Cosmic rays [old stuff]

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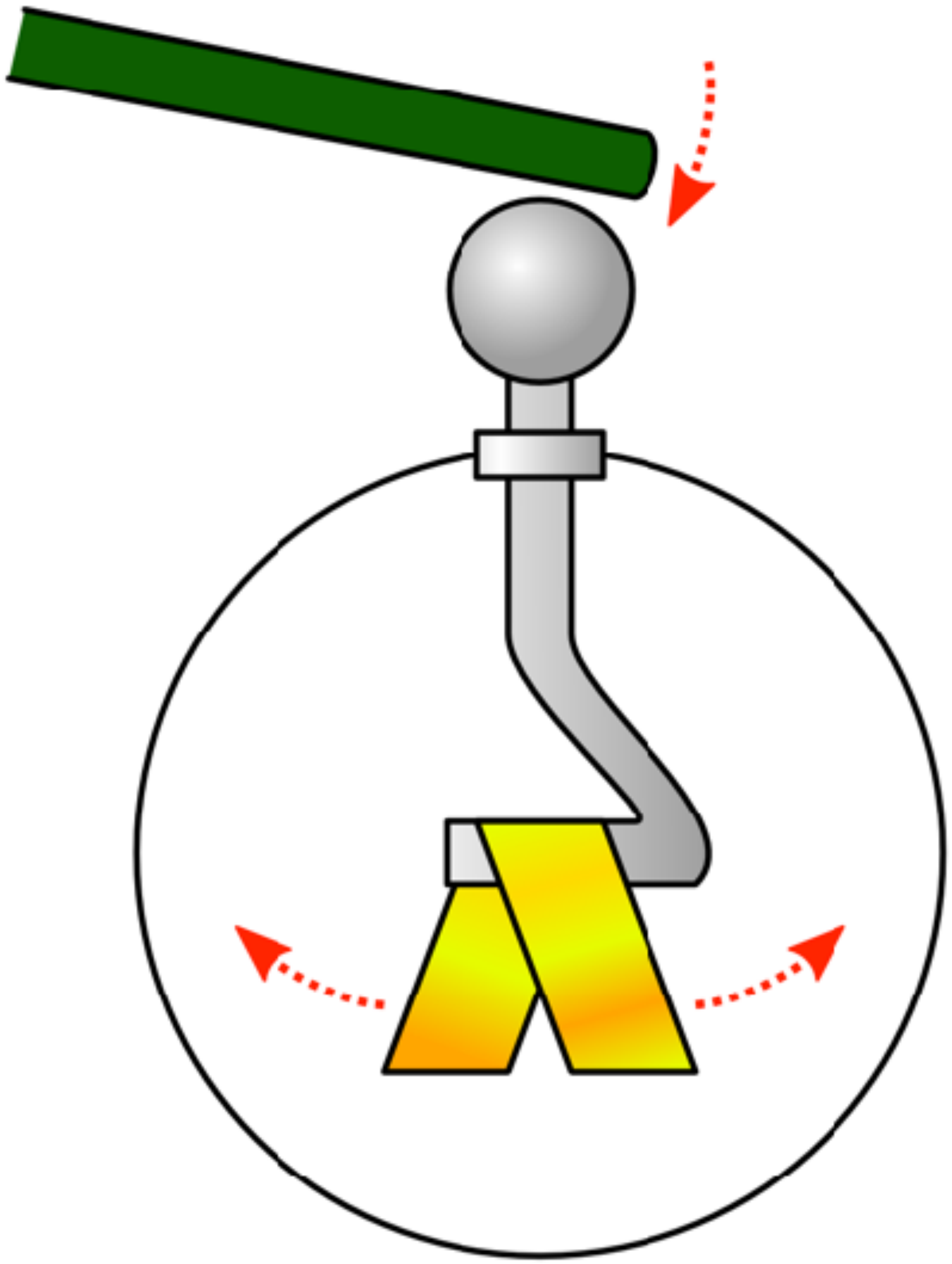
[1] History

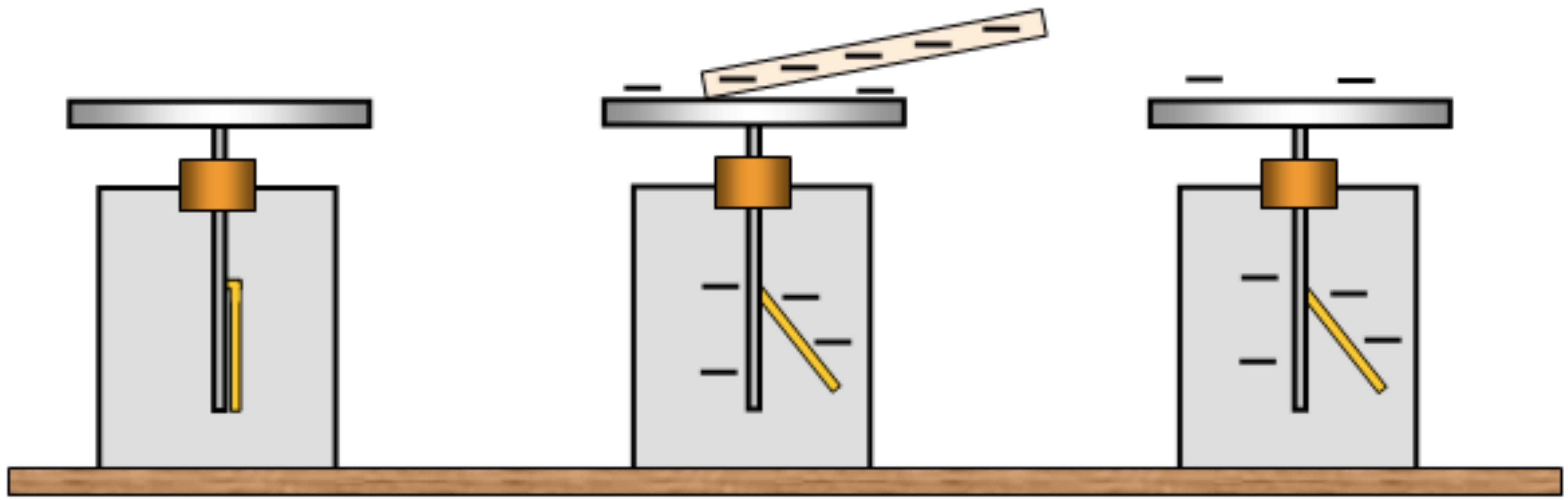
The electroscope

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

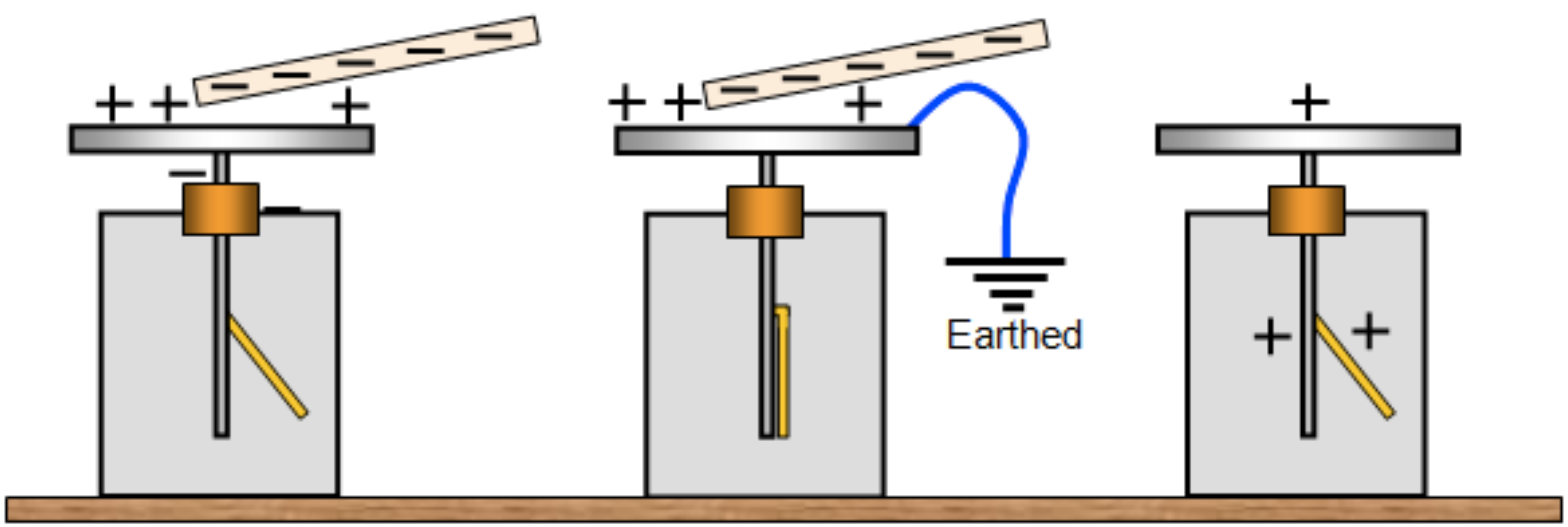


ELECTROSCOPE

How does it work



Charging by contact

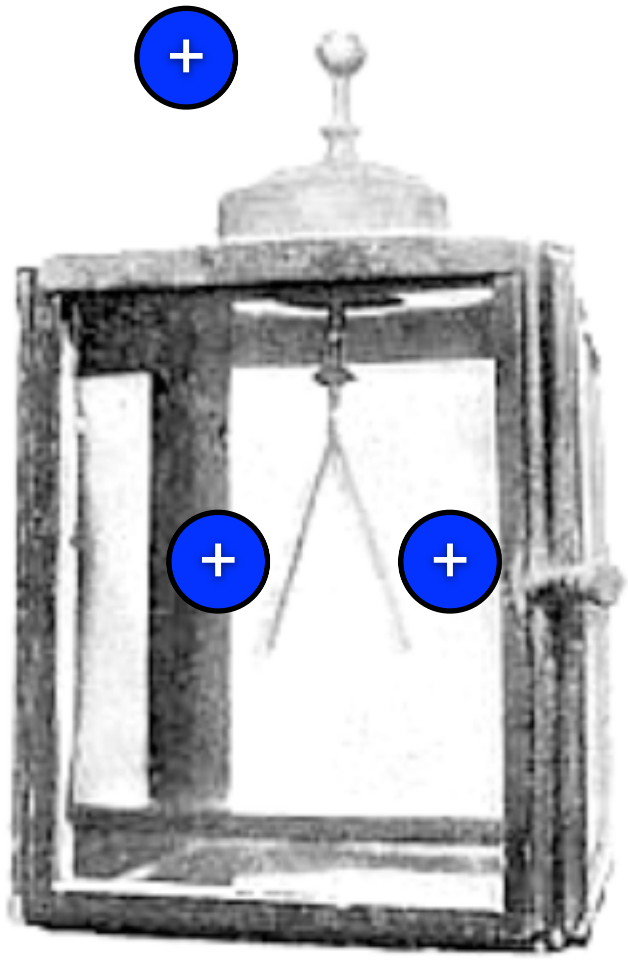


Charging by induction

The problem...

- in **1785 Coulomb** noted that charged electroscopes 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 Bequerel** discovers **radioactivity**

Radioactivity from the Earth



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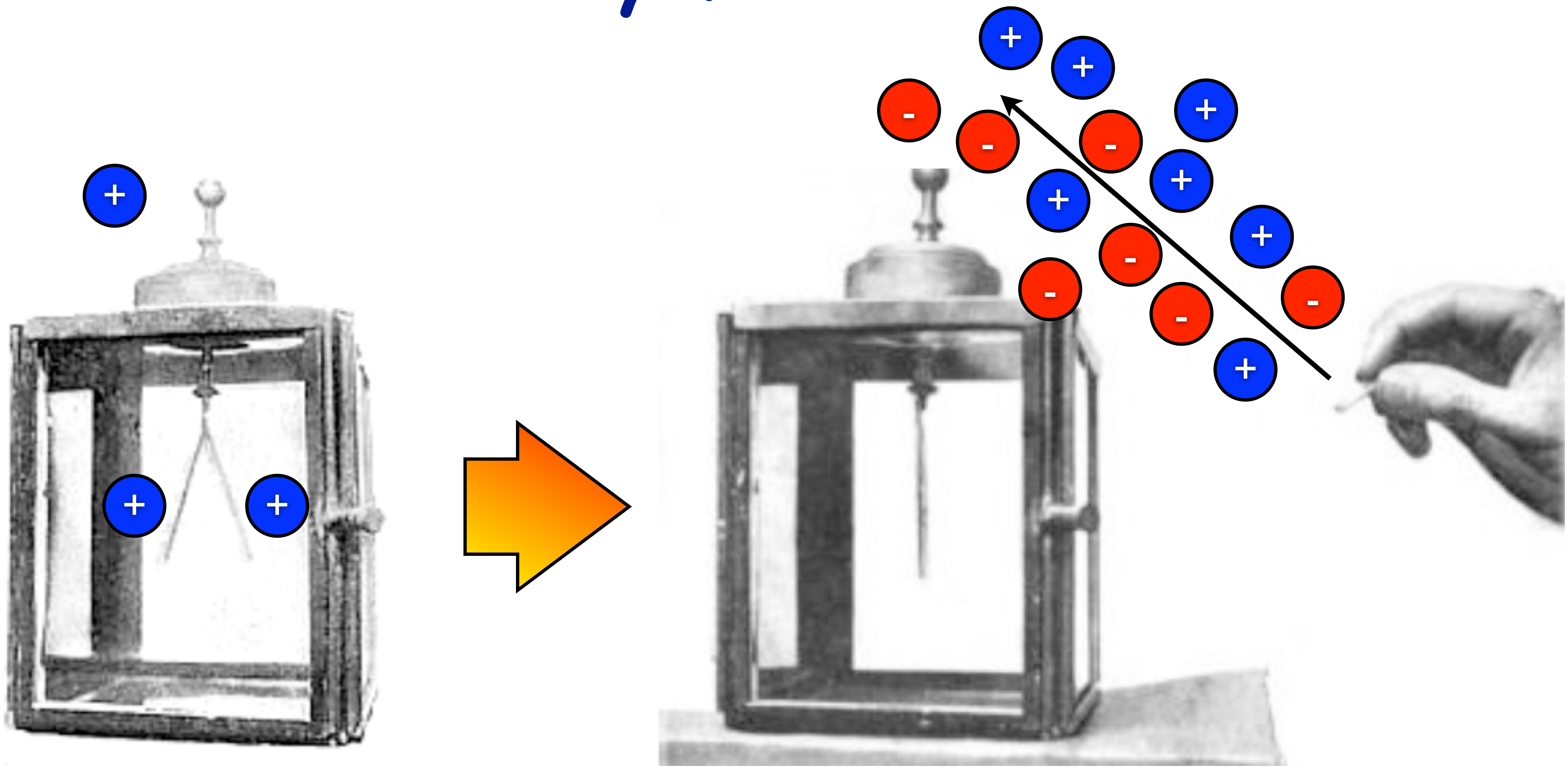

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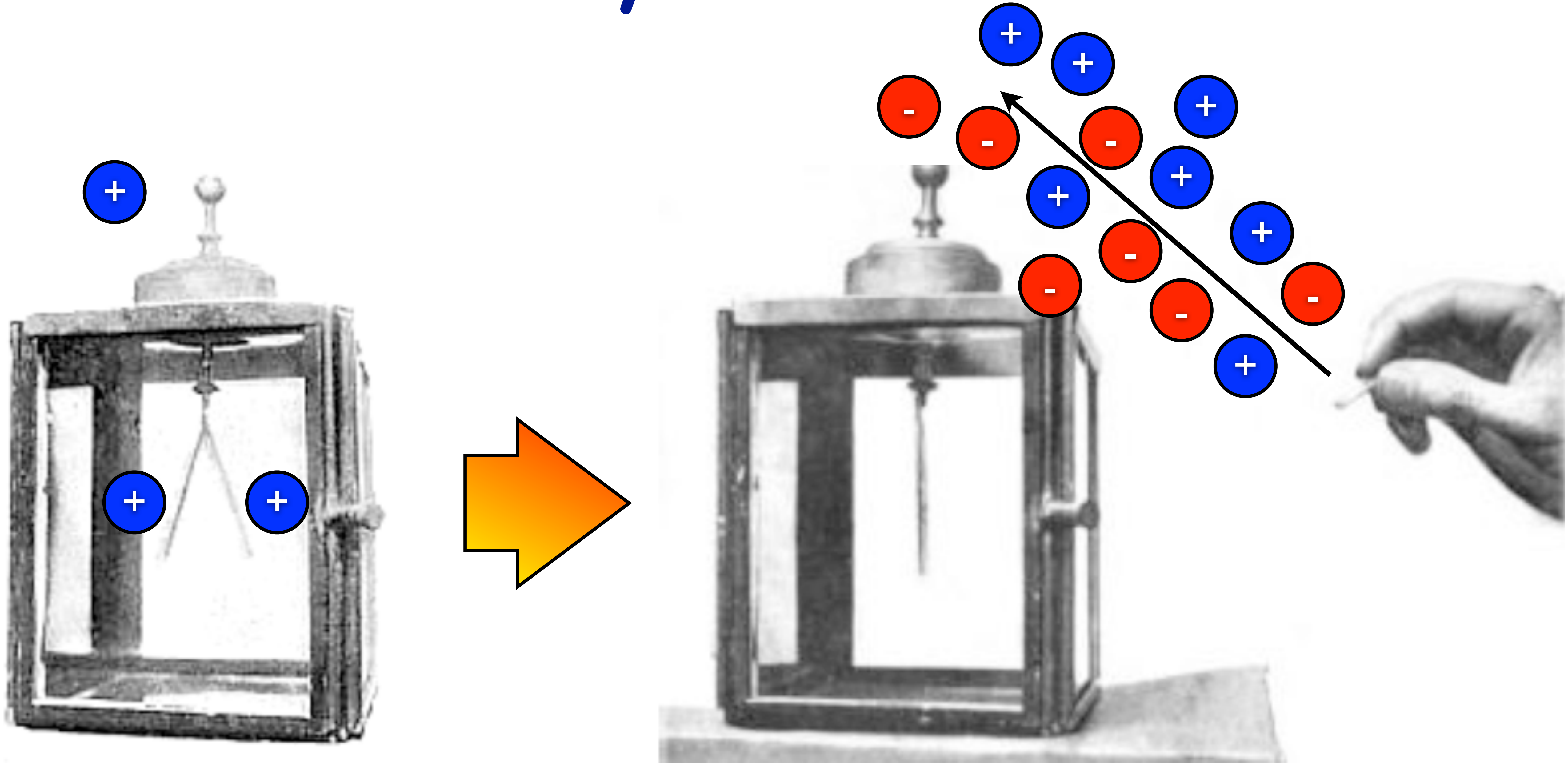

hypothesis: the Earth's crust contains radioactive isotopes (natural radioactivity) -> this might be the source of the ionizing radiation needed to explain the spontaneous discharge of electroscopes.

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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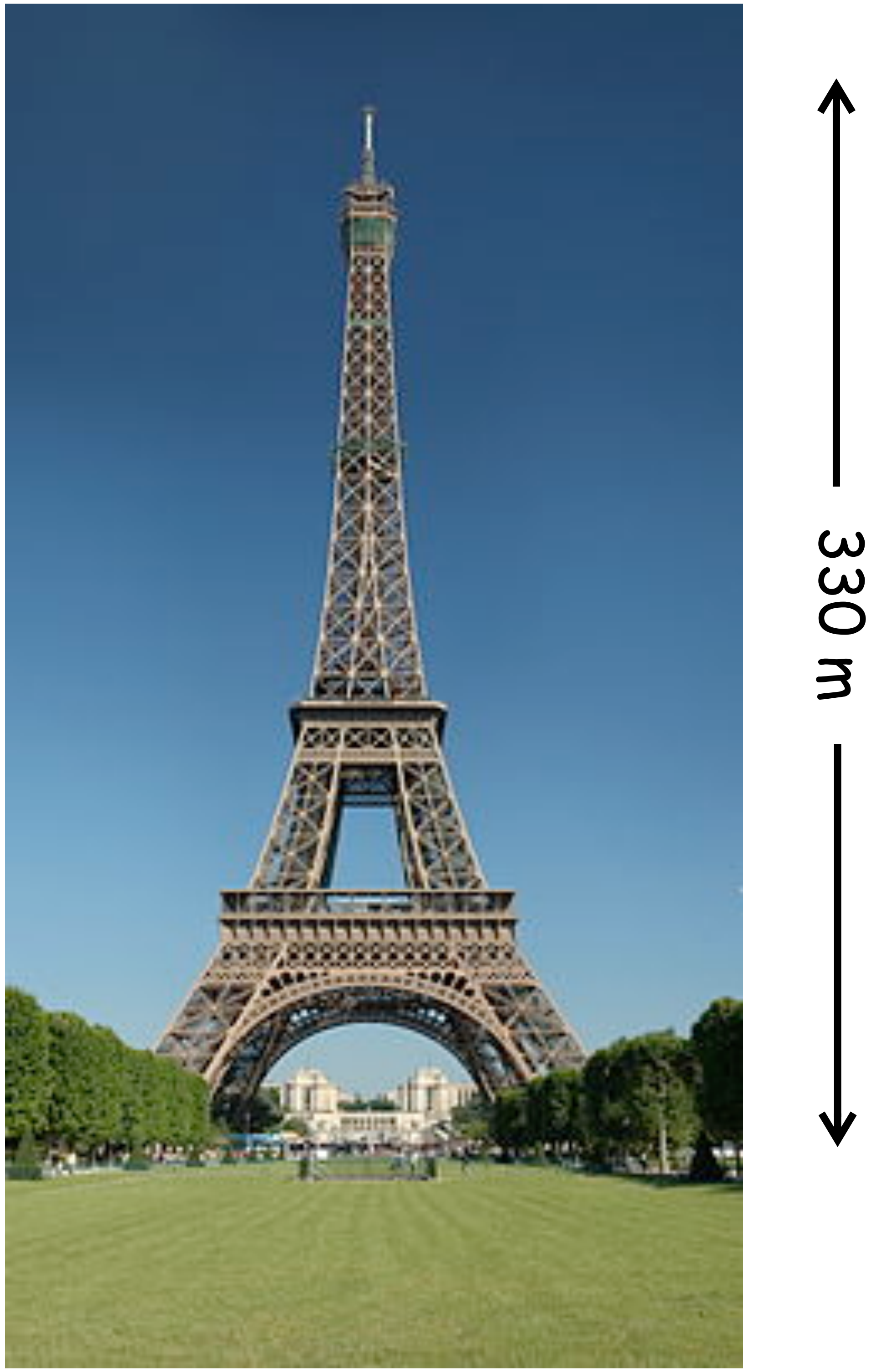
- in **1910** spends his Easter holidays in Paris, where he brings his electroscopes to measure the discharge time at the top and at the bottom of the Eiffel tower, during the day and during the night (the sun?);



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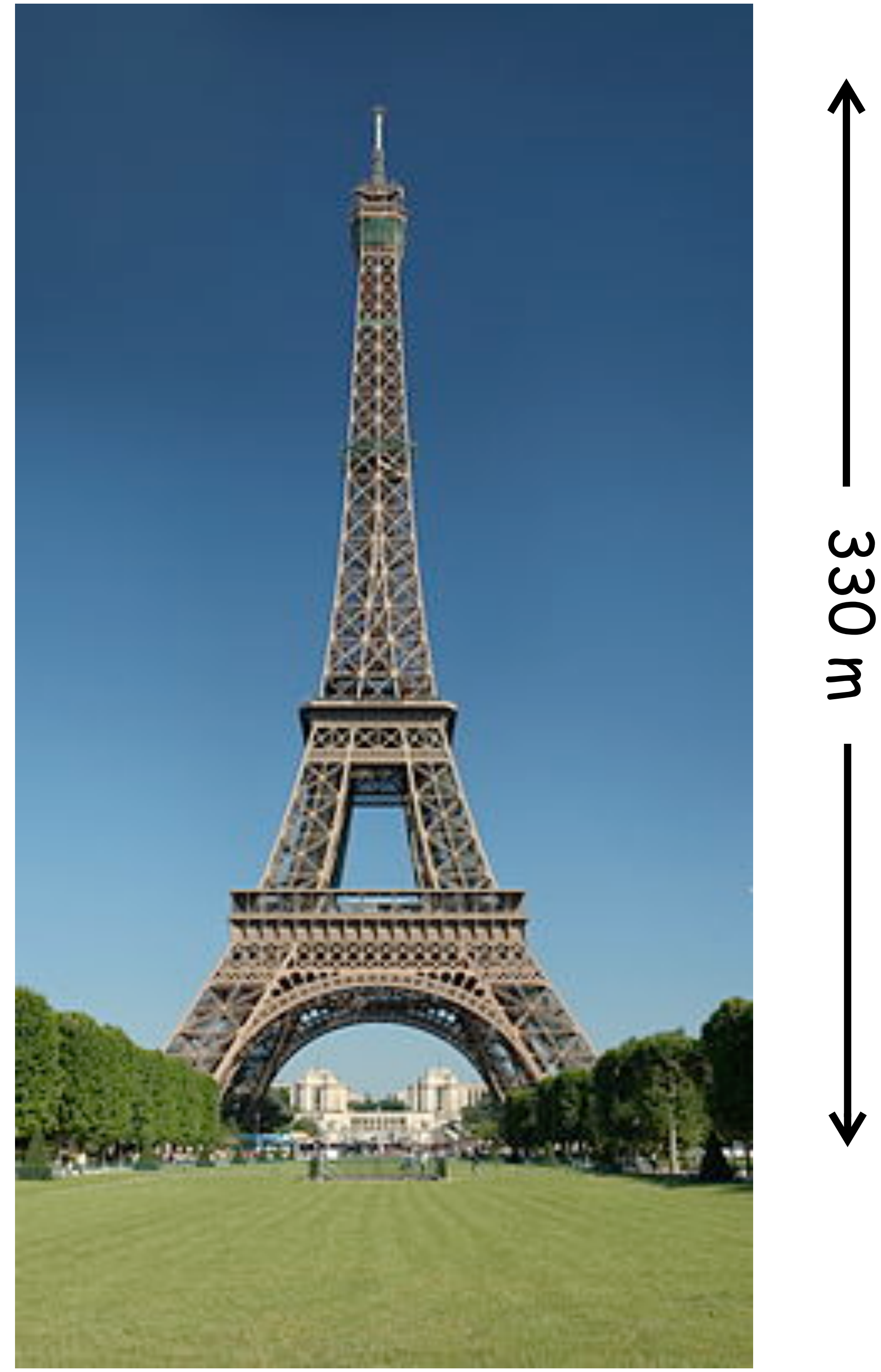
31. "	" "	14,4
1. April	" "	15,0
2. "	" "	17,2
3. "	" Boden	18,3
4. "	Valkenburg	22,0



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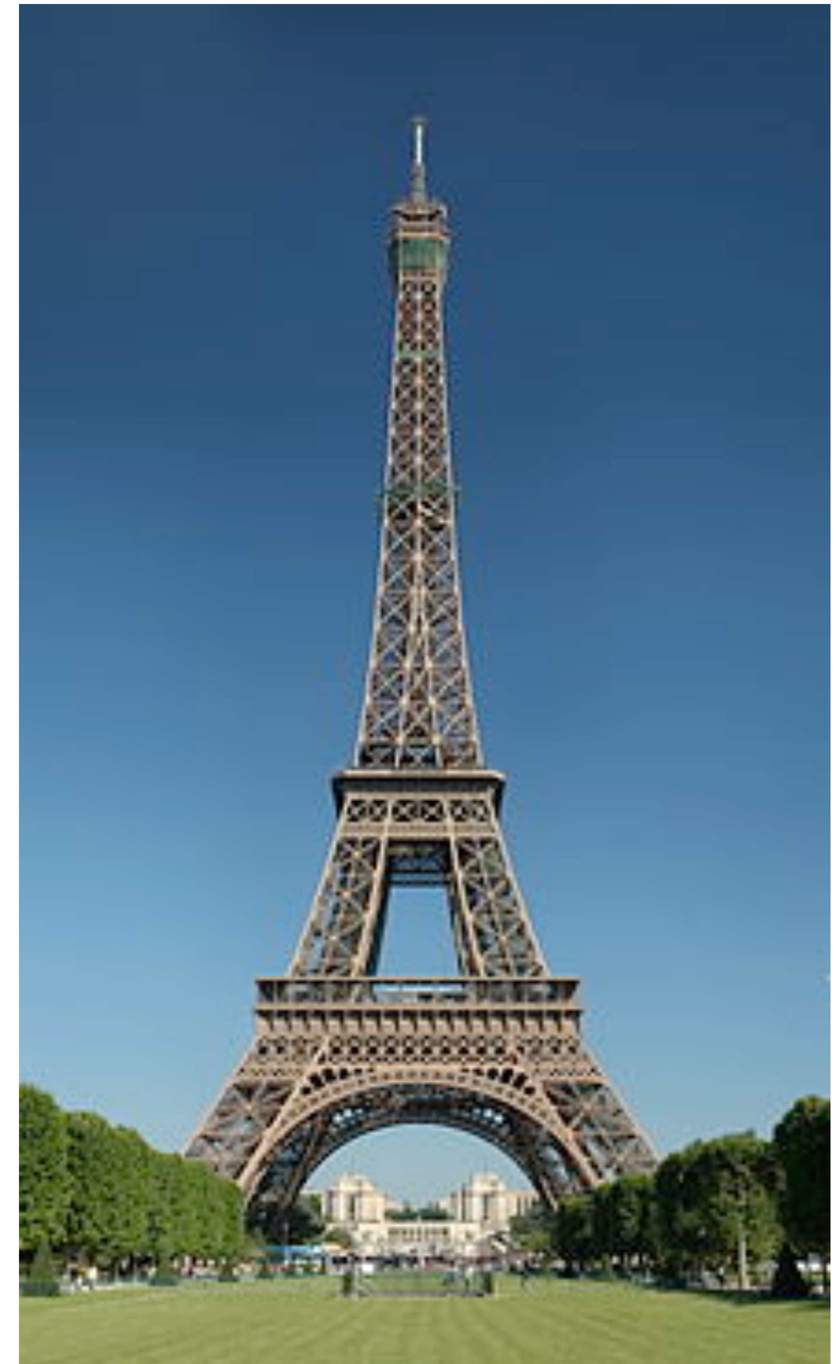

330 m

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
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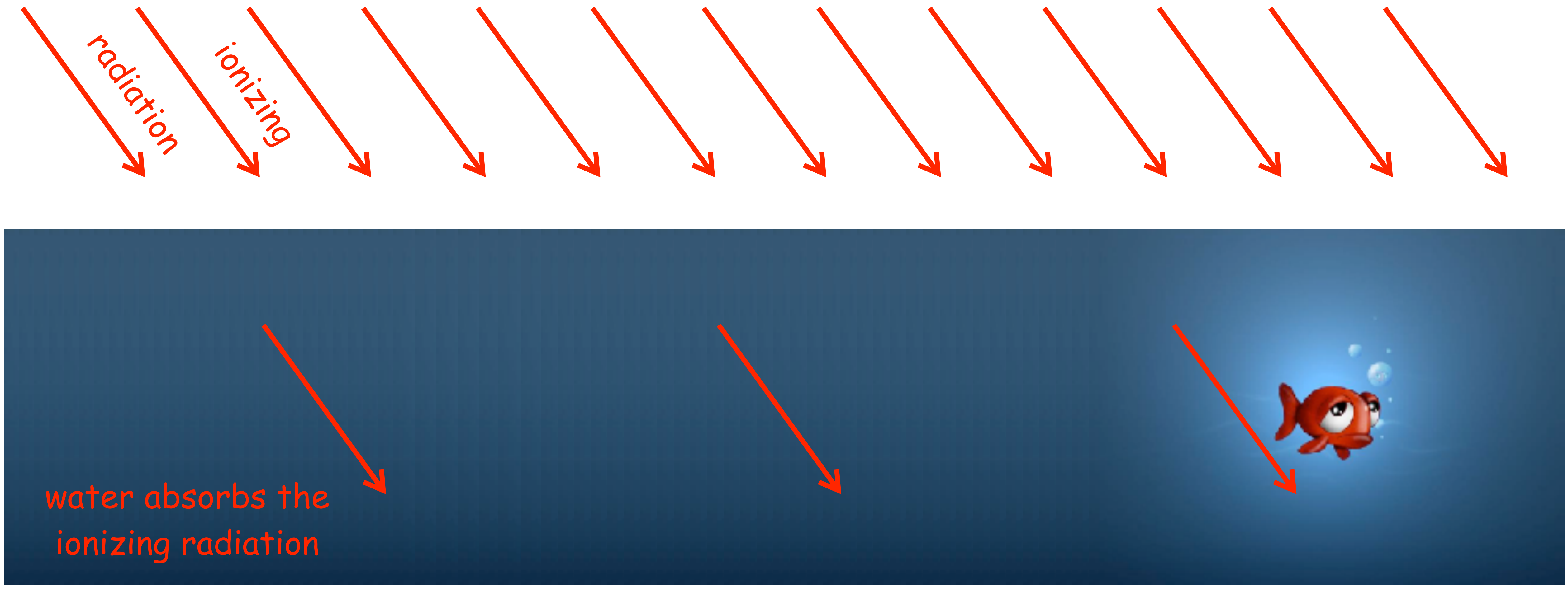
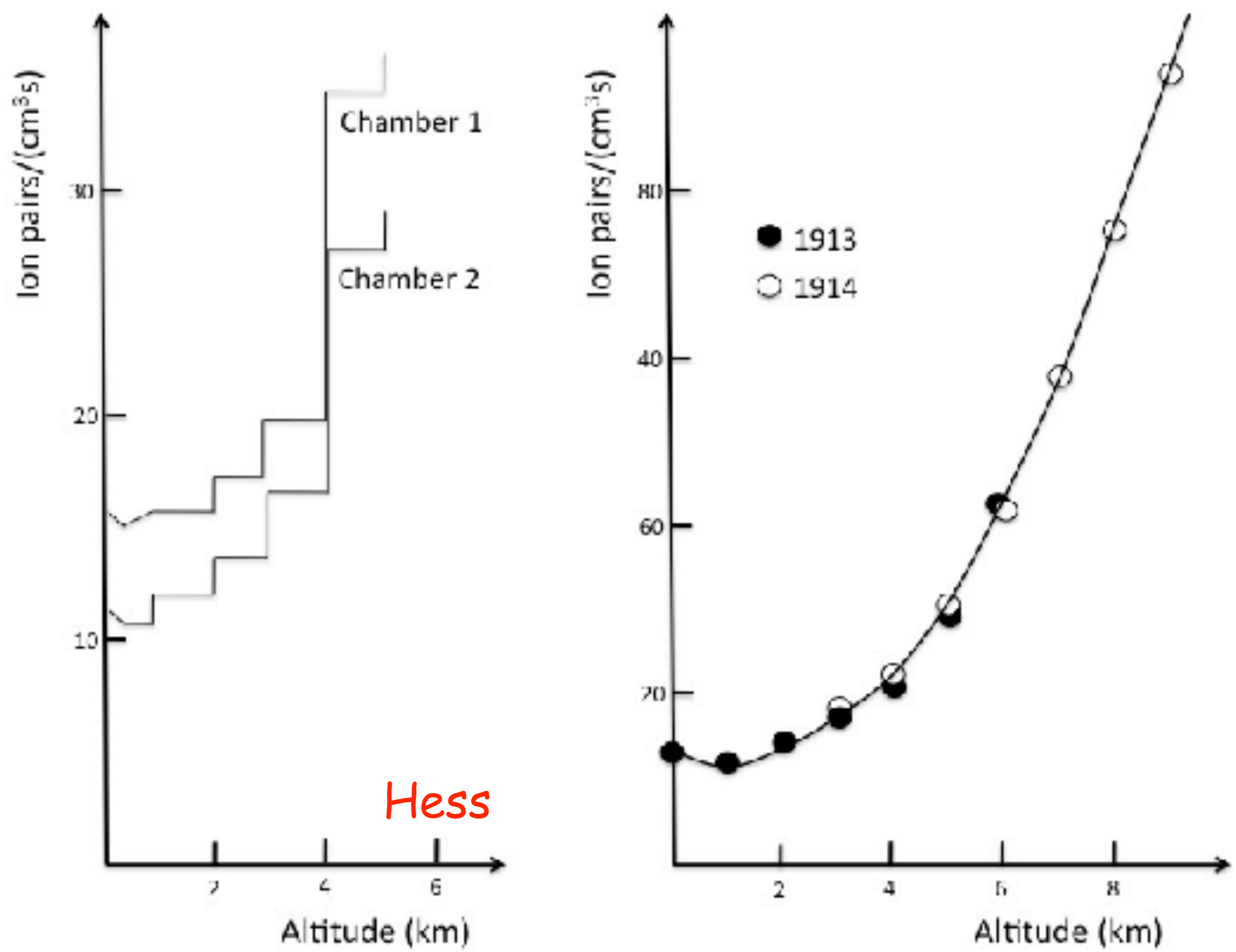


Which is the nature of the ionizing radiation in the atmosphere?

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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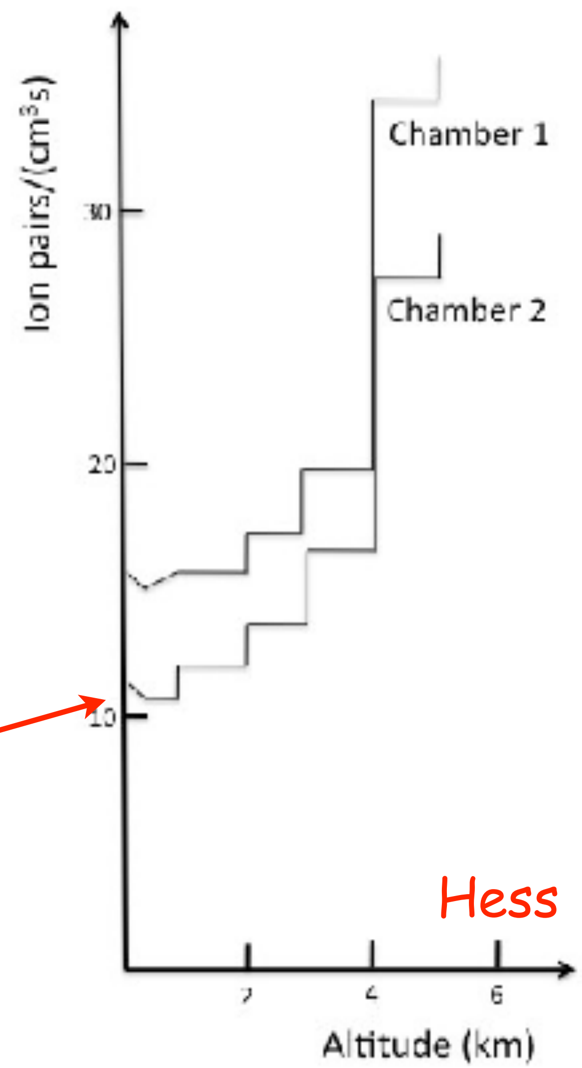

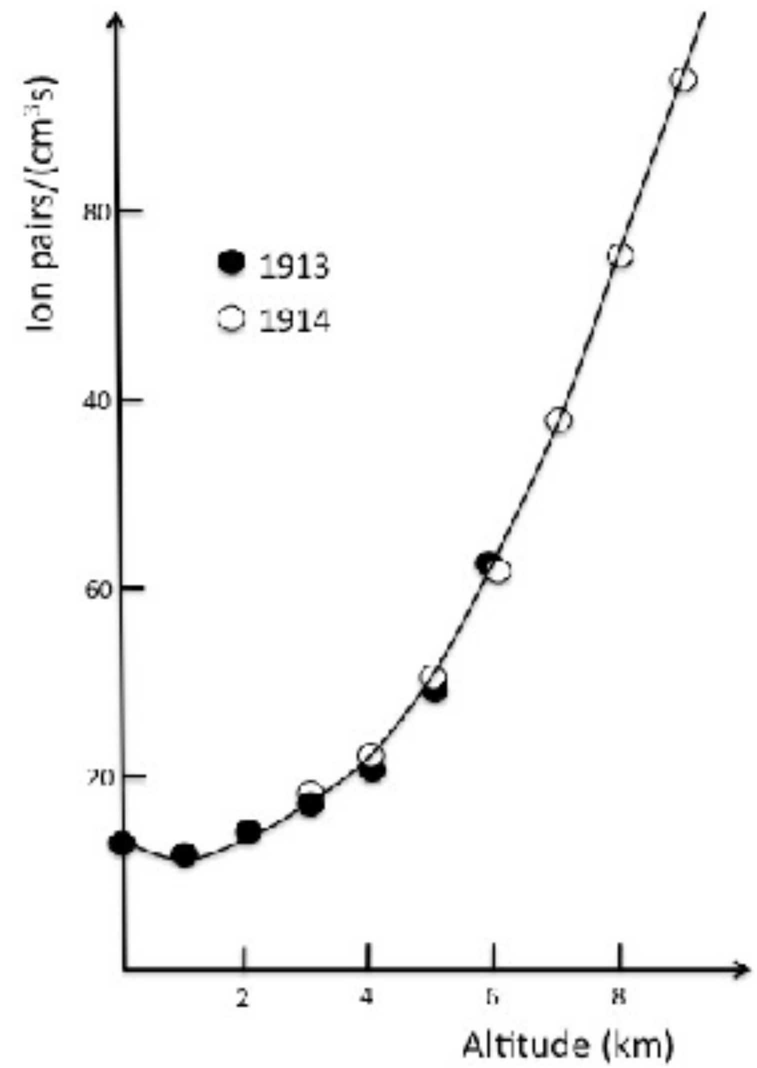

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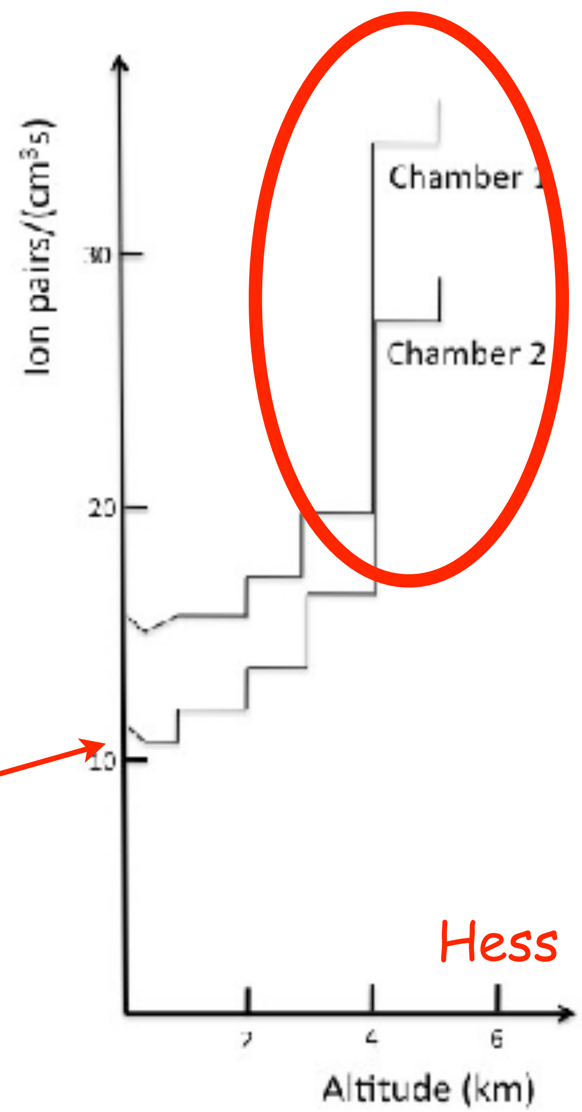

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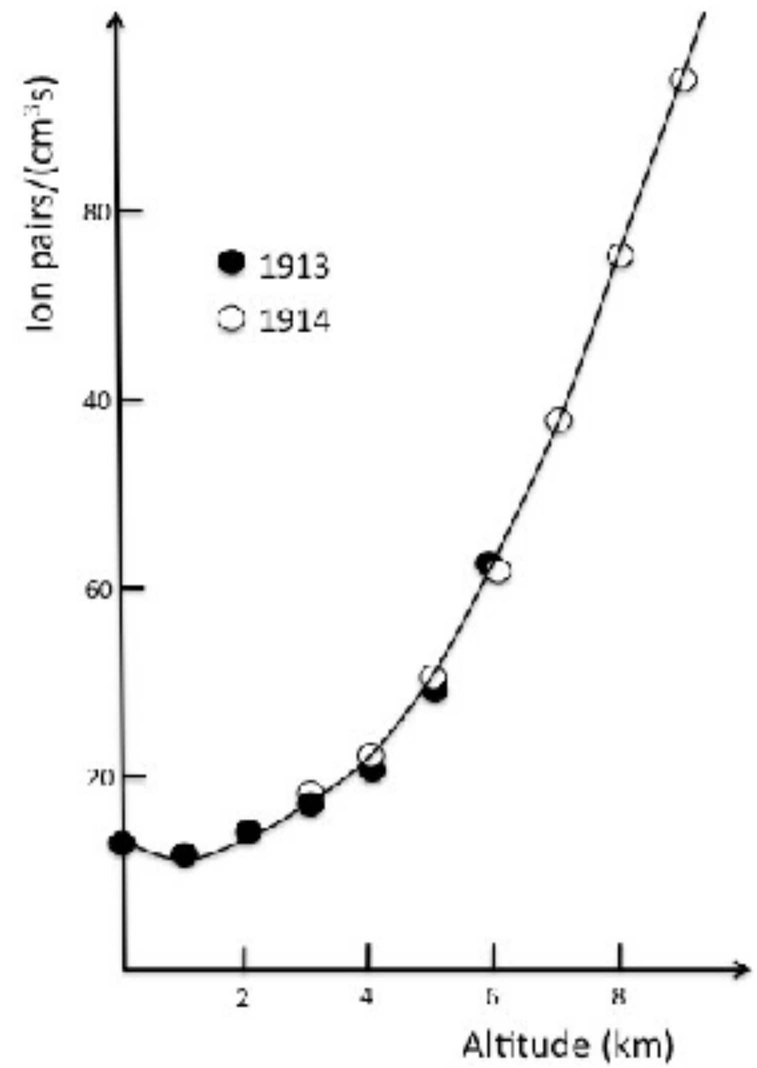

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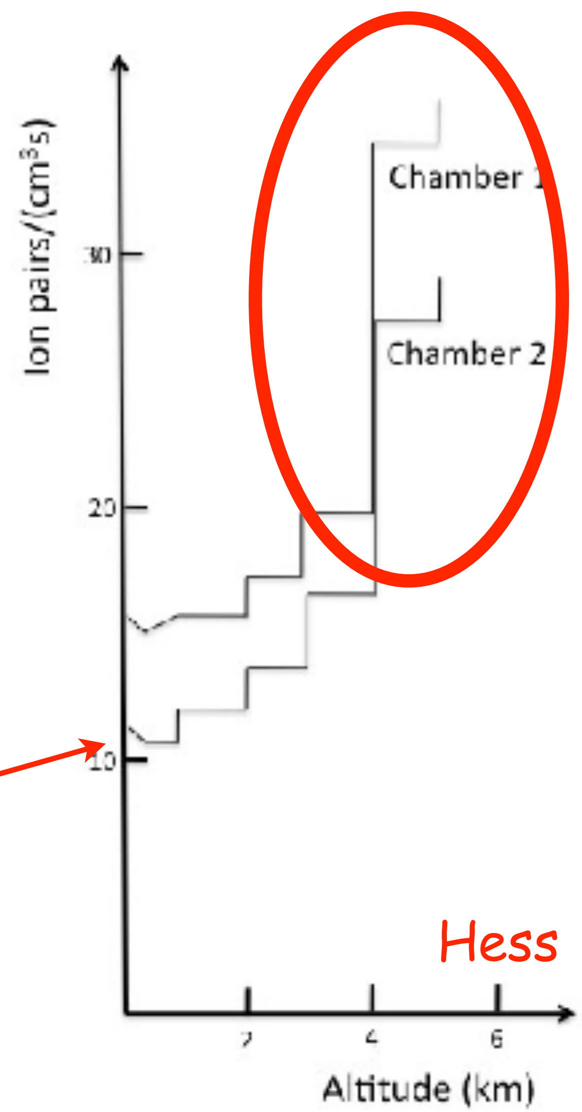

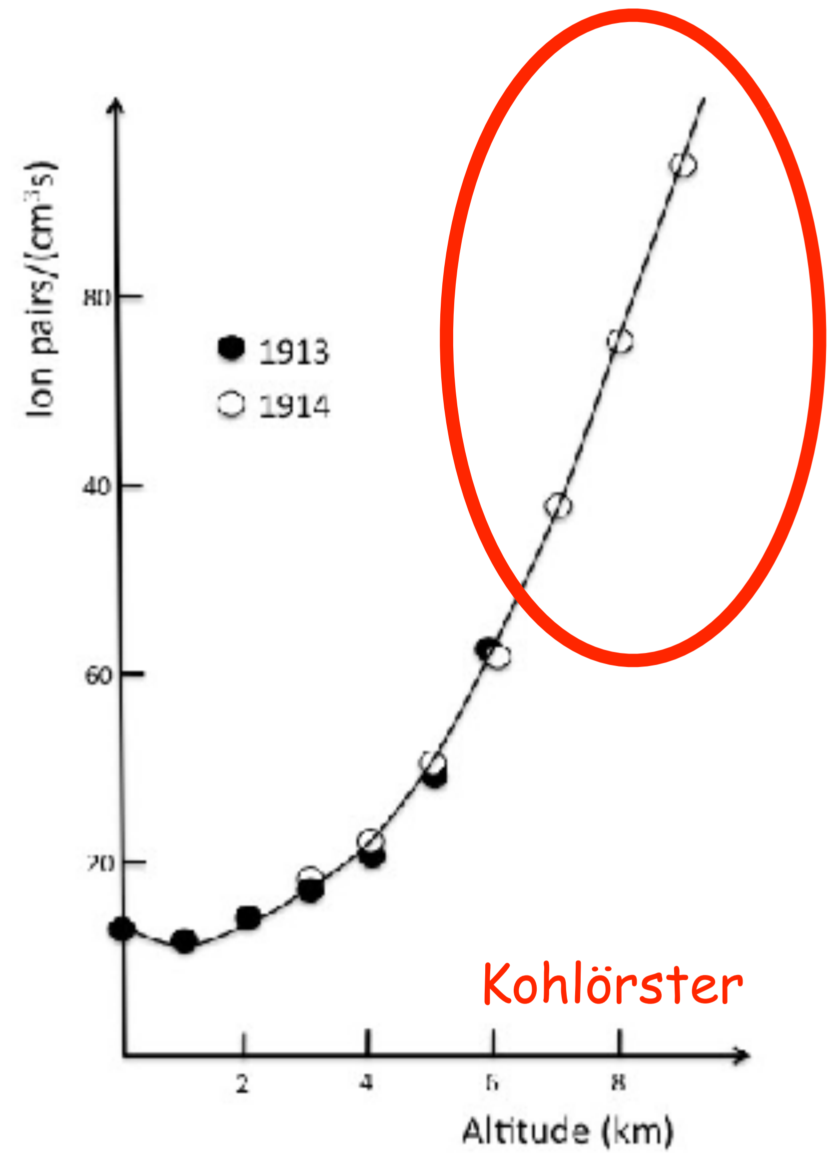

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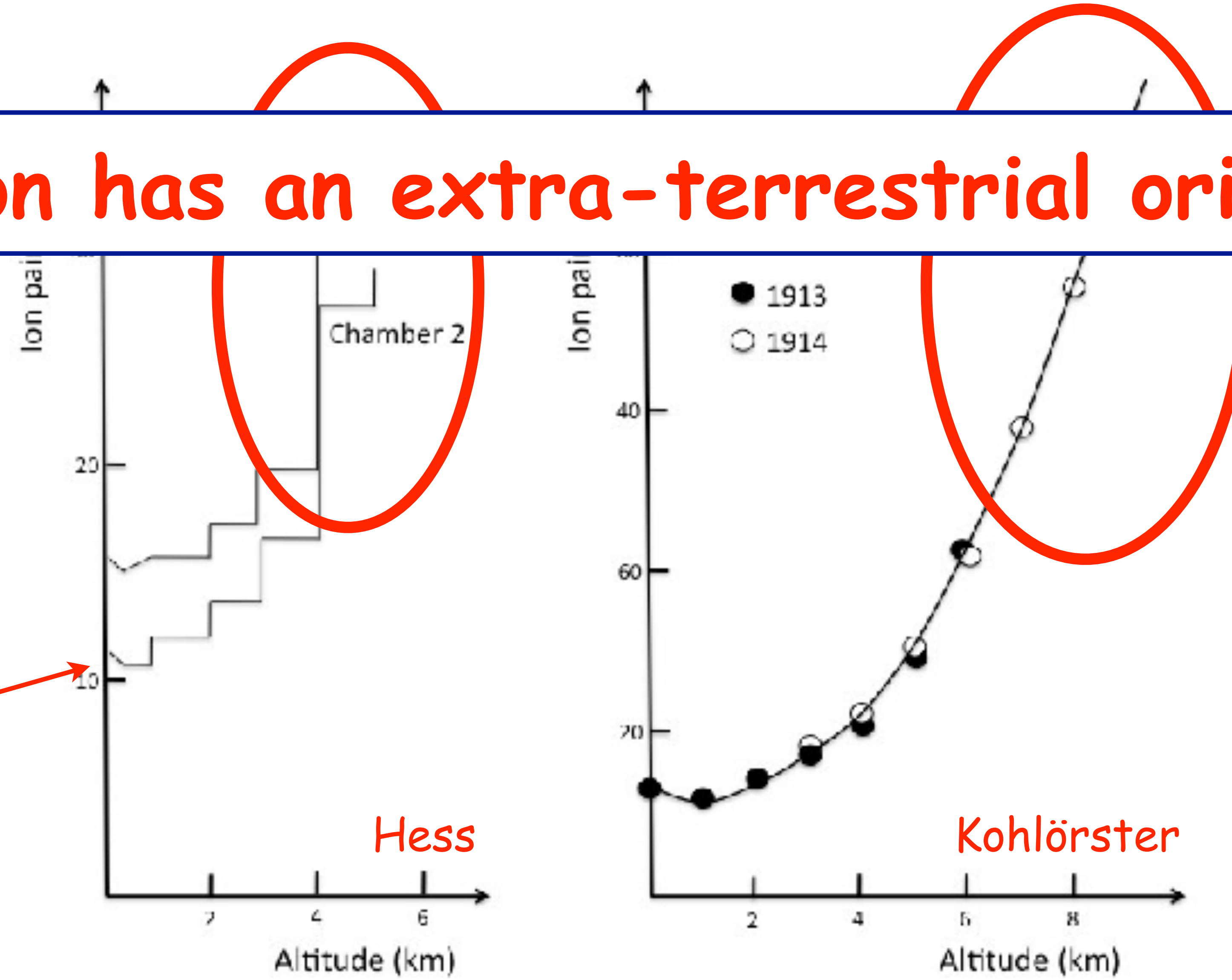
The ionizing radiation has an extra-terrestrial origin



Wulf was right!

[2] What are cosmic rays?

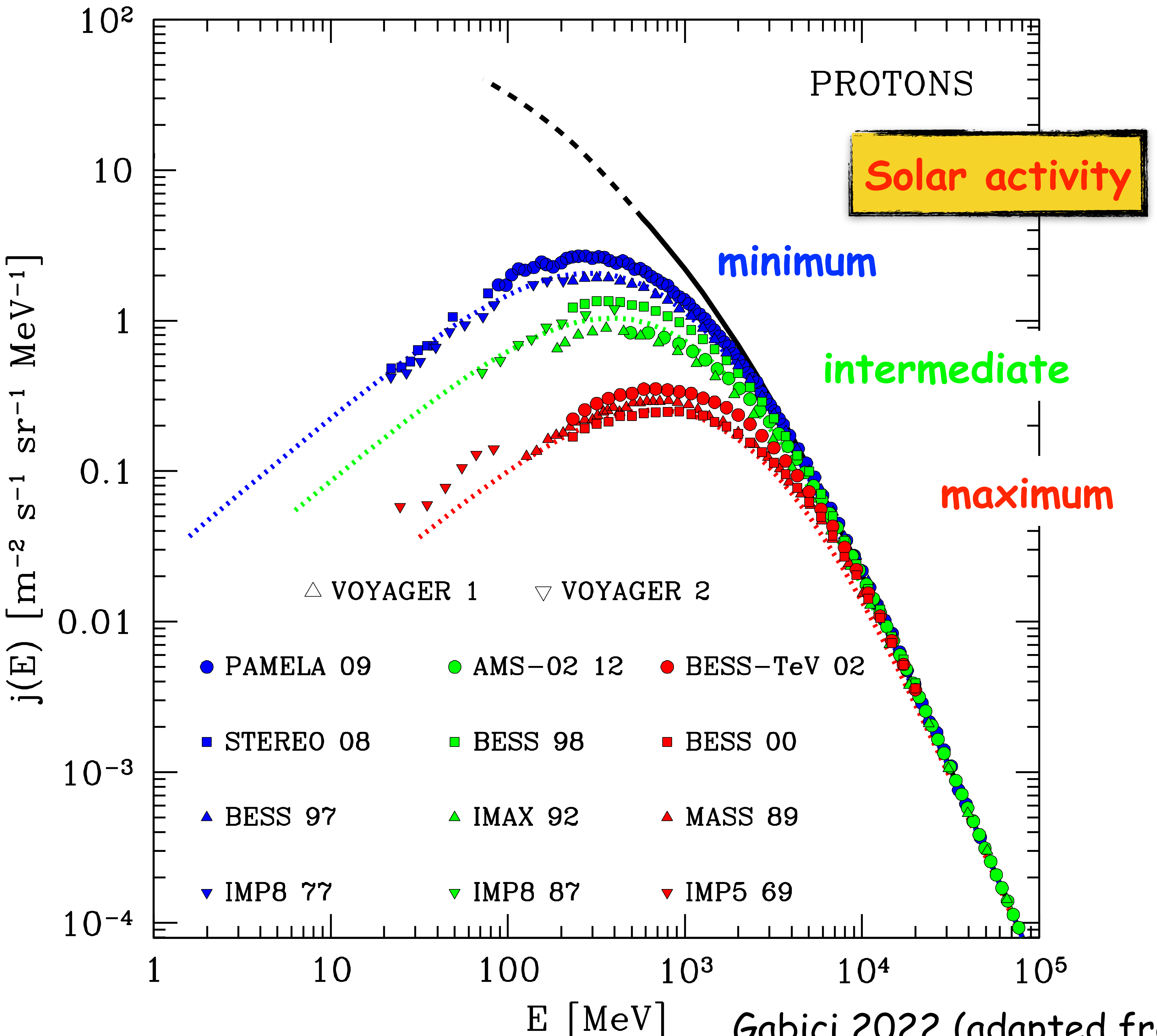
What are Cosmic Rays?

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"

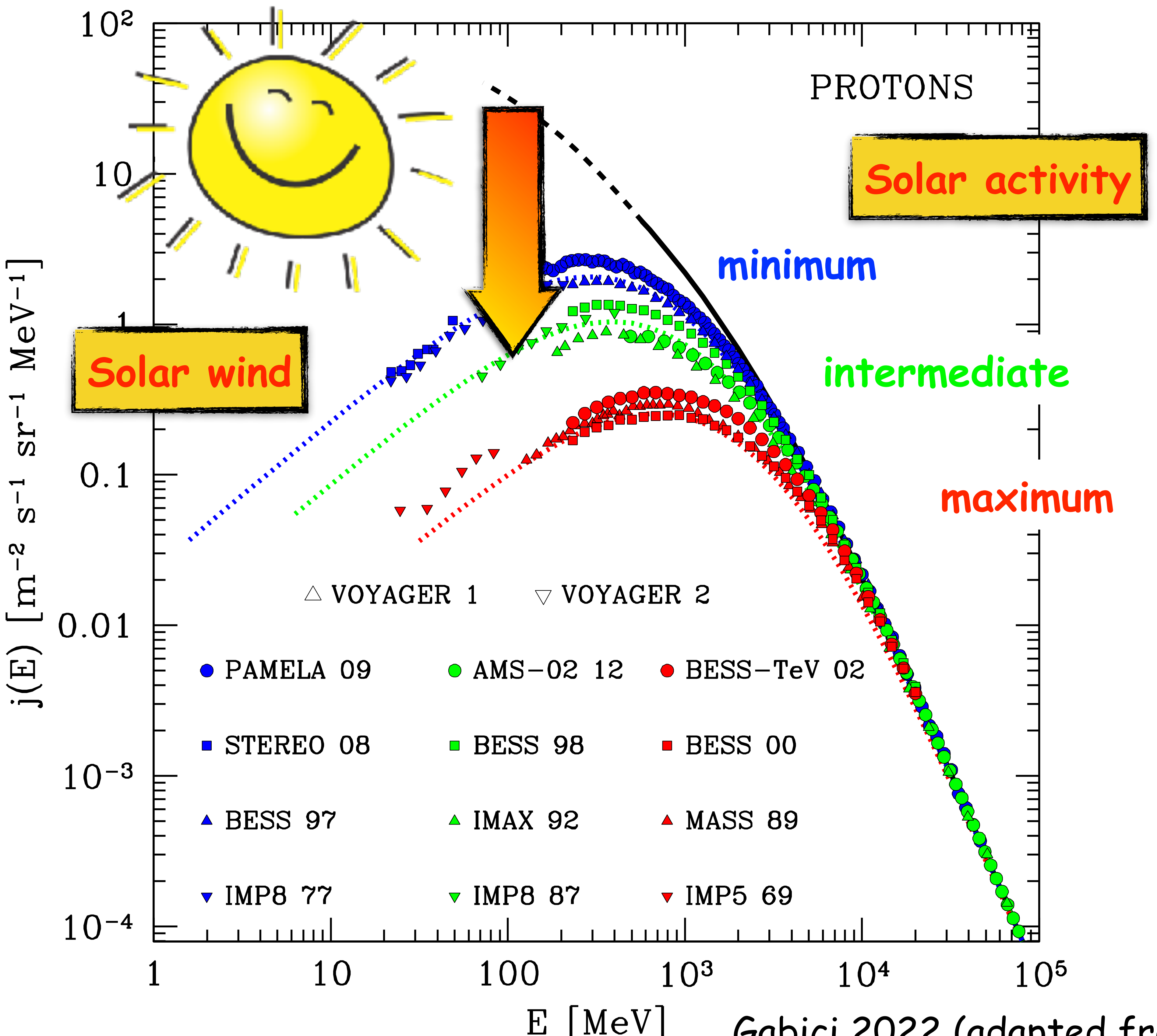
Also **electrons** are present in the cosmic radiation -> **~ 1%**

Solar modulation



Gabici 2022 (adapted from Vos & Potgieter 2015)

Solar modulation



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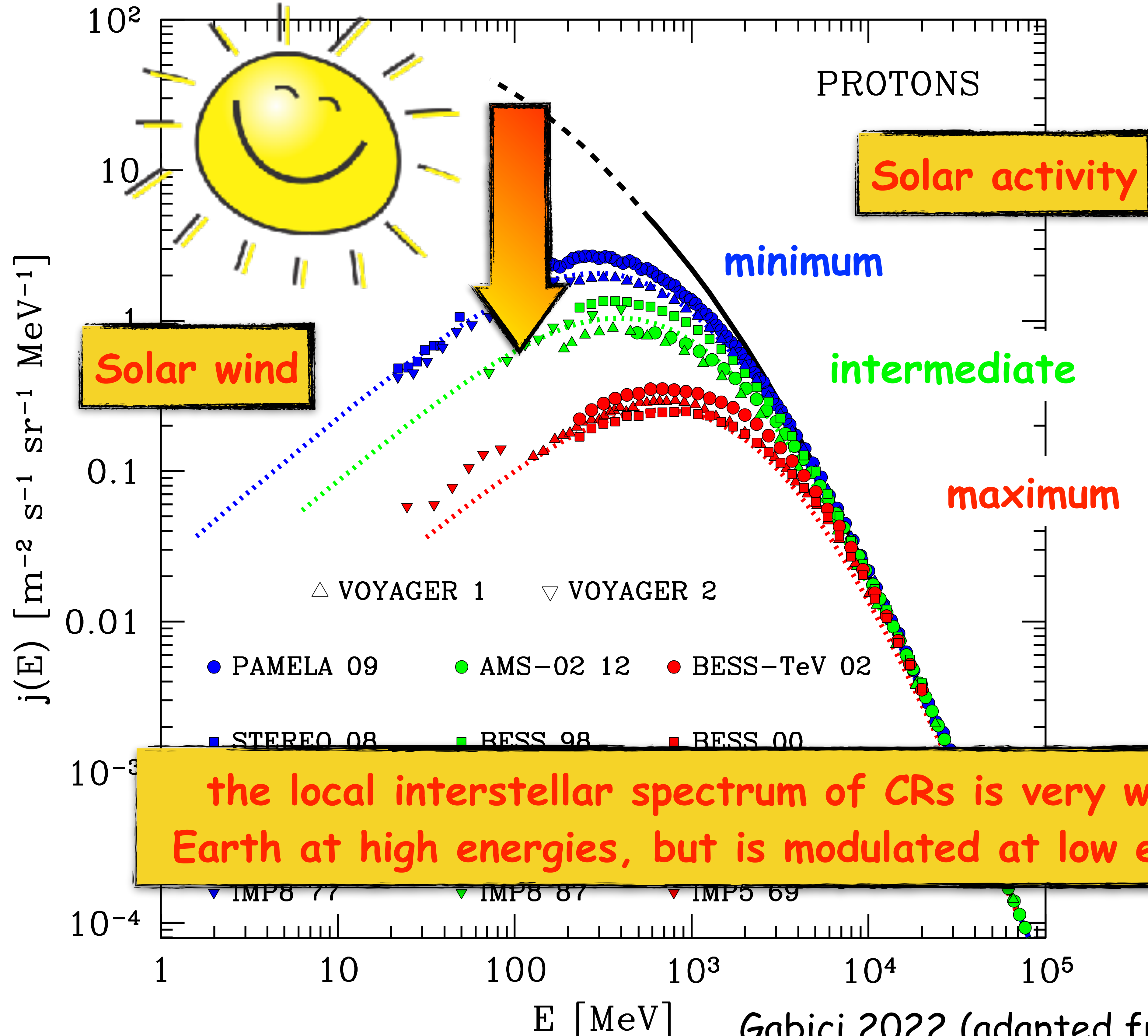

the local interstellar spectrum of CRs is very well measured from Earth at high energies, but is modulated at low energyes (< 20 GeV)

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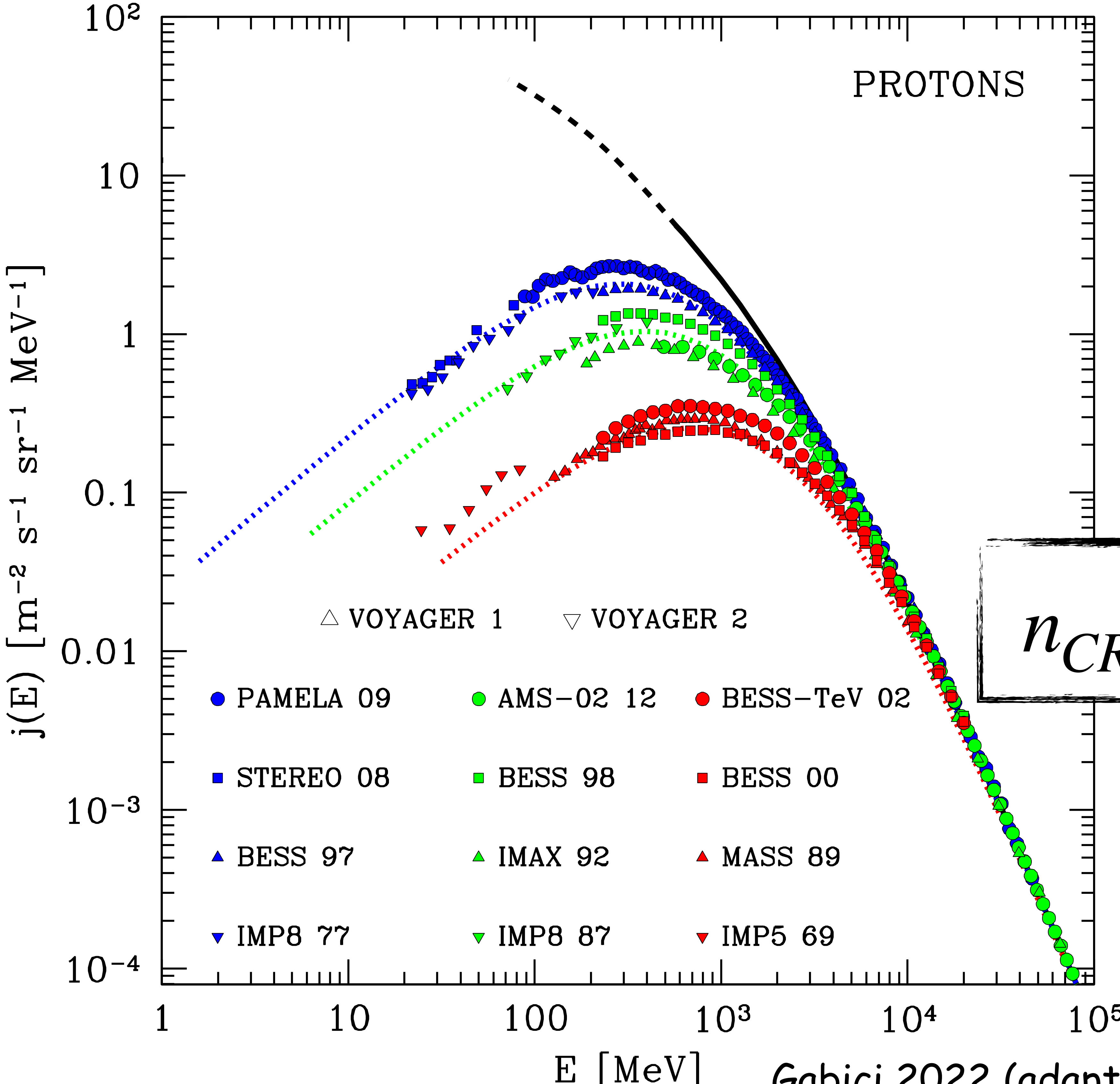
Solar modulation



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

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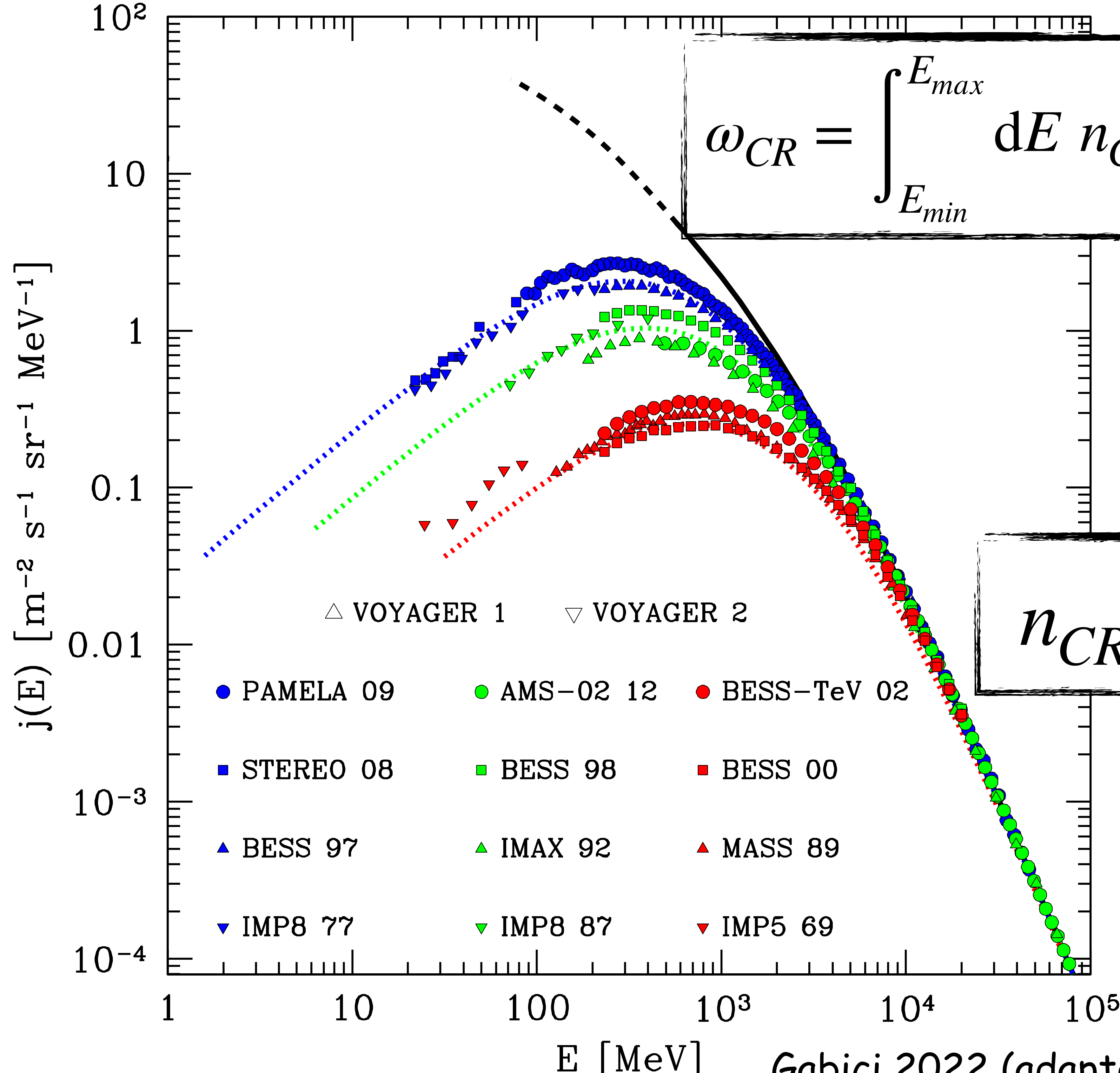
Solar modulation



$$\omega_{CR} = \int_{E_{min}}^{E_{max}} \mathrm{d}E \; n_{CR}(E) E \propto E_{min}^{-0.7} \xrightarrow{E_{min} \to 0} \infty$$

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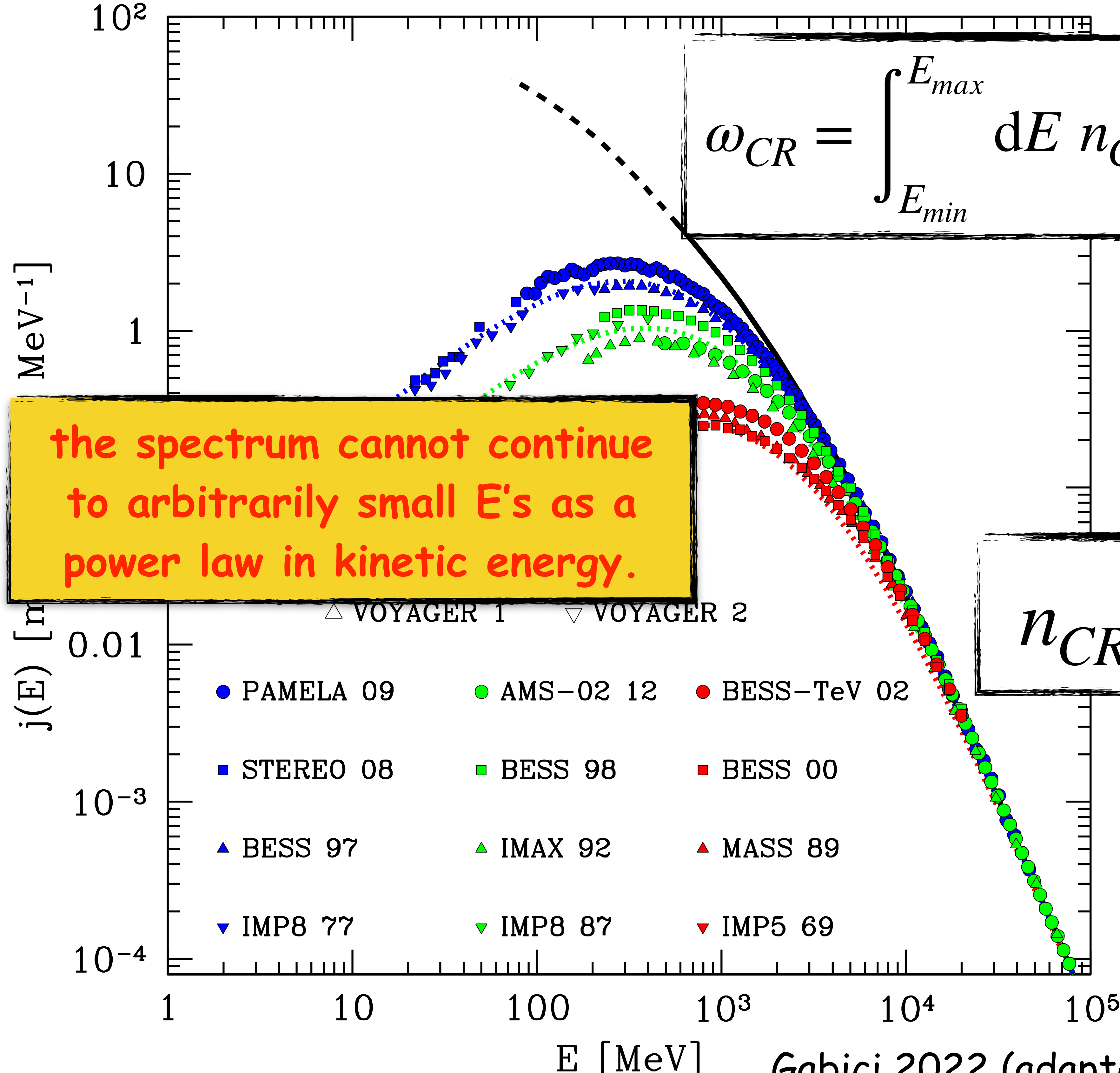

the spectrum cannot continue to arbitrarily small E's as a power law in kinetic energy.

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

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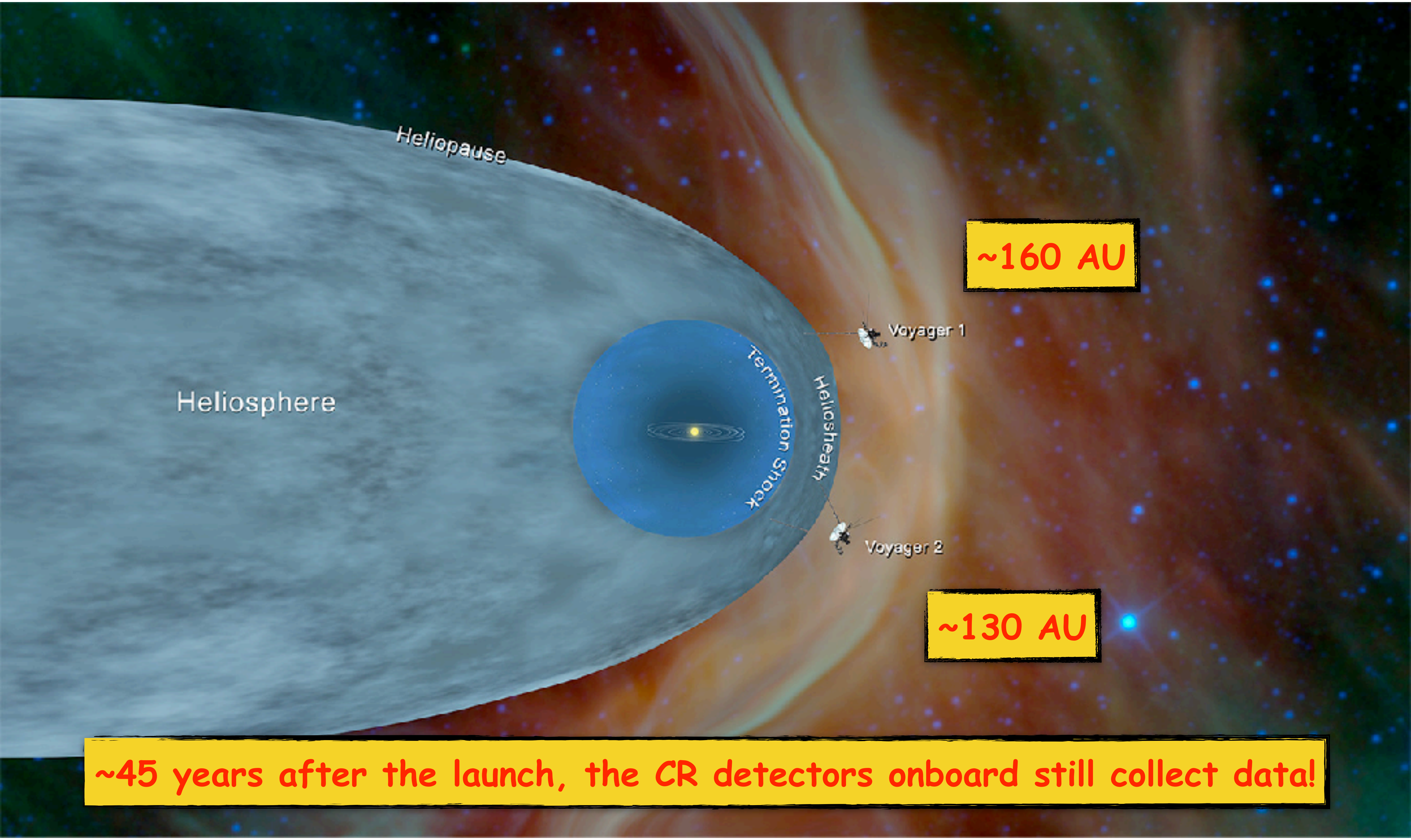
Voyager probes

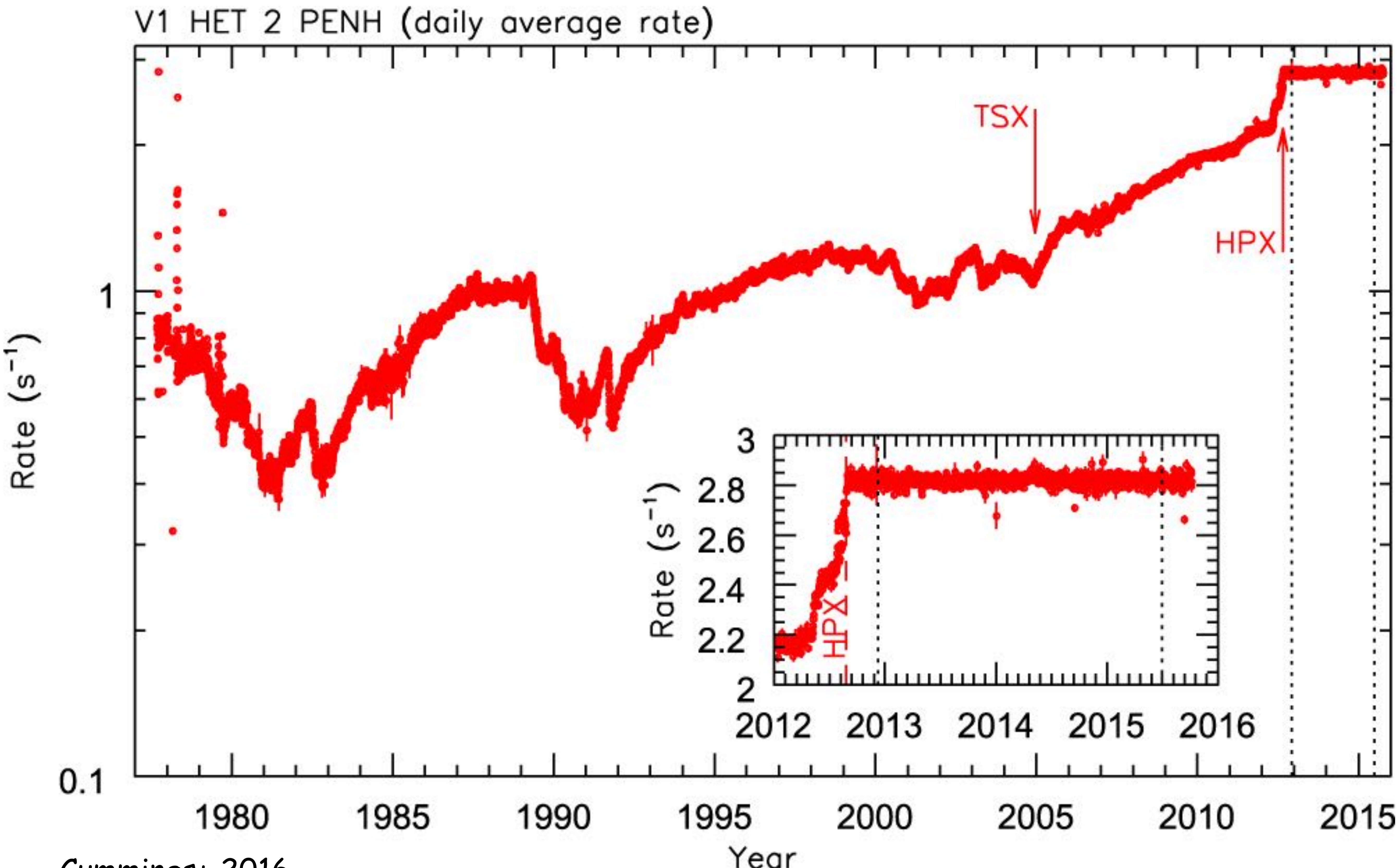
September 5 1977
the launch of Voyager 1

August 20 1977 launch of the twin probe Voyager 2

Voyager probes crossed the heliopause



An epic journey



Cummings+ 2016

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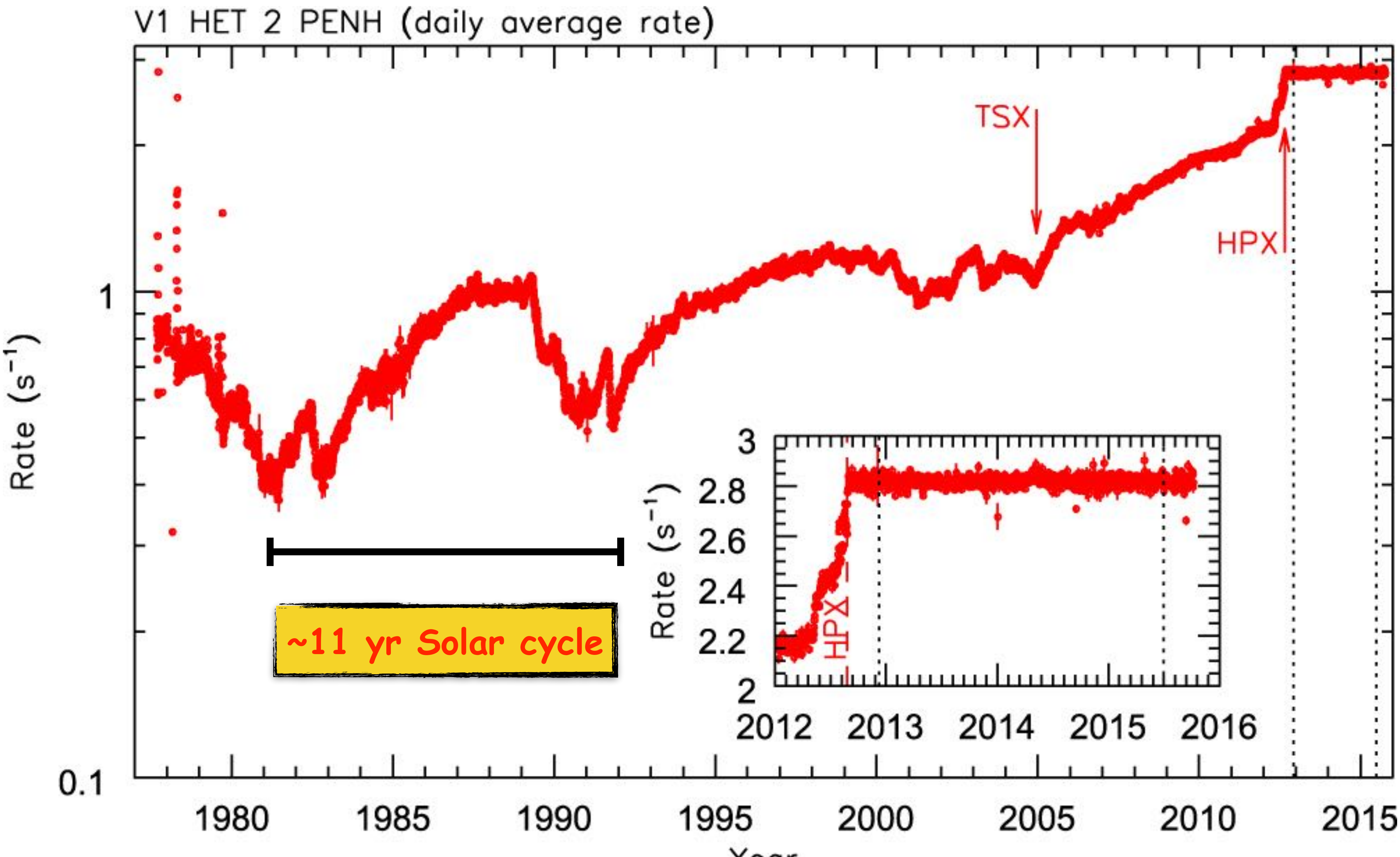

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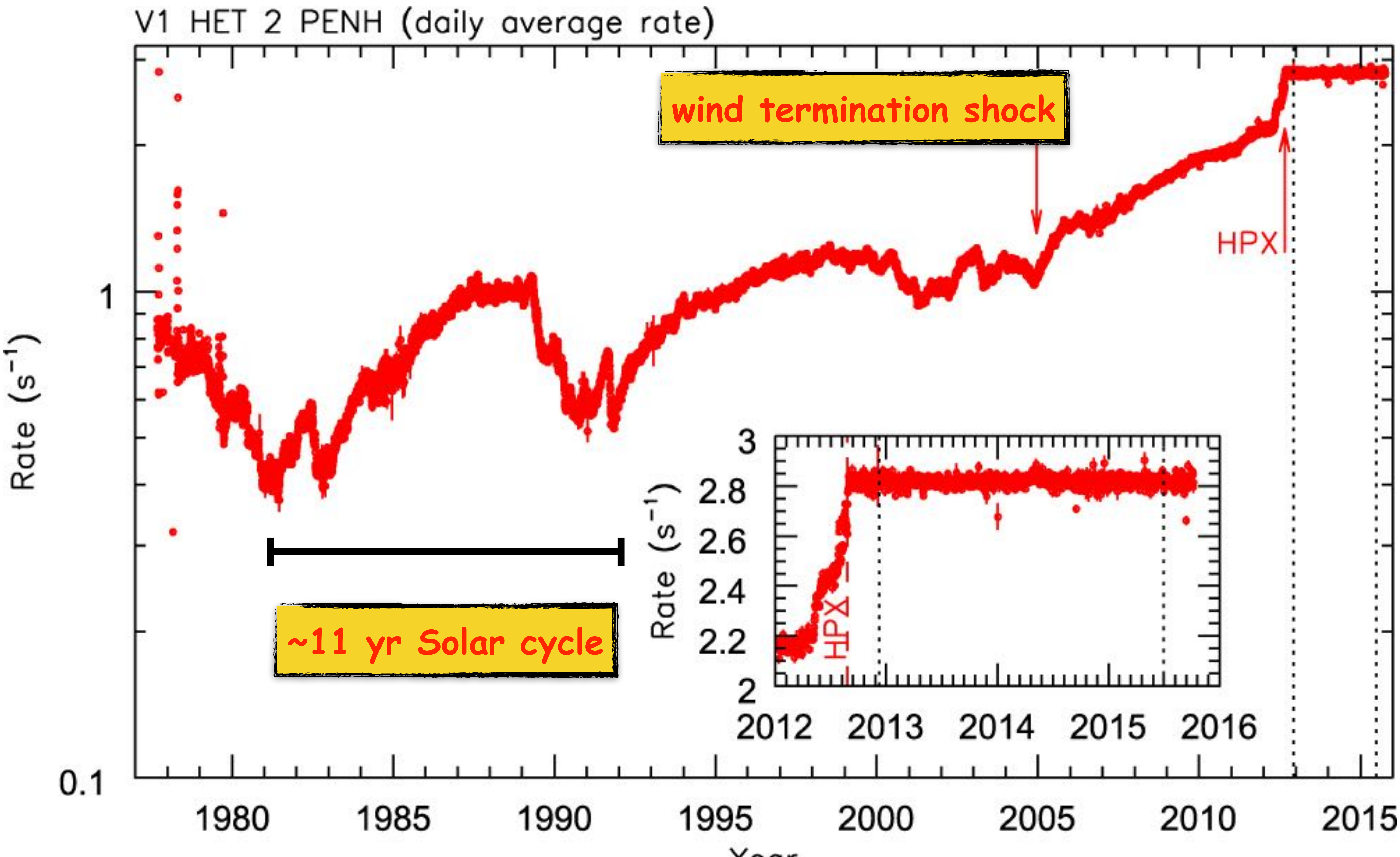

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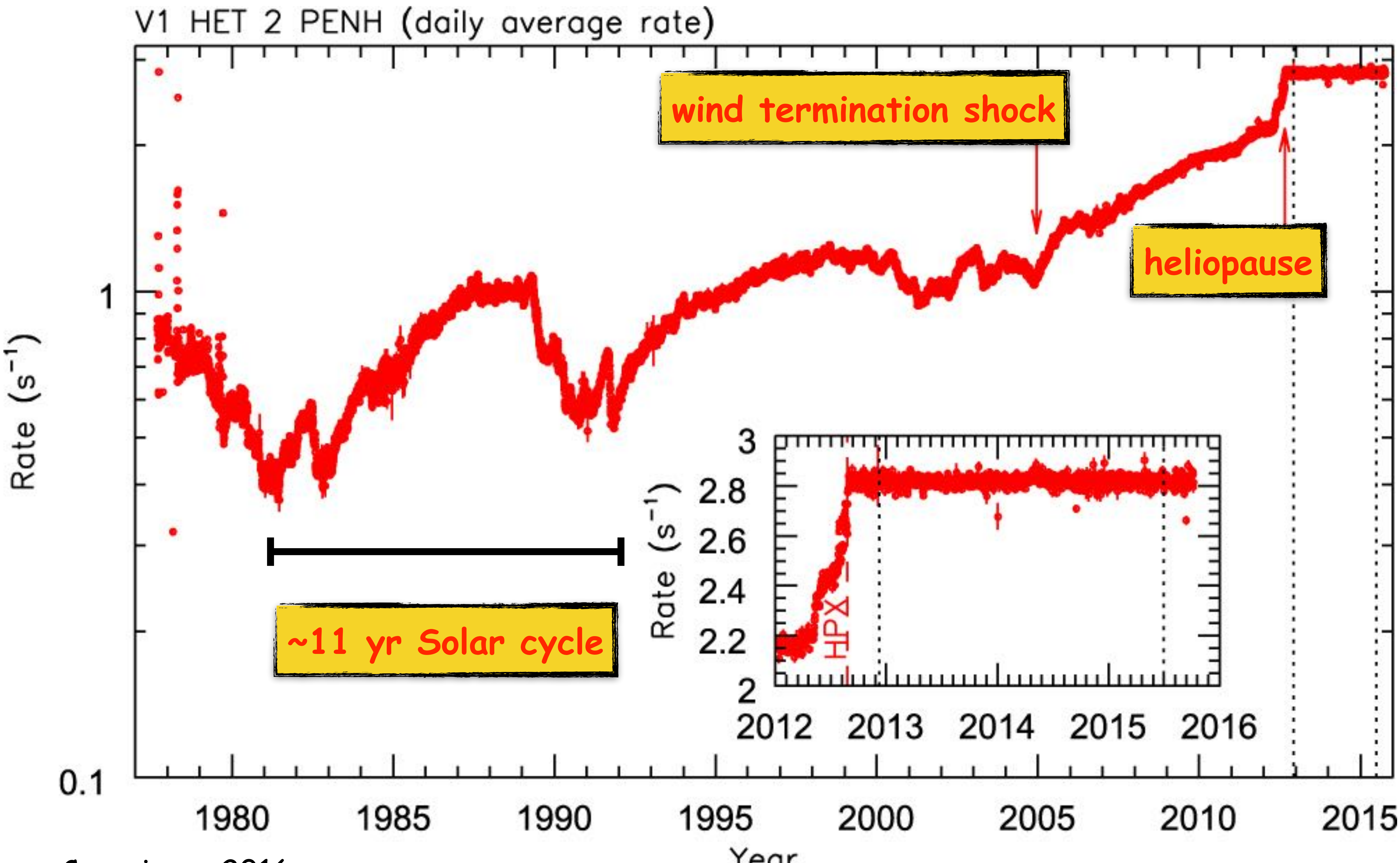

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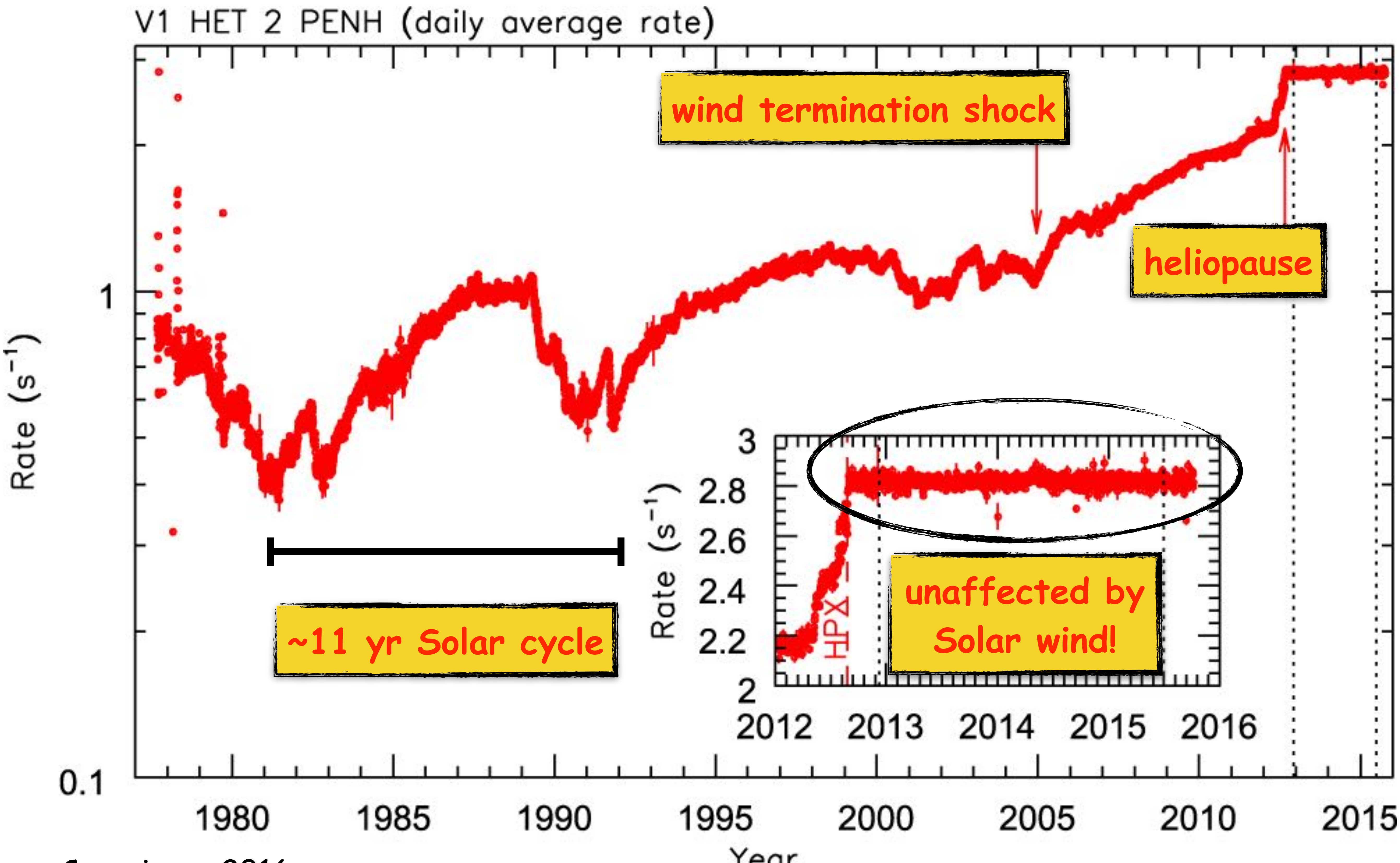

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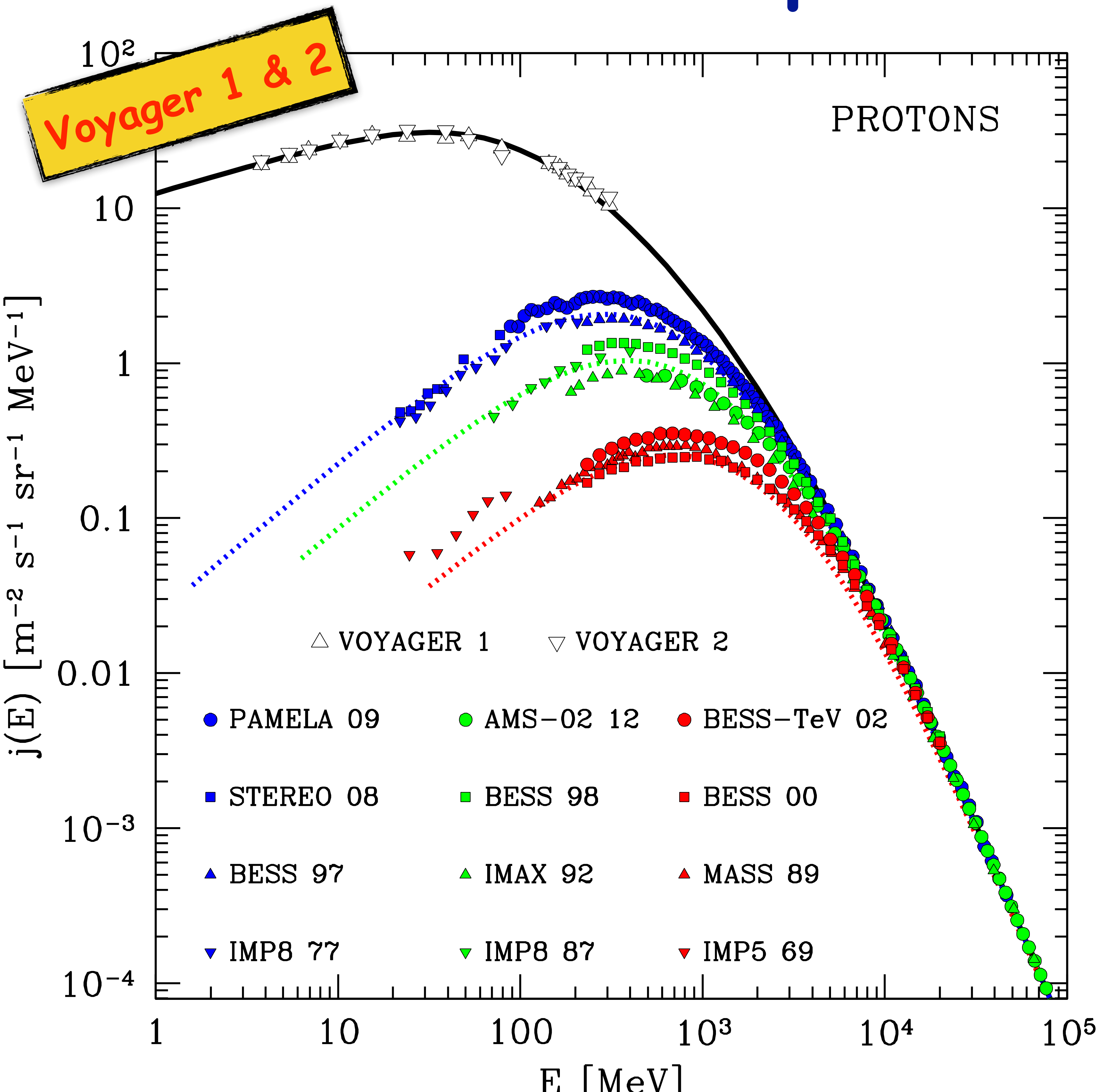
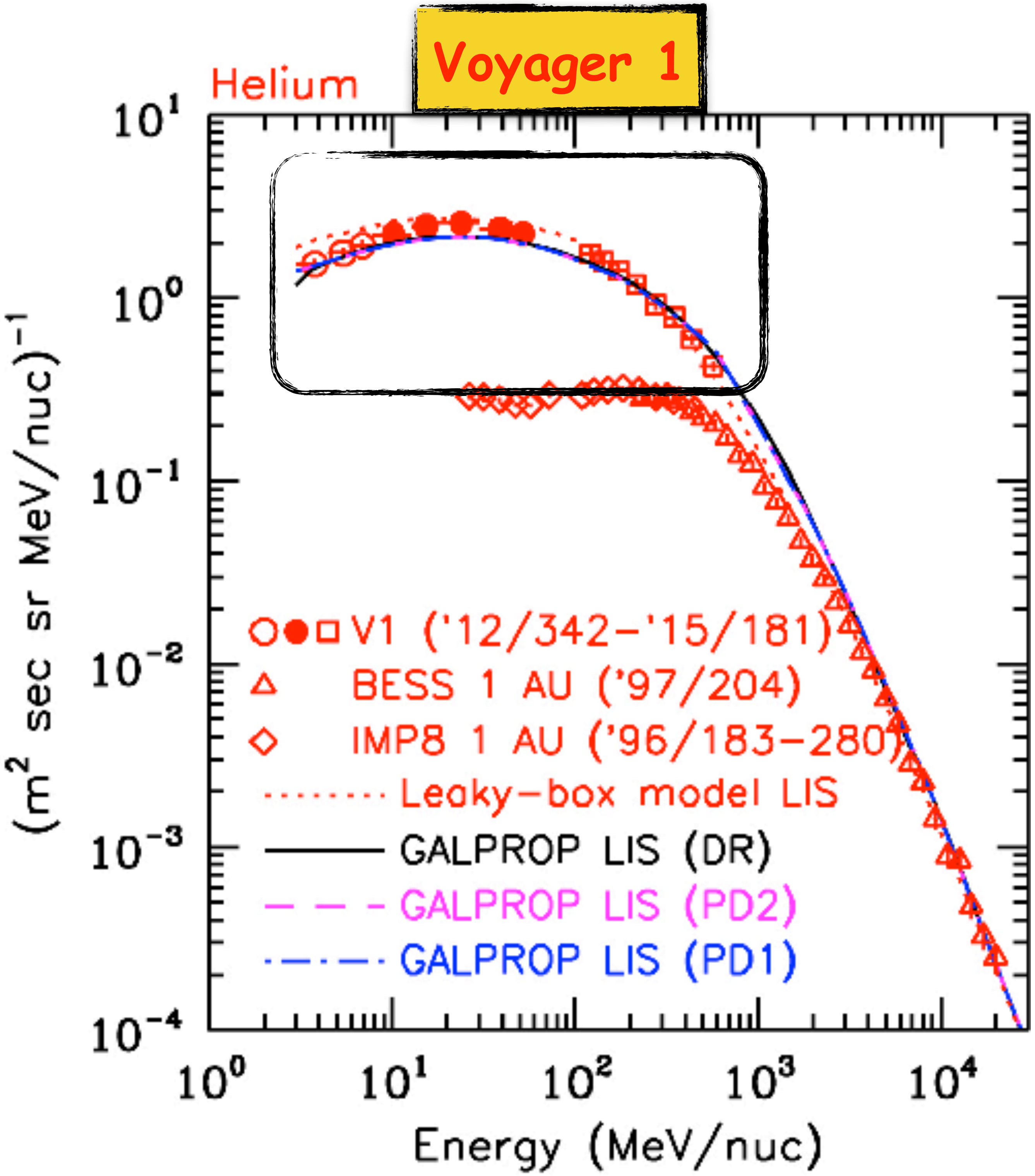
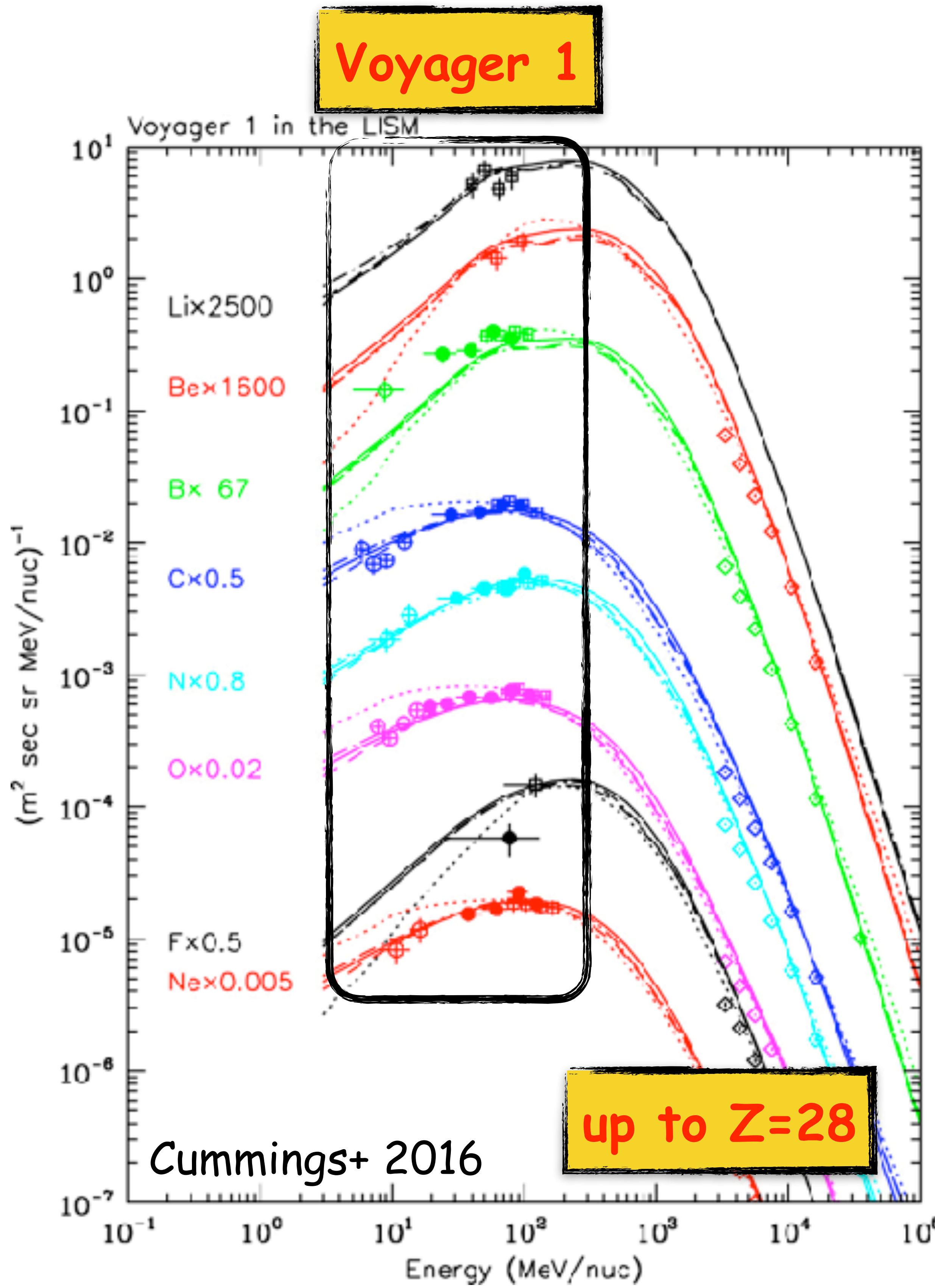
The local interstellar spectrum of CRs



Gabici 2022 (adapted from Vos & Potgieter 2015)

Spectra of nuclei in the local ISM





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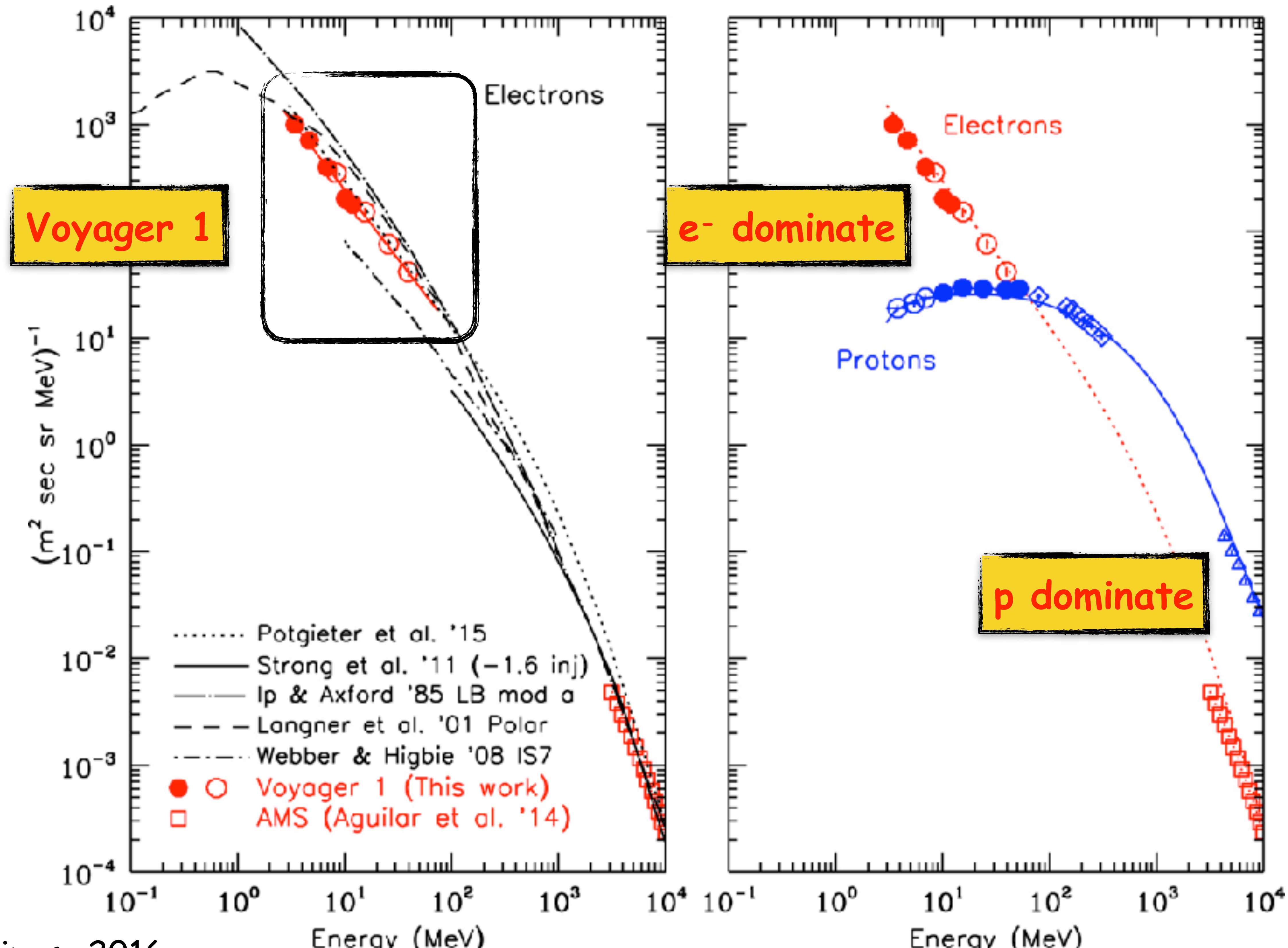
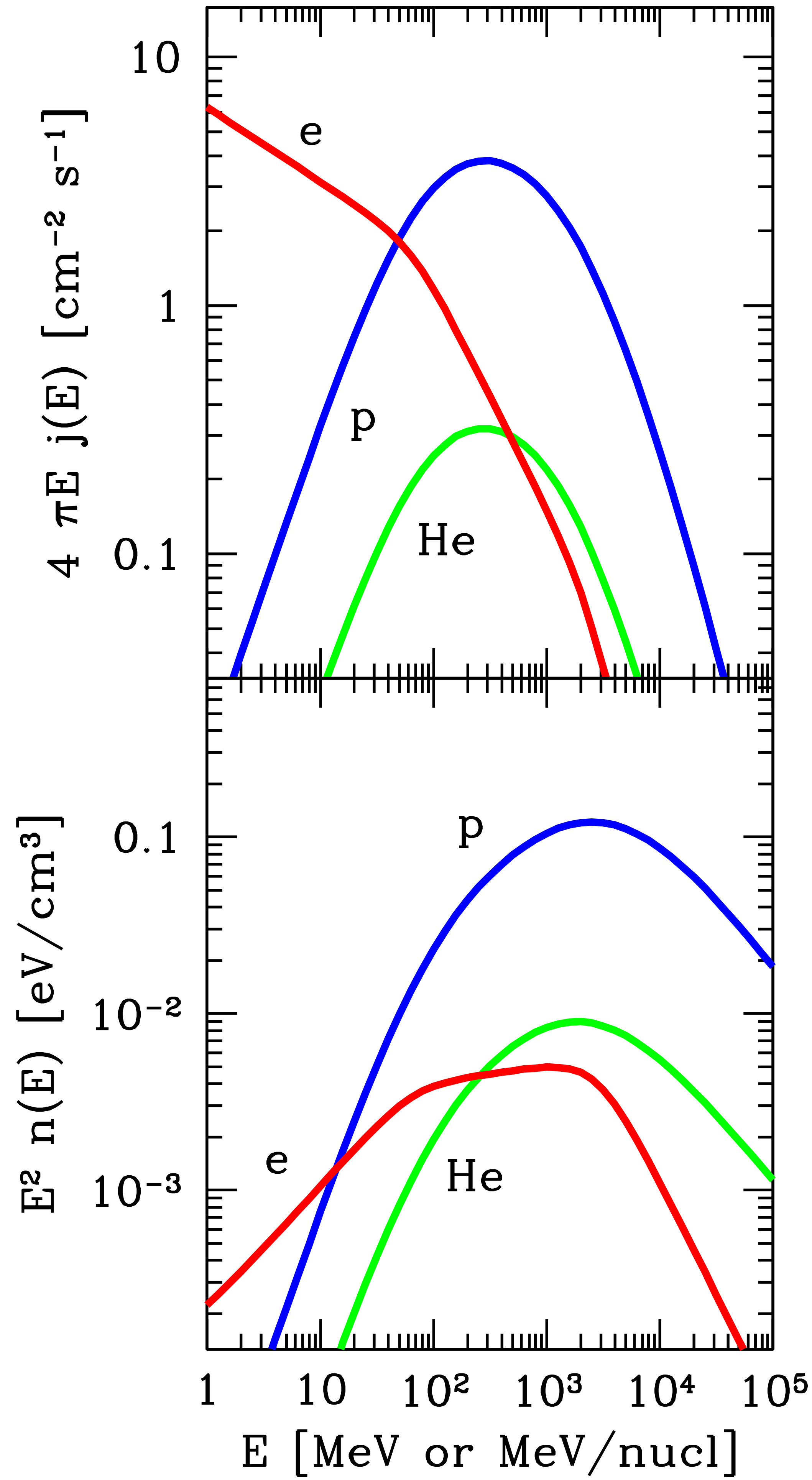
Electron spectrum in the local ISM



Cummings+ 2016

flux of particles

spectral energy distribution



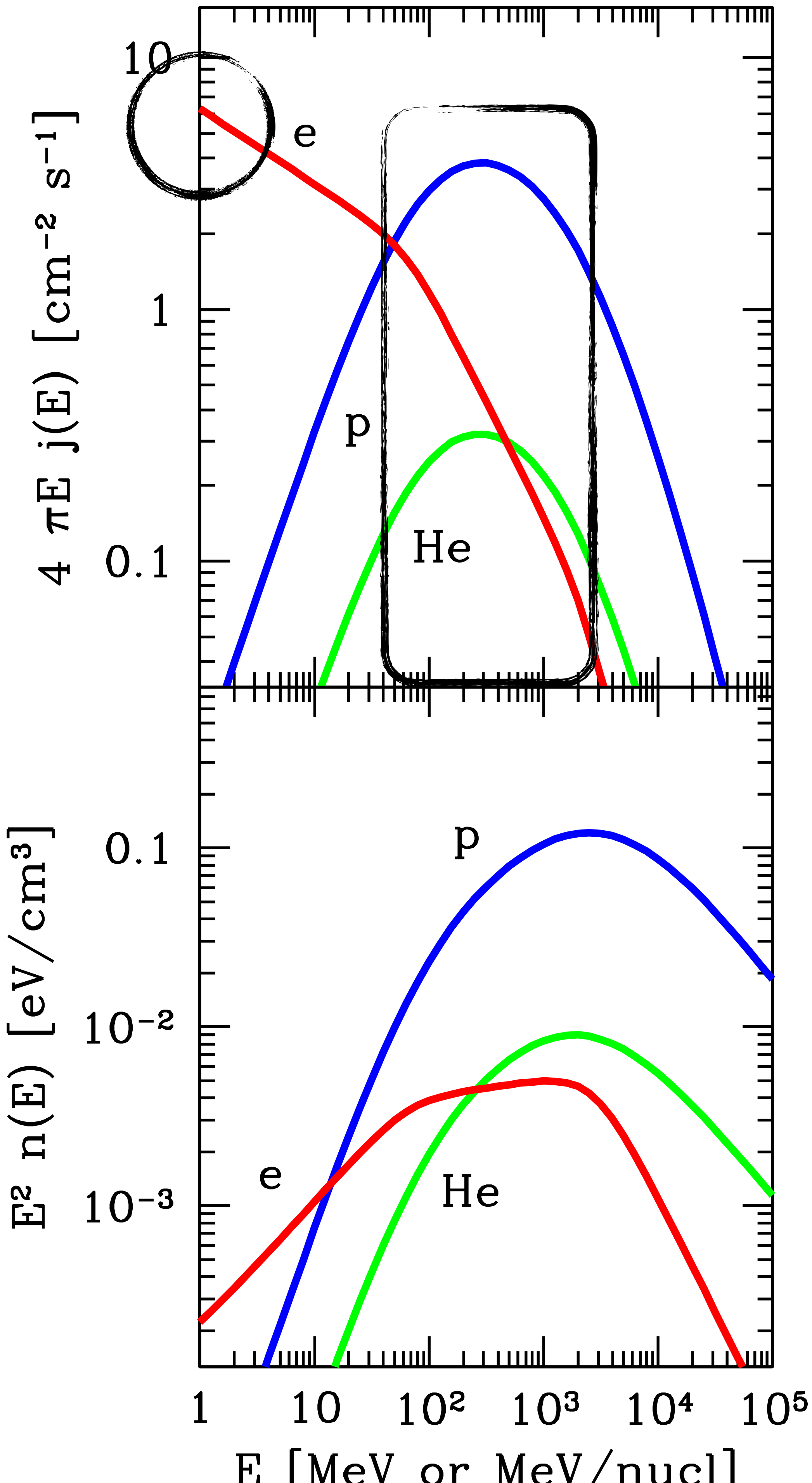
Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution



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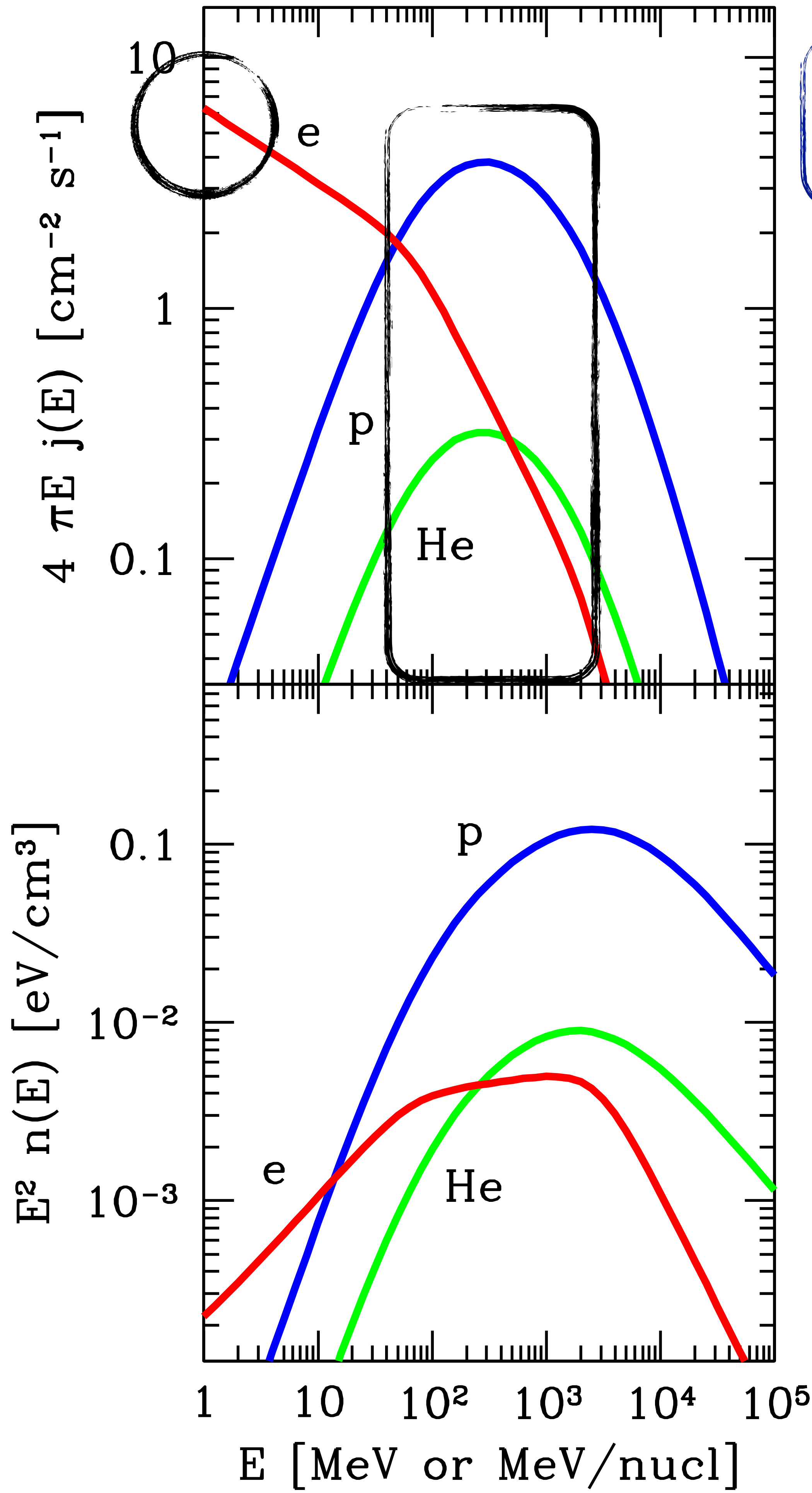

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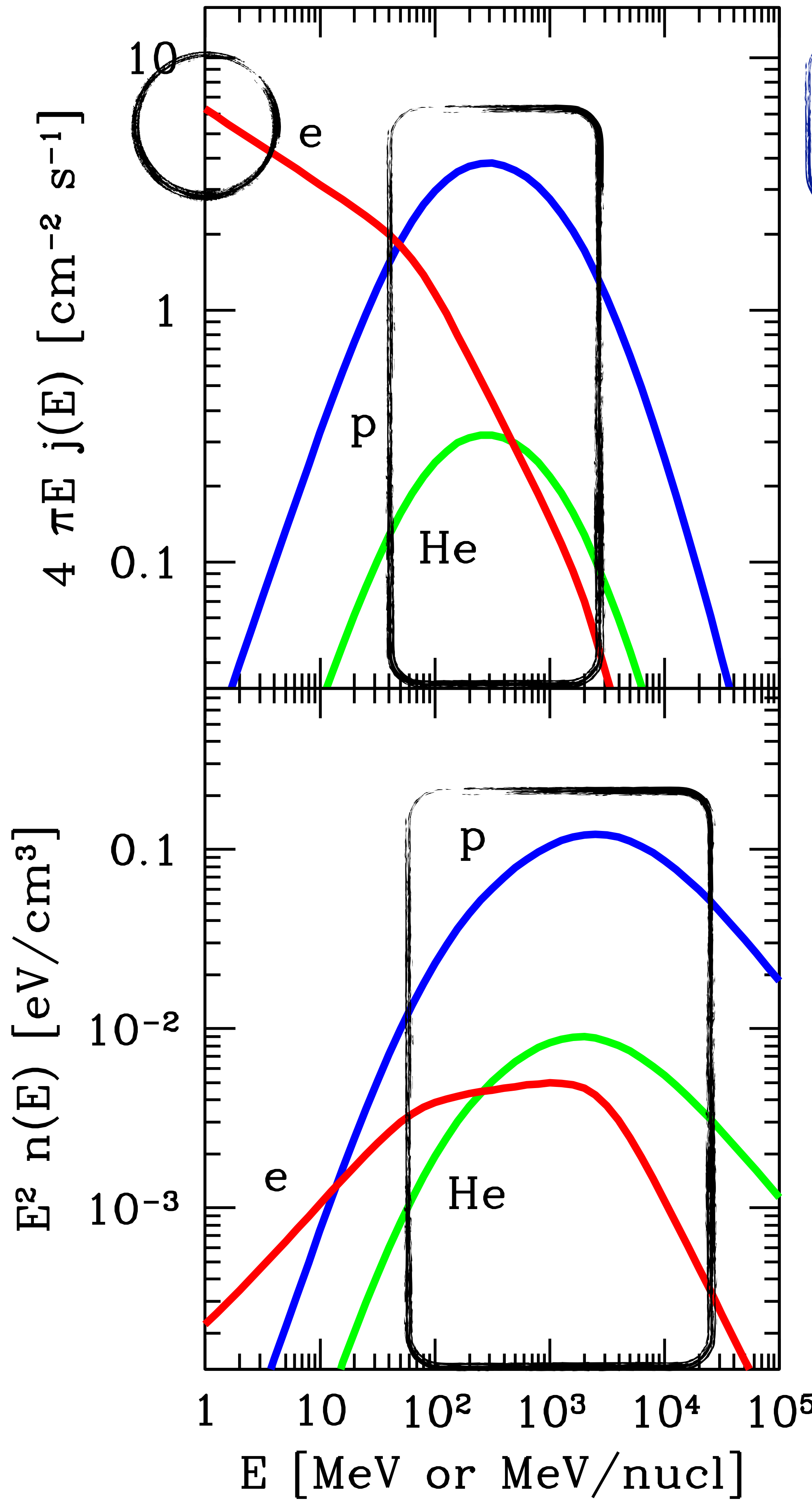

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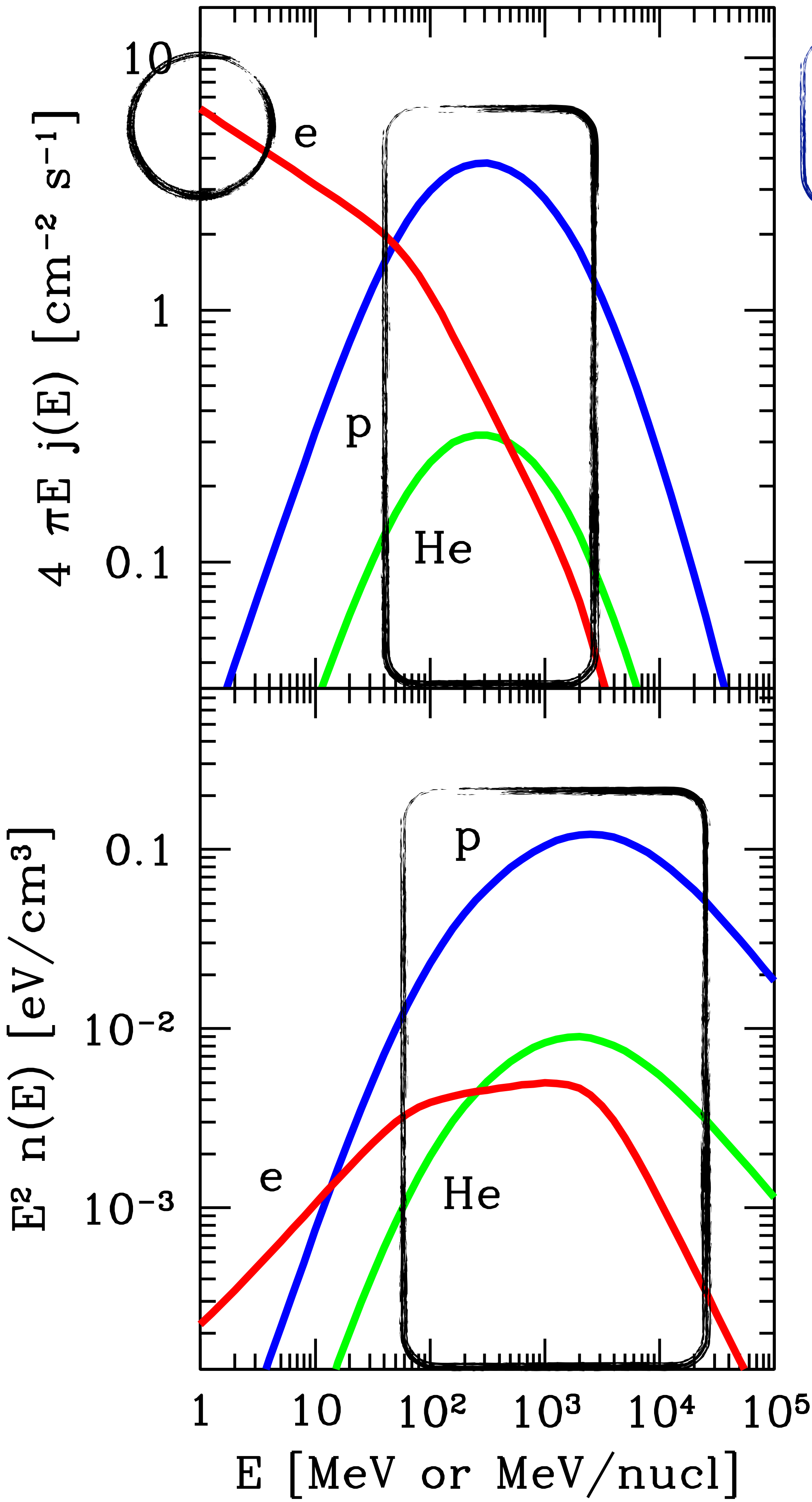

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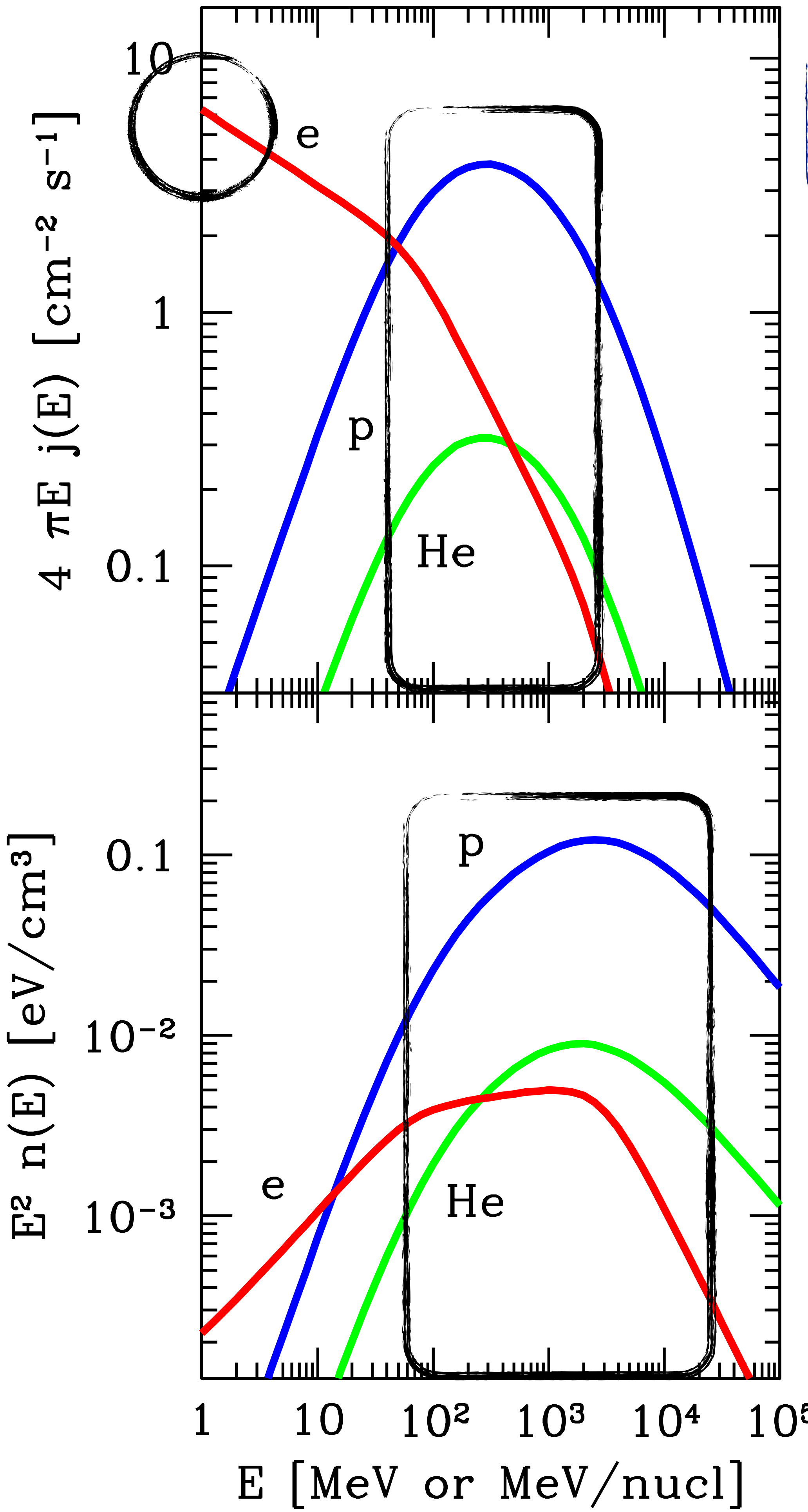

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compare with ISM density...

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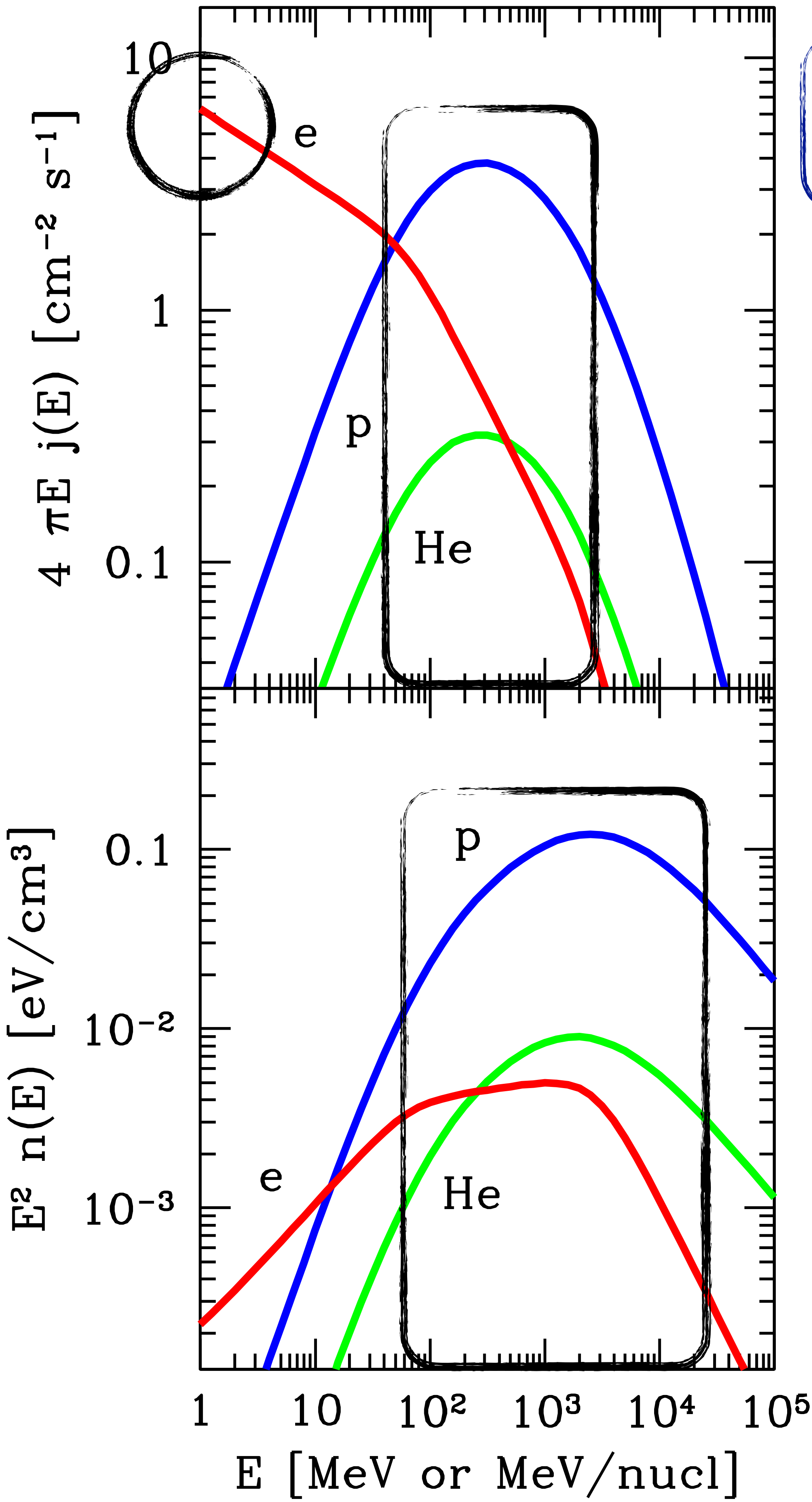

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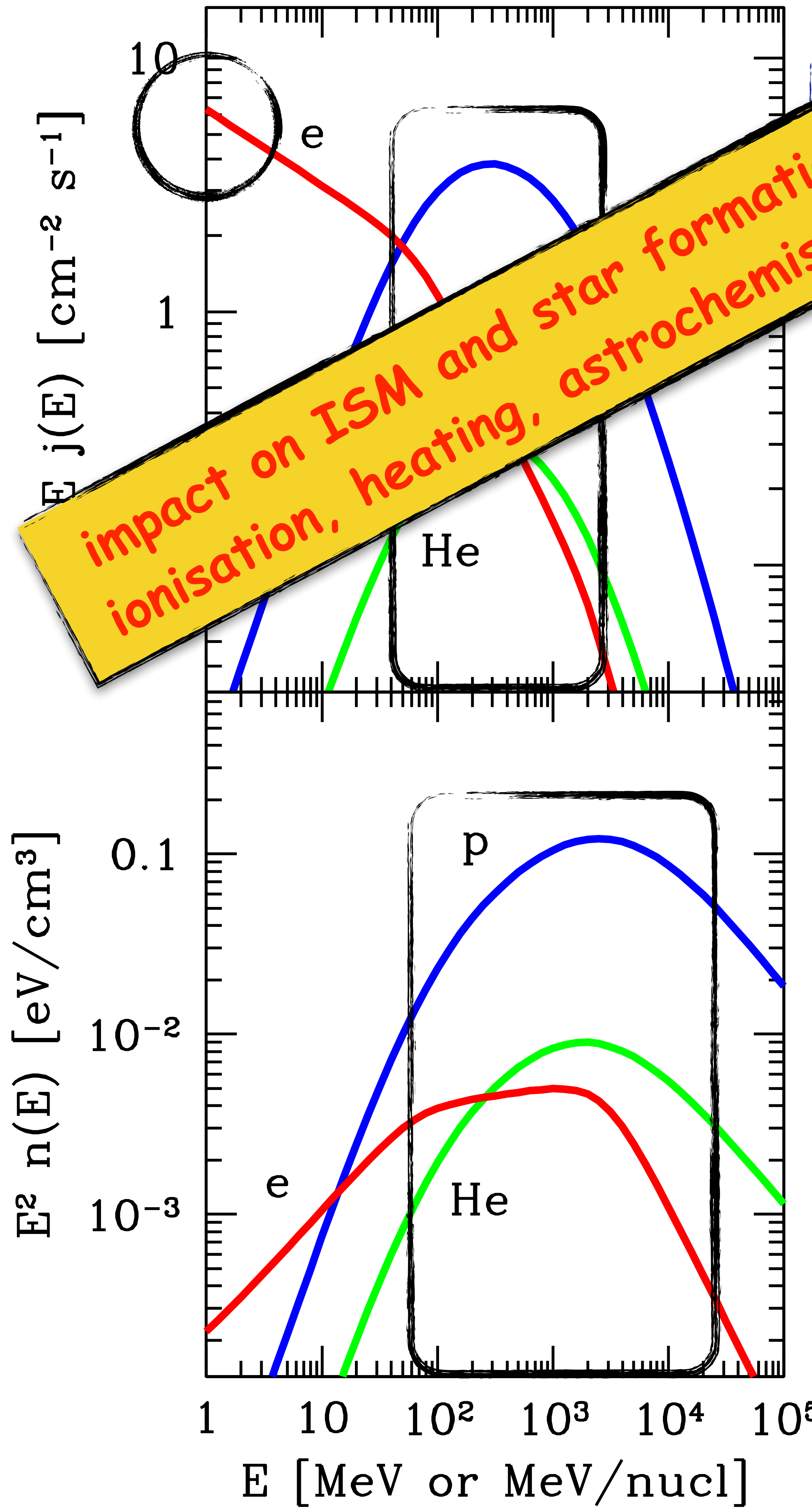

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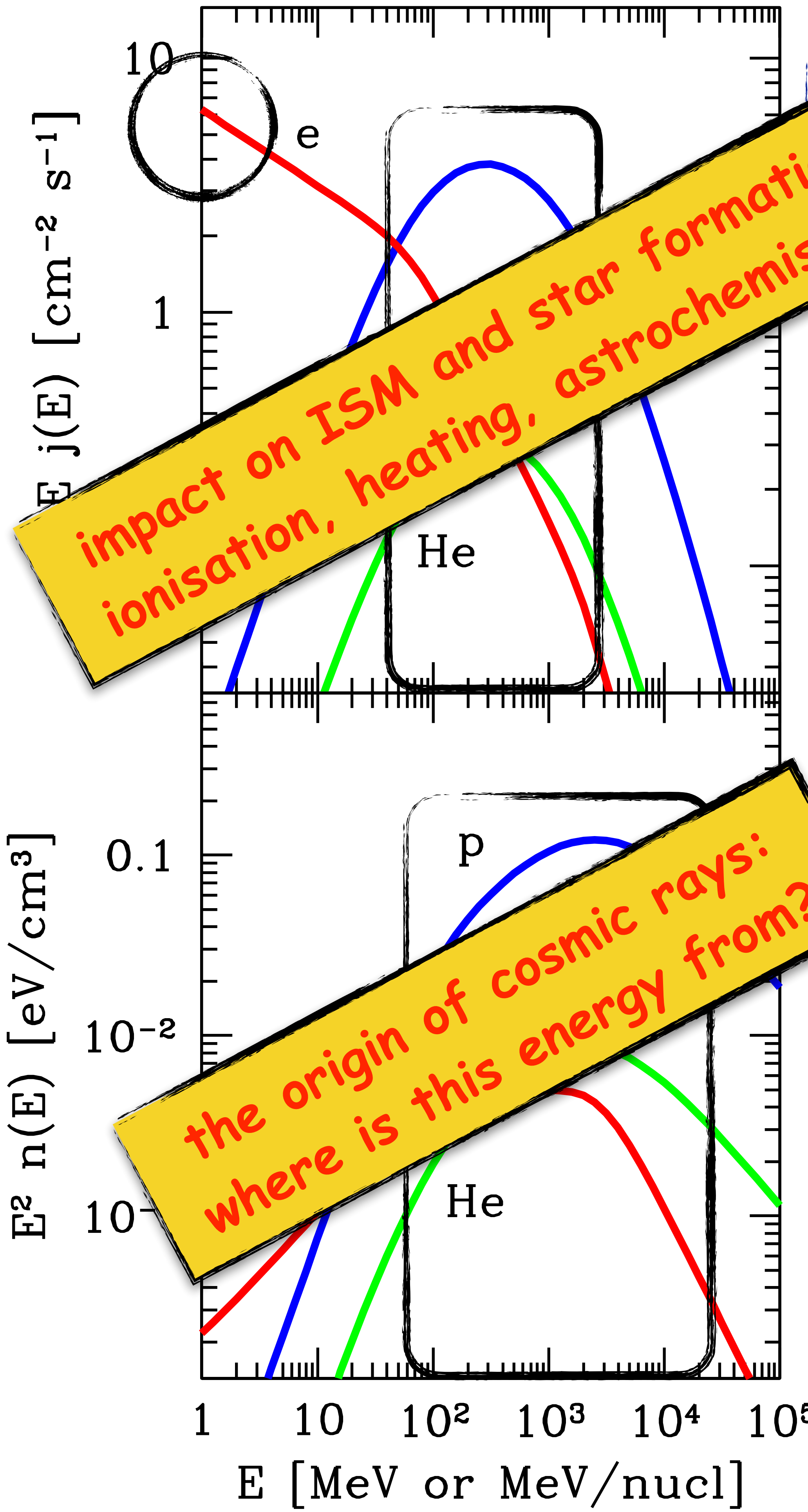

impact on ISM and star formation: ionisation, heating, astrochemistry...

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

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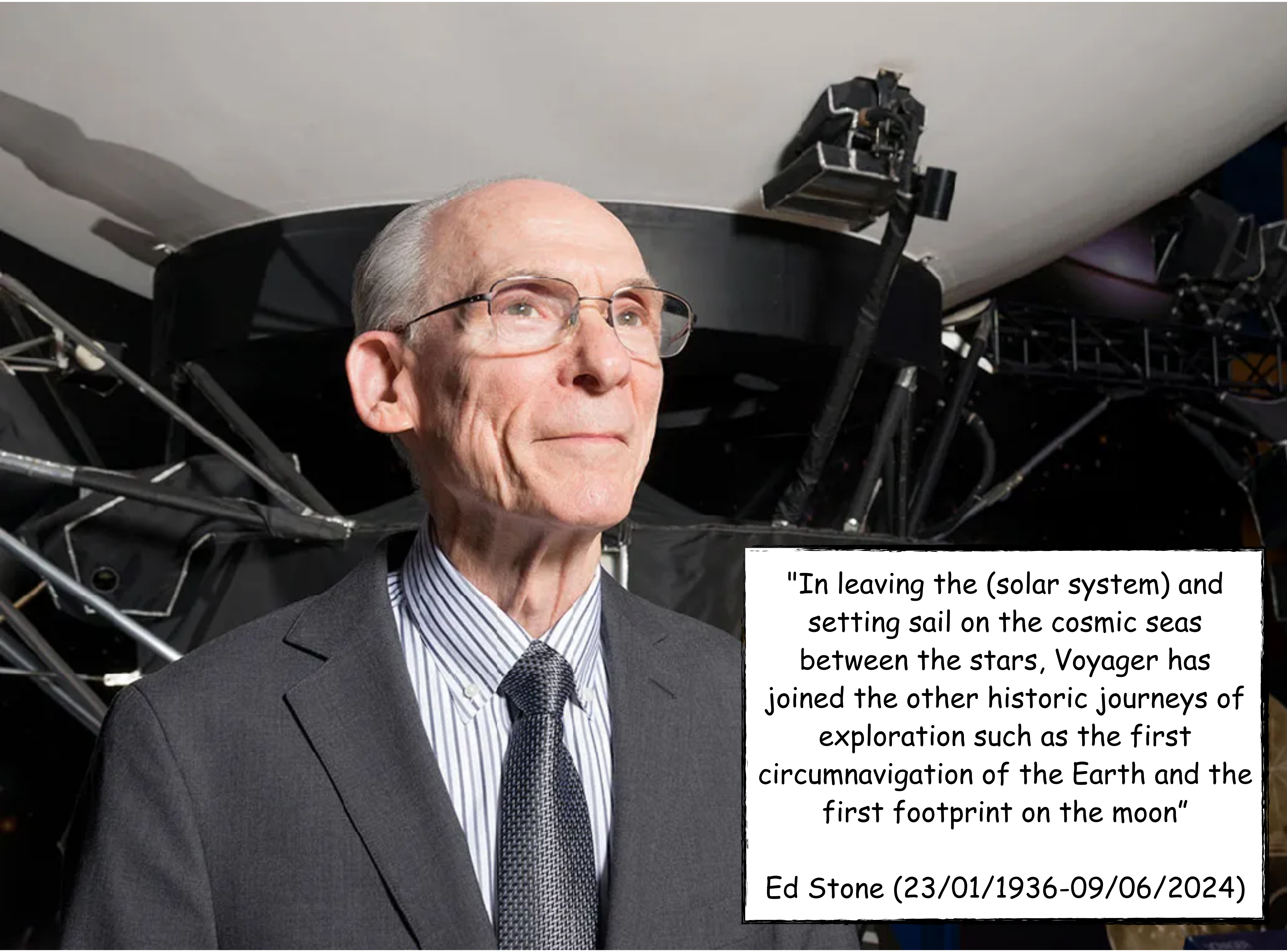
≈ 1 eV/cm^3

Gabici 2022


"In leaving the (solar system) and setting sail on the cosmic seas between the stars, Voyager has joined the other historic journeys of exploration such as the first circumnavigation of the Earth and the first footprint on the moon"
Ed Stone (23/01/1936-09/06/2024)

[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)

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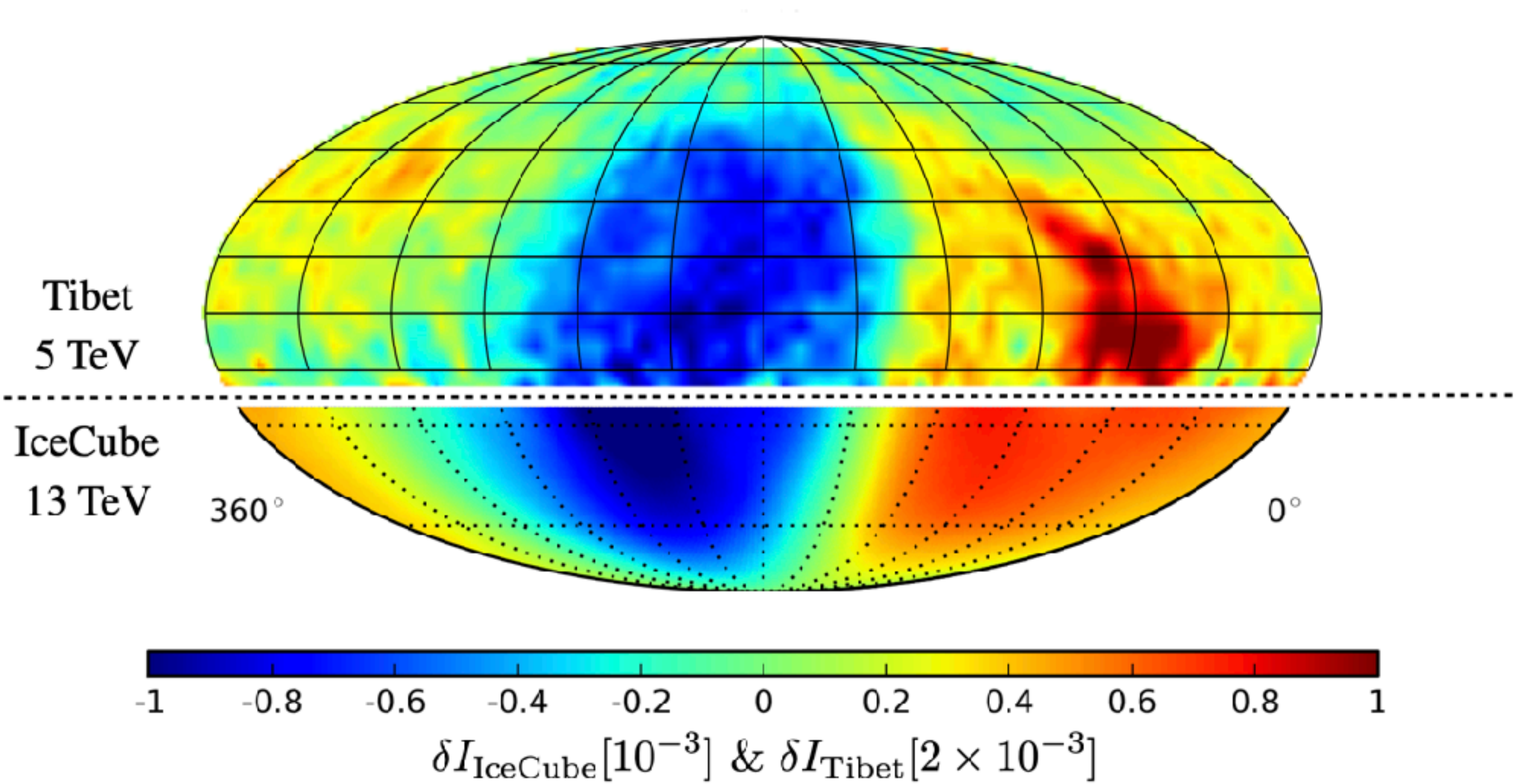
Stability in time and (hints for) spatial homogeneity

Cosmic rays are almost isotropic



see review by Mertsch & Ahlers 2017

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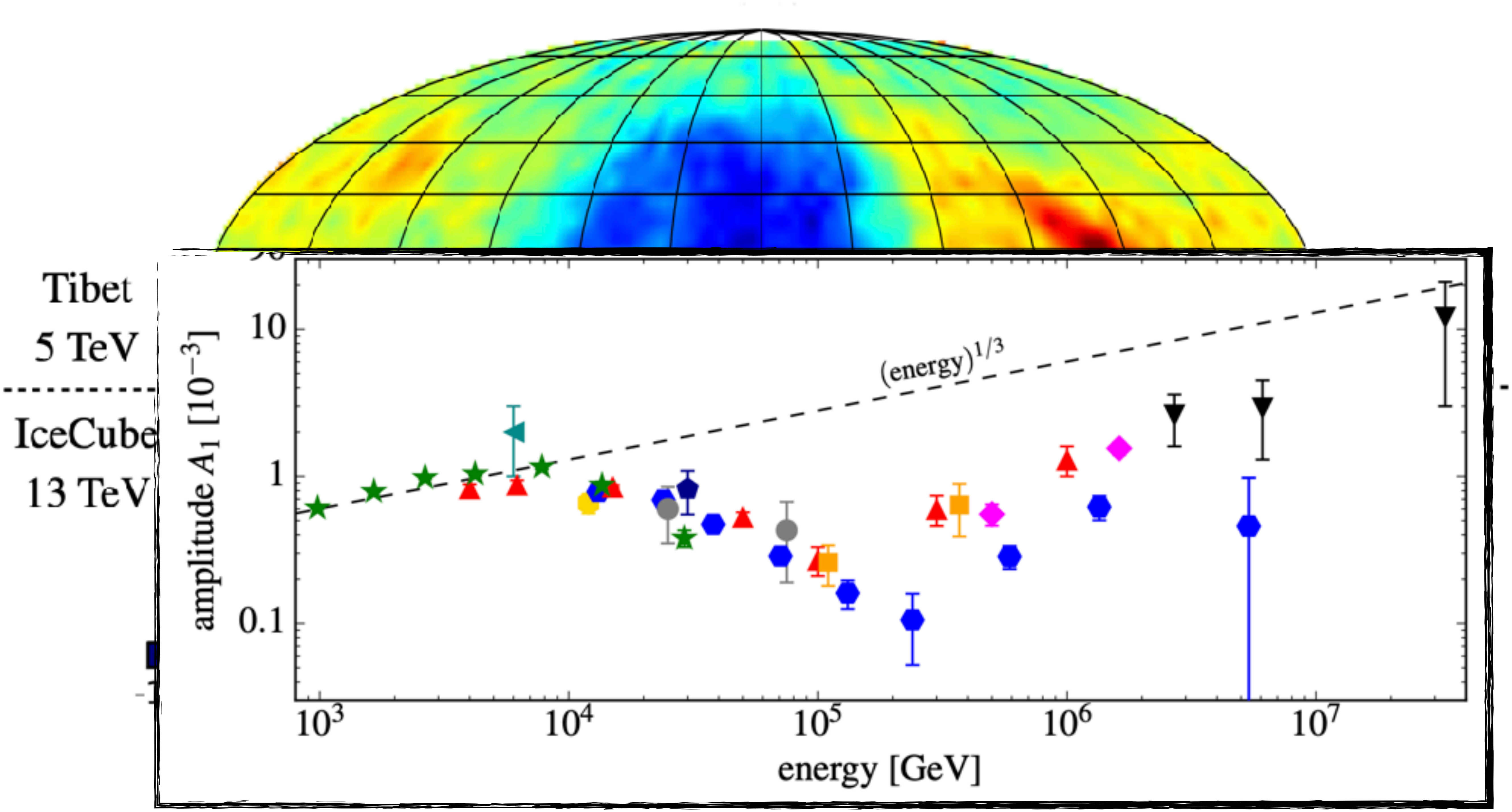

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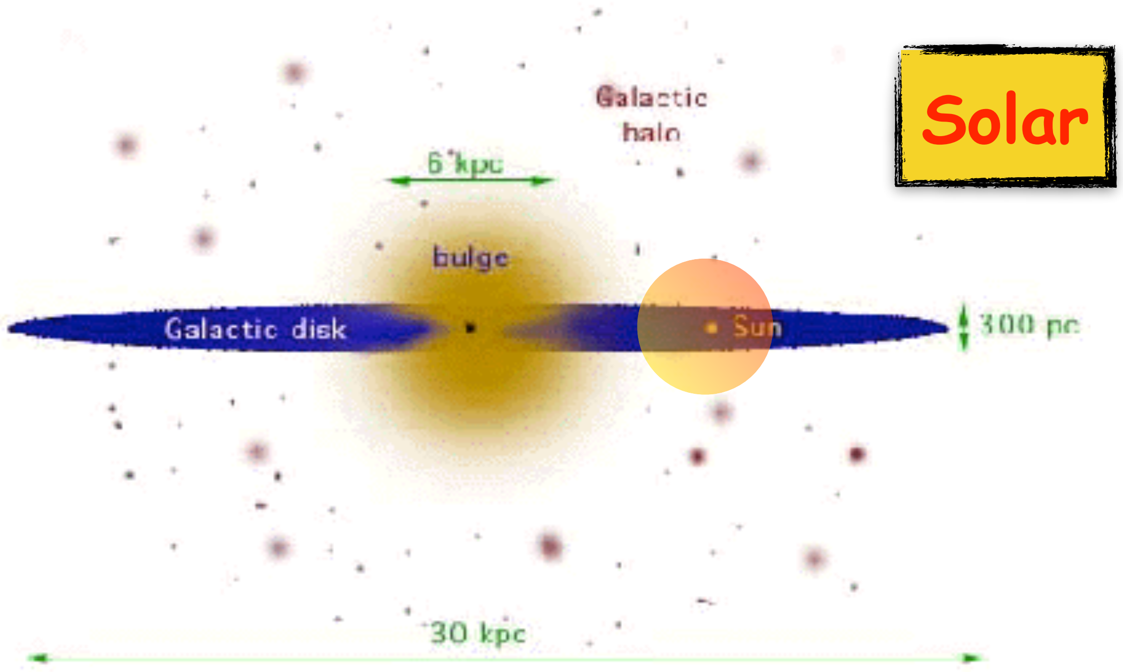
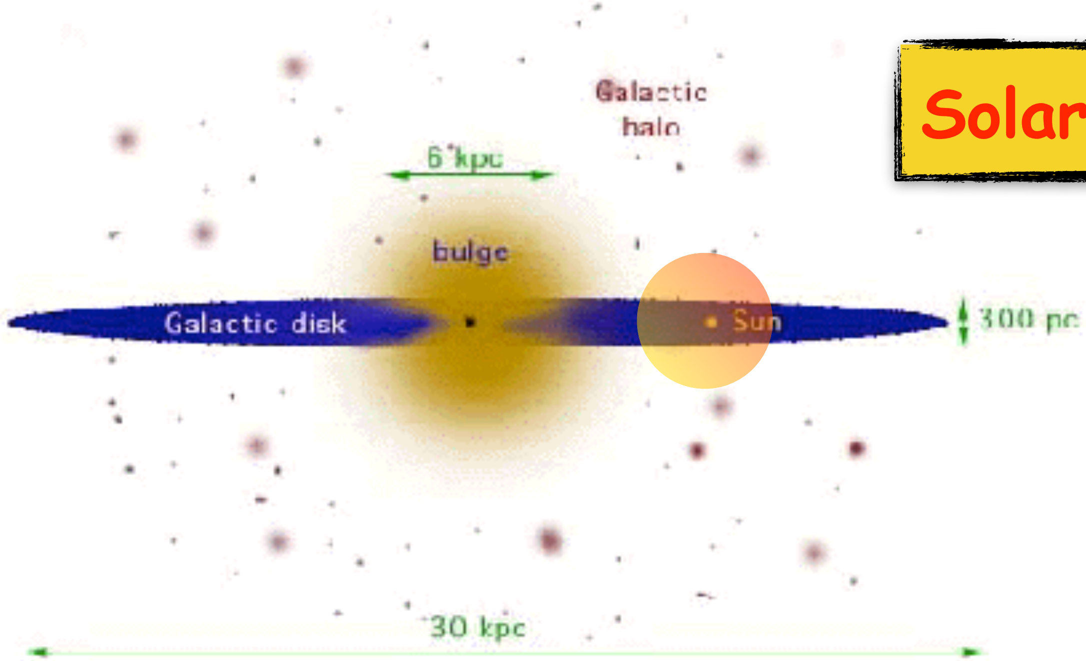


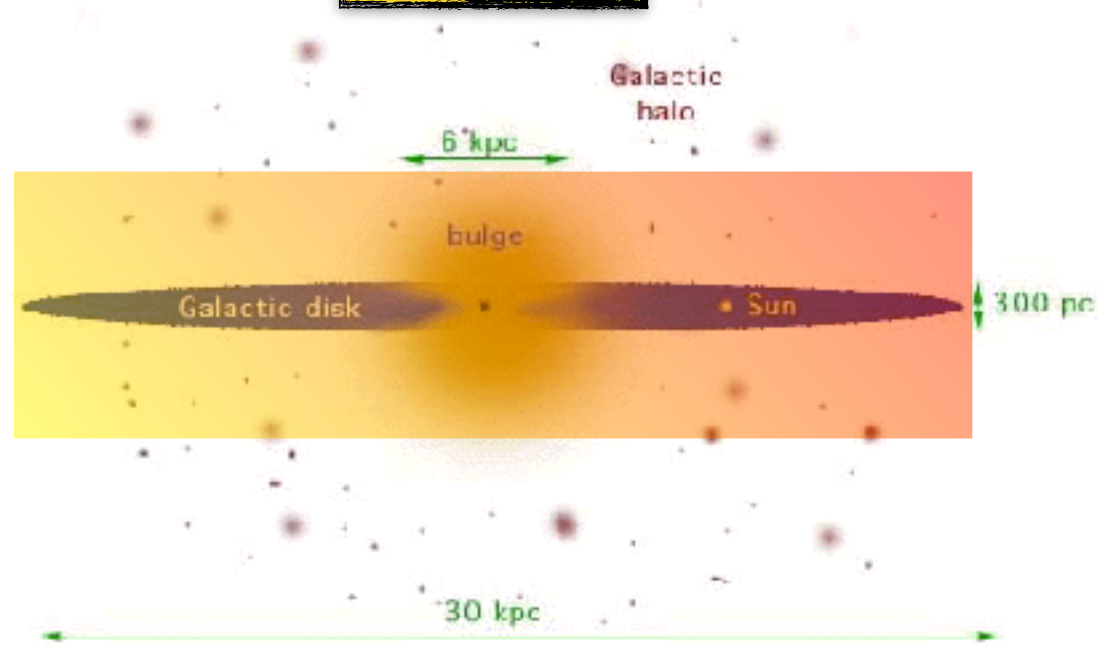
Three scenarios

Three scenarios

Solar

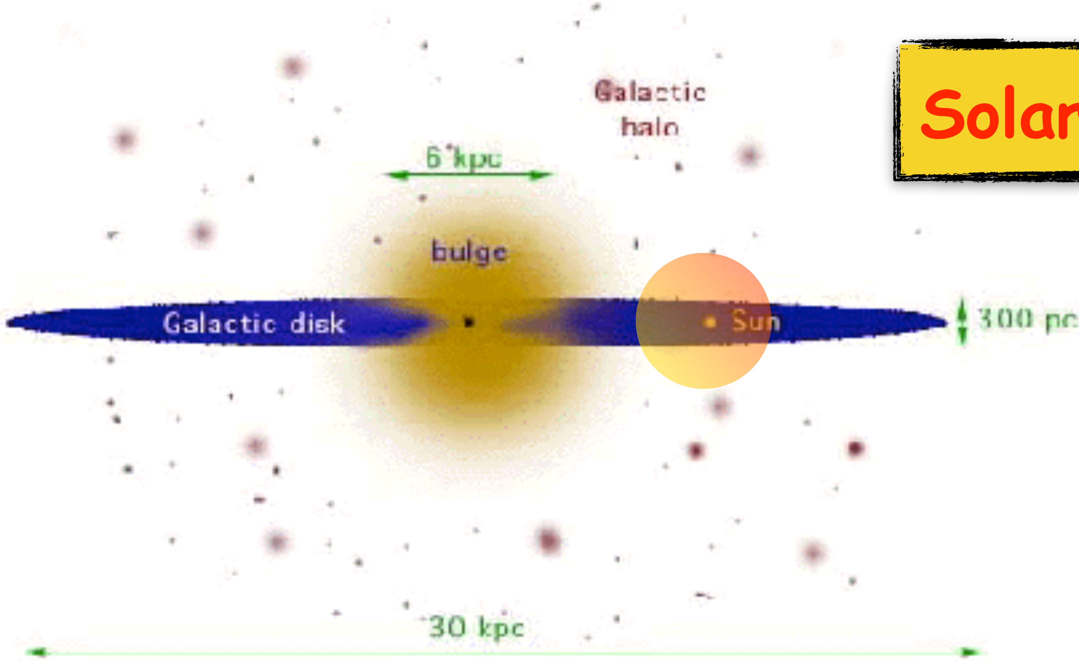


Galactic

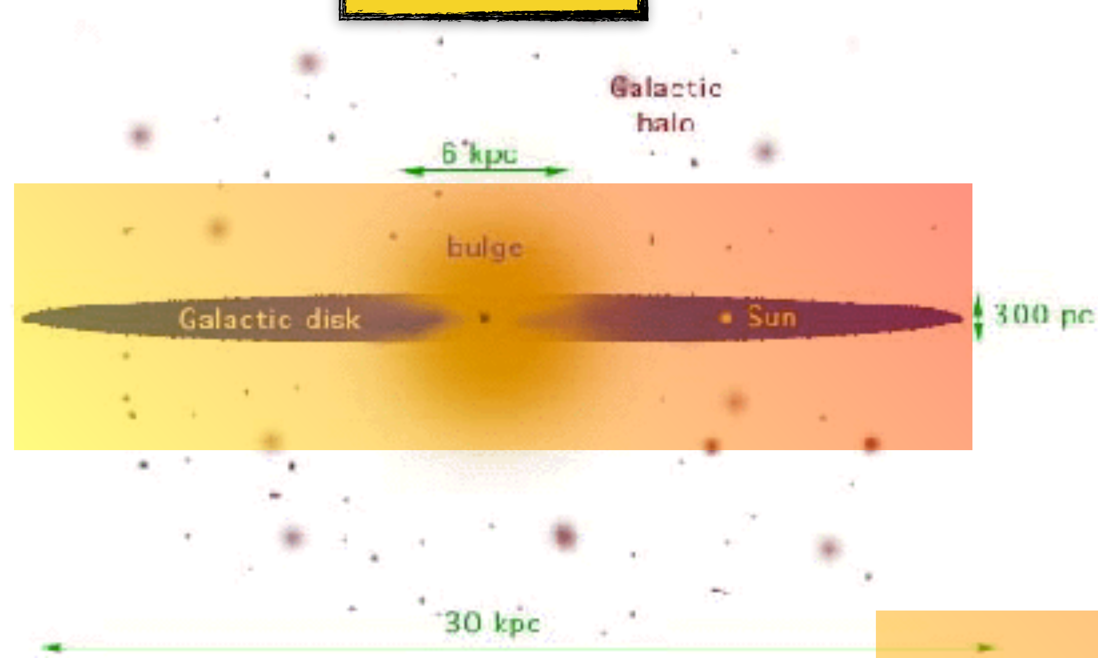


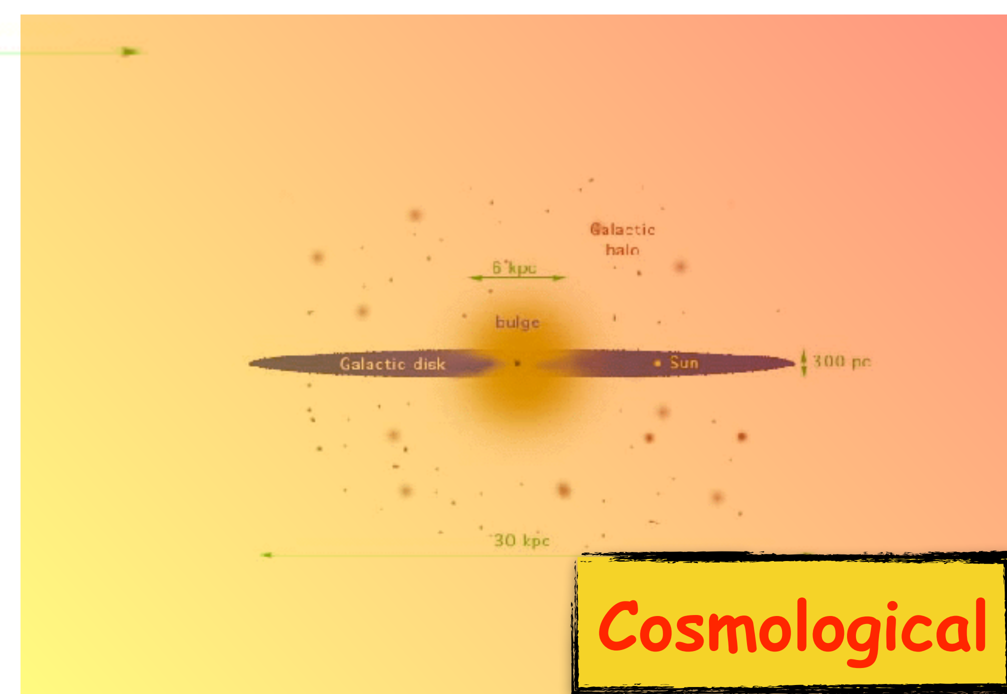
Three scenarios

Solar



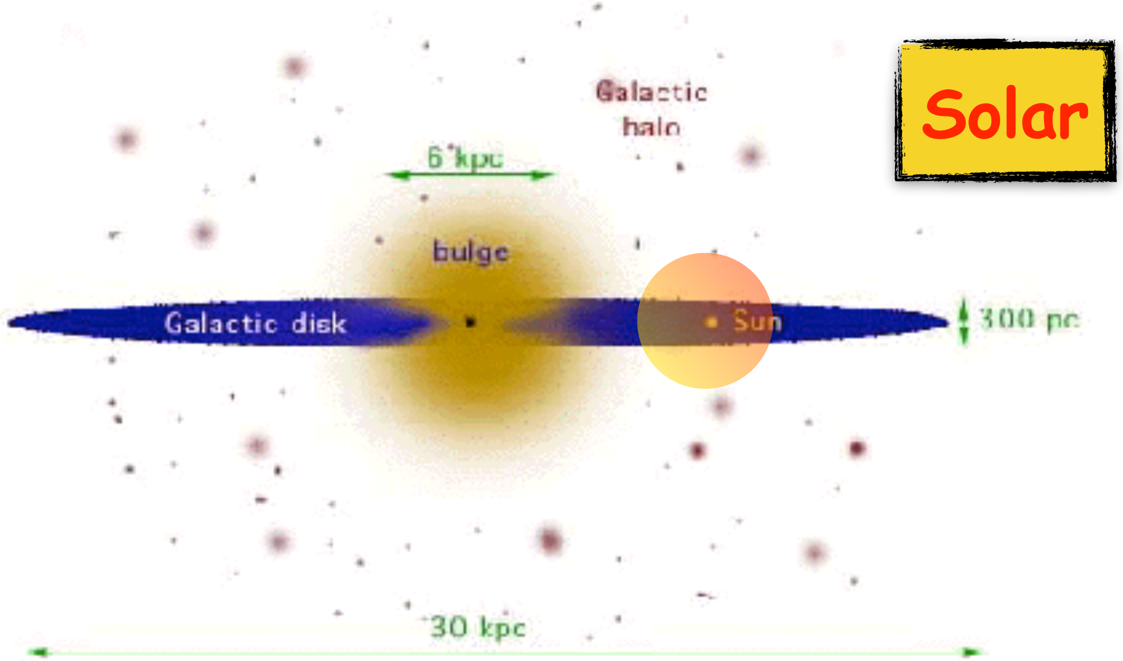
Galactic

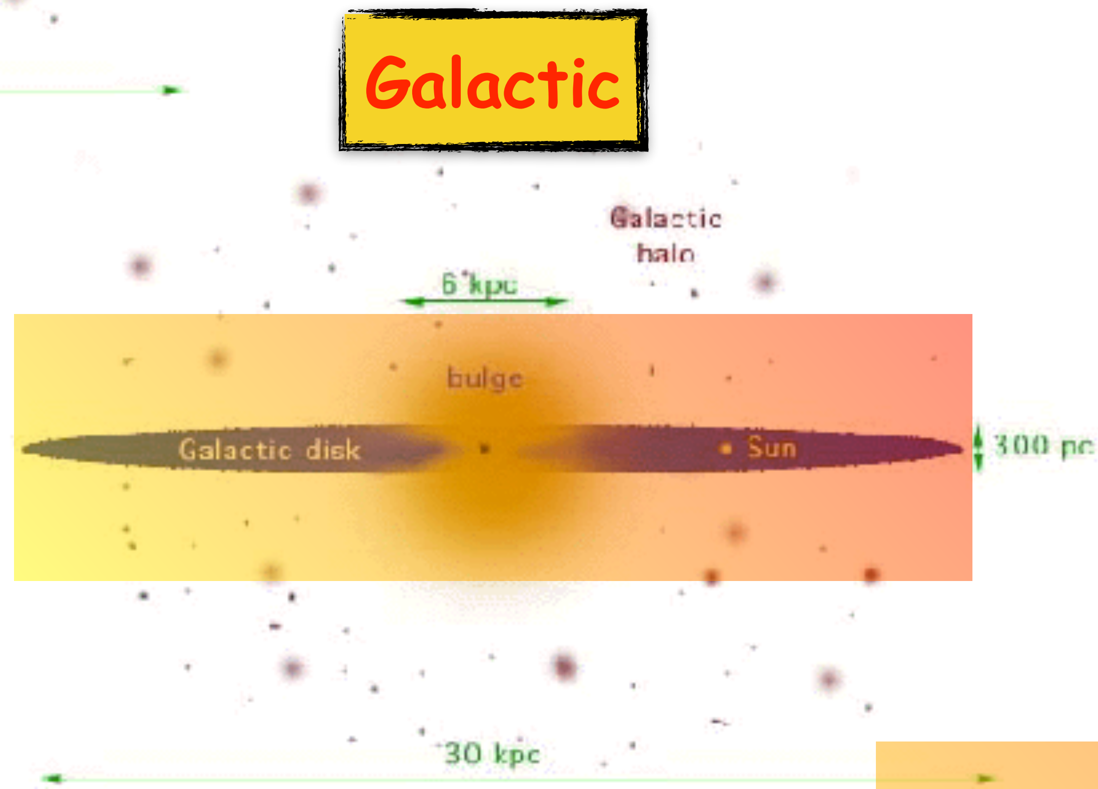


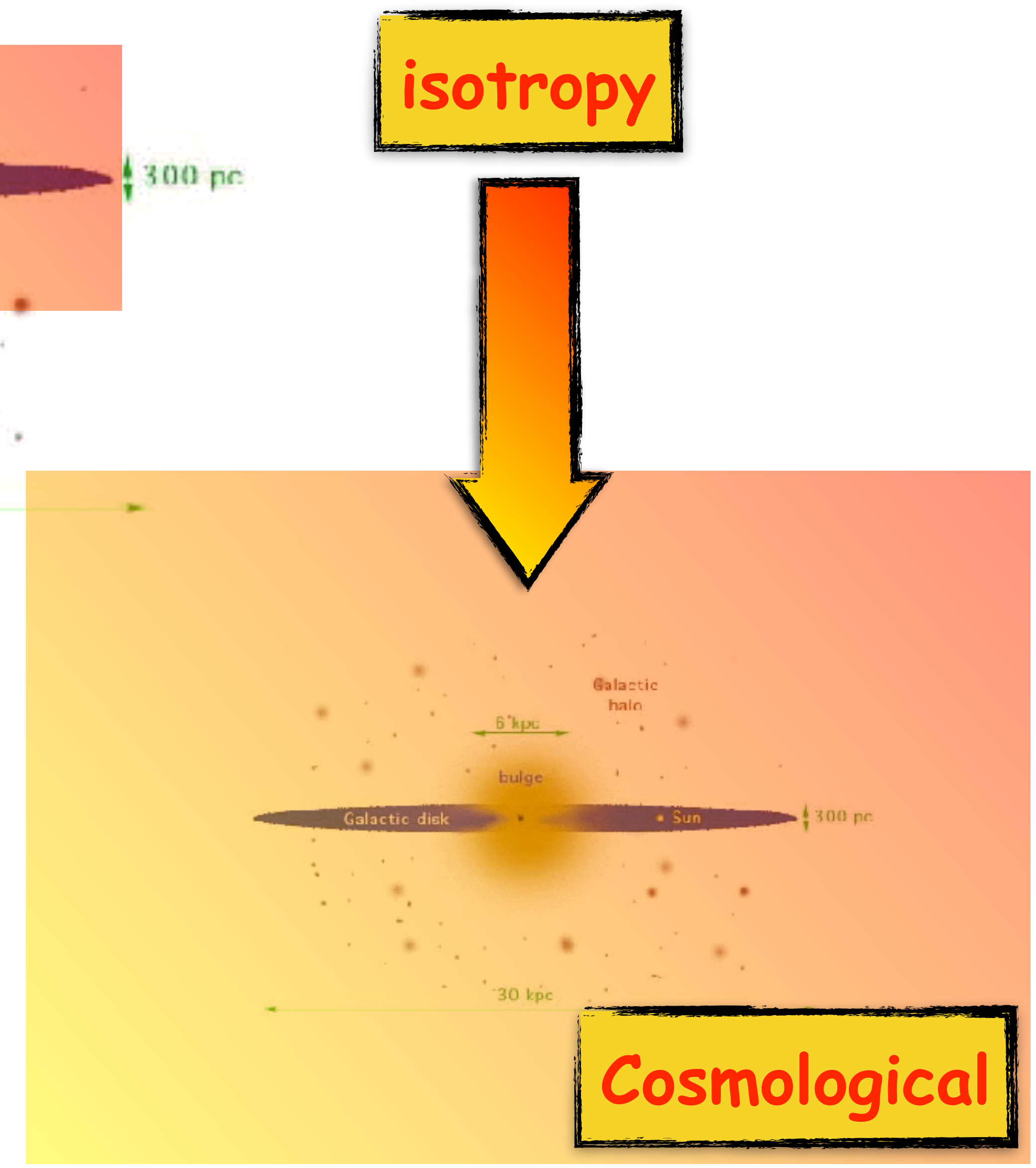


Cosmological

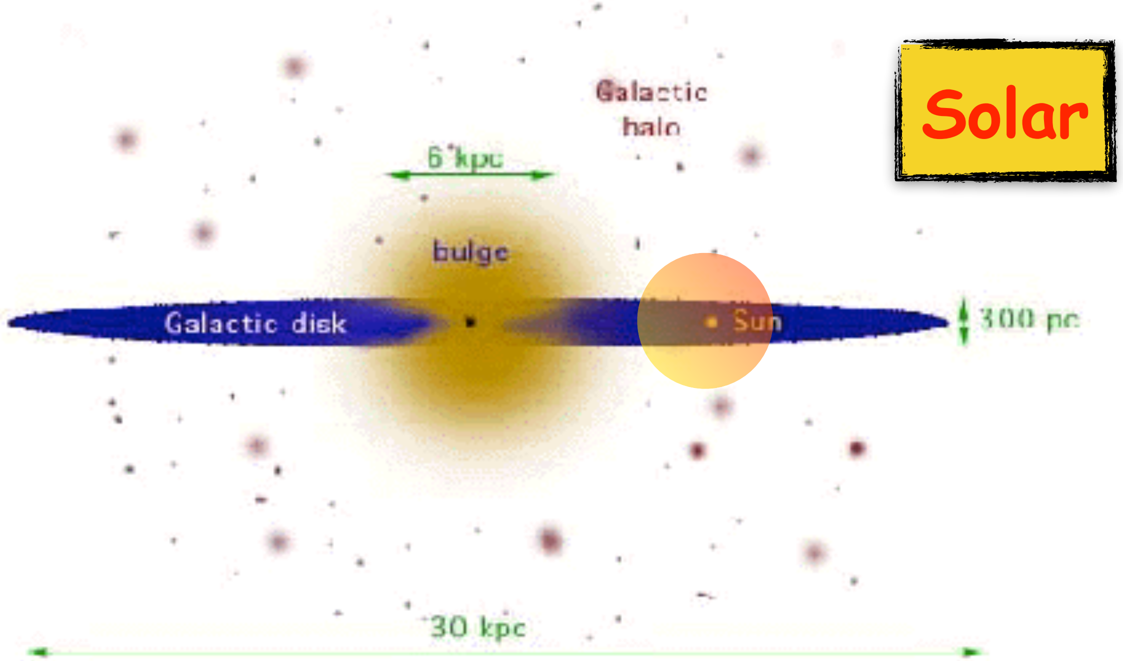
Three scenarios

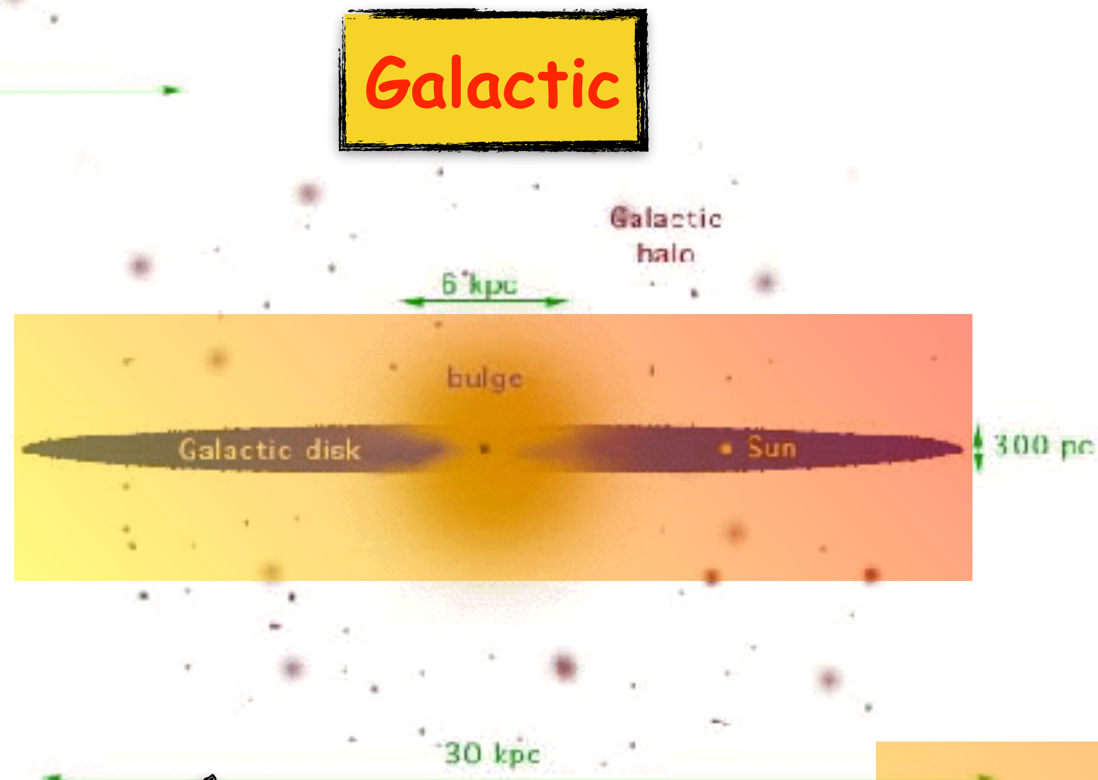


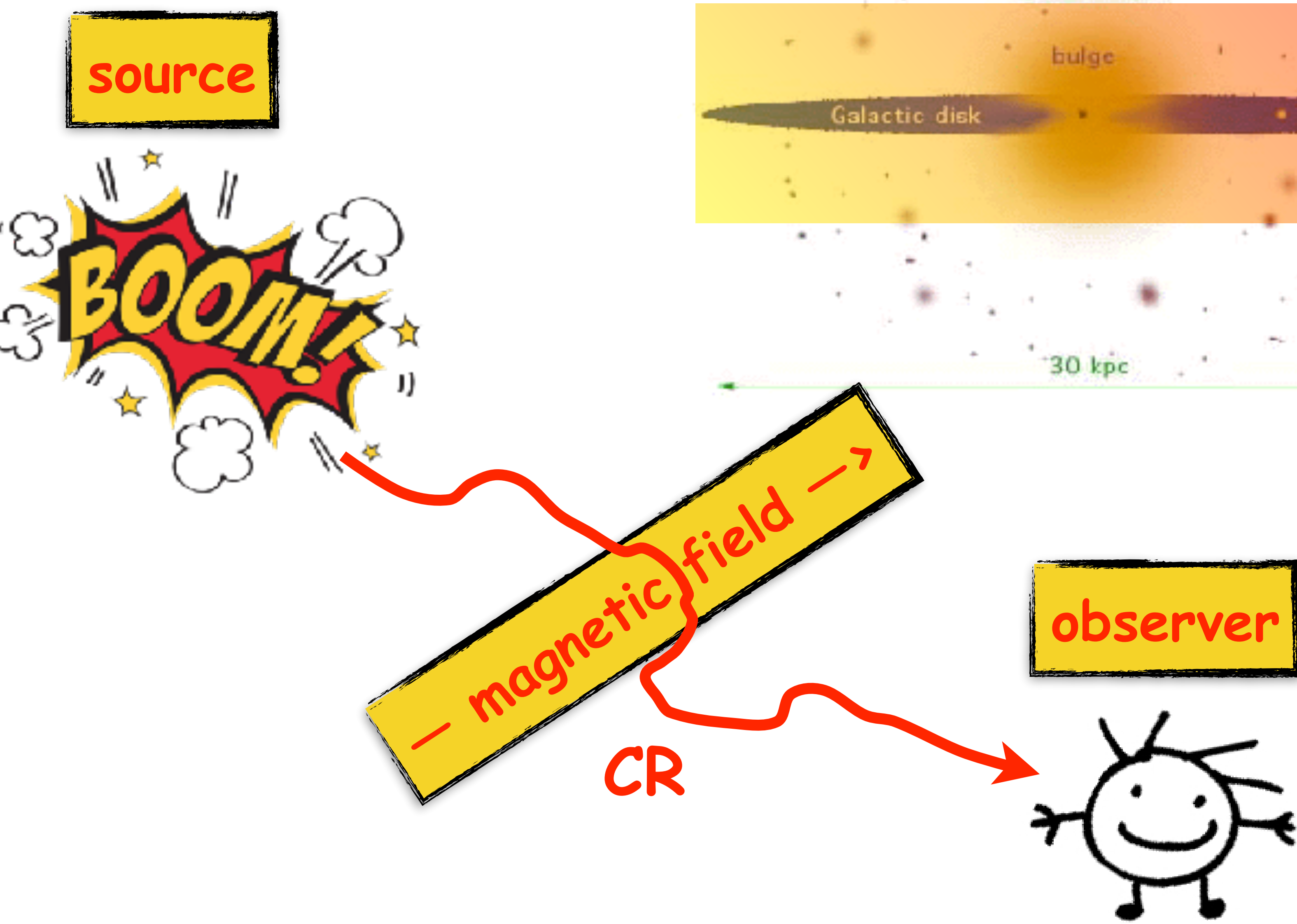


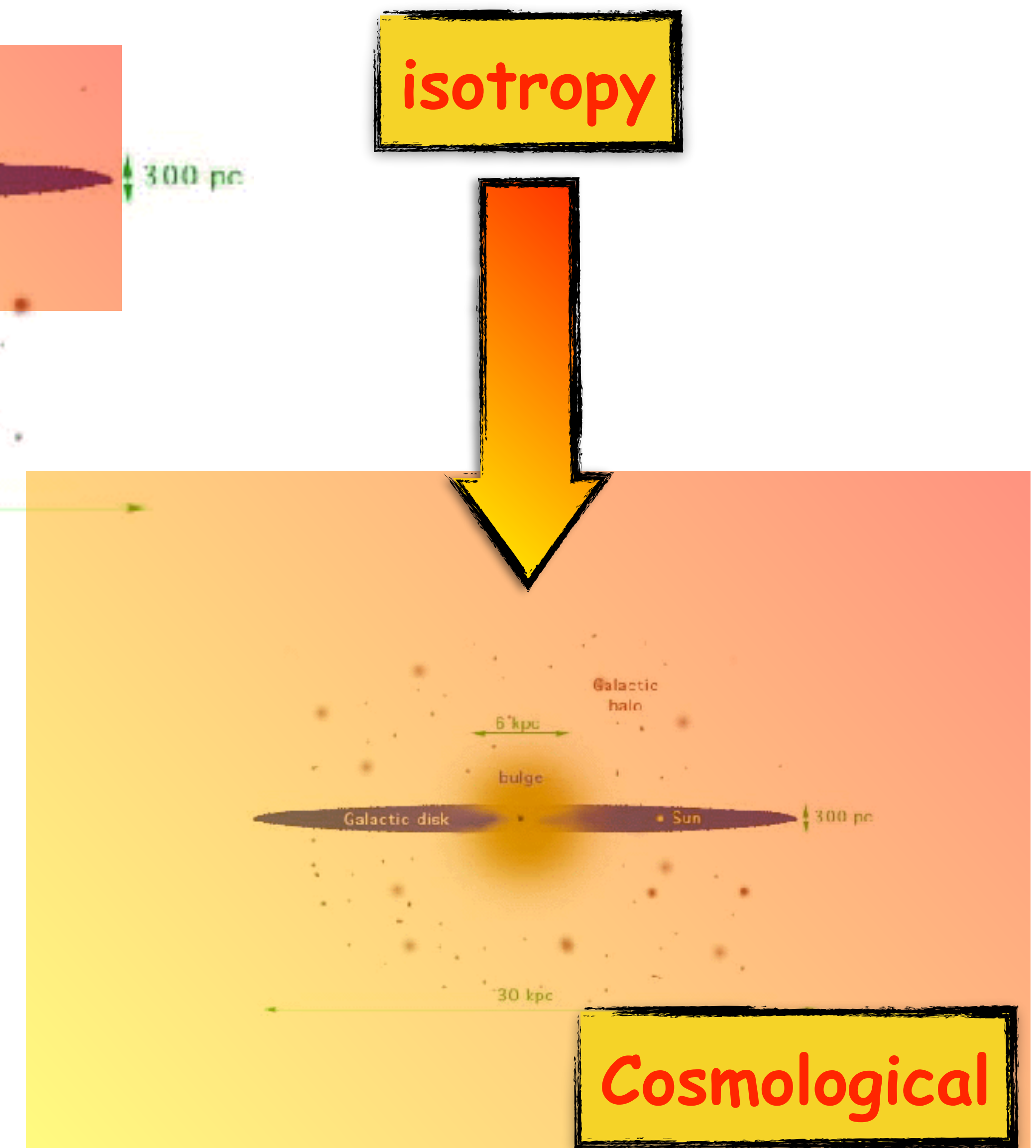


Three scenarios

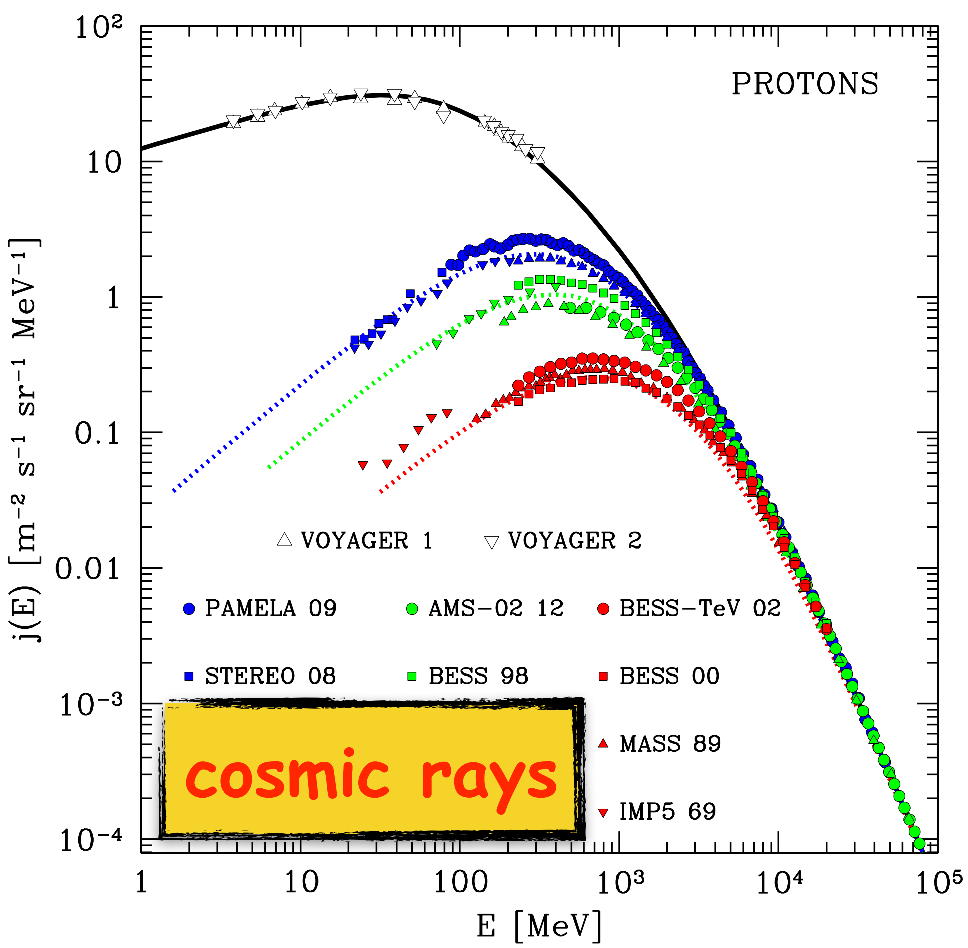








Hayakawa's test (1952): diffuse emission



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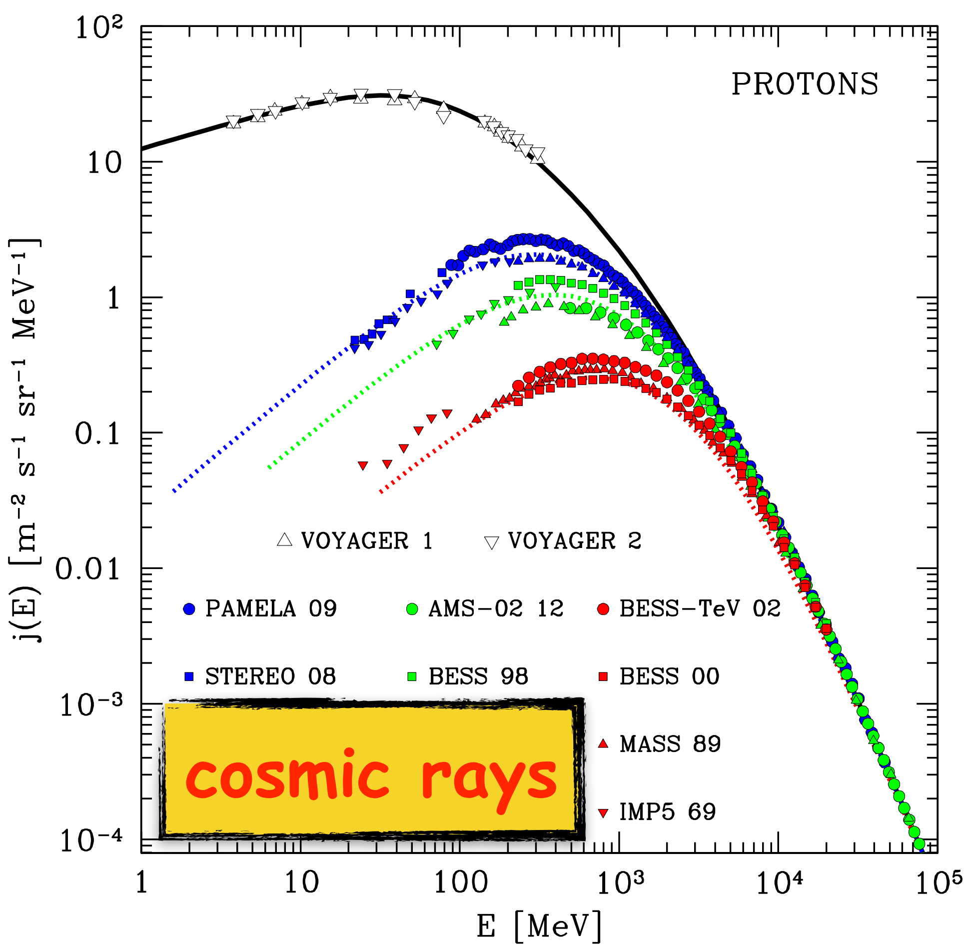

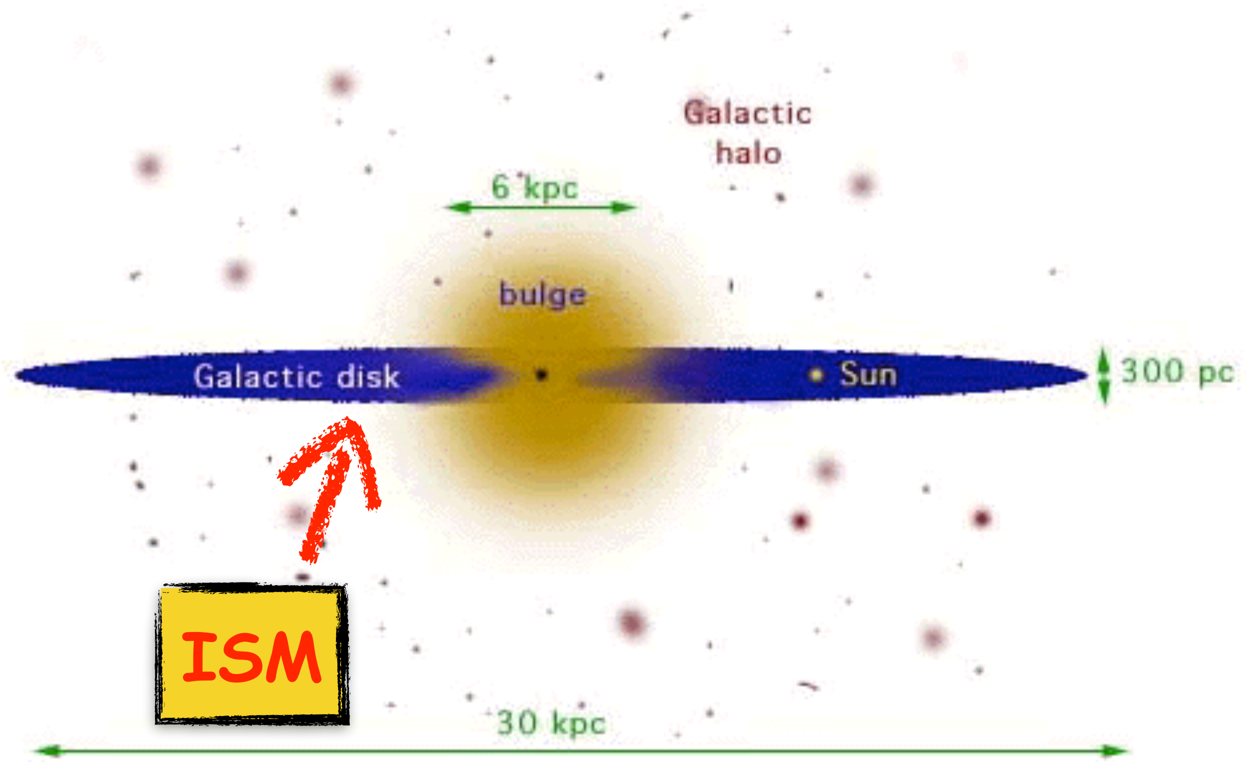

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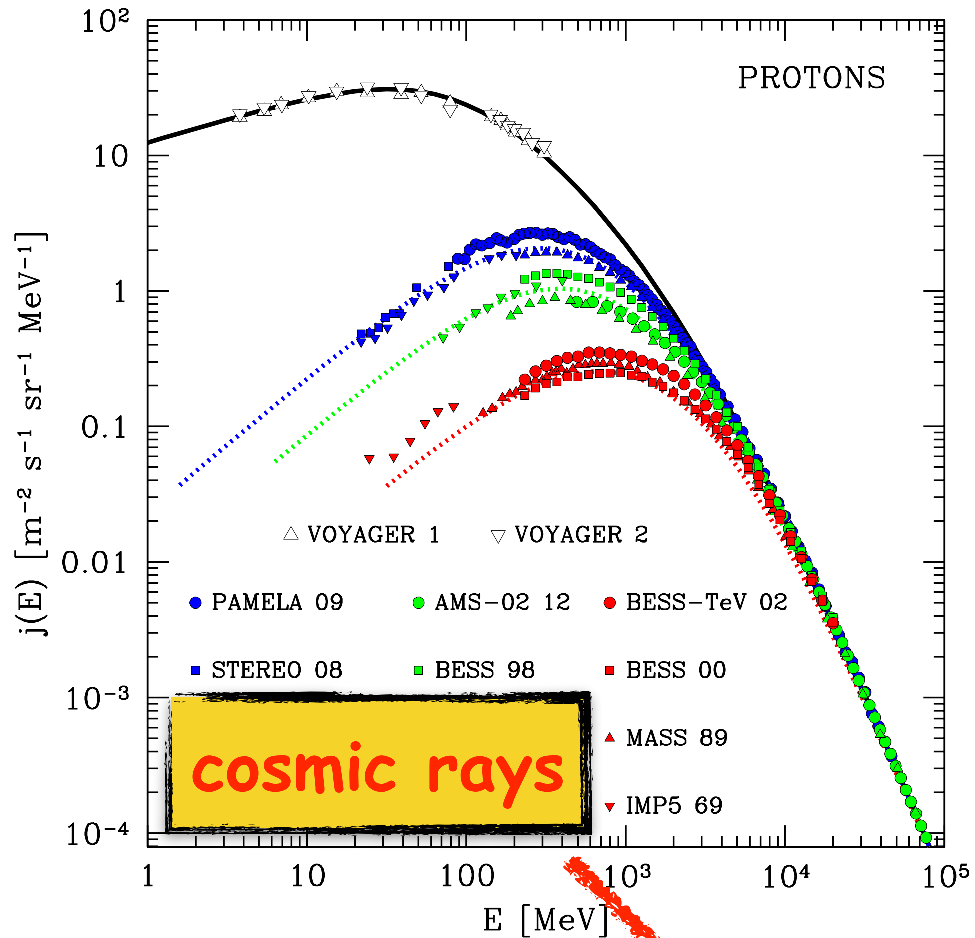
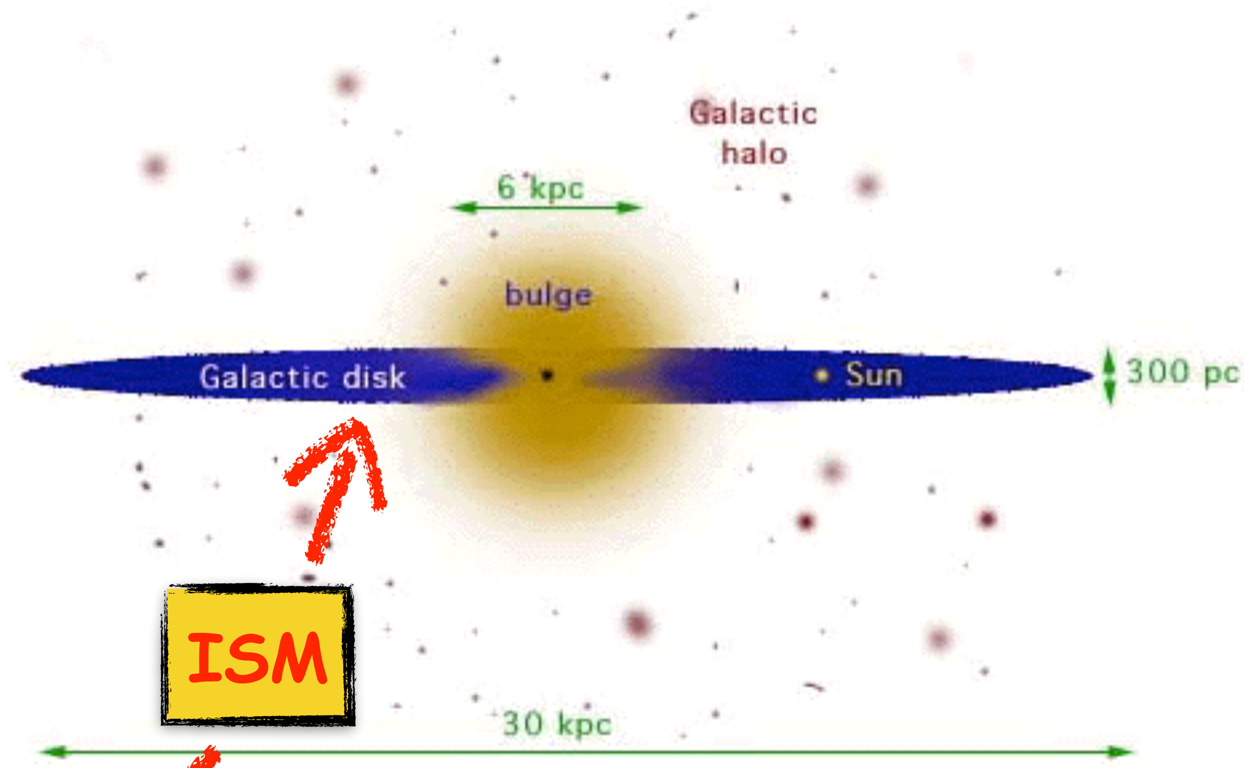
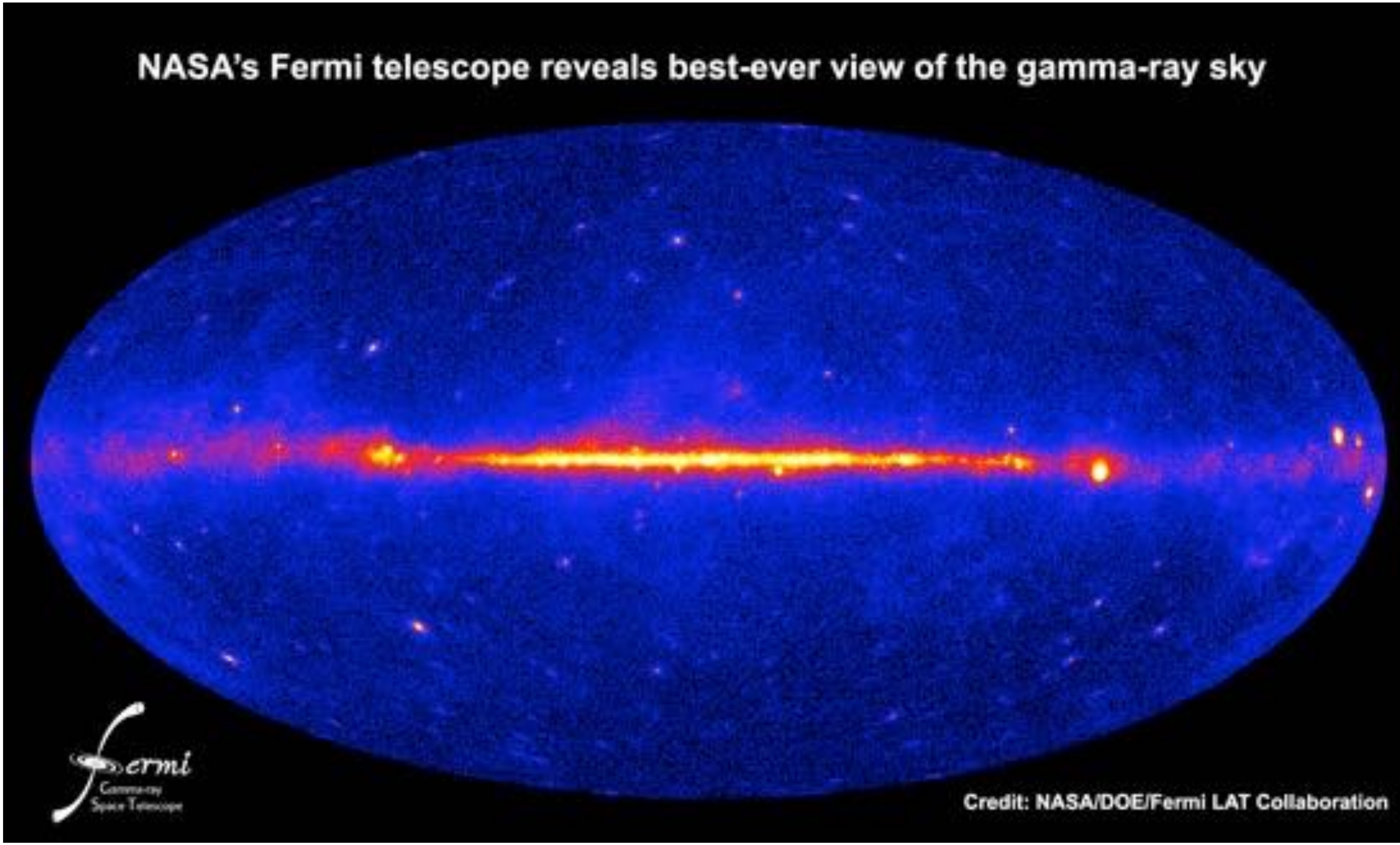




$$p + p \rightarrow p + p + \pi^0$$

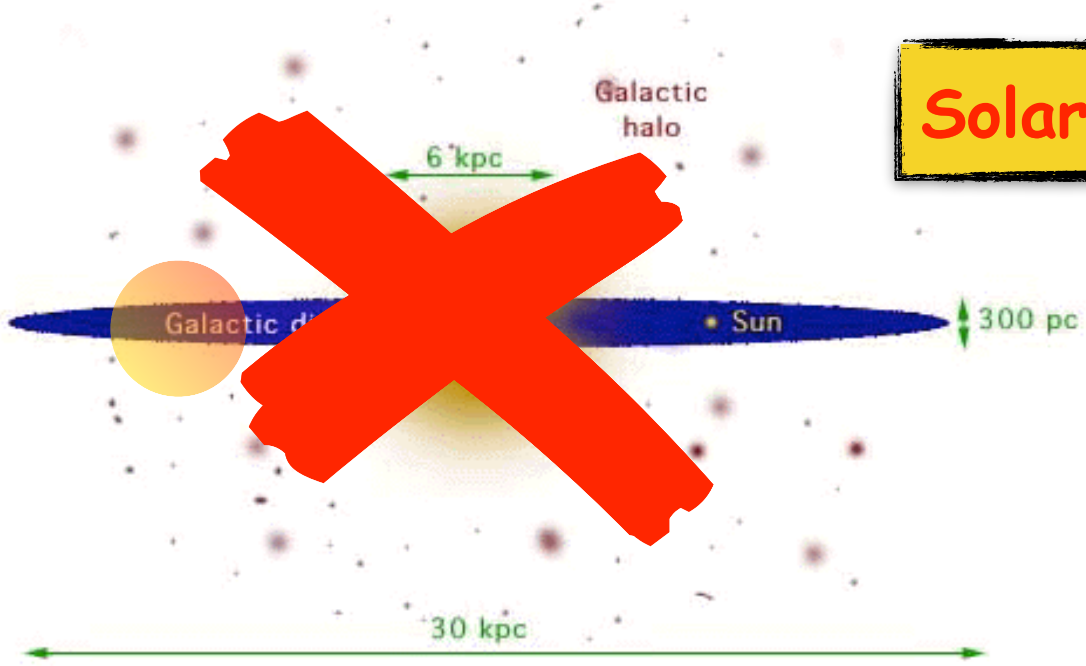
$$\pi^0 \rightarrow \gamma + \gamma$$

Hayakawa's test (1952): diffuse emission

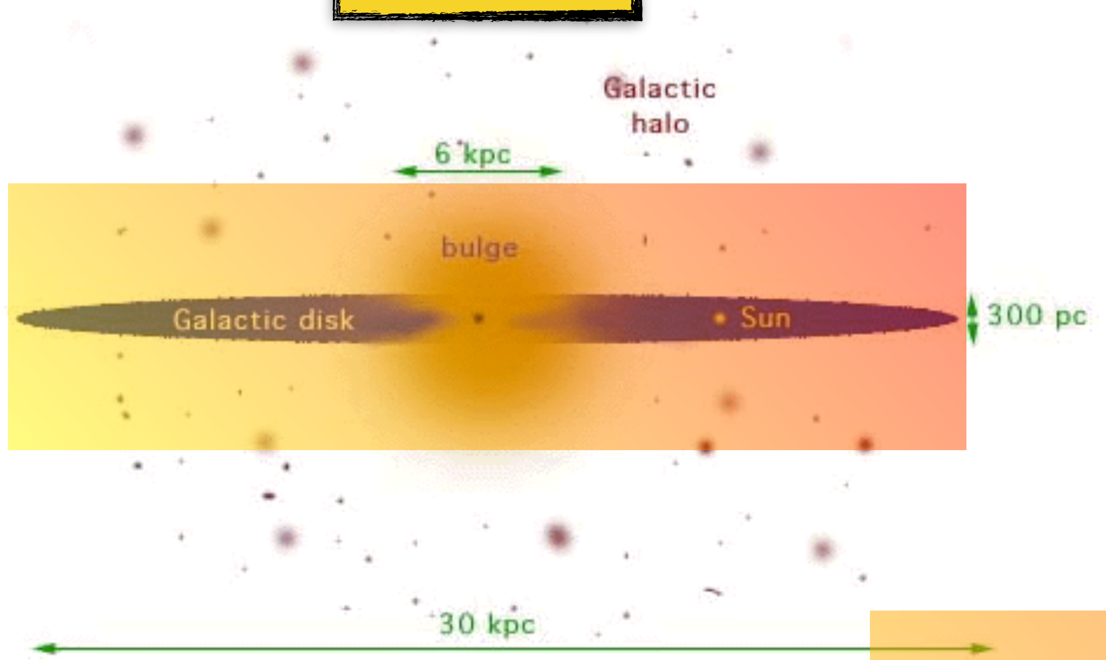


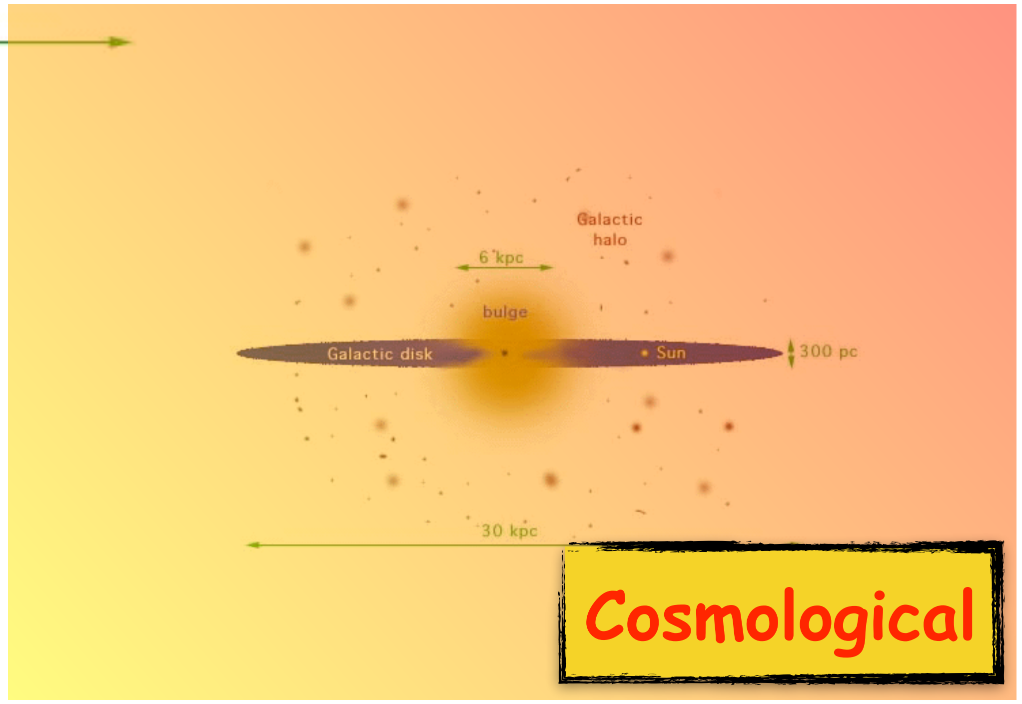
Three scenarios

Solar



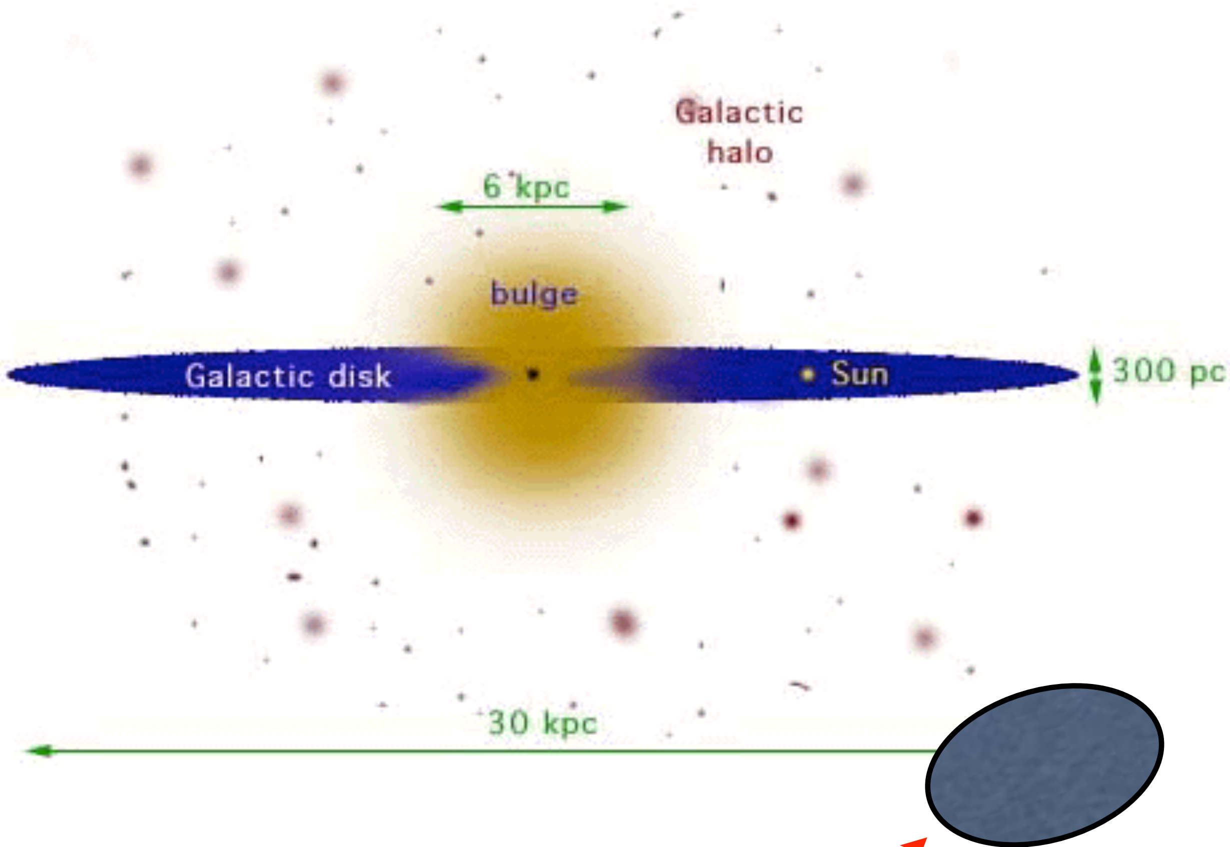
Galactic





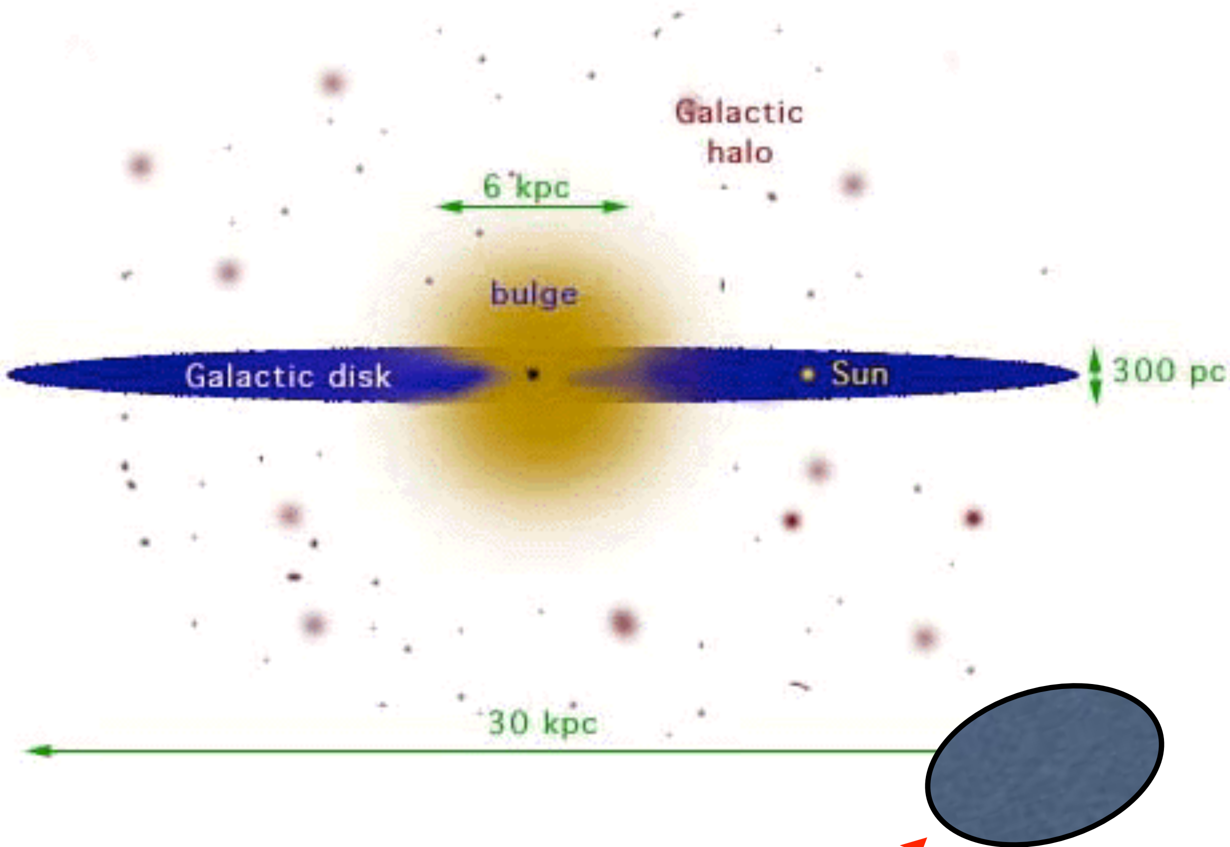
Cosmological

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

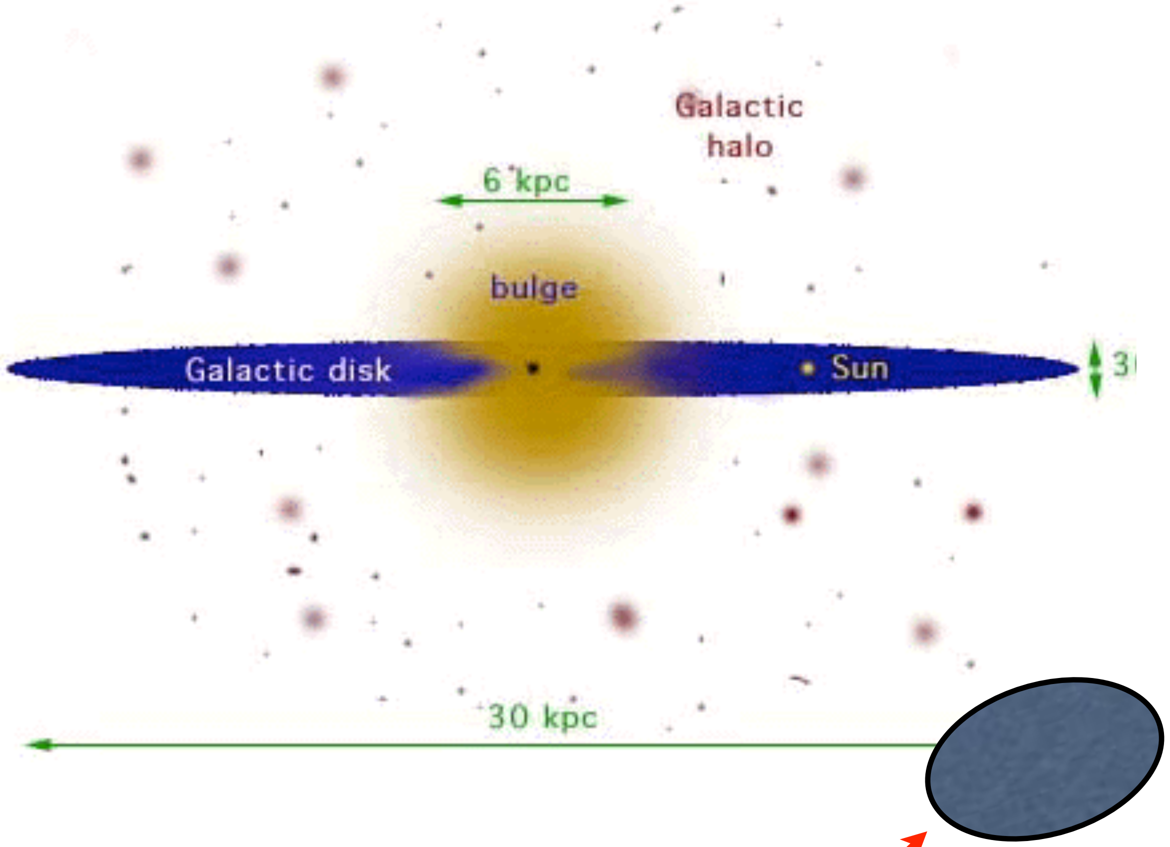
—> we can predict the gamma-ray flux from the SMC

—> it should have been detected by EGRET

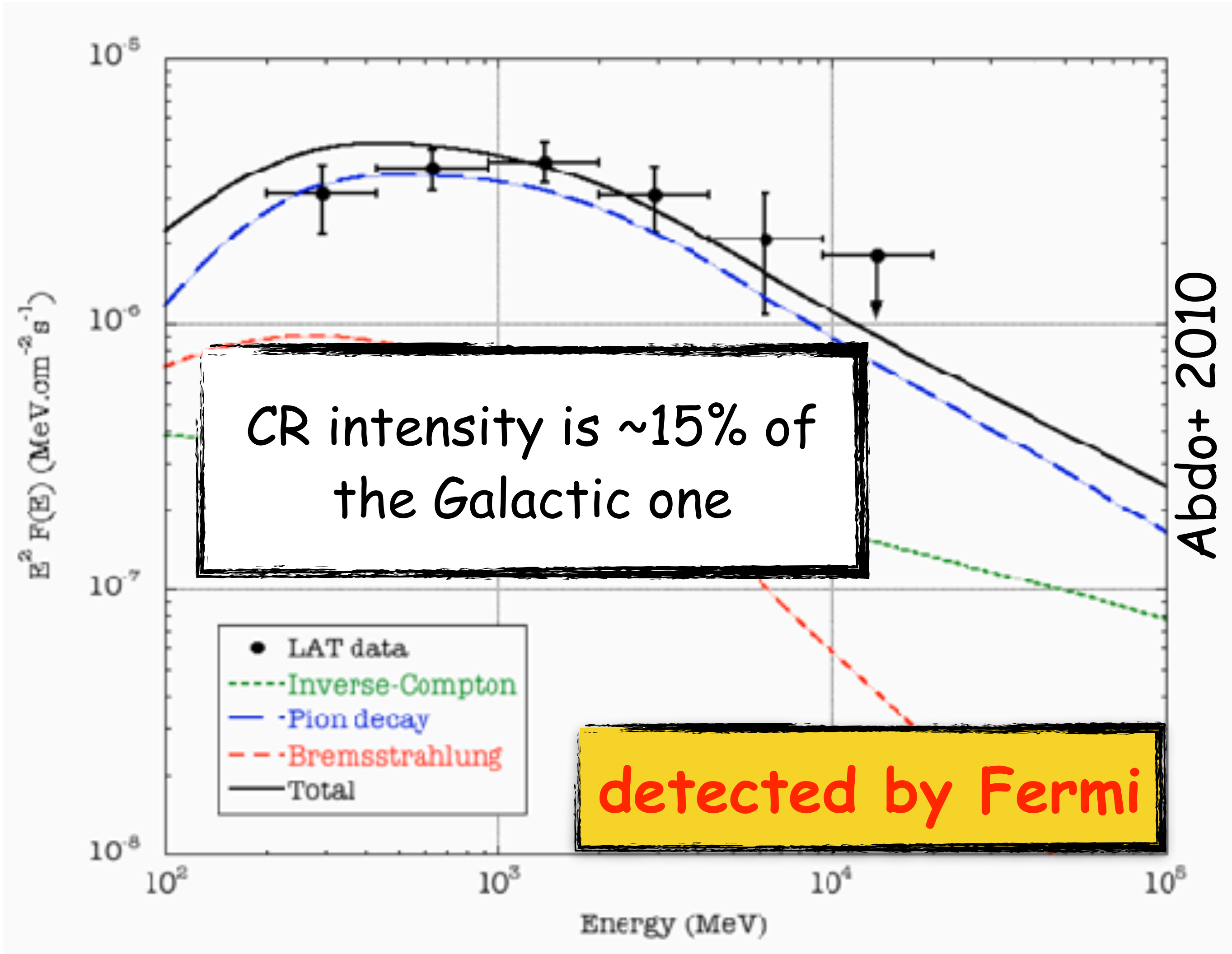
—> but it was not! (Sreekumar+ 1993)

—> CRs are **NOT cosmological**

Diffuse emission in other galaxies



Small Magellanic Cloud



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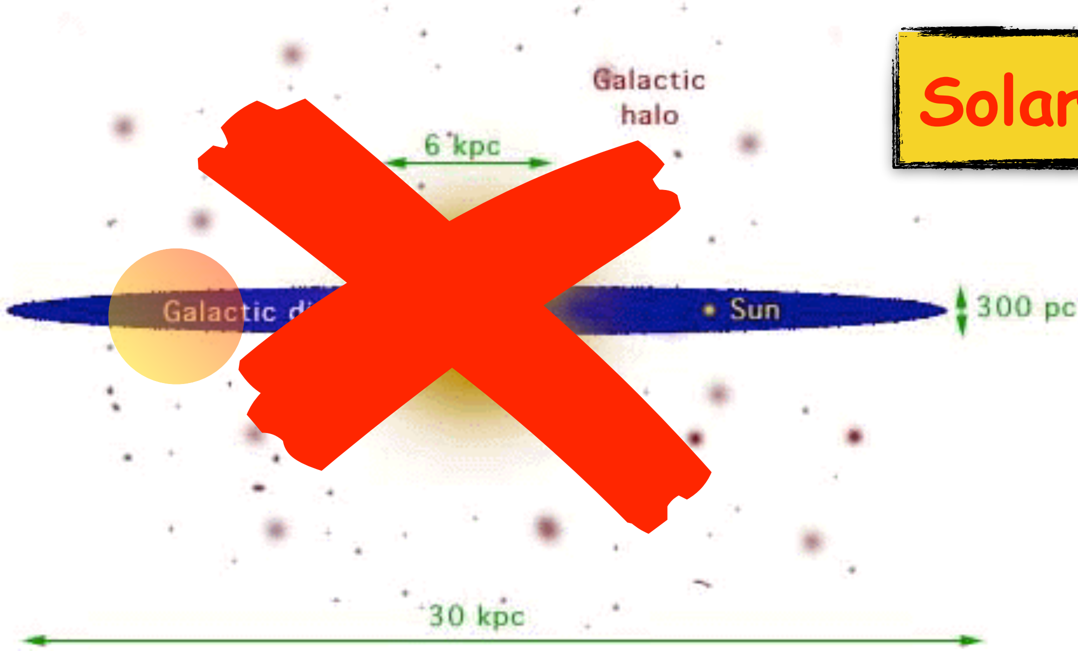
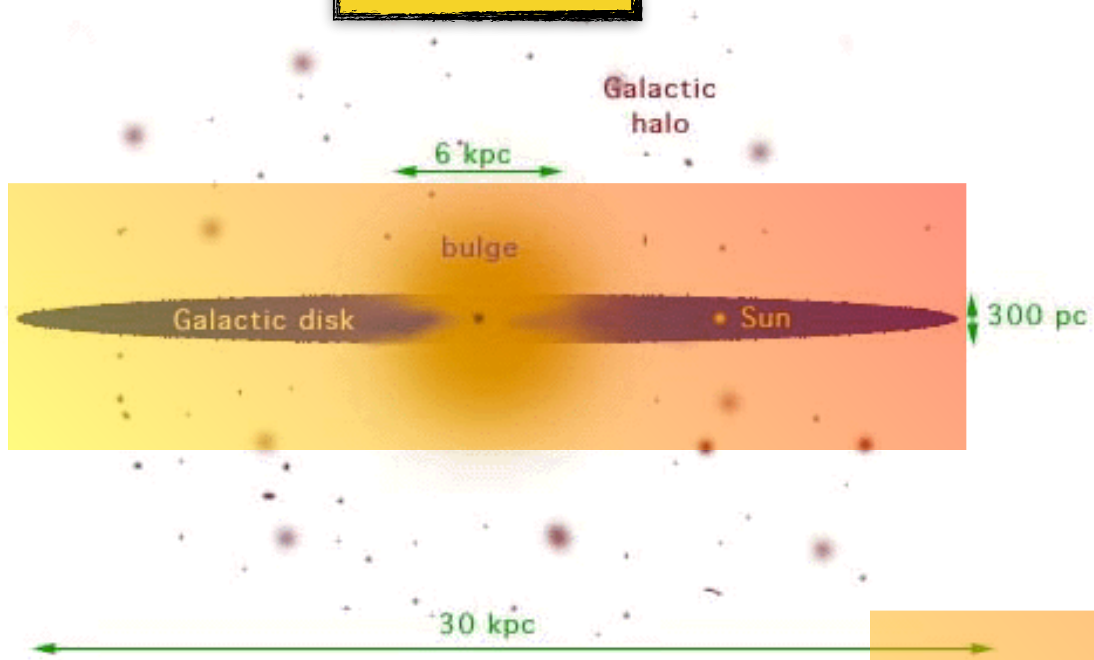
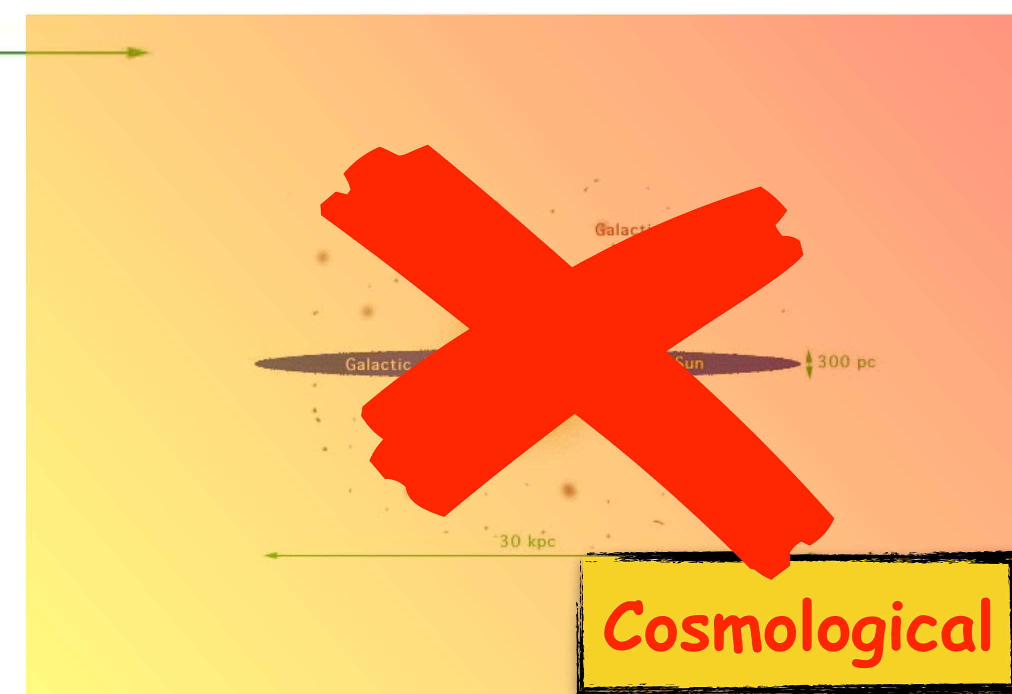
CRs are Galactic

Solar



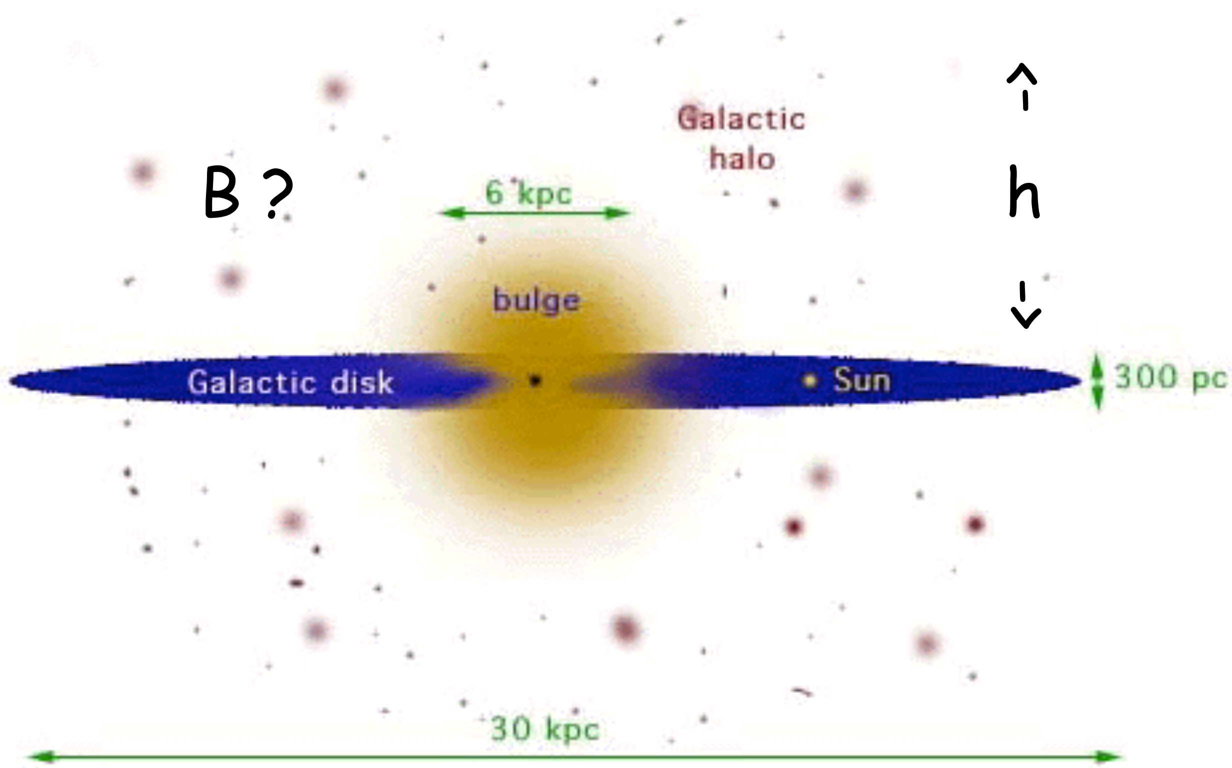
Galactic





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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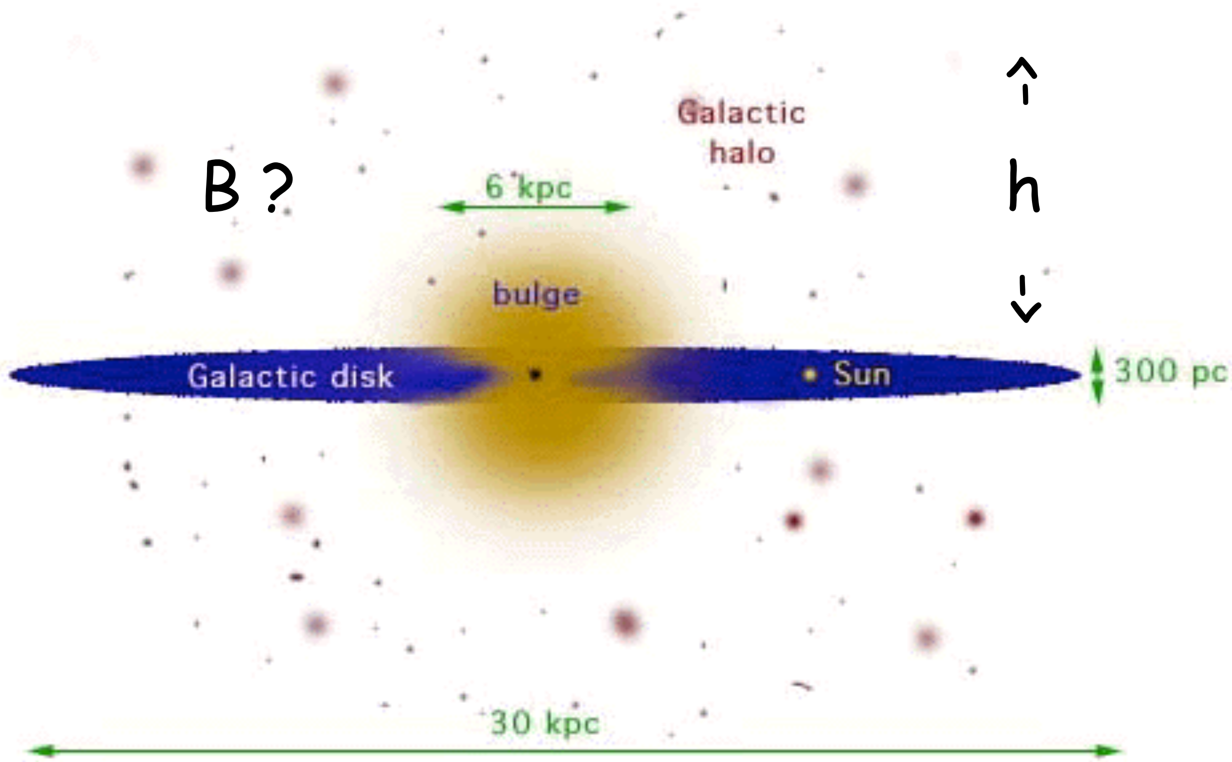

It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

Confinement condition:

$$R_L < h$$

Larmor radius

halo size

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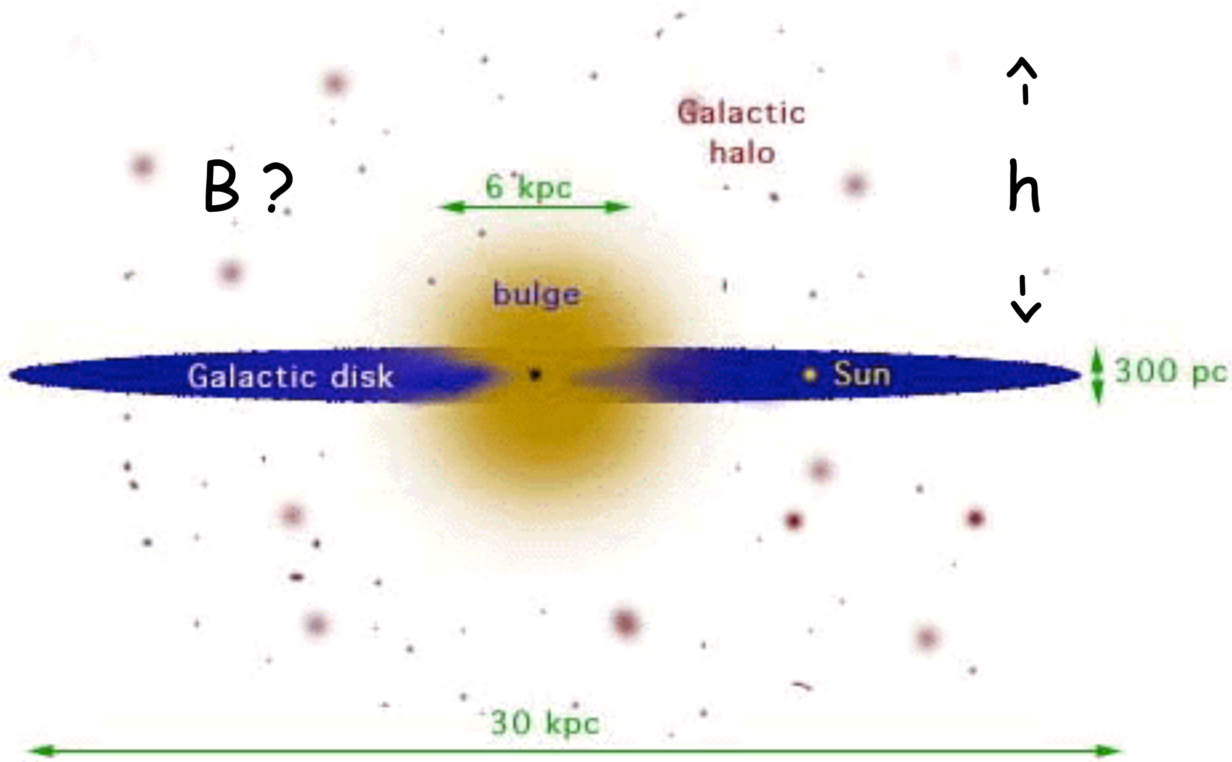


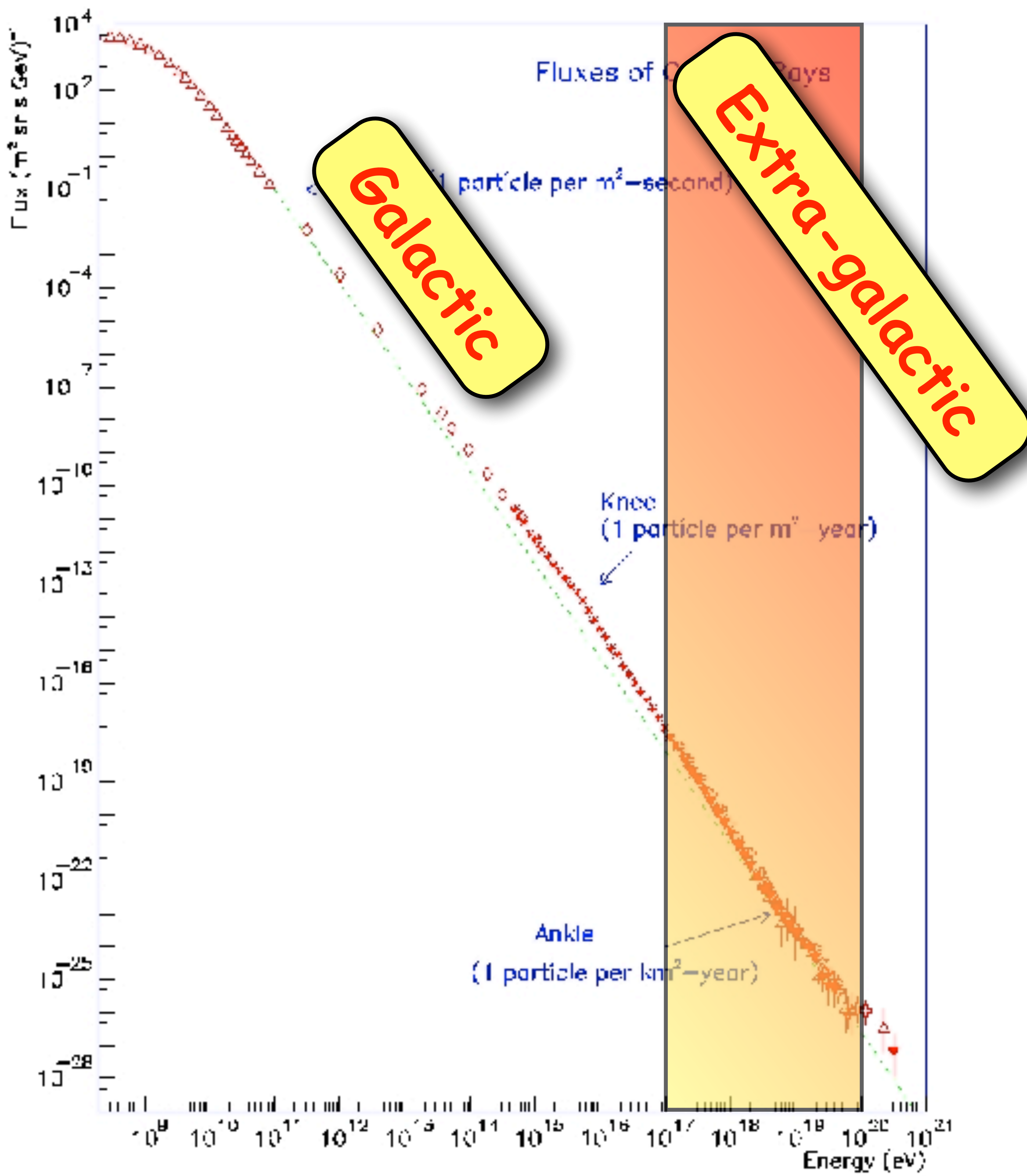
It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

Confinement condition:

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

(cm) Larmor radius halo size 1 - 10 0.1 - 10

Galactic or extra-galactic?



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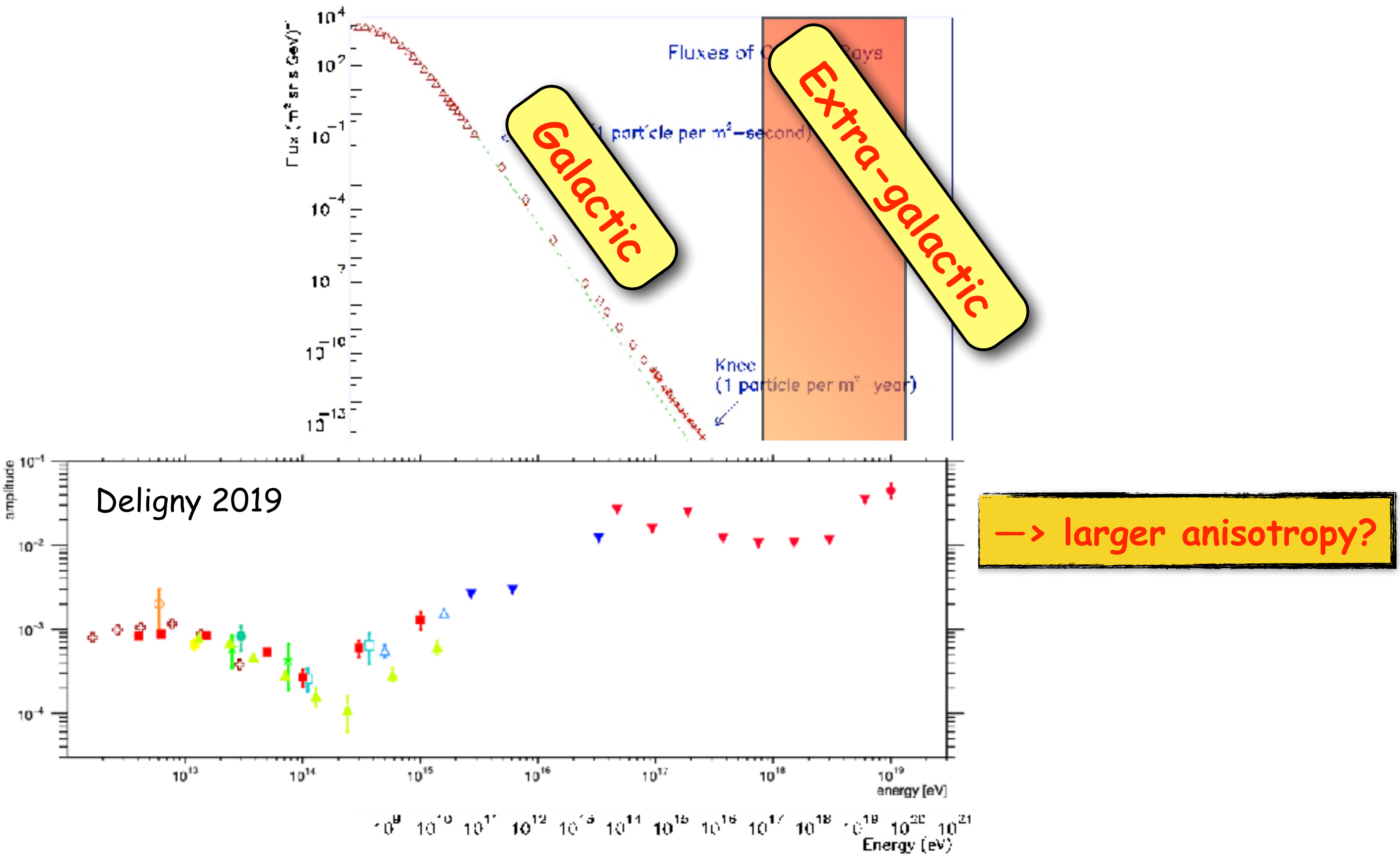
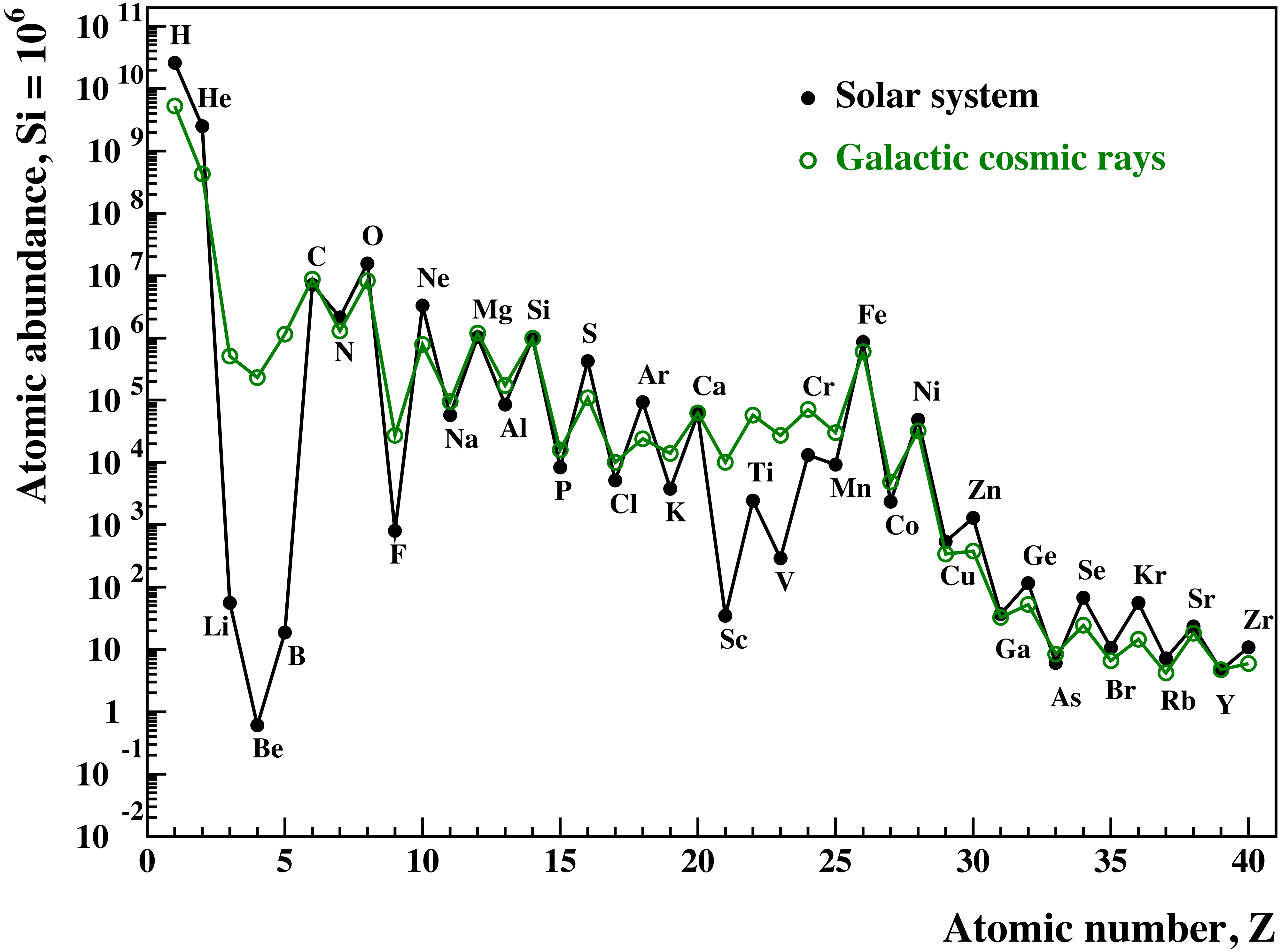


[4] Composition

Composition: striking anomalies



Tatischeff & SG, 2018

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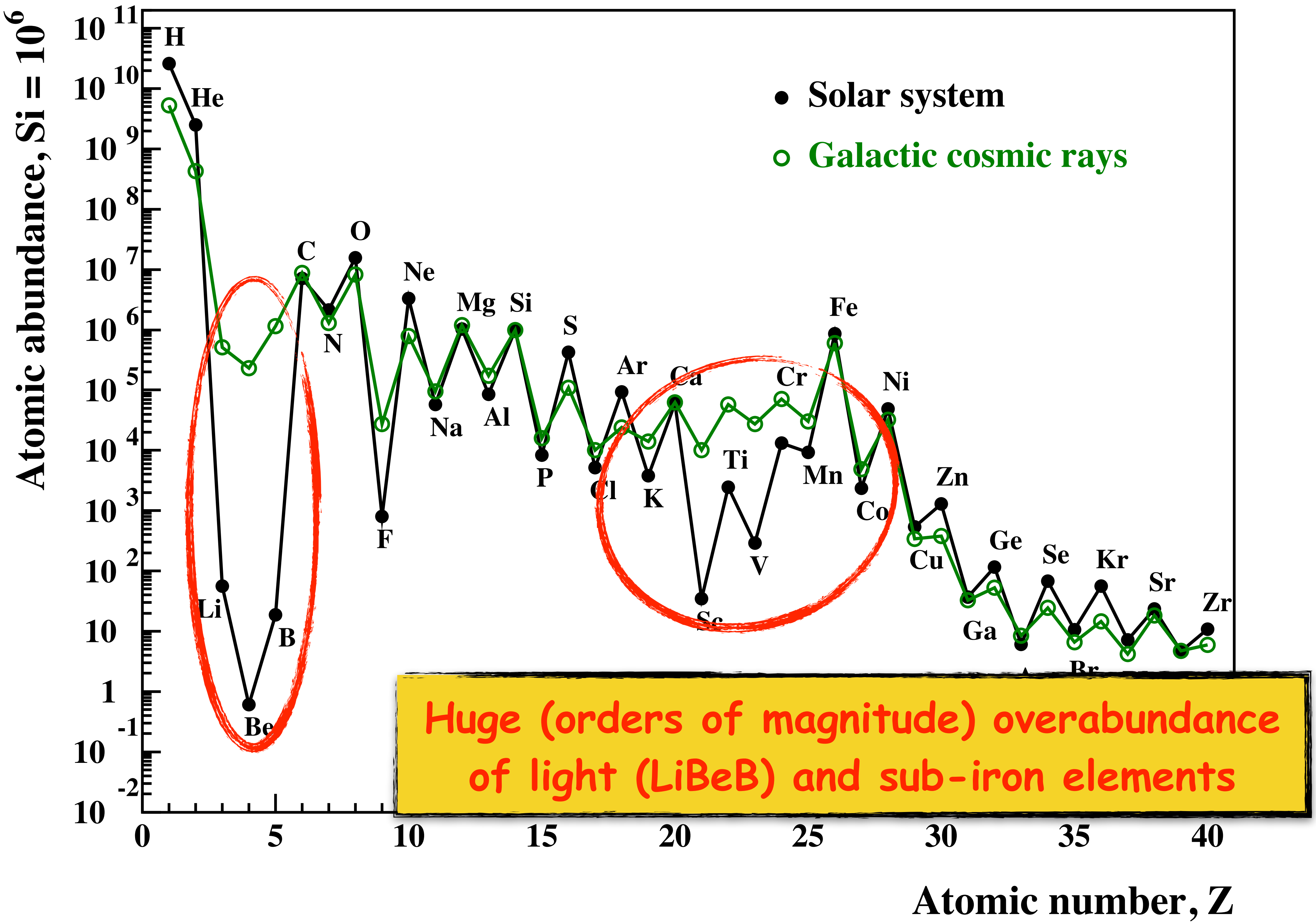
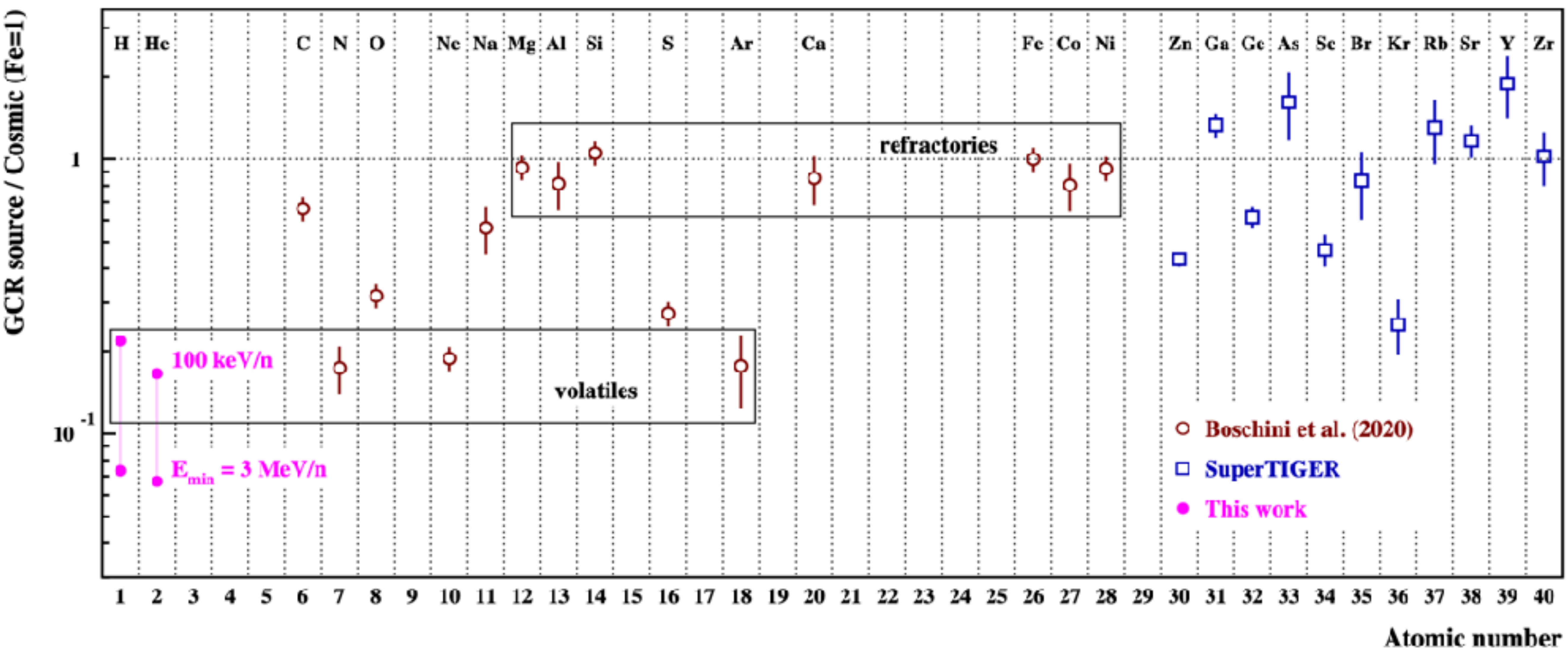


Tatischeff & SG, 2018

Composition: volatiles and refractories



Tatischeff, Raymond, Duprat, SG, Recchia, 2021

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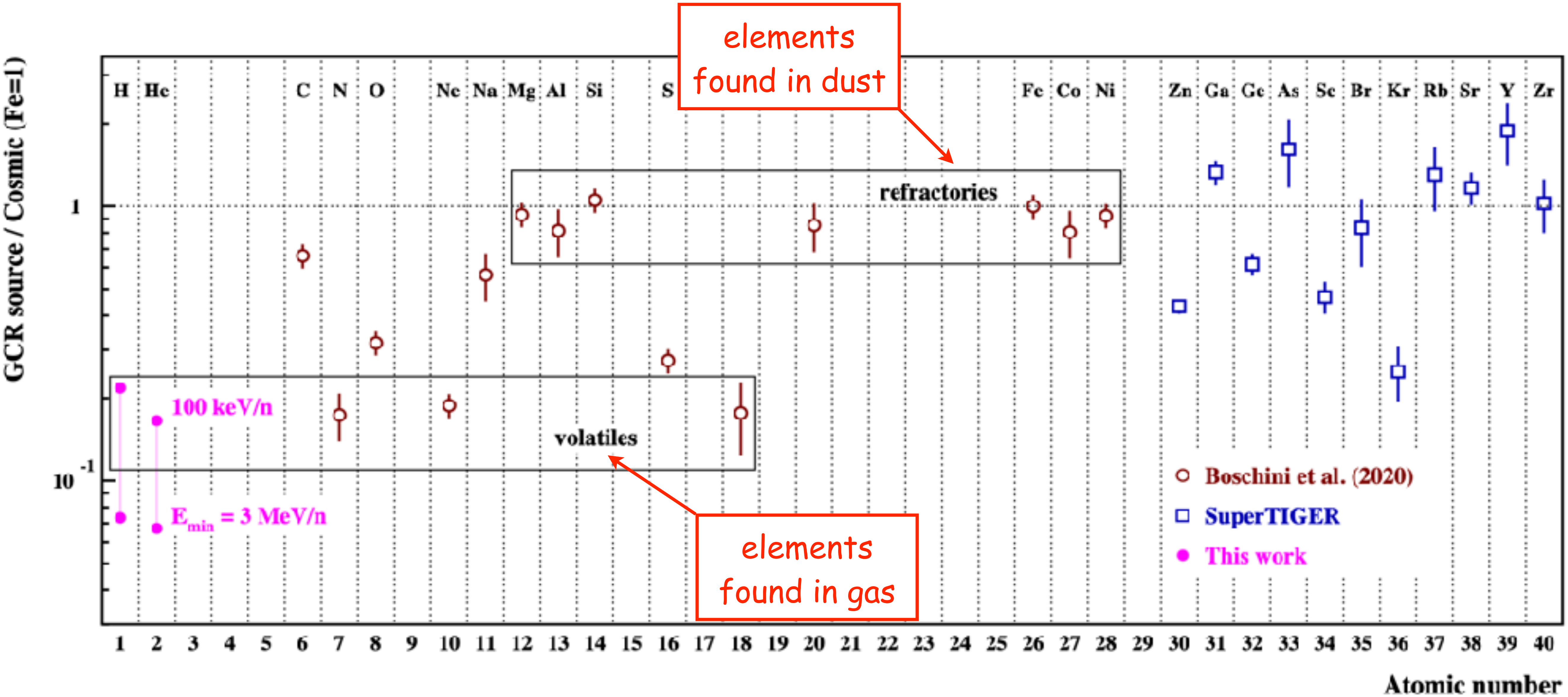

Tatischeff, Raymond, Duprat, SG, Recchia, 2021

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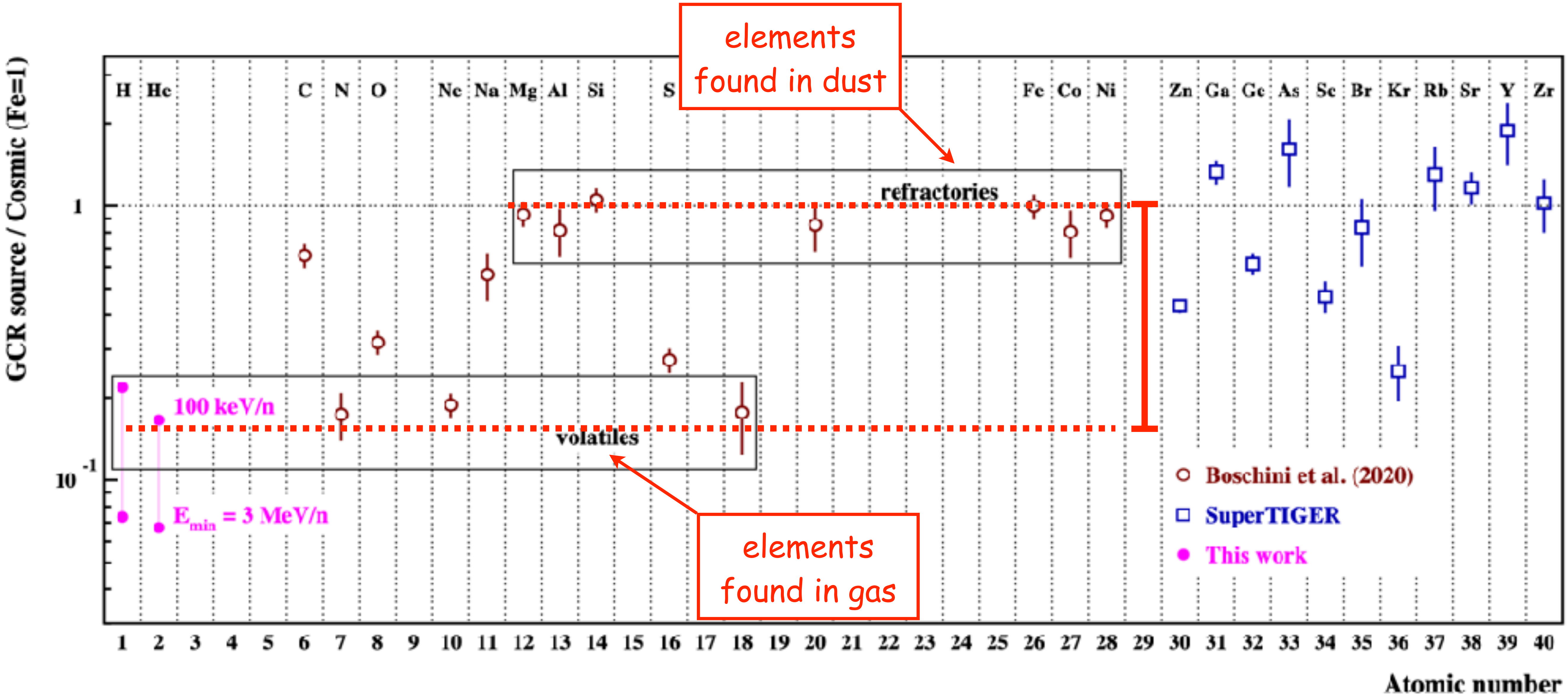
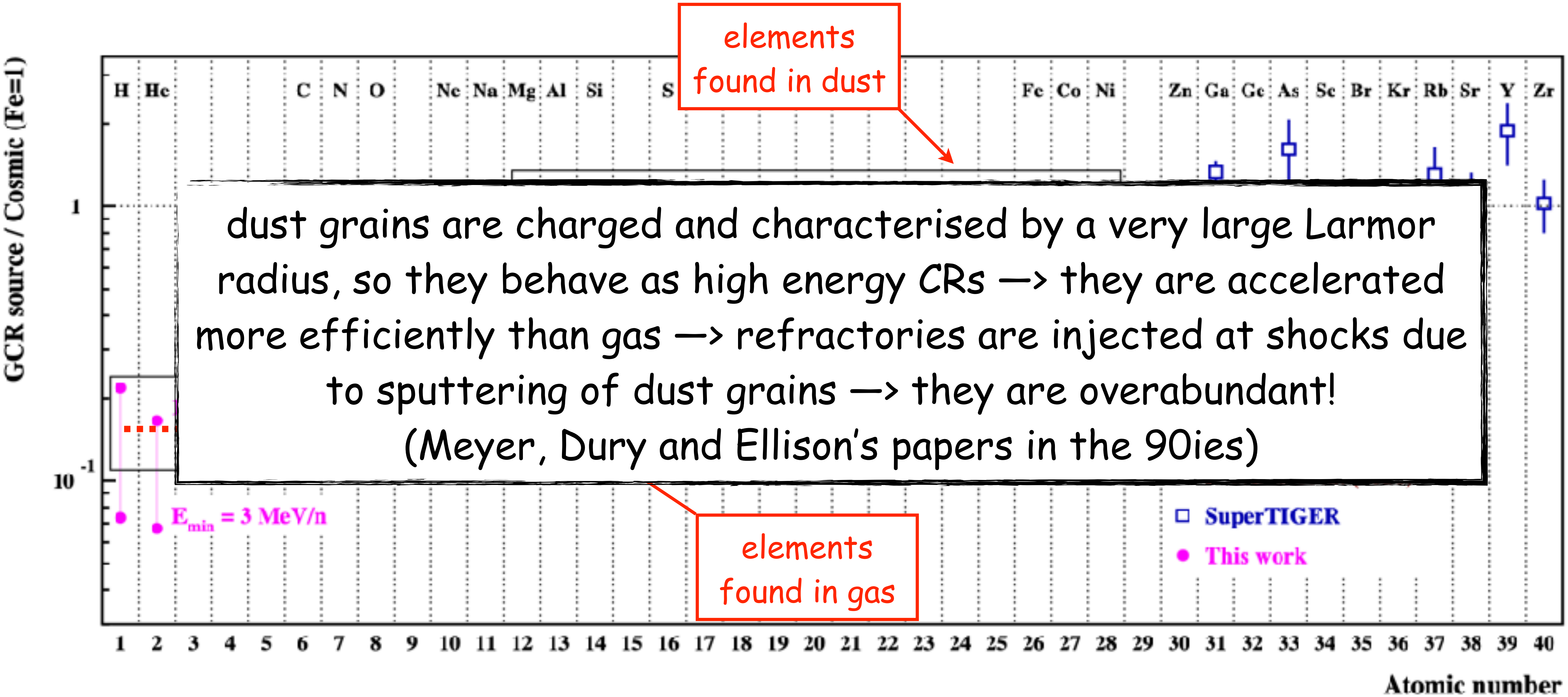


less pronounced but still very clear differences
—> volatiles versus refractories? —> dust must play a role...

Tatischeff, Raymond, Duprat, SG, Recchia, 2021

Composition: volatiles and refractories

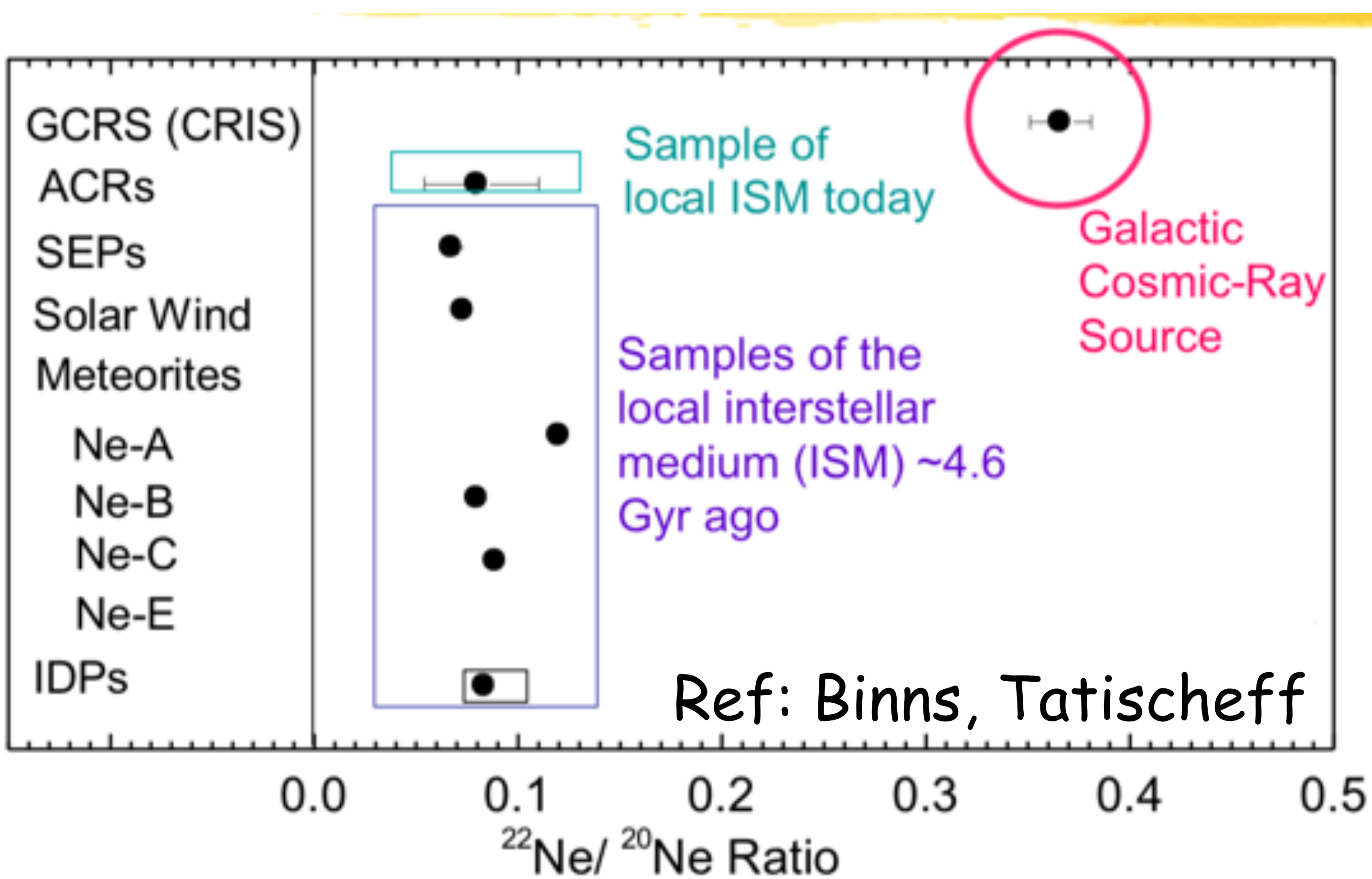


dust grains are charged and characterised by a very large Larmor radius, so they behave as high energy CRs —> they are accelerated more efficiently than gas —> refractories are injected at shocks due to sputtering of dust grains —> they are overabundant!
(Meyer, Dury and Ellison's papers in the 90ies)

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

Tatischeff, Raymond, Duprat, SG, Recchia, 2021

Composition: isotopic anomalies



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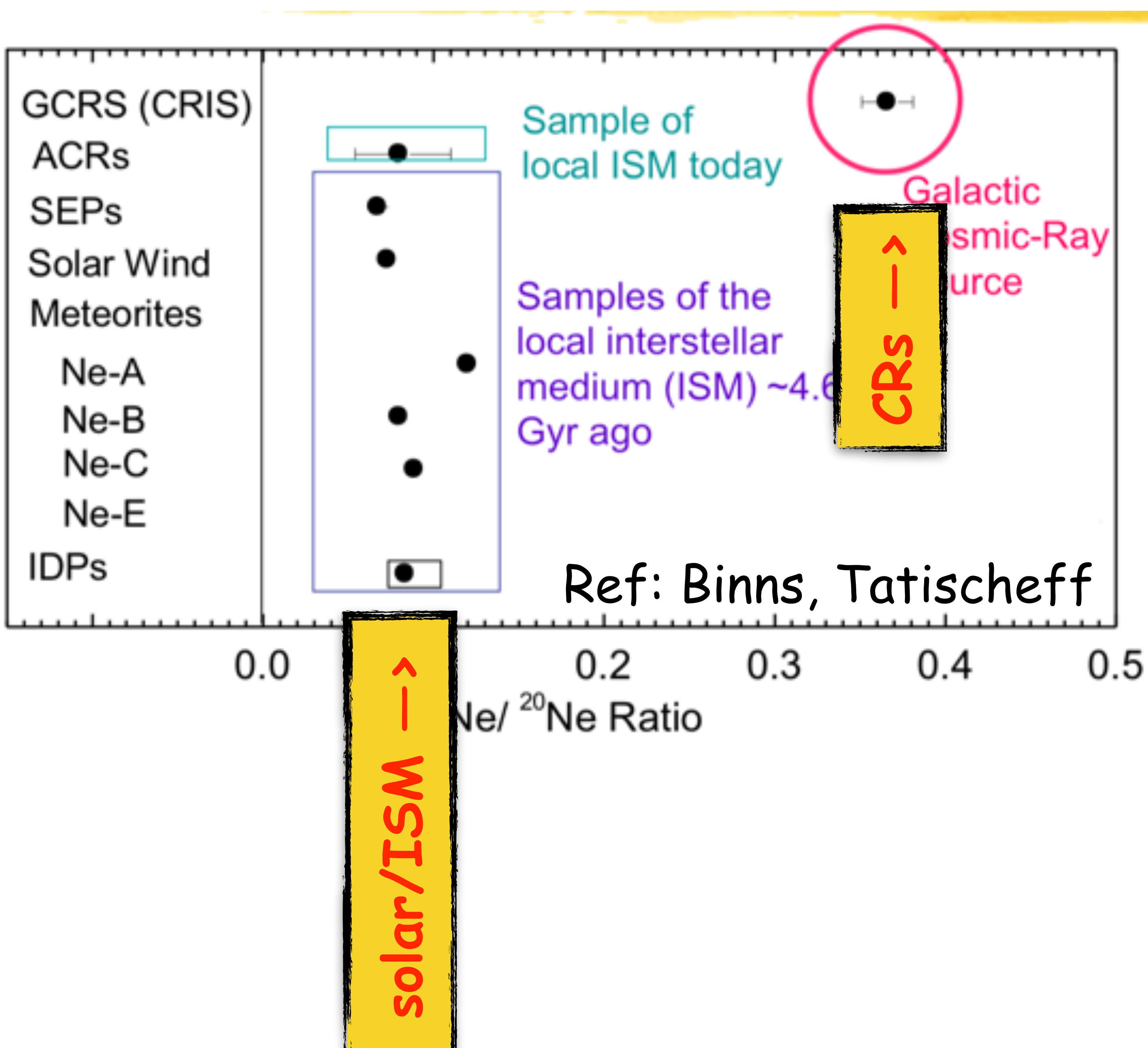

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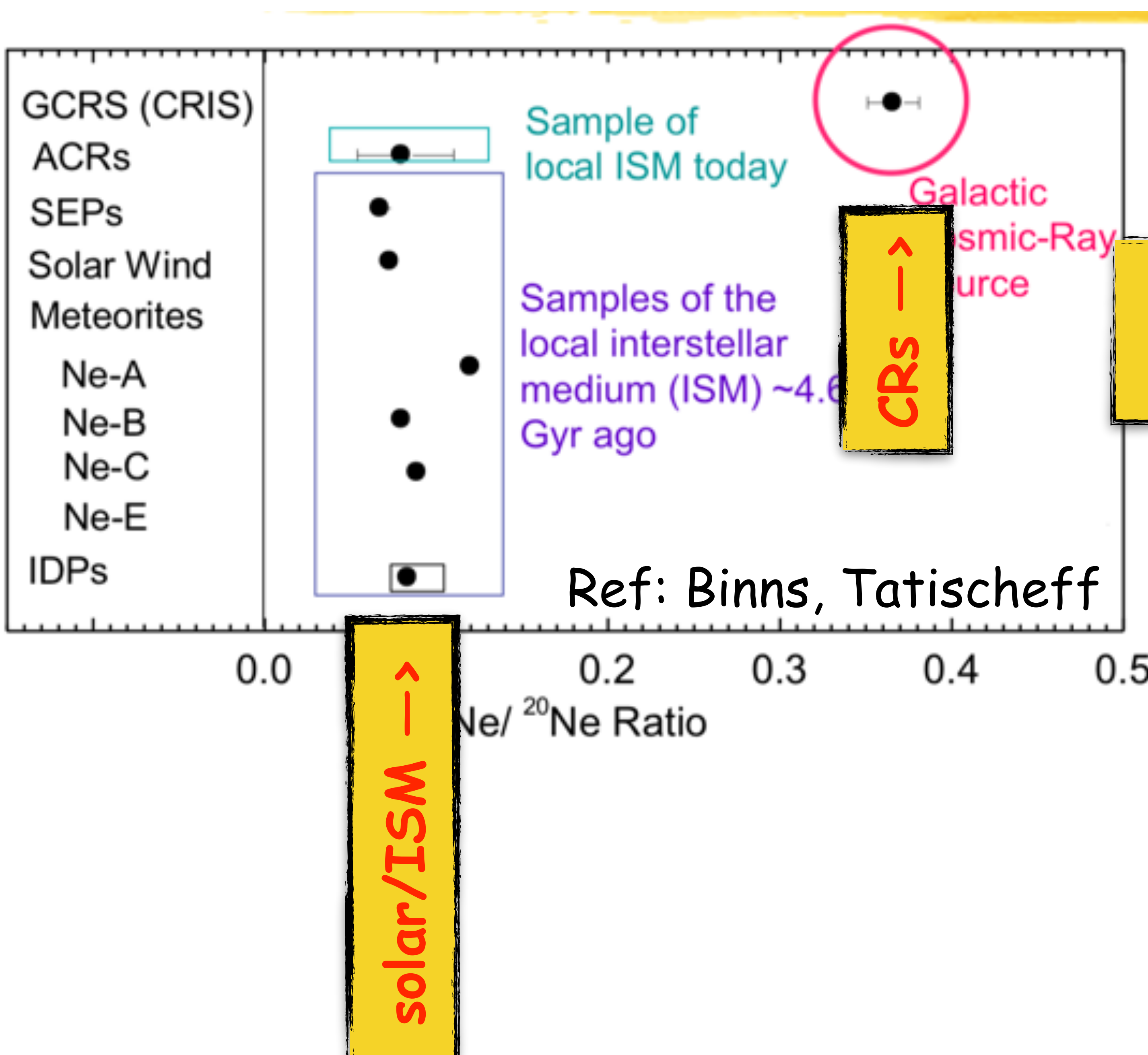
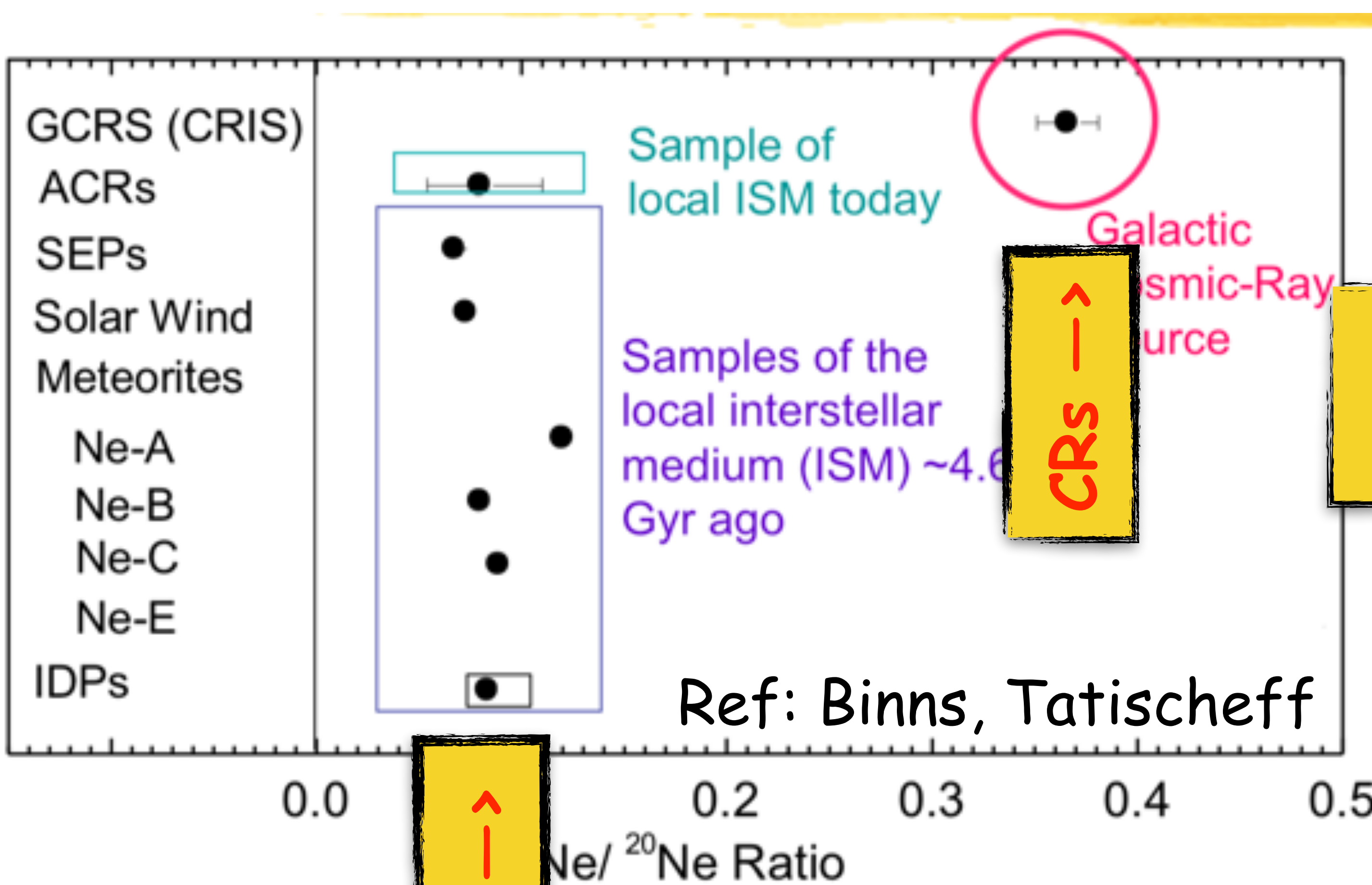


^{22}Ne is abundant in the wind material of Wolf-Rayet stars

Composition: isotopic anomalies



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

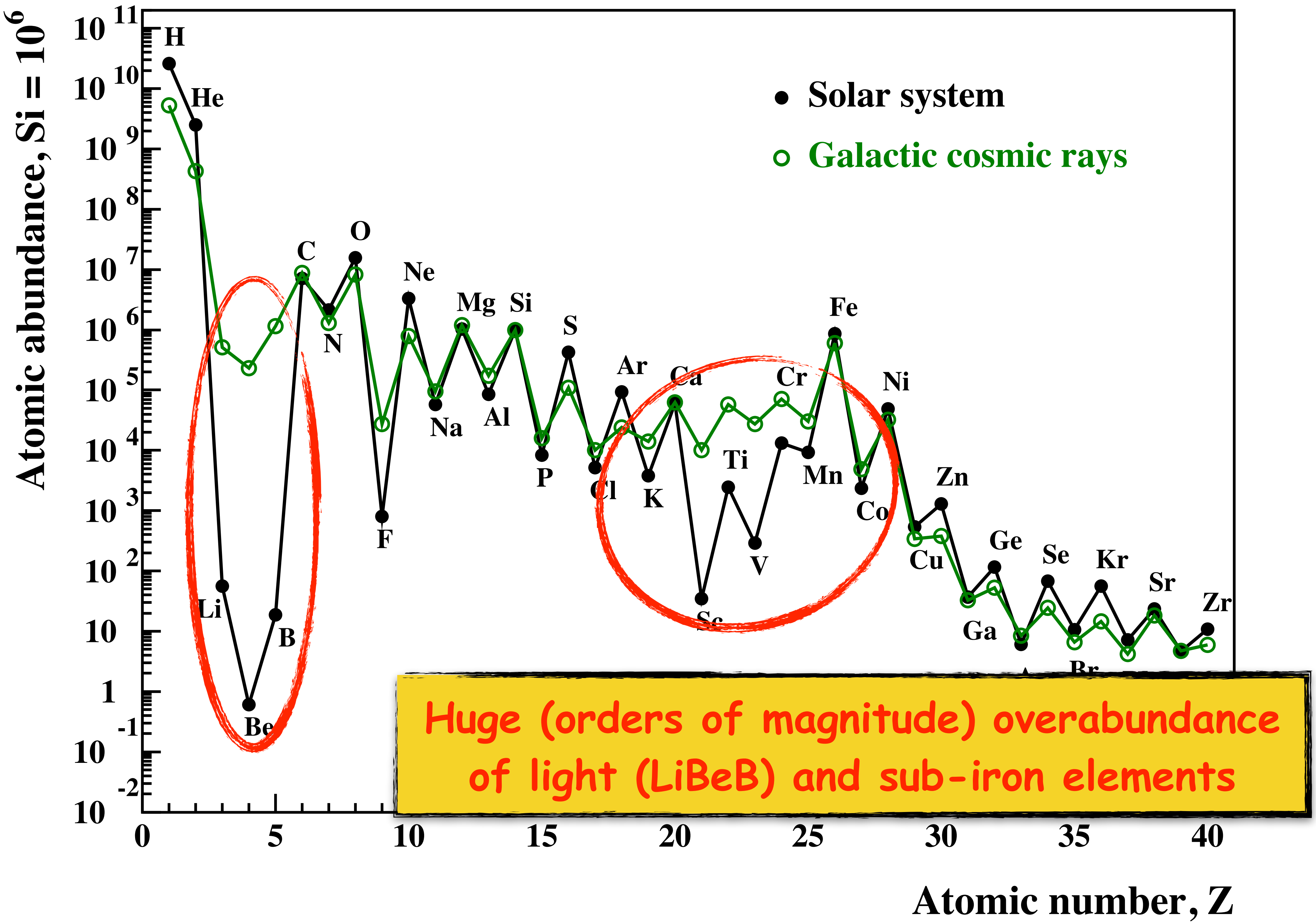
—> stellar winds must play a role in CR acceleration!

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}Ne/^{20}Ne anomaly)

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

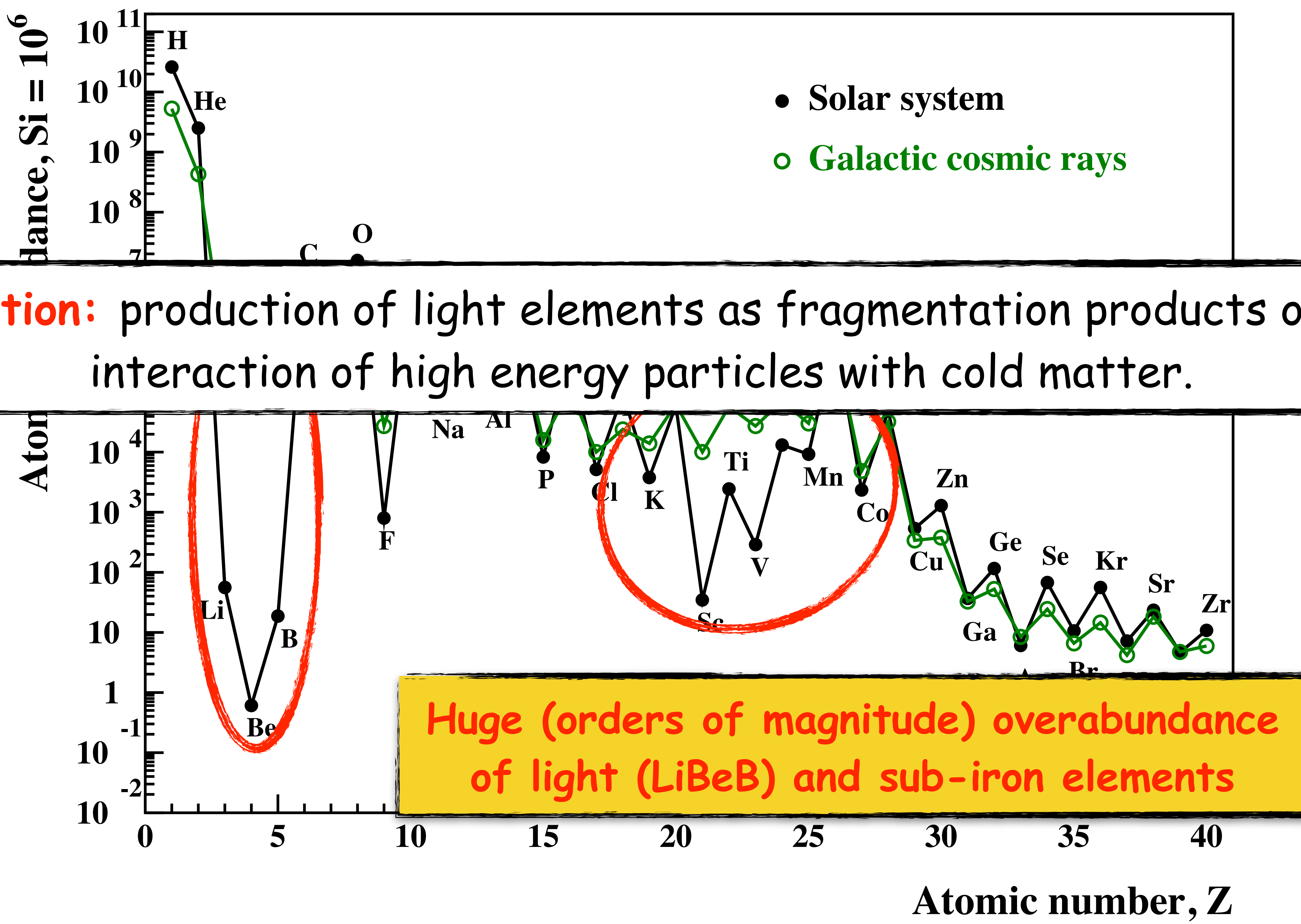
Composition: striking anomalies



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

Tatischeff & SG, 2018

Composition: striking anomalies

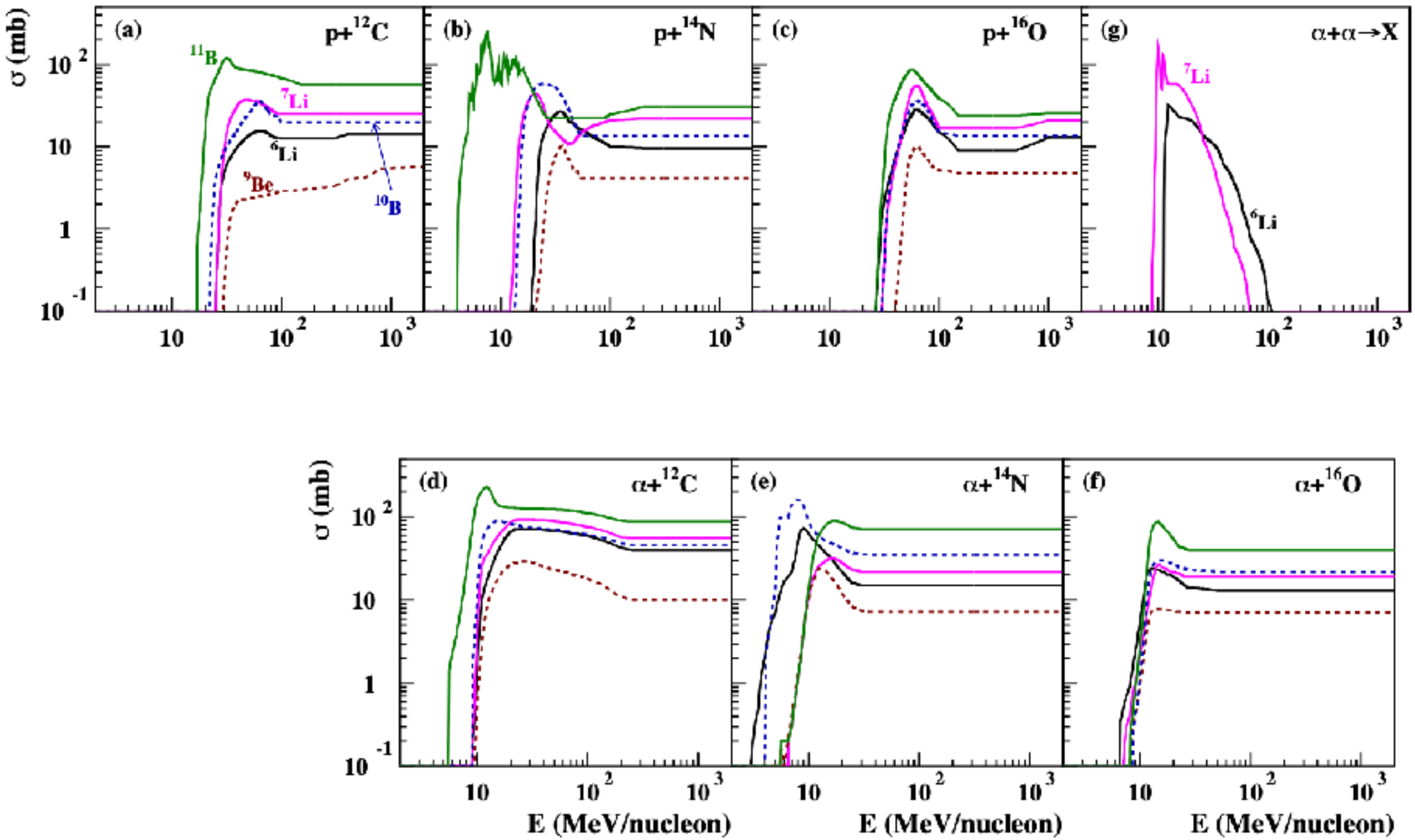


Spallation: production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

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

Tatischeff & SG, 2018

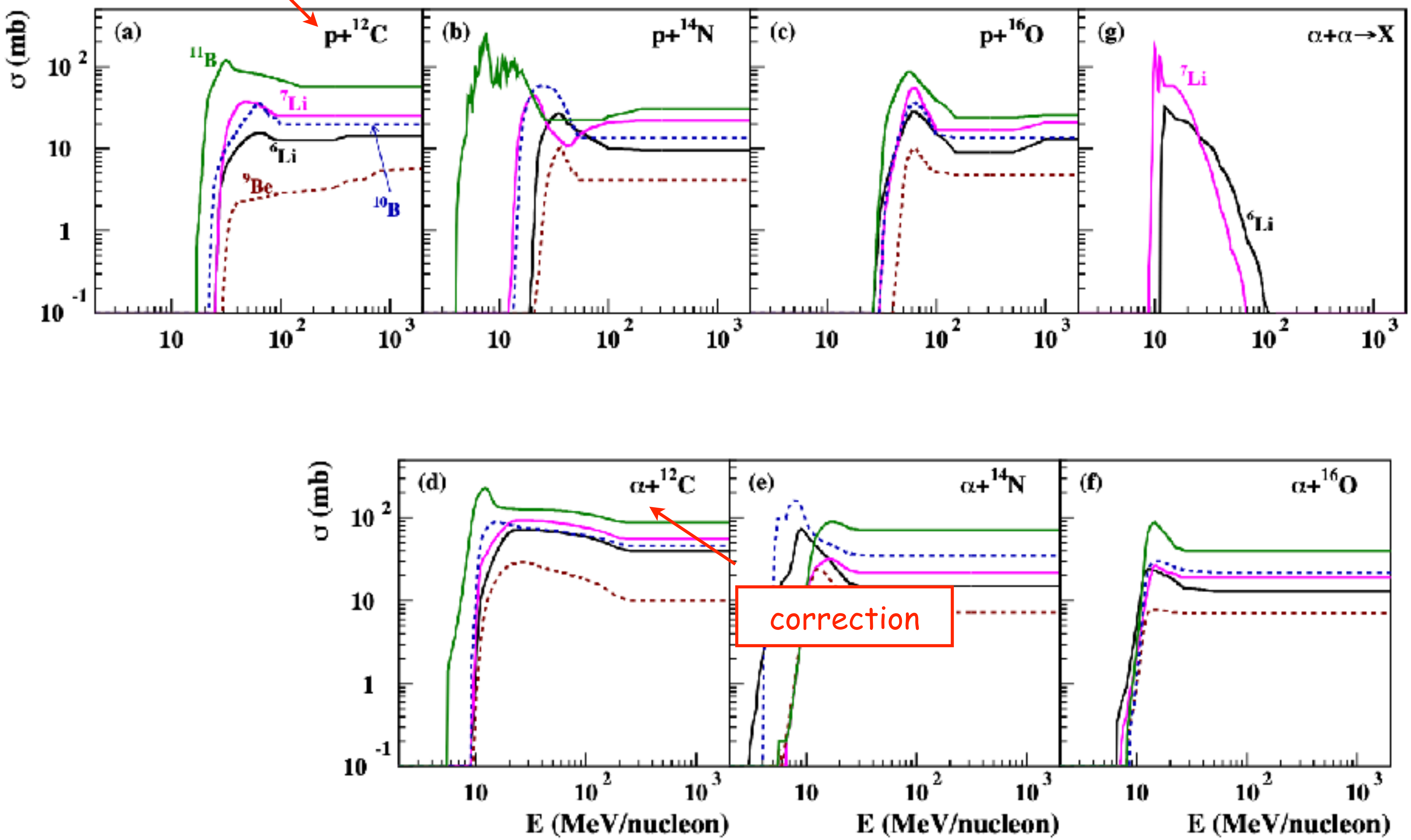
Spallation cross sections



Tatischeff & SG, 2018

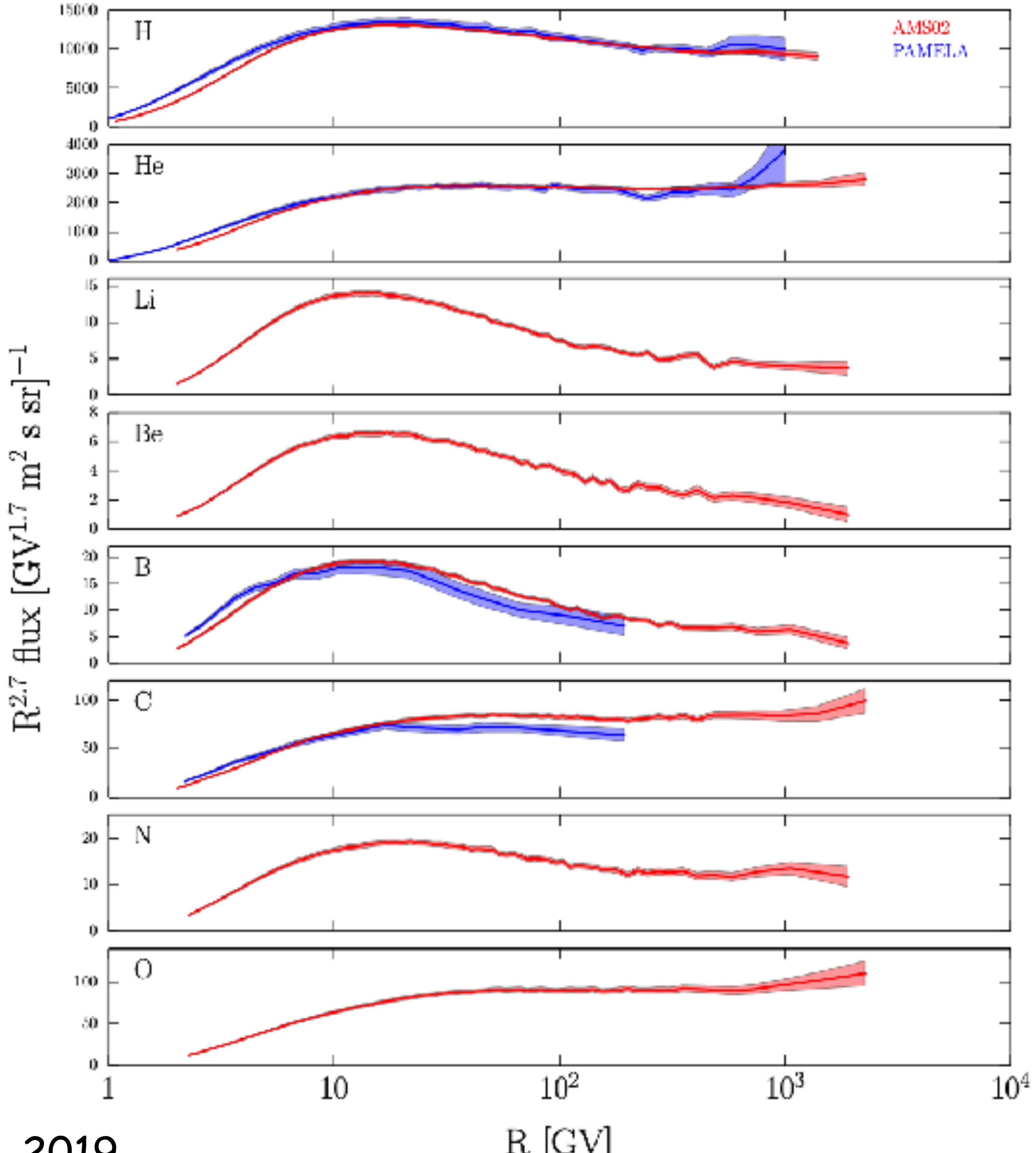
Spallation cross sections

main contribution



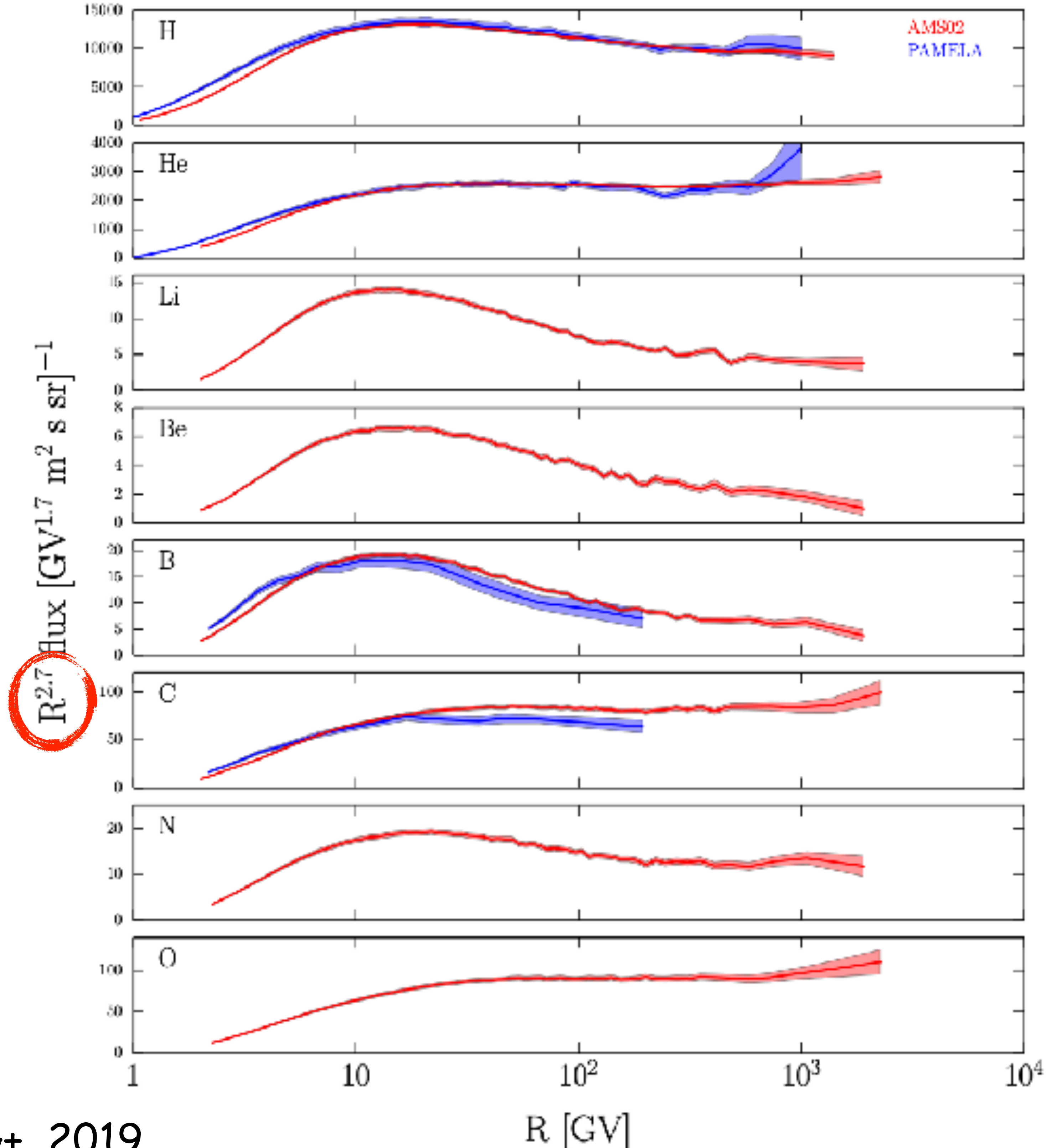
Tatischeff & SG, 2018

Spectra of light elements



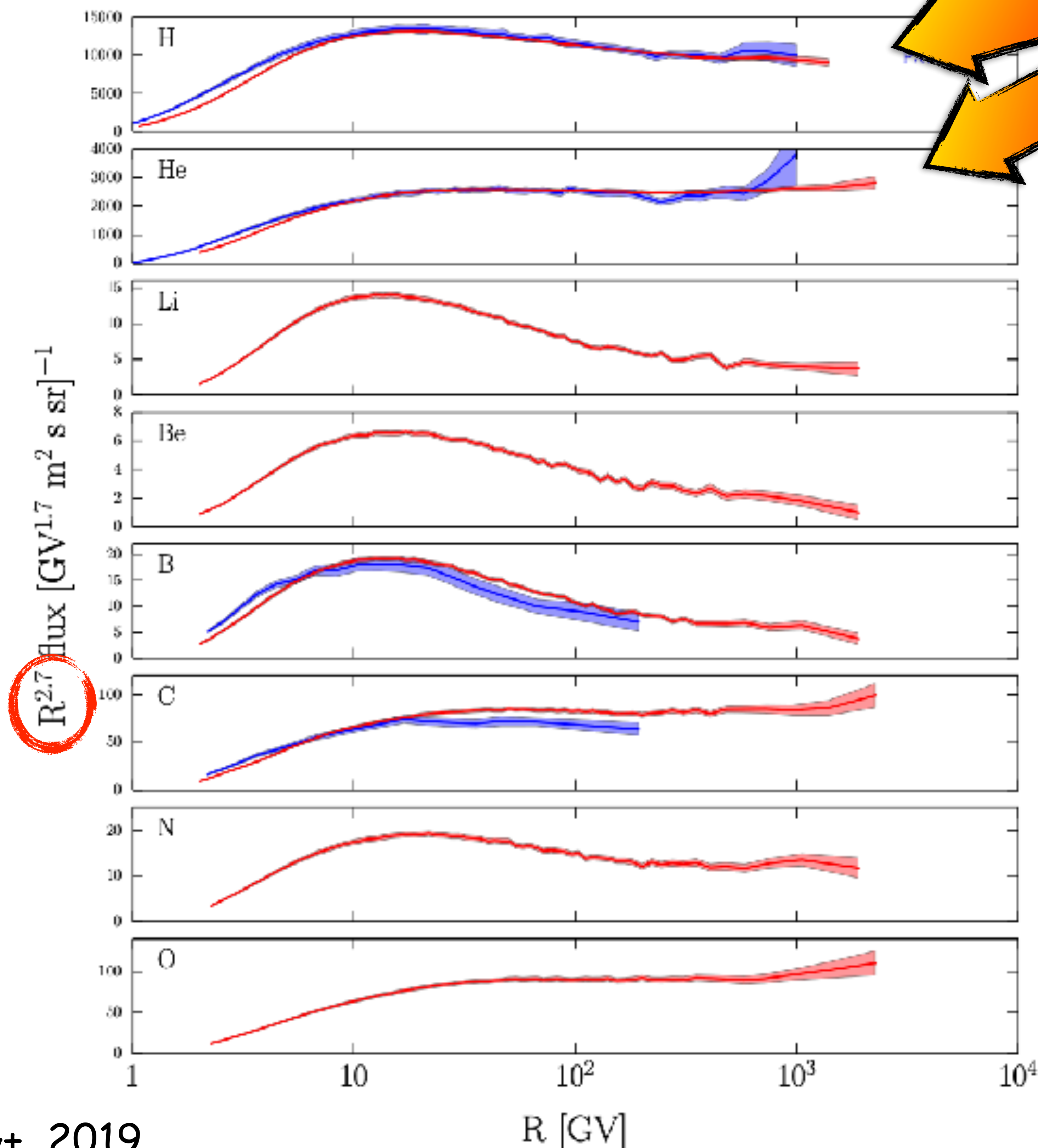
SG+, 2019

Spectra of light elements



SG+, 2019

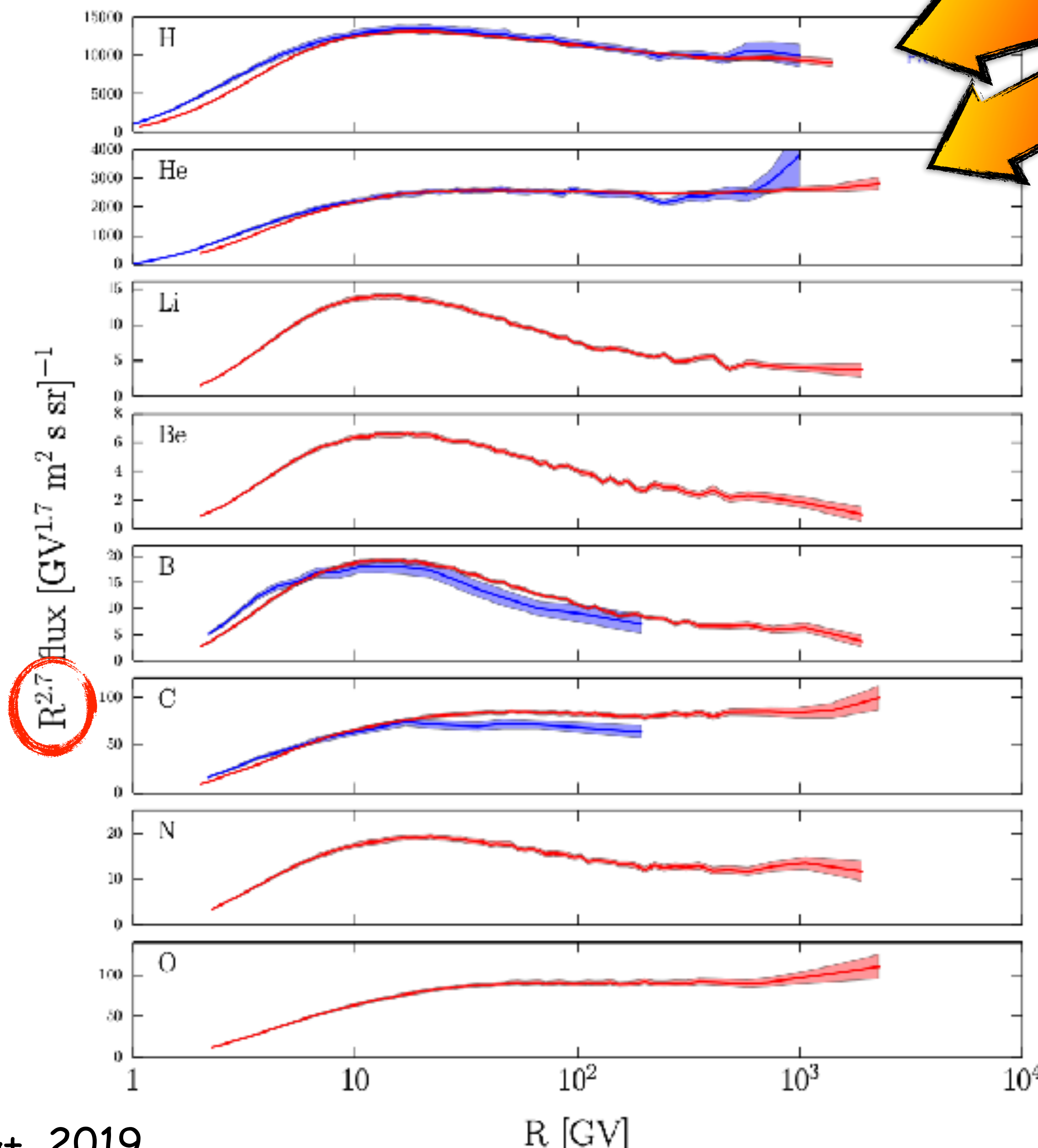
Spectra of light elements



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

SG+, 2019

Spectra of light elements



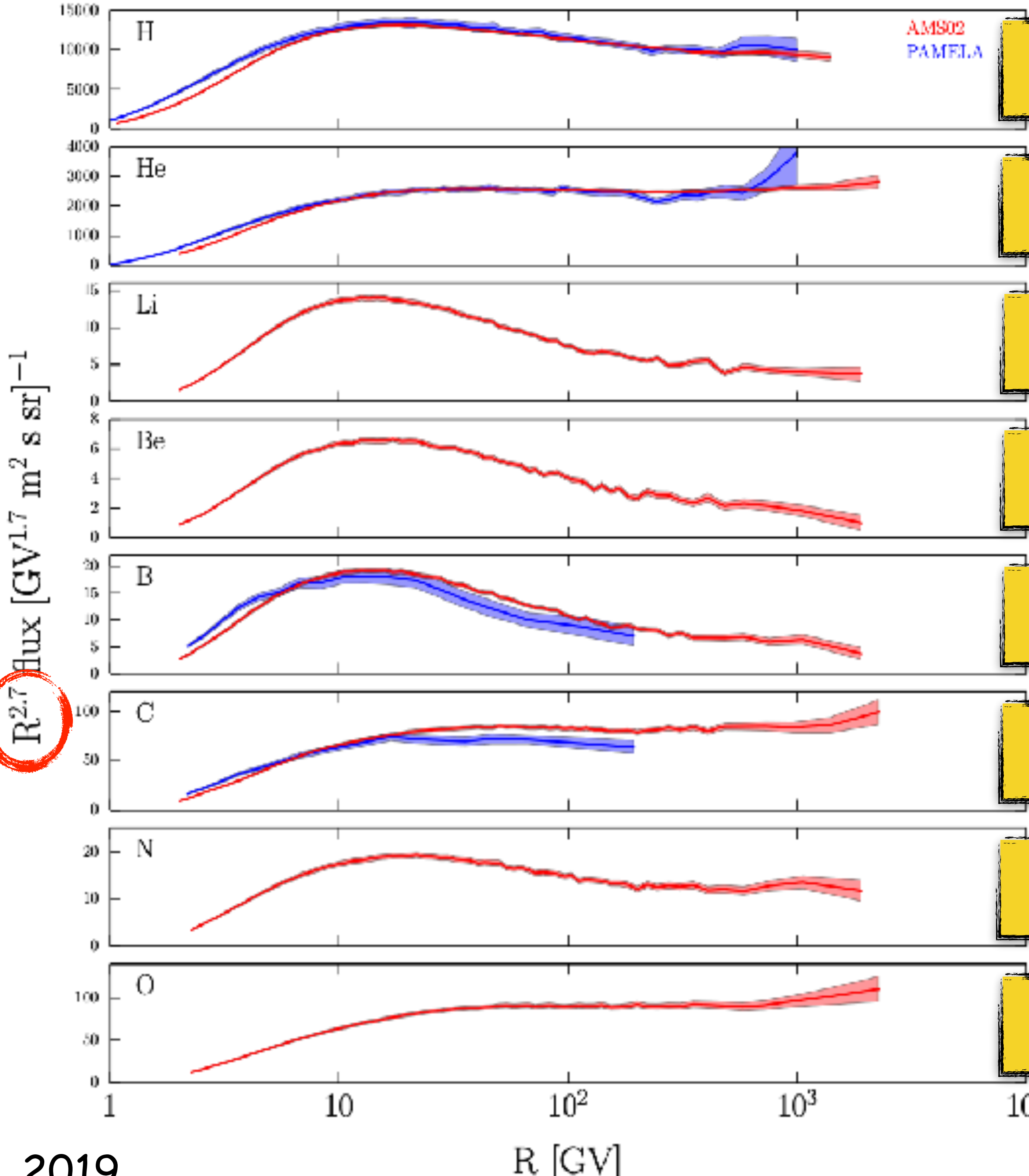
SG+, 2019

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



—> ???

—> flat

—> markedly steeper

—> markedly steeper

—> markedly steeper

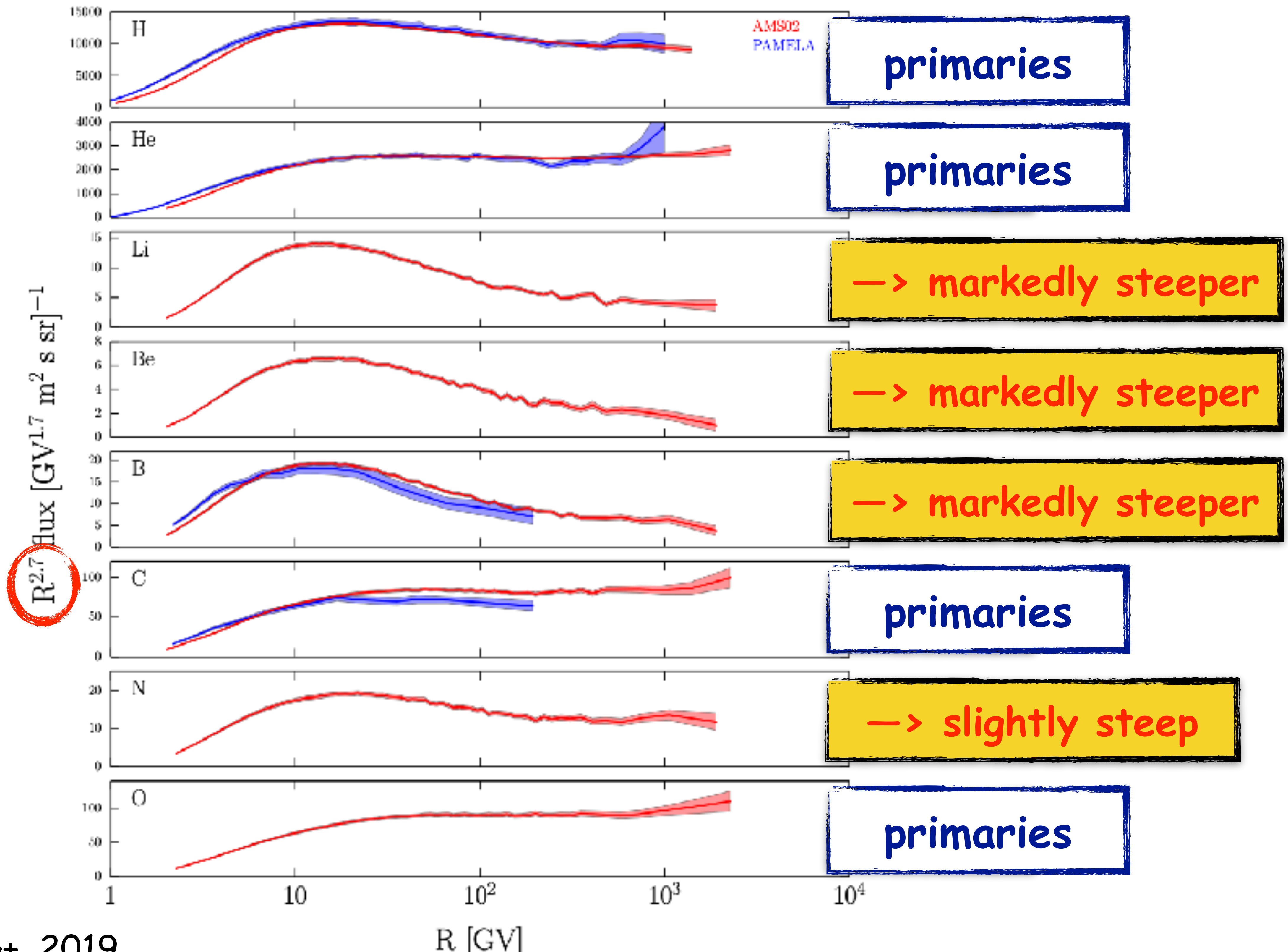
—> flat

—> slightly steep

—> flat

SG+, 2019

Spectra of light elements: an hypothesis



SG+, 2019

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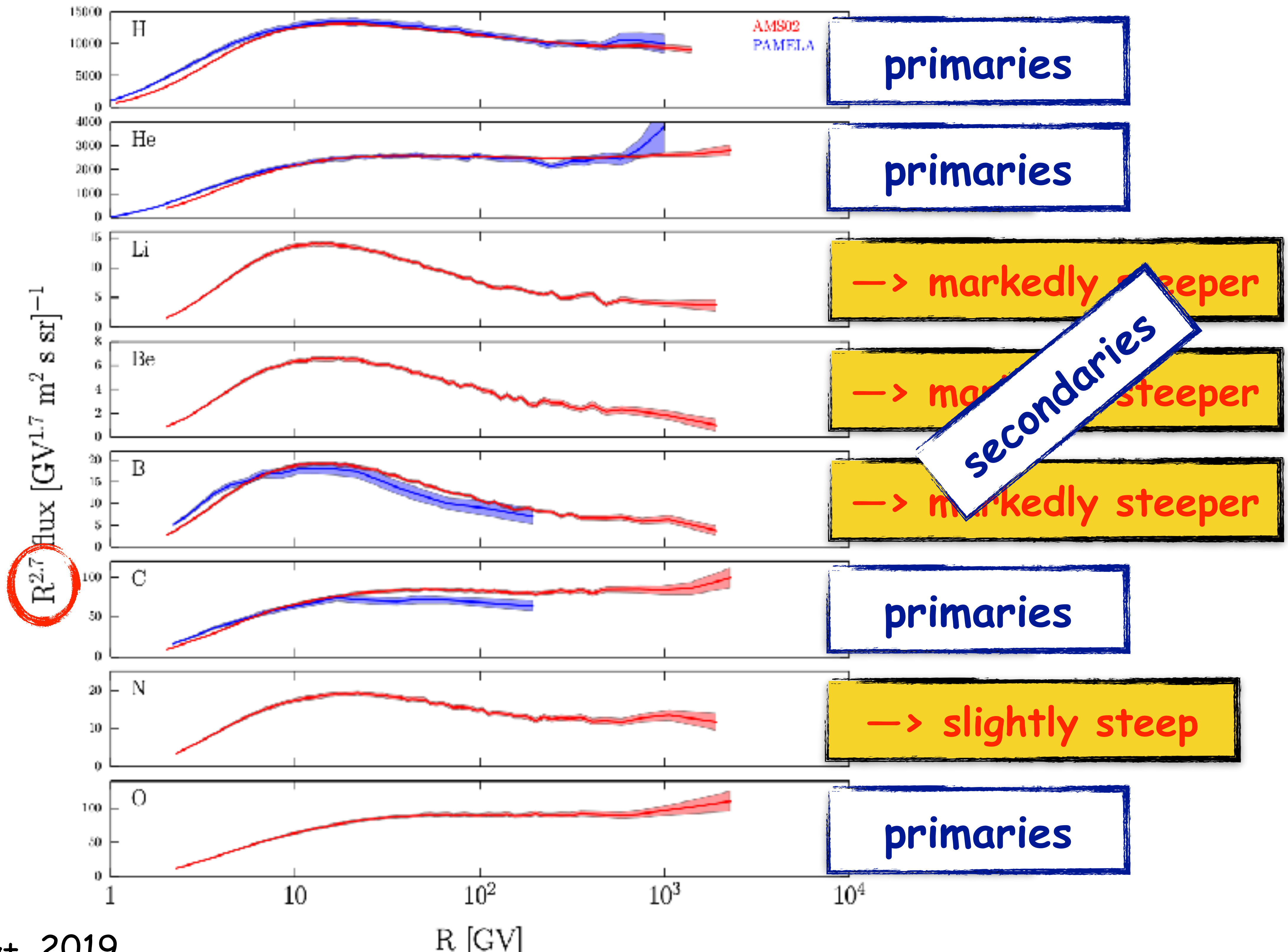

SG+, 2019

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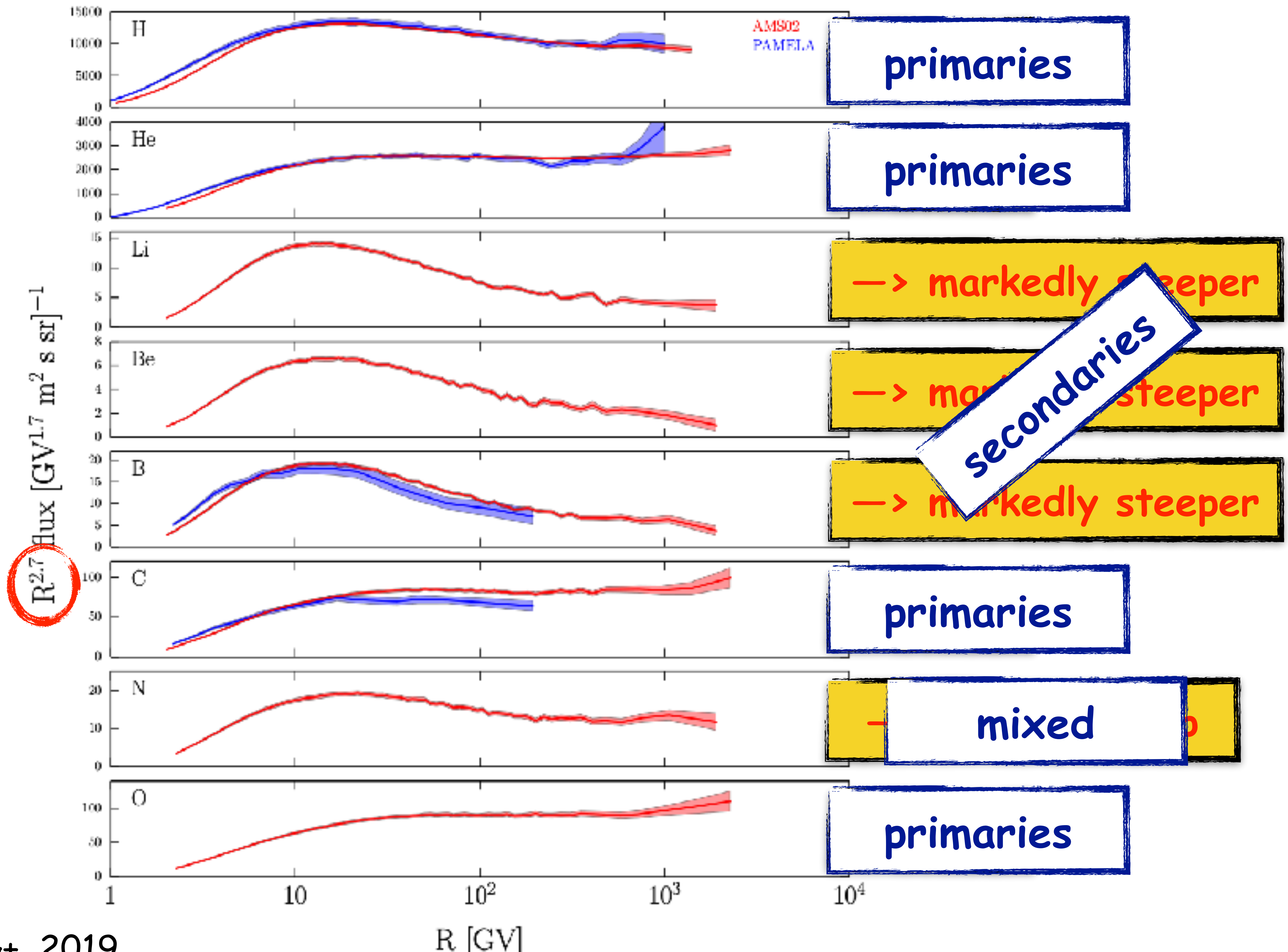
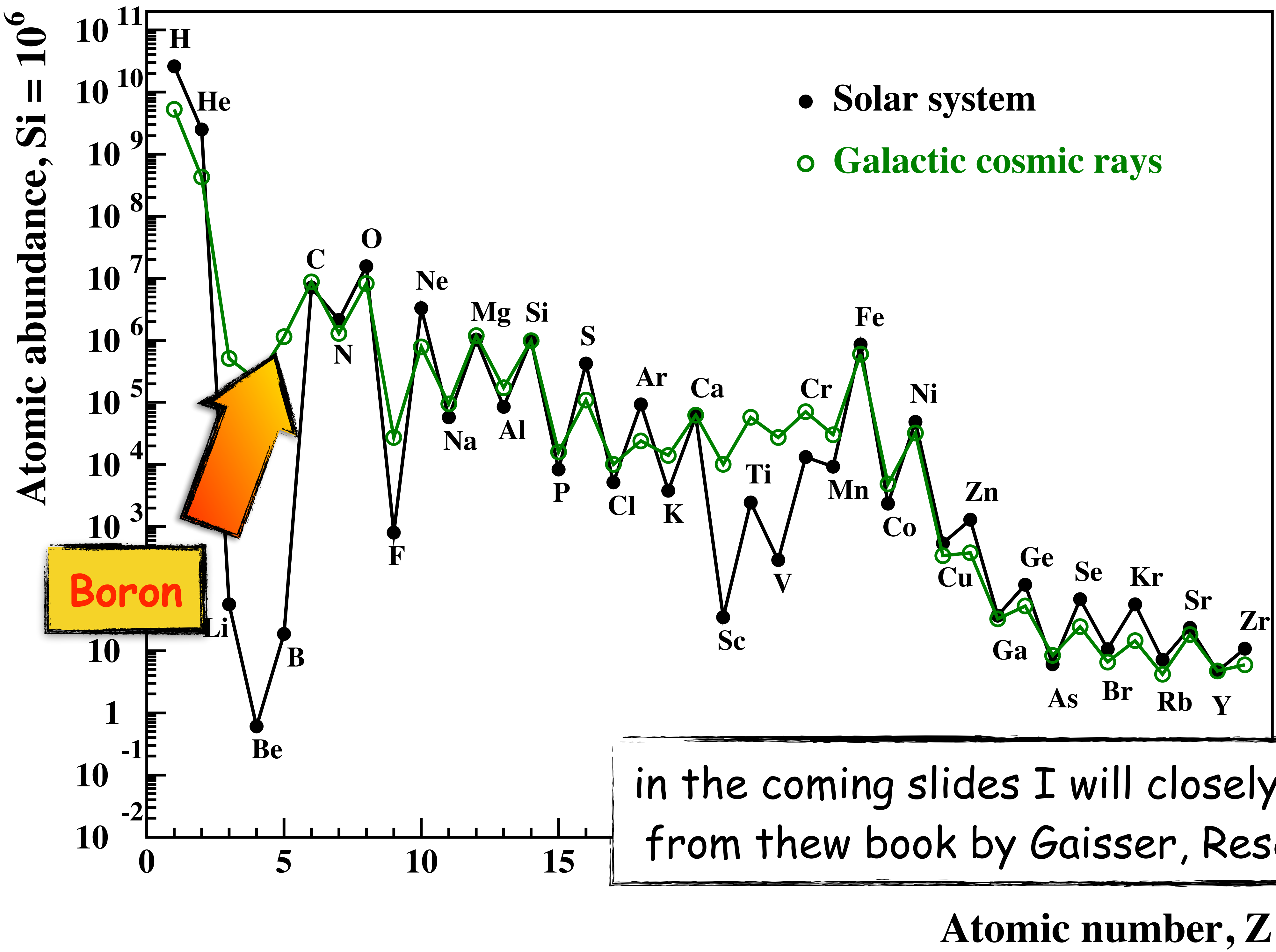


SG+, 2019

Production of B due to spallation

who does that?



in the coming slides I will closely follow the approach from thew book by Gaisser, Resconi & Engels (2016)

Production of B due to spallation

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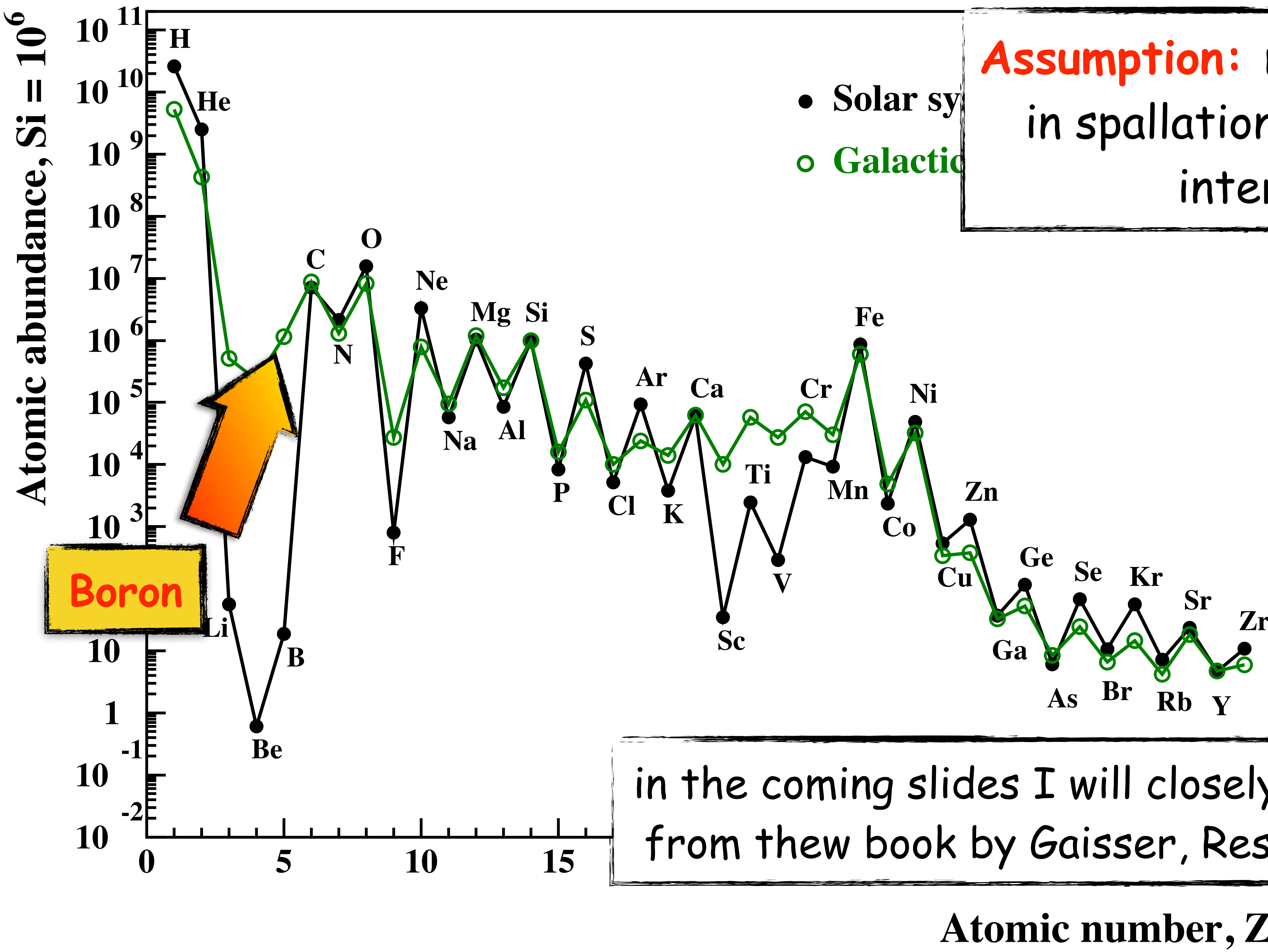

Assumption: most B is produced in spallation of C and O with interstellar H

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Production of B due to spallation

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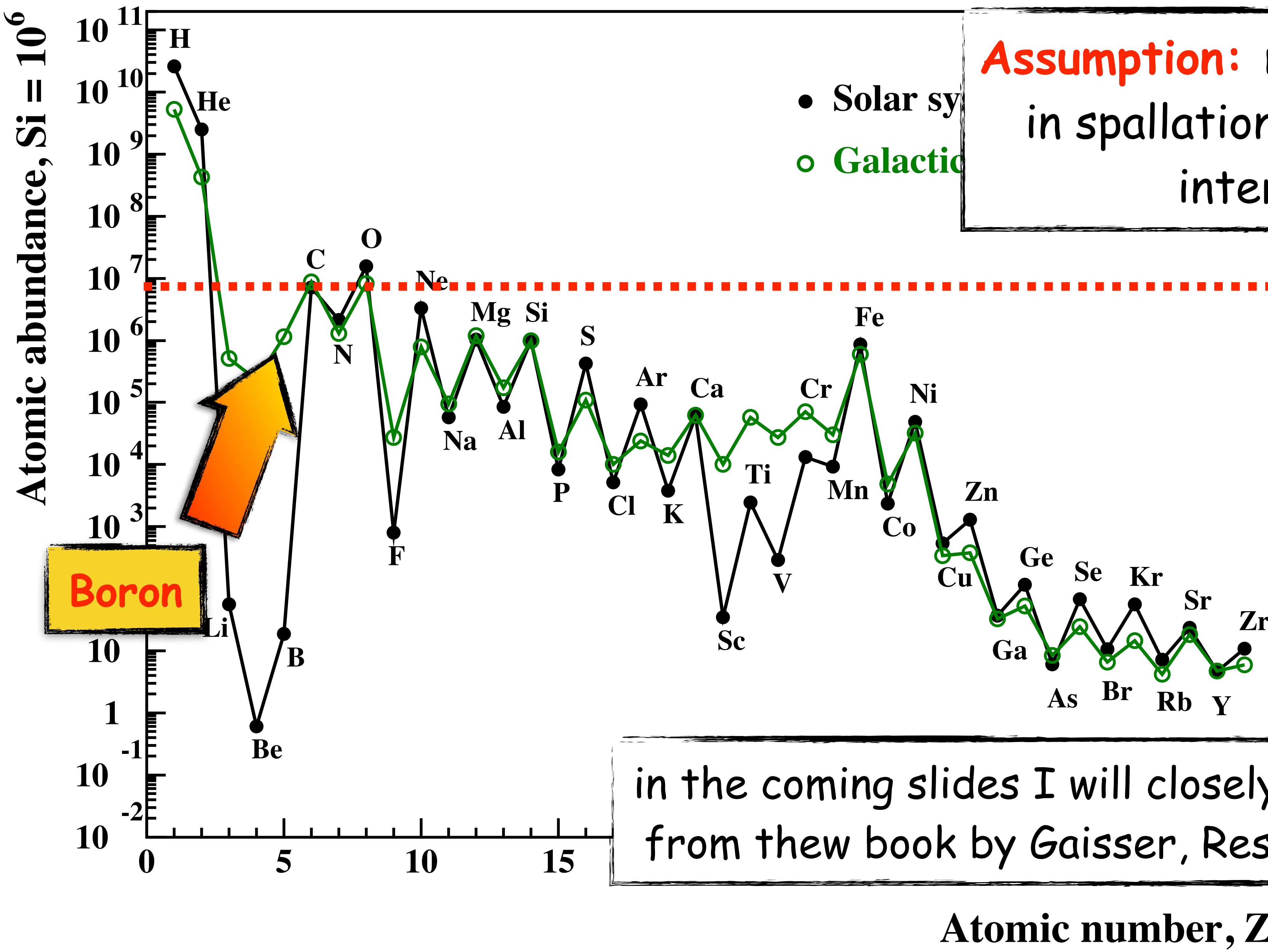

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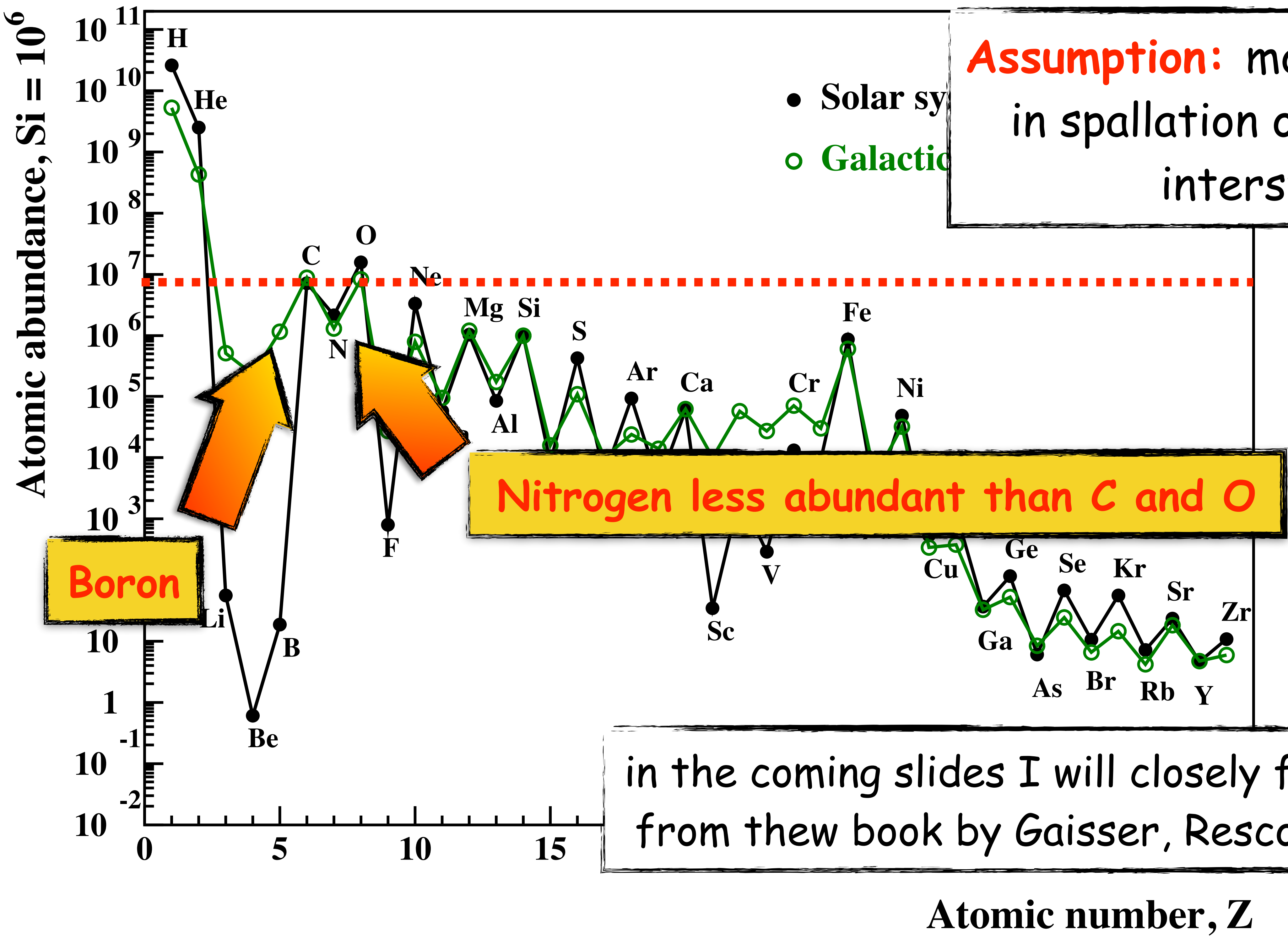

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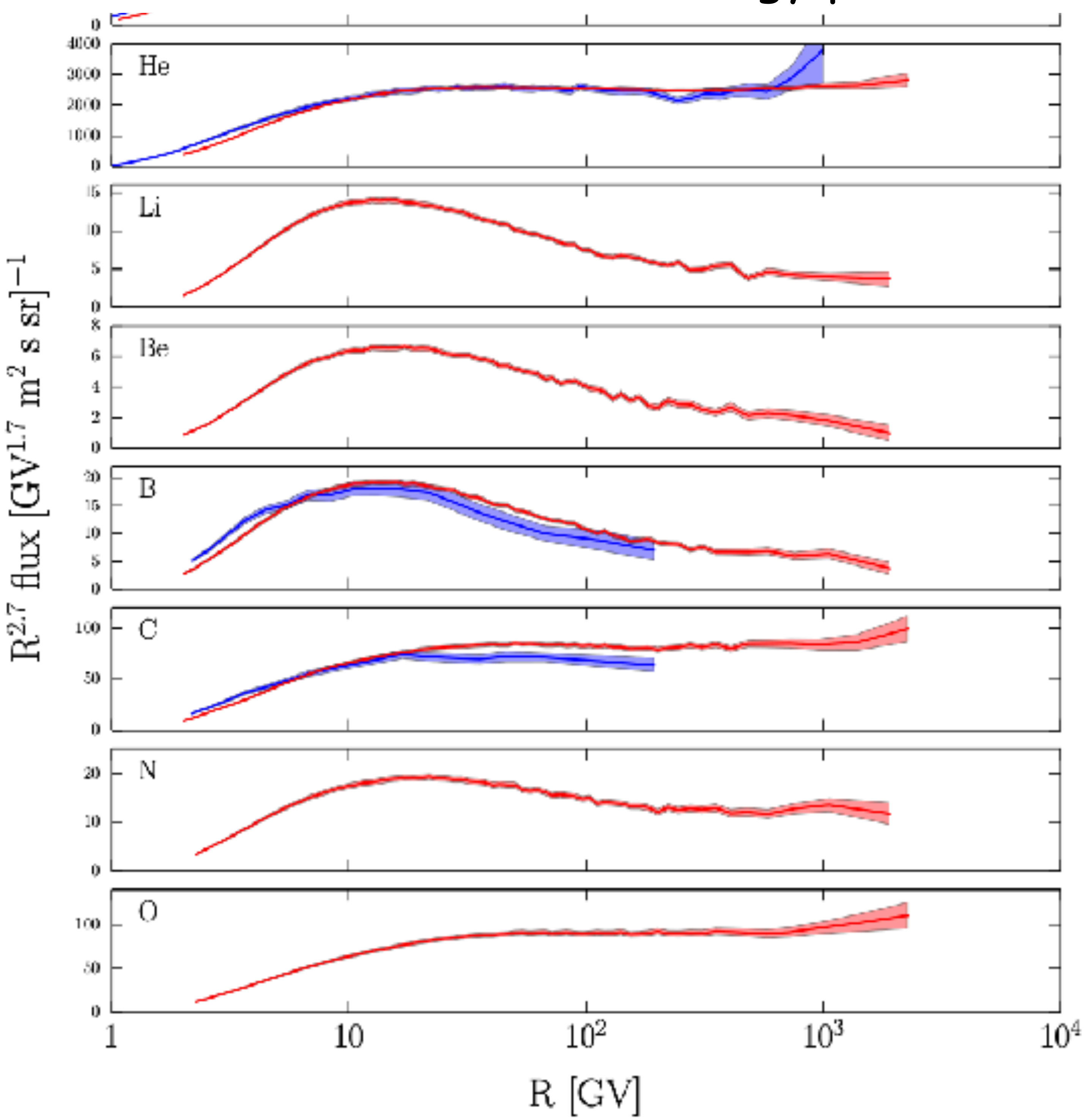
Local production rate of B

—> energy per nucleon is approximatively conserved in spallation reactions

—> same energy per nucleon = same velocity



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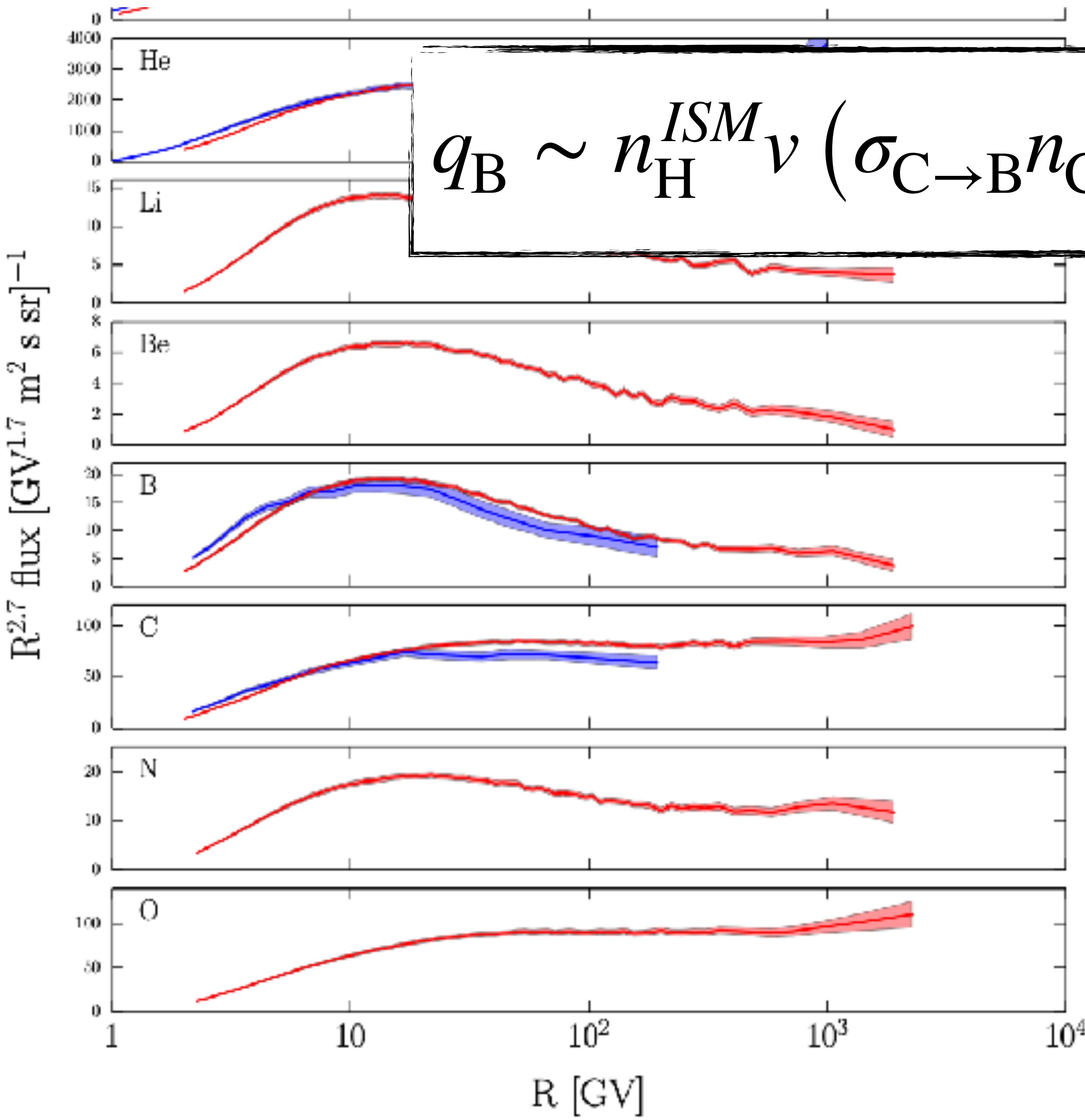

$$q_{\rm B} \sim n_{\rm H}^{ISM} v \left(\sigma_{\rm C \to B} n_{\rm C} + \sigma_{\rm O \to B} n_{\rm O} \right)$$

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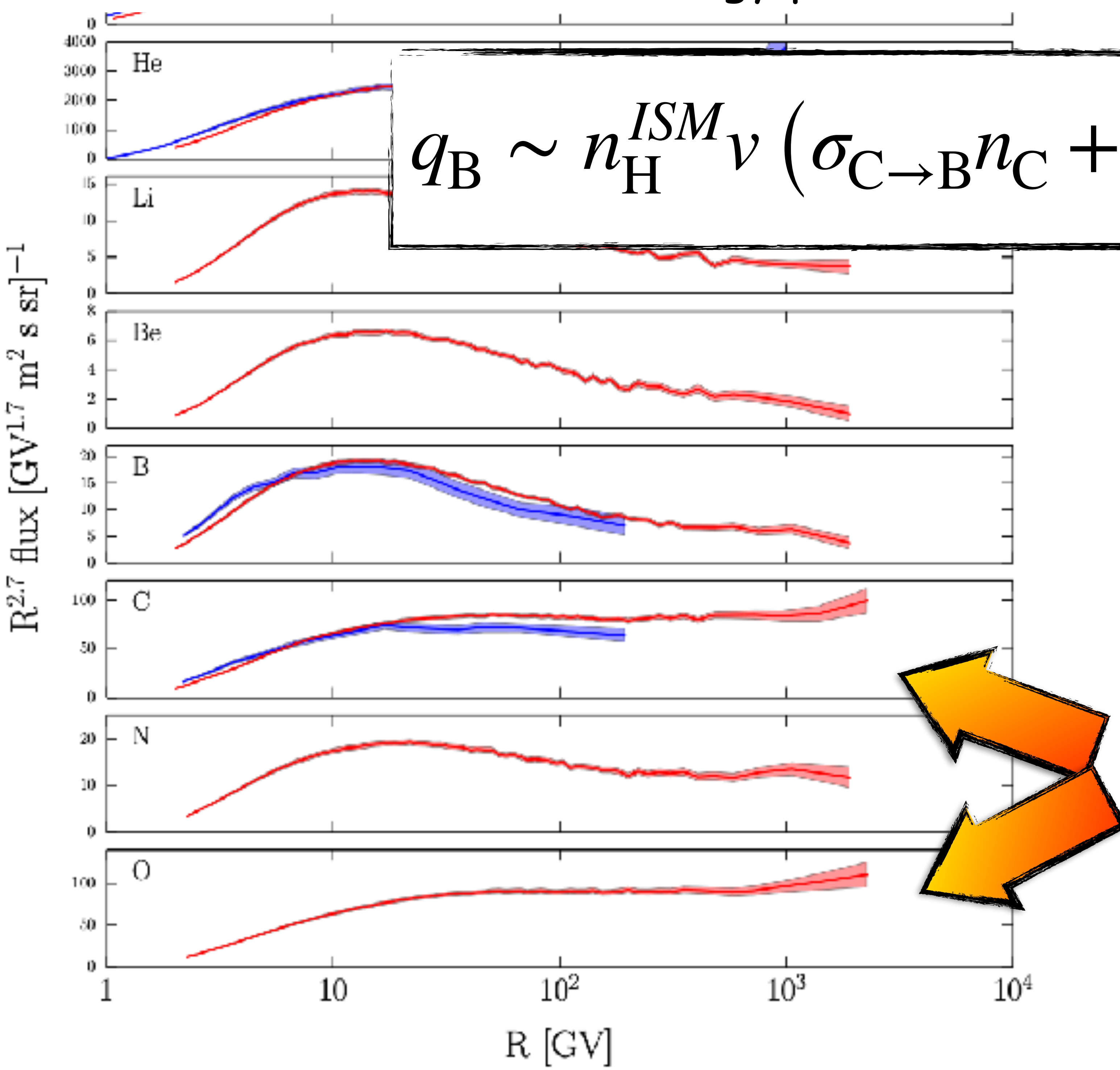

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very similar spectra!

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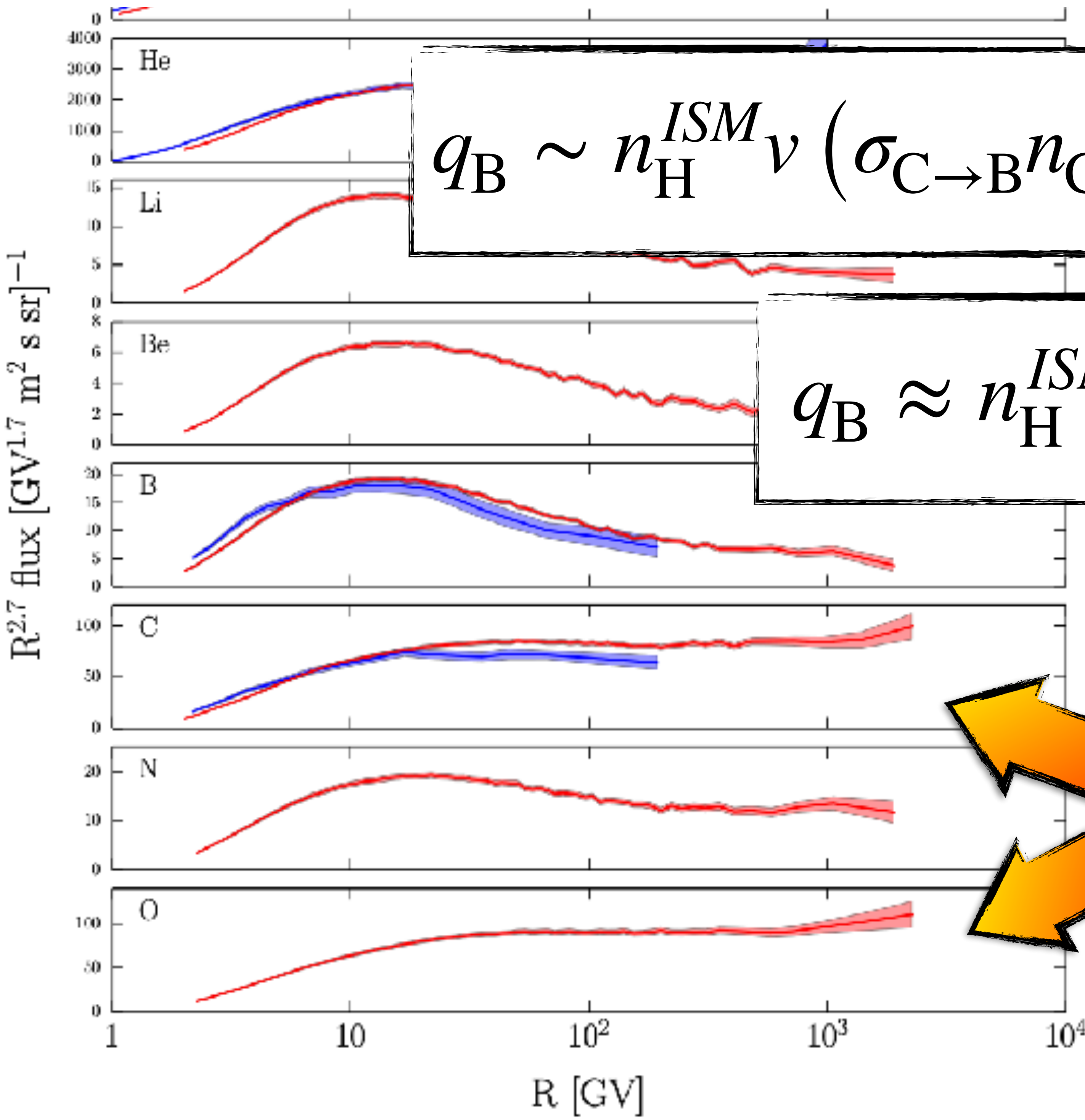

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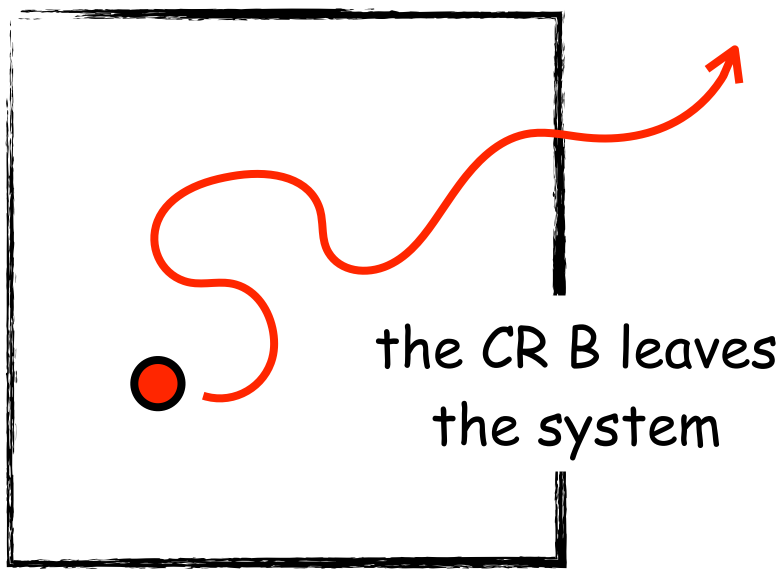

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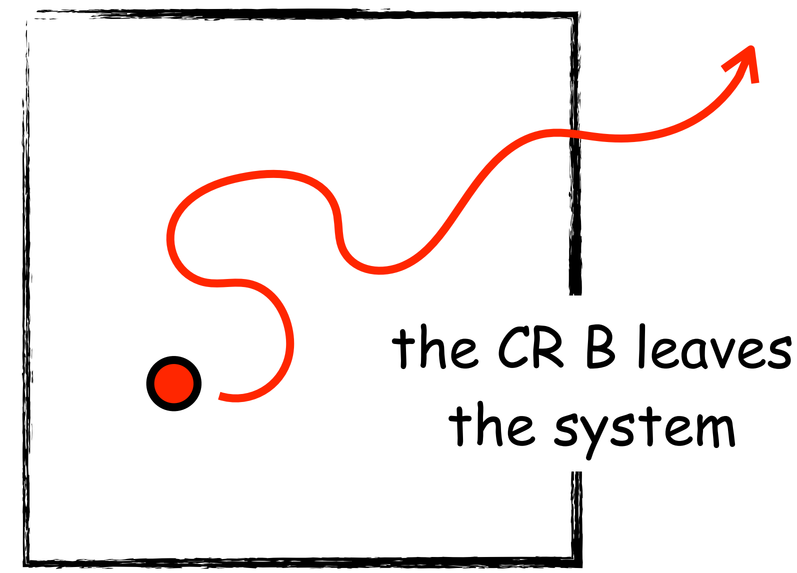
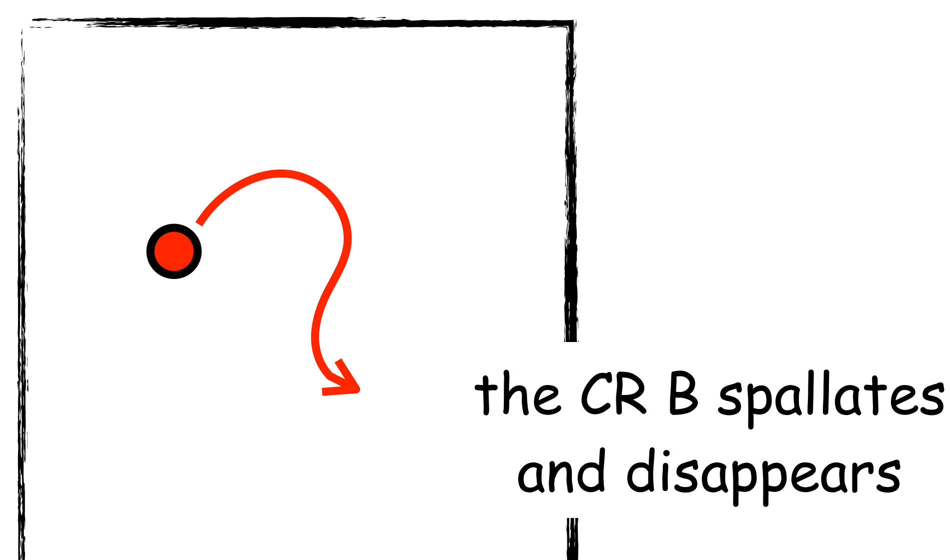


escape τ_{ISM}

spallate $\tau_{\mathrm{B}} = \left(n_{\mathrm{H}}^{ISM} \sigma_{\mathrm{B}} v \right)^{-1}$



The equilibrium spectrum of B

transport equation at equilibrium

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

production rate

destruction rate
(escape)

destruction rate
(spallation)

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production rate

destruction rate (escape)

destruction rate (spallation)

effective "destruction" time —>

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

$$\frac{n_{\mathrm{B}}}{\tau_{eff}} = q_{\mathrm{B}}$$

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

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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

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

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$$\frac{n_{\mathrm{B}}}{\tau_{ISM}} + \frac{n_{\mathrm{B}}}{\tau_{\mathrm{B}}} = q_{\mathrm{B}} \approx n_{\mathrm{H}}^{ISM} v \; n_{\mathrm{C}} \left(\sigma_{\mathrm{C}\to\mathrm{B}} + \sigma_{\mathrm{O}\to\mathrm{B}}\right)$$

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

B/C ratio —>

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The B/C ratio: avoid this mistake!

$$\frac{n_{\rm B}}{n_{\rm C}} \approx \frac{X_{ISM}}{1+\frac{X_{ISM}}{X_{\rm B}}} \frac{\sigma_{\rm C\to B}+\sigma_{\rm O\to B}}{m_p}$$

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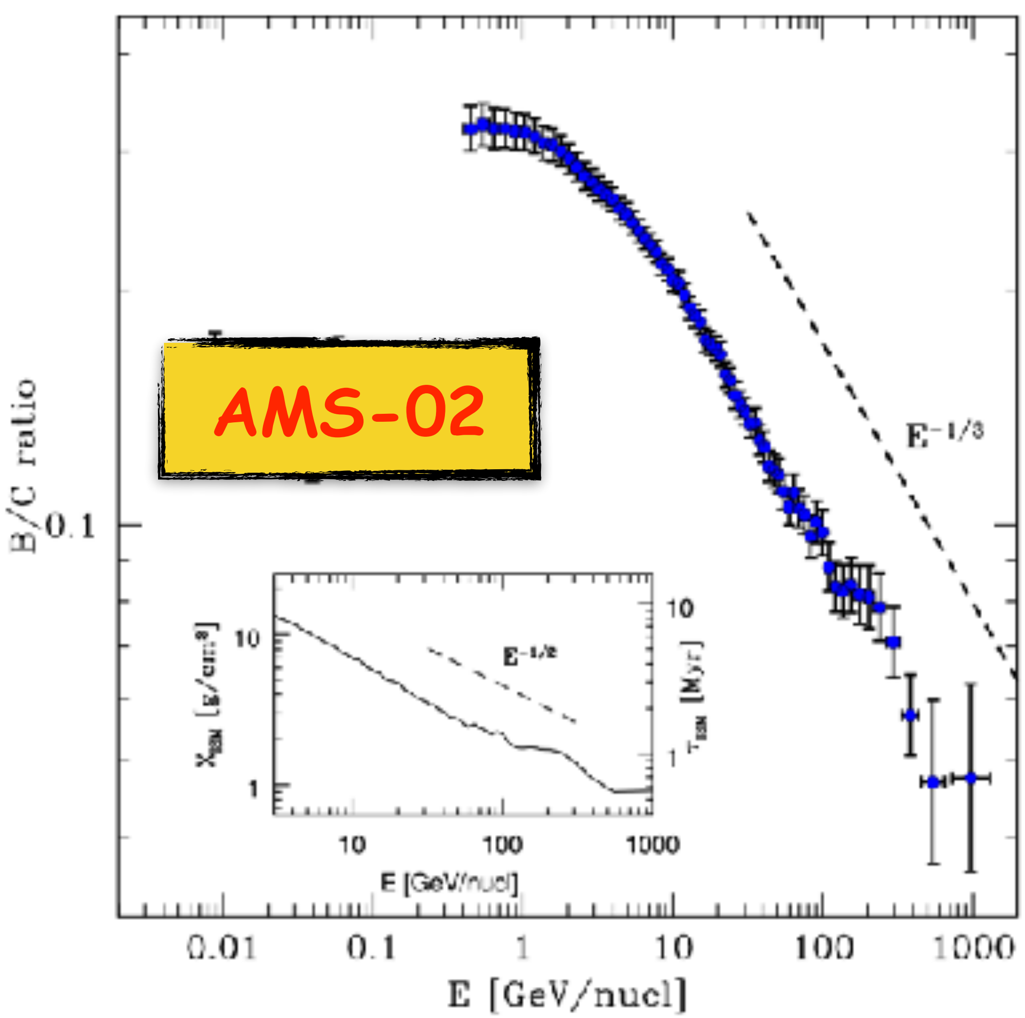

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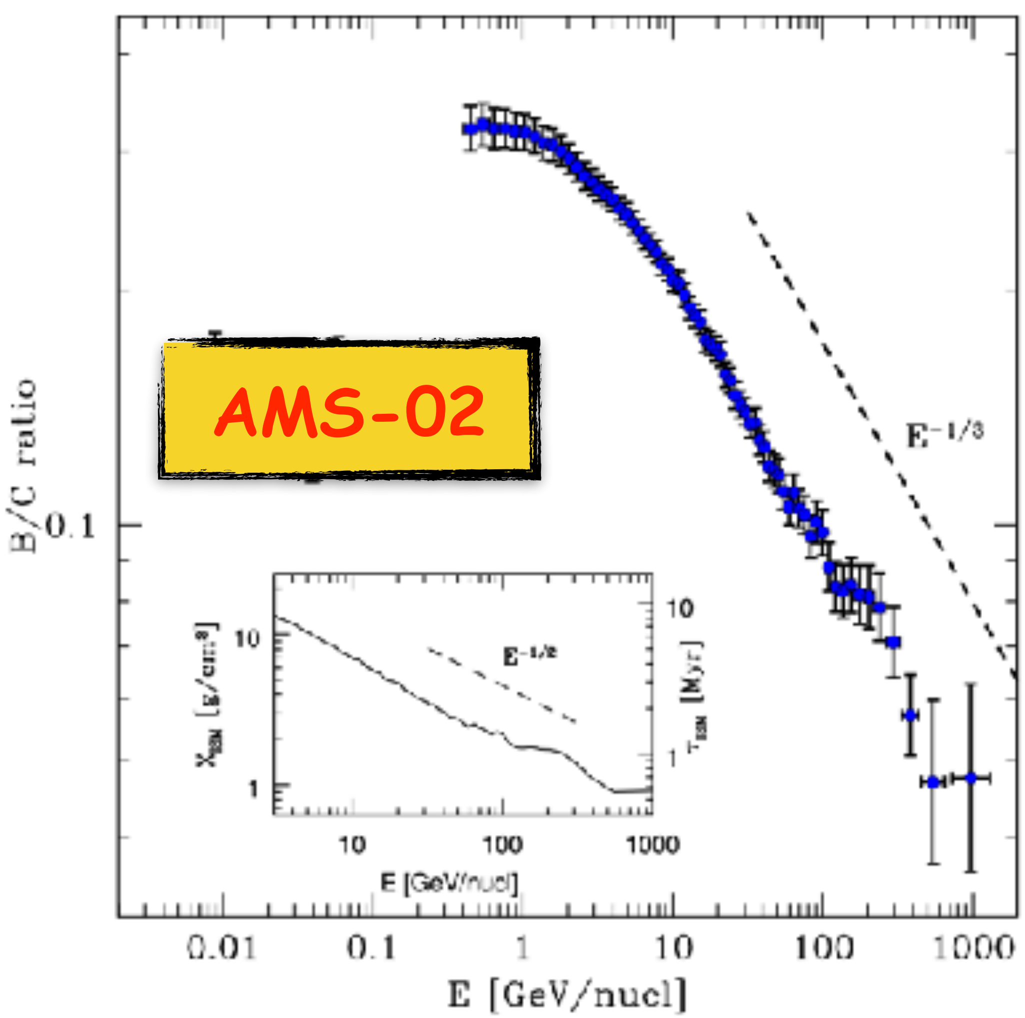

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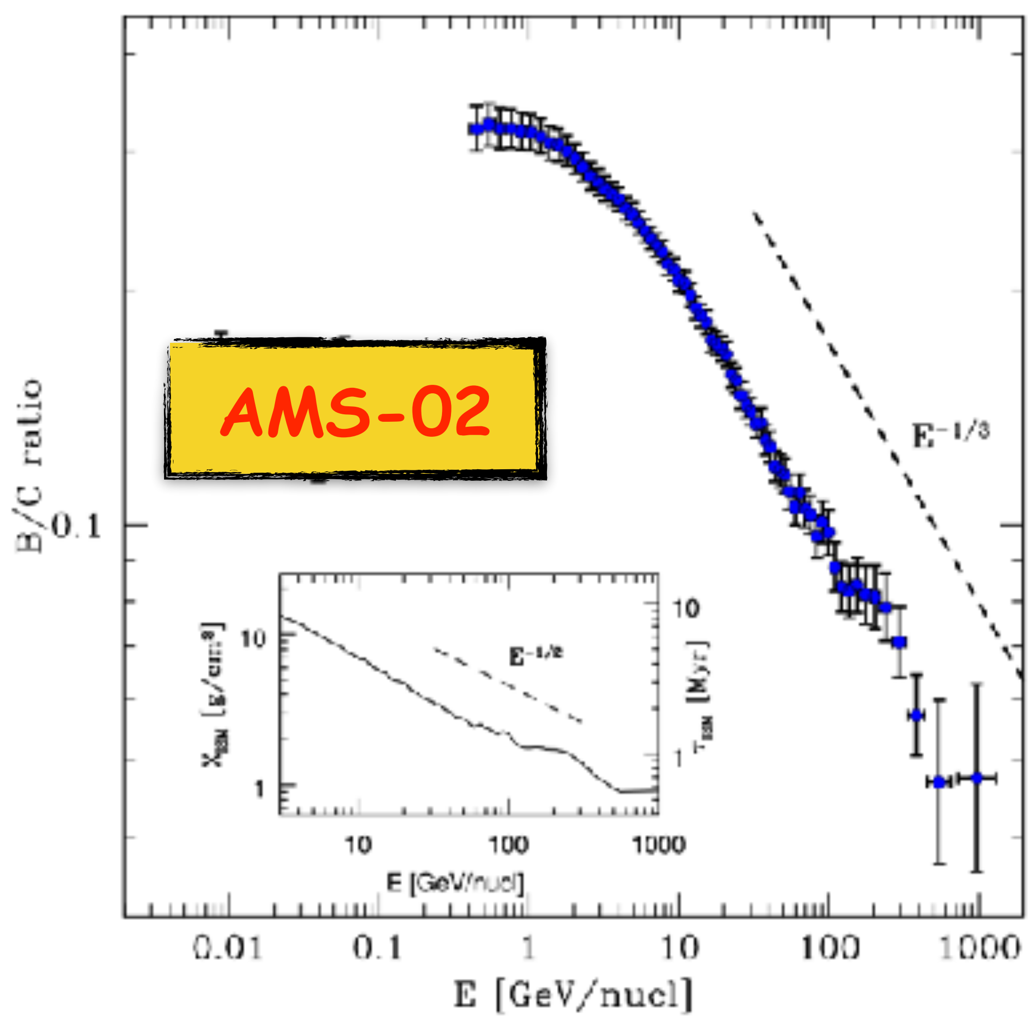

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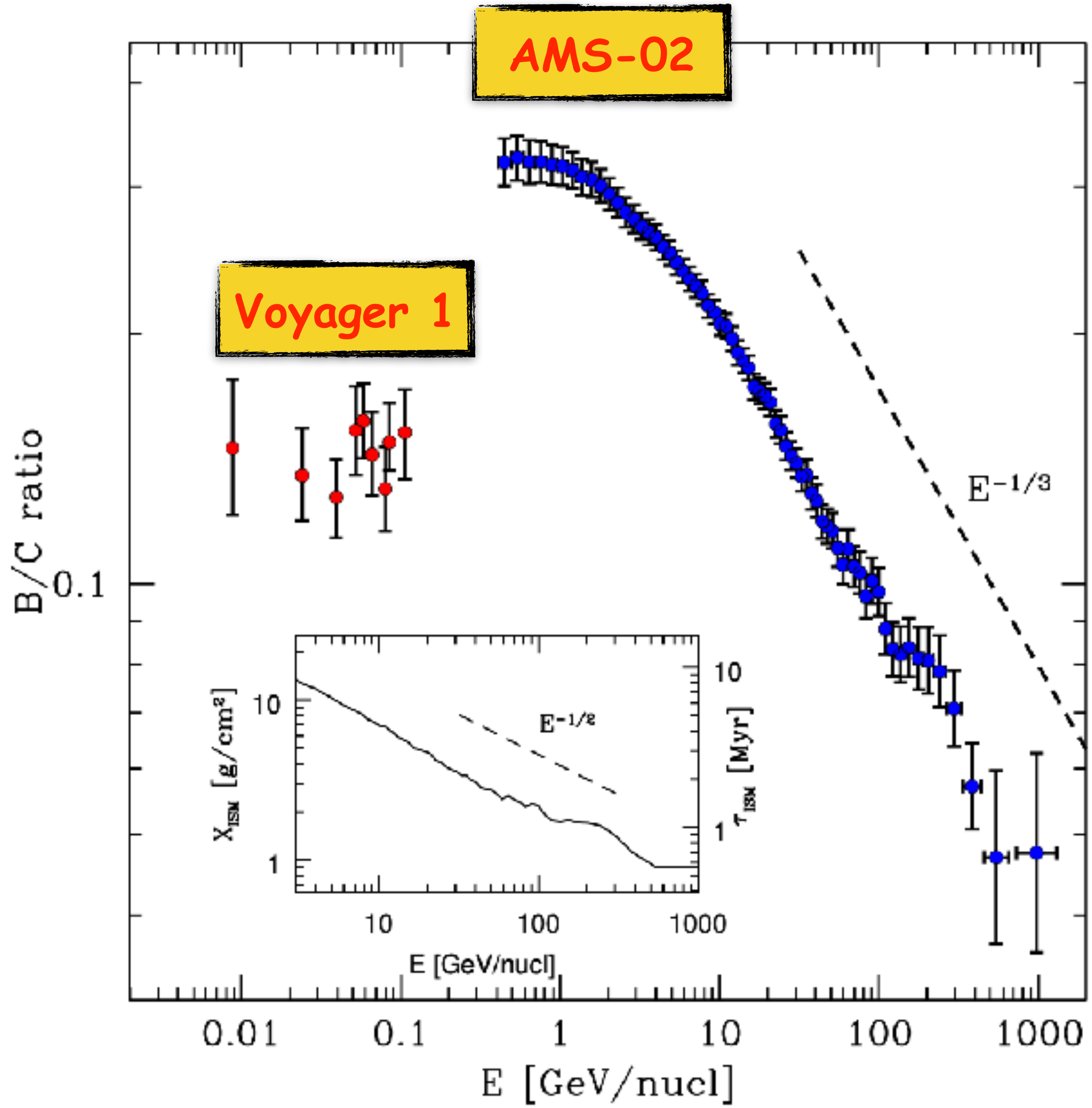

Gabici 2022

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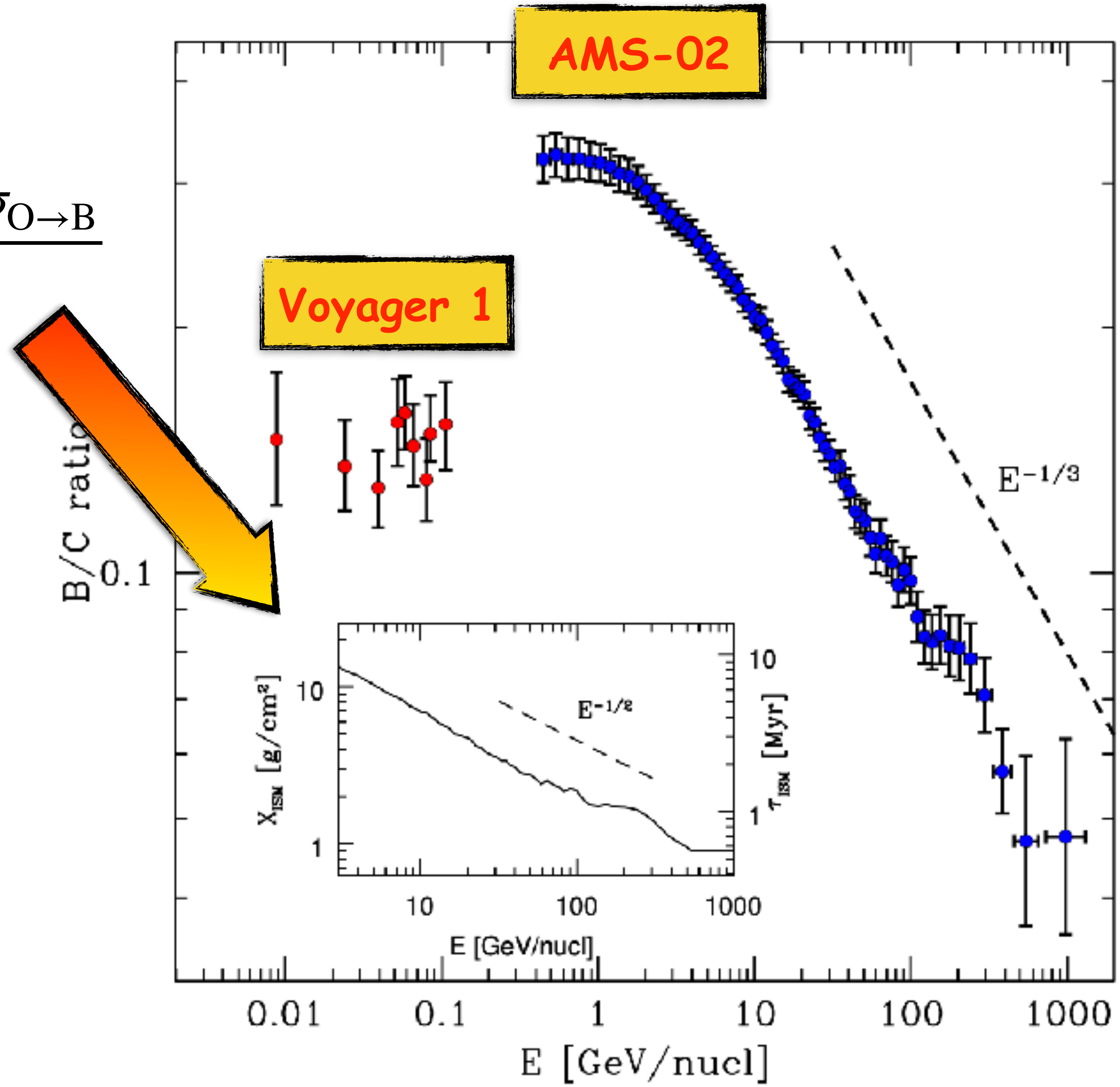

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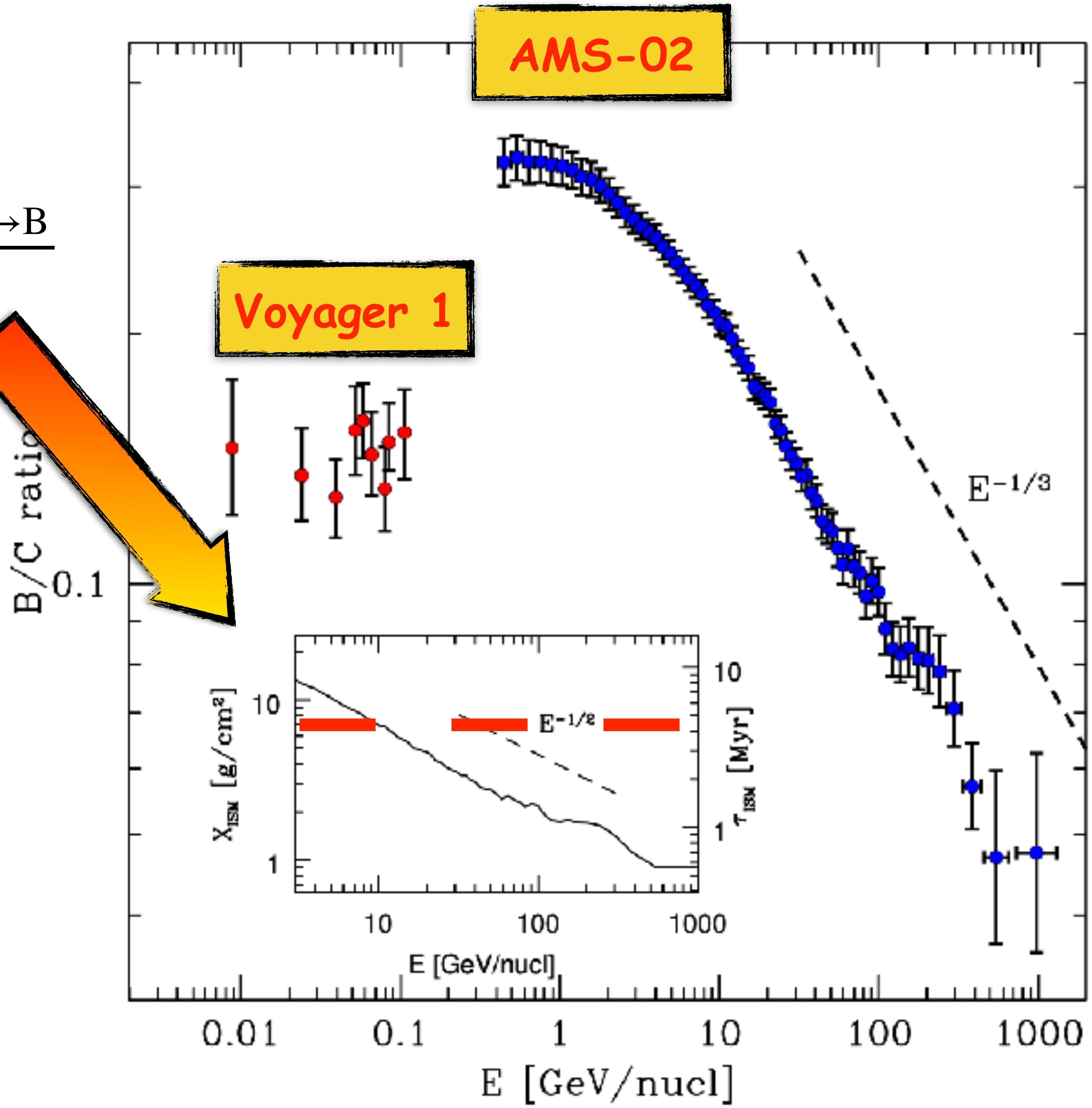

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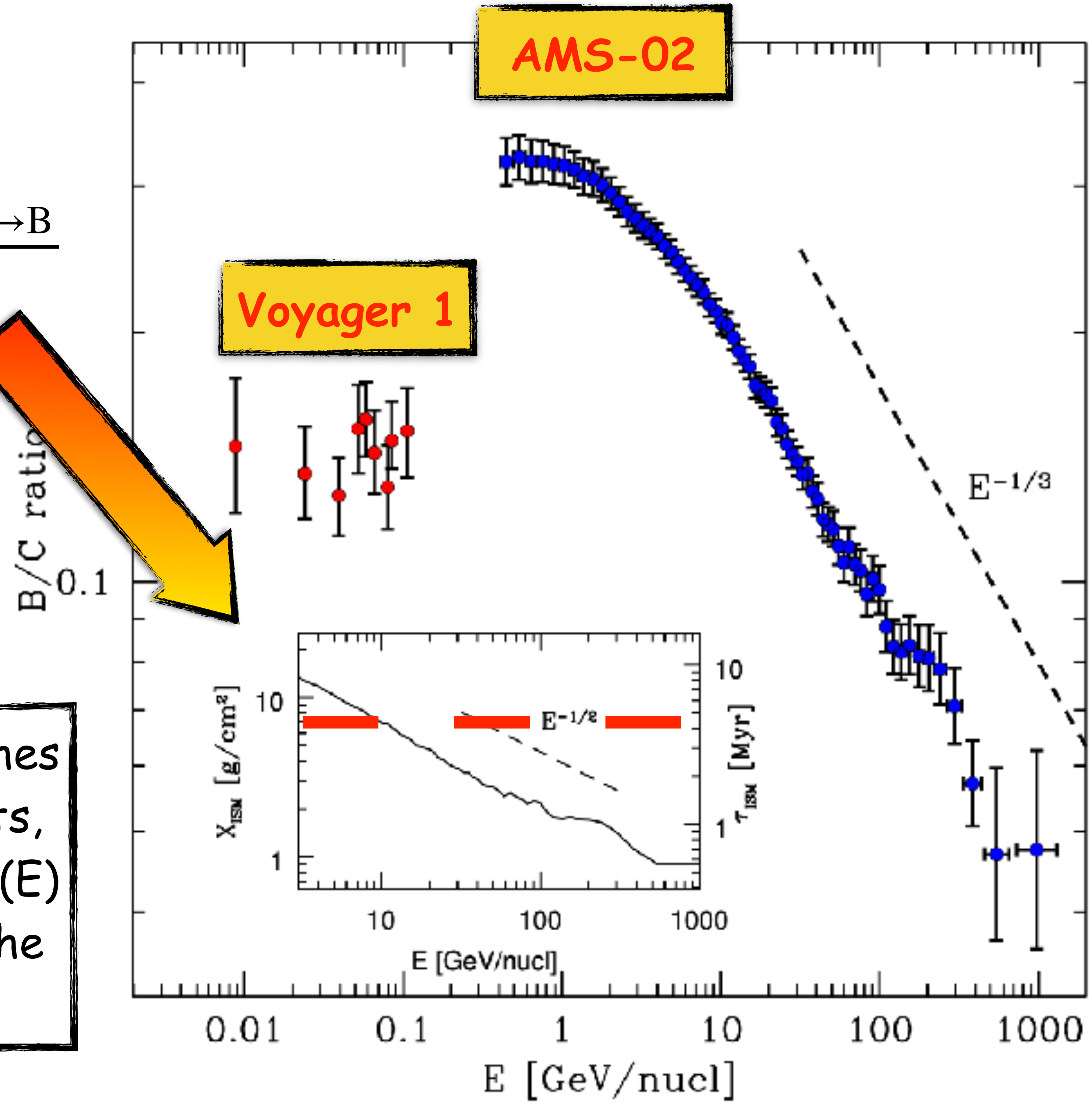


more sophisticated approaches exist and give similar results, just keep in mind that [B/C](E) and X_{ISM}(E) do NOT have the same slope!

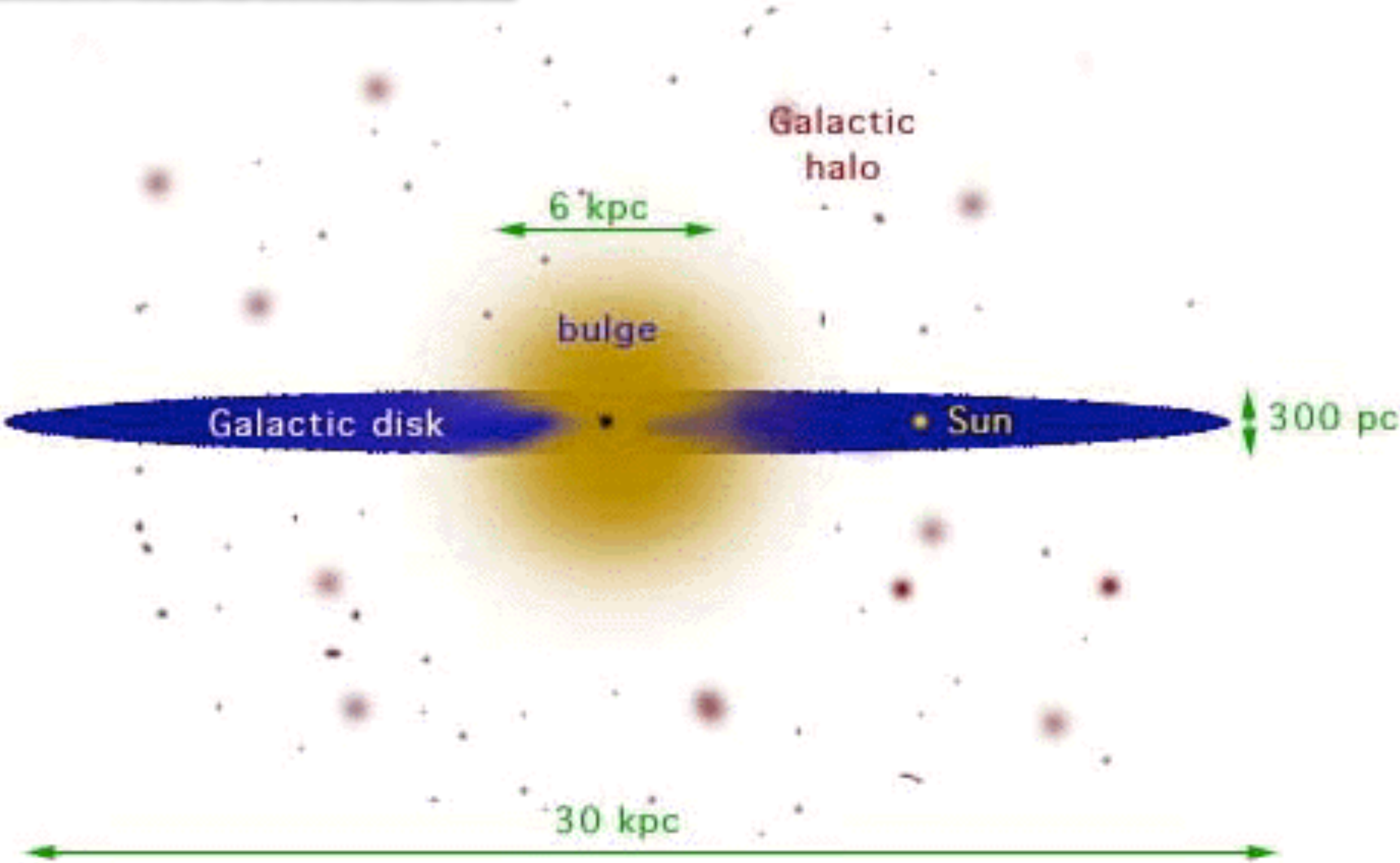
Gabici 2022

Escape time or residence time?

surface density of the disk —>

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

(see review by Ferriere, 2001)



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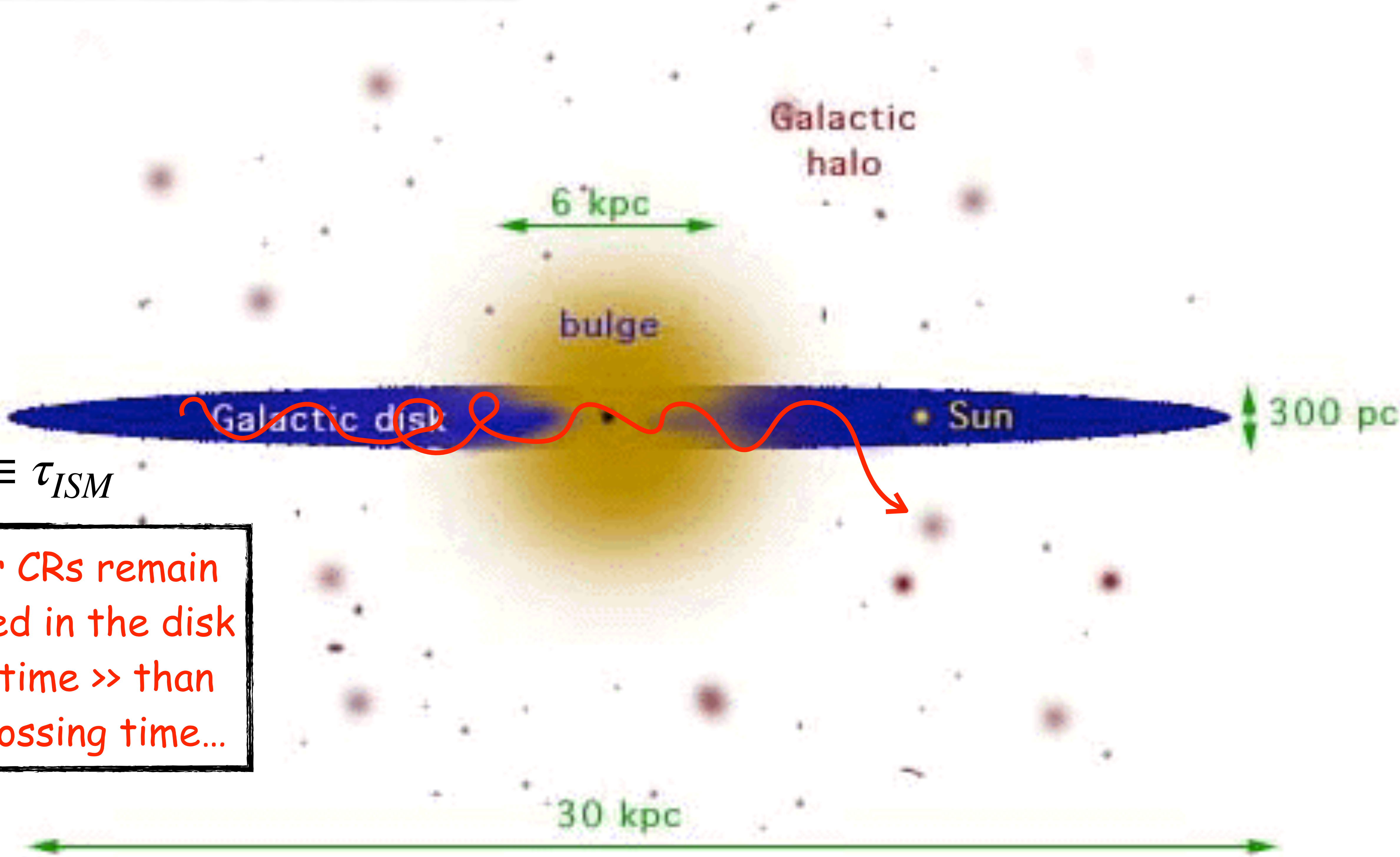

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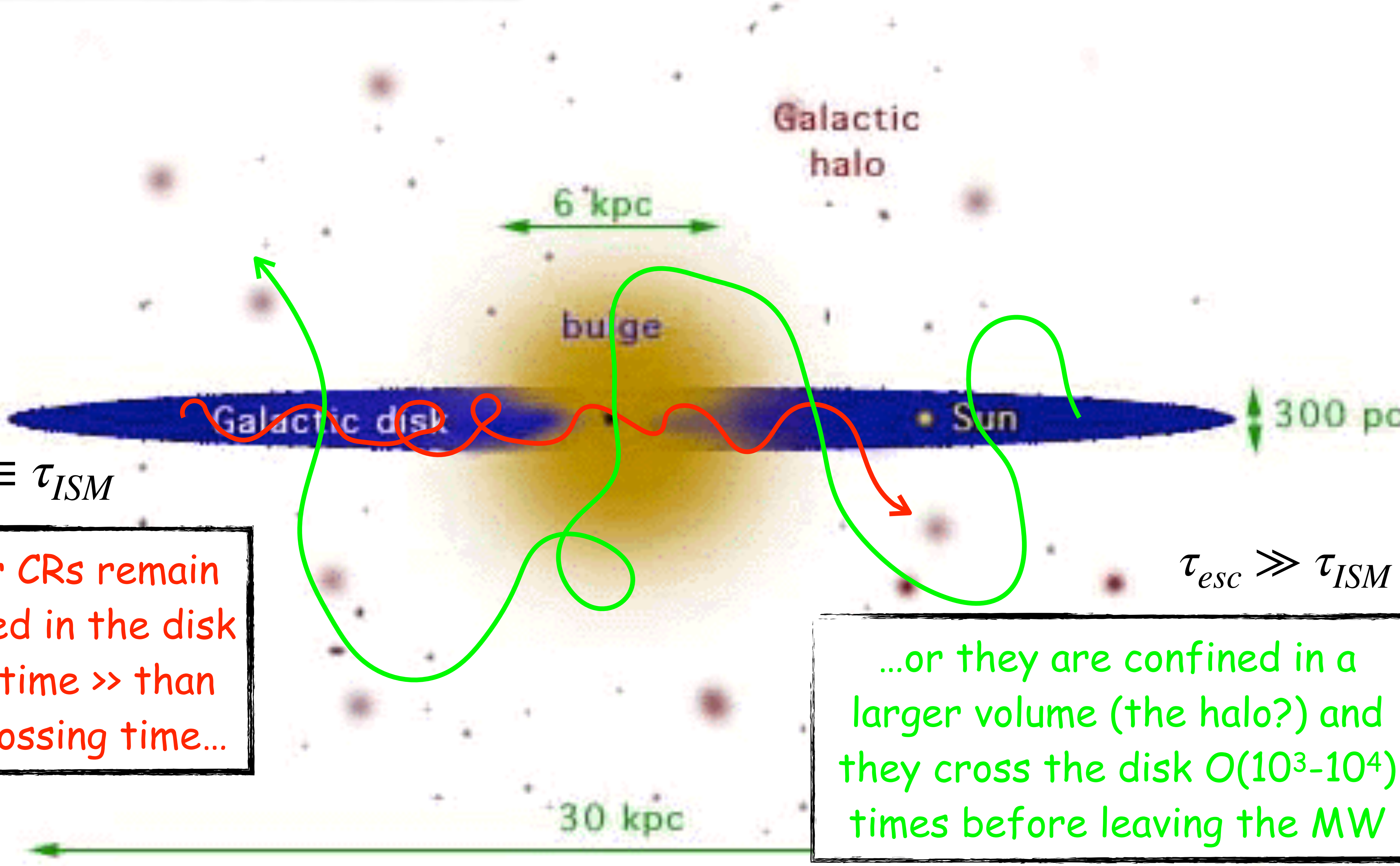

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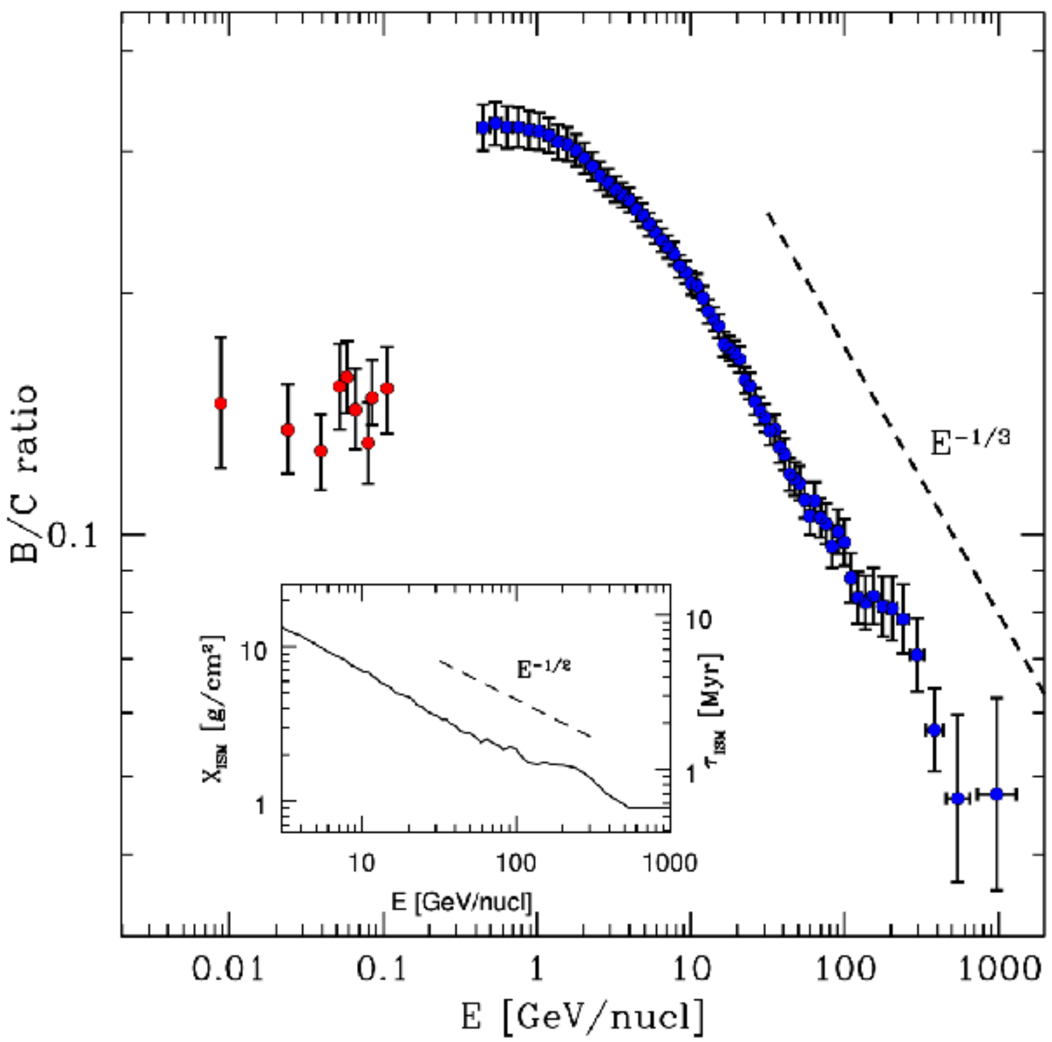
either CRs remain confined in the disk for a time >> than the crossing time...

$\tau_{esc} \gg \tau_{ISM}$

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

Escape time or residence time?



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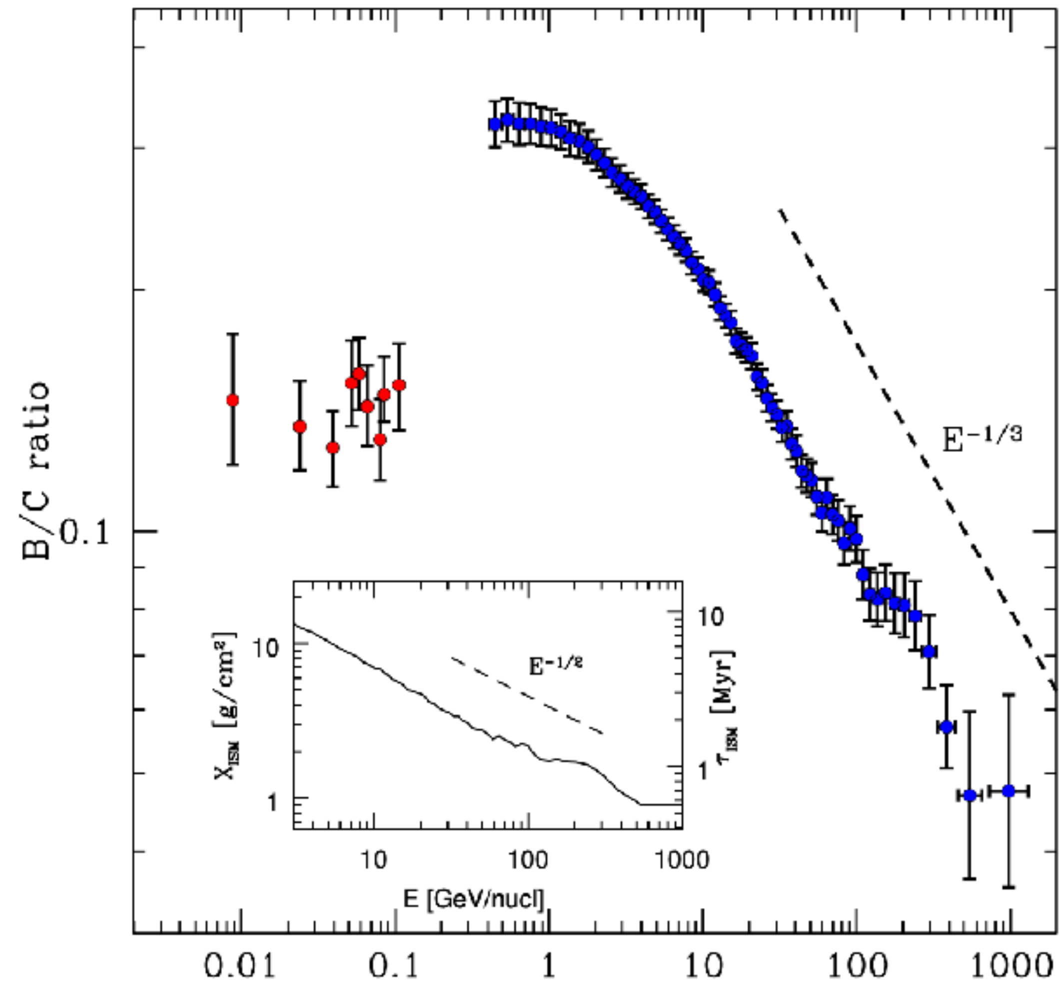

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we need a clock to measure how much time CRs spend in the halo (if any!)

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

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

stable isotope!

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

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$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \approx \frac{q(^{10}\mathrm{Be})}{q(^{9}\mathrm{Be})} \times \frac{\gamma \tau_{rad}}{\tau_{esc}}$$

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~0.8

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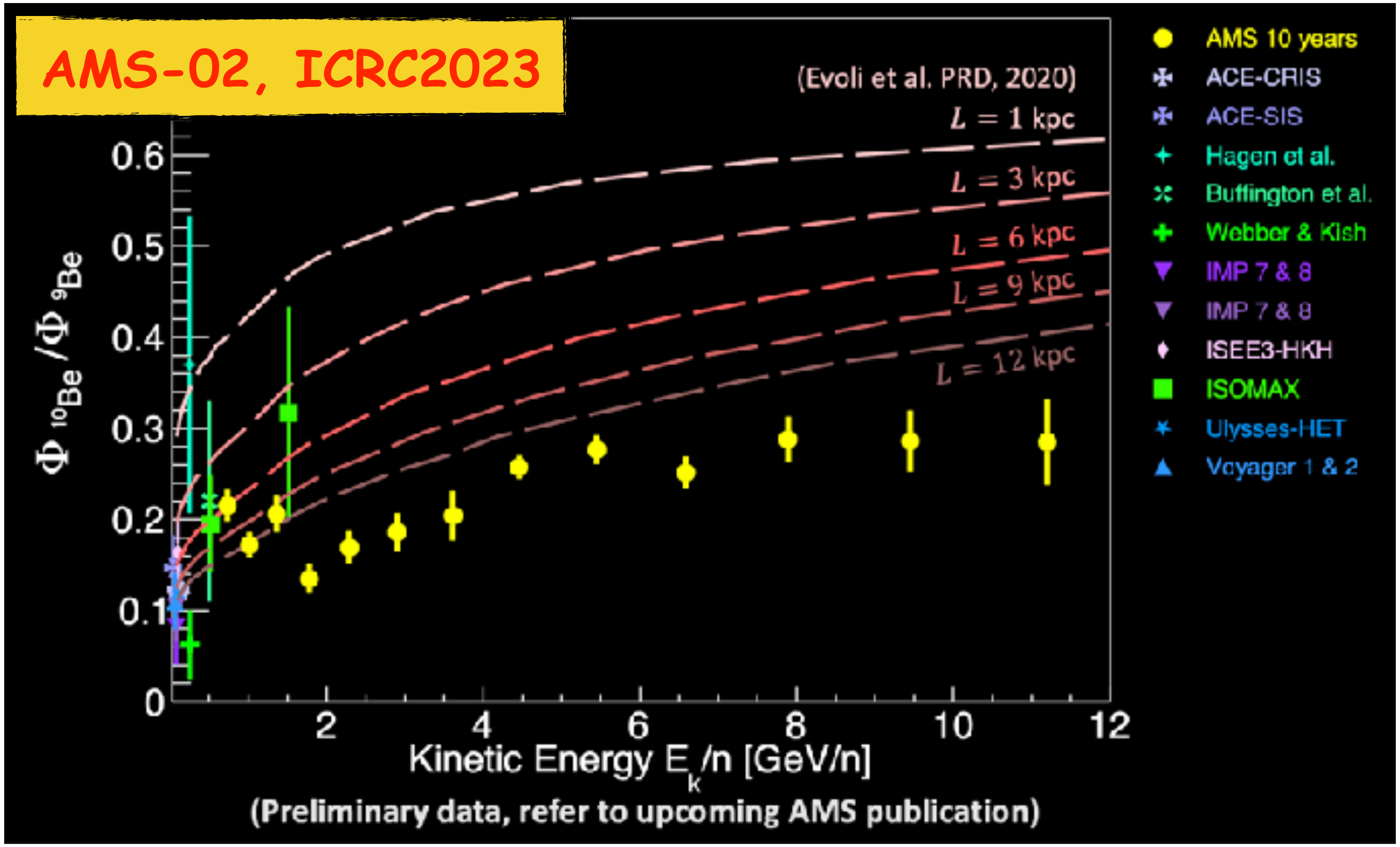
known

^{10}Be/^{9}Be ratio

$$\underbrace{\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})}}_{\sim 0.3} \approx \underbrace{\frac{q(^{10}\mathrm{Be})}{q(^{9}\mathrm{Be})}}_{\sim 0.8} \times \underbrace{\frac{\gamma\tau_{rad}}{\tau_{esc}}}_{\text{known}}$$



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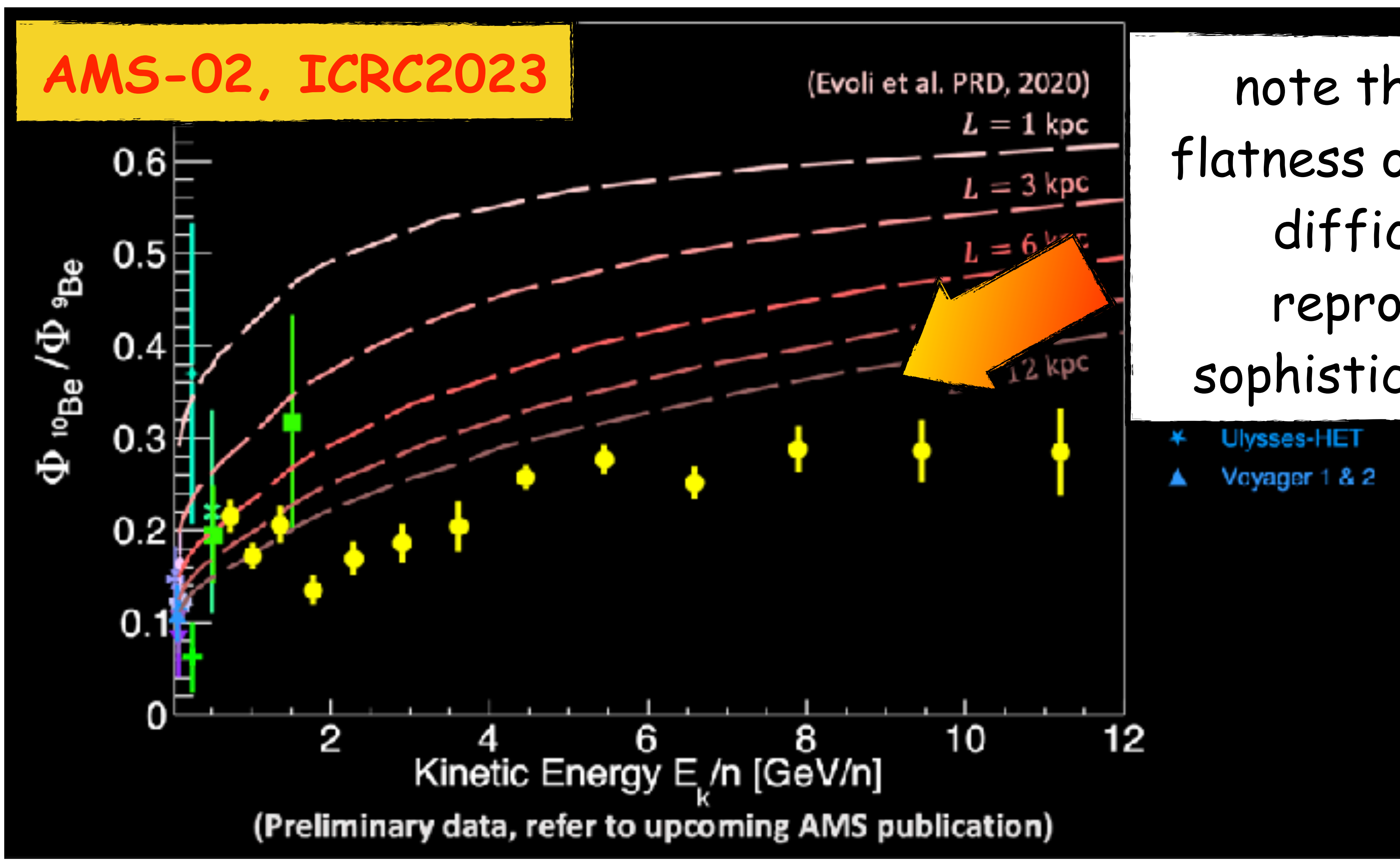

note that the the flatness of the ratio is difficult to be reproduced by sophisticated models

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

~0.8

~0.3 $$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \approx \frac{q(^{10}\mathrm{Be})}{q(^{9}\mathrm{Be})} \times \frac{\gamma\tau_{rad}}{\tau_{esc}}$$ ~20 Myr

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$$10 \text{ GeV/n} \longrightarrow \tau_{esc} \approx 50 \text{ Myr} \gg 4 \text{ Myr} \approx \tau_{ISM}$$

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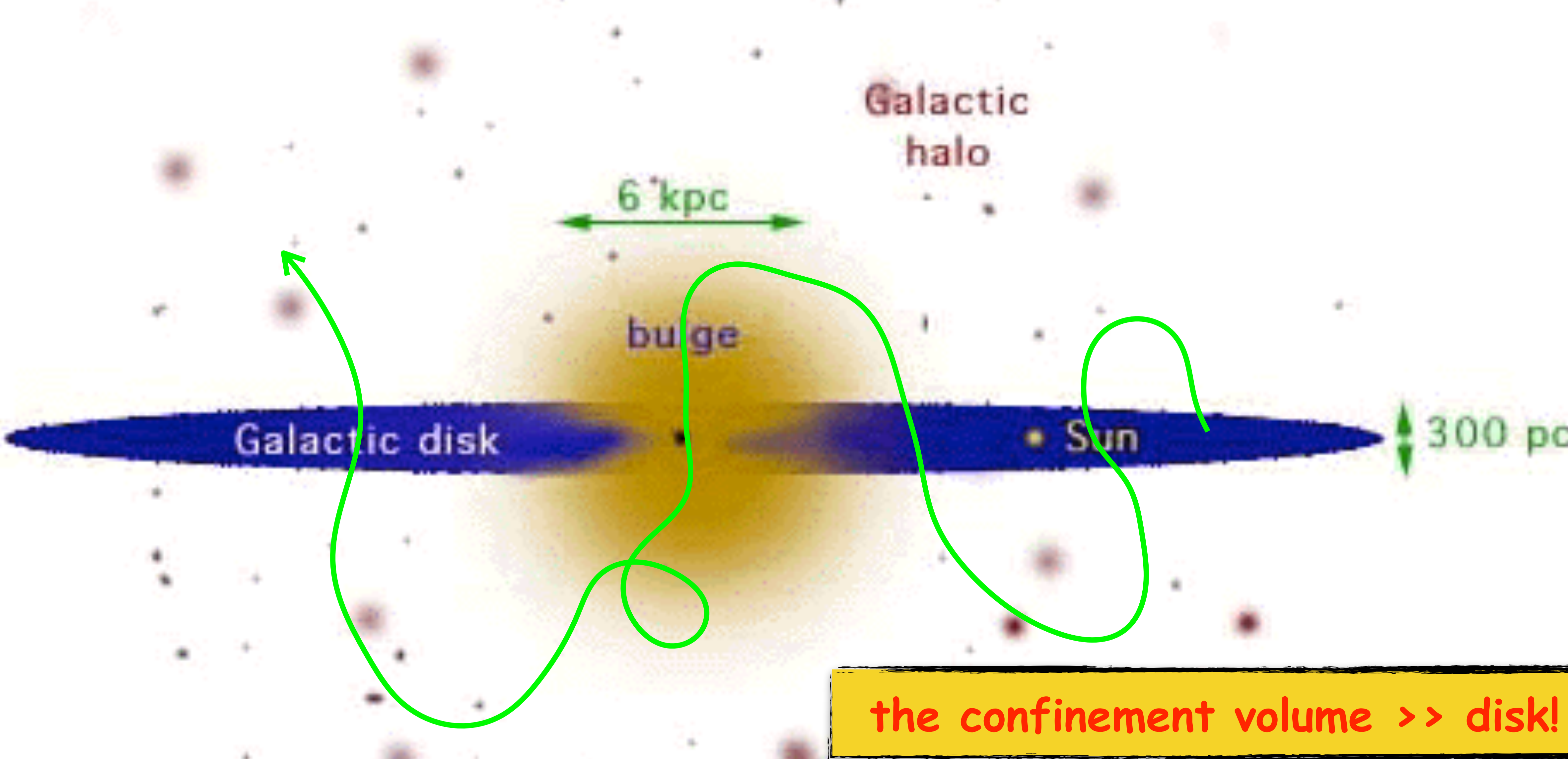
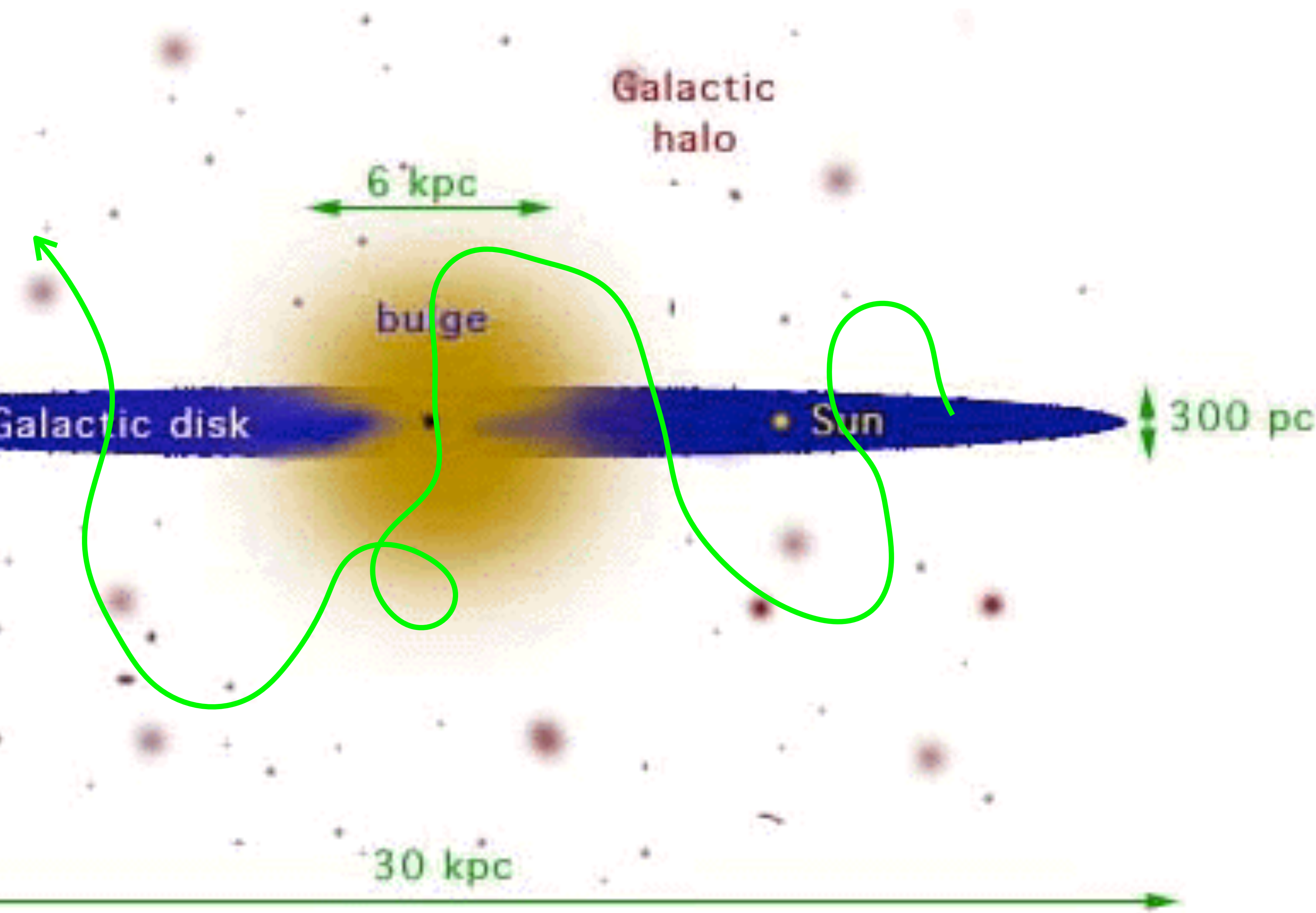


the confinement volume >> disk!

[6] Diffusive models for CR transport

Diffusive models



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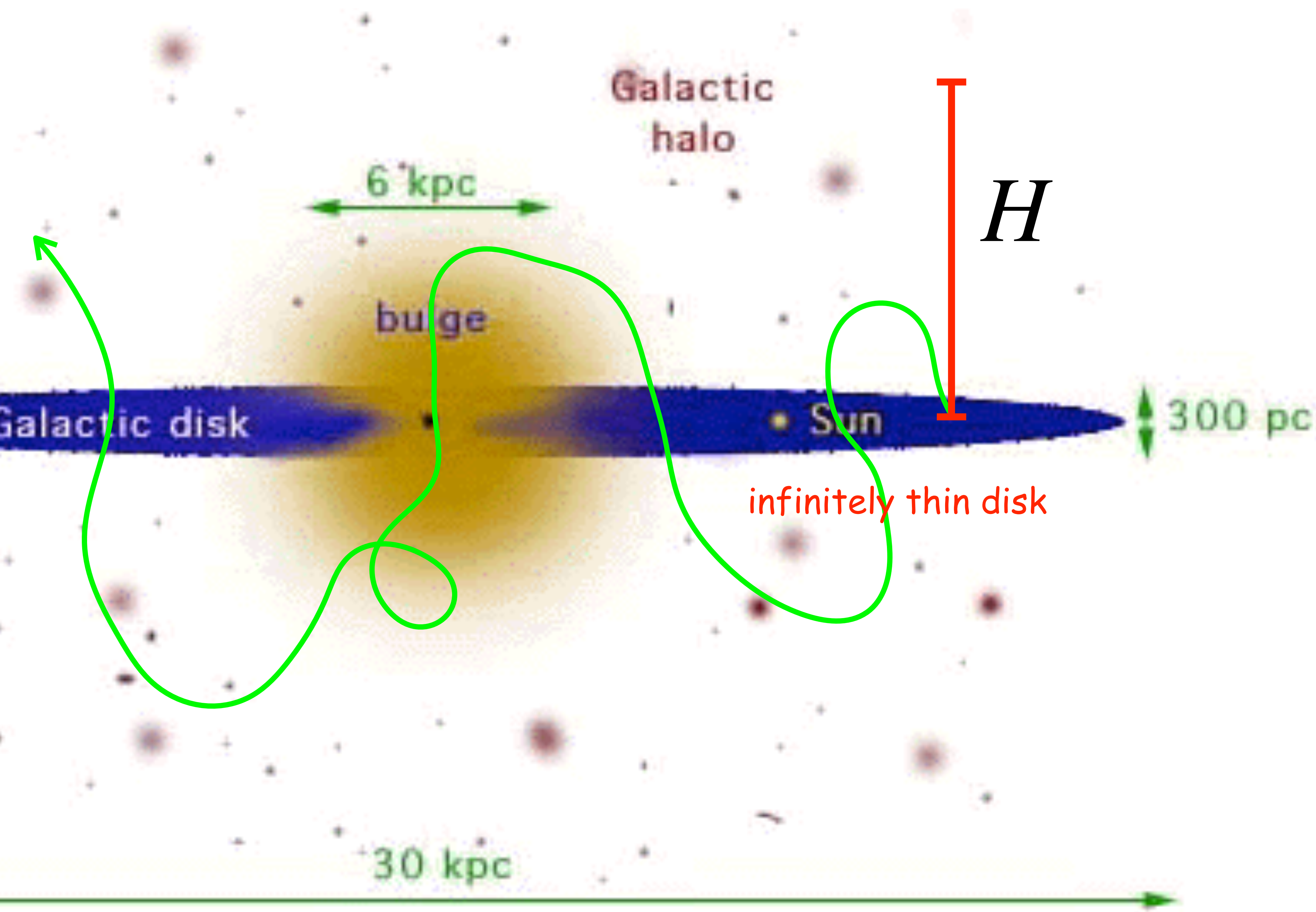

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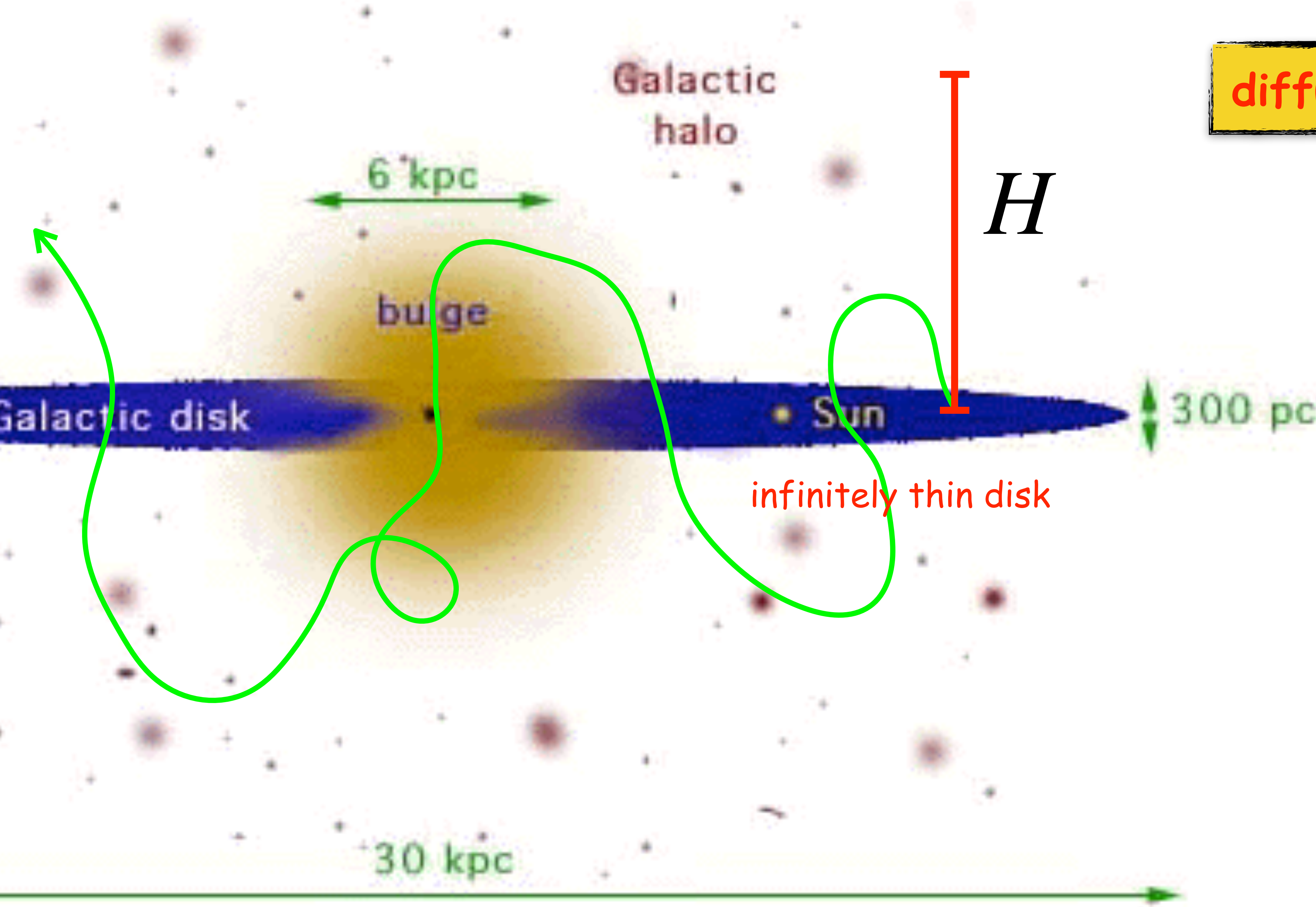


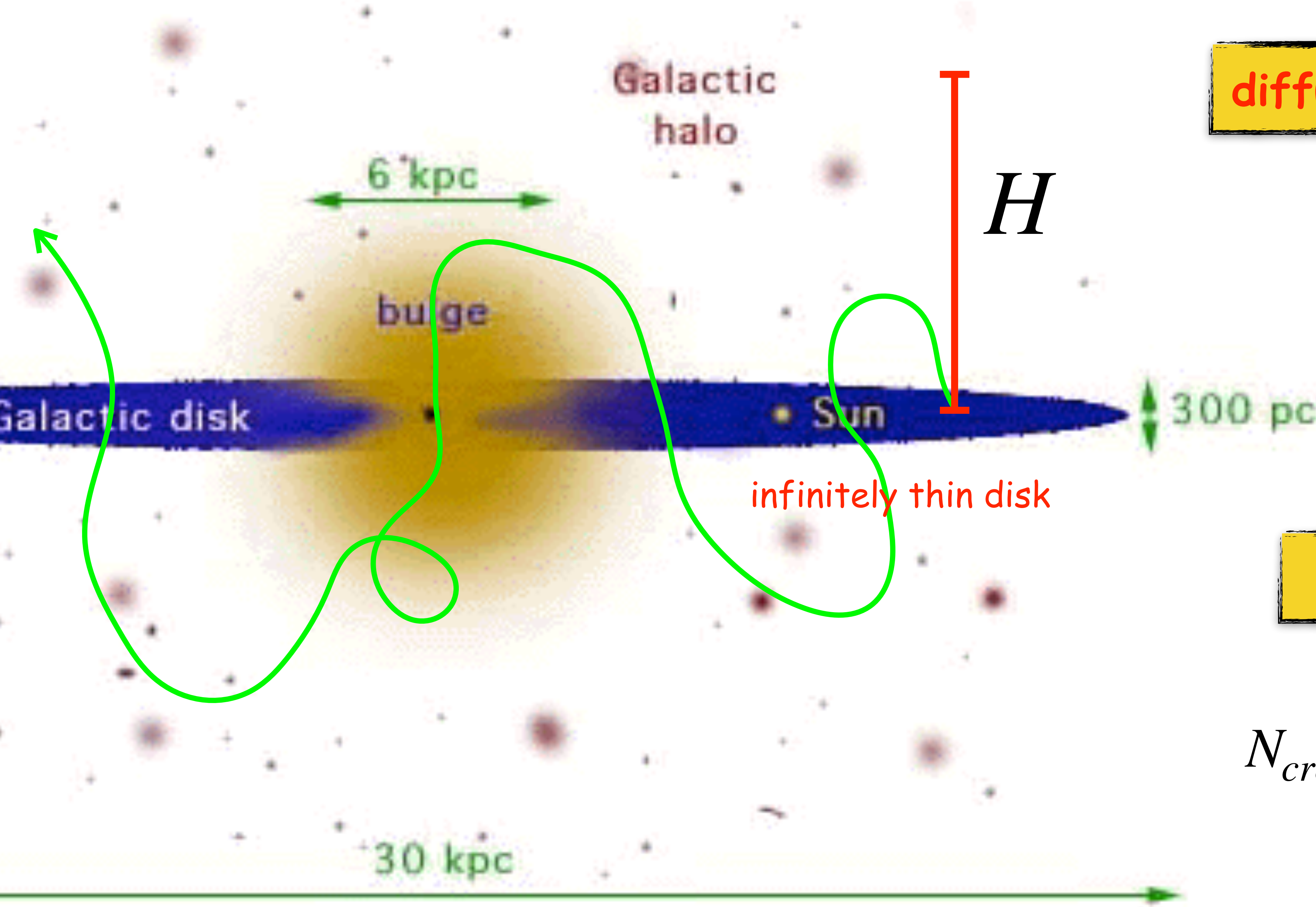
diffusion coefficient

mean free path

$$D \sim \lambda v$$

velocity

Diffusive models



diffusion coefficient

mean free path

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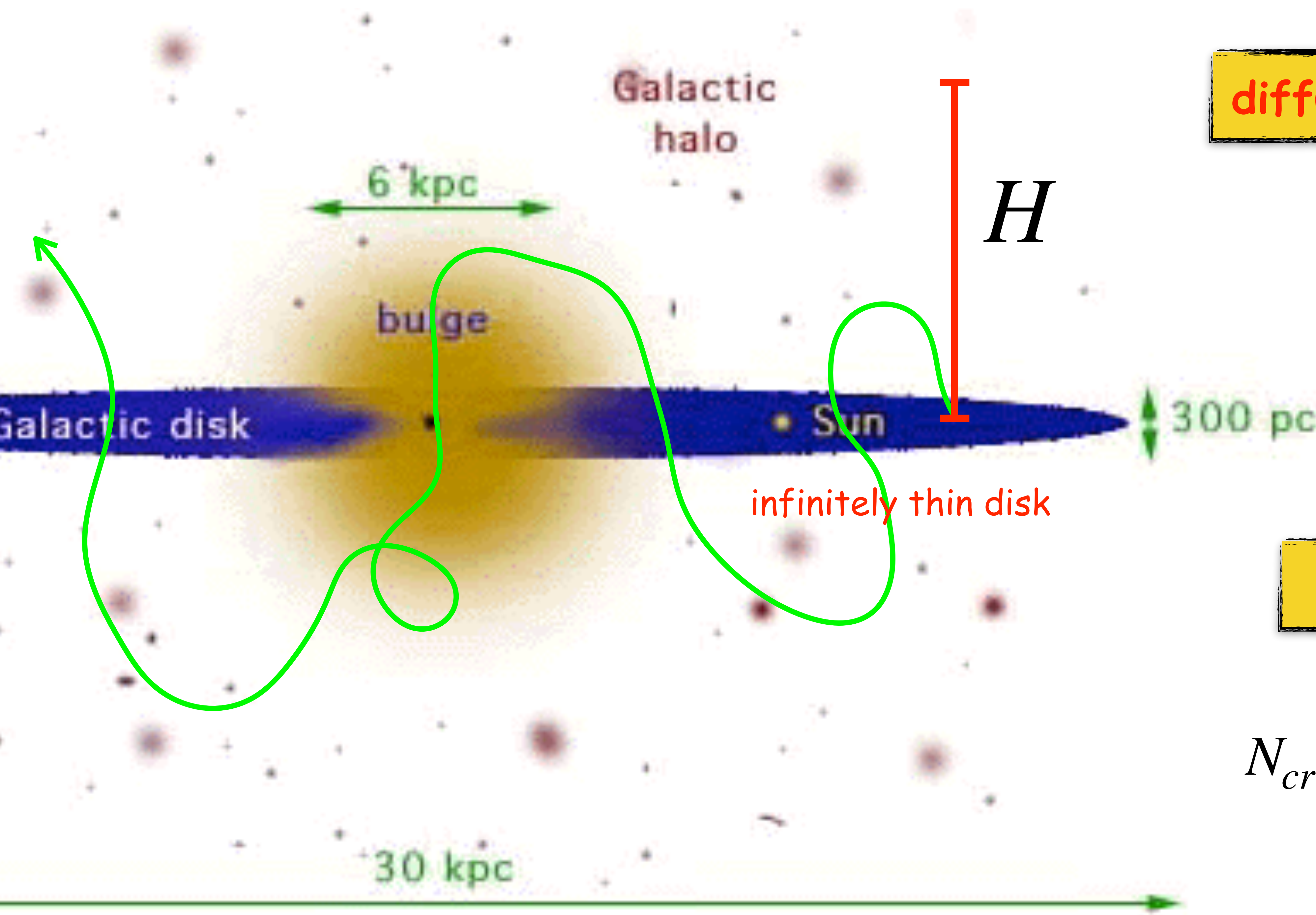
velocity

# of crossings

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

Diffusive models



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velocity

# of crossings

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

grammage —> $X_{ISM} \sim N_{cross} X_{disk}$

Diffusive models

B/C constrains a combination of H and D

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

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^{10}Be diffuses over a distance

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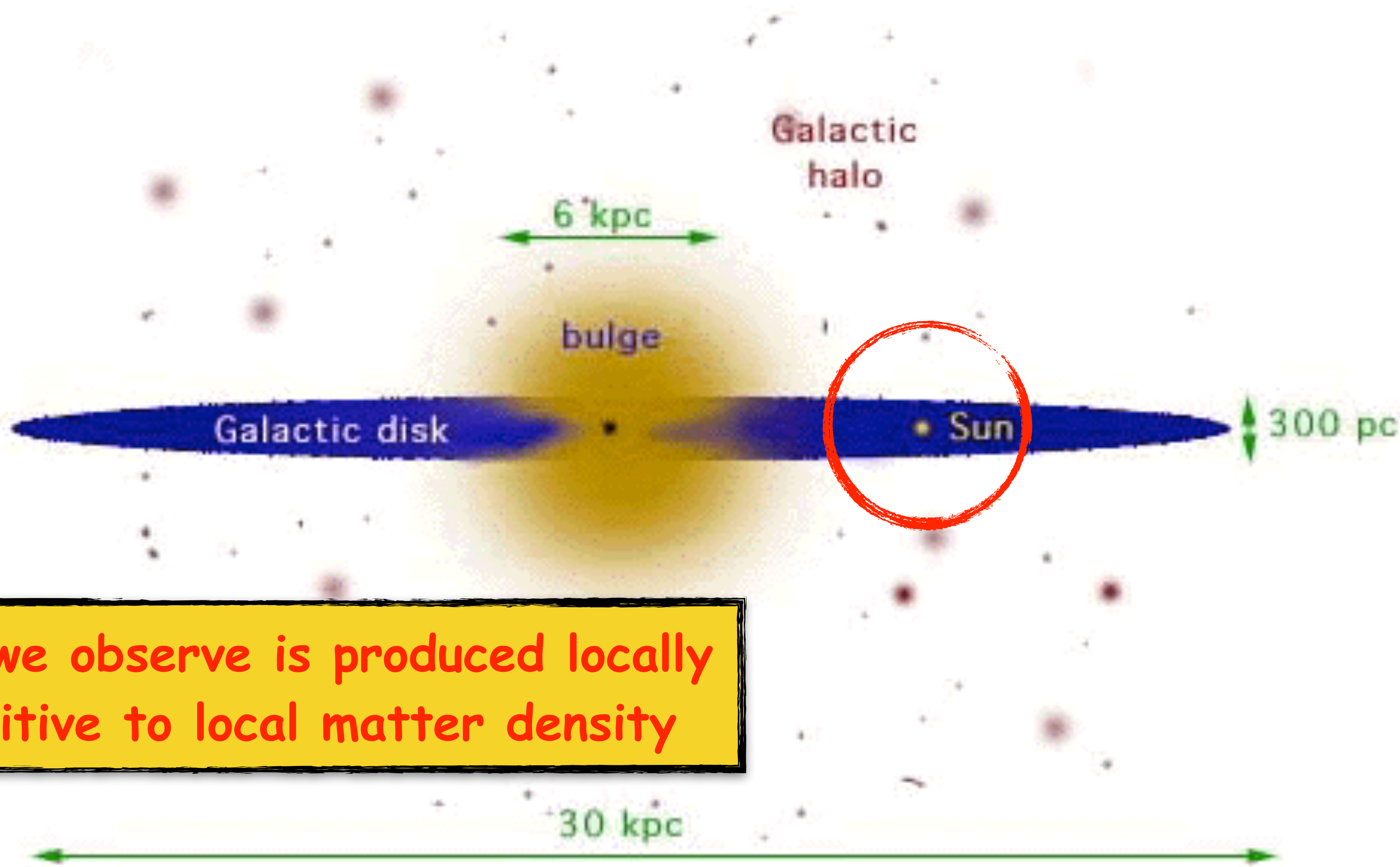
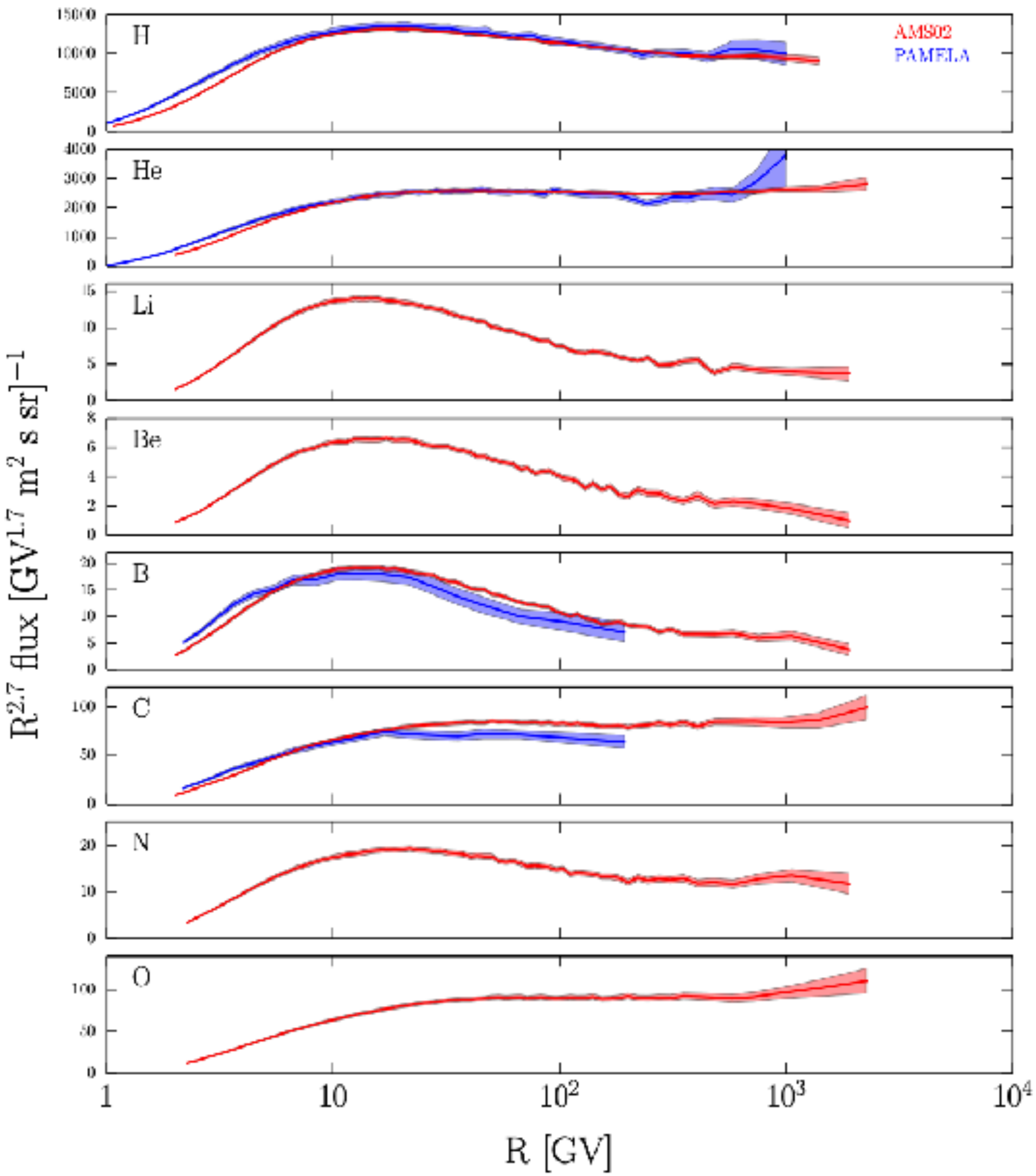


the ^{10}Be we observe is produced locally
—> sensitive to local matter density

Let's go back to CR spectra



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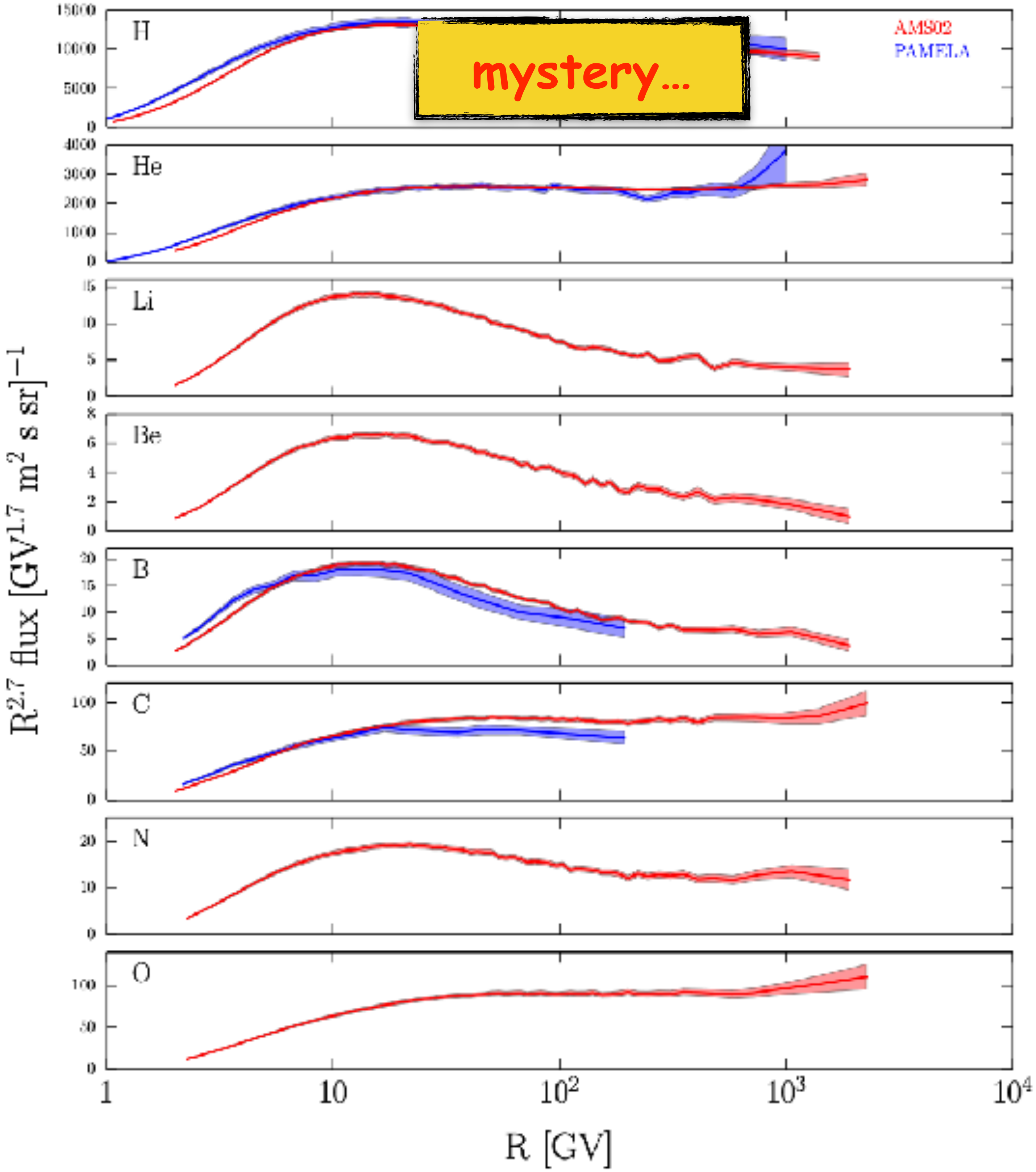

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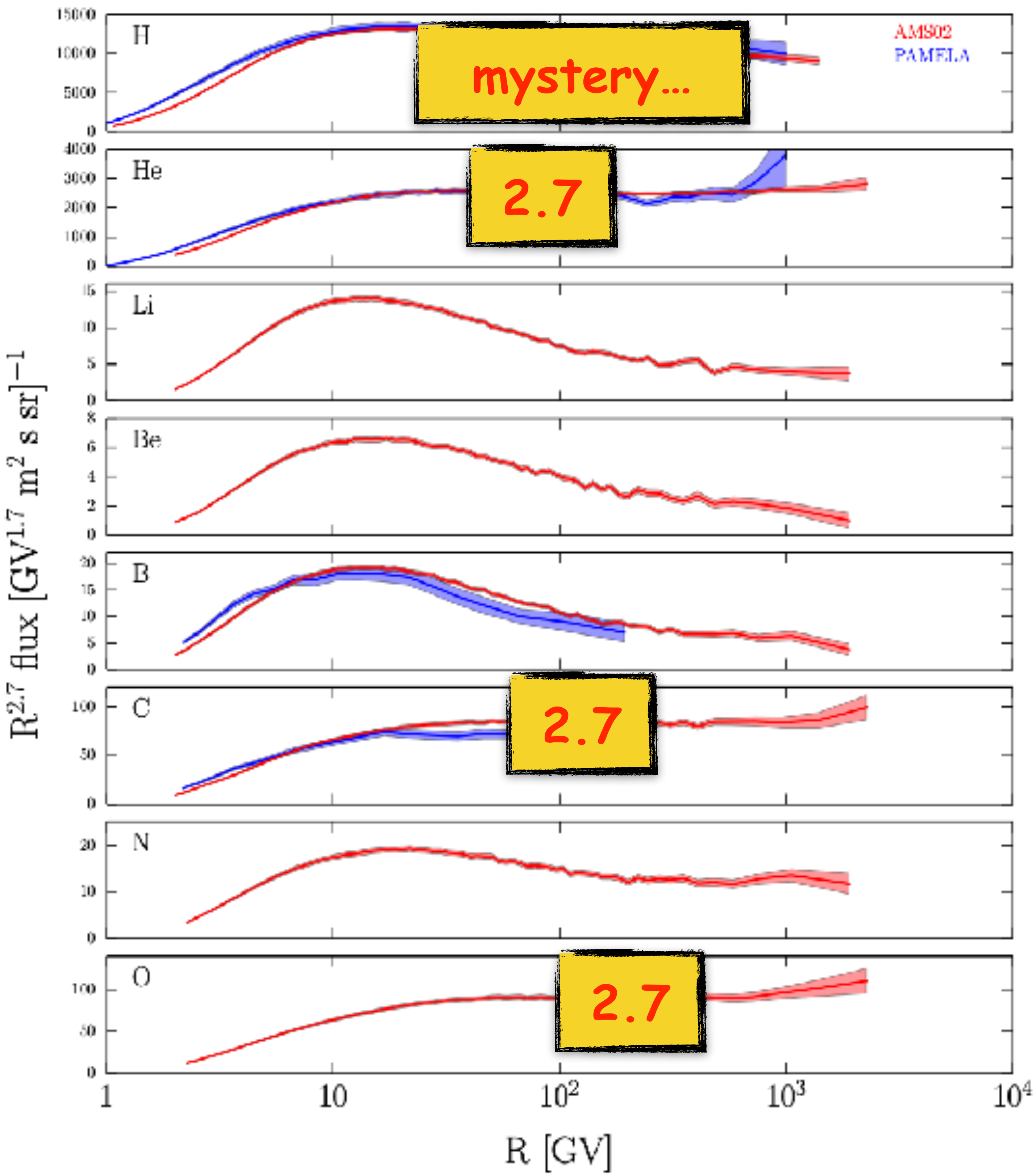

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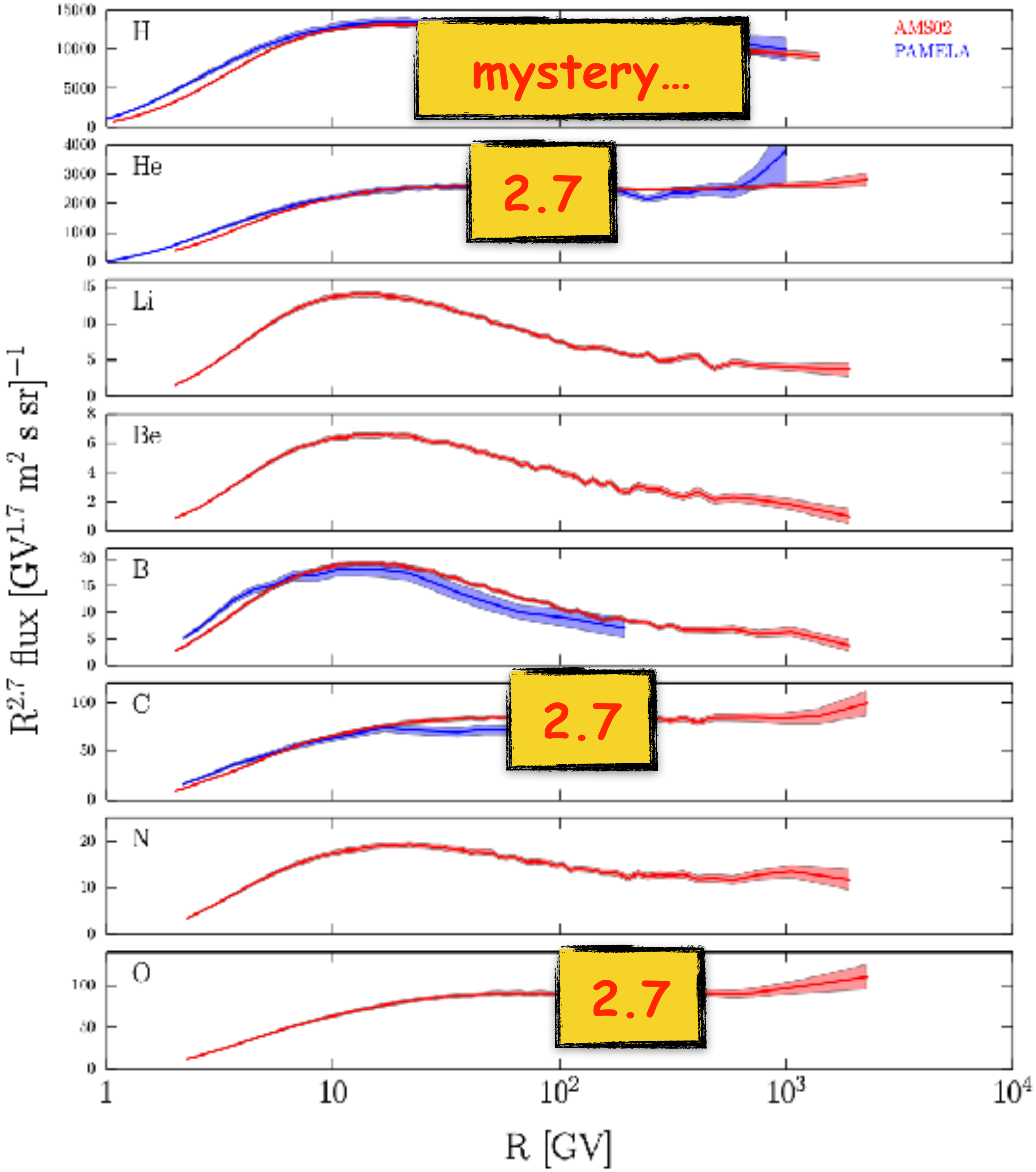

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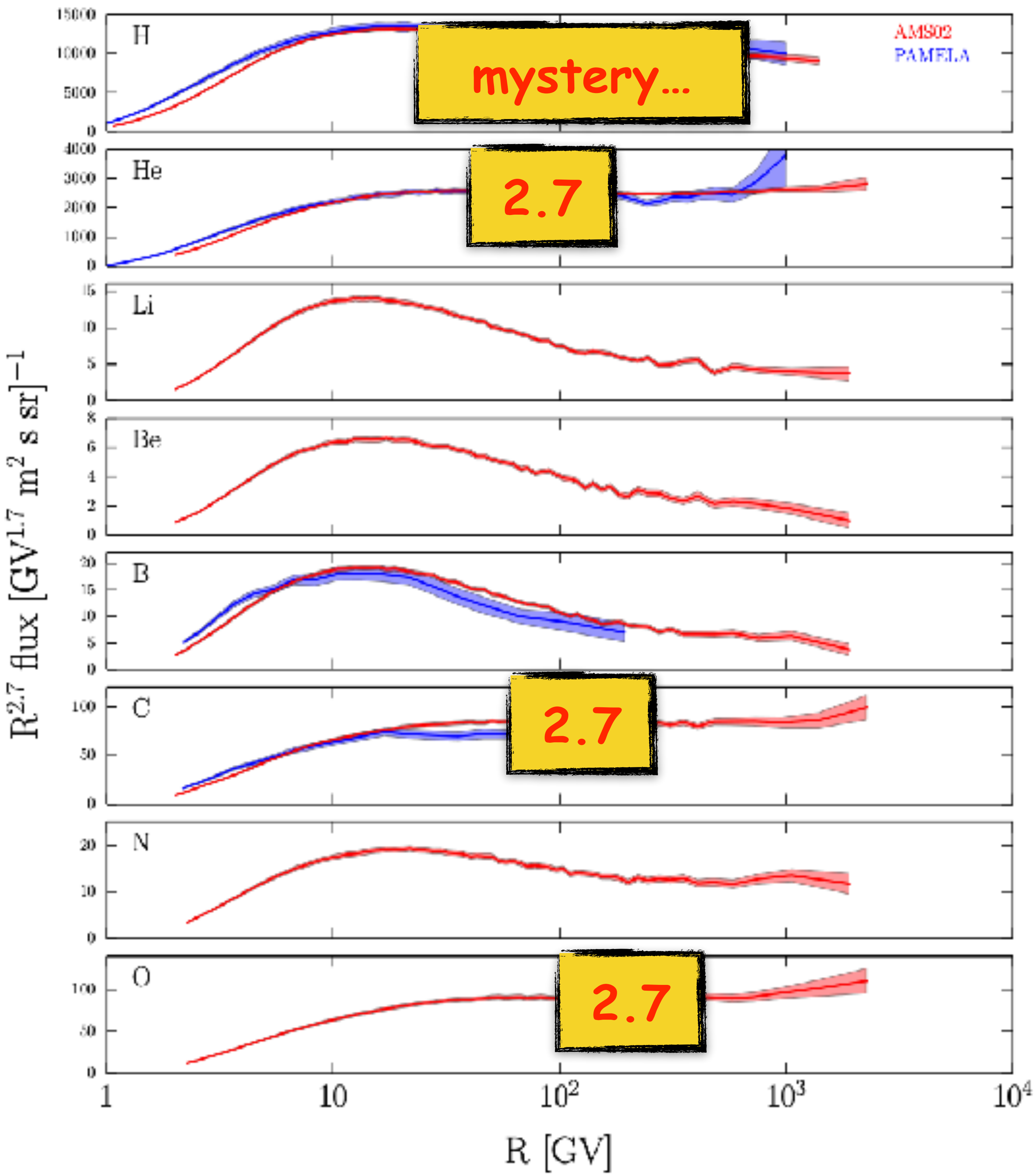

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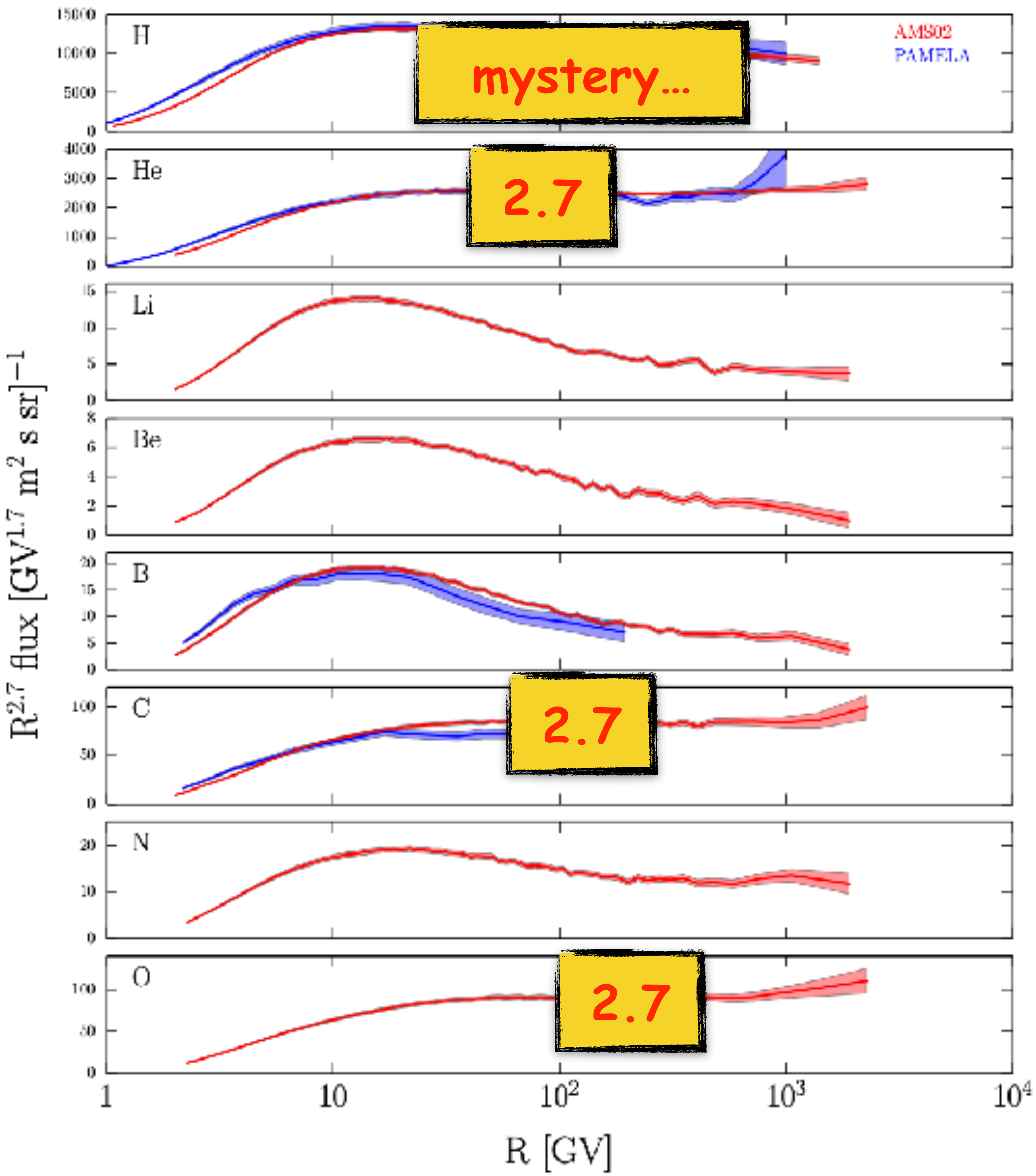

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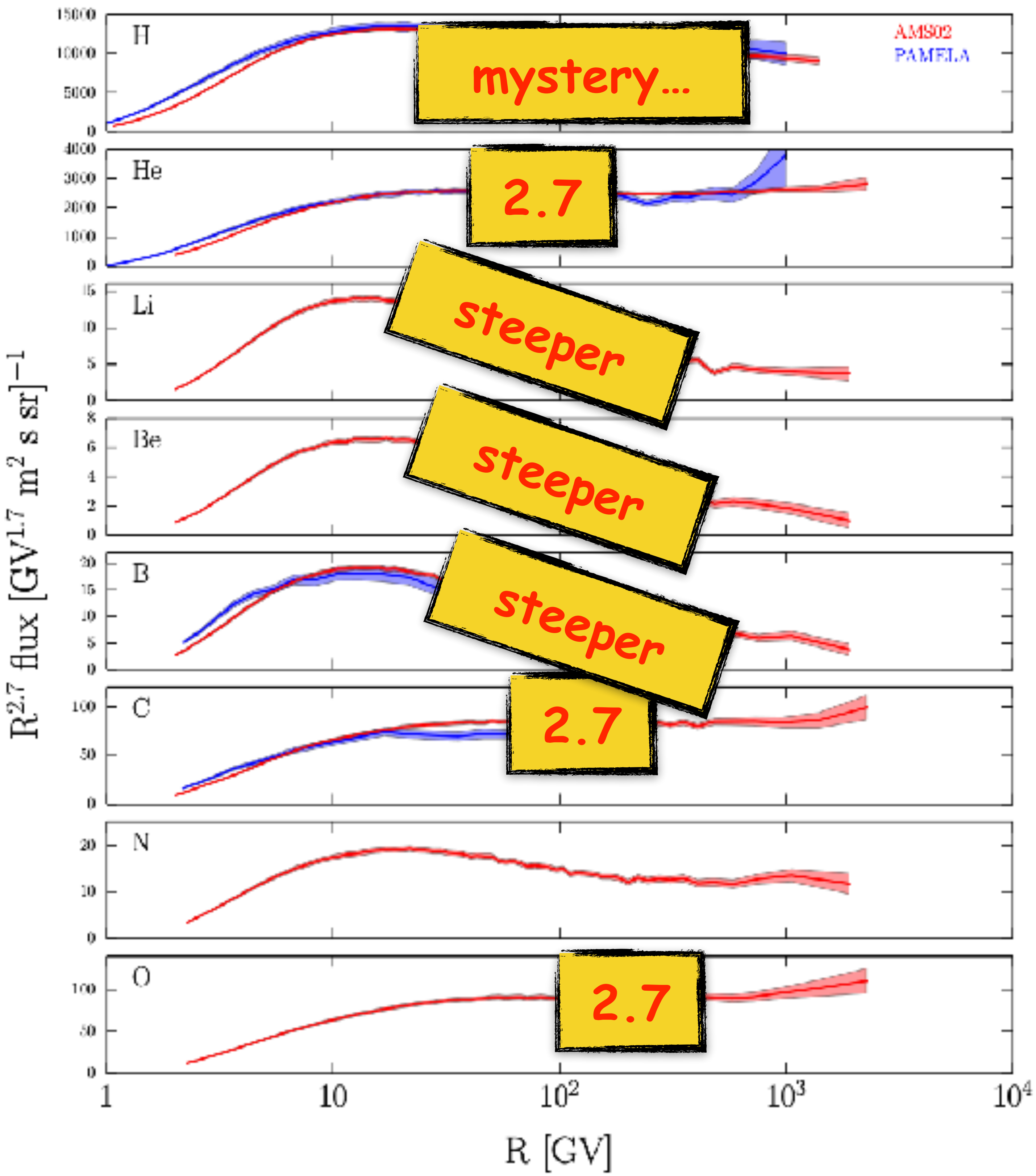

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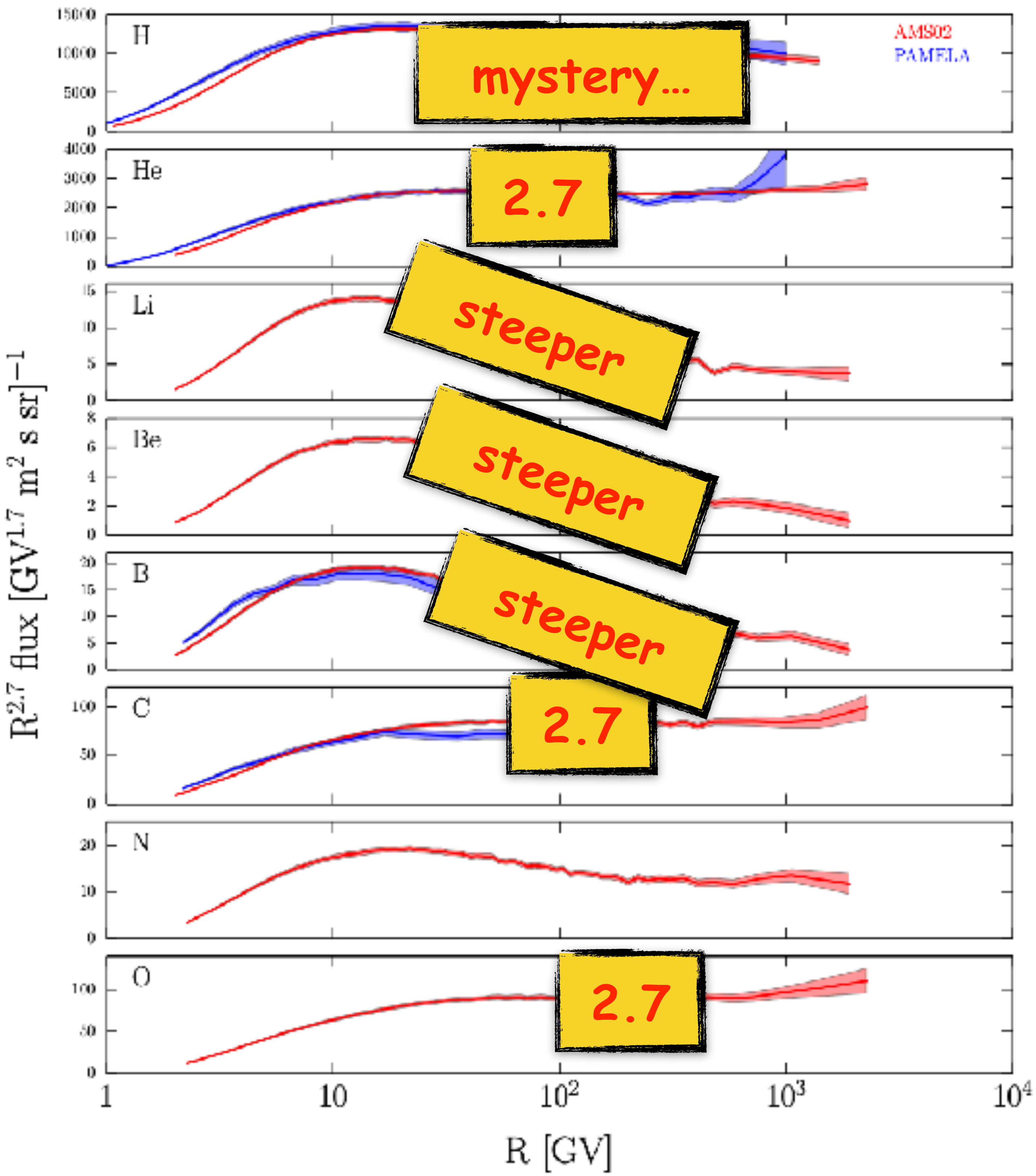

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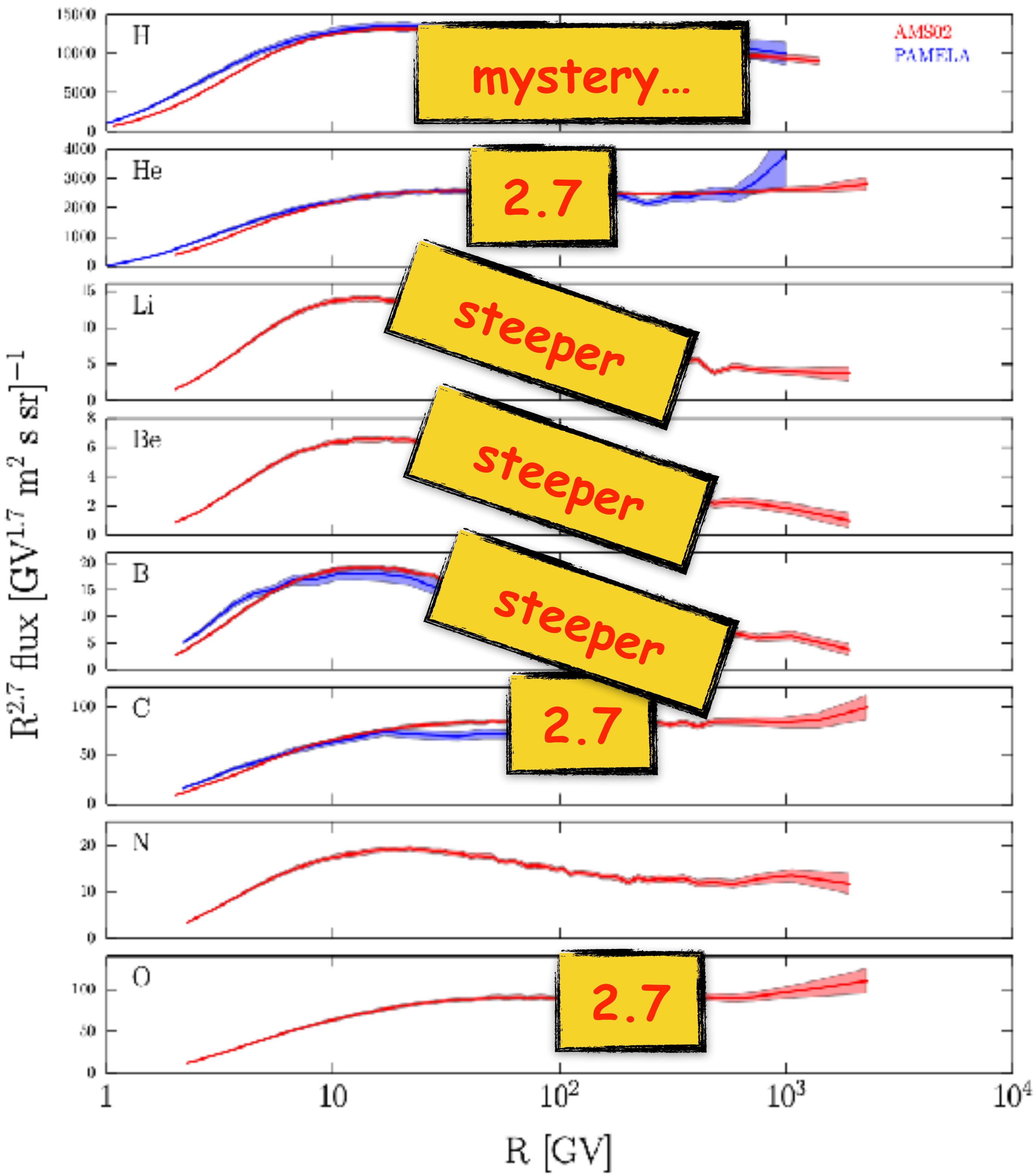

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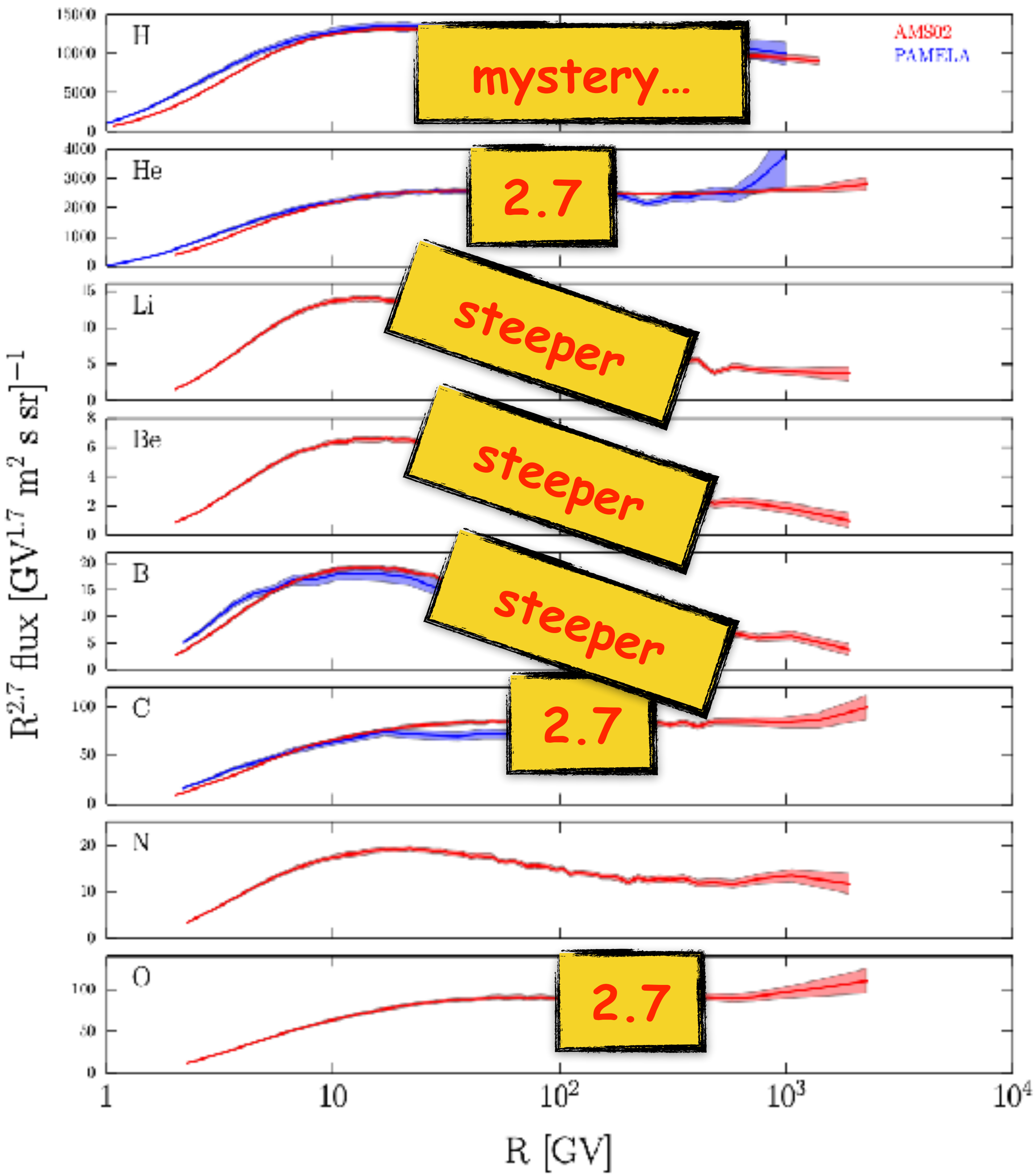

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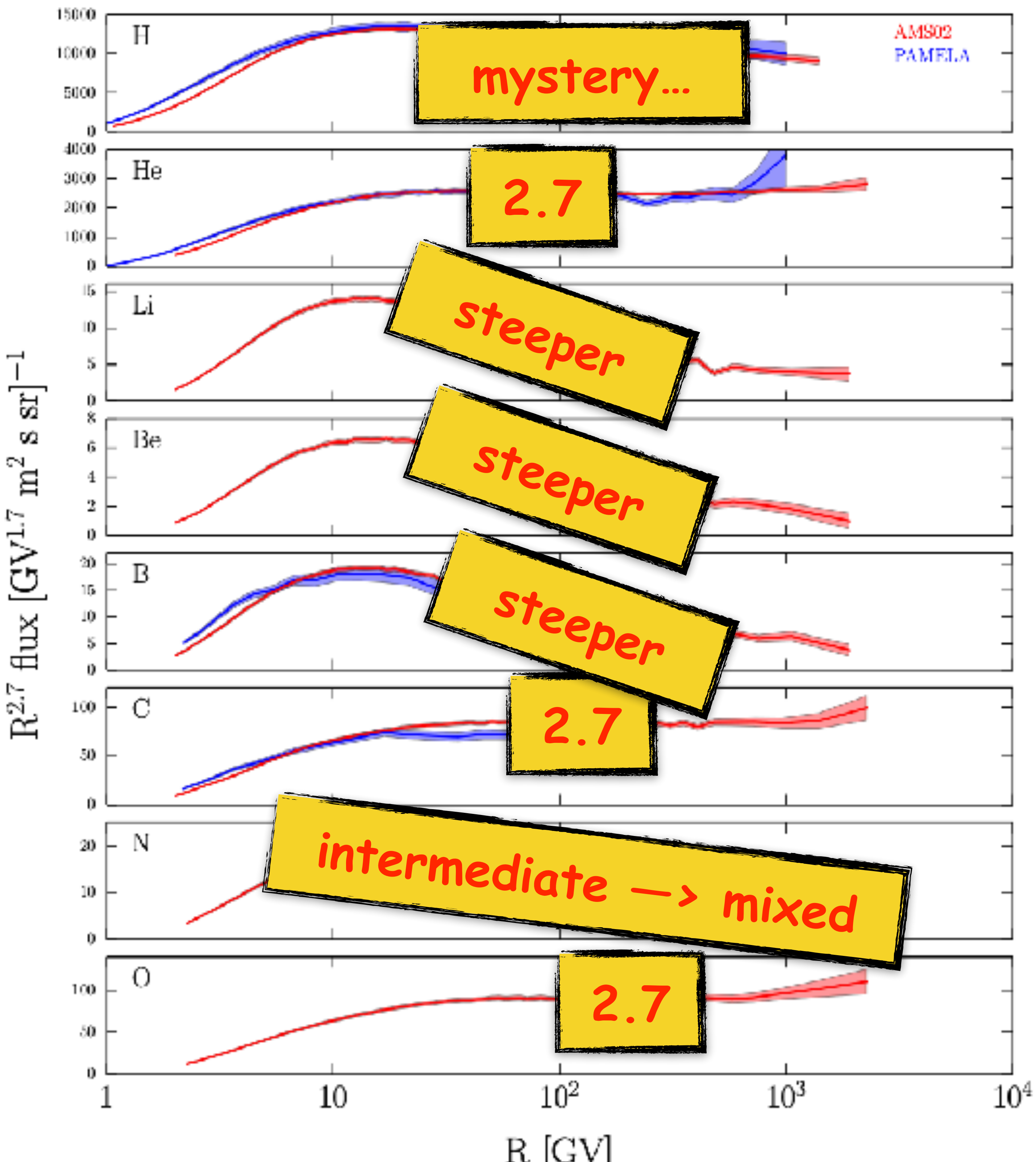

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…and we can proceed further and estimate the source power!

local energy density

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

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

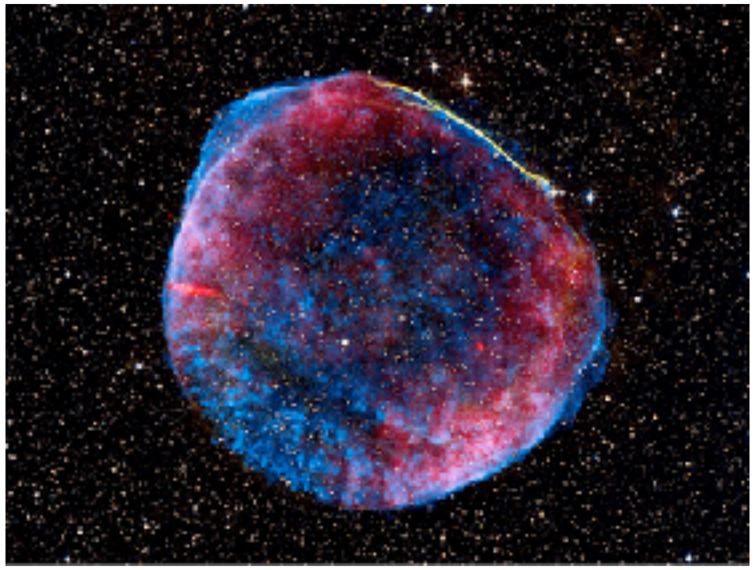
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

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 1950

The supernova remnant origin of CRs



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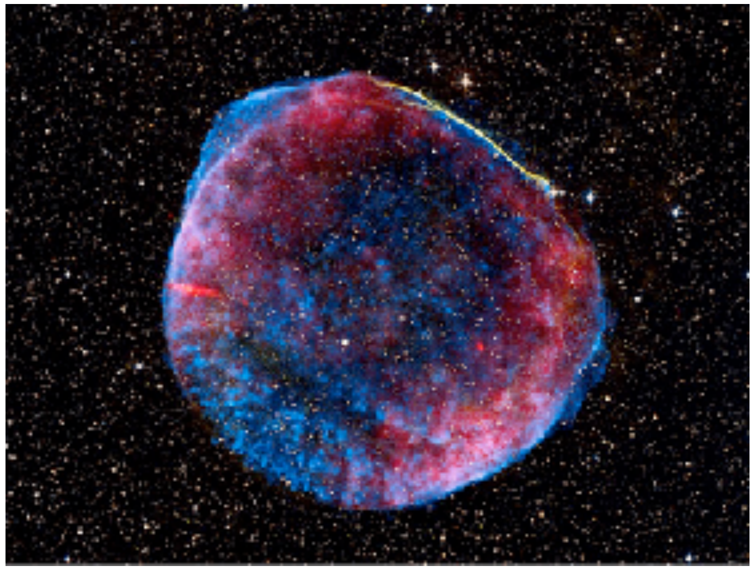

modern formulation of the hypothesis

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

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

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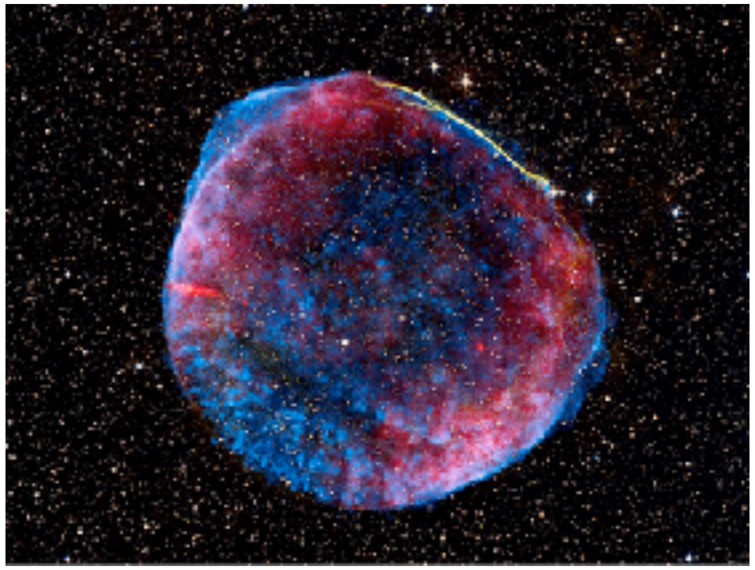

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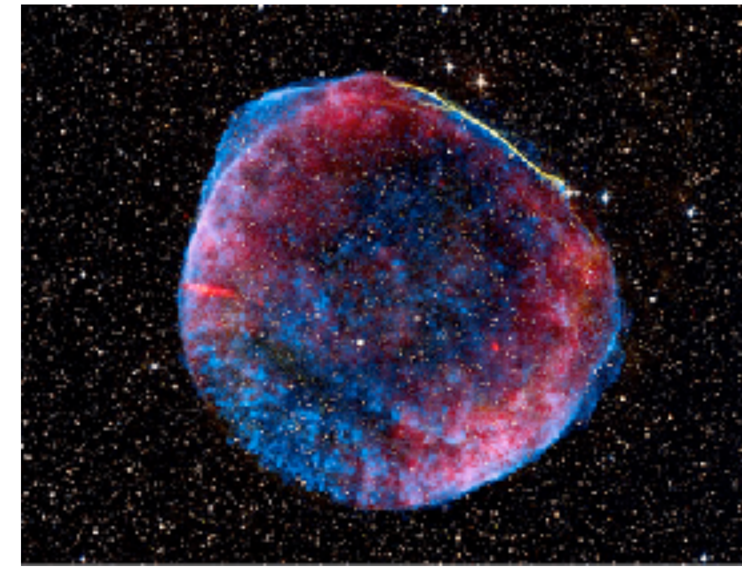

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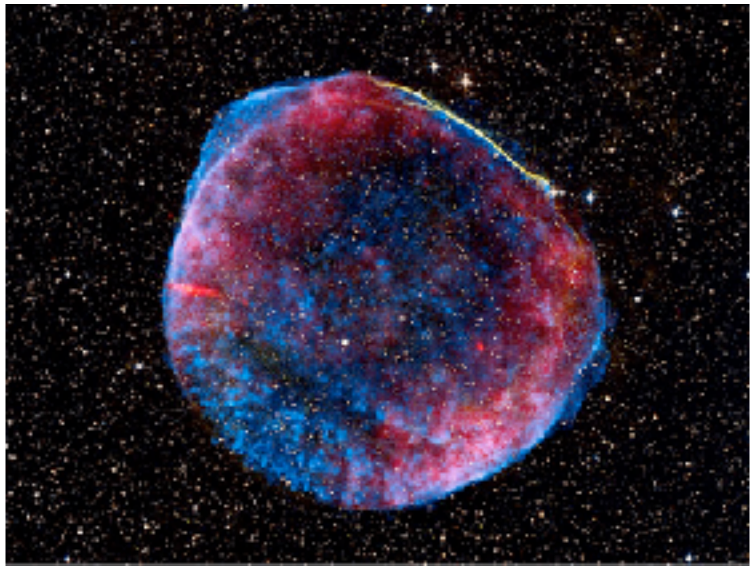

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why remnants? —> radio observations —> particle acceleration at SNR shocks!

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

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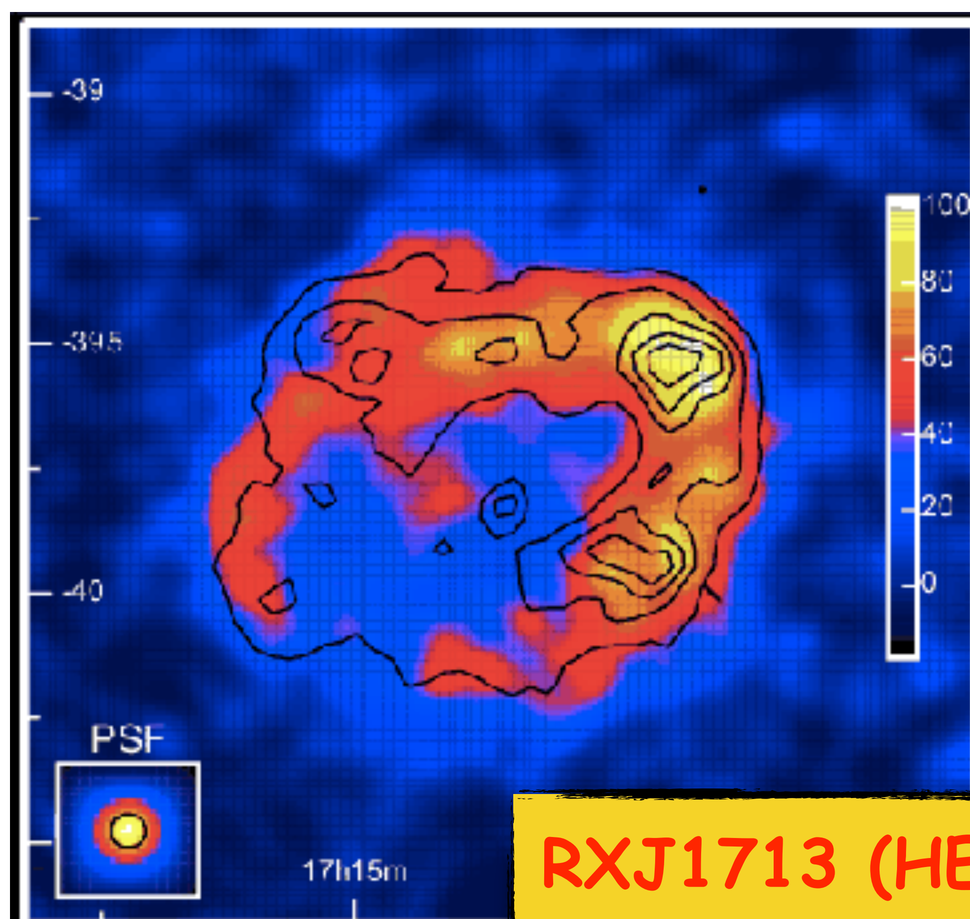

RXJ1713 (HESS)

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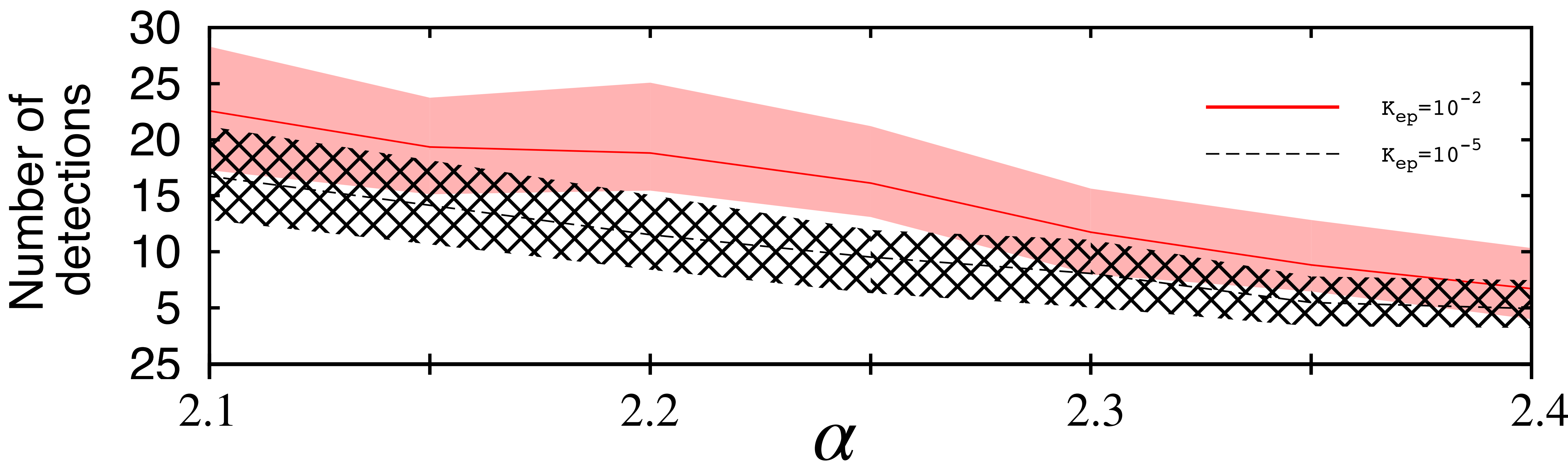

Cristofari+ 2013

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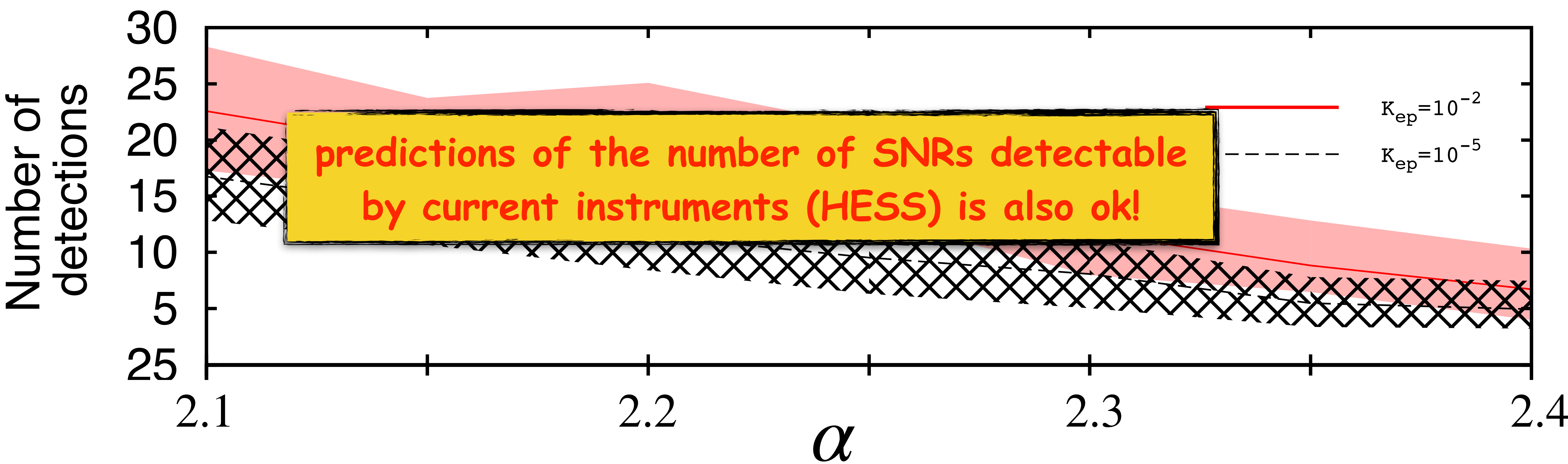

Cristofari+ 2013

[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

follow the physics…

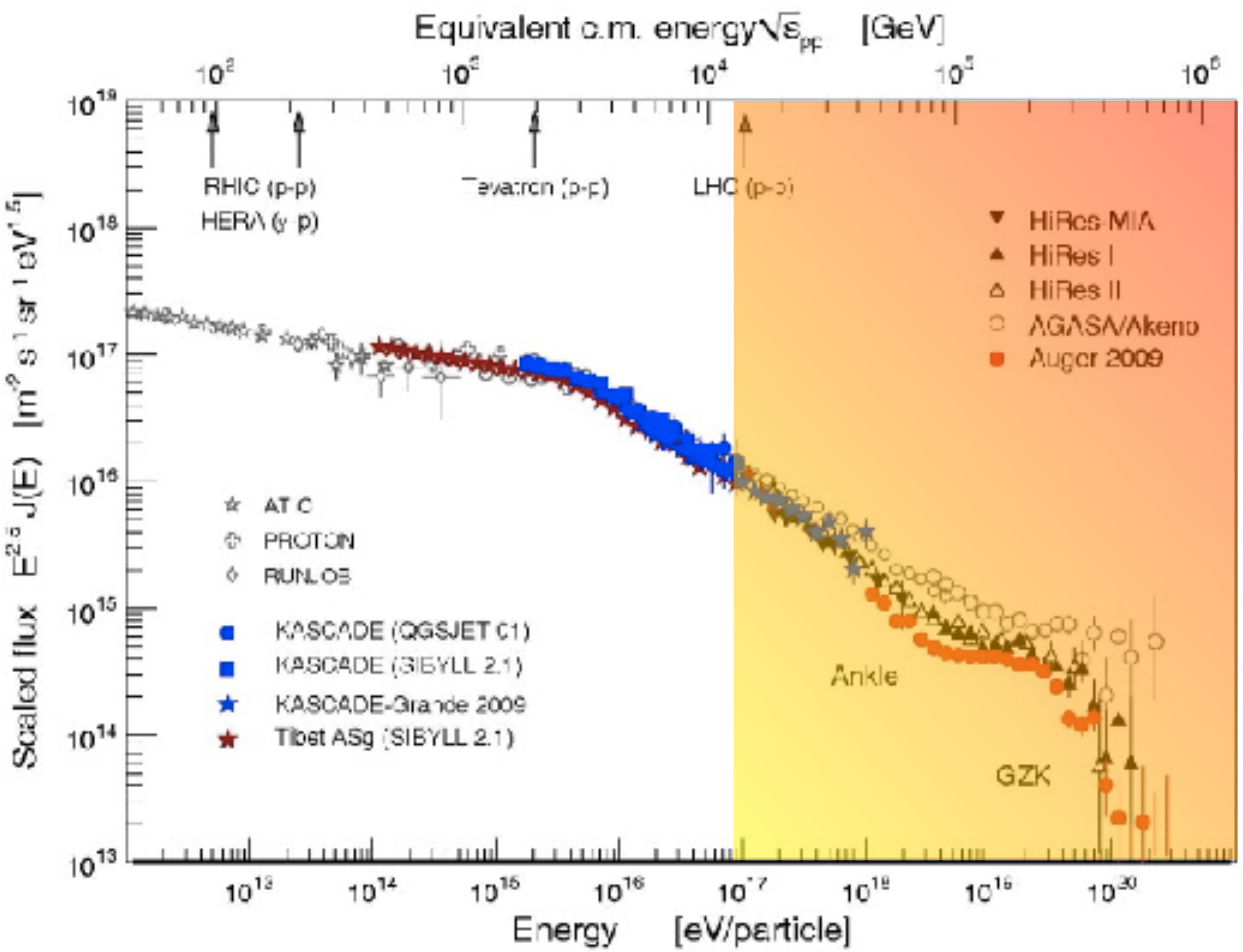
The orthodoxy (3)

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

follow the physics…

…and the mass…

(At least) three serious issues remains



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

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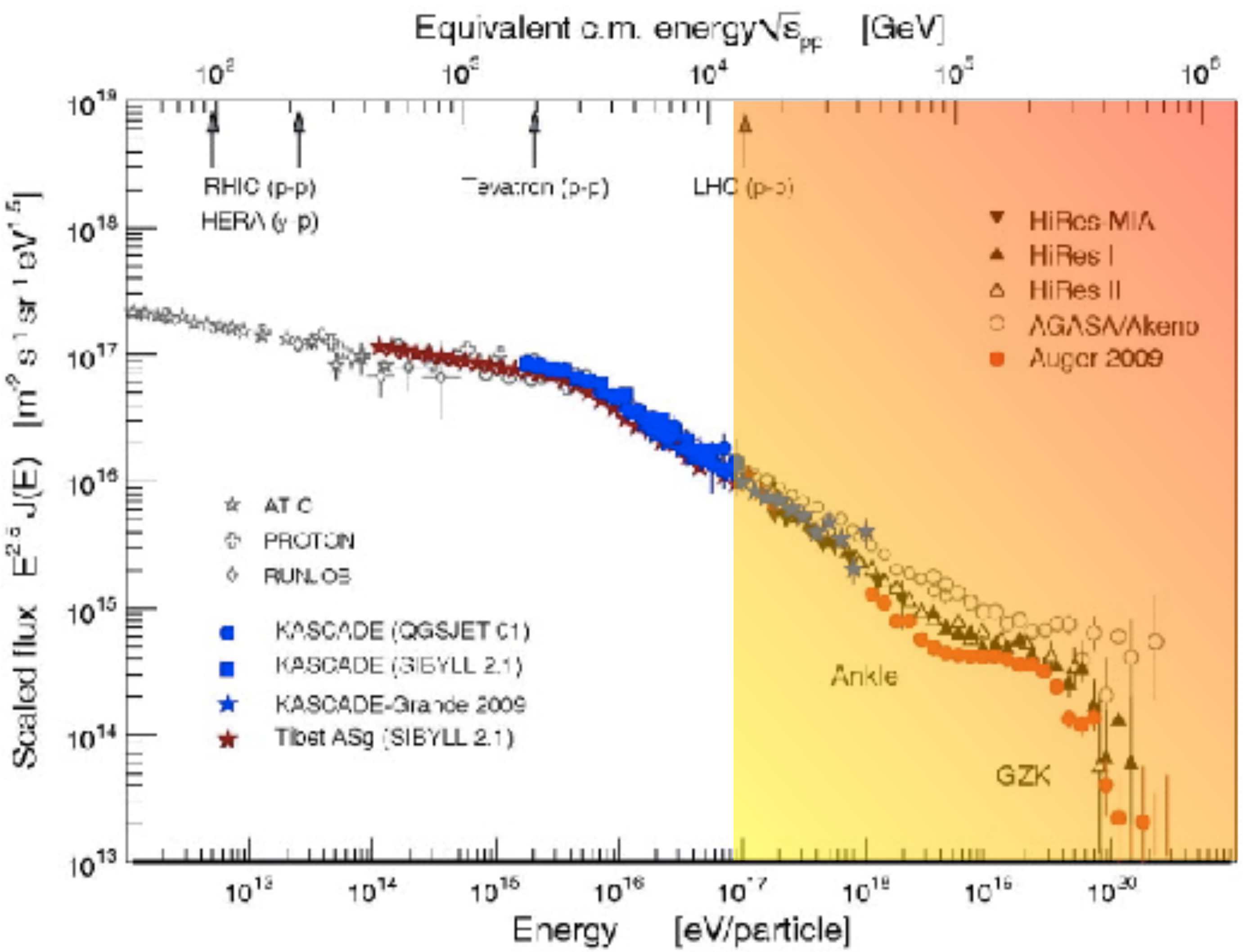

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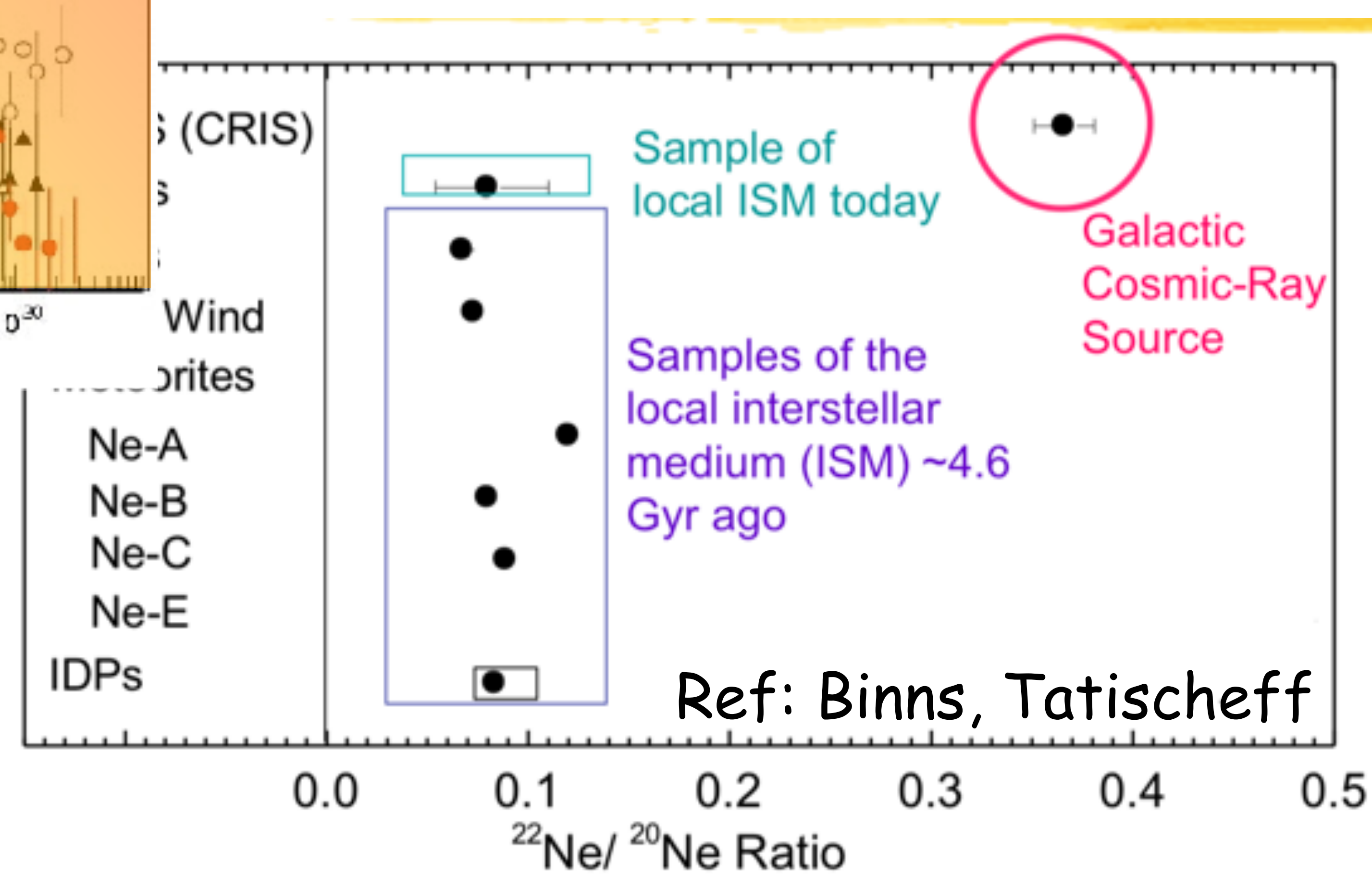

Ref: Binns, Tatischeff

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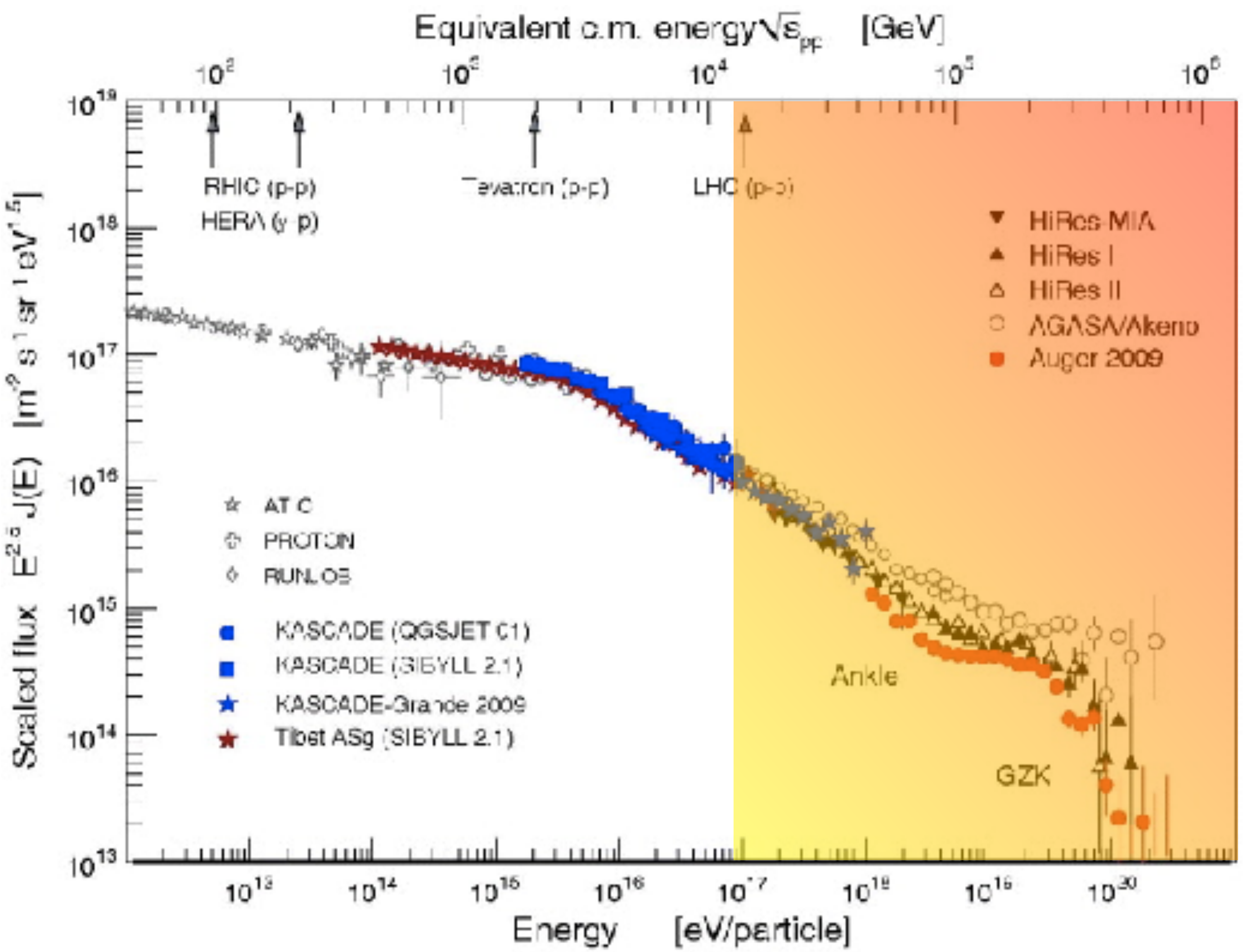

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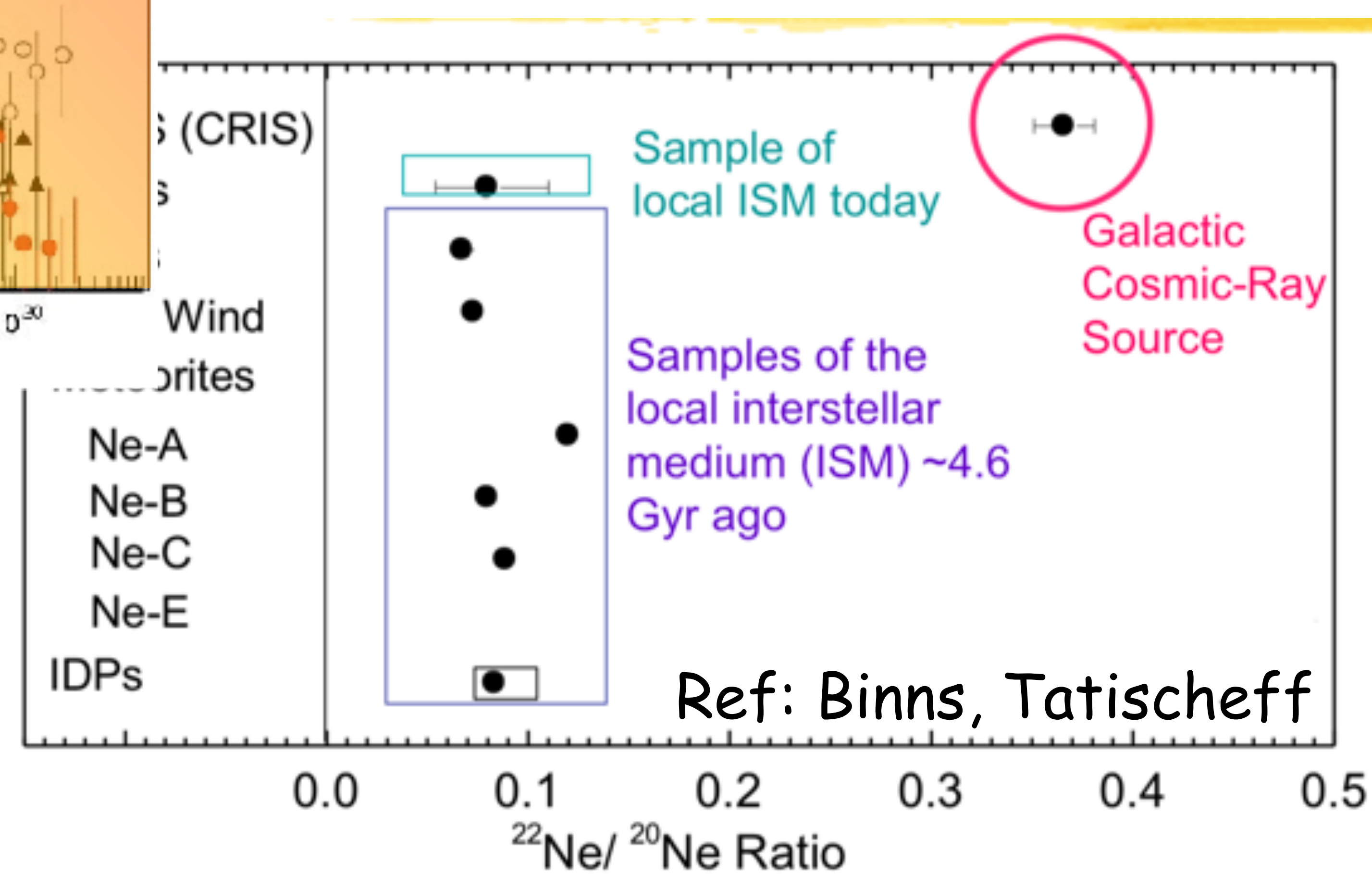

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