Cosmic rays: an introduction

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

Stefano Gabici
APC, Paris
gabici@apc.in2p3.fr

www.cnrs.fr

Plan of the course

Lecture 1: cosmic rays

[1] Cosmic rays: an introduction

[2] Particle acceleration: why it is a problem

Plan of the course

Lecture 1: cosmic rays

[1] Cosmic rays: an introduction
[2] Particle acceleration: why it is a problem

Lecture 2: acceleration

[3] Hillas criterion, Fermi's idea...
[4] Fermi II and Fermi I (diffusive shock acceleration)
[5] Acceleration at relativistic shocks (general considerations)

Plan of the course

Lecture 1: cosmic rays

[1] Cosmic rays: an introduction
[2] Particle acceleration: why it is a problem

Lecture 2: acceleration

[3] Hillas criterion, Fermi's idea…
[4] Fermi II and Fermi I (diffusive shock acceleration)
[5] Acceleration at relativistic shocks (general considerations)

Lecture 3: supernova remnants

[6] Applications to supernova remnant shocks
[7] Particle escape from SNRs
[8] Conclusions

Plan of the lecture

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

Introduction

Plan of the lecture

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

Introduction

The standard scenario for cosmic ray origin

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

Plan of the lecture

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

Introduction

The standard scenario for cosmic ray origin

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

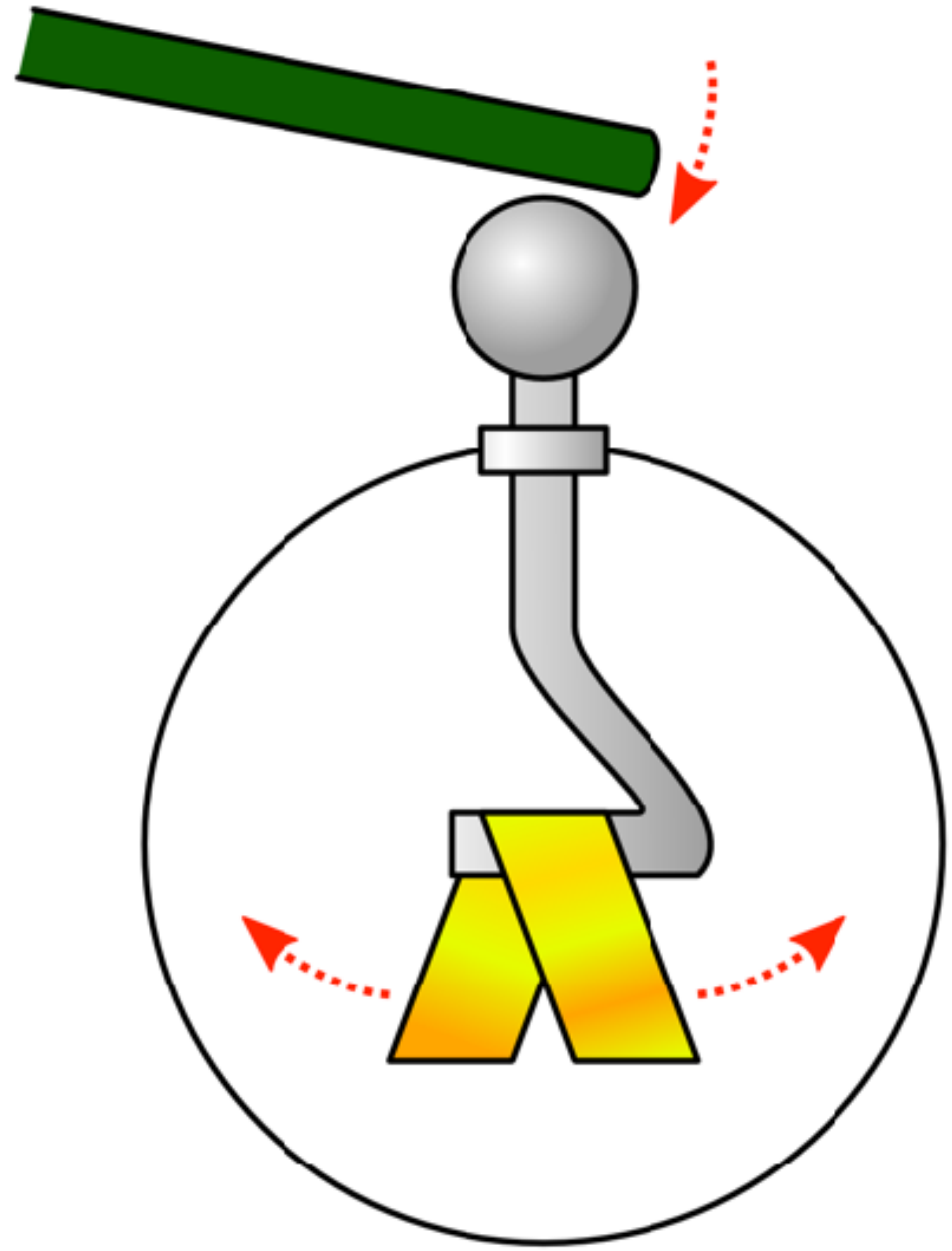
The problem of particle acceleration in astrophysics

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

[1] History

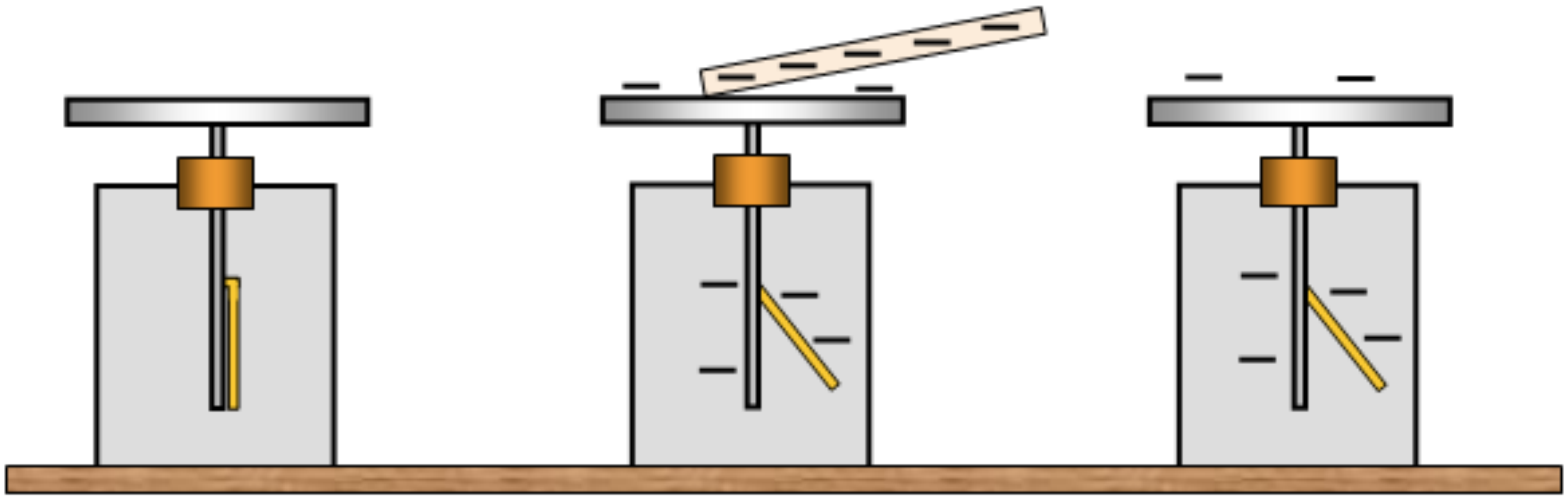
The electroscope

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

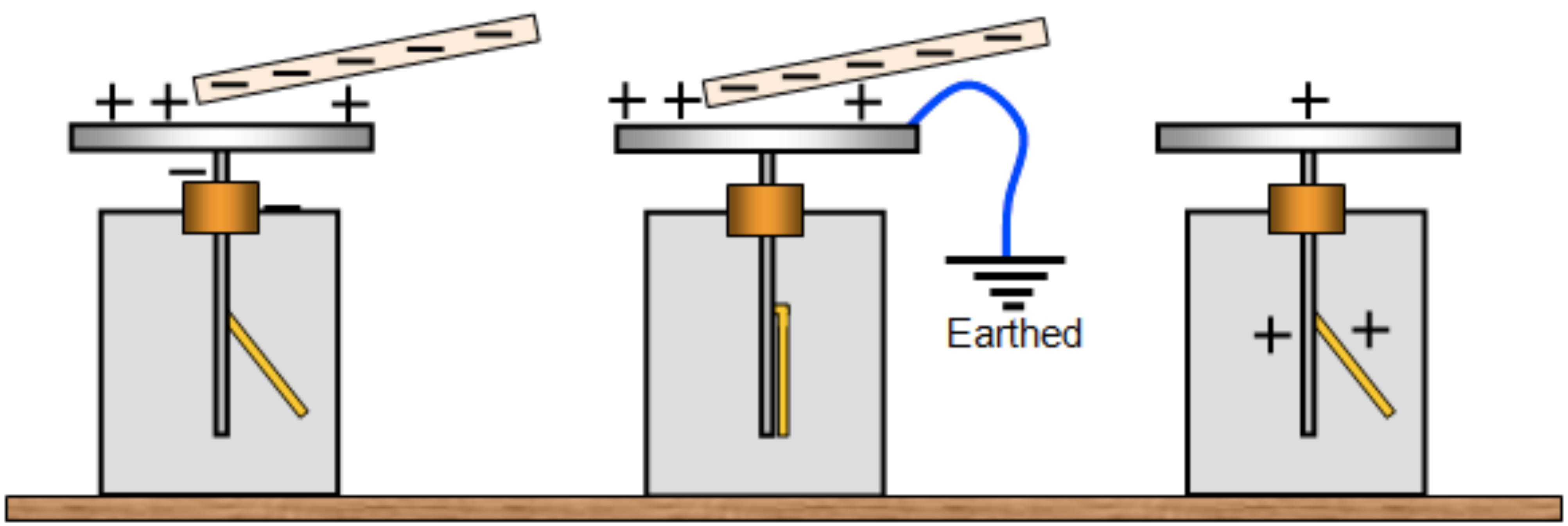


ELECTROSCOPE

How does it work



Charging by contact

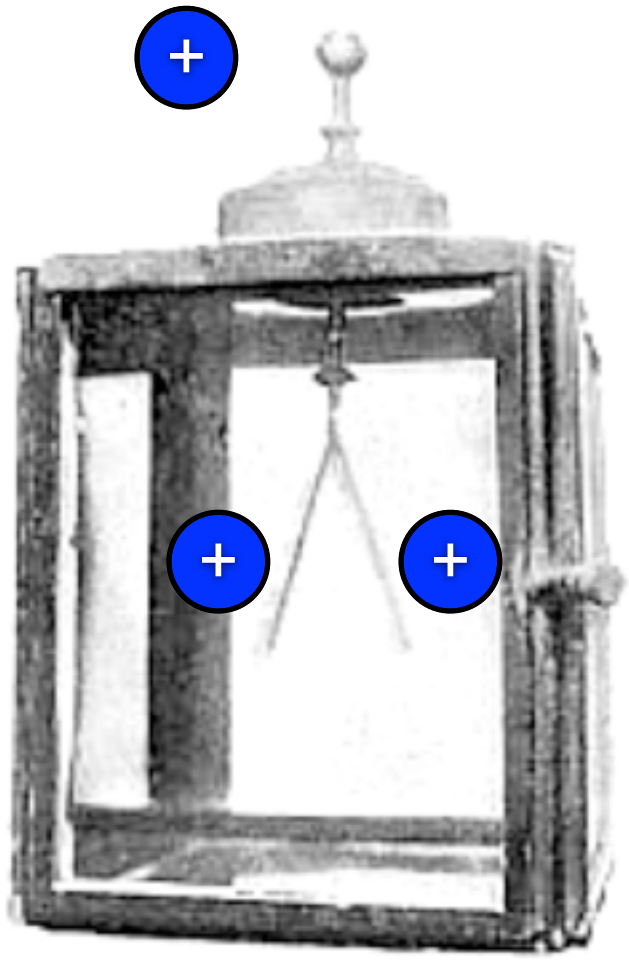


Charging by induction

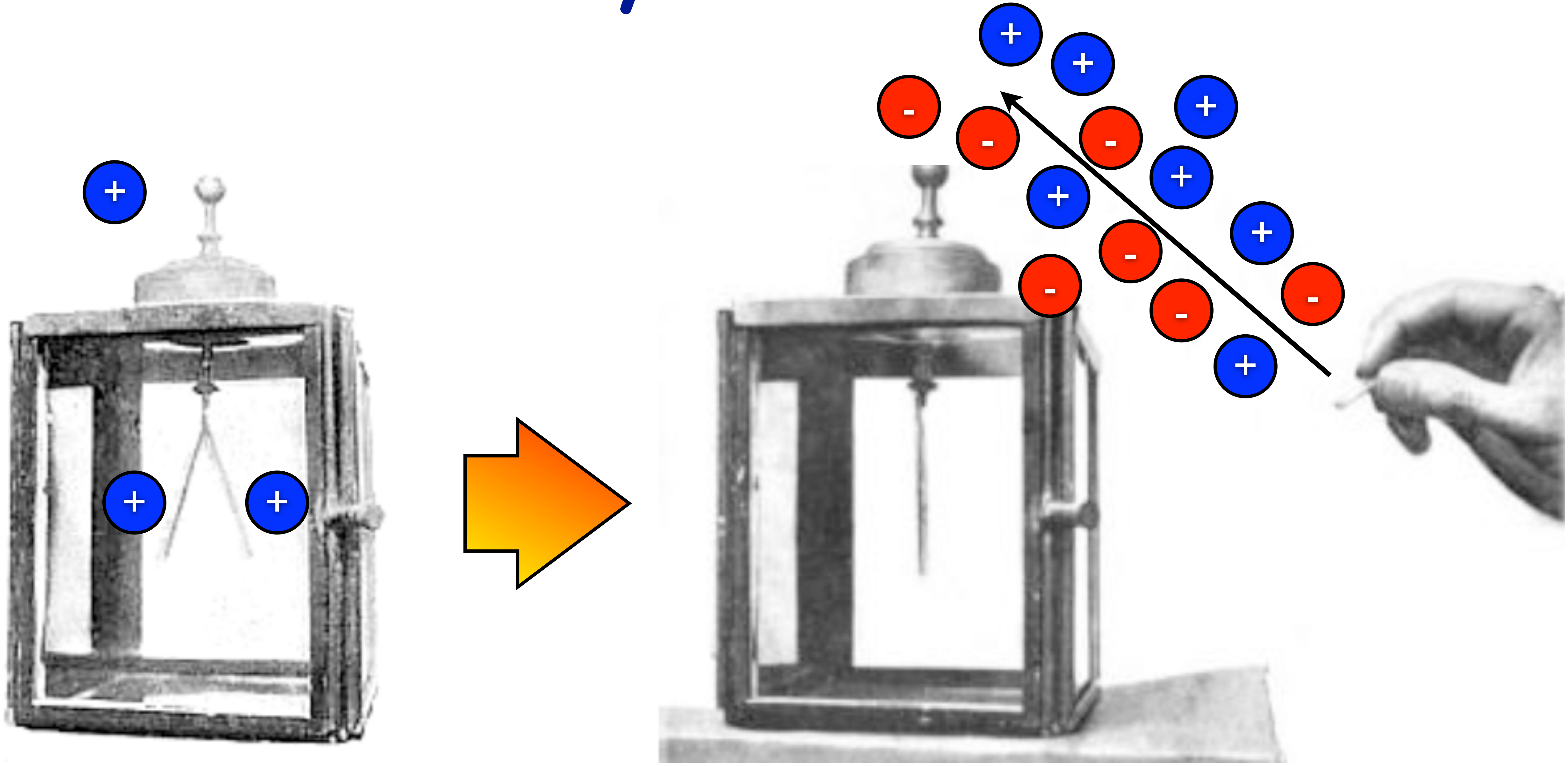
The problem...

- in **1785 Coulomb** noted that charged 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**

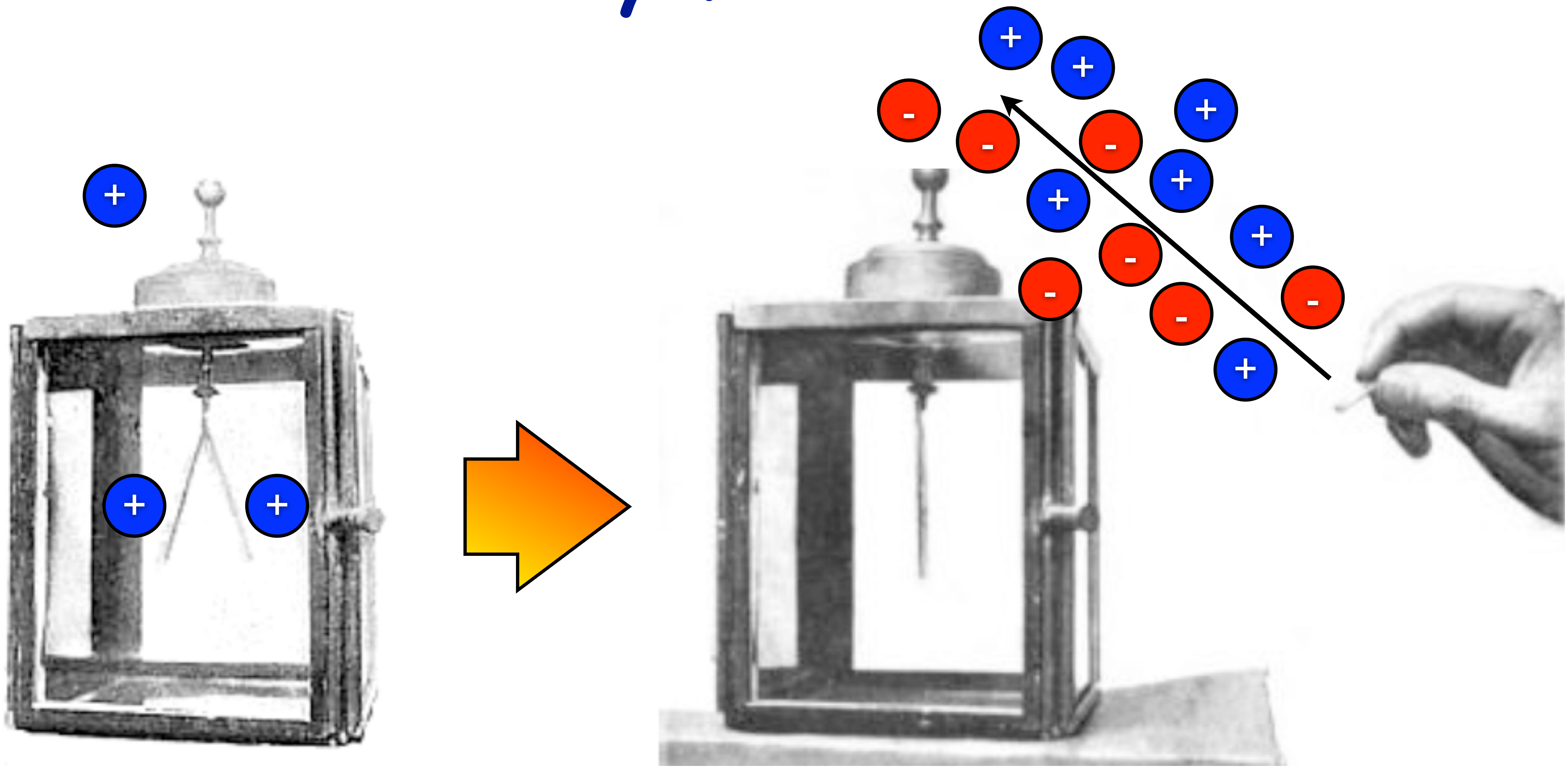
Radioactivity from the Earth



Radioactivity from the Earth



Radioactivity from the Earth



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

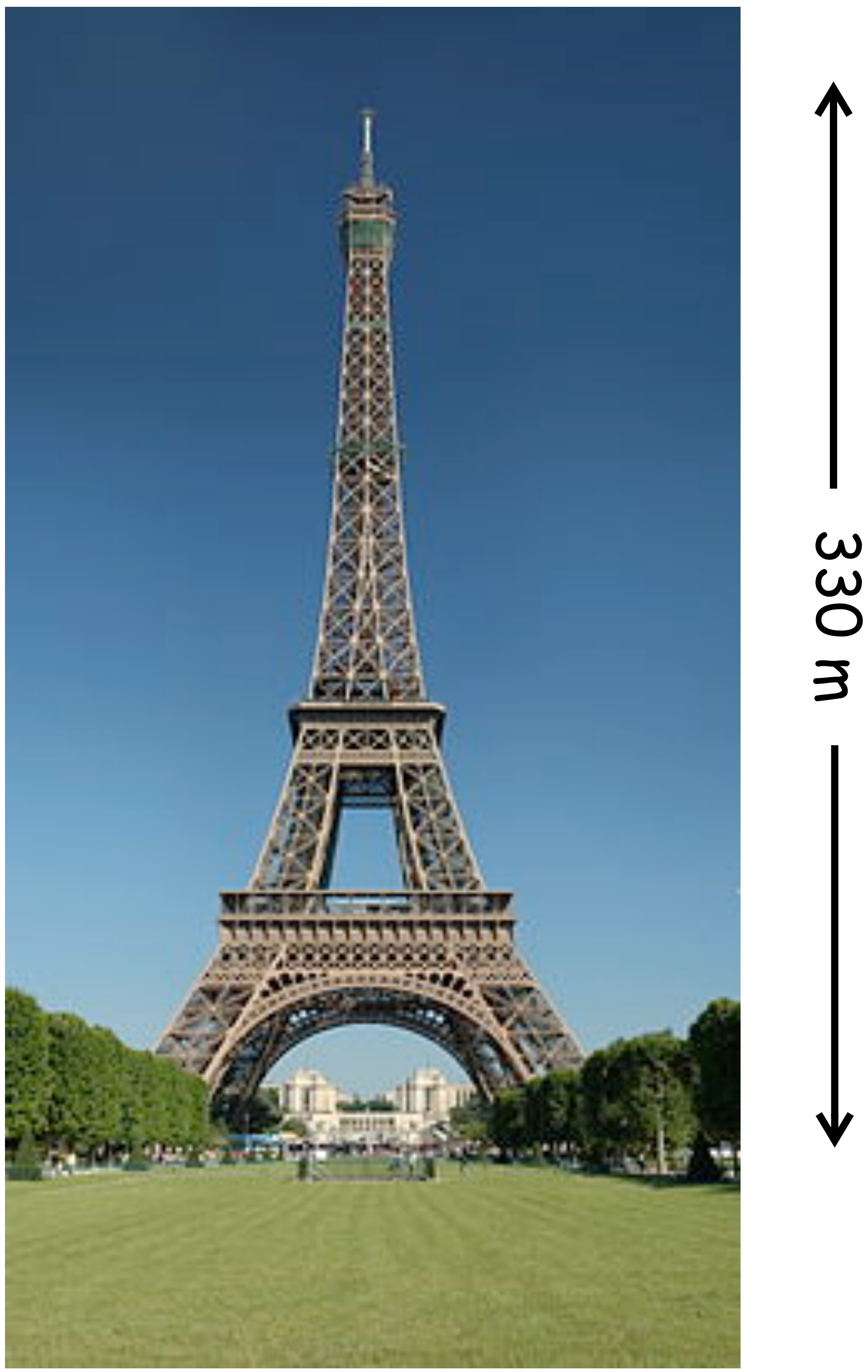
Father Theodor Wulf on the Tour Eiffel

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

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.

- in **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
- 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?);



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.

- in **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
- 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?);

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

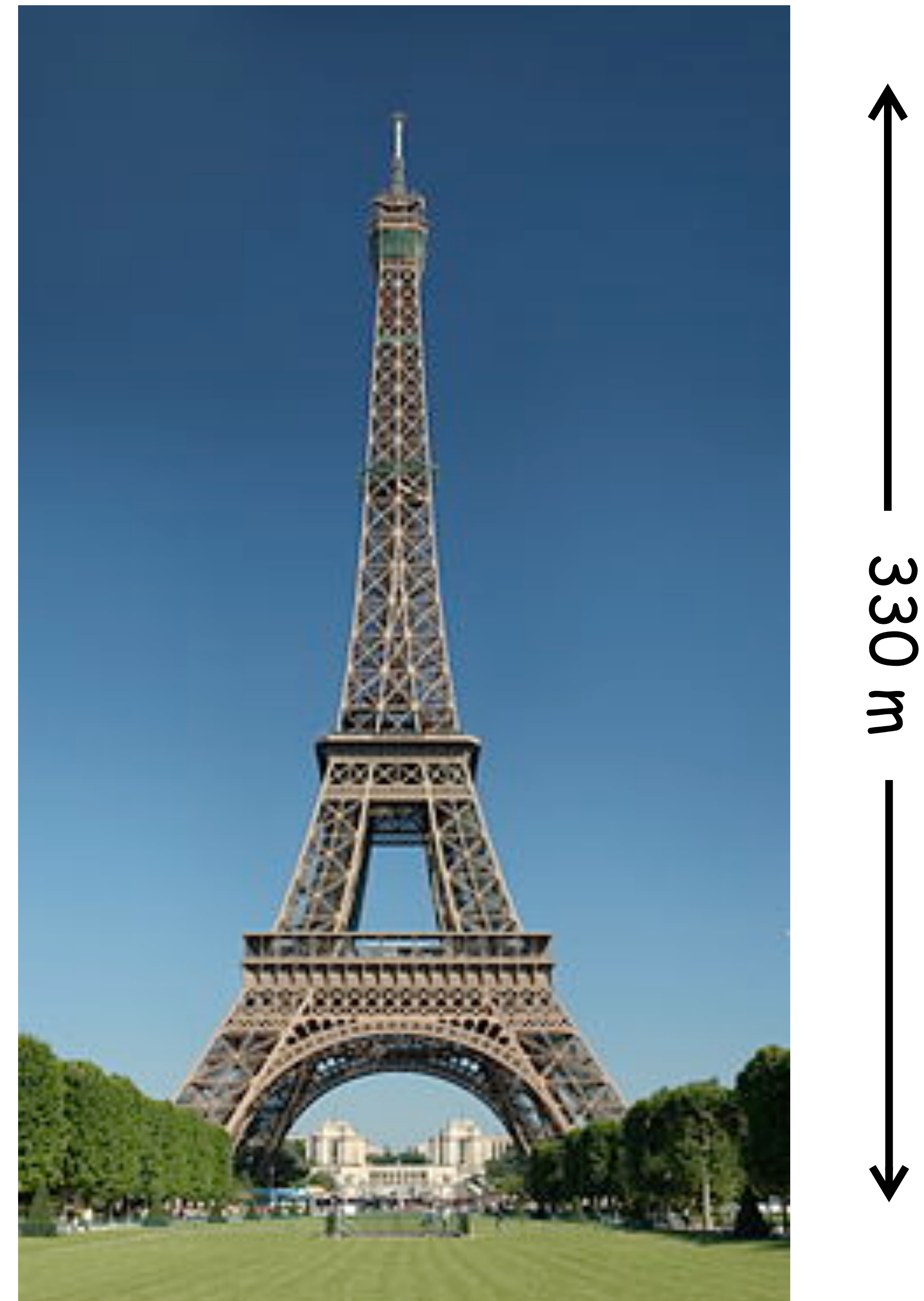
330 m

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.

- in **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
- 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?);

Datum	Ort	Ionen / ccm sec
28. März	Valkenburg	22,5
29. „	Paris, Boden	17,5
30. „	„ Eiffelturm	16,2
31. „	„ „	14,4



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

Pacini's (forgotten) experiment

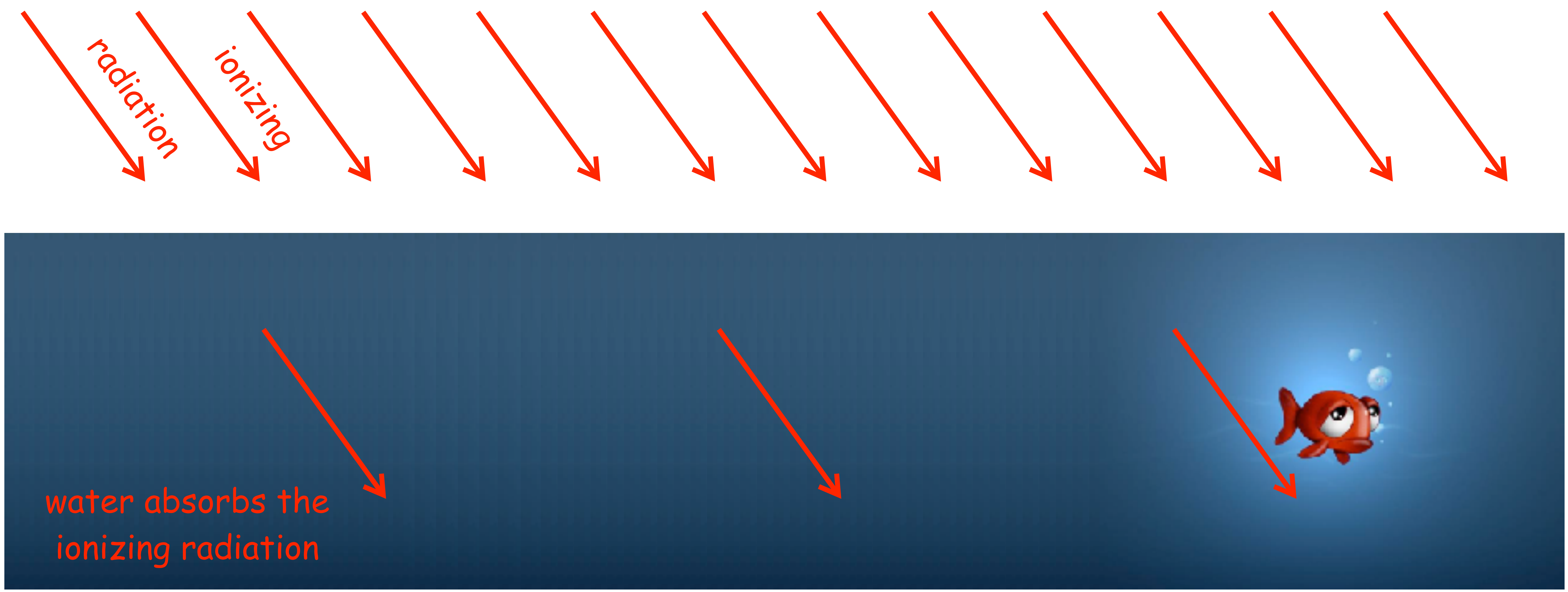
in **1911** Pacini performed measurements on a boat off the coast of Livorno (300 m from the coast). Measurements were performed on the sea surface (8 m from sea bottom) and at 3 m of depth.

~20% drop of the ionization rate underwater
-> the ionization radiation comes from the atmosphere and NOT from the Earth!

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.

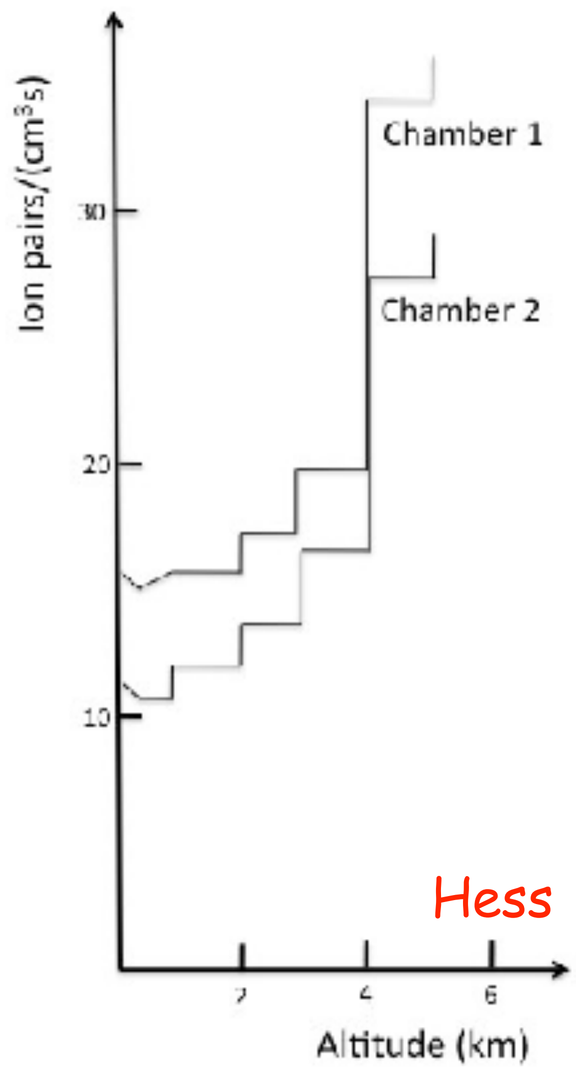
~20% drop of the ionization rate underwater
-> the ionization radiation comes from the atmosphere and NOT from the Earth!

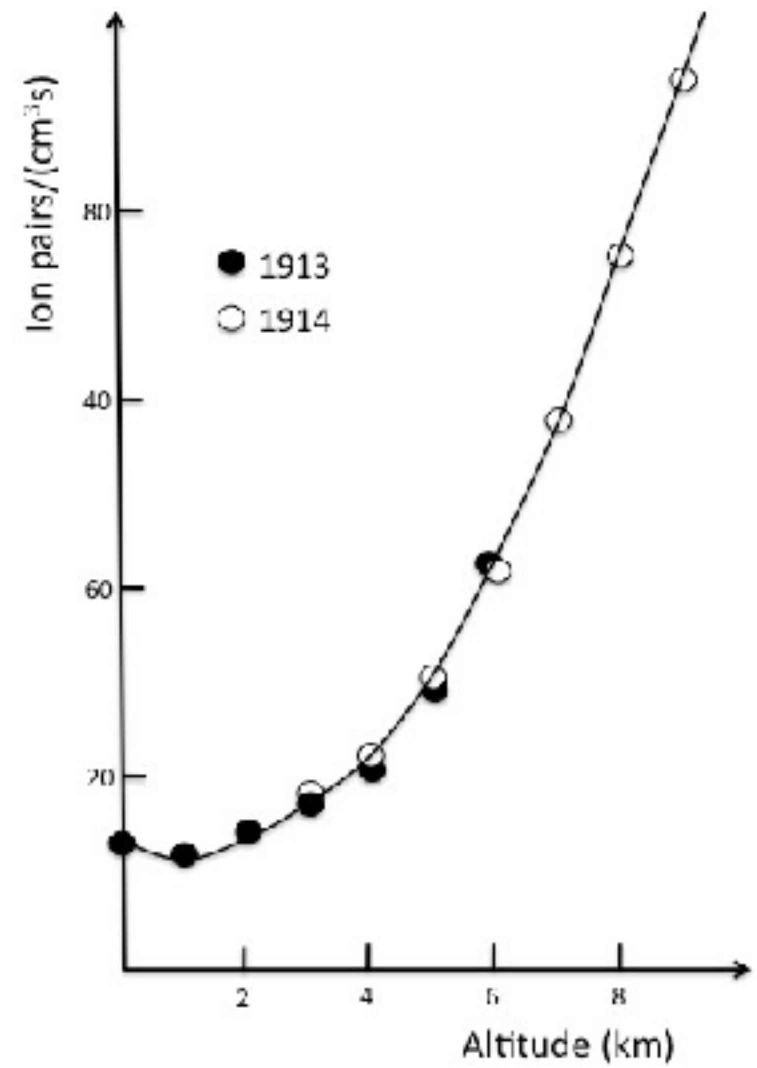


Which is the nature of the ionizing radiation in the atmosphere?

Victor Hess flies on a balloon

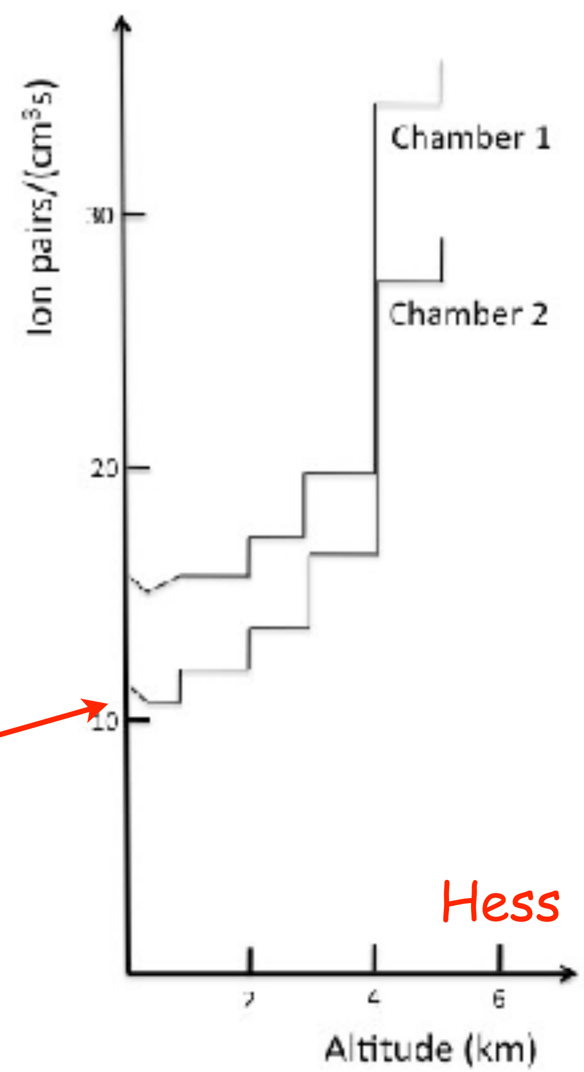
Between April and August **1912** Hess performed 7 balloon flights. During the 7th flight he reached an altitude of 5200 meters.

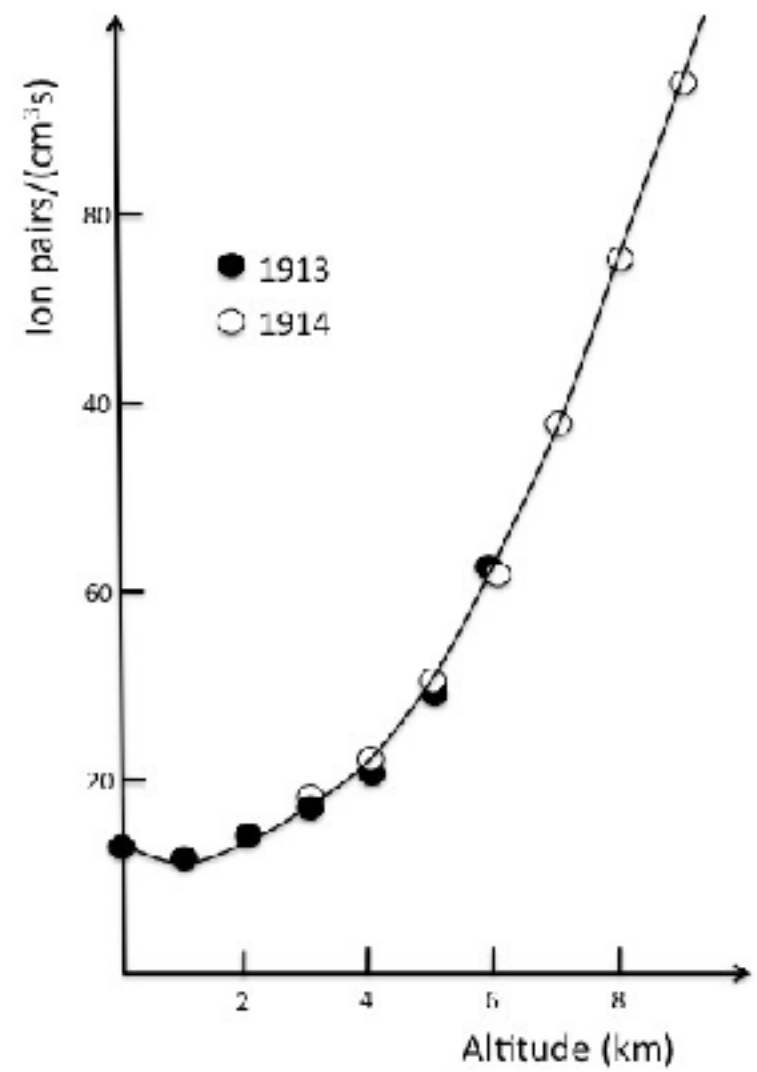




Victor Hess flies on a balloon

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



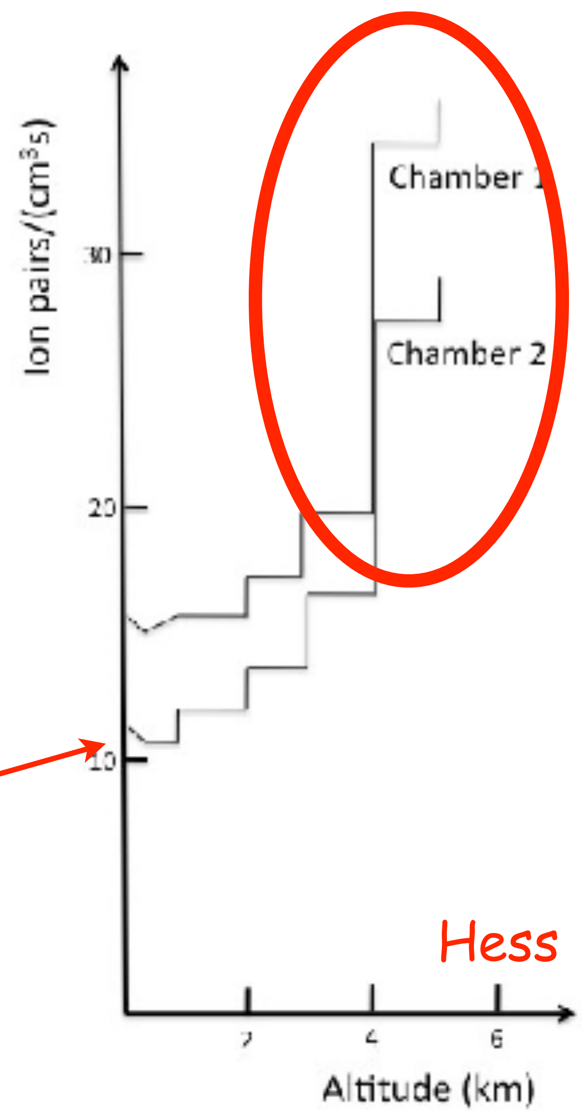


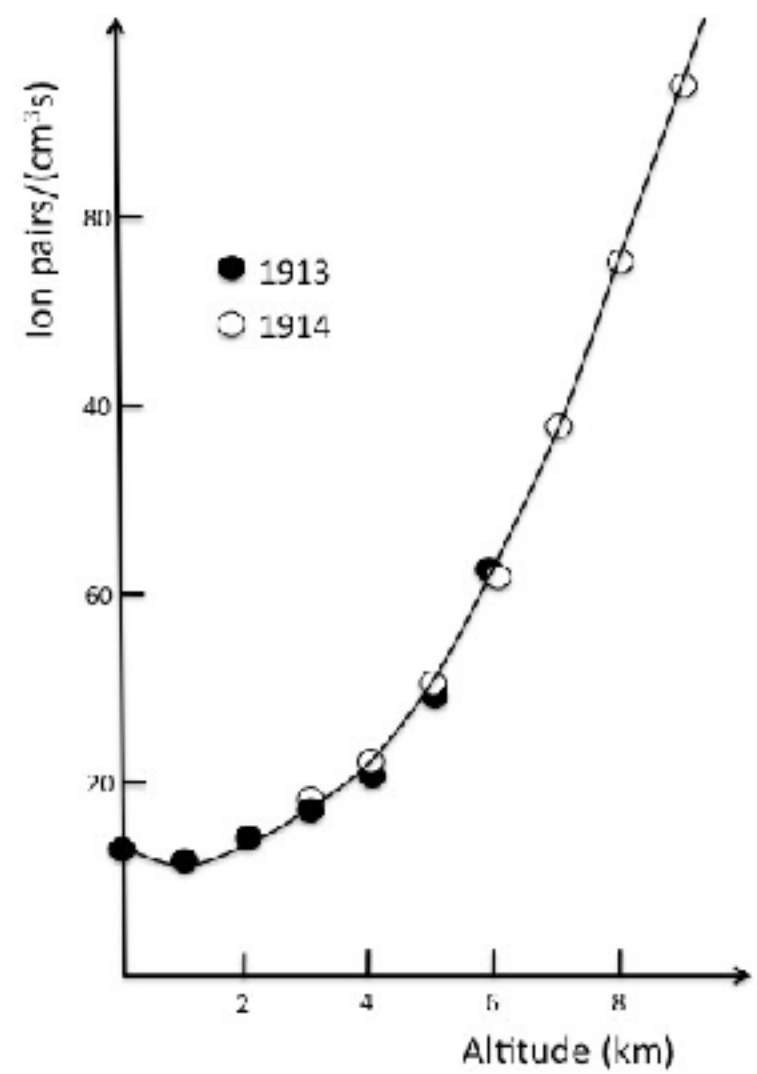
Wulf was right!

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.

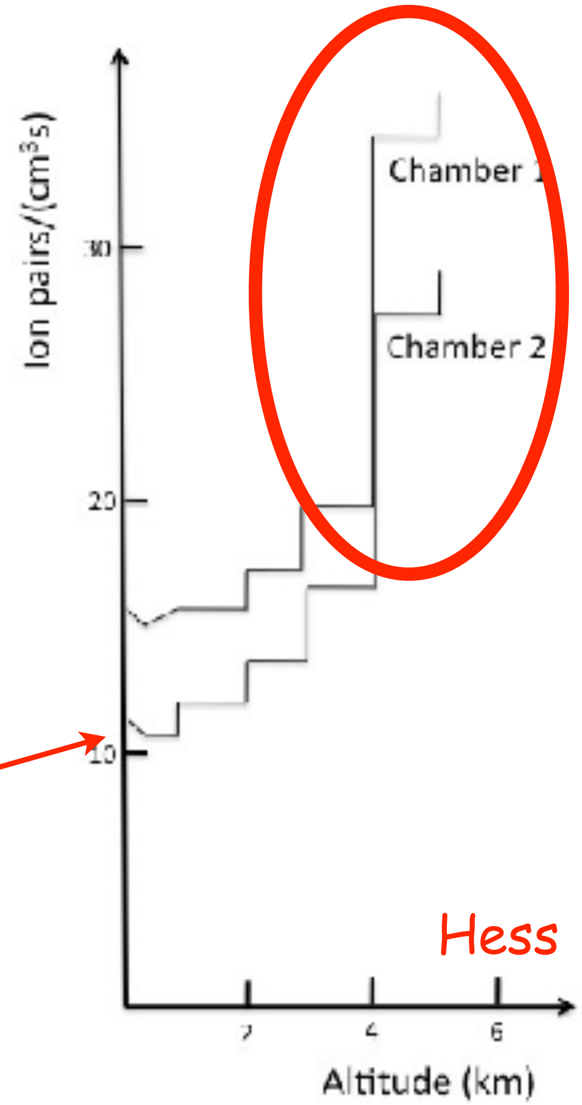
Wulf was right!

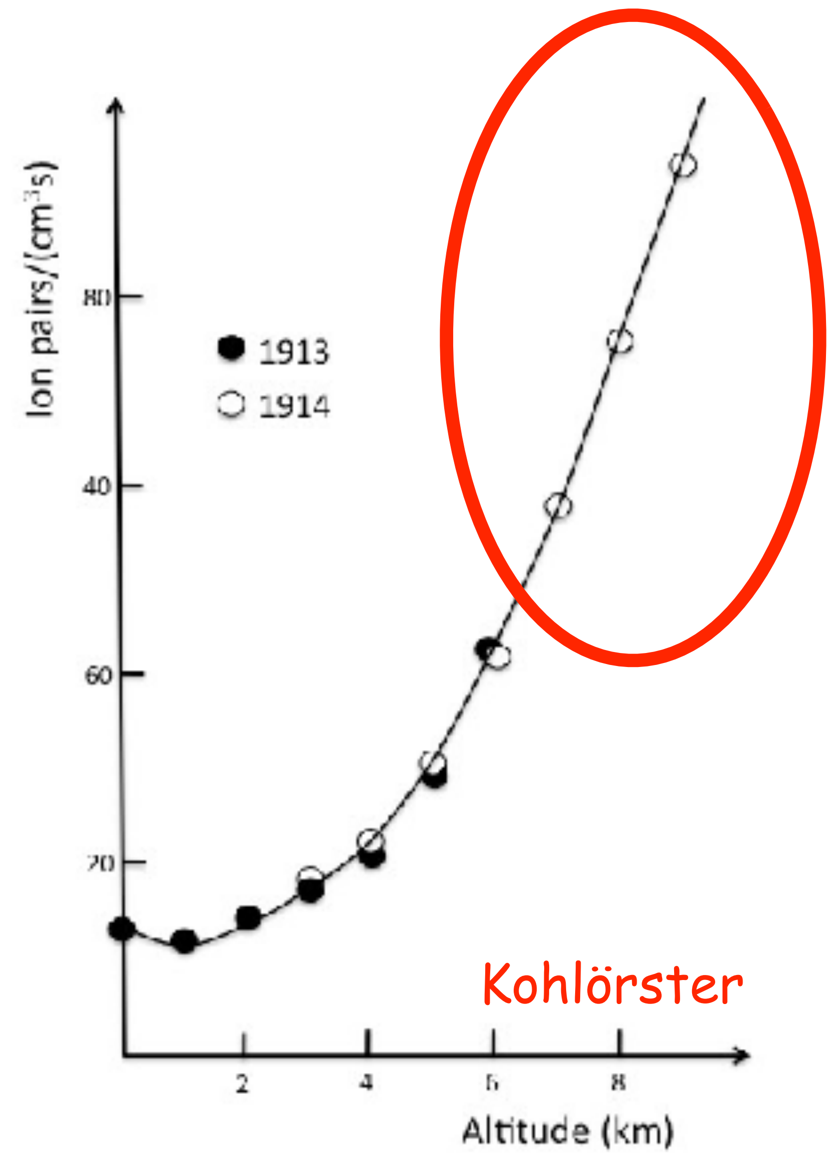




Victor Hess flies on a balloon

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





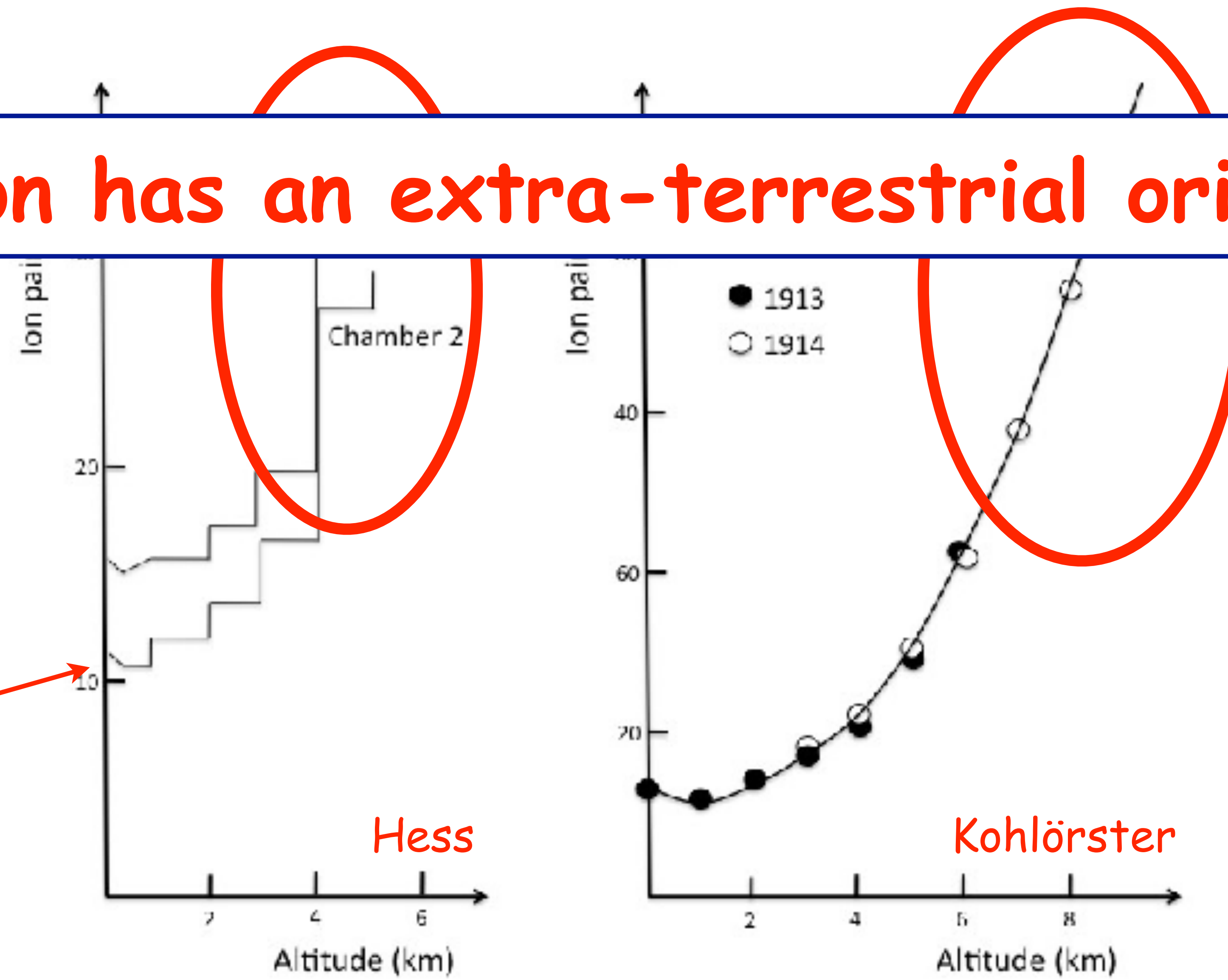
Wulf was right!

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.

The ionizing radiation has an extra-terrestrial origin

Wulf was right!



[2] What are cosmic rays?

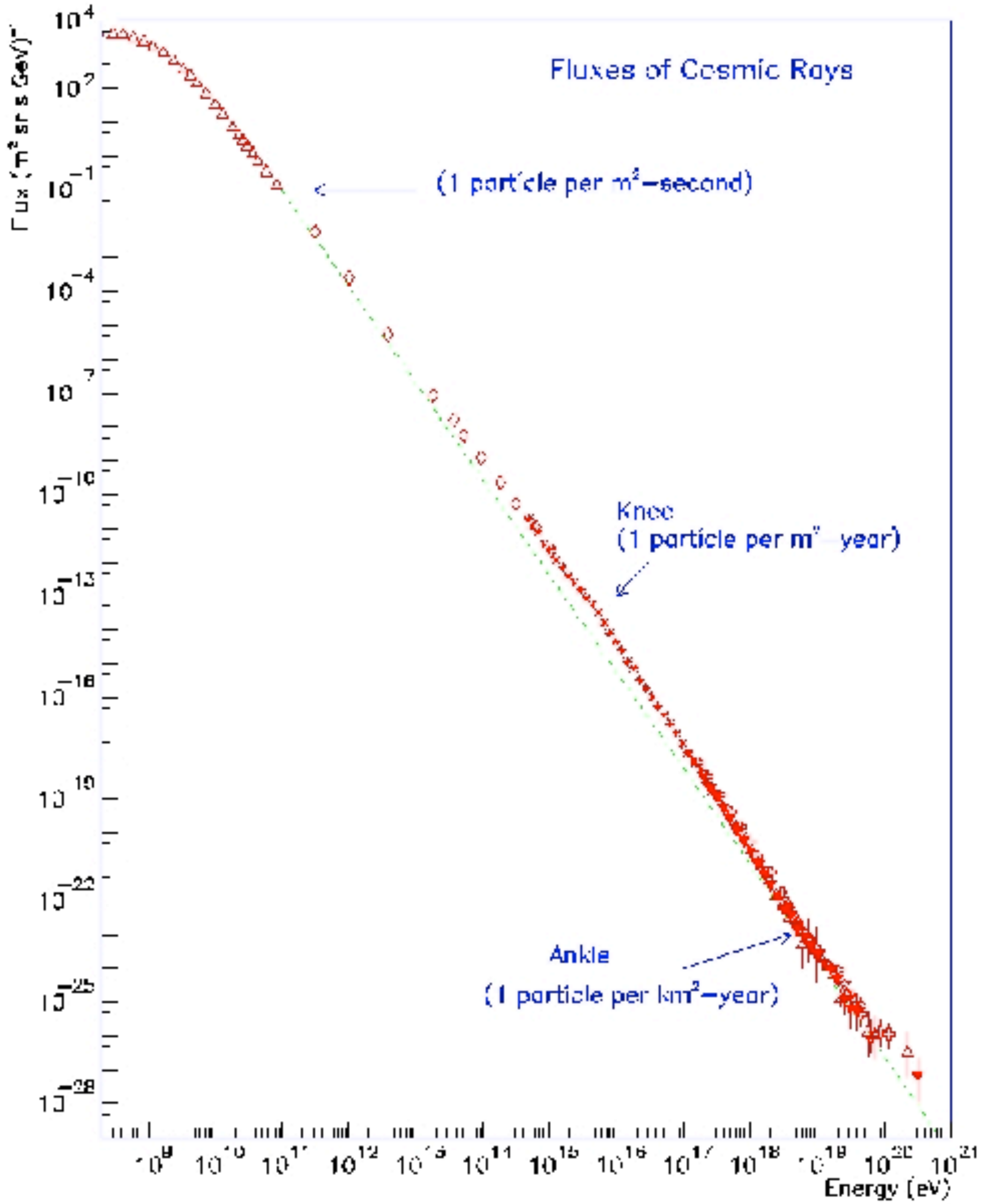
What are Cosmic Rays?

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

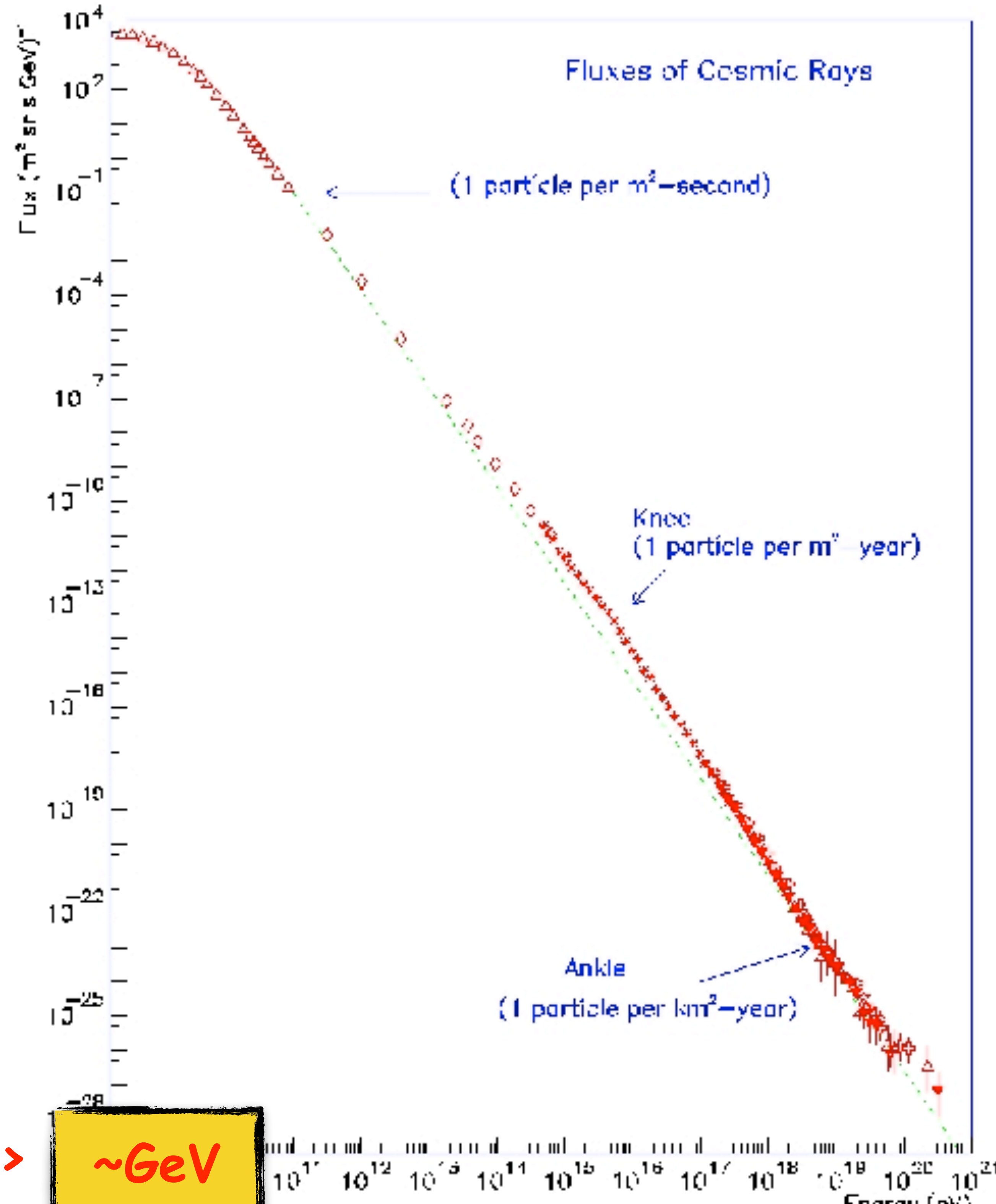
T. Gaisser "Cosmic Rays and Particle Physics"

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

The (local) Cosmic Ray spectrum

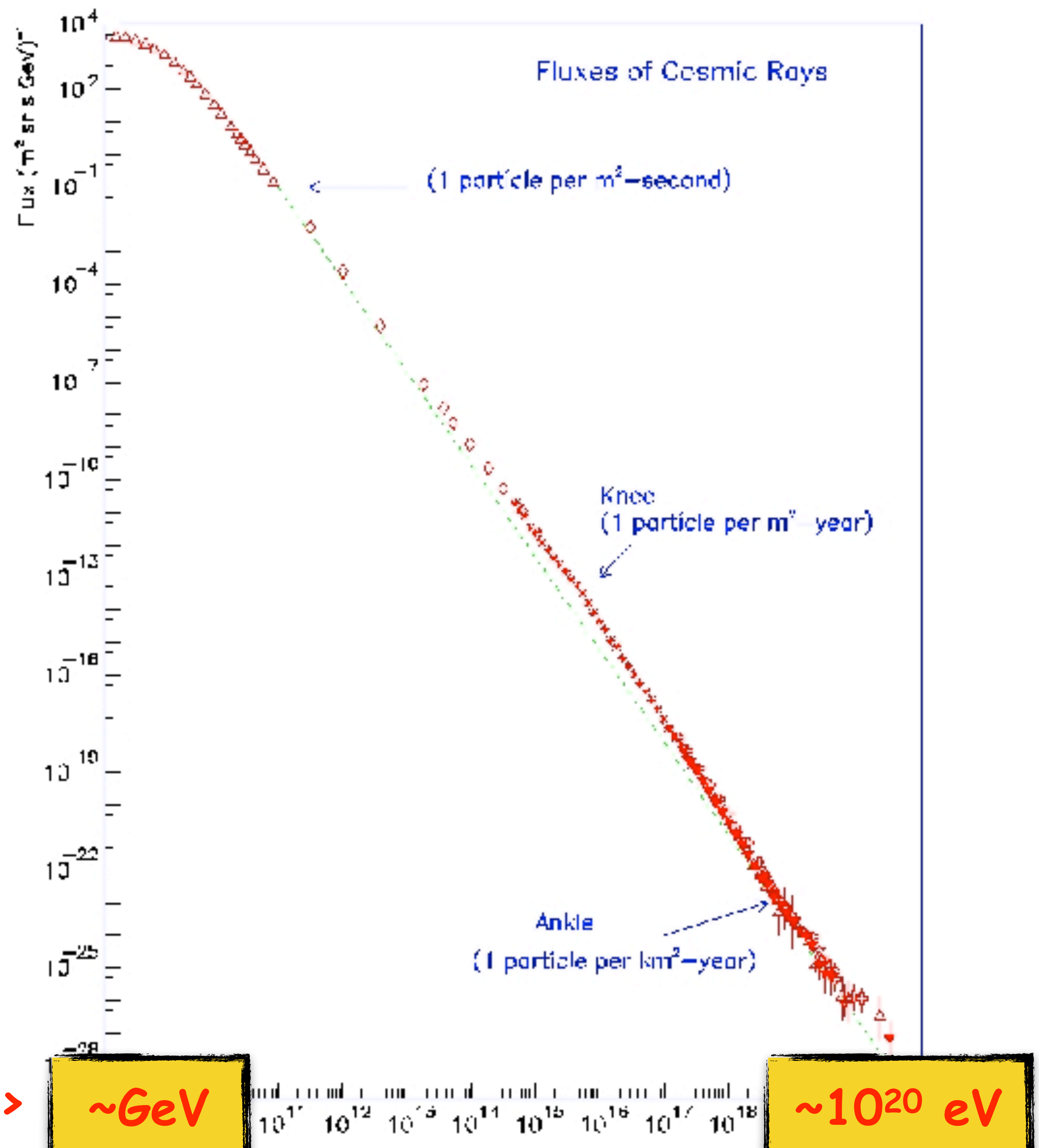


The (local) Cosmic Ray spectrum



mean energy -> ~GeV

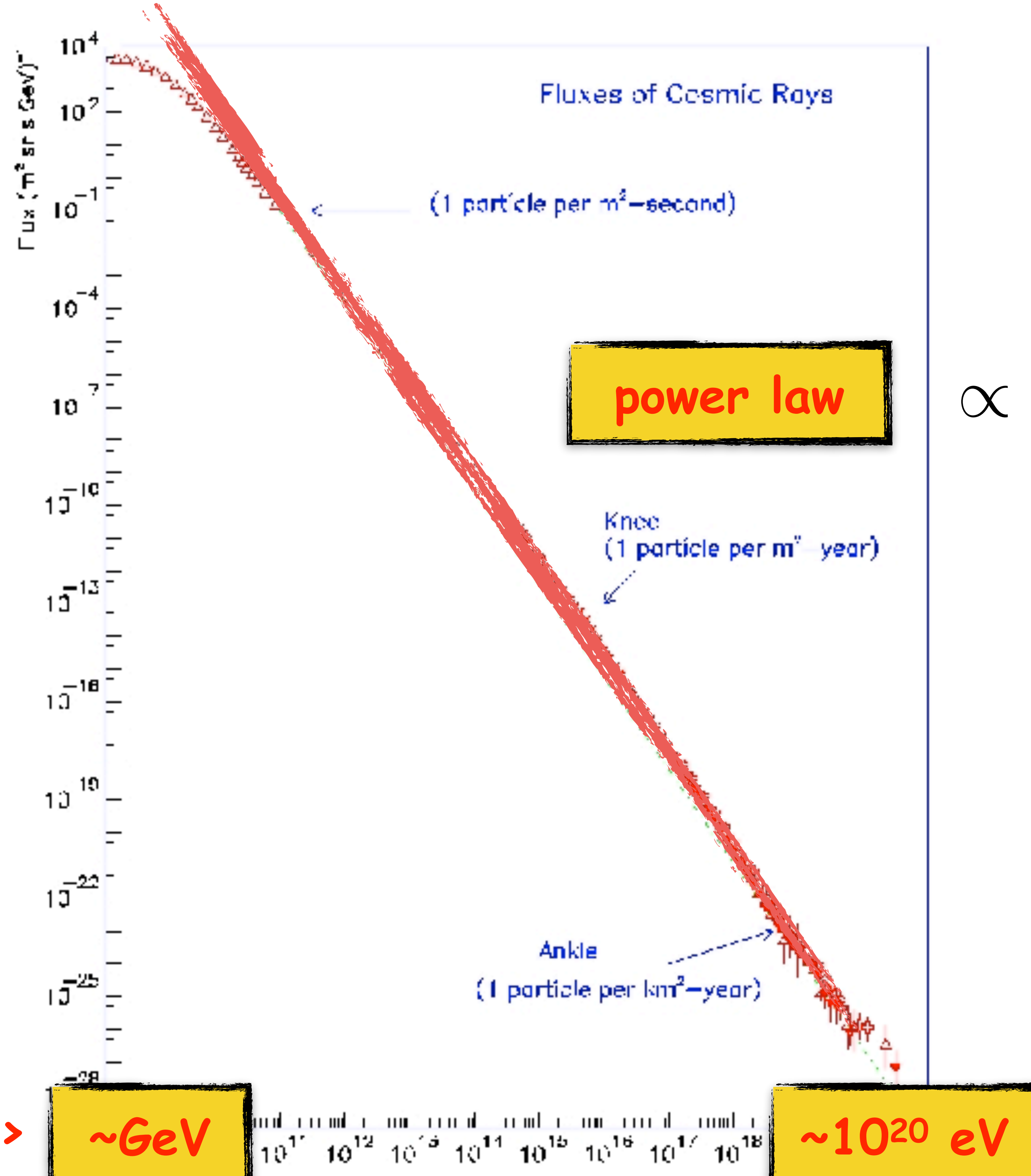
The (local) Cosmic Ray spectrum



mean energy -> ~GeV

~10^{20} eV <- maximum energy

The (local) Cosmic Ray spectrum

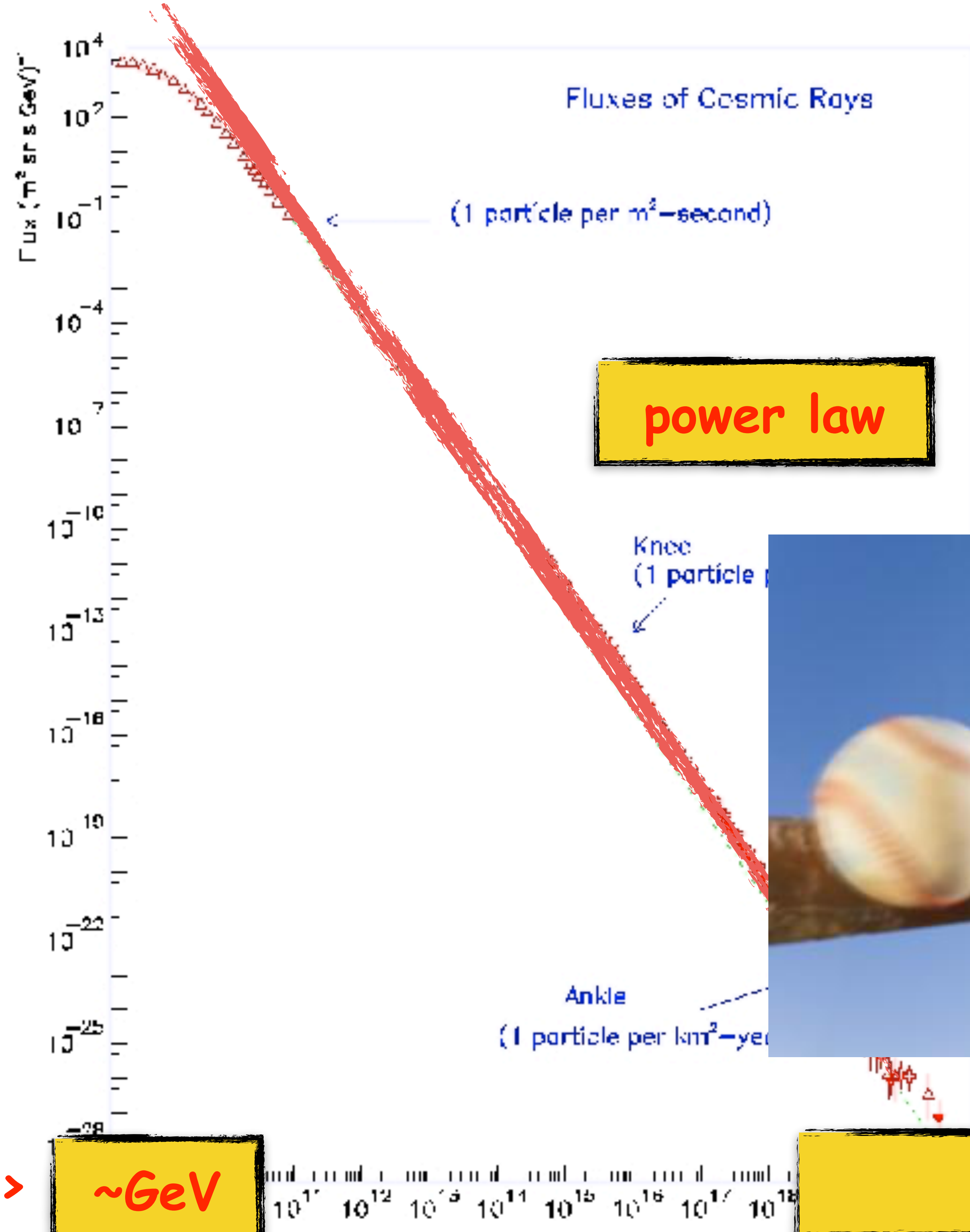


$$\propto E^{-2.7} - E^{-3}$$

mean energy -> ~GeV

~10^{20} eV <- maximum energy

The (local) Cosmic Ray spectrum



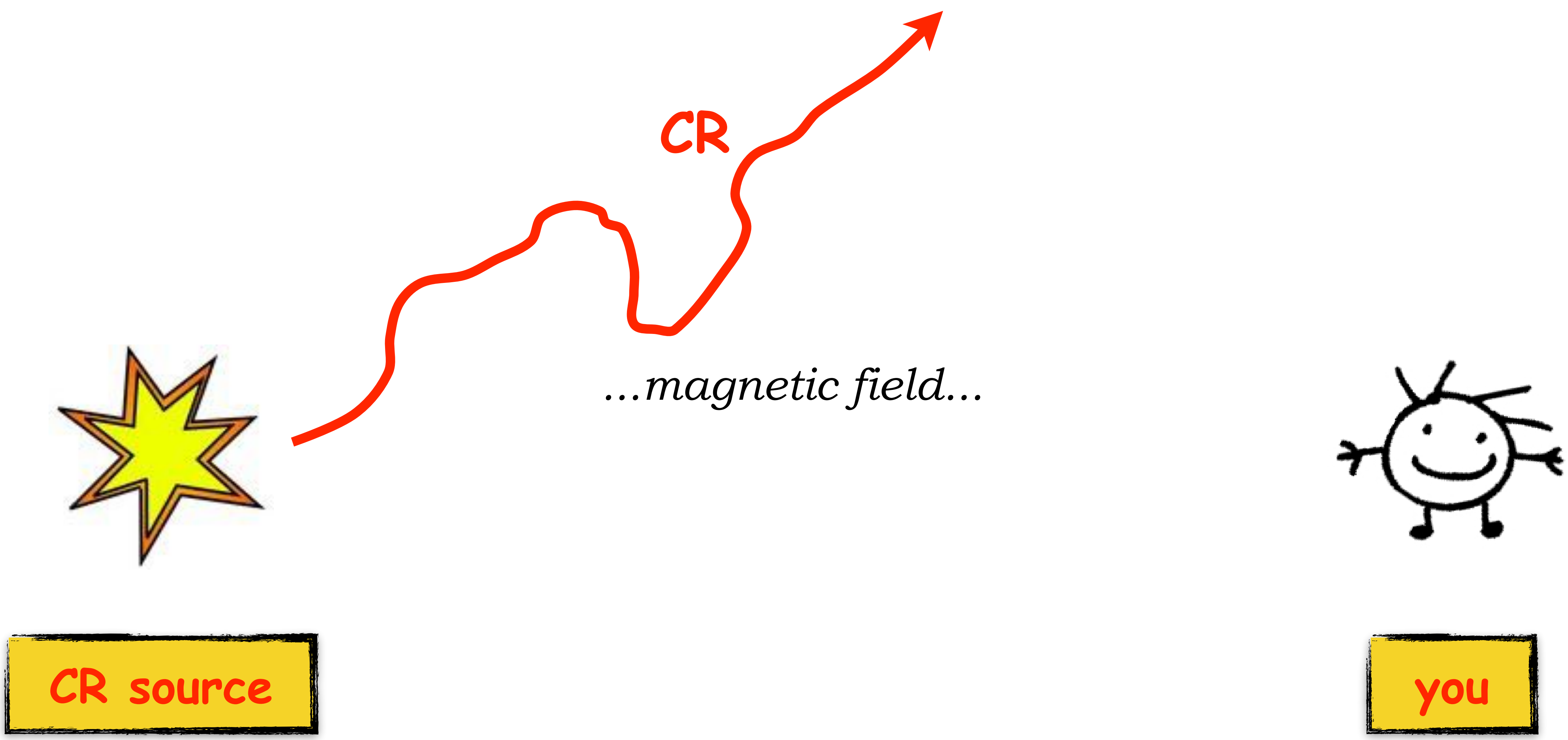
power law

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

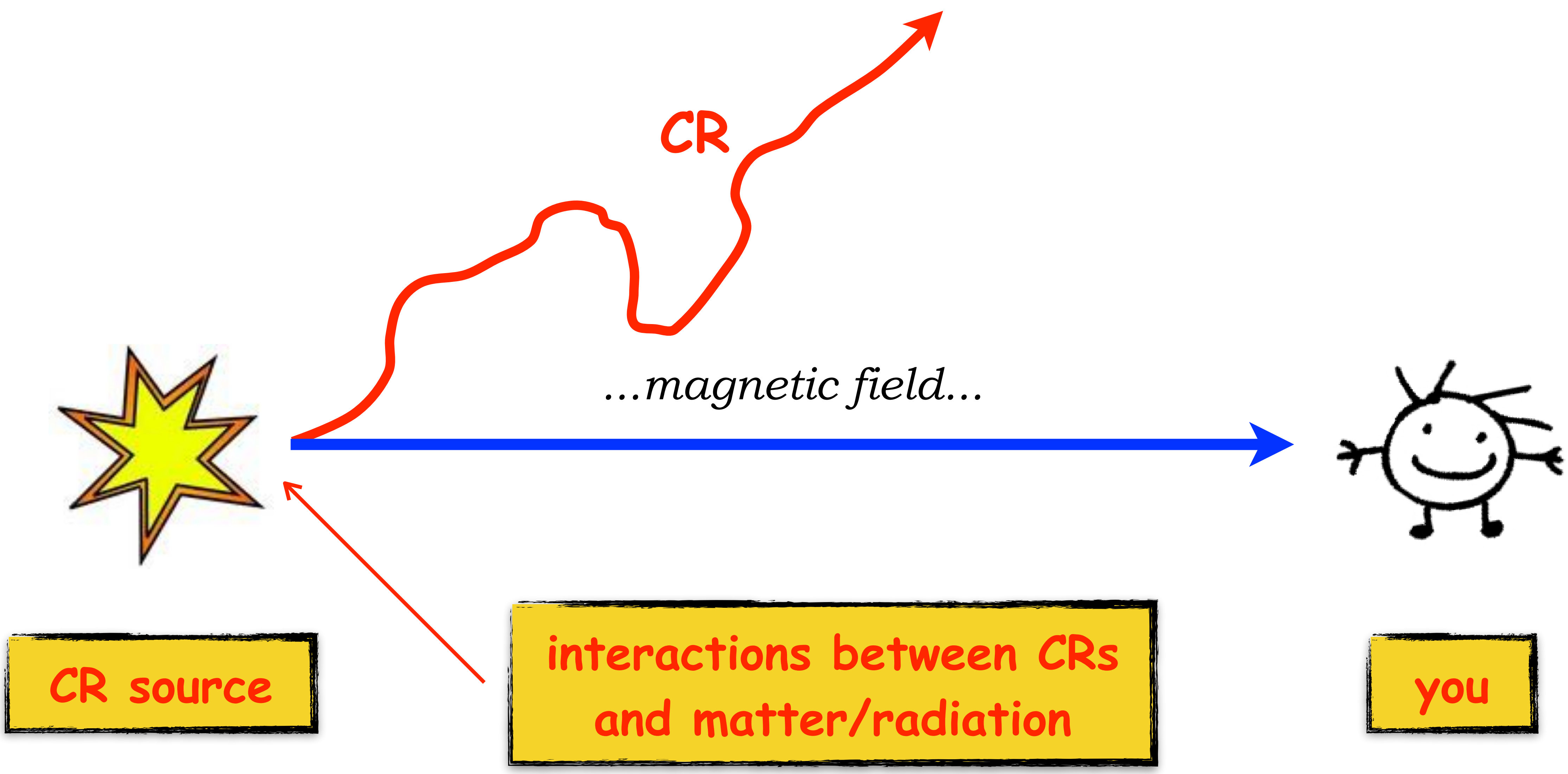
mean energy -> ~GeV

tens of Joules!

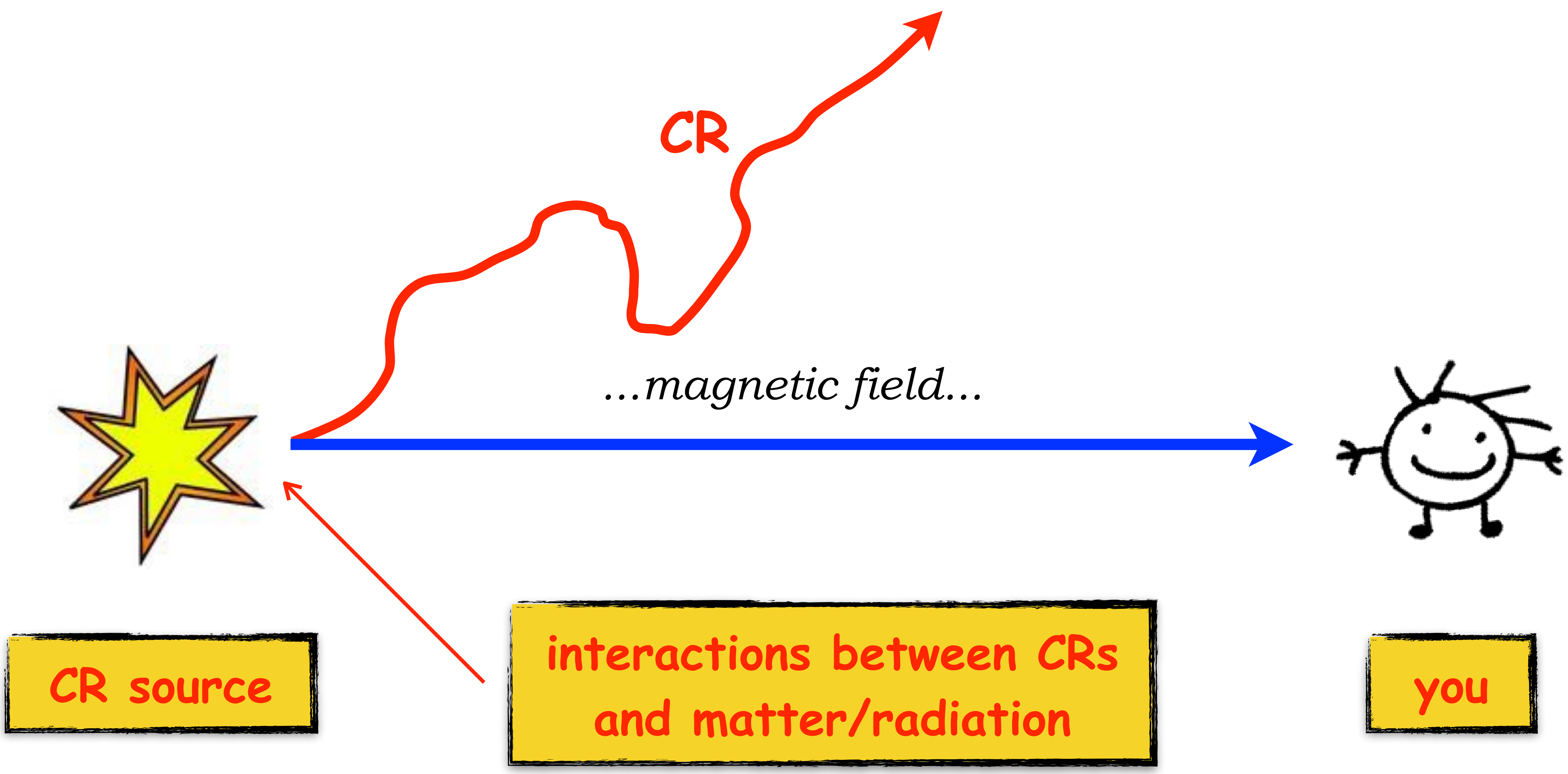
Cosmic ray sources: why is it so difficult?



Cosmic ray sources: why is it so difficult?



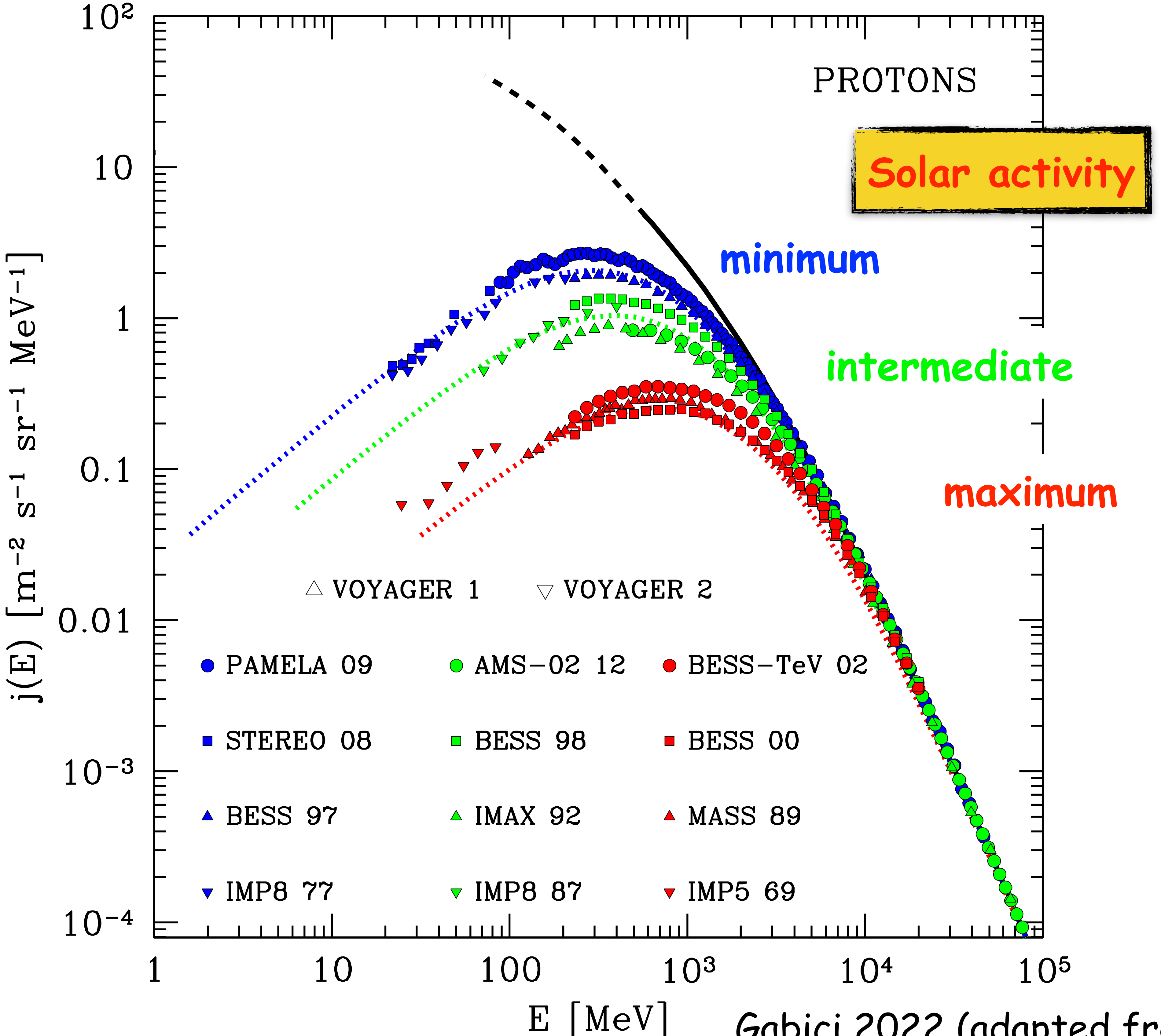
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

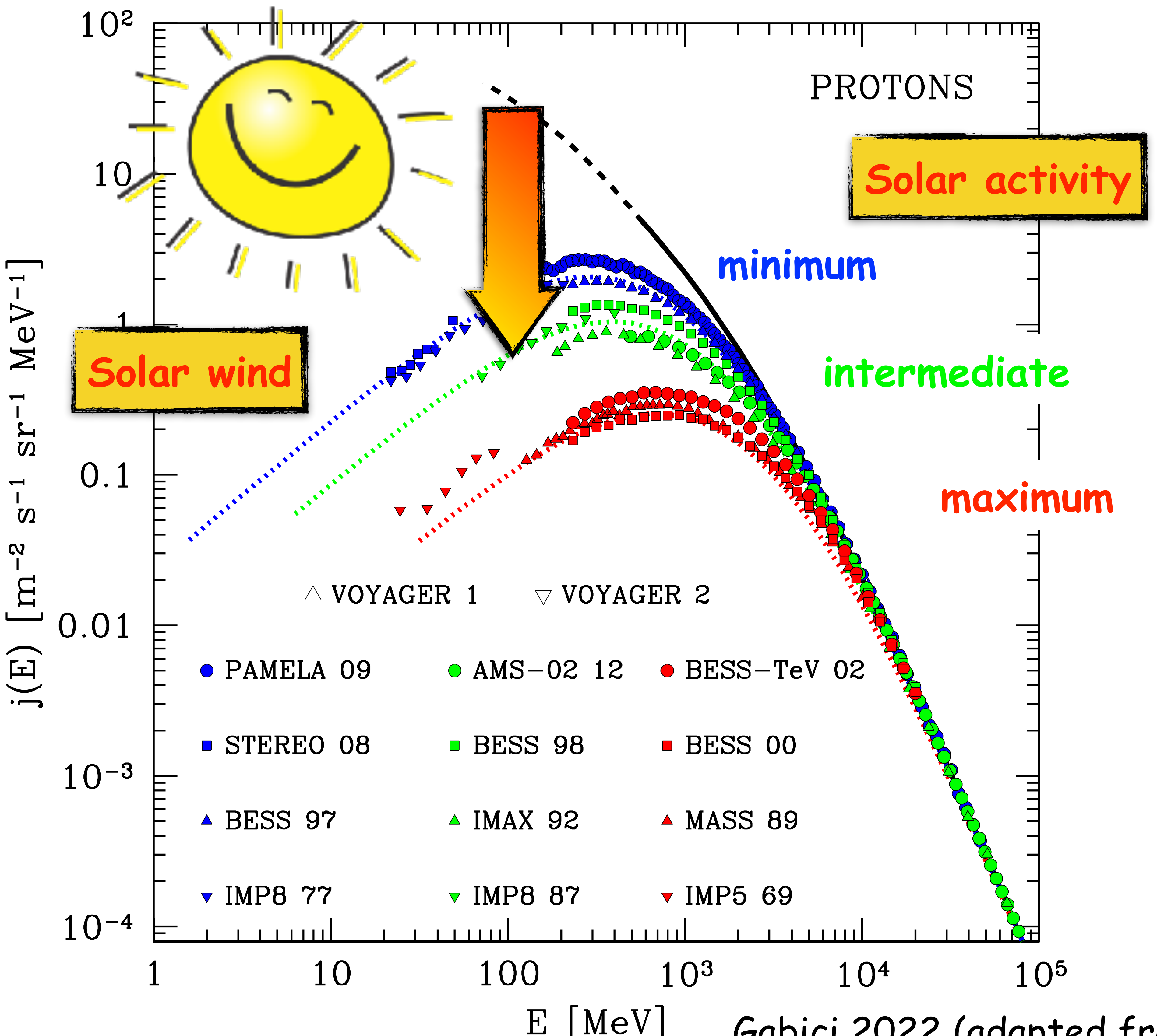
Need for indirect identification of CR sources.

Solar modulation



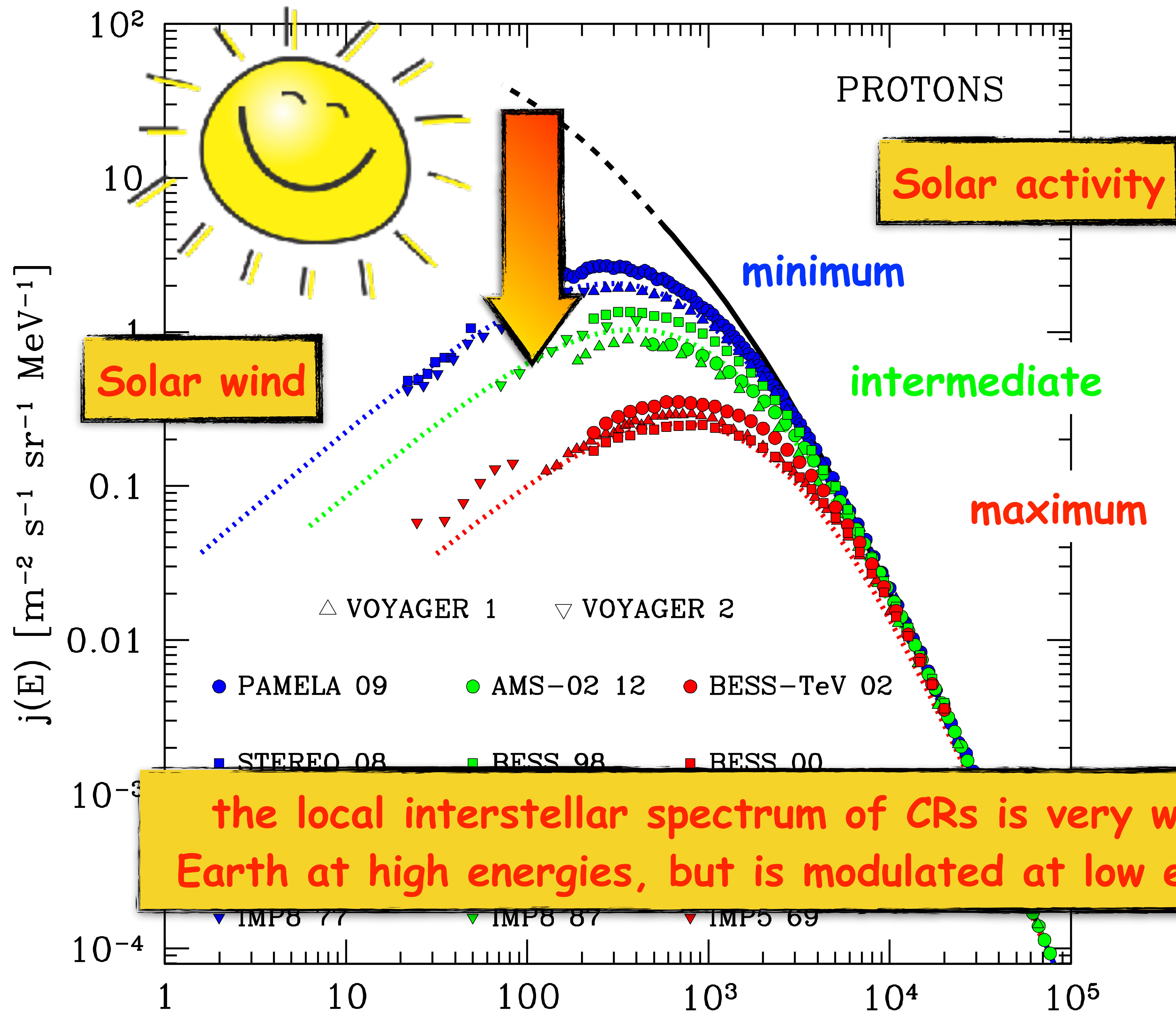
Gabici 2022 (adapted from Vos & Potgieter 2015)

Solar modulation



Gabici 2022 (adapted from Vos & Potgieter 2015)

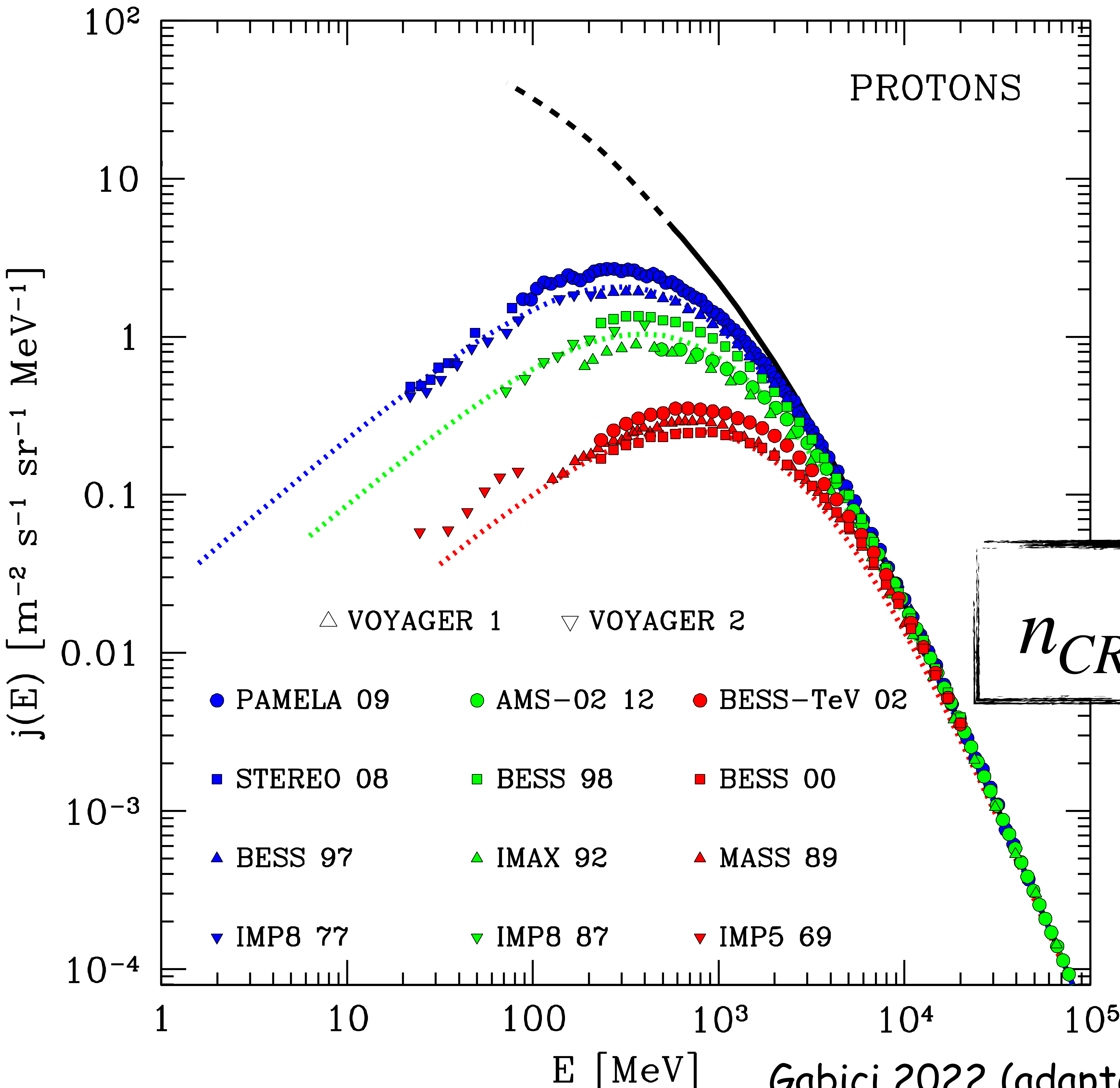
Solar modulation



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)

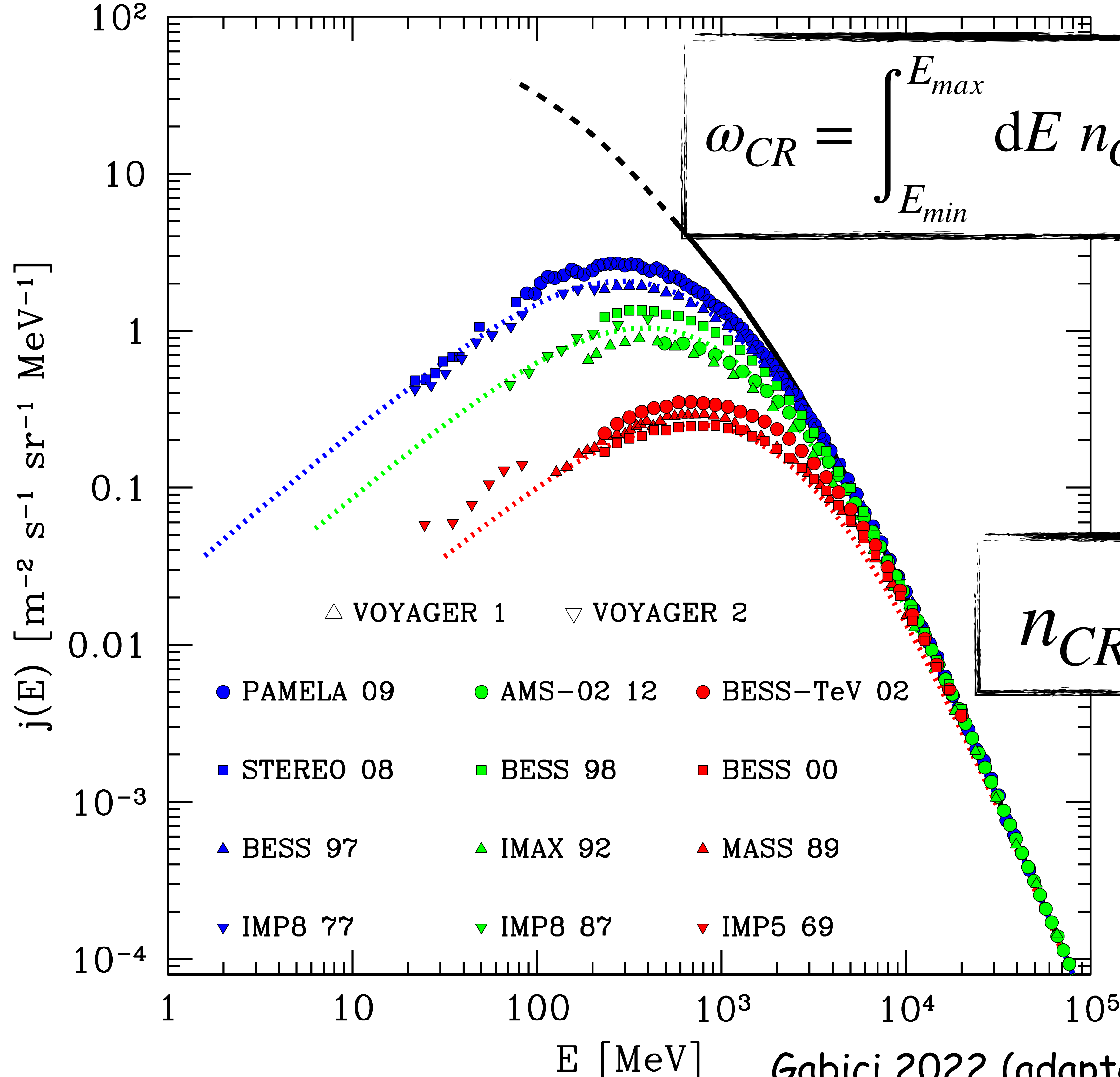
Solar modulation



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

Gabici 2022 (adapted from Vos & Potgieter 2015)

Solar modulation

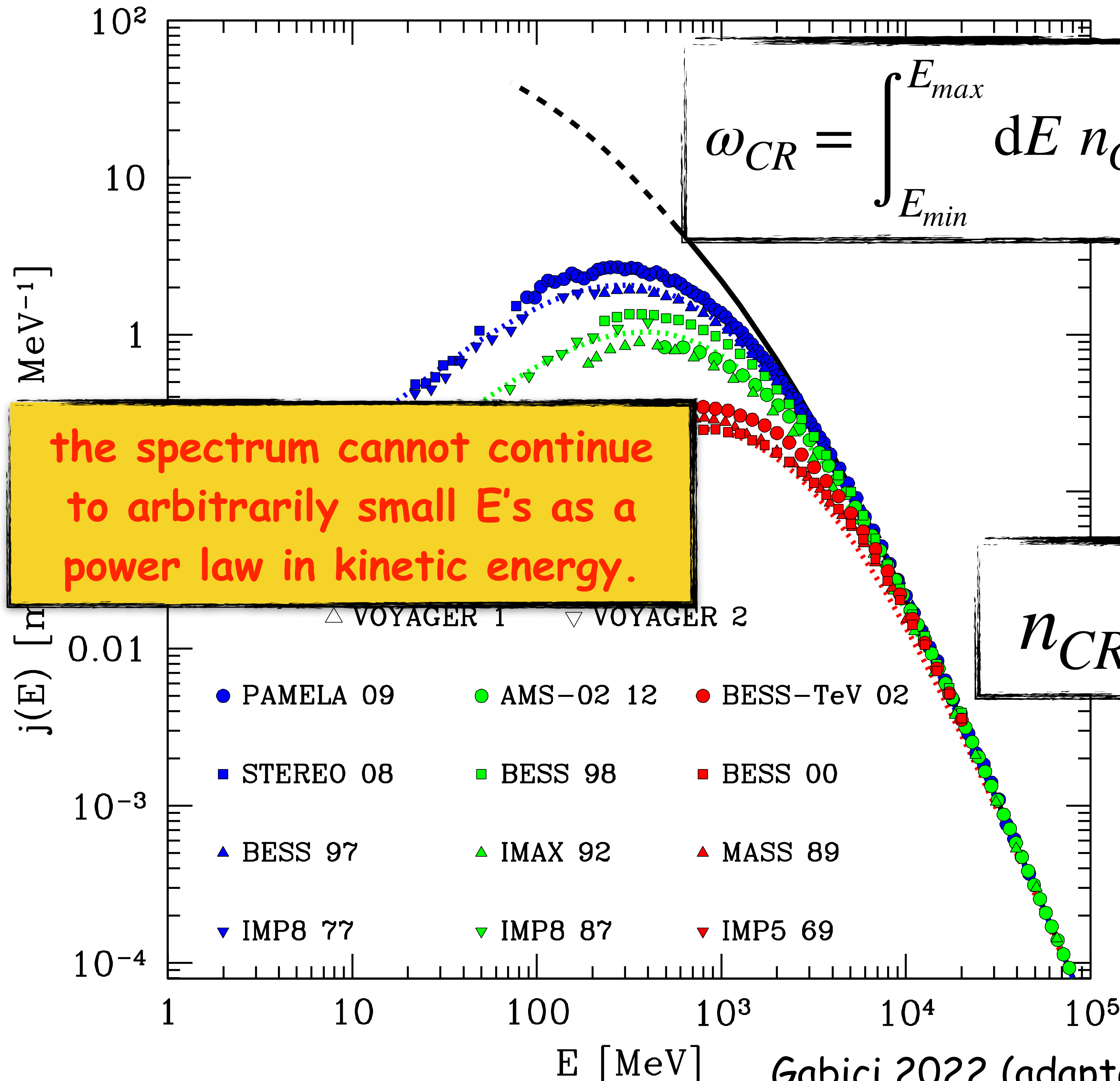


$$\omega_{CR} = \int_{E_{min}}^{E_{max}} \mathrm{d}E \; n_{CR}(E) E \propto E_{min}^{-0.7} \xrightarrow{E_{min} \to 0} \infty$$

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

Gabici 2022 (adapted from Vos & Potgieter 2015)

Solar modulation



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

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

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

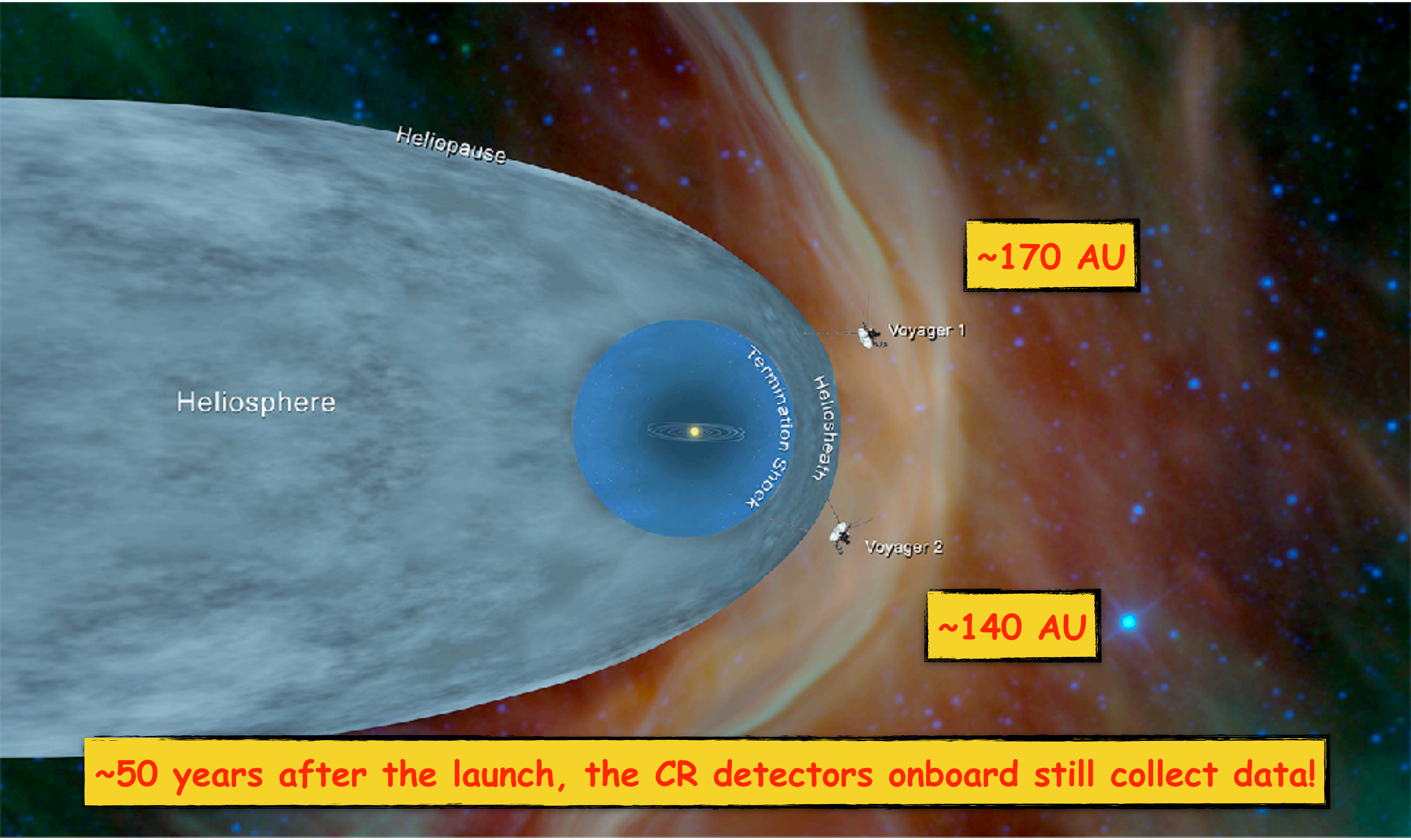
Gabici 2022 (adapted from Vos & Potgieter 2015)

Voyager probes

September 5 1977
the launch of Voyager 1

August 20 1977 launch of the twin probe Voyager 2

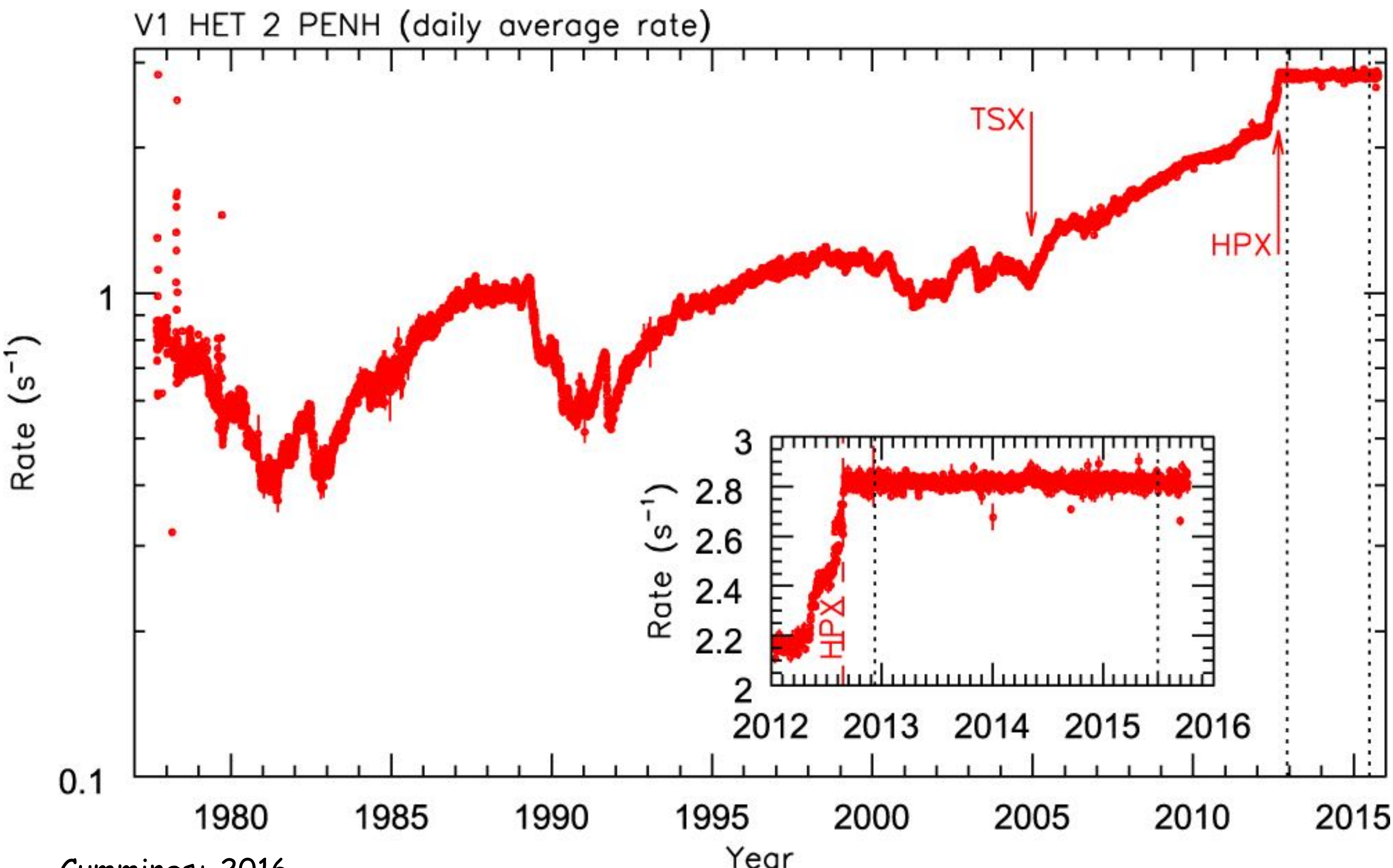
Voyager probes crossed the heliopause



Instrument	Voyager 1	Voyager 2
Cosmic Ray Subsystem (CRS)	Off to save power (Feb 25, 2025)	On
Low-Energy Charged Particles (LECP)	On	Off to save power (Mar 24, 2025)
Magnetometer (MAG)	On	On
Plasma Wave Subsystem (PWS)	On	On
Plasma Science (PLS)	Off because of degraded performance (Feb 1, 2007)	Off to save power (Sep 26, 2024)
Imaging Science Subsystem (ISS)	Wide-angle and narrow-angle cameras off to save power (Feb. 14, 1990)	Wide-angle and narrow angle cameras off to save power (Oct 10 and Dec 5, 1989)
Infrared Interferometer Spectrometer and Radiometer (IRIS)	Off to save power (Jun 3, 1998)	Off to save power (Feb 1, 2007)
Photopolarimeter Subsystem (PPS)	Off because of degraded performance (Jan 29, 1980)	Off because of degraded performance (Apr 3, 1991)
Planetary Radio Astronomy (PRA)	Off to save power (Jan 15, 2008)	Off to save power (Feb 21, 2008)
Ultraviolet Spectrometer (UVS)	Off to save power (Apr 19, 2016)	Off to save power (Nov 12, 1998)

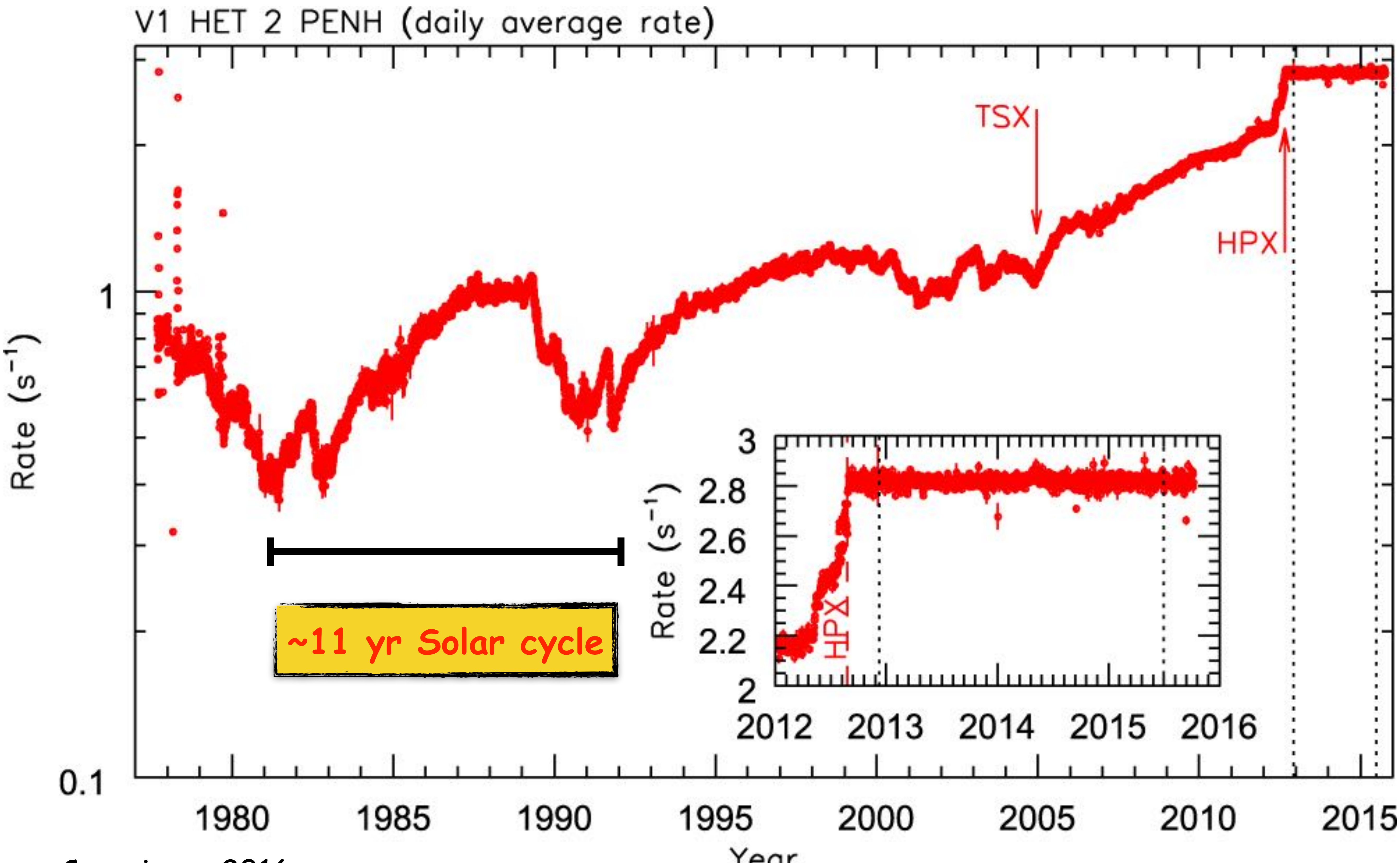
Instrument	Voyager 1	Voyager 2
Cosmic Ray Subsystem (CRS)	Off to save power (Feb 25, 2025)	On
Low-Energy Charged Particles (LECP)	On	Off to save power (Mar 24, 2025)
Magnetometer (MAG)	On	On
Plasma Wave Subsystem (PWS)	On	On
Plasma Science (PLS)	Off because of degraded performance (Feb 1, 2007)	Off to save power (Sep 26, 2024)
Imaging Science Subsystem (ISS)	Wide-angle and narrow-angle cameras off to save power (Feb. 14, 1990)	Wide-angle and narrow angle cameras off to save power (Oct 10 and Dec 5, 1989)
Infrared Interferometer Spectrometer and Radiometer (IRIS)	Off to save power (Jun 3, 1998)	Off to save power (Feb 1, 2007)
Photopolarimeter Subsystem (PPS)	Off because of degraded performance (Jan 29, 1980)	Off because of degraded performance (Apr 3, 1991)
Planetary Radio Astronomy (PRA)	Off to save power (Jan 15, 2008)	Off to save power (Feb 21, 2008)
Ultraviolet Spectrometer (UVS)	Off to save power (Apr 19, 2016)	Off to save power (Nov 12, 1998)

An epic journey



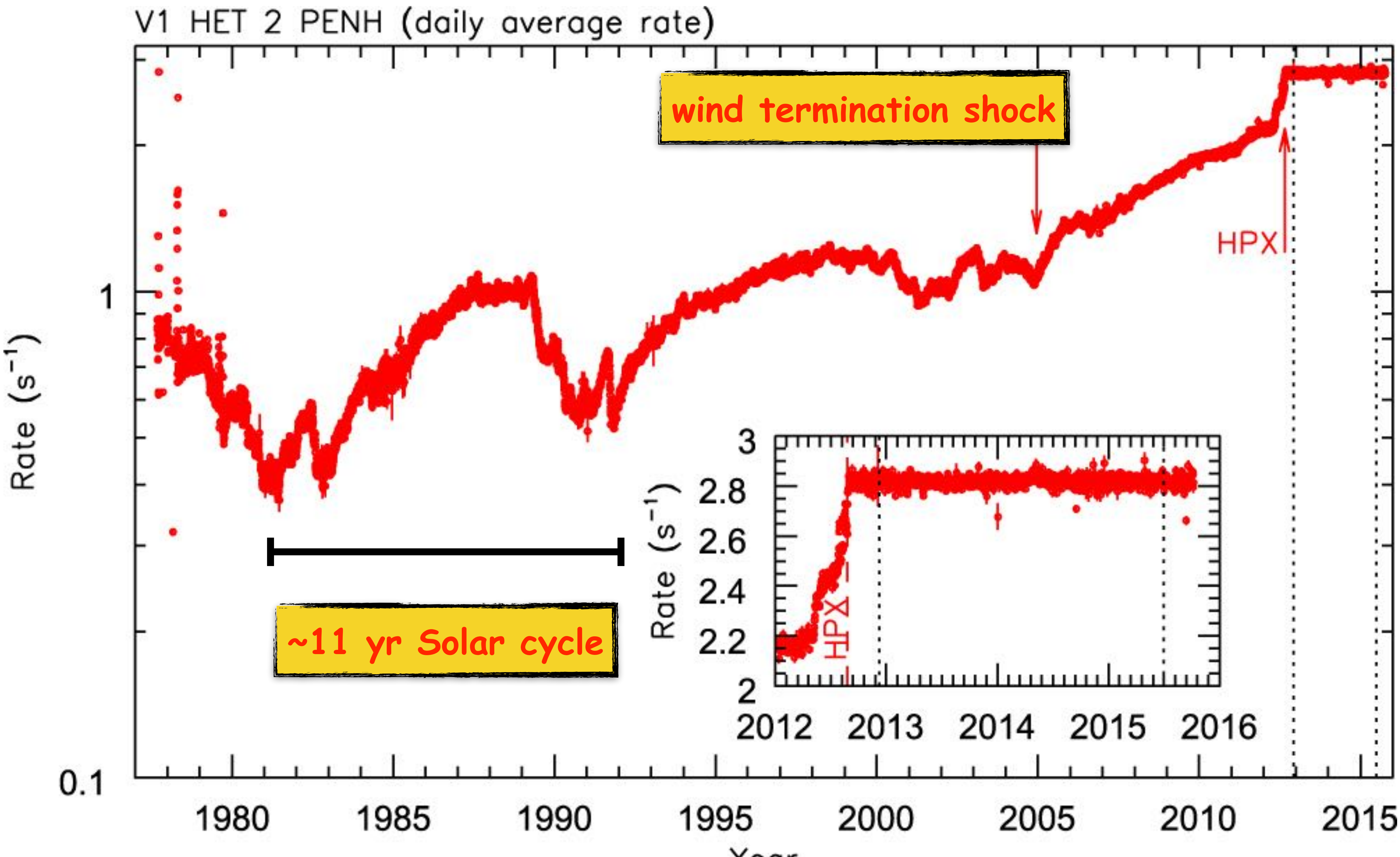
Cummings+ 2016

An epic journey



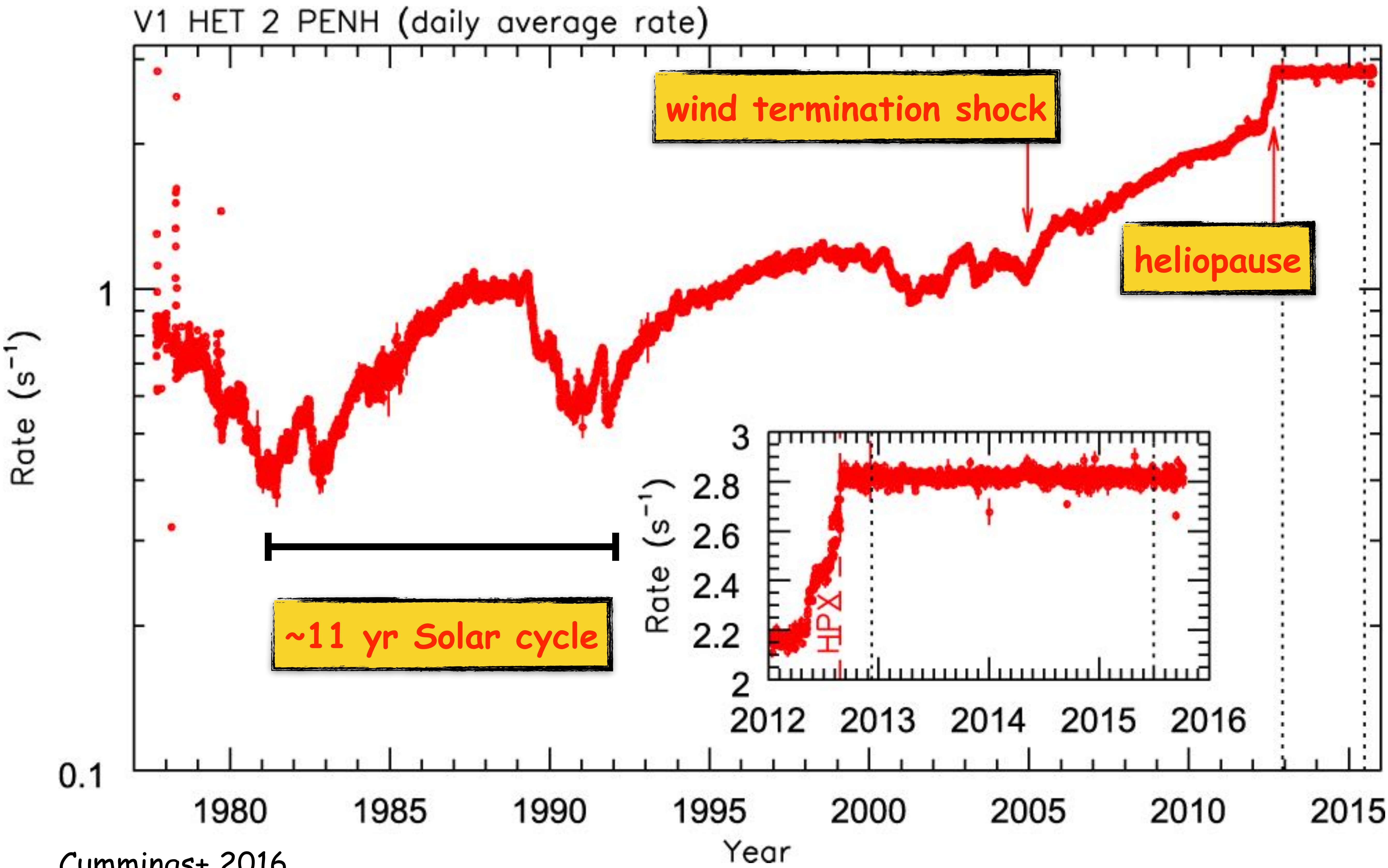
Cummings+ 2016

An epic journey



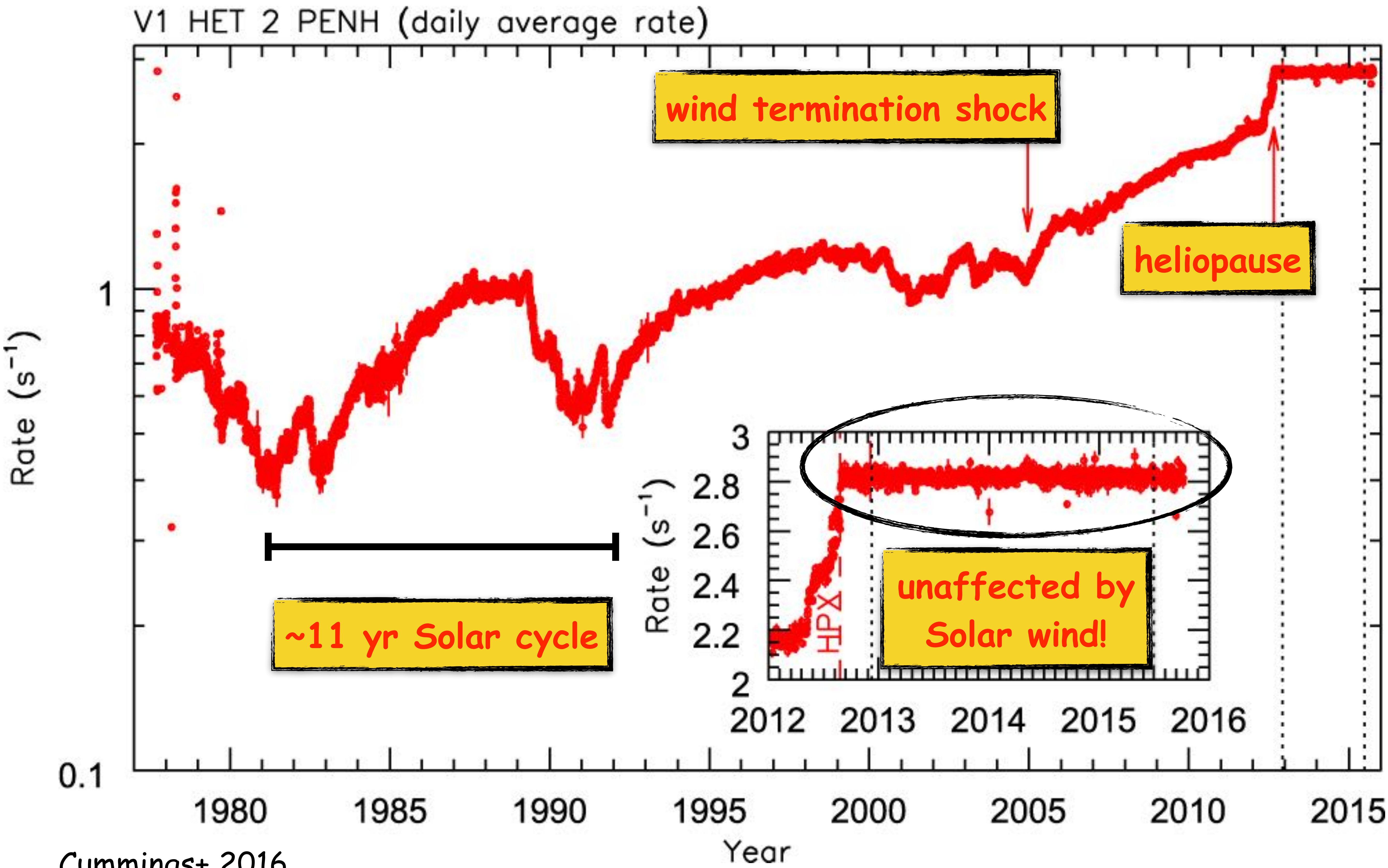
Cummings+ 2016

An epic journey



Cummings+ 2016

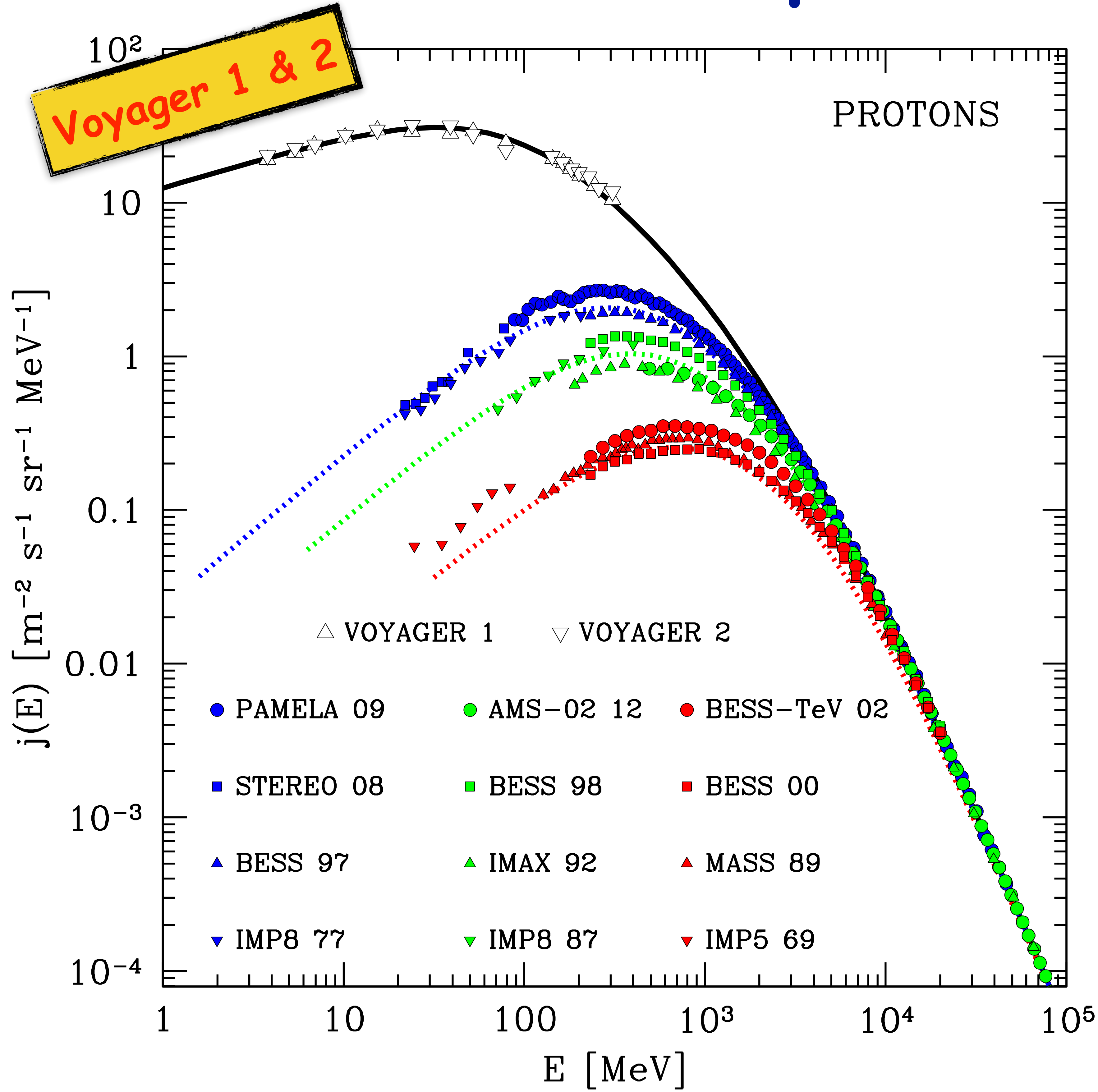
An epic journey



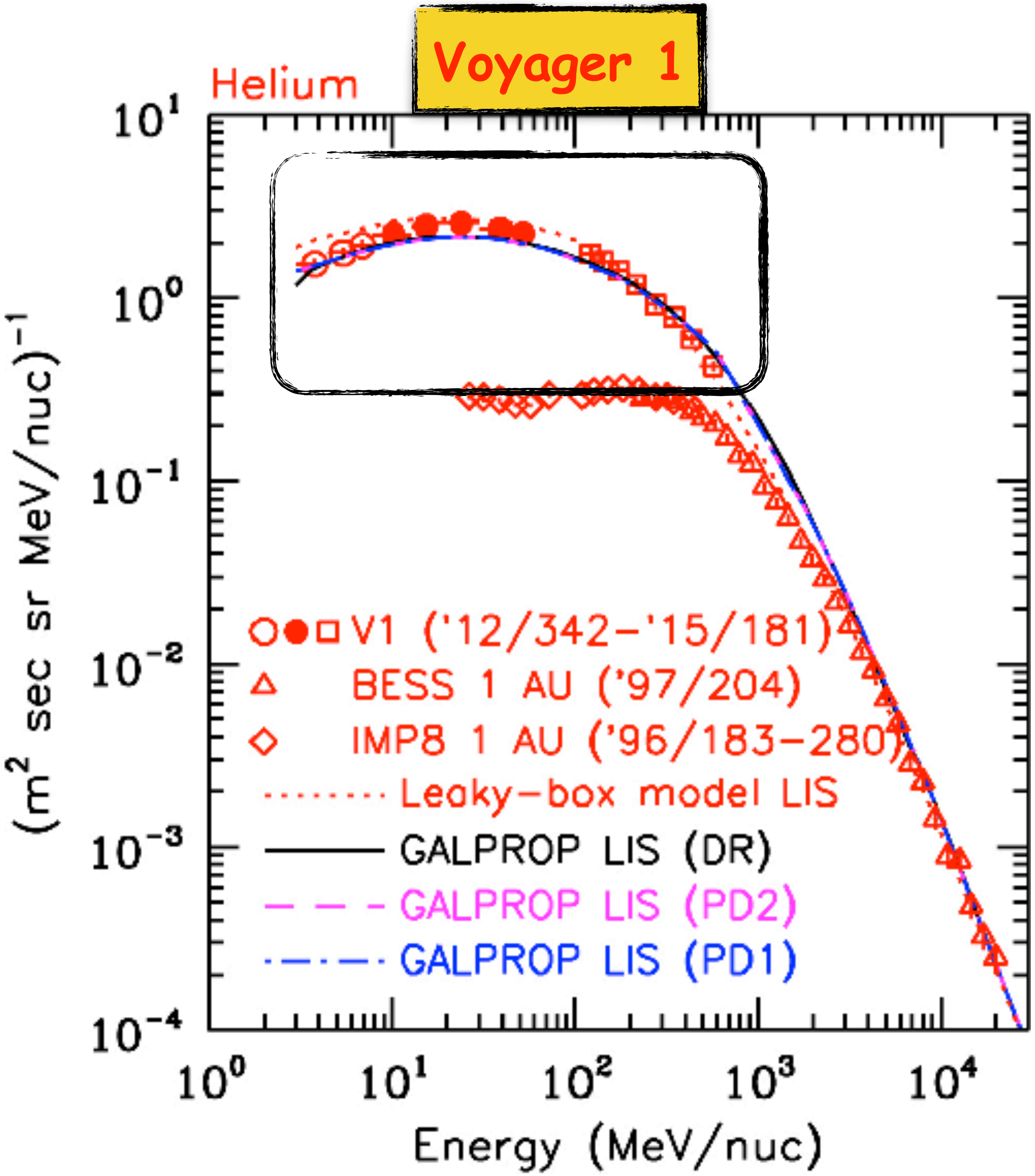
Cummings+ 2016

The local interstellar spectrum of CRs

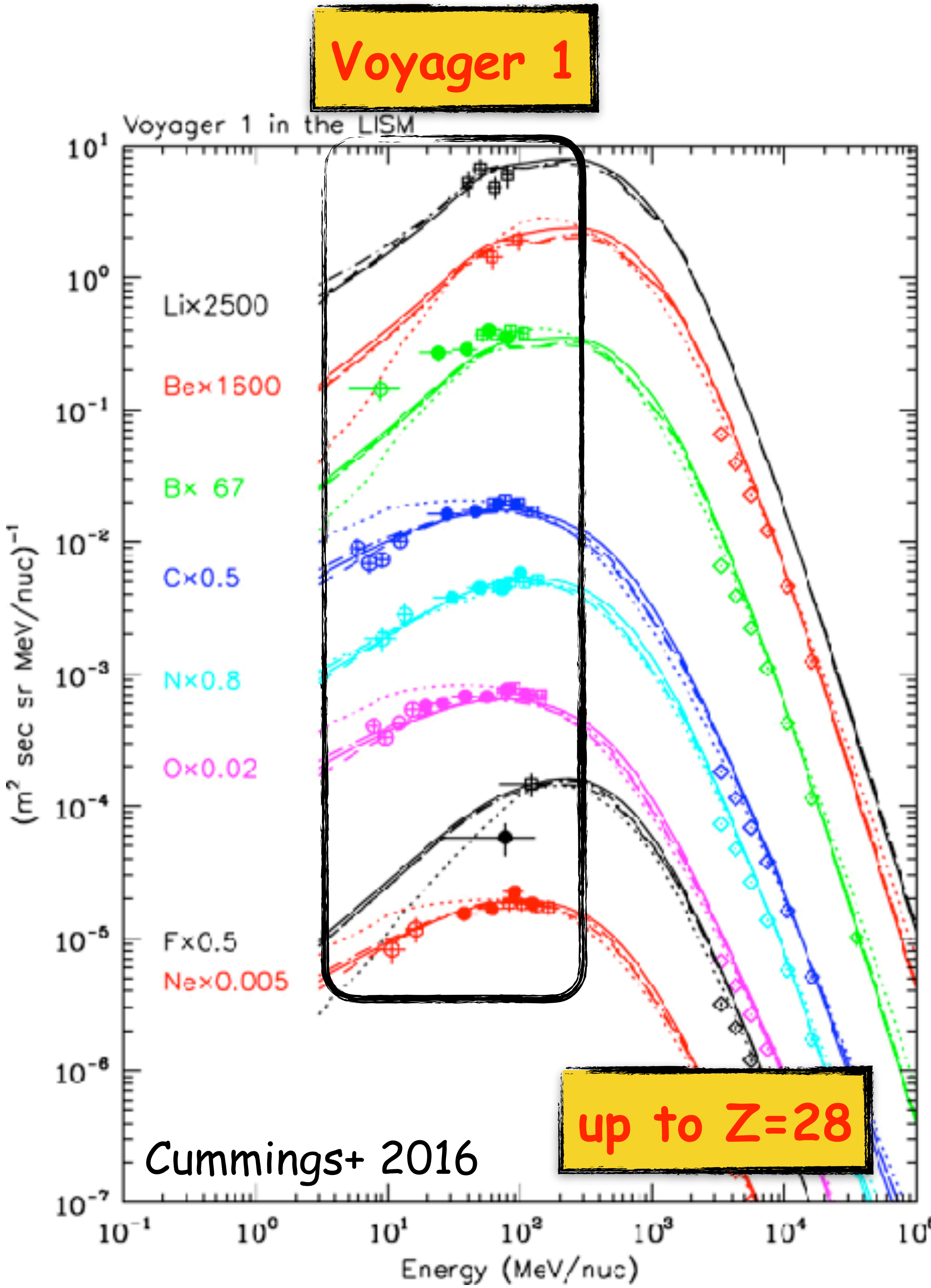
Gabici 2022 (adapted from Vos & Potgieter 2015)



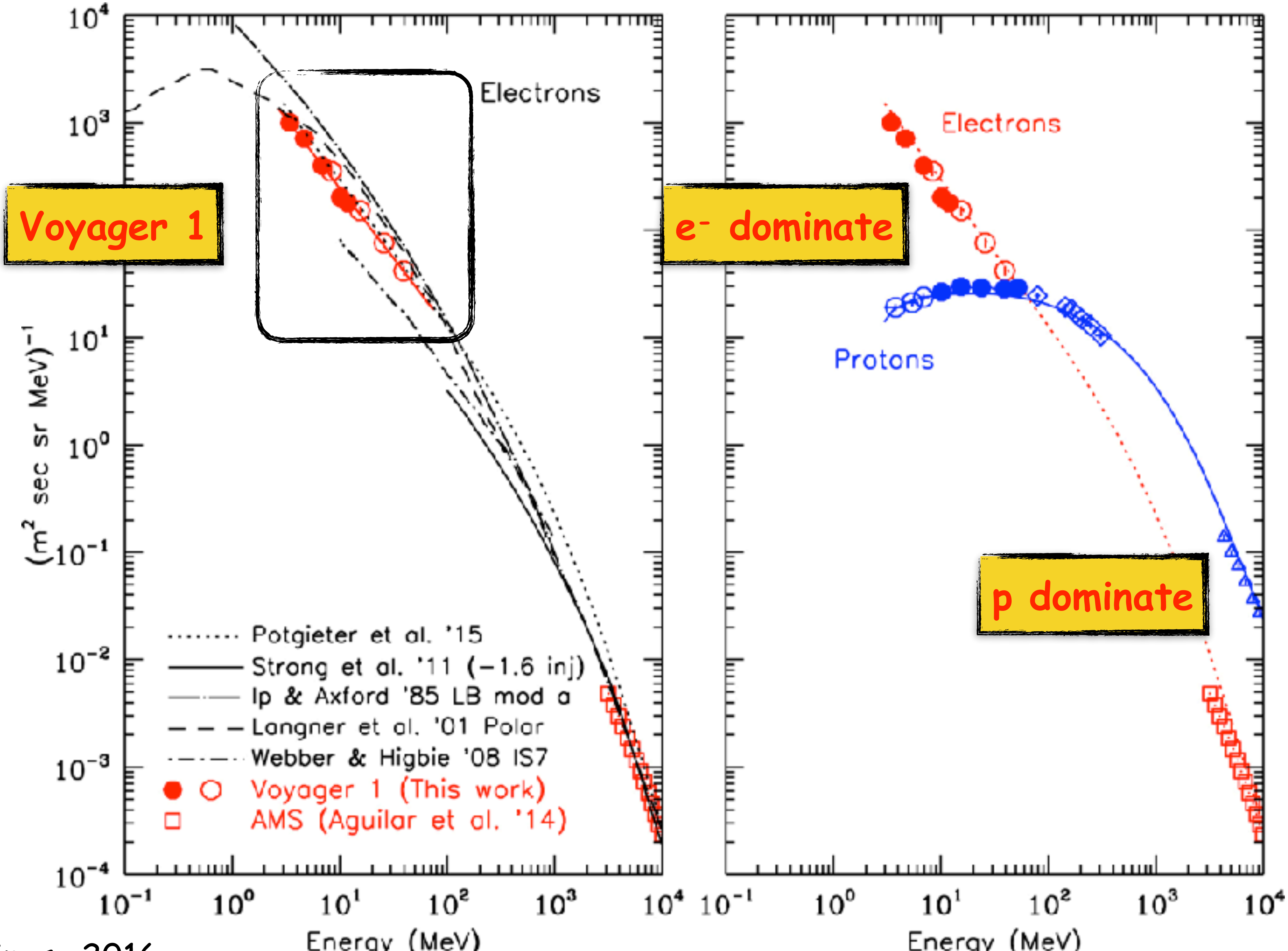
Spectra of nuclei in the local ISM



Cummings+ 2016



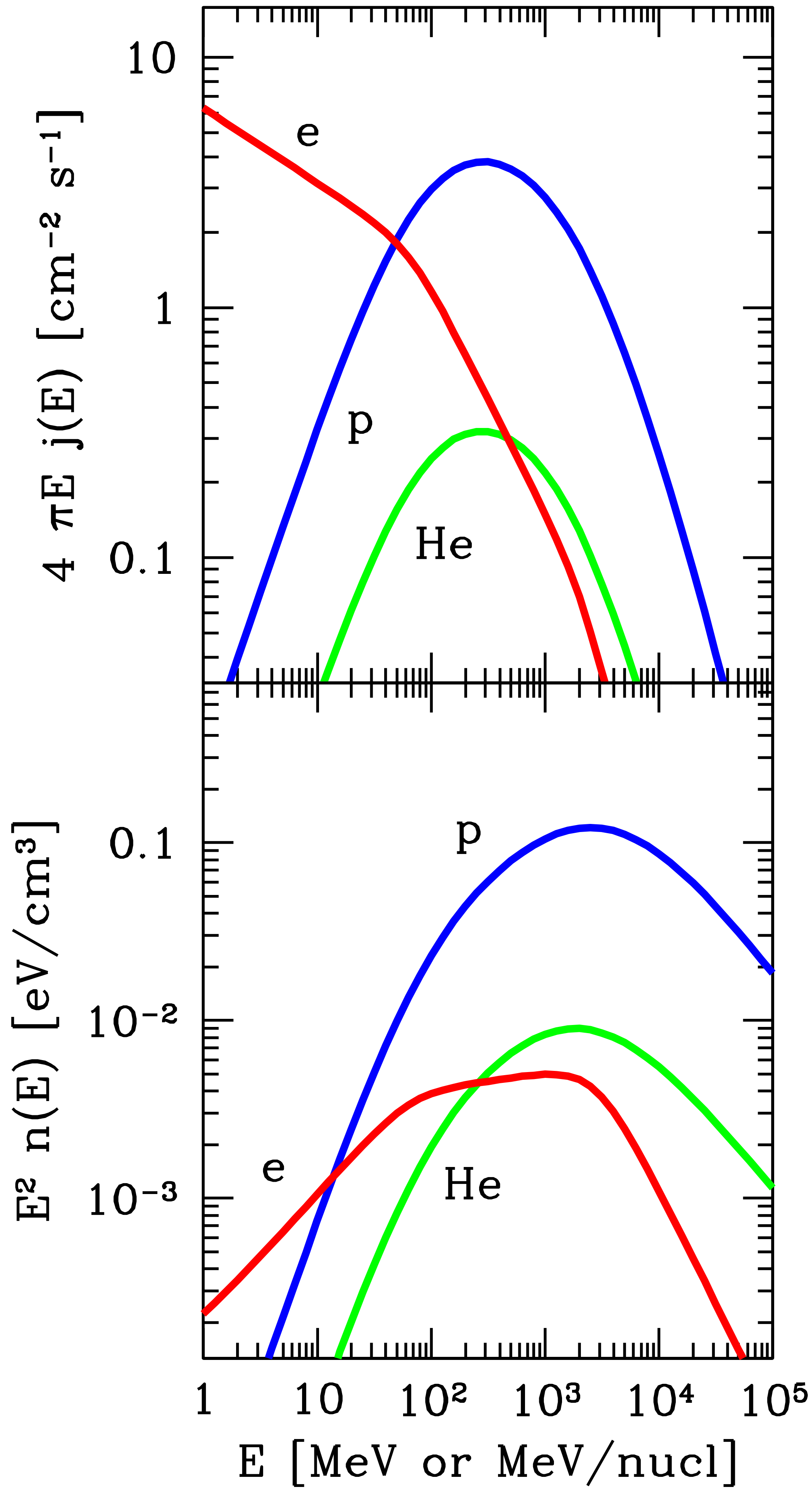
Electron spectrum in the local ISM



Cummings+ 2016

flux of particles

spectral energy distribution



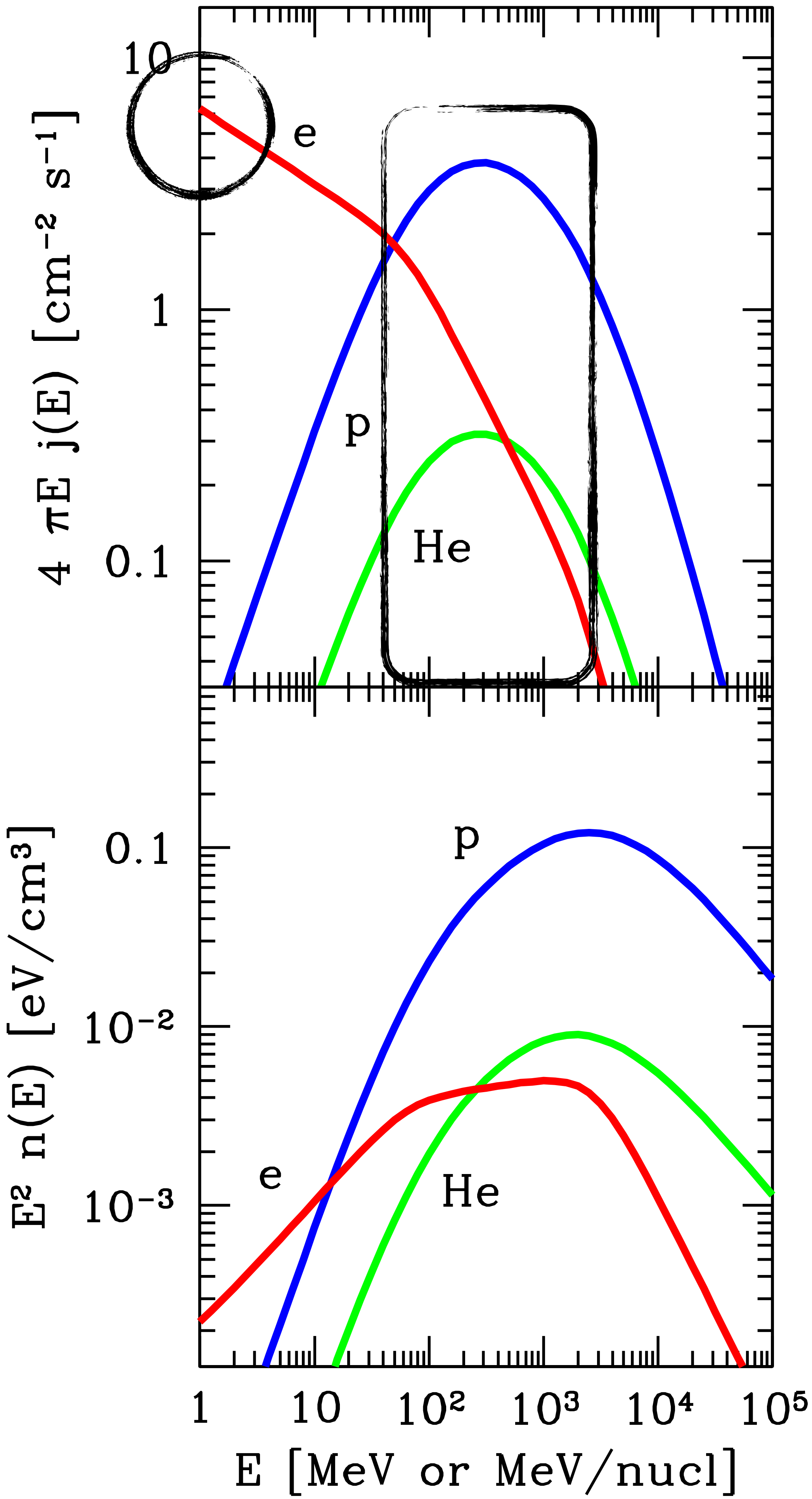
Gabici 2022

flux of particles

most nuclei have
energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution



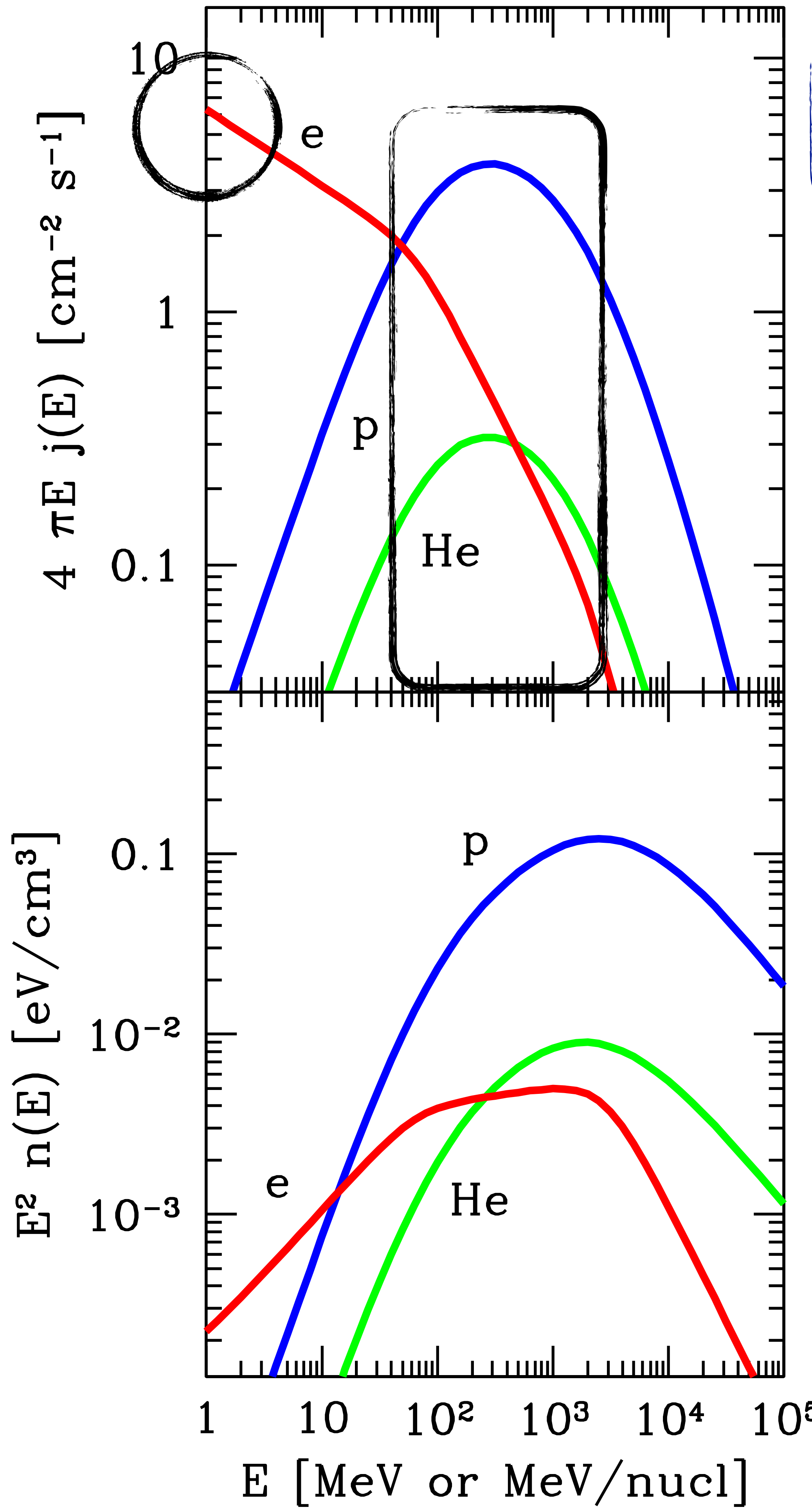
Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution



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

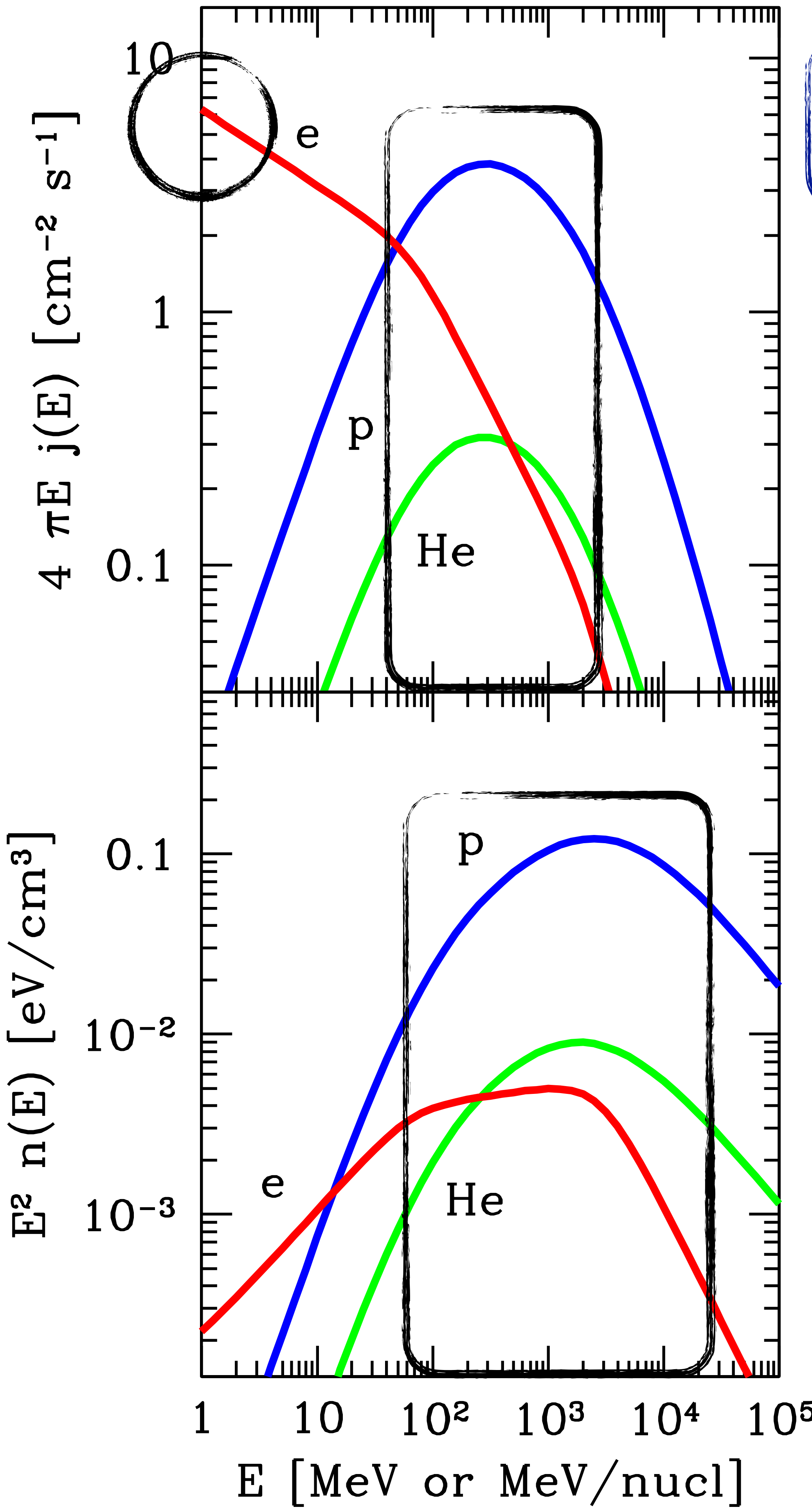
Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

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



spectral energy distribution

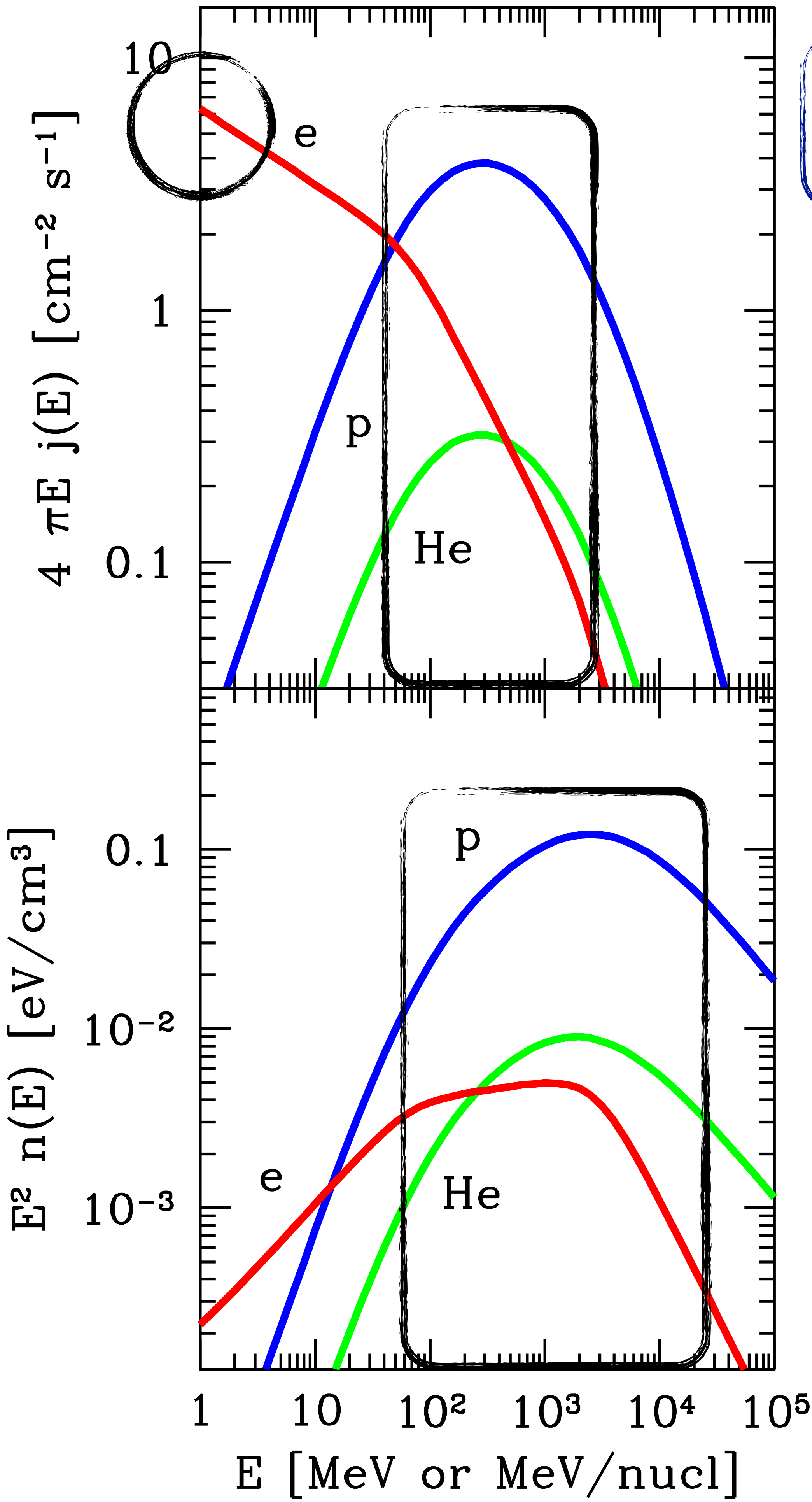
energy is carried mainly by particles of energy 100 MeV-10 GeV

Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?



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

spectral energy distribution

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

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

Gabici 2022

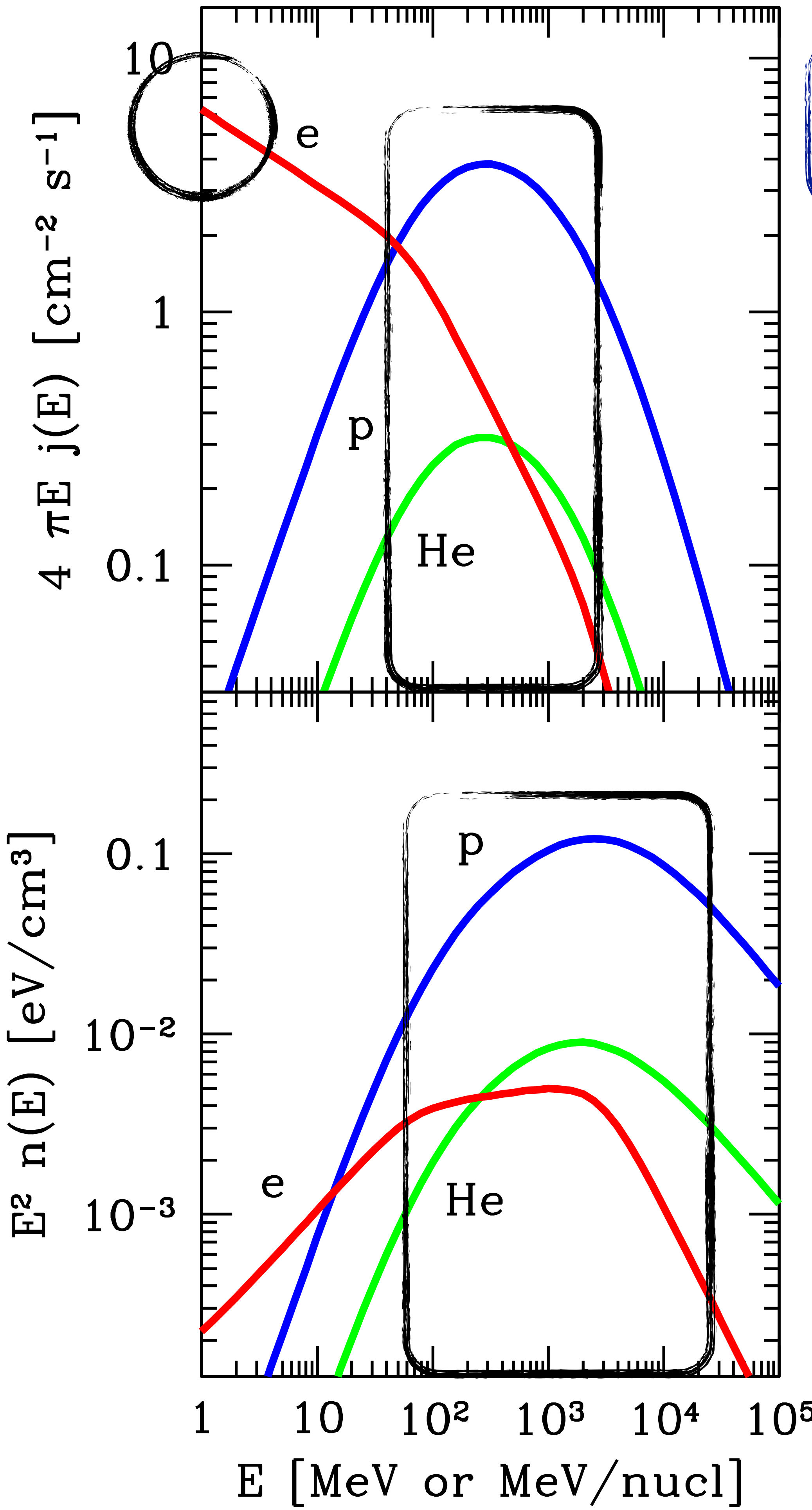
flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

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



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

compare with ISM density...

$\approx 0.1 - 1\ \text{cm}^{-3}$

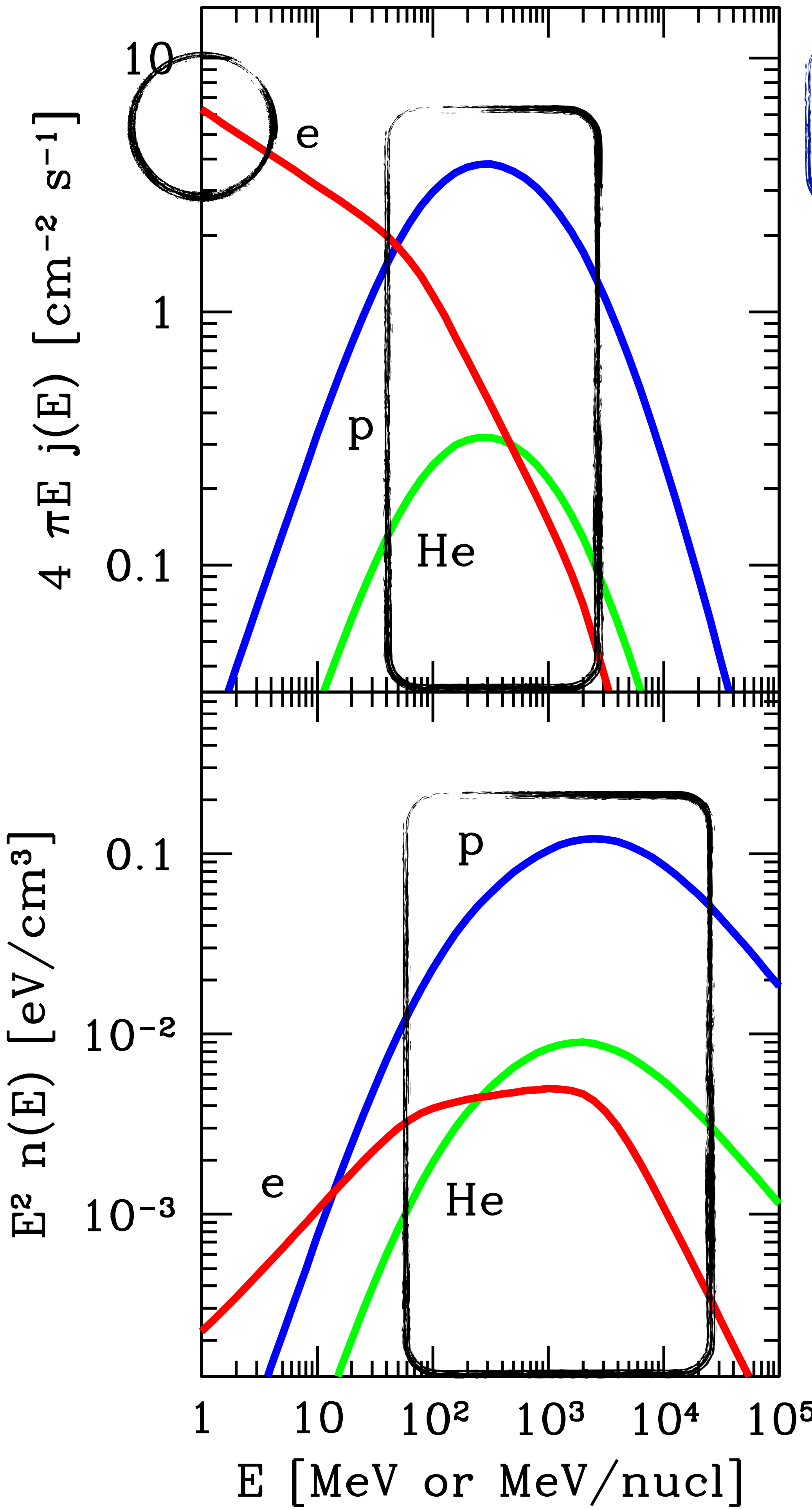
$\approx 1\ \text{eV/cm}^3$

Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?



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

compare with ISM density...

$$\approx 0.1 - 1 \text{ cm}^{-3}$$

spectral energy distribution

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

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

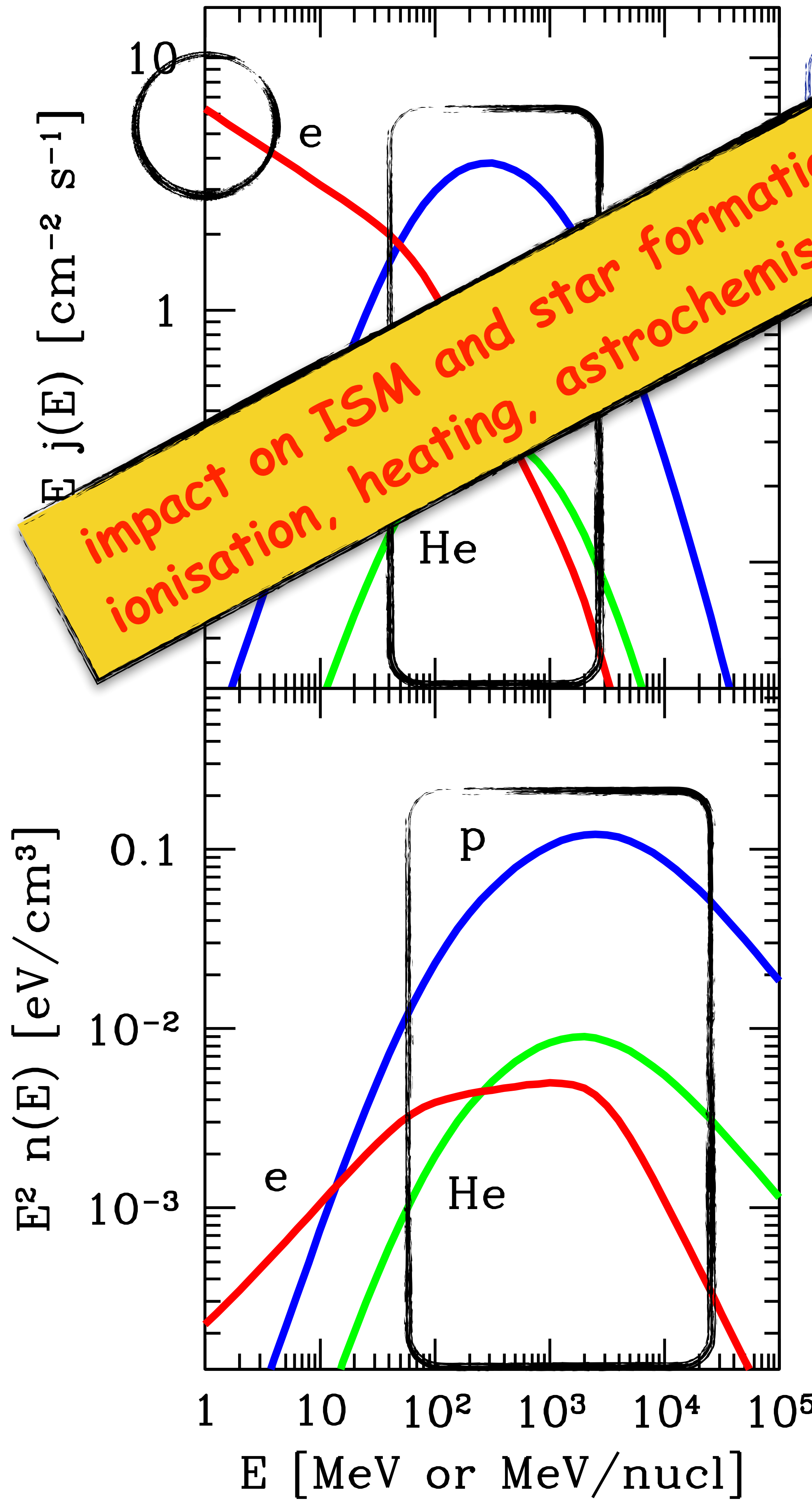
$$\approx 1 \text{ eV/cm}^3$$

Gabici 2022

flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?



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

$0^{-9} - 10^{-10}\ \mathrm{cm}^{-3}$

compare with ISM density…

$\approx 0.1 - 1\ \mathrm{cm}^{-3}$

spectral energy distribution

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

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

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

Gabici 2022

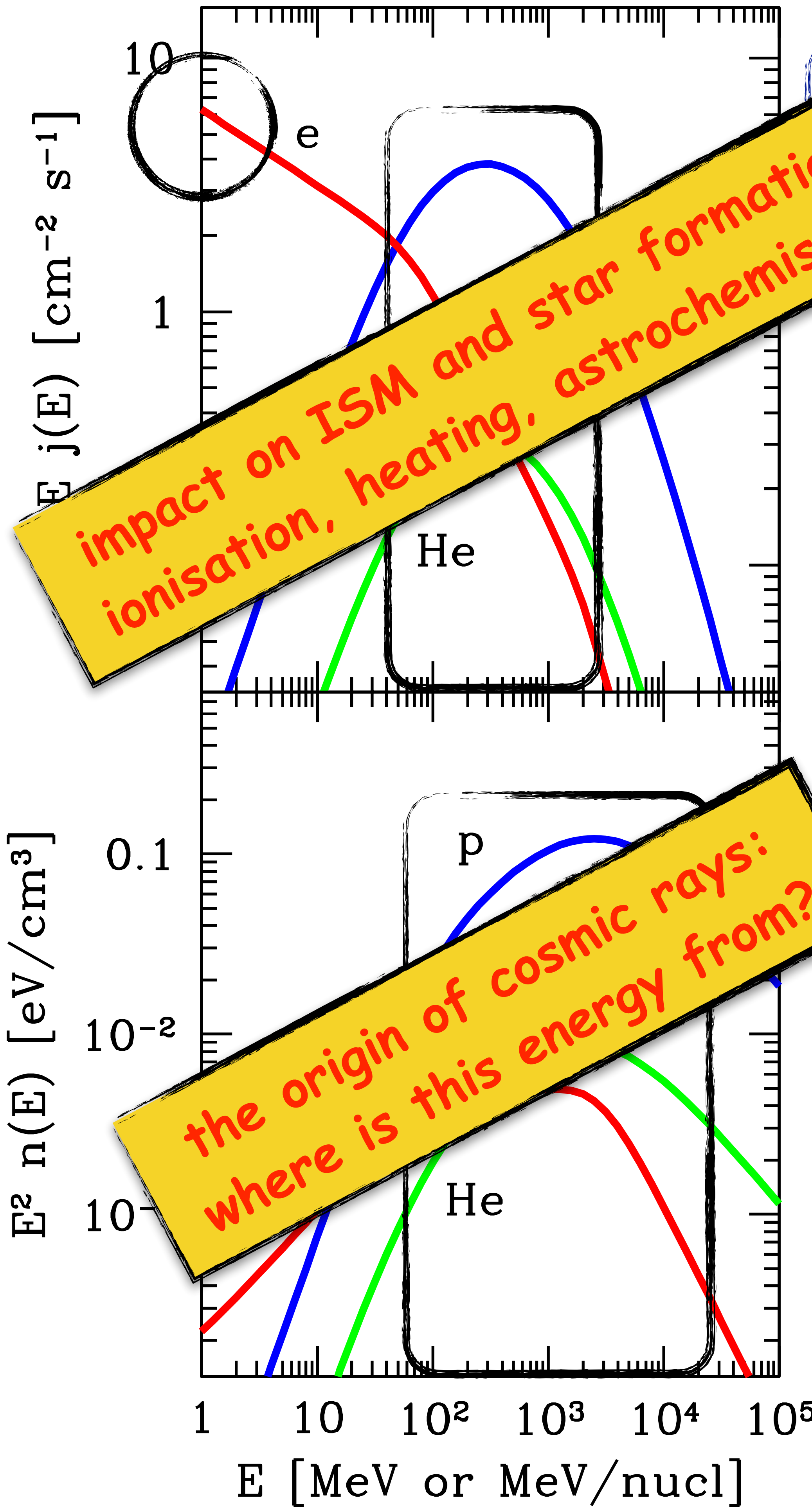
flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

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



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

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

$0^{-9} - 10^{-10}\ \mathrm{cm}^{-3}$

compare with ISM density…

$\approx 0.1 - 1\ \mathrm{cm}^{-3}$

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

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

Gabici 2022

[3] Local or global?

Variations in time and space

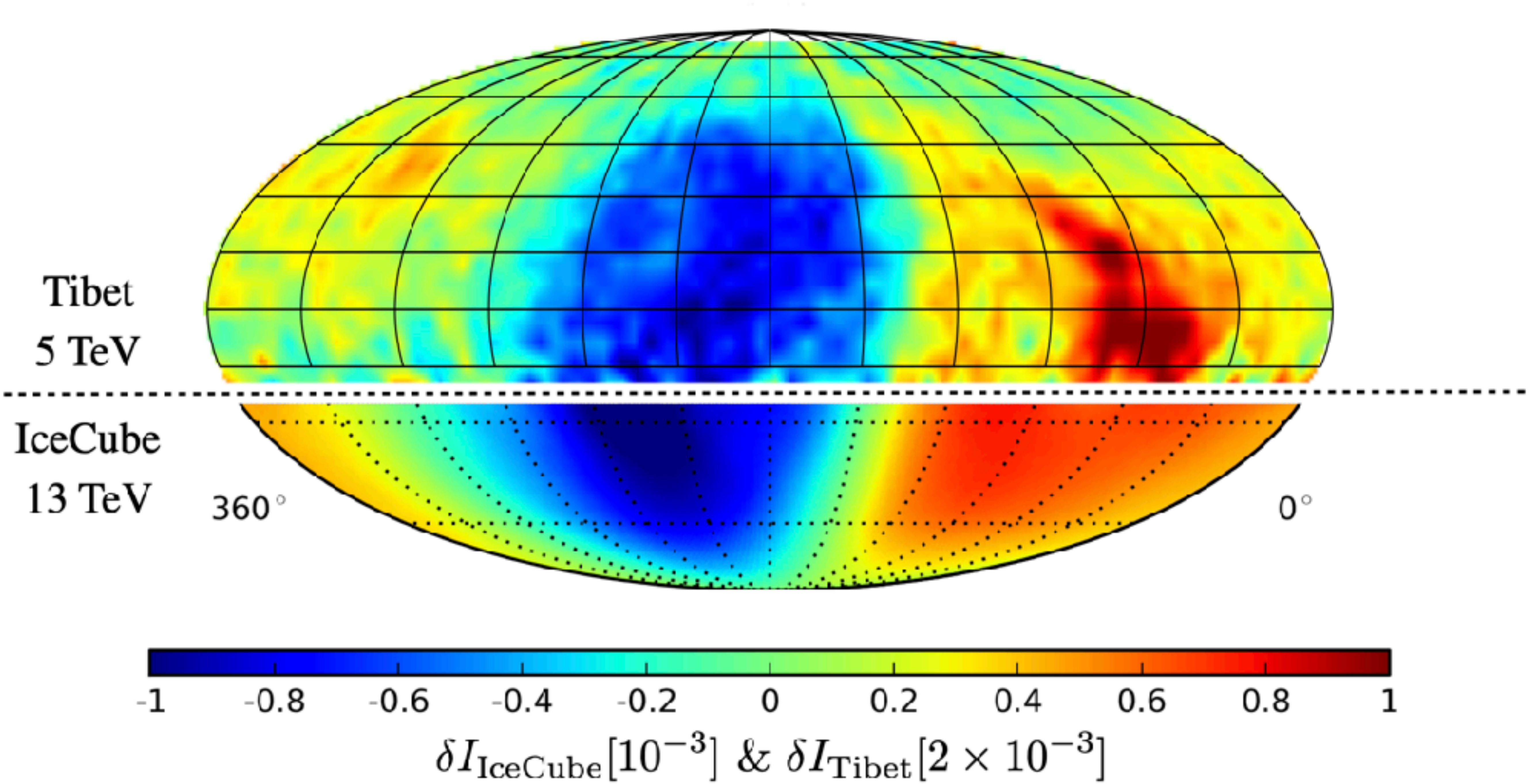
- CR flux at Earth **constant during the last 10^9 yr** (from radiation damages in geological and biological samples, meteorites, and lunar rocks)
- thus the CR flux must be **constant along the orbit of the Sun** around the galactic centre (many revolutions in a Gyr)

Variations in time and space

- 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)

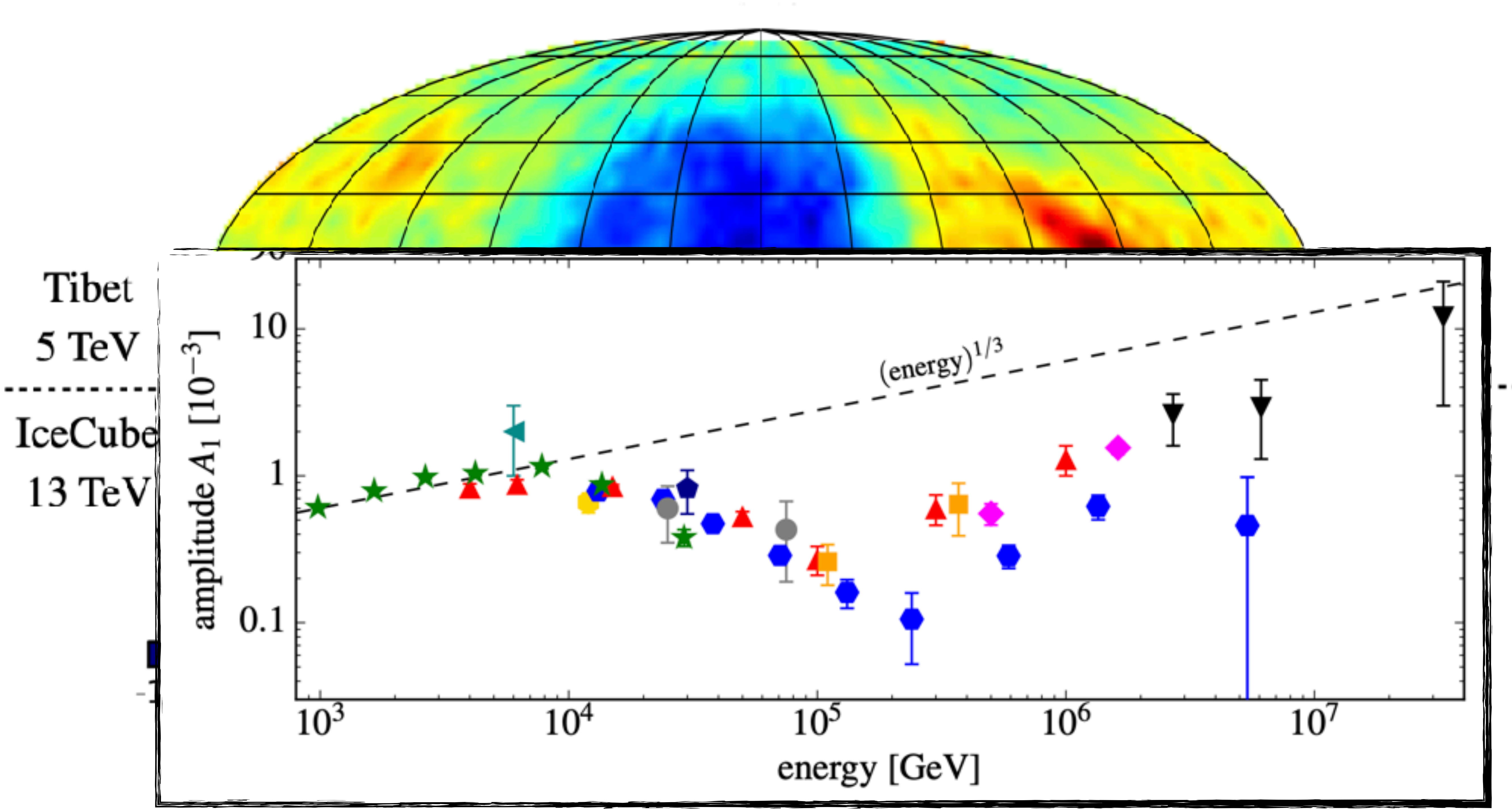
Stability in time and (hints for) spatial homogeneity

Cosmic rays are almost isotropic

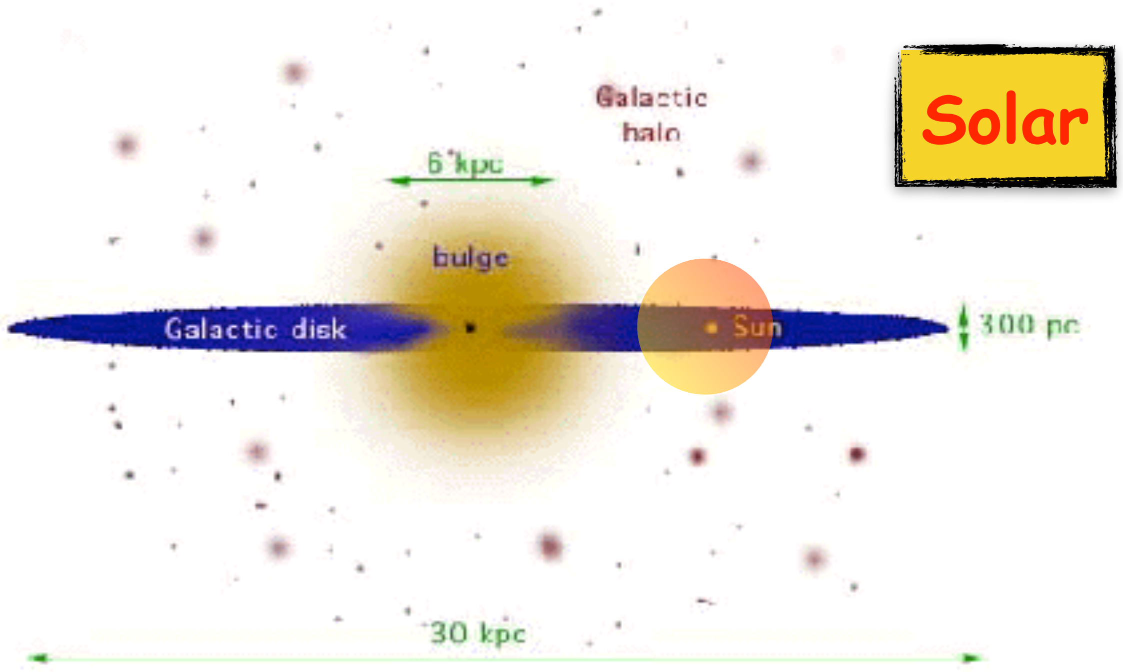


see review by Mertsch & Ahlers 2017

Cosmic rays are almost isotropic



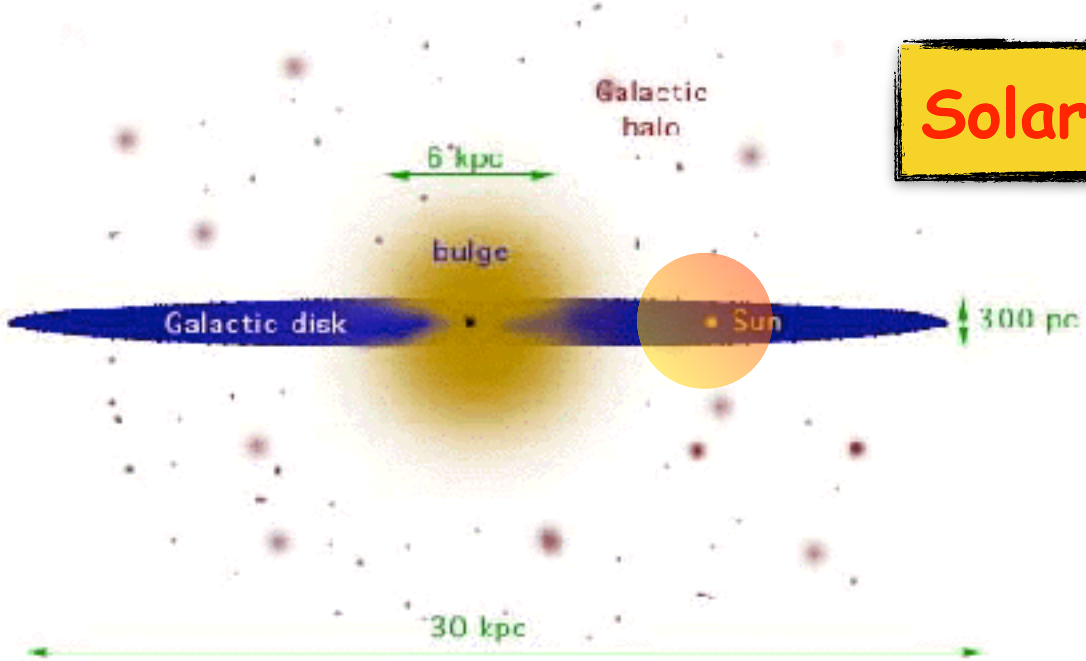
see review by Mertsch & Ahlers 2017



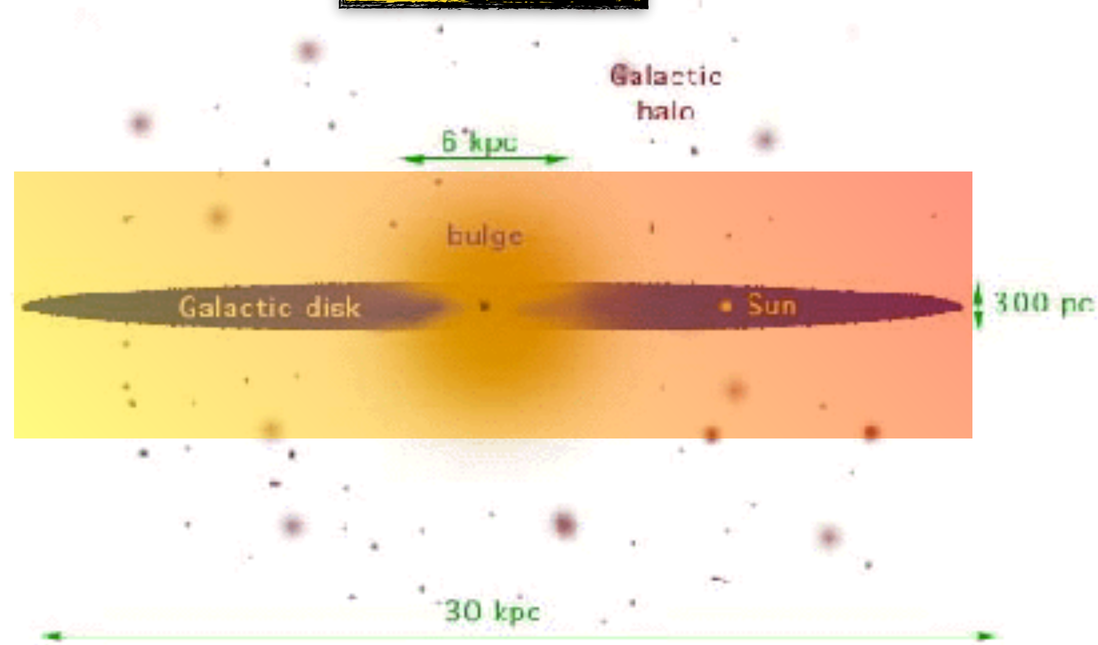
Three scenarios

Three scenarios

Solar

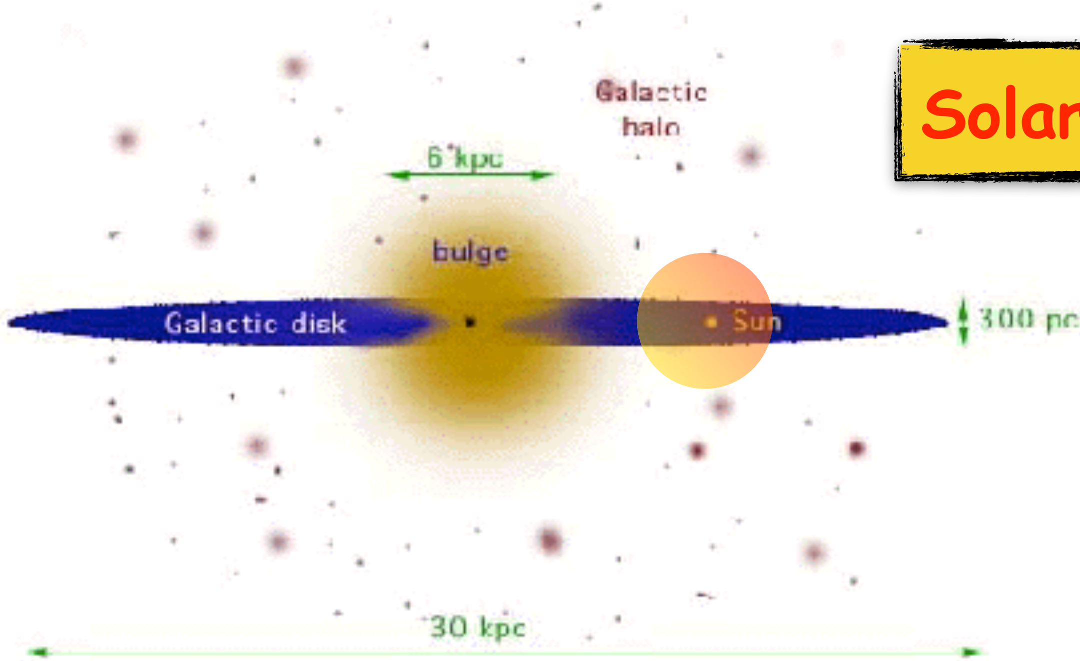


Galactic

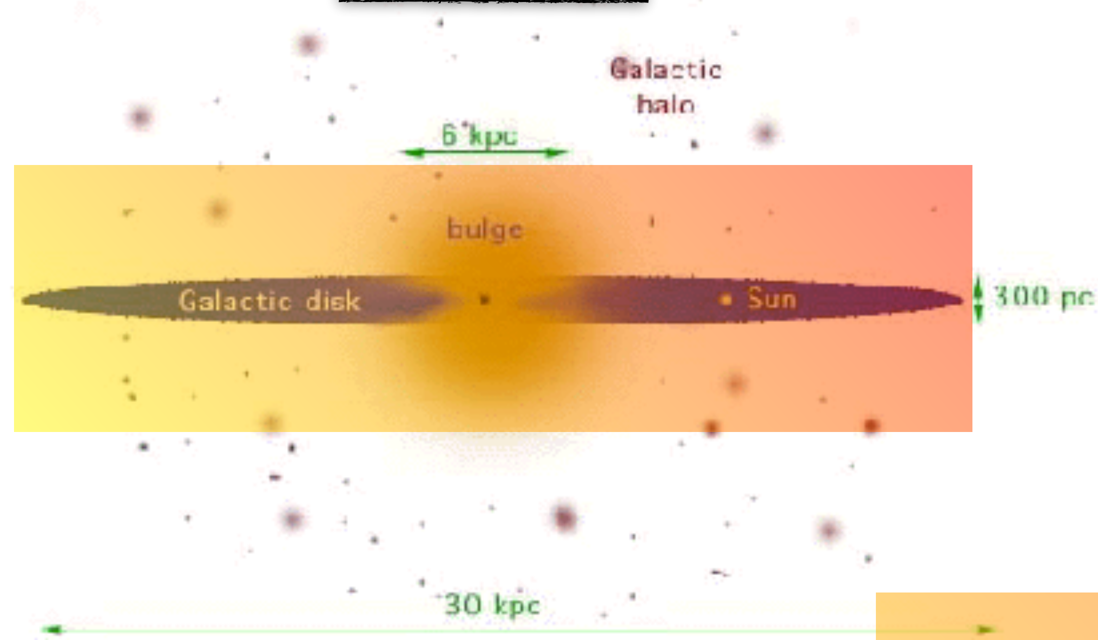


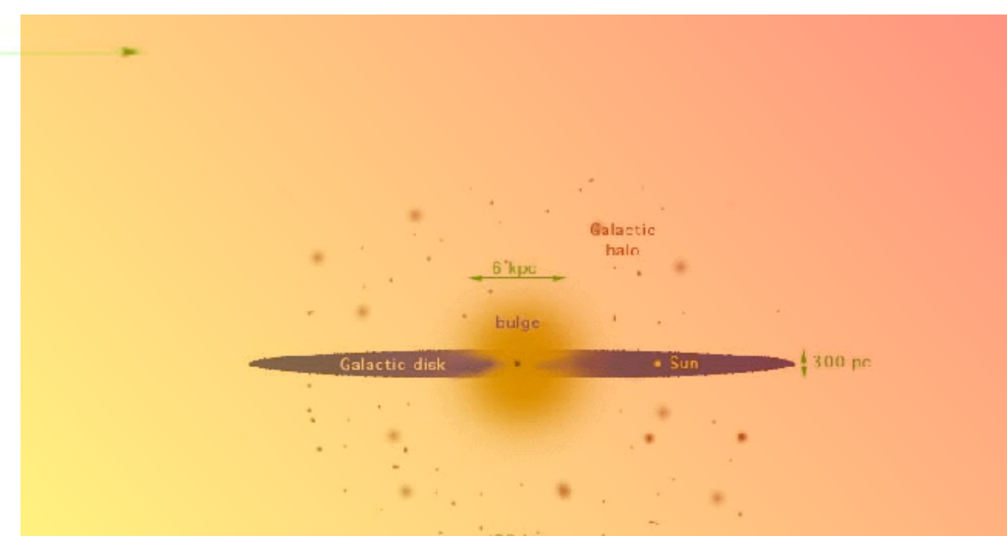
Three scenarios

Solar



Galactic

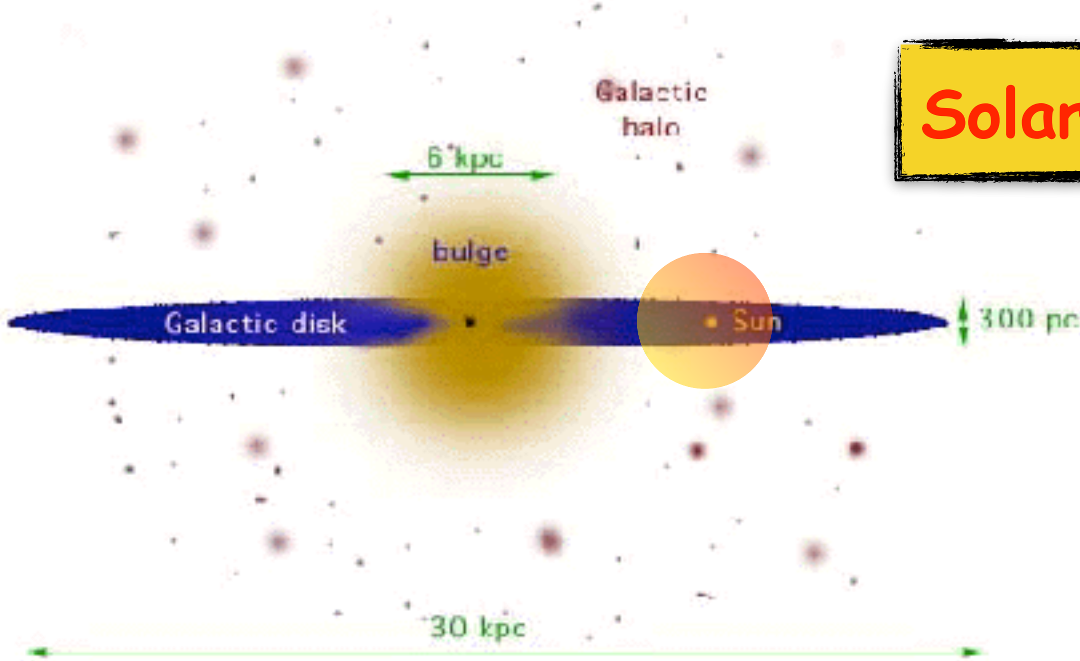




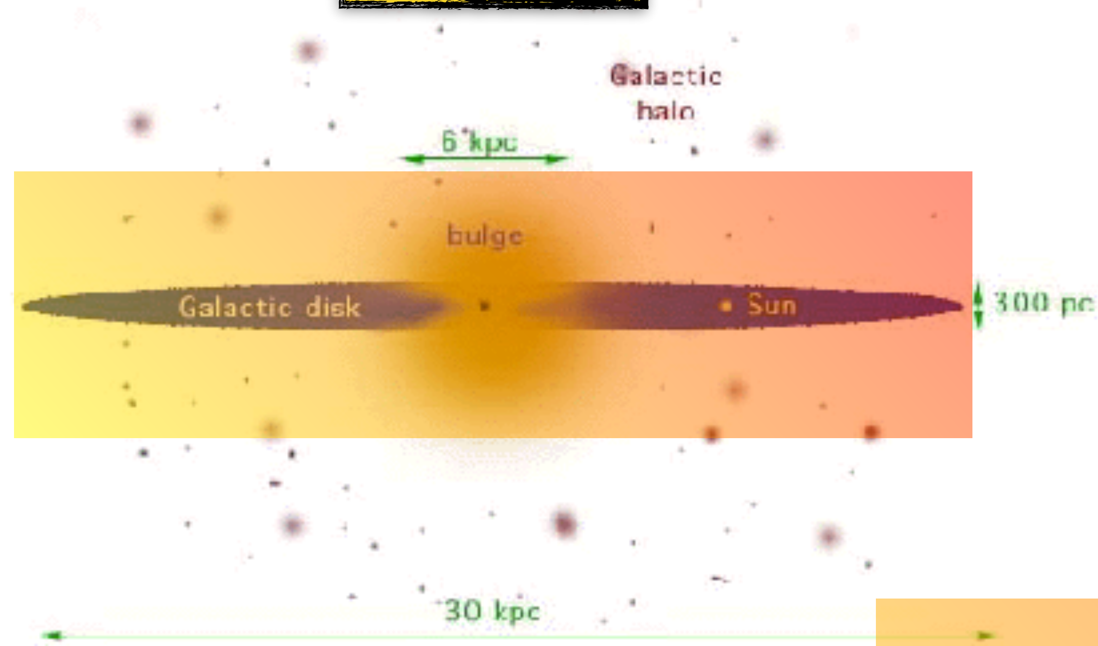
Cosmological

Three scenarios

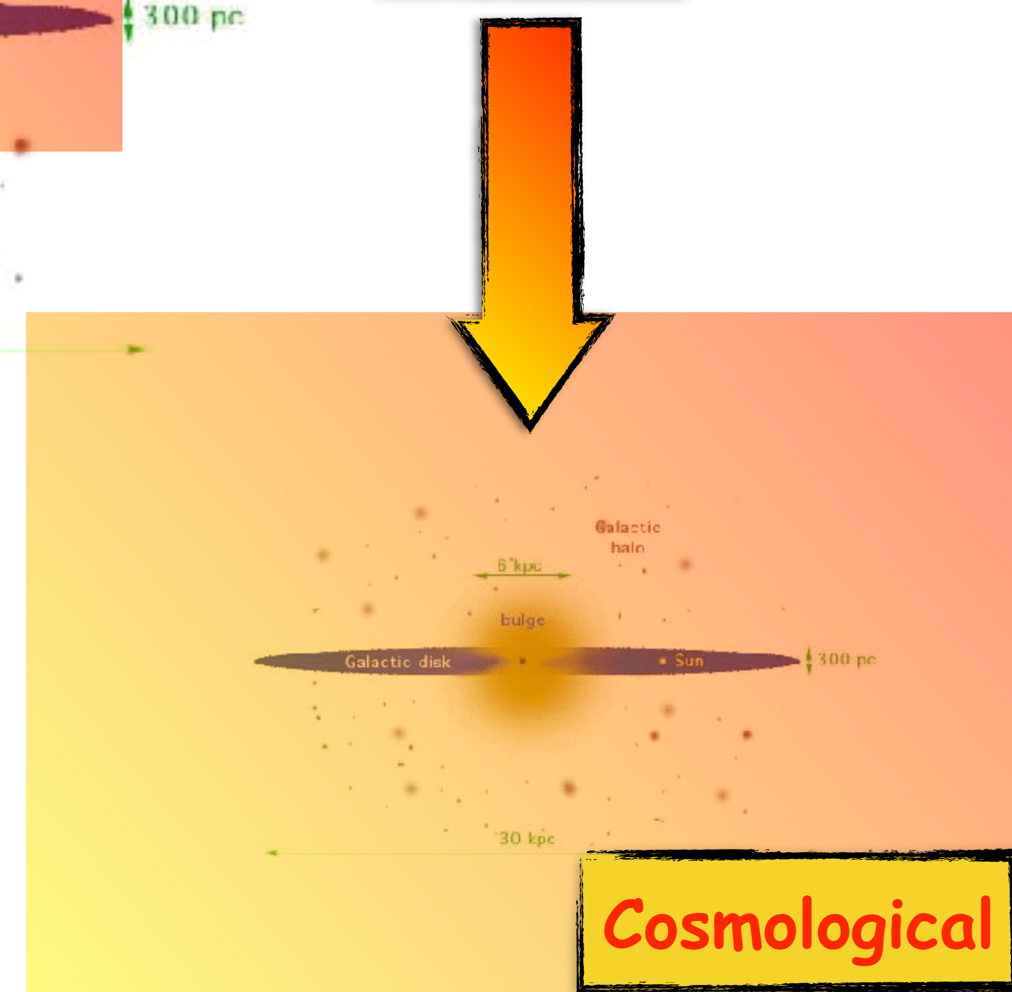
Solar



Galactic

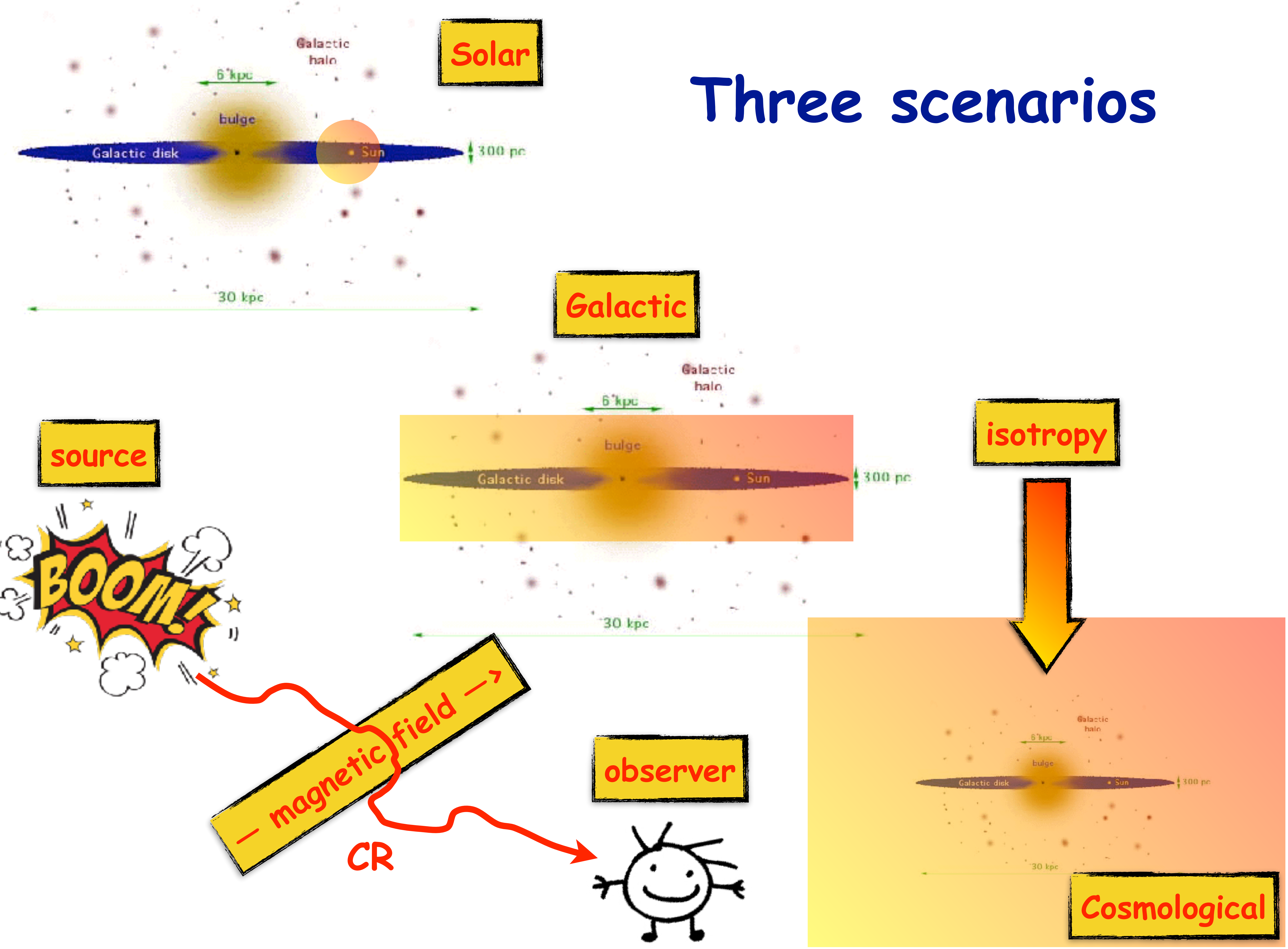


isotropy

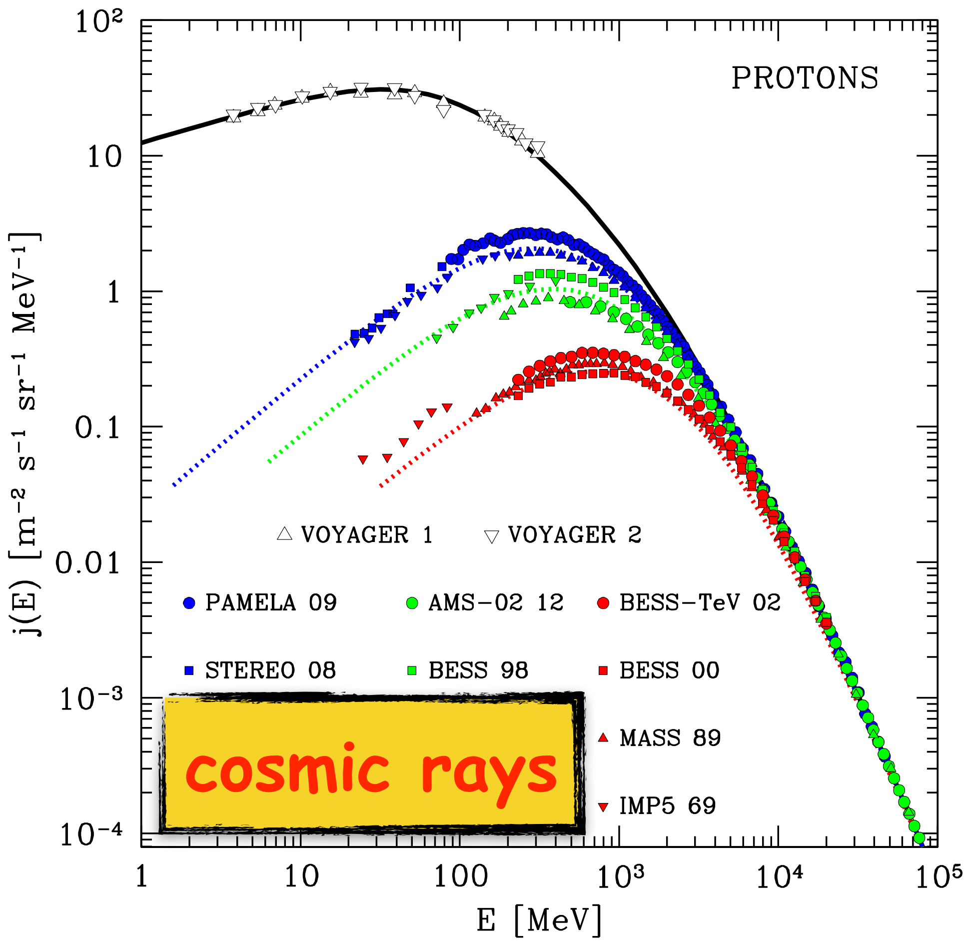


Cosmological

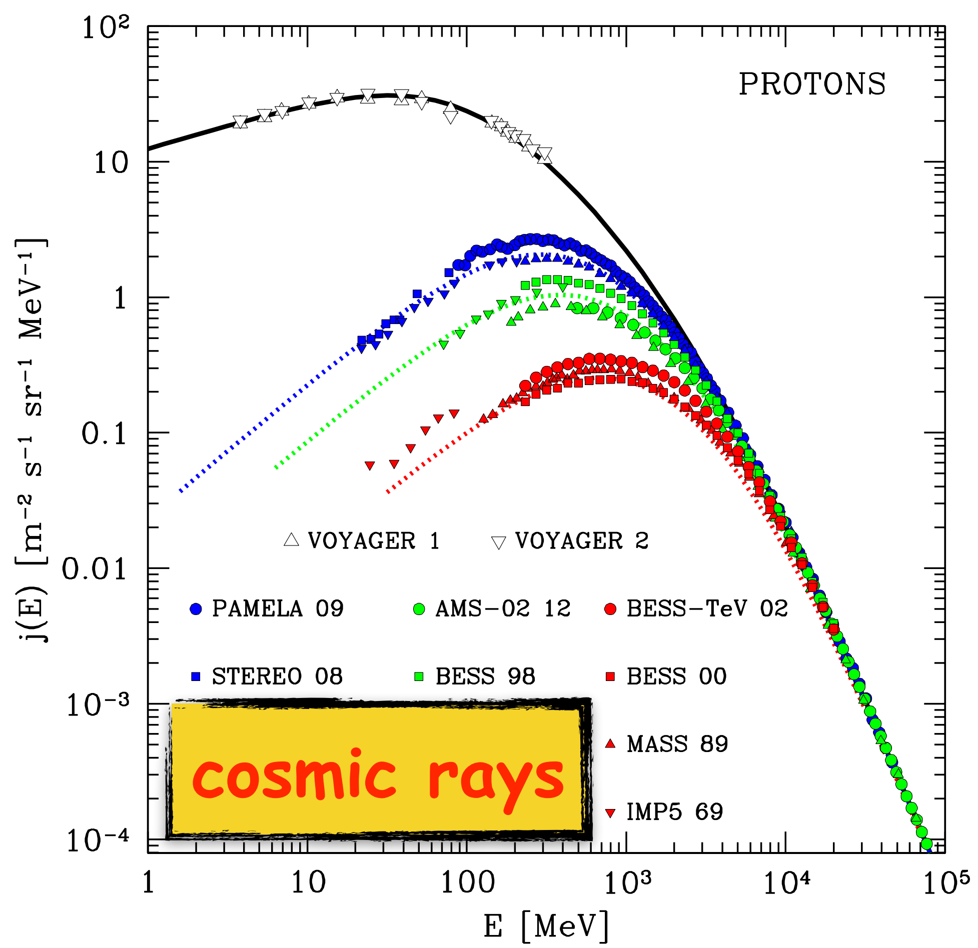
Three scenarios

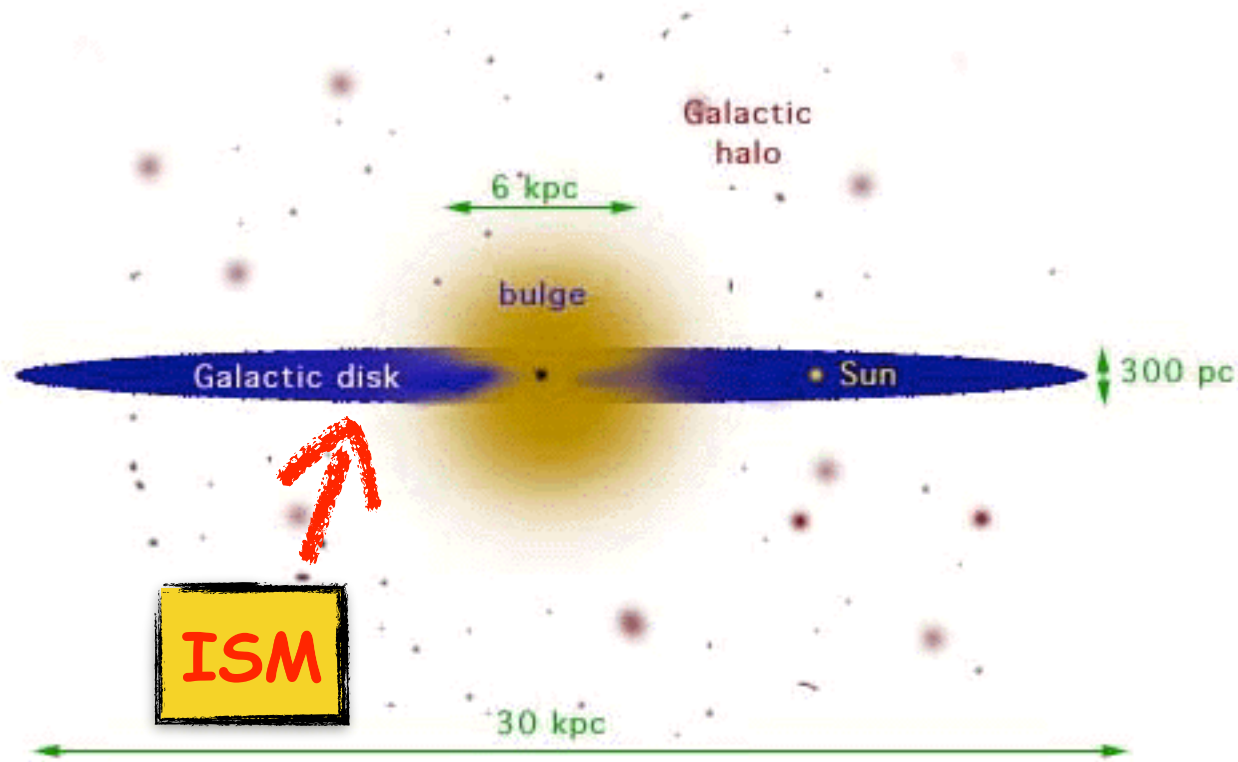


Hayakawa's test (1952): diffuse emission

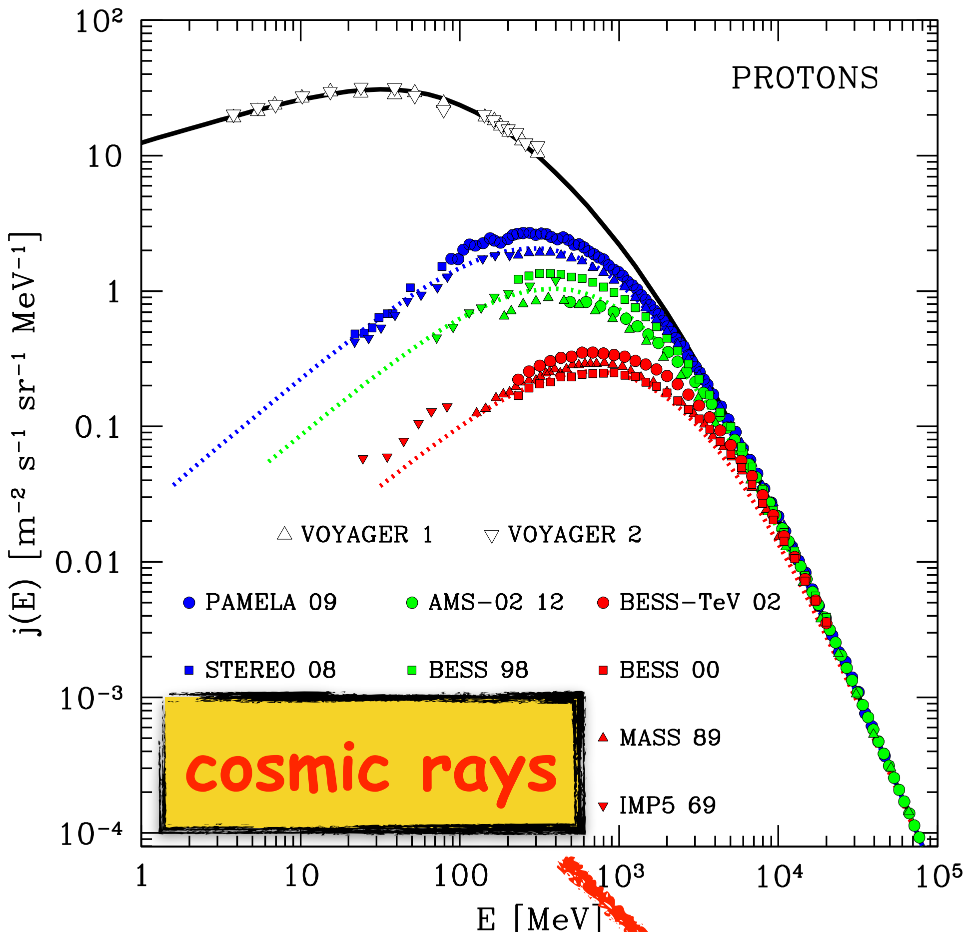


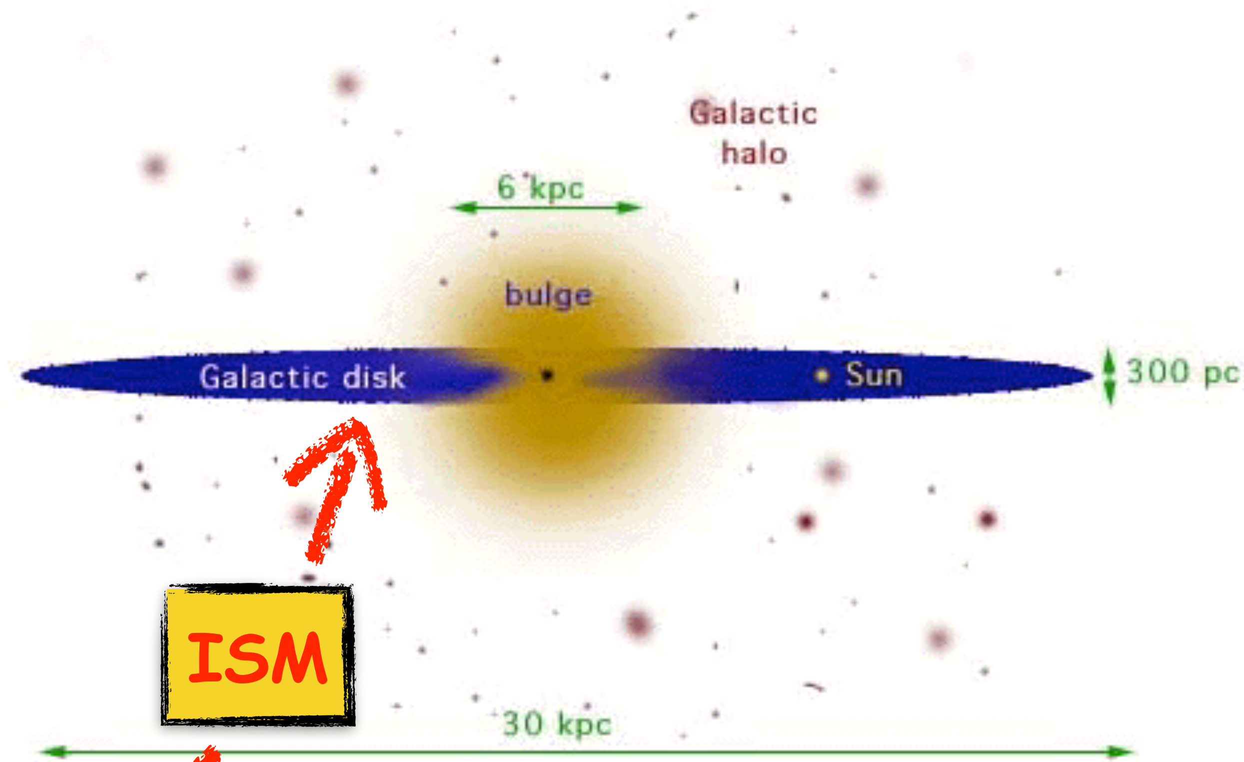
Hayakawa's test (1952): diffuse emission





Hayakawa's test (1952): diffuse emission

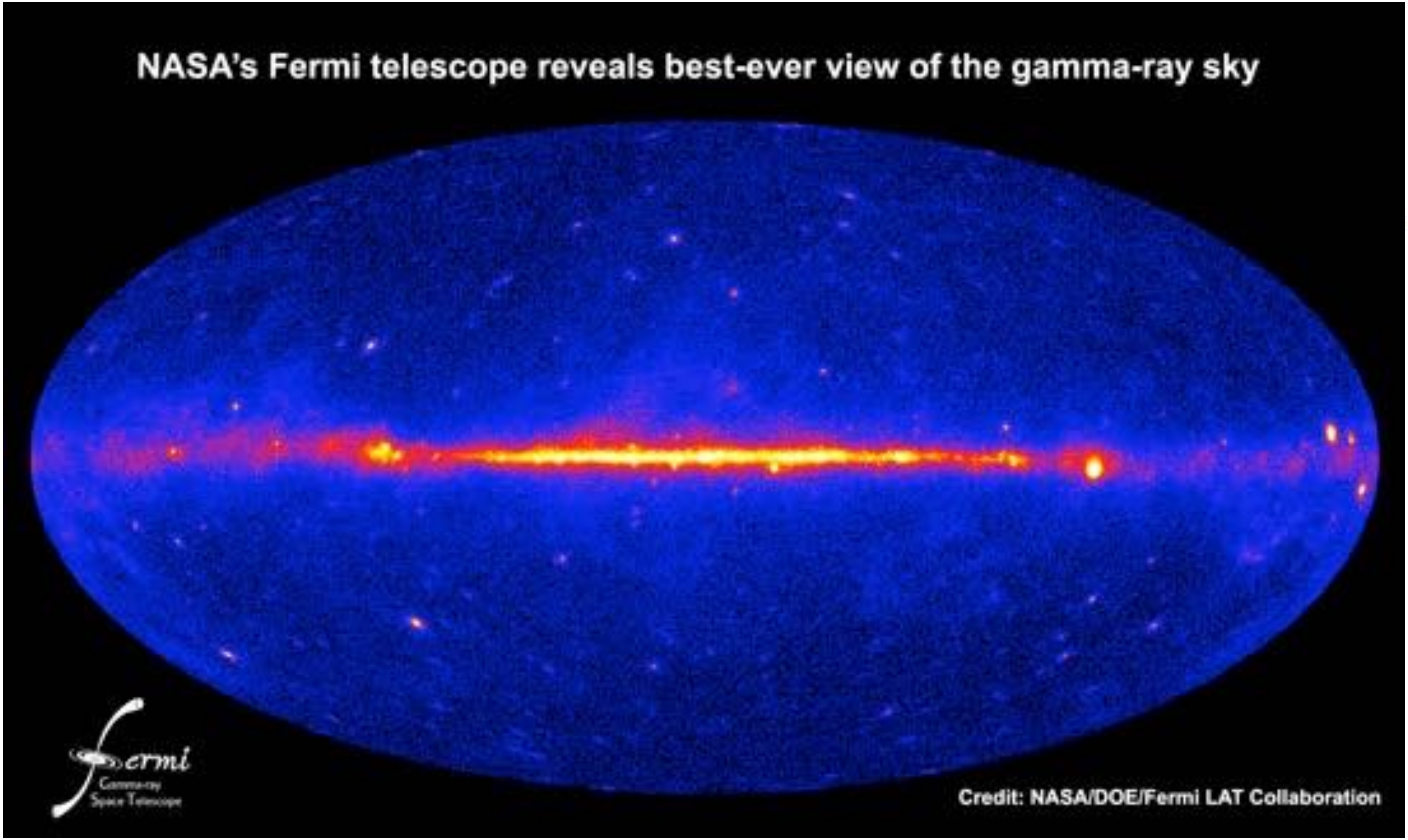




$$p + p \rightarrow p + p + \pi^0$$

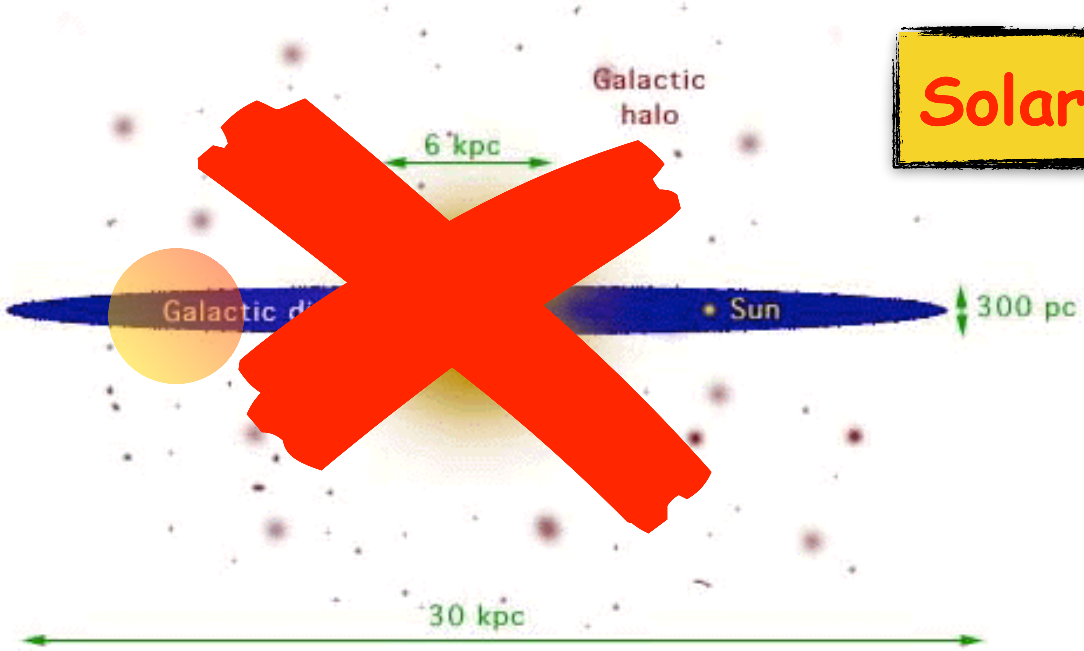
$$\pi^0 \rightarrow \gamma + \gamma$$

Hayakawa's test (1952): diffuse emission

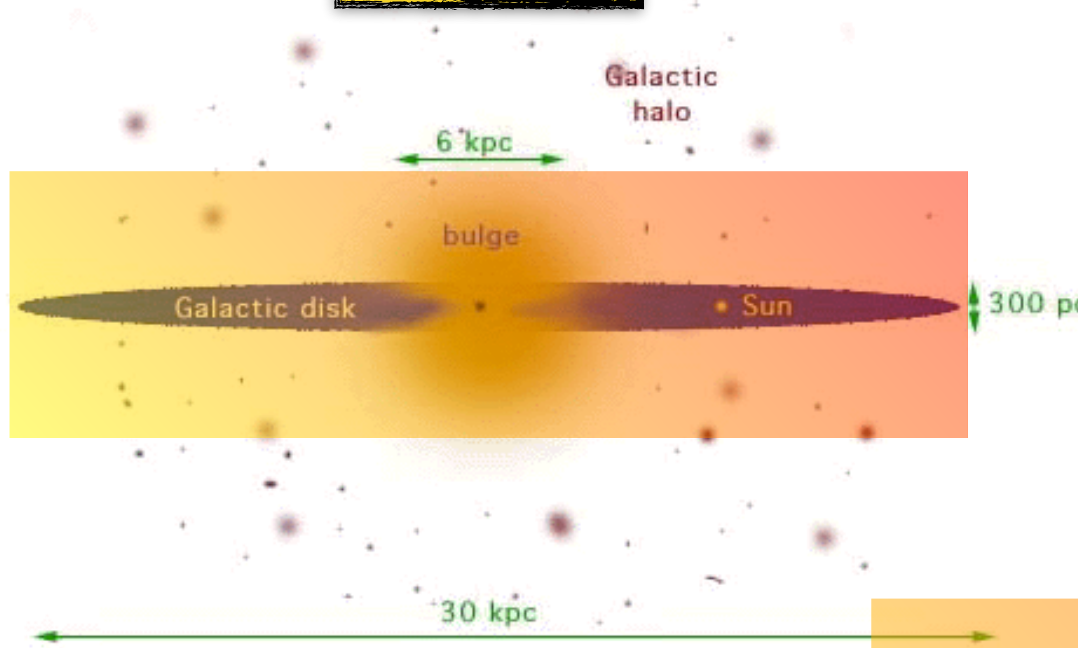


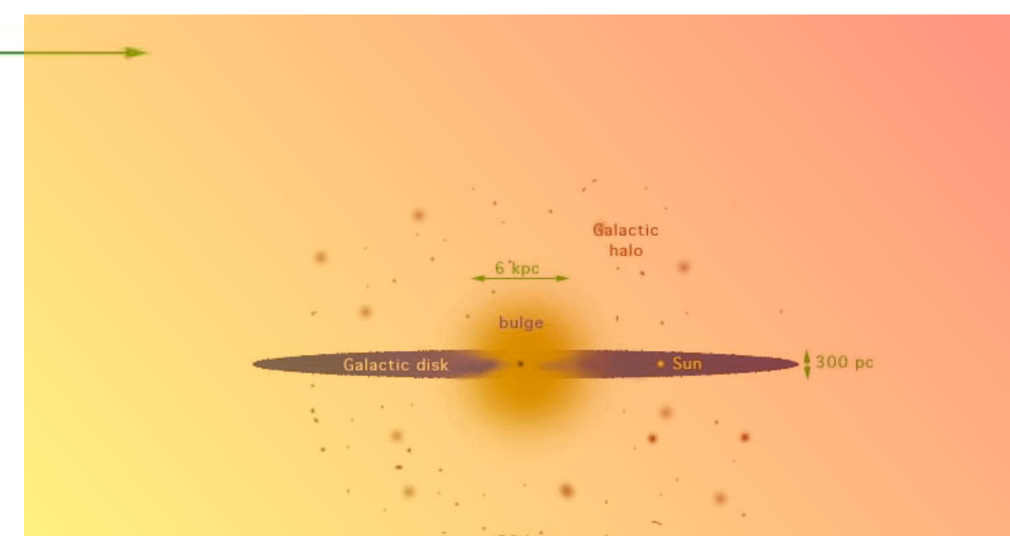
Three scenarios

Solar



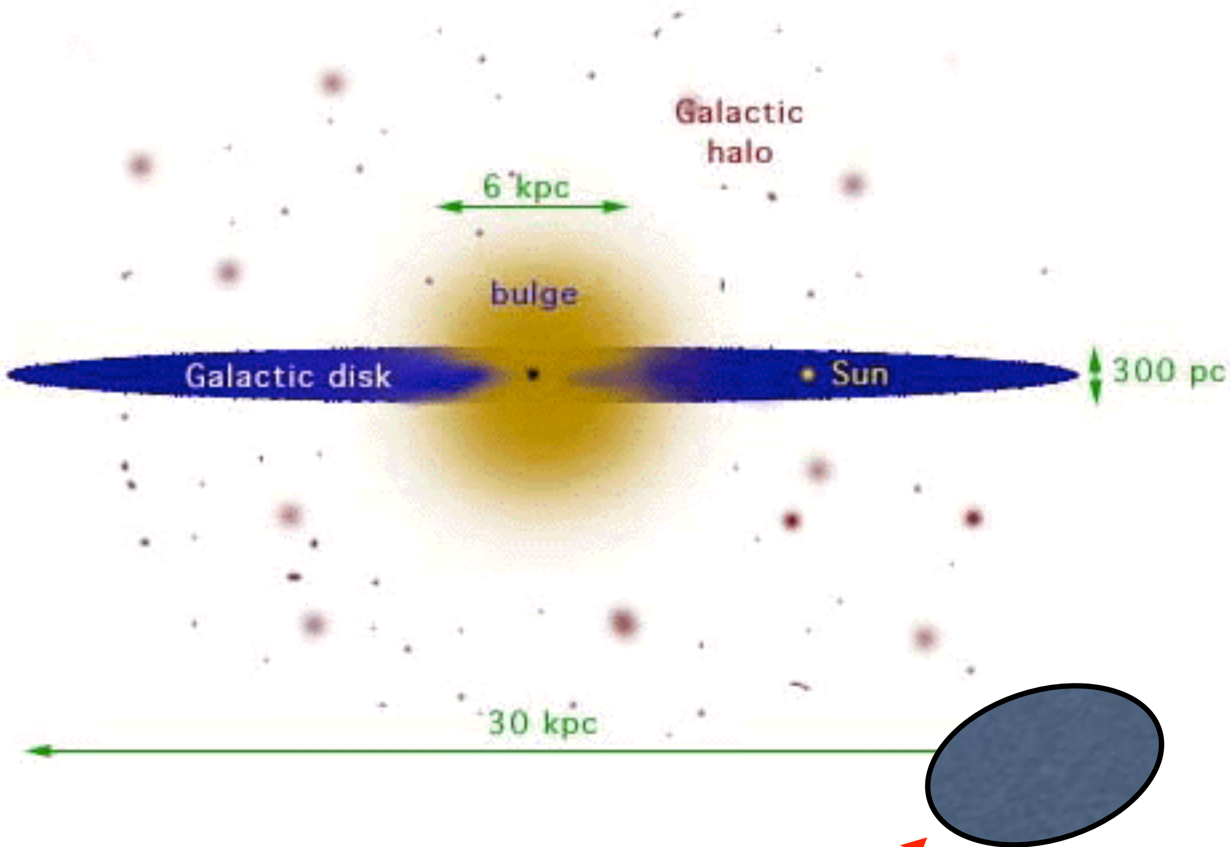
Galactic





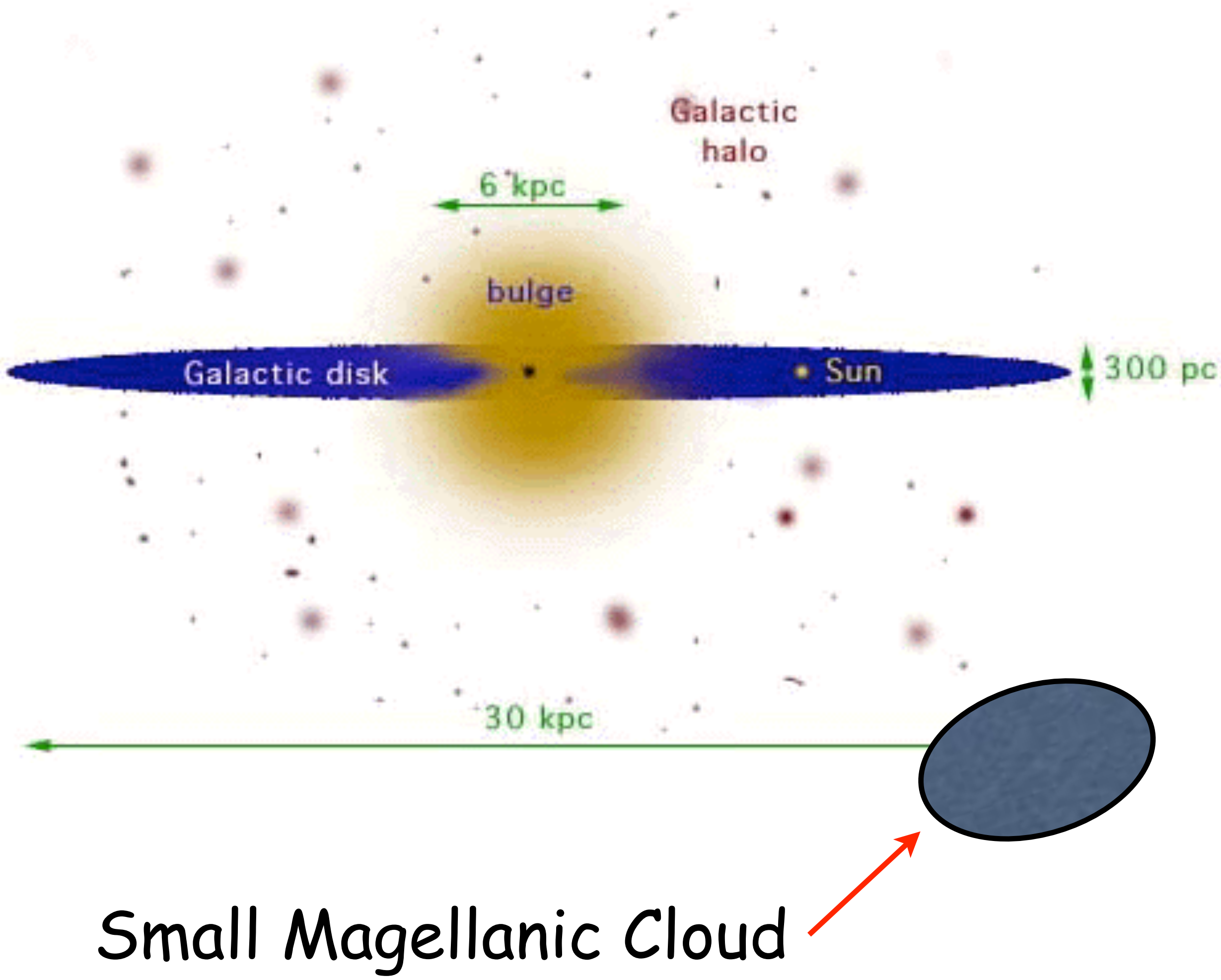
Cosmological

Diffuse emission in other galaxies



Small Magellanic Cloud

Diffuse emission in other galaxies



Cosmological —> same CR intensity here (measured) & in the SMC

—> mass of ISM in the SMC is known

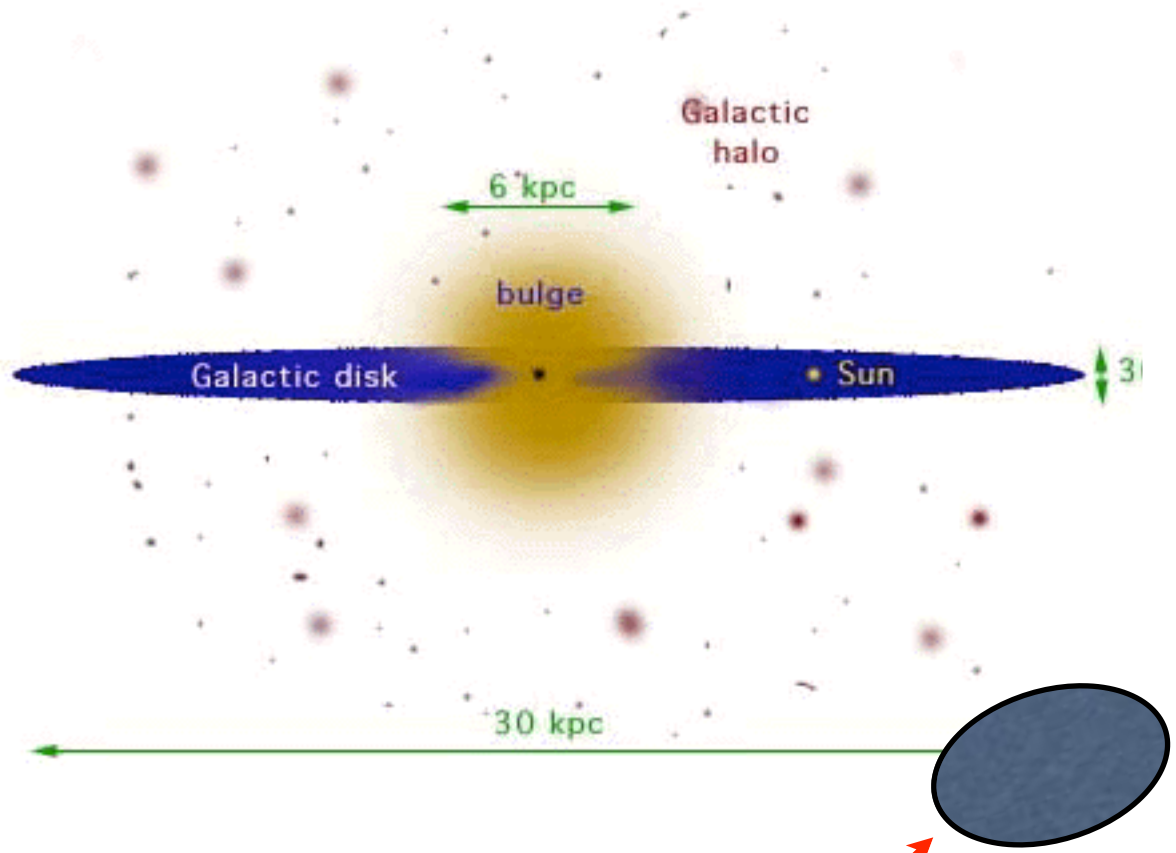
—> we can predict the gamma-ray flux from the SMC

—> it should have been detected by EGRET

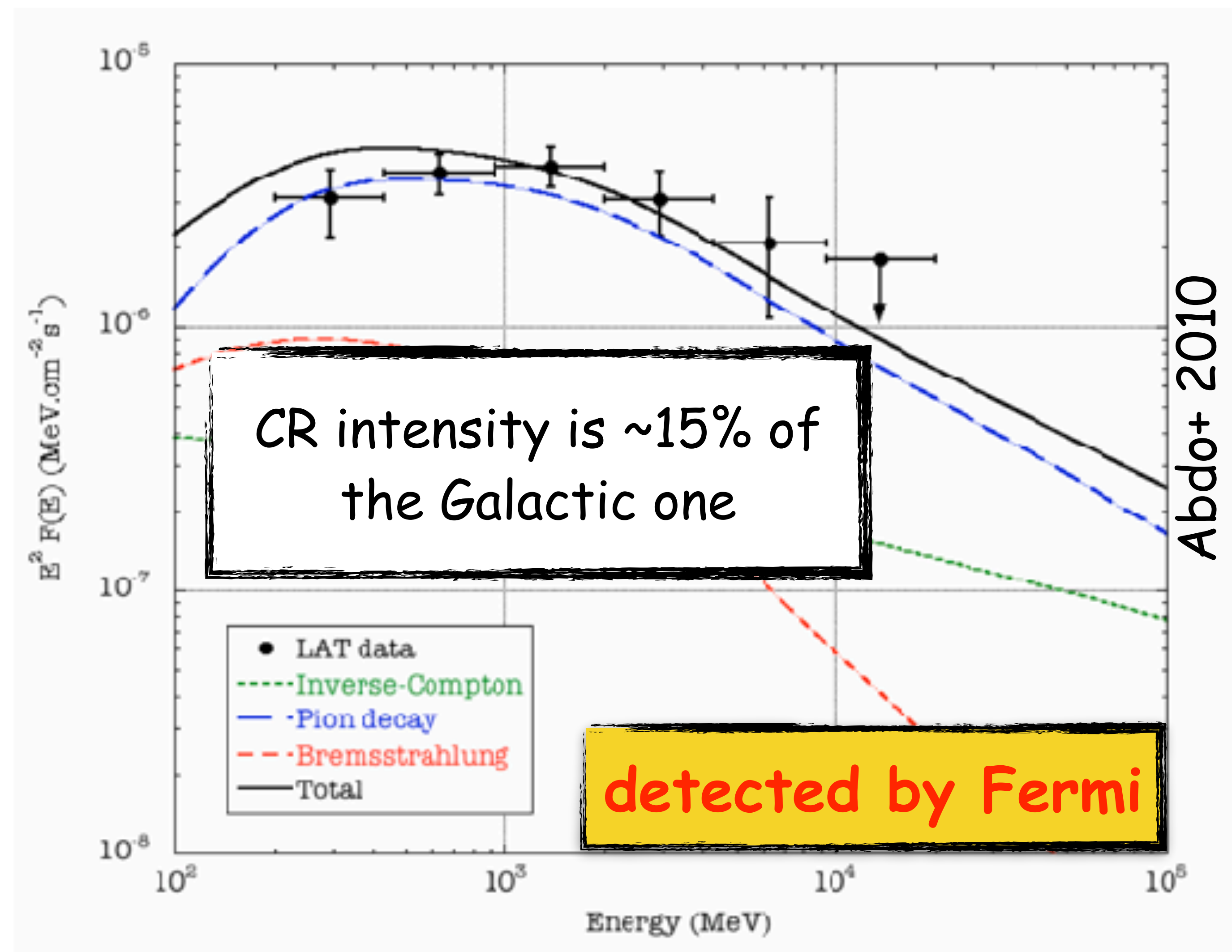
—> but it was not! (Sreekumar+ 1993)

—> CRs are **NOT cosmological**

Diffuse emission in other galaxies



Small Magellanic Cloud



Cosmological —> same CR intensity here (measured) & in the SMC

—> mass of ISM in the SMC is known

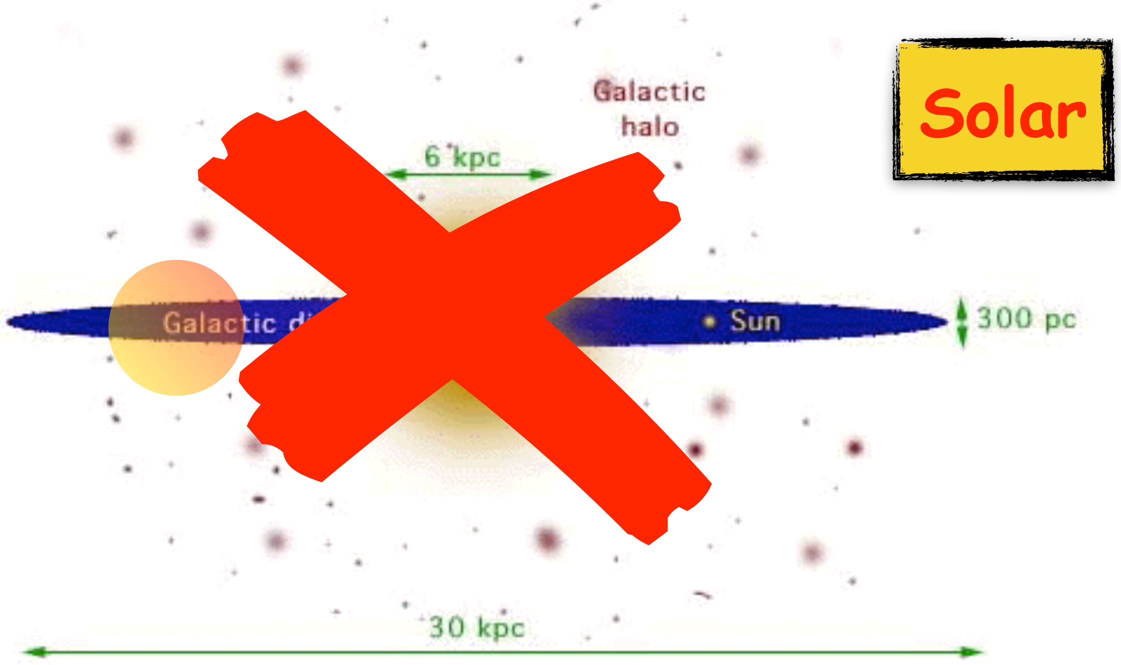
—> we can predict the gamma-ray flux from the SMC

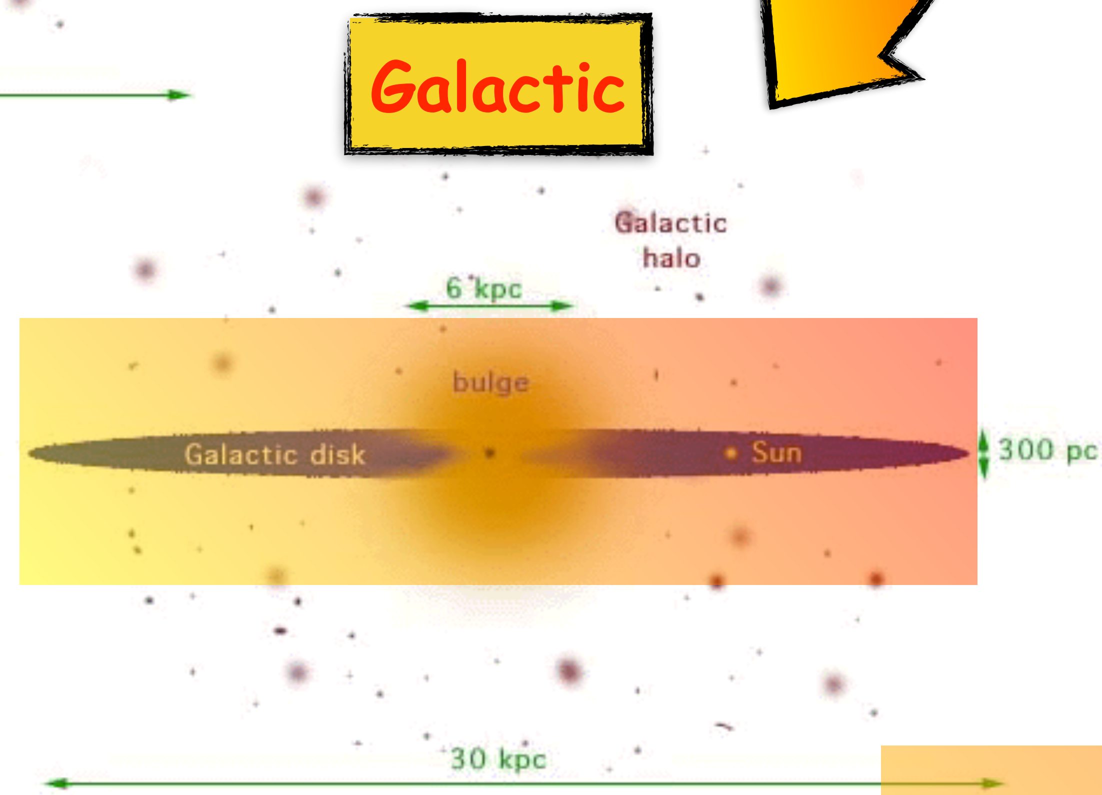
—> it should have been detected by EGRET

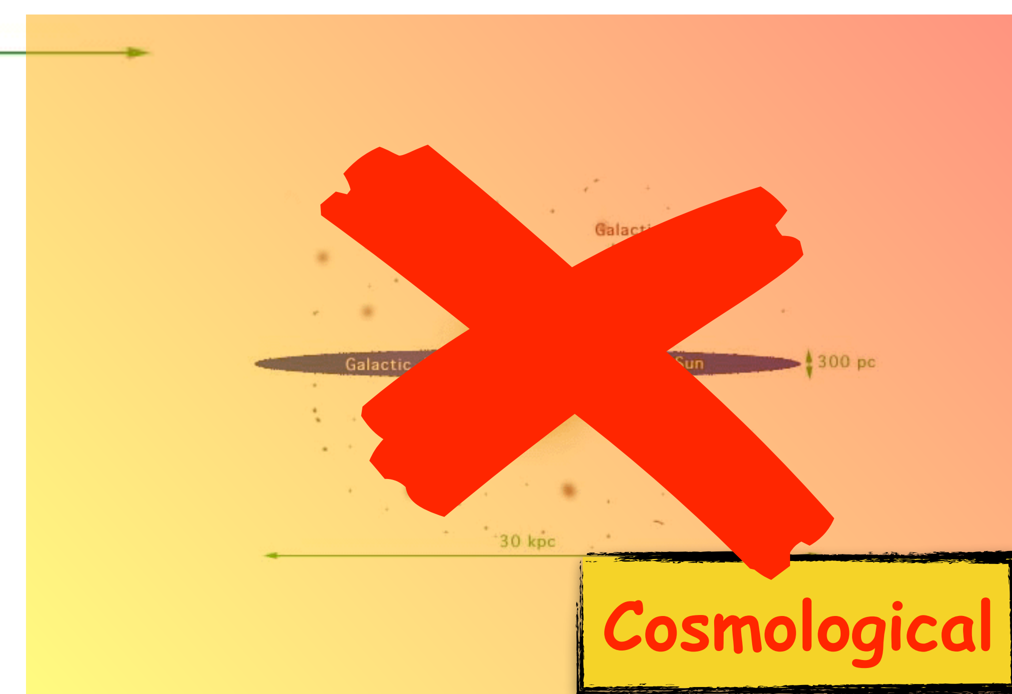
—> but it was not! (Sreekumar+ 1993)

—> CRs are **NOT cosmological**

CRs are Galactic

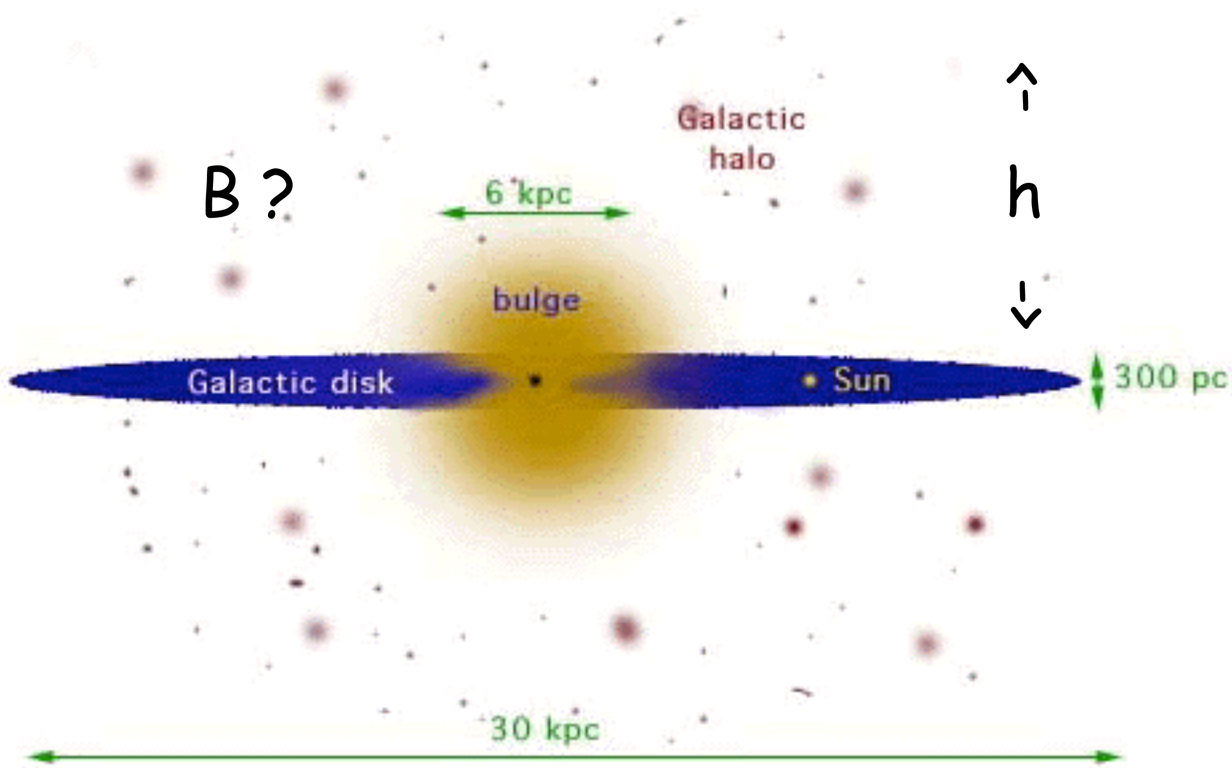






In fact, MOST CRs are Galactic…

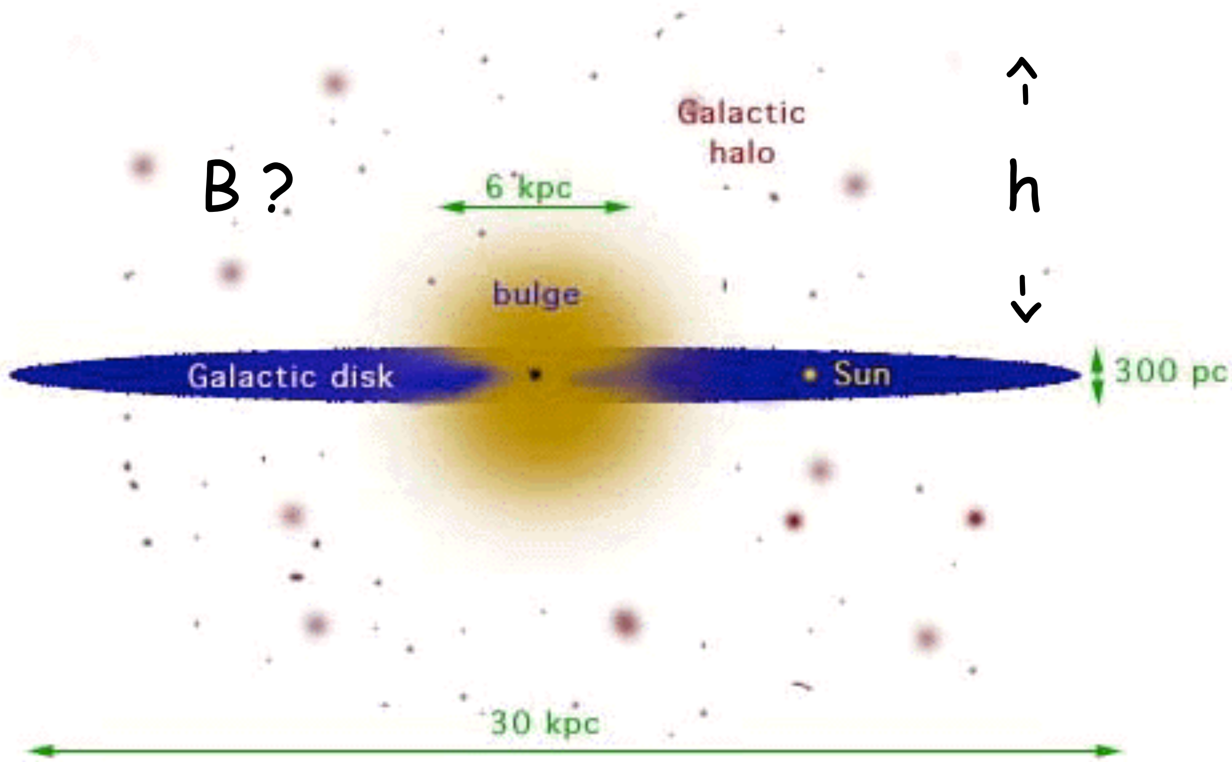
Which CRs are confined in the Galaxy?



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

In fact, MOST CRs are Galactic...

Which CRs are confined in the Galaxy?



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

Confinement condition:

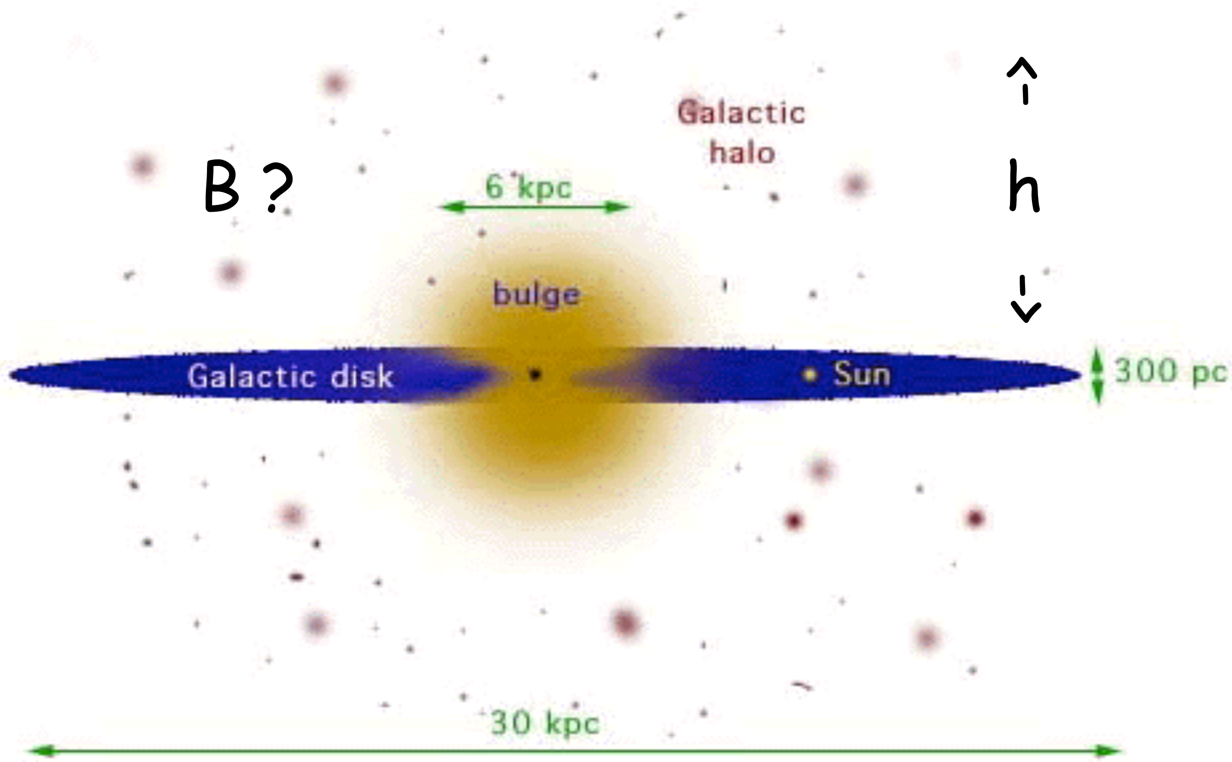
$$R_L < h$$

Larmor radius

halo size

In fact, MOST CRs are Galactic...

Which CRs are confined in the Galaxy?



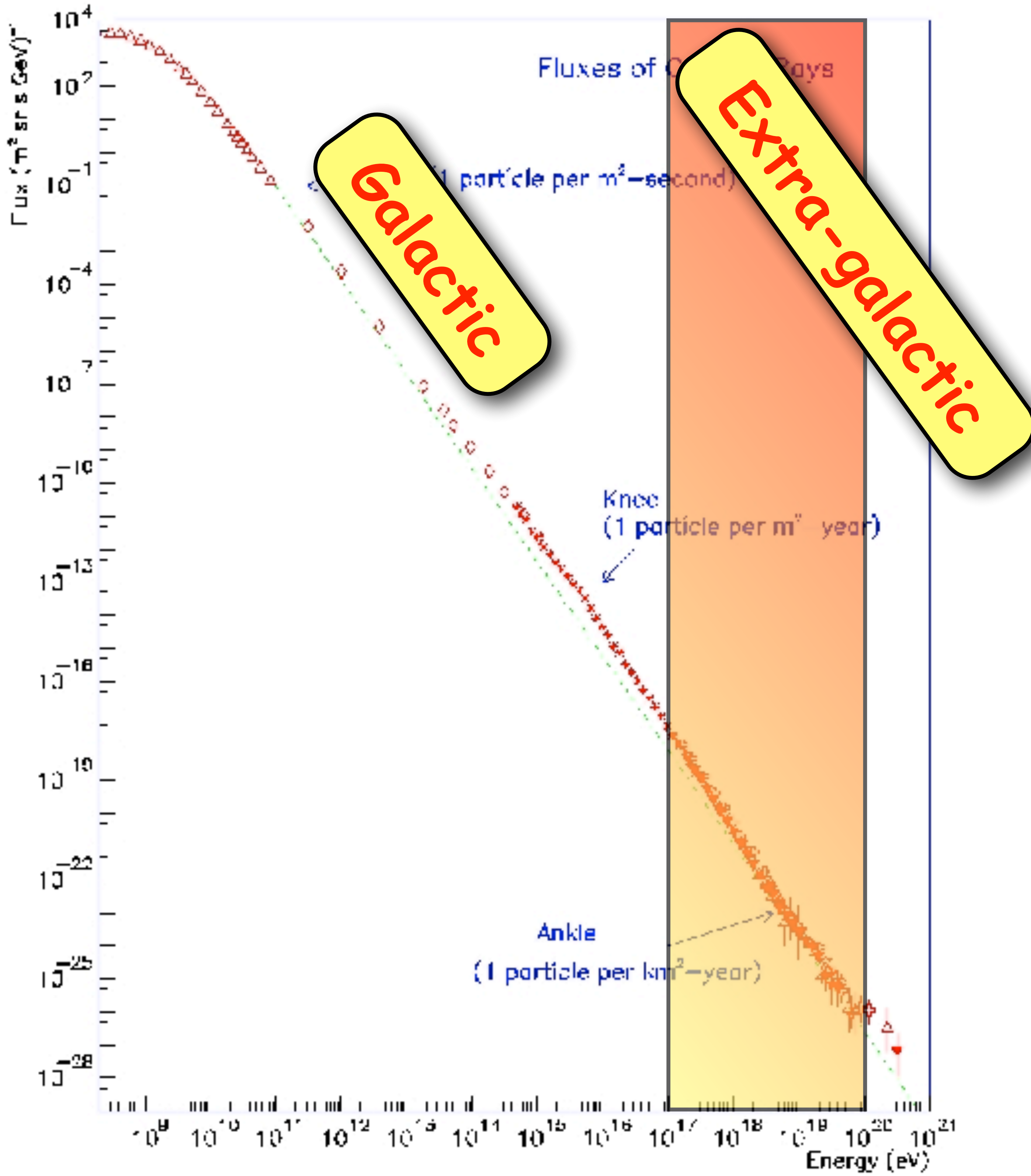
It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

Confinement condition:

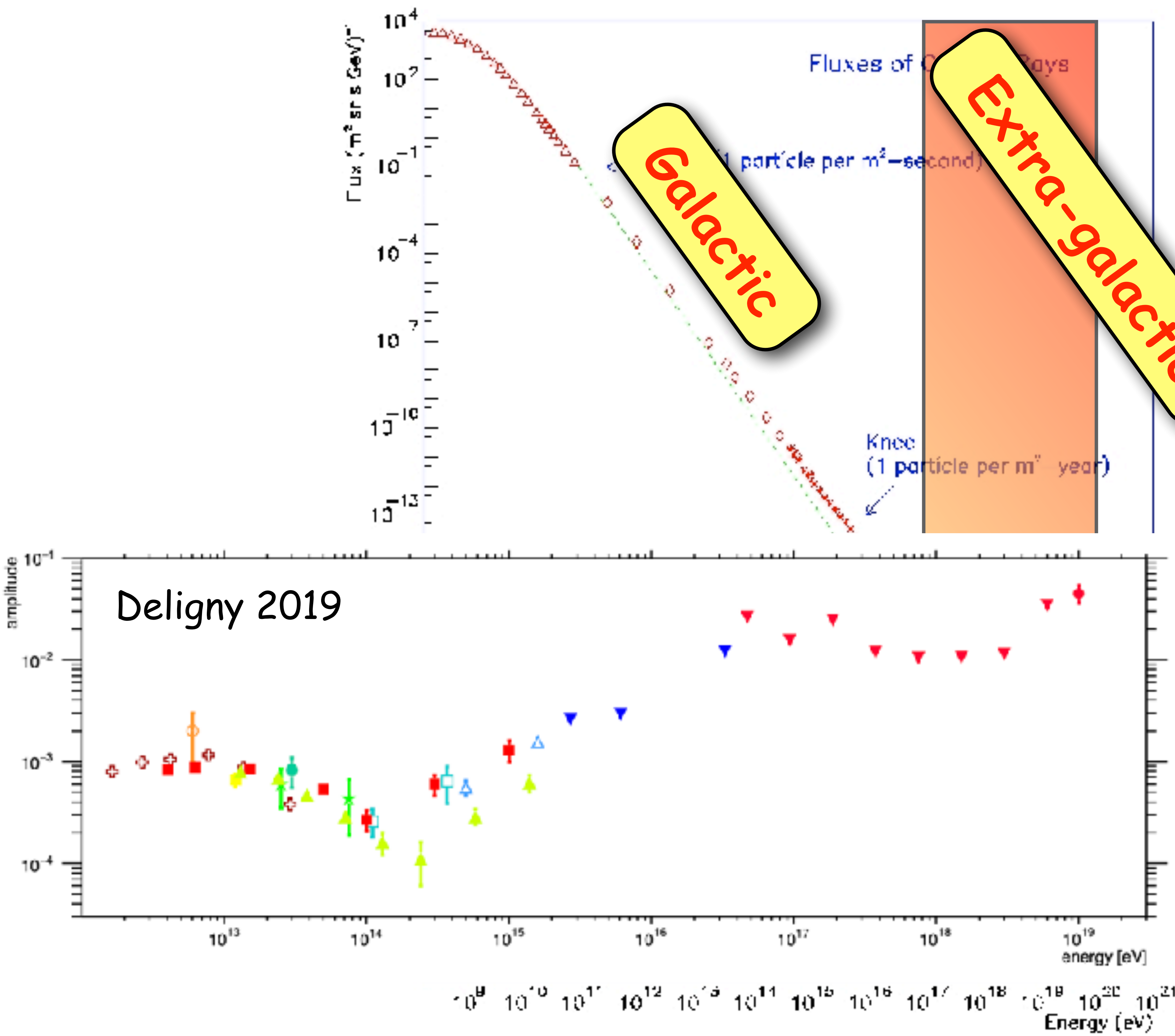
$$\frac{E(\mathrm{eV})}{300\ B(\mathrm{G})} = R_L < h \quad \Rightarrow \quad E < 10^{18} \left(\frac{h}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{eV} = 10^{17} \div 10^{20}\ \mathrm{eV}$$

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

Galactic or extra-galactic?



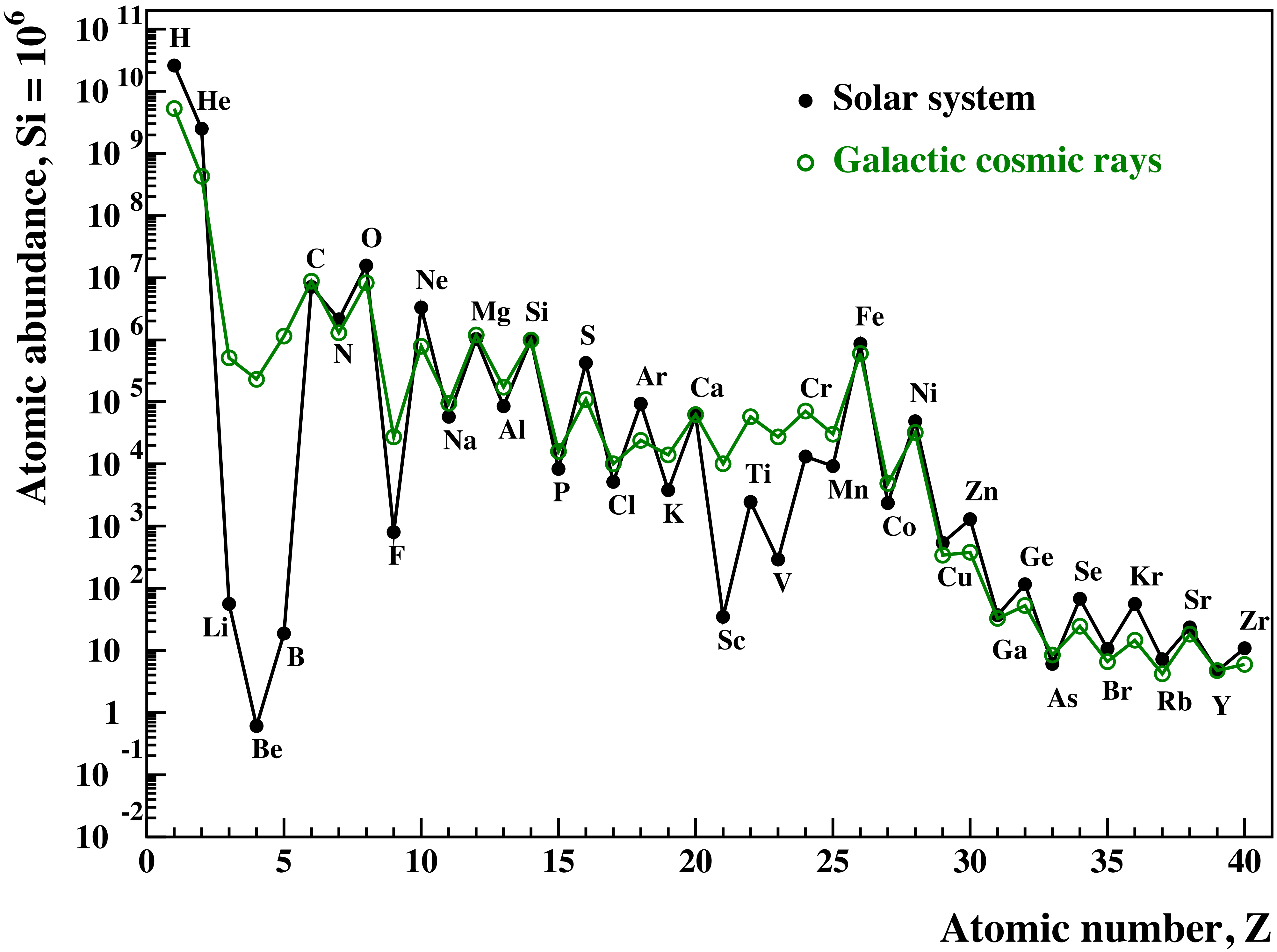
Galactic or extra-galactic?



—> larger anisotropy?

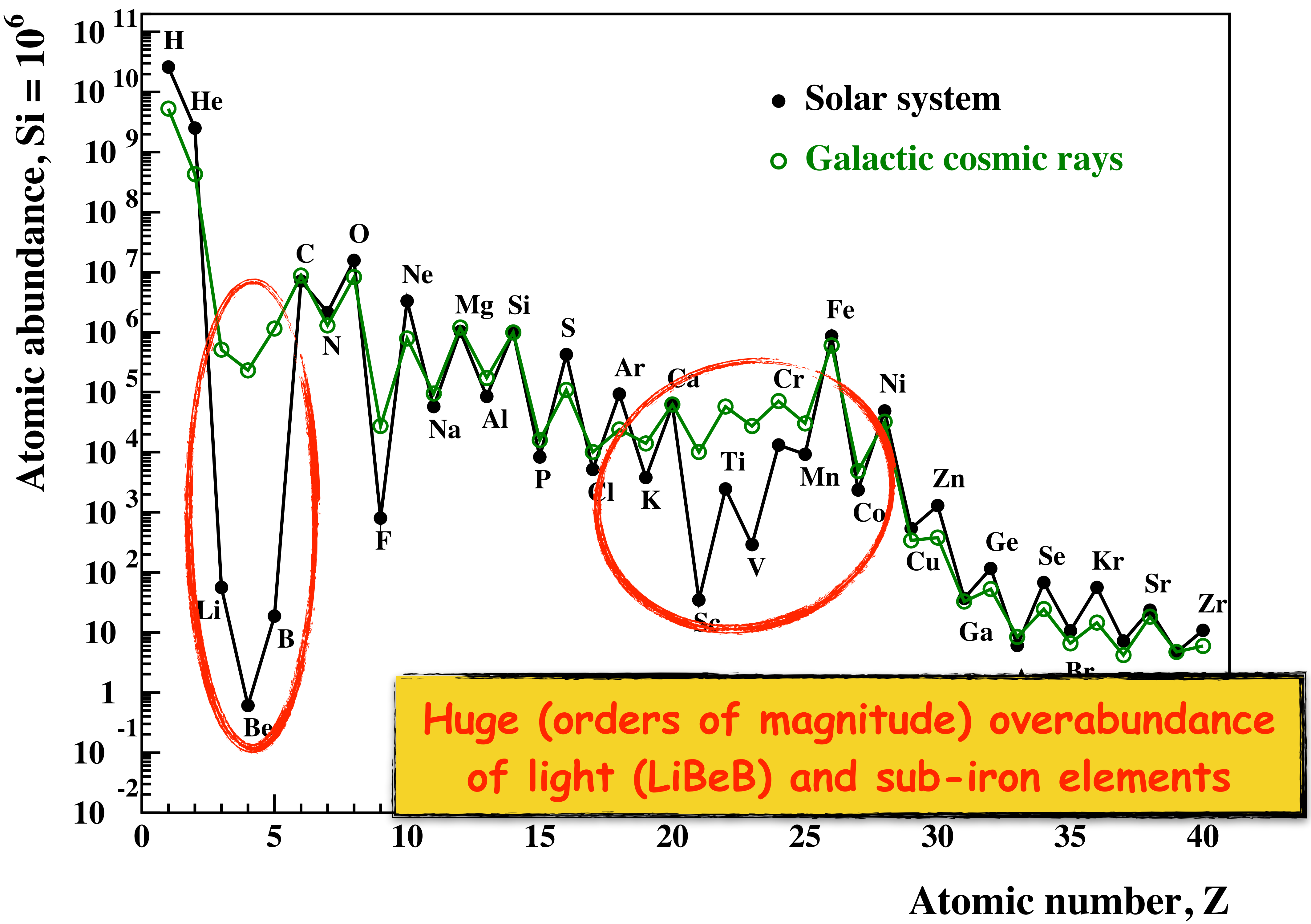
[4] Composition

Composition: striking anomalies



Tatischeff & SG, 2018

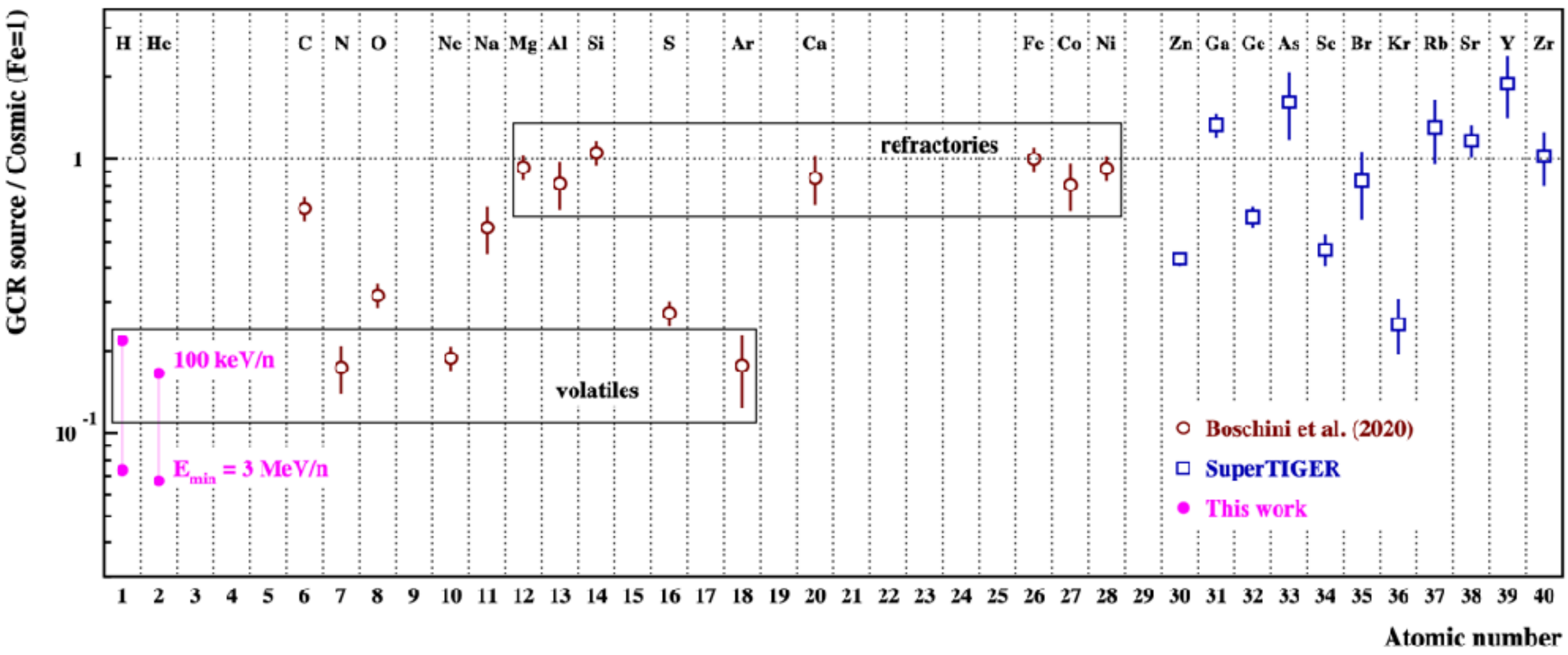
Composition: striking anomalies



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

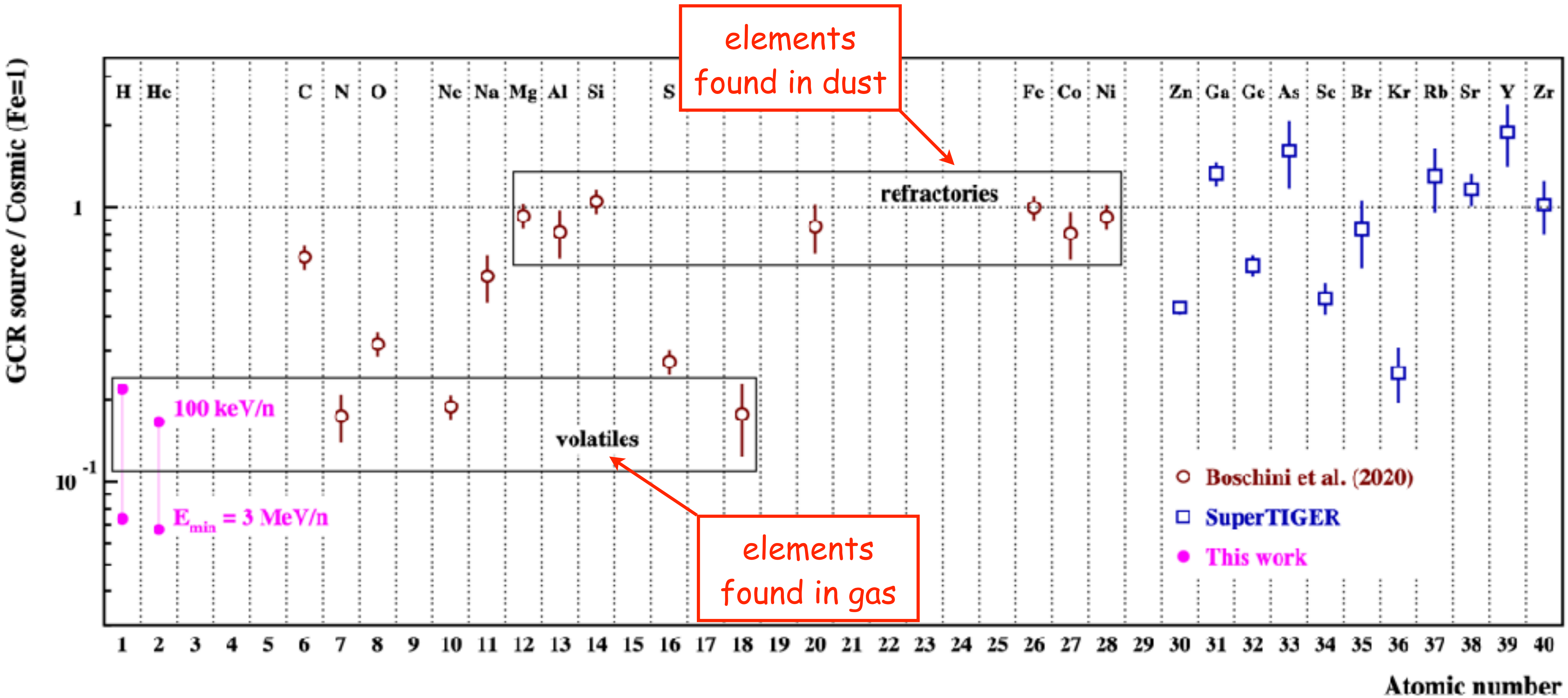
Tatischeff & SG, 2018

Composition: volatiles and refractories



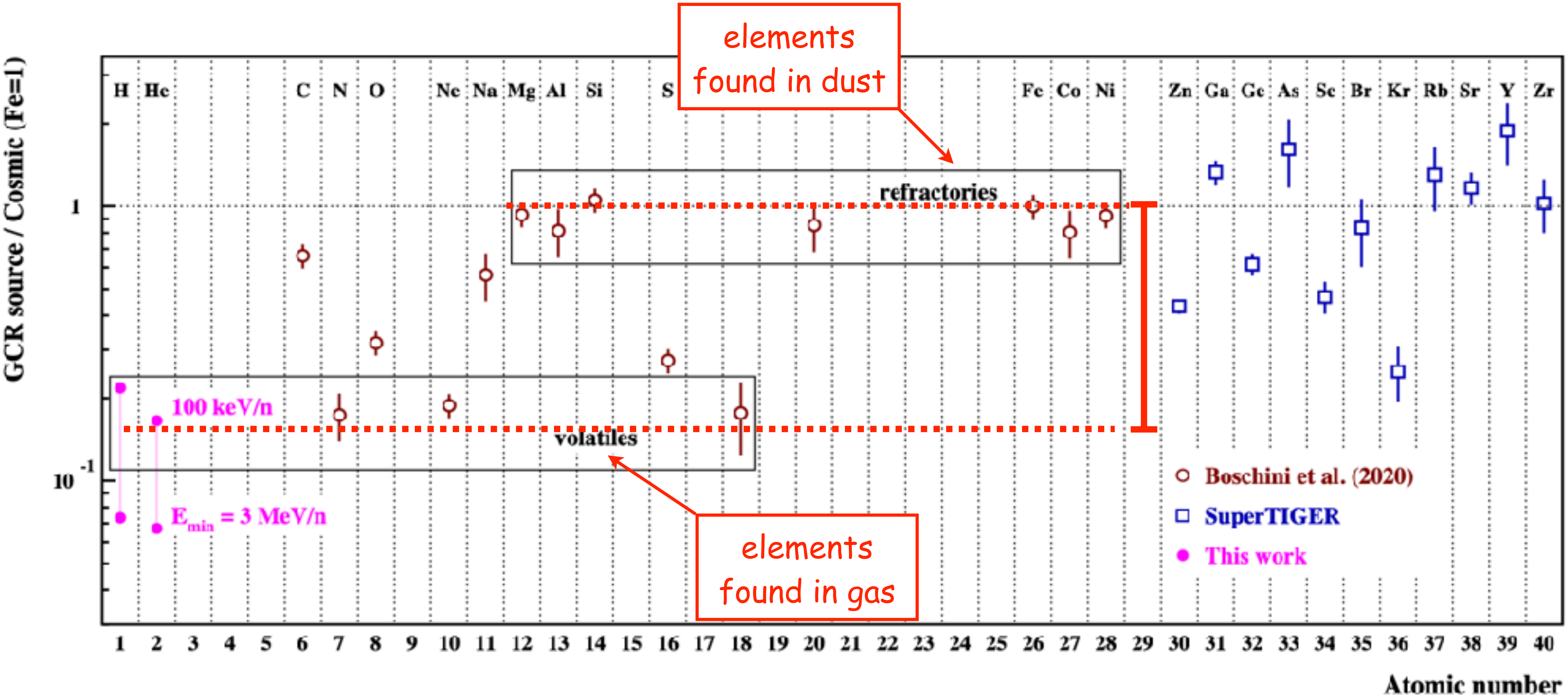
Tatischeff, Raymond, Duprat, SG, Recchia, 2021

Composition: volatiles and refractories



Tatischeff, Raymond, Duprat, SG, Recchia, 2021

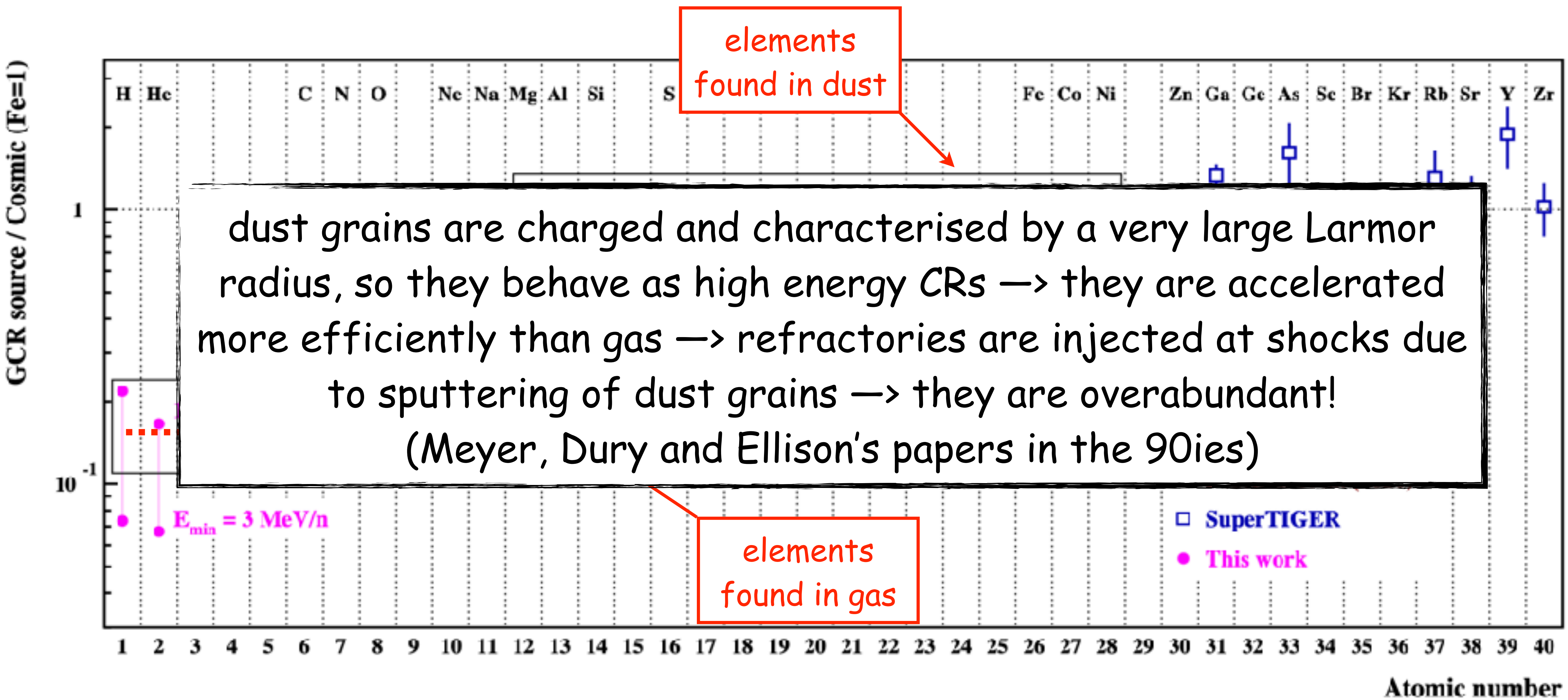
Composition: volatiles and refractories



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

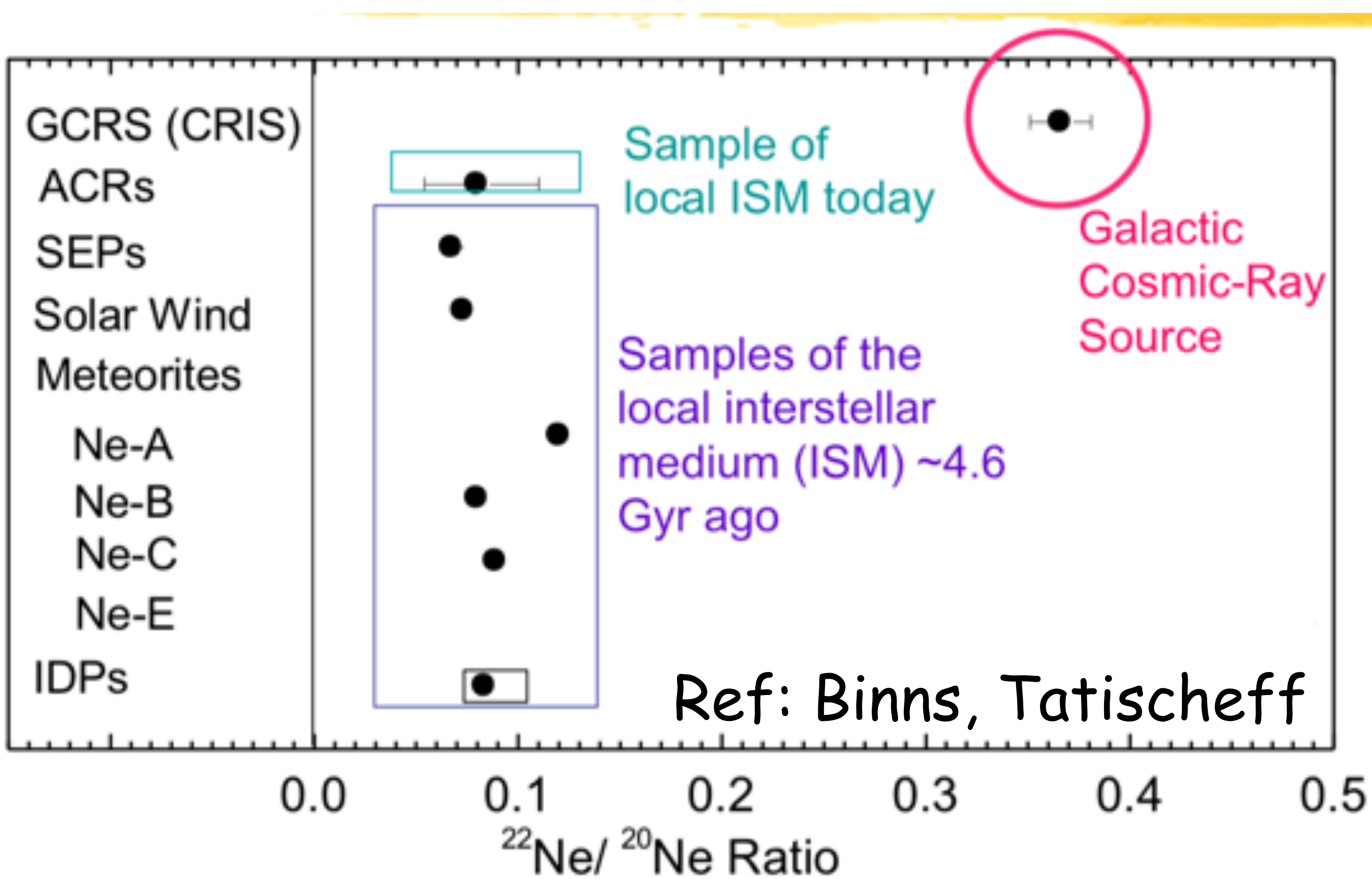


dust grains are charged and characterised by a very large Larmor radius, so they behave as high energy CRs —> they are accelerated more efficiently than gas —> refractories are injected at shocks due to sputtering of dust grains —> they are overabundant!
(Meyer, Dury and Ellison's papers in the 90ies)

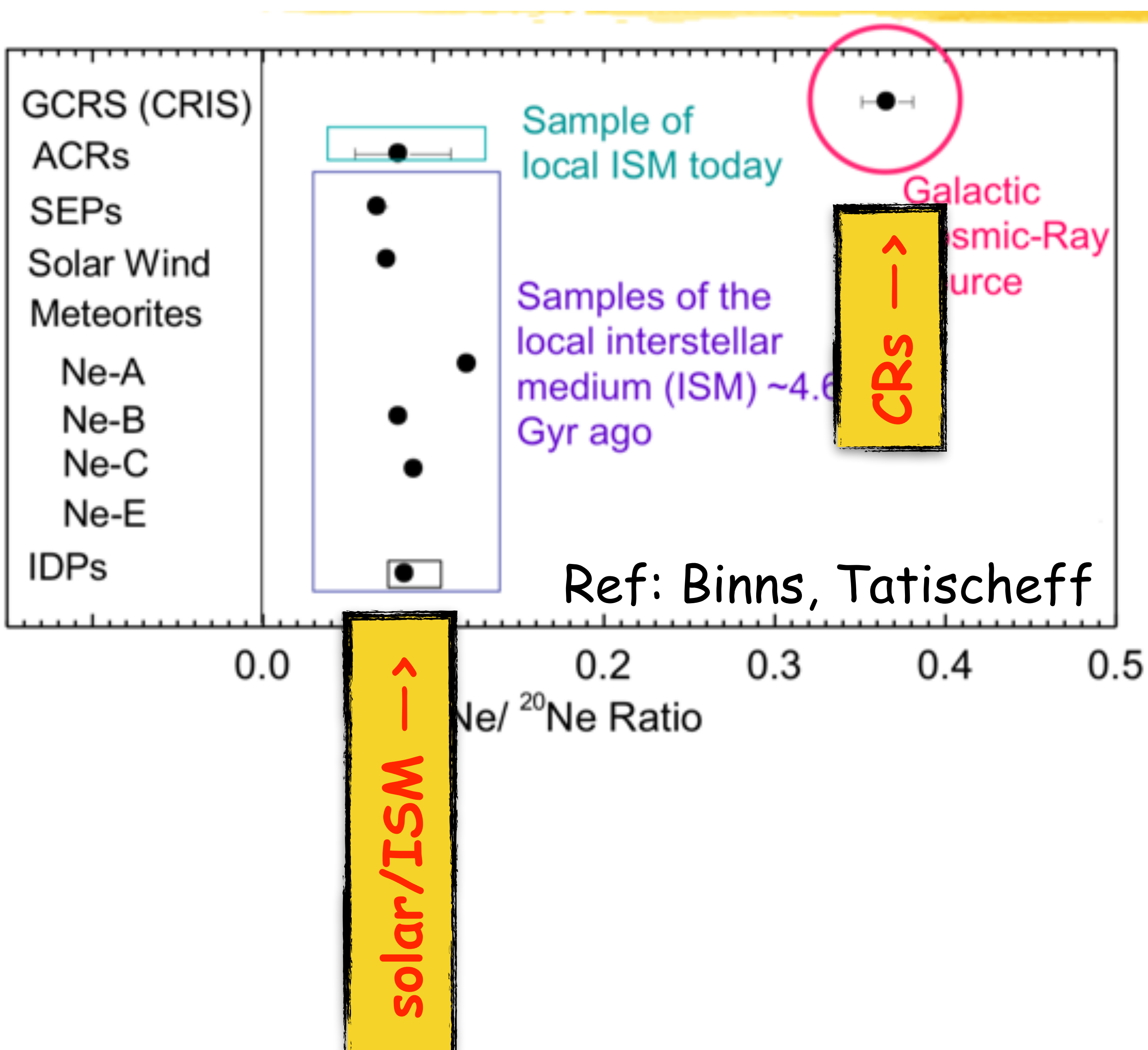
less pronounced but still very clear differences
—> volatiles versus refractories? —> dust must play a role…

Tatischeff, Raymond, Duprat, SG, Recchia, 2021

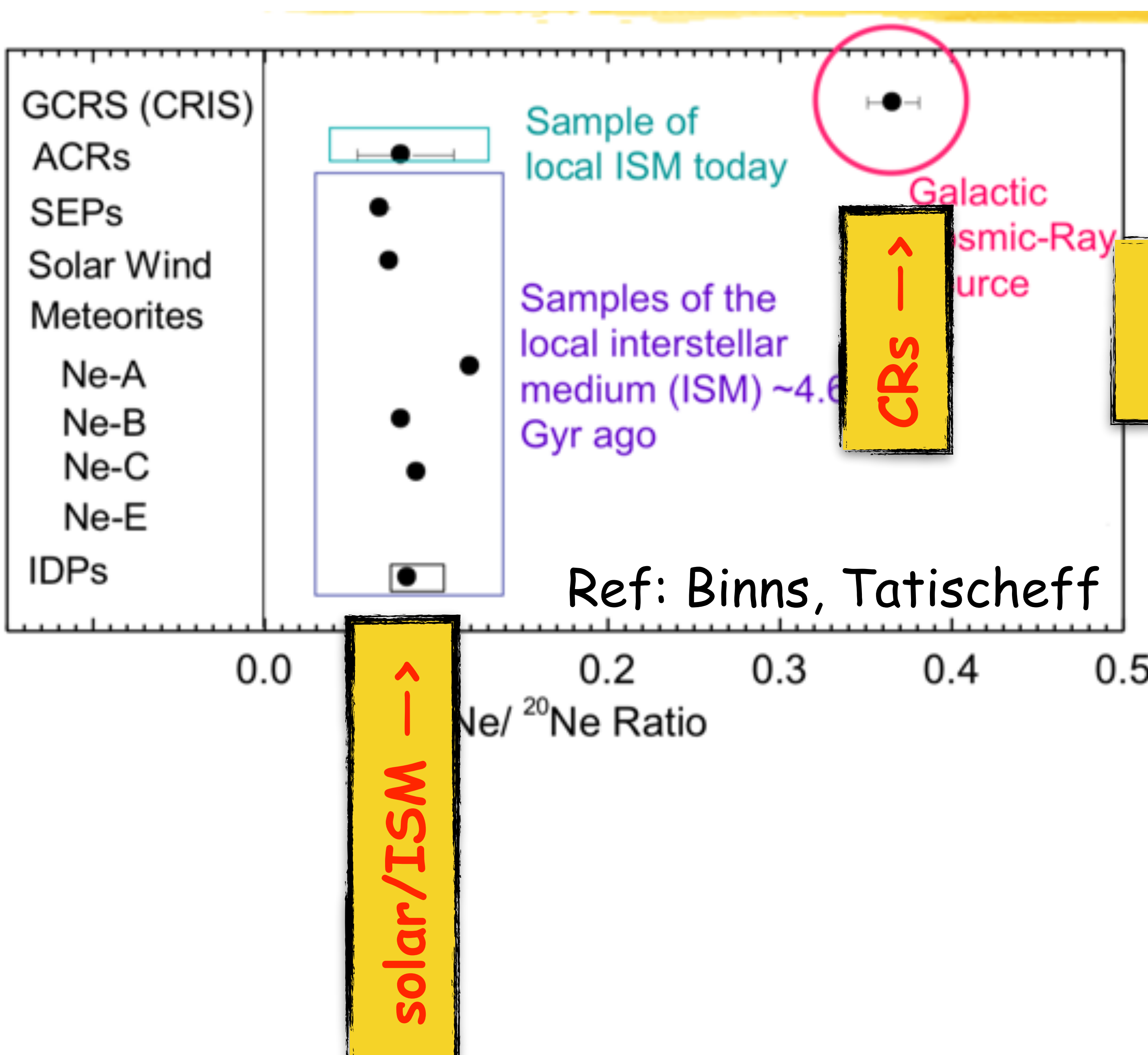
Composition: isotopic anomalies



Composition: isotopic anomalies



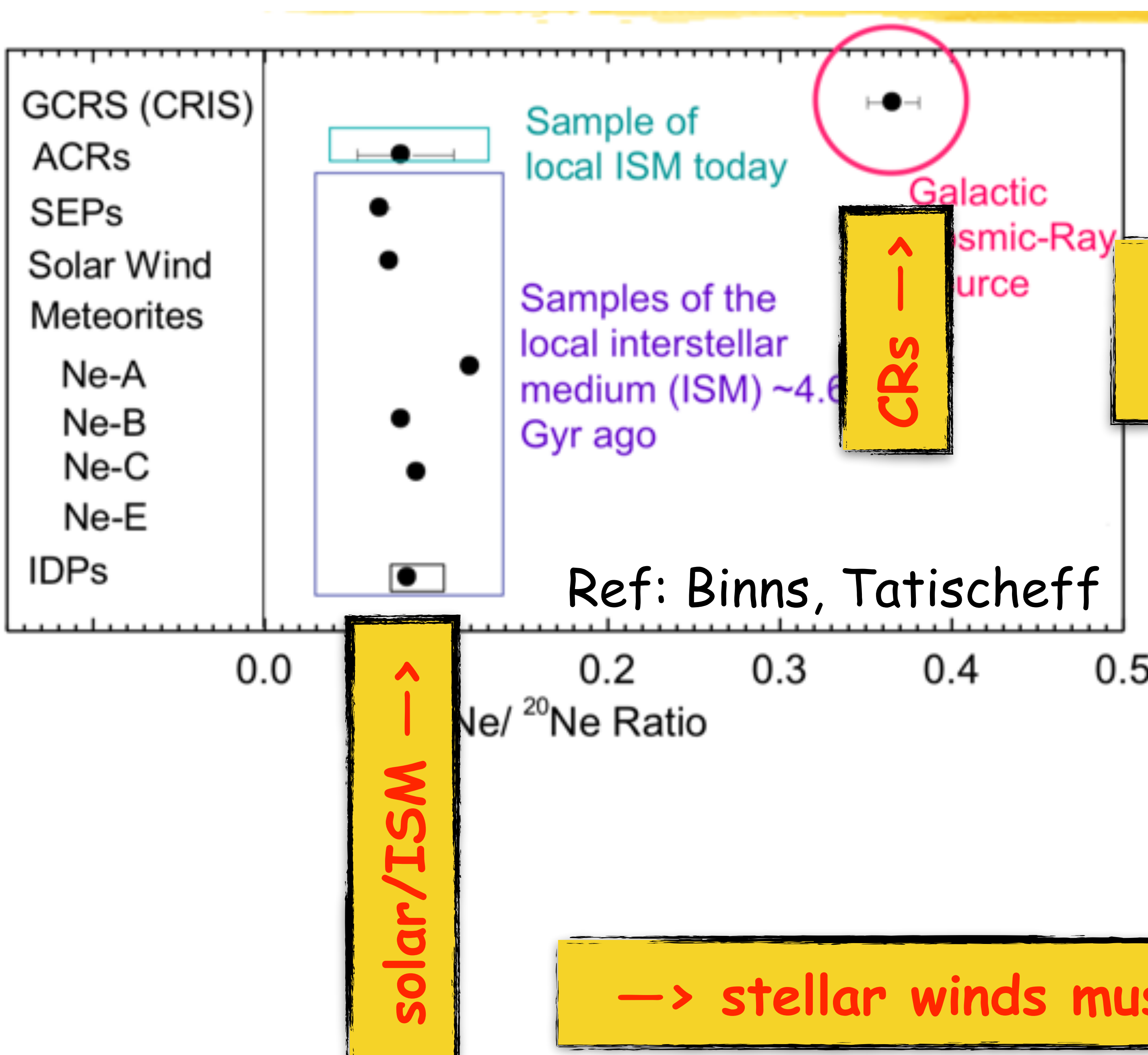
Composition: isotopic anomalies



Ref: Binns, Tatischeff

^{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

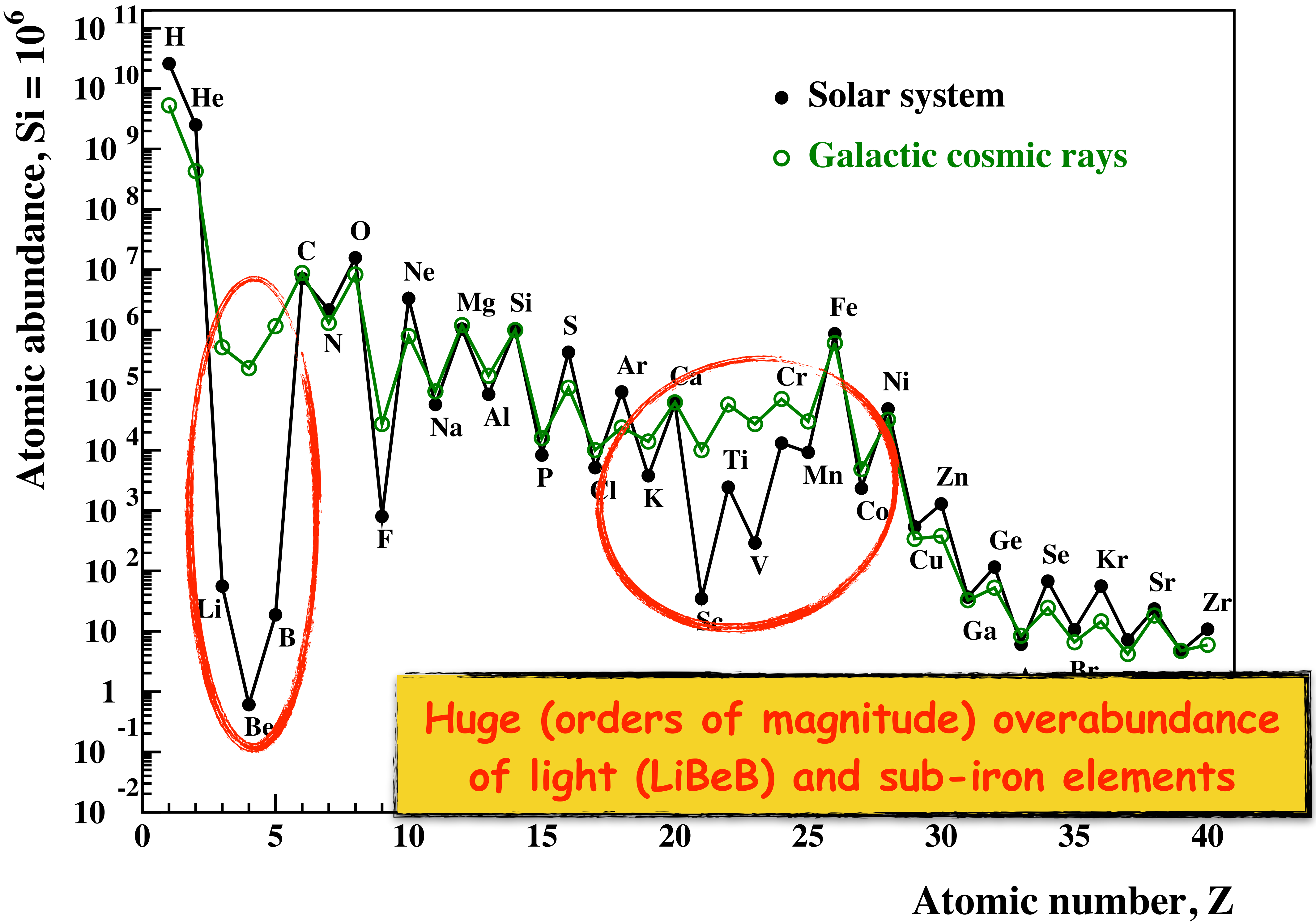
—> stellar winds must play a role in CR acceleration!

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?

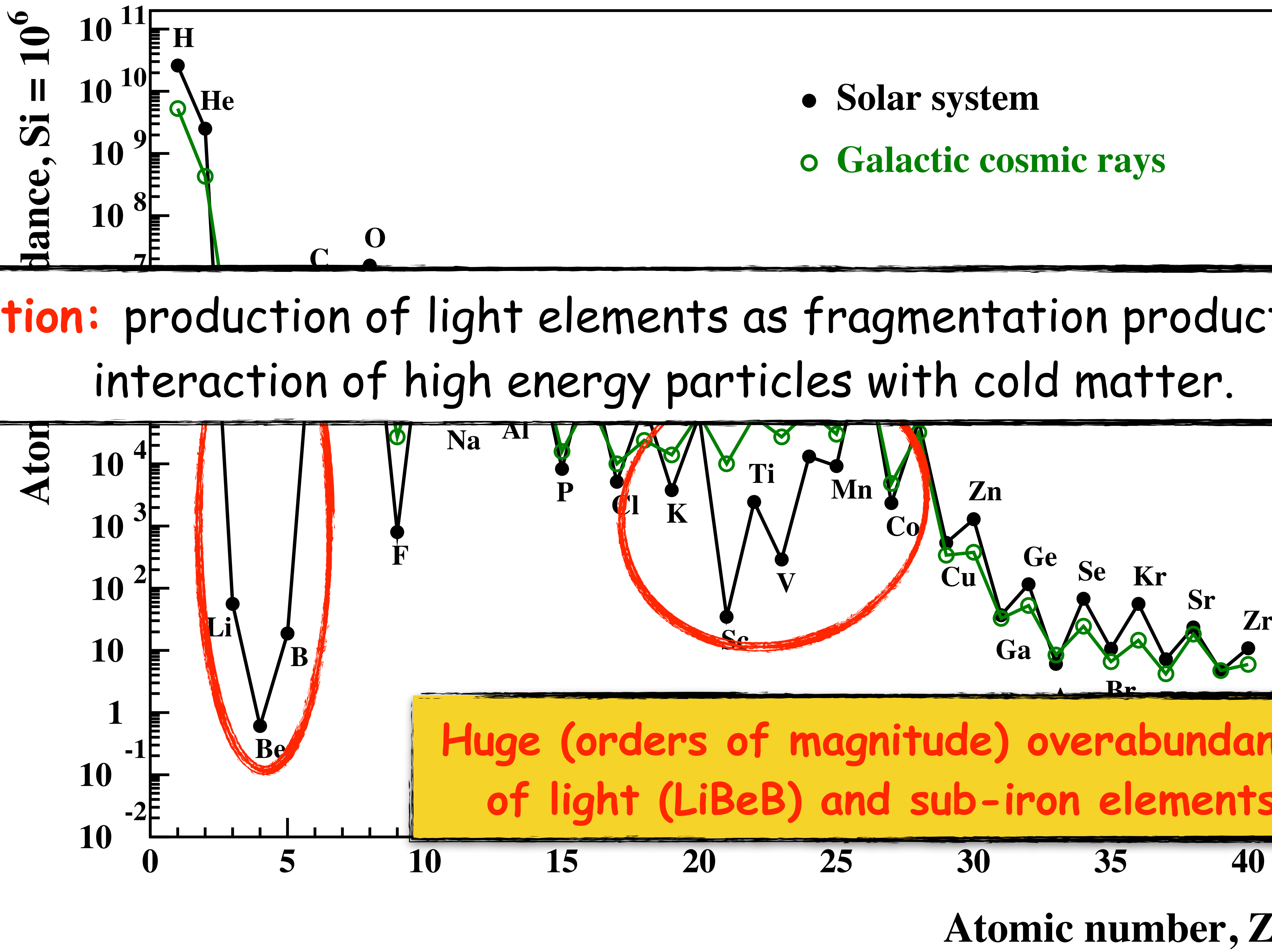
Composition: striking anomalies



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

Tatischeff & SG, 2018

Composition: striking anomalies

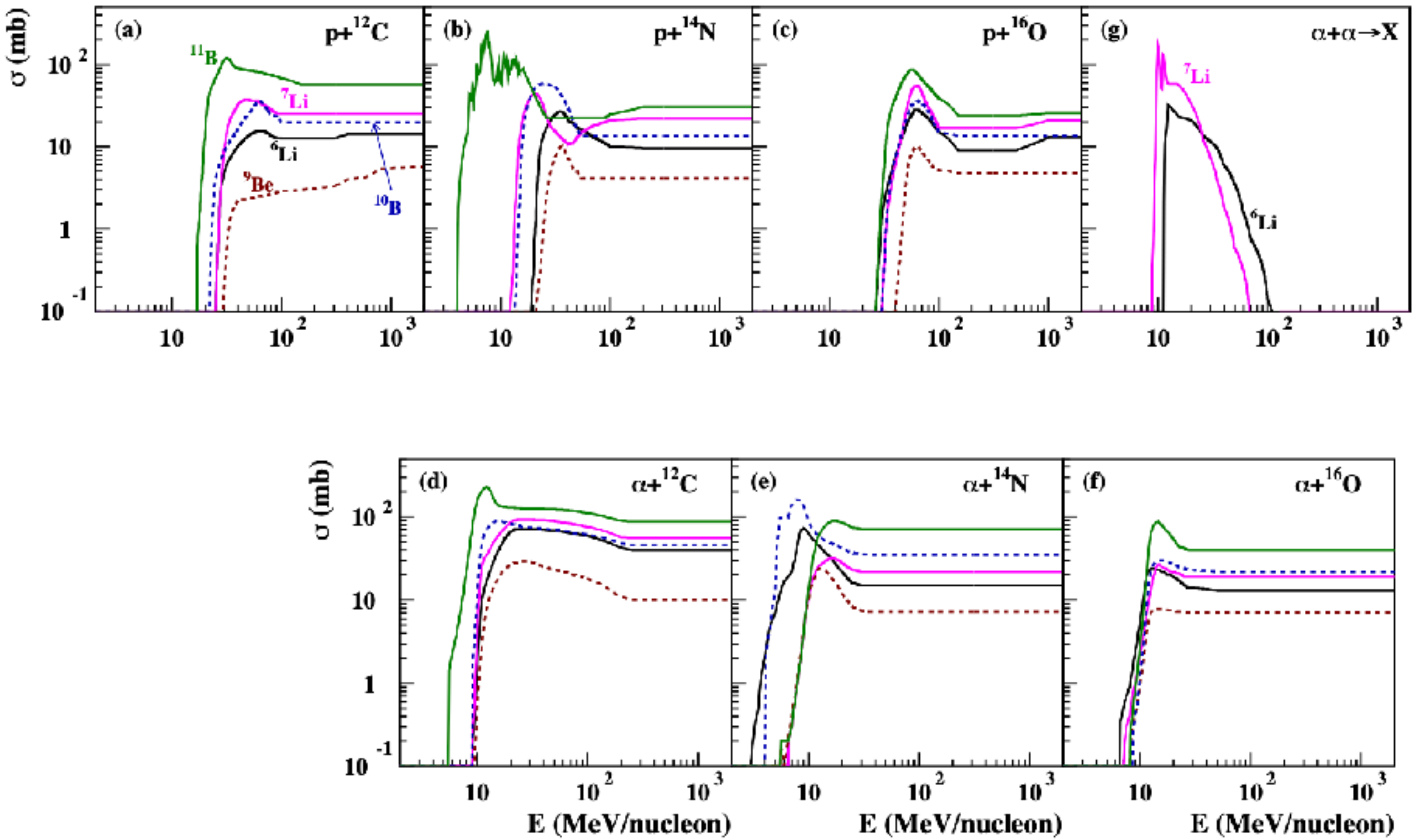


Spallation: production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

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

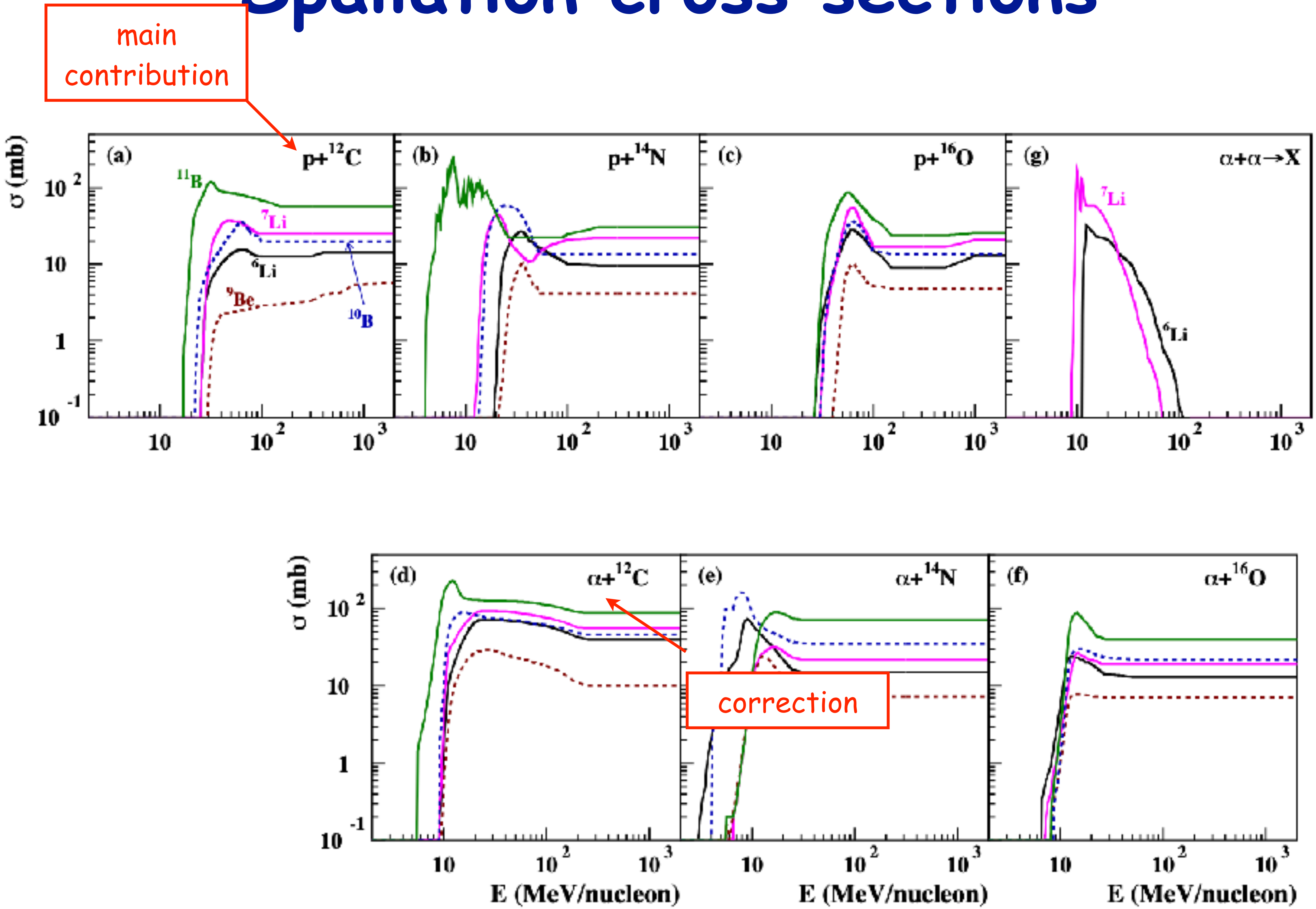
Tatischeff & SG, 2018

Spallation cross sections



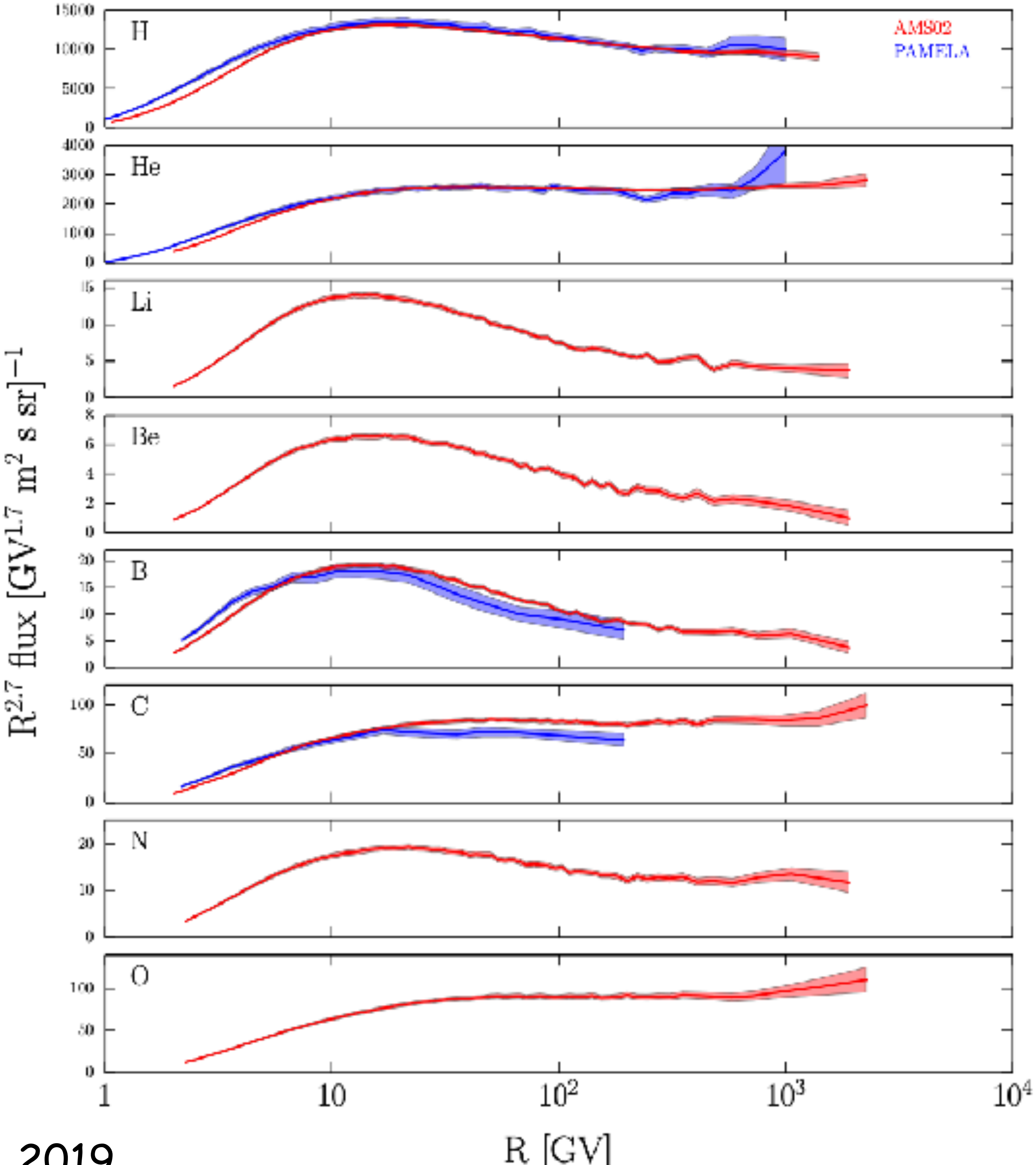
Tatischeff & SG, 2018

Spallation cross sections



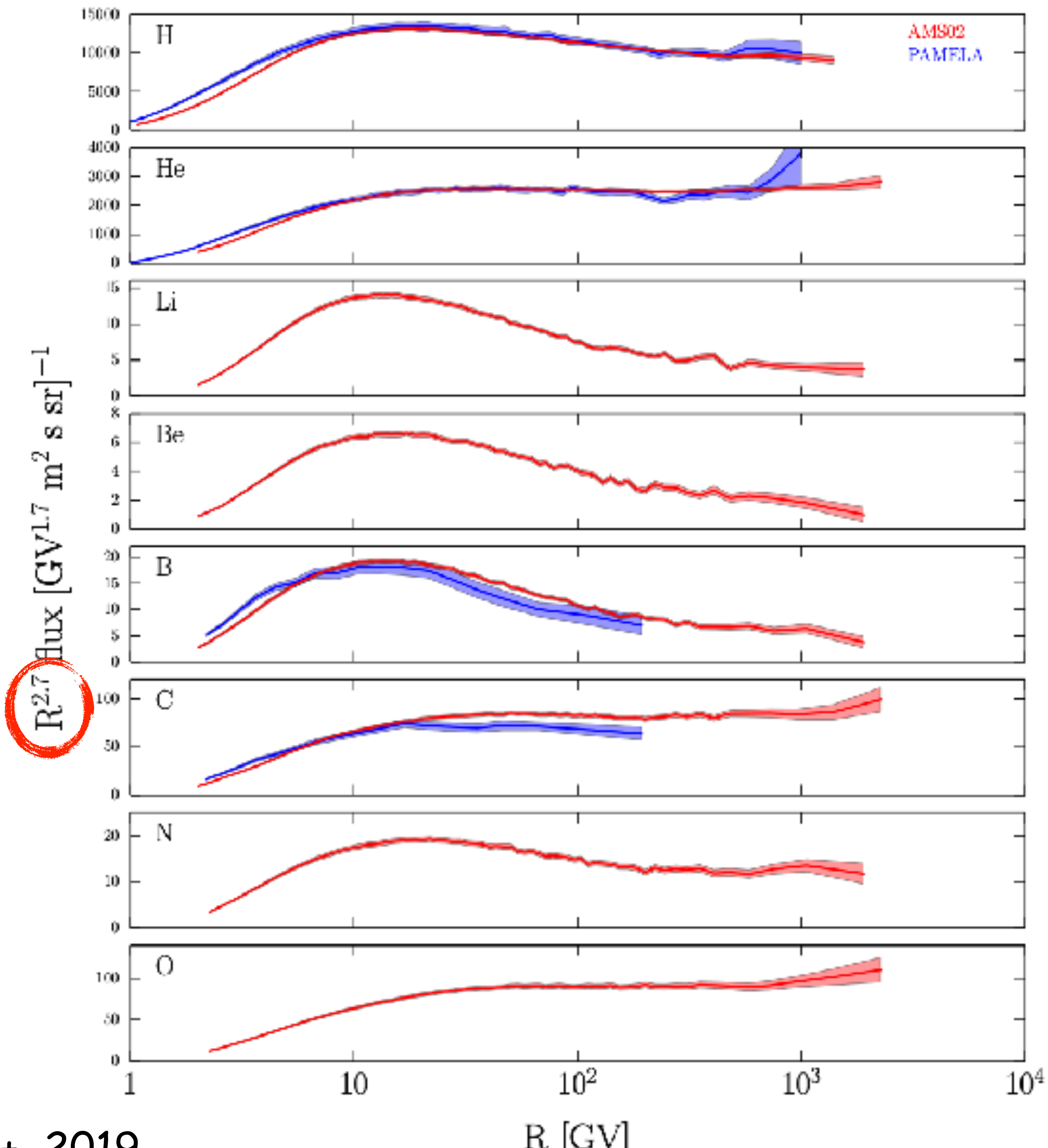
Tatischeff & SG, 2018

Spectra of light elements



SG+, 2019

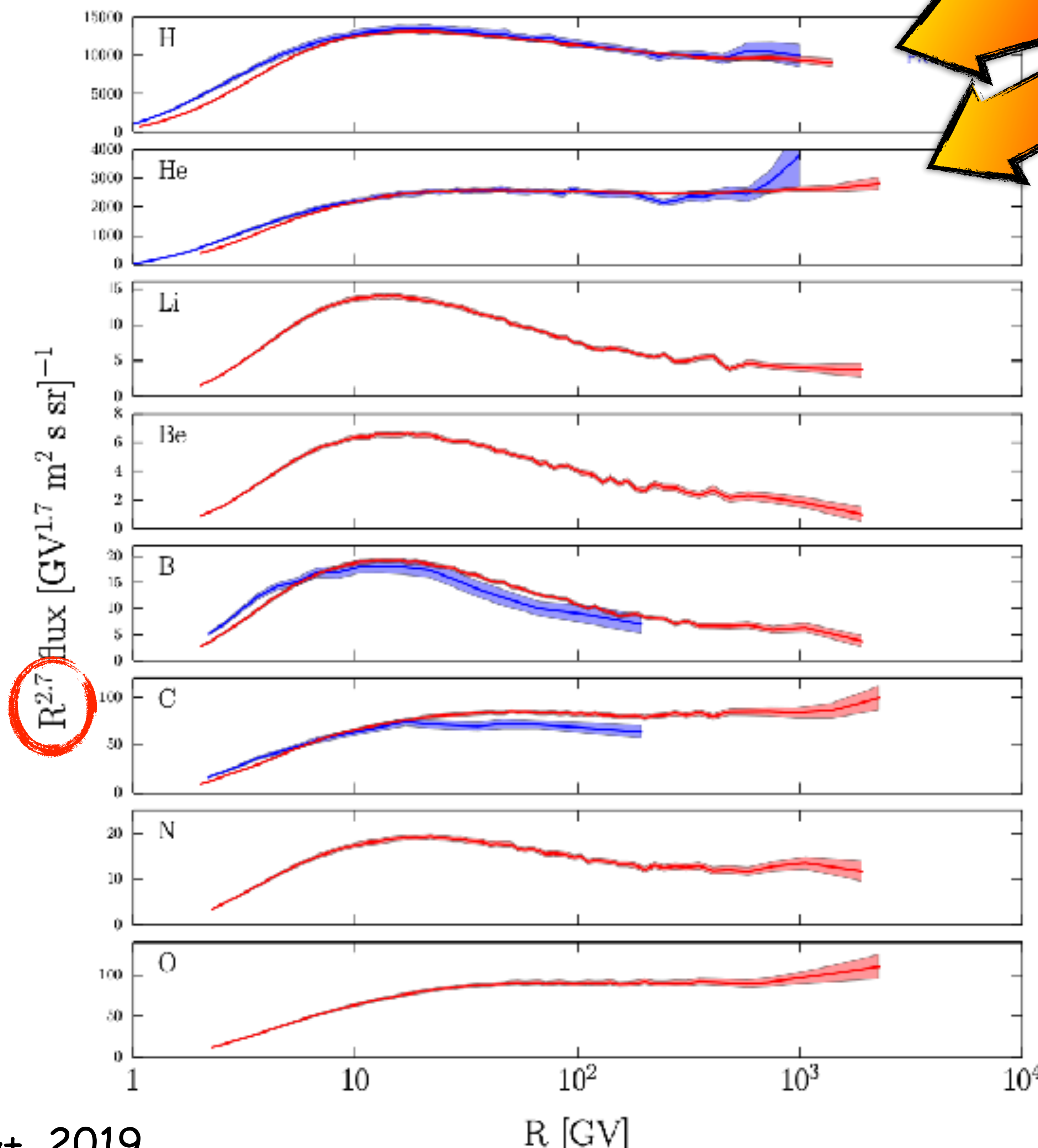
Spectra of light elements



SG+, 2019

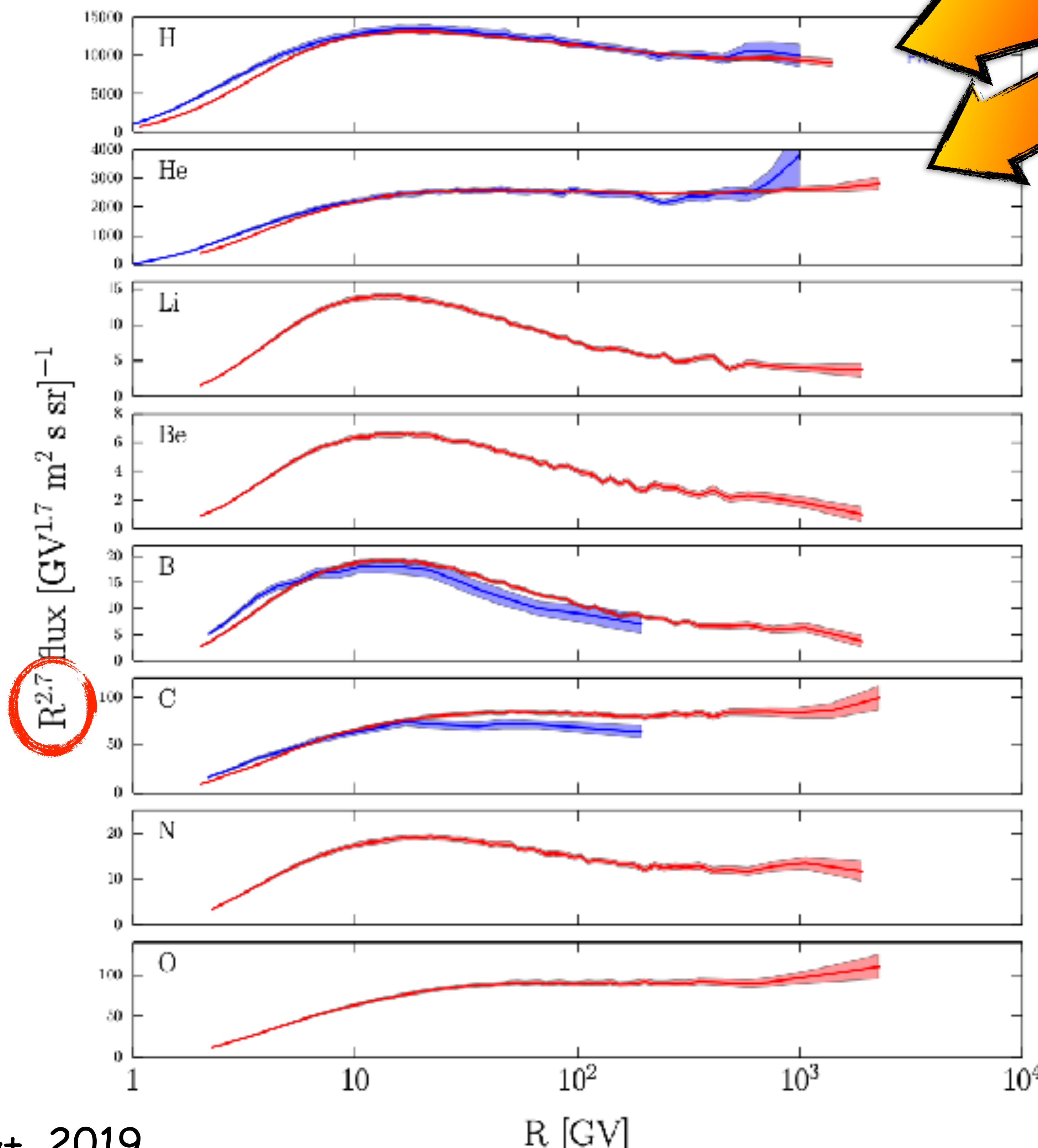
Spectra of light elements

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



SG+, 2019

Spectra of light elements



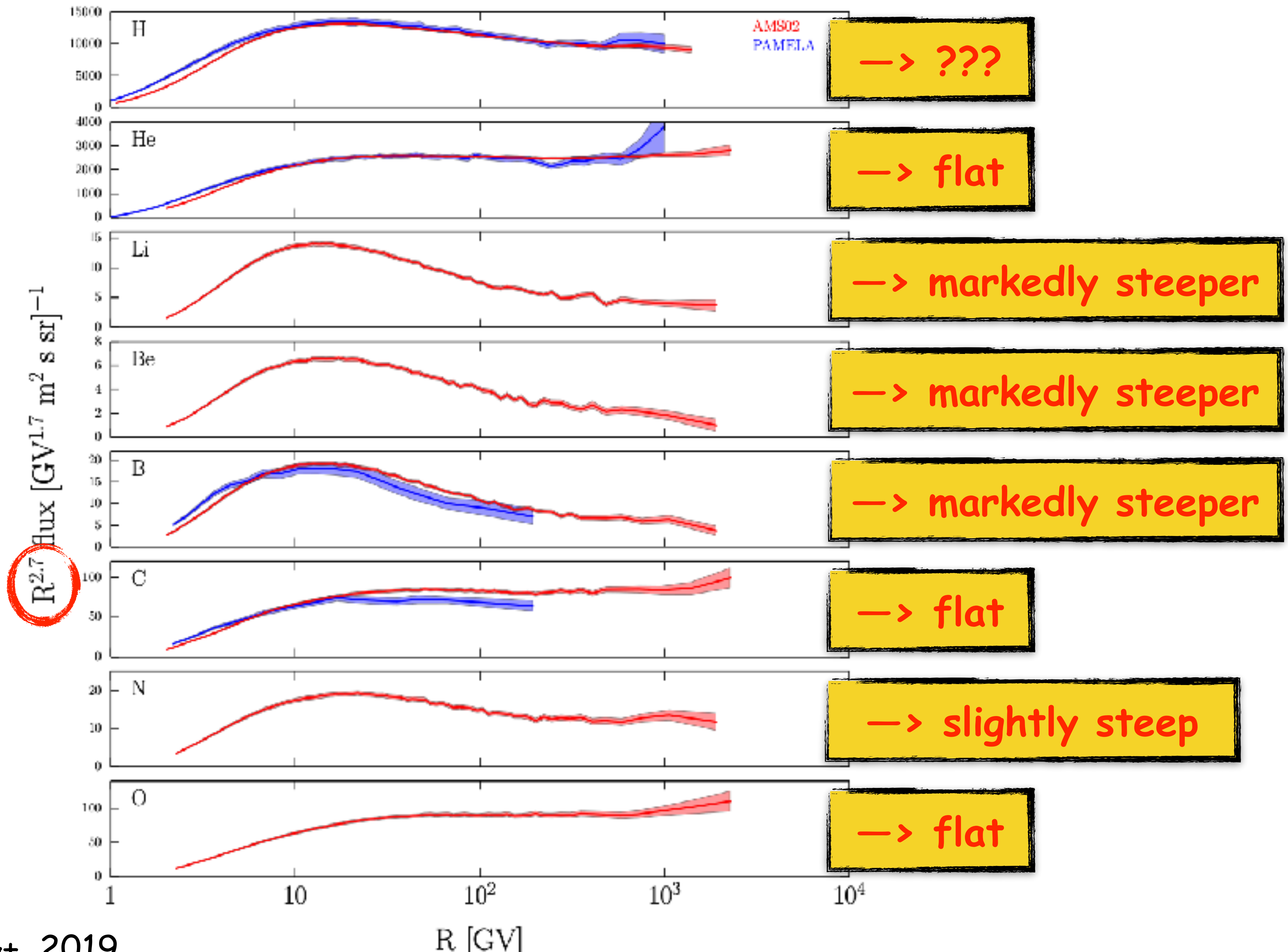
SG+, 2019

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

Possibilities:

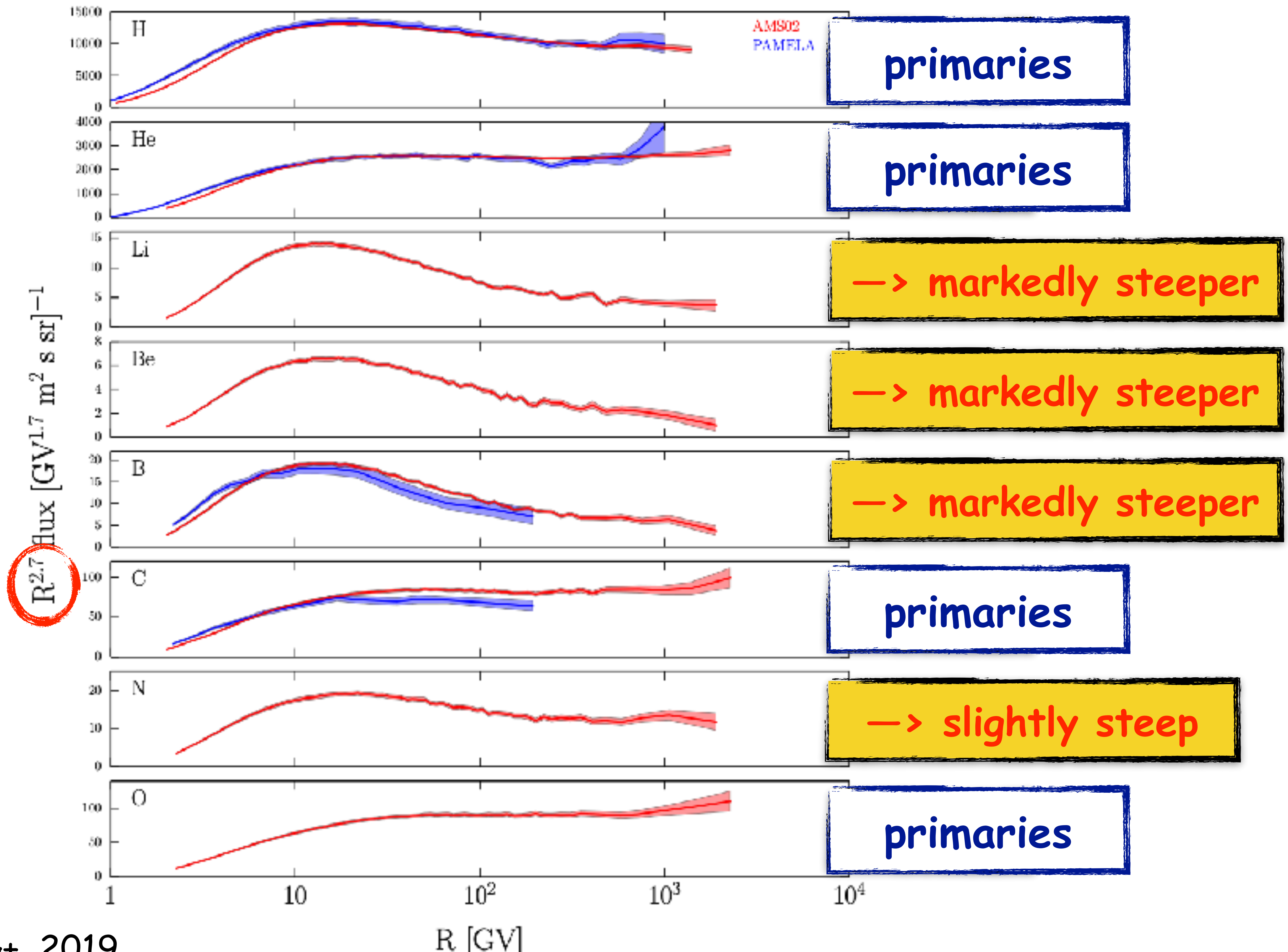
1) He does something that H doesn't —> spallation?
—> is it ok with heavier elements?
2) He and H are accelerated in a different way
—> aren't acceleration mechanisms "universal"?
3) He and H are accelerated in different places —> environmental effect
—> fine tuning? (e.g. local source in the right environment,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

Spectra of light elements: an hypothesis



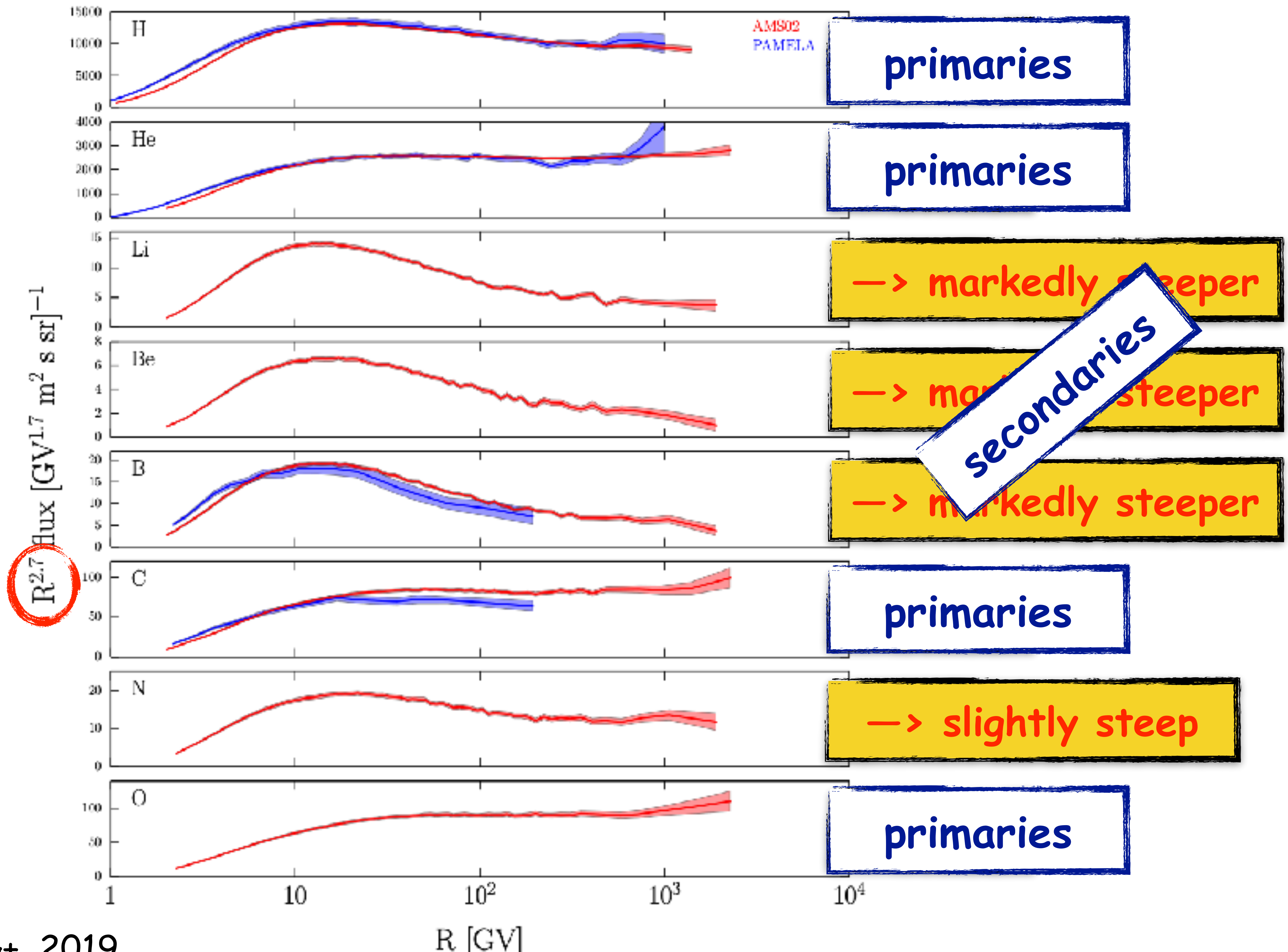
SG+, 2019

Spectra of light elements: an hypothesis



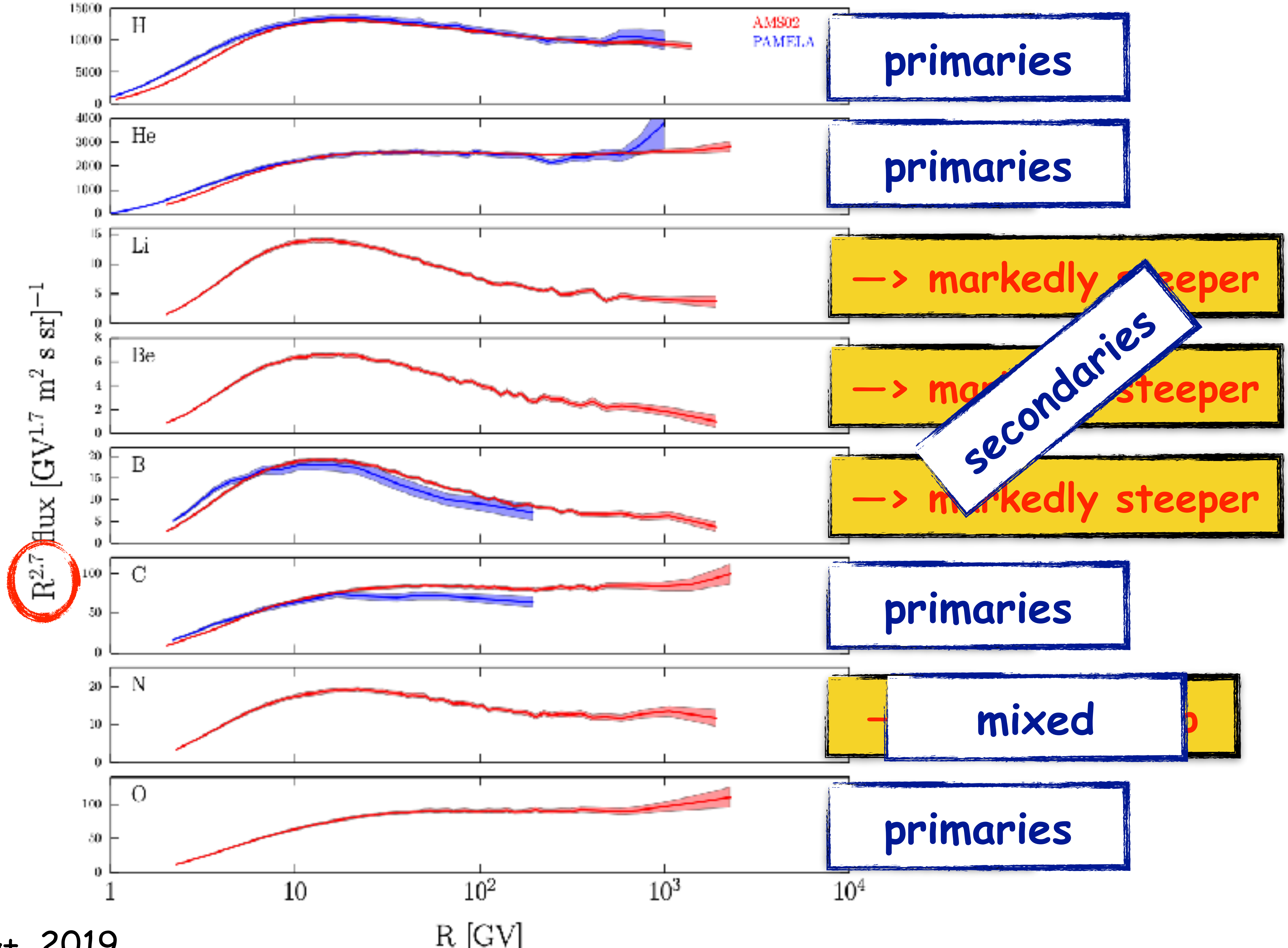
SG+, 2019

Spectra of light elements: an hypothesis



SG+, 2019

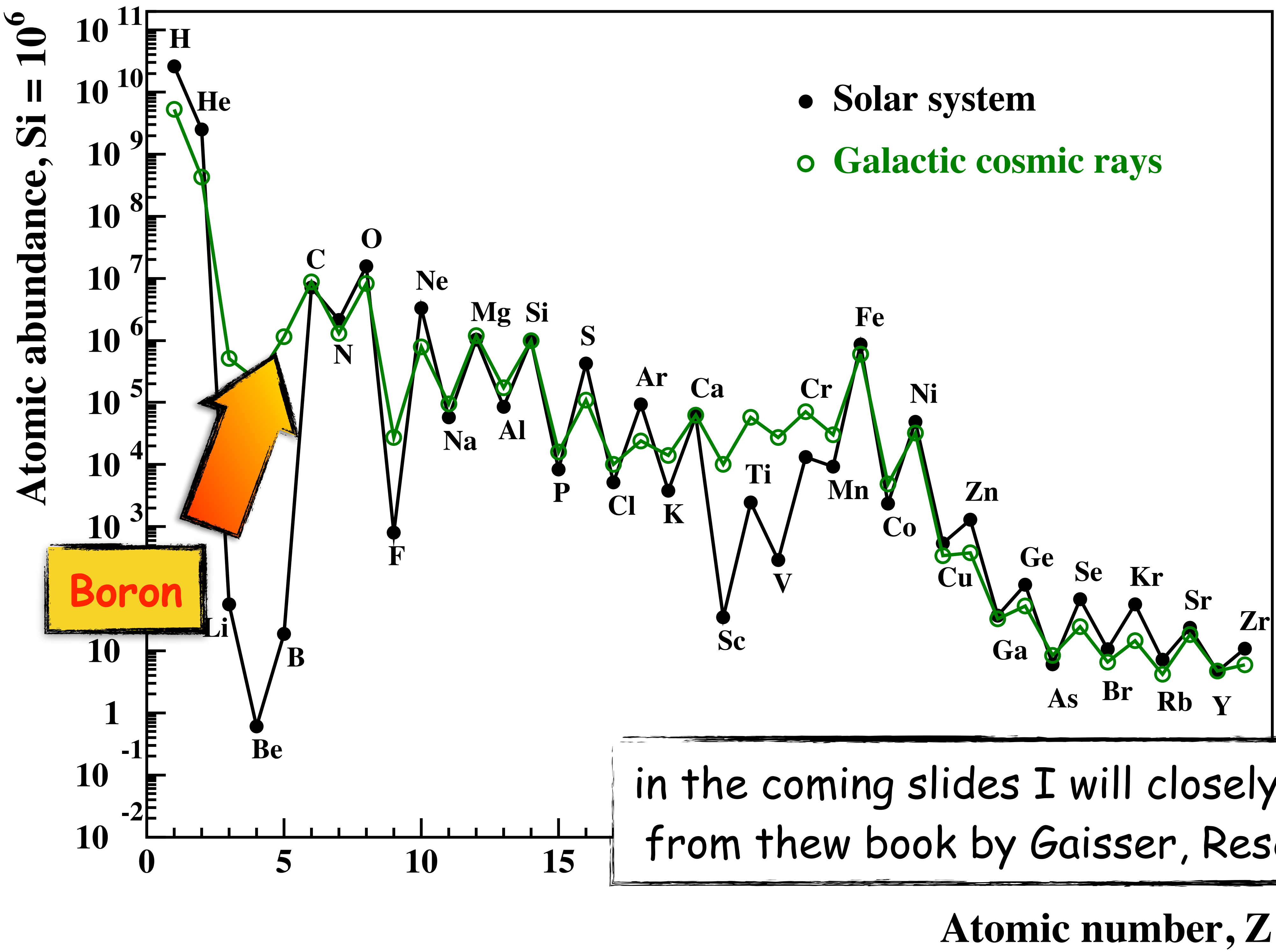
Spectra of light elements: an hypothesis



SG+, 2019

Production of B due to spallation

who does that?

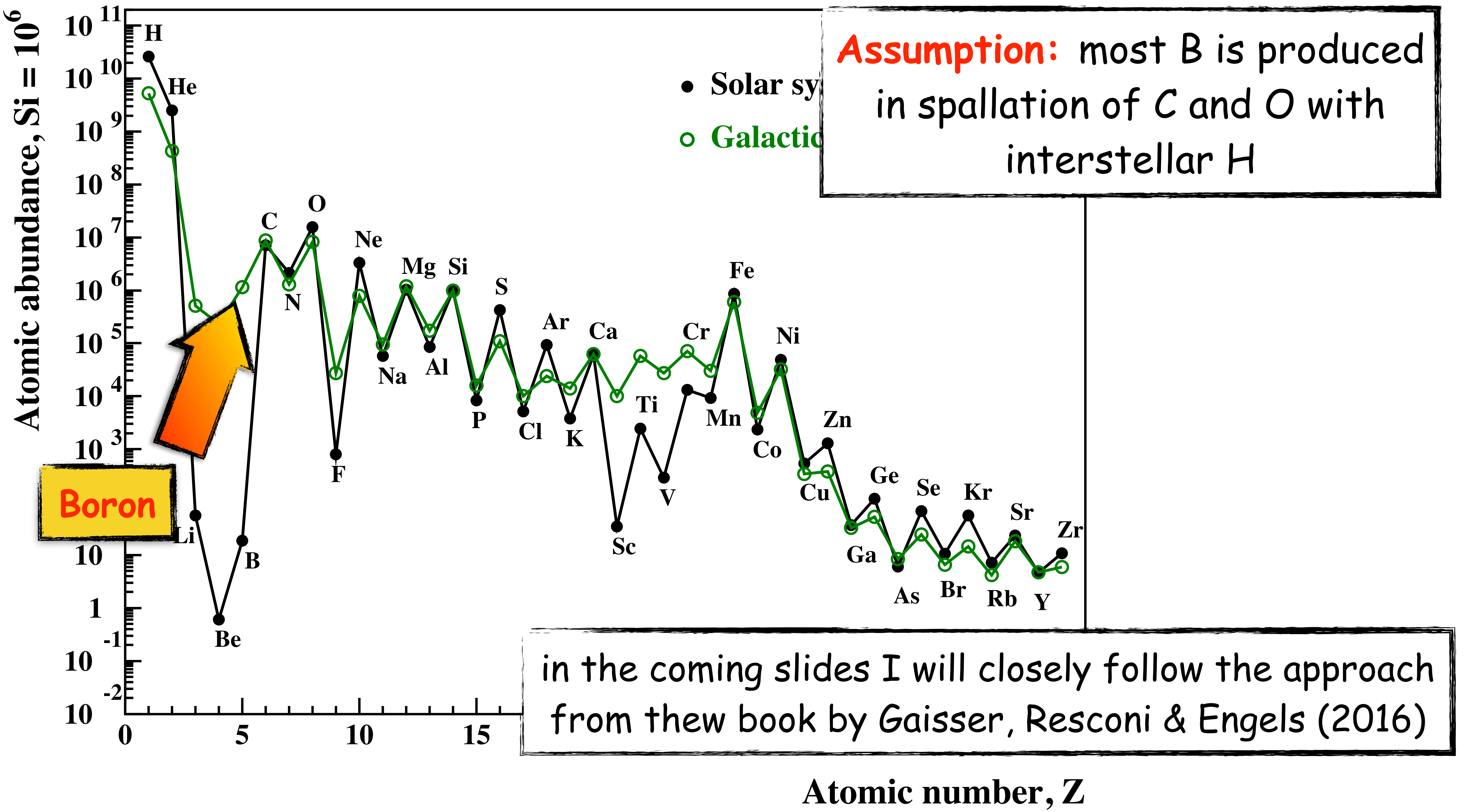


in the coming slides I will closely follow the approach from thew book by Gaisser, Resconi & Engels (2016)

Production of B due to spallation

who does that?

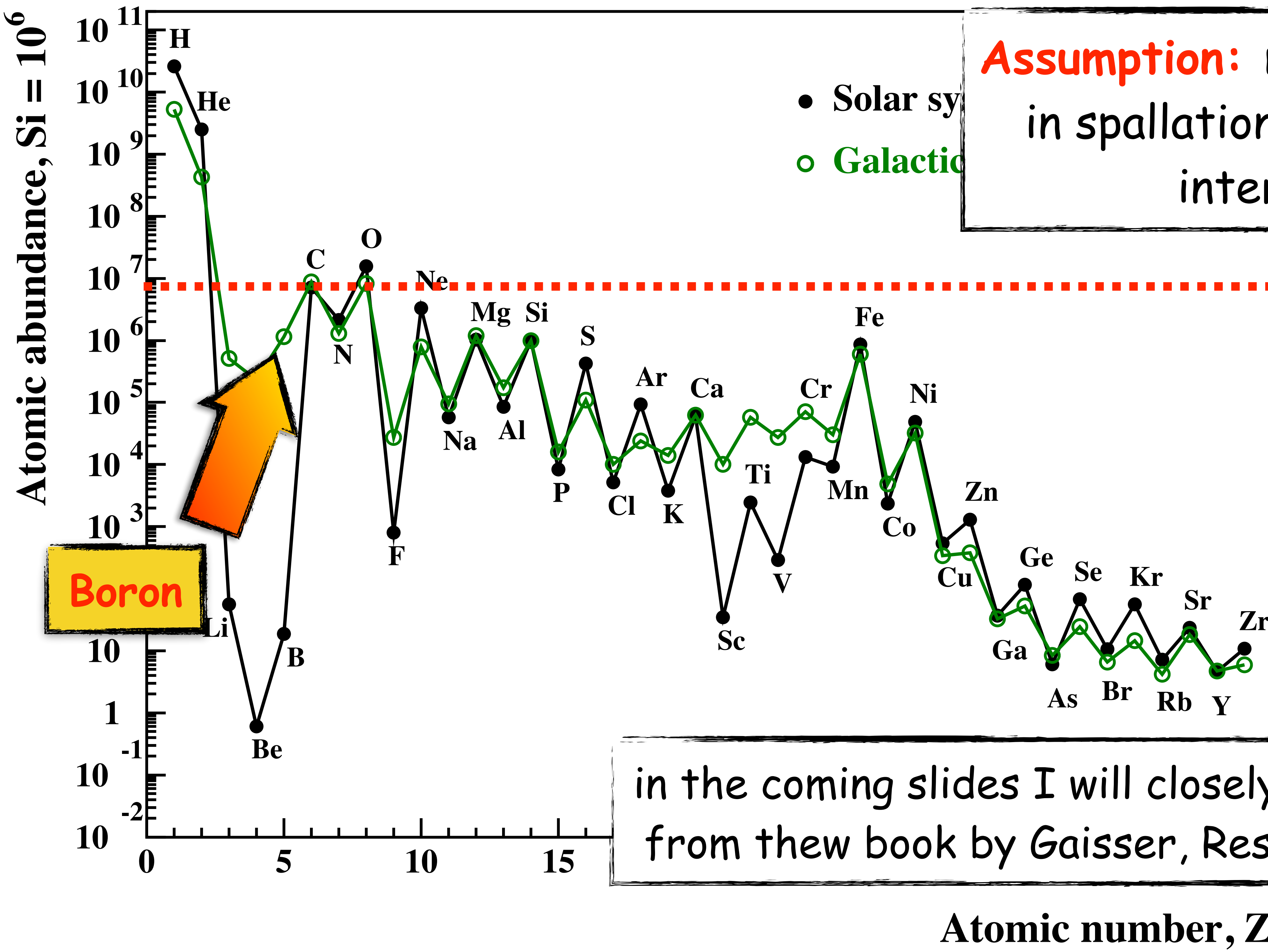
Assumption: most B is produced in spallation of C and O with interstellar H



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

Production of B due to spallation

who does that?

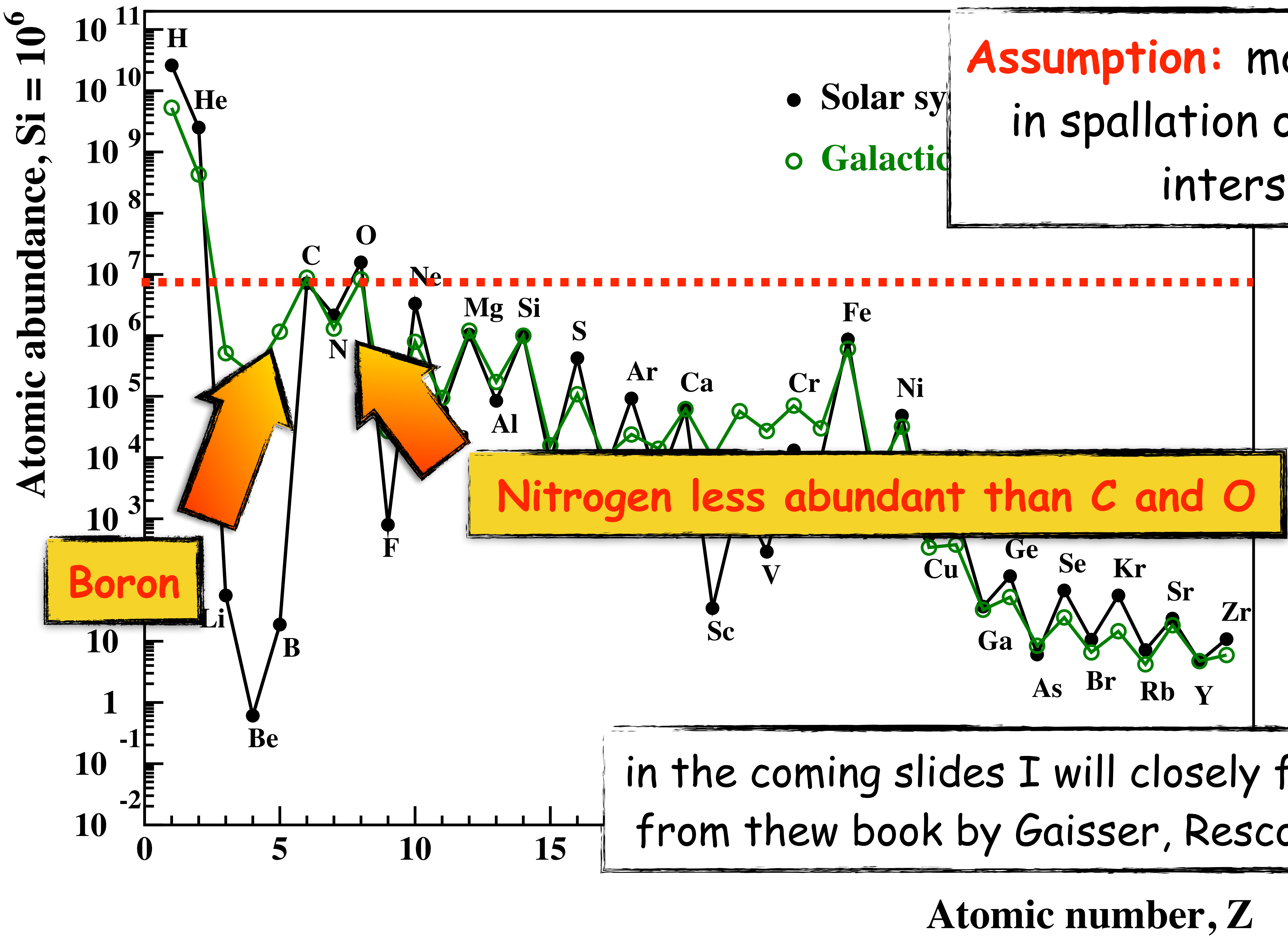


Assumption: most B is produced in spallation of C and O with interstellar H

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

Production of B due to spallation

who does that?



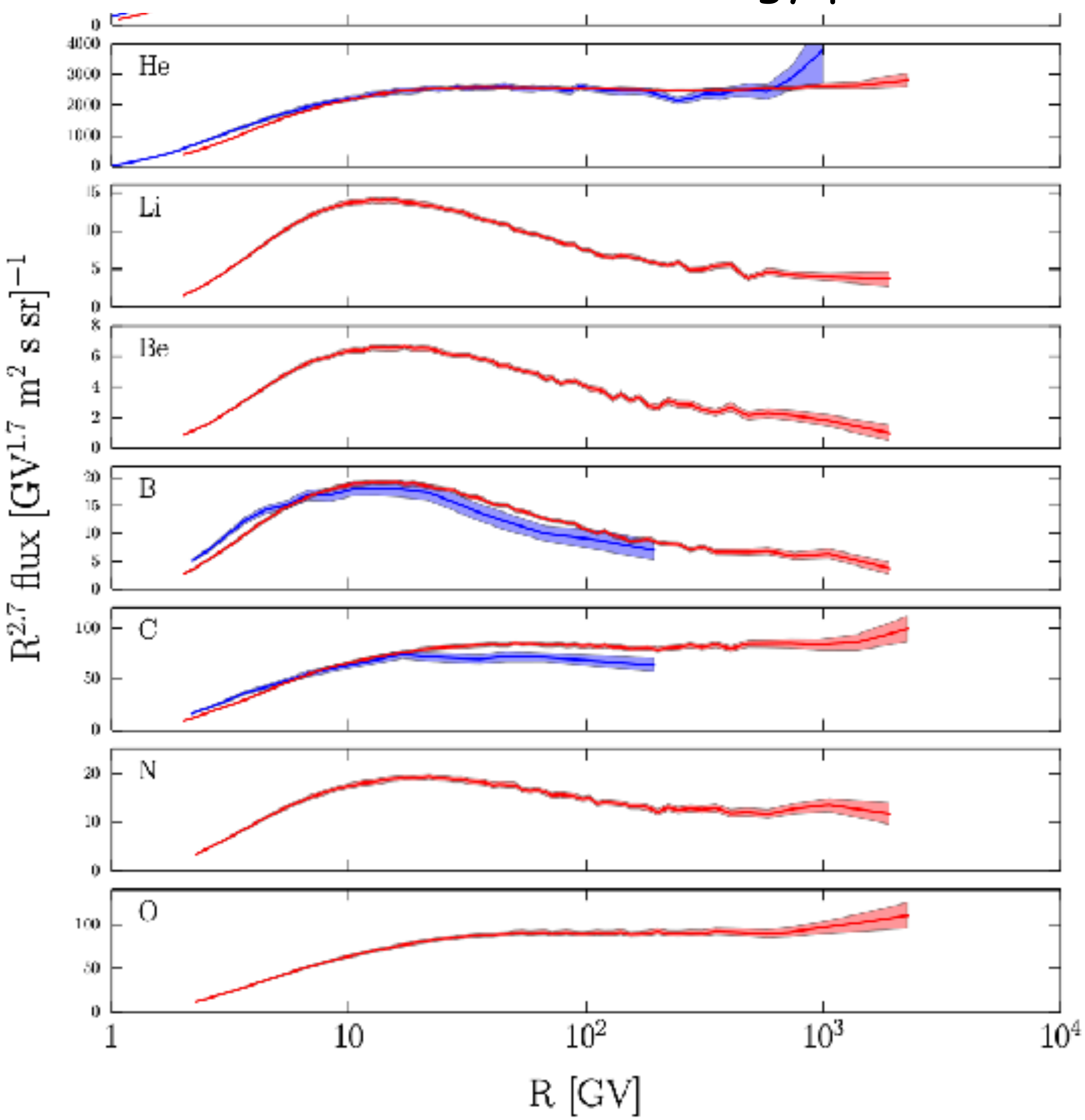
Assumption: most B is produced in spallation of C and O with interstellar H

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

Local production rate of B

—> energy per nucleon is approximatively conserved in spallation reactions

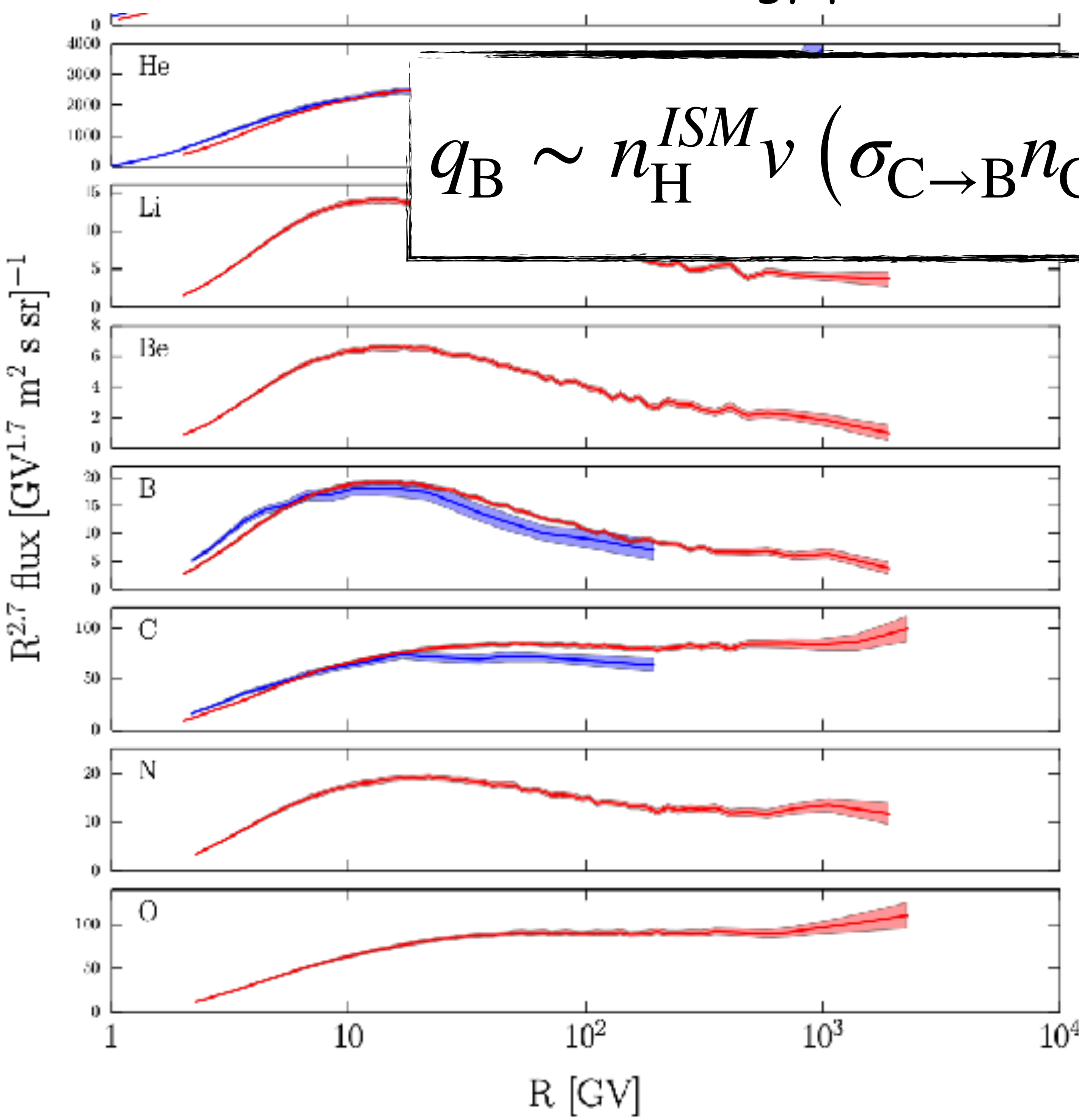
—> same energy per nucleon = same velocity



Local production rate of B

—> energy per nucleon is approximatively conserved in spallation reactions

—> same energy per nucleon = same velocity



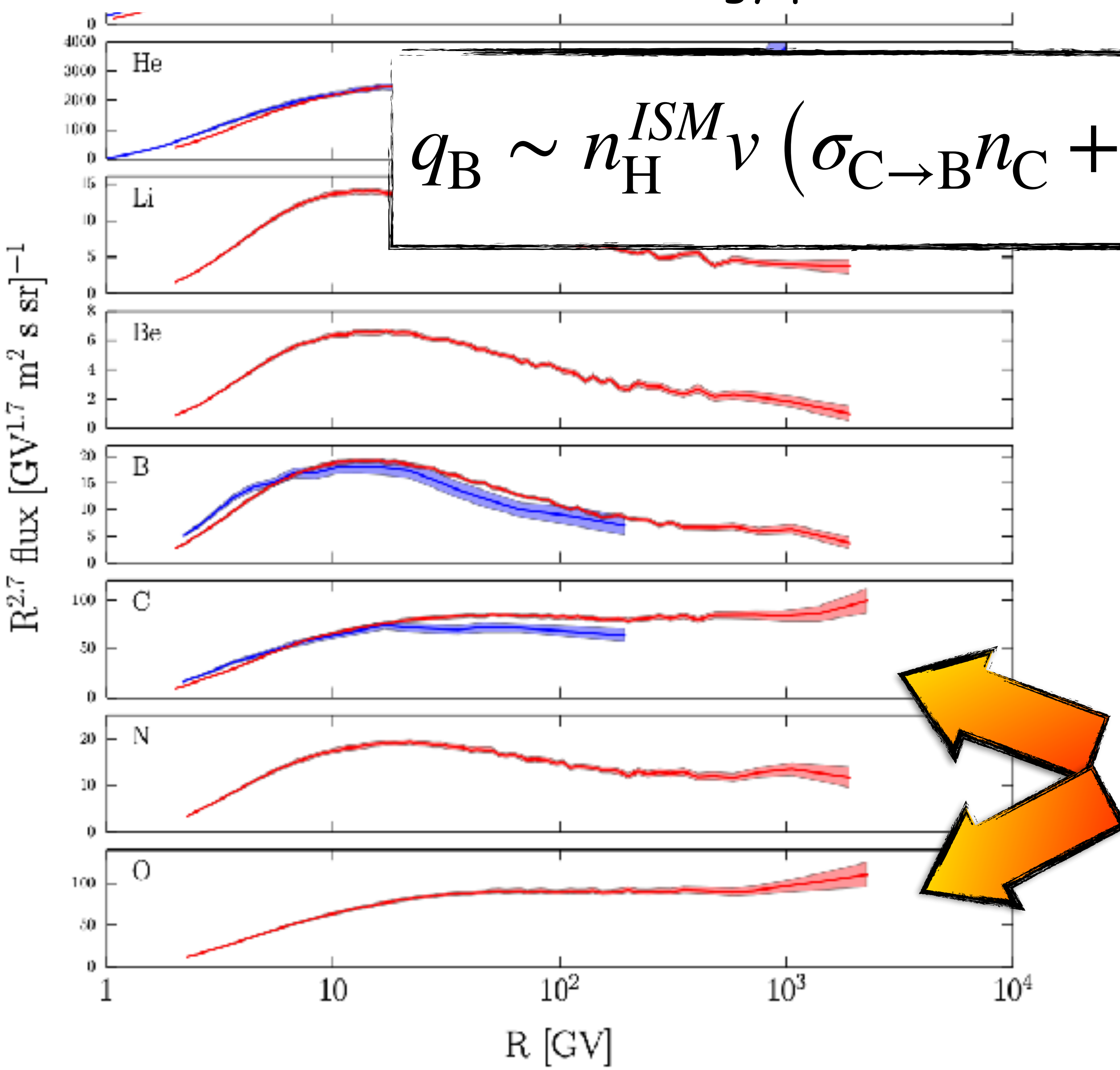
$$q_{\mathrm{B}} \sim n_{\mathrm{H}}^{ISM} v \left(\sigma_{\mathrm{C}\to\mathrm{B}} n_{\mathrm{C}} + \sigma_{\mathrm{O}\to\mathrm{B}} n_{\mathrm{O}} \right)$$

Local production rate of B

—> energy per nucleon is approximatively conserved in spallation reactions

—> same energy per nucleon = same velocity

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

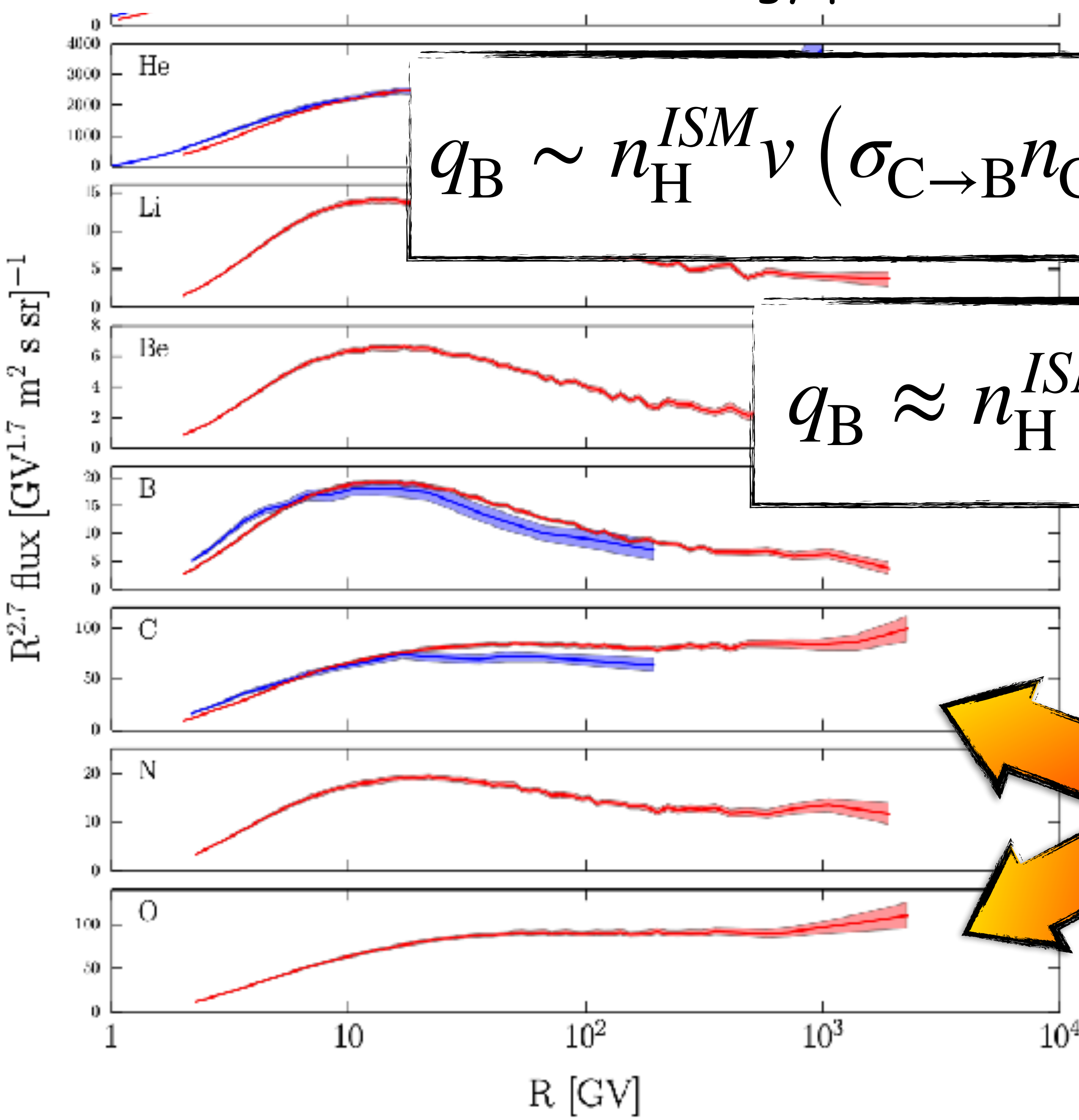


very similar spectra!

Local production rate of B

—> energy per nucleon is approximatively conserved in spallation reactions

—> same energy per nucleon = same velocity



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

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

very similar spectra!

The fate of CR Boron nuclei

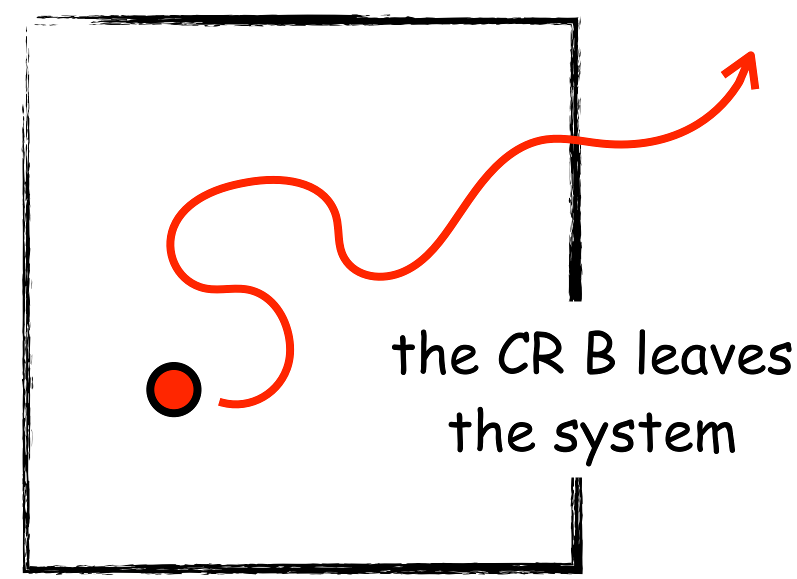
at this point we need to assume that the local spectra of CRs are representative for the entire system (which is the Galactic disk as we need target material for spallation reactions)

The fate of CR Boron nuclei

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

Two possibilities:

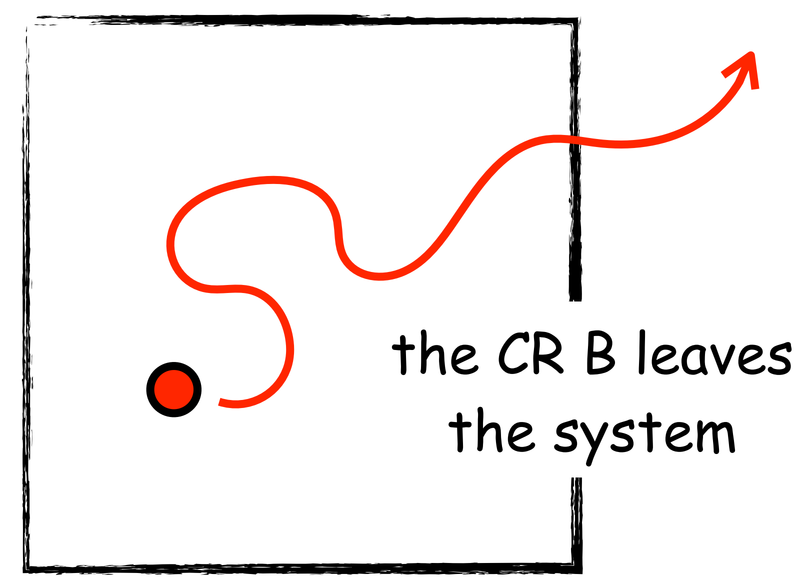
escape τ_{ISM}



The fate of CR Boron nuclei

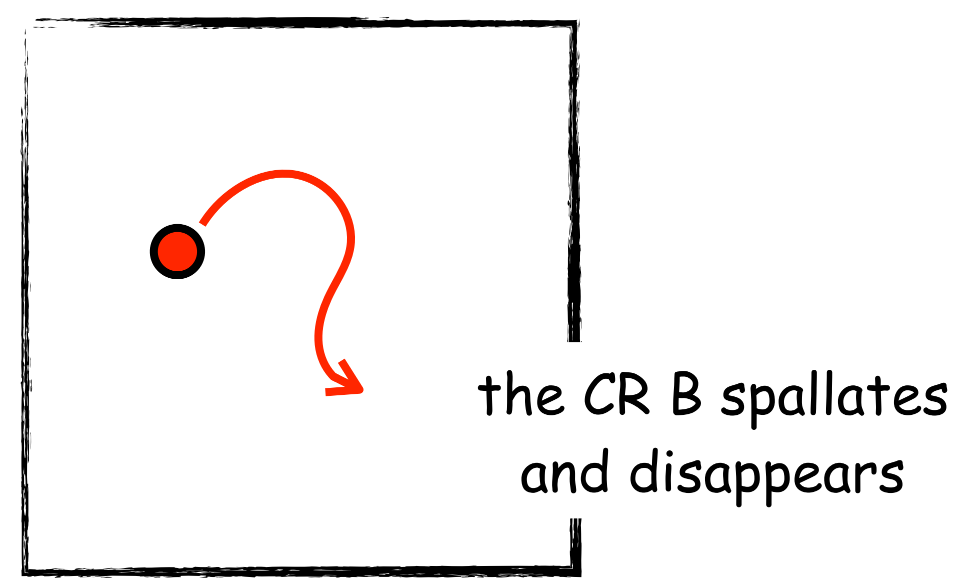
at this point we need to assume that the local spectra of CRs are representative for the entire system (which is the Galactic disk as we need target material for spallation reactions)

Two possibilities:



escape τ_{ISM}

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



The equilibrium spectrum of B

transport equation at equilibrium

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

production rate

destruction rate
(escape)

destruction rate
(spallation)

The equilibrium spectrum of B

transport equation at equilibrium

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

production rate

destruction rate (escape)

destruction rate (spallation)

effective "destruction" time —>

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

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

Grammage

it is customary to use the **grammage** instead of the escape time

the grammage has units of g/cm^2 and represents the amount of interstellar mass crossed by CRs before escaping the system

Grammage

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

$$X_{ISM} = m_p n_H^{ISM} v \tau_{ISM}$$

we assume an ISM made of H only

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

$$X_{ISM} = m_p n_H^{ISM} v \tau_{ISM}$$

we assume an ISM made of H only

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

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

The B/C ratio

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

The B/C ratio

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

$$\frac{n_{\rm B}}{n_{\rm H}^{ISM} v} \left(\frac{1}{\tau_{ISM}} + \frac{1}{\tau_{\rm B}} \right) \approx n_{\rm C} \left(\sigma_{\rm C\to B} + \sigma_{\rm O\to B} \right)$$

The B/C ratio

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

$$\frac{n_{\mathrm{B}}}{n_{\mathrm{H}}^{ISM} v} \left(\frac{1}{\tau_{ISM}} + \frac{1}{\tau_{\mathrm{B}}} \right) \approx n_{\mathrm{C}} \left(\sigma_{\mathrm{C}\to\mathrm{B}} + \sigma_{\mathrm{O}\to\mathrm{B}}\right)$$

$$n_{\mathrm{B}} \left(\frac{1}{\mathrm{X}_{ISM}} + \frac{1}{\mathrm{X}_{\mathrm{B}}} \right) \approx n_{\mathrm{C}} \frac{\sigma_{\mathrm{C}\to\mathrm{B}} + \sigma_{\mathrm{O}\to\mathrm{B}}}{m_p}$$

The B/C ratio

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

$$\frac{n_{\rm B}}{n_{\rm H}^{ISM} v} \left(\frac{1}{\tau_{ISM}} + \frac{1}{\tau_{\rm B}} \right) \approx n_{\rm C} \left(\sigma_{\rm C \to B} + \sigma_{\rm O \to B}\right)$$

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

B/C ratio —>

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

The B/C ratio

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

$$\frac{n_{\rm B}}{n_{\rm H}^{ISM} v} \left(\frac{1}{\tau_{ISM}} + \frac{1}{\tau_{\rm B}} \right) \approx n_{\rm C} \left(\sigma_{\rm C\to B} + \sigma_{\rm O\to B}\right)$$

$$n_{\rm B} \left(\frac{1}{X_{ISM}} + \frac{1}{X_{\rm B}} \right) \approx n_{\rm C} \frac{\sigma_{\rm C\to B} + \sigma_{\rm O\to B}}{}$$

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

B/C ratio —>

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

The B/C ratio: avoid this mistake!

$$\frac{n_{\mathrm{B}}}{n_{\mathrm{C}}} \approx \frac{\mathrm{X}_{ISM}}{1+\frac{\mathrm{X}_{ISM}}{\mathrm{X}_{\mathrm{B}}}} \frac{\sigma_{\mathrm{C}\to\mathrm{B}}+\sigma_{\mathrm{O}\to\mathrm{B}}}{m_p}$$

The B/C ratio: avoid this mistake!

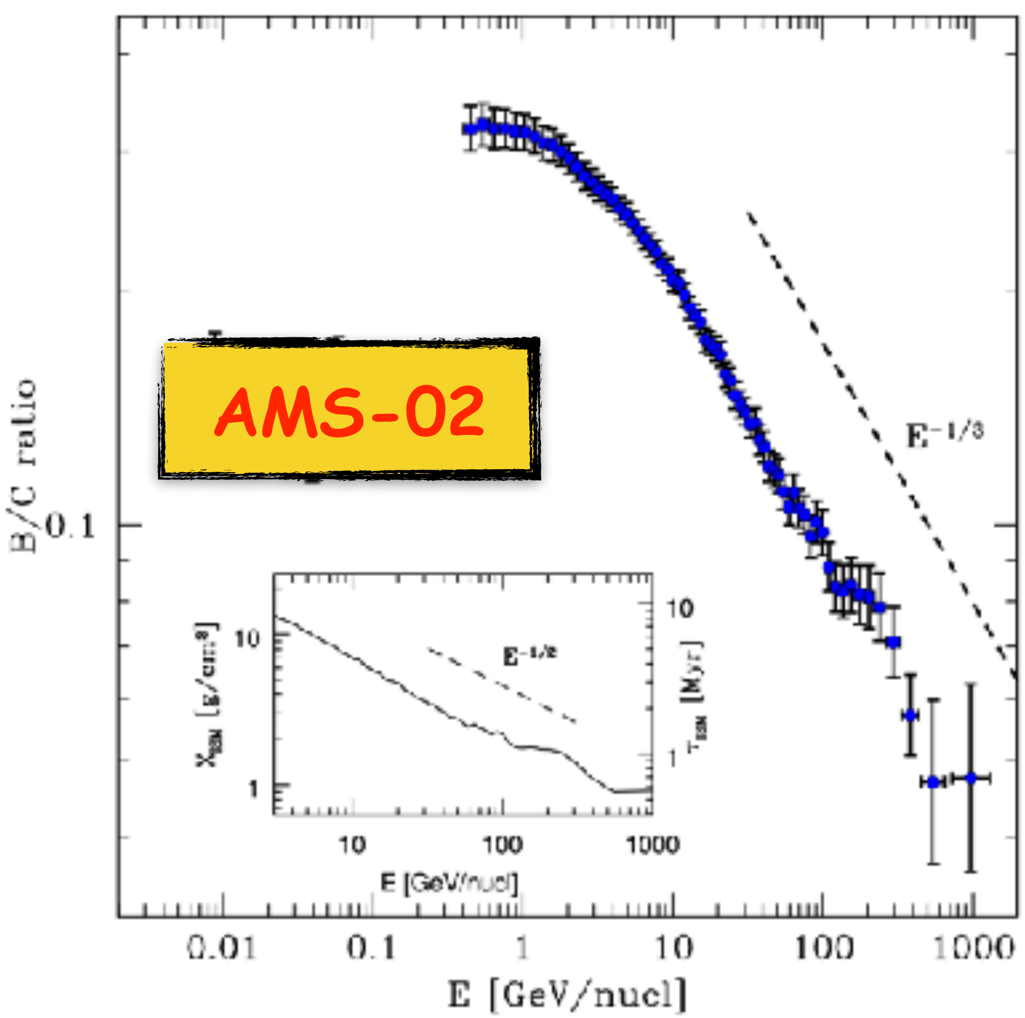
$$\frac{n_{\mathrm{B}}}{n_{\mathrm{C}}} \approx \frac{X_{ISM}}{1 + \frac{X_{ISM}}{X_{\mathrm{B}}}} \frac{\sigma_{\mathrm{C}\to\mathrm{B}} + \sigma_{\mathrm{O}\to\mathrm{B}}}{m_p}$$

$$X_{\mathrm{B}} \gg X_{ISM} \longrightarrow \frac{n_{\mathrm{B}}(E)}{n_{\mathrm{C}}(E)} \propto X_{ISM}(E) \propto \tau_{ISM}(E)$$

The B/C ratio: avoid this mistake!

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

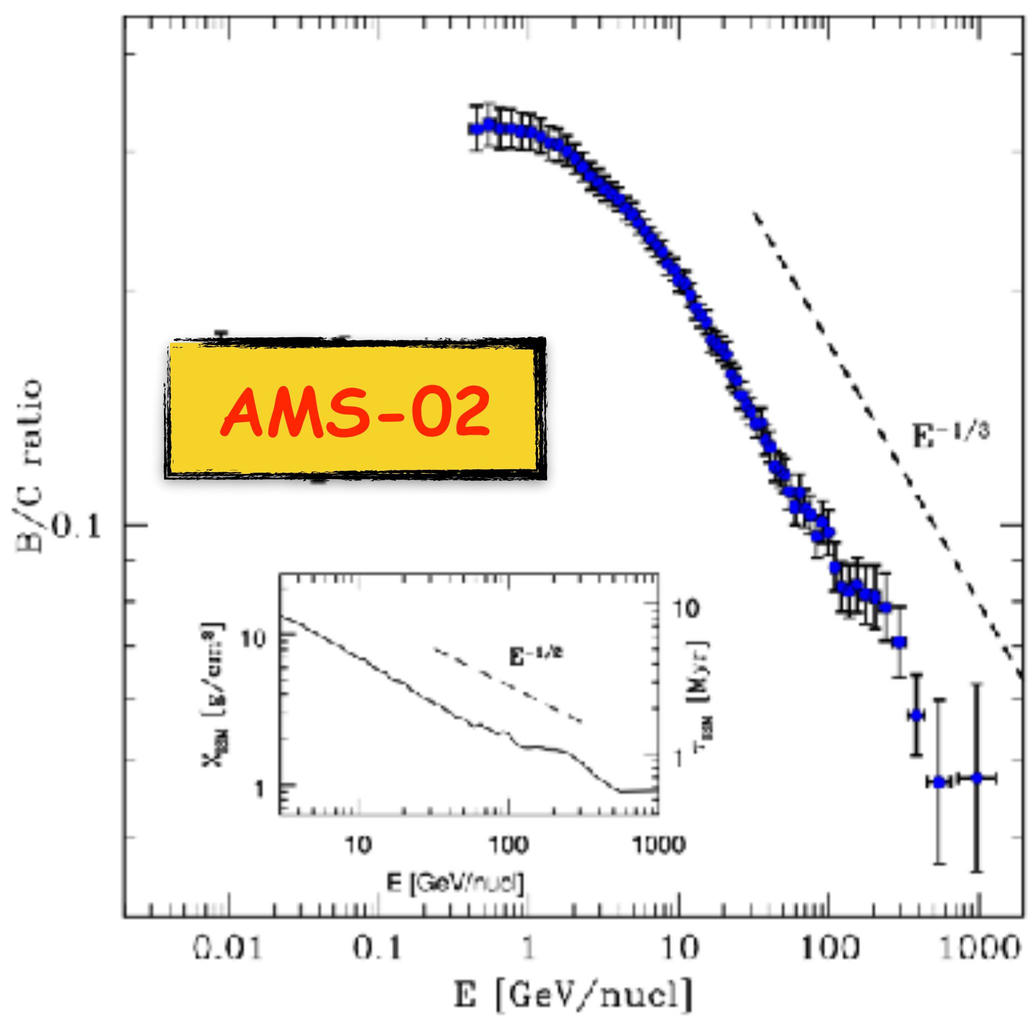
$$X_{\rm B} \gg X_{ISM} \longrightarrow \frac{n_{\rm B}(E)}{n_{\rm C}(E)} \propto X_{ISM}(E) \propto \tau_{ISM}(E)$$



The B/C ratio: avoid this mistake!

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

$$X_{\rm B} \gg X_{ISM} \longrightarrow \frac{n_{\rm B}(E)}{n_{\rm C}(E)} \propto X_{ISM}(E) \propto \tau_{ISM}(E)$$

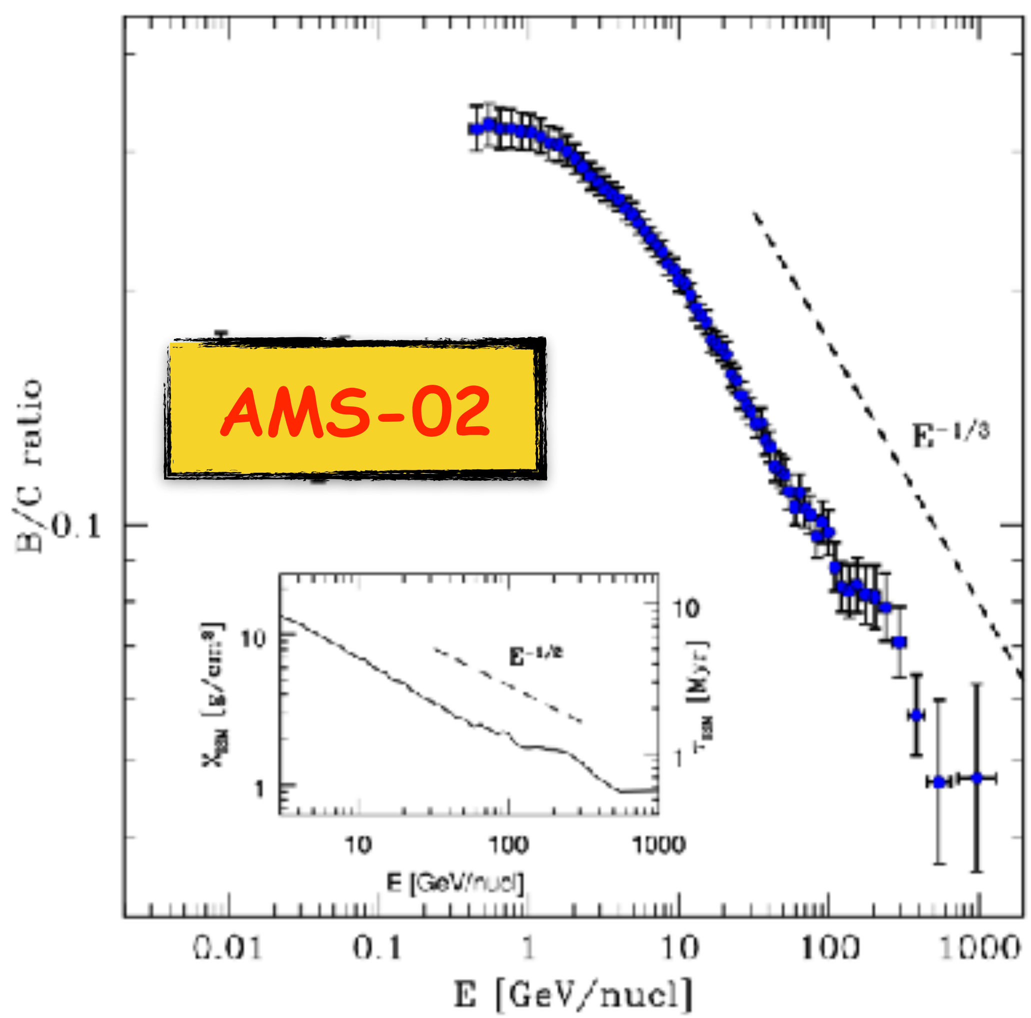


$$\tau_{ISM}(E) \propto E^{-1/3}$$

The B/C ratio: avoid this mistake!

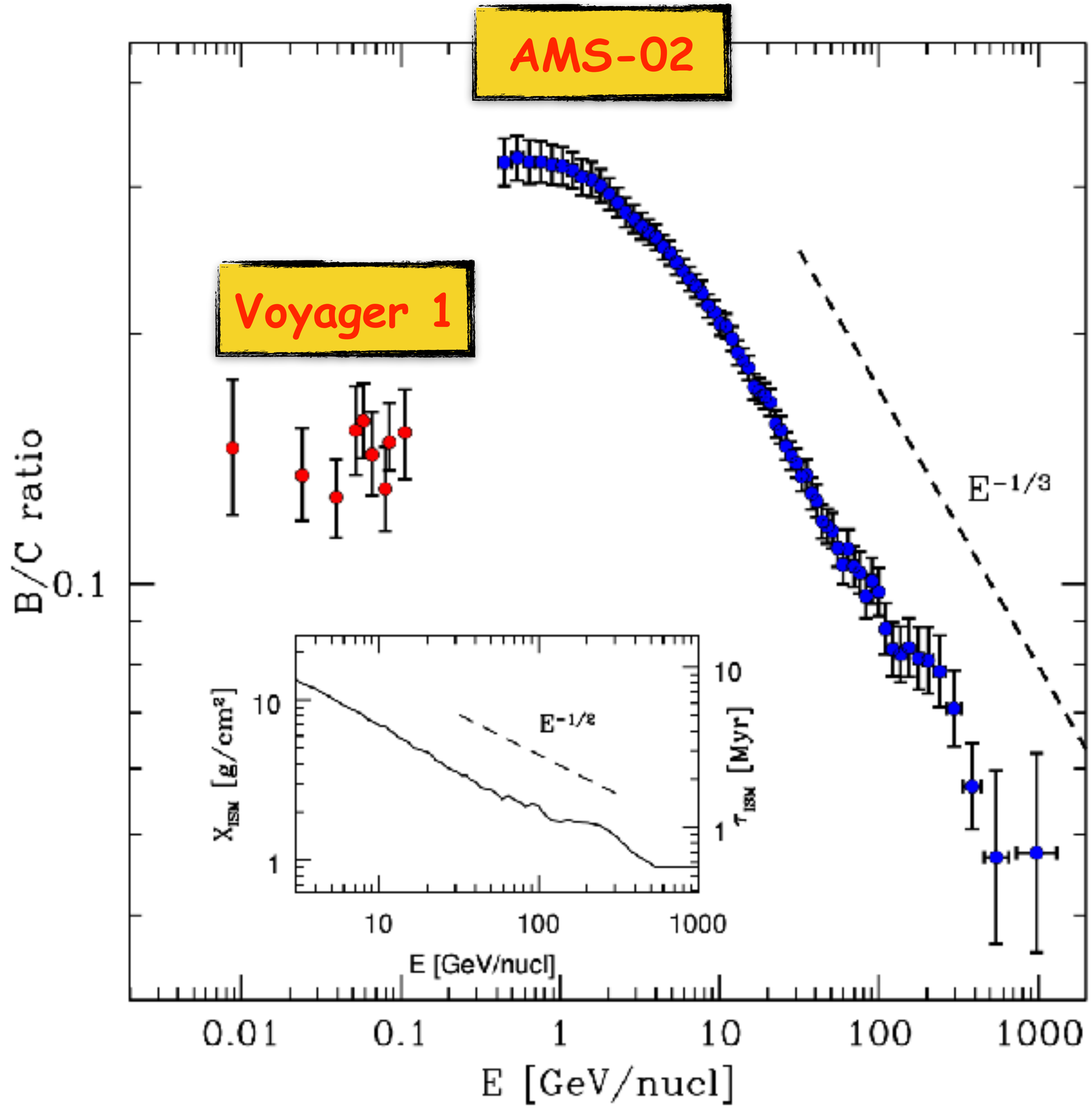
$$\frac{n_{\rm B}}{n_{\rm C}} \approx \frac{X_{ISM}}{1+\frac{X_{ISM}}{X_{\rm B}}} \frac{\sigma_{\rm C\to B}+\sigma_{\rm O\to B}}{m_p}$$

$$X_{\rm B} \gg X_{ISM} \longrightarrow \frac{n_{\rm B}(E)}{n_{\rm C}(E)} \propto X_{ISM}(E) \propto \tau_{ISM}(E)$$



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

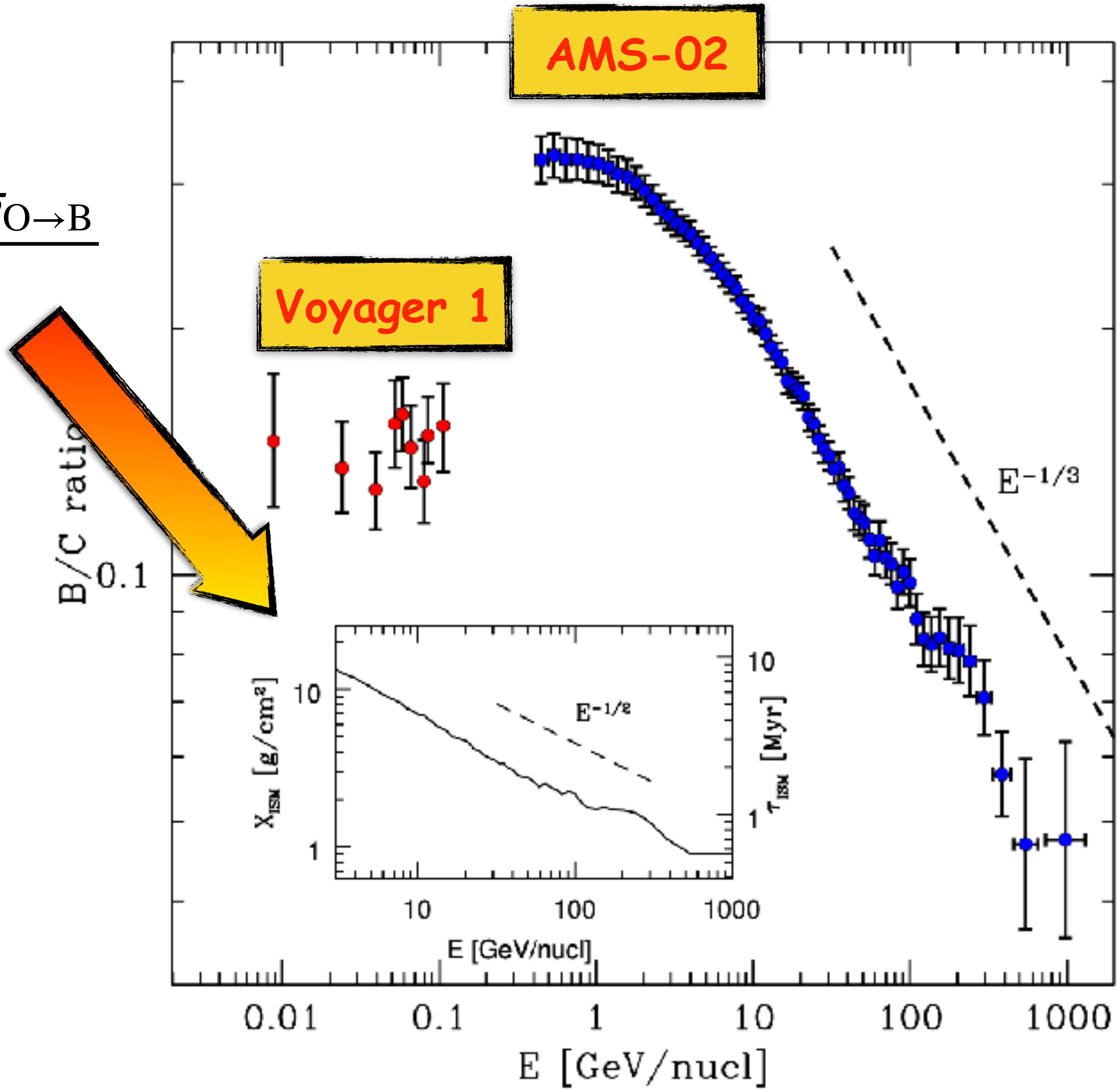
The B/C ratio



Gabici 2022

The B/C ratio

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

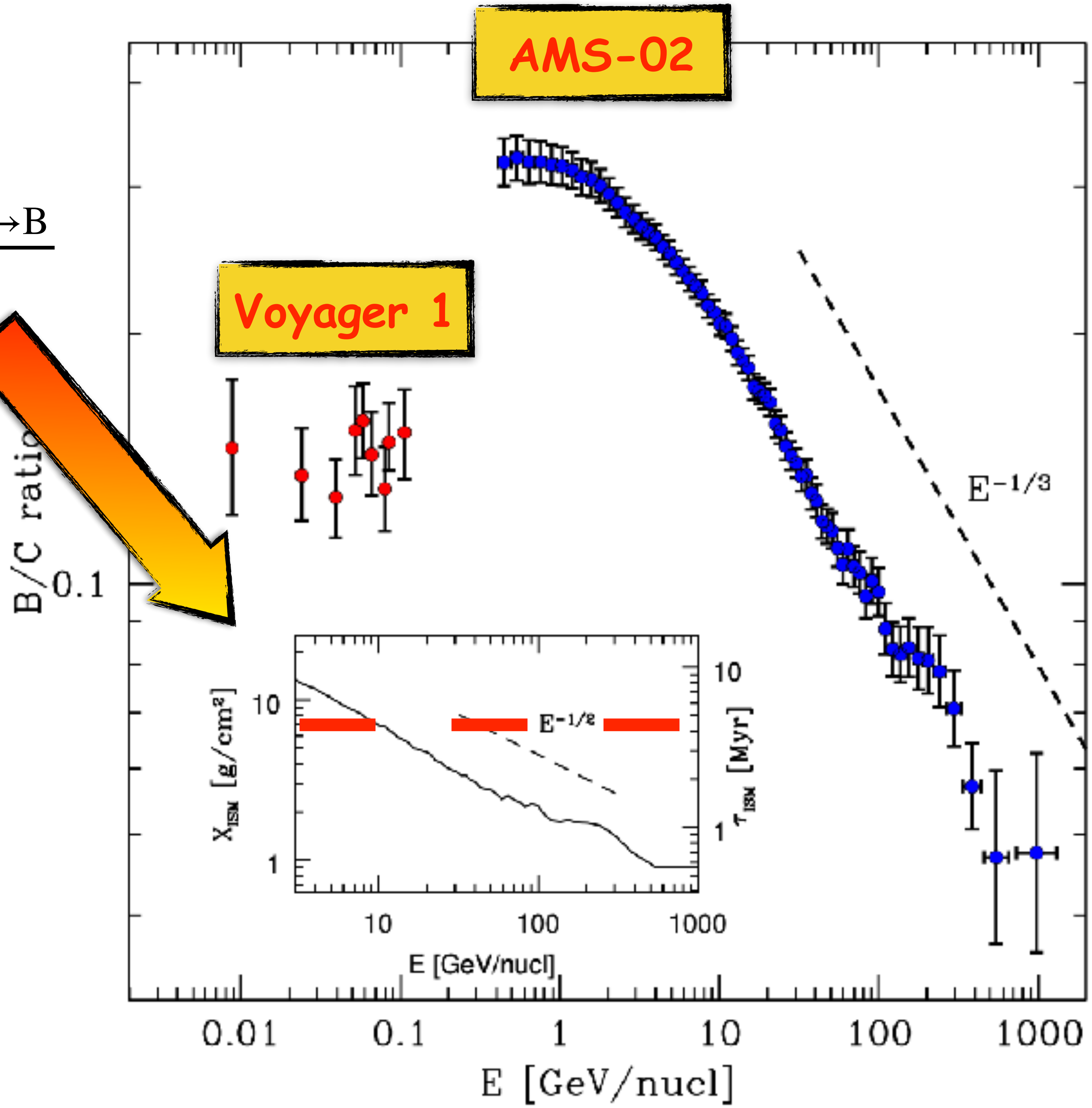


Gabici 2022

The B/C ratio

$$\frac{n_B}{n_C} \approx \frac{X_{ISM}}{1 + \frac{X_{ISM}}{X_B}} \frac{\sigma_{C\to B} + \sigma_{O\to B}}{m_p}$$

$X_B \sim 7 \text{ g/cm}^2$

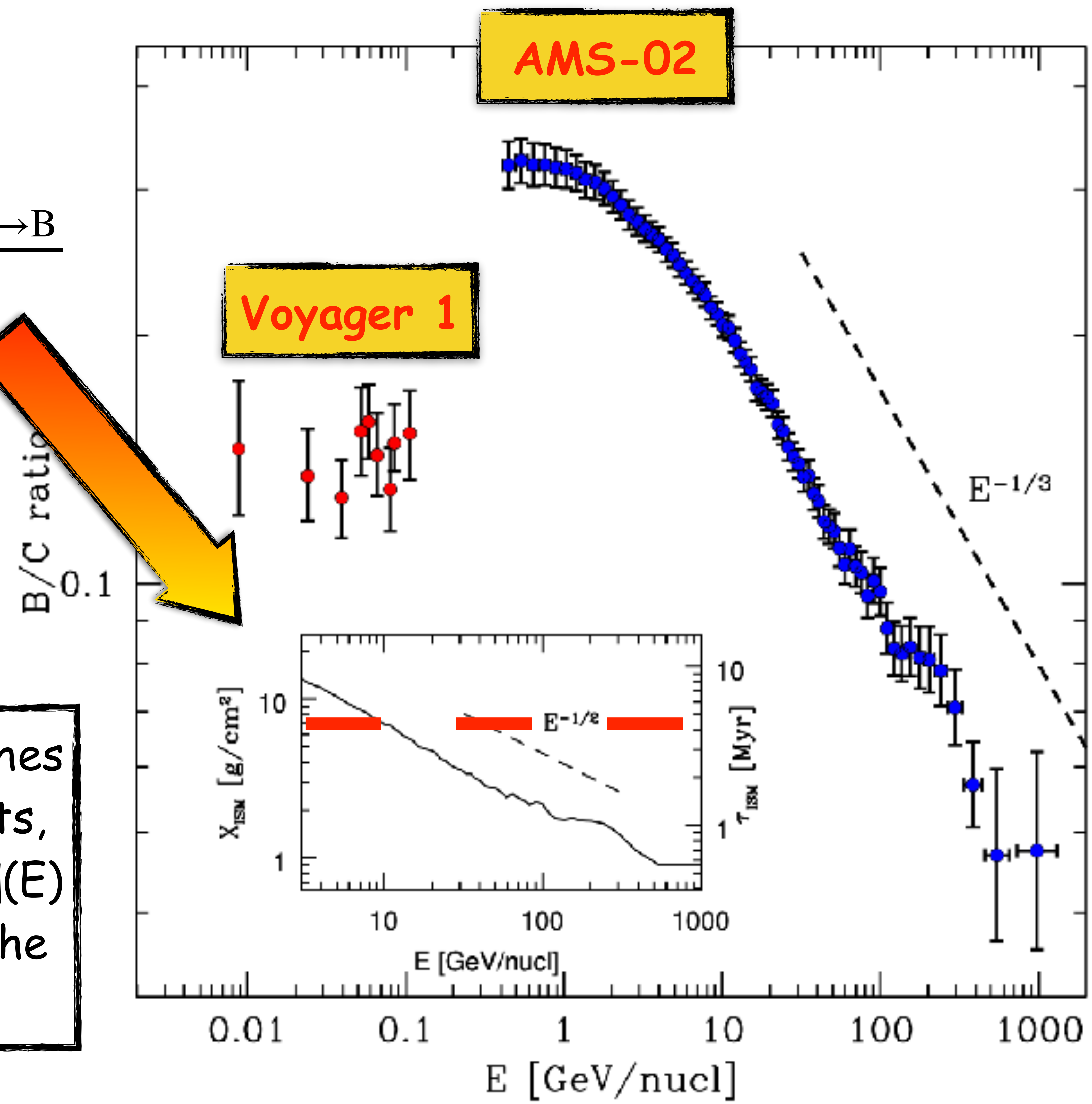


Gabici 2022

The B/C ratio

$$\frac{n_B}{n_C} \approx \frac{X_{ISM}}{1+\frac{X_{ISM}}{X_B}} \frac{\sigma_{C\to B}+\sigma_{O\to B}}{m_p}$$

$$X_B \sim 7 \ \mathrm{g/cm^2}$$



Gabici 2022

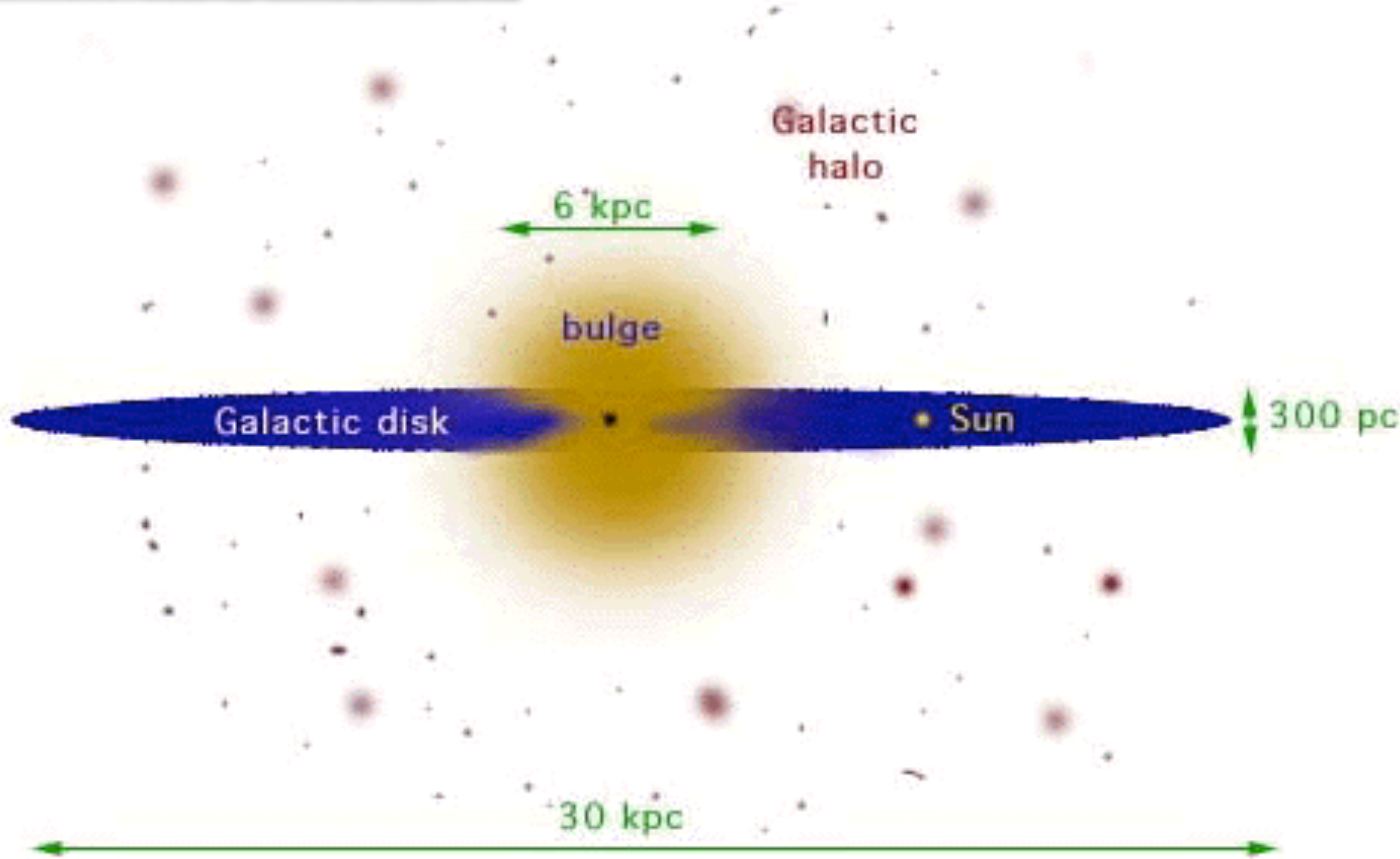
more sophisticated approaches exist and give similar results, just keep in mind that [B/C](E) and X_{ISM}(E) do NOT have the same slope!

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)

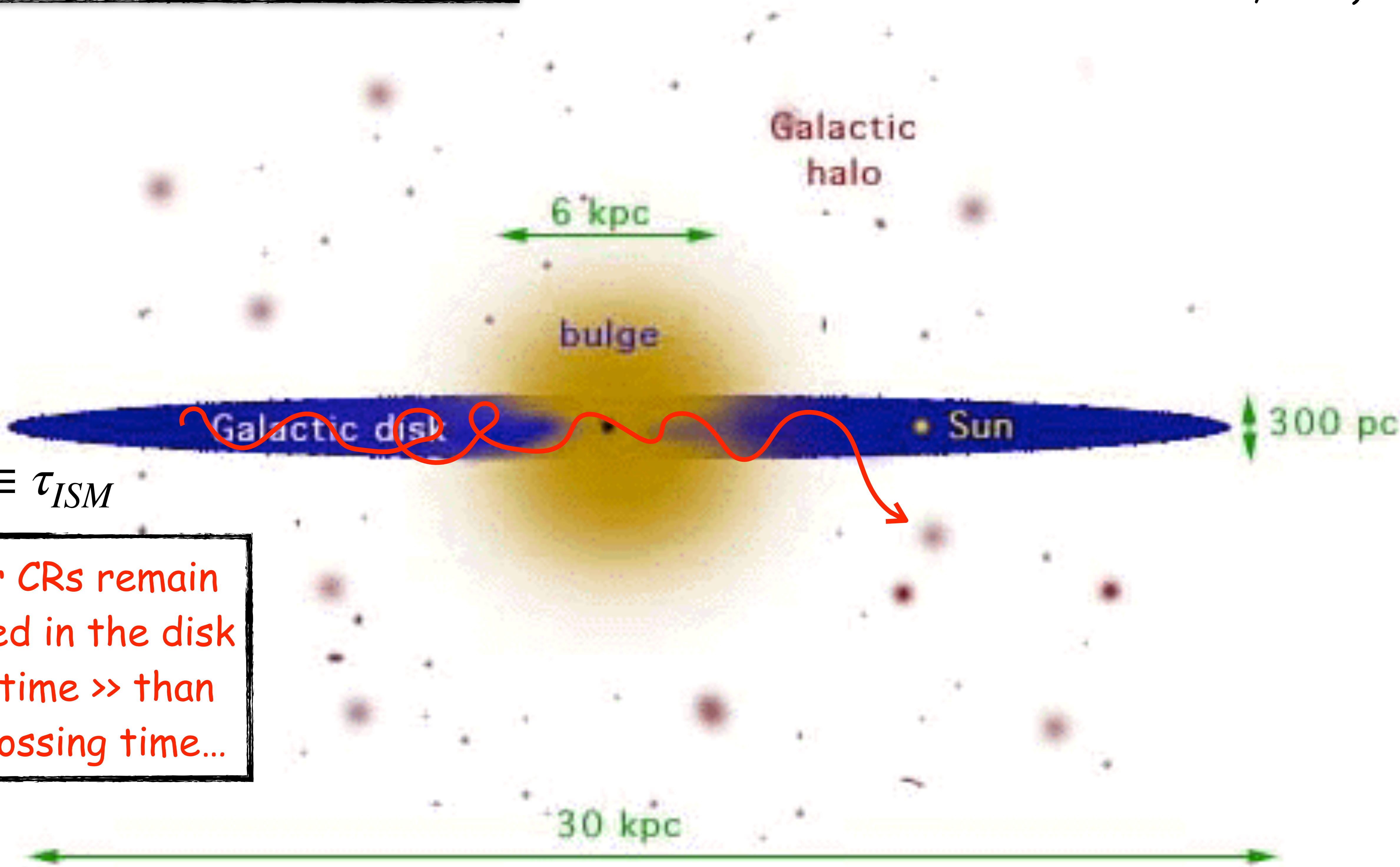


Escape time or residence time?

surface density of the disk —>

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

(see review by Ferriere, 2001)



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

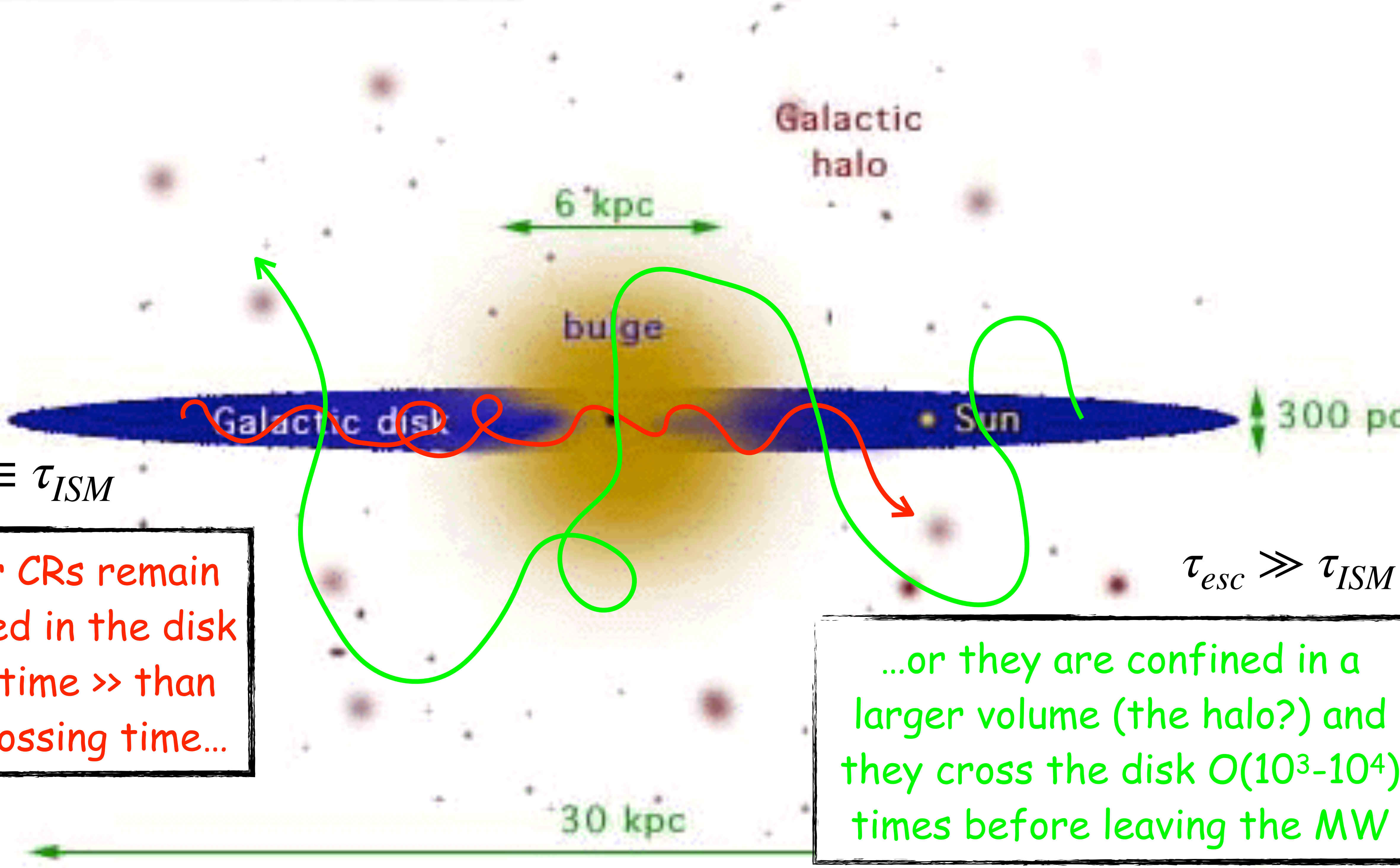
either CRs remain confined in the disk for a time >> than the crossing time...

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)



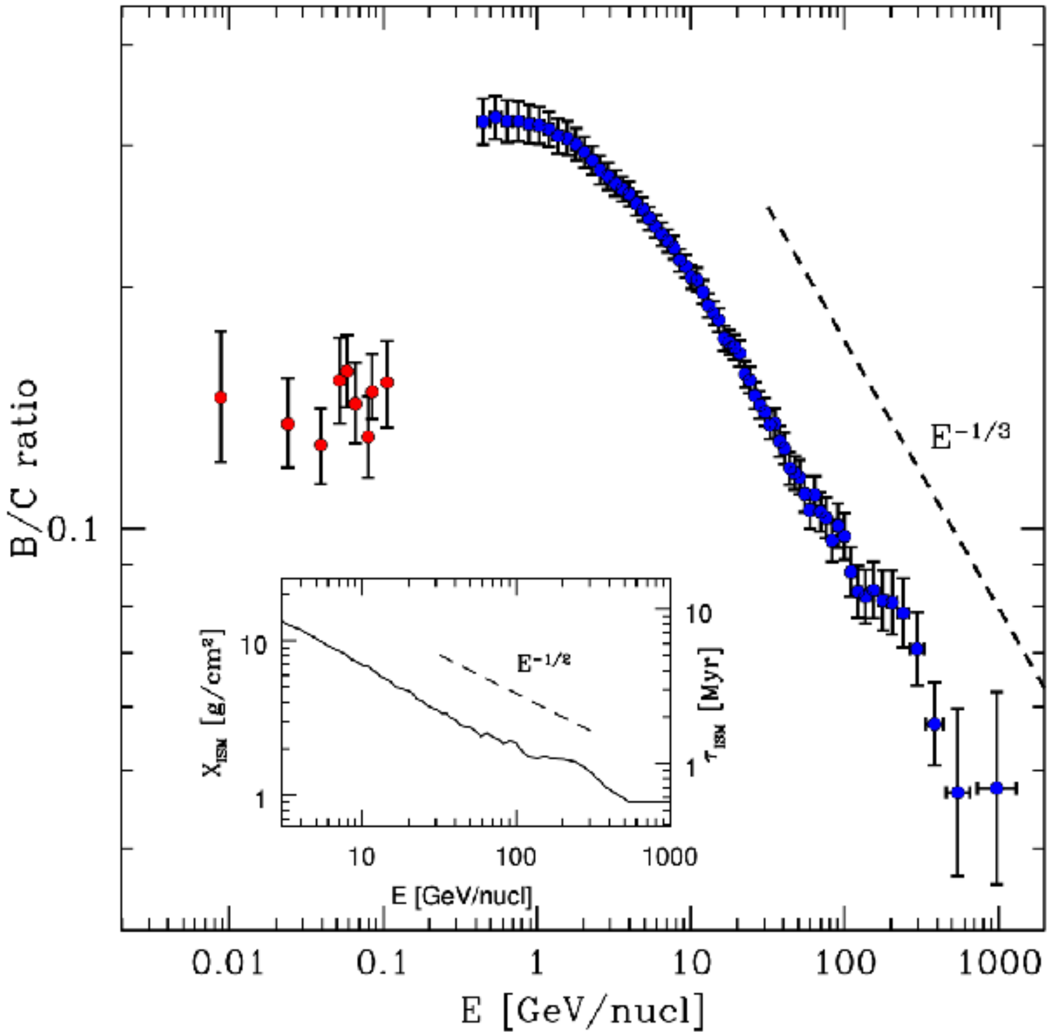
$\tau_{esc} \equiv \tau_{ISM}$

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

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

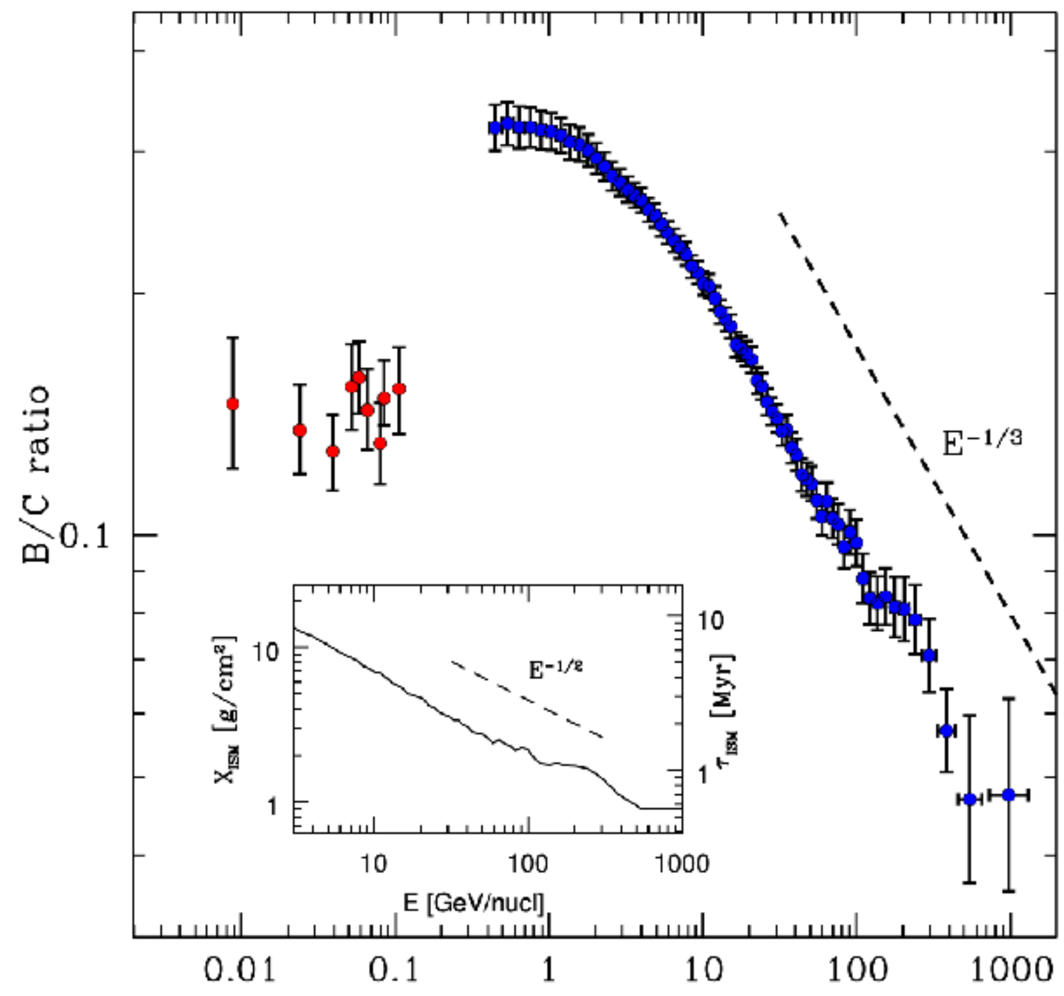
…or they are confined in a larger volume (the halo?) and they cross the disk $O(10^3$-$10^4)$ times before leaving the MW

Escape time or residence time?



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

Escape time or residence time?



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

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

Short lived radionuclides: ^{10}Be

short-lived radionuclides of lifetime τ_{rad} are produced in the spallation of CRs by interstellar matter

Short lived radionuclides: ^{10}Be

short-lived radionuclides of lifetime τ_{rad} are produced in the spallation of CRs by interstellar matter

$$E \sim 10 \text{ GeV/n} \longrightarrow \mathrm{X}_{ISM} \approx 7 \text{ g/cm}^2 \longrightarrow \tau_{ISM} \approx 4 \text{ Myr}$$

Short lived radionuclides: ^{10}Be

short-lived radionuclides of lifetime τ_{rad} are produced in the spallation of CRs by interstellar matter

$$E \sim 10 \text{ GeV/n} \longrightarrow \mathrm{X}_{ISM} \approx 7 \text{ g/cm}^2 \longrightarrow \tau_{ISM} \approx 4 \text{ Myr}$$

$\tau_{rad} \gg \tau_{esc}$ —> the radioactive nuclide behaves as stable isotopes

Short lived radionuclides: ^{10}Be

short-lived radionuclides of lifetime τ_{rad} are produced in the spallation of CRs by interstellar matter

$$E \sim 10 \text{ GeV/n} \longrightarrow \mathrm{X}_{ISM} \approx 7 \text{ g/cm}^2 \longrightarrow \tau_{ISM} \approx 4 \text{ Myr}$$

$\tau_{rad} \gg \tau_{esc}$ —> the radioactive nuclide behaves as stable isotopes

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

Short lived radionuclides: ^{10}Be

short-lived radionuclides of lifetime τ_{rad} are produced in the spallation of CRs by interstellar matter

$$E \sim 10 \text{ GeV/n} \longrightarrow \mathrm{X}_{ISM} \approx 7 \text{ g/cm}^2 \longrightarrow \tau_{ISM} \approx 4 \text{ Myr}$$

$\tau_{rad} \gg \tau_{esc}$ —> the radioactive nuclide behaves as stable isotopes

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

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

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

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

stable isotope!

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

stable isotope!

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

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

stable isotope!

this can be measured

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

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

stable isotope!

isotopic ratio at production is known (cross sections)

this can be measured

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

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

stable isotope!

isotopic ratio at production is known (cross sections)

this can be measured

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

known

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

stable isotope!

isotopic ratio at production is known (cross sections)

this can be measured

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

known

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

~0.8

this can be measured

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

known

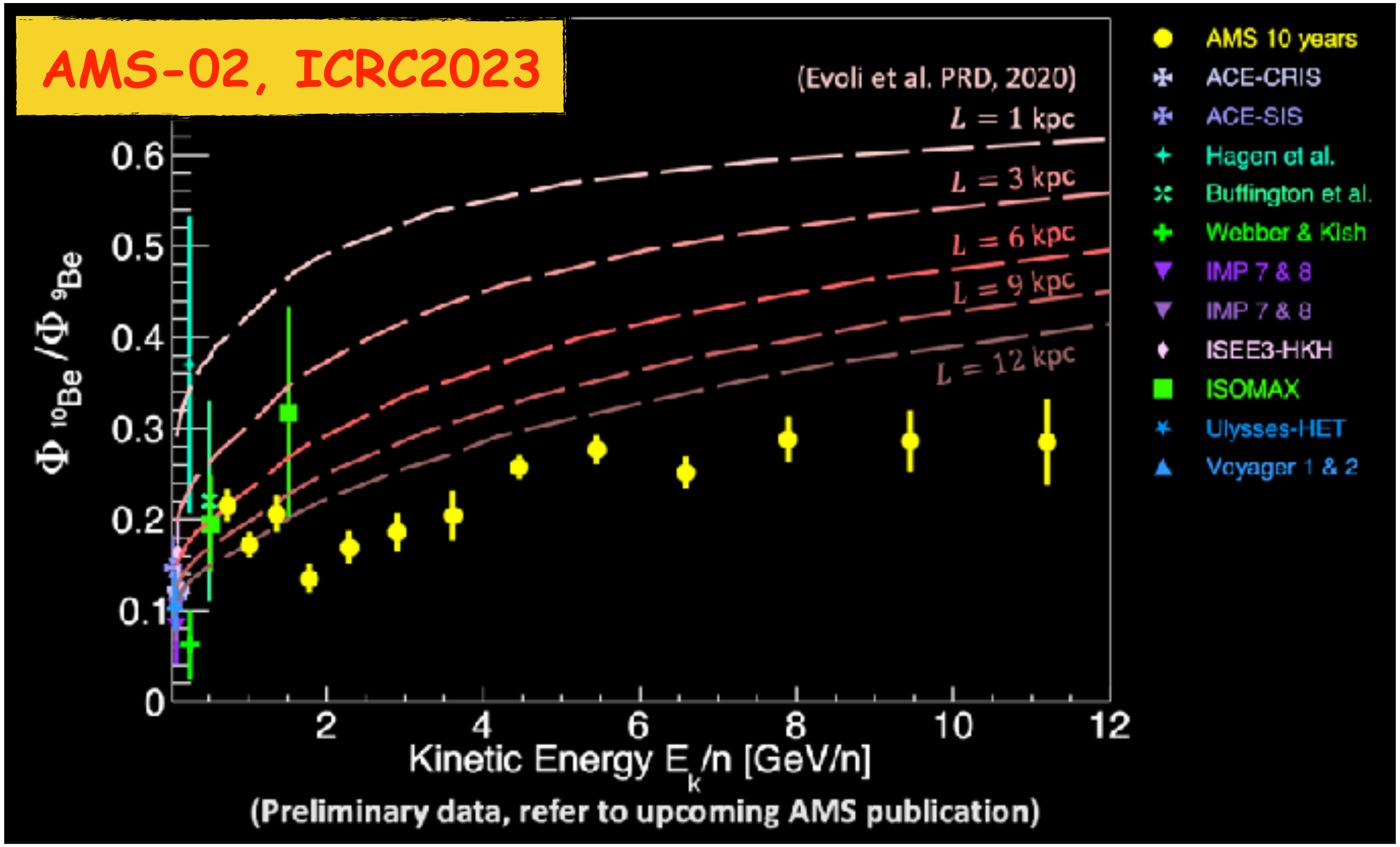
^{10}Be/^{9}Be ratio

~0.8

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

~0.3

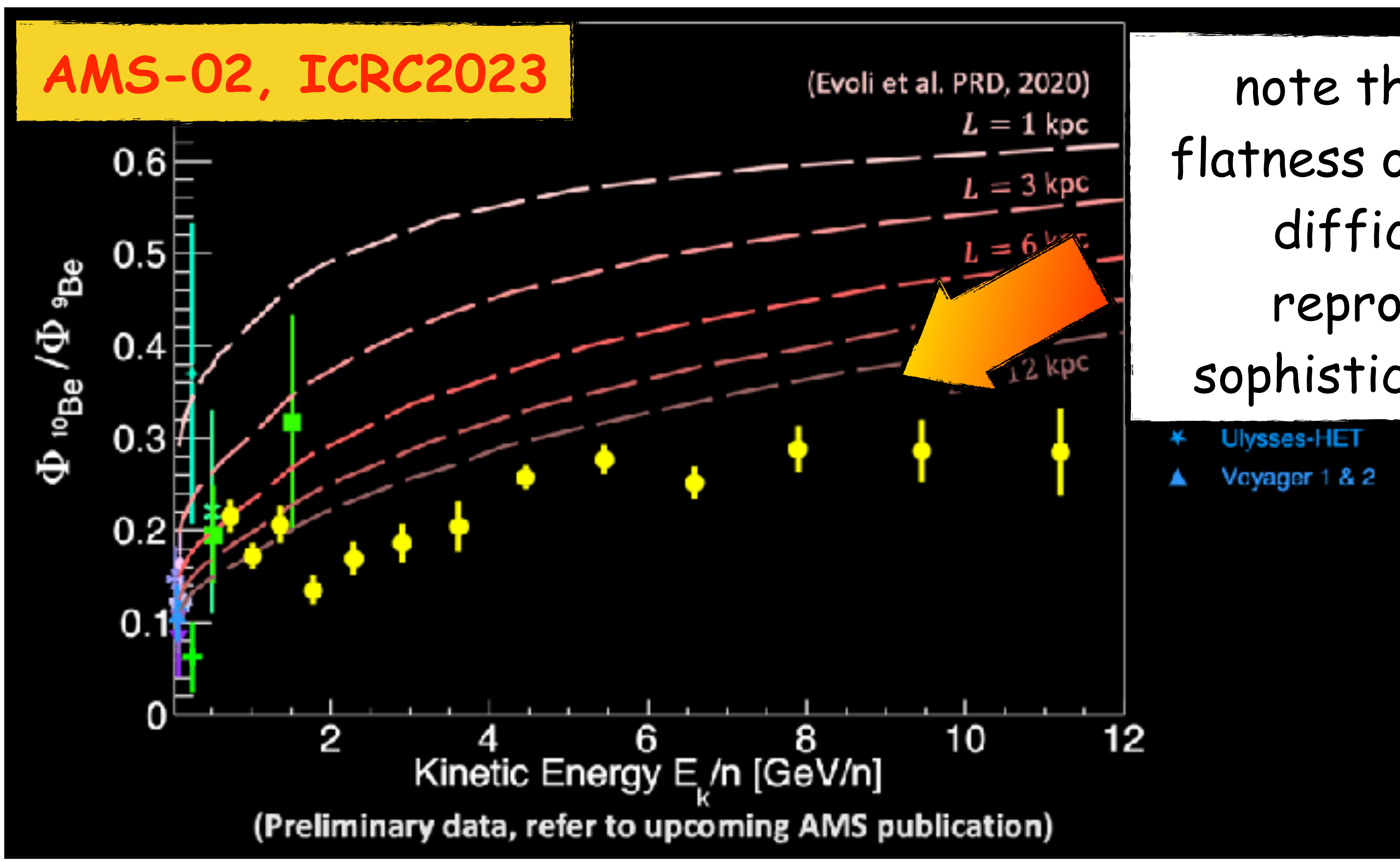
known



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

~0.8

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



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

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

~0.8

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

~0.3

~20 Myr

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

~0.8

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

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

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

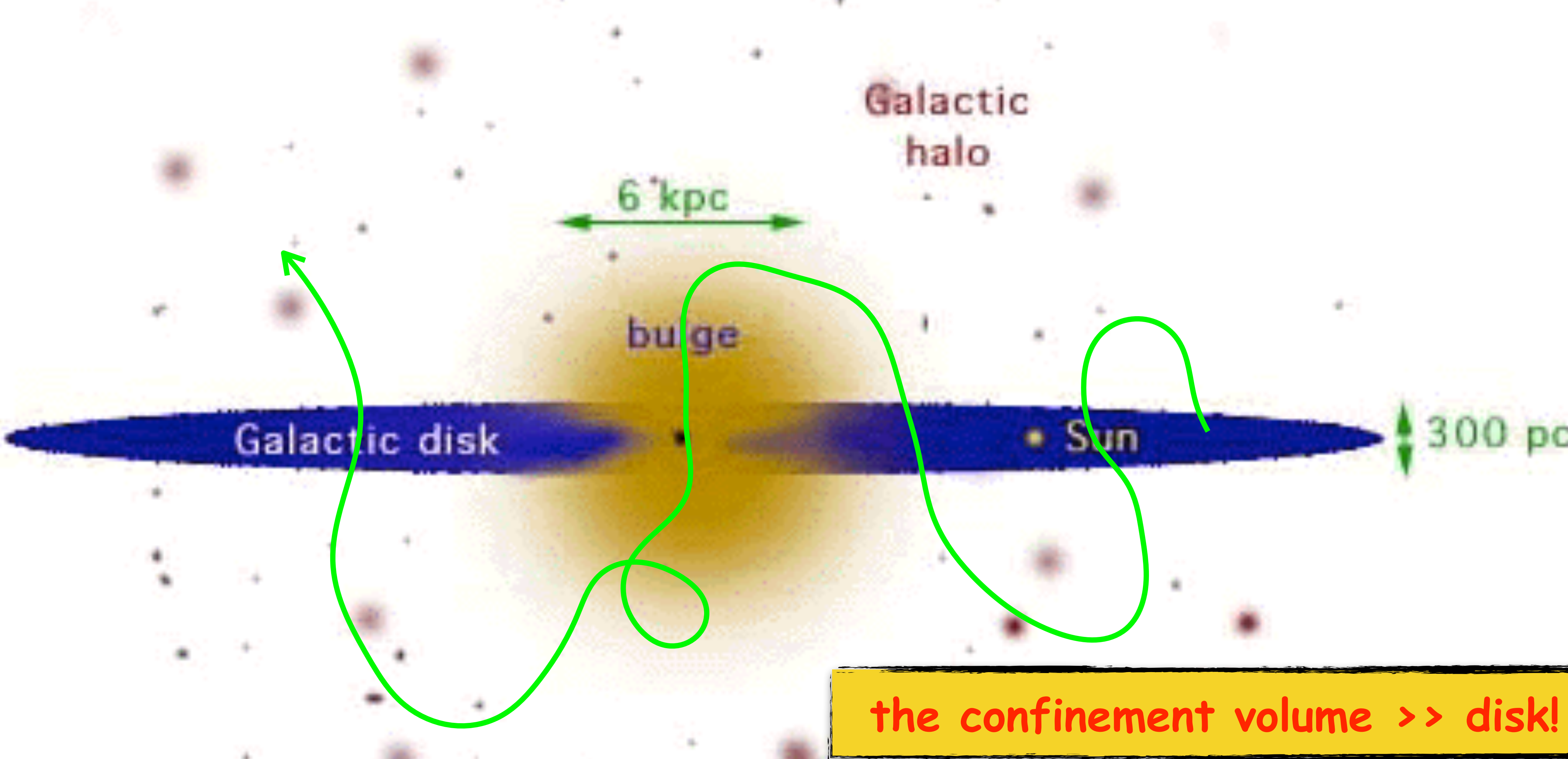
$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \approx \frac{q(^{10}\mathrm{Be})}{q(^{9}\mathrm{Be})} \times \frac{\gamma\tau_{rad}}{\tau_{esc}}$$

~0.3

~0.8

~20 Myr

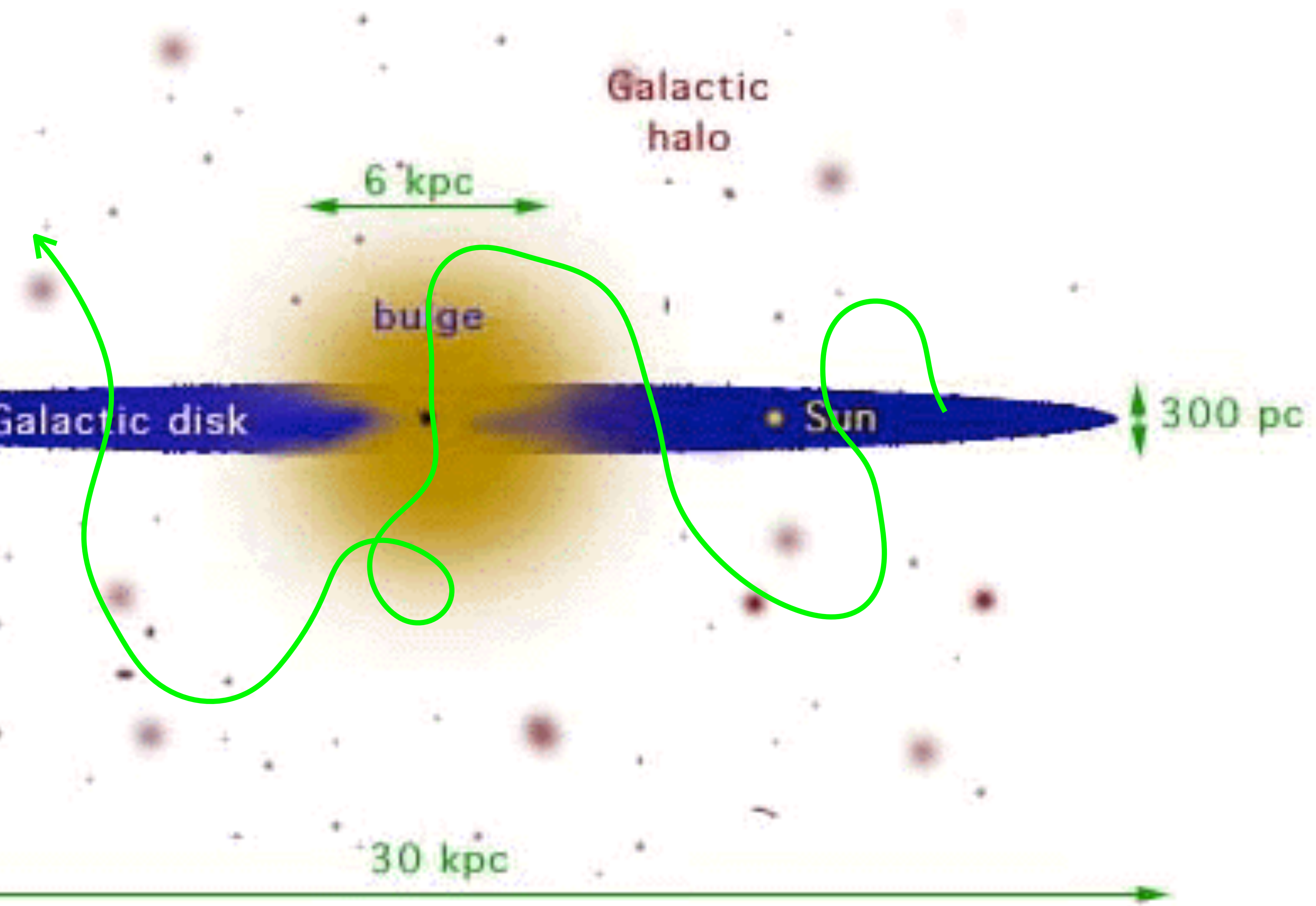
$$10 \text{ GeV/n} \longrightarrow \tau_{esc} \approx 50 \text{ Myr} \gg 4 \text{ Myr} \approx \tau_{ISM}$$



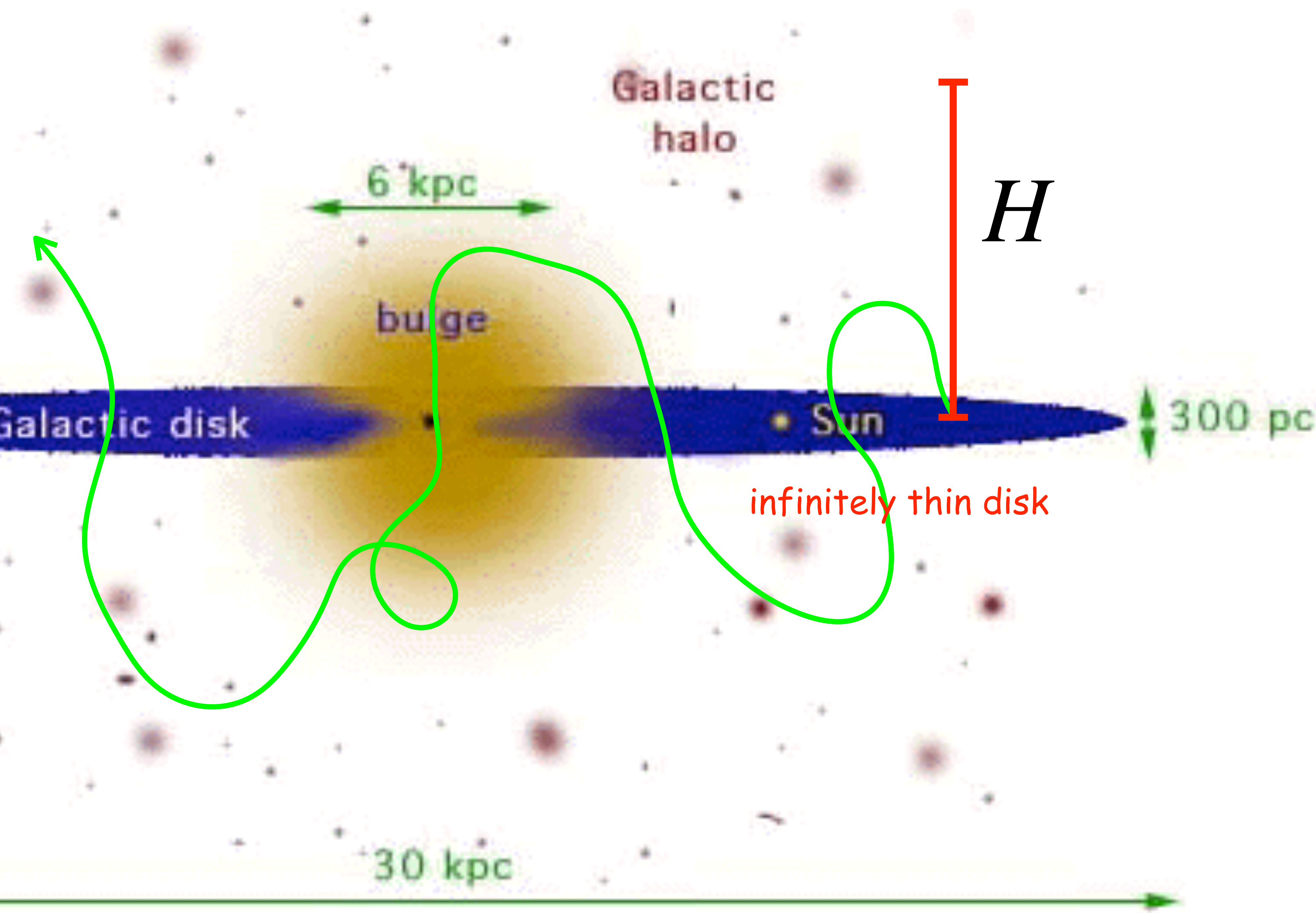
the confinement volume >> disk!

[6] Diffusive models for CR transport

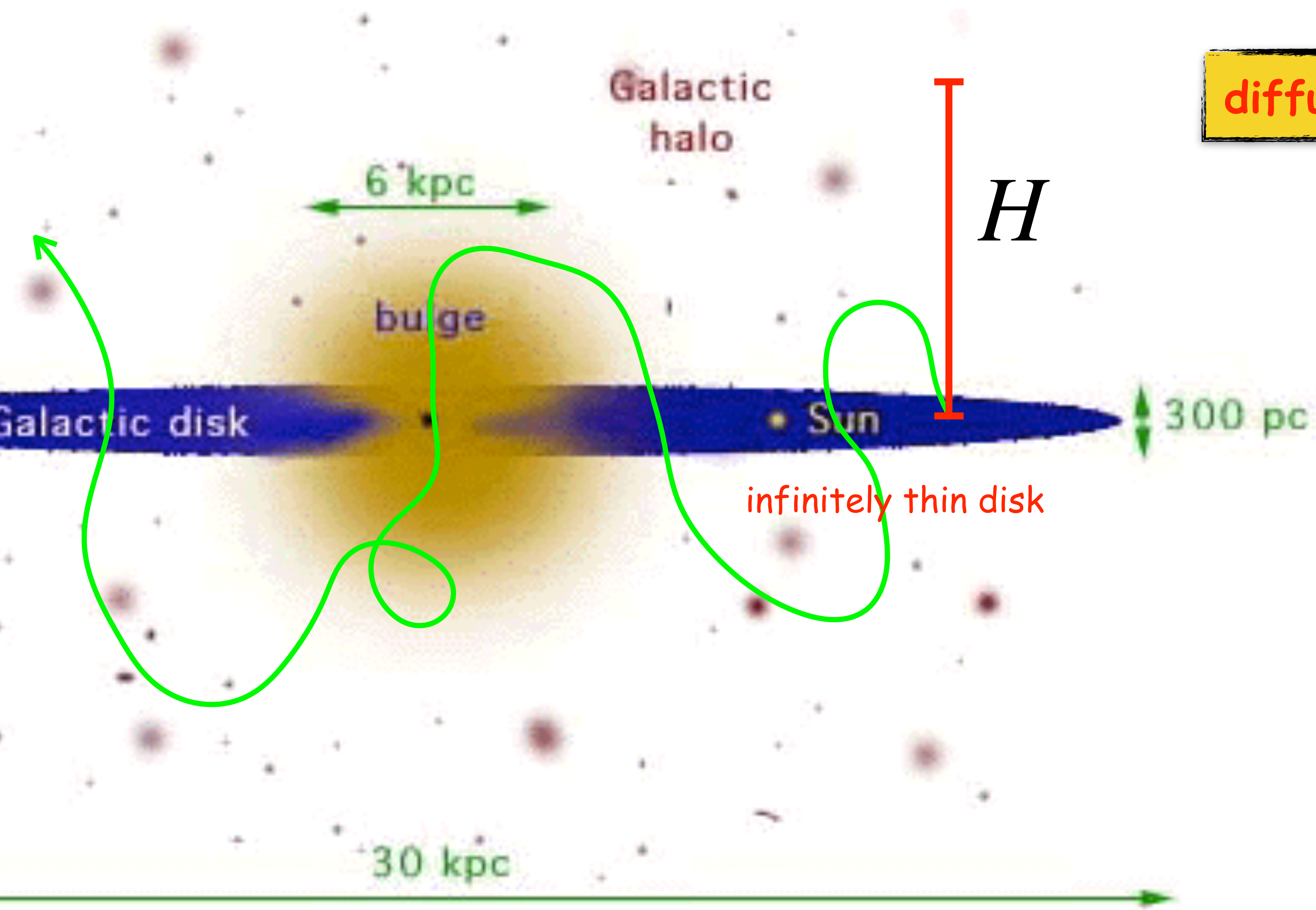
Diffusive models



Diffusive models



Diffusive models



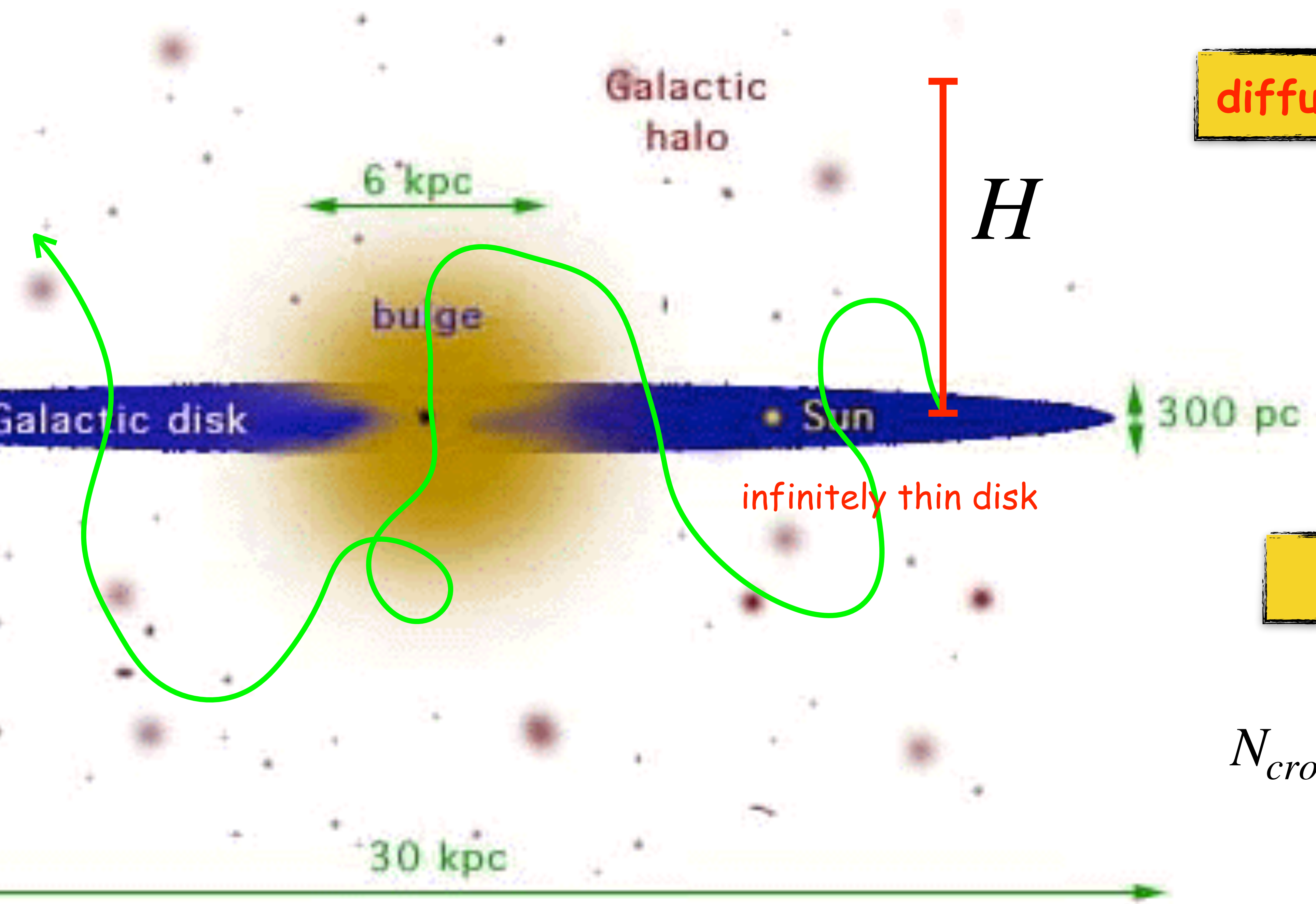
diffusion coefficient

mean free path

$$D \sim \lambda v$$

velocity

Diffusive models



diffusion coefficient

mean free path

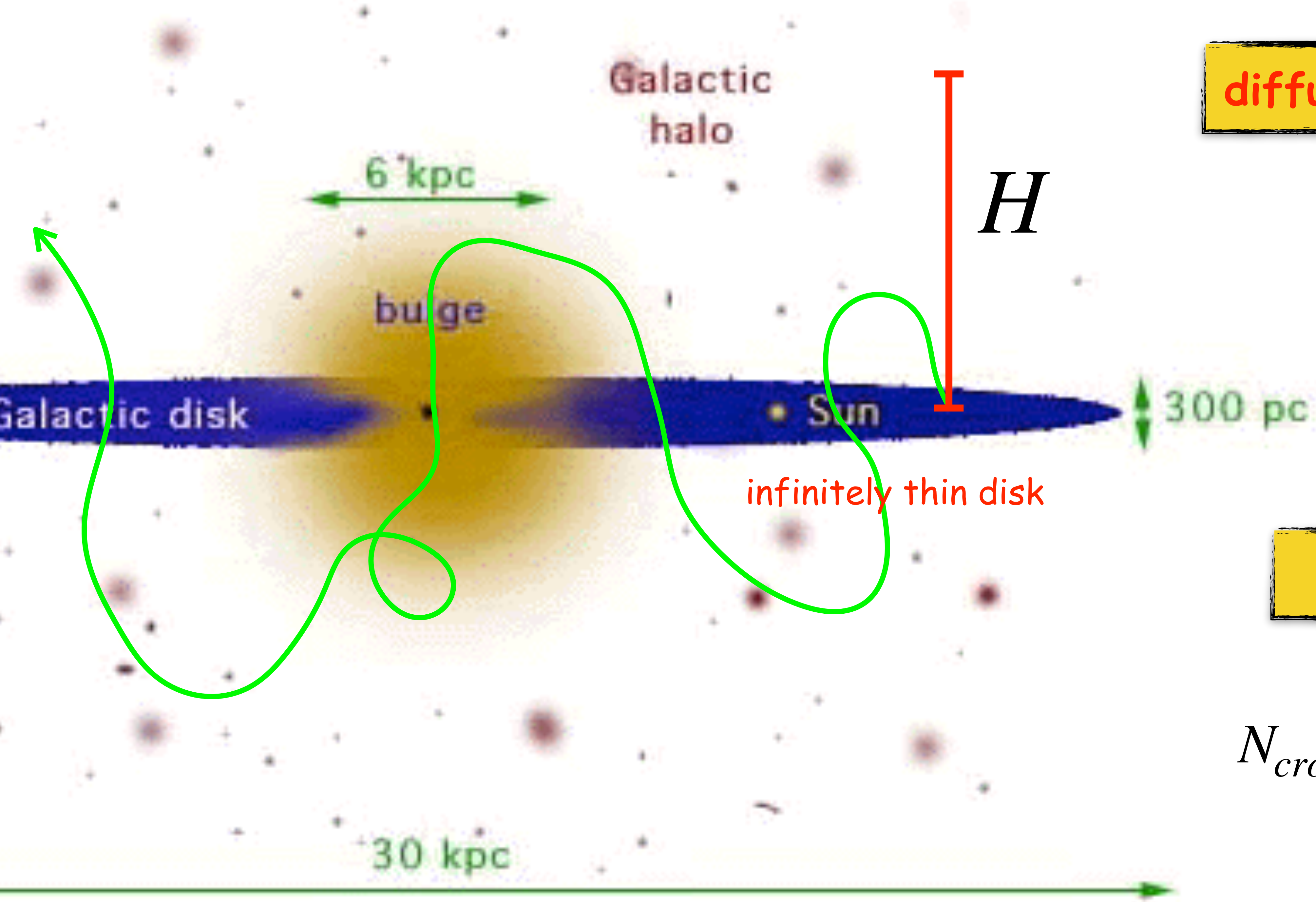
velocity

$$D \sim \lambda v$$

# of crossings

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

Diffusive models



diffusion coefficient

mean free path

velocity

$$D \sim \lambda v$$

# 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

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

Diffusive models

B/C constrains a combination of H and D

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

^{10}Be/^{9}Be constrains τ_{esc}

$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \longrightarrow \tau_{esc} \sim \frac{H^2}{D}$$

Diffusive models

B/C constrains a combination of H and D

$$\frac{n_B}{n_C} \longrightarrow X_{ISM} \propto \frac{H}{D}$$

$^{10}Be/^{9}Be$ constrains τ_{esc}

$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \longrightarrow \tau_{esc} \sim \frac{H^2}{D}$$

0.002 g/cm²

$$X_{ISM} \sim N_{cross} X_{disk} \sim \frac{Hv}{D} X_{disk} \sim \frac{\tau_{esc} v X_{disk}}{H} \longrightarrow H \sim \tau_{esc} v \frac{X_{disk}}{X_{ISM}} \sim 4 \text{ kpc}$$

Diffusive models

B/C constrains a combination of H and D

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

^{10}Be/^{9}Be constrains τ_{esc}

$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \longrightarrow \tau_{esc} \sim \frac{H^2}{D}$$

0.002 g/cm²

$$X_{ISM} \sim N_{cross} X_{disk} \sim \frac{Hv}{D} X_{disk} \sim \frac{\tau_{esc} v X_{disk}}{H} \longrightarrow H \sim \tau_{esc} v \frac{X_{disk}}{X_{ISM}} \sim 4 \text{ kpc}$$

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

Diffusive models

B/C constrains a combination of H and D

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

^{10}Be/^{9}Be constrains τ_{esc}

$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \longrightarrow \tau_{esc} \sim \frac{H^2}{D}$$

0.002 g/cm^2

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

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

Diffusive models

B/C constrains a combination of H and D

$$\frac{n_B}{n_C} \longrightarrow X_{ISM} \propto \frac{H}{D}$$

^{10}Be/^{9}Be constrains τ_{esc}

$$\frac{n(^{10}\mathrm{Be})}{n(^{9}\mathrm{Be})} \longrightarrow \tau_{esc} \sim \frac{H^2}{D}$$

0.002 g/cm^2

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

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

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

^{10}Be: local effects are important

^{10}Be diffuses over a distance $l \sim \sqrt{D\tau_{rad}}$

^{10}Be: local effects are important

^{10}Be diffuses over a distance $l \sim \sqrt{D\tau_{rad}}$

for stable isotopes we have $H \sim \sqrt{D\tau_{esc}}$

^{10}Be: local effects are important

^{10}Be diffuses over a distance

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

for stable isotopes we have

$$H \sim \sqrt{D\tau_{esc}}$$

$$l \sim \sqrt{\frac{\tau_{rad}}{\tau_{esc}}} H \ll H$$

^{10}Be: local effects are important

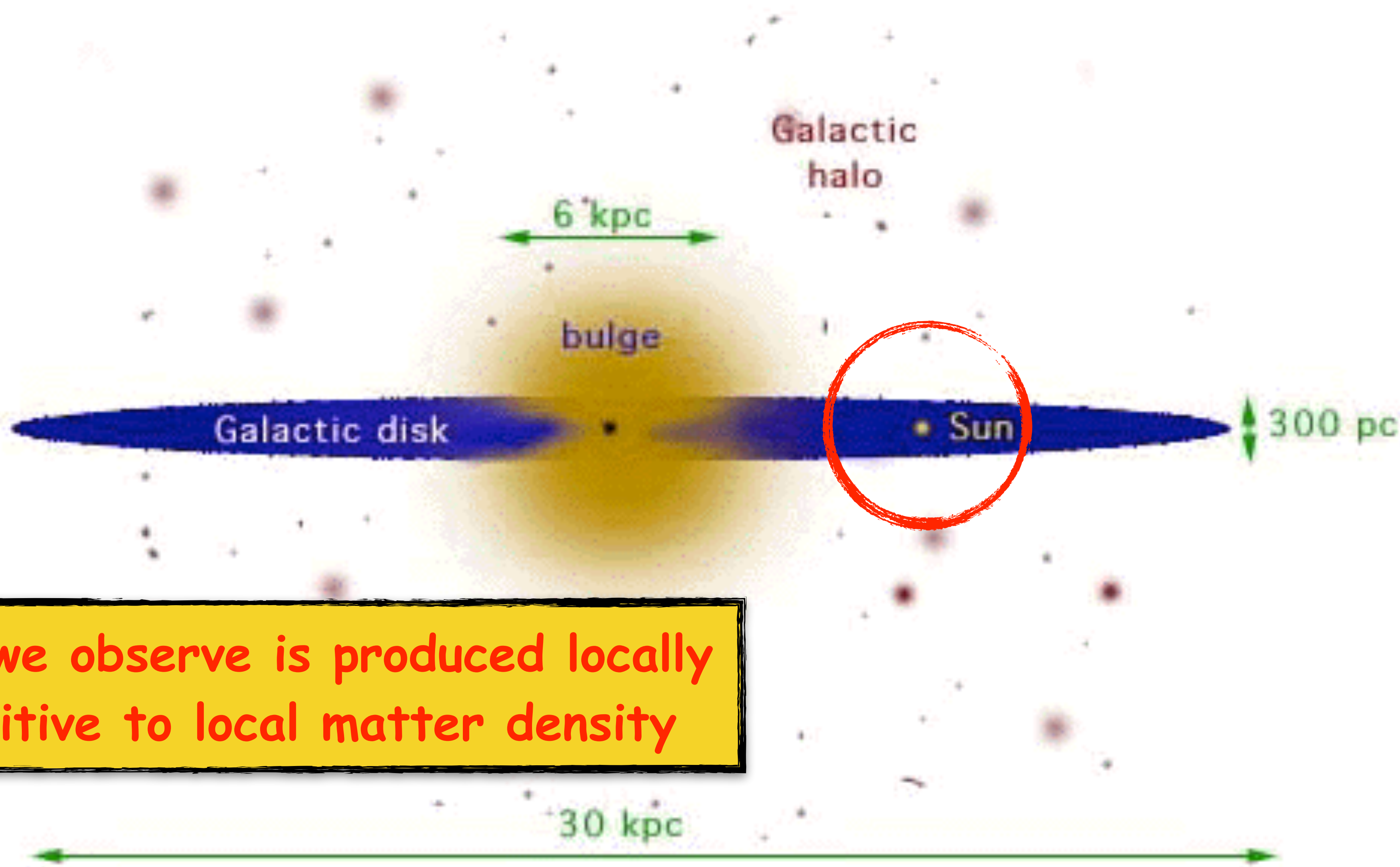
^{10}Be diffuses over a distance

for stable isotopes we have

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

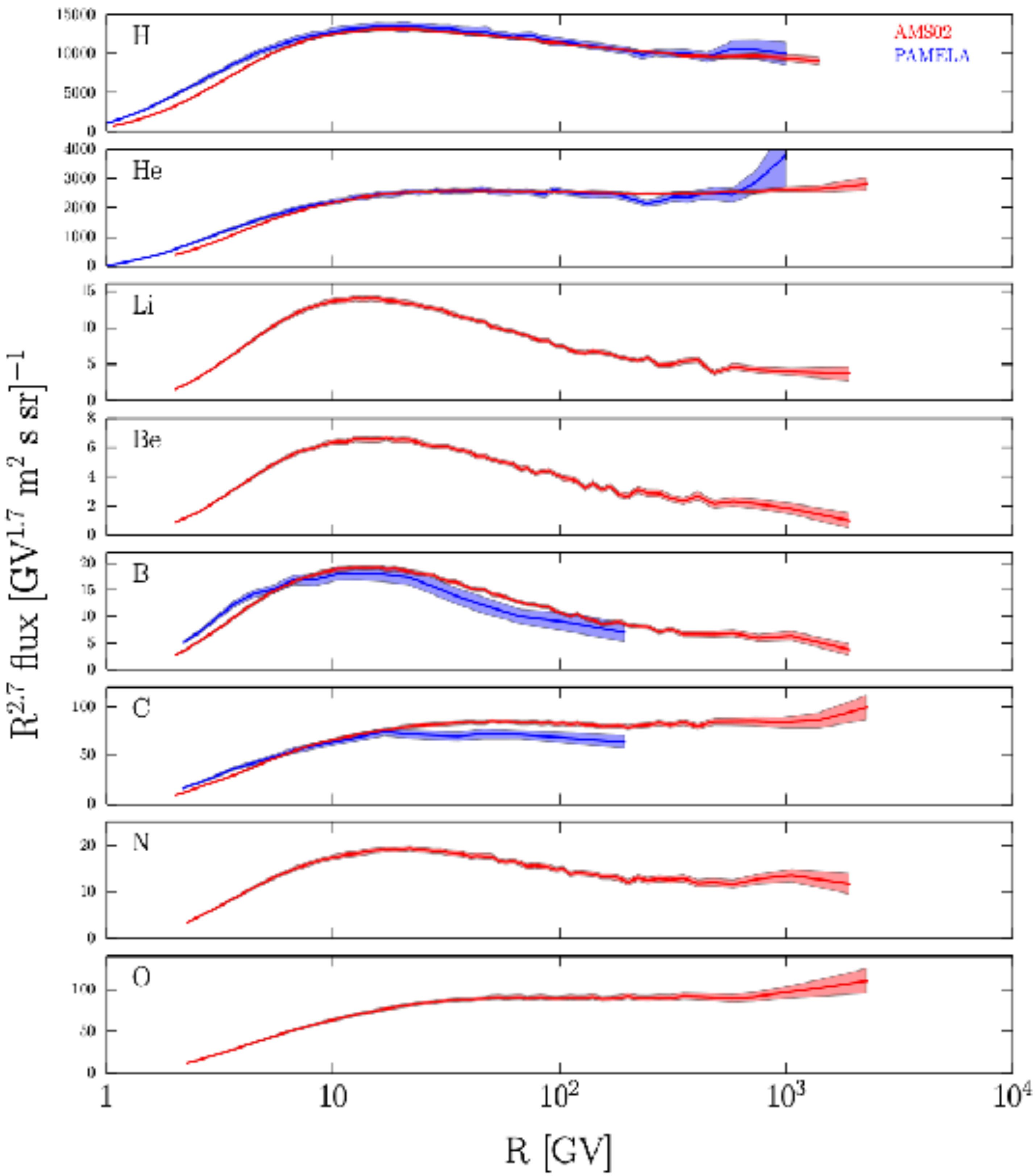
$$H \sim \sqrt{D\tau_{esc}}$$

$$l \sim \sqrt{\frac{\tau_{rad}}{\tau_{esc}}} H \ll H$$

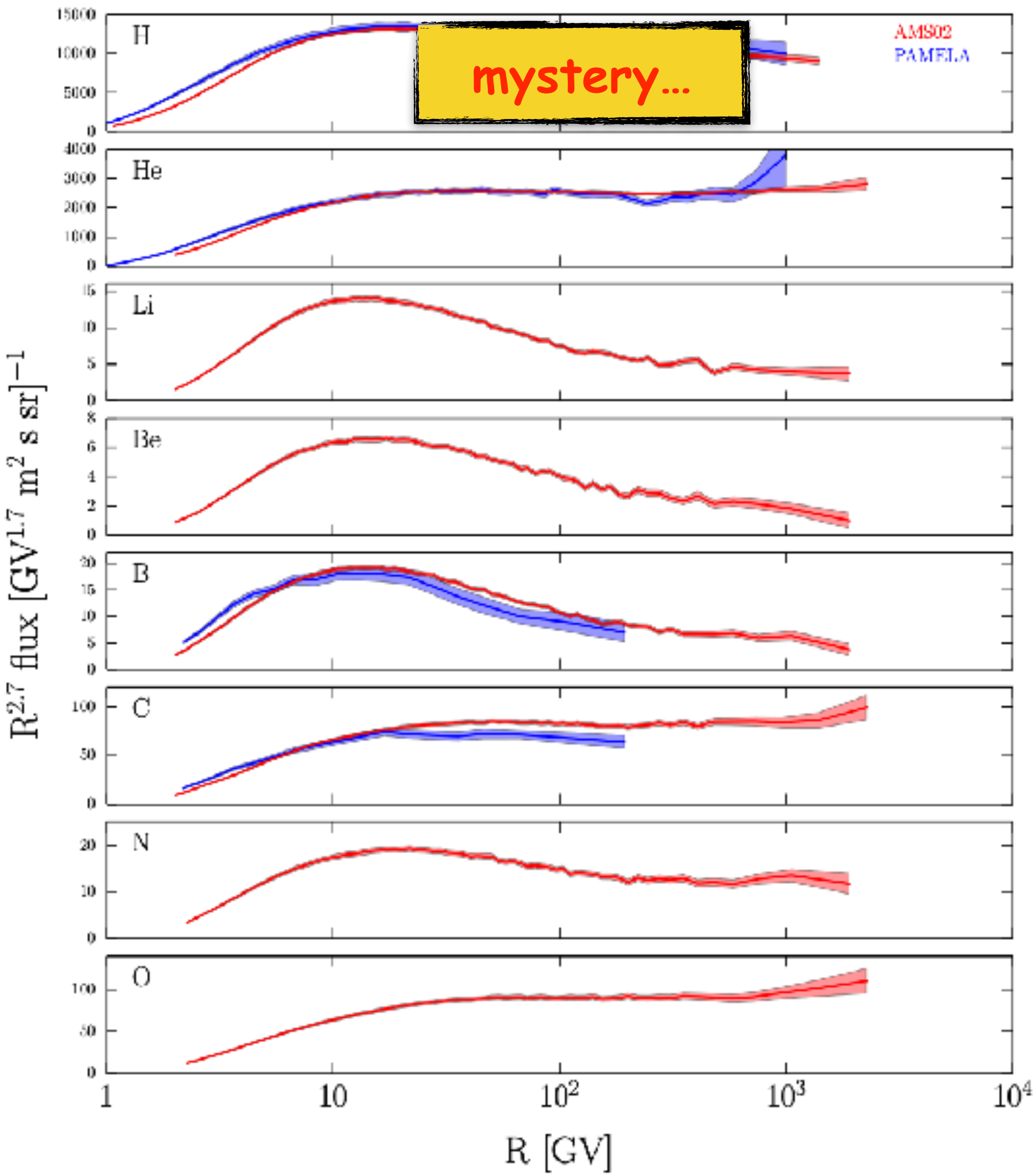


the ^{10}Be we observe is produced locally
—> sensitive to local matter density

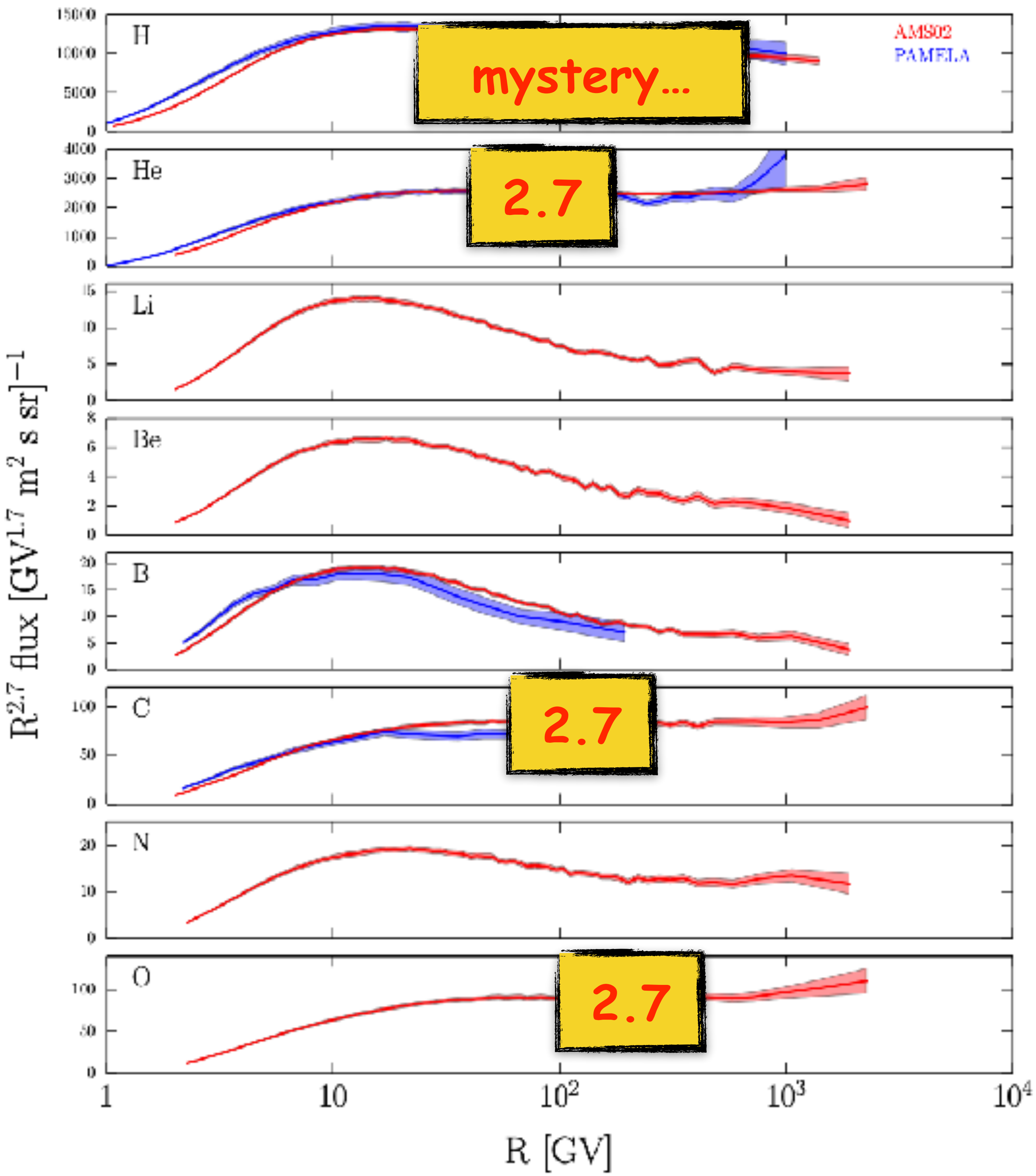
Let's go back to CR spectra



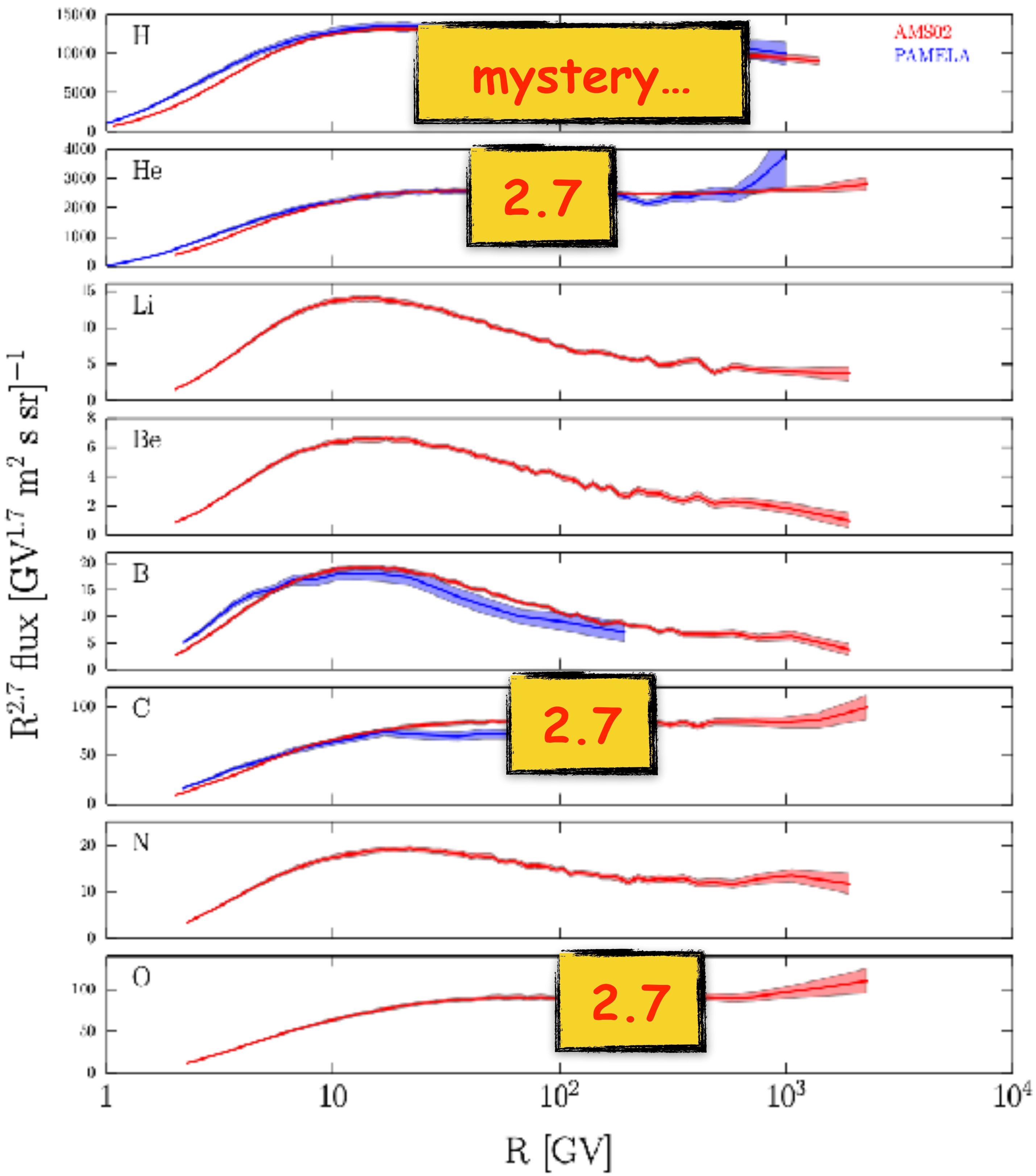
Let's go back to CR spectra



Let's go back to CR spectra



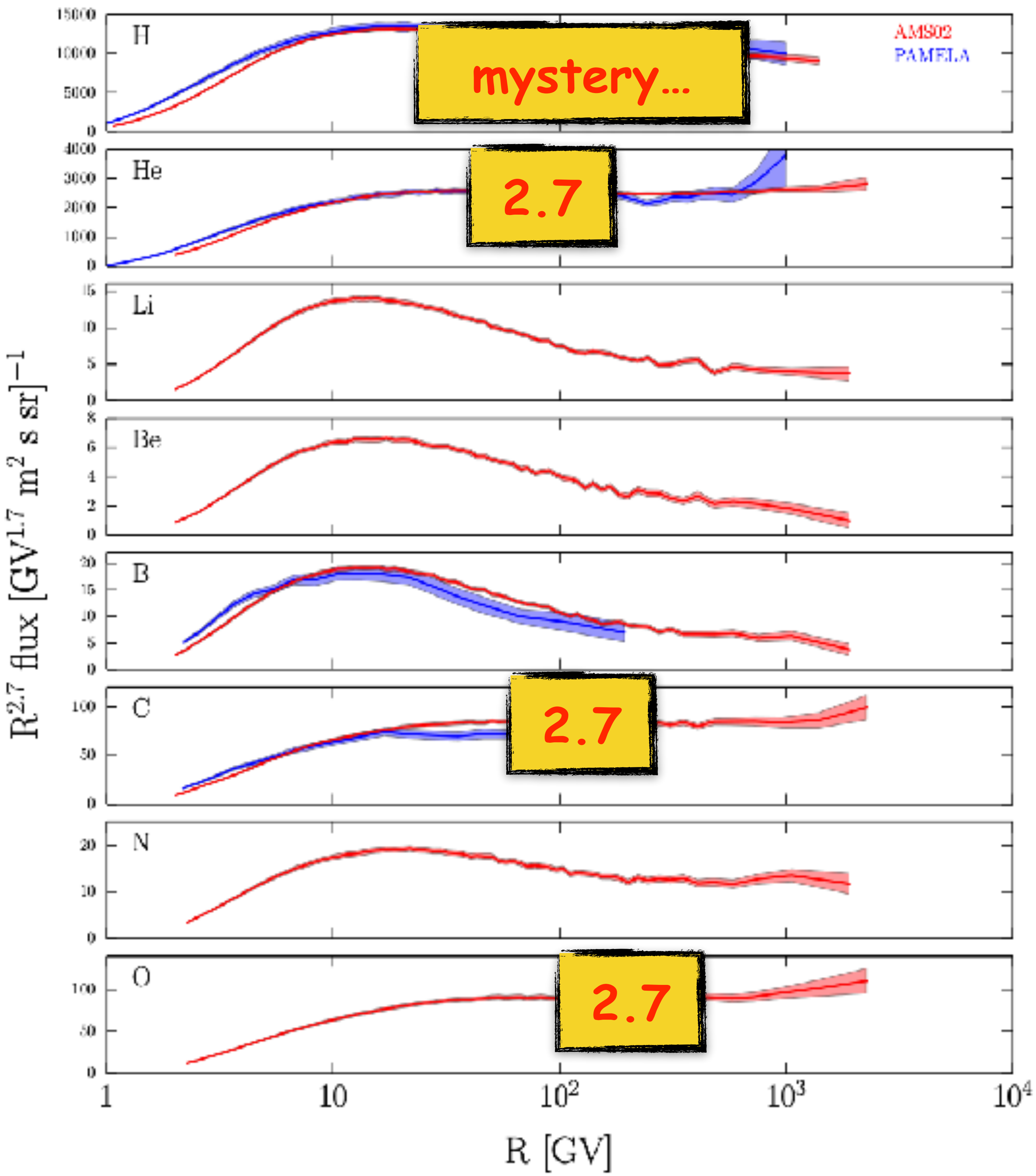
Let's go back to CR spectra



primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

Let's go back to CR spectra

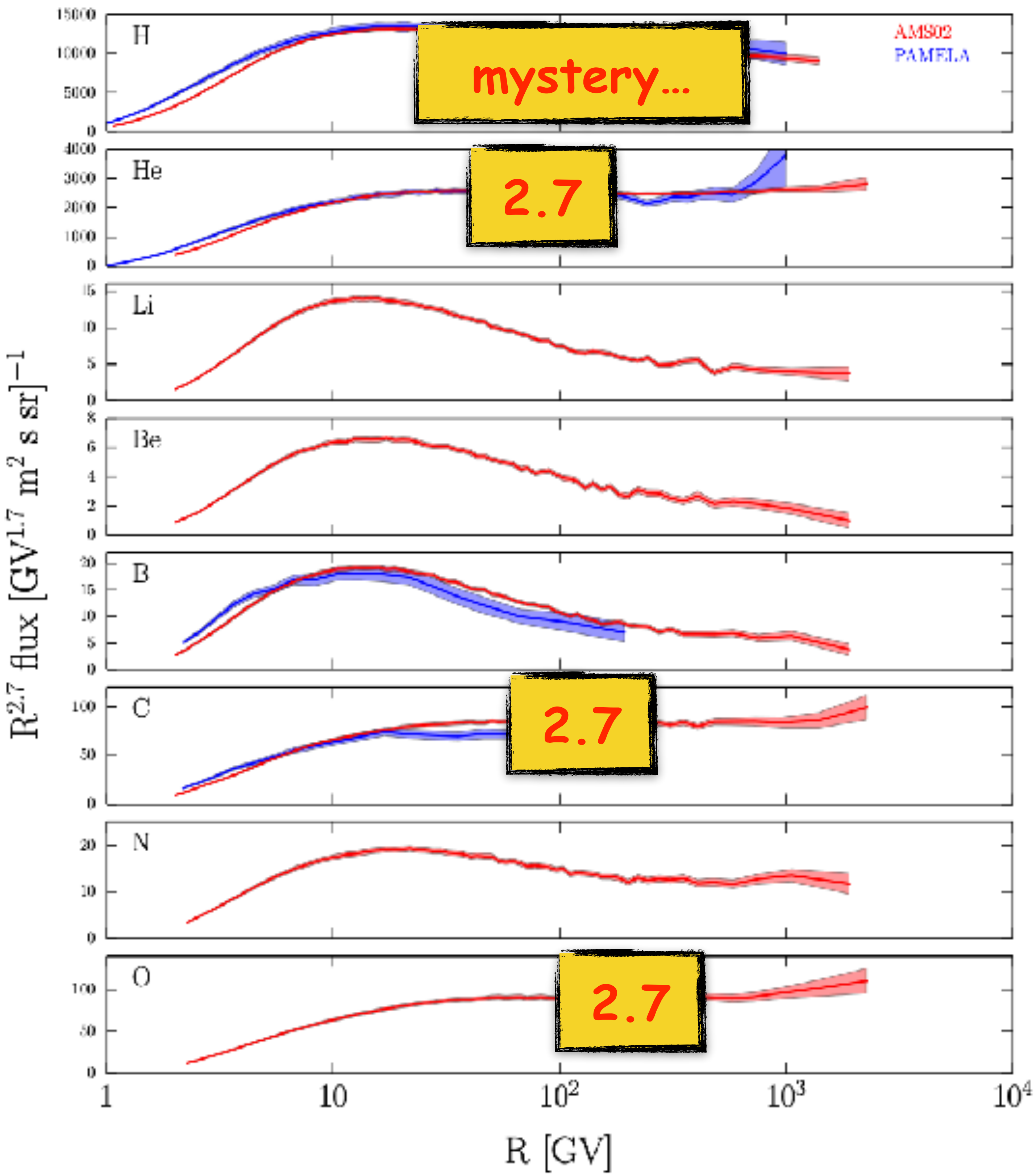


primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

Let's go back to CR spectra



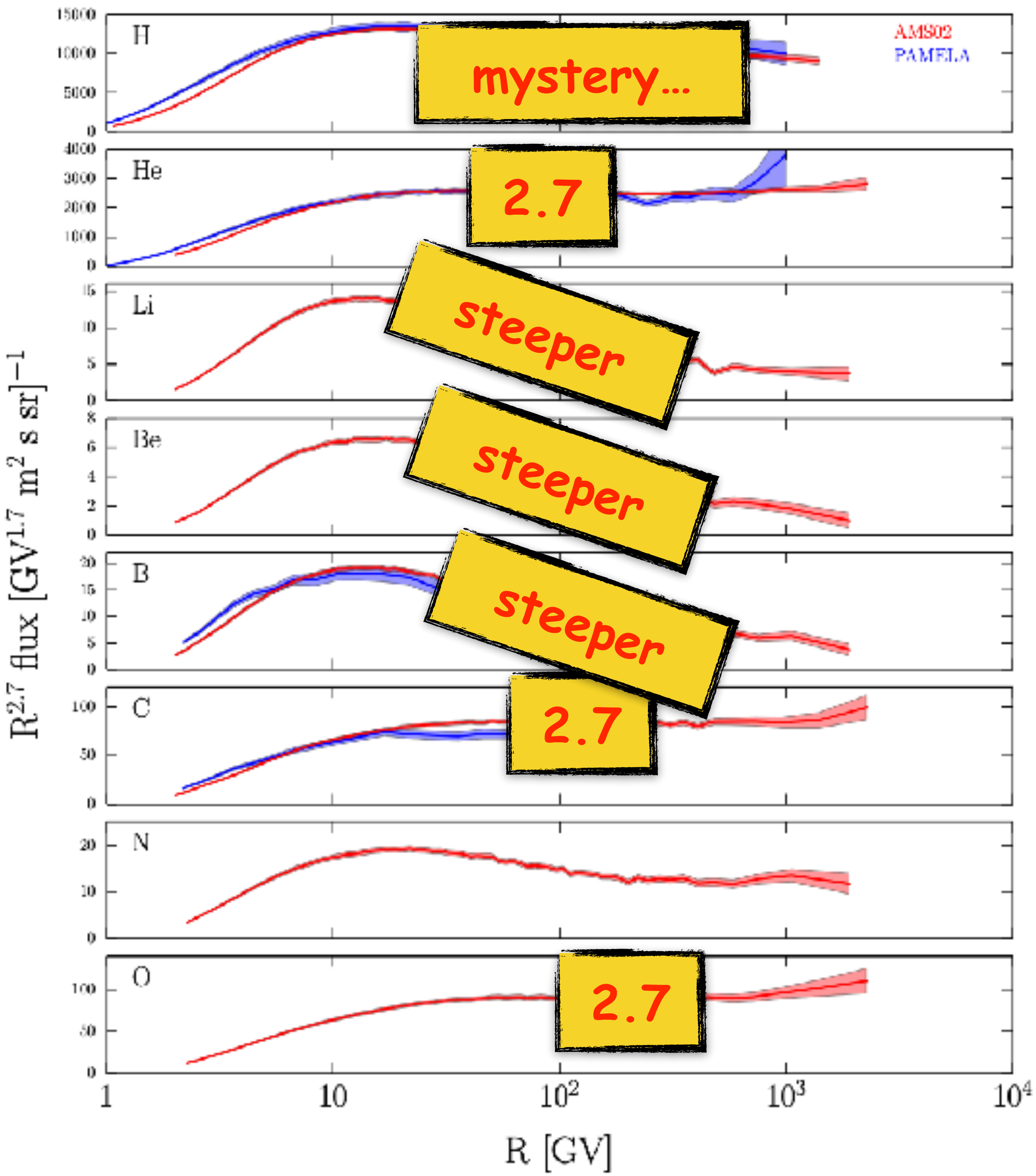
primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

$$q_P(E) \propto E^{-2.2}$$

Let's go back to CR spectra



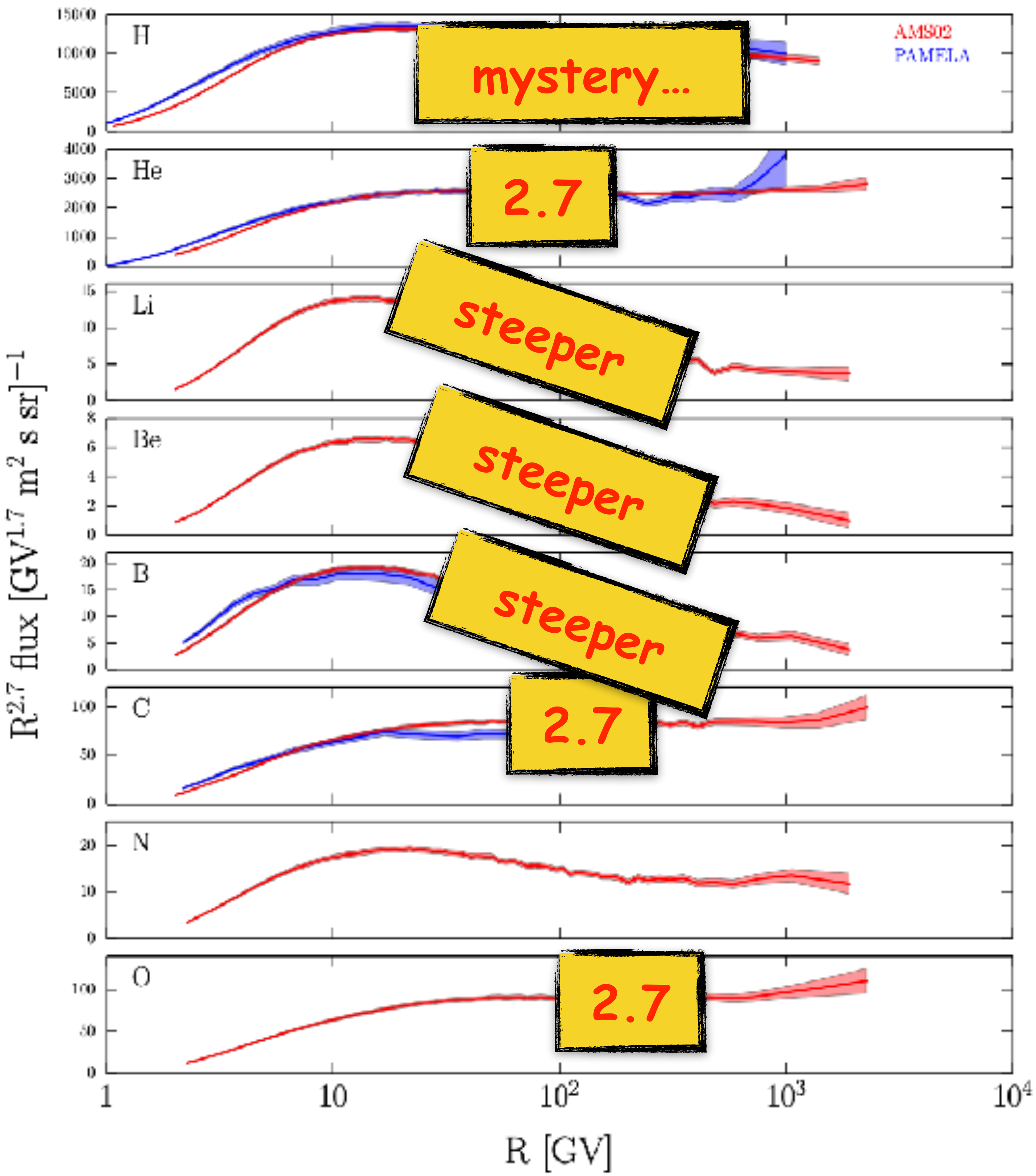
primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

$$q_P(E) \propto E^{-2.2}$$

Let's go back to CR spectra



primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

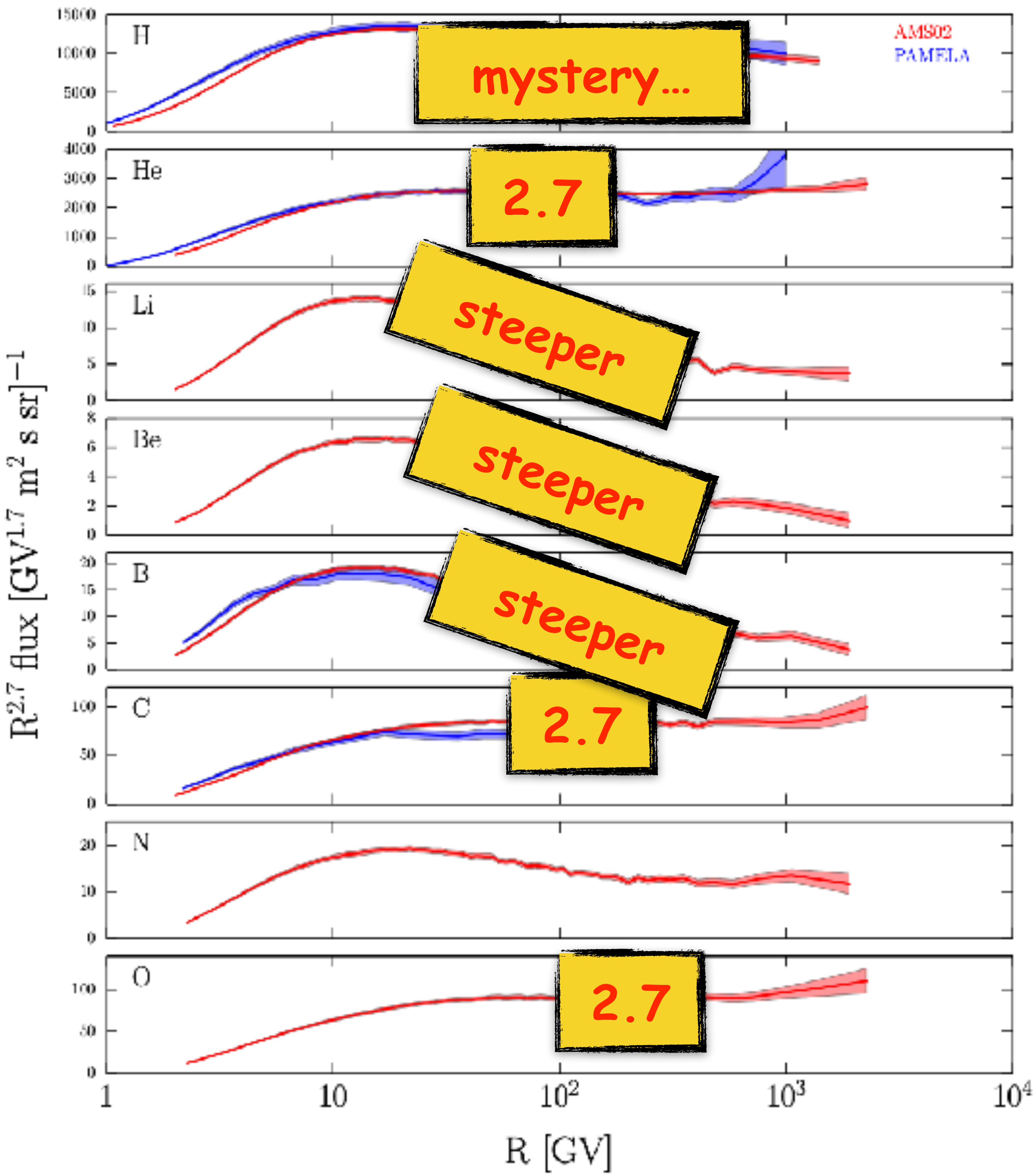
$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

$$q_P(E) \propto E^{-2.2}$$

secondaries

$$q_S(E) \propto n_P(E)$$

Let's go back to CR spectra



primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

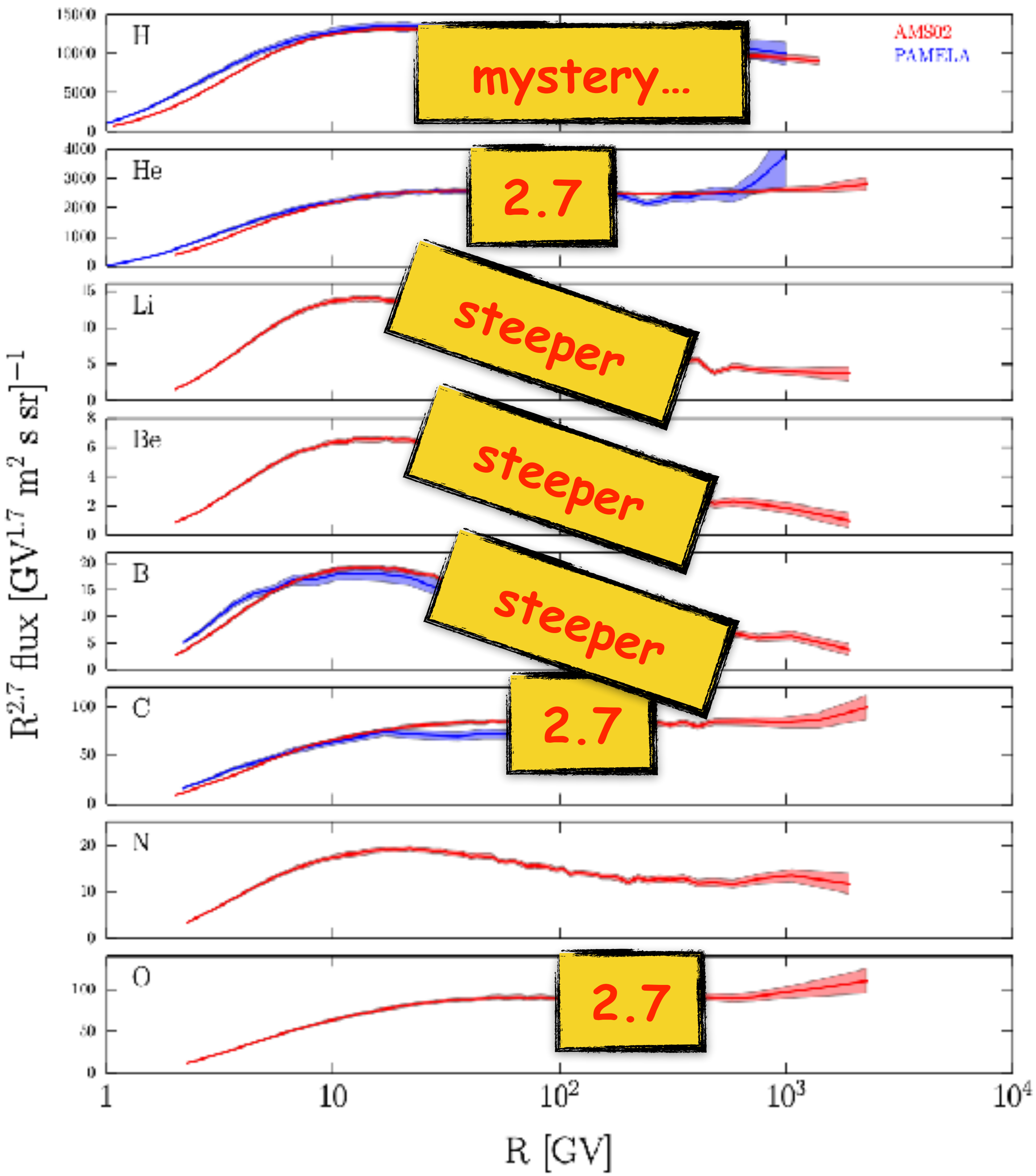
$$q_P(E) \propto E^{-2.2}$$

secondaries

$$q_S(E) \propto n_P(E)$$

$$n_S \sim q_S \times \tau_{esc} \propto n_P \times \tau_{esc}$$

Let's go back to CR spectra



primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

$$q_P(E) \propto E^{-2.2}$$

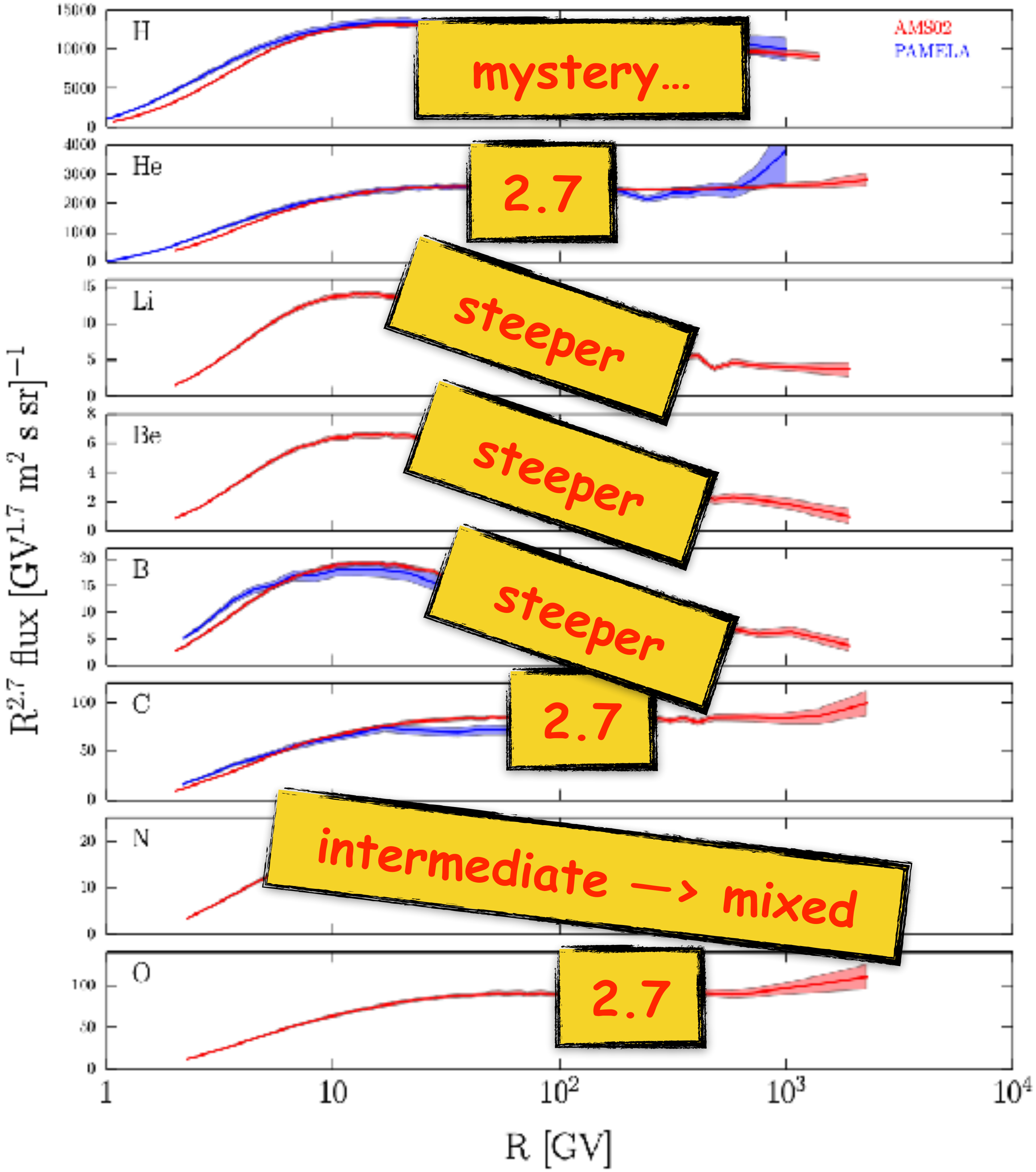
secondaries

$$q_S(E) \propto n_P(E)$$

$$n_S \sim q_S \times \tau_{esc} \propto n_P \times \tau_{esc}$$

steeper!

Let's go back to CR spectra



primaries

$$n_P(E) \sim q_P(E) \times \tau_{esc}(E)$$

$$\tau_{esc}(E) \propto X_{ISM} \propto E^{-0.5}$$

$$q_P(E) \propto E^{-2.2}$$

secondaries

$$q_S(E) \propto n_P(E)$$

$$n_S \sim q_S \times \tau_{esc} \propto n_P \times \tau_{esc}$$

steeper!

Why is this so remarkable?

CR sources MUST inject: $q_P(E) \propto E^{-2.2}$

Why is this so remarkable?

CR sources MUST inject: $q_P(E) \propto E^{-2.2}$

we said NOTHING about the nature of sources!
who they are, where they are, how they accelerate particles etc... this result is very solid because it is virtually model independent!

Why is this so remarkable?

CR sources MUST inject: $q_P(E) \propto E^{-2.2}$

we said NOTHING about the nature of sources!
who they are, where they are, how they accelerate particles etc… this result is very solid because it is virtually model independent!

…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

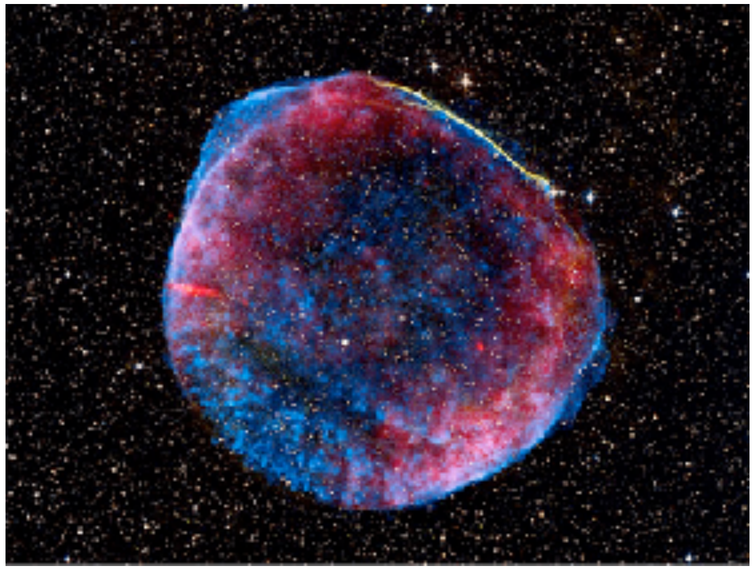
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

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.

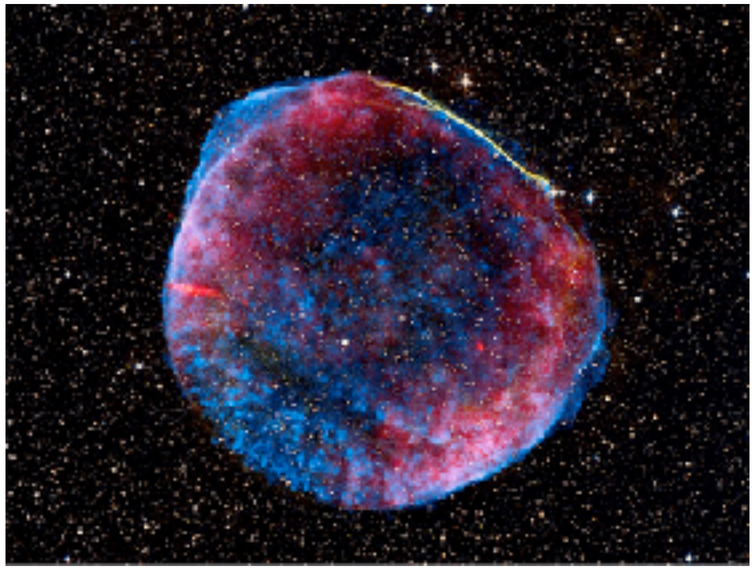
to my knowledge, the first paper invoking **Galactic** supernovae as sources of CRs is Ter Haar 1950

The supernova remnant origin of CRs



The supernova remnant origin of CRs

modern formulation of the hypothesis

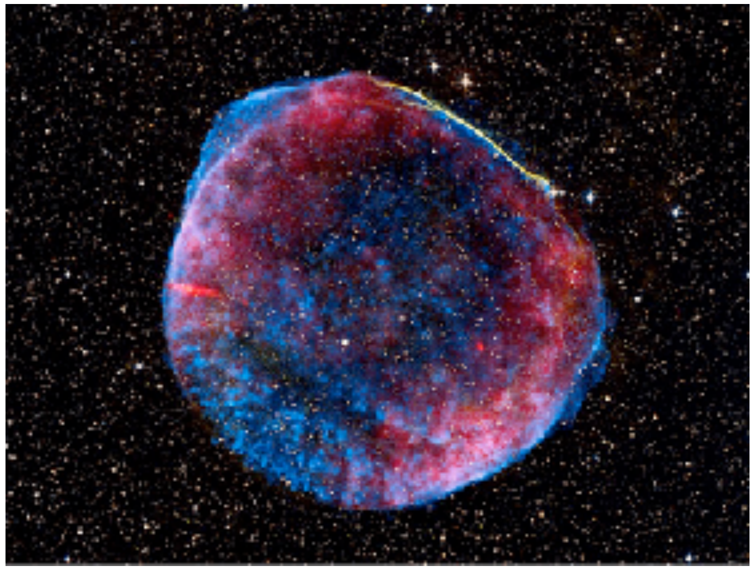


3 SN/century in the Galaxy, each one releases
10^{51} erg in form of kinetic energy.

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

The supernova remnant origin of CRs

modern formulation of the hypothesis



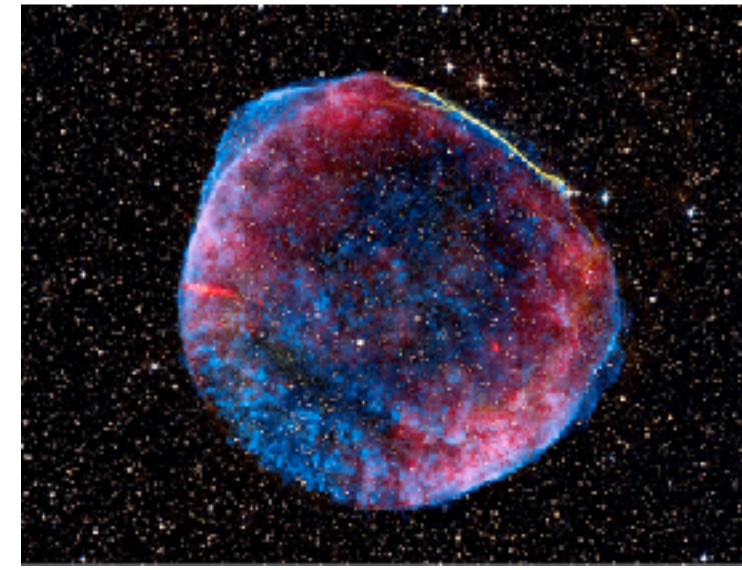
3 SN/century in the Galaxy, each one releases 10^{51} erg in form of kinetic energy.

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

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

The supernova remnant origin of CRs

modern formulation of the hypothesis



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

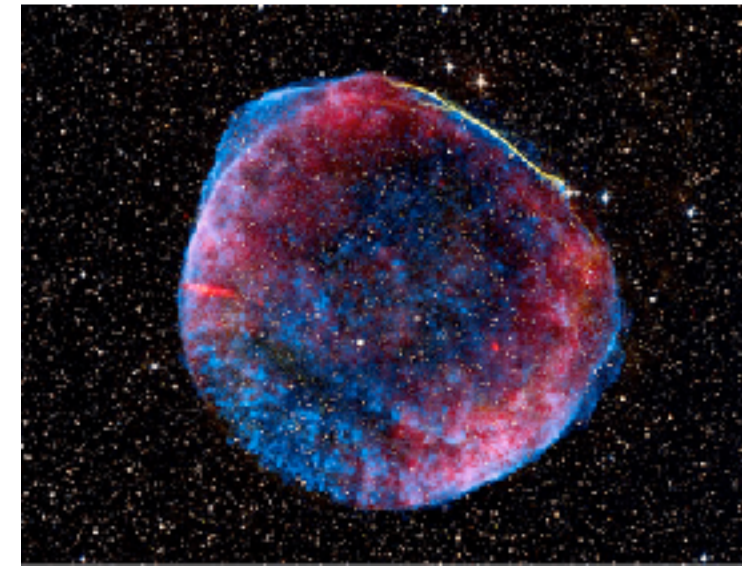
$$W_{SN} = 10^{42} \left(\frac{E_{SN}}{10^{51}\mathrm{erg}} \right) \left(\frac{\ldots}{\ldots\mathrm{ntury}} \right) \mathrm{erg/s}$$

~10% acceleration efficiency

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

The supernova remnant origin of CRs

modern formulation of the hypothesis



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

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

~10% acceleration efficiency

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

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

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

$$E_{SN} \sim 10^{51}\mathrm{erg}$$

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

$$E_{SN} \sim 10^{51}\text{erg} \longrightarrow E_{CR} \sim 10^{50}\text{erg}$$

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

$$E_{SN} \sim 10^{51}\text{erg} \longrightarrow E_{CR} \sim 10^{50}\text{erg}$$

$$n_{ISM} \sim 1\ \text{cm}^{-3}$$

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

$$E_{SN} \sim 10^{51}\mathrm{erg} \longrightarrow E_{CR} \sim 10^{50}\mathrm{erg}$$

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

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

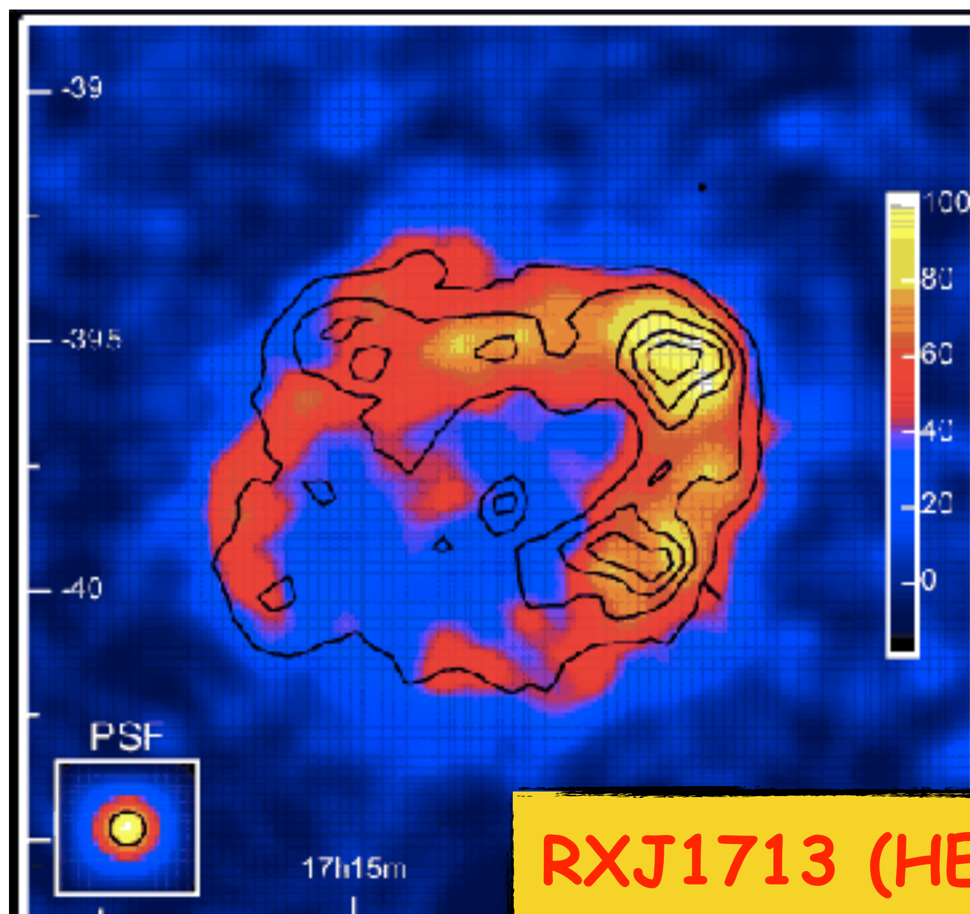
$$E_{SN} \sim 10^{51}\mathrm{erg} \longrightarrow E_{CR} \sim 10^{50}\mathrm{erg}$$

$$p + p \to p + p + \pi^0$$

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

$$\pi^0 \to \gamma + \gamma$$

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



RXJ1713 (HESS)

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

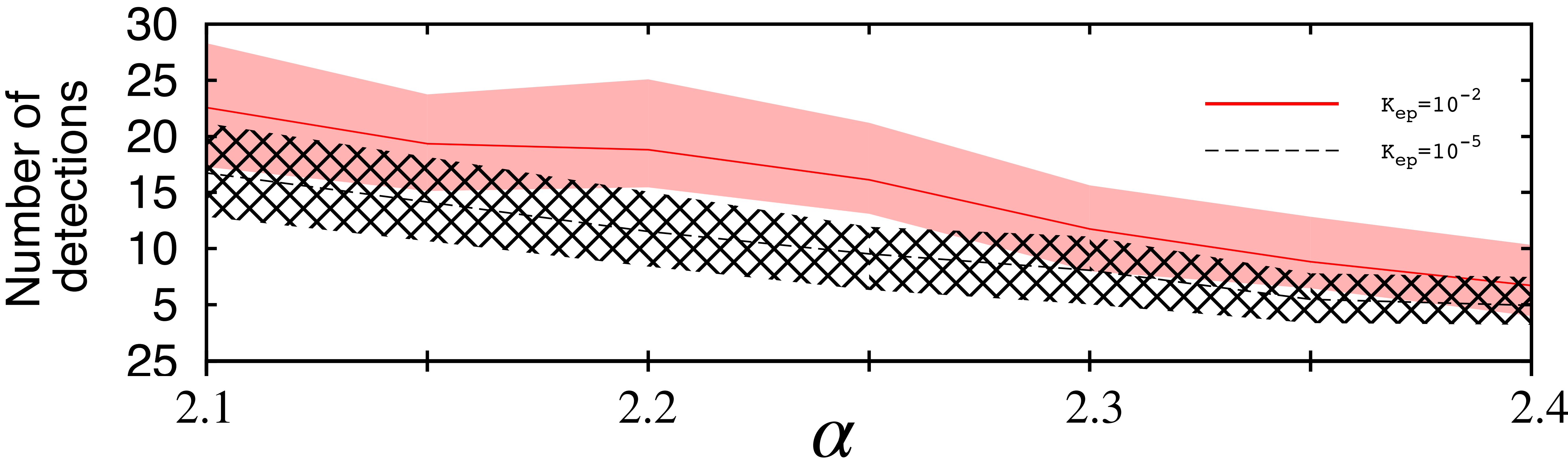
$$E_{SN} \sim 10^{51}\text{erg} \longrightarrow E_{CR} \sim 10^{50}\text{erg}$$

$$n_{ISM} \sim 1\ \text{cm}^{-3}$$

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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



Cristofari+ 2013

γ-rays from SNRs: a test for CR origin

Drury, Aharonian, Volk 1994

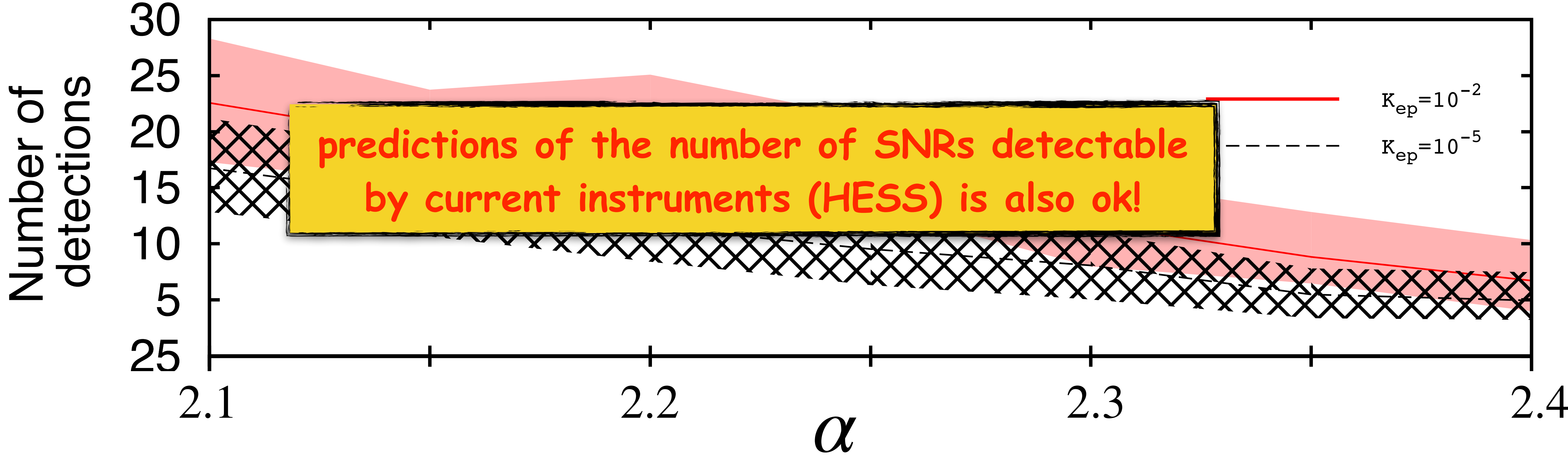
$$E_{SN} \sim 10^{51}\text{erg} \longrightarrow E_{CR} \sim 10^{50}\text{erg}$$

$$n_{ISM} \sim 1\ \text{cm}^{-3}$$

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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



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

Cristofari+ 2013

[8] The three pillars of orthodoxy

The orthodoxy (1)

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

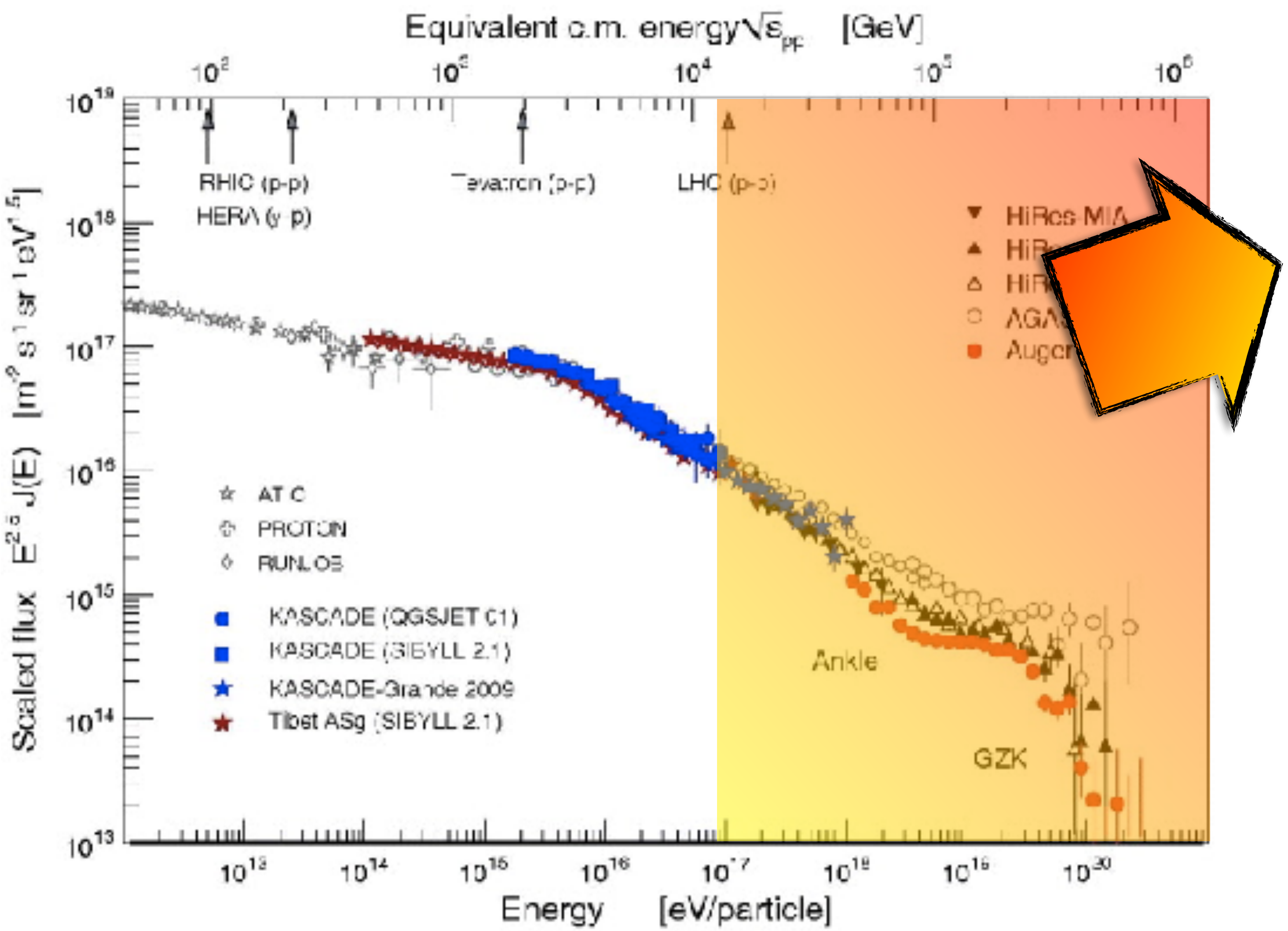
The orthodoxy (2)

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

The orthodoxy (3)

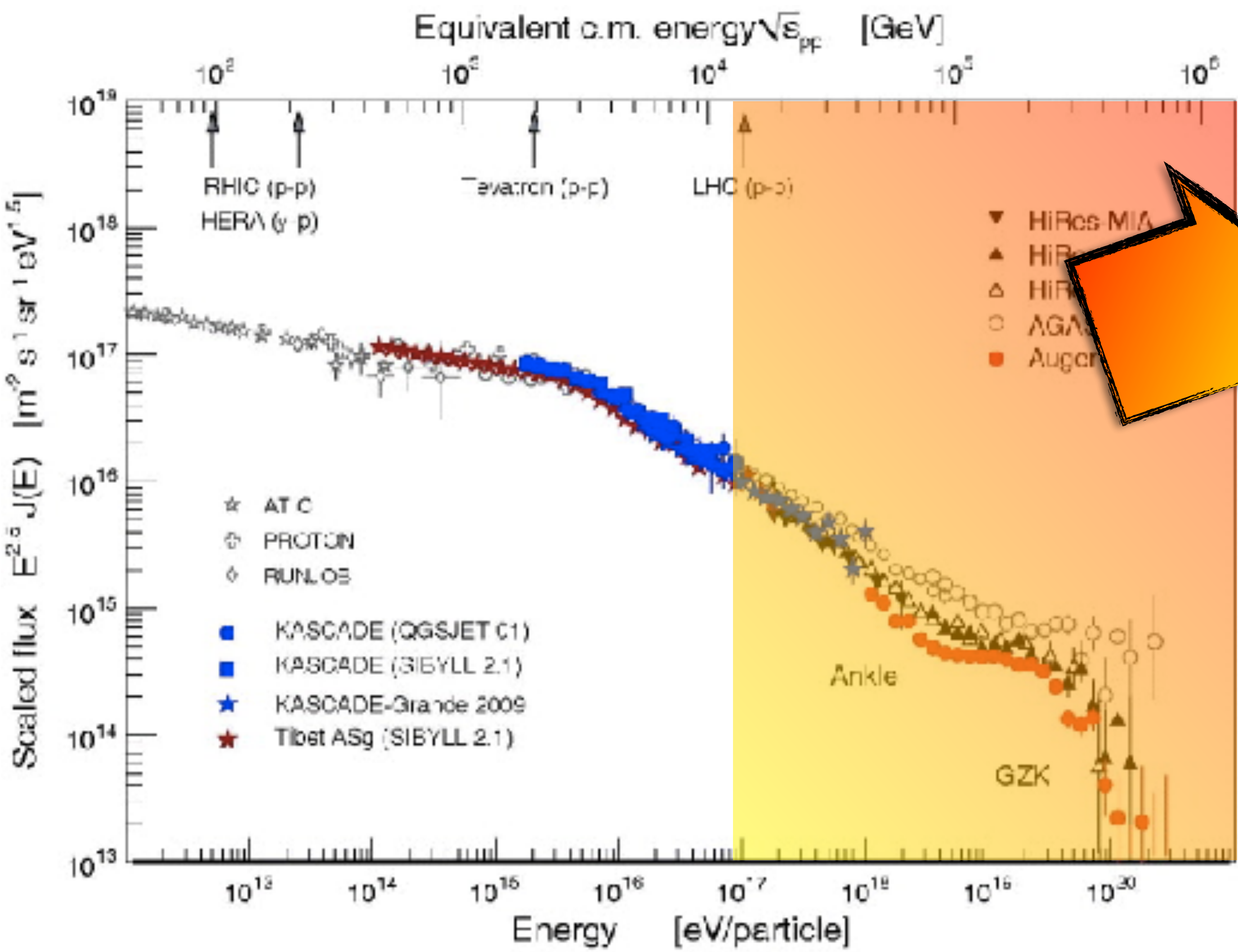
- Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

(At least) three serious issues remains



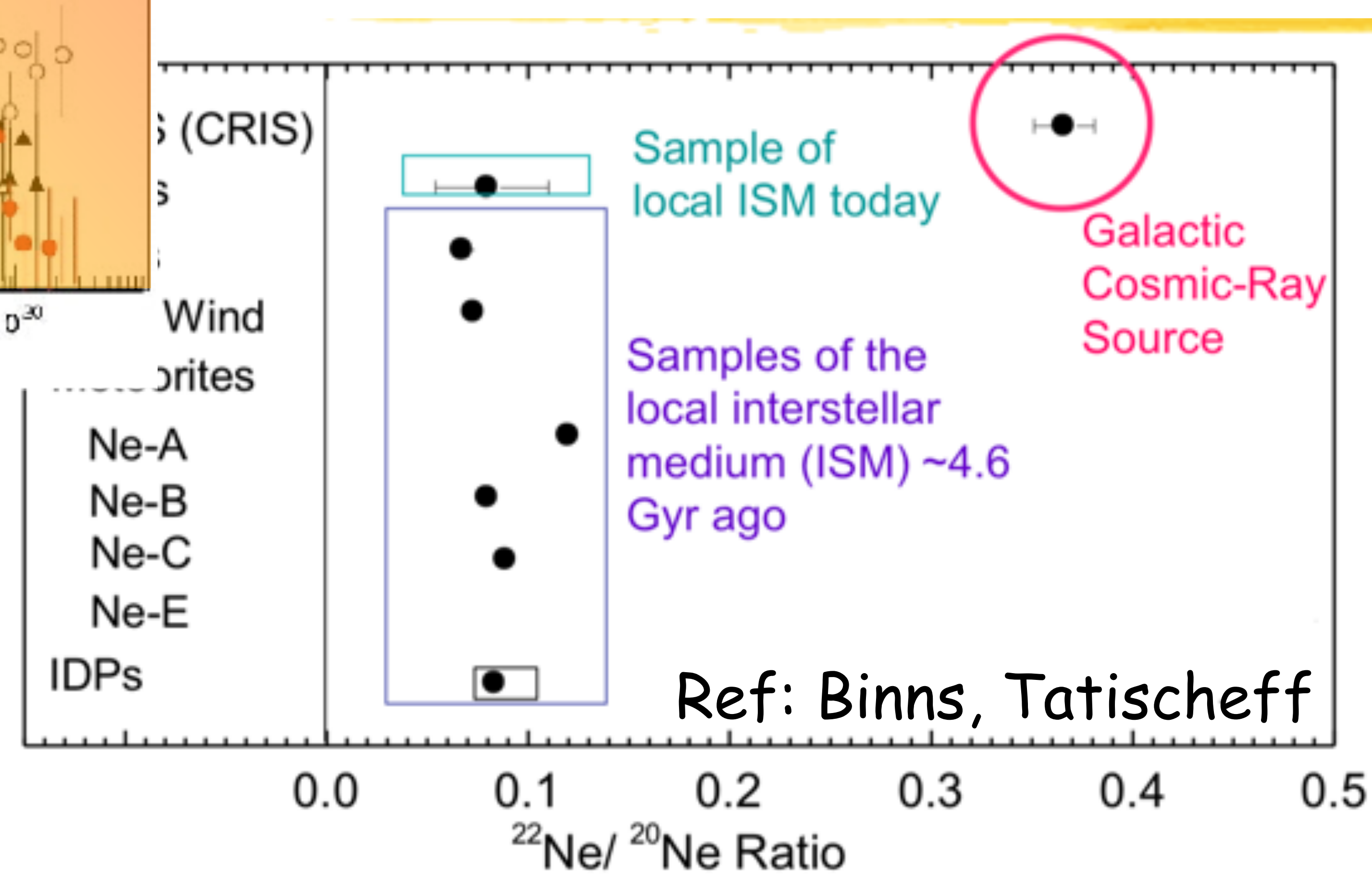
[1] can SNR shocks accelerate particles up to the largest observed energies?

(At least) three serious issues remains



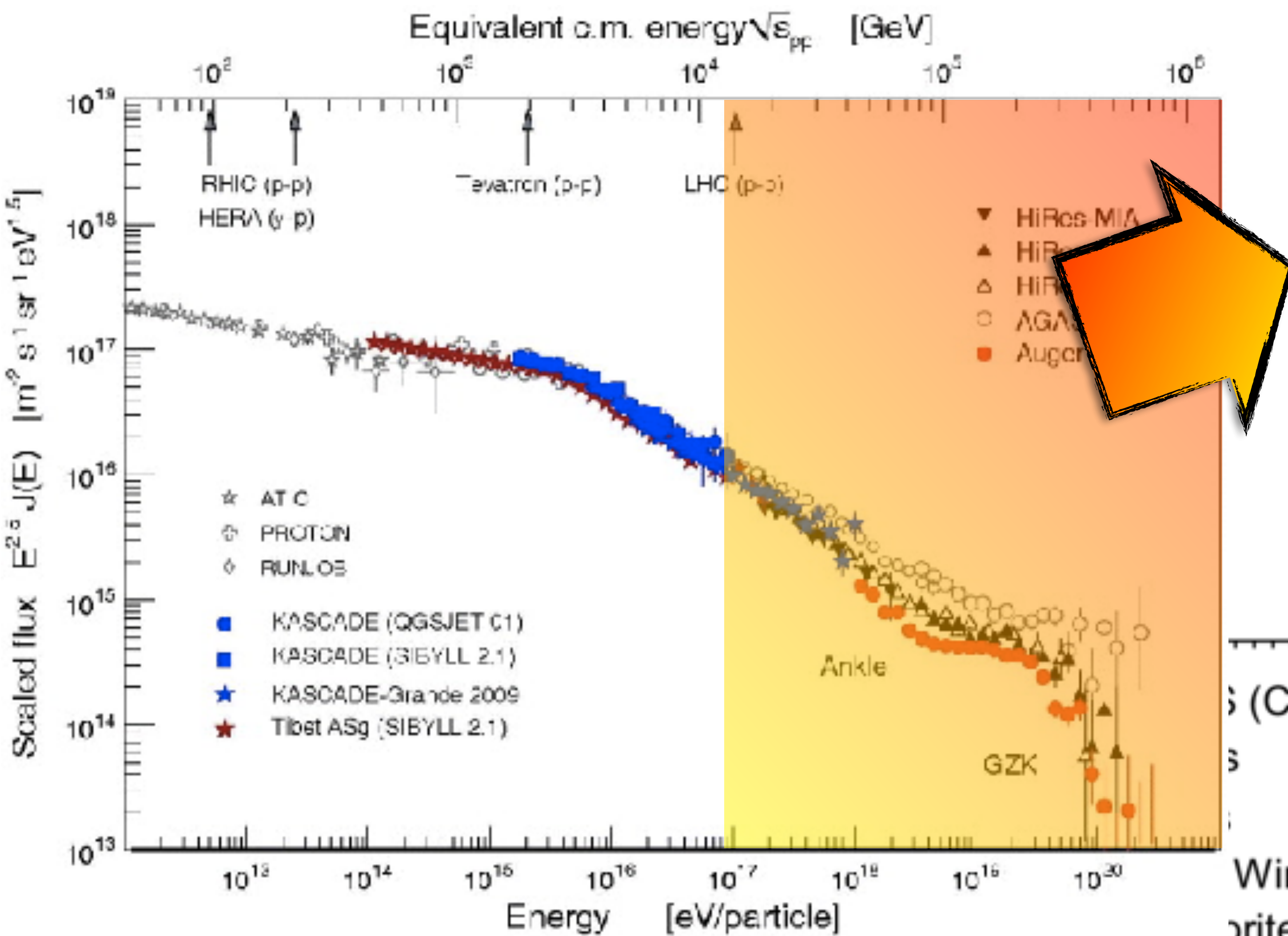
[1] can SNR shocks accelerate particles up to the largest observed energies?

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

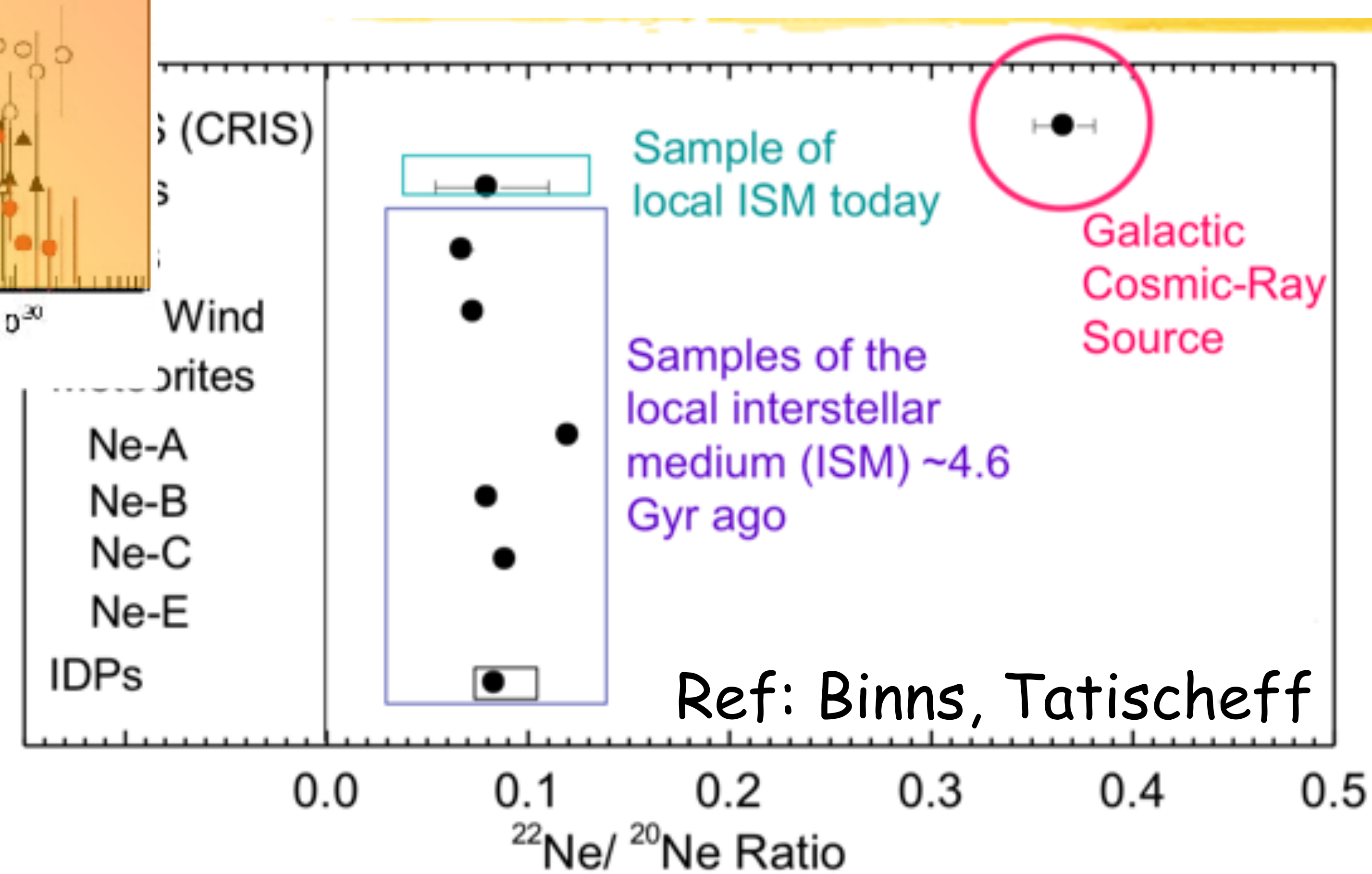


Ref: Binns, Tatischeff

(At least) three serious issues remains



[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?

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

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

Charged particles and electromagnetic fields

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

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

Charged particles and electromagnetic fields

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

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

Simplifying assumption —> consider only constant fields

Charged particles and electromagnetic fields

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

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

Simplifying assumption —> consider only constant fields

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

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

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

Charged particles and electromagnetic fields

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

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

Simplifying assumption —> consider only constant fields

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

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

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

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

…because we deal with plasmas

to accelerate particles, you need an electric field

…because we deal with plasmas

to accelerate particles, you need an electric field

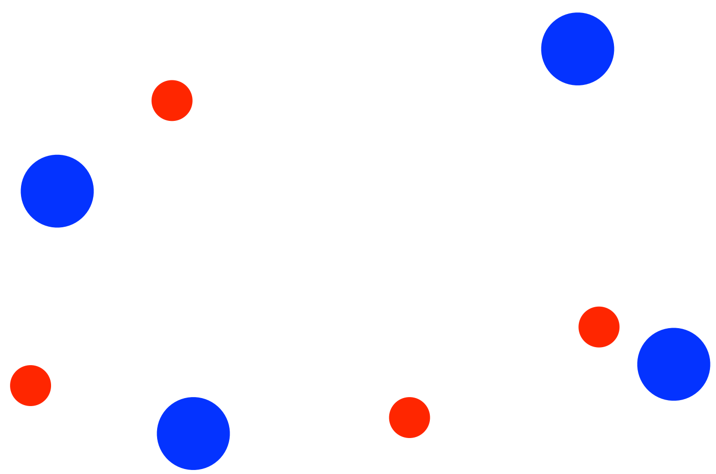
An excess of electrical charge is needed to maintain a static electric field. However we should remember…

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

(Lyman Spitzer "Physics of fully ionised gases")

Quasi-neutrality

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



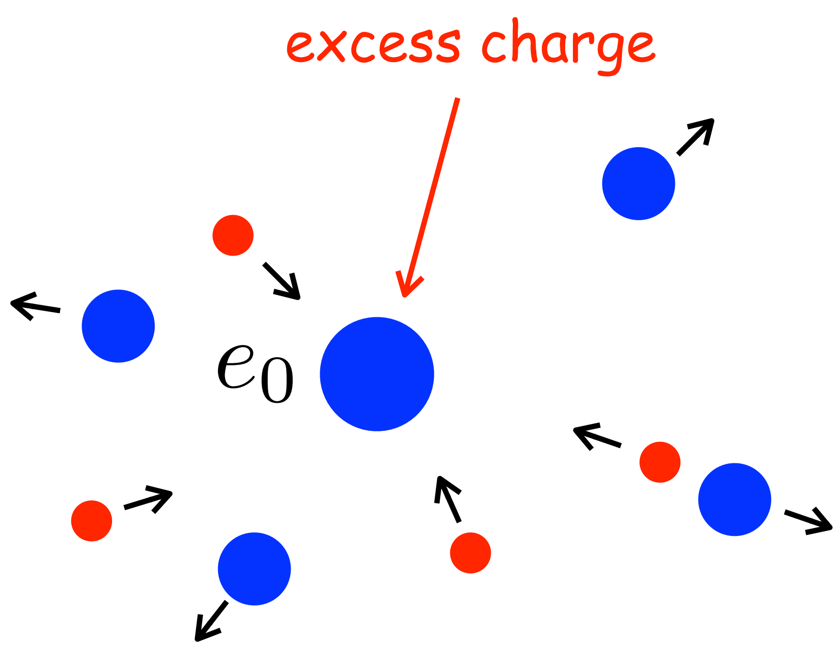
protons

electrons

$\Big\}$ thermal equilibrium $T_e = T_p = T$ -> Boltzmann distribution

Quasi-neutrality

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



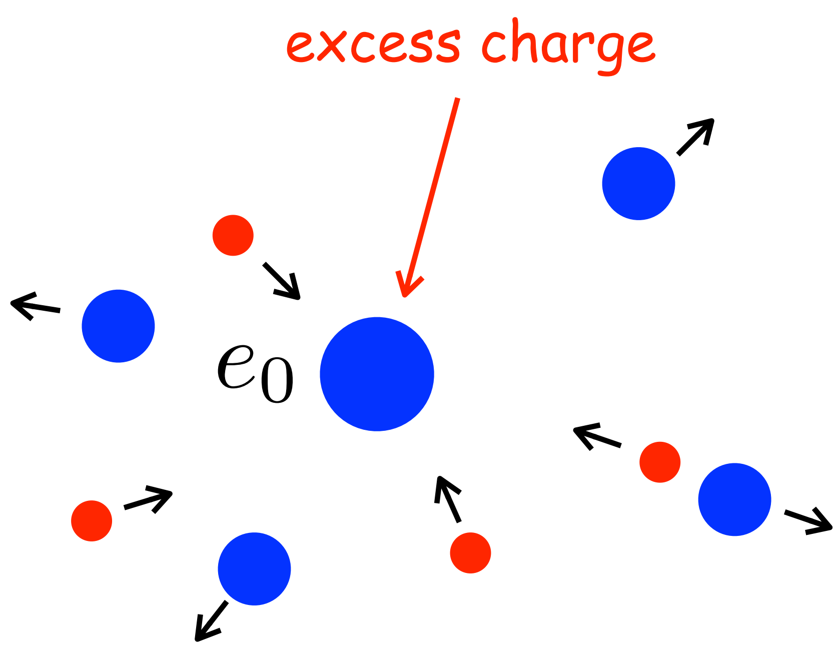
protons
electrons

thermal equilibrium $T_e = T_p = T$ -> Boltzmann distribution

Quasi-neutrality

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

$$\nabla \cdot \vec{E} = -\nabla^2 \phi = 4\pi \varrho = 4\pi e(n_i - n_e) + 4\pi e_0 \delta(\vec{R})$$



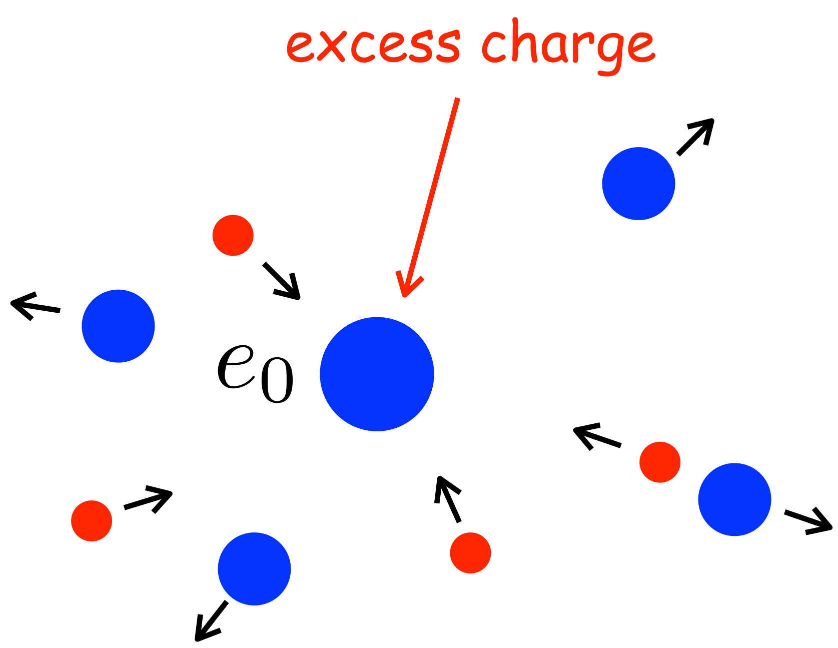
protons
electrons

thermal equilibrium $T_e = T_p = T$ -> Boltzmann distribution

Quasi-neutrality

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

$$\nabla \cdot \vec{E} = -\nabla^2 \phi = 4\pi \varrho = 4\pi e(n_i - n_e) + 4\pi e_0 \delta(\vec{R})$$



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

$\left.\begin{array}{l}\text{protons} \\ \text{electrons}\end{array}\right\}$ thermal equilibrium $T_e = T_p = T$ -> Boltzmann distribution

Quasi-neutrality

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

Quasi-neutrality

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

An analytic solution can be found when: $\longrightarrow$ $\quad \dfrac{e\phi}{kT} \ll 1$

Quasi-neutrality

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

An analytic solution can be found when: $\longrightarrow$ $\quad \dfrac{e\phi}{kT} \ll 1$

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

Quasi-neutrality

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

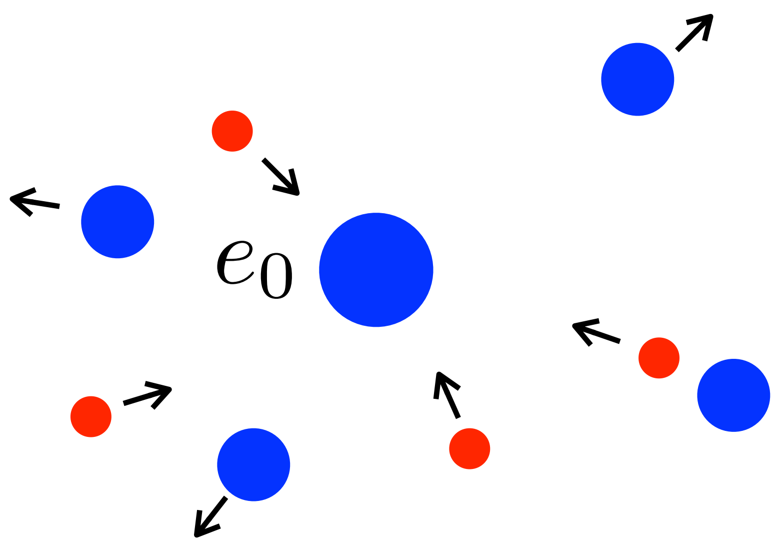
An analytic solution can be found when: $\longrightarrow$ $$\frac{e\phi}{kT} \ll 1$$

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

$$\begin{aligned}\frac{1}{R^2}\frac{\mathrm{d}}{\mathrm{d}R}\left(R^2\frac{\mathrm{d}\phi}{\mathrm{d}R}\right) &= 8\pi n_0 e\frac{e\phi}{kT} - 4\pi e_0\delta(\vec{R}) \\ &= \frac{\phi}{\lambda^2} - 4\pi e_0\delta(\vec{R})\end{aligned}$$

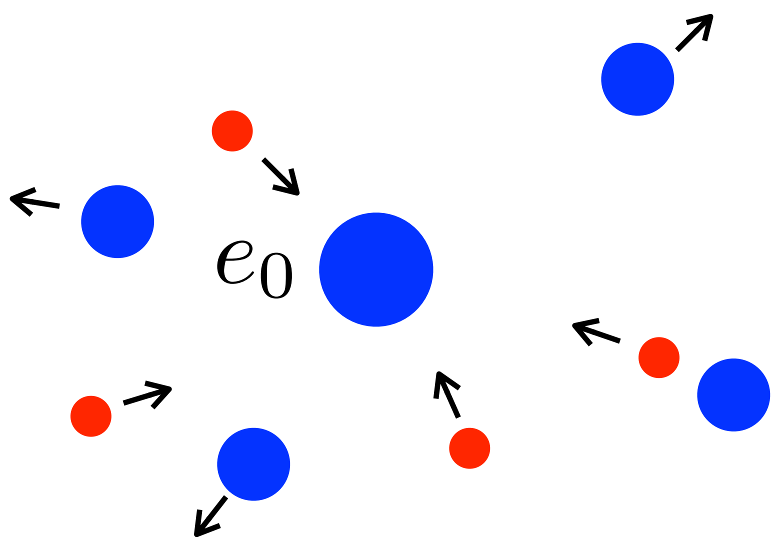
$$\boxed{\lambda = \left(\frac{kT}{8\pi n_0 e^2}\right)^{1/2}}$$

Quasi-neutrality: Debye length



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

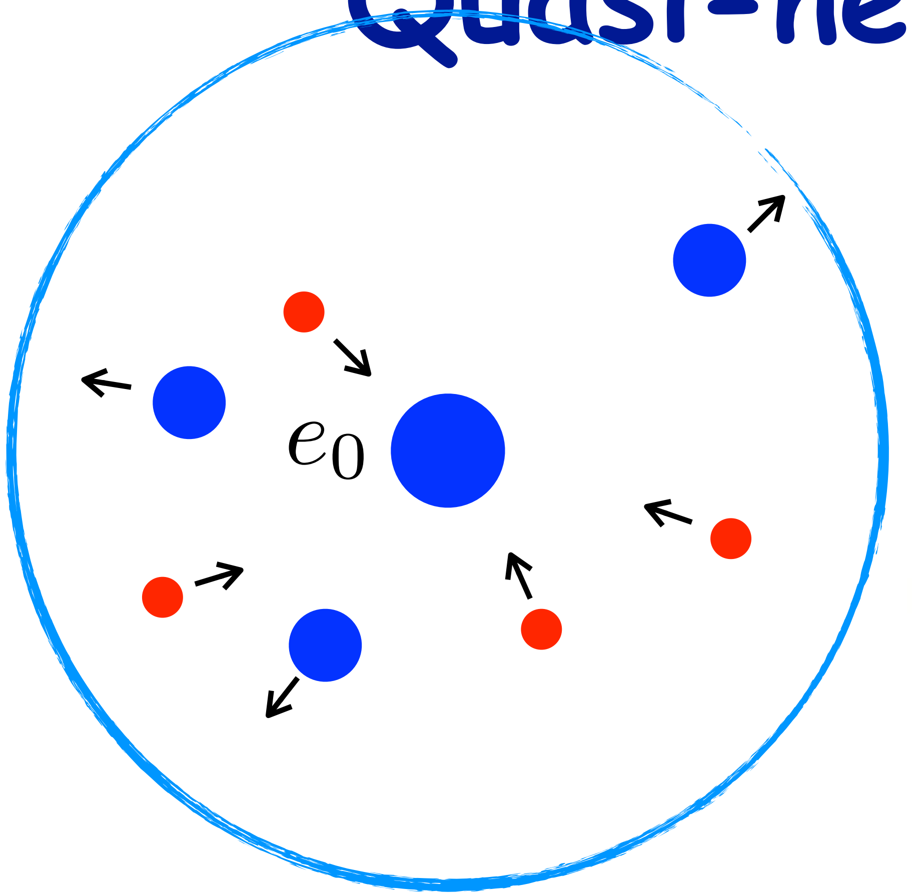
Quasi-neutrality: Debye length



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

Coulomb potential

Quasi-neutrality: Debye length

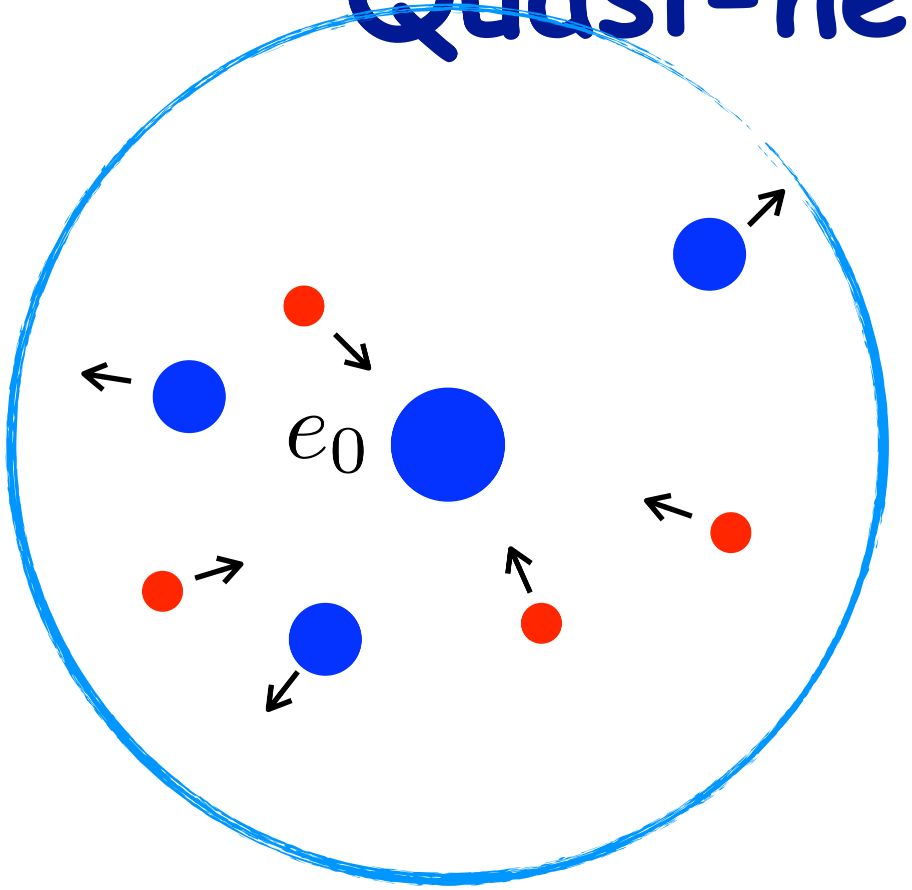


$$\phi = \boxed{\frac{e_0}{R}}\,\boxed{e^{-\frac{R}{\lambda}}}$$

screened!

Coulomb potential

Quasi-neutrality: Debye length



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

screened!

Coulomb potential

Excess charges are screened on a scale called Debye length

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

extremely small!

it does NOT depend on the charge excess!

How long it takes?

dimensionally —>

$$\tau \sim \frac{\lambda}{v_{th}}$$

plasma frequency

$$\omega_p \sim 1/\tau$$

How long it takes?

dimensionally —>

$$\tau \sim \frac{\lambda}{v_{th}} = \sqrt{\frac{m_e}{16\pi n_0 e^2}} \approx 10^{-5} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

$$\frac{1}{2} m_e v_{th}^2 \sim kT \to v_{th} \sim \sqrt{\frac{2kT}{m_e}}$$

plasma frequency

$$\omega_p \sim 1/\tau$$

How long it takes?

dimensionally —>

$$\tau \sim \frac{\lambda}{v_{th}} = \sqrt{\frac{m_e}{16\pi n_0 e^2}} \approx 10^{-5} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

$$\frac{1}{2} m_e v_{th}^2 \sim kT \rightarrow v_{th} \sim \sqrt{\frac{2kT}{m_e}}$$

time to react to the presence of an electric charge

plasma frequency

$$\omega_p \sim 1/\tau$$

How long it takes?

dimensionally —>

$$\tau \sim \frac{\lambda}{v_{th}} = \sqrt{\frac{m_e}{16\pi n_0 e^2}} \approx 10^{-5} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

$$\frac{1}{2} m_e v_{th}^2 \sim kT \rightarrow v_{th} \sim \sqrt{\frac{2kT}{m_e}}$$

time to react to the presence of an electric charge

plasma frequency

$$\omega_p \sim 1/\tau$$