# Cosmic rays [old stuff]

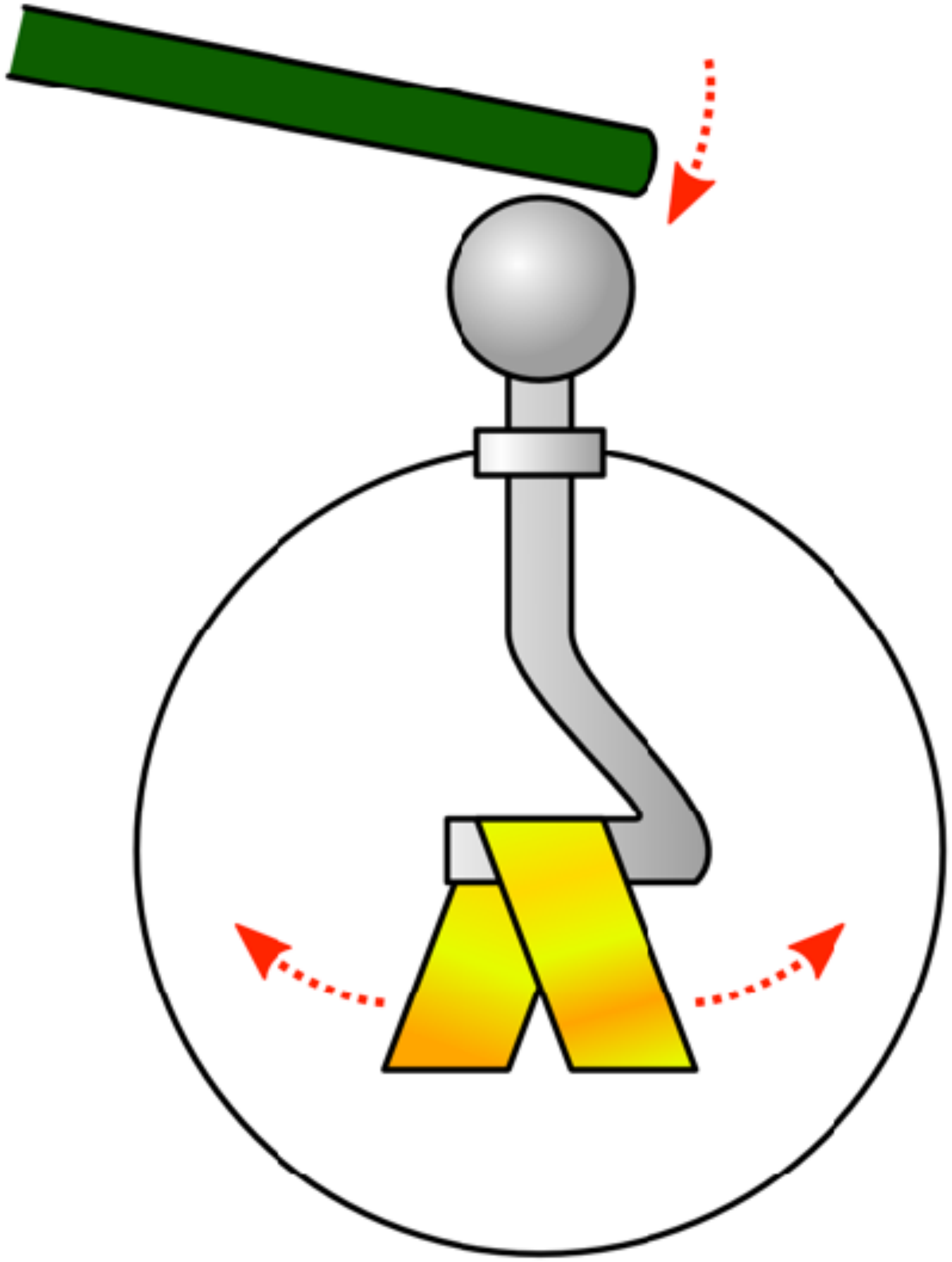
Stefano Gabici
APC, Paris

www.cnrs.fr

# [1] History

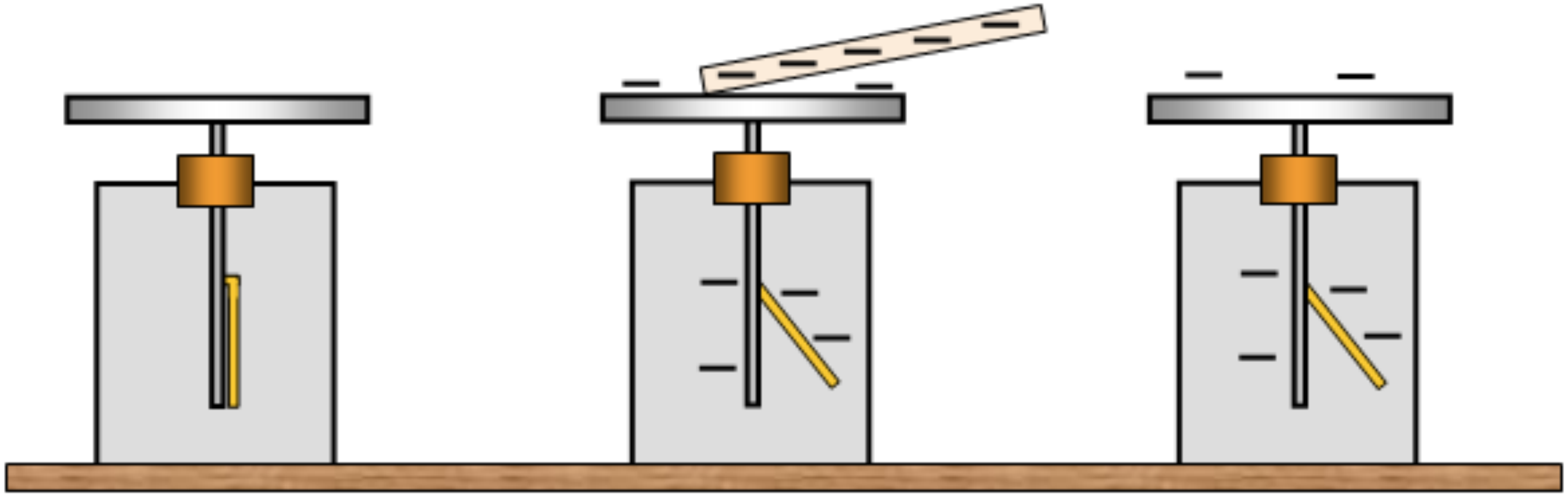
# The electroscope

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

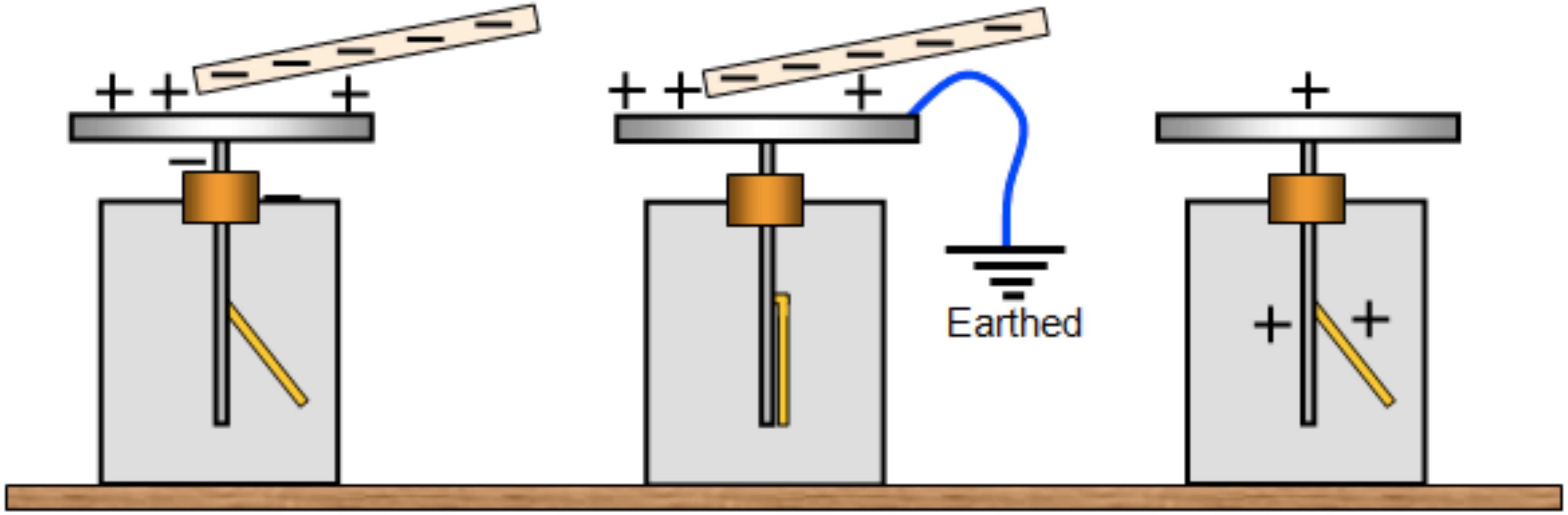


ELECTROSCOPE

# How does it work



Charging by contact

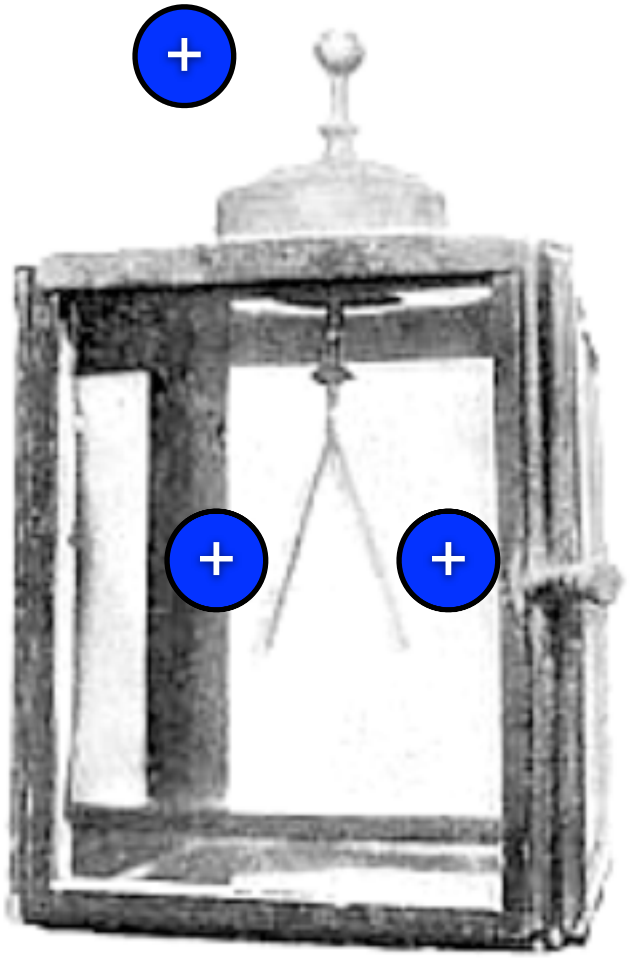


Charging by induction

# 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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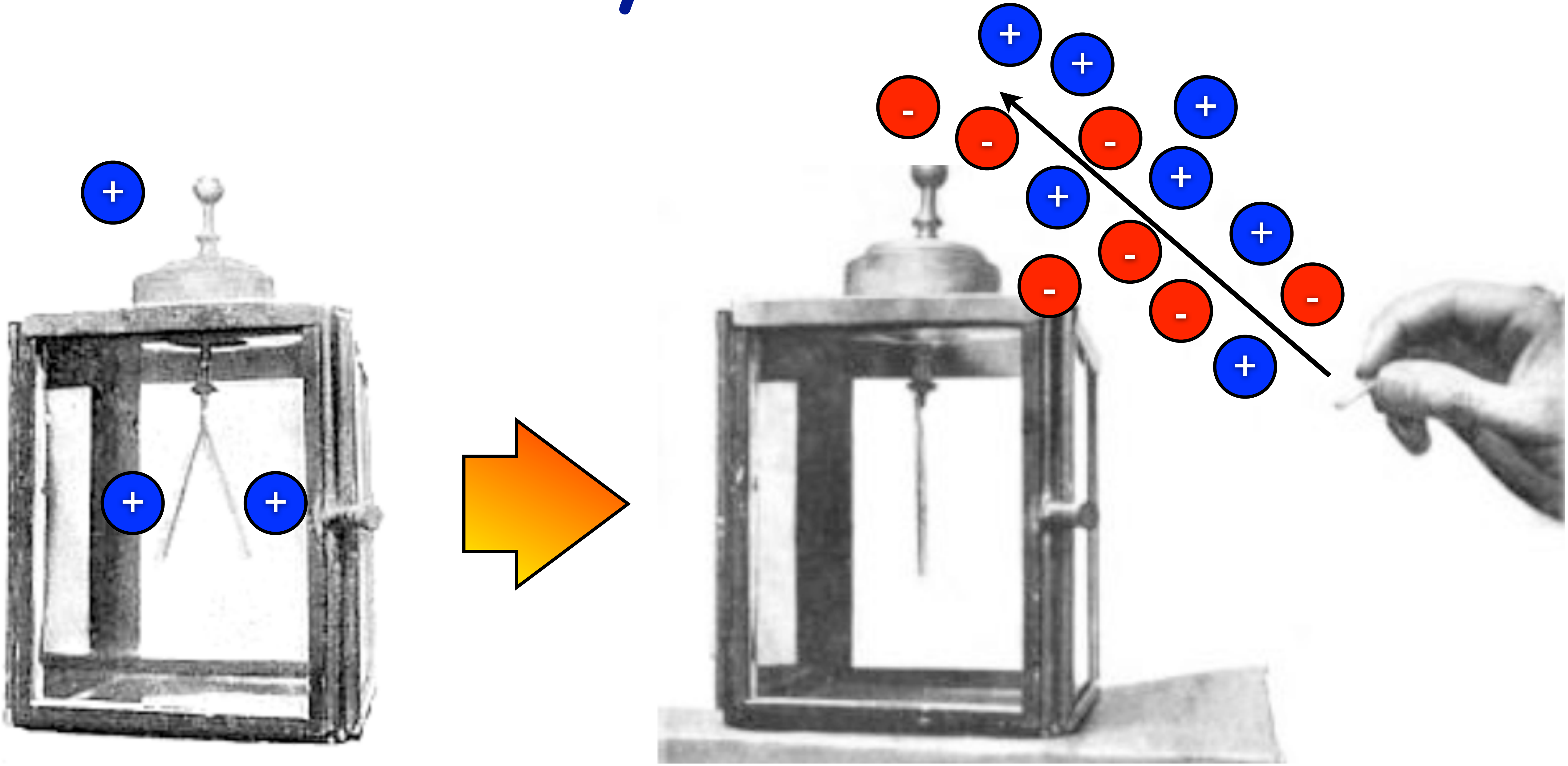

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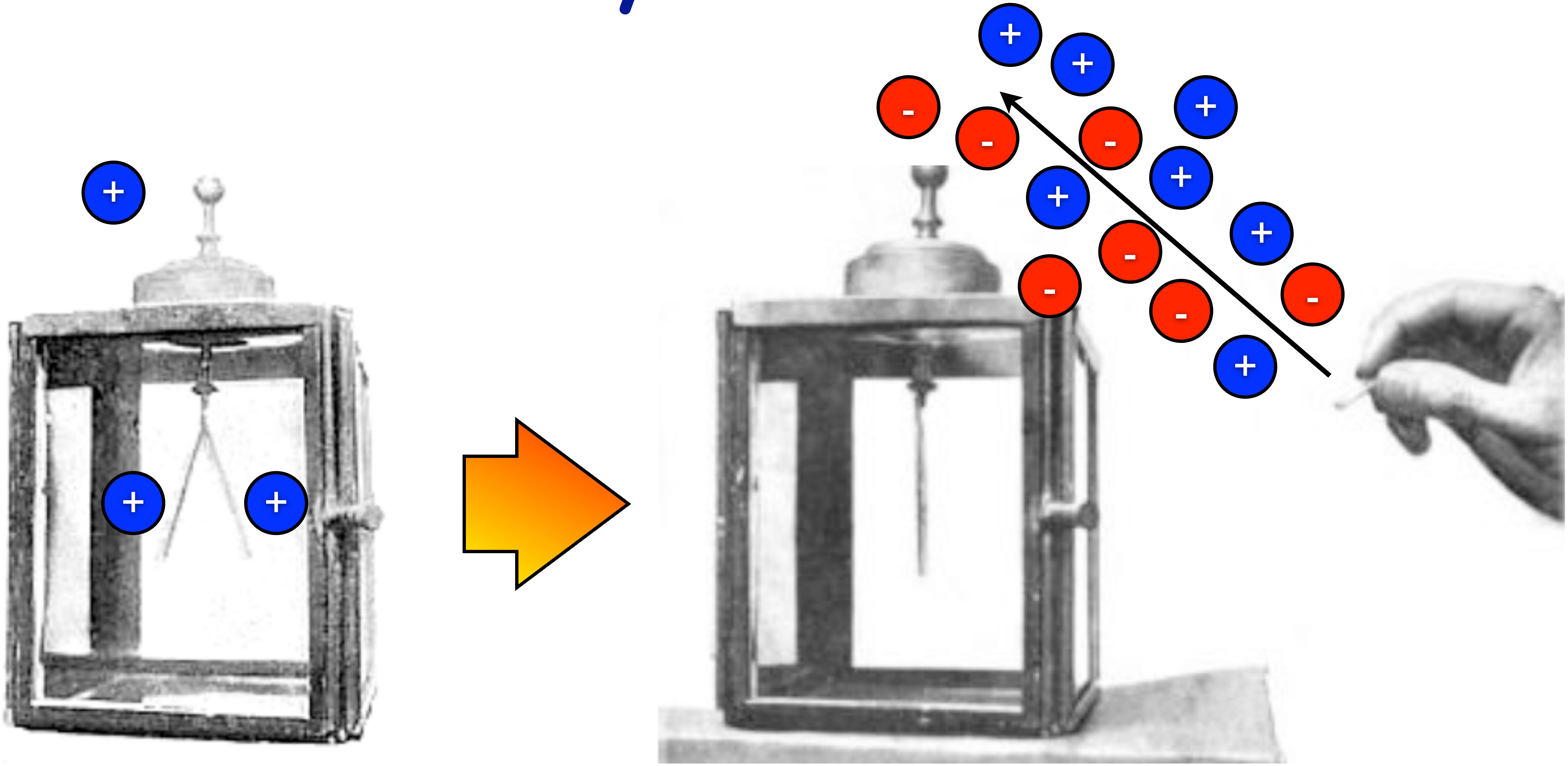

**hypothesis:** the Earth's crust contains radioactive isotopes (natural radioactivity) -> this might be the source of the ionizing radiation needed to explain the spontaneous discharge of electroscopes.

# 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 **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
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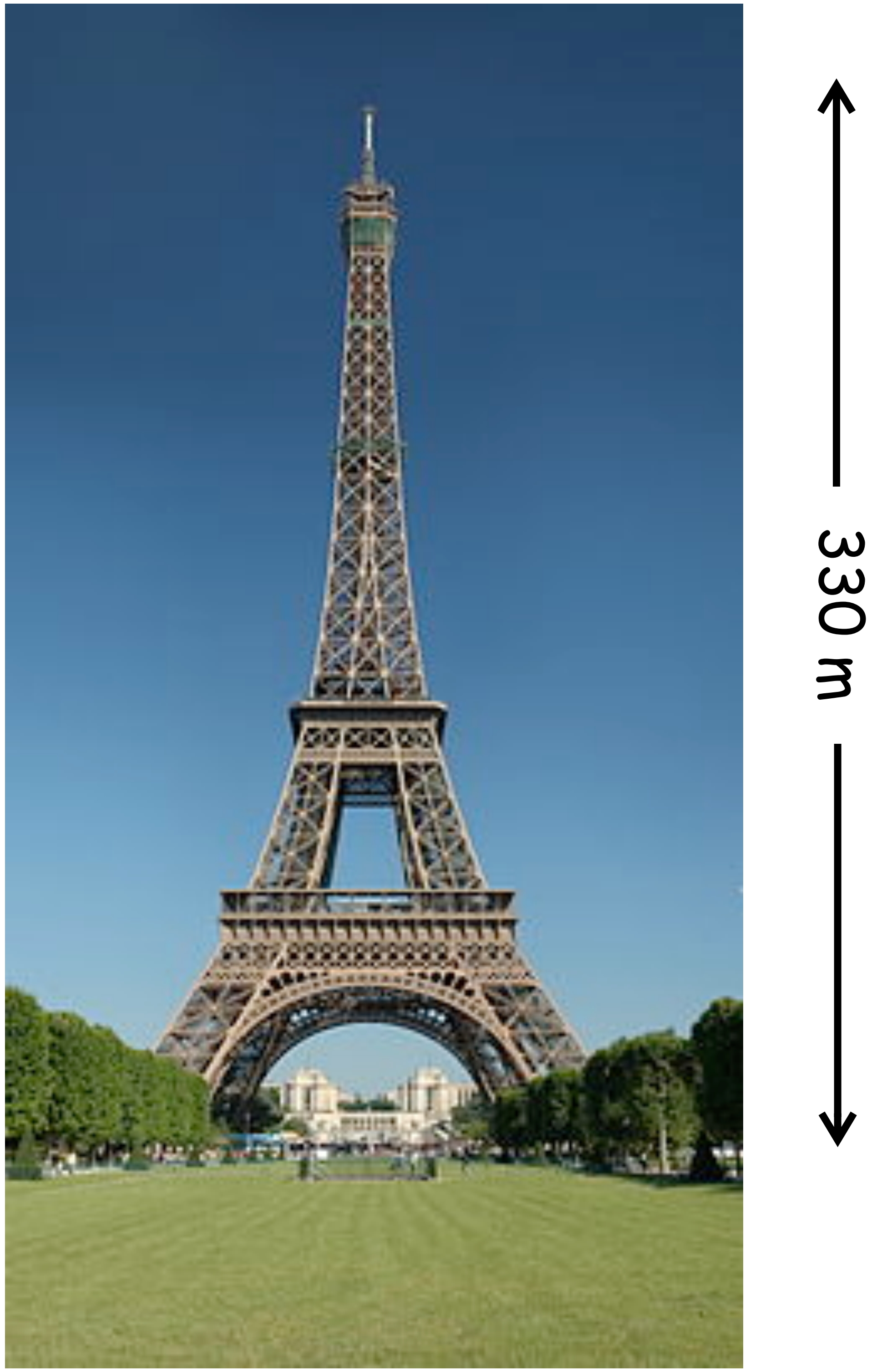

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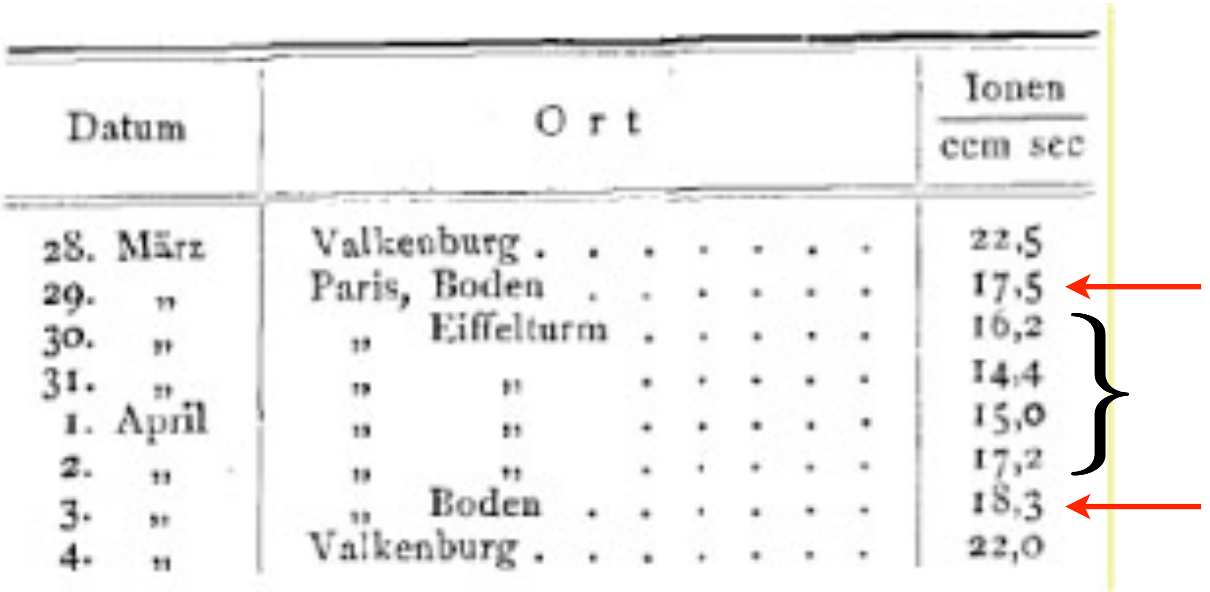

| Datum | Ort | $\frac{\text{Ionen}}{\text{ccm sec}}$ |
|---|---|---|
| 28. März | Valkenburg | 22,5 |
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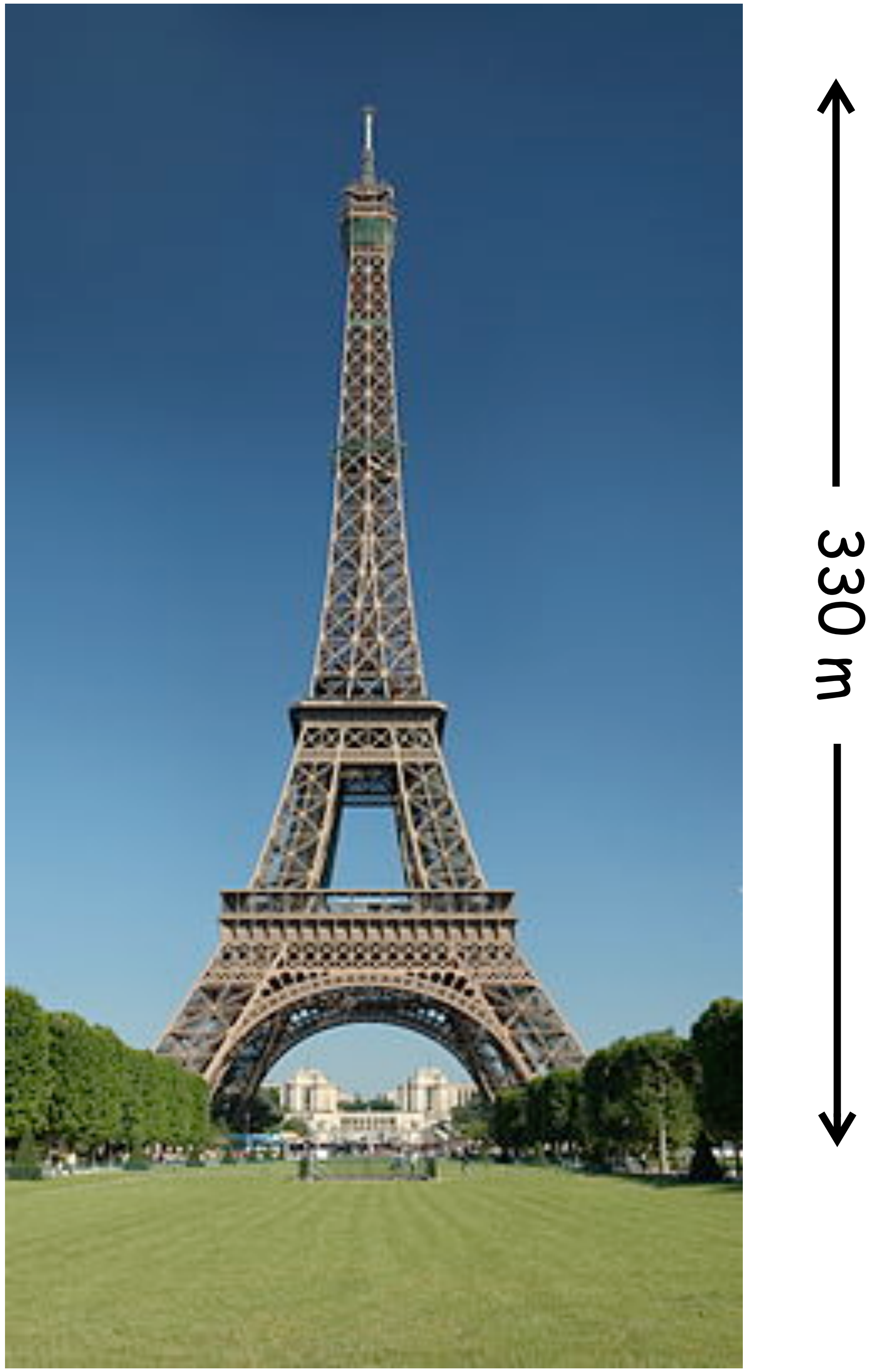

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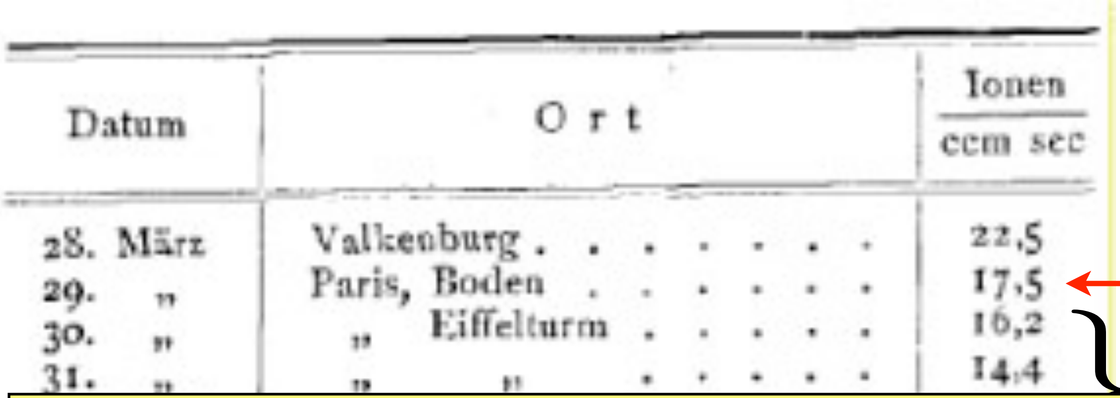

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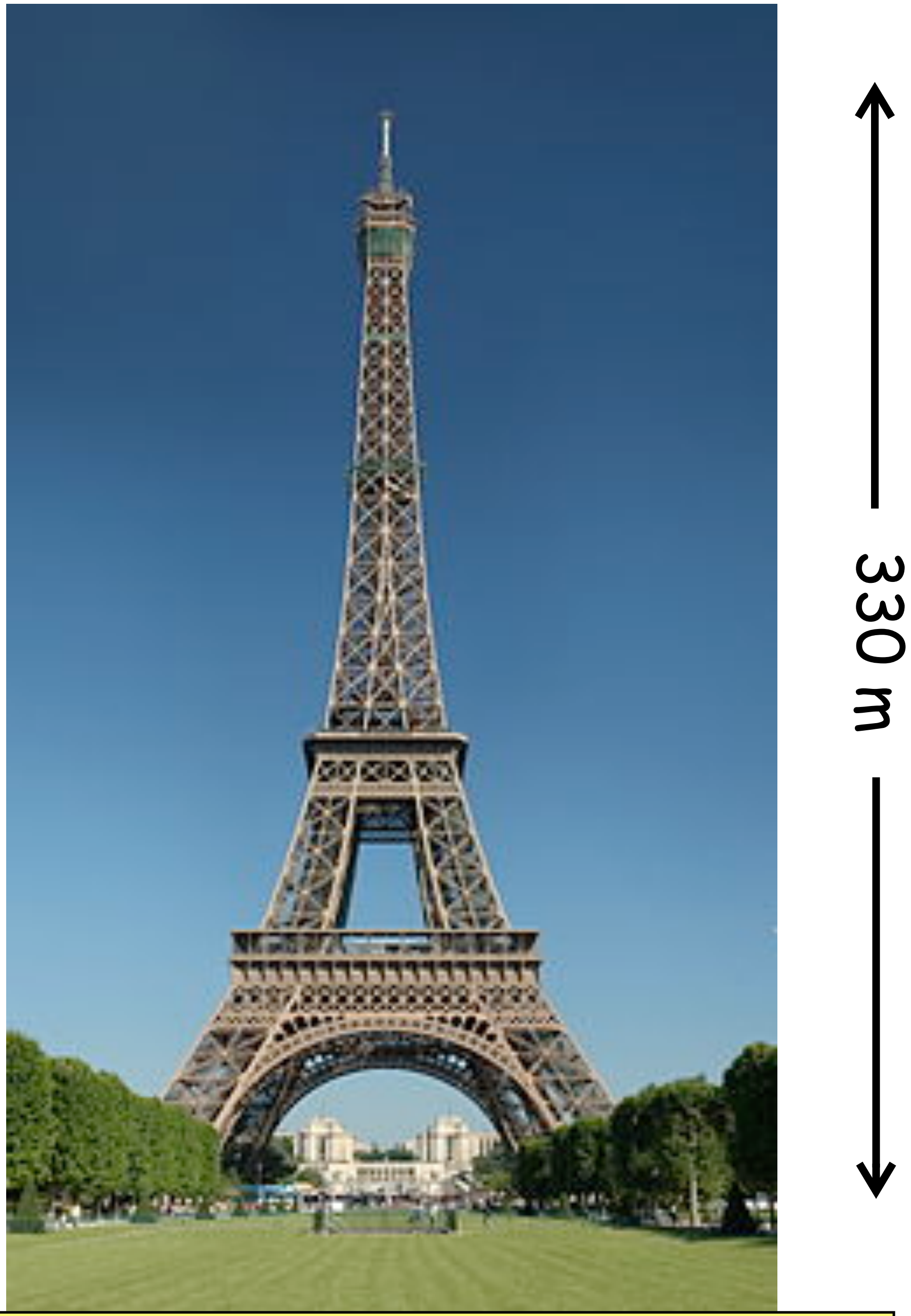

**though the effect was smaller than expected, Wulf concluded that Earth's radioactivity remained the most plausible hypothesis**

# 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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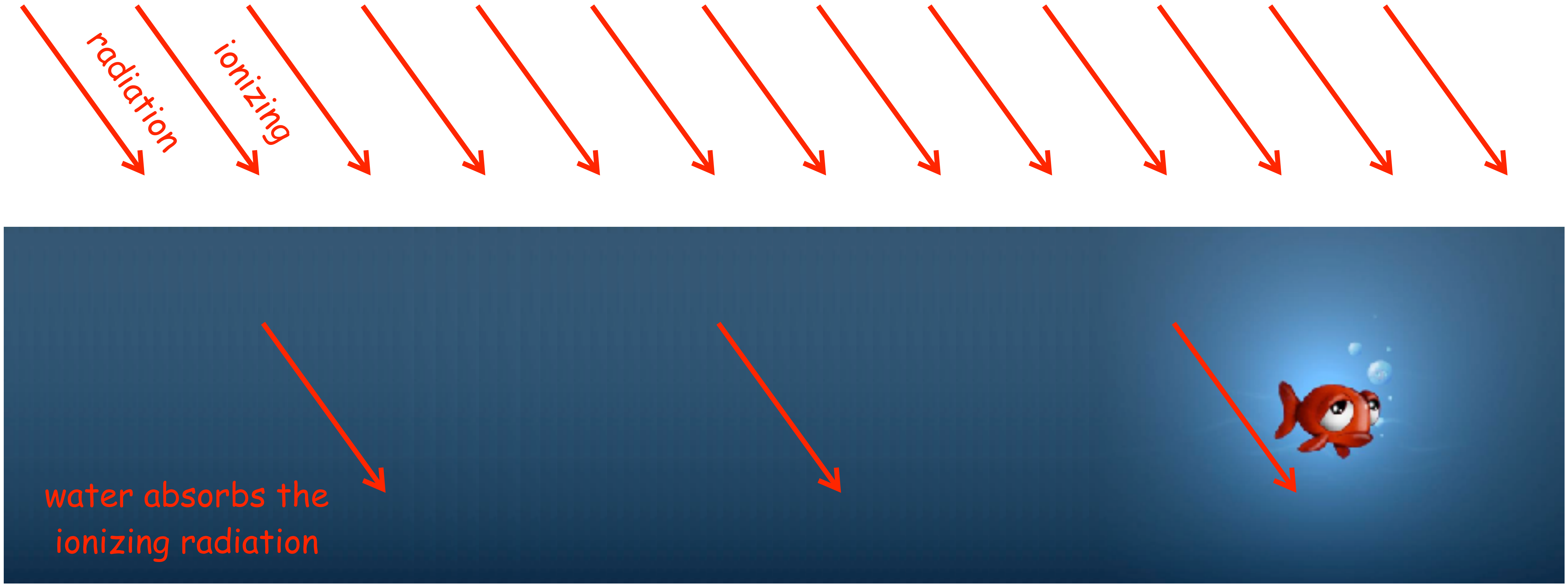
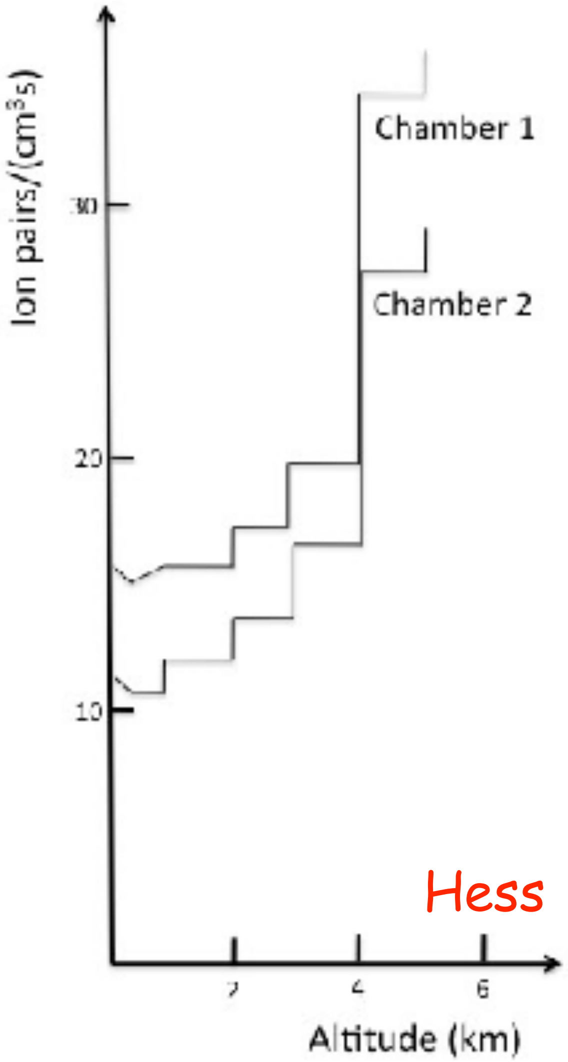


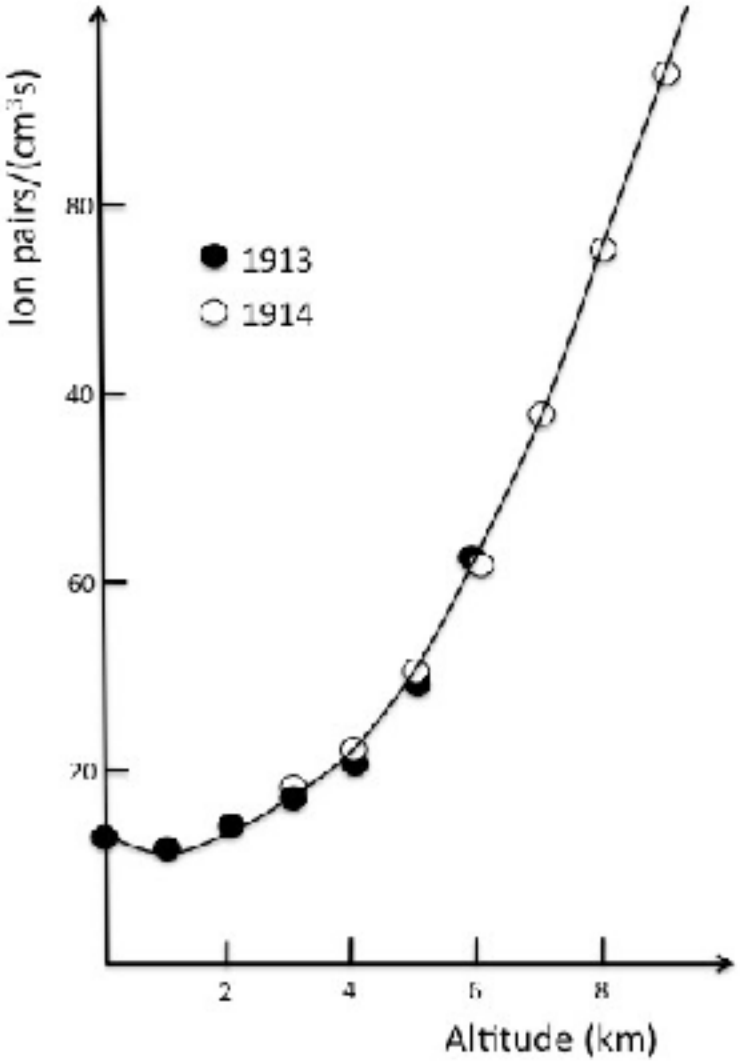
water absorbs the ionizing radiation

**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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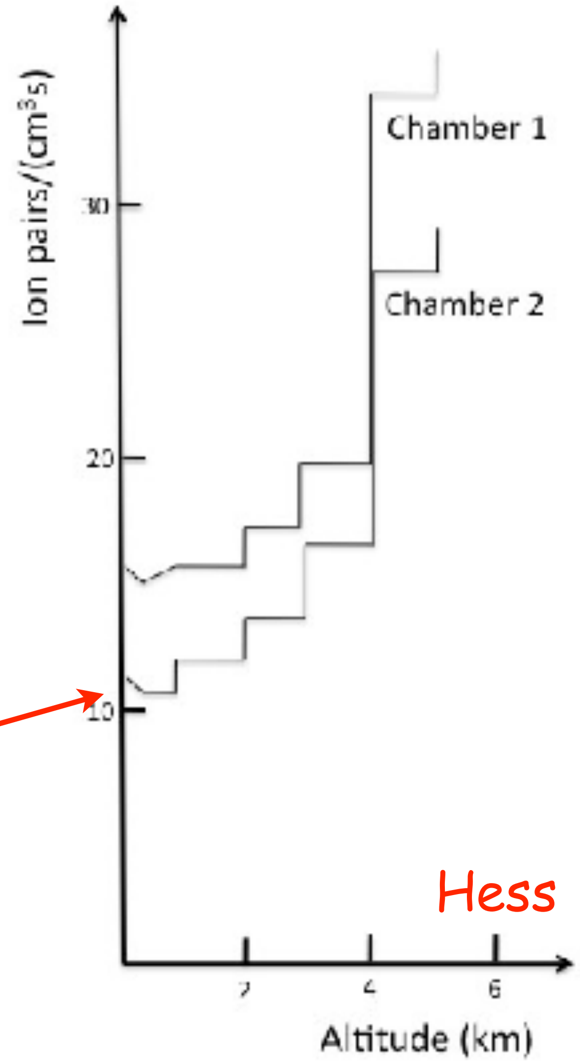
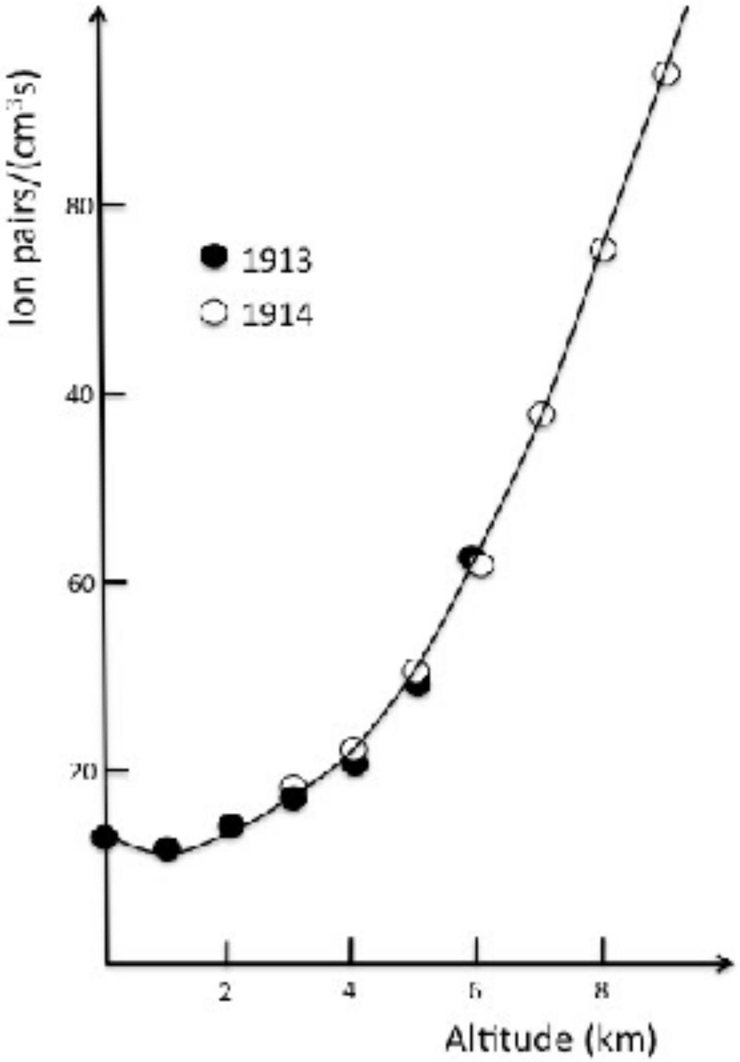


Hess



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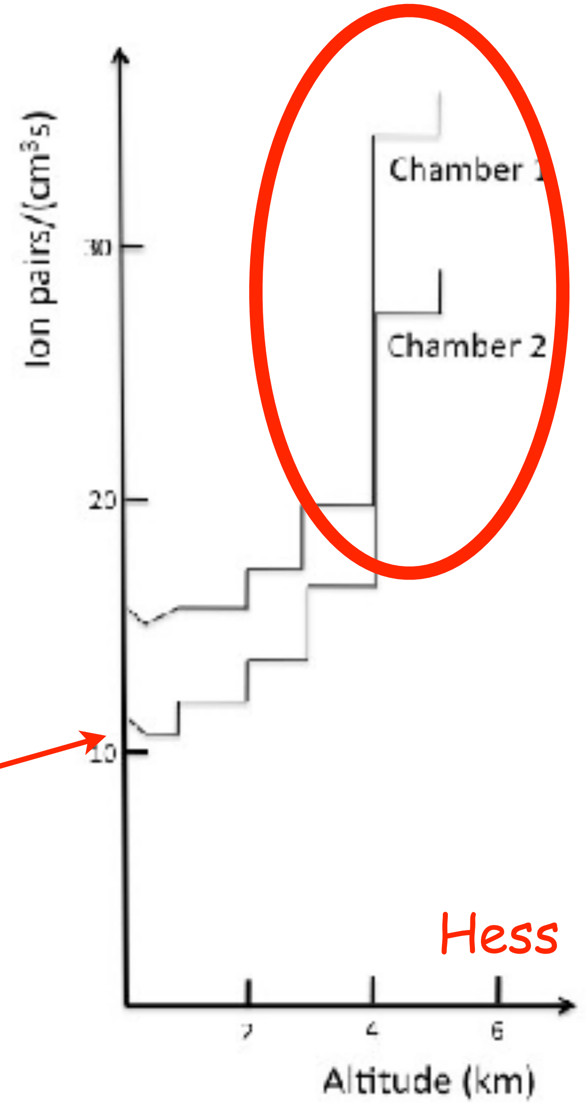

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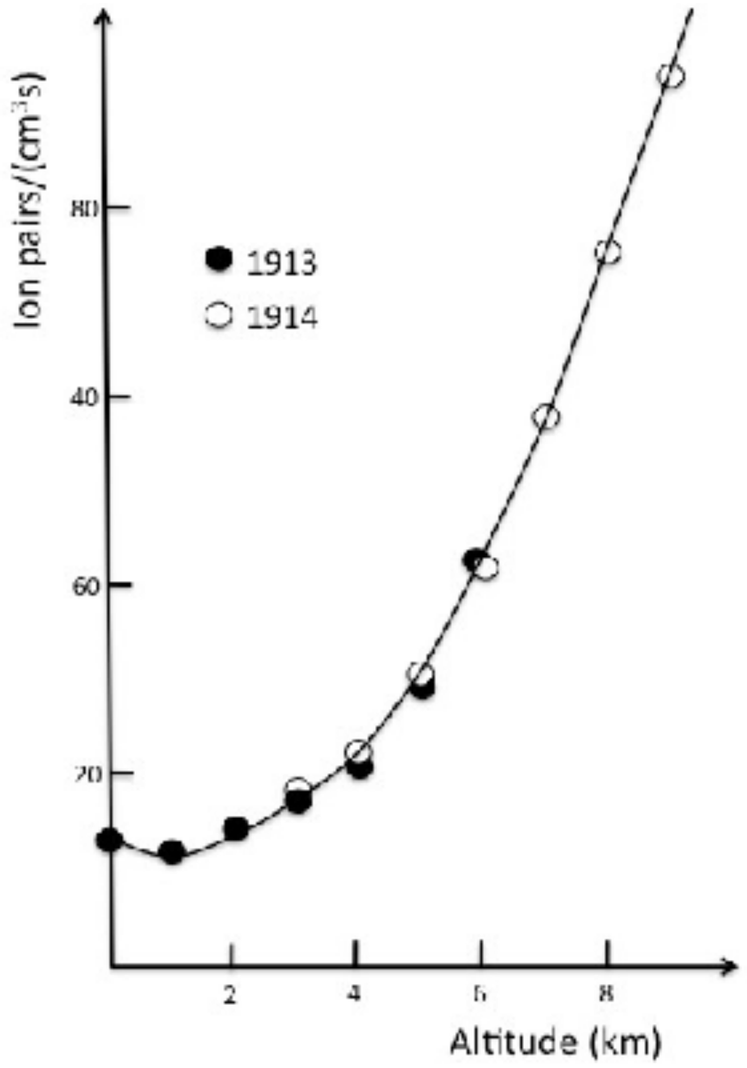

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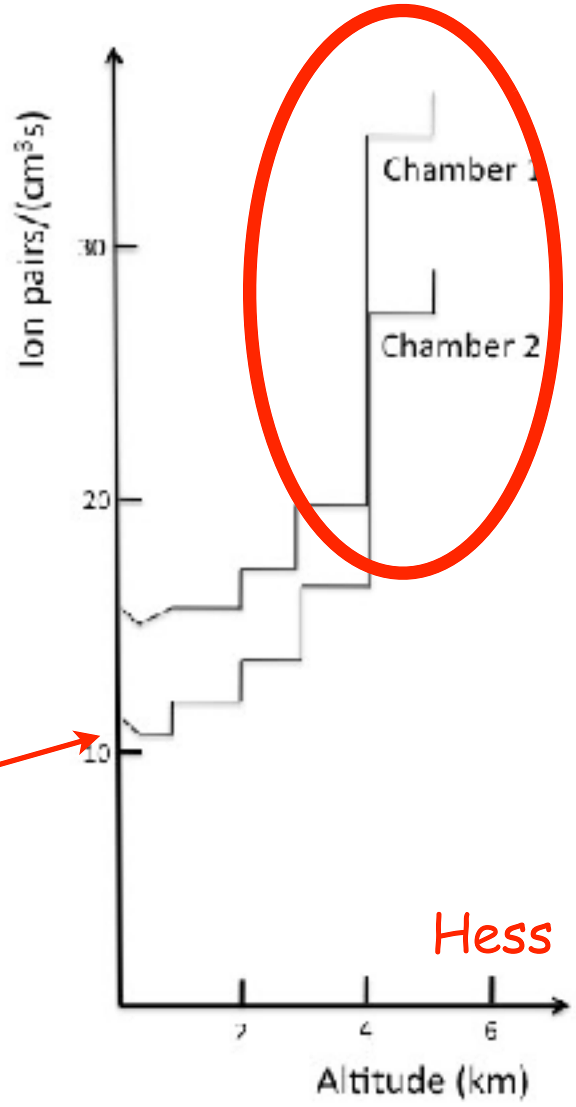

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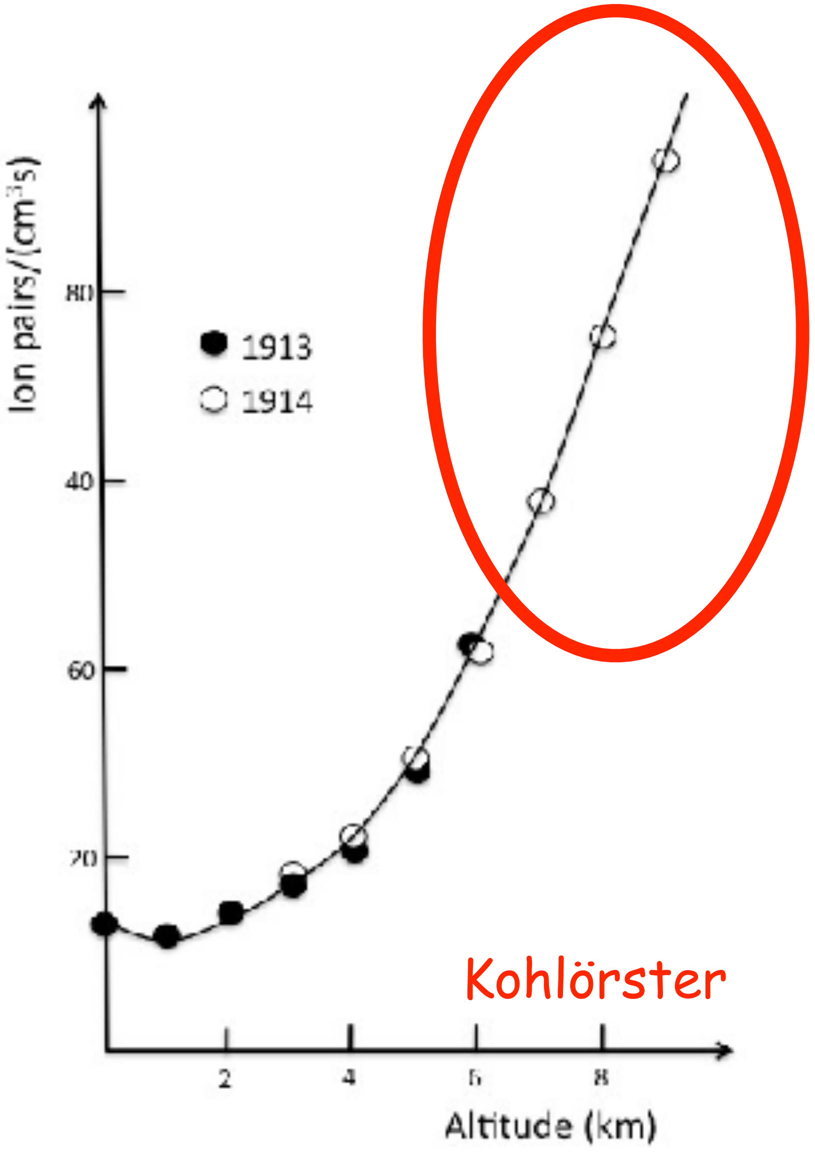

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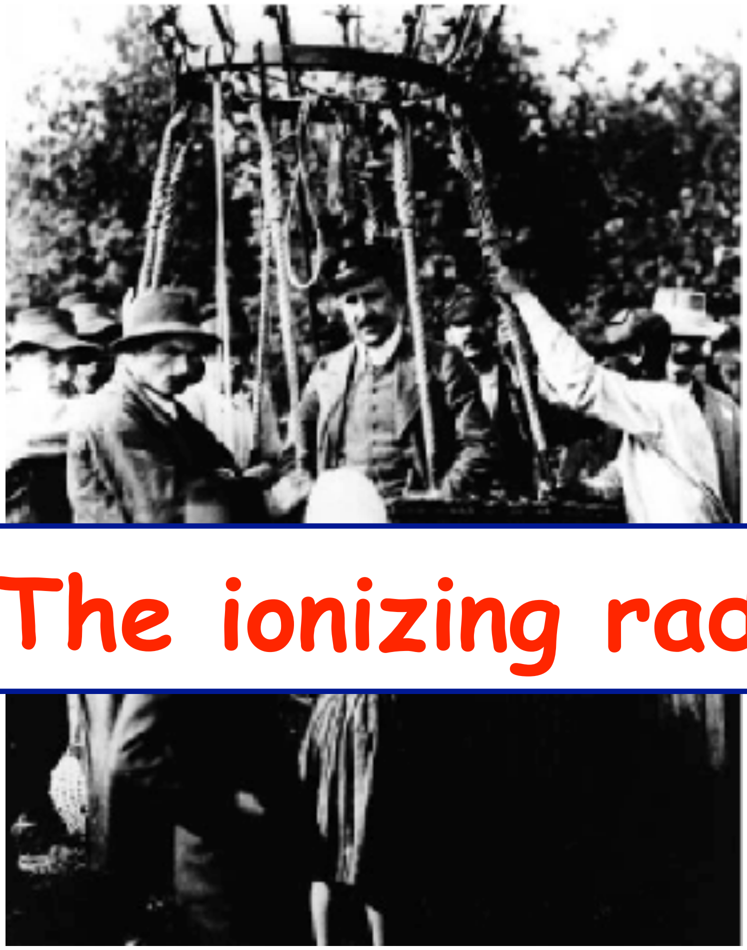

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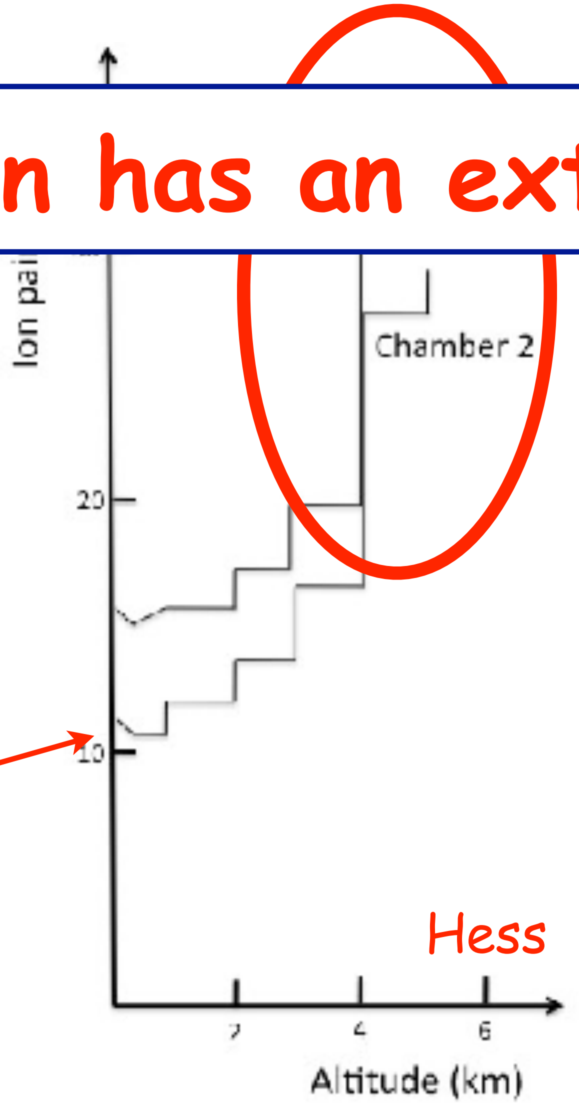
**The ionizing radiation has an extra-terrestrial origin**



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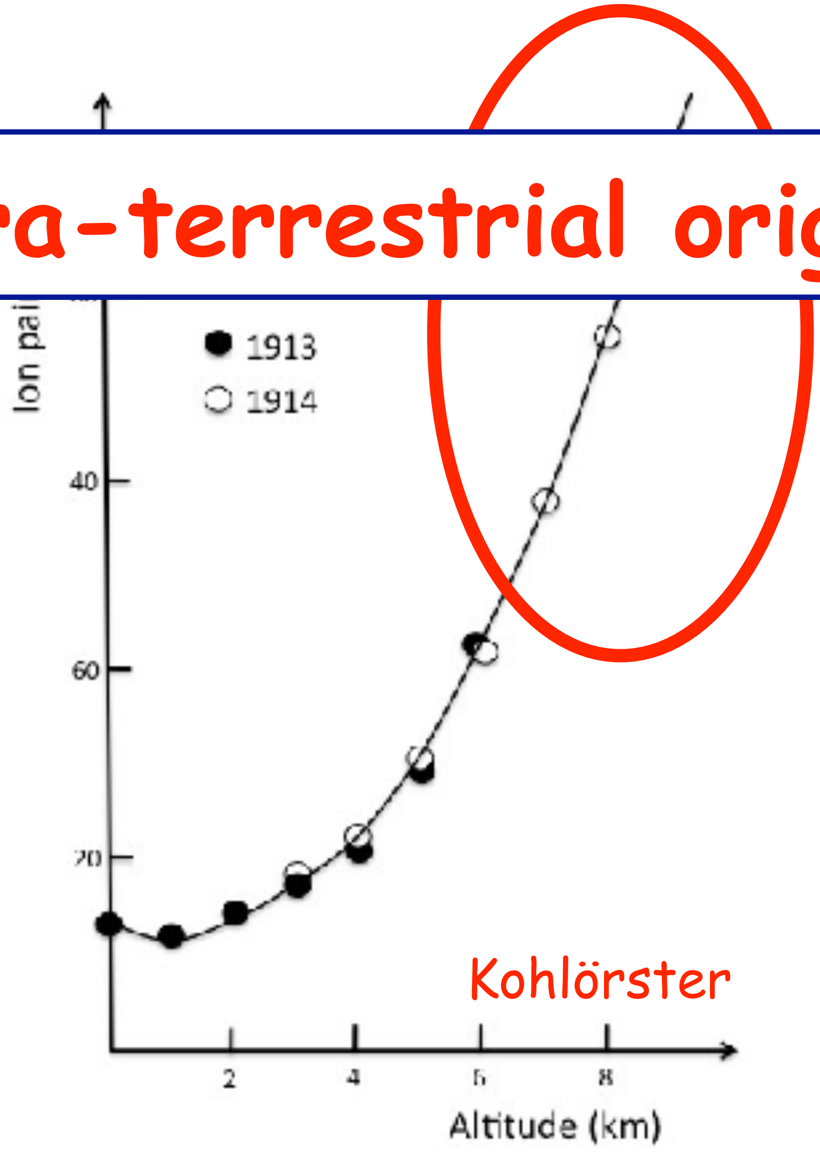


# [2] What are cosmic rays?

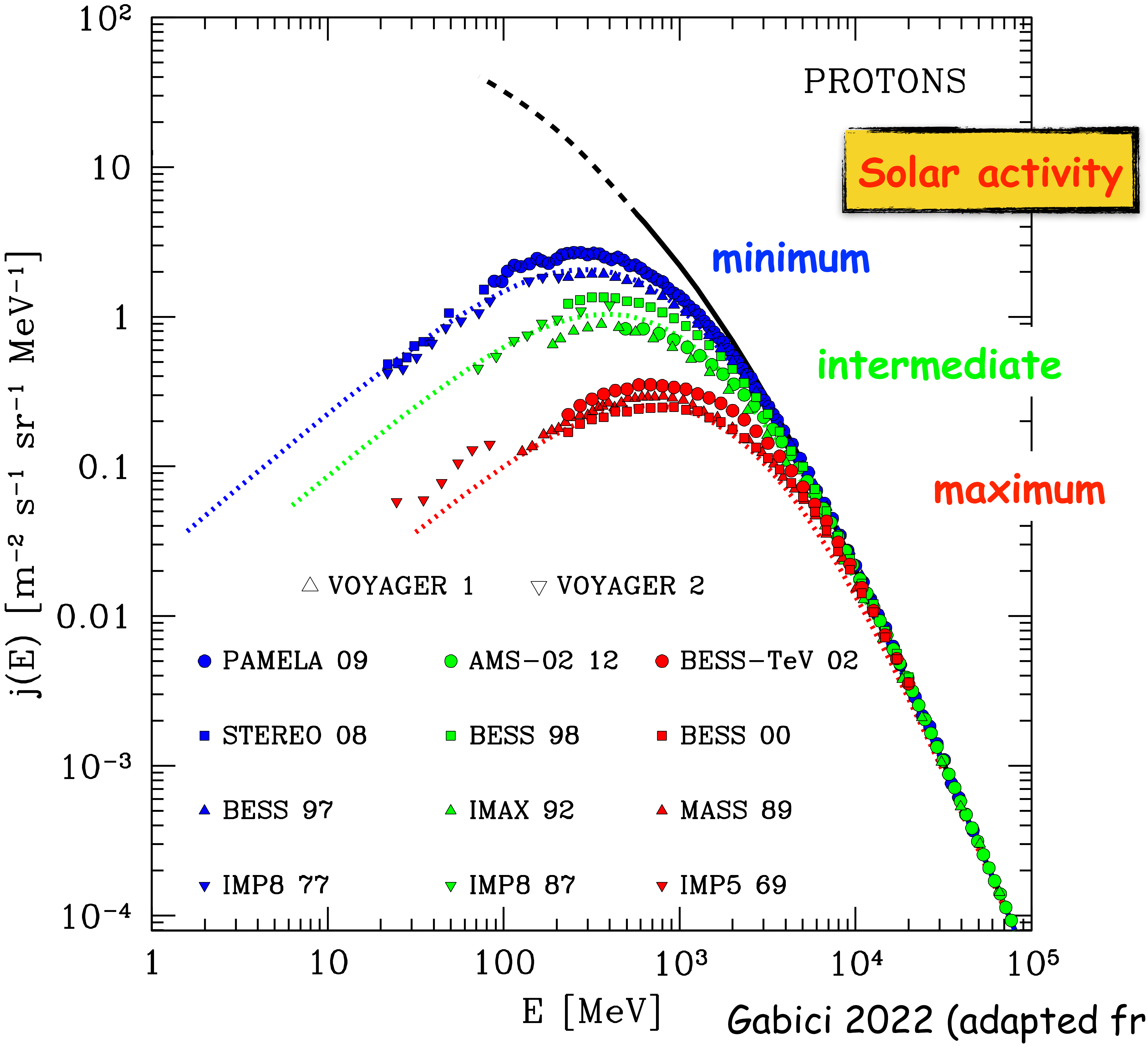
# What are Cosmic Rays?

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"

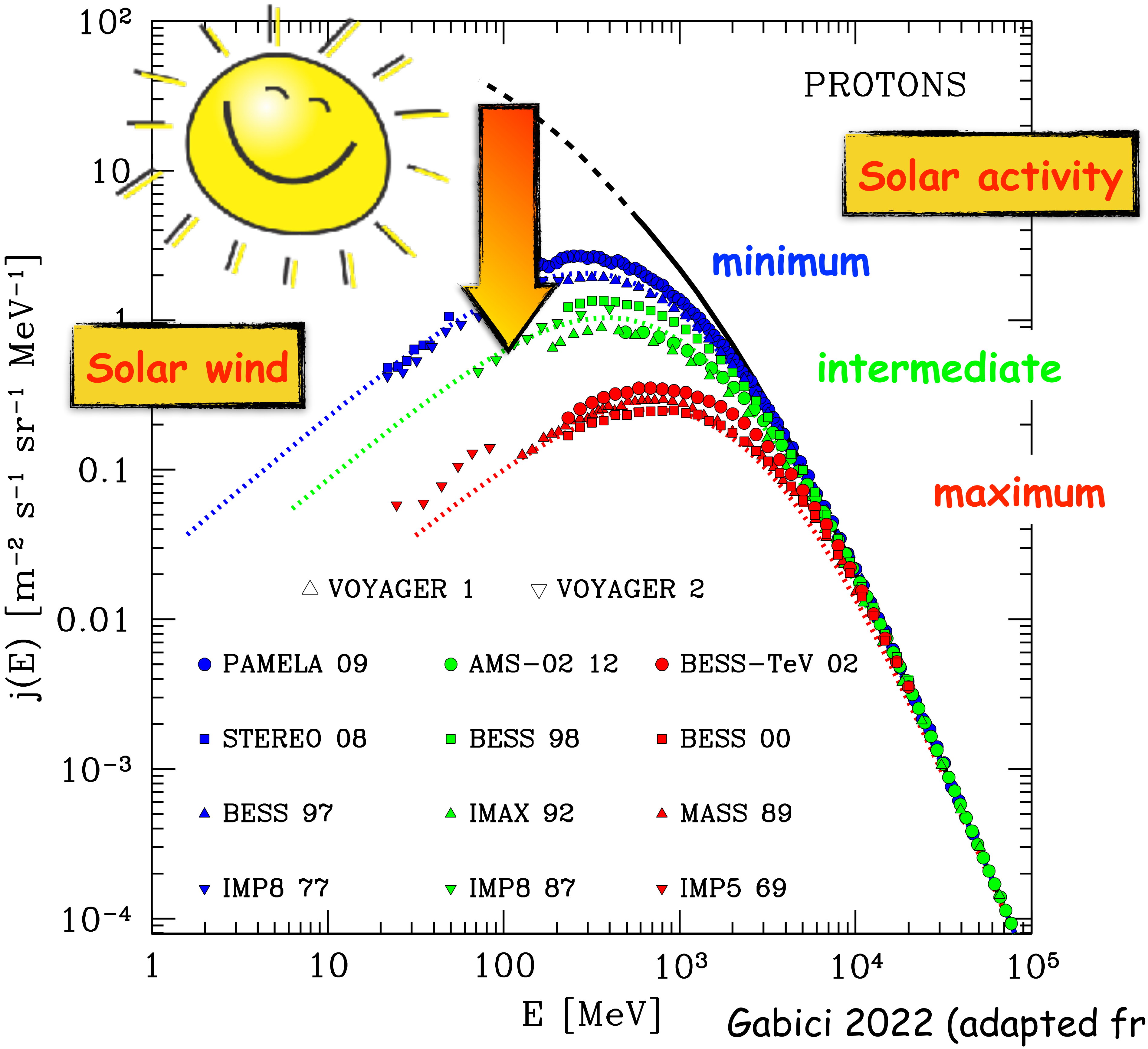
Also **electrons** are present in the cosmic radiation -> **~ 1%**

# Solar modulation



Gabici 2022 (adapted from Vos & Potgieter 2015)

# Solar modulation



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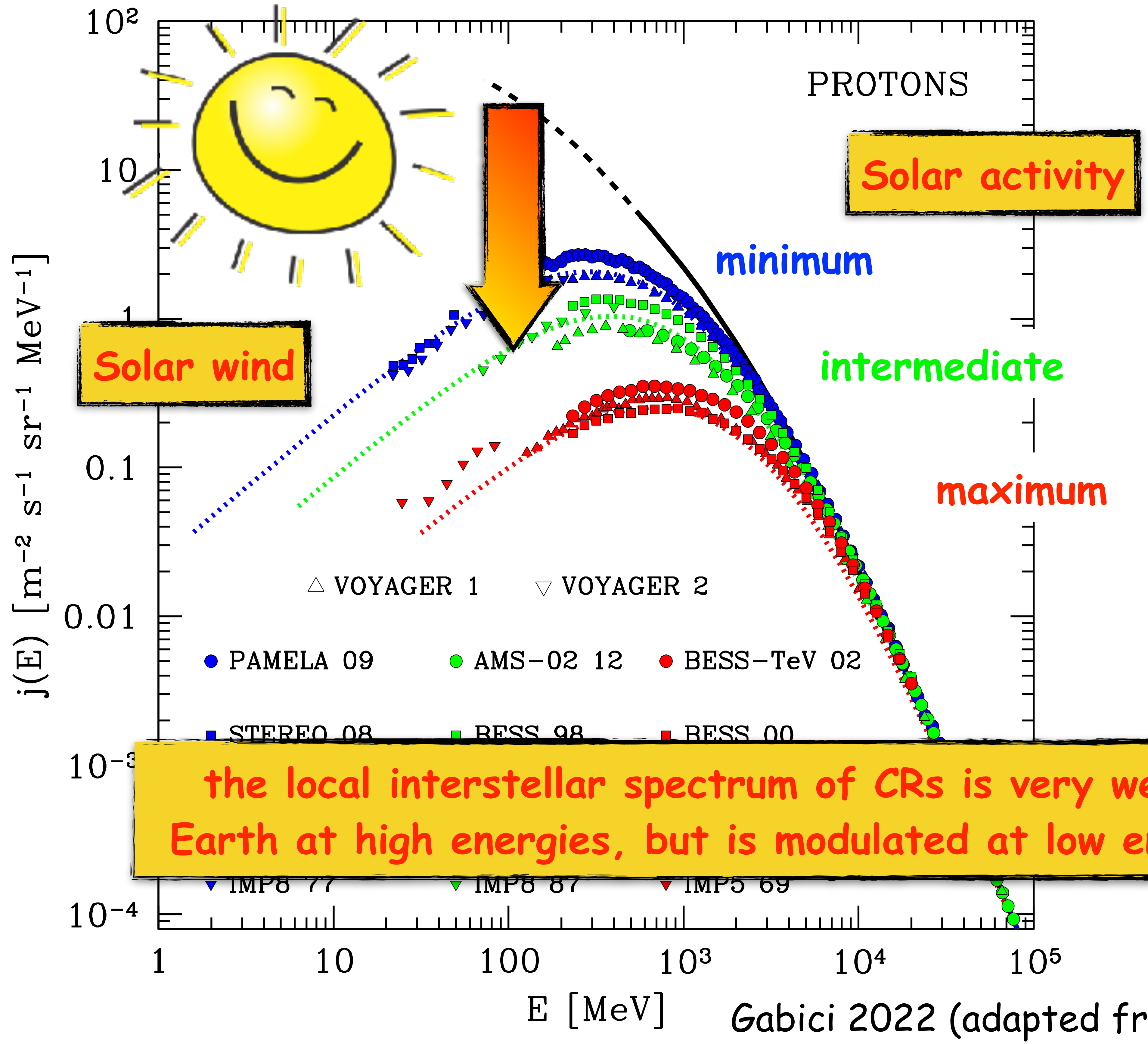

the local interstellar spectrum of CRs is very well measured from Earth at high energies, but is modulated at low energyes (< 20 GeV)

Gabici 2022 (adapted from Vos & Potgieter 2015)

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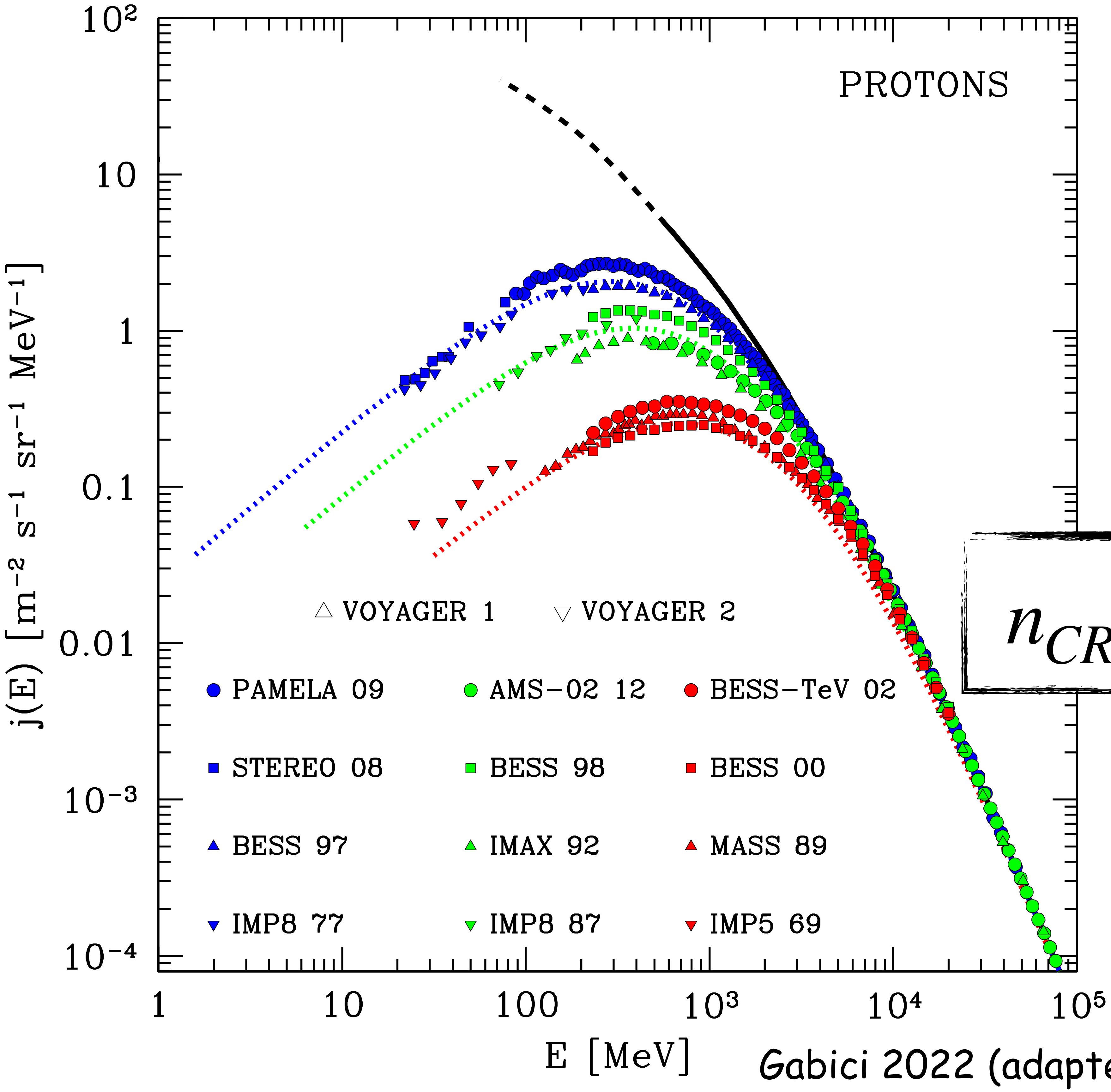

$$\boxed{n_{CR}(E) \propto E^{-2.7}}$$

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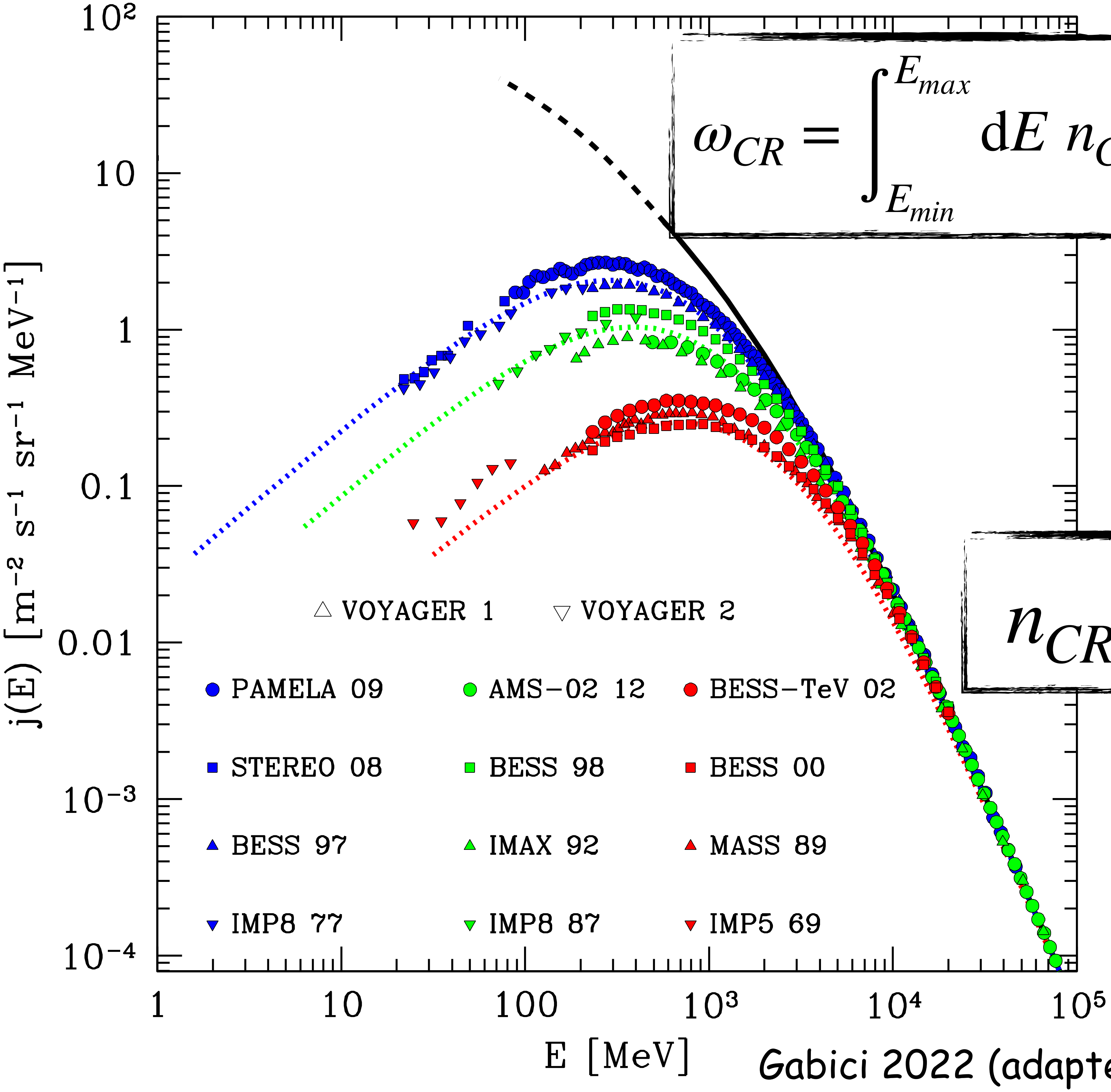

$$\omega_{CR} = \int_{E_{min}}^{E_{max}} \mathrm{d}E\, n_{CR}(E) E \propto E_{min}^{-0.7} \xrightarrow{E_{min} \to 0} \infty$$

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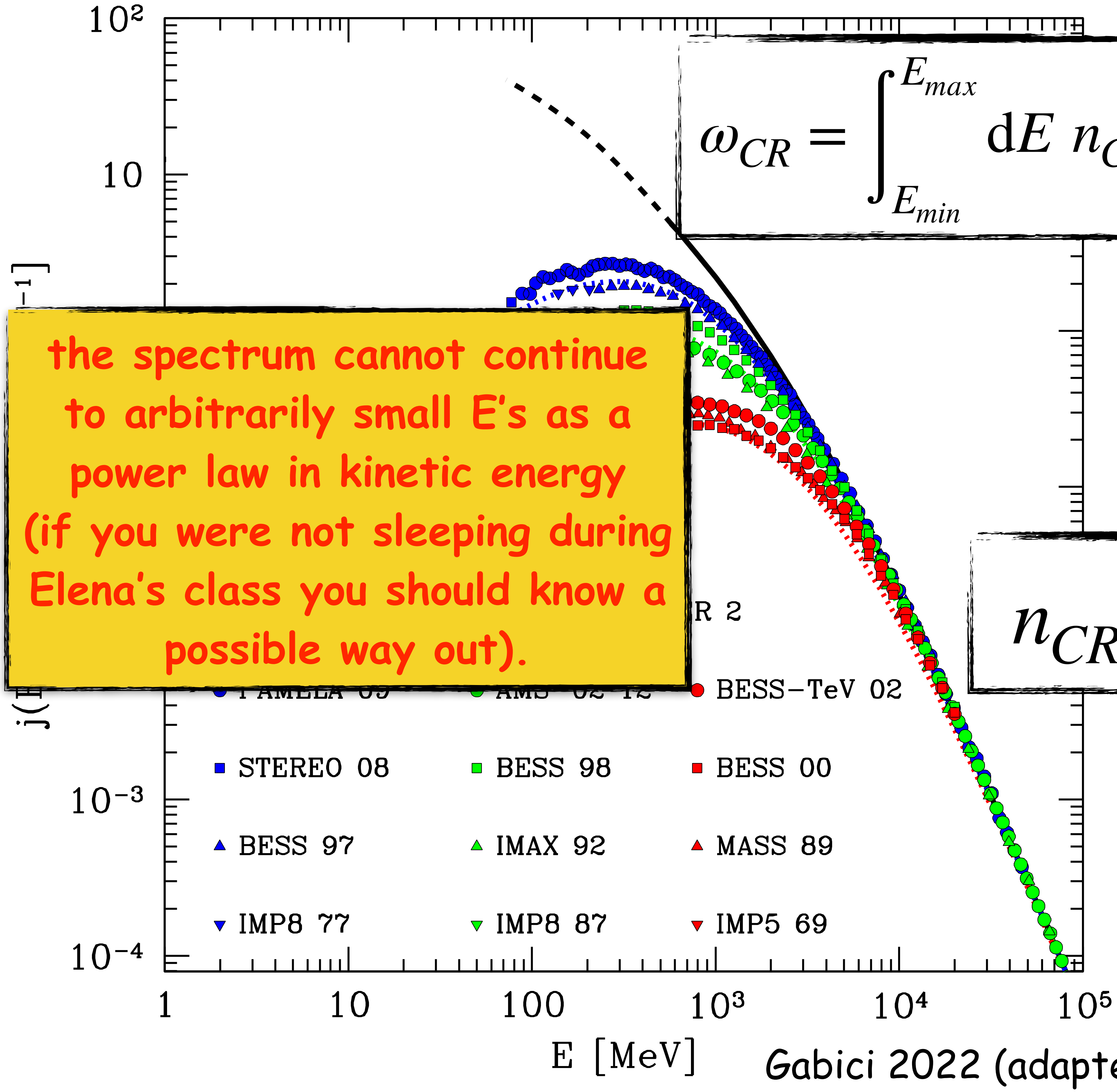

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the spectrum cannot continue to arbitrarily small E's as a power law in kinetic energy (if you were not sleeping during Elena's class you should know a possible way out).

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

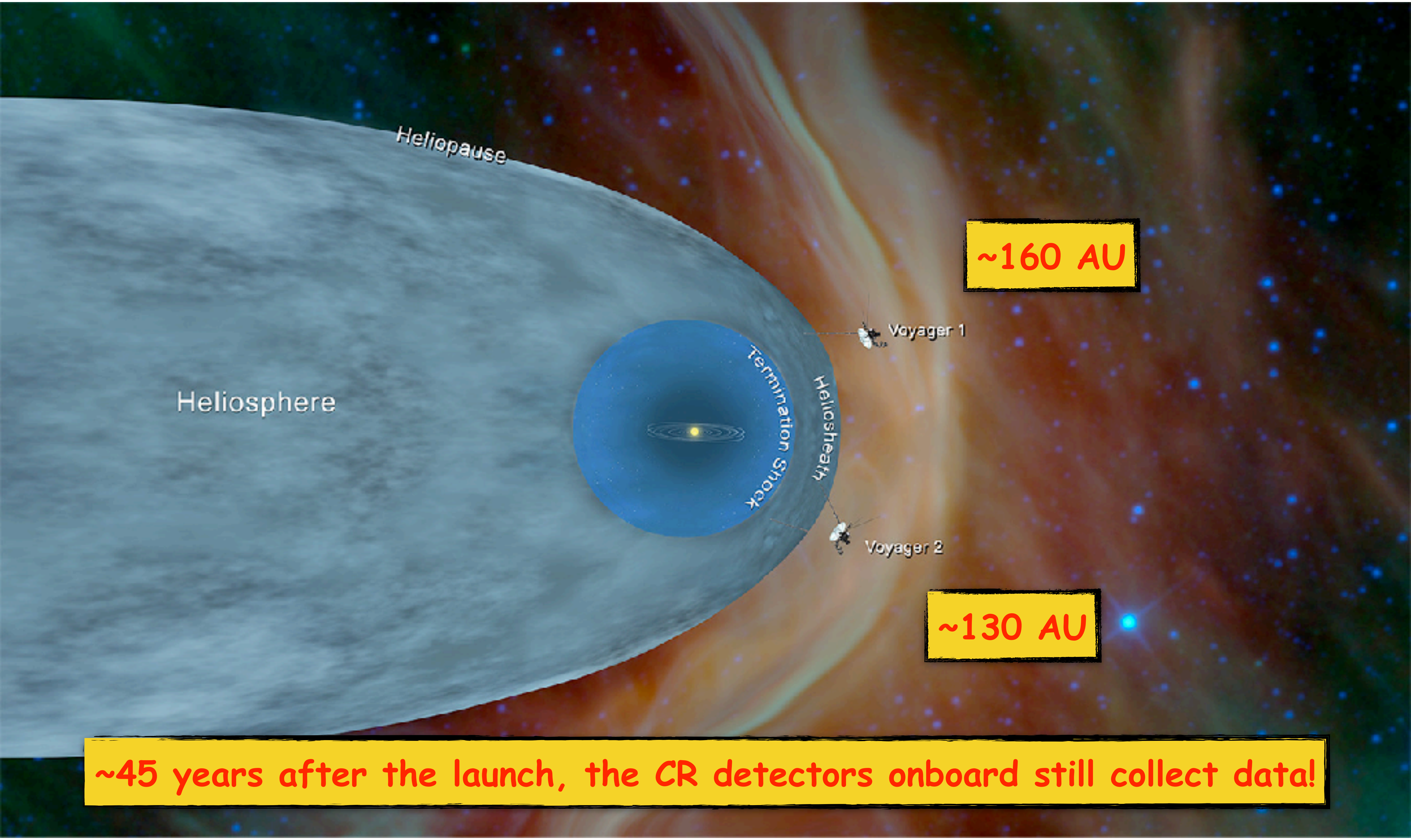
Gabici 2022 (adapted from Vos & Potgieter 2015)

# 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

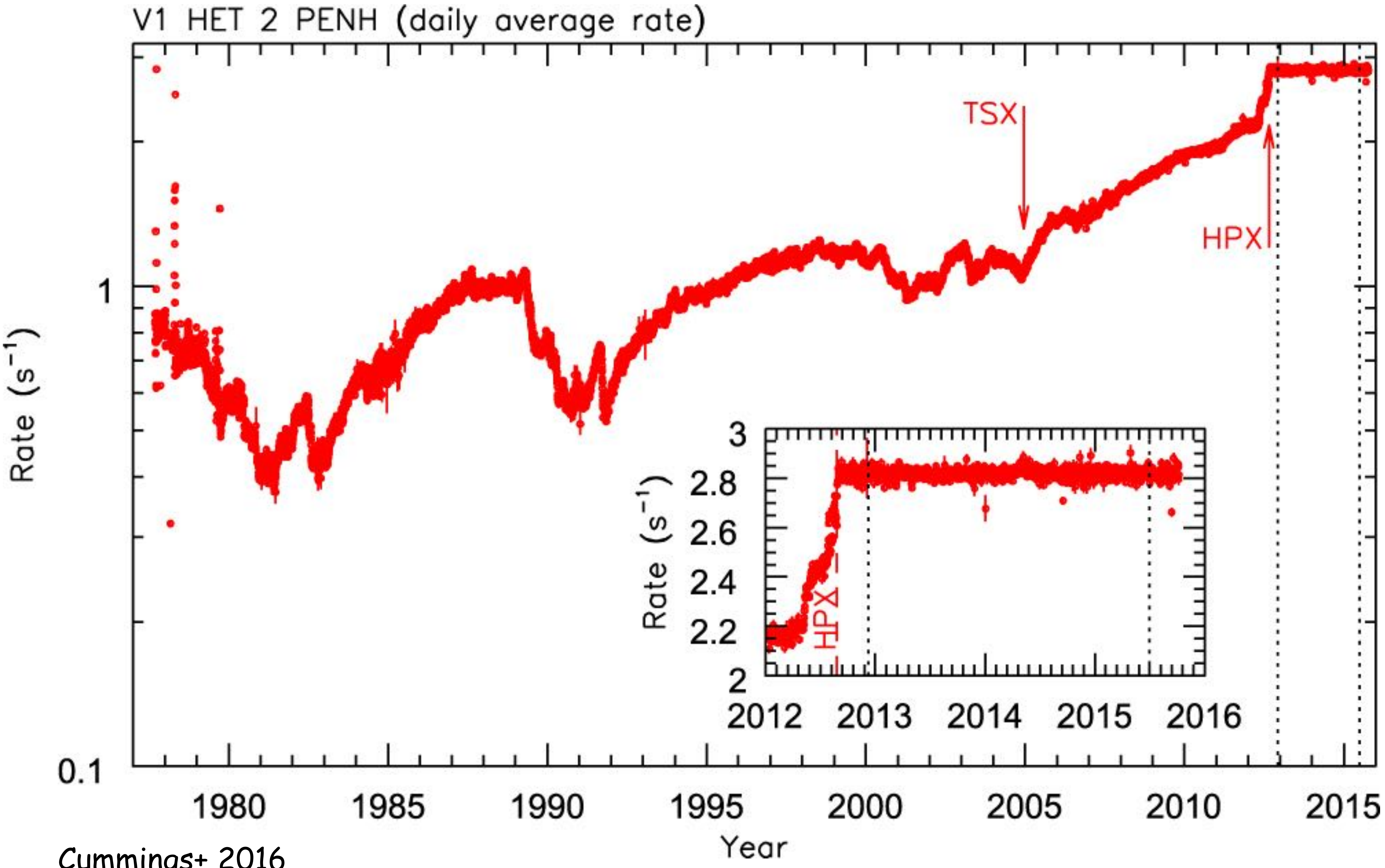


~160 AU

~130 AU

~45 years after the launch, the CR detectors onboard still collect data!

# An epic journey



Cummings+ 2016

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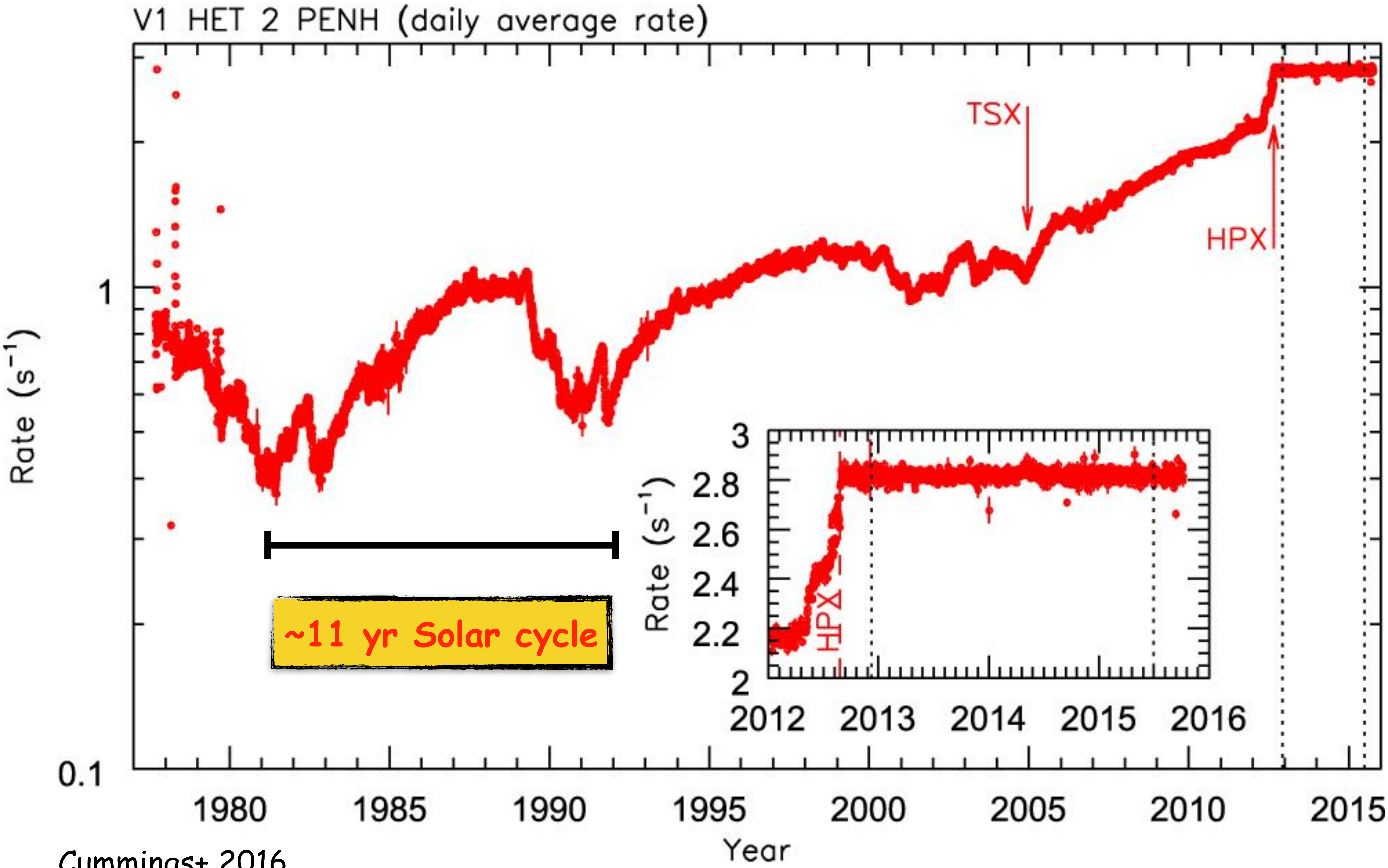

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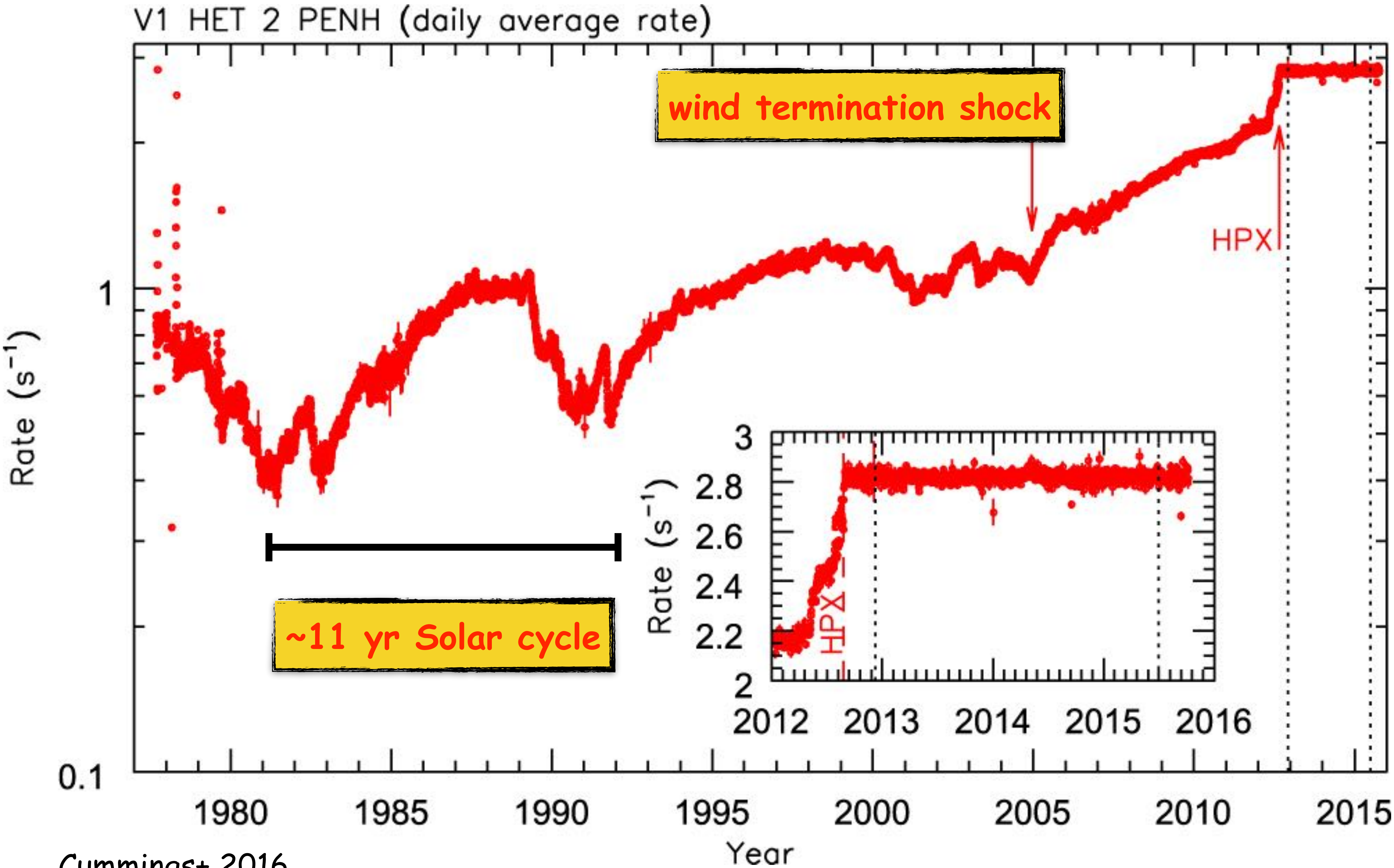

wind termination shock

~11 yr Solar cycle

Cummings+ 2016

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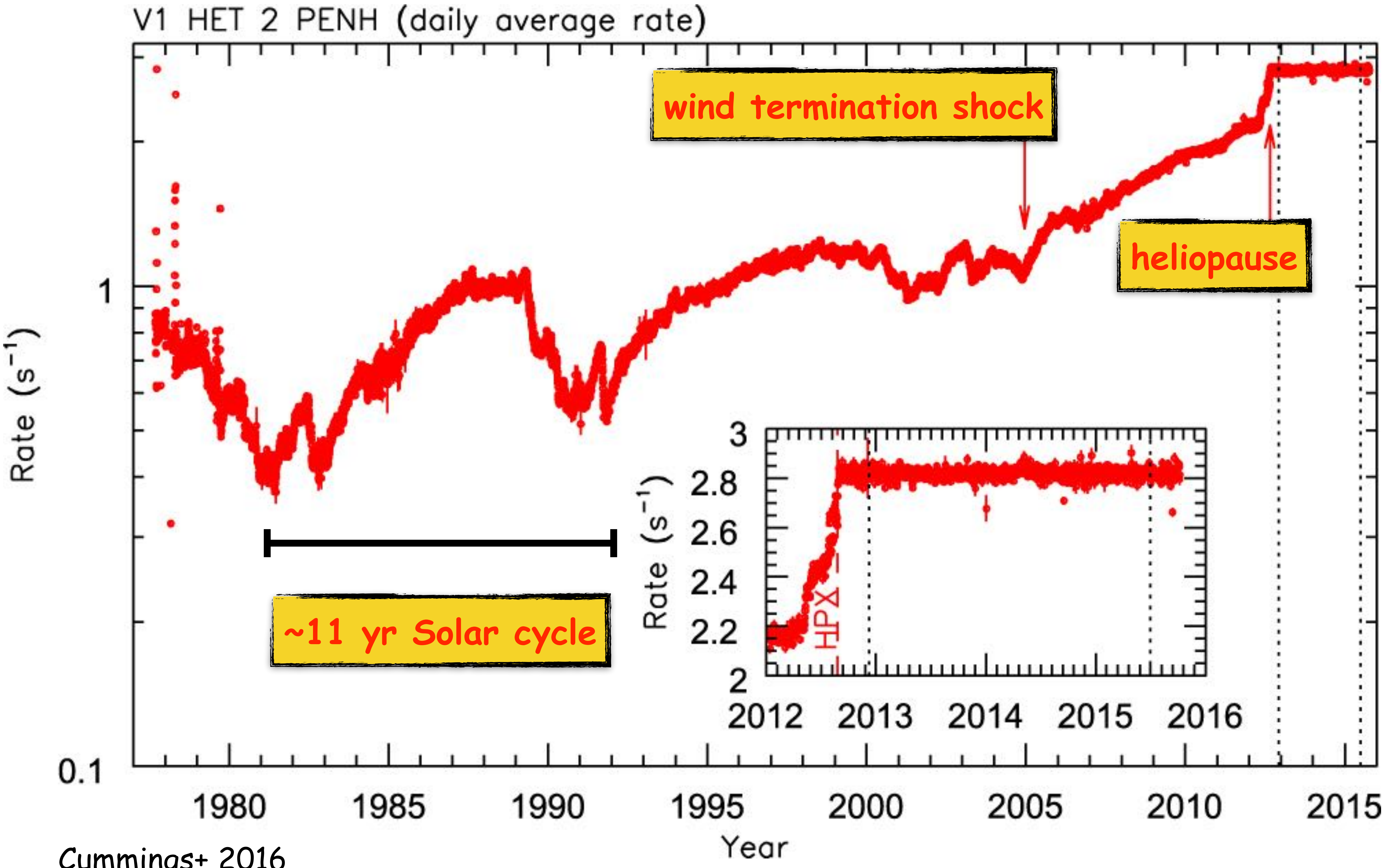

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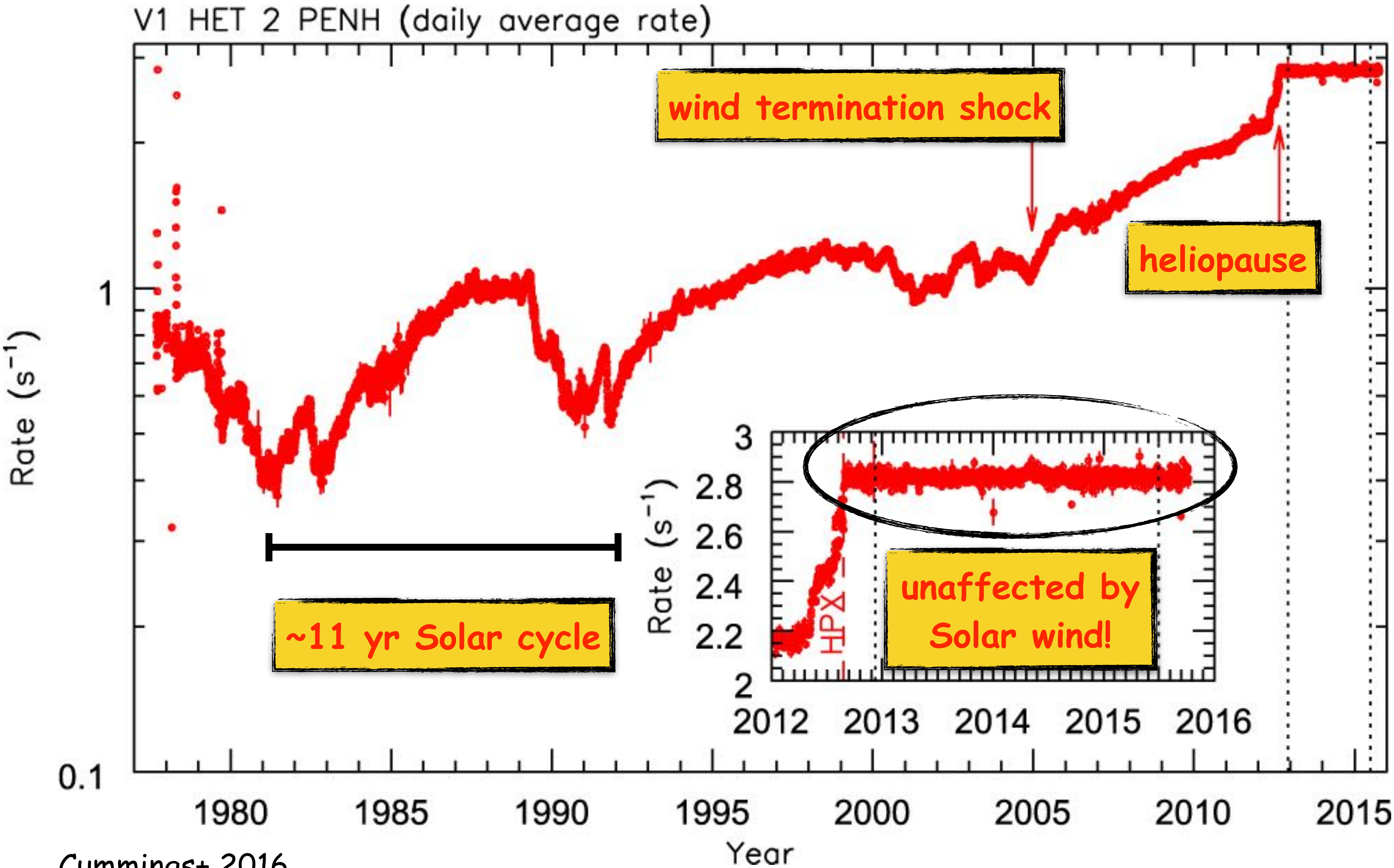
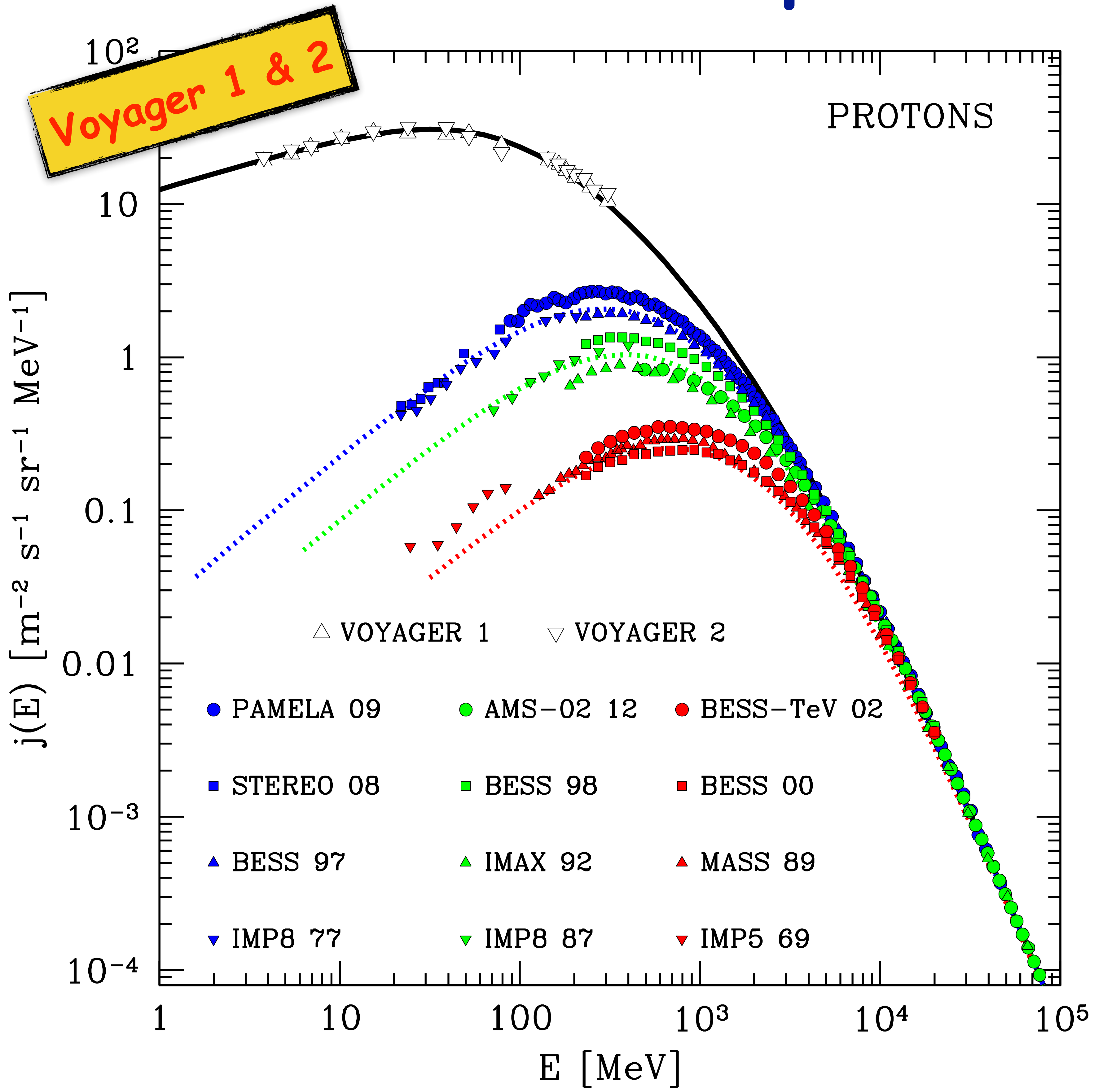


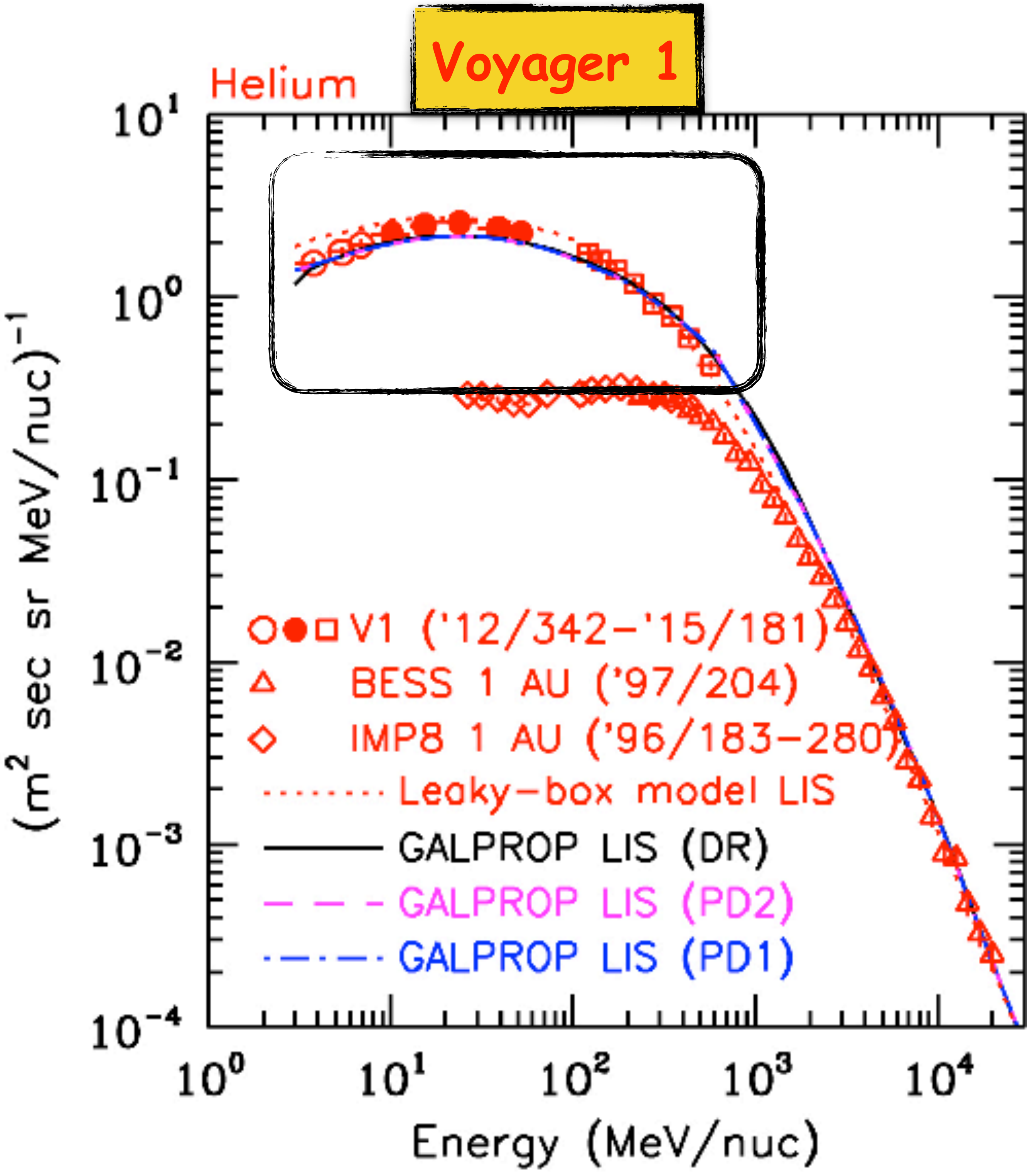
Cummings+ 2016

# The local interstellar spectrum of CRs


Voyager 1 & 2

Gabici 2022 (adapted from Vos & Potgieter 2015)

# Spectra of nuclei in the local ISM


Voyager 1

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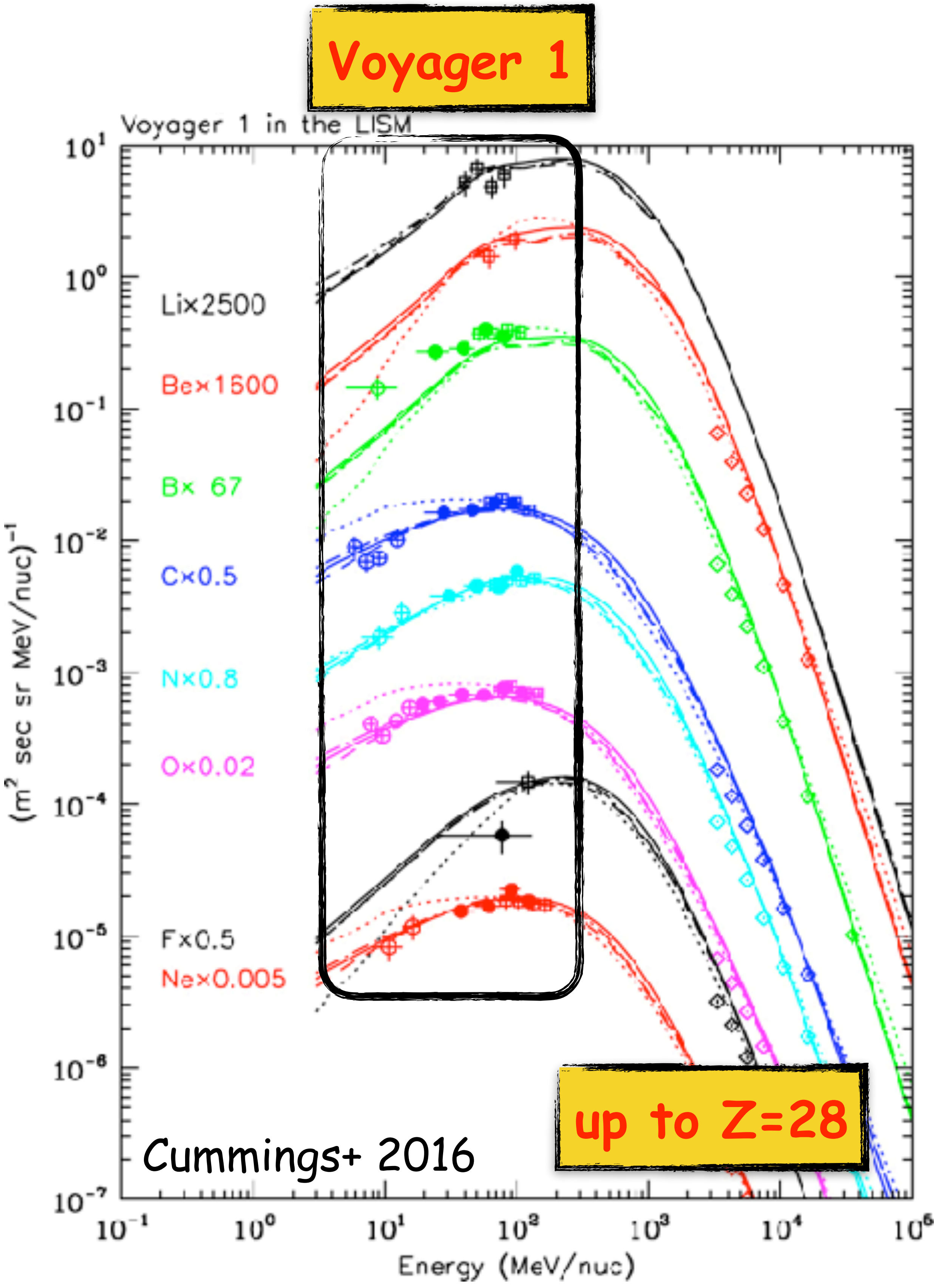
Voyager 1

up to Z=28

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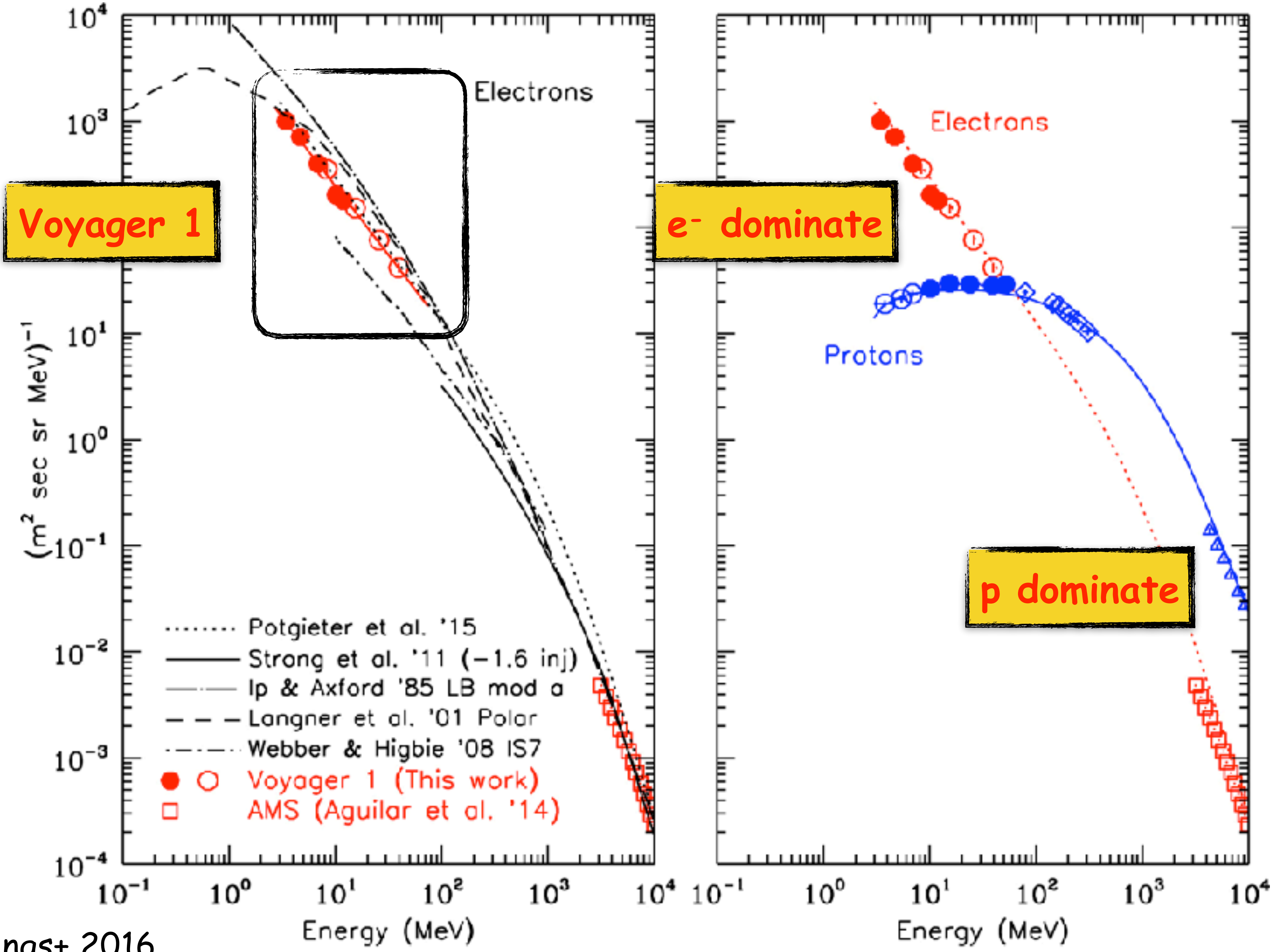
# Electron spectrum in the local ISM



Voyager 1

e⁻ dominate

p dominate

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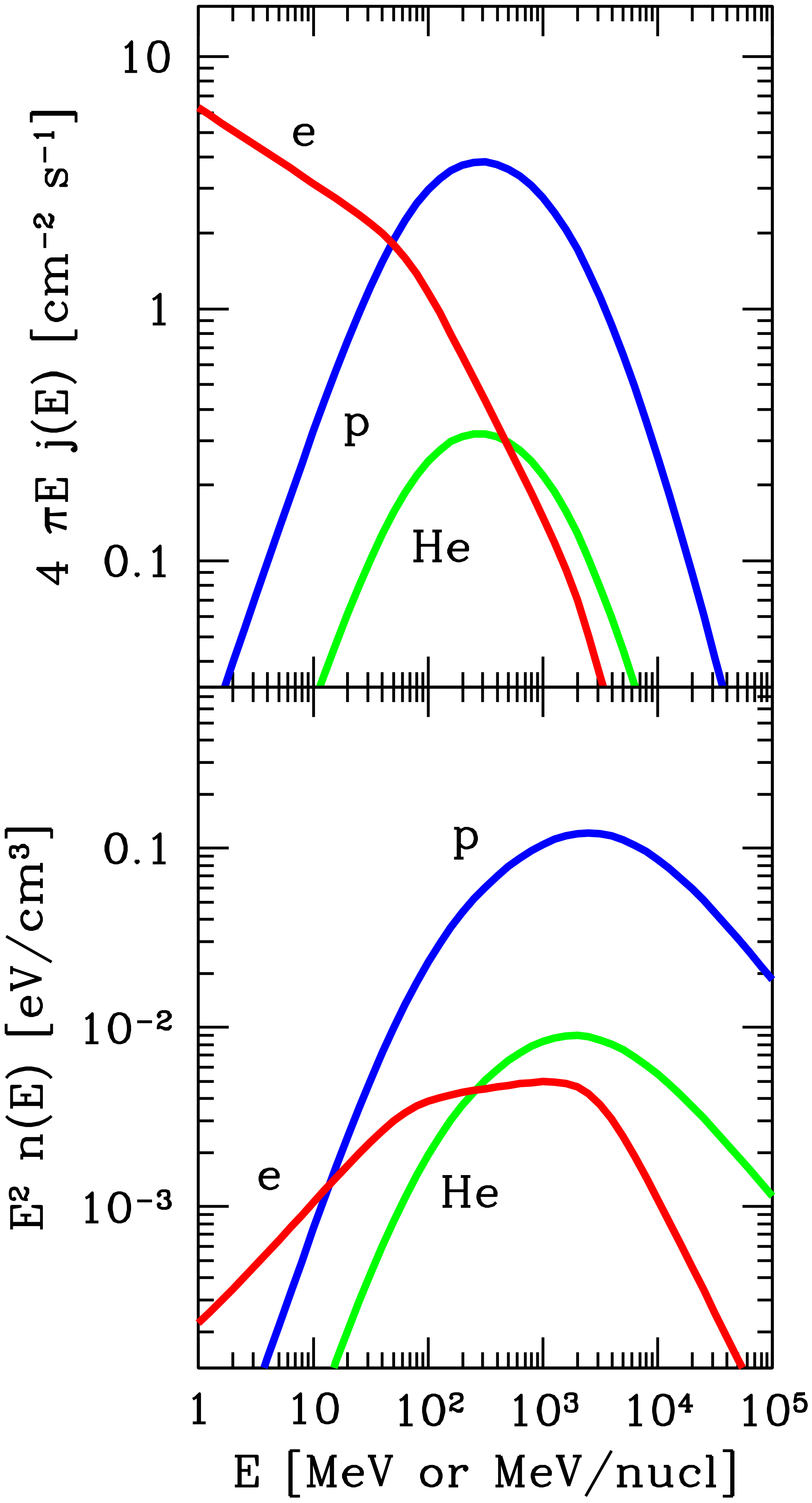
**flux of particles**

**spectral energy distribution**



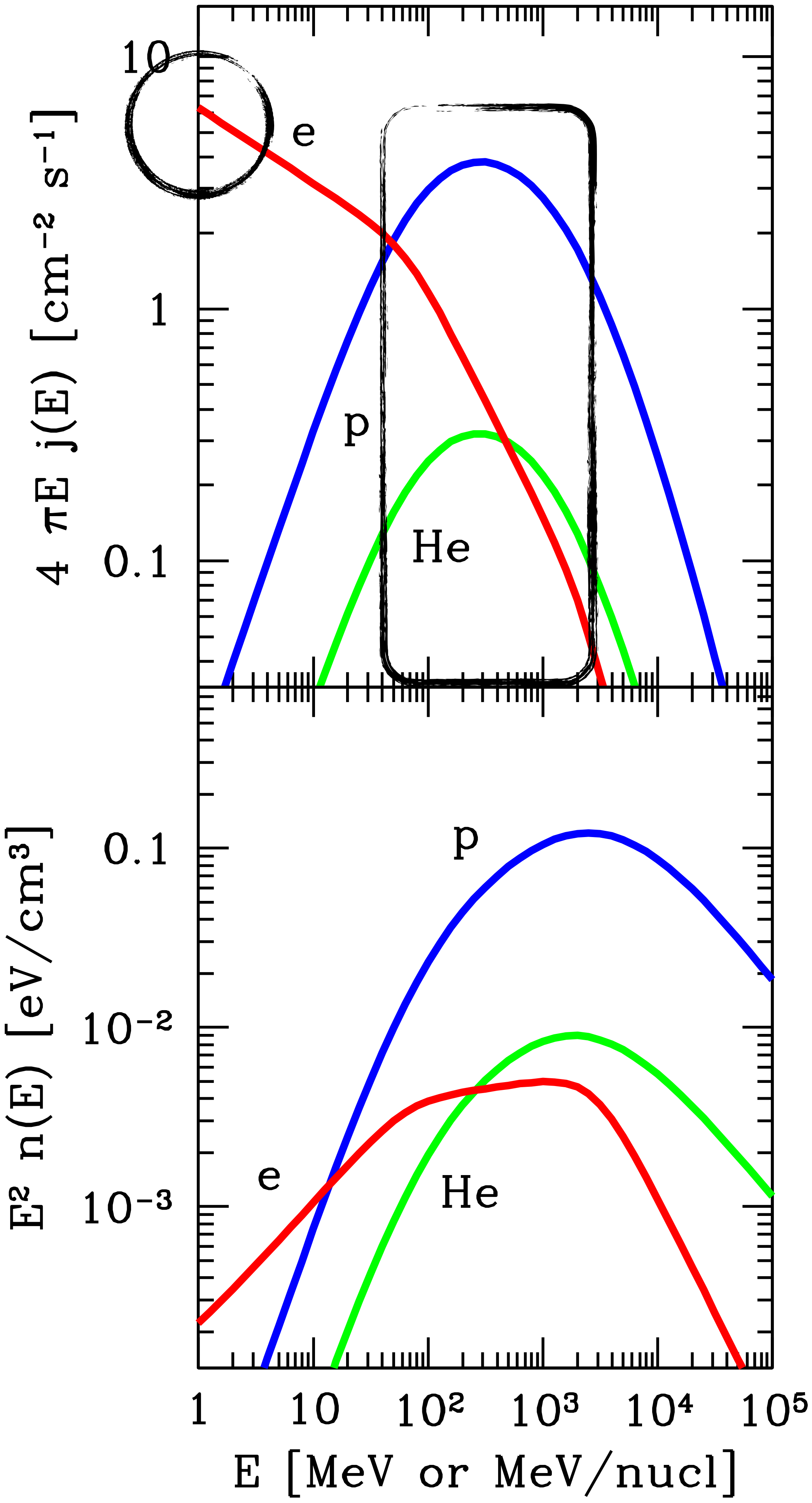
Gabici 2022

**flux of particles**

most nuclei have
energies 100 MeV-1 GeV

how many CR electrons?

**spectral energy distribution**



Gabici 2022

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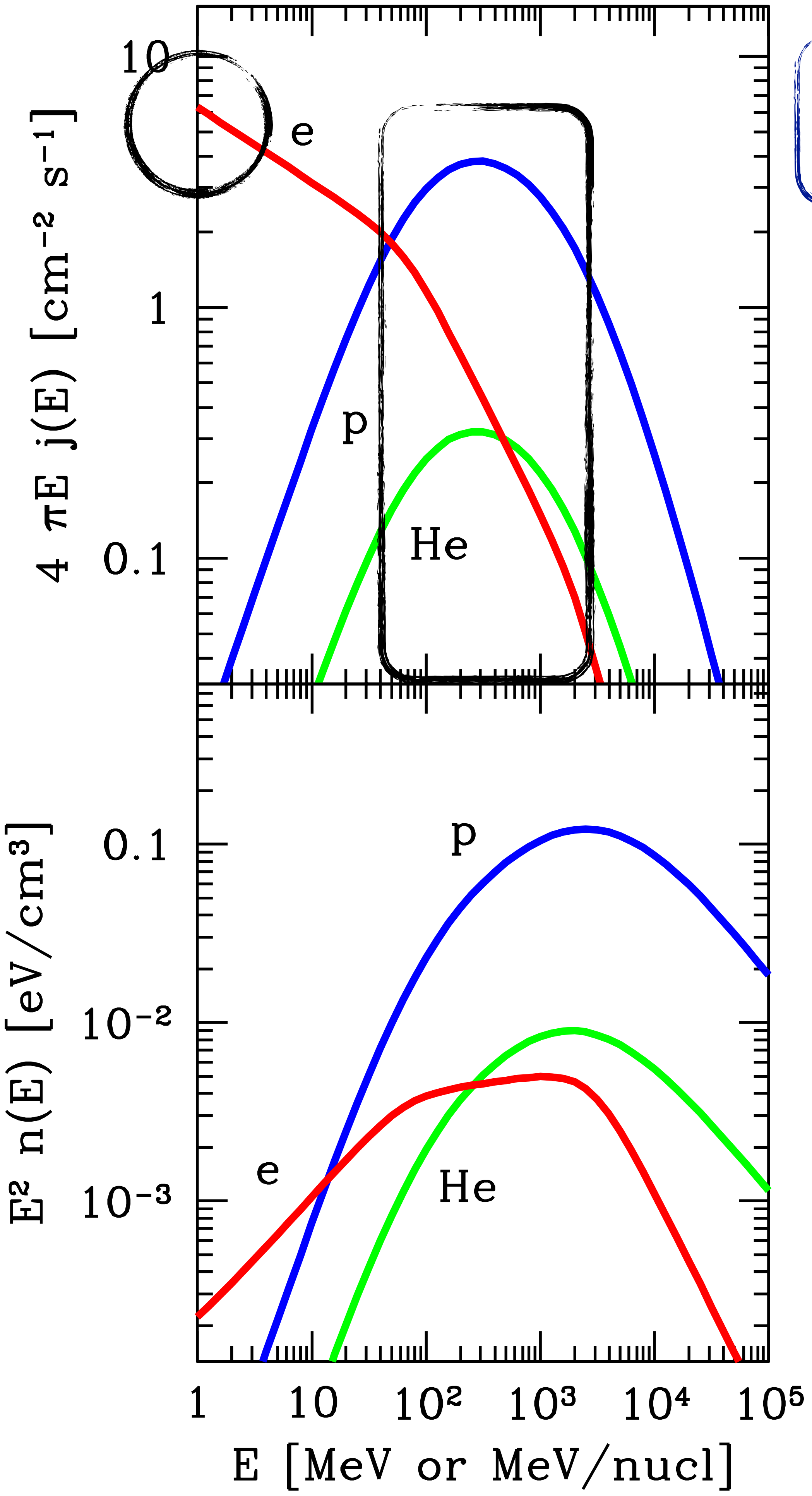
$$\approx 10^{-9} - 10^{-10}\ \mathrm{cm}^{-3}$$



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Gabici 2022

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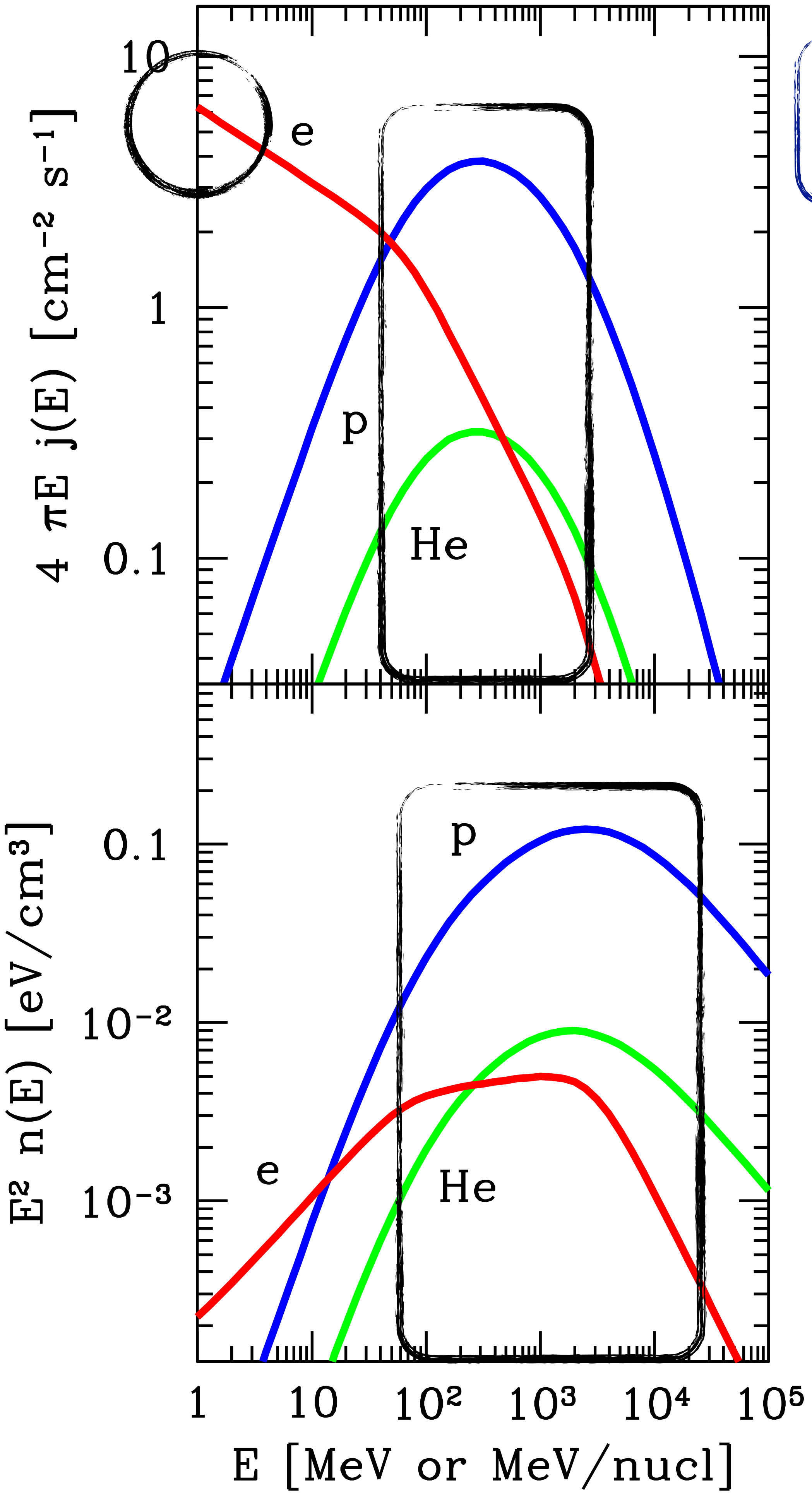

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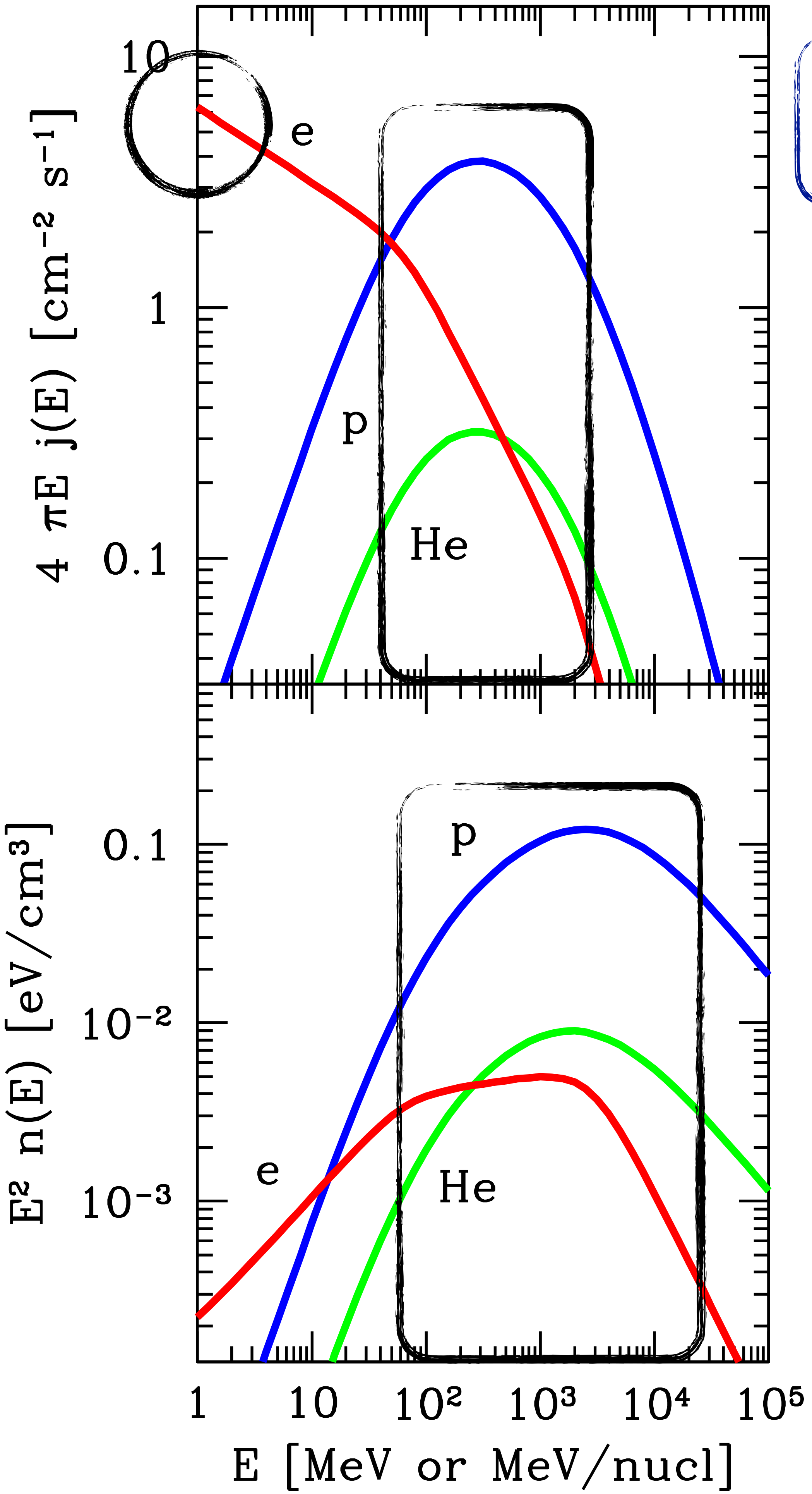

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Gabici 2022

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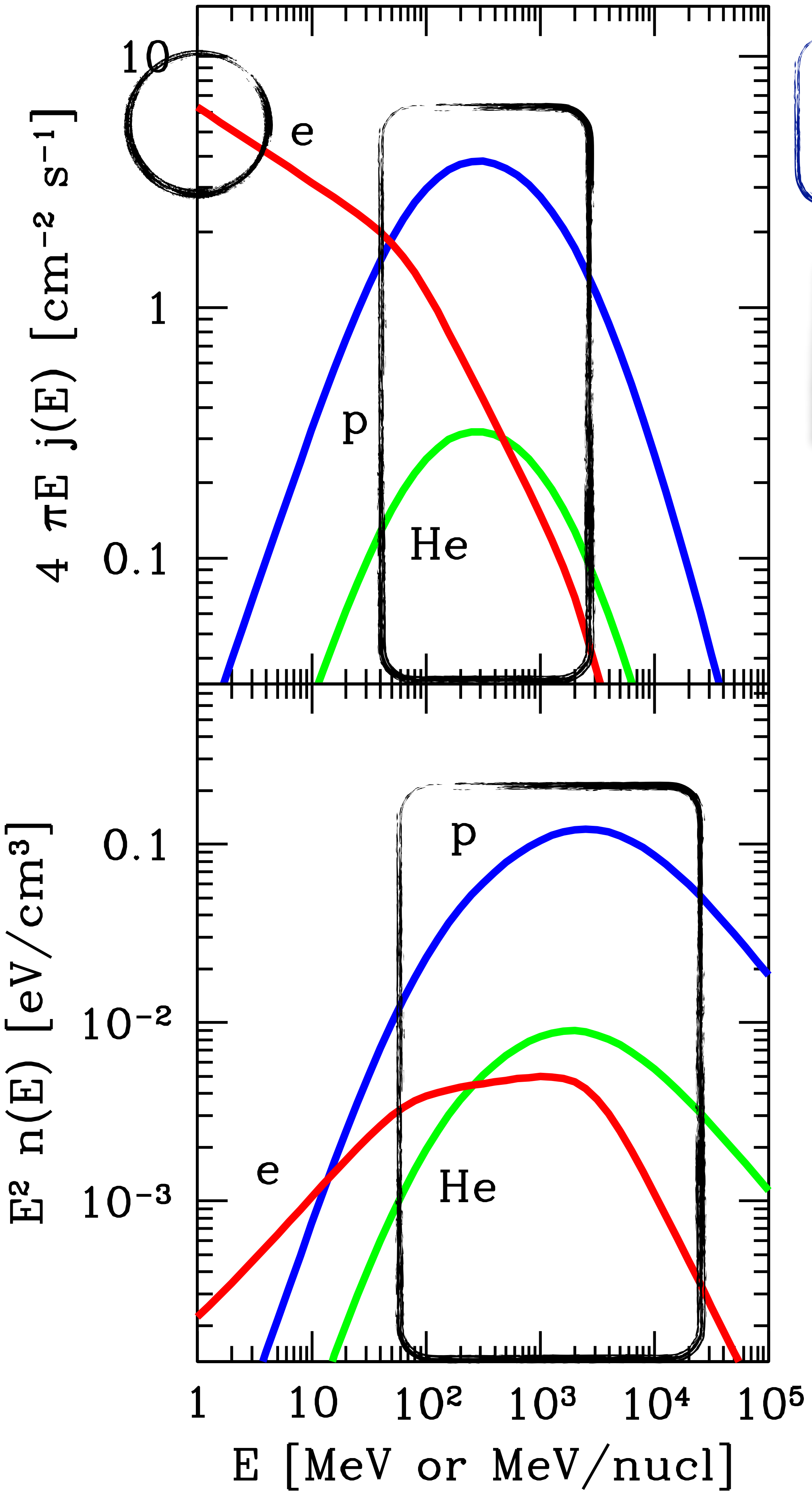

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**compare with ISM density...**

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Gabici 2022

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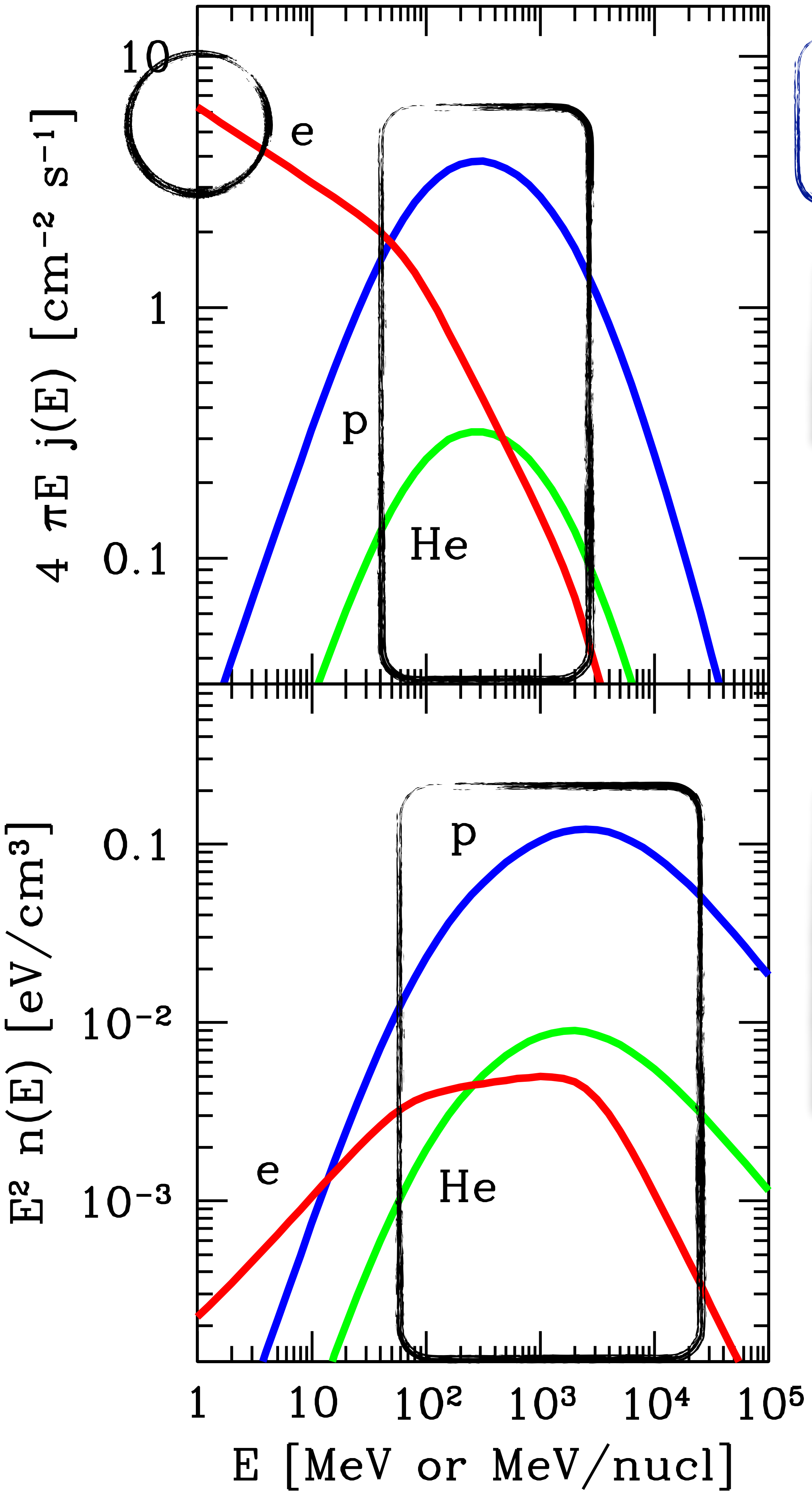

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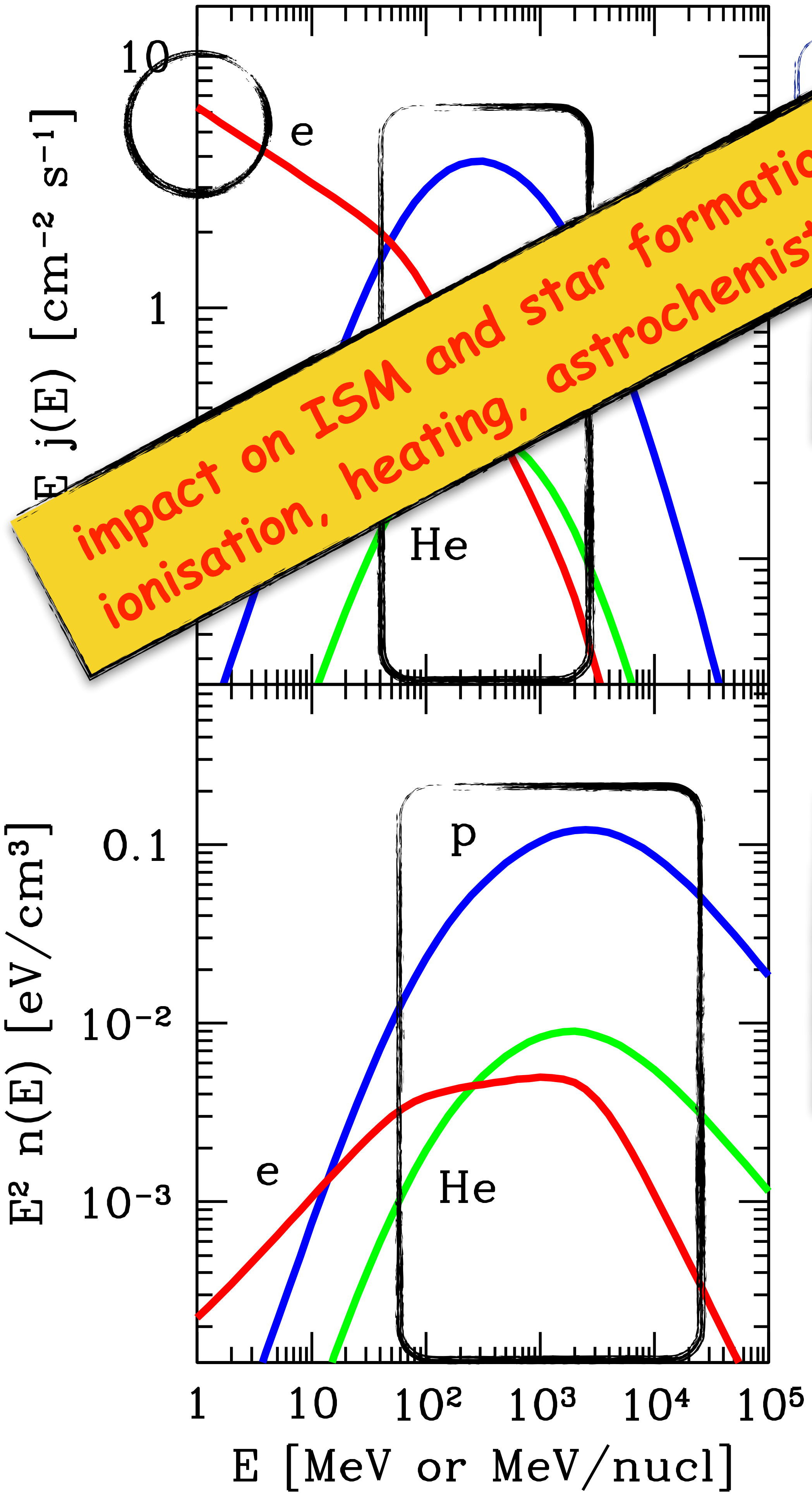

**impact on ISM and star formation:
ionisation, heating, astrochemistry…**

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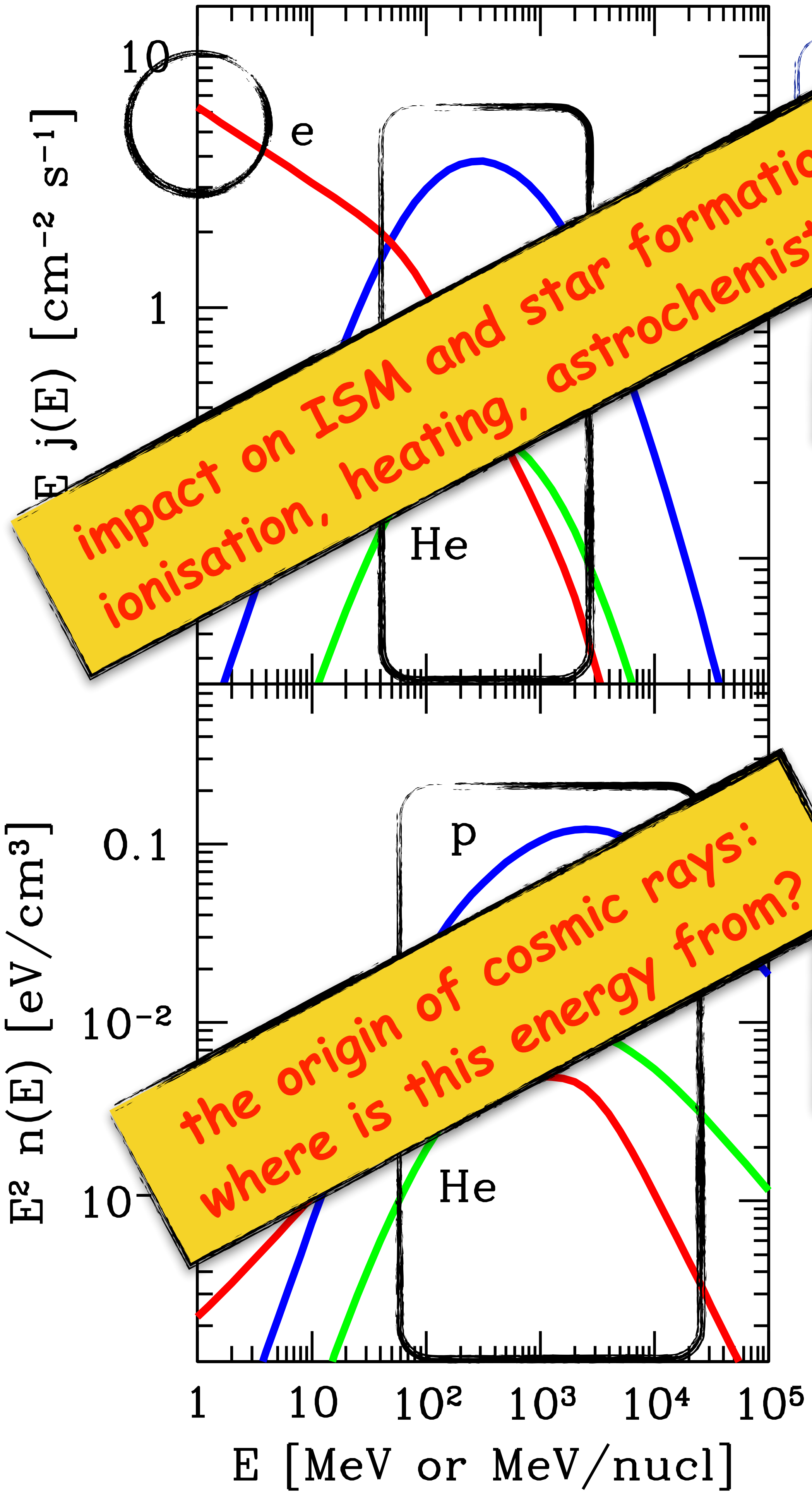

**impact on ISM and star formation: ionisation, heating, astrochemistry…**

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

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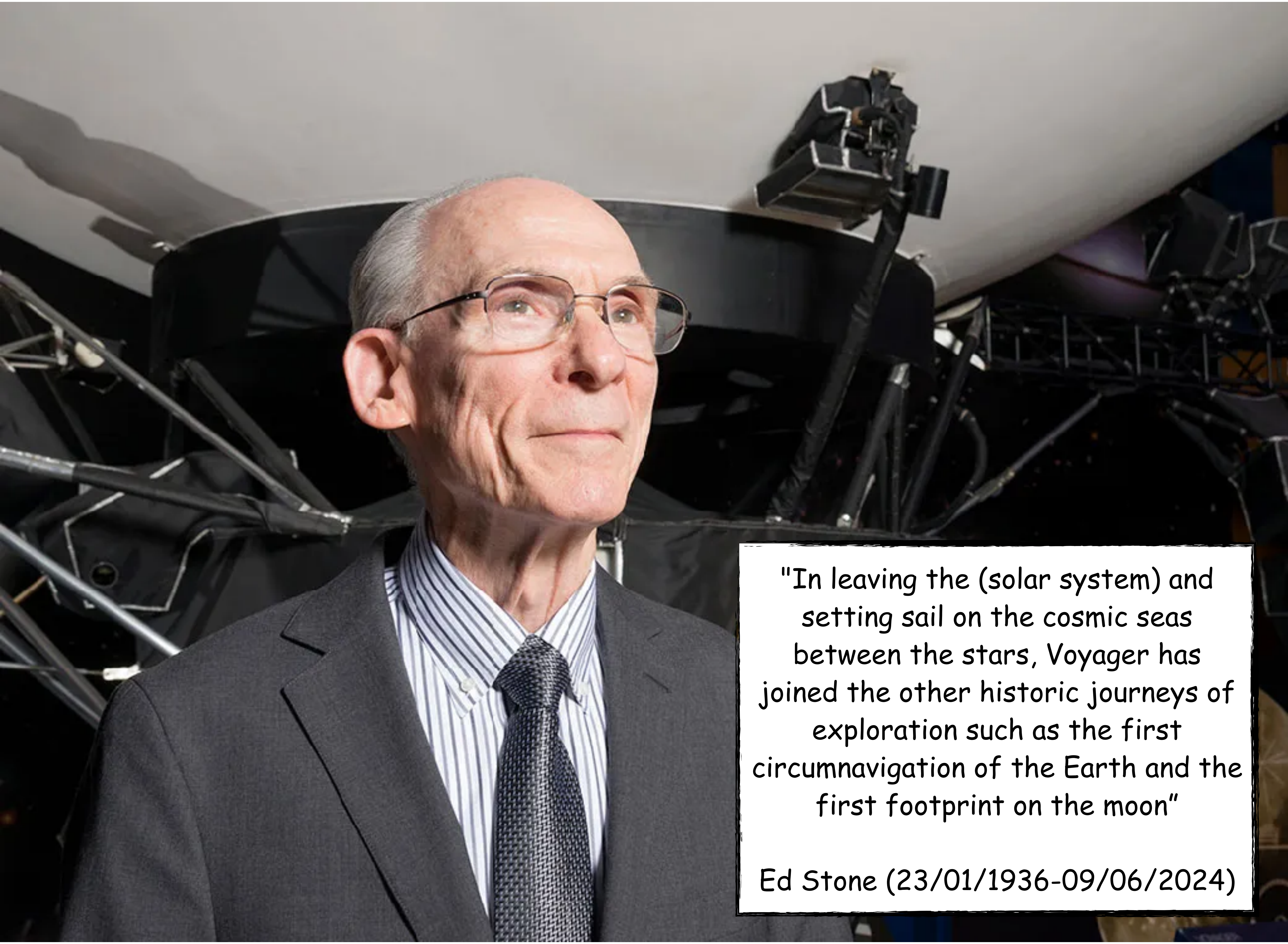
**same order as magnetic, thermal, and turbulent energy in the ISM!**

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



"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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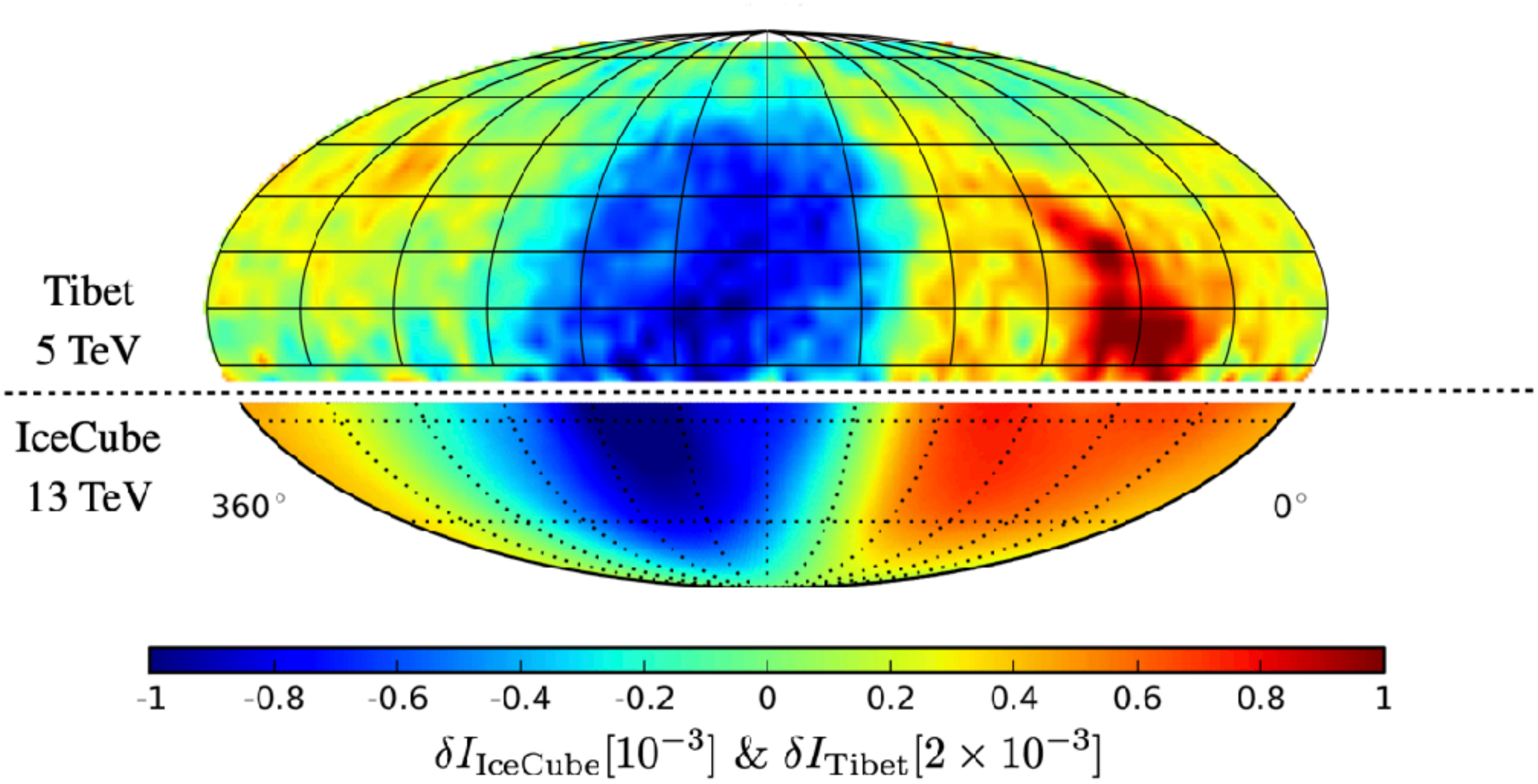
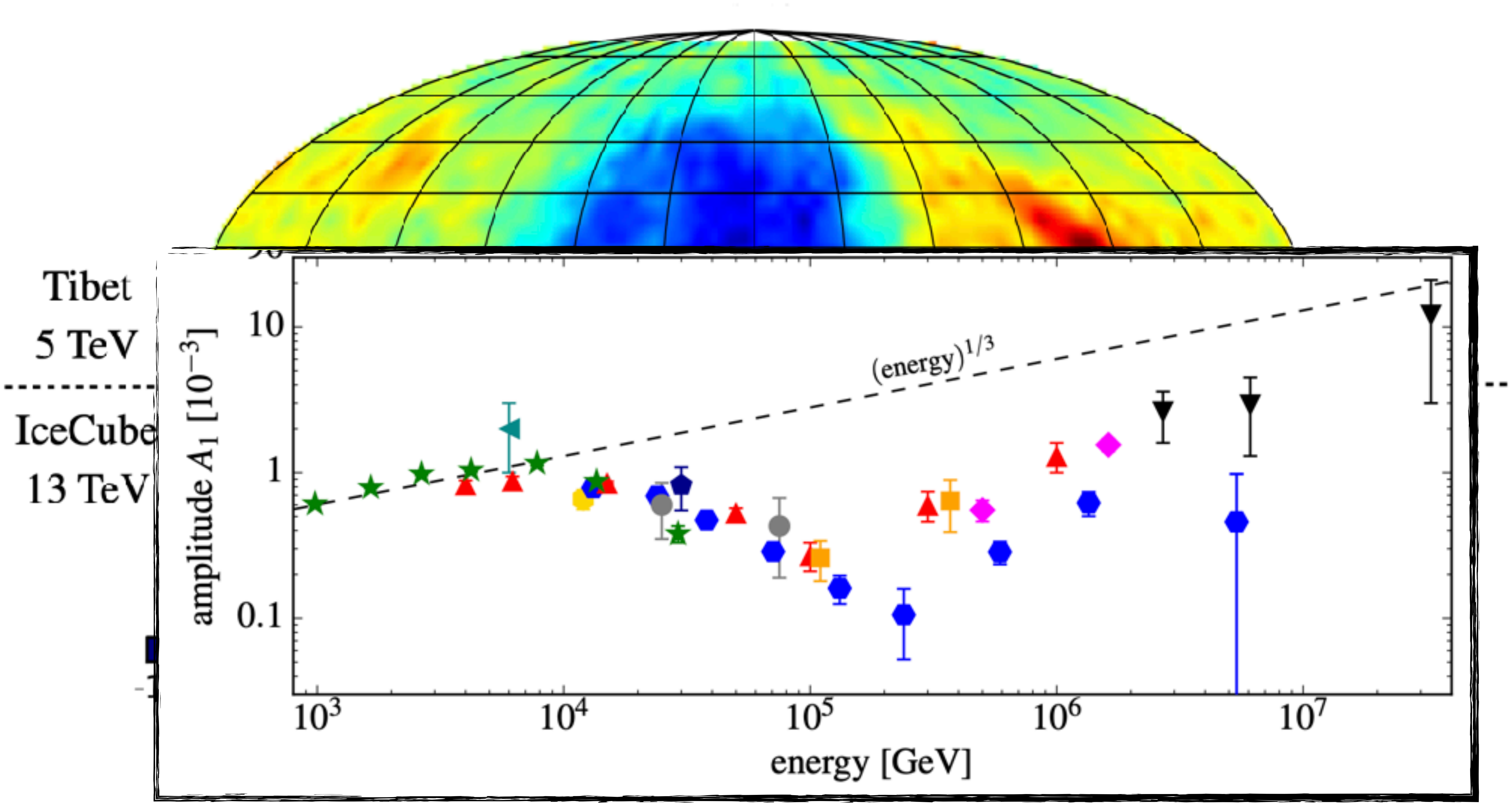
**Stability in time and (hints for) spatial homogeneity**

# Cosmic rays are almost isotropic



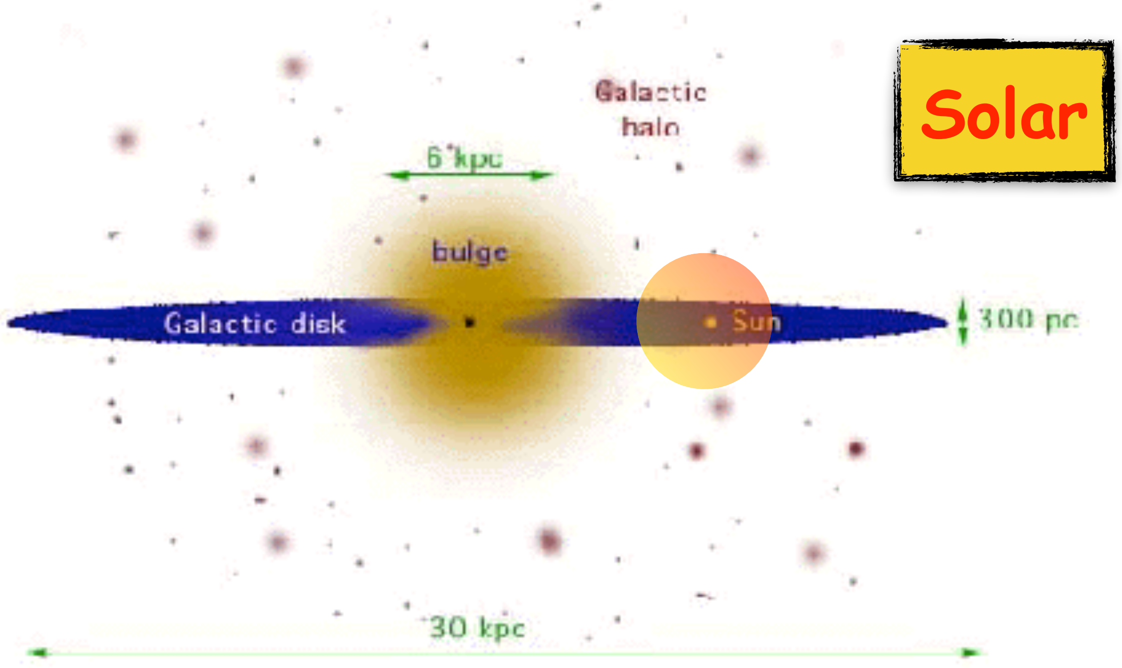
see review by Mertsch & Ahlers 2017

# Cosmic rays are almost isotropic



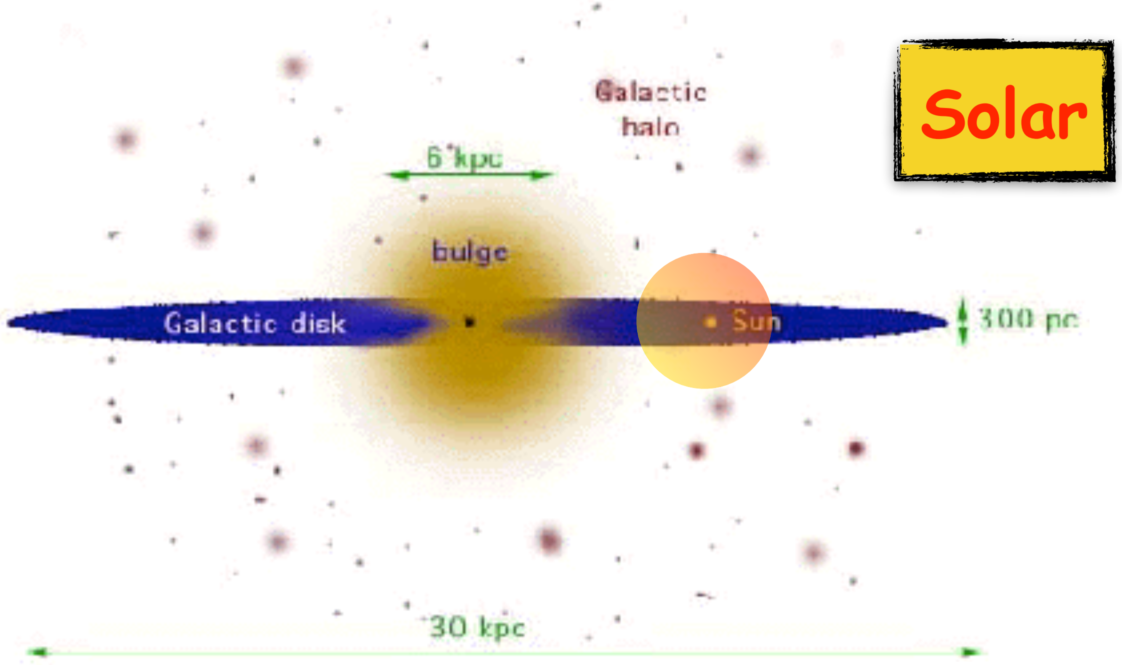
see review by Mertsch & Ahlers 2017

# Three scenarios

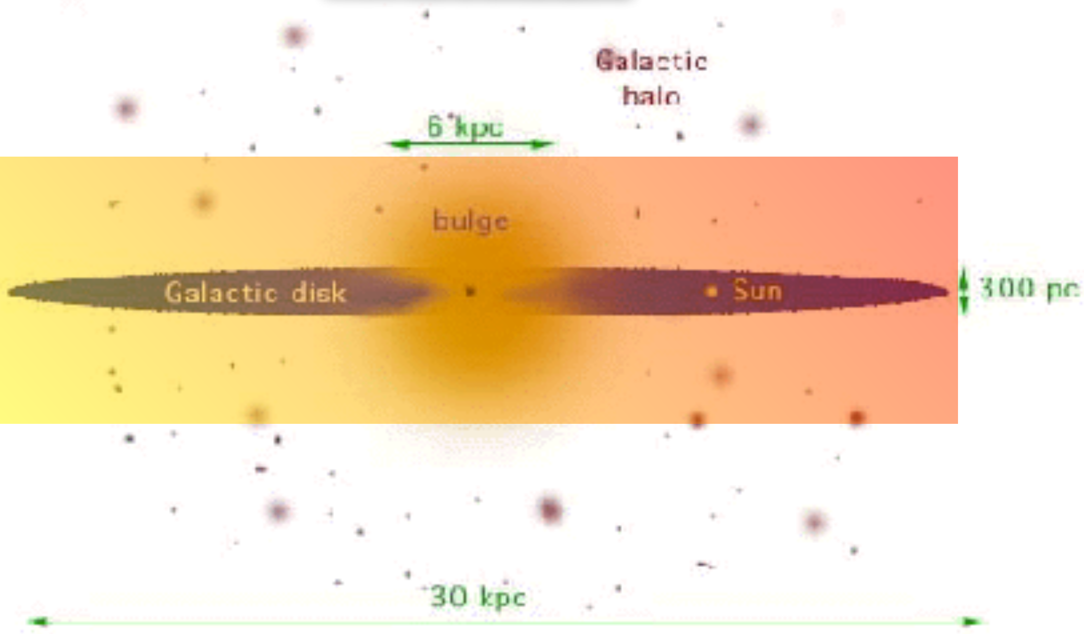


# Three scenarios

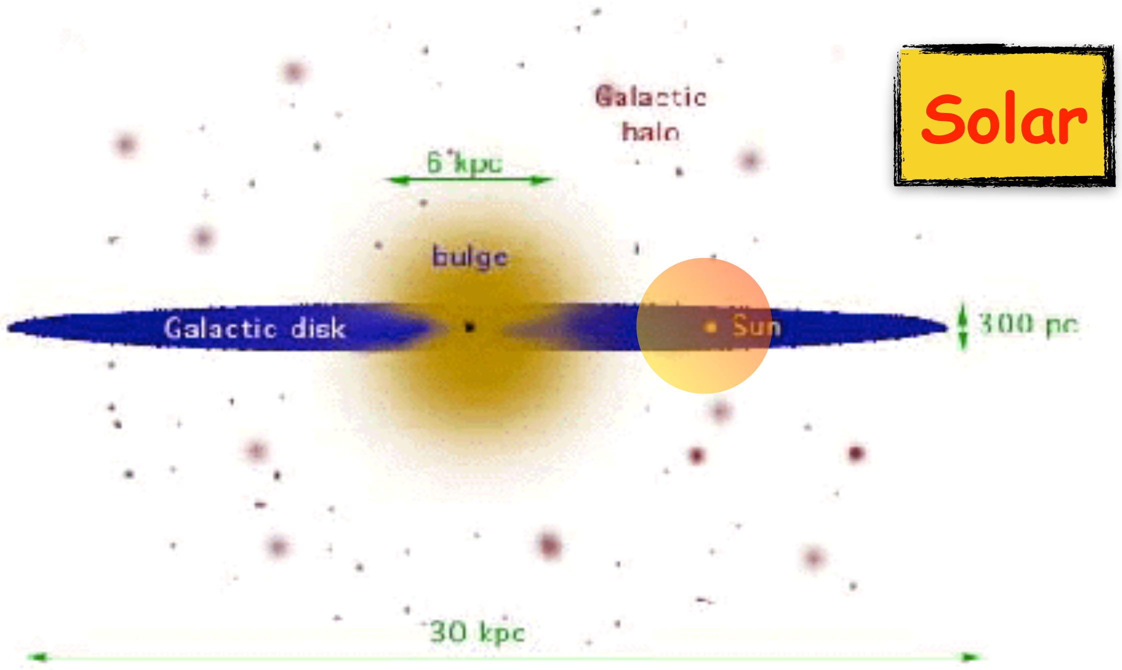
**Solar**



**Galactic**

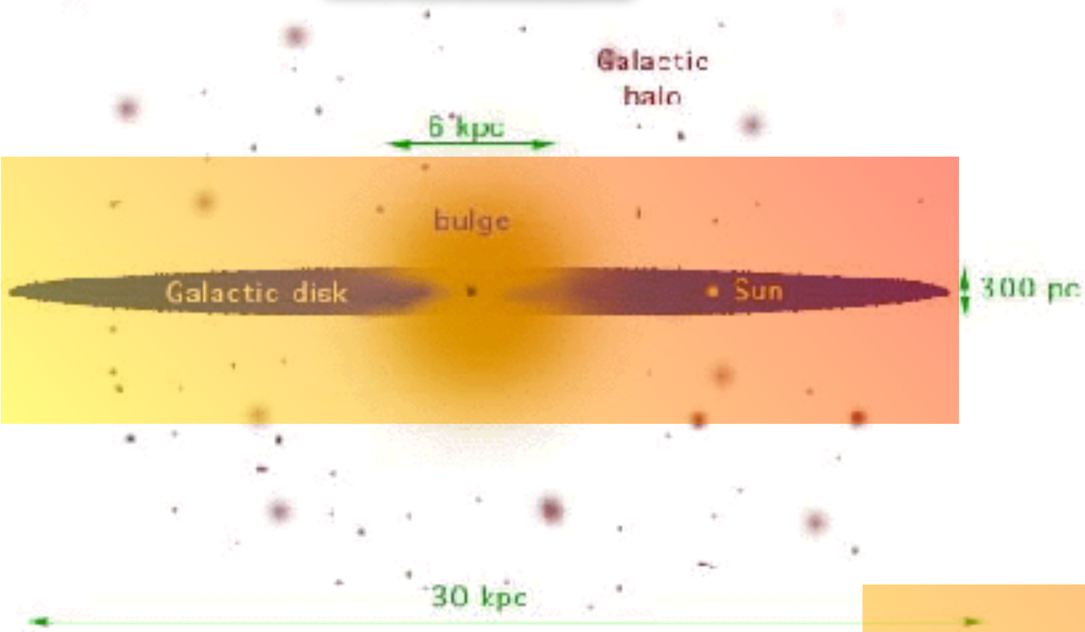


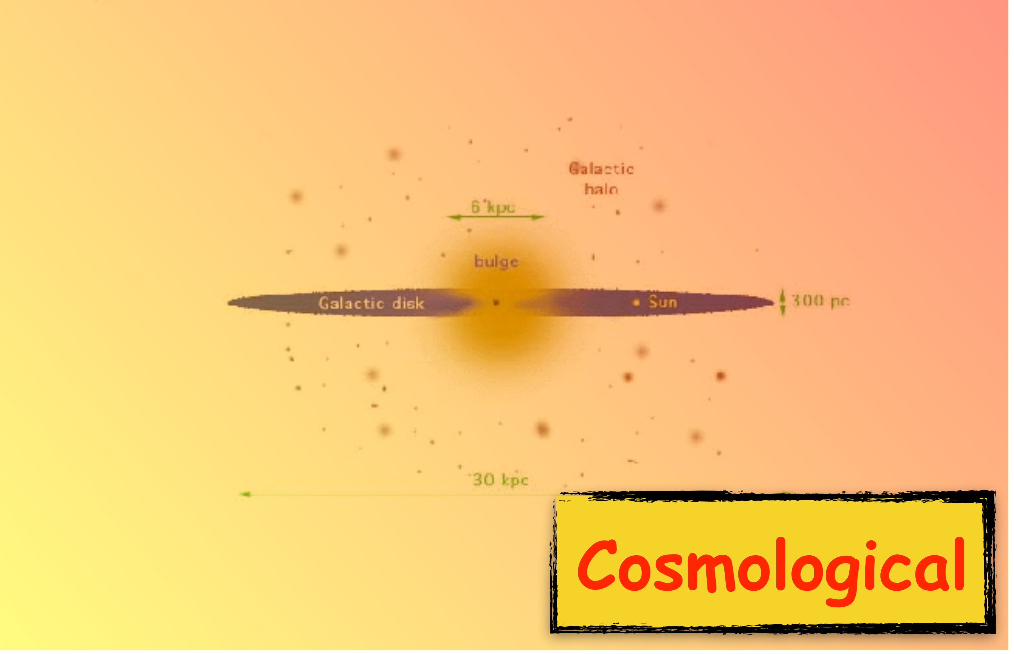
# Three scenarios



Solar

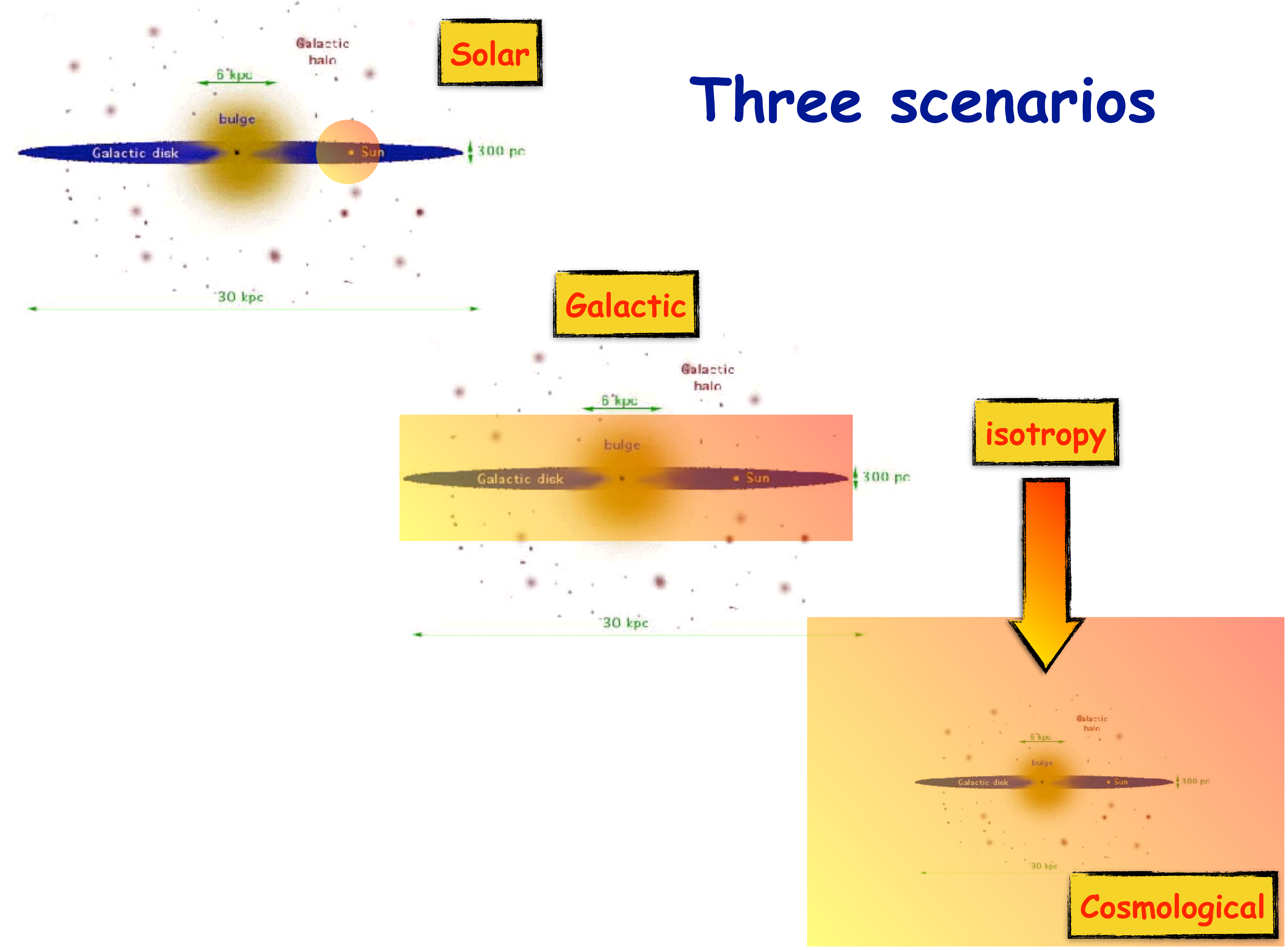
Galactic





Cosmological

# Three scenarios



Solar

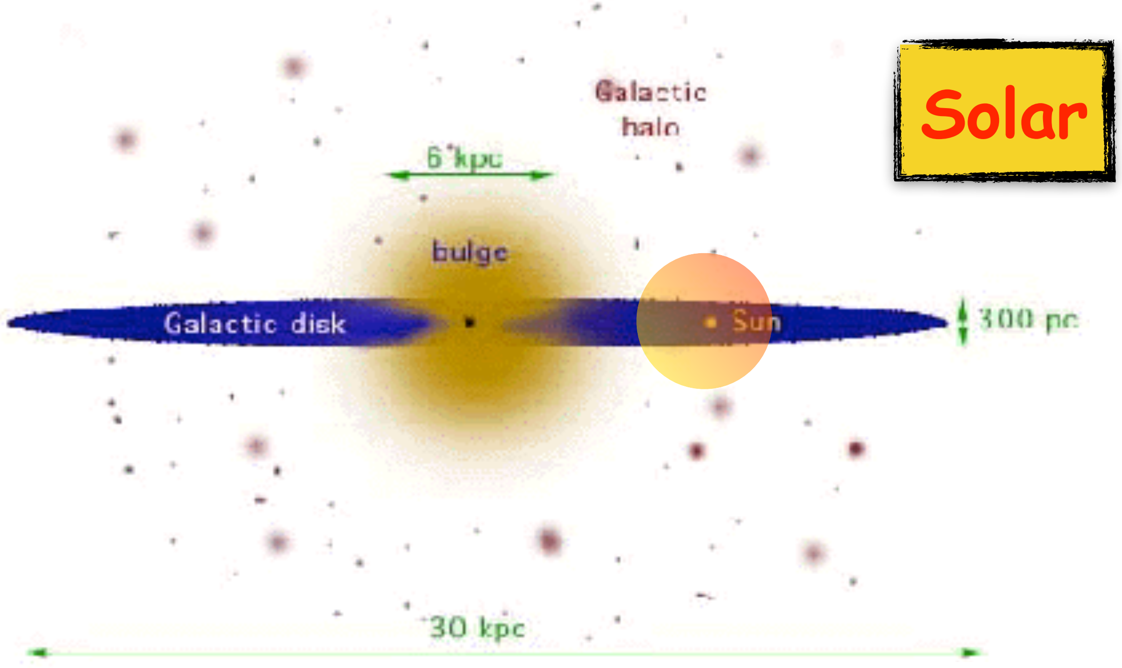
Galactic

isotropy

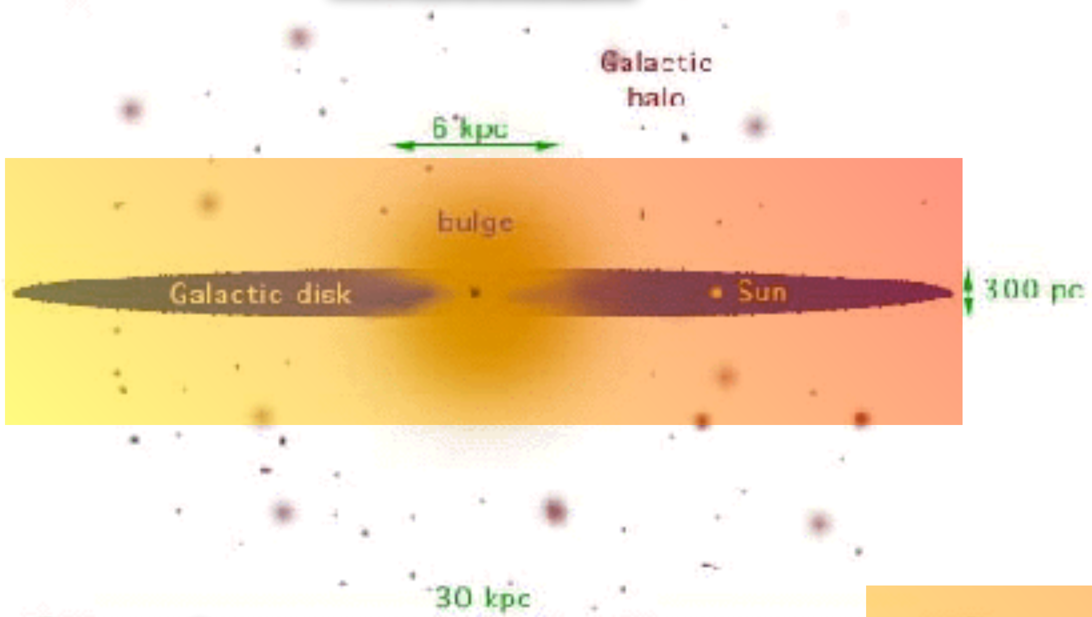
Cosmological

# Three scenarios

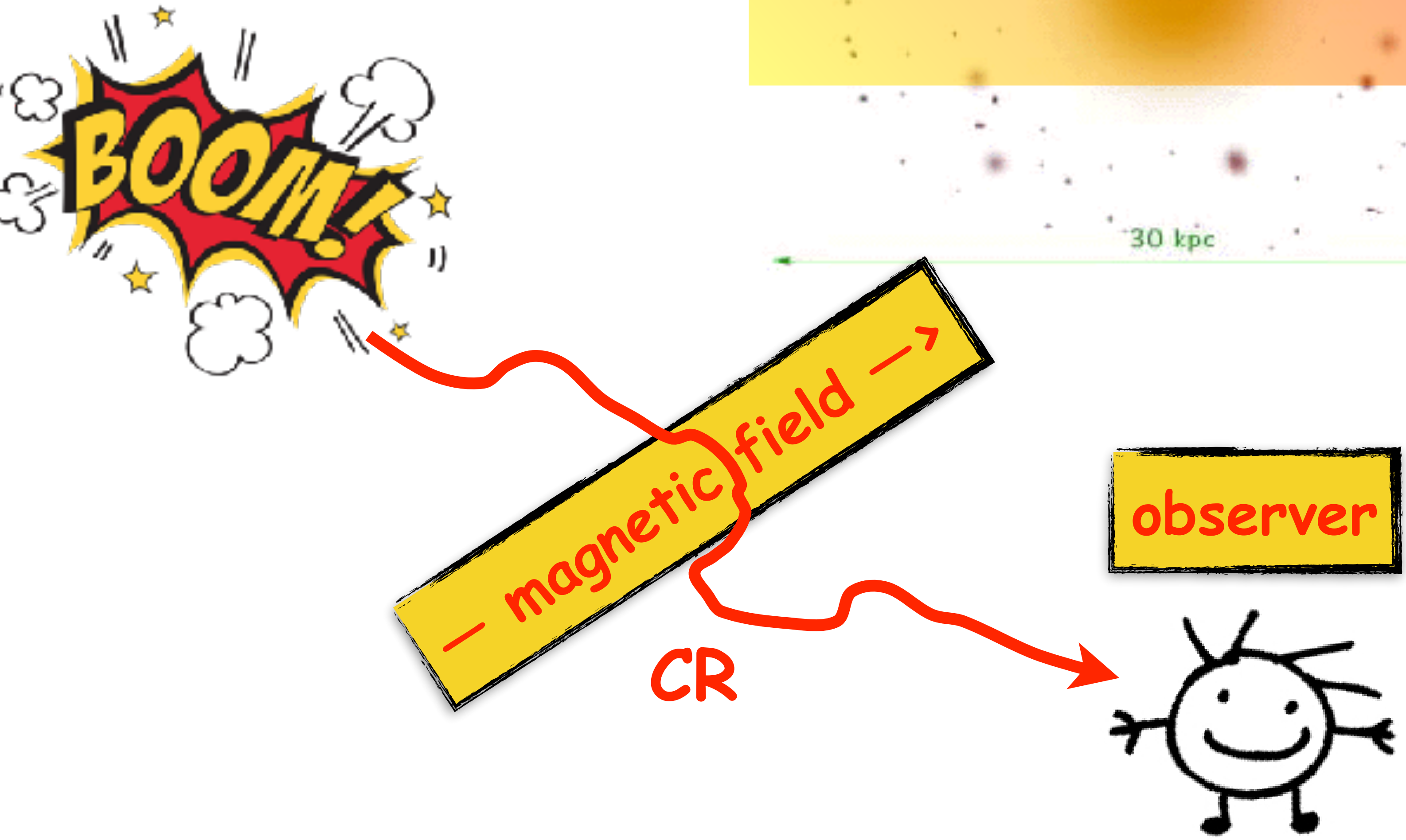
**Solar**



**Galactic**

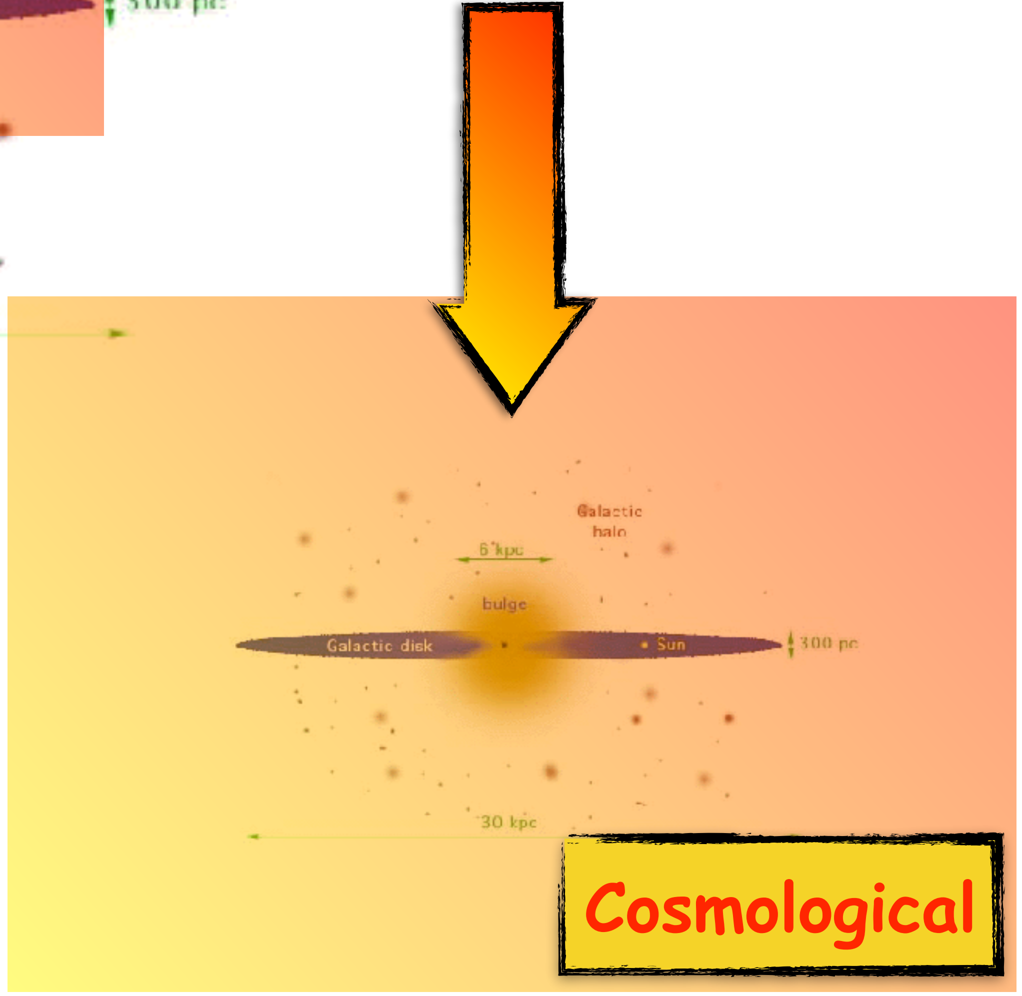


**source**



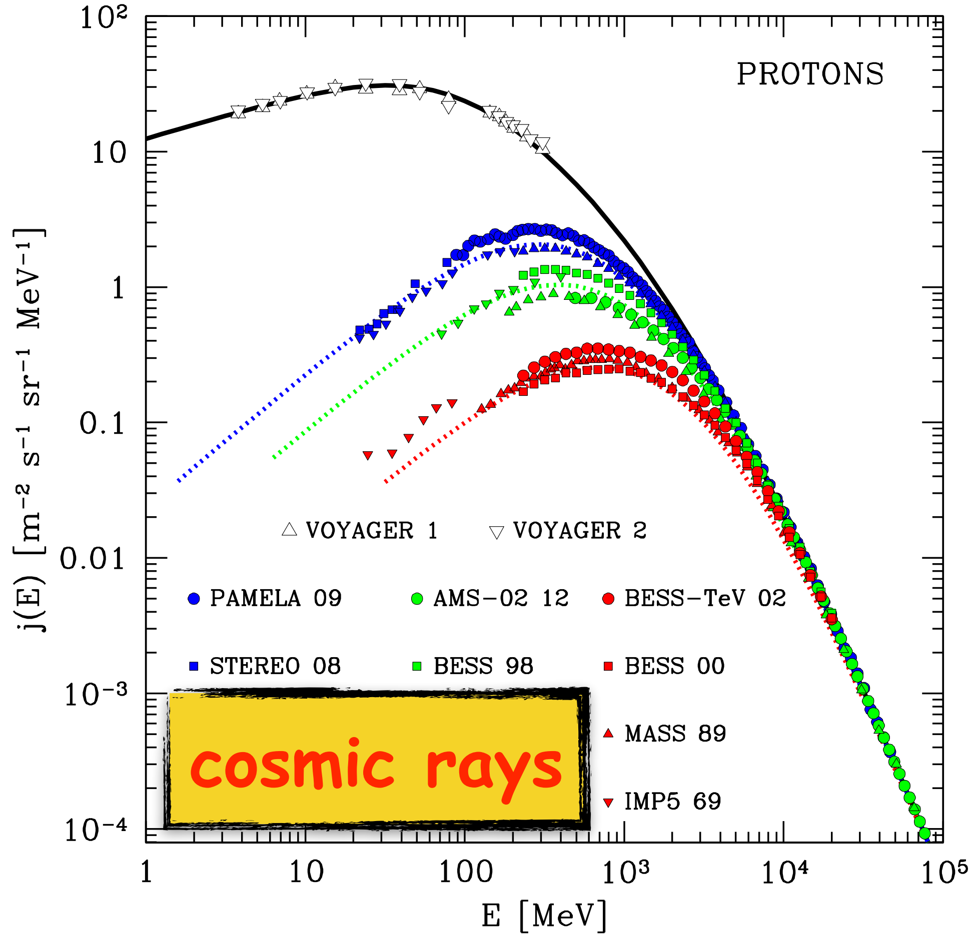
**observer**

**isotropy**

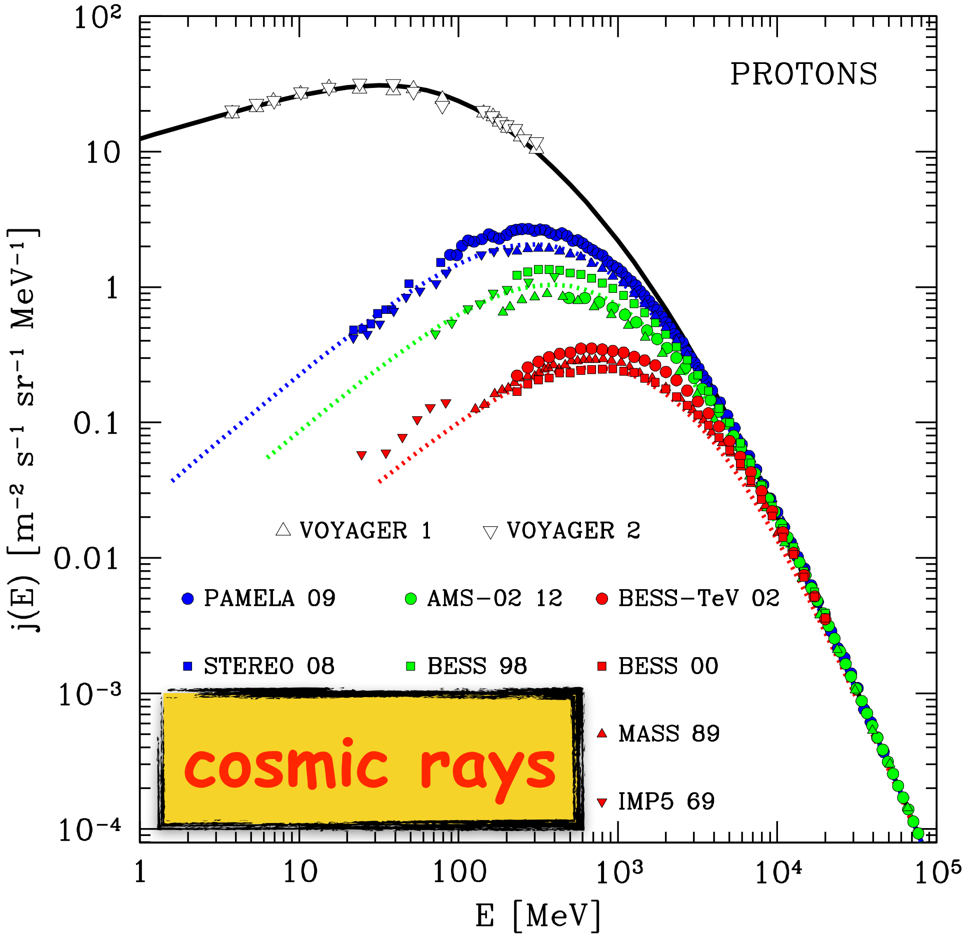


**Cosmological**

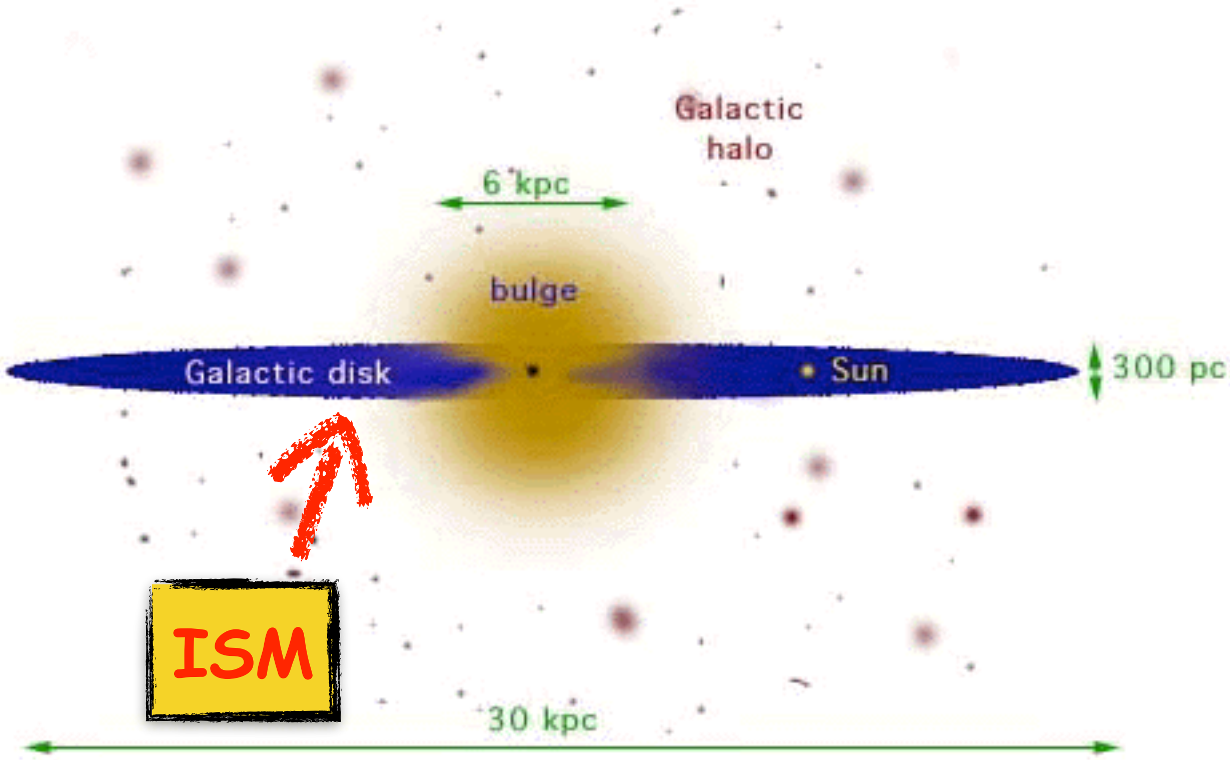
# Hayakawa's test (1952): diffuse emission



# Hayakawa's test (1952): diffuse emission

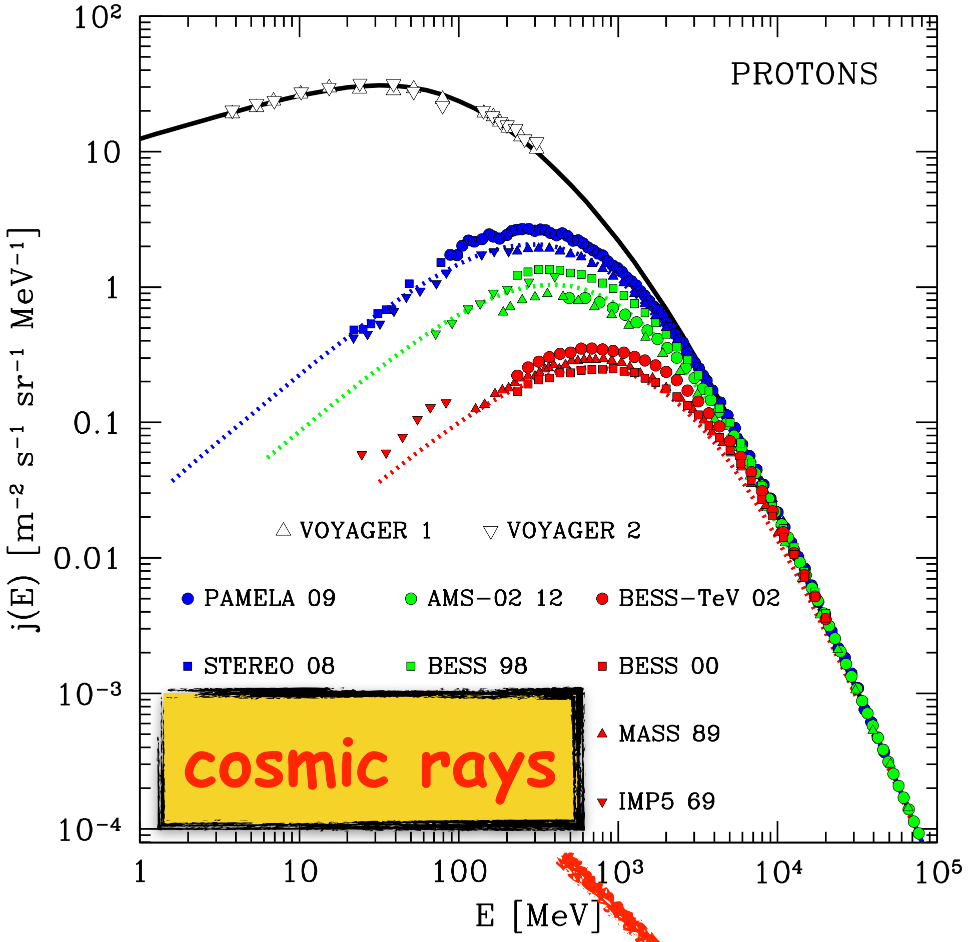


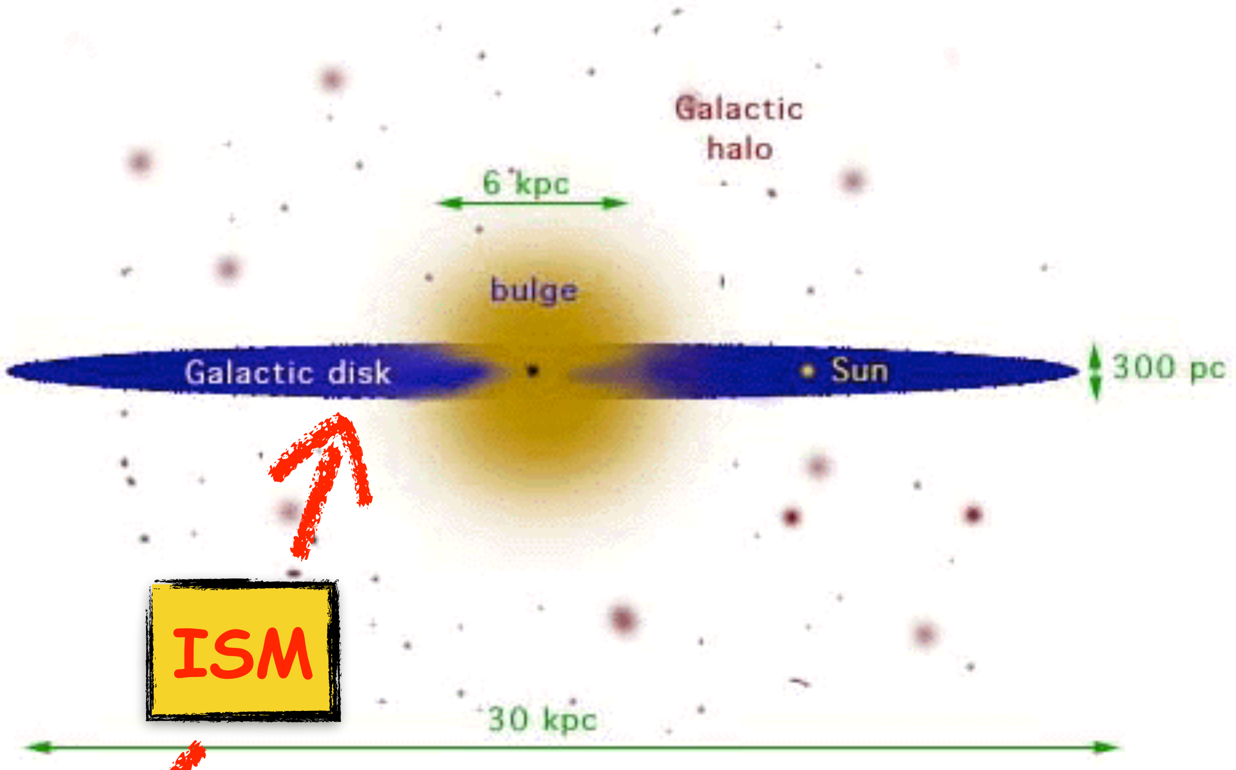
cosmic rays



ISM

# Hayakawa's test (1952): diffuse emission

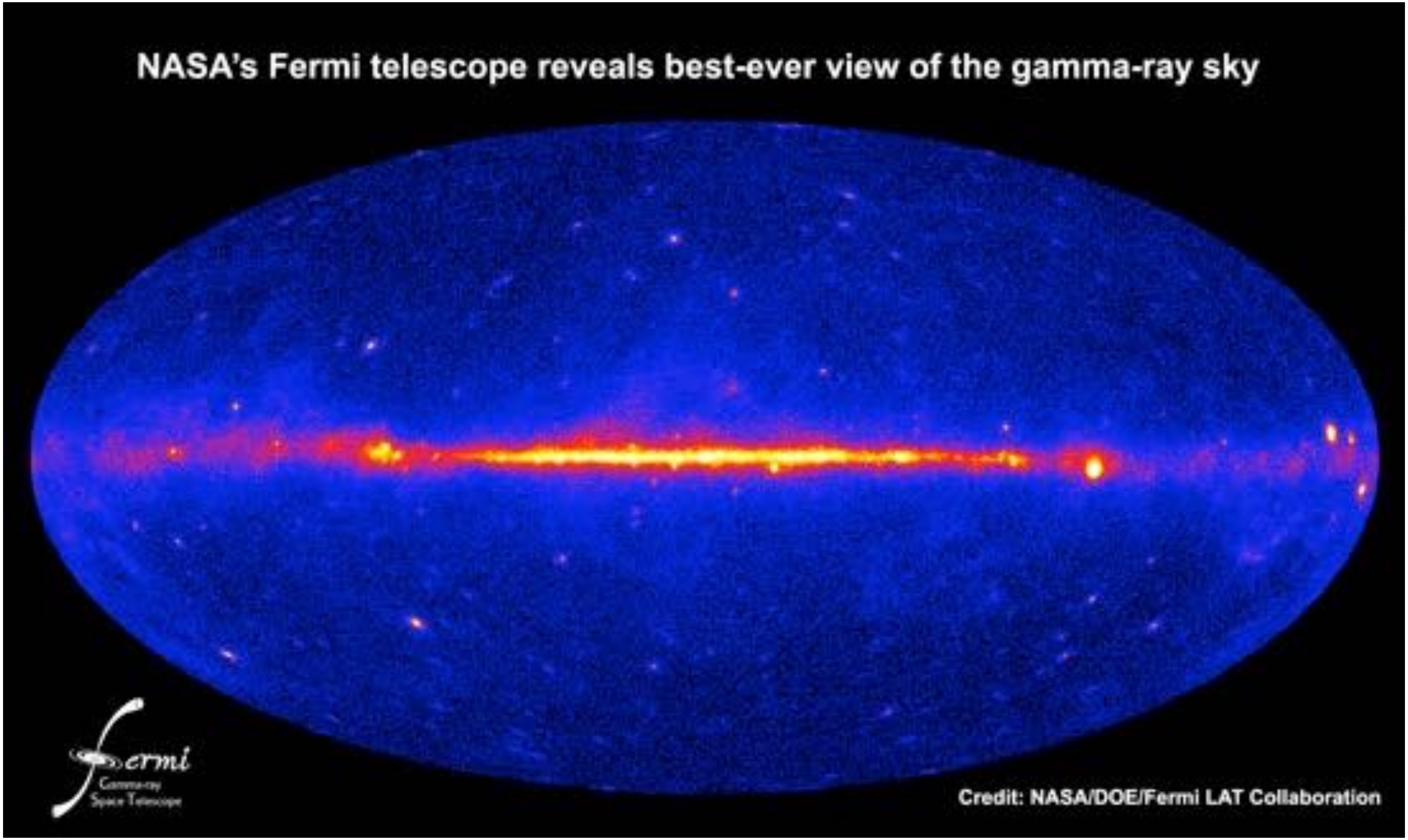




$$p + p \rightarrow p + p + \pi^0$$

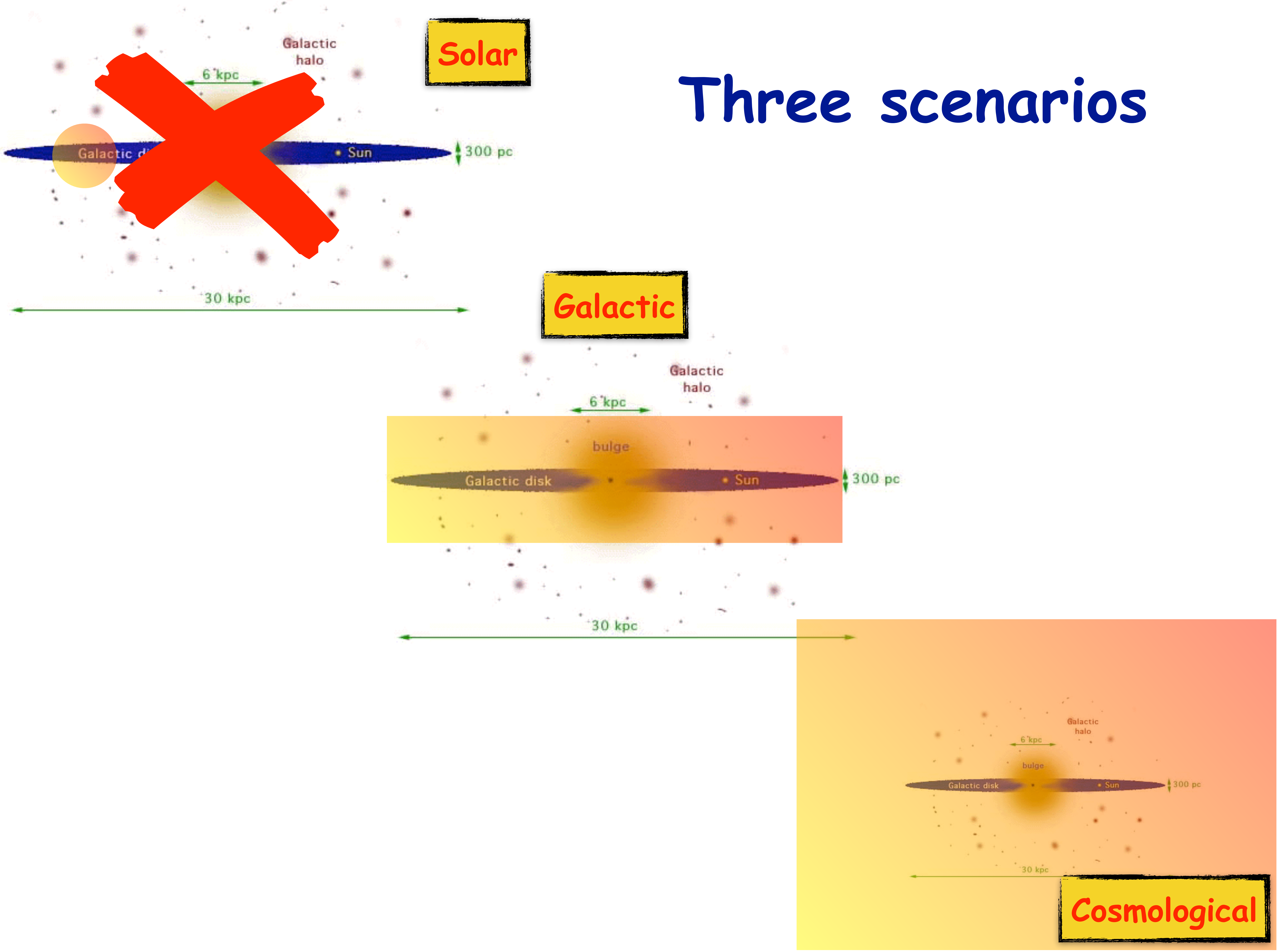
$$\pi^0 \rightarrow \gamma + \gamma$$

# 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

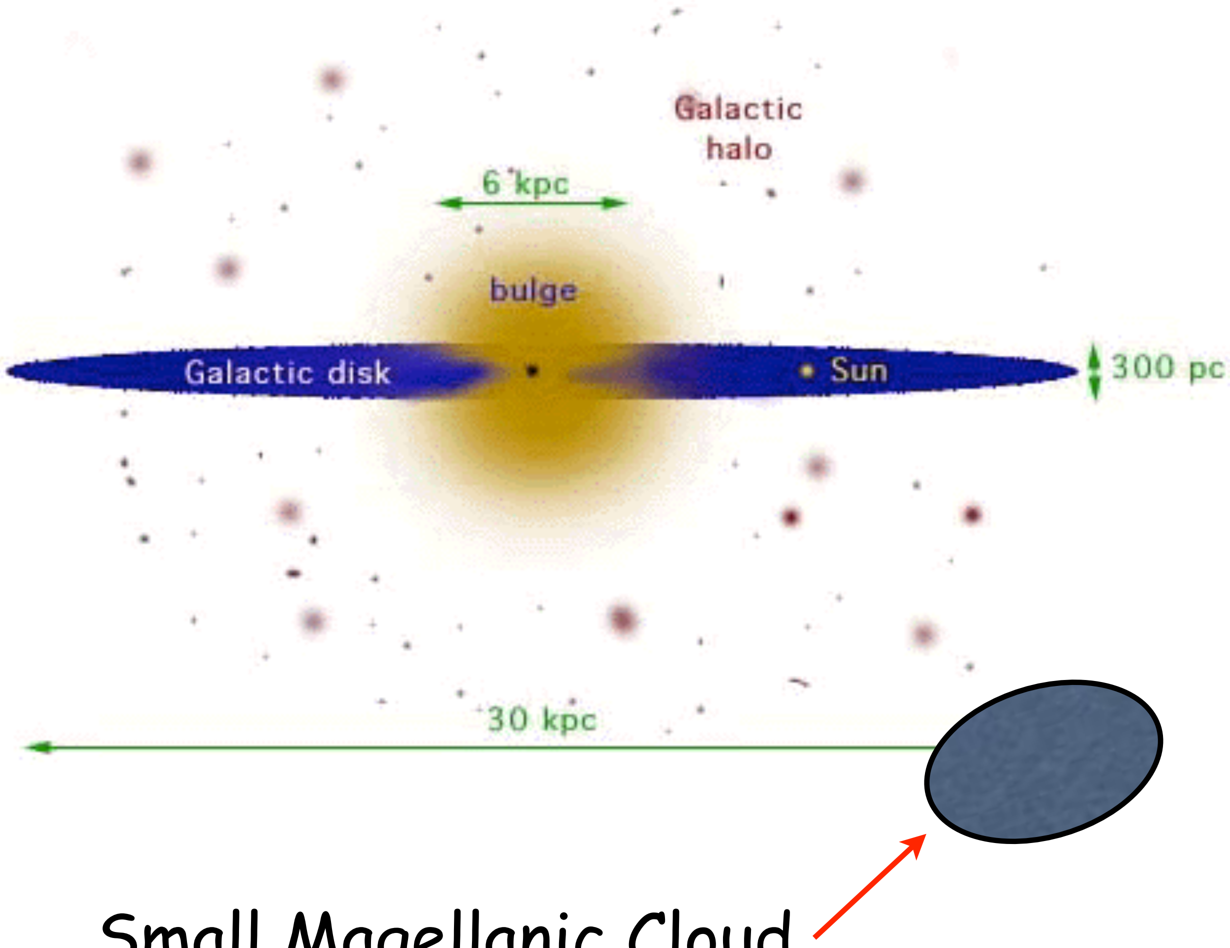


Solar

Galactic

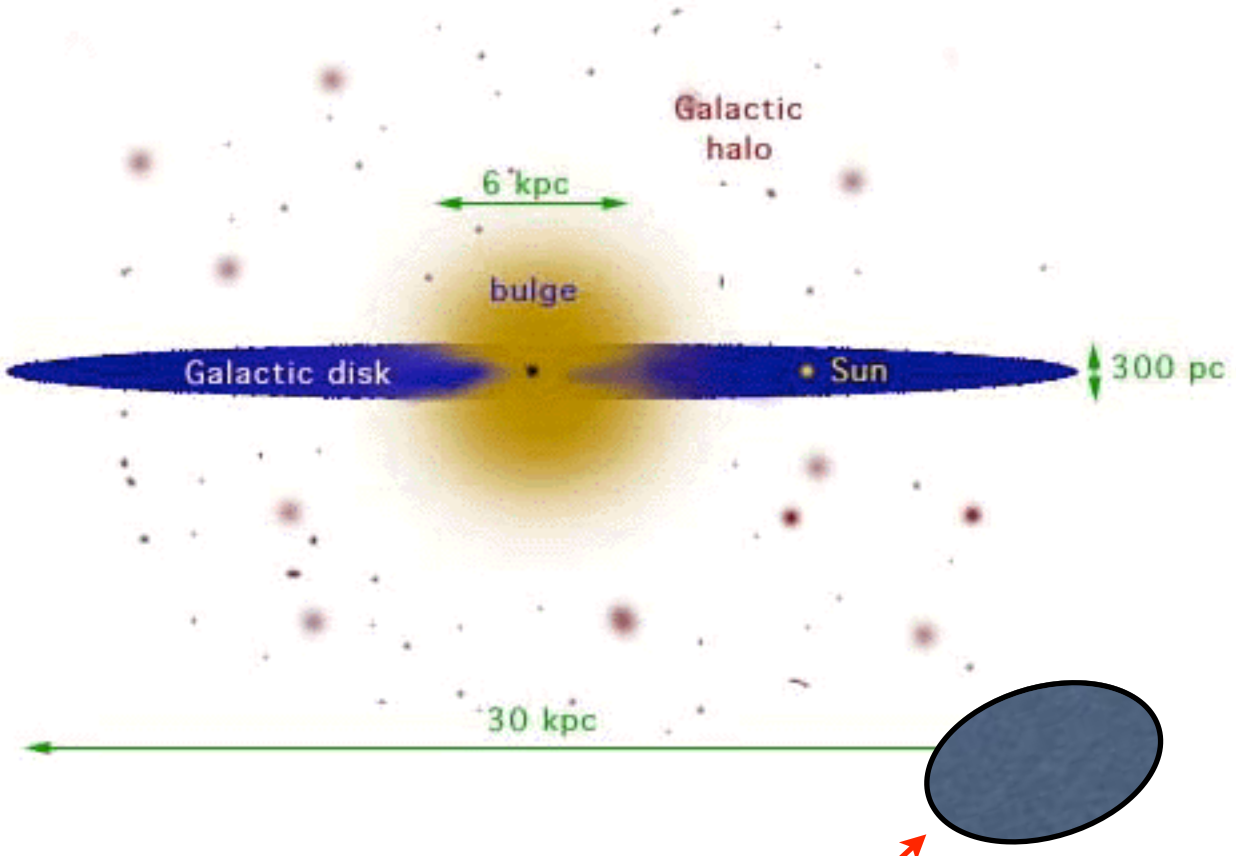
Cosmological

# 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

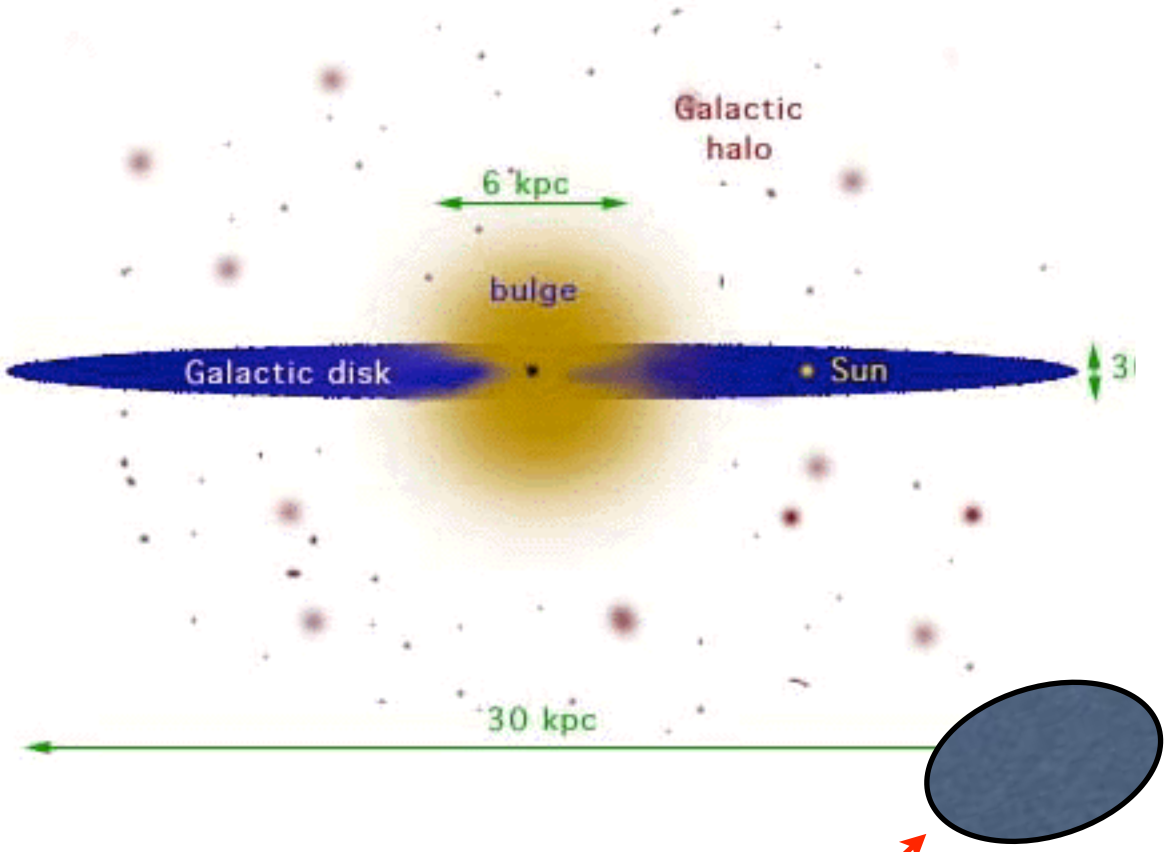
—> we can predict the gamma-ray flux from the SMC

—> it should have been detected by EGRET

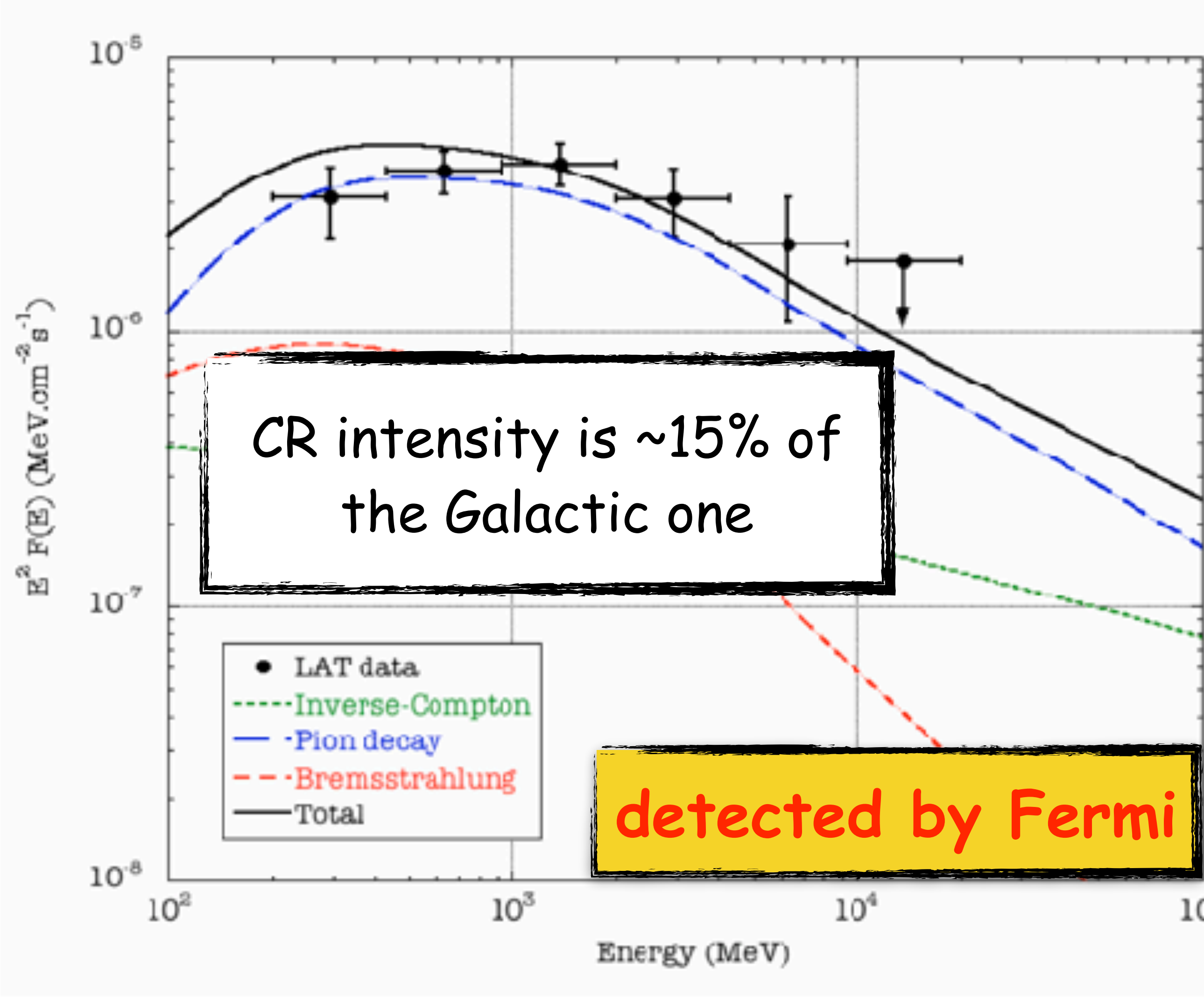
—> but it was not! (Sreekumar+ 1993)

—> CRs are **NOT cosmological**

# Diffuse emission in other galaxies



Small Magellanic Cloud



CR intensity is ~15% of the Galactic one

**detected by Fermi**

Abdo+ 2010

**Cosmological —>**

same CR intensity here (measured) & in the SMC

—> mass of ISM in the SMC is known

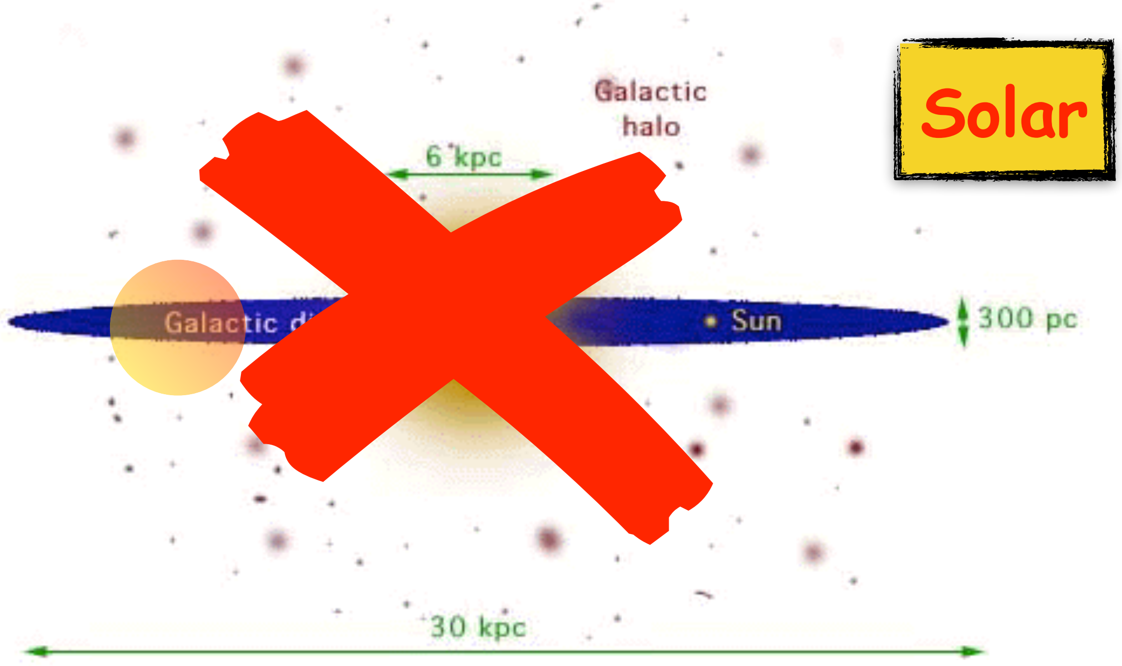
—> we can predict the gamma-ray flux from the SMC

—> it should have been detected by EGRET

—> but it was not! (Sreekumar+ 1993)

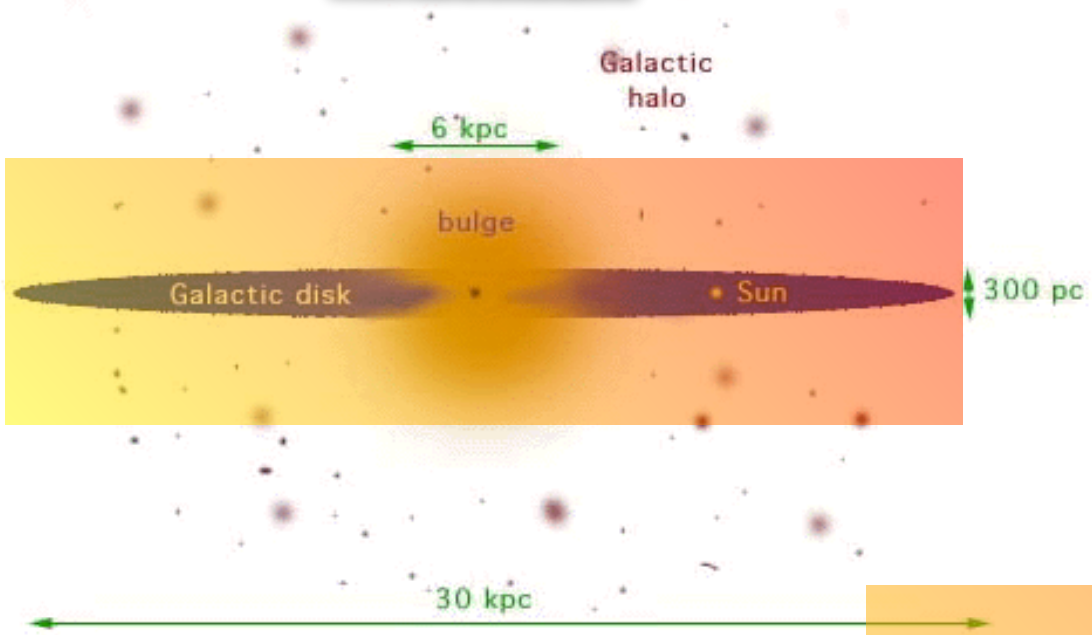
—> CRs are **NOT cosmological**

# CRs are Galactic



**Solar**

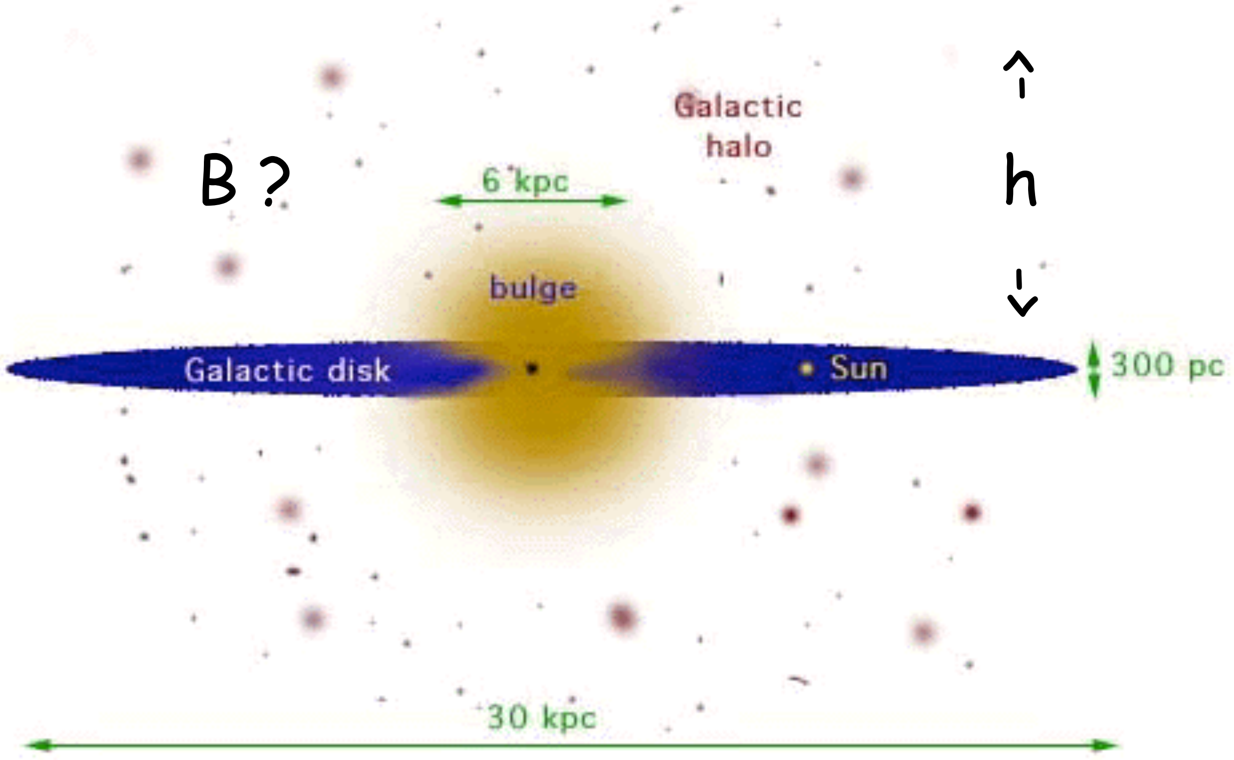
**Galactic**



**Cosmological**

# 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…)

# In fact, MOST CRs are Galactic...

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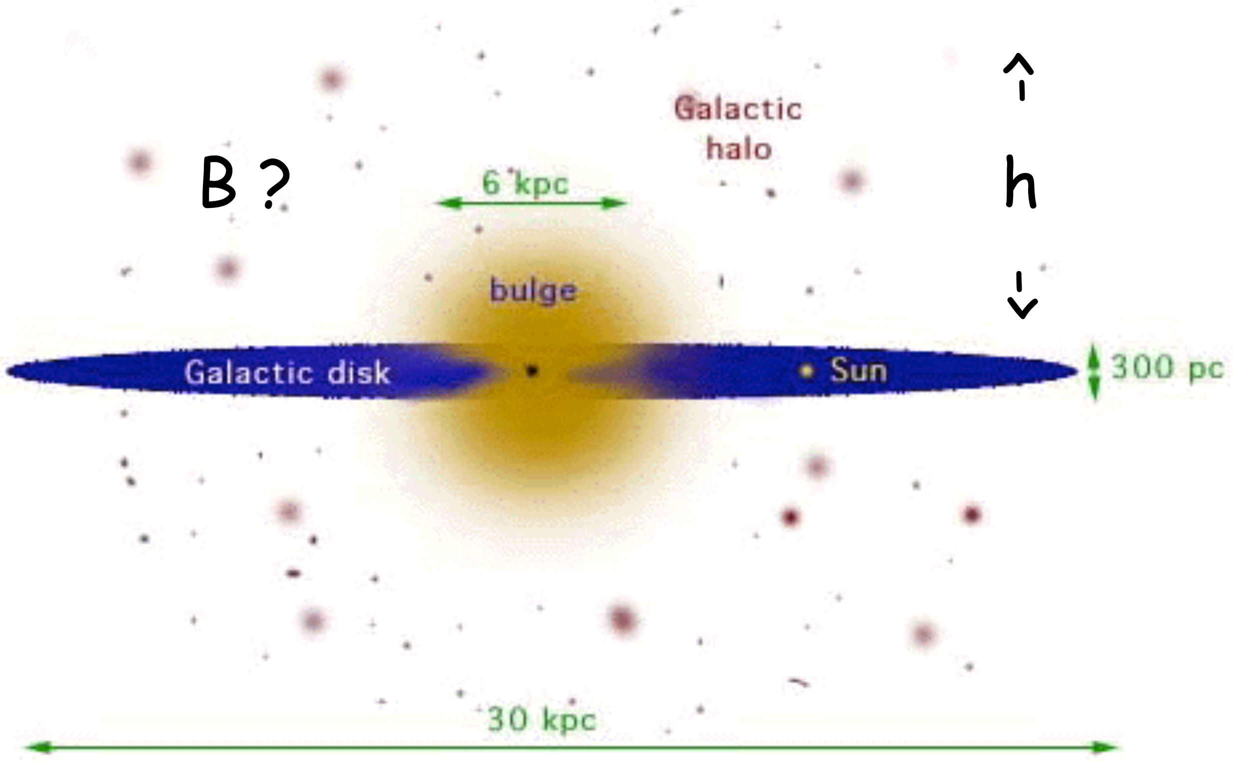

It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

## Confinement condition:

$$R_L < h$$

Larmor radius

halo size

# In fact, MOST CRs are Galactic...

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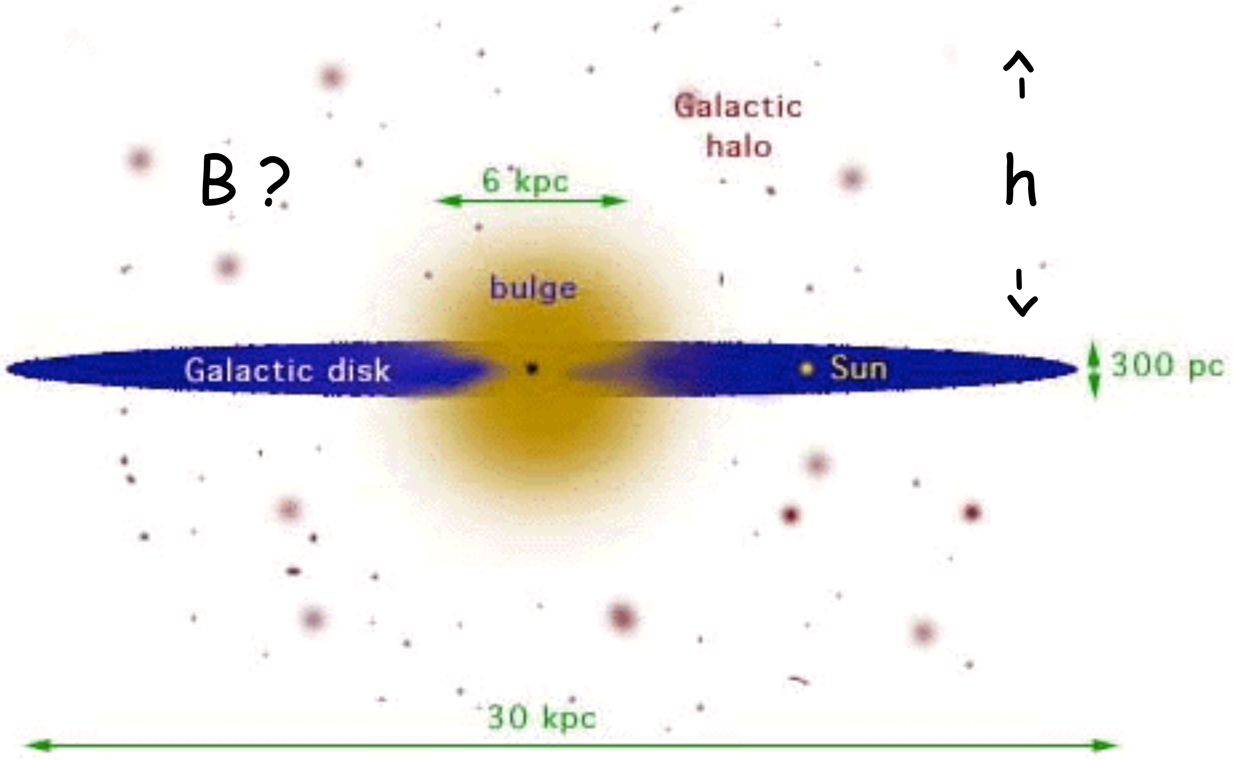


It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

## Confinement condition:

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

(cm)

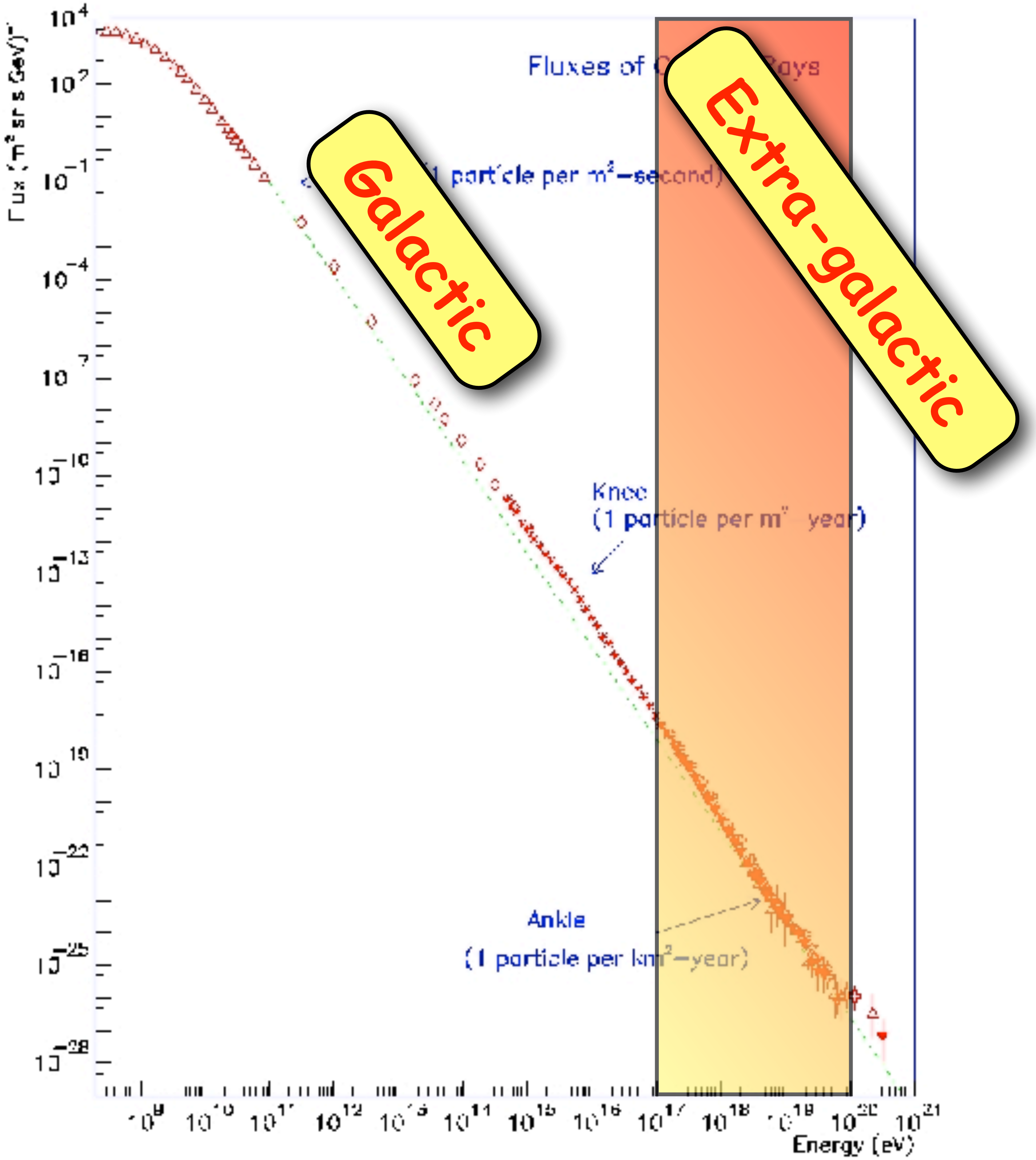
Larmor radius

halo size

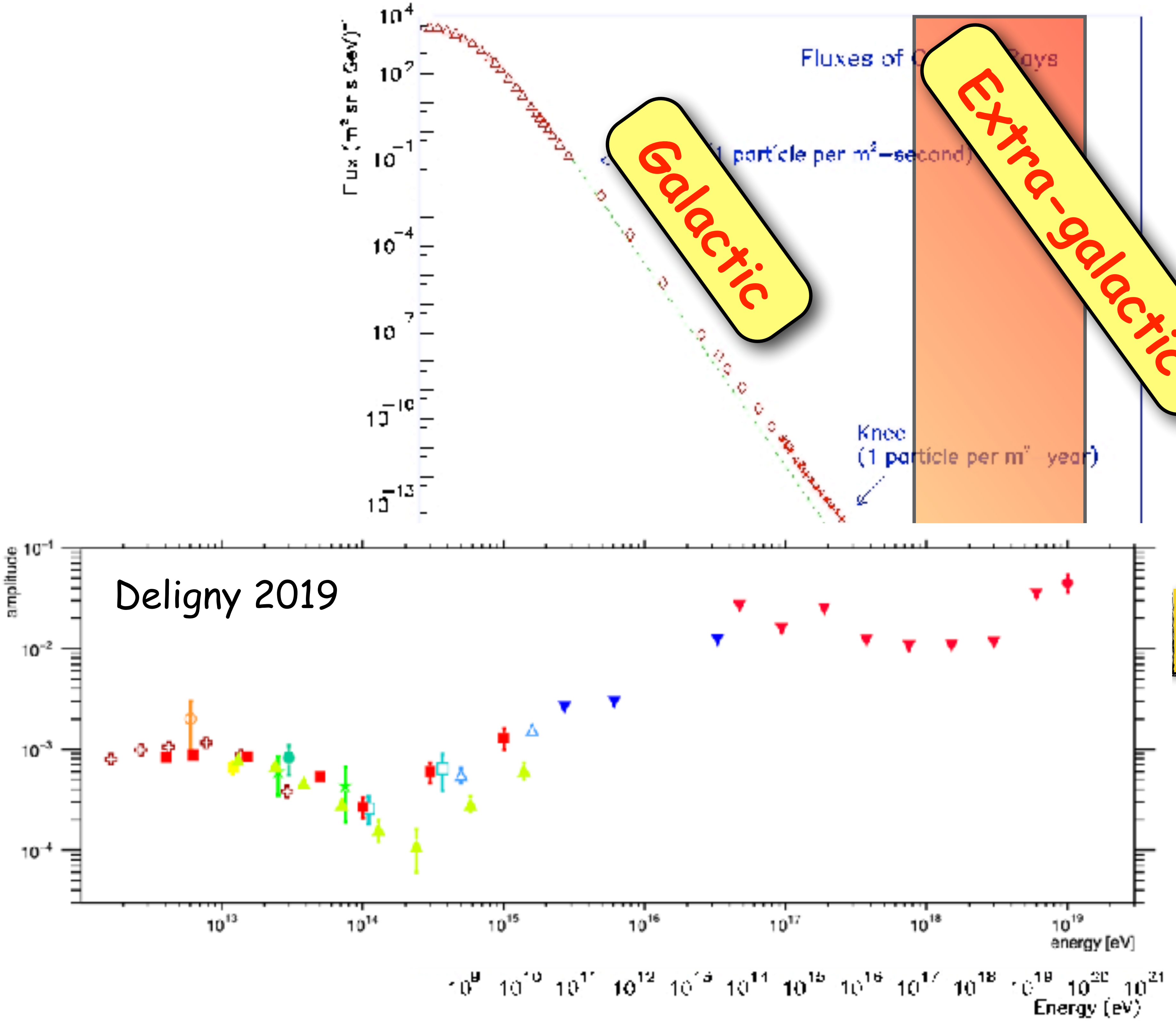
1 - 10

0.1 - 10

# Galactic or extra-galactic?



# Galactic or extra-galactic?



Galactic

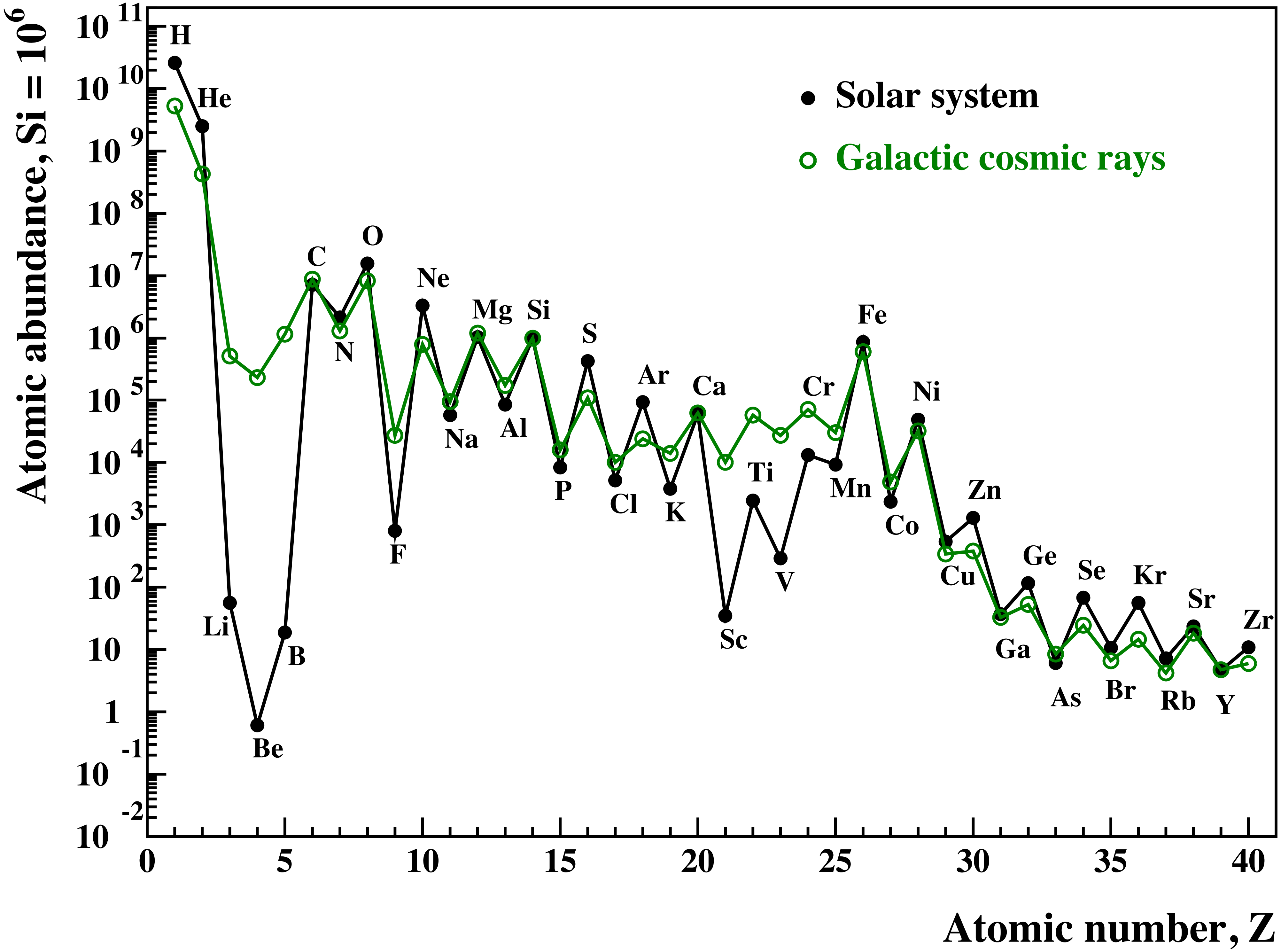
Extra-galactic

Deligny 2019

—> larger anisotropy?

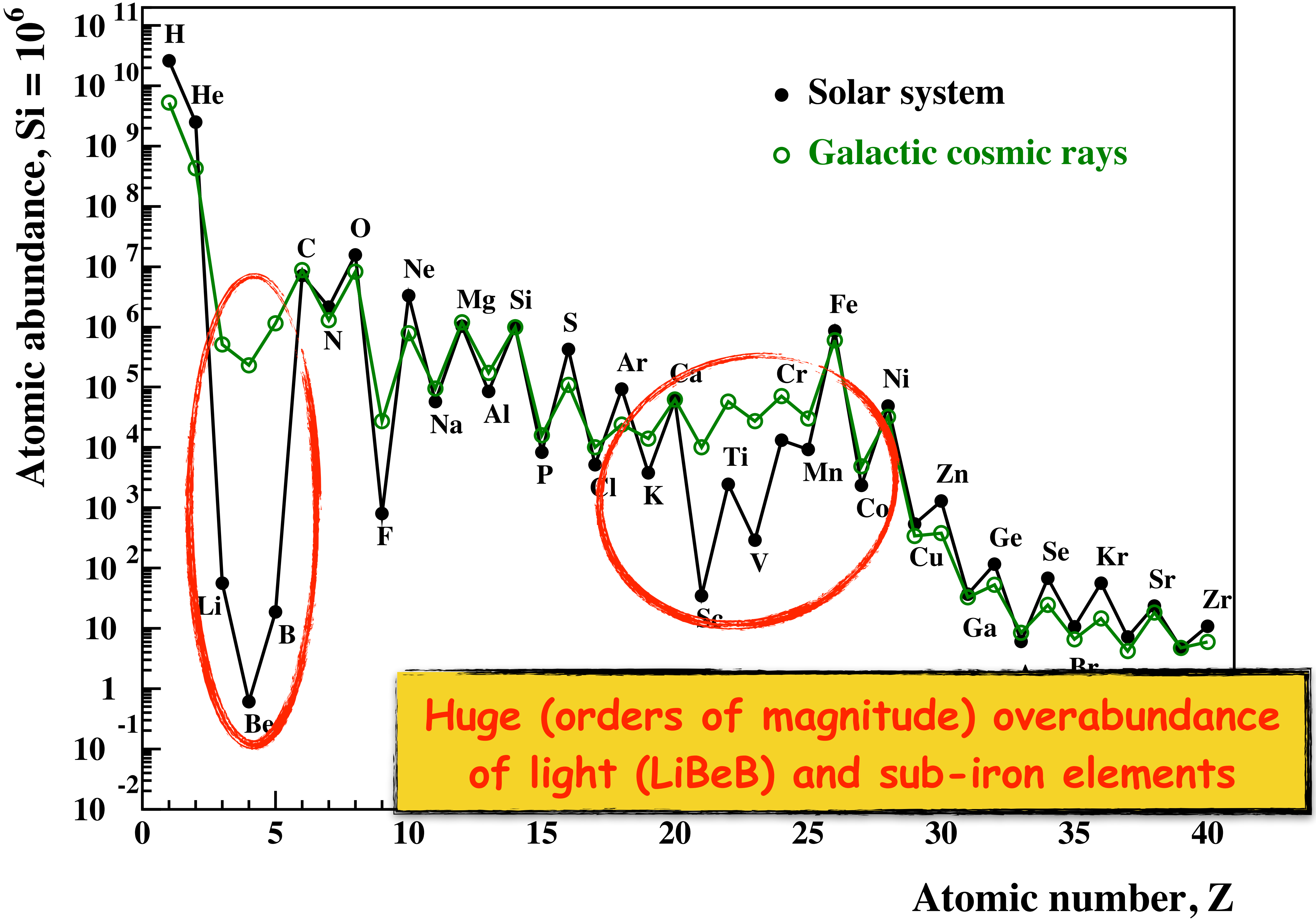
# [4] Composition

# Composition: striking anomalies



Tatischeff & SG, 2018

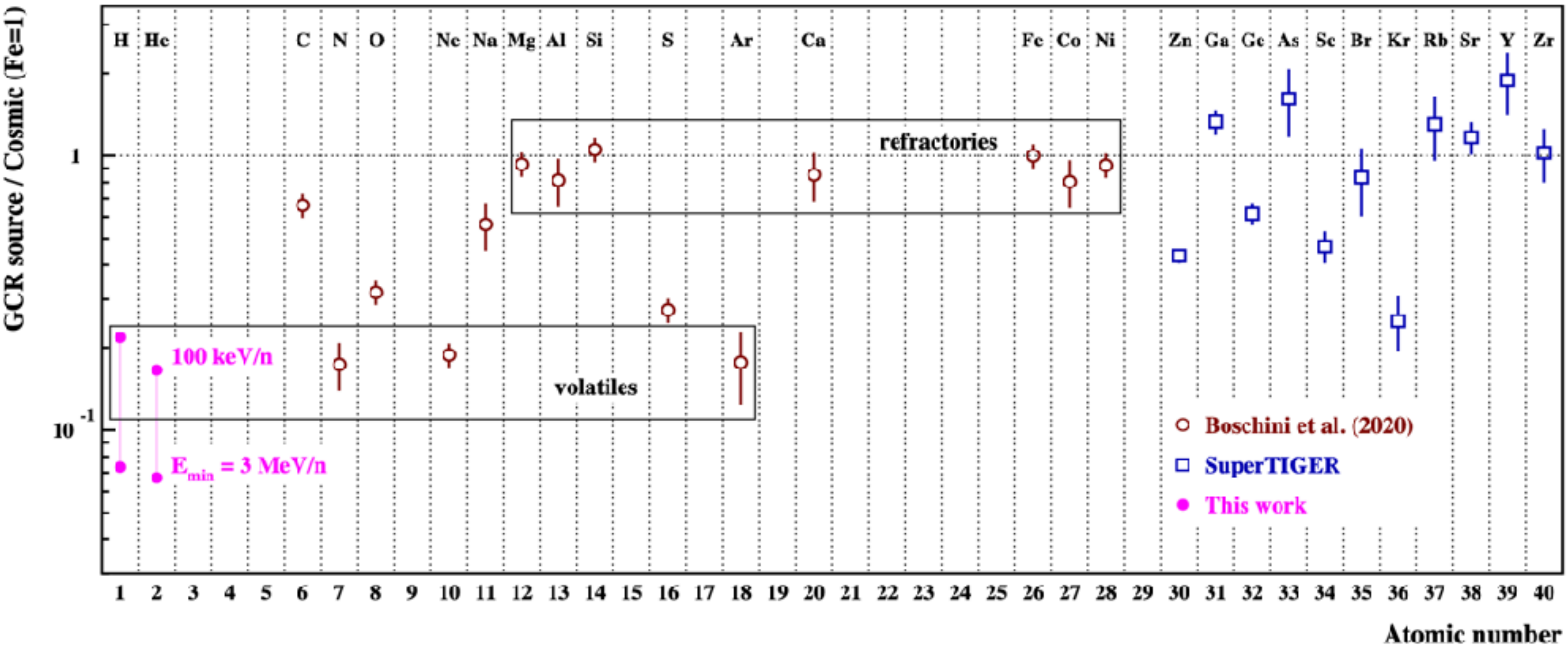
# Composition: striking anomalies



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

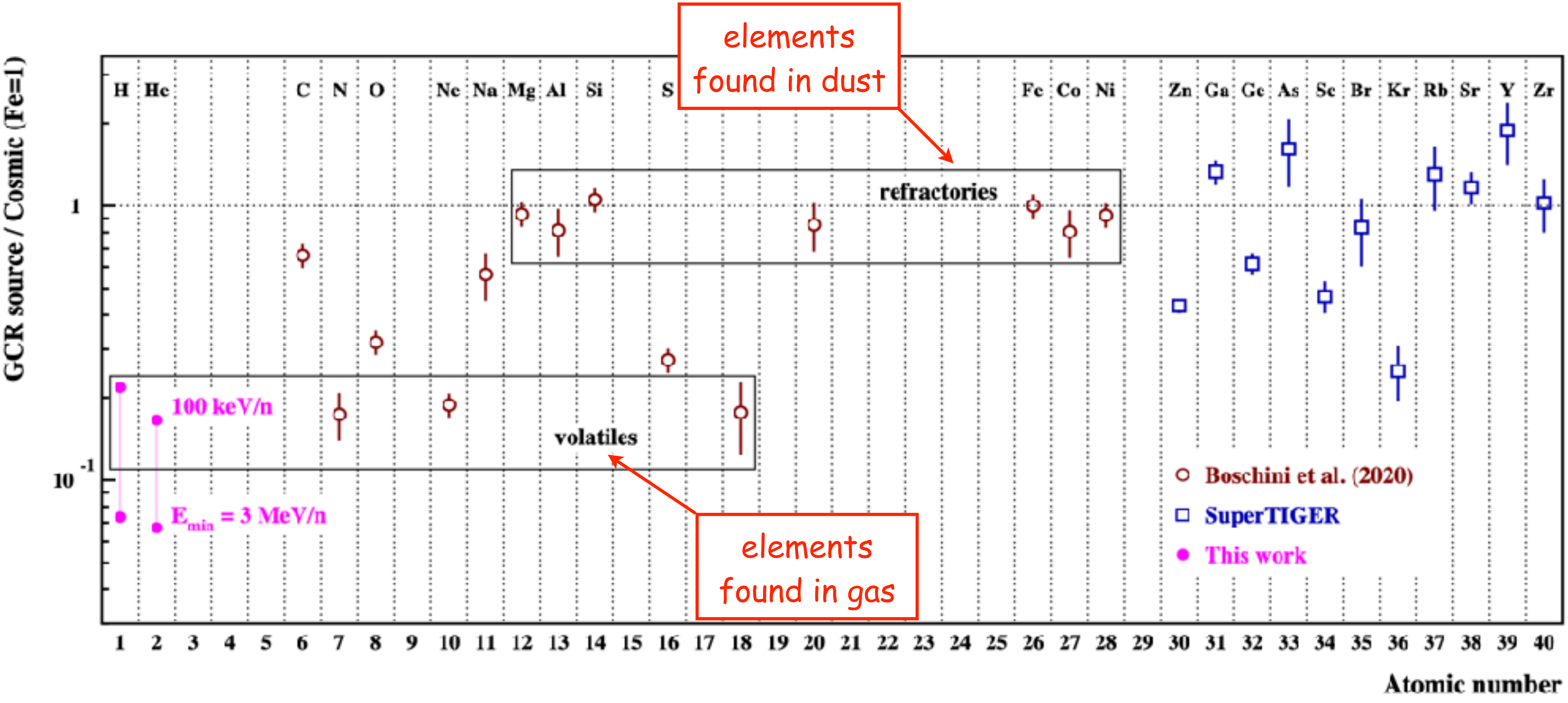
Tatischeff & SG, 2018

# Composition: volatiles and refractories



Tatischeff, Raymond, Duprat, SG, Recchia, 2021

# Composition: volatiles and refractories

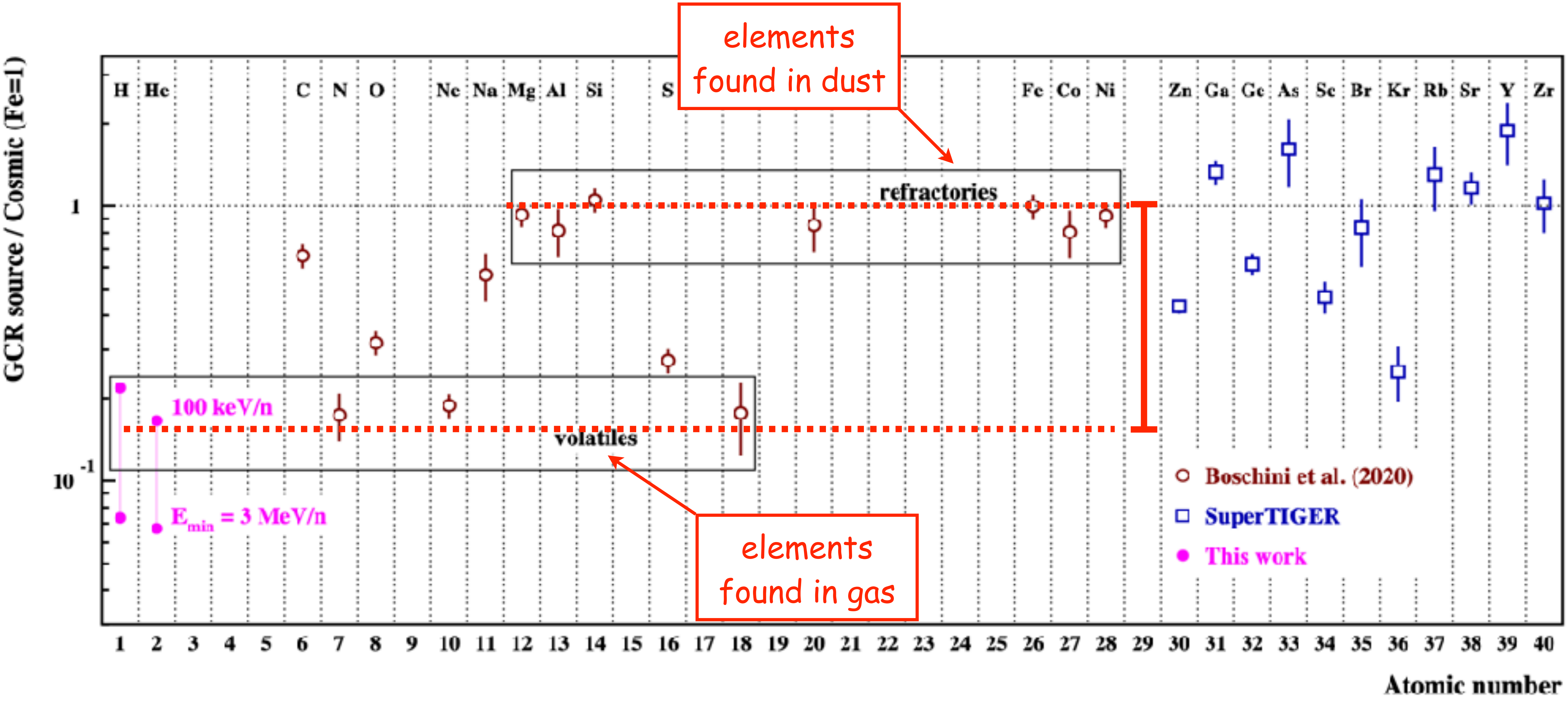


elements found in dust

elements found in gas

Tatischeff, Raymond, Duprat, SG, Recchia, 2021

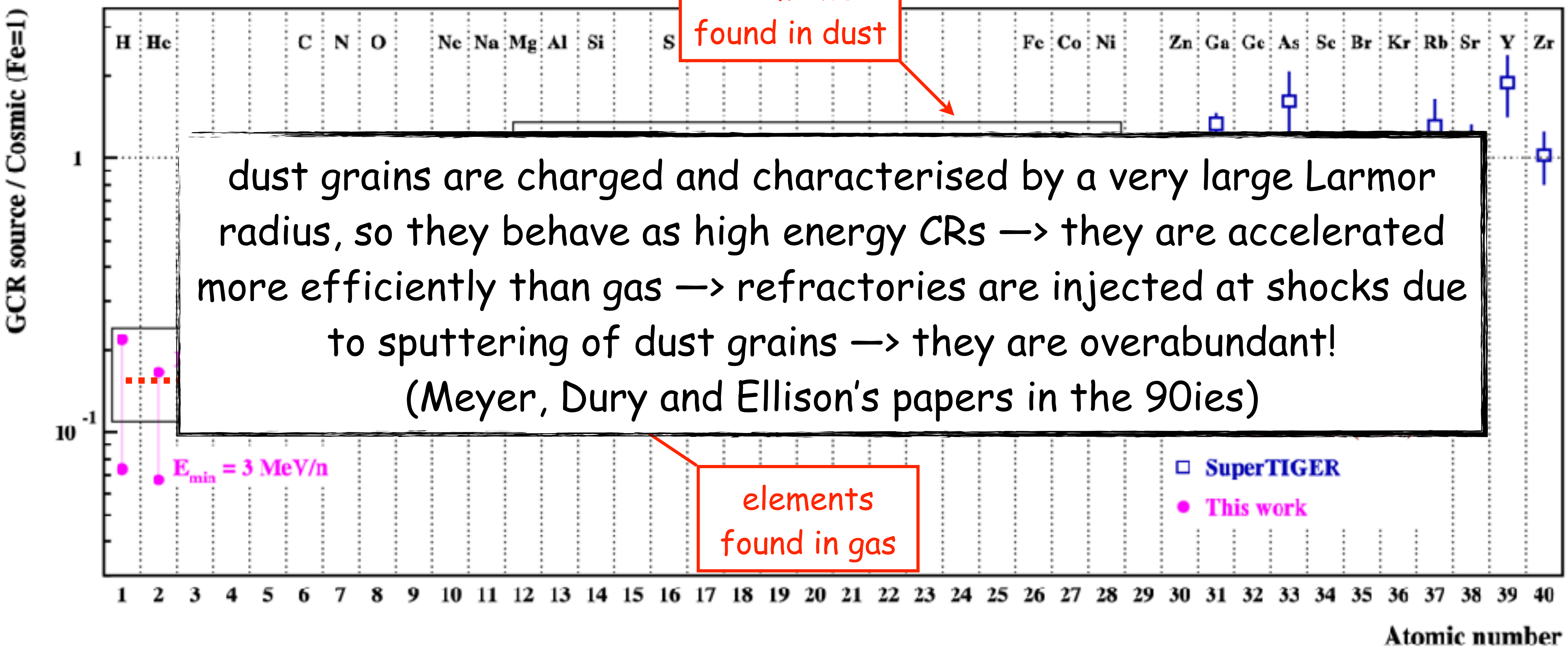
# Composition: volatiles and refractories



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



elements found in dust

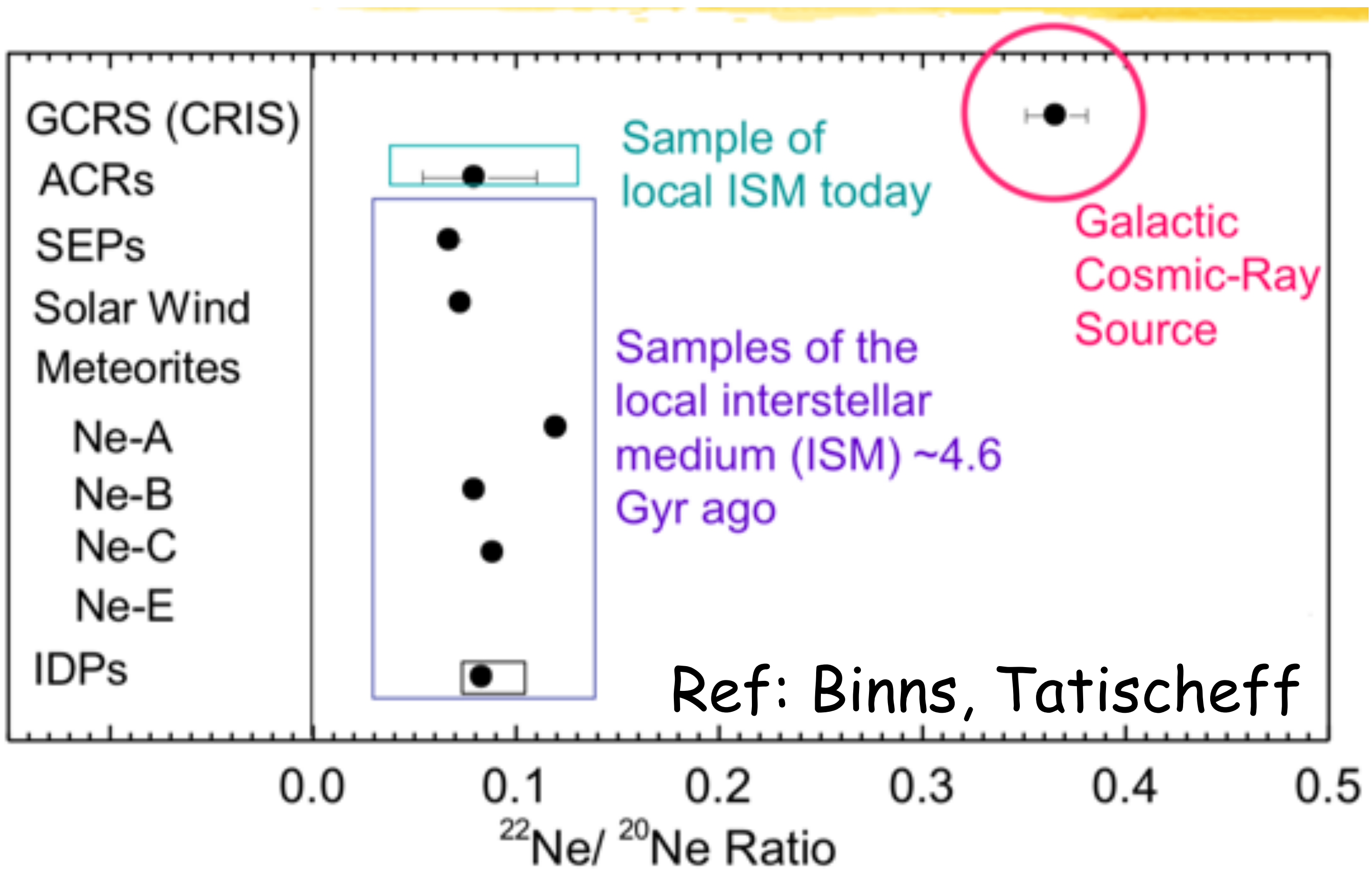
dust grains are charged and characterised by a very large Larmor radius, so they behave as high energy CRs —> they are accelerated more efficiently than gas —> refractories are injected at shocks due to sputtering of dust grains —> they are overabundant!
(Meyer, Dury and Ellison's papers in the 90ies)

elements found in gas

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

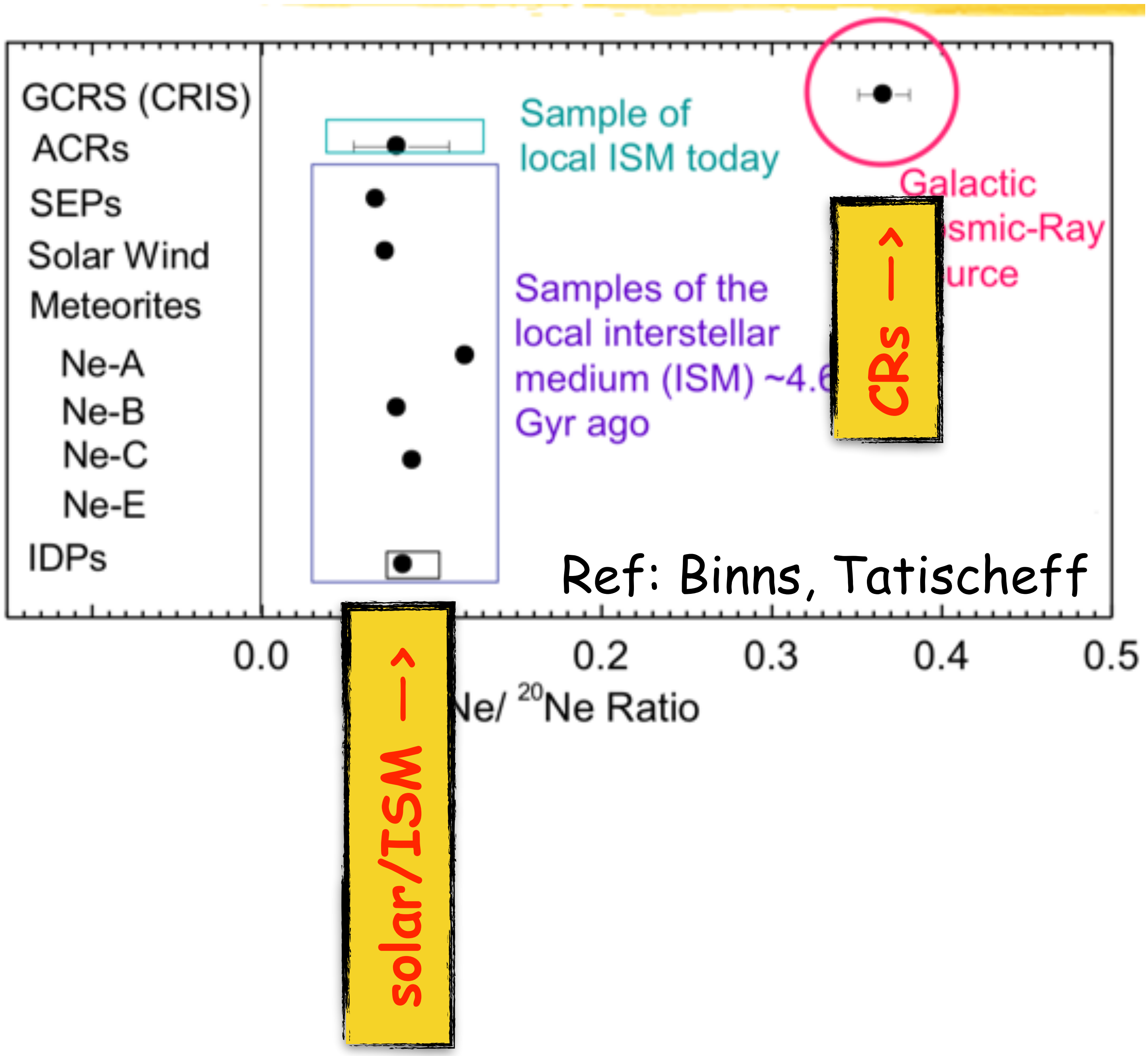
Tatischeff, Raymond, Duprat, SG, Recchia, 2021

# Composition: isotopic anomalies



Ref: Binns, Tatischeff

# Composition: isotopic anomalies



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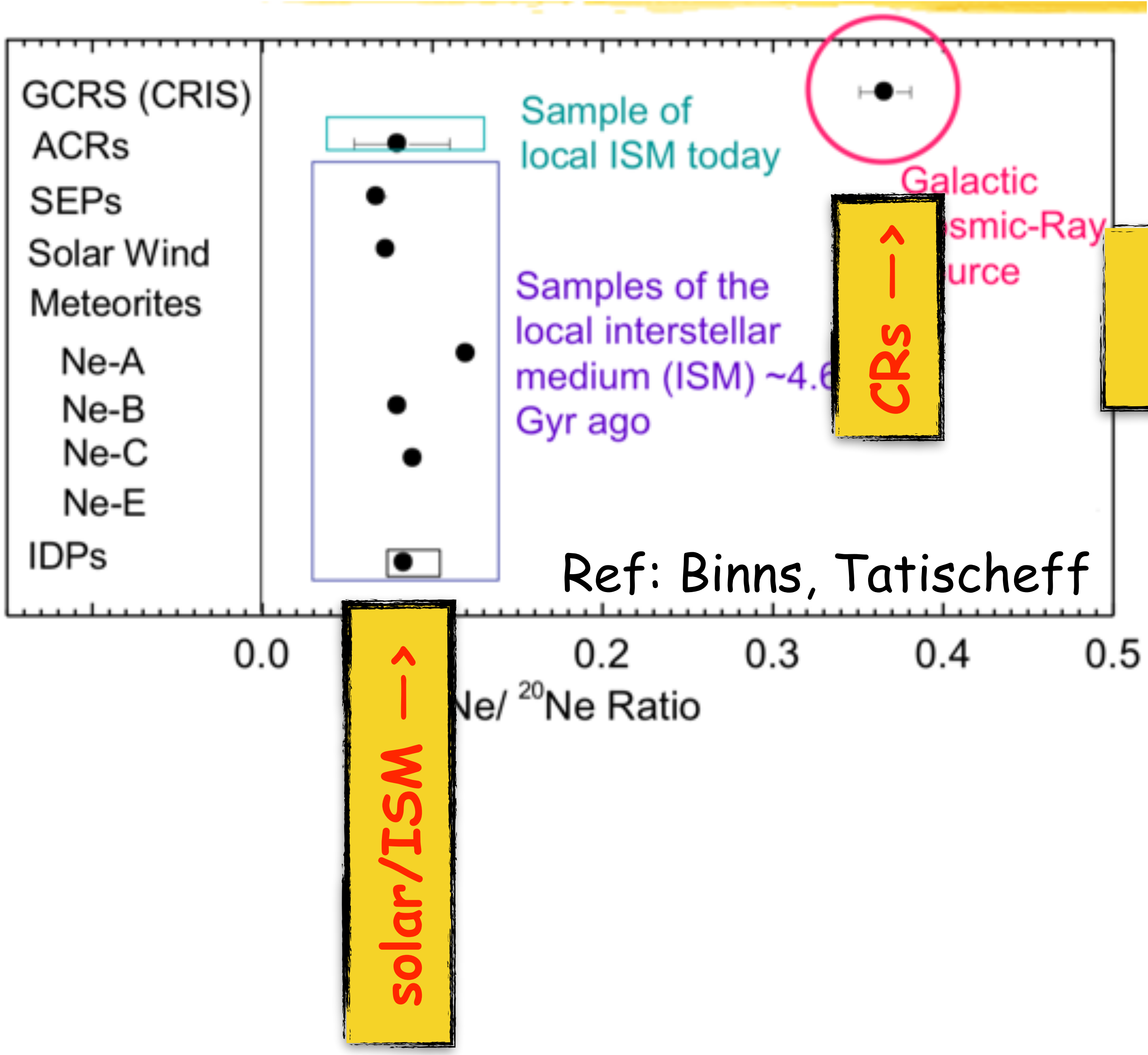
# Composition: isotopic anomalies



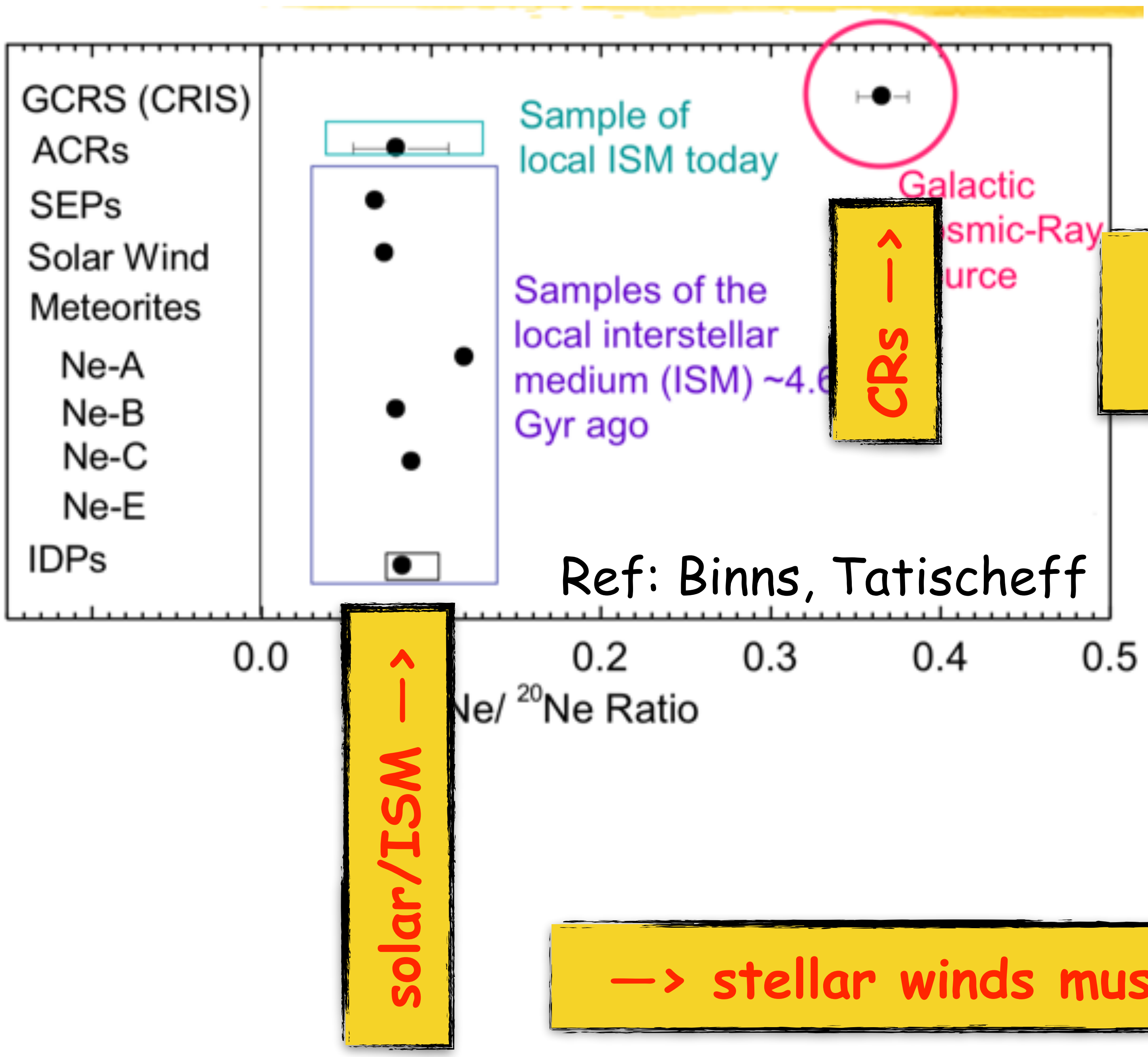
CRs --->

solar/ISM --->

Ref: Binns, Tatischeff

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

# Composition: isotopic anomalies



Ref: Binns, Tatischeff

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

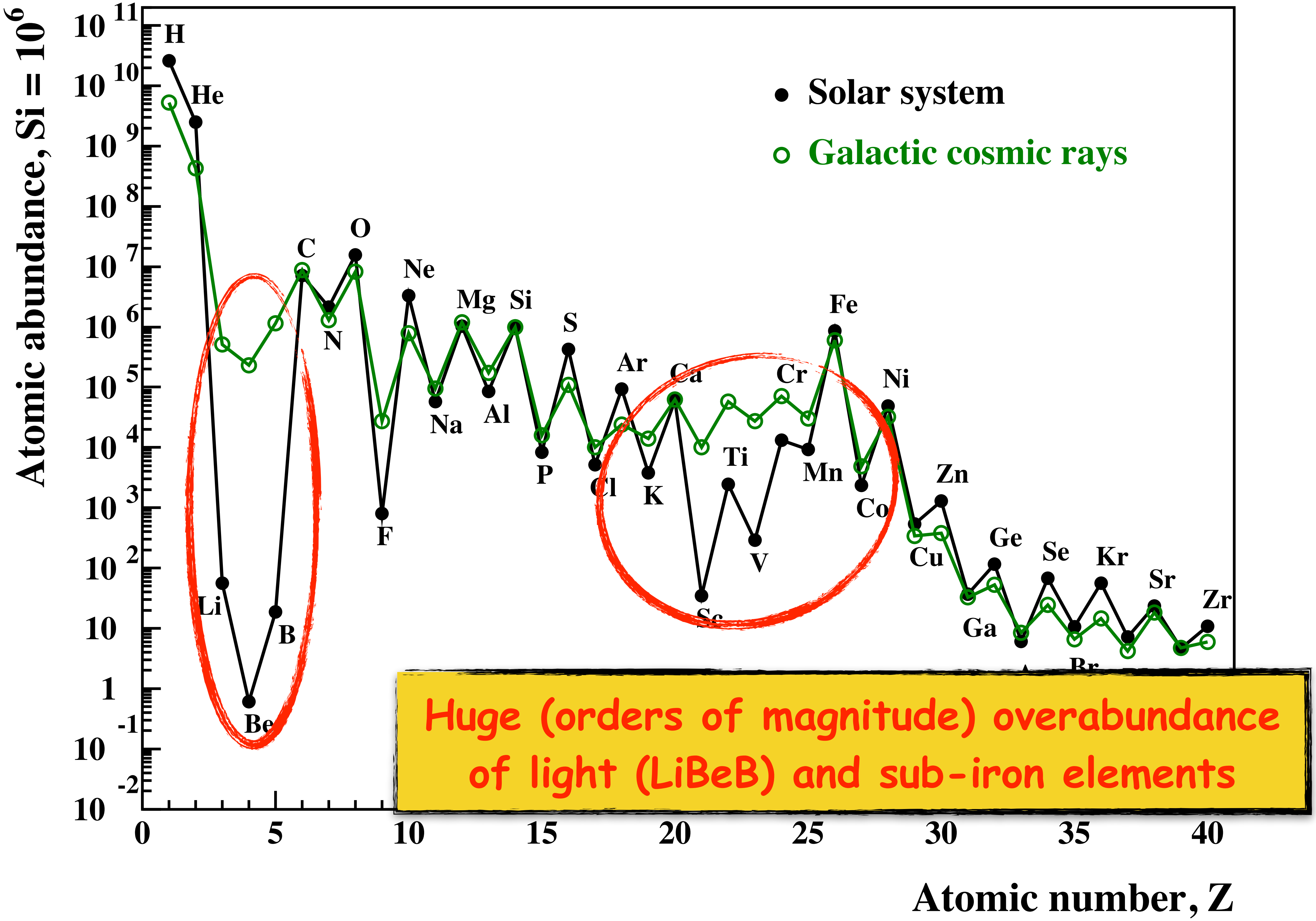
—> stellar winds must play a role in CR acceleration!

# 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?

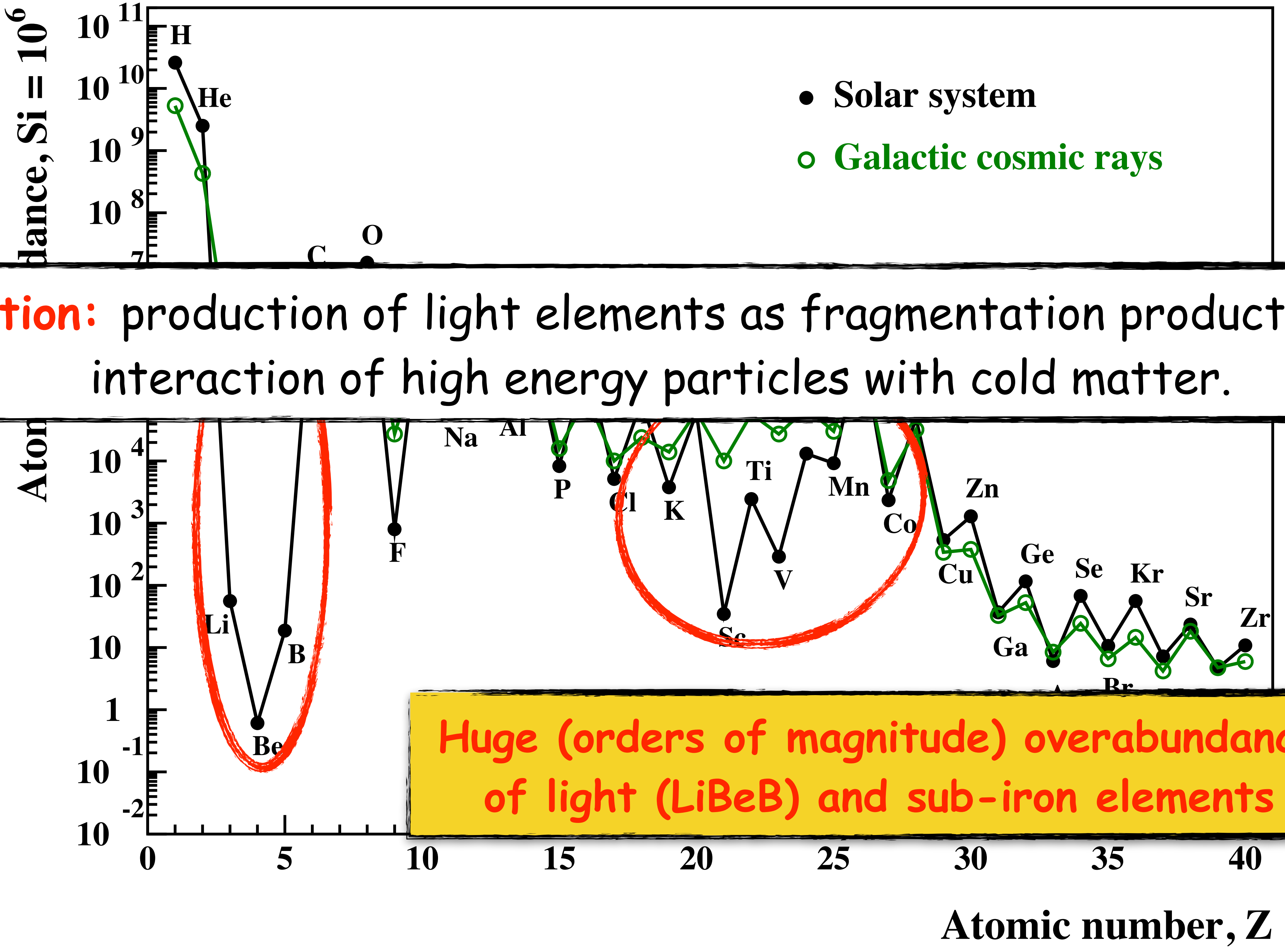
# Composition: striking anomalies



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

Tatischeff & SG, 2018

# Composition: striking anomalies

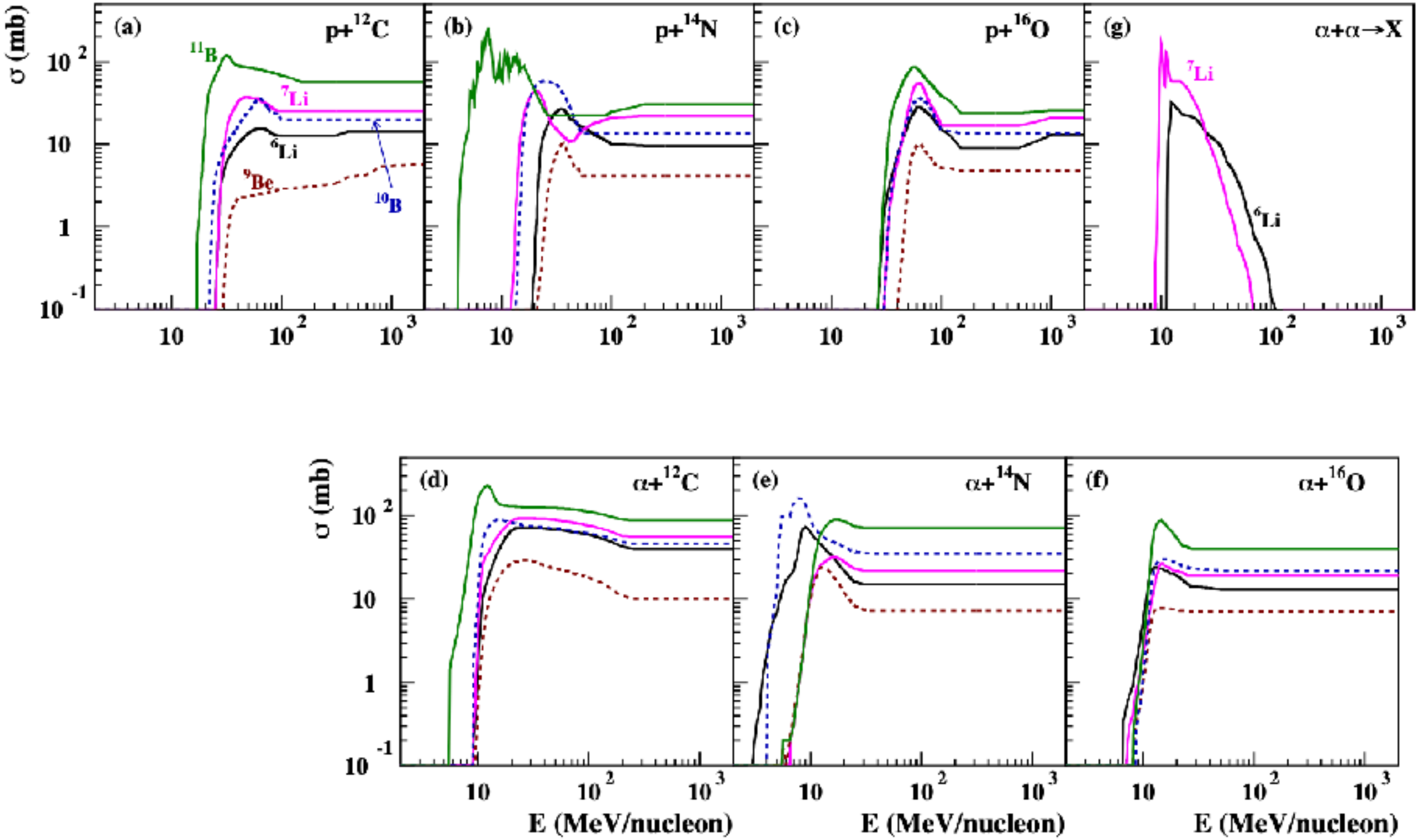


**Spallation:** production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

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

Tatischeff & SG, 2018

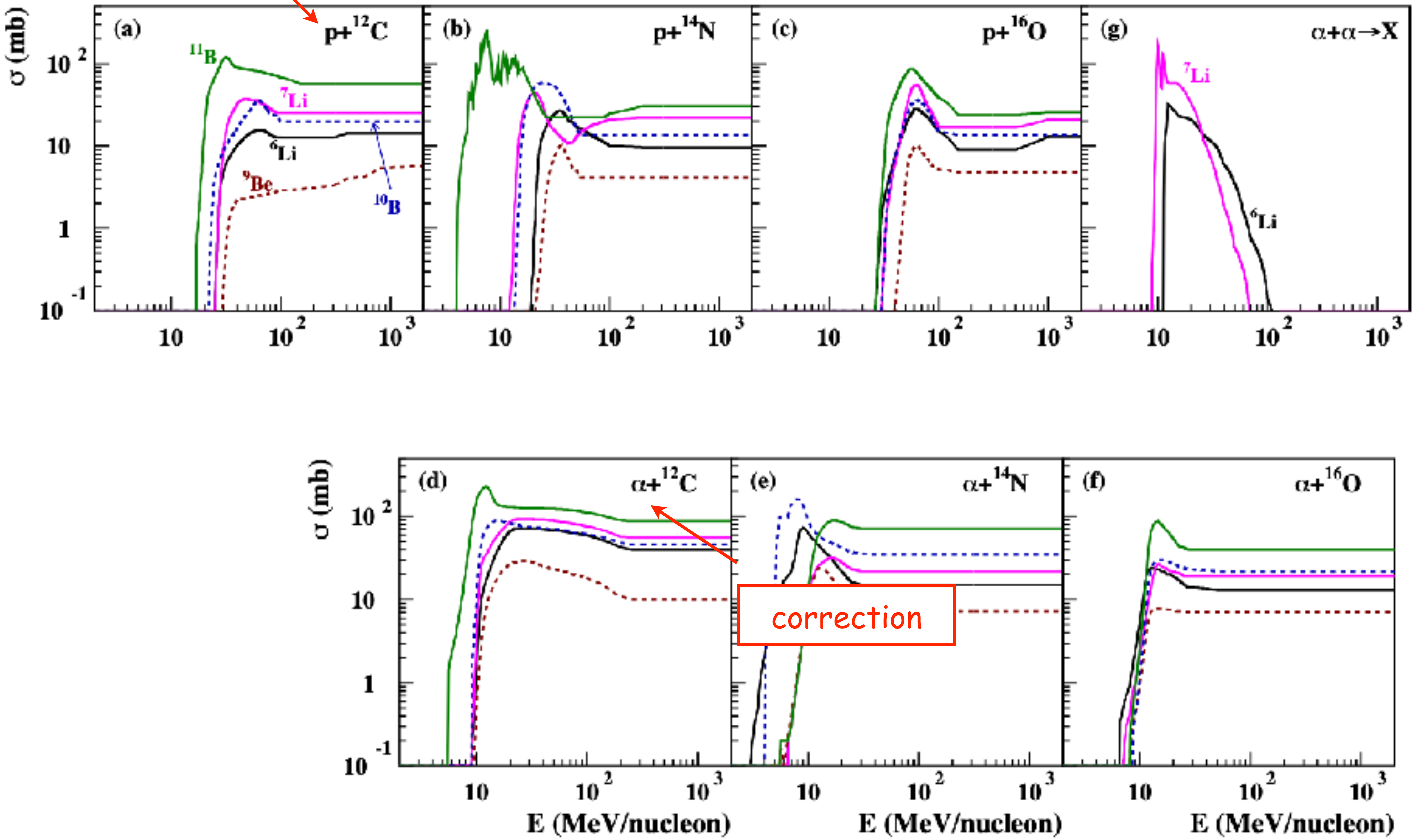
# Spallation cross sections



Tatischeff & SG, 2018

# Spallation cross sections

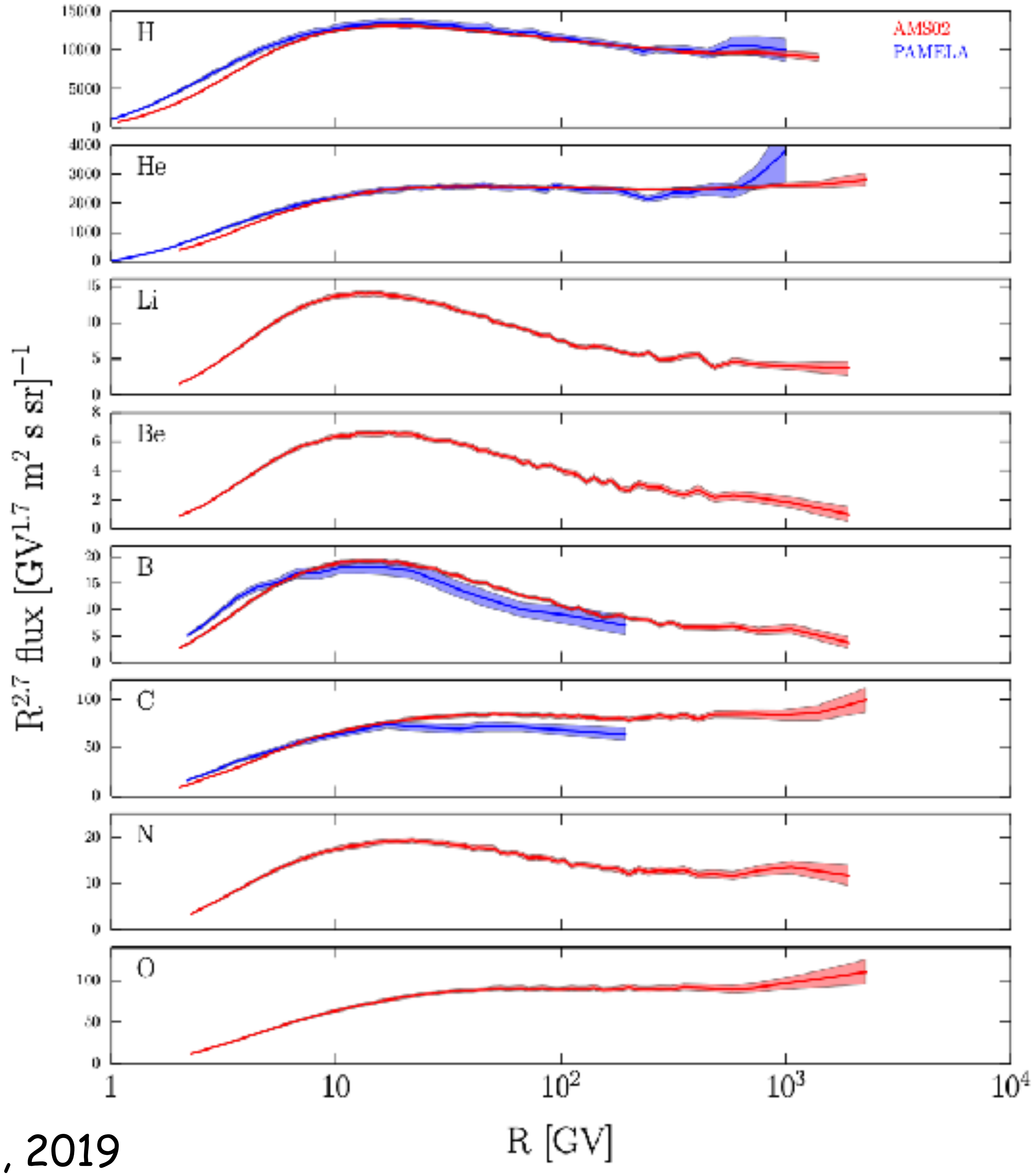
main contribution



correction

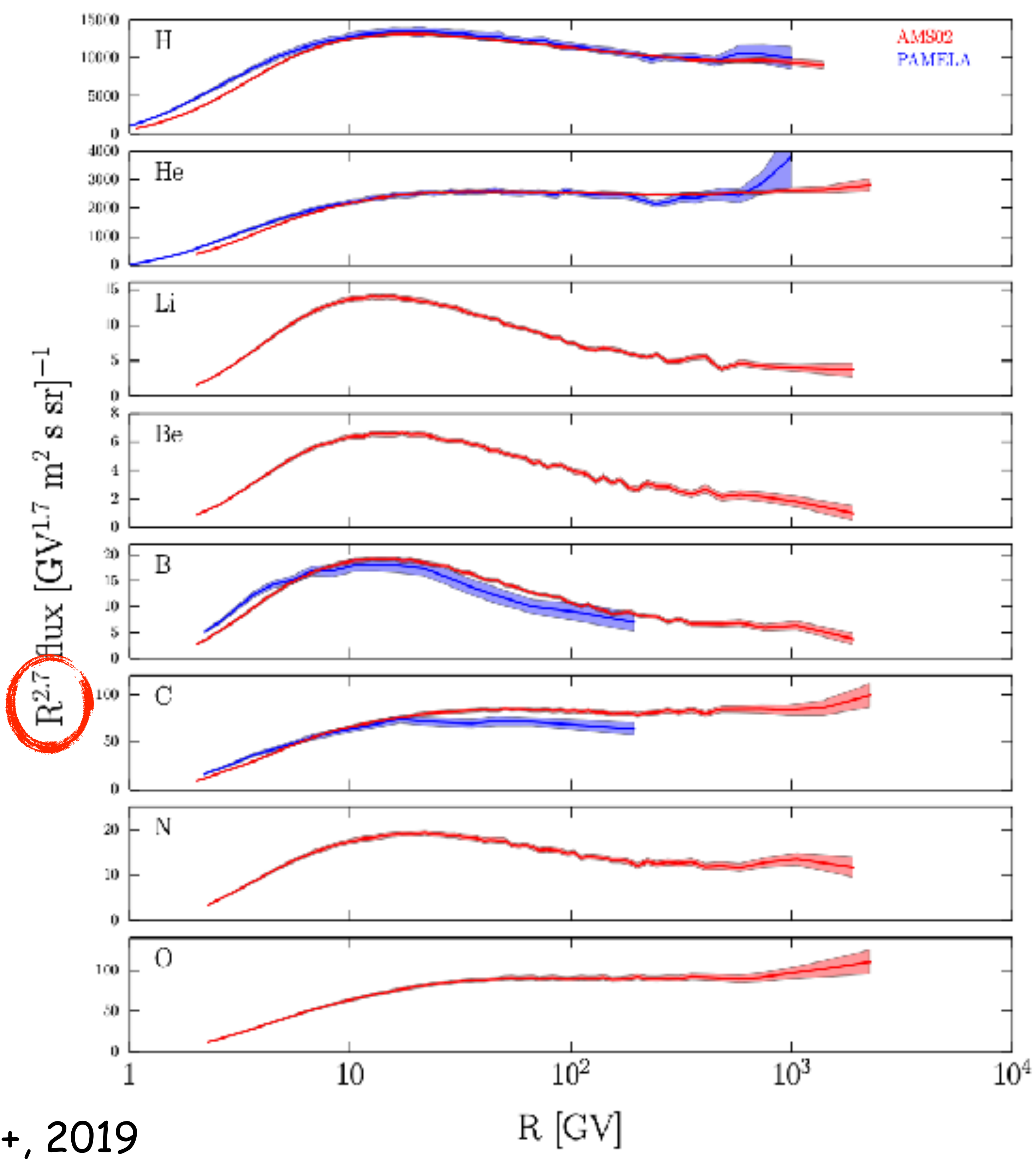
Tatischeff & SG, 2018

# Spectra of light elements



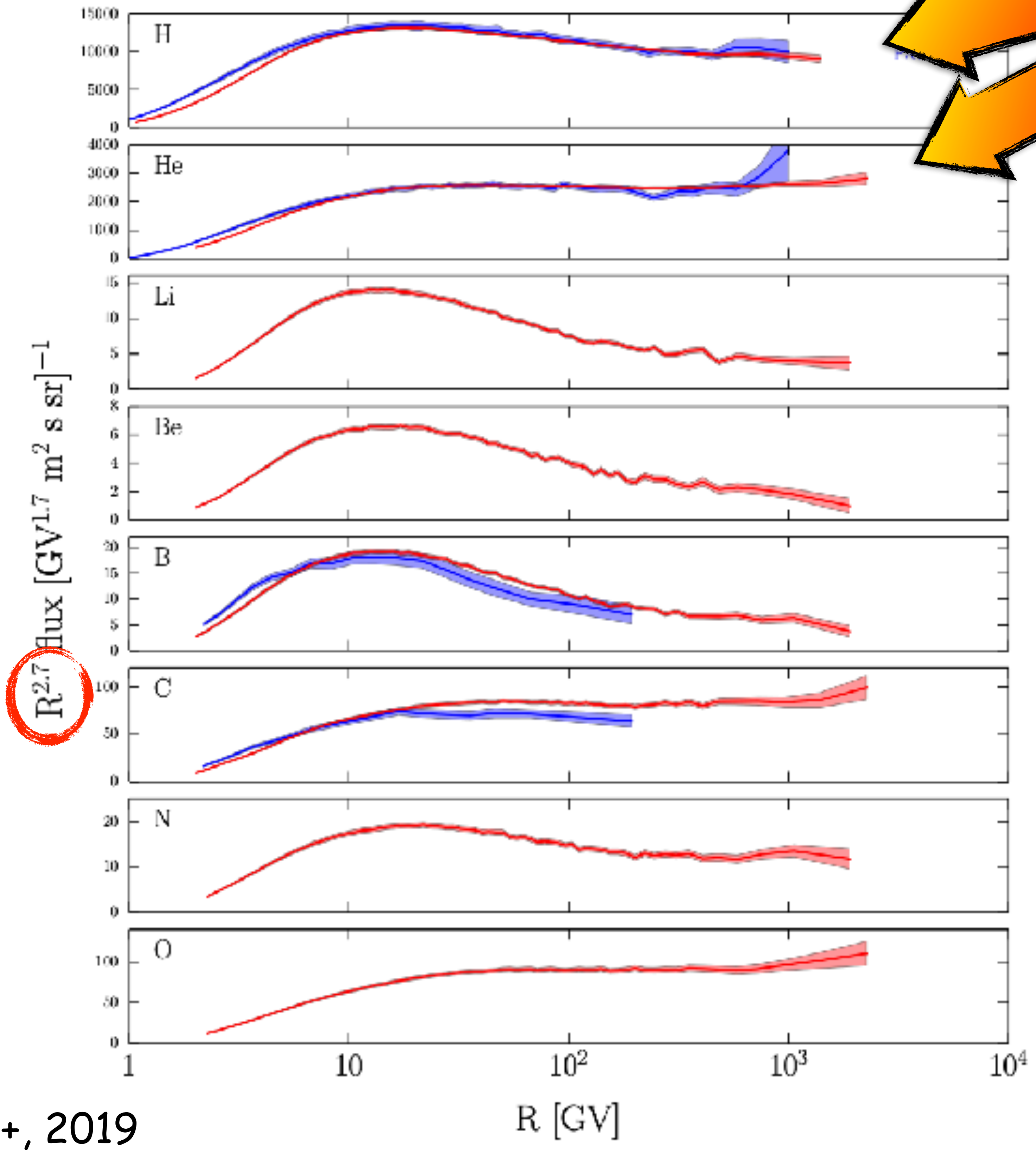
SG+, 2019

# Spectra of light elements



SG+, 2019

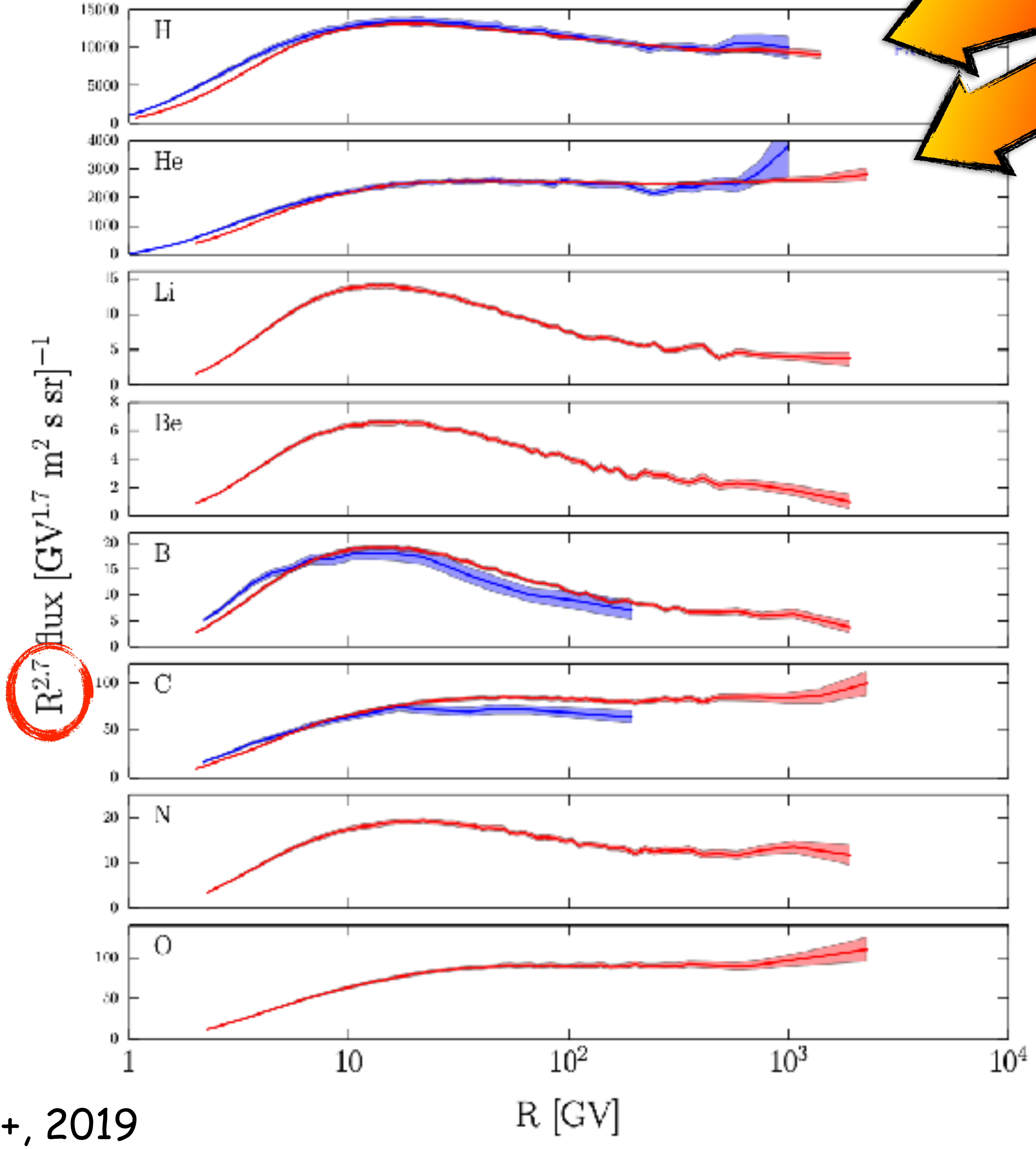
# Spectra of light elements



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

SG+, 2019

# Spectra of light elements



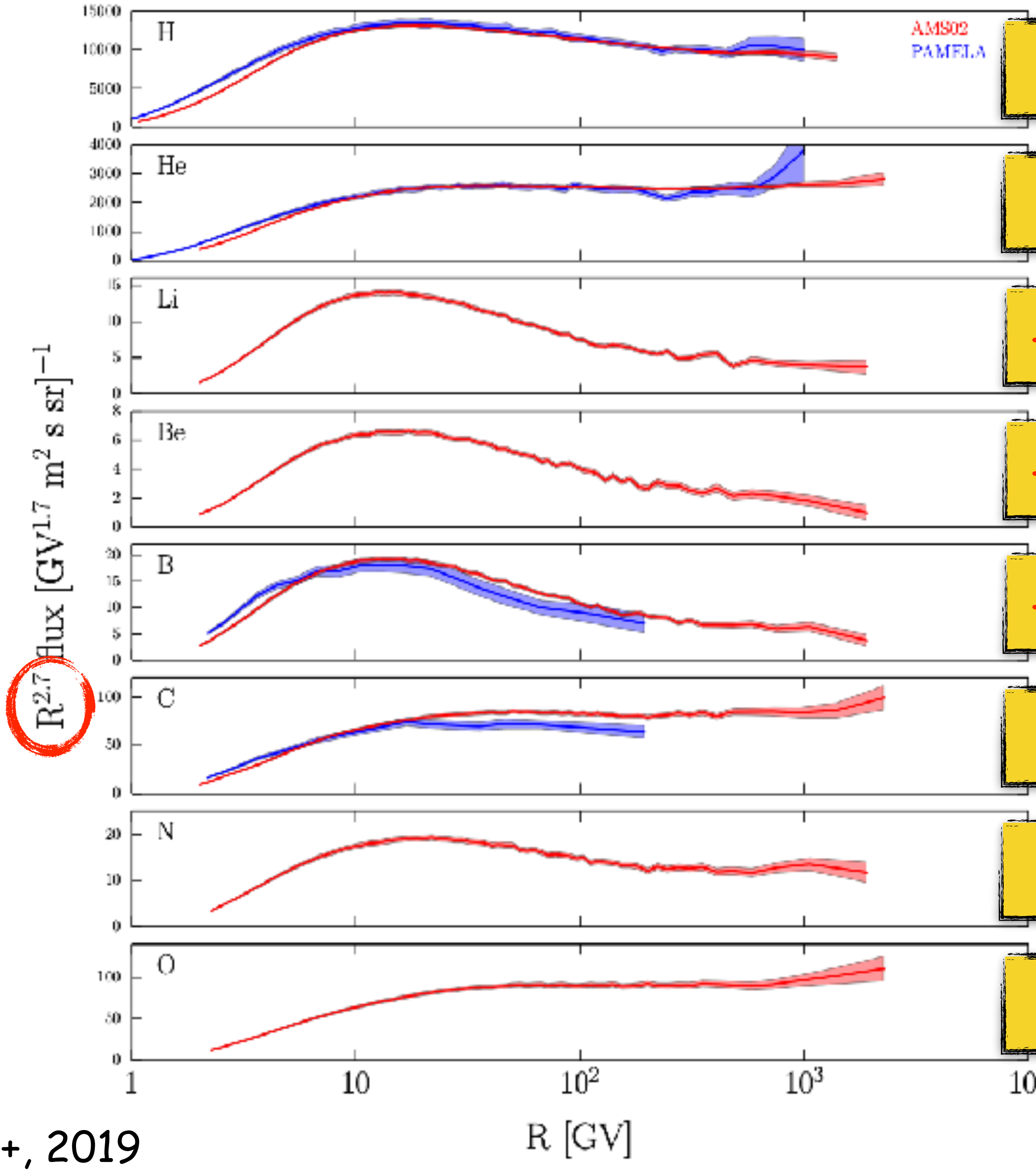
SG+, 2019

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

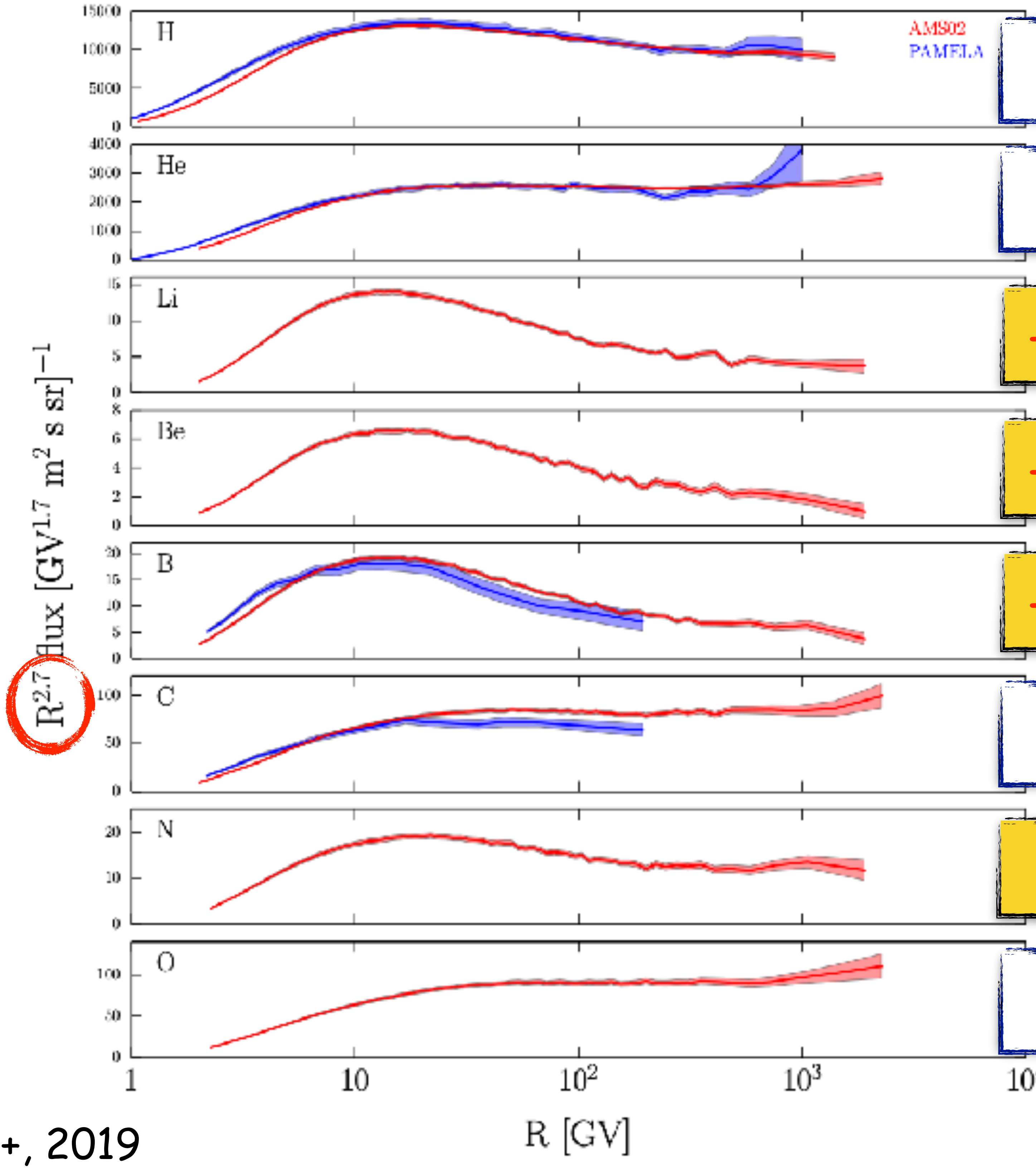
—> flat

—> slightly steep

—> flat

SG+, 2019

# Spectra of light elements: an hypothesis



primaries

primaries

—> markedly steeper

—> markedly steeper

—> markedly steeper

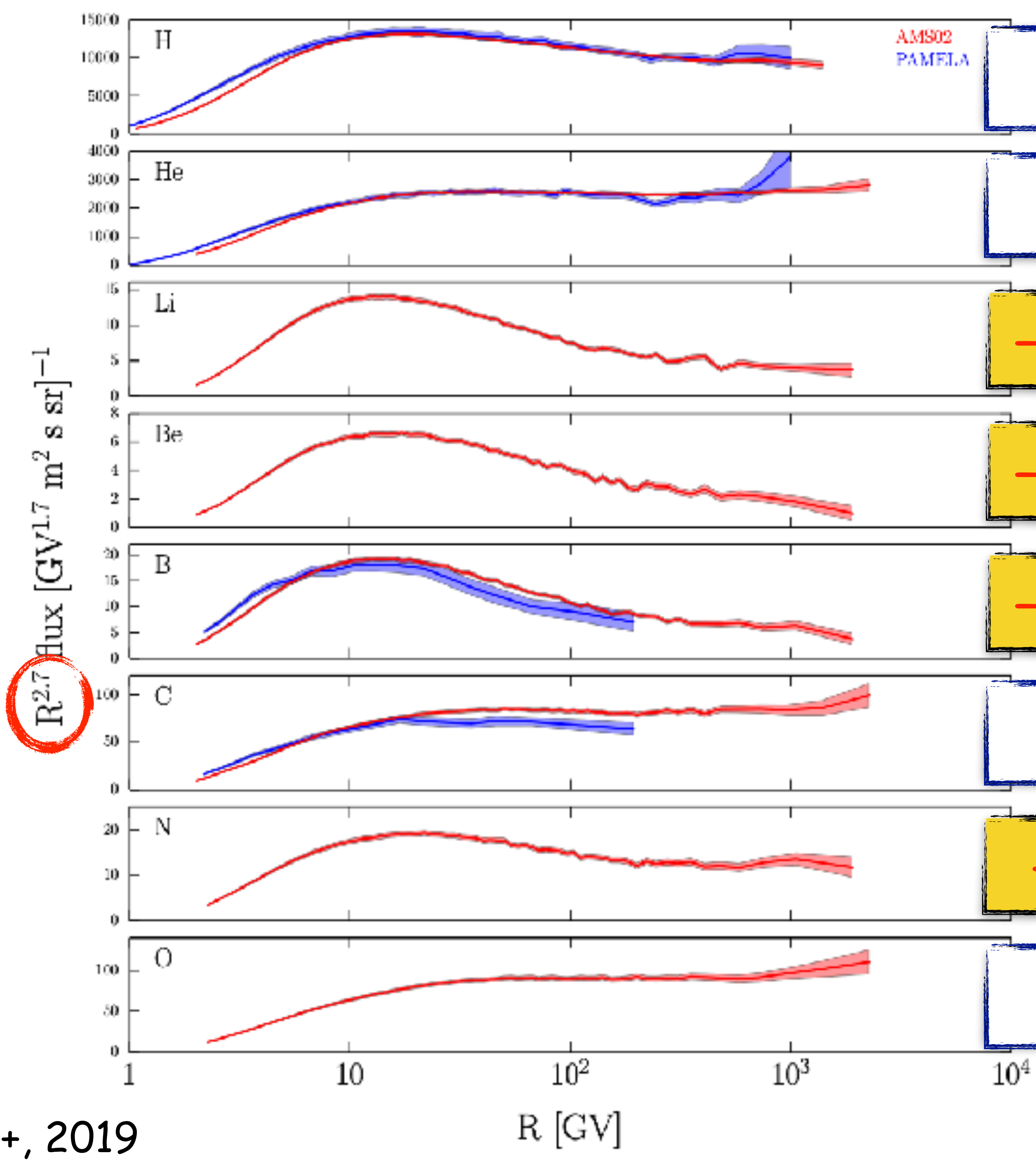
primaries

—> slightly steep

primaries

SG+, 2019

# Spectra of light elements: an hypothesis



primaries

primaries

—> markedly eeper

—> ma steeper

—> m rkedly steeper

secondaries

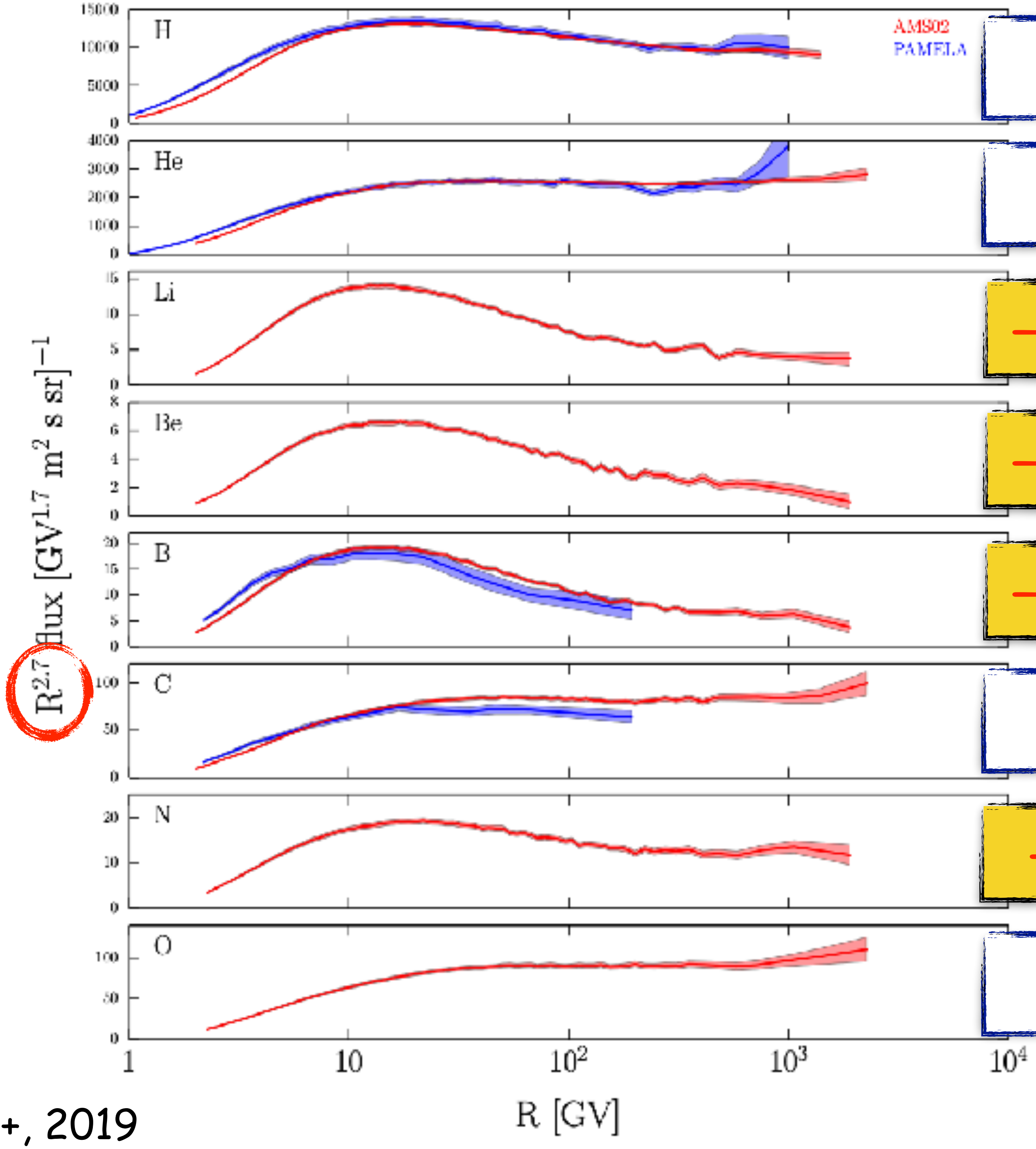
primaries

—> slightly steep

primaries

SG+, 2019

# Spectra of light elements: an hypothesis



primaries

primaries

—> markedly s eeper

—> ma steeper

—> m rkedly steeper

secondaries

primaries

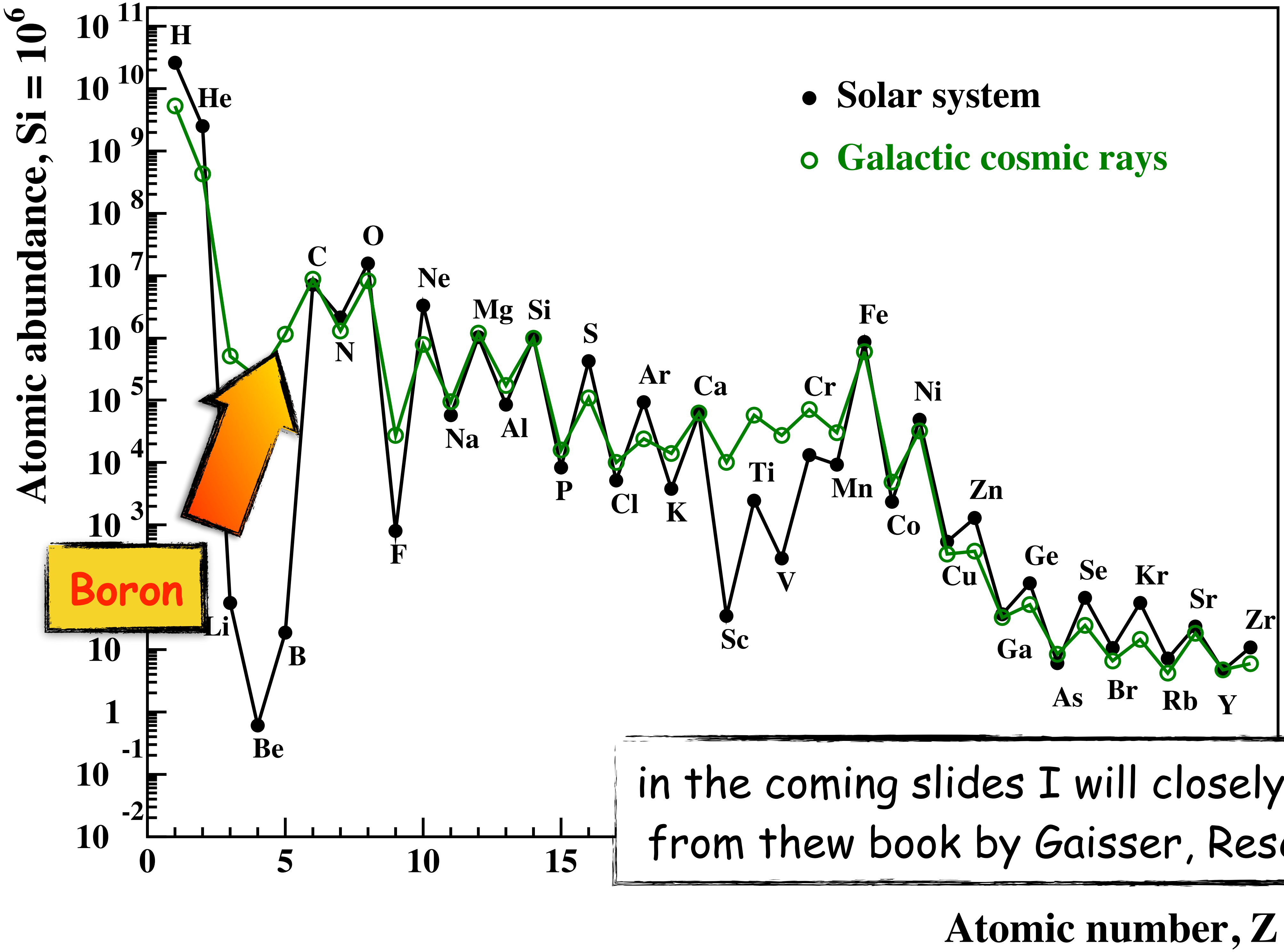
mixed

primaries

SG+, 2019

# Production of B due to spallation

who does that?



Boron

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

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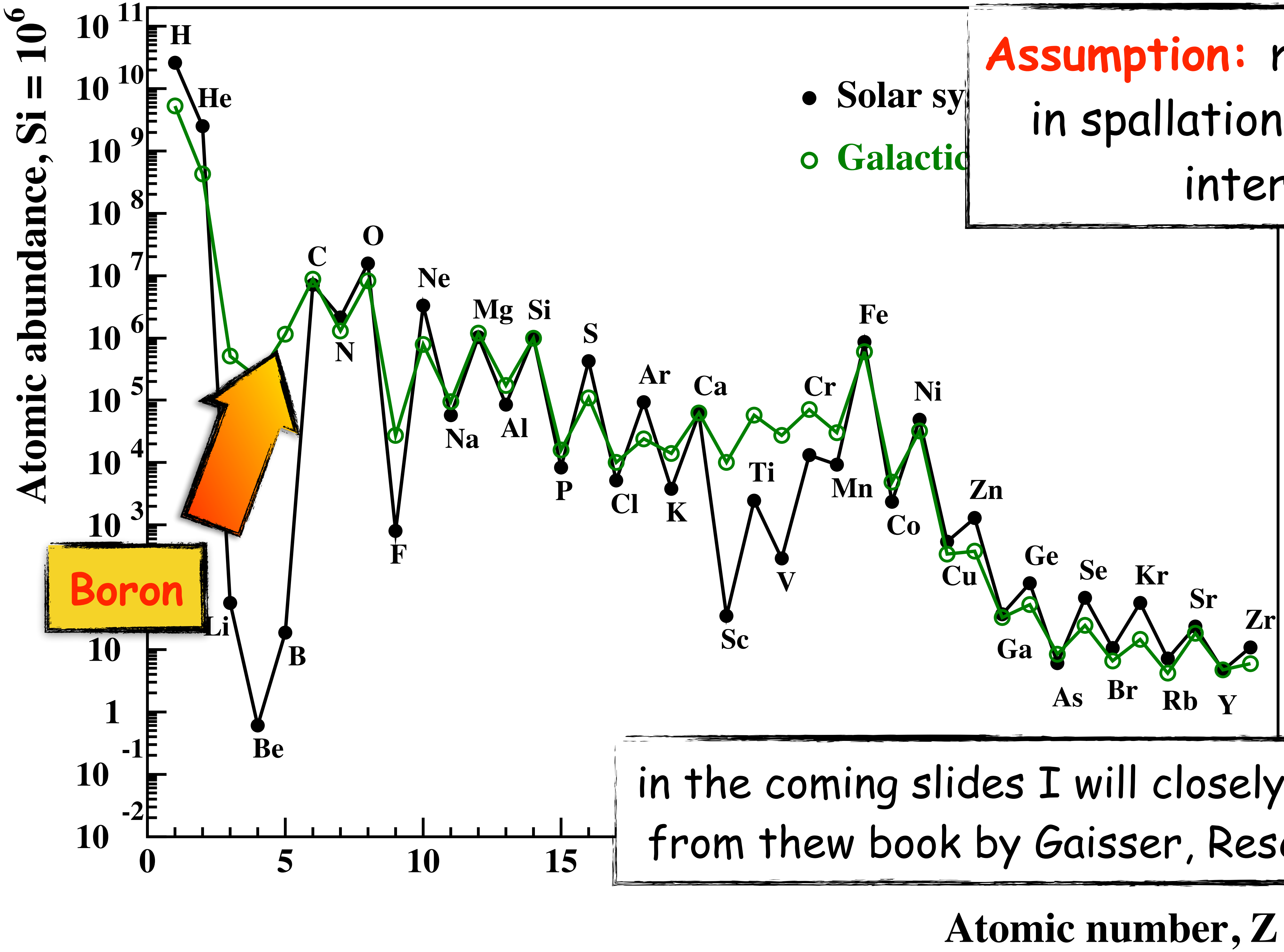

Boron

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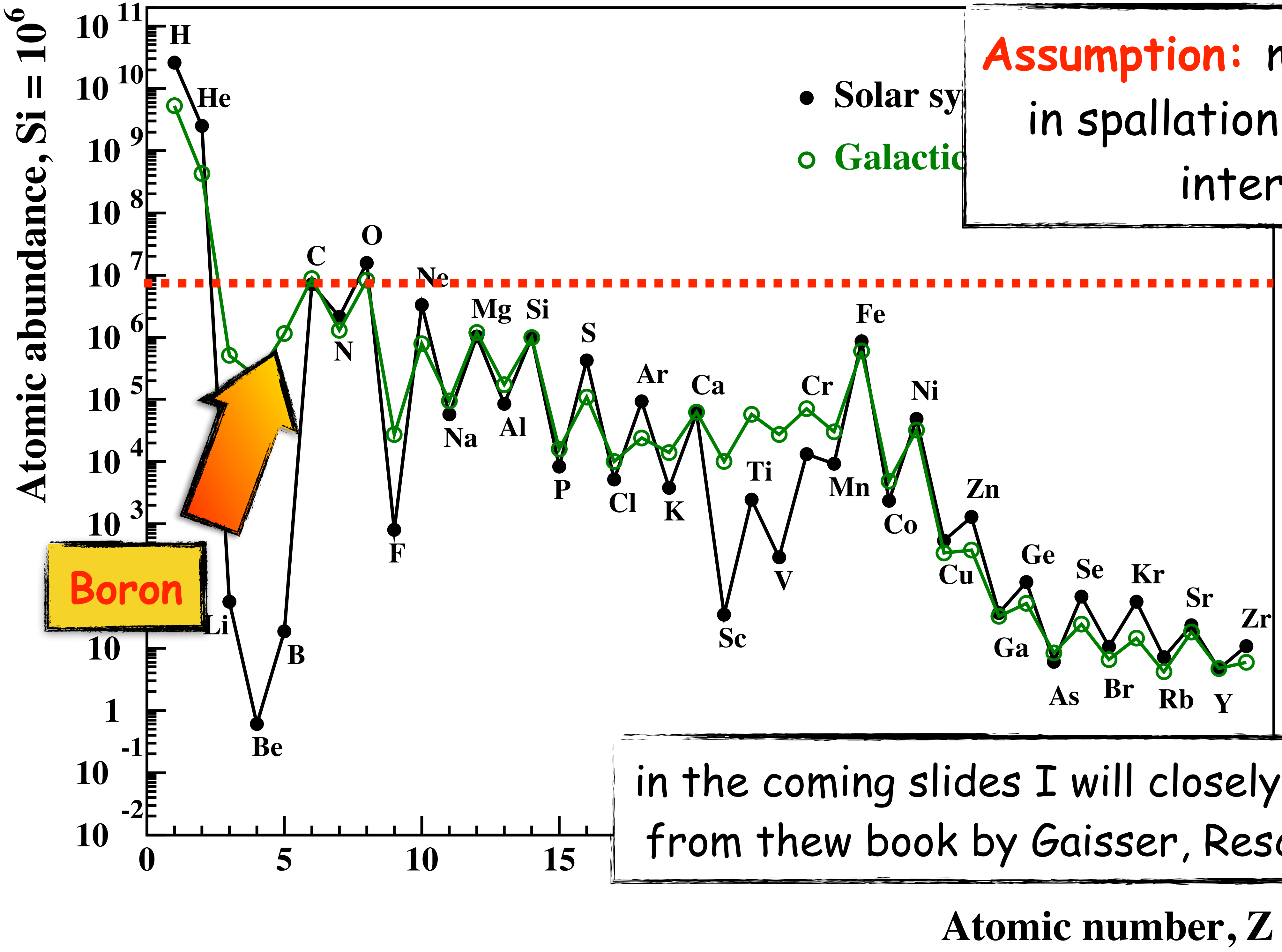

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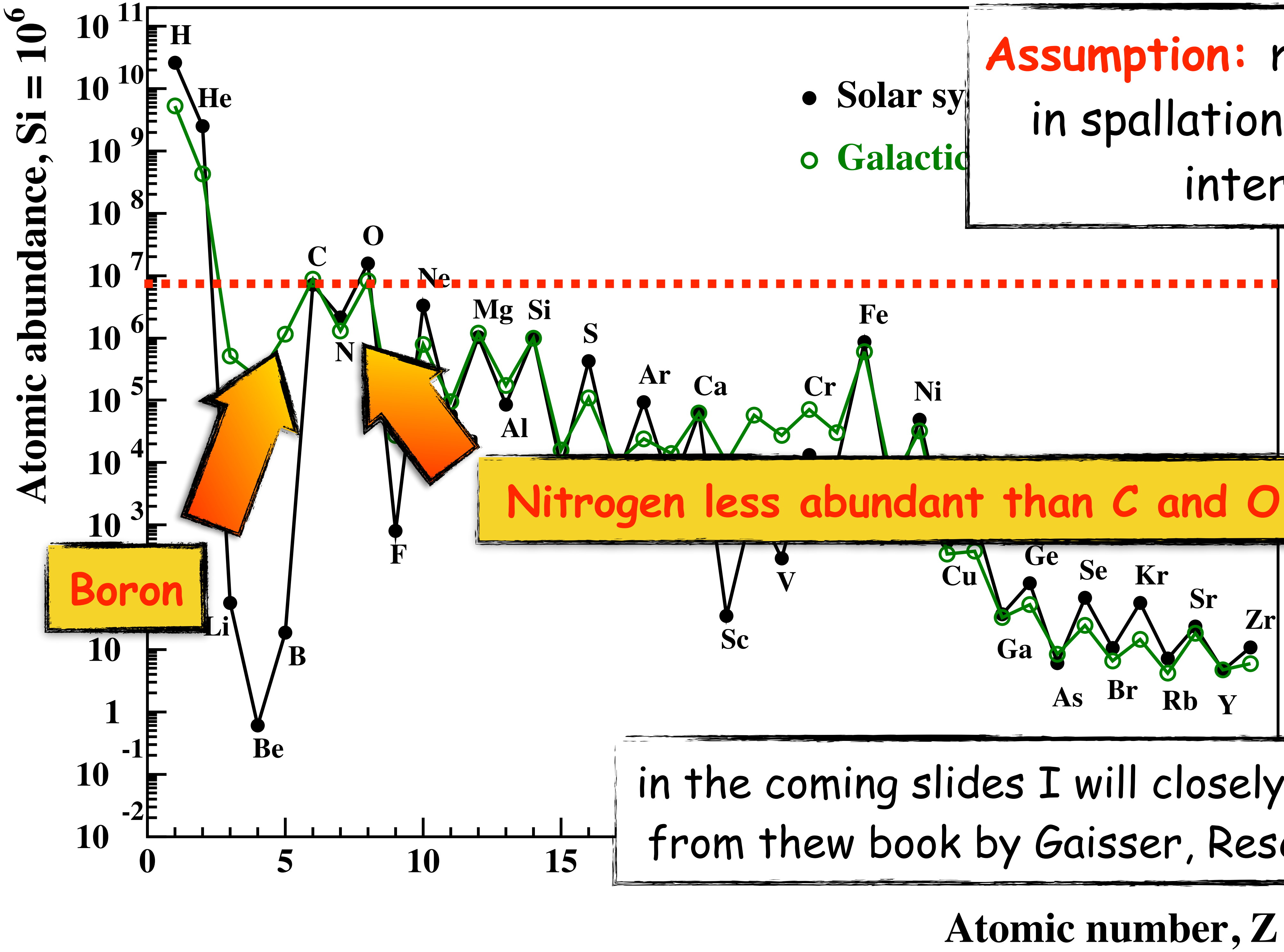

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Nitrogen less abundant than C and O

Boron

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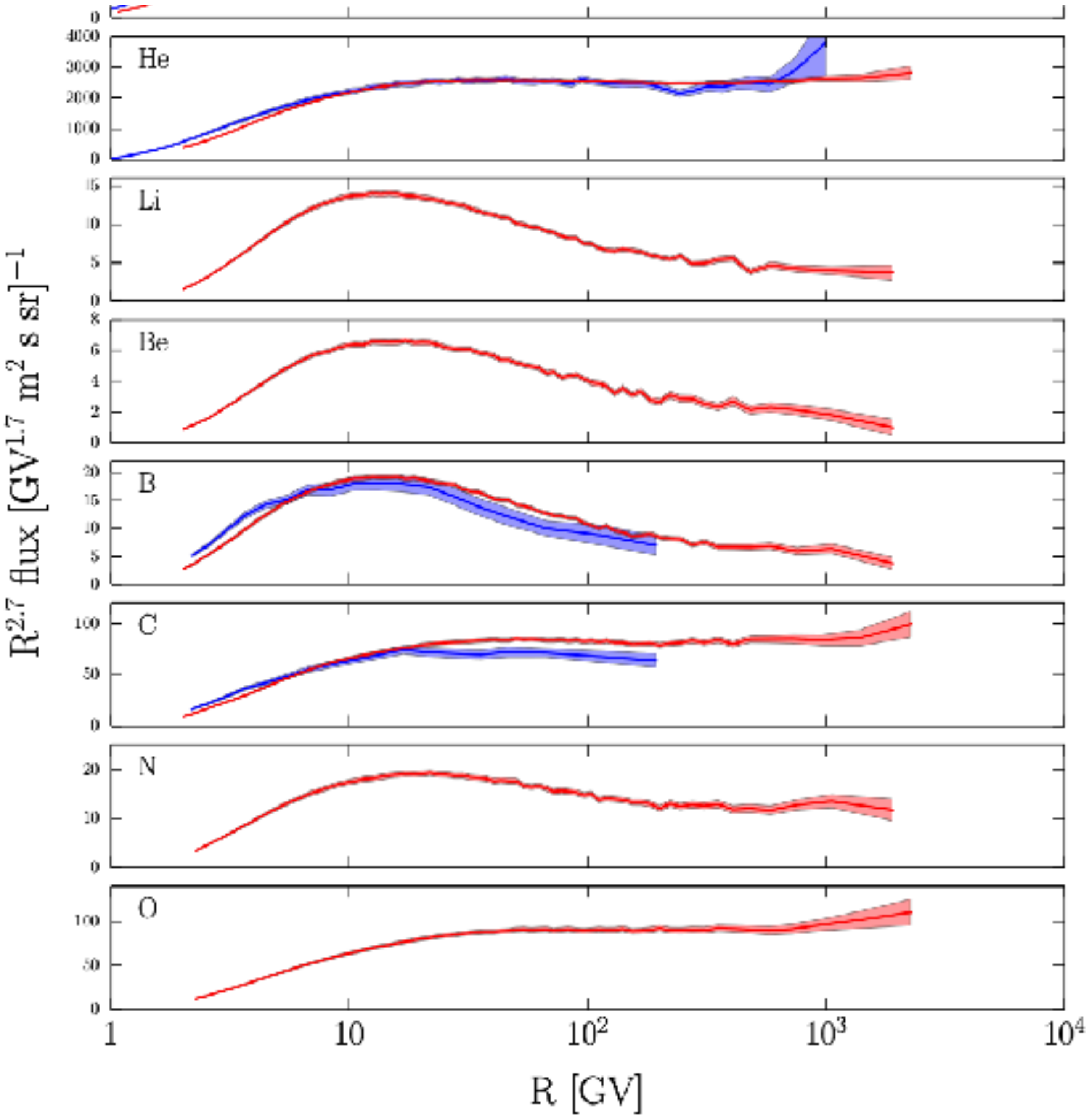
# *Local* production rate of B

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



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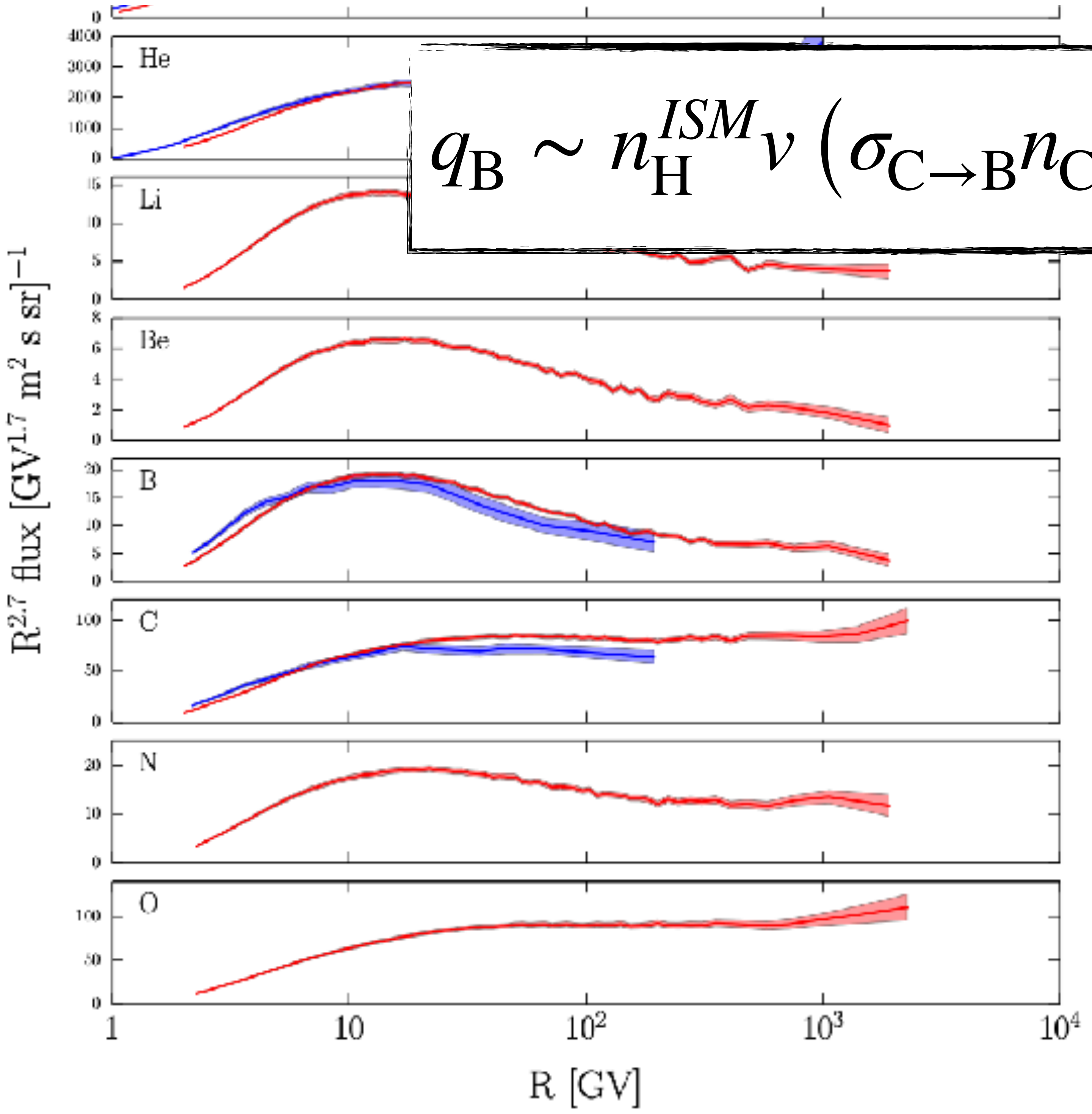

$$q_{\rm B} \sim n_{\rm H}^{ISM} v \left(\sigma_{\rm C \to B} n_{\rm C} + \sigma_{\rm O \to B} n_{\rm O}\right)$$

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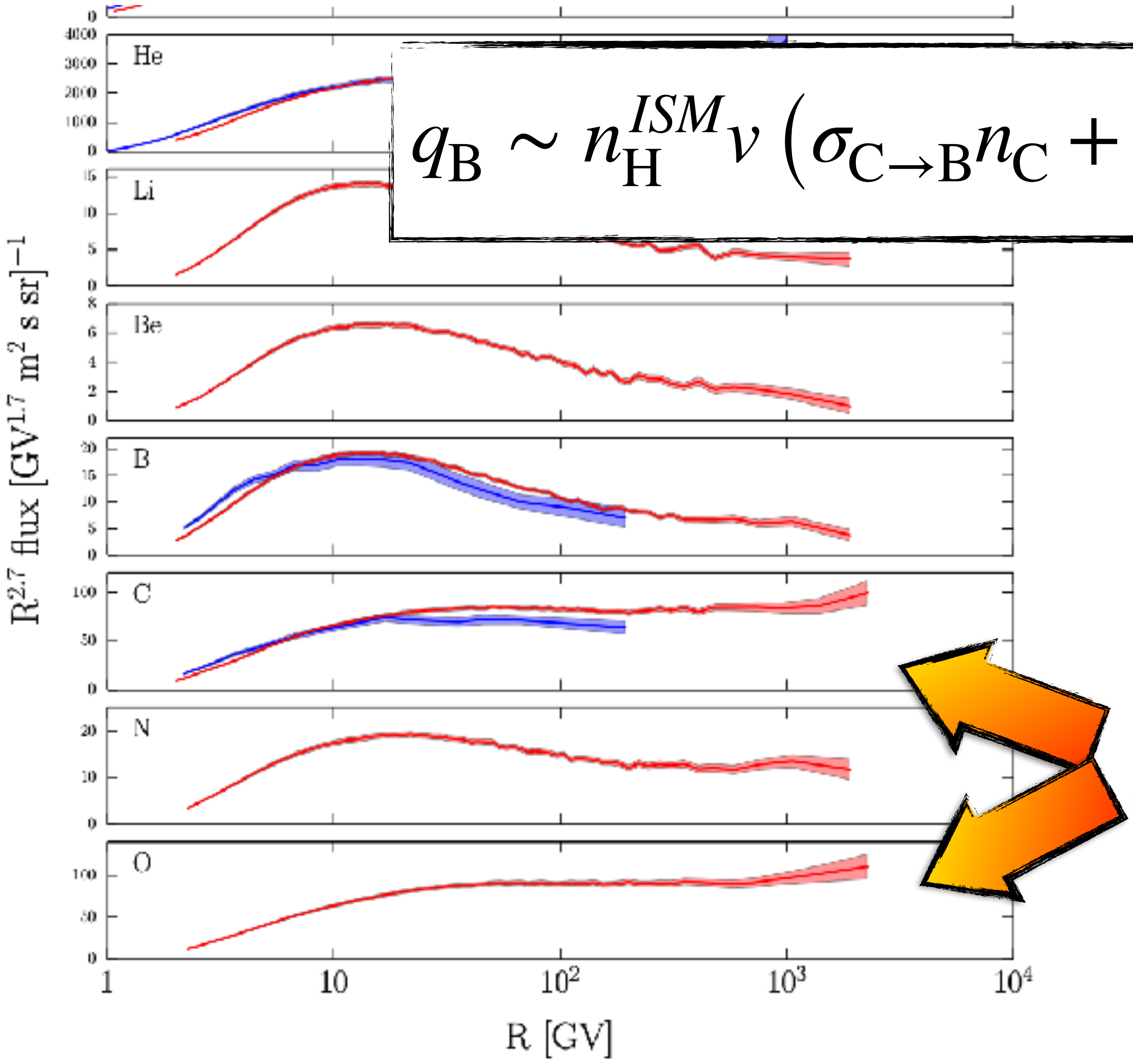

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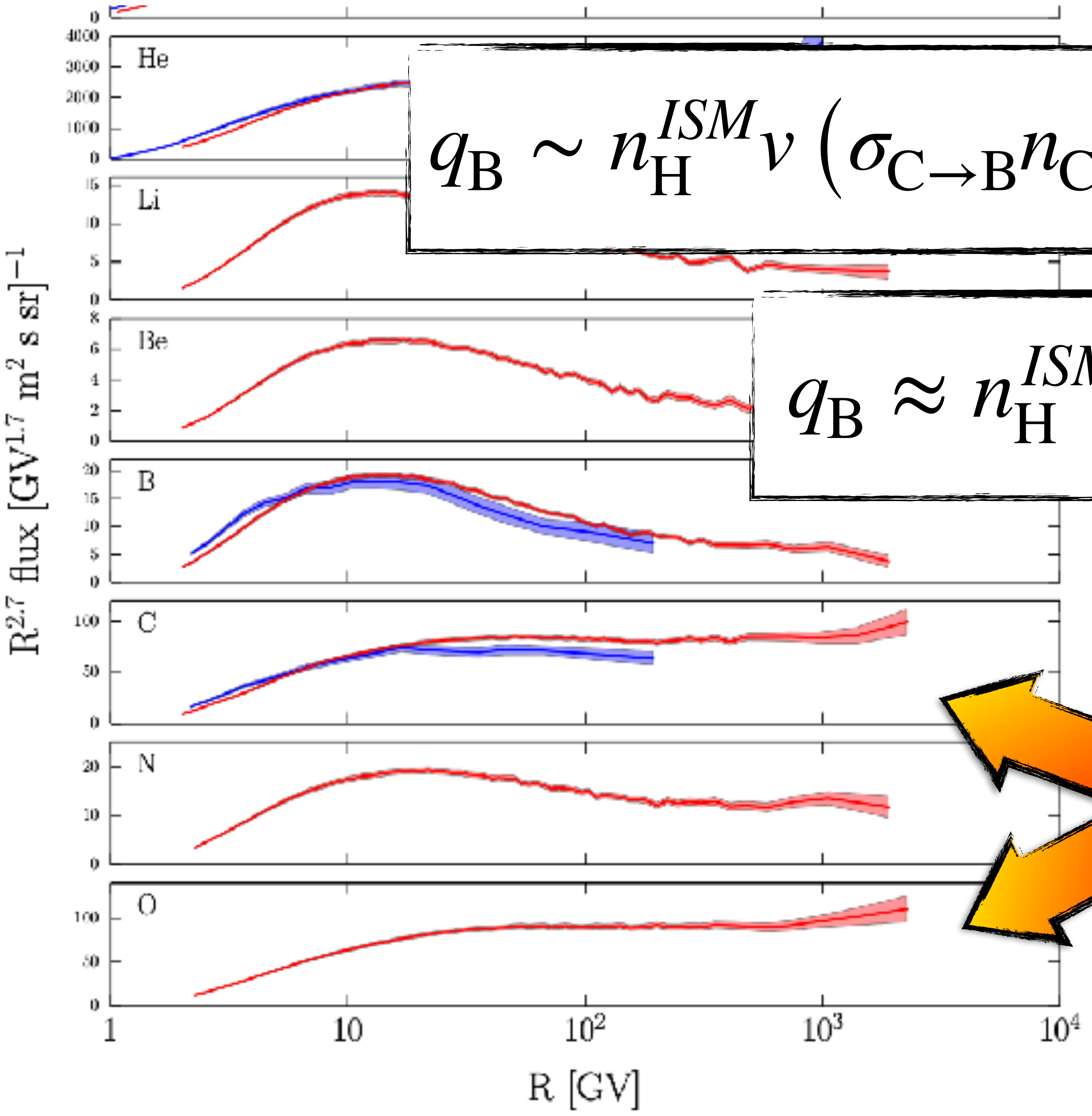

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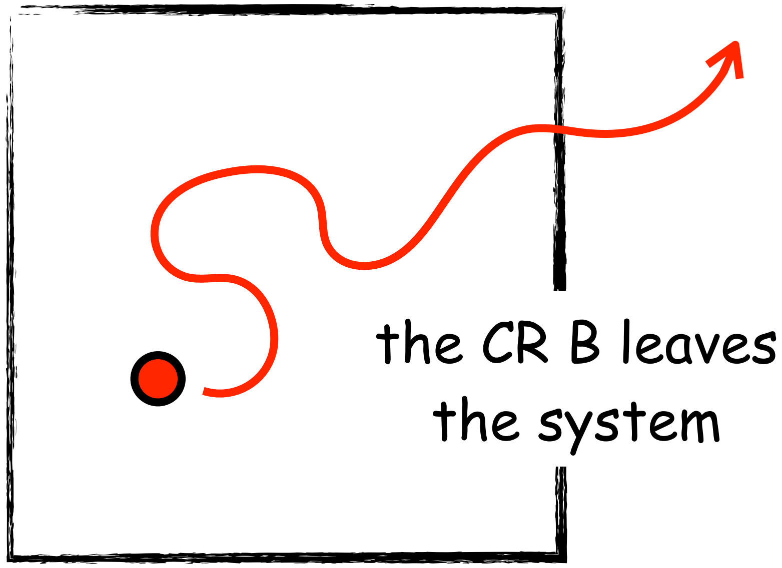

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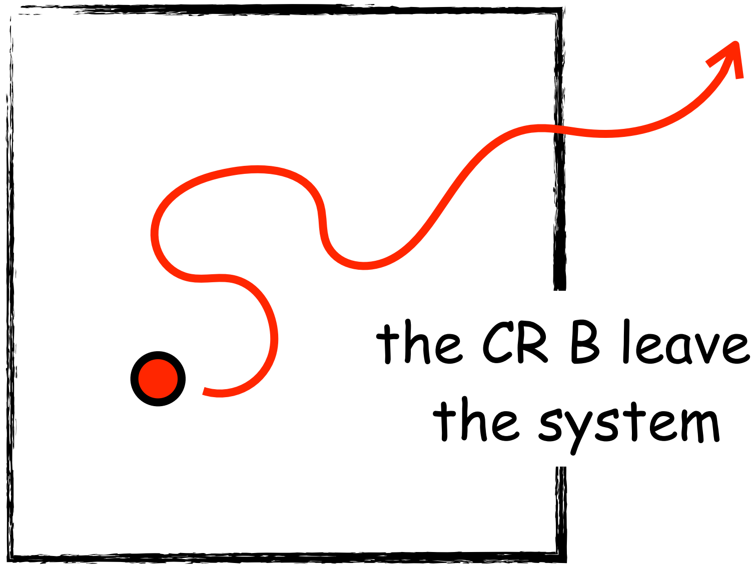

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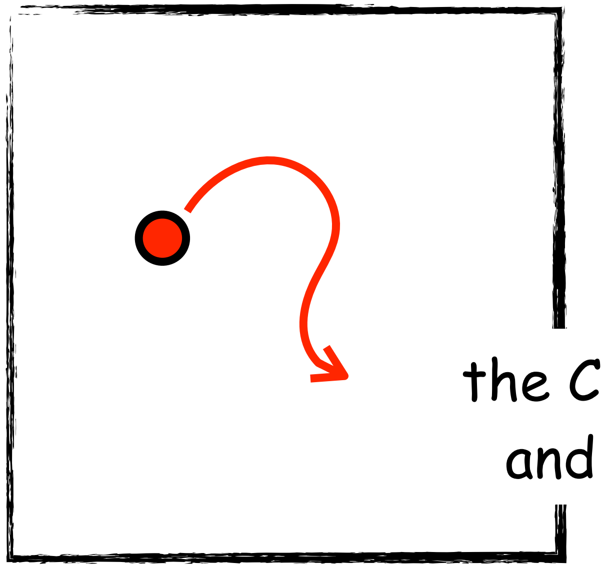
**spallate** $\tau_{\rm B} = \left(n_{\rm H}^{ISM} \sigma_{\rm B} v\right)^{-1}$



the CR B spallates
and disappears

# The equilibrium spectrum of B

**transport equation at equilibrium**

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

destruction rate
(escape)

destruction rate
(spallation)

production rate

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destruction rate
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production rate

**effective "destruction" time —>**

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

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

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

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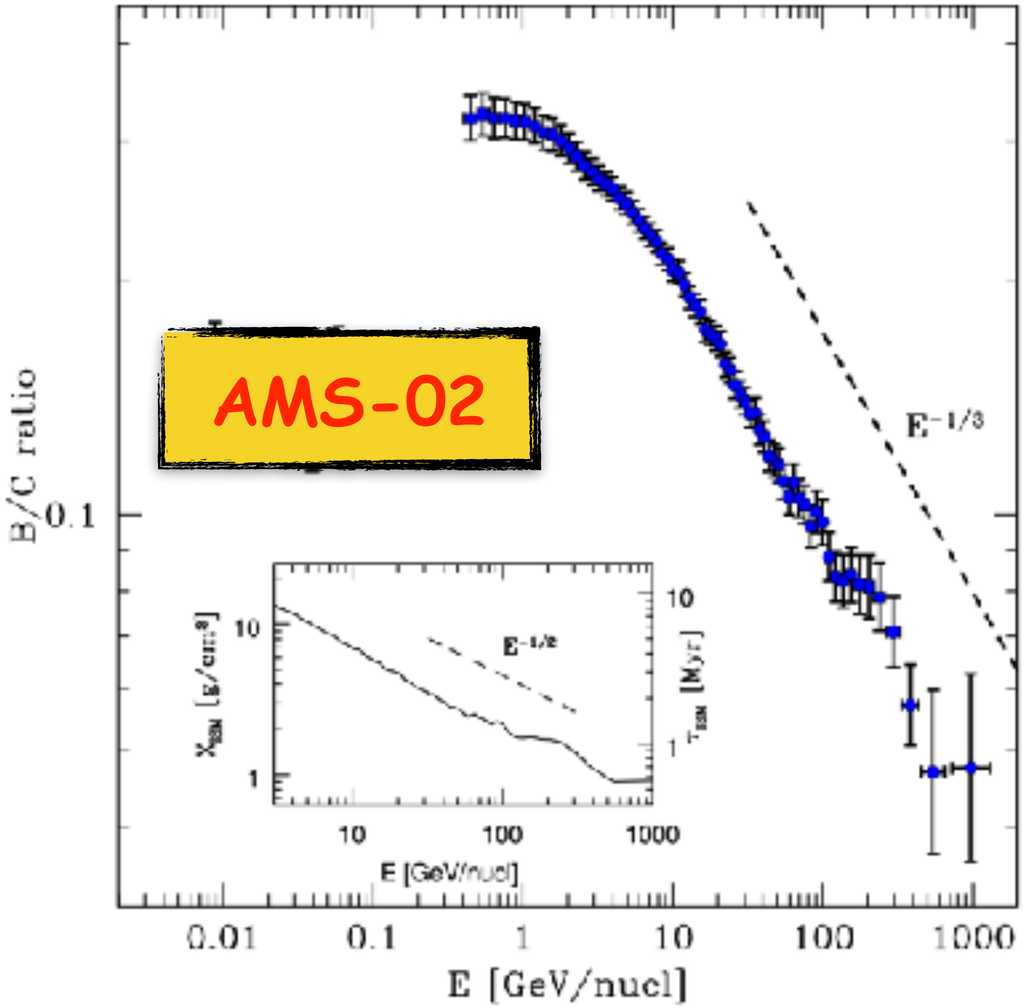

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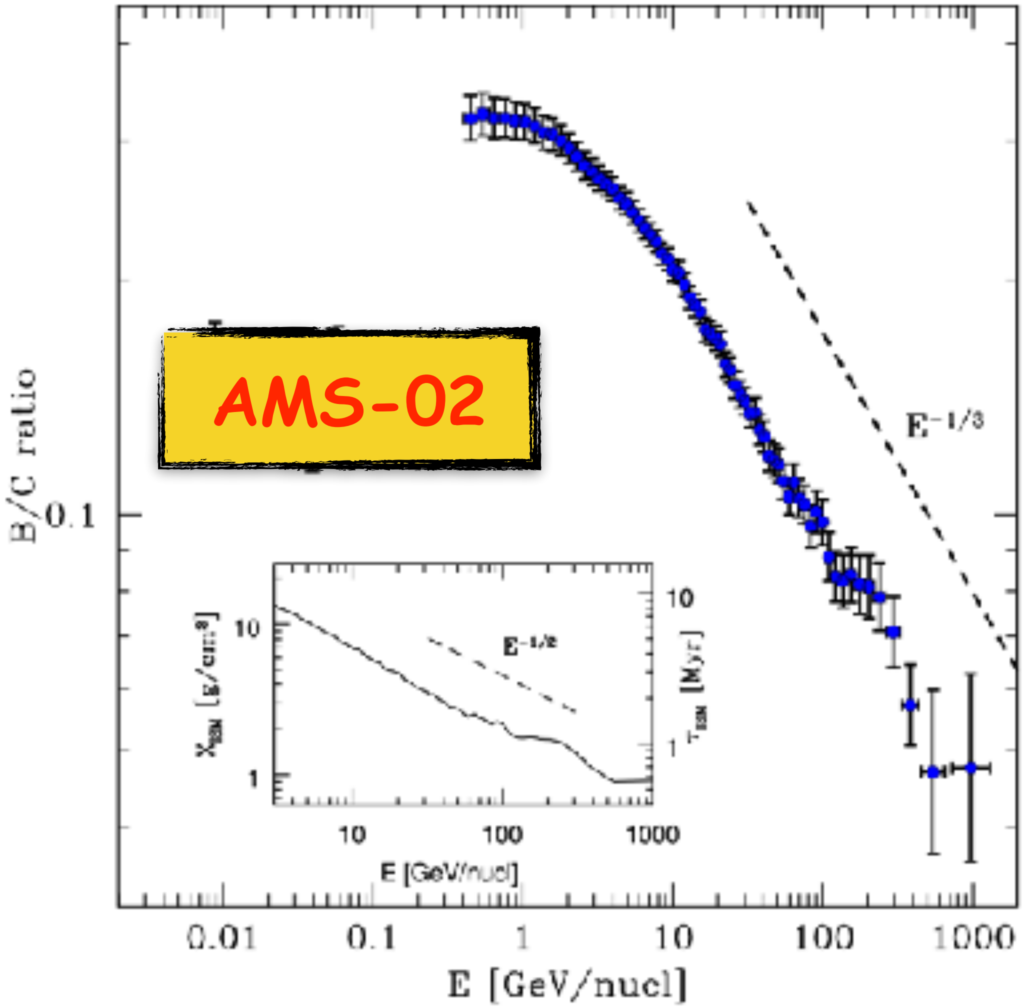

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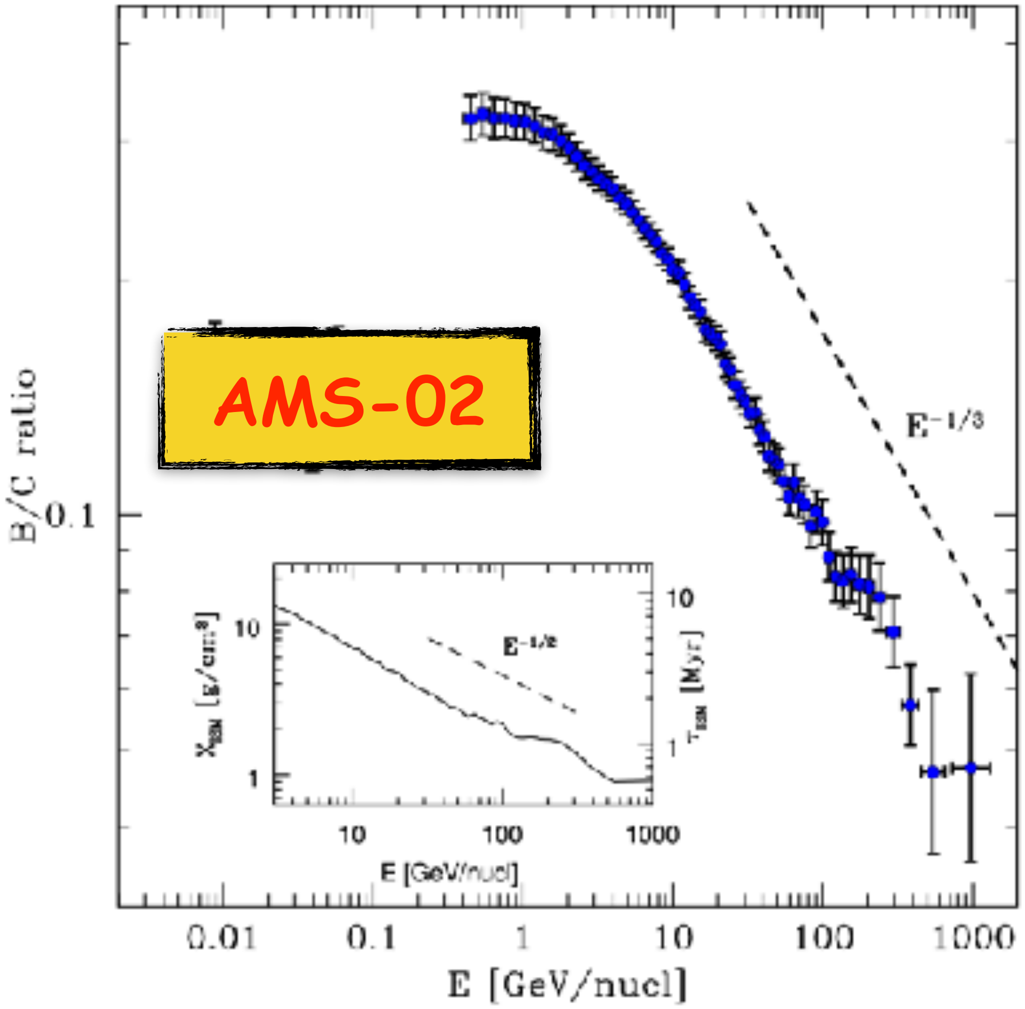

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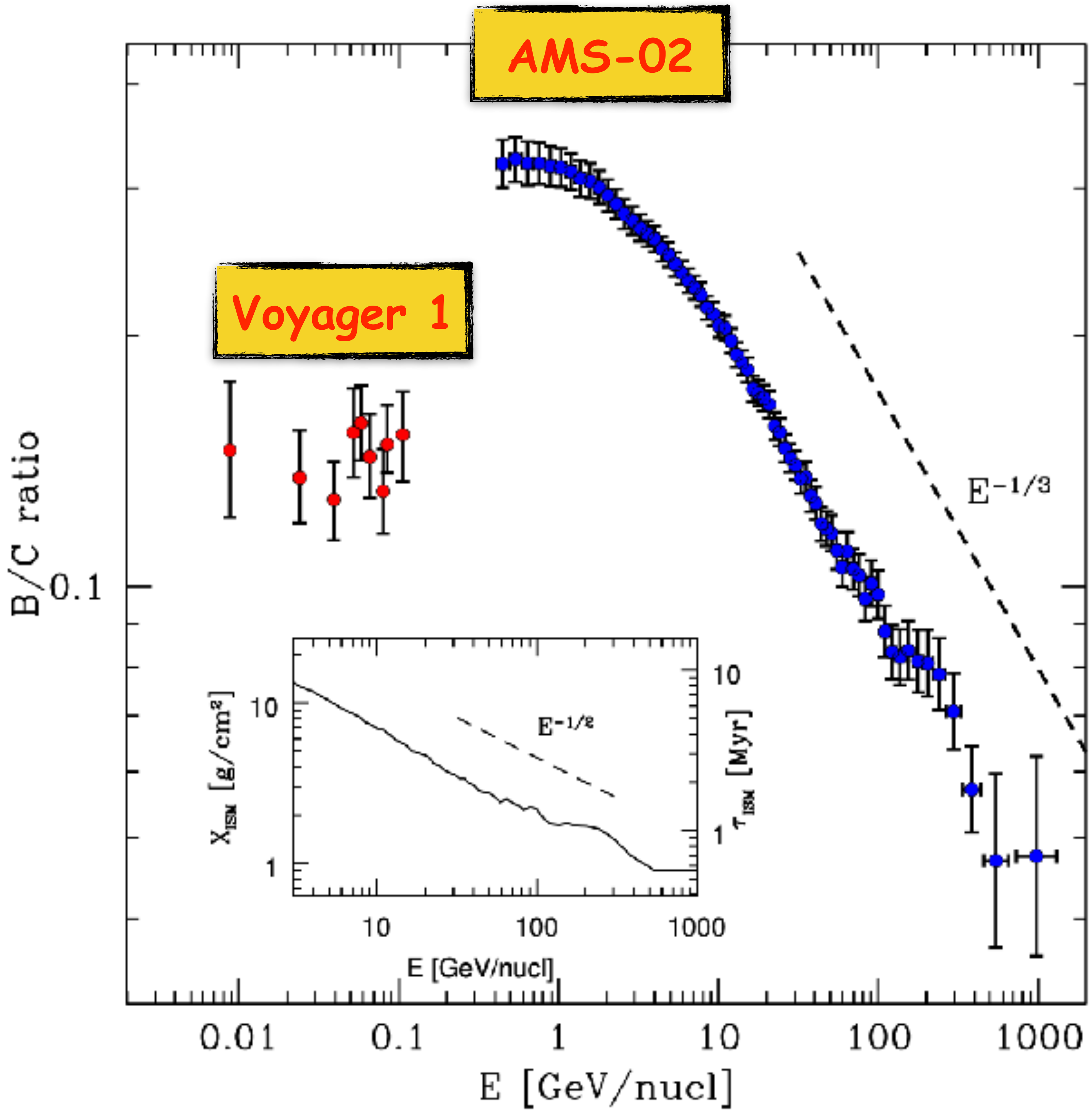

Gabici 2022

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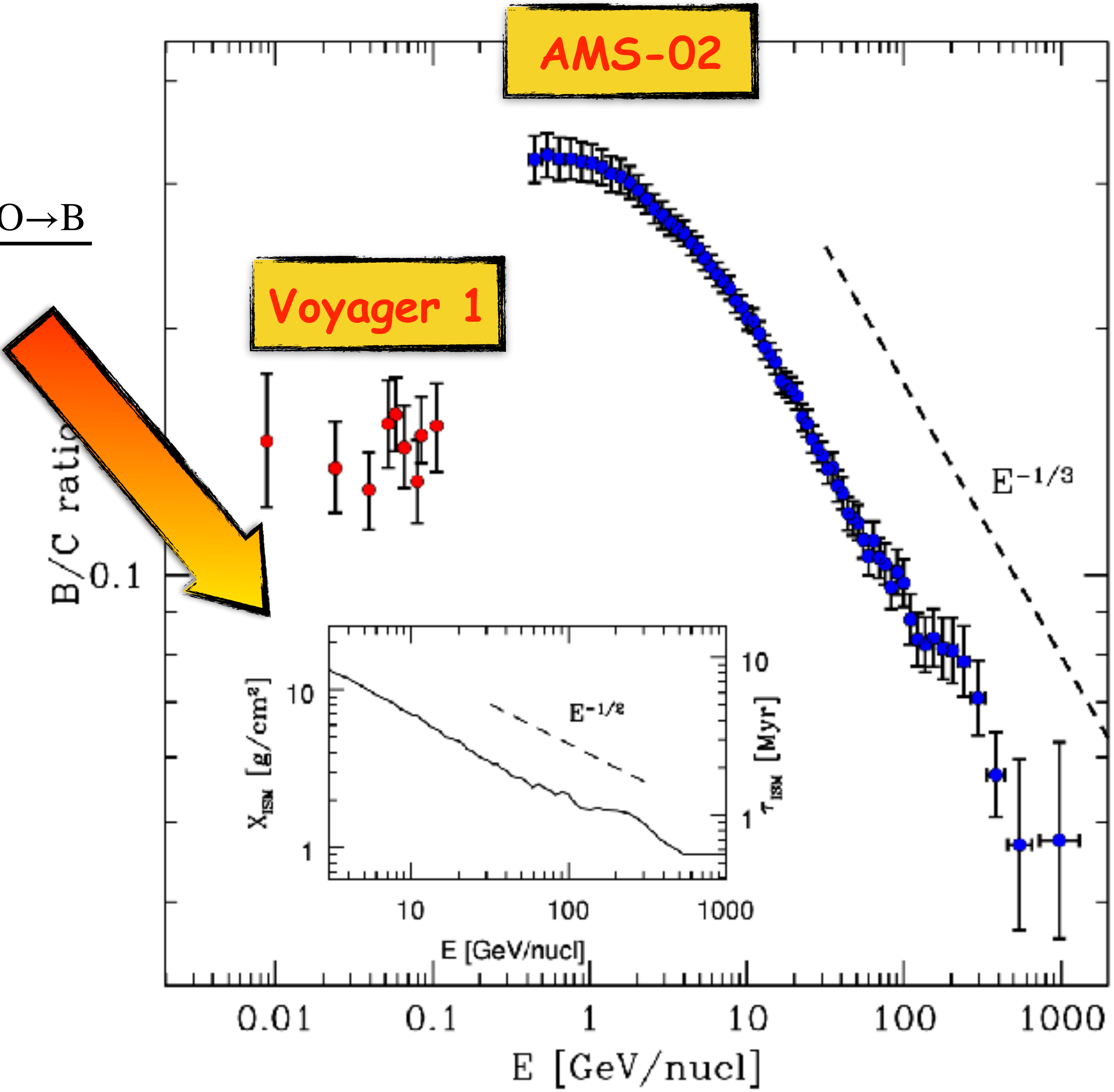

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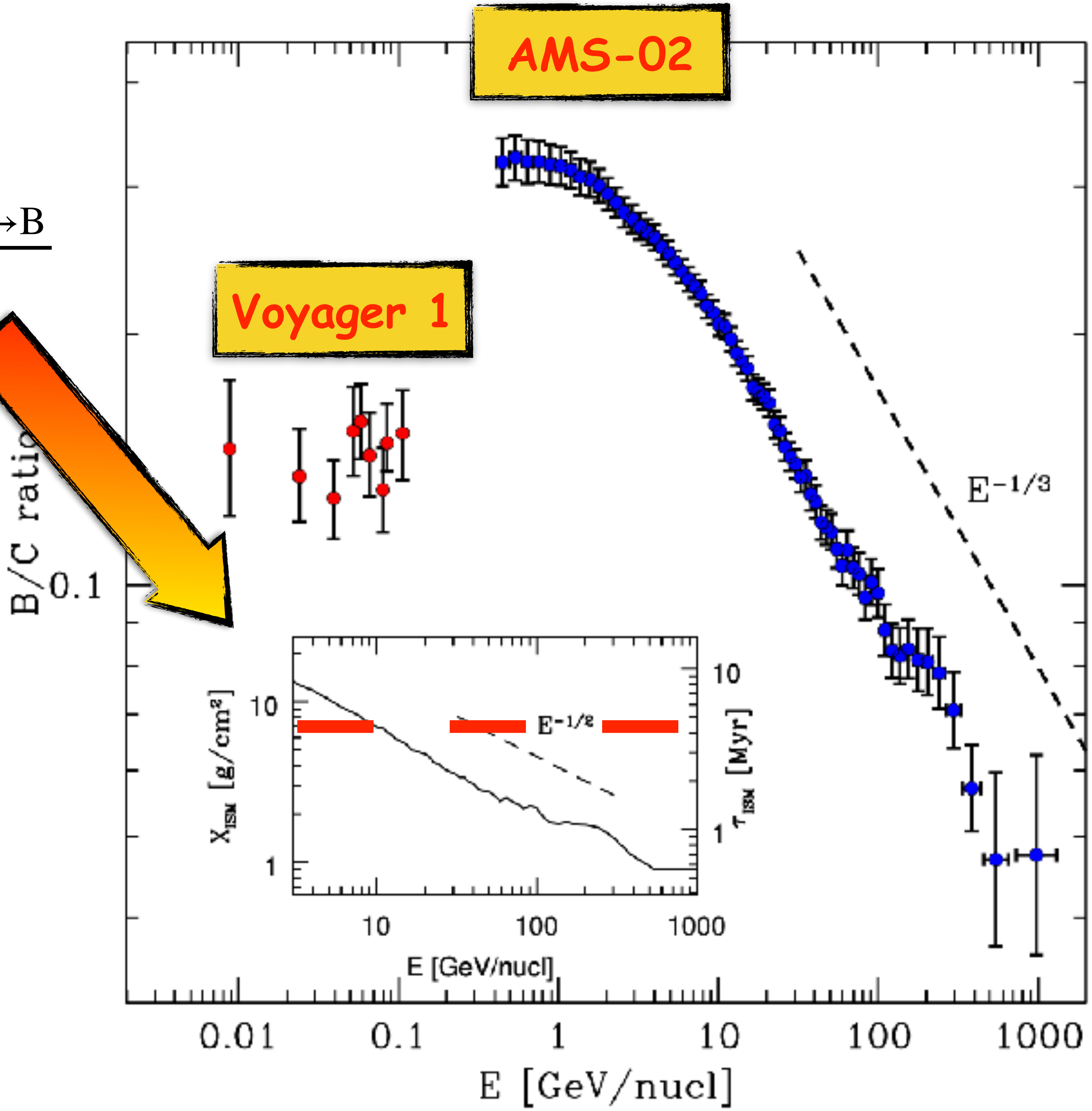

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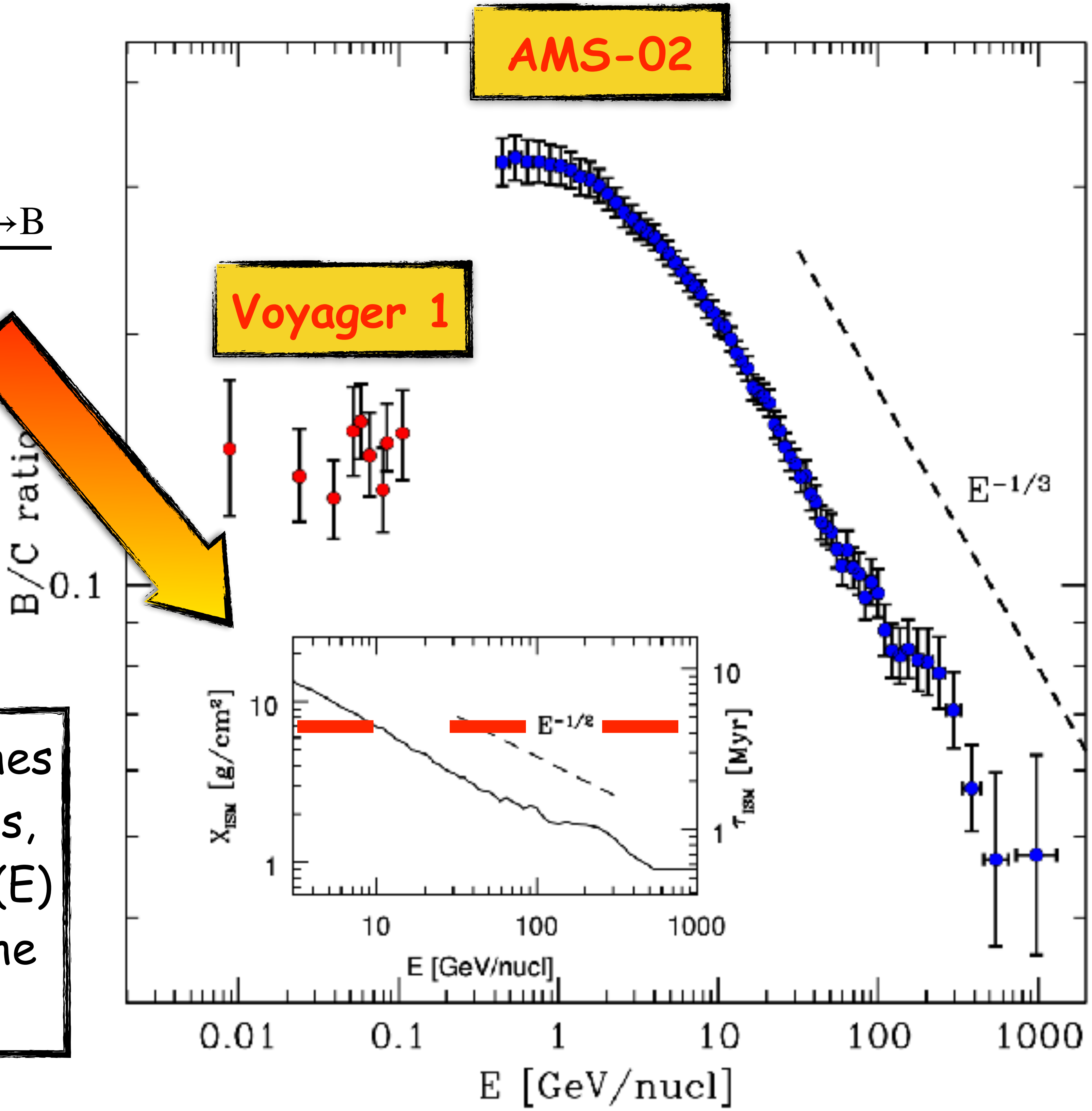


**AMS-02**

**Voyager 1**

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

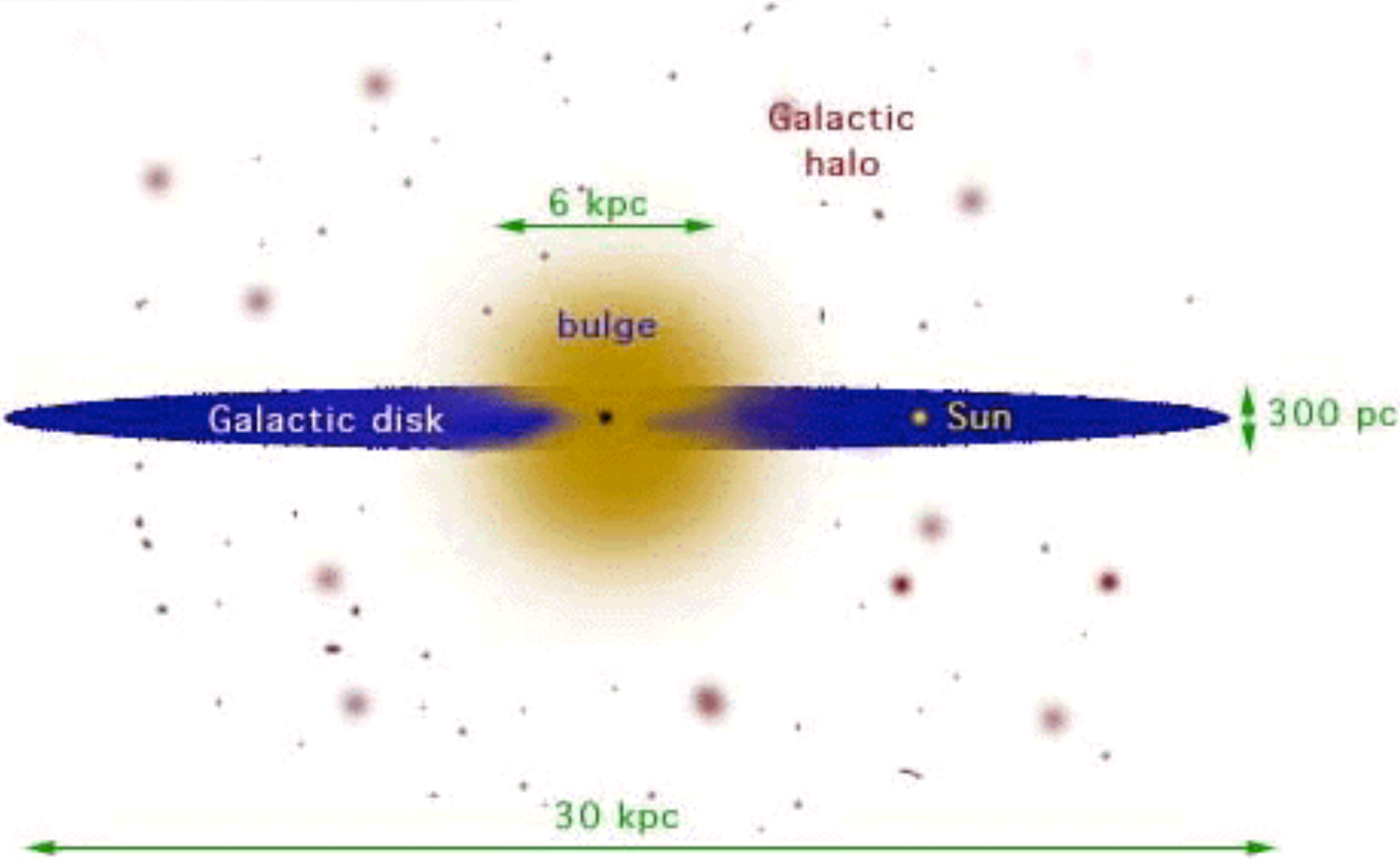
Gabici 2022

# 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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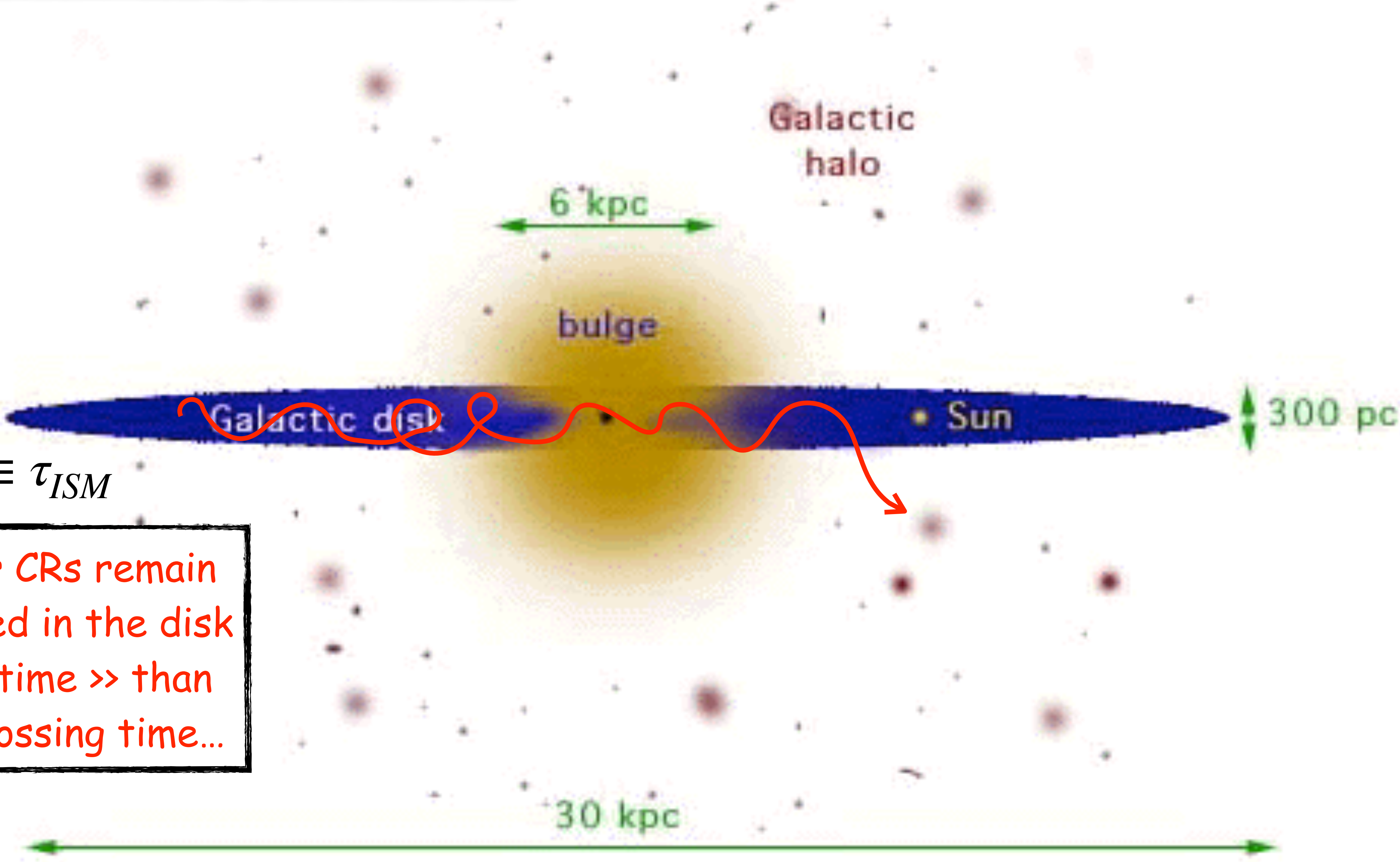

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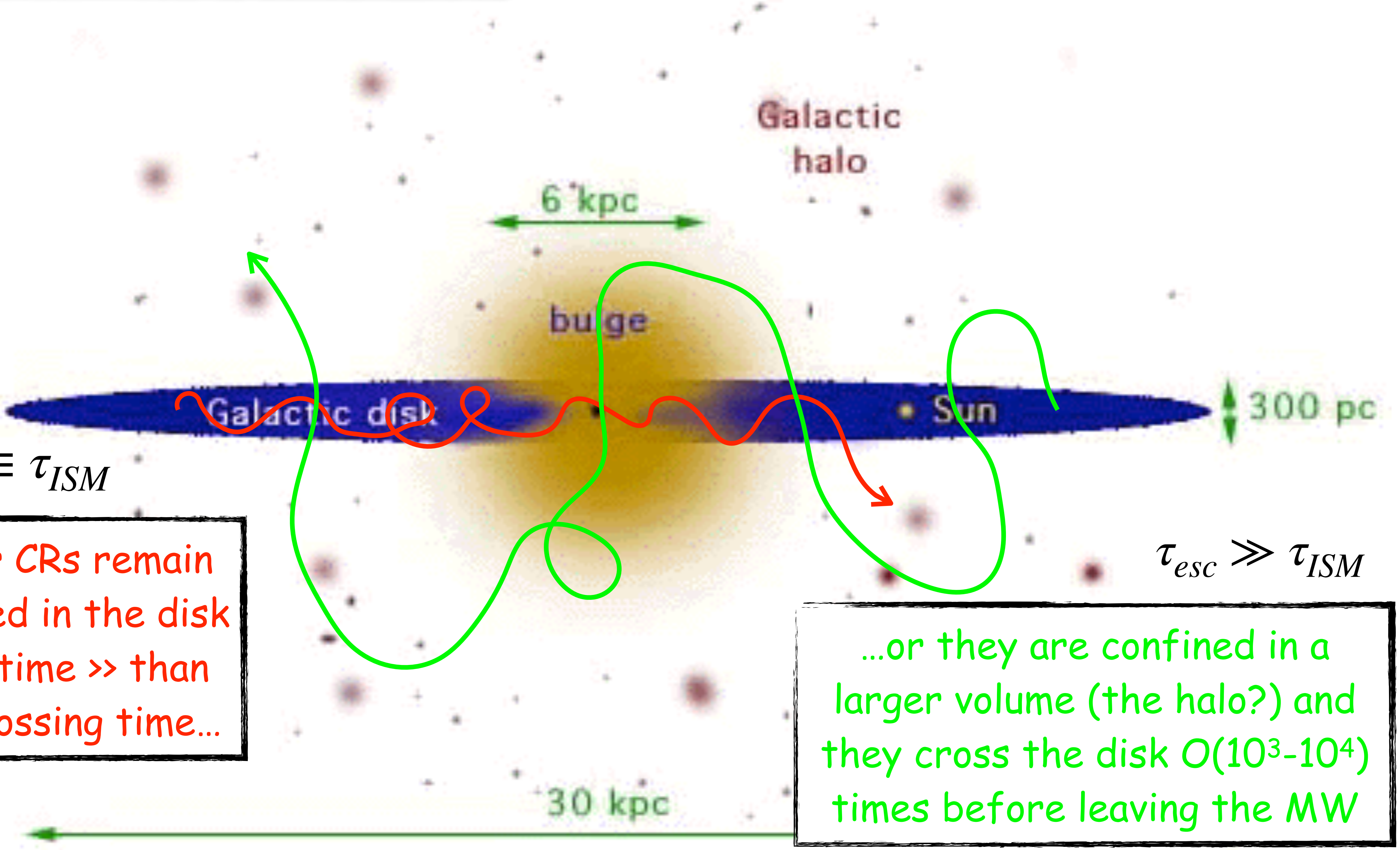

$\tau_{esc} \equiv \tau_{ISM}$

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($10^3$-$10^4$) times before leaving the MW

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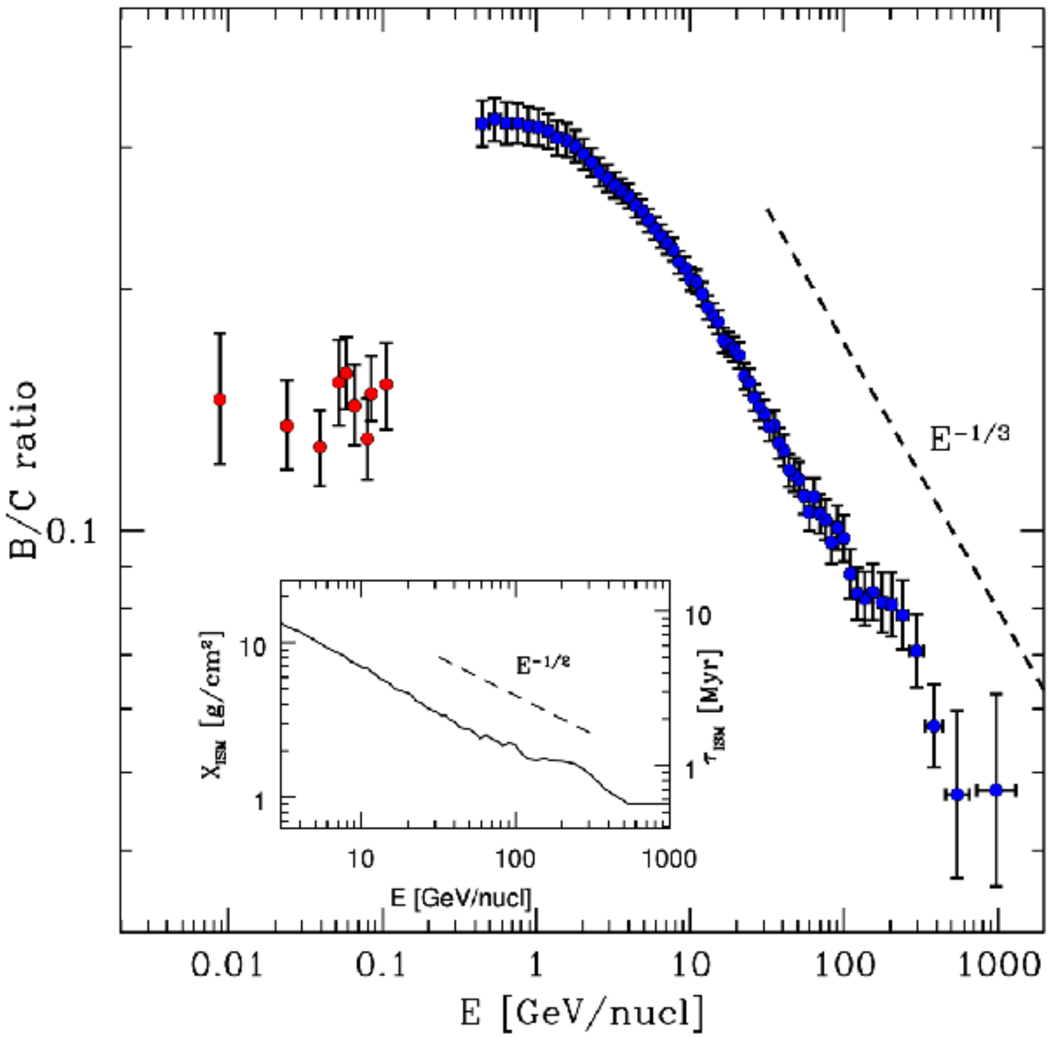

the B/C ratio is sensitive ONLY to the amount of matter crossed by cosmic rays, and not to the way in which this matter is accumulated (when CRs enter the halo the grammage does not increase until the CRs go back to the disk...)

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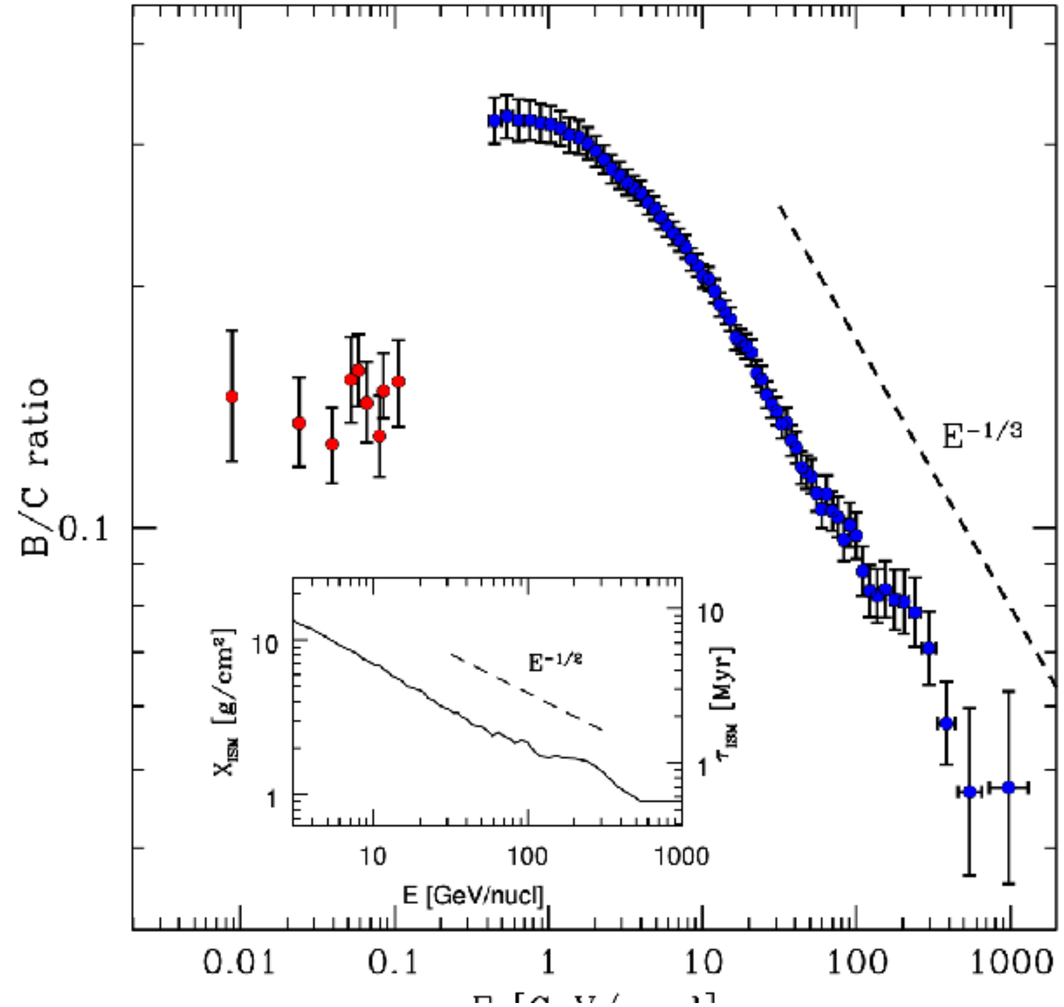

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**we need a clock to measure how much time CRs spend in the halo (if any!)**

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$\tau_{rad} \lesssim \tau_{esc}$ —> the radioactive nuclide decays before escaping the MW

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

* 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

stable isotope!

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

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

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~0.8

this can be measured

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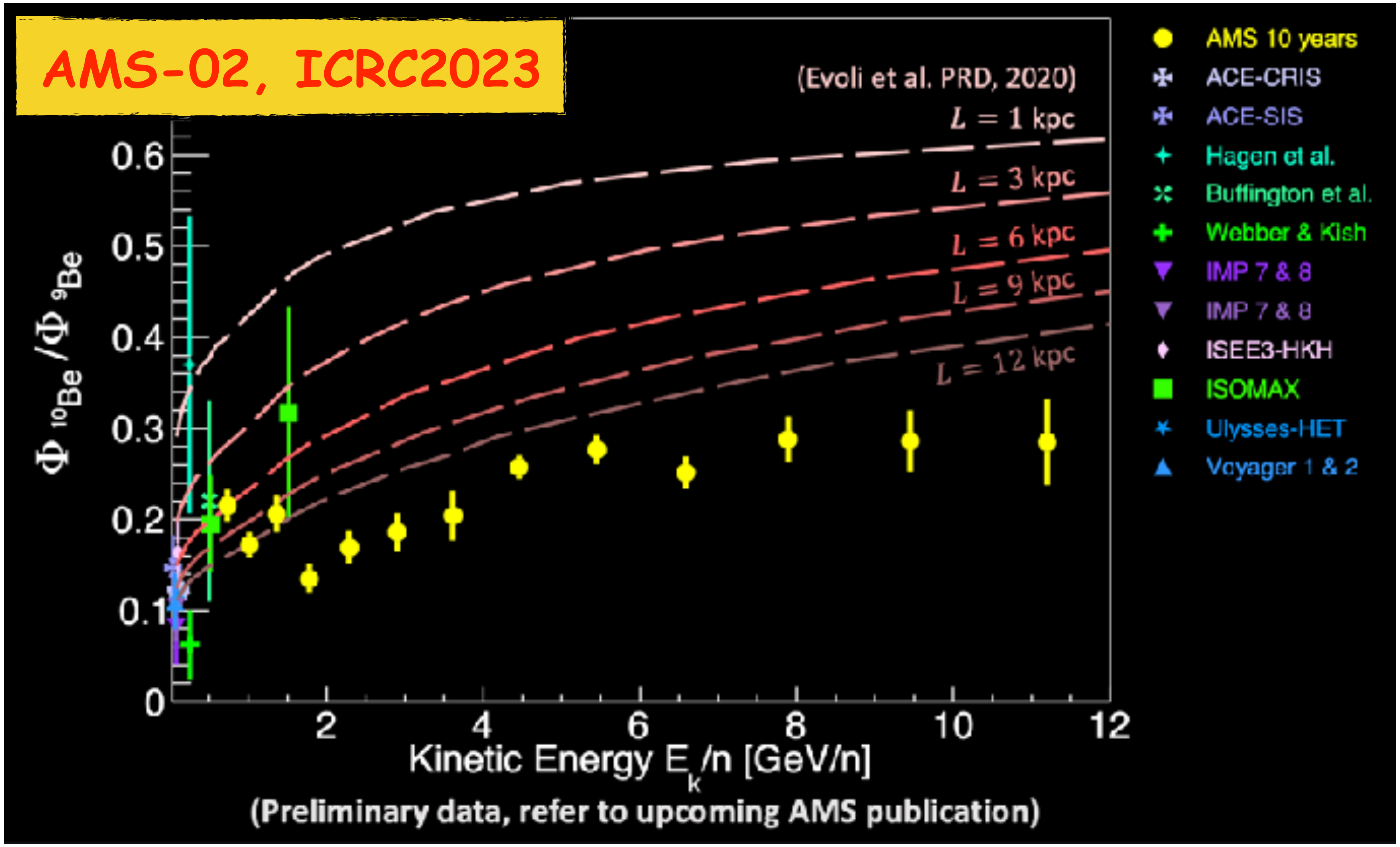

**AMS-02, ICRC2023**

(Evoli et al. PRD, 2020)

(Preliminary data, refer to upcoming AMS publication)

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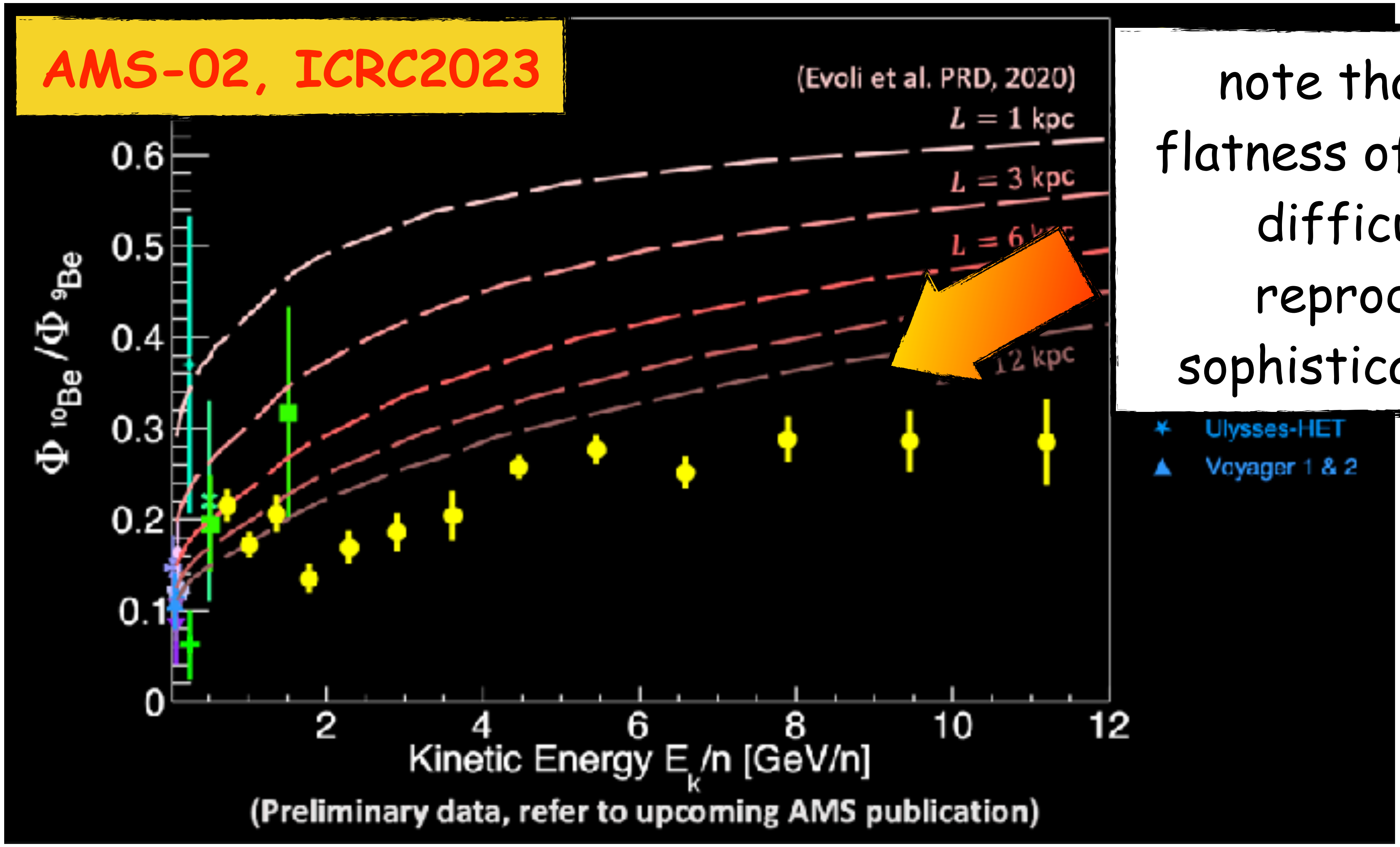
~0.8

~0.3 → $$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \approx \frac{q(^{10}\mathrm{Be})}{q(^{9}\mathrm{Be})} \times \frac{\gamma\tau_{rad}}{\boxed{\tau_{esc}}}$$ ← known



(Preliminary data, refer to upcoming AMS publication)

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

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

$$\overset{\sim 0.8}{\phantom{x}}$$

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

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

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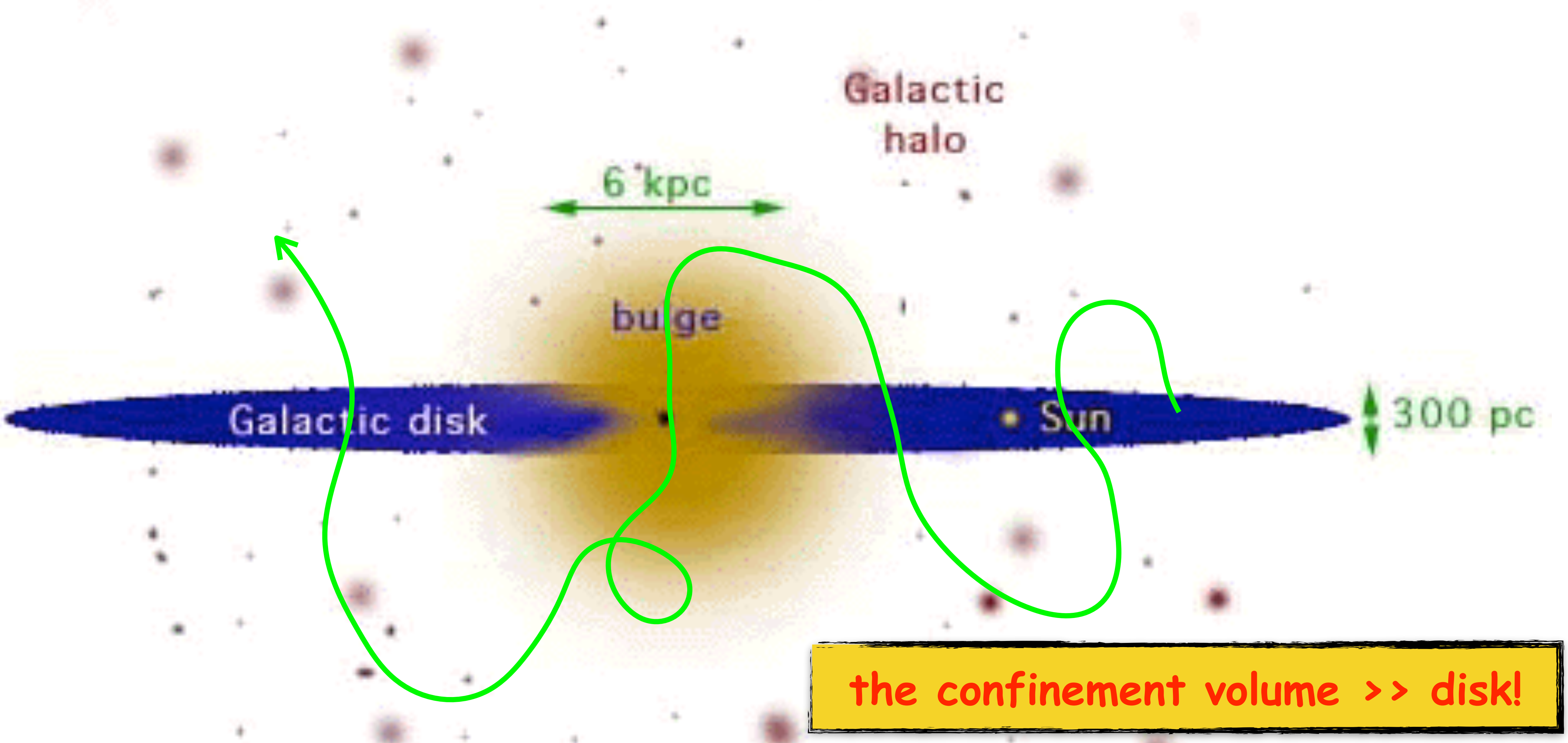
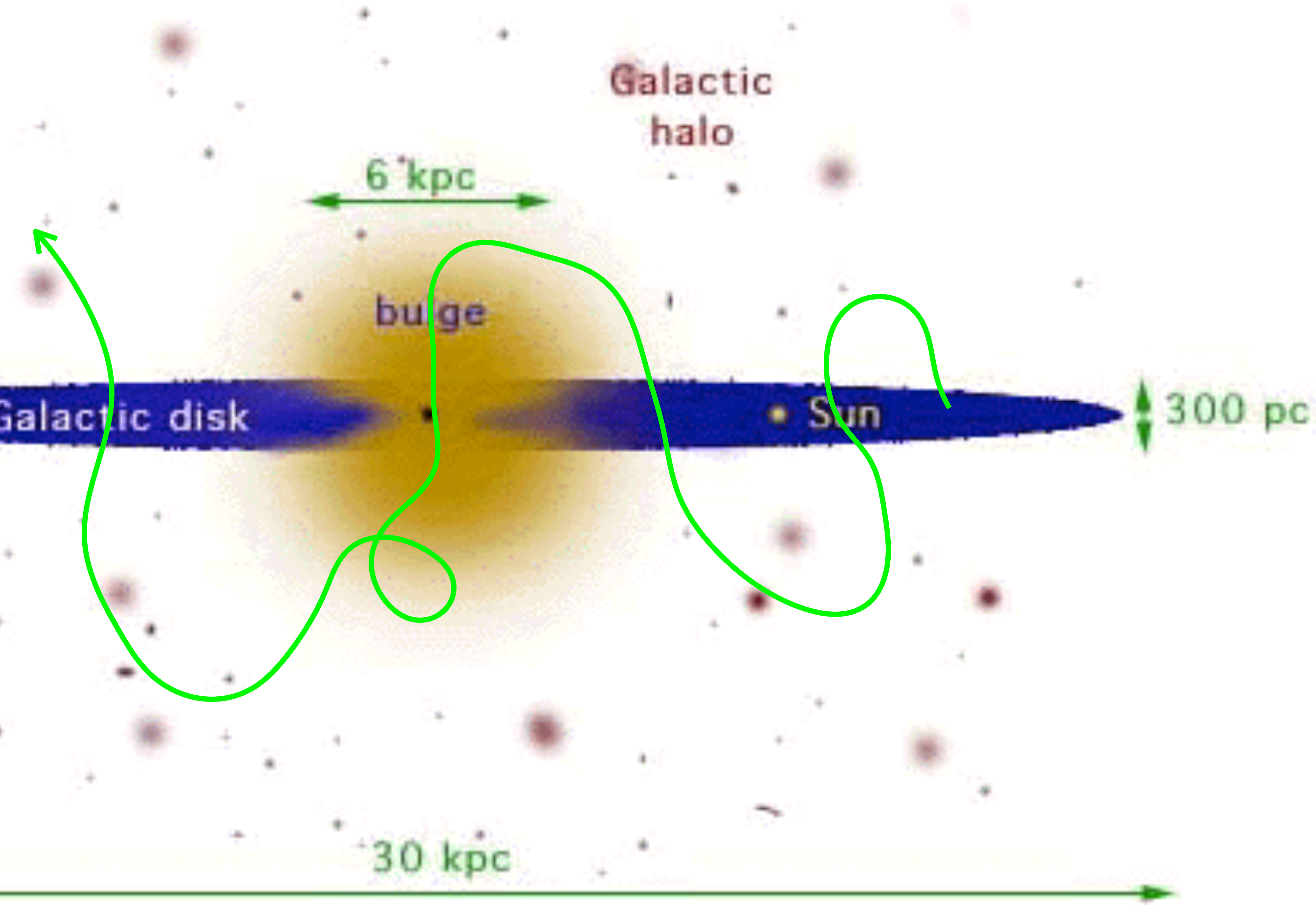


**the confinement volume >> disk!**

# [6] Diffusive models for CR transport

# Diffusive models



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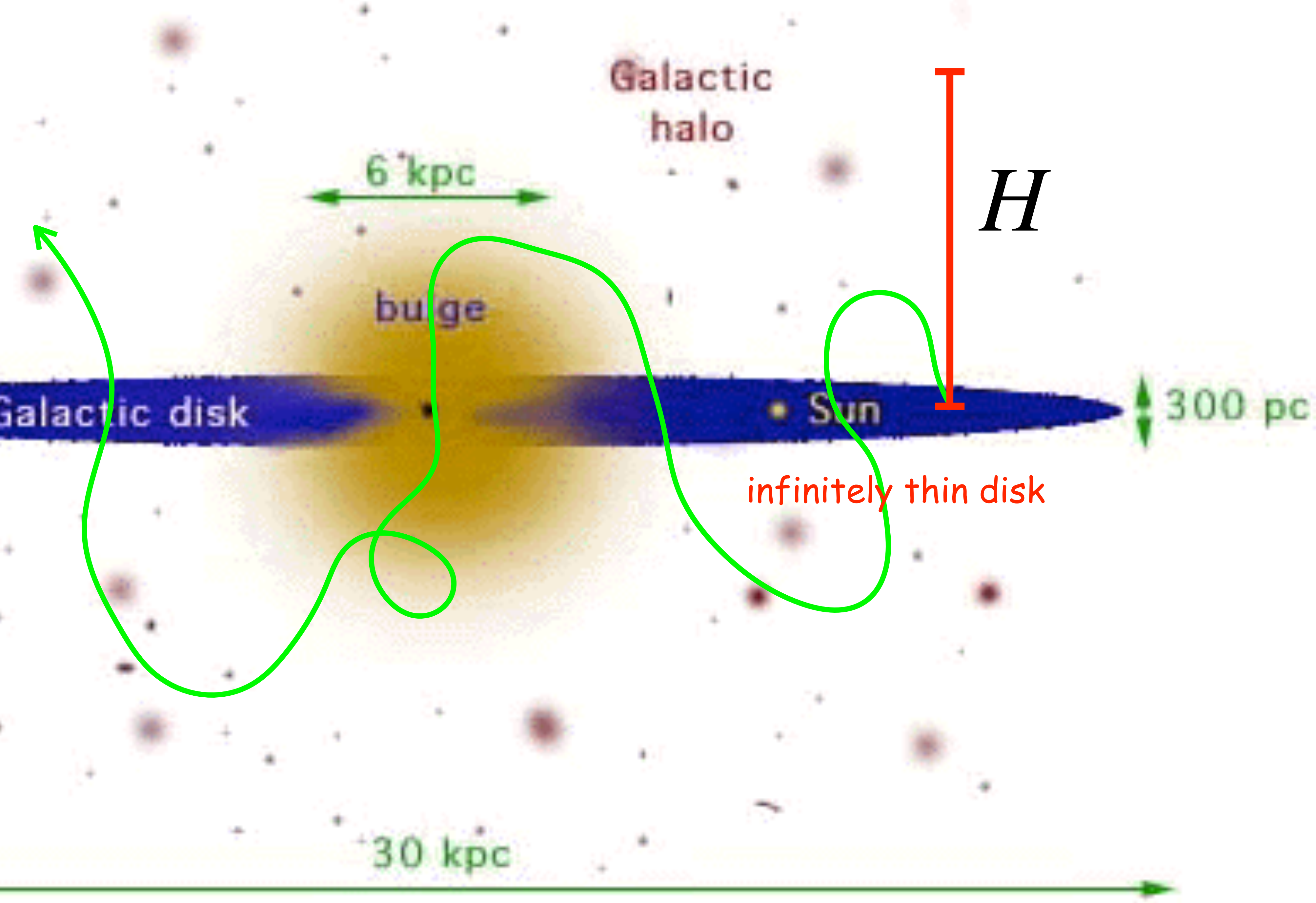

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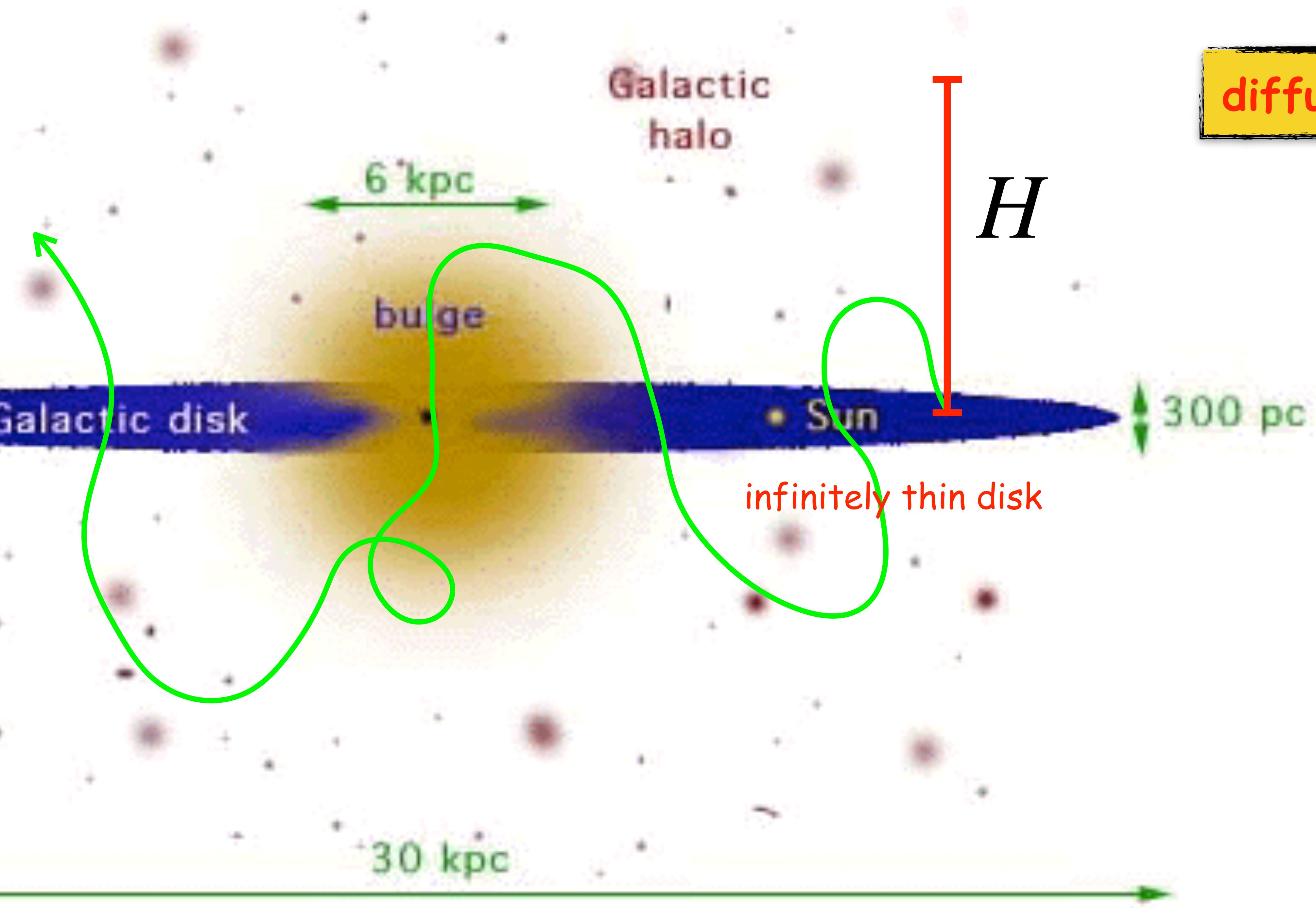


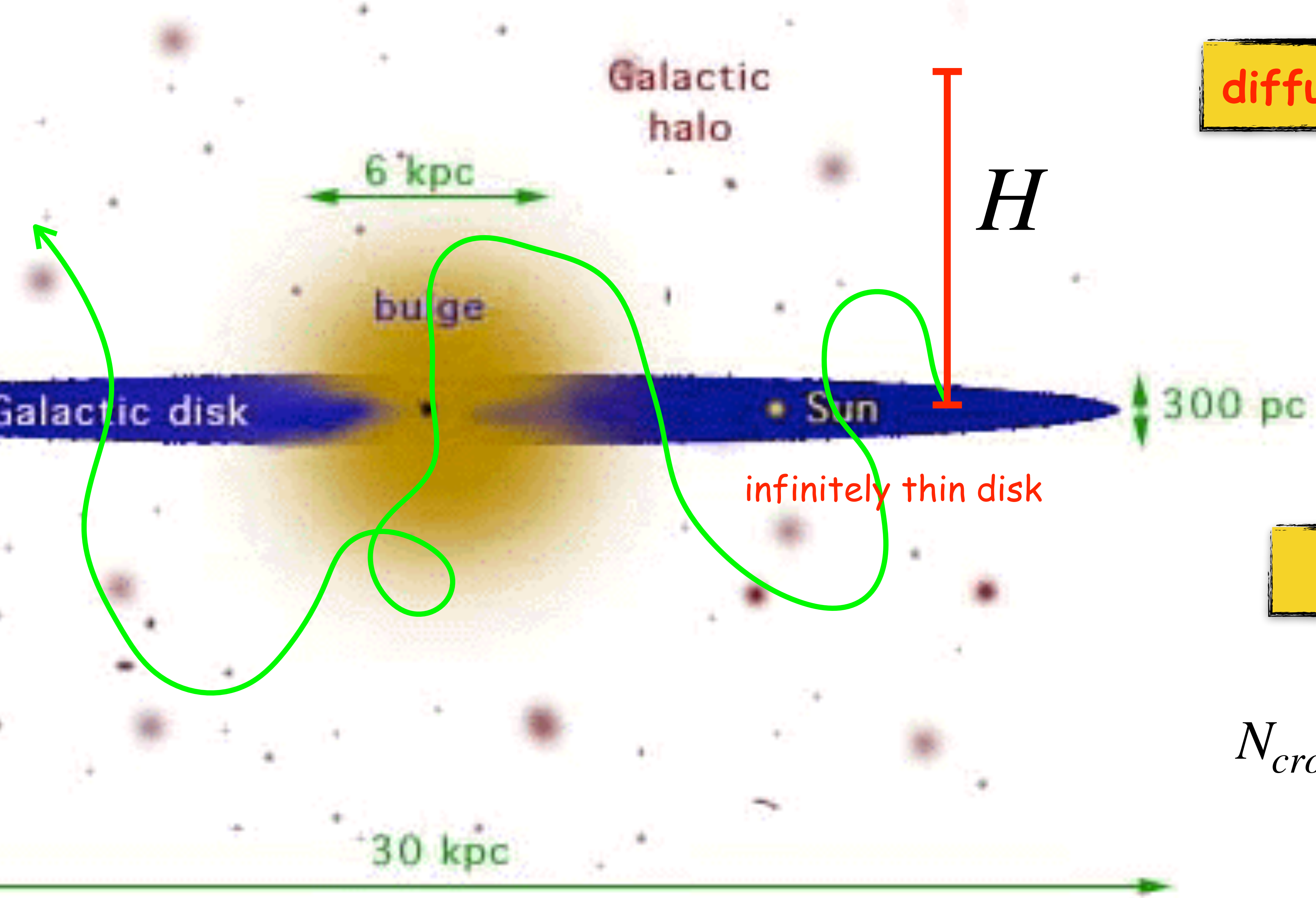
**diffusion coefficient**

mean free path

$$D \sim \lambda v$$

velocity

# Diffusive models



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**# of crossings**

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

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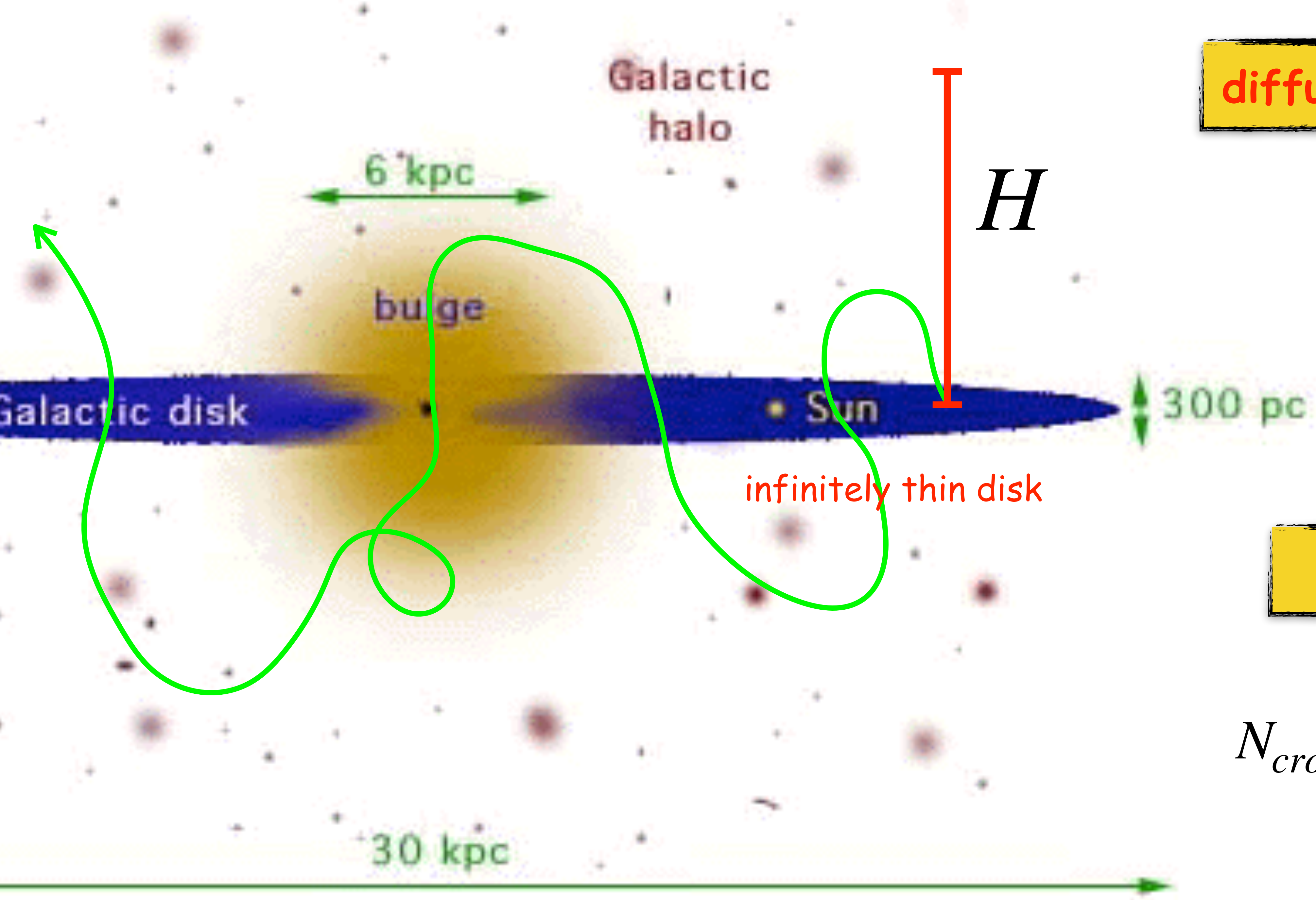

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mean free path

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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

$$\frac{n_{\mathrm{B}}}{n_{\mathrm{C}}} \longrightarrow \mathrm{X}_{ISM} \propto \frac{H}{D}$$

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0.002 g/cm$^2$

$$\mathrm{X}_{ISM} \sim N_{cross}\mathrm{X}_{disk} \sim \frac{Hv}{D}\mathrm{X}_{disk} \sim \frac{\tau_{esc} v \mathrm{X}_{disk}}{H} \longrightarrow H \sim \tau_{esc} v \frac{\mathrm{X}_{disk}}{\mathrm{X}_{ISM}} \sim 4\ \mathrm{kpc}$$

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$$D(10\ \mathrm{GeV/n}) \sim \frac{H^2}{\tau_{esc}} \lesssim \boxed{10^{29} \mathrm{cm}^2/\mathrm{s}}$$

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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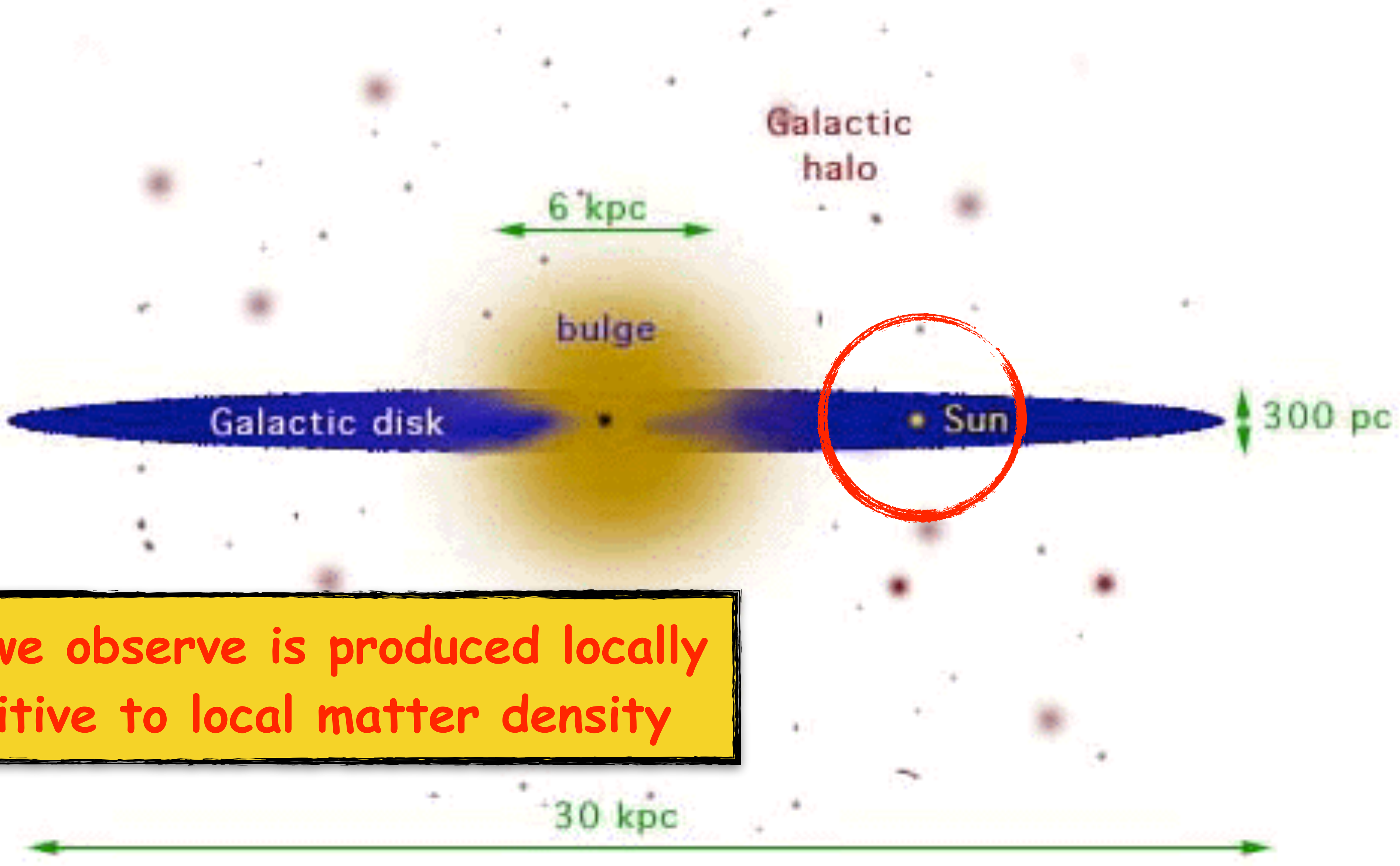
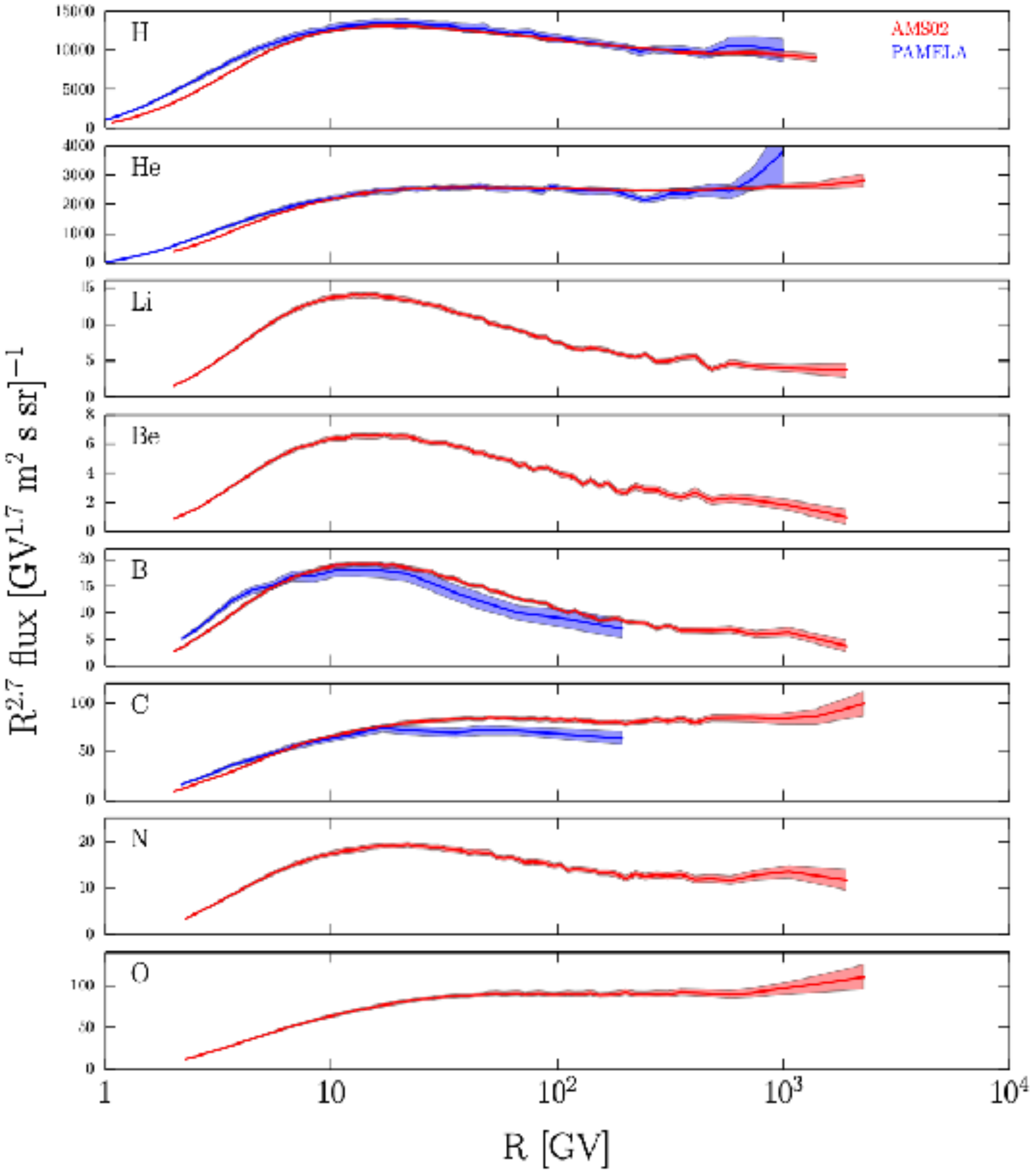


the $^{10}$Be we observe is produced locally
—> sensitive to local matter density

# Let's go back to CR spectra



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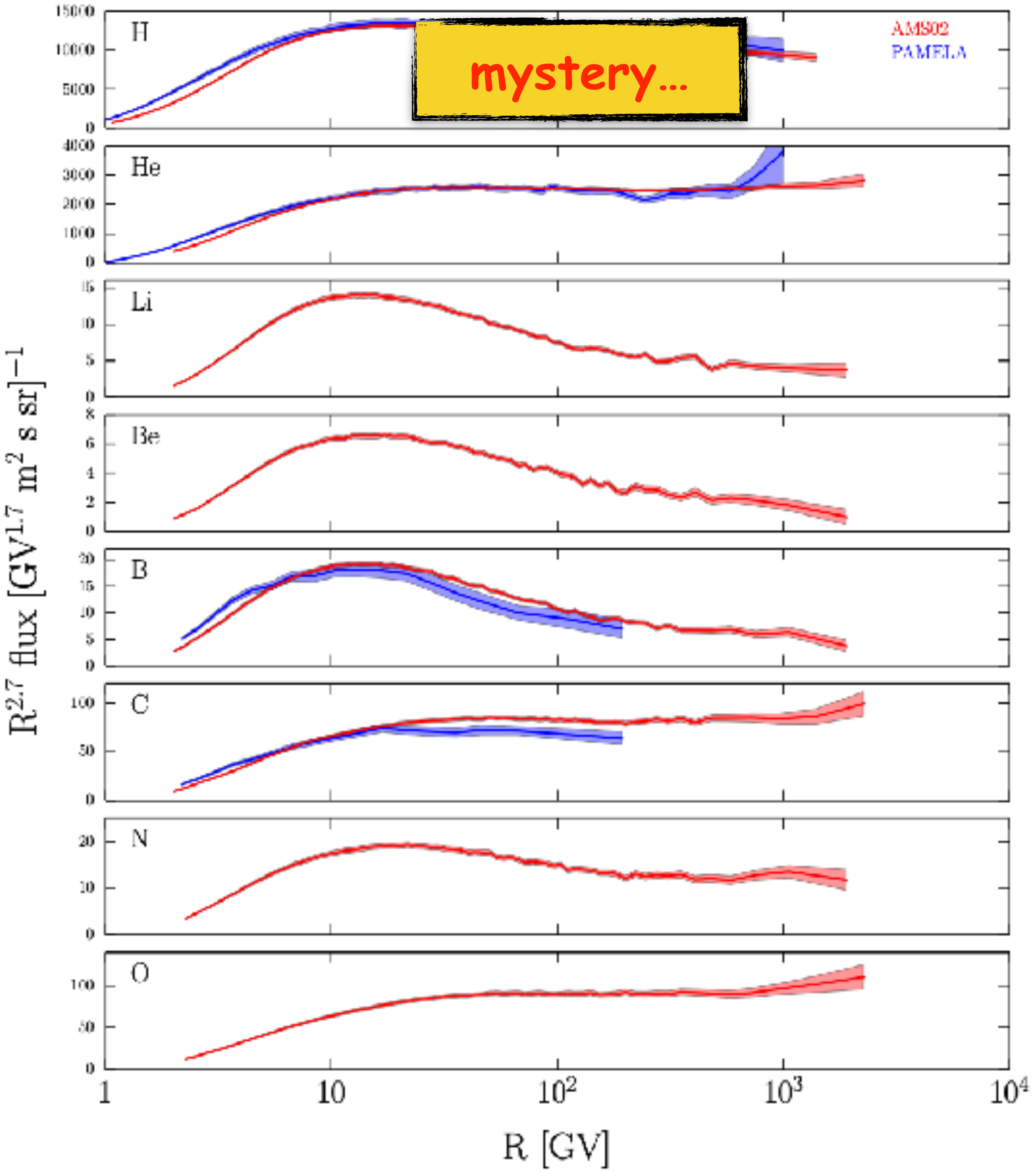

mystery...

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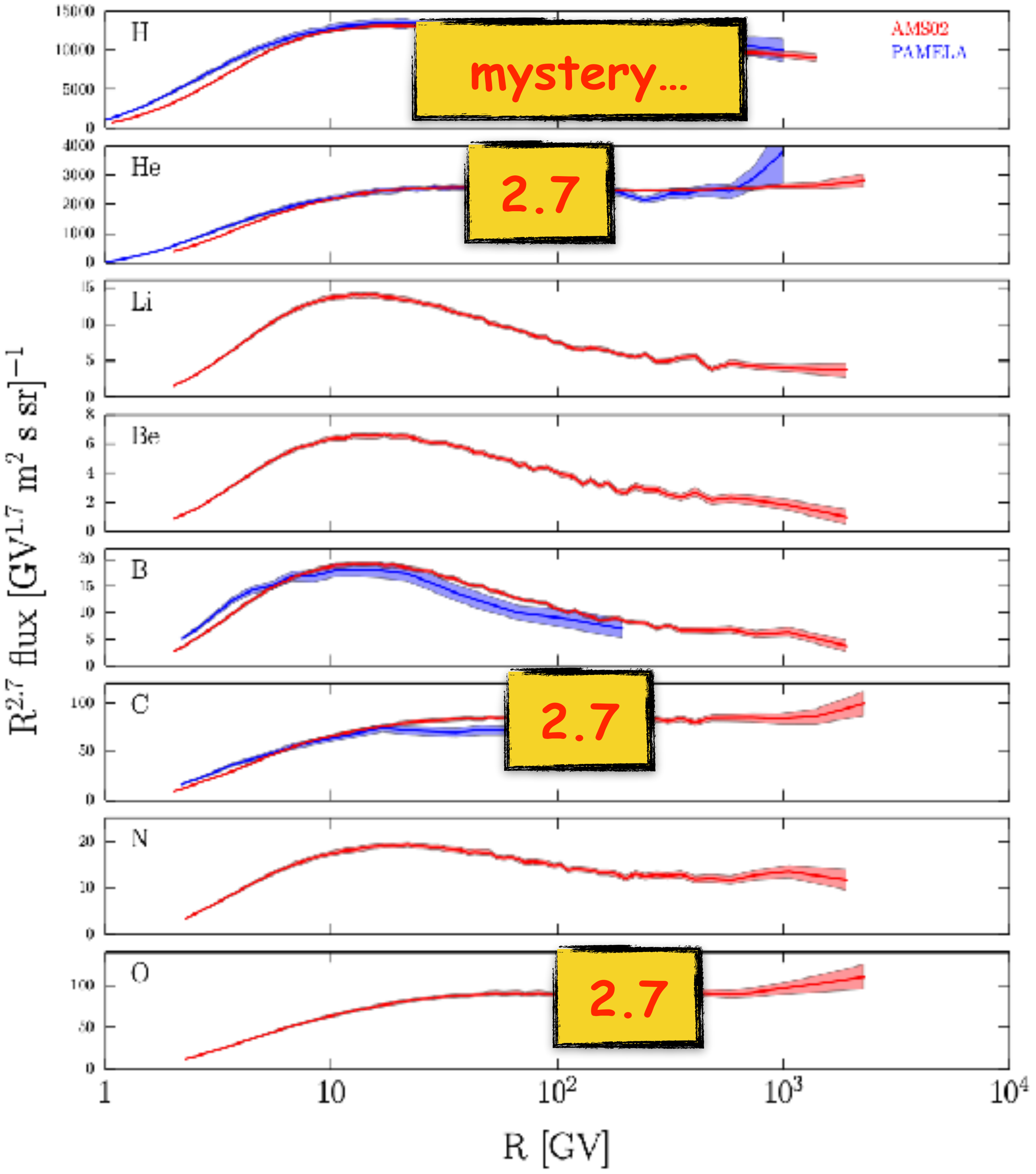

mystery…

2.7

2.7

2.7

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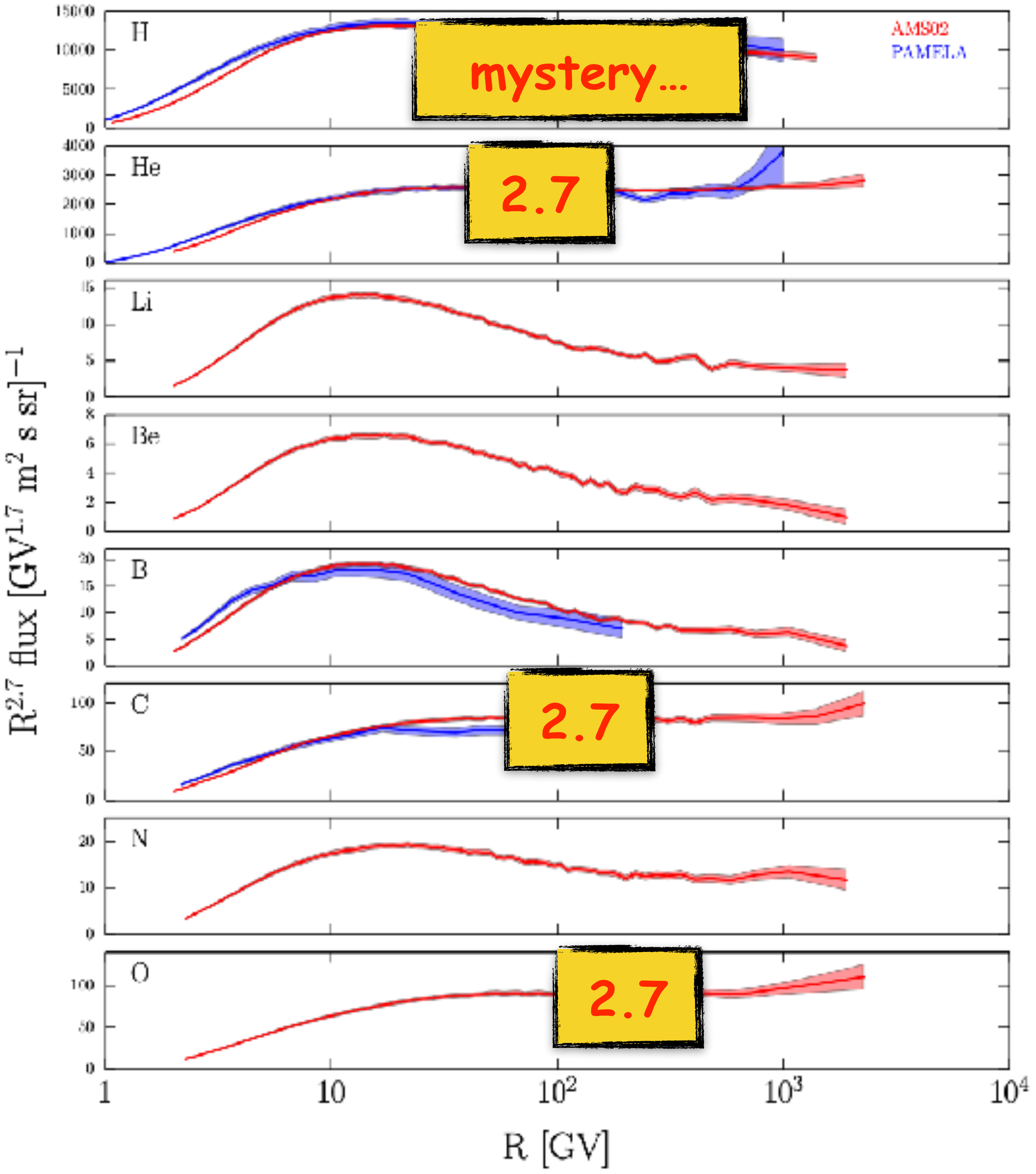

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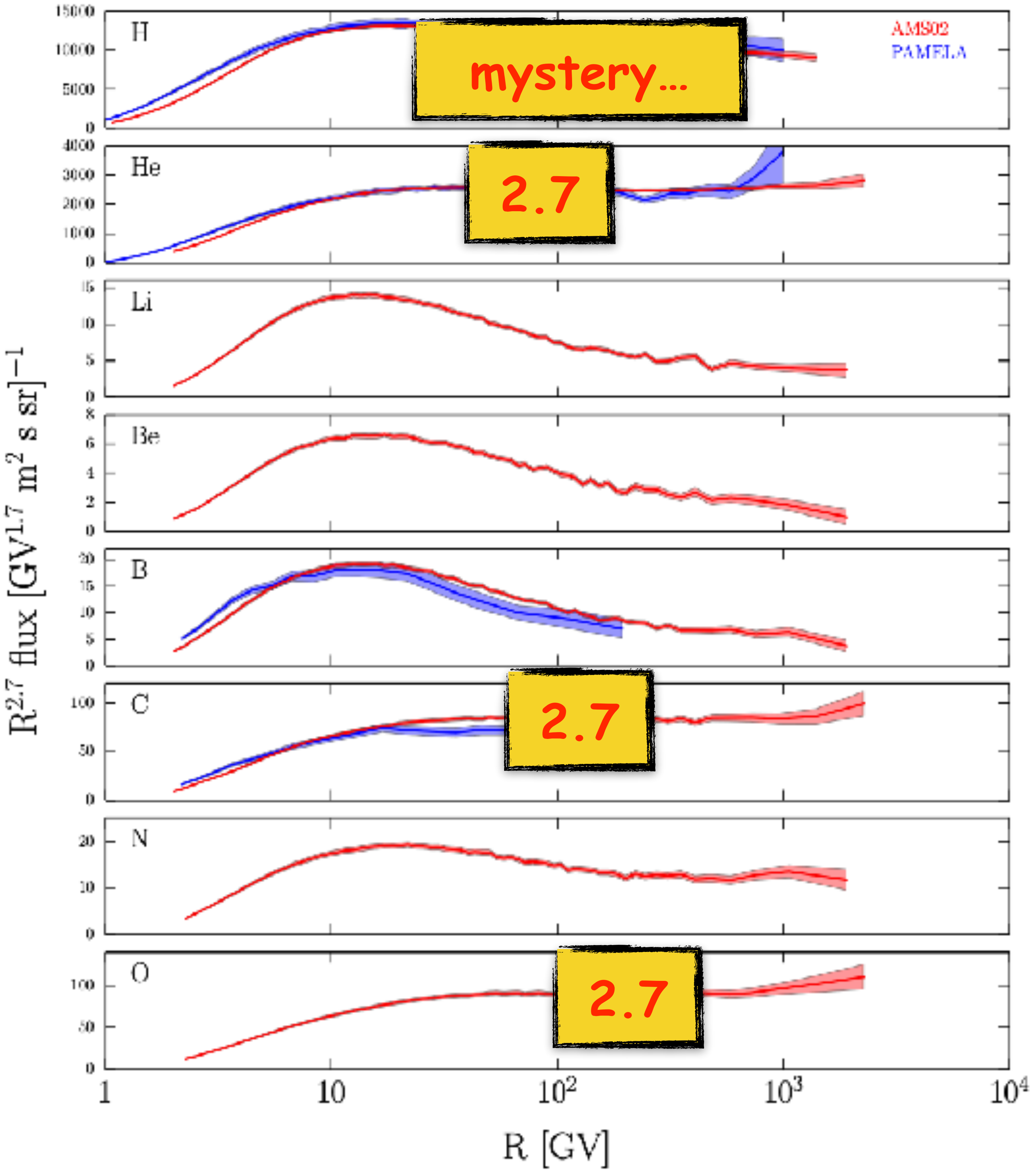

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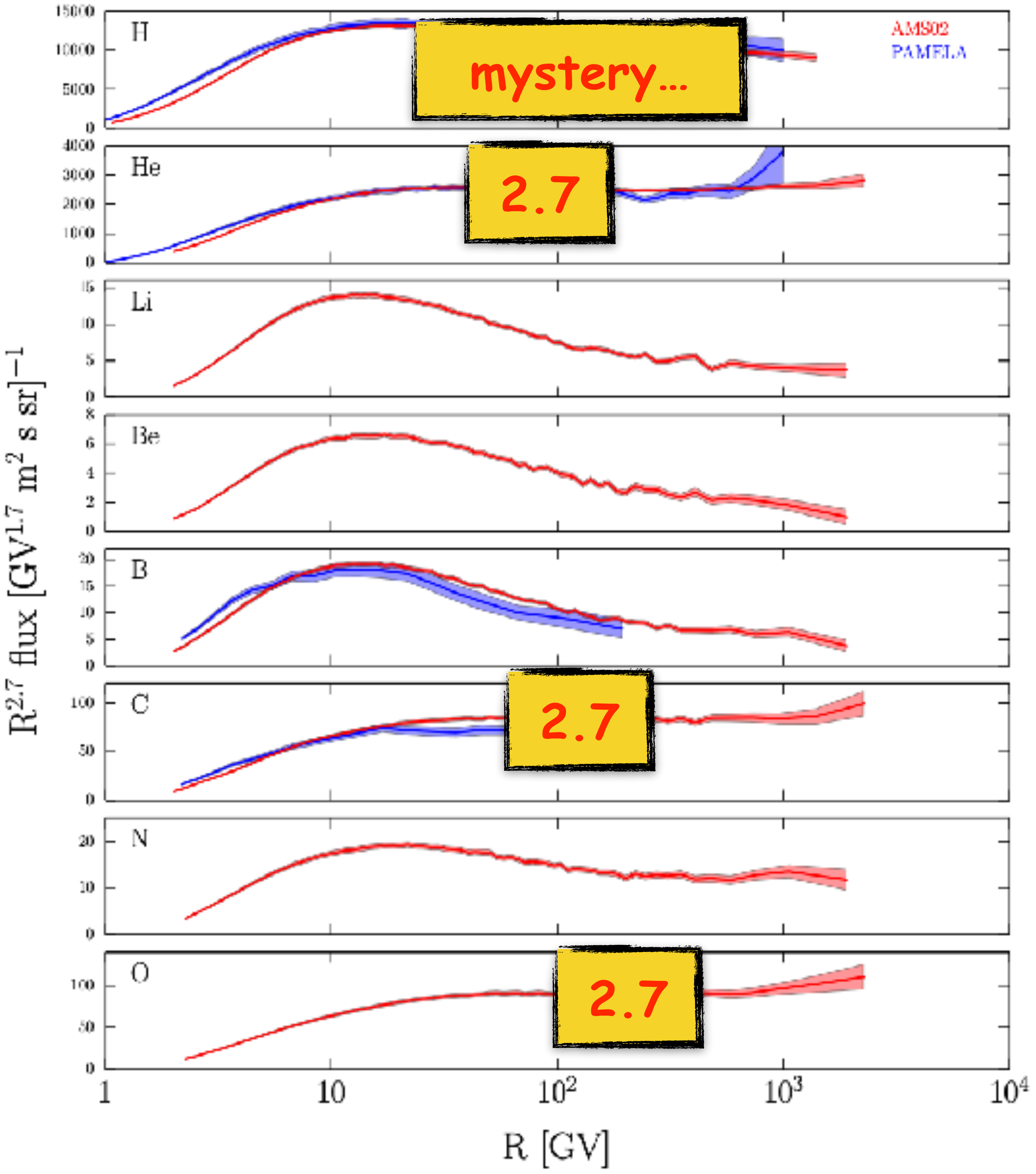

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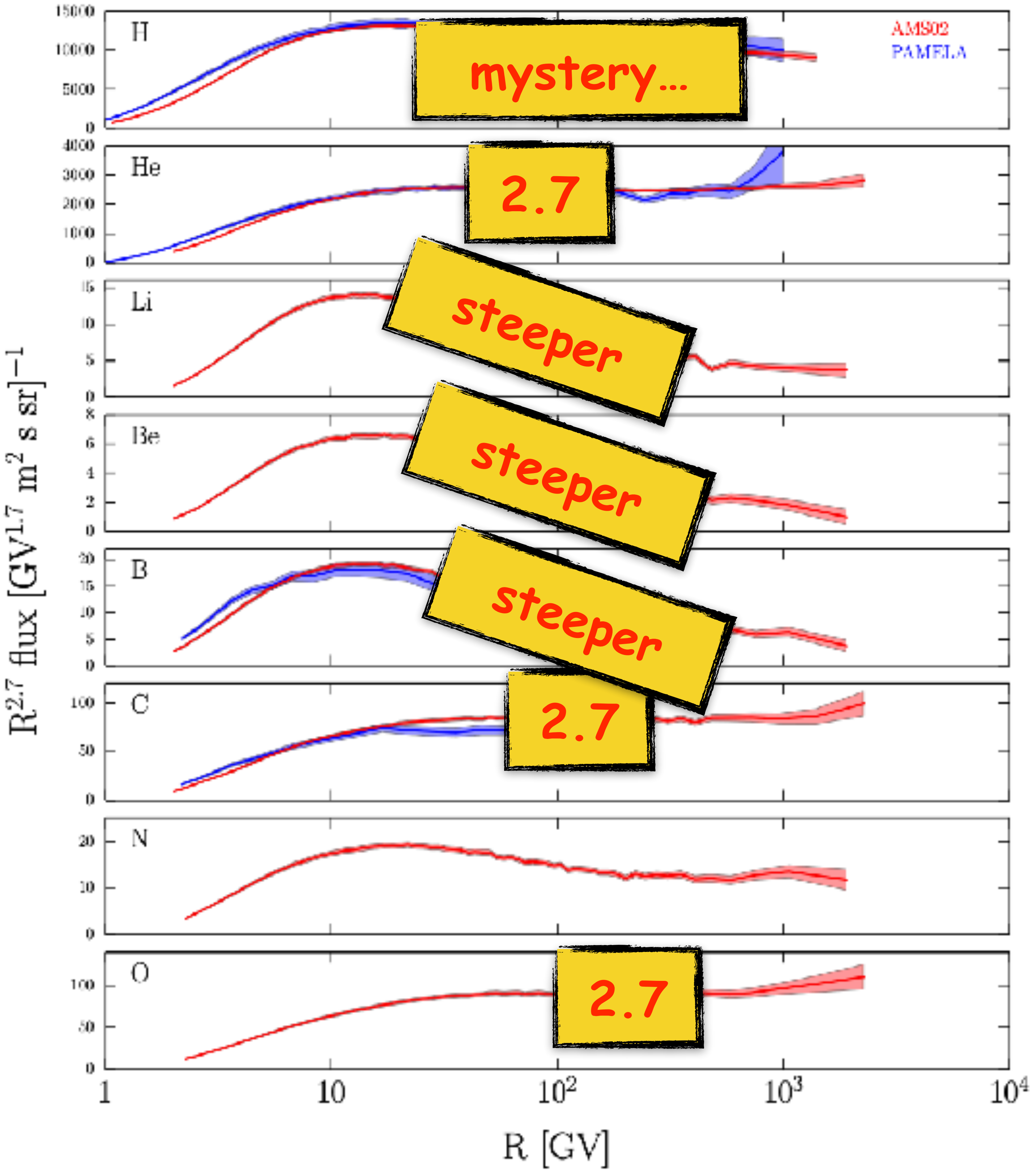

mystery...

2.7

steeper

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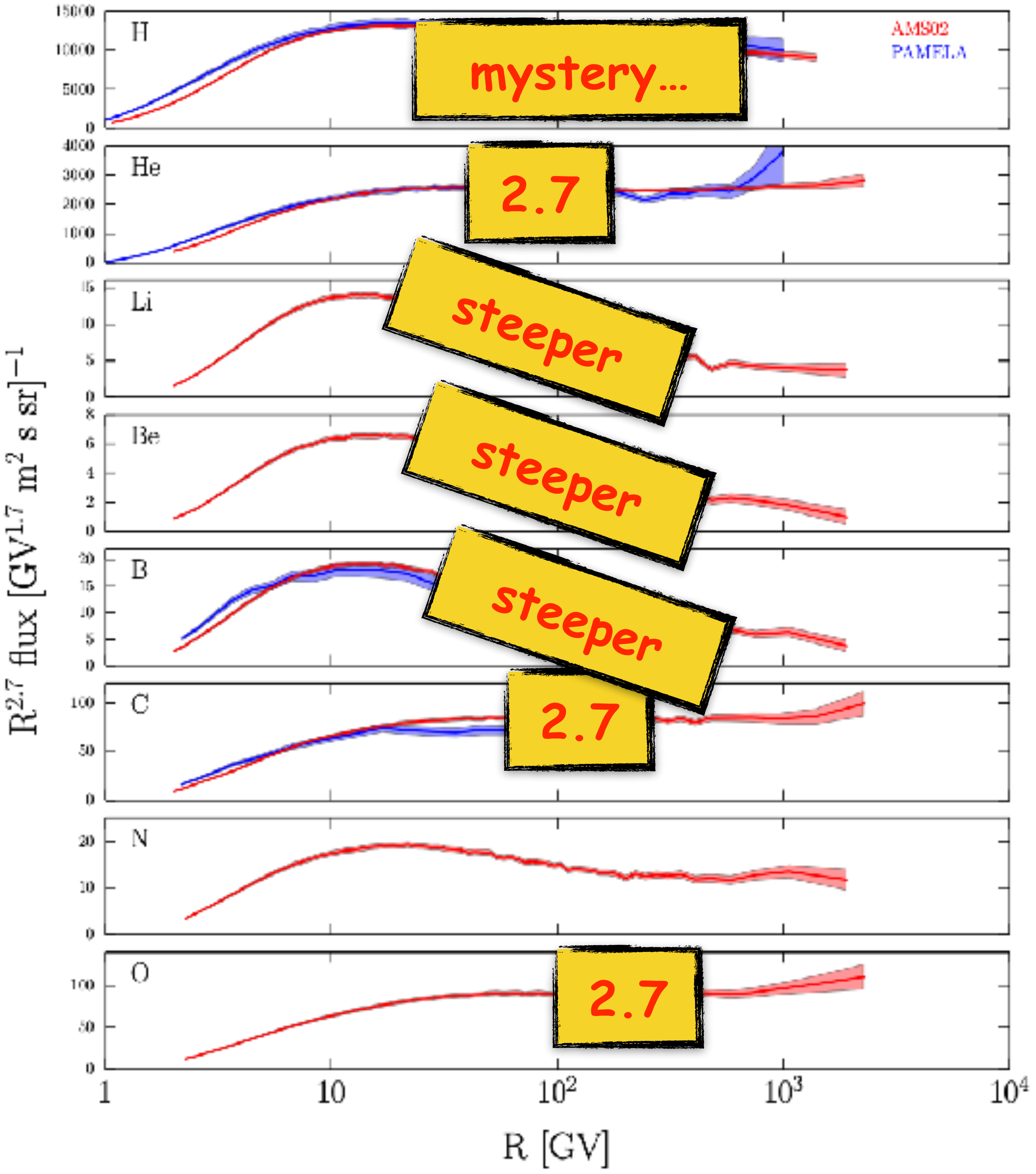

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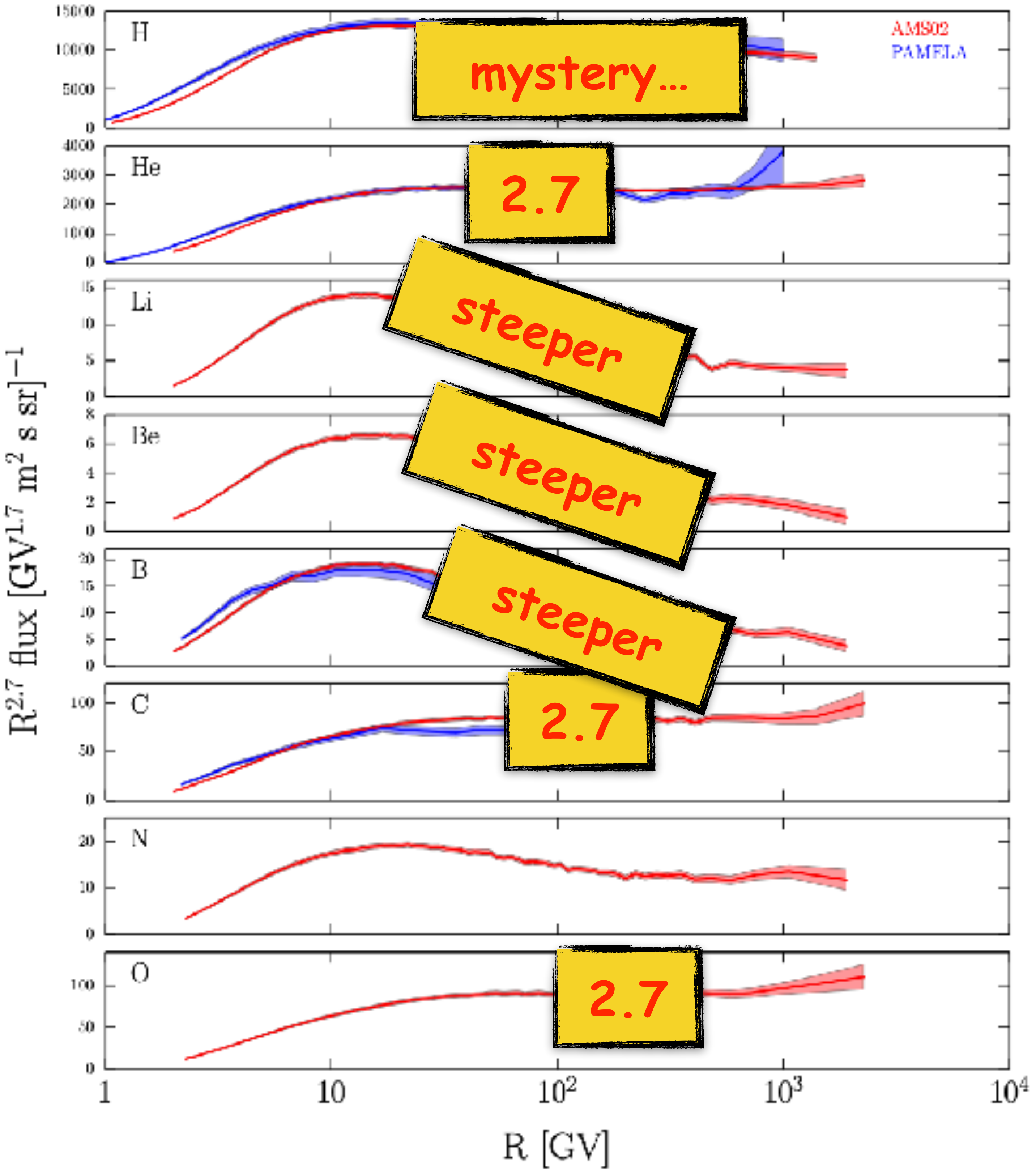

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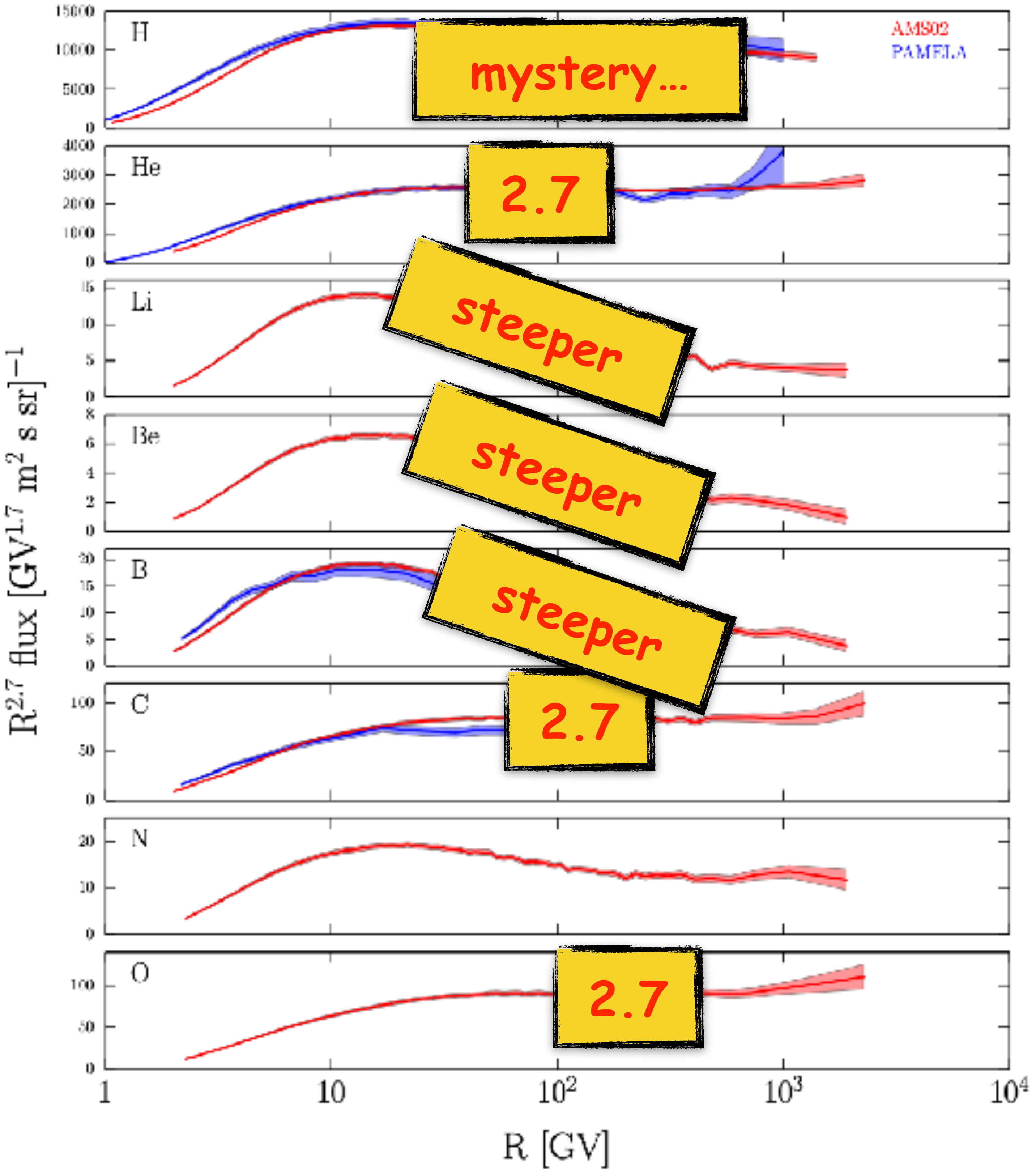

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**steeper!**

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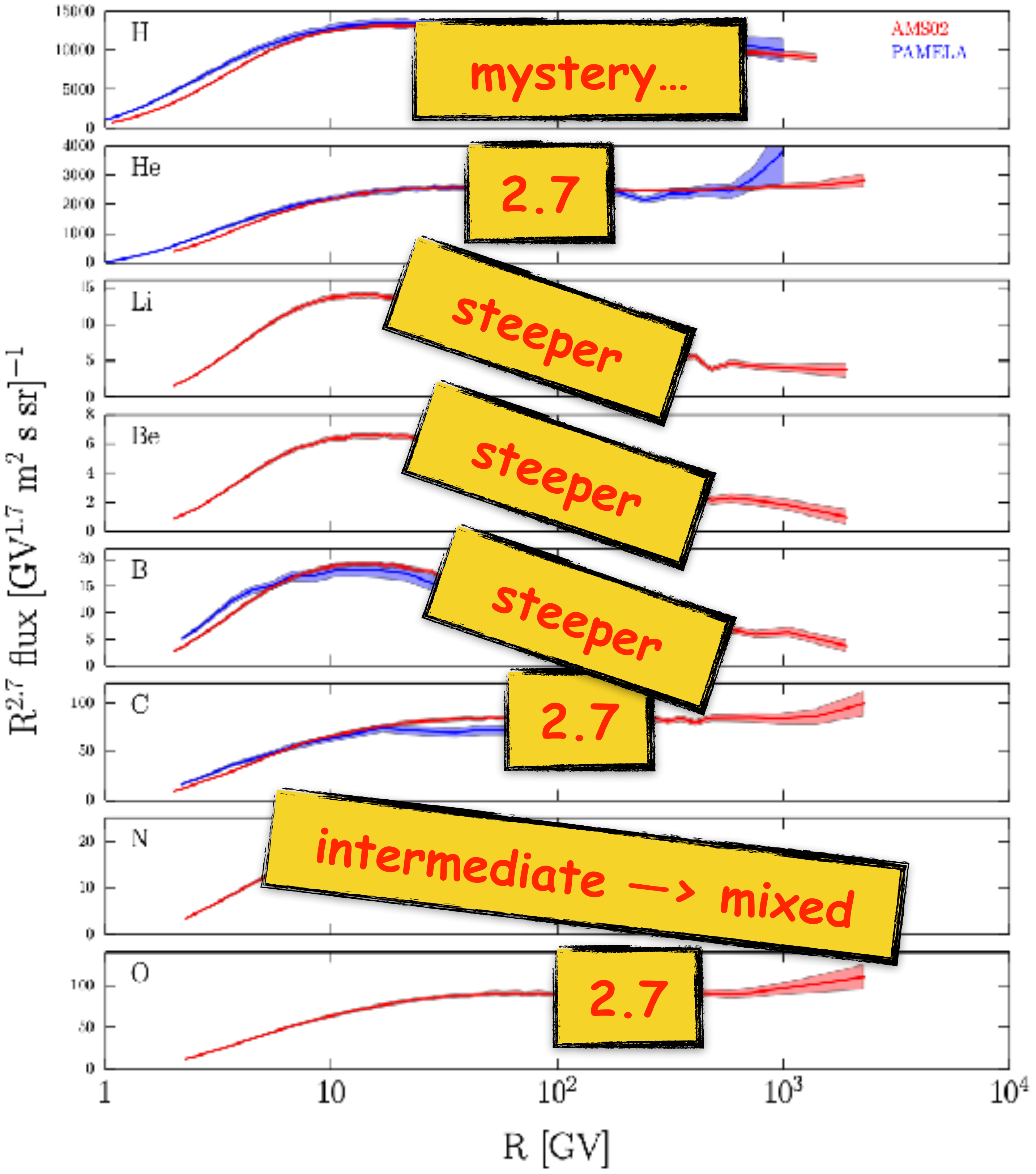

mystery…

2.7

steeper

steeper

steeper

2.7

intermediate —> mixed

2.7

**primaries**

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

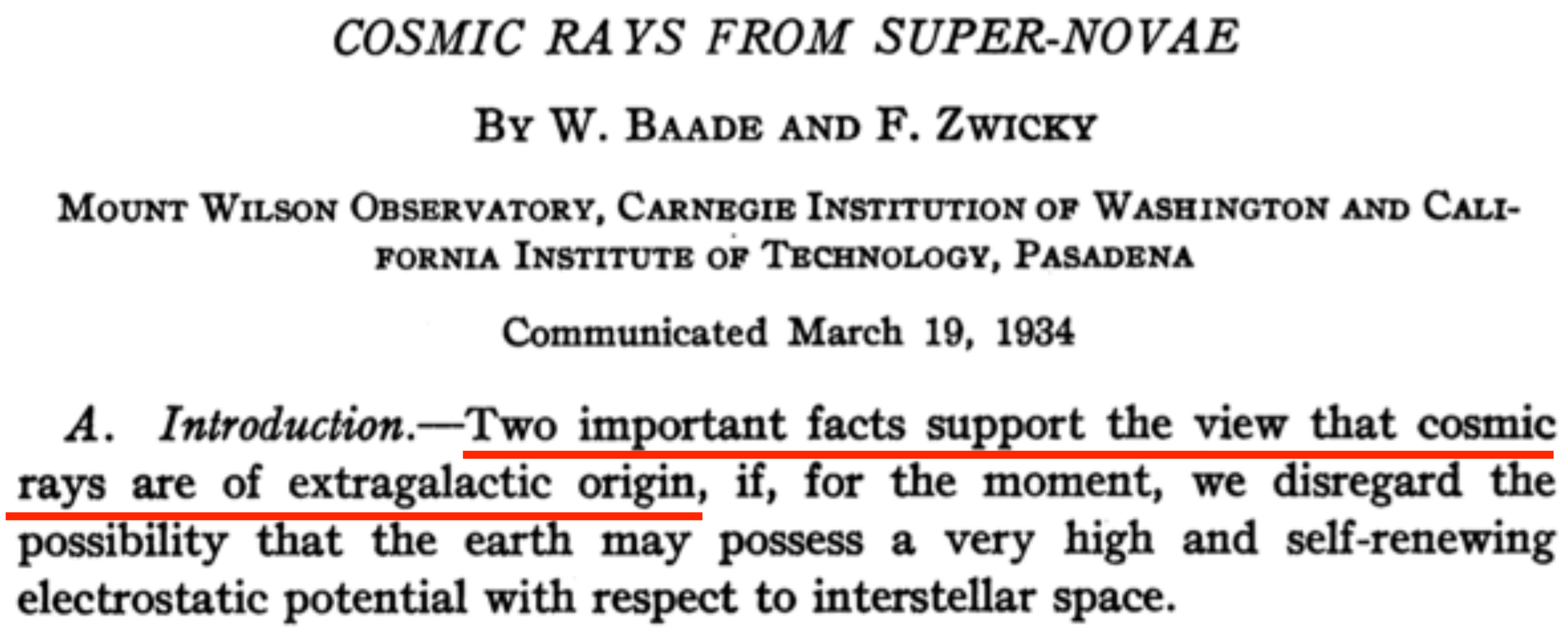
local energy density

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

**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

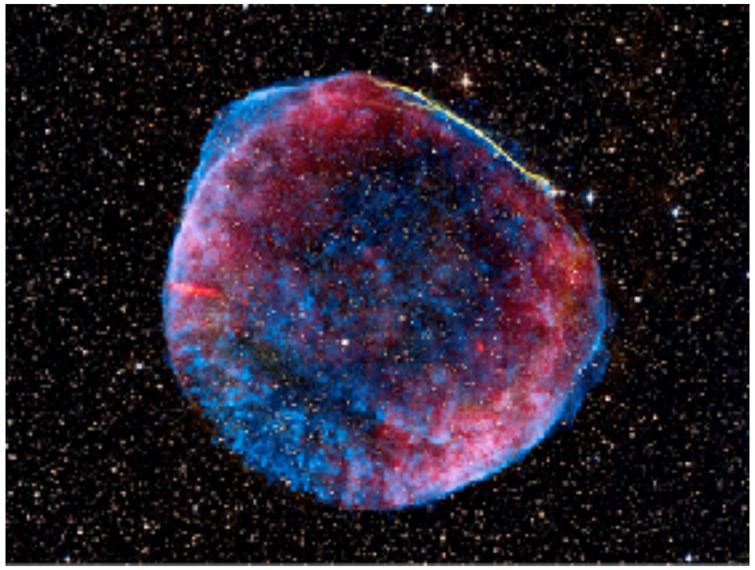
MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

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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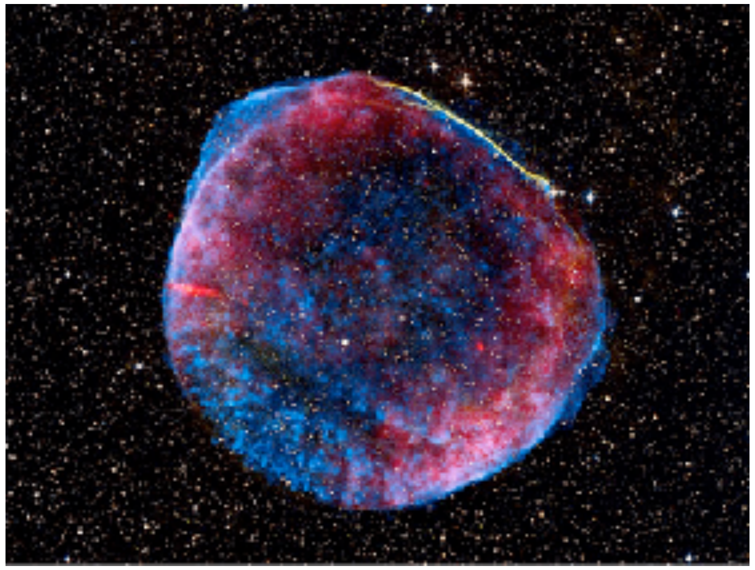

## modern formulation of the hypothesis

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

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

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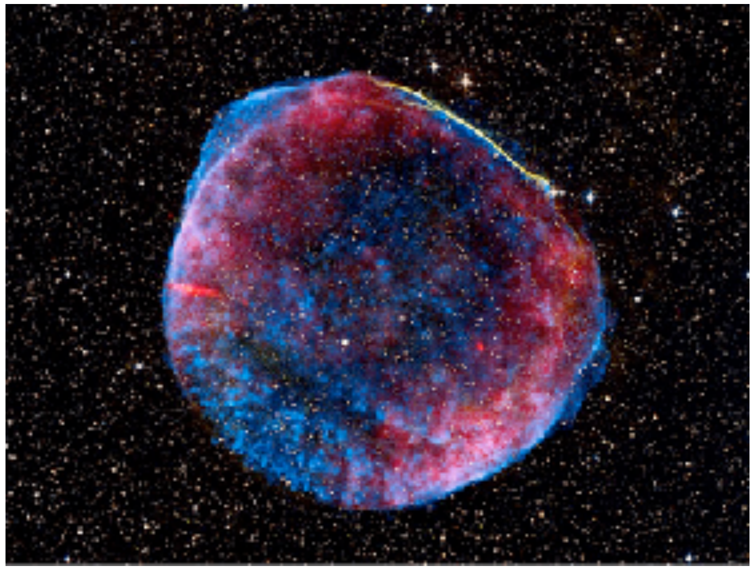

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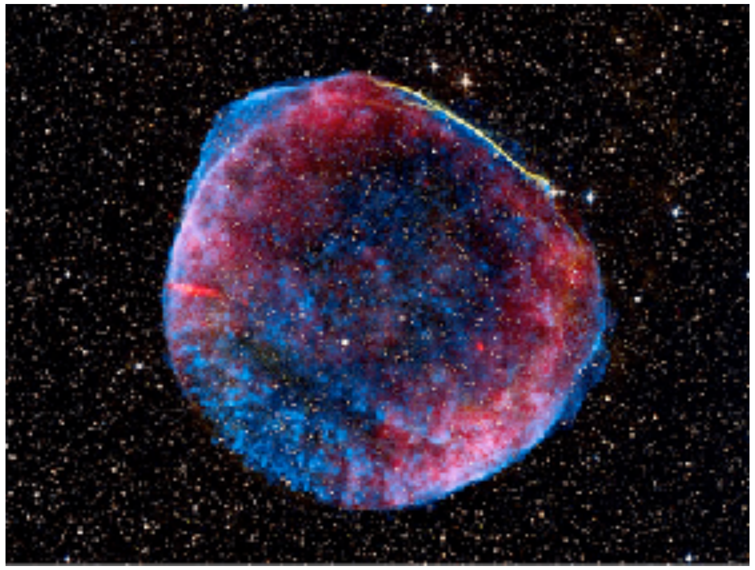

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~10% acceleration efficiency

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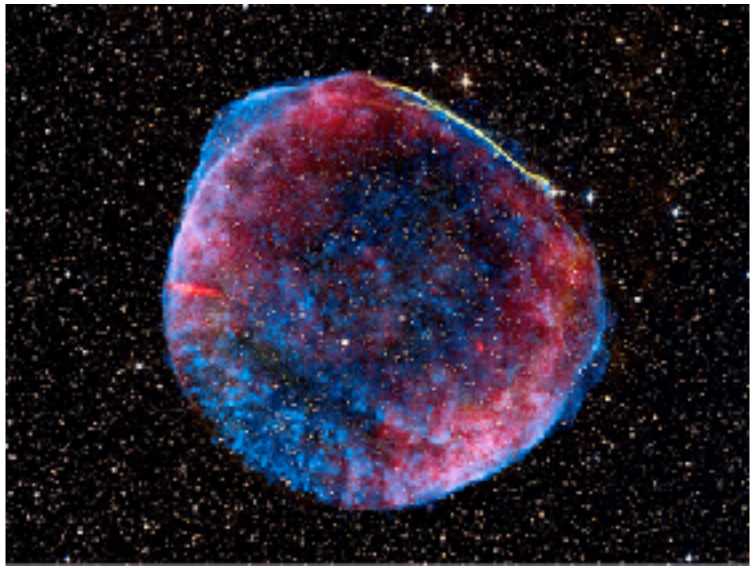

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~10% acceleration efficiency

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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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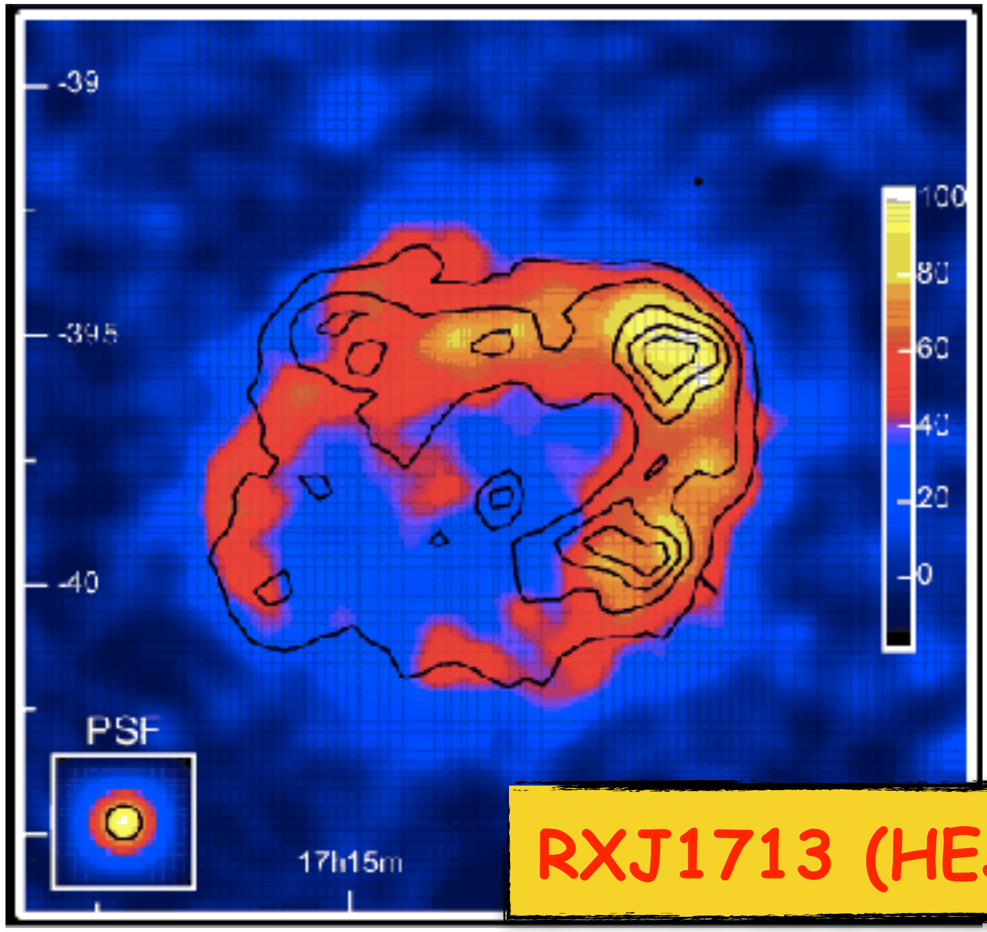

**RXJ1713 (HESS)**

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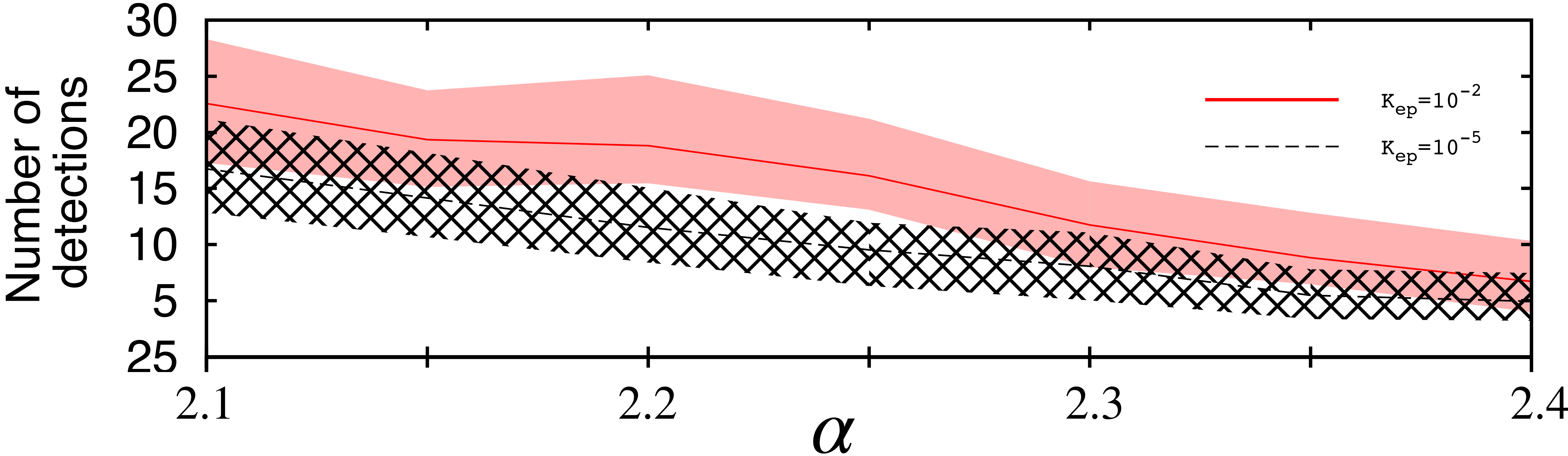

Cristofari+ 2013

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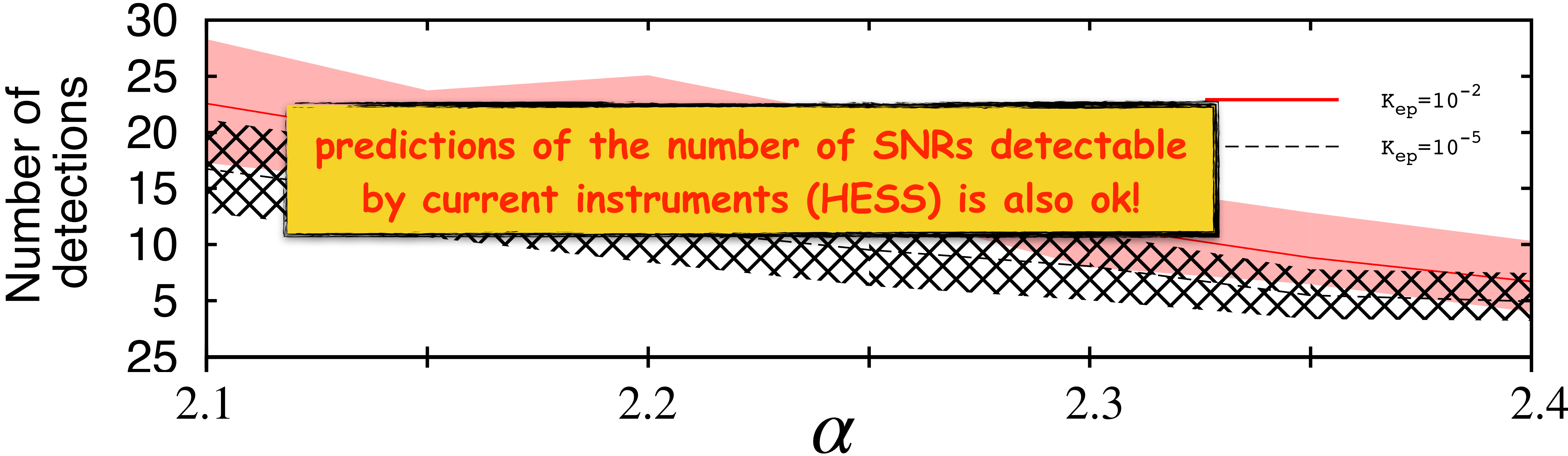


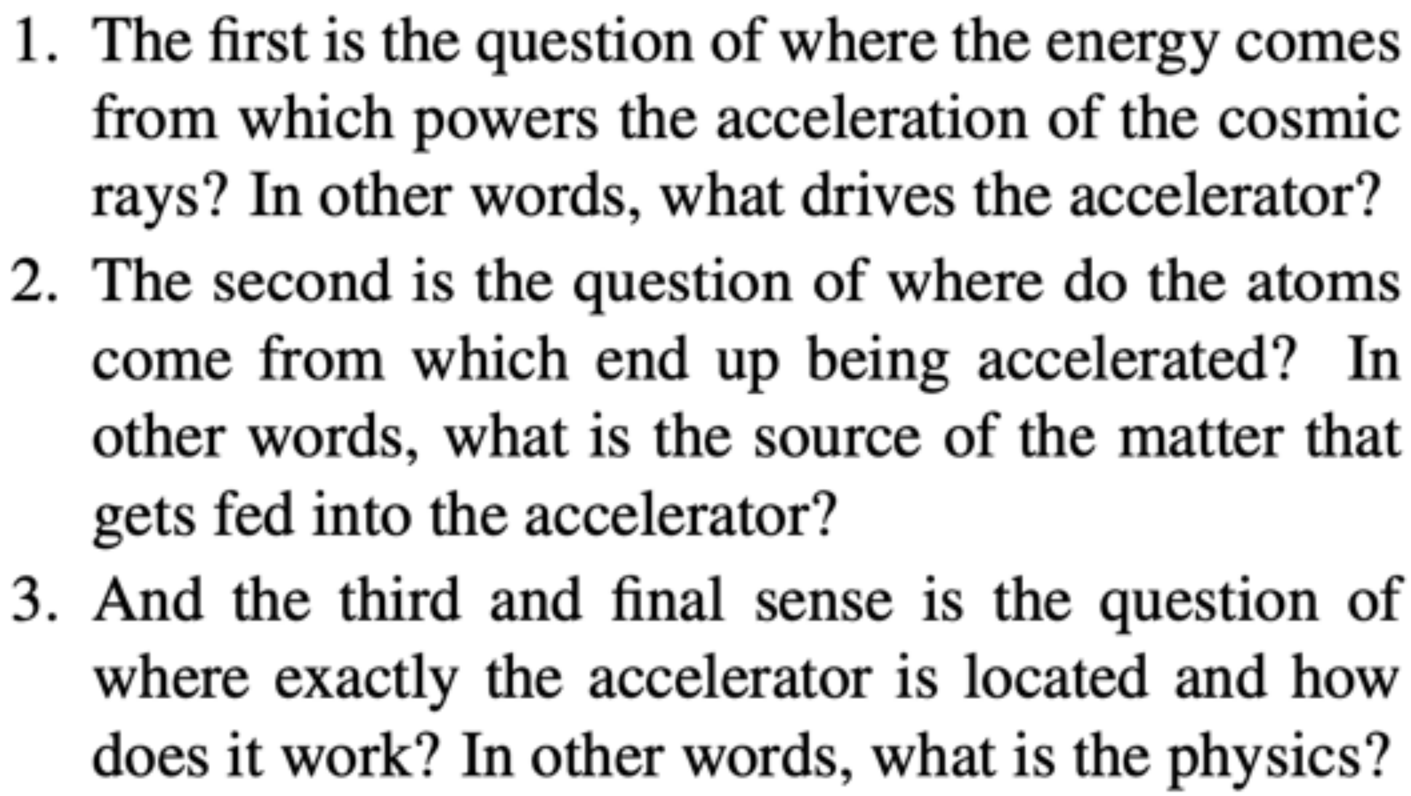
predictions of the number of SNRs detectable by current instruments (HESS) is also ok!

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?
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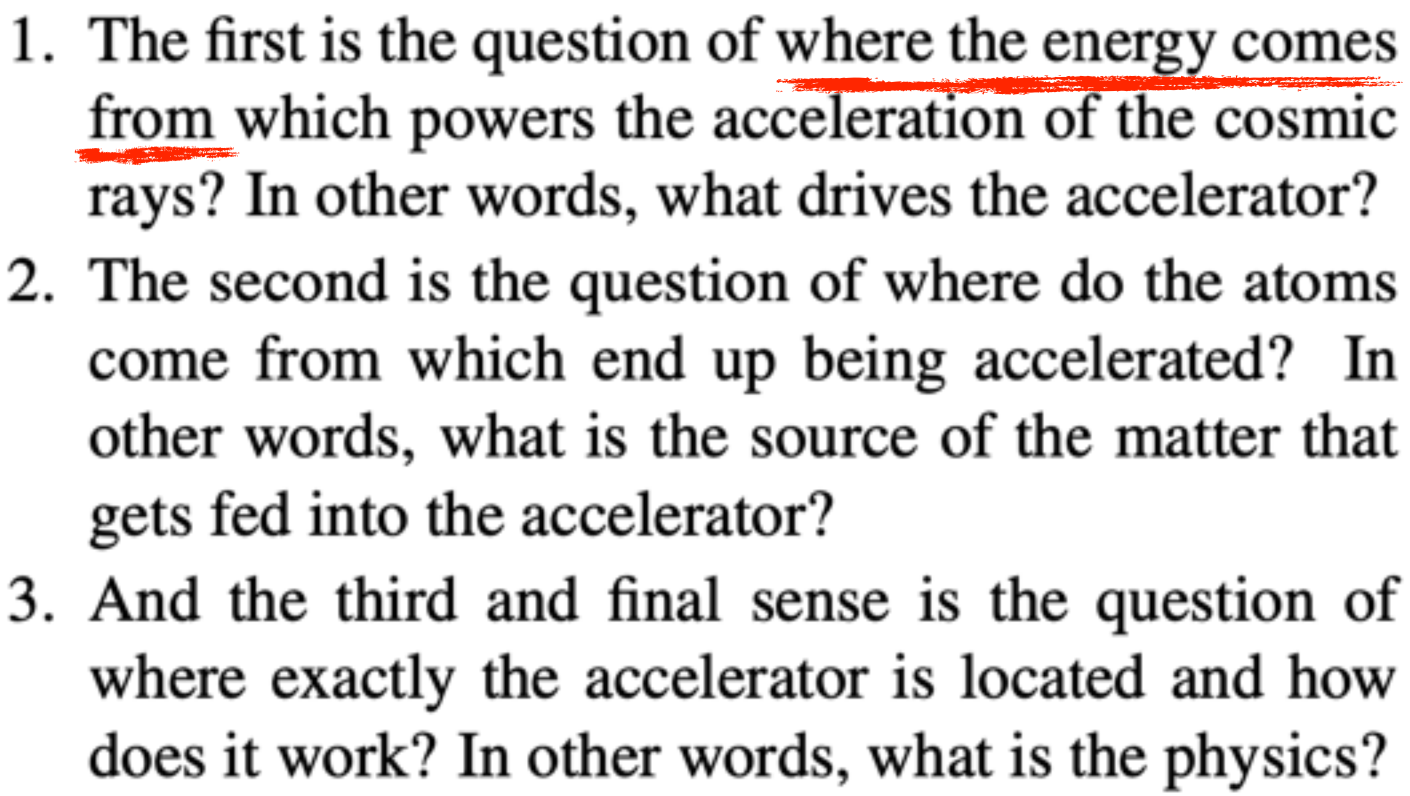
# Luke's questions

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



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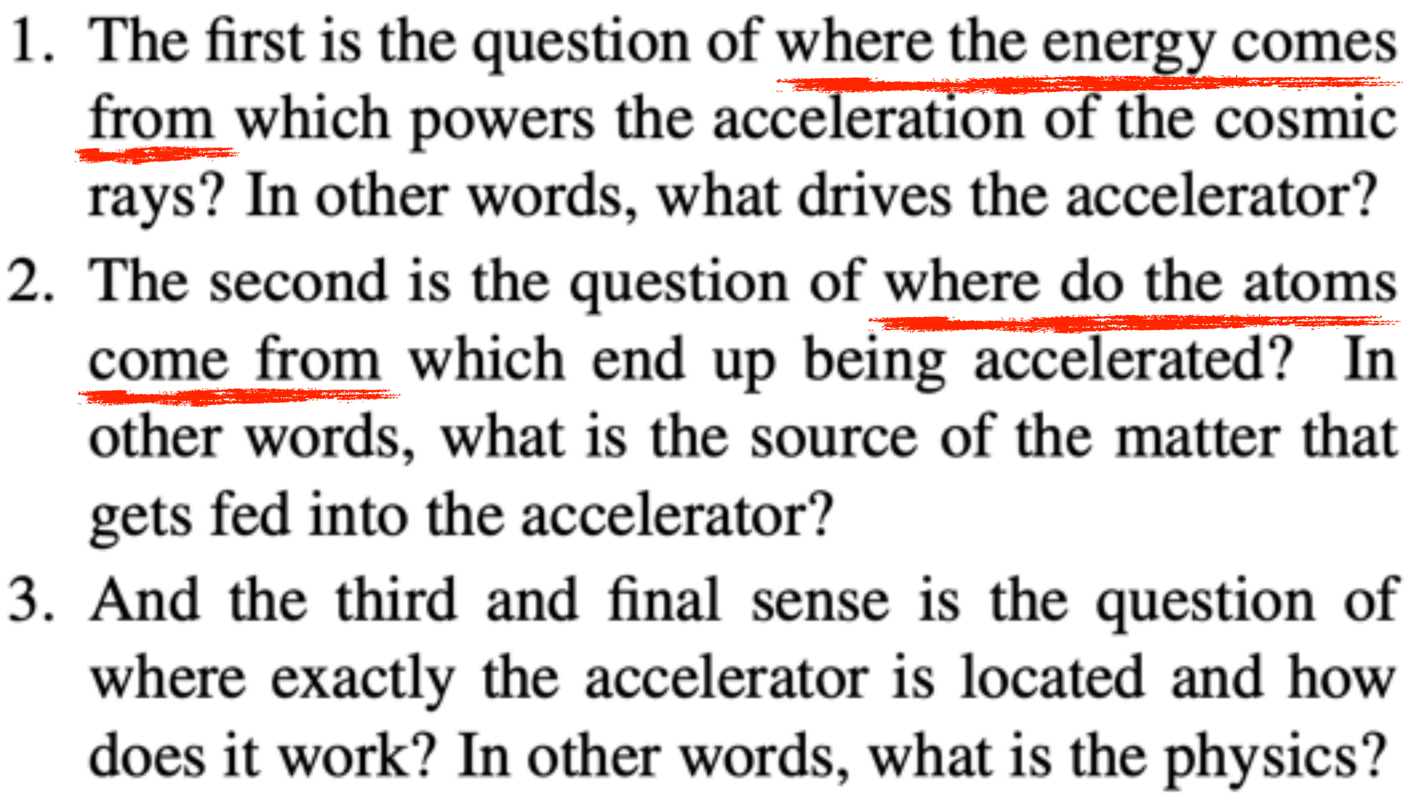

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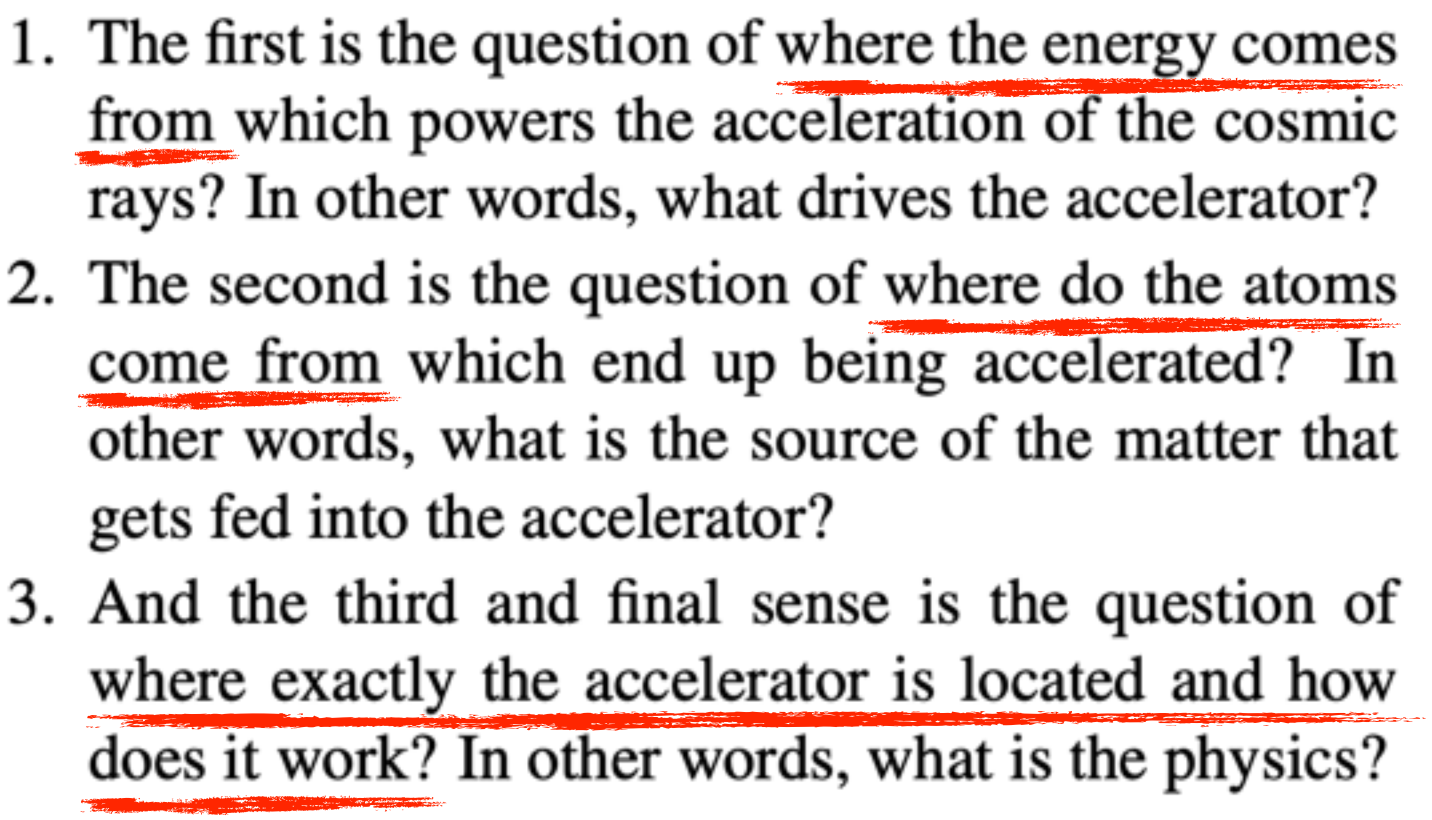

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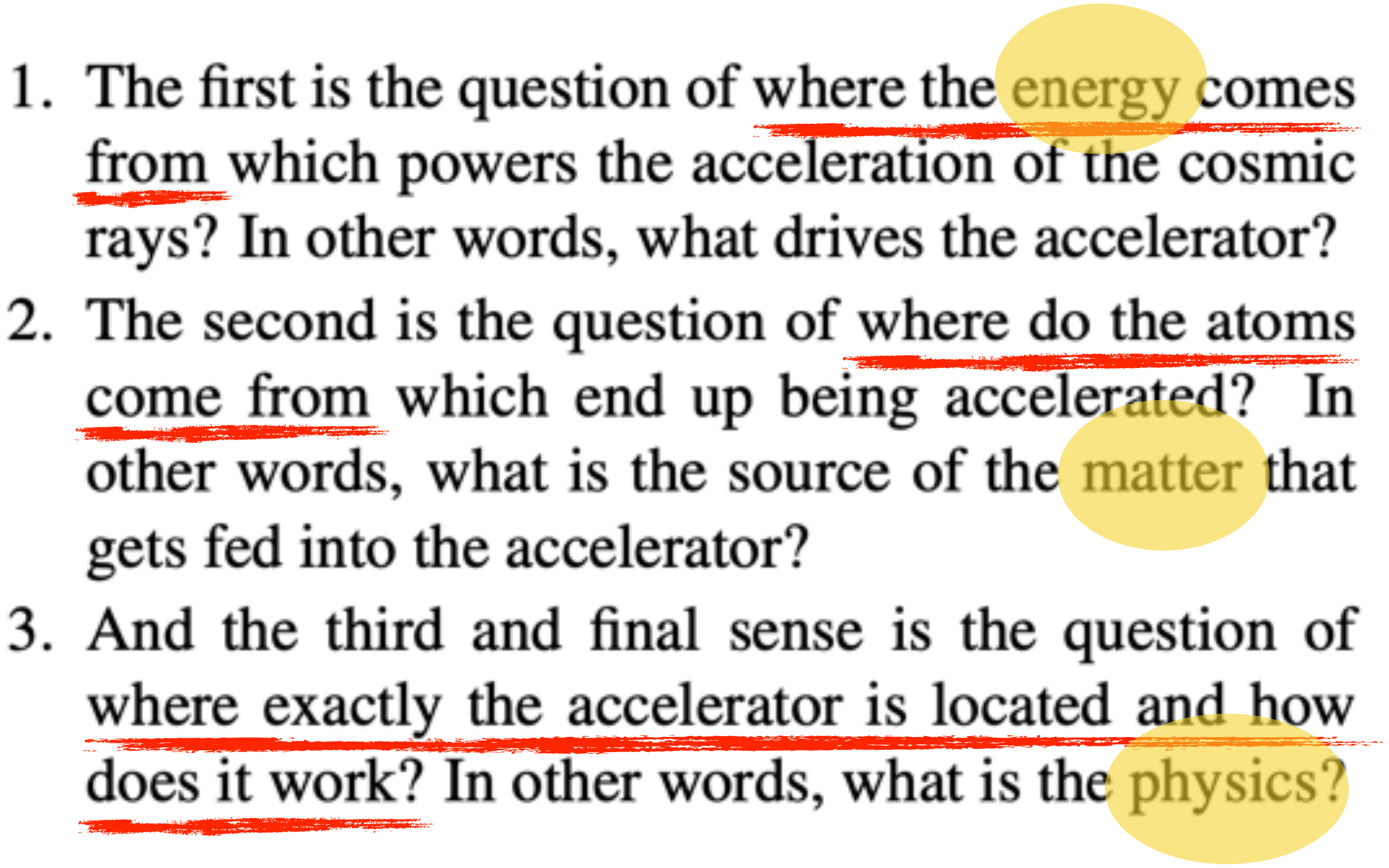

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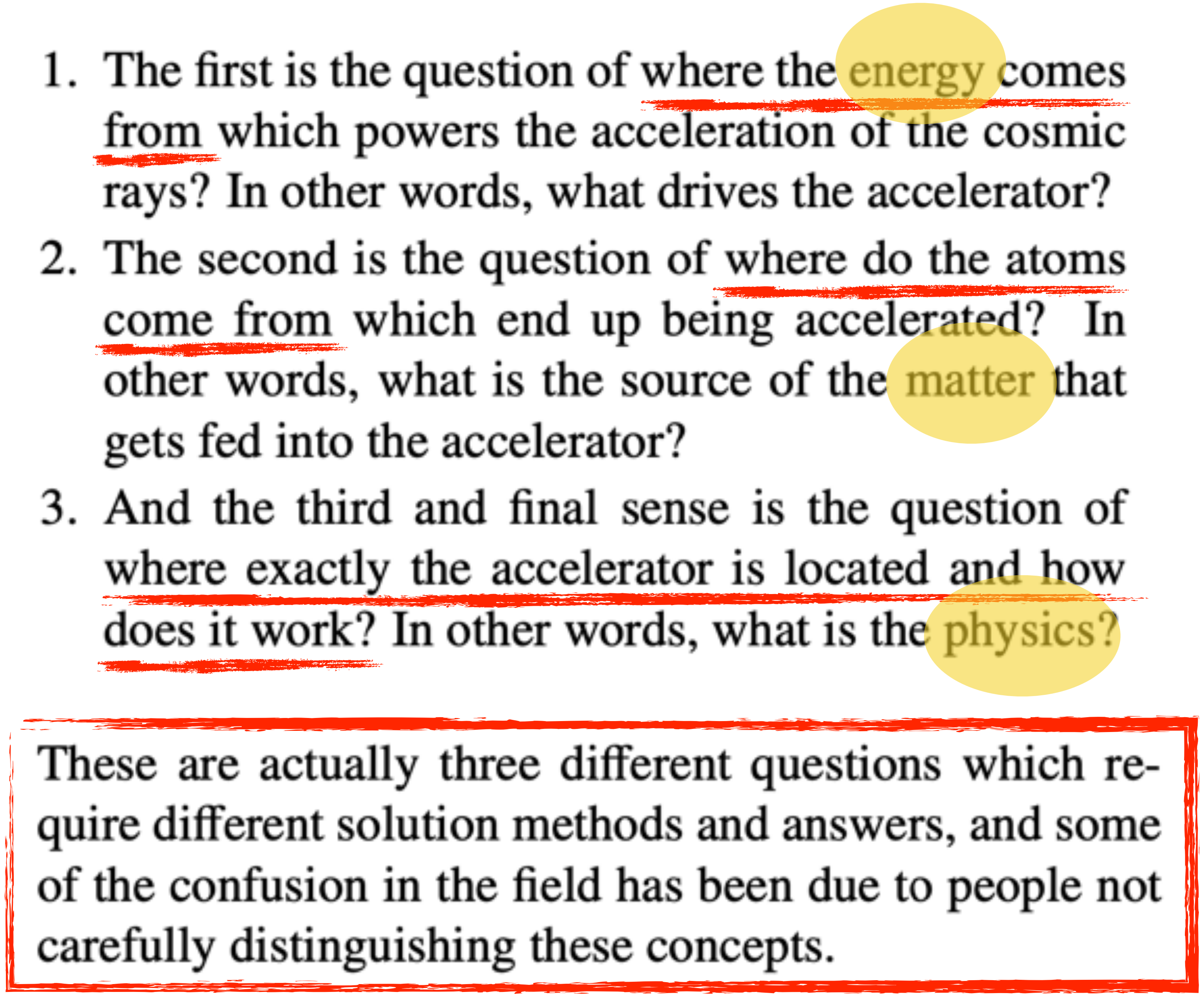

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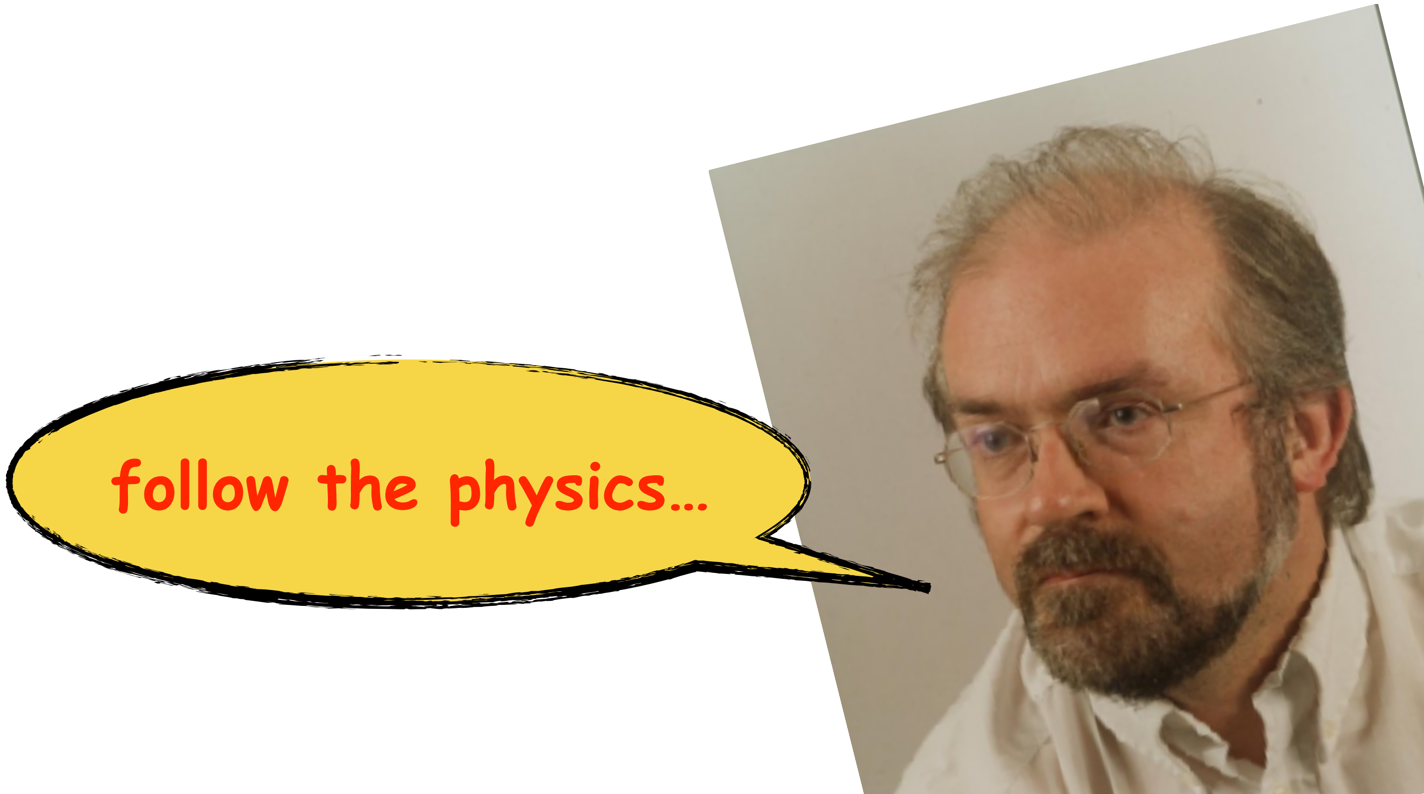
These are actually three different questions which require different solution methods and answers, and some of the confusion in the field has been due to people not carefully distinguishing these concepts.

# The orthodoxy (1)

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

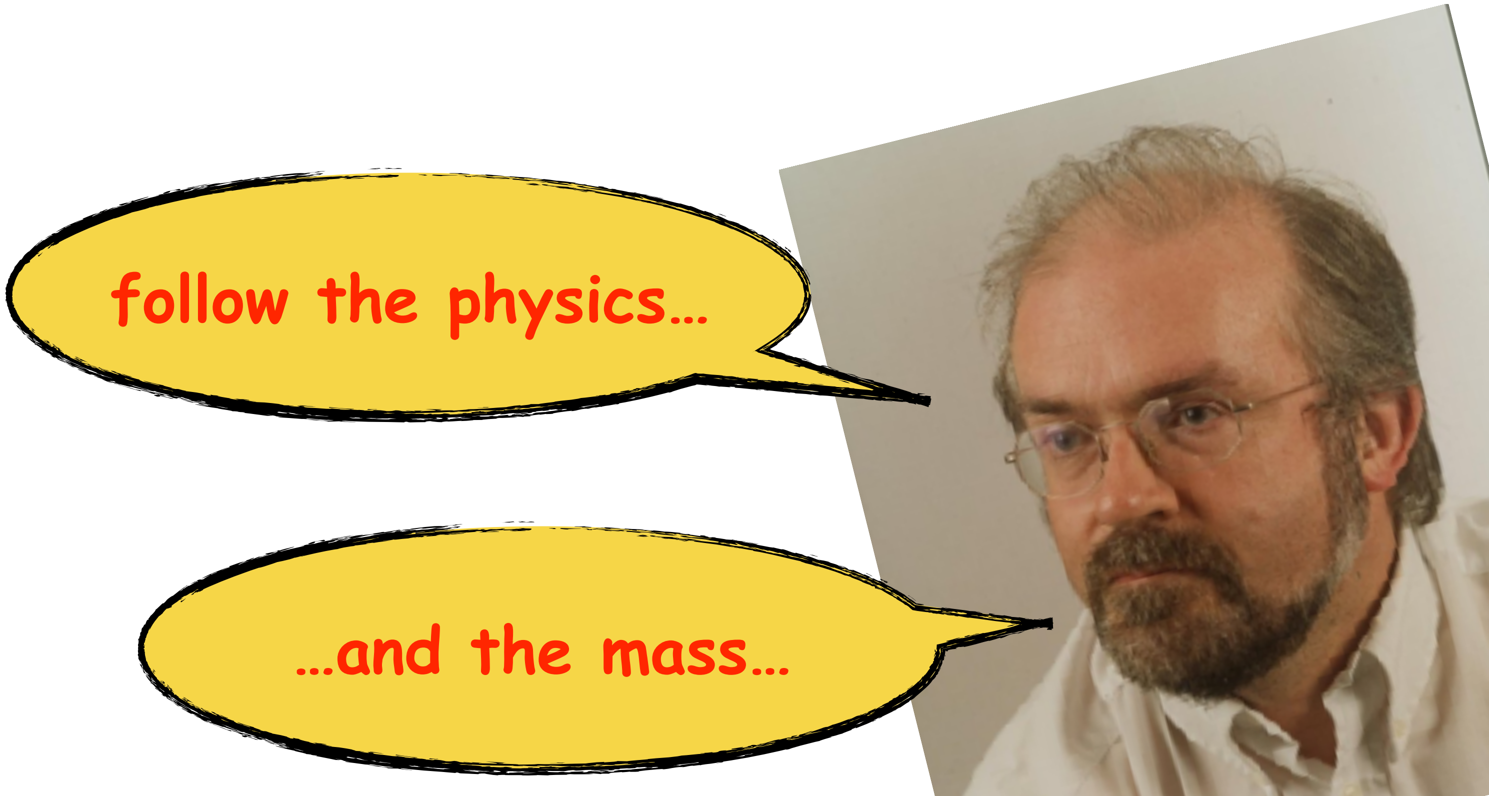
# The orthodoxy (2)

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

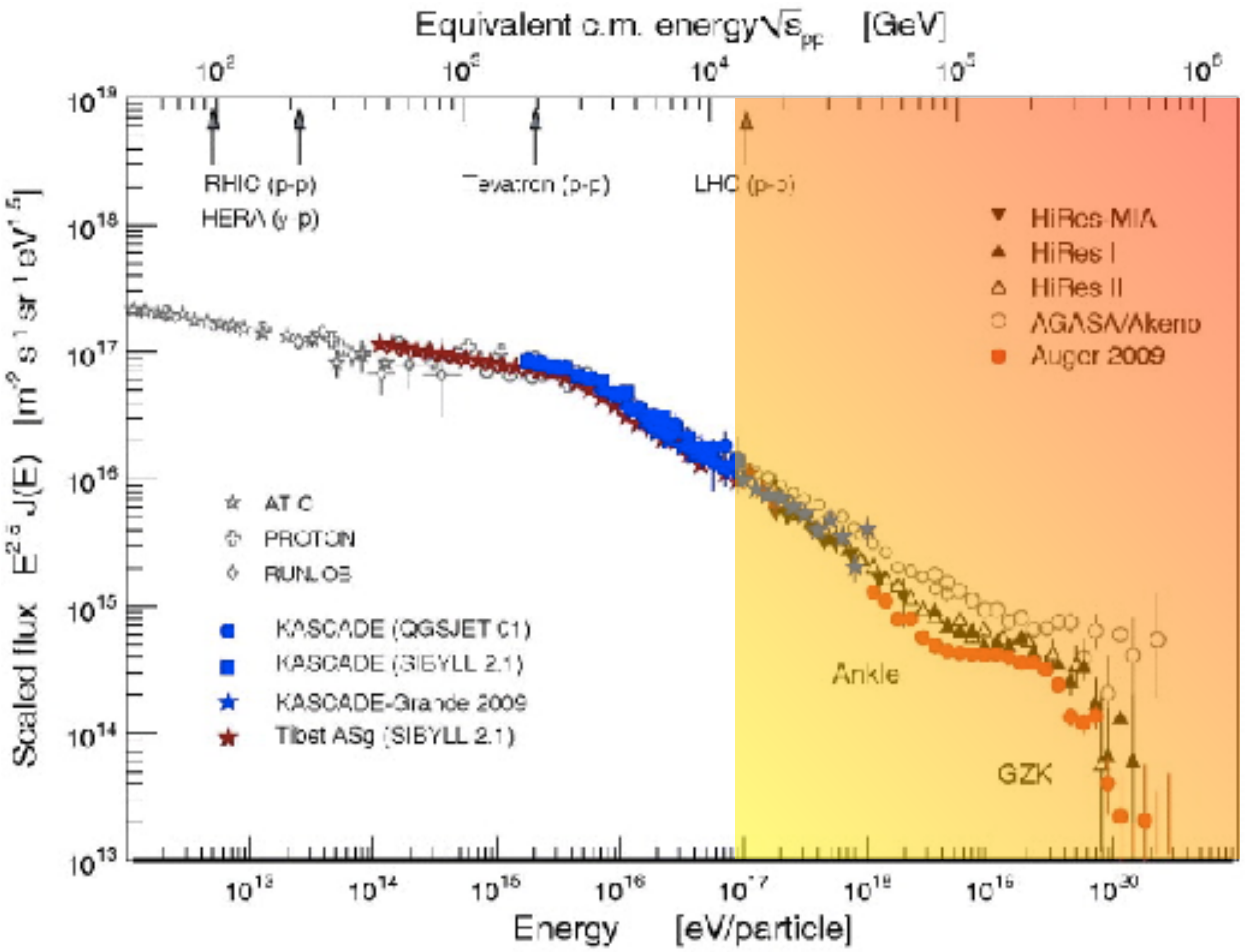


# The orthodoxy (3)

- 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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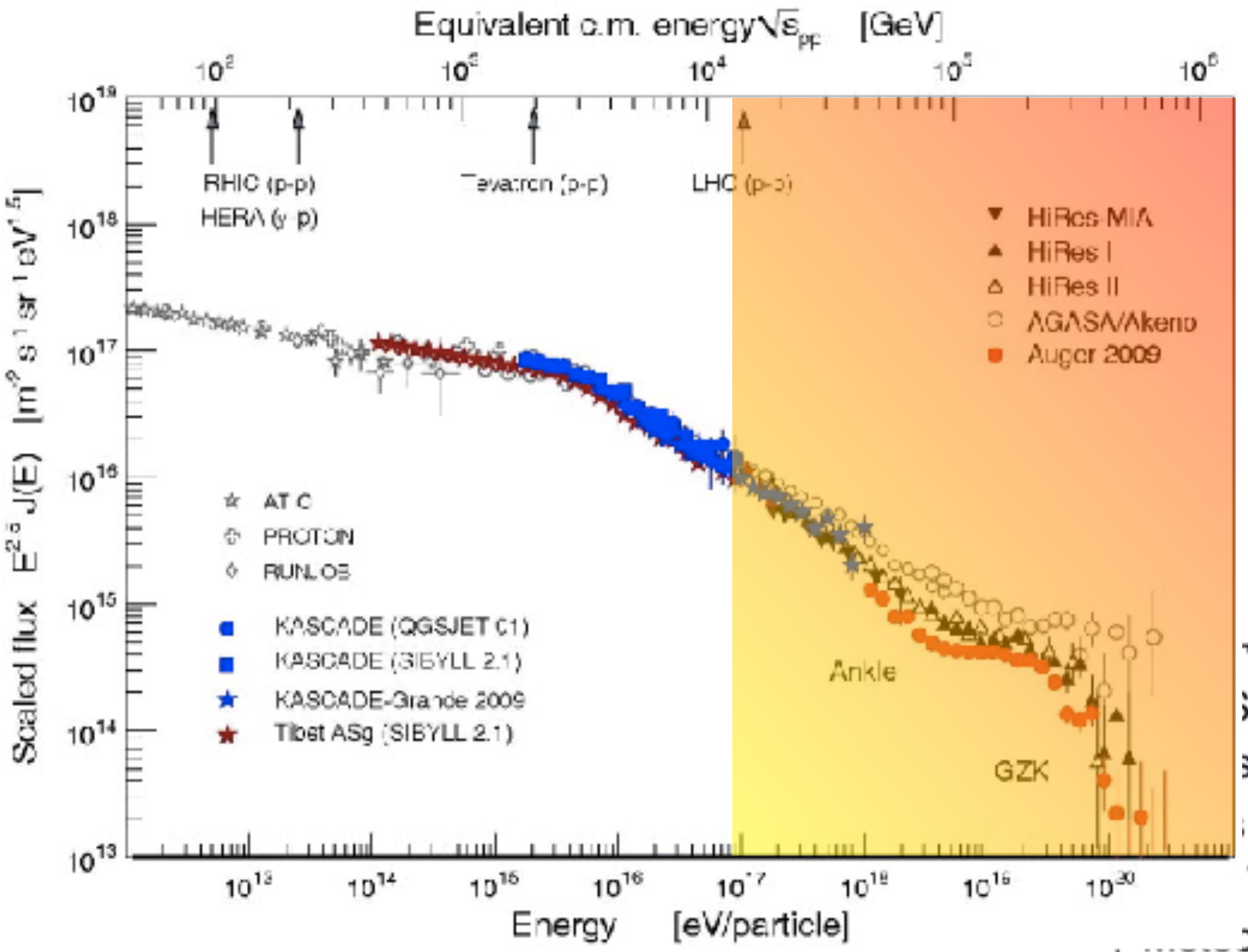
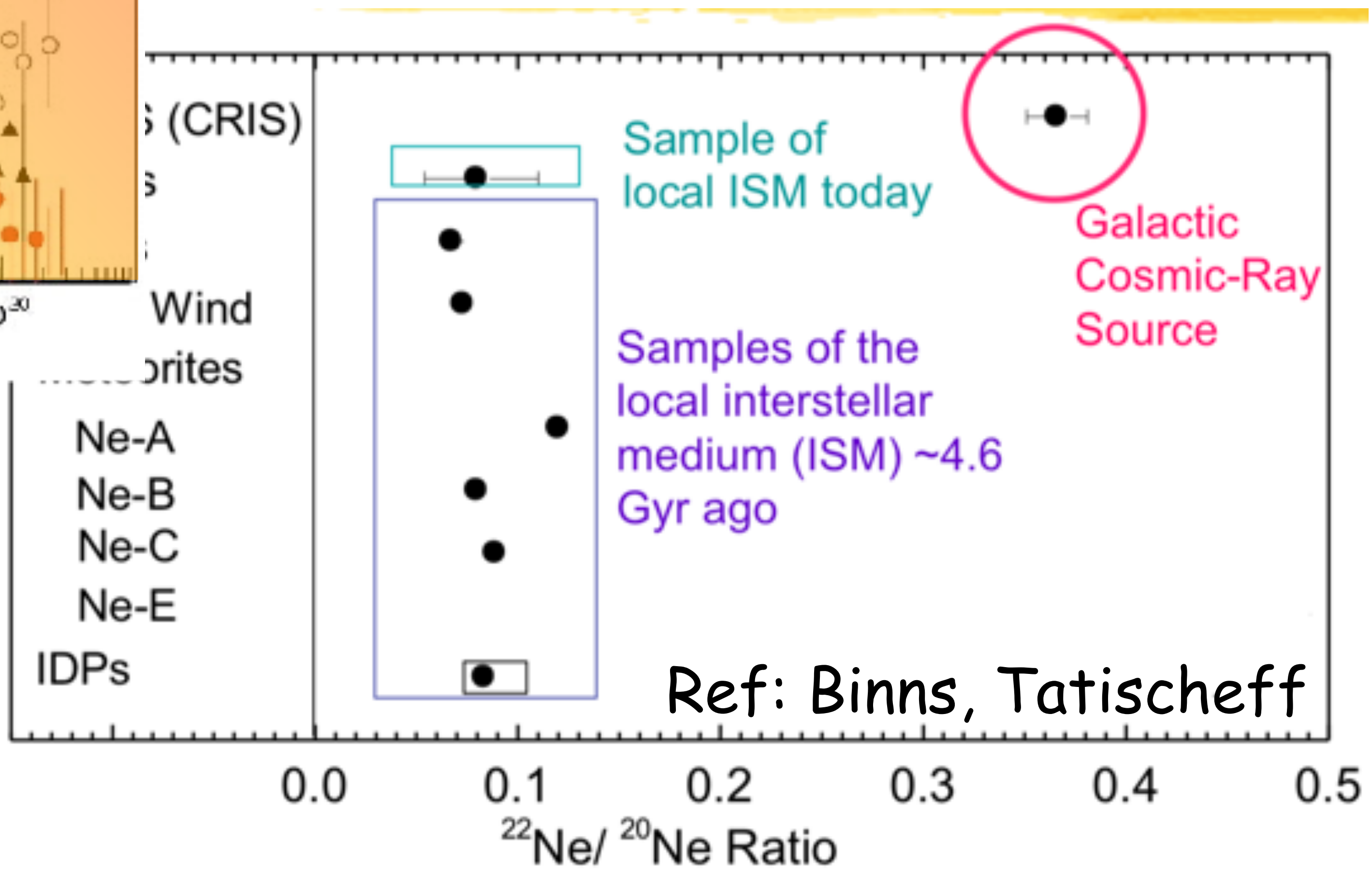


[1] can SNR shocks accelerate particles up to the largest observed energies?

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



Ref: Binns, Tatischeff

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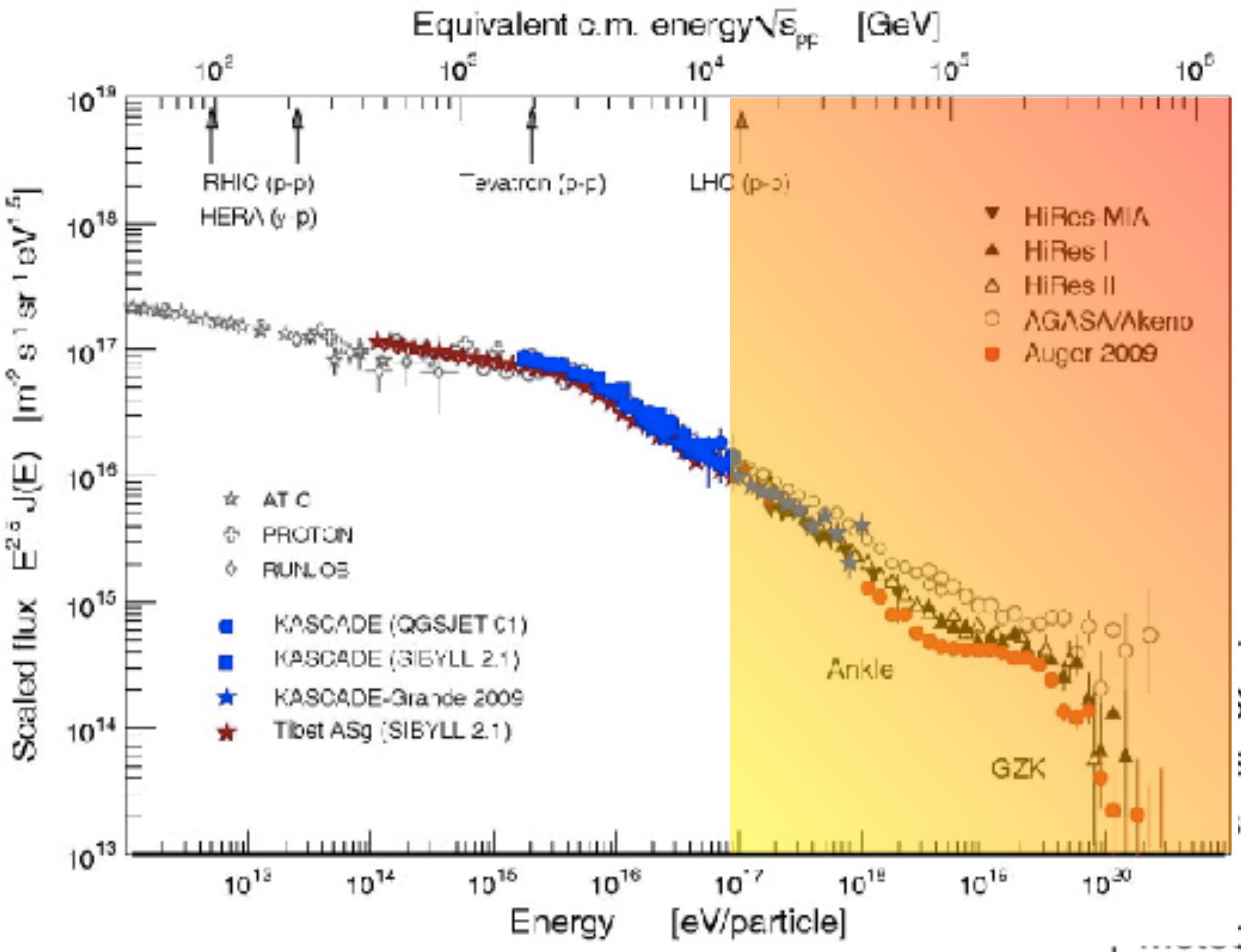

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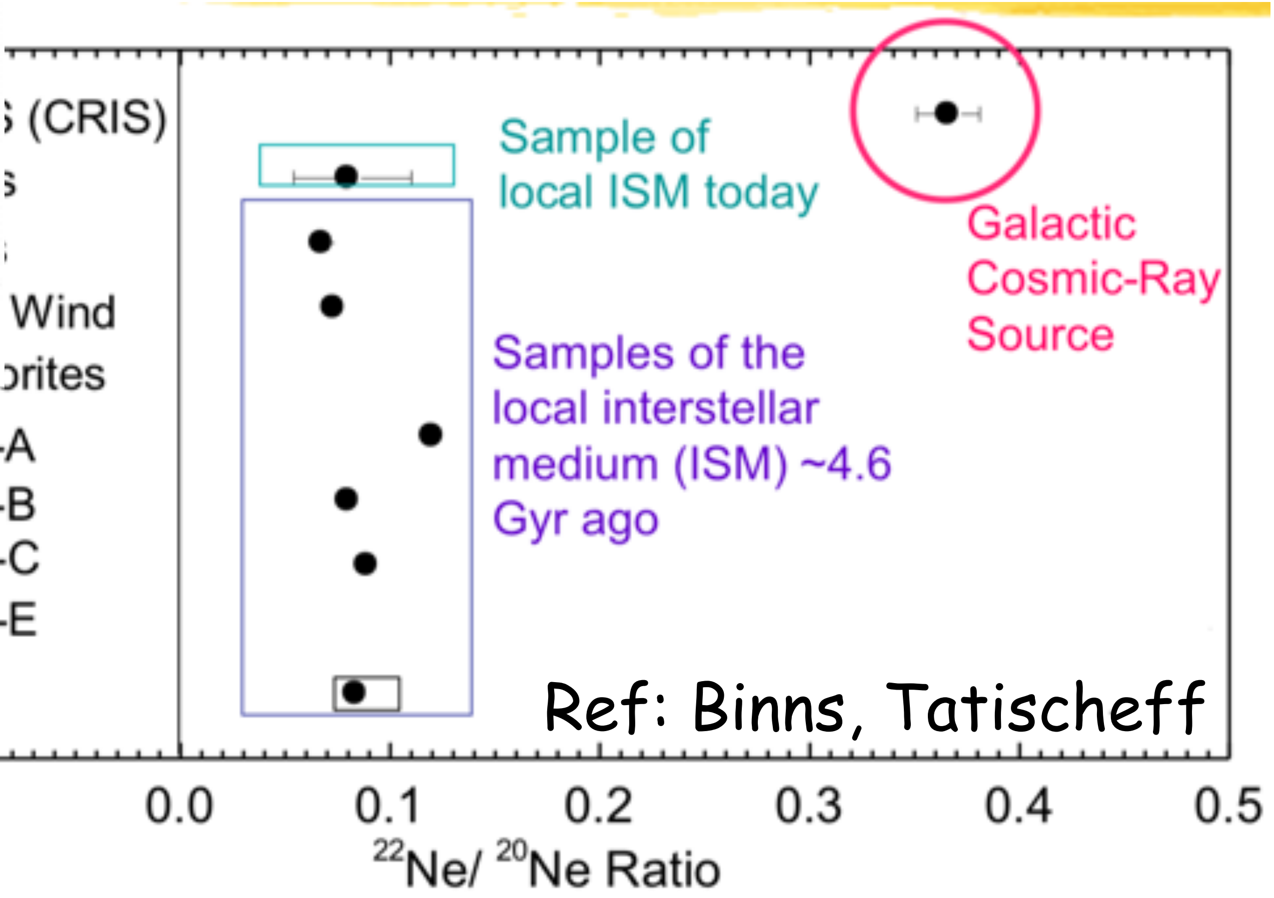

Ref: Binns, Tatischeff

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

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