

Introductory talk on Galactic Cosmic Rays



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APC, Paris



www.cnrs.fr

Some recent review articles

not recent, but: Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD (2019)

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3 CDHY speakers!

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3 CDHY speakers!

some reviews that appeared since 2020 (the list is certainly incomplete!)

Mertsch, "Test particle simulations of cosmic rays" (2020)

Boezio+, "Cosmic ray detection in space" (2020)

Recchia, "Cosmic ray driven galactic winds" (2020)

Cristofari, "The Hunt for Pevatrons: The Case of Supernova Remnants" (2021)

Tibaldo+, "Gamma Rays as Probes of Cosmic-Ray Propagation and Interactions in Galaxies" (2021)

Gabici, "Low-energy cosmic rays: regulators of the dense interstellar medium" (2022)

Lazarian+, "Cosmic ray propagation in turbulent magnetic fields" (2023)

de Oña Wilhelmi+, "The hunt for PeVatrons as the origin of the most energetic photons observed in the Galaxy" (2024)

Marcowith, "Cosmic rays escape from their sources" (2025)

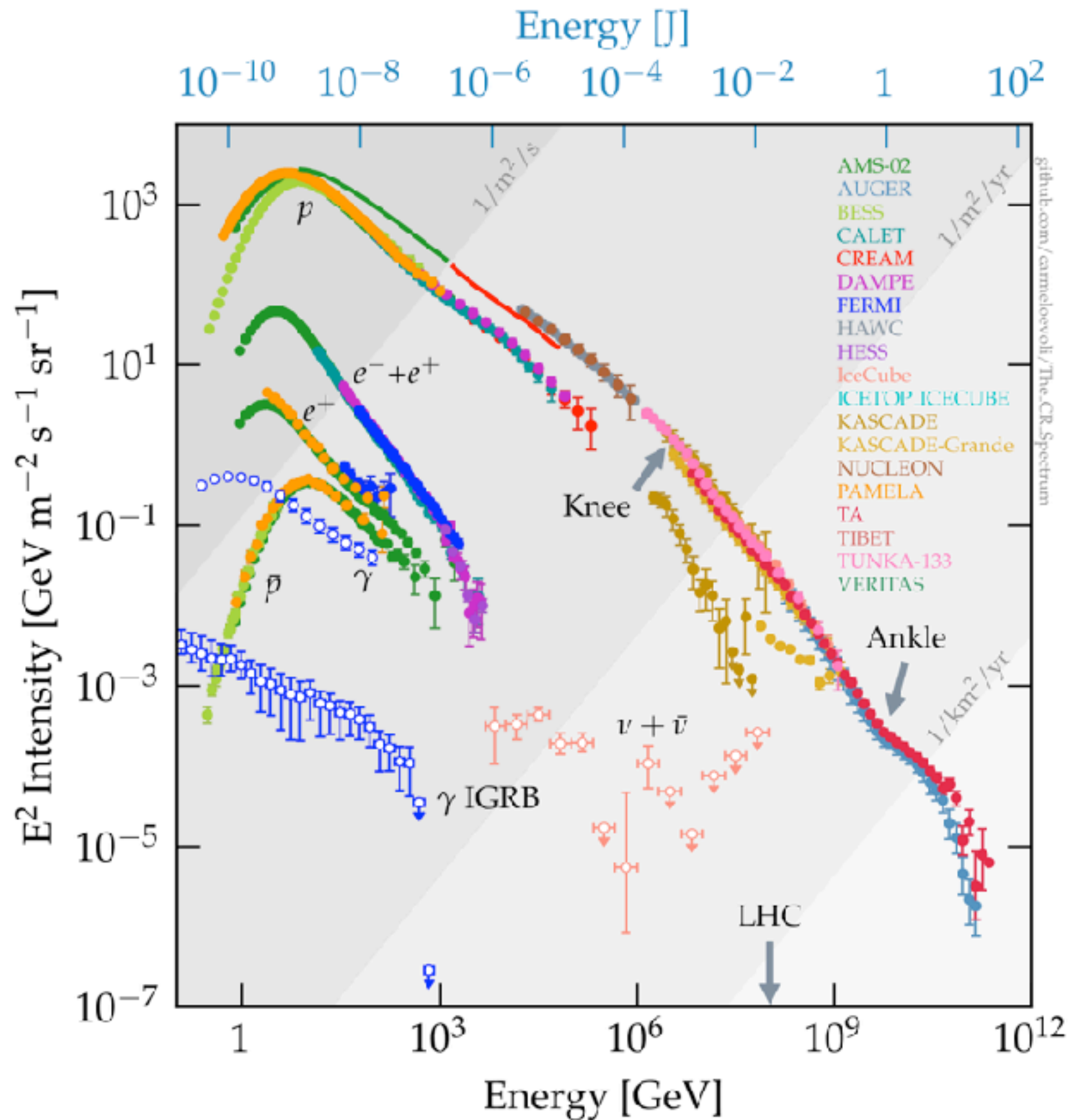
basic things only!

Plan of the talk

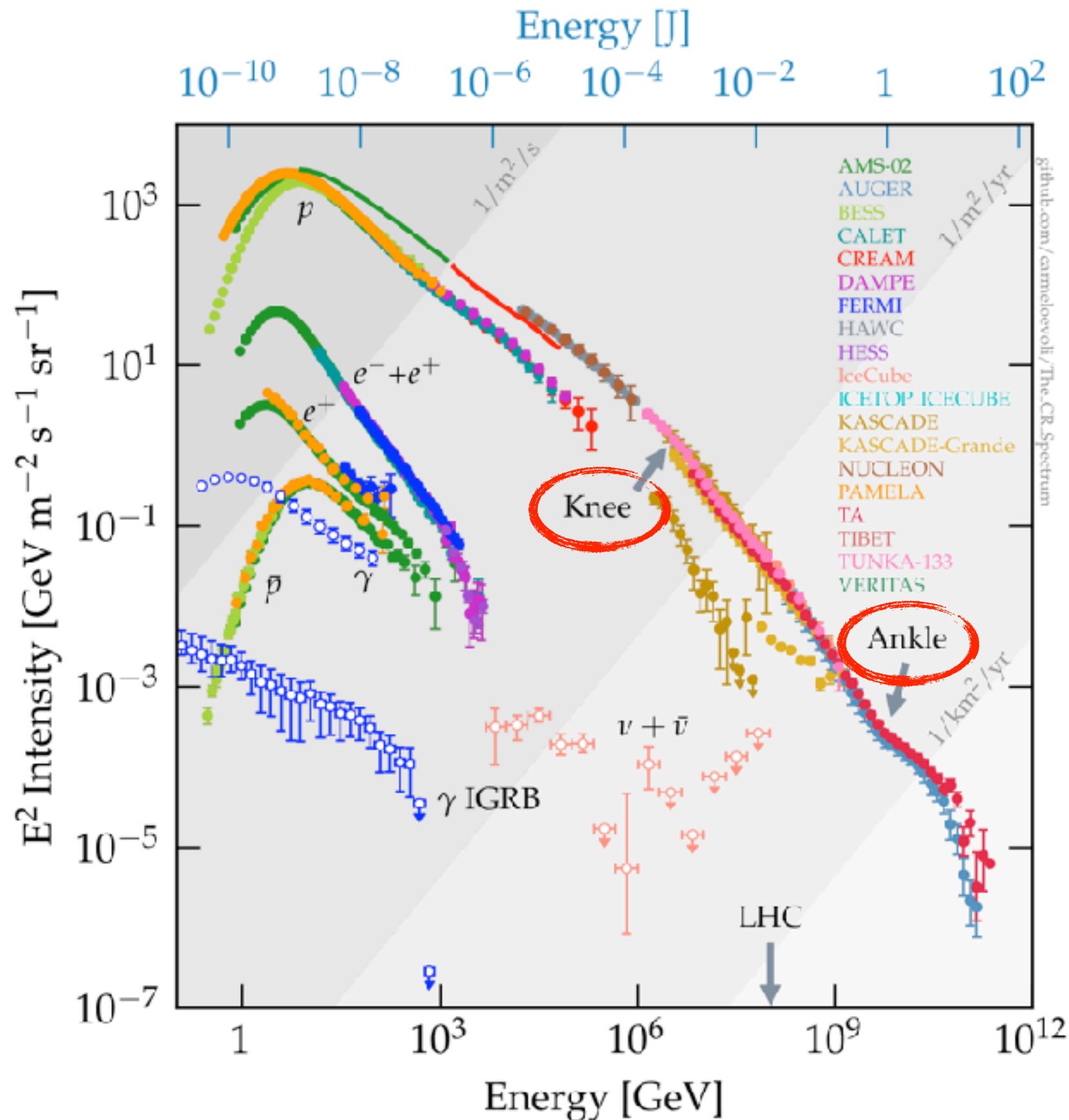
- What cosmic rays are
- What cosmic rays do
- What we know
- The orthodoxy: the supernova remnant paradigm
- Successes and problems of the SNR paradigm
- Supernova remnants & friends
- Is a coherent picture emerging?
- What we don't know
- Cosmic ray sources in our neighbourhood
- Conclusions

What cosmic rays are

Carmelo's famous plot (v24.10 !)

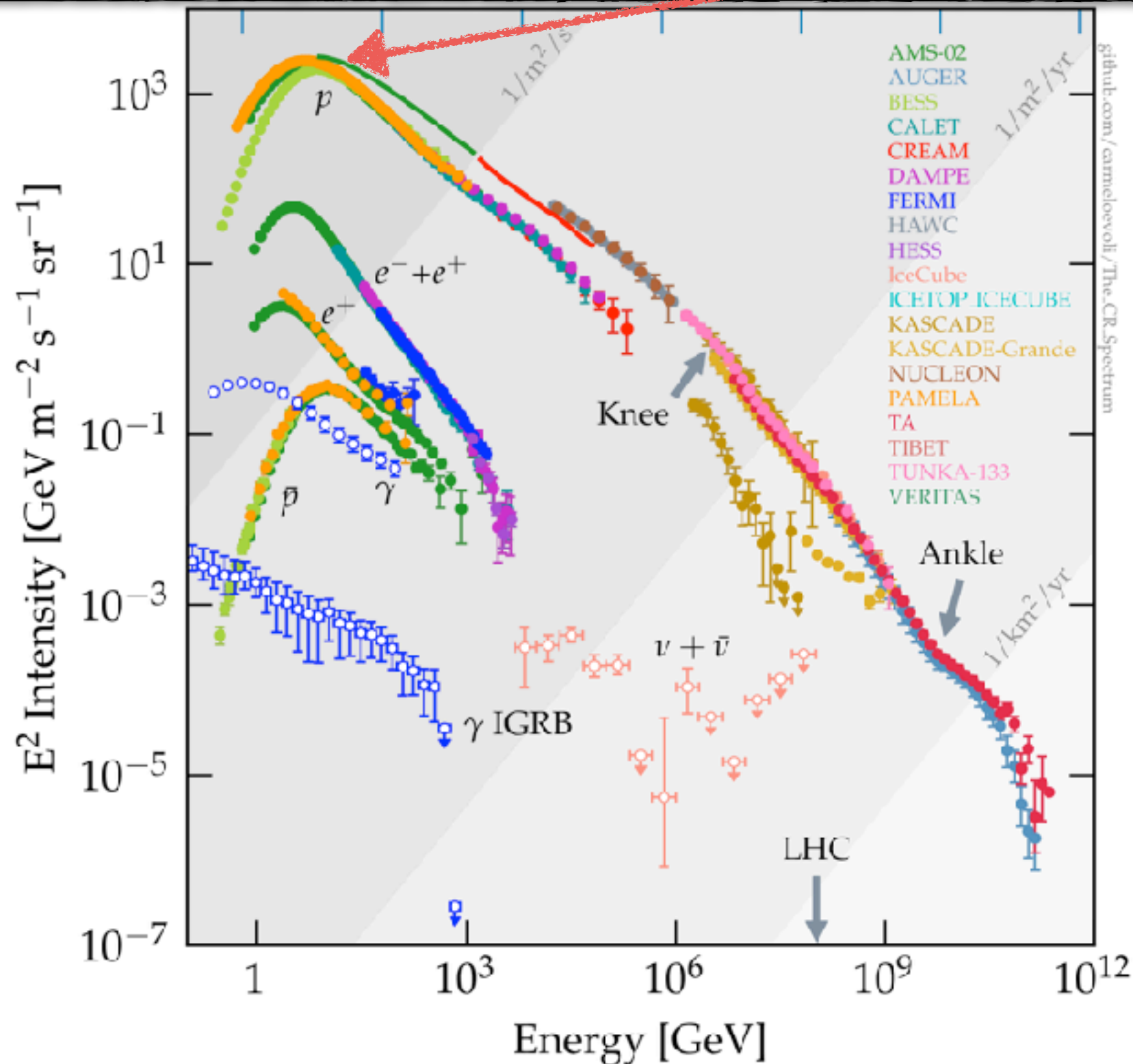


Carmelo's famous plot (v24.10 !)



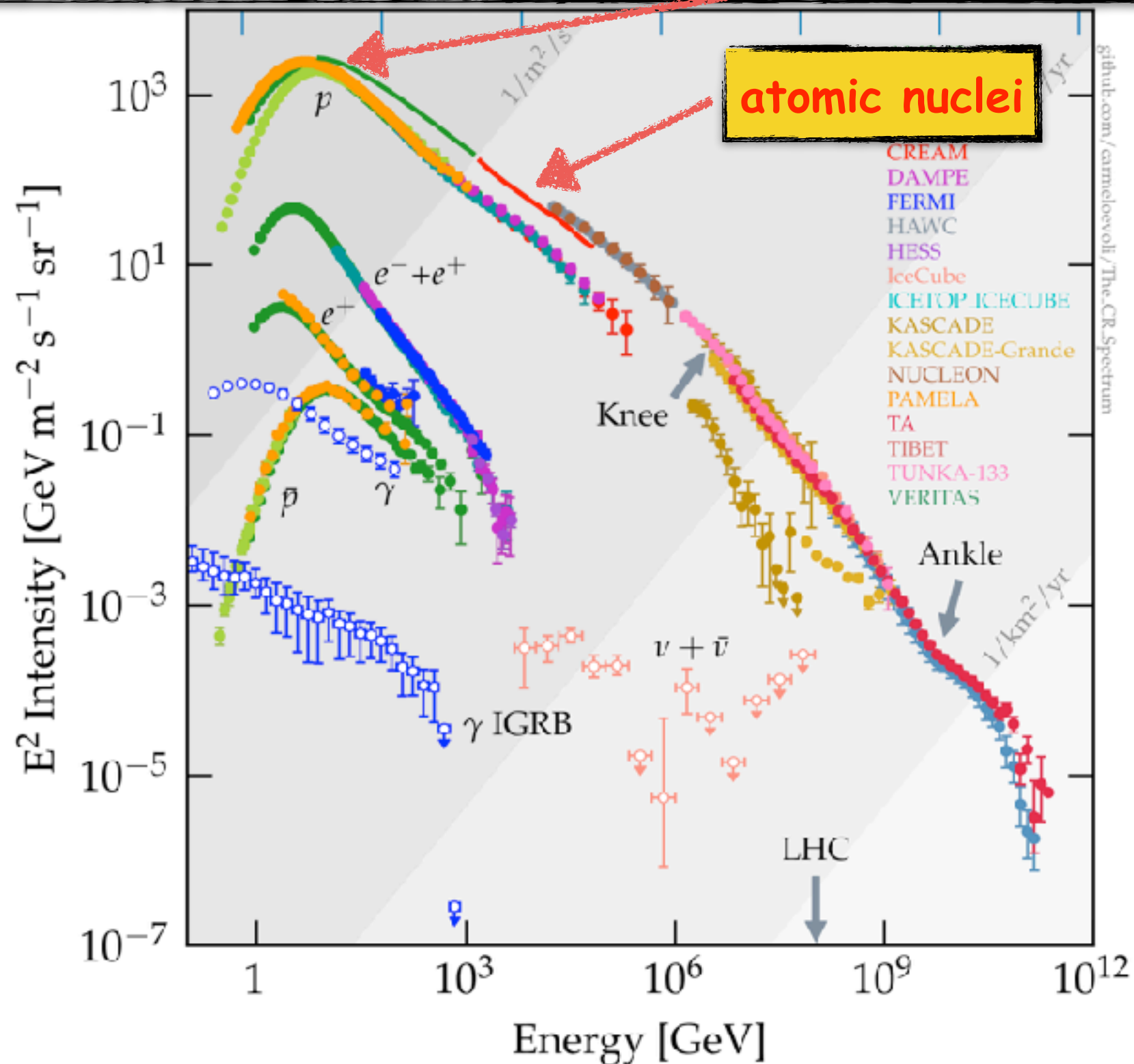
What cosmic rays are

energetic particles bombarding the Earth's atmosphere from any direction in the sky (anisotropy $\sim 10^{-3}$) at a rate $O(1000) \text{ m}^{-2} \text{ s}^{-1}$



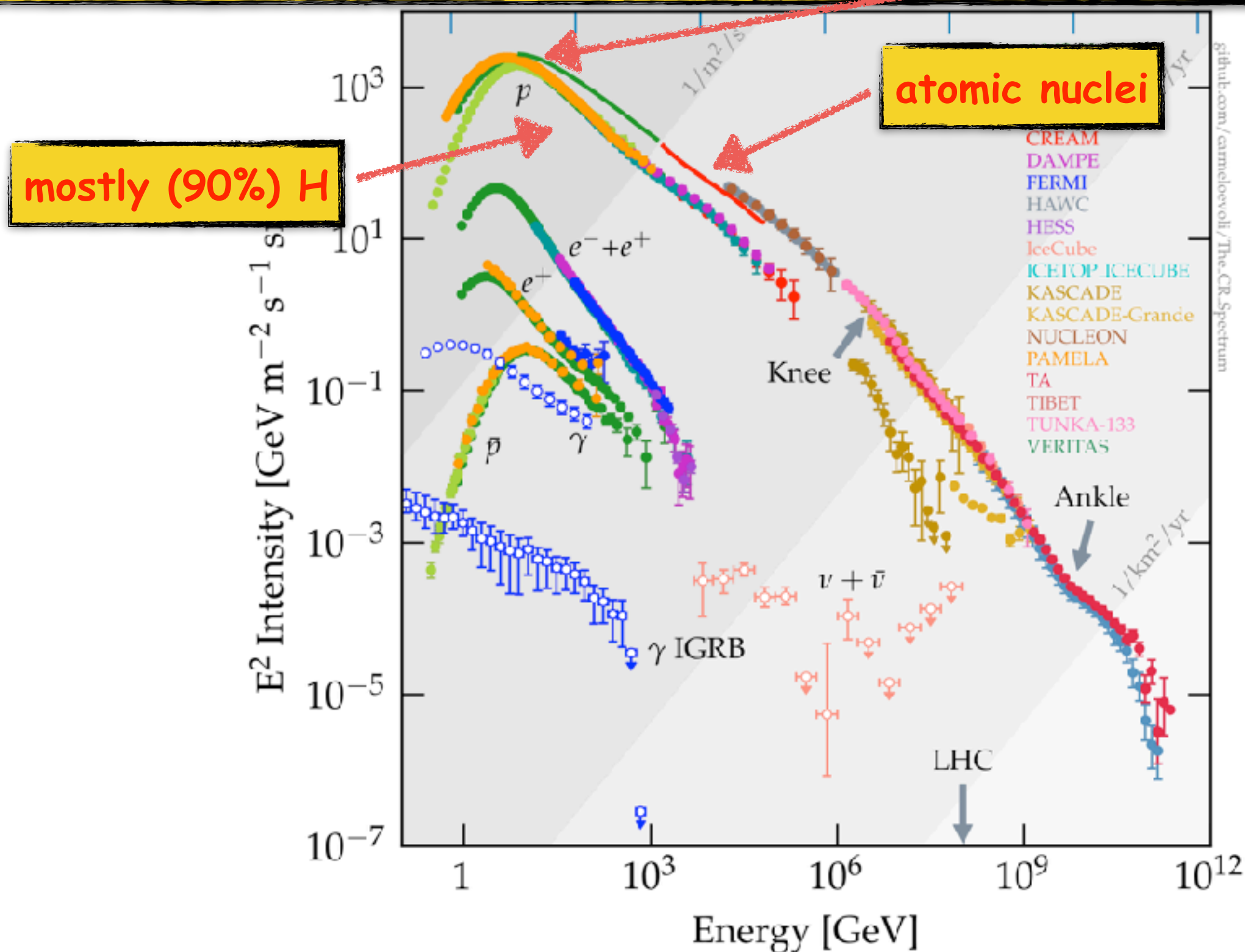
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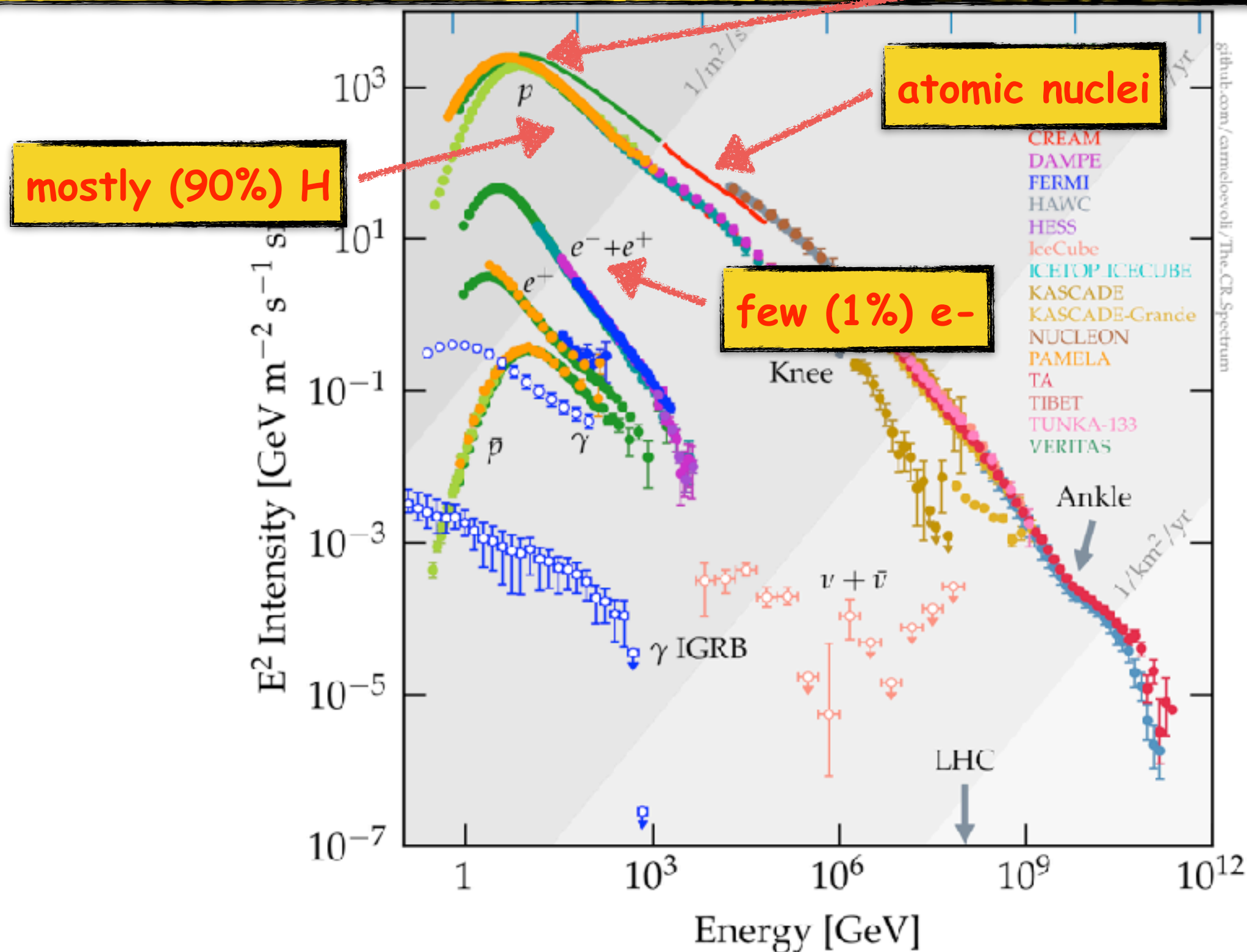
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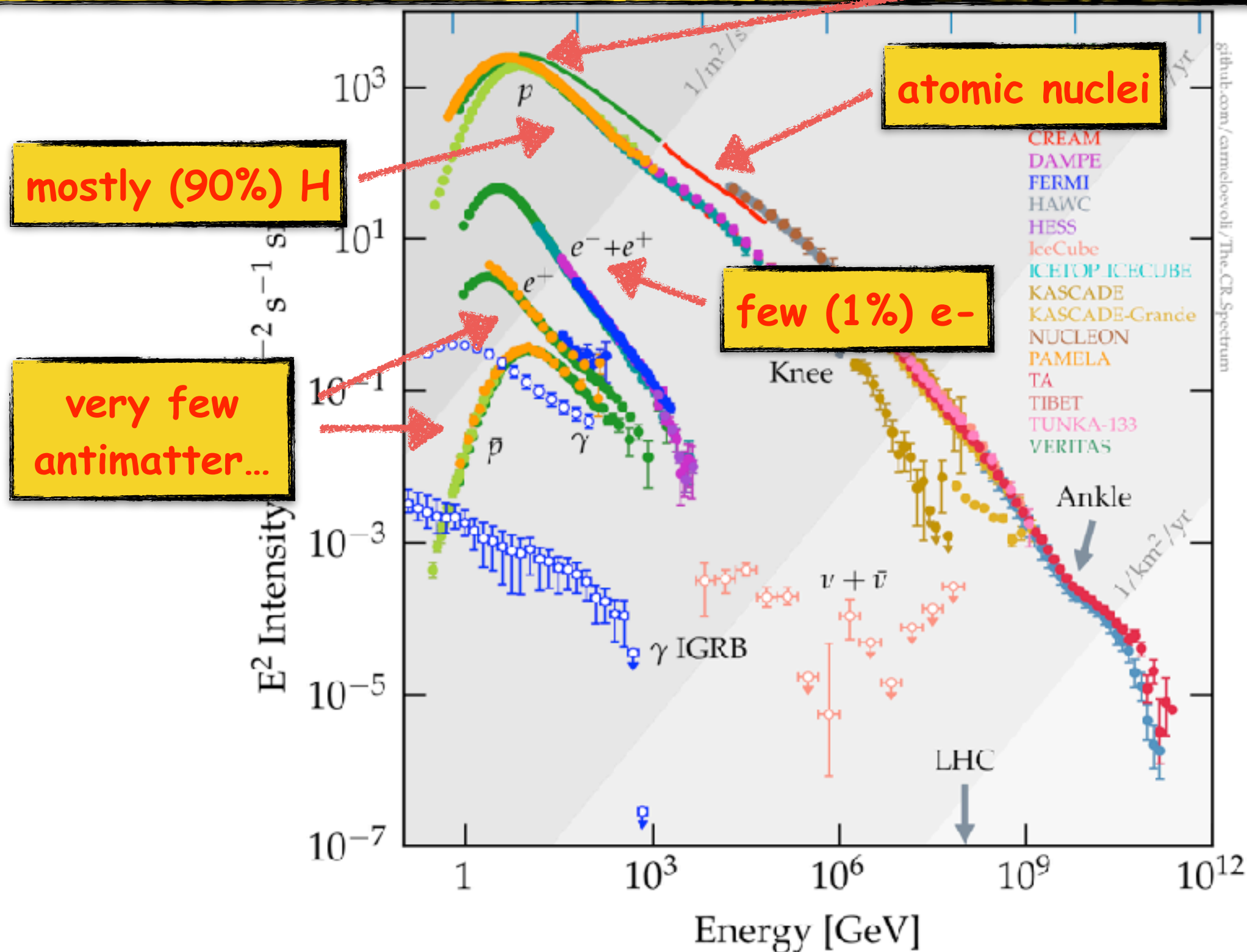
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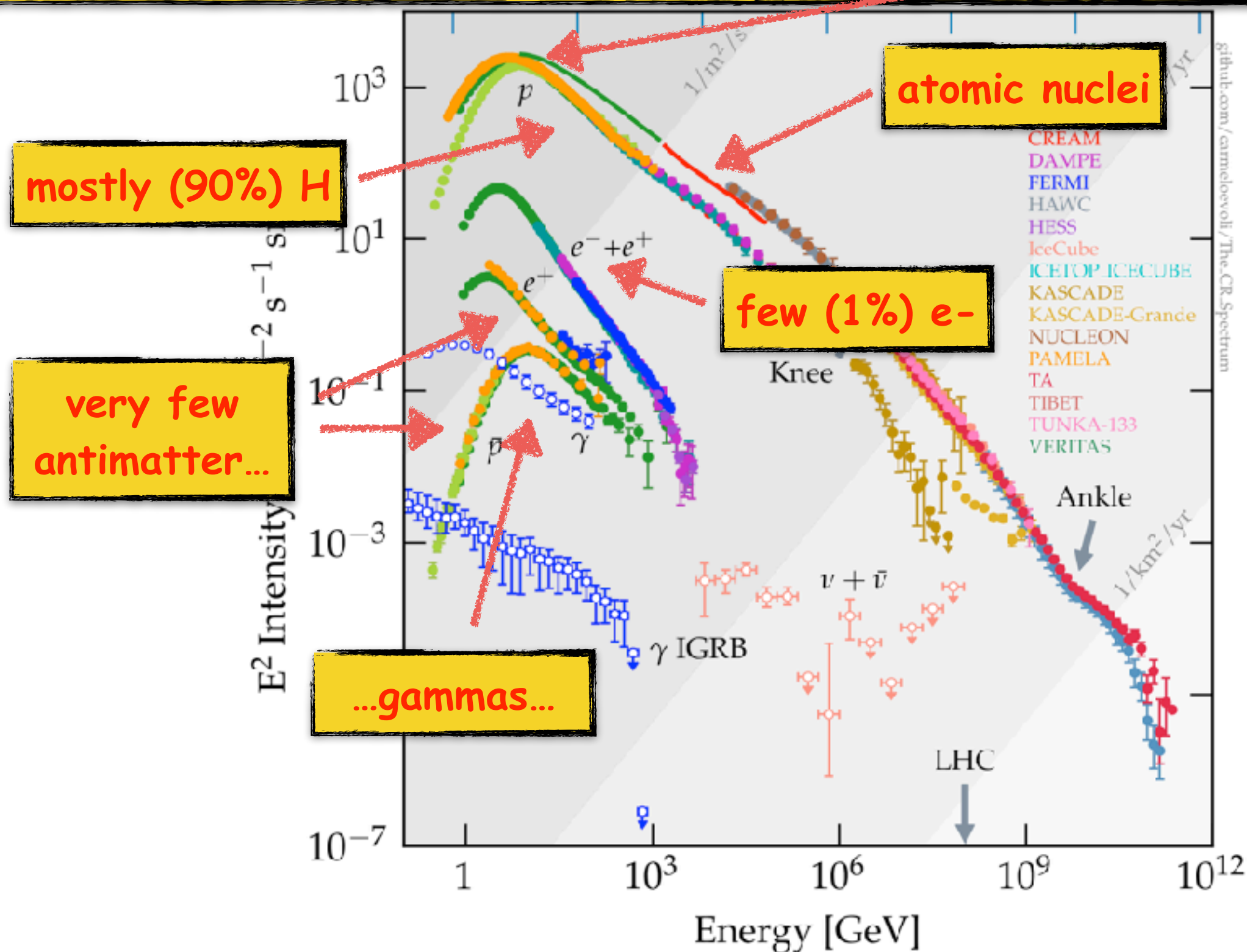
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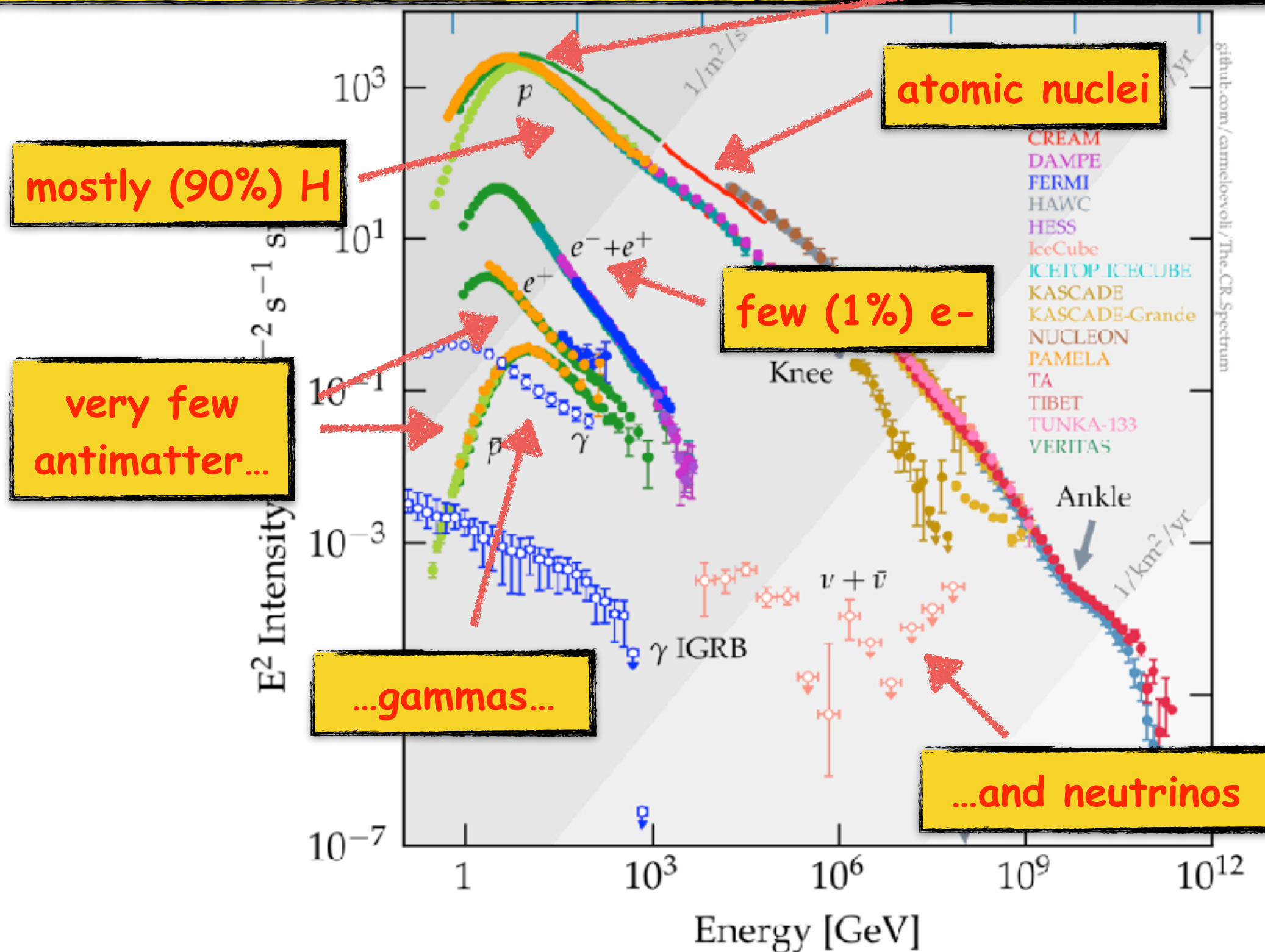
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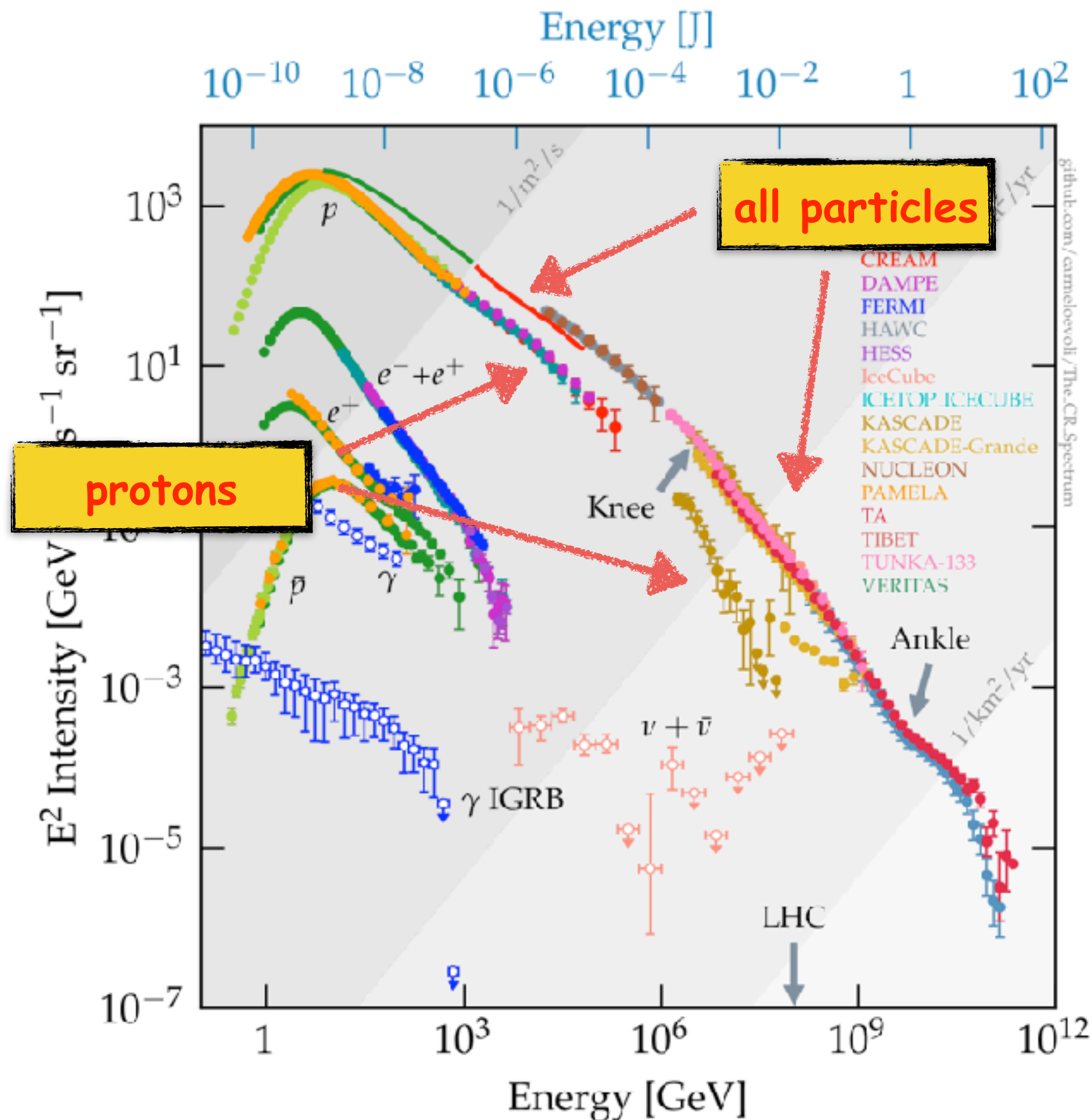


What cosmic rays are

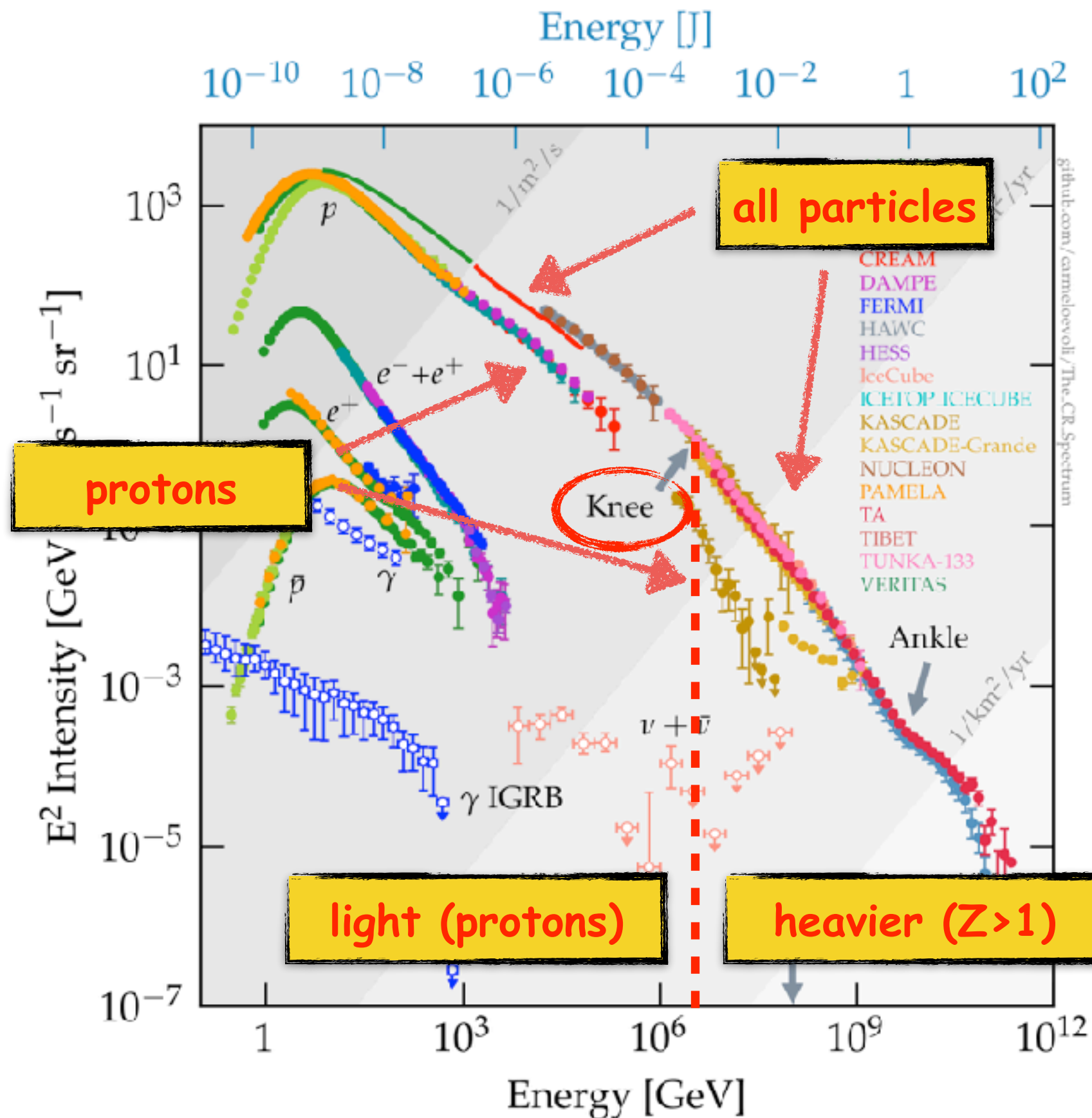
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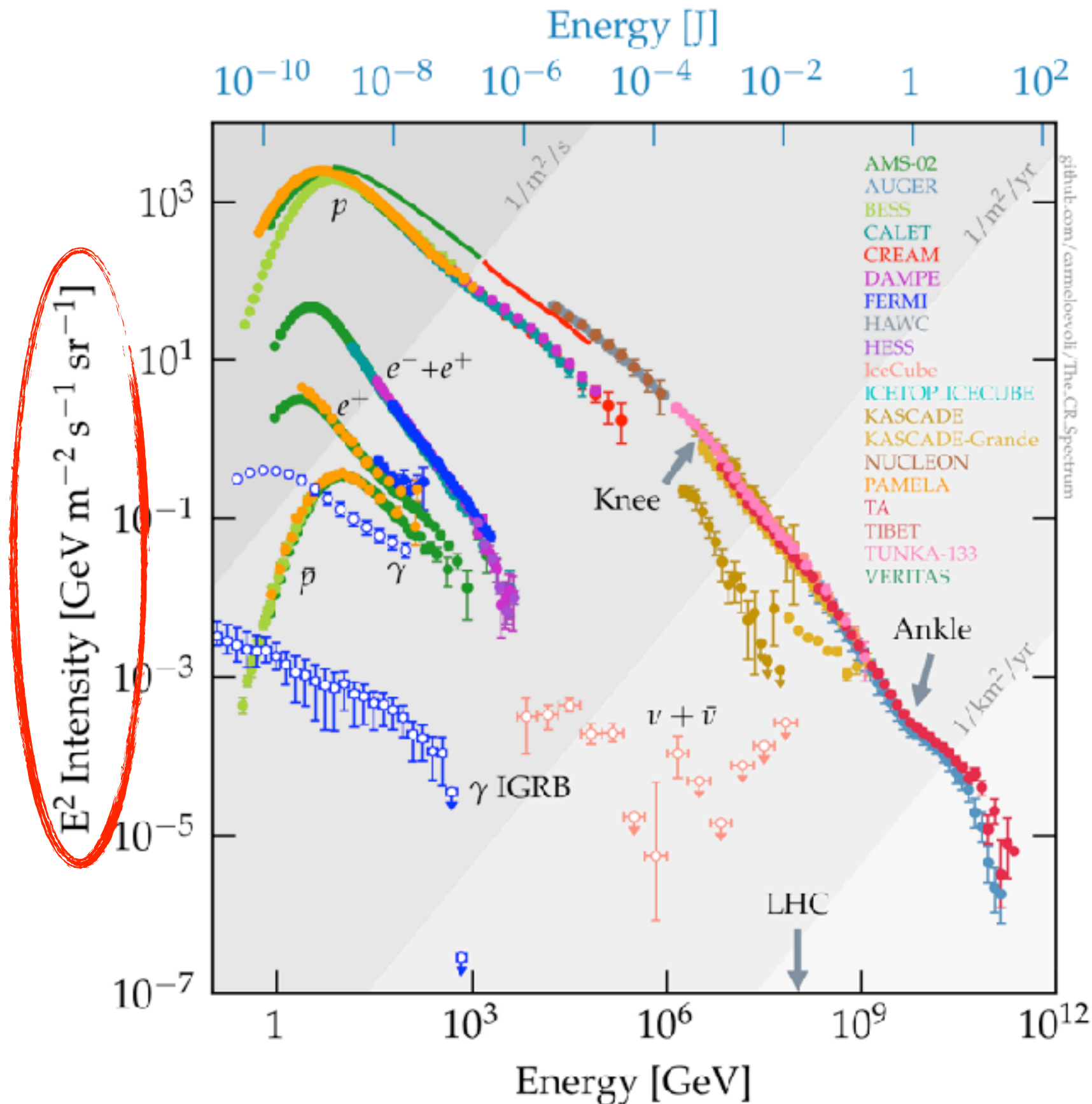
What cosmic rays are



What cosmic rays are



What cosmic rays are: energy density



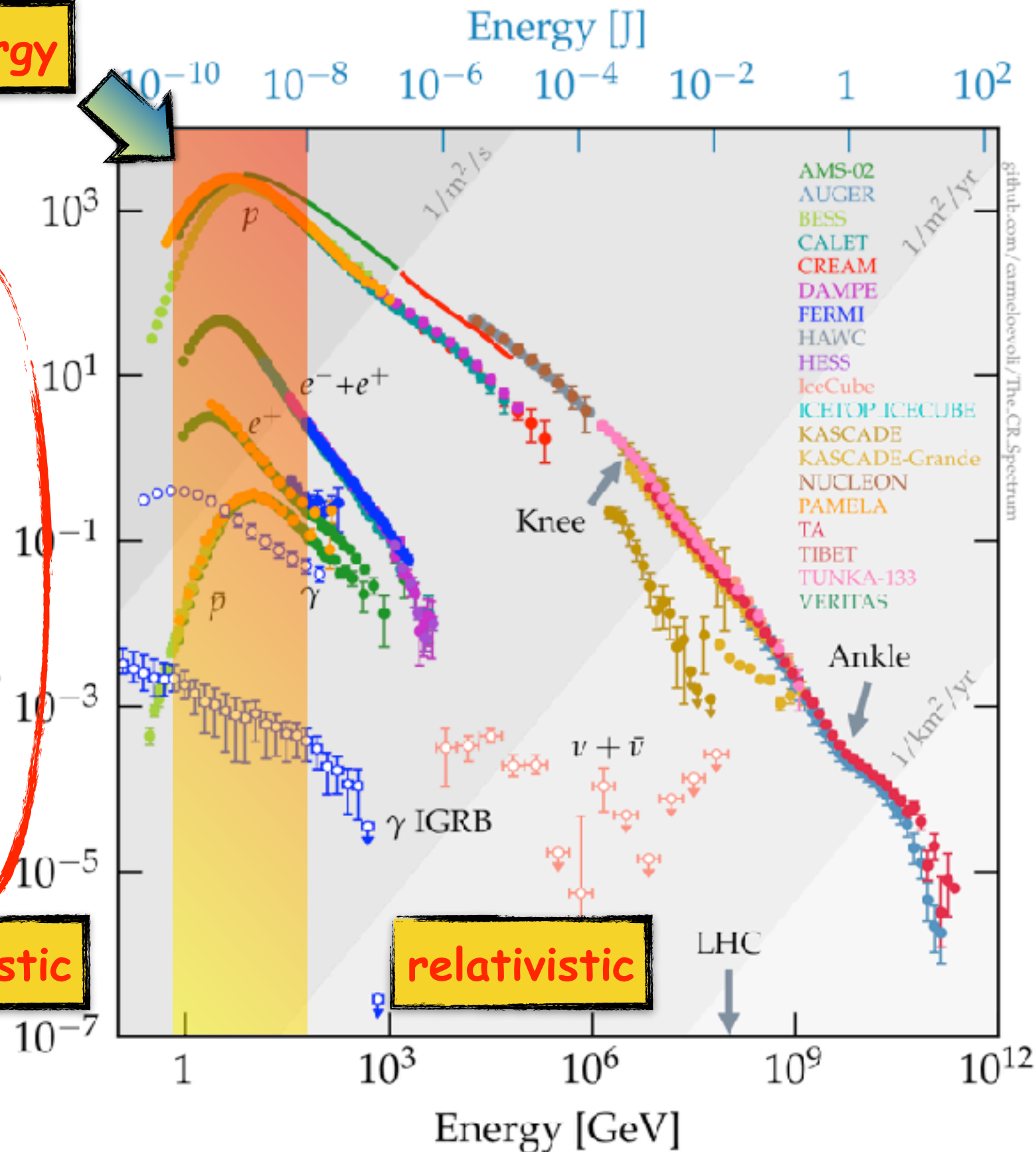
What cosmic rays are: energy density

bulk of the energy

$E^2 \text{ Intensity } [\text{GeV m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

non-relativistic

relativistic



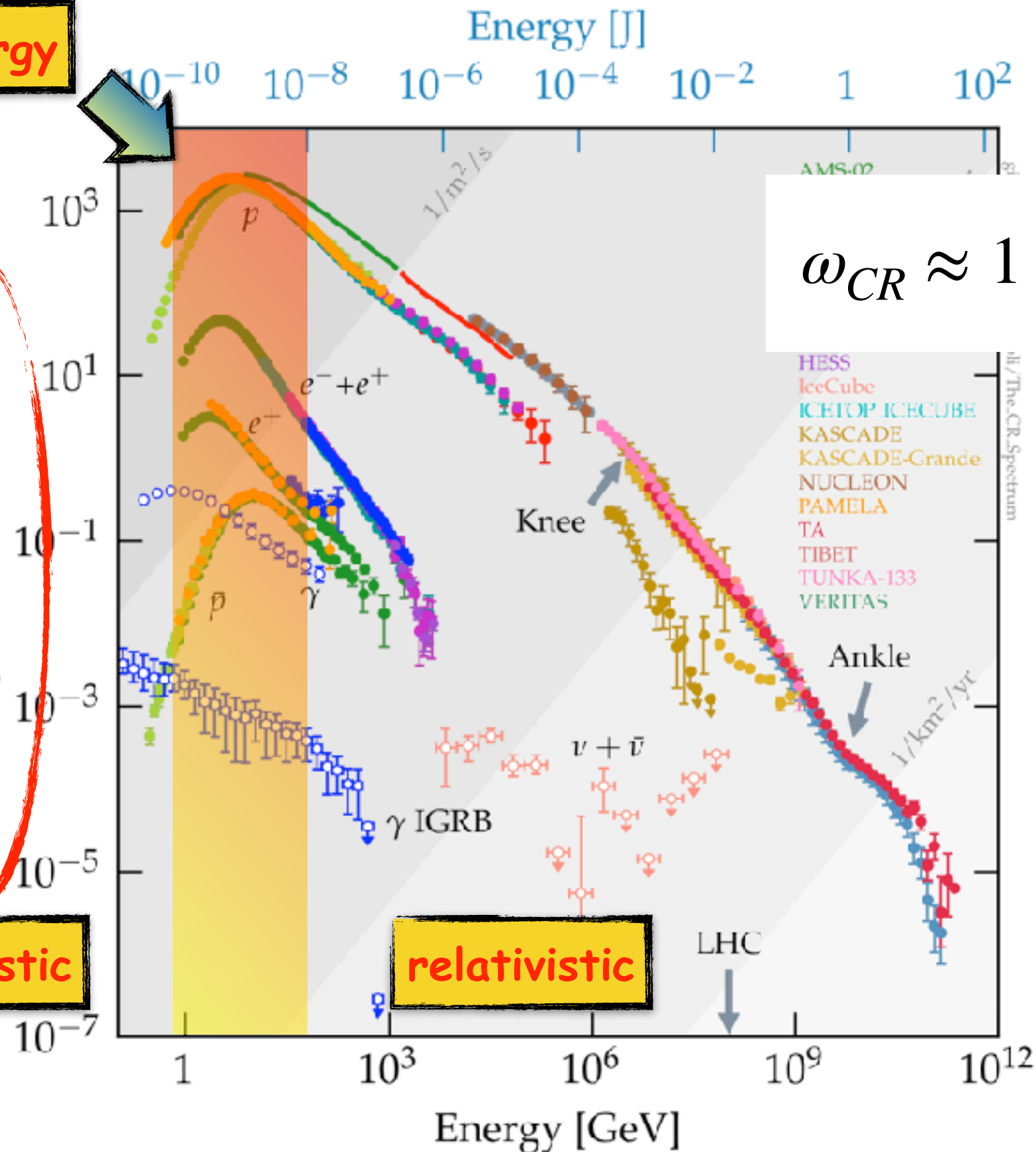
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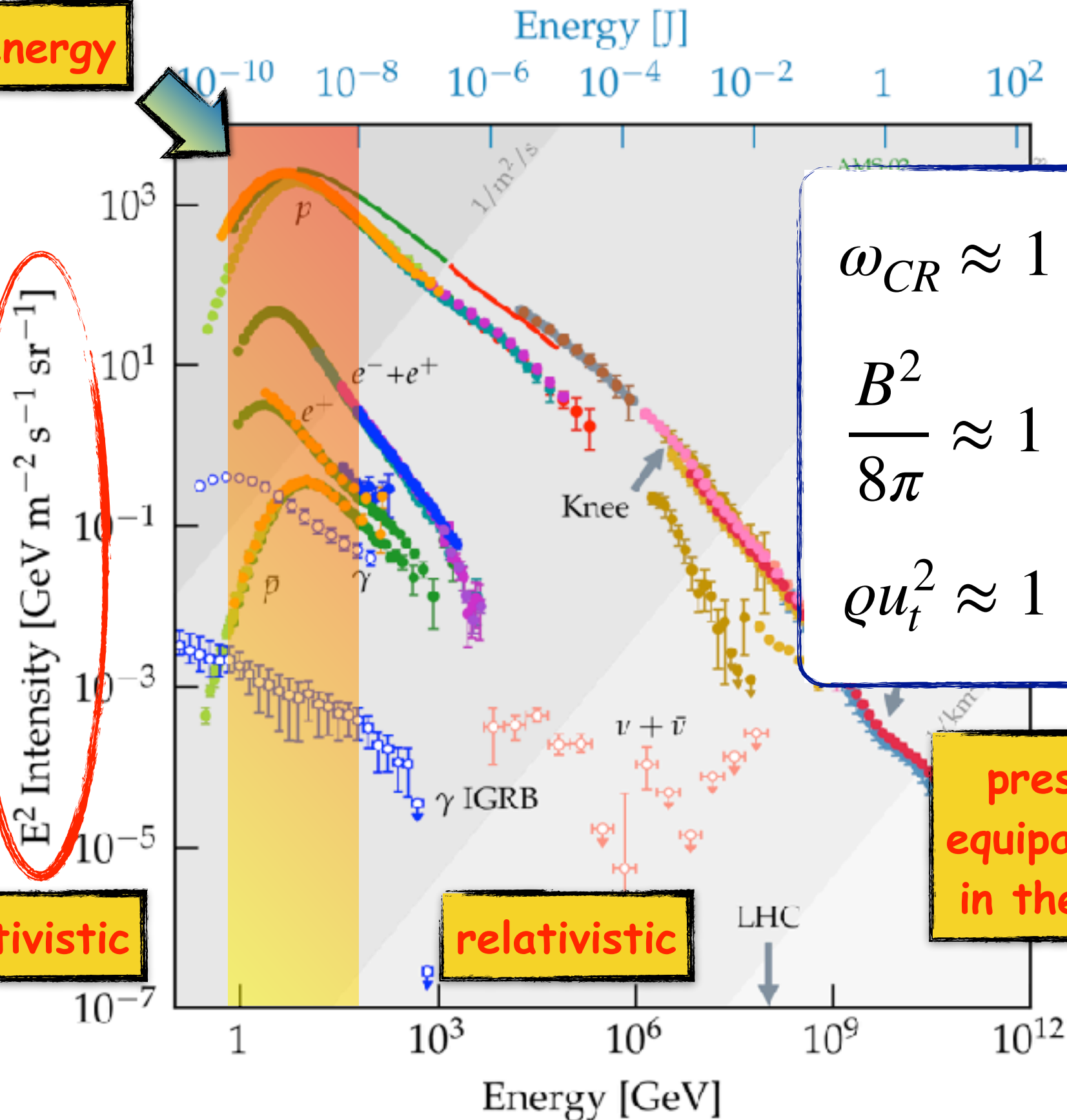
relativistic



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

What cosmic rays are: energy density

bulk of the energy



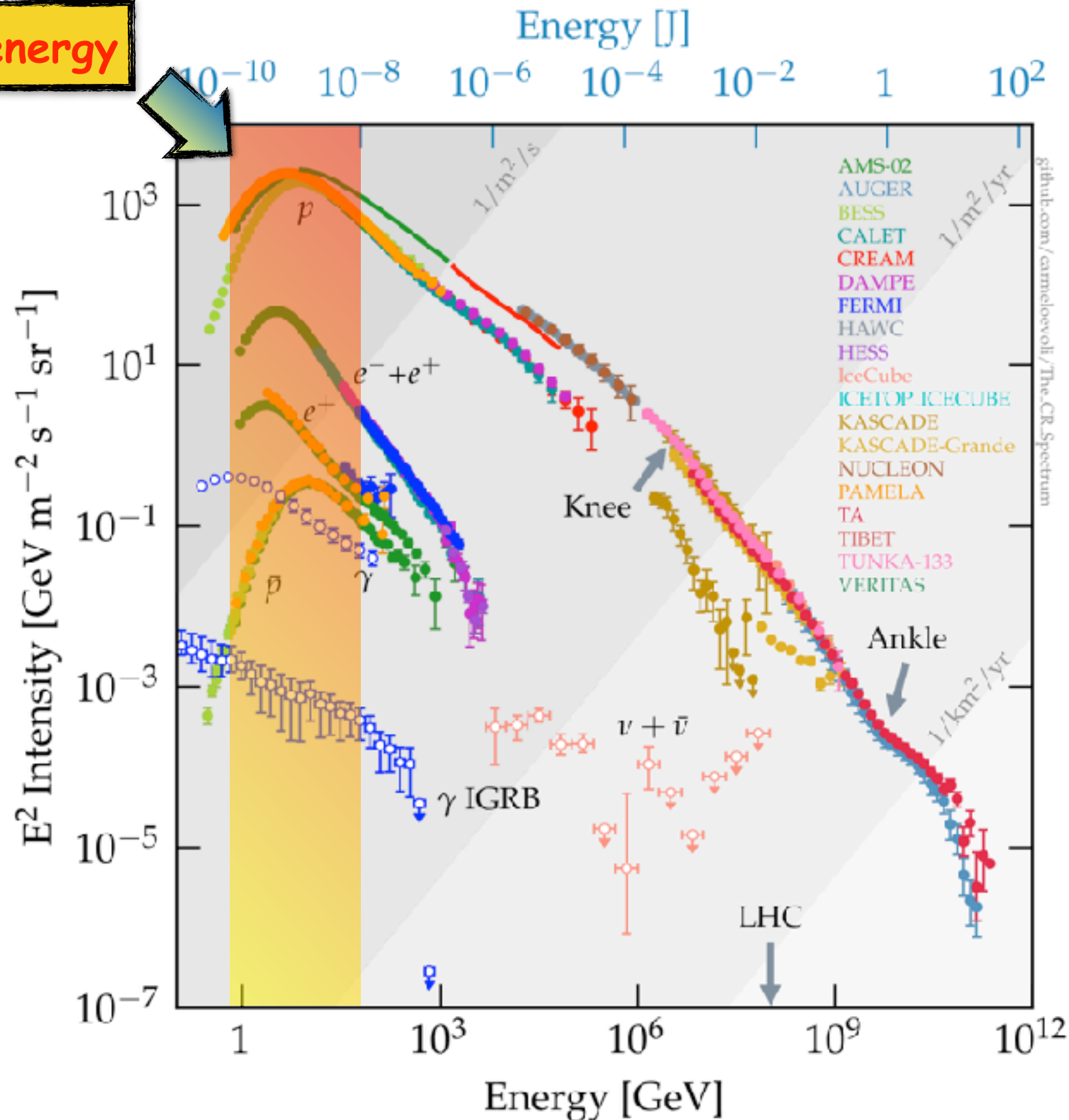
$$\omega_{CR} \approx 1 \text{ eV/cm}^{-3}$$

$$\frac{B^2}{8\pi} \approx 1 \text{ eV/cm}^{-3}$$

$$\rho u_t^2 \approx 1 \text{ eV/cm}^{-3}$$

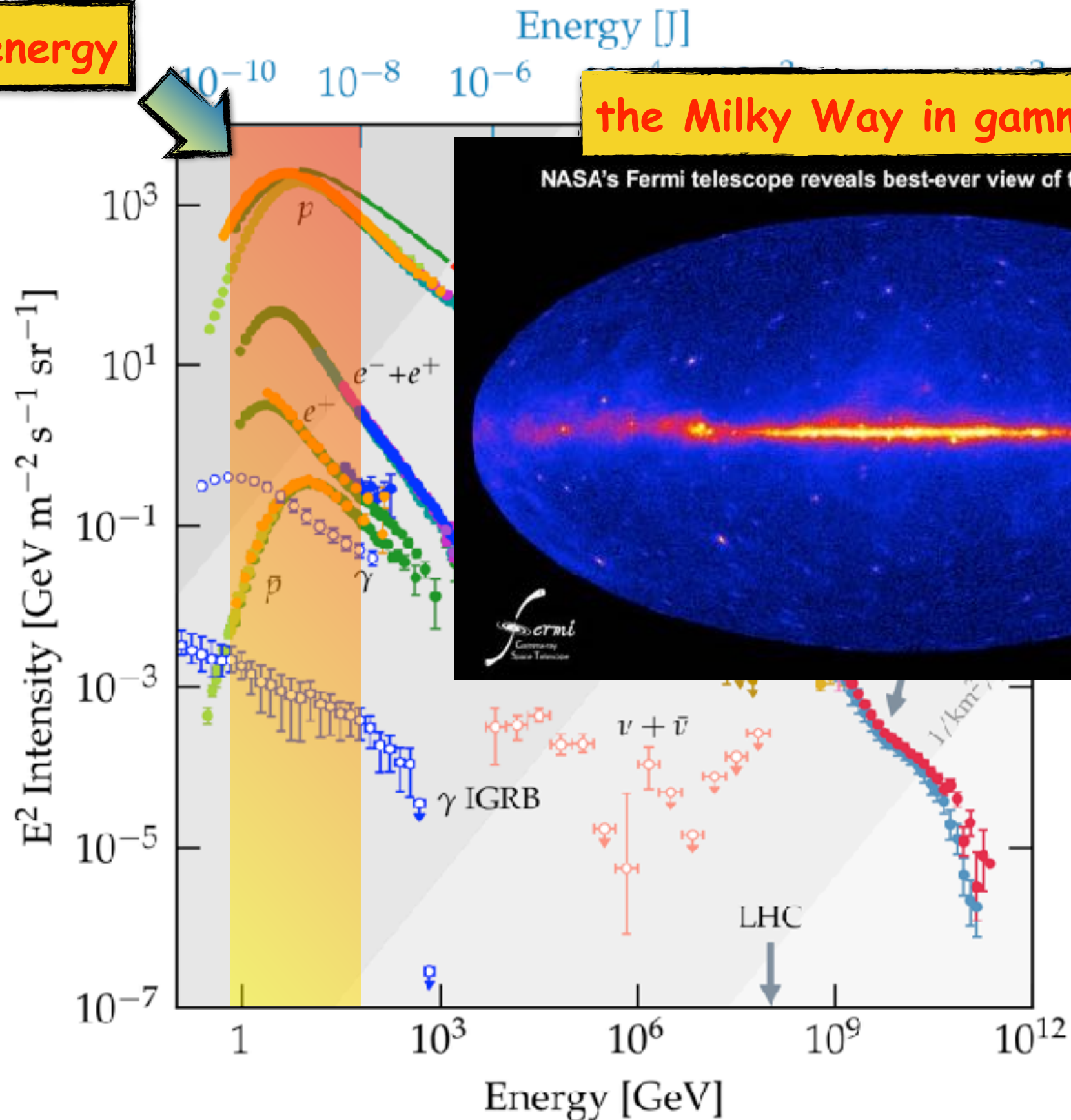
What cosmic rays are: total energy

bulk of the energy



What cosmic rays are: total energy

bulk of the energy



the Milky Way in gamma rays

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

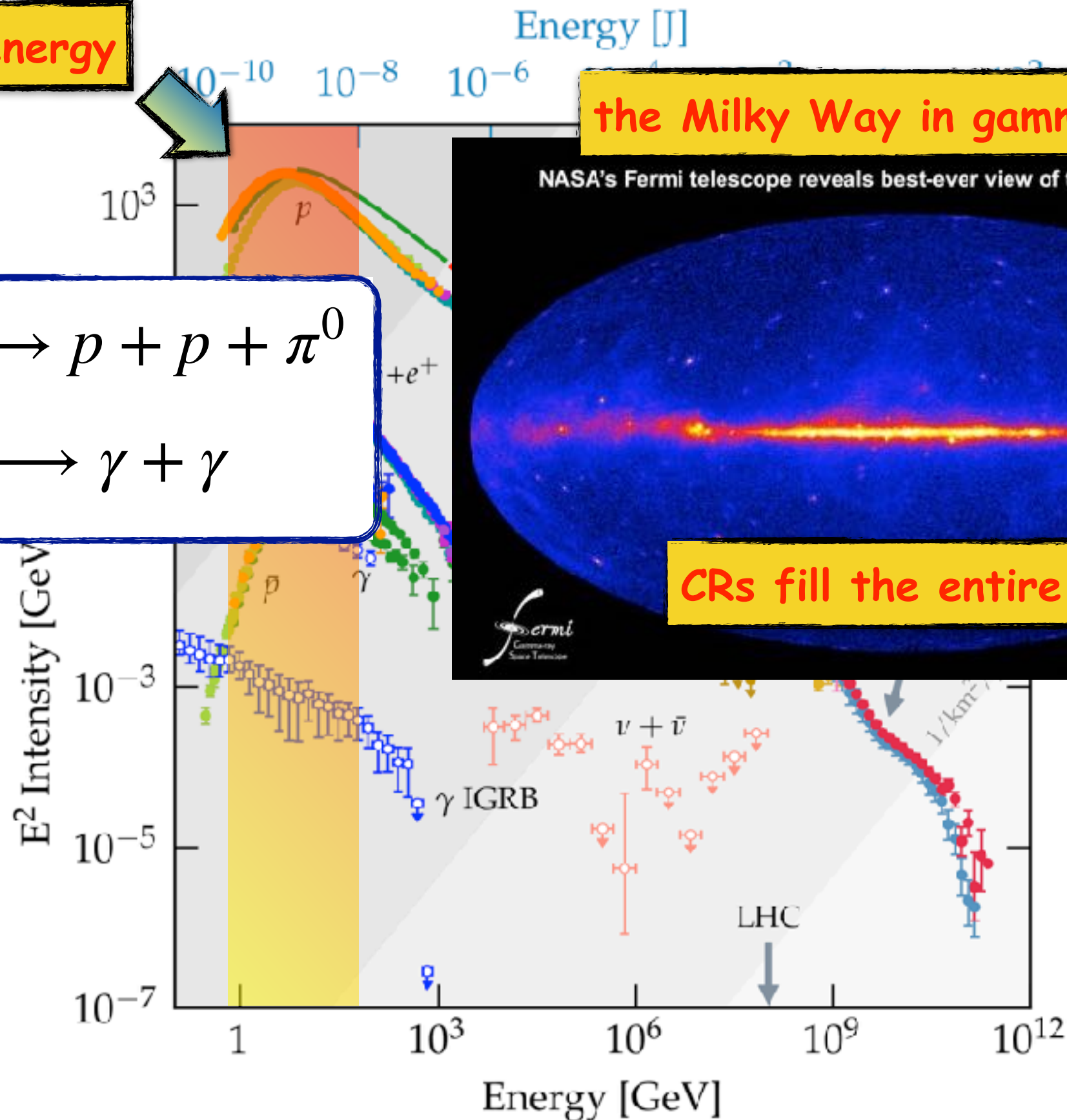
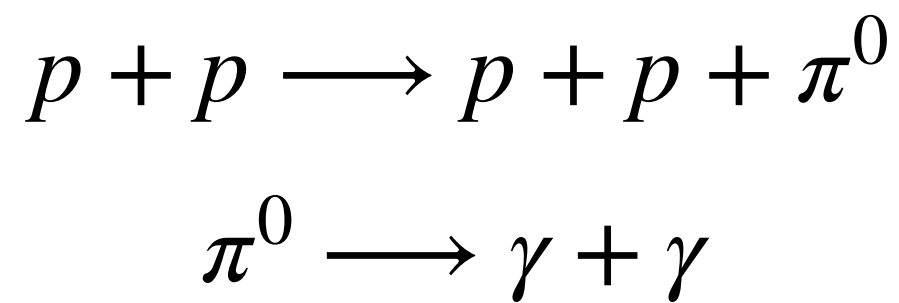
Fermi
Gamma-ray
Space Telescope

Credit: NASA/DOE/Fermi LAT Collaboration

What cosmic rays are: total energy

bulk of the energy

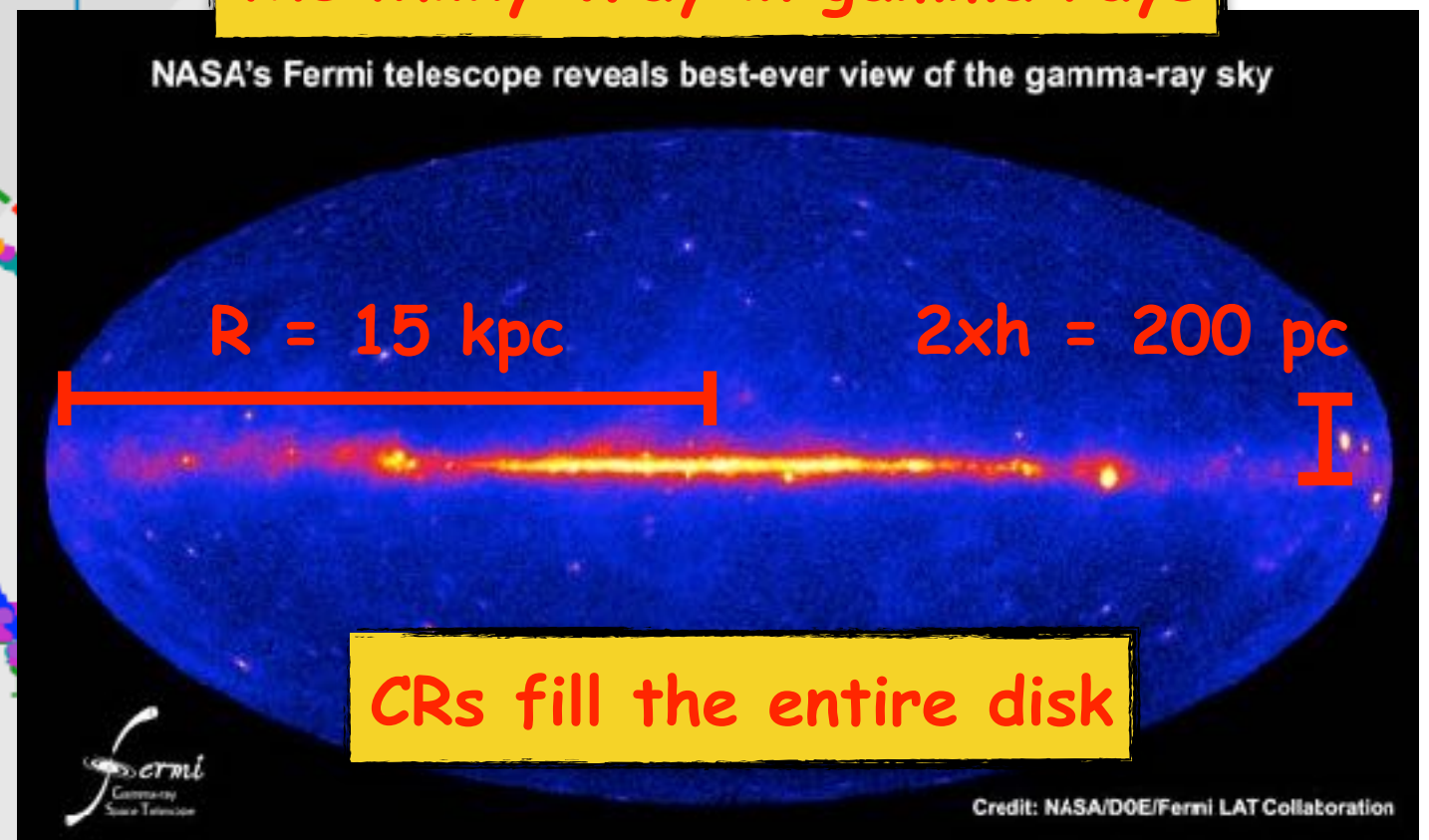
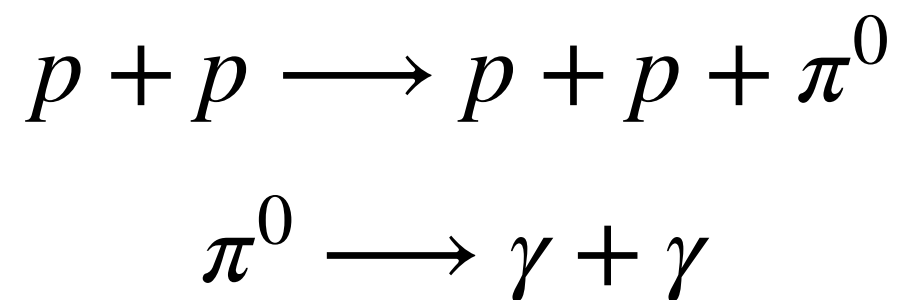
the Milky Way in gamma rays



What cosmic rays are: total energy

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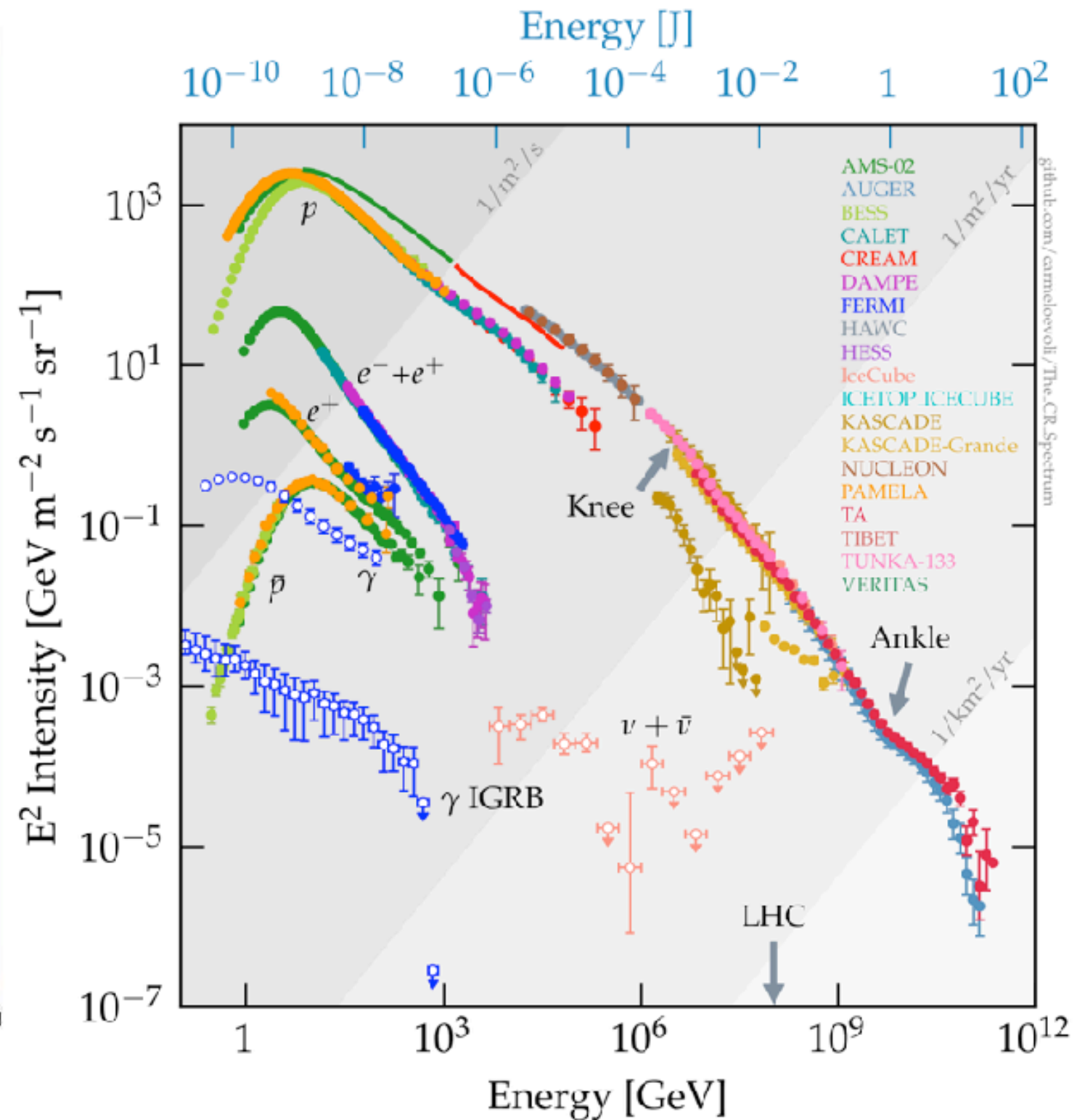
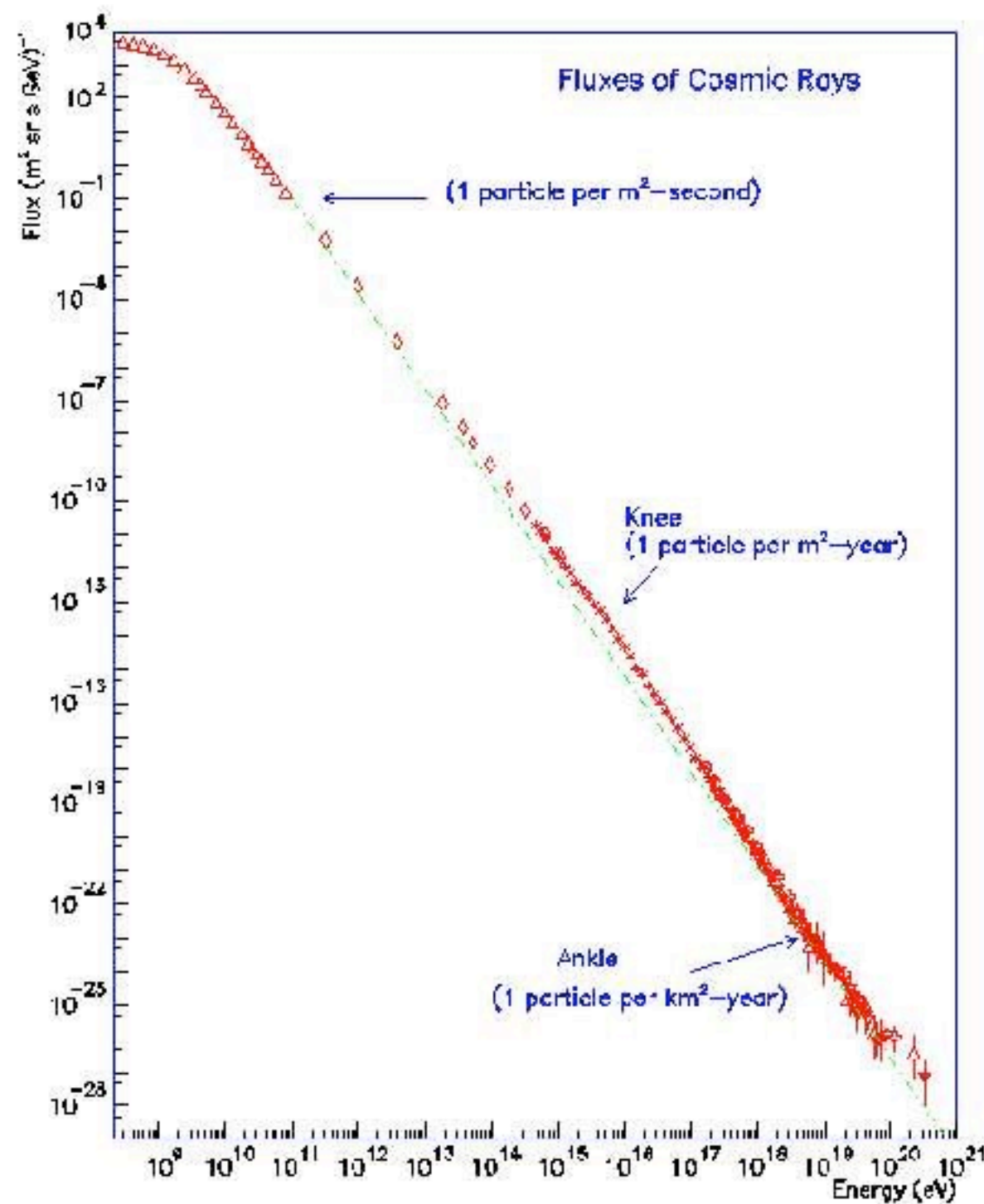


CRs fill the entire disk

total CR energy in the disk

$$W_{CR} = \omega_{CR} \times V \approx 7 \times 10^{54} \left(\frac{R}{15 \text{ kpc}} \right)^2 \left(\frac{h}{100 \text{ pc}} \right) \text{ erg}$$

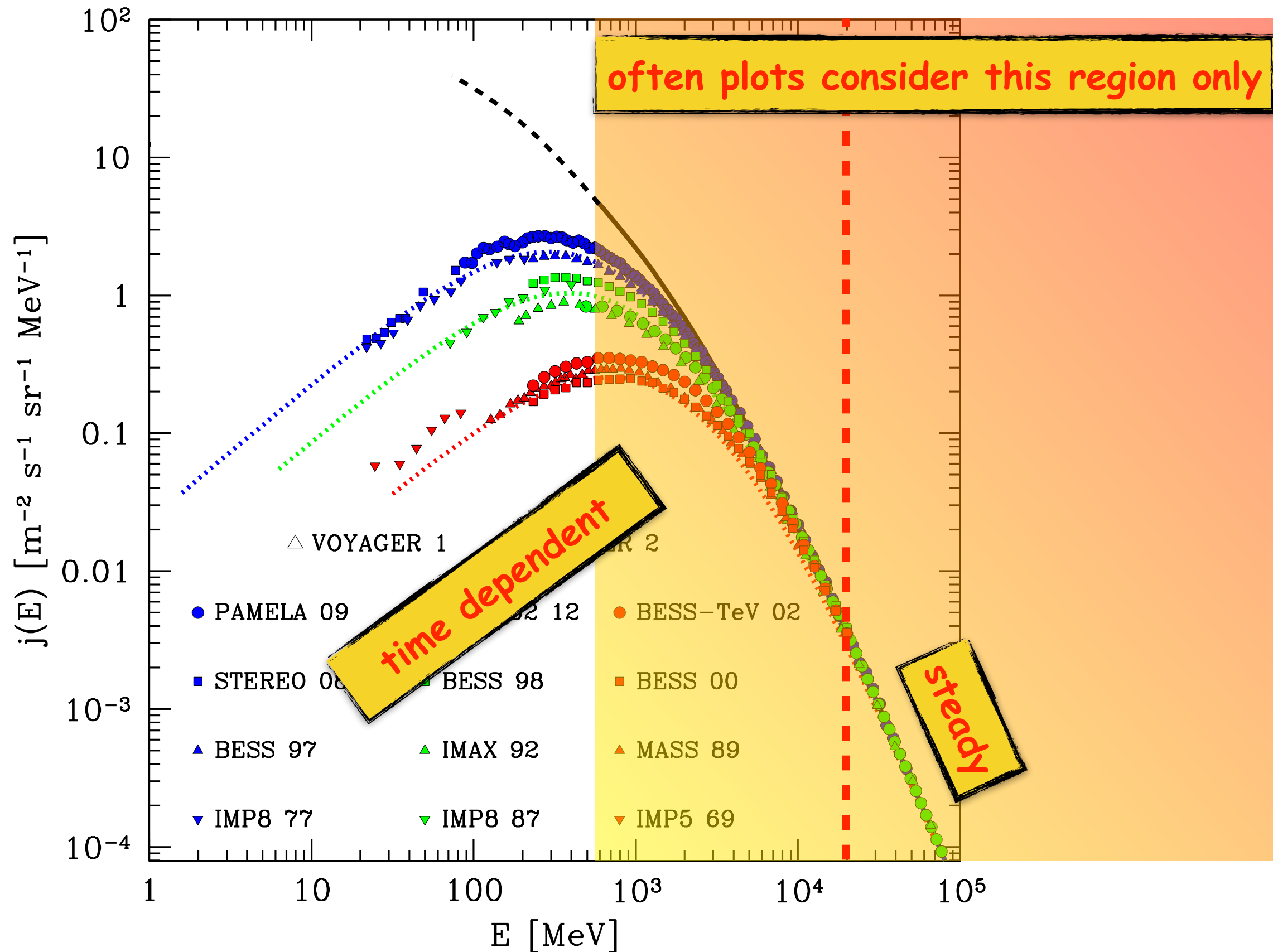
Something is often missing...



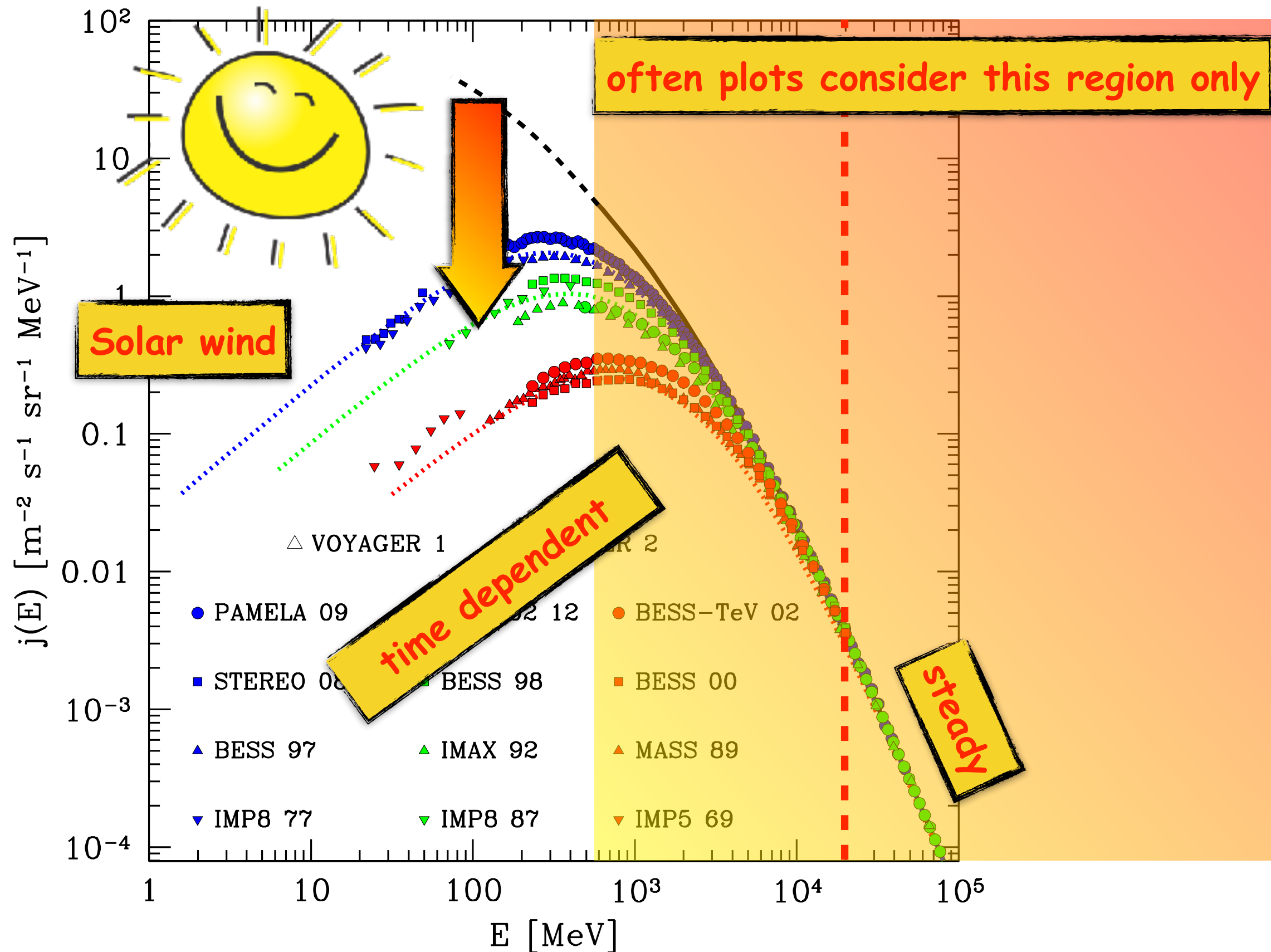
Swordy 2001 (originally prepared for Cronin,
Gaisser & Sword, SciAm, 1996)

Evoli 2020

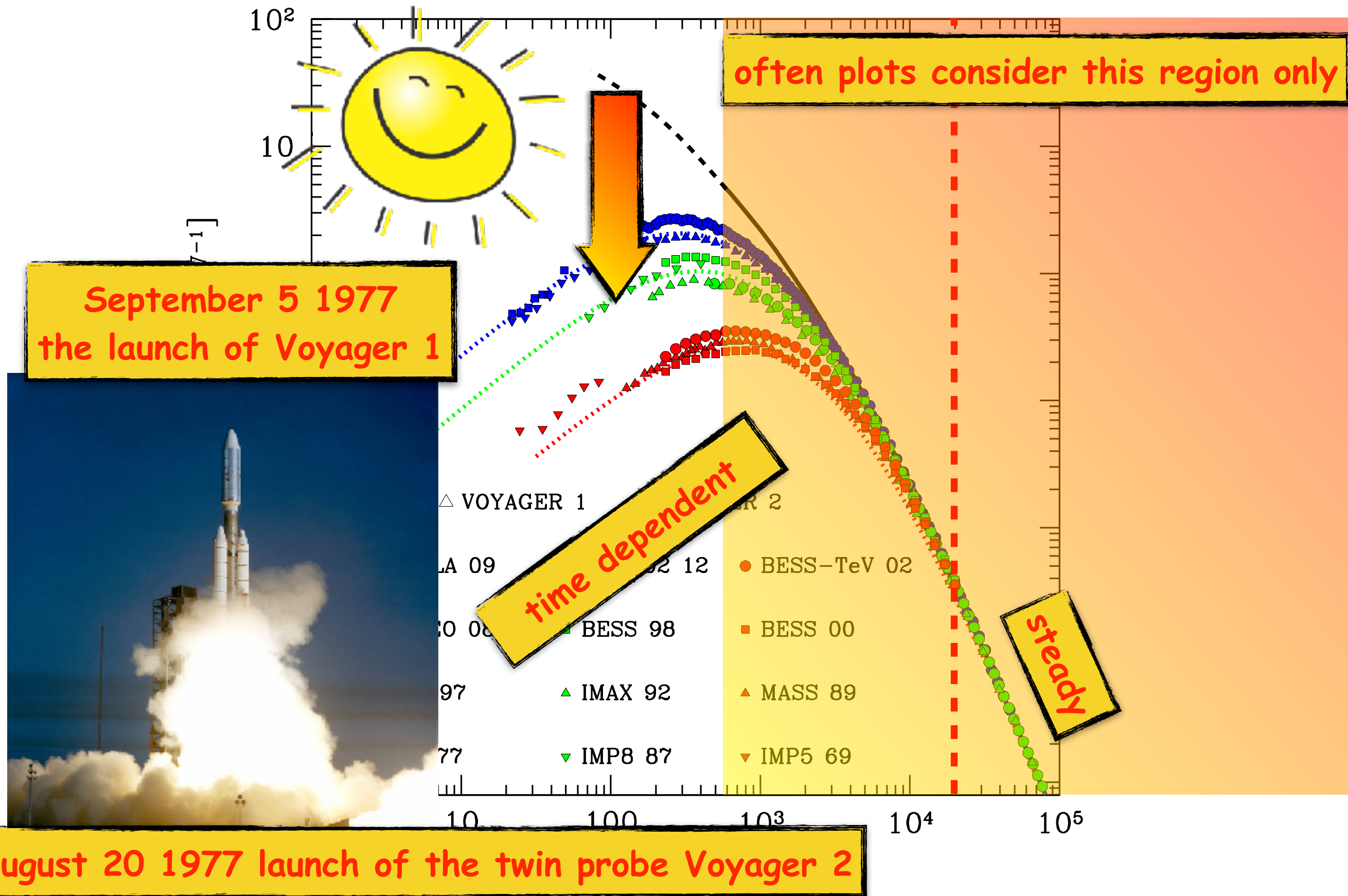
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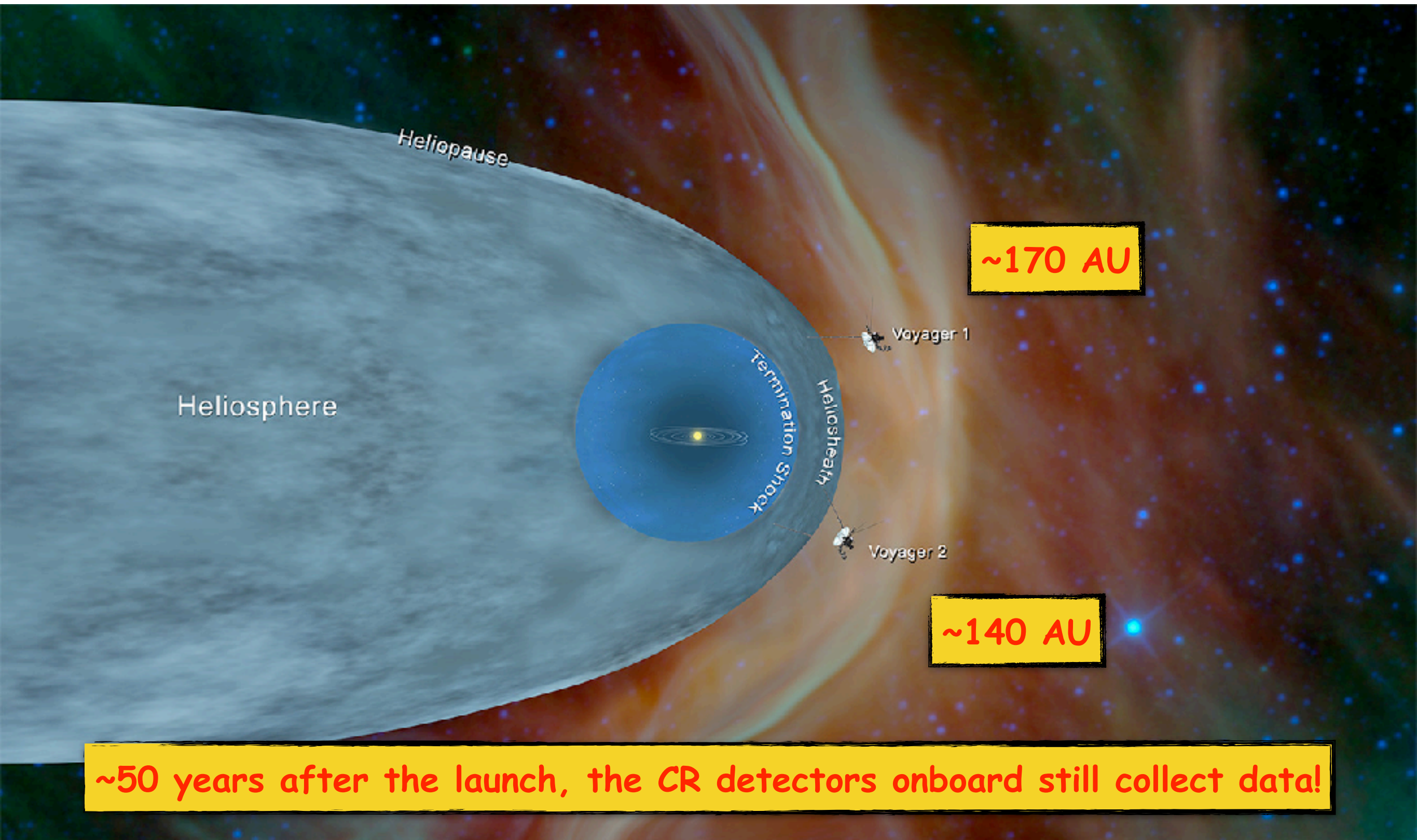
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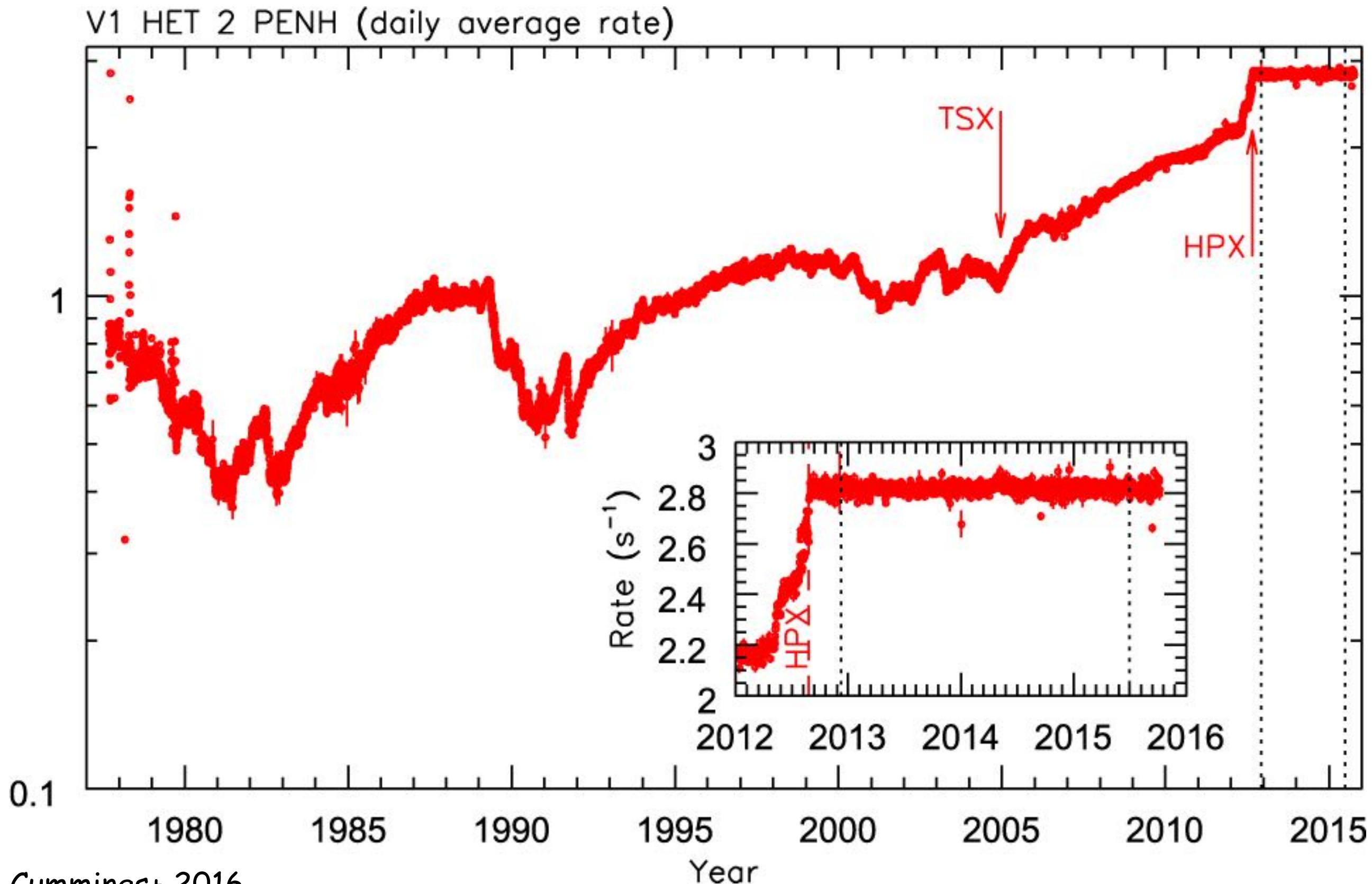
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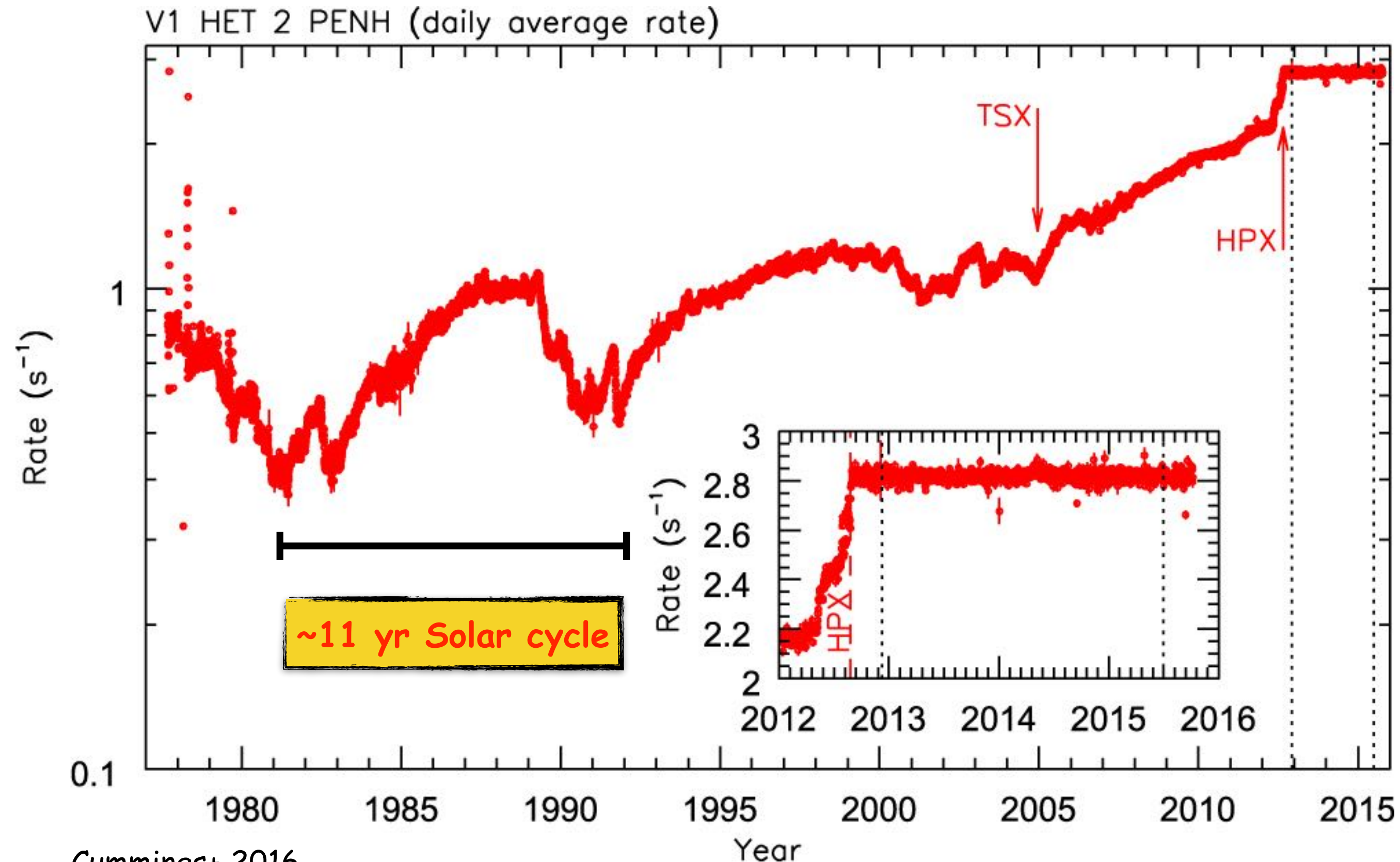
Voyager probes crossed the heliopause



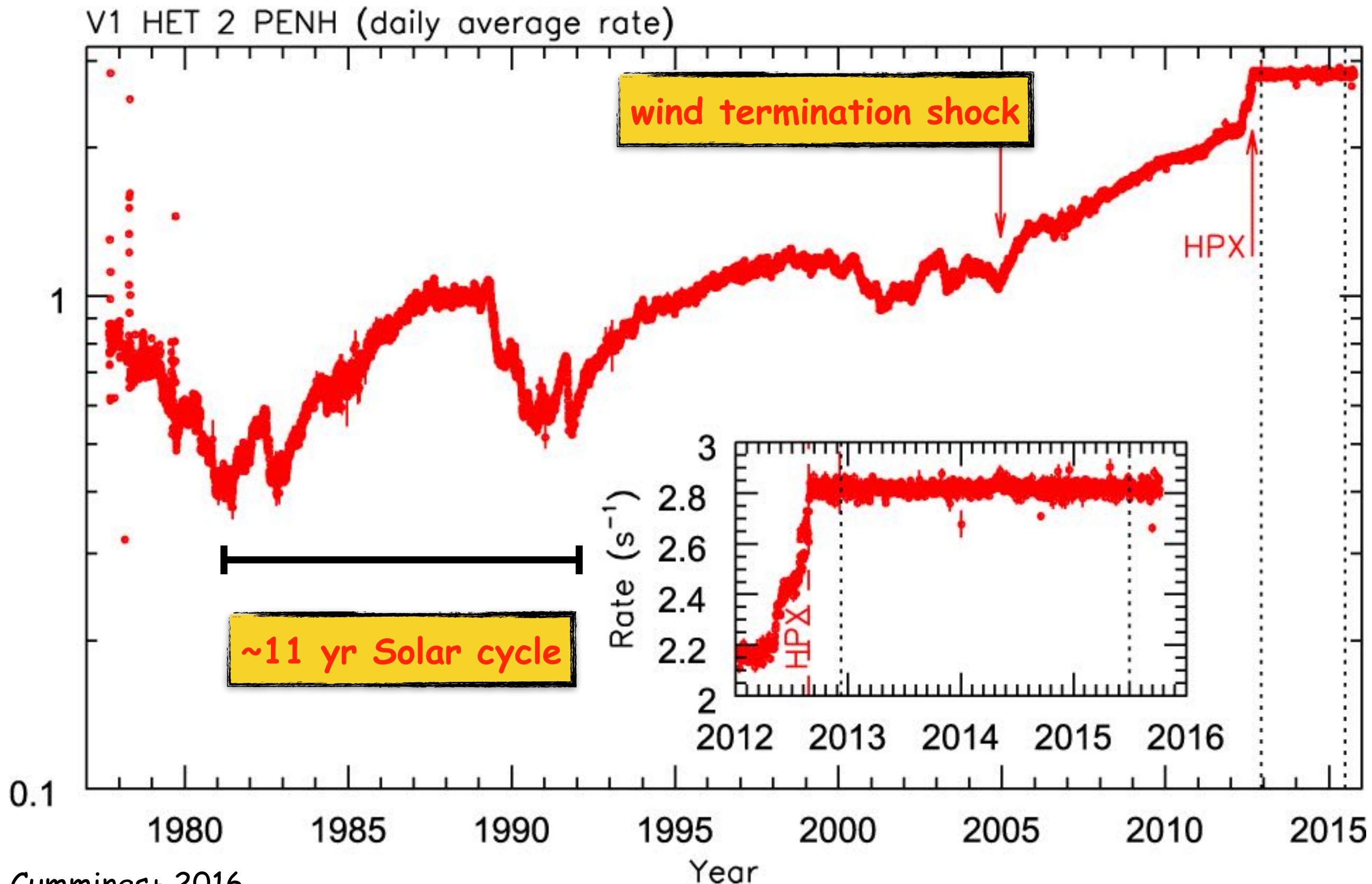
My favourite plot on cosmic rays



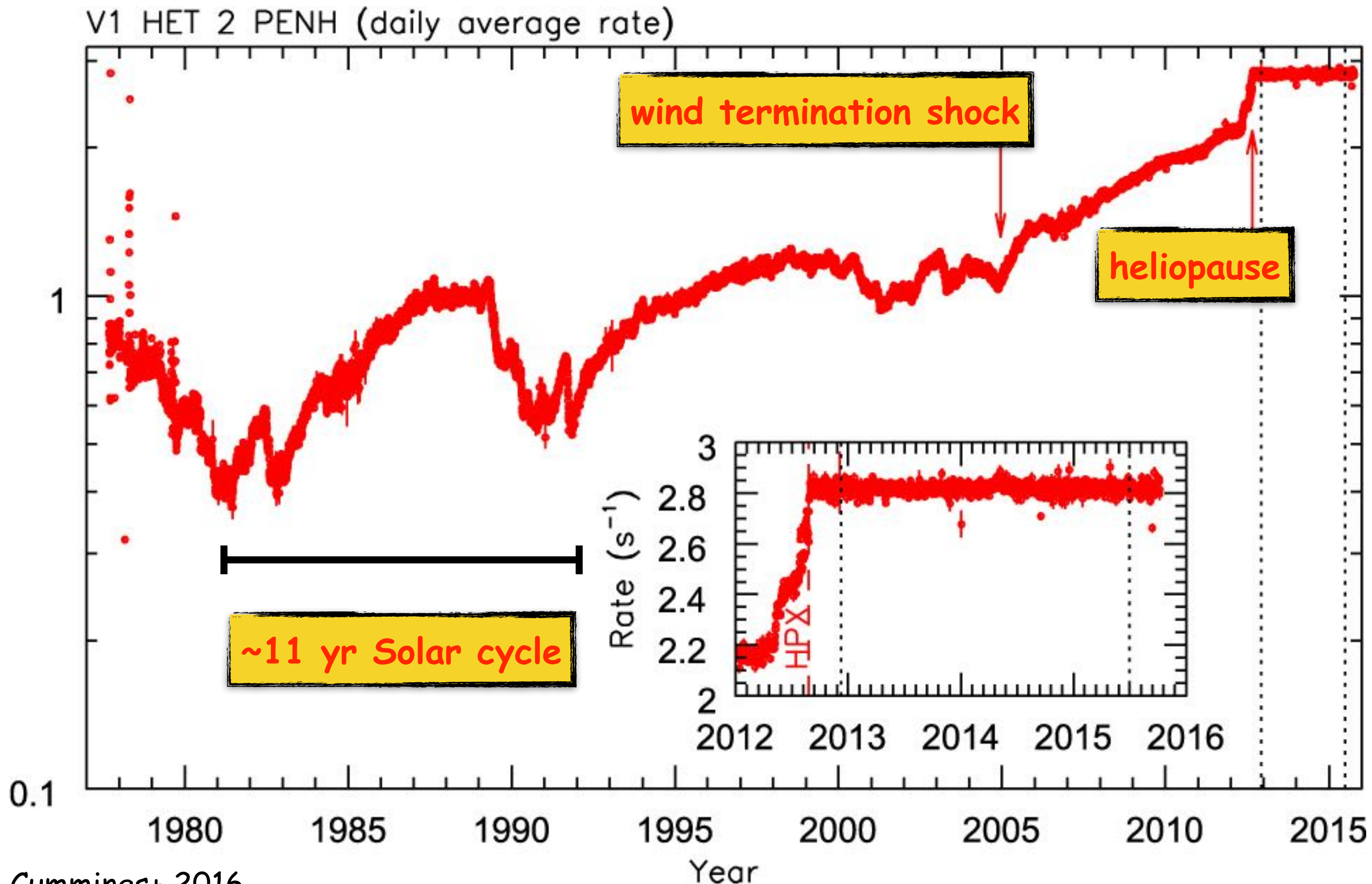
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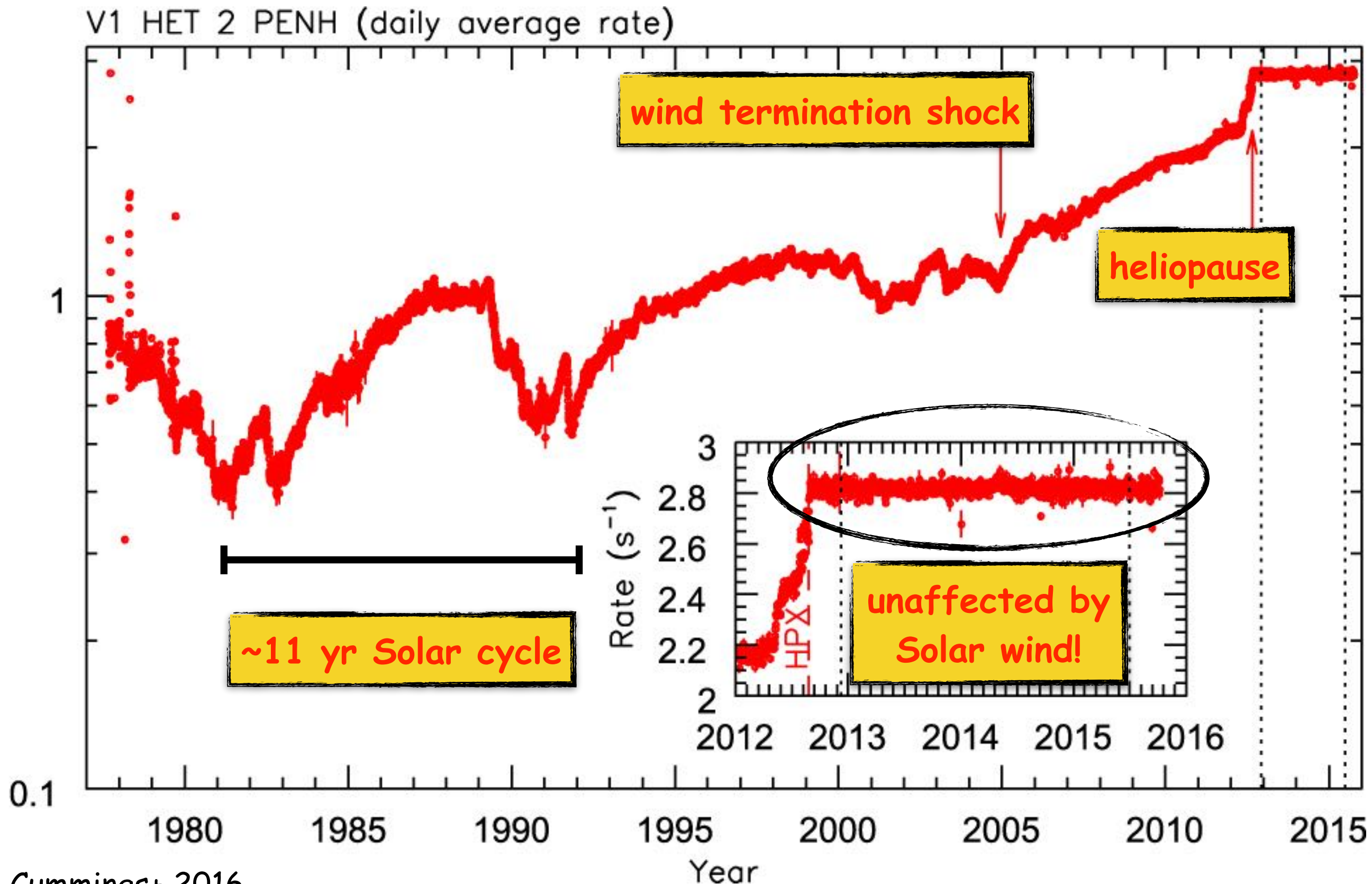
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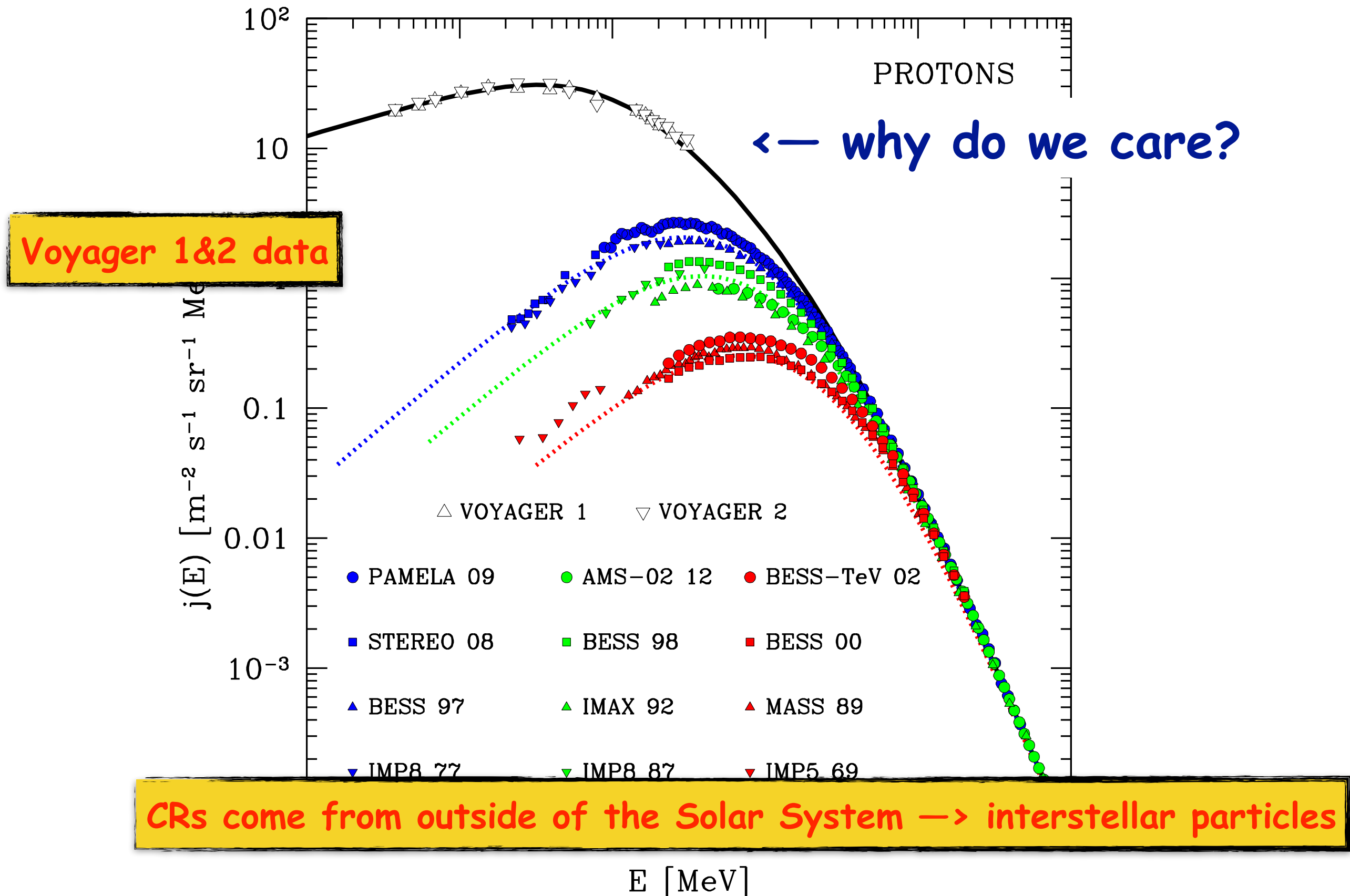
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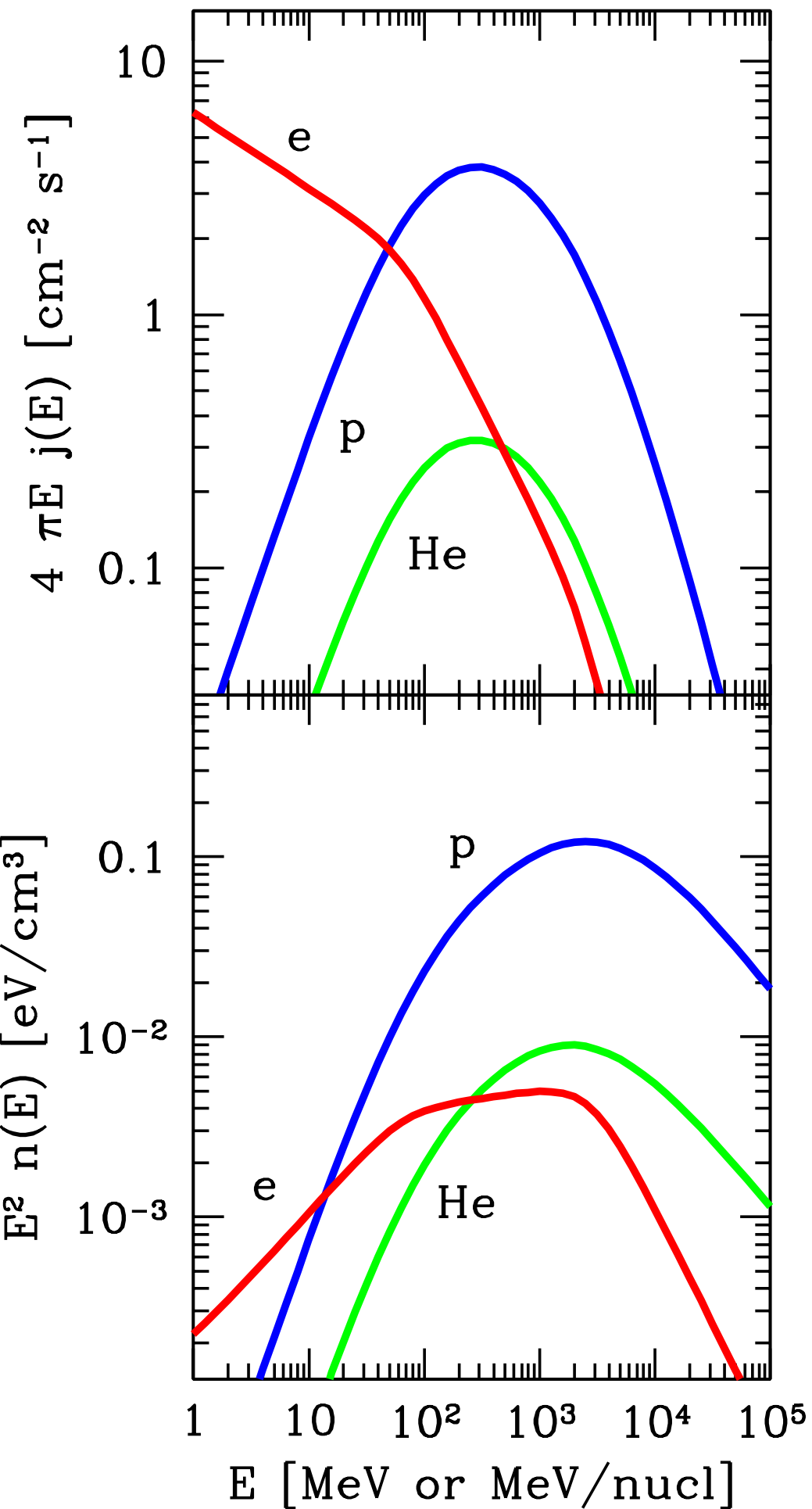
My favourite plot on cosmic rays



Interstellar CR spectrum down to 3 MeV



flux of particles



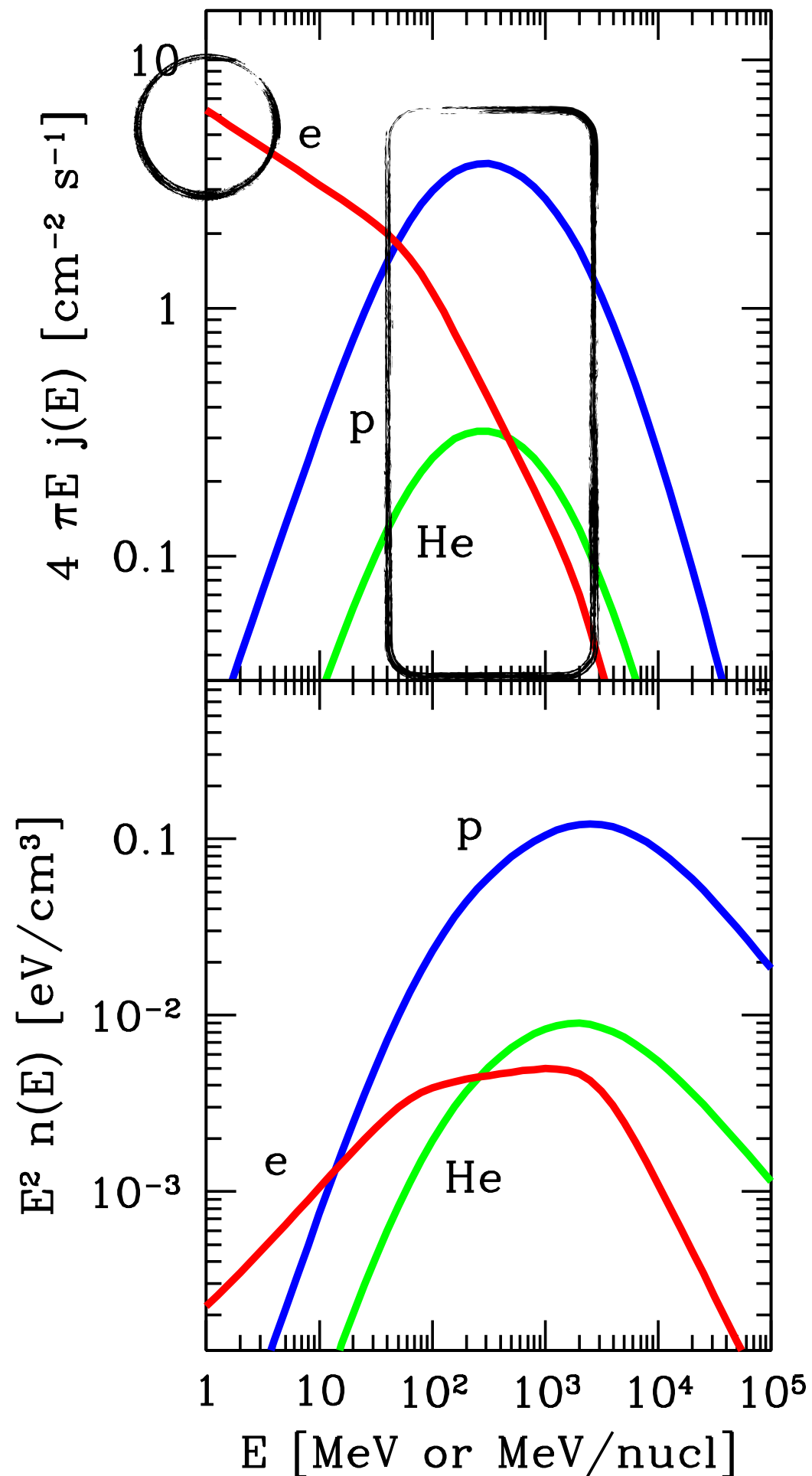
spectral energy
distribution

flux of particles

most nuclei have
energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

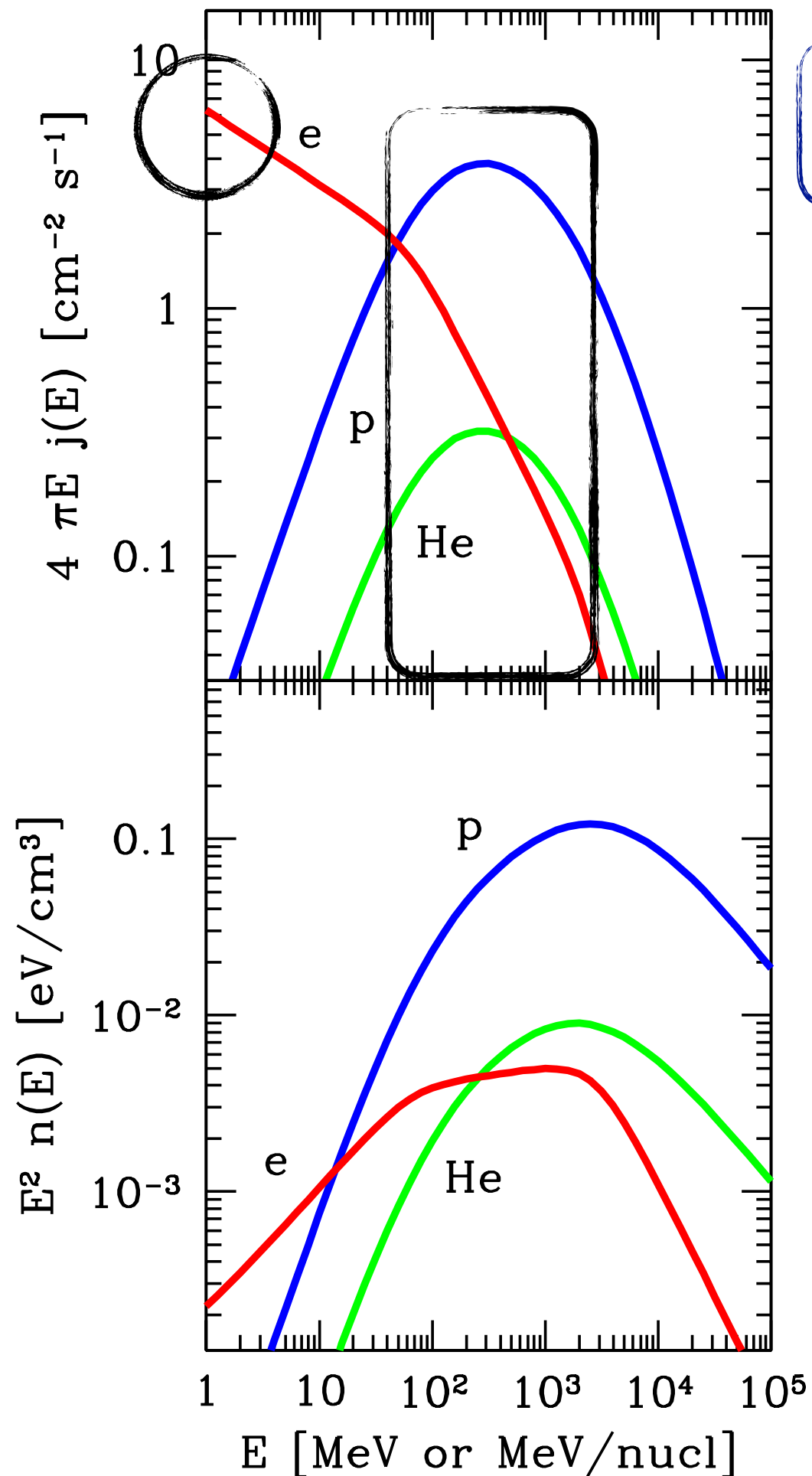


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$$\approx 10^{-9} - 10^{-10} \text{ cm}^{-3}$$

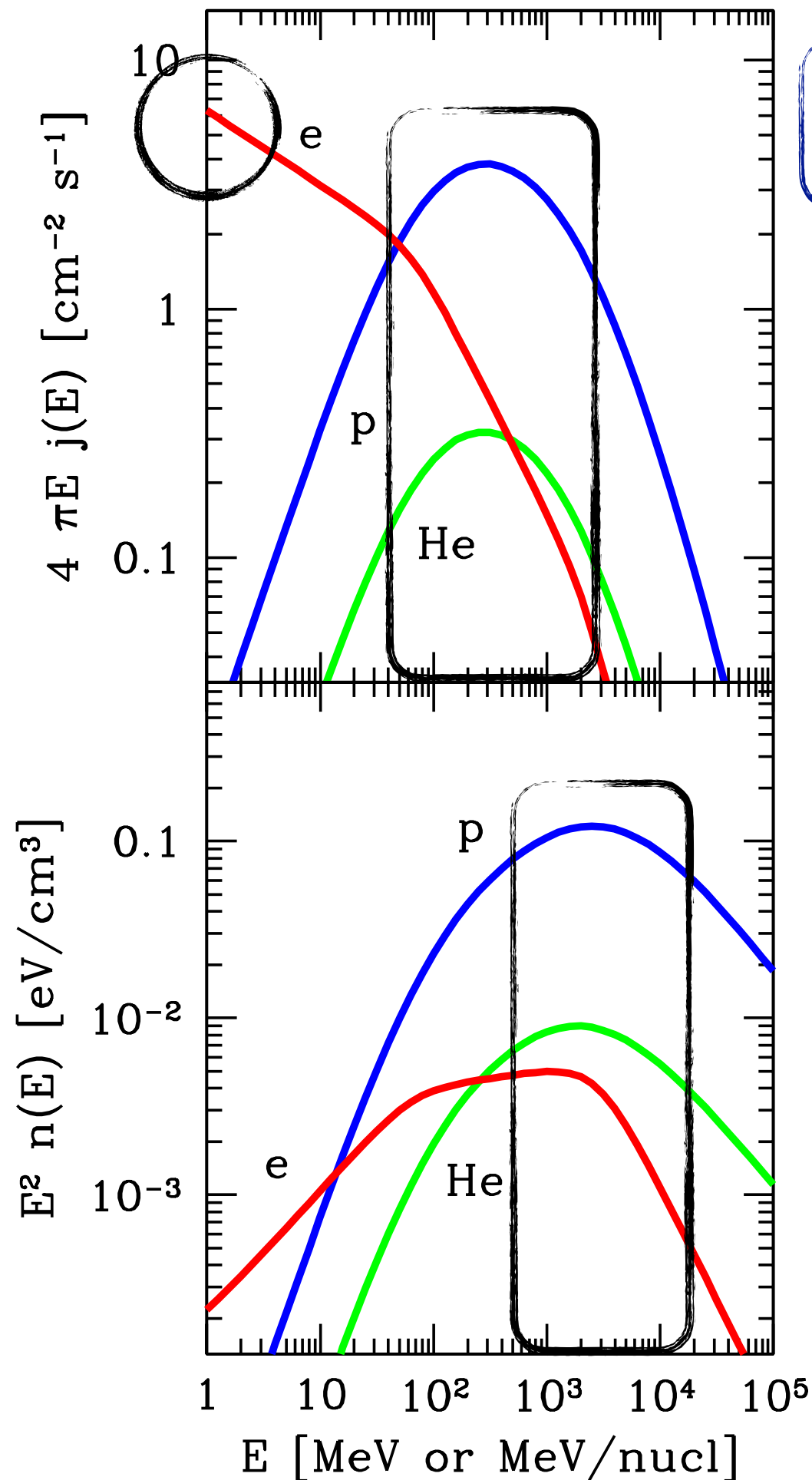
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energy is carried mainly
by particles of energy
1-10 GeV



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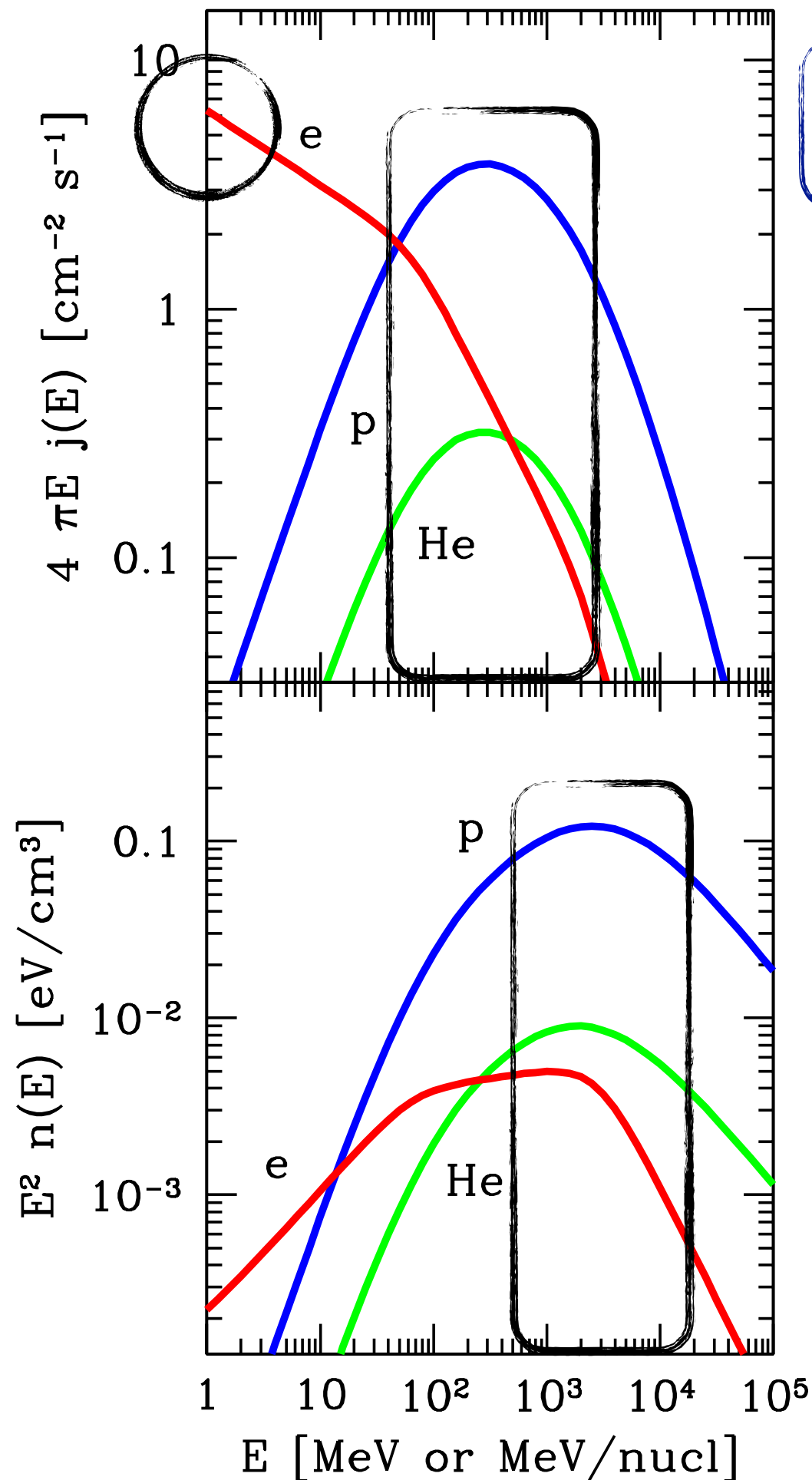
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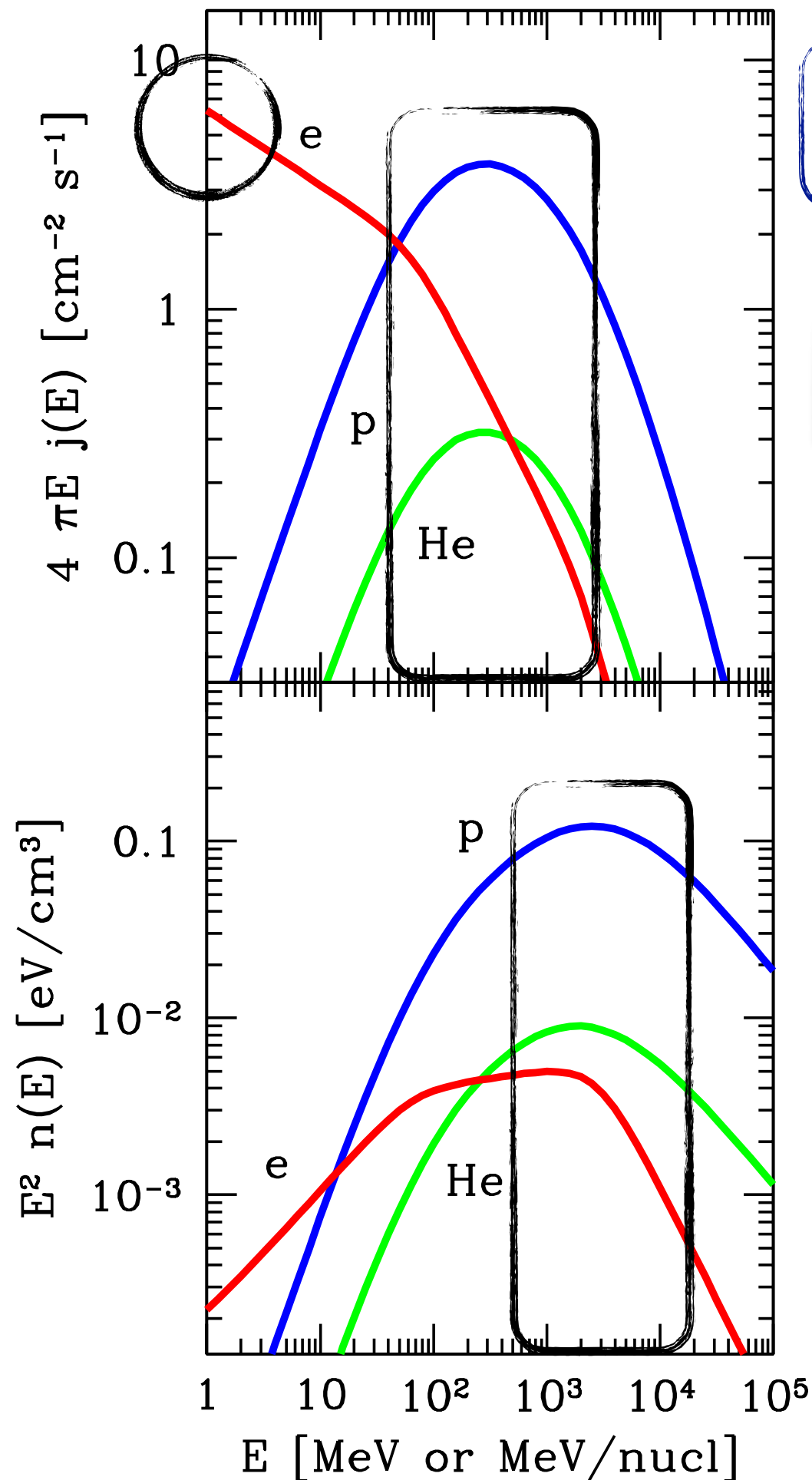
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compare with ISM
density...

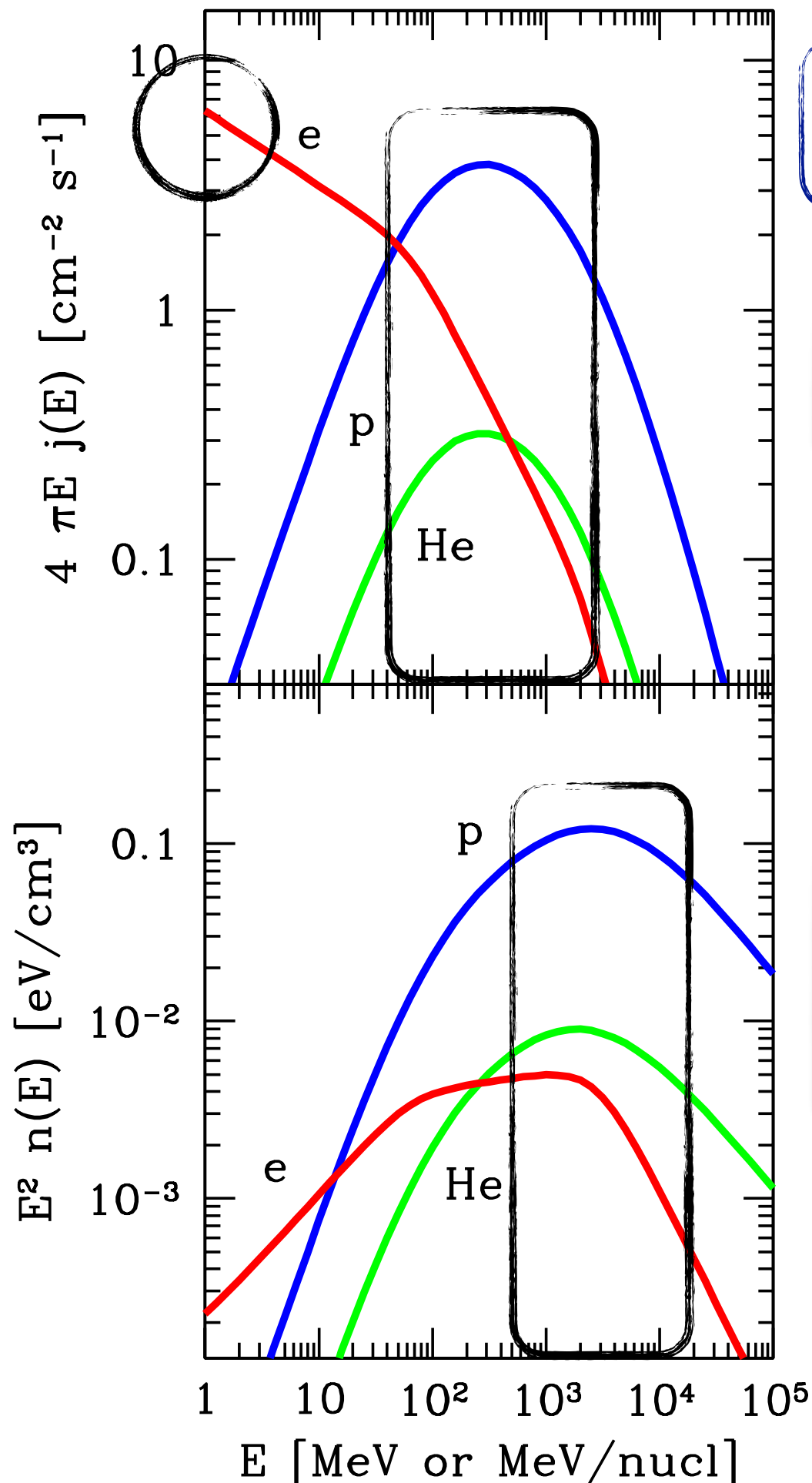
$$\approx 0.1 - 1 \text{ cm}^{-3}$$

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

flux of particles

most nuclei have
energies 100 MeV-1 GeV

how many CR electrons?



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

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spectral energy distribution

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

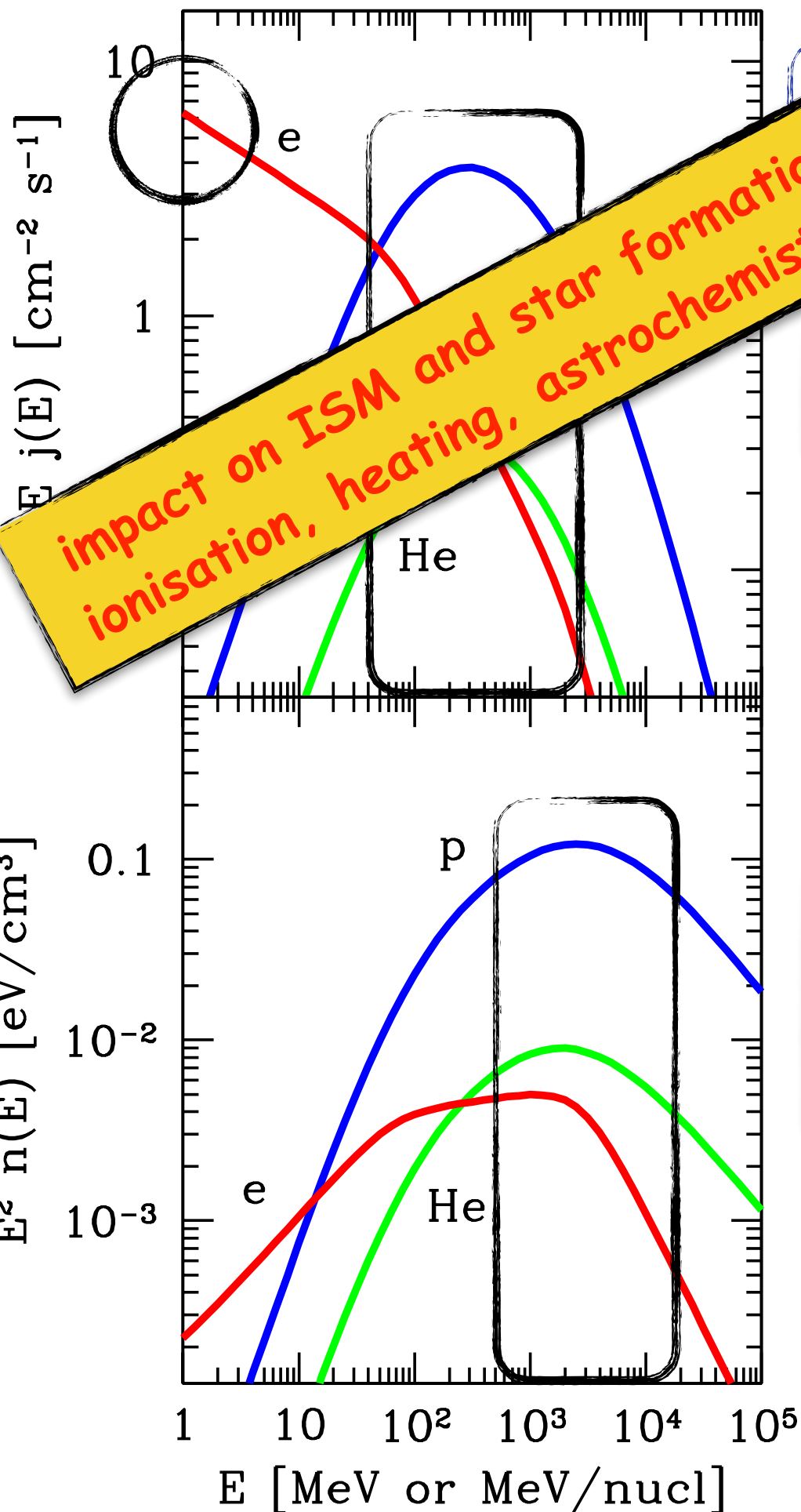
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flux of particles

most nuclei have
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how many CR electrons?

spectral energy distribution

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

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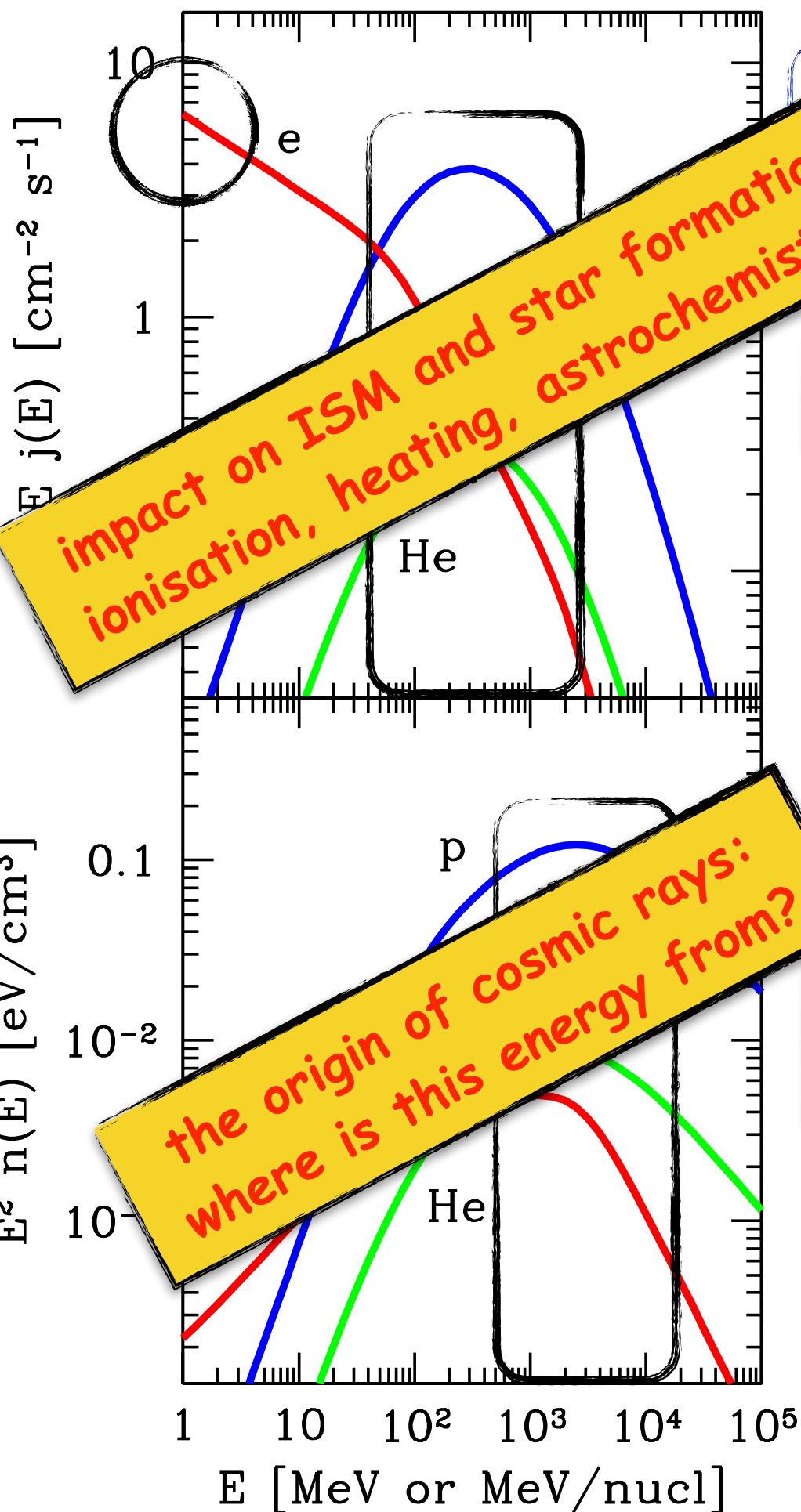
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spectral energy distribution

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

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

compare with ISM
density...

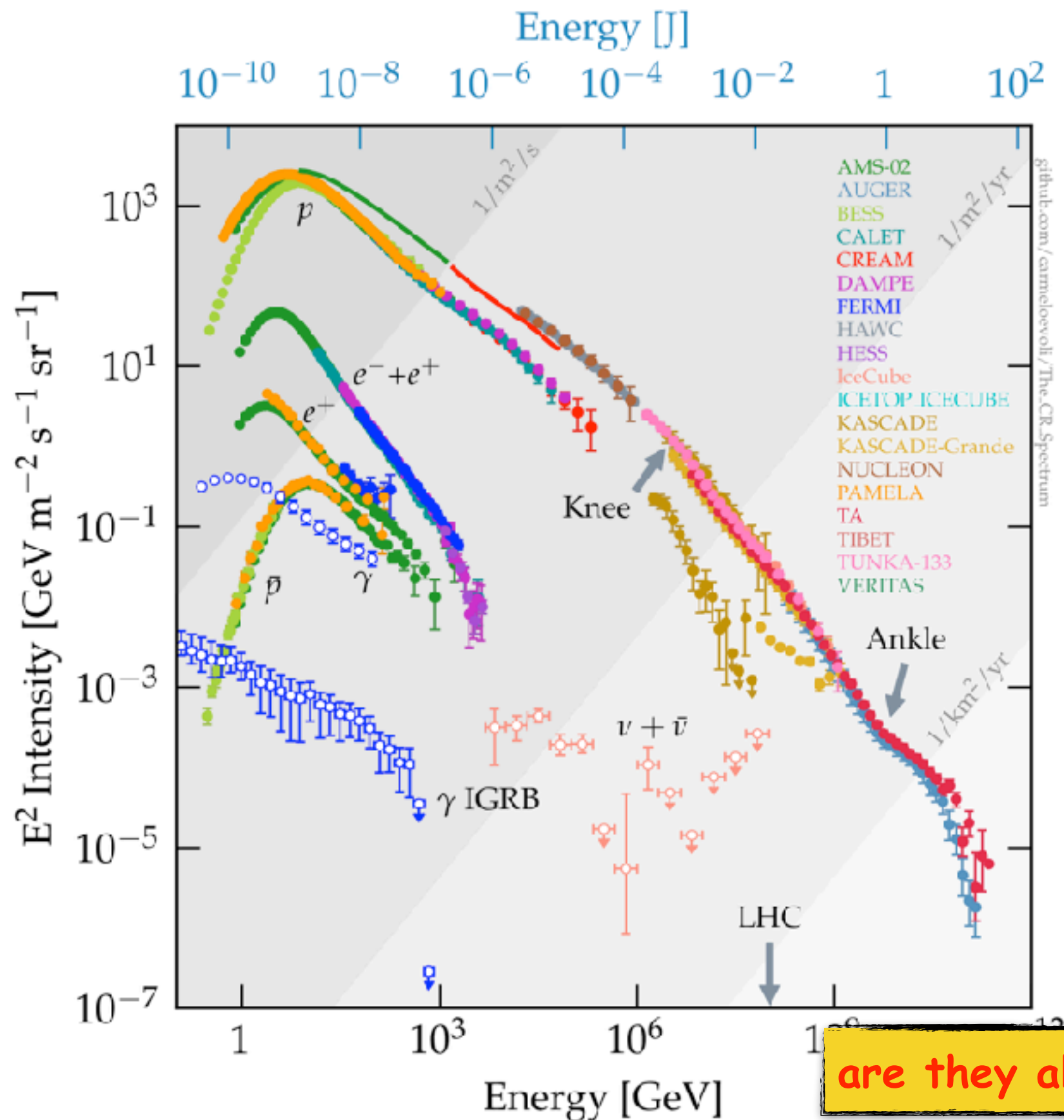
$$\approx 0.1 - 1 \text{ cm}^{-3}$$

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

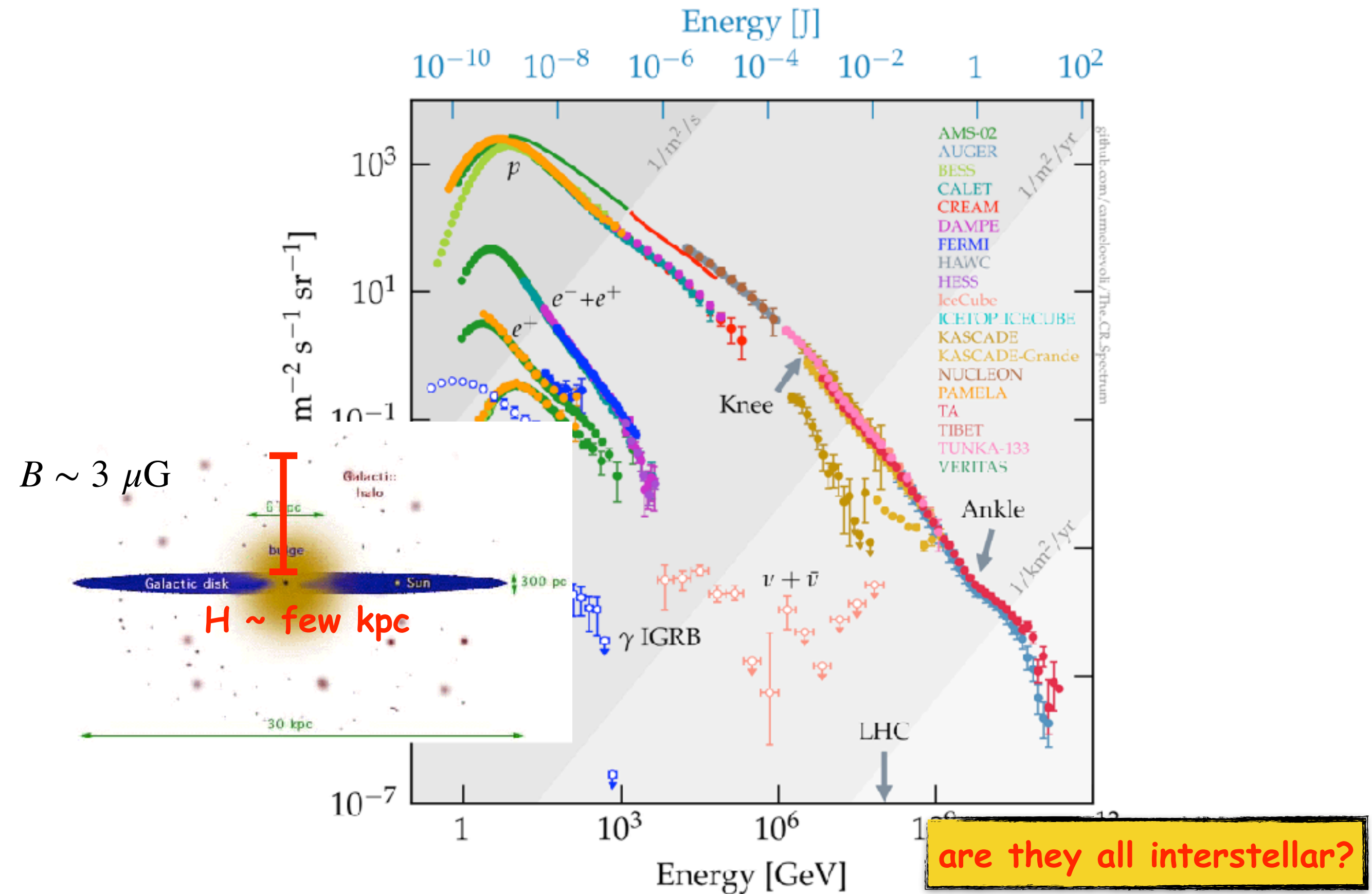
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$$\approx 1 \text{ eV/cm}^3$$

What CRs are: interstellar particles?



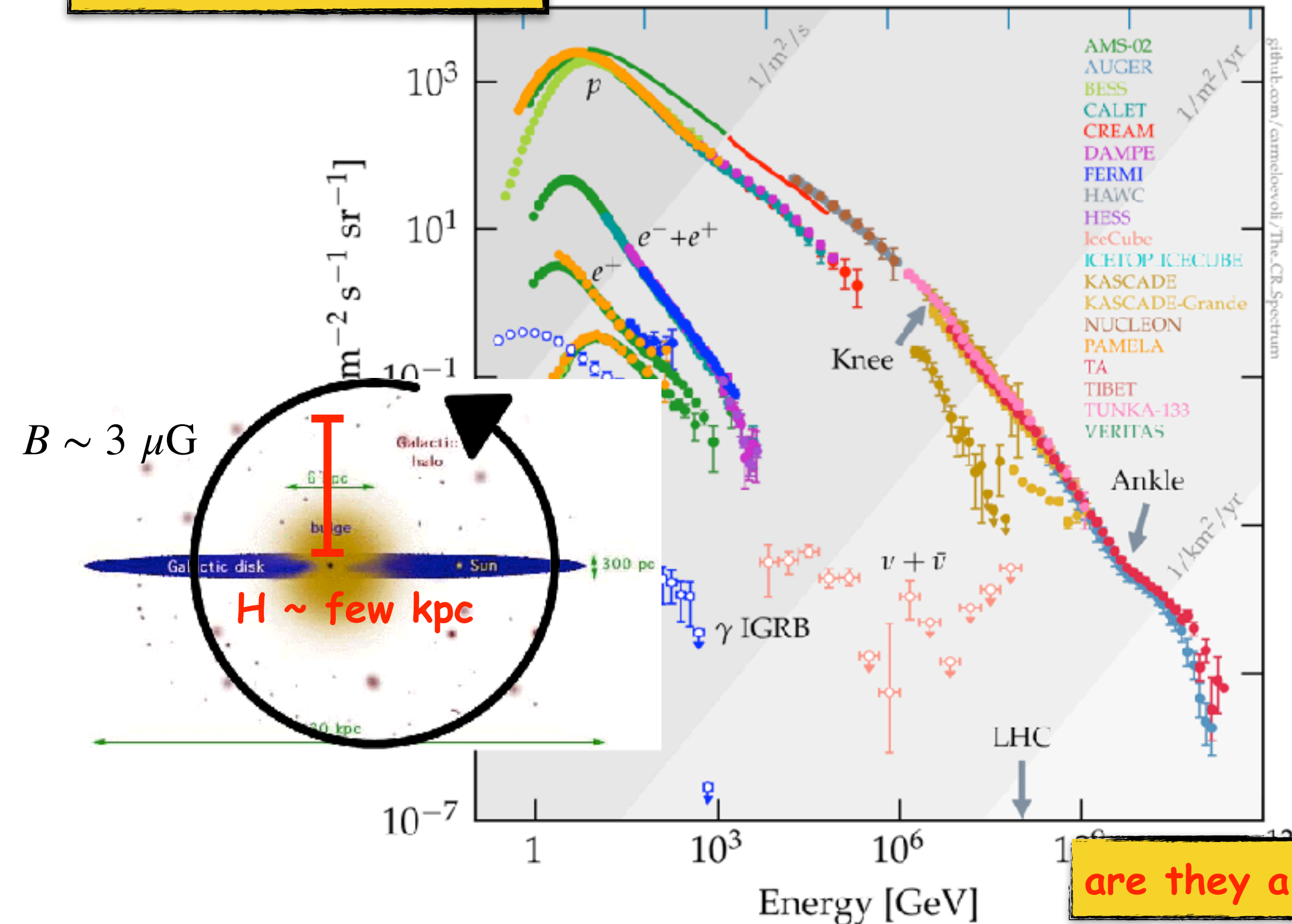
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What CRs are: interstellar particles?

confinement condition
on Larmor radius

$$R_L < H \longrightarrow E < 3 \times 10^{18} Z^{-1} \left(\frac{H}{\text{kpc}} \right) \text{eV}$$

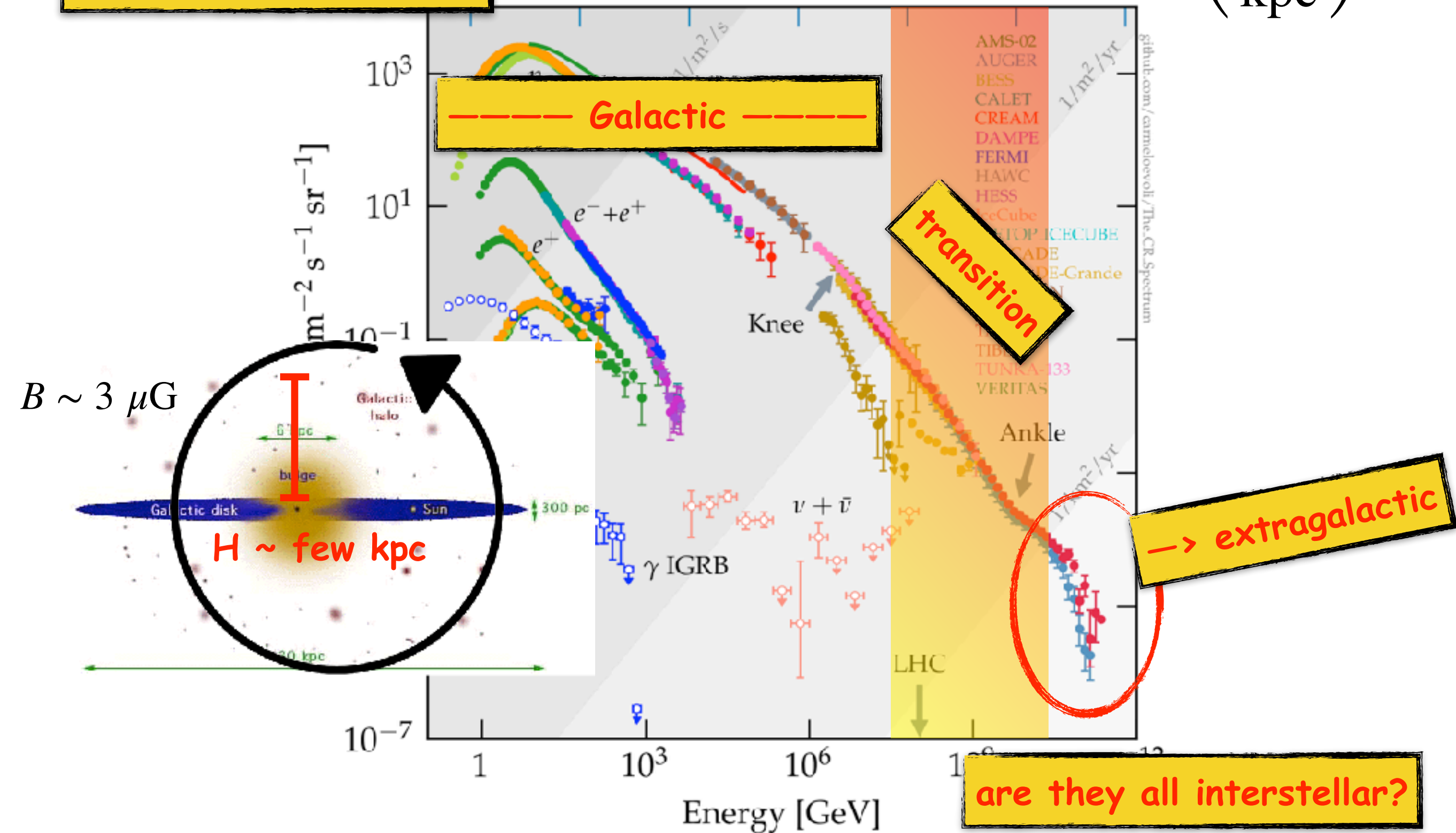


are they all interstellar?

What CRs are: interstellar particles?

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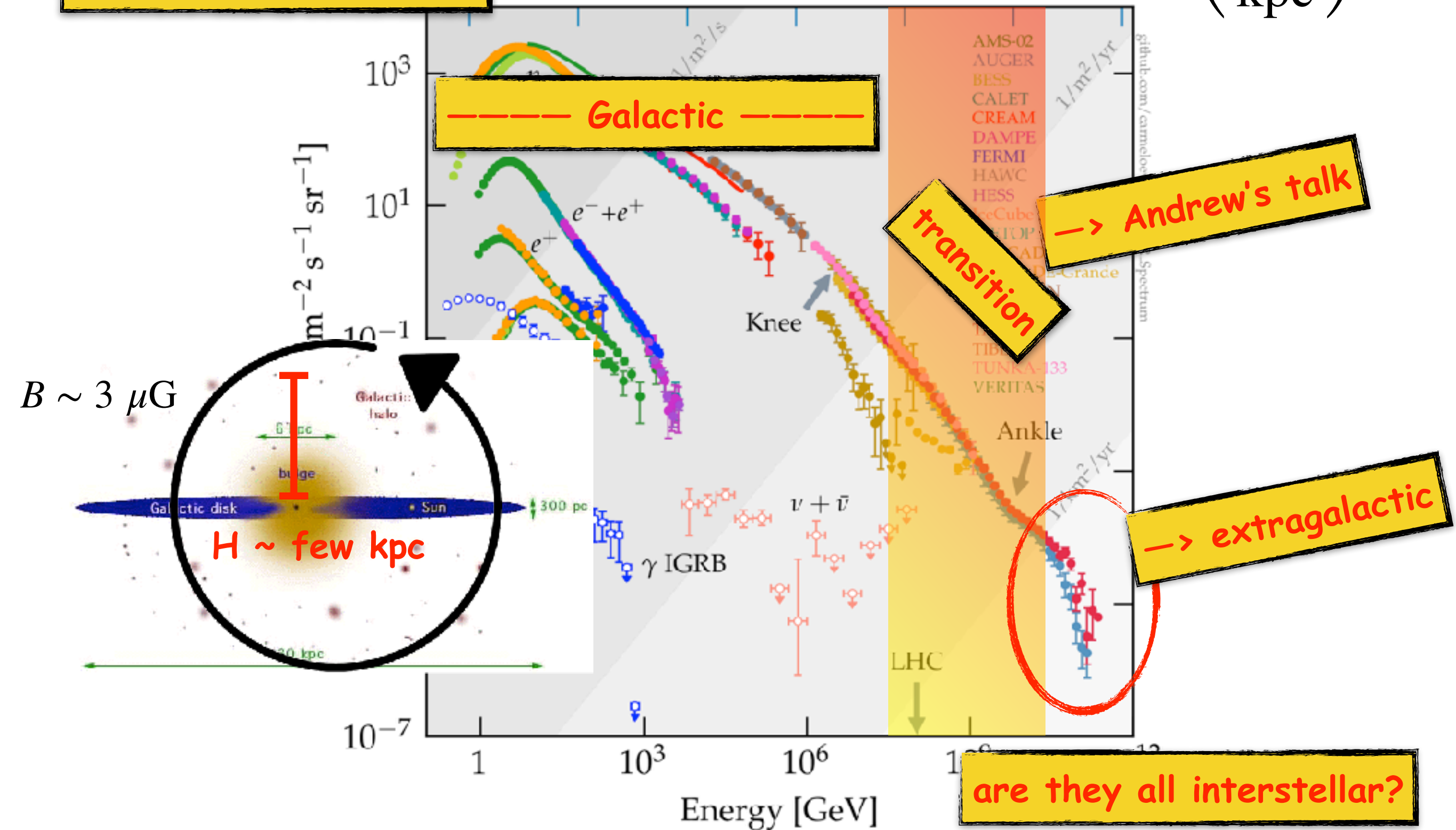
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What cosmic rays do

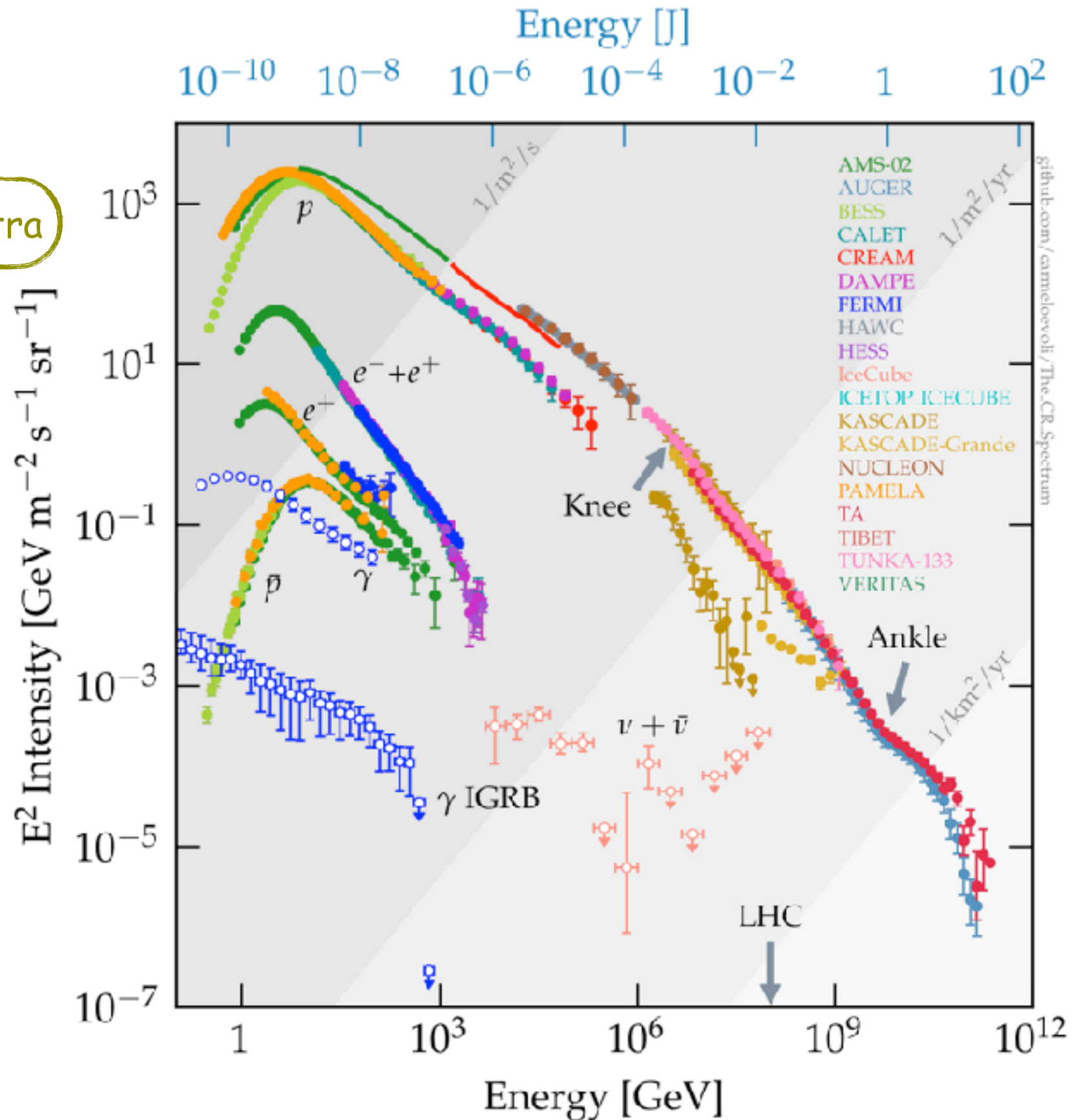
The four energy variables

energy

Good for:

E_{tot}

all-particle spectra



The four energy variables

energy

Good for:

E_{tot}

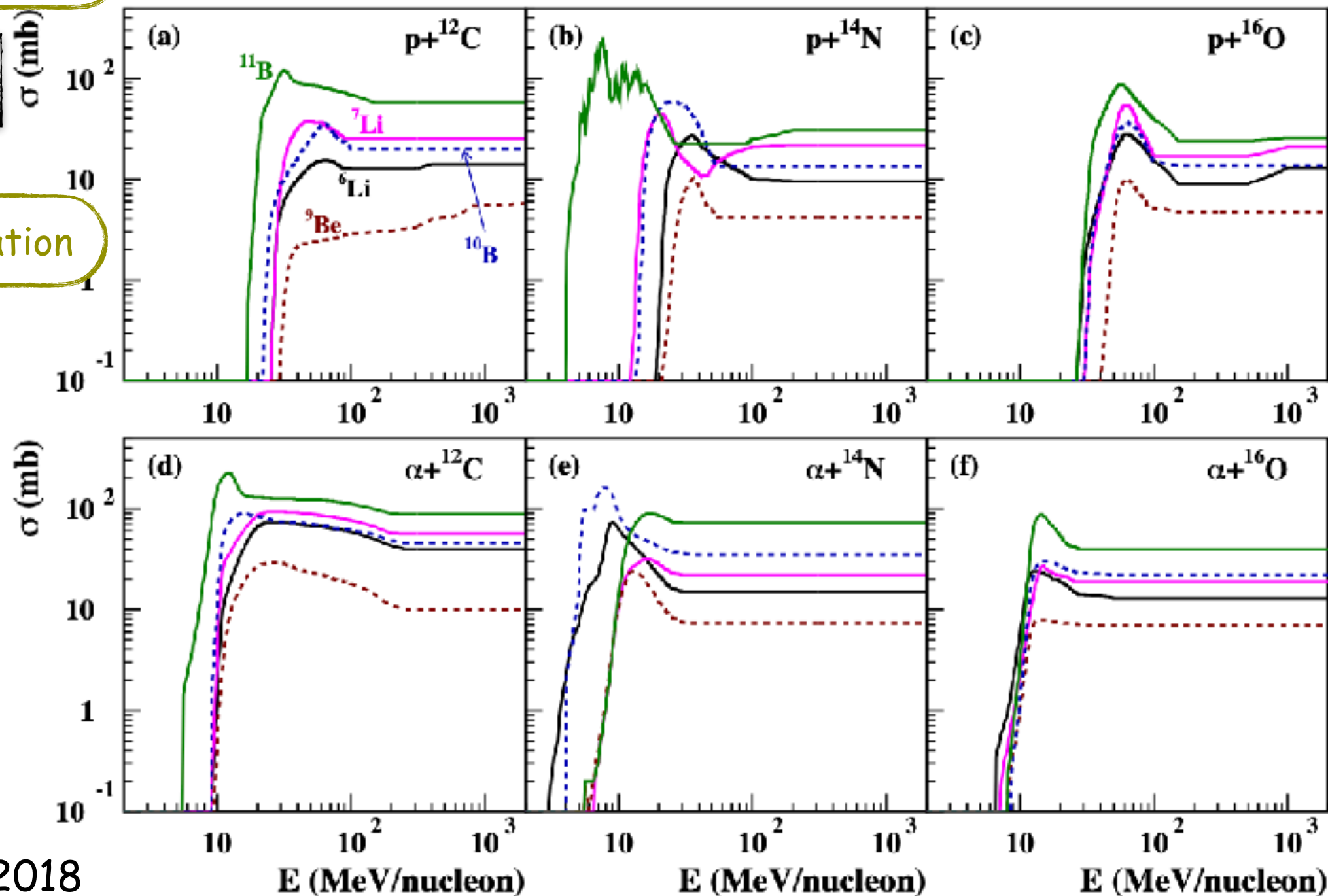
all-particle spectra

energy per nucleon

$$E = \frac{E_{tot}}{A}$$

spallation

energy/nucleon is ~conserved in spallation reactions



The four energy variables

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Good for:

E_{tot}

all-particle spectra

energy per nucleon

$$E = \frac{E_{tot}}{A}$$

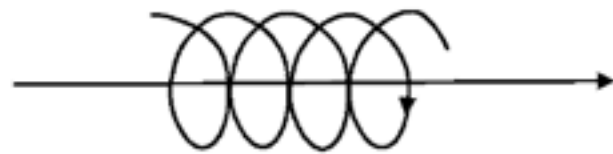
spallation

rigidity

$$R_L = \frac{R}{B} \propto \frac{A}{Z}$$

transport

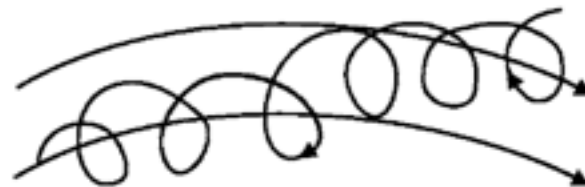
Larmor gyration



scattering



drift



reflection



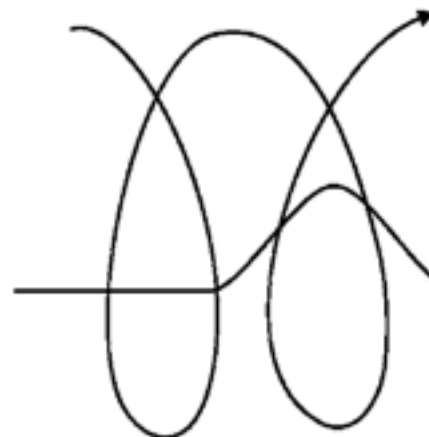
drift



trapping



no effect



cross field diffusion



same $R_L \rightarrow$ similar statistical transport behaviour

The four energy variables

energy

Good for:

transport equation derived by Parker in 1965
using ENERGY as a variable but...

E_{tot}

all-particle spectra

energy per nucleon

adiabatic term

scale!

$$E = \frac{E_{tot}}{A}$$

spallation

$$\frac{p}{3} (\nabla \cdot u) \frac{\partial f}{\partial p} \longrightarrow \frac{E}{3} (\nabla \cdot u) \left(\frac{E + 2mc^2}{E + mc^2} \right) \frac{\partial f}{\partial E}$$

rigidity

$$R_L = \frac{R}{B} \propto \frac{A}{Z}$$

transport

momentum

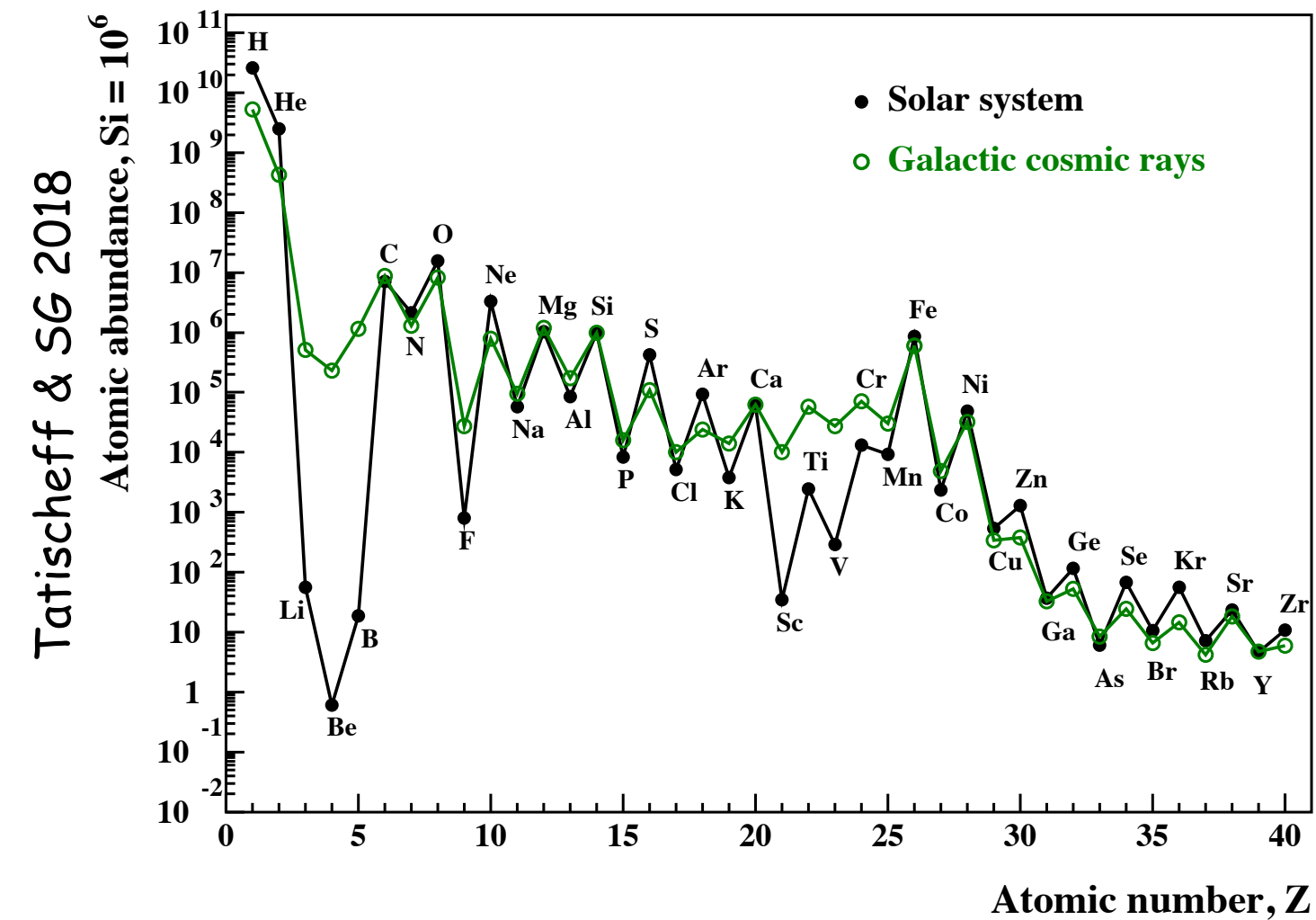
p

theoreticians

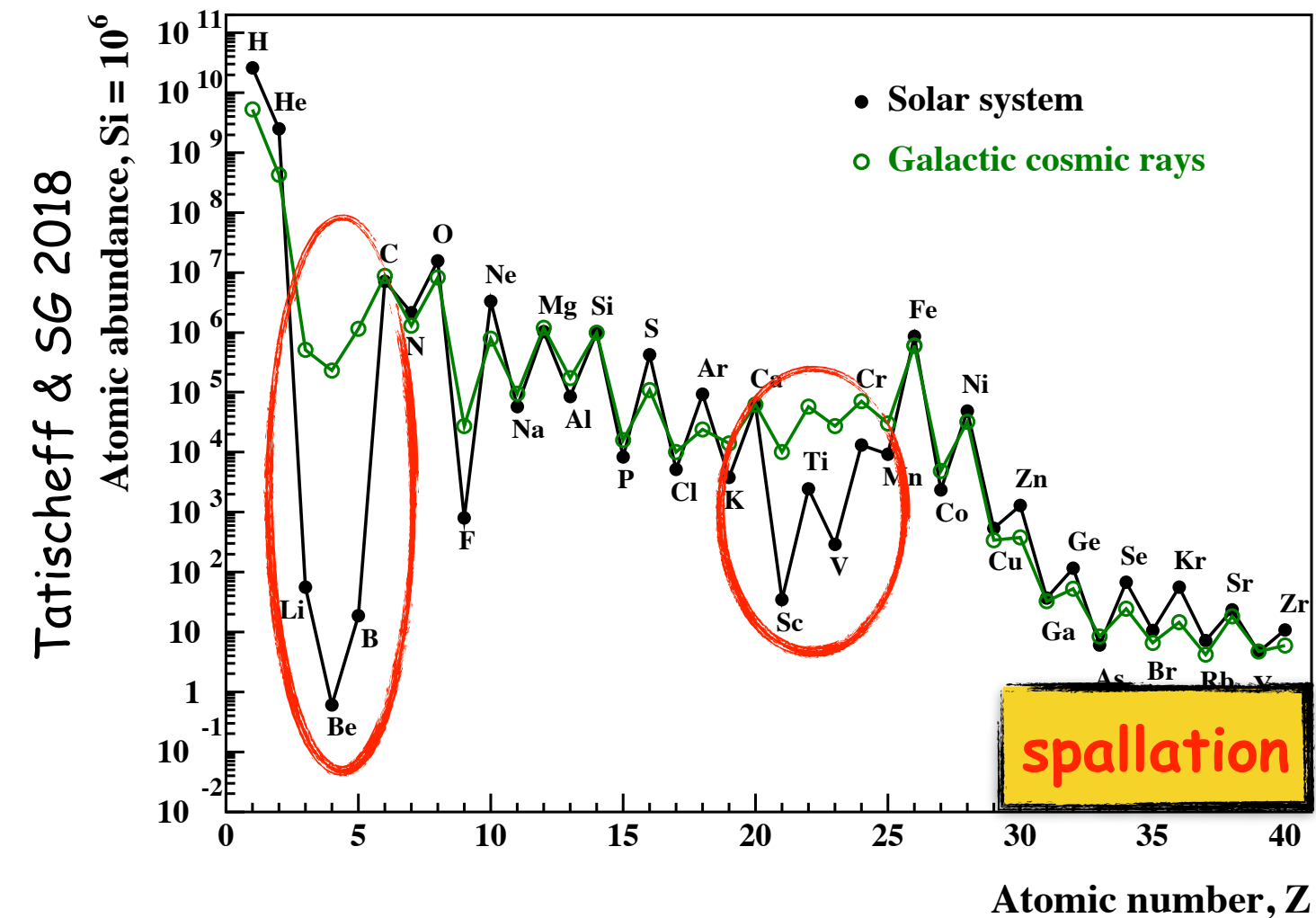
- spectrum of CRs accelerated at shocks is a power law in p and not in E (BOBALSky 1978)
- p is a canonical variable, $f(p)$ Lorentz invariant (Forman 1970), etc...

What we know

Striking anomalies in CR composition

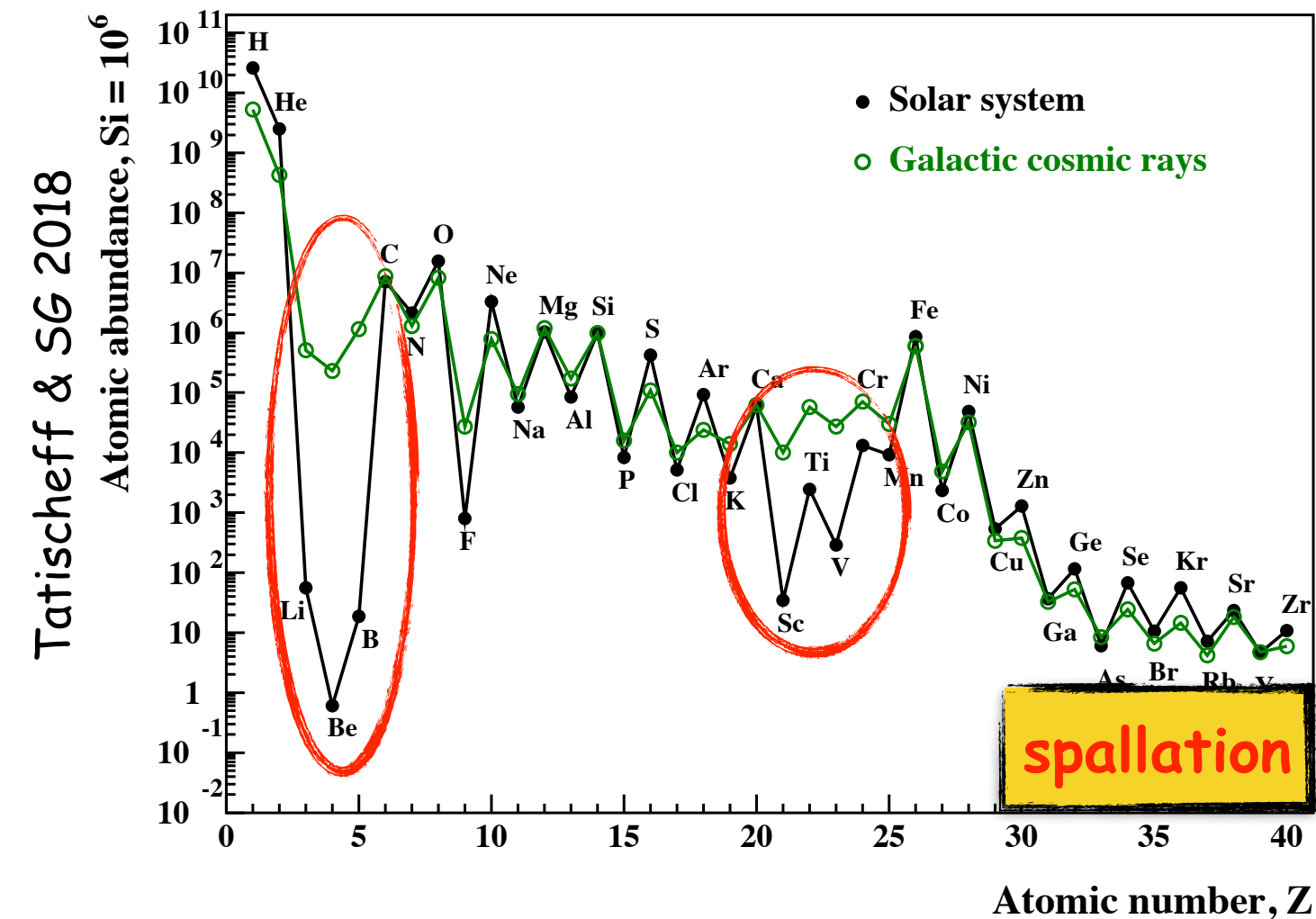


Striking anomalies in CR composition

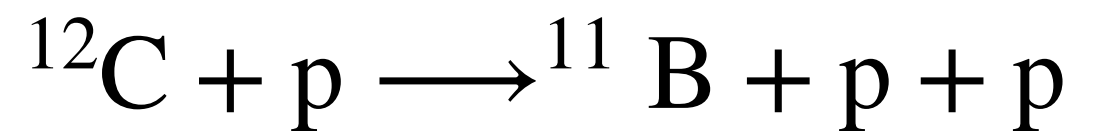


- ▶ energy/nucleon is conserved in spallation reactions
- ▶ Boron (secondary) is produced mainly in spallation reactions involving Carbon (primary)

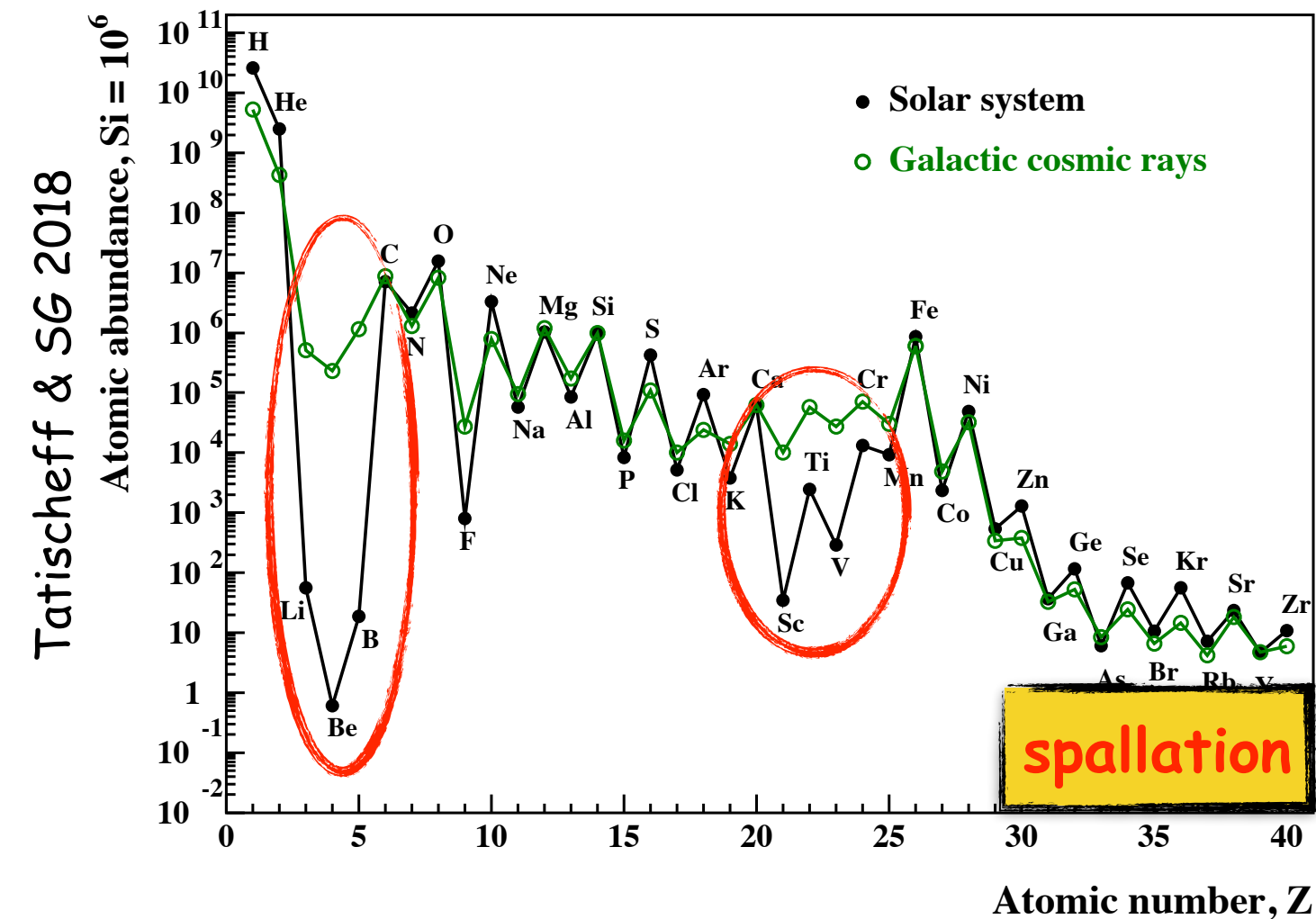
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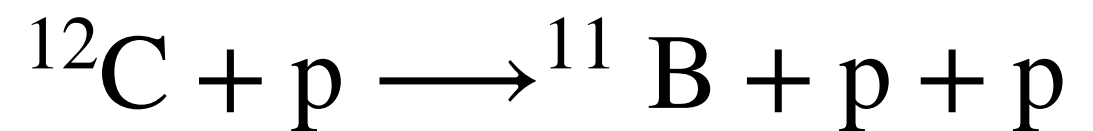
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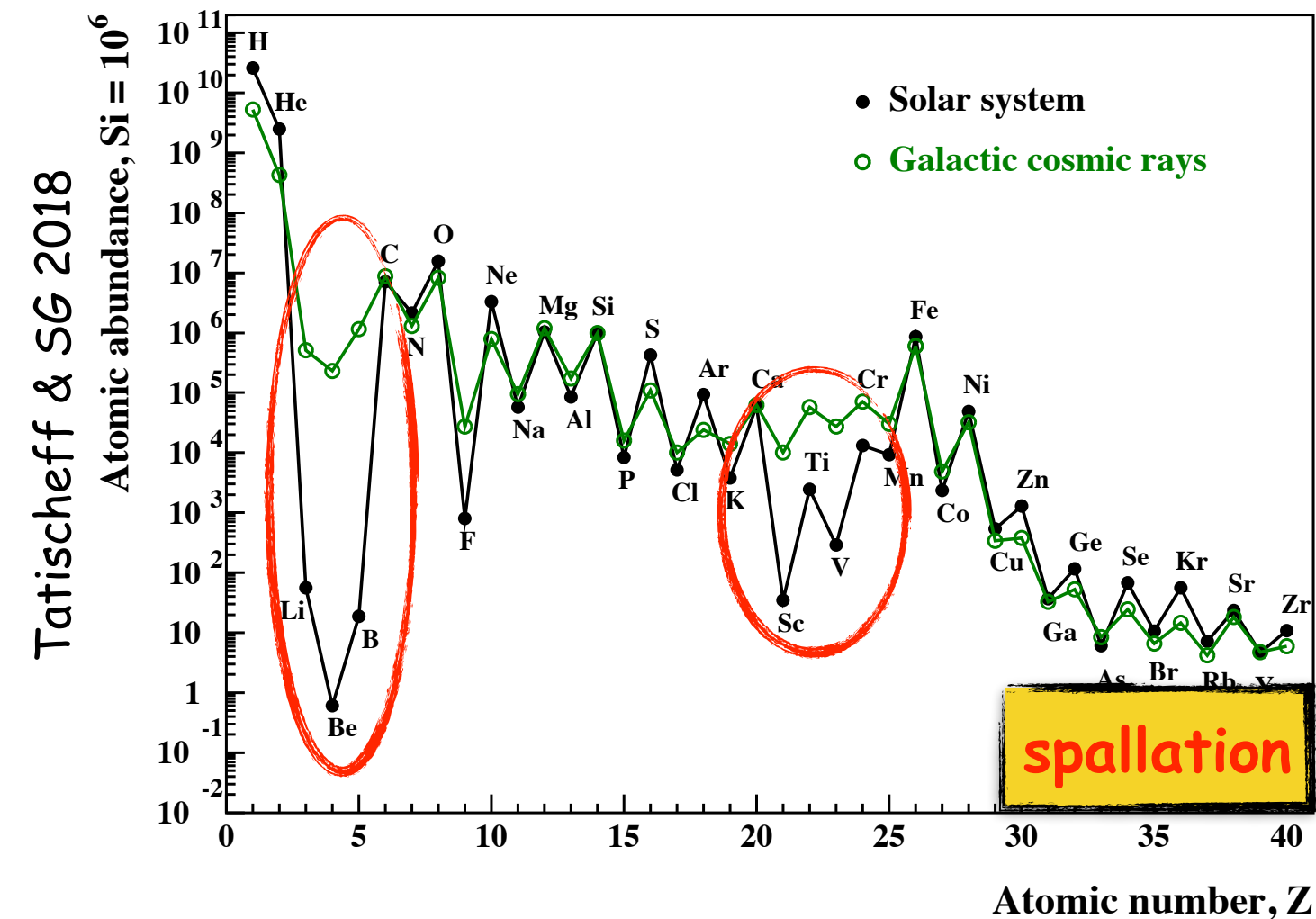
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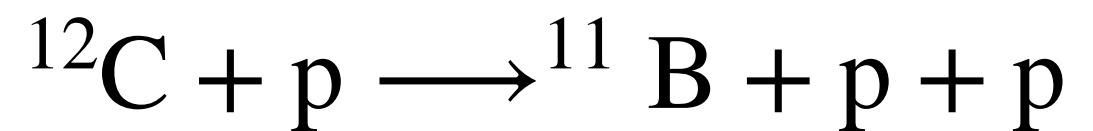
production rate of B

$$q_B \sim n_C \sigma_s n_{ISM} c$$

Striking anomalies in CR composition



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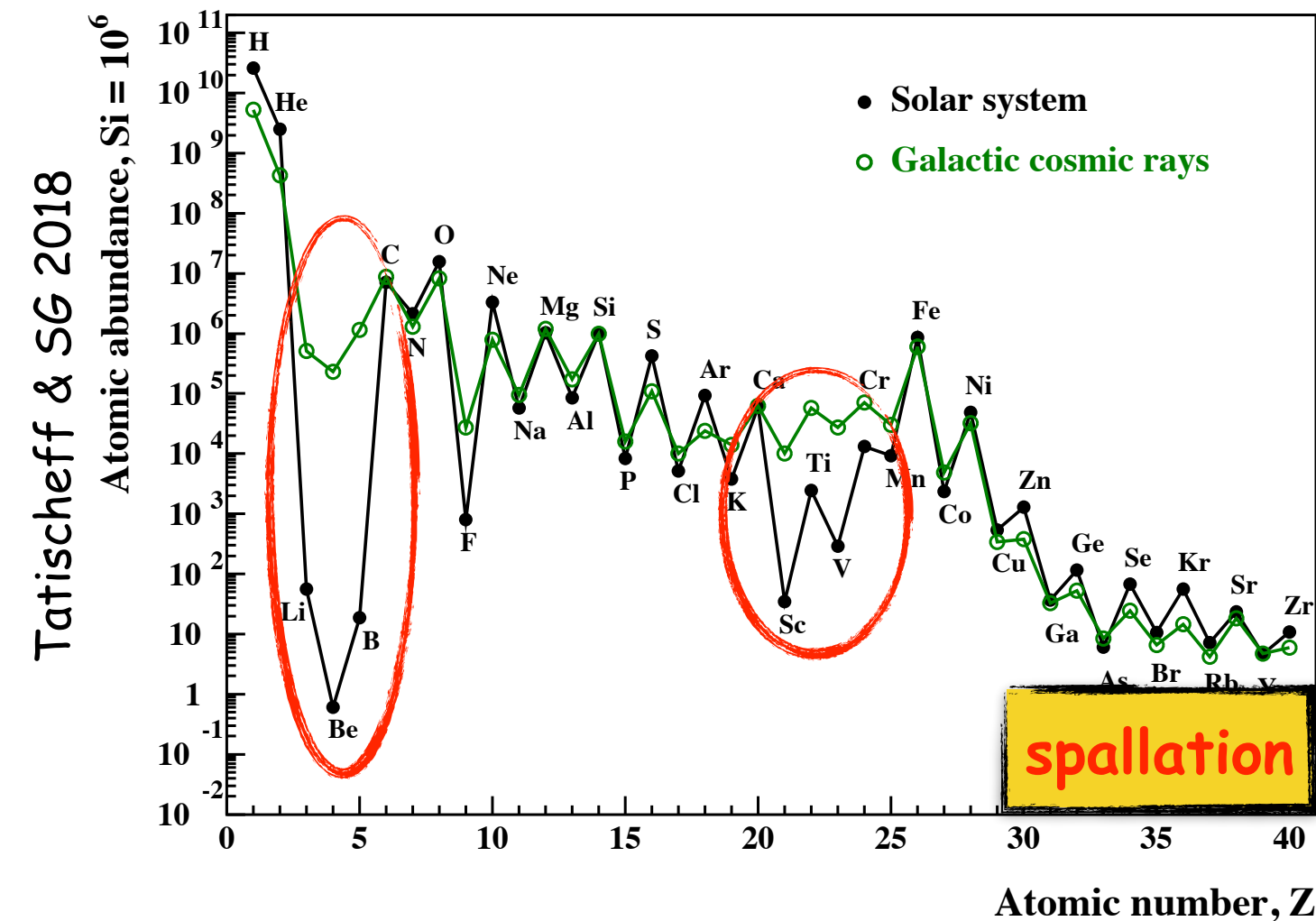
production rate of B

$$q_B \sim n_C \sigma_s n_{ISM} c$$

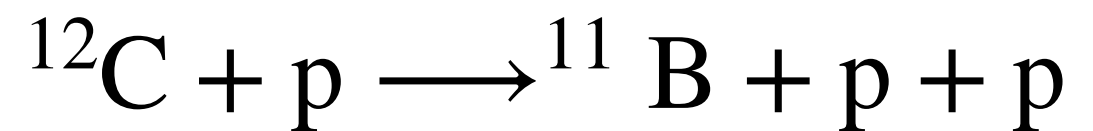
equilibrium density of B

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Striking anomalies in CR composition



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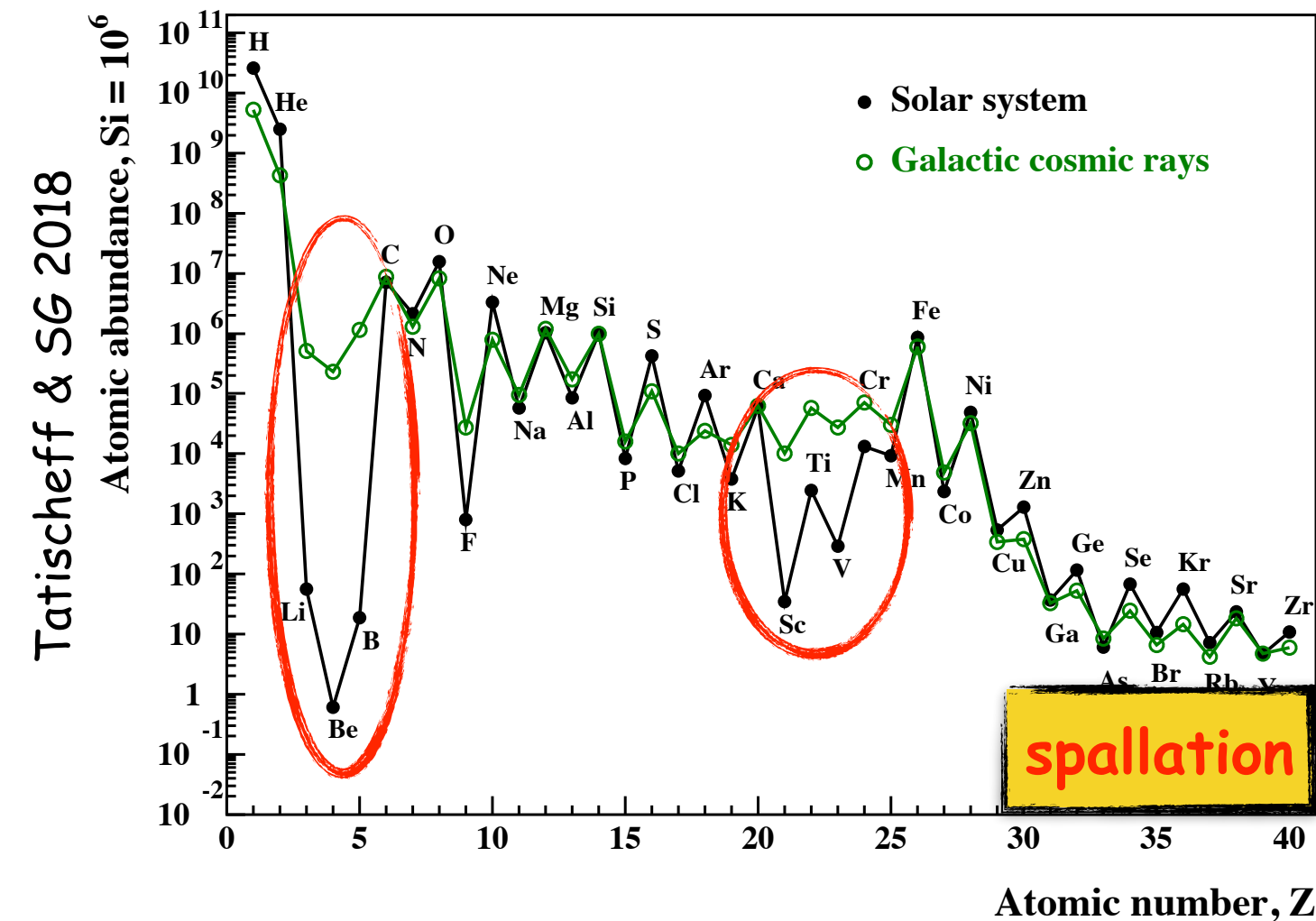
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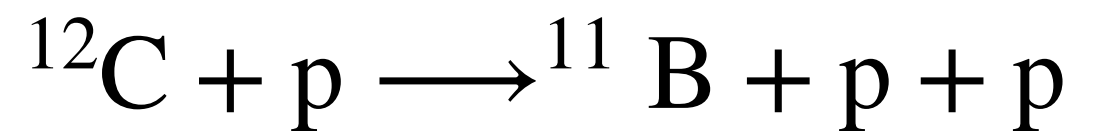
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equilibrium density of B

grammage

$$\Lambda_g = \mu m_p n_{ISM} \tau_{disk} c \longrightarrow$$

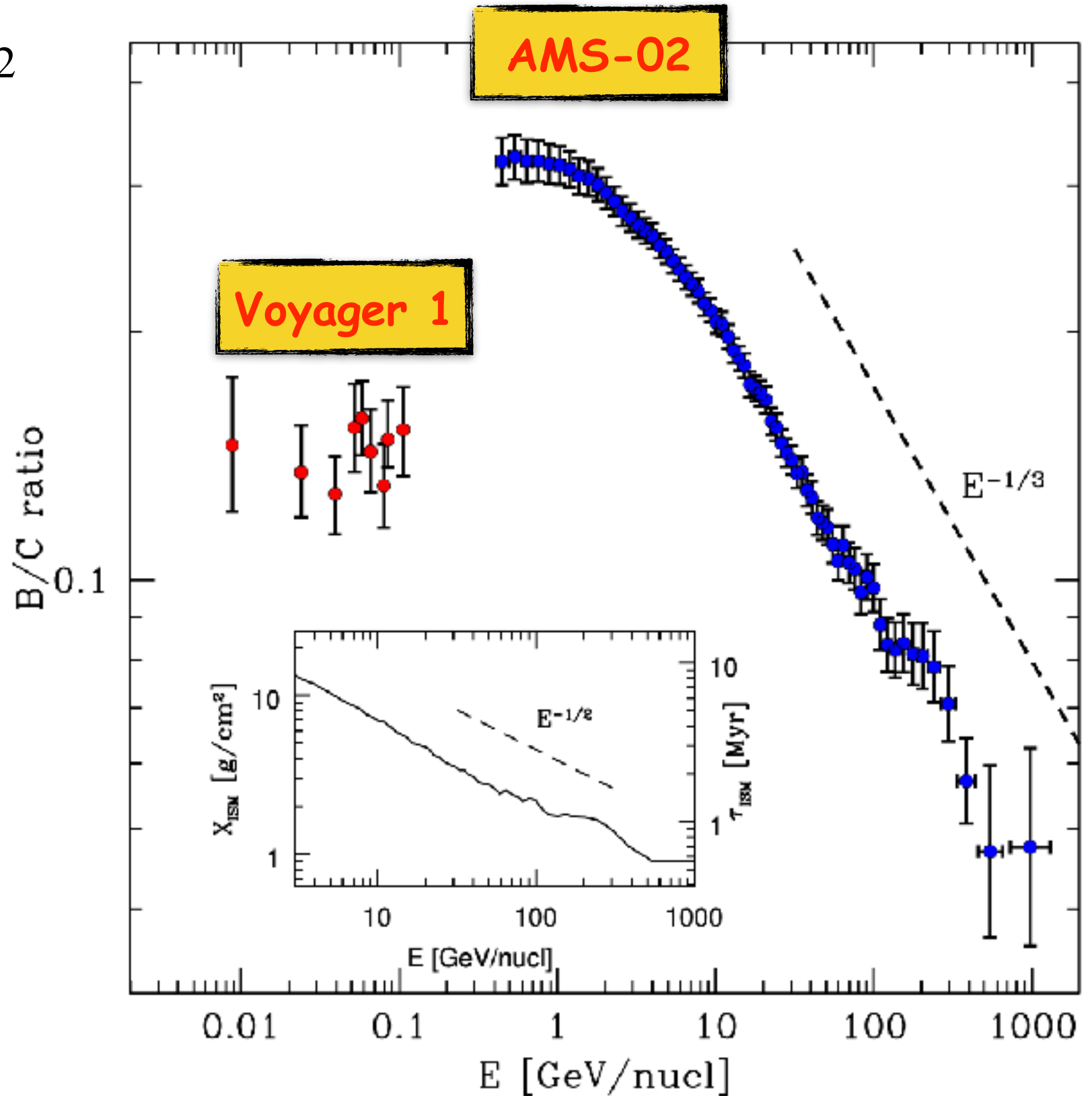
$$\frac{n_B}{n_C} \sim \frac{\sigma_s}{\mu m_p} \Lambda_g$$

The CR power of the Milky Way

$$\Lambda_g \approx 40 \frac{n(B)}{n(C)} \text{ g/cm}^2$$

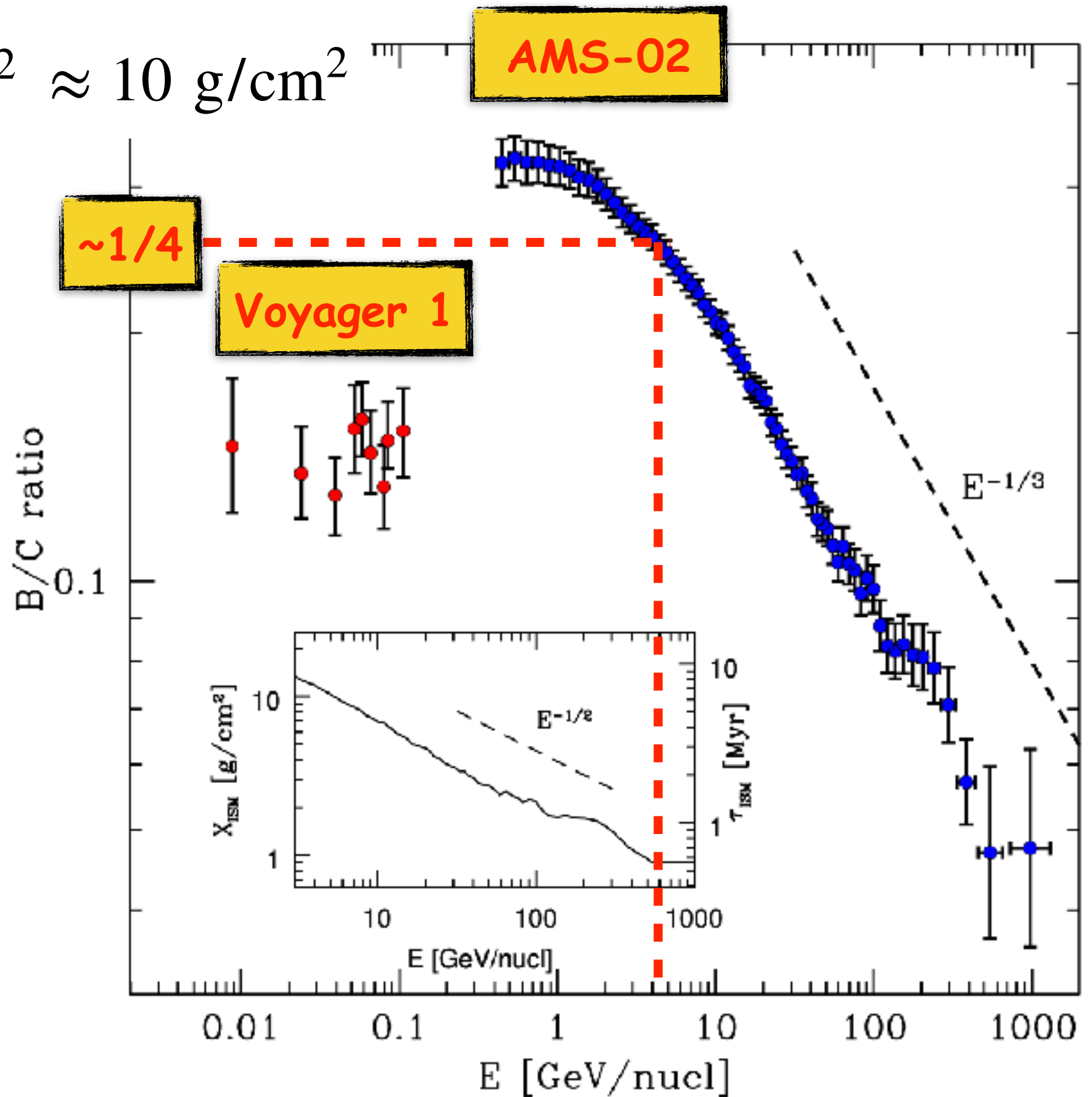
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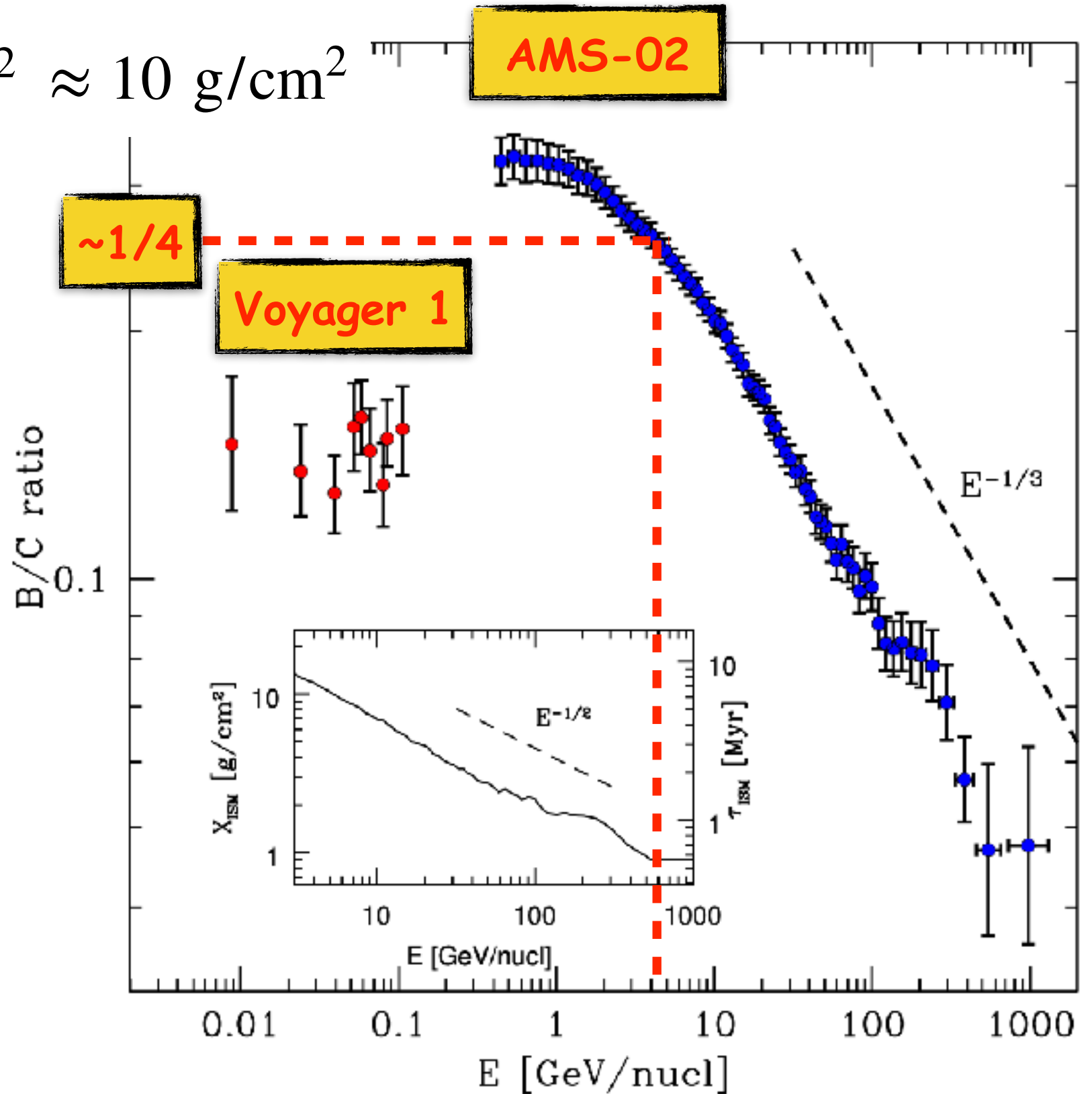
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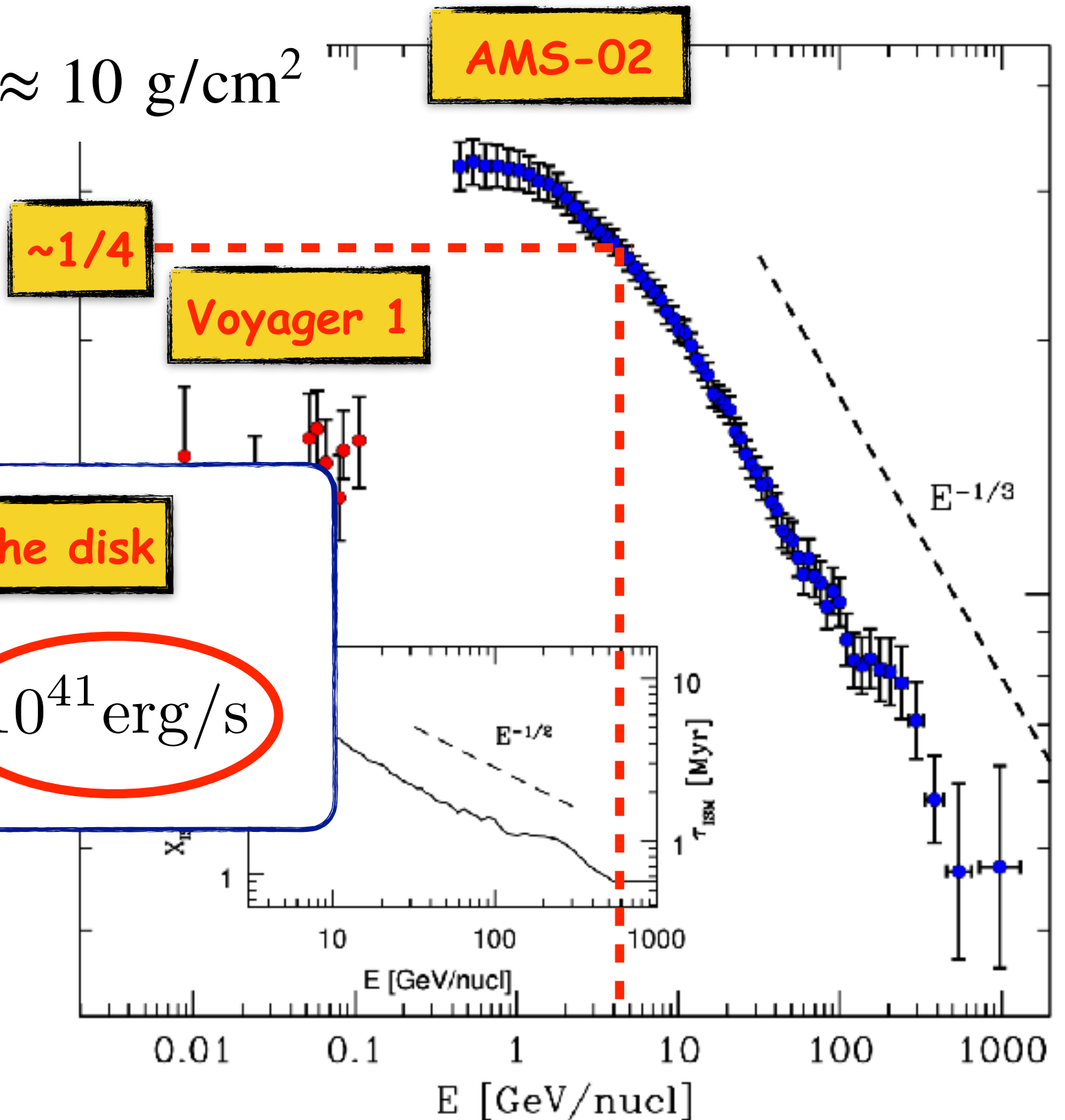
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$$L_{CR} = W_{CR} / \tau_{disk} \sim 10^{41} \text{ erg/s}$$



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~1/4

Voyager 1

AMS-02

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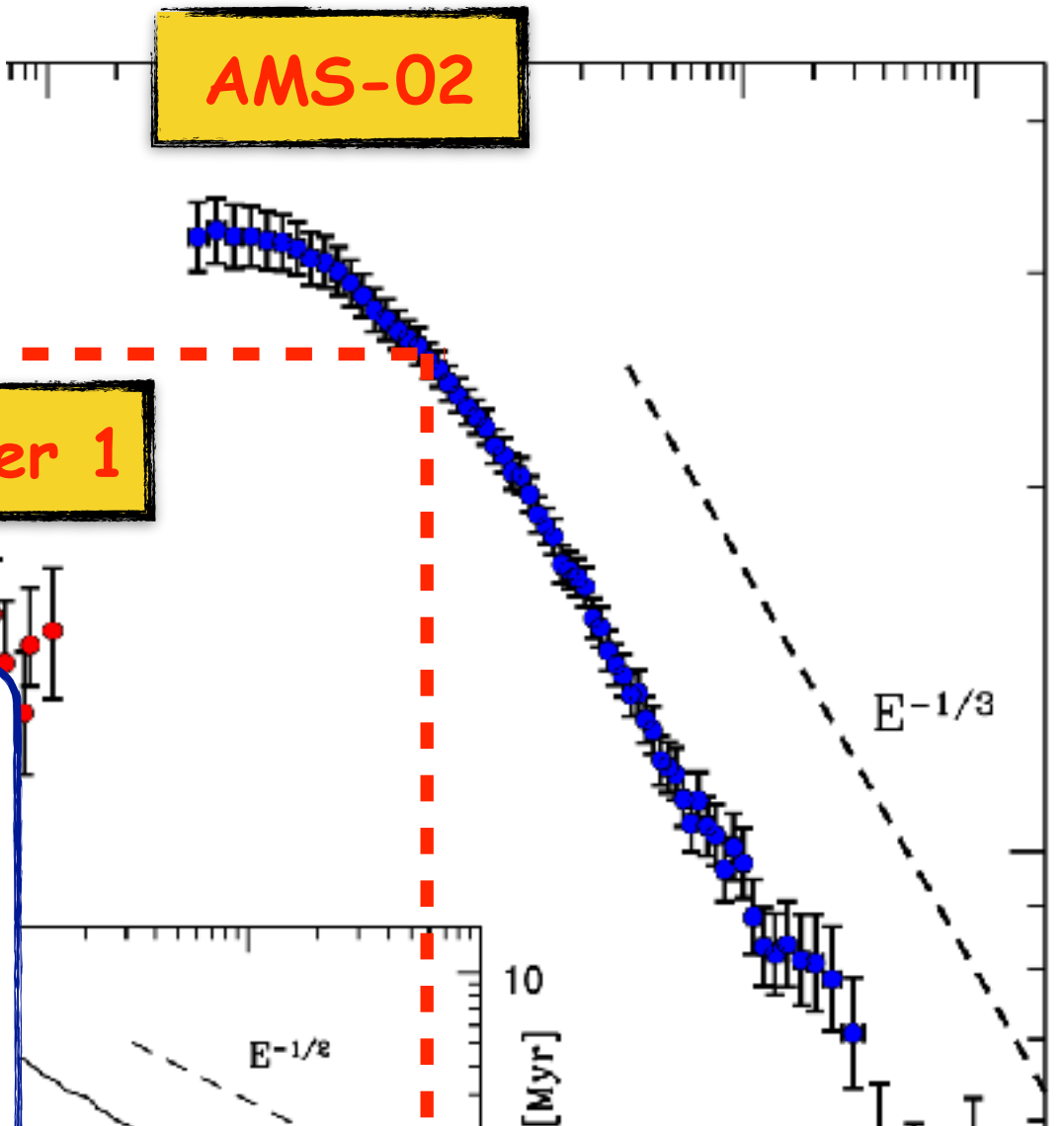
Power of Galactic SN explosions

10^{51} erg

3/century

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

Gabici 2022

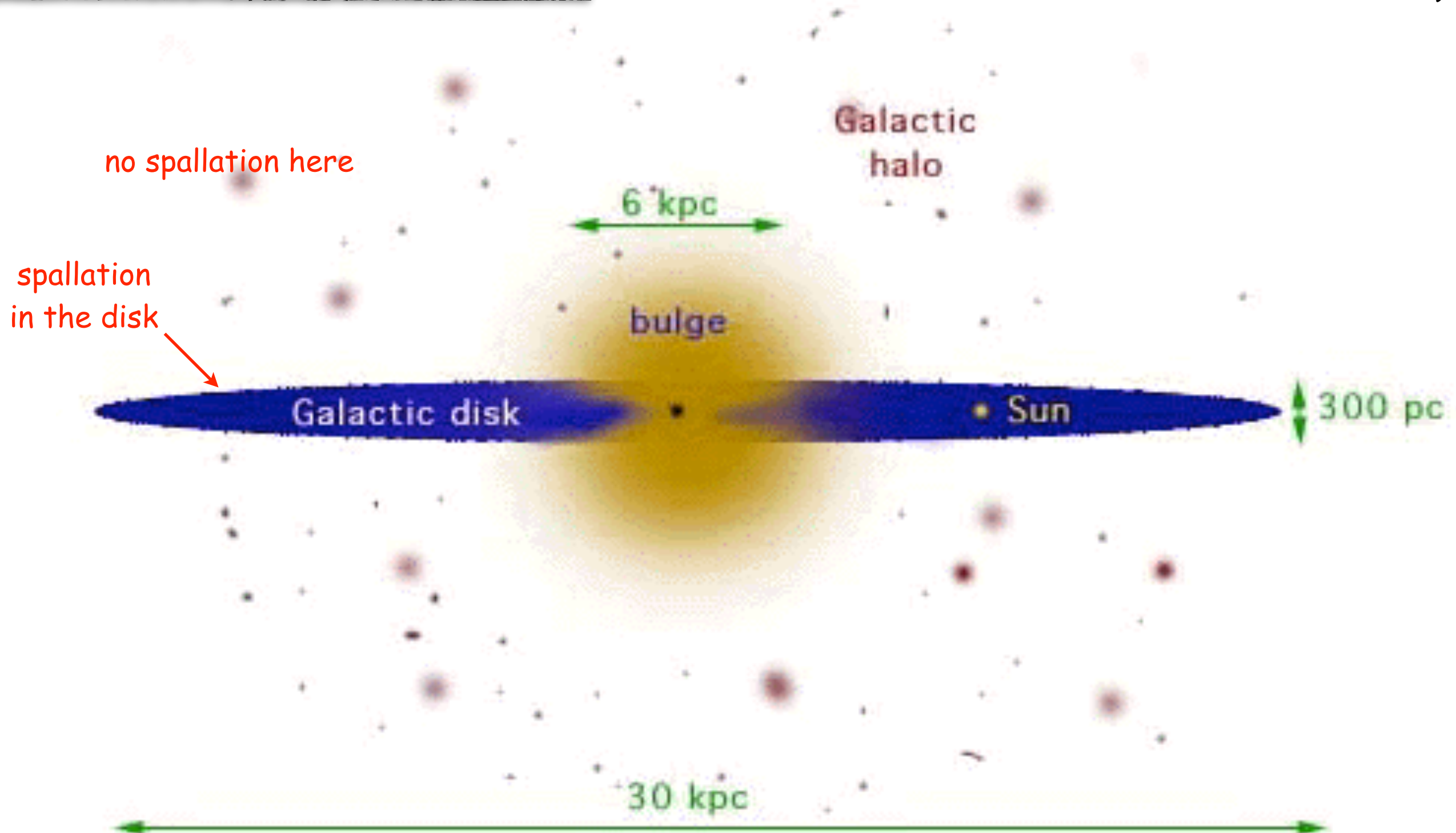


Escape time or residence time?

surface density of the disk →

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

(see reviews by
Ferriere 01; Cox 05)



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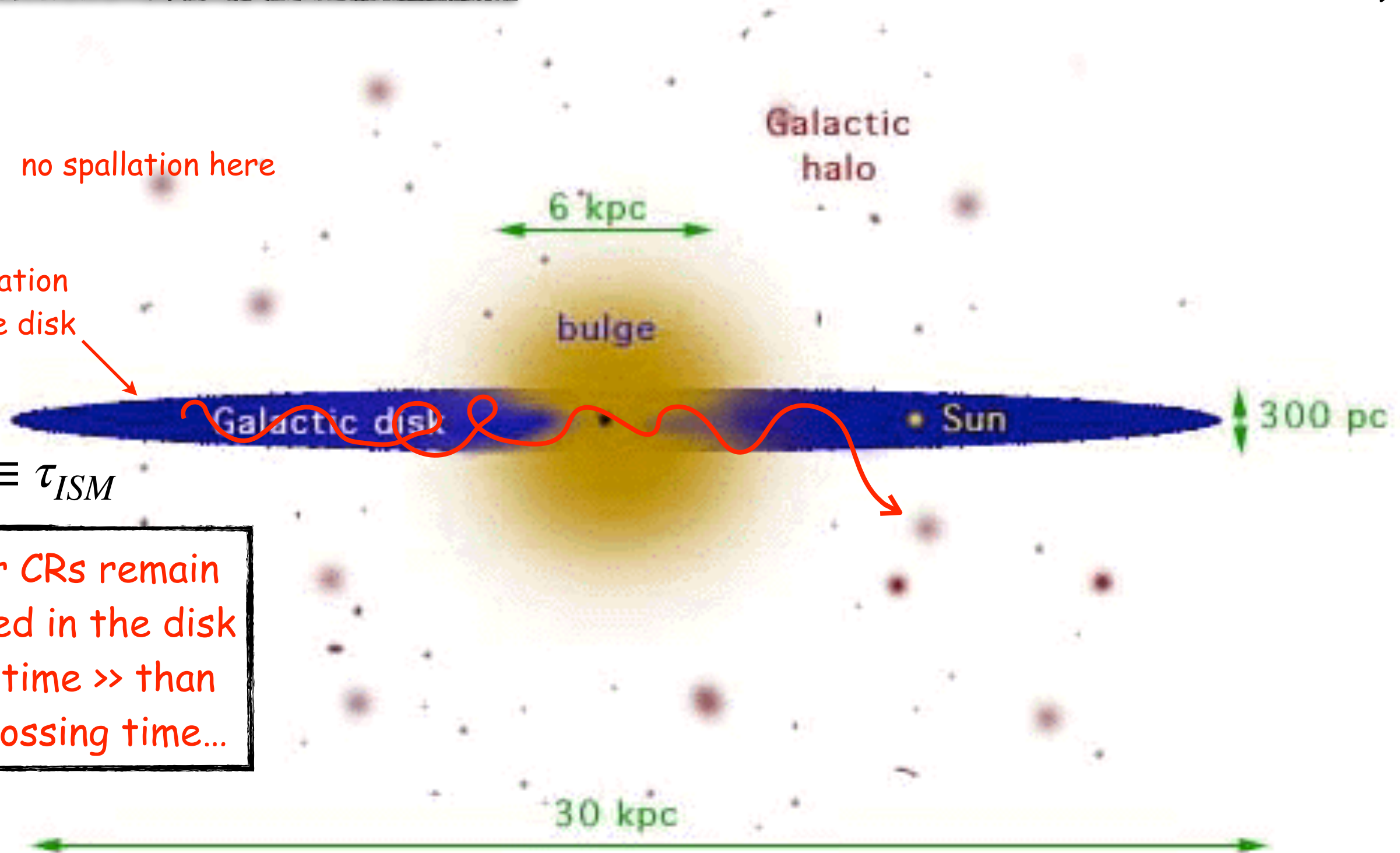
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no spallation here

spallation
in the disk

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

either CRs remain
confined in the disk
for a time $\gg$ than
the crossing time...



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Galactic
halo

6 kpc

bulge

Galactic disk

Sun

300 pc

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

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

30 kpc

Escape time or residence time?

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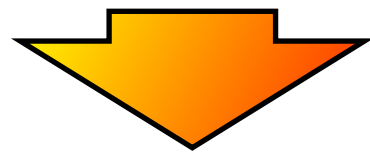
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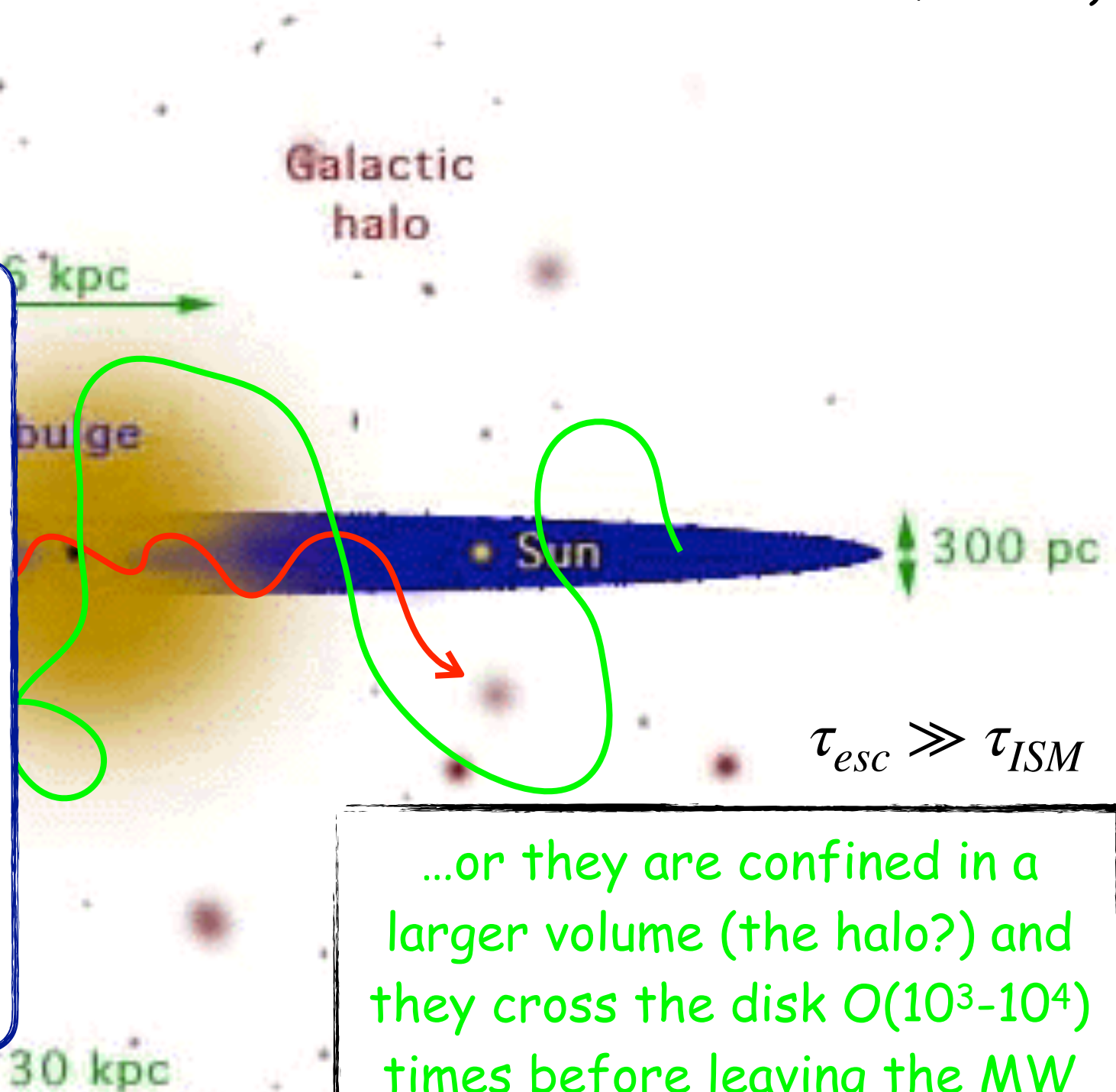
unstable secondaries

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

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



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



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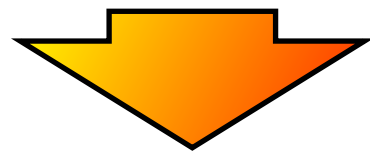
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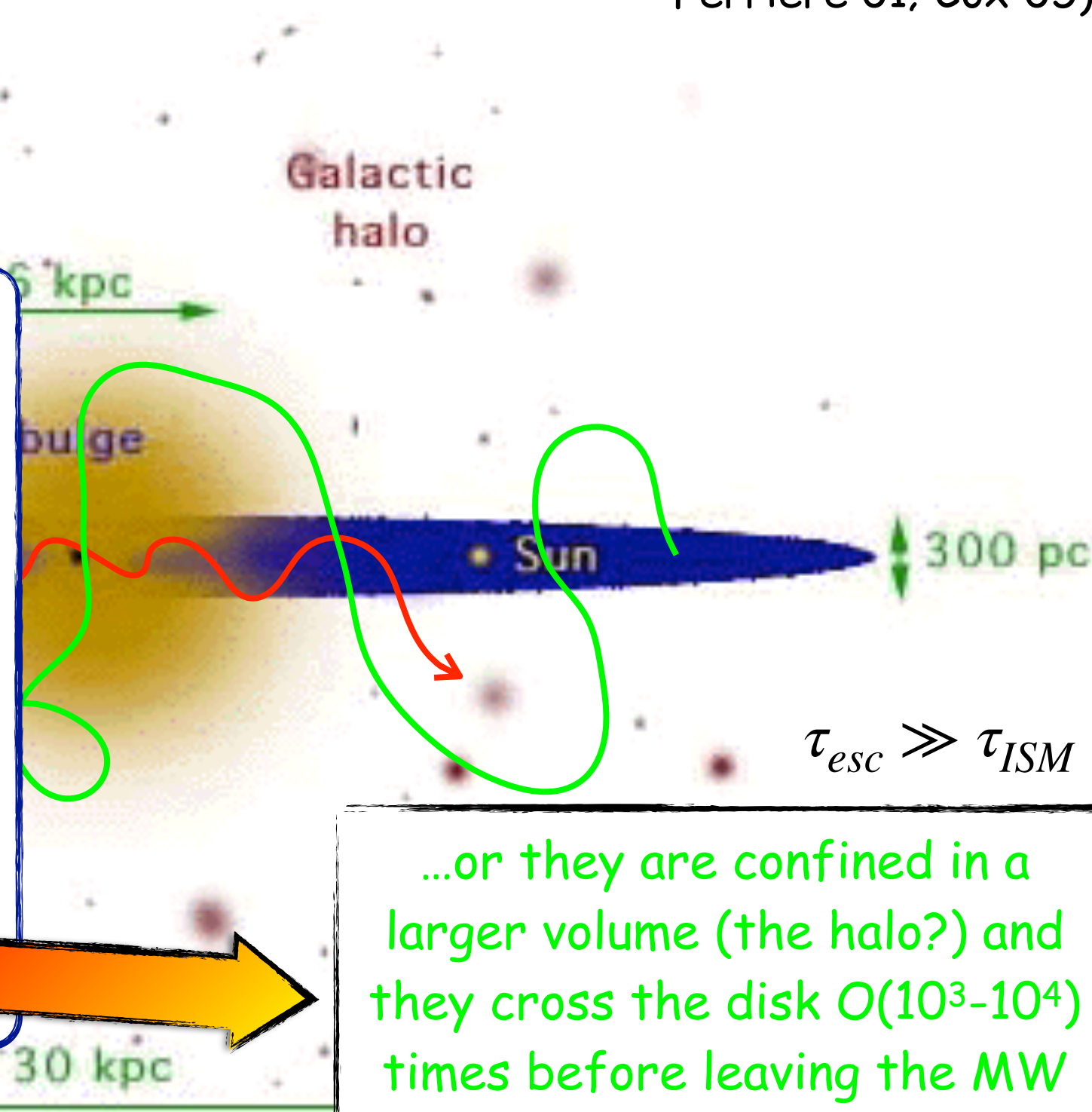
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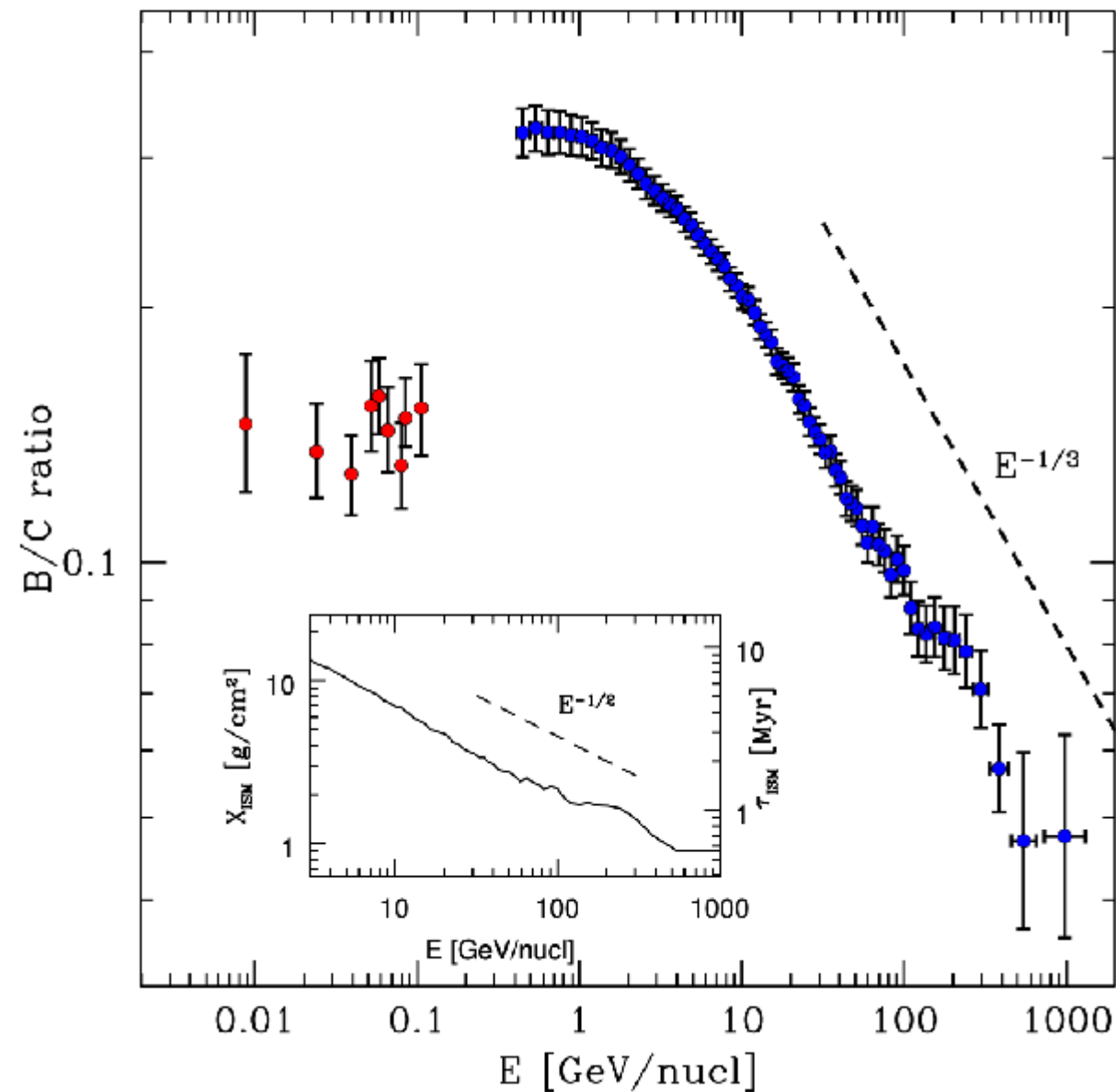


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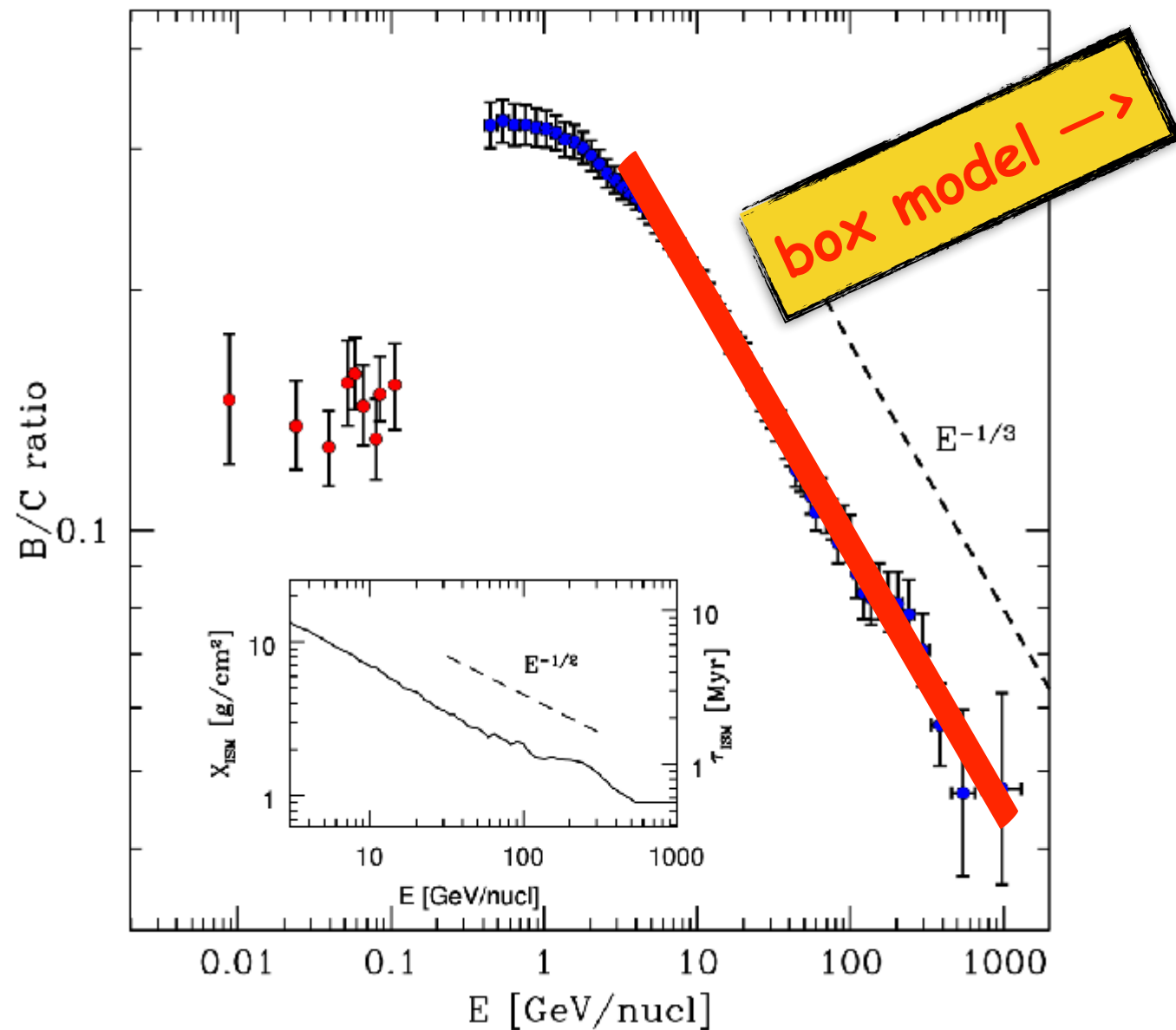
$$\tau_{esc} \gg \tau_{ISM}$$

Diffusive shock acceleration at supernova remnant shocks

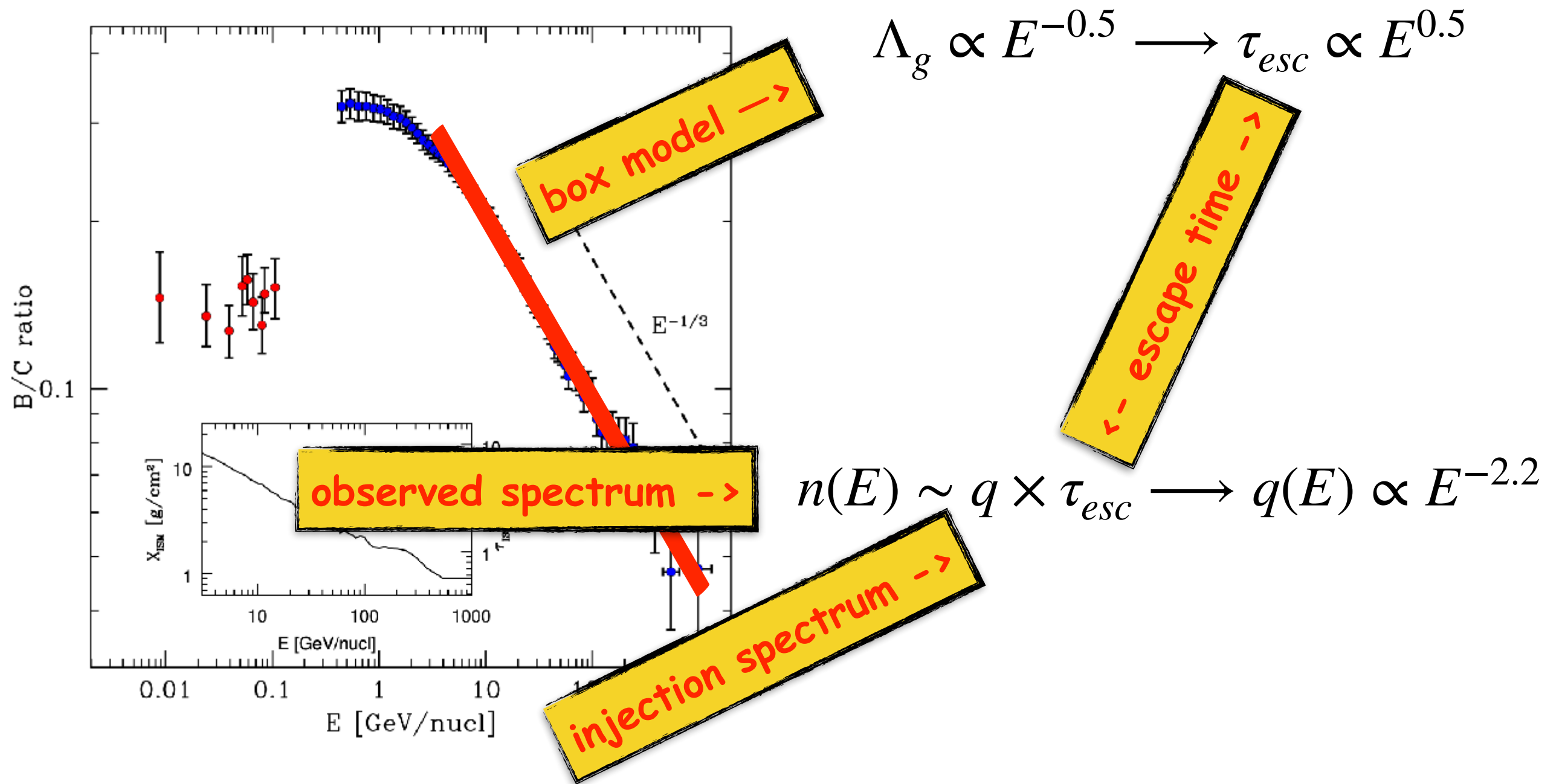


Diffusive shock acceleration at supernova remnant shocks

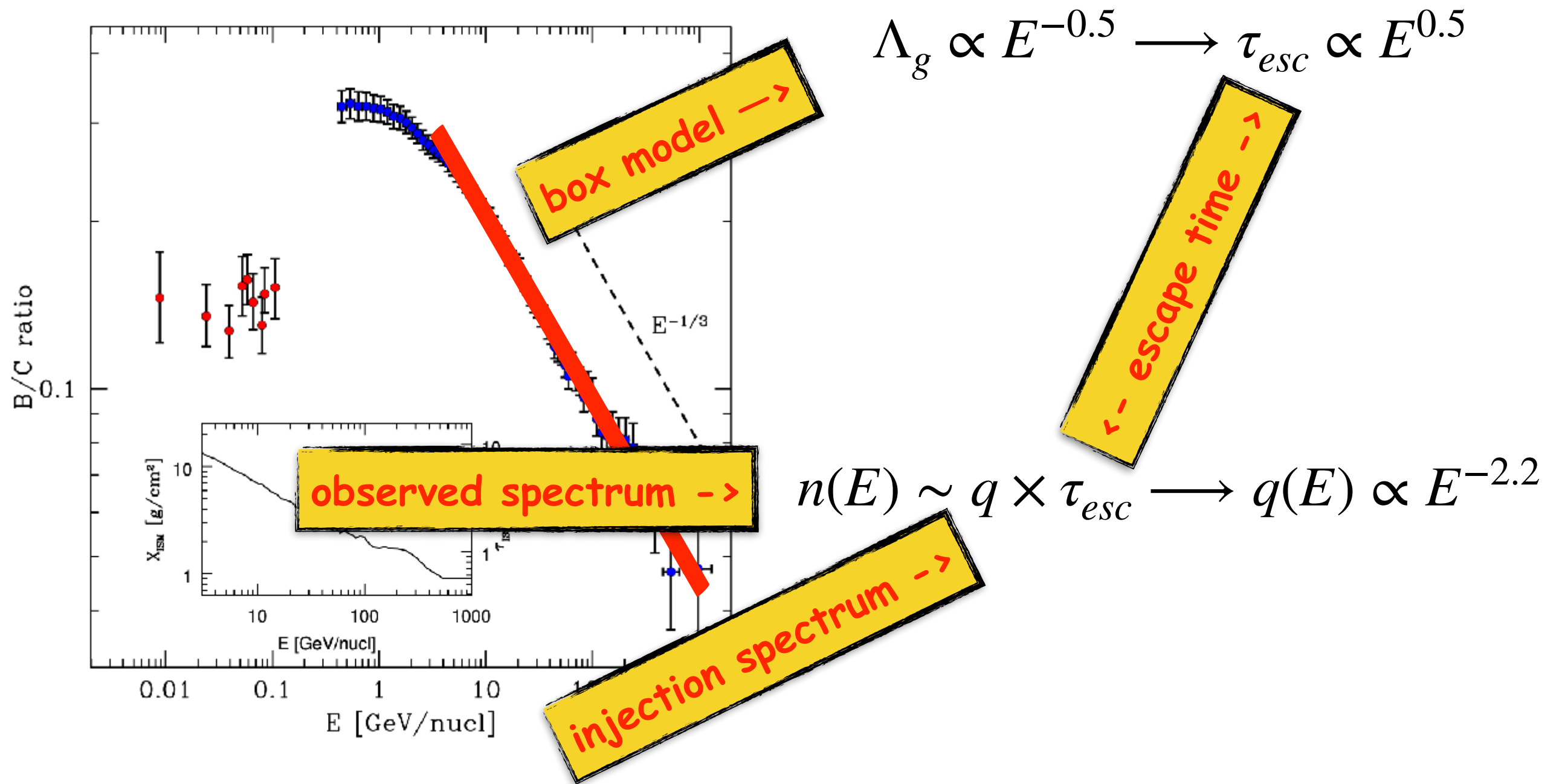
$$\Lambda_g \propto E^{-0.5} \longrightarrow \tau_{esc} \propto E^{0.5}$$



Diffusive shock acceleration at supernova remnant shocks

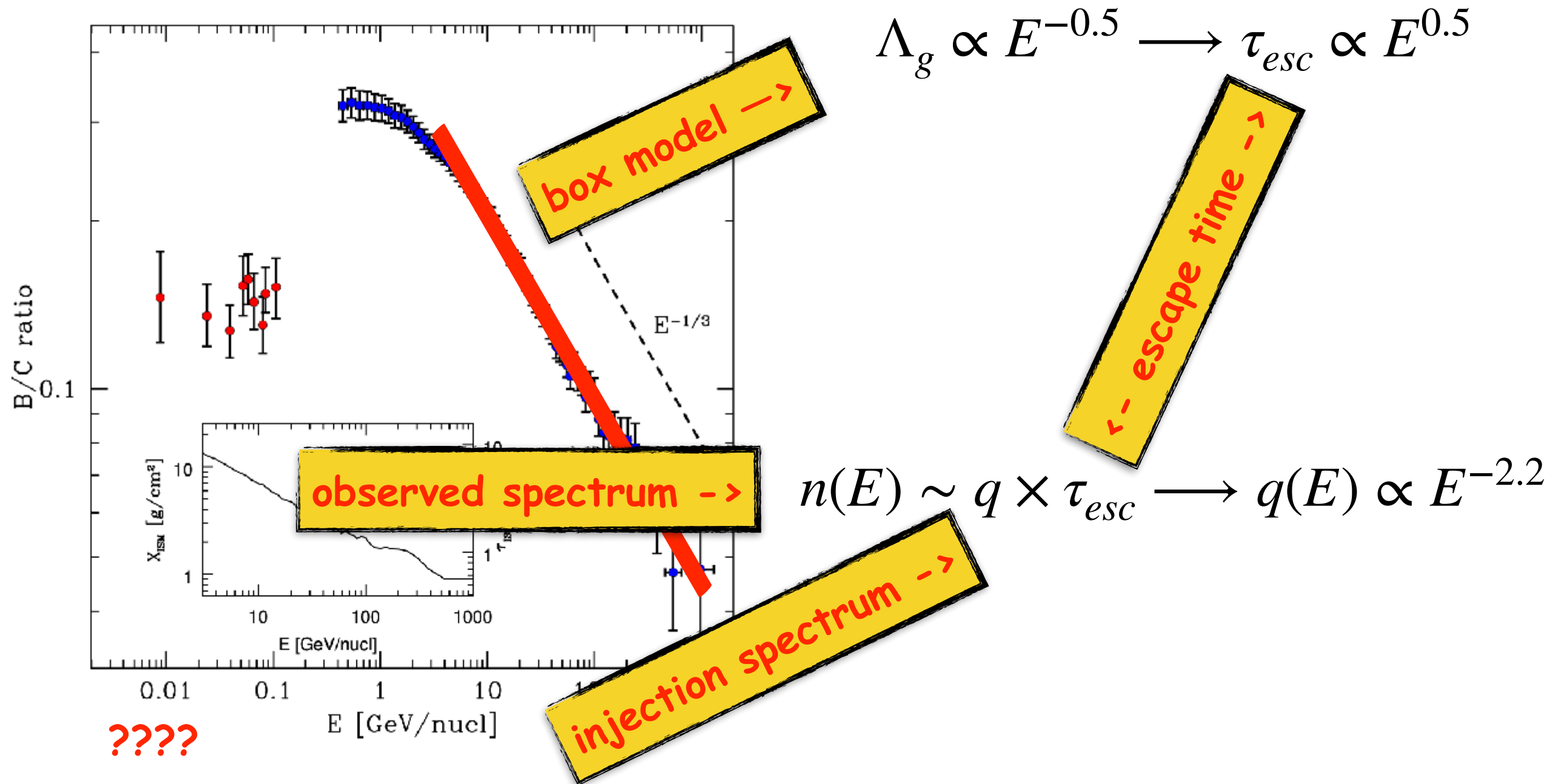


Diffusive shock acceleration at supernova remnant shocks



quite close to the predictions of diffusive shock acceleration $\rightarrow$

Diffusive shock acceleration at supernova remnant shocks

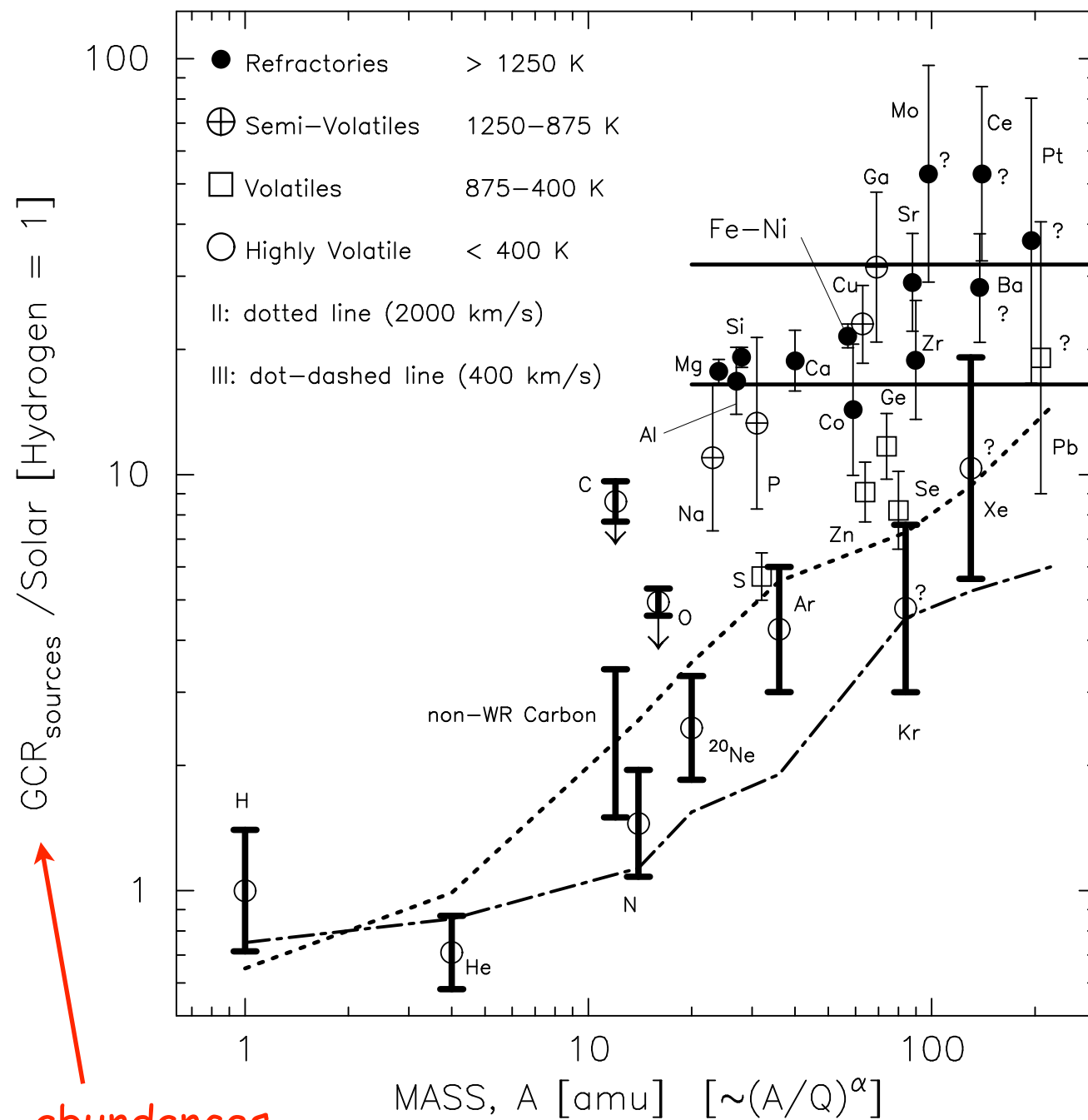


quite close to) the predictions of diffusive shock acceleration ->

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

Dust MUST play a role

Ellison, Drury, Meyer (1997)



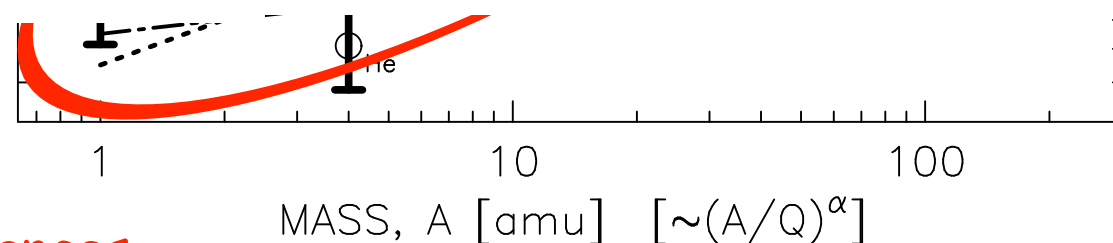
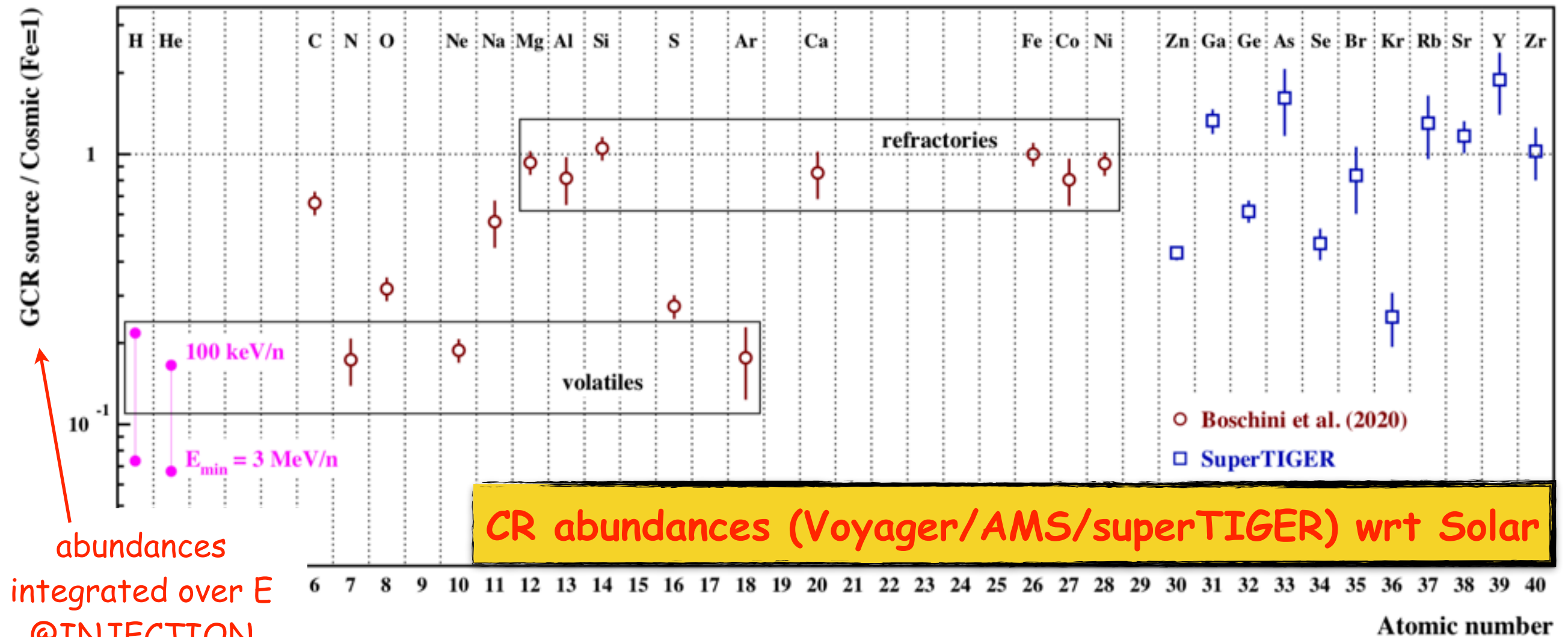
abundances
measured at a fixed
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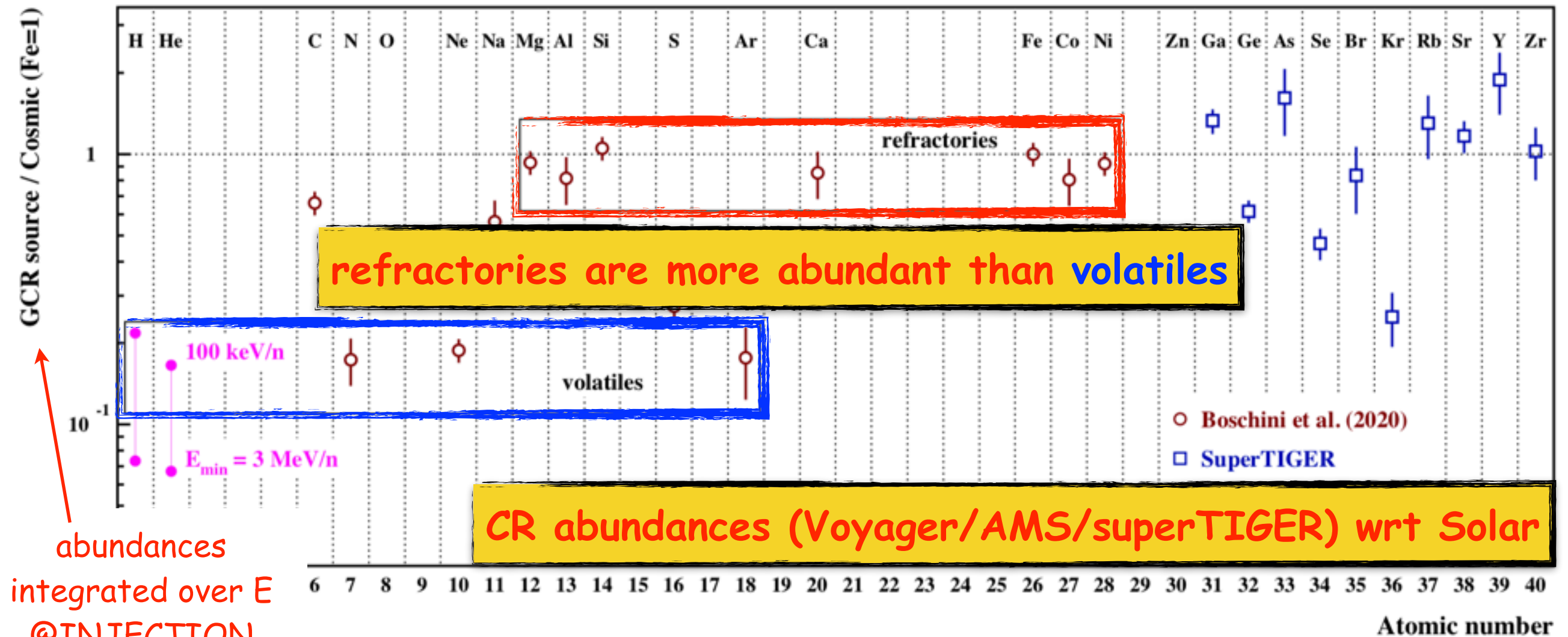
Tatischeff+ 2021



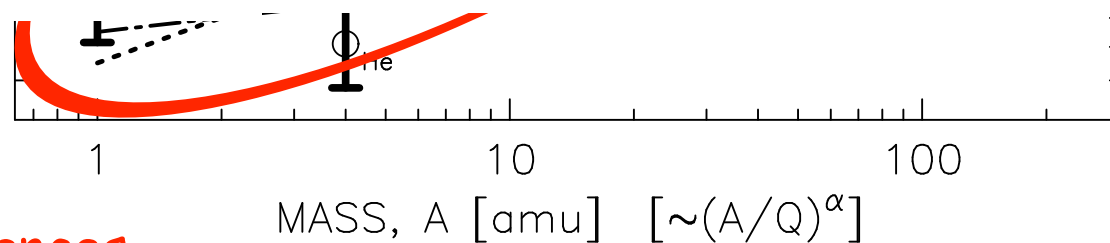
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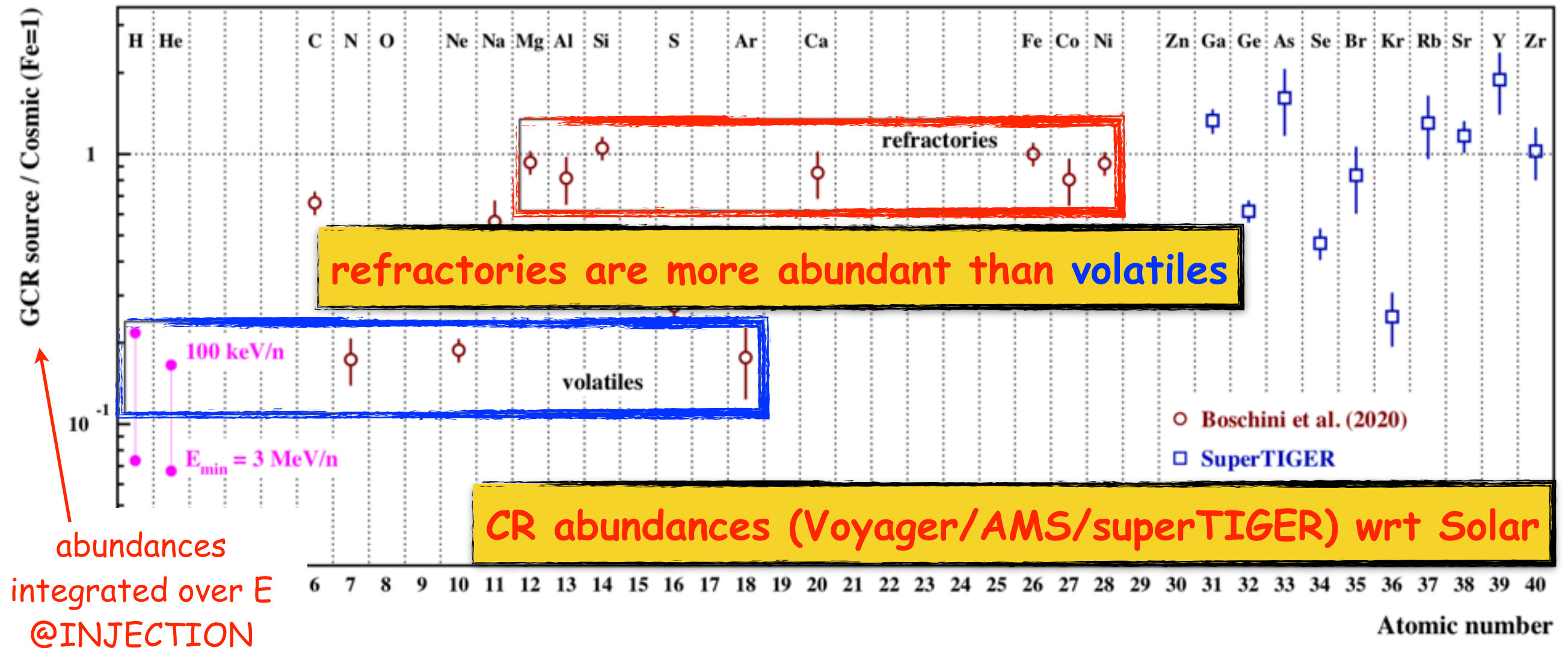
abundances
integrated over E
@INJECTION



abundances
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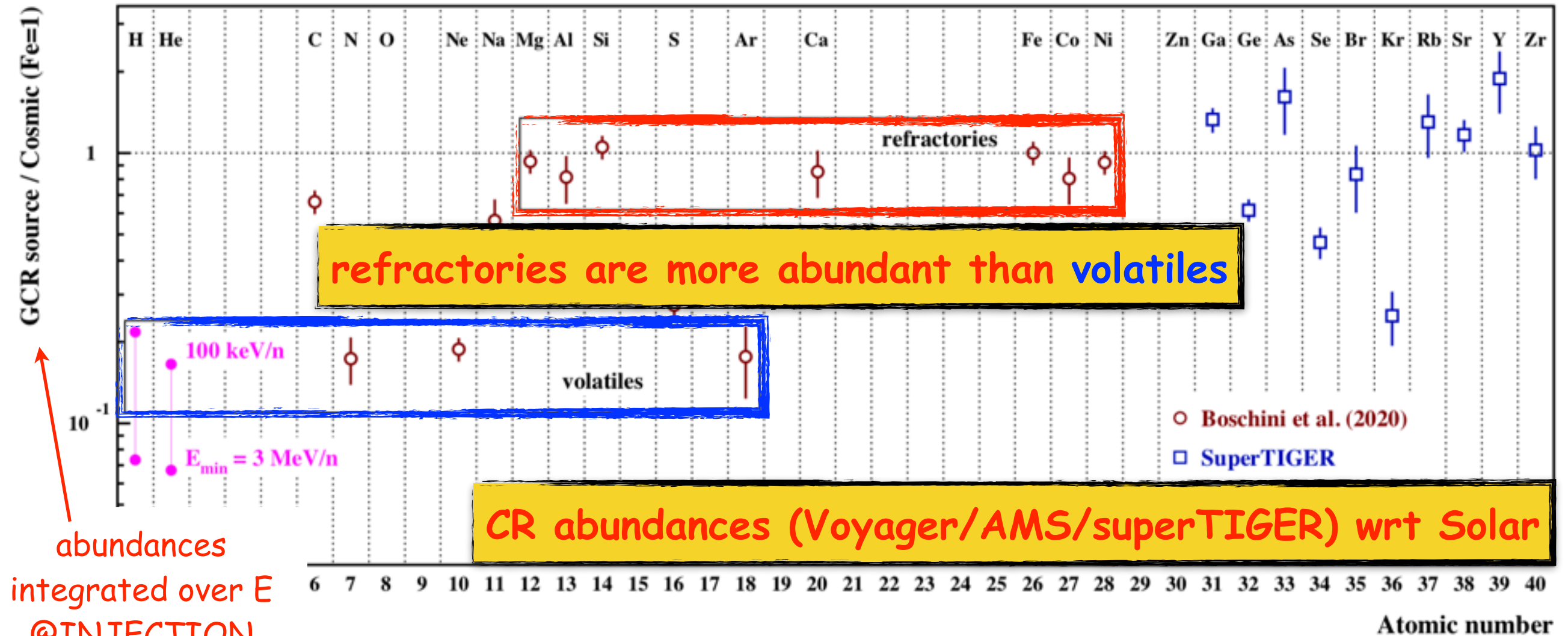
Tatischeff+ 2021



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

Dust MUST play a role

Tatischeff+ 2021



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Ellison+1997, Caprioli+ 2017, Hanusch+ 2019 →

WHY?
 preferential acceleration of dust at shocks
 → large A/Z
 (Larmor radius)

The three pillars of orthodoxy

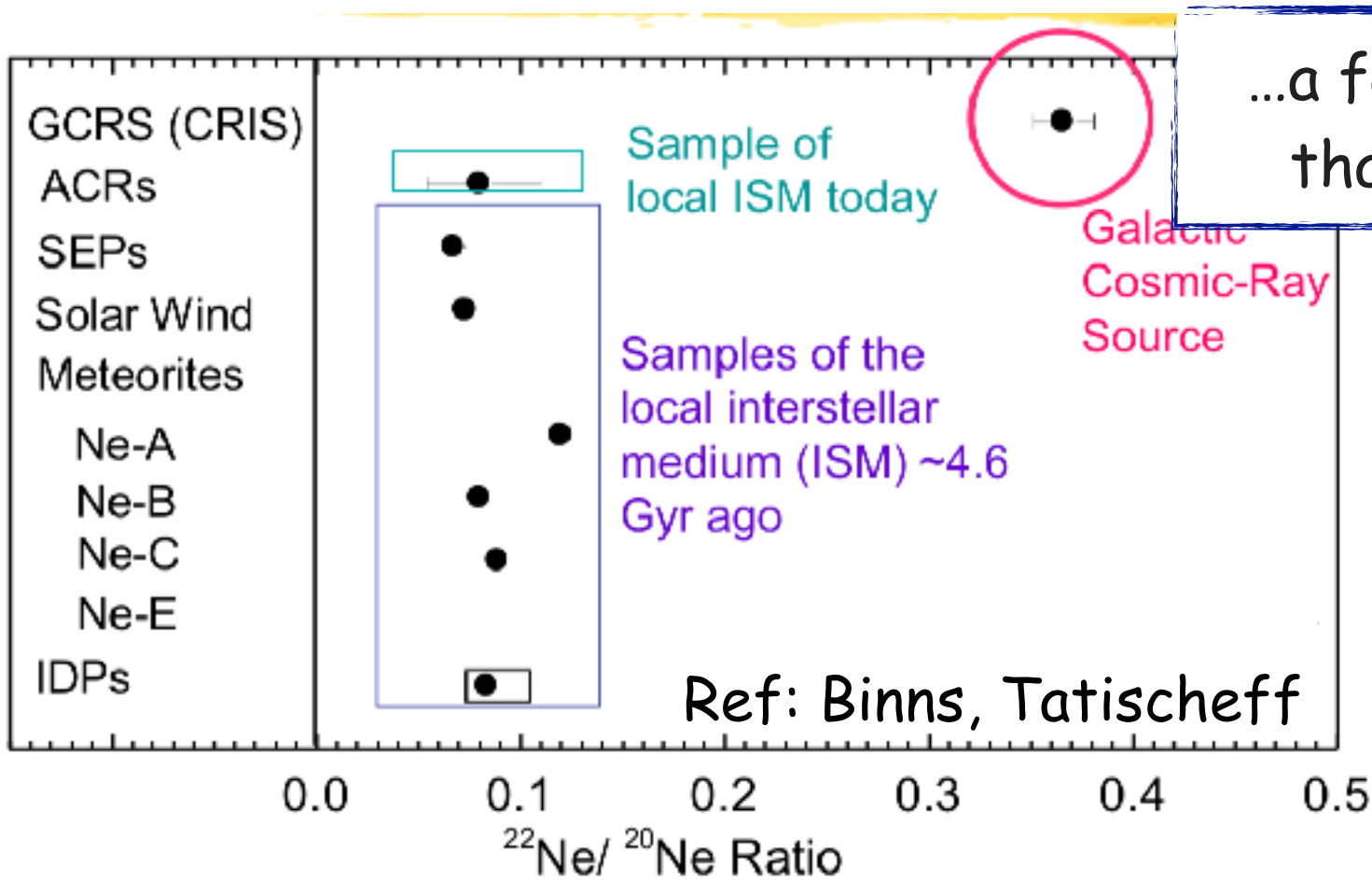
the supernova remnant paradigm for the origin of cosmic rays

- ▶ The bulk of the energy of cosmic rays originates from supernova explosions in the Galactic disk
- ▶ Cosmic rays are diffusively confined within an extended and magnetised Galactic halo
- ▶ Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

Two old standing problems
with the SNR paradigm

Anomaly in the isotopic ratio $^{22}\text{Ne}/^{20}\text{Ne}$

old stuff, the anomaly was first observed by Garcia-Munoz, Simpson & Wefel 1979

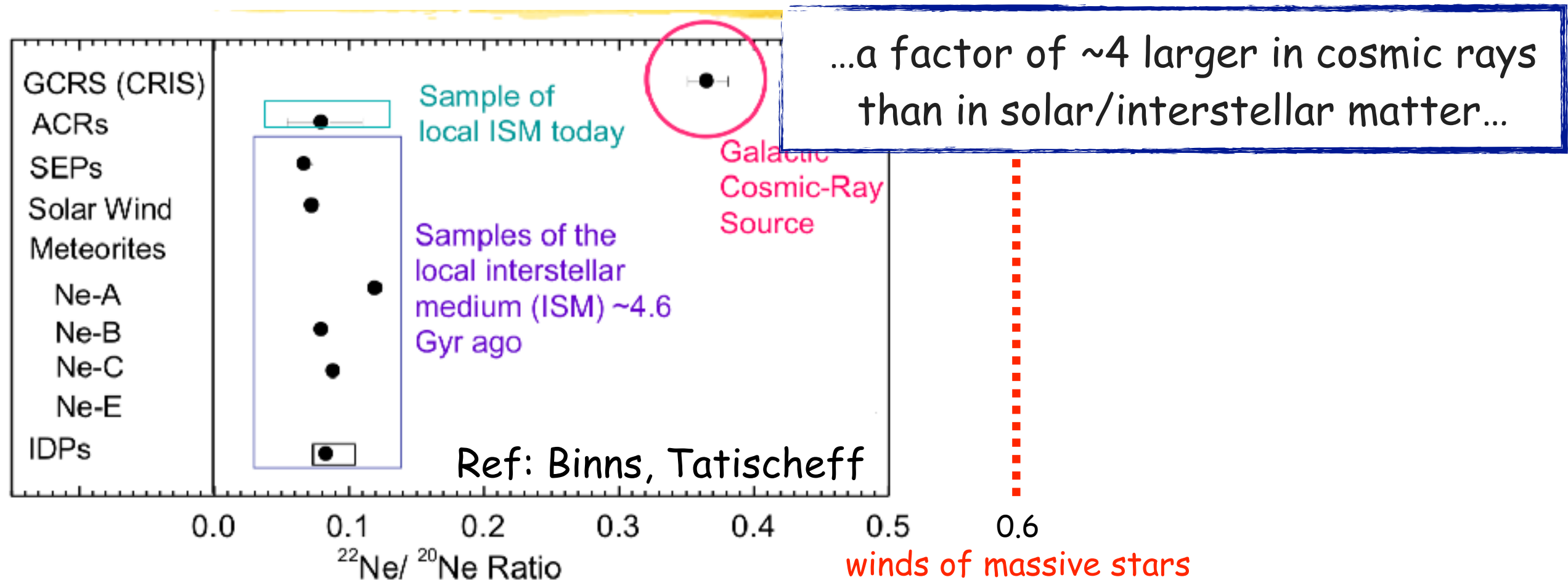


...a factor of ~ 4 larger in cosmic rays than in solar/interstellar matter...

Ref: Binns, Tatischeff

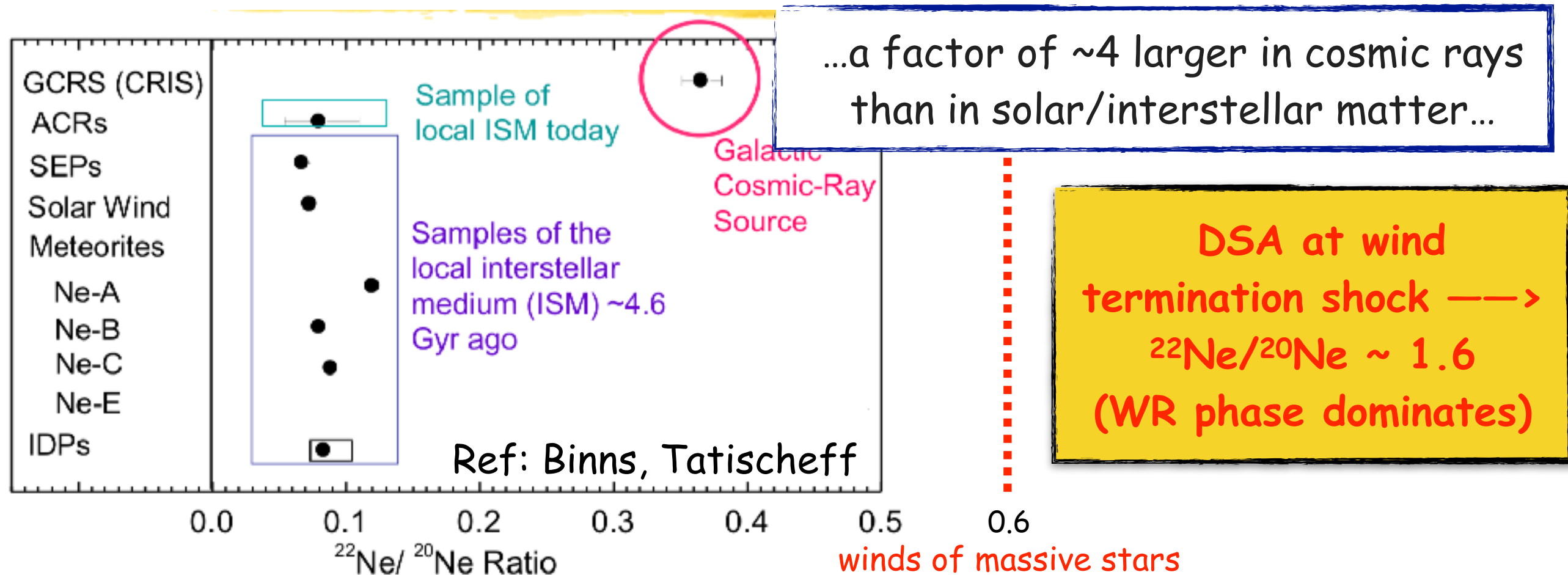
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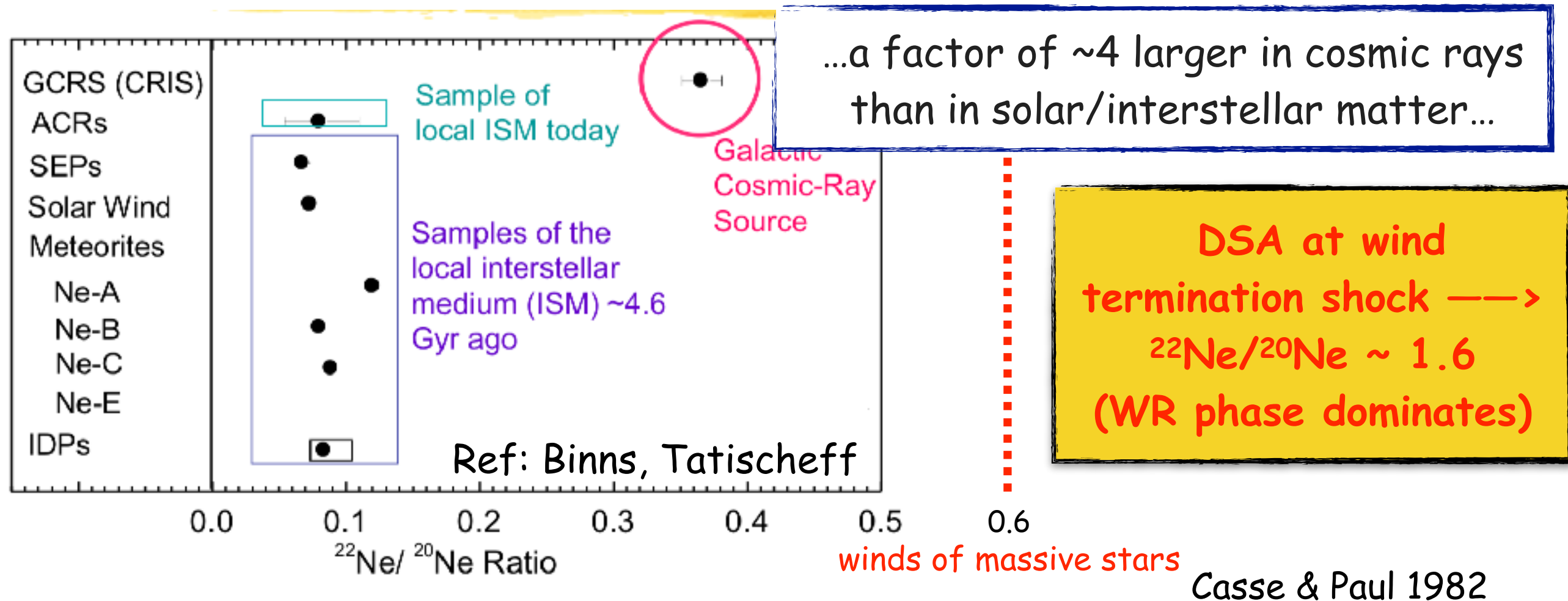
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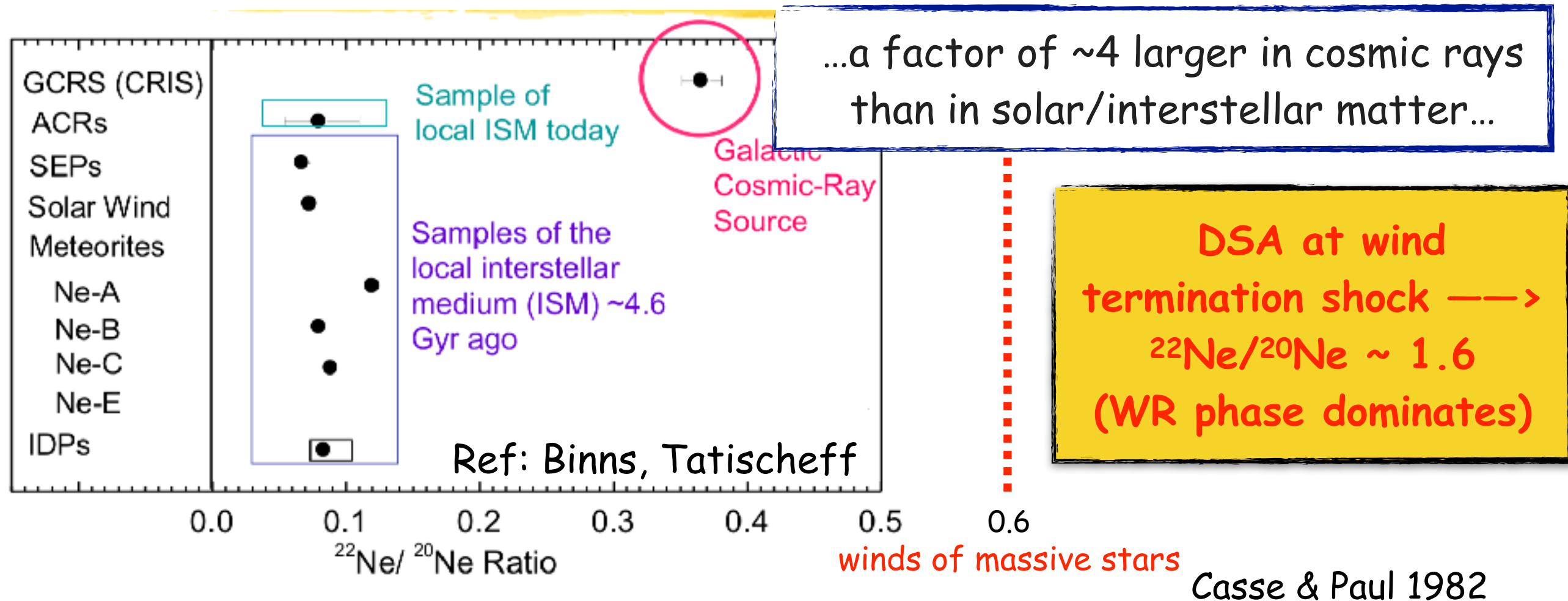
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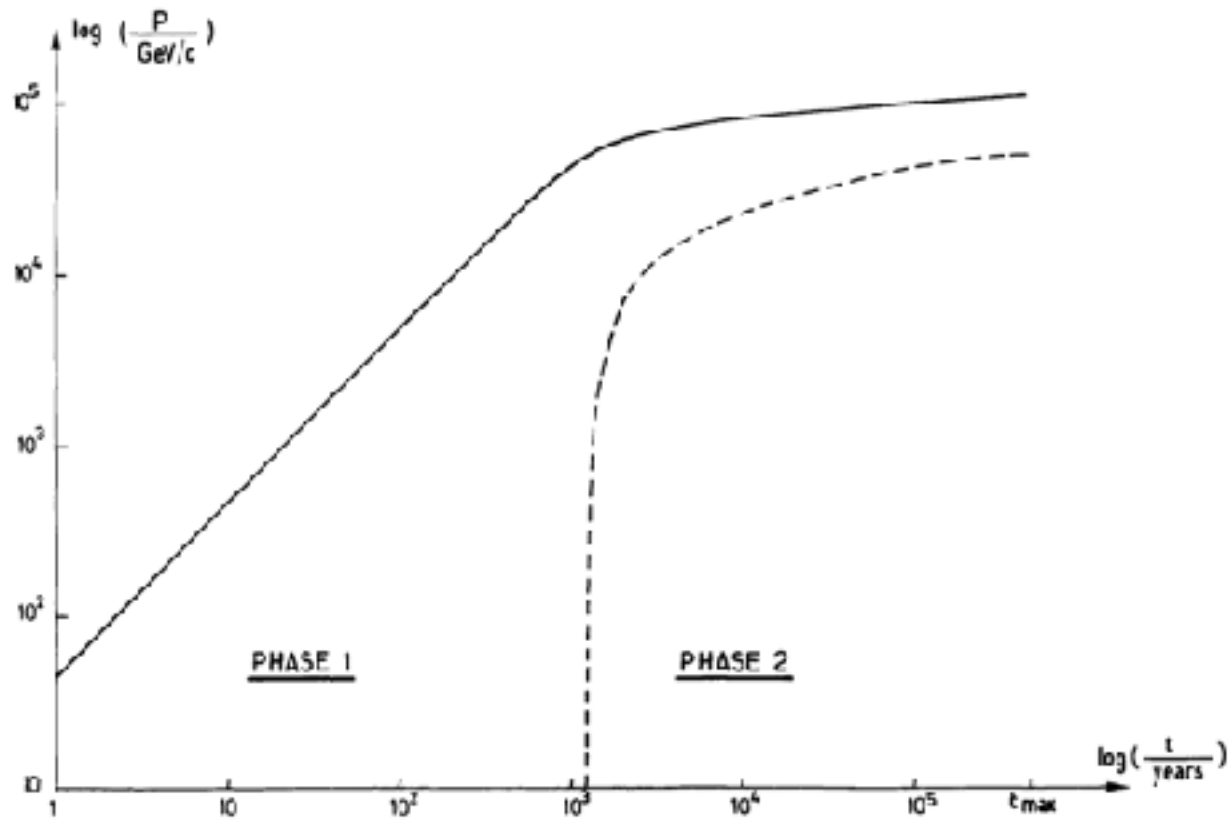


CRs are accelerated out of interstellar matter PLUS a bit of wind material

Cesarsky & Montmerle 83 $\longrightarrow$ SN power larger by a factor of several than wind power in the MW
 $\longrightarrow$ stellar winds can accelerate AT MOST a minor (but non-negligible) fraction of CRs

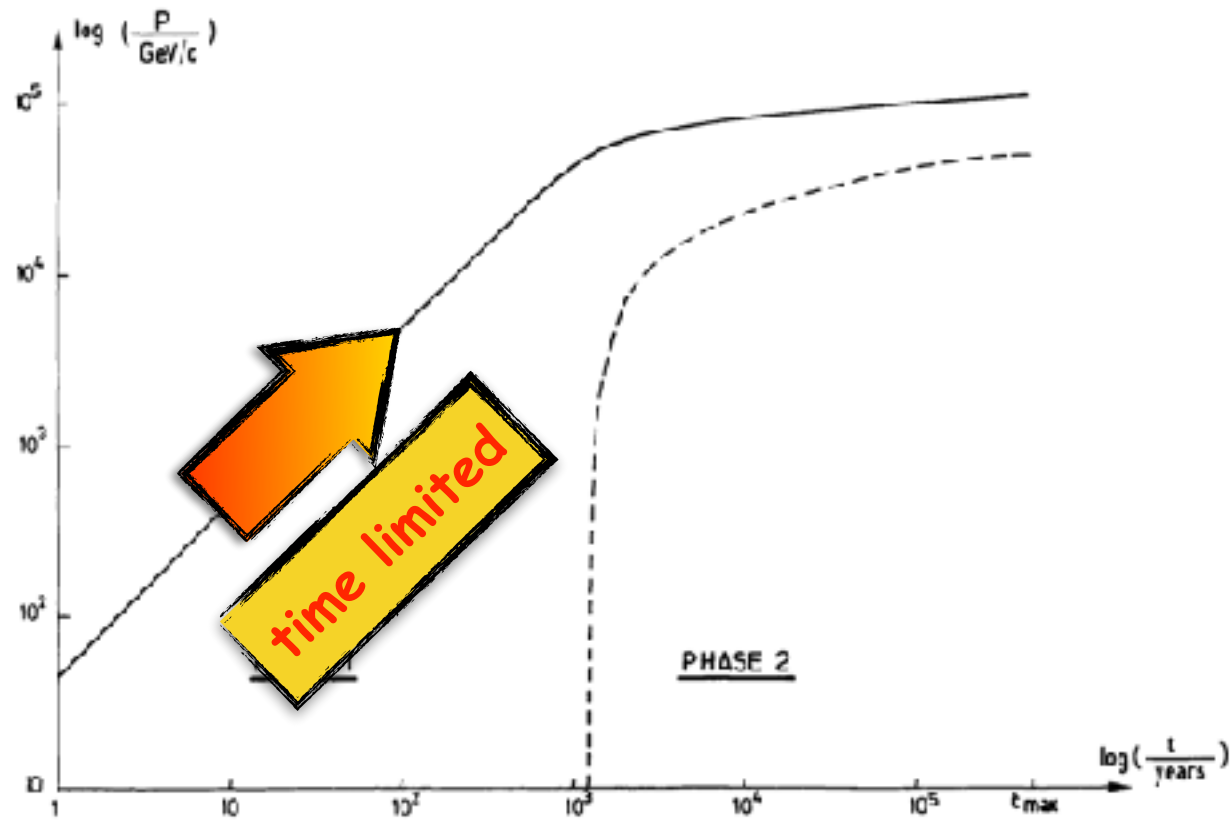
Can SNRs accelerate CRs to the knee?

Lagage & Cesarsky 1983



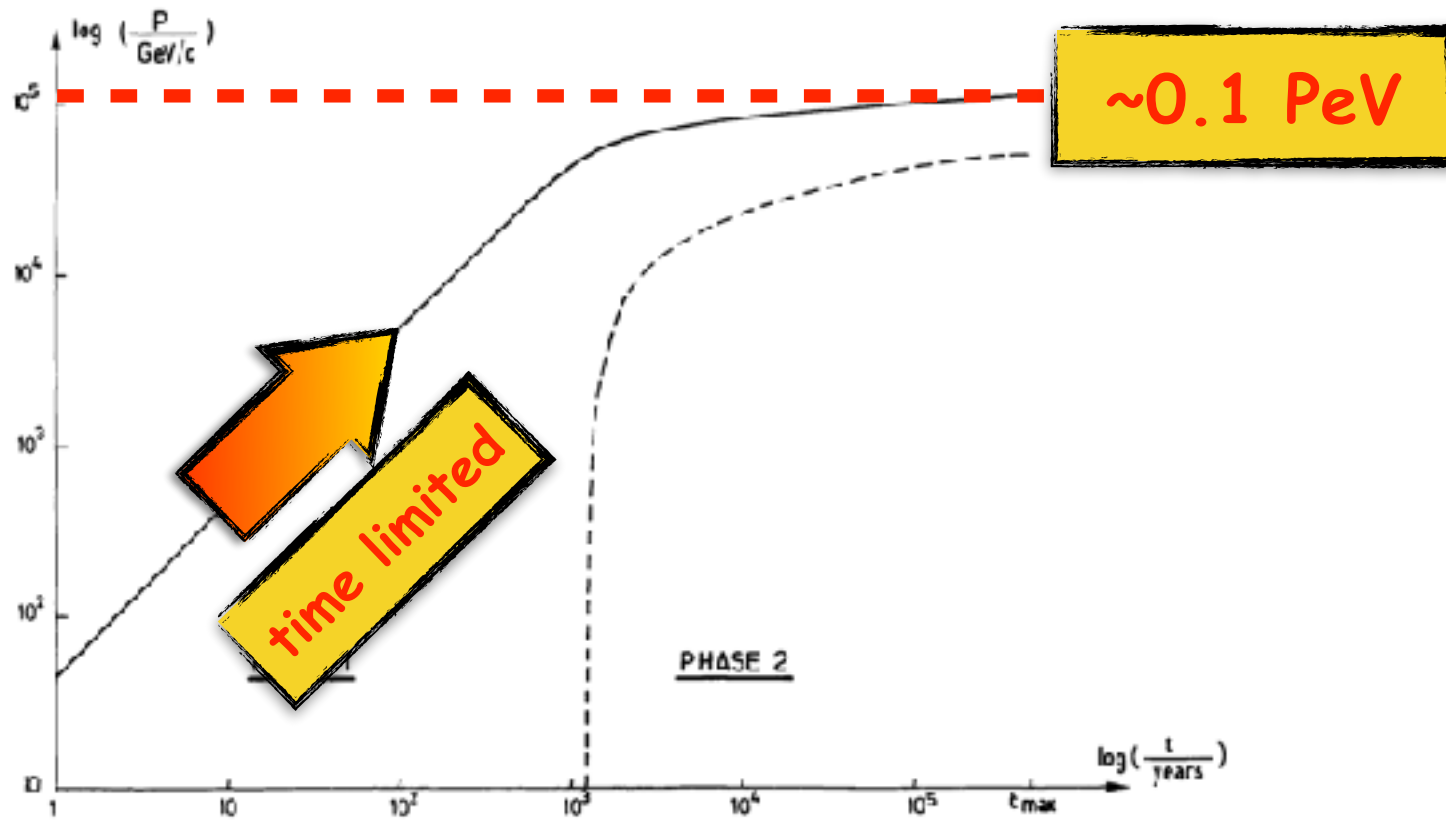
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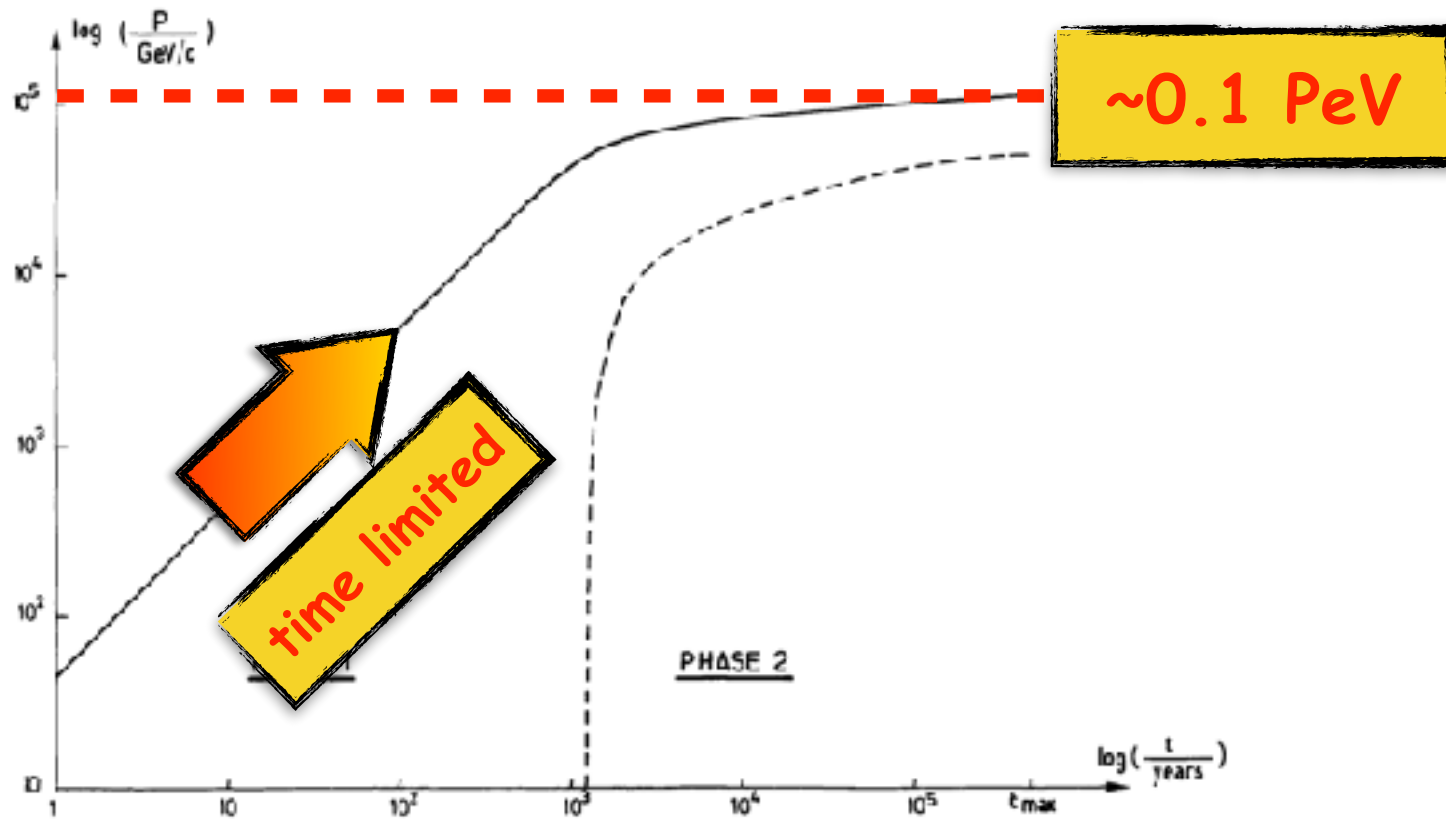
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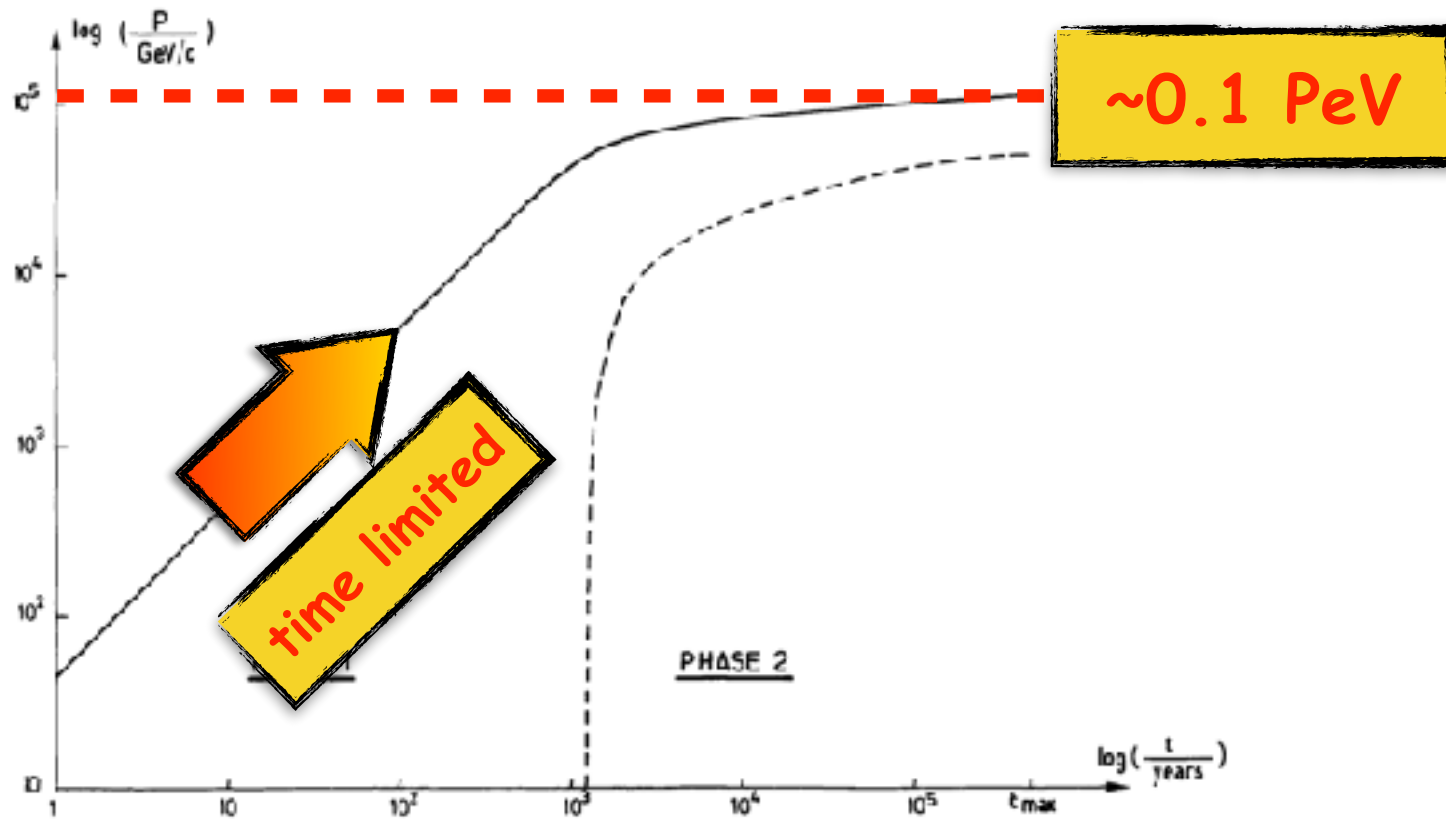


whatever you do you end up with Hillas

$$E_{max} \sim \frac{q}{c} B u R$$

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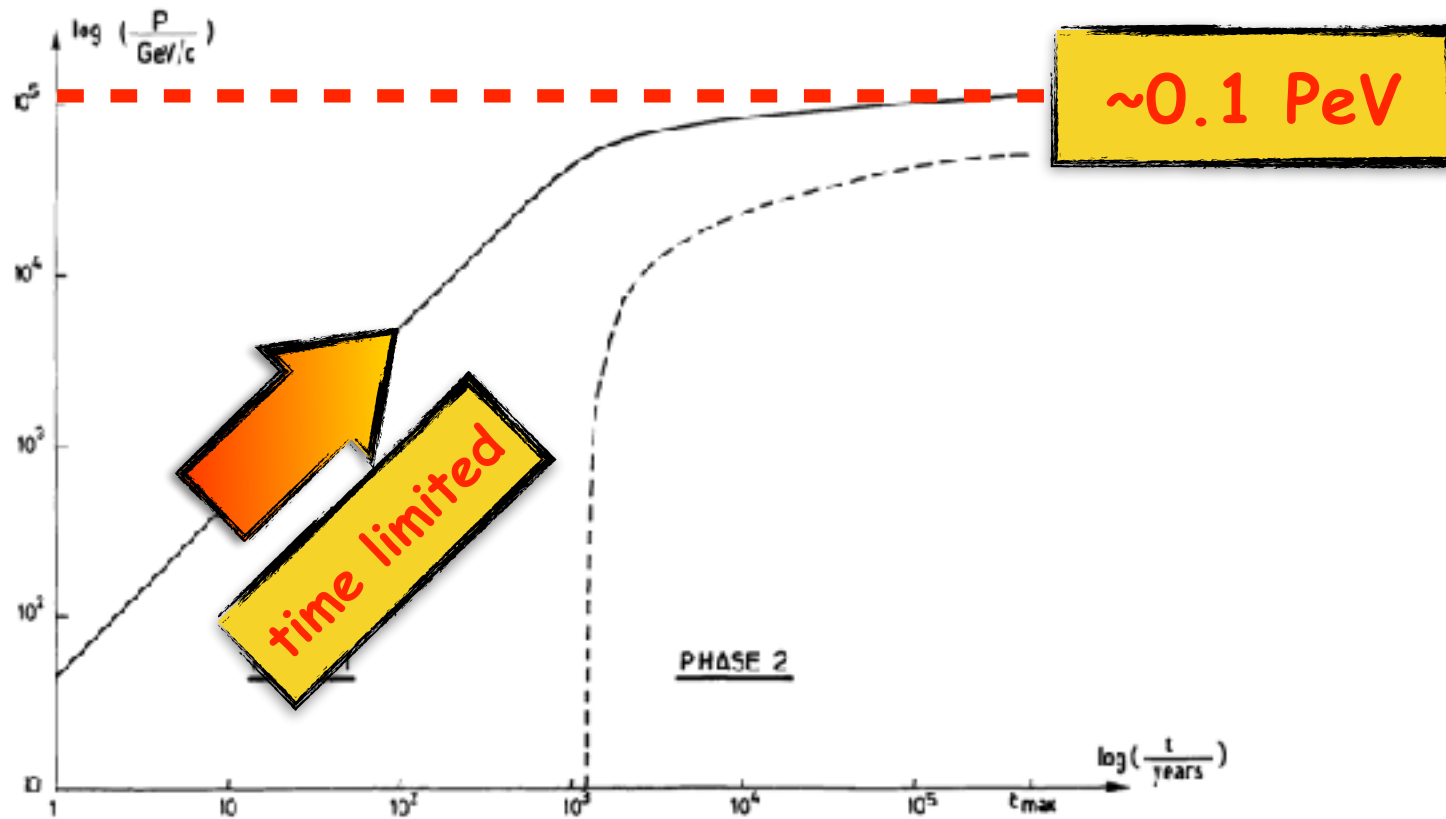
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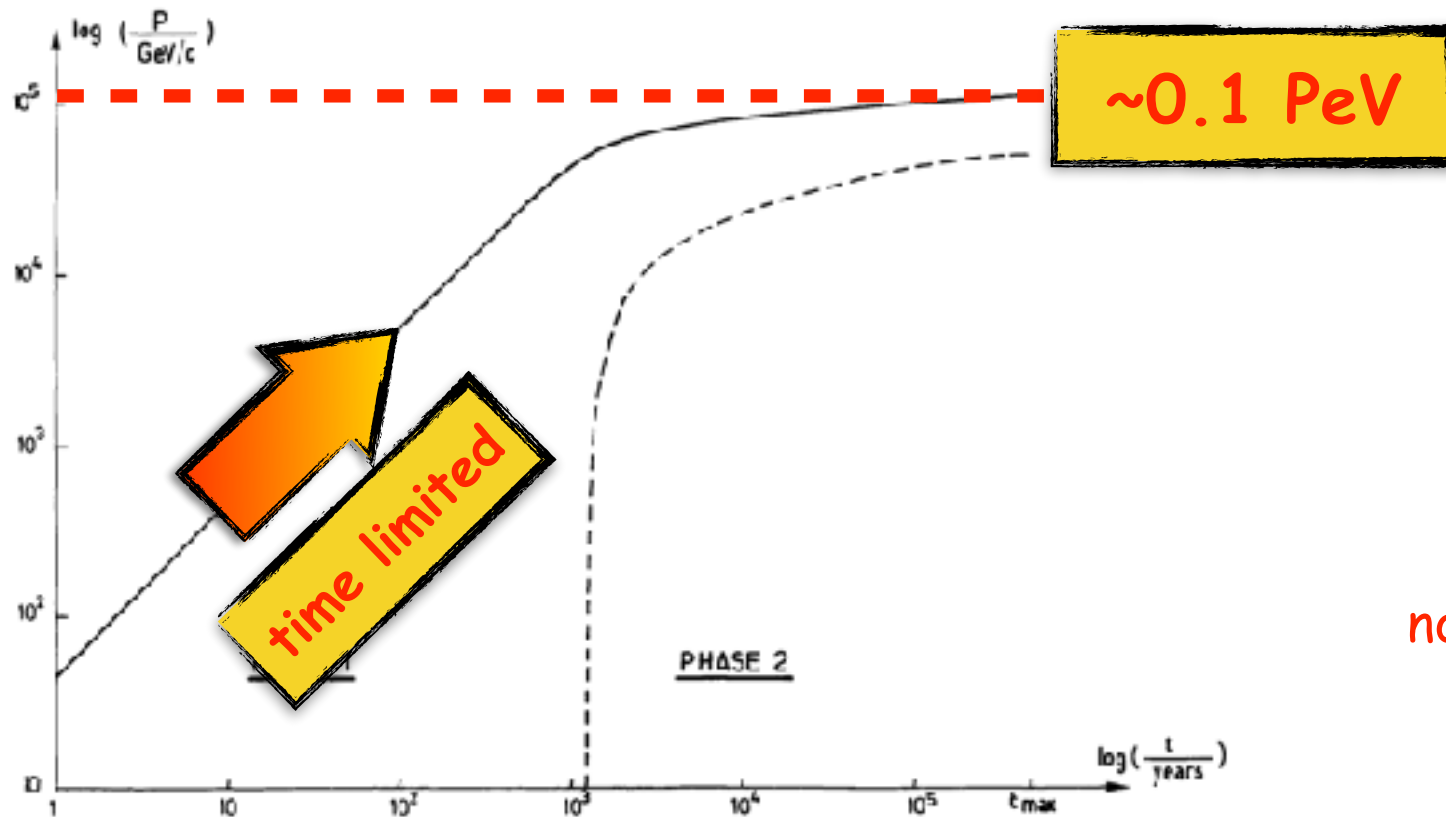
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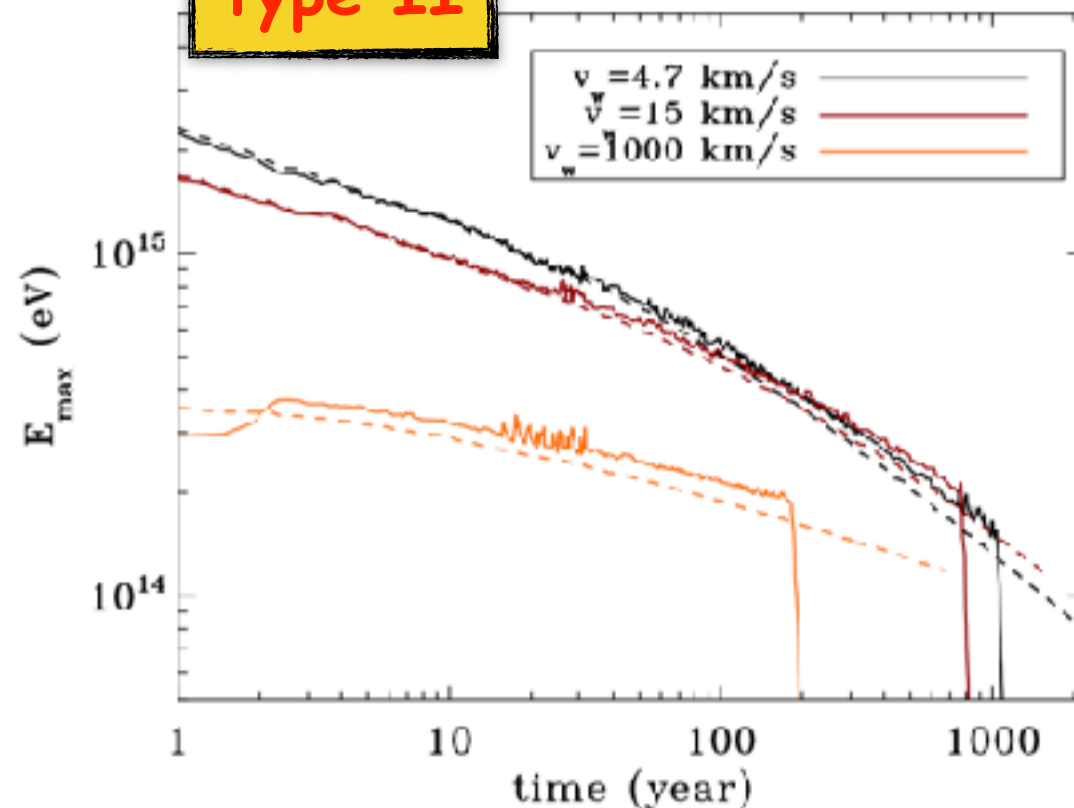
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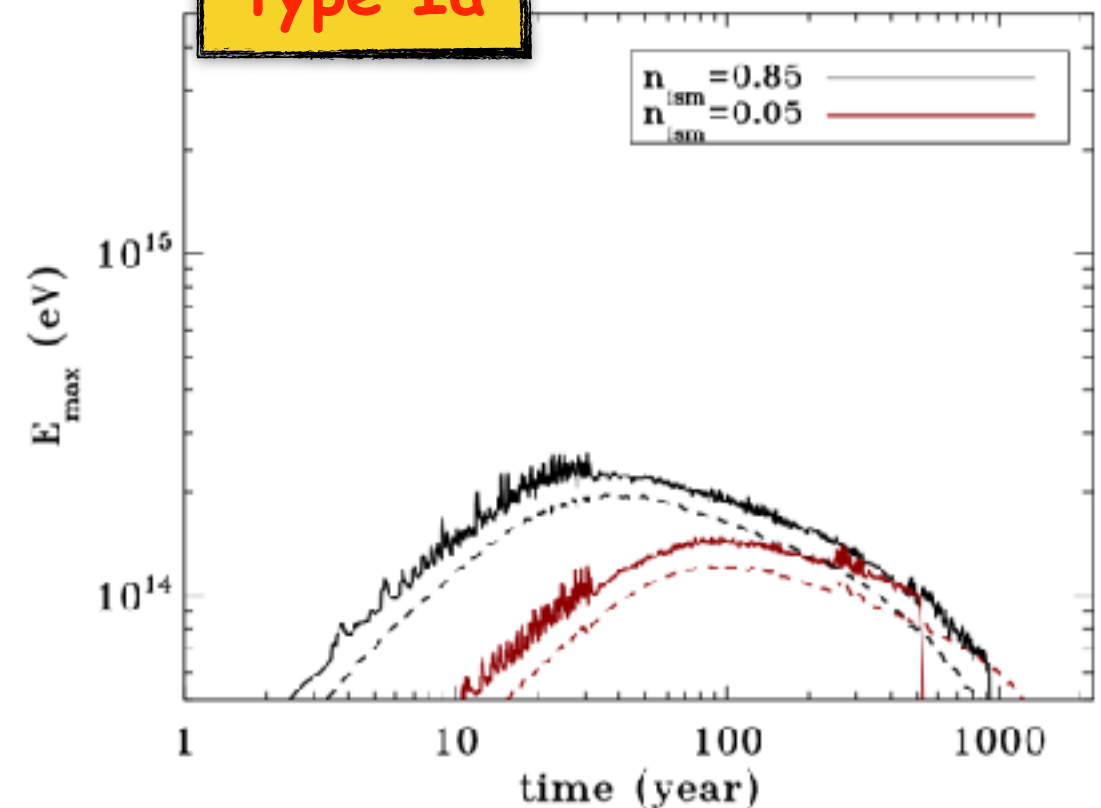
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non-resonant CR instability

type II



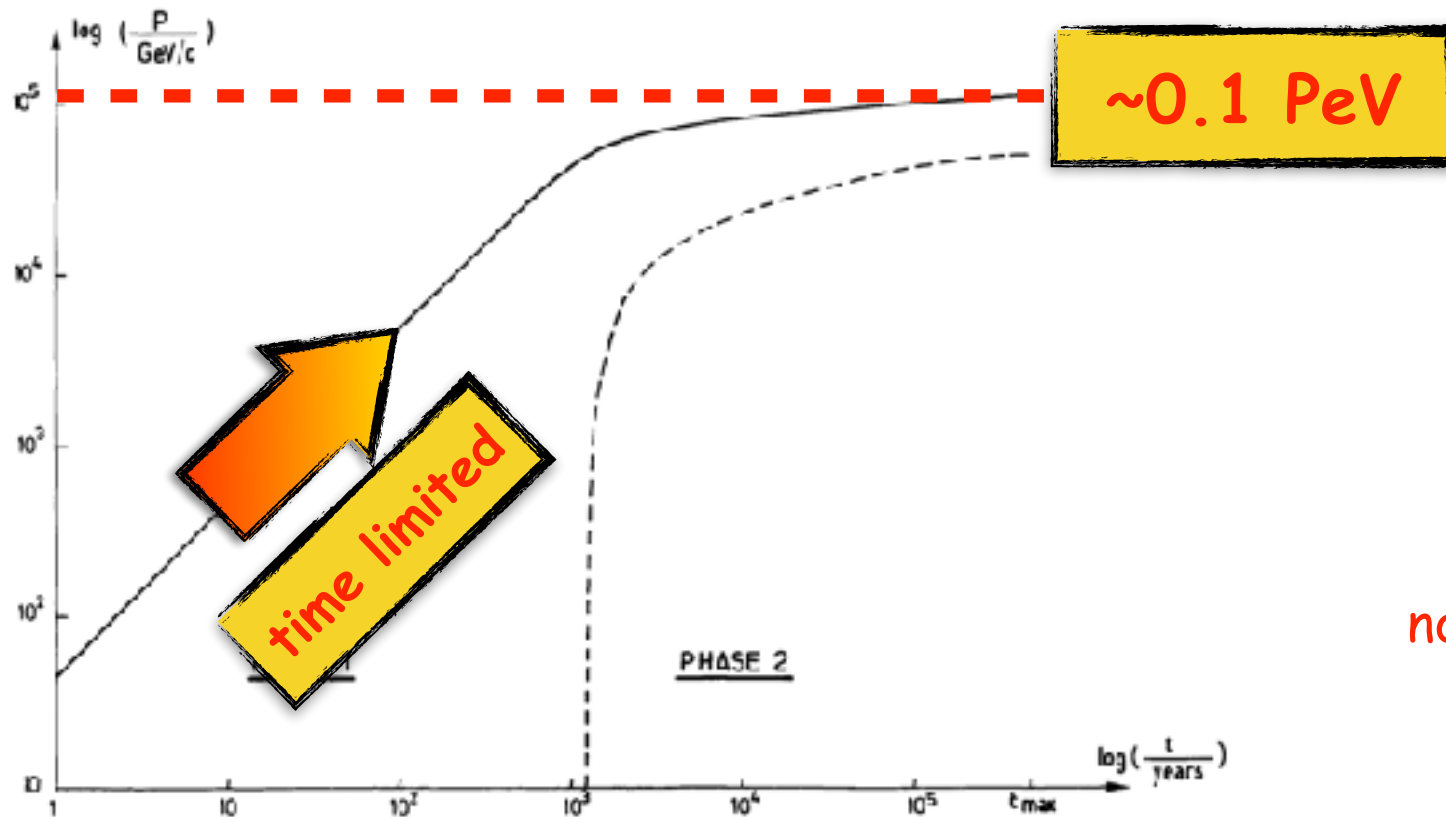
type Ia



Schure & Bell 2013

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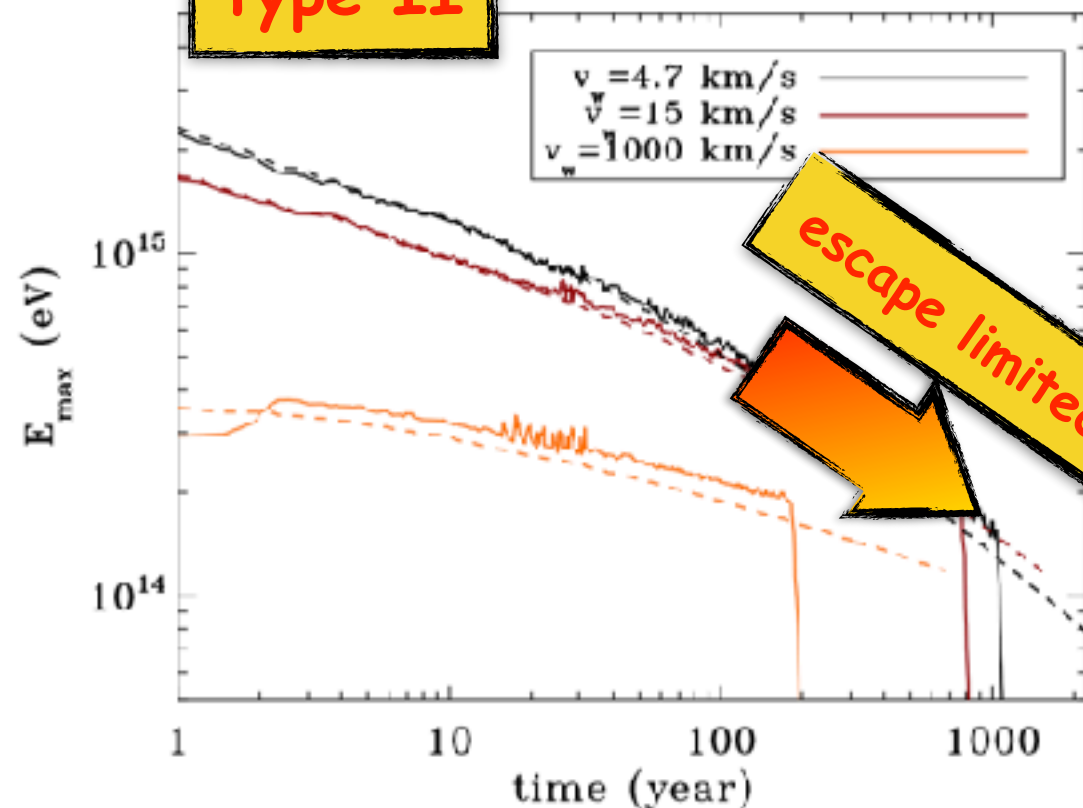
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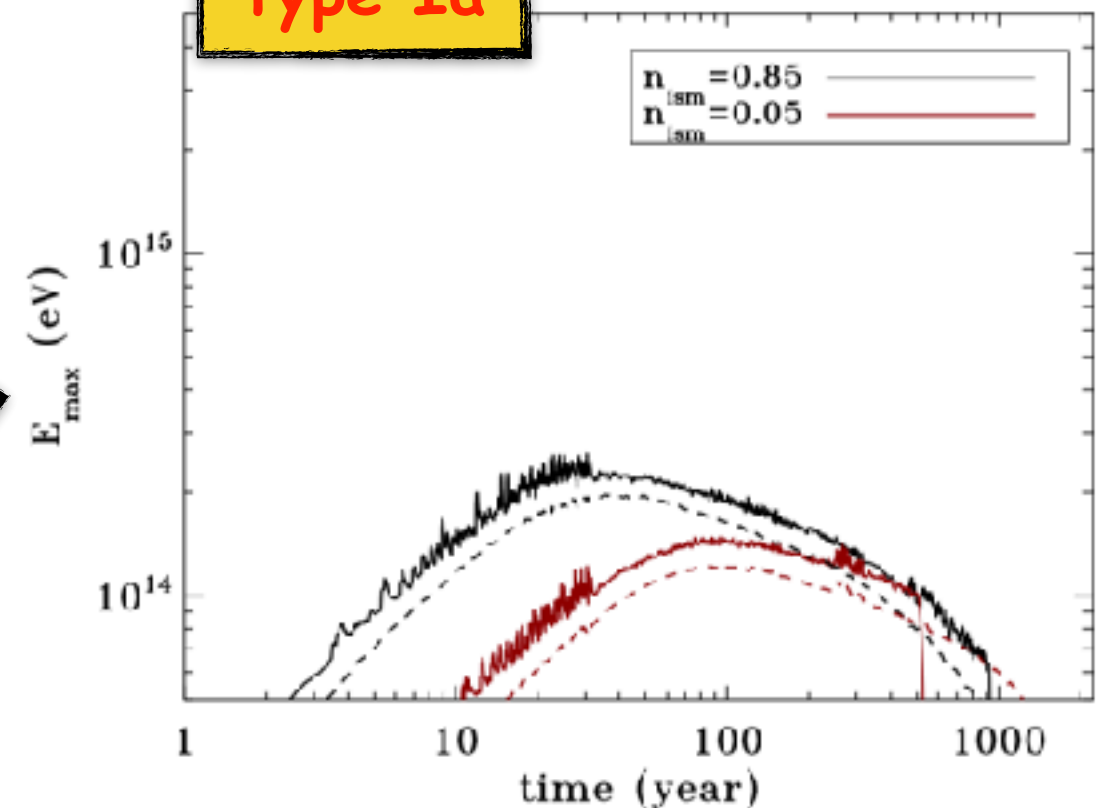
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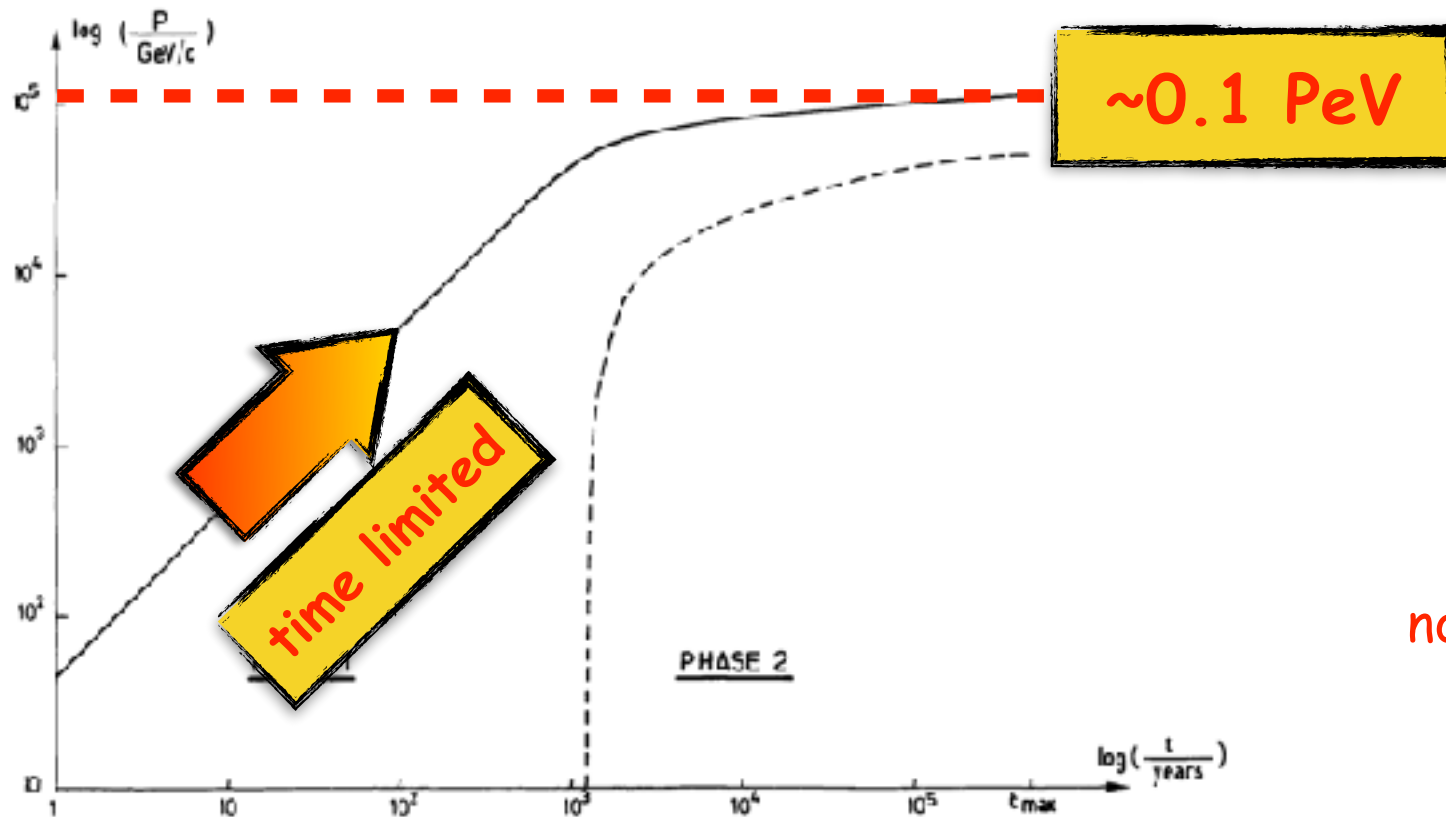
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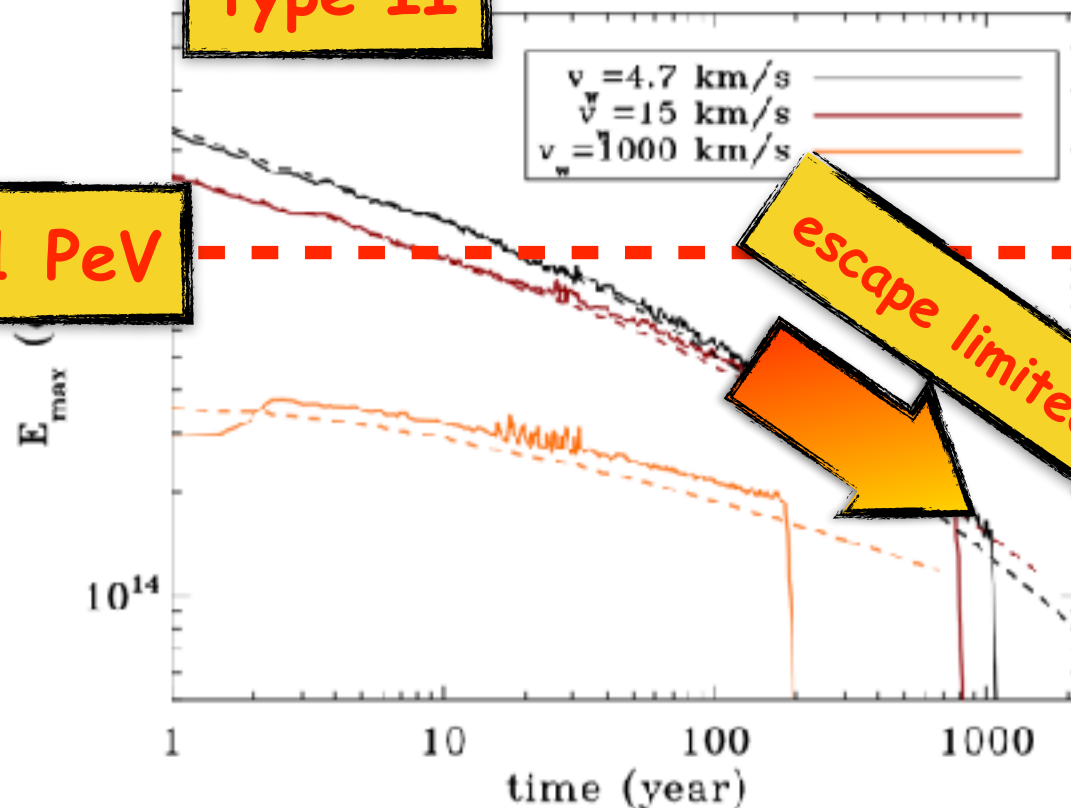
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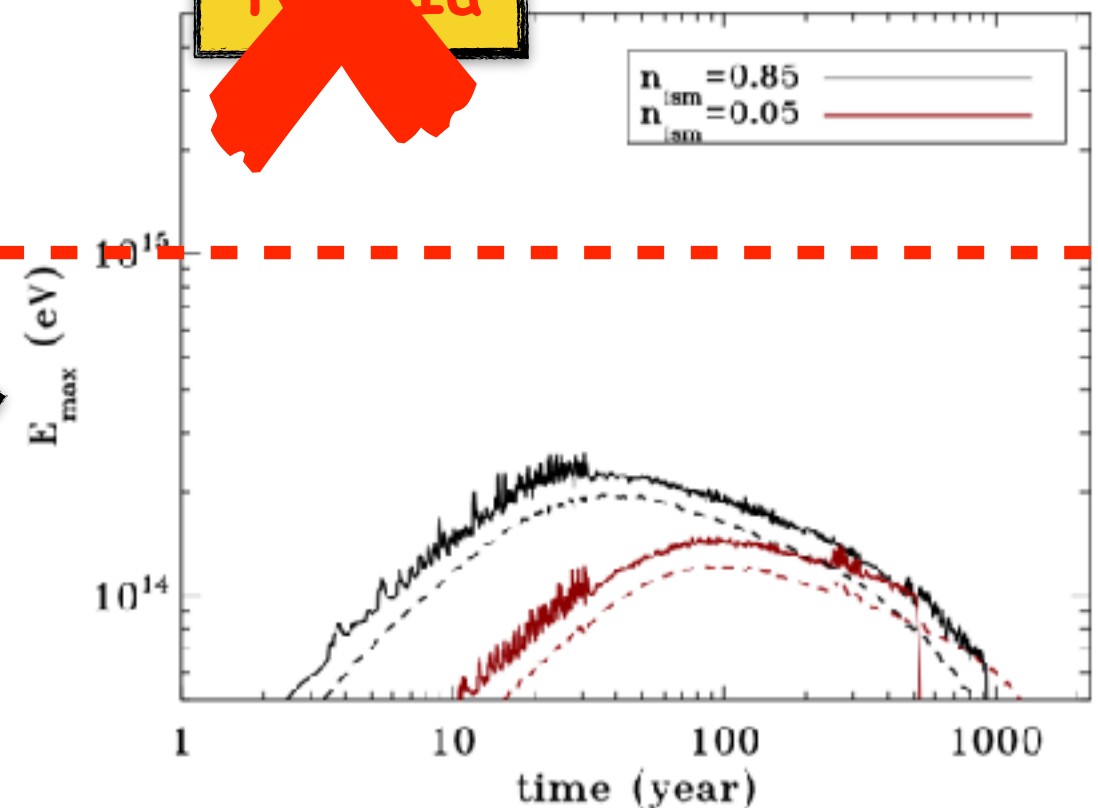
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type II

1 PeV



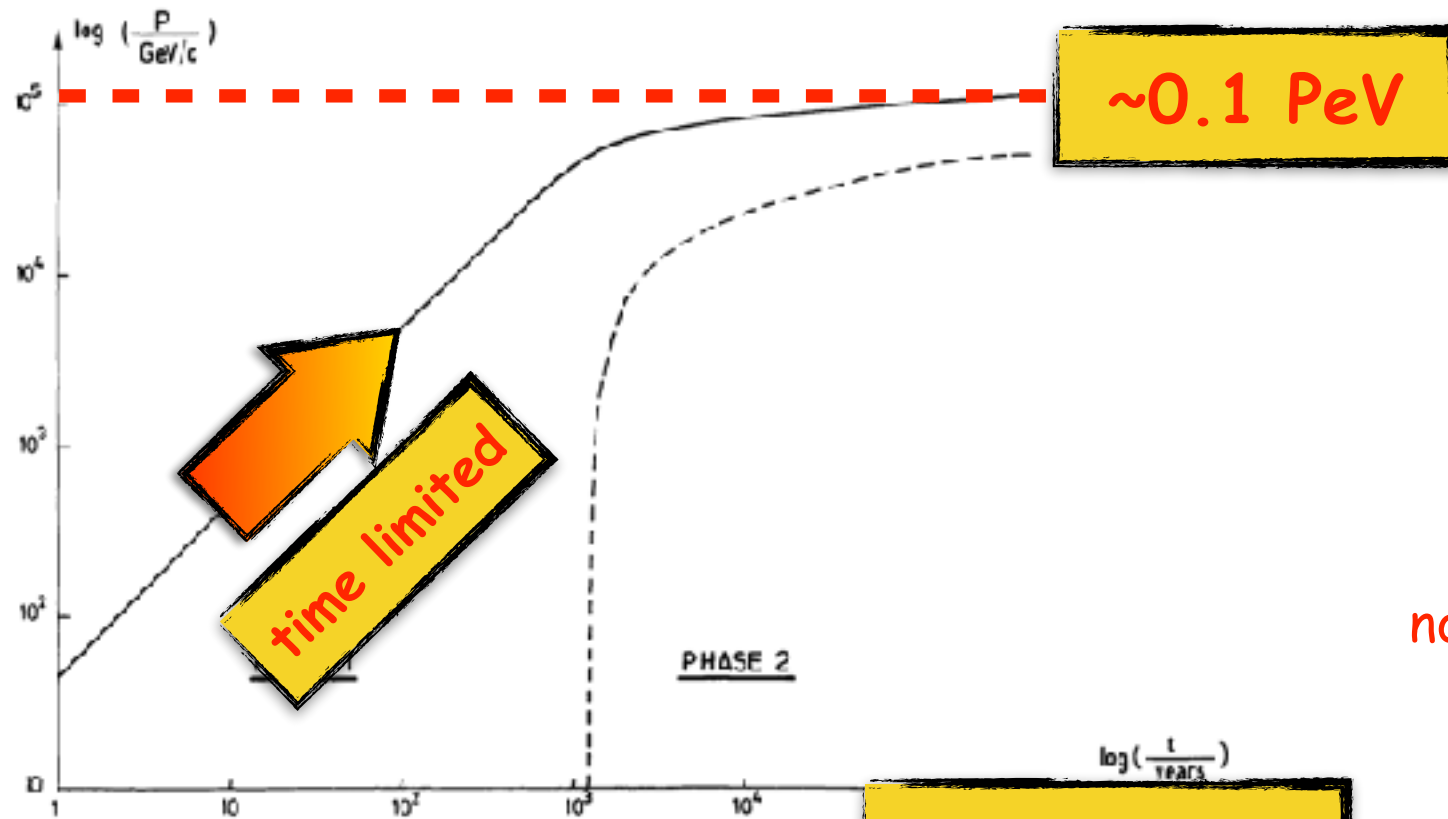
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Schure & Bell 2013

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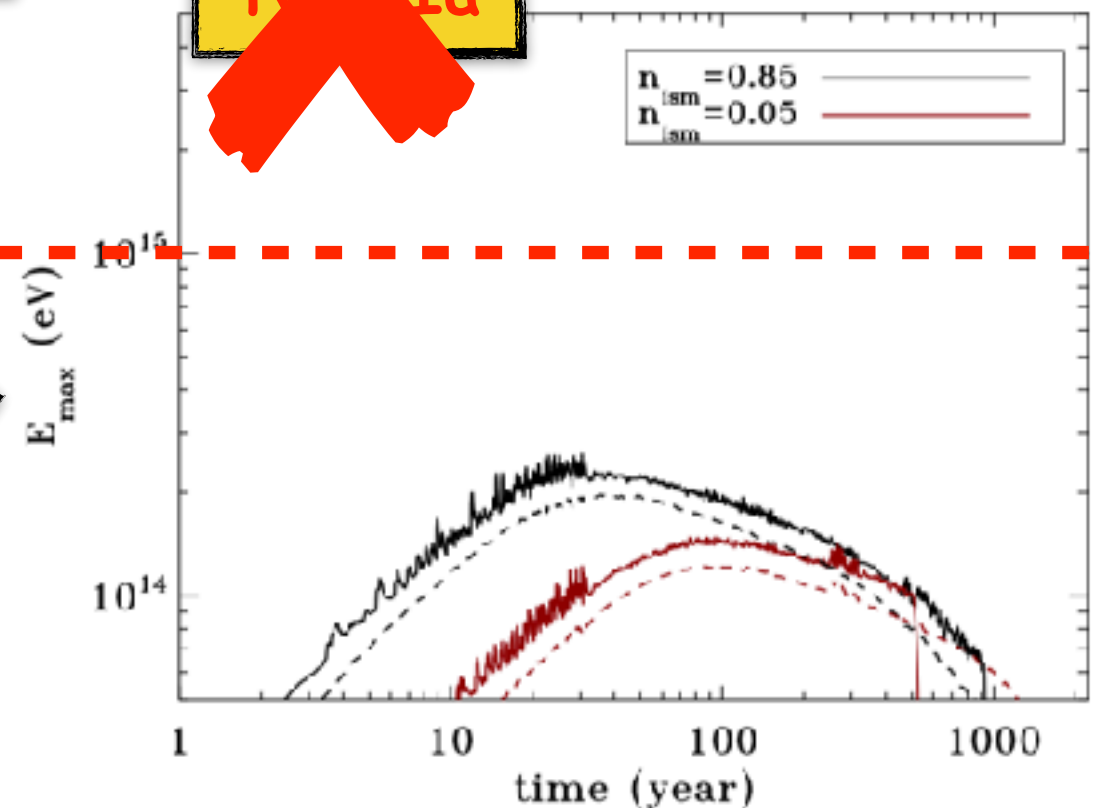
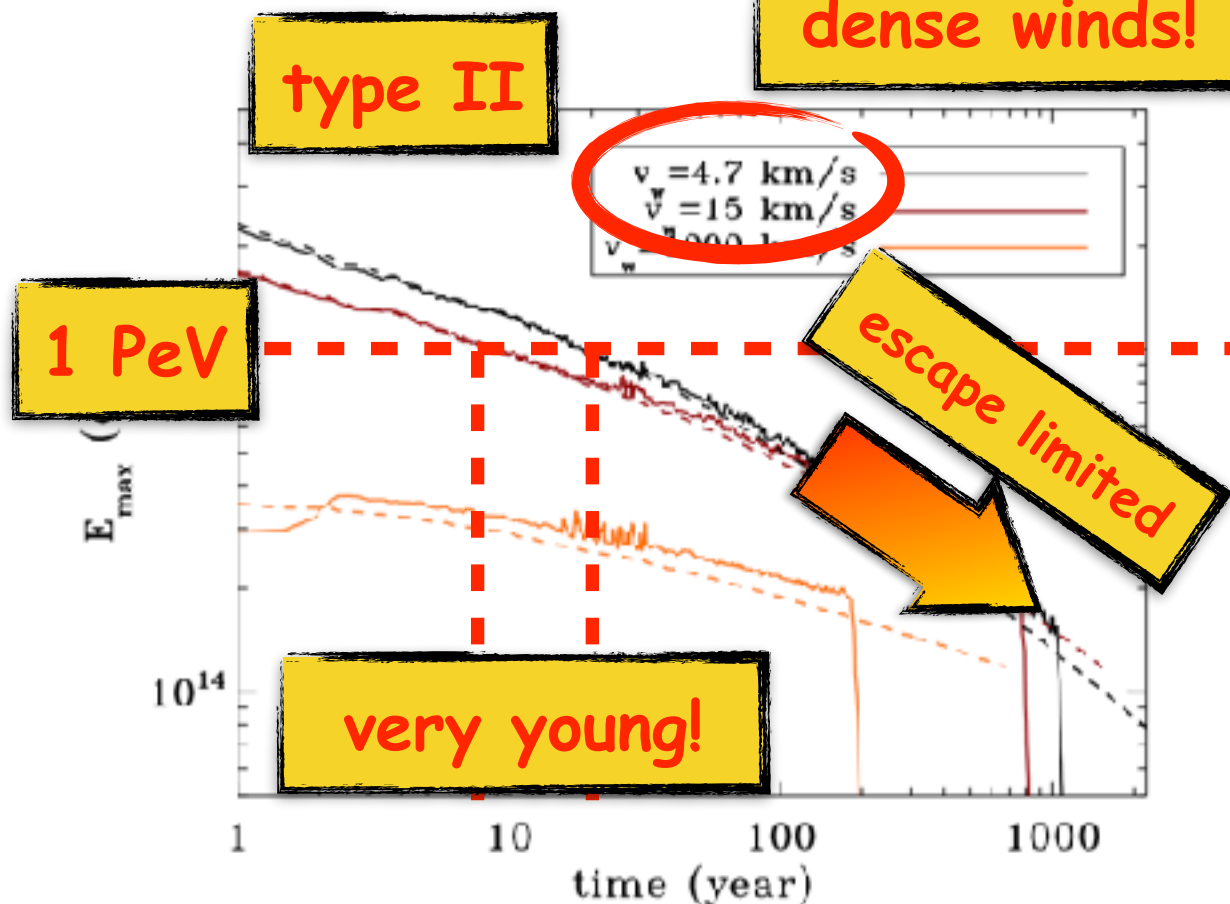
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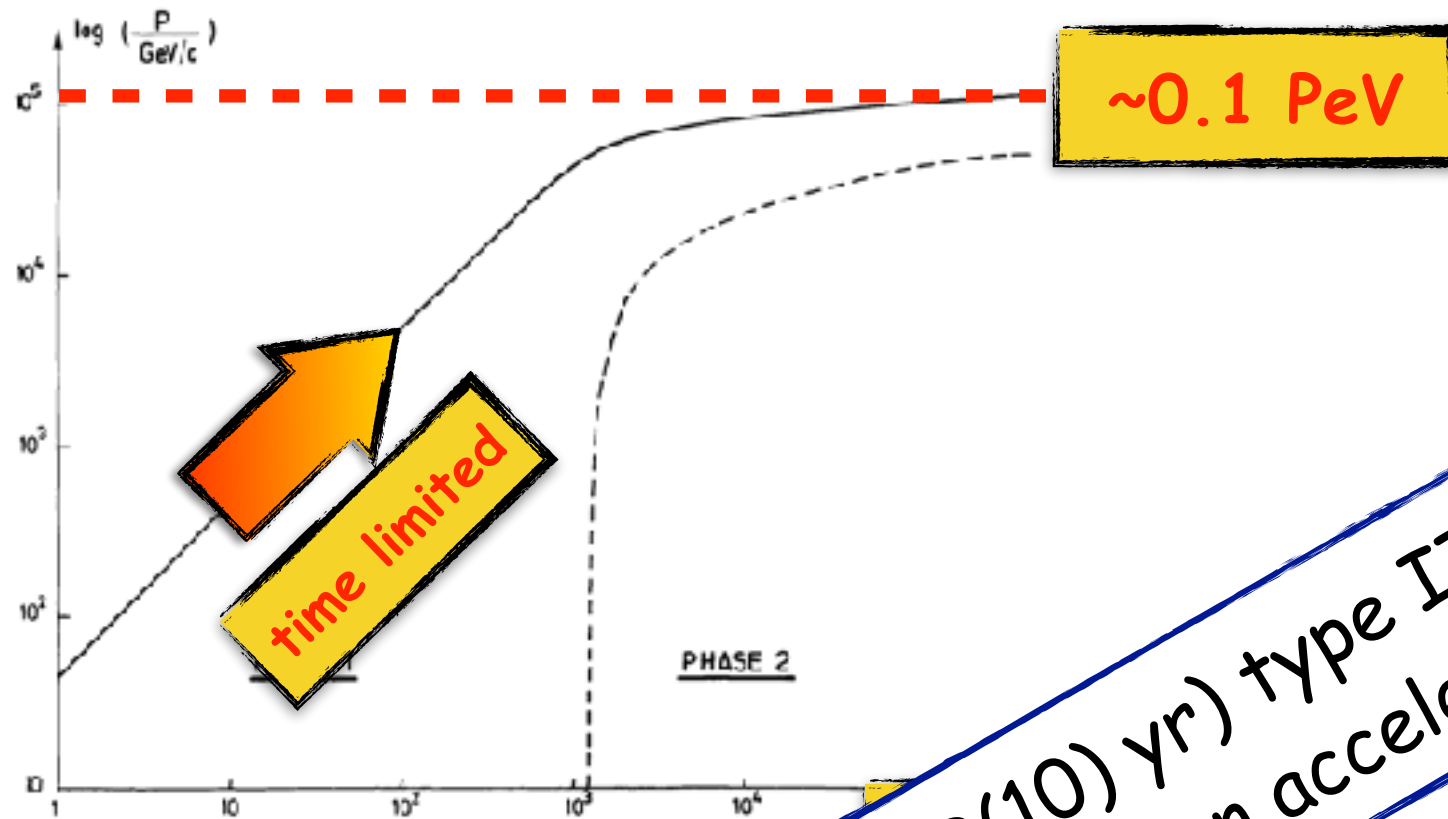
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Schure & Bell 2013

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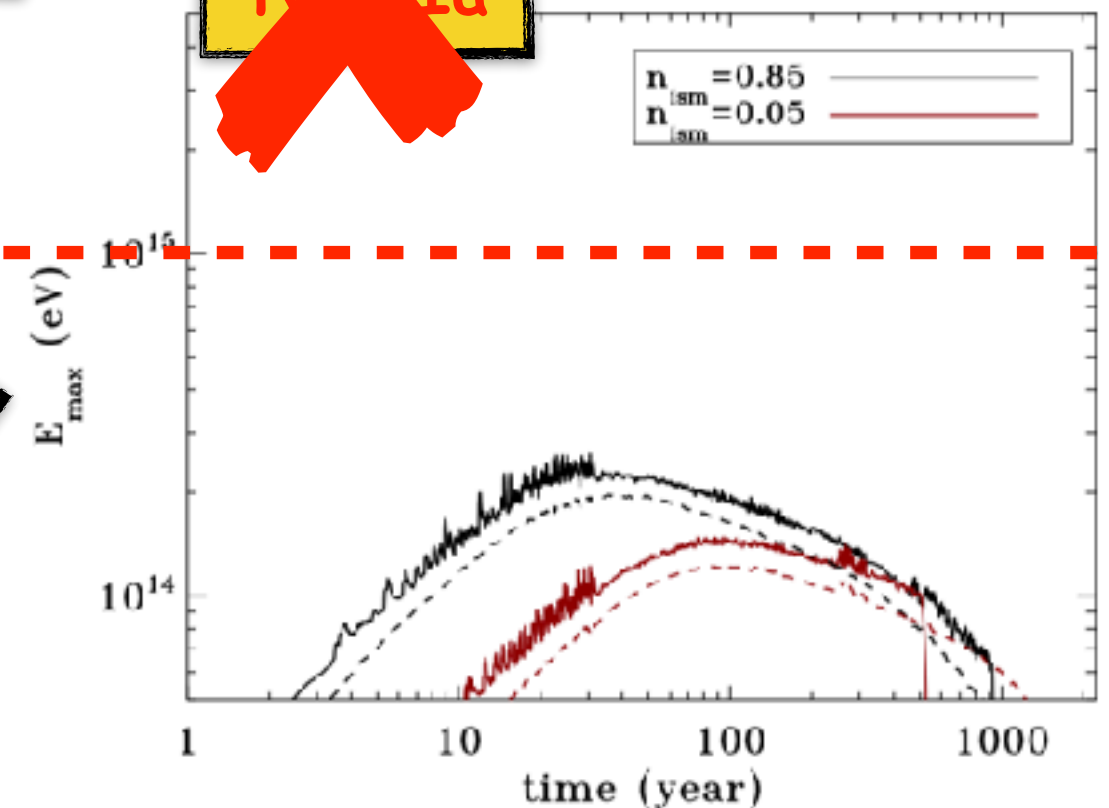
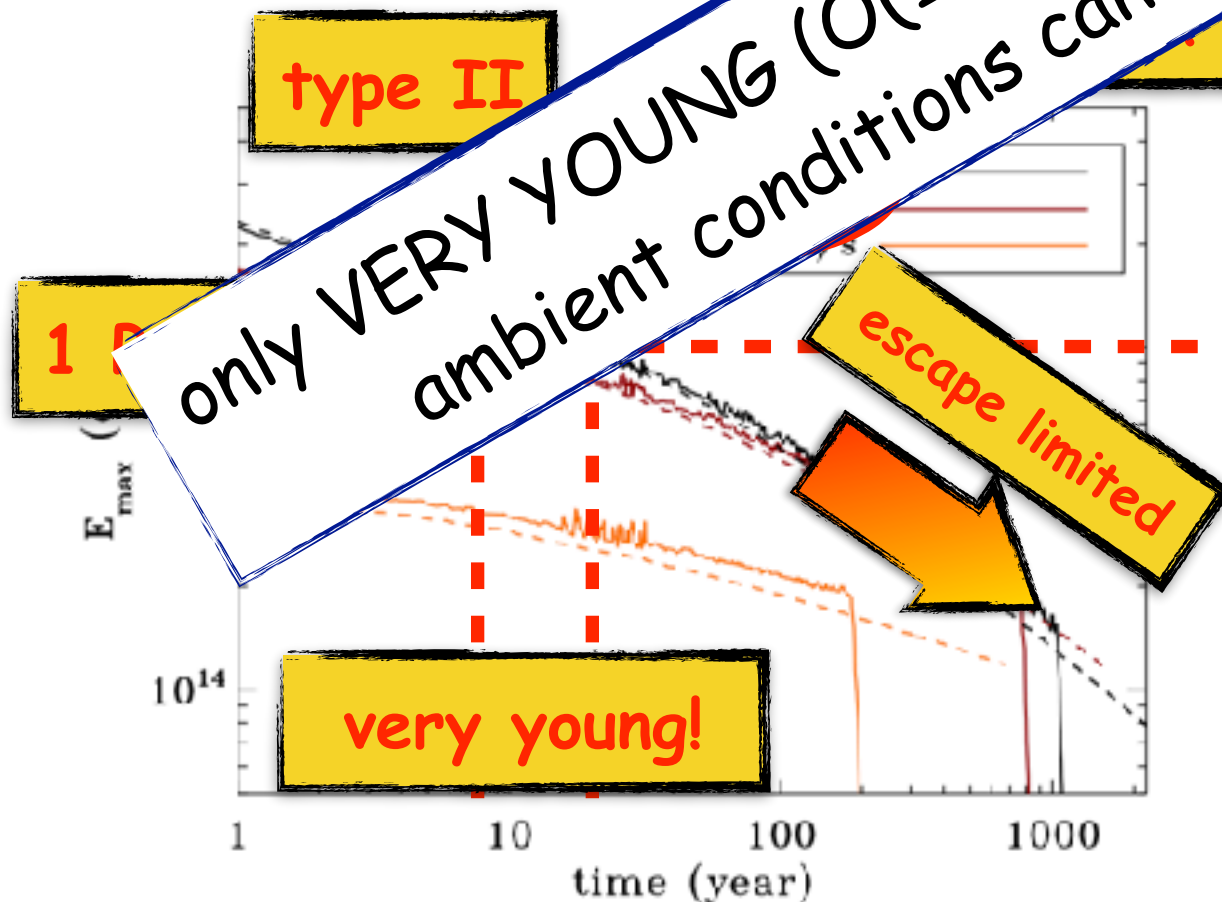
whatever you do you end up with Hillas

only VERY YOUNG ($O(10) \text{ yr}$) type II SNRs in favourable ambient conditions can accelerate to the knee

$$E_{\max} \propto R$$

these are well measured

CR instability



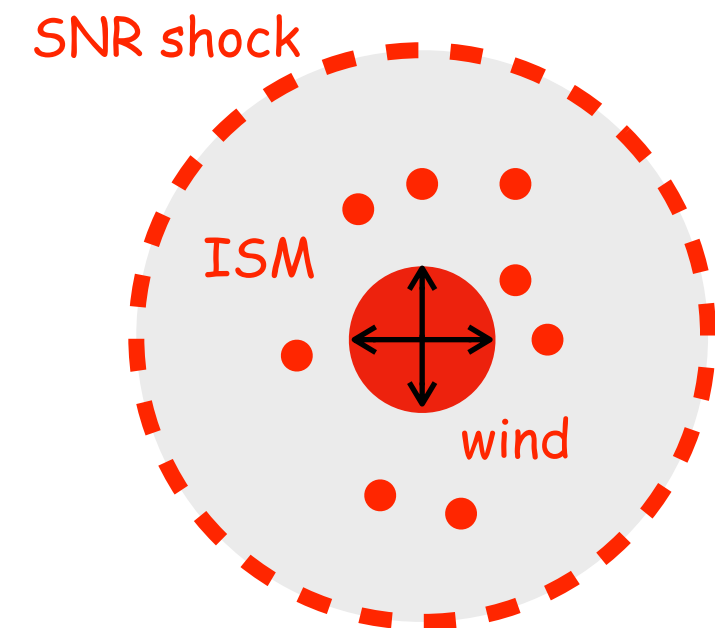
Schure & Bell 2013

Supernova remnants and friends

Do SNRs accelerate all CRs? ($^{22}\text{Ne}/^{20}\text{Ne}$)

YES? →

the SNR shock MUST sweep the wind material (Prantzos, several papers)



$$M_{wind} \approx 0.01 M_{ISM}$$

wind material concentrated close to the star → SNR in free expansion phase → not much energy is dissipated there → DSA should stop DSA at $u_s \sim 2000 \text{ km/s}$ → why?

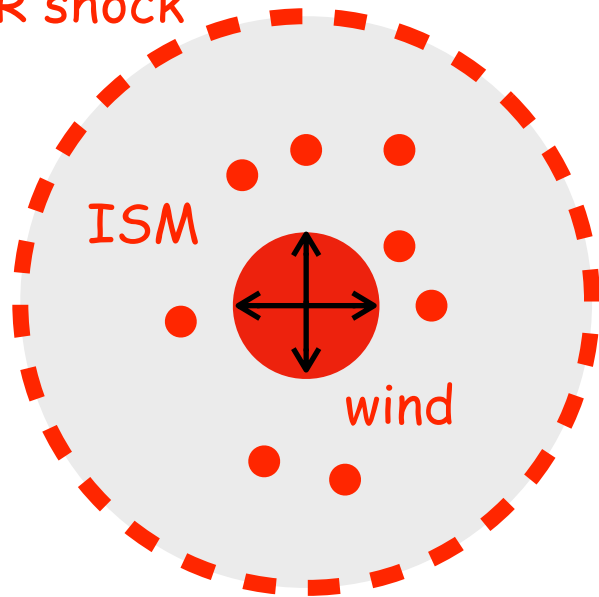
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SNR shock



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YES? →

star clusters inflate superbubbles → winds pollute the ISM → then the shocks accelerate it (several papers by Lingenfelter and collaborators)

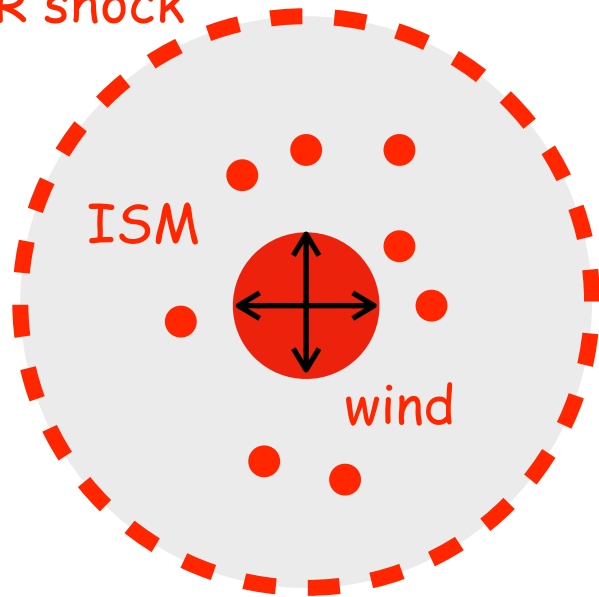
most recent stellar yields → metallicity close to solar in super bubbles
also, X-ray spectra should reveal large metallicity...

Do SNRs accelerate all CRs? ($^{22}\text{Ne}/^{20}\text{Ne}$)

YES? →

the SNR shock MUST sweep the wind material (Prantzos, several papers)

SNR shock



$$M_{wind} \approx 0.01 M_{ISM}$$

wind material concentrated close to the star → SNR in free expansion phase → not much energy is dissipated there → DSA should stop DSA at $u_s \sim 2000$ km/s → why?

+ do very massive stars explode? (failed supernovae)

YES? →

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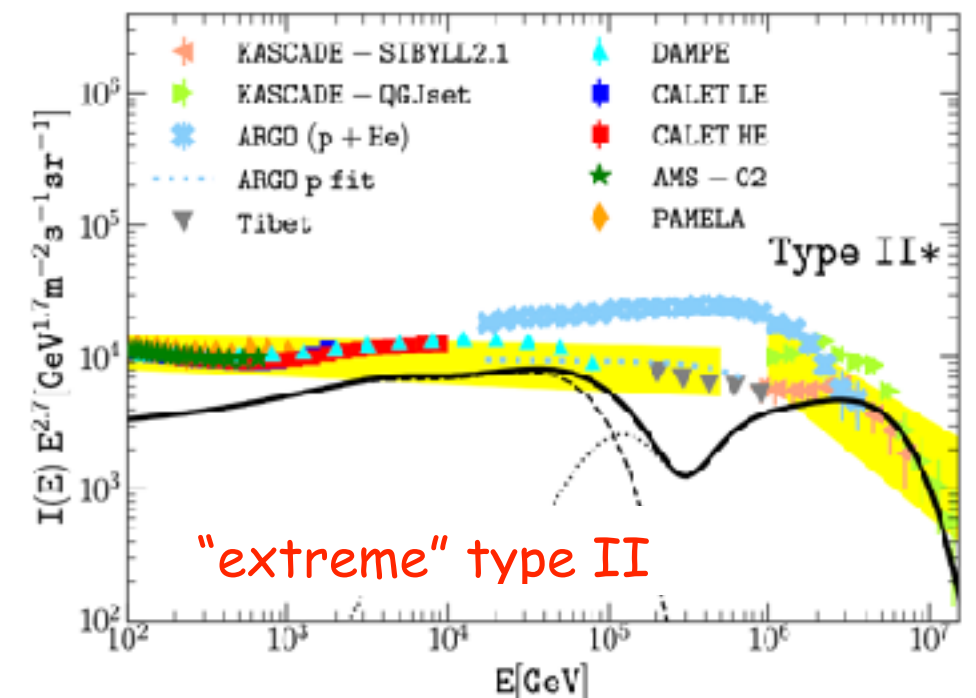
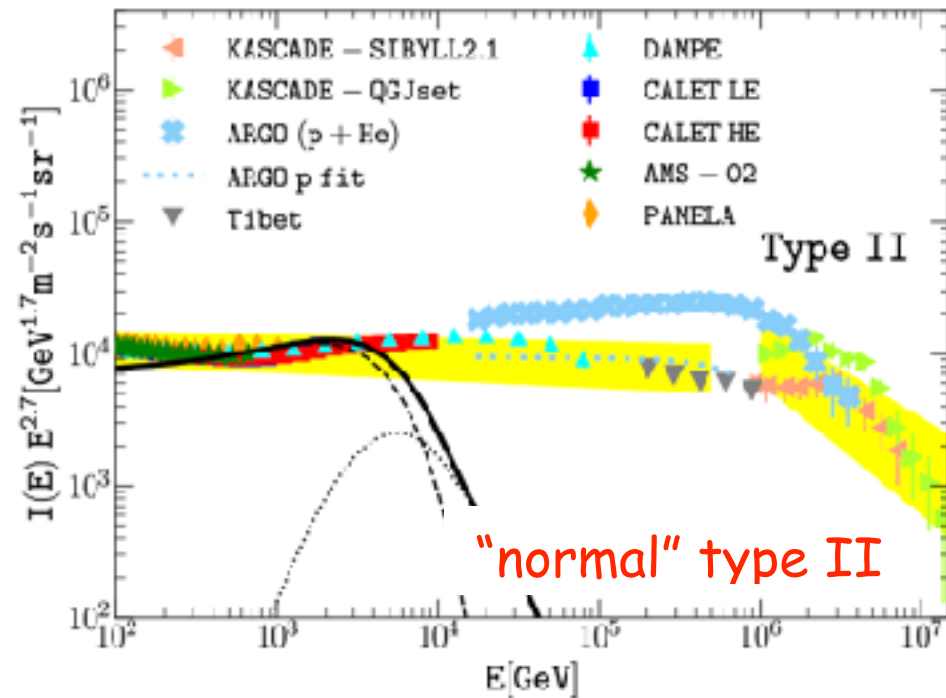
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NO? →

wind material MUST flow across the wind termination shock → DSA operates there (Gupta+ 2020, Tatischeff+ 2021)

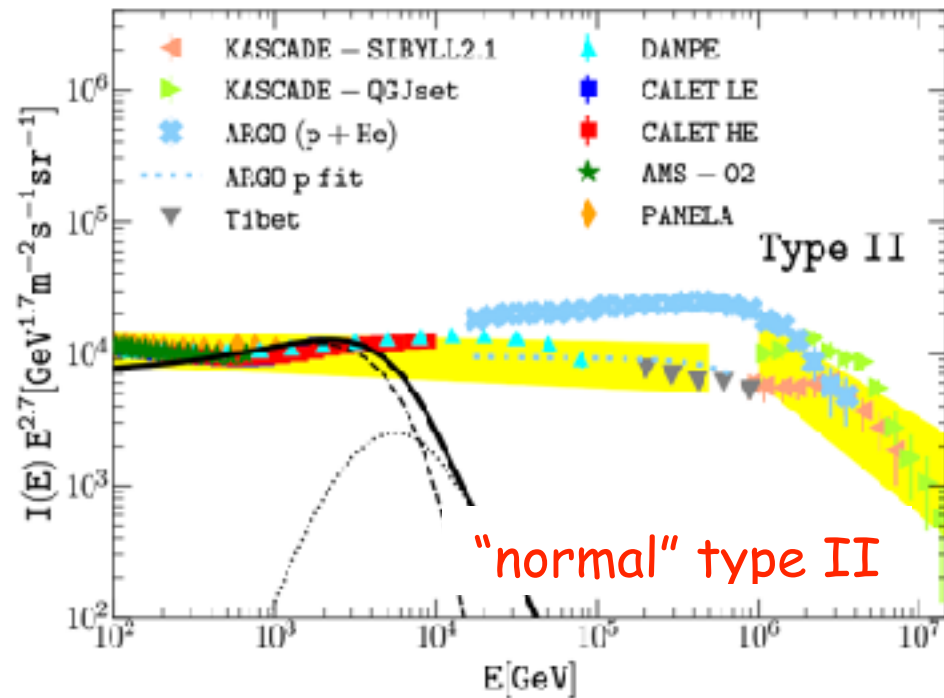
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Cristofari+ 2020

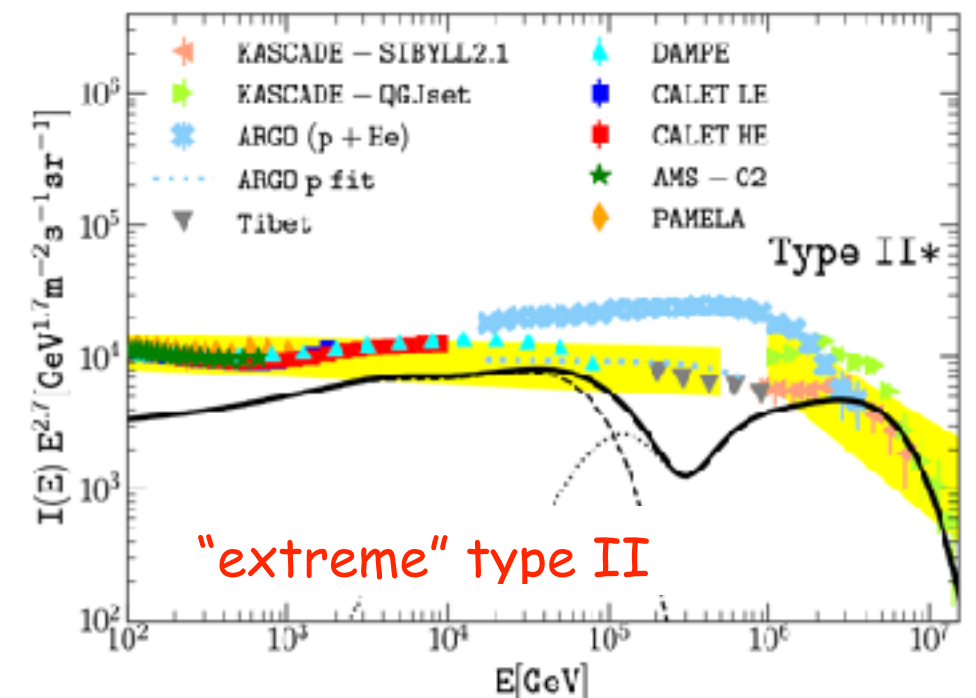


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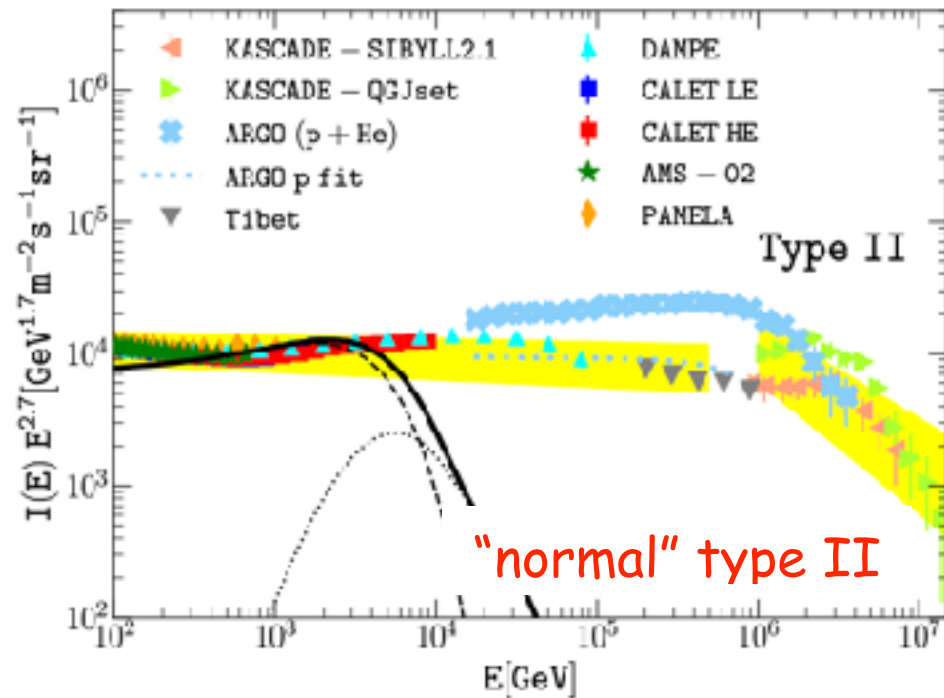


if only extreme
SNRs
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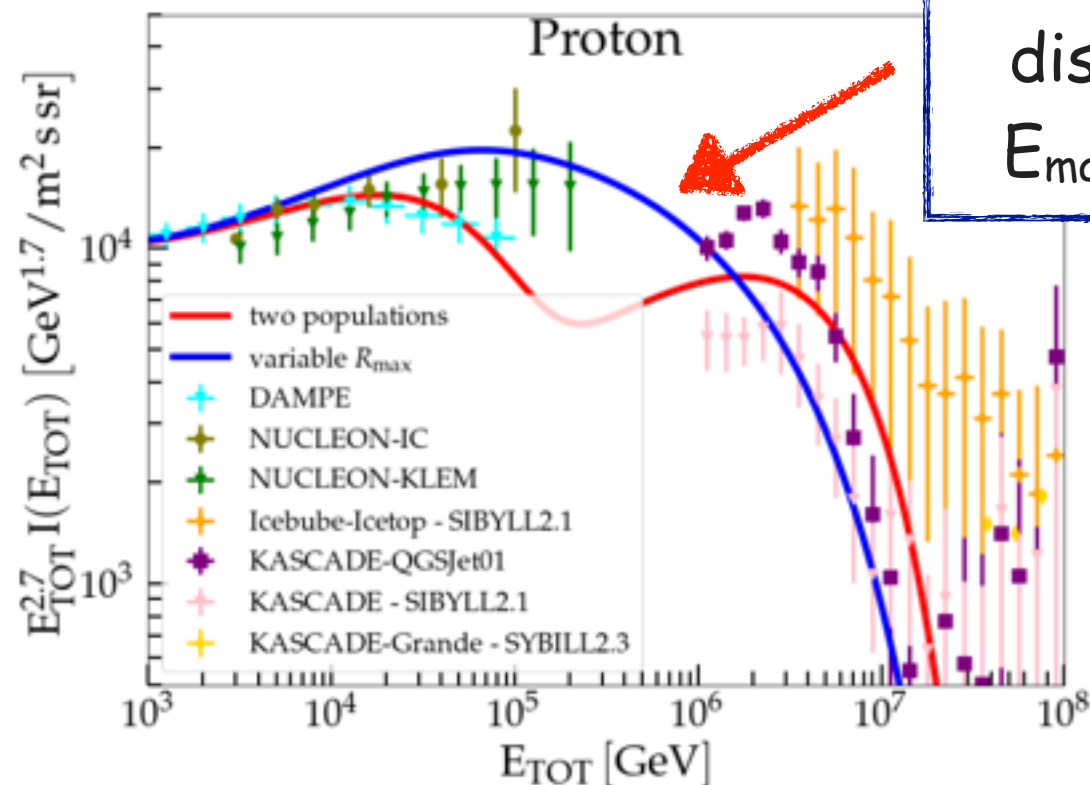
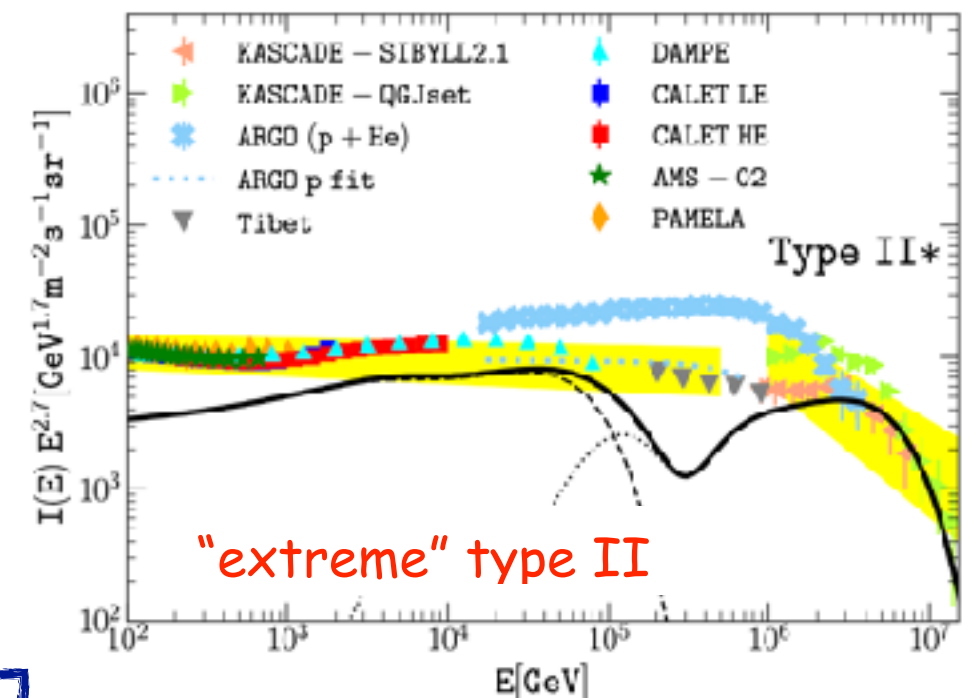


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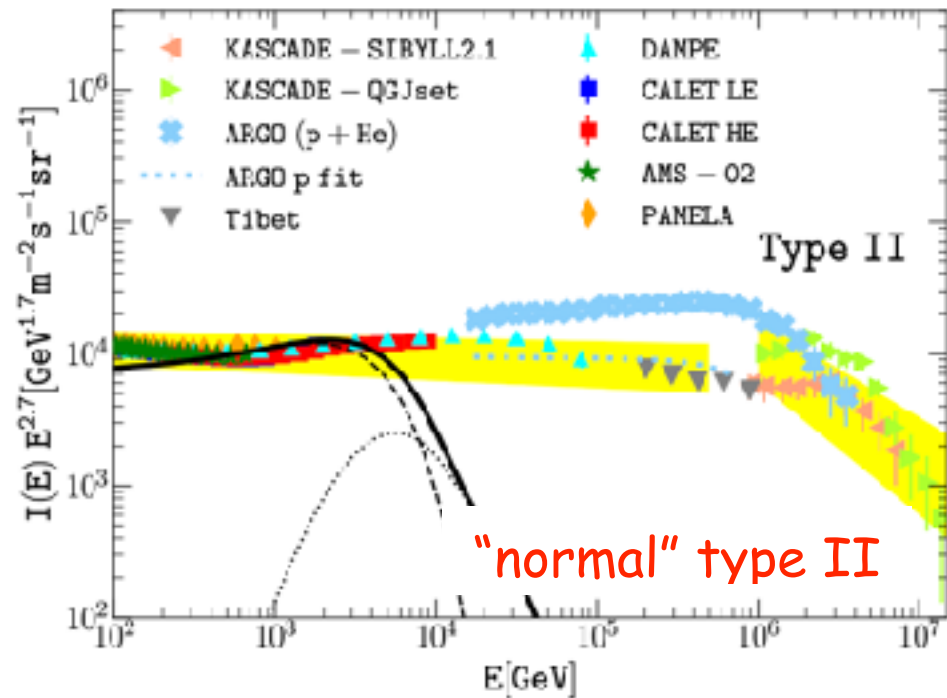


smooth
distribution of
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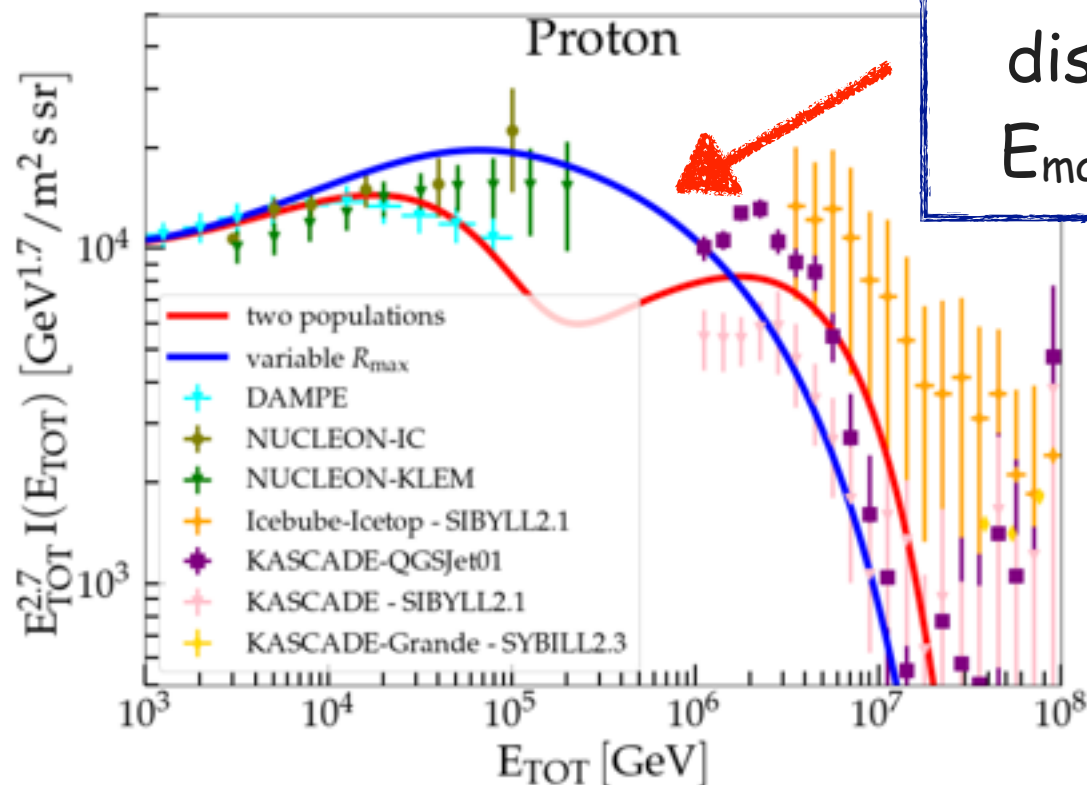
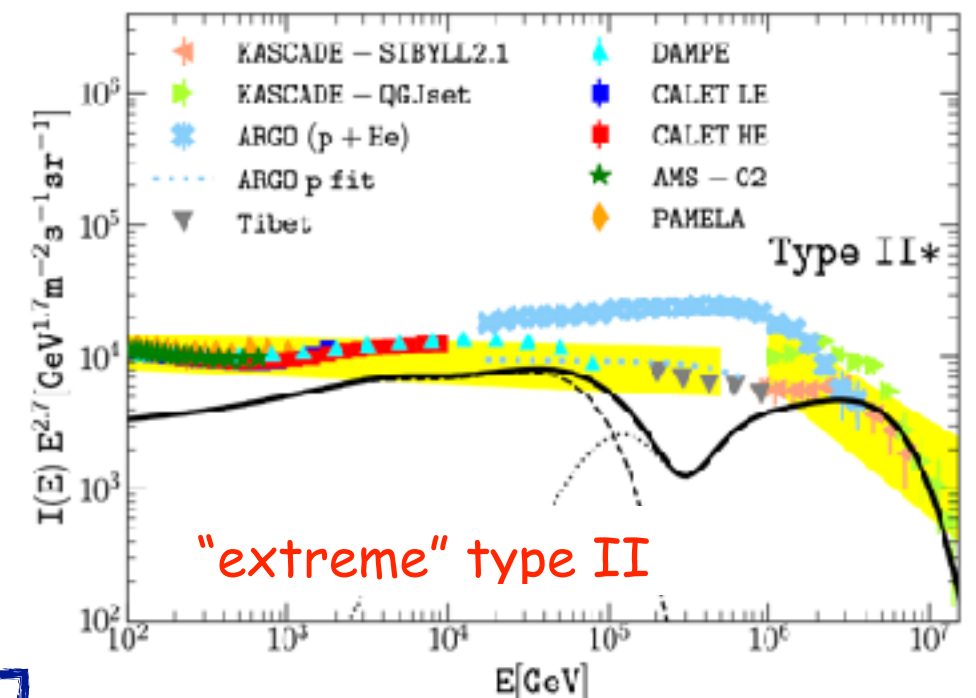
Recchia&Gabici 2024

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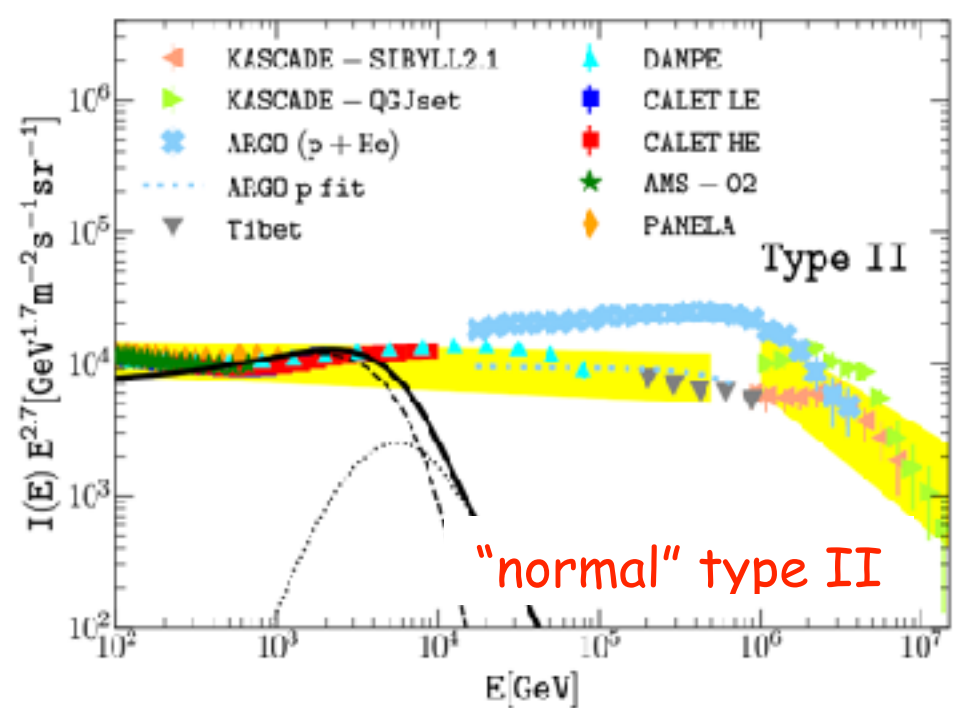
is the knee just a local feature?
single nearby extreme source?

Erlykin&Wolfendale 1997 ... Prevotat+ 2025

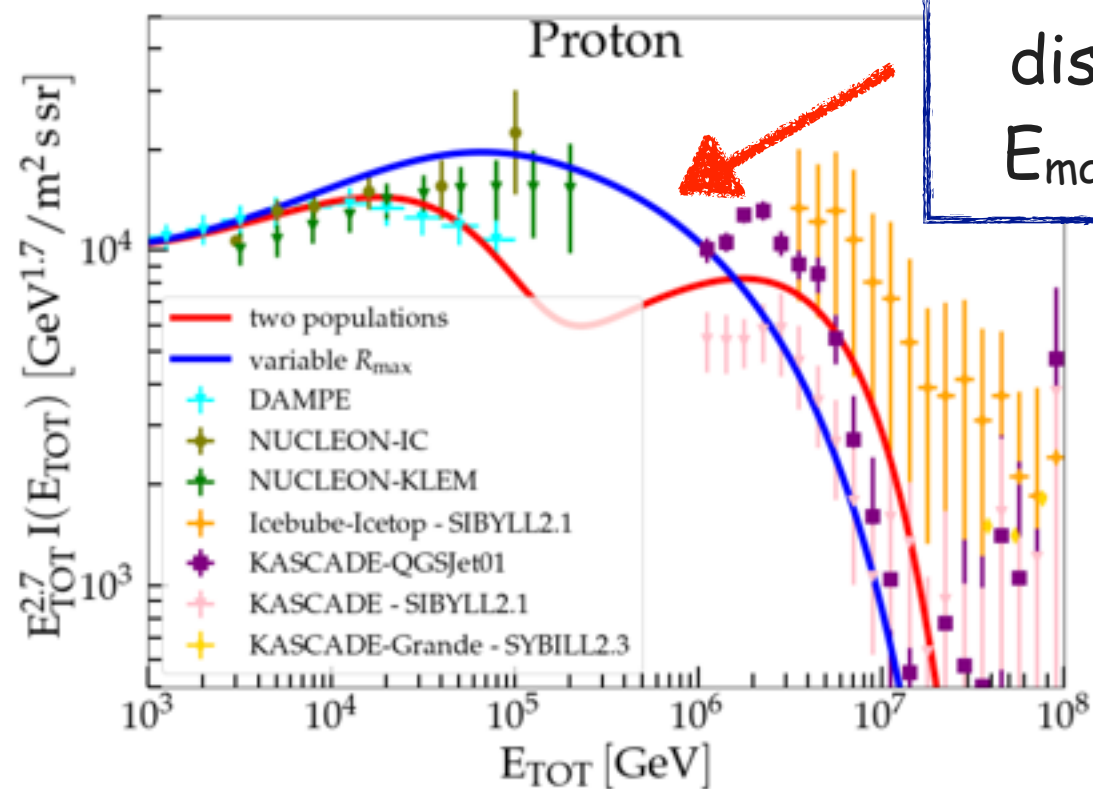
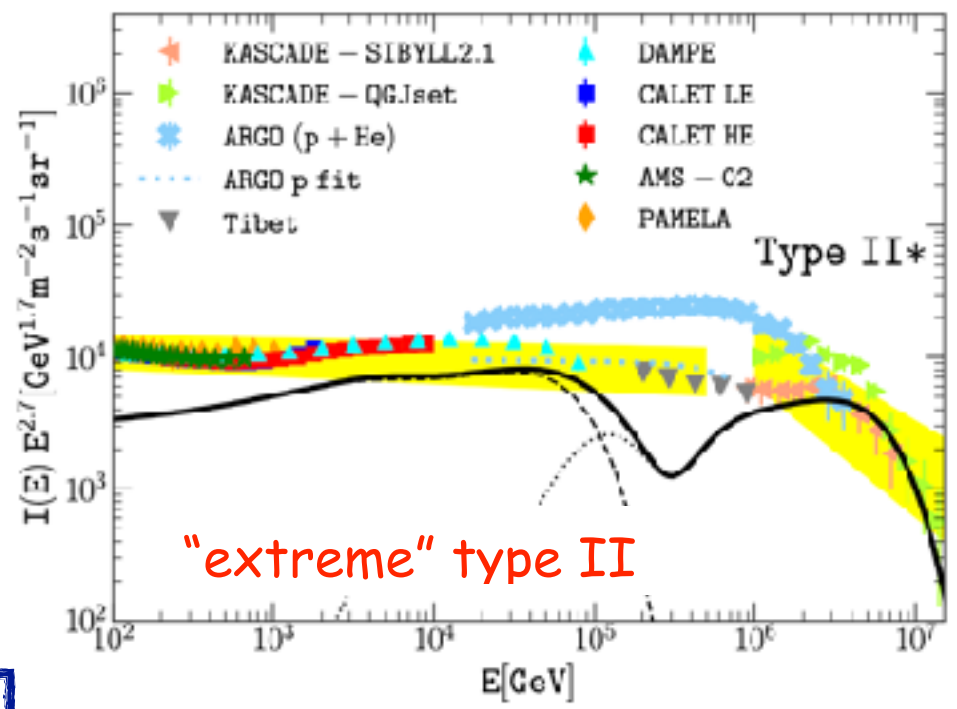
Recchia&Gabici 2024

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Cristofari+ 2020



if only extreme SNRs accelerate PeV CRs why is the knee so smooth?



smooth distribution of E_{max} at sources

LHAASO diffuse emission!

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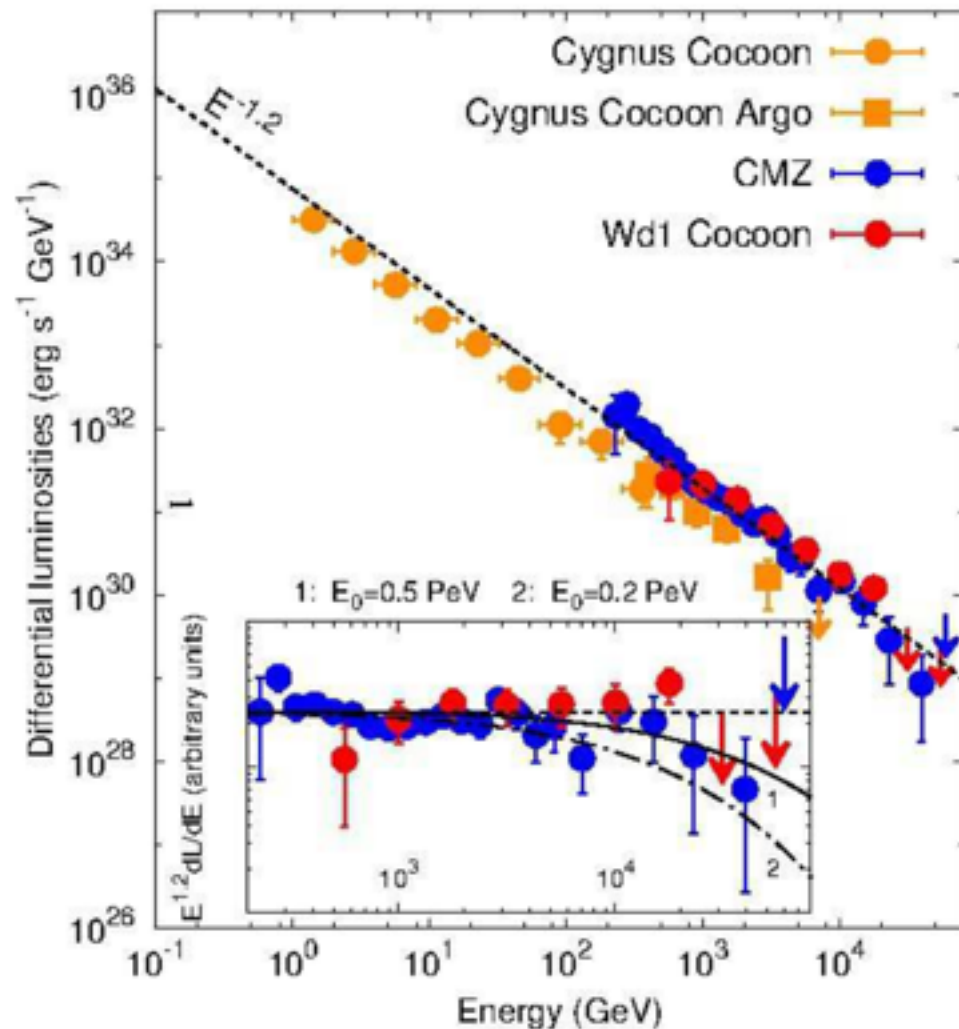
Can star clusters solve both issues?

well known fact: most massive stars belong to star clusters

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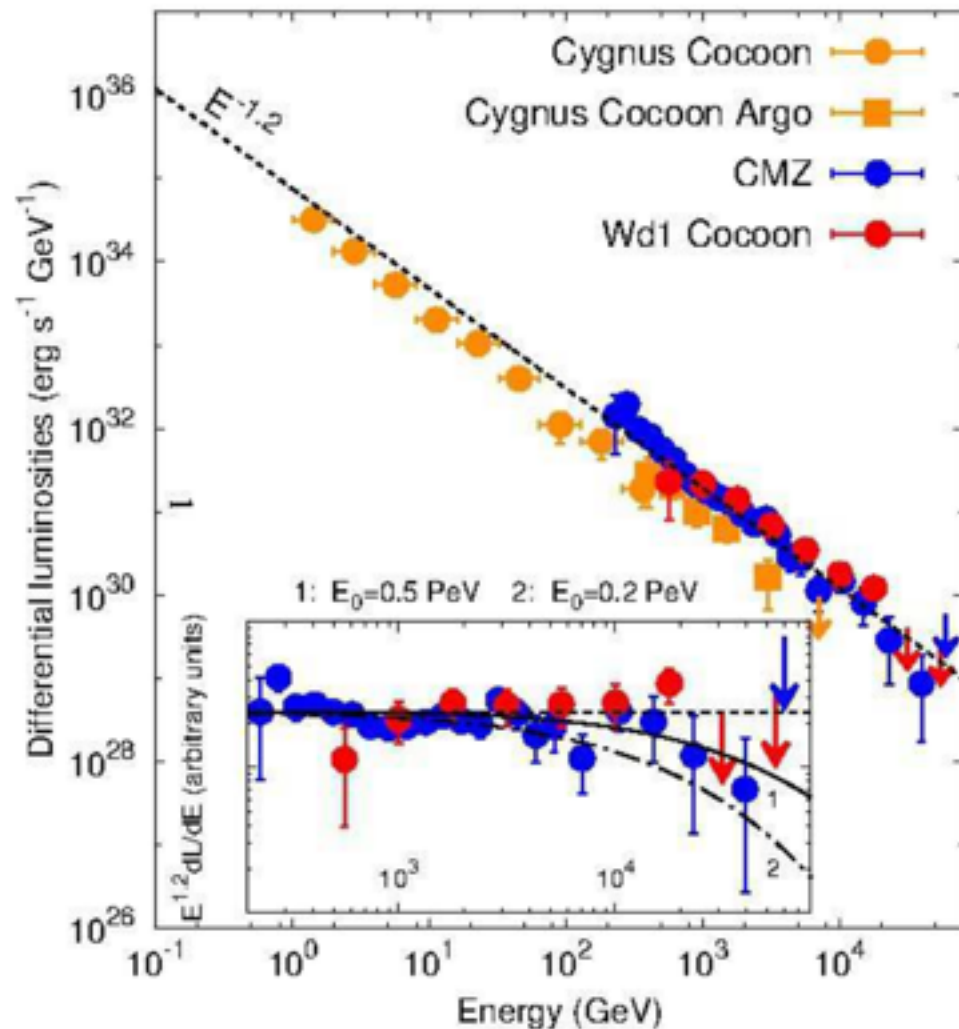
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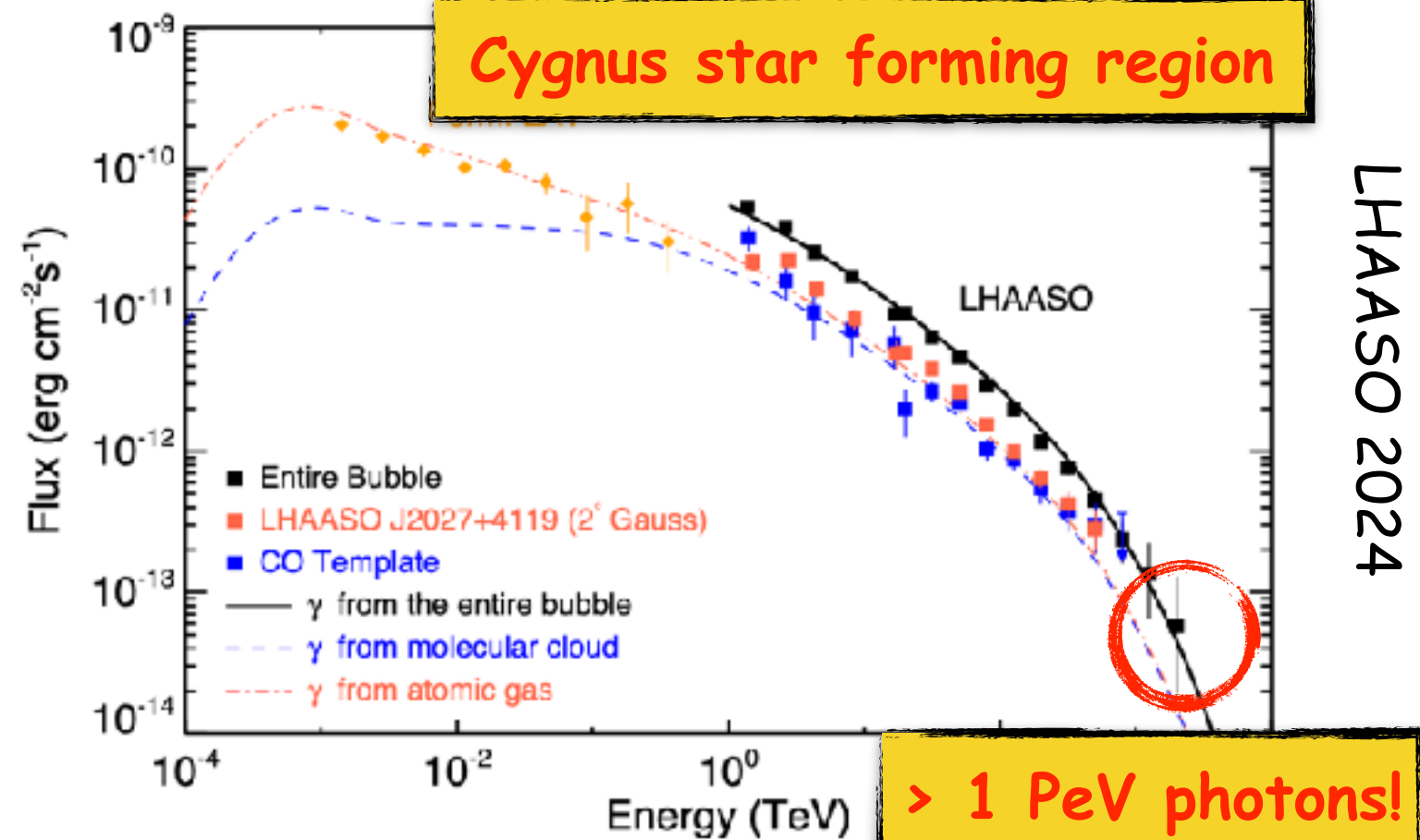
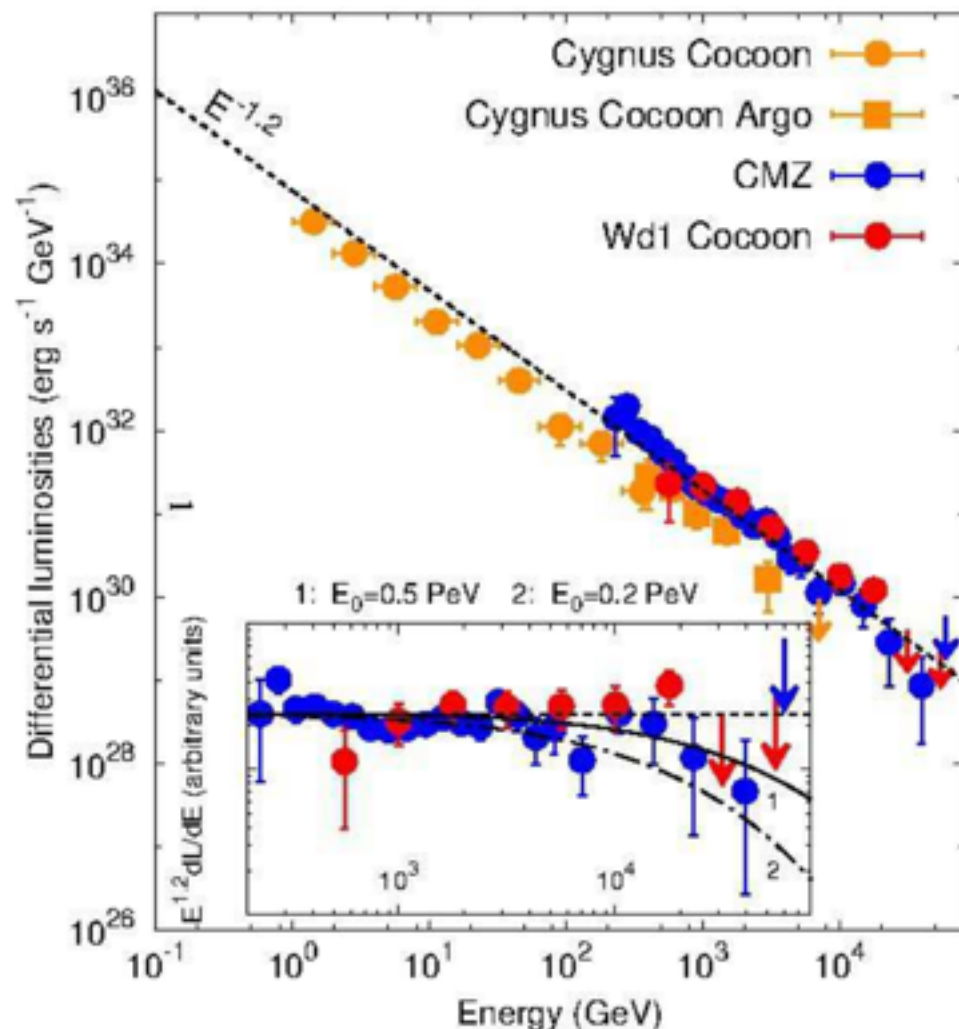


The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

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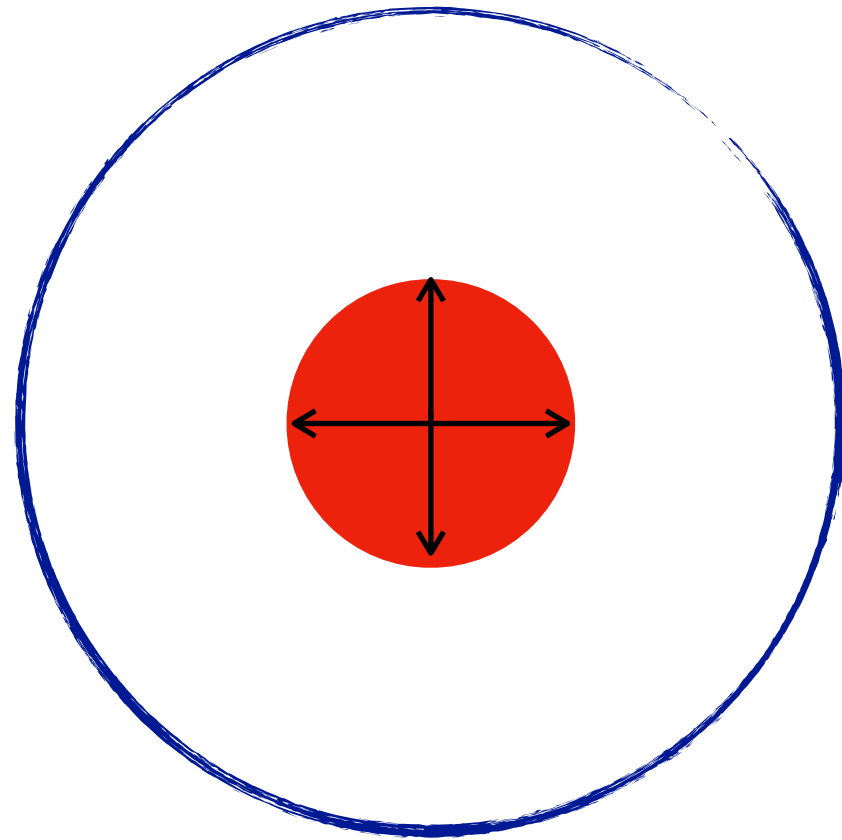
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Star clusters and the CR knee

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Recent papers by Bykov, Gupta, Vieu, Morlino and collaborators...

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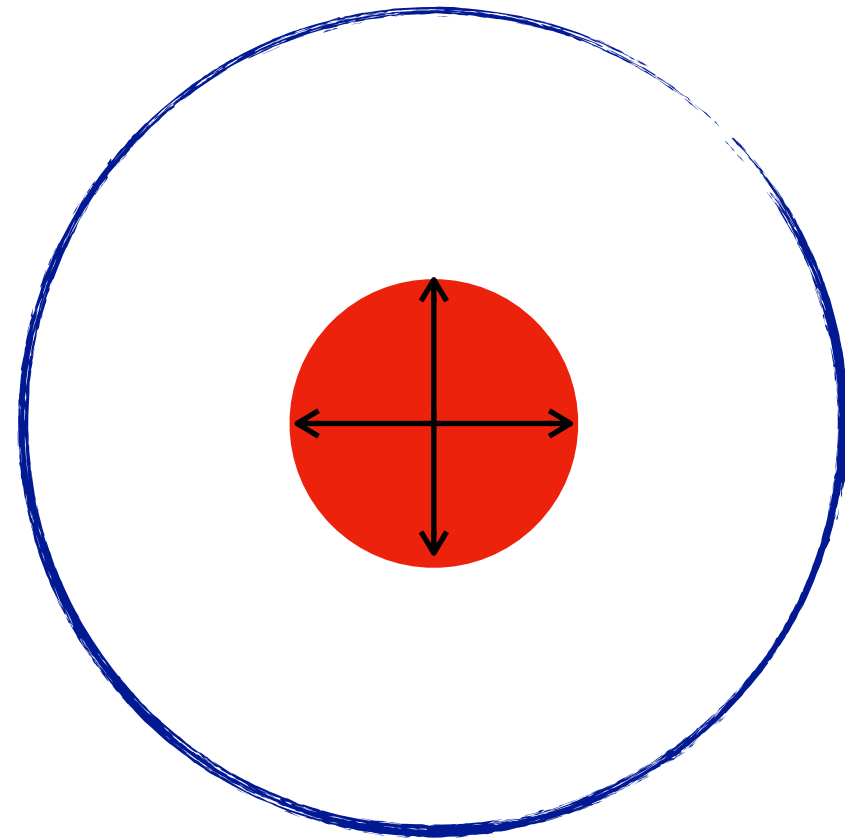
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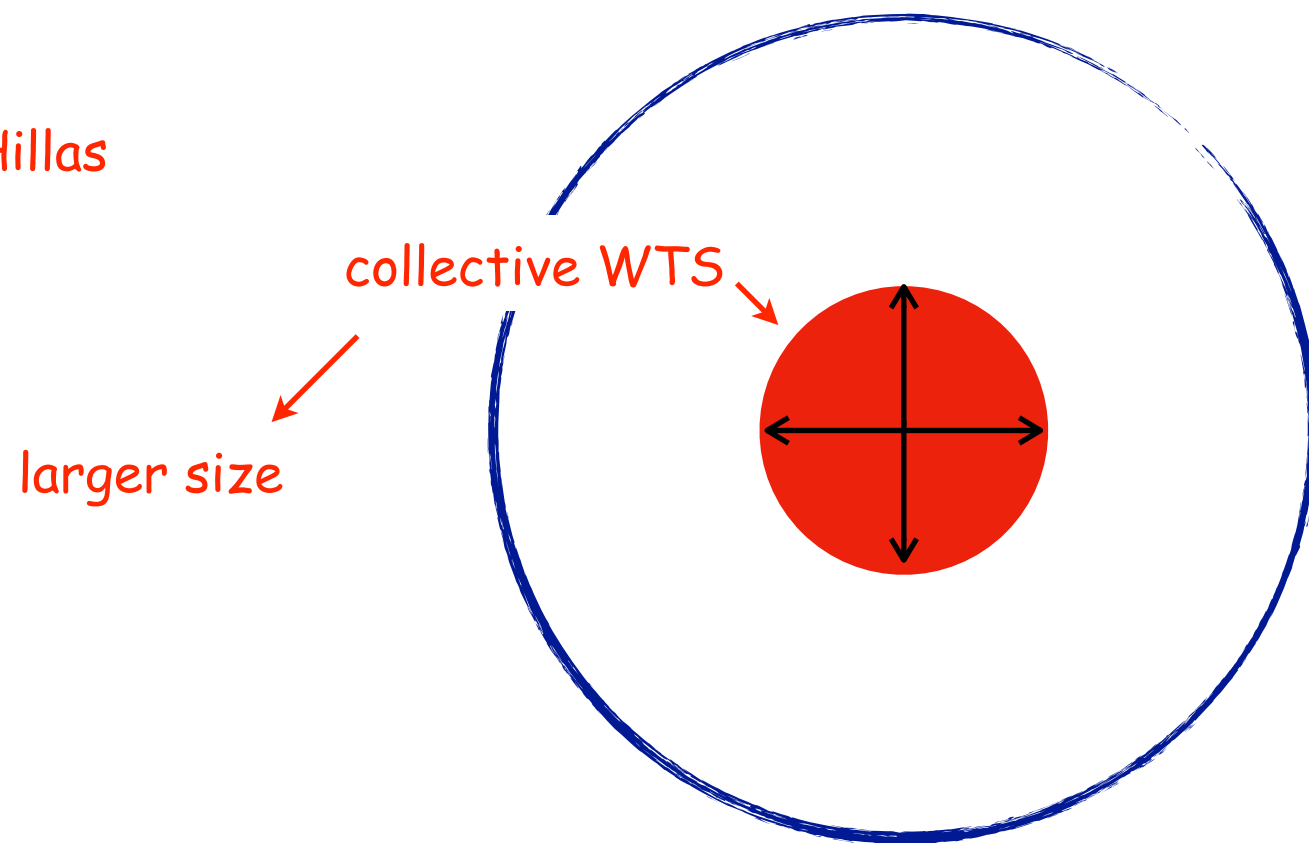
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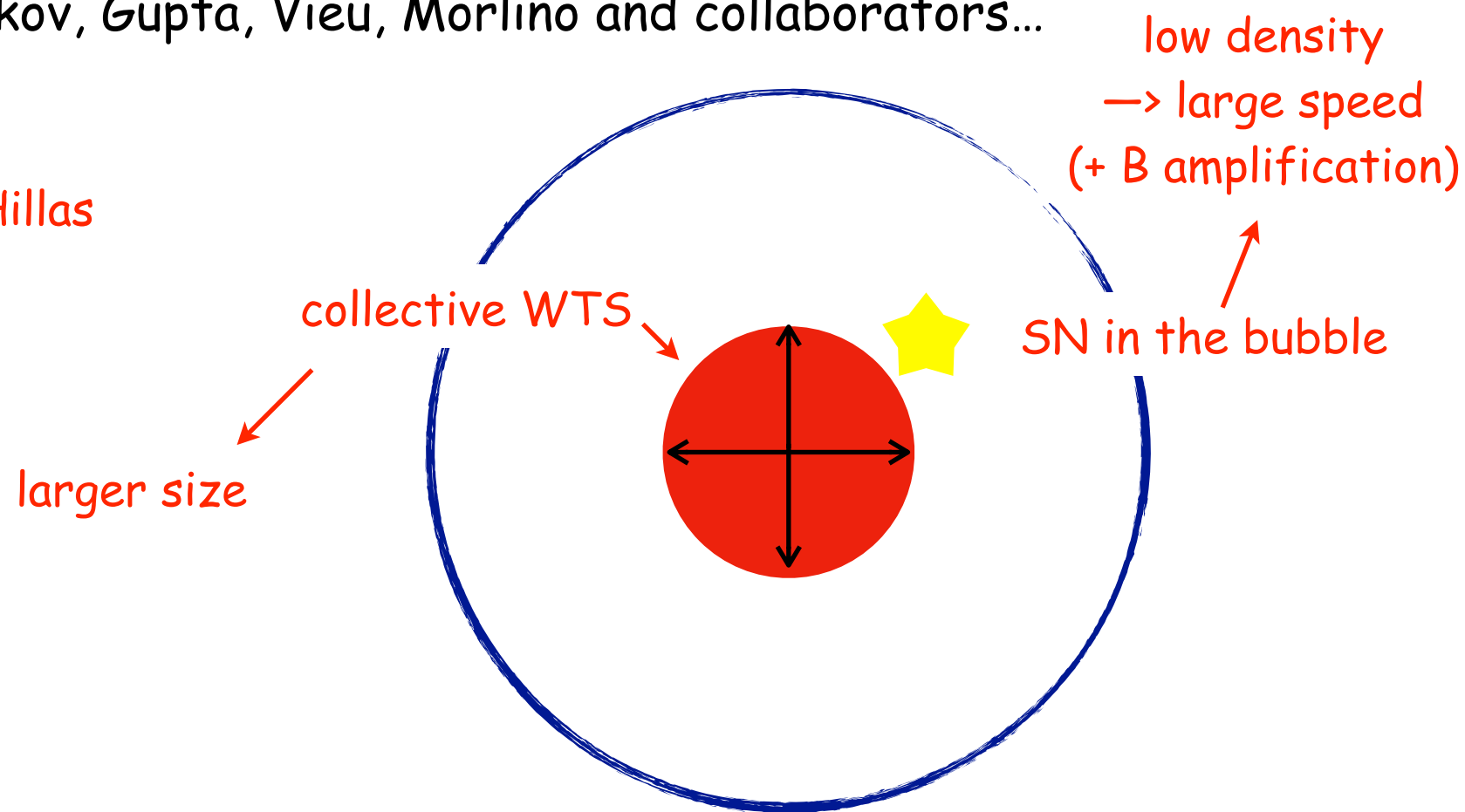
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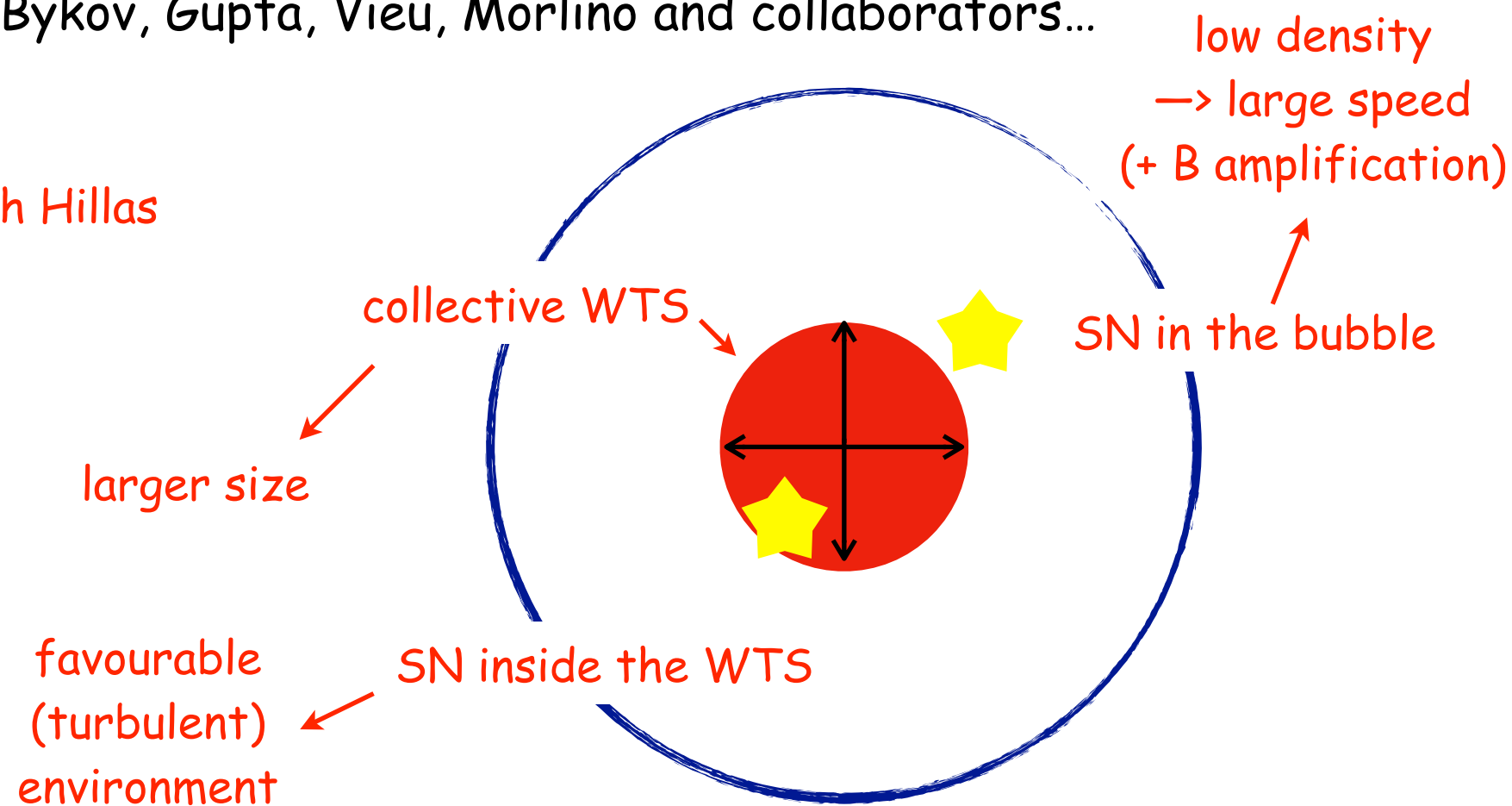
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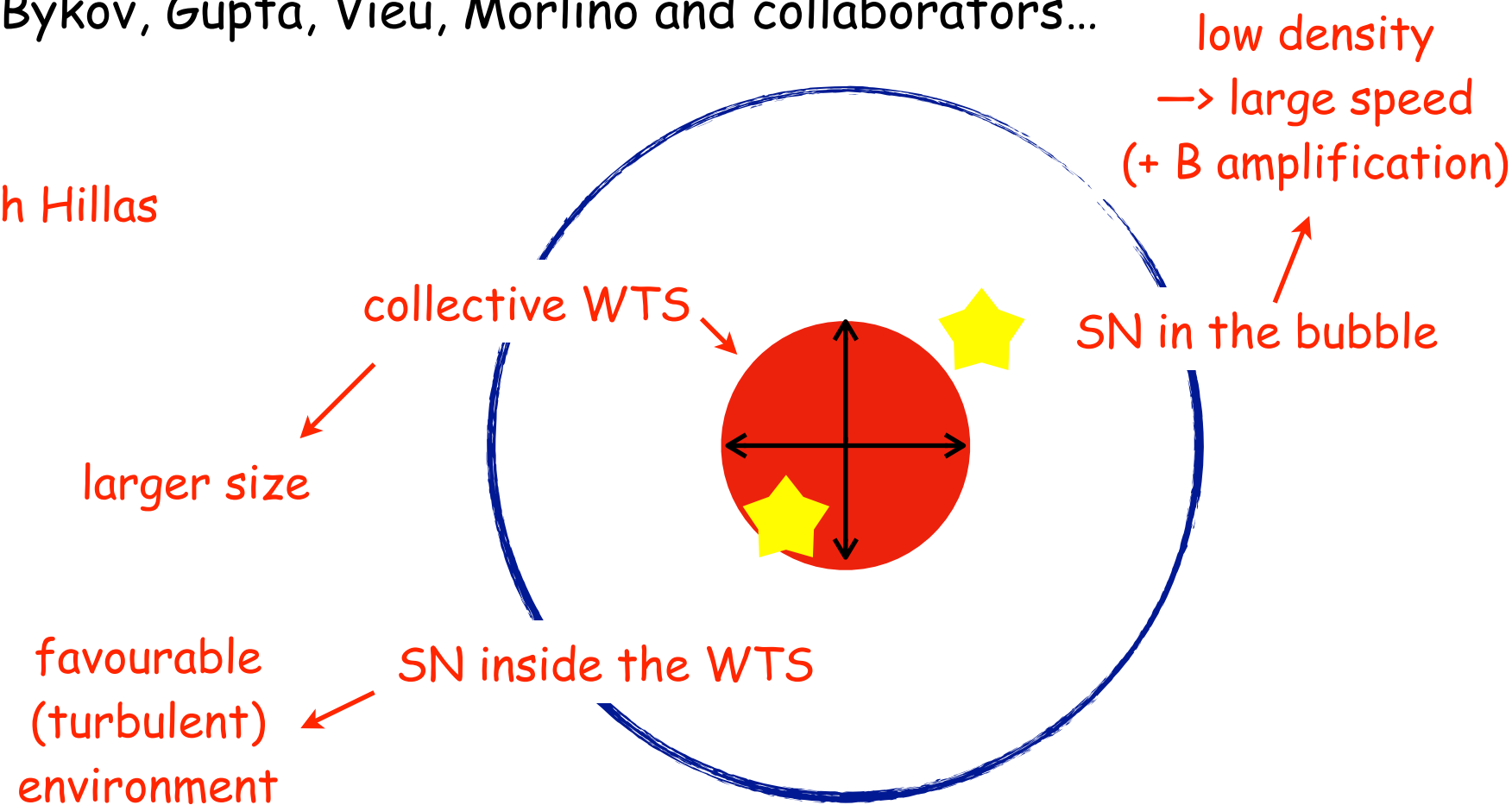
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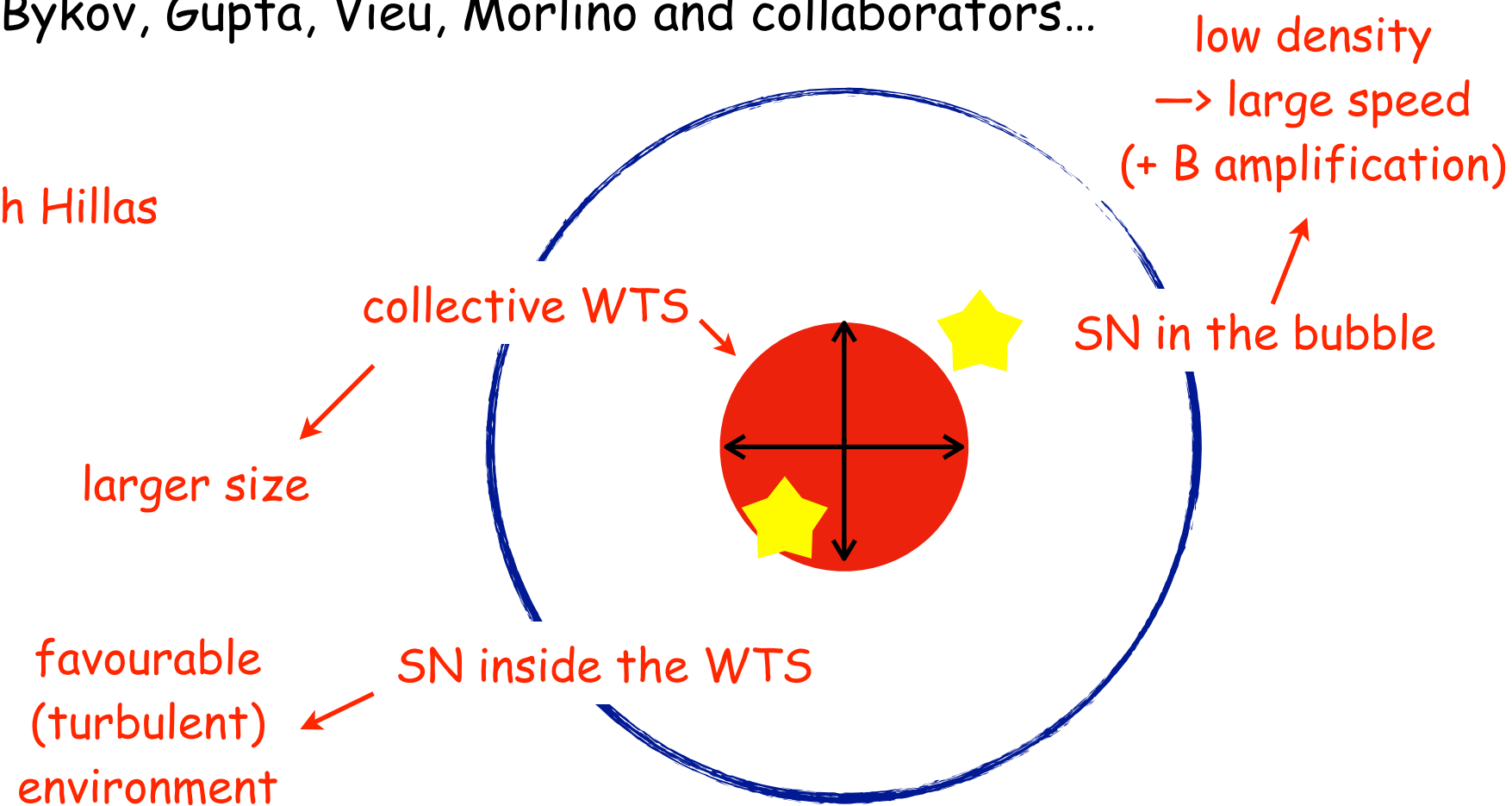
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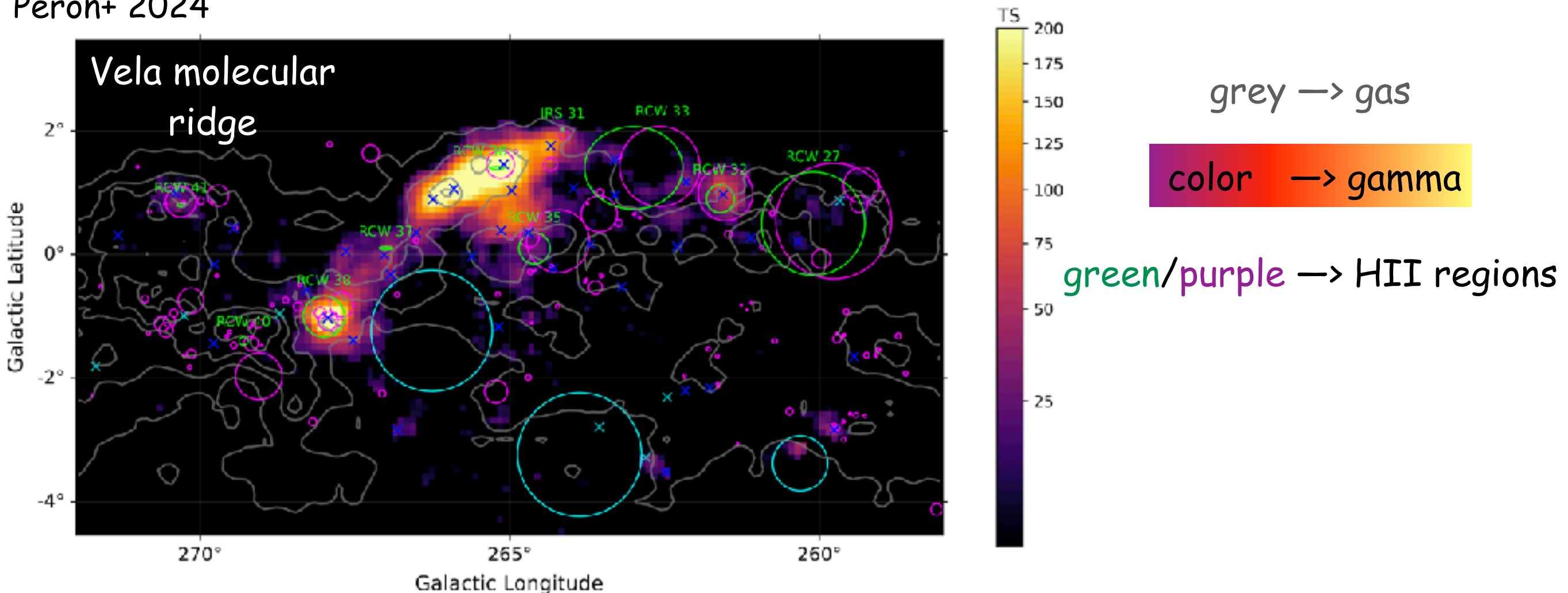
**personal opinion:
possible but some
optimism is required**



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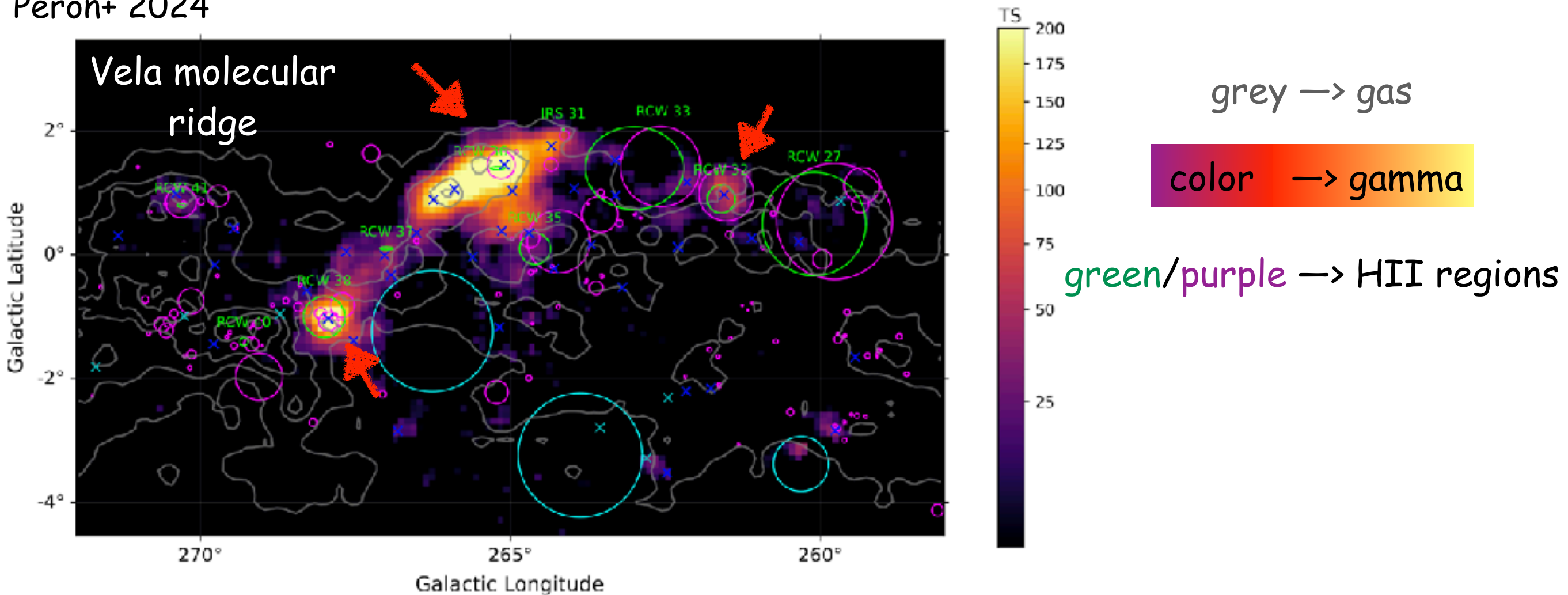
Star clusters and $^{22}\text{Ne}/^{20}\text{Ne}$

Peron+ 2024



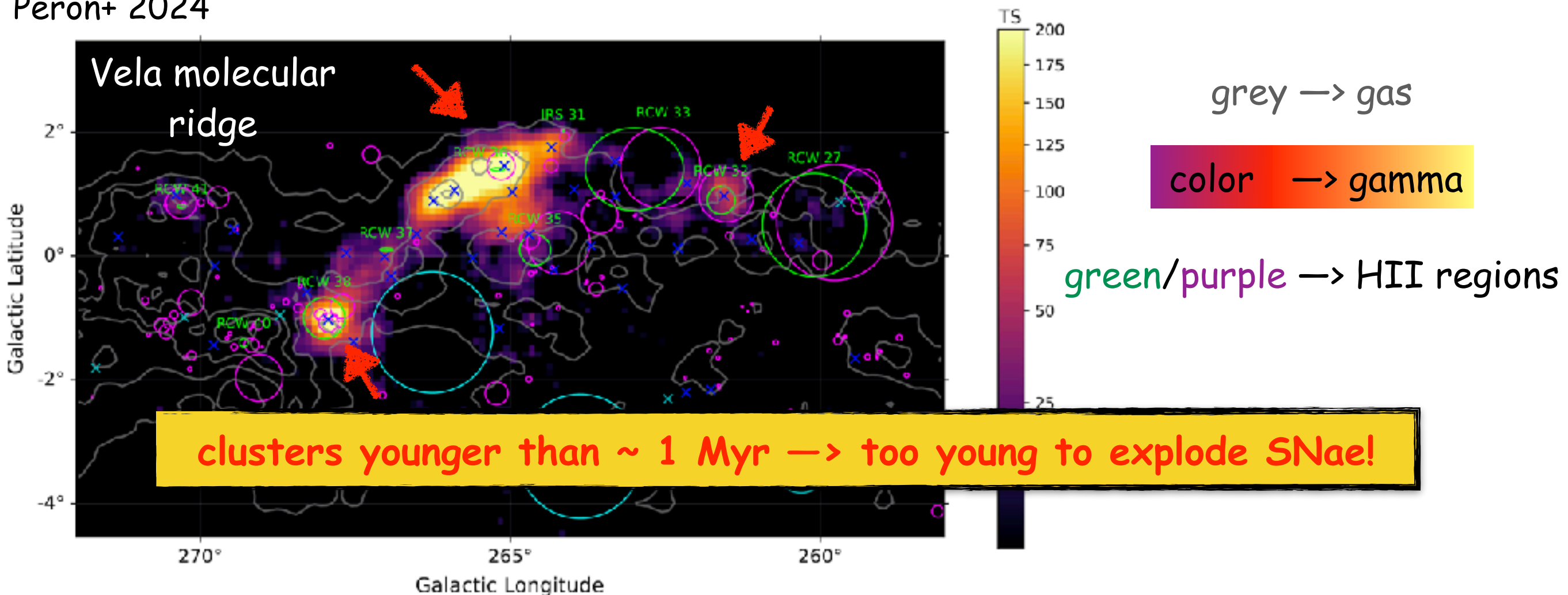
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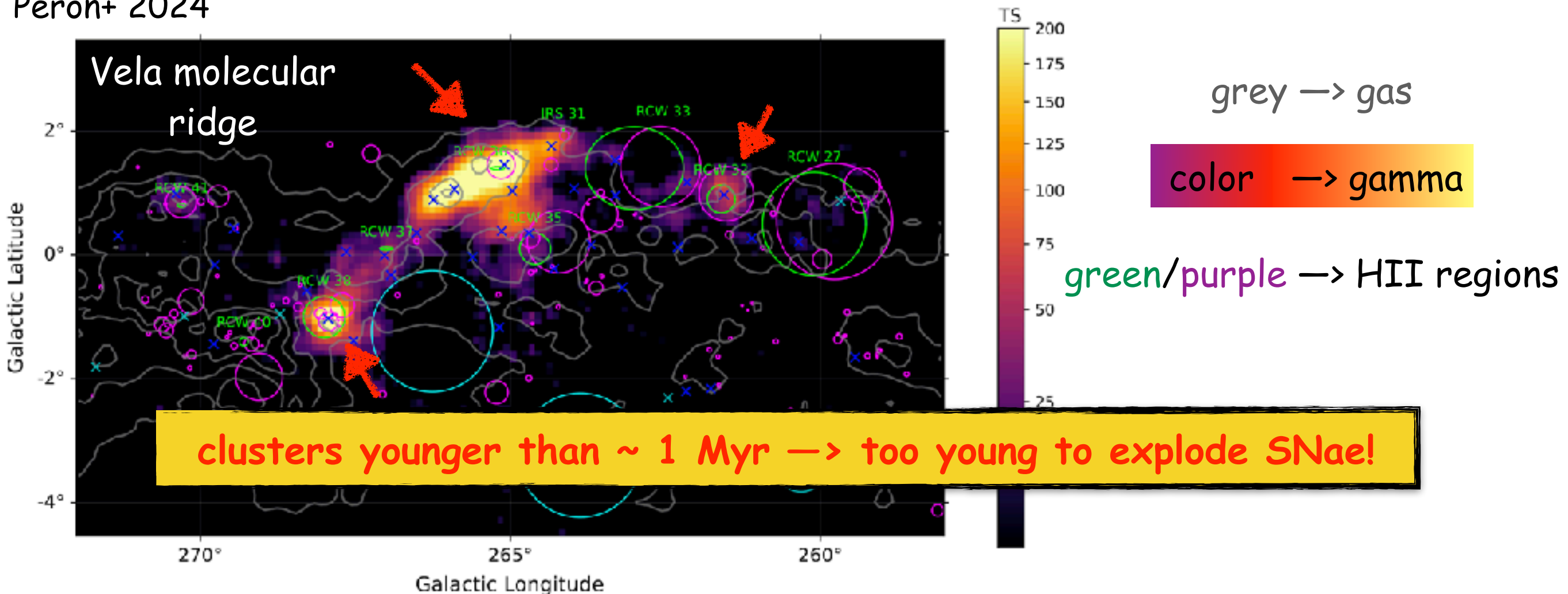
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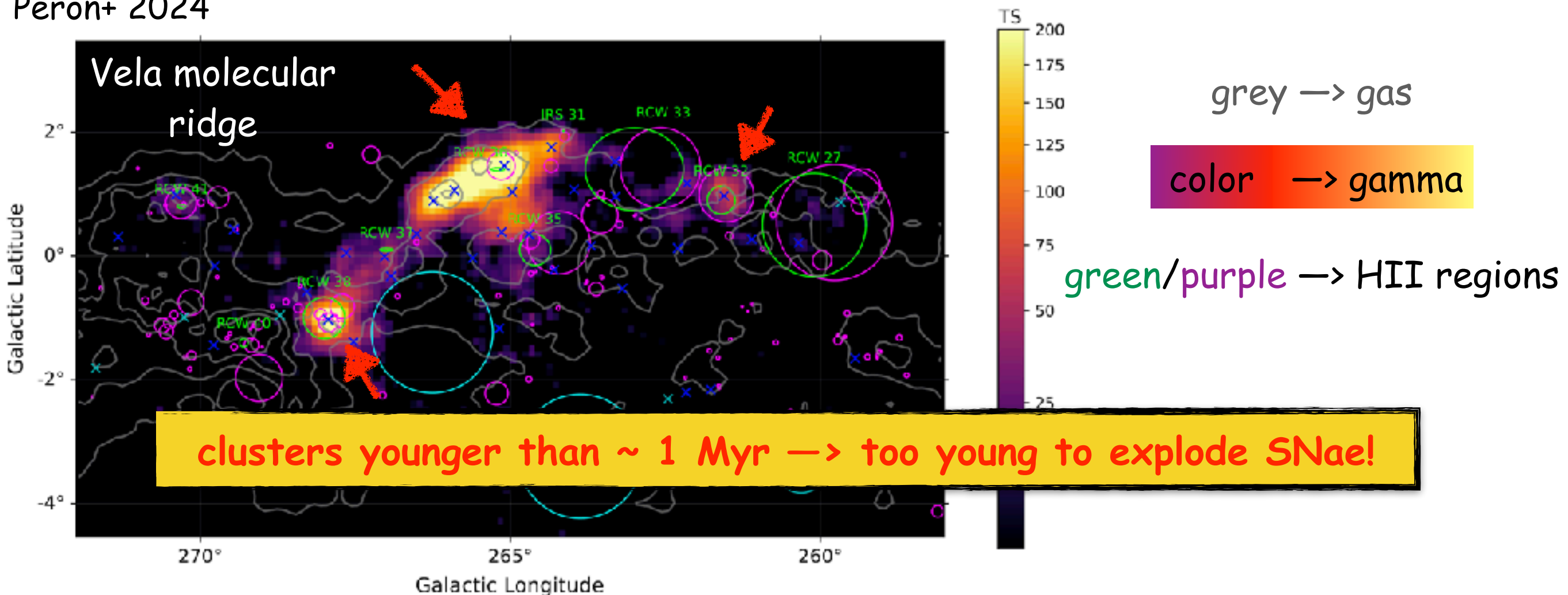


strict lower bound on the CR
acceleration efficiency (energy)

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

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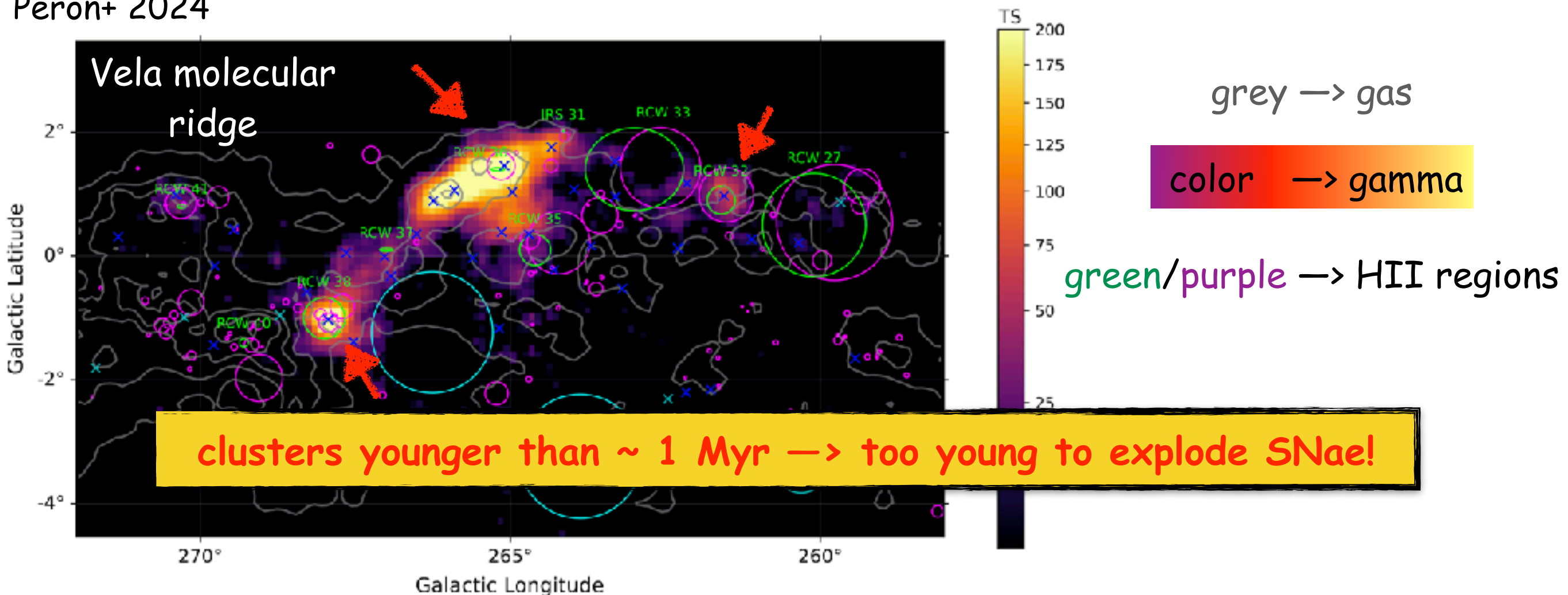
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$$X_{CR} \sim \eta_w X_w + (1 - \eta_w) X_S \sim 0.09 > X_S$$

isotopic ratio
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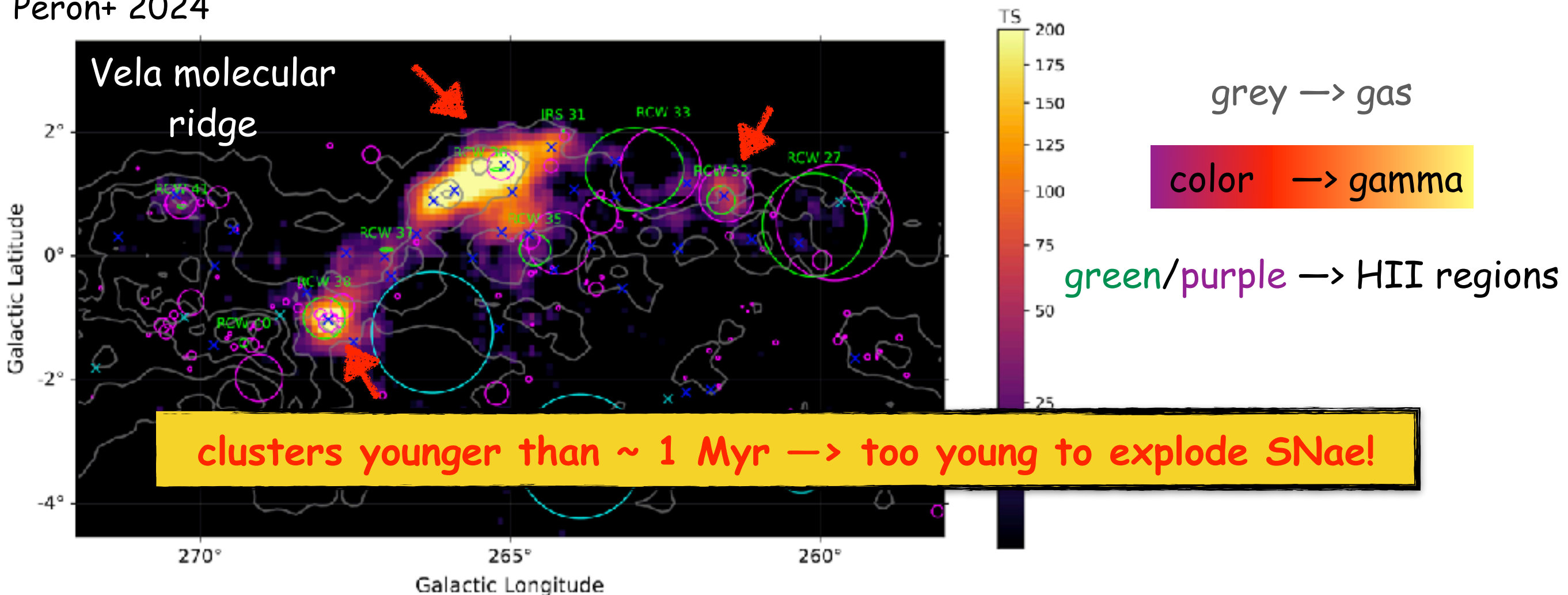
fraction of CRs
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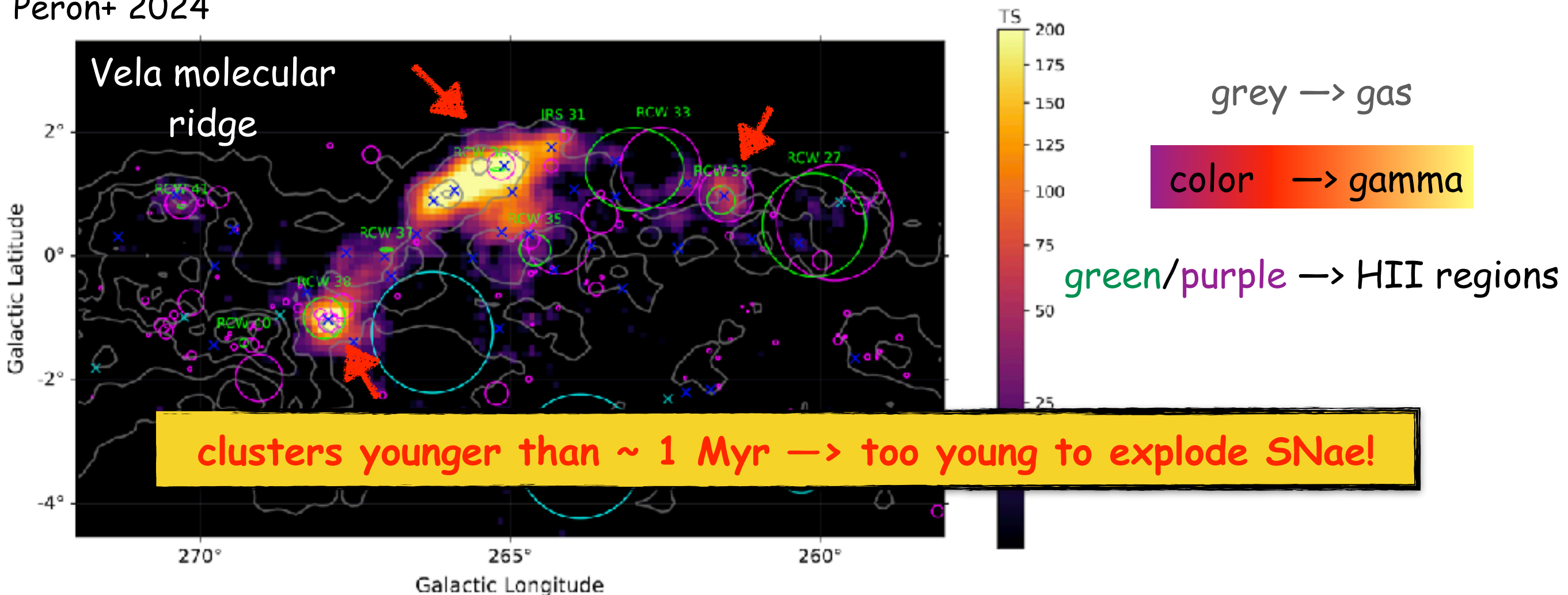
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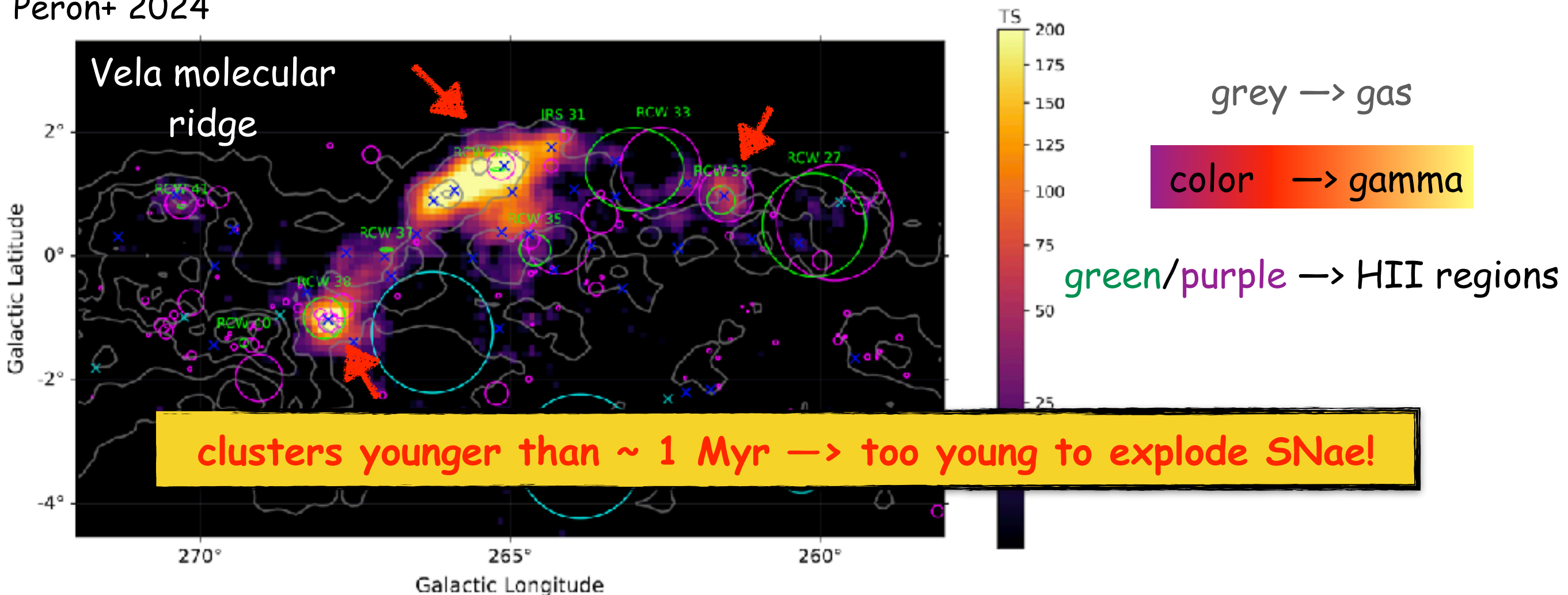
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if we set $\eta_w = 0.01$

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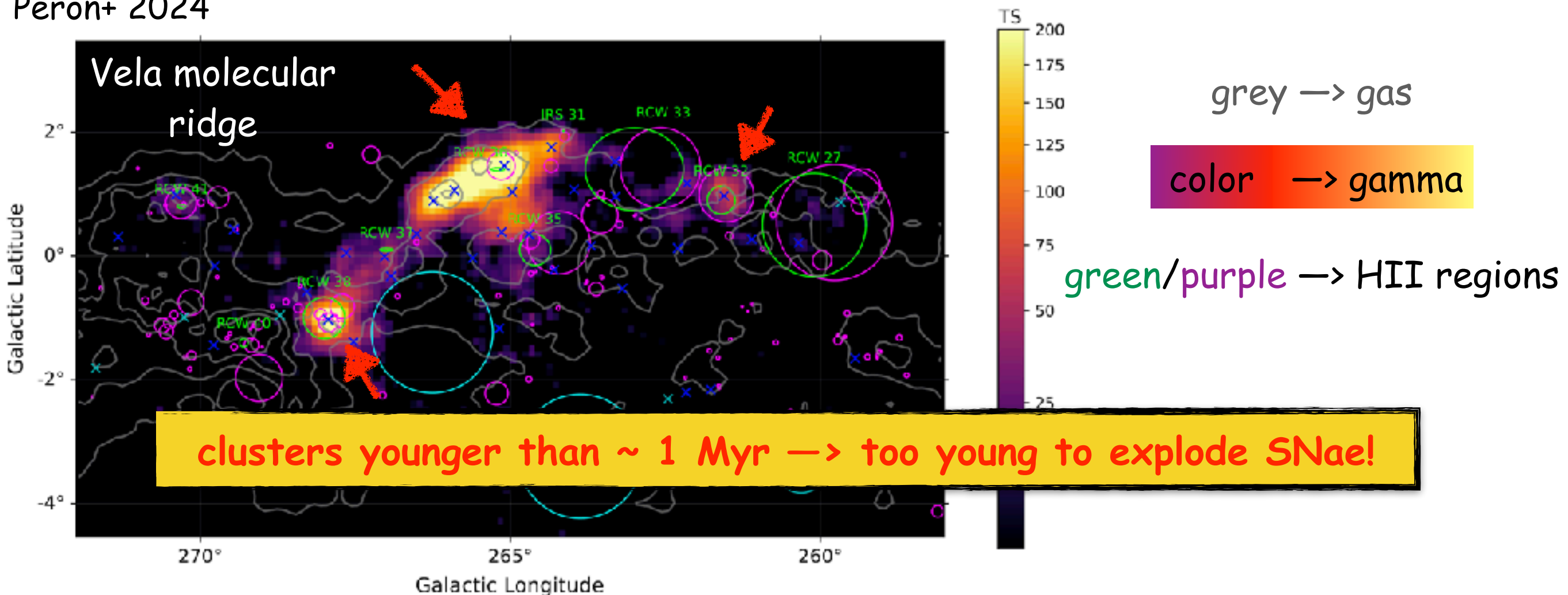
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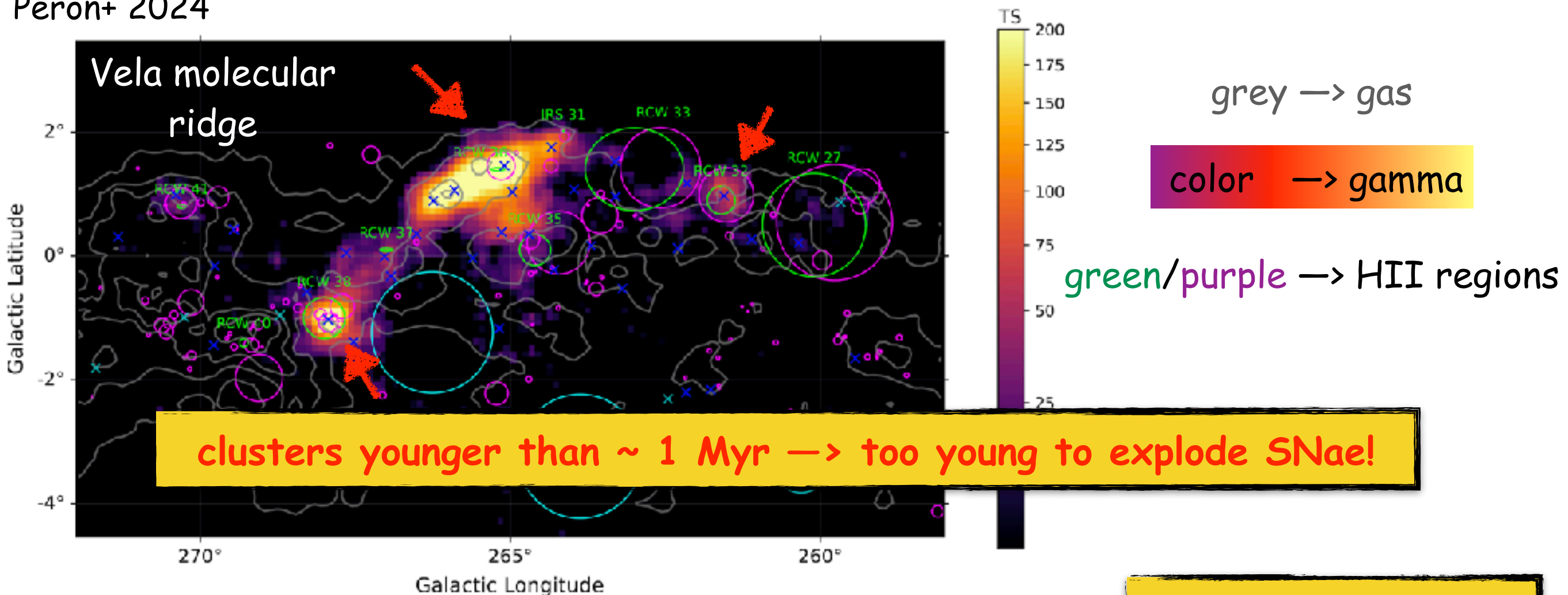
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Solar/interstellar ratio

$\rightarrow$ excess!

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Peron+ 2024



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more accurate estimate: $\eta_w \sim 5\%$

Tatischeff+ 2021

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Star clusters inflate hot superbubbles

acceleration efficiency at shocks $\sim (A/Q)^a$

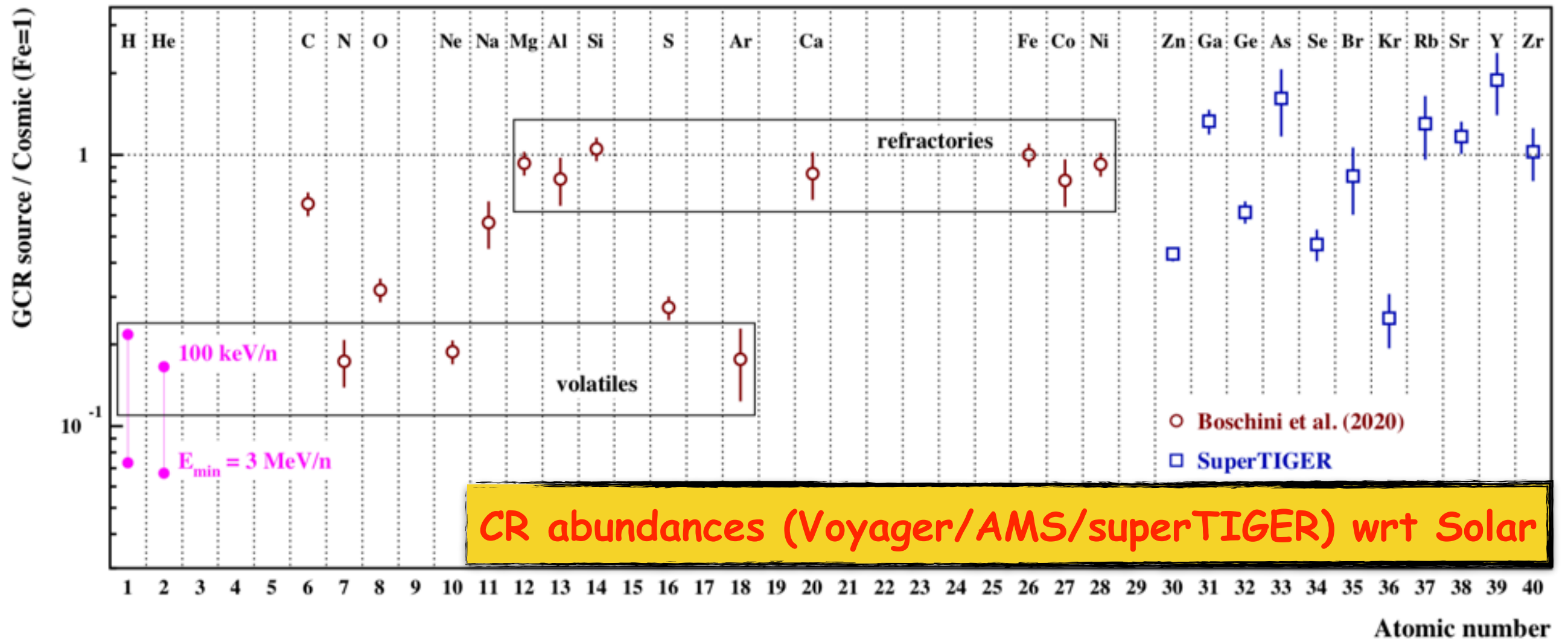
Ellison+ 1997, Caprioli+ 2017

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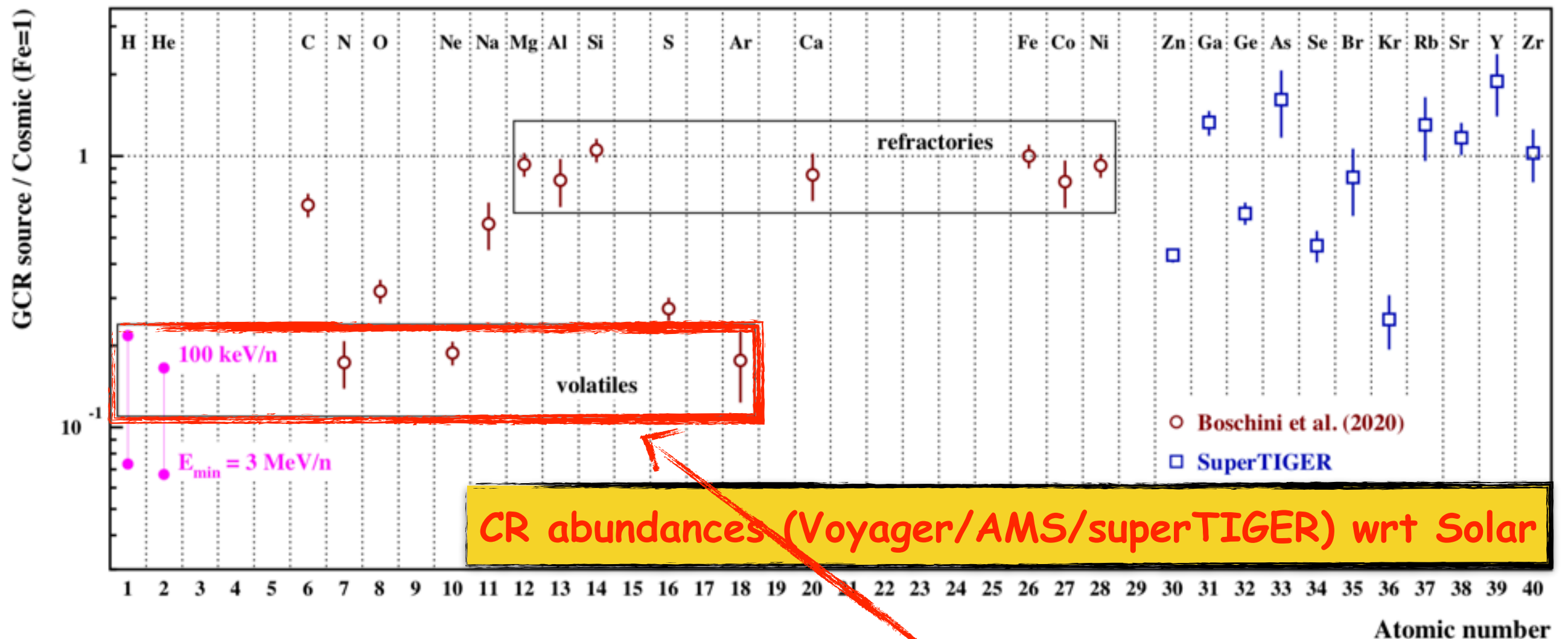


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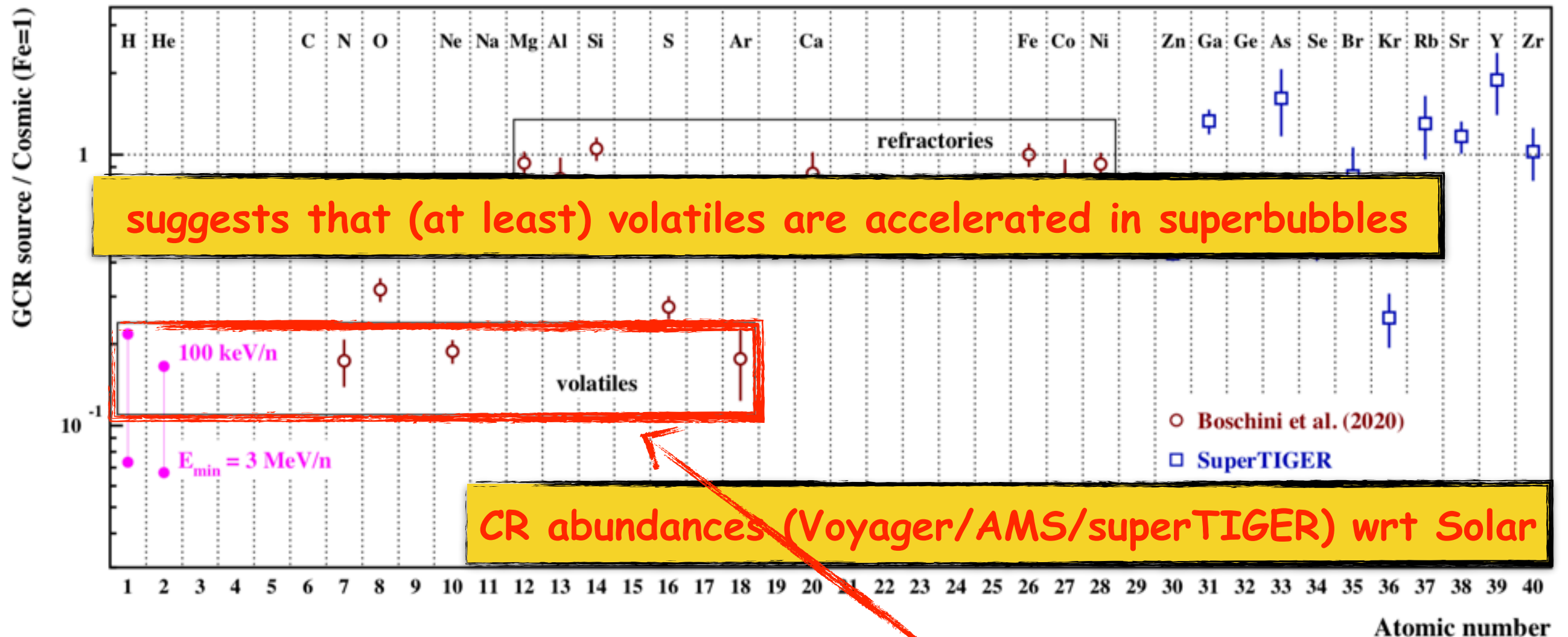
SBs are hot $\rightarrow A/Q \sim 2$ for all elements $\rightarrow$ flat abundance/solar ratio

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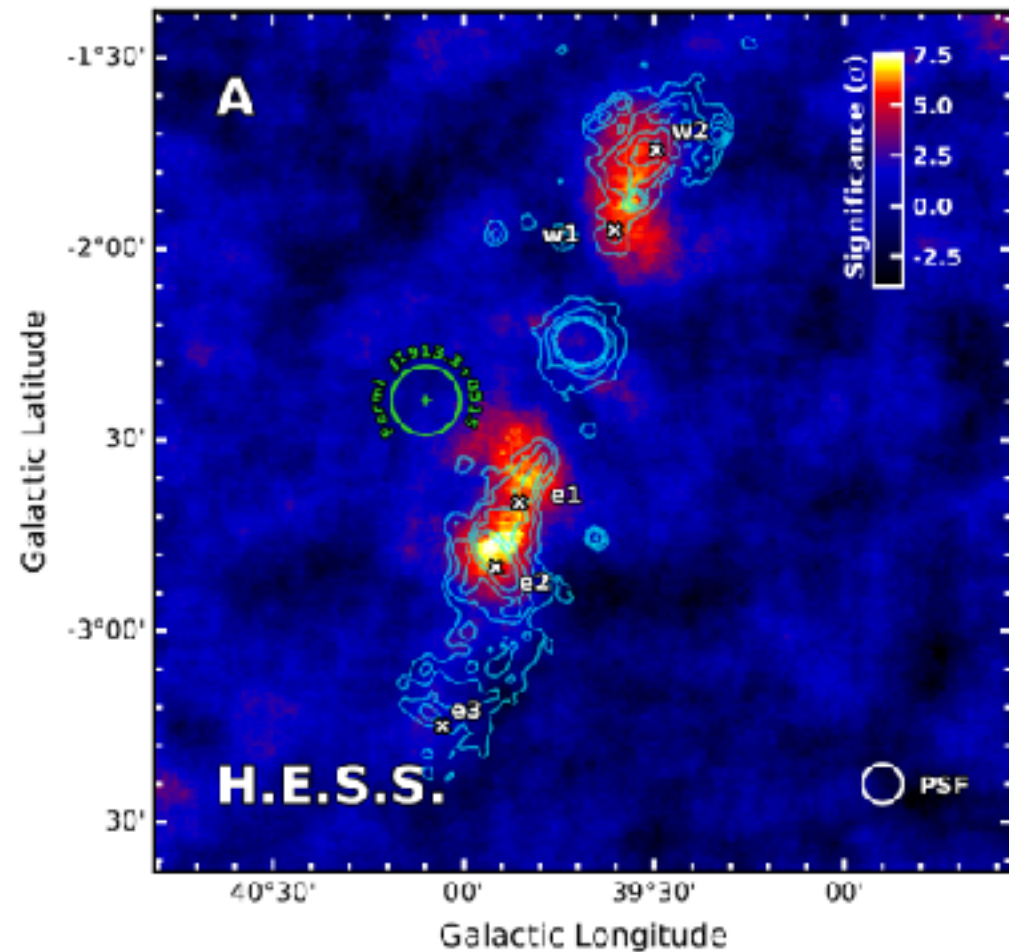


CR abundances (Voyager/AMS/superTIGER) wrt Solar

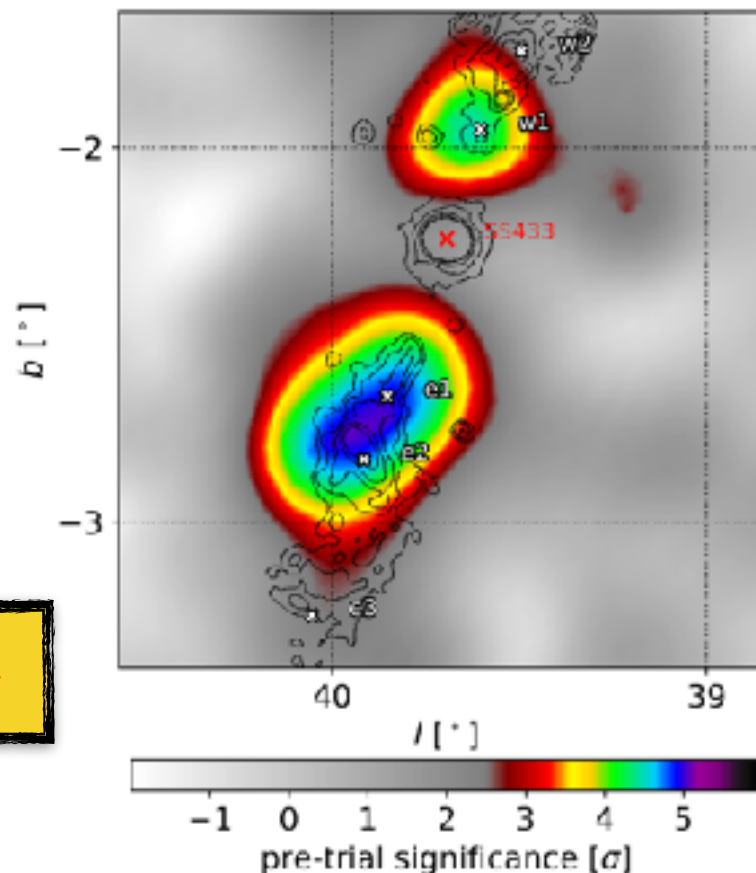
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Can microquasar solve the issue with the knee?

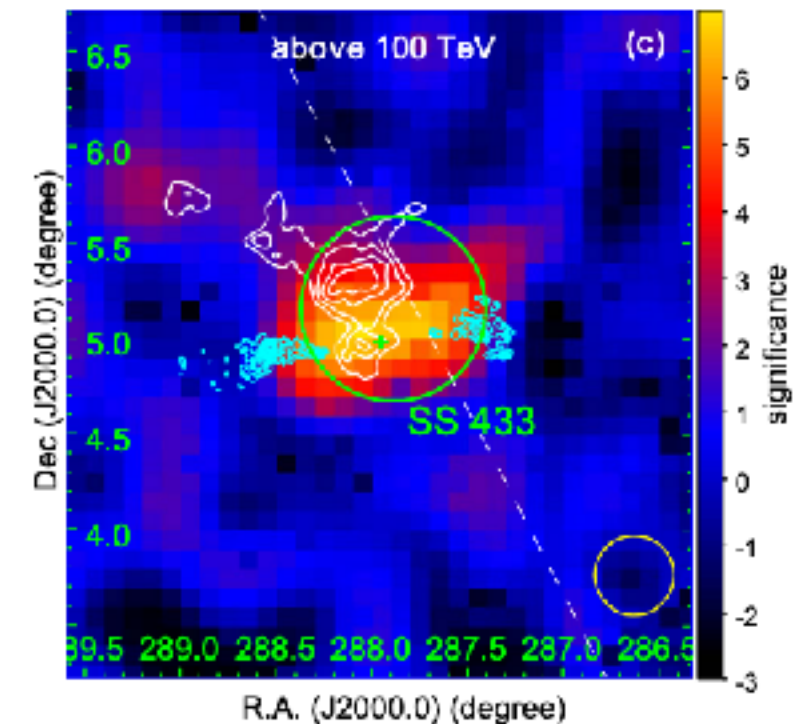
a handful of micro quasars detected in very-high-energy gamma-rays



← HESS 2024



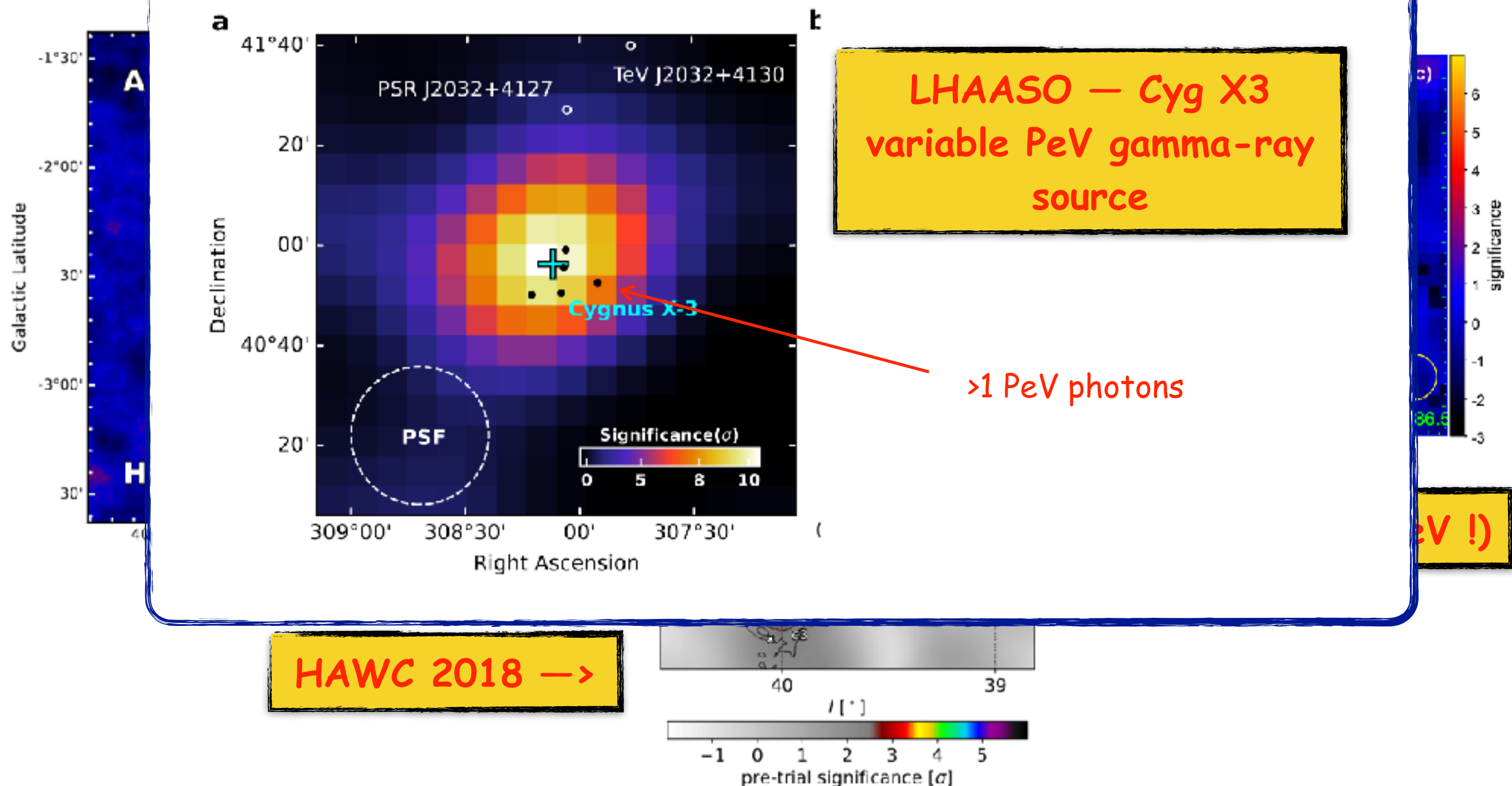
HAWC 2018 →



LHAASO (>100 TeV !)

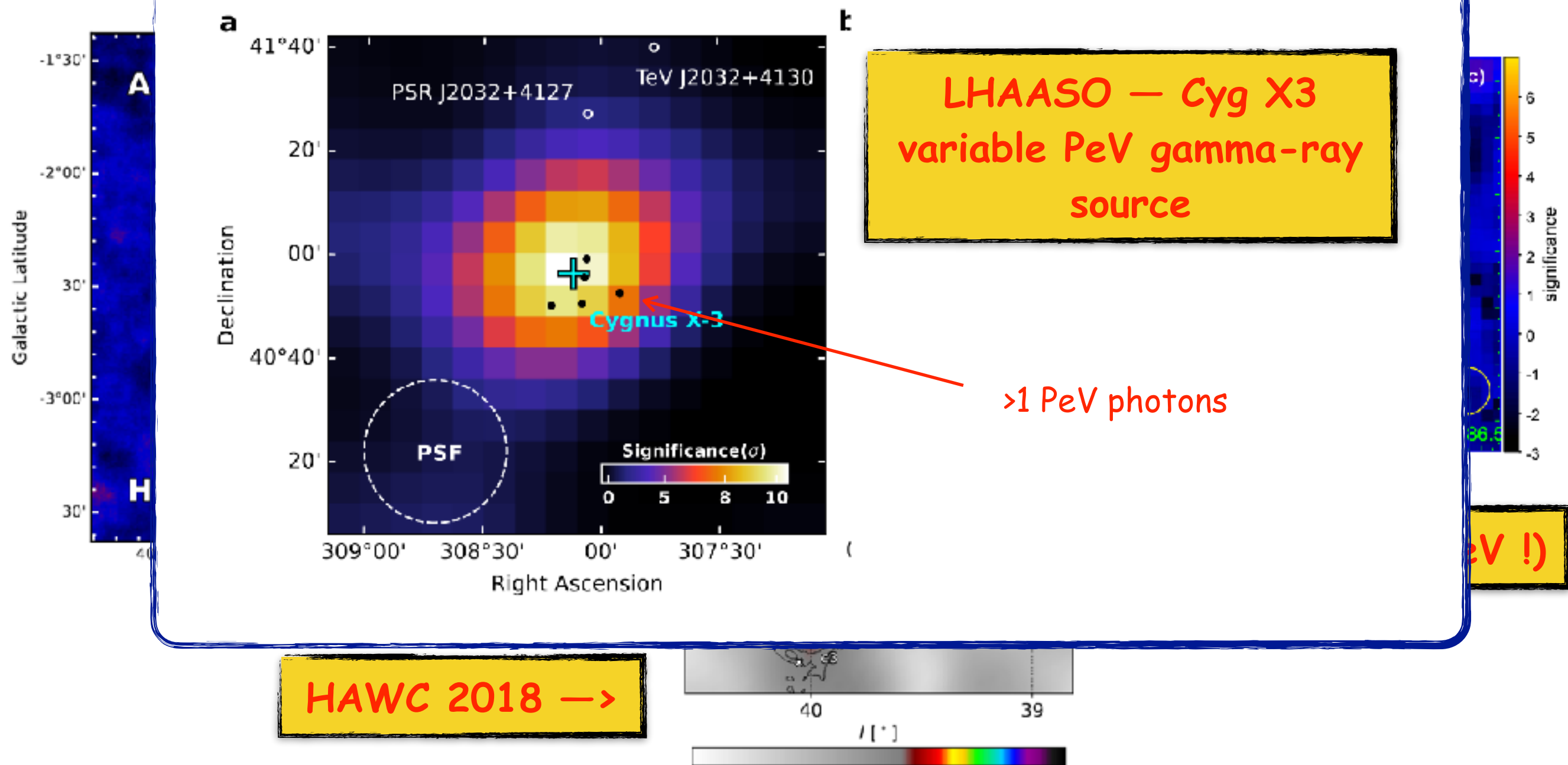
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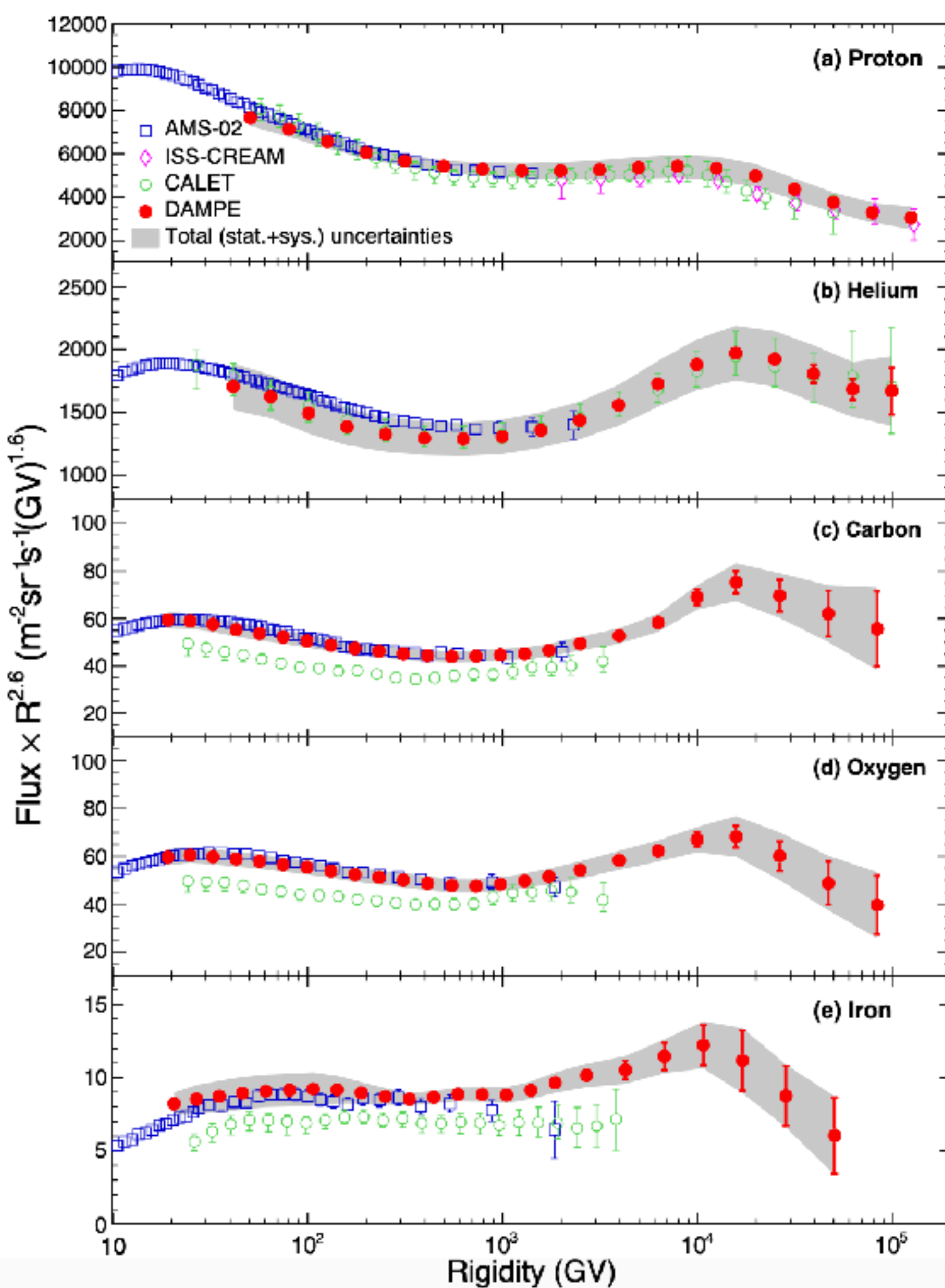
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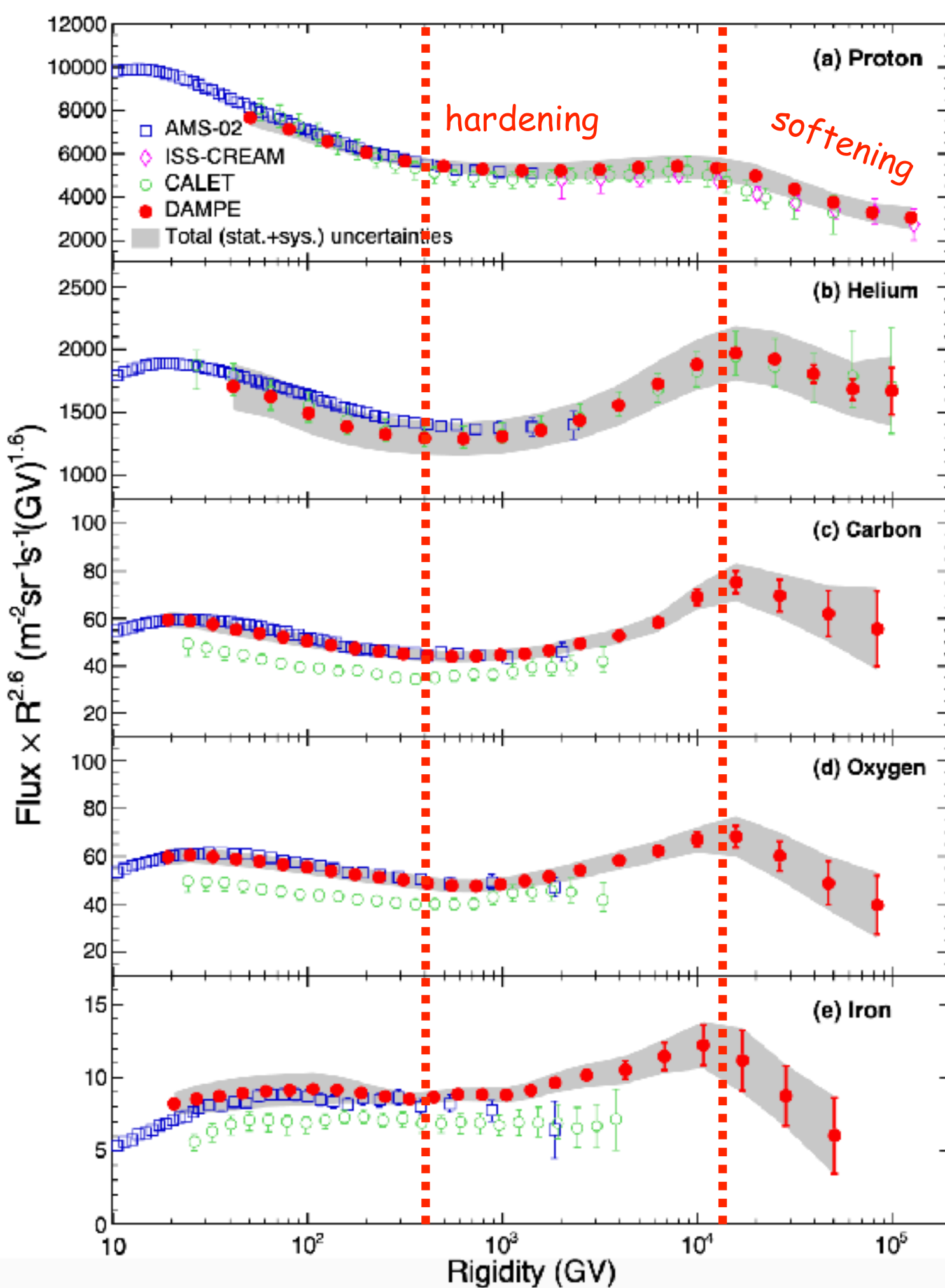
do they contribute to the knee? Peretti+ Wang+ Kaci+ 2025

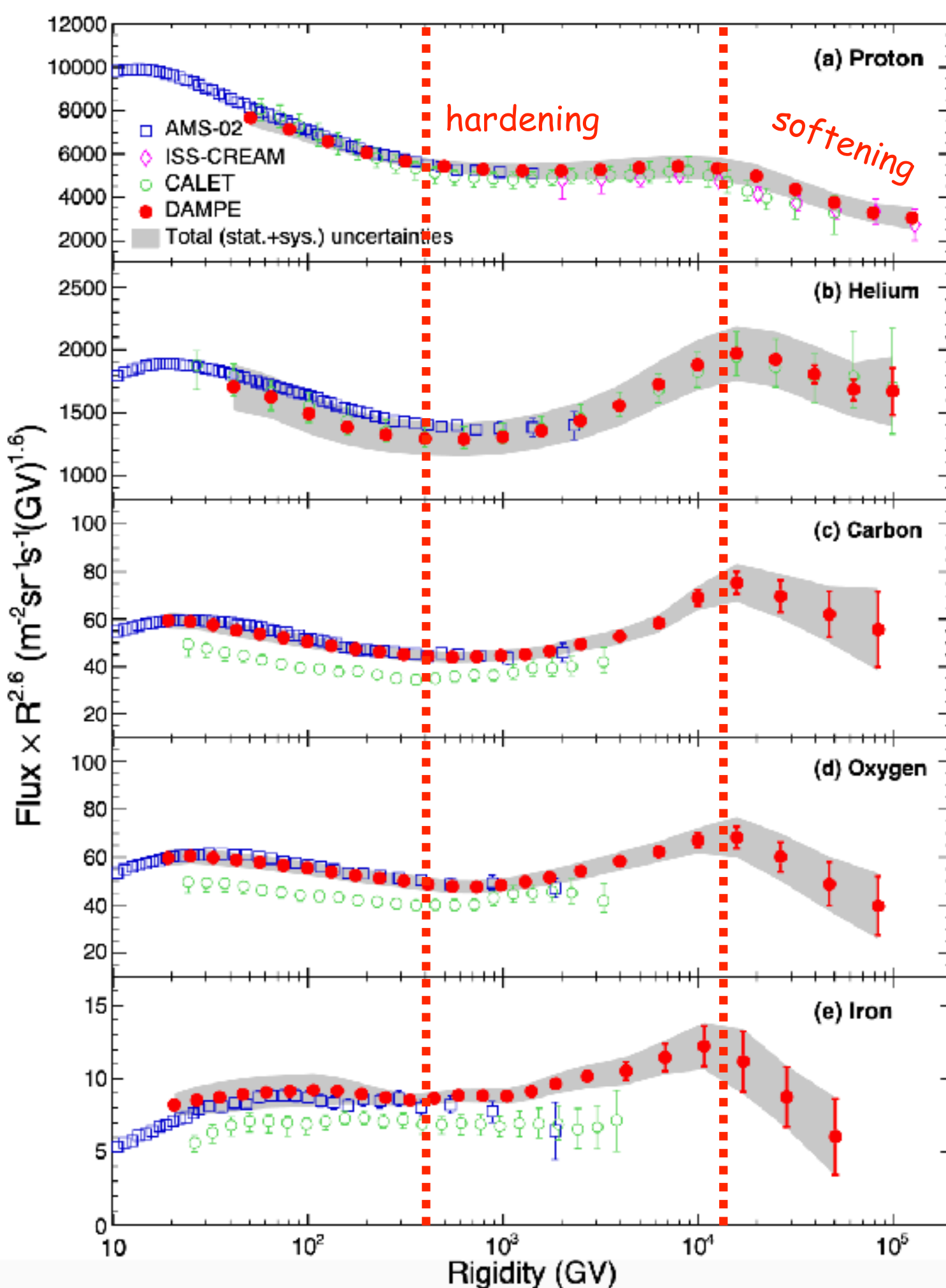
A coherent picture?

spectra of primary CRs nicely align
when plotted versus RIGIDITY



spectra of primary CRs nicely align
when plotted versus RIGIDITY

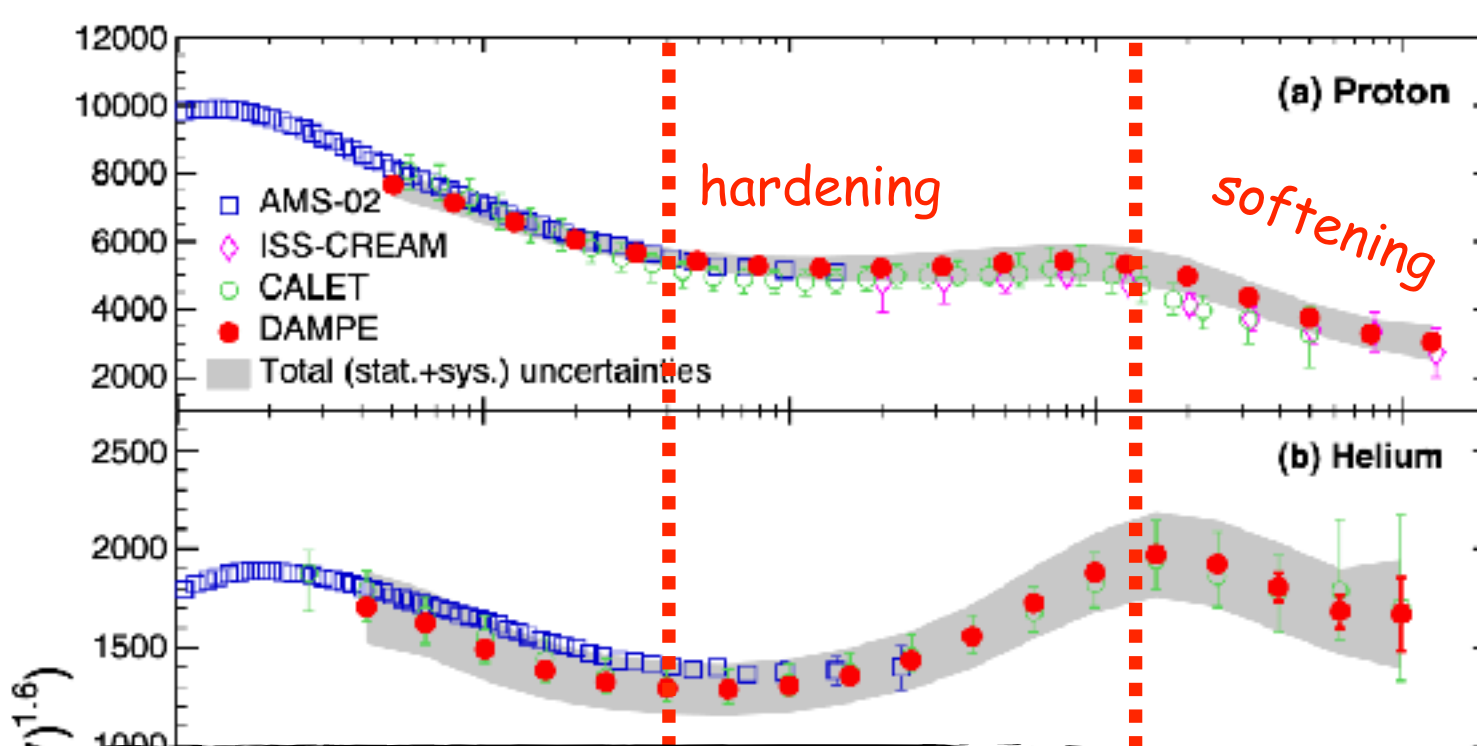




spectra of primary CRs nicely align
when plotted versus RIGIDITY



transport, either in the ISM or
inside the source (acceleration)



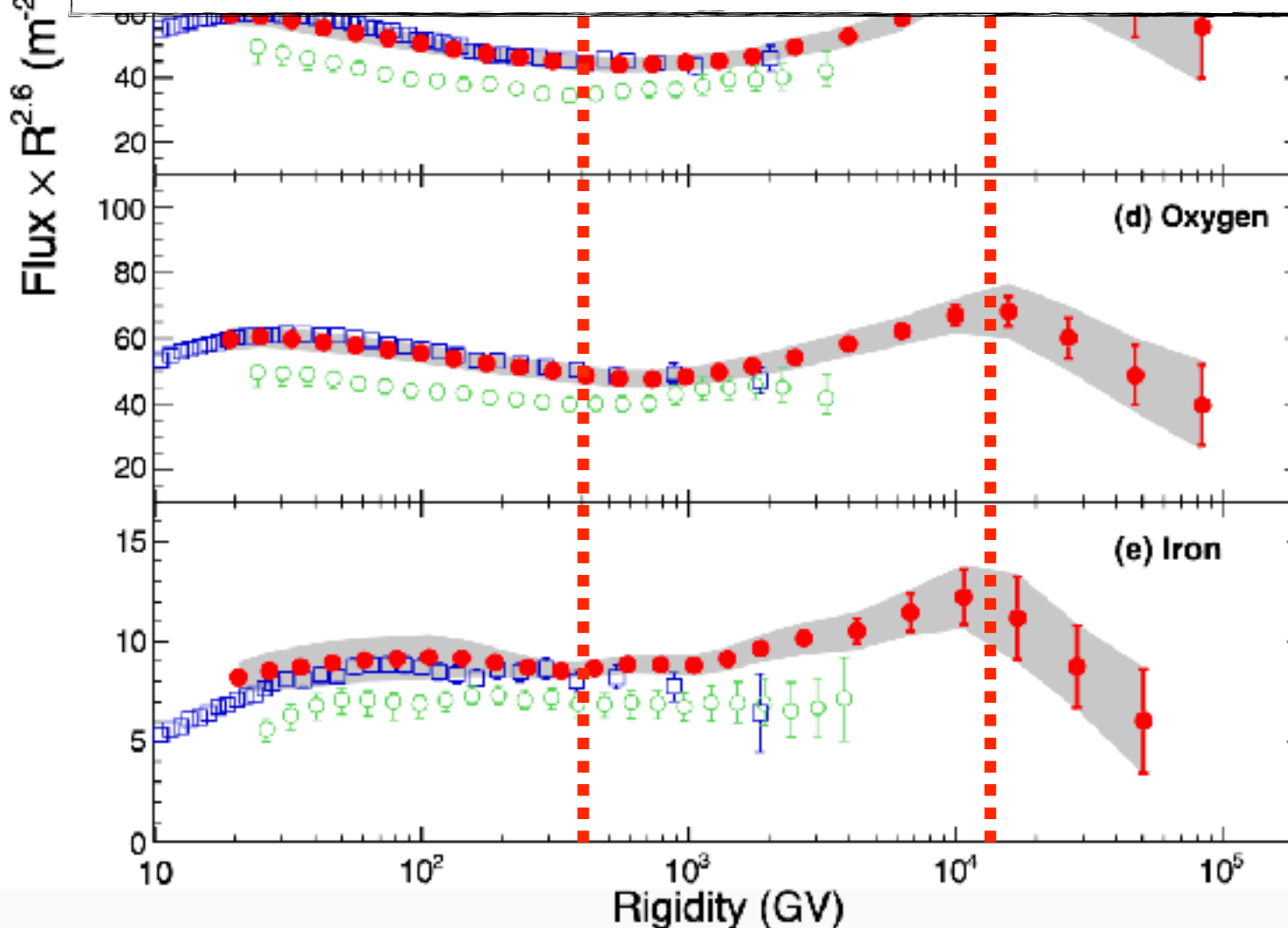
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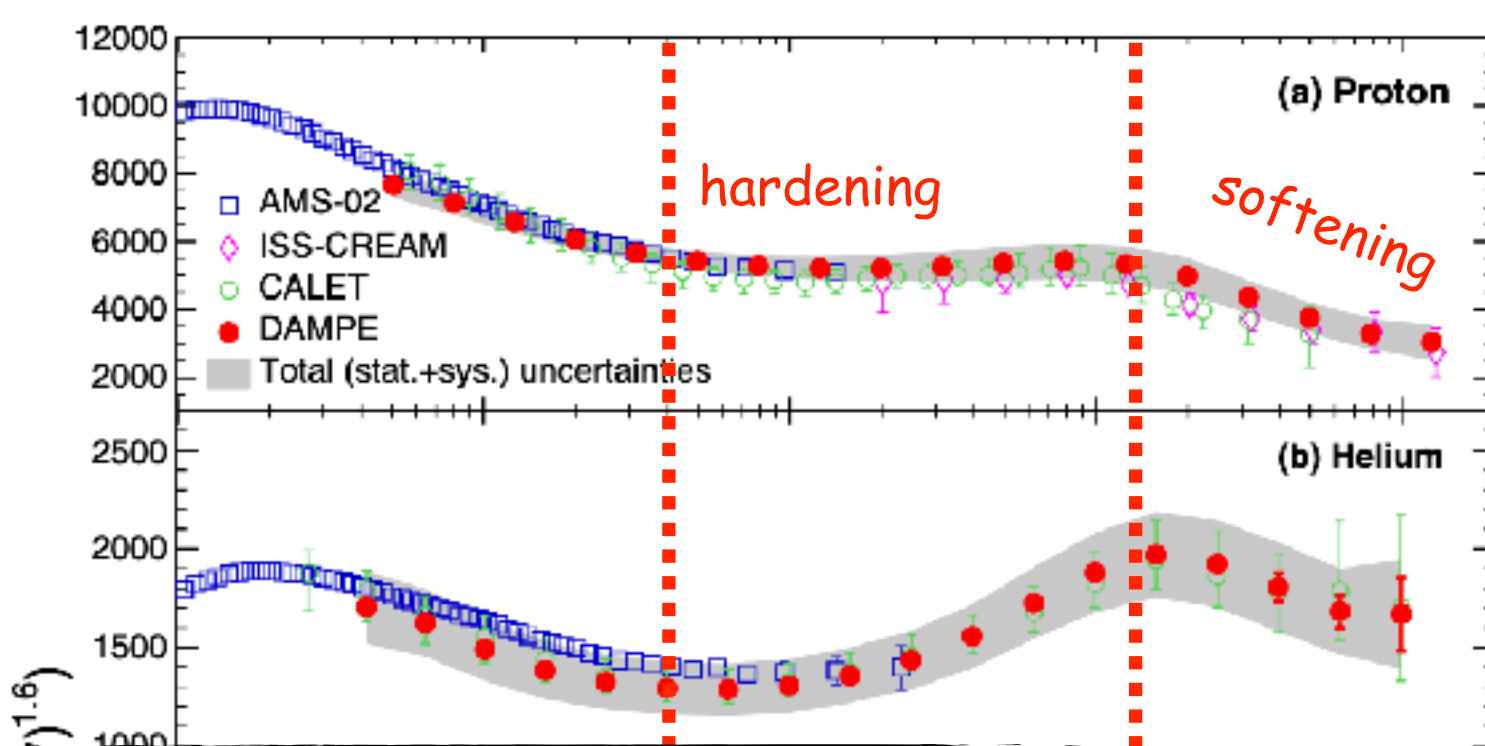


transport, either in the ISM or
inside the source (acceleration)

primaries = acceleration + transport

secondaries = primaries + transport = acceleration + transport + transport





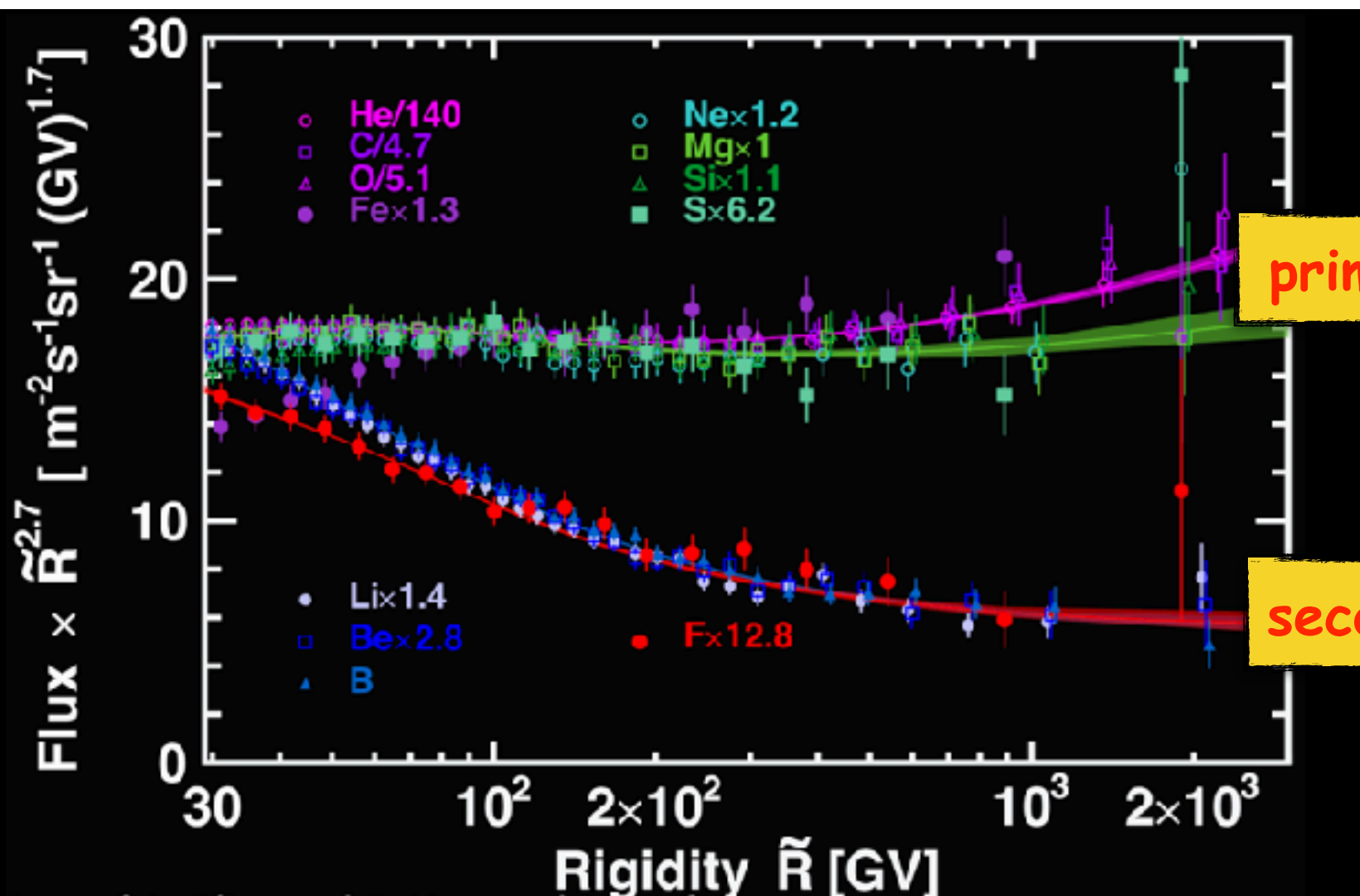
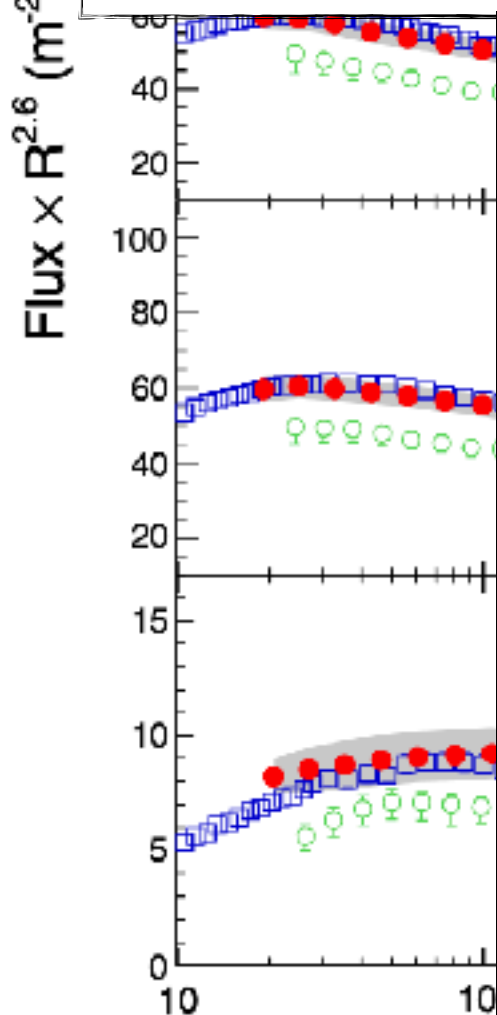
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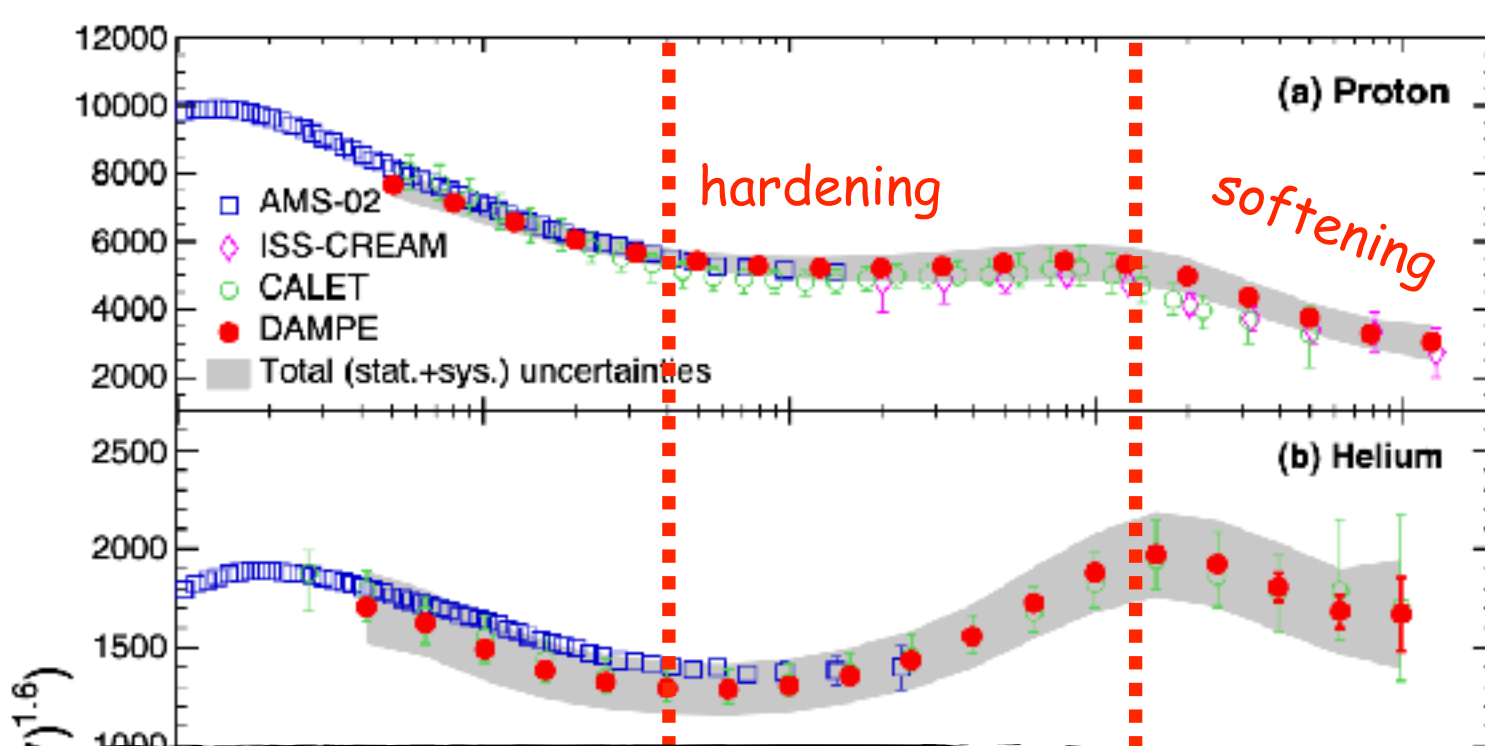


primaries

AMS02,
ICRC2023

secondaries

DAMPE 2025



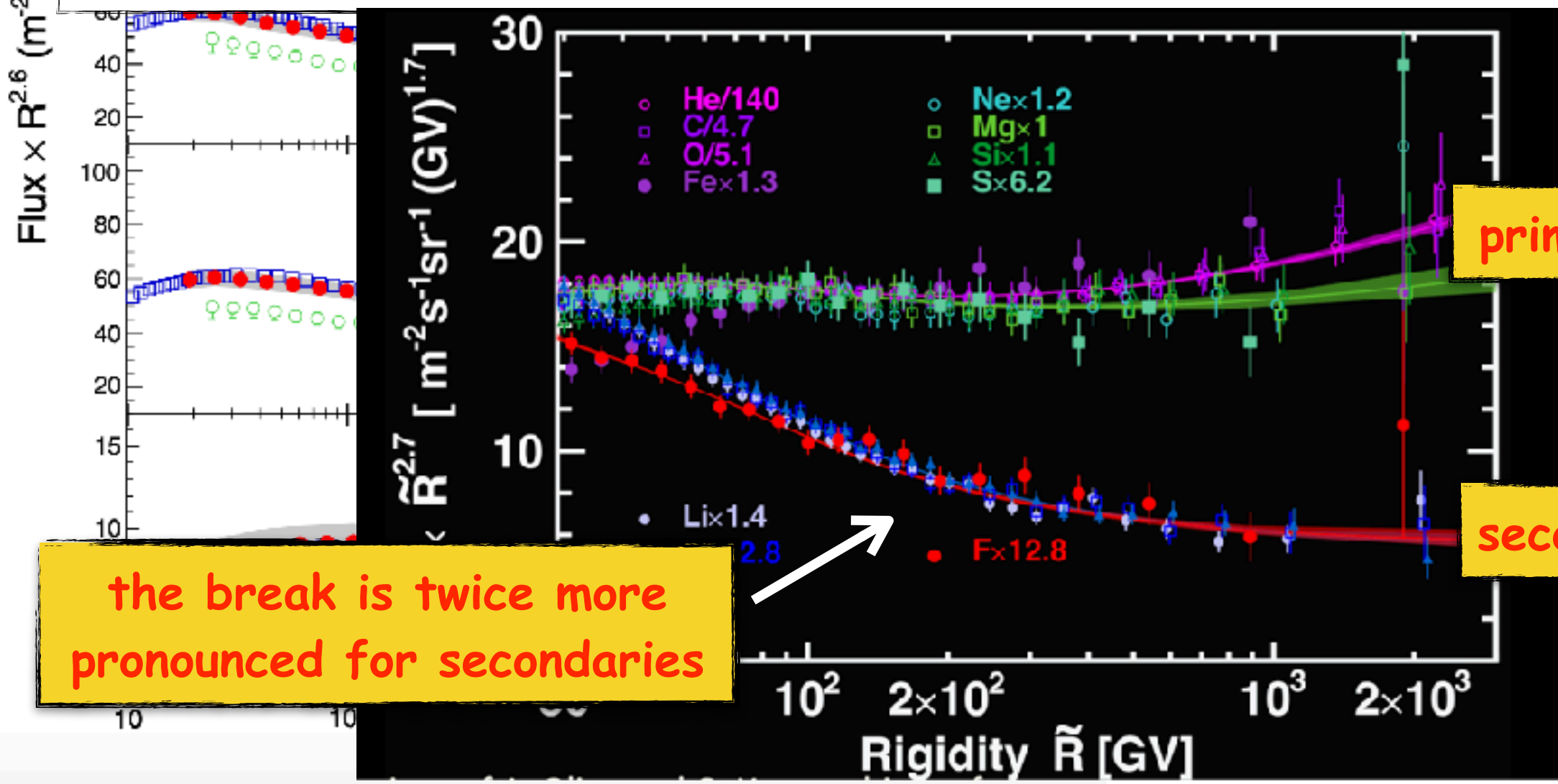
spectra of primary CRs nicely align when plotted versus RIGIDITY



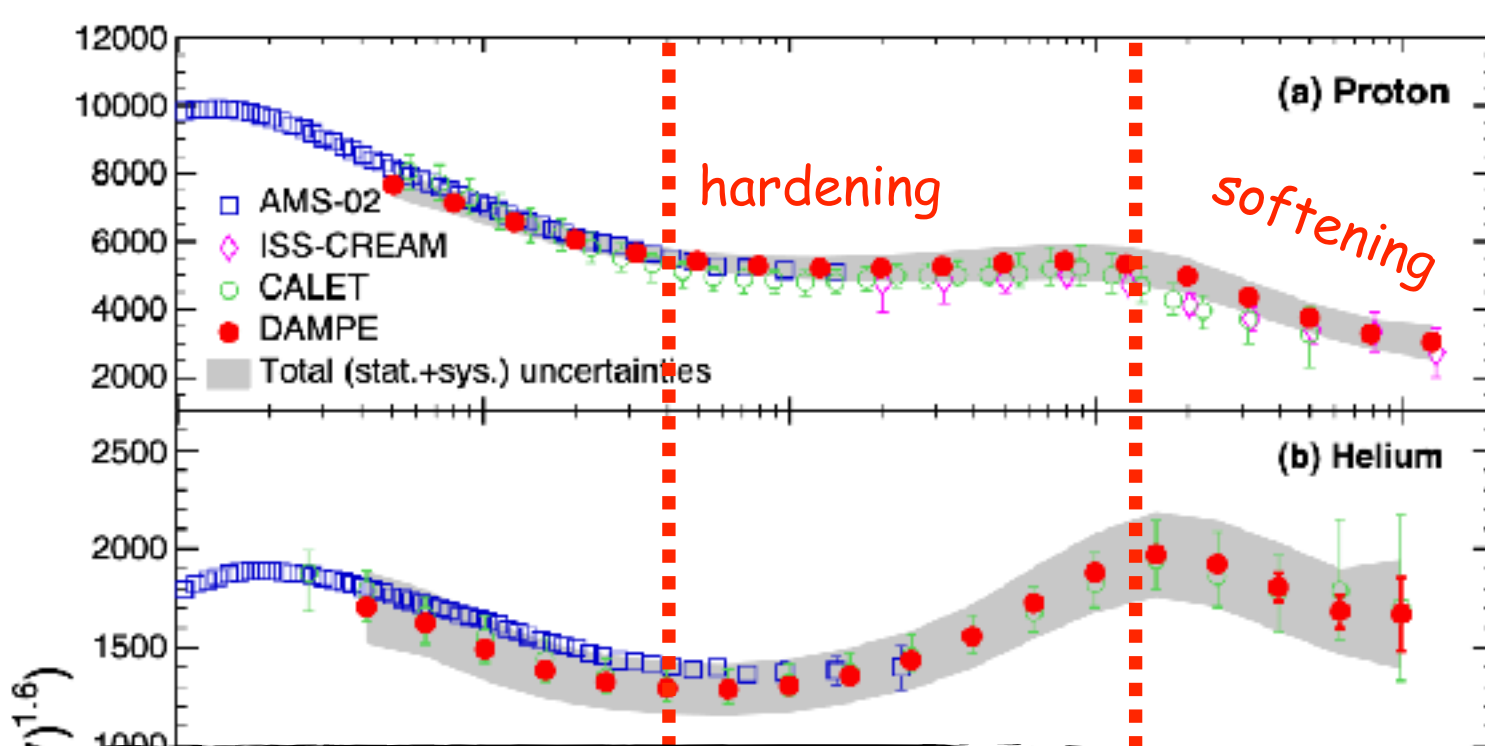
transport, either in the ISM or inside the source (acceleration)

primaries = acceleration + transport

secondaries = primaries + transport = acceleration + transport + transport



the break is twice more pronounced for secondaries



spectra of primary CRs nicely align when plotted versus RIGIDITY



transport, either in the ISM or inside the source (acceleration)

primaries = acceleration + transport

secondaries = primaries + transport = acceleration + transport + transport



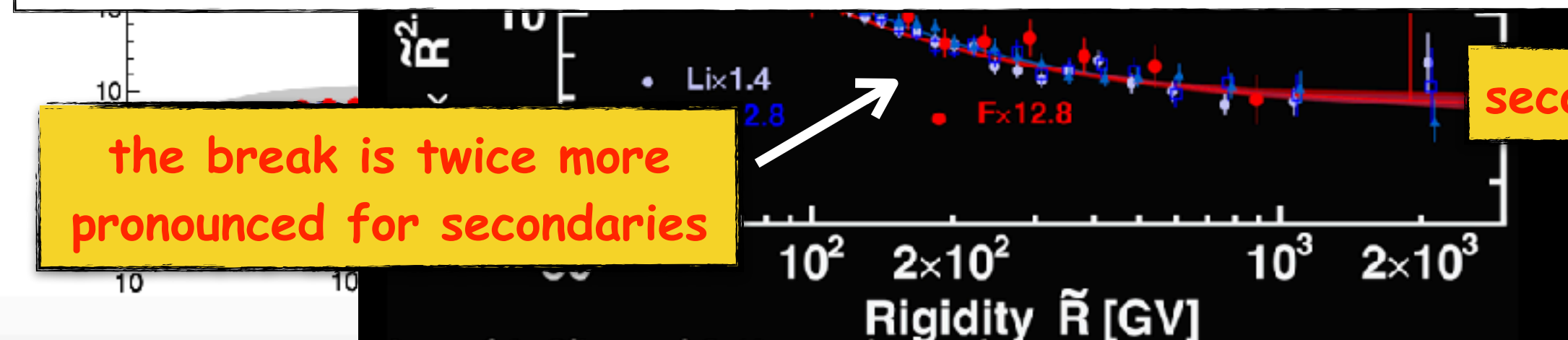
transport in the ISM changes at $O(100)$ GV

→ transition from CR self confinement to scattering on ambient turbulence

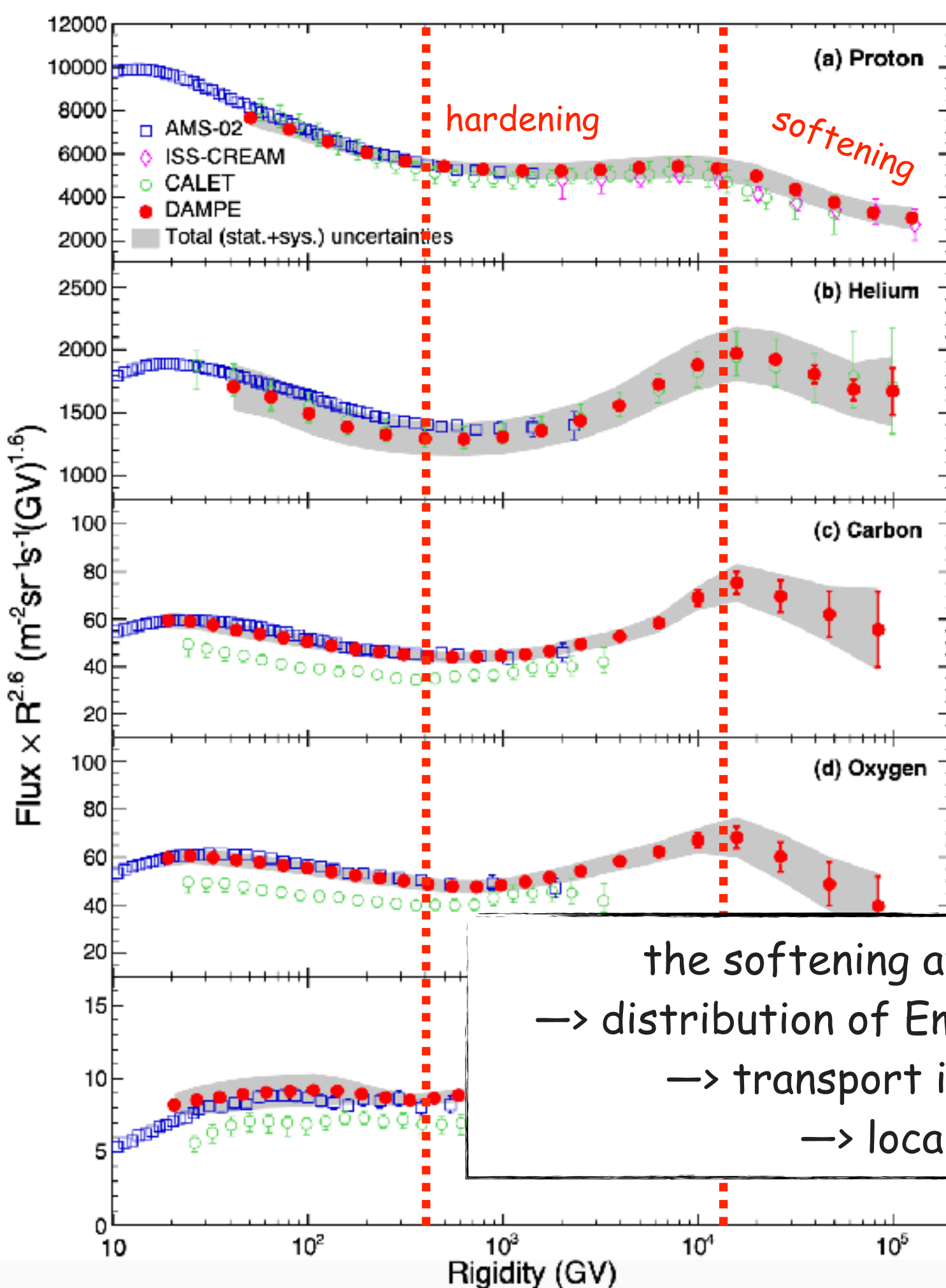
papers by Blasi+, incredibly prescient papers by Wentzel 74, Farmer&Goldreich 04

→ interplay of transport in Galactic disk and halo

Tomassetti, Recchia&Gabici



secondaries



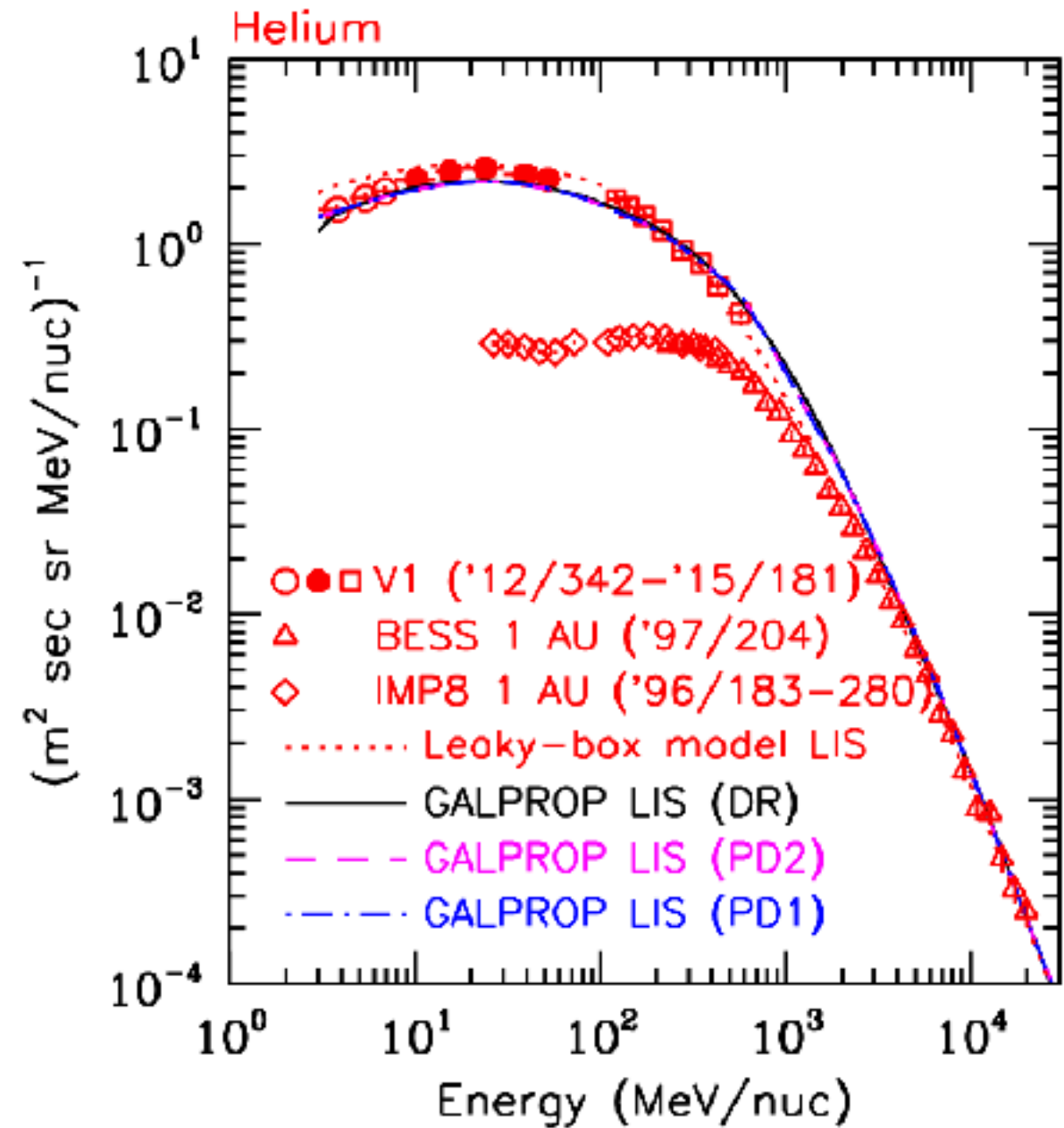
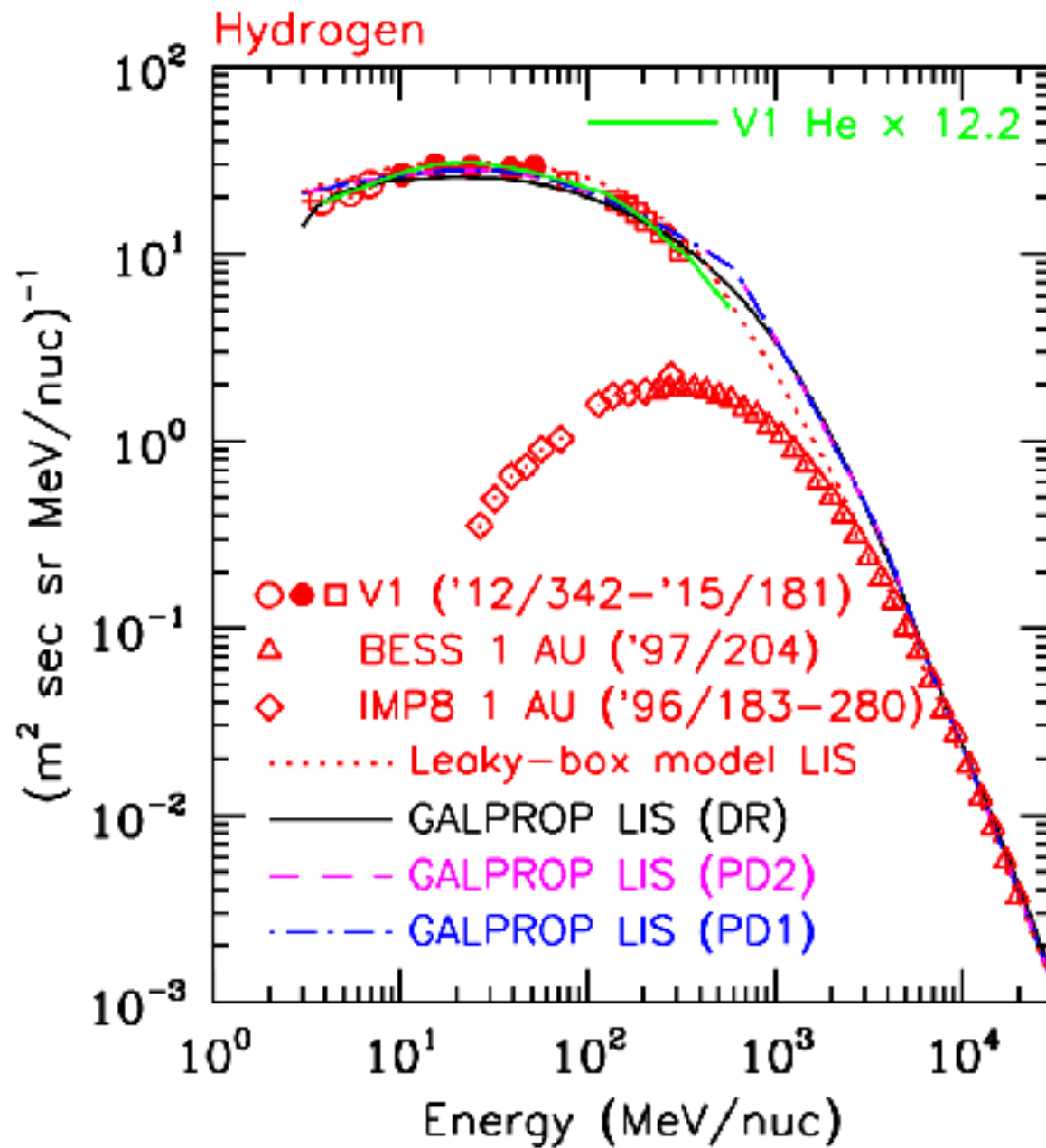
spectra of primary CRs nicely align
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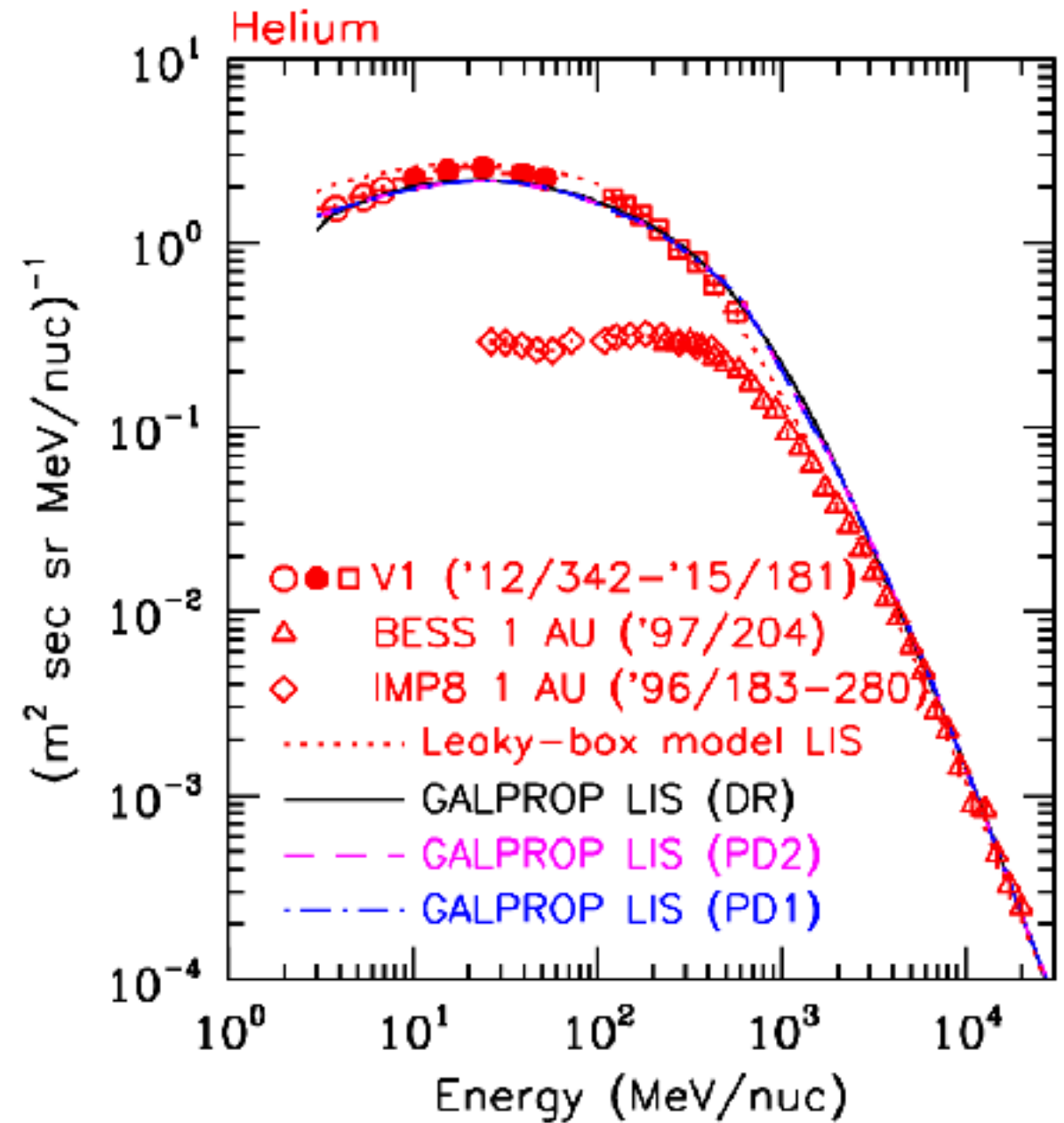
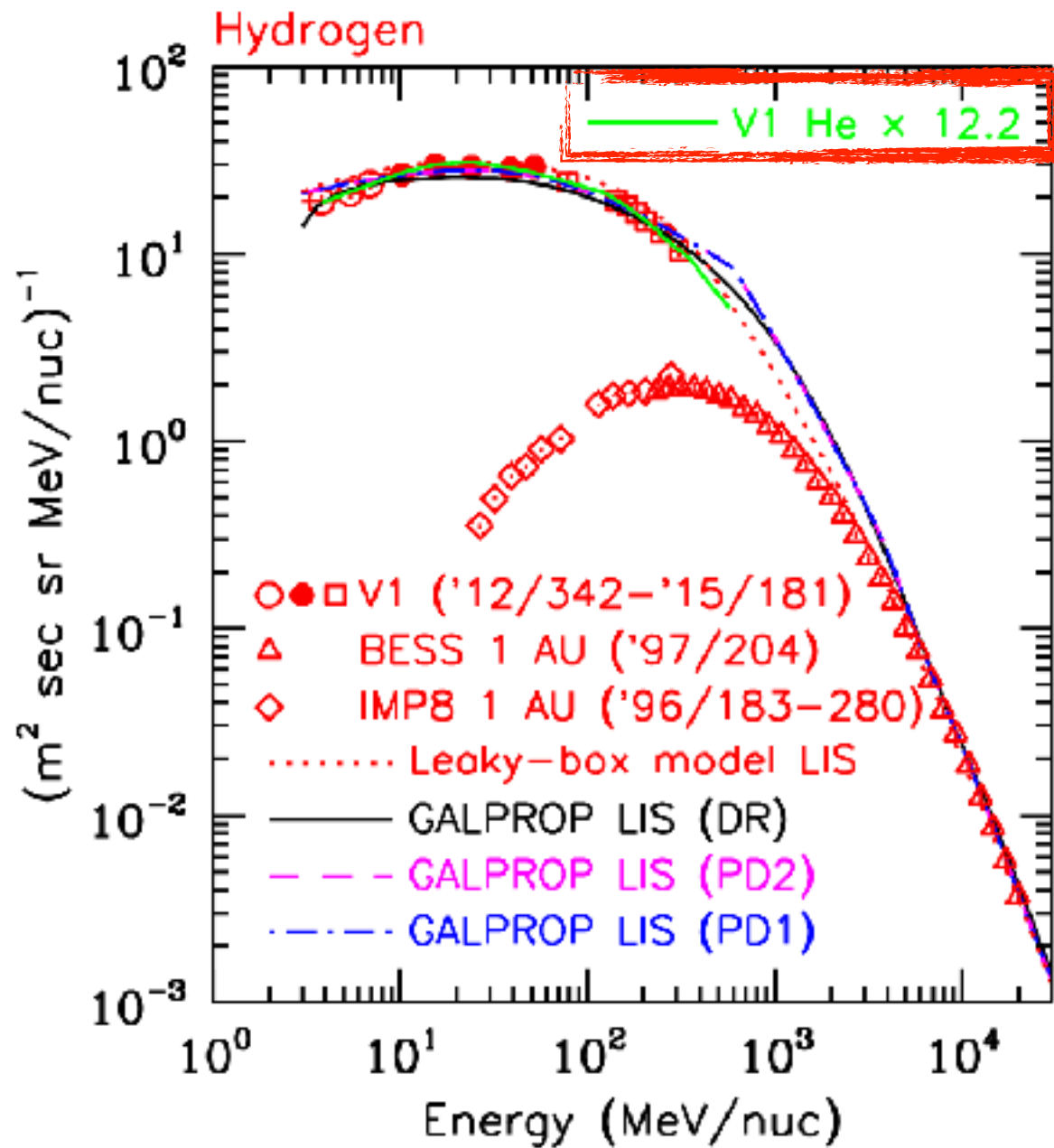
transport, either in the ISM or
inside the source (acceleration)

the softening at $O(10)$ TV is more debated
 $\rightarrow$ distribution of E_{max} of sources, Recchia&Gabici ...
 $\rightarrow$ transport in the halo, Ivlev, Dogliel ...
 $\rightarrow$ local source? Malkov+ ...

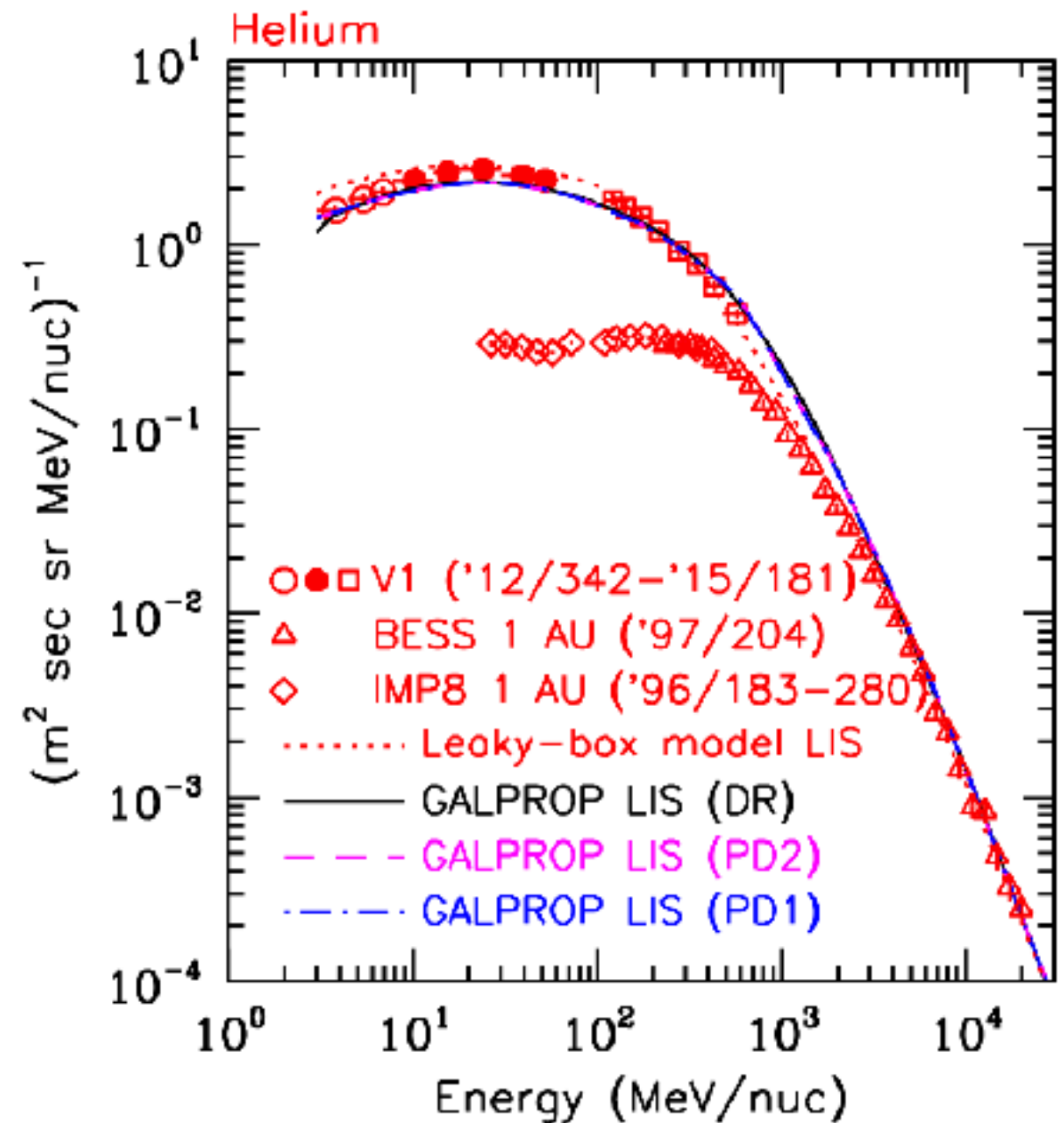
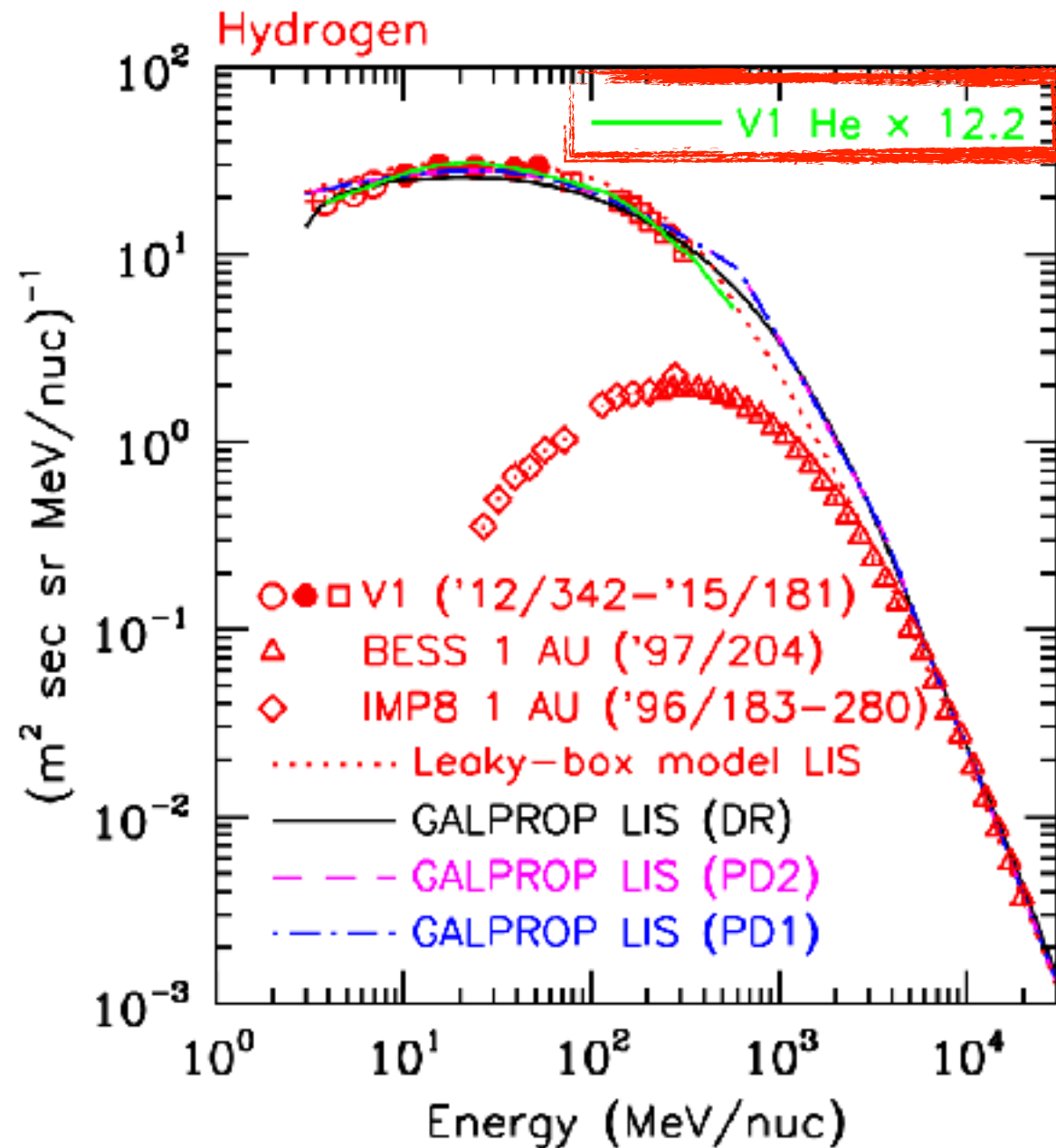
What if we plot versus E/nucleon?



What if we plot versus E/nucleon?



What if we plot versus E/nucleon?



Cummings+ 2016

in the MeV domain spectra have the same shape when plotted versus E/nucleon!

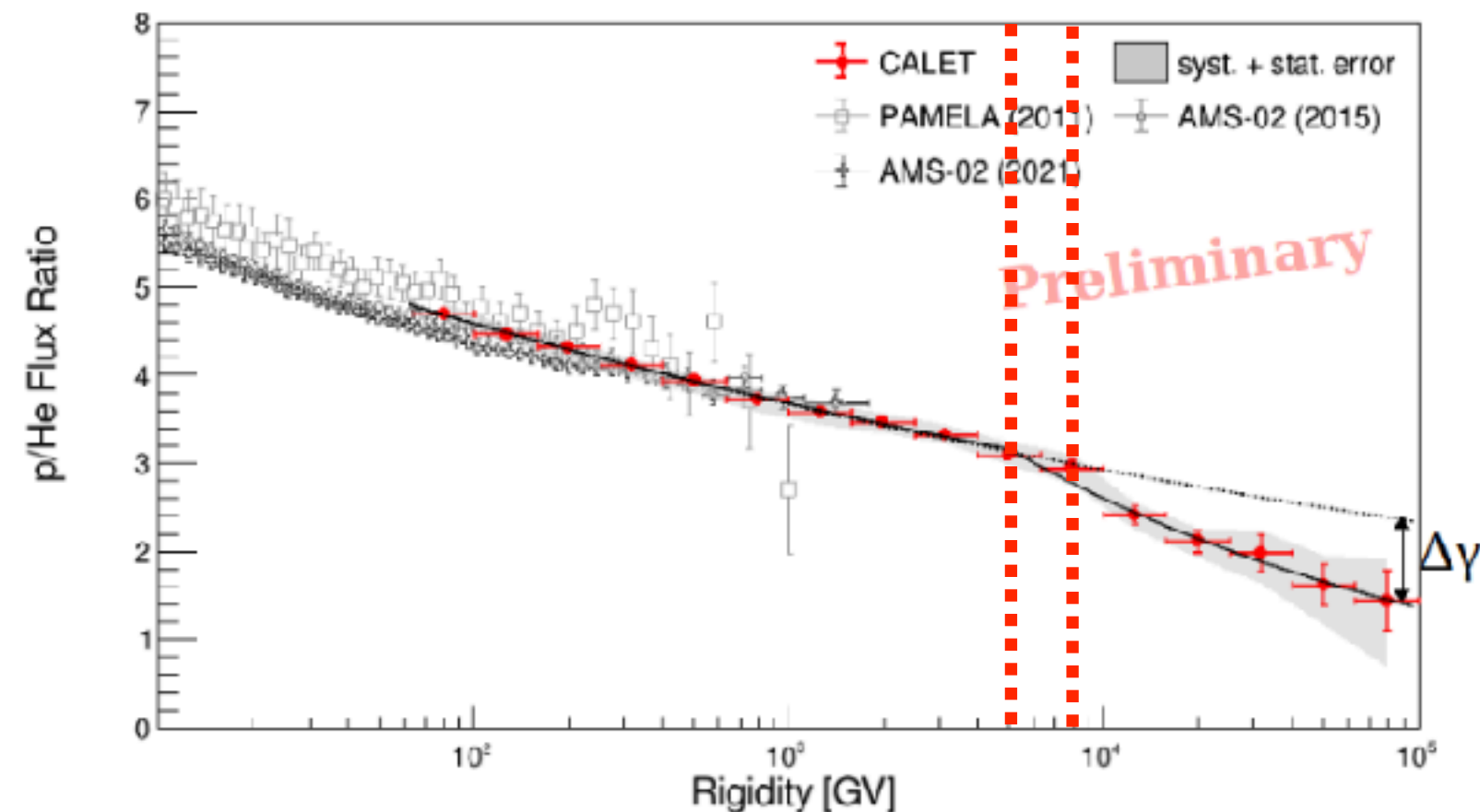
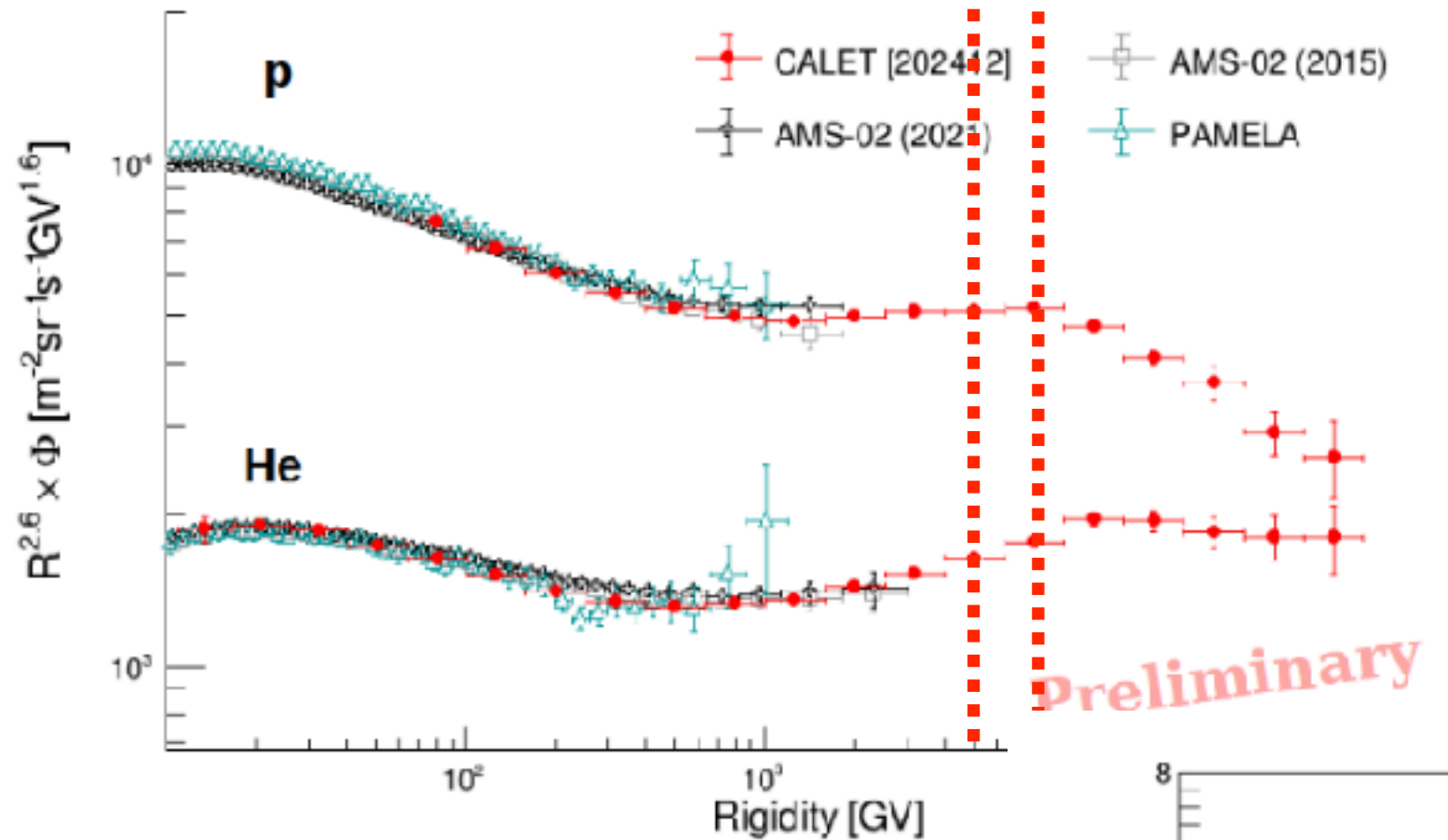
—> this is not transport!

—> what is it? ionisation losses? $dE/dt \sim Z^2 = A$ for H and He

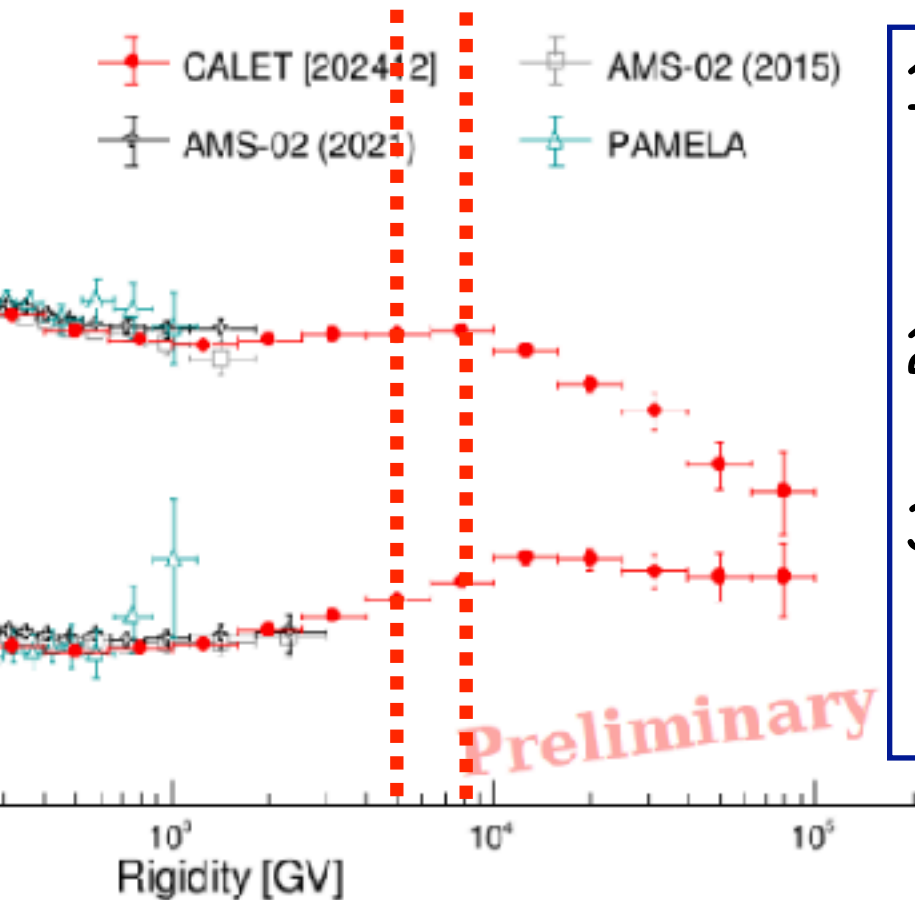
—> is this telling us something?

Other things we don't know

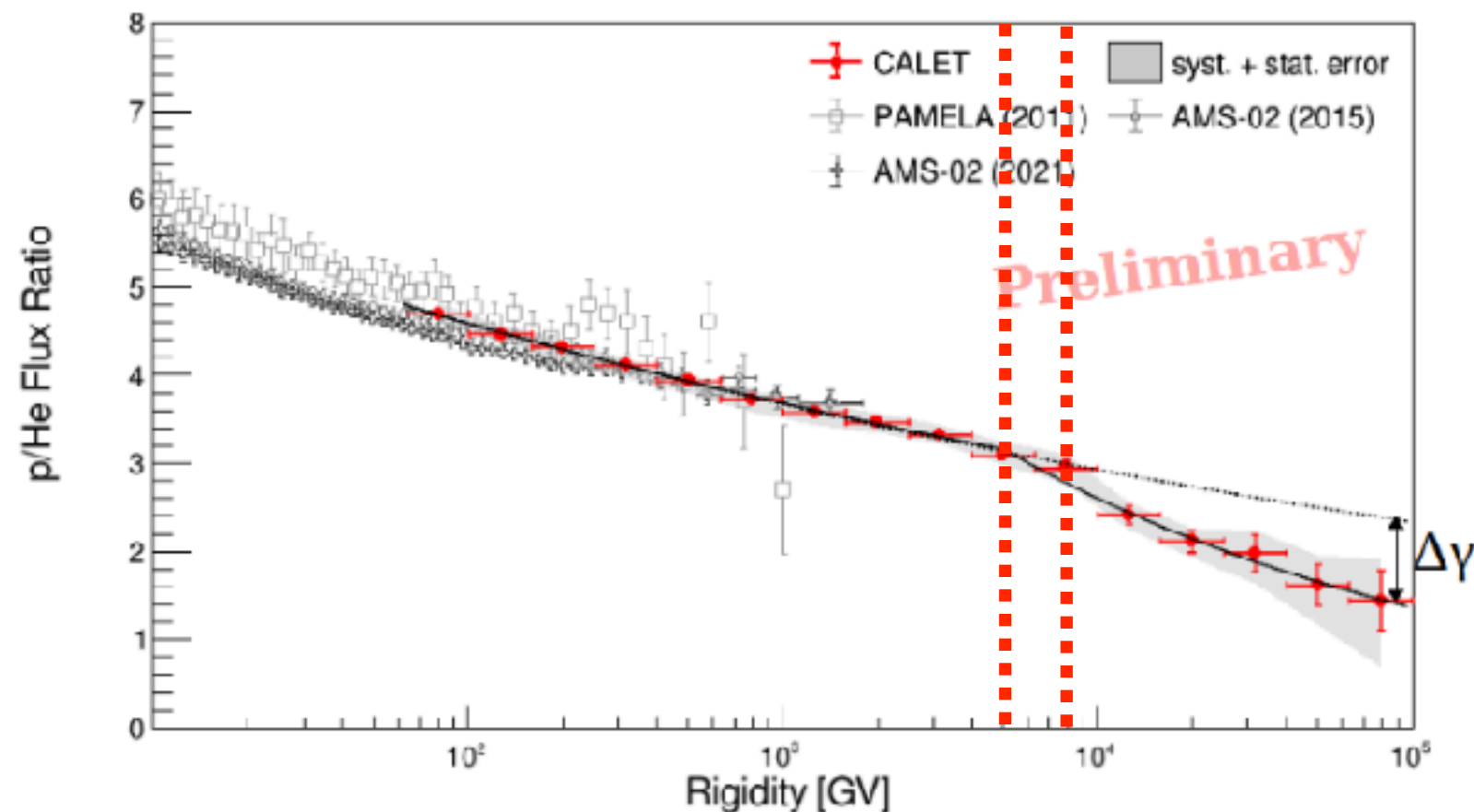
Why H and He spectra are different?



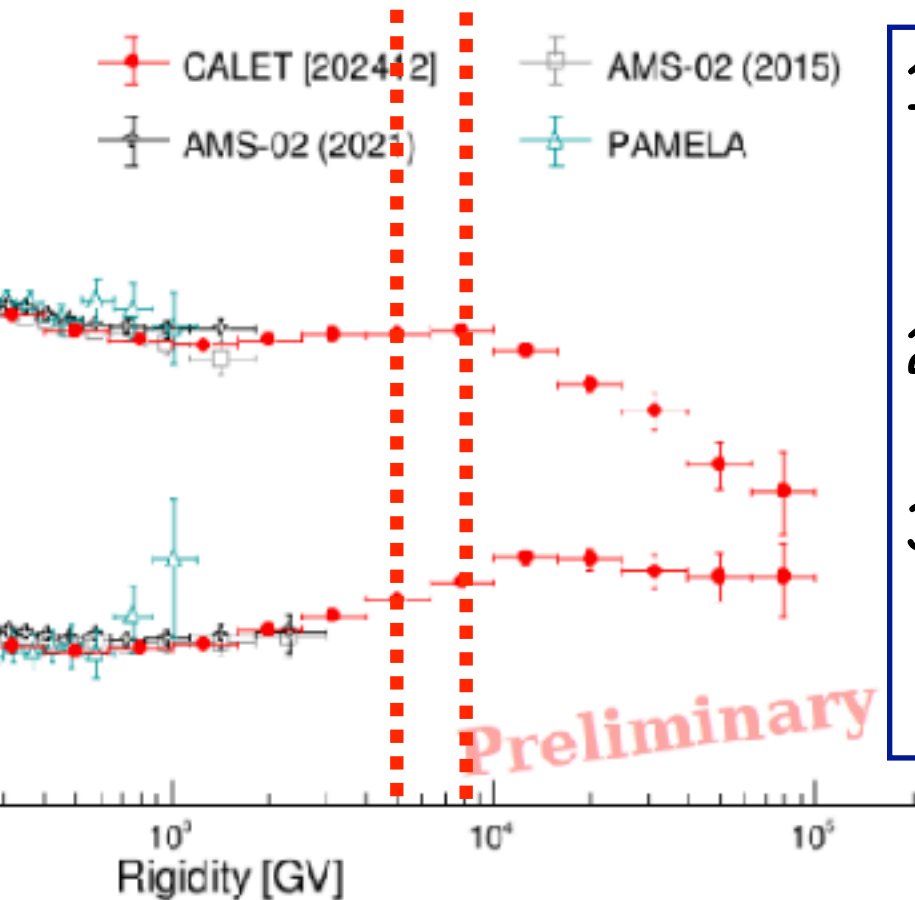
Why H and He spectra are different?



- 1) **He does something that H doesn't**
 → spallation?
 → is it ok with heavier elements? (no)
- 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? (local source in the right environment)

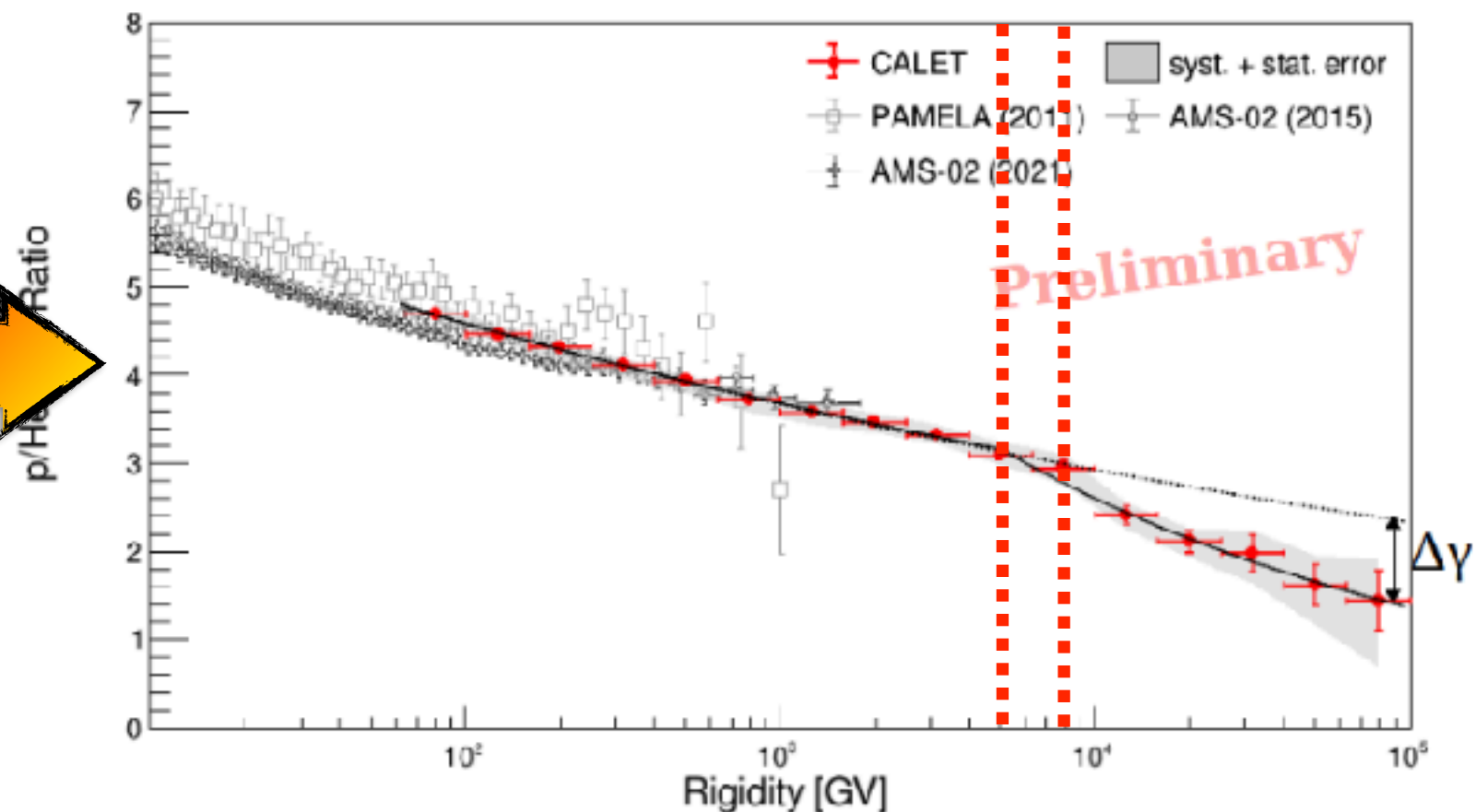
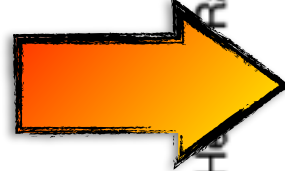


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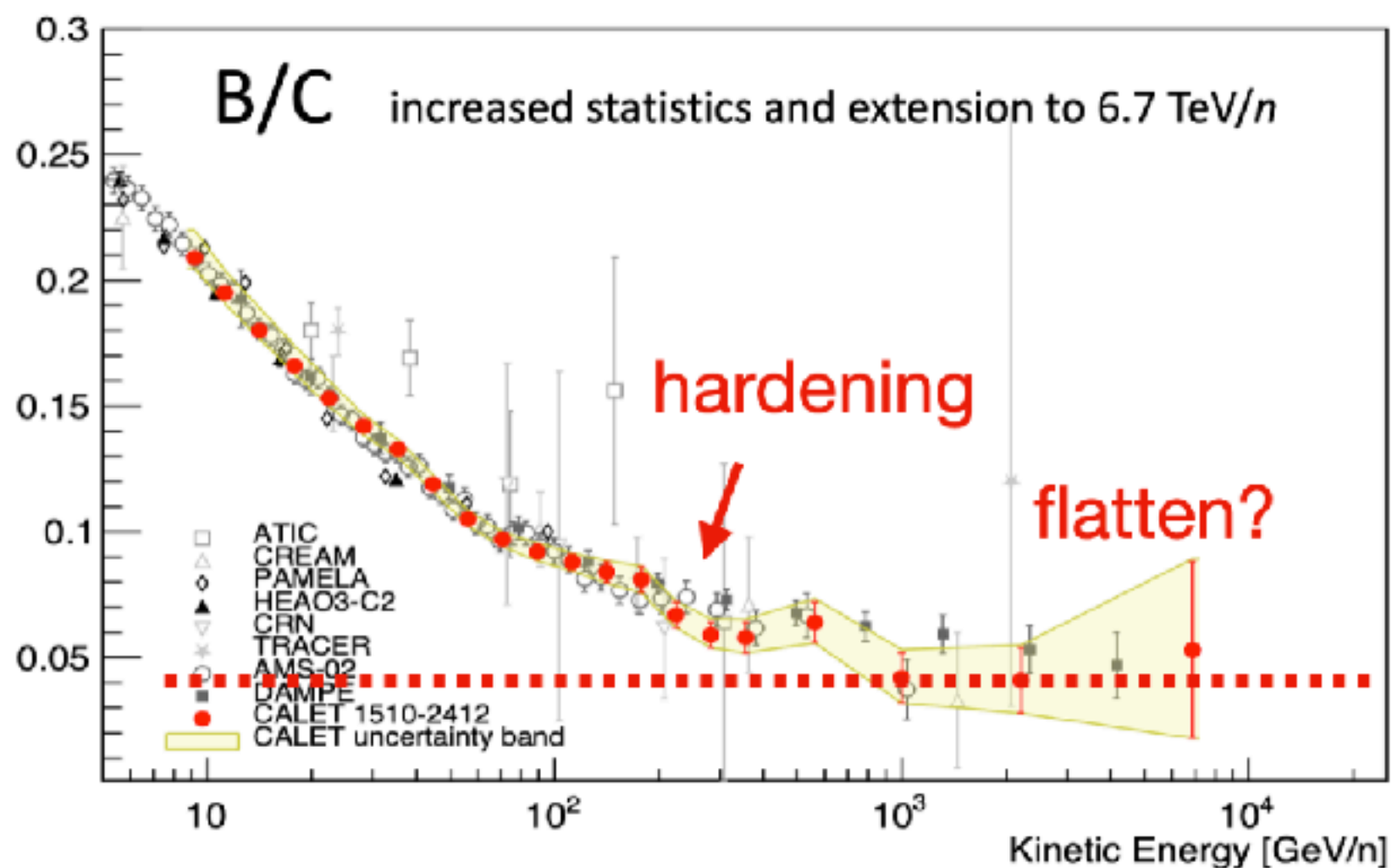


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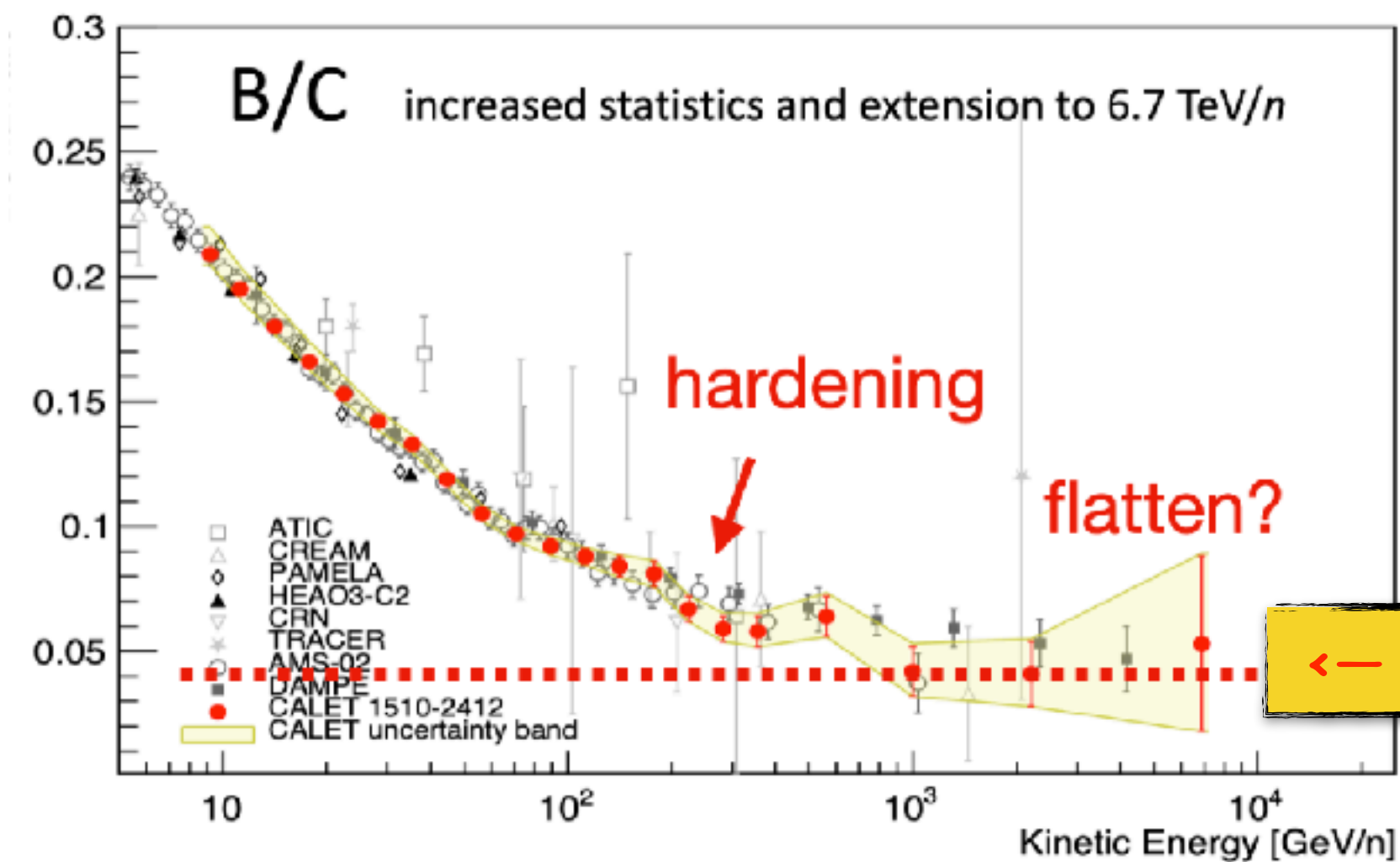
personal opinion:
3 was my favourite,
and after this it is
even more so



Flattening of the B/C at high energies

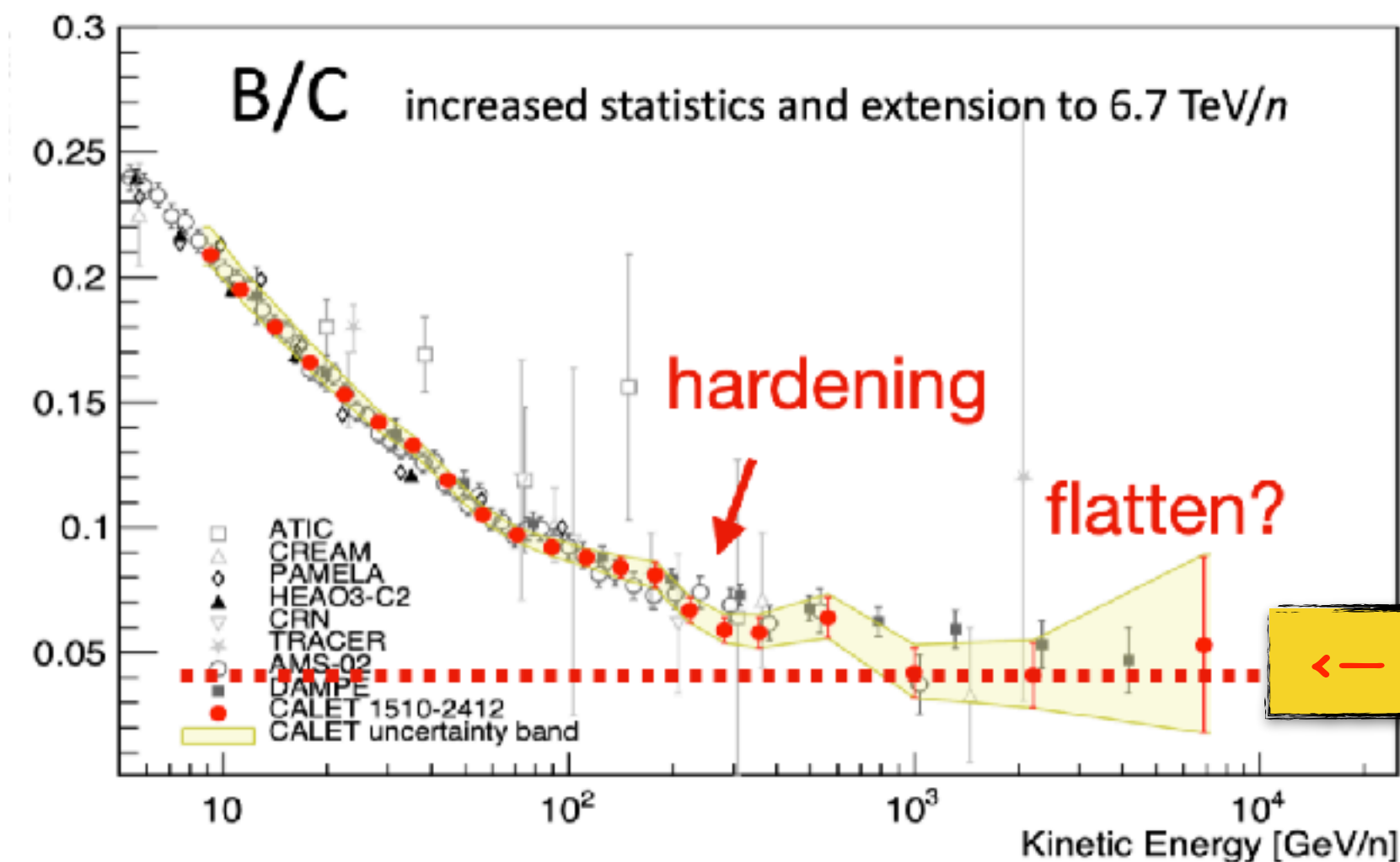


Flattening of the B/C at high energies



← source grammage? d'Angelo+ 16

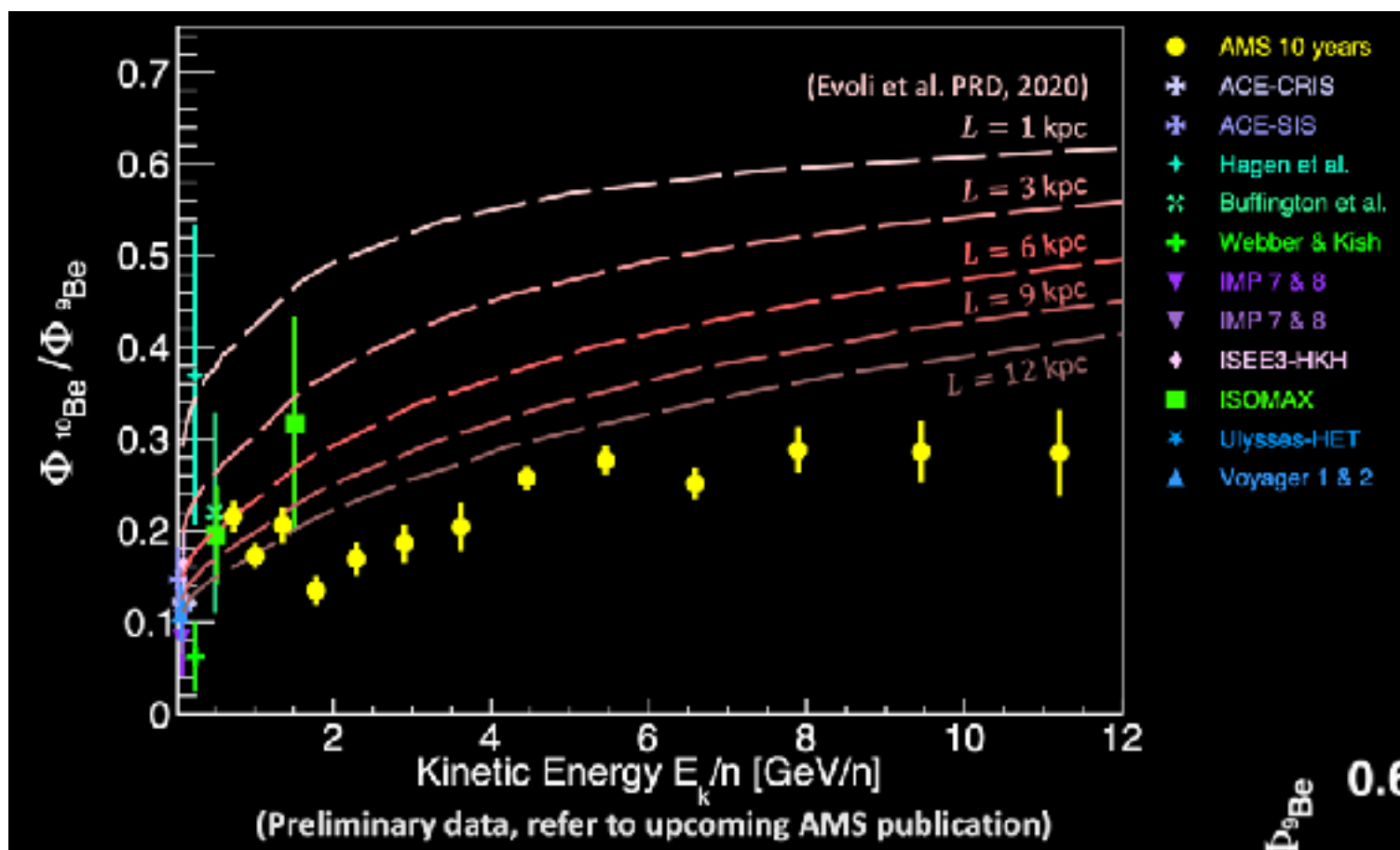
Flattening of the B/C at high energies



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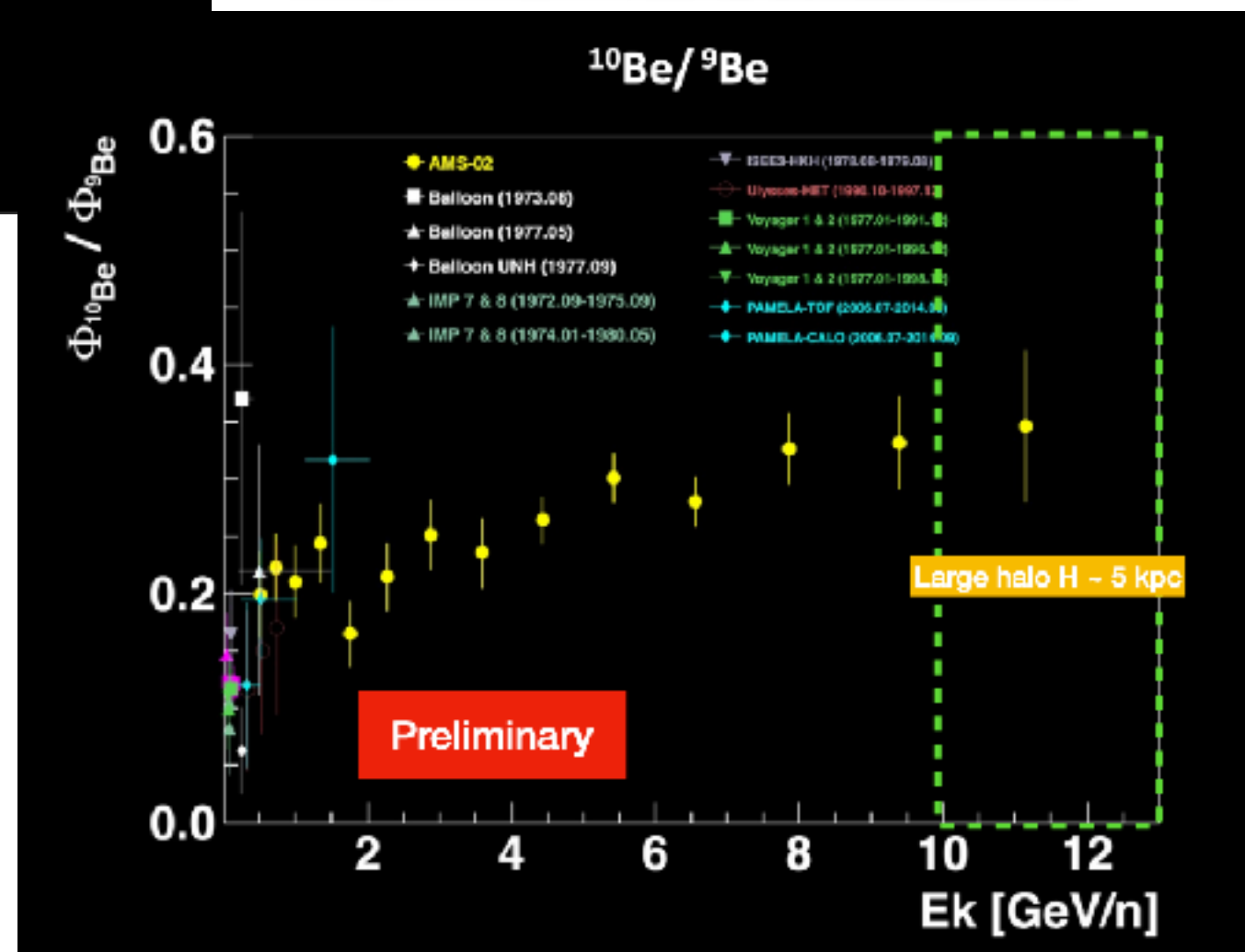
difficult to confine CRs long enough around sources (Nava+ 16, Recchia+ 22)
→ energy independent transport? (Recchia&Gabici 24)

Why is the $^{10}\text{Be}/^9\text{Be}$ so flat/small?

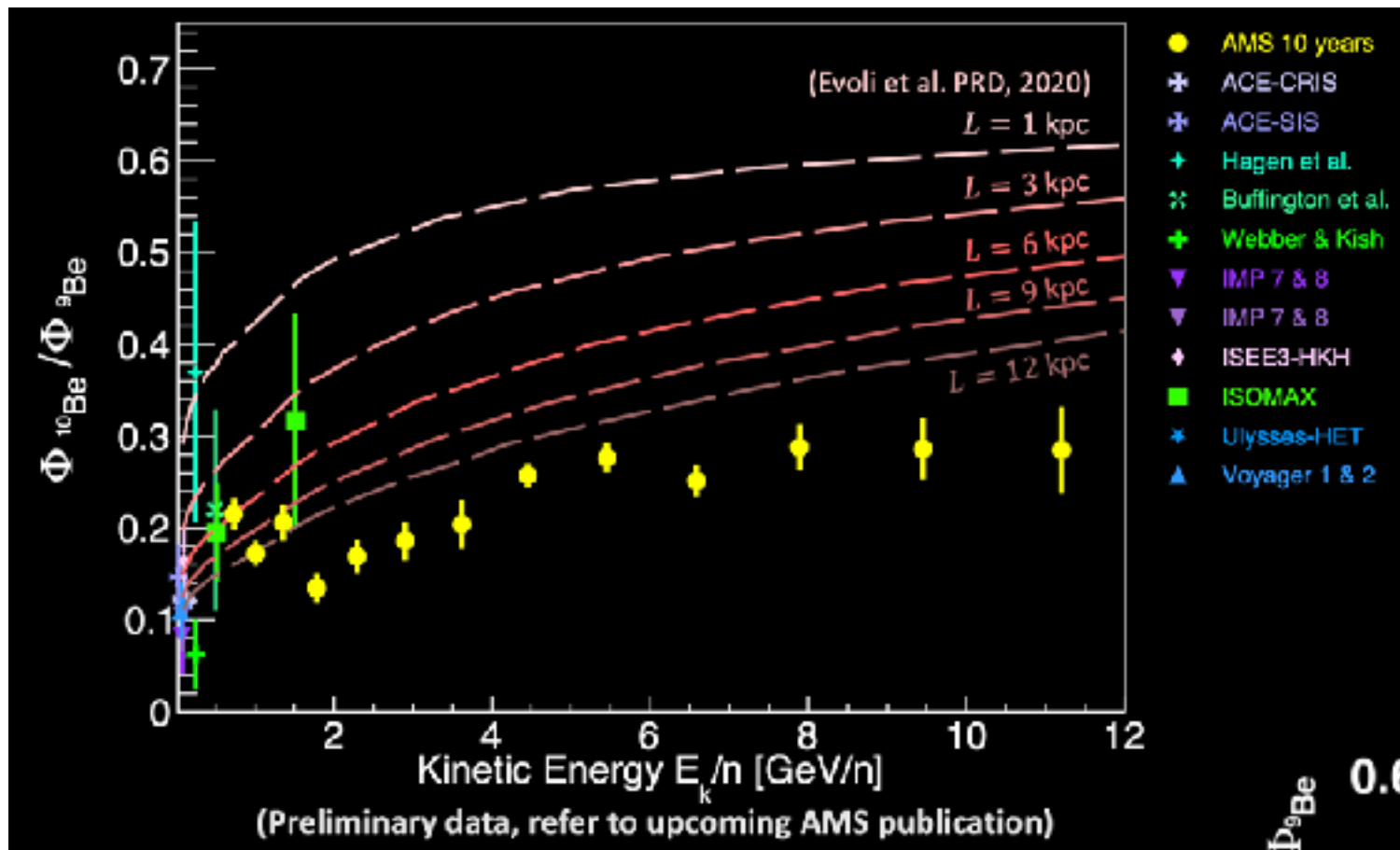


← AMS02 ICRC2023

AMS02 ICRC2025

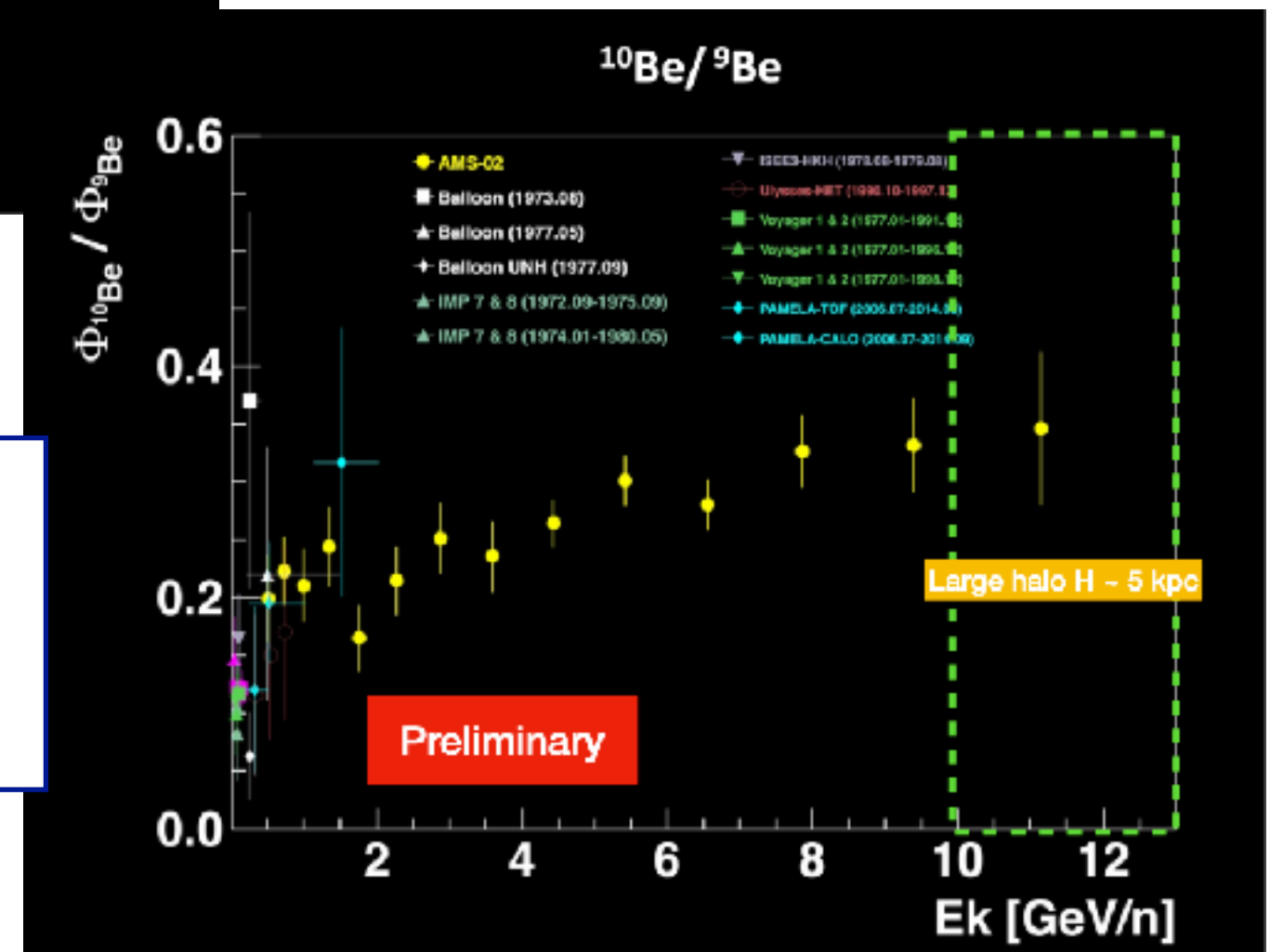


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AMS02 ICRC2025



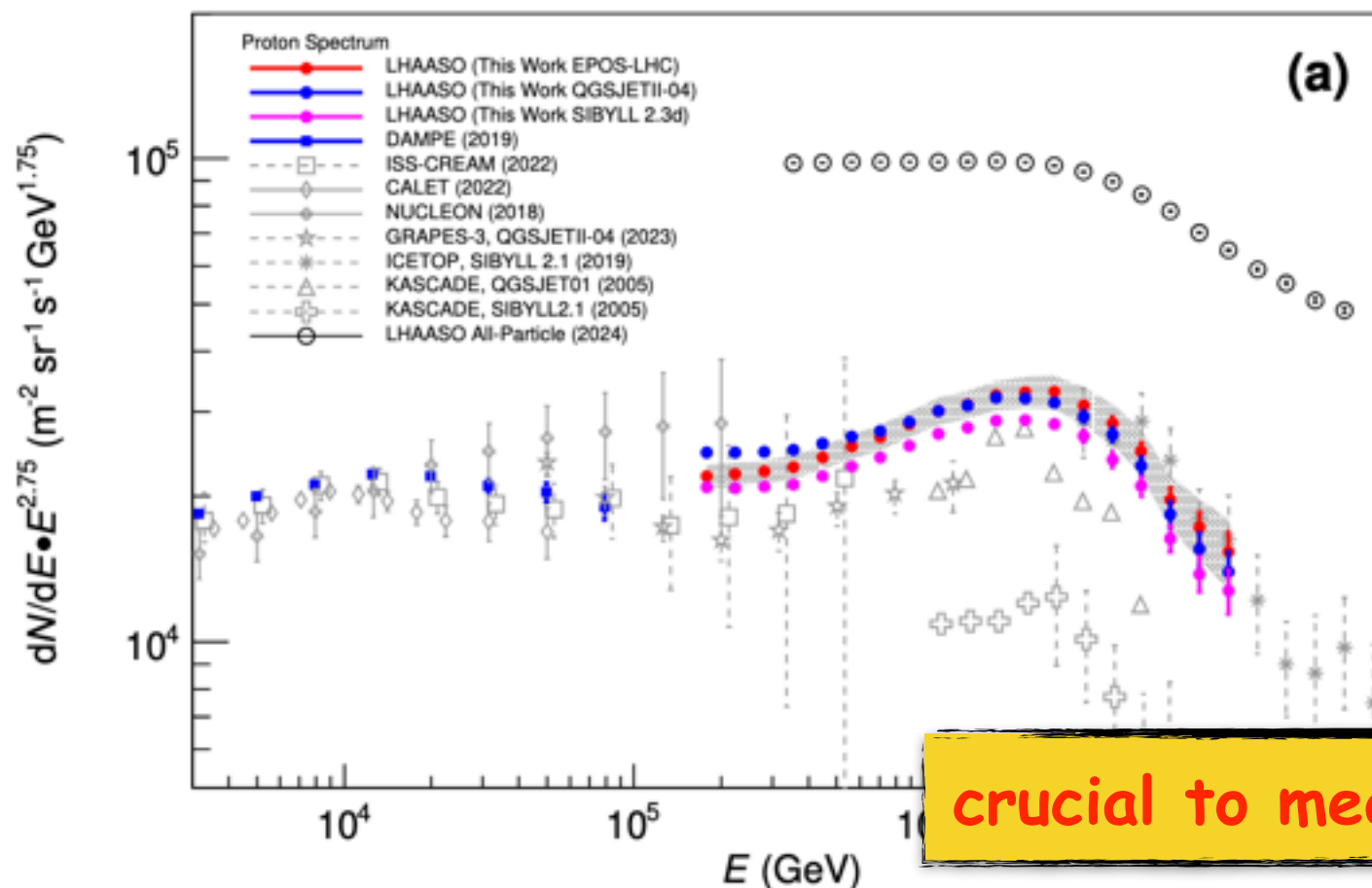
1) **large Galactic halo?**

→ Evoli's rapporteur talk ICRC2025

2) **pockets of slow diffusion in the disk?**

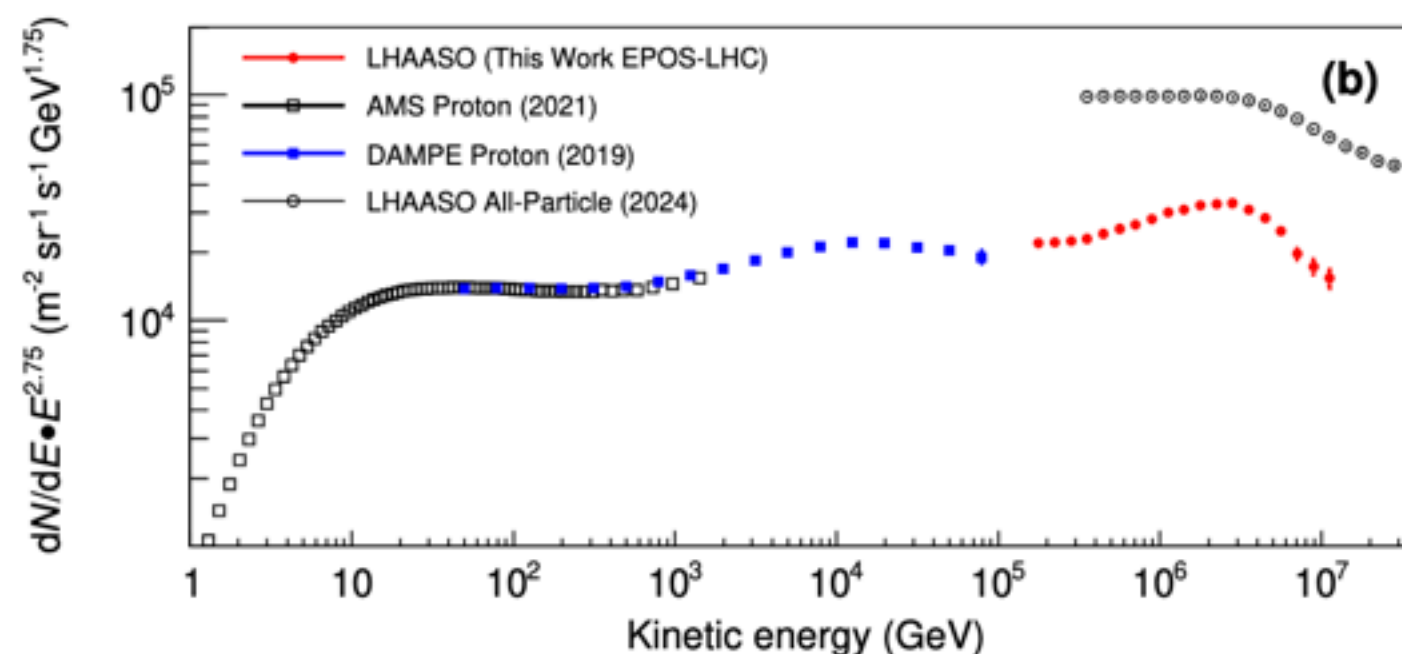
→ Jacobs+ 2023

LHAASO IS OBSERVING THE KNEE!



proton knee ~ all particles knee
protons provide a fraction of it

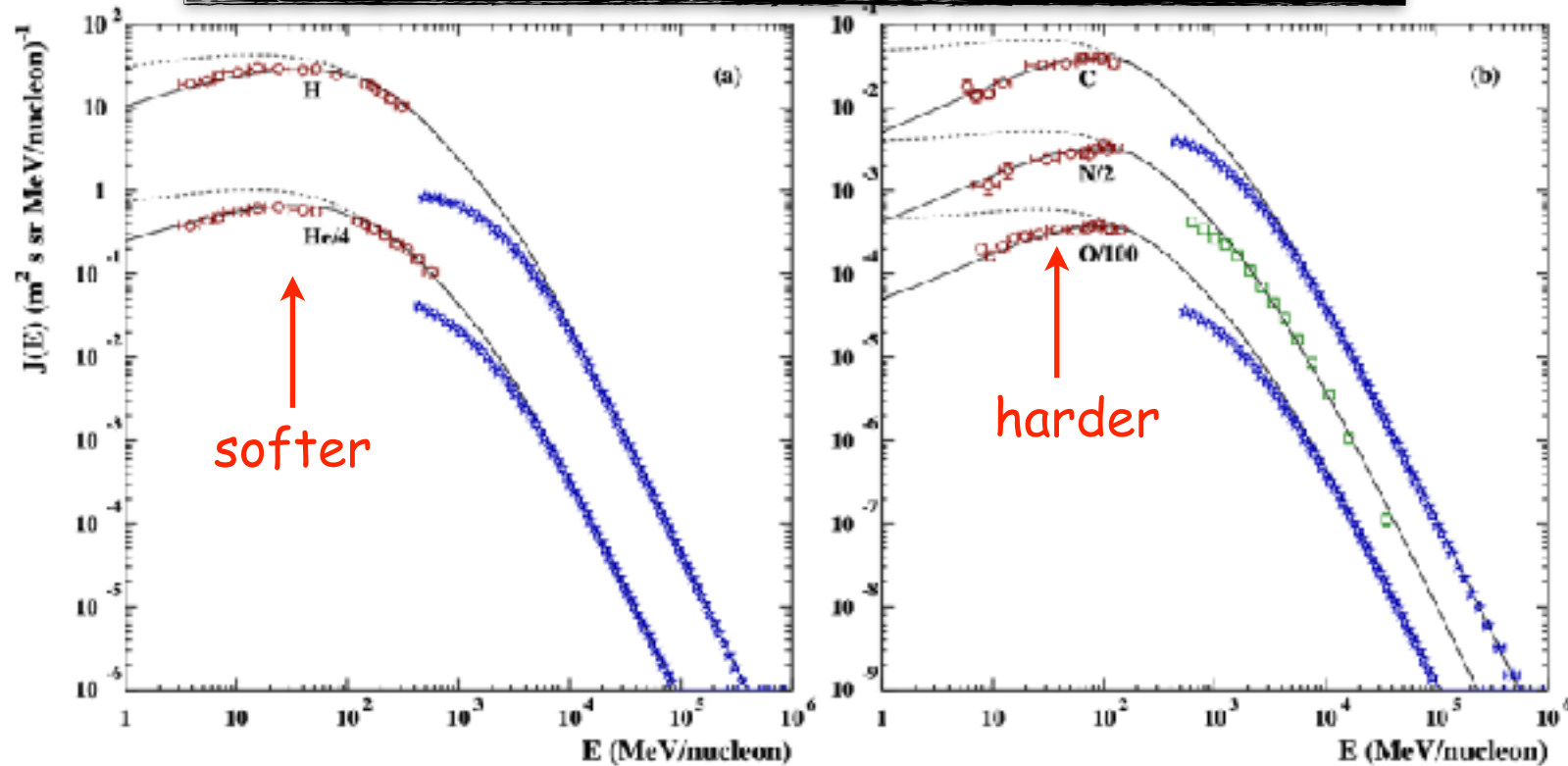
crucial to measure spectra of heavier elements



connection with DAMPE
—> hardening
—> new component?

Why Voyager's (H and He) spectra are different from other elements' spectra?

different injection spectra needed

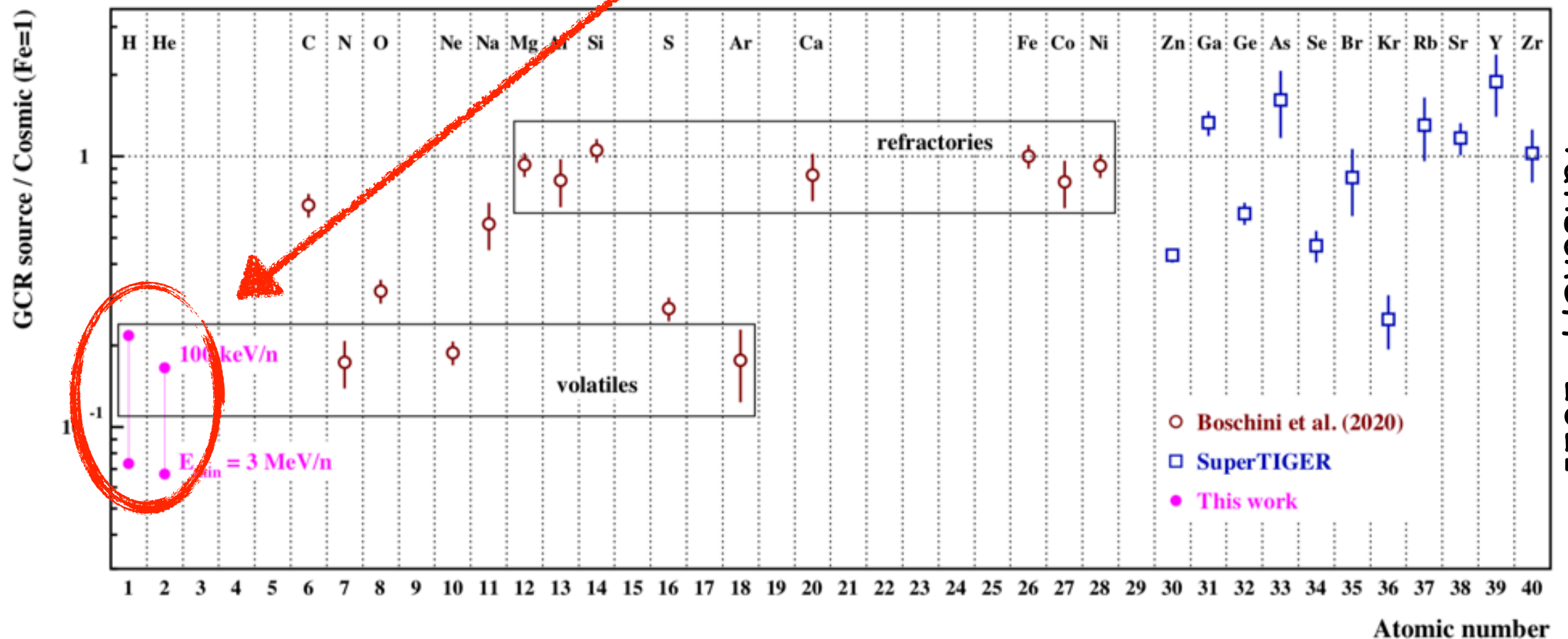
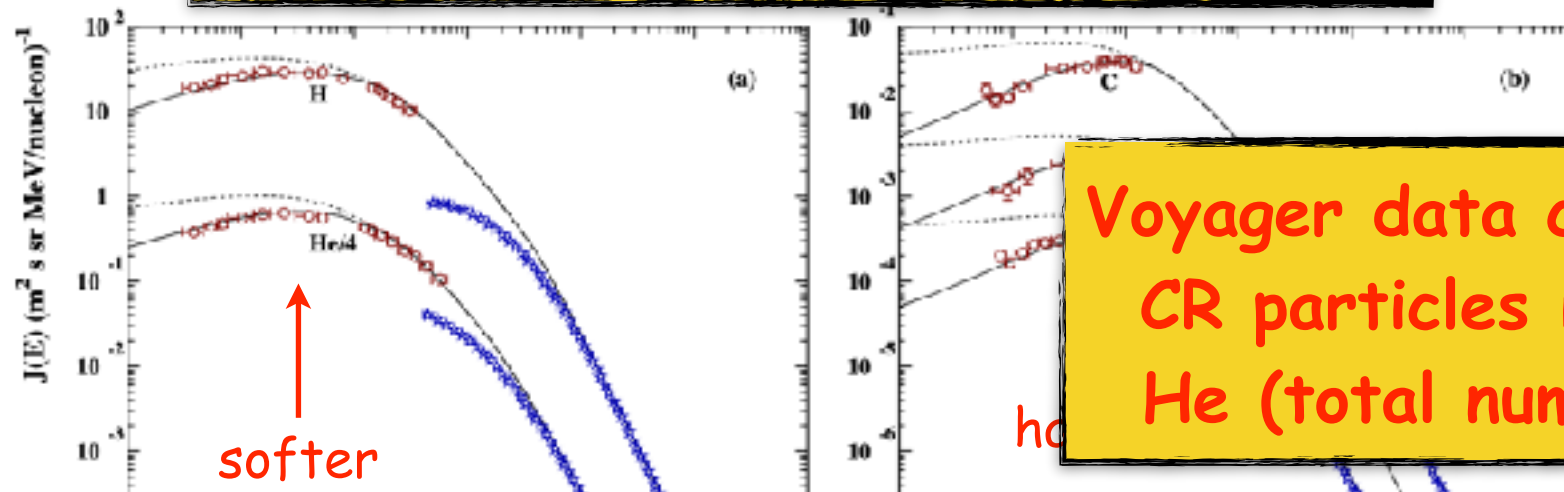


Why Voyager's (H and He) spectra are different from other elements' spectra?

different injection spectra needed

Voyager data constrain the total amount of CR particles injected EXCEPT for H and He (total number diverge for $E_{\min} \rightarrow 0$)

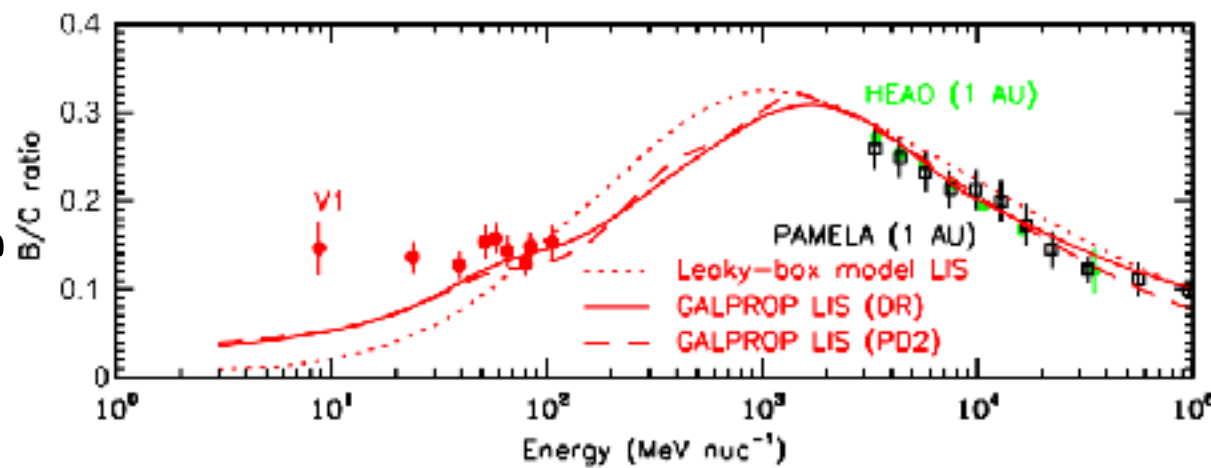
Tatischeff&Gabici 2018



Tatischeff+ 2021

Why is Voyager's B/C so flat?*

Cummings+ 2016



Webber+ 2016

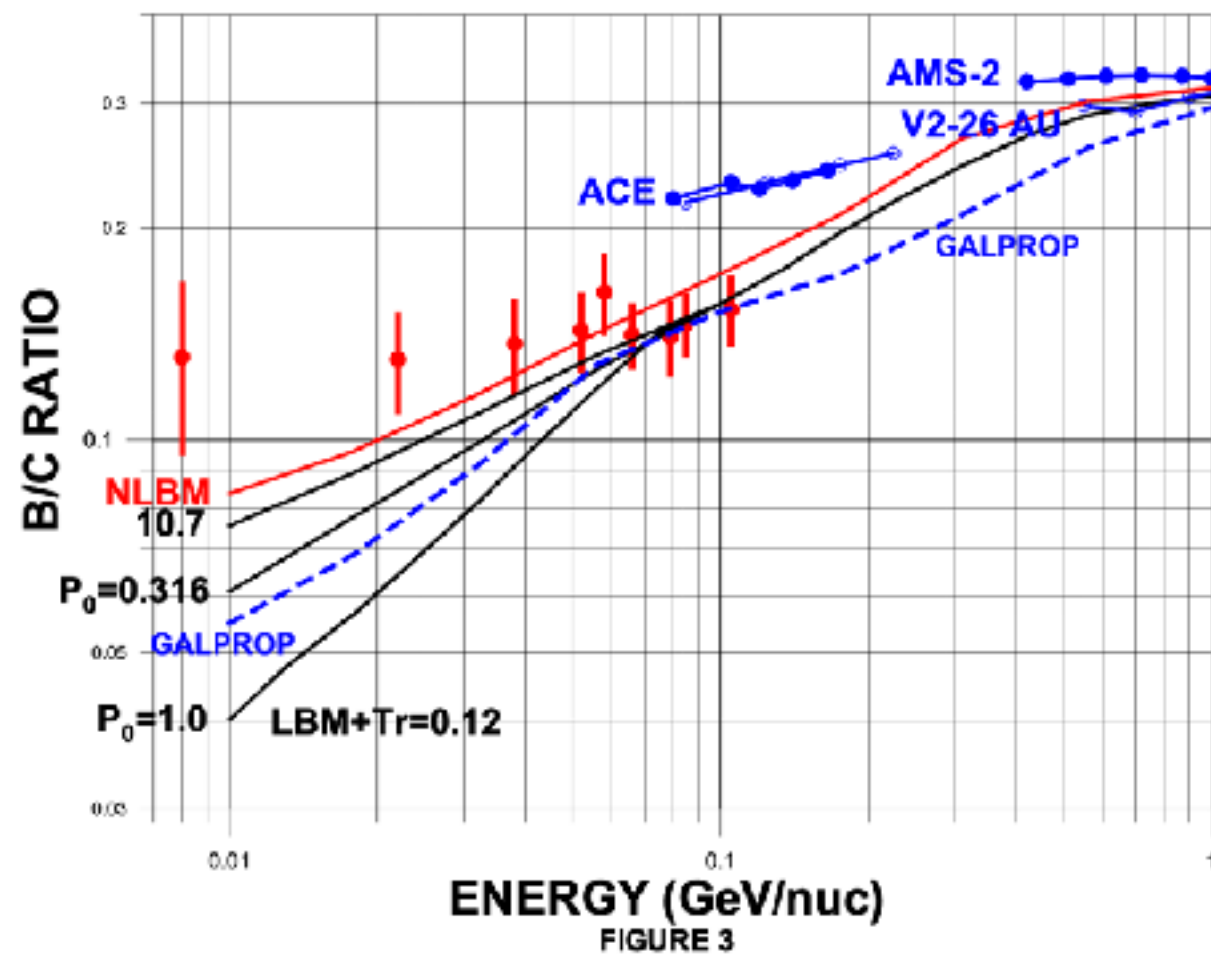
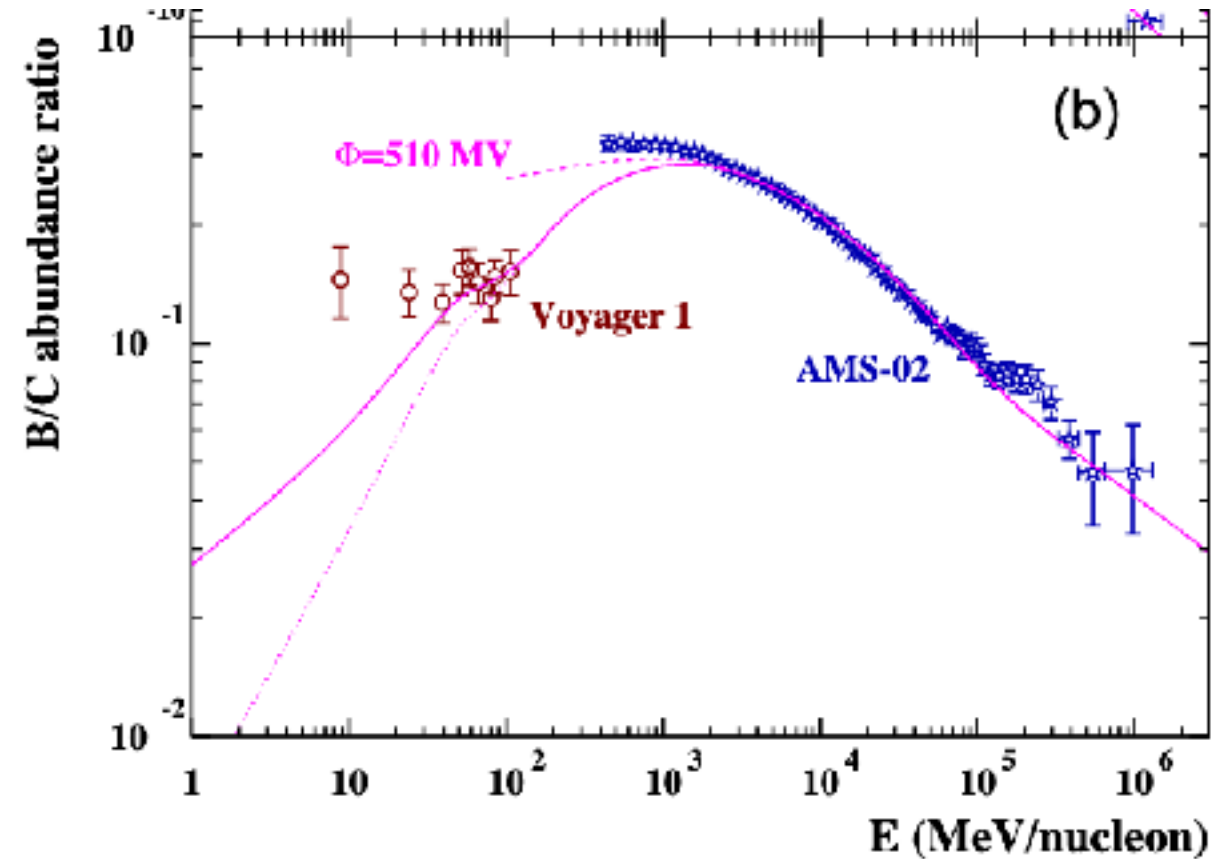


FIGURE 3

I wouldn't call these good fits...

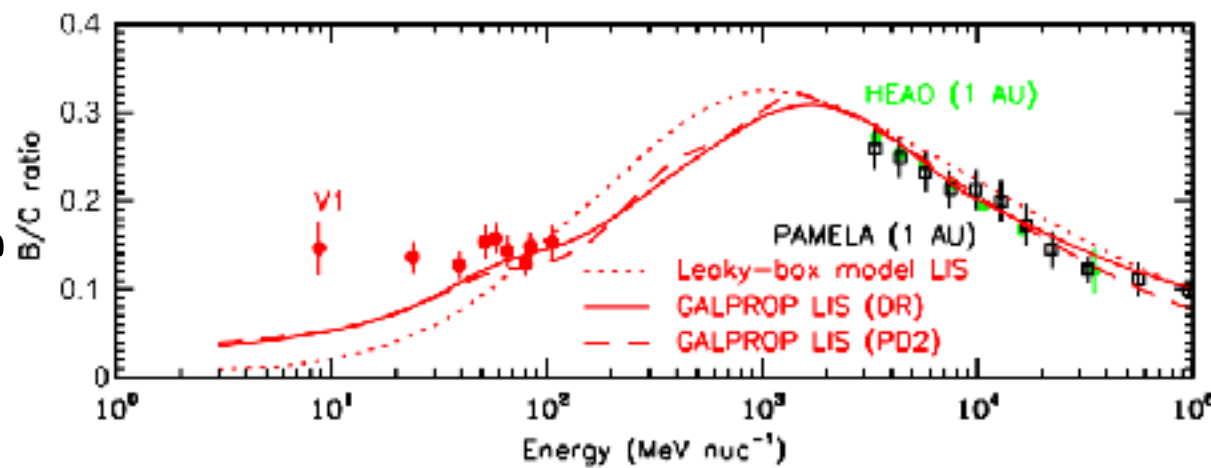


Tatischeff+ 2021

*it is an excess of B

Why is Voyager's B/C so flat?*

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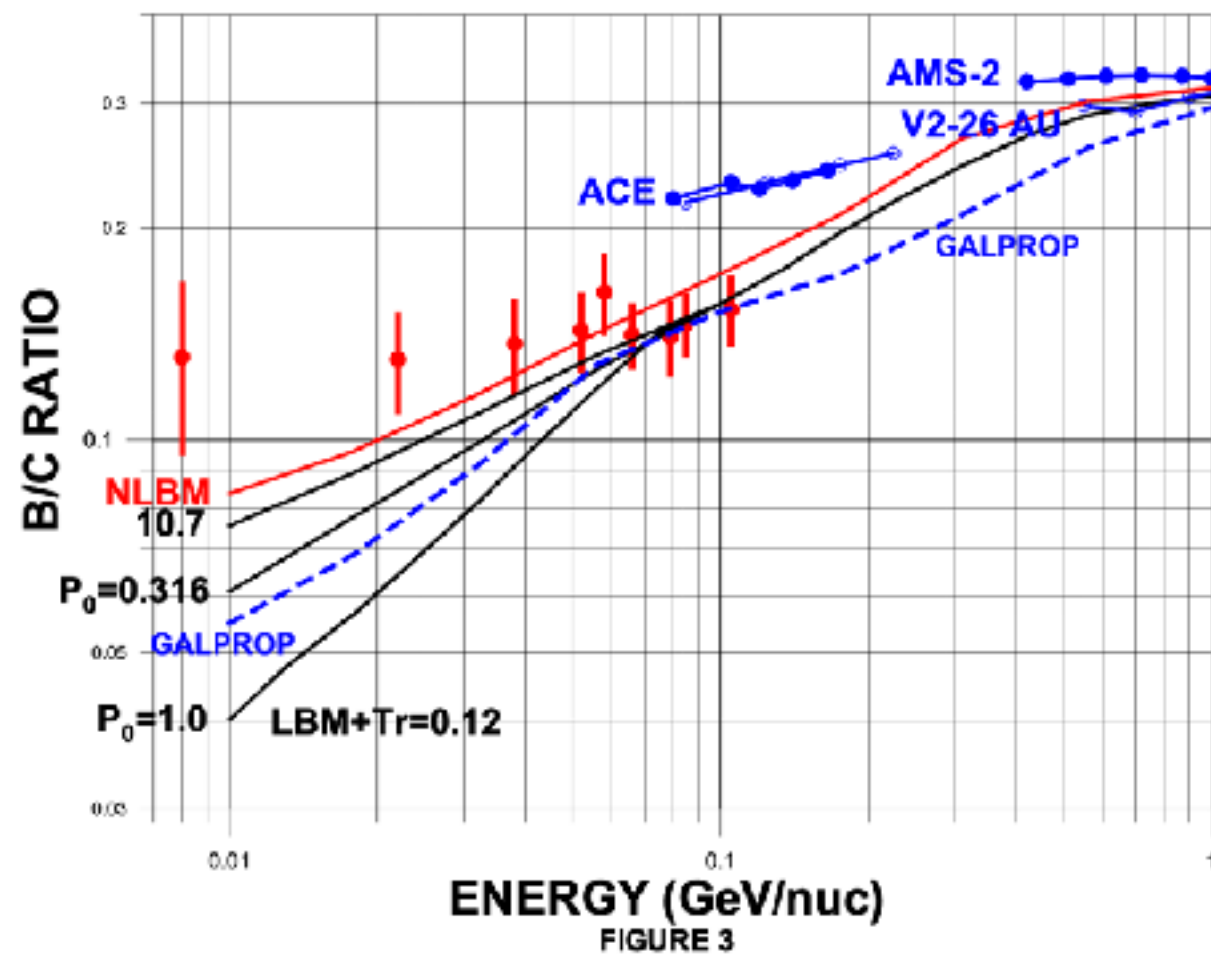
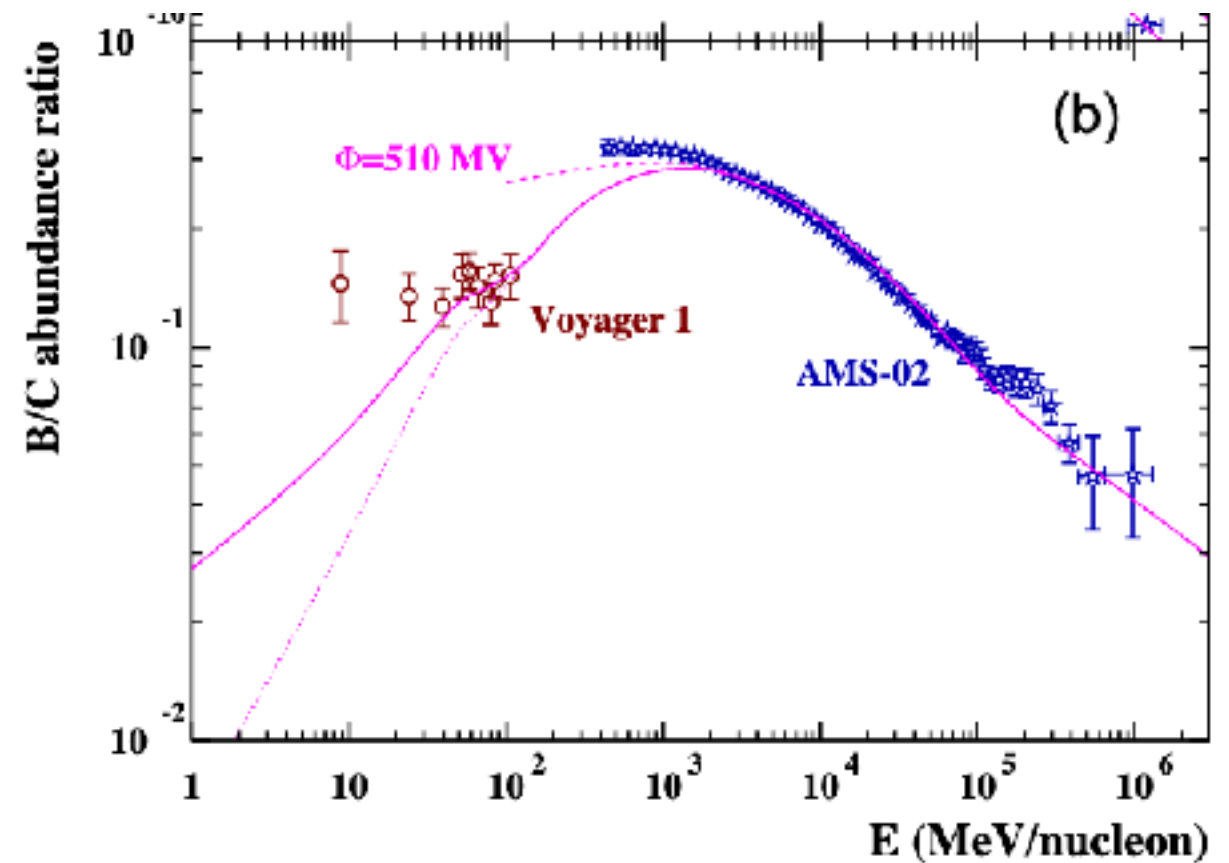


FIGURE 3

Tatischeff+ 2021



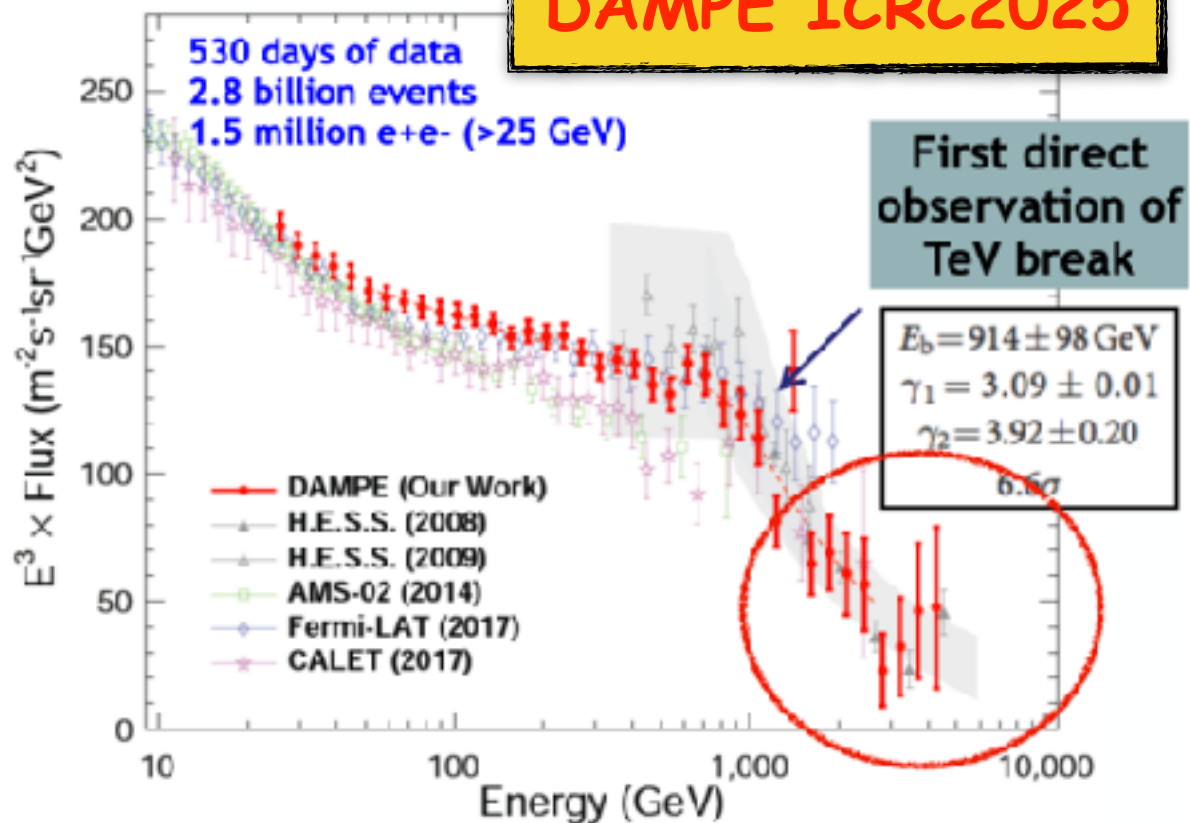
“global” models for CR propagation
(uniform “jelly” of sources)
—> discrete sources or local effects?

I wouldn't call these good fits...

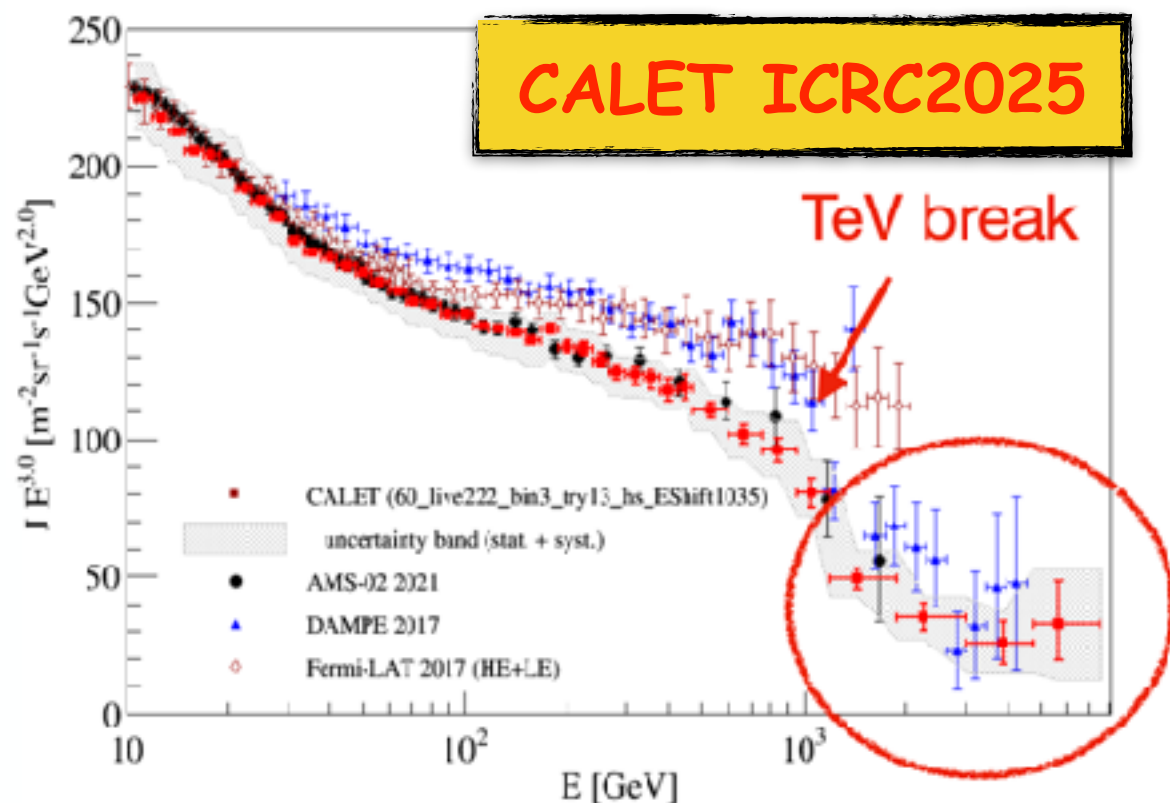
*it is an excess of B

Who accelerates CR electrons?

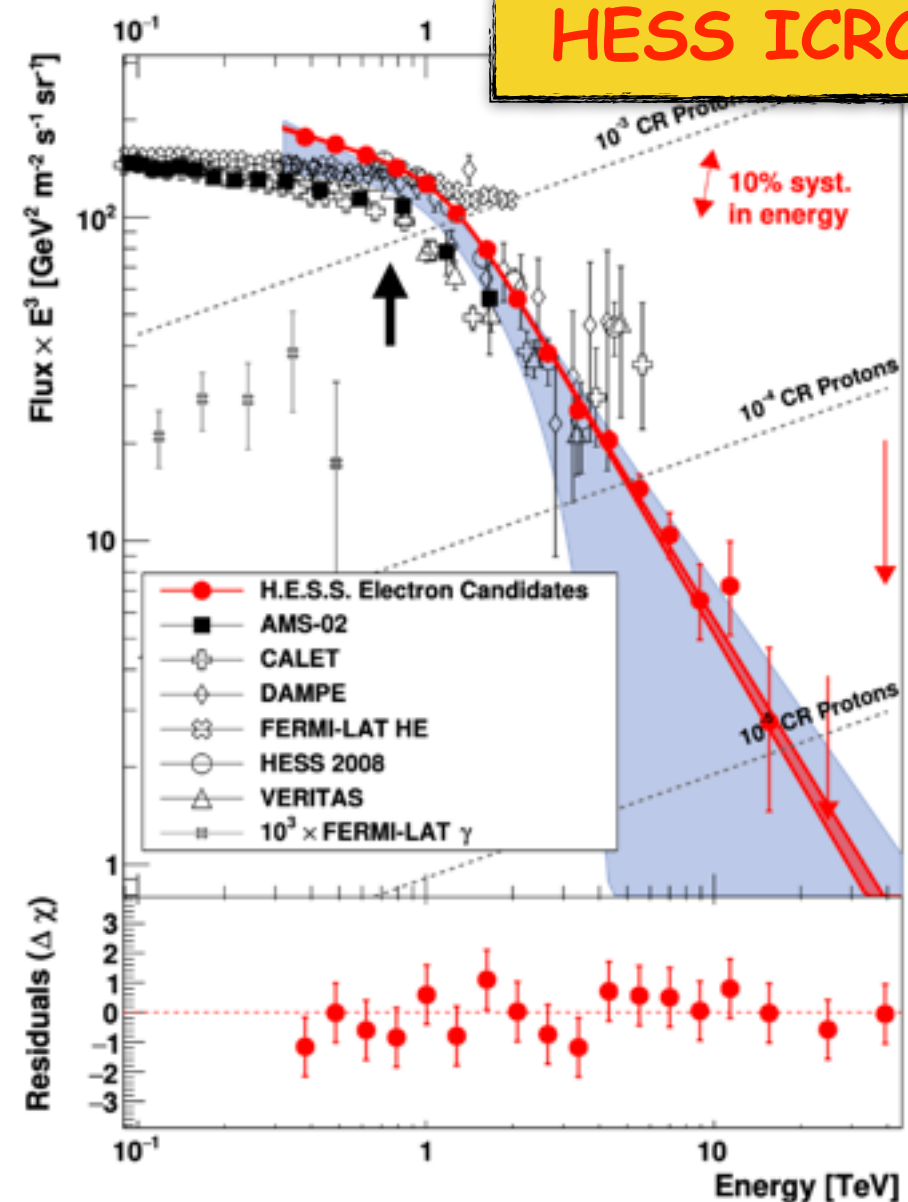
DAMPE ICRC2025



CALET ICRC2025

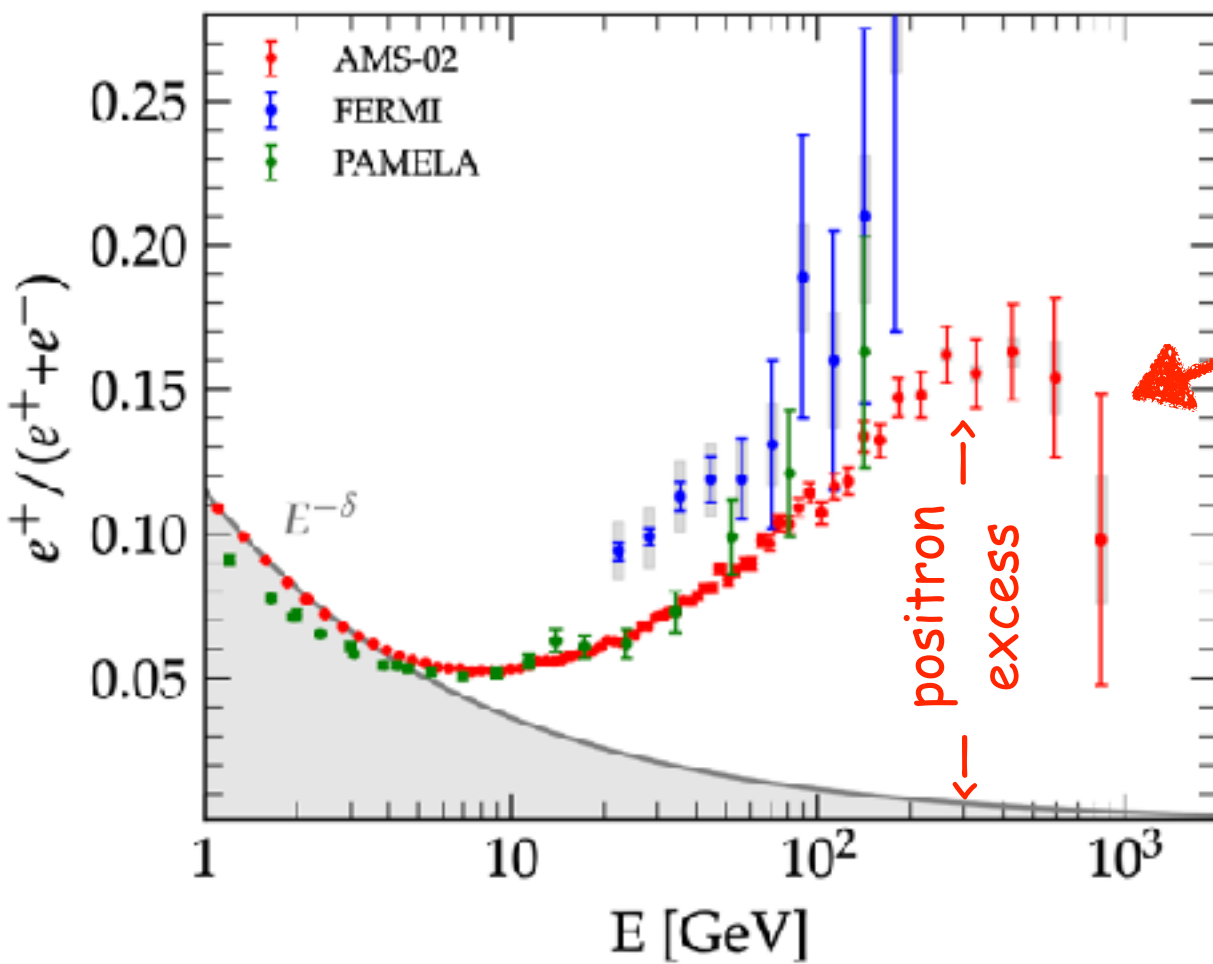


HESS ICRC2025



- > most prominent feature in CR spectra
- > origin of the break debated
- > **actually, do we know where are CR electrons from?**

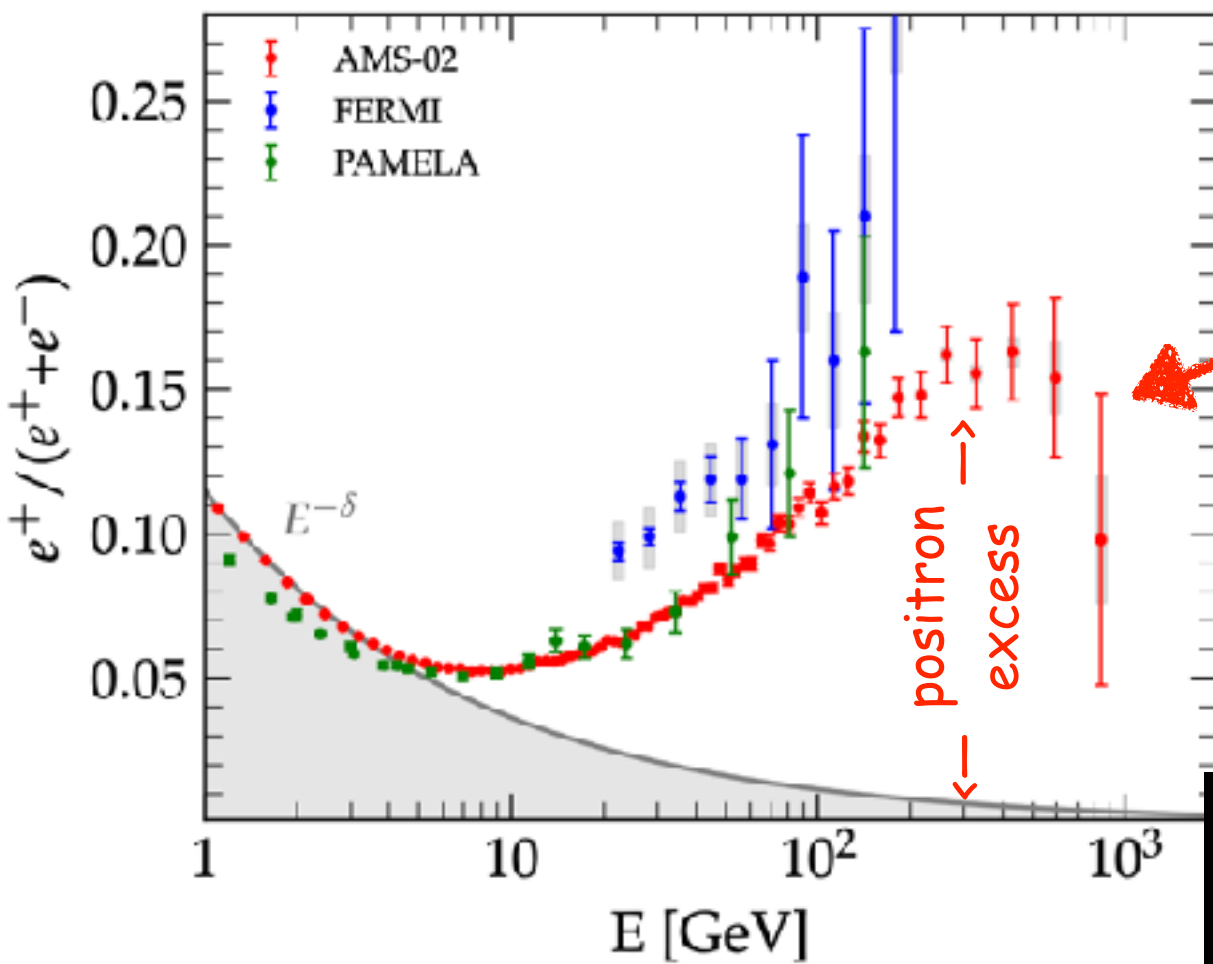
Antimatter, anisotropies...



pulsars likely candidates, need to extend to larger energies to test competing model based on dark matter

Evoli, ICRC 2025 rapporteur

Antimatter, anisotropies...

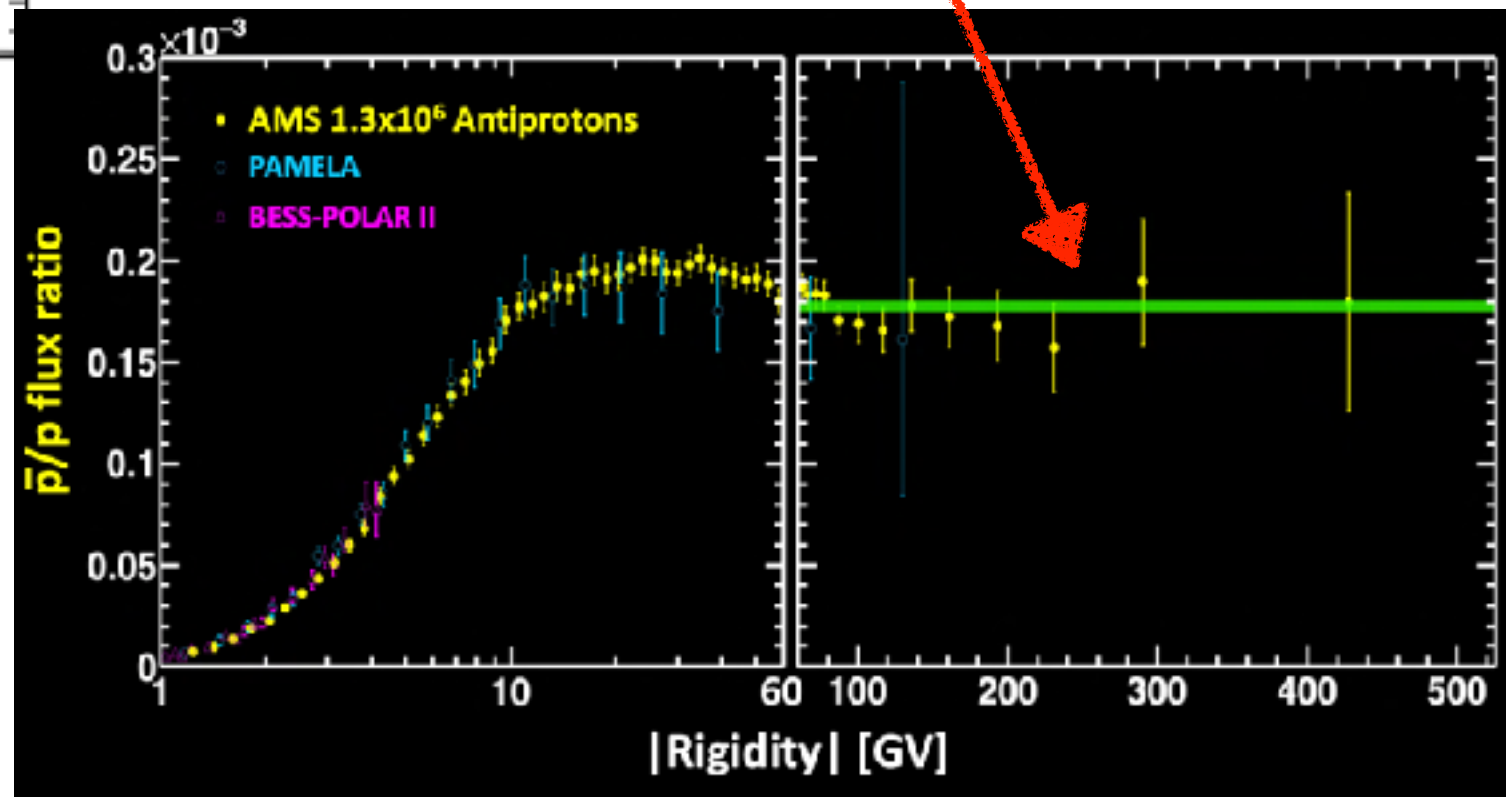


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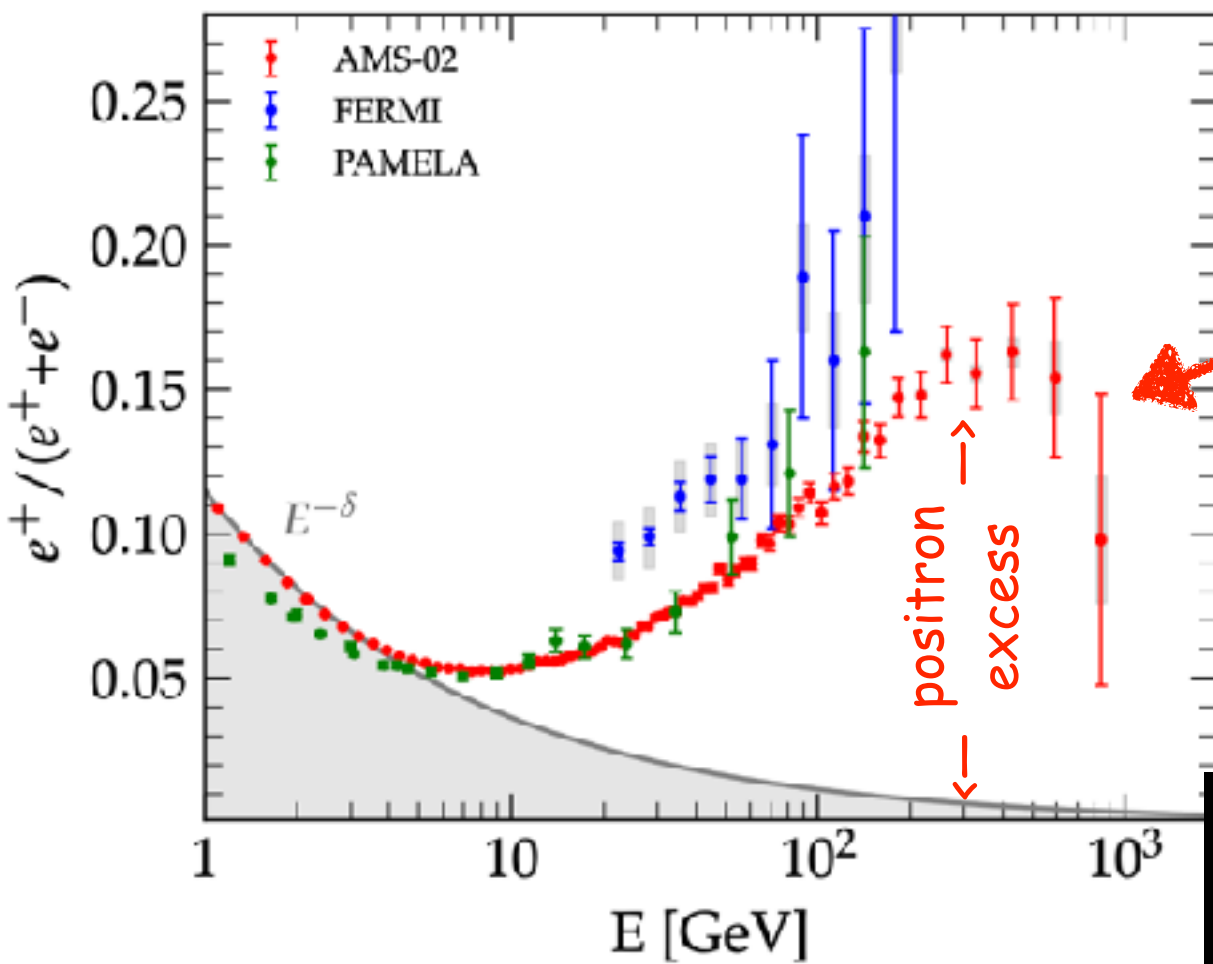
difficult to explain why this is flat

Evoli, ICRC 2025 rapporteur

AMS02, ICRC 2025



Antimatter, anisotropies...

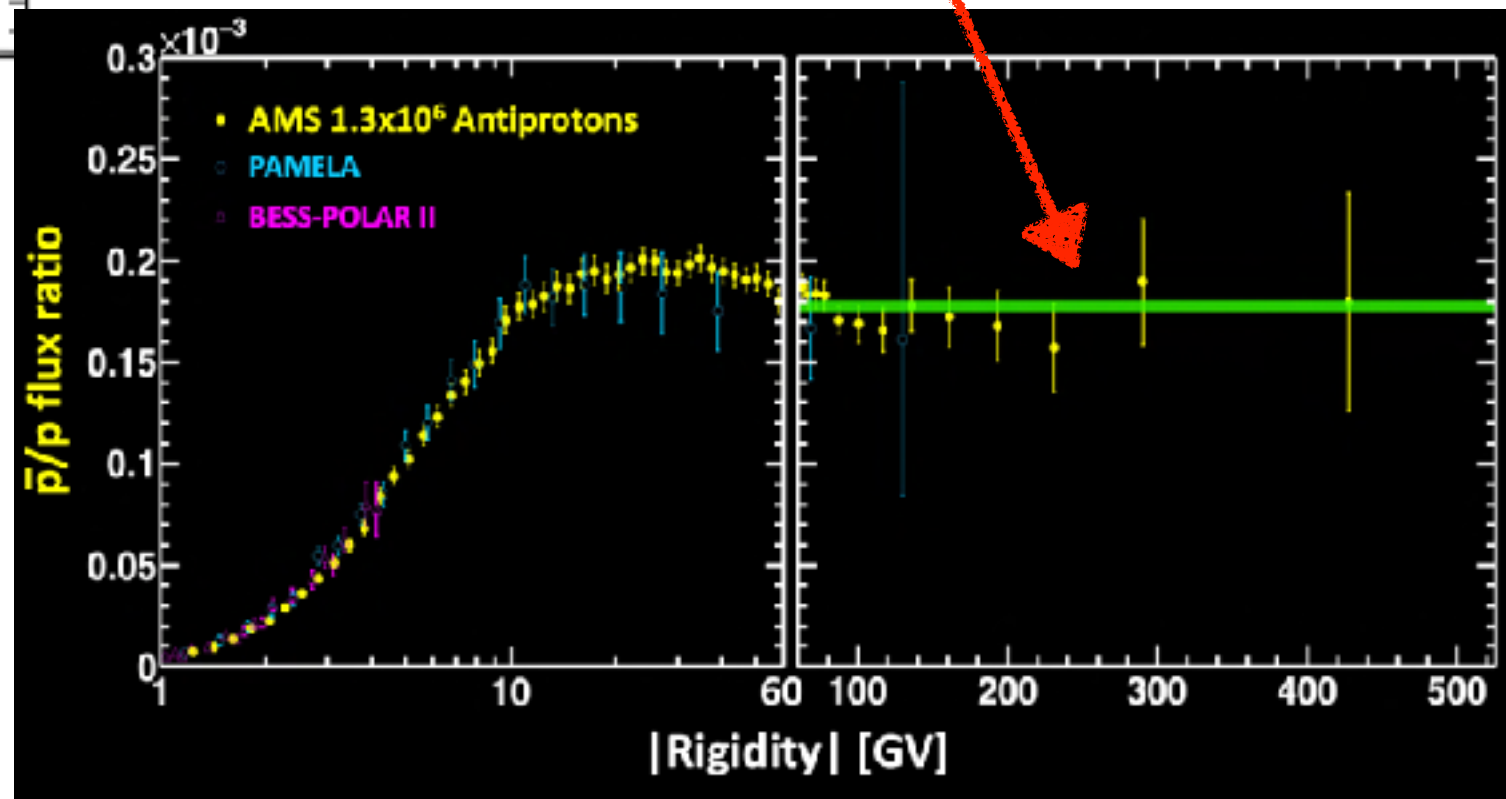


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AMS02, ICRC 2025

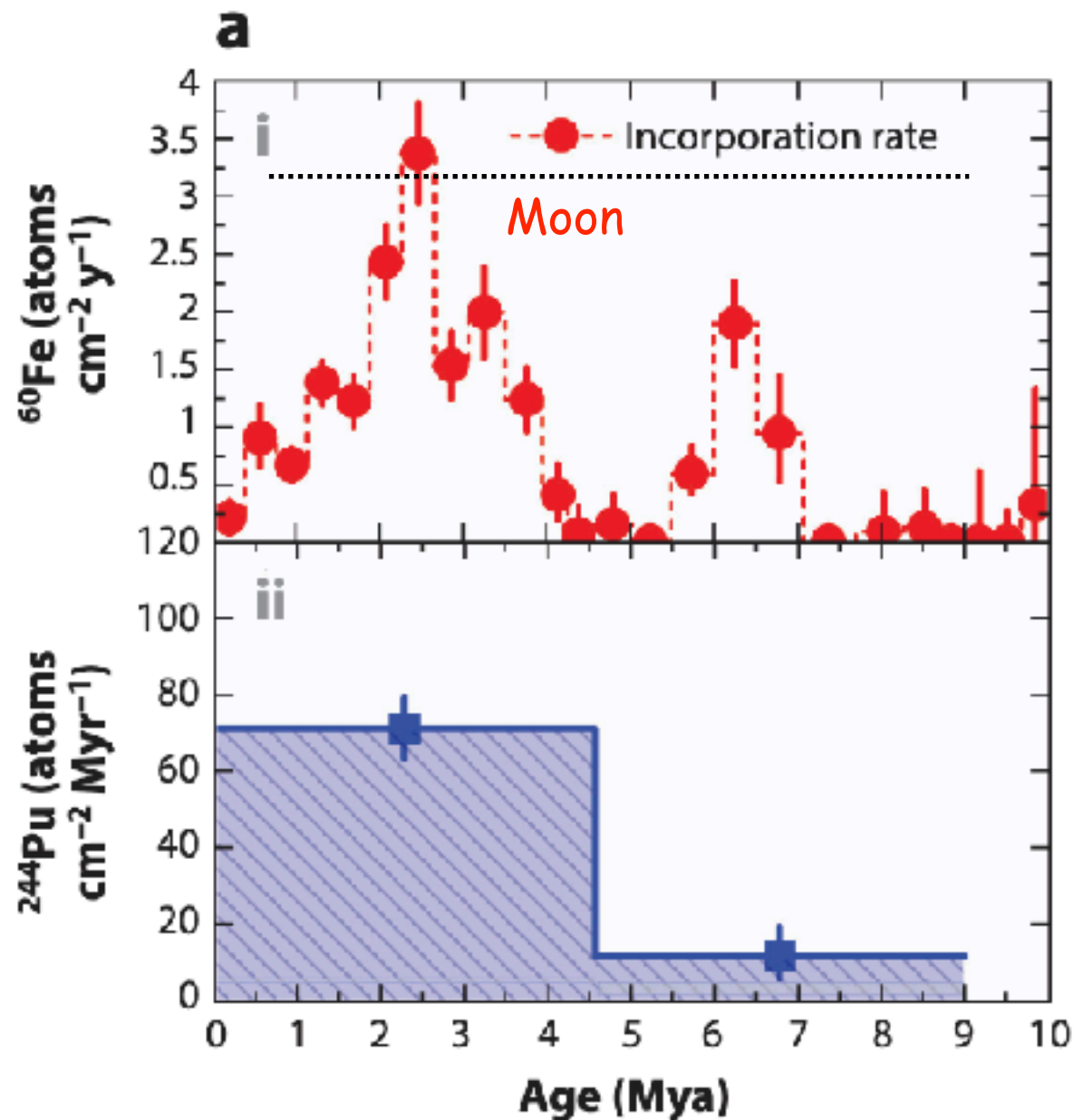


rapporteur ICRC2023(me)/2025(Carmelo): nothing to report on anisotropies, WHY?

**Pinpoint cosmic ray sources
in our neighbourhood**

^{60}Fe in the bottom of the ocean, on the Moon and in cosmic rays

Binns+ 2016

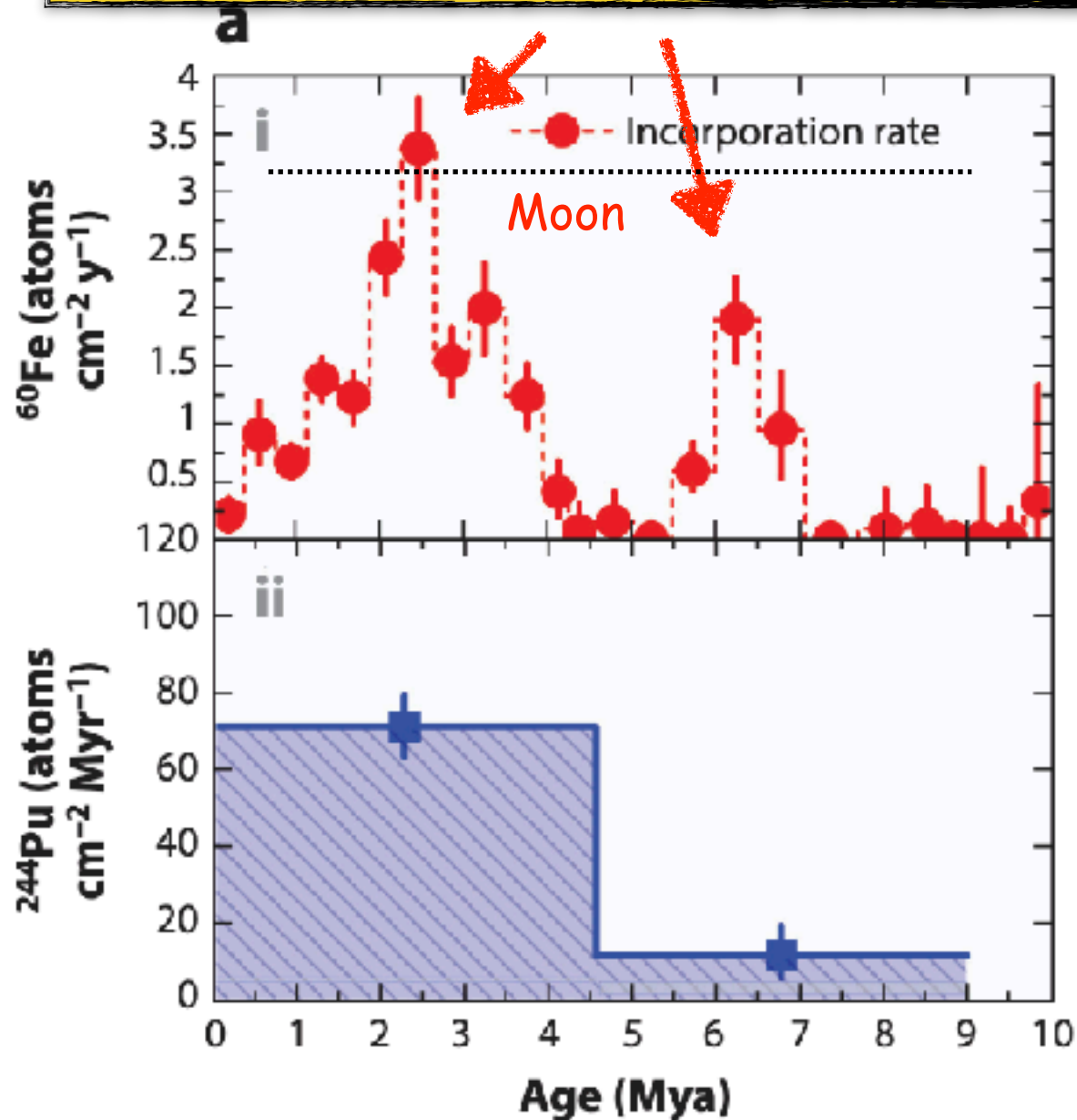


$\tau(^{60}\text{Fe}) \sim 2.6 \text{ Myr}$

^{60}Fe in the bottom of the ocean, on the Moon and in cosmic rays

Binns+ 2016

2 SNaE in the LOCAL O(100) pc ISM

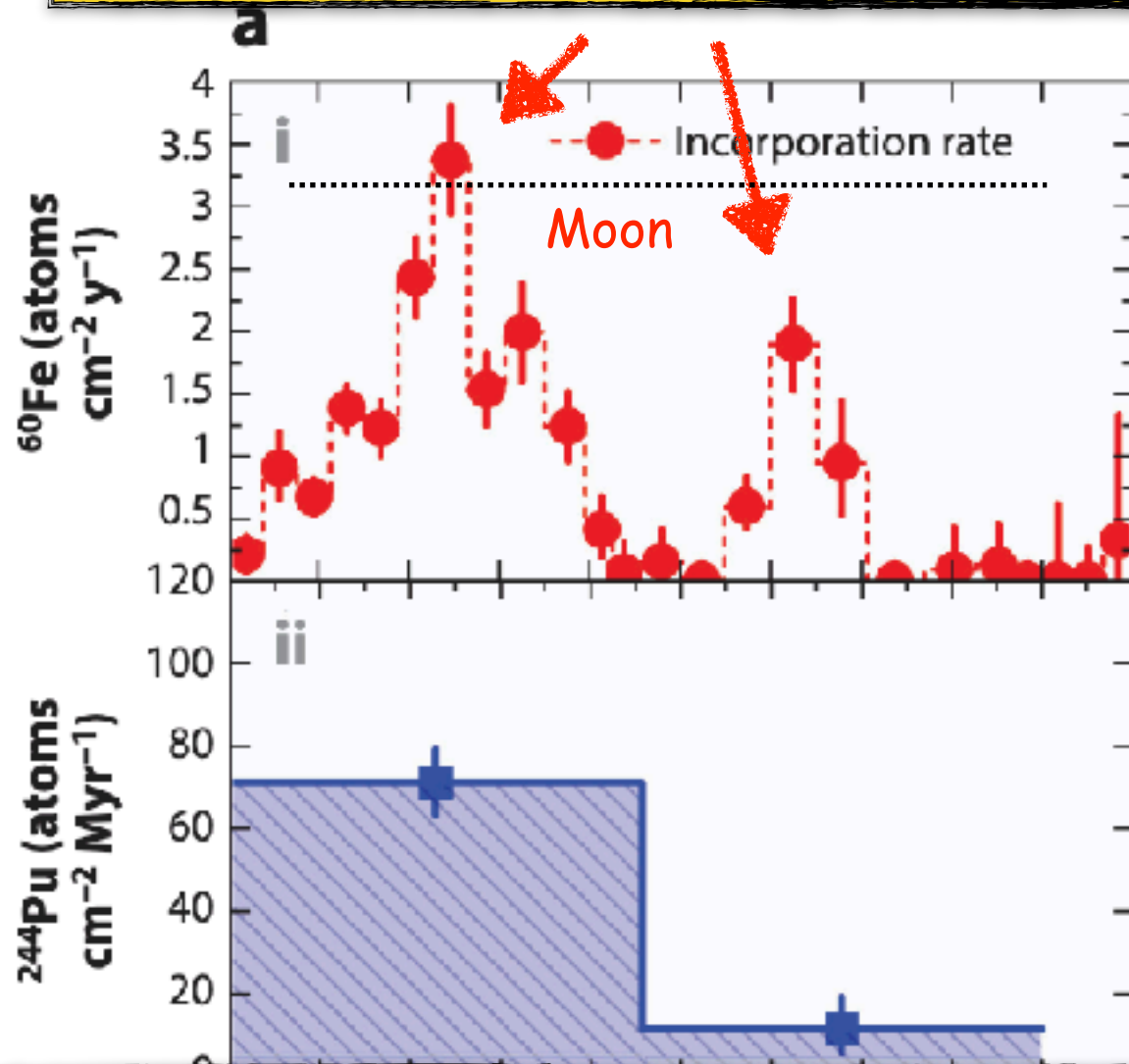


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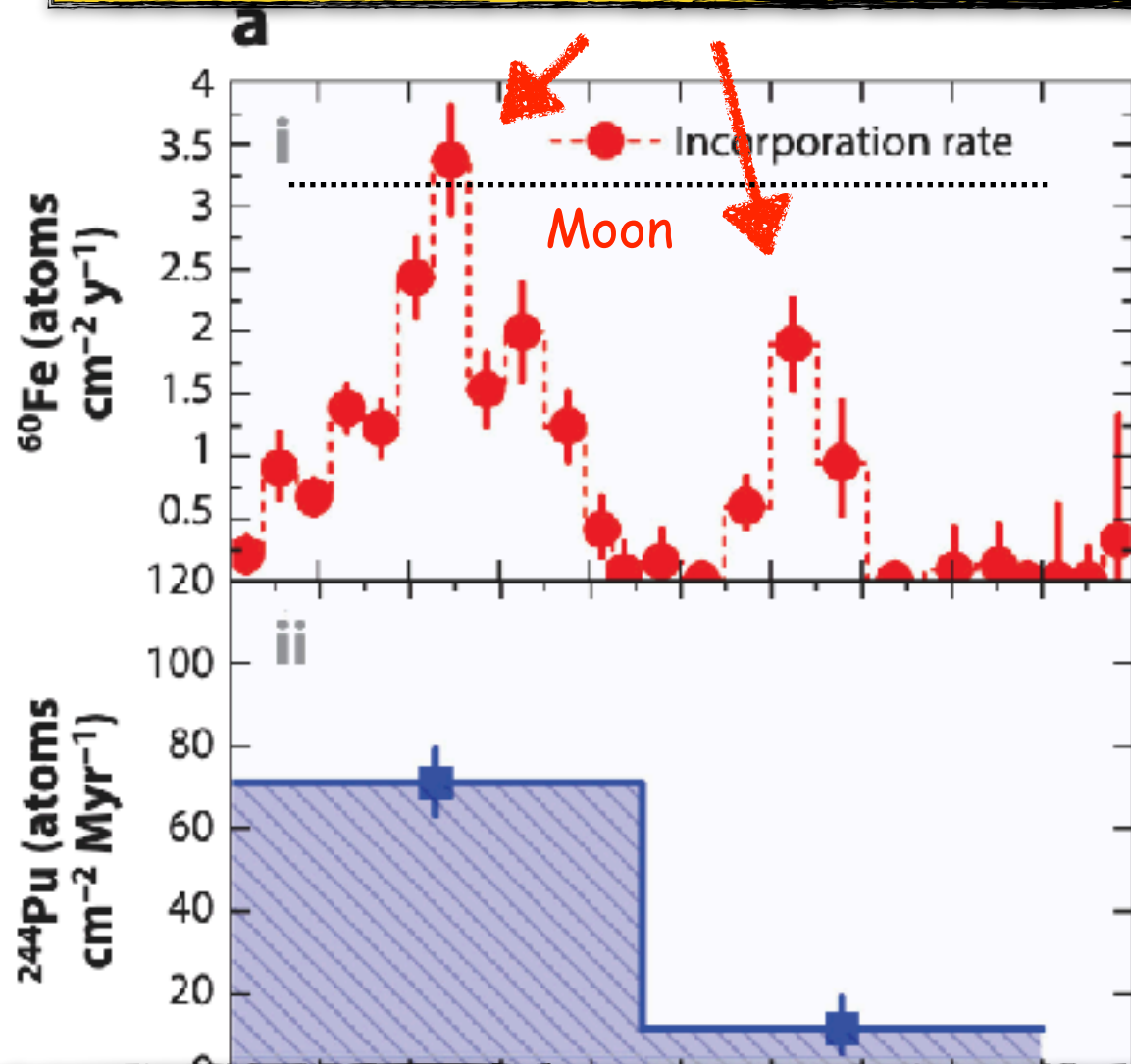


^{244}Pu (~80 Myr) produced in r-process
 $^{60}\text{Fe}/^{244}\text{Pu}$ too low $\rightarrow$ other source?
(neutron star merger?)

$\tau(^{60}\text{Fe}) \sim 2.6 \text{ Myr}$

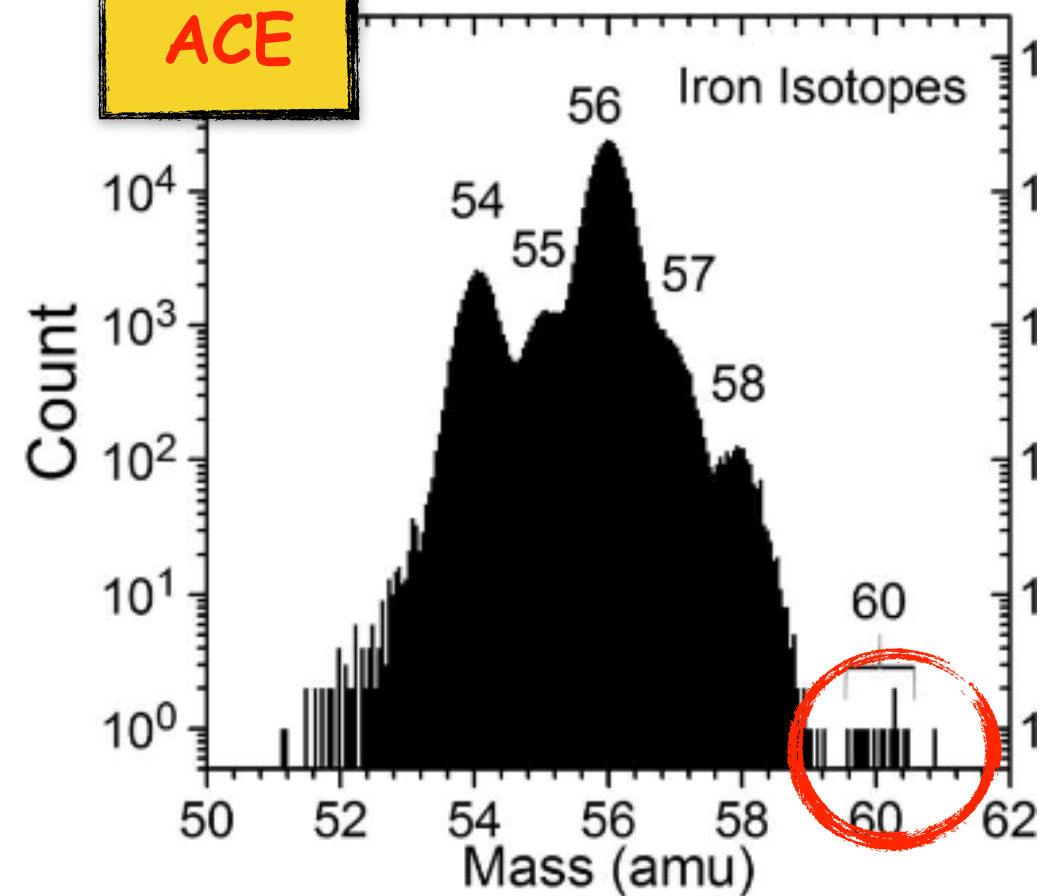
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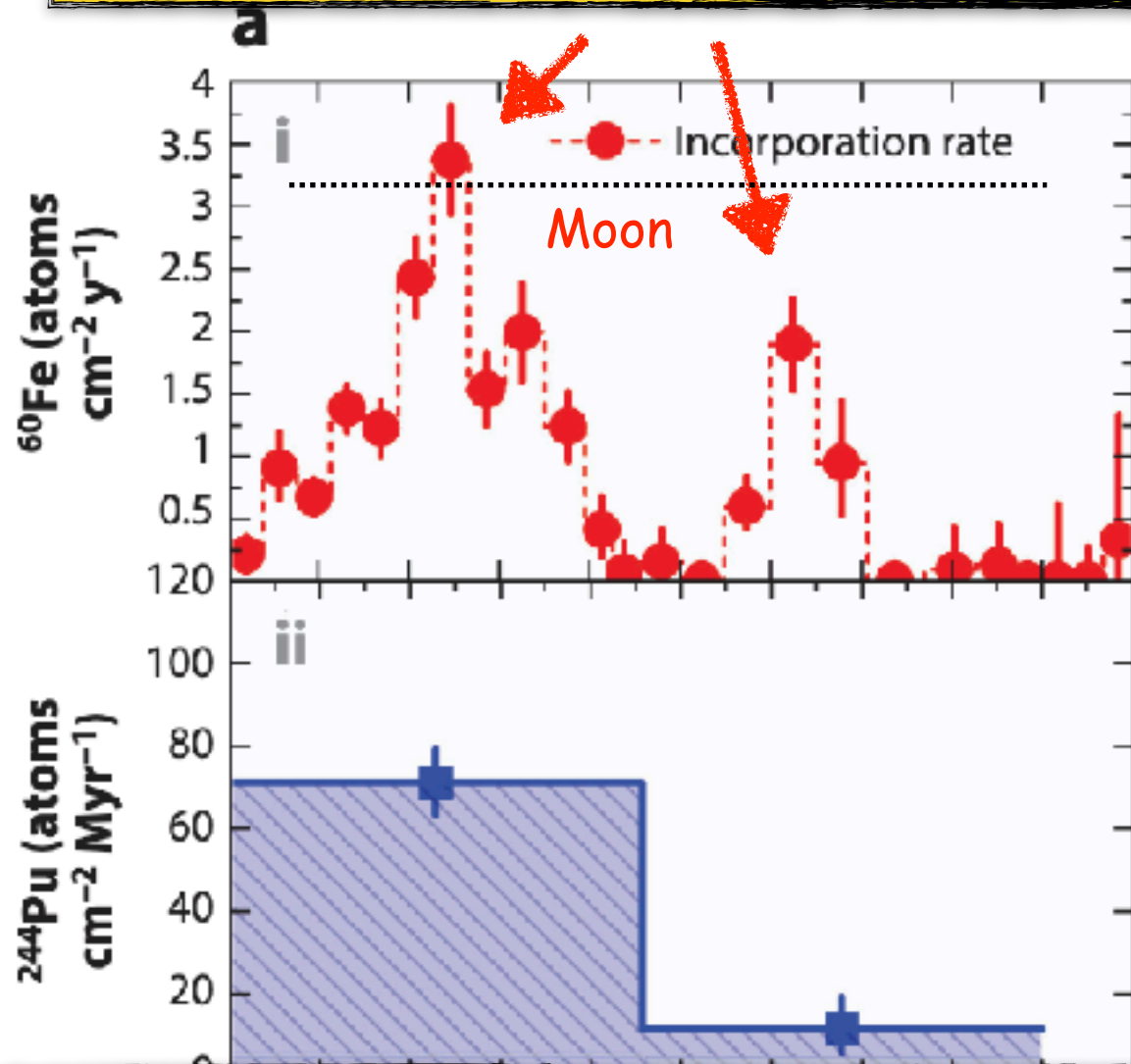
ACE



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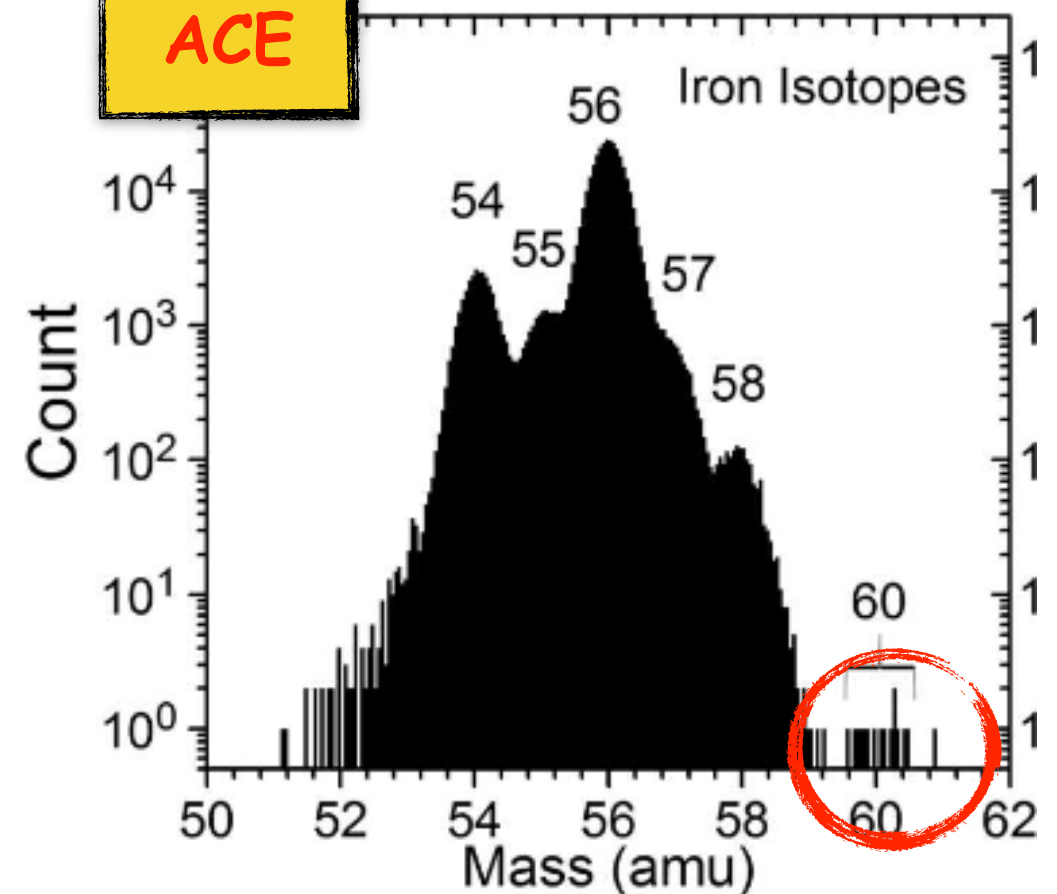
^{60}Fe in the bottom of the ocean, on the Moon and in cosmic rays

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ACE



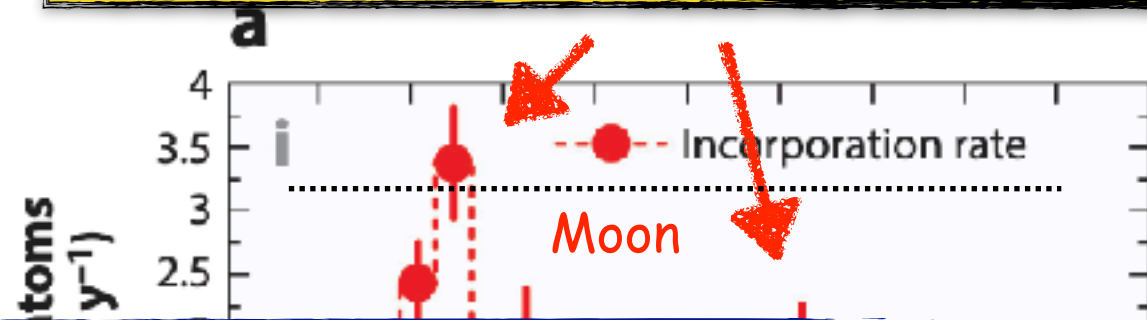
$$d_{\max} \sim \sqrt{D \gamma \tau} \approx 2 \text{ kpc}$$

Lorentz factor

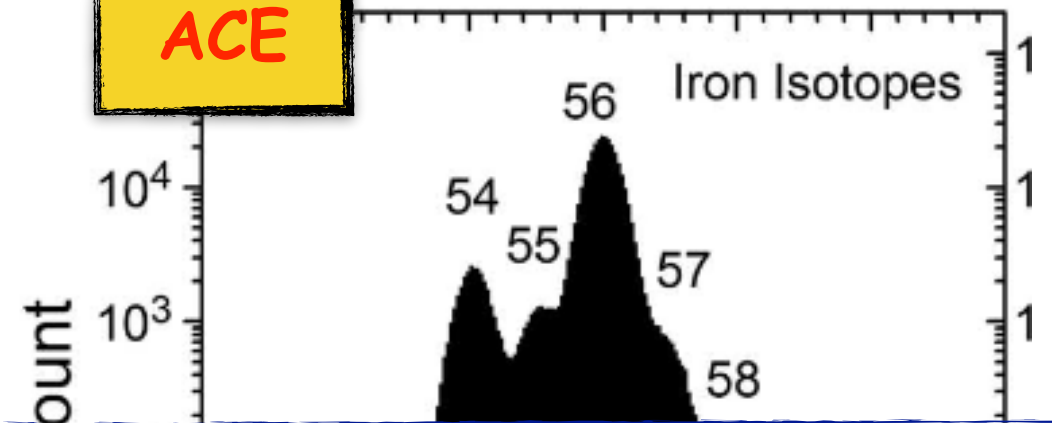
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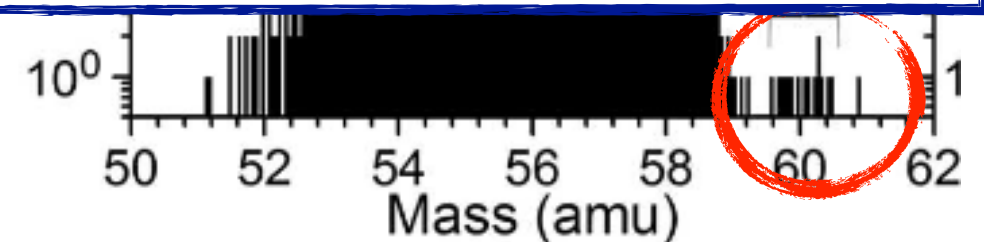
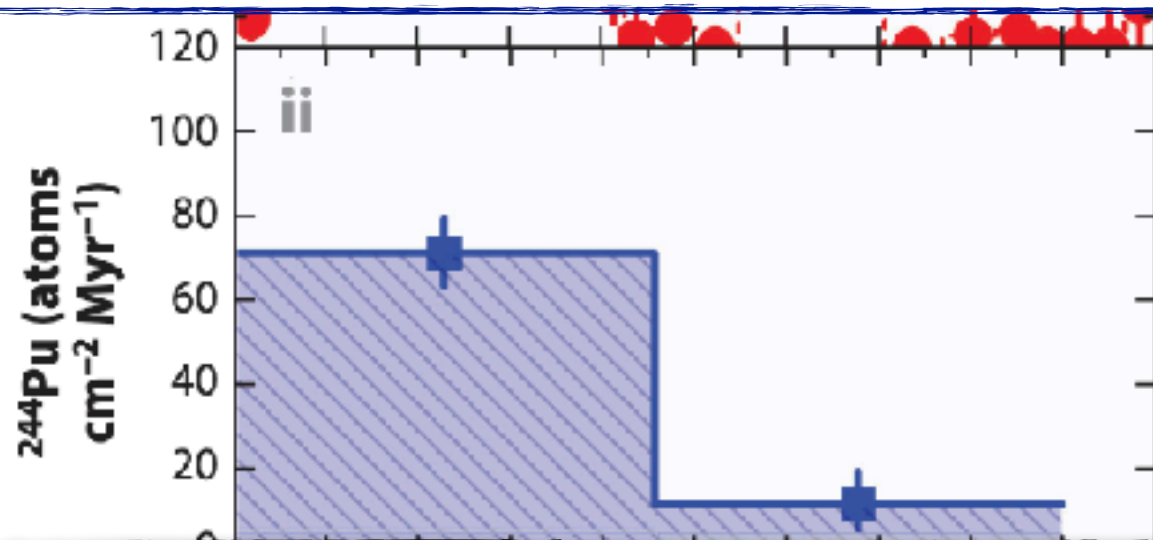
2 SNaE in the LOCAL O(100) pc ISM



ACE



both "cold" and CR ^{60}Fe likely come from supernovae in the Sco-Cen association (~ 150 pc) $\rightarrow$ several papers by Breitschwerdt+, de Sereville+ 2025



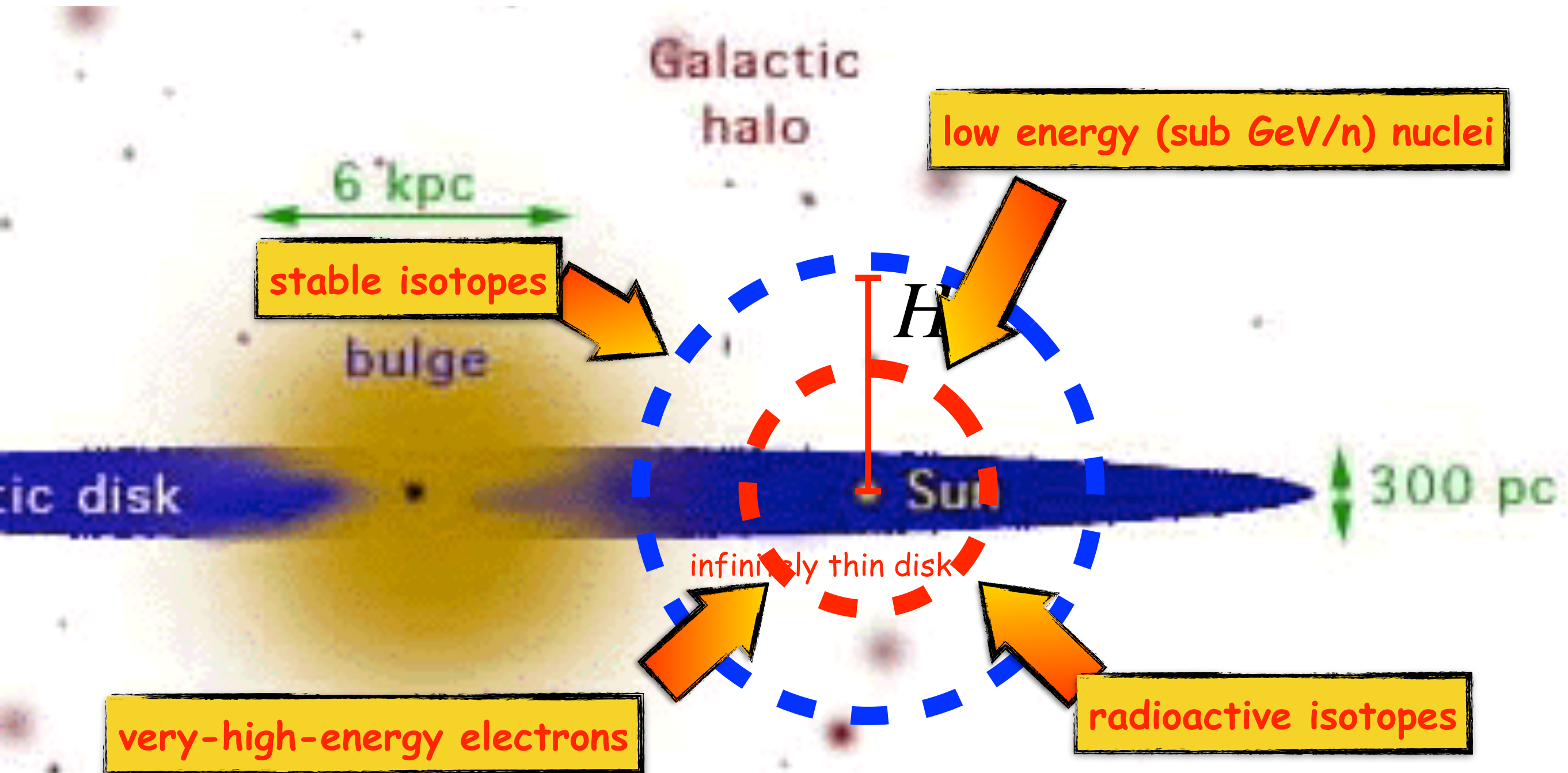
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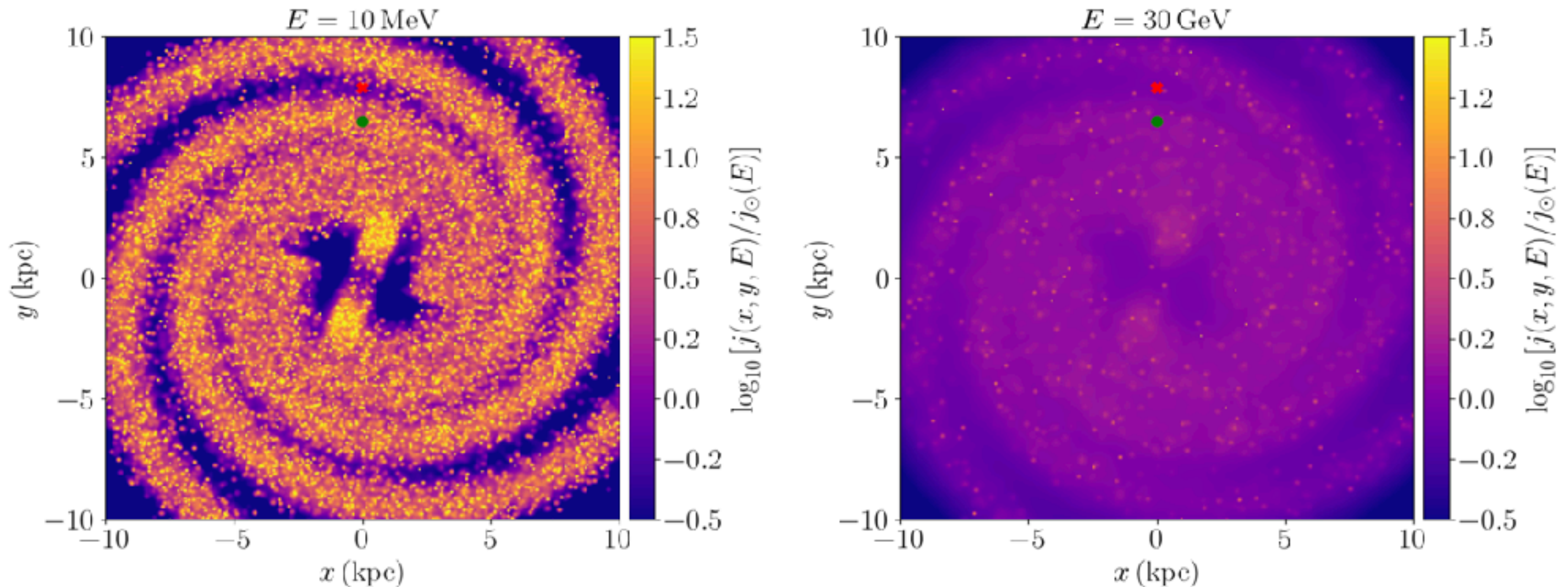
How far do CRs come from?



radioactive (primary) isotopes, low energy CRs and VHE e^- to "see through the fog" and identify the sites of CR acceleration?

Low energy CRs are not uniformly distributed in the Galaxy

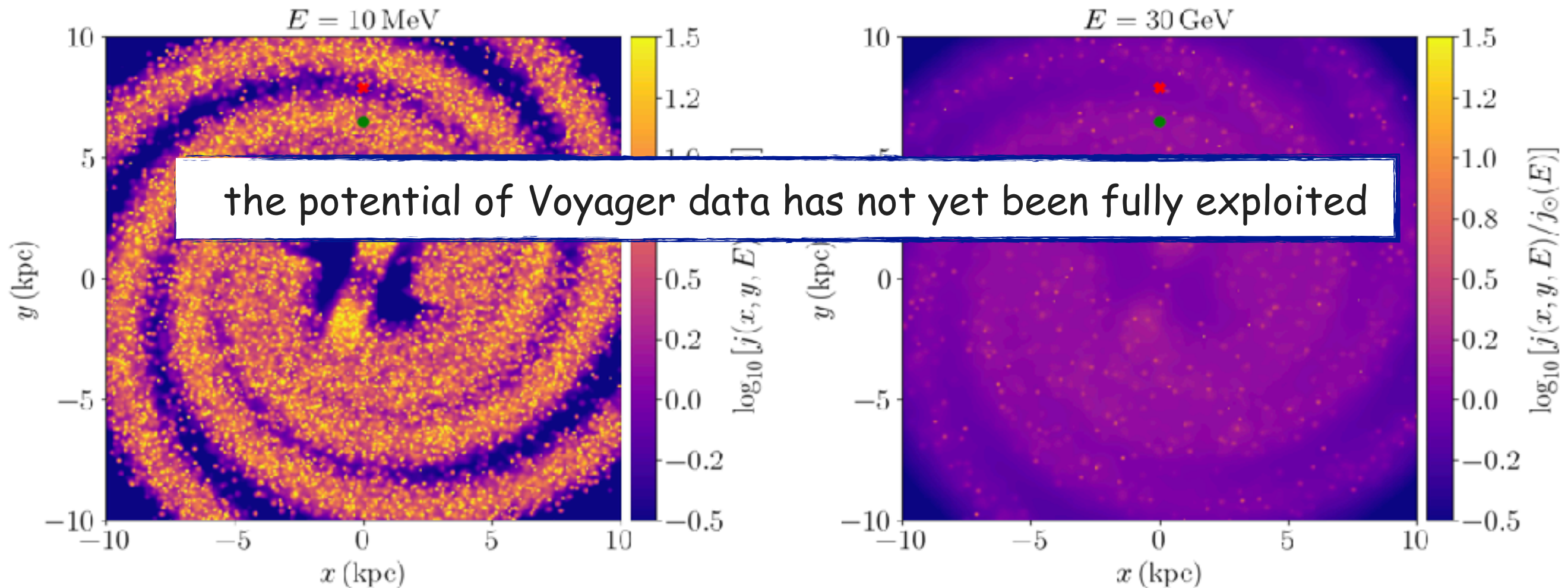
Phan+ 2023



more clumpiness might be expected for PRIMARY radioactive isotopes?
(they disappear, while low energy CRs cool)

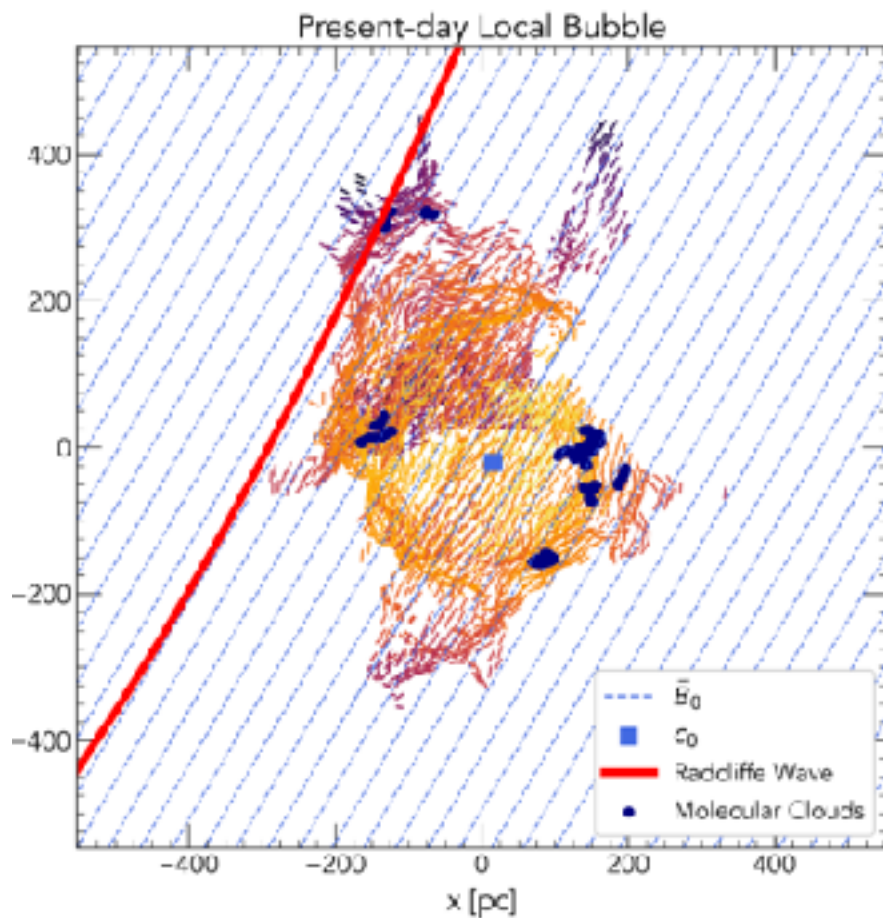
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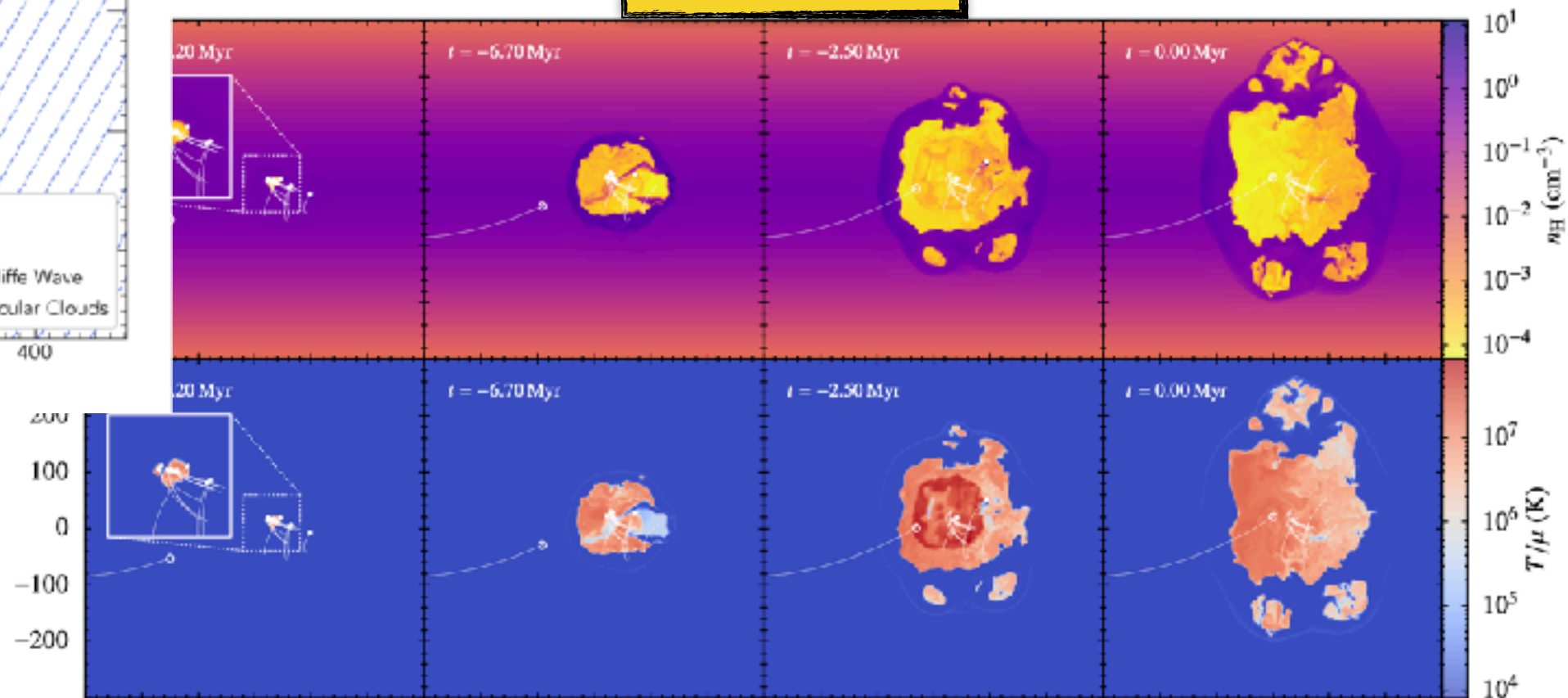
Local effects are interesting because we are in a special location: local bubble



← reconstructed from data

simulations

Schulreich+ 2023



O'Neill+ 2025
see also Pilgrims 2020

B-field structures are likely to affect CR transport, e.g. Bouyahiaoui+

Conclusions

- energy budget + isotopic anomaly → SNRs + ~5-10% WTSs may explain the bulk
- rigidity pattern is now very well established (except, maybe not surprisingly, for low energies) → transport
- the knee? rare powerful accelerators? Why is it so smooth? how many of them? is it local? which species dominate the knee? gamma-ray observations in the VHE and UHE regime drive us: star clusters, microquasars, who's next?
- star clusters: most massive stars are found there, so no wonder we are studying them!
- where are electrons from?
- many more spectral features/anomalies than expected: H/He, ~10 TV break, flat B/C, MeV spectra, positron excess, antiproton flat spectrum, flat ^{10}Be , TeV break for electrons... — what are they?
- we live inside a bubble and sources are stochastic → don't ignore that
- use data from very different sources (ocean, moon, cosmic rays...) to learn that part of the cosmic rays we see were accelerated following a SN that exploded 2 Myr ago in the Sco-Cen association (which, by the way, is believed to have hosted the SNaE that inflated the local bubble), isn't this amazing?