GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

COSMIC RAY TRANSPORT IN THE GALAXY: Status and Prospects

Pasquale Blasi

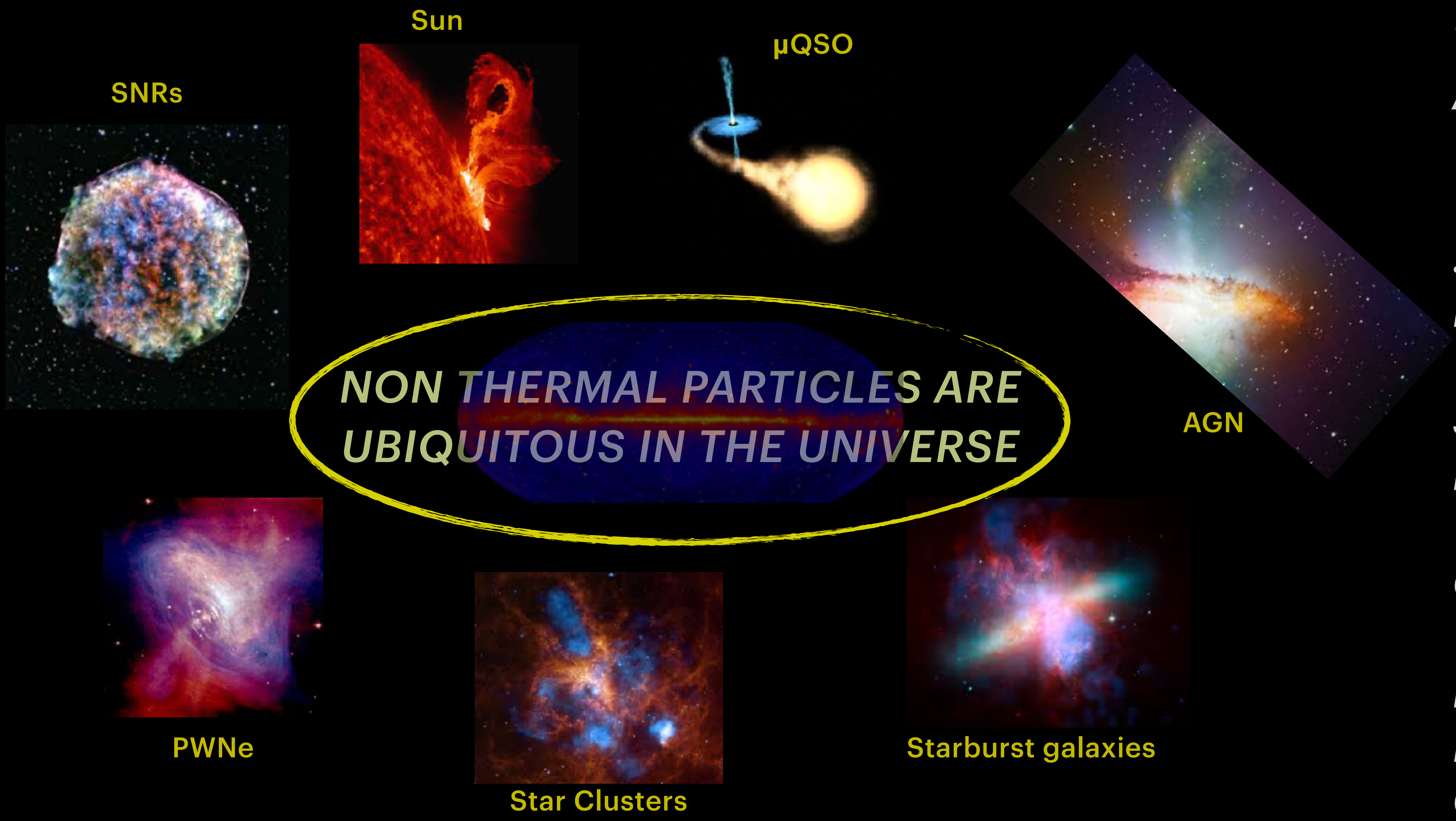
Gran Sasso Science Institute, Italy

Geneva, 18/05/2022

PLAN

- Pedagogical introduction to the theory of CR transport
- Phenomenology vs observations of nuclei (H, He, ...)
- A short incursion into lepton-land
- Bases of non-linear CR transport
- Possible implications

NON THERMAL PARTICLES AND COSMIC RAYS



THESE PHENOMENA REQUIRE ACCELERATION MECHANISMS TO BE AT WORK…

…AND TRANSPORT MECHANISMS THAT TAKE PARTICLES FROM A TO B

SOMETIMES THE NON-THERMAL PARTICLES PRODUCED IN THESE SOURCES MAKE THEIR WAY TO THE EARTH— AT THAT POINT WE CALL THEM COSMIC RAYS

FOR ALL THESE PROBLEMS, THE CRUCIAL ISSUE IS STILL THE TRANSPORT OF CHARGED PARTICLES IN SPACE AND ENERGY

INNER SPACE – OUTER SPACE

PARTICLE PHYSICS
(SMALL SCALES)

↔

UNIVERSE
(LARGE SCALES)

INNER SPACE – OUTER SPACE

PARTICLE PHYSICS (SMALL SCALES) ↔ UNIVERSE (LARGE SCALES)

PARTICLE PHYSICS+PLASMA PHYSICS (SMALL SCALES) ↔ COSMIC RAYS (LARGE SCALES)

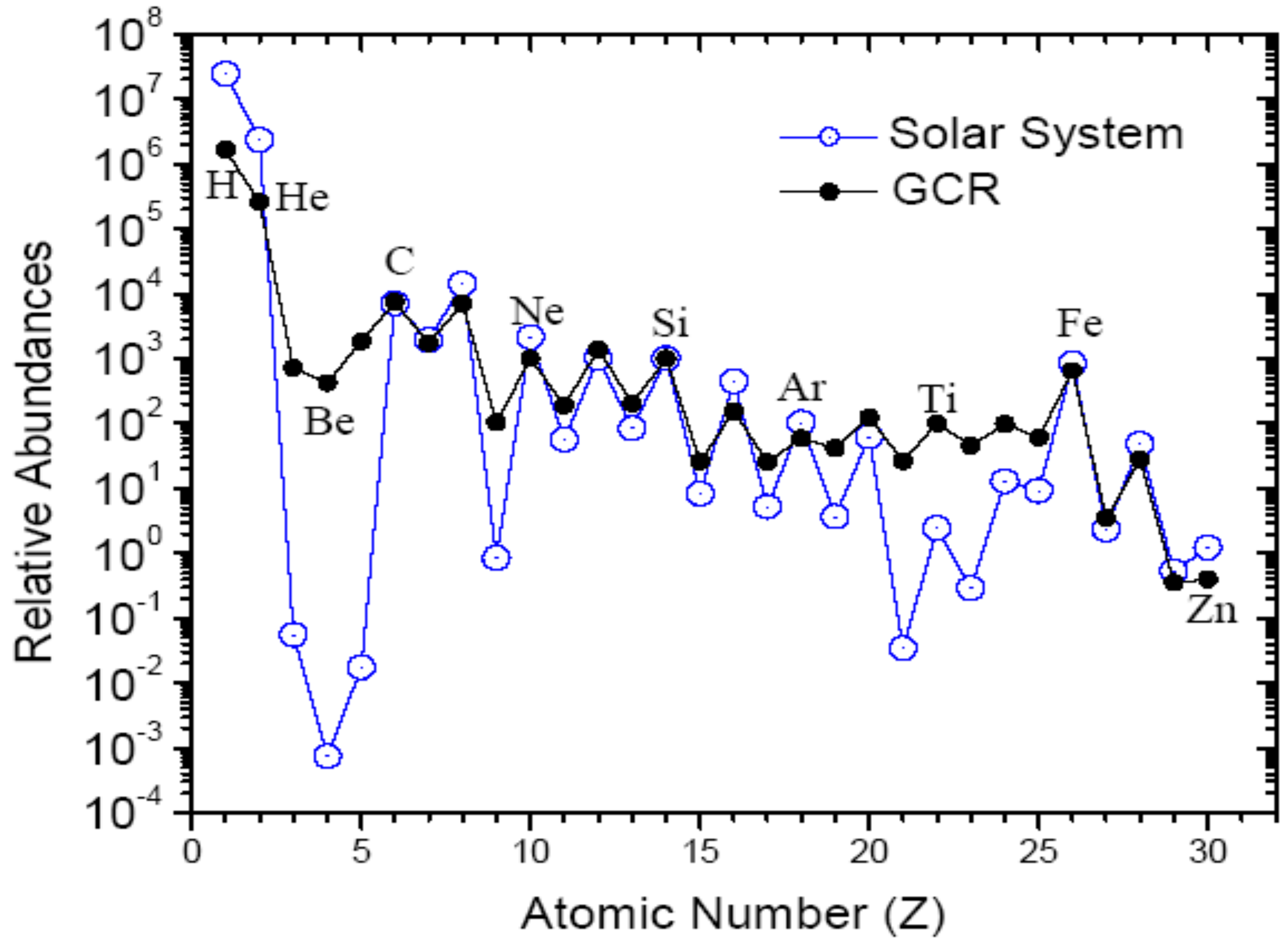
INNER SPACE – OUTER SPACE

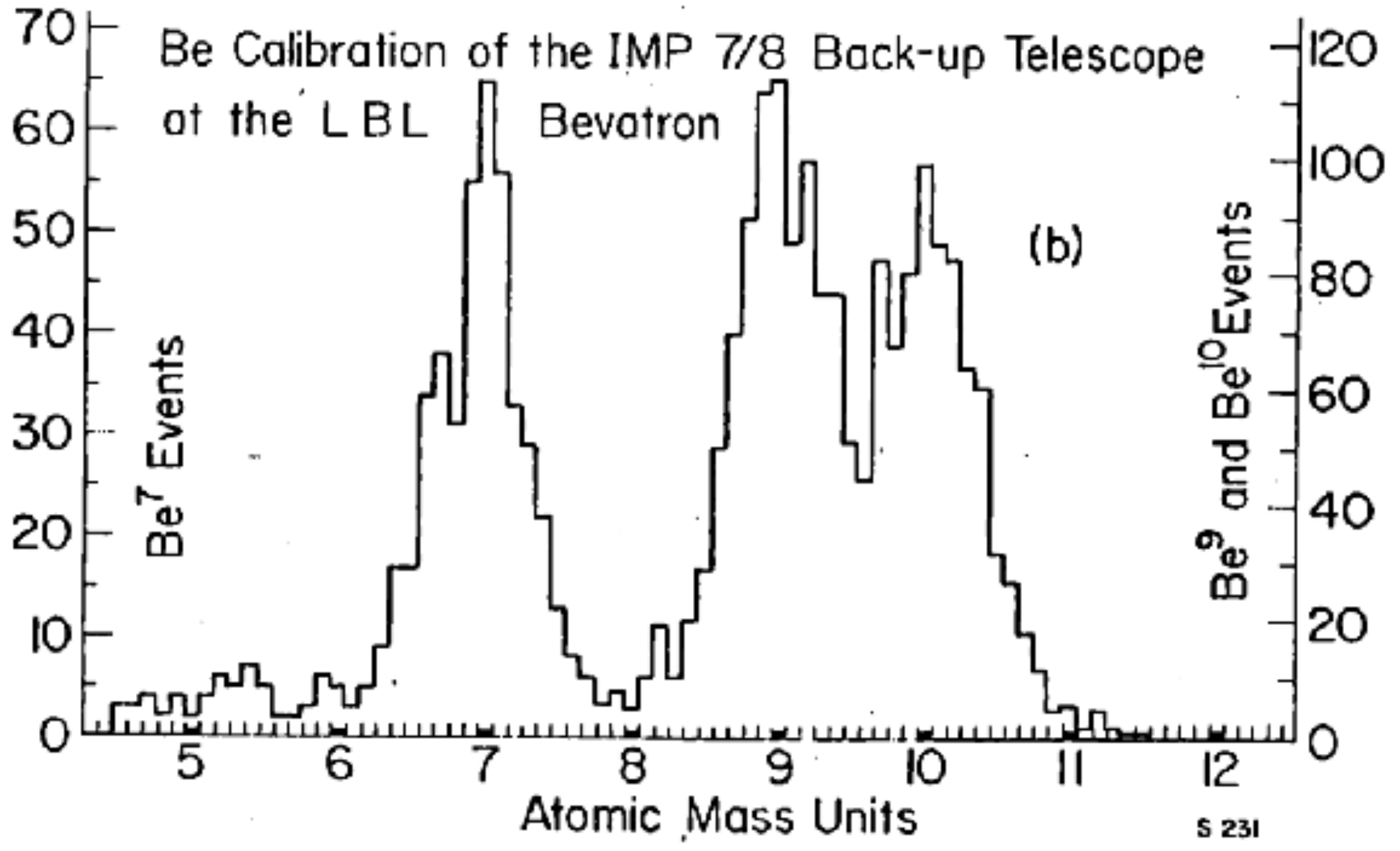
PARTICLE PHYSICS (SMALL SCALES)	⟷	UNIVERSE (LARGE SCALES)
PARTICLE PHYSICS+PLASMA PHYSICS (SMALL SCALES)	⟷	COSMIC RAYS (LARGE SCALES)

We parametrize the unknowns (diffusion coefficients, advection speeds) in a way that things seem to fit (analog to introducing dark energy and dark matter) but our microphysical description is far from complete

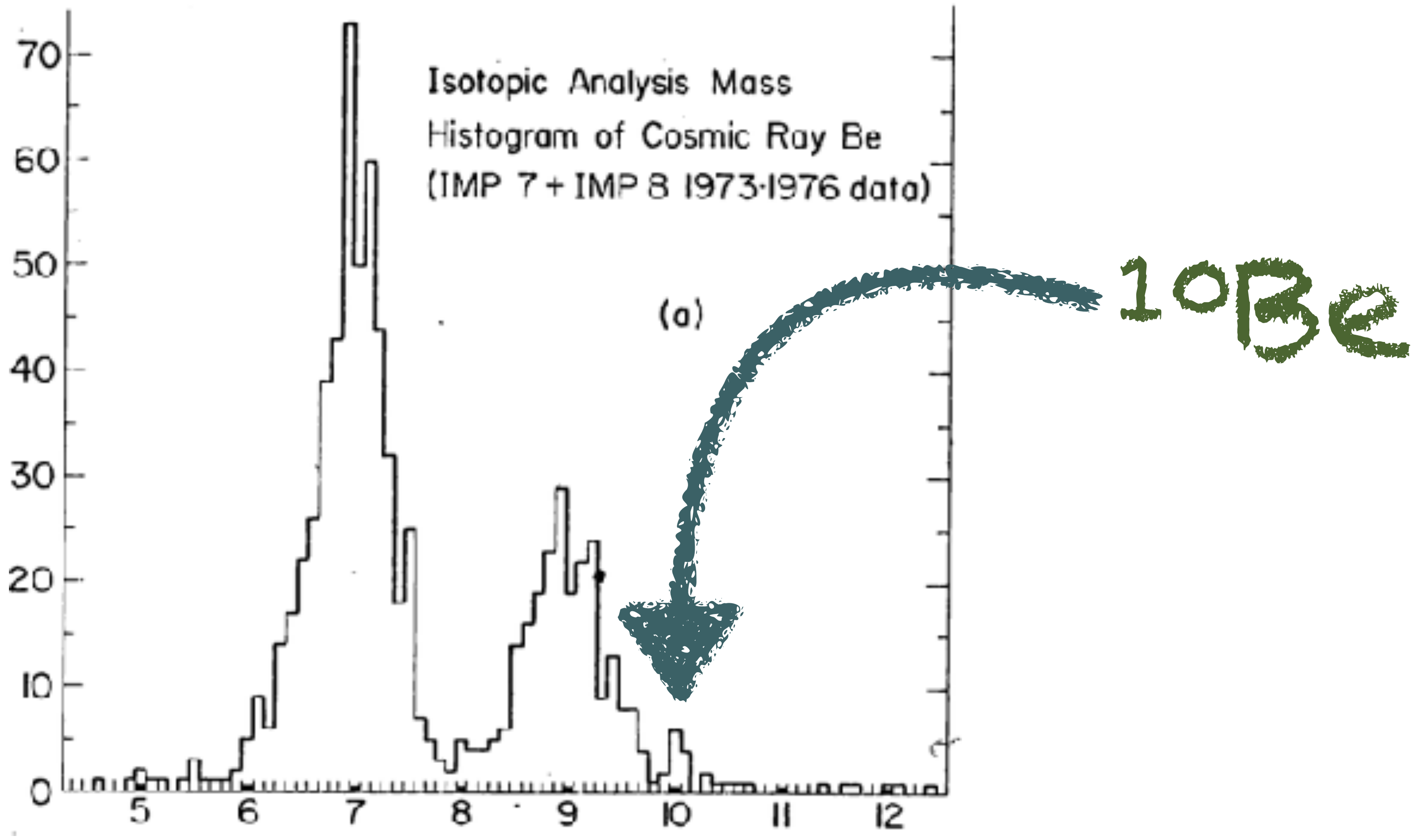
A SHORT PEDAGOGICAL INTRODUCTION TO CR TRANSPORT

COSMIC CLOCKS: CR motion is complex!

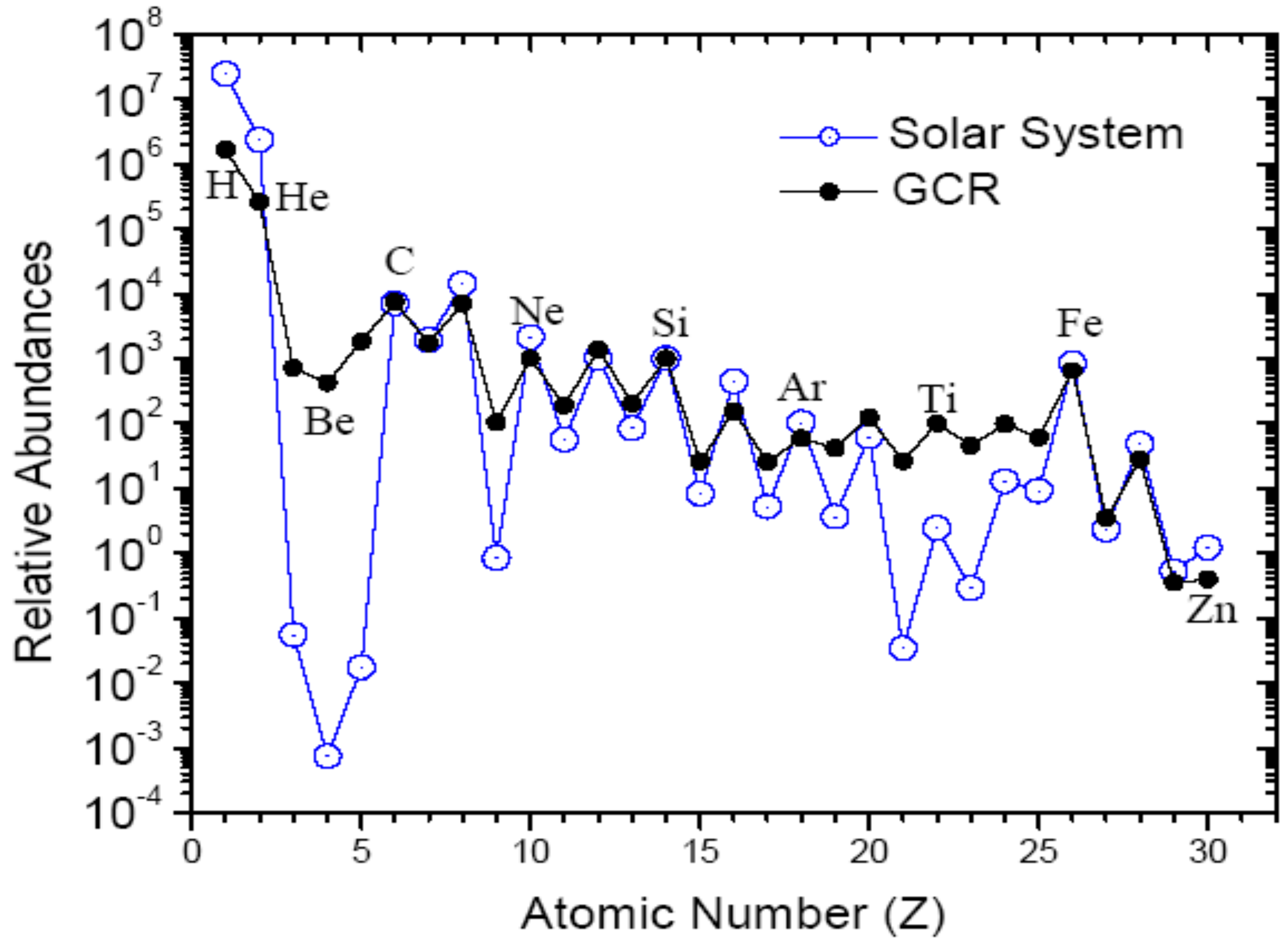




Garcia-Munoz et al. 1977



COSMIC CLOCKS: CR motion is complex!

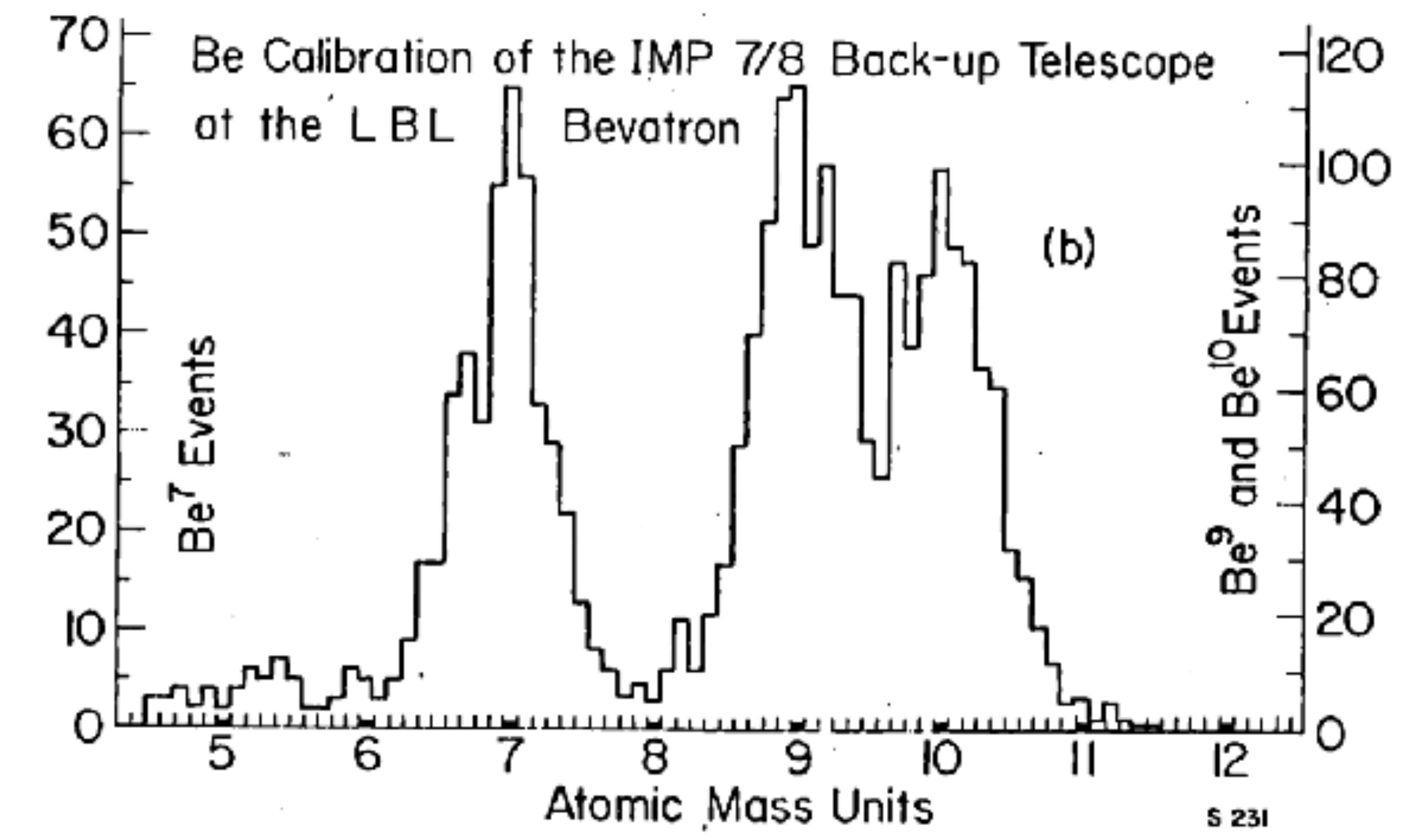


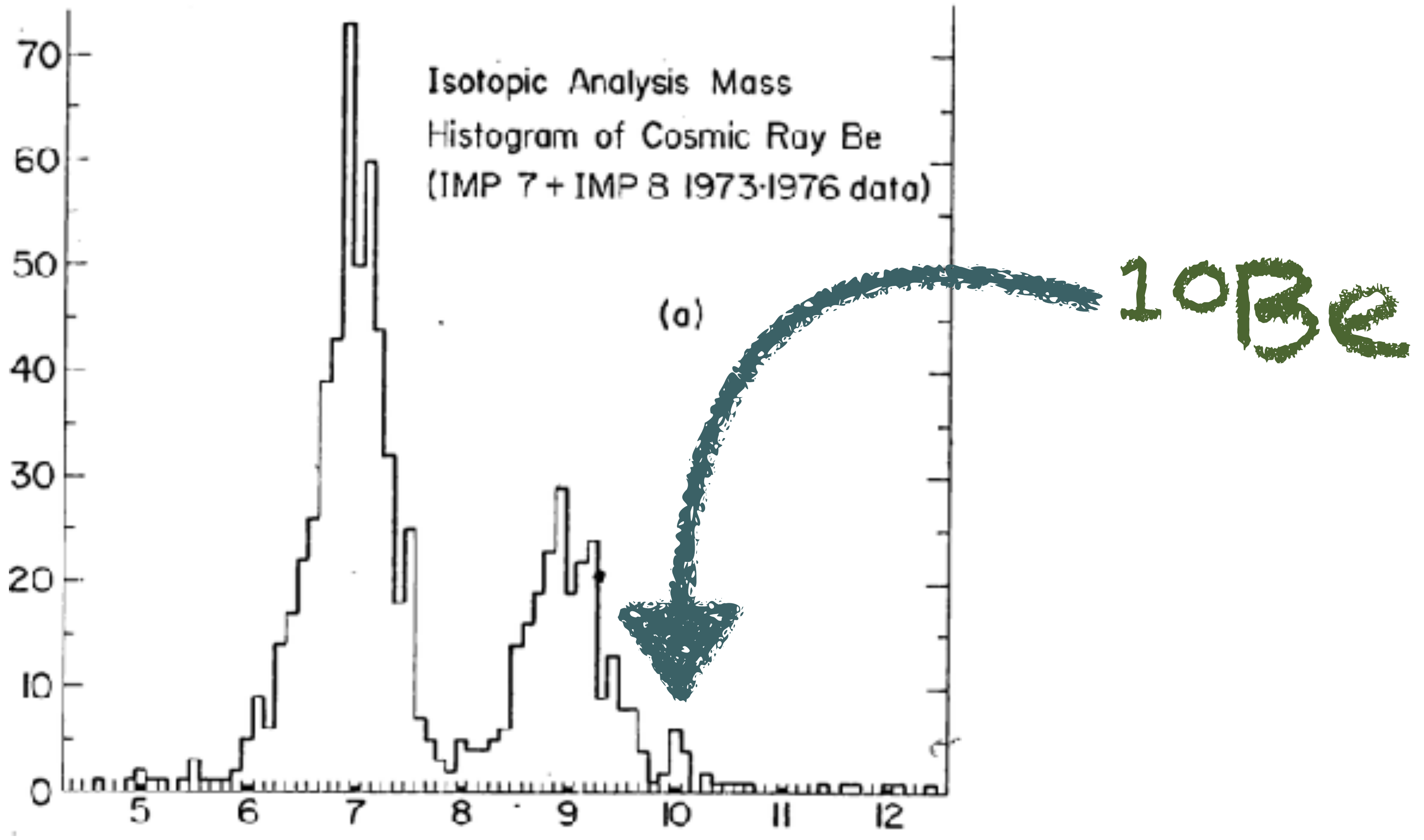
Measurements of the B-Li-Be in CRs show that CR stay in the Galaxy for very long times >> H/c

DIFFUSIVE TRANSPORT

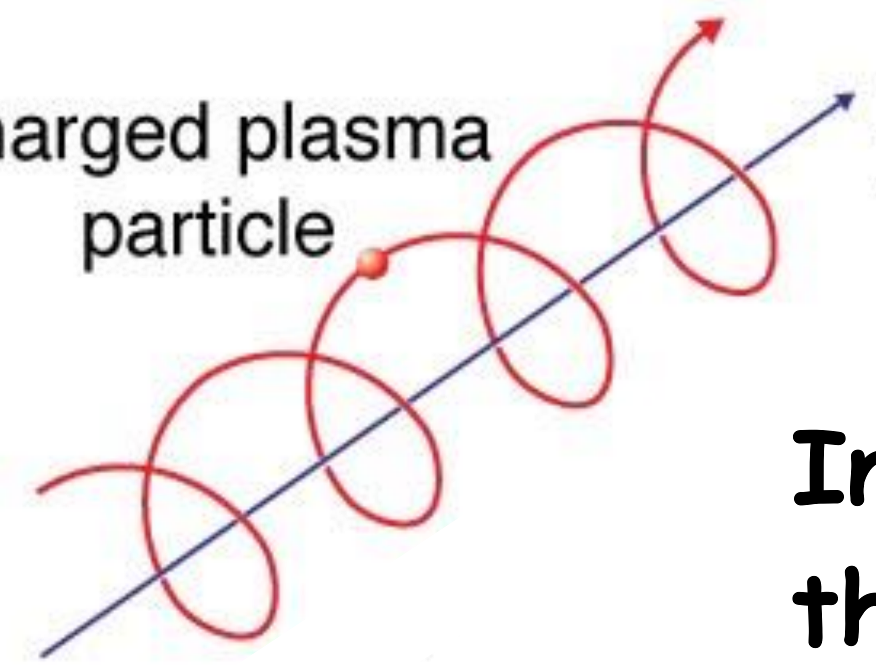
at ~10 GeV/n CR are required to stay in the Galaxy for about 100 Myr !

Garcia-Munoz et al. 1977





CHARGED PARTICLES IN A REGULAR B FIELD



$$\frac{d\vec{p}}{dt} = q\left[\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right]$$

In the absence of an electric field one obtains the well known solution:

$$p_z = \text{Constant}$$

$$v_x = V_0 \cos[\Omega\, t]$$

$$v_y = V_0 \sin[\Omega\, t]$$

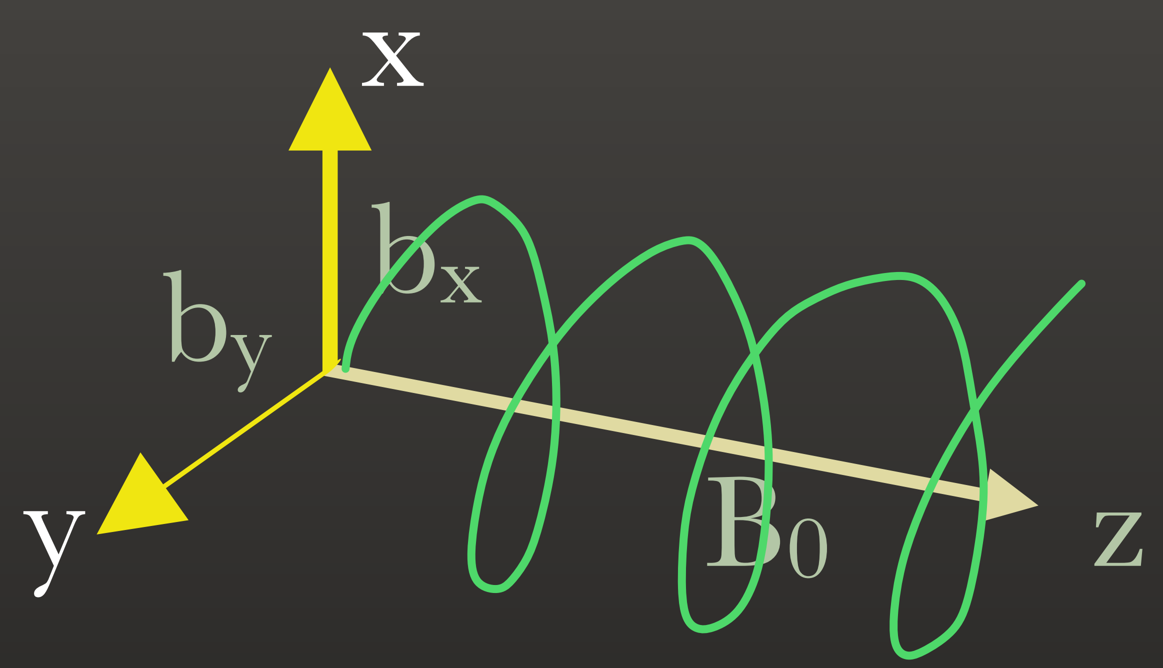
LARMOR FREQUENCY

$$\Omega = \frac{q\, B_0}{m\, c\, \gamma}$$

BASICS OF CR TRANSPORT

Assume that in addition to a regular field B_0 there is a small perturbation b, that you can decompose in its Fourier modes

A charged particle moving in a field B_0+b, with |b|<<B and b perpendicular to B_0 is:



THIS CHANGES $p_z = p\,\mu$

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times \left(\vec{B}_0 + \vec{b}\right)$$

THIS ONLY CHANGES p_x and p_y

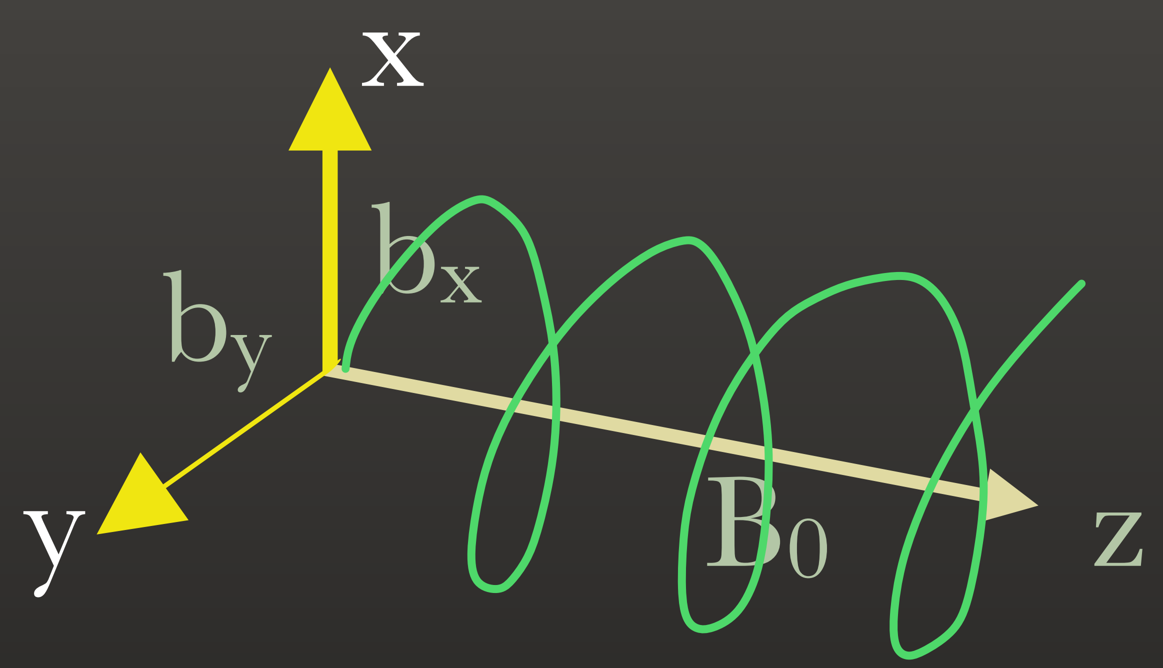
$$\frac{d\mu}{dt} = \frac{qv}{pc}(1-\mu^2)^{1/2} b\,cos(\Omega t - kz + \psi), \qquad \Omega = \frac{qB_0}{mc\gamma}$$

Gyration Frequency

BASICS OF CR TRANSPORT

Assume that in addition to a regular field B_0 there is a small perturbation b, that you can decompose in its Fourier modes

A charged particle moving in a field B_0+b, with |b|<<B and b perpendicular to B_0 is:



THIS CHANGES $p_z = p\,\mu$

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times \left(\vec{B}_0 + \vec{b}\right)$$

THIS ONLY CHANGES p_x and p_y

$$\frac{d\mu}{dt} = \frac{qv}{pc}(1-\mu^2)^{1/2} b\, cos(\Omega t - kz + \psi), \qquad \Omega = \frac{qB_0}{mc\gamma}$$

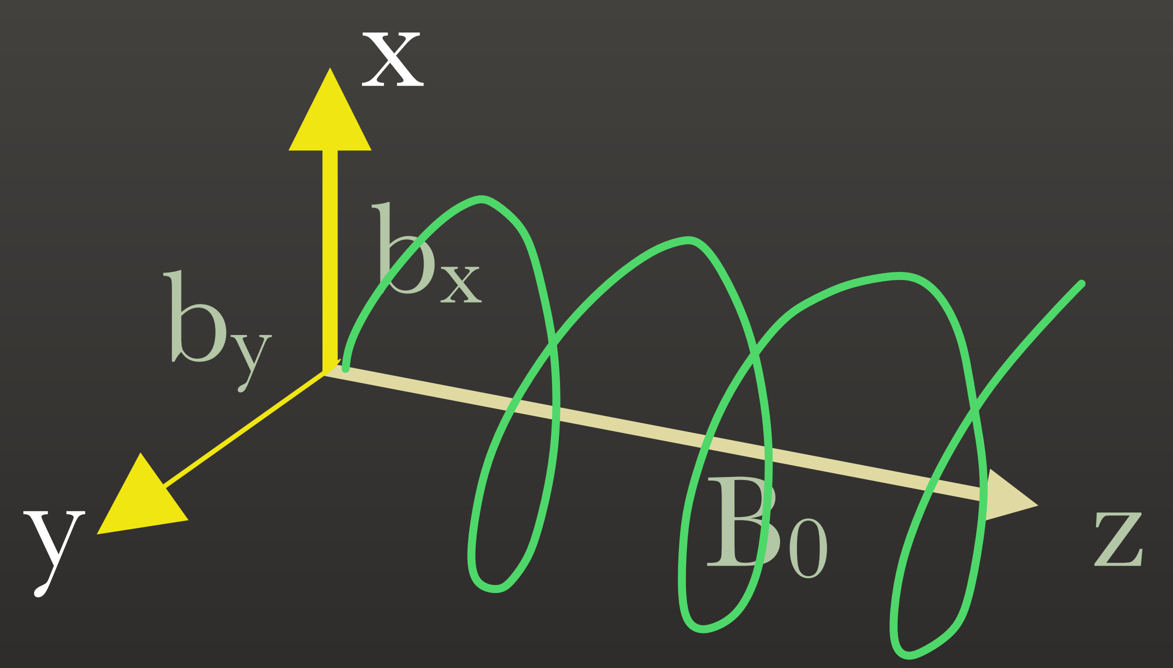
Gyration Frequency

$$\langle \delta\mu \rangle_{\psi.t} = 0$$

BASICS OF CR TRANSPORT

Assume that in addition to a regular field B_0 there is a small perturbation b, that you can decompose in its Fourier modes

A charged particle moving in a field B_0+b, with |b|<<B and b perpendicular to B_0 is:



THIS CHANGES $p_z = p\,\mu$

$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times \left(\vec{B}_0 + \vec{b}\right)$$

THIS ONLY CHANGES p_x and p_y

$$\frac{d\mu}{dt} = \frac{qv}{pc}(1-\mu^2)^{1/2} b\, cos(\Omega t - kz + \psi), \qquad \Omega = \frac{qB_0}{mc\gamma}$$

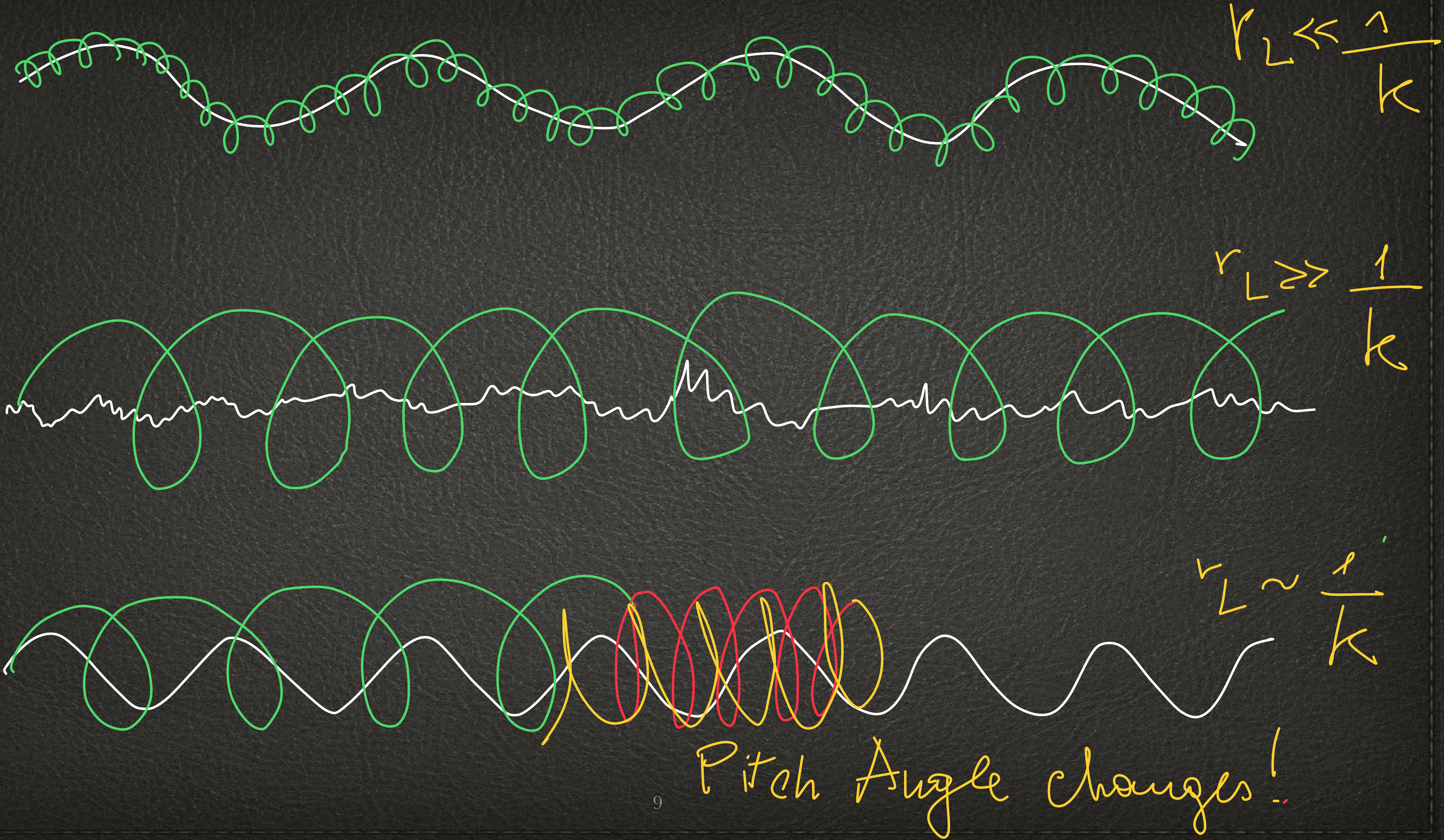
Gyration Frequency

$$\langle \delta\mu \rangle_{\psi.t} = 0$$

Resonance

$$\langle \delta\mu\delta\mu \rangle_{\psi.t} = \frac{q^2v^2(1-\mu^2)b^2}{c^2p^2\mu}\delta(k-\Omega/v\mu)\delta t \propto \delta t$$

Diffusion


$r_L \ll \frac{1}{k}$
$r_L \gg \frac{1}{k}$
$r_L \sim \frac{1}{k}$
Pitch Angle changes!

BASICS OF CR TRANSPORT

IF THERE ARE MANY SUCH WAVES WITH A POWER SPECTRUM F(k), THEN

$$D_{\mu\mu} = \langle \frac{\Delta\mu\Delta\mu}{\Delta t} \rangle = \frac{\pi}{2}\Omega(1-\mu^2)\mathcal{F}(k_{res})$$

$$k_{res} = \frac{\Omega}{v\mu} = \frac{1}{r_L\mu}$$

$$\mathcal{F}(k_{res}) = k_{res}F(k_{res}) = \frac{\delta B^2(k_{res})}{B_0^2}$$

THEY DEFLECT BY 90 DEGREES IN A TIME:

$$\tau_{90} \approx \frac{1}{D_{\mu\mu}} \sim \frac{1}{\Omega\mathcal{F}(k_{res})}$$

THE DIFFUSION OF PARTICLES IN PITCH ANGLE ALSO IMPLIES THEIR DIFFUSION IN SPACE

$$D_{zz} = \langle \frac{\Delta z\Delta z}{\Delta t} \rangle = \frac{1}{3}v\lambda = \frac{1}{3}v^2\tau_{90} = \frac{1}{3}\frac{v^2}{\Omega\mathcal{F}(k_{res})} = \frac{1}{3}r_L(p)v\frac{1}{\mathcal{F}(k_{res})}$$

- *NOTICE THAT THERE ARE NO ELECTRIC FIELDS IN THESE EXPRESSIONS*

- *IN ASTROPHYSICAL PLASMAS, DUE TO THE VERY HIGH CONDUCTIVITY, IT IS HARD TO HAVE ELECTRIC FIELDS, ASIDE FROM THOSE INDUCED BY PLASMA MOTION*

- *THIS IS THE VERY REASON WHY IT IS TREMENDOUSLY HARD TO ACCELERATE PARTICLES TO NON-THERMAL ENERGIES!* ***ONLY ELECTRIC FIELDS CAN CHANGE PARTICLE ENERGY!!!***

- *IN PRINCIPLE THE SMALL ELECTRIC FIELDS ASSOCIATED TO THE FACT THAT THE PERTURBATIONS ARE NON STATIONARY WOULD LEAD TO DIFFUSION IN MOMENTUM SPACE: THAT IS WHAT WE CALL SECOND ORDER FERMI ACCELERATION, PRETTY WEAK AND UNEVENTFUL PHENOMENON IN MOST CASES*

- *THE EFFECT OF DIFFUSION IS TO ISOTROPIZE THE DIRECTIONS OF MOTION OF PARTICLES IN THE REFERENCE FRAME OF THE PERTURBATIONS*

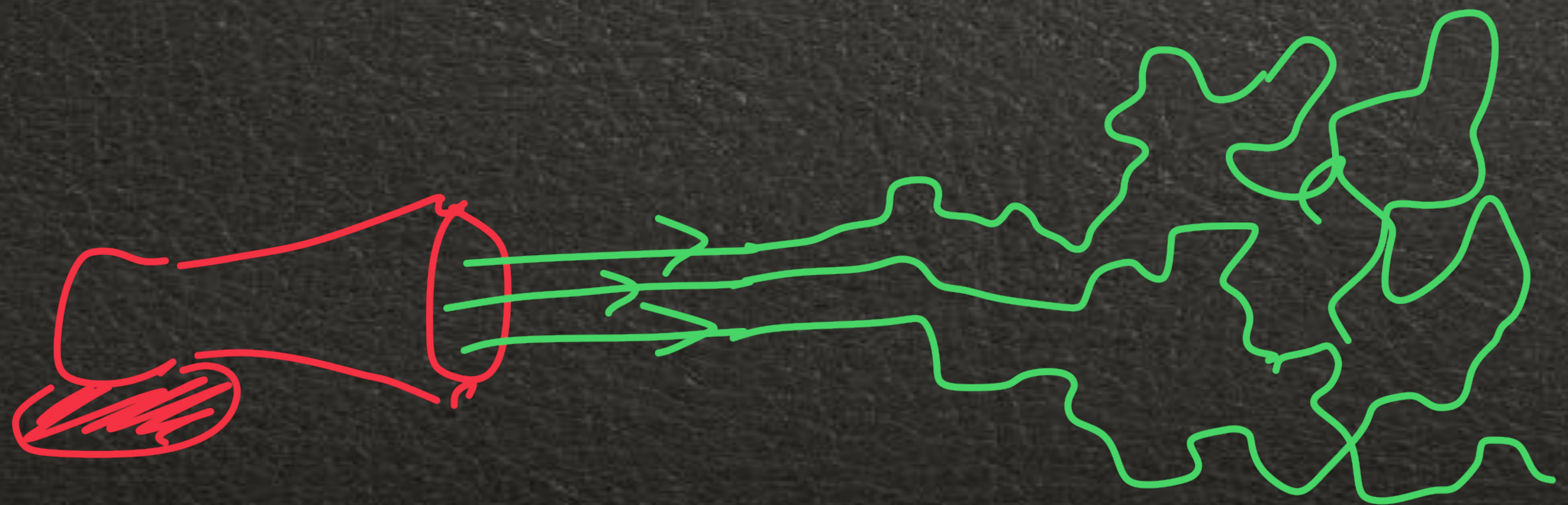
- *NOTICE THAT THERE ARE NO ELECTRIC FIELDS IN THESE EXPRESSIONS*

- *IN ASTROPHYSICAL PLASMAS, DUE TO THE VERY HIGH CONDUCTIVITY, IT IS HARD TO HAVE ELECTRIC FIELDS, ASIDE FROM THOSE INDUCED BY PLASMA MOTION*

- *THIS IS THE VERY REASON WHY IT IS TREMENDOUSLY HARD TO ACCELERATE PARTICLES TO NON-THERMAL ENERGIES!* ***ONLY ELECTRIC FIELDS CAN CHANGE PARTICLE ENERGY!!!***

- *IN PRINCIPLE THE SMALL ELECTRIC FIELDS ASSOCIATED TO THE FACT THAT THE PERTURBATIONS ARE NON STATIONARY WOULD LEAD TO DIFFUSION IN MOMENTUM SPACE: THAT IS WHAT WE CALL SECOND ORDER FERMI ACCELERATION, PRETTY WEAK AND UNEVENTFUL PHENOMENON IN MOST CASES*

- *THE EFFECT OF DIFFUSION IS TO ISOTROPIZE THE DIRECTIONS OF MOTION OF PARTICLES IN THE REFERENCE FRAME OF THE PERTURBATIONS*



Cosmic Rays isotropize under the effect of pitch angle Diffusion

SELF-GENERATION
PARTICLES AFFECT THE ENVIRONMENT

The net effect of spatial diffusion is to reduce the momentum of the particles in the z direction… forcing them, eventually, to move at the same speed as the waves v_w

$$n_{CR} m v_{dr} \rightarrow n_{CR} m v_w \rightarrow \frac{dp_{CR}}{dt} = \frac{n_{CR}(v_{dr} - v_w)}{\tau_{90}}$$

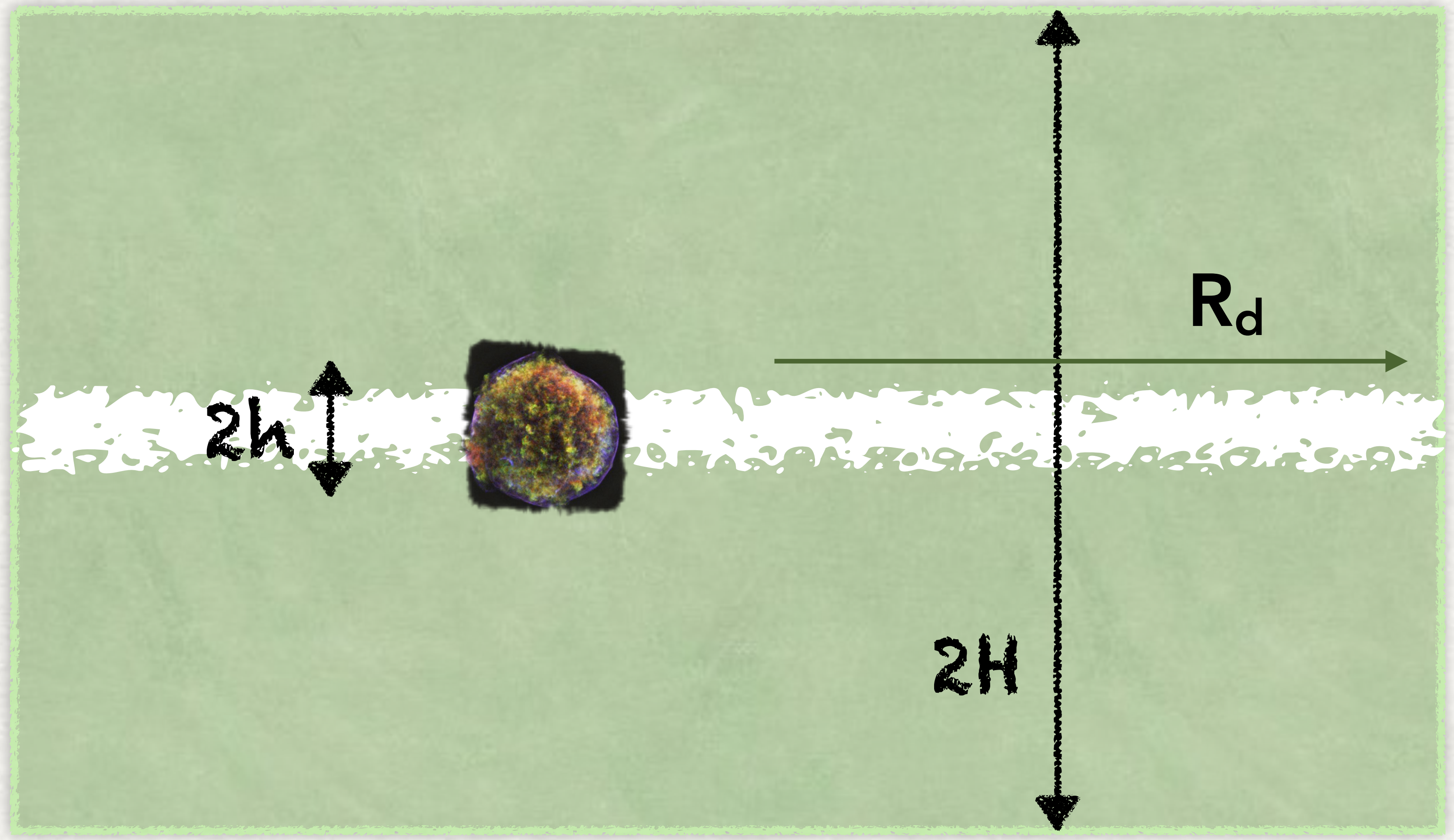
$$\frac{dp_w}{dt} = \Gamma_{CR} \frac{b^2}{8\pi v_w}$$

And requiring some balance between the two:

$$\Gamma_{CR} \approx \frac{n_{CR}}{n_i} \frac{v_{dr} - v_w}{v_w} \Omega_{cyc}$$

If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down… this process is known as self-generation of waves

A TOY MODEL FOR PROTONS IN OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

1. *CR are injected in an infinitely thin disc*
2. *CR diffuse in the whole volume*
3. *CR freely escape from a boundary*

1 $$Q(p,z) = \frac{Q_0(p)}{\pi R_d^2}\delta(z)$$

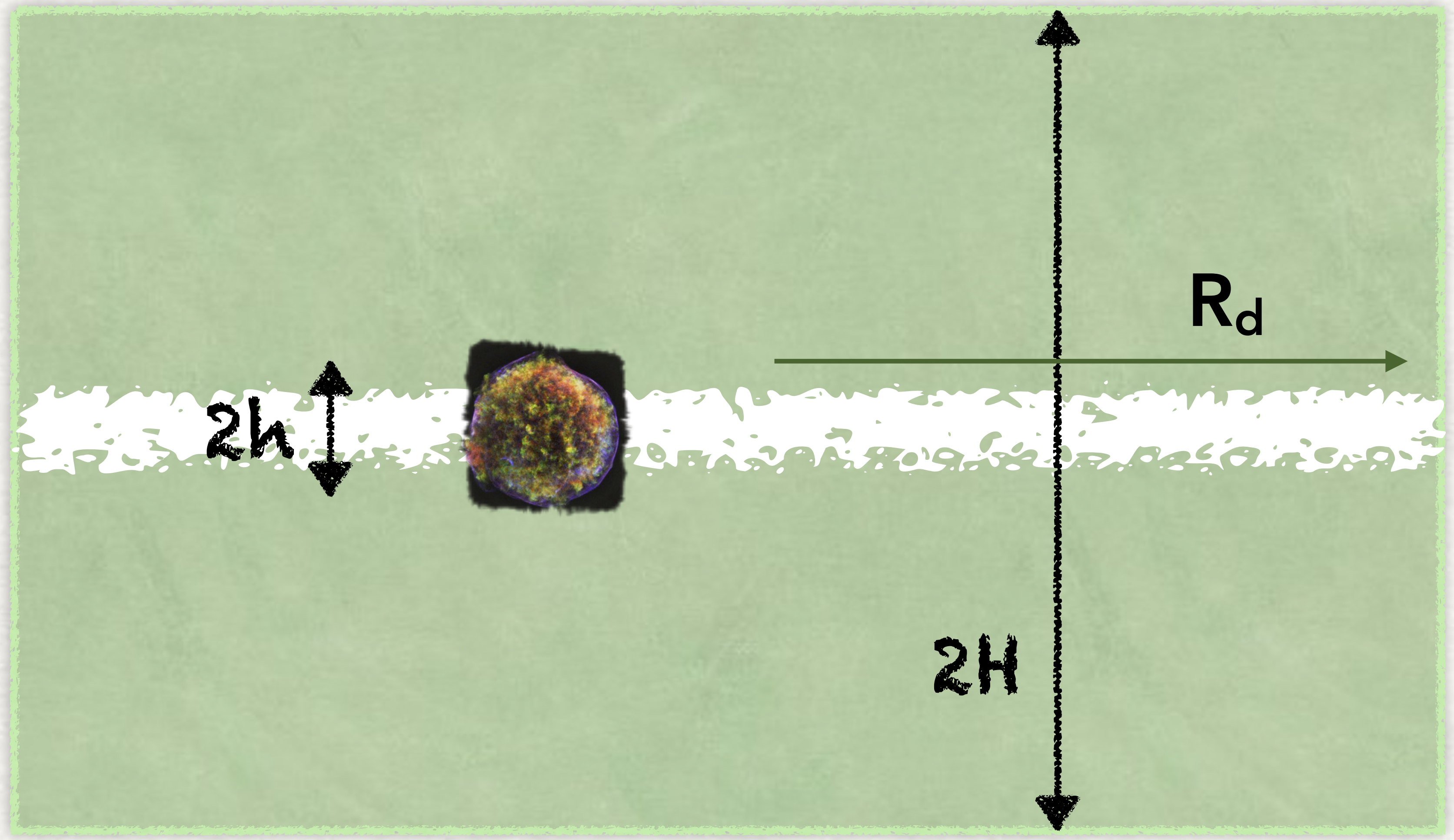
2 $$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q(p,z)$$

DIFFUSION EQUATION

3 $$f(z=H,p) = 0$$

FREE ESCAPE BOUNDARY

A TOY MODEL FOR PROTONS IN OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

1. *CR are injected in an infinitely thin disc*
2. *CR diffuse in the whole volume*
3. *CR freely escape from a boundary*

1. $$Q(p,z) = \frac{Q_0(p)}{\pi R_d^2}\delta(z)$$

2. $$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q(p,z)$$

DIFFUSION EQUATION

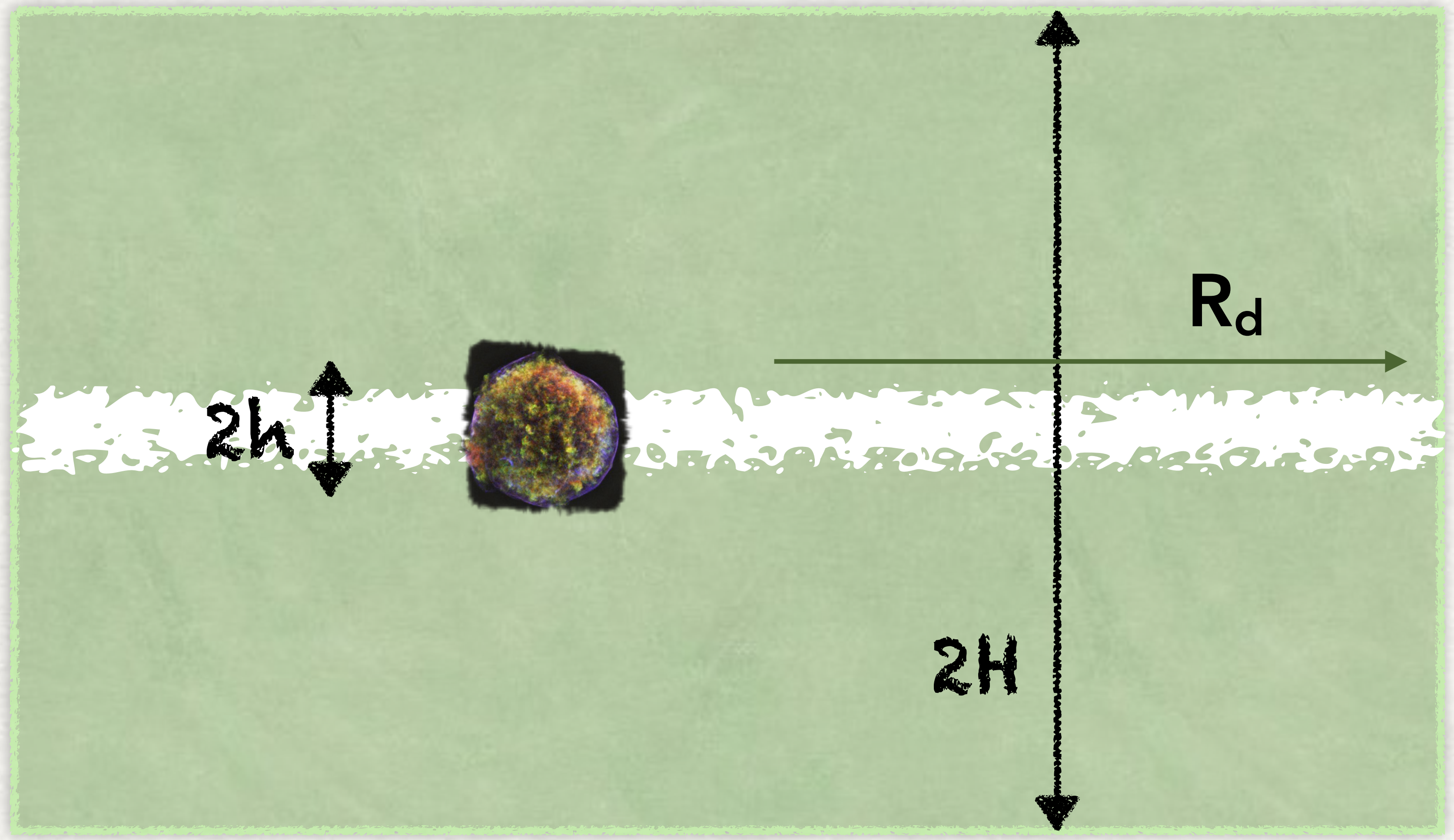
3. $$f(z=H,p)=0$$

FREE ESCAPE BOUNDARY

For $z \neq 0$:

$$D\frac{\partial f}{\partial z} = Constant \rightarrow f(z) = f_0\left(1-\frac{z}{H}\right)$$

A TOY MODEL FOR PROTONS IN OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

1. *CR are injected in an infinitely thin disc*
2. *CR diffuse in the whole volume*
3. *CR freely escape from a boundary*

1 $$Q(p,z) = \frac{Q_0(p)}{\pi R_d^2}\delta(z)$$

2 $$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = Q(p,z)$$

DIFFUSION EQUATION

3 $$f(z=H,p) = 0$$

FREE ESCAPE BOUNDARY

For z≠0:

$$D\frac{\partial f}{\partial z} = Constant \rightarrow f(z) = f_0\left(1-\frac{z}{H}\right)$$

$$D\frac{\partial f}{\partial z}|_{z=0^+} = -D\frac{f_0}{H}$$

A TOY MODEL FOR OUR GALAXY

Let us now integrate the diffusion equation around z=0

$$-\frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] = \frac{Q_0(p)}{\pi R_d^2}\delta(z) \Rightarrow -2D\frac{\partial f}{\partial z}|_{z=0^+} = \frac{Q_0(p)}{\pi R_d^2}$$

and recalling that

$$D\frac{\partial f}{\partial z}|_{z=0^+} = -D\frac{f_0}{H} \Rightarrow f_0(p) = \frac{Q_0(p)}{2\pi R_d^2}\frac{H}{D} = \frac{Q_0(p)}{2\pi R_d^2 H}\frac{H^2}{D}$$

Diffusion Time

Rate of injection per unit volume

Since $Q_0(p) \sim p^{-\gamma}$ and $D(p) \sim p^{\delta}$
$f_0(p) \sim p^{-\gamma-\delta}$

MEANING OF FREE ESCAPE BOUNDARY?

The physics of CR transport is as much regulated by diffusion as it is by boundary conditions (this is true for toy models as well as it is for GALPROP)

What does "free escape" mean? $f(z=H,p)=0$

Conservation of flux at the boundary implies:

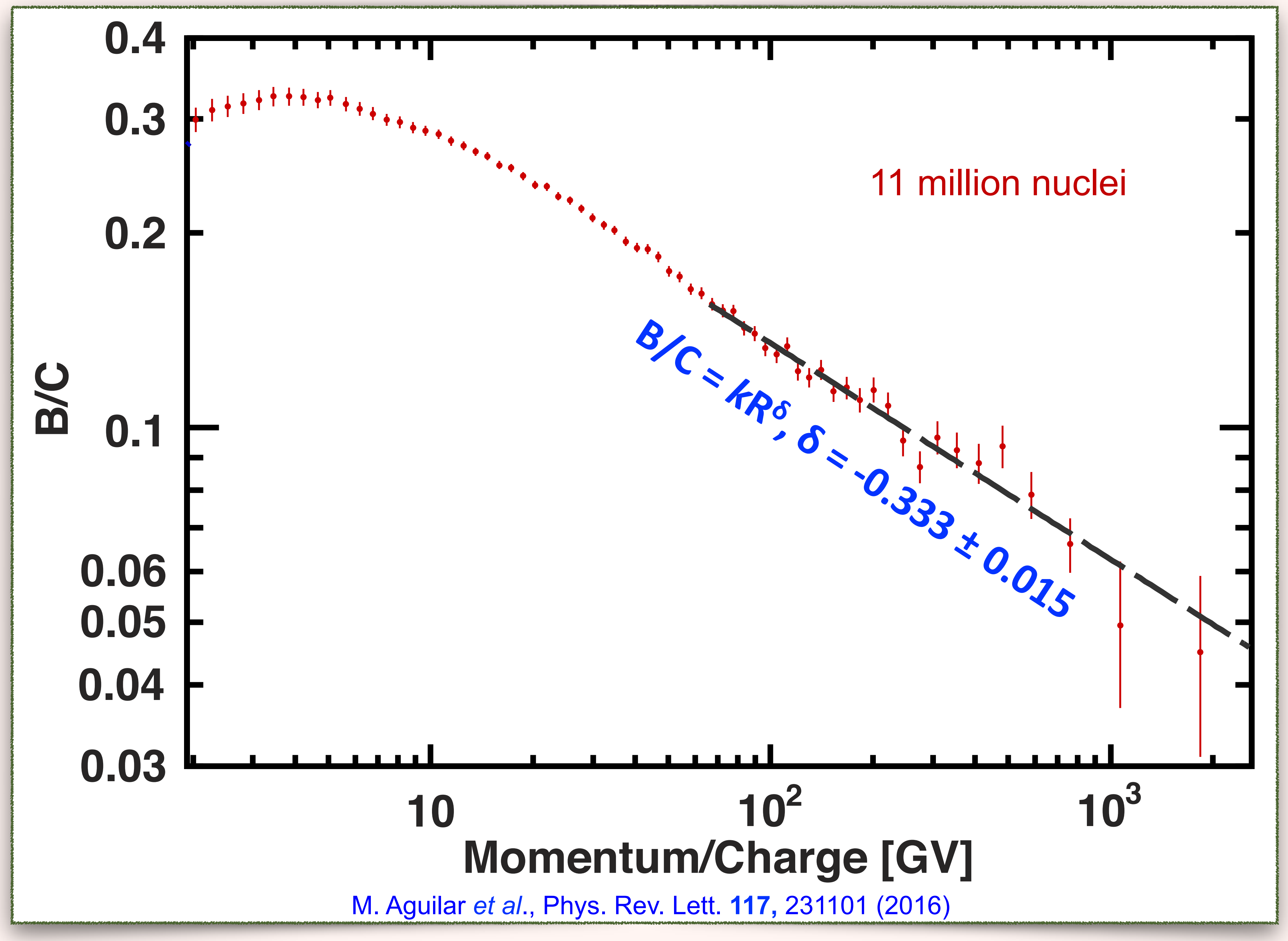
$$D\frac{\partial f}{\partial z}|_{z=H} = \frac{c}{3} f_{out}$$

$$D\frac{f_0}{H} = \frac{c}{3} f_{out} \rightarrow f_{out} = \frac{3D}{cH} f_0 \approx \frac{\lambda(p)}{H} f_0 \ll f_0$$

Beware that despite the great importance of this assumption we do not have any handle on what determines the halo size or wether the halo size depends on energy *(but see Evoli, PB, Aloisio & Morlino 2018 for a theoretical approach to this important topic)*

SECONDARY/PRIMARY: B/C

Evidence for CR diffusive transport



primary equilibrium

$$n_{pr}(E/n) \propto Q(E/n)\tau_{diff}(E/n)$$

rate of secondary injection

$$q_{sec}(E/n) \approx n_{pr}(E/n)\sigma v n_{gas}$$

secondary equilibrium

$$n_{sec}(E/n) \approx q_{sec}(E/n)\tau_{diff}(E/n)$$

$$\frac{n_{sec}}{n_{pr}} \approx \frac{\sigma}{m_p}[v n_{gas} m_p \tau_{diff}]$$

GRAMMAGE: $X(E/n) \propto \tau_{diff}(E/n) \sim 1/D(E/n)$

Phenomenology vs observations of nuclei (H, He, ...)

DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k=p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha'>\alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha'\to\alpha}\delta(z) I_{\alpha'}(E_k)$$

THIS IS A SET OF ABOUT 80 COUPLED PARTIAL DIFFERENTIAL EQUATIONS FOR STABLE AND UNSTABLE PRIMARY AND SECONDARY NUCLEI

DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k = p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

DIFFUSION

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha'>\alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha'\to\alpha}\delta(z) I_{\alpha'}(E_k)$$

THIS IS A SET OF ABOUT 80 COUPLED PARTIAL DIFFERENTIAL EQUATIONS FOR STABLE AND UNSTABLE PRIMARY AND SECONDARY NUCLEI

DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k = p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

DIFFUSION

SPALLATION OF NUCLEI **α**

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha' > \alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha' \to \alpha}\delta(z) I_{\alpha'}(E_k)$$

THIS IS A SET OF ABOUT 80 COUPLED PARTIAL DIFFERENTIAL EQUATIONS FOR STABLE AND UNSTABLE PRIMARY AND SECONDARY NUCLEI

DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k = p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

DIFFUSION

SPALLATION OF NUCLEI **α**

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha' > \alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha' \to \alpha}\delta(z) I_{\alpha'}(E_k)$$

INJECTION OF NUCLEI **α**

THIS IS A SET OF ABOUT 80 COUPLED PARTIAL DIFFERENTIAL EQUATIONS FOR STABLE AND UNSTABLE PRIMARY AND SECONDARY NUCLEI

DESCRIPTION OF TRANSPORT OF NUCLEI

For nuclei of mass A, it is customary to introduce the flux as a function of the kinetic energy per nucleon E_k: $I_\alpha(E_k)dE_k = p^2 F_\alpha(p)\, v(p)\, dp$ which implies: $I_\alpha(E_k) = Ap^2 F_\alpha(p)$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{\partial I_\alpha(E_k)}{\partial z}\right] + 2h_d n_d v(E_k)\sigma_\alpha \delta(z) I_\alpha(E_k) =$$

DIFFUSION

SPALLATION OF NUCLEI **α**

$$= 2Ap^2 h_d q_{0,\alpha}(p)\delta(z) + \sum_{\alpha'>\alpha} 2h_d n_d\, v(E_k)\sigma_{\alpha'\to\alpha}\delta(z) I_{\alpha'}(E_k)$$

INJECTION OF NUCLEI **α**

CONTRIBUTION TO NUCLEI **α** FROM SPALLATION OF NUCLEI **α'>α**

THIS IS A SET OF ABOUT 80 COUPLED PARTIAL DIFFERENTIAL EQUATIONS FOR STABLE AND UNSTABLE PRIMARY AND SECONDARY NUCLEI

A PHENOMENOLOGICAL APPROACH

To start with we can try to solve these equations by using physics-inspired forms for the diffusion coefficient and available data/fits for the cross sections

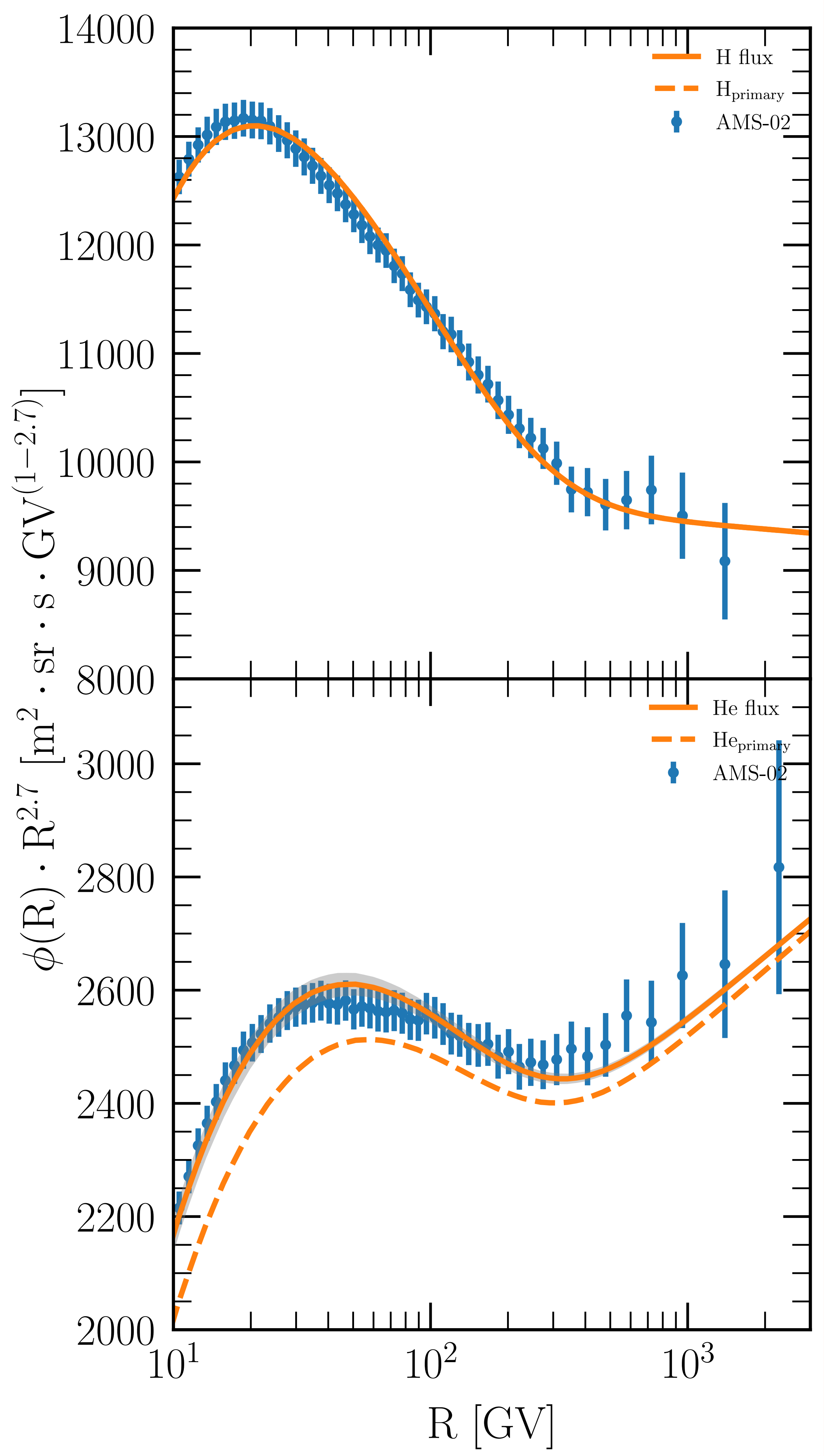
$$D(R) = 2v_A H + \beta D_0 \frac{(R/\mathrm{GV})^{\delta}}{[1+(R/R_b)^{\Delta\delta/s}]^{s}}$$

The plateau at low energies is inspired by self-generated solutions. The break is required to describe the breaks in the spectra of primary and secondary nuclei. The parameter s determines the smoothness of the break.

The injection spectra are inspired by DSA theory but they are allowed to be different for H, He and heavier nuclei. NO EXPLANATION IS CURRENTLY AVAILABLE FOR THIS PHENOMENON.

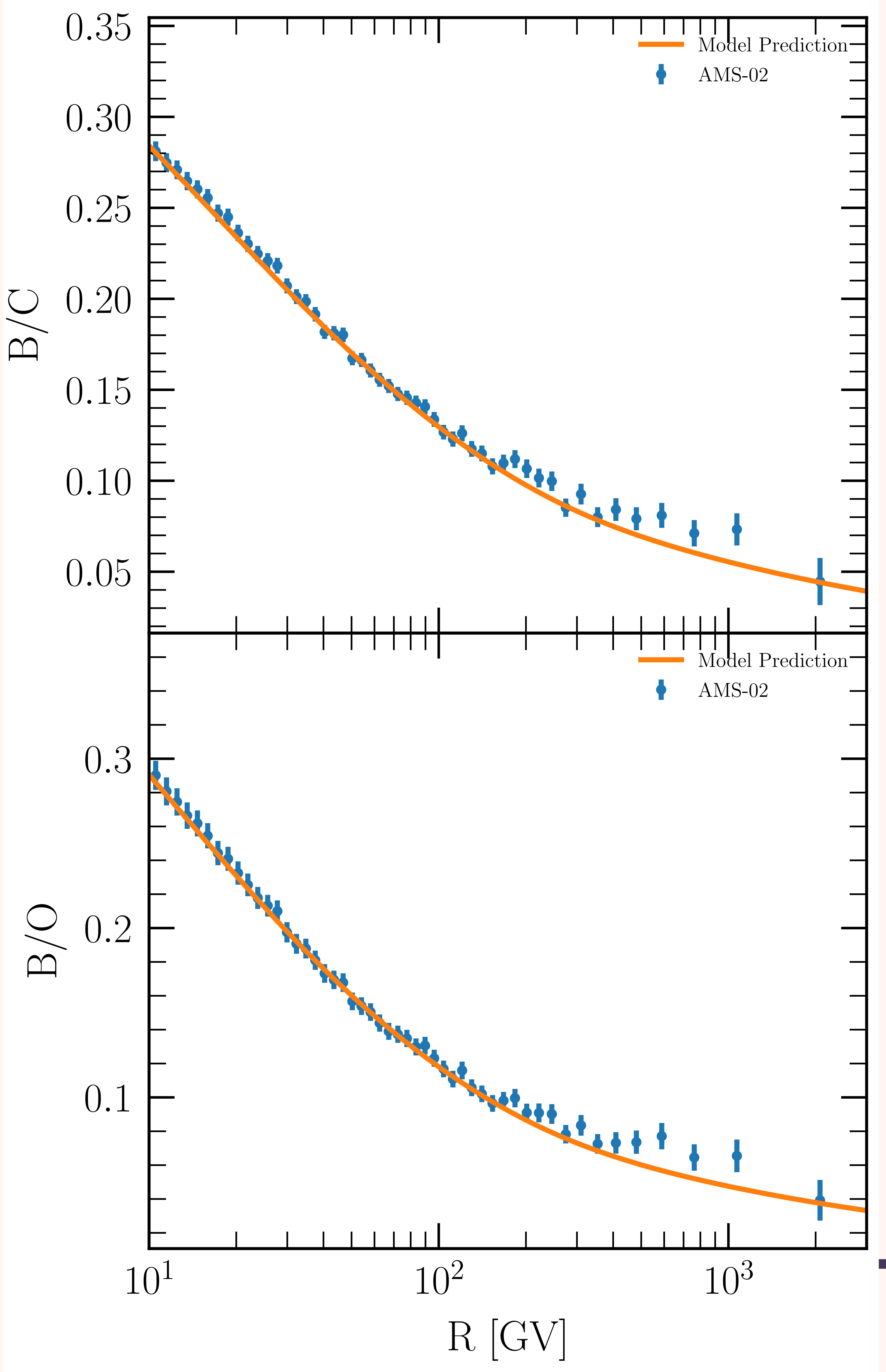
Most inclusive cross sections are known within a 30% error in the energy region around 0.1-10 GeV but in most cases the energy dependence is extrapolated. Moreover the branching ratios for A—> A′ are often affected by much larger uncertainties

SPECTRA OF PROTONS AND HELIUM NUCLEI



- The slopes of the injection spectra for H (4.37) and He (4.31) are slightly different. So far there is no obvious explanation…
- In data from previous generation experiments this difference would not have been seen…
- Notice that this slope does not necessarily reflect the spectrum of accelerated particles (escape, temporal evolution of SNR, other sources)
- Both spectra show a break at rigidity around 300 GV
- The He spectrum as measured by AMS-02 (but also by DAMPE, CALET) is contaminated by ^{3}He resulting from spallation of He and heavier elements

CR CLOCKS: STABLE ELEMENTS



- The B/C and B/O ratios confirm that the diffusion coefficient requires a break at about 300 GV
- These ratios are all degenerate with respect to the ratio H/D_0 but they do fix such ratio (NOT H^2/D, the diffusion time)
- The ratio returns the energy dependence of D(E), assuming that the only thing that we are seeing in these ratios is the energy dependence of the diffusion coefficient and, if any, cross sections
- But at high energies this is not so

IMPORTANT POINT ON SECONDARY/PRIMARY RATIOS

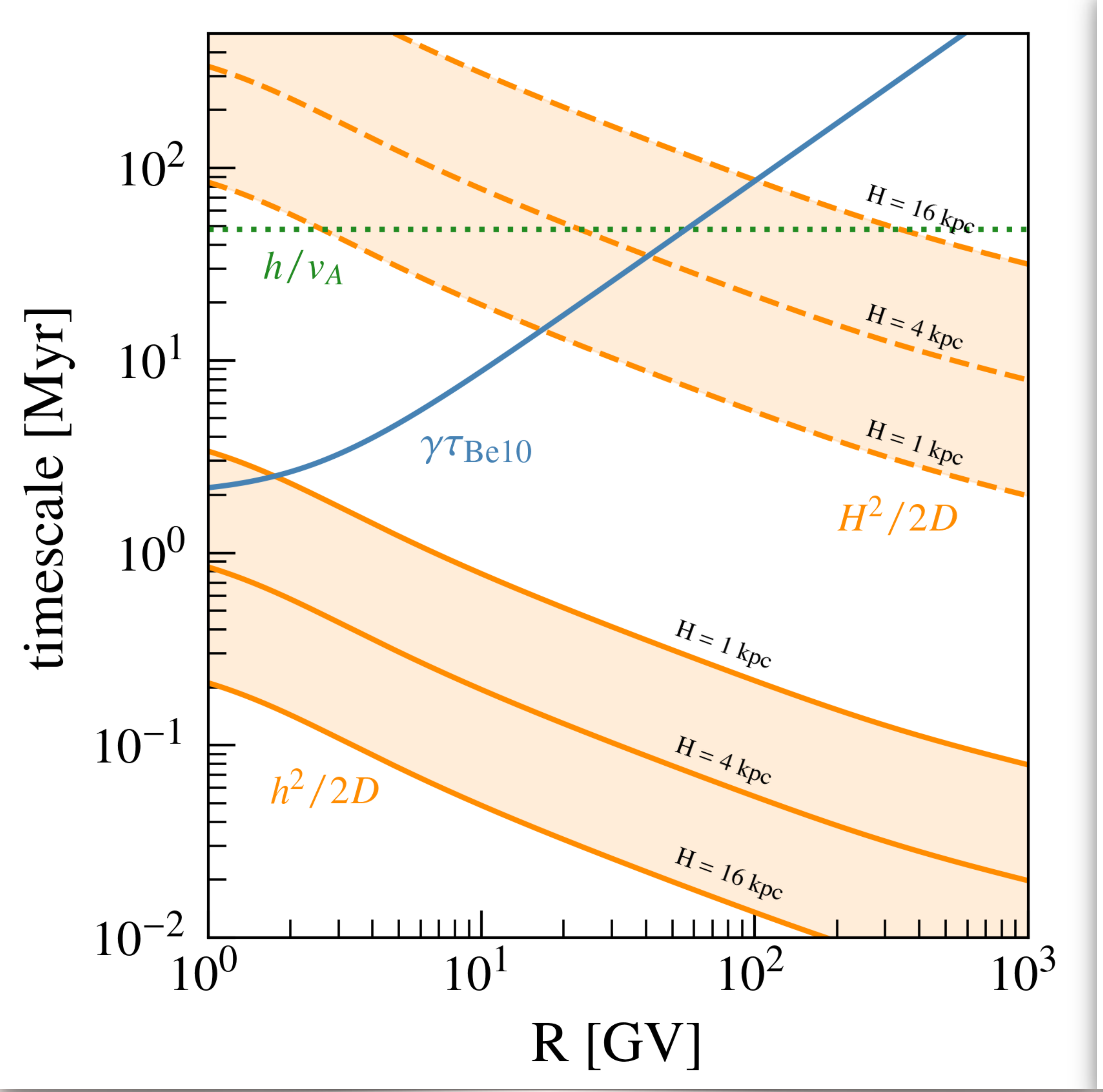
THESE RATIOS ARE OFTEN CONSIDERED AS RELIABLE INDICATORS OF THE GRAMMAGE: ~S/P~$X(R)^{-1}$

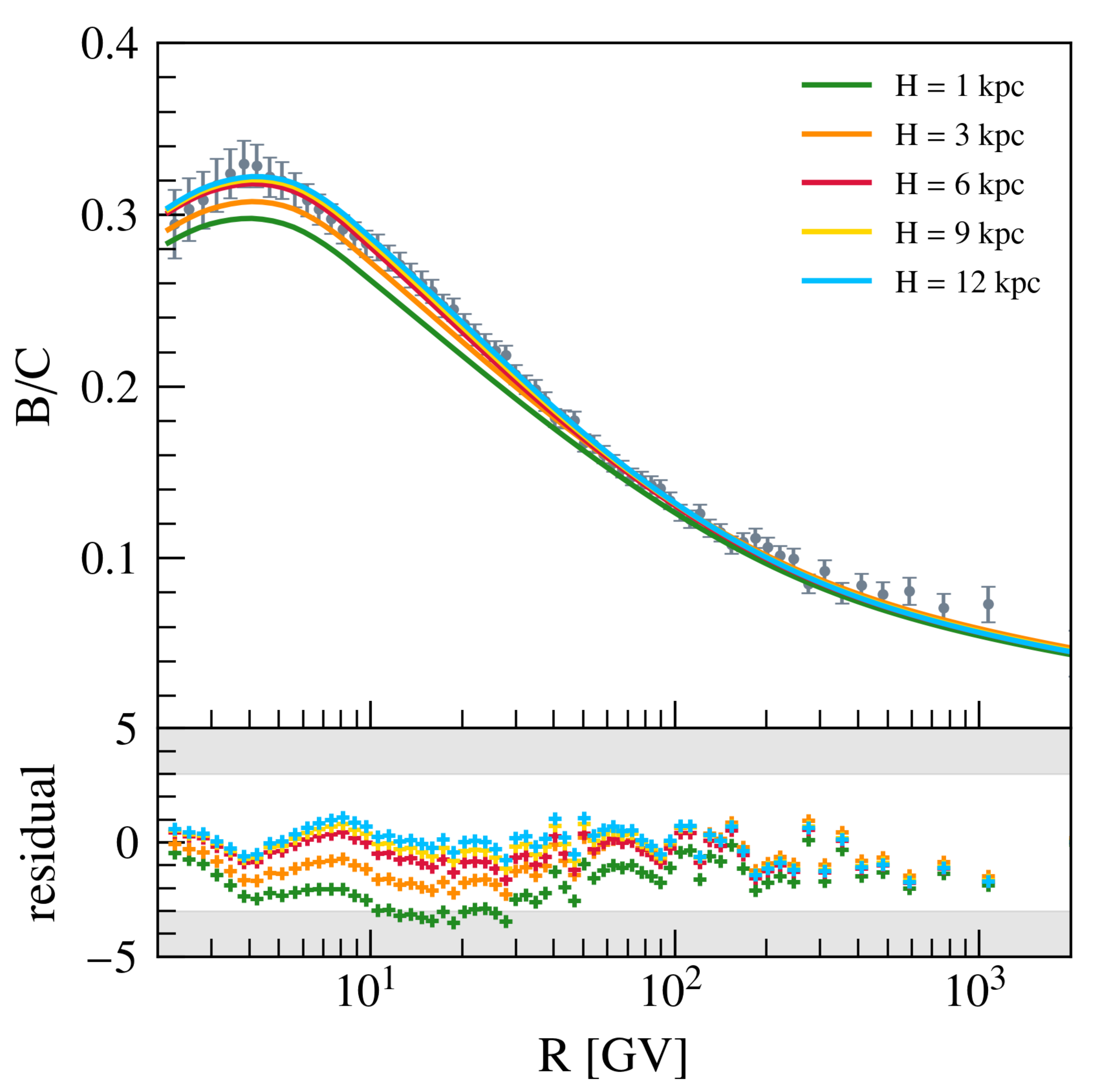
HOWEVER, AT LOW ENERGIES THESE ARE AFFECTED BY UNCERTAINTIES ON WHETHER THERE IS SOME LEVEL OF REACCELERATION (INCOMPATIBLE WITH HAVING SELF-GENERATED WAVES) AND AT HIGH ENERGIES AFFECTED BY:

a) **GRAMMAGE AT THE SOURCE**
b) **PRODUCTION OF SECONDARIES INSIDE THE ACCELERATION REGION** (PB 2009, PB&Serpico 2009,Mertsch+ 2009)
c) **FIRST ORDER RE-ENERGIZATION OF SECONDARY NUCLEI AT THE SOURCES** (PB 2017, Bresci+ 2019)

TO SOME EXTENT ALL OF THESE EFFECTS LEAD TO A FLATTENING OF THE SECONDARY/PRIMARY RATIOS AT HIGH ENERGIES (>TeV/n)

CR CLOCKS: UNSTABLE ELEMENTS





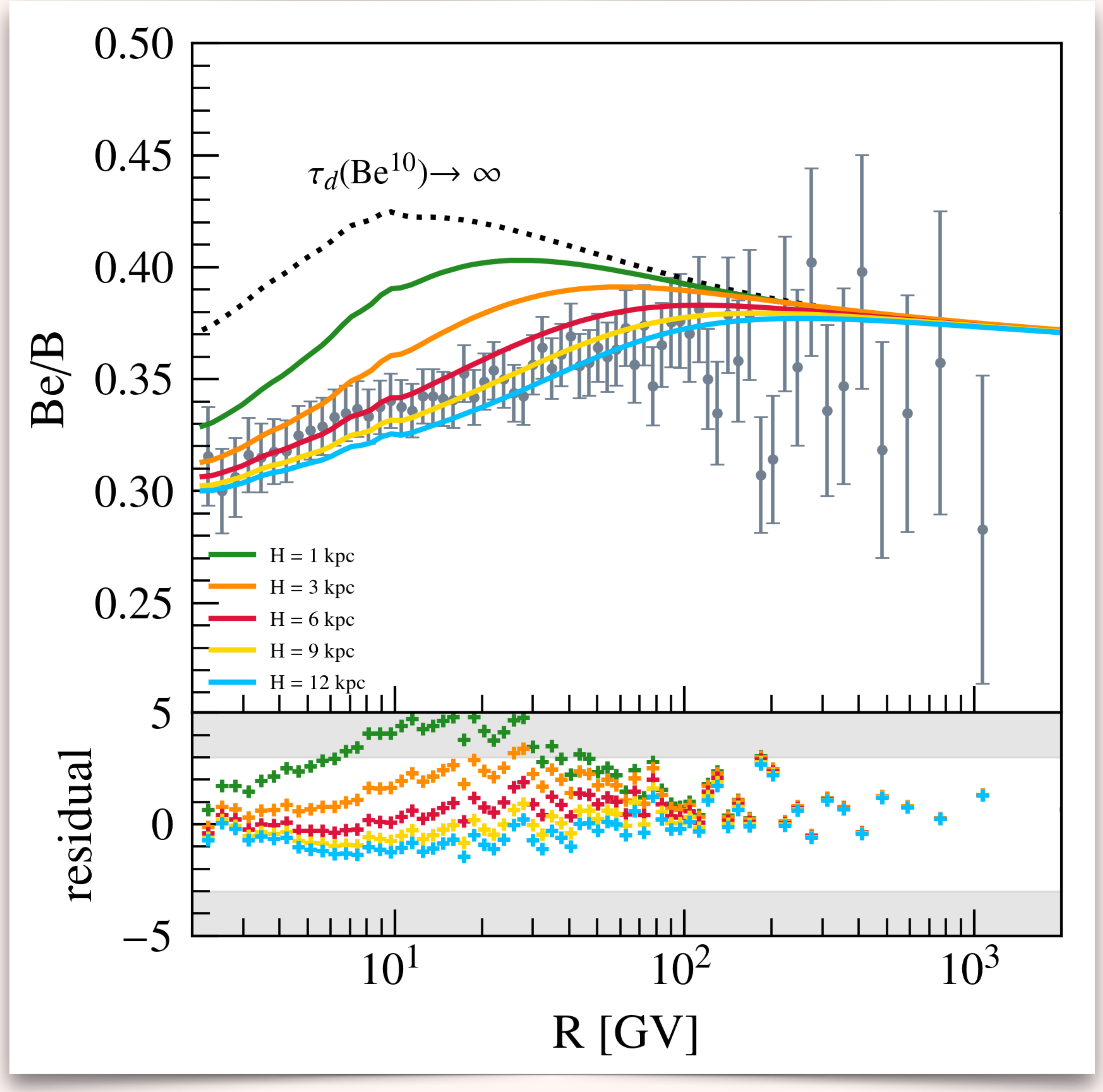
For ^{10}Be with sufficiently high E the Lorentz boosted decay time become longer than the diffusion time

At low energies the decay of ^{10}Be leads to additional production of ^{10}B

IT is easy to understand the ^{10}Be is sensitive to the diffusion time, not only the ratio H/D

Evoli et al. 2020

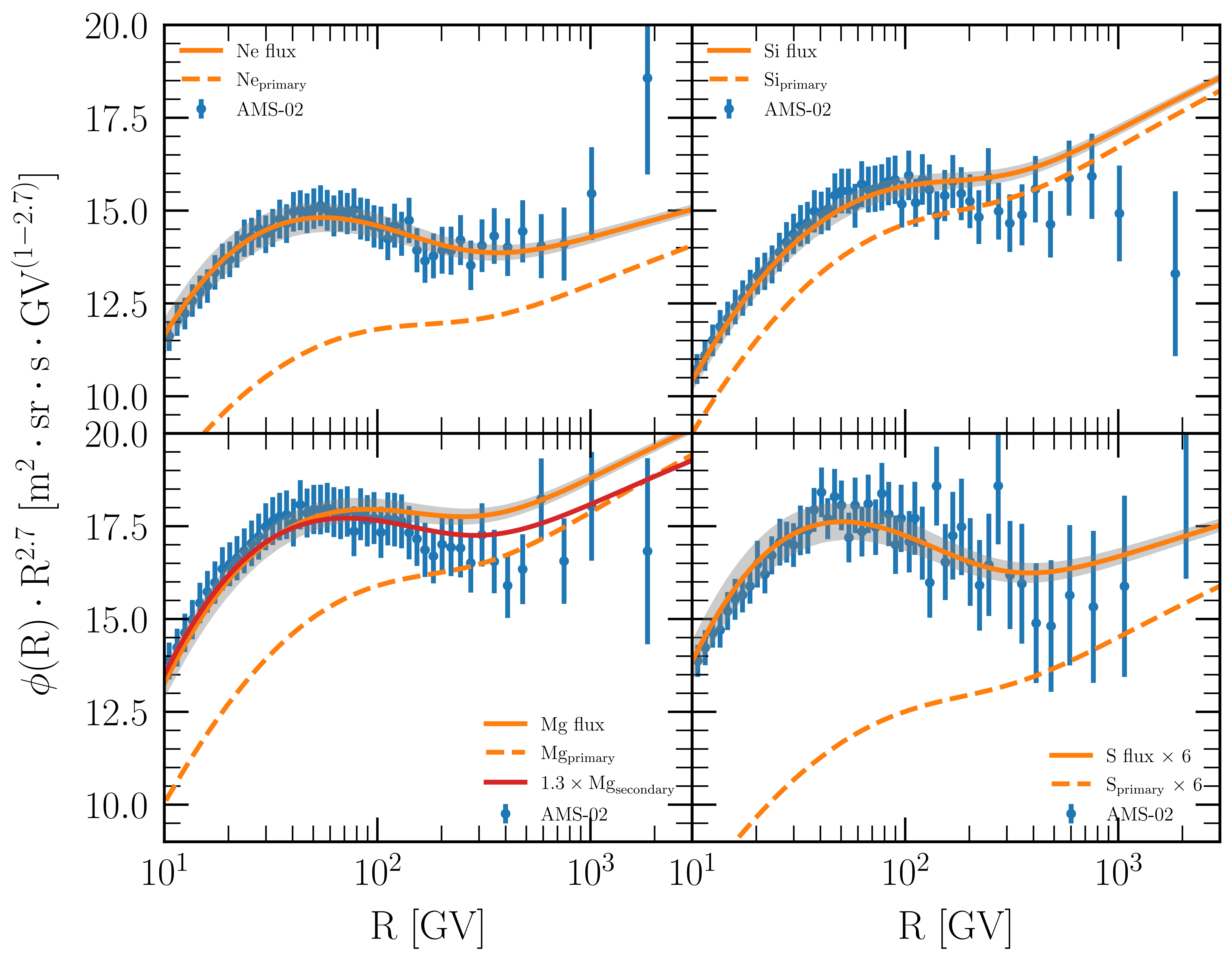
CR CLOCKS: UNSTABLE ELEMENTS

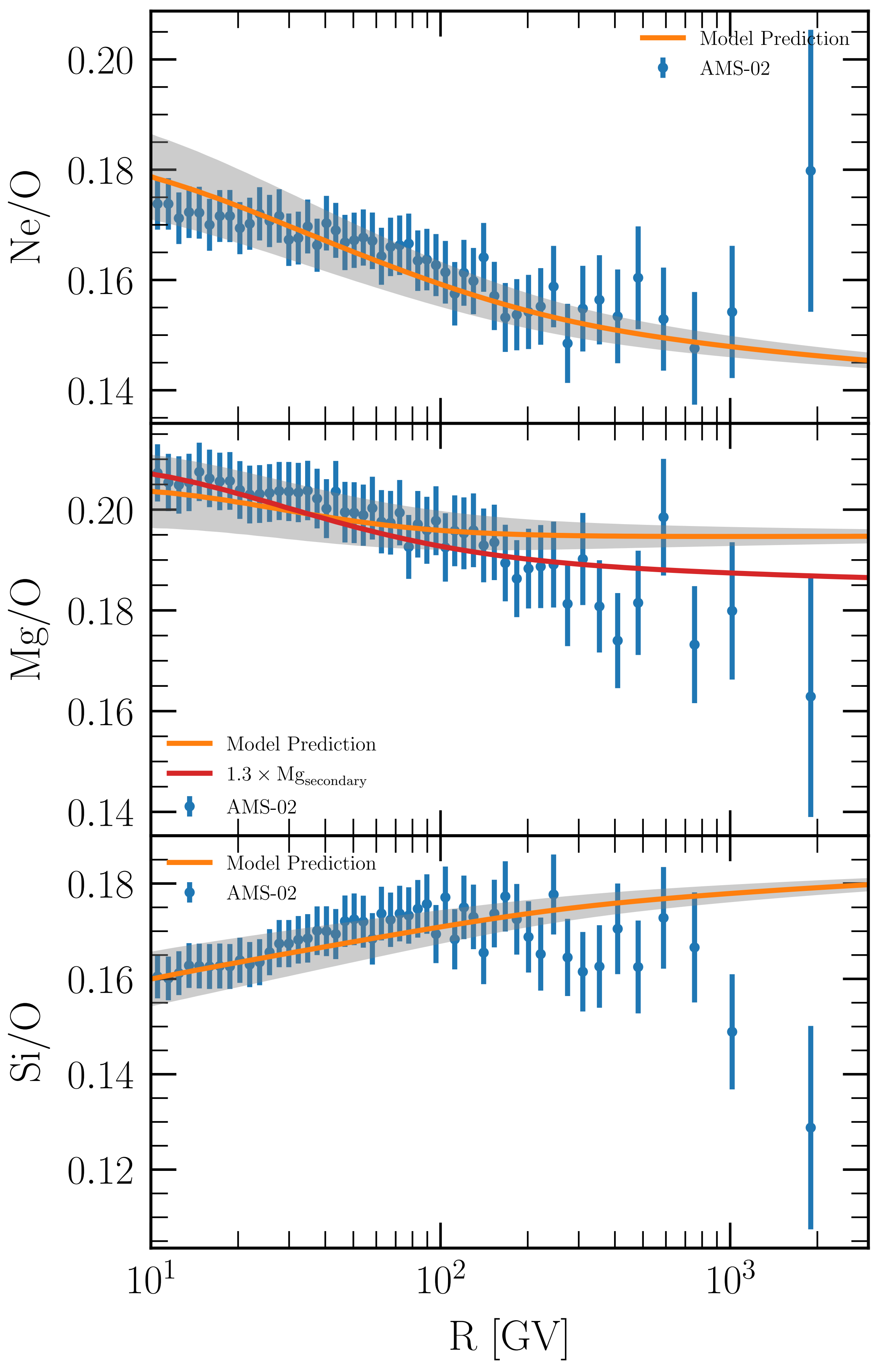


- The Be/B ratio is sensitive to the diffusion time, because the decays of ^{10}Be decrease the numerator and increase the denominator
- The data suggest a halo size larger than 5 kpc
- The main source of uncertainty is related to the cross sections for Be and B production

Evoli et al. 2020

INTERMEDIATE MASS SPECTRA



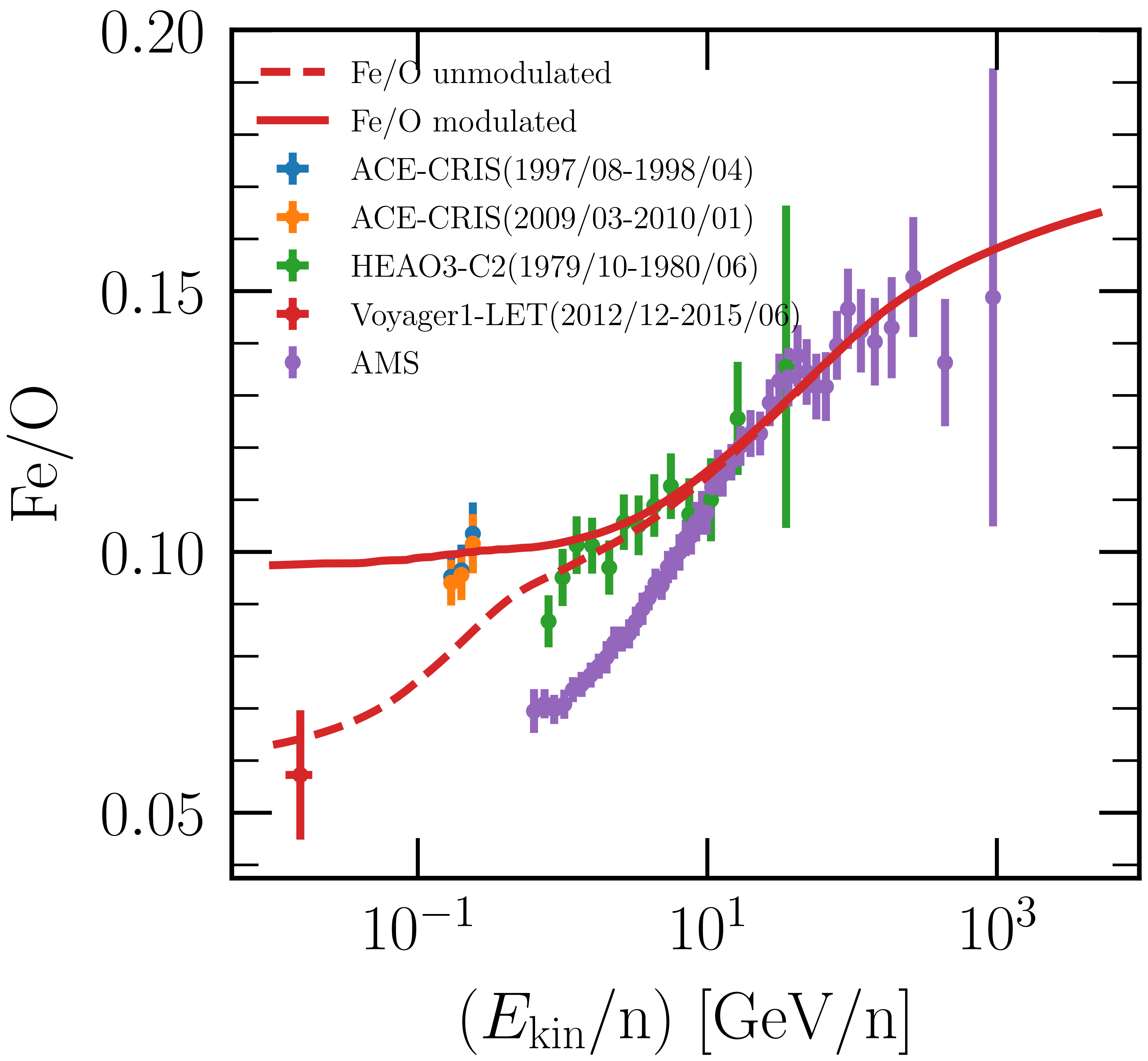


The spectra of intermediate mass elements are all compatible with standard propagation and the same injection spectrum with slope 4.33

Schroer, Evoli & PB 2021

THE CASE OF IRON: the Fe/O ratio

Schroer, Evoli & PB 2022

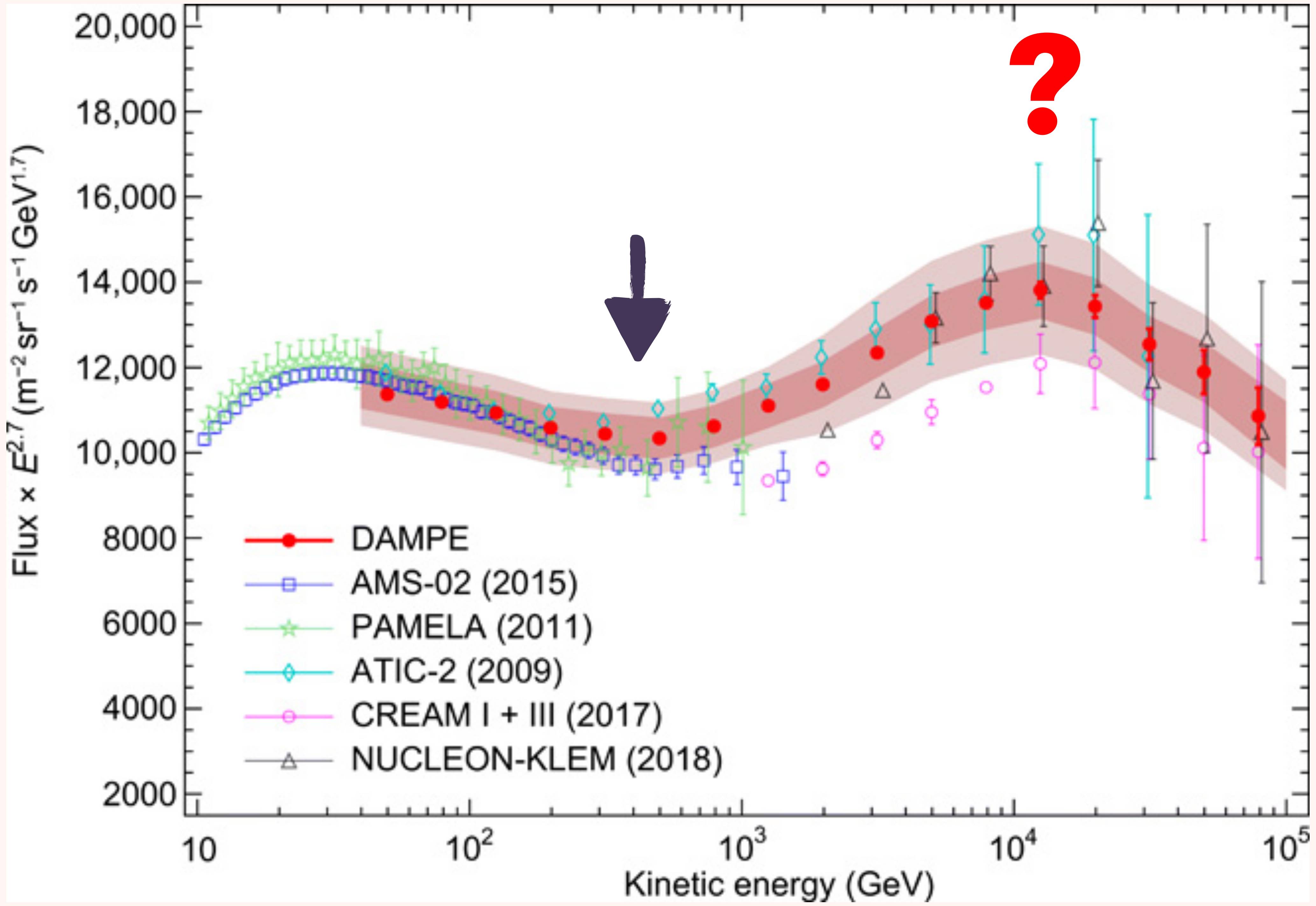


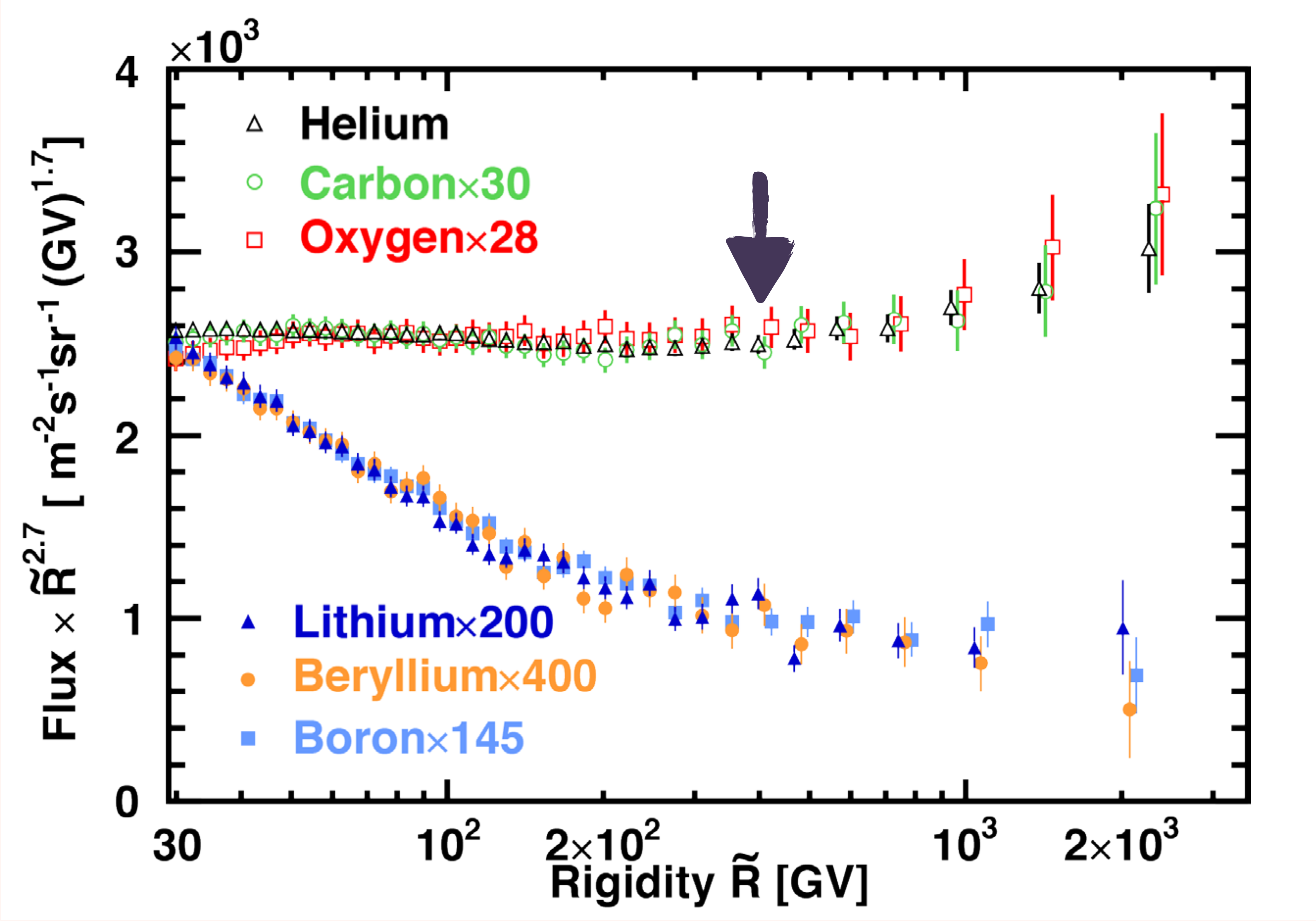
1. *THE CALCULATED RATIO OF MODULATED FLUXES IS IN THE BAD AGREEMENT WITH AMS-02 RESULTS BELOW A FEW TENS GV*
2. *HOWEVER IT IS IN EXCELLENT AGREEMENT WITH PREVIOUS MEASUREMENTS, FOR INSTANCE BY ACE-CRIS AND HEAO03*
3. *THE RATION OF UNMODULATED FLUXES CAN ALSO BE COMPARED WITH VOYAGER DATA, AND AGAIN IT SEEMS IN GOOD AGREEMENT*

WE TRIED SEVERAL POSSIBLE SOURCES OF THEORETICAL UNCERTAINTIES BUT NONE OF THEM TURNS OUT TO BE SUFFICIENT TO EXPLAIN DATA

IT IS WORTH STRESSING THAT FOR IRON THE EFFECTS OF INTERACTIONS IN THE APPARATUS ARE DRAMATIC… MORE INFO IS NEEDED TO CHECK WHAT WOULD BE THE RELATIVE IMPORTANCE OF INTRACTIONS IN AMS FOR O AND Fe

SPECTRUM OF LIGHT AND INTERMEDIATE MASS CR





- ❑ *THE SPECTRA OF SECONDARY NUCLEI ARE BEST EXPLAINED IF THEY ALSO HAVE A BREAK*
- ❑ *ALL PRIMARY NUCLEI HAVE A SPECTRAL BREAK AT AROUND 300 GV RIGIDITY*
- ❑ *HENCE THE BREAK ITSELF MUST FOLLOW FROM A CHANGE IN THE DIFFUSION PROPERTIES OF THE ISM AND NOT IN THE INJECTION OF PARTICLES (IN THIS LATTER CASE THE SECONDARY NUCLEI WOULD SHOW NO BREAK)*

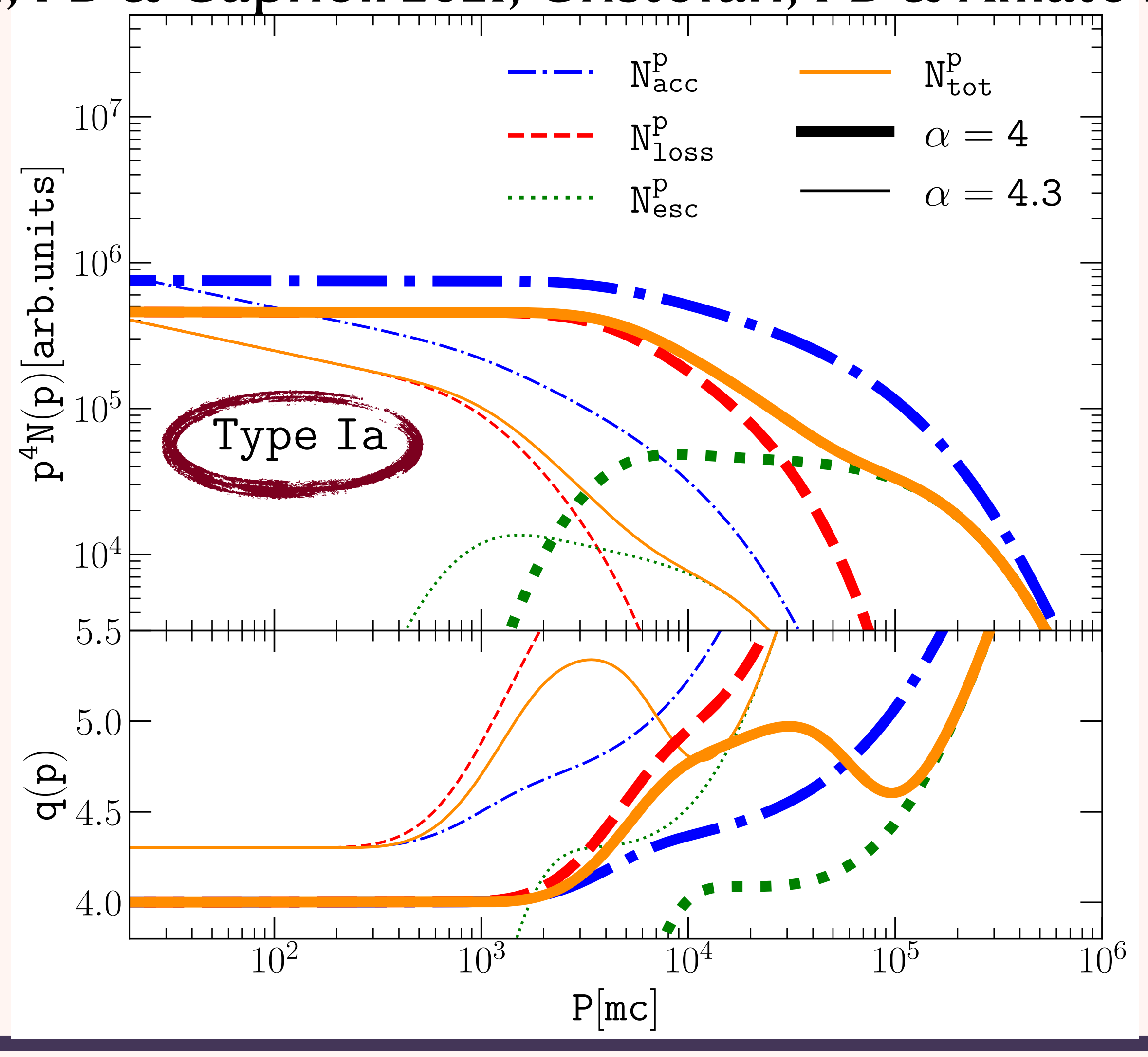
SOME REFLECTIONS ON THE DAMPE FEATURE @ 10 TEV

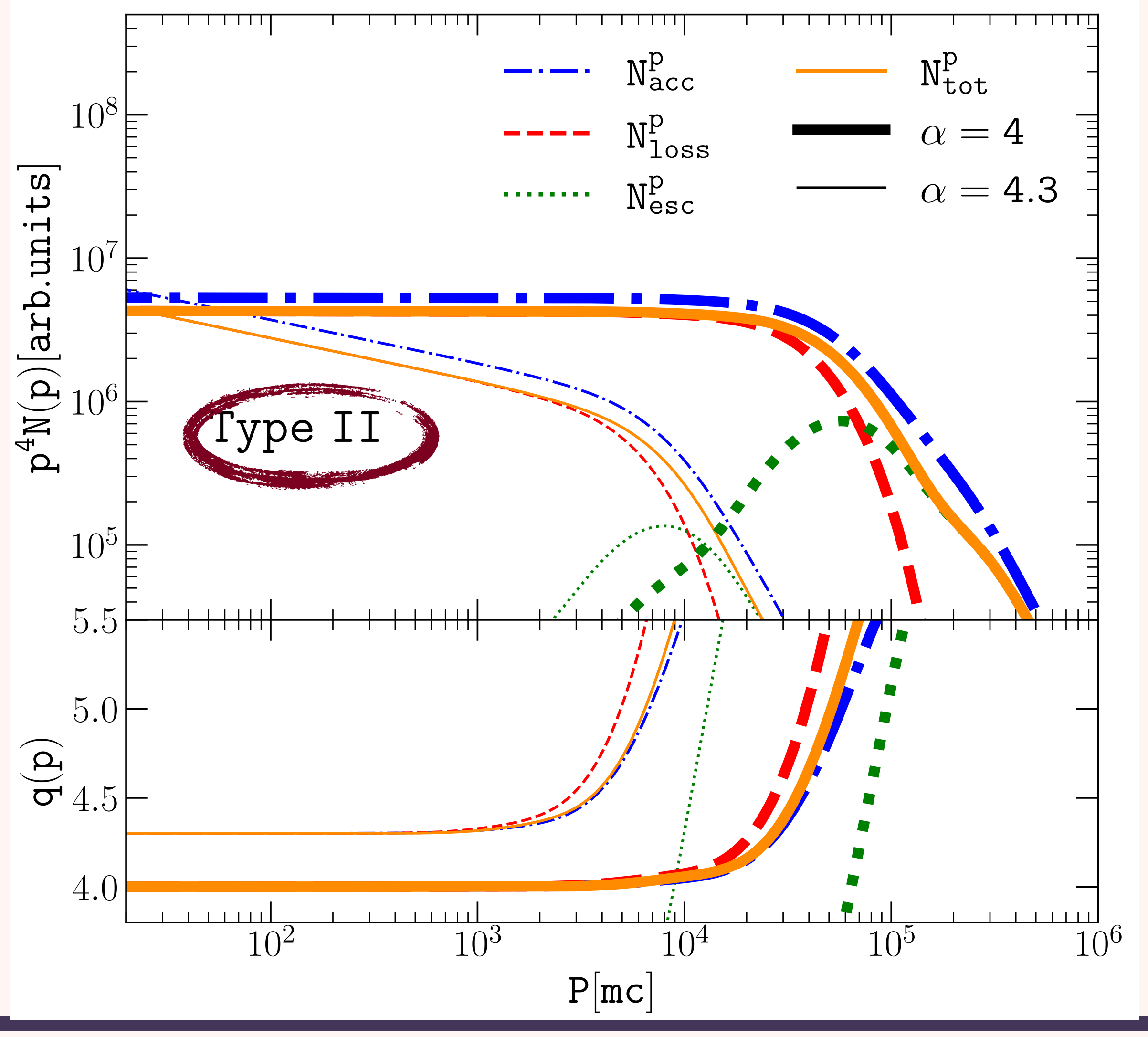
- THE FEATURE HAS NO CURRENT ACCEPTED EXPLANATION

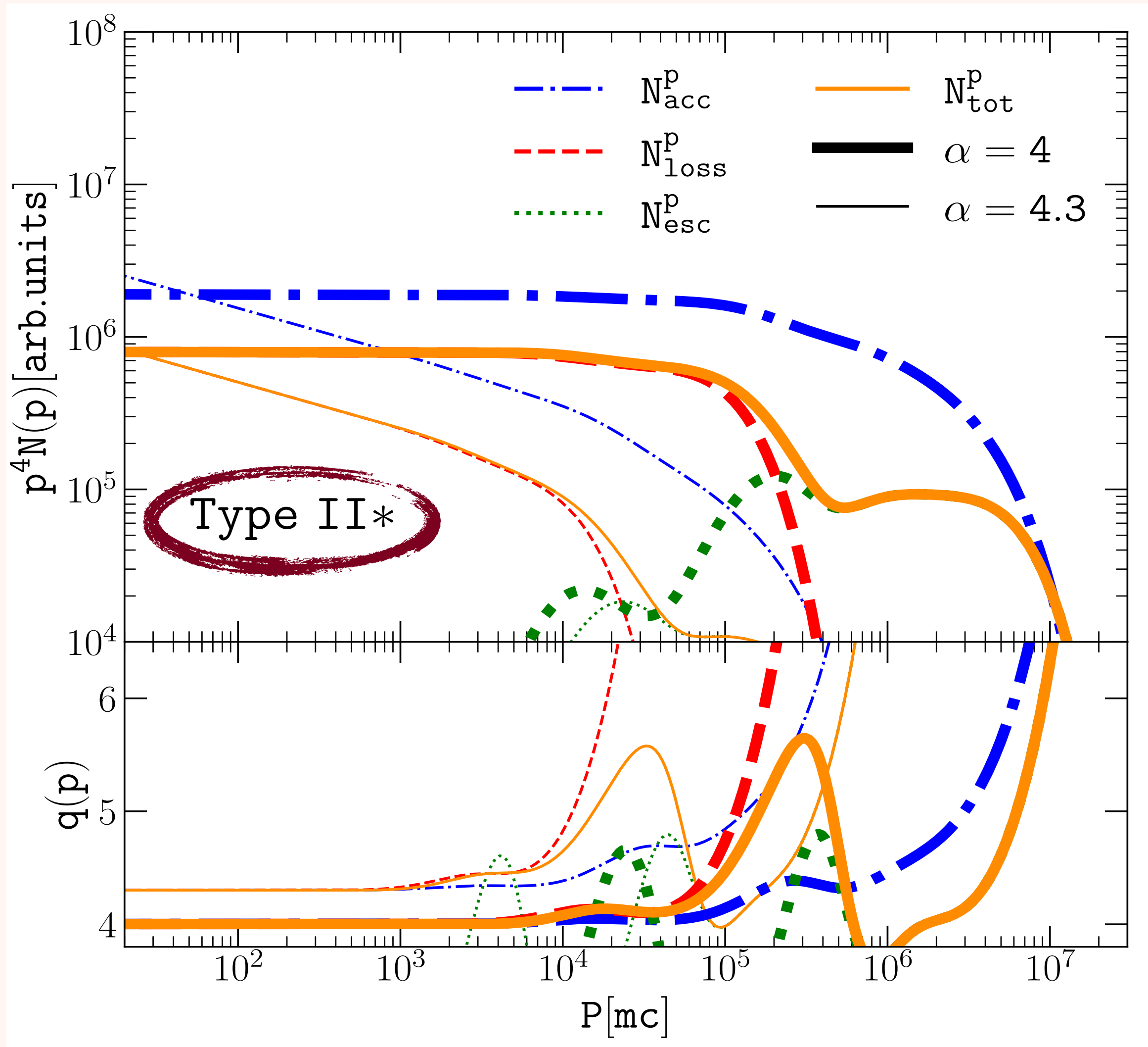
- FLUCTUATIONS IN THE CR PROTON/NUCLEI SPECTRA AT 10 TeV ARE NEGLIGIBLE HENCE IT IS UNLIKELY TO BE DUE TO A LOCAL SOURCE

- THERE ARE SEVERAL CLASSES OF SNR WITH DIFFERENT EMAX… THE DAMPE FEATURE MIGHT BE ASSOCIATED WITH TYPE Ia SNe, OR DIPS IN THE SPECTRA OF CORE COLLAPSE SNe

Cristofari, PB & Caprioli 2021, Cristofari, PB & Amato 2020

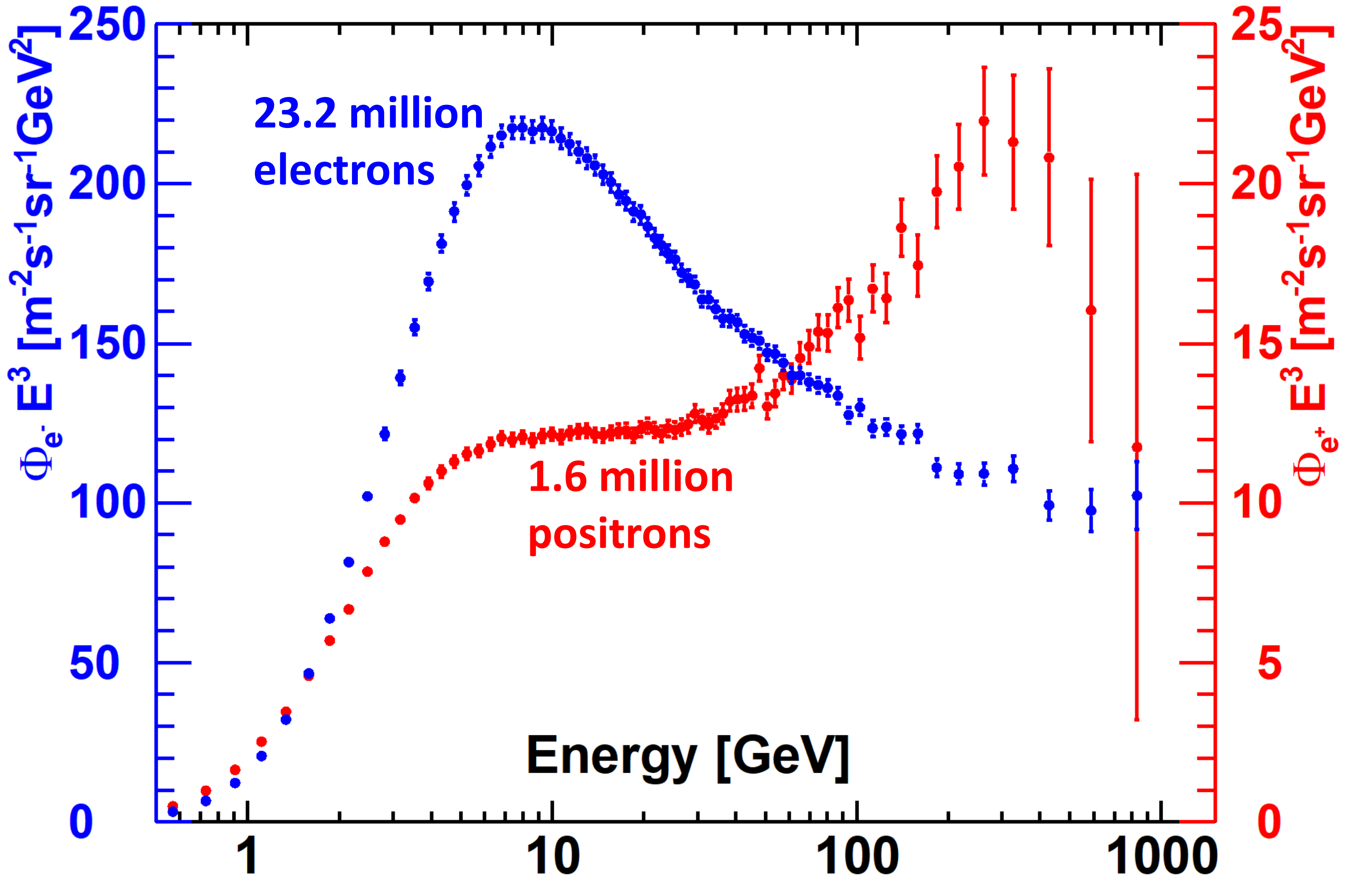


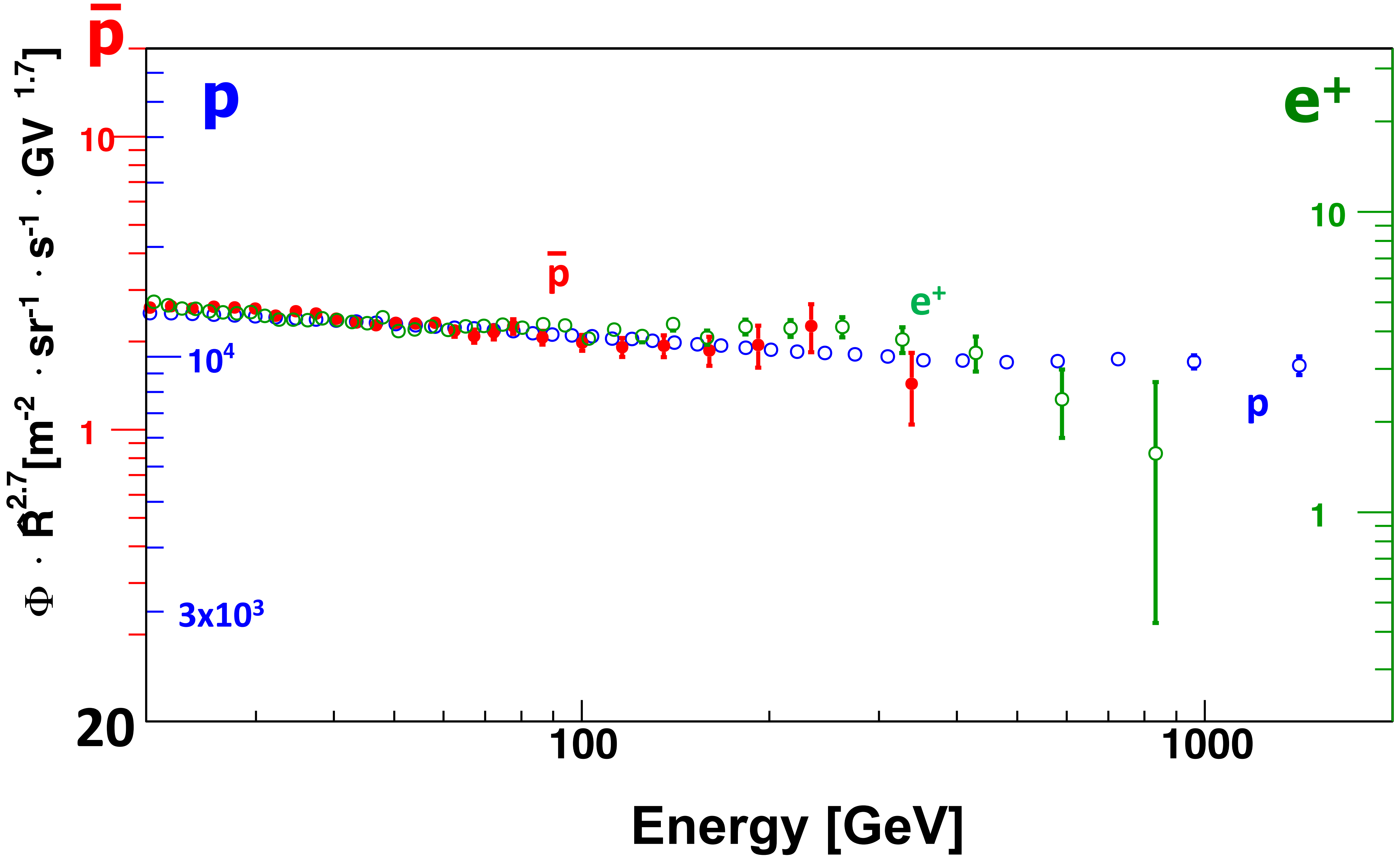




A brief incursion into lepton land

LEPTONS AND ANTIMATTER

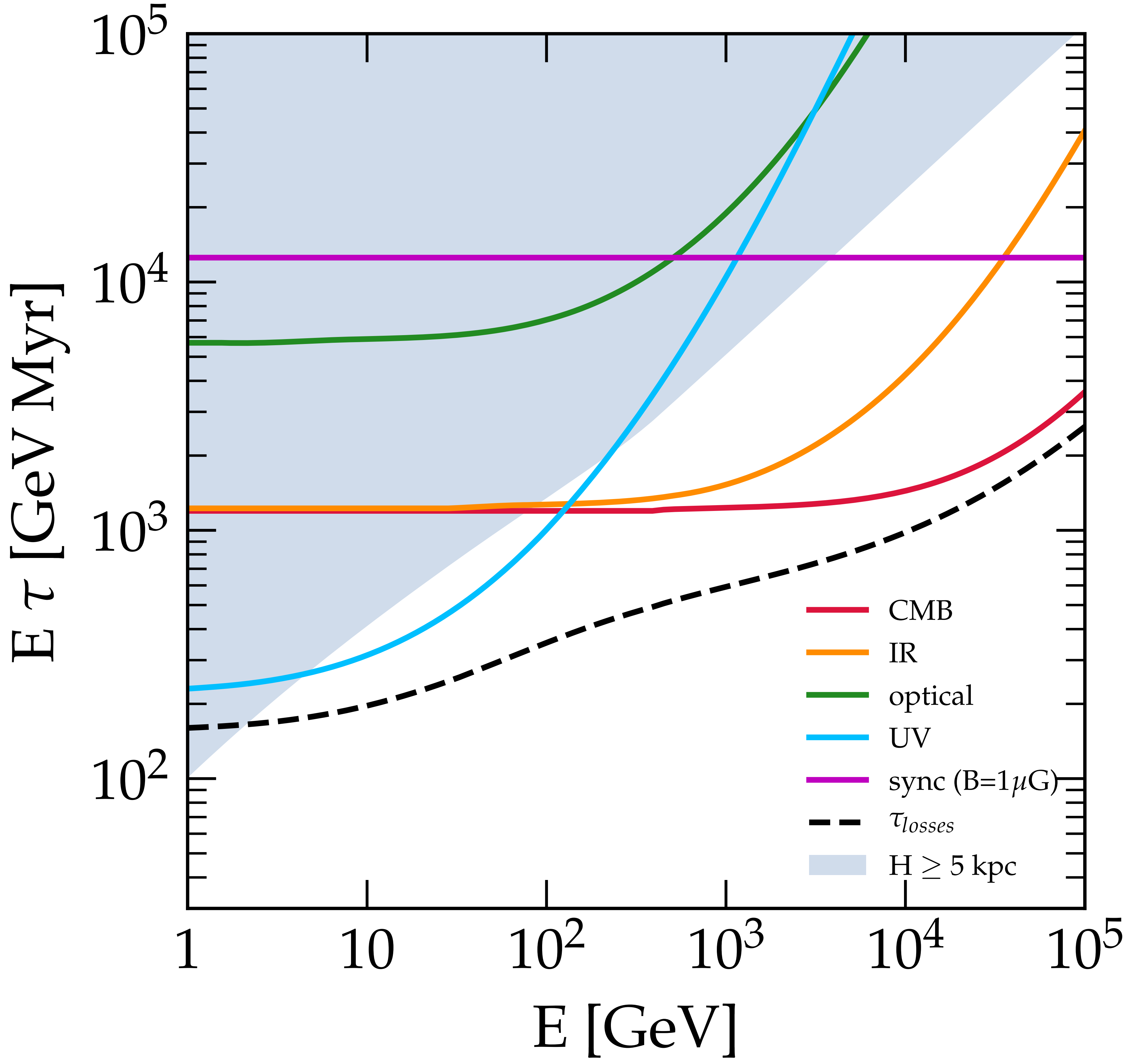


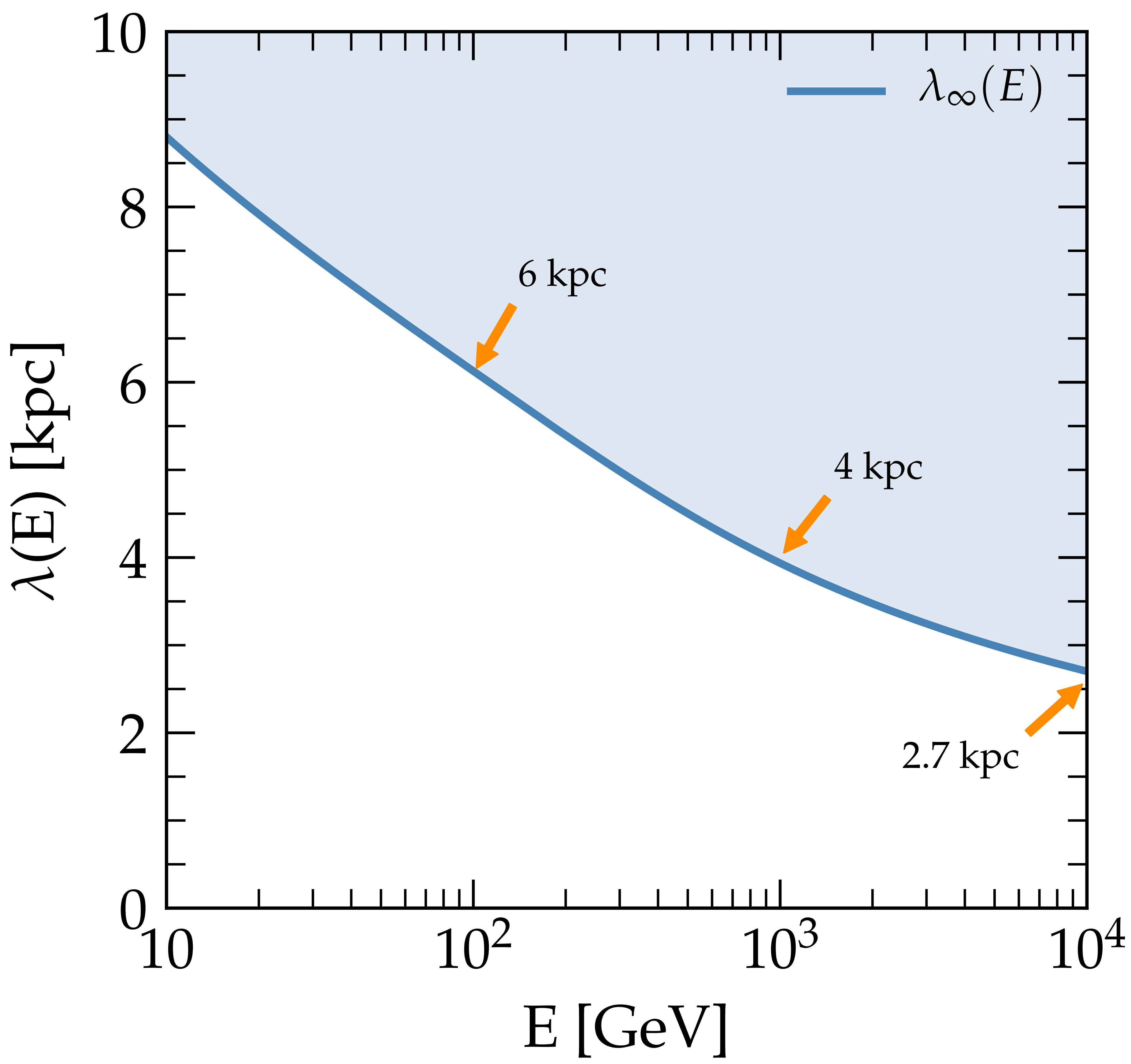


- THE SPECTRA OF ELECTRONS AND POSITRONS ARE DIFFERENT. ELECTRONS ARE MAINLY PRIMARIES
- RATHER PUZZLINGLY THE SPECTRUM OF POSITRONS AND ANTIPROTONS APPEARS IDENTICAL DESPITE LEPTONIC RADIATIVE LOSSES … COINCIDENCE?
- EVEN MORE PUZZLING: SPECTRA OF POSITRONS AND ANTIPROTONS VERY CLOSE TO PROTONS (PRIMARIES)

Physics of CR Leptons: energy losses

Evoli, Amato, PB & Aloisio 2021, PRD 103, 083010

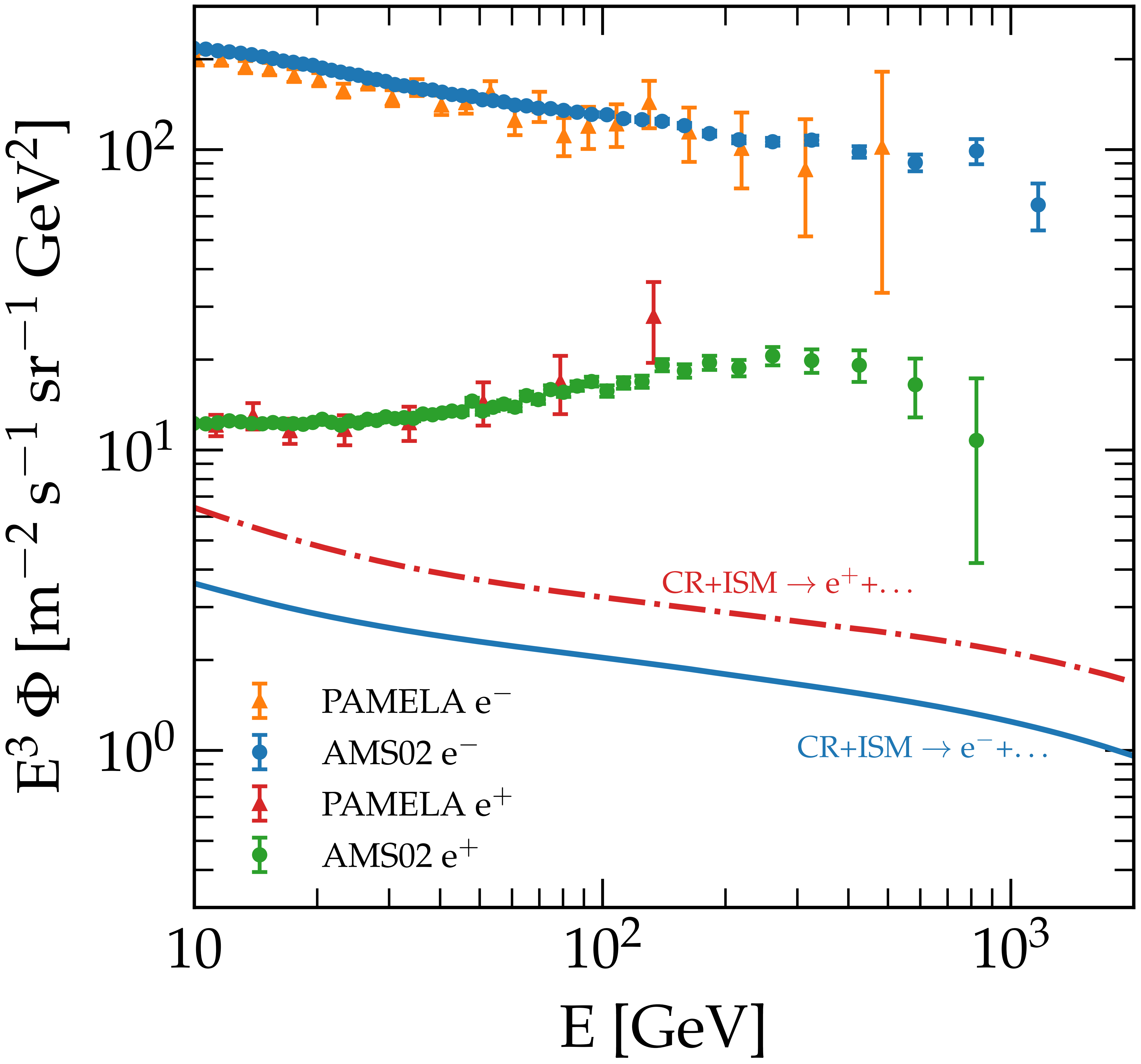




USING THE DIFFUSION COEFFICIENT DERIVED FROM A BEST FIT TO THE HADRONS, THE LEPTONS TRANSPORT IS FIXED. AT HIGH ENERGIES, LOSSES ARE DOMINATED BY ICS AND SYNCHROTRON. ICS ON THE UV LIGHT IS SUBJECT TO A TRANSITION TO KLEIN-NISHINA. THIS INDUCES A FEATURE IN THE LOSS TIMES SCALES, AND AS A RESULT ALSO IN THE ELECTRONS SPECTRUM AT E>40 GeV. THIS LATTER POINT REQUIRES SPIRAL ARMS TO BE TAKEN INTO ACCOUNT

Physics of CR Leptons: secondaries

Evoli, Amato, PB & Aloisio 2021, PRD 103, 083010



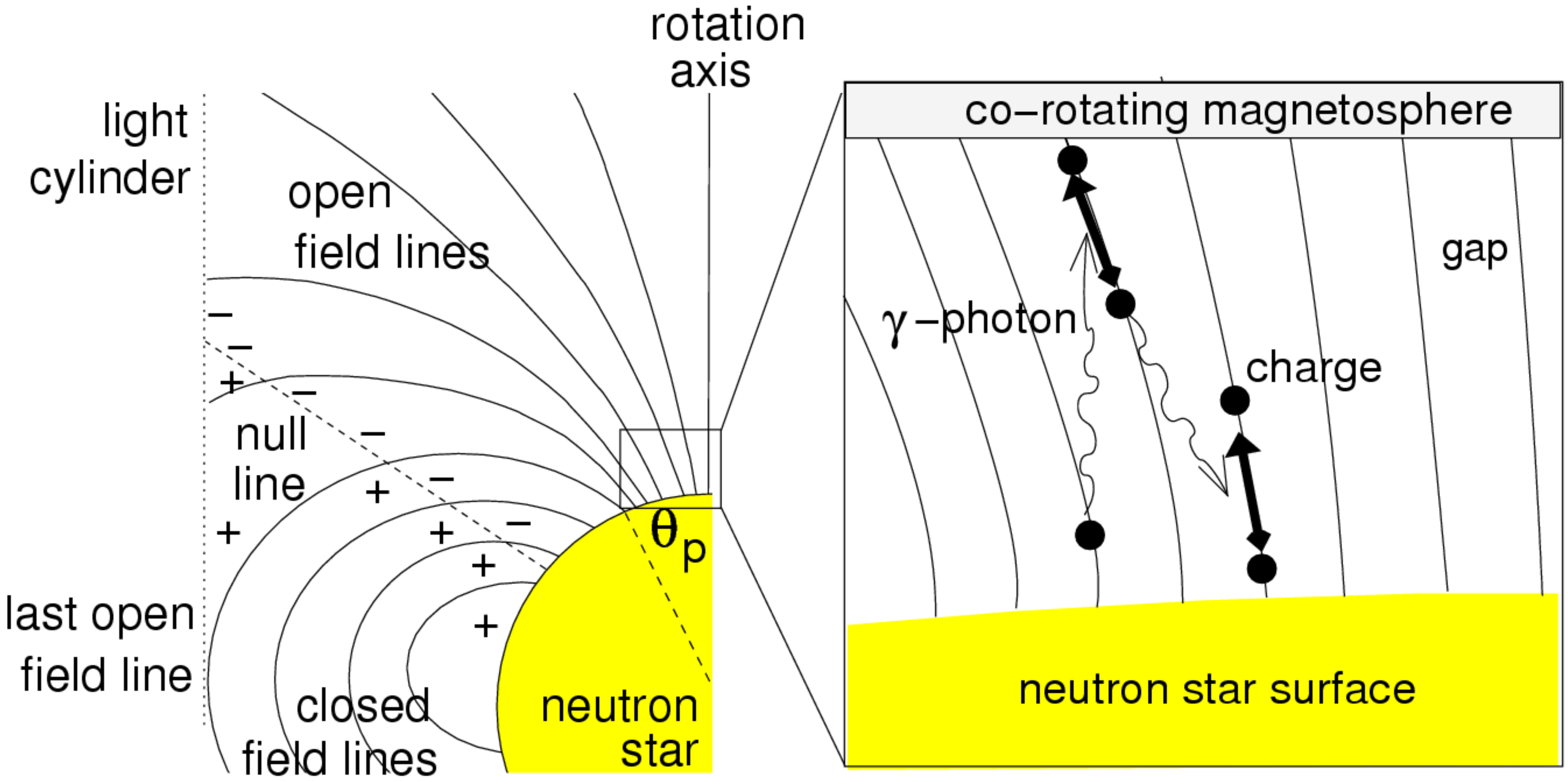
- IT IS CLEAR THAT THE FLUXES OF SECONDARY ELECTRONS AND POSITRONS, FIXED BASED ON THE SECONDARY/PRIMARY RATIOS ARE MUCH LOWER THAN OBSERVATIONS
- AS A CONSEQUENCE, THERE IS A NEED FOR A SOURCE OF ELECTRONS AND A SOURCE OF POSITRONS
- THE TWO SOURCES CANNOT BE THE SAME
- THE HARD SPECTRUM OF POSITRONS LEAVES LIMITED OPTIONS

PULSAR WIND NEBULAE

IDEAL ELECTRON-POSITRON FACTORIES

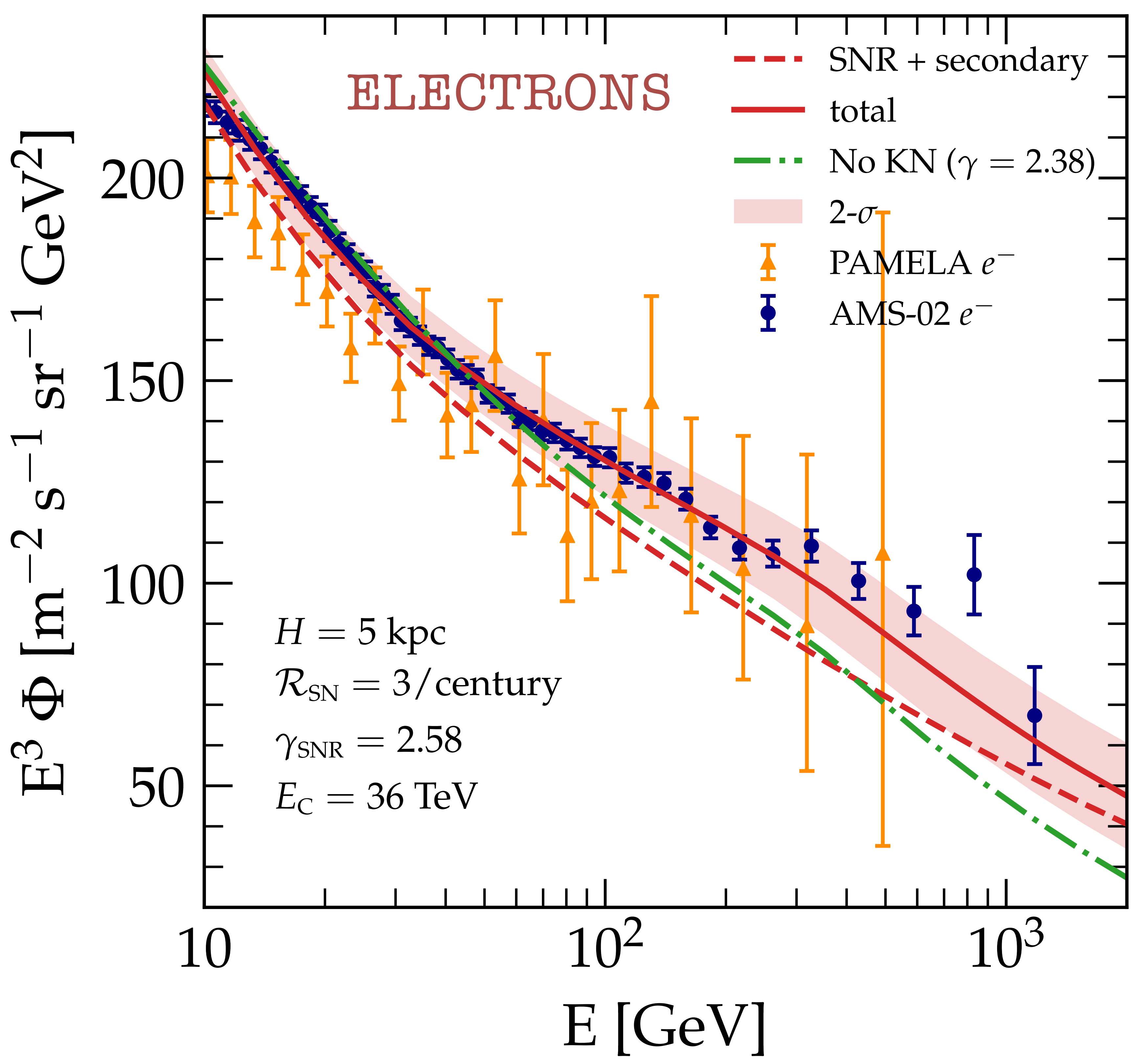
Papers by: Hooper, PB & Serpico, 2008; Grasso et al. 2009; PB & Amato 2010, 2012, 2018, Evoli, Amato, PB & Aloisio 2021

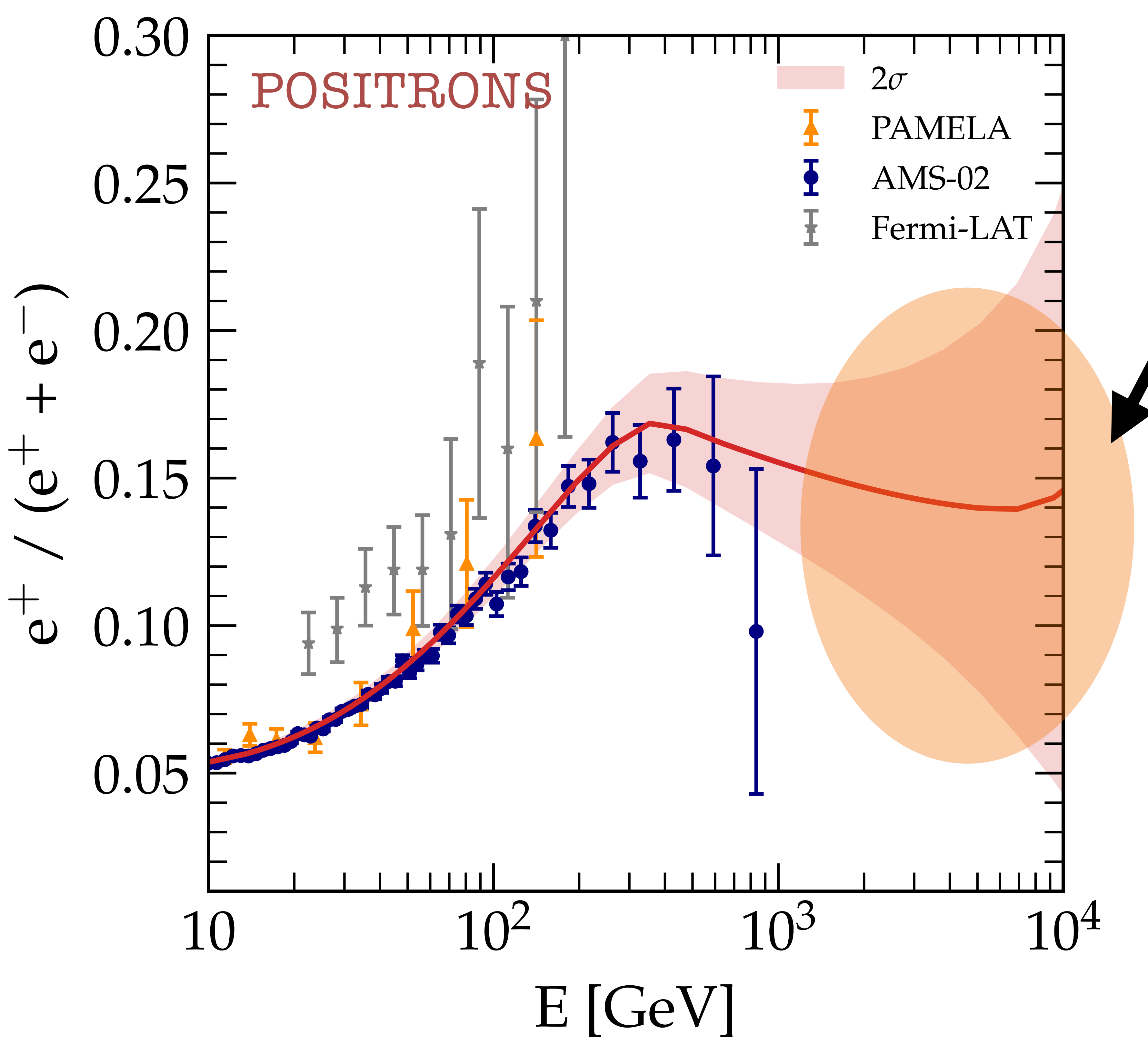
Formation of a PWN



A SUMMARY OF COSMIC RAY LEPTONS

Evoli, Amato, PB & Aloisio 2021, PRD 103, 083010





When CR transport turns non-linear

NON LINEAR CR TRANSPORT

WHAT DOES IT MEAN AND WHY YOU CAN'T IGNORE IT?

- **COSMIC RAYS ARE NOT PASSIVE SPECTATORS OF THEIR OWN TRANSPORT**
- **THEY CONTRIBUTE TO GENERATING THEIR OWN SCATTERING**
- **THEY CAN EXERT A FORCE ON THE PLASMA IN WHICH THEY MOVE**
- **WHAT YOU SEE AND MEASURE IS VISIBLY AFFECTED BY THESE PHENOMENA** (both during acceleration and during transport in the Galaxy, or around sources, or around galaxies, ...)
- **ESPECIALLY IMPORTANT FOR PARTICLE ACCELERATION**: WITHOUT THESE EFFECTS THE MAXIMUM ENERGY WOULD BE ~GeV

NON-LINEAR TRANSPORT

COSMIC RAYS STIR MAGNETIC FIELDS ON THE SCALE OF THEIR OWN LARMOR RADIUS (STREAMING INSTABILITY)

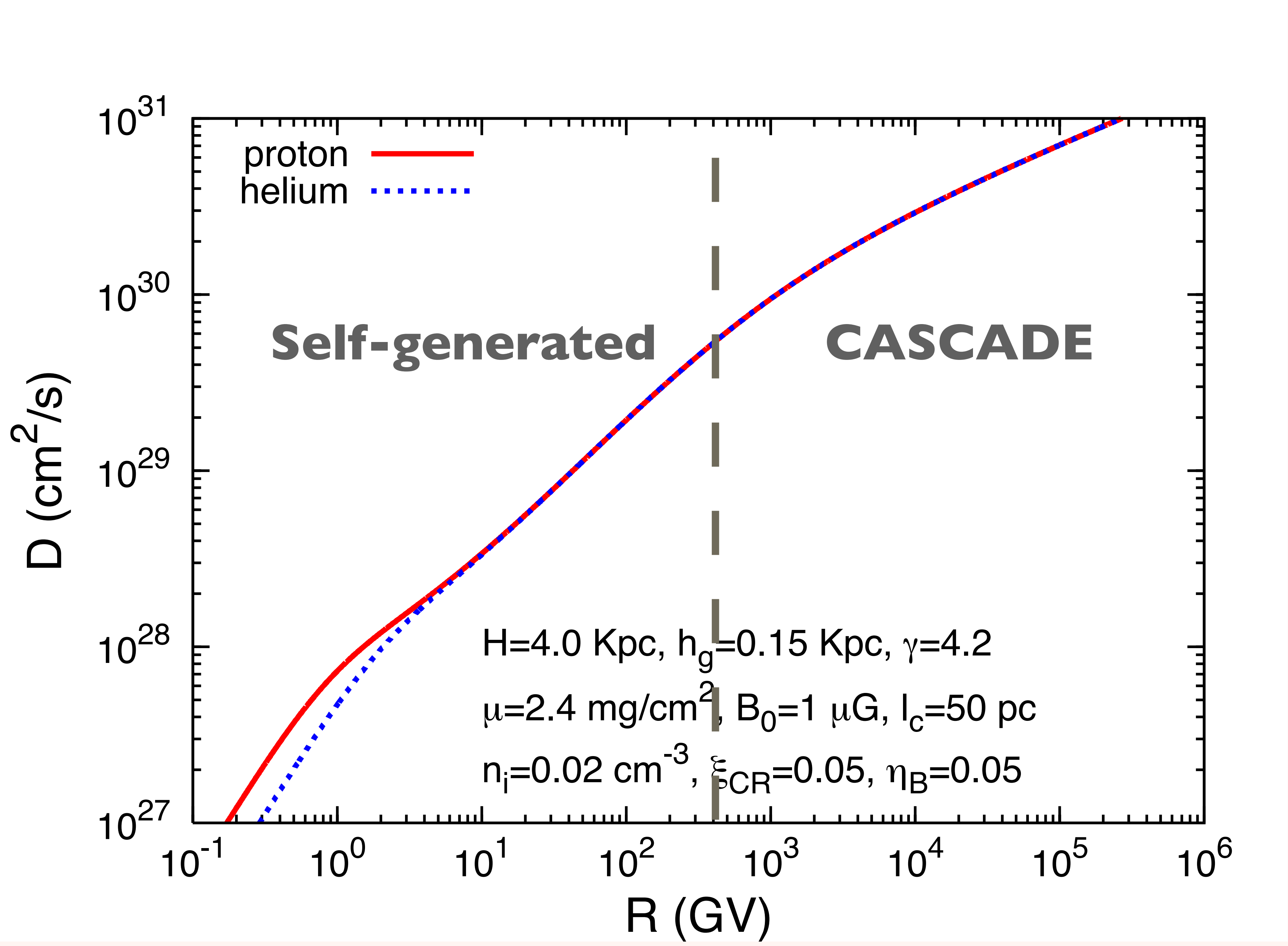
↑

THIS MECHANISM IS VERY IMPORTANT BELOW A FEW HUNDRED GV

D(E,Z) OUTPUT OF THE PROBLEM

TURBULENCE IS ALSO INJECTED BY SN EXPLOSIONS, WINDS etc. AND CASCADES TOWARDS SMALLER SCALES

NON LINEAR GALACTIC TRANSPORT



PB, Amato & Serpico 2012
Aloisio & PB 2013
Evoli, PB, Aloisio & Morlino, 2018

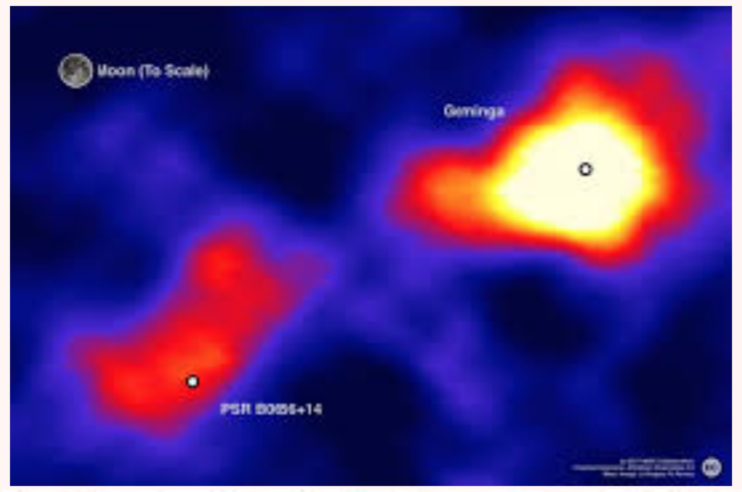
Notice that in these approaches, the diffusion coefficient is an output and is regulated by injection efficiency of CR in sources. It is such efficiency that also determines the position of the break, as balance between self-generated and pre-existing turbulence. The break naturally appears around a few hundred GV

DEVELOPMENTS

- THE SITUATION BECOMES MORE COMPLEX ON GALACTIC SCALES BECAUSE OF SEVERAL INTERVENING PHENOMENA:
  - THE CASCADE OF PRE-EXISTING ALFVENIC TURBULENCE IS PREDICTED TO DEVELOP IN AN ANISOTROPIC WAY —> REDUCED SCATTERING (Goldreich & Sridhar 1994)
  - ONE COULD INVOKE FAST MAGNETOSONIC TURBULENCE (ISOTROPIC) (Yan & Lazarian 2004) …DAMPING? (Kempske & Quataert 2022)
  - BOTH THE SELF-GENERATION AND THE CASCADING DEPEND RATHER SENSIBLY UPON THE ENVIRONMENT (IONIZATION, DENSITY, TEMPERATURE, B FIELD) (D'Angelo et al. 2016, Kempske & Quataert 2022)

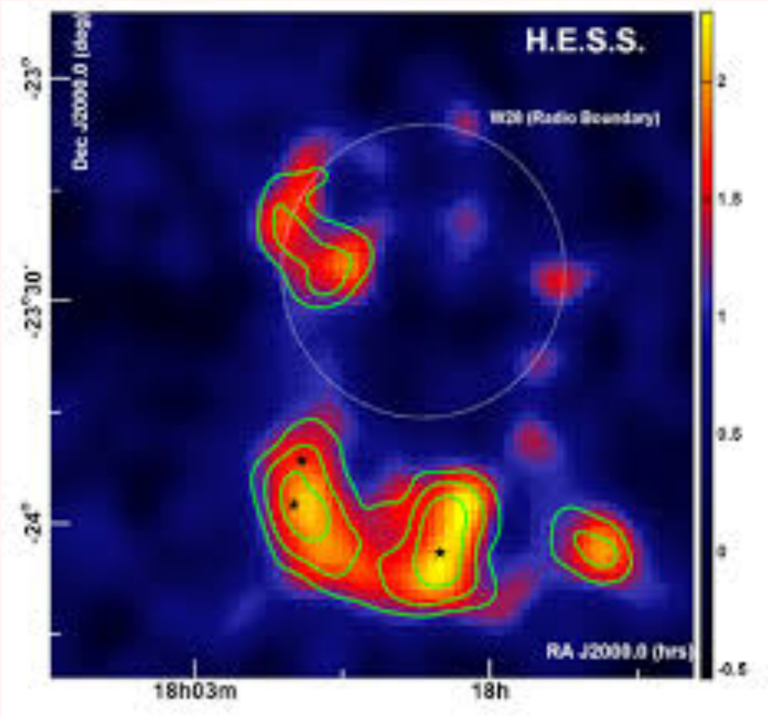
REDUCED DIFFUSIVITY AROUND SOURCES: TEV HALOS

INDEPENDENT SIGNATURES OR REGIONS OF REDUCED DIFFUSIVITY AROUND SOURCES (PULSARS, STAR CLUSTERS, SUPERNOVA REMNANTS)



HAWC has recently detected regions of extended gamma ray emission around selected PWNe, in the >TeV energy region, suggesting that the diffusion coefficient in these regions is ~1/100 of the Galactic one [Abeysekara+ 2017]

HESS observations of several star clusters have also shown extended regions (~100 pc) with TeV gamma ray emission, with inferred D(E)<< than the Galactic one [Aharonian+ 2018]

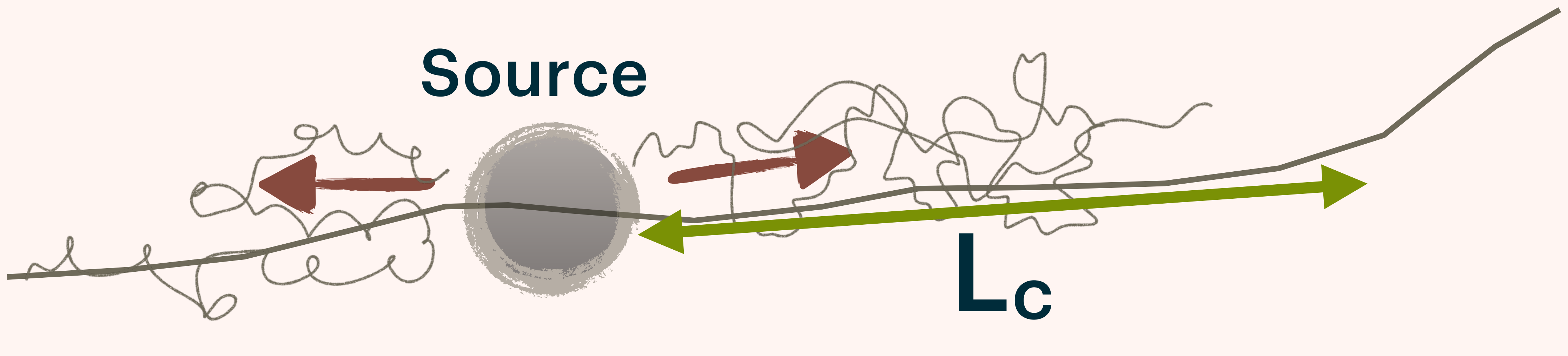


Already years back there was evidence from gamma ray observations of gamma ray emission from molecular clouds positioned at different distances from SNRs (for instance W28) that the diffusion coefficient is ~1/40 of the Galactic one [Gabici+ 2010]

EVIDENCE FOR NON LINEAR TRANSPORT?

- ☑ *THE COPIOUS PRESENCE OF COSMIC RAYS IN THE NEAR SOURCE REGION SUGGESTS THAT THEY MIGHT BE PLAYING AN IMPORTANT ROLE FOR E<TeV [Malkov+2013,D'angelo,PB&Amato+2016,Nava+2016]*

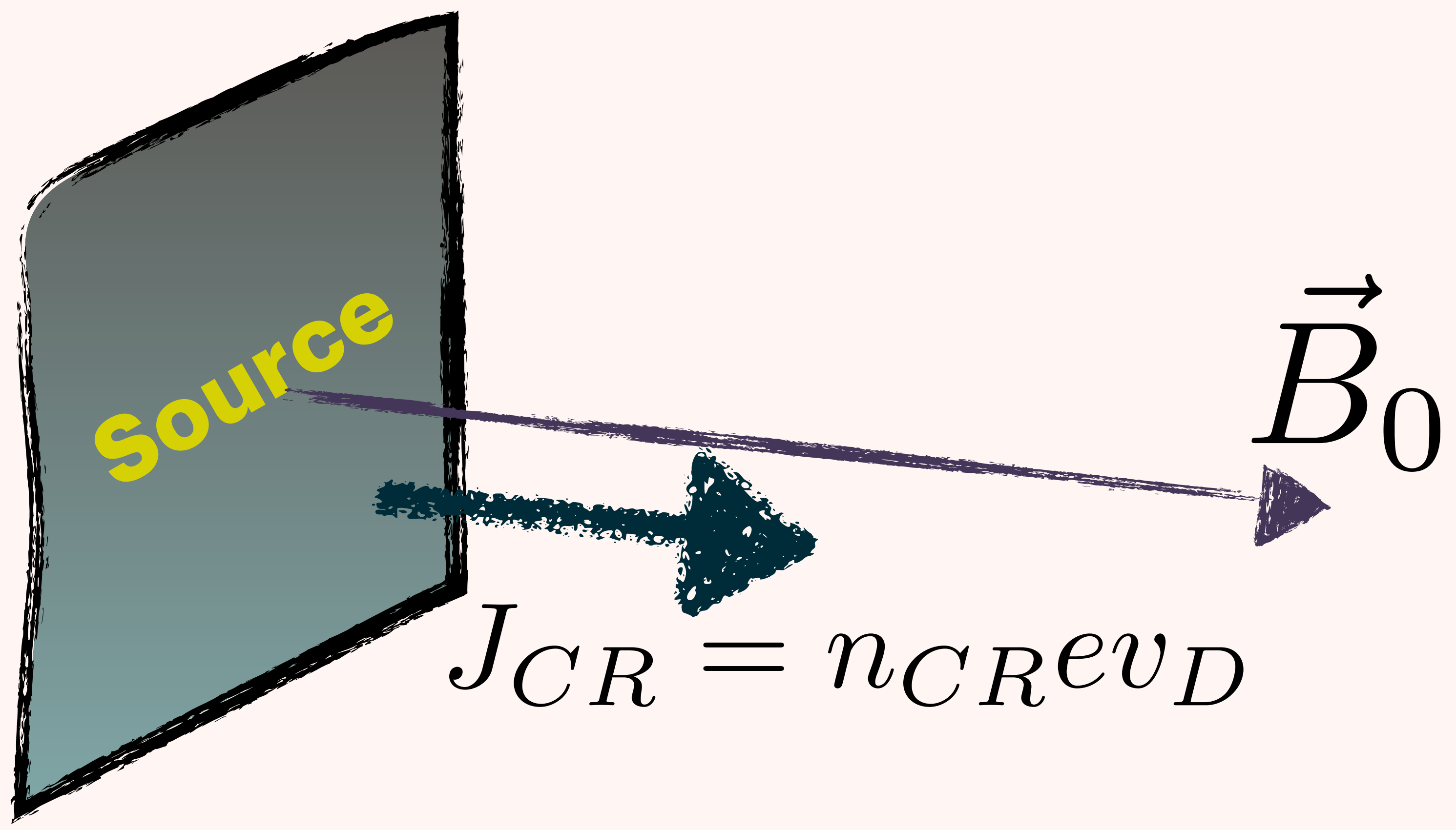
- ☑ *THE SUPPRESSED DIFFUSIVITY AROUND SOURCES OF CR HAS POTENTIALLY DRAMATIC IMPLICATIONS FOR THE GRAMMAGE:*



$$\frac{L_c^2}{D_{nl}} n_d = \frac{H^2}{D_{gal}} n_d \frac{h}{H} \rightarrow \frac{D_{nl}}{D_{gal}} = \frac{L_c^2}{Hh} \sim \frac{1}{40}$$

THE GRAMMAGE IN THE NEAR SOURCE REGION EASILY EXCEEDS THE GALACTIC ONE UNLESS THE REGION IS EVACUATED

CR CURRENT INDUCED INSTABILITY AROUND A SOURCE



WE ASSUME HERE THAT THE CR CURRENT IS MADE OF POSITIVE CHARGES AND THAT THE BACKGROUND PLASMA IS MADE OF PROTONS (n_i) AND ELECTRONS (n_e)

A RELATIVE MOTION BETWEEN ELECTRON AND PROTONS IS ESTABLISHED SO AS TO COMPENSATE THE CR CURRENT AND MAINTAIN CHARGE NEUTRALITY

$$n_{CR} + n_i = n_e$$

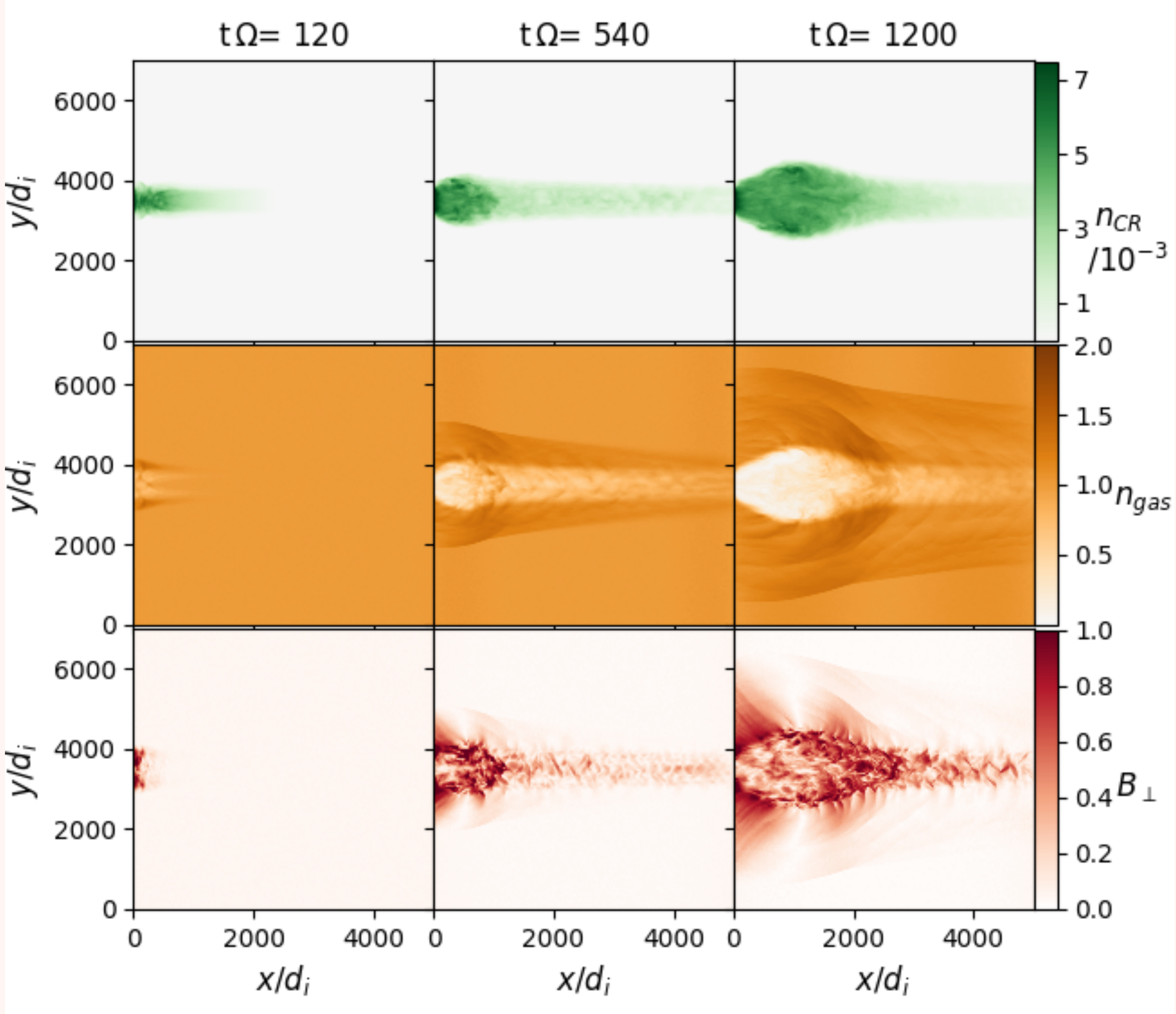
A CURRENT DRIVEN INSTABILITY IS EXCITED WHEN THE ENERGY DENSITY IN THE CURRENT EXCEEDS THE ENERGY DENSITY OF THE PRE-EXISTING FIELD $B_0^2/4\pi$ [Bell 2004]

$$n_{CR}(>E)E\frac{v_D}{c} \geq \frac{B_0^2}{4\pi}$$

THE ELECTRON CURRENT COMPENSATING THE CR CURRENT MAKES THE INSTABILITY GROW THE FASTEST ON SCALES MUCH SMALLER THAN THE LARMOR RADIUS!!! BUT EBENTUALLY SATURATE AT THE RESONANCE WHEN:

$$n_{CR}(>E)E\frac{v_D}{c} = \frac{\delta B^2}{4\pi}$$

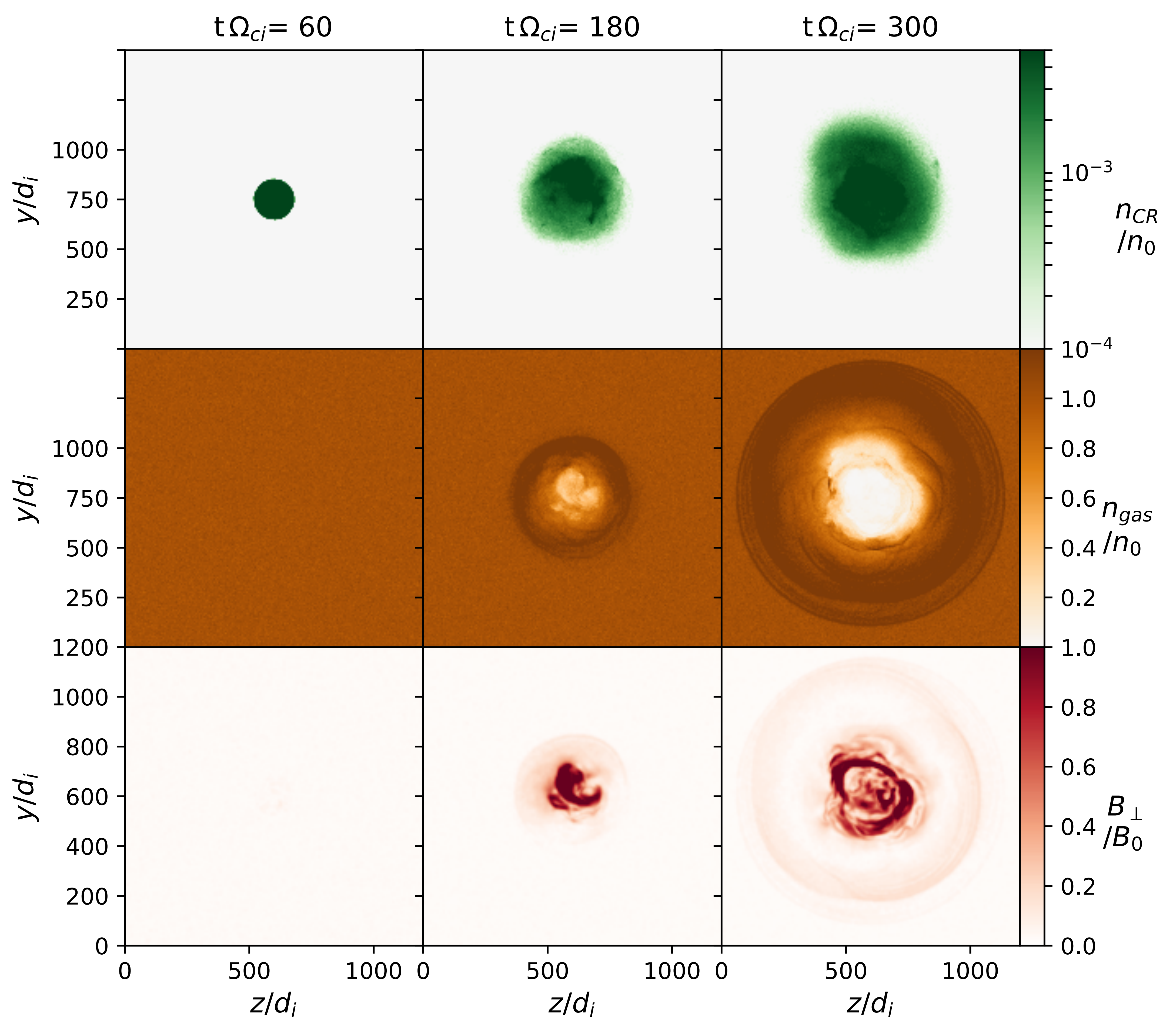
2D HYBRID SIMULATIONS OF THIS PHENOMENON



- THE EXCITATION OF THE INSTABILITY LEADS TO STRONG PARTICLE SCATTERING, WHICH IN TURN INCREASES CR DENSITY NEAR THE SOURCE
- THE PRESSURE GRADIENT THAT DEVELOPS CREATES A FORCE THAT LEADS TO THE INFLATION OF A BUBBLE AROUND THE SOURCE
- THE SAME FORCE EVACUATES THE BUBBLE OF MOST PLASMA
- THERE IS NO FIELD IN THE PERP DIRECTION TO START WITH, BUT CR CREATE IT AT LATER TIMES (SUPPRESSED DIFFUSION, about 10 times Bohm)

Schroer+, 2021, *Dynamical effects of cosmic rays leaving their sources*

CONFIRMED IN 3D SIMULATIONS

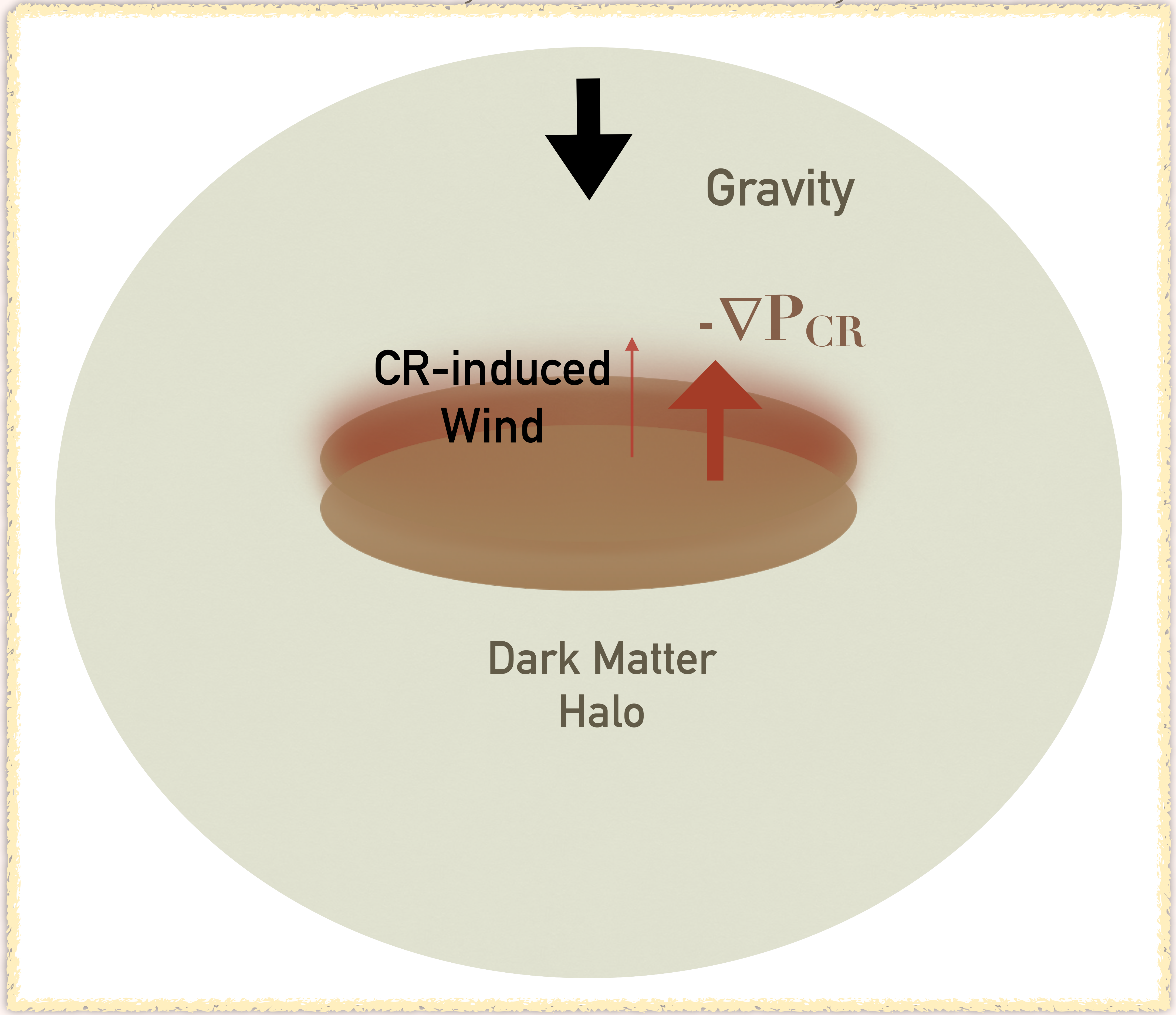


- THE PHENOMENON IS QUALITATIVELY THE SAME IN 3D
- THE EXCITATION OF THE INSTABILITY LEADS TO STRONG PARTICLE SCATTERING, AND EXCAVATION OF A 3D BUBBLE
- COMPARED WITH 2D MORE MIXING BETWEEN THE BUBBLE AND THE ISM
- CLEAR SIGNATURES OF THE EXCITATION OF BOTH RESONANT AND NON-RESONANT MODES

Schroer+, 2022, *Cosmic-ray generated bubbles around their sources*

Cosmic Rays vs Gravity: Cosmic Ray Induced Galactic Winds

Breitschwerdt et al. 1991, Recchia et al. 2016, Zweibel & Everett 2007



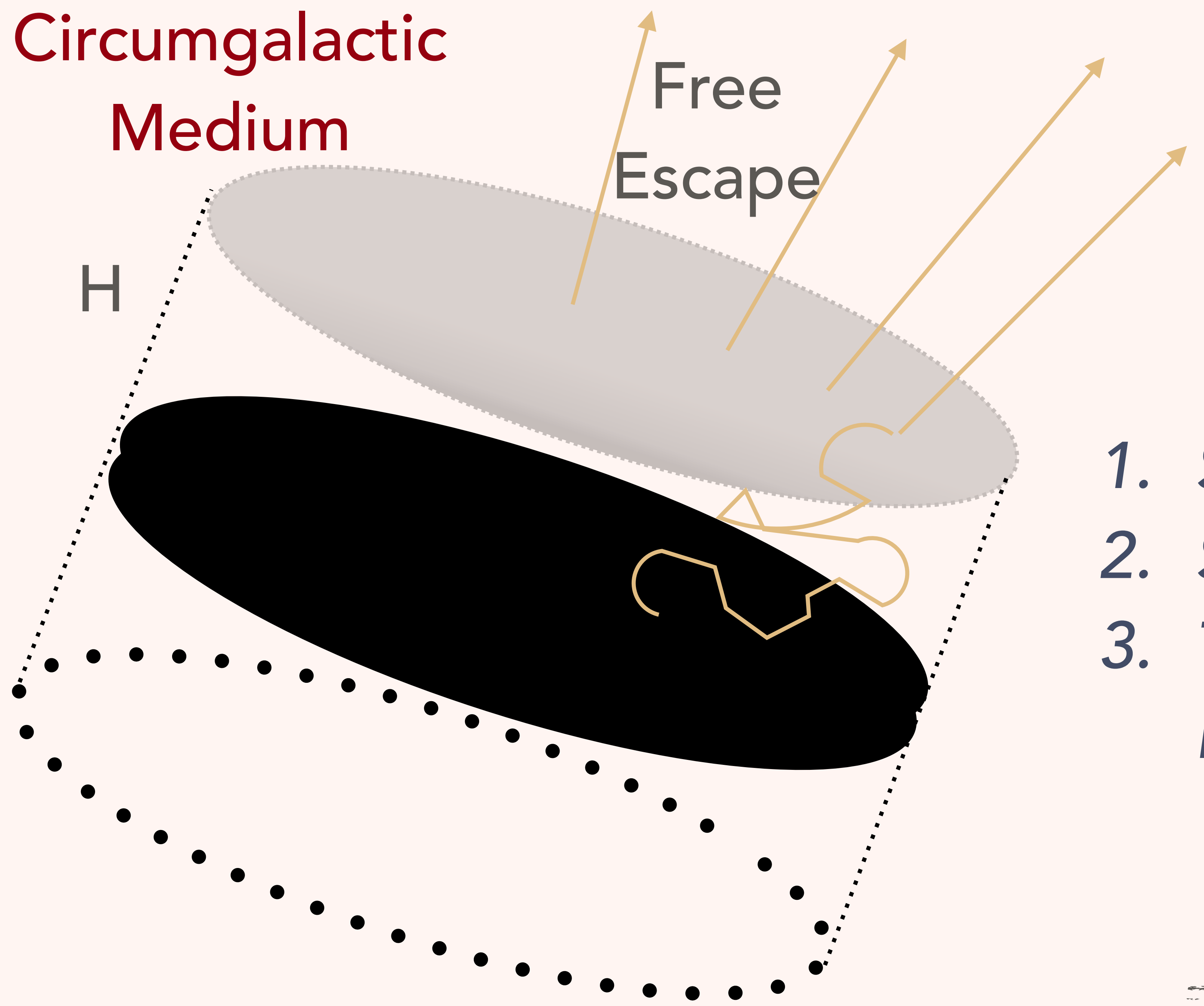
The force exerted by CR is proportional to the gradient of their pressure

Gravitational force dominated by the halo of dark matter

In general, for a Galaxy like the Milky Way there are regions where the CR force overcomes gravity

At some locations outflows or winds can be launched because of the CR pressure gradient

REFLECTIONS ON FREE ESCAPE FROM THE GALAXY

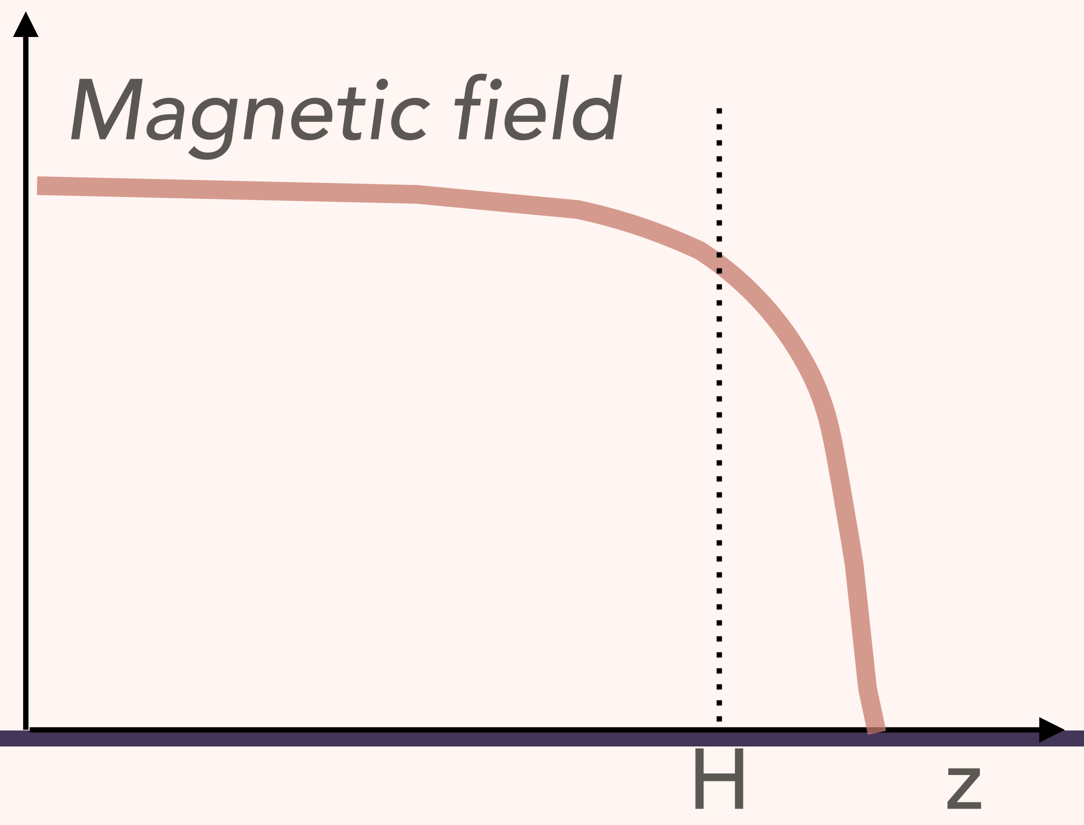


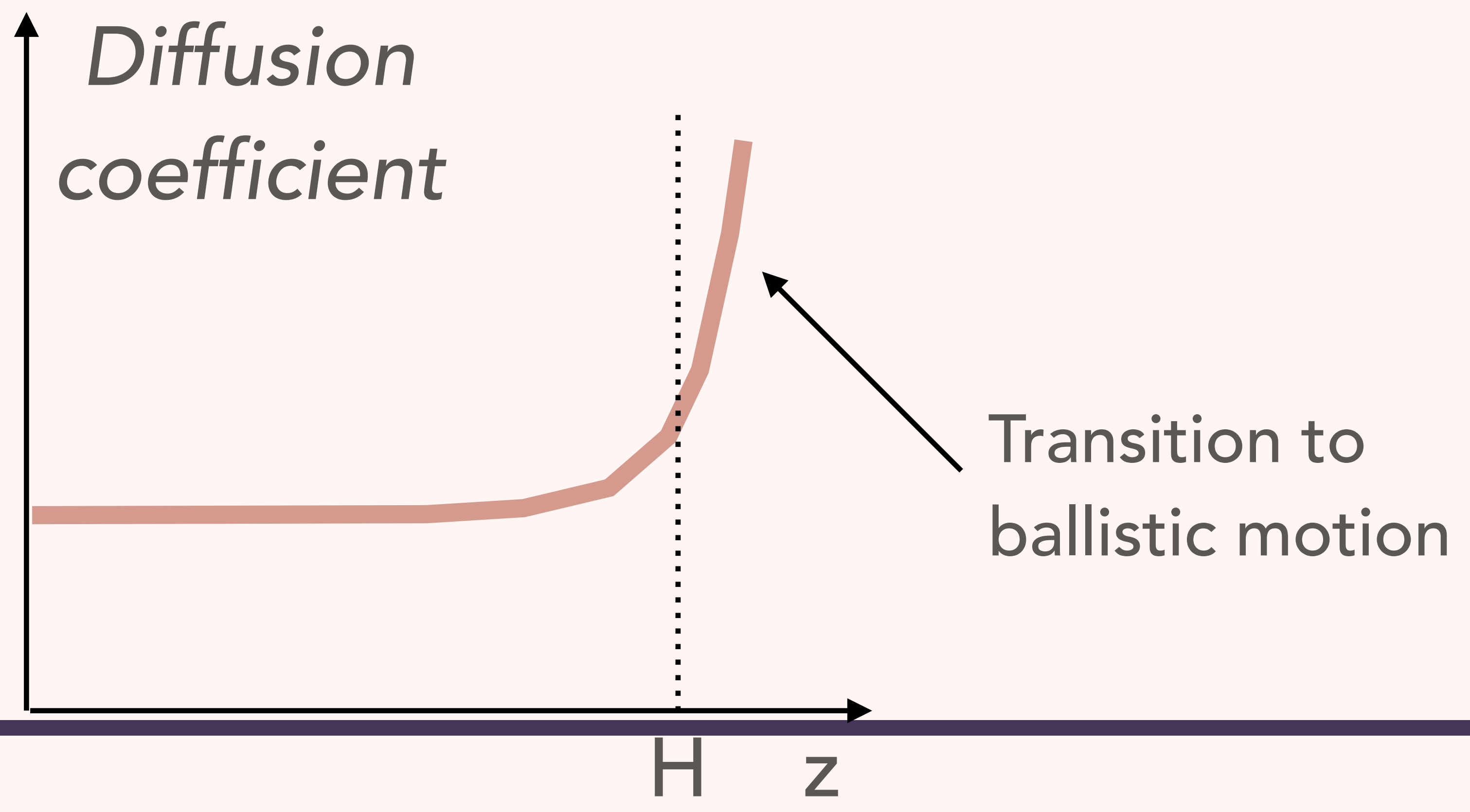
$$n_{CR}(z,E) = n_{gal}(E)\left(1 - \frac{|z|}{H}\right)$$

$$\phi_{CR}(E) = -D(E)\frac{\partial n_{gal}}{\partial z} = D\frac{n_{gal}}{H} = \frac{L_{CR}}{2\pi R_d^2 \Lambda} E^{-2}$$

1. *Stationarity —> escape flux = injected flux*
2. *Spectrum of escaping particles = injected spectrum*
3. *The current of escaping particles is very well known, independent of details*

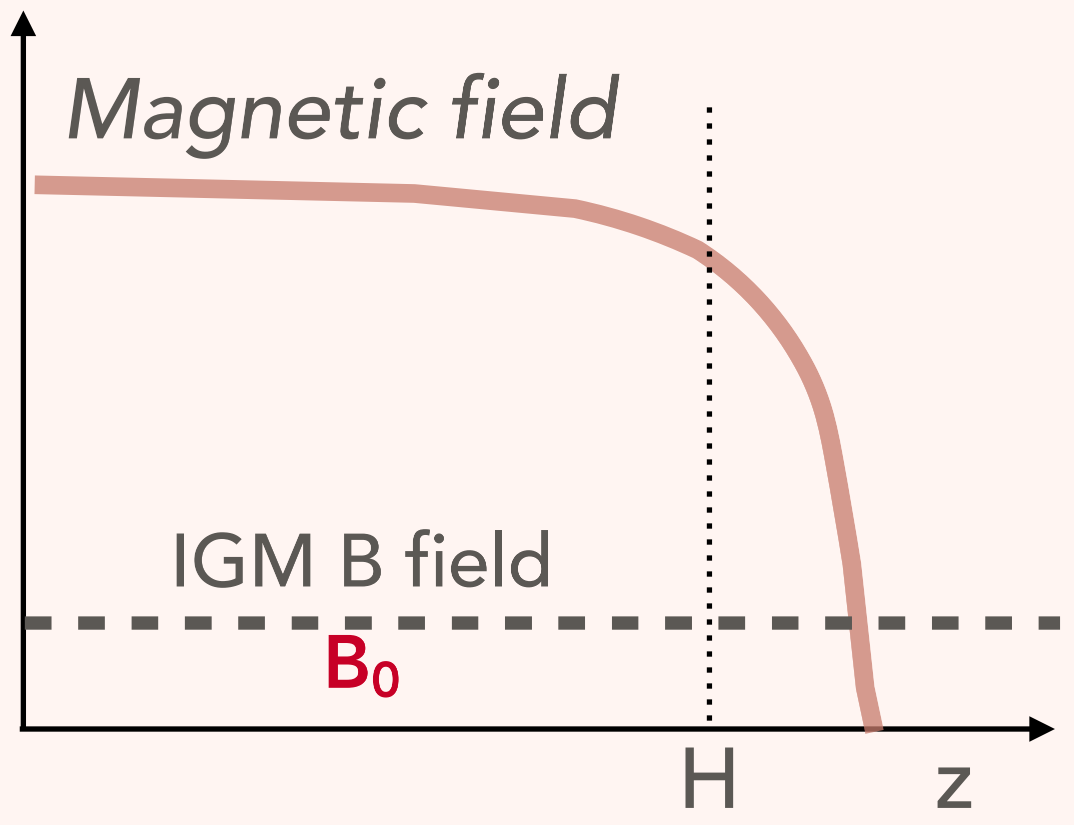
A PHYSICAL PICTURE OF ESCAPE





PB & Amato 2019

REFLECTIONS ON FREE ESCAPE FROM THE GALAXY



A non resonant instability is excited when the flux of CRs escaping the Galaxy reaches a region where the background field is small enough:

$$\frac{E^2 \phi_{CR}}{c} > \frac{B_0^2}{4\pi} \Rightarrow B_0 \leq B_{sat} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1} \text{ G}$$

IN THIS PHASE THE INSTABILITY GROWS RAPIDLY, AT A RATE:

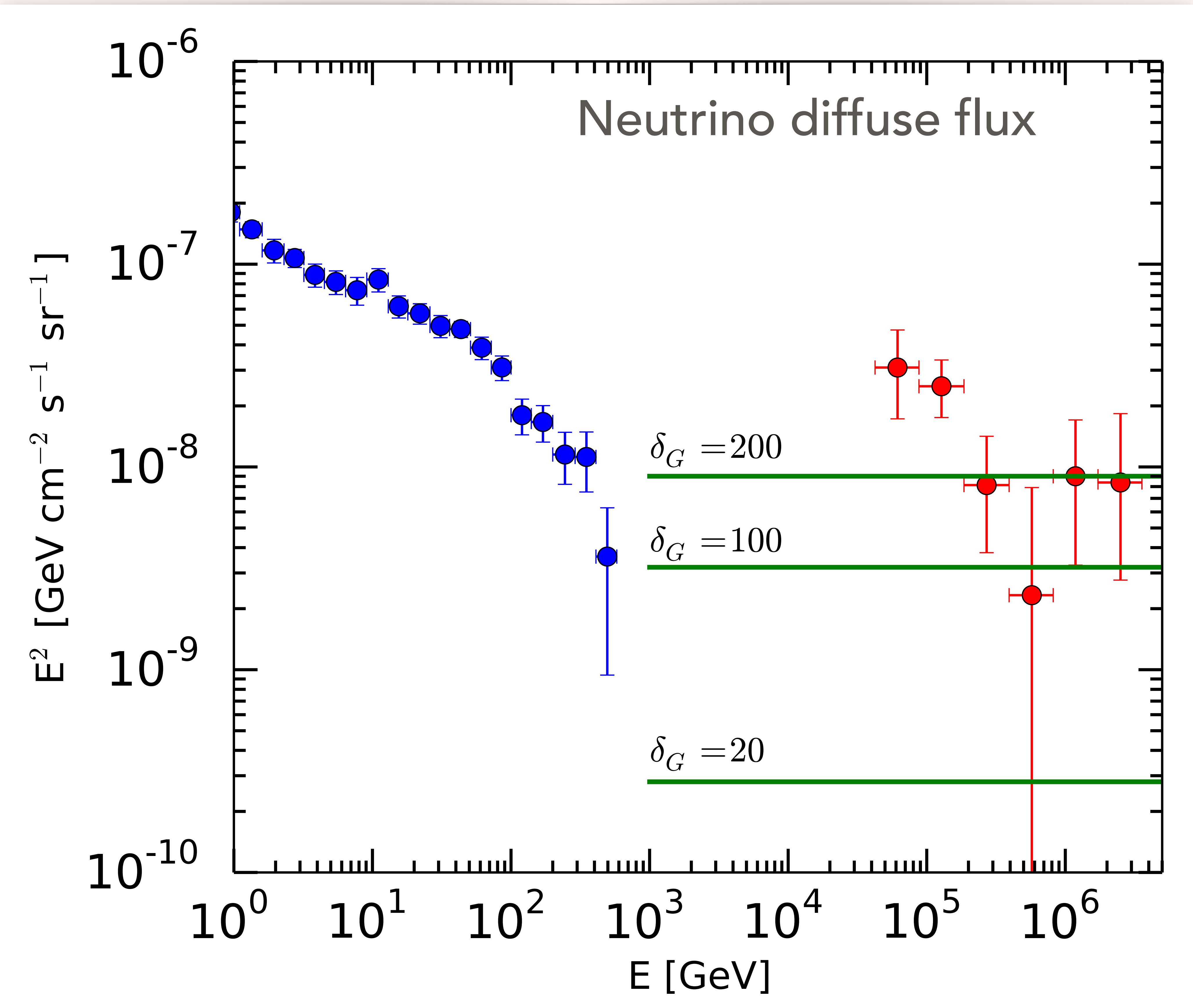
$$\gamma_{max} = k_{max} v_A \approx 0.5 \text{ yr}^{-1} \; \delta_G^{-1/2} E_{\text{GeV}}^{-1} L_{41} R_{10}^{-2}$$

Gas overdensity in the circumgalactic medium

UNTIL THE FIELD SATURATES AT B_{sat}

OUR GALAXY AND IN FACT ANY GALAXY SHOULD BE SURROUNDED BY AN EXTENDED MAGNETZIED REGION WITH MAGNETIC FIELD PROPORTIONAL TOT HE SQUARE ROOT OF THE SOURCE CR LUMINOSITY

REFLECTIONS ON COSMIC RAY ESCAPE FROM THE GALAXY



PB & Amato 2019

1) ESCAPING COSMIC RAYS LEAD TO THE FORMATION OF A REGION OF SIZE TENS OF KPC WITH B~0.02 MICROGAUSS

2) COSMIC RAYS DO NOT REALLY ESCAPE FREELY FROM A GALAXY

3) ESCAPING COSMIC RAYS ARE RESPONSIBLE FOR INDUCING A DISPLACEMENT OF THE IGM WITH 10-100 KM/S SPEED

4) INELASTIC INTERACTIONS OF CR IN THE IGM LEAD TO A NEUTRINO FLUX COMPARABLE WITH THAT MEASURED BY ICECUBE

OUTLOOK

- *A GENERAL PICTURE OF CR TRANSPORT WITH ADVECTION, DIFFUSION, ENERGY LOSSES, SPALLATION SEEMS ABLE TO DESCRIBE A LARGE COLLECTION OF DATA*
- *A FEW EXCEPTIONS: POSITRONS, DAMPE FEATURE, REGIONS OF REDUCED DIFFUSIVITY*
- *BUT NUMEROUS HOLES IN FUNDAMENTAL KNOWLEDGE: NATURE OF SCATTERING WAVES, INTERPLAY WITH SELF-GENERATION, SOME INCONSISTENCIES IN ACCELERATION, PHYSICAL MEANING OF FREE ESCAPE*
- *GROWING INTEREST IN IMPLICATIONS OF COSMIC RAYS IN GALAXY FORMATION, GALACTIC WINDS (NON LINEAR TRANSPORT)*
- *NON LINEAR TRANSPORT CRUCIAL AROUND SOURCES AND AROUND GALAXIES, A WEALTH OF OBSERVATIONS EXPECTED WITH HAWC, LHASSO, CTA*