

Cosmic rays: an introduction

(and why it is a problem to understand particle acceleration in astrophysics)



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Plan of the lecture

- [1] Some history: how cosmic rays (CRs) were discovered
- [2] What are cosmic rays?
- [3] Are CRs a local or global phenomenon?
- [4] CR composition

Introduction

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Introduction

**The standard scenario
for cosmic ray origin**

- [5] How long do CRs stay within the Milky Way?
- [6] Diffusive models for CR transport
- [7] Supernovae and the origin of cosmic rays
- [8] The three pillars of orthodoxy

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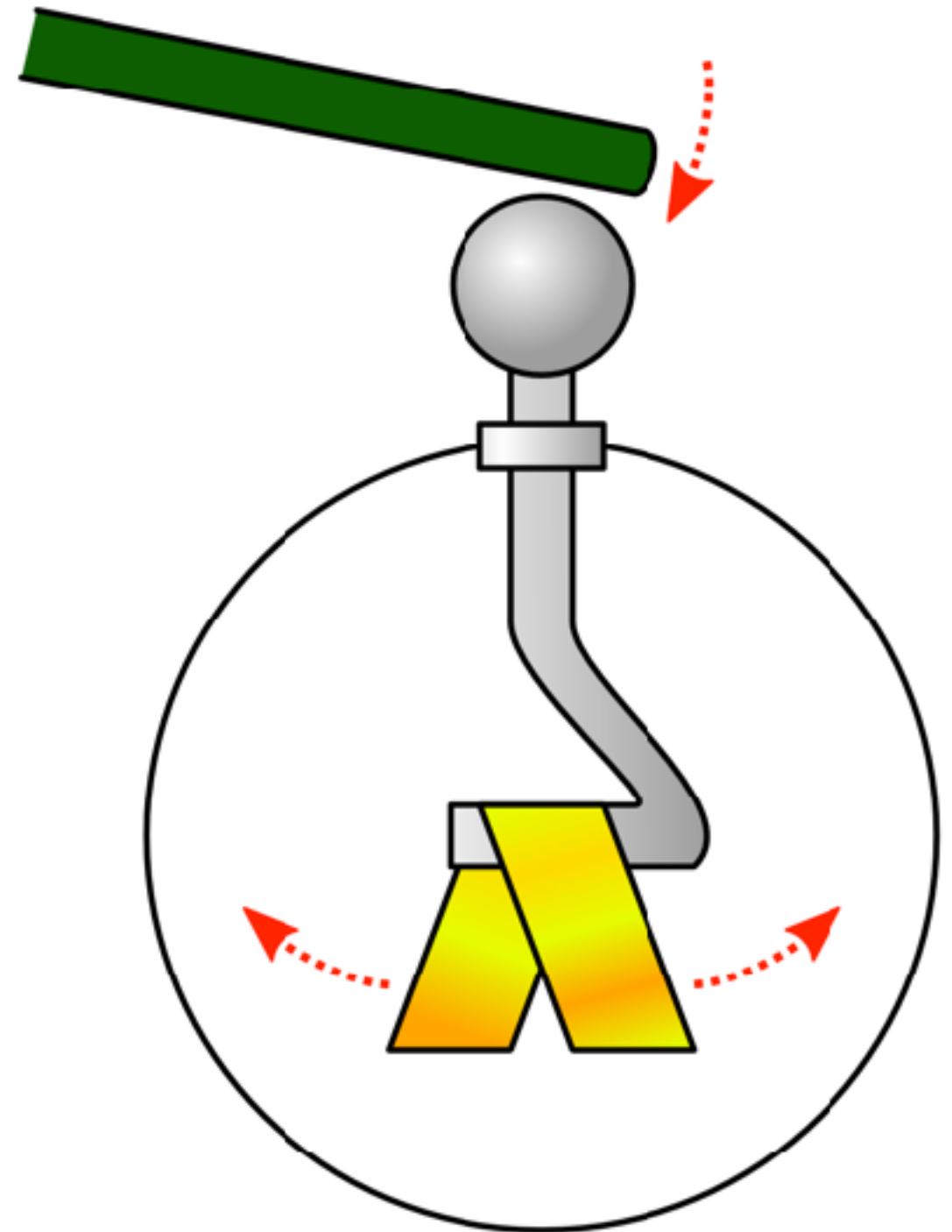
The problem of particle acceleration in astrophysics

- [9] Why it is a problem to understand particle acceleration in astrophysics

[1] History

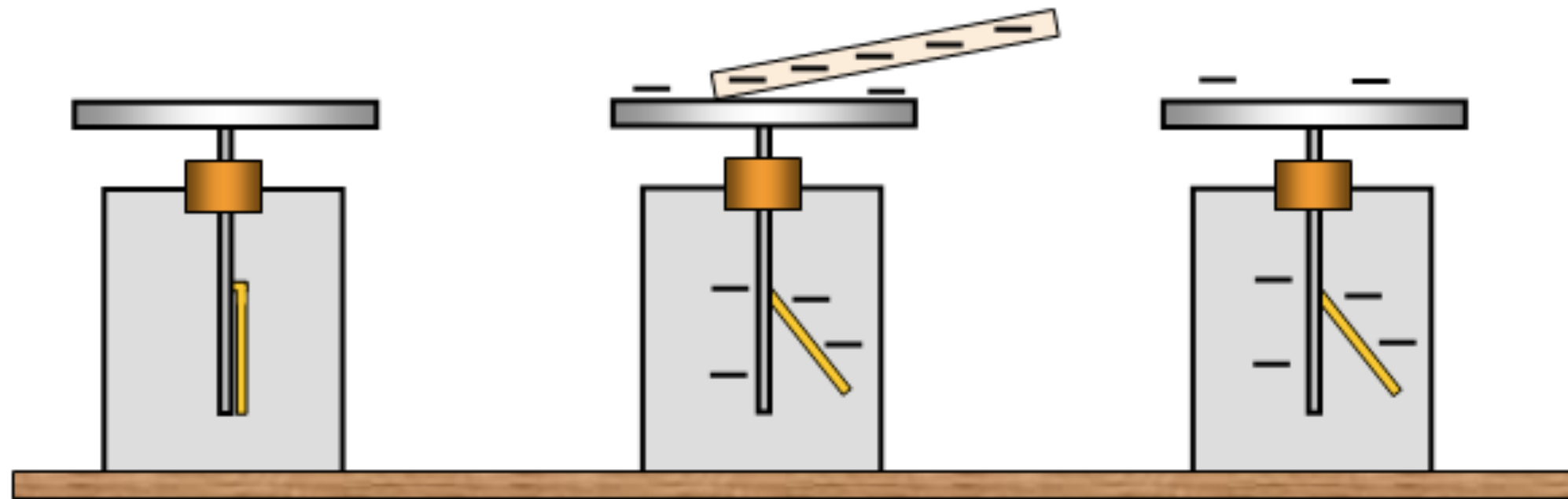
The electroscope

- simple device used to measure the electric charge of objects;
- it works because of the repulsion of objects of like charge

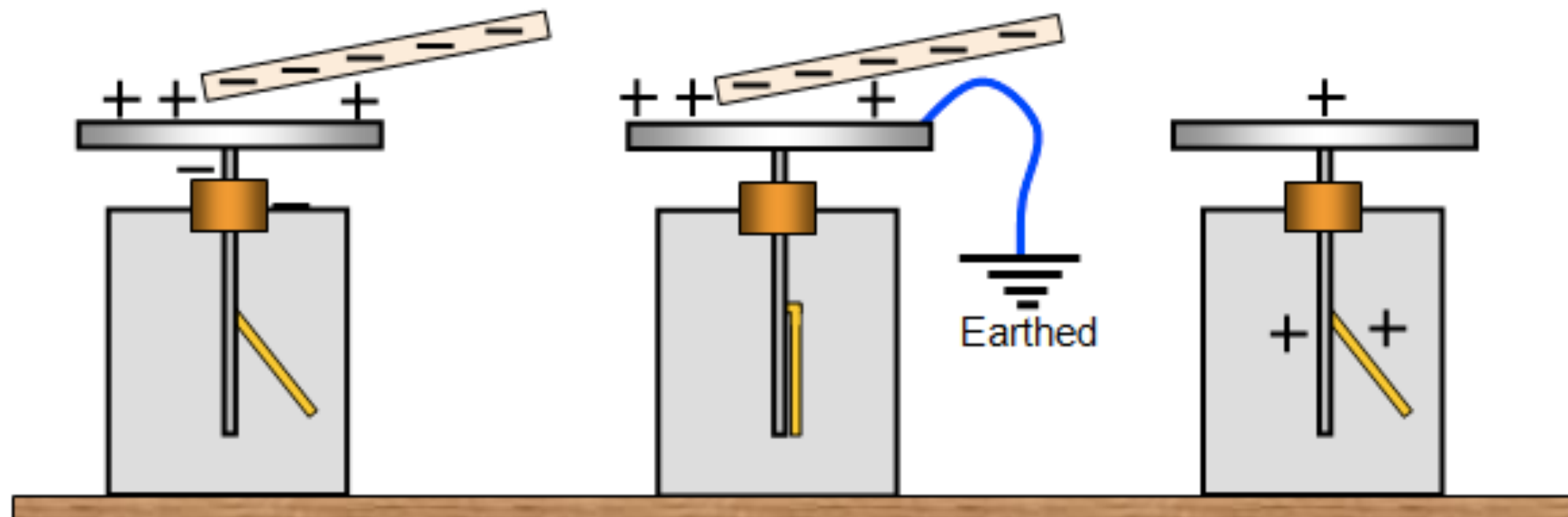


ELECTROSCOPE

How does it work



Charging by contact



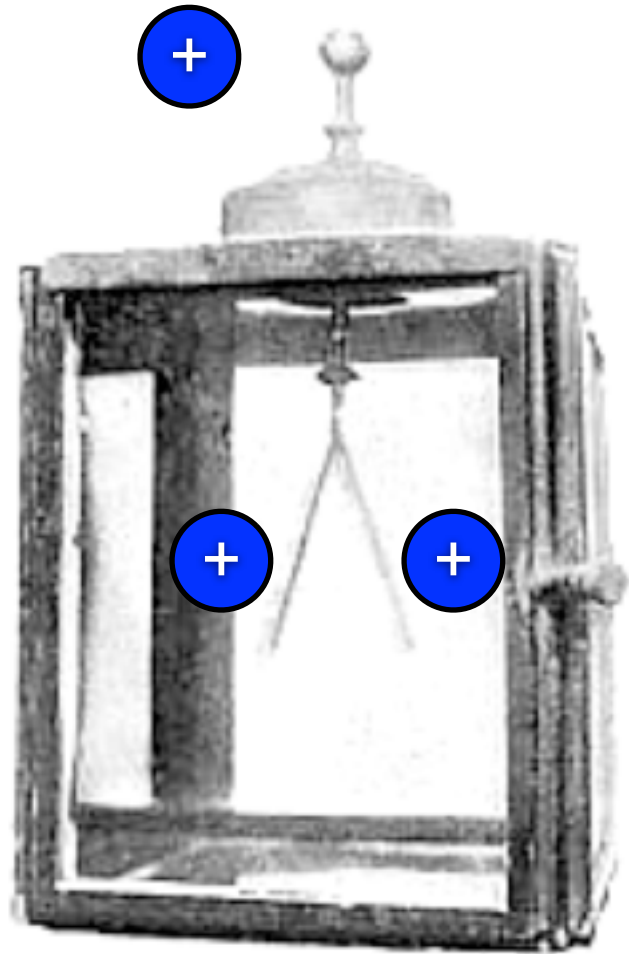
Charging by induction

The problem...

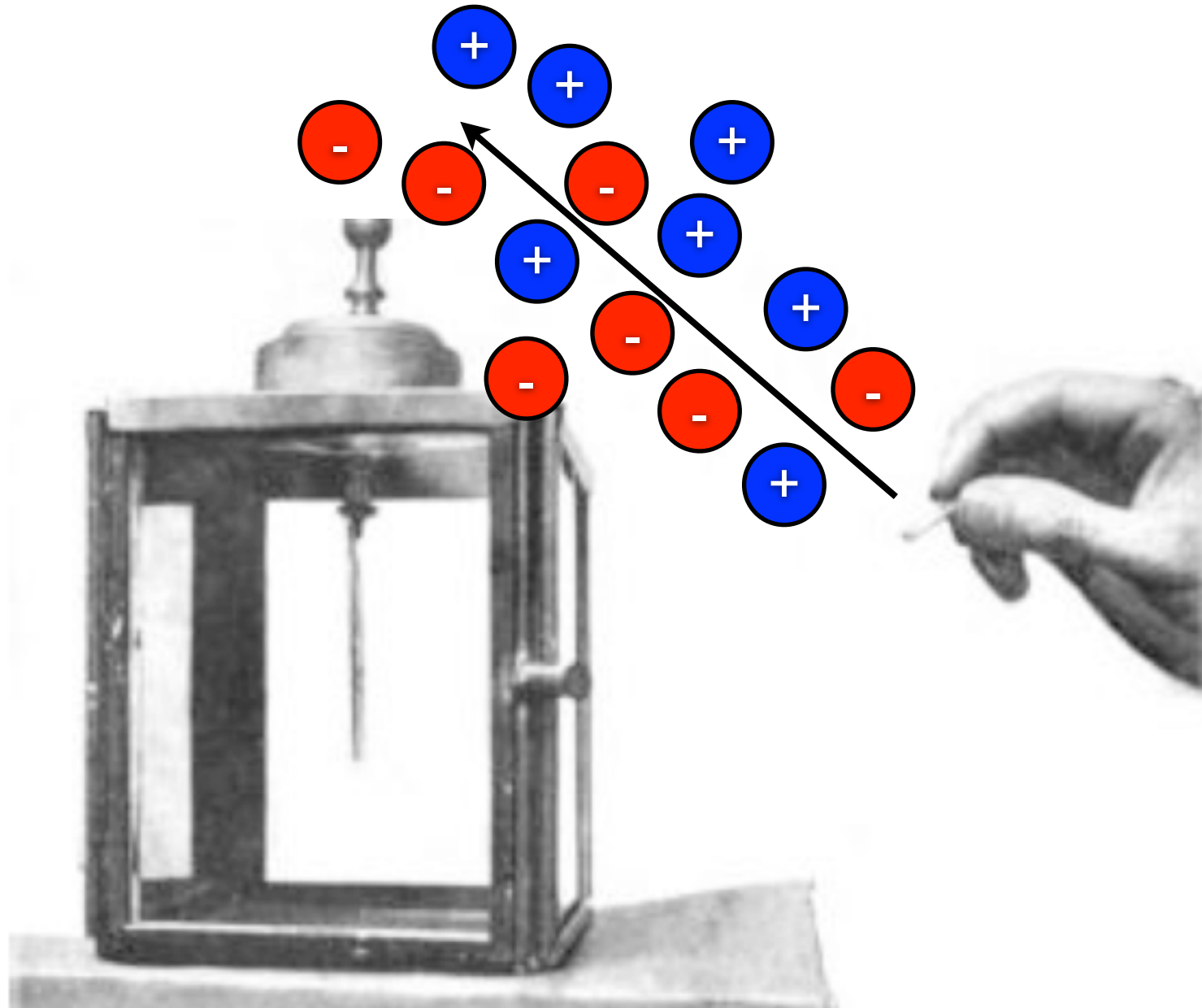
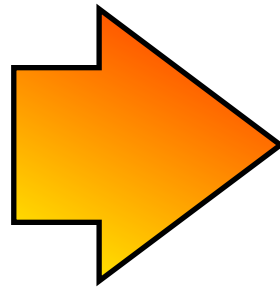
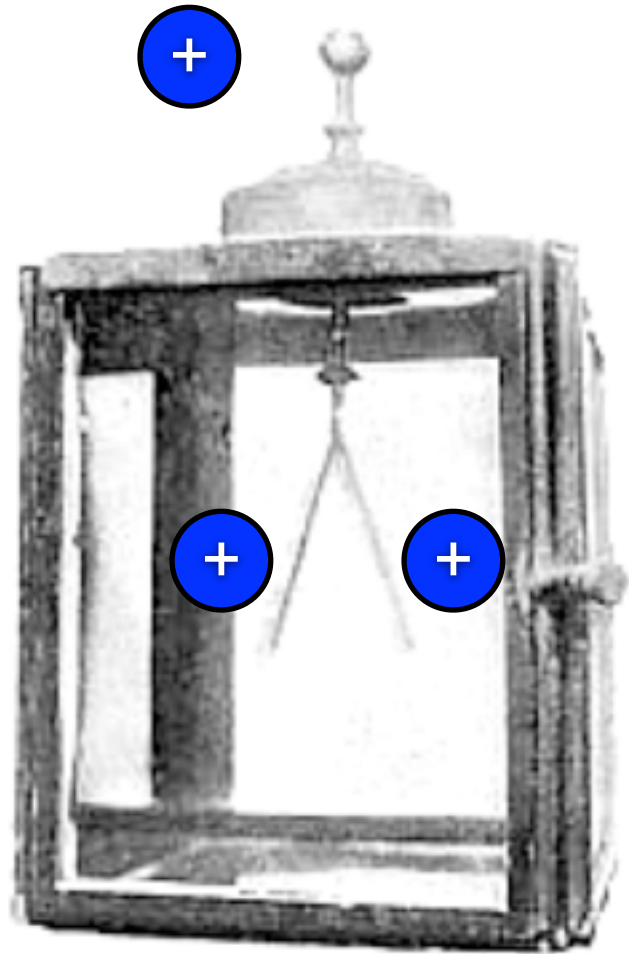


- in **1785 Coulomb** noted that charged electrosopes discharge spontaneously;
- in **1835 Faraday** confirmed Coulomb's results, using a better insulation system
-> it is not an instrumental problem;
- in **1879 Crookes** noted that the discharge time changes with the pressure of the air -> **the discharge is induced by the ionisation of the air**
- in **1896 Becquerel** discovers **radioactivity**

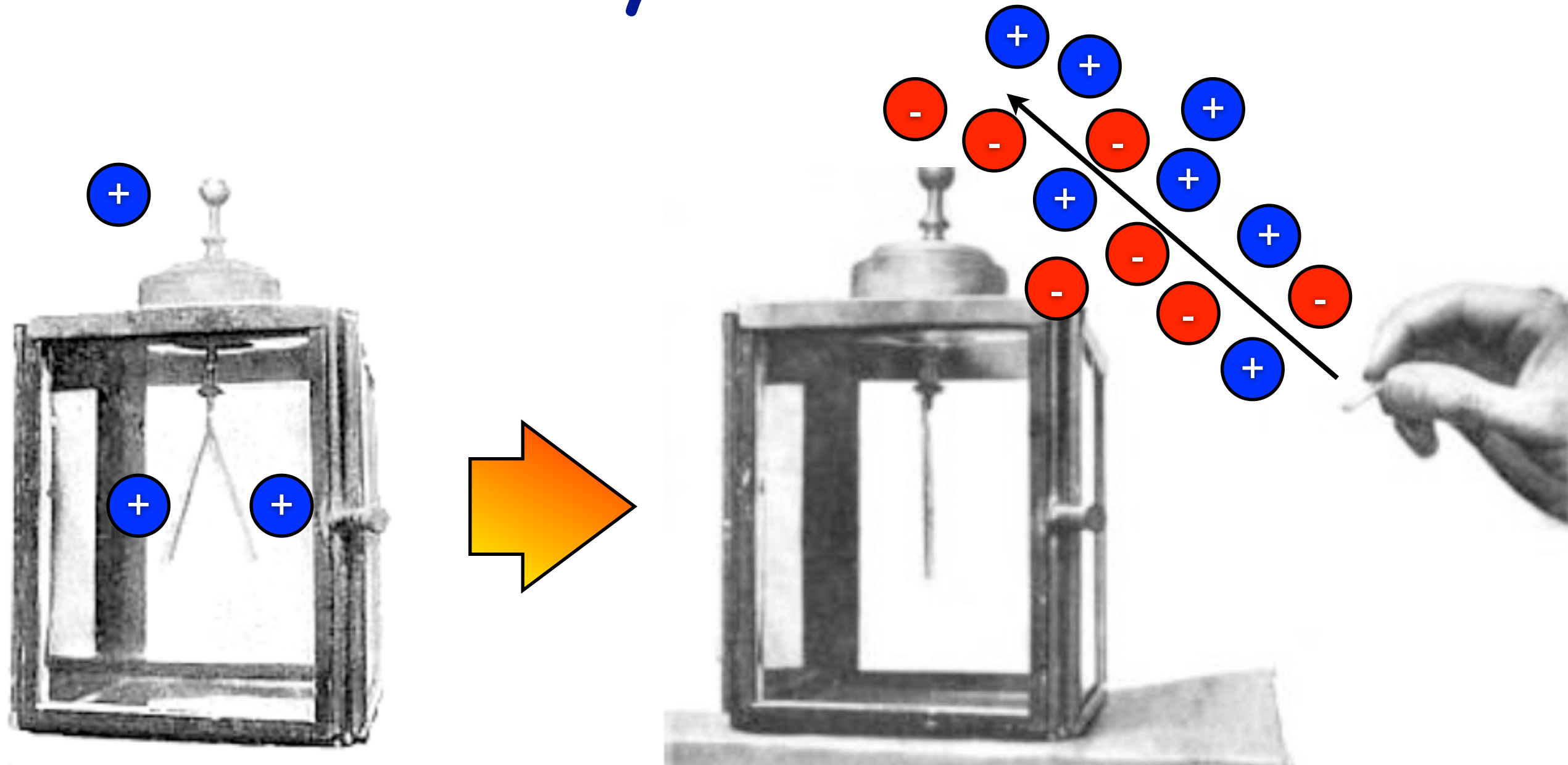
Radioactivity from the Earth



Radioactivity from the Earth



Radioactivity from the Earth



hypothesis: the Earth's crust contains radioactive isotopes (natural radioactivity) -> this might be the source of the ionizing radiation needed to explain the spontaneous discharge of electroscopes.

Father Theodor Wulf on the Tour Eiffel

Idea: if the source of radioactivity is the Earth, electroscopes should discharge less rapidly when located far away from it.

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- ☀ in **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
- ☀ in **1910** spends his Easter holidays in Paris, where he brings his electrosopes to measure the discharge time at the top and at the bottom of the Eiffel tower, during the day and during the night (the sun?);



330 m

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28. März	Valkenburg	22,5
29. "	Paris, Boden	17,5
30. "	" Eiffelturm	16,2
31. "	" "	14,4
1. April	" "	15,0
2. "	" "	17,2
3. "	" Boden	18,3
4. "	Valkenburg	22,0



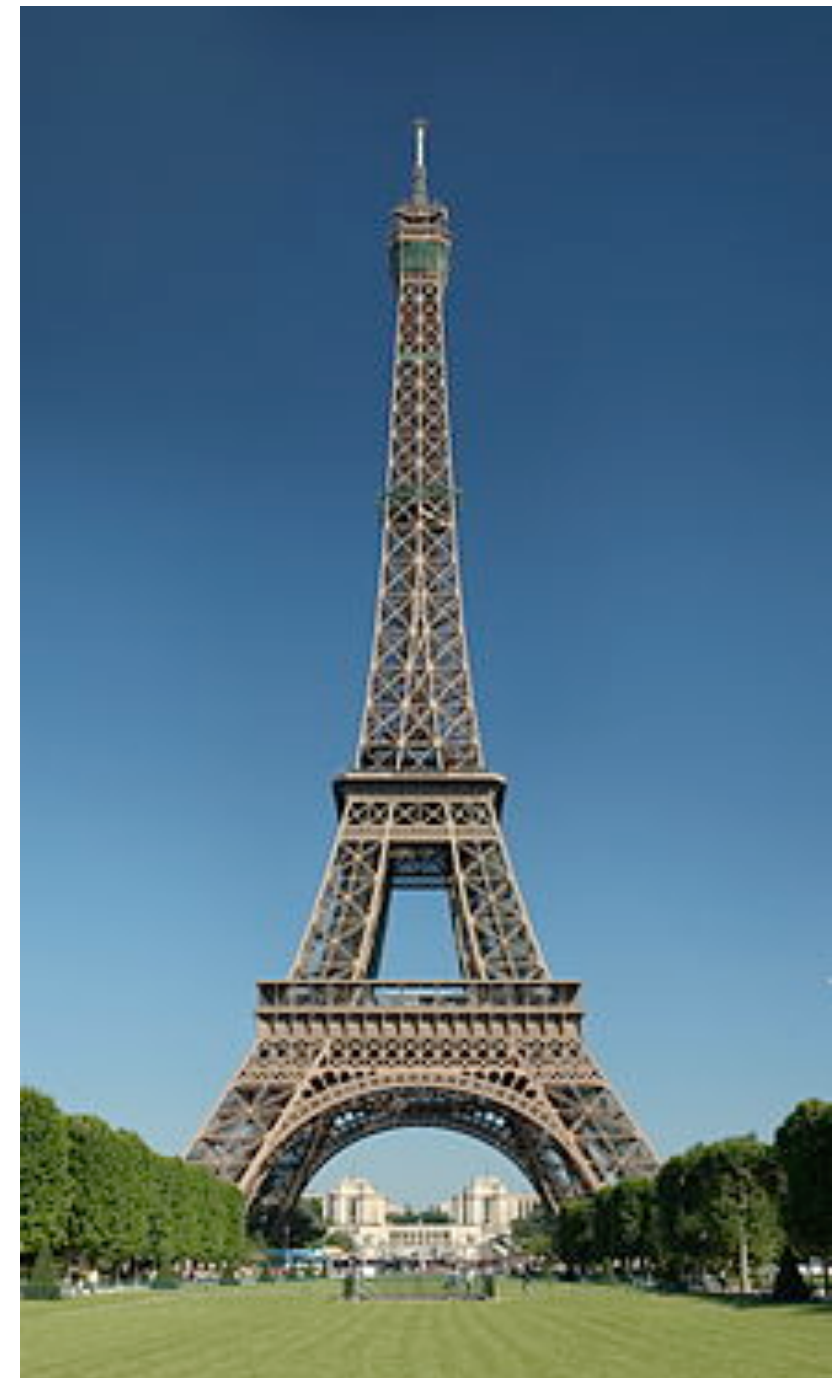
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though the effect was smaller than expected, Wulf concluded that Earth's radioactivity remained the most plausible hypothesis

Pacini's (forgotten) experiment

in **1911** Pacini performed measurements on a boat off the coast of Livorno (300 m from the coast). Measurements were performed on the sea surface (8 m from sea bottom) and at 3 m of depth.

~20% drop of the ionization rate underwater

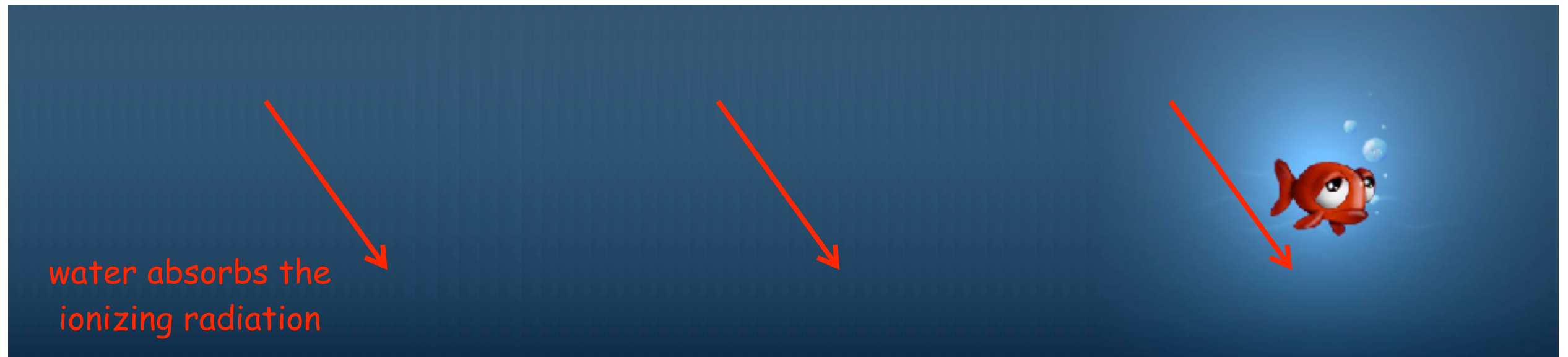
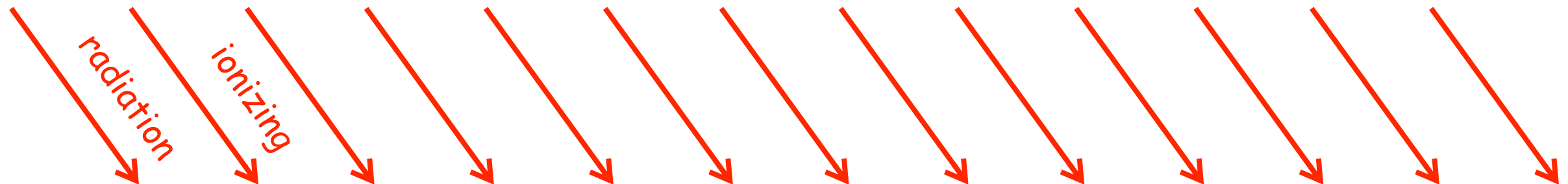
-> the ionization radiation comes from the atmosphere and NOT from the Earth!

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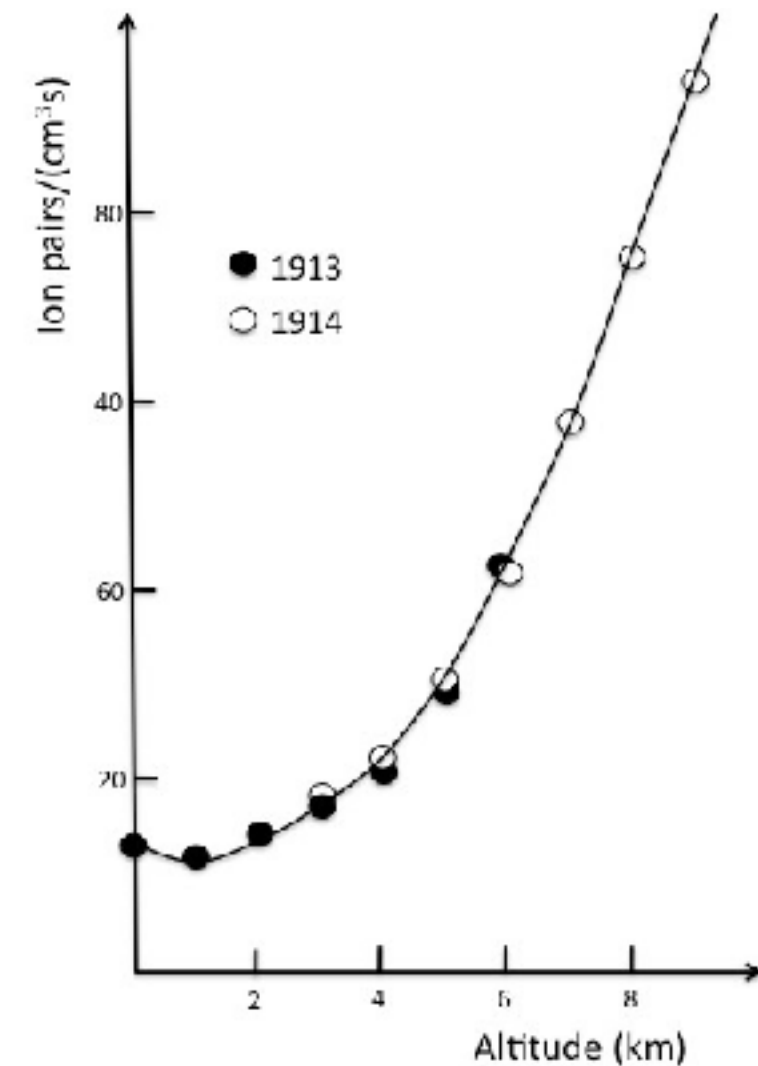
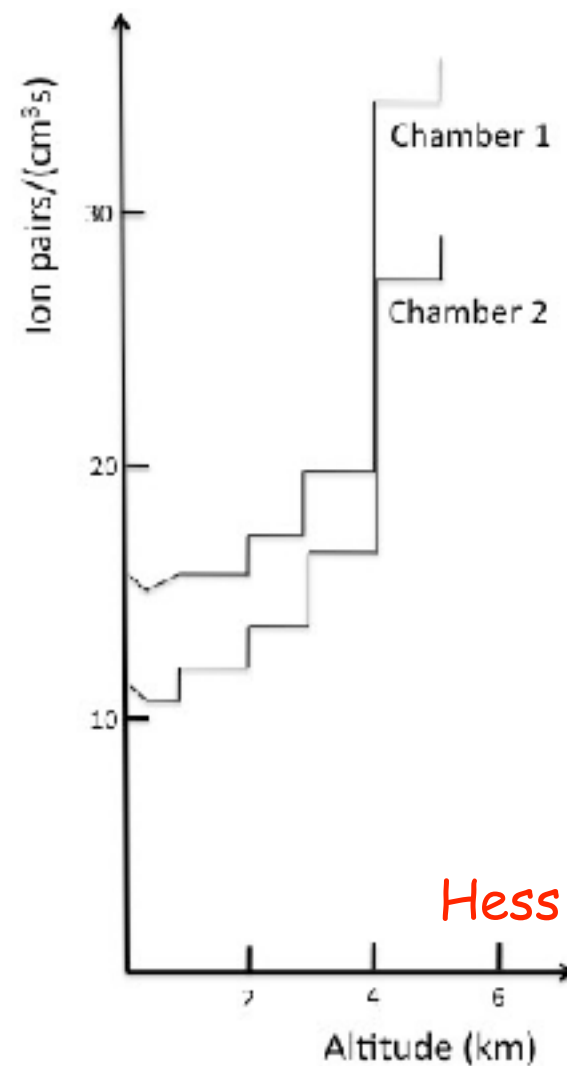


Which is the nature of the ionizing radiation in the atmosphere?

Victor Hess flies on a balloon



Between April and August **1912** Hess performed 7 balloon flights. During the 7th flight he reached an altitude of 5200 meters.

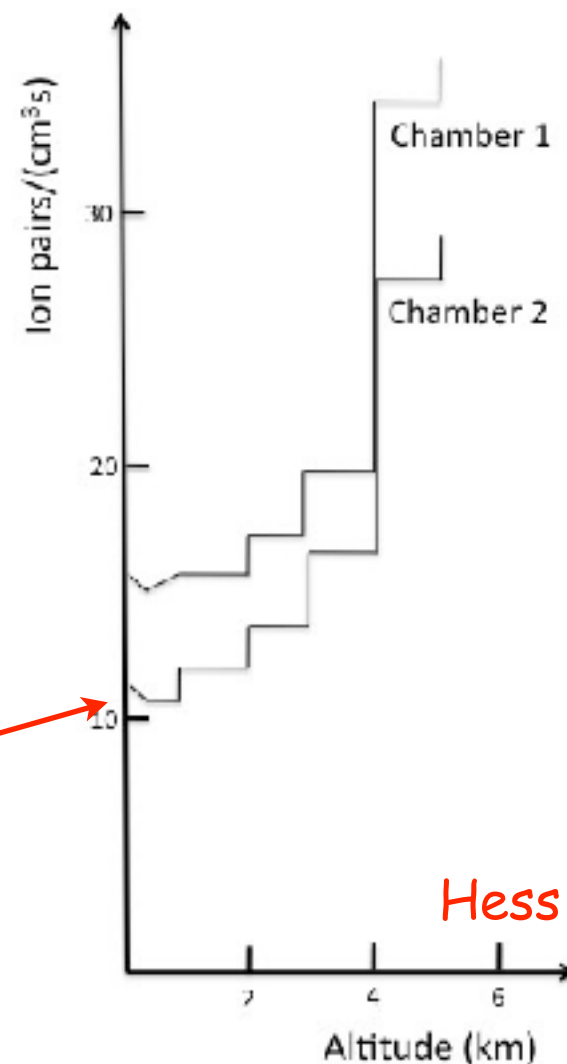


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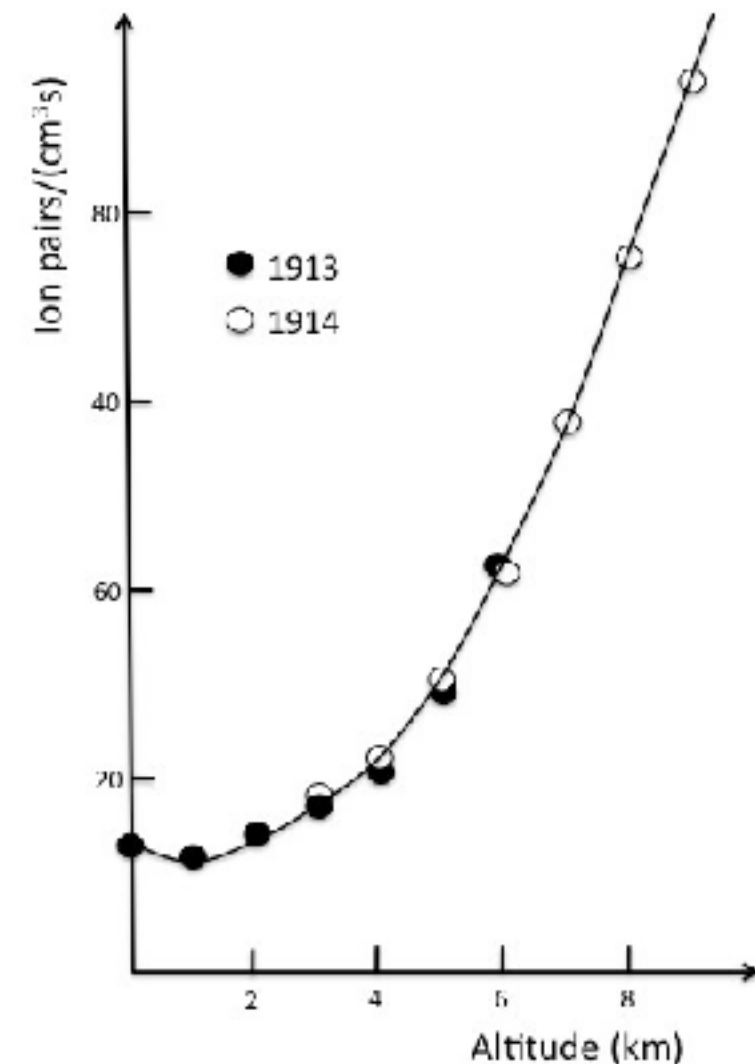


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Wulf was right!



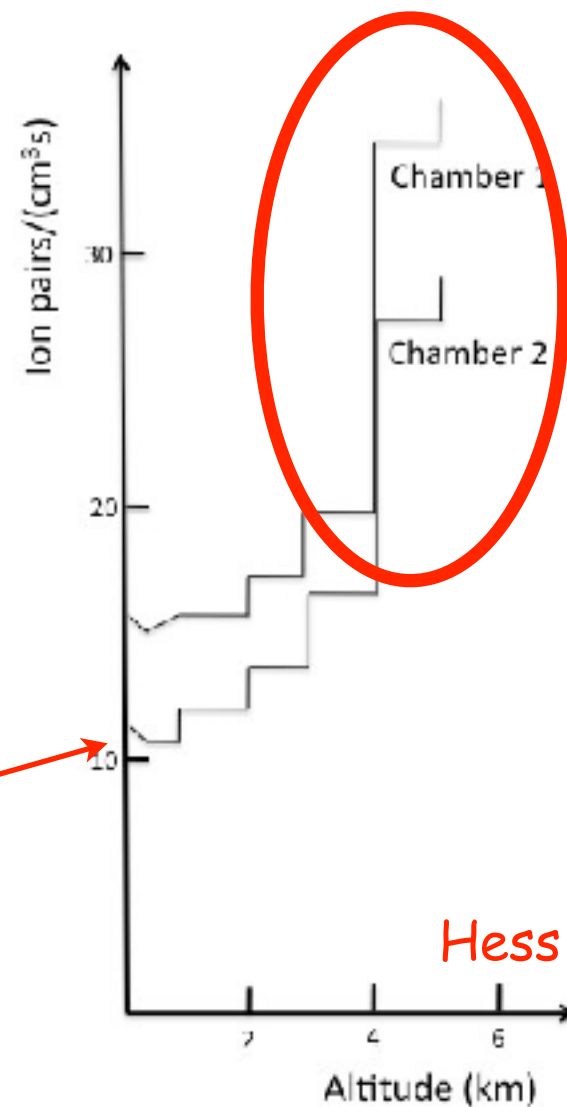
Hess



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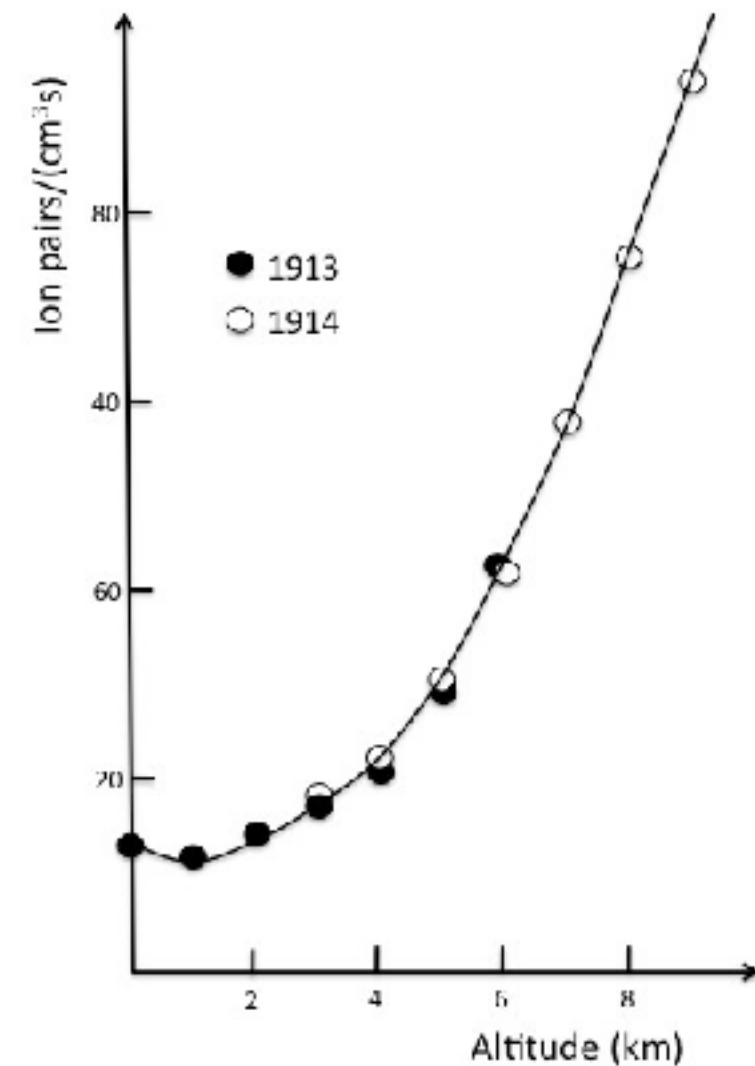


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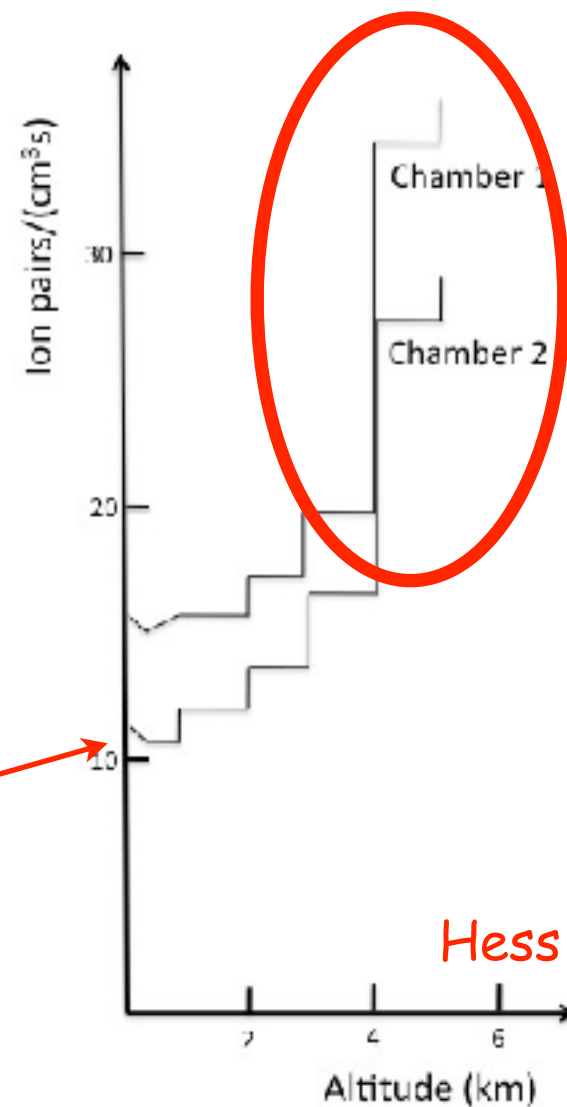
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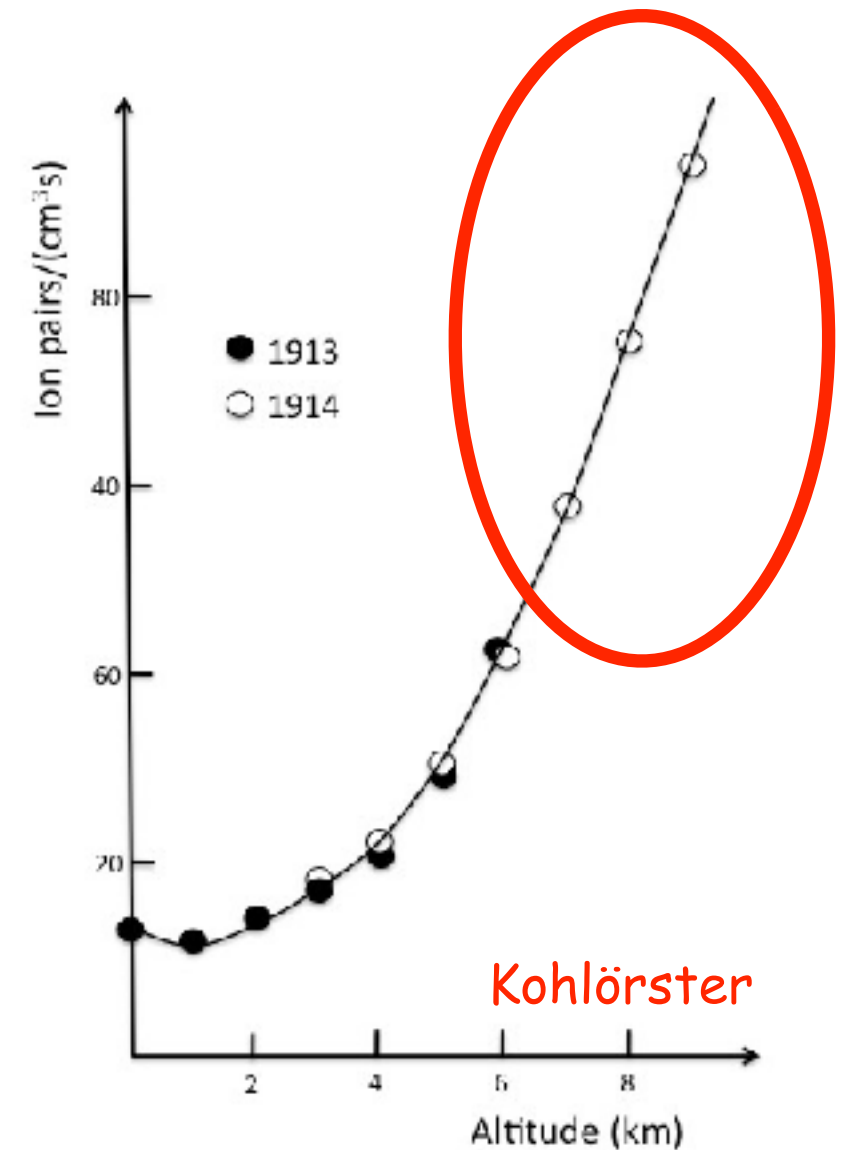
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Hess



Kohlörster

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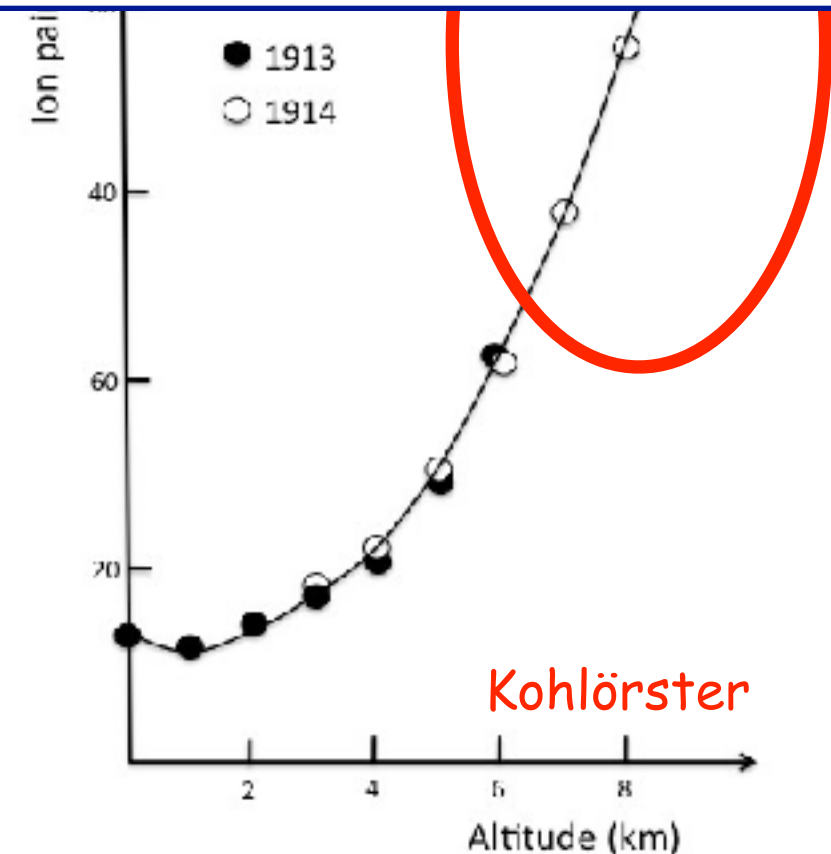
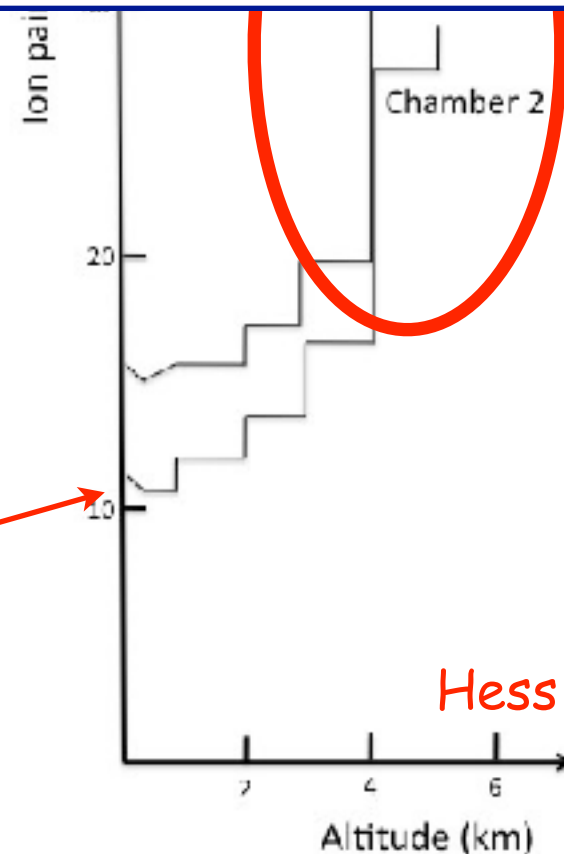


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The ionizing radiation has an extra-terrestrial origin



Wulf was right!



[2] What are cosmic rays?

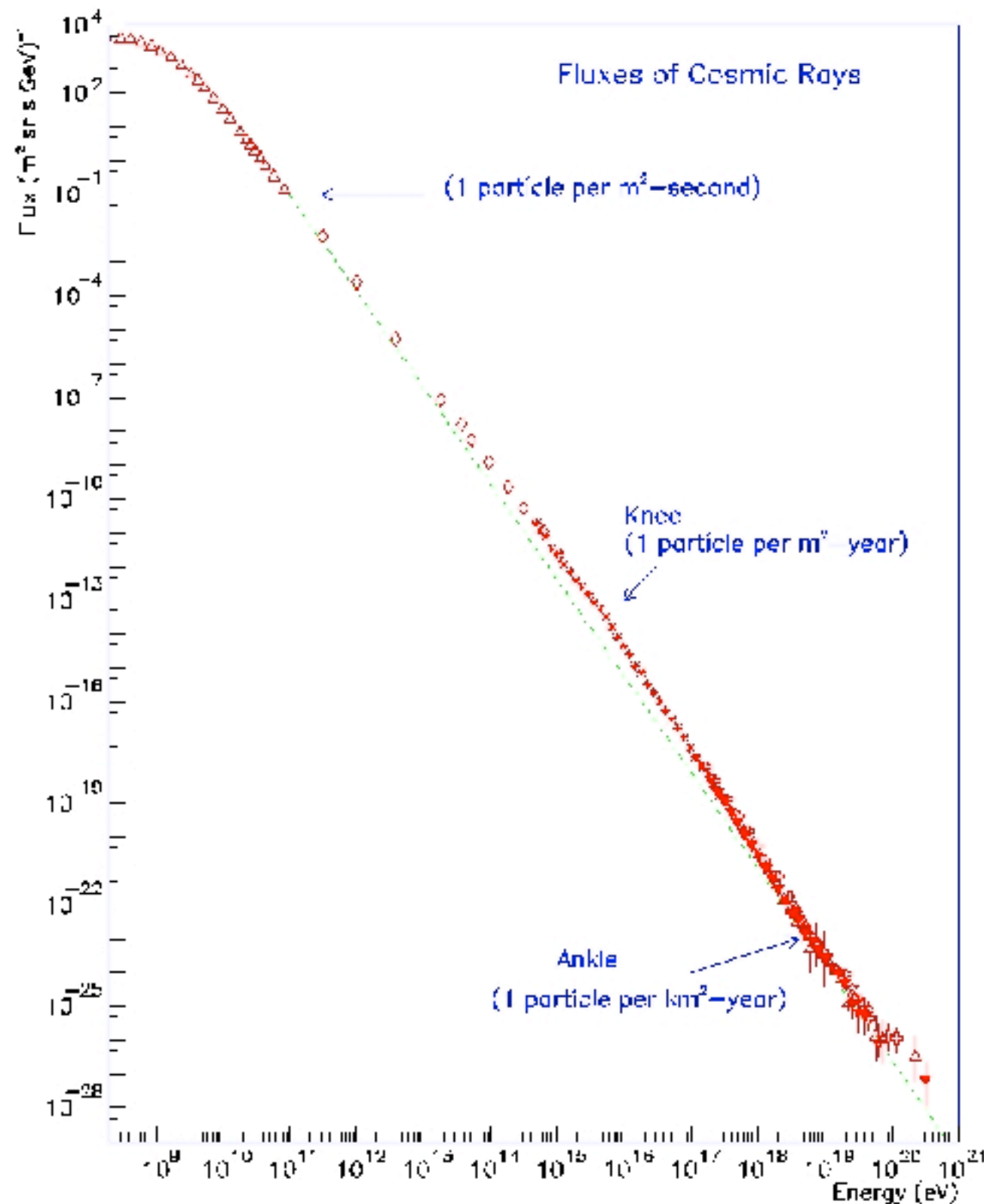
What are Cosmic Rays?

Cosmic rays 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 heavy nuclei - and they are distinguished by their high energies. Most cosmic rays are **relativistic**, having energies comparable or somewhat greater than their masses. A very few of them have ultrarelativistic energies extending up to 10^{20} eV (about 20 Joules), eleven order of magnitudes 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?**".

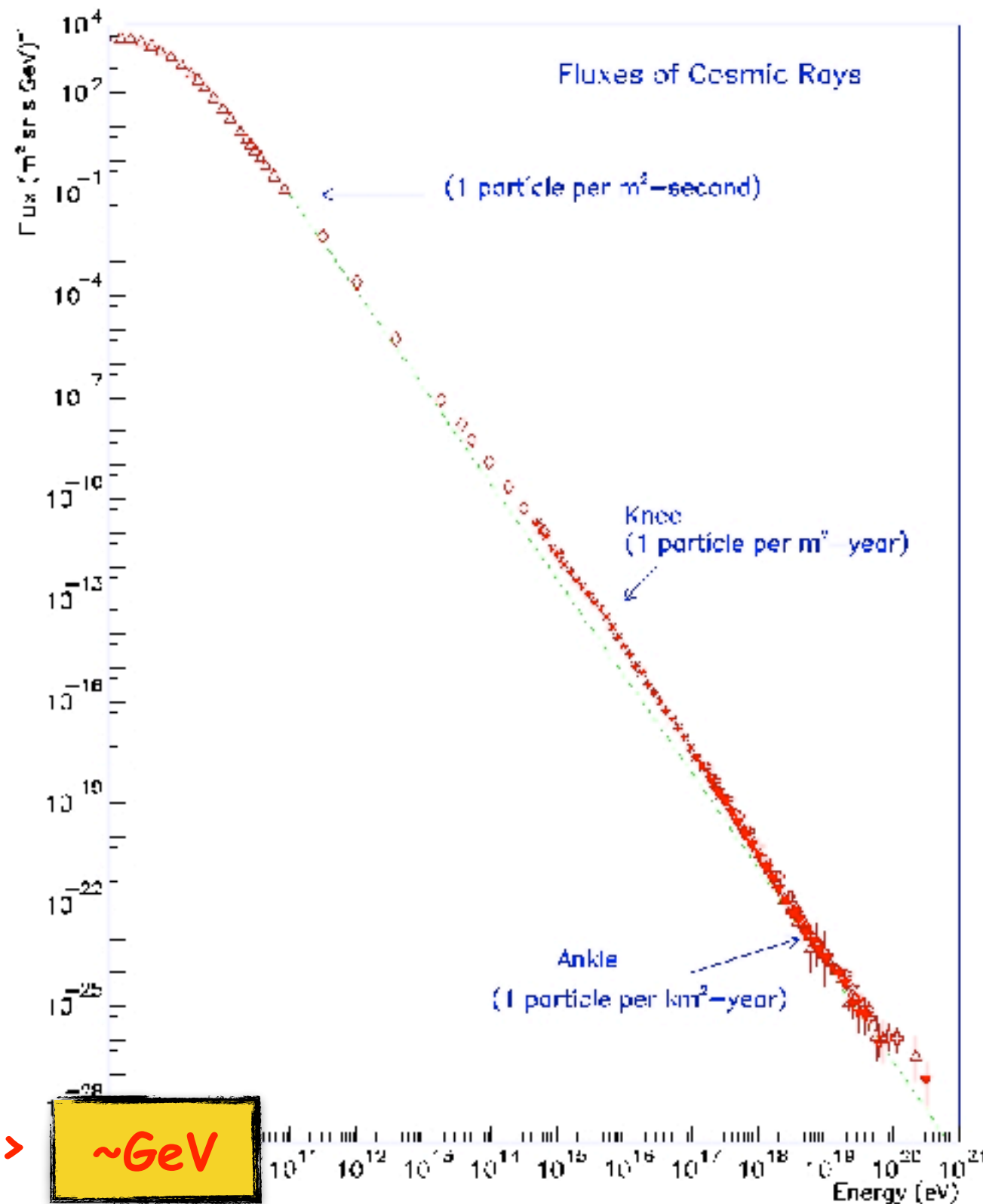
T. Gaisser "Cosmic Rays and Particle Physics"

Also **electrons** are present in the cosmic radiation -> **~ 1%**

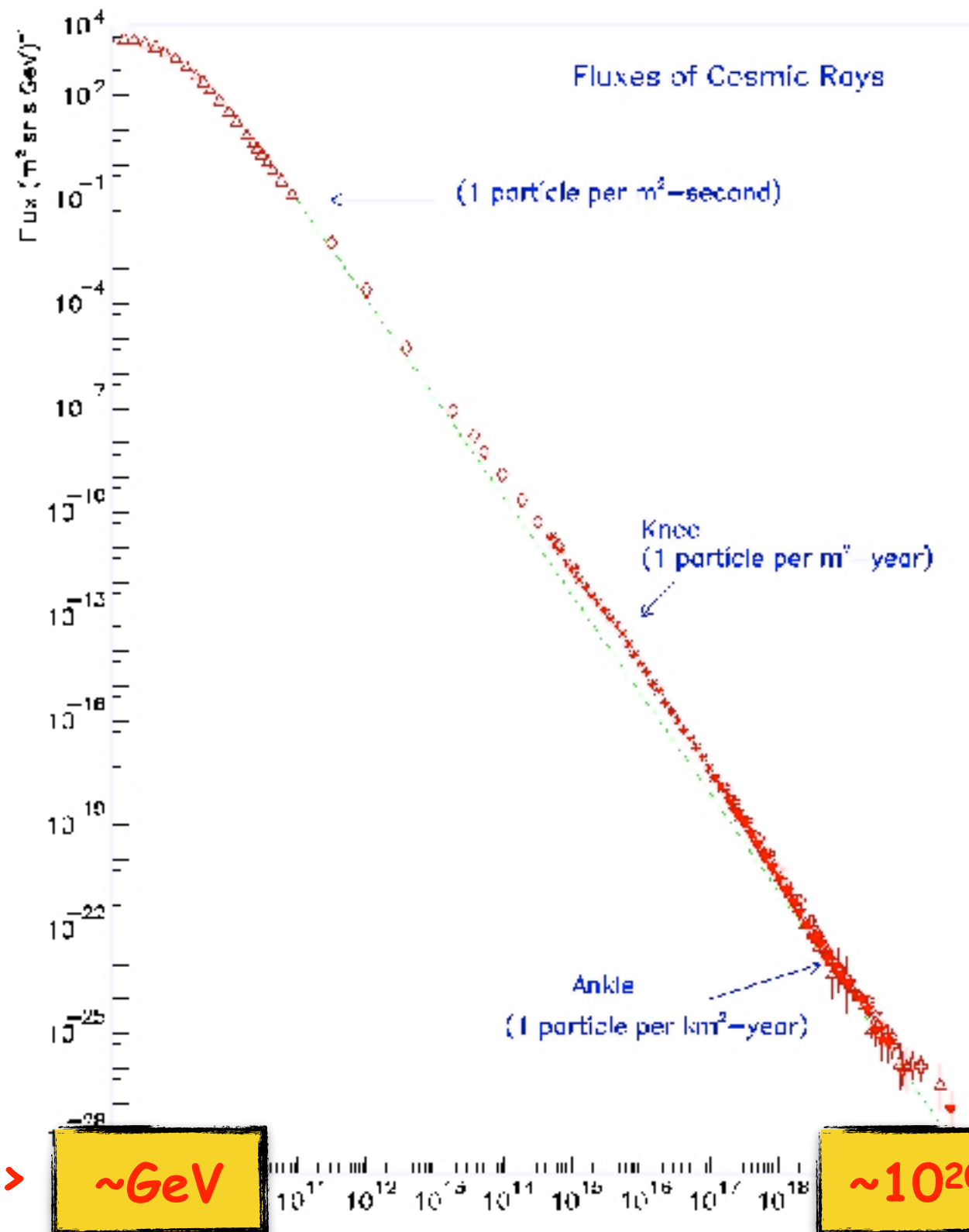
The (local) Cosmic Ray spectrum



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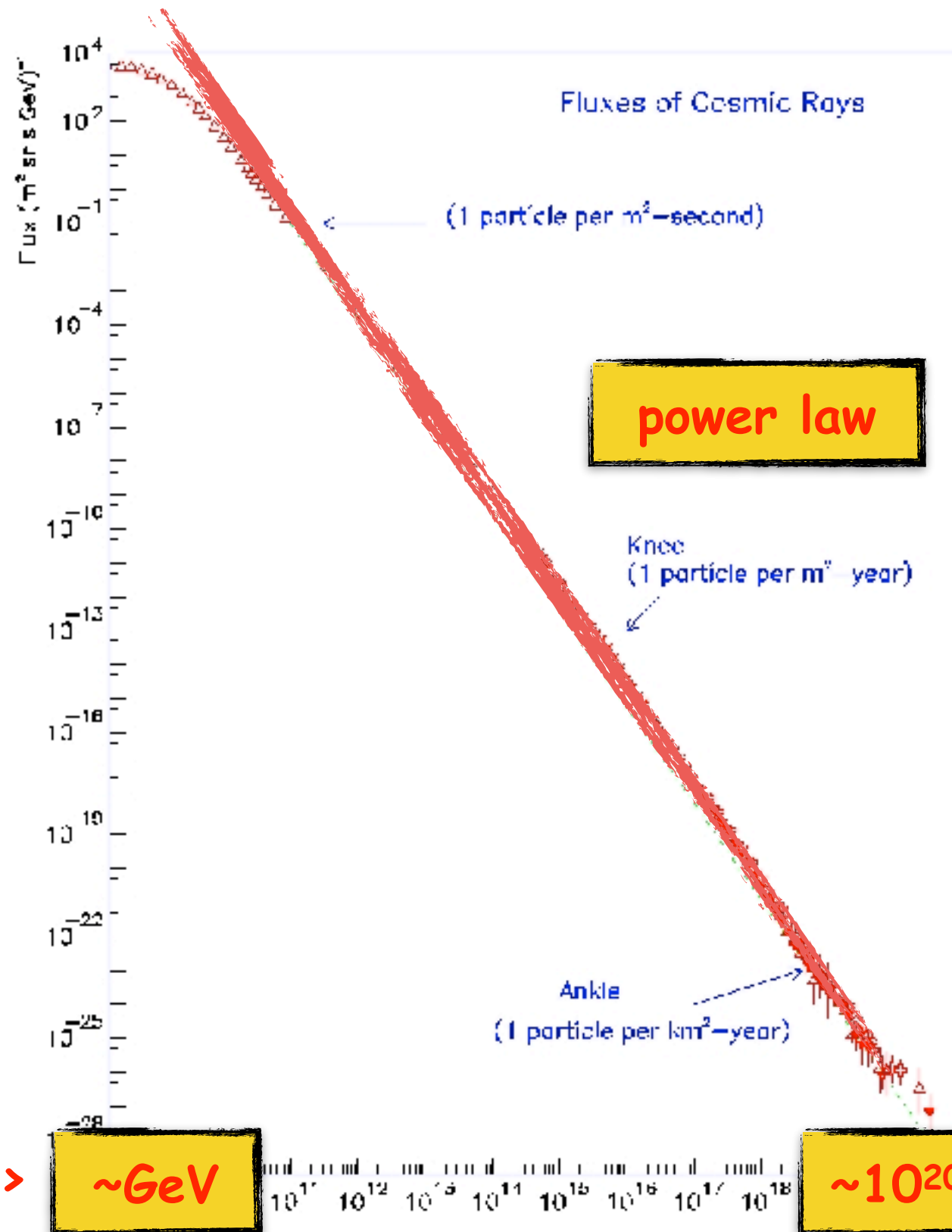
mean energy ->

$\sim \text{GeV}$

$\sim 10^{20} \text{ eV}$

< - maximum energy

The (local) Cosmic Ray spectrum



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

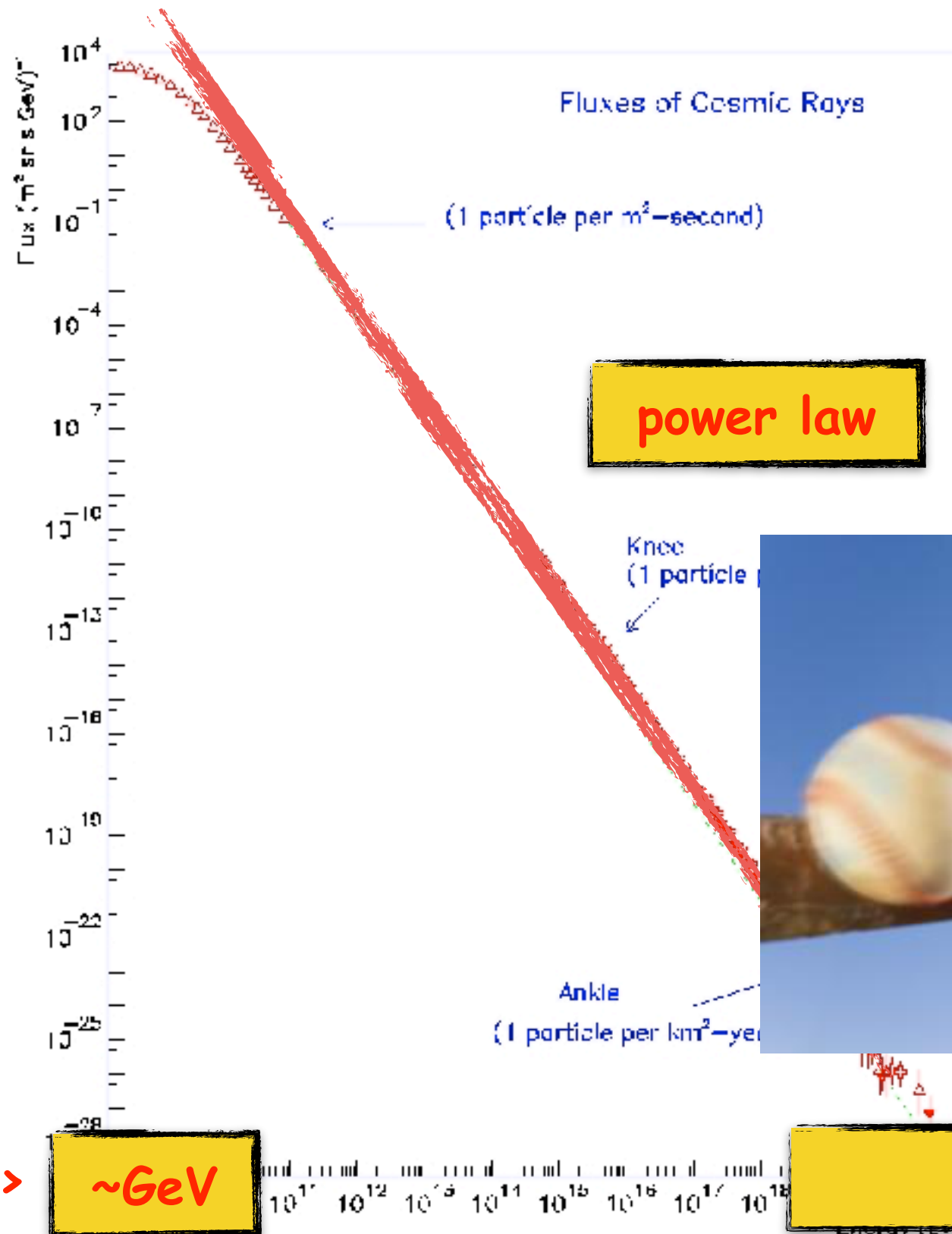
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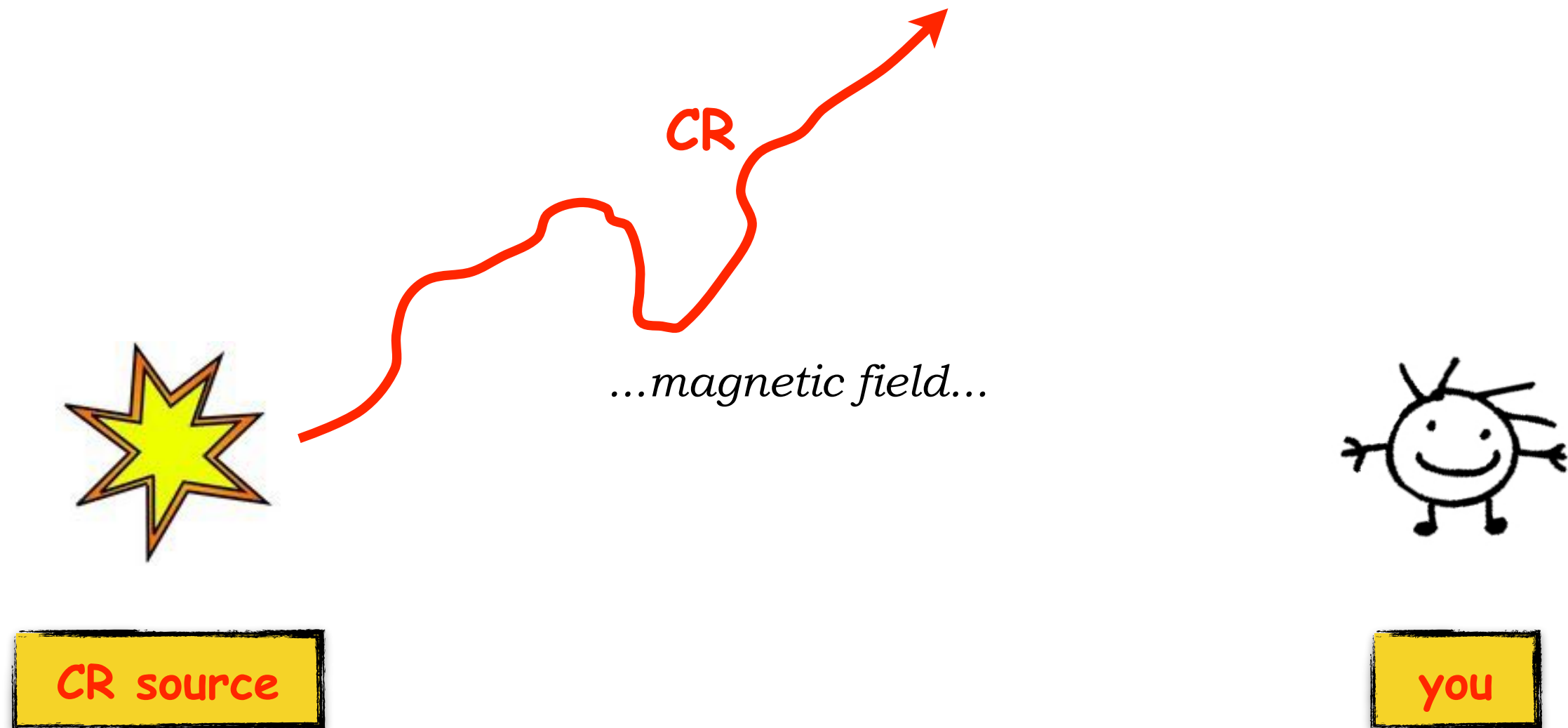


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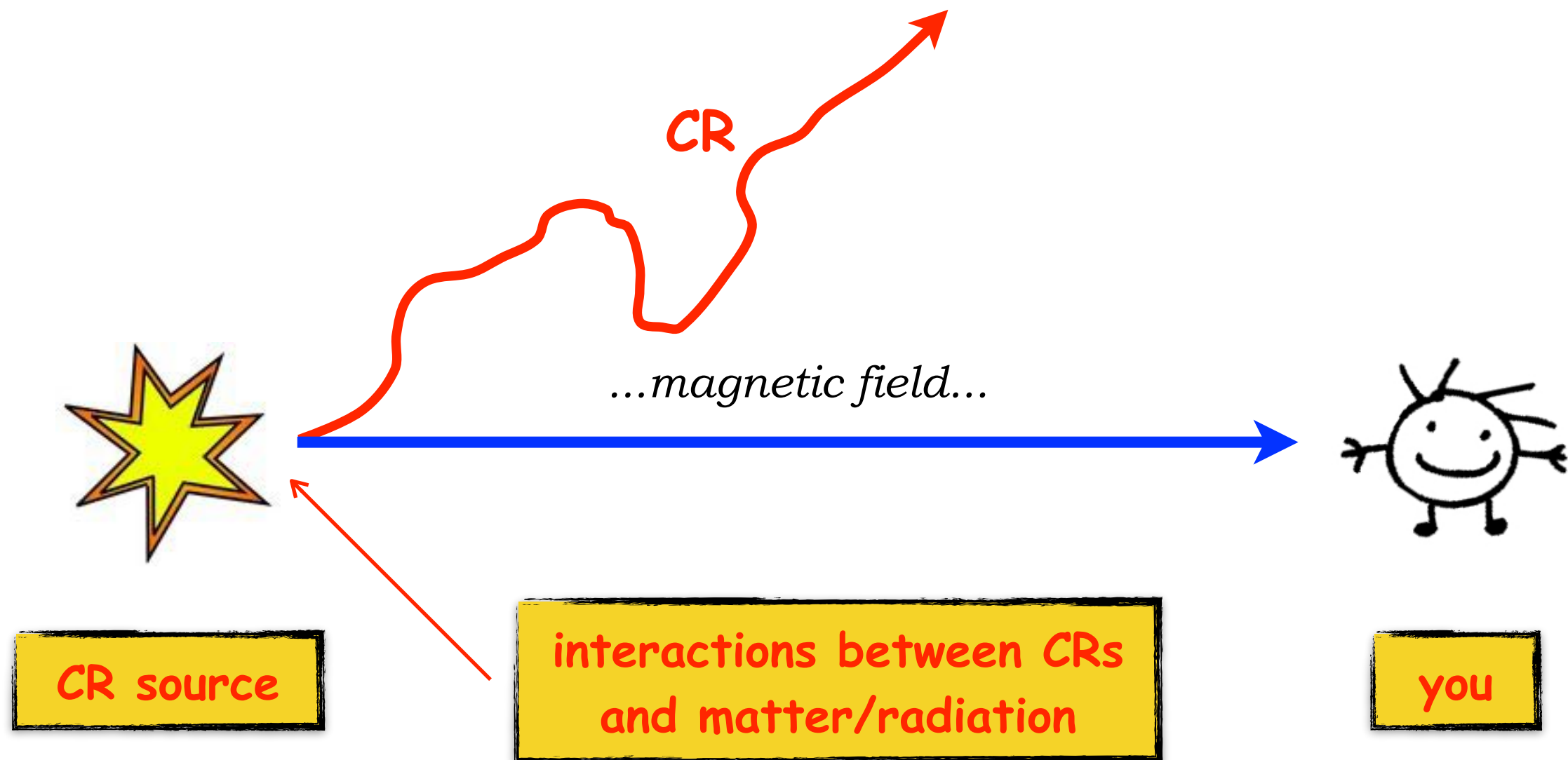


tens of Joules!

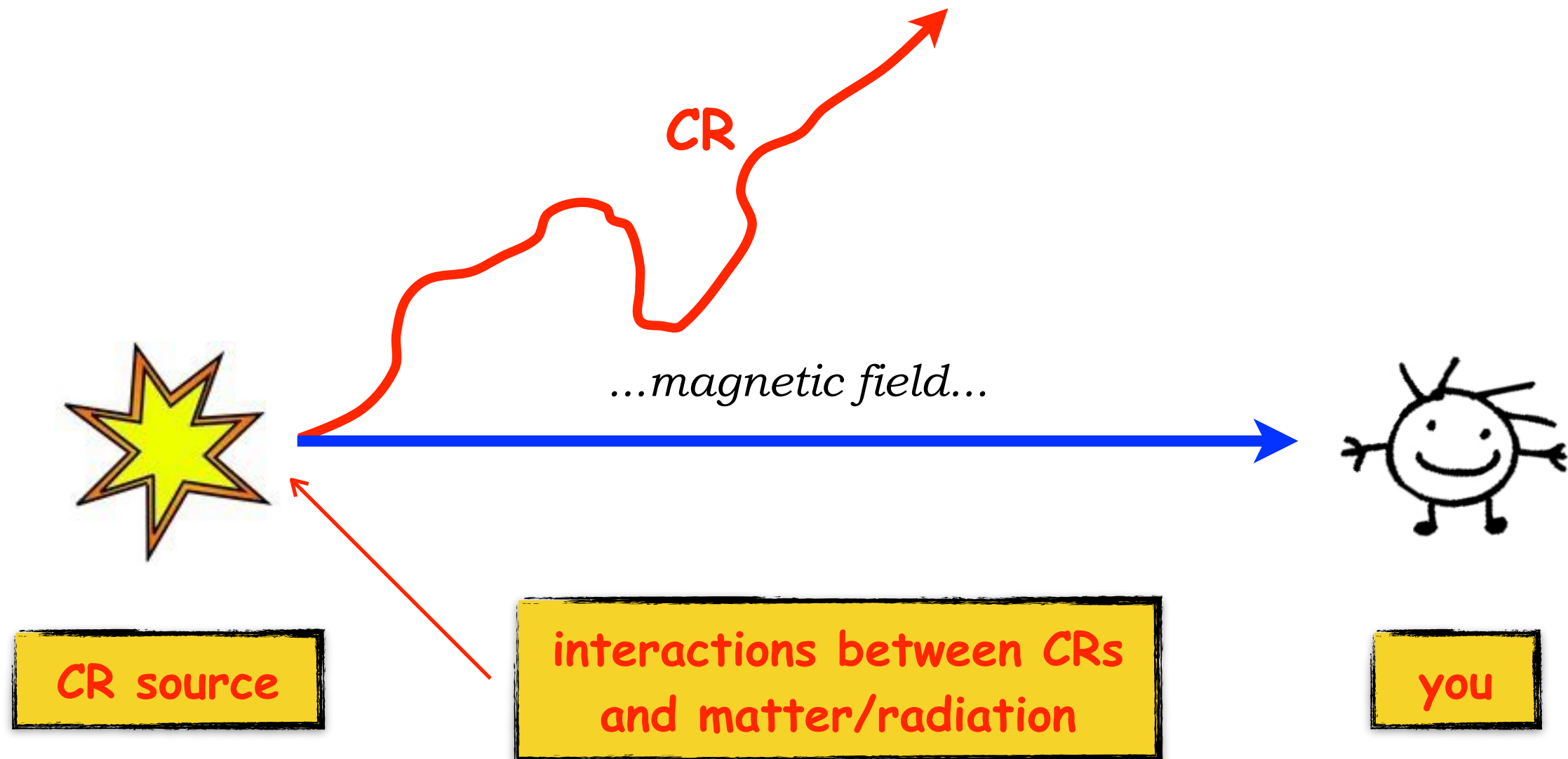
Cosmic ray sources: why is it so difficult?



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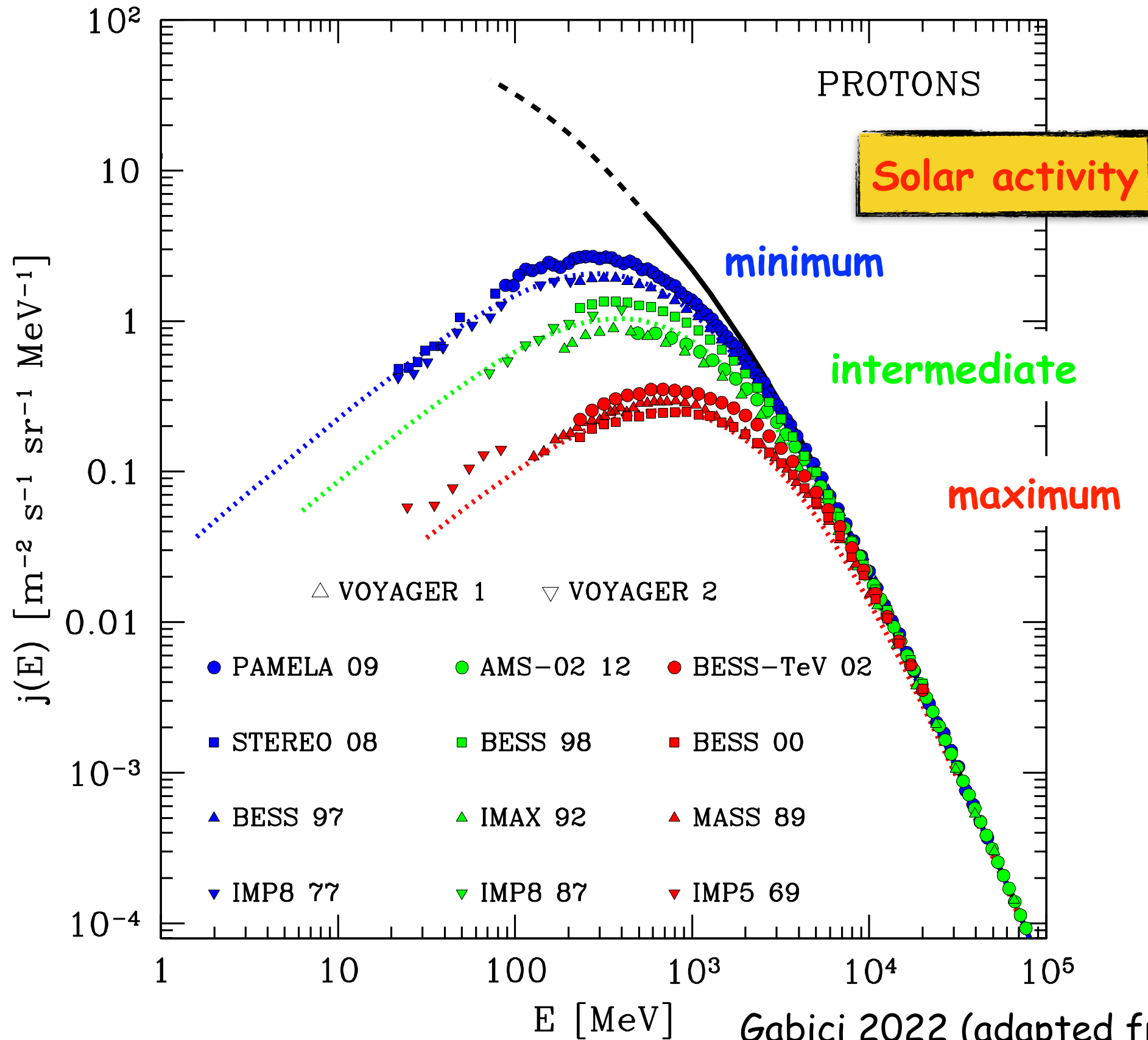
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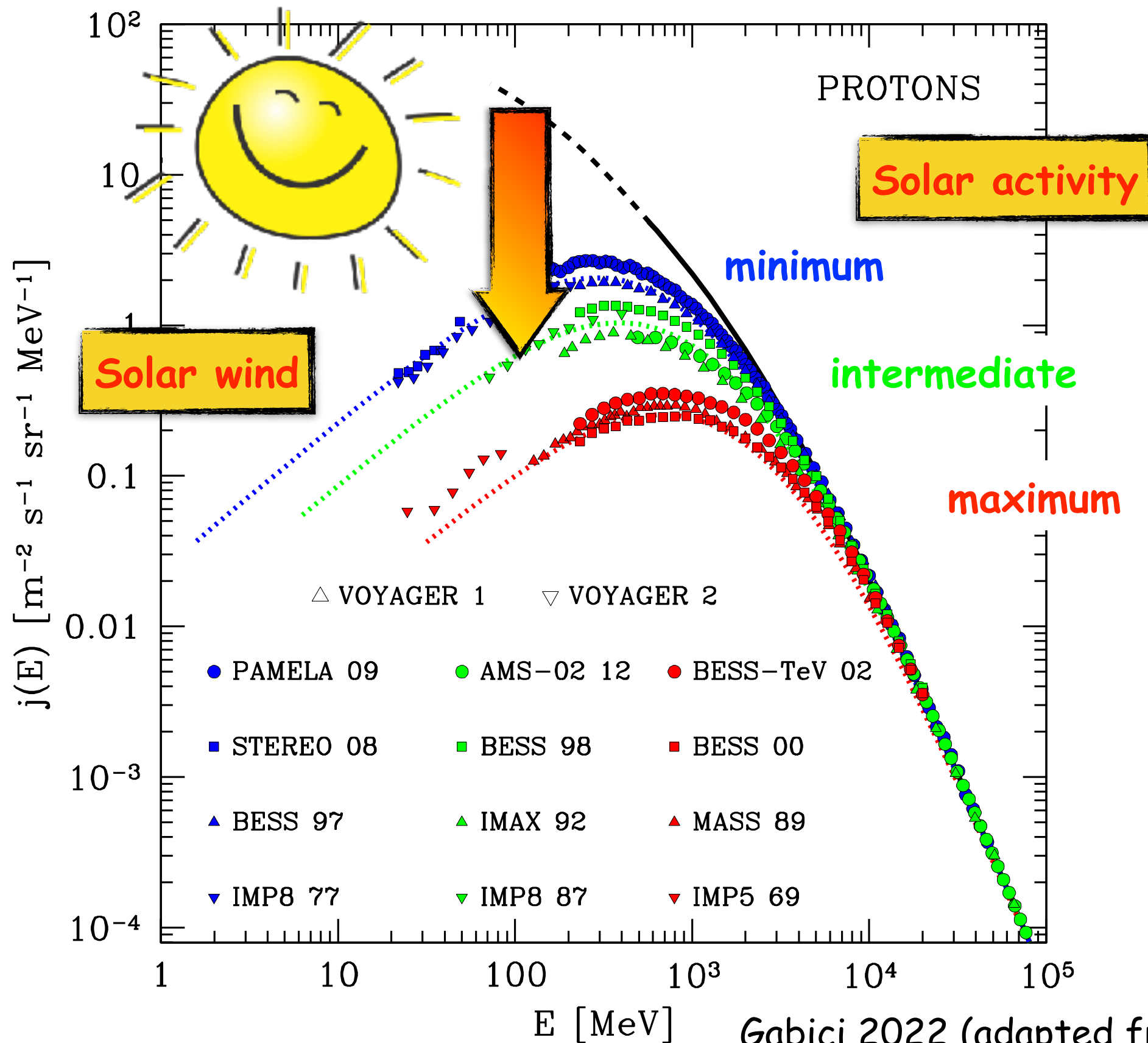
We cannot do CR Astronomy.

Need for indirect identification of CR sources.

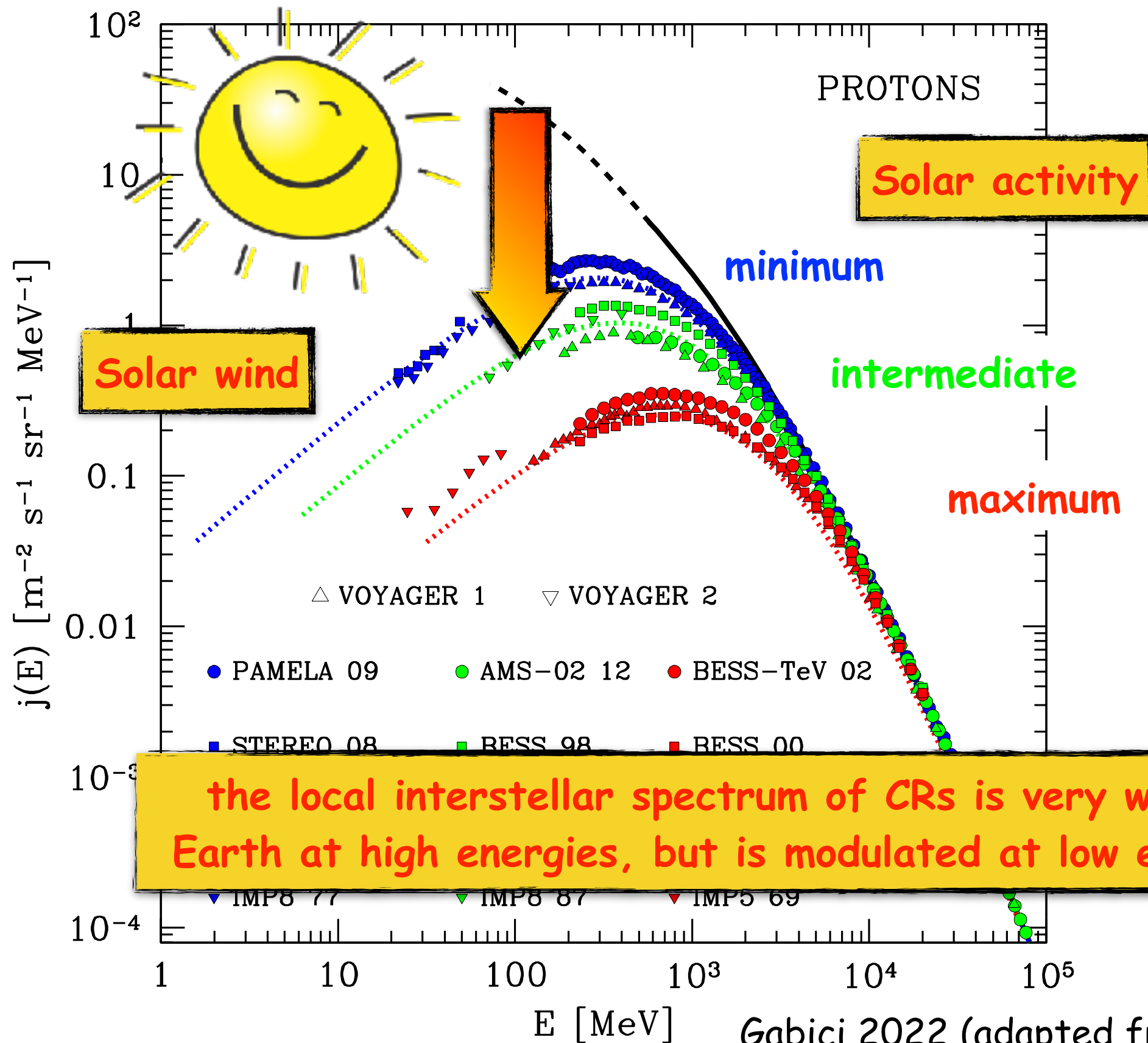
Solar modulation



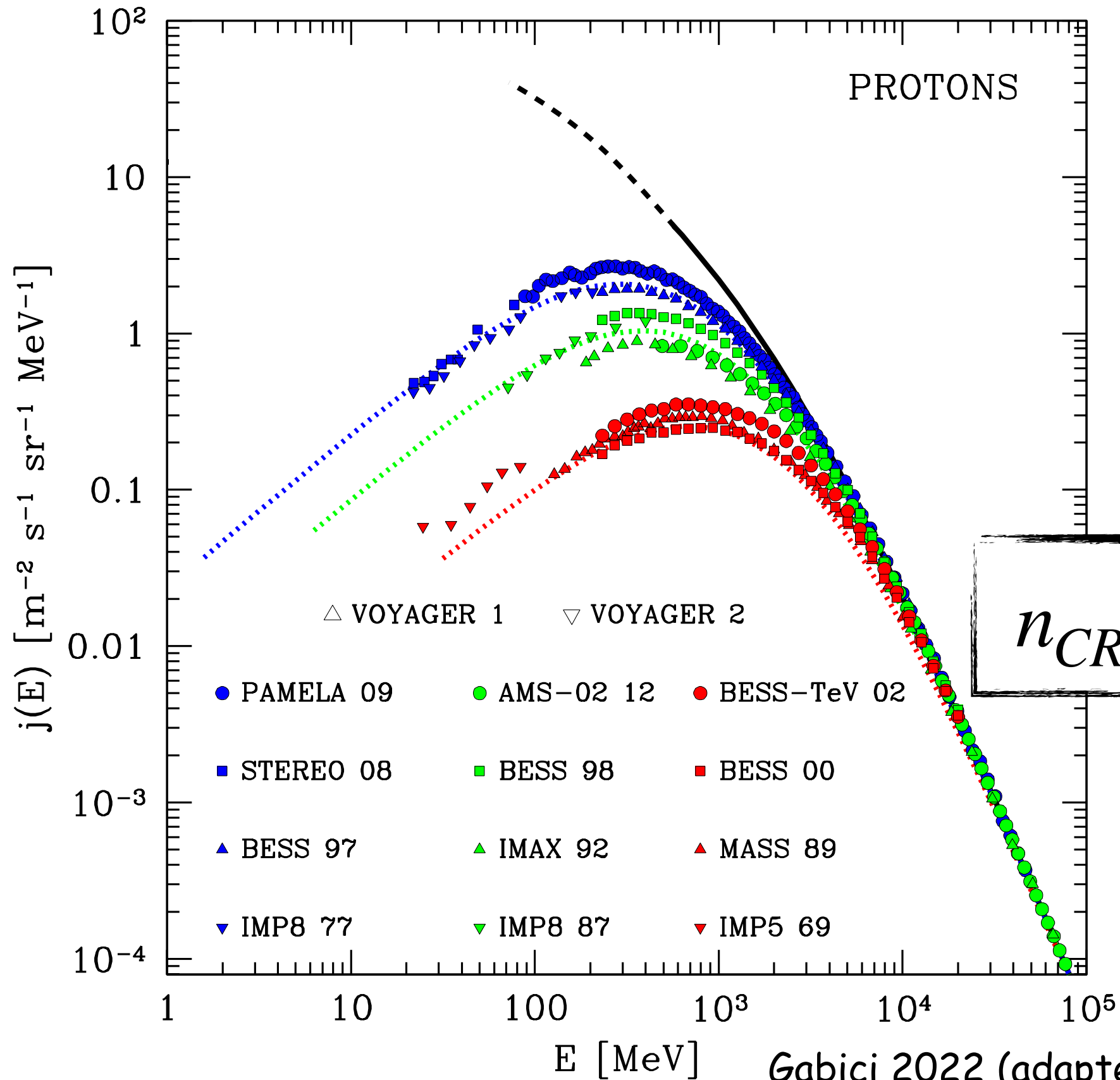
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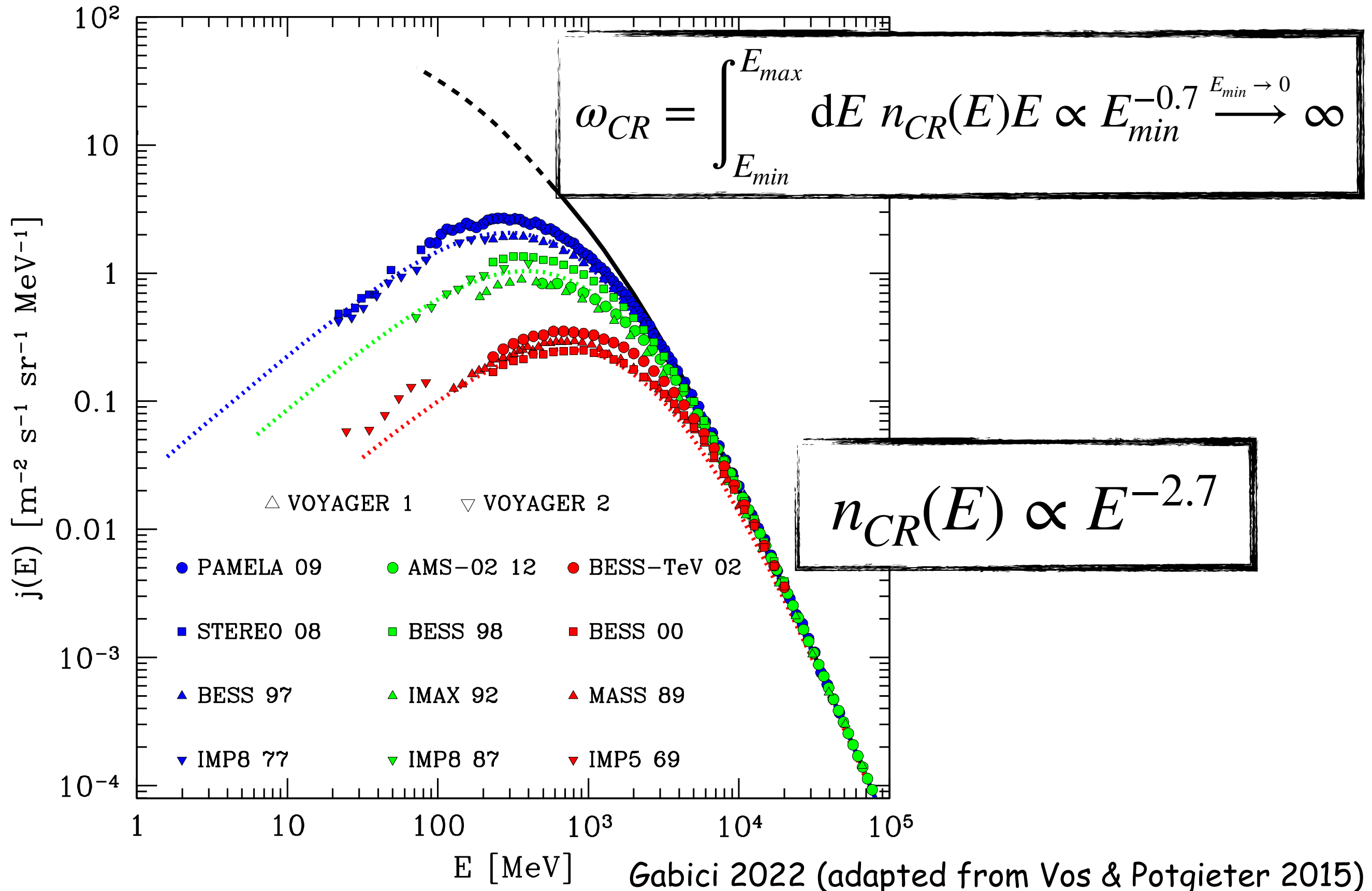


Solar modulation

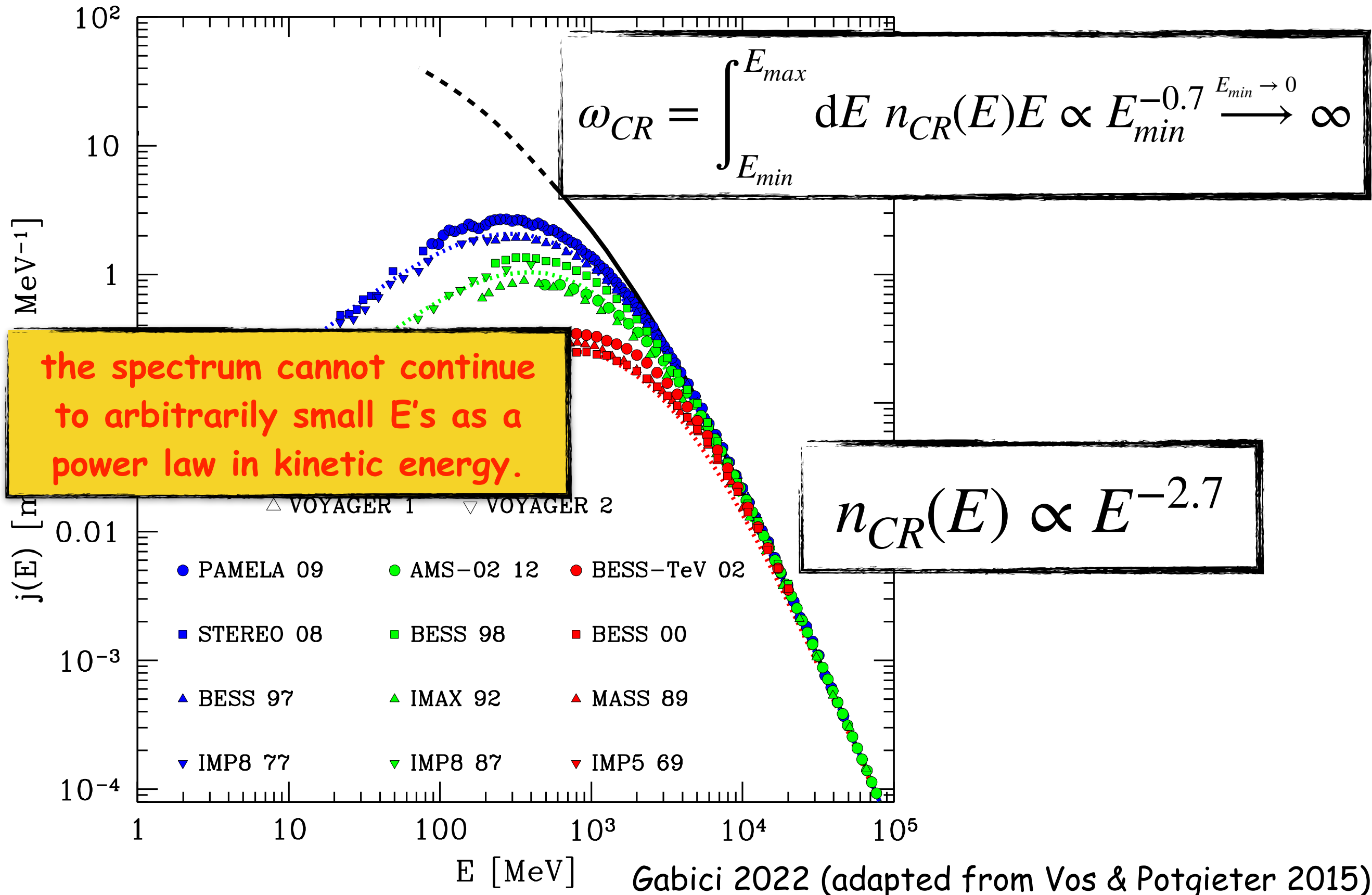


$$n_{CR}(E) \propto E^{-2.7}$$

Solar modulation



Solar modulation



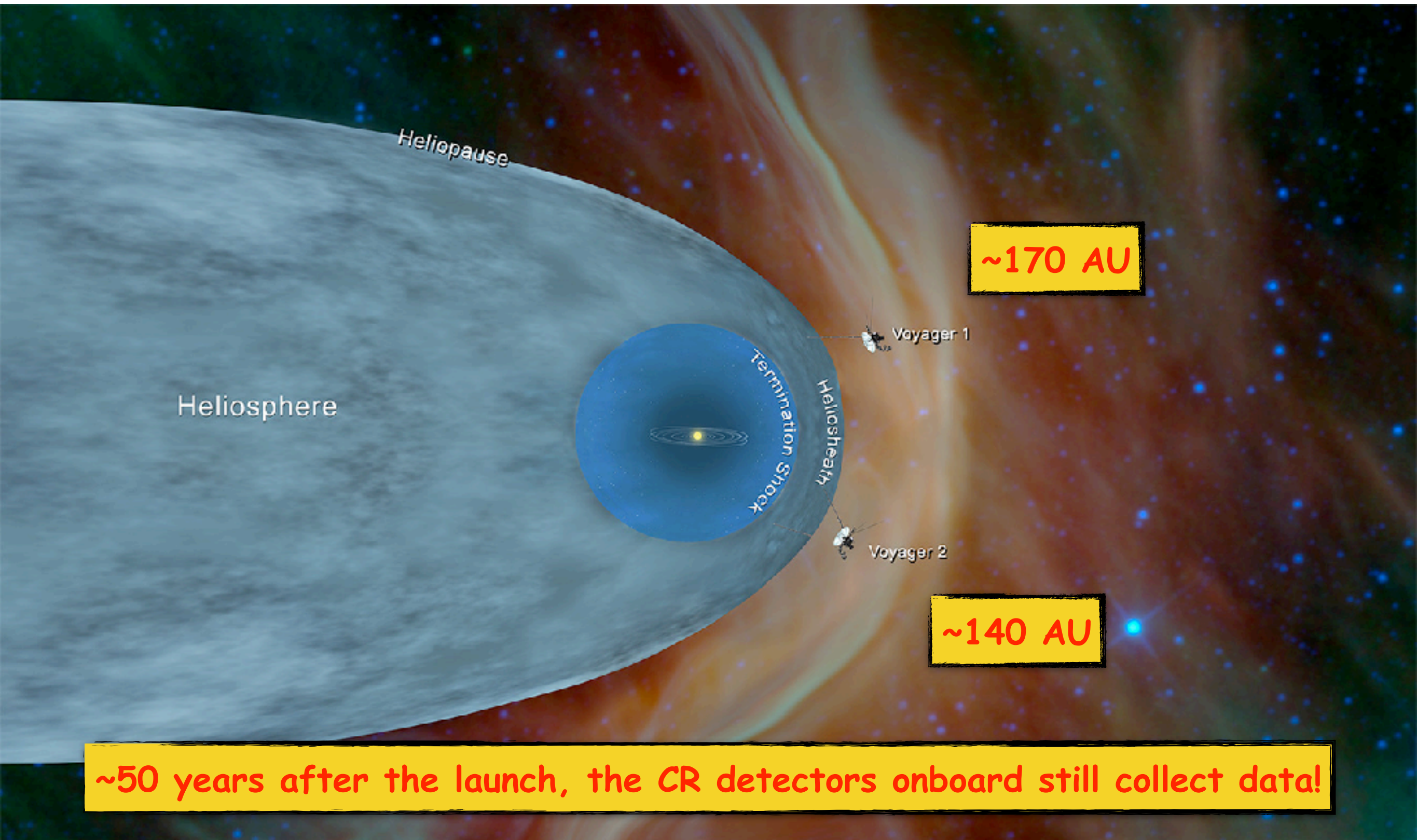
Voyager probes

September 5 1977
the launch of Voyager 1



August 20 1977 launch of the twin probe Voyager 2

Voyager probes crossed the heliopause



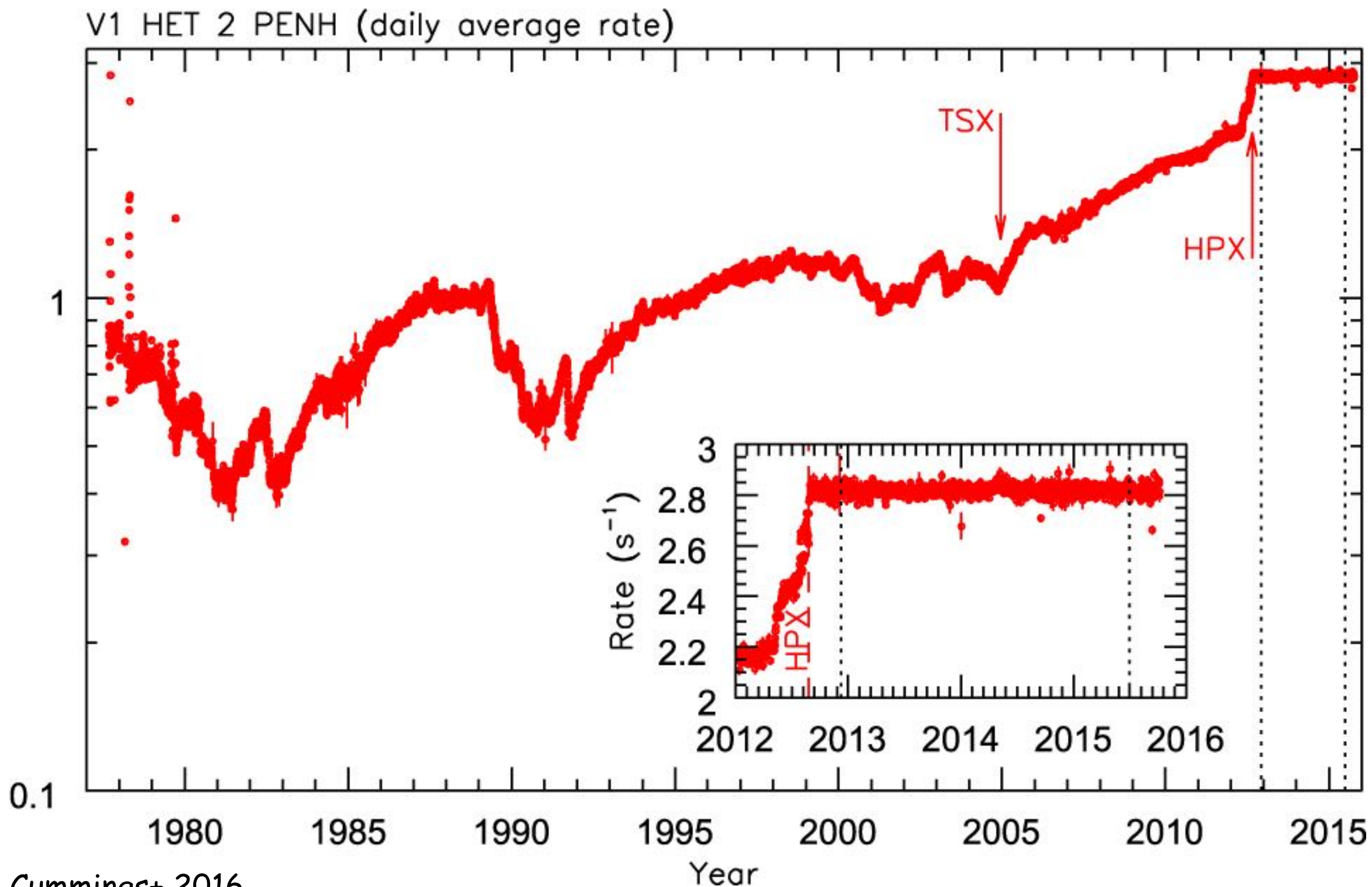
Instrument	Voyager 1	Voyager 2
Cosmic Ray Subsystem (CRS)	Off to save power (Feb. 25, 2025)	On
Low-Energy Charged Particles (LECP)	Off to save power (April 17, 2026)	Off to save power (March 24, 2025)
Magnetometer (MAG)	On	On
Plasma Wave Subsystem (PWS)	On	On
Plasma Science (PLS)	Off because of degraded performance (Feb. 1, 2007)	Off to save power (Sept. 26, 2024)
Imaging Science Subsystem (ISS)	Wide-angle and narrow-angle cameras off to save power (Feb. 14, 1990)	Wide-angle and narrow angle cameras off to save power (Oct. 10 and Dec. 5, 1989)
Infrared Interferometer Spectrometer and Radiometer (IRIS)	Off to save power (June 3, 1998)	Off to save power (Feb. 1, 2007)
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Updated April 17, 2026

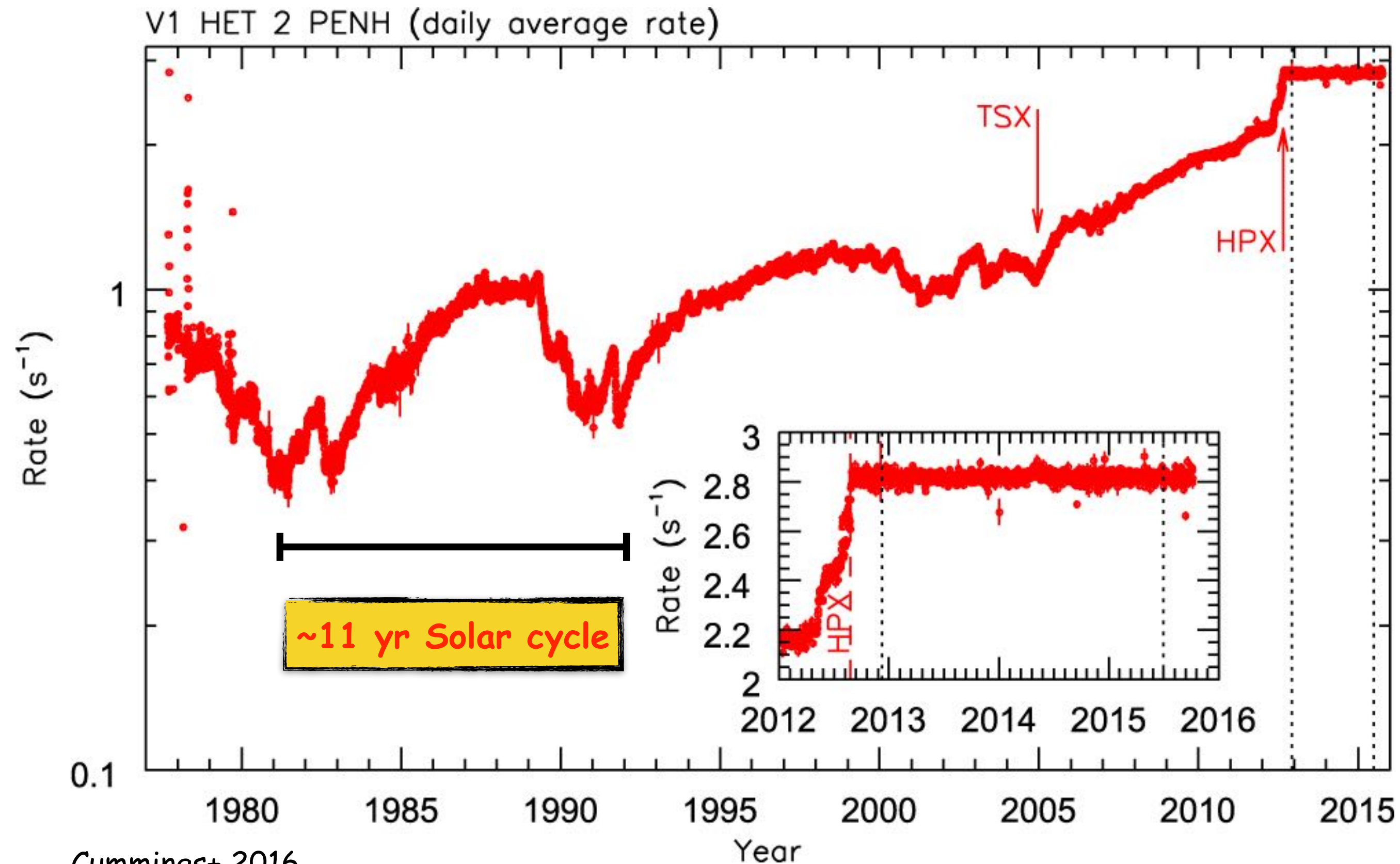
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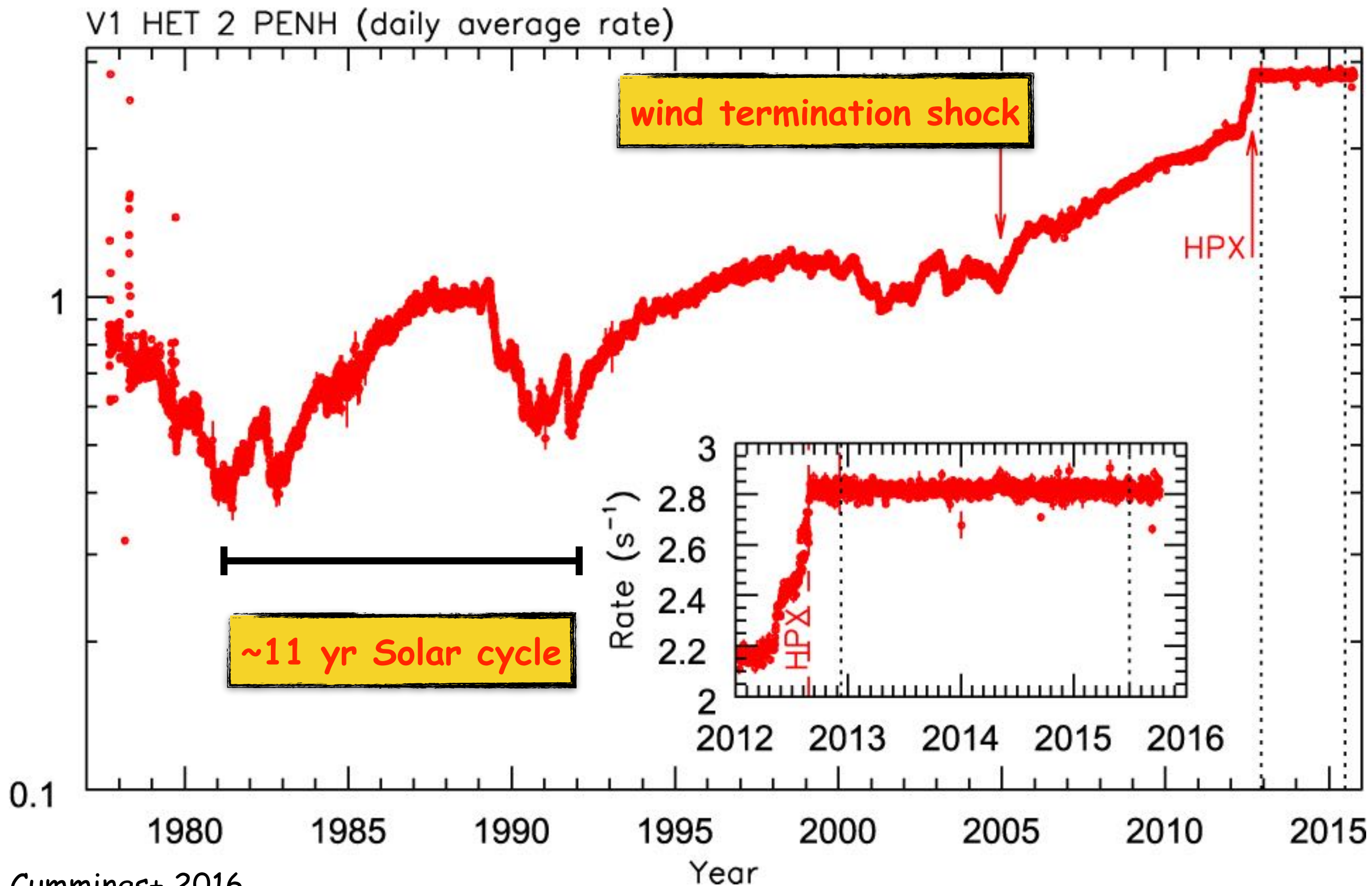
An epic journey



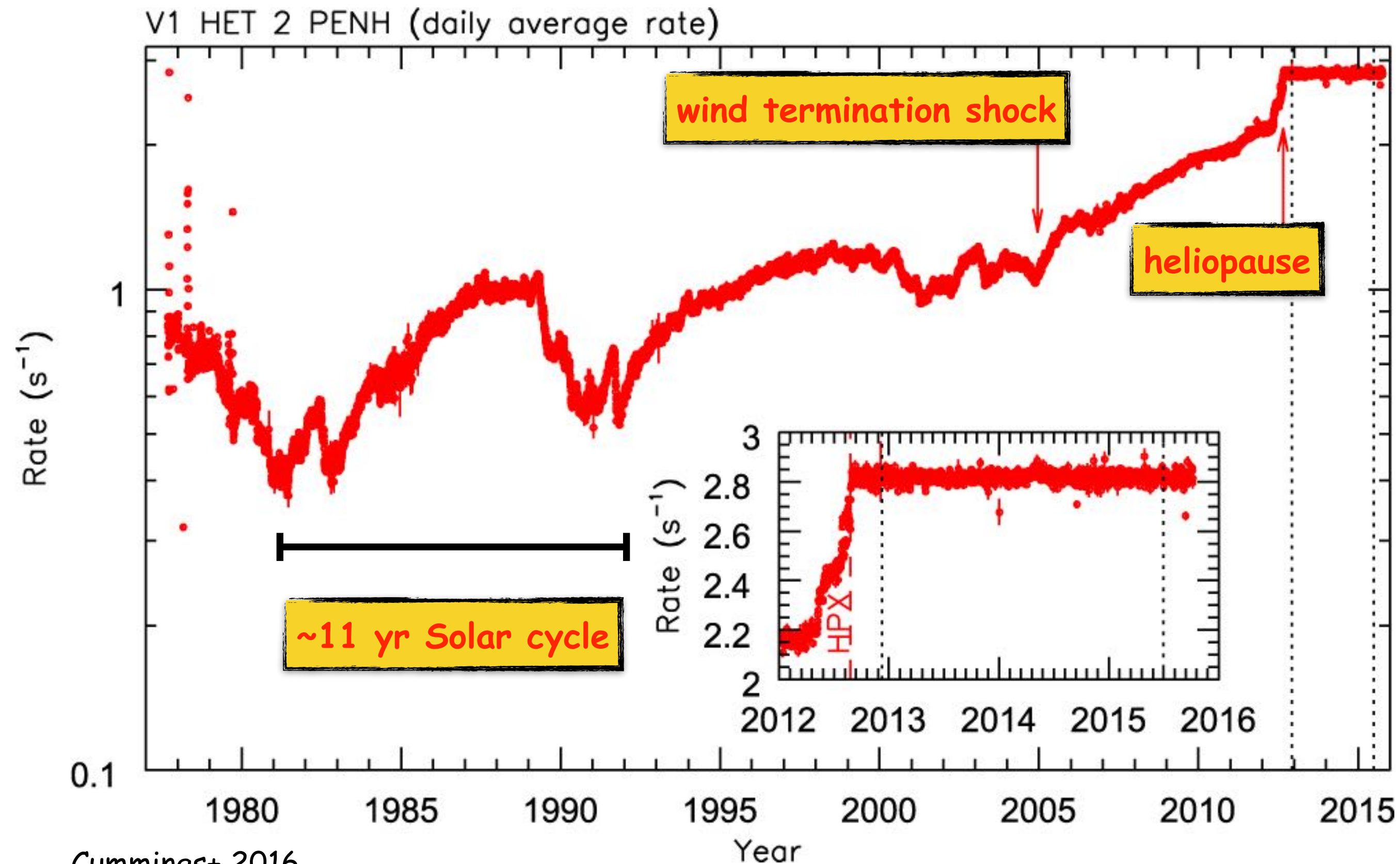
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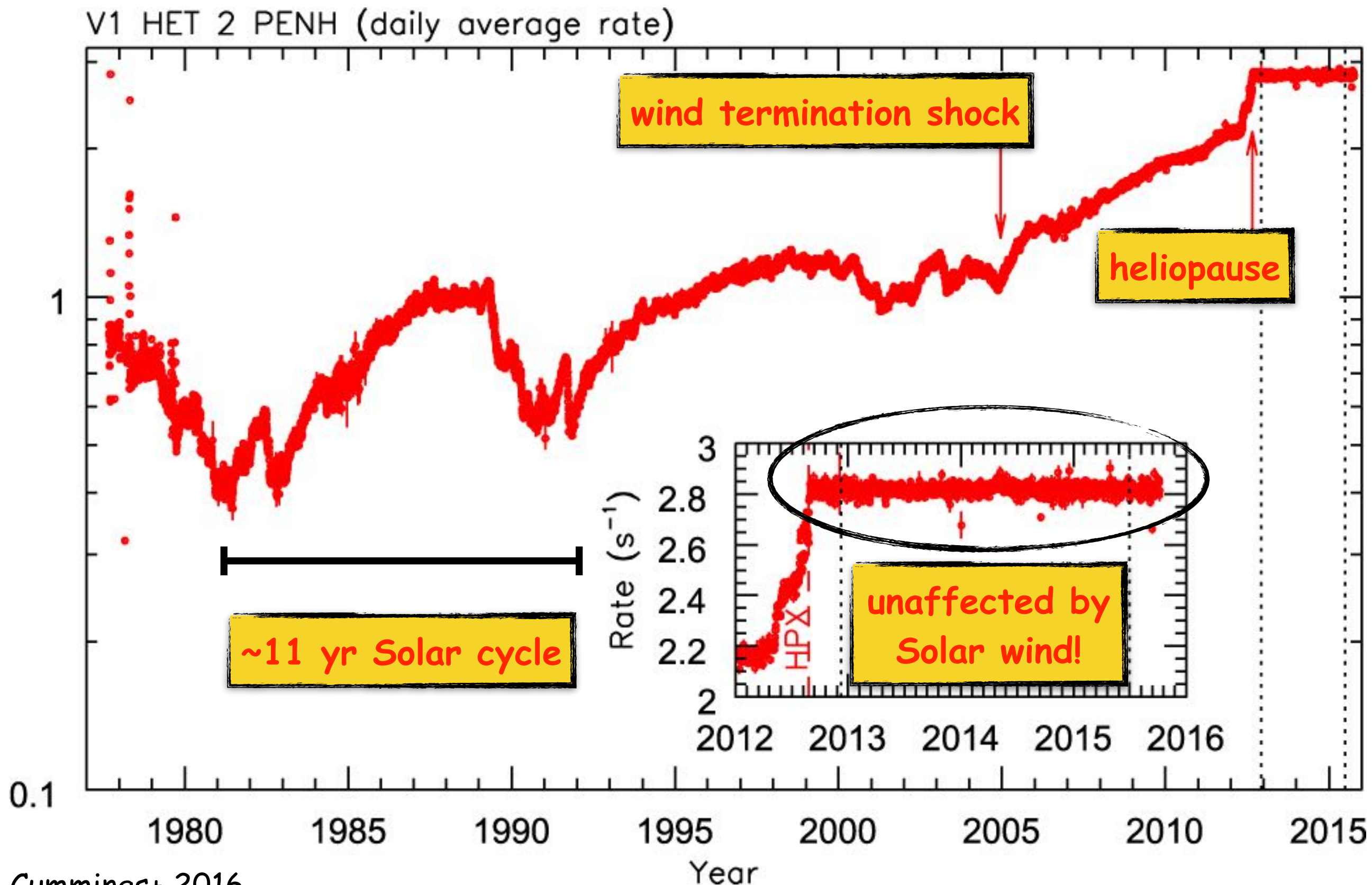
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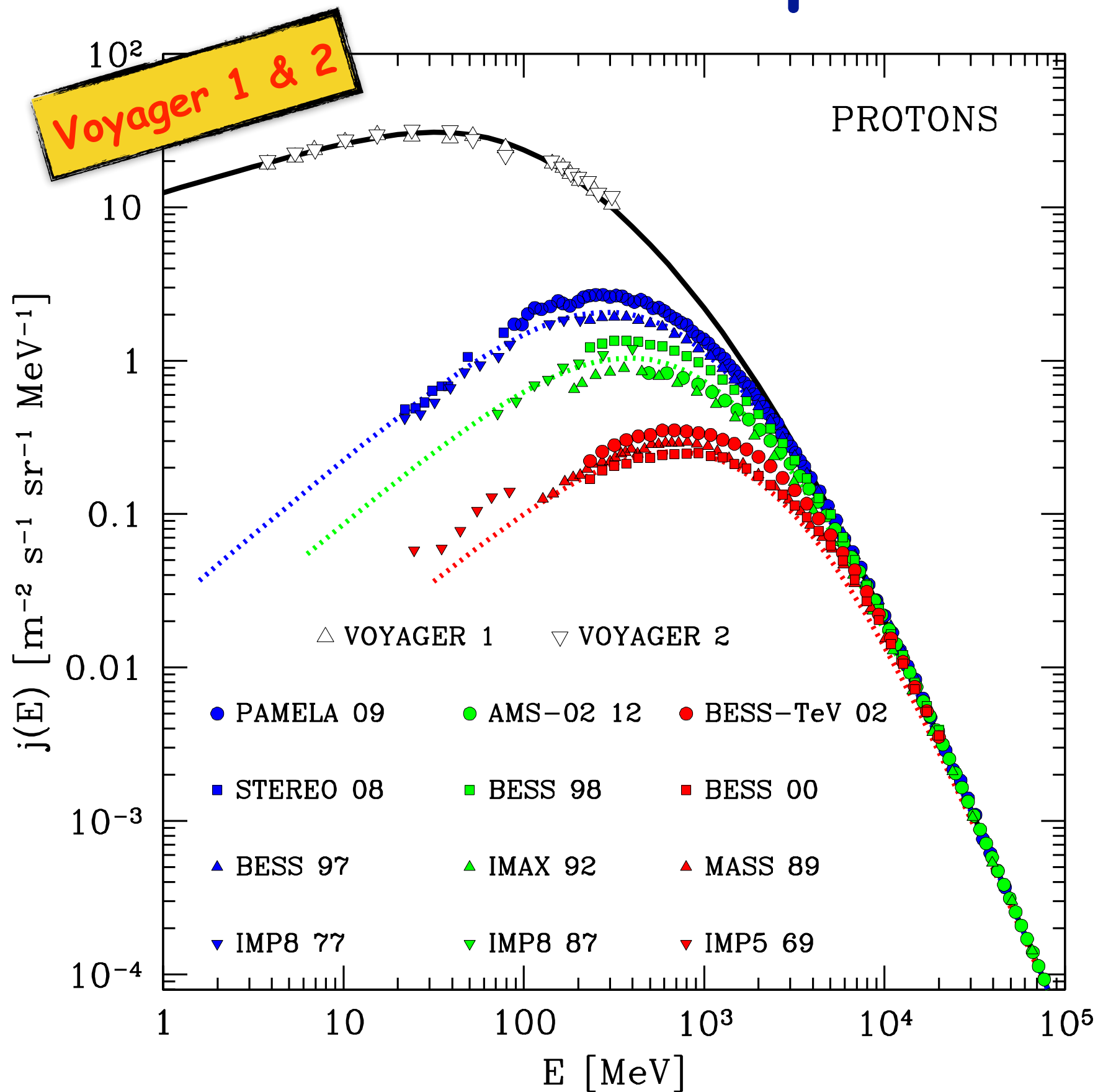
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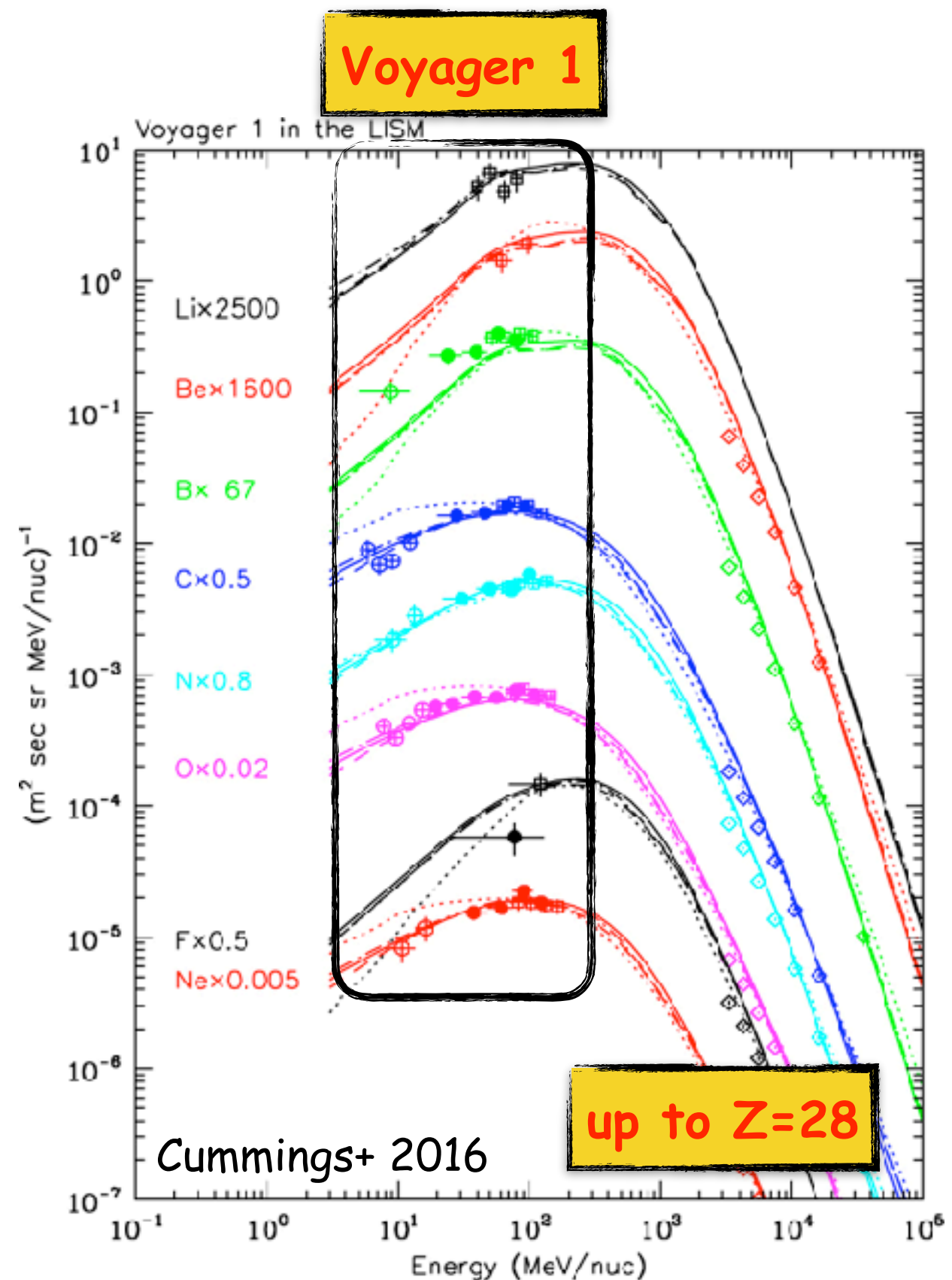
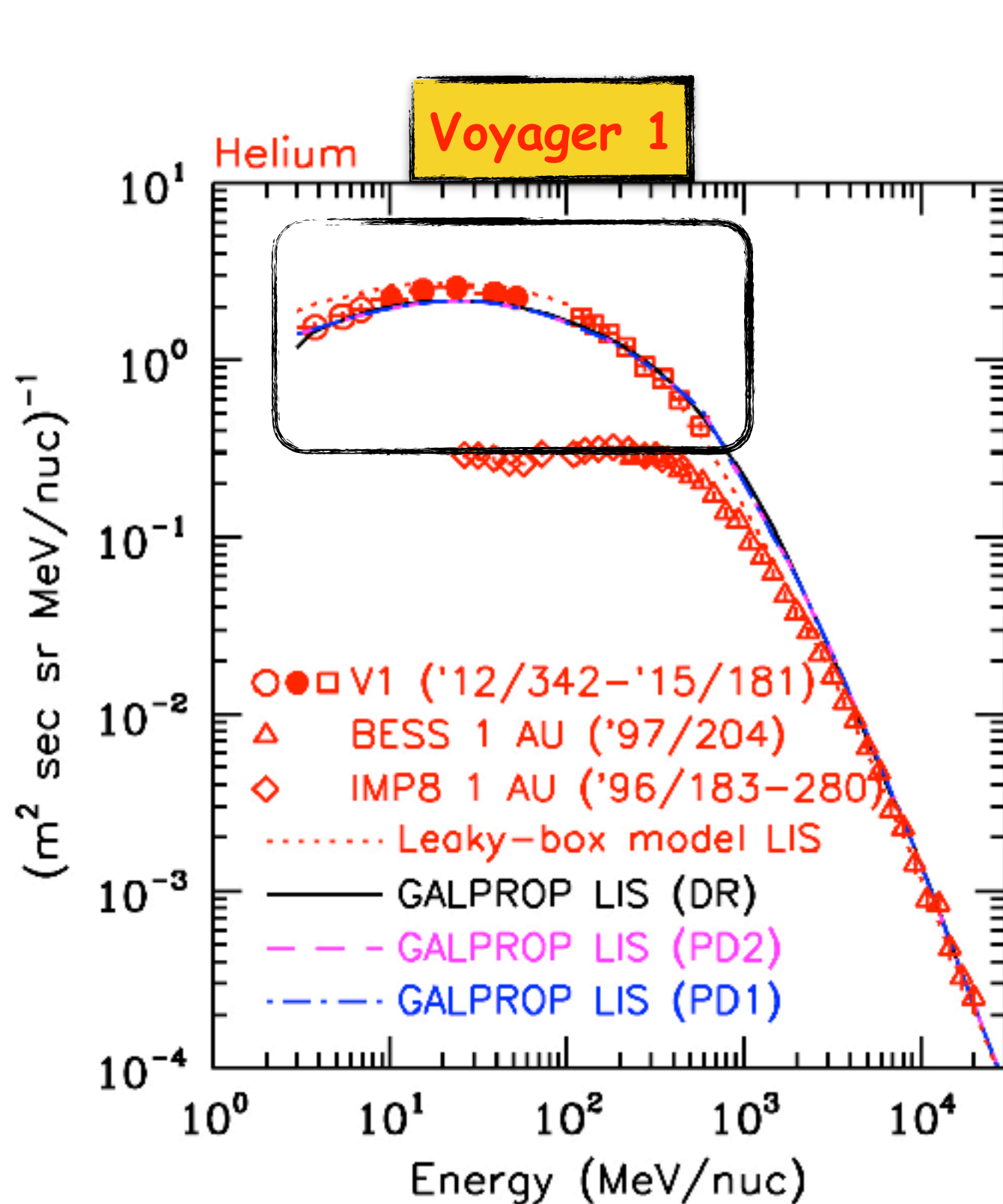
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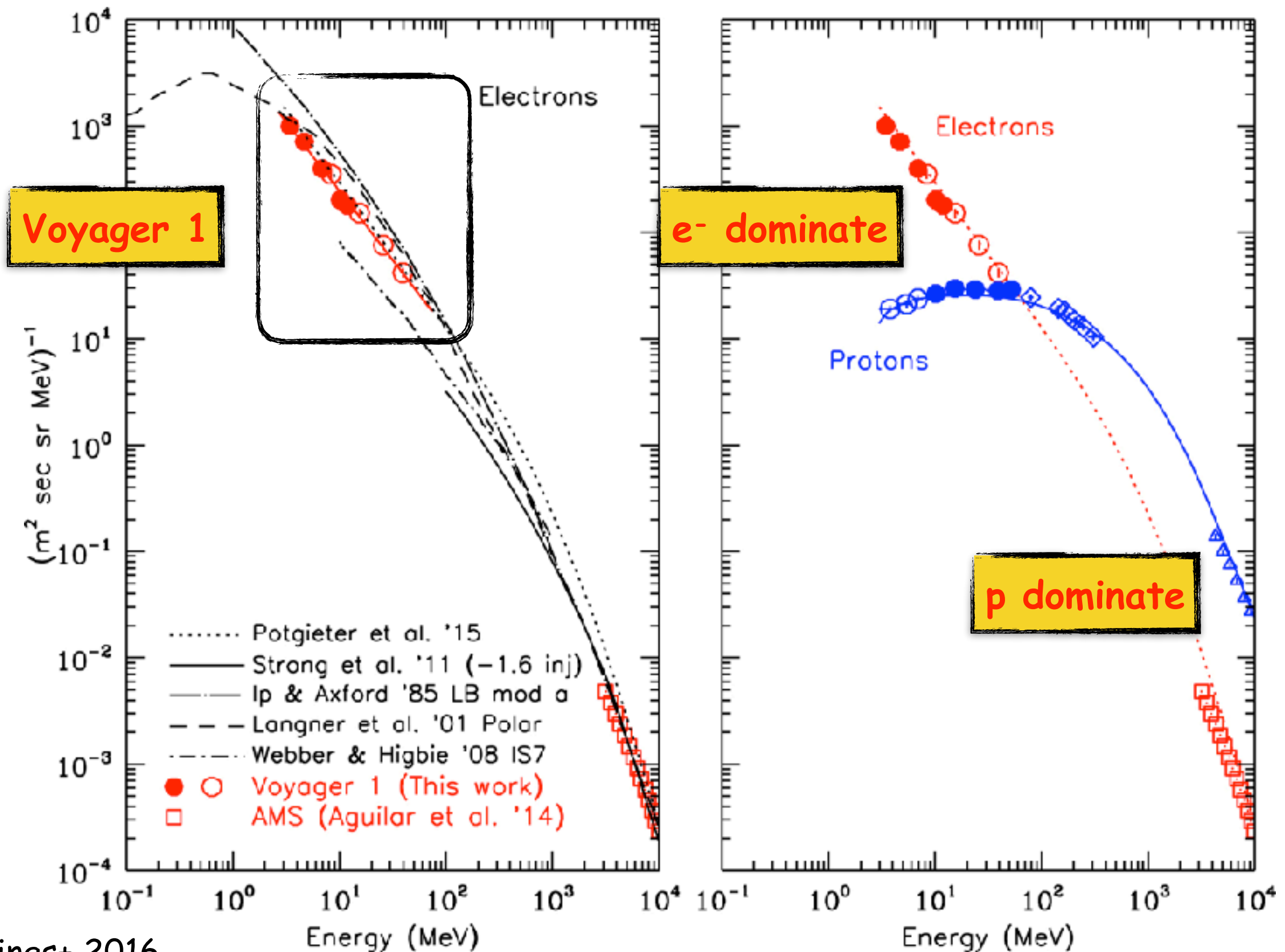
The local interstellar spectrum of CRs



Spectra of nuclei in the local ISM

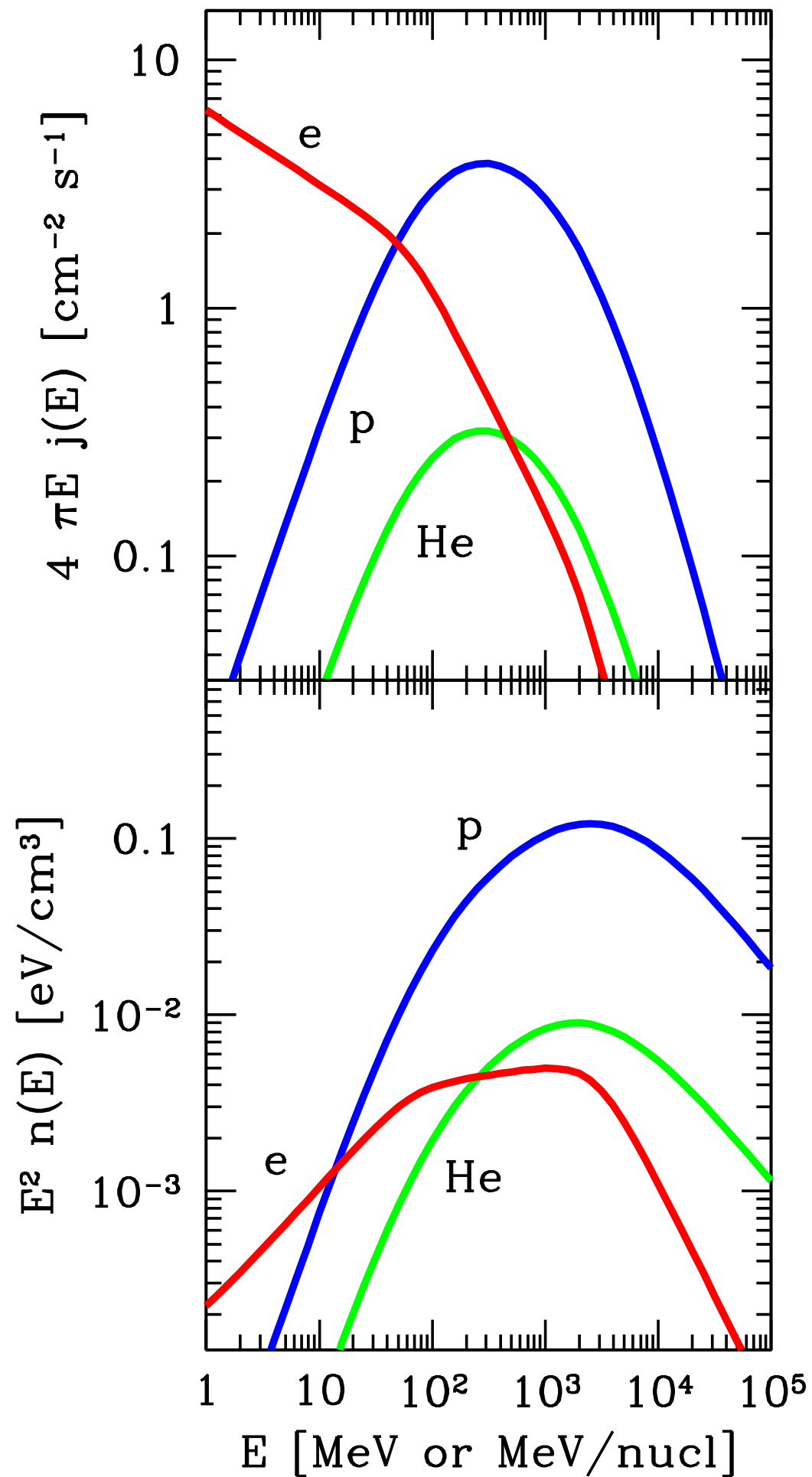


Electron spectrum in the local ISM



flux of particles

spectral energy
distribution

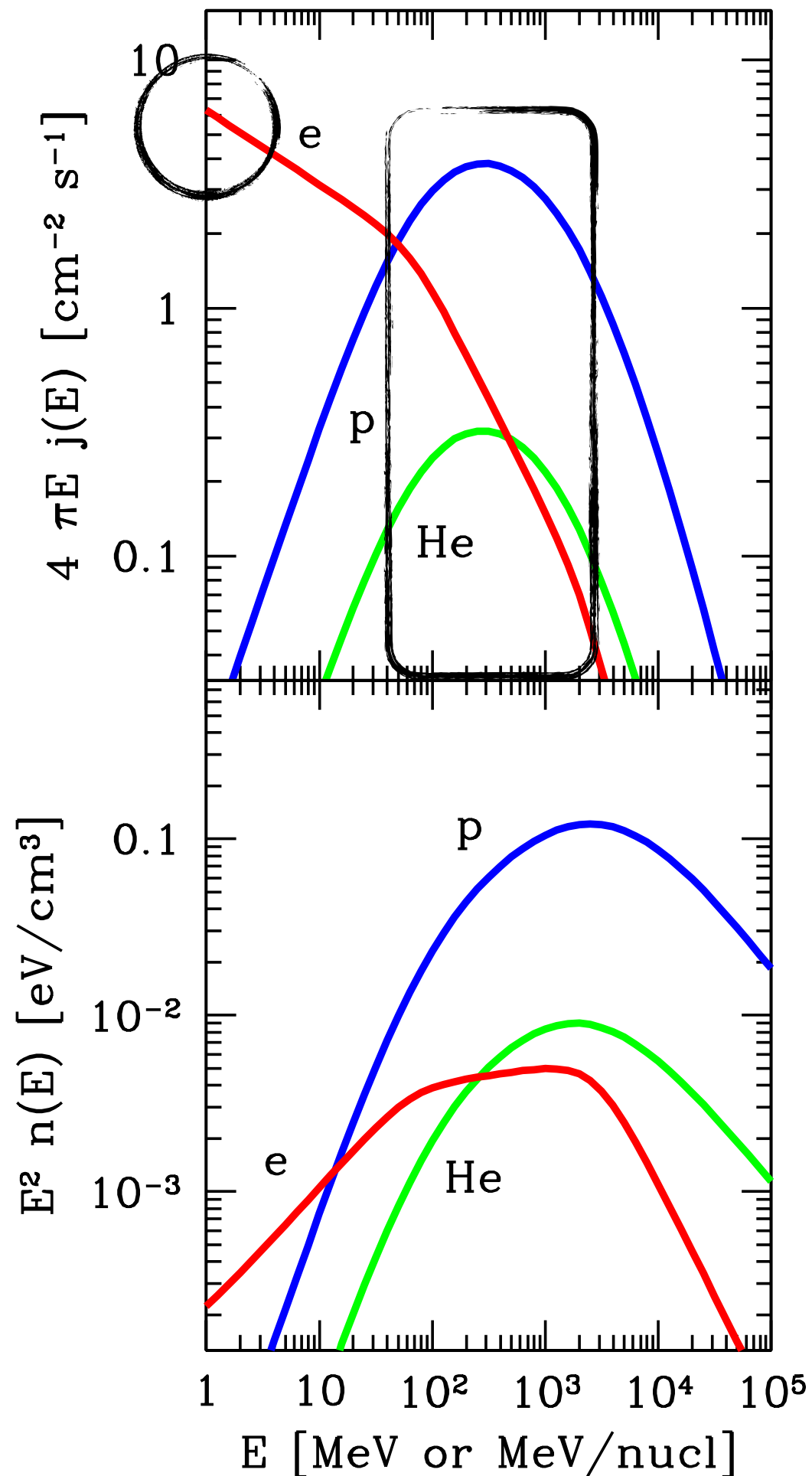


flux of particles

most nuclei have
energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

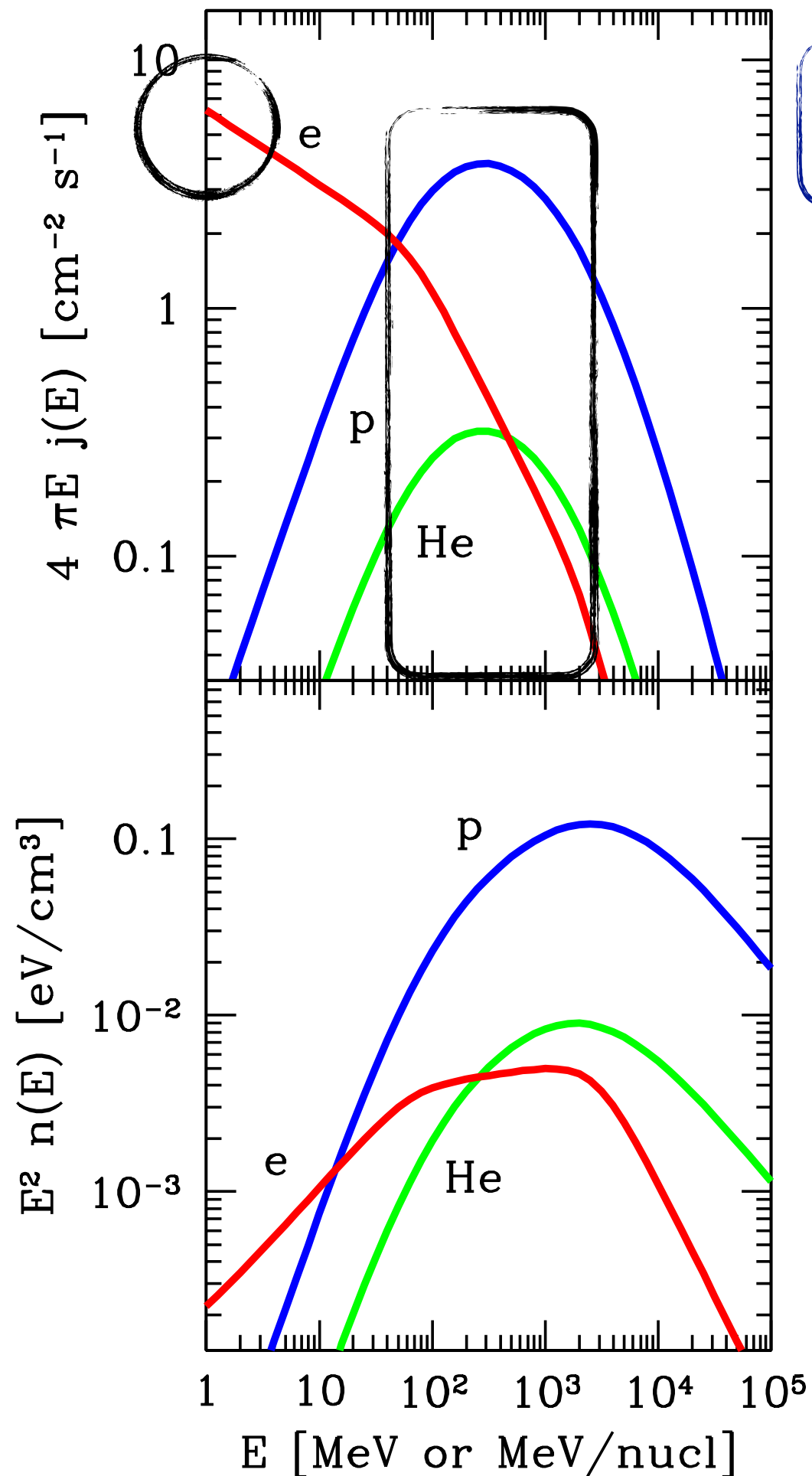


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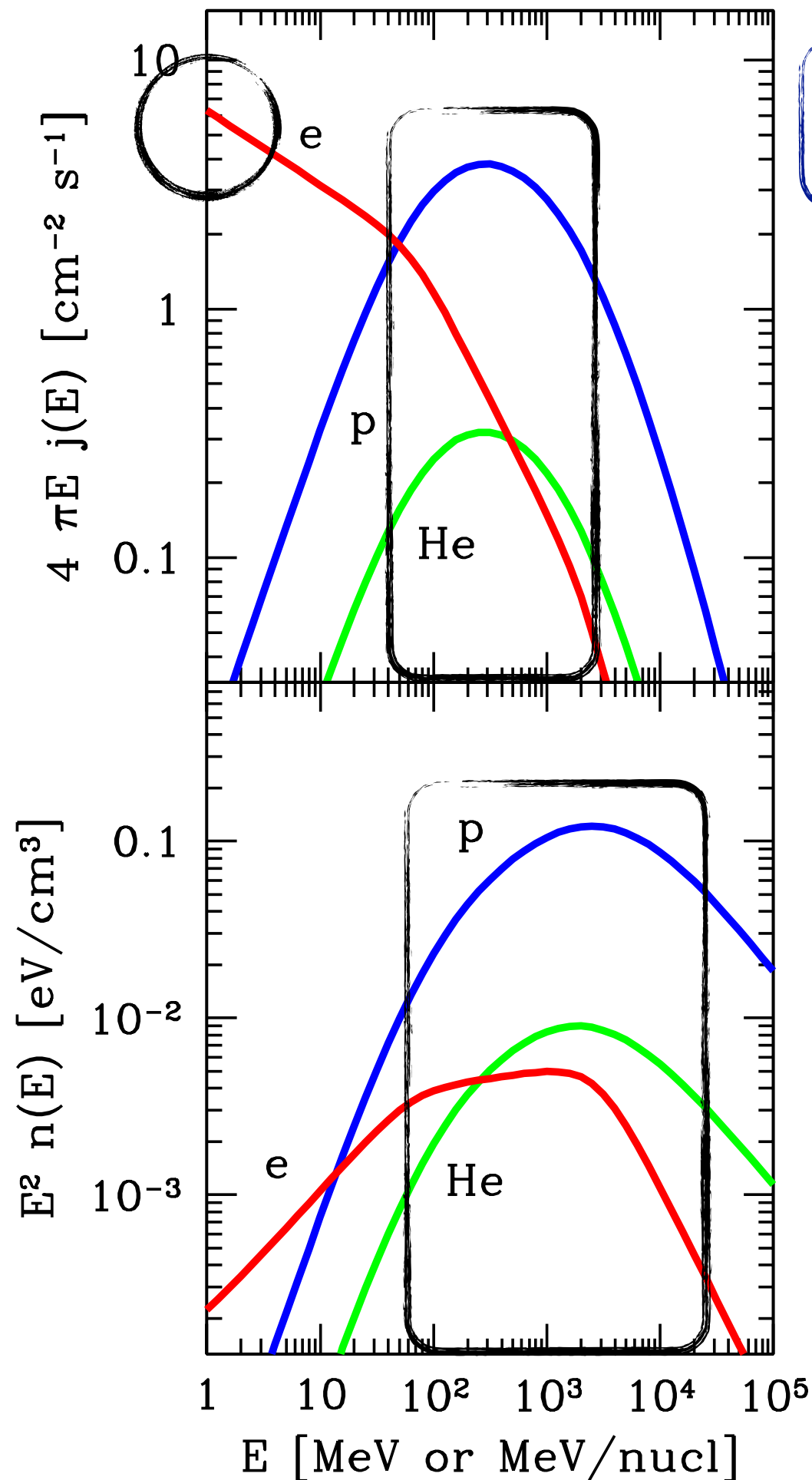
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energy is carried mainly
by particles of energy
100 MeV-10 GeV



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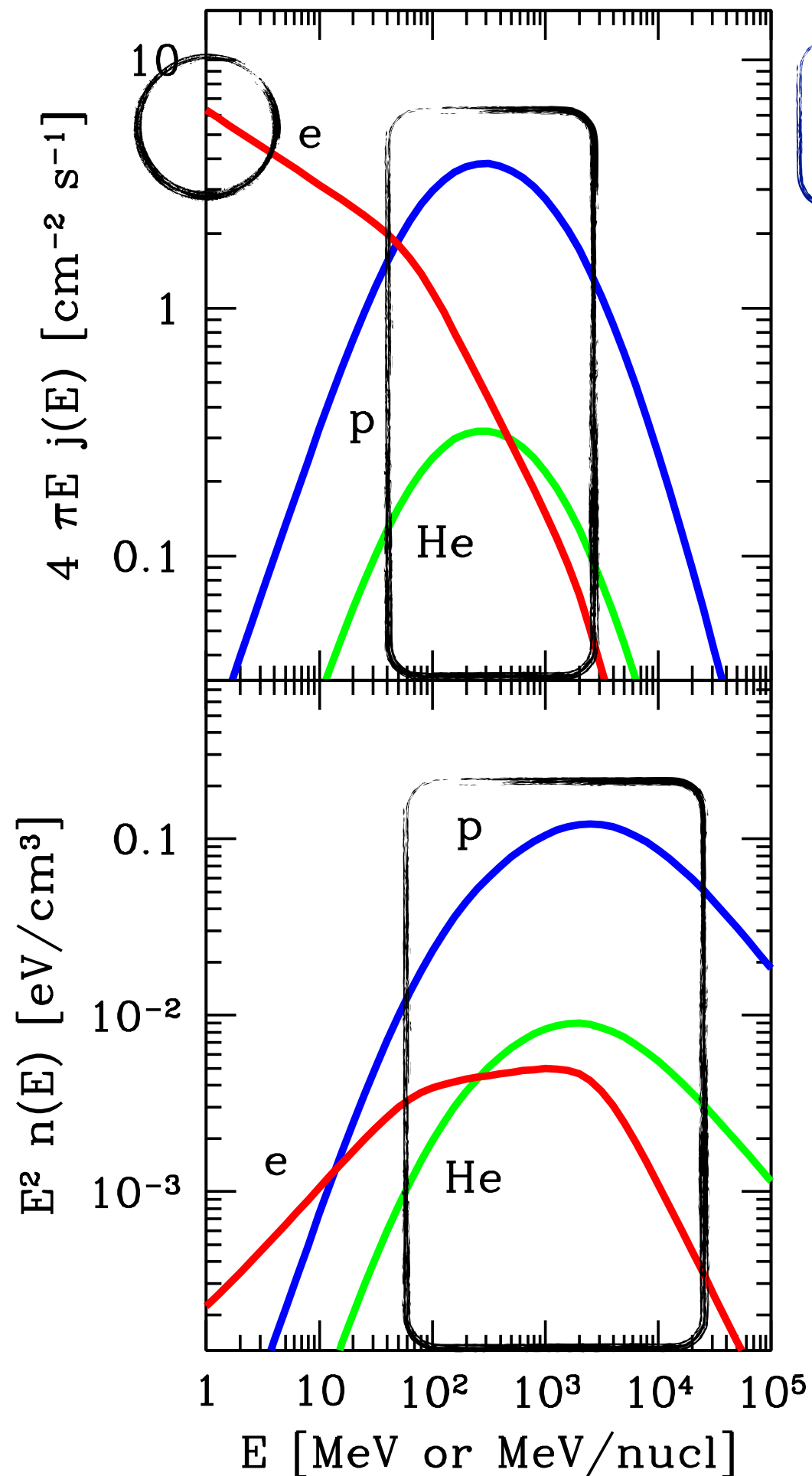
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$$\approx 1 \text{ eV}/\text{cm}^3$$

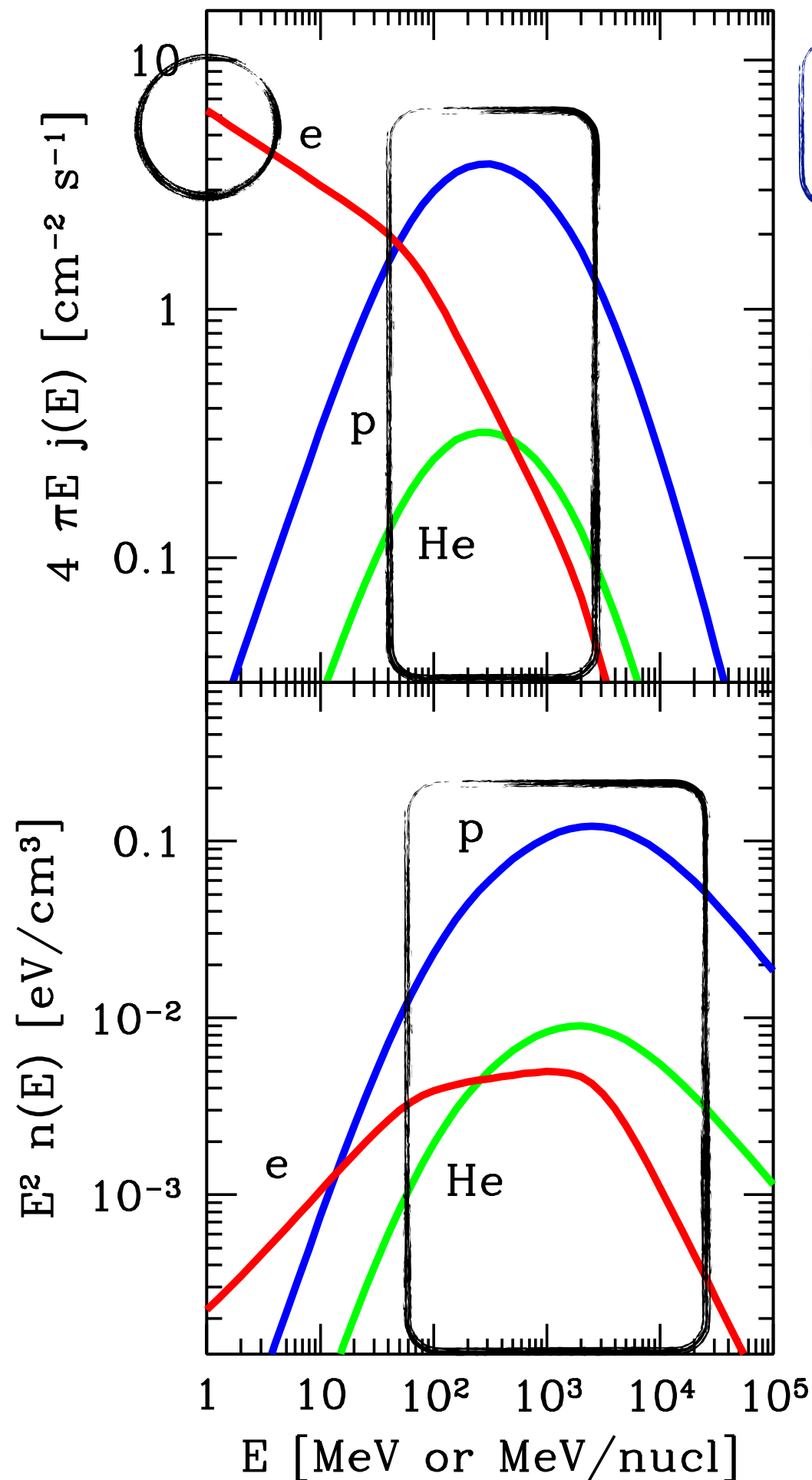
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compare with ISM
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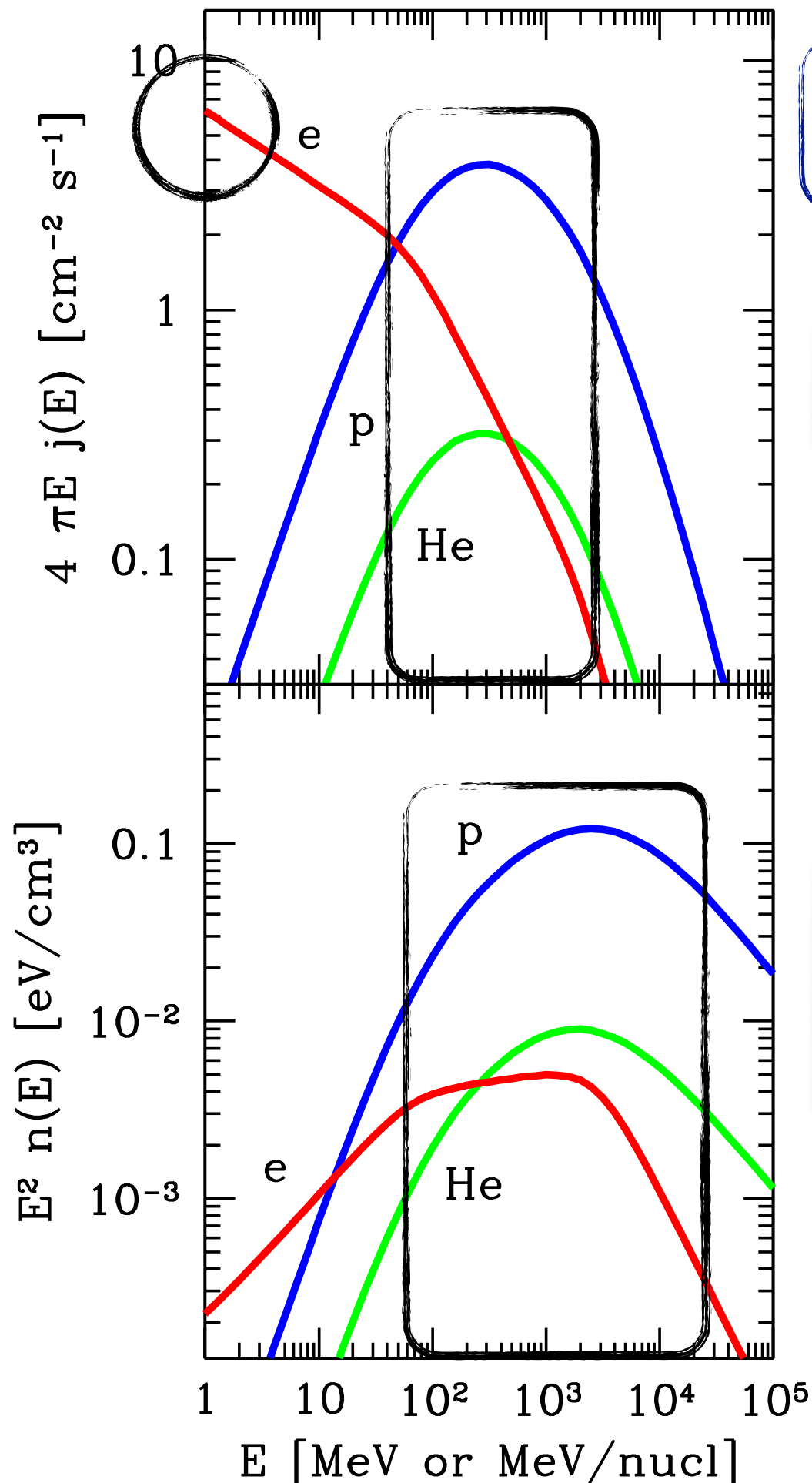
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same order as
magnetic, thermal, and
turbulent energy in the
ISM!

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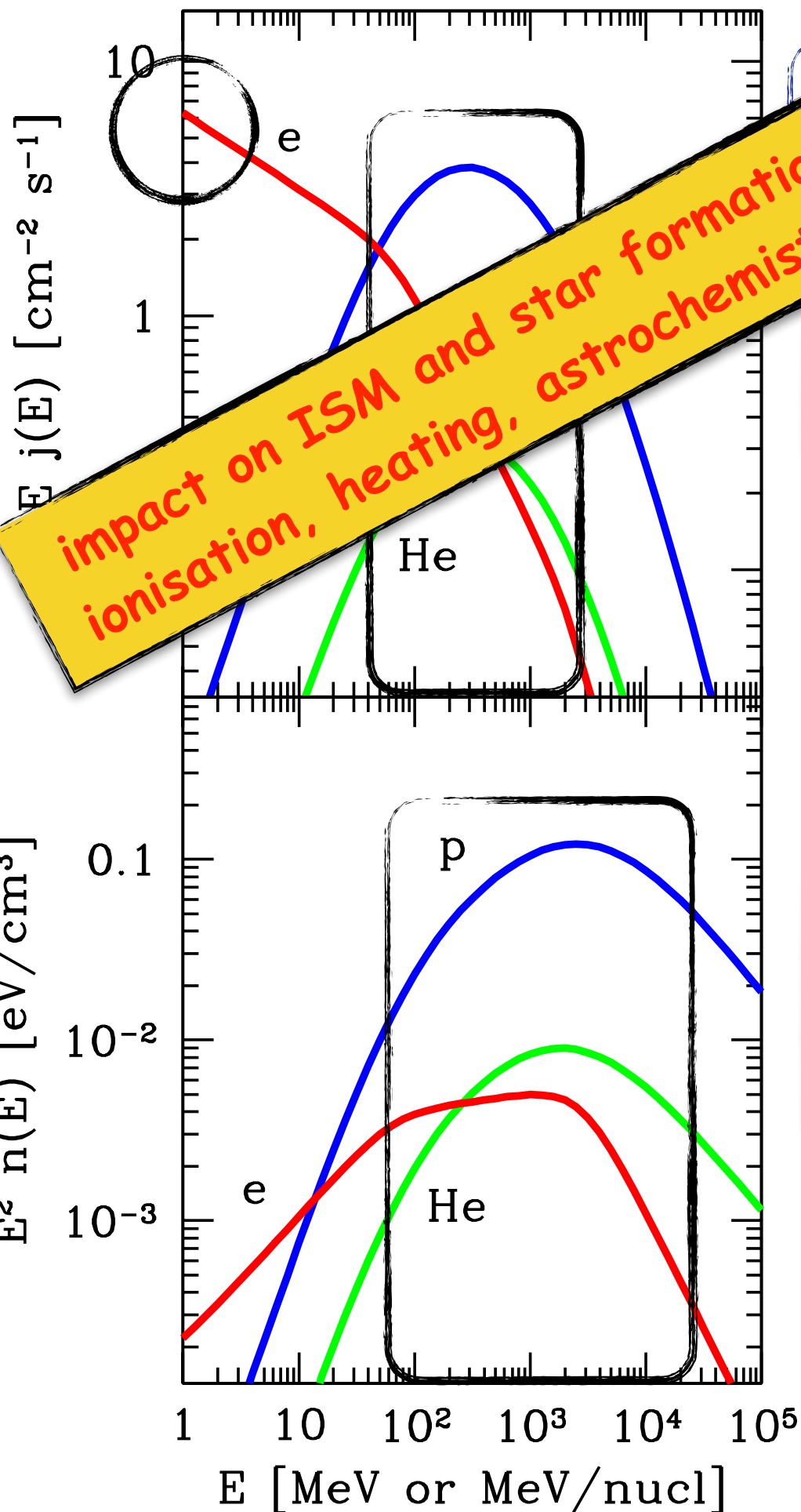
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spectral energy distribution

energy is carried mainly
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impact on ISM and star formation:
ionisation, heating, astrochemistry...

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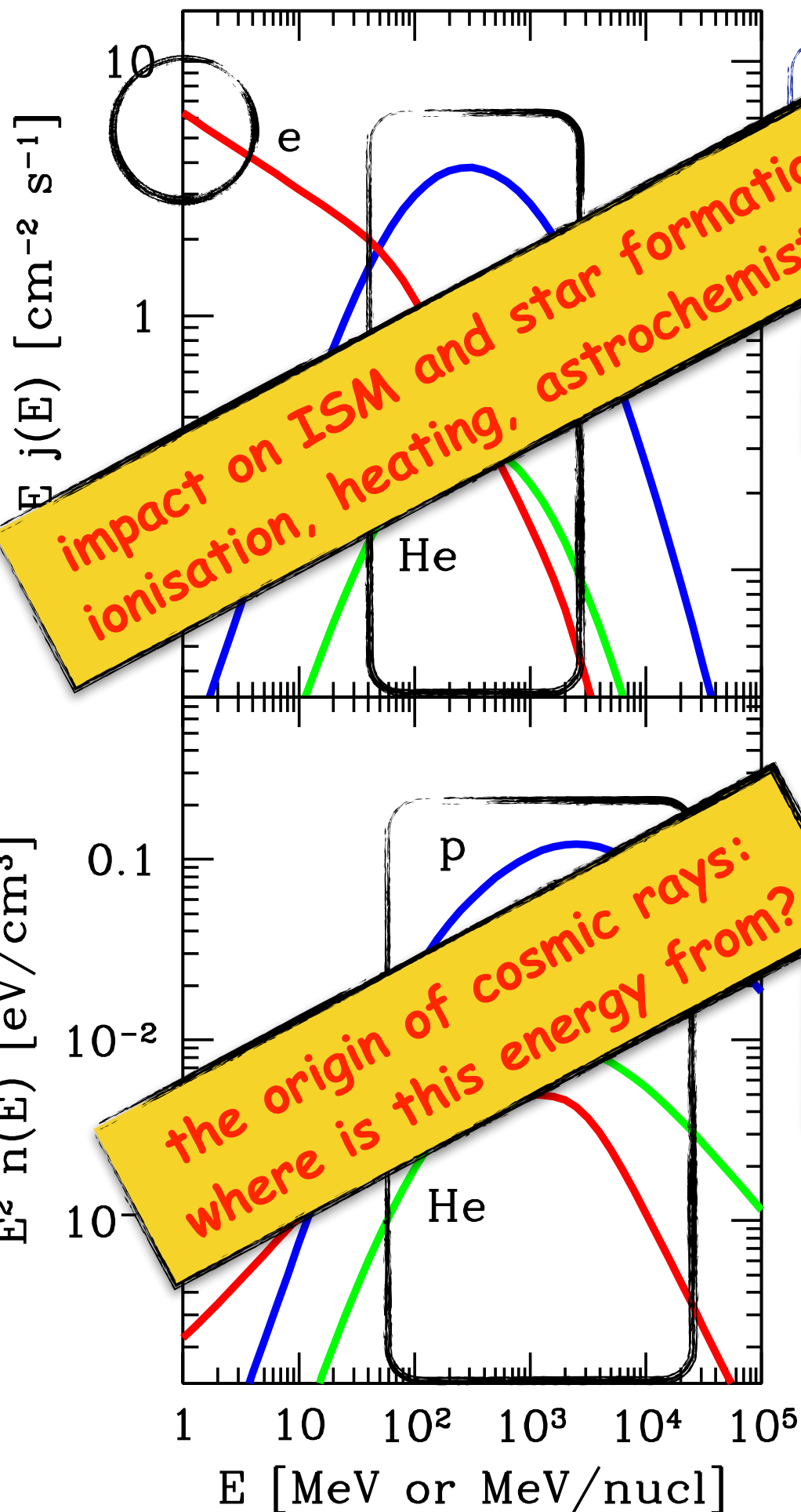
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$$10^{-9} - 10^{-10} \text{ cm}^{-3}$$

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

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turbulent energy in the
ISM!

$$\approx 1 \text{ eV}/\text{cm}^3$$

[3] *Local or global?*

Variations in time and space

- ☀ CR flux at Earth **constant during the last 10^9 yr**

(from radiation damages in geological and biological samples, meteorites, and lunar rocks)

- ☀ thus the CR flux must be **constant along the orbit of the Sun** around the galactic centre (many revolutions in a Gyr)

Variations in time and space

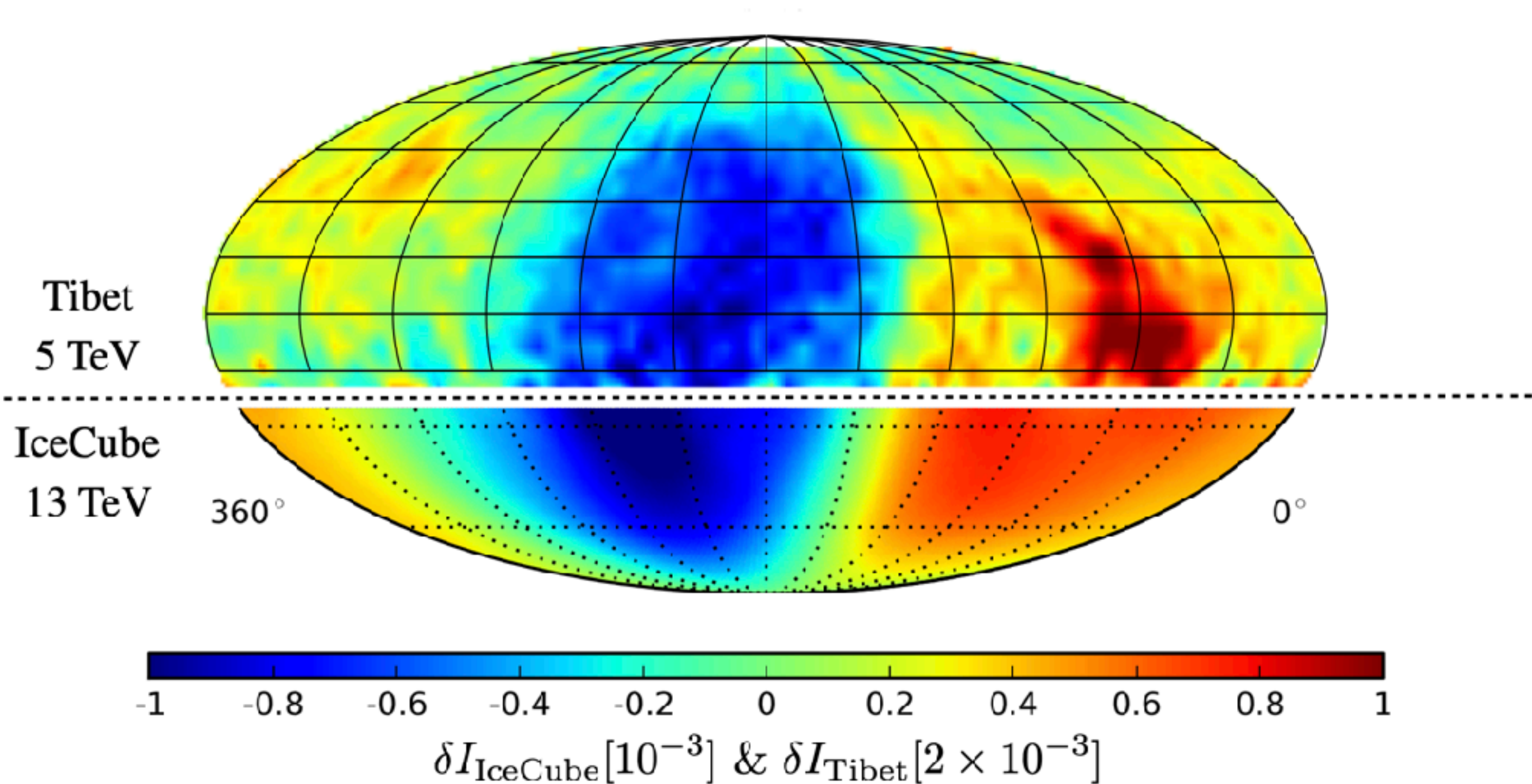
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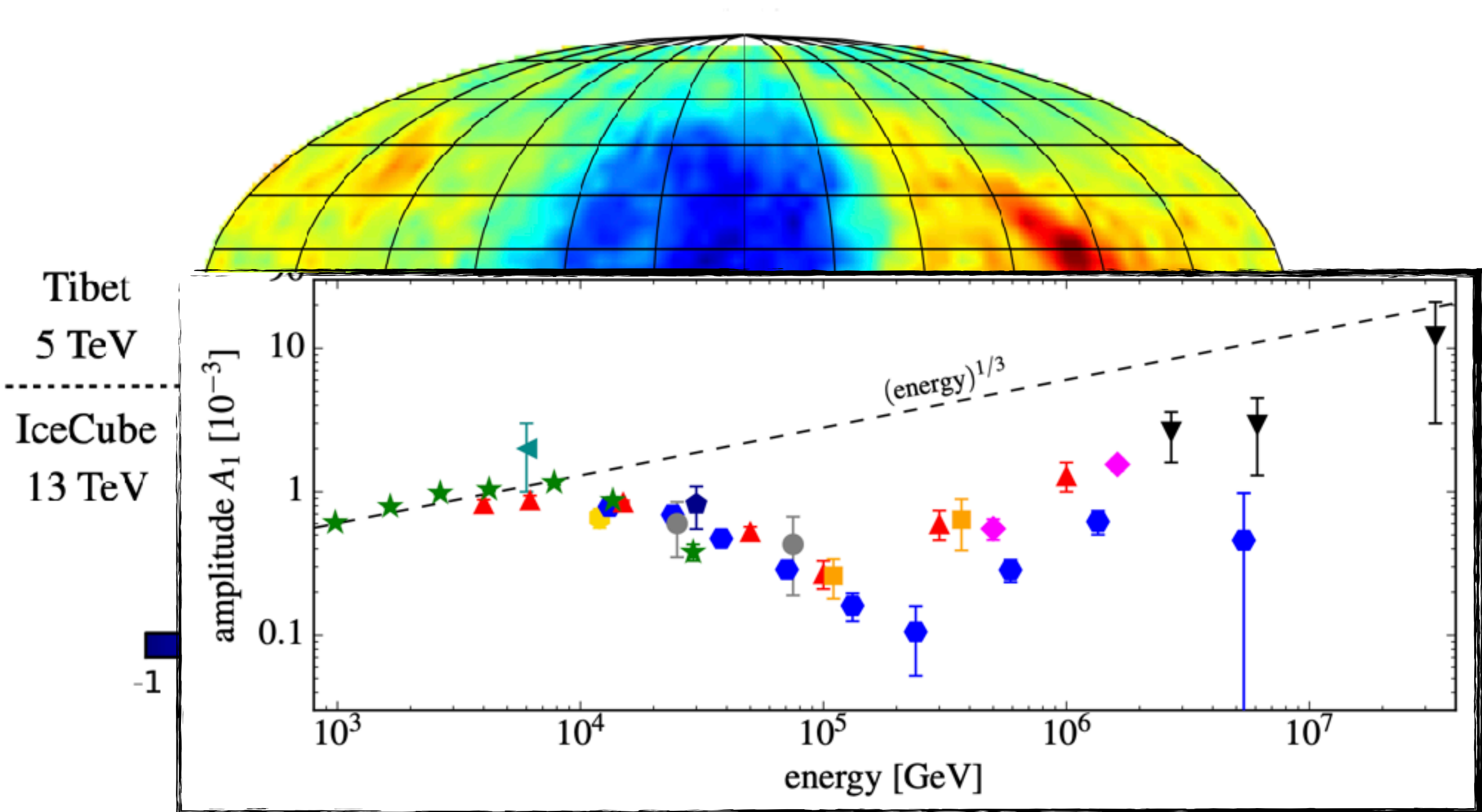
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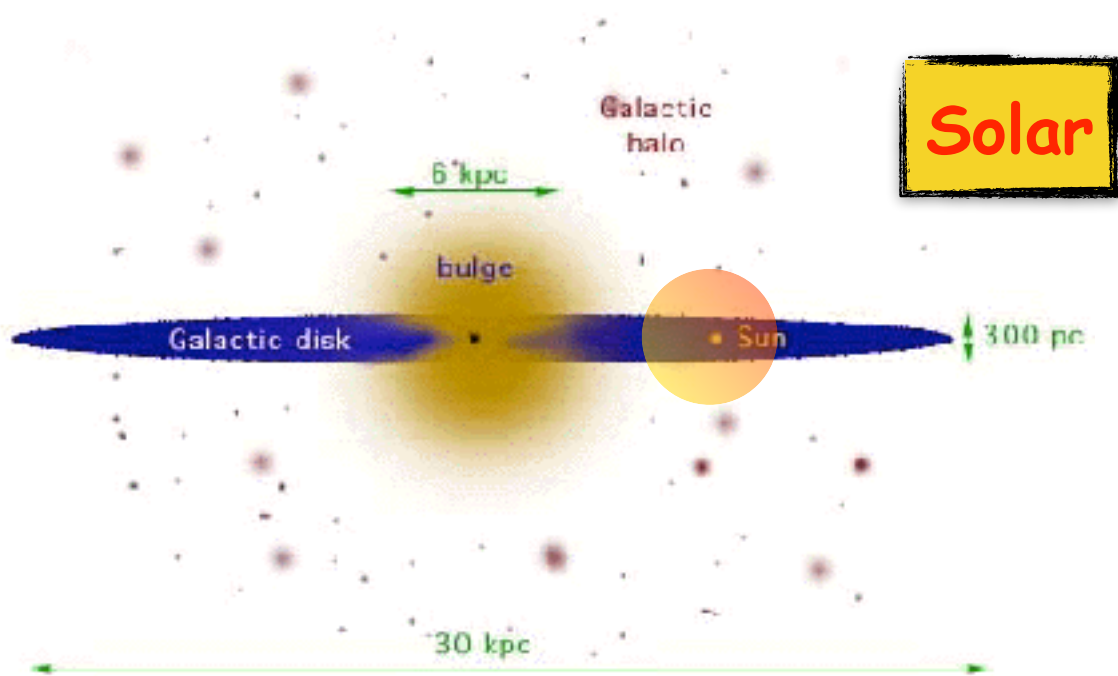
Stability in time and (hints for) spatial homogeneity

Cosmic rays are almost isotropic



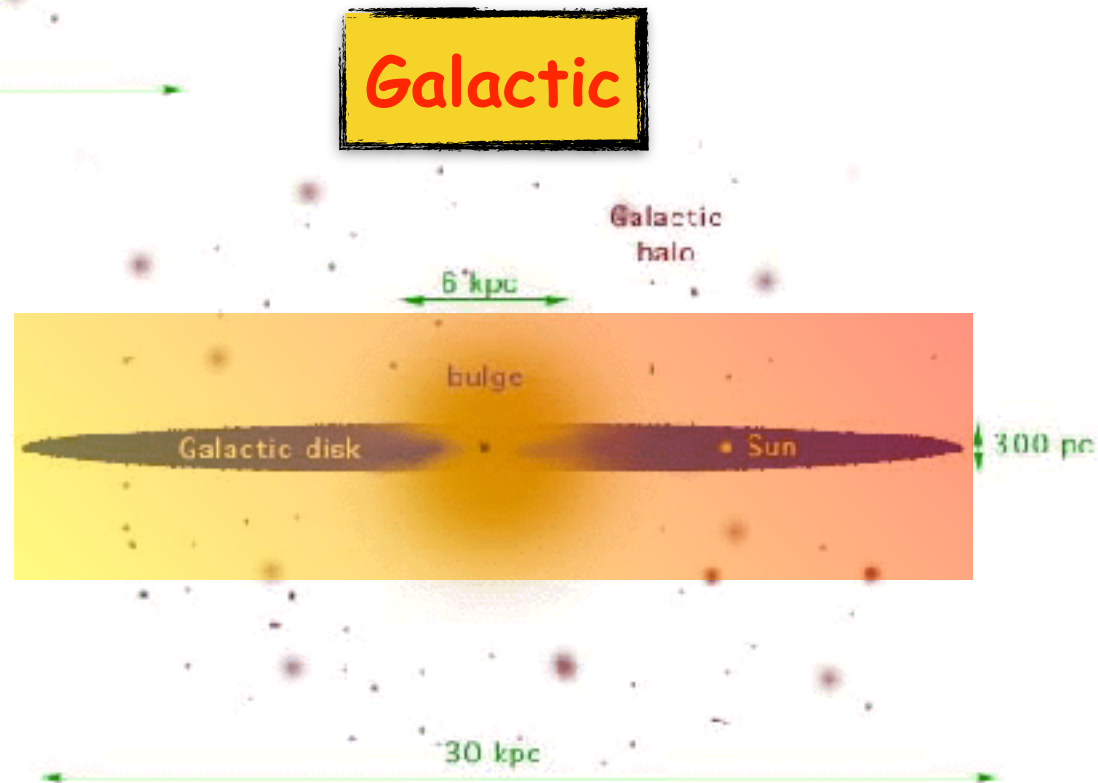
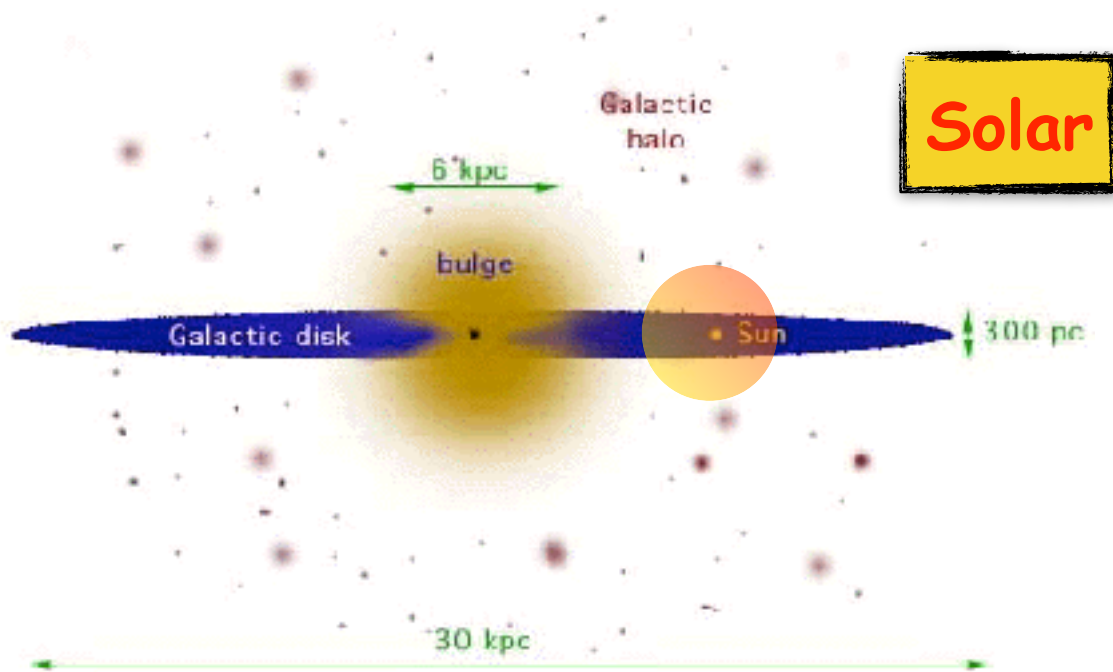
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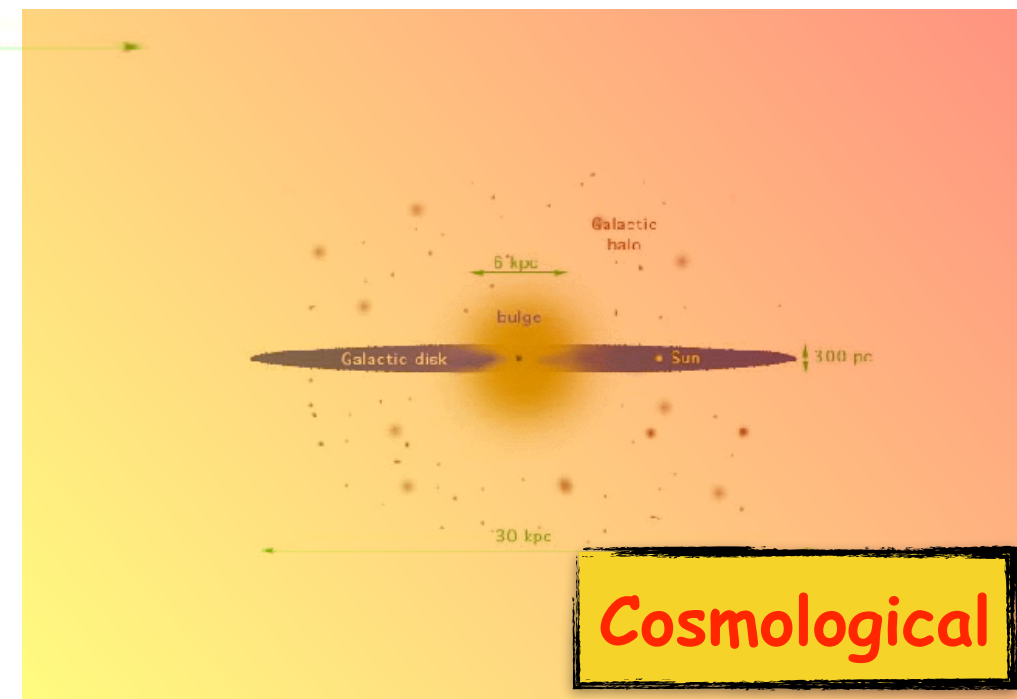
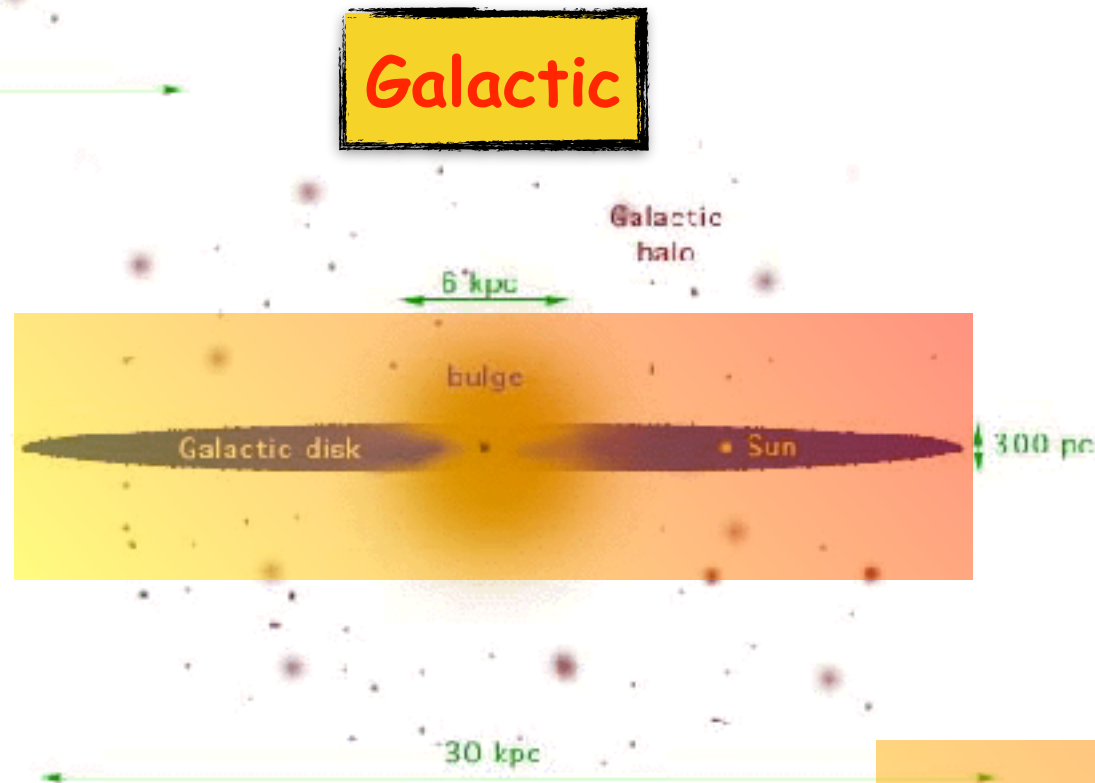
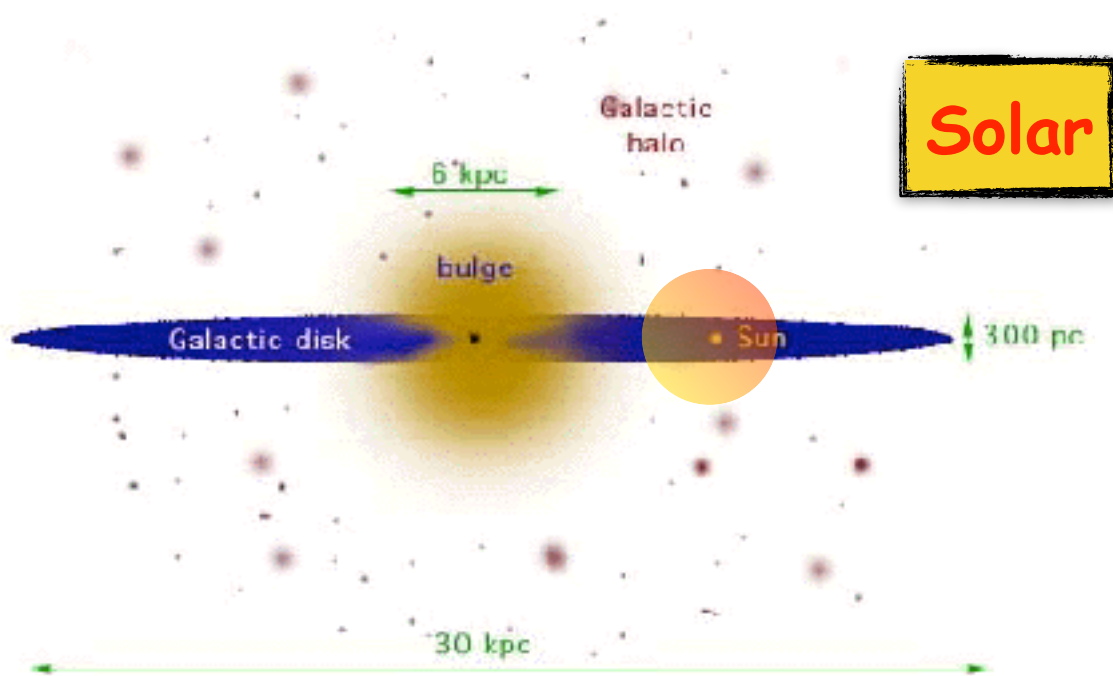


Three scenarios

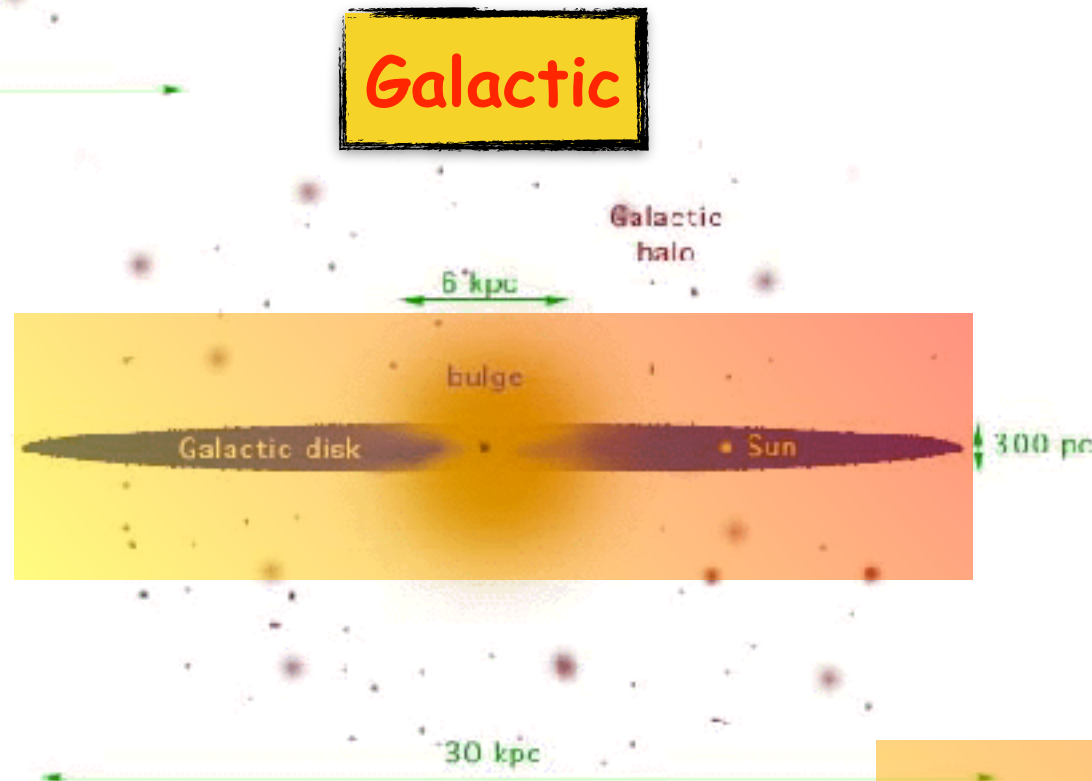
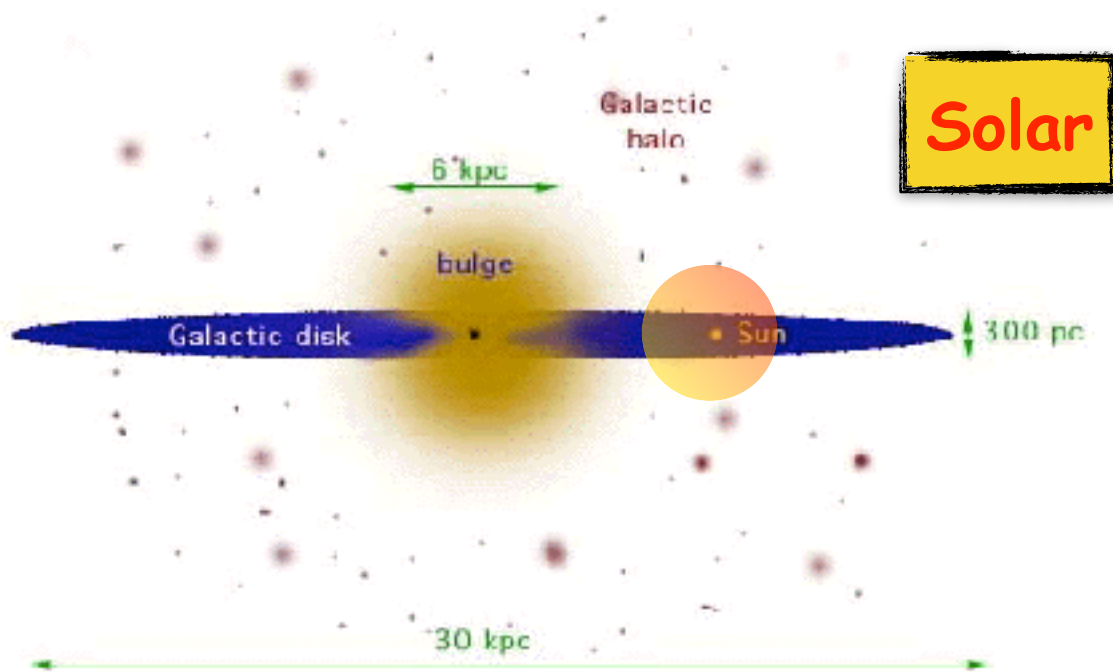
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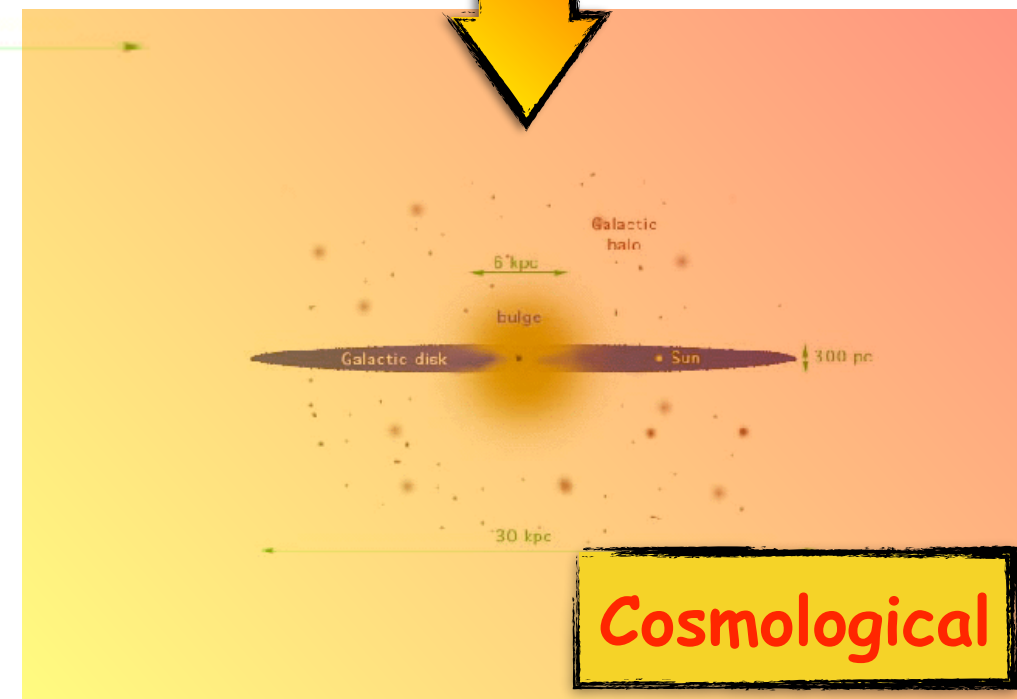
Three scenarios



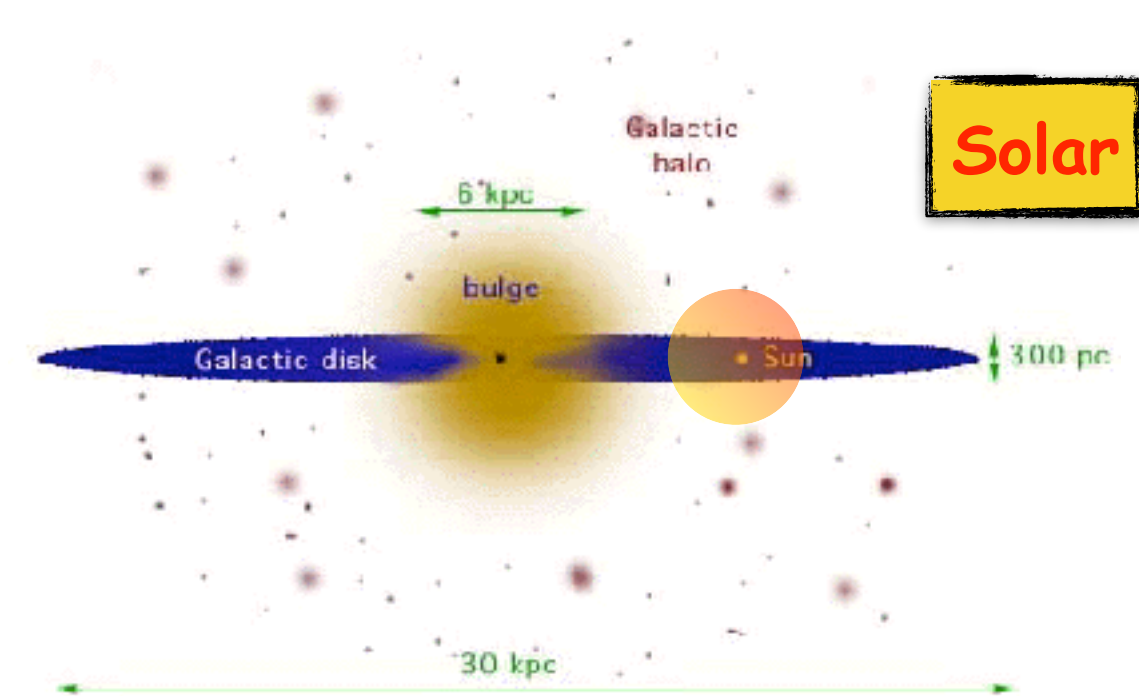
Three scenarios



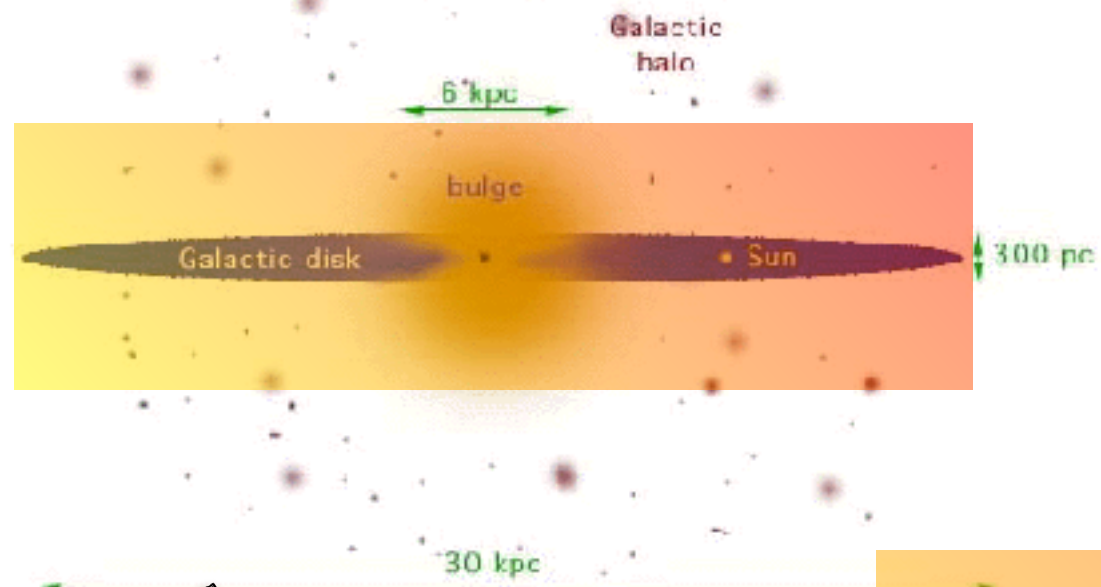
isotropy



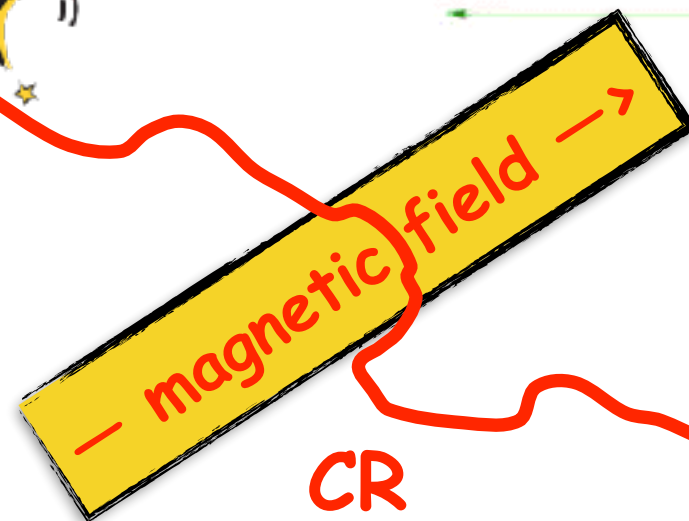
Three scenarios



Galactic



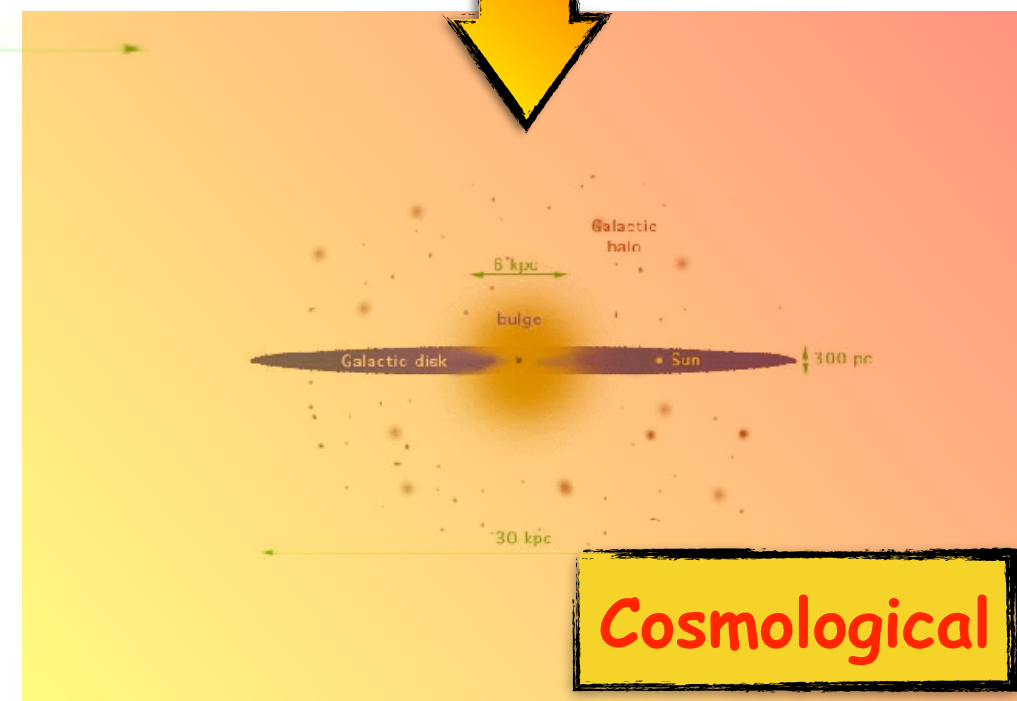
source



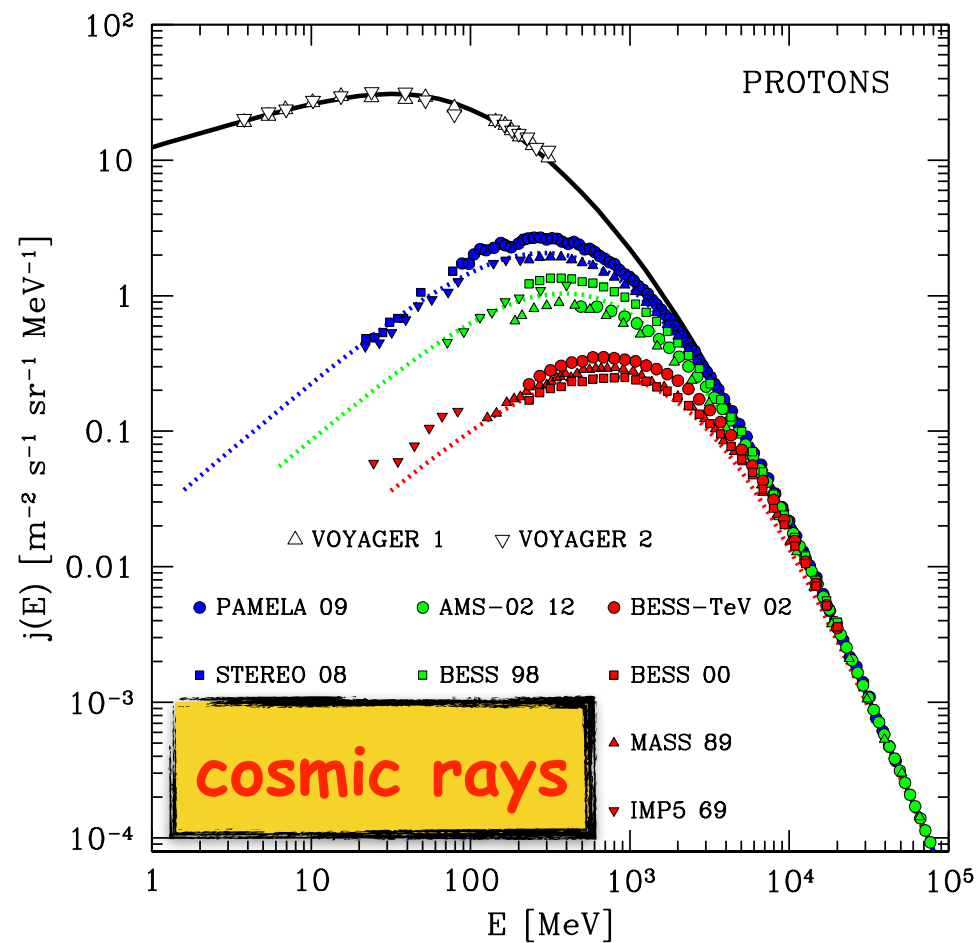
observer



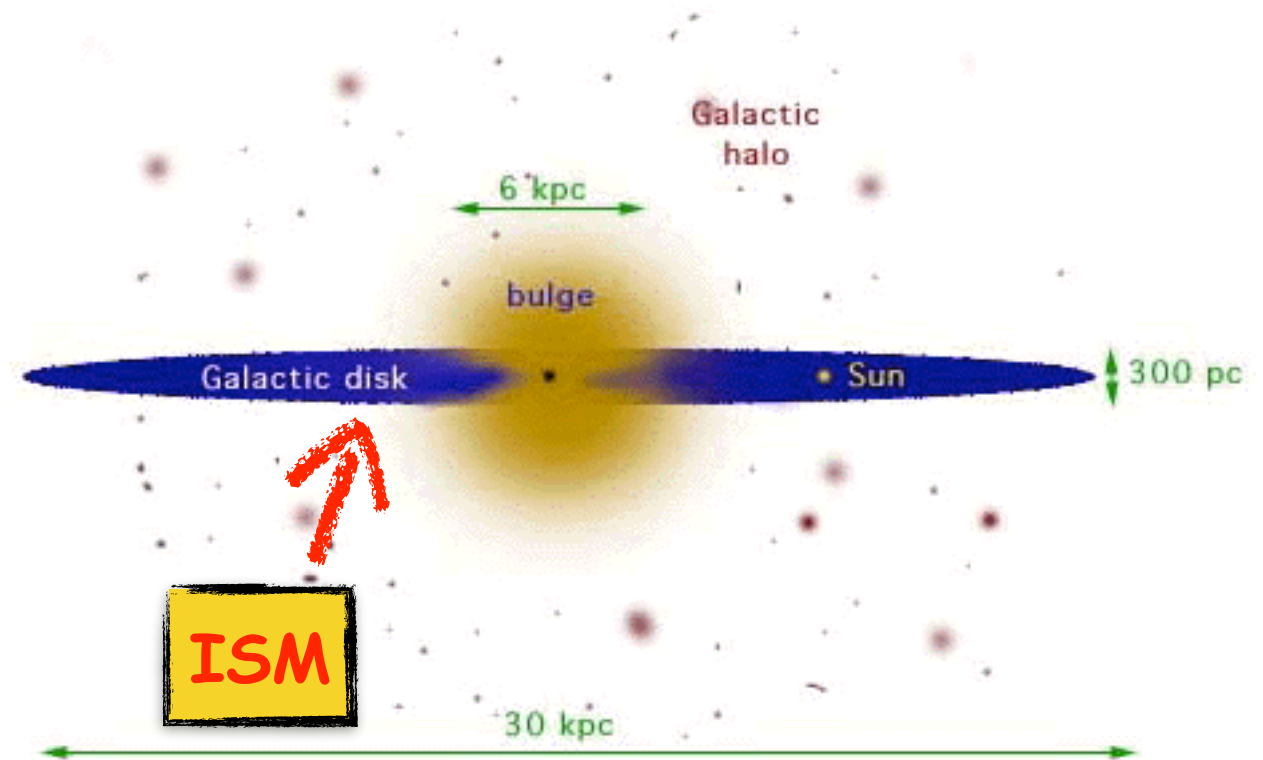
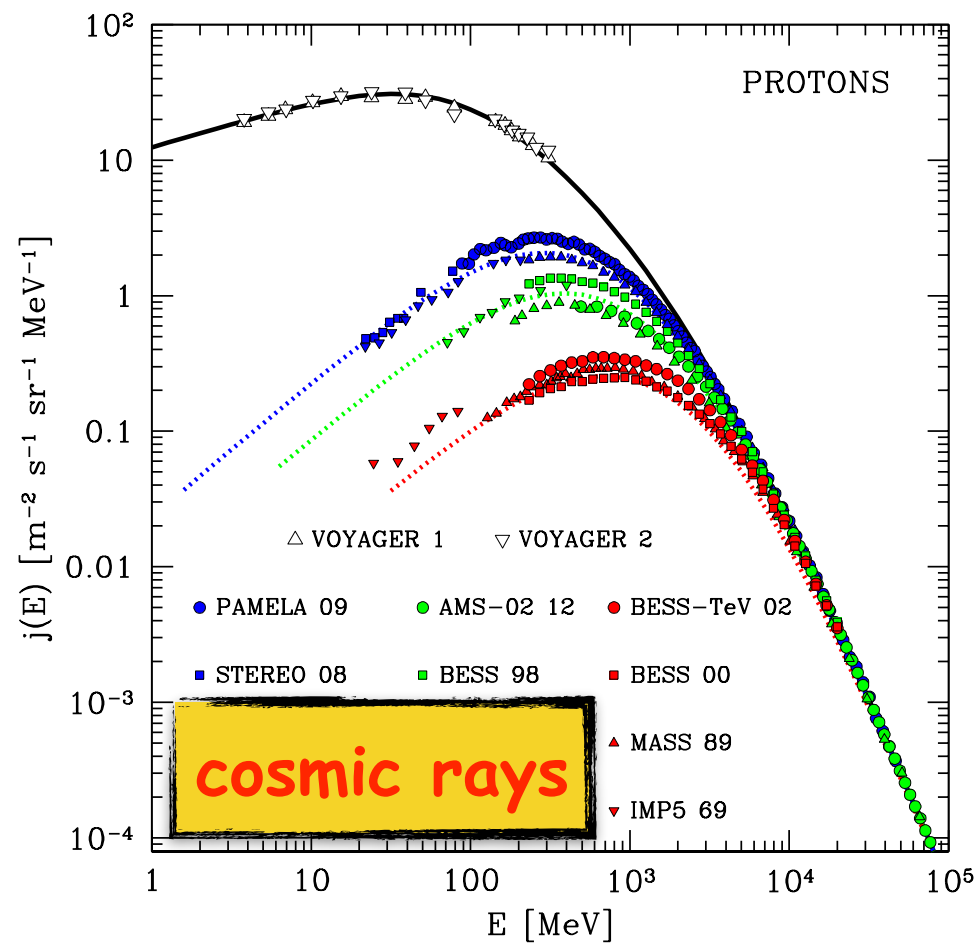
isotropy



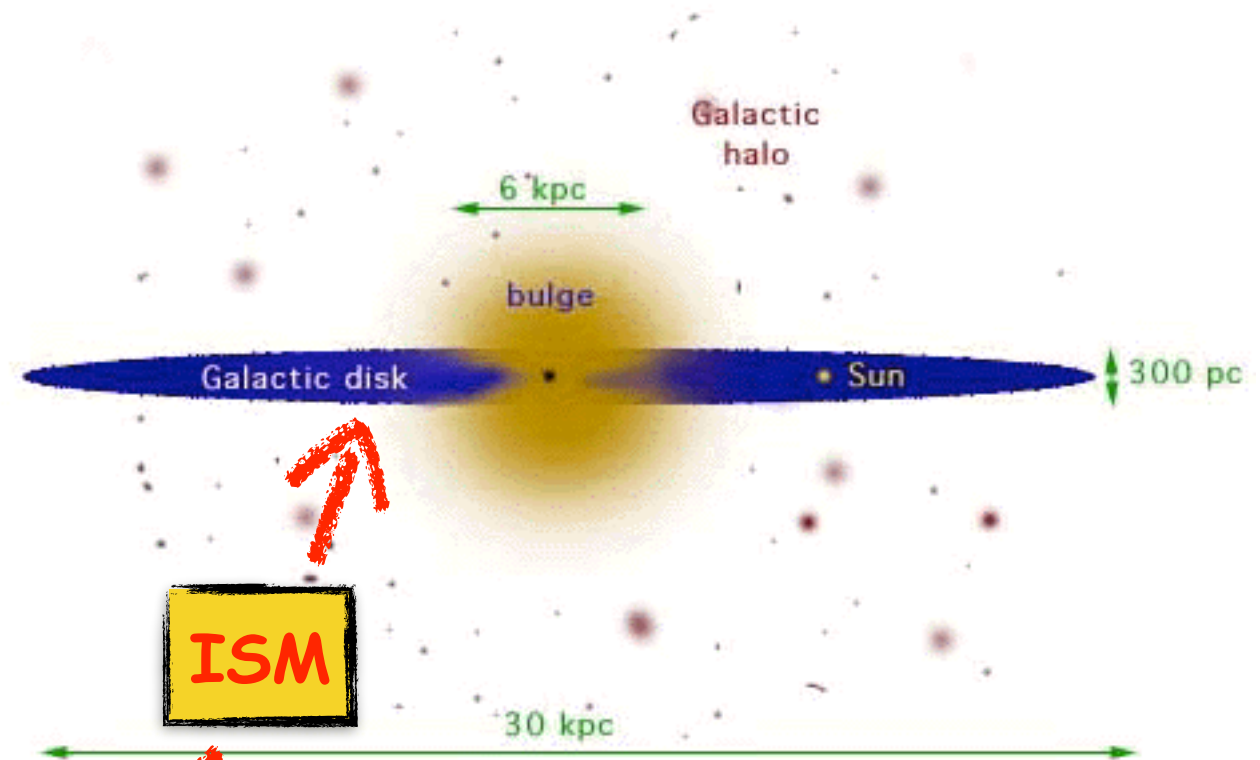
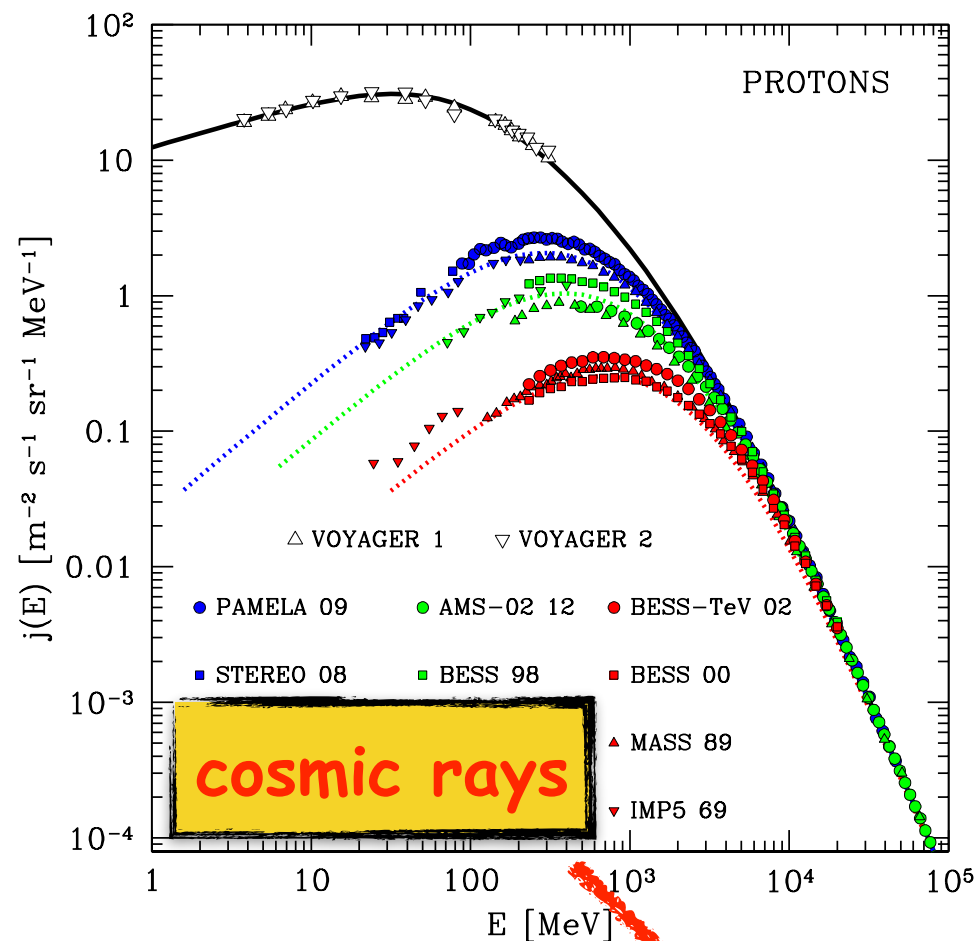
Hayakawa's test (1952): diffuse emission



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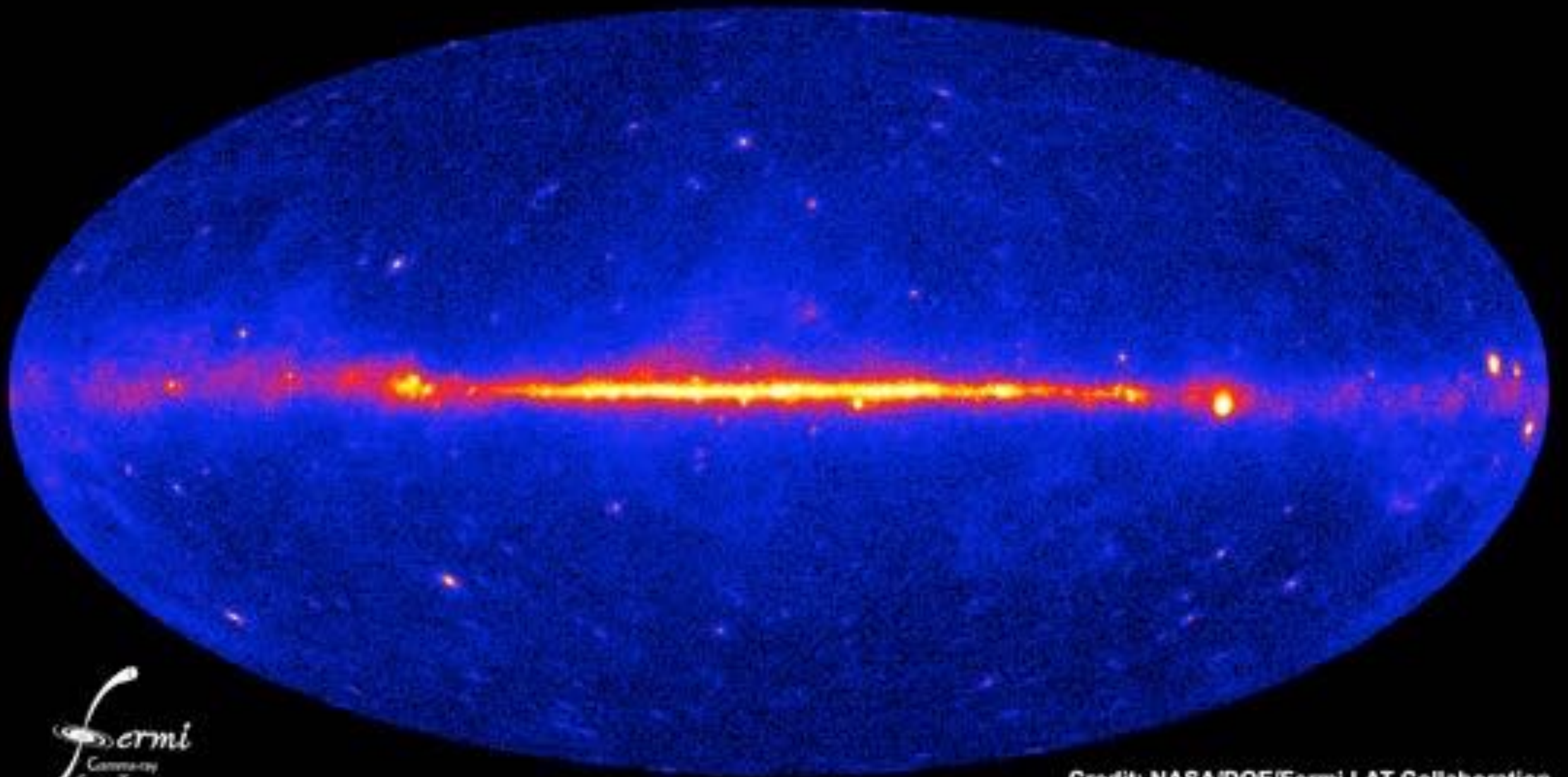


$$p + p \rightarrow p + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

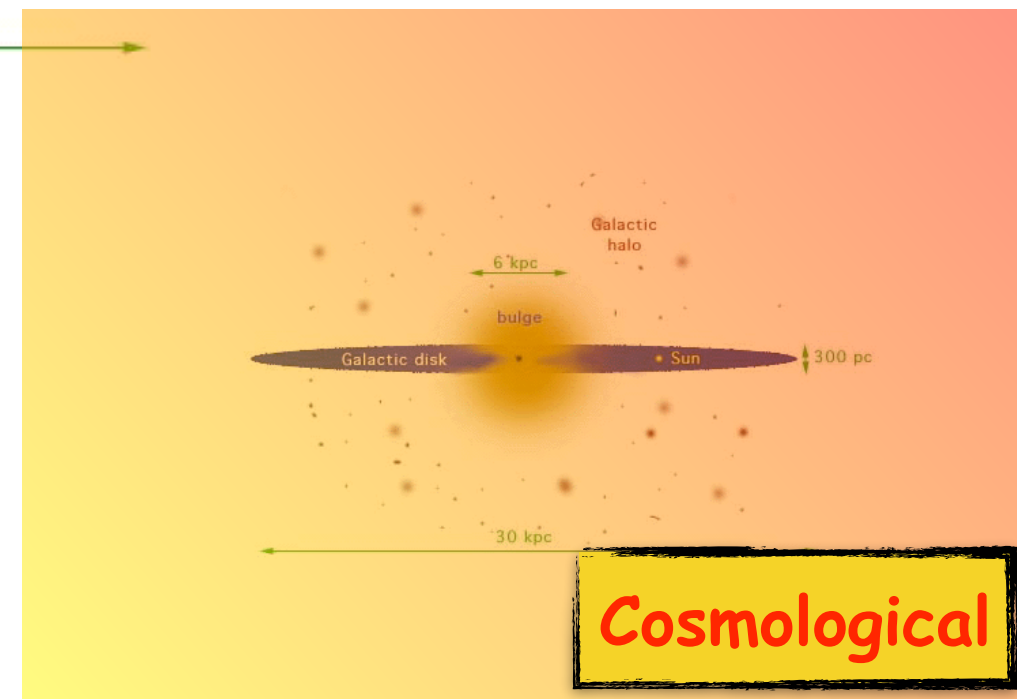
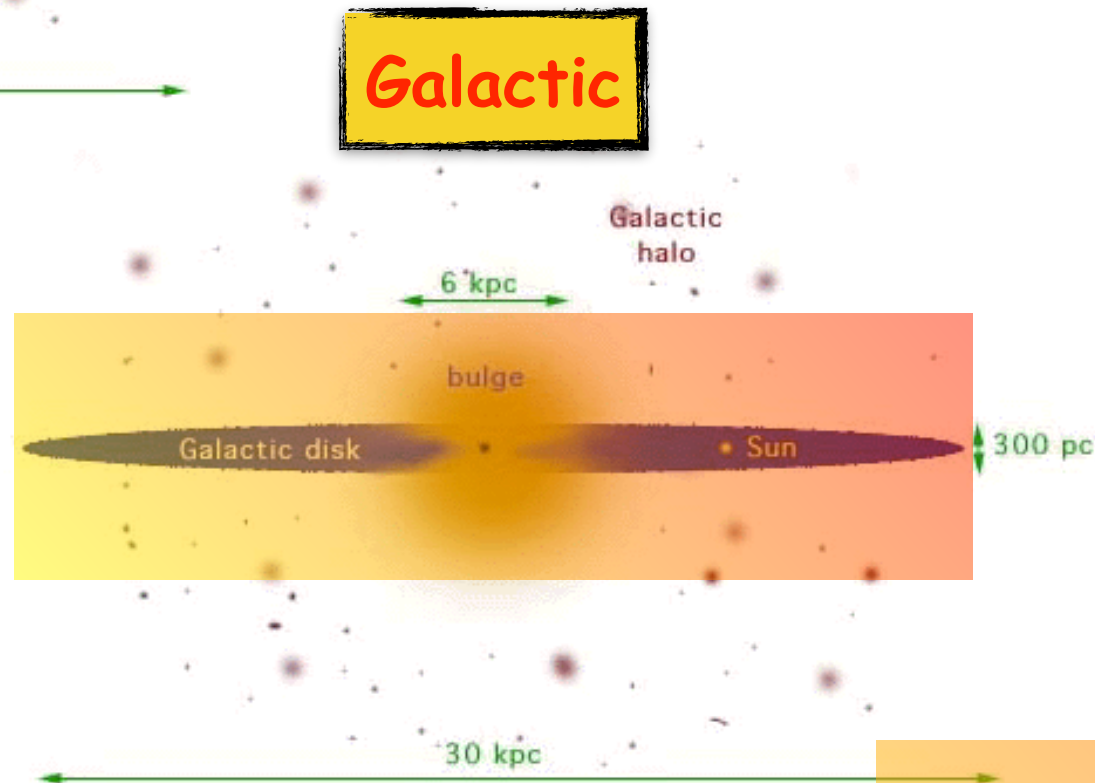
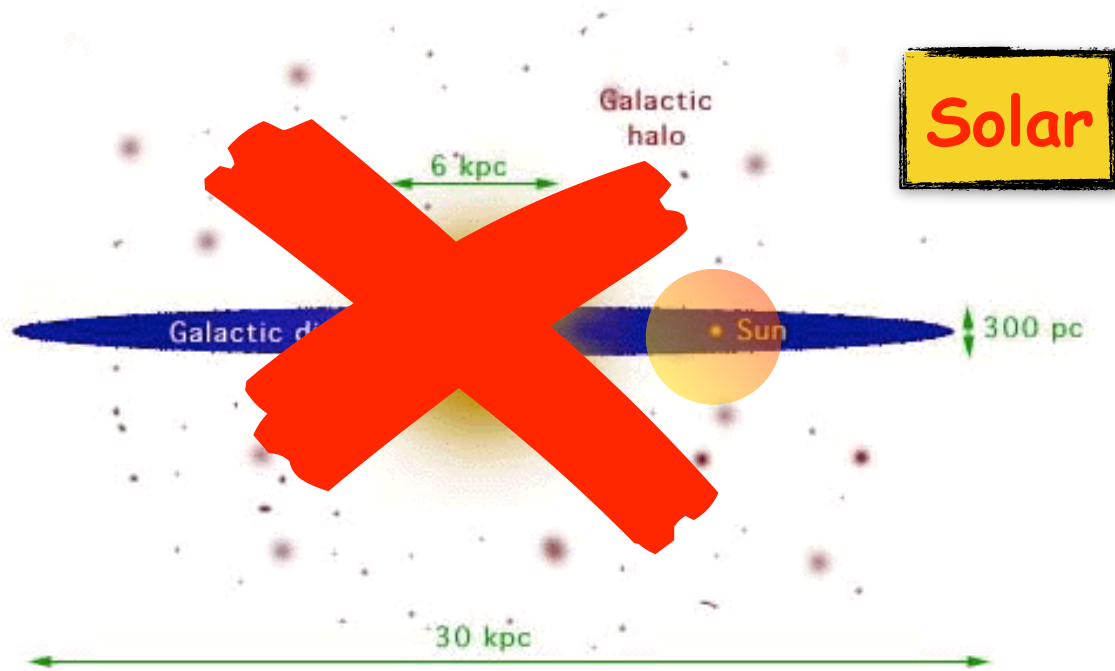
Hayakawa's test (1952): diffuse emission

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

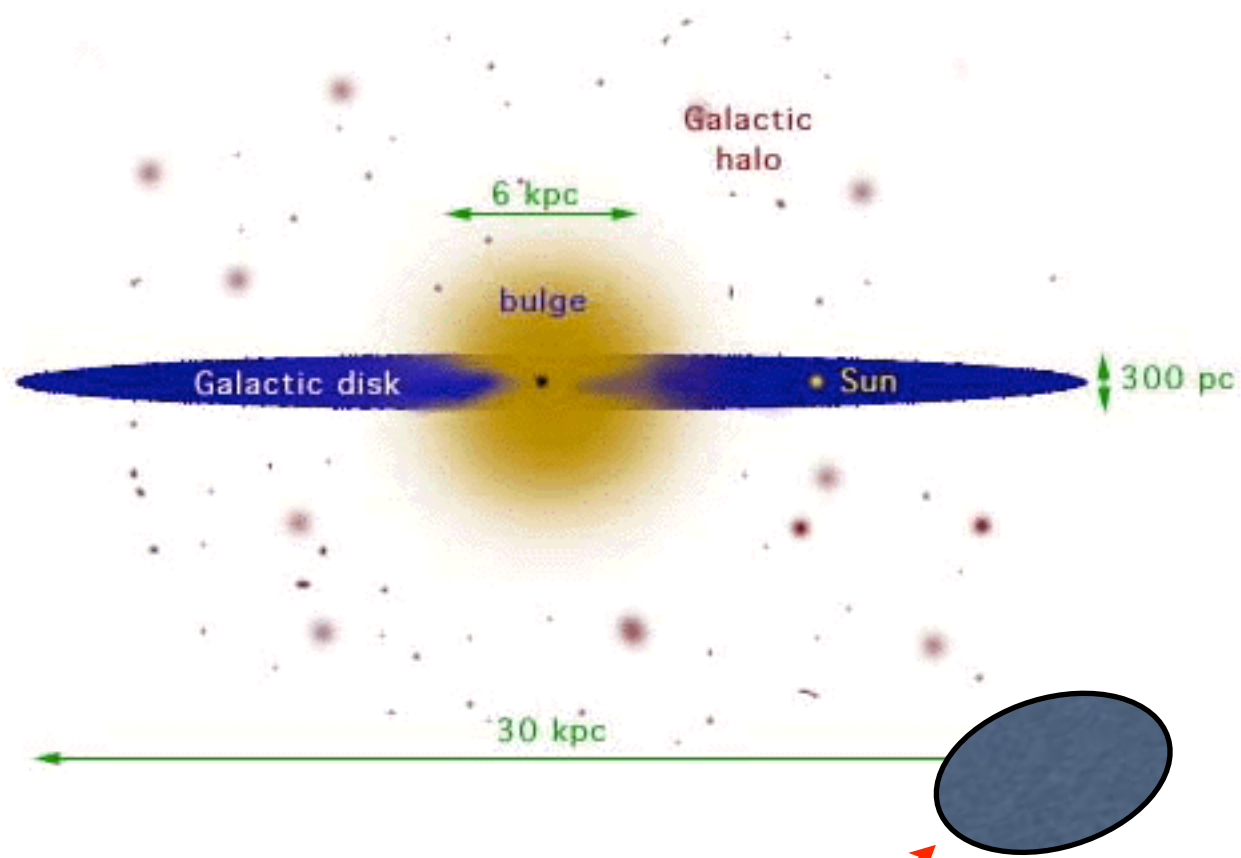


Credit: NASA/DOE/Fermi LAT Collaboration

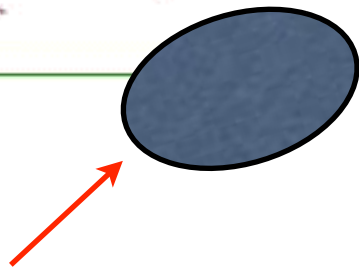
Three scenarios



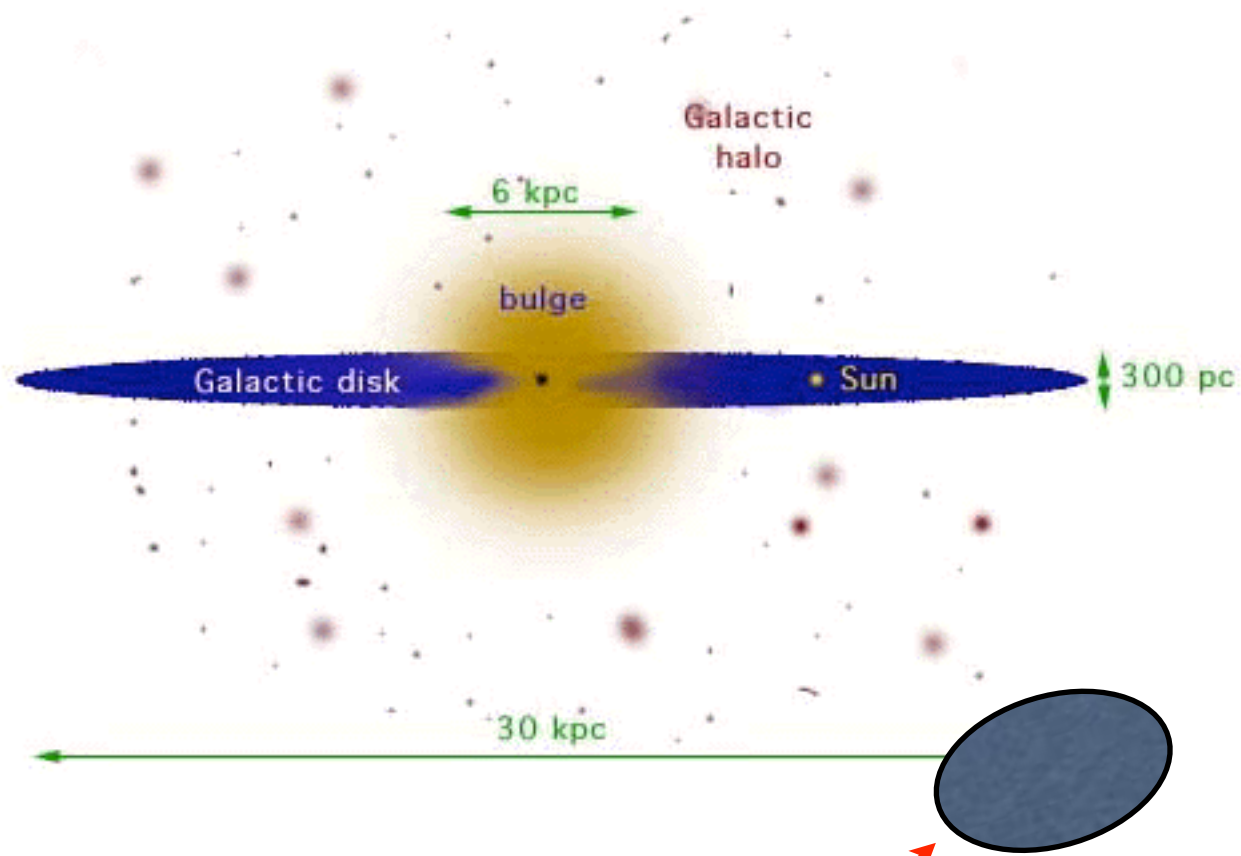
Diffuse emission in other galaxies



Small Magellanic Cloud



Diffuse emission in other galaxies

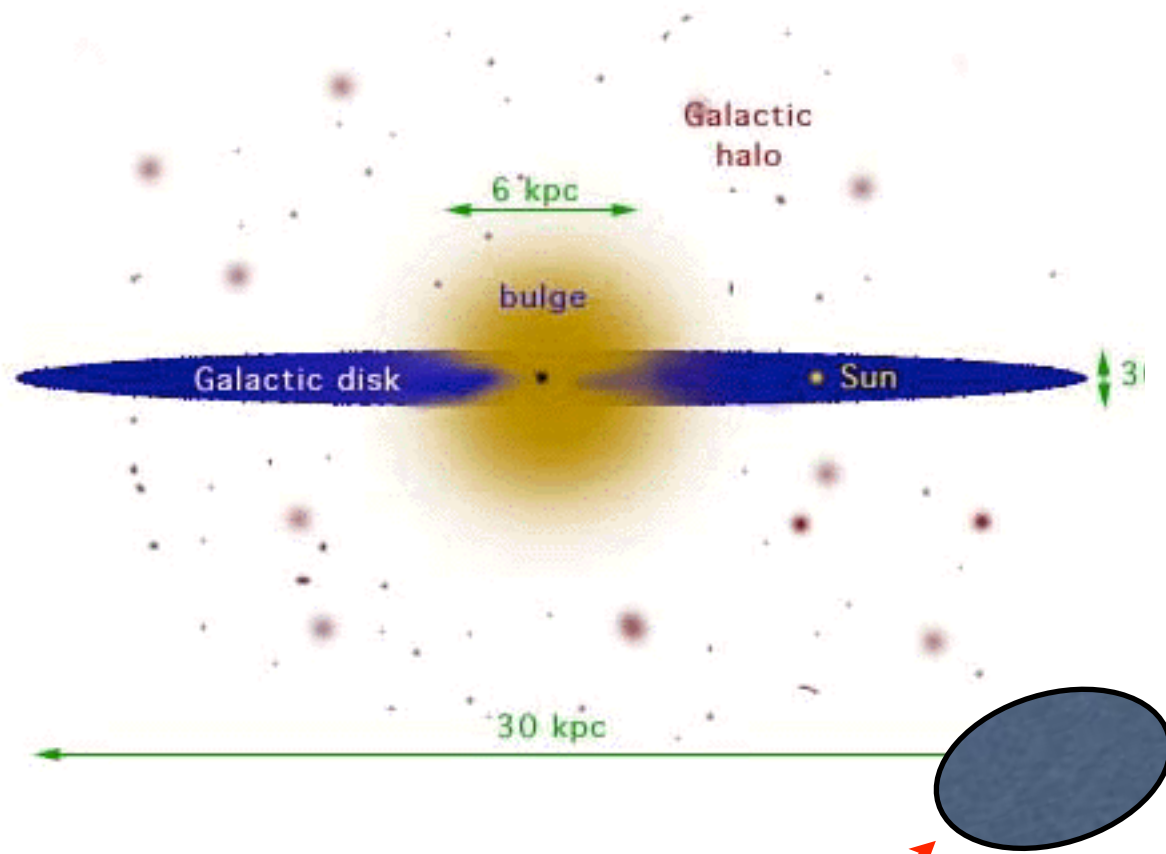


Small Magellanic Cloud

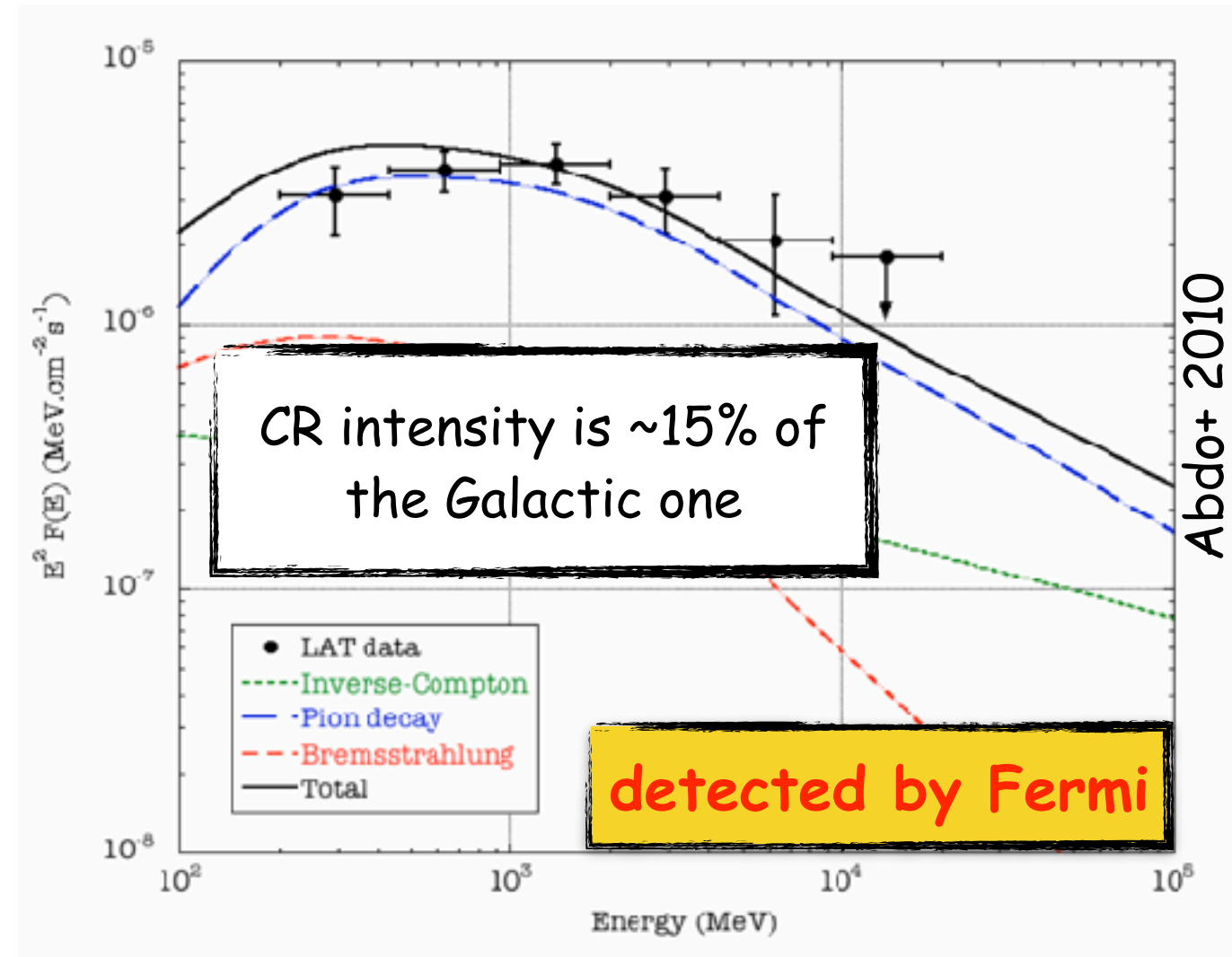
Cosmological —>

- same CR intensity here (measured) & in the SMC
- > mass of ISM in the SMC is known
- > we can predict the gamma-ray flux from the SMC
- > it should have been detected by EGRET
- > but it was not! (Sreekumar+ 1993)
- > CRs are **NOT cosmological**

Diffuse emission in other galaxies



Small Magellanic Cloud



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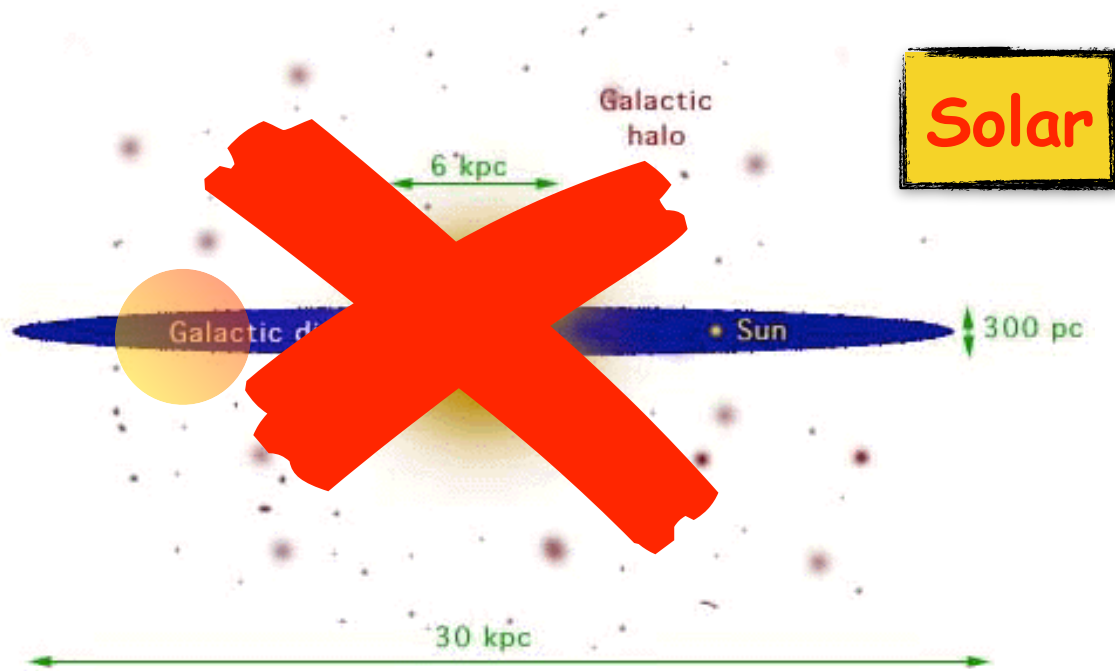
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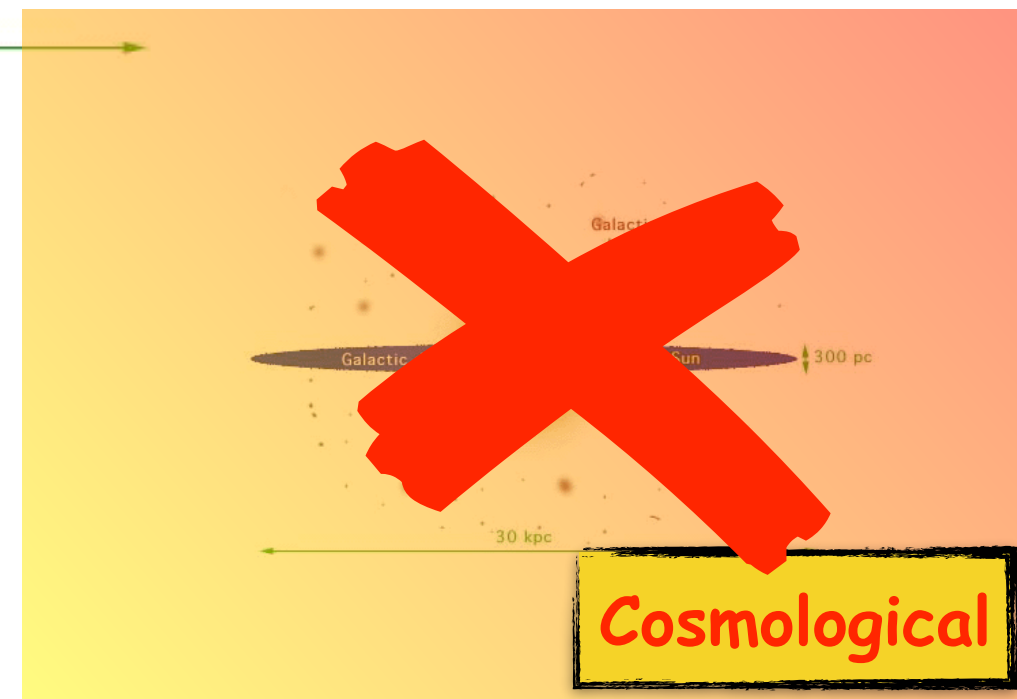
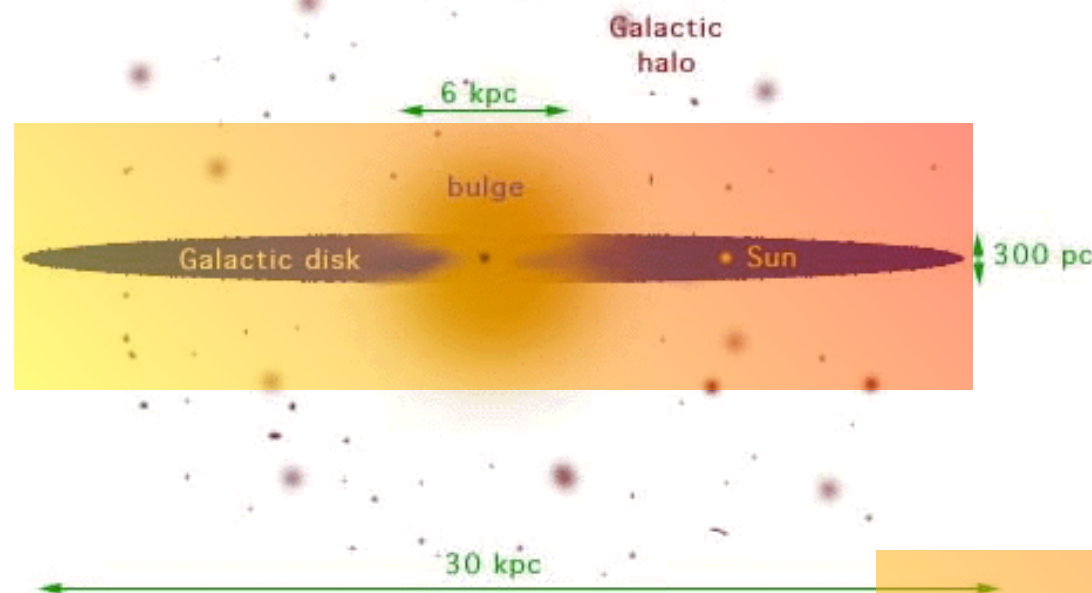
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CRs are Galactic

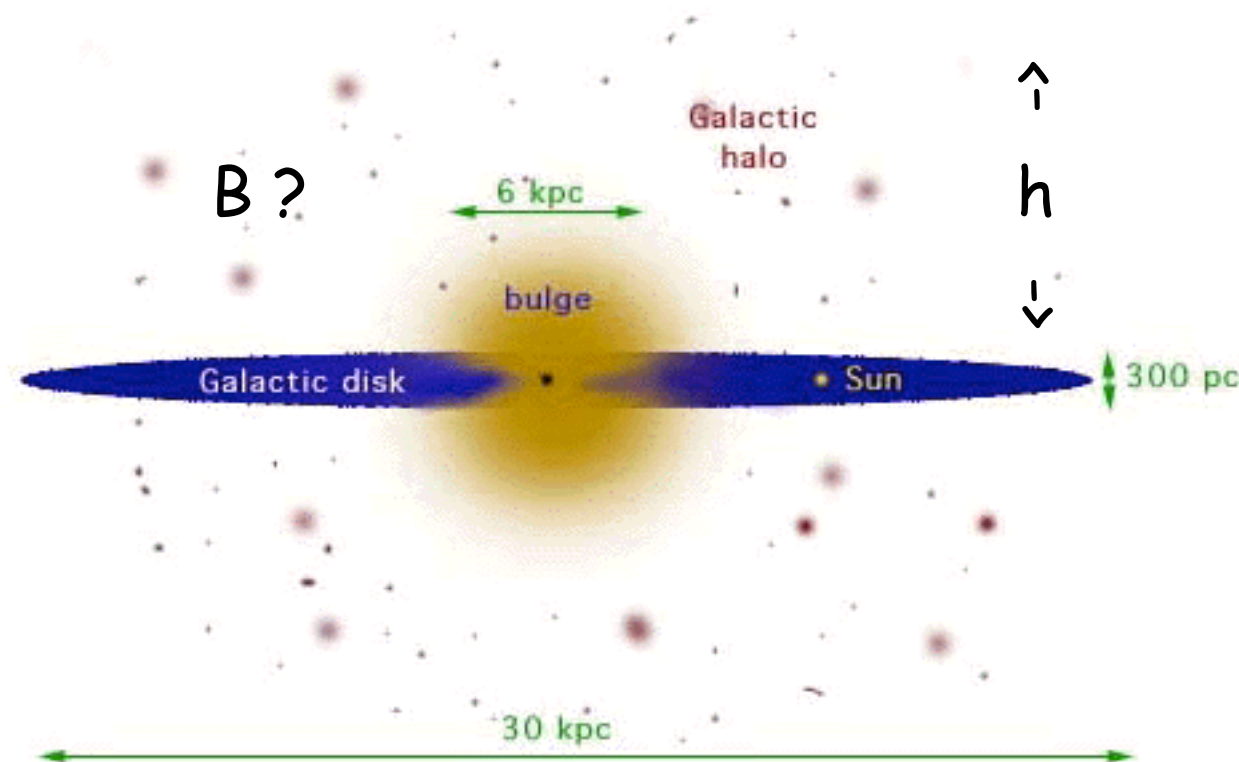


Galactic



In fact, MOST CRs are Galactic...

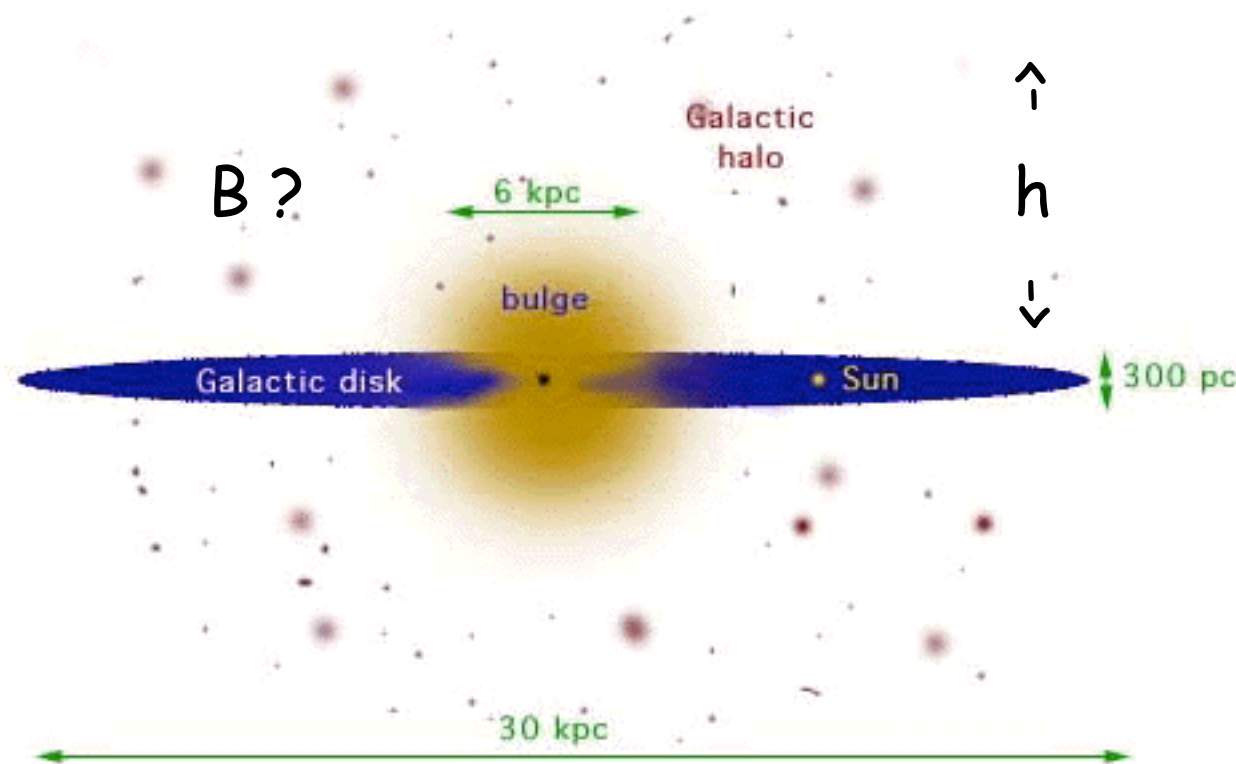
Which CRs are confined in the Galaxy?



It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

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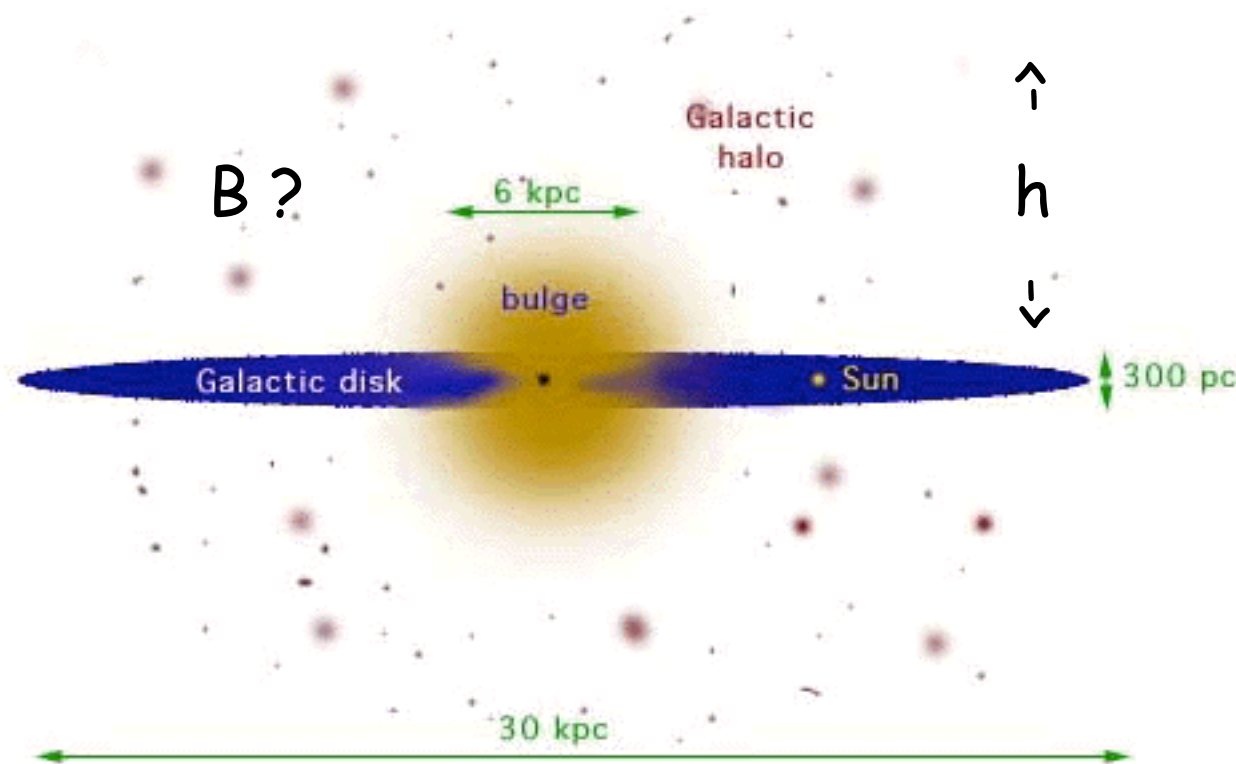
Confinement condition:

$$R_L < h$$

Larmor radius halo size

In fact, MOST CRs are Galactic...

Which CRs are confined in the Galaxy?



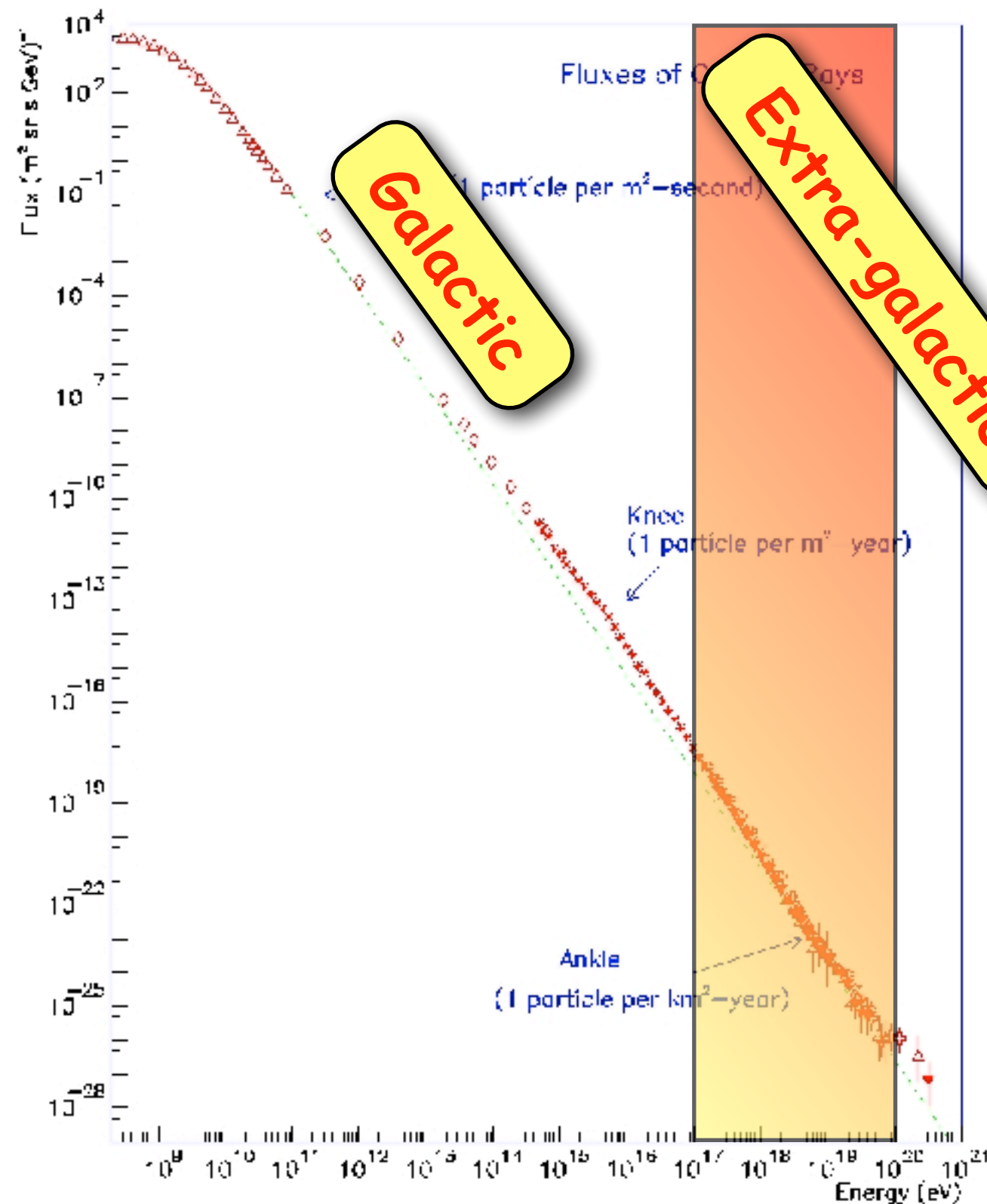
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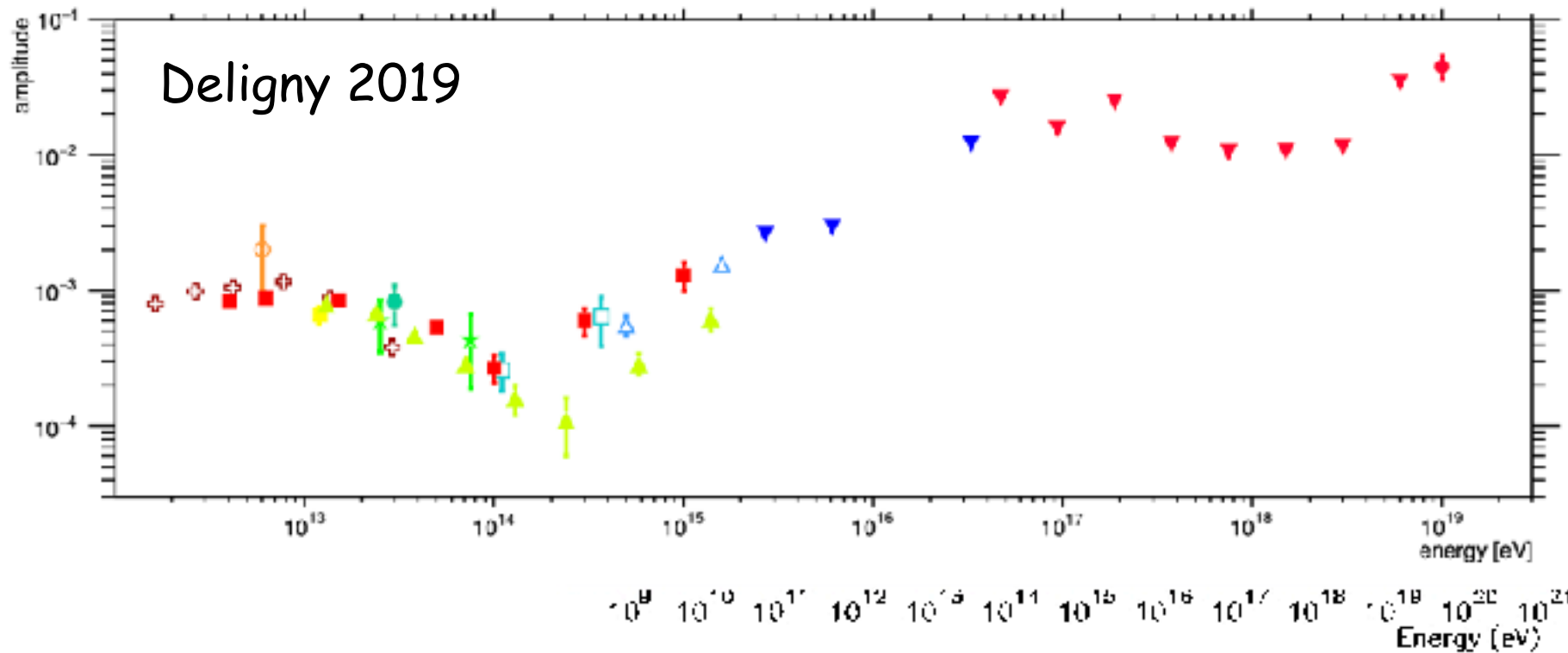
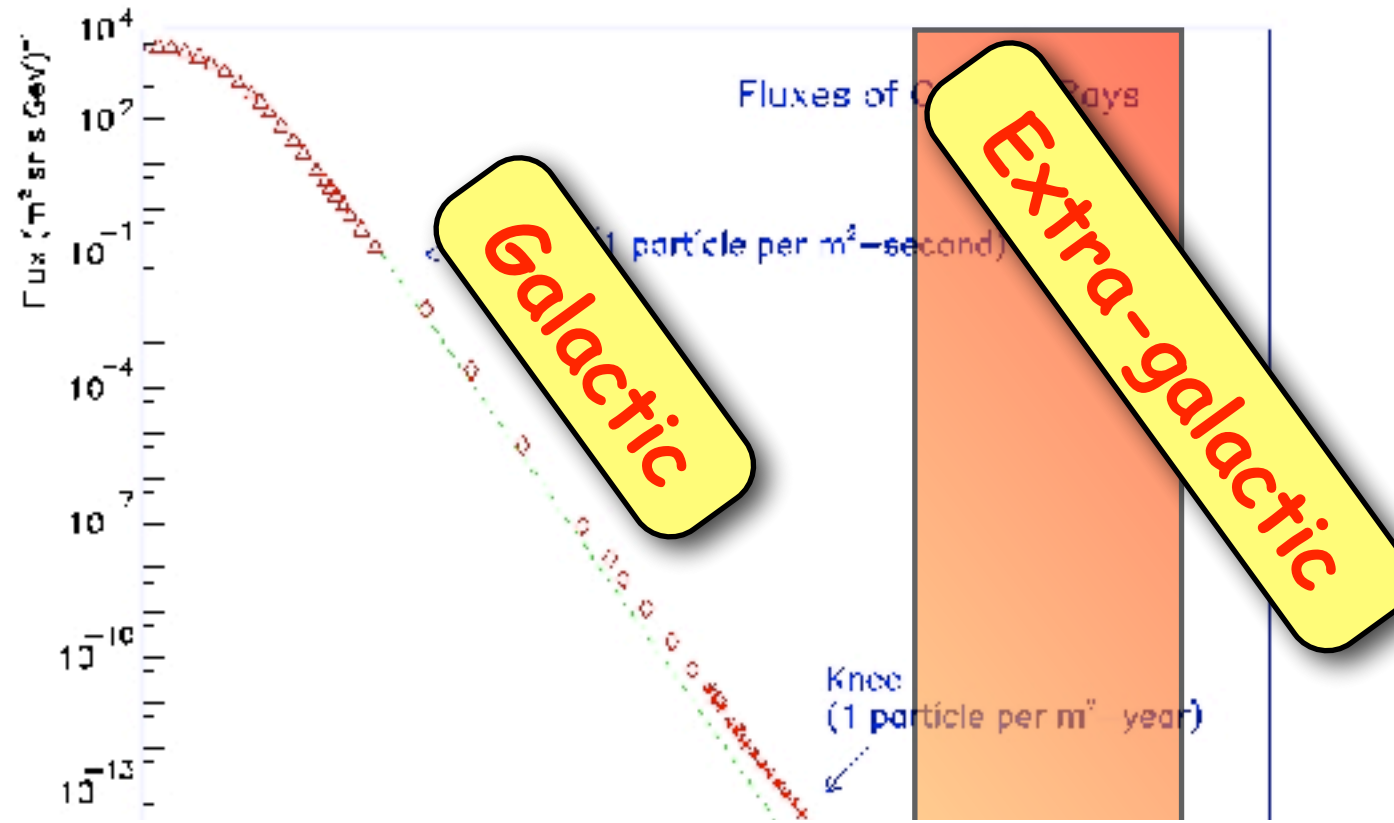
$$\frac{E(\text{eV})}{300 B(\text{G})} = R_L < h \Rightarrow E < 10^{18} \left(\frac{h}{\text{kpc}} \right) \left(\frac{B}{\mu\text{G}} \right) \text{eV} = 10^{17} \div 10^{20} \text{eV}$$

$\frac{E(\text{eV})}{300 B(\text{G})}$ (cm) $\nearrow$ Larmor radius
 R_L $\nwarrow$ halo size
 h $\nwarrow$ halo size
 $\left(\frac{h}{\text{kpc}} \right)$ 1 - 10
 $\left(\frac{B}{\mu\text{G}} \right)$ 0.1 - 10

Galactic or extra-galactic?



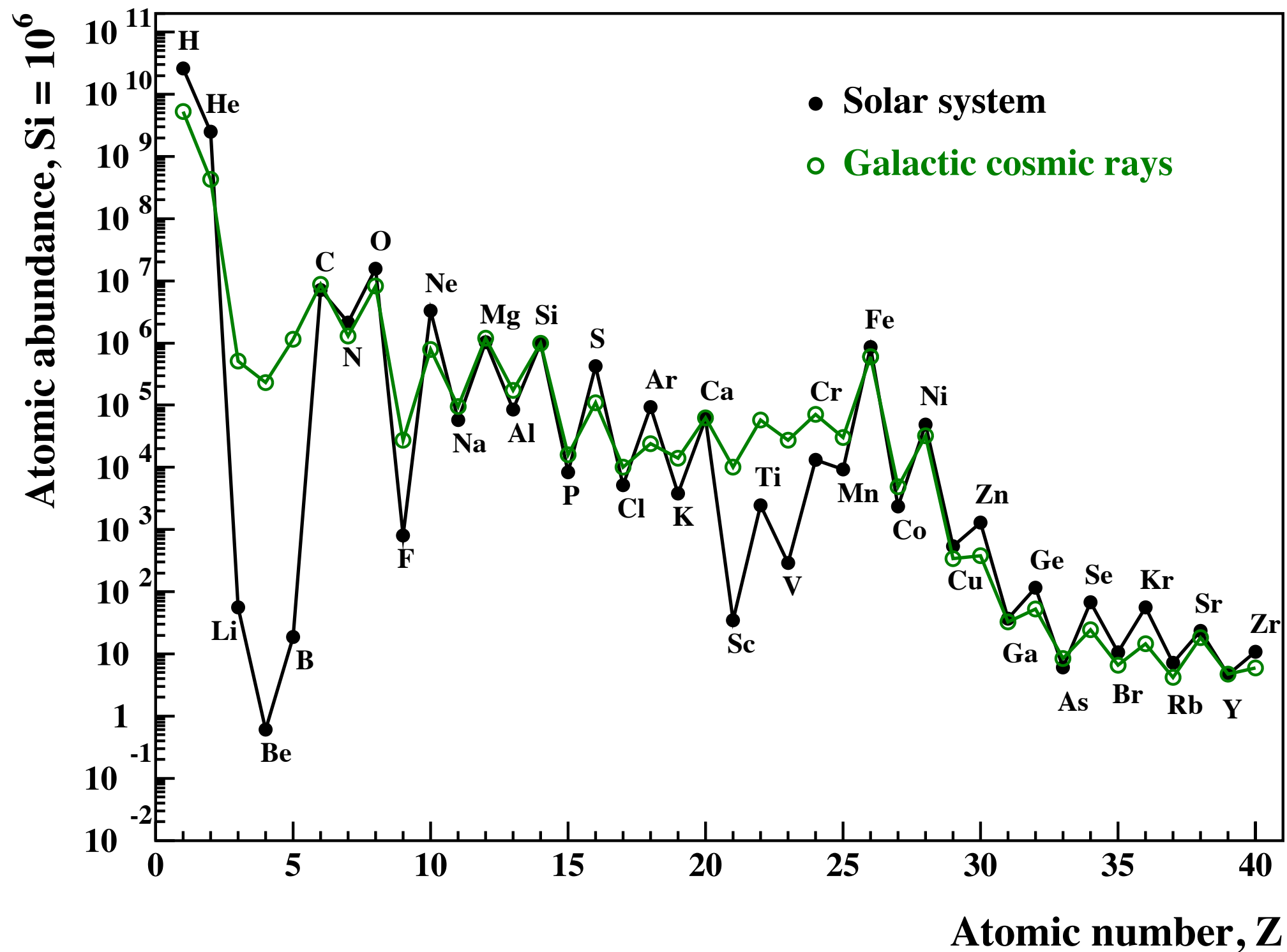
Galactic or extra-galactic?



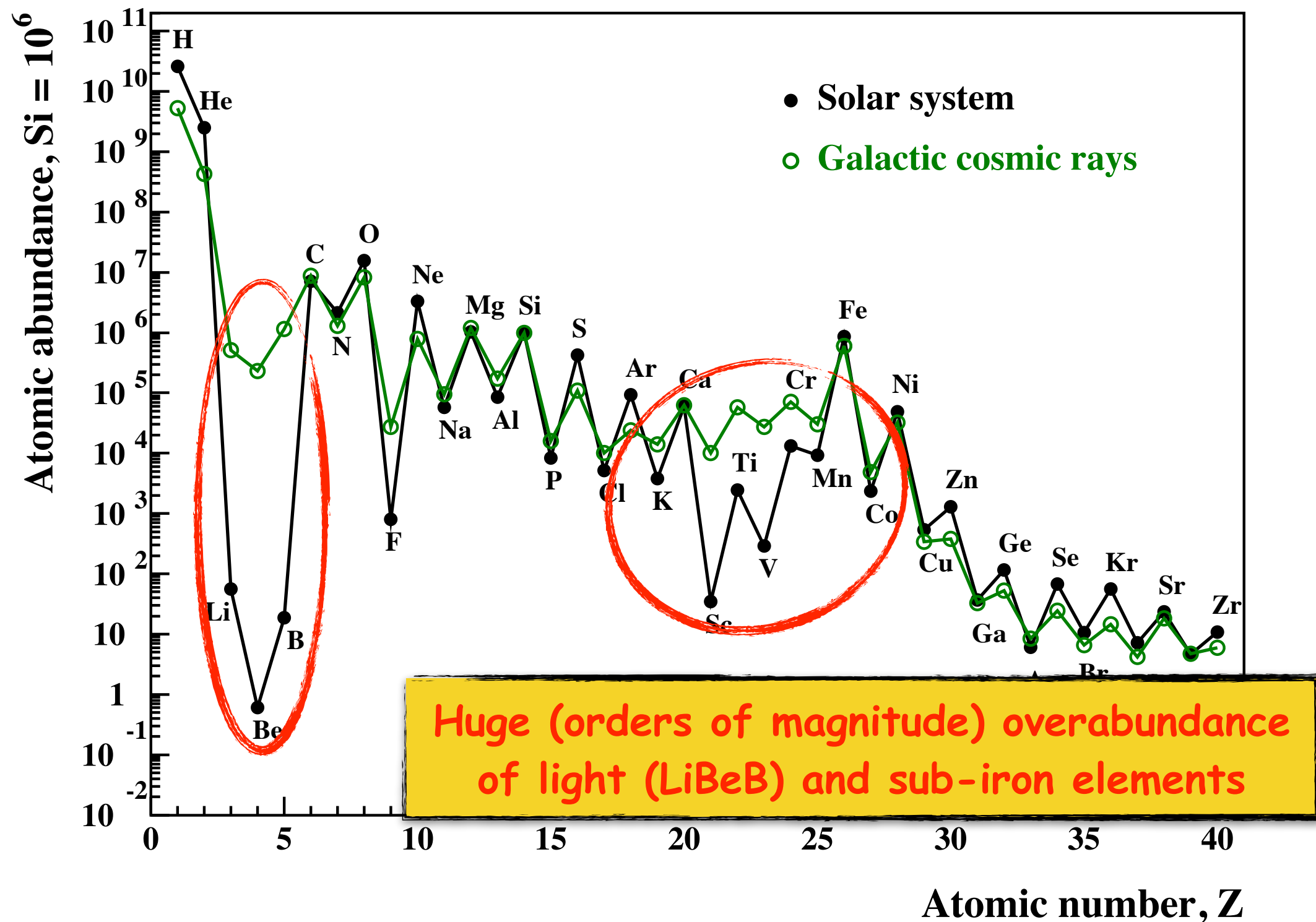
→ larger anisotropy?

[4] Composition

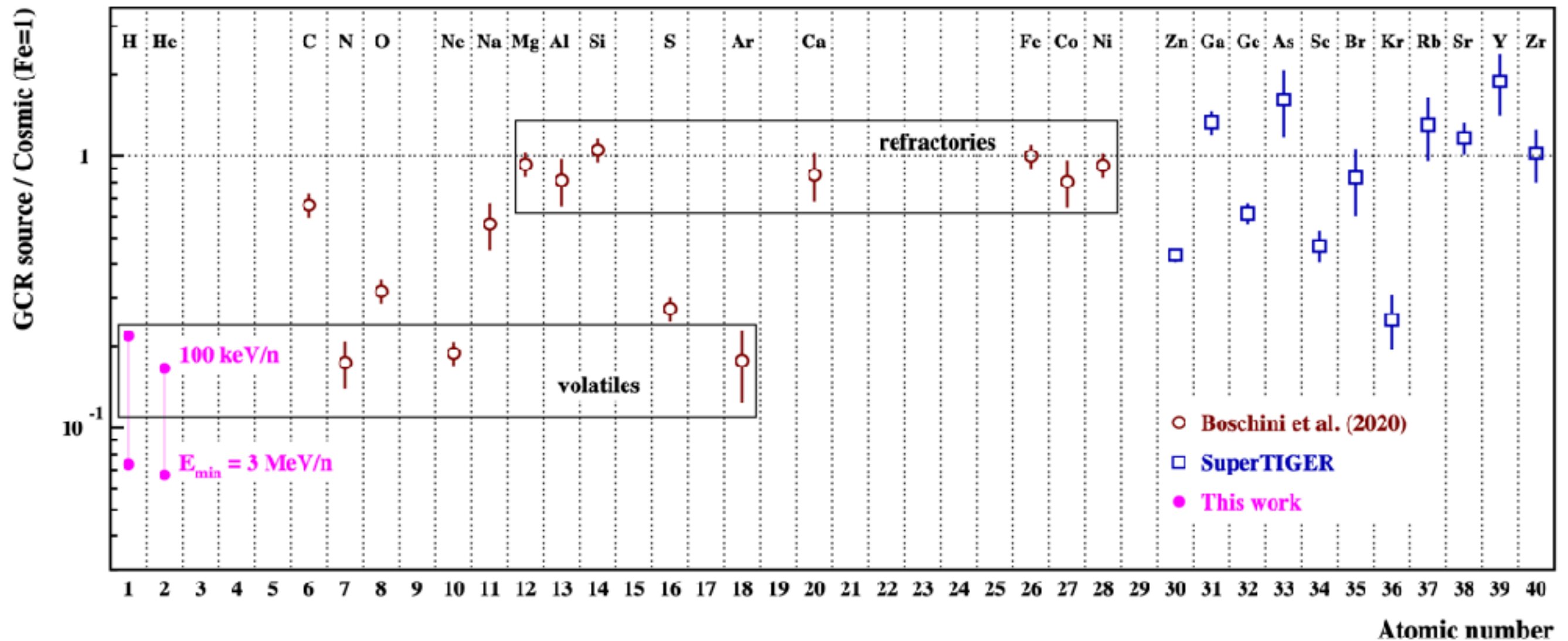
Composition: striking anomalies



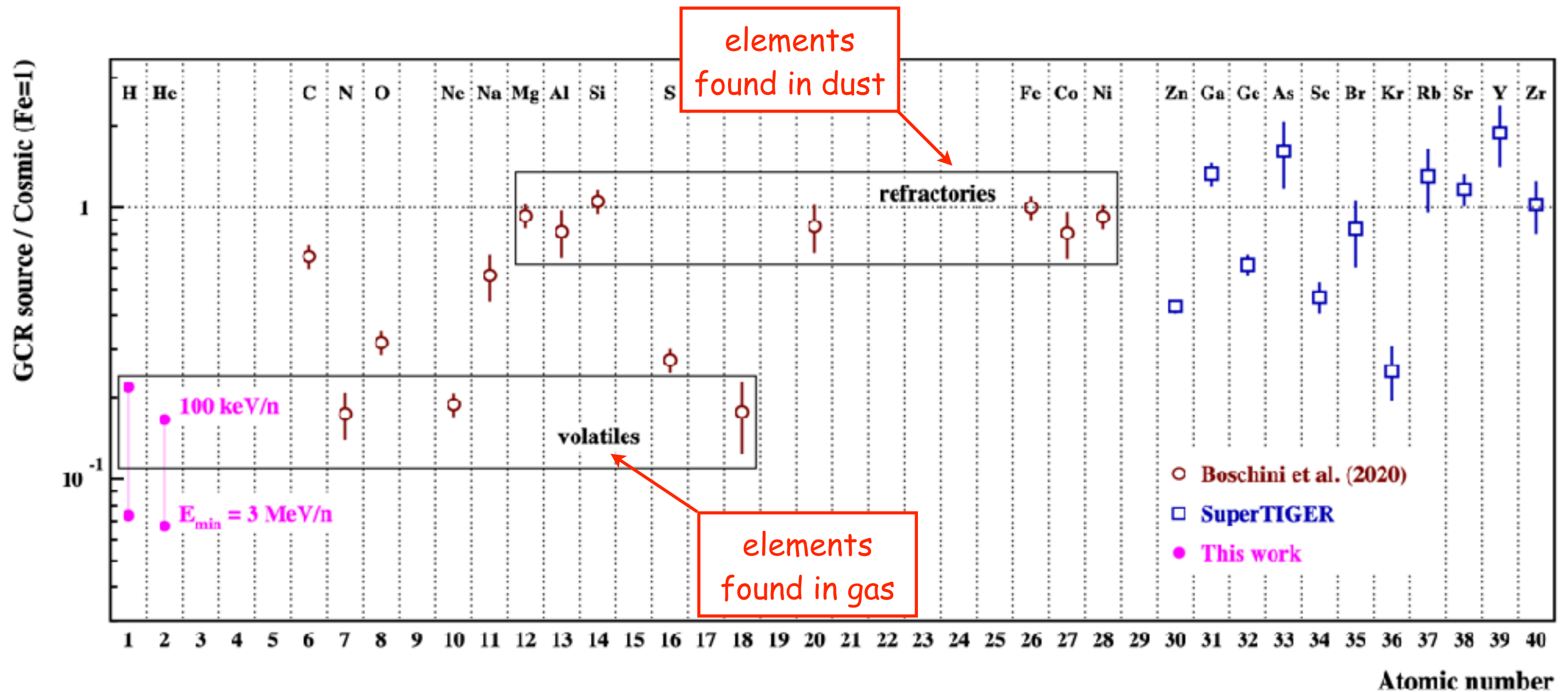
Composition: striking anomalies



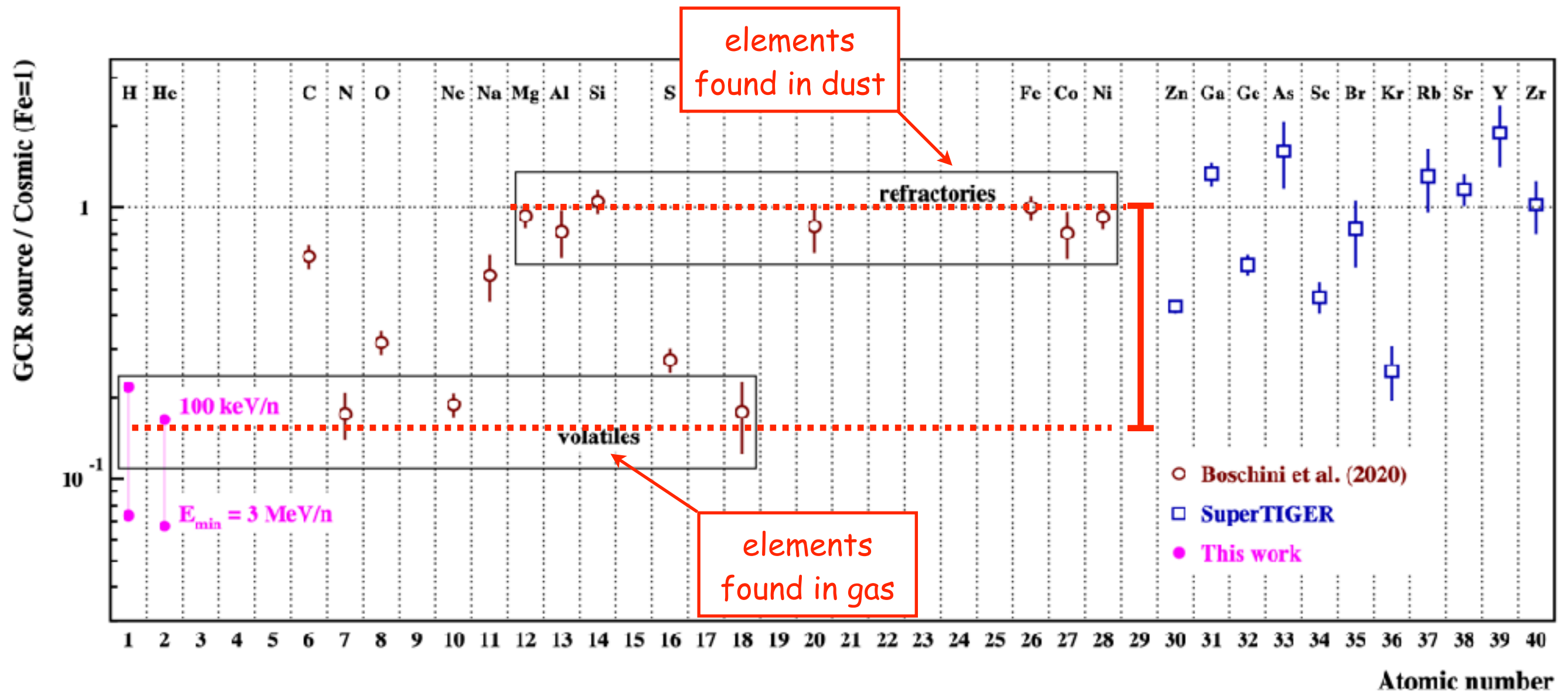
Composition: volatiles and refractories



Composition: volatiles and refractories

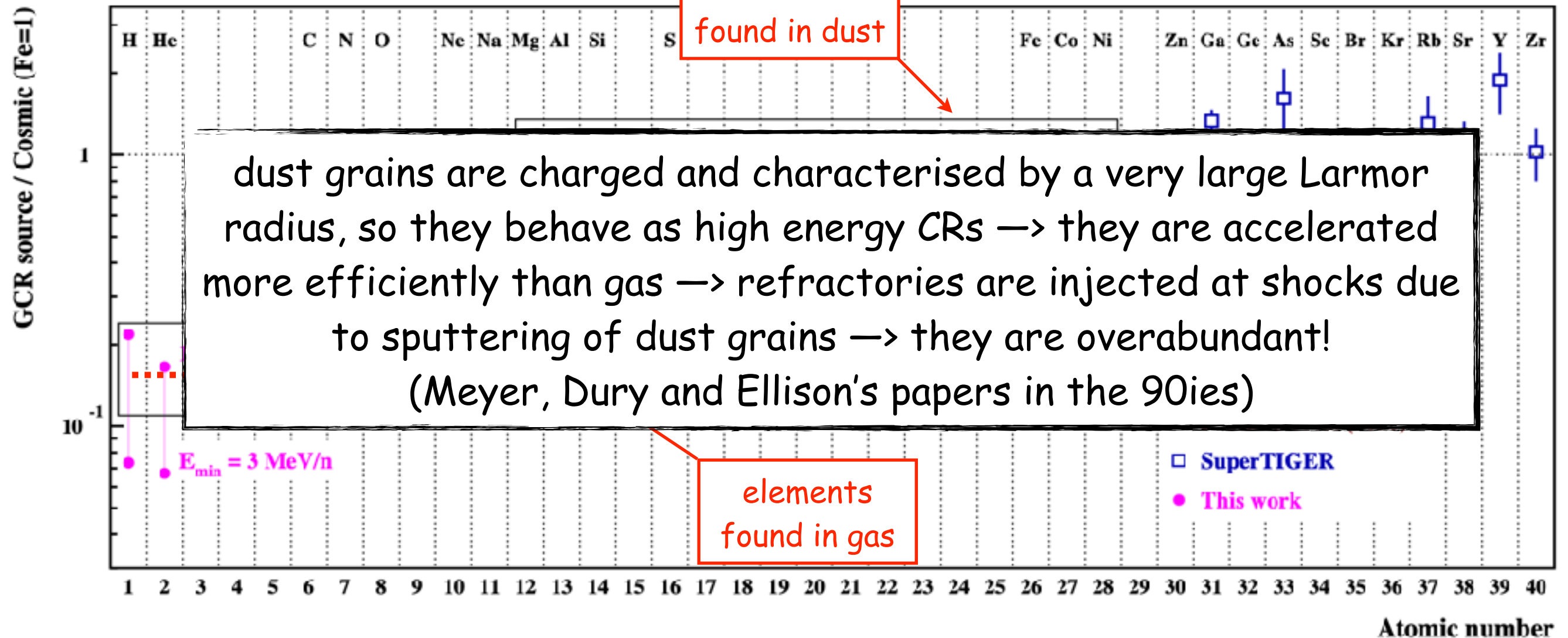


Composition: volatiles and refractories



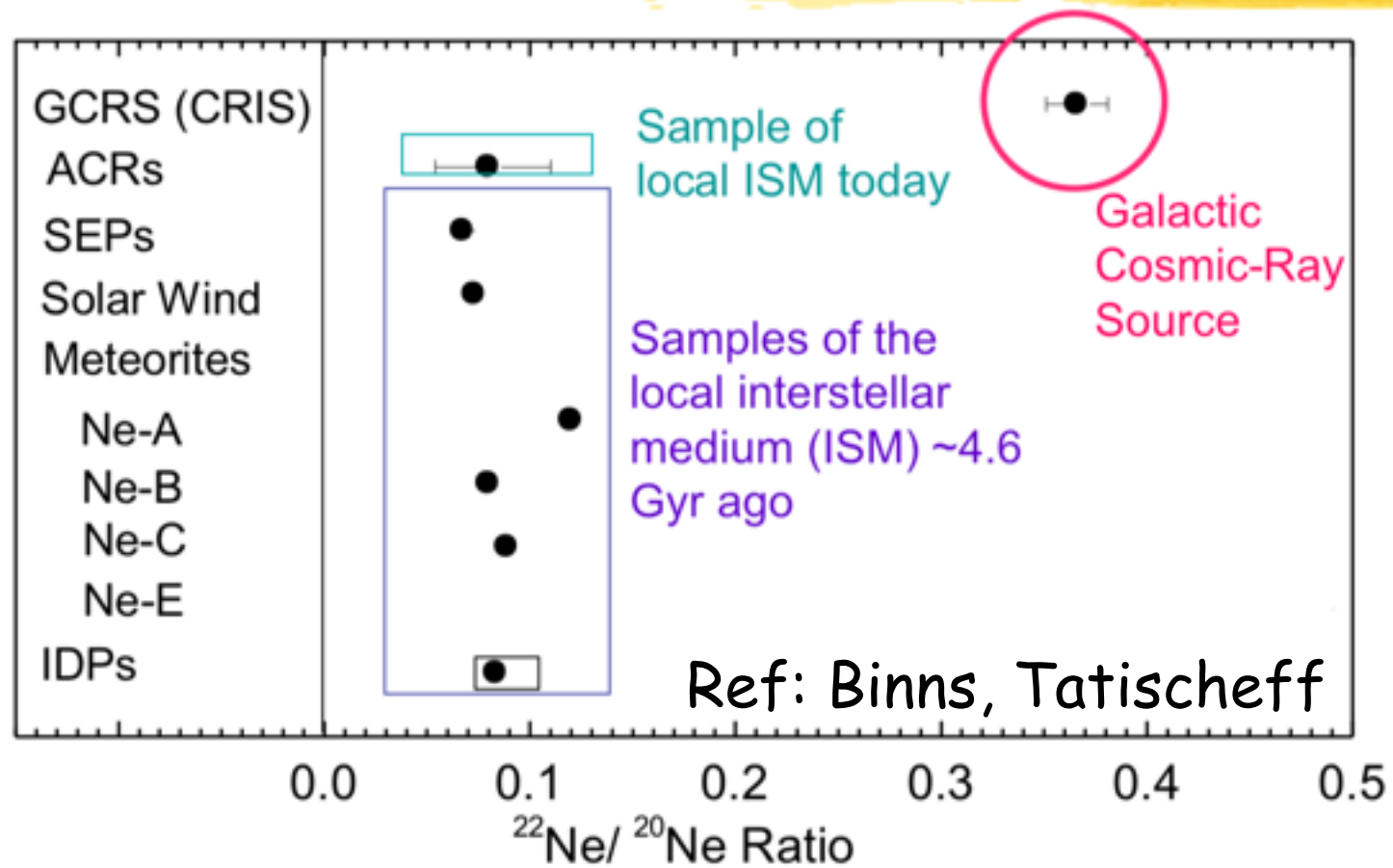
less pronounced but still very clear differences
 —> volatiles versus refractories? —> dust must play a role...

Composition: volatiles and refractories

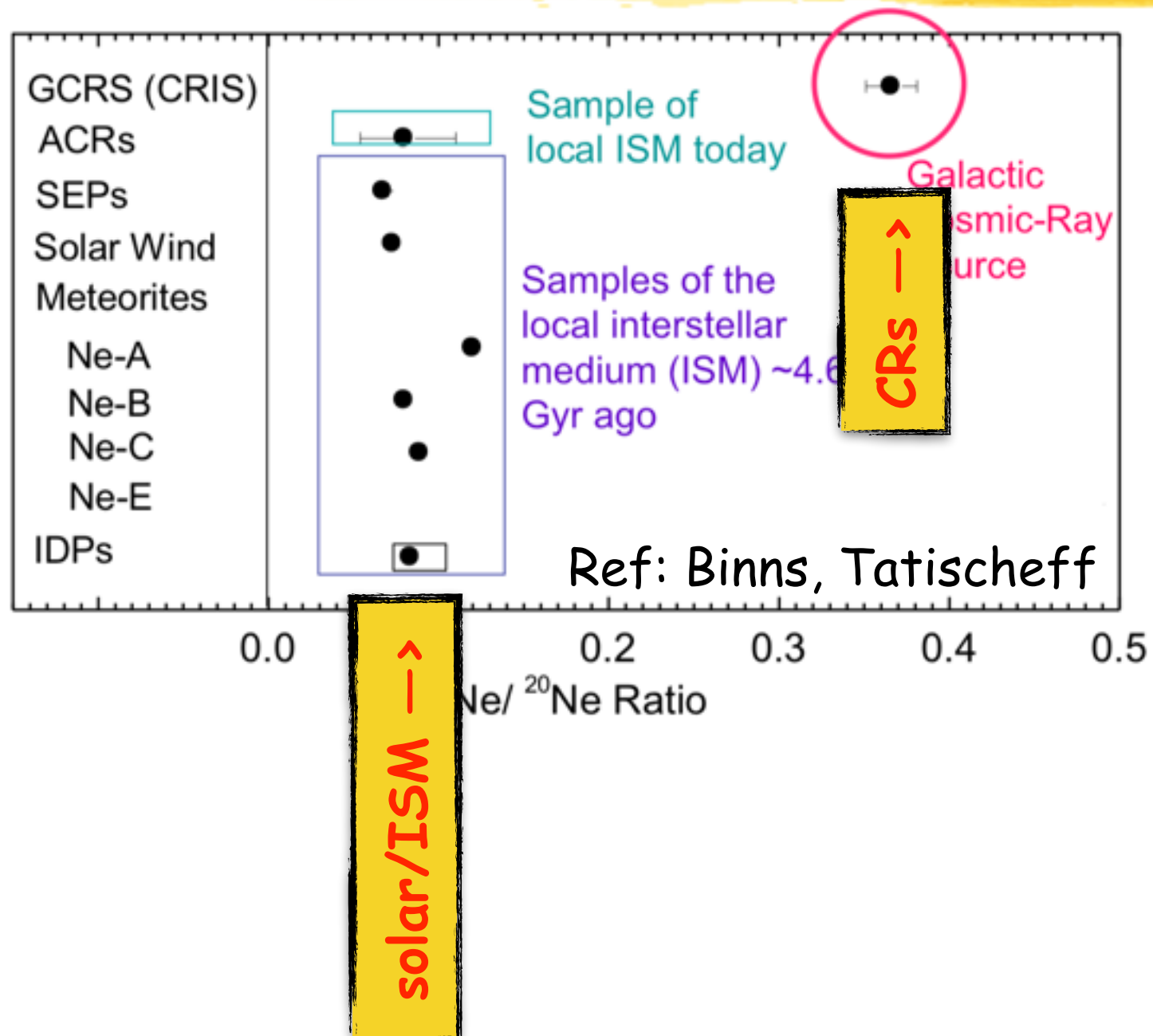


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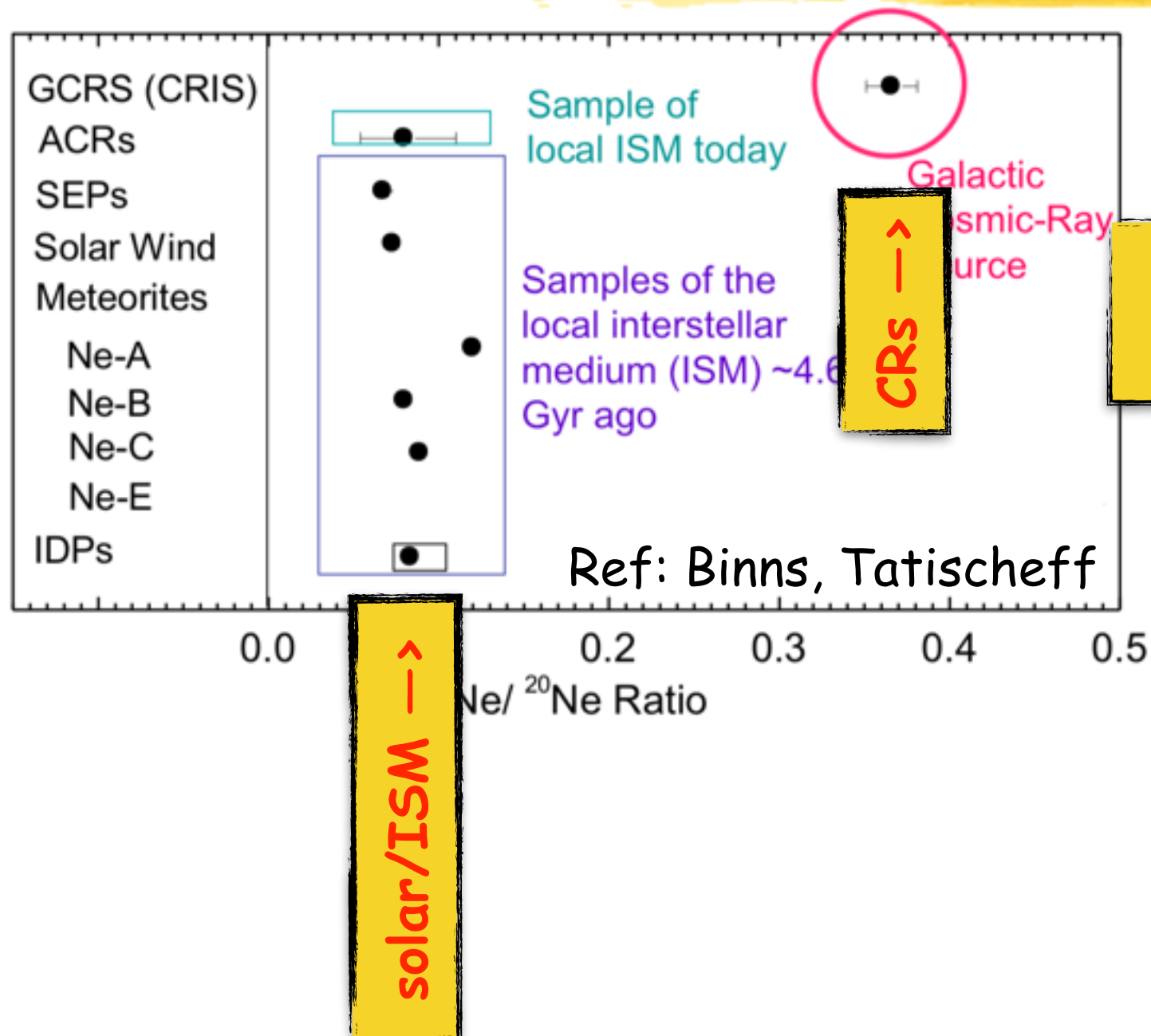
Composition: isotopic anomalies



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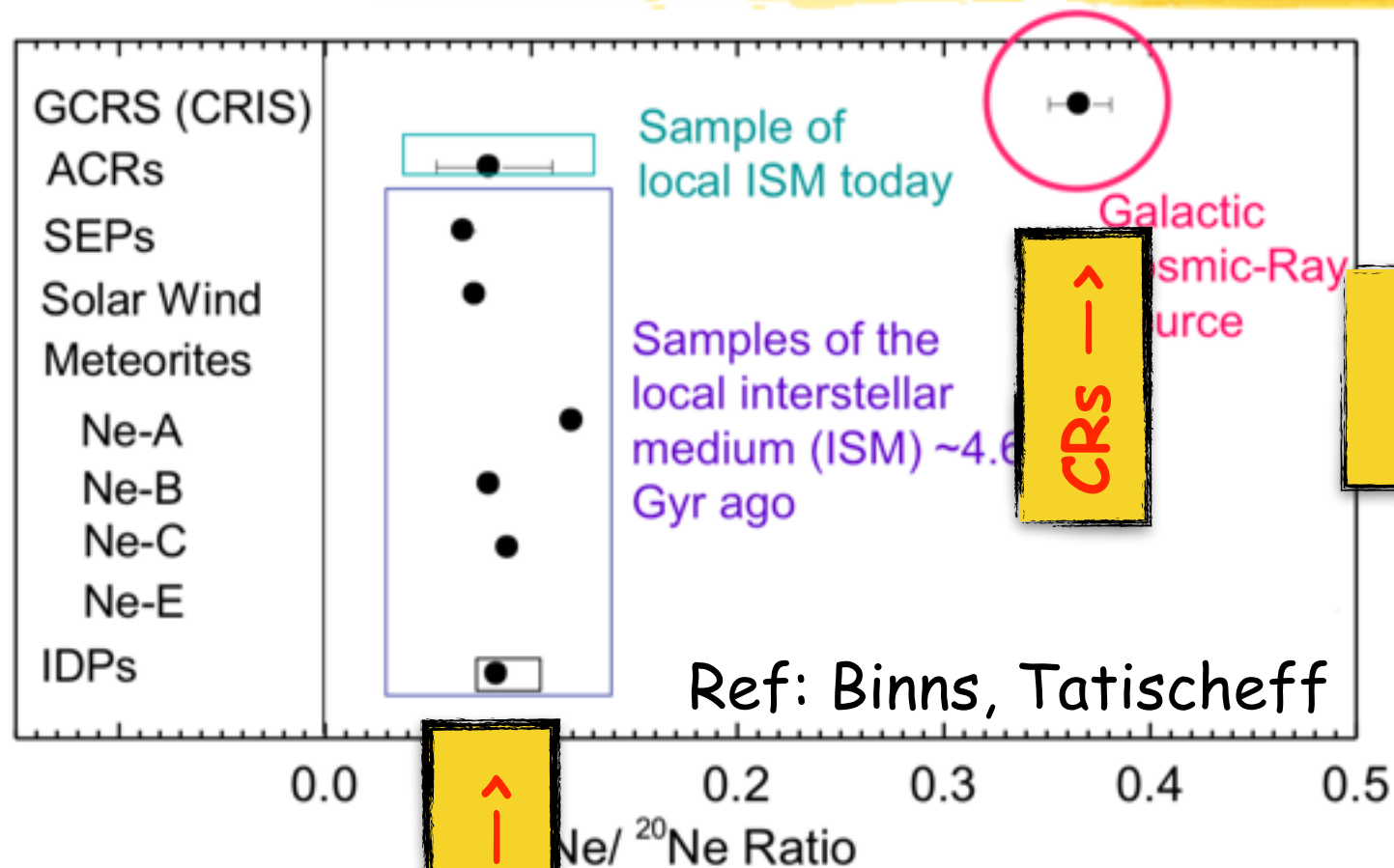


Composition: isotopic anomalies



^{22}Ne is abundant in the wind material of Wolf-Rayet stars

Composition: isotopic anomalies



^{22}Ne is abundant in the wind material of Wolf-Rayet stars

—> stellar winds must play a role in CR acceleration!

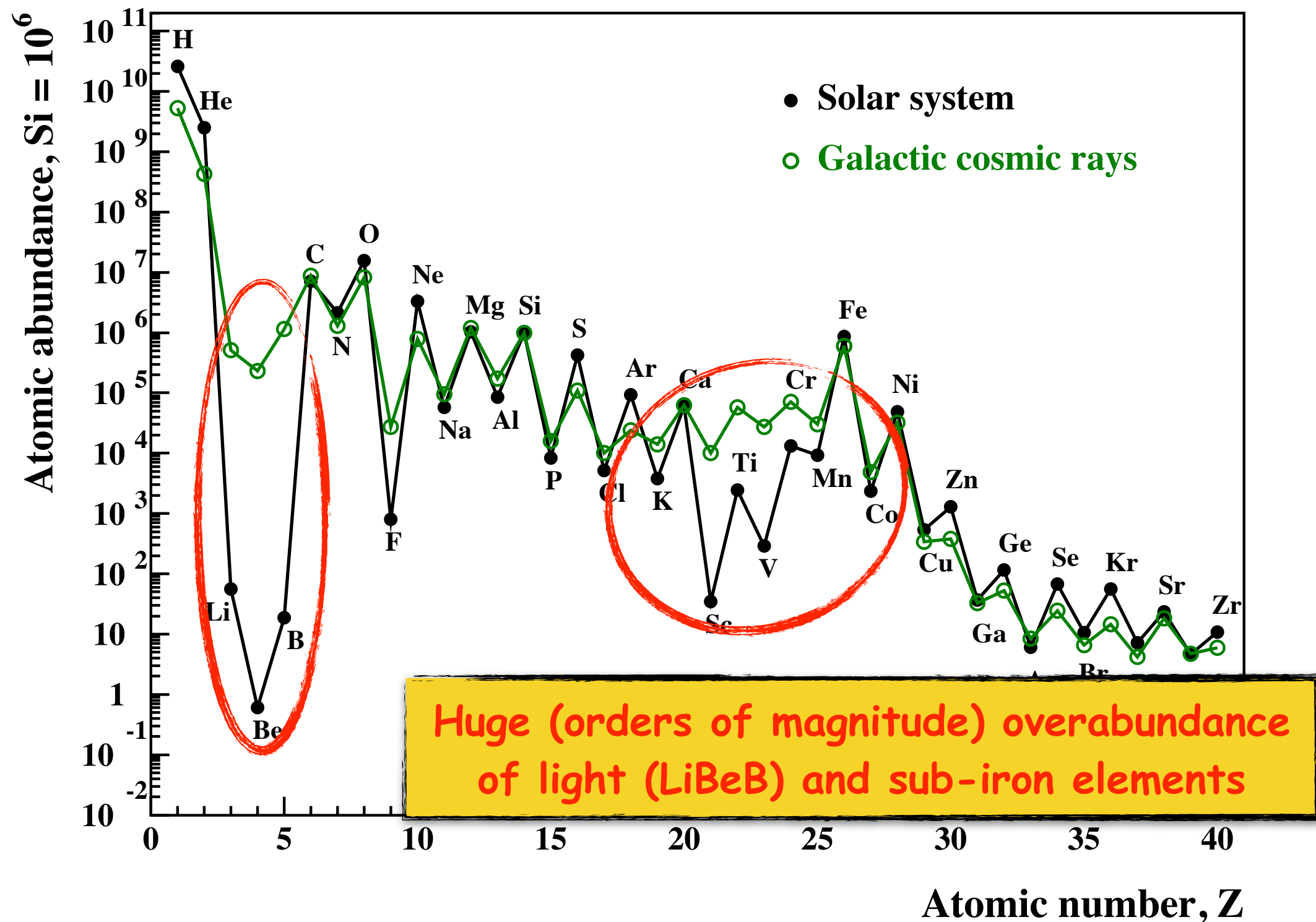
Summary:

what we have learned from data

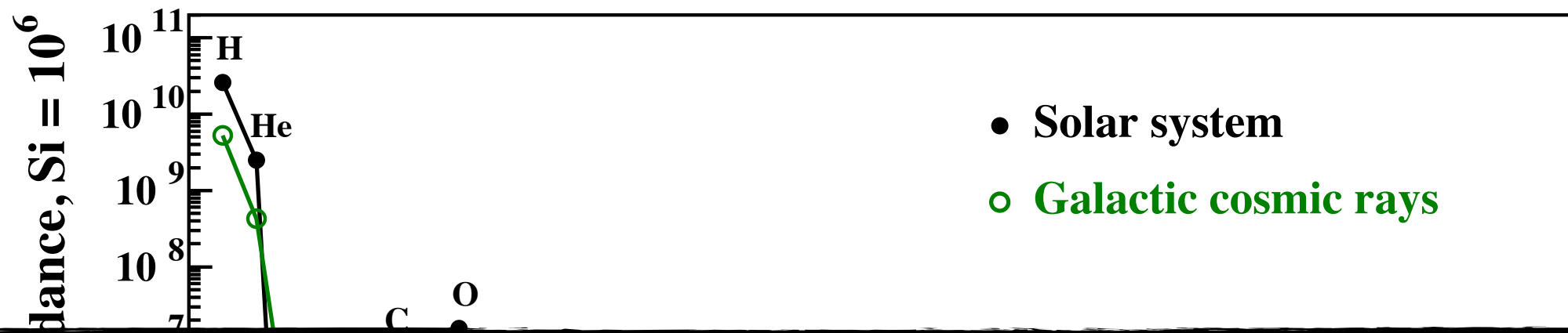
- CR intensity is very stable in time (meteorites, lunar rocks, etc)
- CRs are distributed roughly homogeneously in the Galactic disk (gamma rays)
- most CRs are Galactic, at least those with E up to 10^{17} - 10^{19} eV (gamma rays+physics)
- CRs must be deflected (a lot!) by magnetic fields (isotropy)
- CRs carry a lot of energy (same as thermal and magnetic energy of the ISM)
- dust must play a role (composition, refractories/volatiles)
- stellar winds must play a role ($^{22}\text{Ne}/^{20}\text{Ne}$ anomaly)

[5] How long do CRs stay
within the Milky Way?

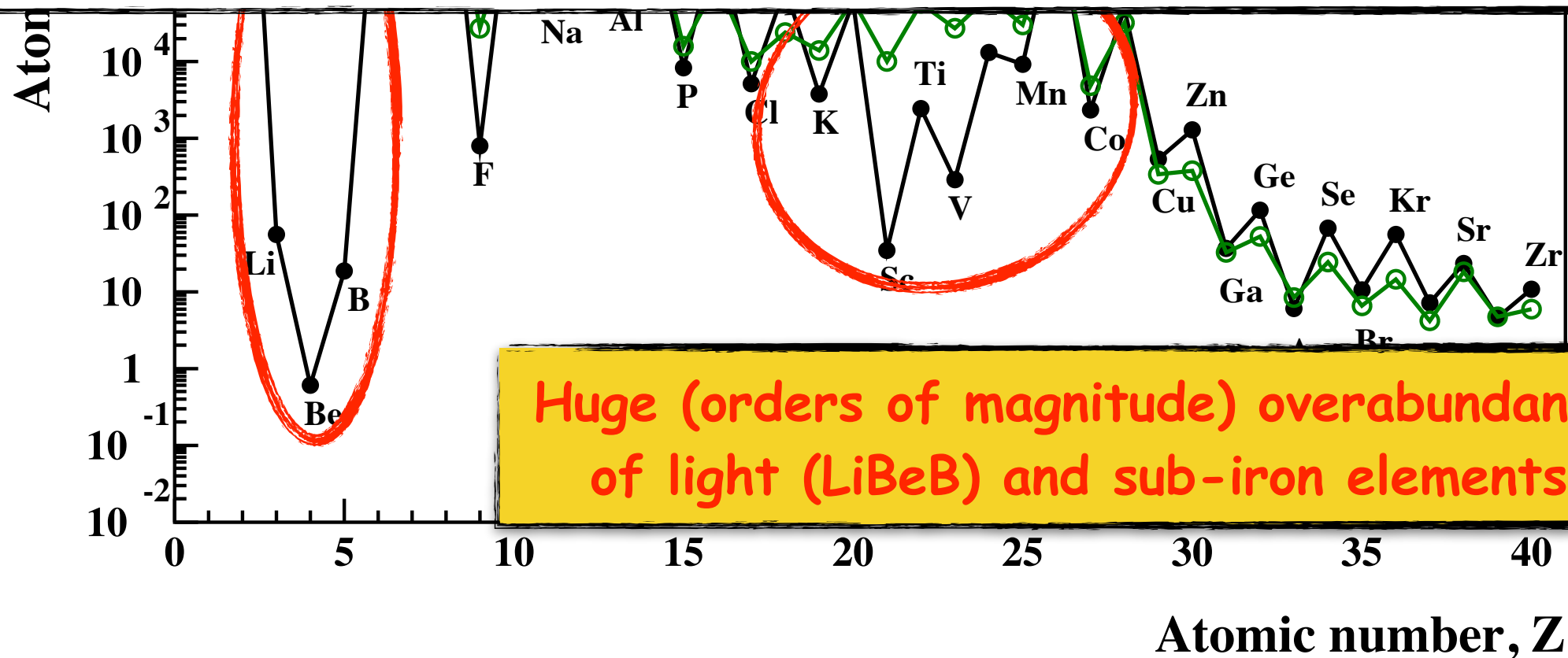
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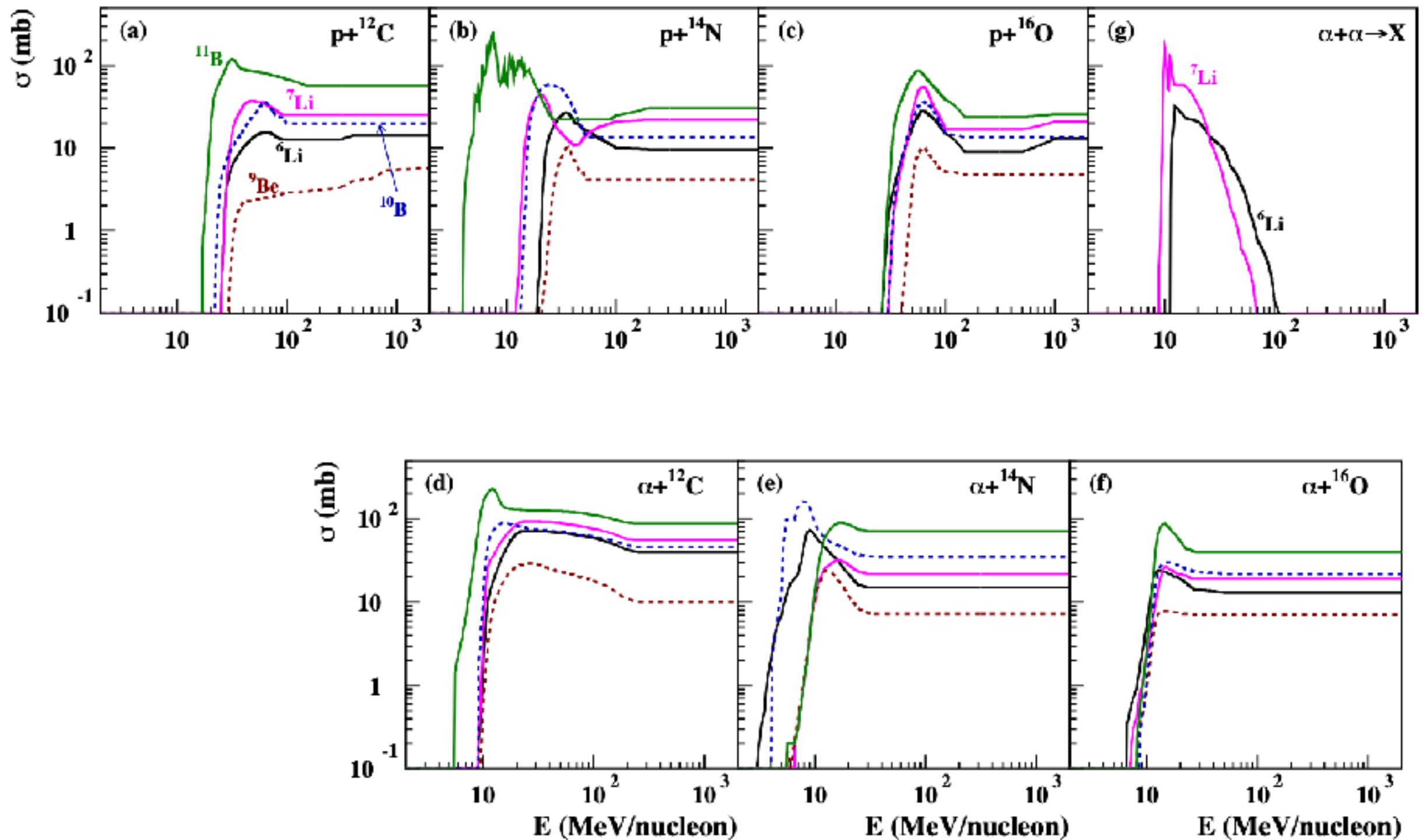


Spallation: production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

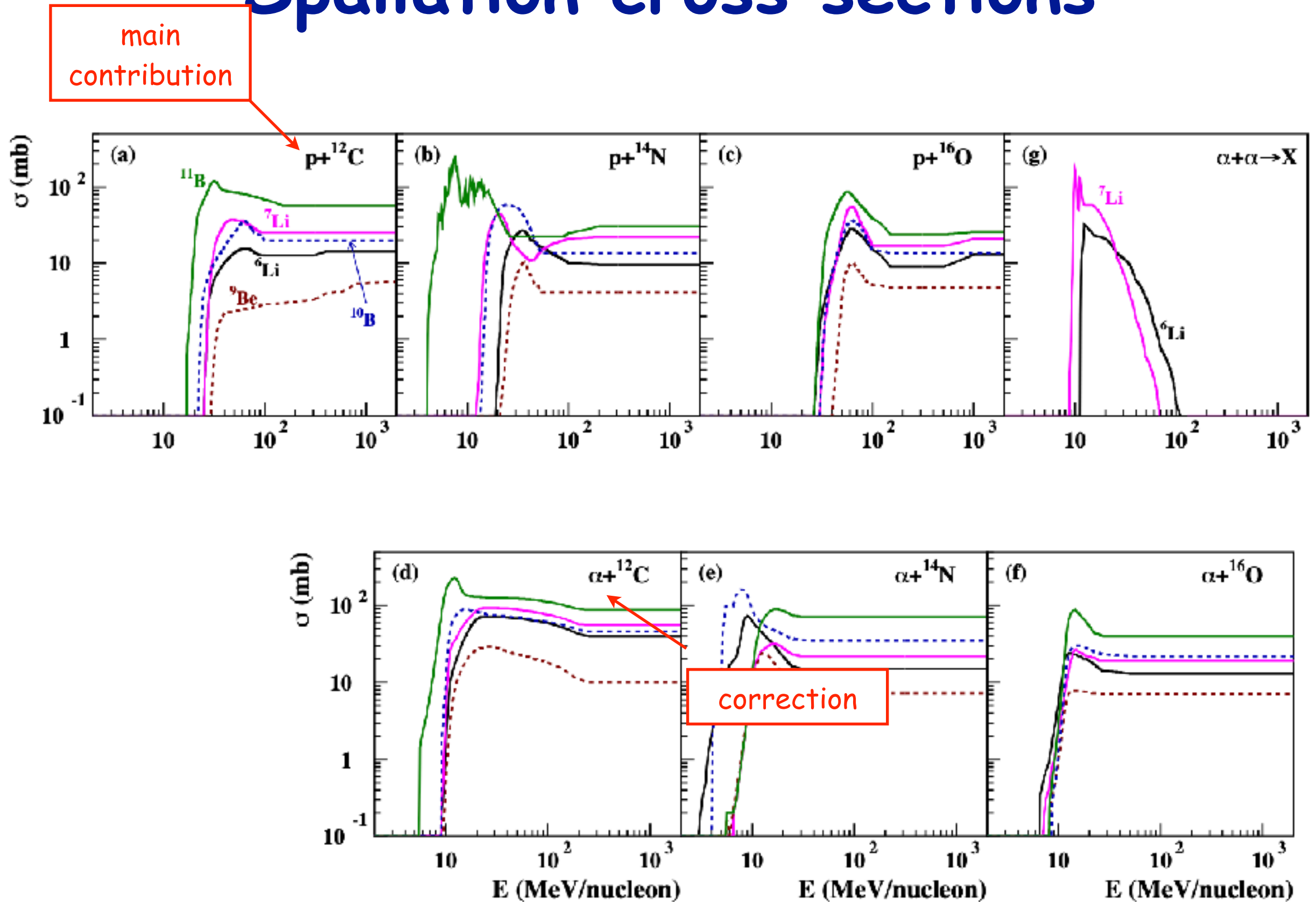


Huge (orders of magnitude) overabundance of light (LiBeB) and sub-iron elements

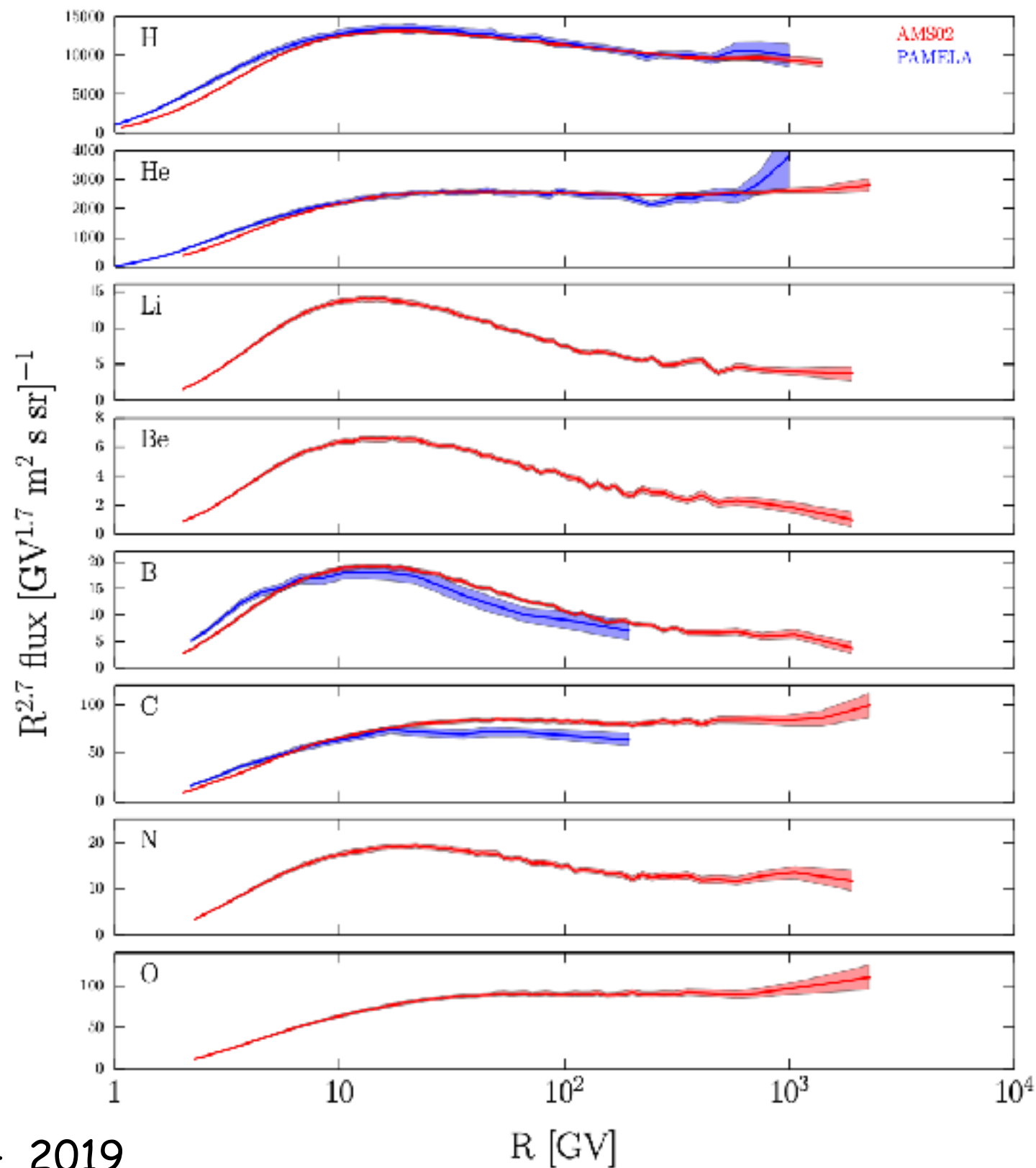
Spallation cross sections



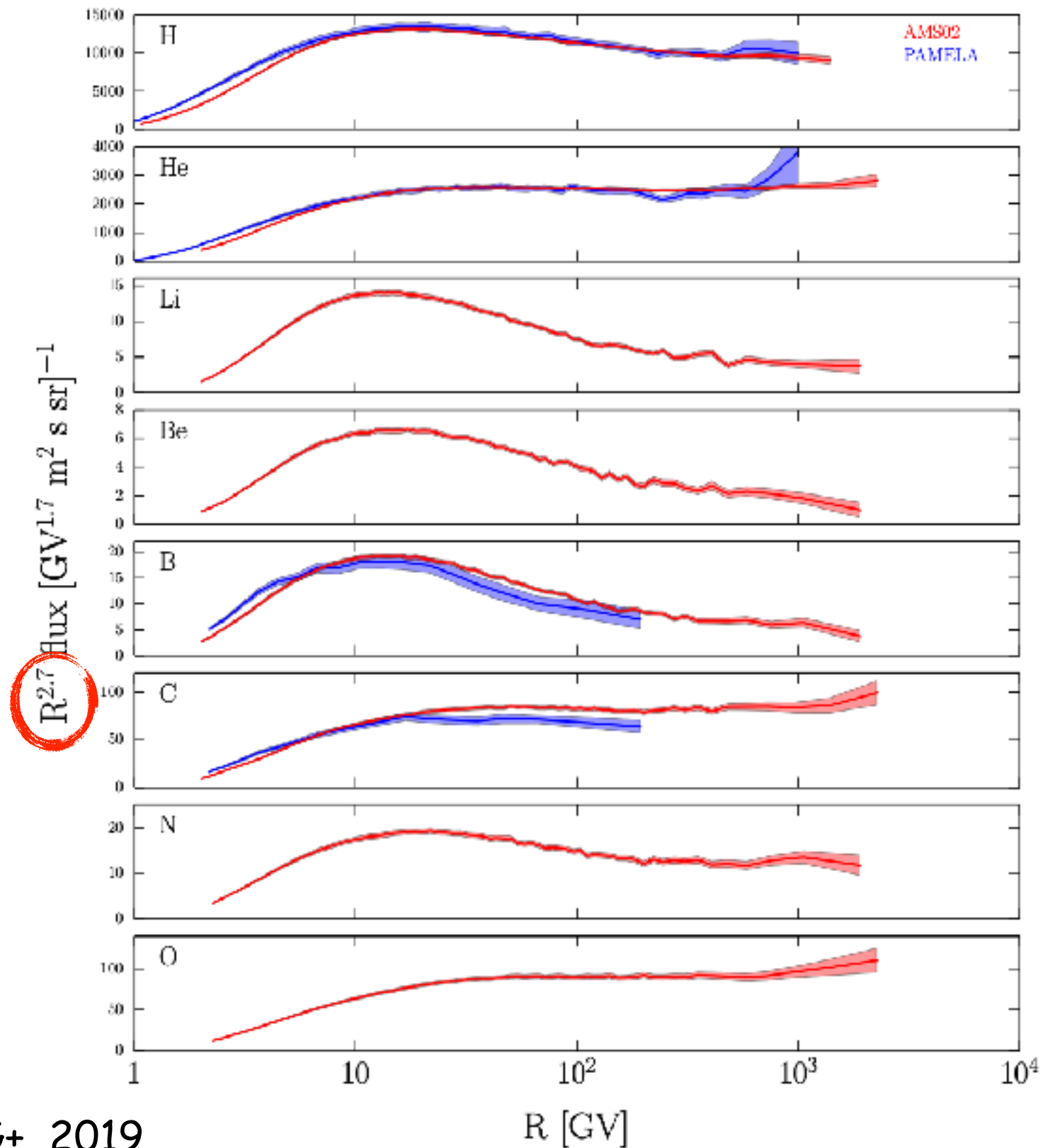
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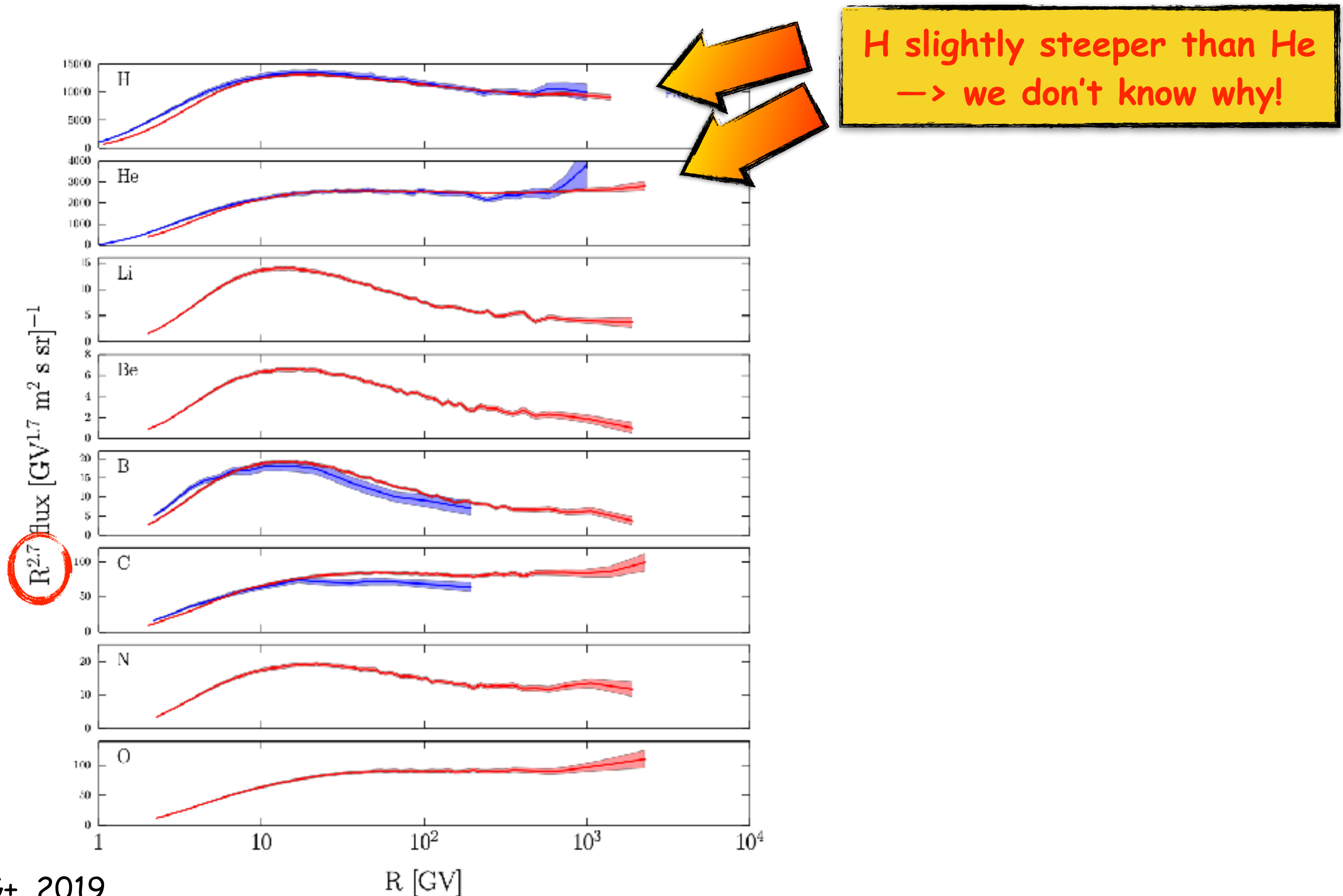
Spectra of light elements



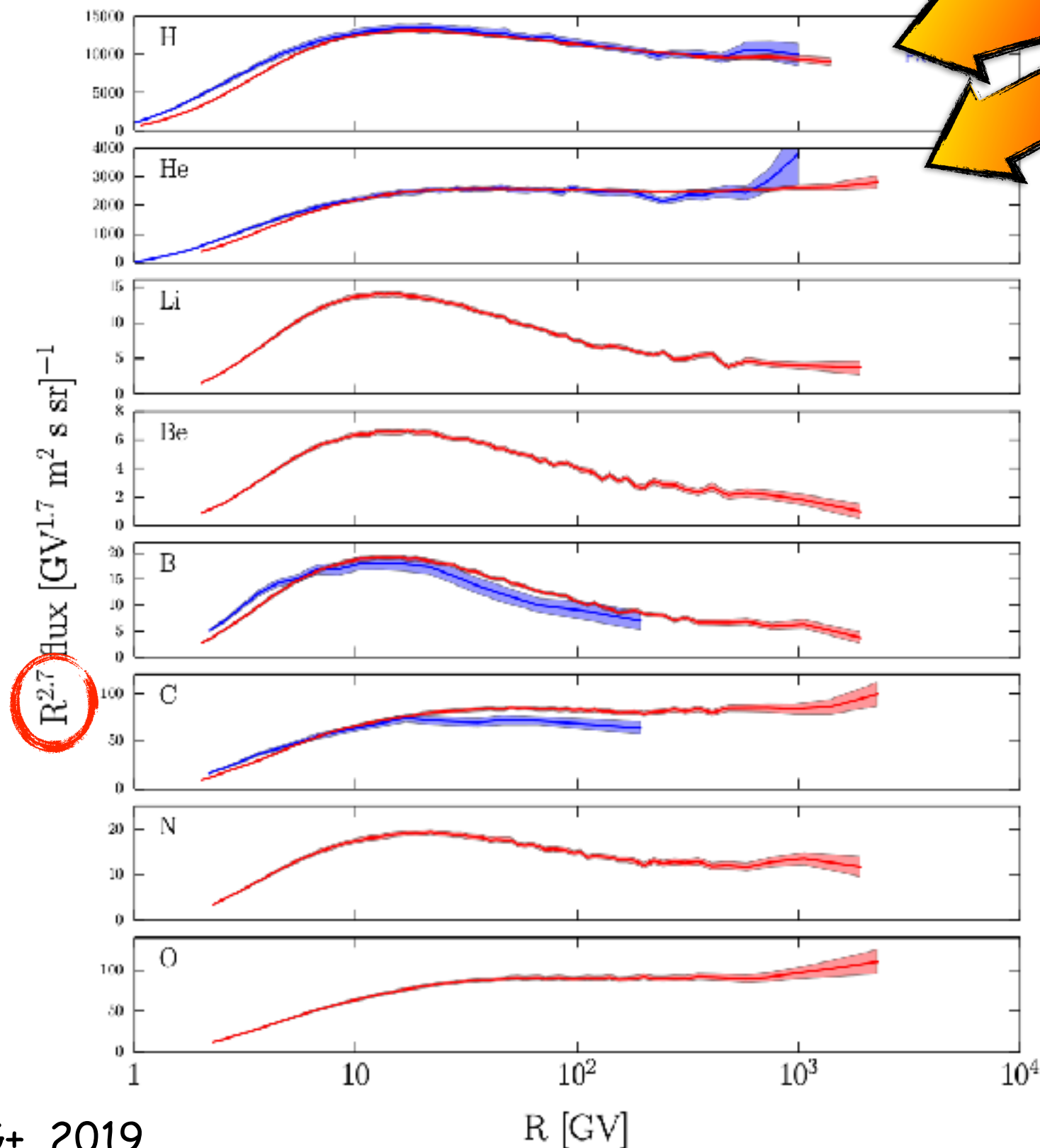
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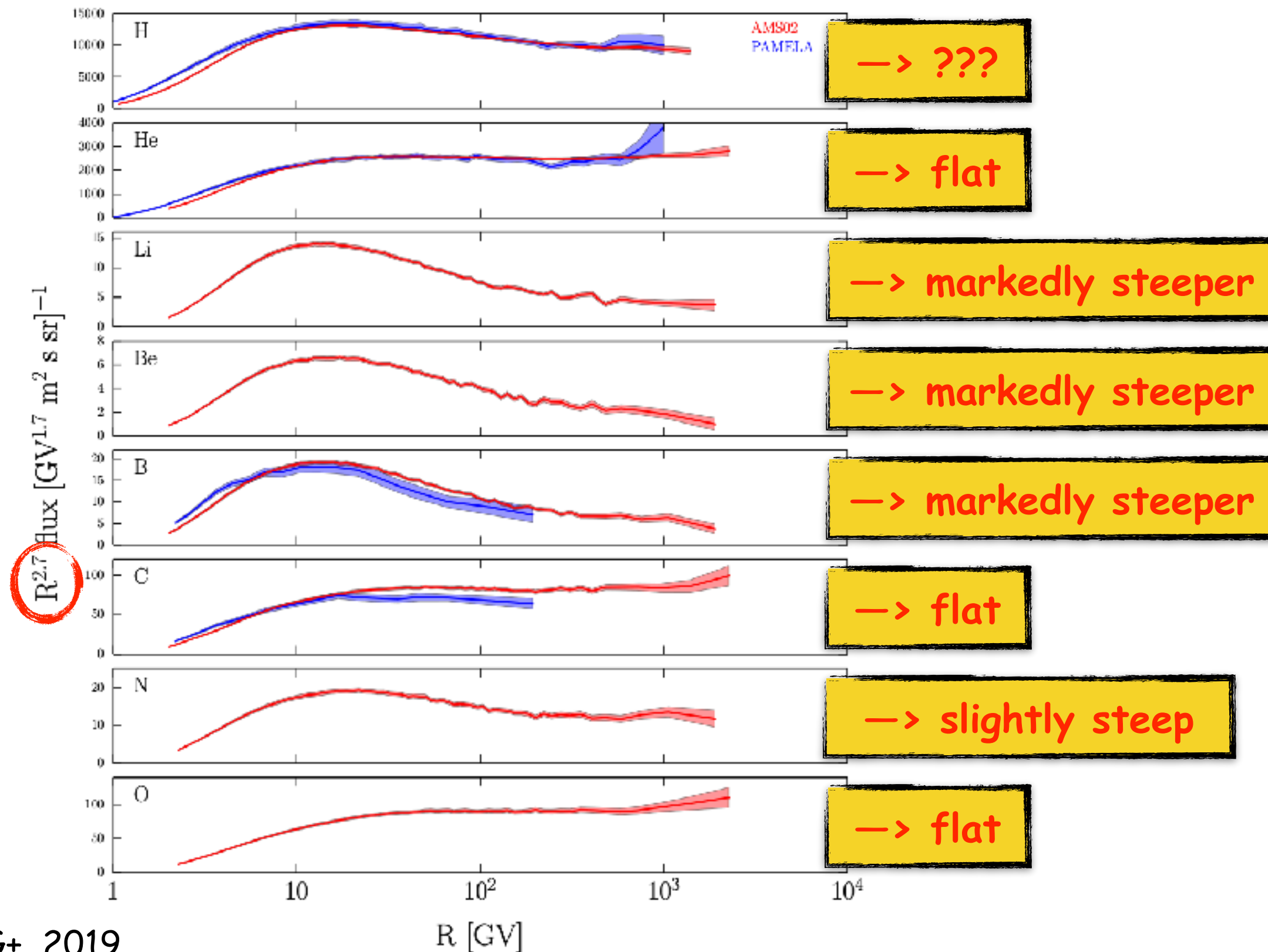


H slightly steeper than He
→ we don't know why!

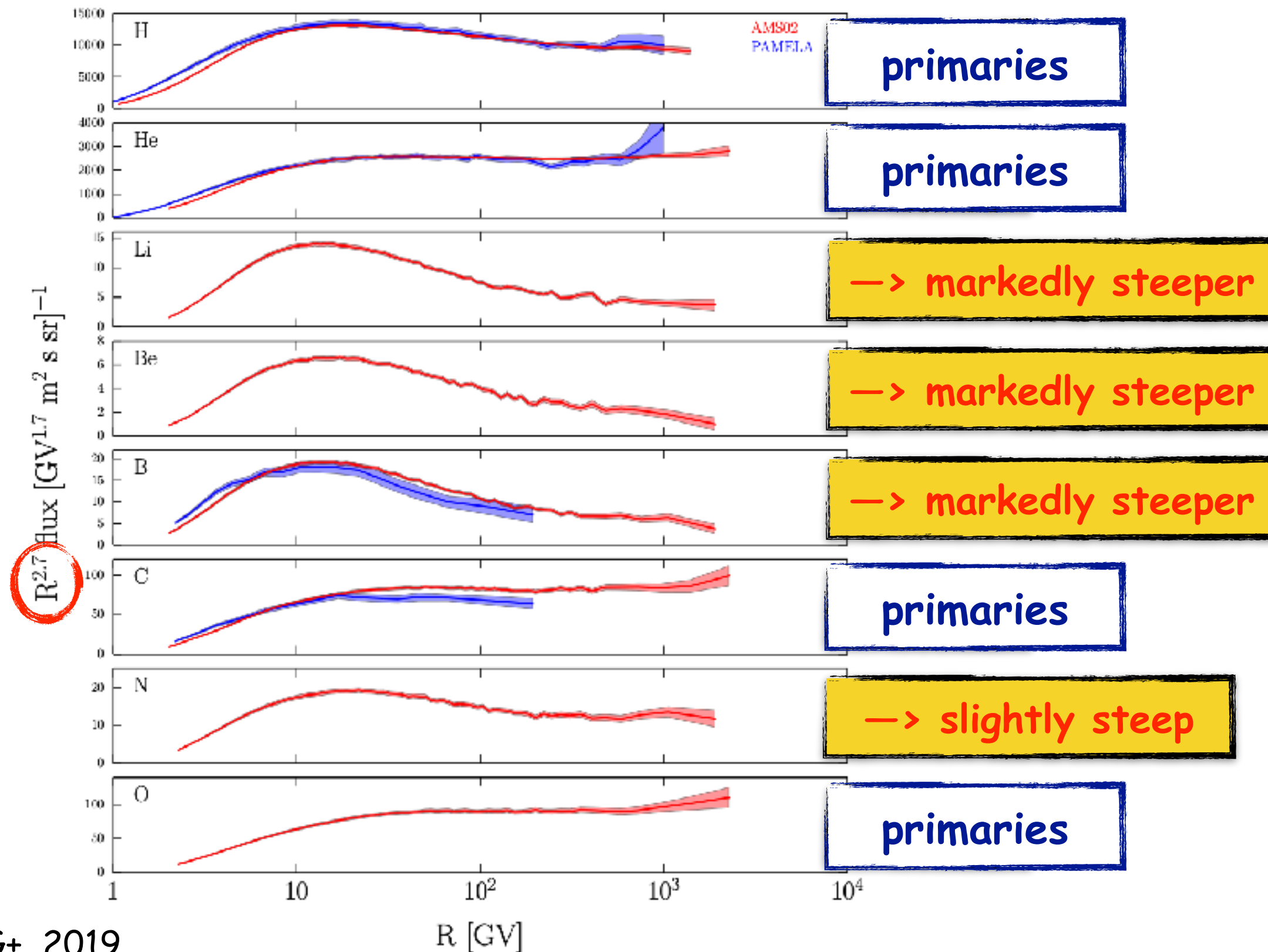
Possibilities:

- 1) **He does something that H doesn't** → spallation?
→ is it ok with heavier elements?
- 2) **He and H are accelerated in a different way**
→ aren't acceleration mechanisms "universal"?
- 3) **He and H are accelerated in different places** → environmental effect
→ fine tuning? (e.g. local source in the right environment, etc)

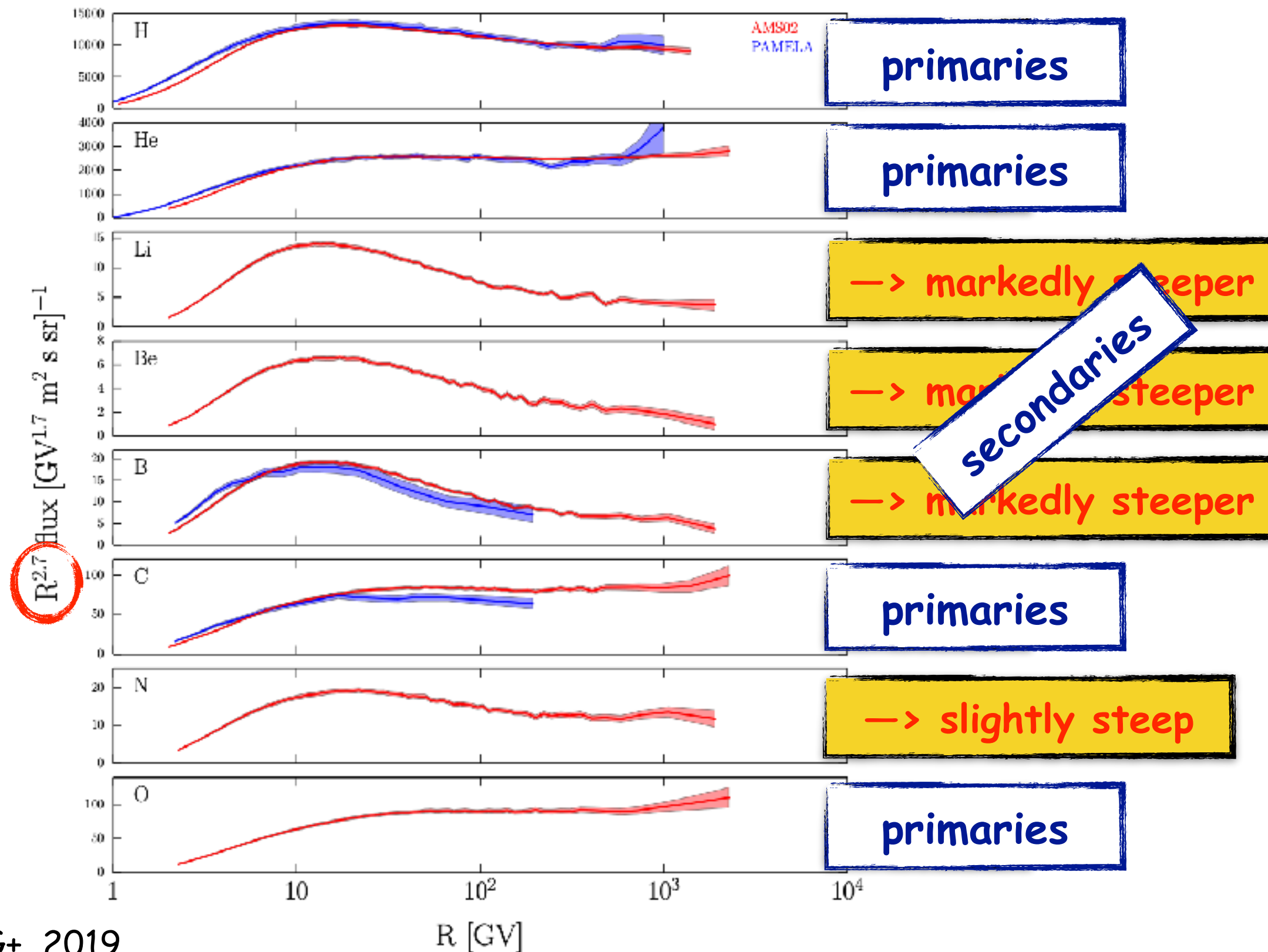
Spectra of light elements: an hypothesis



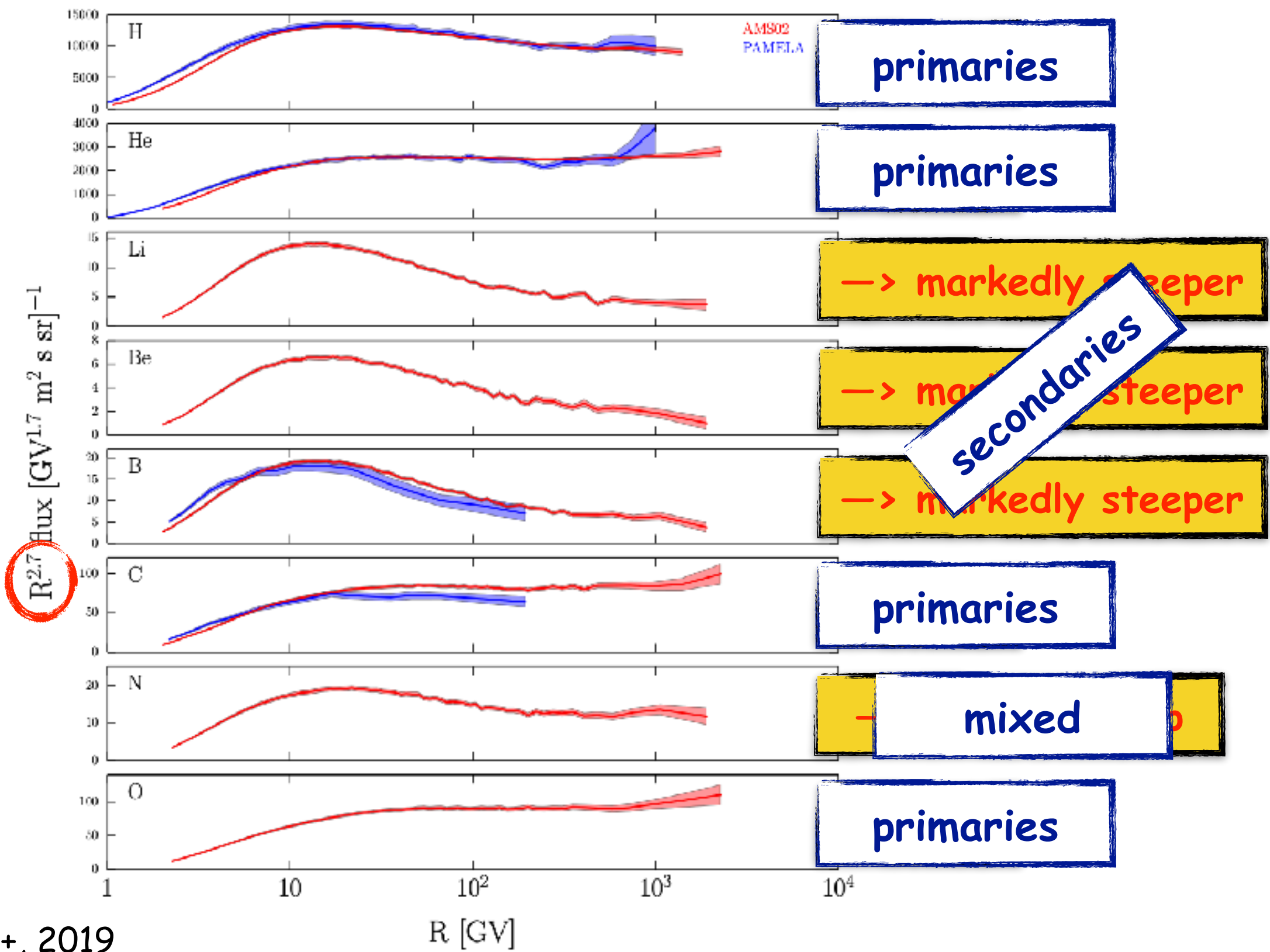
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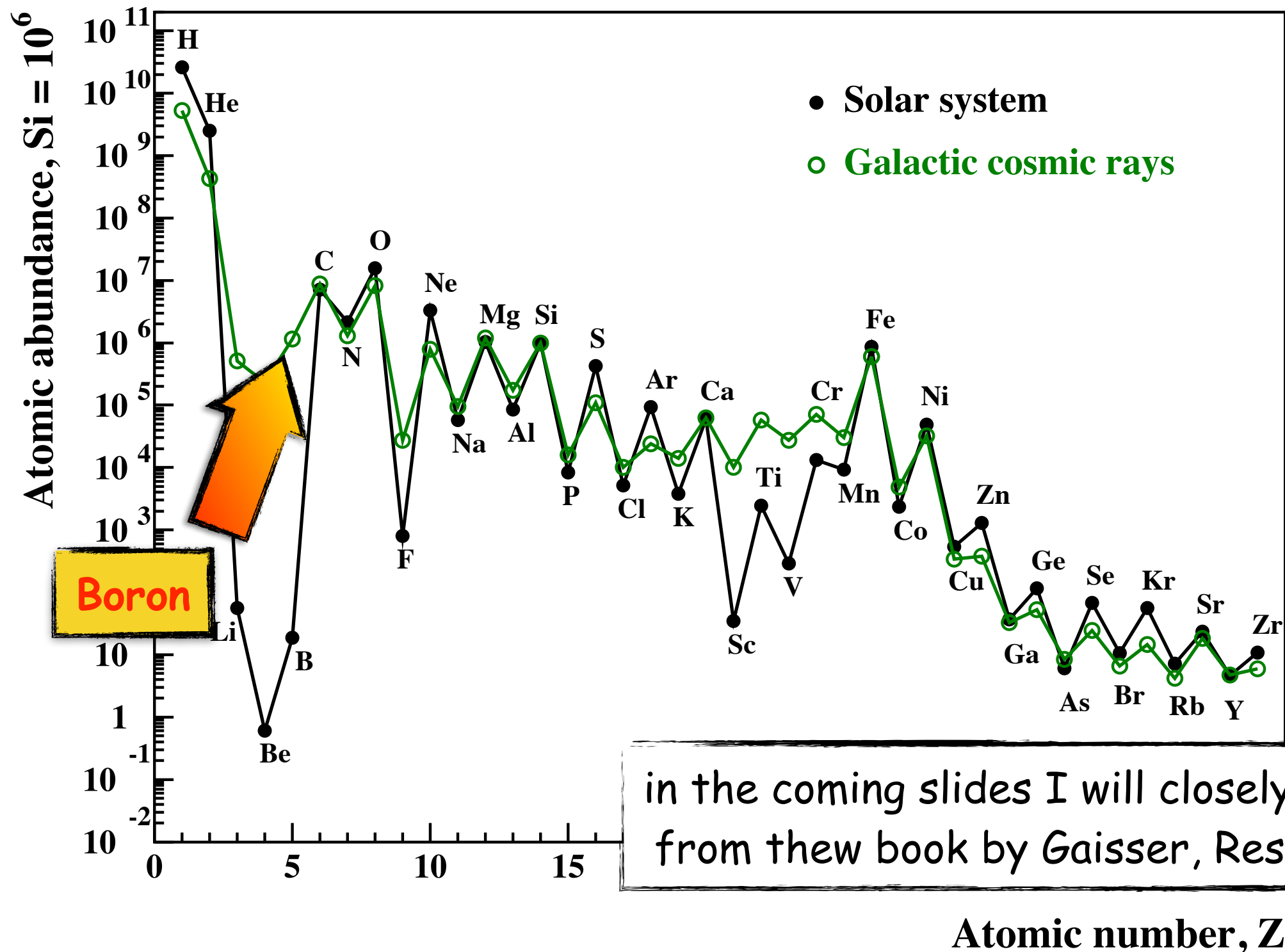


Spectra of light elements: an hypothesis



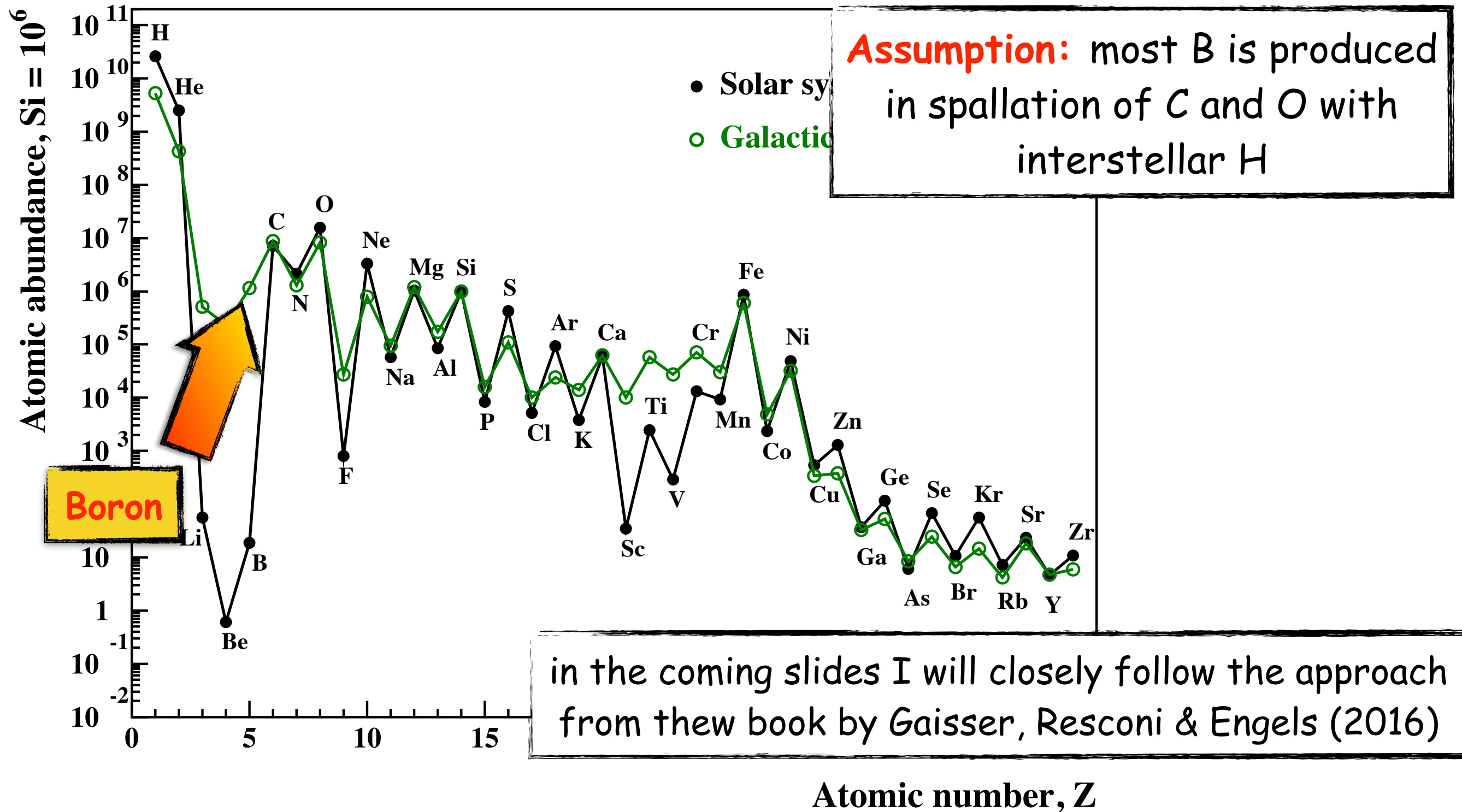
Production of B due to spallation

who does that?



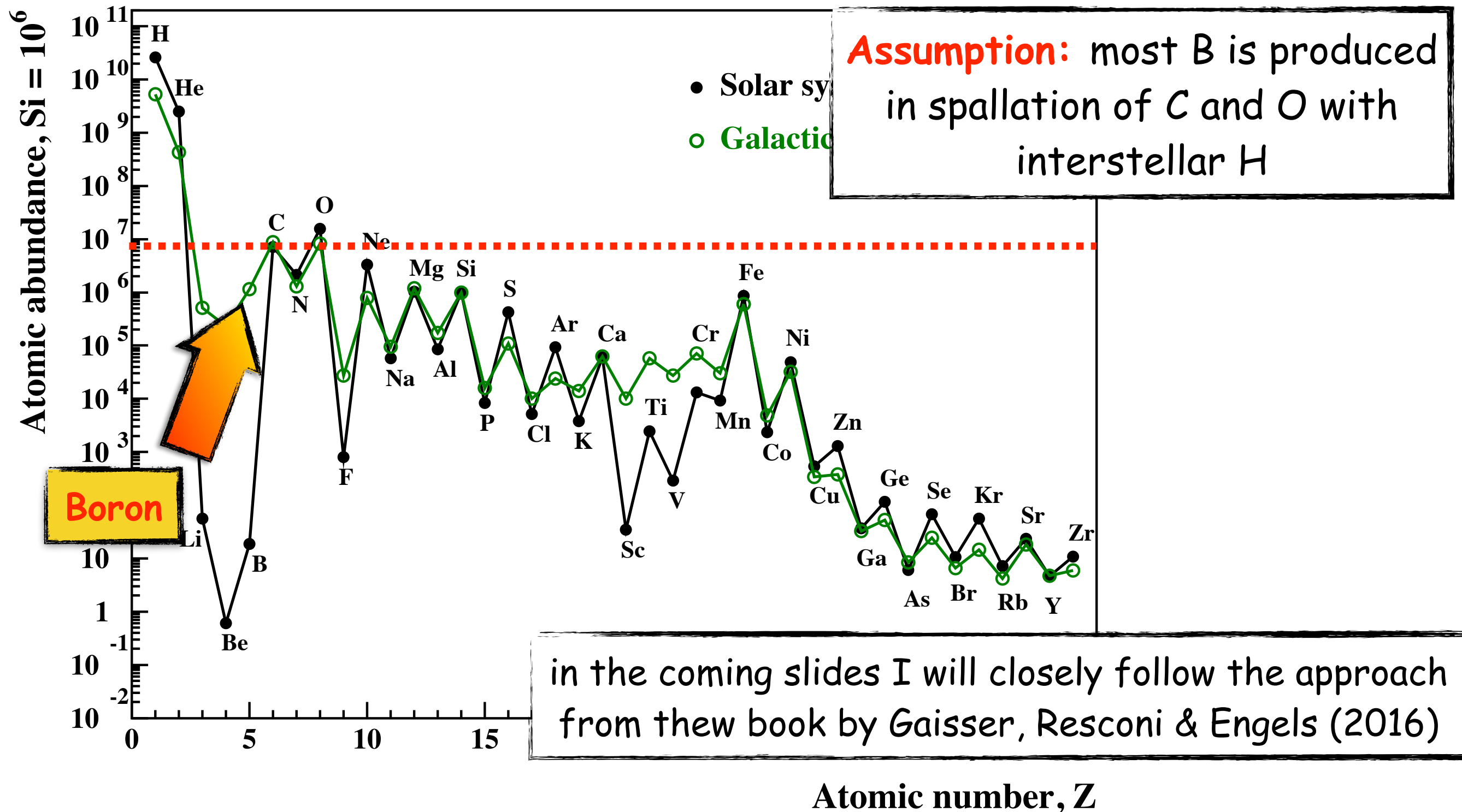
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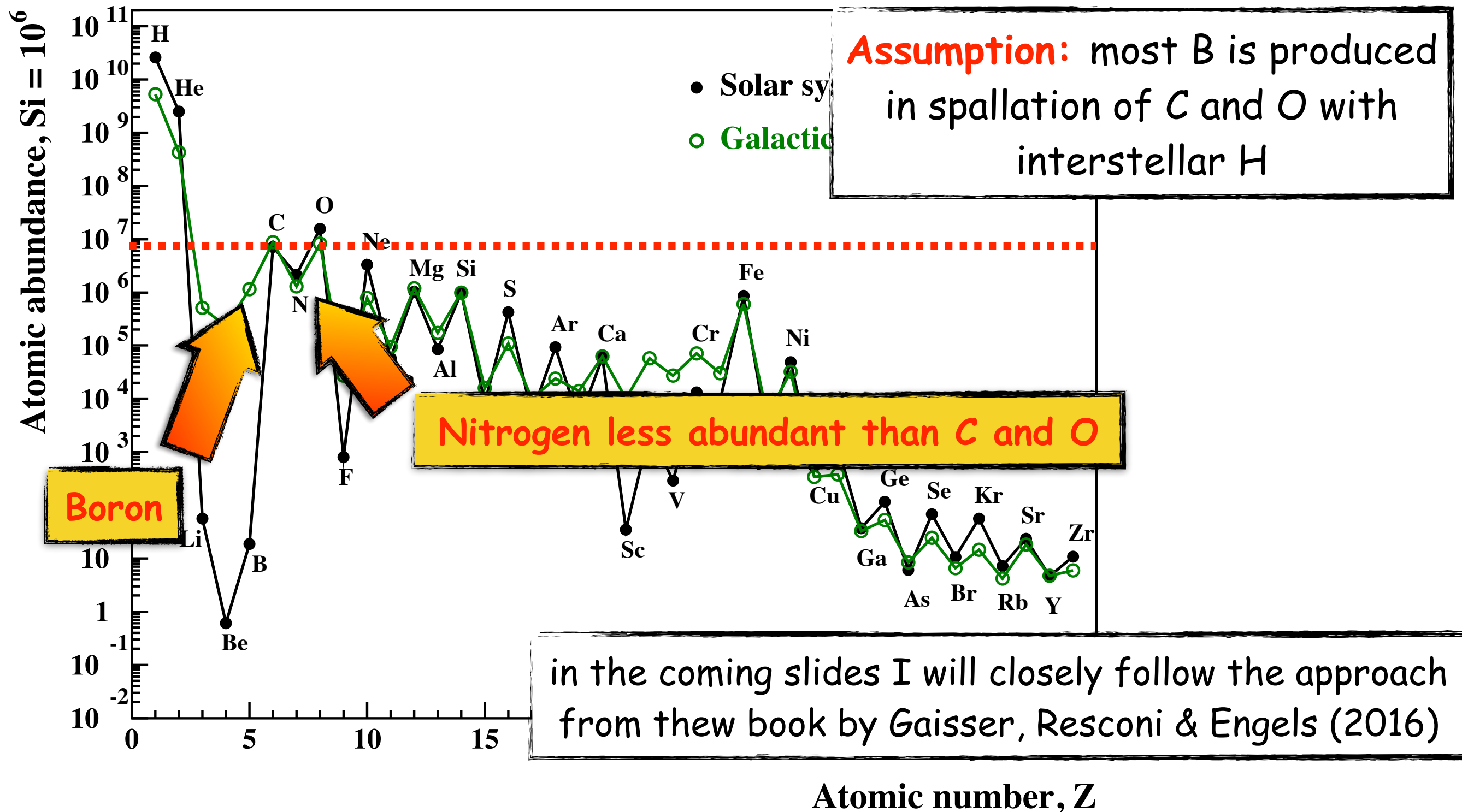
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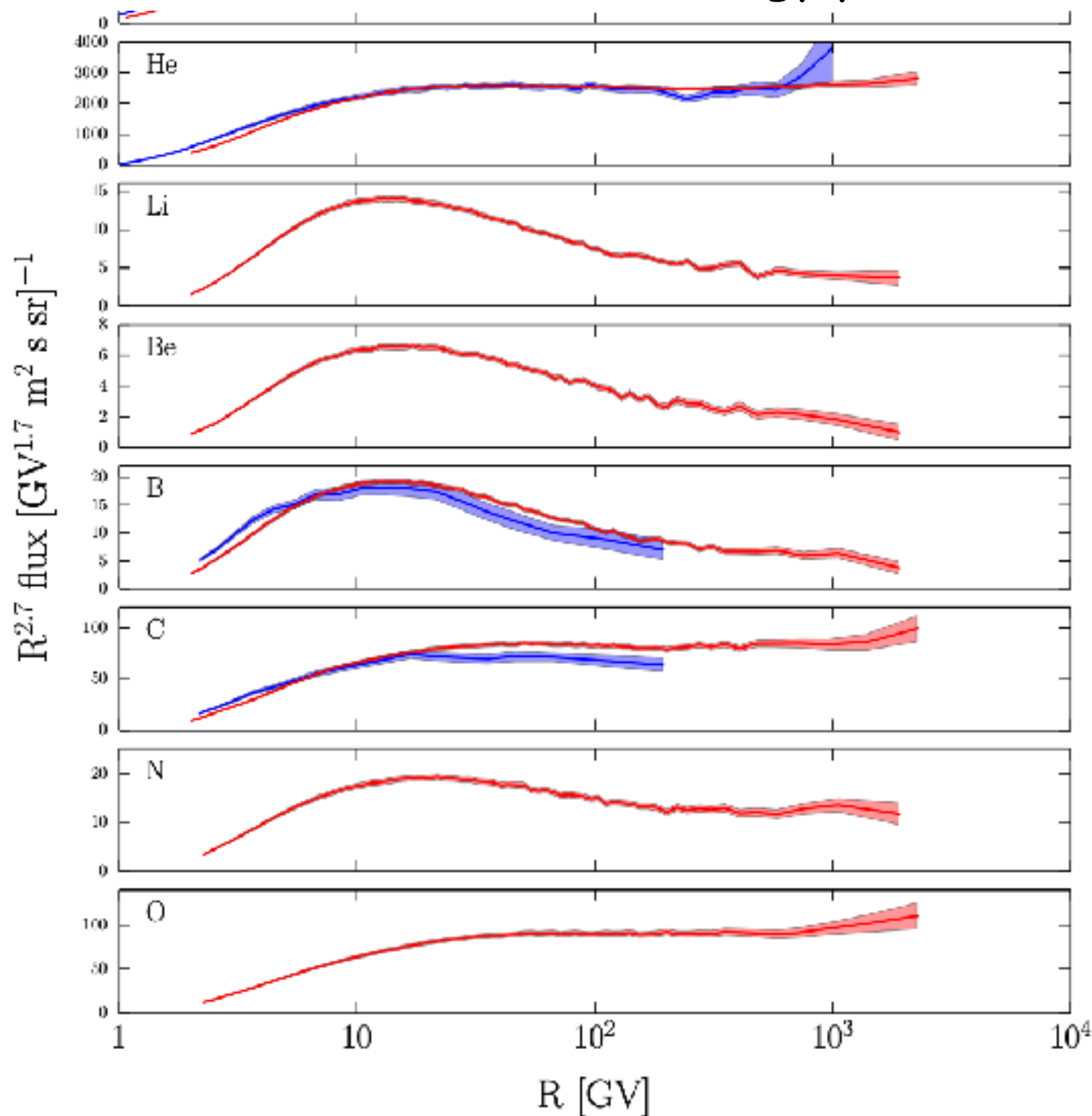
Production of B due to spallation

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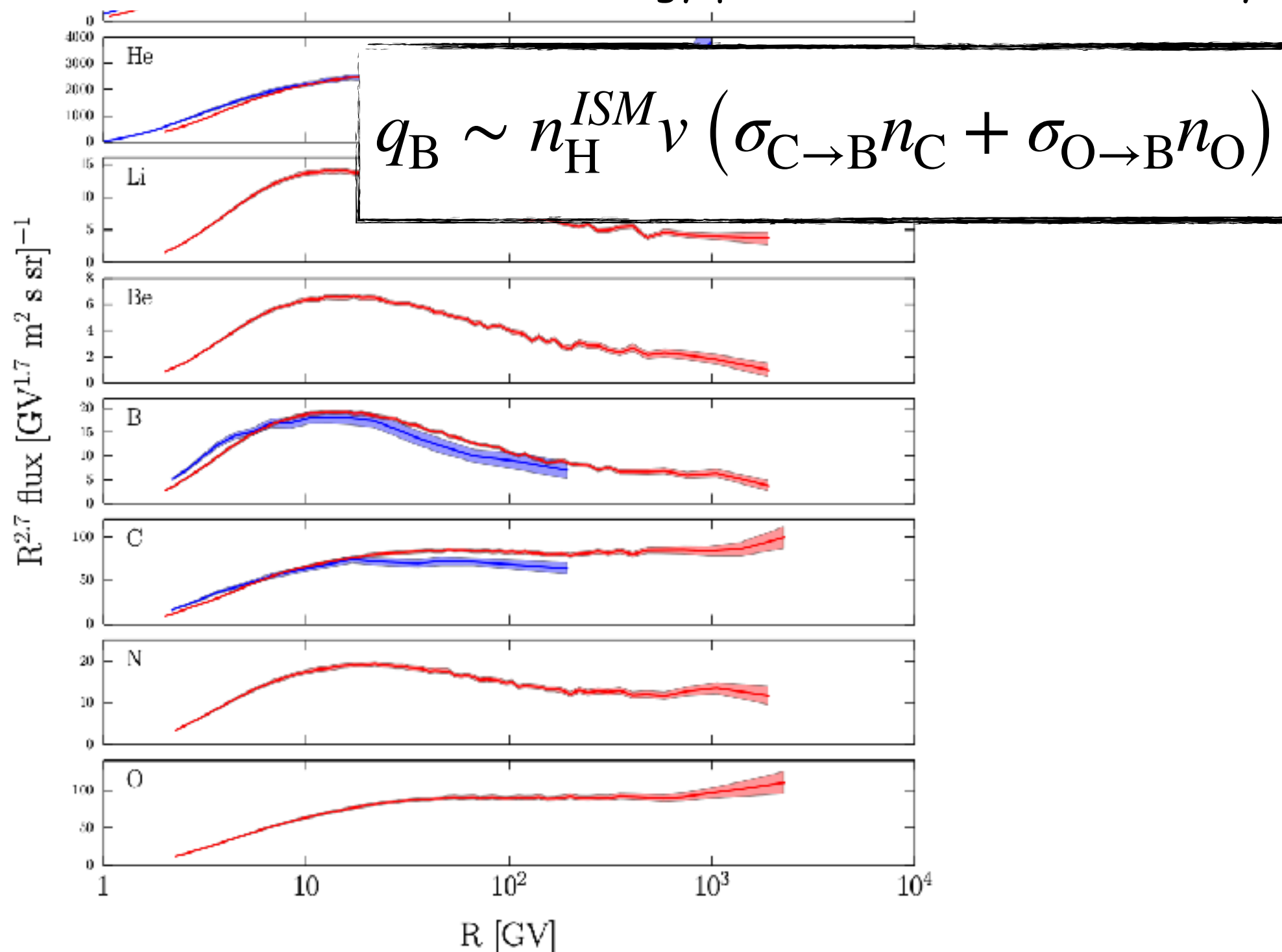
***Local* production rate of B**

- energy per nucleon is approximatively conserved in spallation reactions
- same energy per nucleon = same velocity



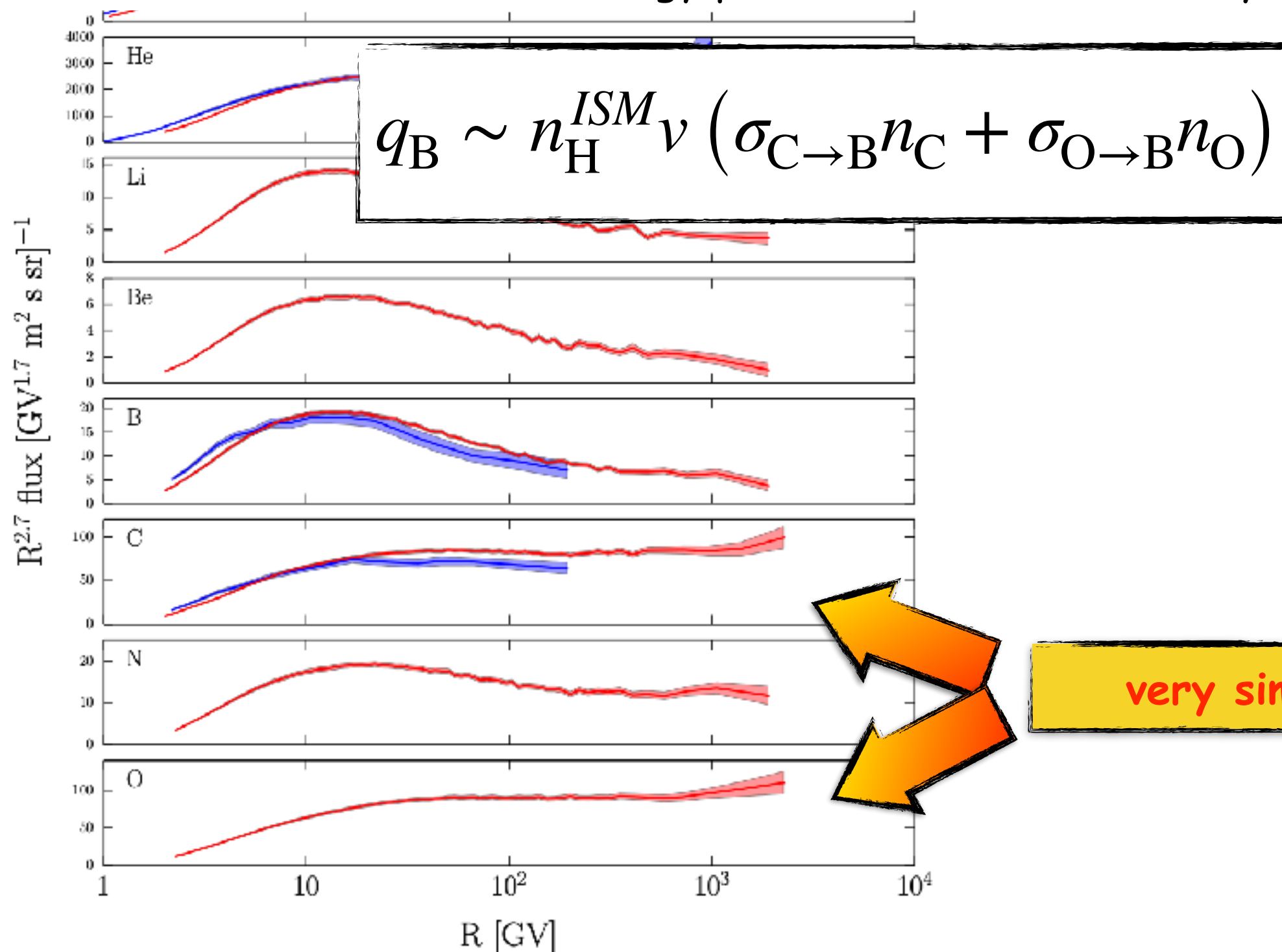
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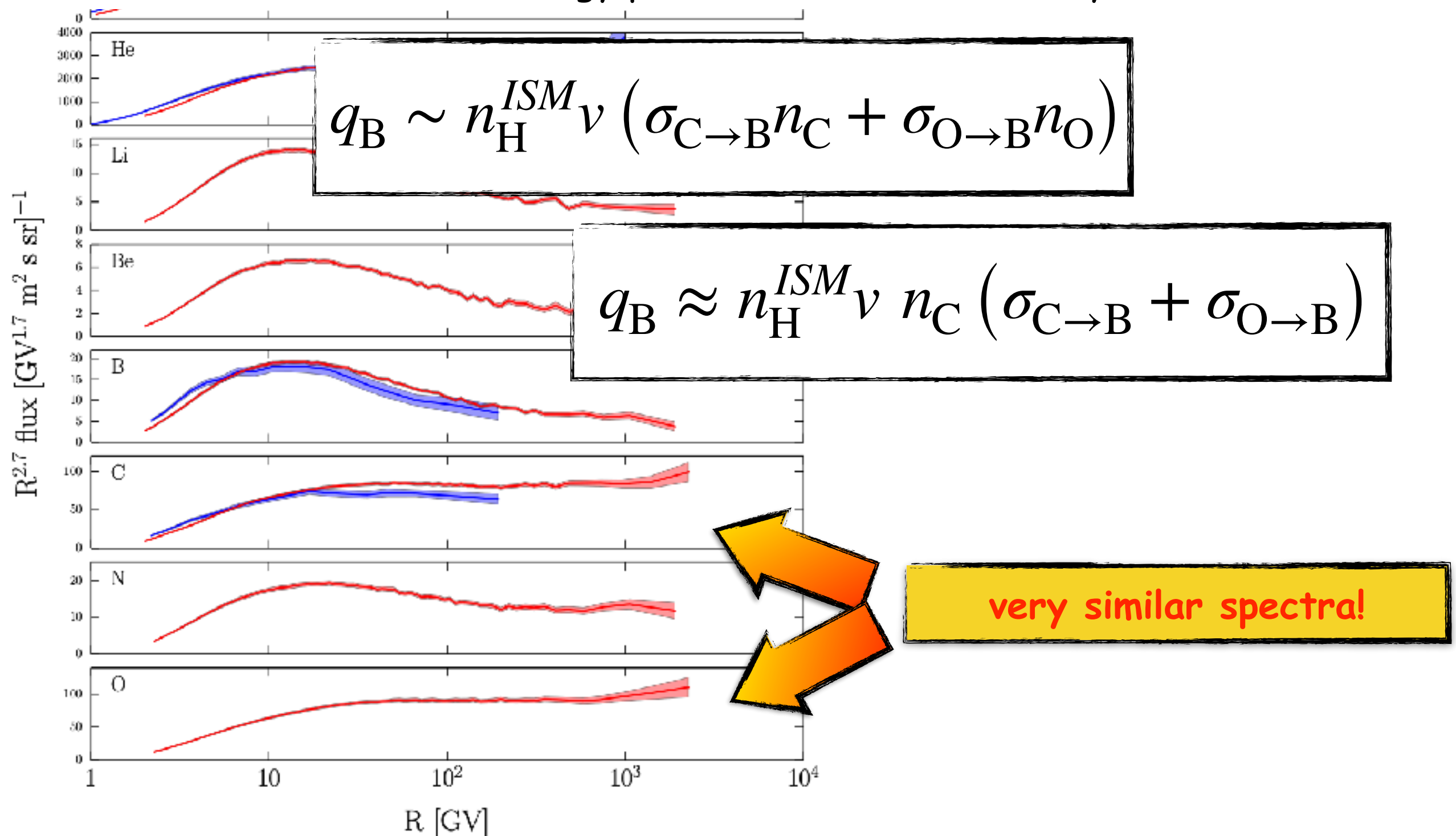
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The fate of CR Boron nuclei

at this point we need to assume that the local spectra of CRs are representative for the entire system (which is the Galactic disk as we need target material for spallation reactions)

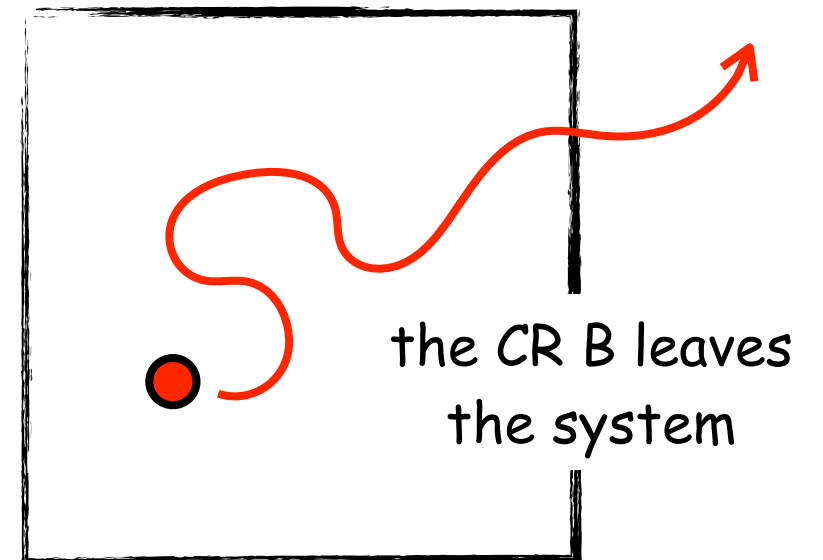
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Two possibilities:

escape

τ_{ISM}



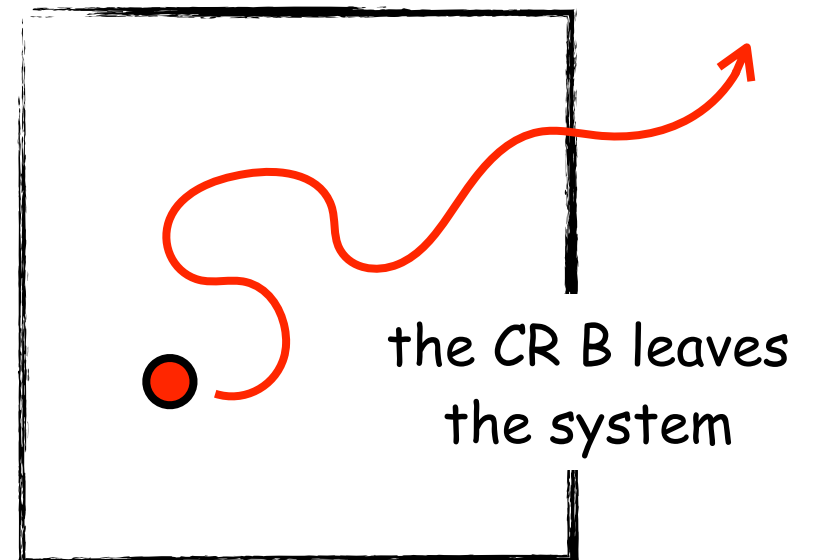
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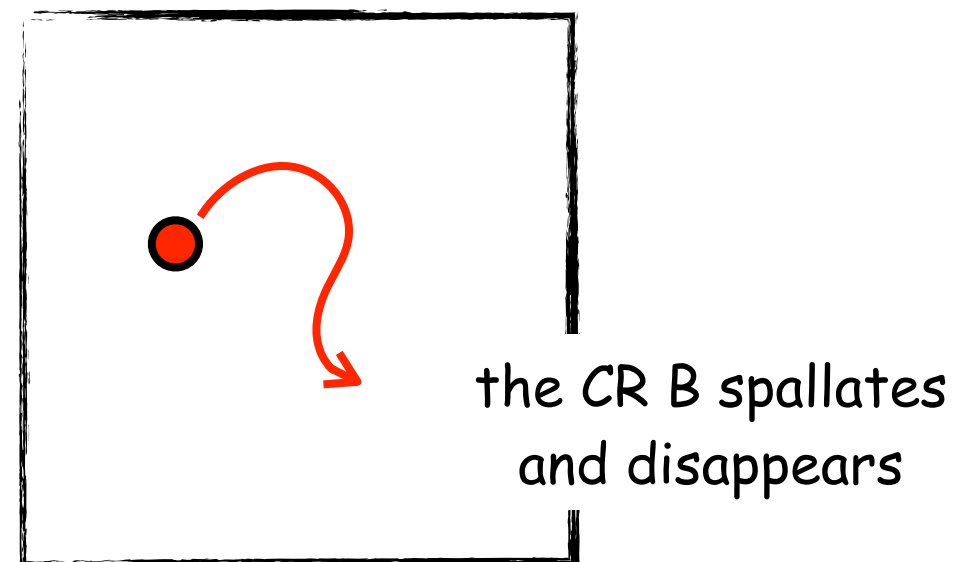
escape

$$\tau_{ISM}$$



spallate

$$\tau_B = (n_H^{ISM} \sigma_B v)^{-1}$$



The equilibrium spectrum of B

transport equation at equilibrium

$$\frac{n_B}{\tau_{ISM}} + \frac{n_B}{\tau_B} = q_B$$

destruction rate
(escape)

destruction rate
(spallation)

production rate

The equilibrium spectrum of B

transport equation at equilibrium

$$\frac{n_B}{\tau_{ISM}} + \frac{n_B}{\tau_B} = q_B$$

↑ destruction rate (escape) ↑ destruction rate (spallation) ↑ production rate

effective "destruction" time →

$$\tau_{eff}^{-1} = \tau_B^{-1} + \tau_{ISM}^{-1}$$

$$\frac{n_B}{\tau_{eff}} = q_B$$

Grammage

it is customary to use the **grammage** instead of the escape time
the grammage has units of g/cm^2 and represents the amount of interstellar
mass crossed by CRs before escaping the system

Grammage

it is customary to use the **grammage** instead of the escape time
the grammage has units of g/cm^2 and represents the amount of interstellar
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we assume an ISM
made of H only



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in a similar way, we can define the grammage needed to get rid of CR Boron due to spallation

$$X_B = m_p n_H^{ISM} v \tau_B$$

The B/C ratio

$$\frac{n_{\text{B}}}{\tau_{ISM}} + \frac{n_{\text{B}}}{\tau_{\text{B}}} = q_{\text{B}}$$

The B/C ratio

$$\frac{n_B}{\tau_{ISM}} + \frac{n_B}{\tau_B} = q_B \approx n_H^{ISM} v n_C (\sigma_{C \rightarrow B} + \sigma_{O \rightarrow B})$$

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measuring B/C is equivalent
to measuring X_{ISM} !

B/C ratio $\rightarrow$

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The B/C ratio: avoid this mistake!

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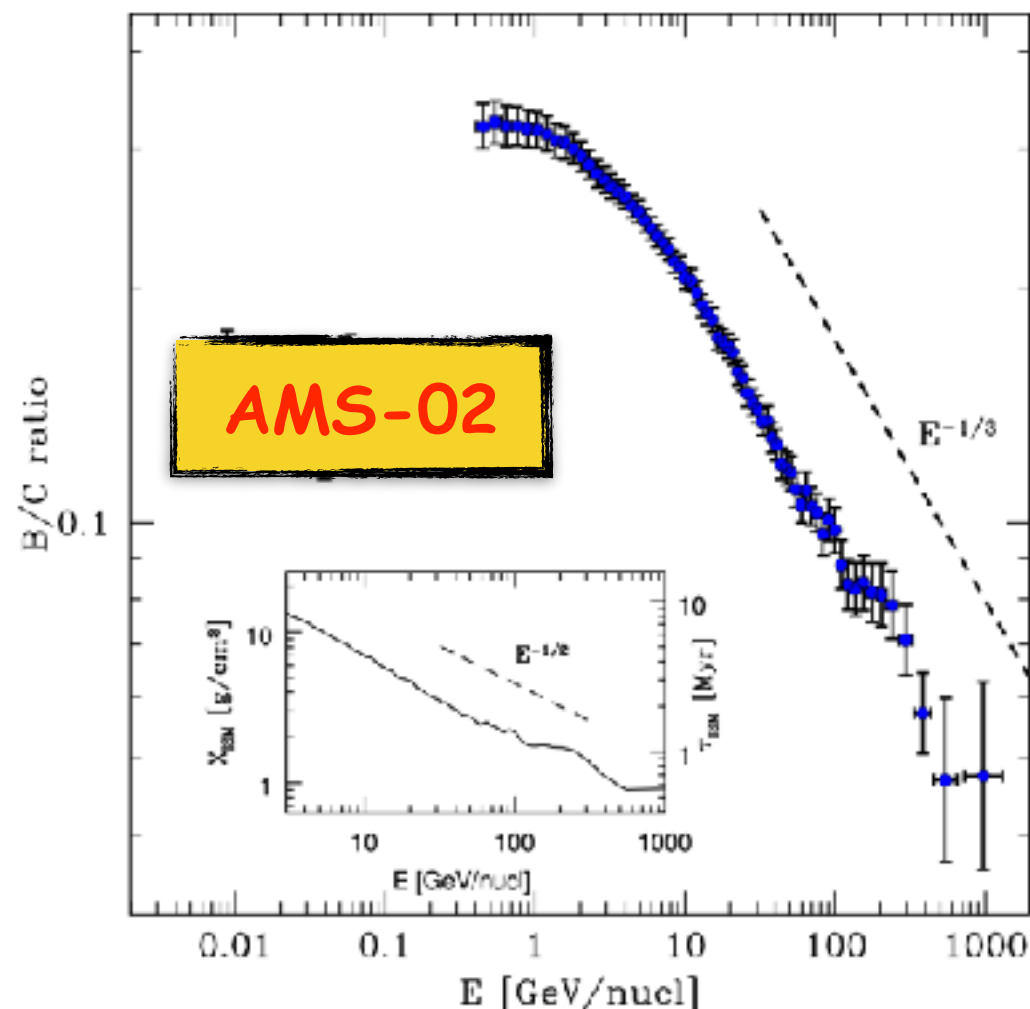
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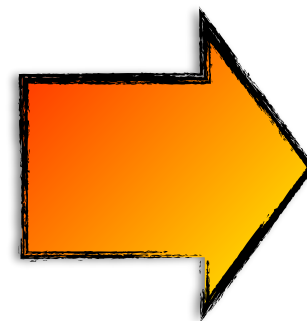
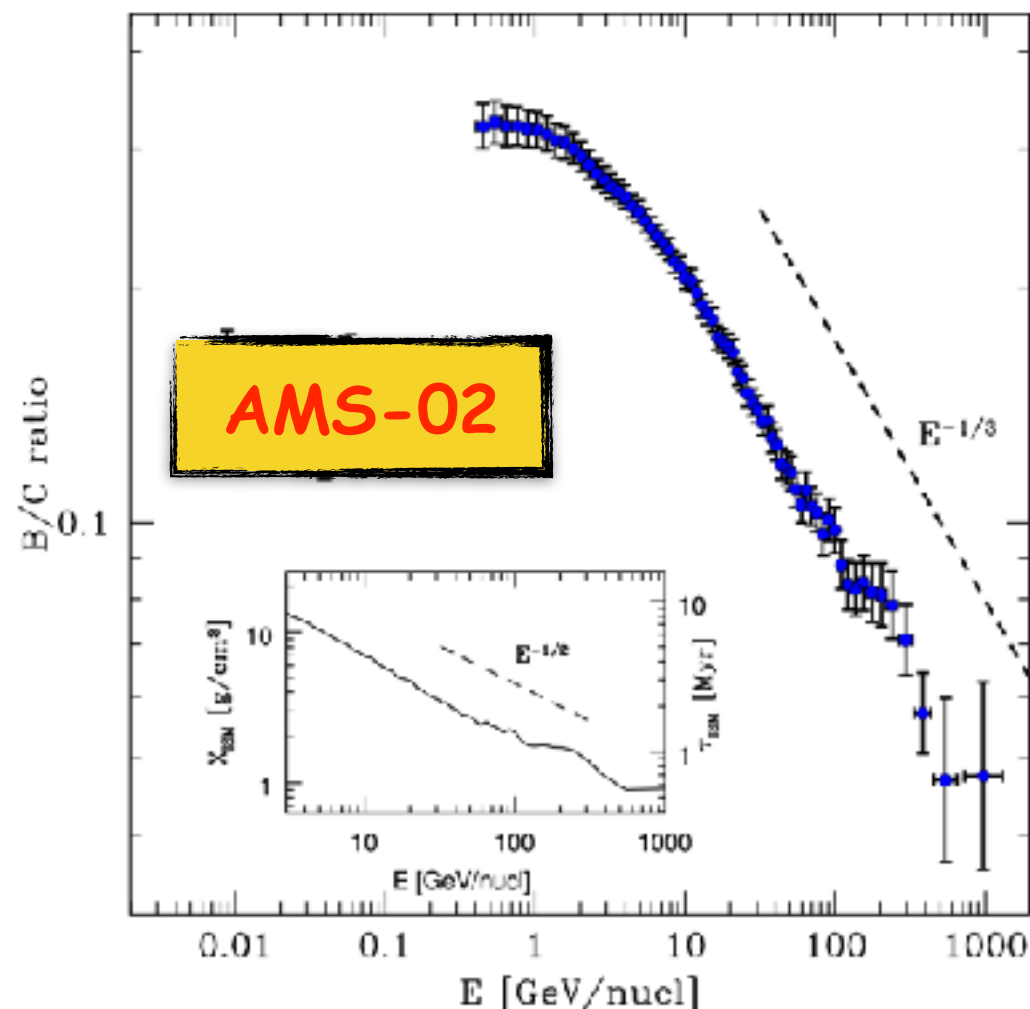
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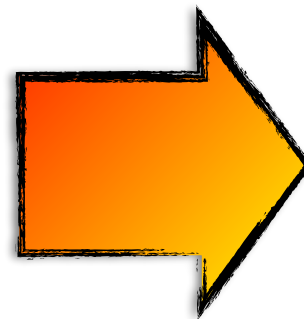
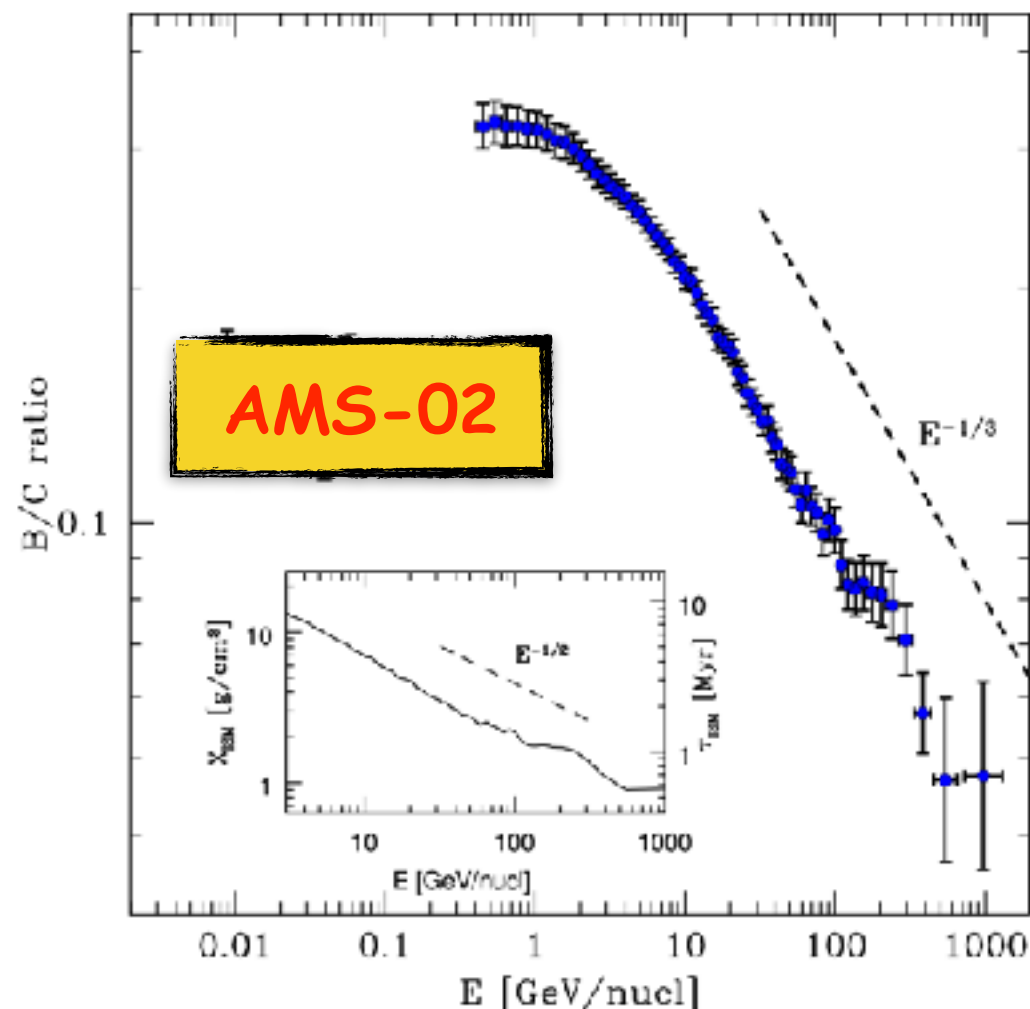


$$\tau_{ISM}(E) \propto E^{-1/3}$$

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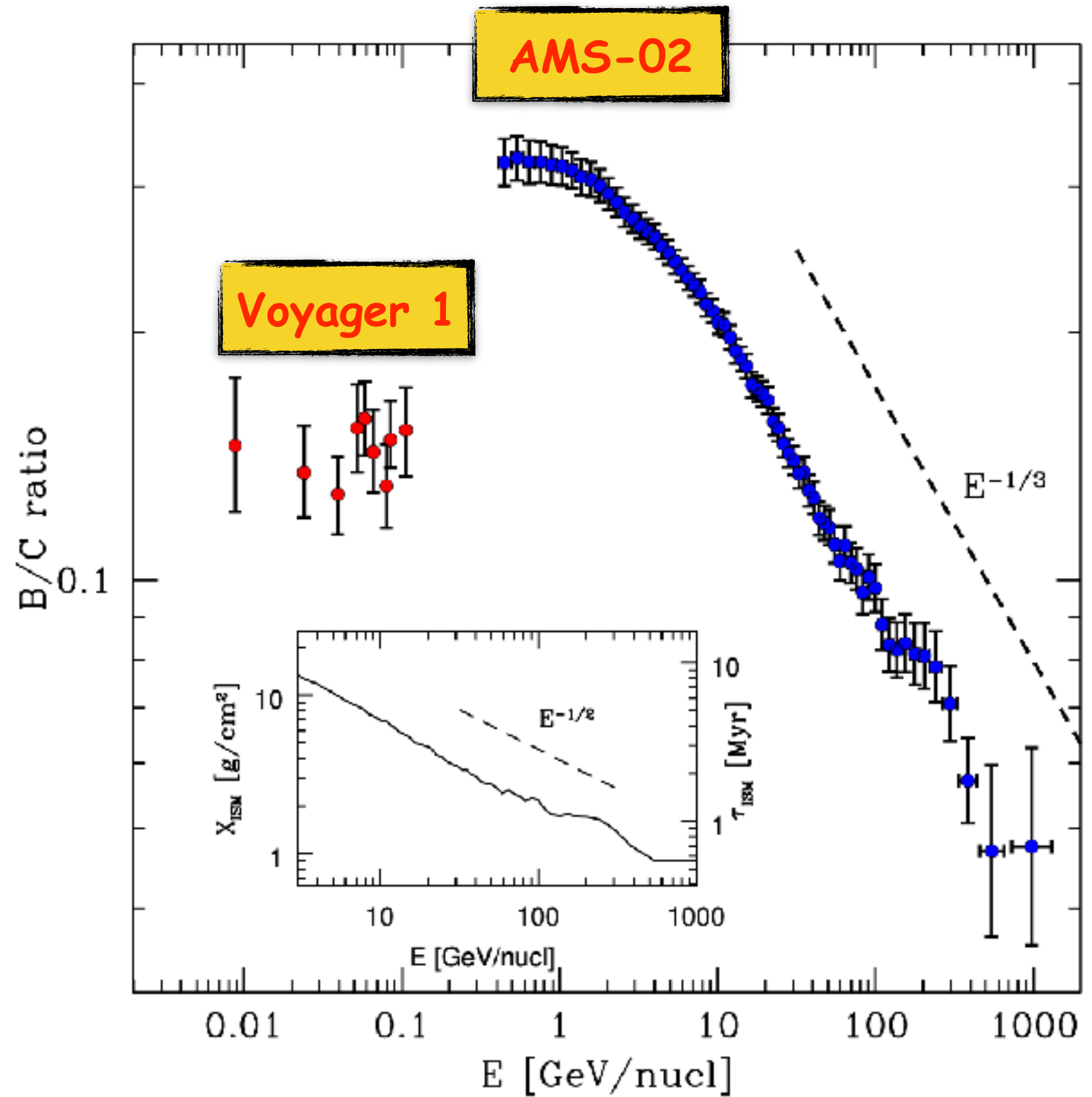
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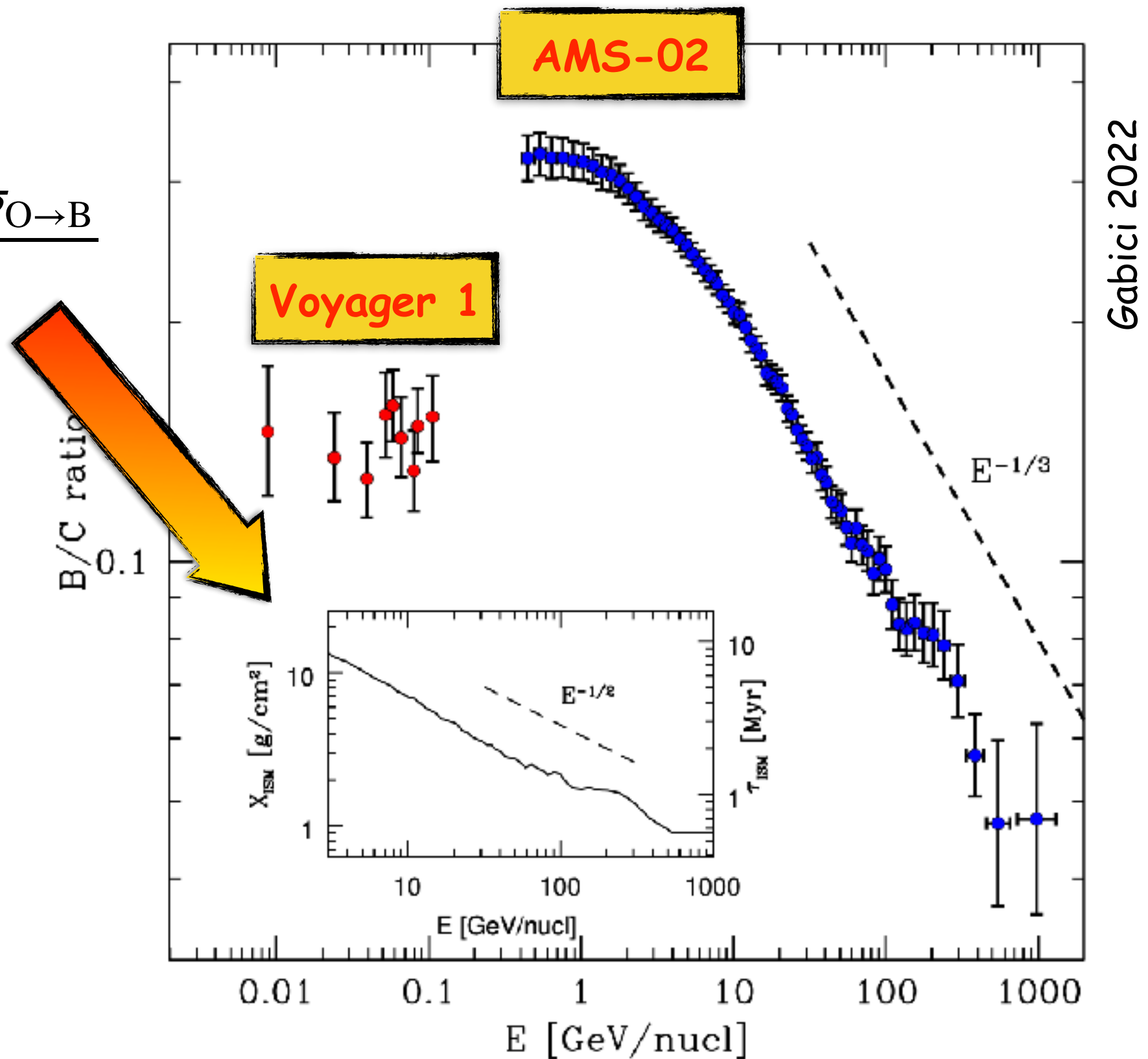
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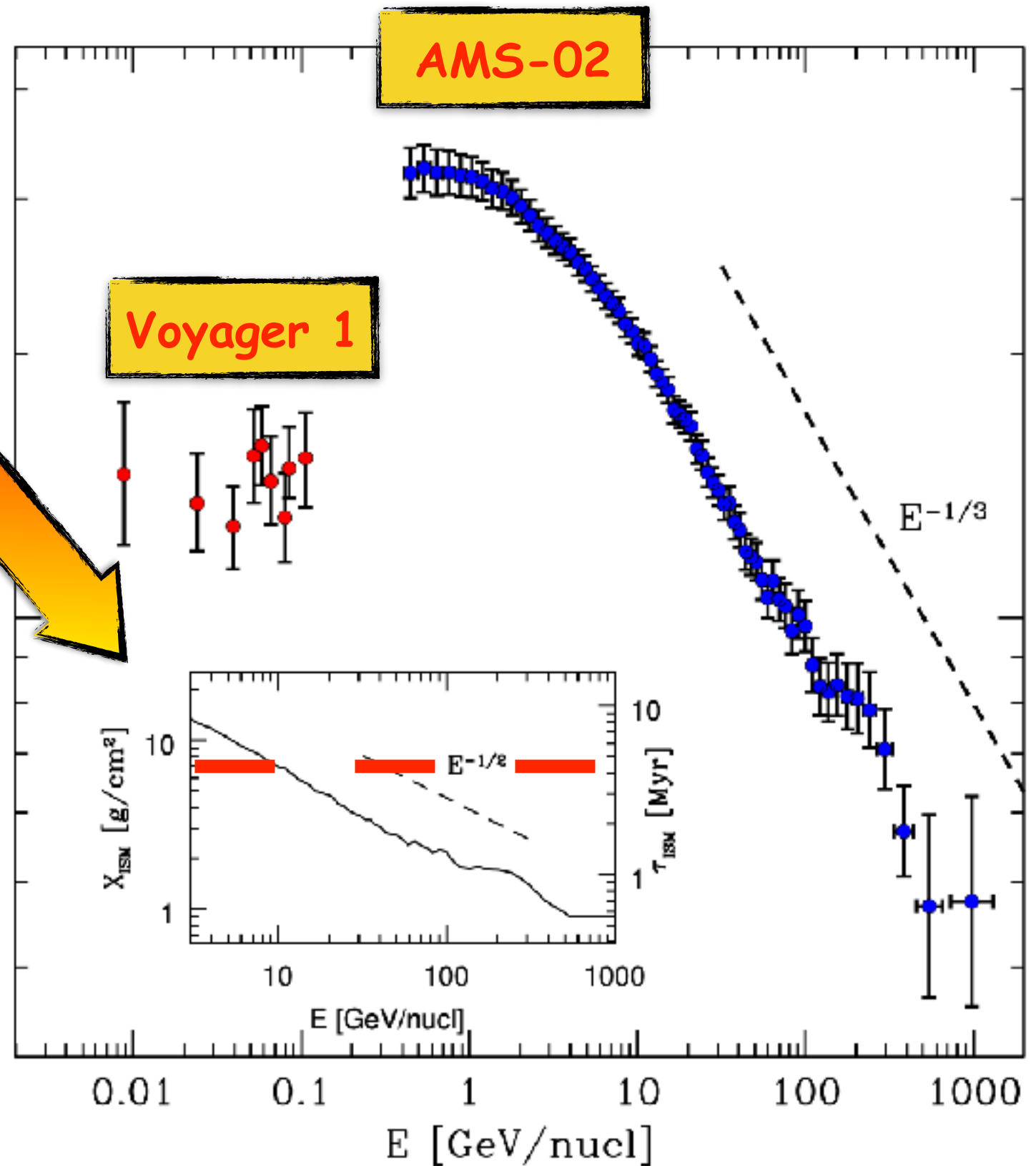
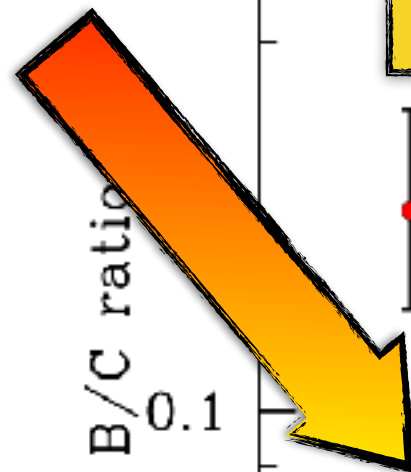
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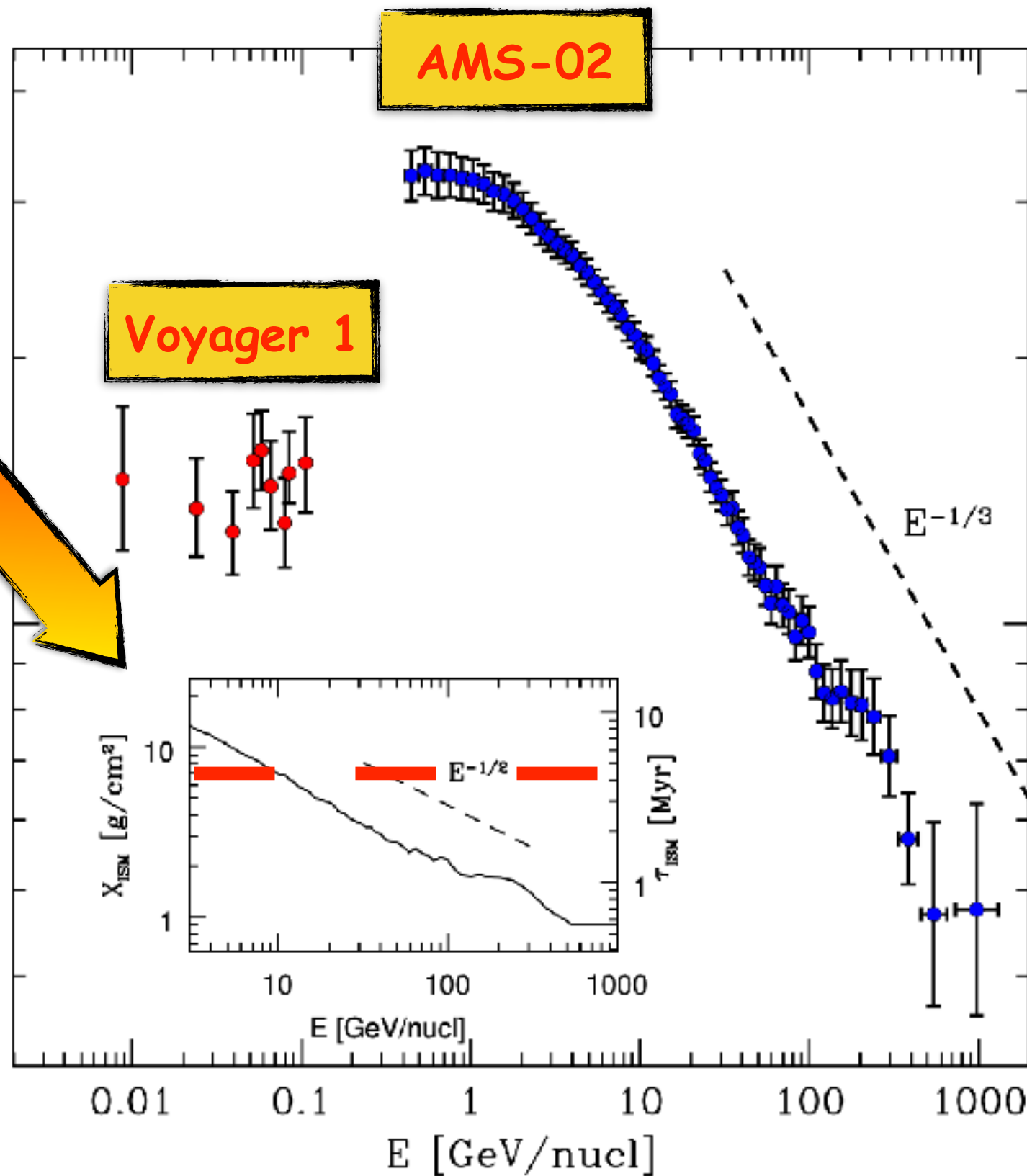
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more sophisticated approaches exist and give similar results, just keep in mind that $[B/C](E)$ and $X_{ISM}(E)$ do NOT have the same slope!

B/C ratio
0.1

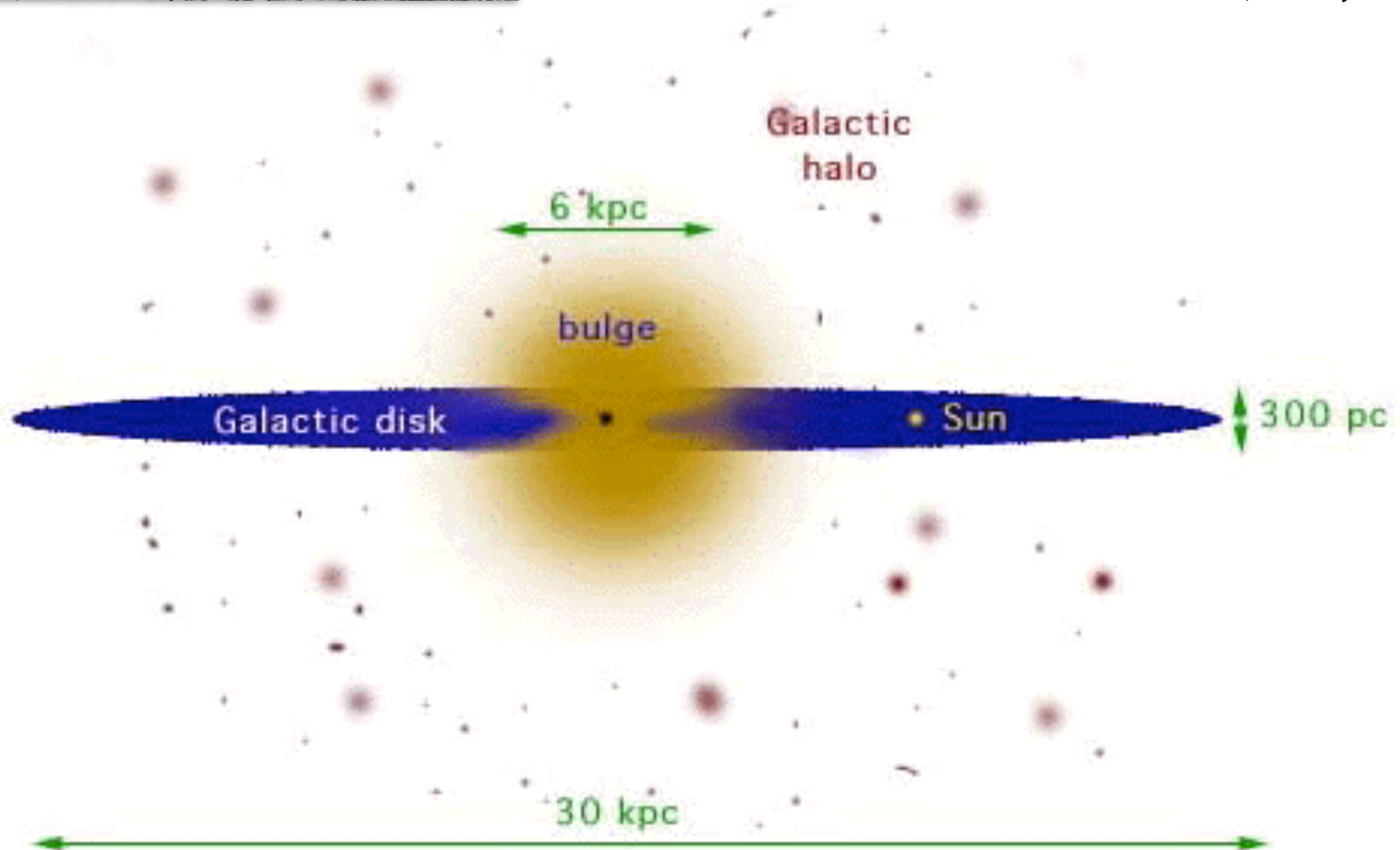


Escape time or residence time?

surface density of the disk →

$$X_{disk} \approx \mathcal{O}(10^{-3}) \text{ g/cm}^2$$

(see review by
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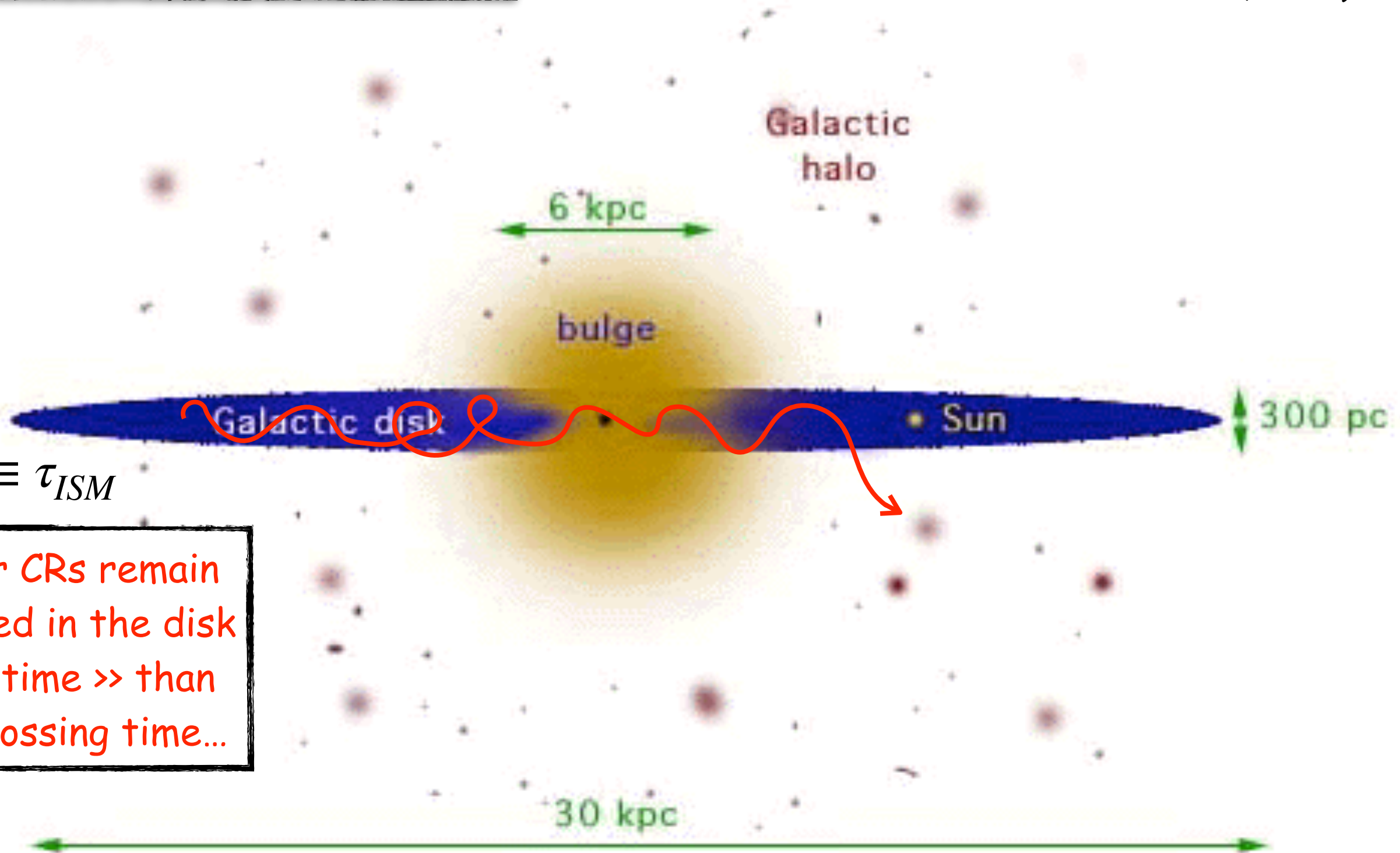
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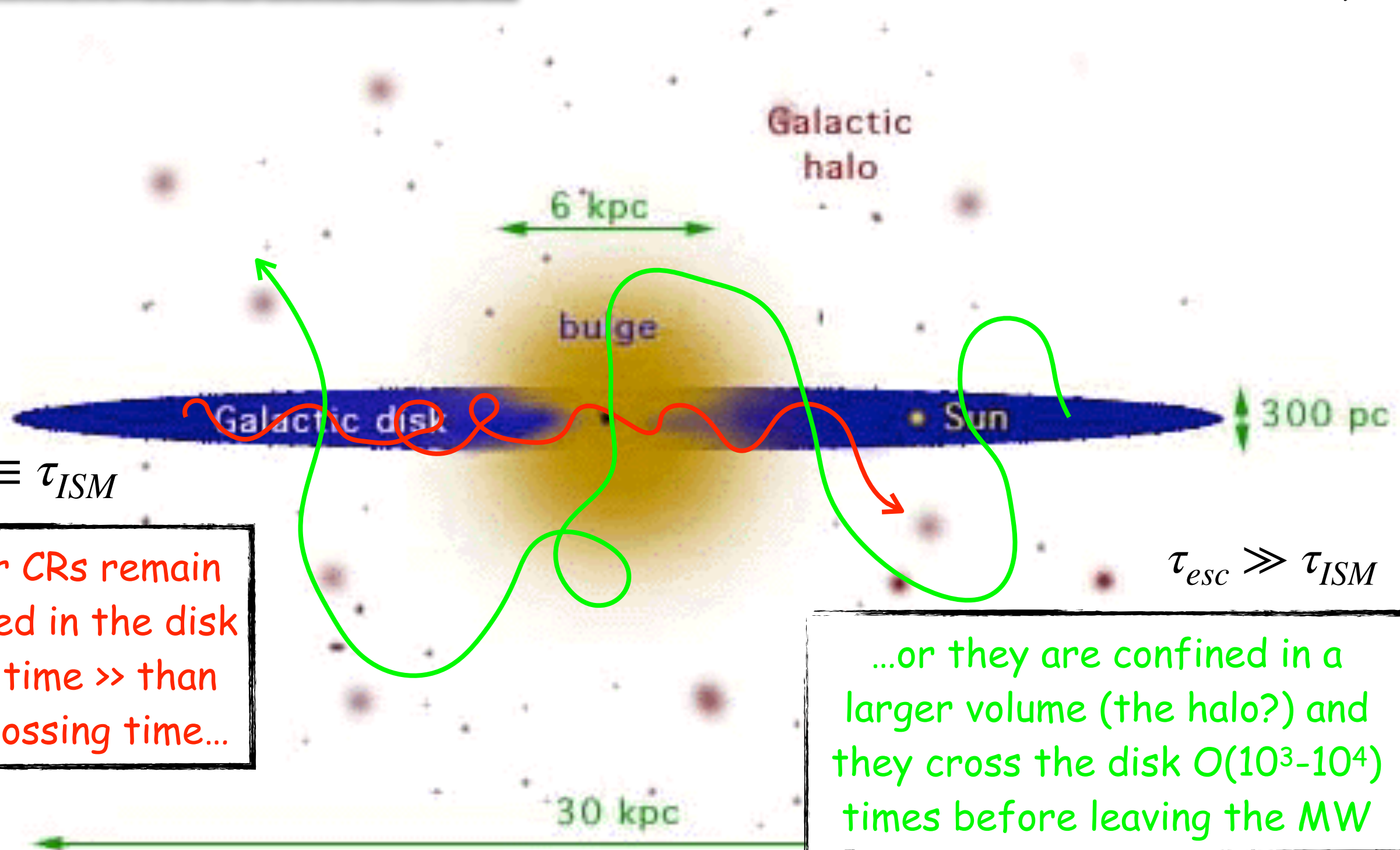
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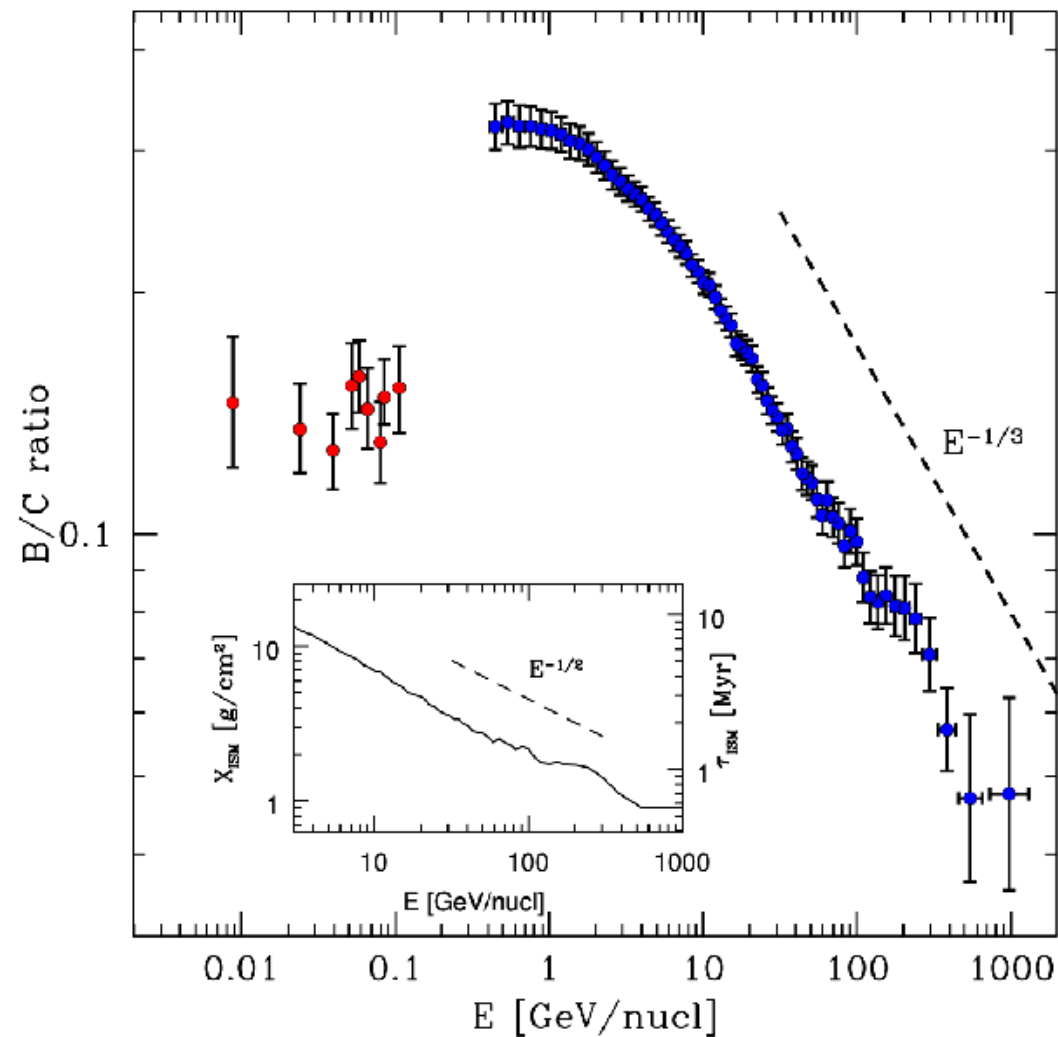
either CRs remain
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$$\tau_{\text{esc}} \gg \tau_{\text{ISM}}$$

...or they are confined in a
larger volume (the halo?) and
they cross the disk $\mathcal{O}(10^3\text{-}10^4)$
times before leaving the MW

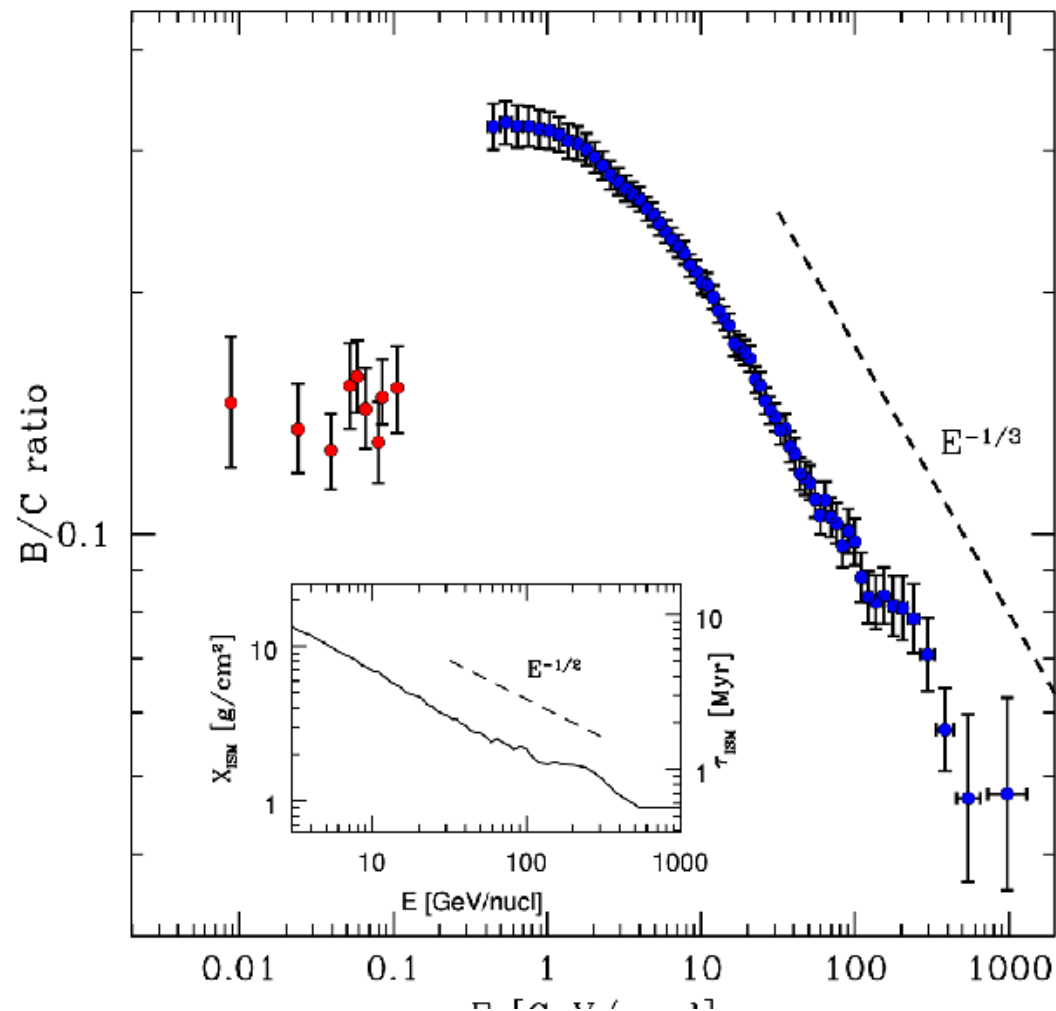


Escape time or residence time?



the B/C ratio is sensitive ONLY to the amount of matter crossed by cosmic rays, and not to the way in which this matter is accumulated (when CRs enter the halo the grammage does not increase until the CRs go back to the disk...)

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we need a clock to measure how much time CRs spend in the halo (if any!)

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$$\tau_{\text{rad}}(^{10}\text{Be}) \sim 2 \text{ Myr}$$

* remember that in the observer rest frame the lifetime is a factor of γ (Lorentz factor of ^{10}Be) larger!

$^{10}\text{Be}/^9\text{Be}$ ratio  stable isotope!

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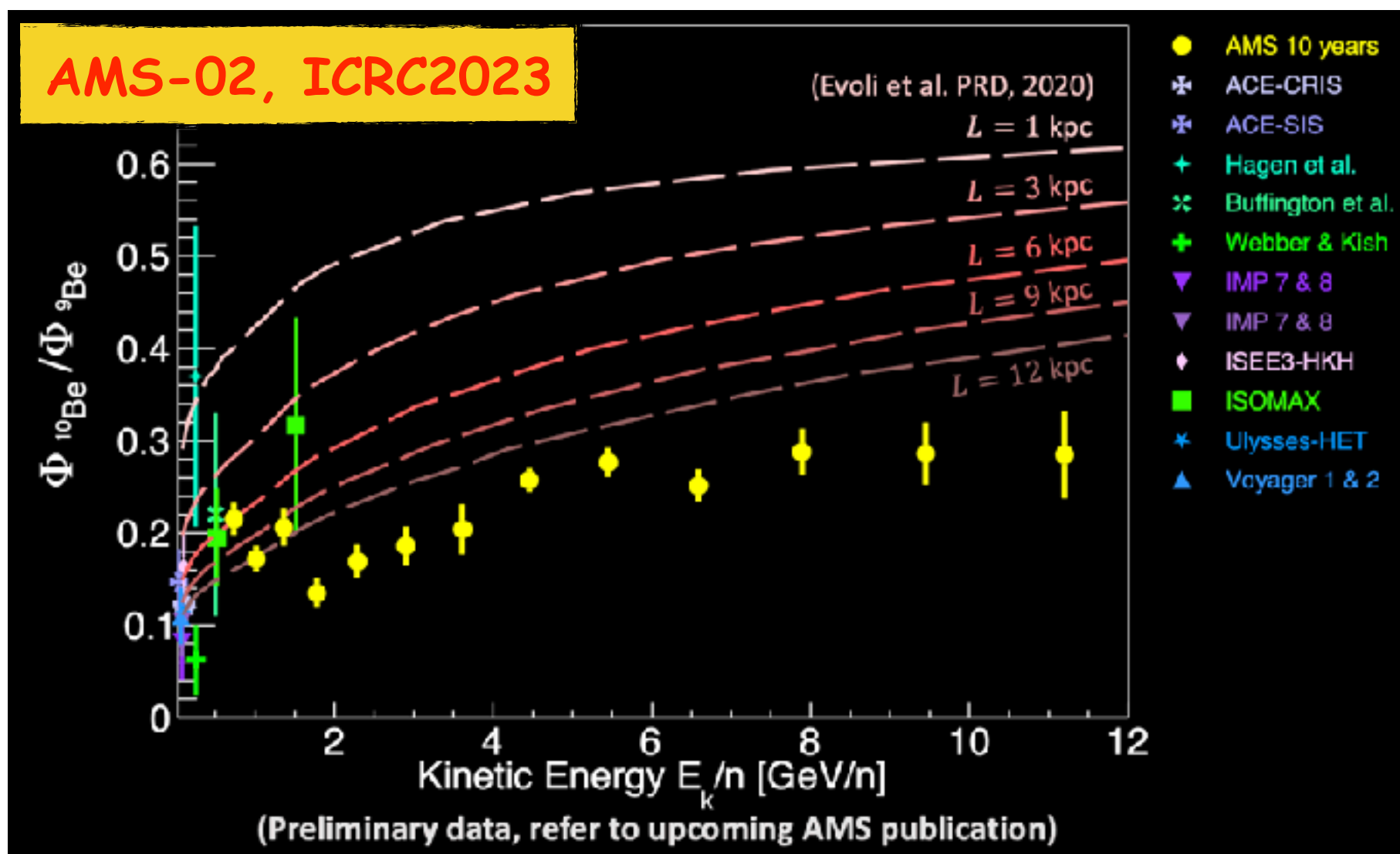
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~ 0.8

known

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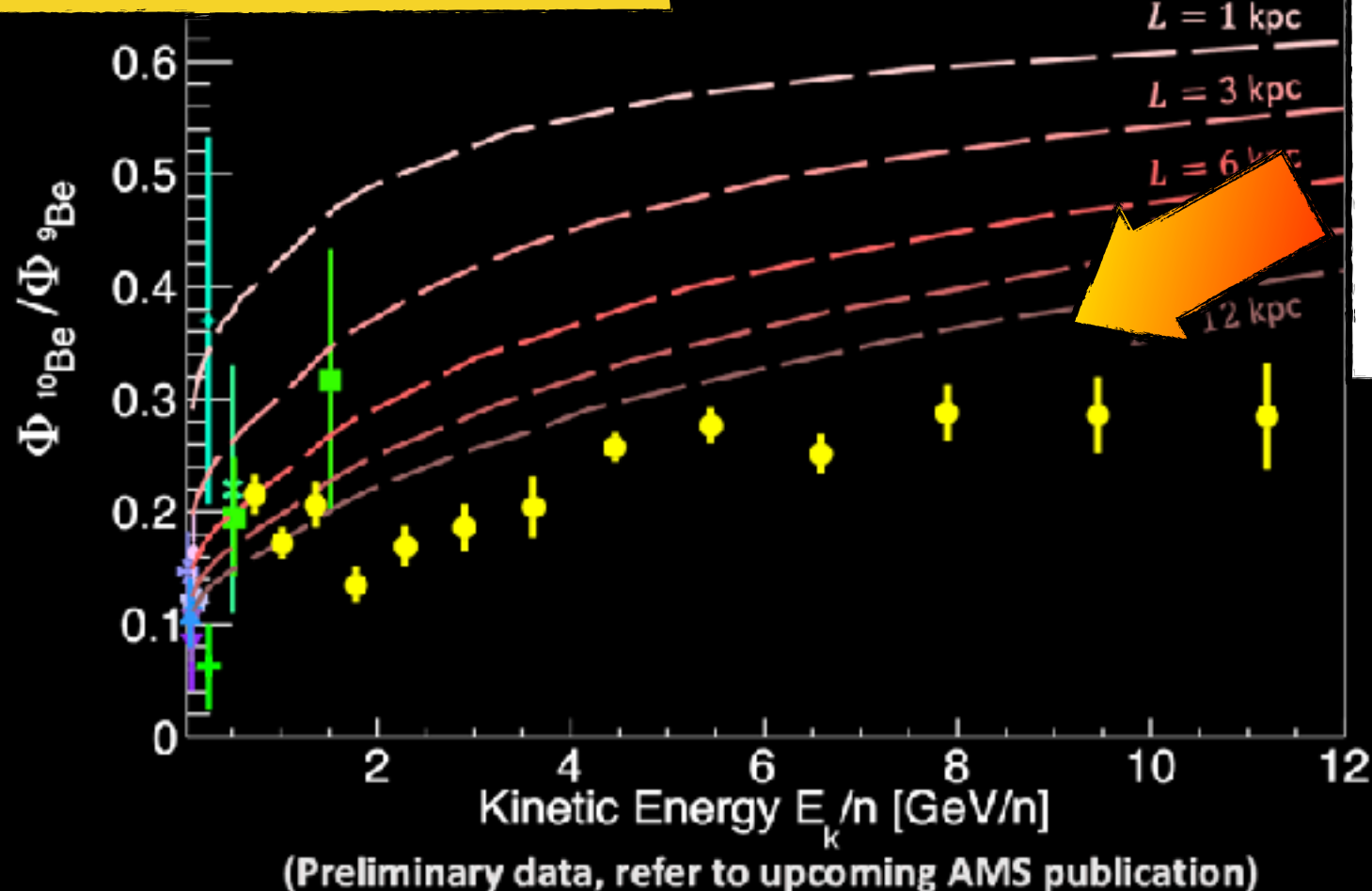
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AMS-02, ICRC2023



note that the the flatness of the ratio is difficult to be reproduced by sophisticated models

$^{10}\text{Be}/^9\text{Be}$ ratio

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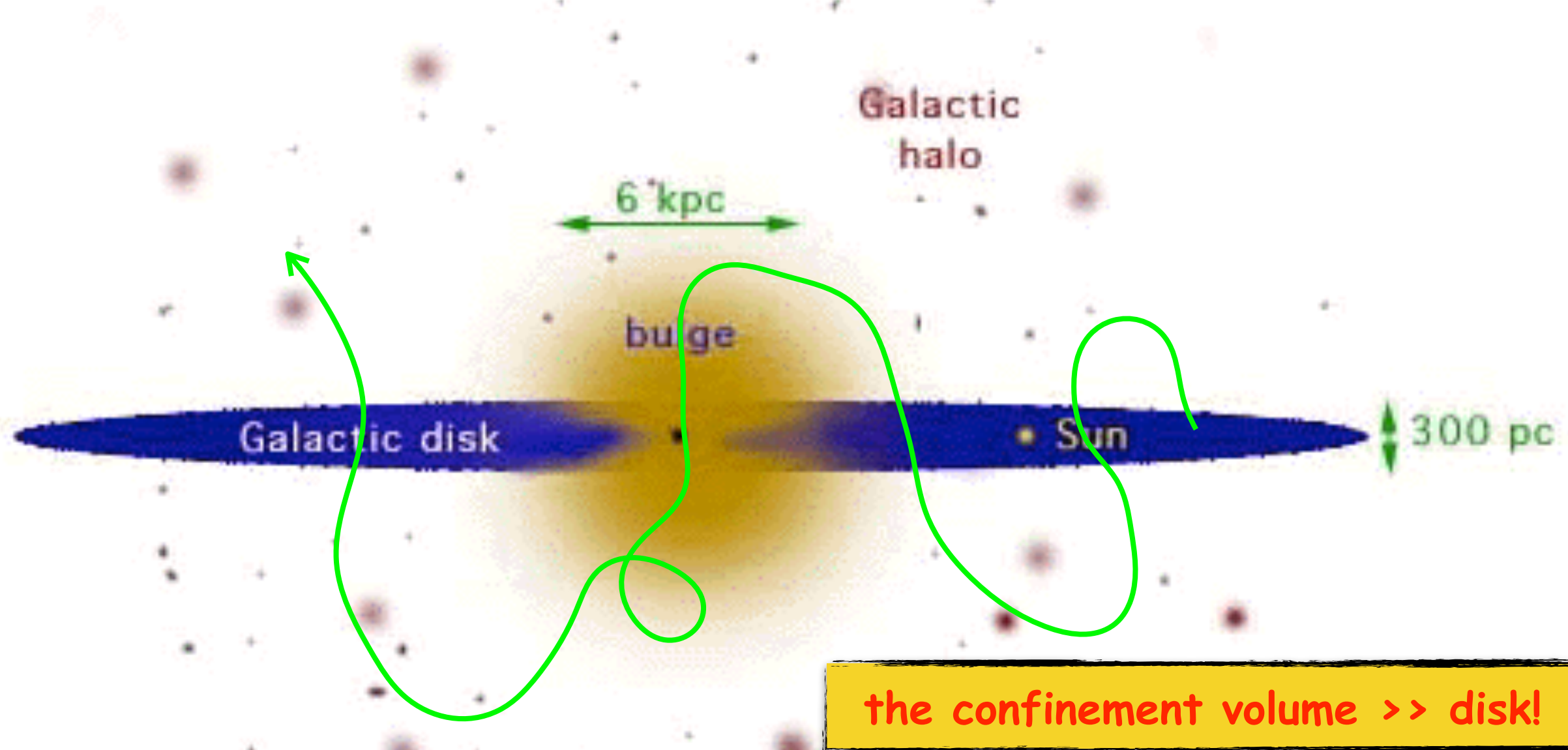
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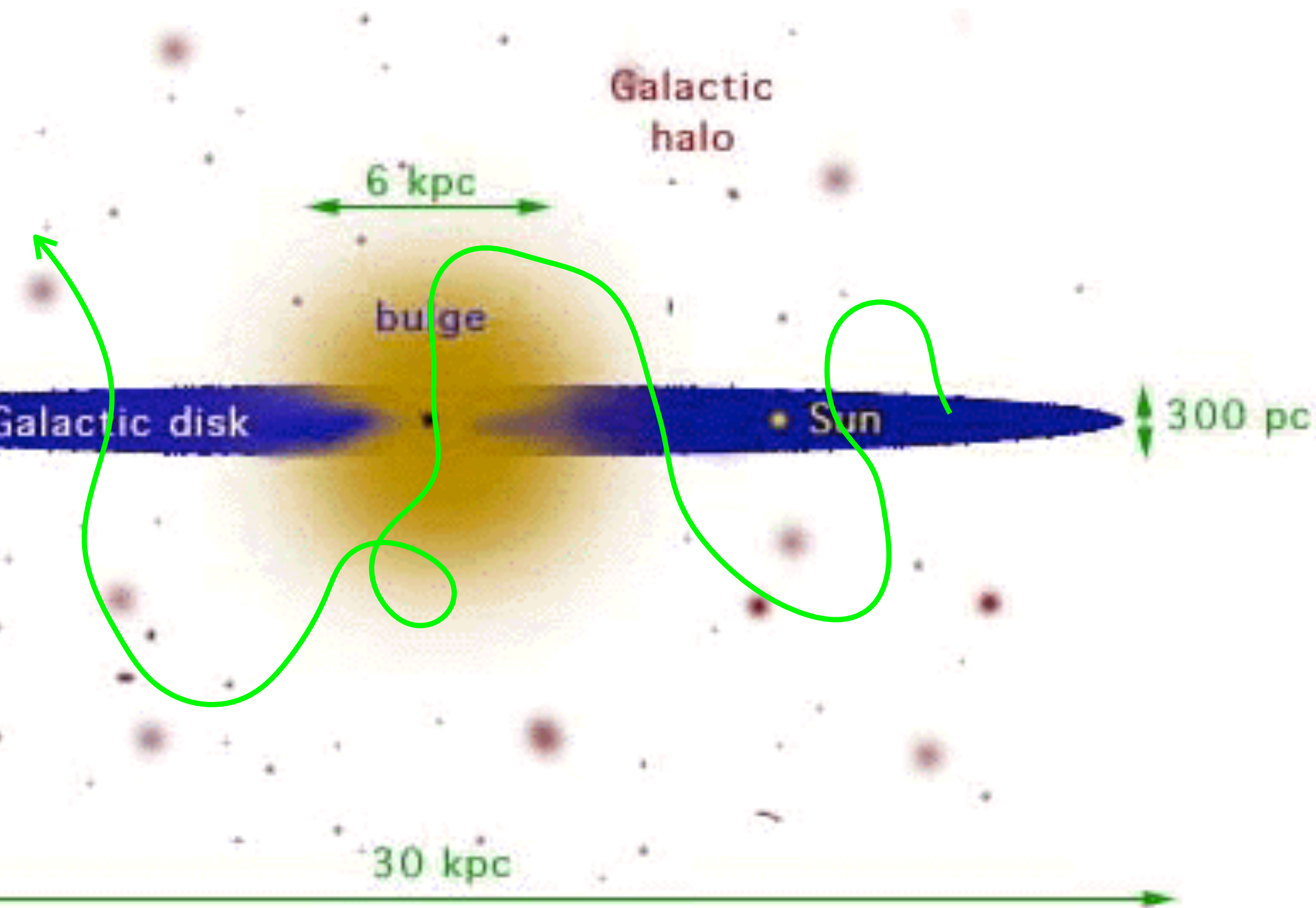
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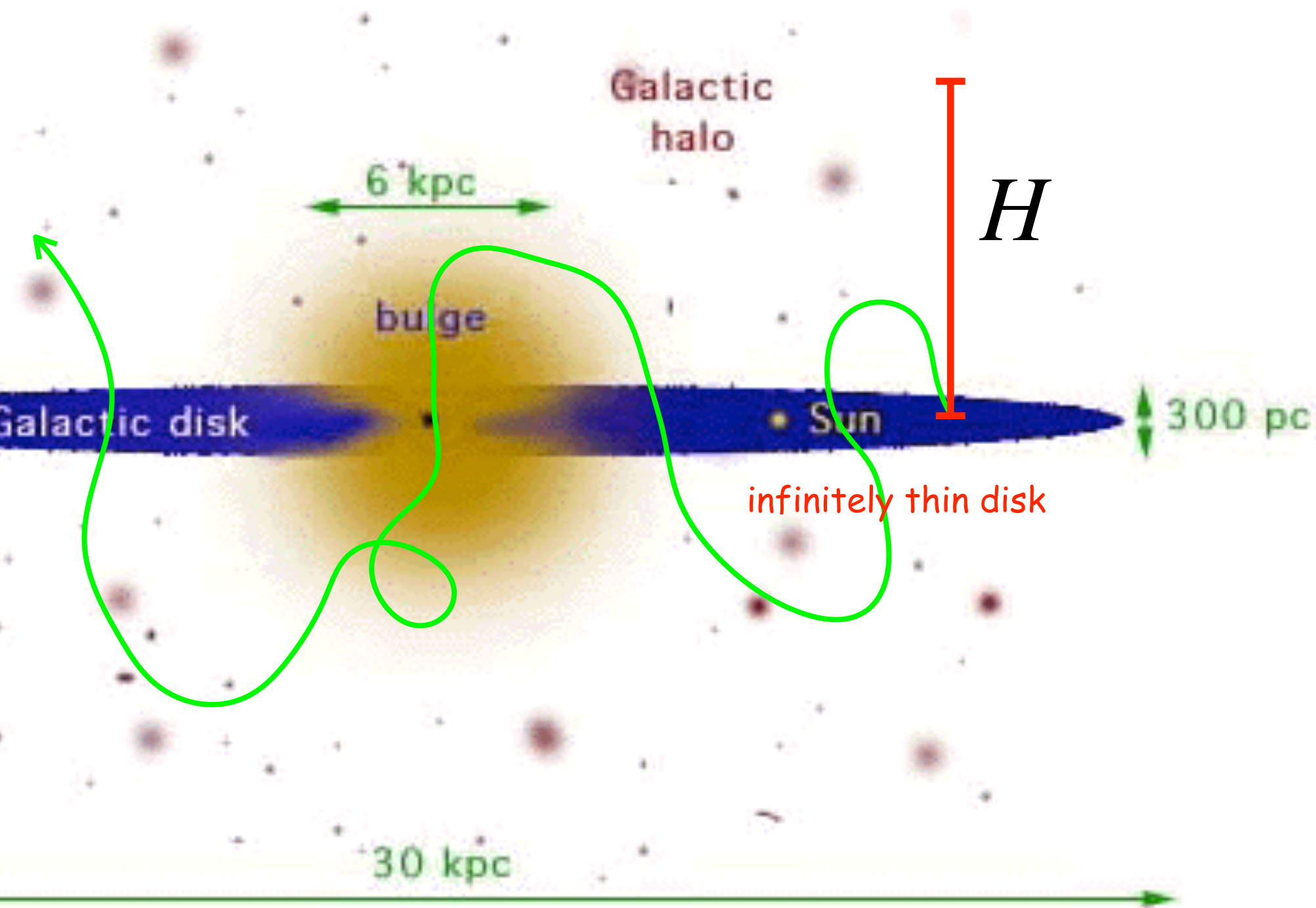


[6] Diffusive models
for CR transport

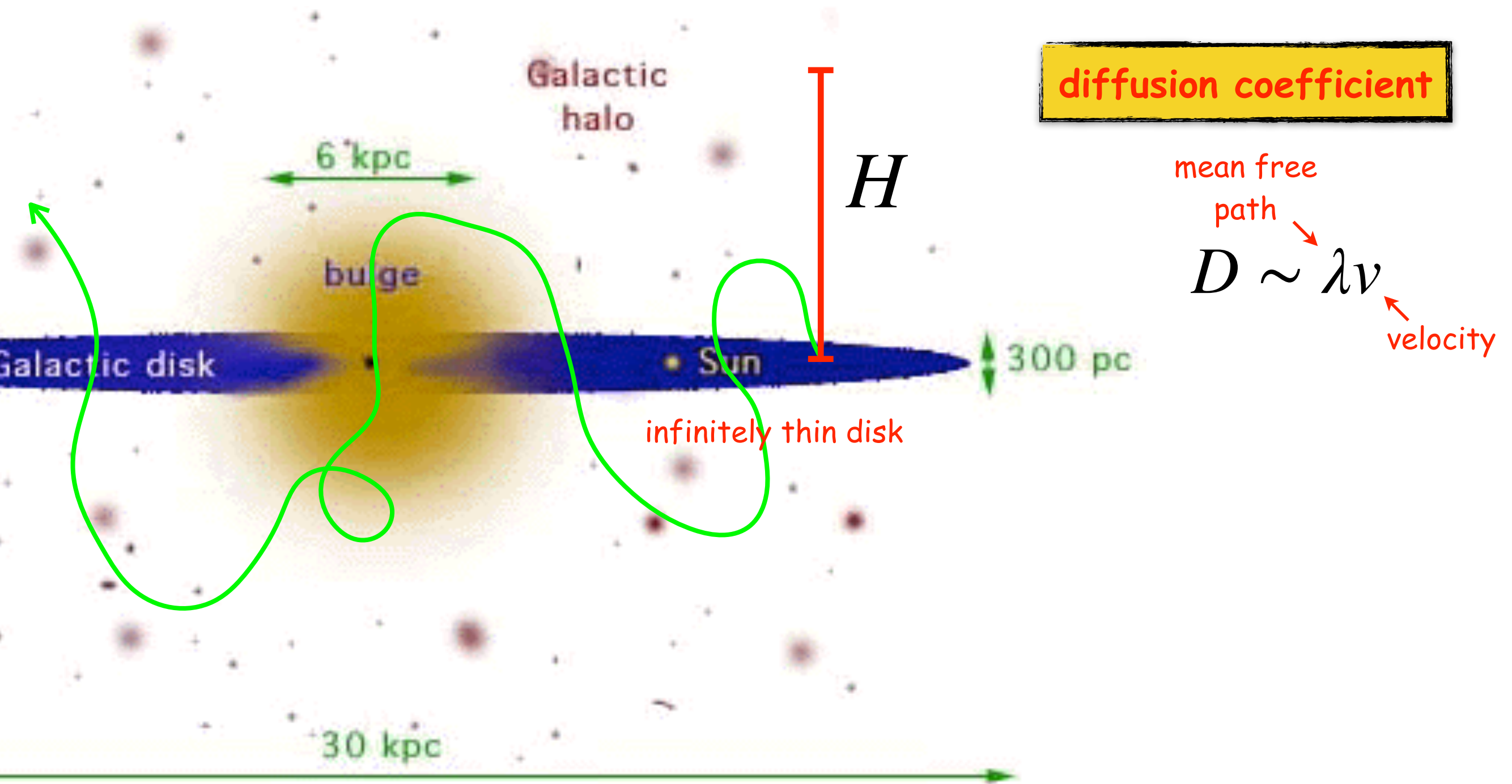
Diffusive models



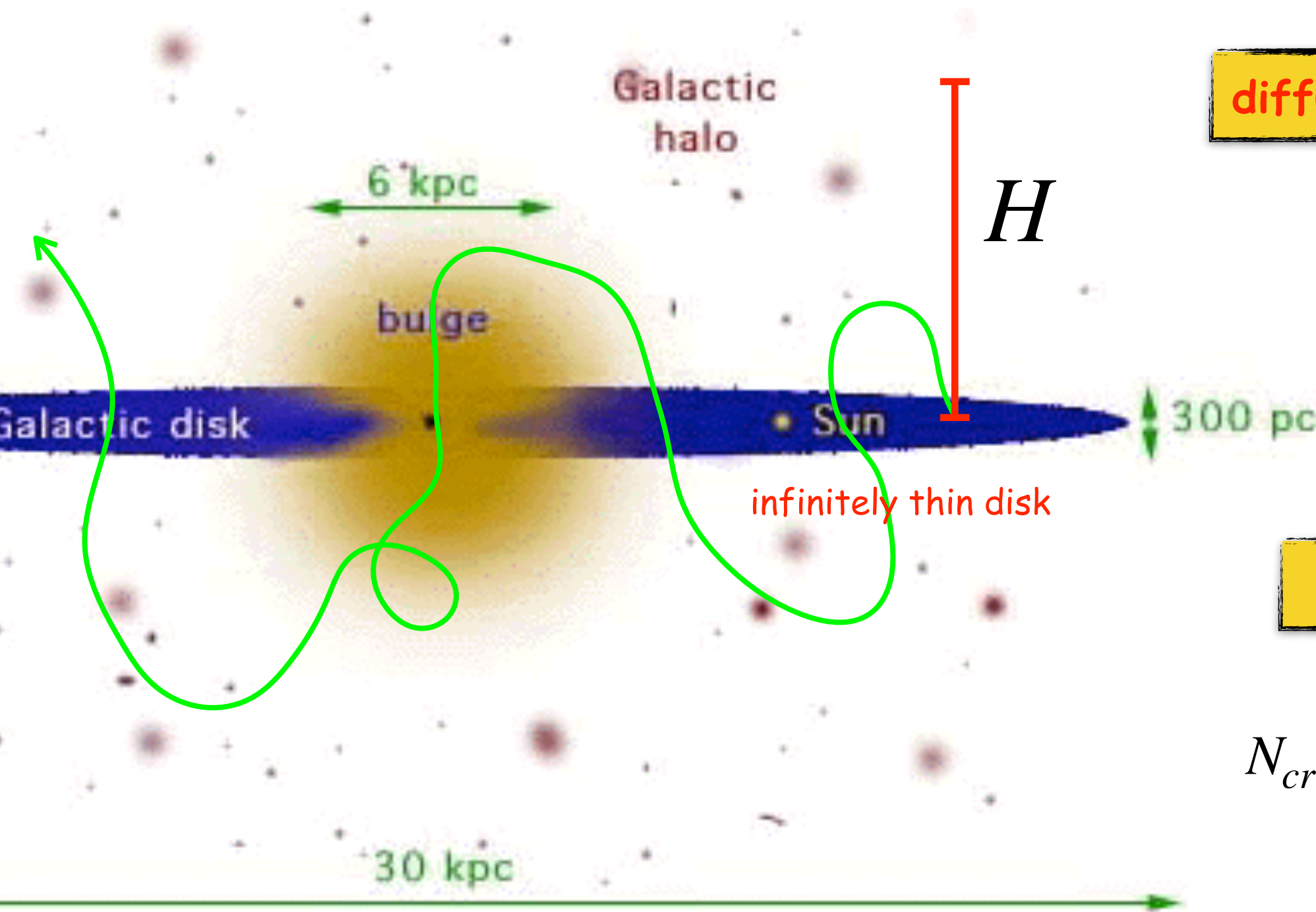
Diffusive models



Diffusive models



Diffusive models



diffusion coefficient

mean free
path

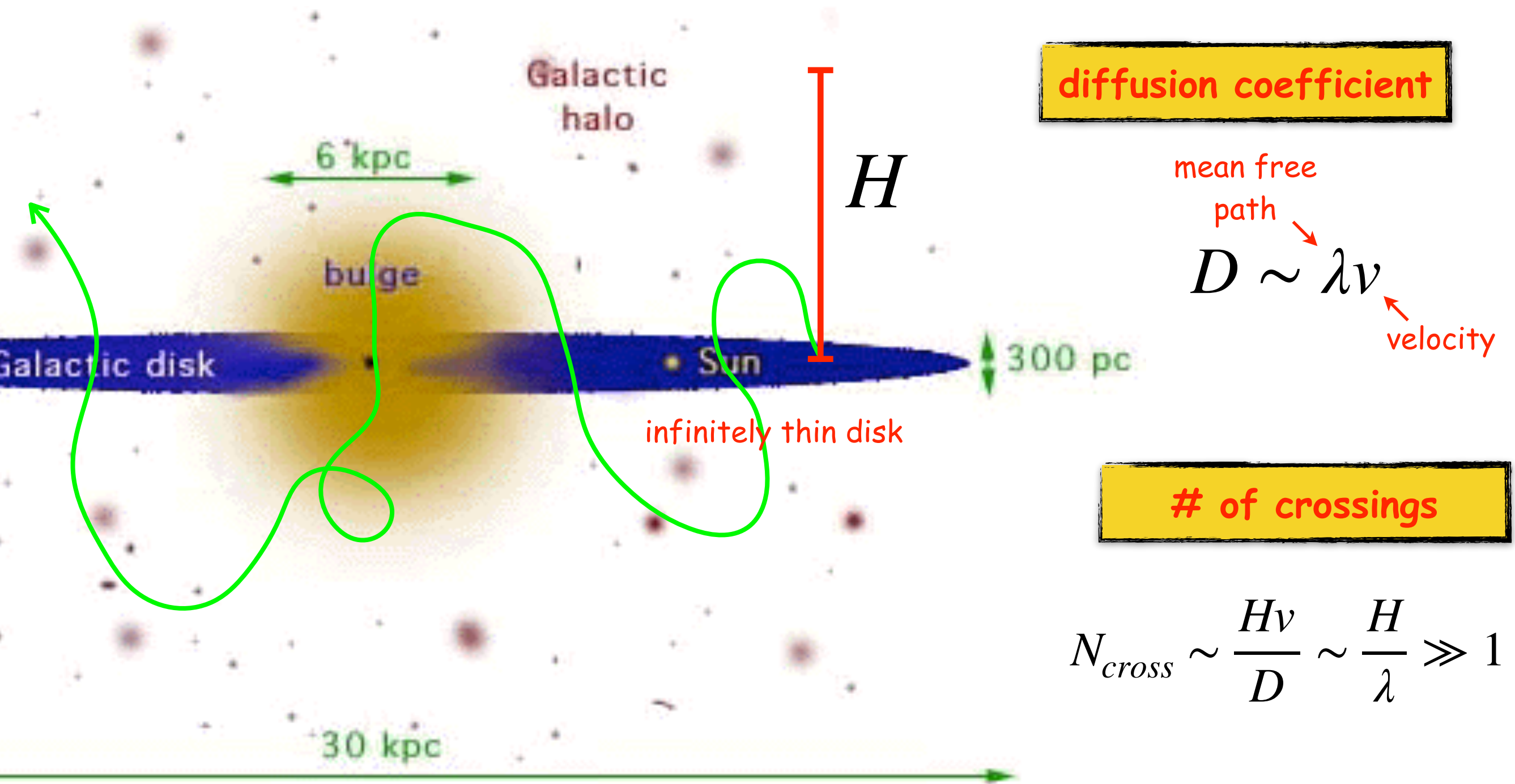
$$D \sim \lambda v$$

velocity

of crossings

$$N_{cross} \sim \frac{Hv}{D} \sim \frac{H}{\lambda} \gg 1$$

Diffusive models



grammage $\rightarrow$

$$X_{ISM} \sim N_{cross} X_{disk}$$

Diffusive models

B/C constrains a combination of H and D

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0.002 g/cm² 

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D slightly larger than what obtained by sophisticated models (Evoli+ 2019)

^{10}Be : local effects are important

^{10}Be diffuses over a distance

$$l \sim \sqrt{D\tau_{rad}}$$

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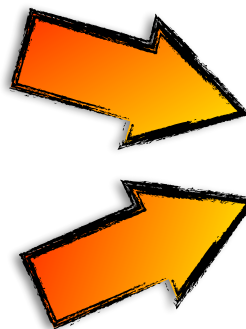
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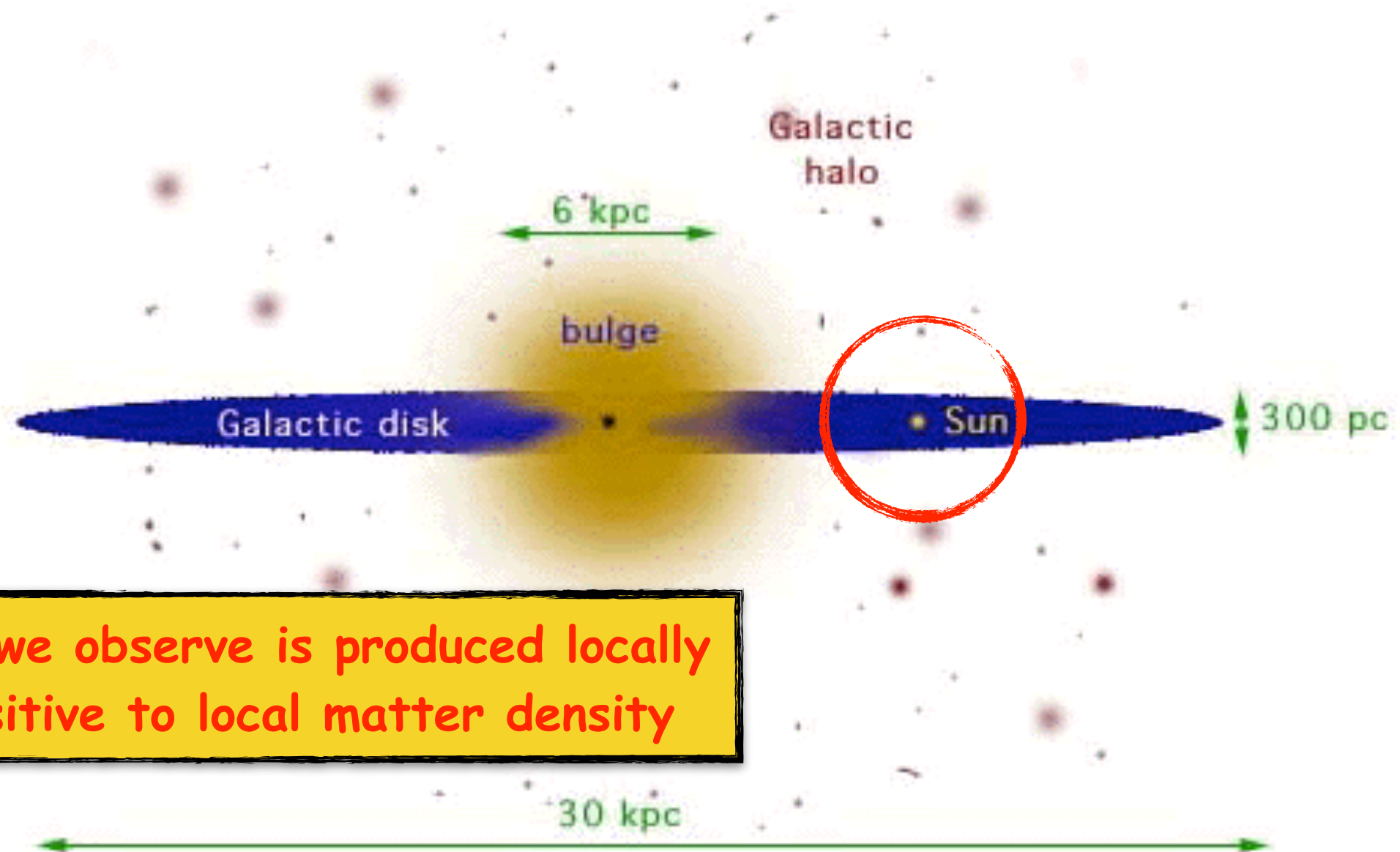
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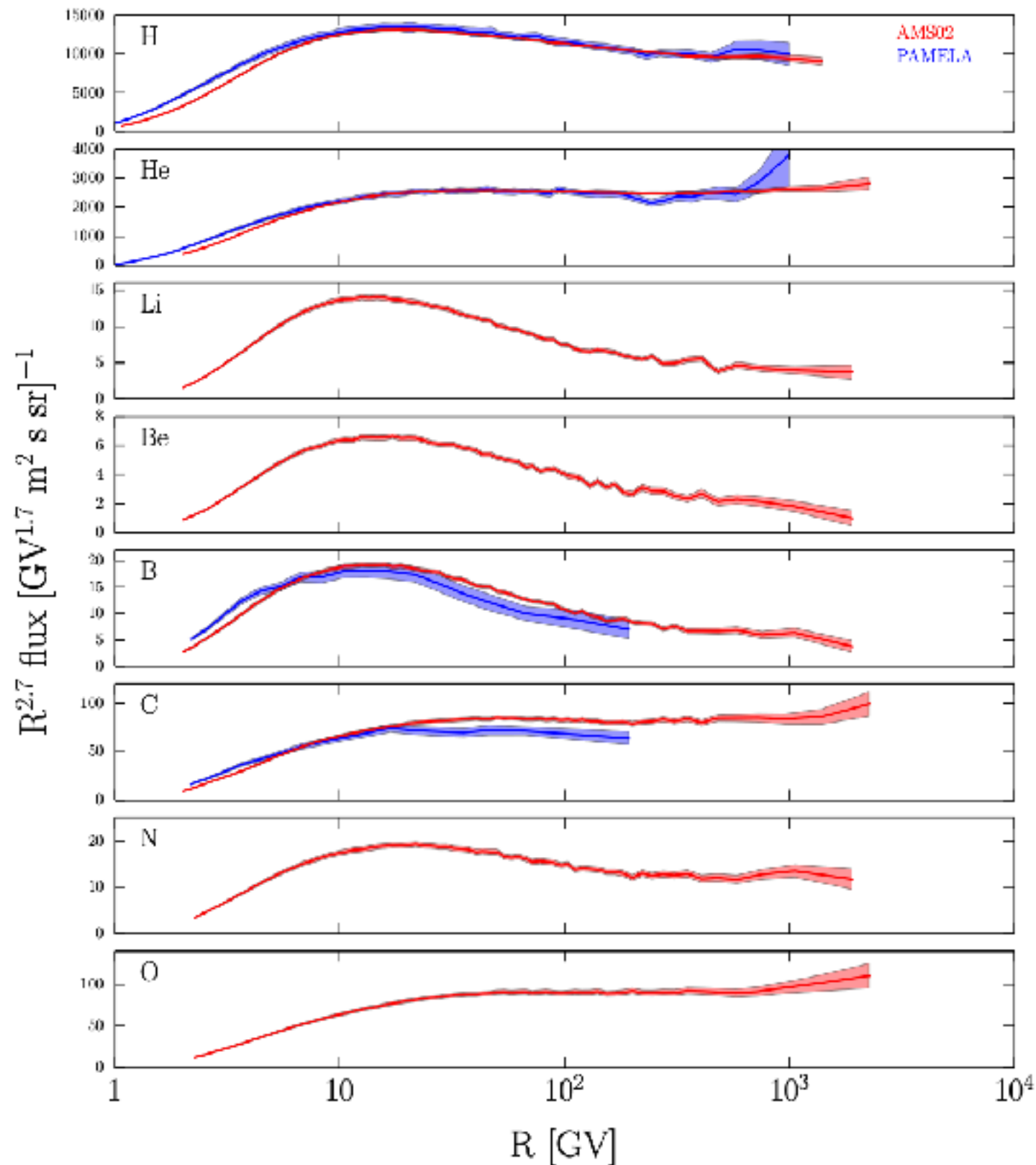
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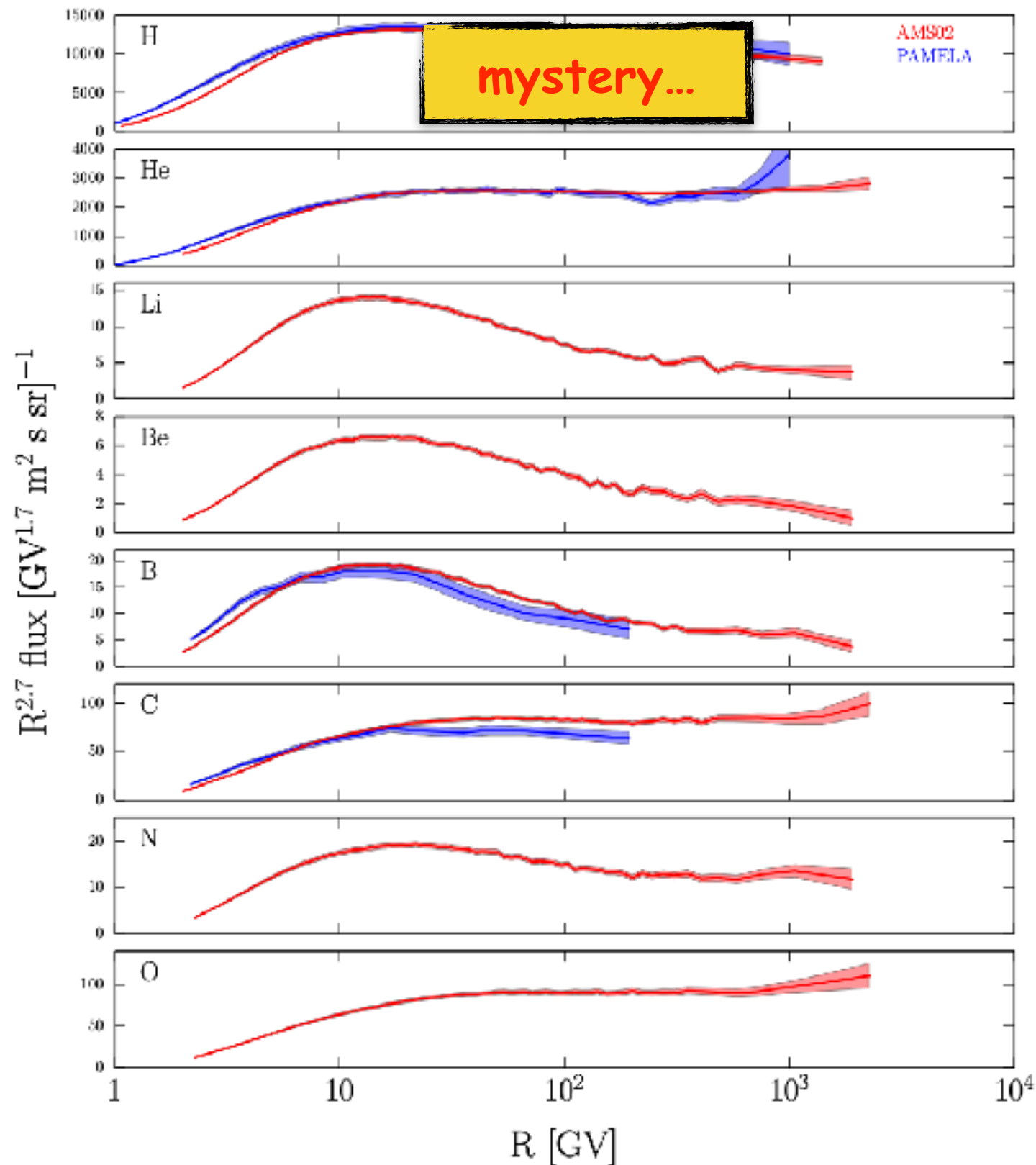


the ^{10}Be we observe is produced locally
—> sensitive to local matter density

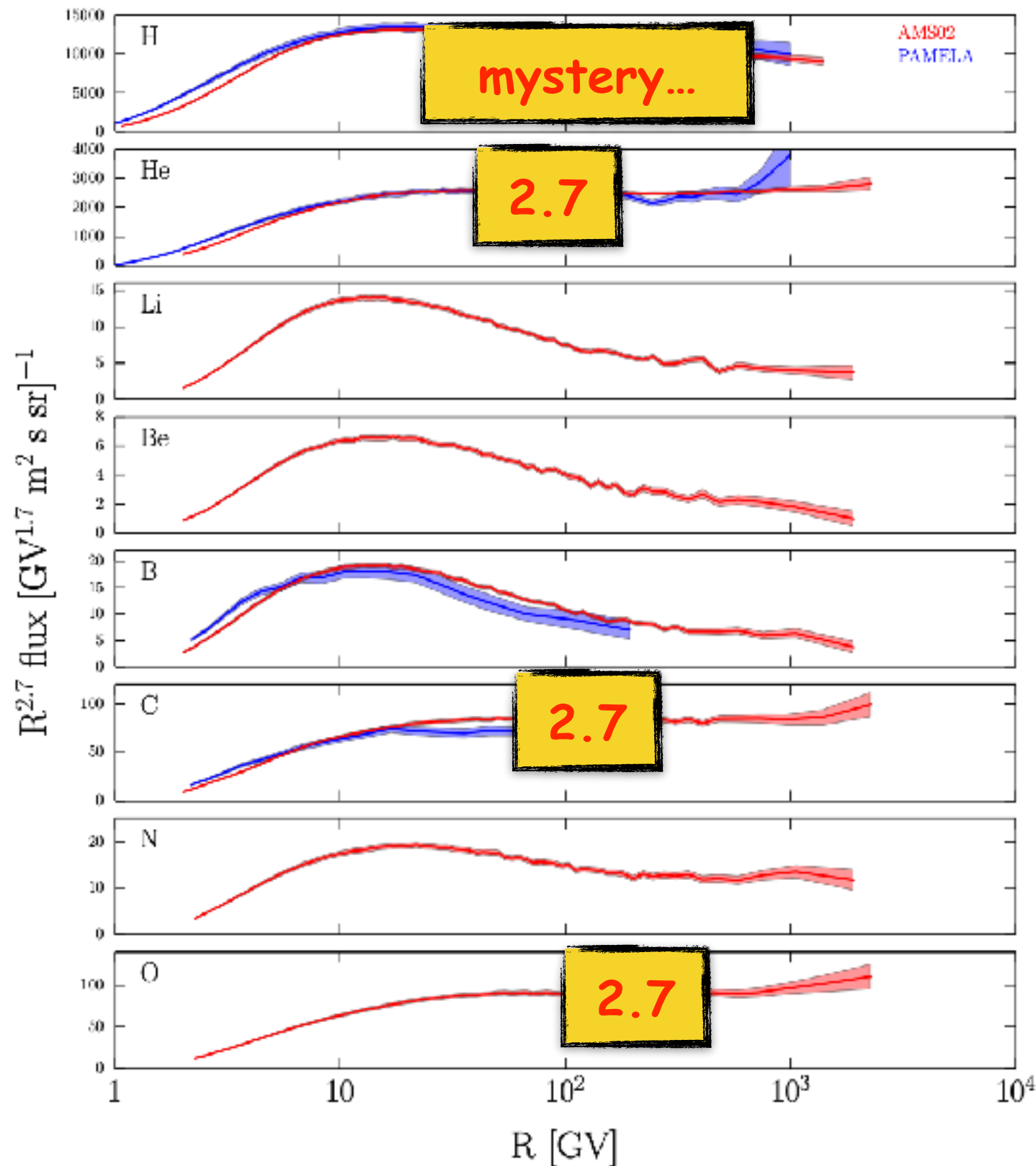
Let's go back to CR spectra



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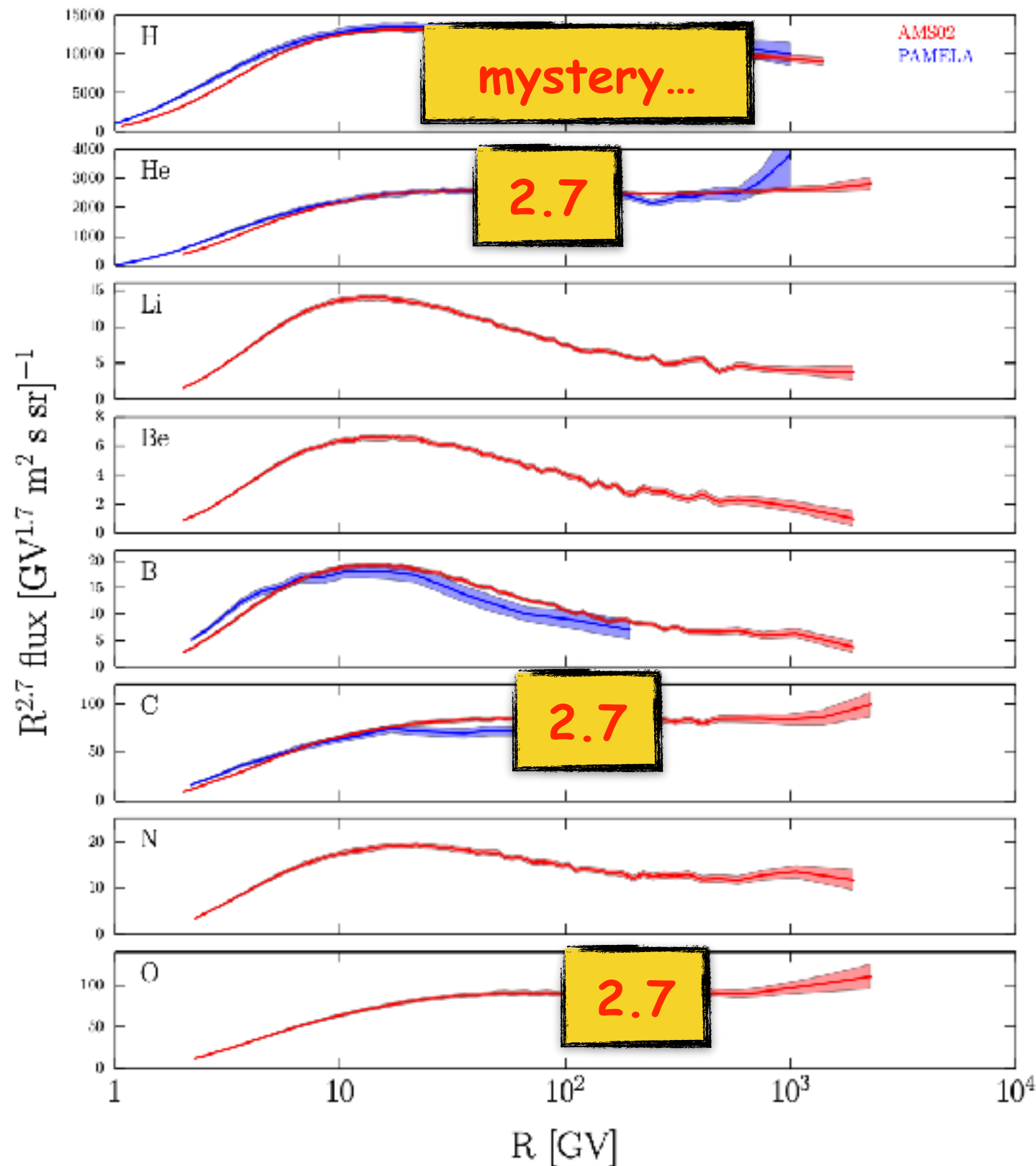


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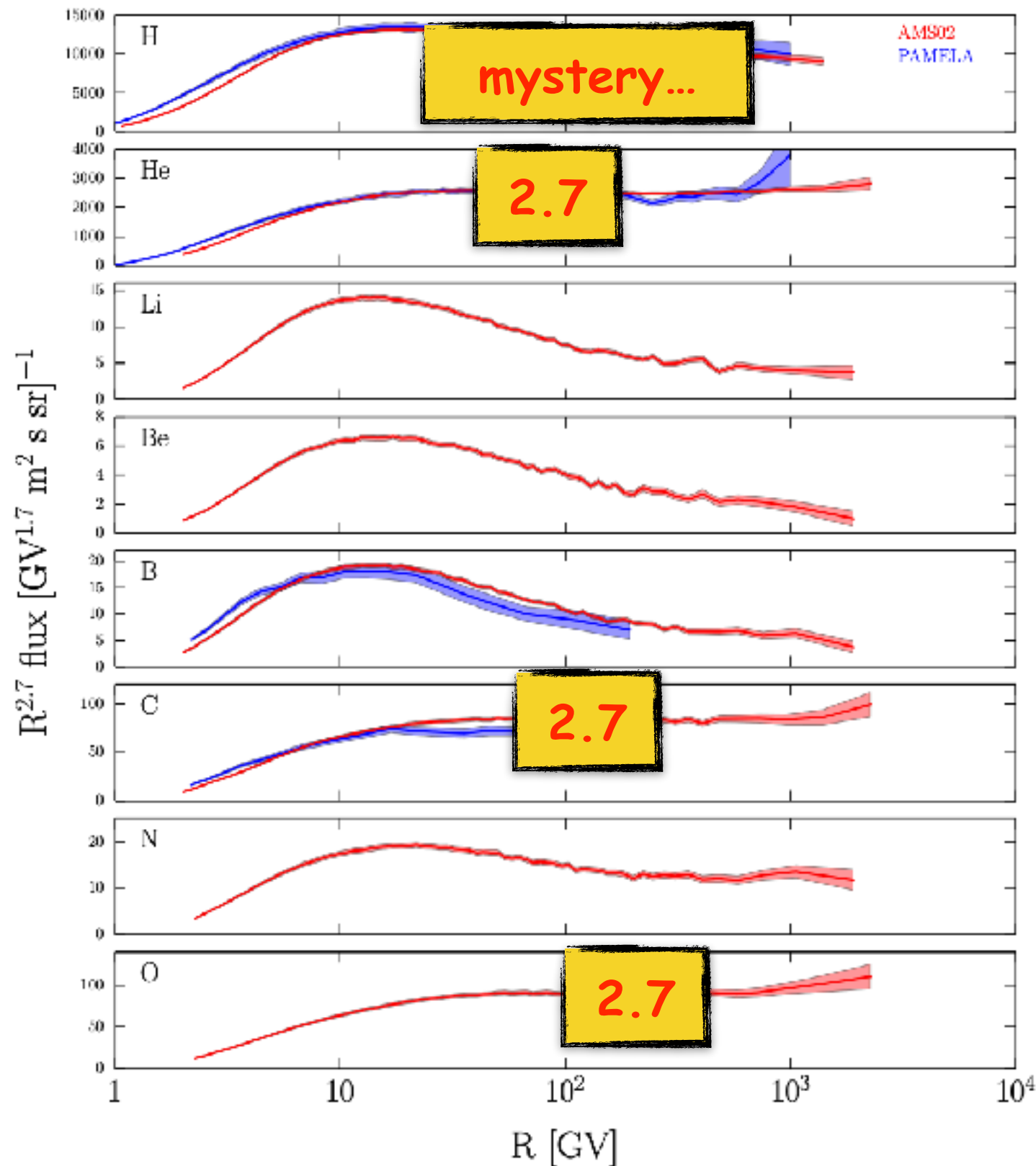
primaries



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Let's go back to CR spectra

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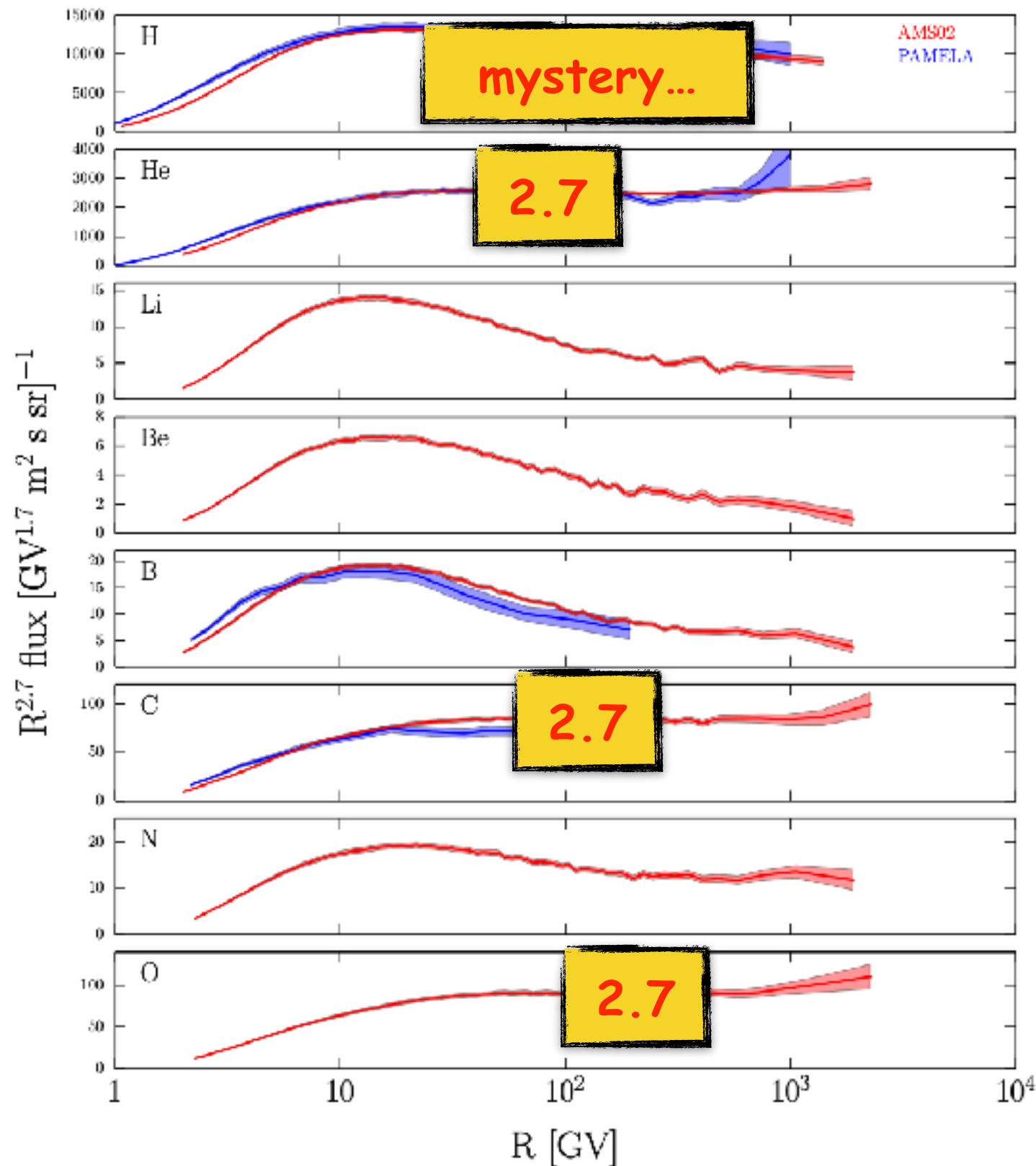


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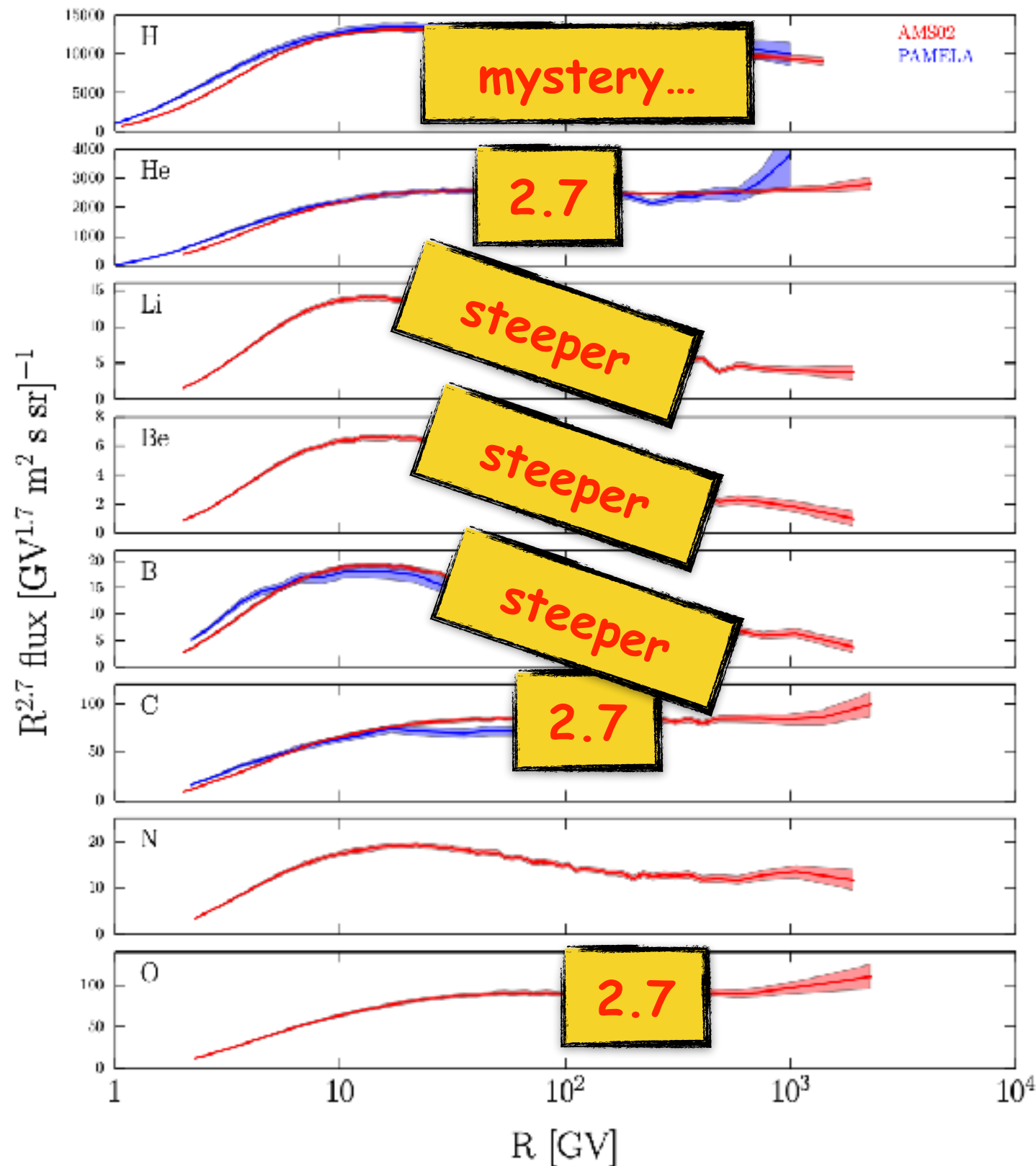


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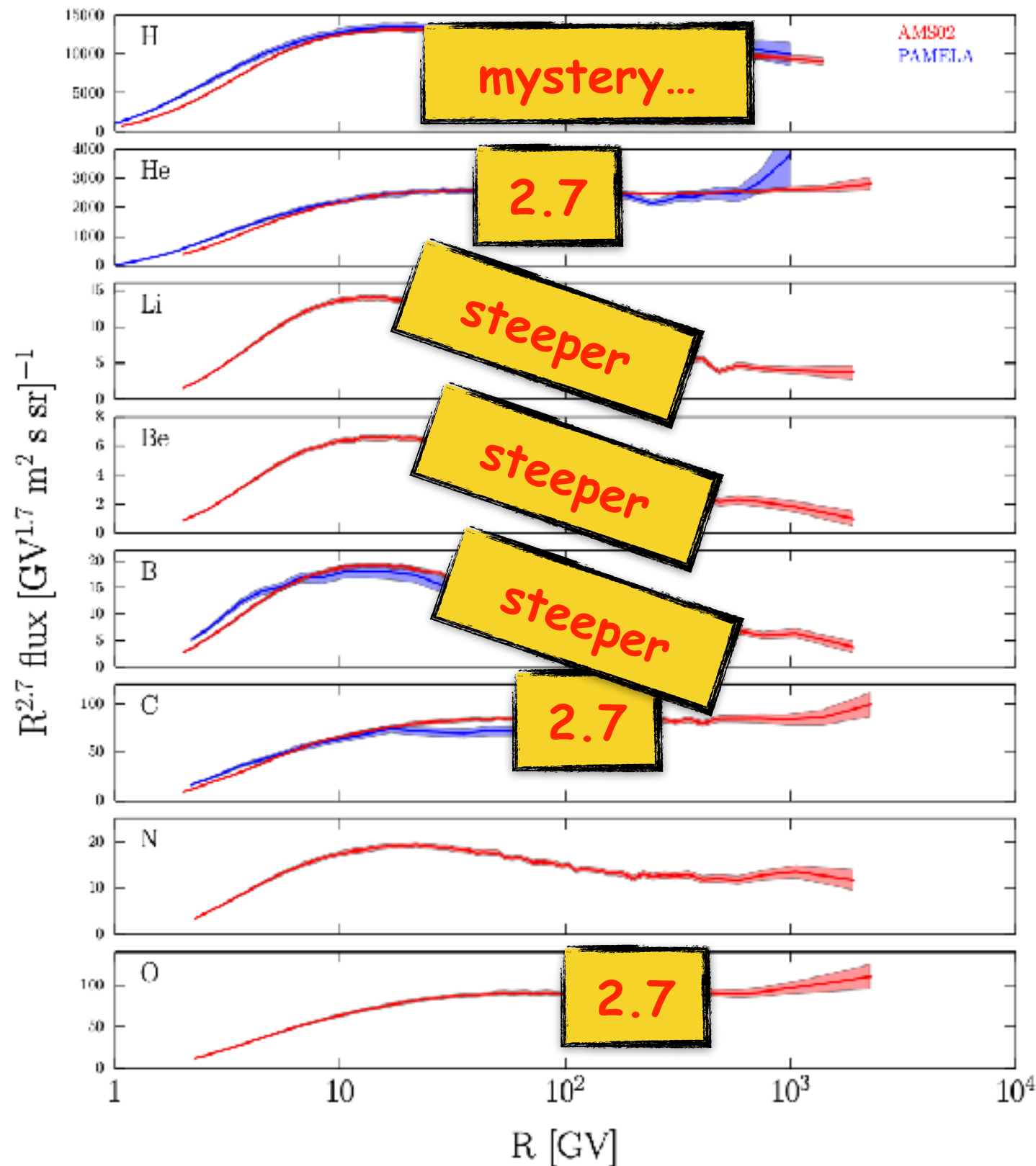
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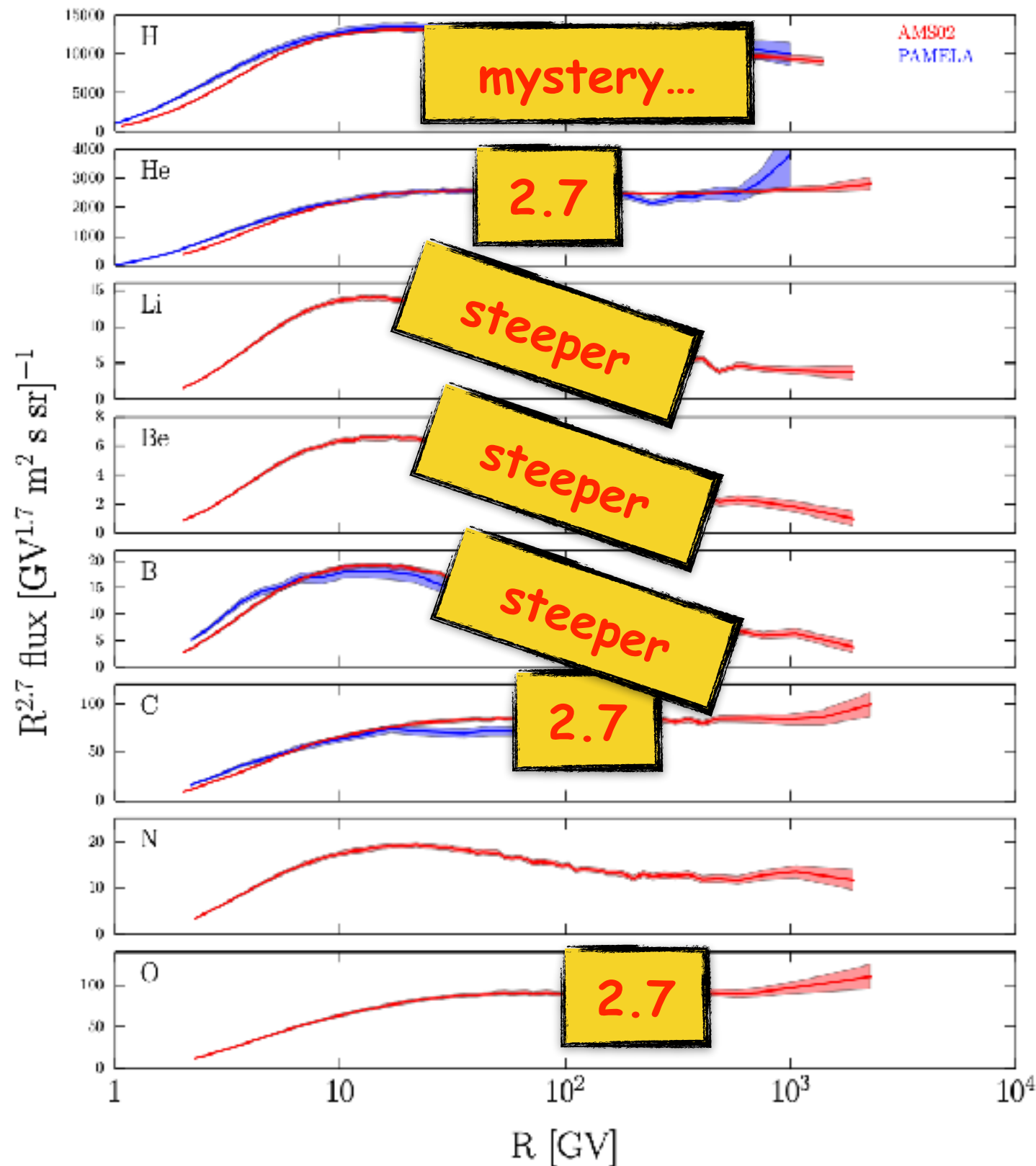
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Let's go back to CR spectra



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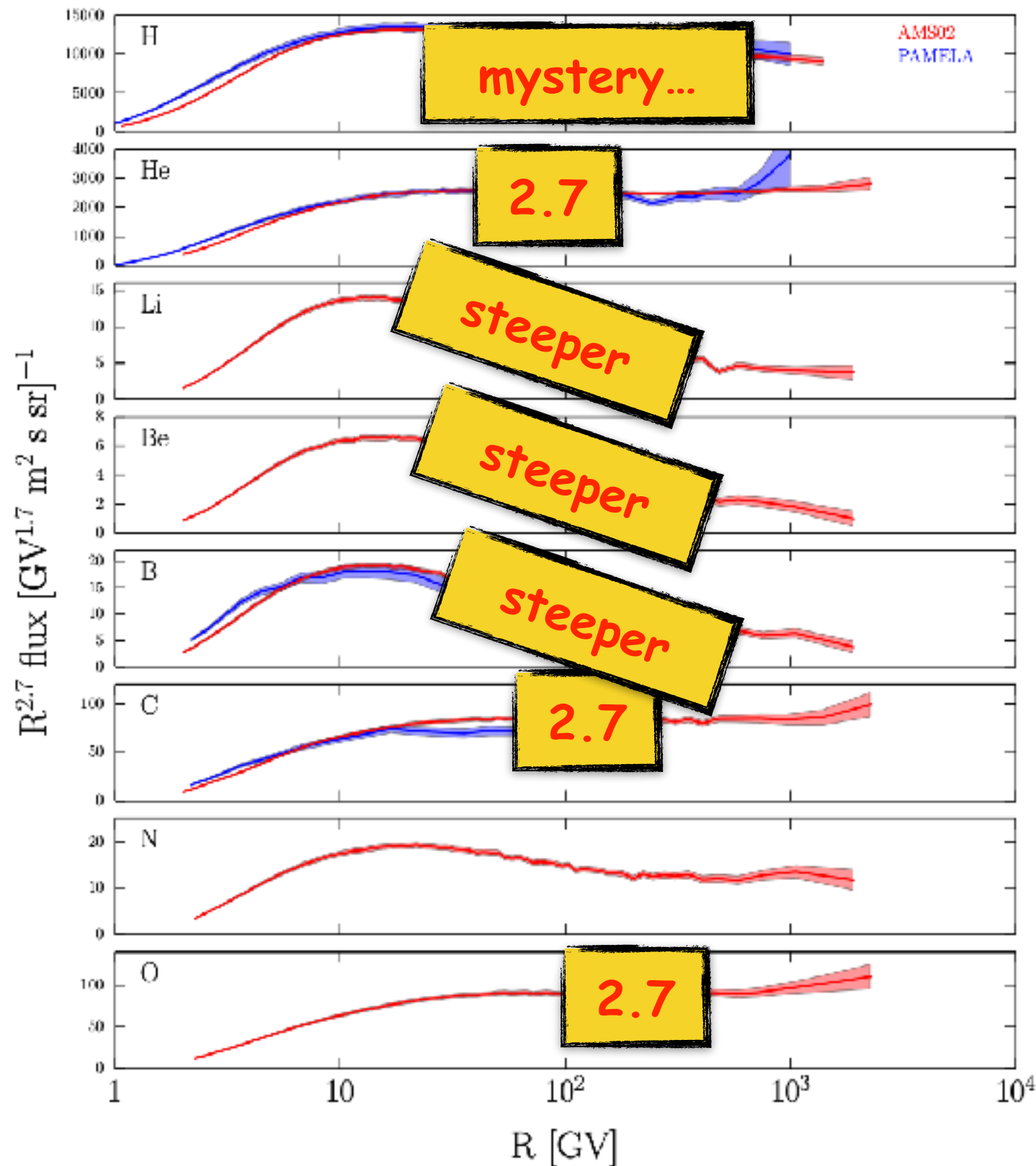
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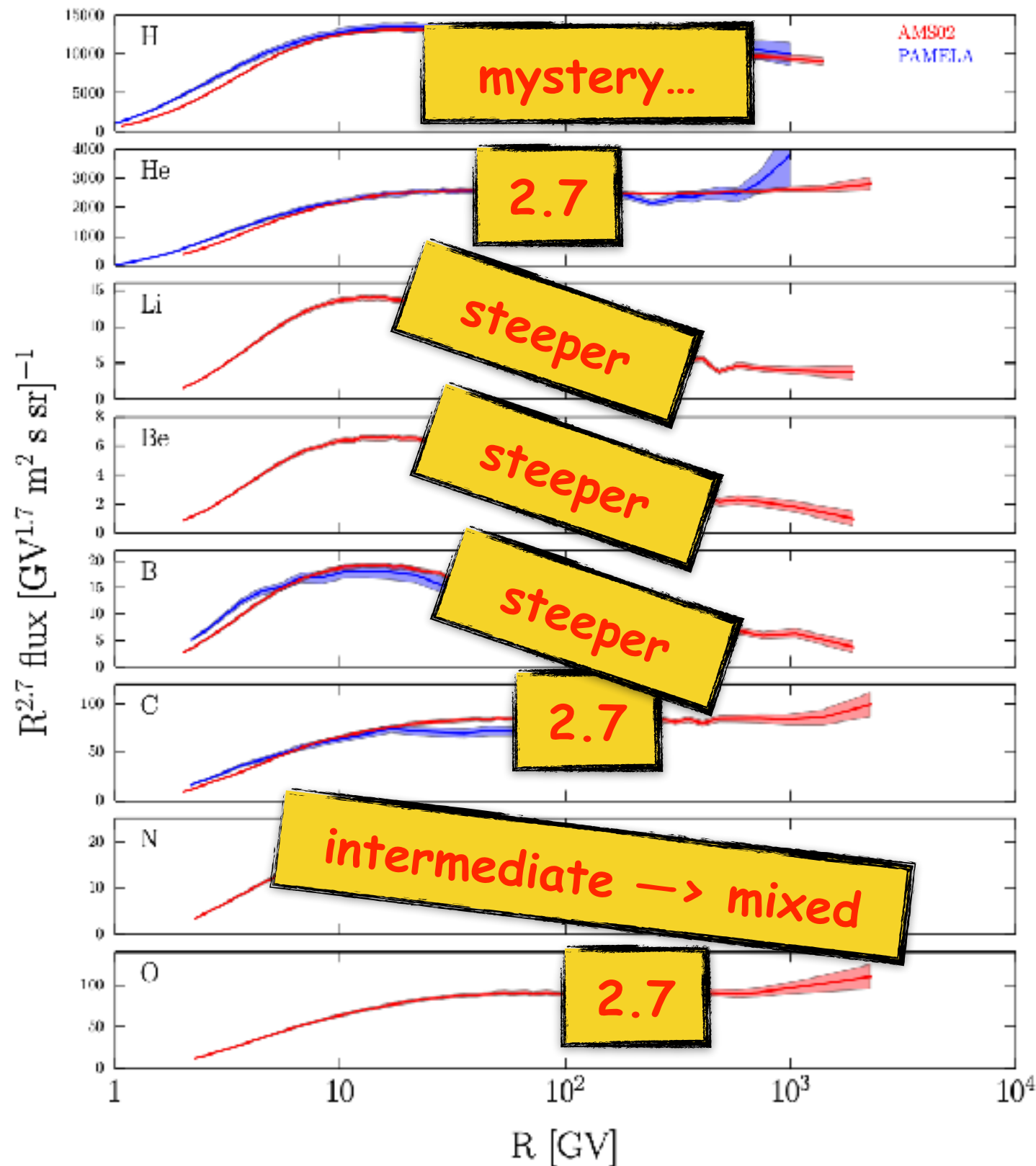
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steeper!

Let's go back to CR spectra



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Why is this so remarkable?

CR sources MUST inject:

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we said NOTHING about the nature of sources!
who they are, where they are, how they accelerate particles etc... this result is very
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...and we can proceed further and estimate the source power!

local energy
density

$$W_{CR} = \frac{\omega_{CR} V_{disk}}{\tau_{ISM}} \approx 10^{41} \text{erg/s}$$

Which is also model independent!

[7] *Supernovae and the
origin of cosmic rays*

First paper on SNae and CRs



COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

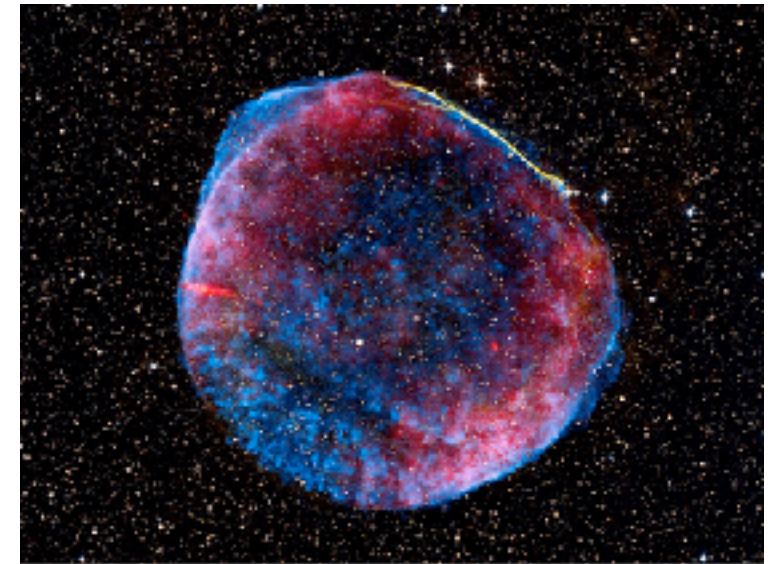
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

to my knowledge, the first paper invoking **Galactic** supernovae as sources of CRs is Ter Haar 1949

The supernova remnant origin of CRs



The supernova remnant origin of CRs

modern formulation of the hypothesis

3 SN/century in the Galaxy, each one releases
 10^{51} erg in form of kinetic energy.



$$W_{SN} = 10^{42} \left(\frac{E_{SN}}{10^{51} \text{erg}} \right) \left(\frac{\nu_{SN}}{3/\text{century}} \right) \text{erg/s}$$

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~10% acceleration efficiency

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why remnants? → radio observations → particle acceleration at SNR shocks!

γ -rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

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$$n_{ISM} \sim 1 \text{ cm}^{-3} \quad \xrightarrow{\hspace{1cm}}$$
$$p + p \rightarrow p + p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

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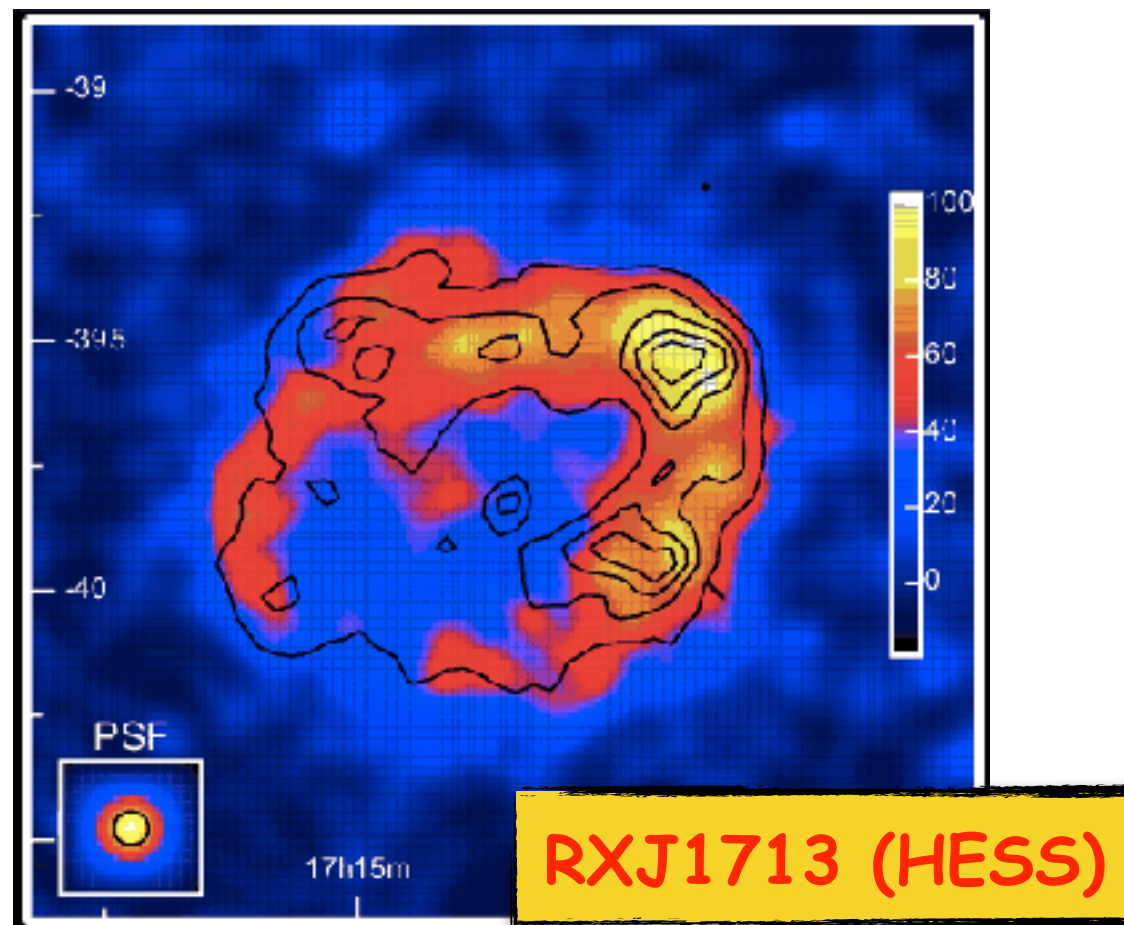
$E^{-2.2}$ spectra $\longrightarrow$ model independent estimate of gamma ray flux!

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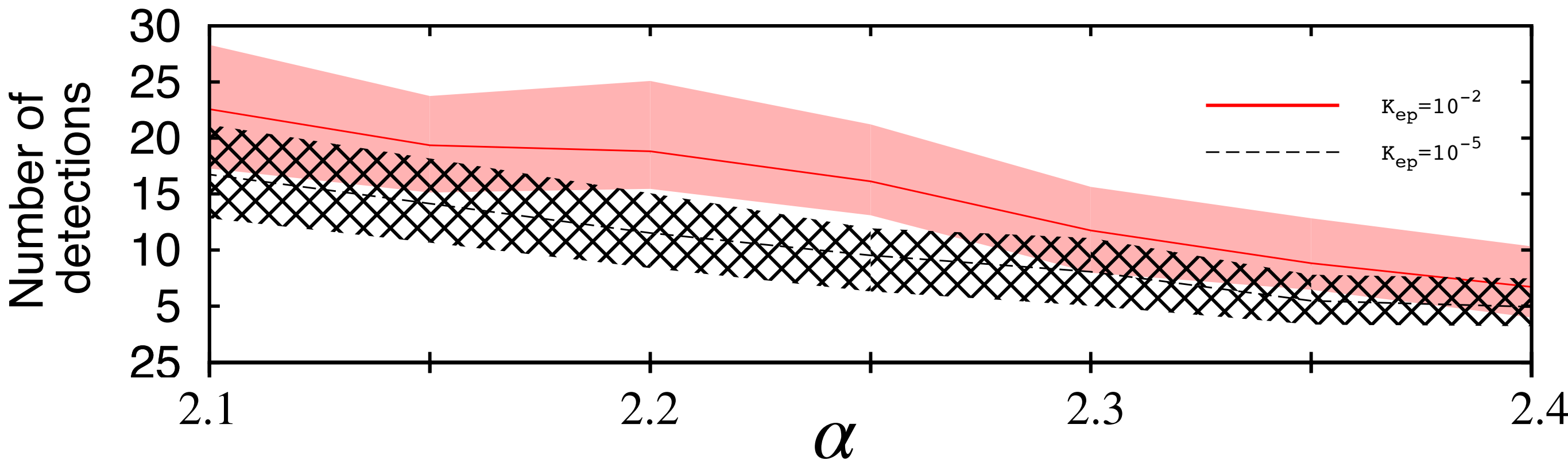


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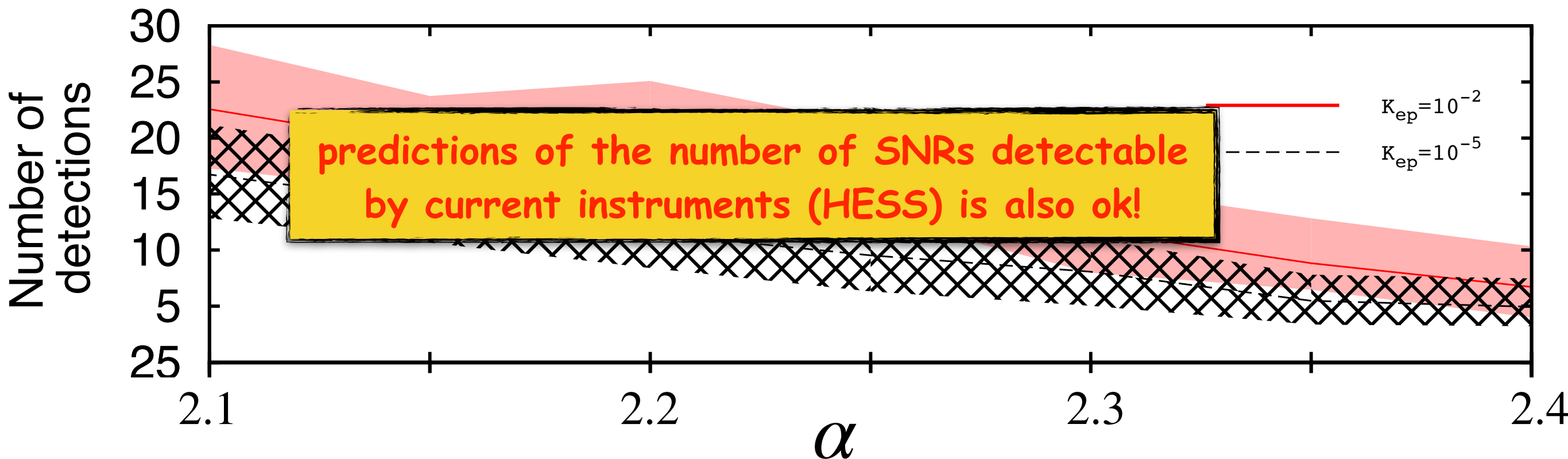
Cristofari+ 2013

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Cristofari+ 2013

[8] The three pillars
of orthodoxy

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

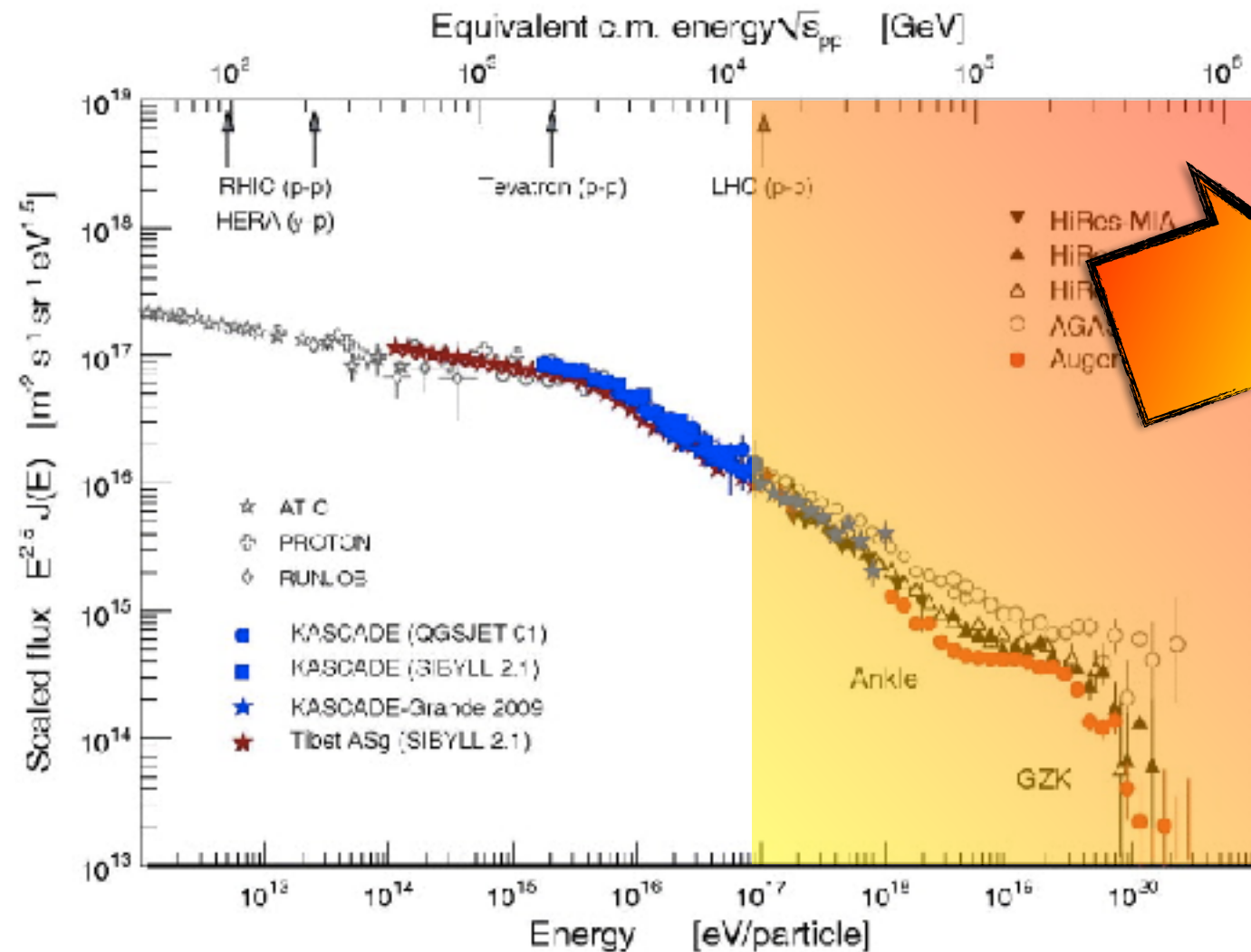
The orthodoxy (2)

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

The orthodoxy (3)

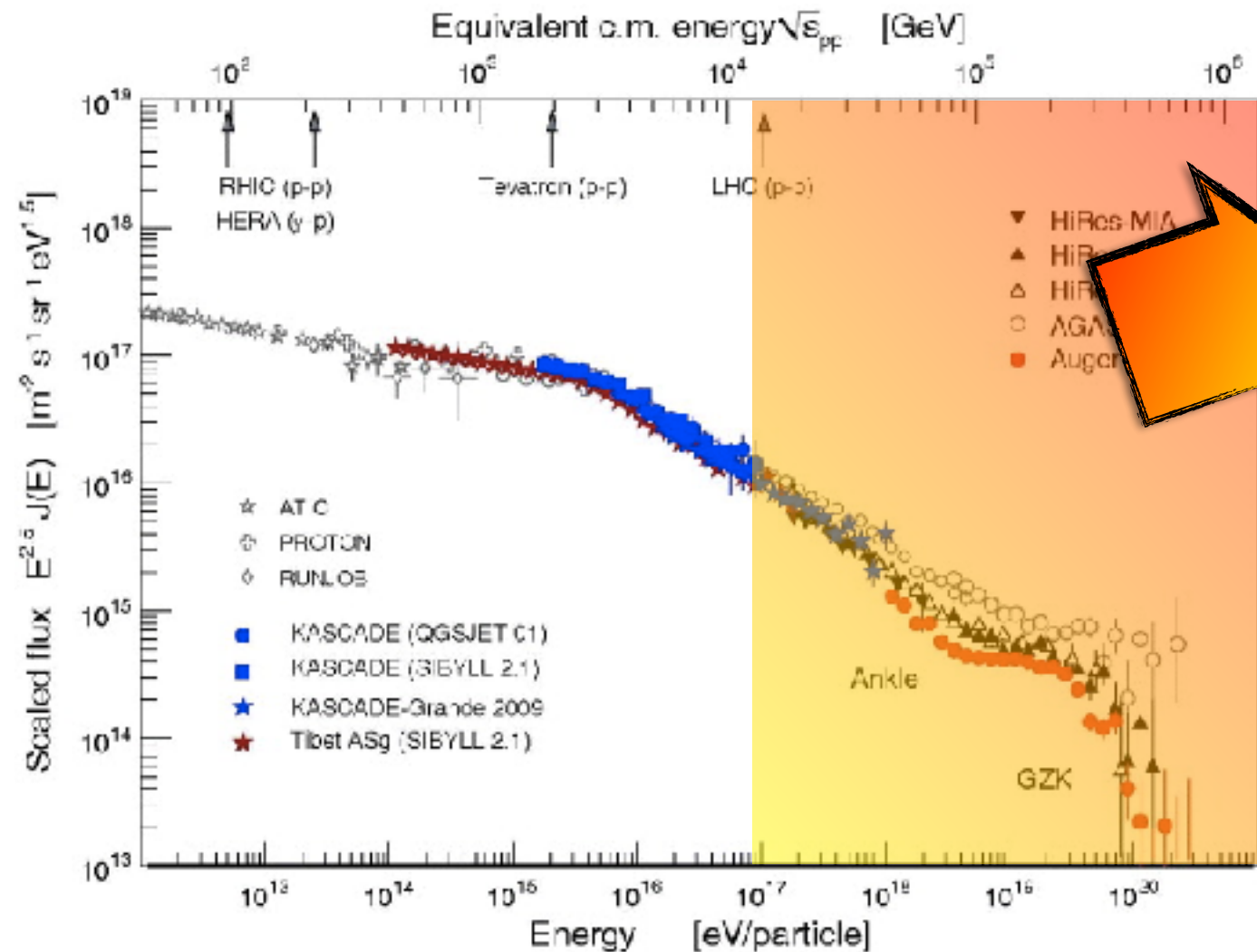
- ▶ Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

(At least) three serious issues remains



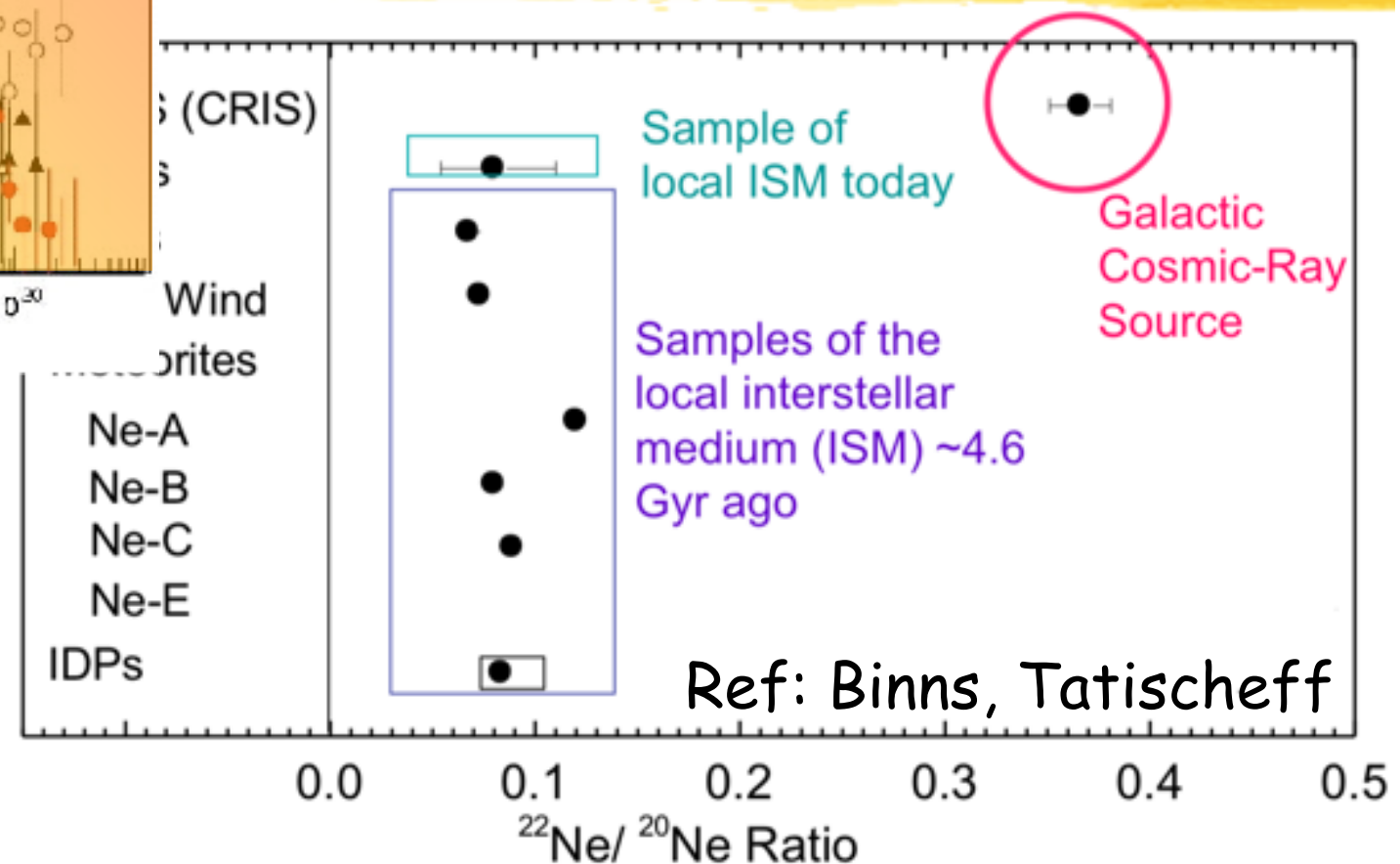
[1] can SNR shocks accelerate particles up to the largest observed energies?

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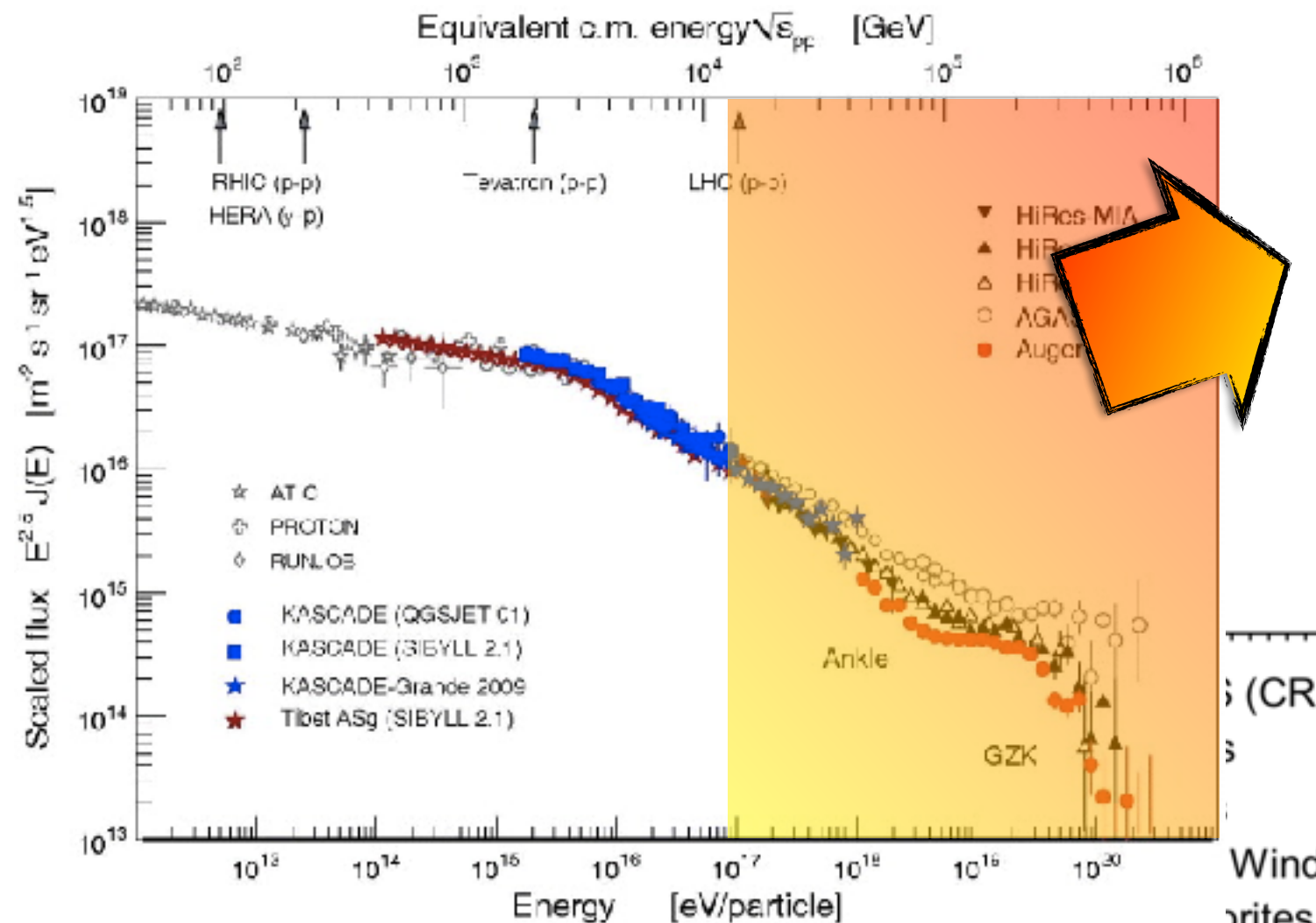


[1] can SNR shocks accelerate particles up to the largest observed energies?

[2] can the SNR paradigm explain the anomalous excess of the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio?

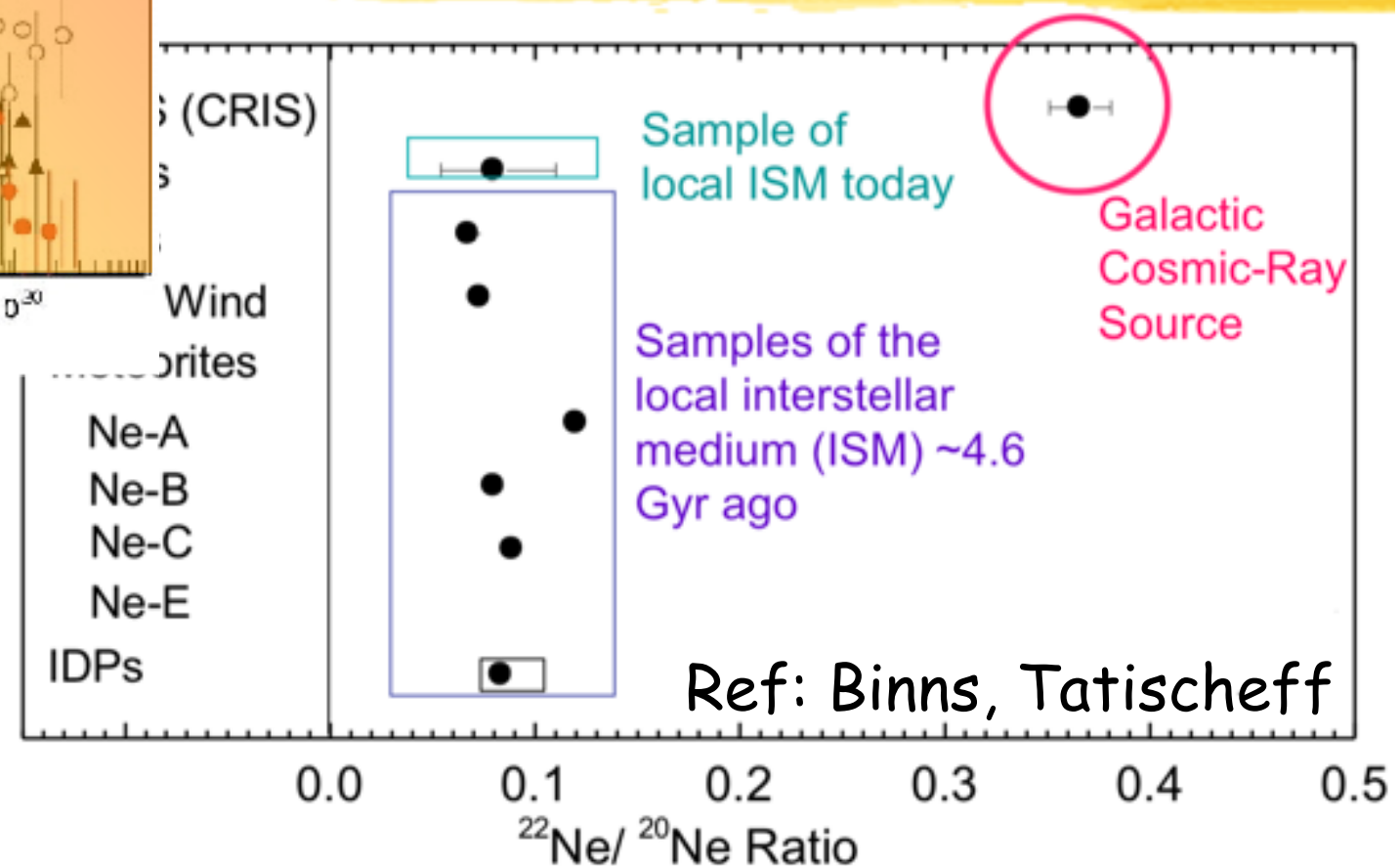


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[1] can SNR shocks accelerate particles up to the largest observed energies?

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[3] DSA predicts E^{-2} spectra, but we need $E^{-2.2}$!

[9] Why it is a problem to
understand particle
acceleration in astrophysics

Charged particles and electromagnetic fields

cosmic rays are charged particles → they are affected by electromagnetic fields

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

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

Charged particles and electromagnetic fields

cosmic rays are charged particles → they are affected by electromagnetic fields

$$\vec{E}(x)$$

$$\vec{B}(x)$$

Simplifying assumption → consider only constant fields

Charged particles and electromagnetic fields

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$$\vec{E}(\vec{r})$$

$$\vec{B}(\vec{r})$$

Simplifying assumption → consider only constant fields

A particle of charge q moving at a velocity $\vec{u}$ will experience a force:

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

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

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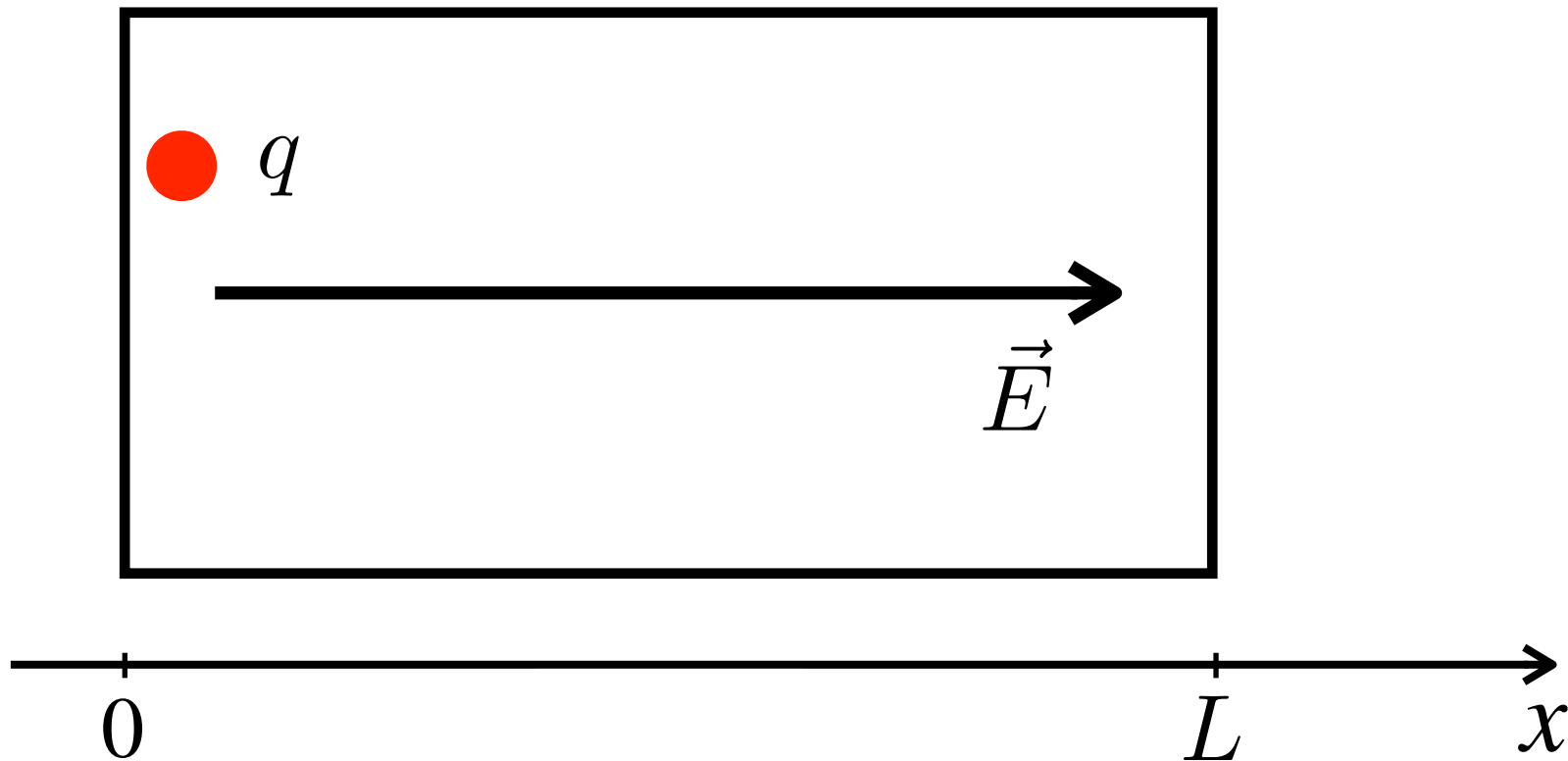
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Lorentz force
⊥ to velocity →
doesn't change
the particle energy!

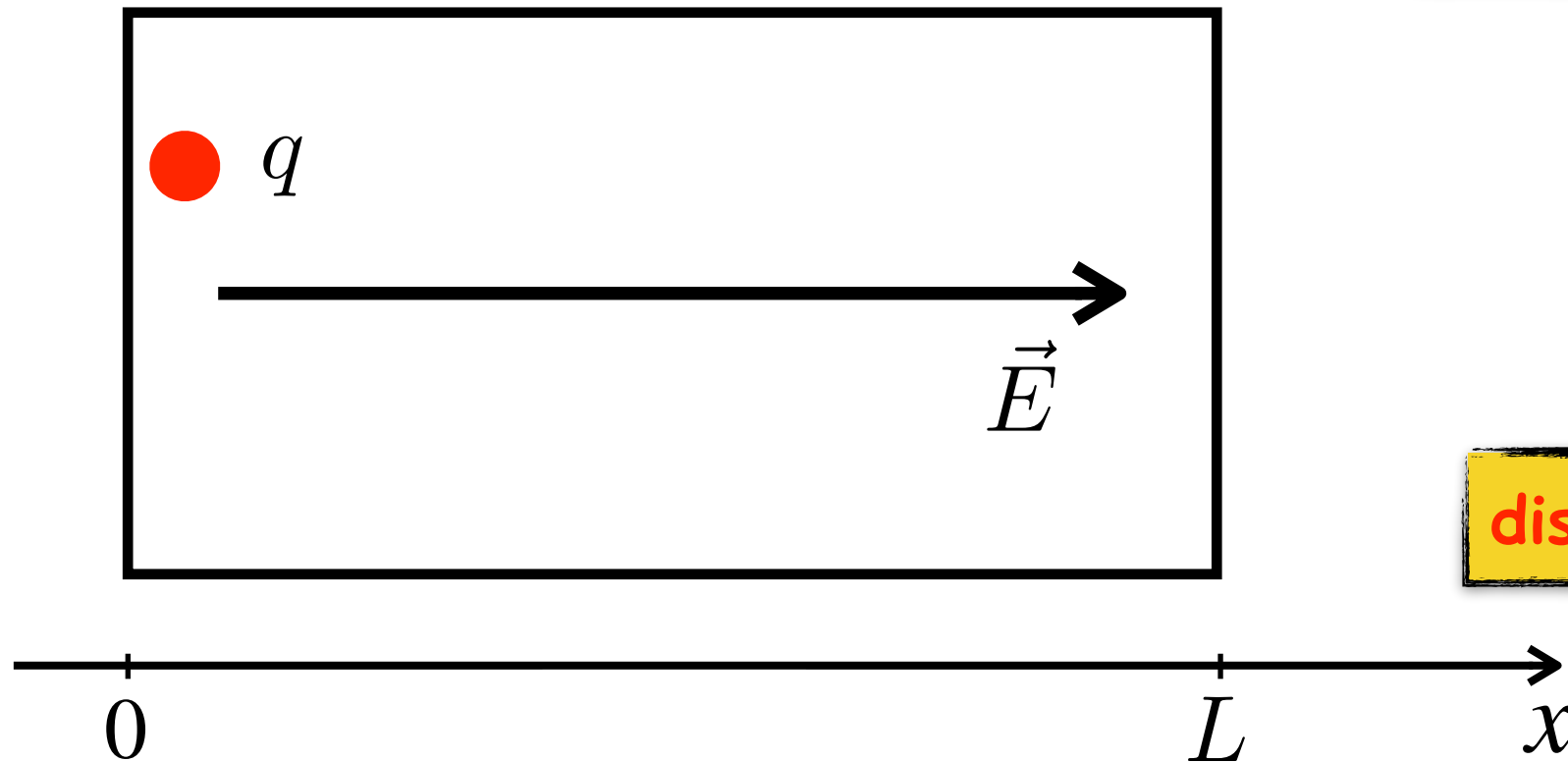
The simplest accelerator

this is an accelerator



The simplest accelerator

this is an accelerator



particle energy

$$\frac{d\mathcal{E}}{dx} = qE$$

displacement

electrostatic
force

The simplest accelerator

this is an accelerator

particle energy



$$\frac{d\mathcal{E}}{dx} = qE$$

displacement

electrostatic
force

$$\mathcal{E}_{max} = q E L$$

large
accelerator

large charge

strong E field

...because we deal with plasmas

to accelerate particles, you need an electric field

...because we deal with plasmas

to accelerate particles, you need an electric field

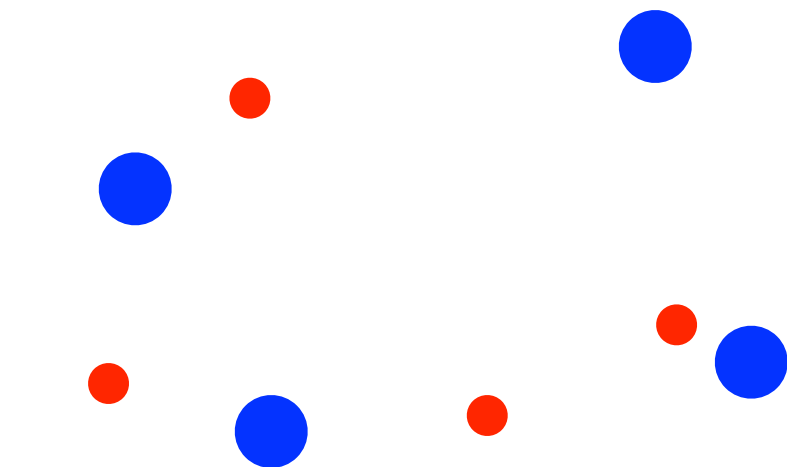
An excess of electrical charge is needed to maintain a static electric field. However we should remember...

"...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."

(Lyman Spitzer "Physics of fully ionised gases")

Quasi-neutrality

Each charge in a plasma is connected to any other charge through Coulomb interactions, which are long-range interactions (potential $\sim 1/R$).

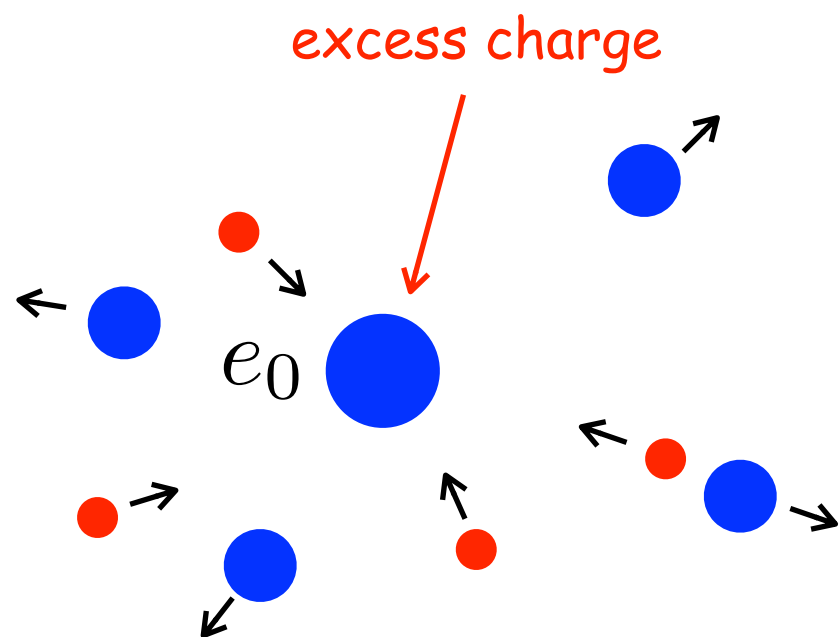


● protons
● electrons

} thermal equilibrium $T_e = T_p = T \rightarrow$ Boltzmann distribution

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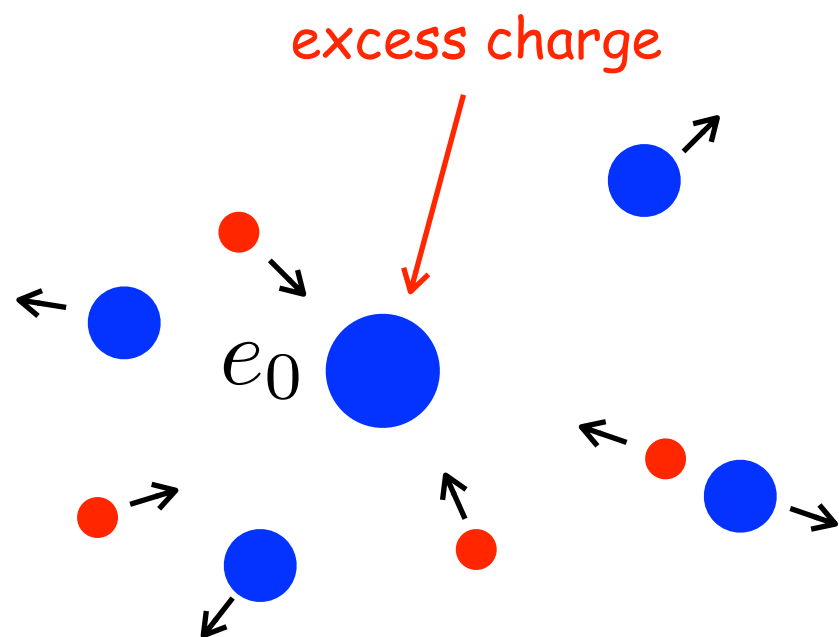
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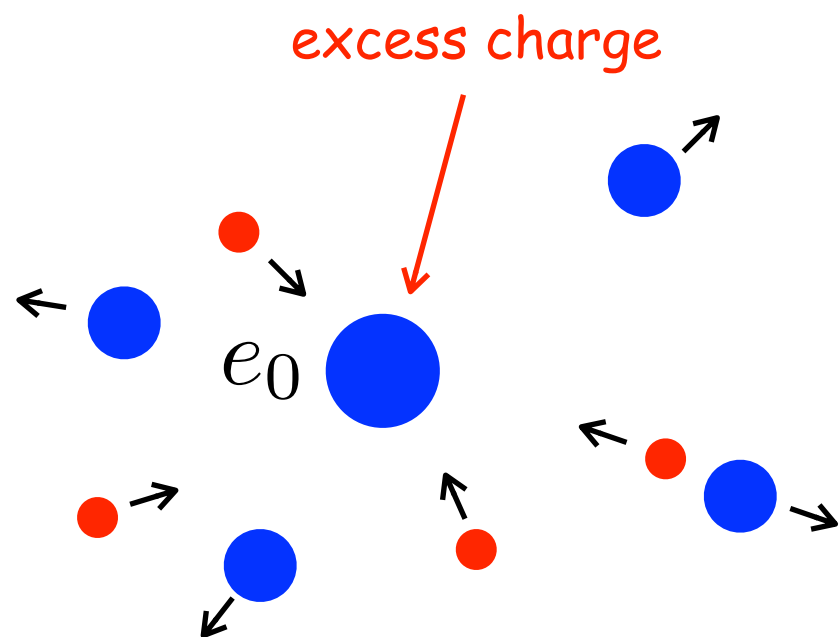
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$$\begin{cases} n_e = n_0 \exp \left[-\frac{(-e\phi)}{kT} \right] \\ n_i = n_0 \exp \left[-\frac{(e\phi)}{kT} \right] \end{cases}$$

● protons
● electrons

} thermal equilibrium $T_e = T_p = T \rightarrow$ Boltzmann distribution

Quasi-neutrality

$$\nabla^2 \phi = 4\pi n_0 e \left[\exp \left(\frac{e\phi}{kT} \right) - \exp \left(\frac{-e\phi}{kT} \right) \right] - 4\pi e_0 \delta(\vec{R})$$

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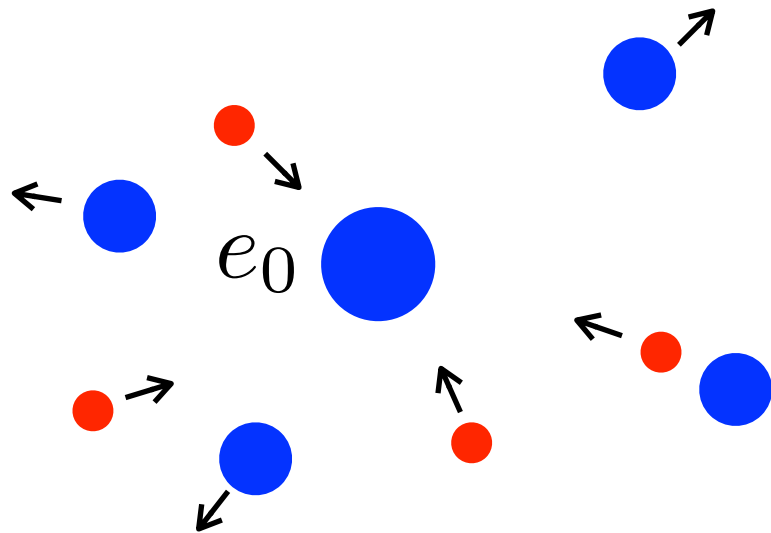
$$\nabla^2 \phi = 8\pi n_0 e \frac{e\phi}{kT} - 4\pi e_0 \delta(\vec{R})$$

$$\frac{1}{R^2} \frac{d}{dR} \left(R^2 \frac{d\phi}{dR} \right) = 8\pi n_0 e \frac{e\phi}{kT} - 4\pi e_0 \delta(\vec{R})$$

$$= \frac{\phi}{\lambda^2} - 4\pi e_0 \delta(\vec{R})$$

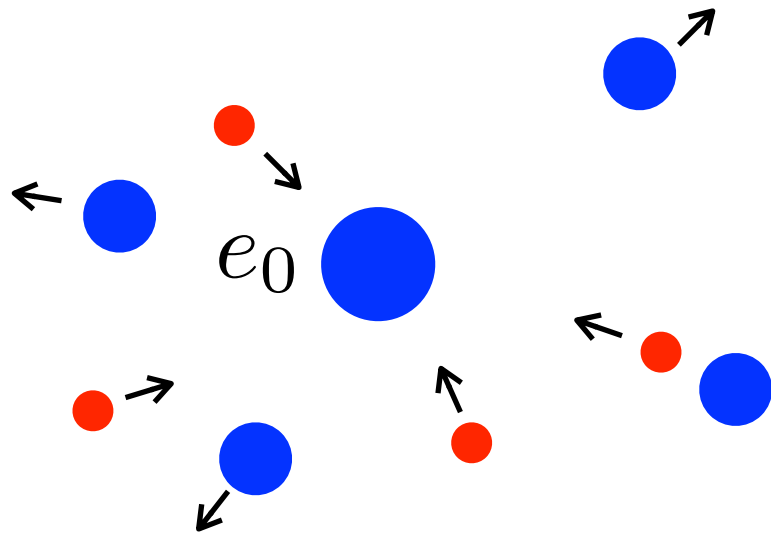
$$\lambda = \left(\frac{kT}{8\pi n_0 e^2} \right)^{1/2}$$

Quasi-neutrality: Debye length



$$\phi = \frac{e_0}{R} e^{-\frac{R}{\lambda}}$$

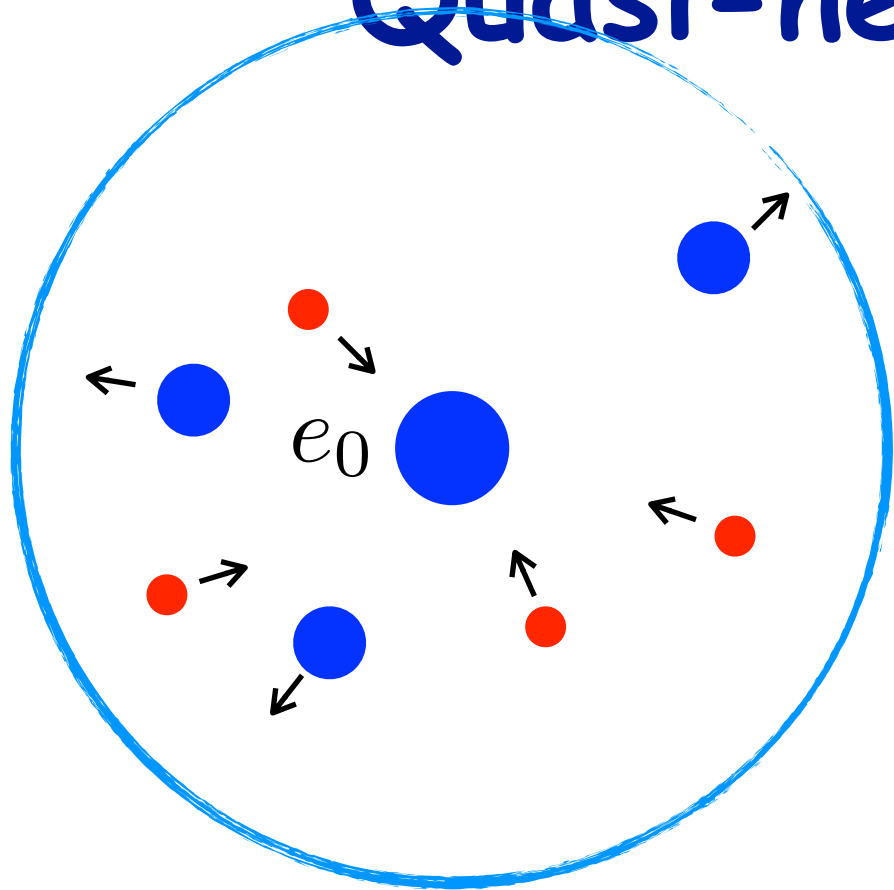
Quasi-neutrality: Debye length



$$\phi = \left[\frac{e_0}{R} \right] e^{-\frac{R}{\lambda}}$$

Coulomb potential

Quasi-neutrality: Debye length

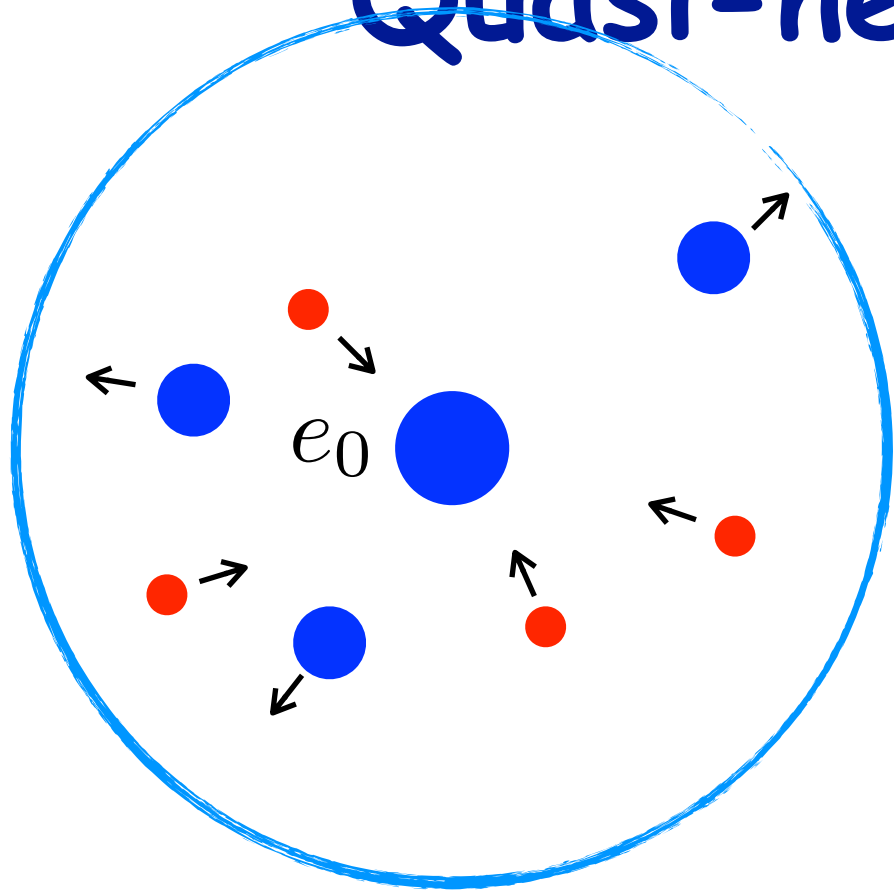


$$\phi = \frac{e_0}{R} e^{-\frac{R}{\lambda}}$$

screened!

Coulomb potential

Quasi-neutrality: Debye length



$$\phi = \frac{e_0}{R} e^{-\frac{R}{\lambda}}$$

screened!

Coulomb potential

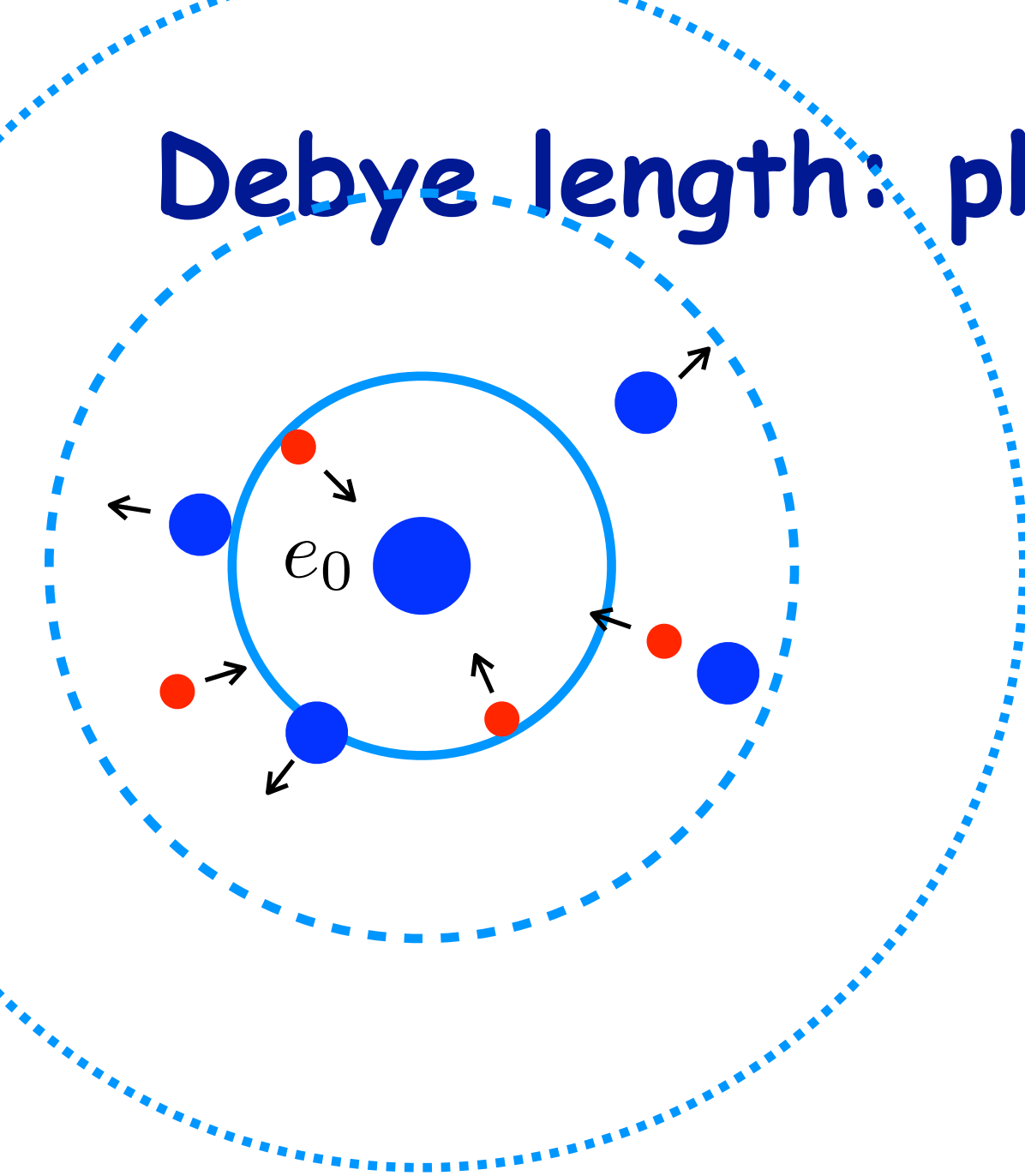
Excess charges are screened on a scale called Debye length

$$\lambda = \left(\frac{kT}{8\pi n_0 e^2} \right)^{1/2} \sim 5 \times 10^2 \left(\frac{T}{10^4 \text{ K}} \right)^{1/2} \left(\frac{n_0}{\text{cm}^{-3}} \right)^{-1/2} \text{ cm}$$

↑
extremely small!

it does NOT depend on
the charge excess!

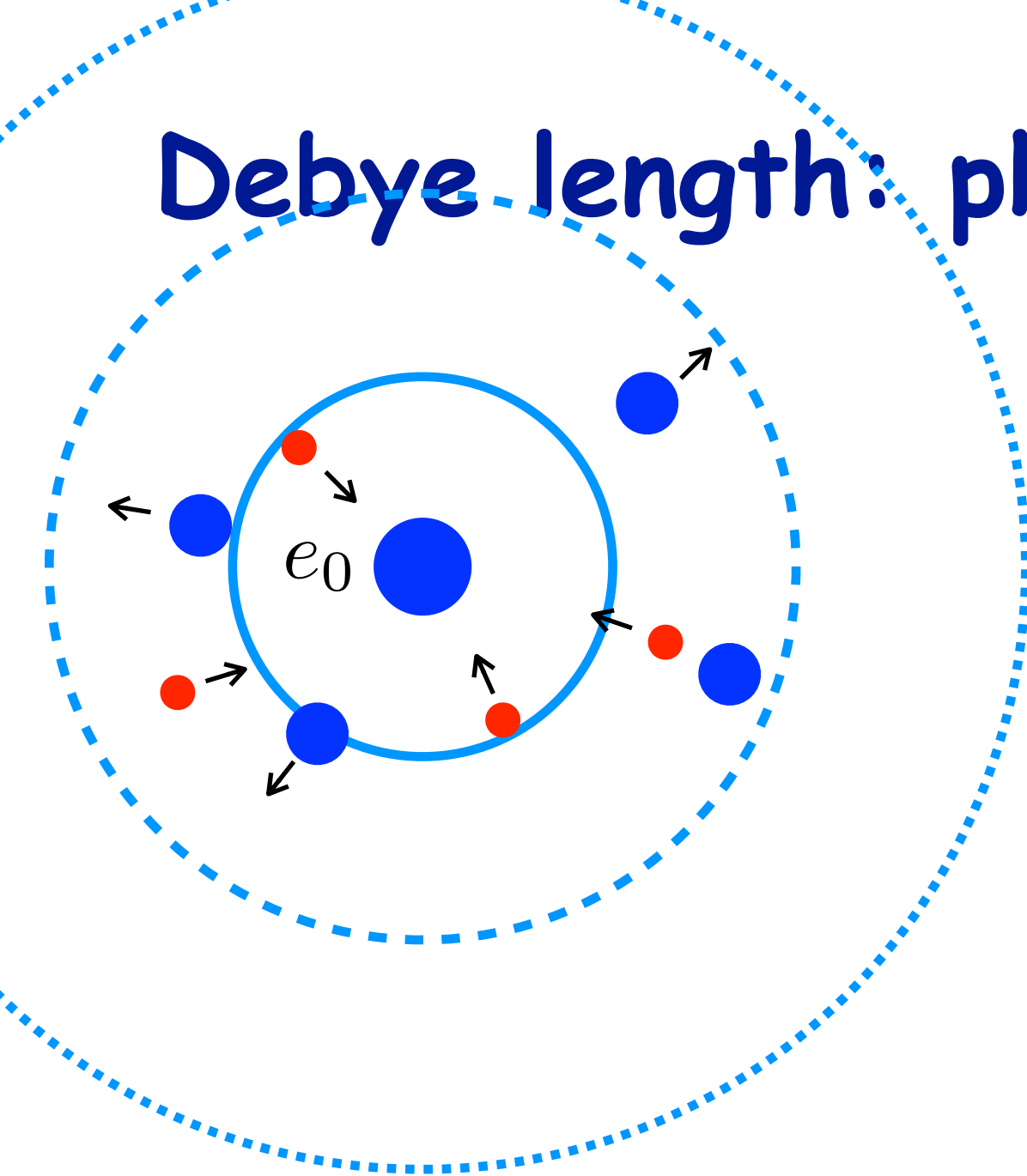
Debye length: physical interpretation



Let's compute the net charge
within a distance R from e_0

$$Q(R) = 4\pi \int_0^R dR R^2 \varrho(R)$$

Debye length: physical interpretation

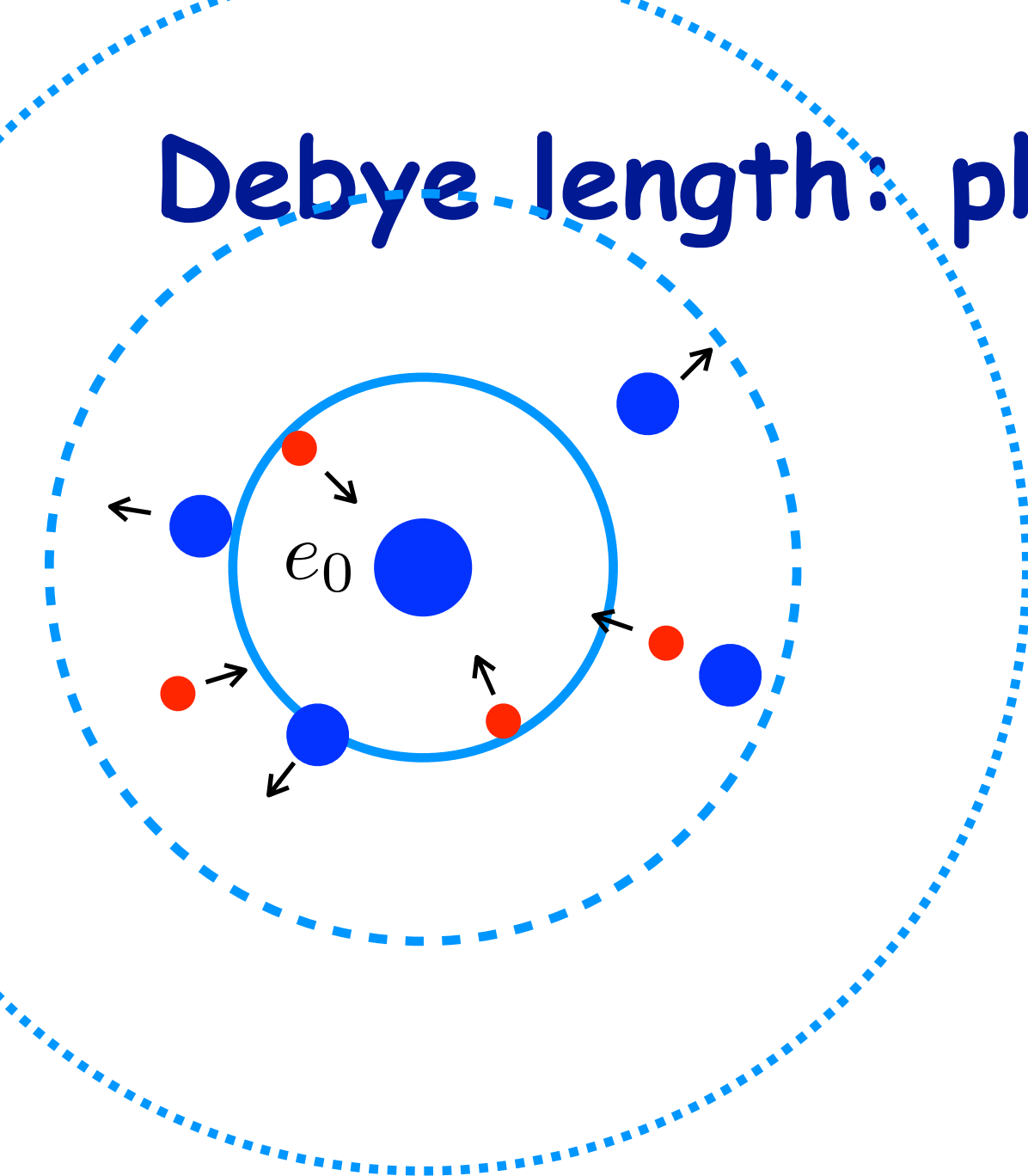


Let's compute the net charge within a distance R from e_0

$$\begin{aligned} Q(R) &= 4\pi \int_0^R dR \, R^2 \varrho(R) = \\ &= - \int_0^R dR \left(\frac{R}{\lambda} \right)^2 \phi + e_0 \end{aligned}$$

$$\nabla^2 \phi = -4\pi \varrho = \frac{\phi}{\lambda^2} - 4\pi e_0 \delta(\vec{R})$$

Debye length: physical interpretation



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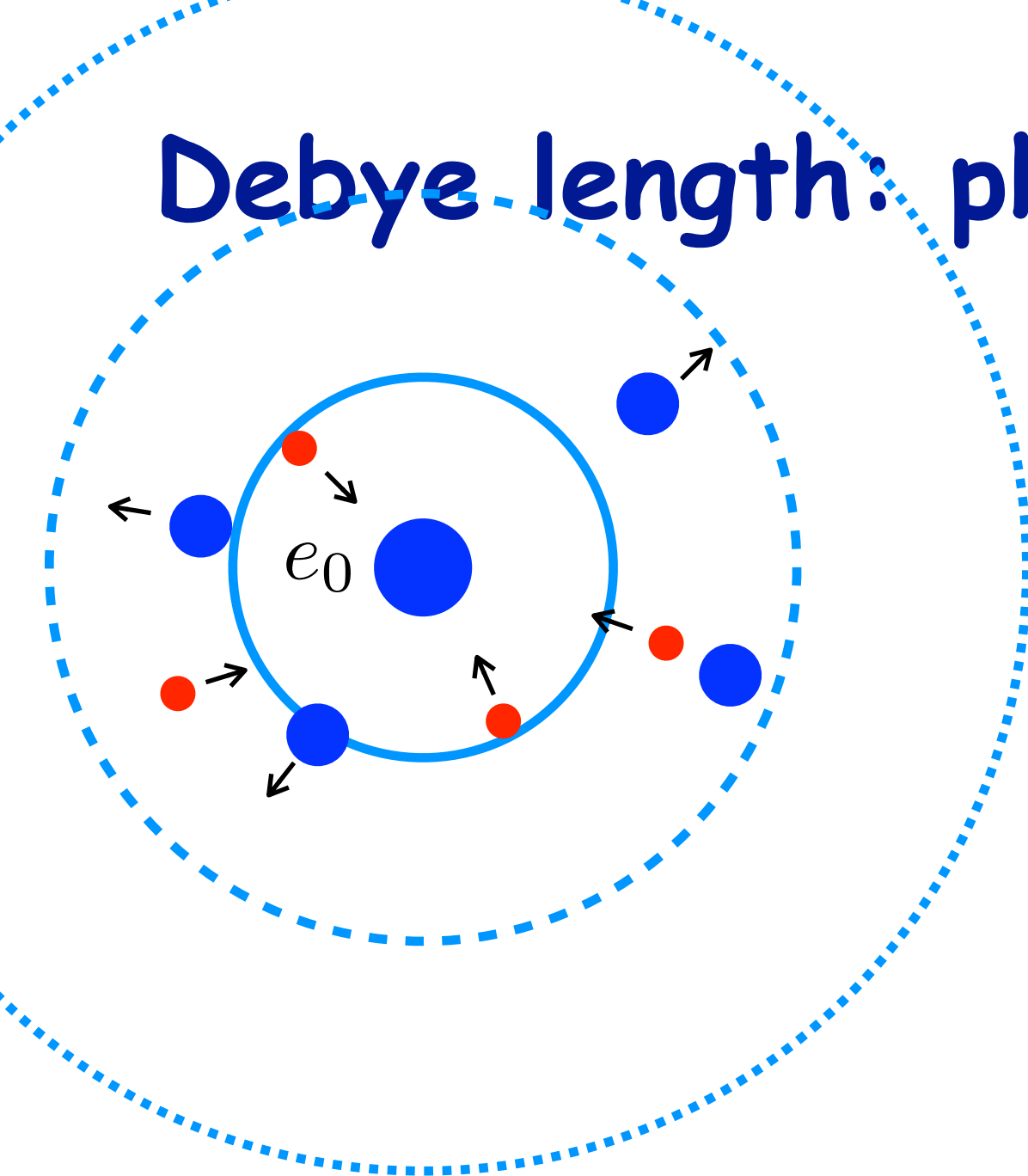
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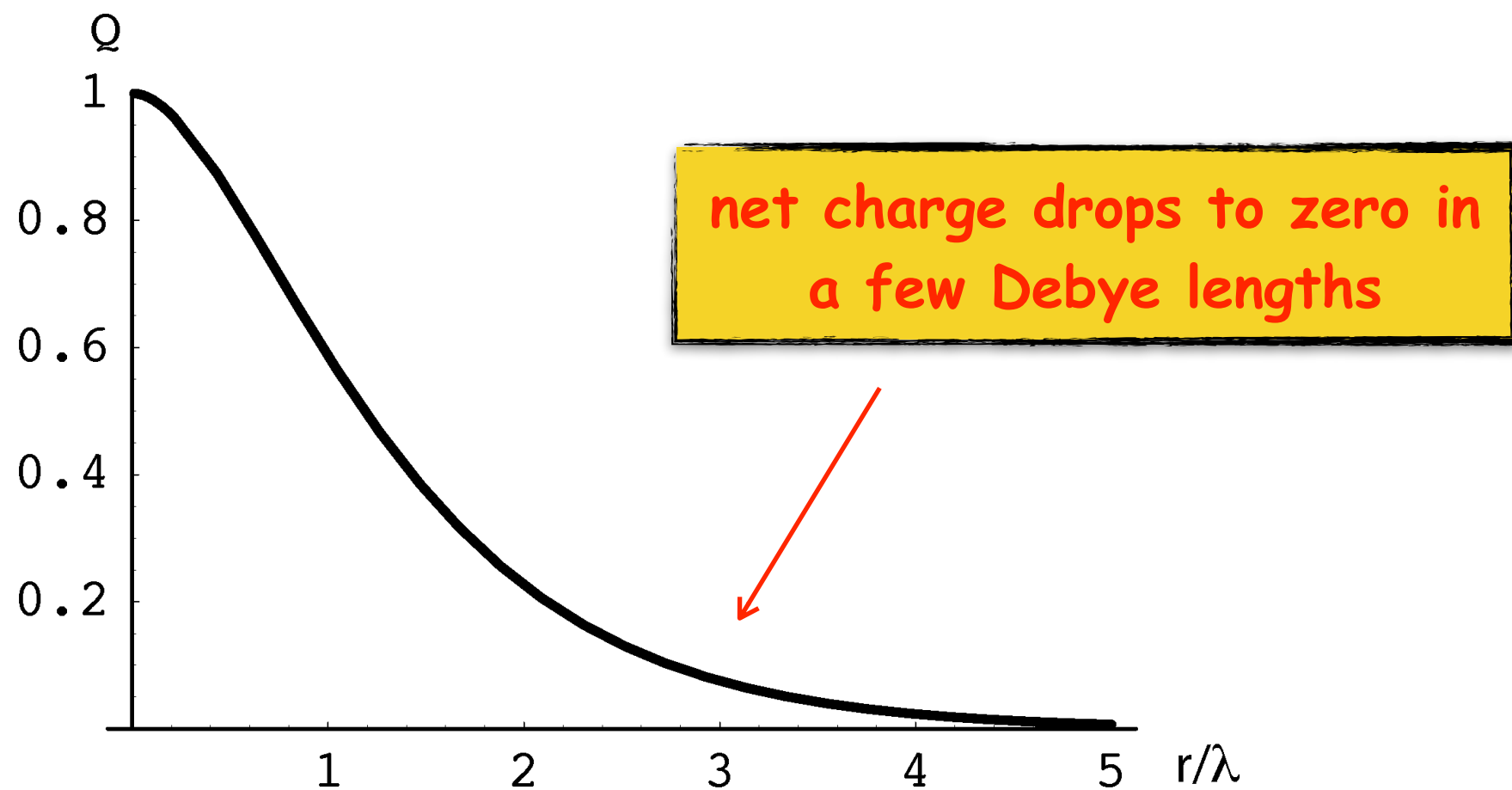
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$$= \text{integration per parts...} =$$

Debye length: physical interpretation

$$Q(R) = e_0 \left(1 + \frac{R}{\lambda} \right) e^{-\frac{R}{\lambda}}$$



How long it takes?

continuity equation (charge) $\rightarrow$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \vec{j} = 0$$

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time it takes to
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very fast! $\rightarrow$ 0.01-1 yr !

So? How are particles
accelerated if $E = 0$?

