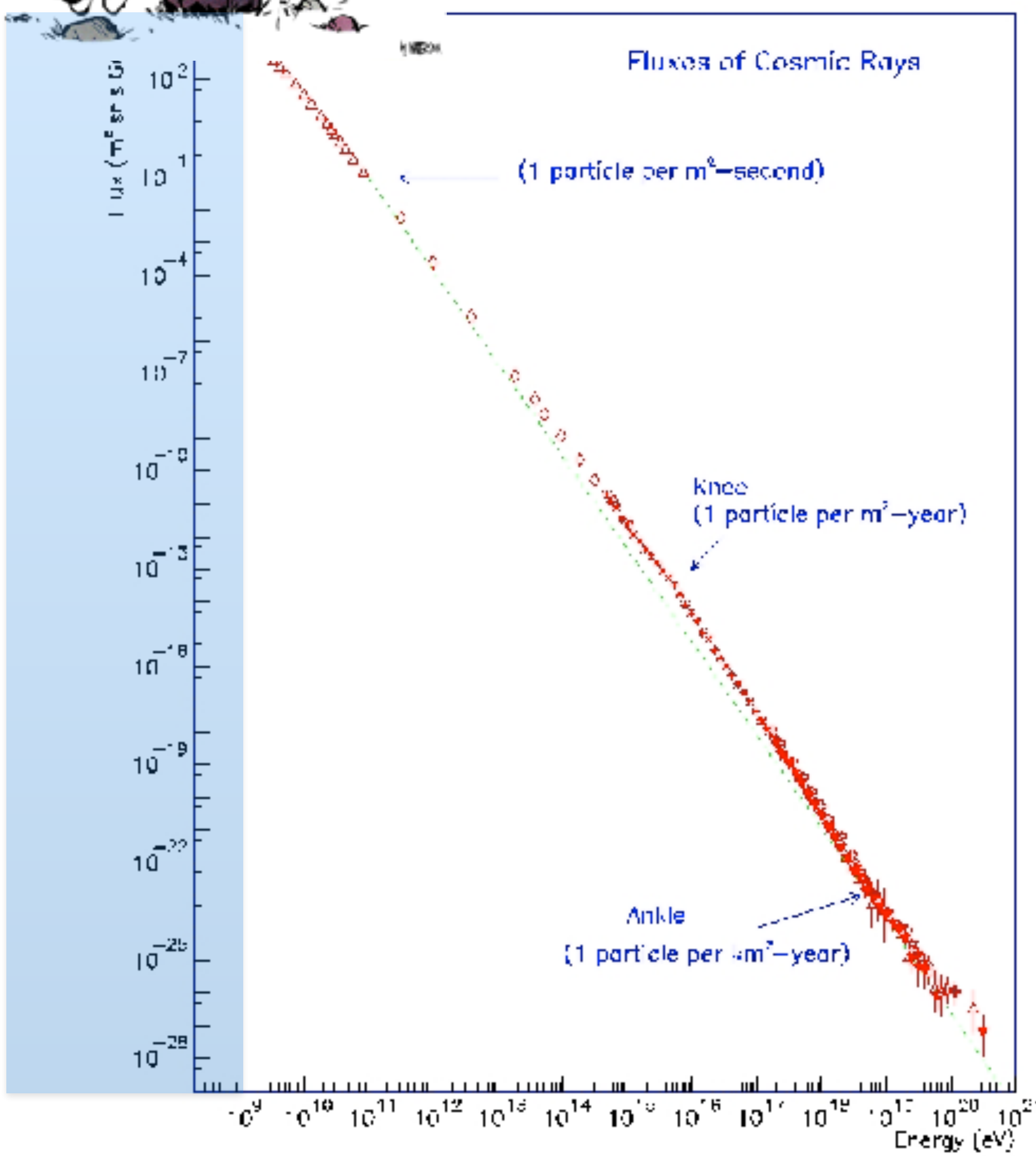
the Sun



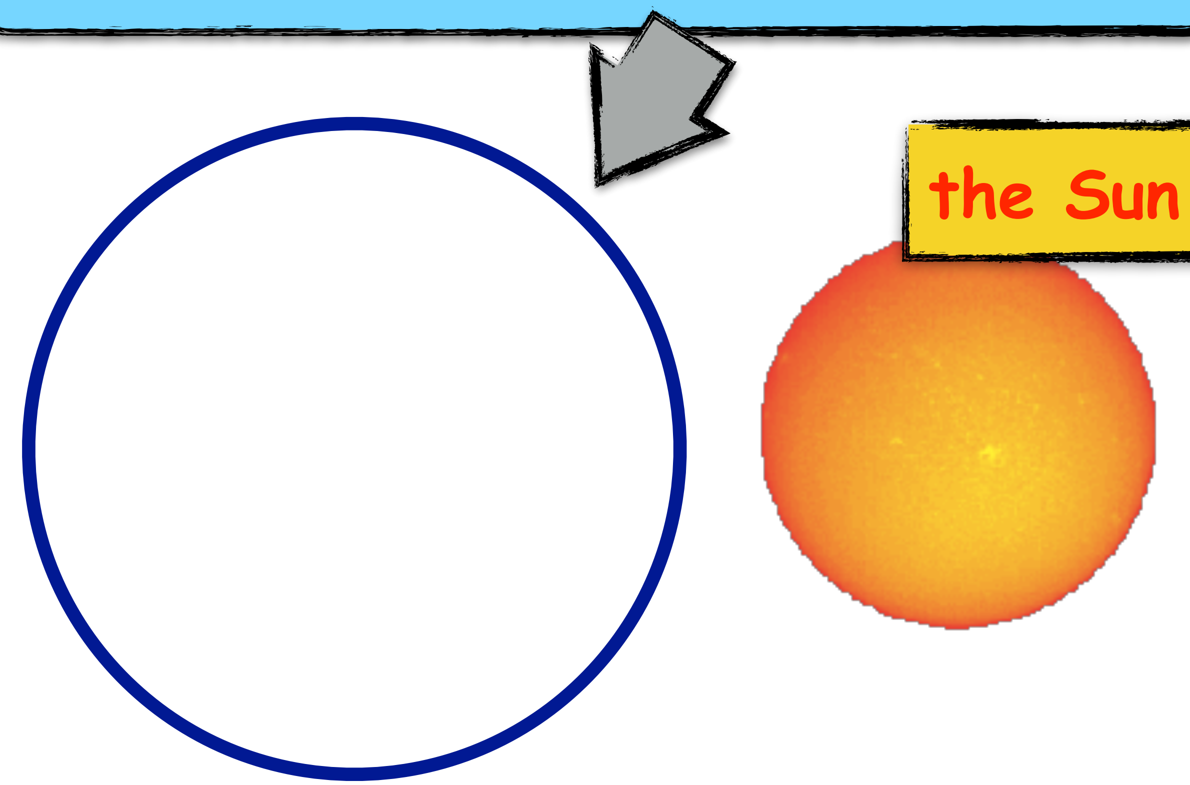
Solar modulation

CR spectrum known with very large uncertainties in the MeV range
-> but see recent Voyager results

The MeV domain



$$R_L(100\ \mathrm{MeV}) \sim 10^{11}\ \mathrm{cm}^{*}$$

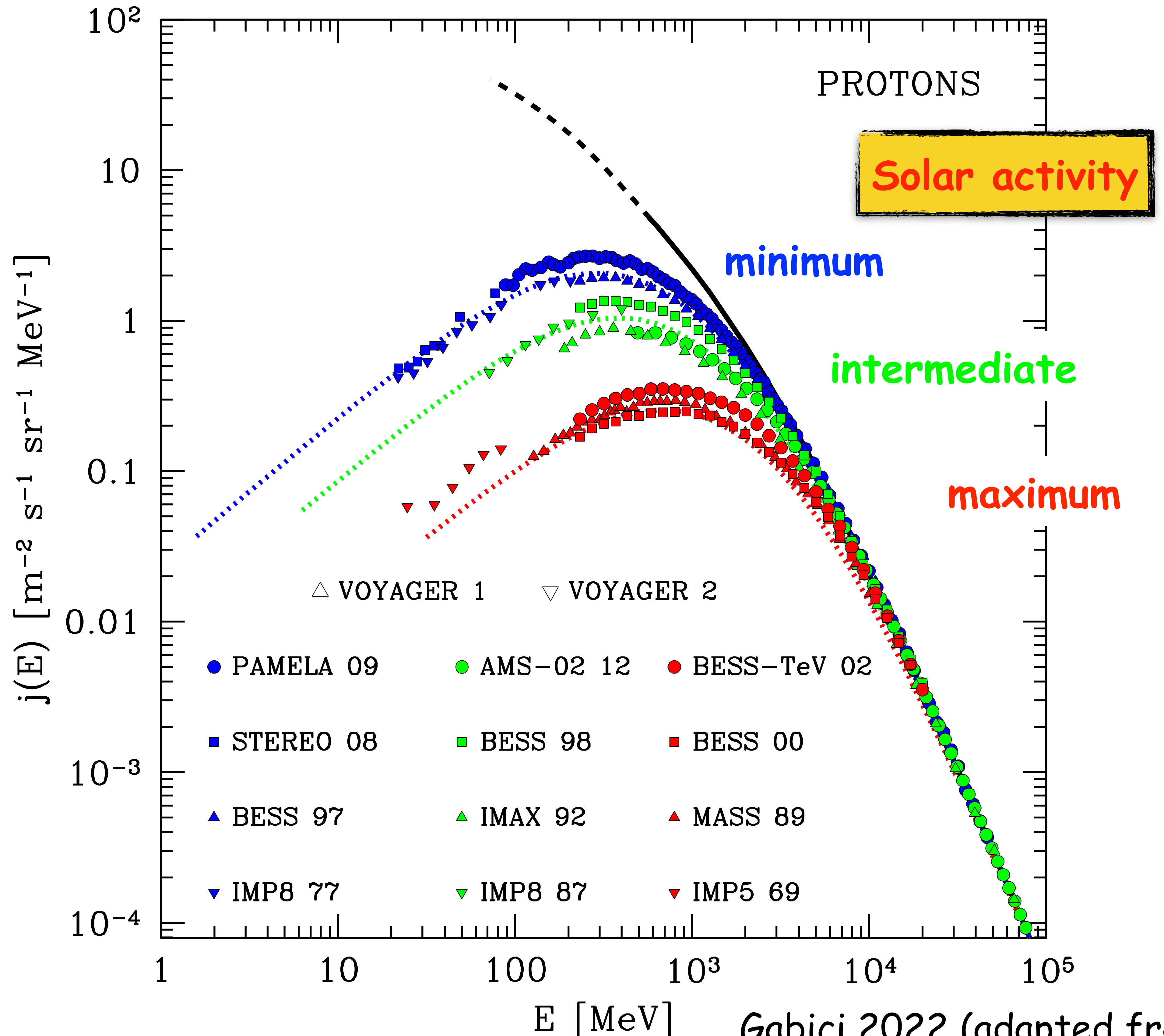


Solar modulation

CR spectrum known with very large uncertainties in the MeV range
-> but see recent Voyager results

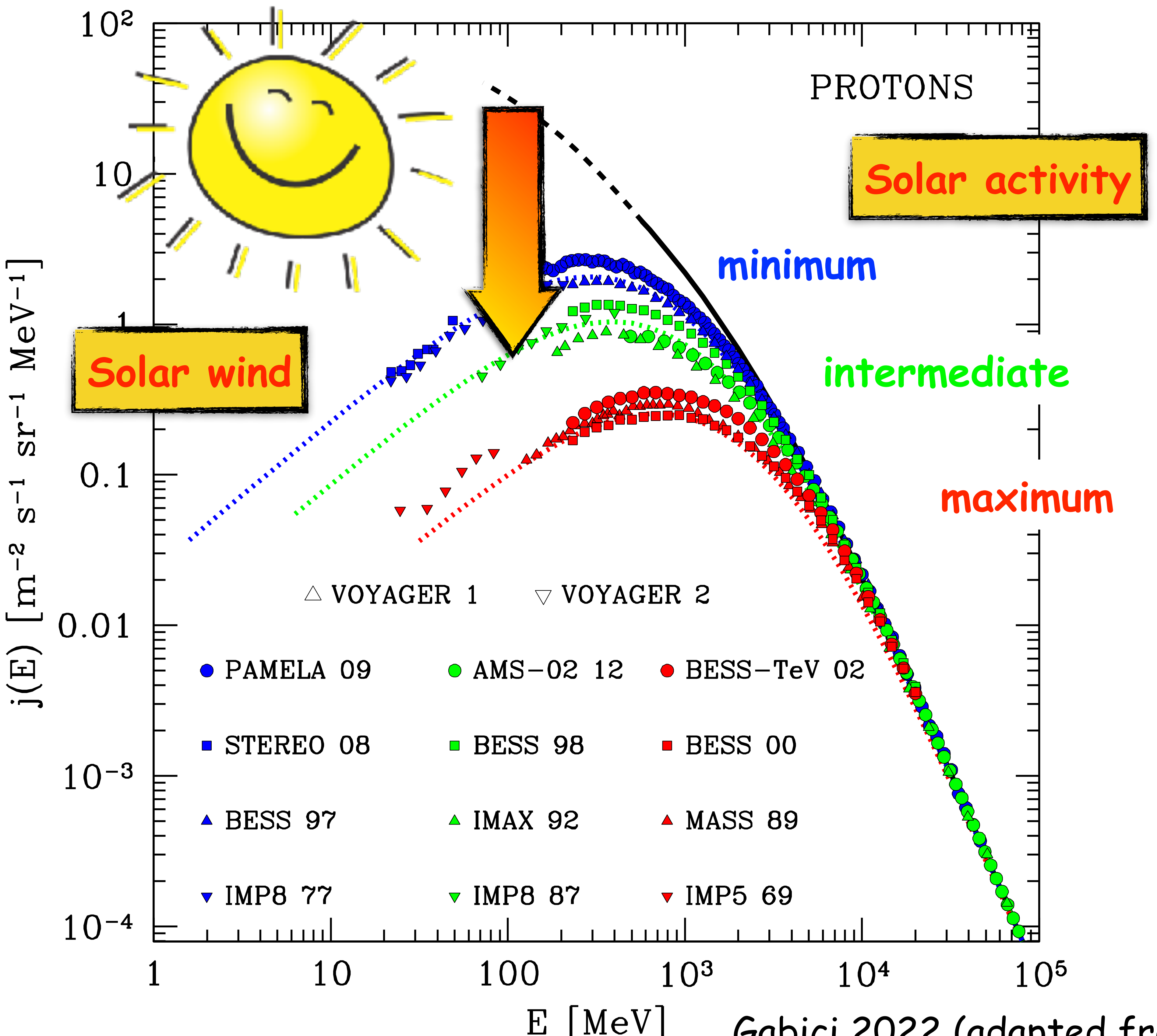
* in an interstellar B field, 10 times smaller at the Earth's locations

Solar modulation



Gabici 2022 (adapted from Vos & Potgieter 2015)

Solar modulation



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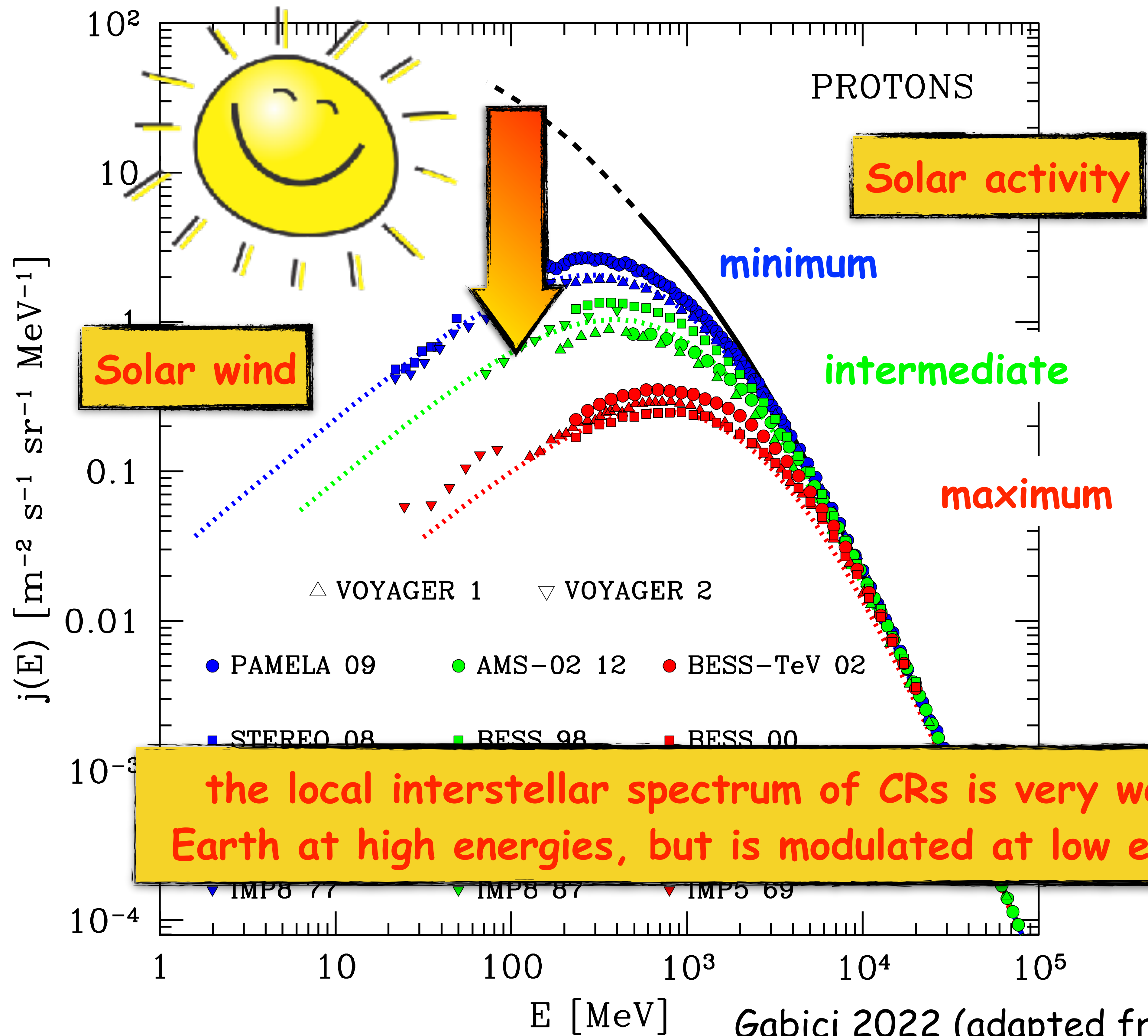
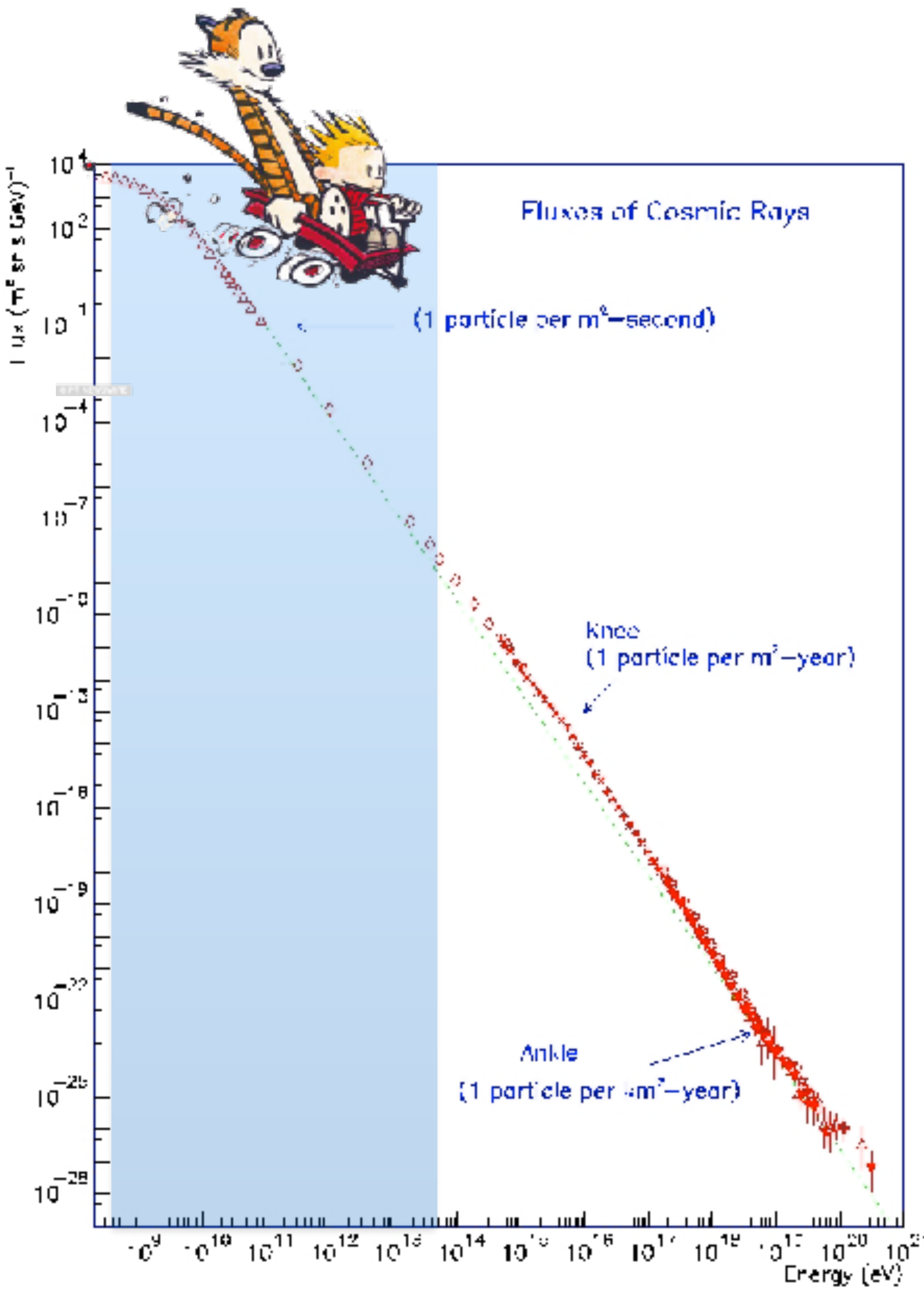


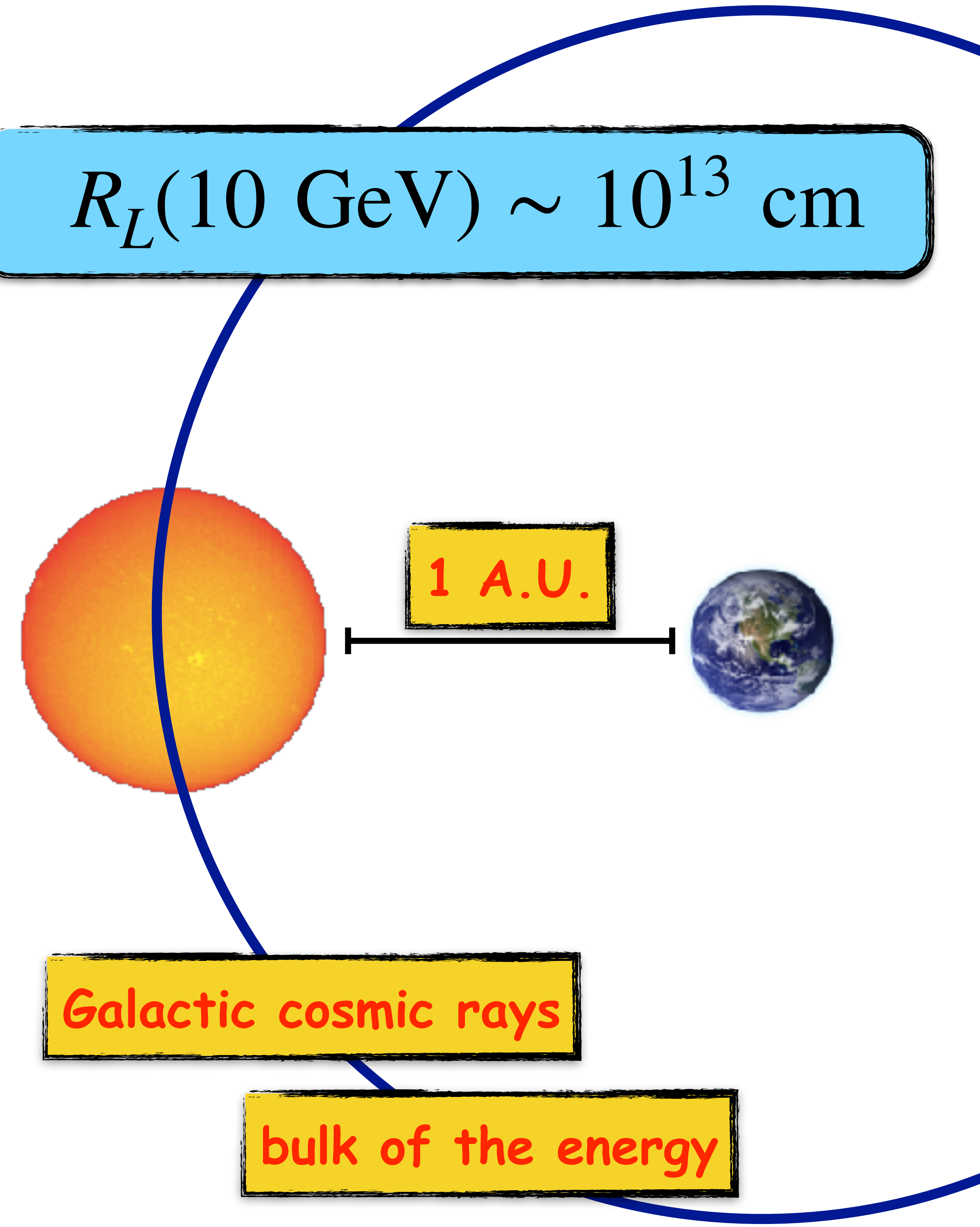
the local interstellar spectrum of CRs is very well measured from Earth at high energies, but is modulated at low energyes (< 20 GeV)

Gabici 2022 (adapted from Vos & Potgieter 2015)

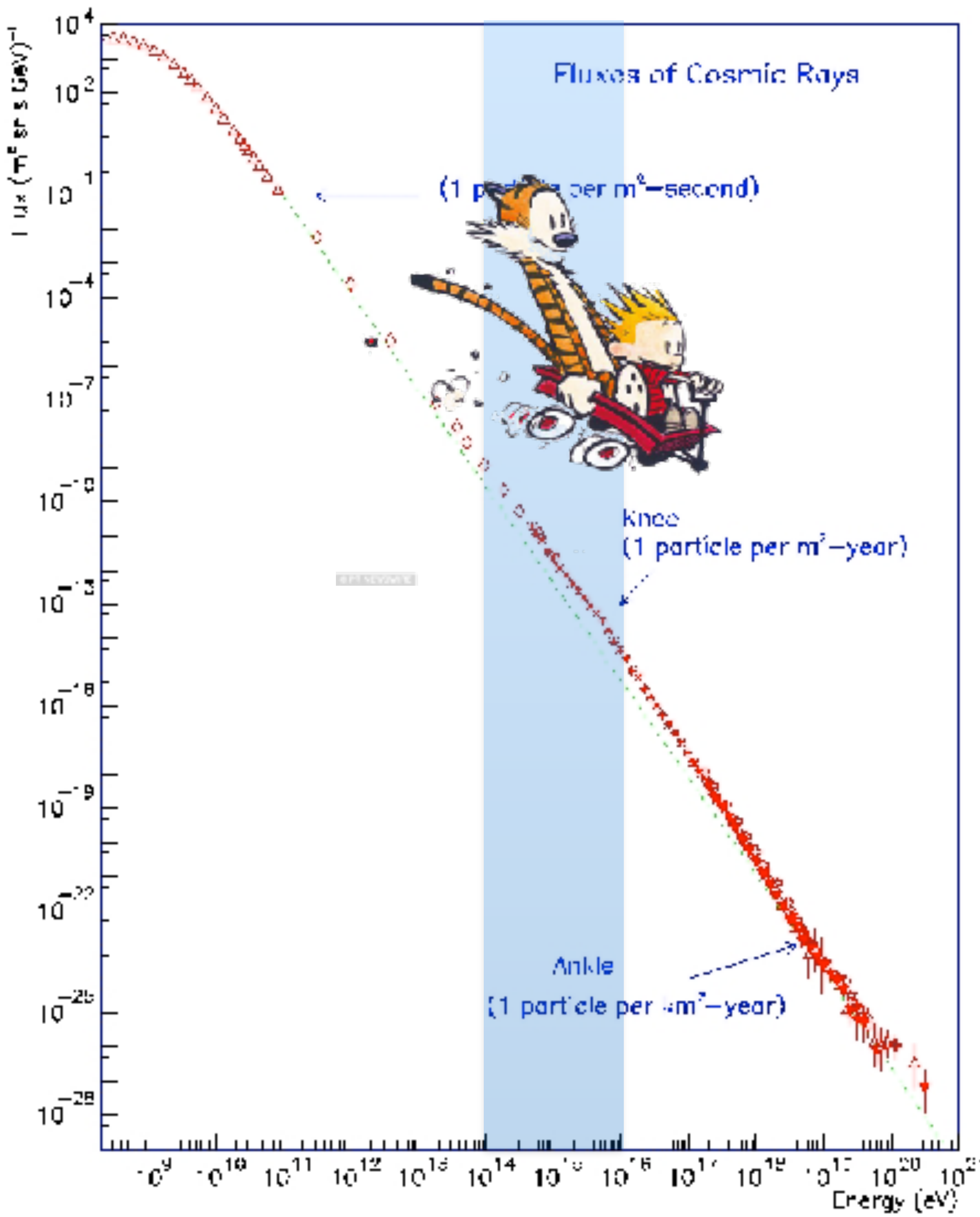
The GeV domain



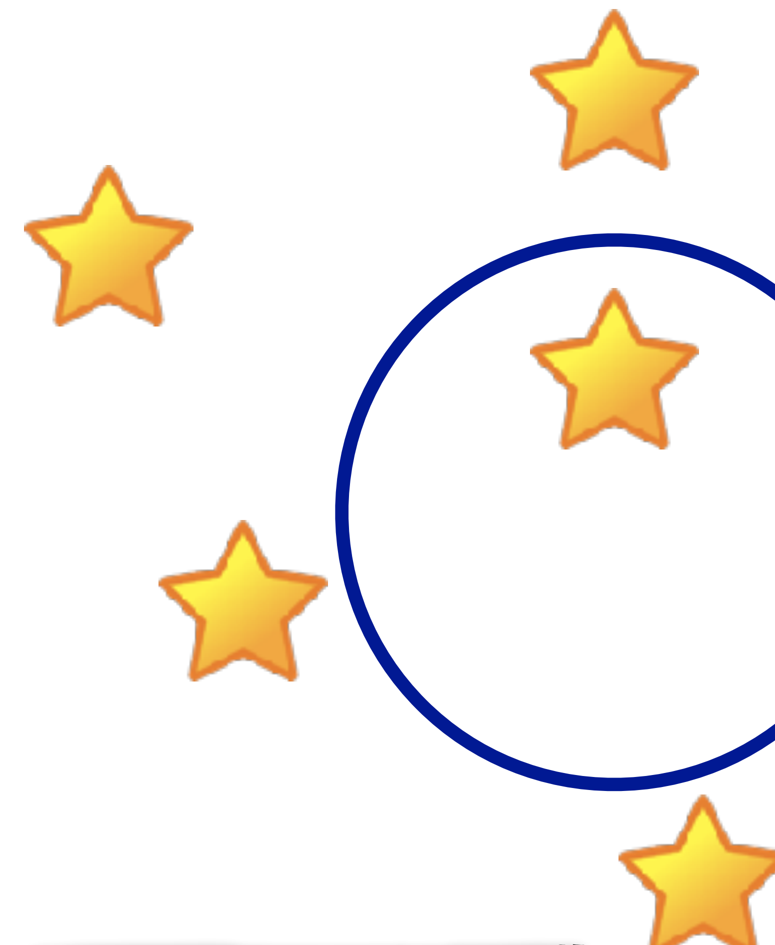
$$R_L(10\ \text{GeV}) \sim 10^{13}\ \text{cm}$$



The PeV domain (100 TeV-10 PeV)



$R_L(3\ \mathrm{PeV}) \sim 1\ \mathrm{pc}$



still Galactic…

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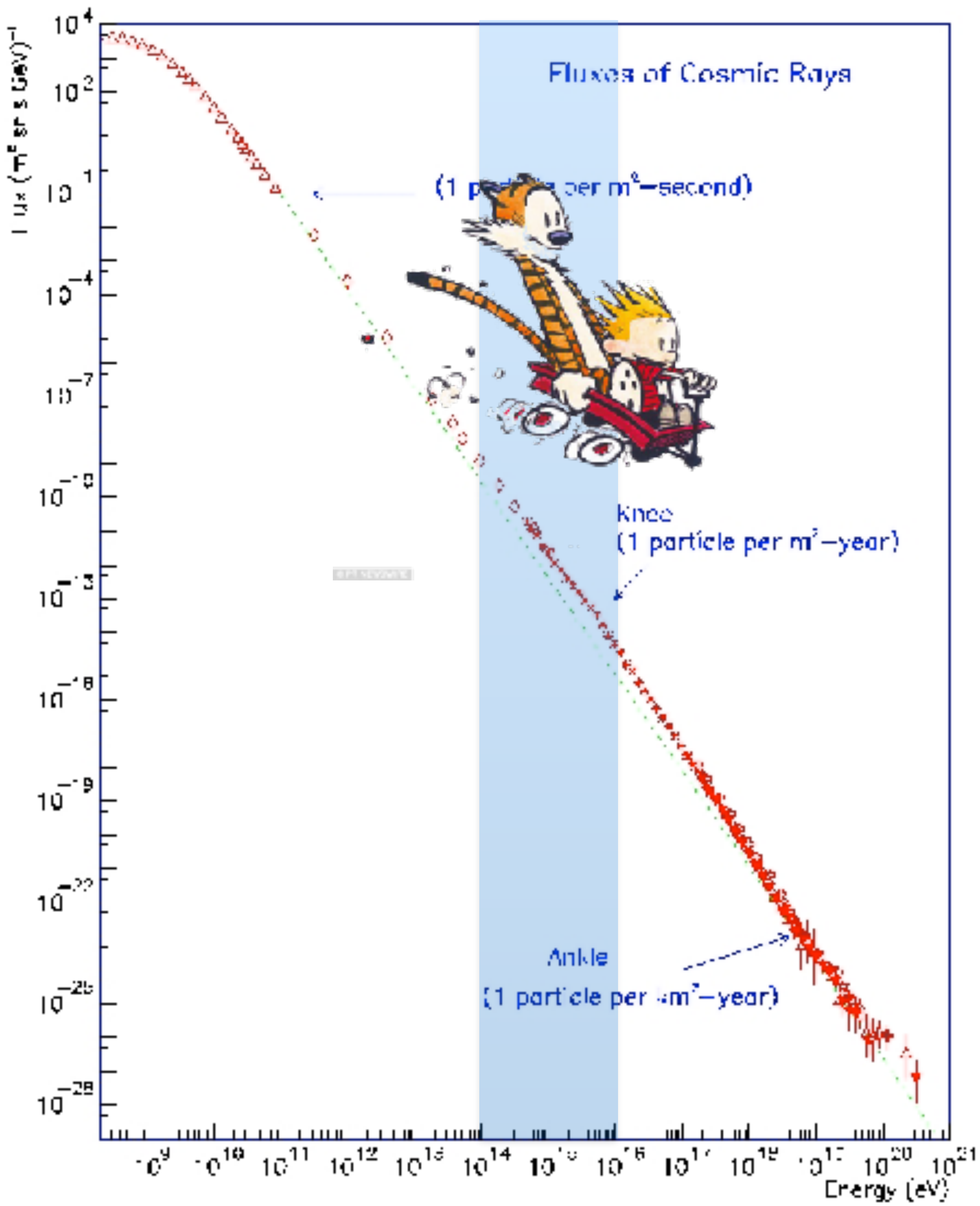

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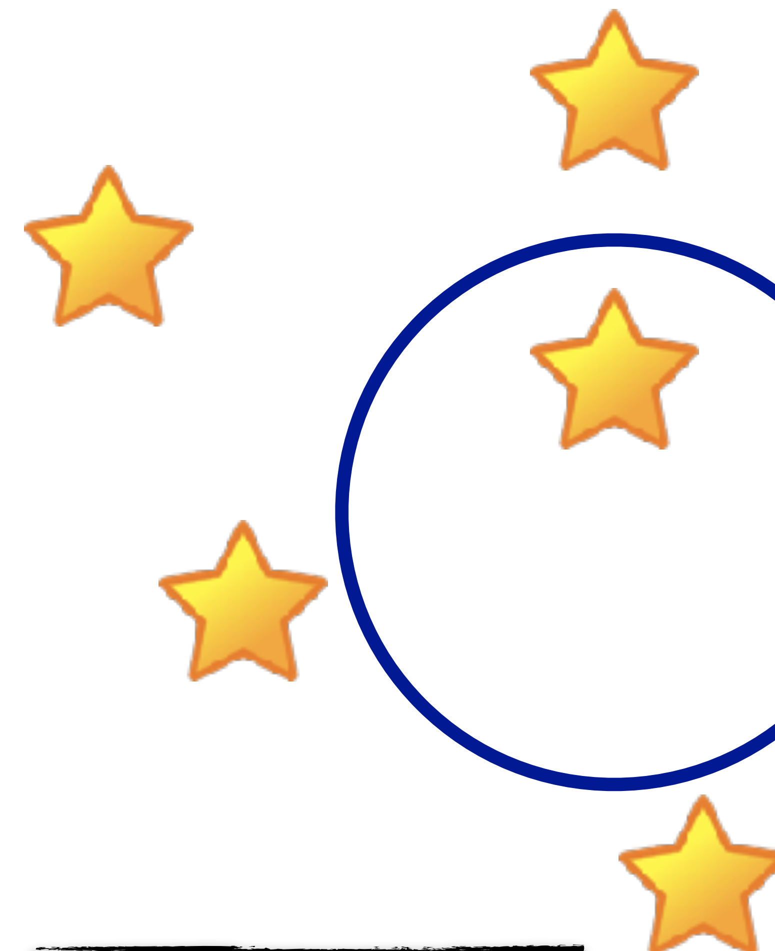
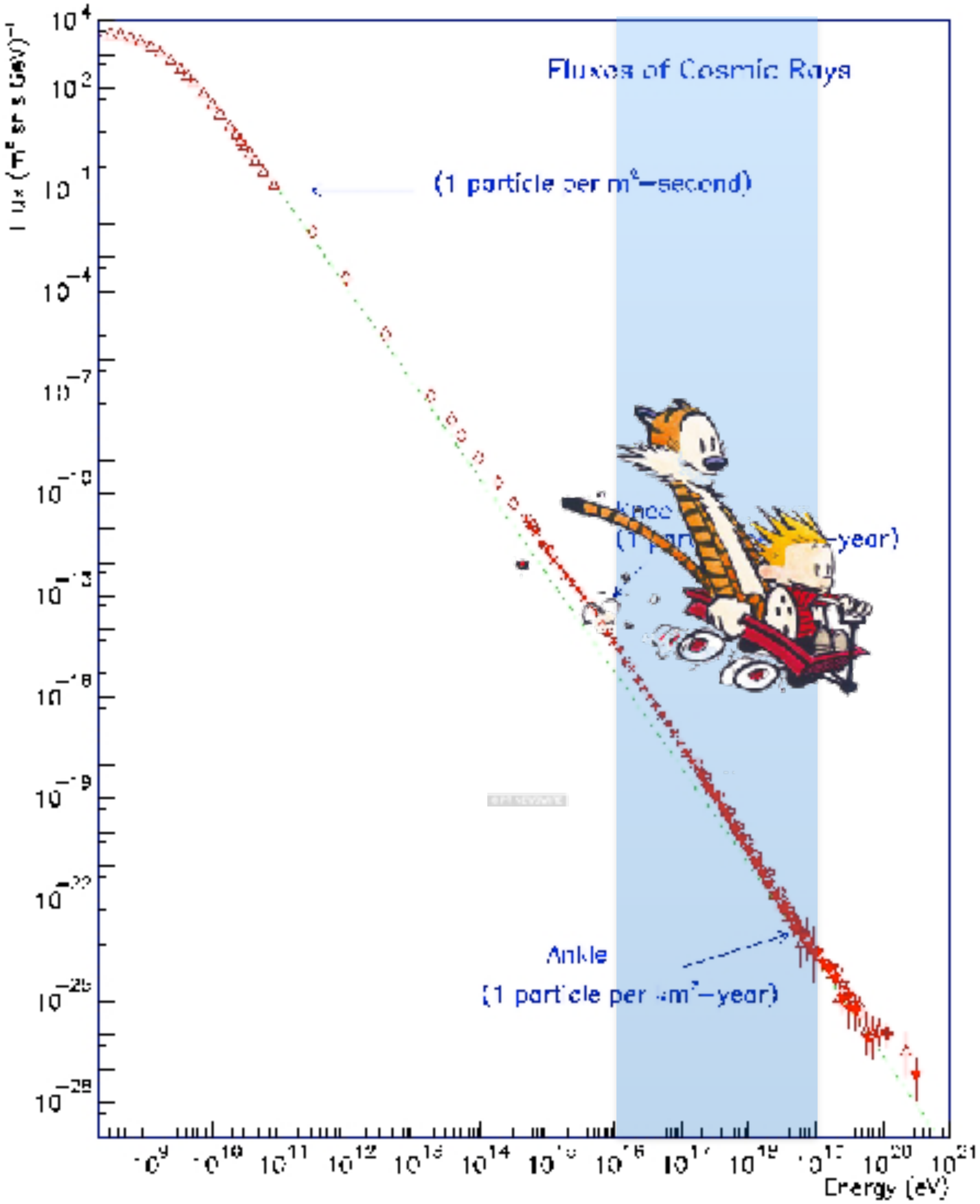


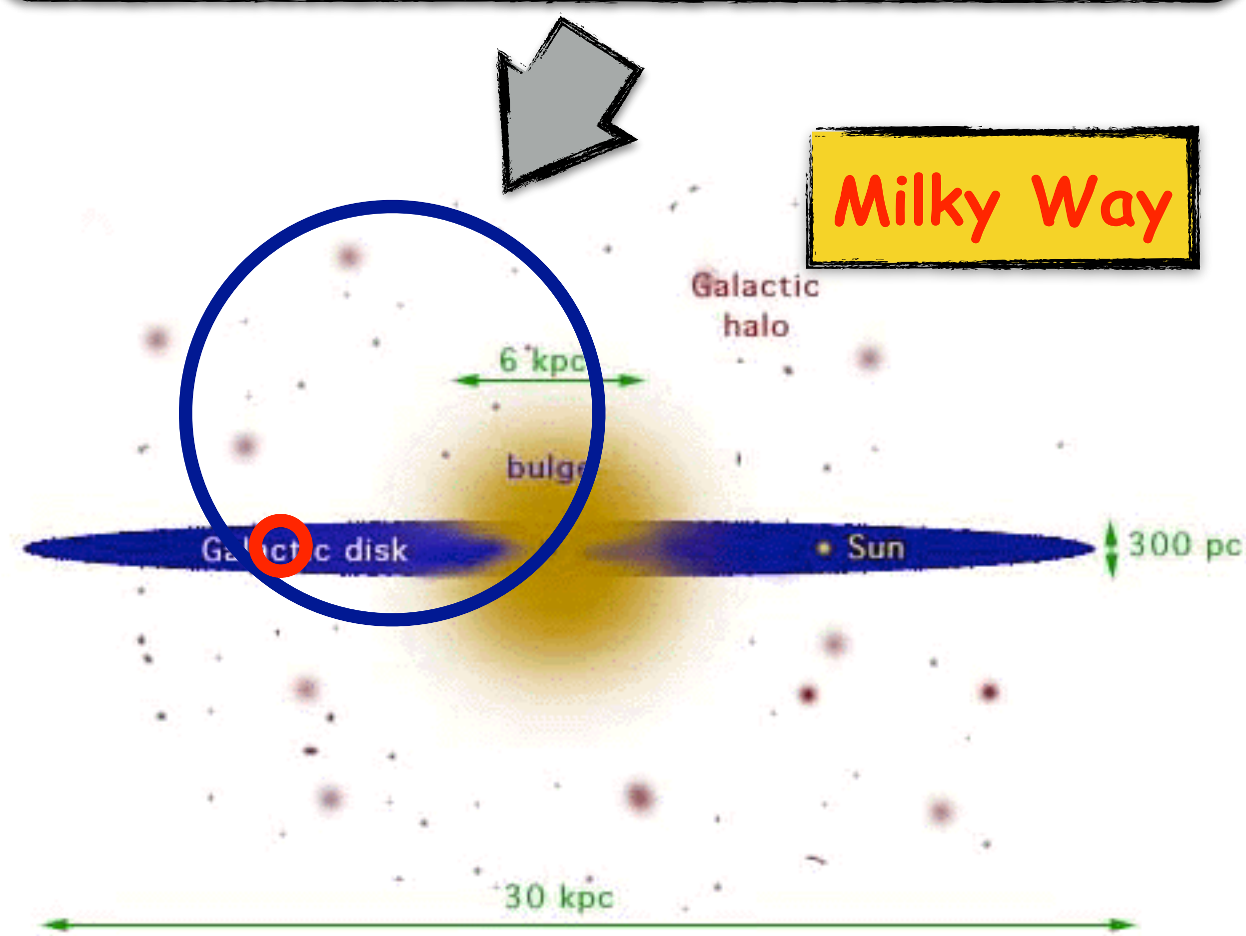
still Galactic...

same order of the size of Galactic objects —> difficult to reach PeV!

The EeV domain (10^{16} eV-10^{19} eV)

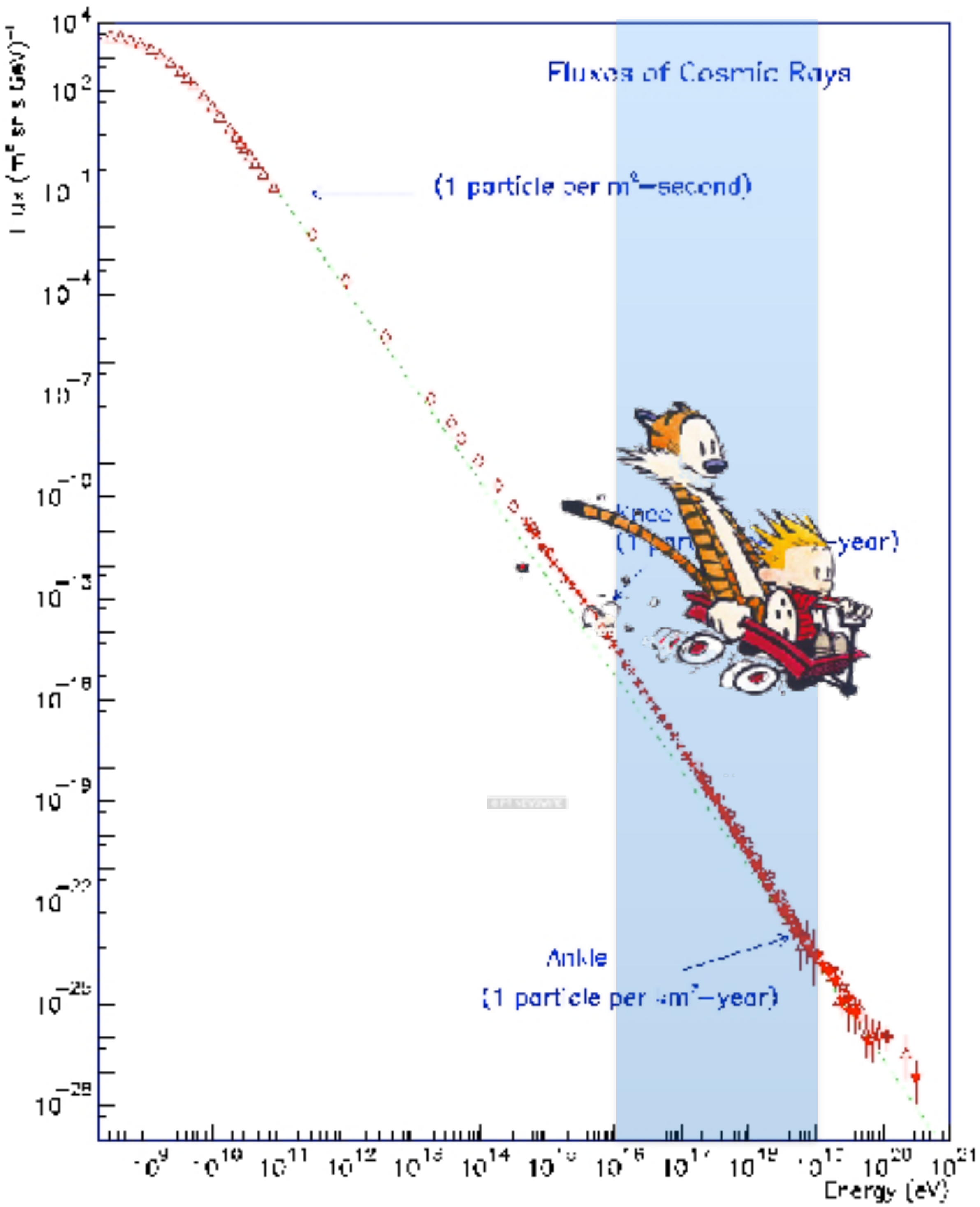


$$R_L(10^{19}\text{ eV}) \sim 4\text{ kpc}$$



Transition from Galactic to extra-galactic Cosmic Rays

The EeV domain (10^{16} eV-10^{19} eV)



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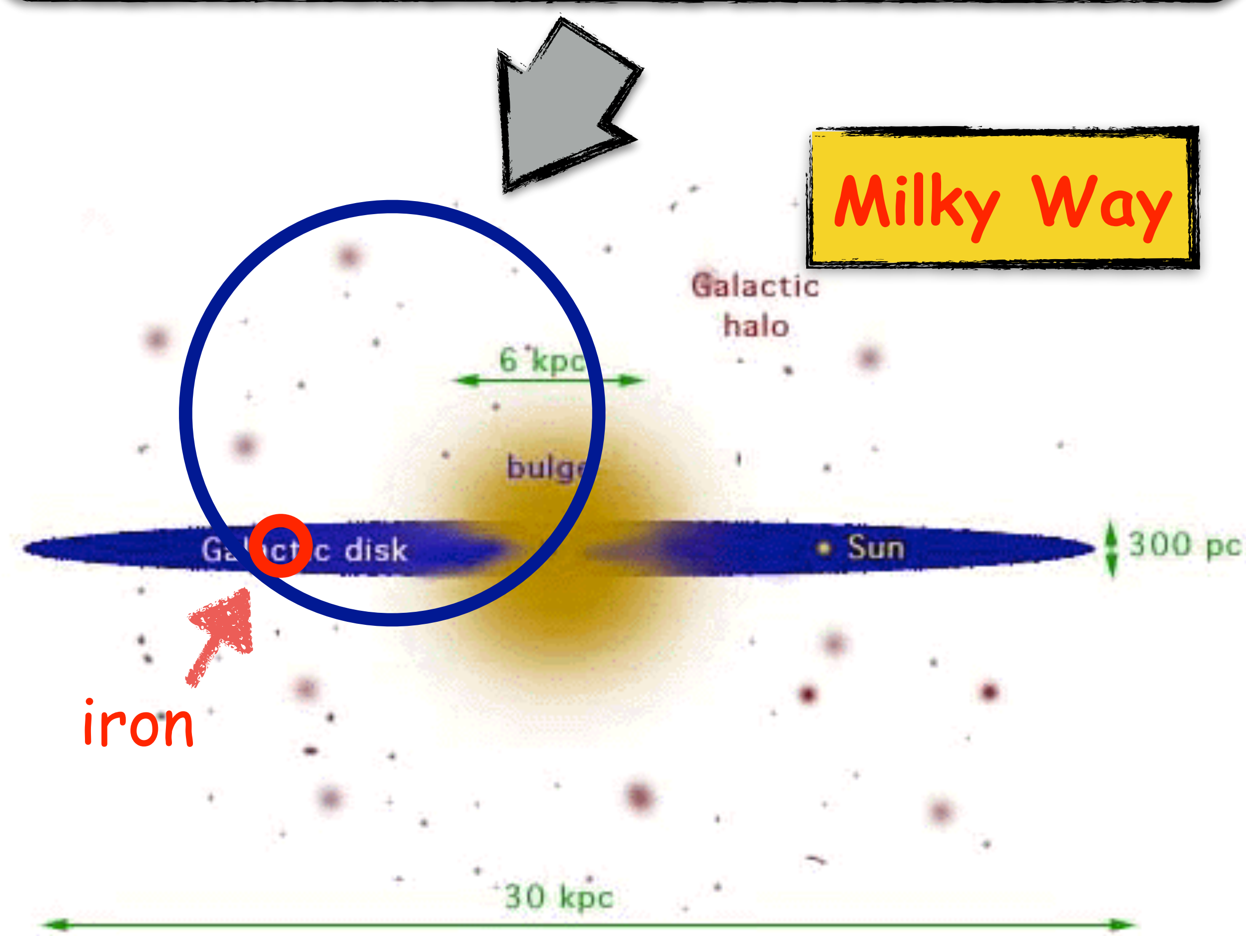
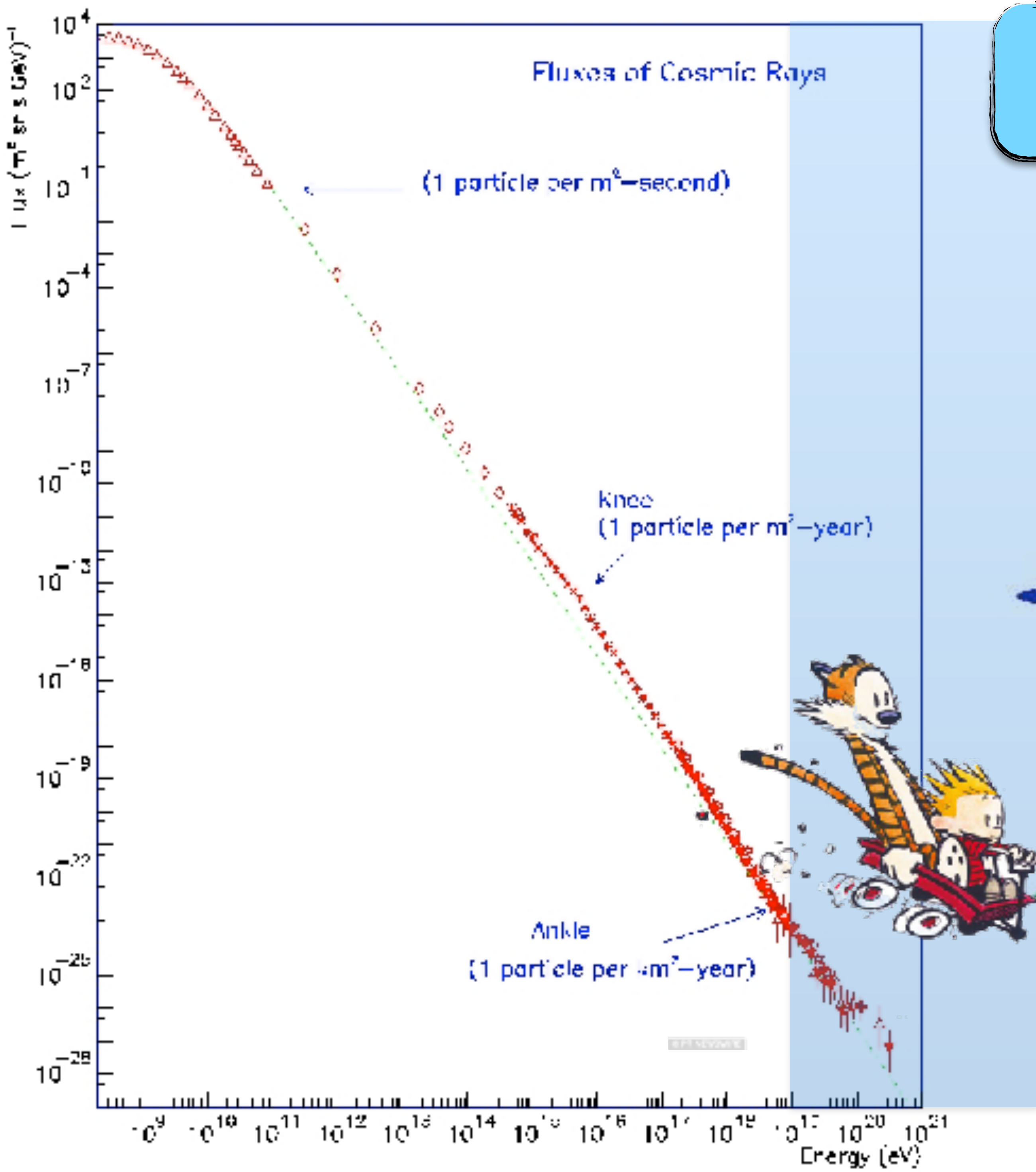


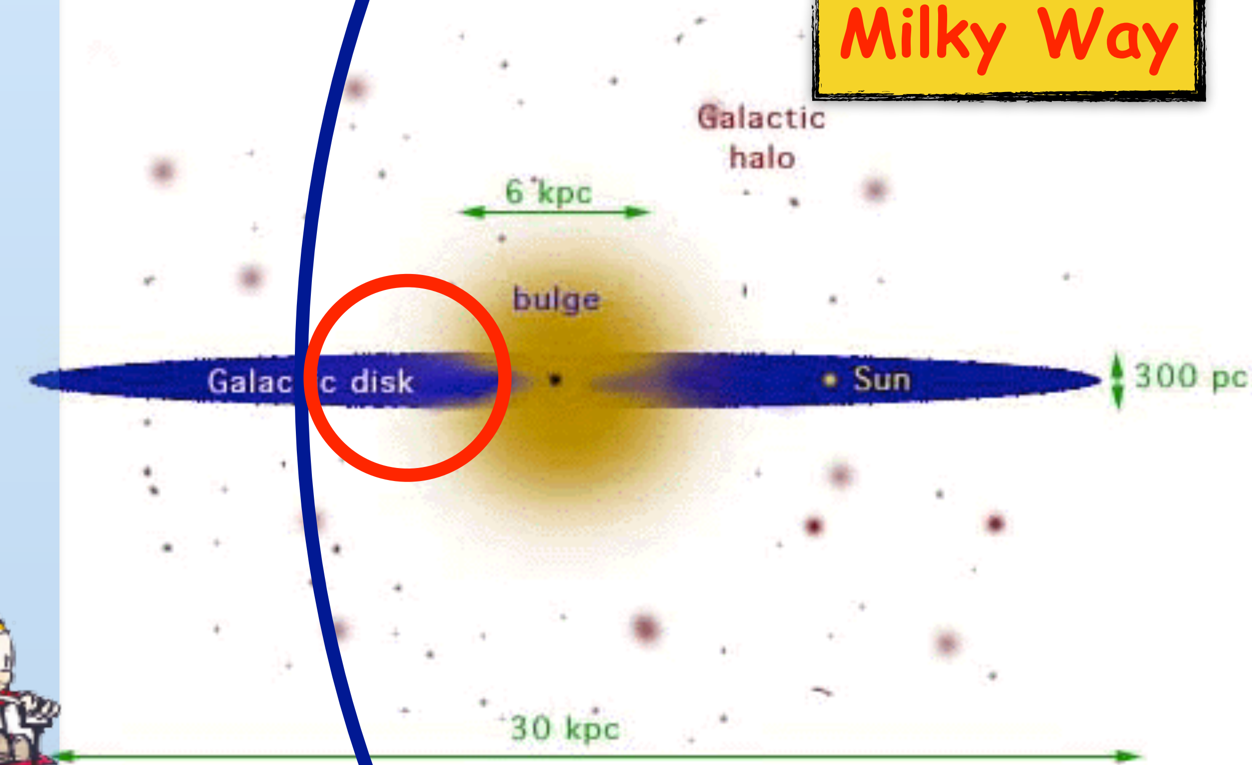
Transition from Galactic to extra-galactic Cosmic Rays

The ZeV domain (> 10^{19} eV)



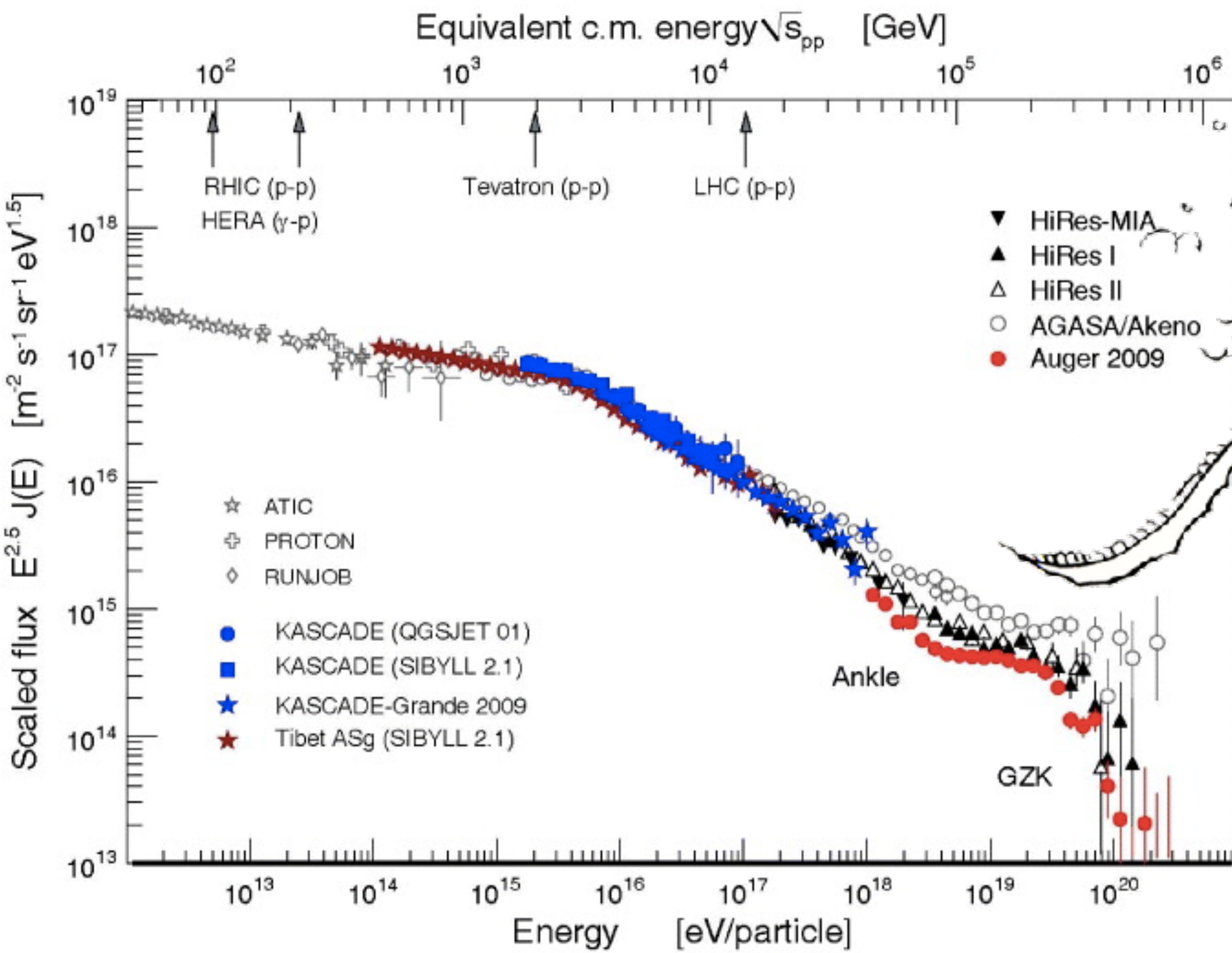
$R_L(10^{20}\ \text{eV}) \sim 40\ \text{kpc}$

Milky Way



extragalactic CRs?

[3] The “orthodoxy”



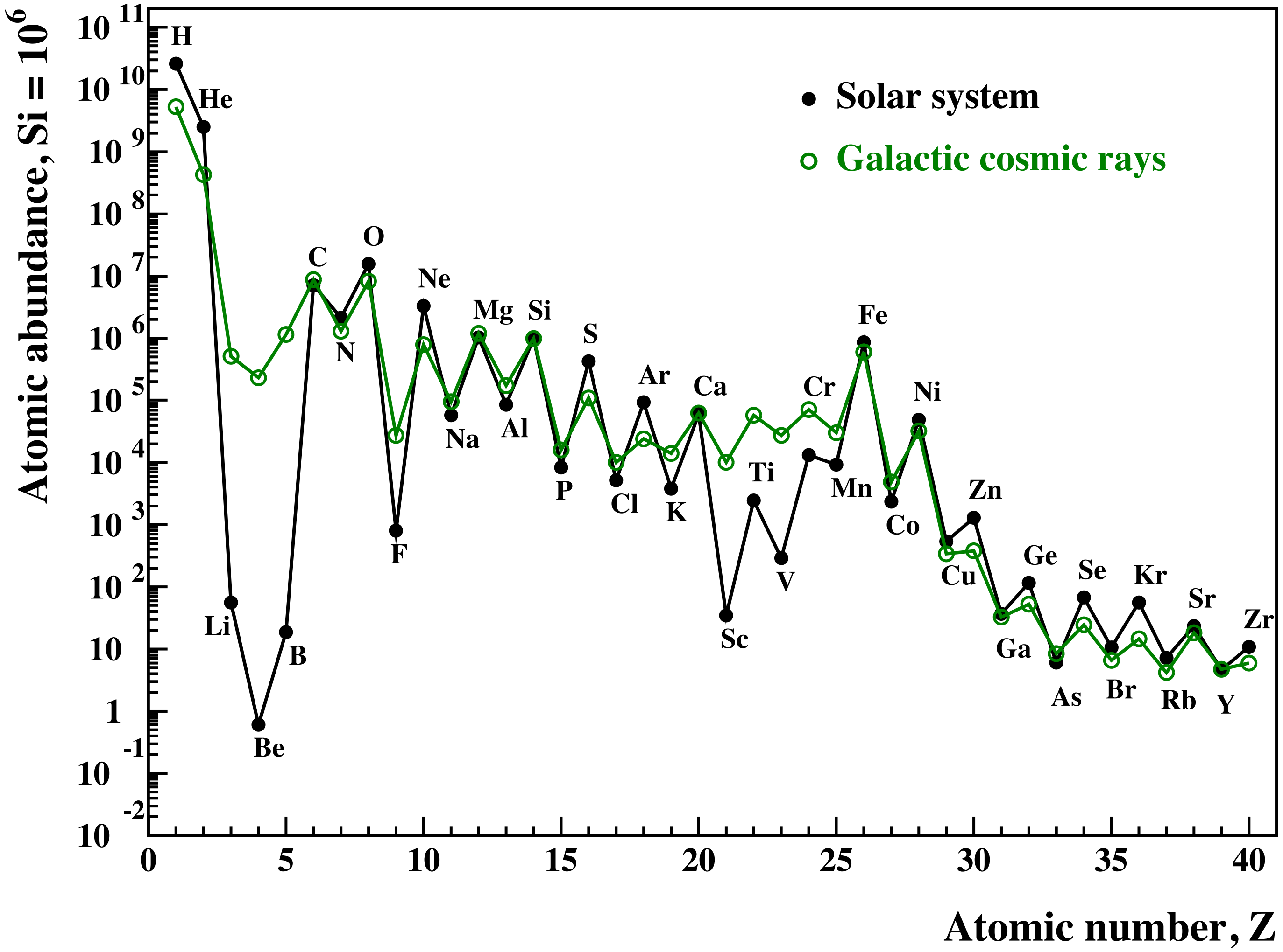
The orthodoxy (1)

- 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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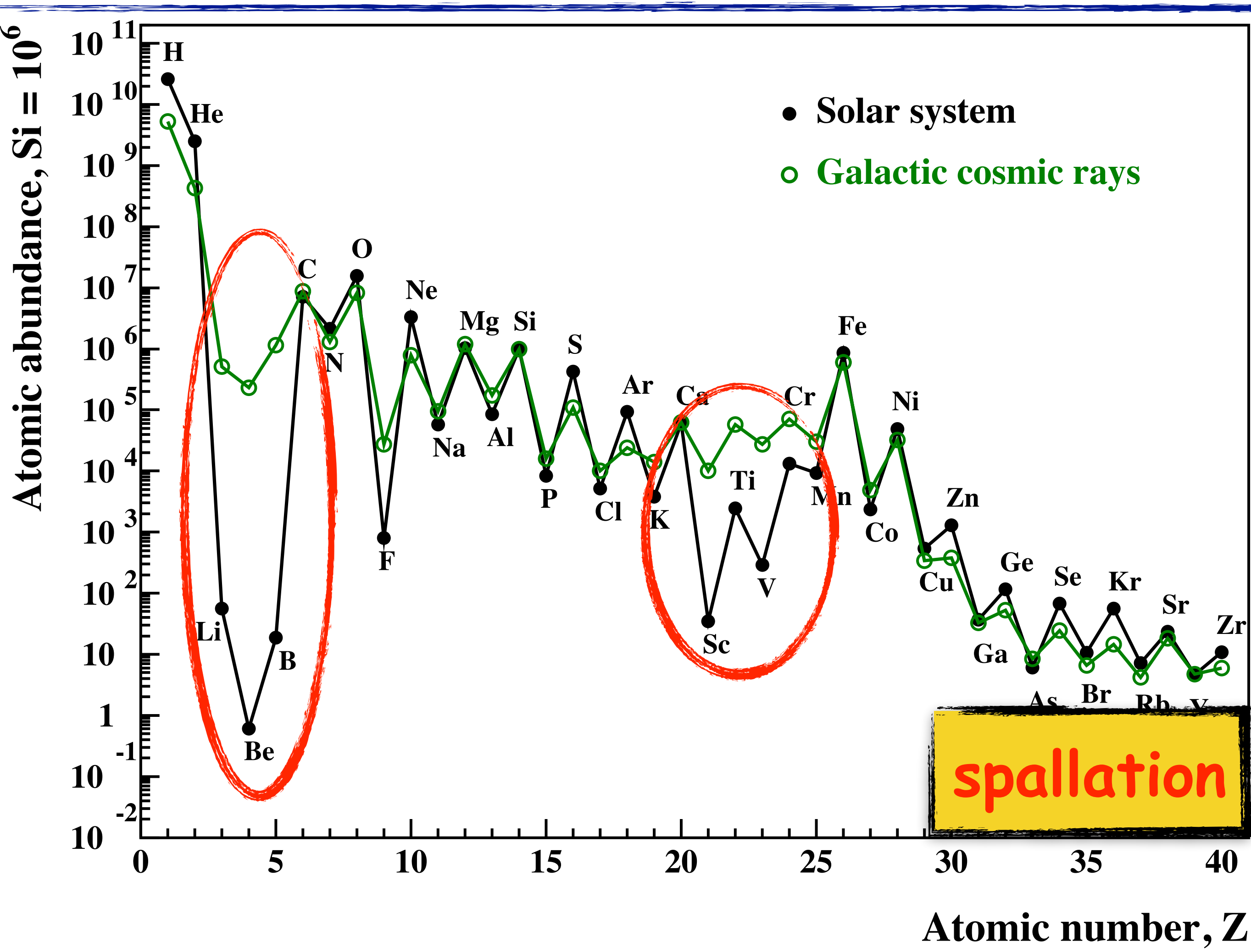

- energy/nucleon is conserved in spallation reactions
- Boron (secondary) is produced mainly in spallation reactions involving Carbon (primary)

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

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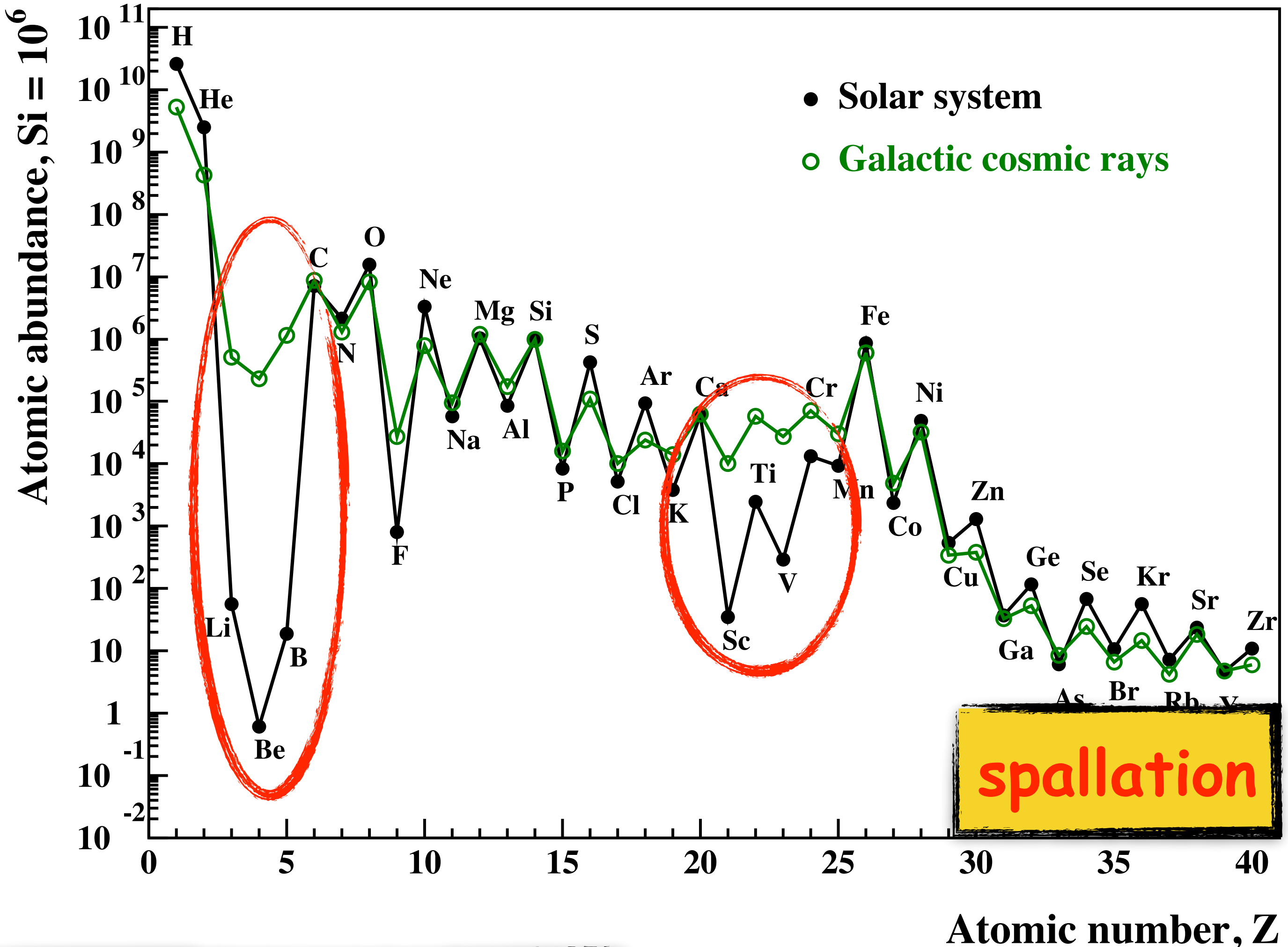

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production rate of B $q_B \sim n_C \; \sigma_s \; n_{ISM} \; c$

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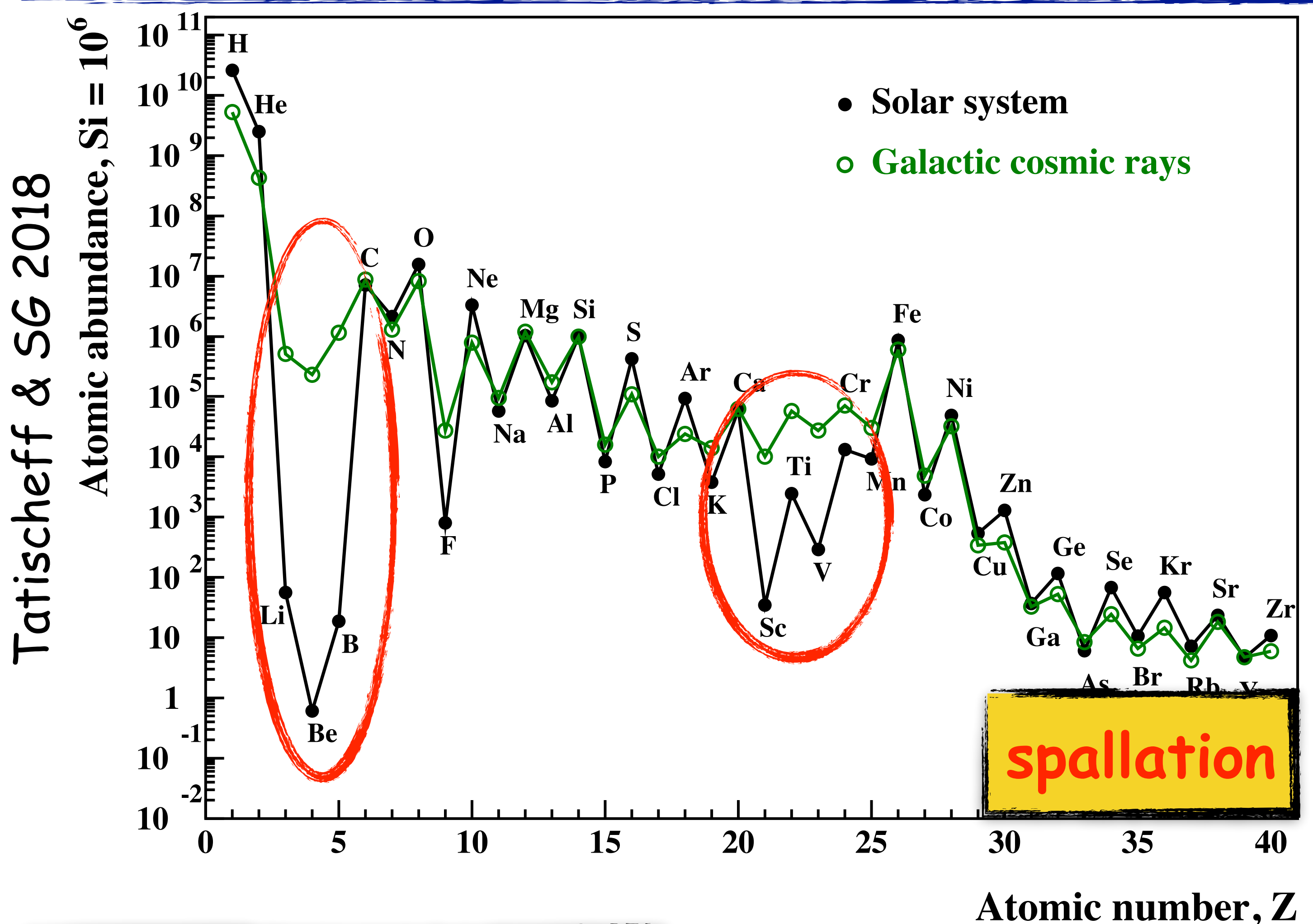

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for a review see e.g. Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

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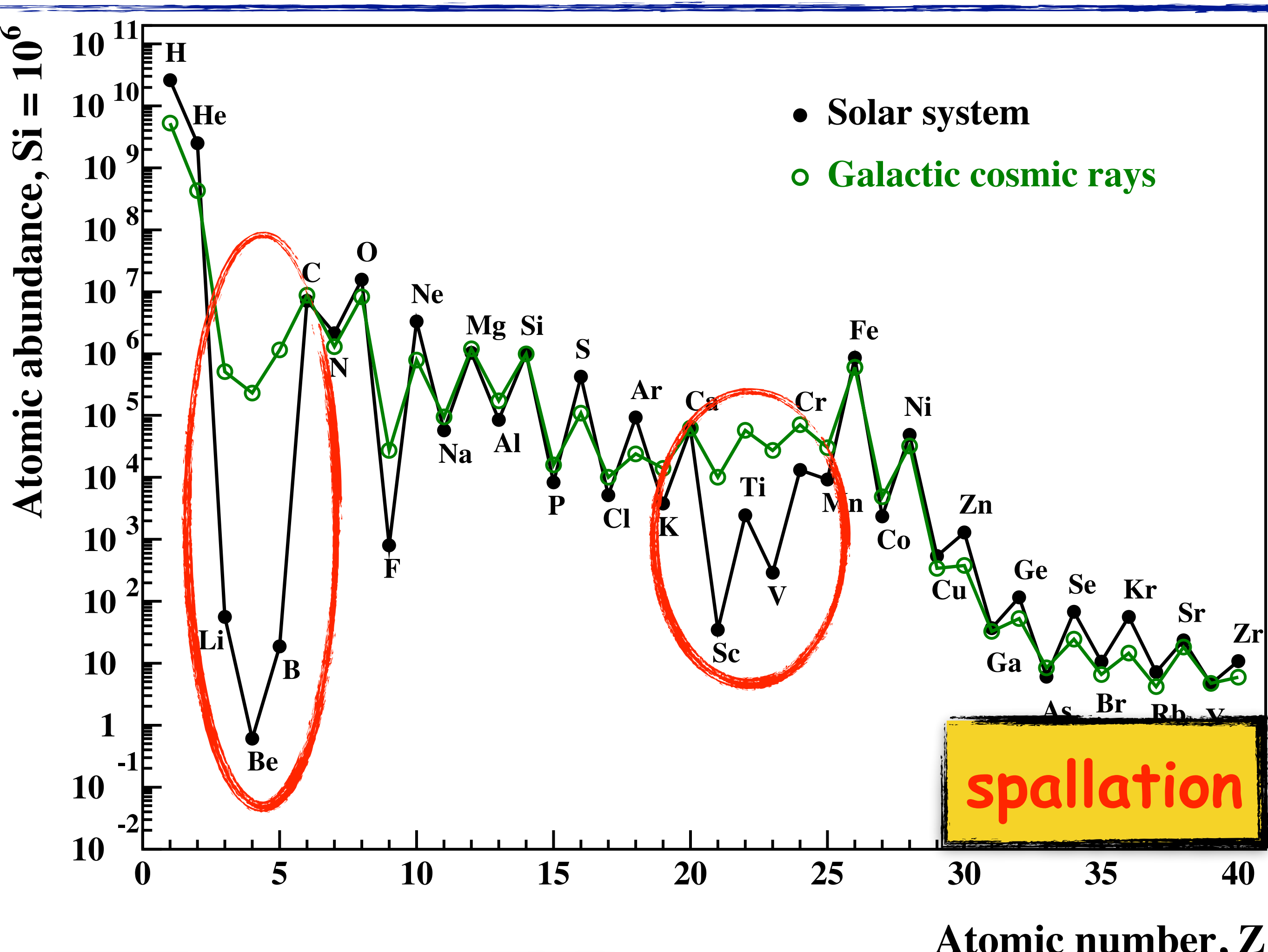

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$$\frac{n_B}{n_C} \sim \sigma_s \; n_{ISM} c \; \tau_{disk}$$

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

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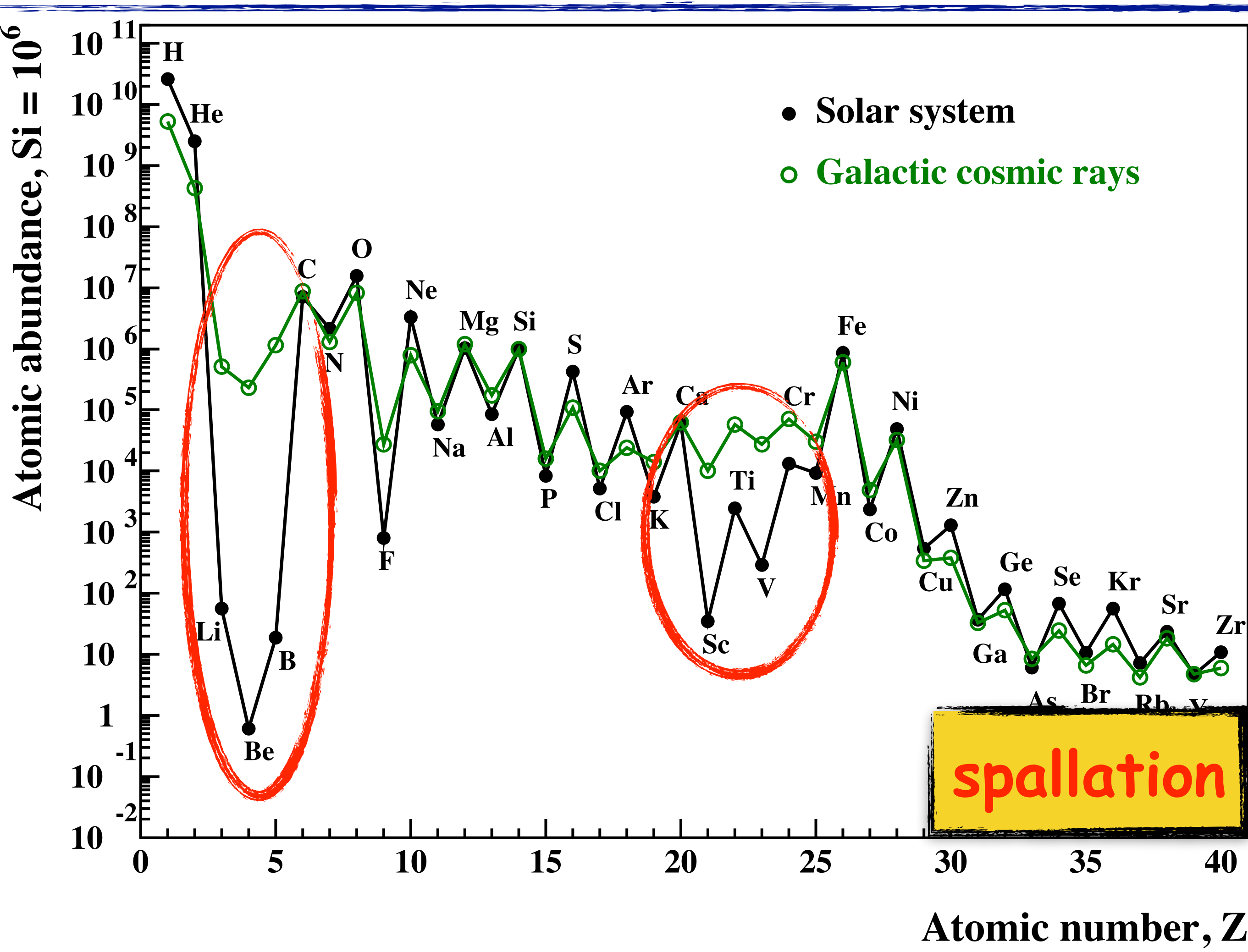

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grammage

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

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

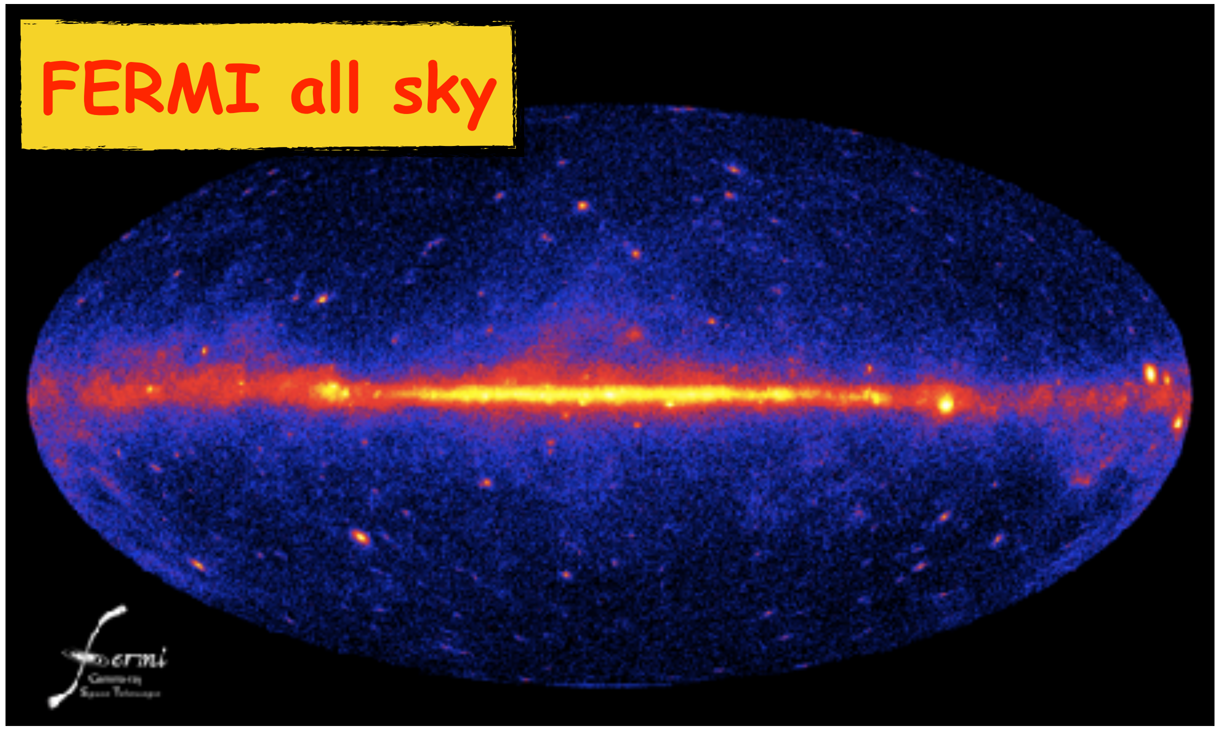
The orthodoxy (1)

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

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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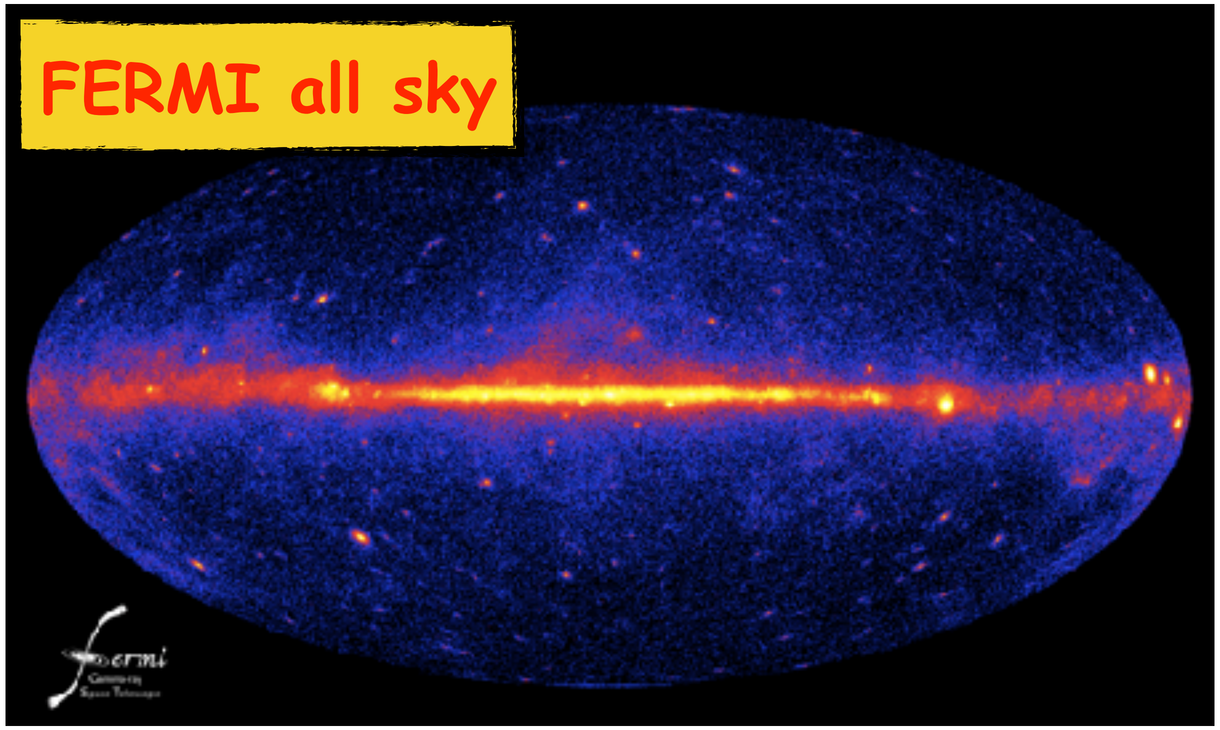
Small spatial gradient

Power of CR sources in the disk

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



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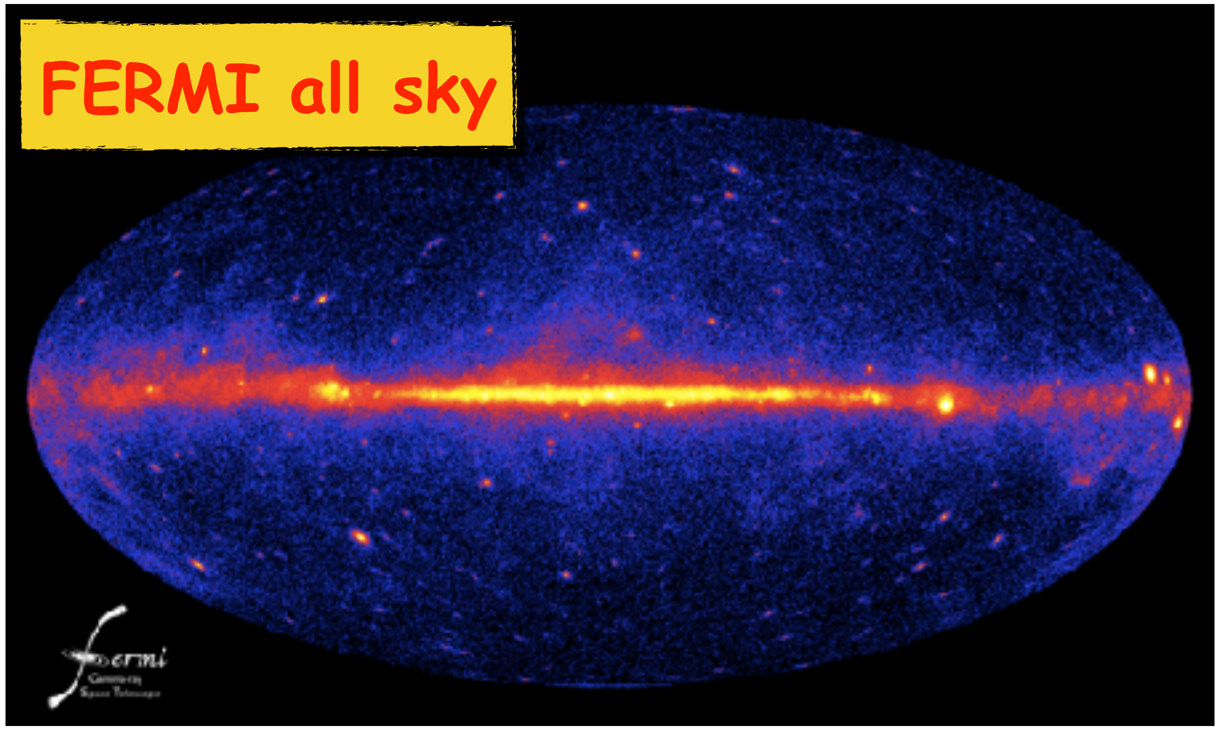


Power of CR sources in the disk

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

Power of Galactic SN explosions

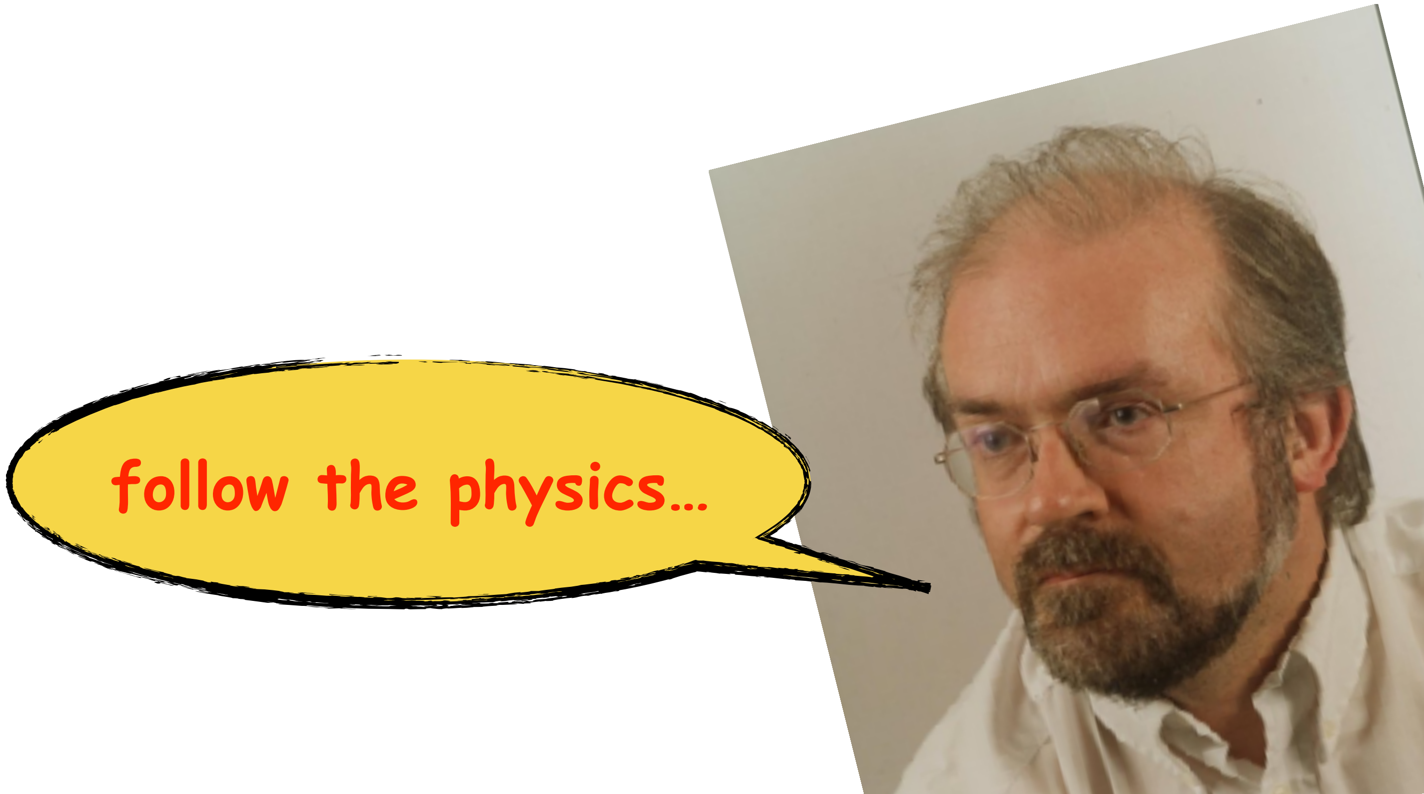
10^{51} erg — 3/century

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

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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▶ CRs are diffusively confined within an extended & magnetised Gal. halo

grammage $\Lambda_g \sim 10 \text{ g/cm}^2 \longrightarrow l_{disk} = \frac{\Lambda_g}{\varrho_{ISM}} \sim 1 \text{ Mpc}$

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

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stable secondaries

$$\tau_{disk} = \frac{l_{disk}}{c} \sim 3 \text{ Myr}$$

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unstable secondaries

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

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

↓

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

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

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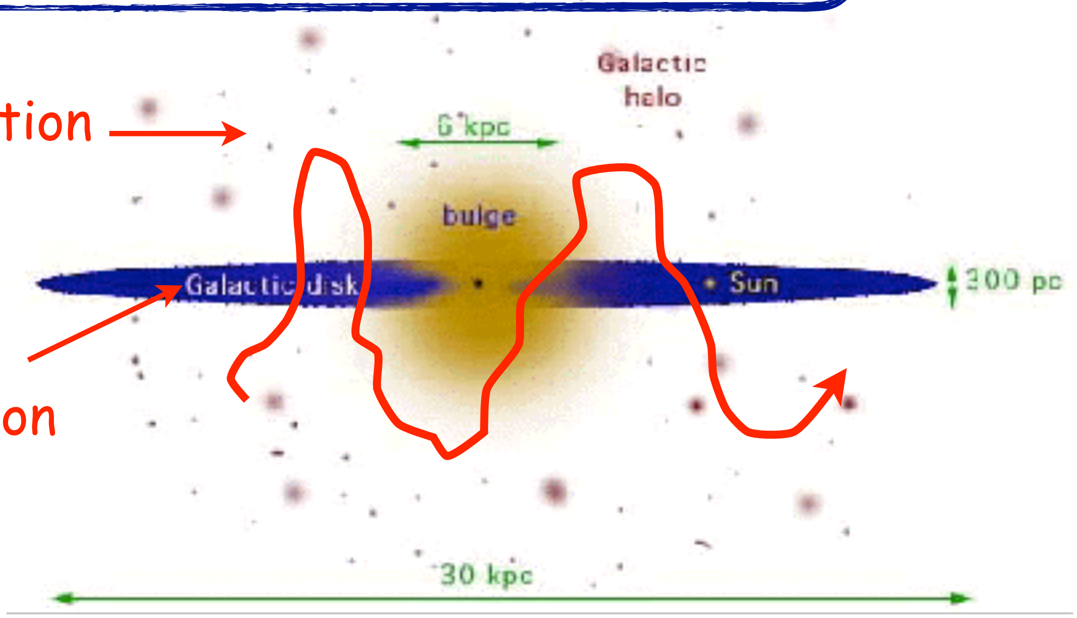
stable secondaries

$$\tau_{disk} = \frac{l_{disk}}{c} \sim 3\ \text{Myr}$$

no spallation

spallation



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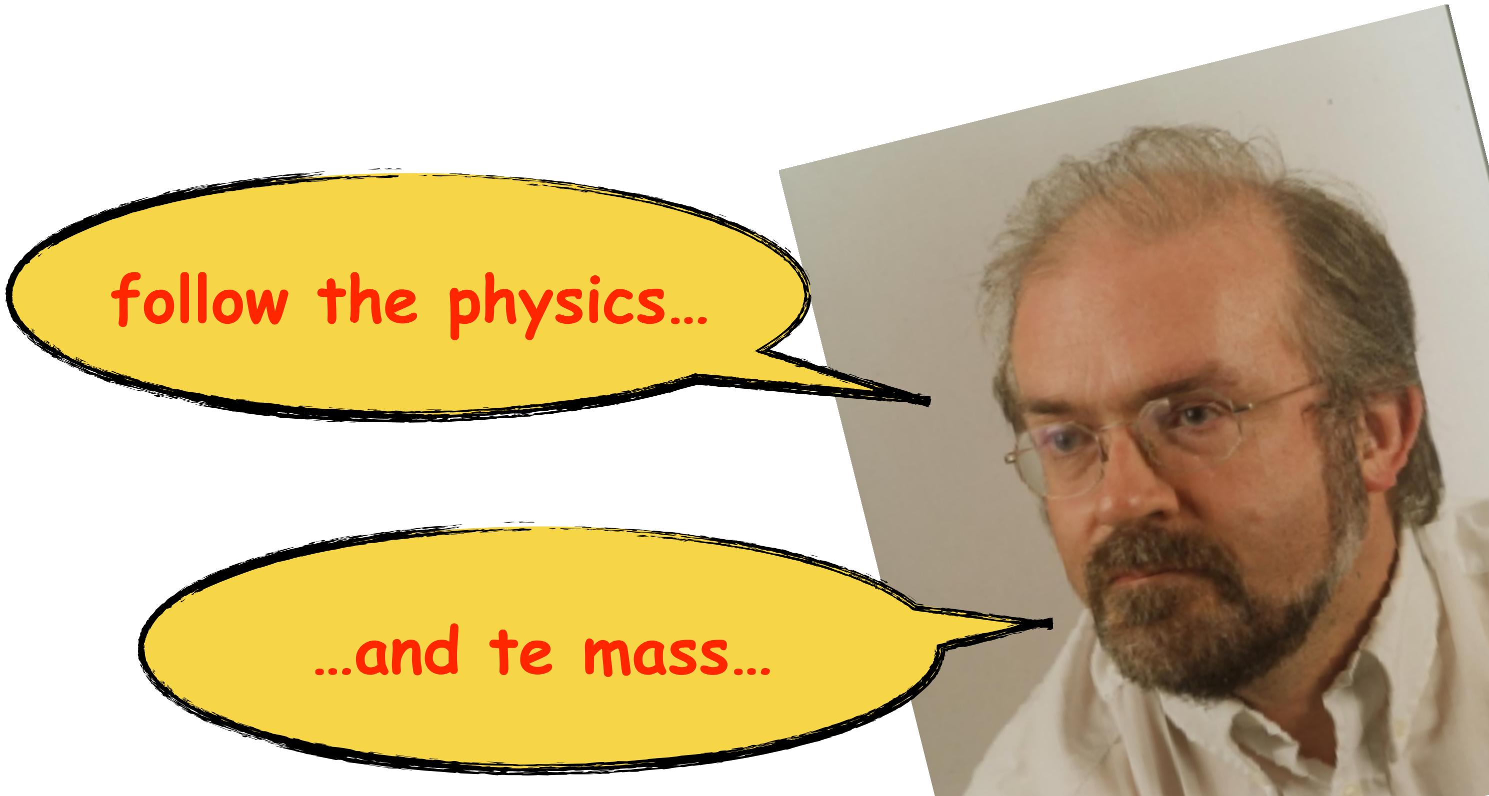
The orthodoxy (3)

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



The orthodoxy (3)

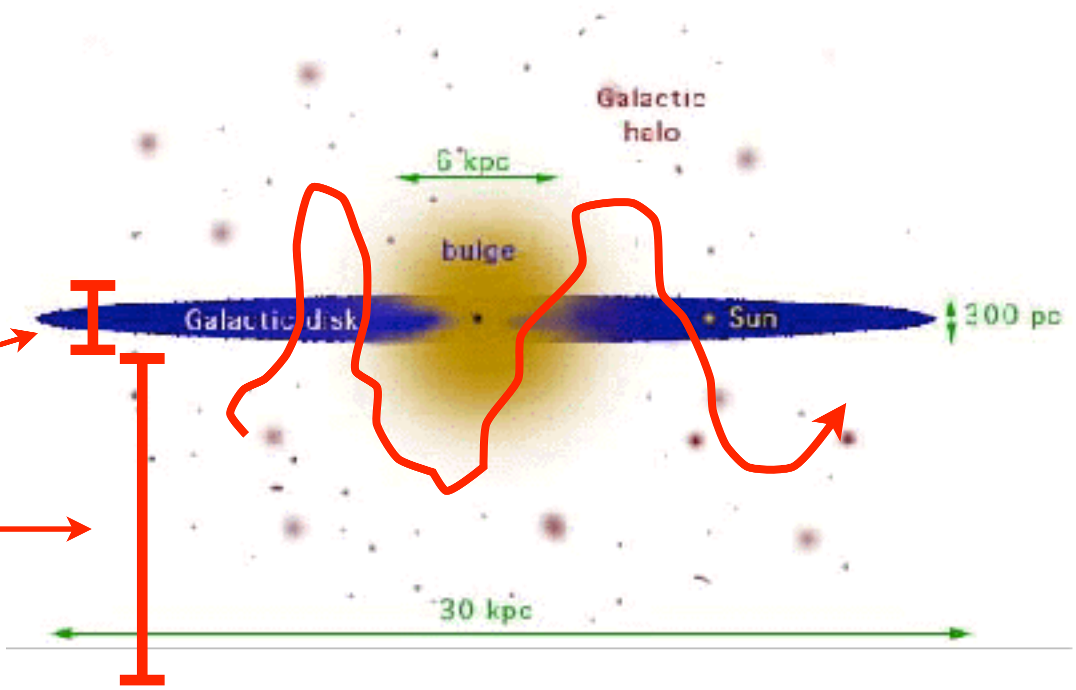
- CRs are accelerated out of the (dusty) ISM through DSA in SNRs

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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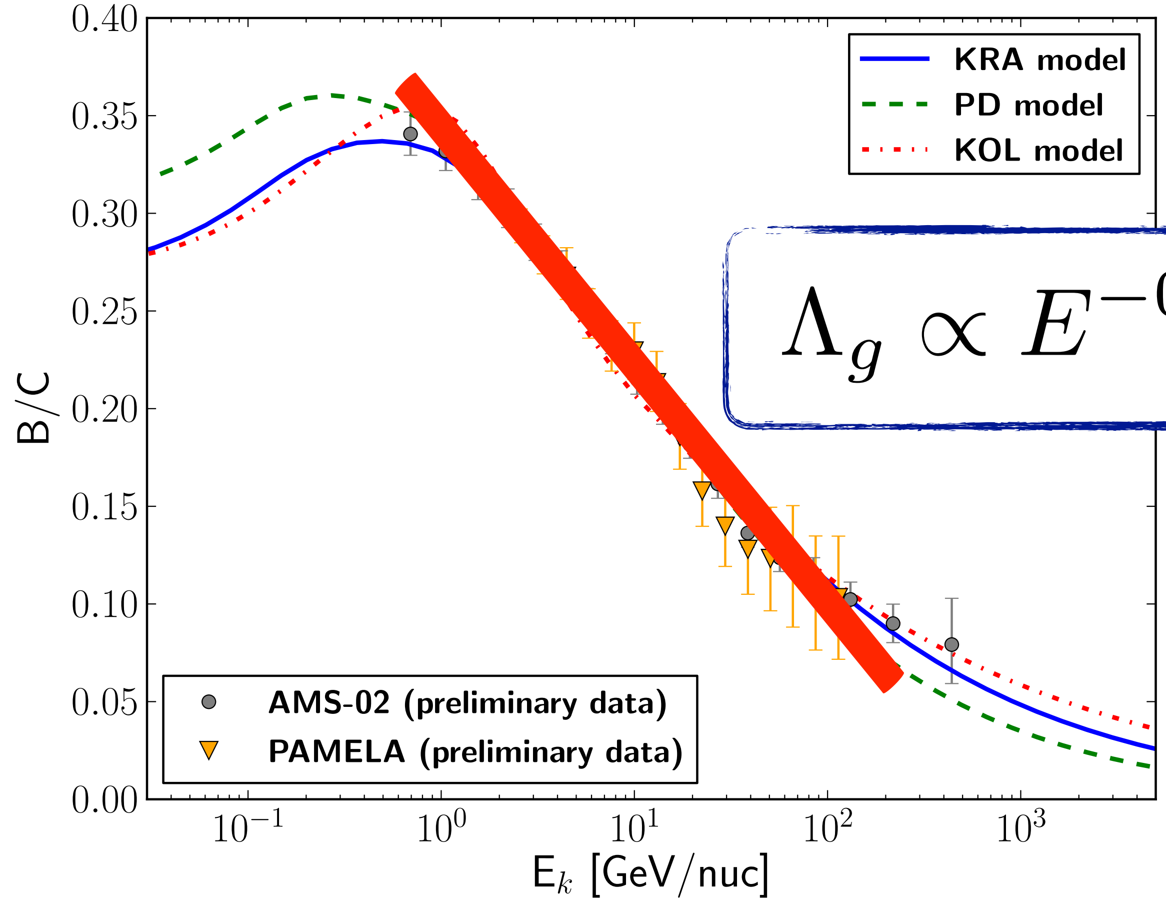
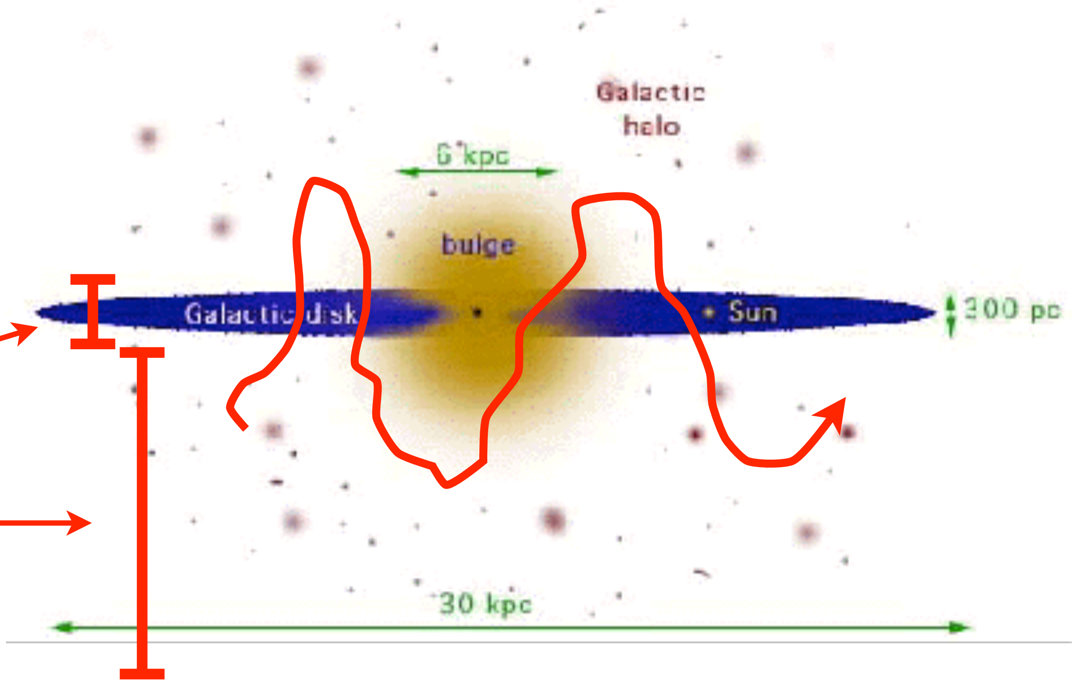
Gaggero et al (2014)



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

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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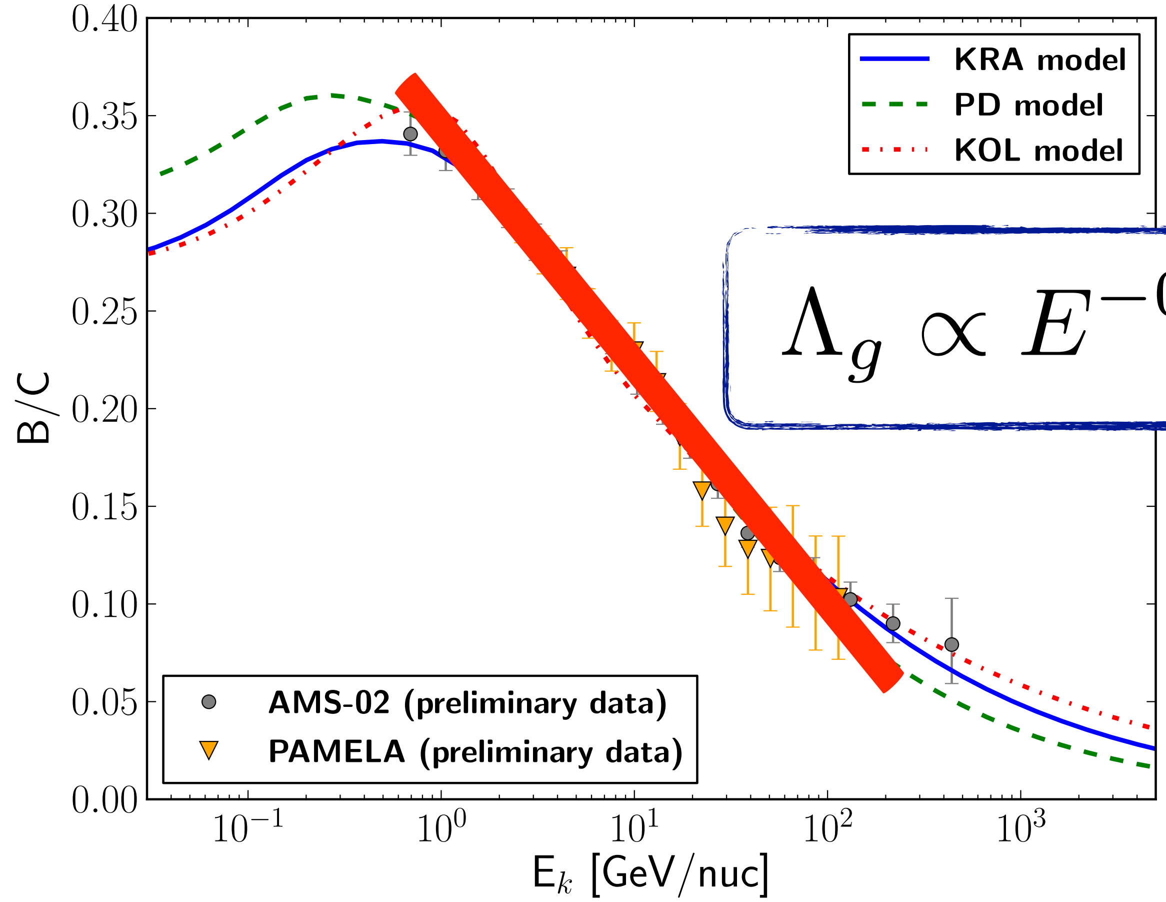

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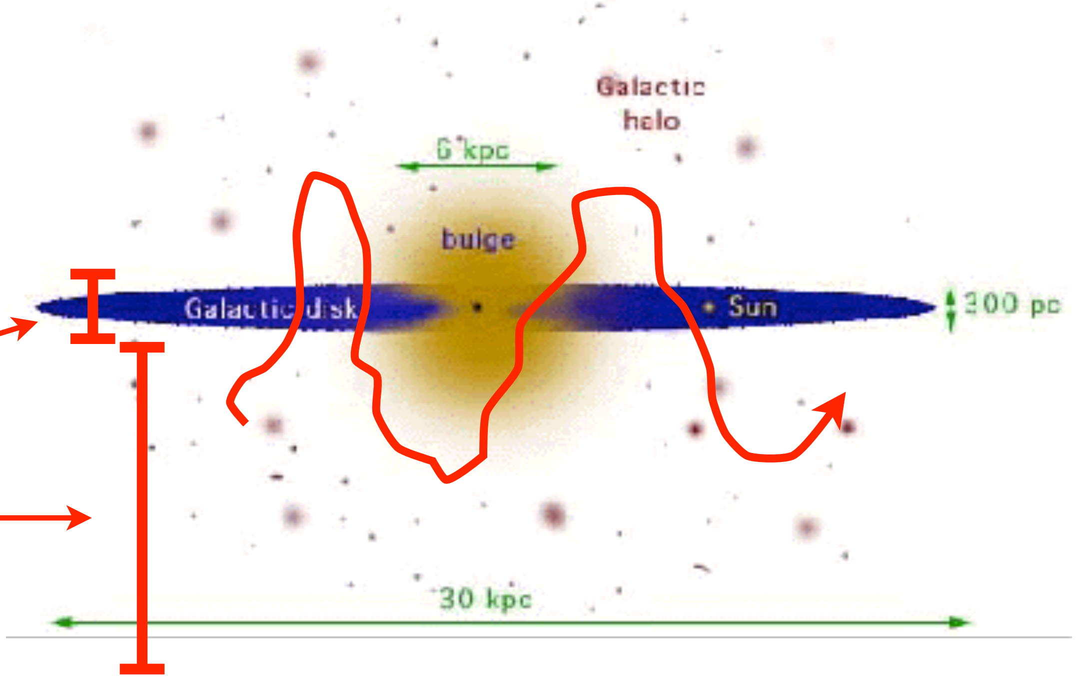

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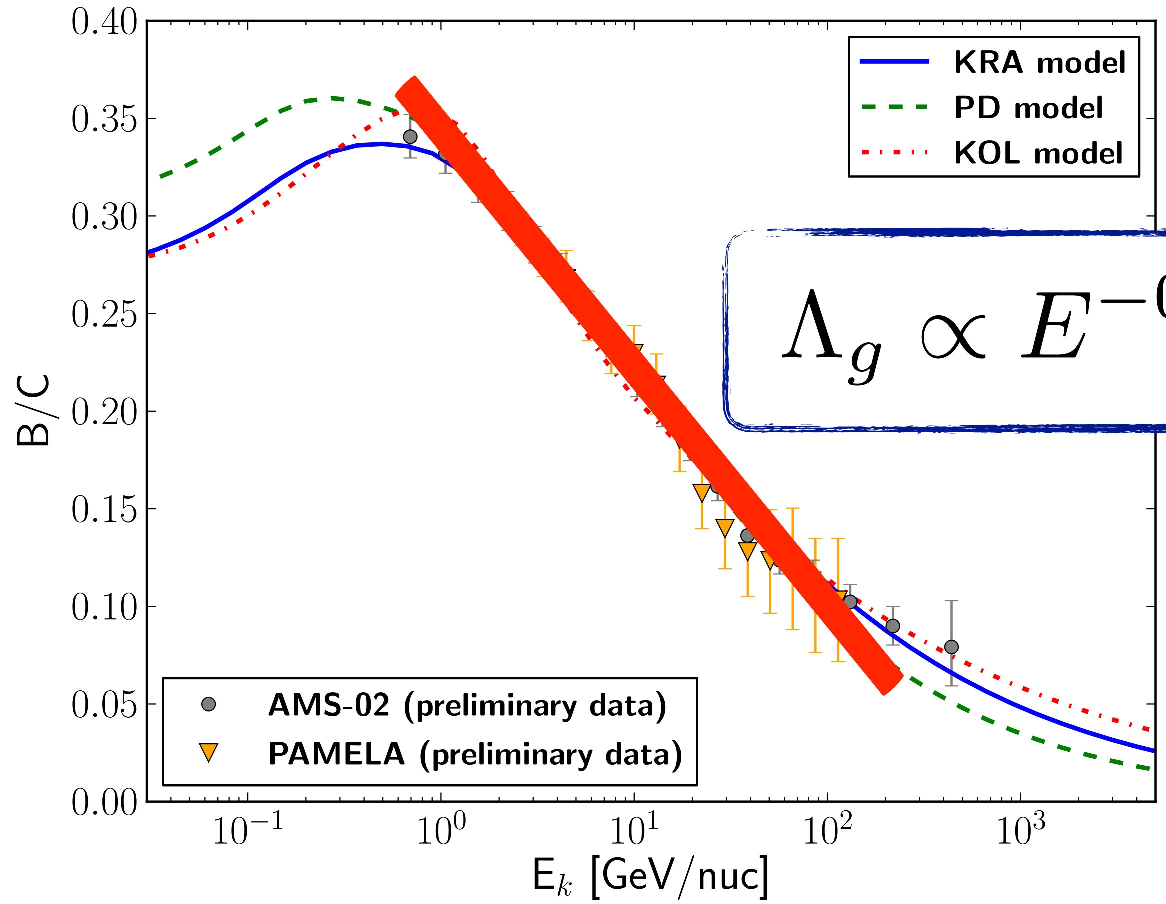

$$\Lambda_g \propto E^{-0.3 *}$$

effective grammage

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

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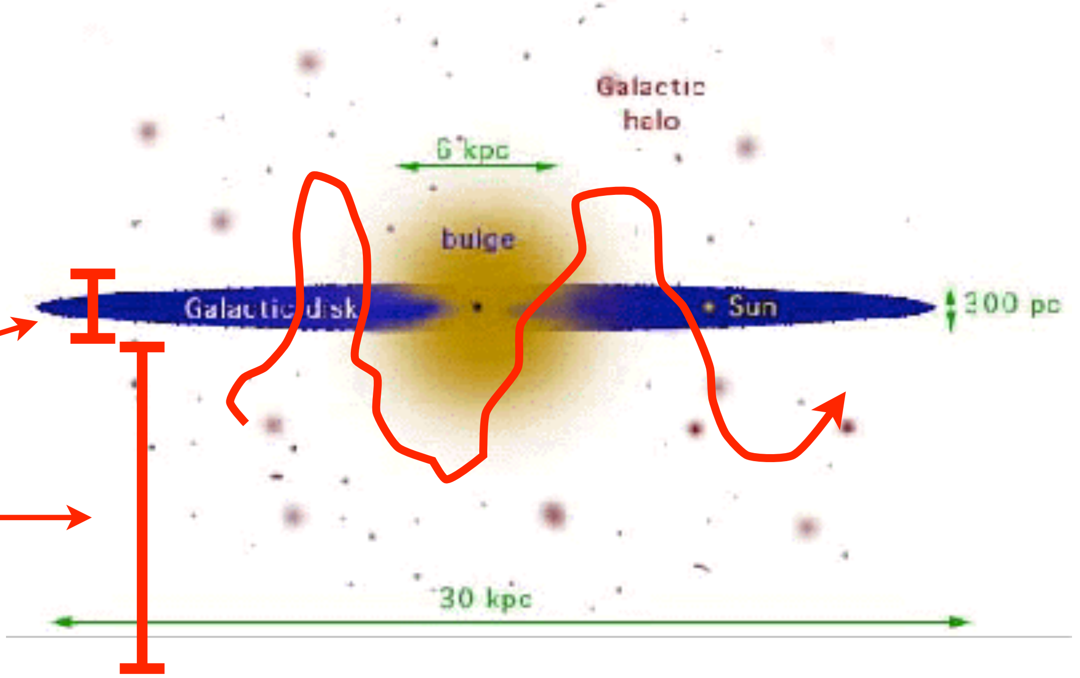

mean density

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

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

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

The orthodoxy (3)

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

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

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

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

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

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

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

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

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

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

The orthodoxy (3)

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

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

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

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

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

????

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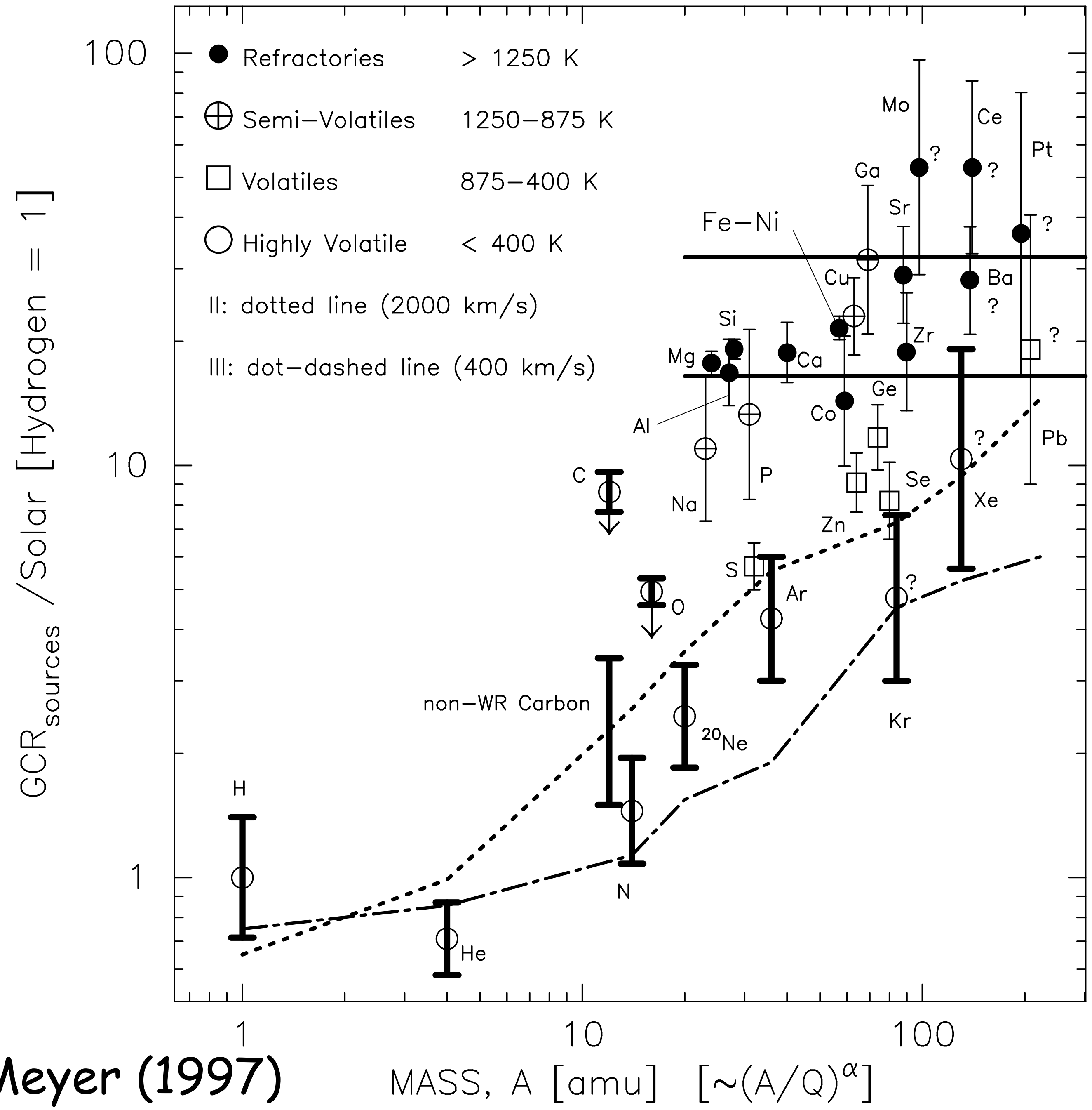
why dusty?



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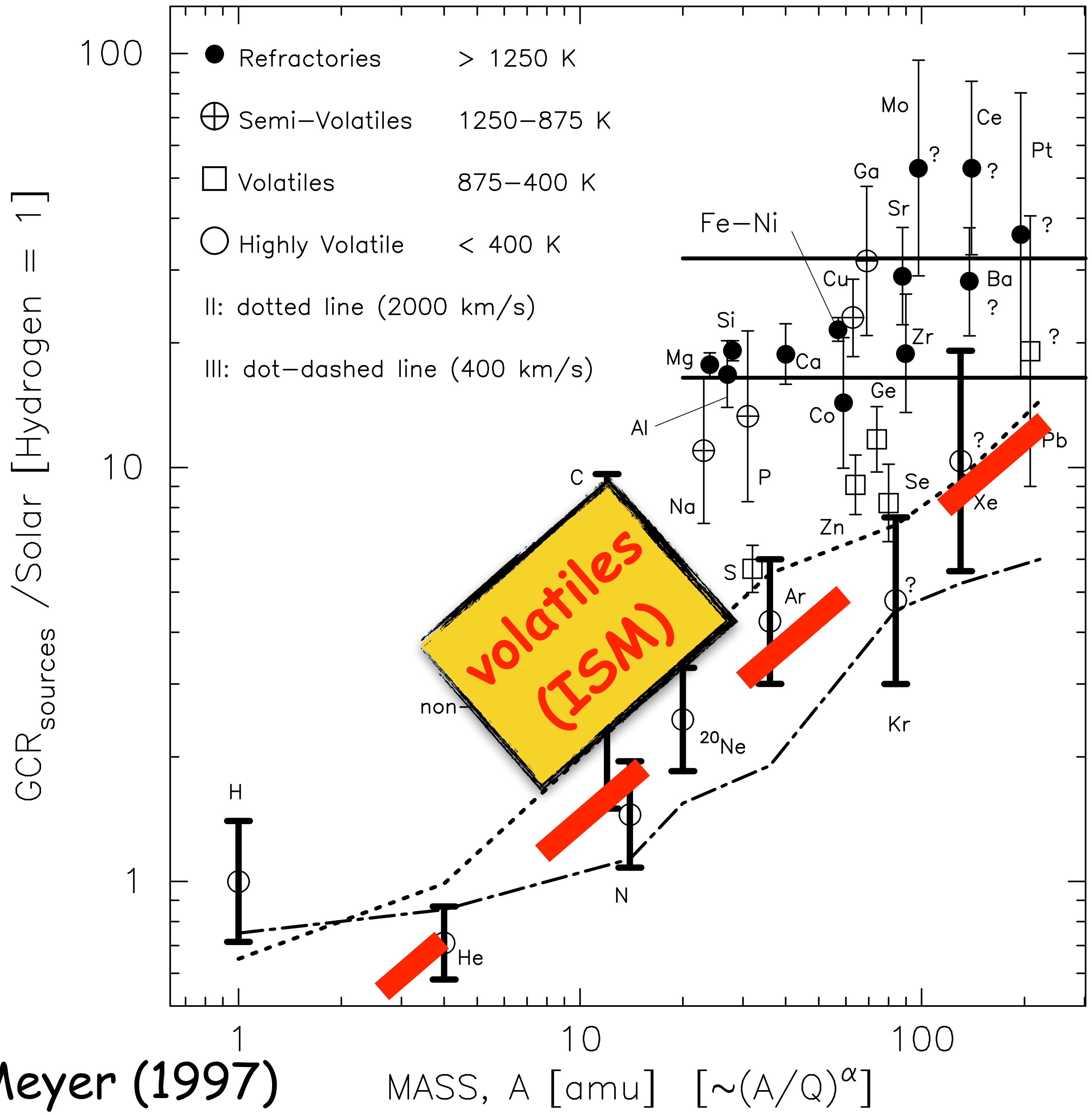

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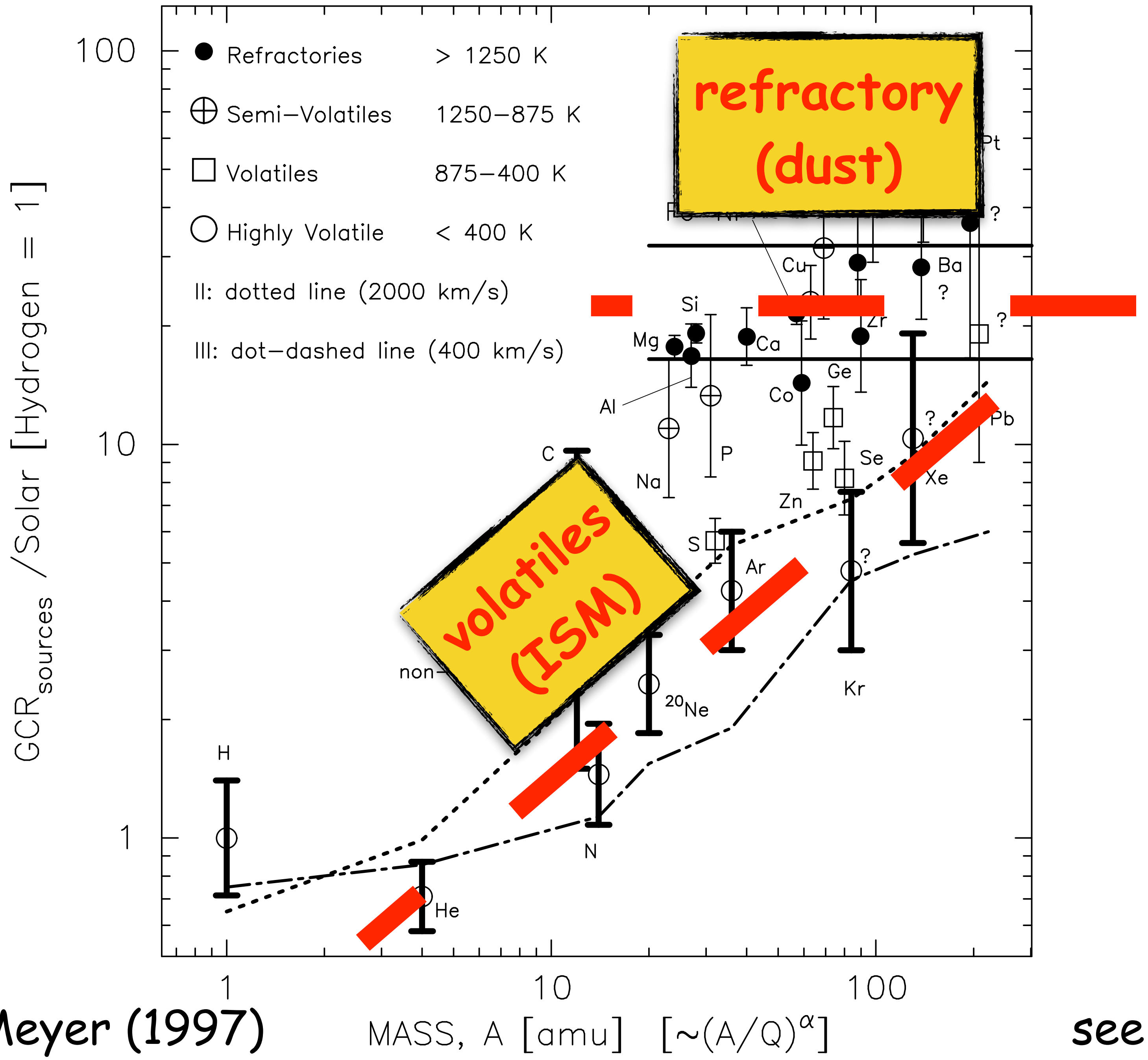

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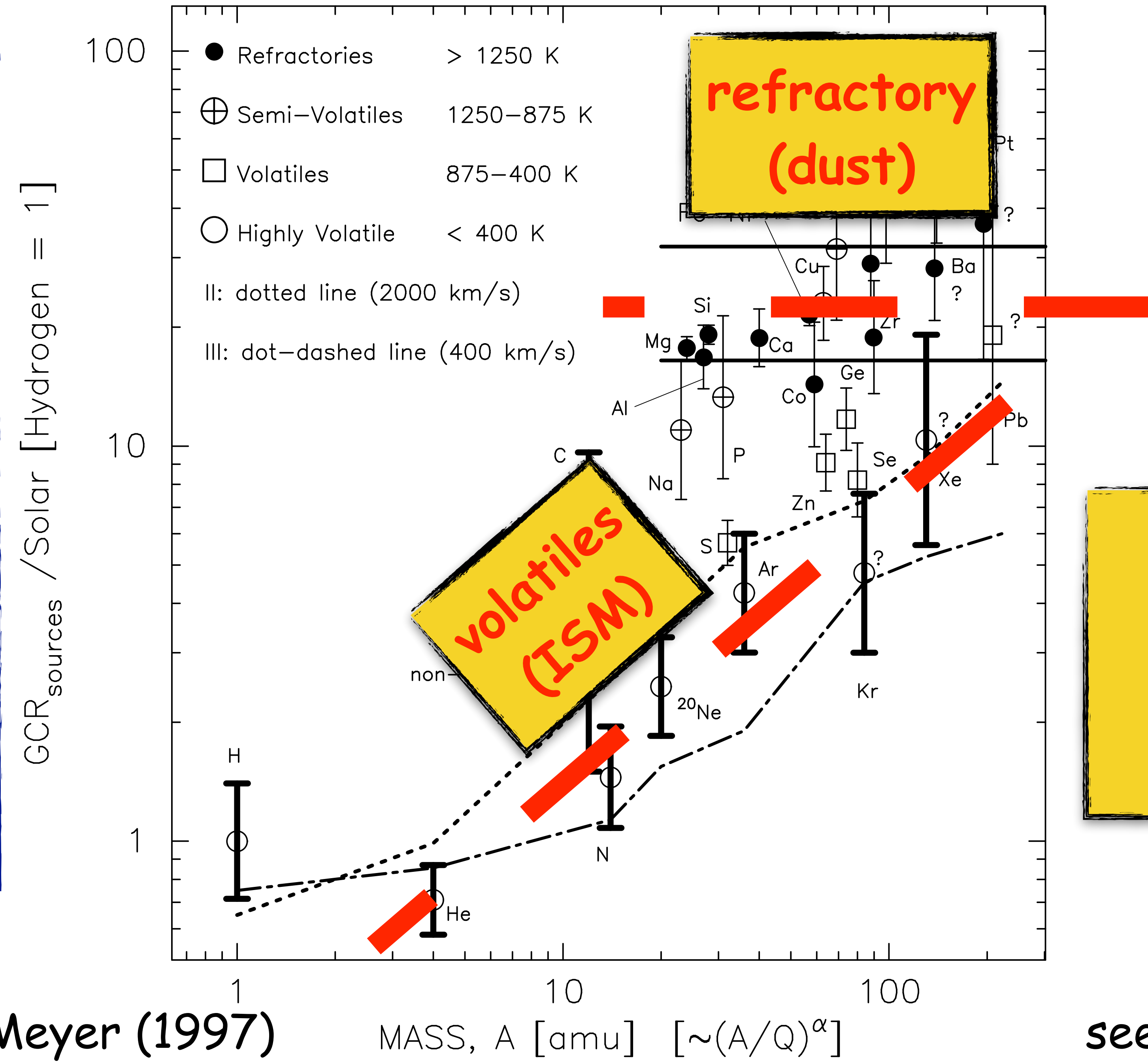
Data are best explained if refractory CRs are injected at shocks through sputtering of pre-accelerated dust grains



why dusty?

MESSAGE
CR composition deserves more attention

Ellison, Drury, Meyer (1997)

see also Caprioli+ 2017

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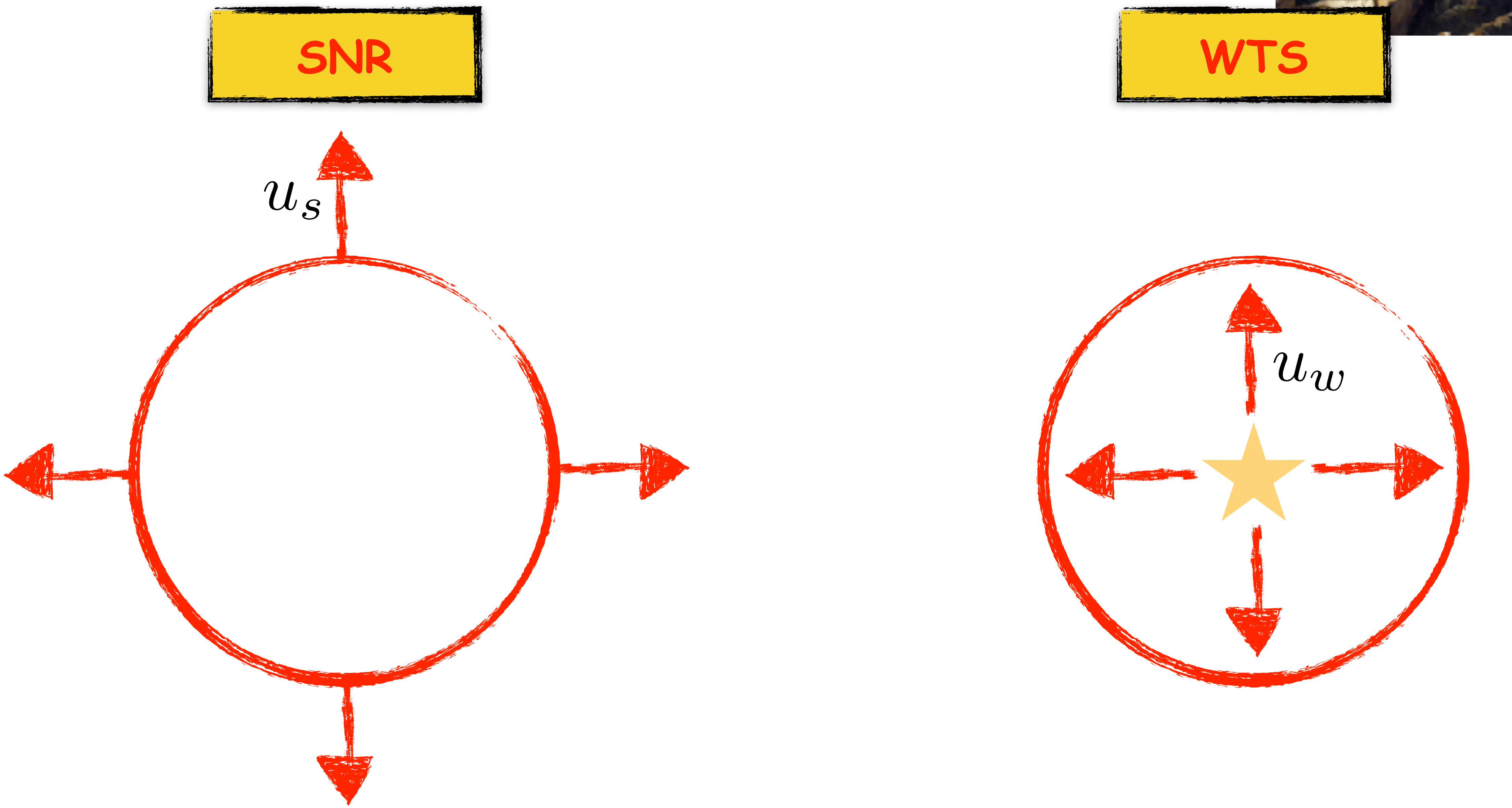
[3] Follow the energy
Is there space left
for other sources?

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983



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

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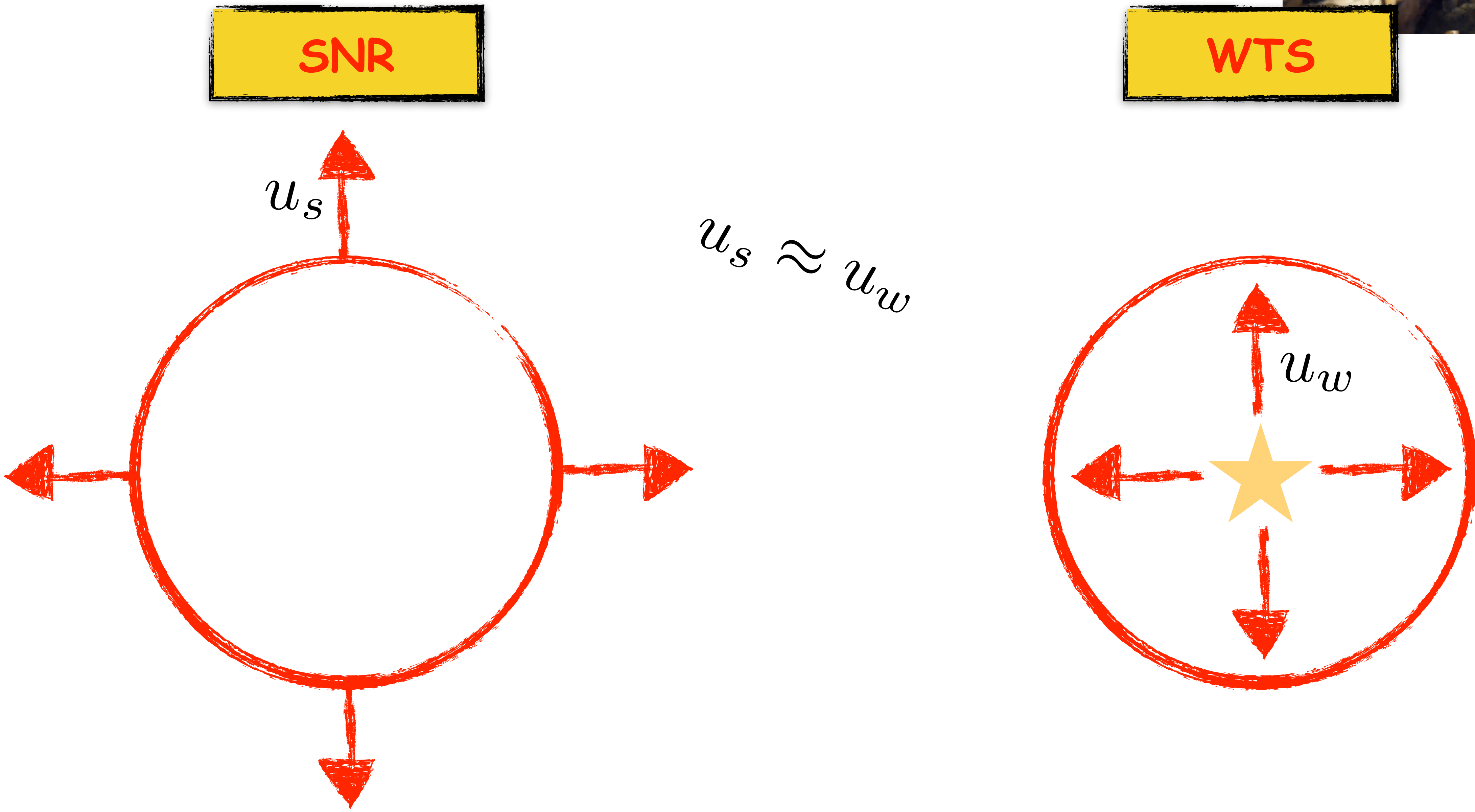

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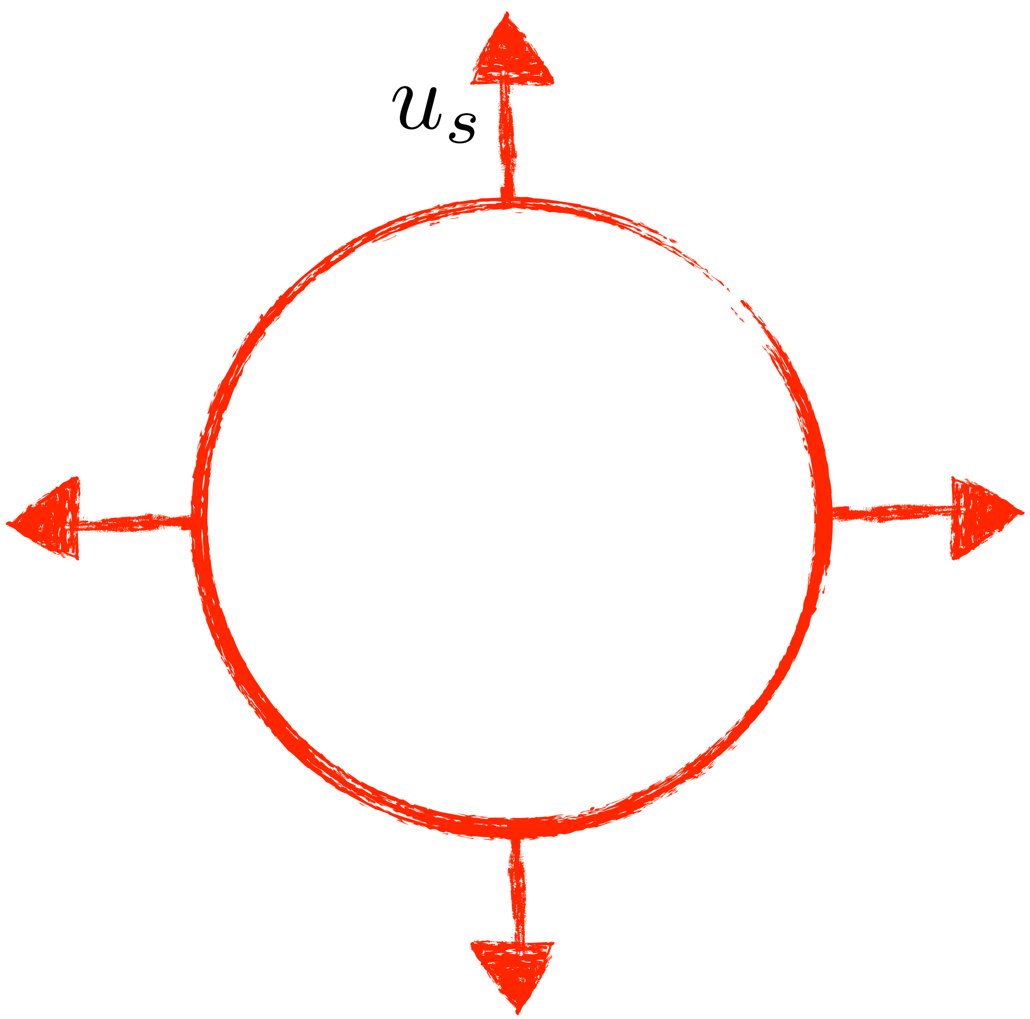
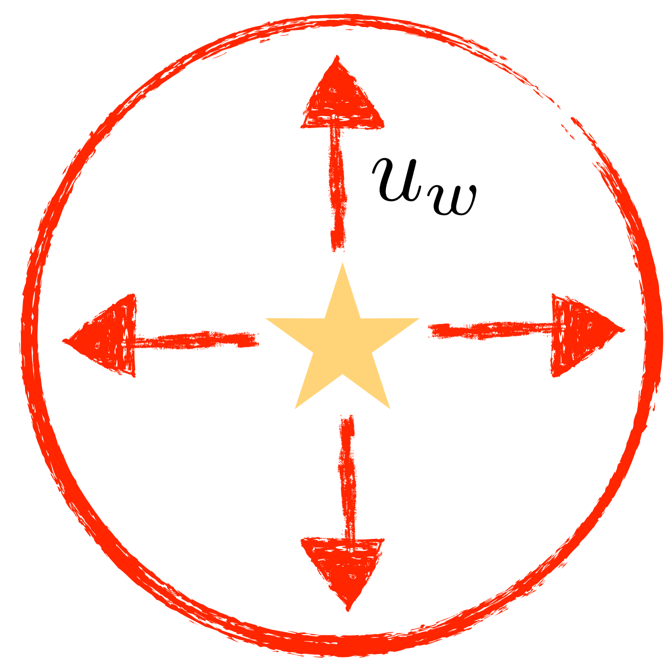


$u_s \approx u_w$

WTS



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

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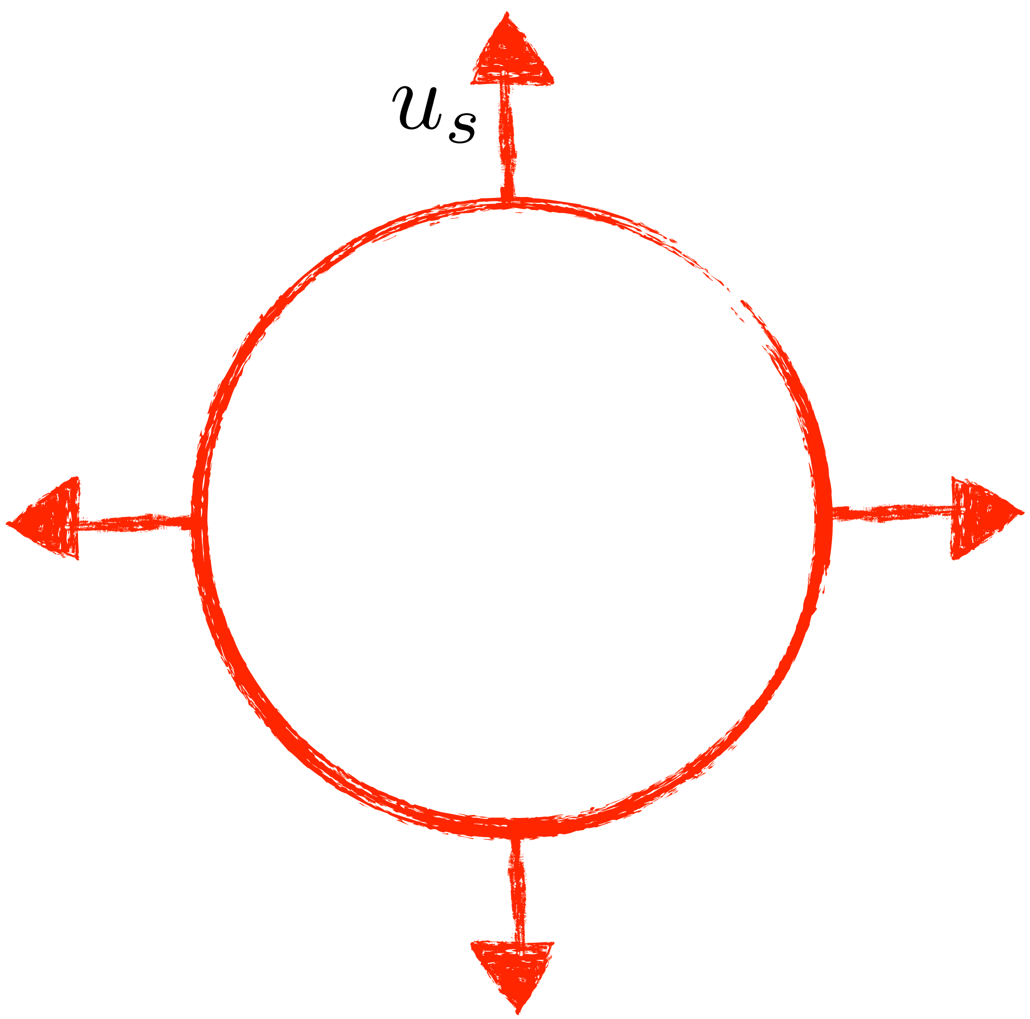

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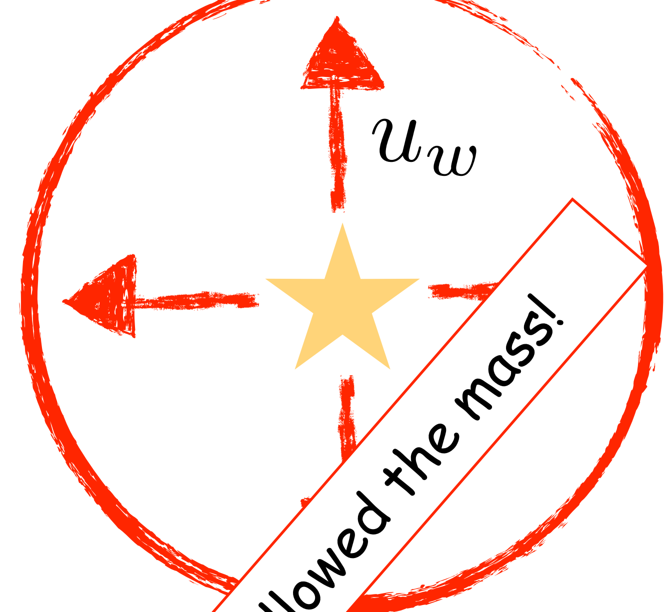


<— These guys followed the mass!

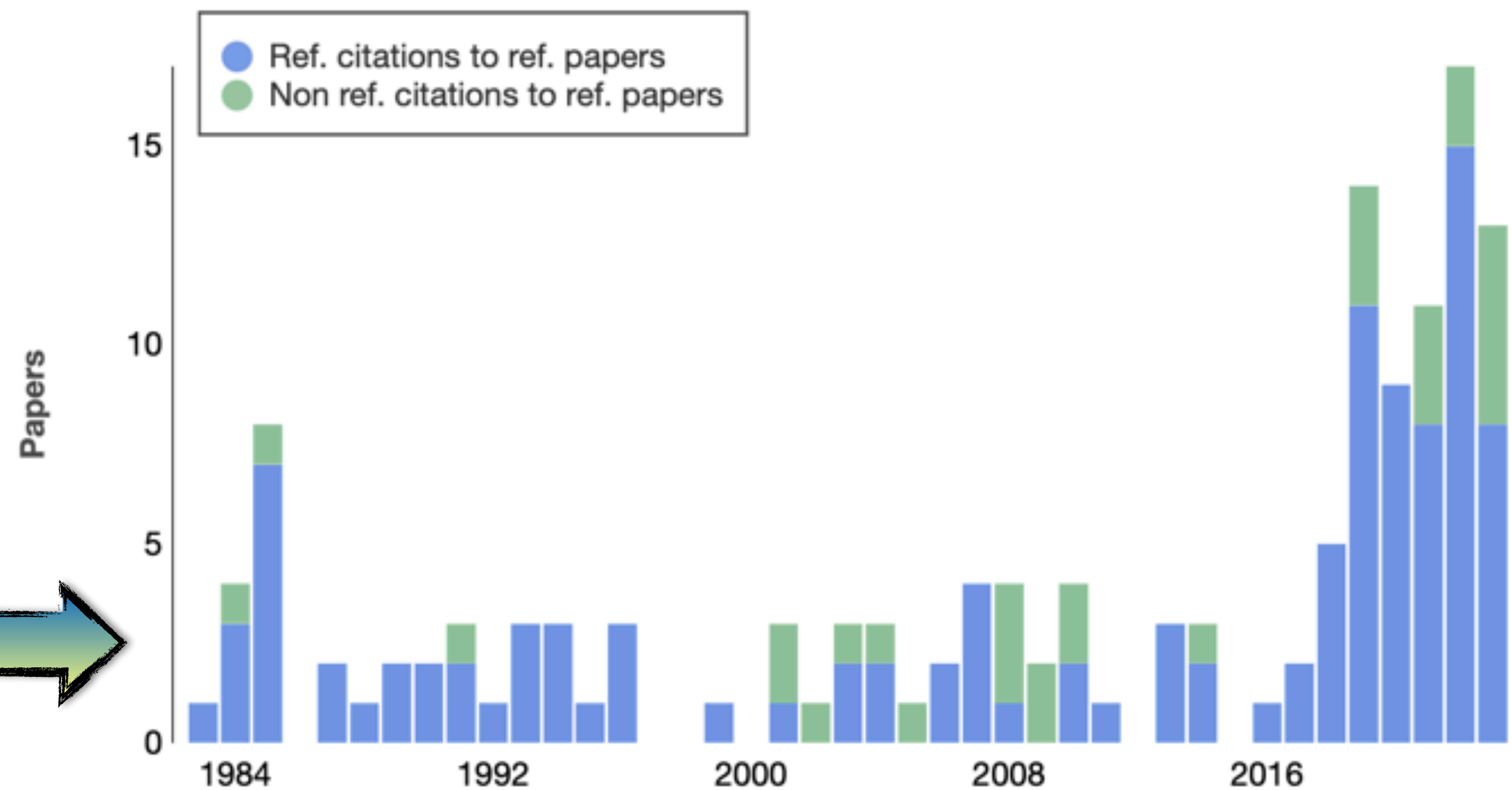
analogy with solar WTS (Parker, Jokipii...) ...SA (BOBALSKy...)

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

Then nobody cared for few decades…

CR physicists thinking about star clusters winds between 1983 and 2019

citation counts for Cesarsky & Montmerle review



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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momentum carried by stellar photons

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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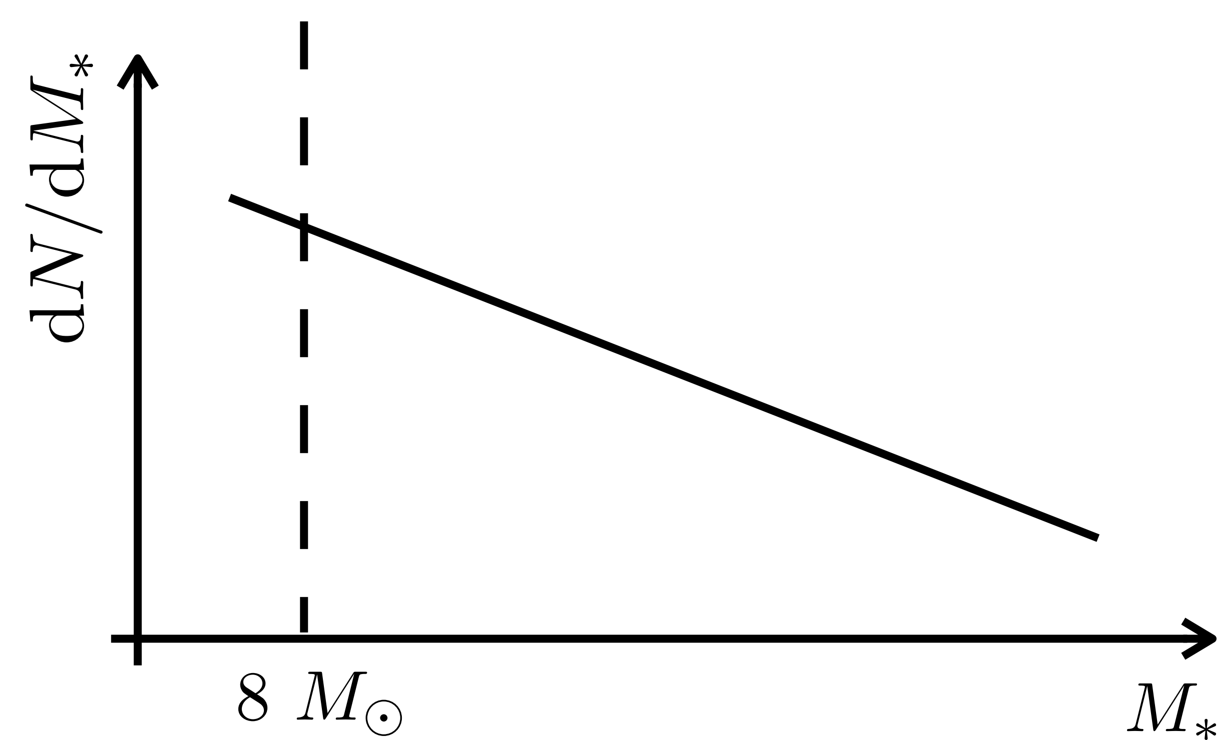

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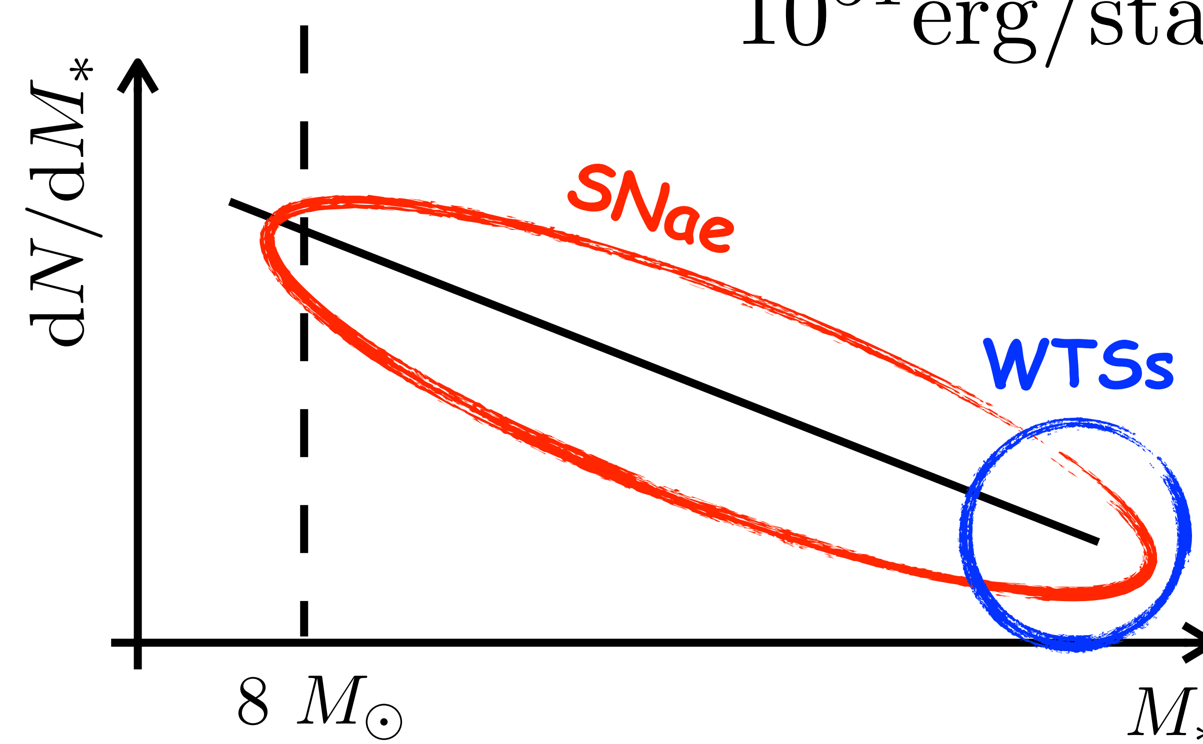

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momentum carried by the wind

momentum ca...
by stell...

total ...
... stars

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

$\approx M_*^3$

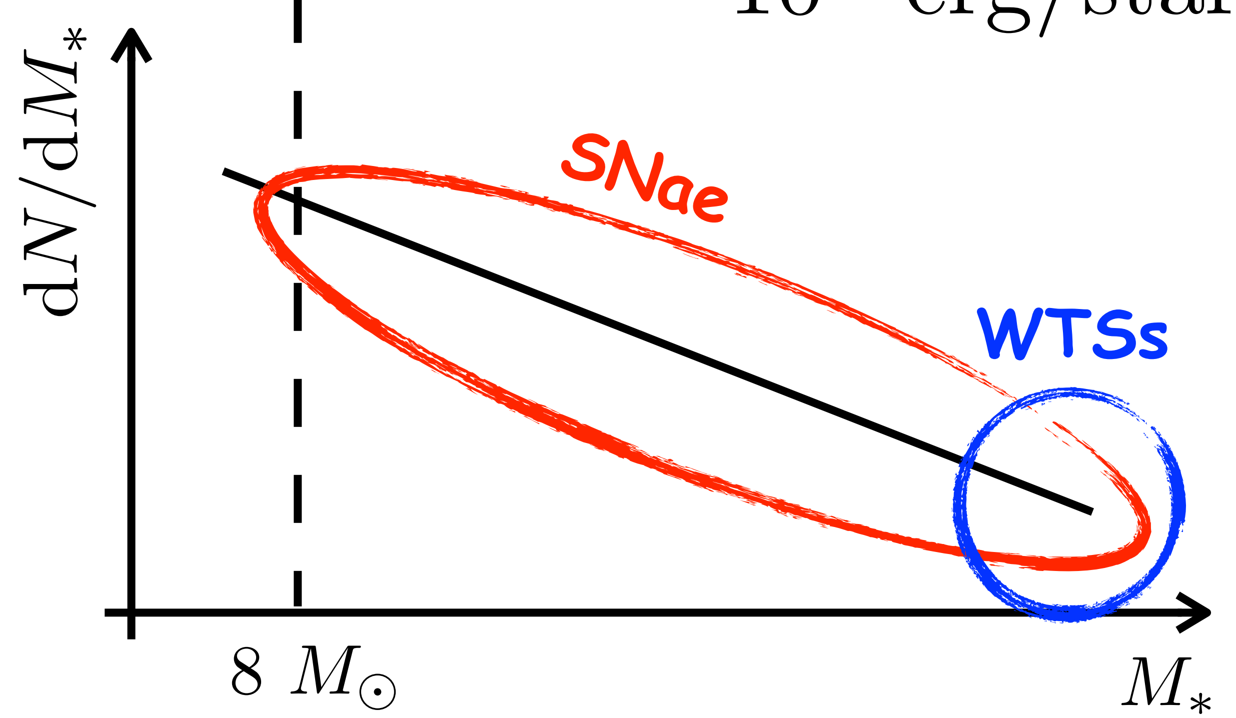
...ssive stars:

$$\int dt\ P_w \approx 10^{51}\mathrm{erg} \sim \mathrm{E_{SN}}$$

—> supernovae win by about a factor of several (caveat: failed SNae?)

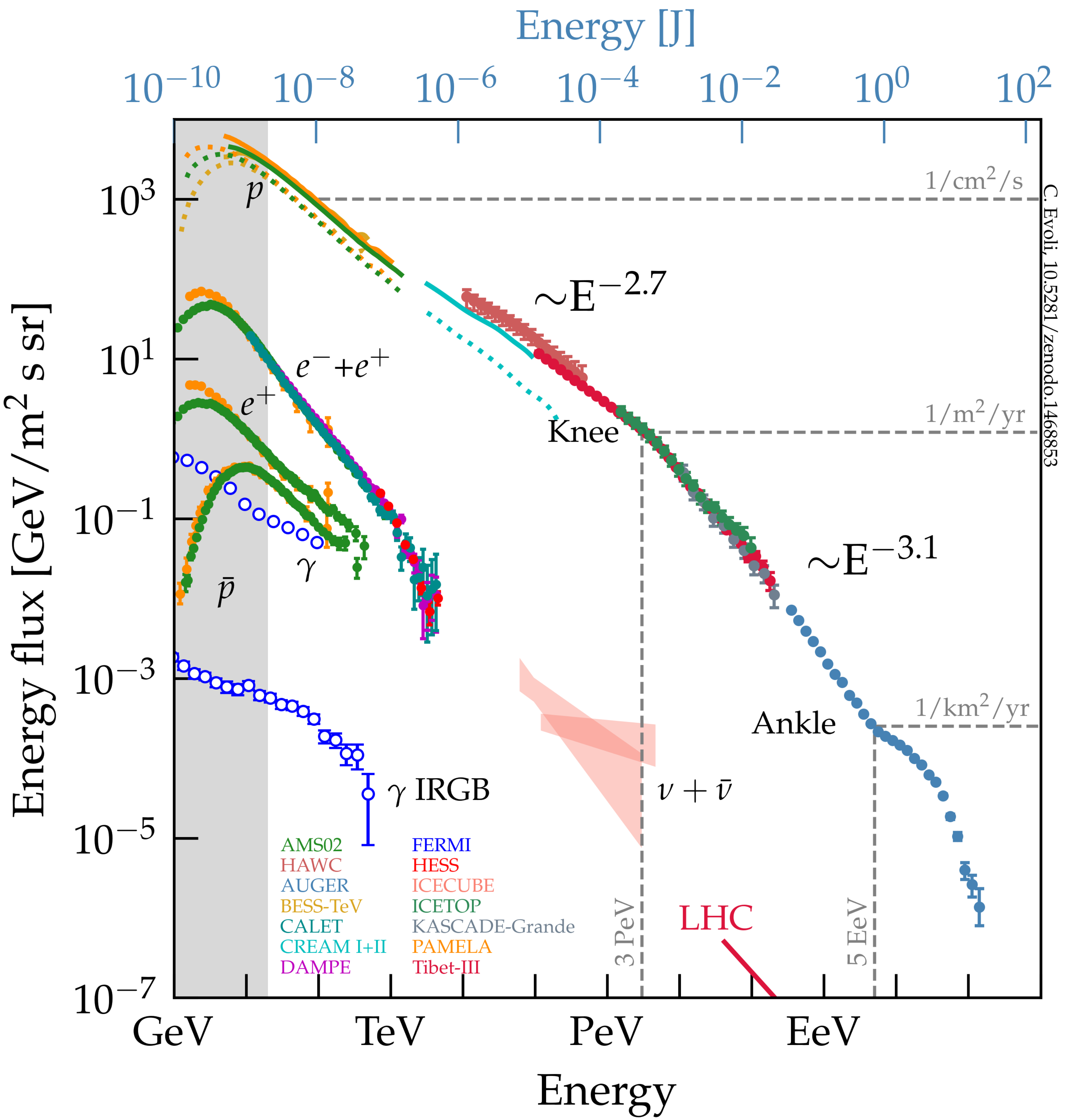
—> WTS could explain a fraction of CRs only

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



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

Energy, energy, energy…



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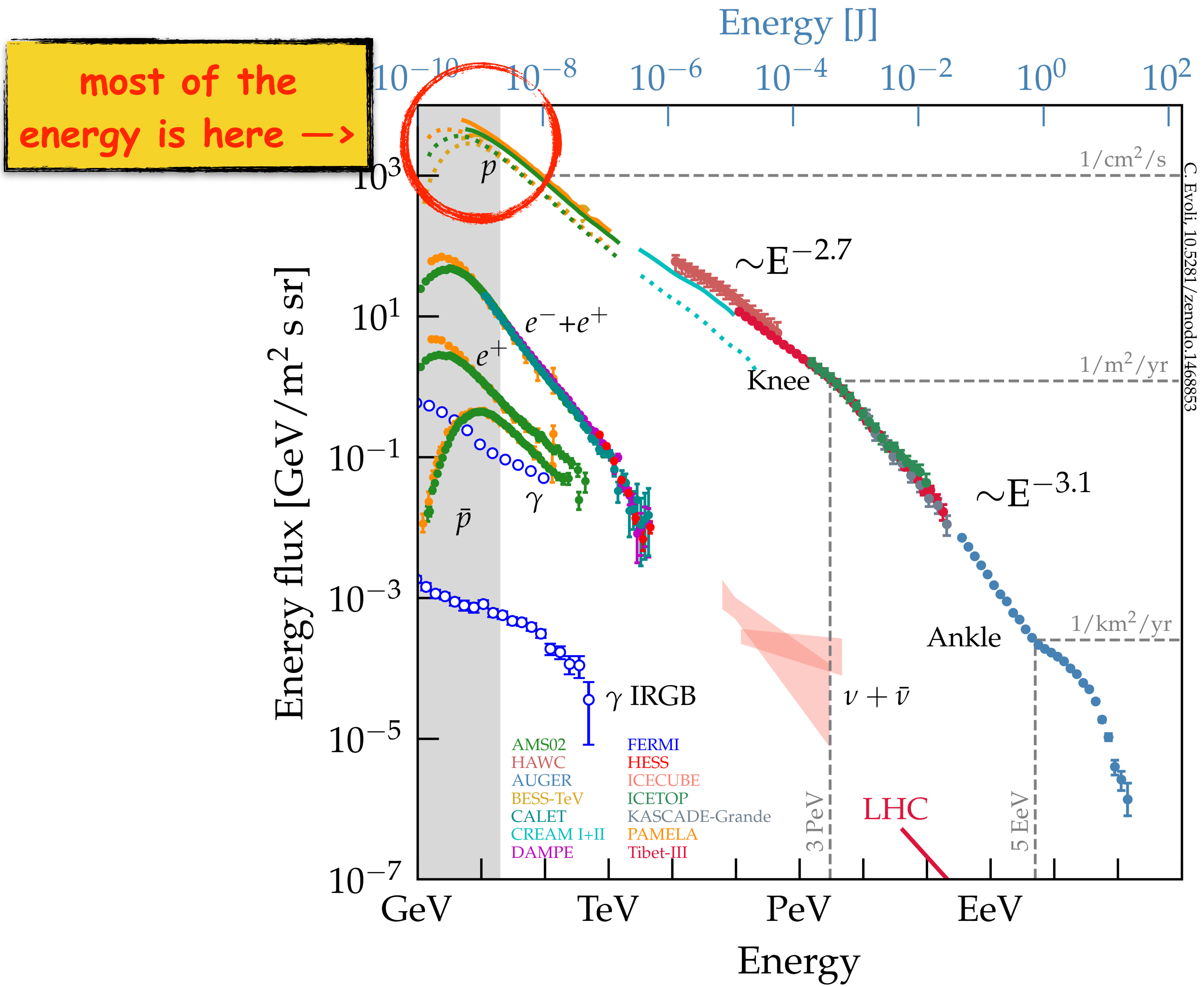

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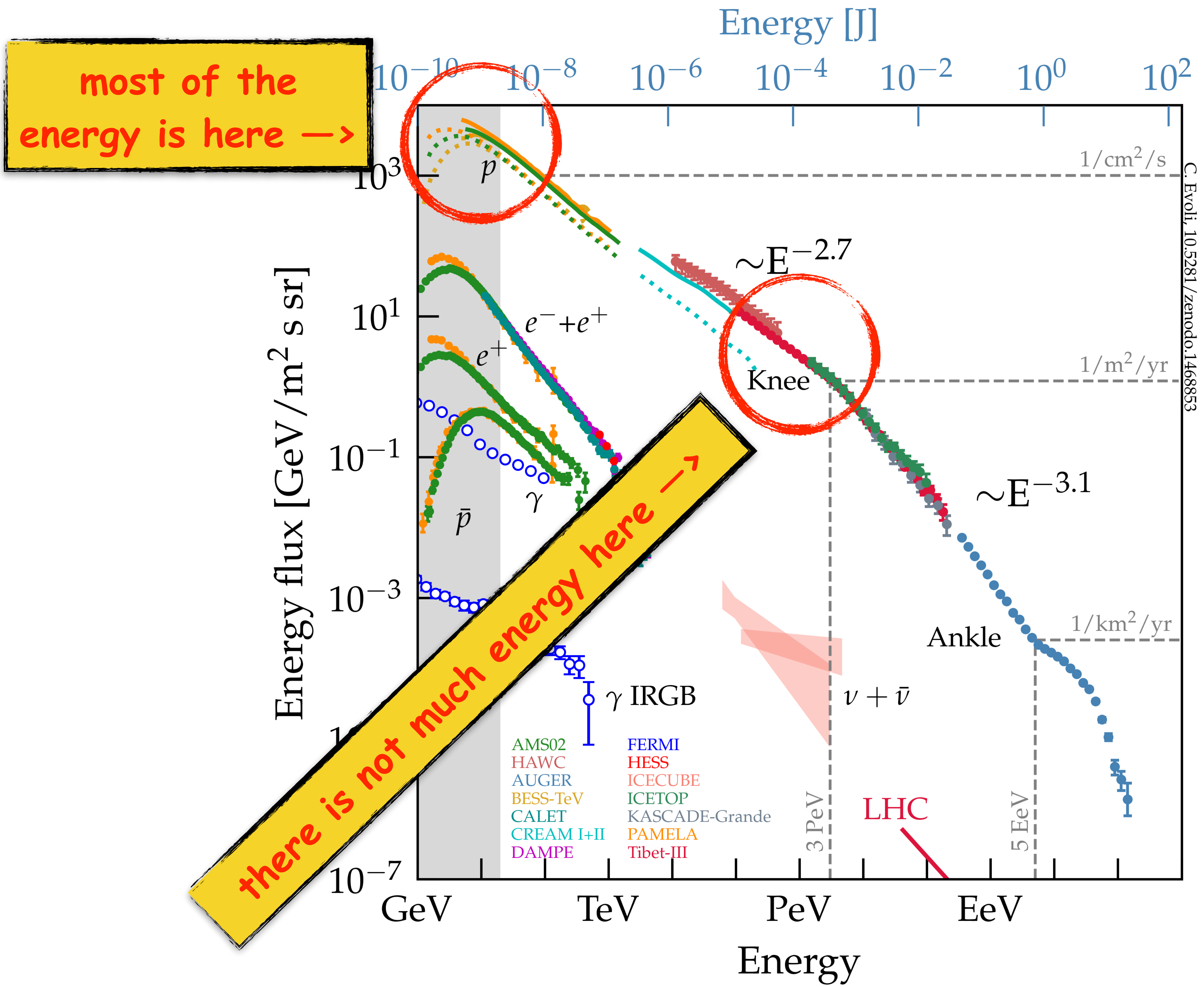

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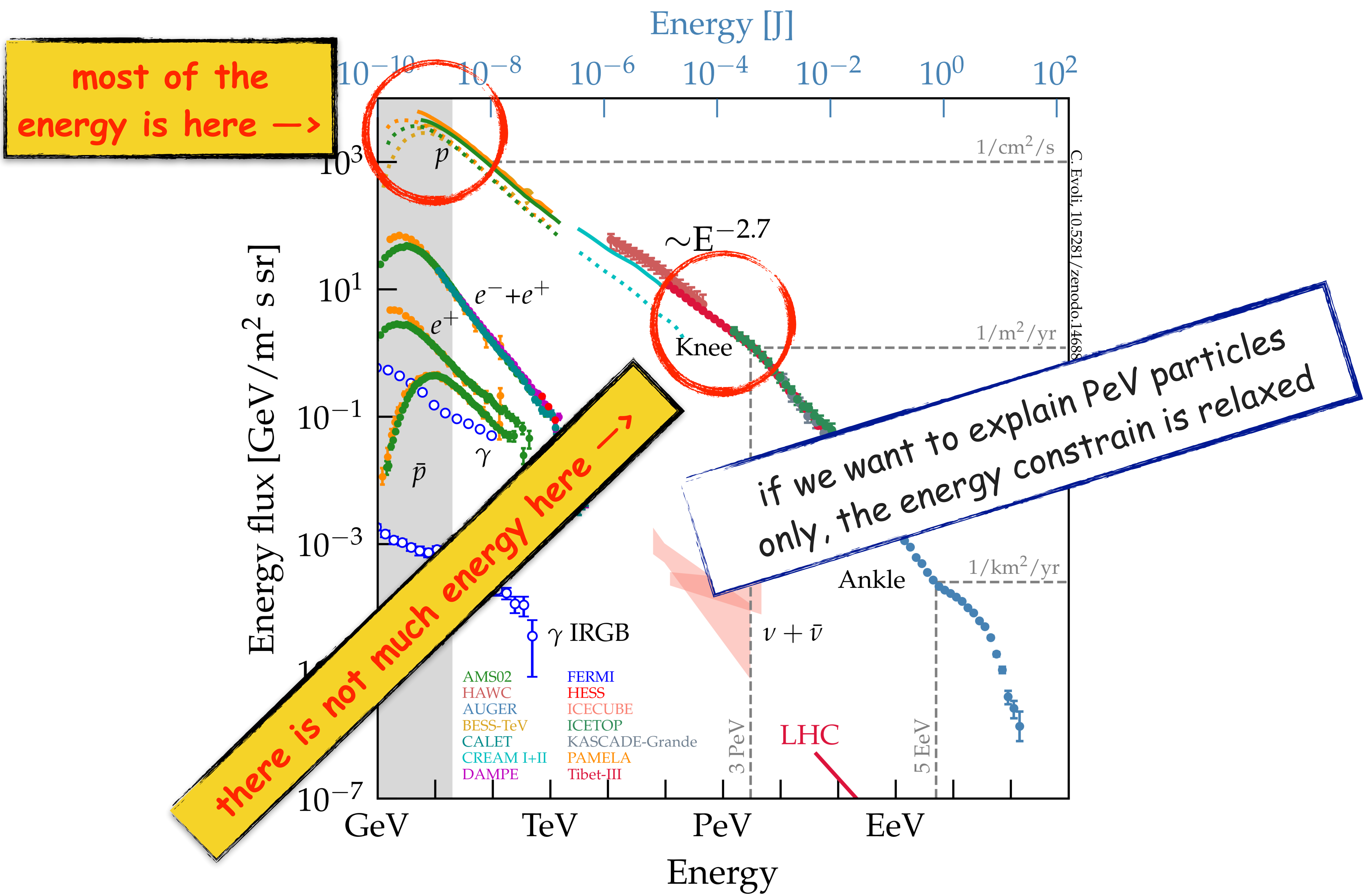

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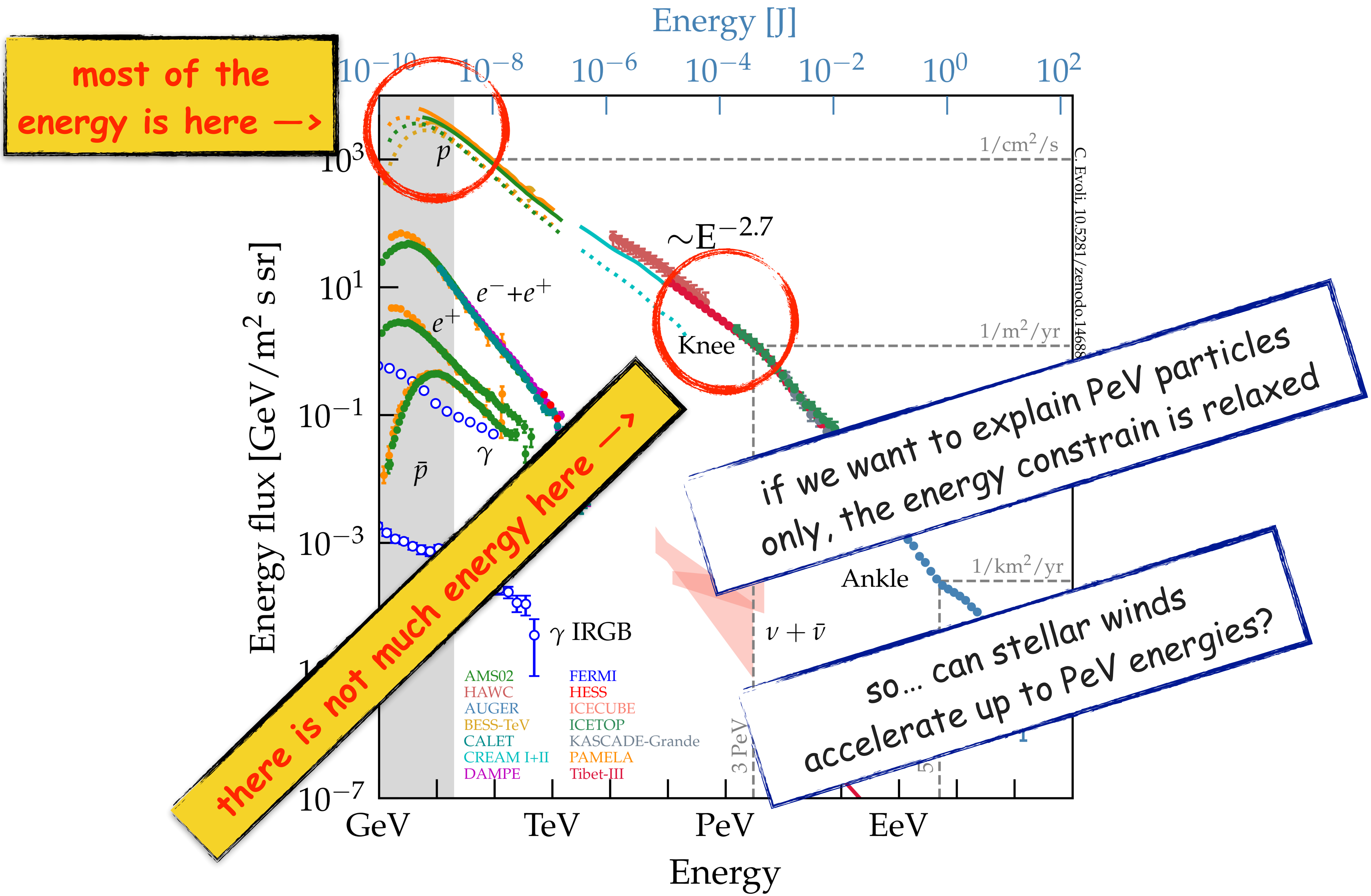
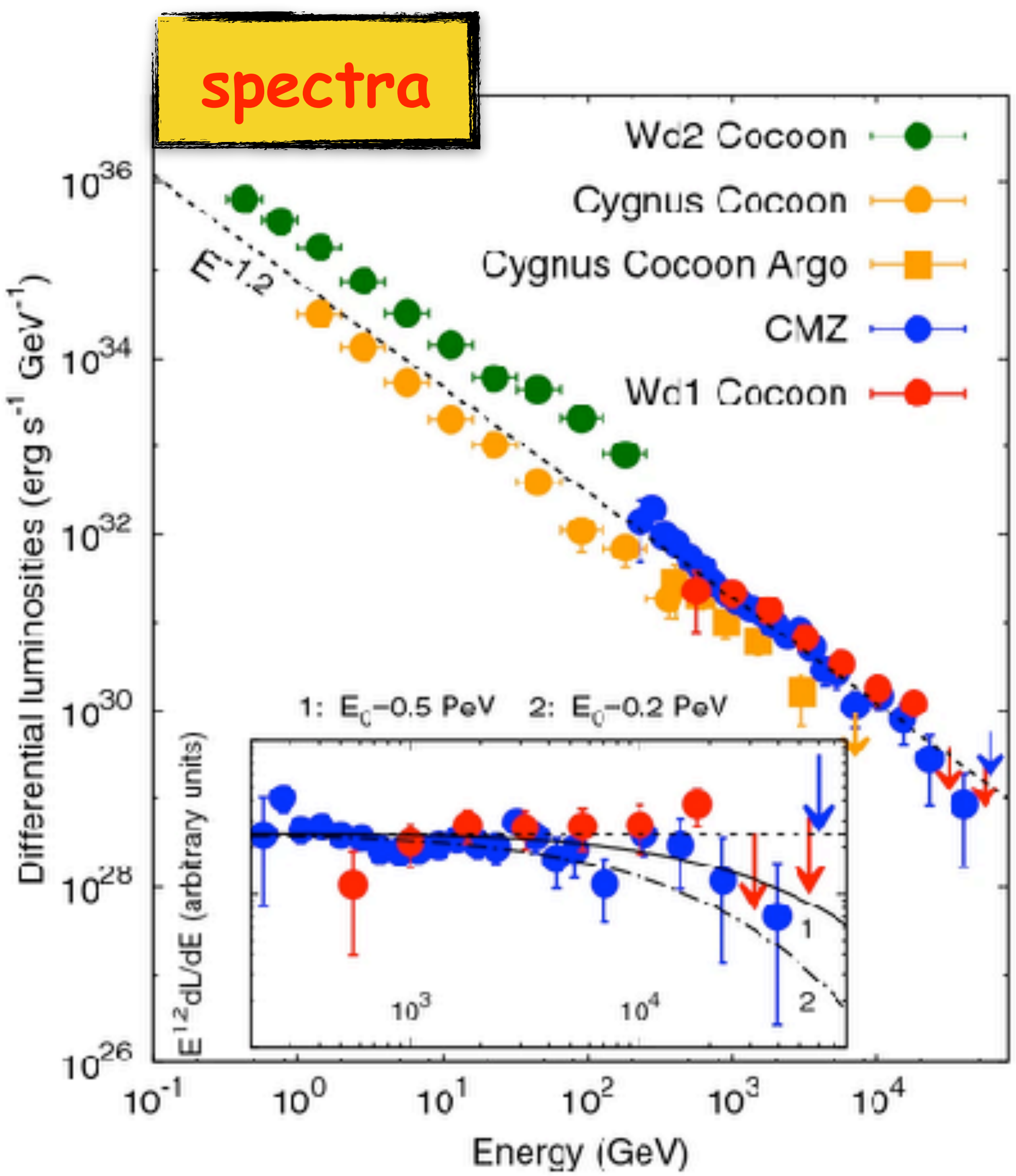
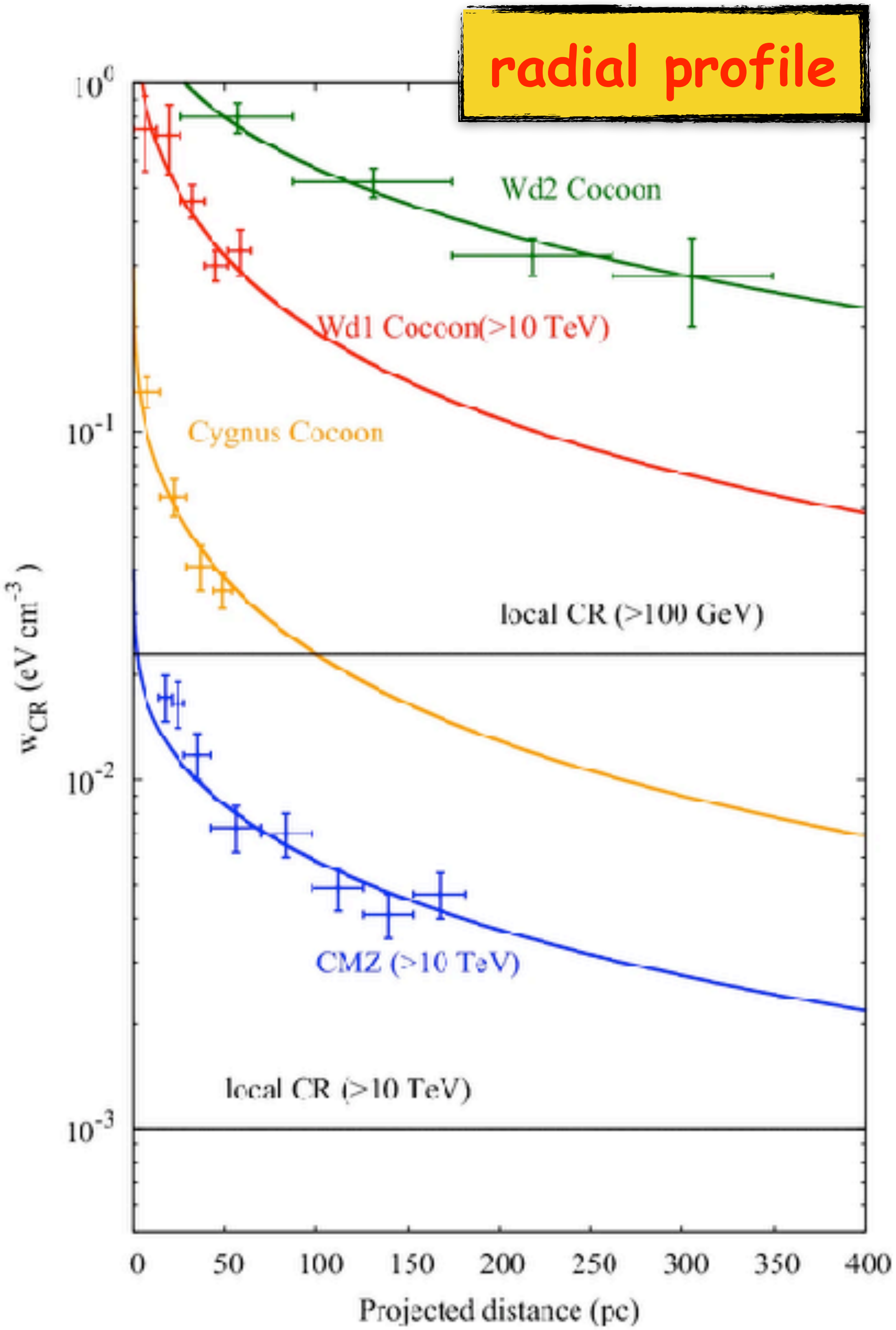


Stars or star clusters? Gamma rays…

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





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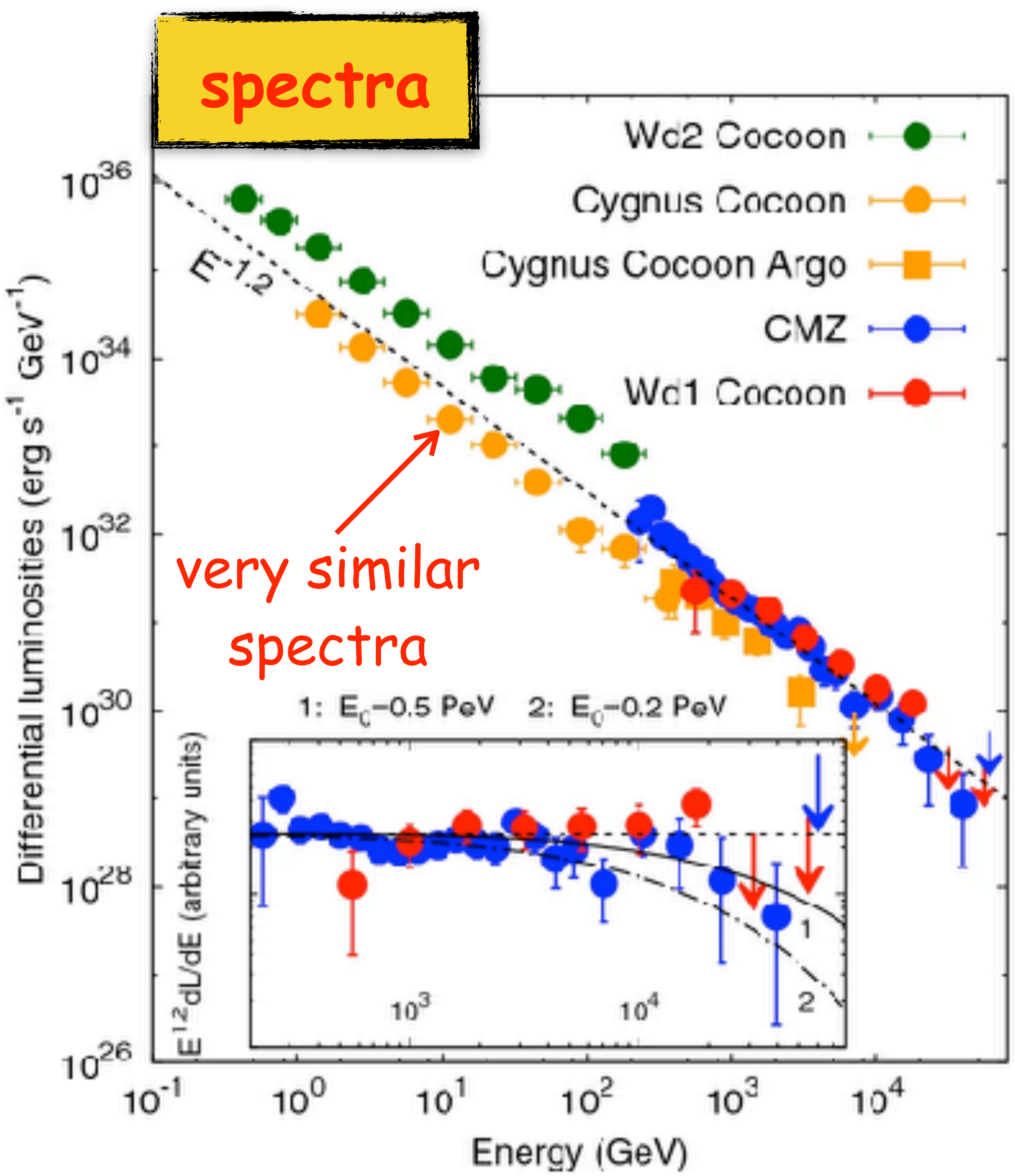

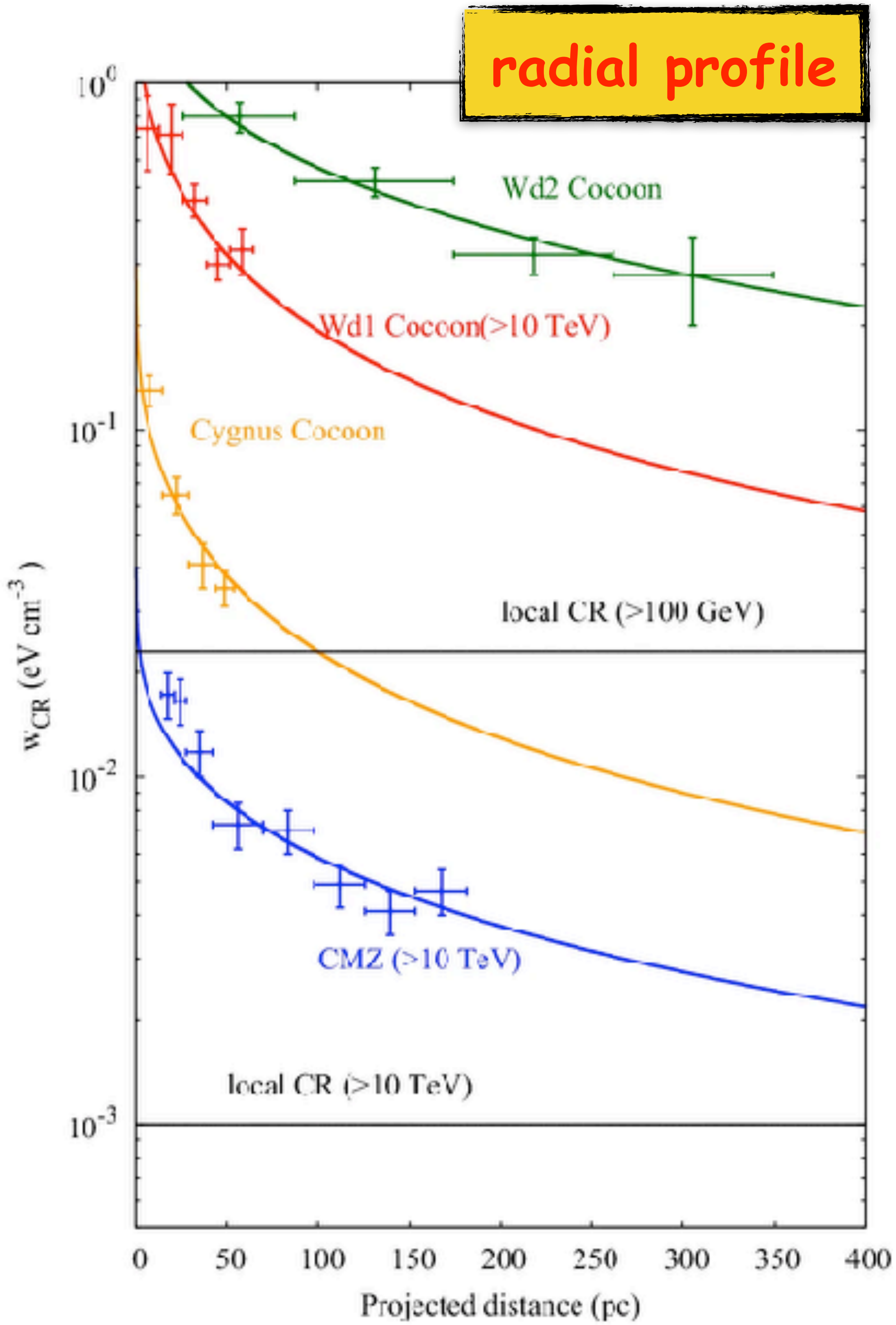

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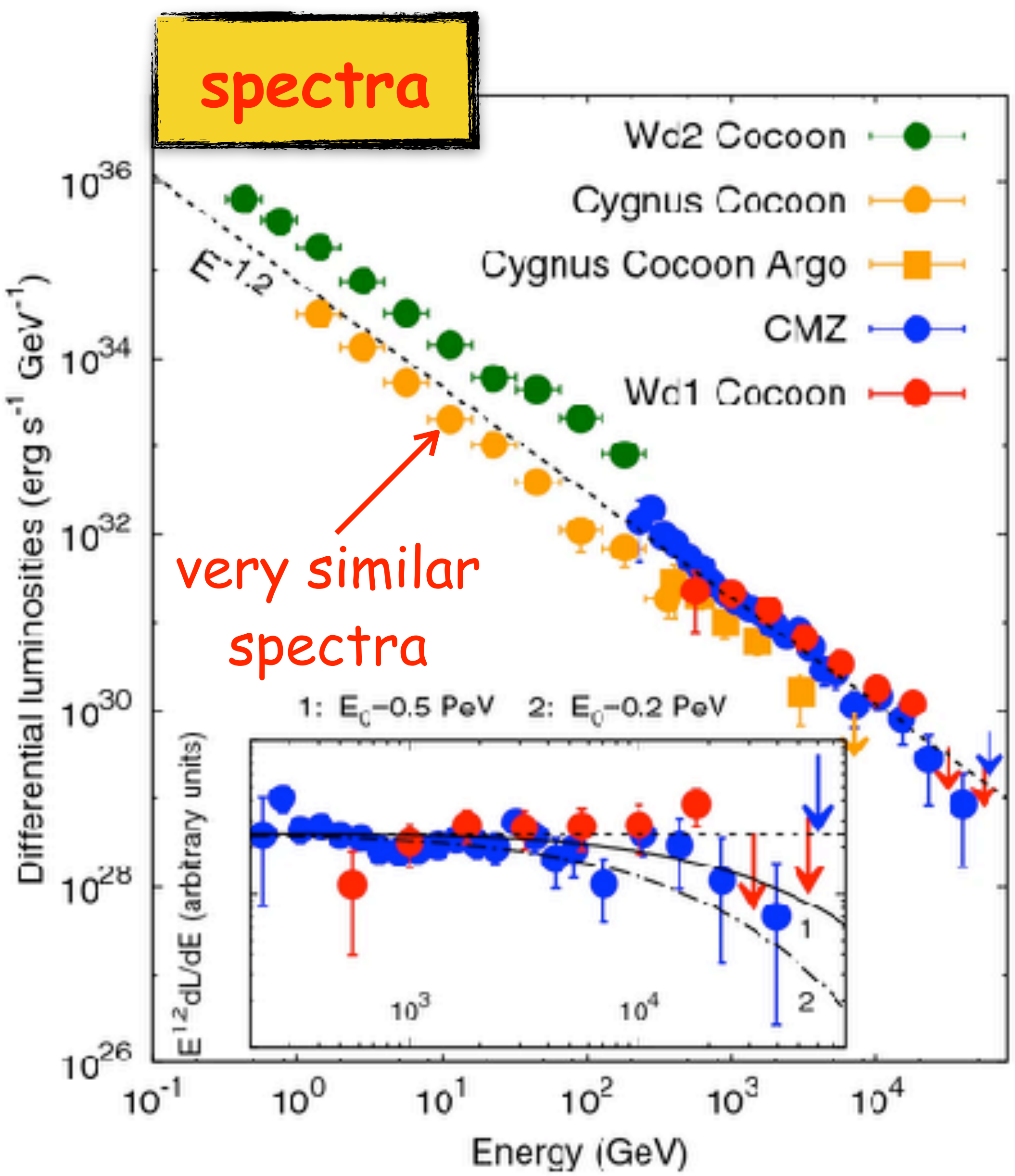

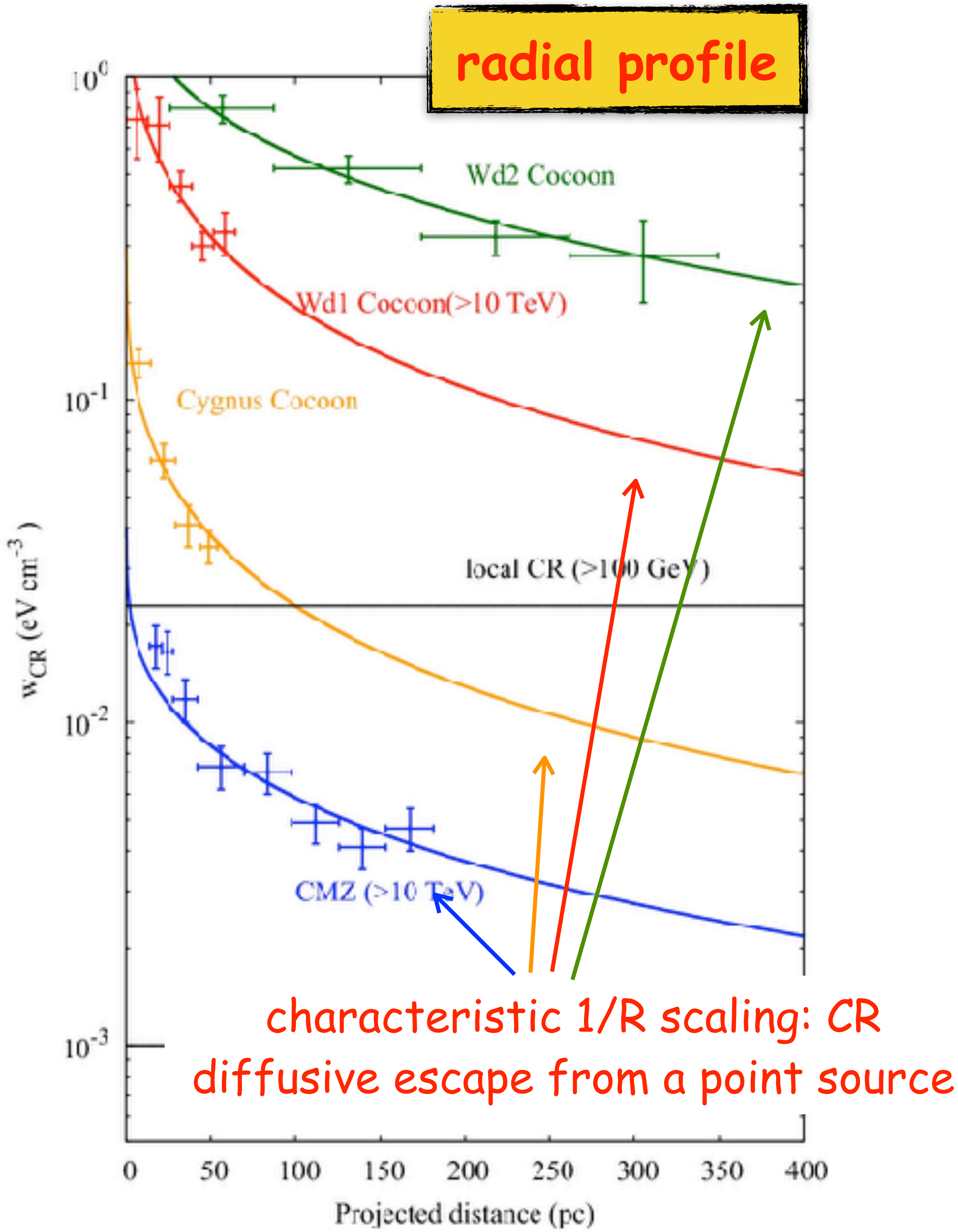

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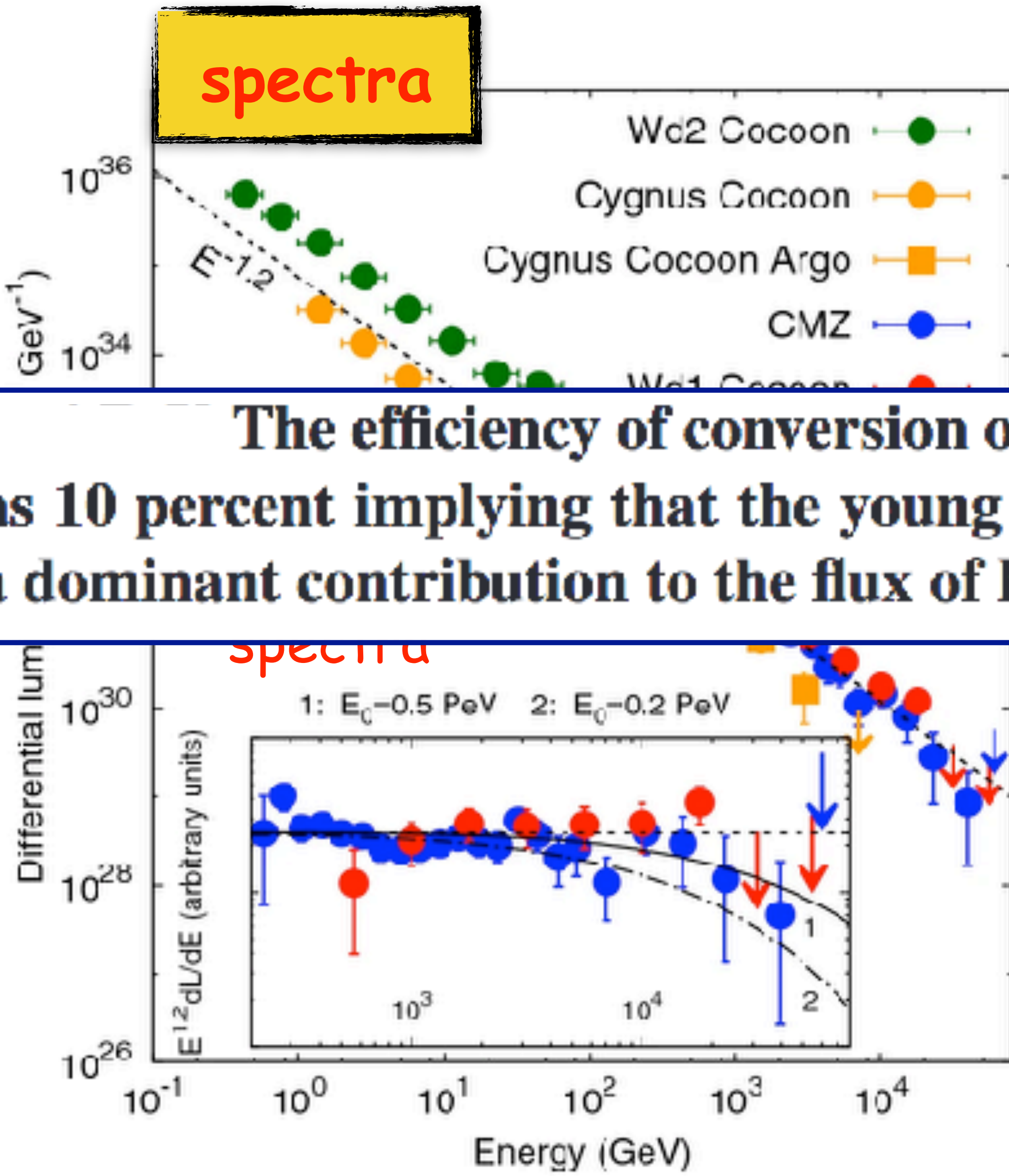

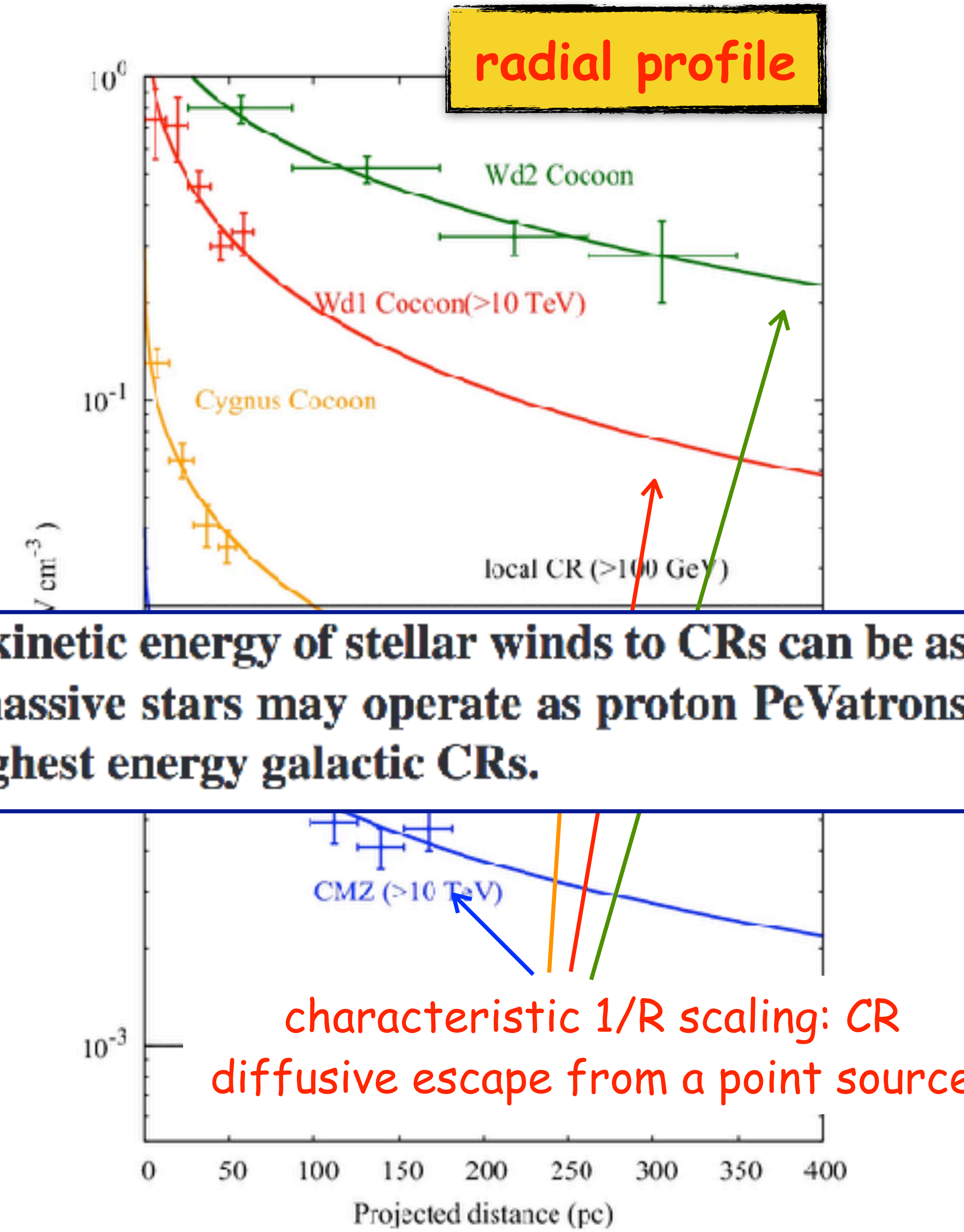

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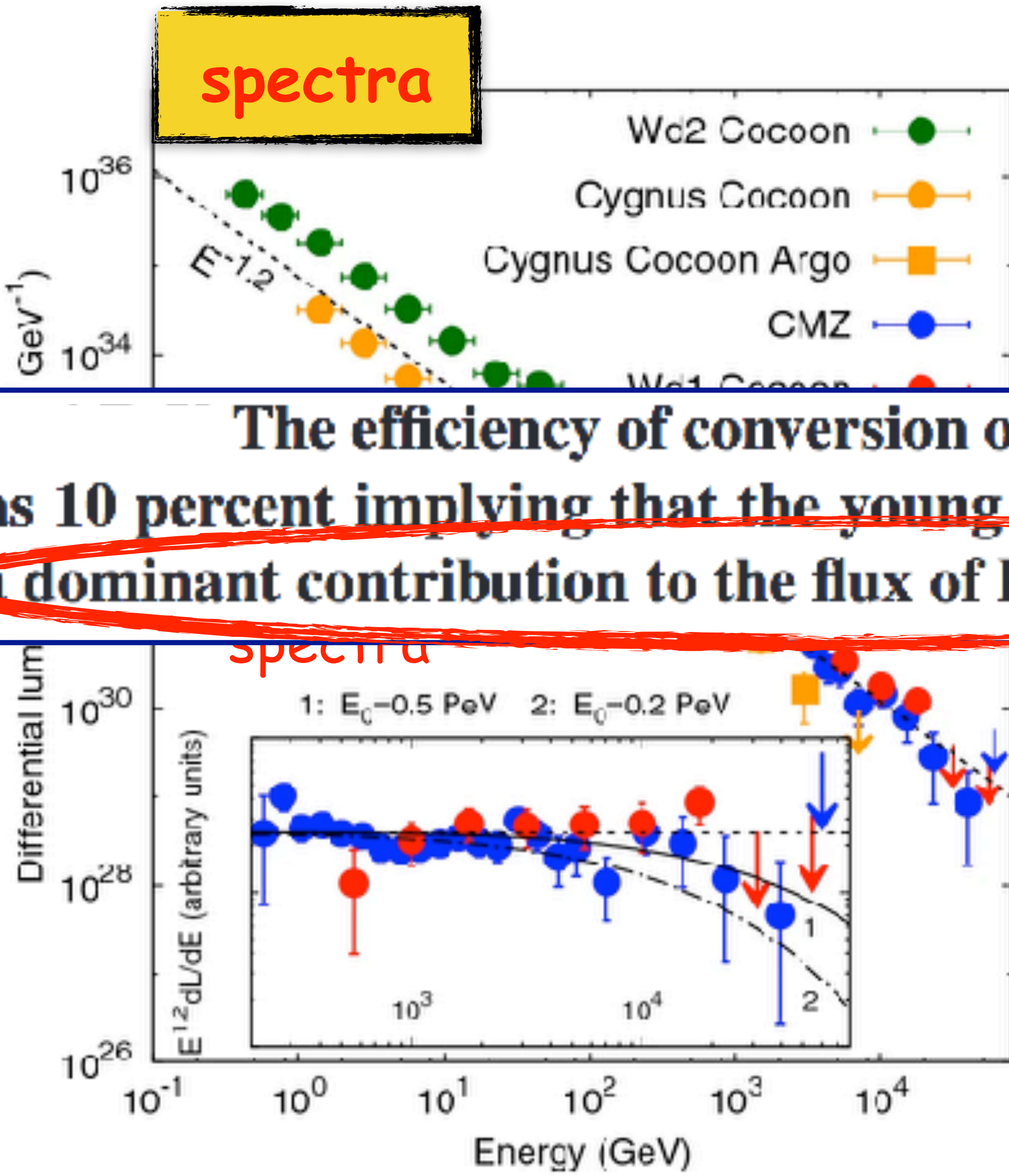

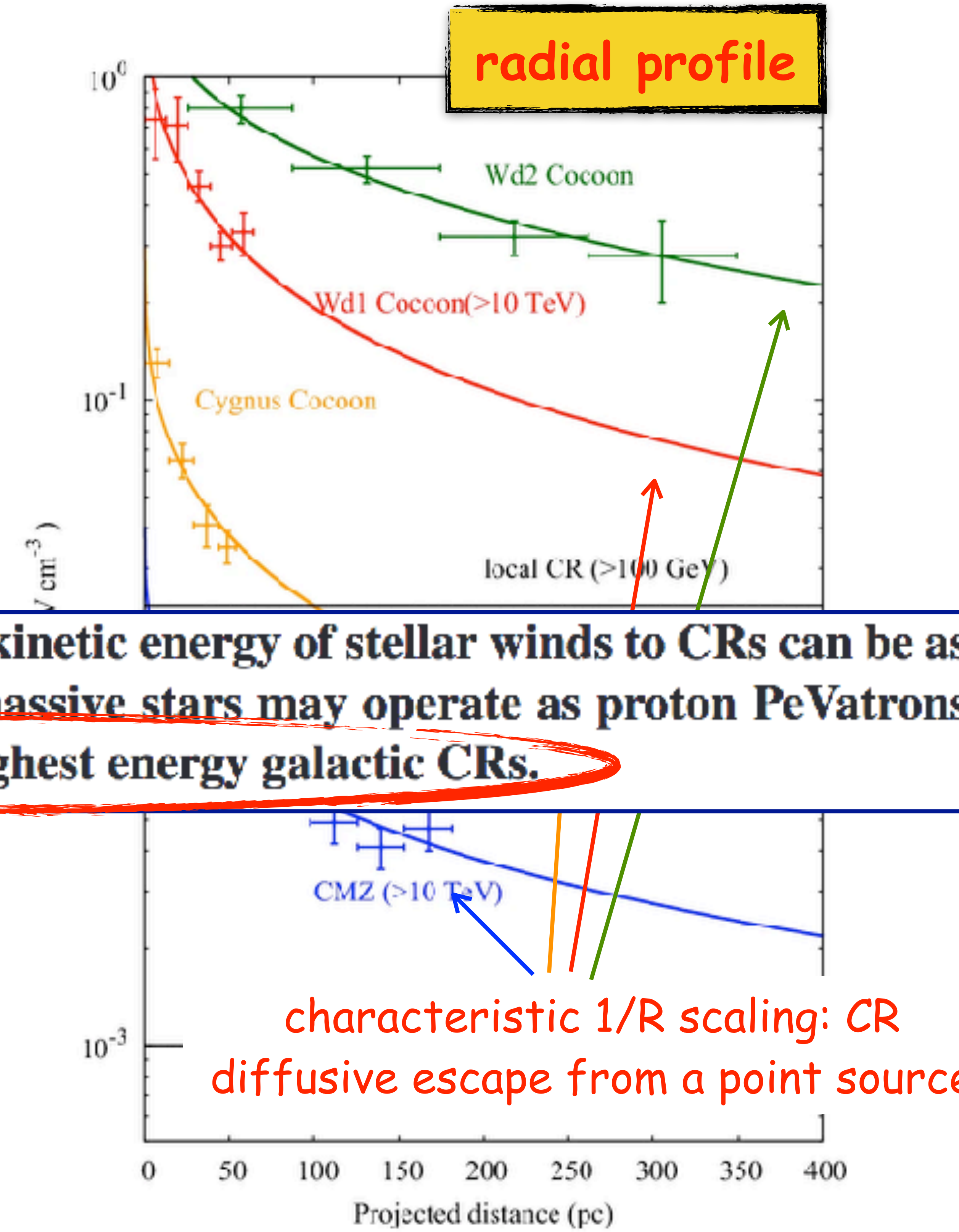

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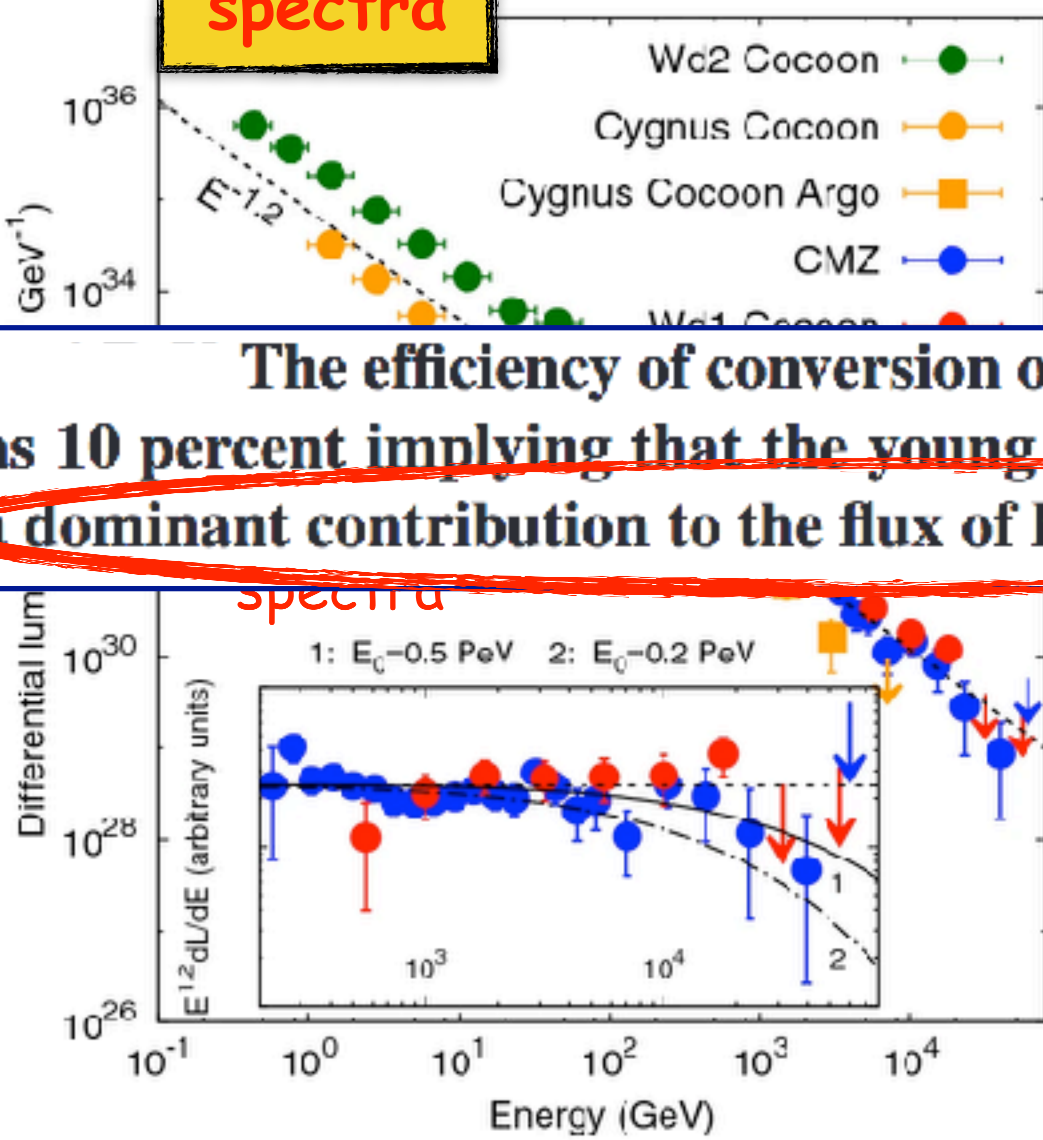
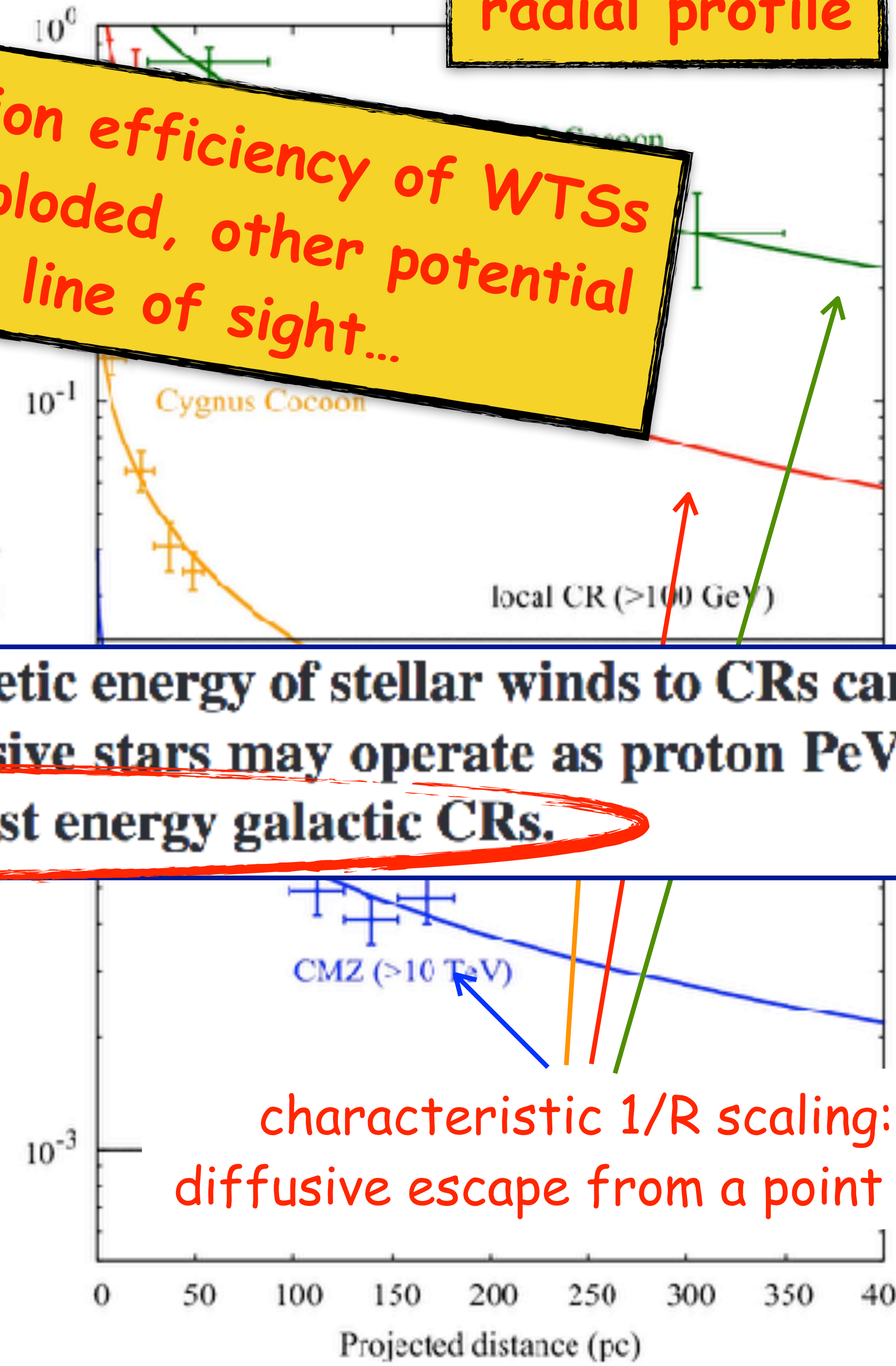
cannot constrain acceleration efficiency of WTSs —> some SNae already exploded, other potential CR source along the line of sight…

spectra



radial profile



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

Charged particles and electromagnetic fields

cosmic rays are charged particles —> they are affected by electromagnetic fields

$$\vec{E}(\vec{r},t) \qquad\qquad \vec{B}(\vec{r},t)$$

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A particle of charge q moving at a velocity u fill experience a force:

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \frac{\vec{u}}{c} \times \vec{B}\right)$$

relativistic momentum $\vec{p} = \gamma m \vec{u}$

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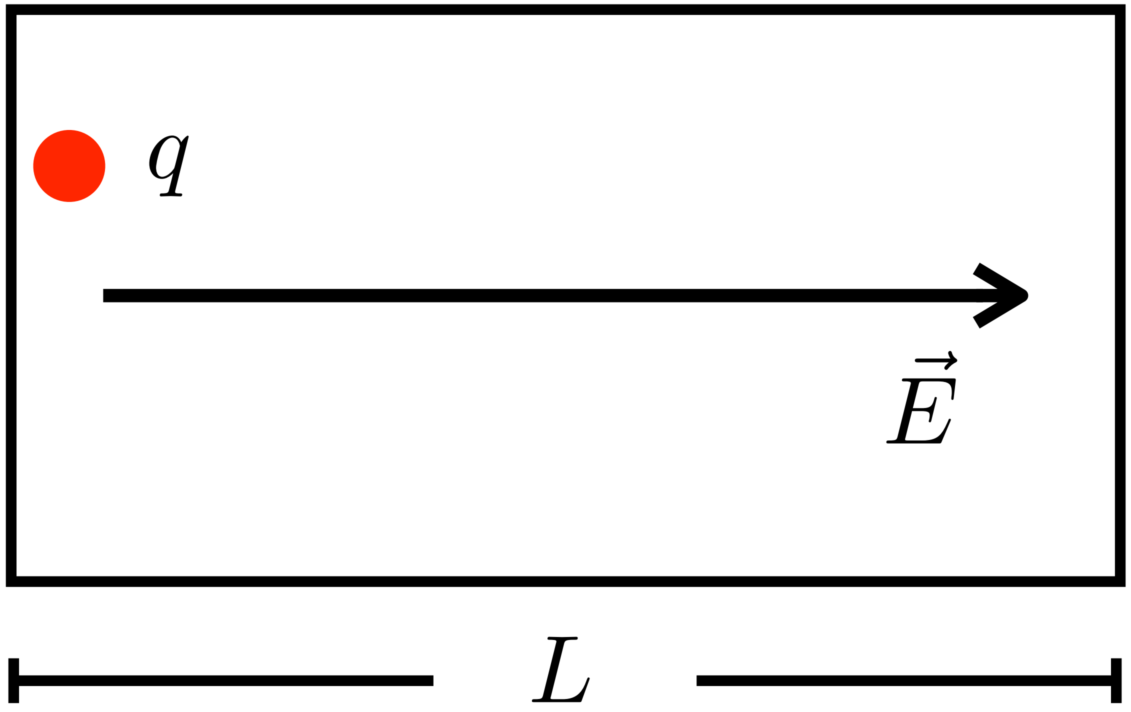
Lorentz force
$\perp$ to velocity —>
doesn't change
the particle energy!

Maximum energy

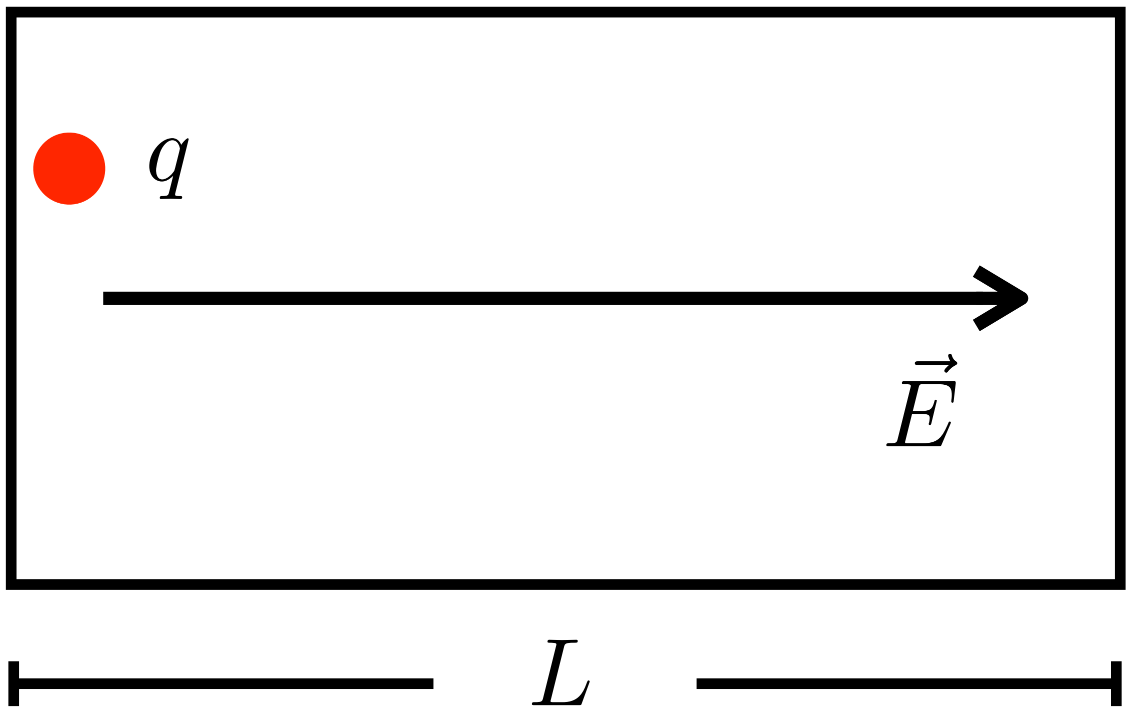
this is an accelerator



$$L \gg \frac{mc^2}{qE}$$

Maximum energy

this is an accelerator



$$L \gg \frac{mc^2}{qE}$$

$$E_t^{max} = qEtc = qEL$$

large charge

strong E field

large accelerator

Can we keep a static and uniform electric field in an astrophysical plasma?

unfortunately, that's quite difficult…

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unfortunately, that's quite difficult…

An excess of electrical charge is needed to maintain a static electric field. However we should remember…

> "…a basic property of plasma, its tendency towards electrical neutrality. If over a large volume the number of electrons per cubic centimeter deviates appreciably from the corresponding number of positive ions, the electrostatic forces resulting yield a potential energy per particle that is enormously greater than the mean thermal energy. Unless very special mechanisms are involved to support such large potentials, the charged particles will rapidly move in such a way as to reduce these potential difference, i.e., to restore electrical neutrality."

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So, the answer is no…

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So, the answer is no...

...but there is still maybe some hope?

Way-out: time varying B

We DO need electric fields to accelerate particles!

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Maxwell equations

$$\nabla \vec{E} = 4\pi\varrho$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

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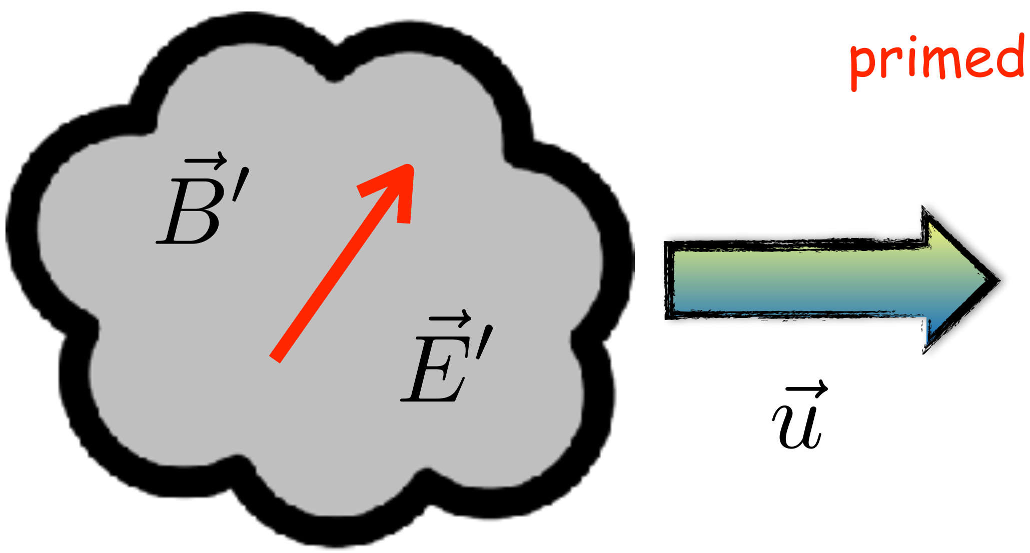
A time varying magnetic field acts as a source of electric field!

An equivalent way: change rest frame

Consider a magnetised cloud of plasma moving at a (non relativistic) velocity u



primed quantities —> cloud frame

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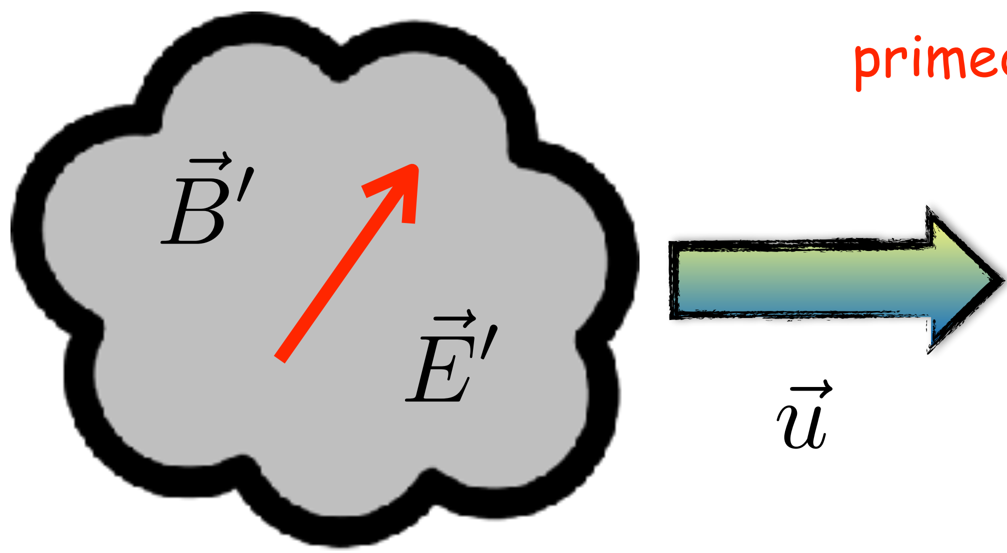

Lorentz transformation

$$\vec{E}' = \vec{E} + \frac{\vec{u}}{c} \times \vec{B}$$

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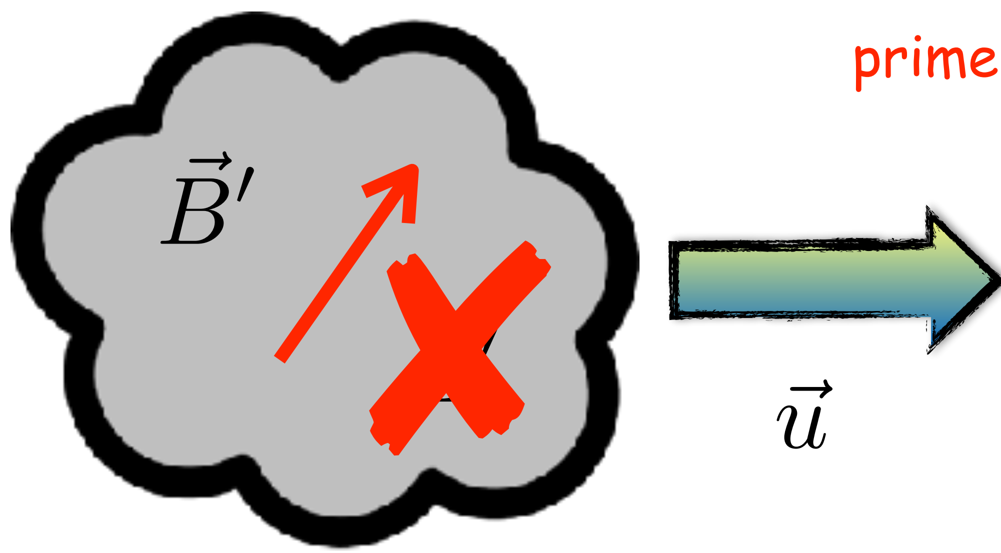

Lorentz transformation

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$$0 = \vec{E} + \frac{\vec{u}}{c} \times \vec{B} \longrightarrow \vec{E} = -\frac{\vec{u}}{c} \times \vec{B}$$

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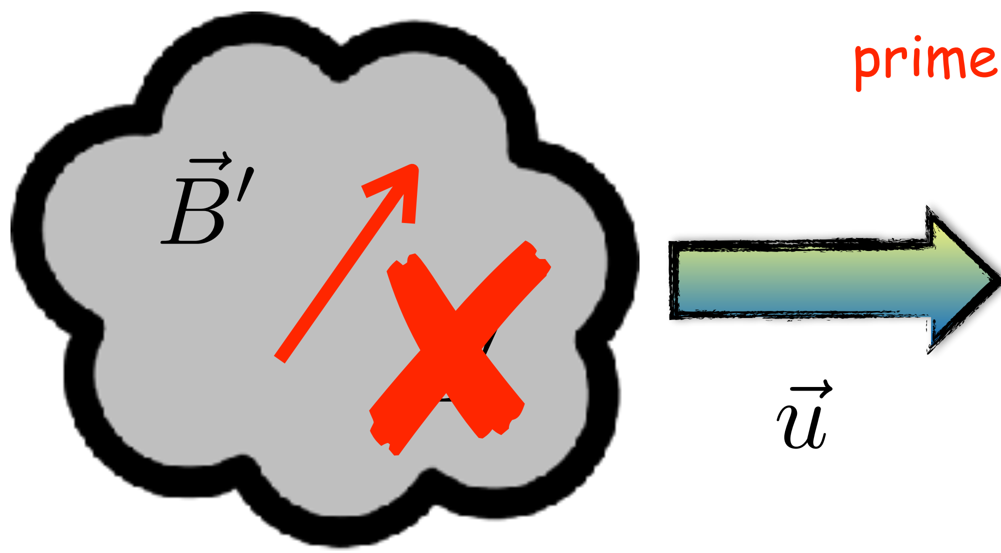

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$$0 = \vec{E} + \frac{\vec{u}}{c} \times \vec{B} \longrightarrow \boxed{\vec{E} = -\frac{\vec{u}}{c} \times \vec{B}}$$

an observer in the lab frame sees an electric field!

Order of magnitude estimates of the induced electric field

time-varying B-field

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

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characteristic length

$$\nabla \times \quad \rightarrow \quad \frac{1}{L}$$

$$\frac{\partial}{\partial t} \quad \rightarrow \quad \frac{1}{T}$$

characteristic time

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$$E \approx \frac{L}{T}\frac{B}{c} \approx \frac{U}{c}B$$

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Hillas criterion

Let's go back to the results obtained for the electrostatic accelerator

$$E_t^{max} = qEL$$

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$$\Rightarrow \quad E_t^{max} \approx \left(\frac{q}{c}\right) B \; U \; L$$

electric charge (q), velocity (U), B-field (B), size (L)

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$$E_t^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{U}{1000\ \mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right) \ \mathrm{eV}$$

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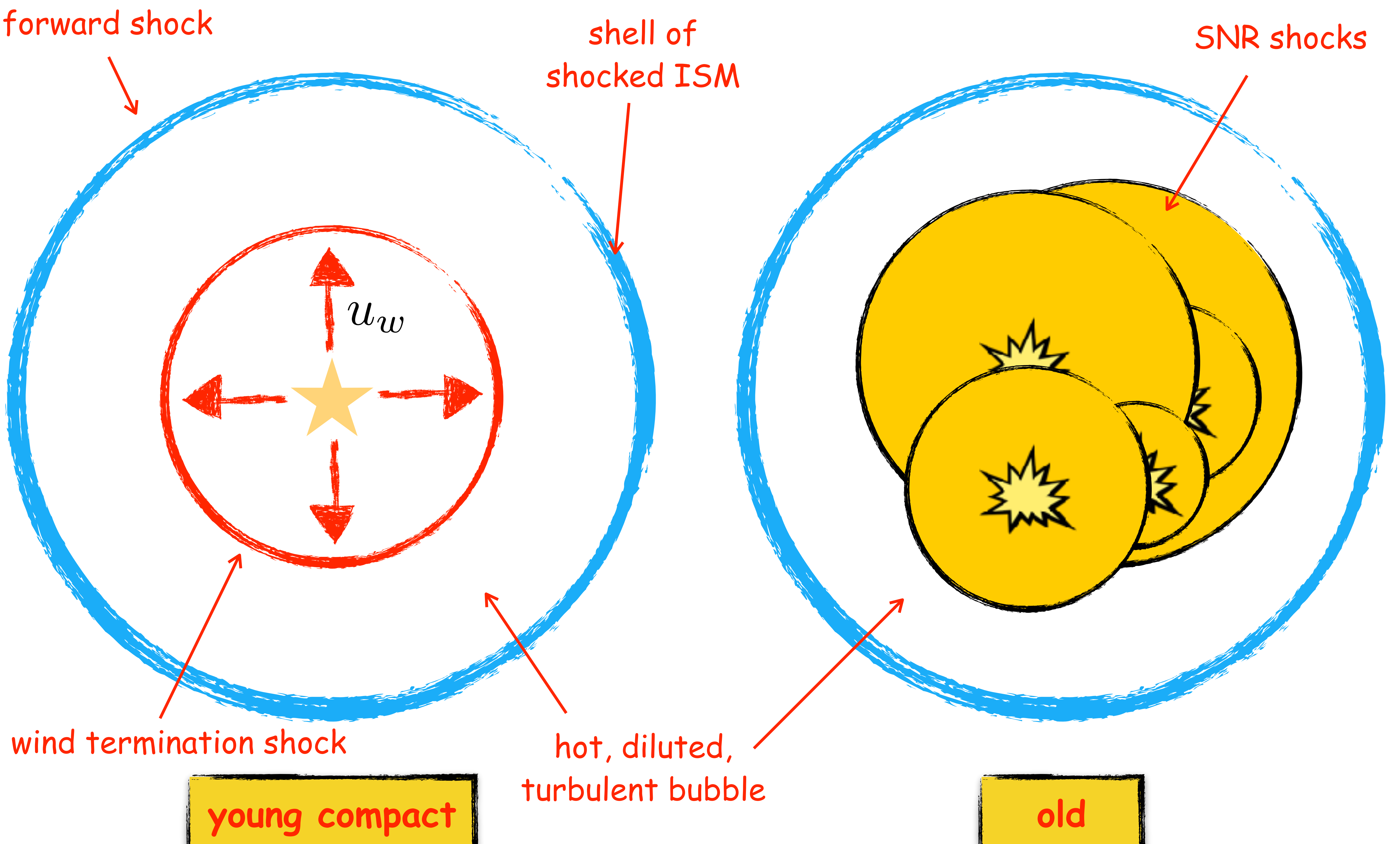
Interstellar bubbles around star clusters

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



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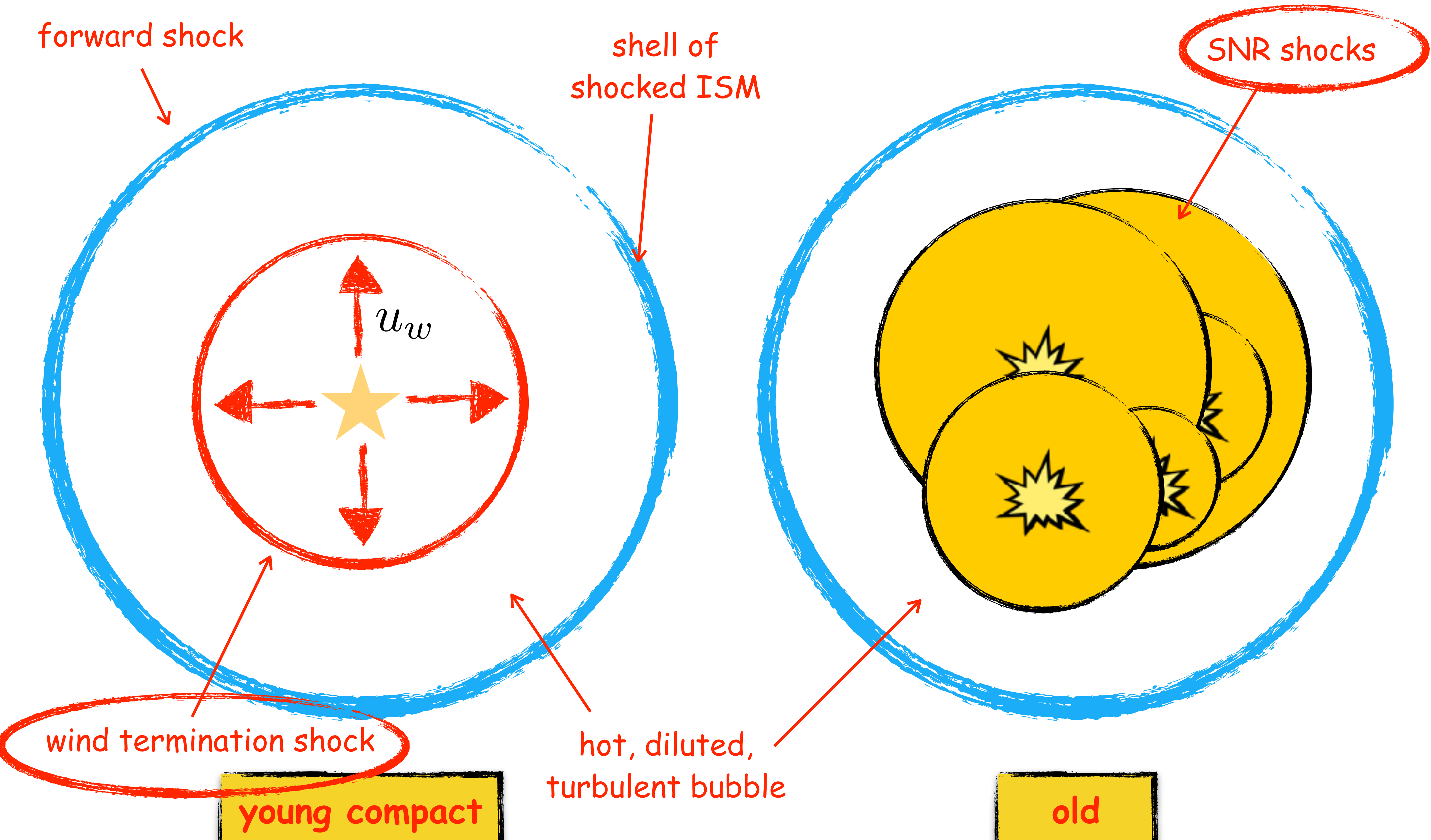

Particle acceleration at WTSs: E_{max}

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

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Morlino+ 2021

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

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

$$\eta_B = 0.1$$

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possible for powerful clusters?

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

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

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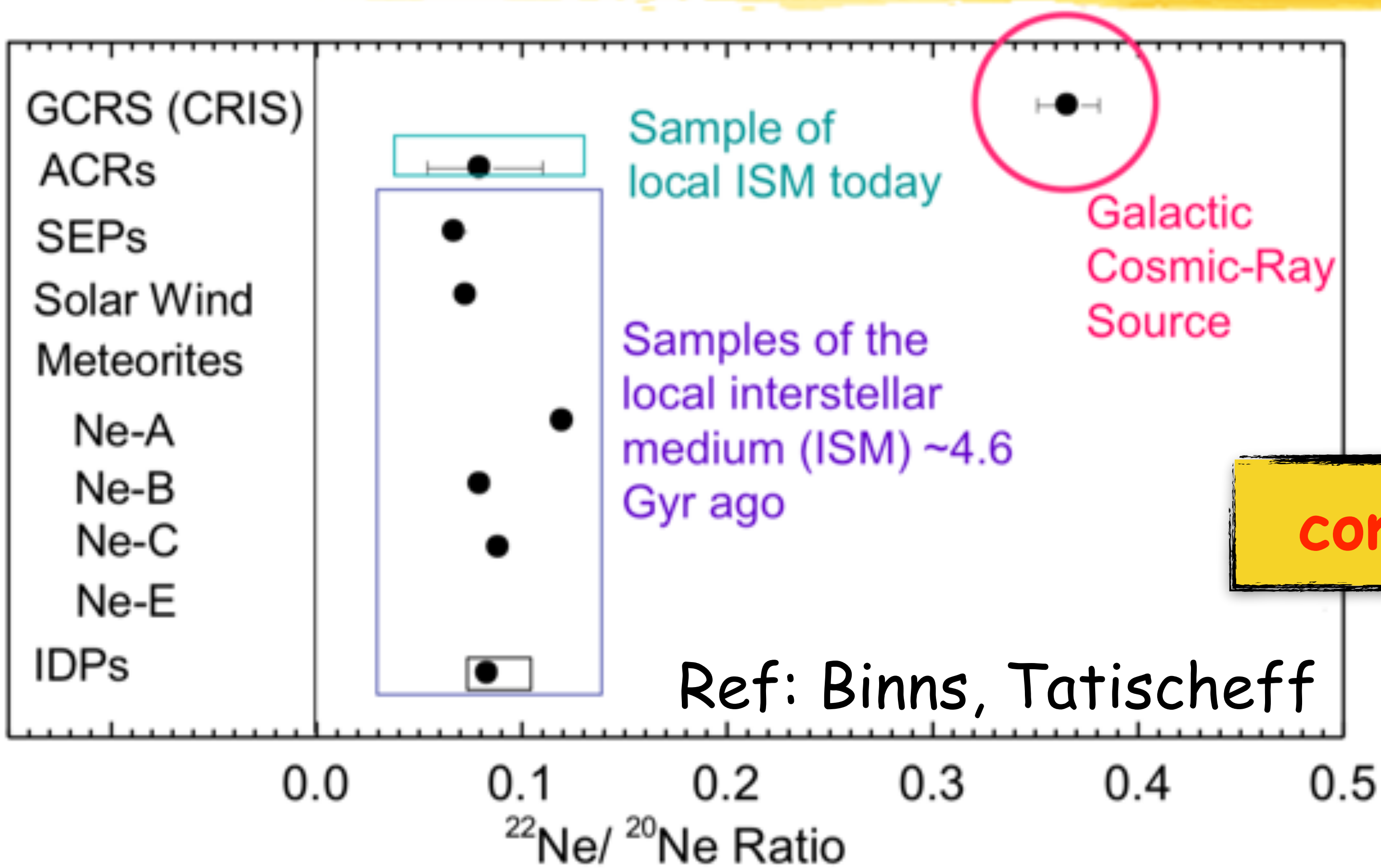
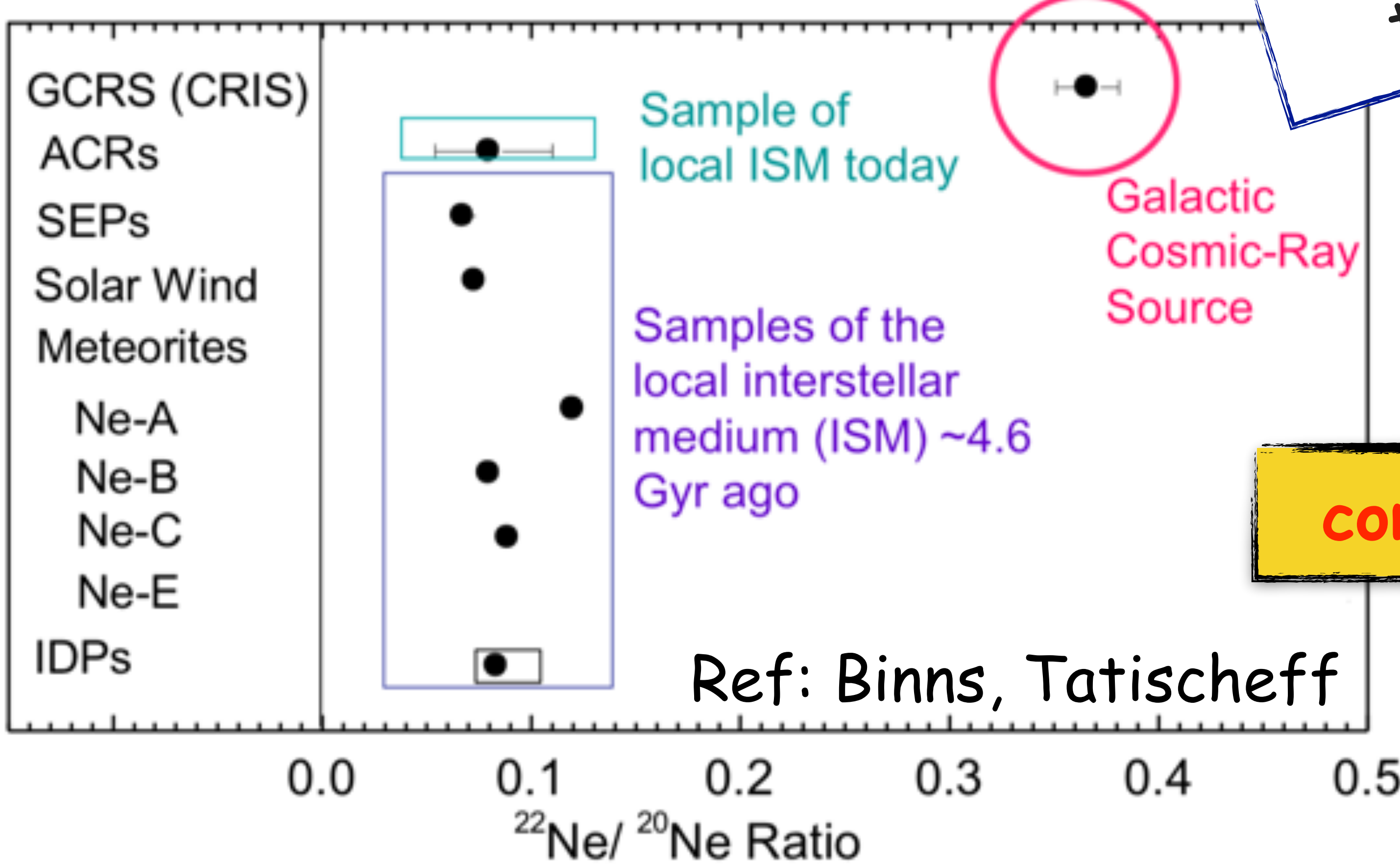


composition

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

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



Ref: Binns, Tatischeff

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+ …)

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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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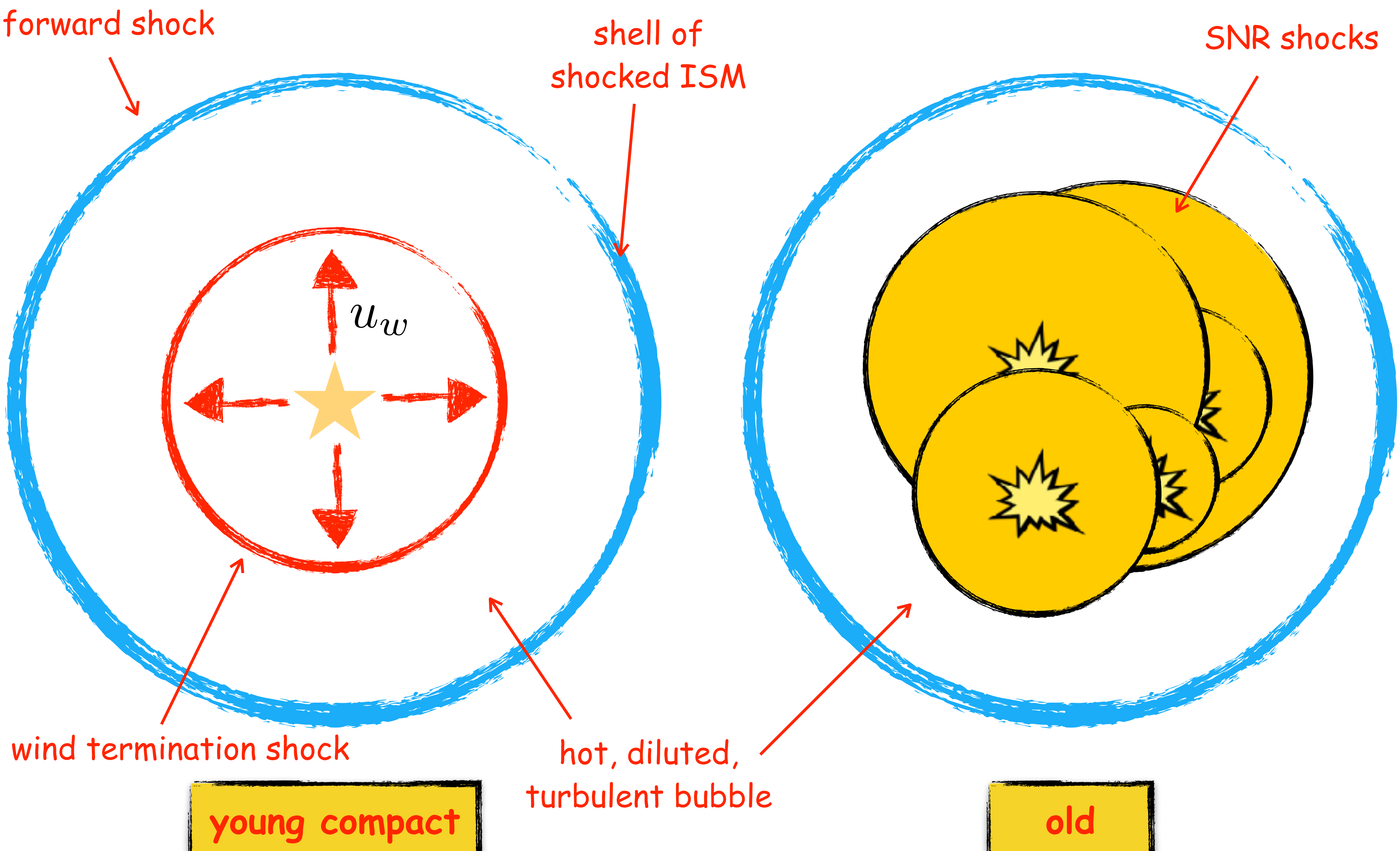

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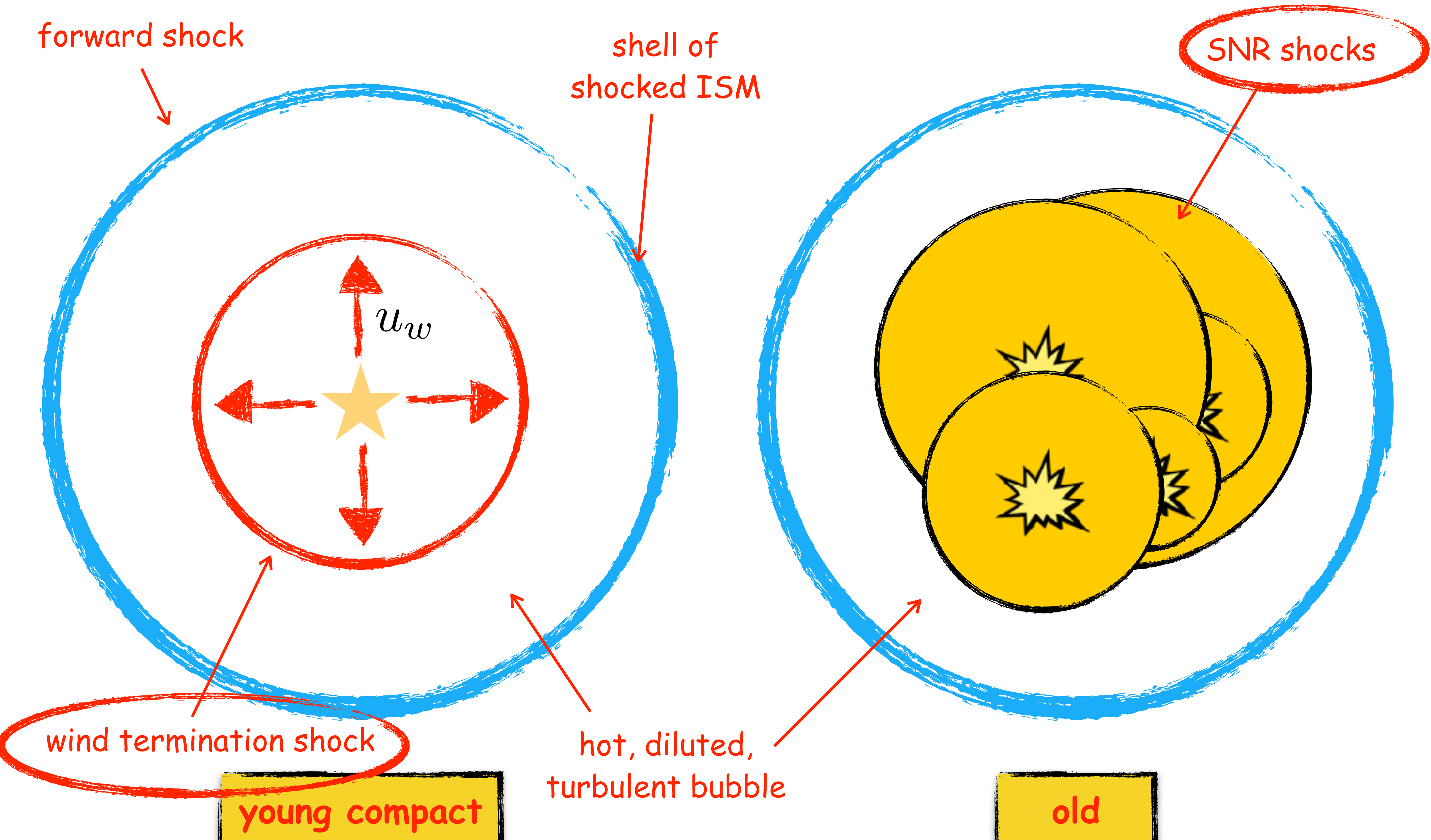

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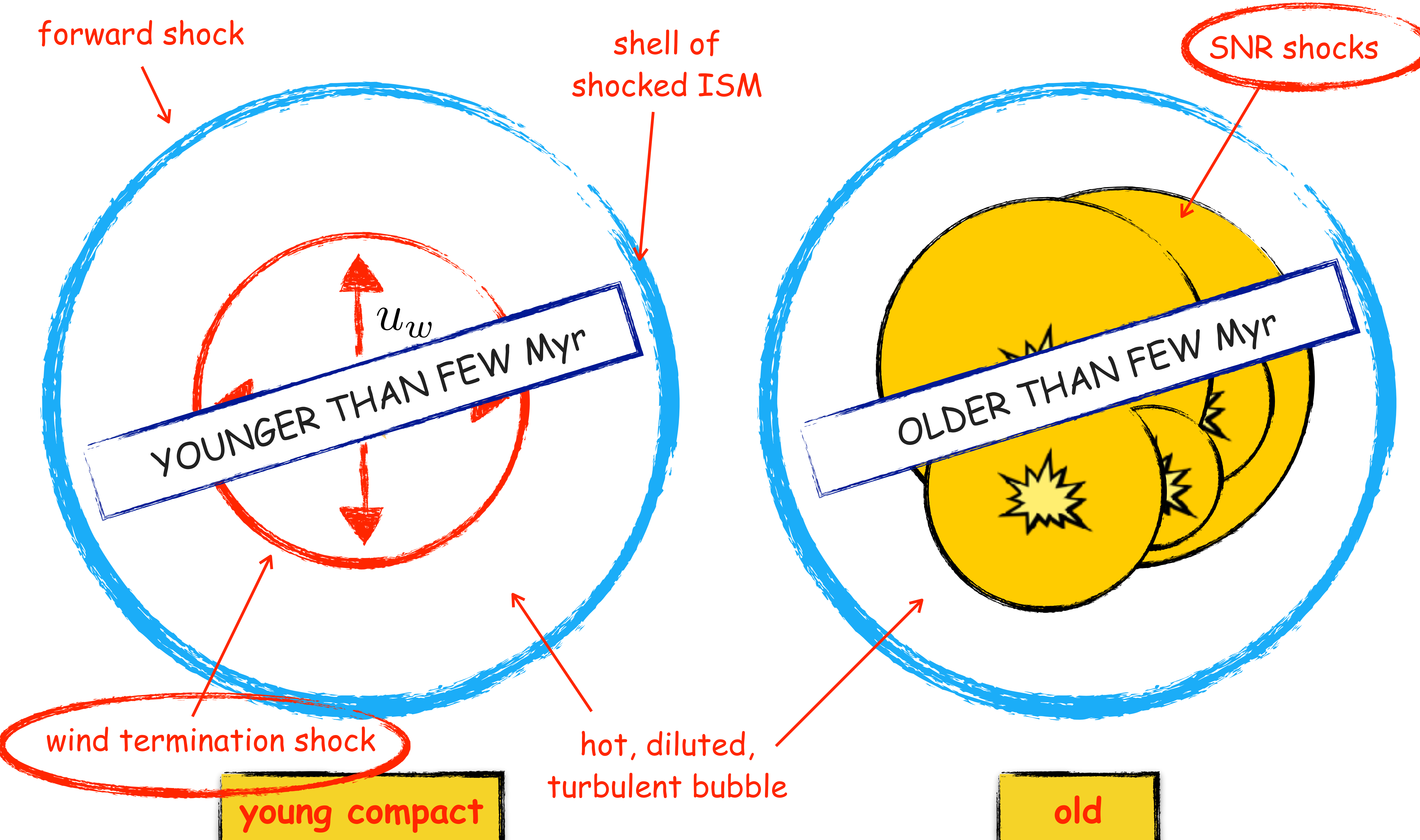
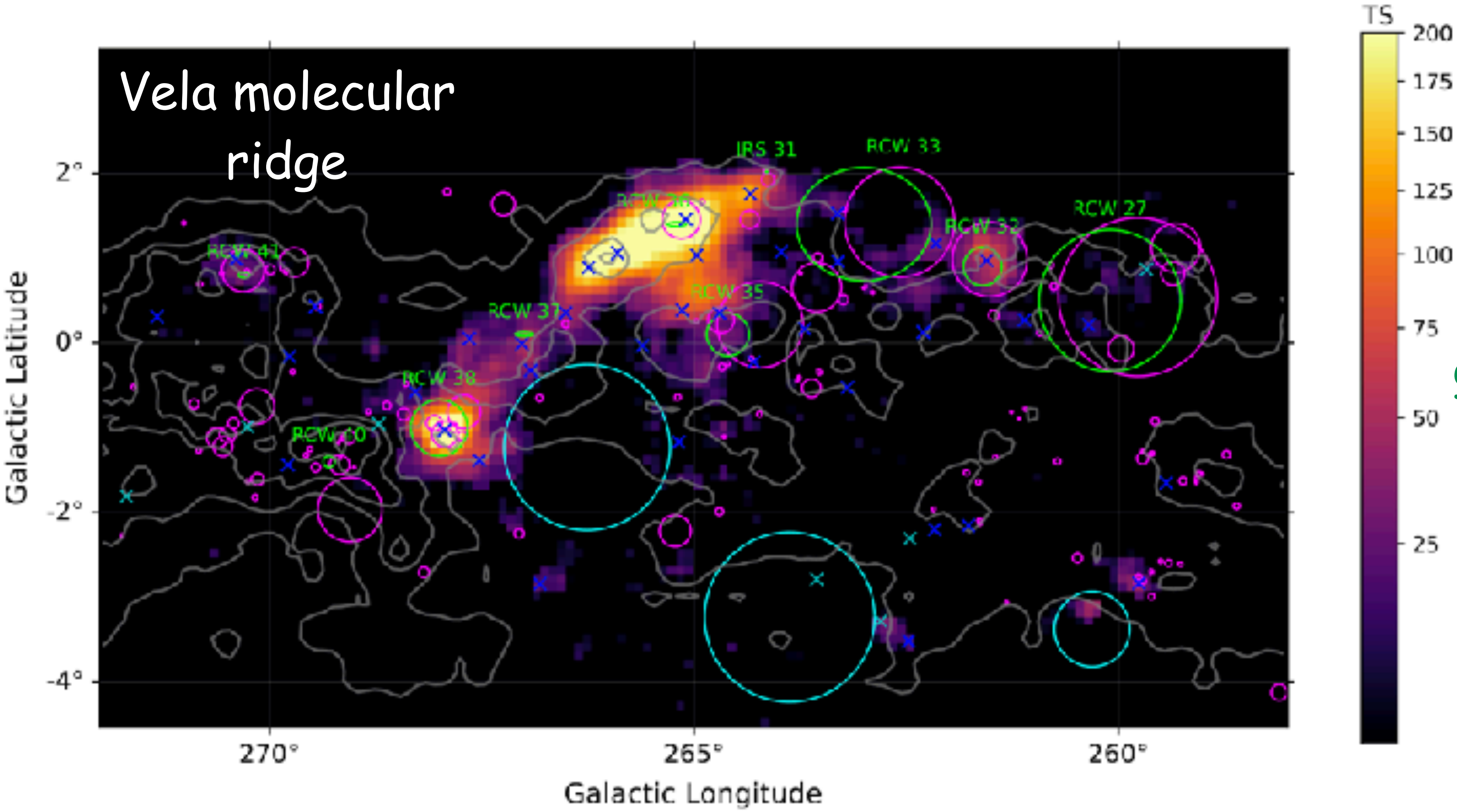


Yes, wind termination shocks do accelerate cosmic rays



grey —> gas

color —> gamma

green/purple —> HII regions

Peron+, Nature Astronomy

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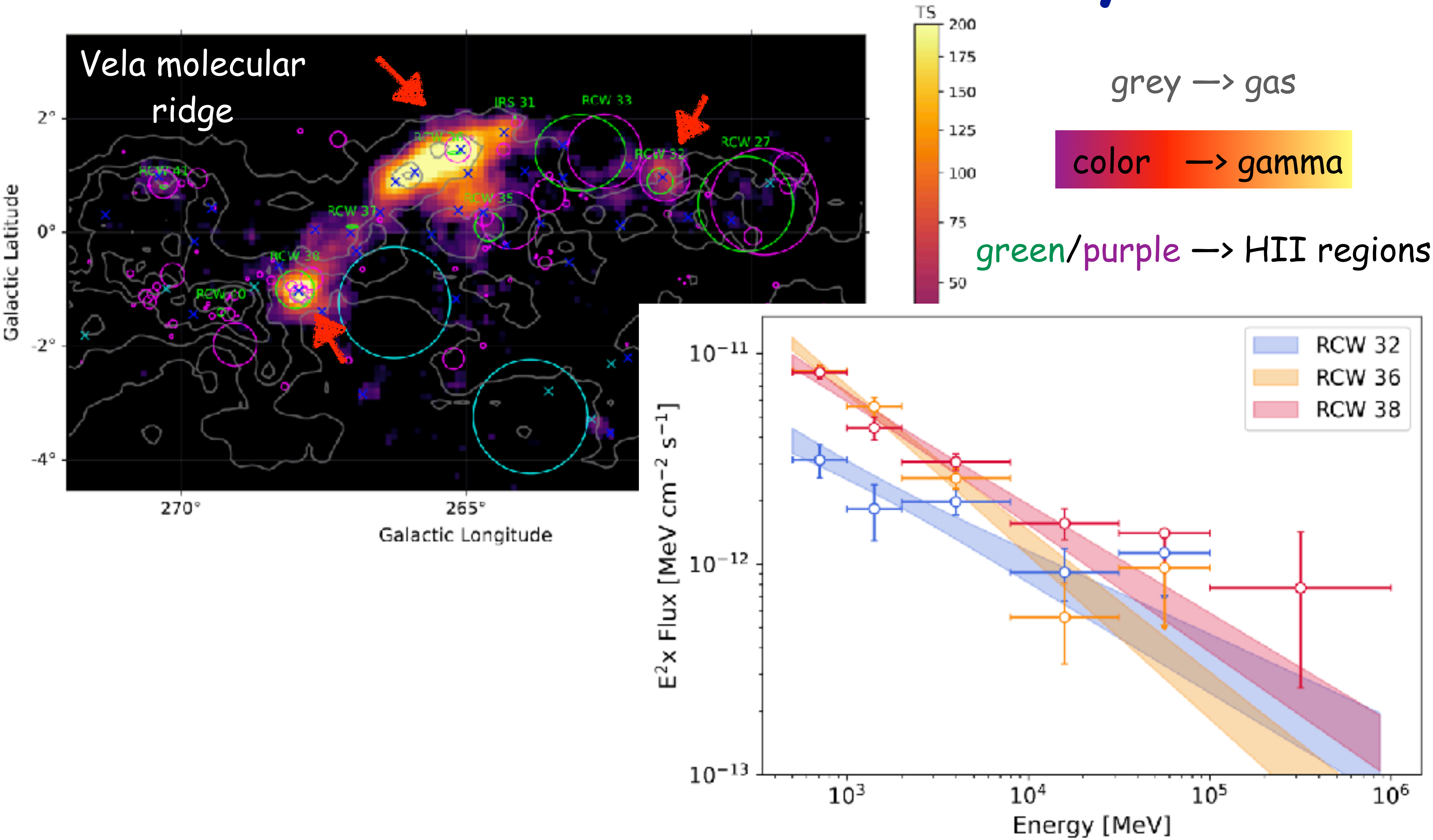

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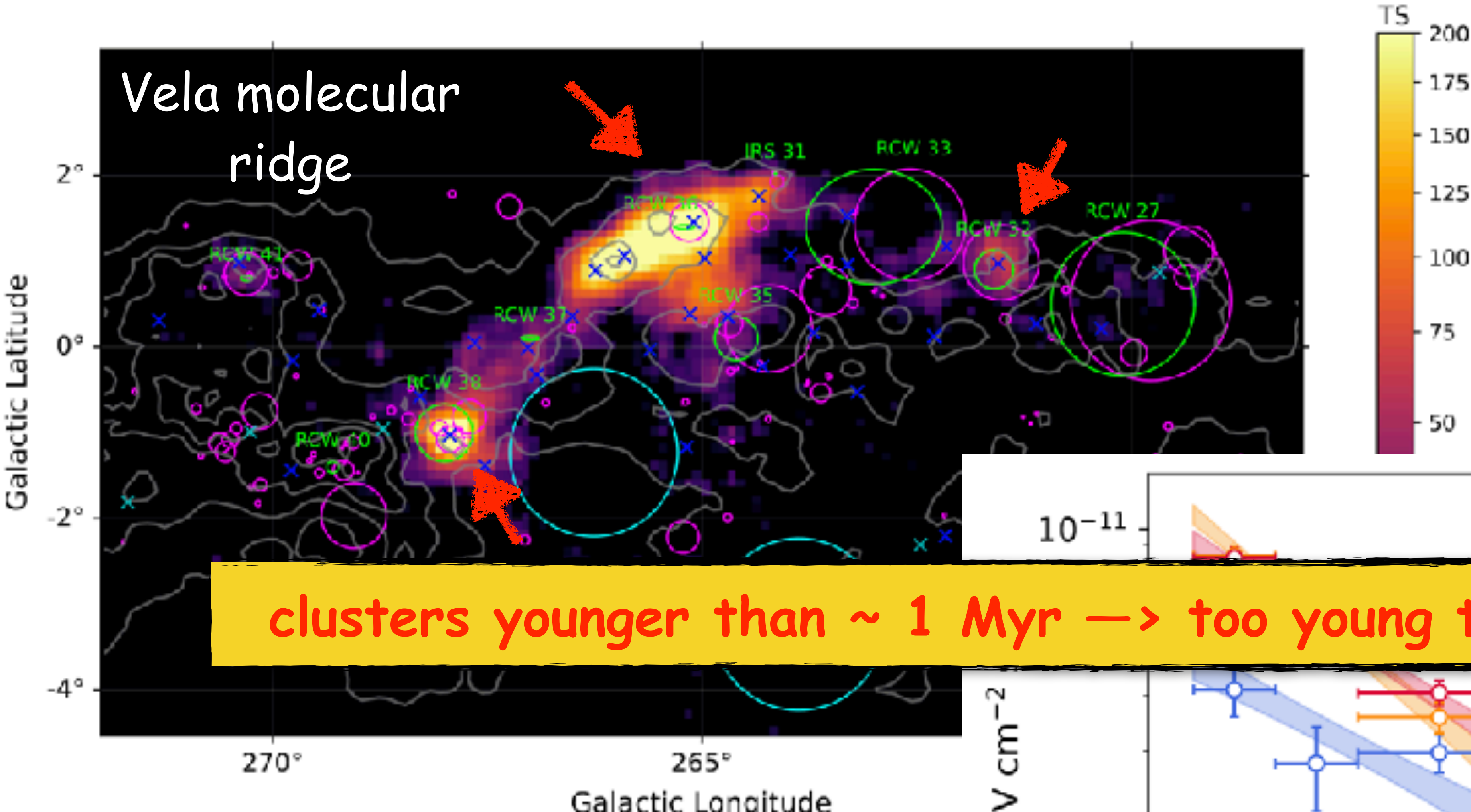

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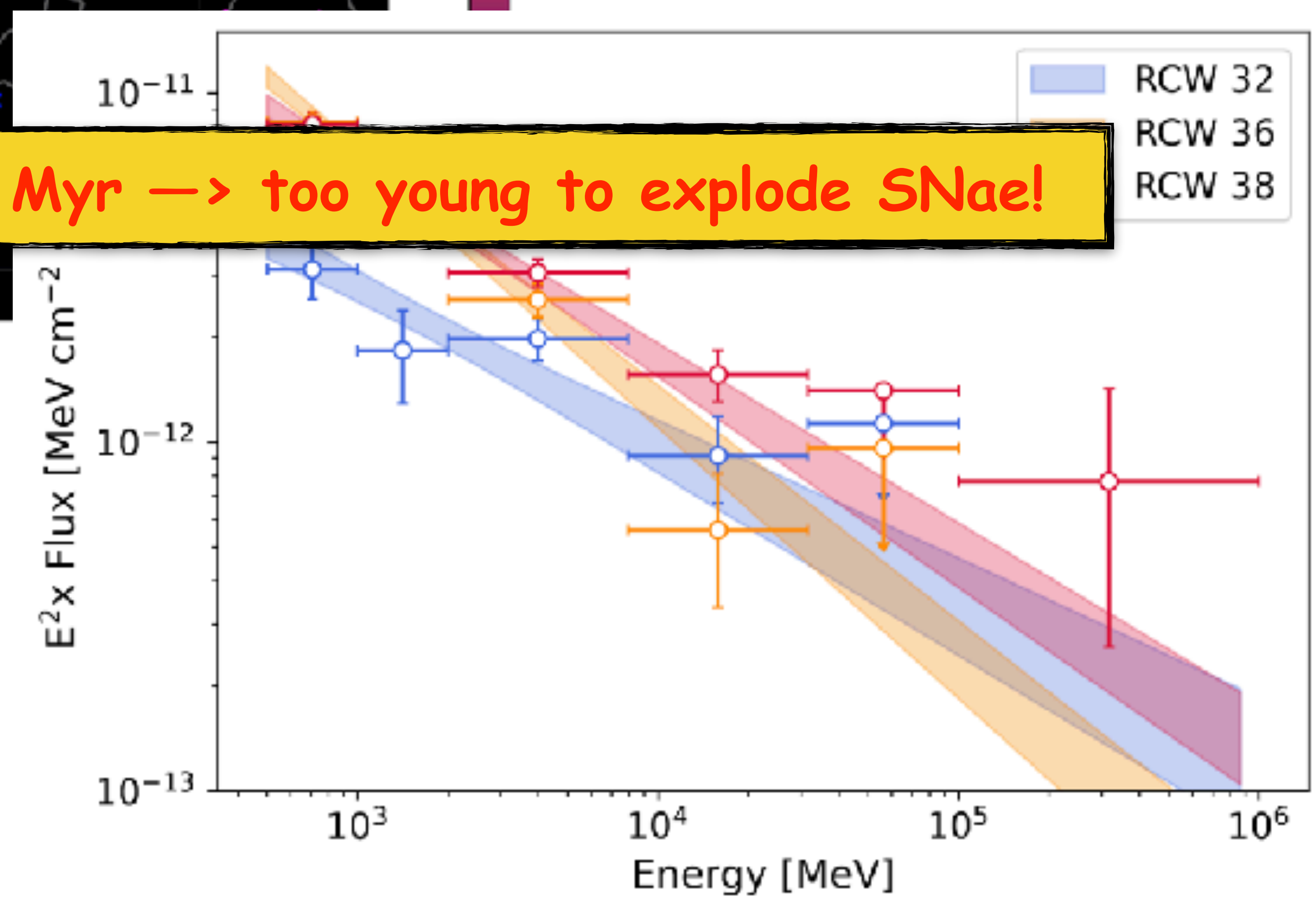
clusters younger than ~ 1 Myr —> too young to explode SNae!



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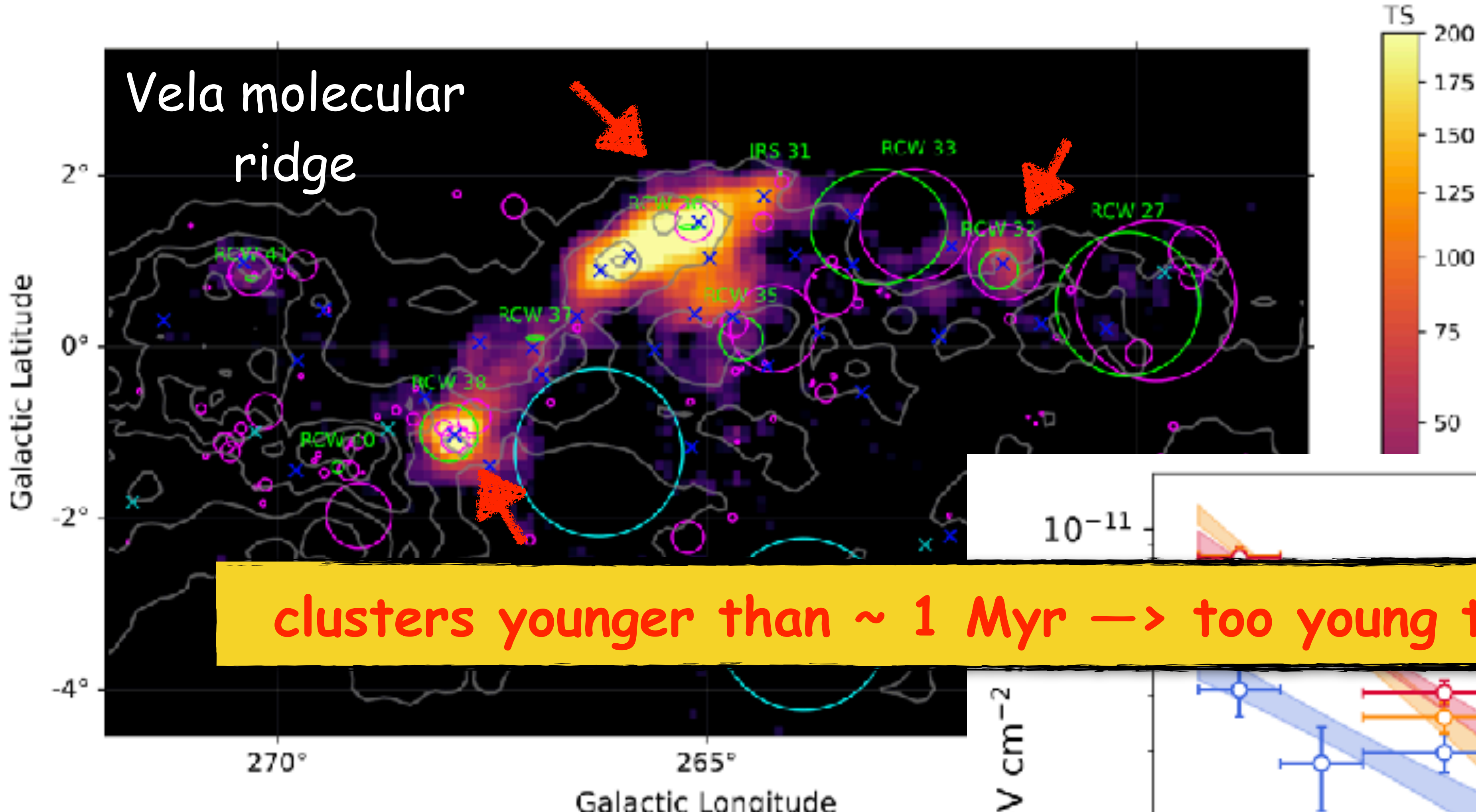

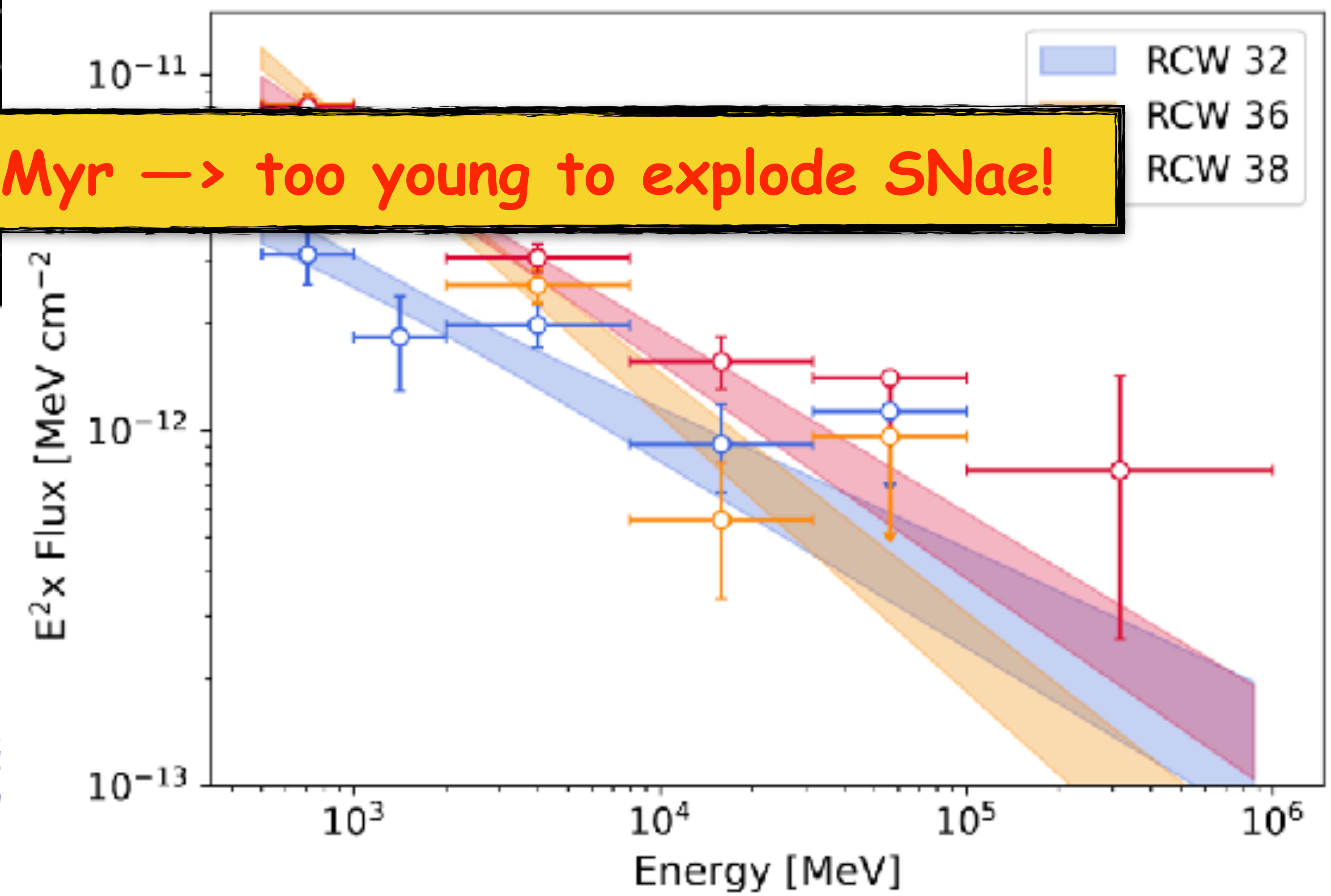

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strict lower bound on the CR acceleration efficiency (energy)

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

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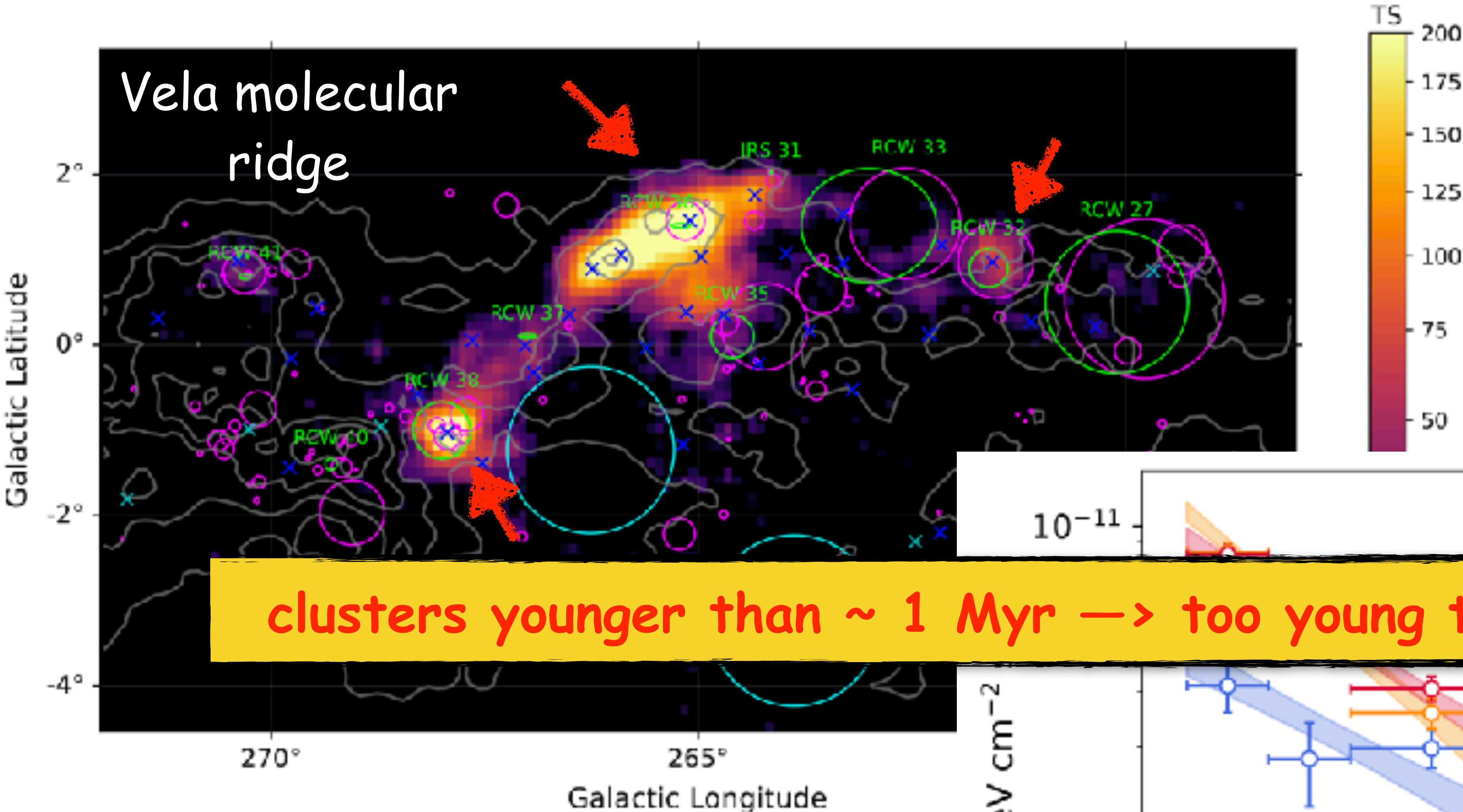

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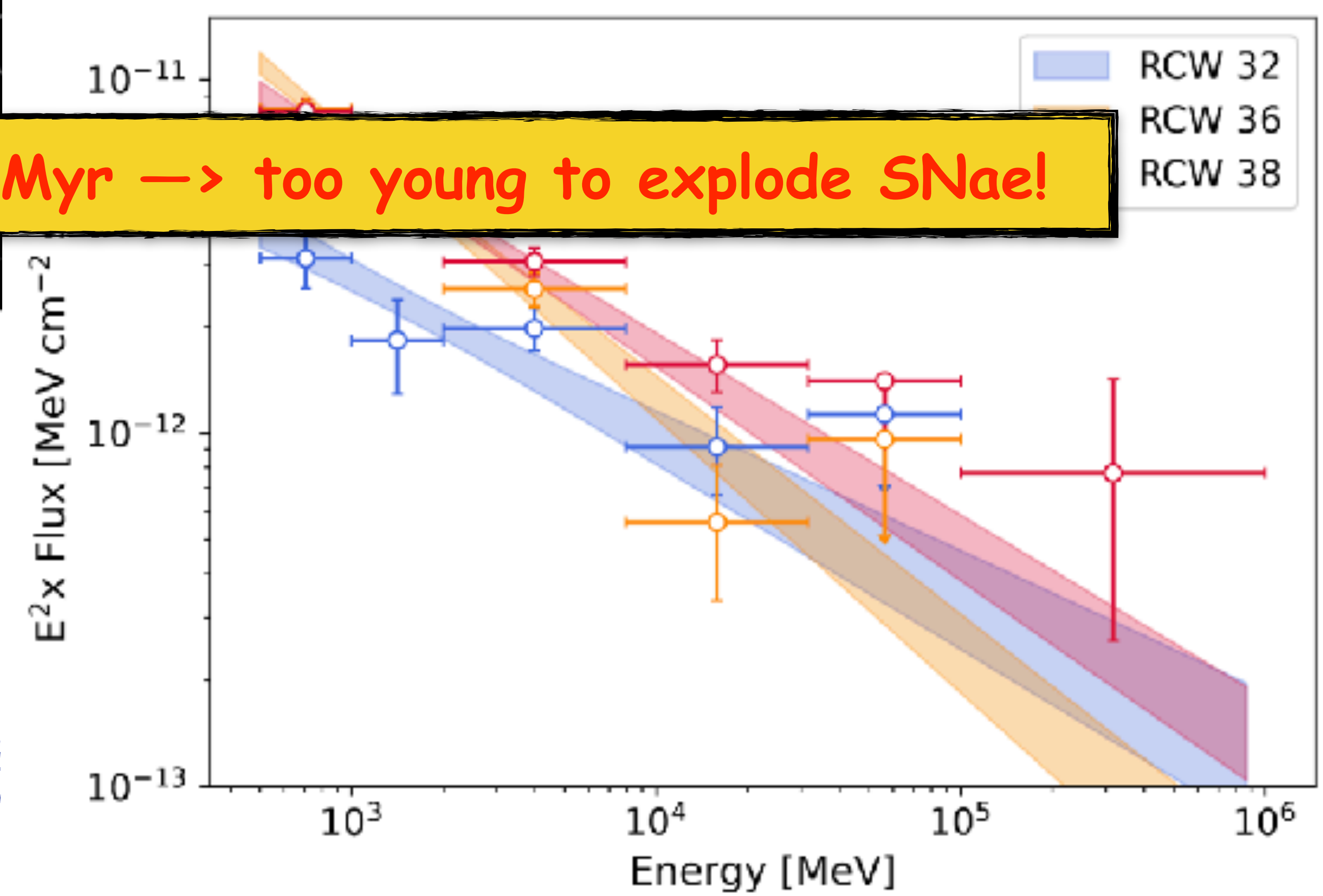

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fraction of CRs coming from stellar winds

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 in winds (corrected for CR efficiency)

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Solar/interstellar isotopic ratio

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

Conclusions: mixed origin fro CRs?

- Supernova remnants most likely provide most CRs —> **follow the energy!**
- Star clusters accelerate CRs (we see gamma rays!)
- YOUNG star clusters accelerate CRs —> 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)