Galactic Cosmic Rays:

LOOSE ENDS OR SHAKING PILLARS?

Pasquale Blasi - *Gran Sasso Science Institute*

SUGAR - Madison, October 14 2024

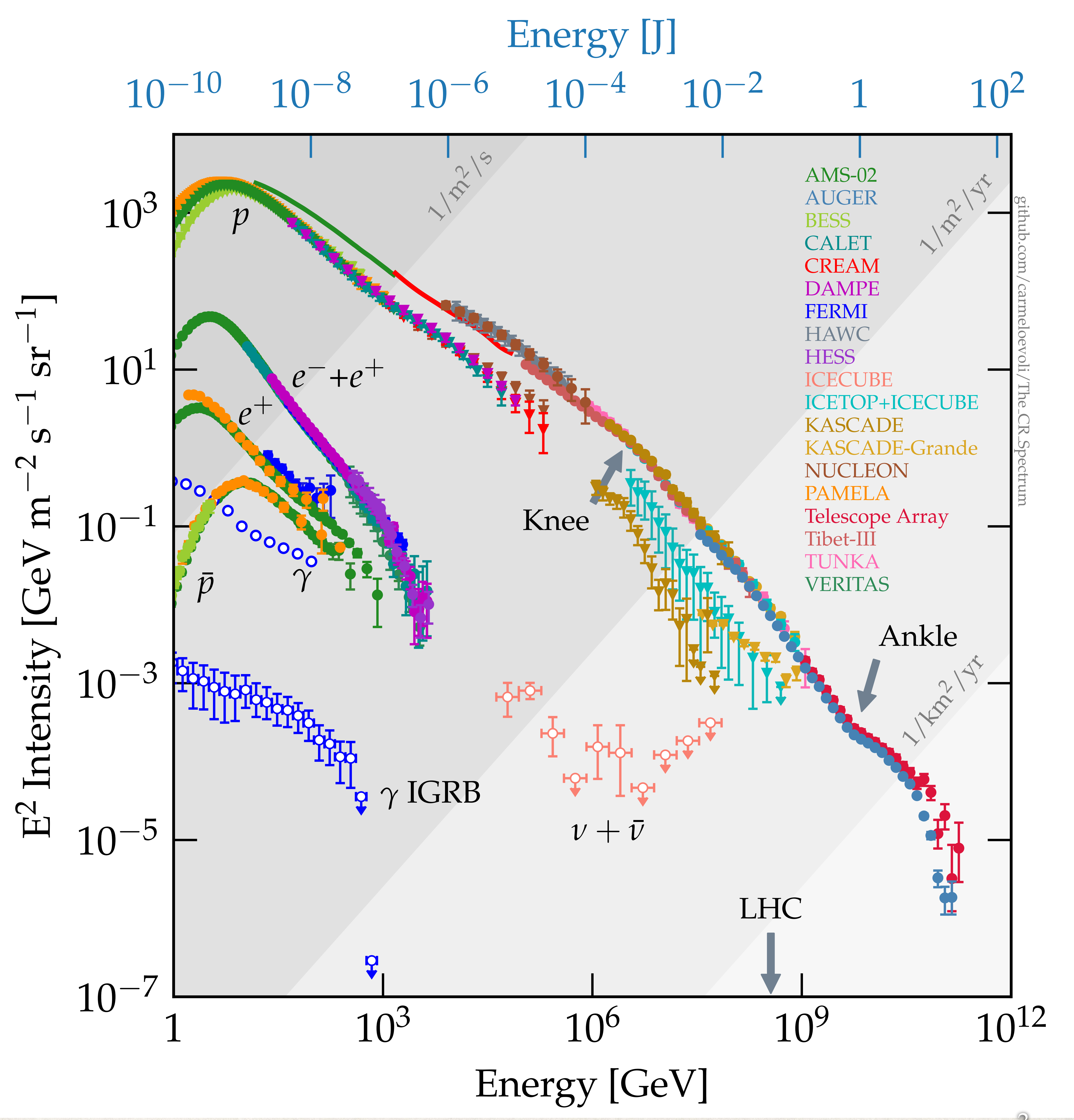
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

“It is quite possible that future historians of science will close the chapter on cosmic rays with the fiftieth anniversary of Hess’s discovery”

–from “Cosmic Rays” Bruno Rossi 1964

Observation of charged Cosmic Rays

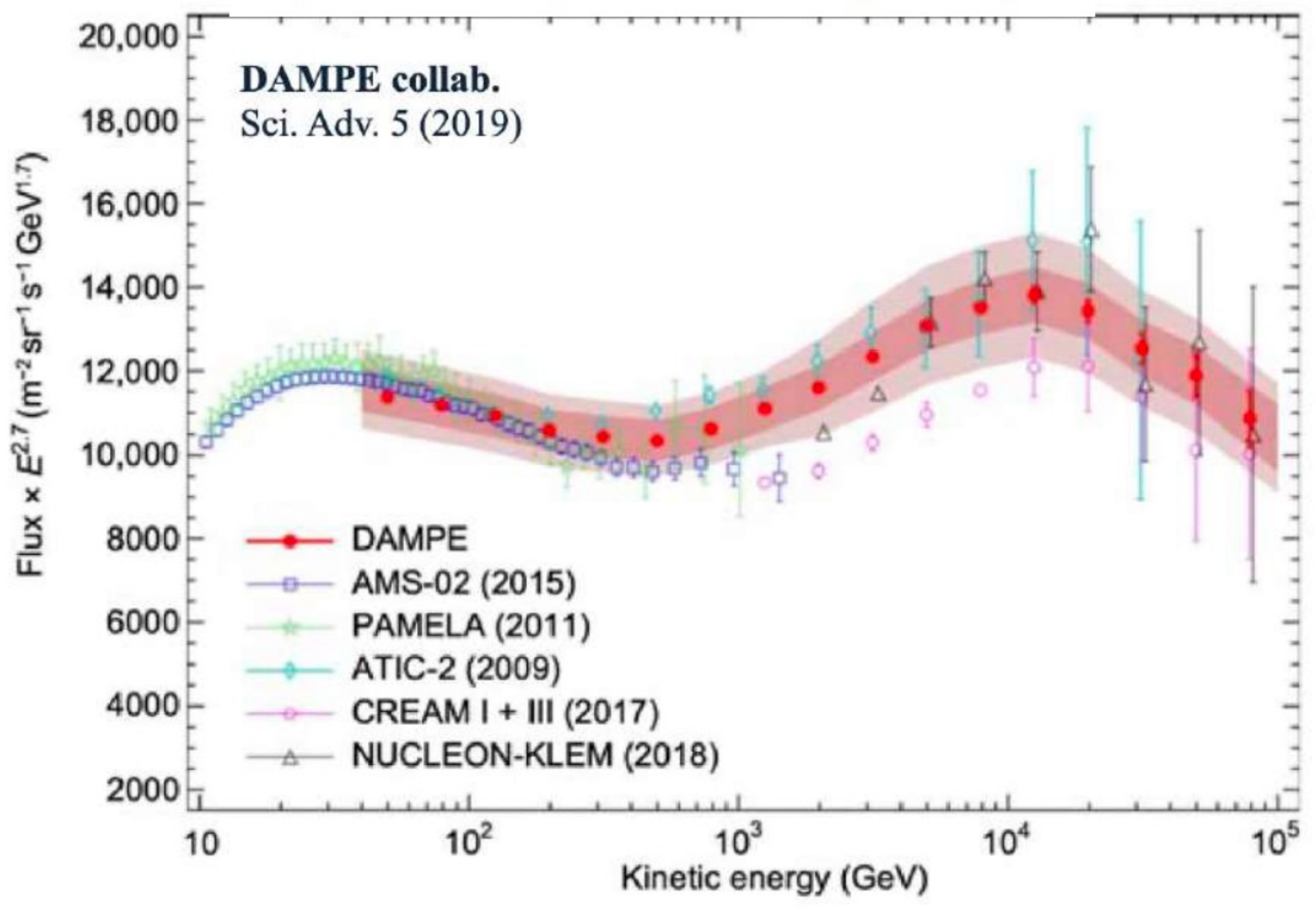
- Spectral features —> Scales where interesting physics appears
- The knee, ankle and the GZK suppression remain the most evident features
- But, for the first time, features are appearing in the spectra of individual elements (H, He, C, …)
- Surprises from anti-matter (positrons, anti-N)
- Diffuse γ-ray (and ν) spectra unexpected
- PeVatrons missing in action…
- **Loose ends? Or something foundational is cracking?**



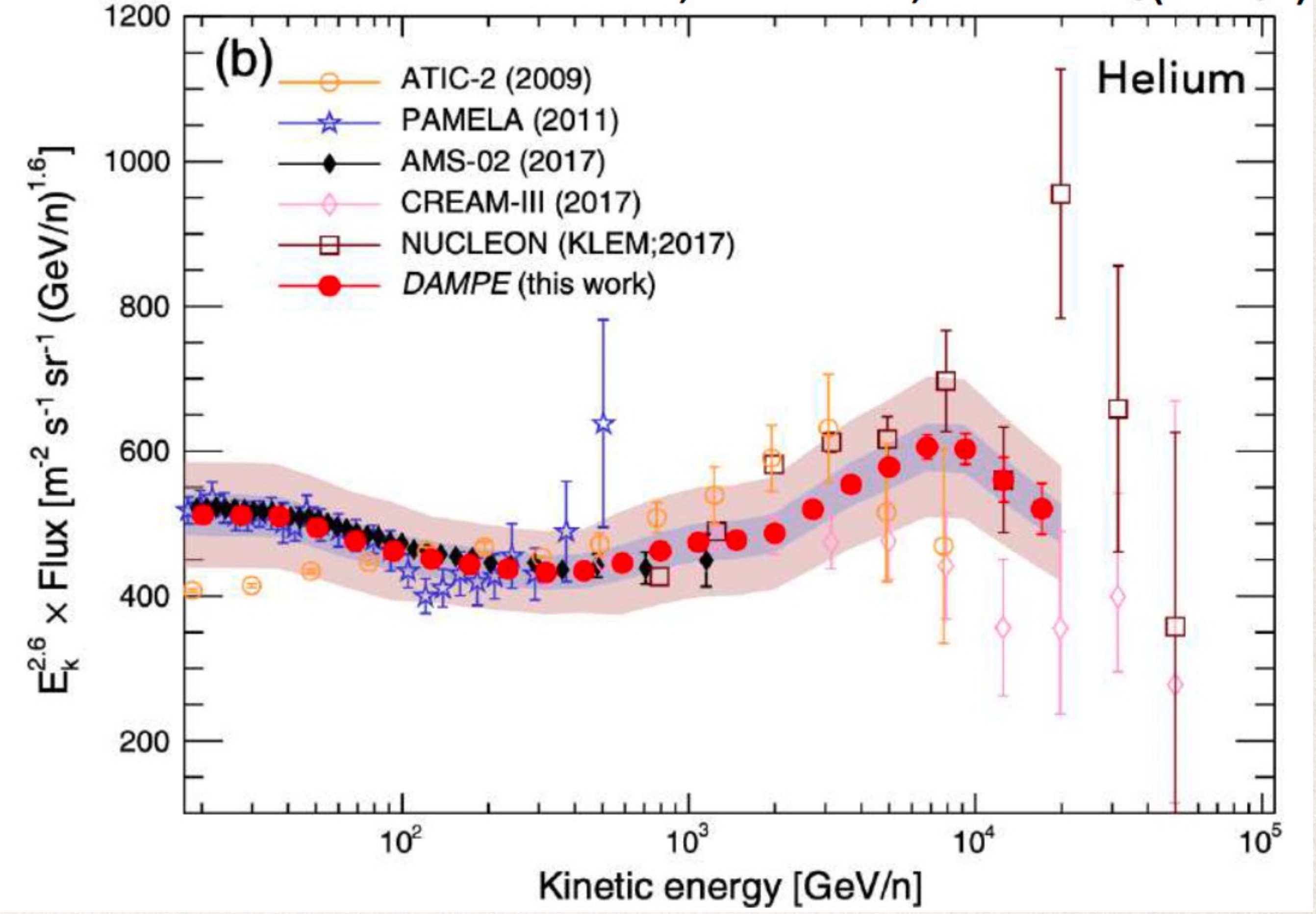
Spectra of Light Elements in CRs

- Spectra of virtually all elements show a feature at rigidity **R~200 GV**
- H and He show a bump at rigidity **~20 TV**
- After correcting for propagation effects (which depend only upon rigidity) the spectra of H and He at the source (still depending only upon rigidity) are required to be different! **VERY SURPRISING!!!**

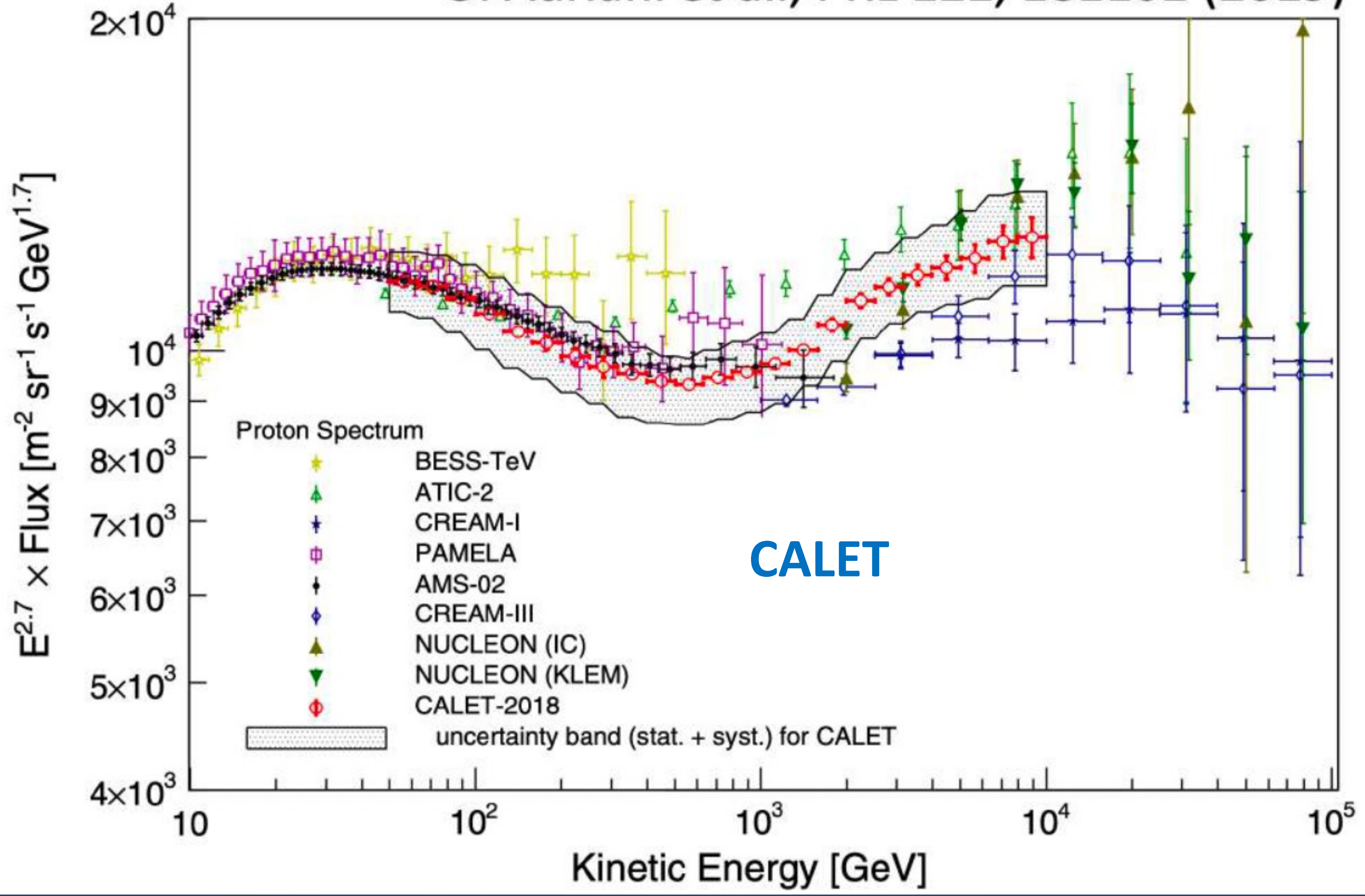
Q. An et al., Sci. Adv. 5 (2019) 9



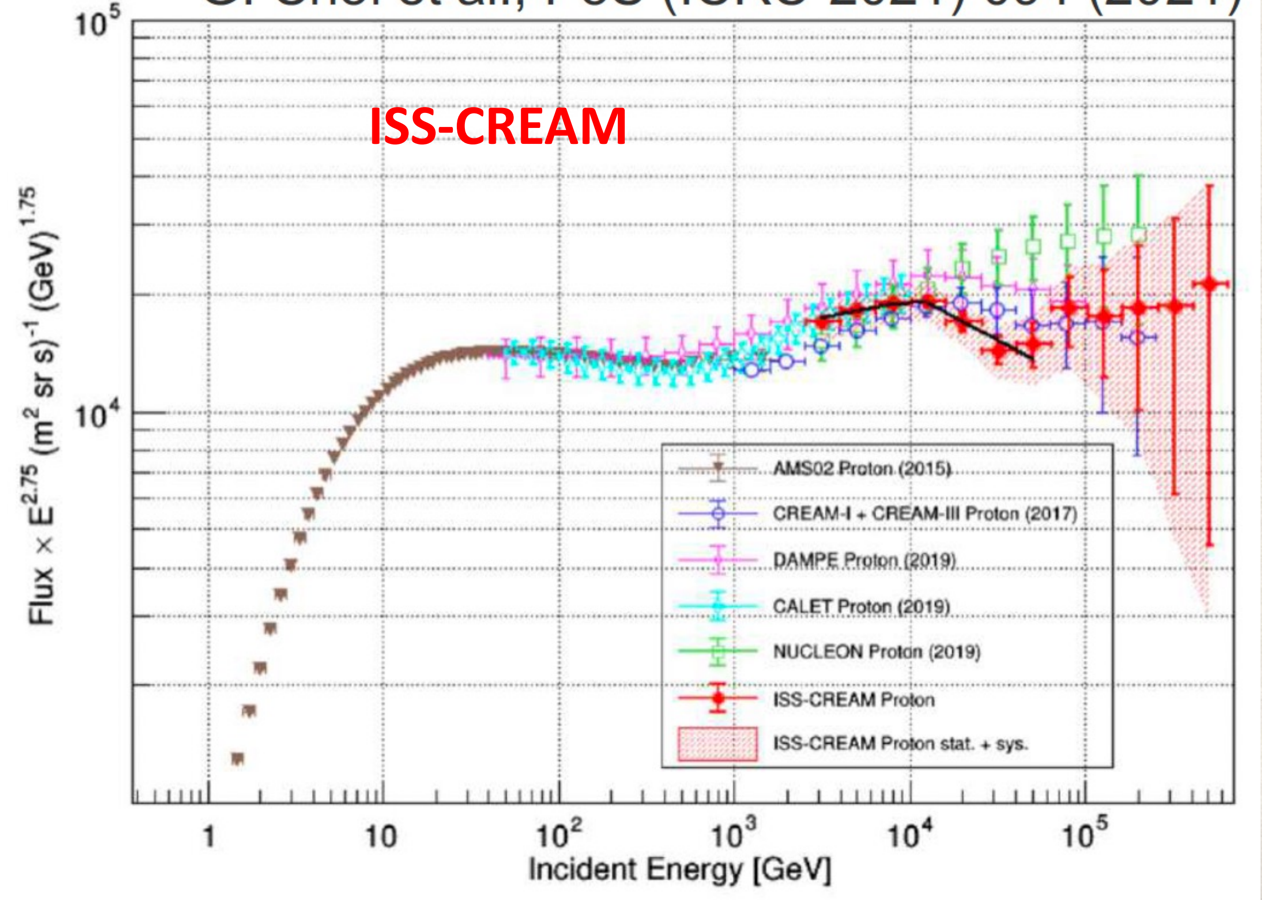
F. Alemanno et al., PRL 126, 201102 (2021)



O. Adriani et al., PRL 122, 181102 (2019)



G. Choi et al., PoS (ICRC-2021) 094 (2021)



How do you get different slopes of H and He?

- Injection of He (on nuclei in general) is known to be more effective than that of H in DSA (Ellison, Jones & Eichler 1981; Caprioli, Dennis & Spitkovsky 2017) for high Mach number

- If the late phases of a SNR (Mach number <10) are important, the time integrated spectrum of H can be made steeper than He (very model dependent) (Malkov, Diamond, Dagdeev 2012)

- If CRs are accelerated in star clusters, spallation reactions of He can harden the spectrum of escaping He (PB & Morlino 2024)

- In this latter case, heavier nuclei cannot escape the star cluster (PB & Morlino 2024)

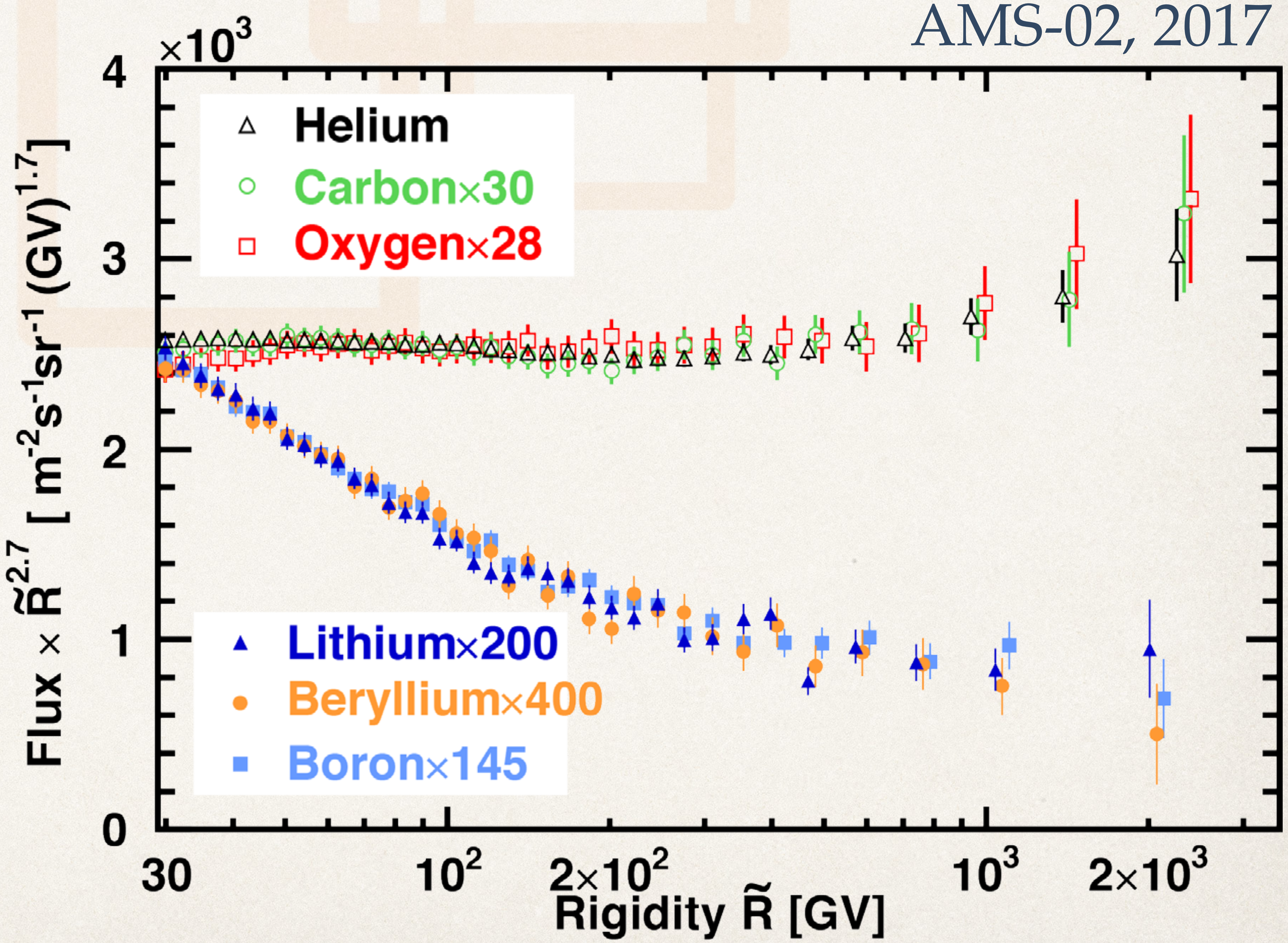
The origin of the break at 300 GV

- A break in the observed spectra can, in principle, either be due to a break in the source spectra or a change in the diffusion properties

- The difference between the two scenarios is that only in the second case the break is visible also in the Secondary/Primary ratios and it is twice as large!

- **Observations show that this is an effect of TRANSPORT**

AMS-02, 2017



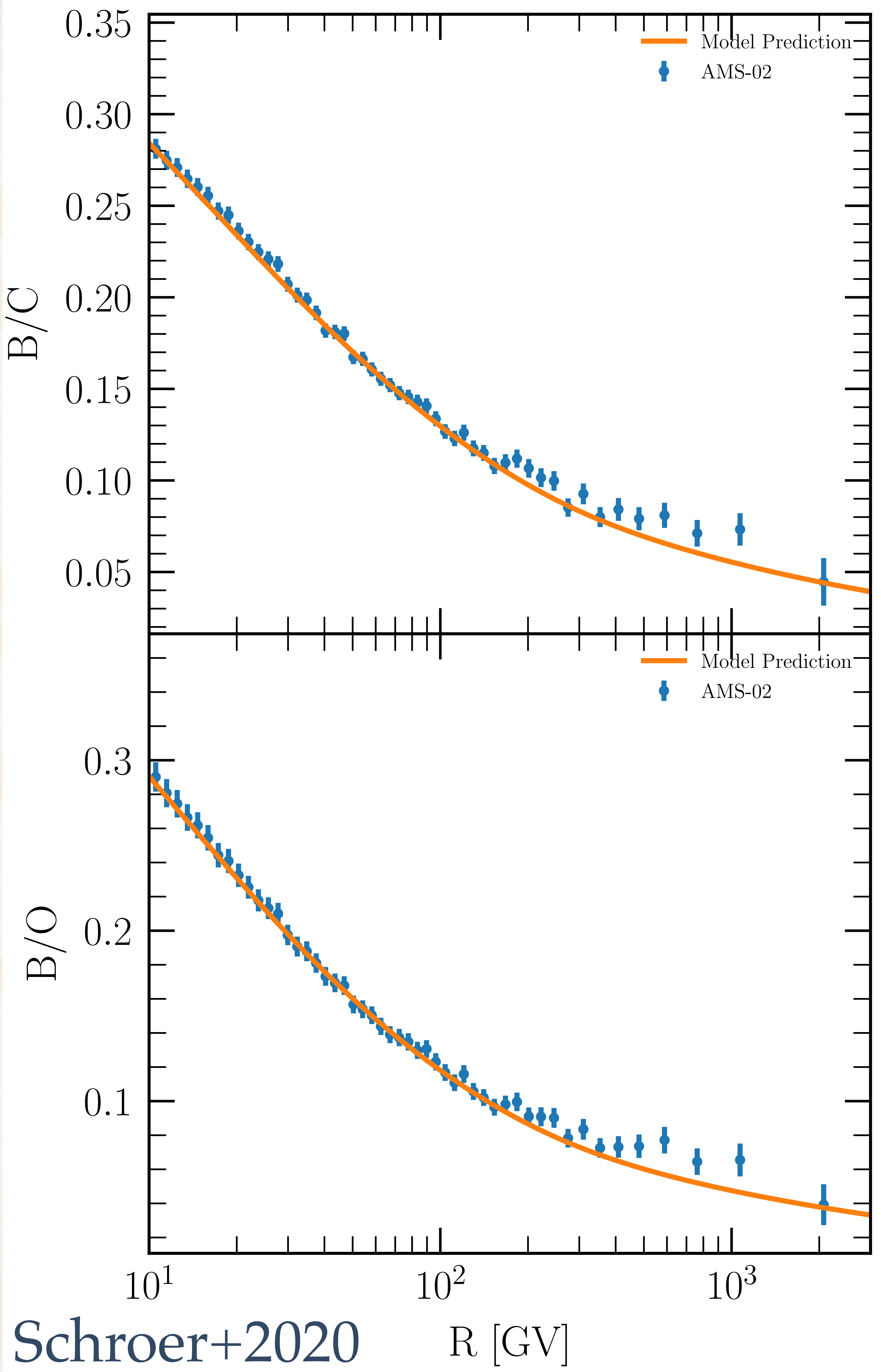
CR clocks: Stable Elements

- The B/C and B/O ratios confirm that the diffusion coefficient **requires a break at about 300 GV —>** **TRANSPORT CHANGES**

- 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)

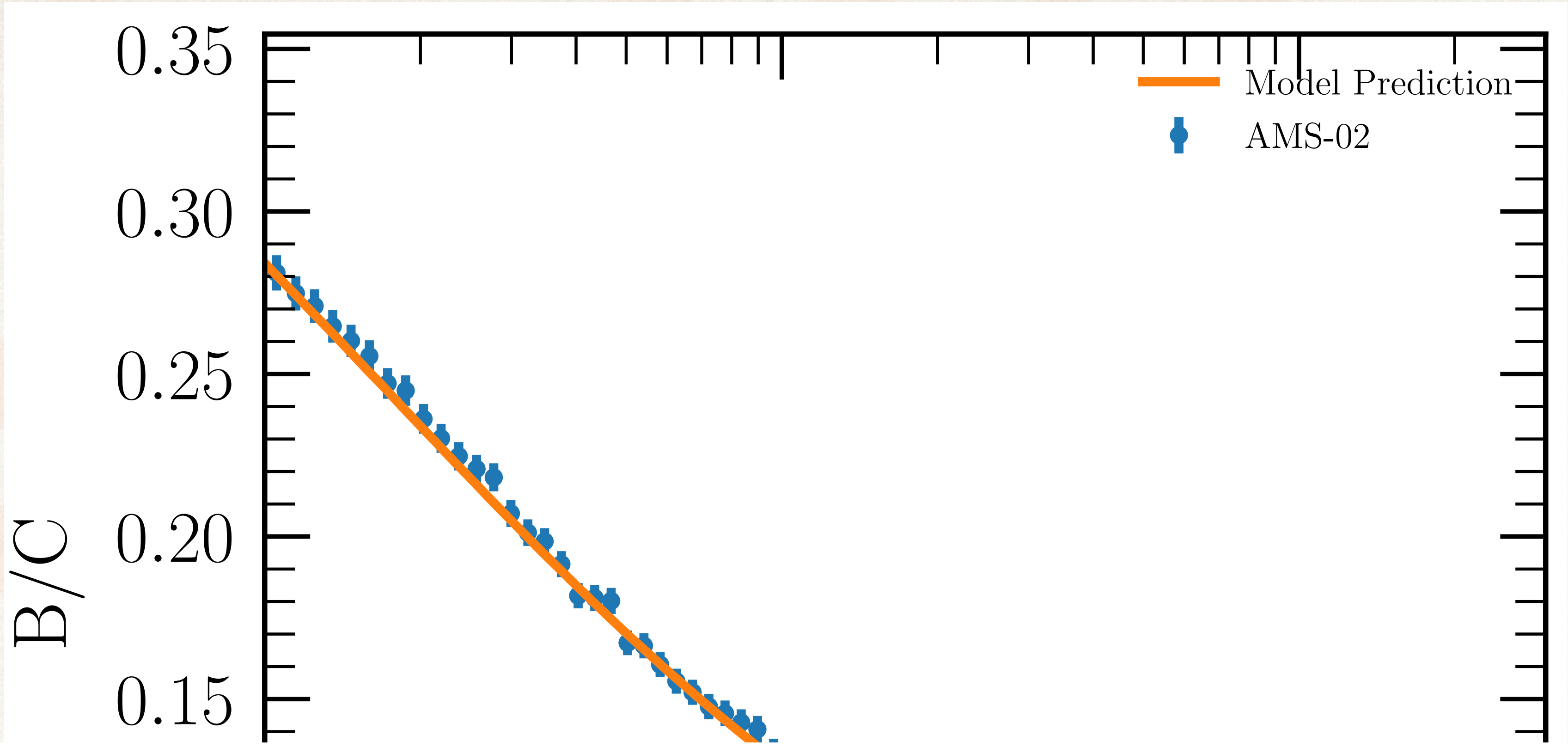
- The ratio returns the **energy dependence of D(E)**

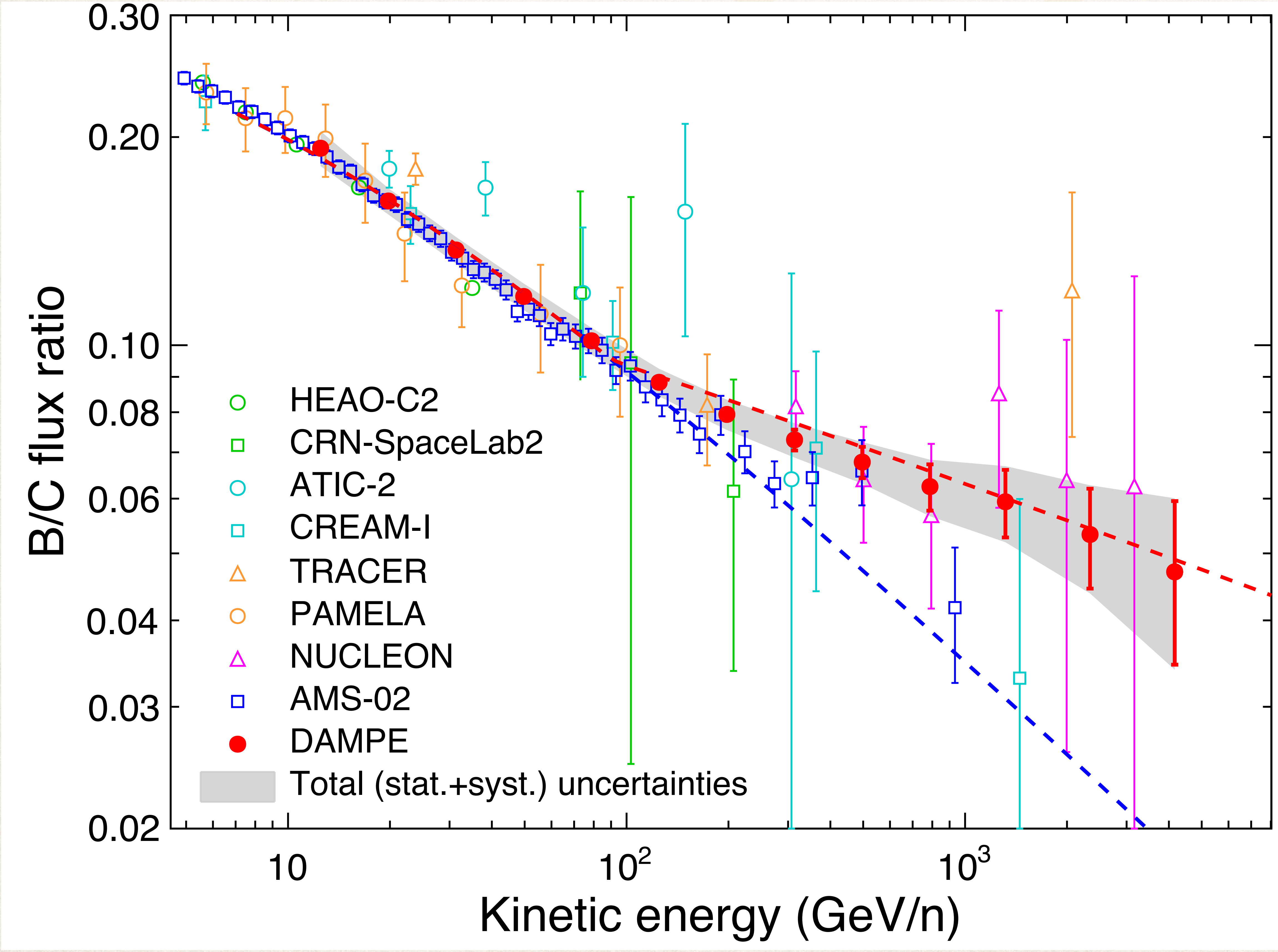
- Recall that **D(E) contains the microphysics** of particle motion, for the first time we are getting detailed info on such microphysics.

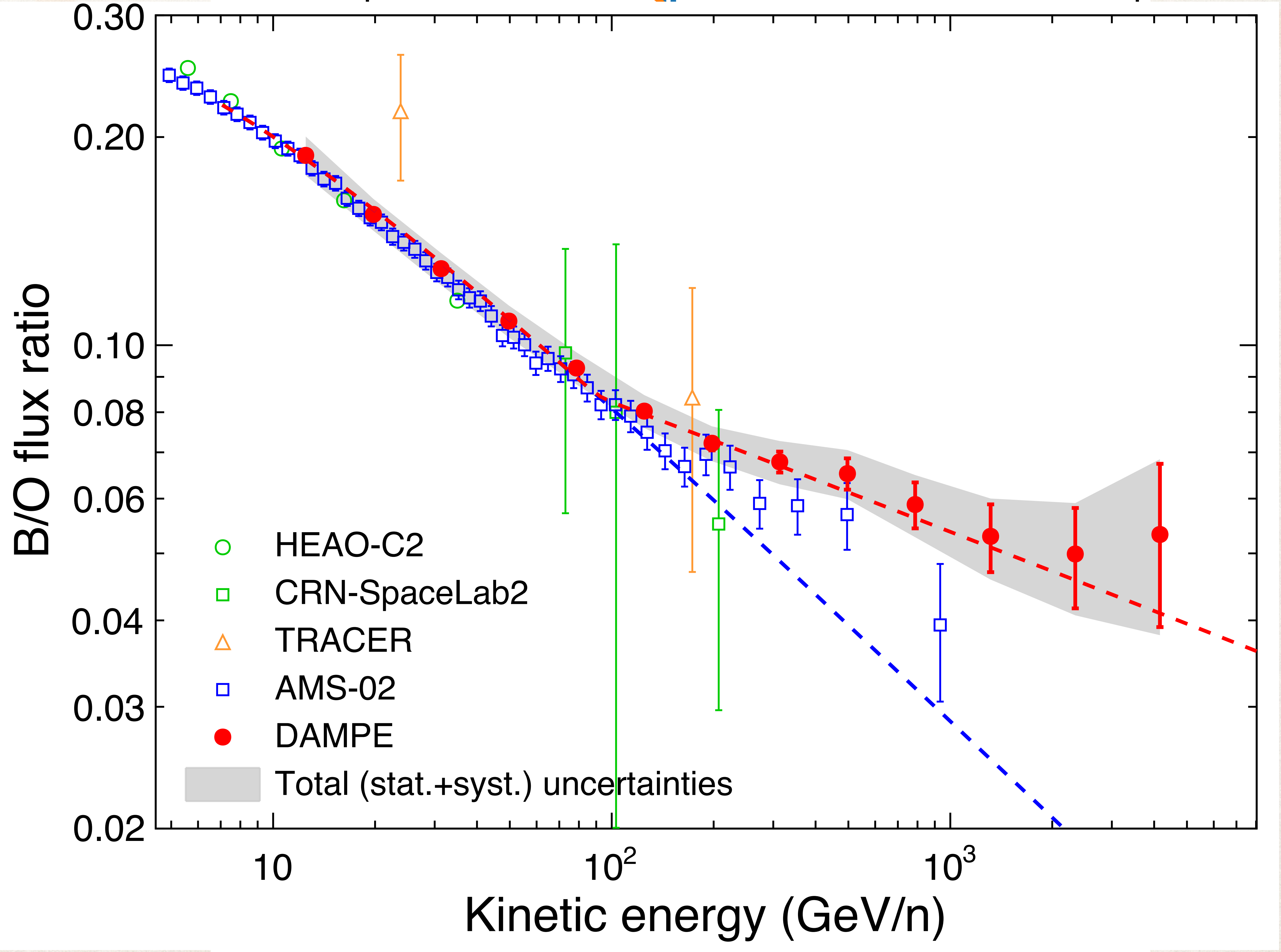


Schroer+2020

CR clocks: Stable Elements







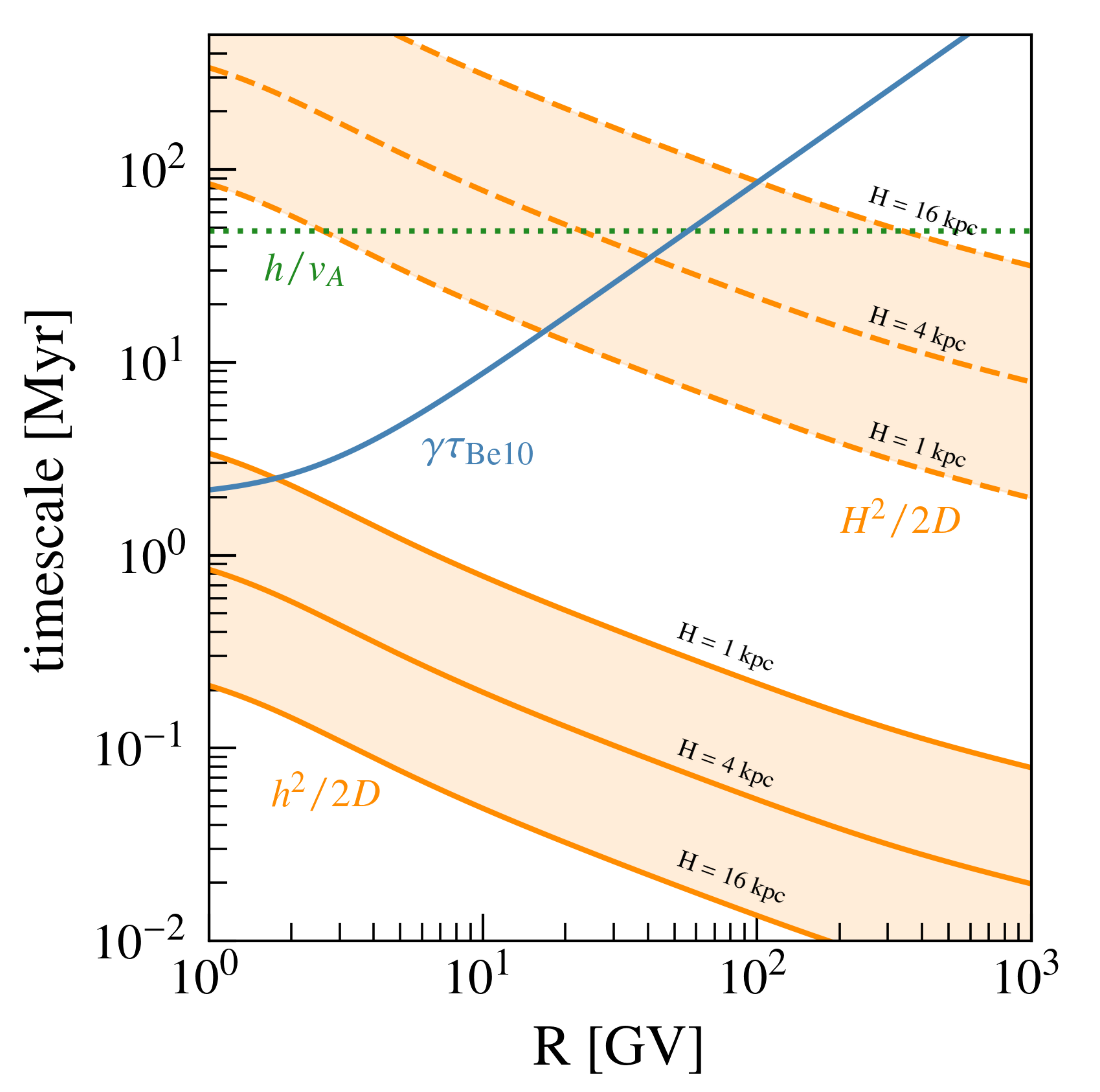
Schroer+2020 R [GV]

CR clocks: Unstable Elements

Of the three isotopes of Beryllium, ^{10}Be is unstable with a lifetime of 1.4 Myr and its decay leads to ^{10}B.

Its abundance, compared with that of the stable isotopes returns the confinement time in the Galaxy

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



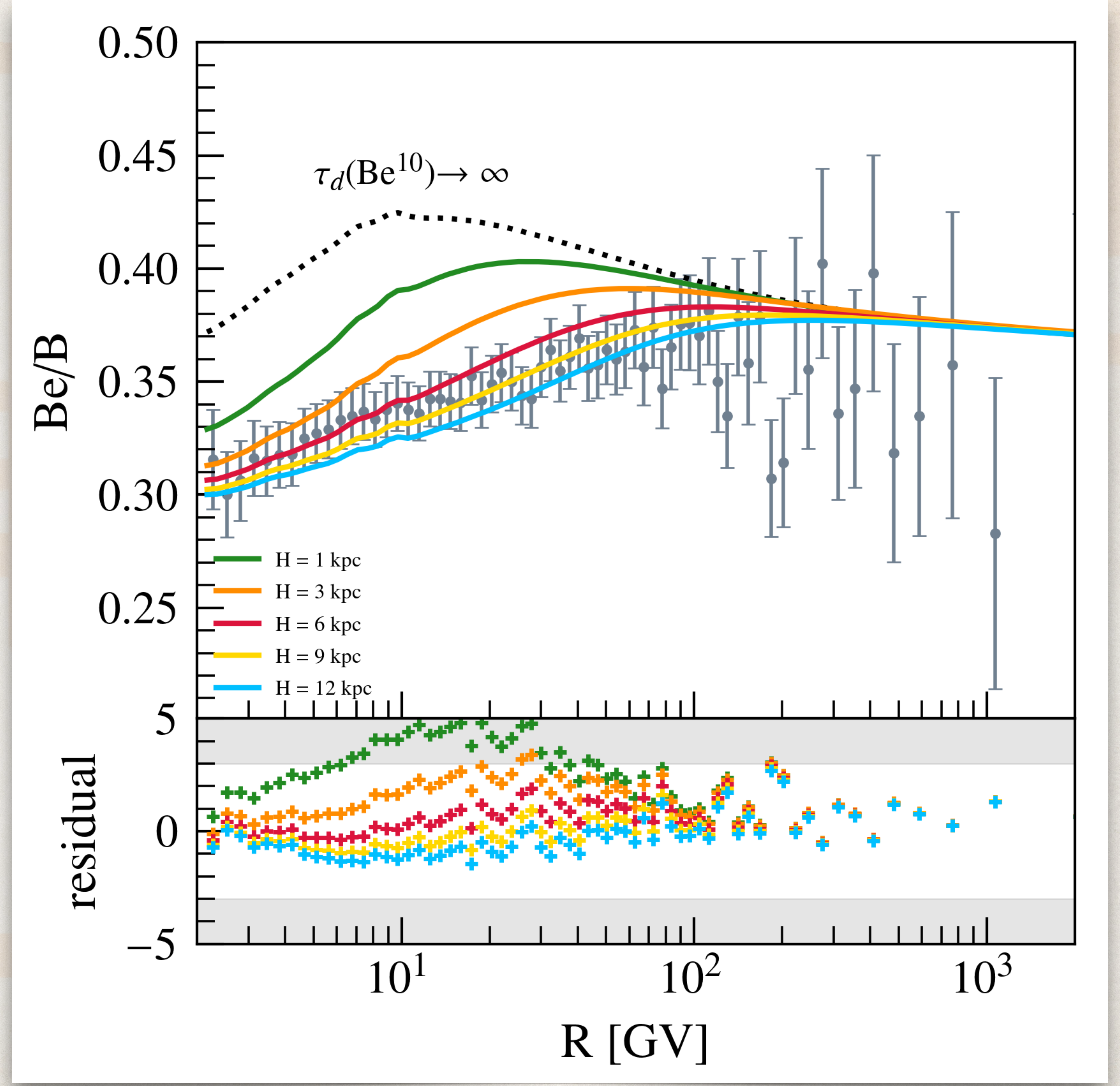
Evoli et al. 2020

Effect of cross sections

- The Be/B ratio is sensitive to the diffusion time, because the decays of ^{10}Be decrease the numerator and increase the denominator

- The AMS-02 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**



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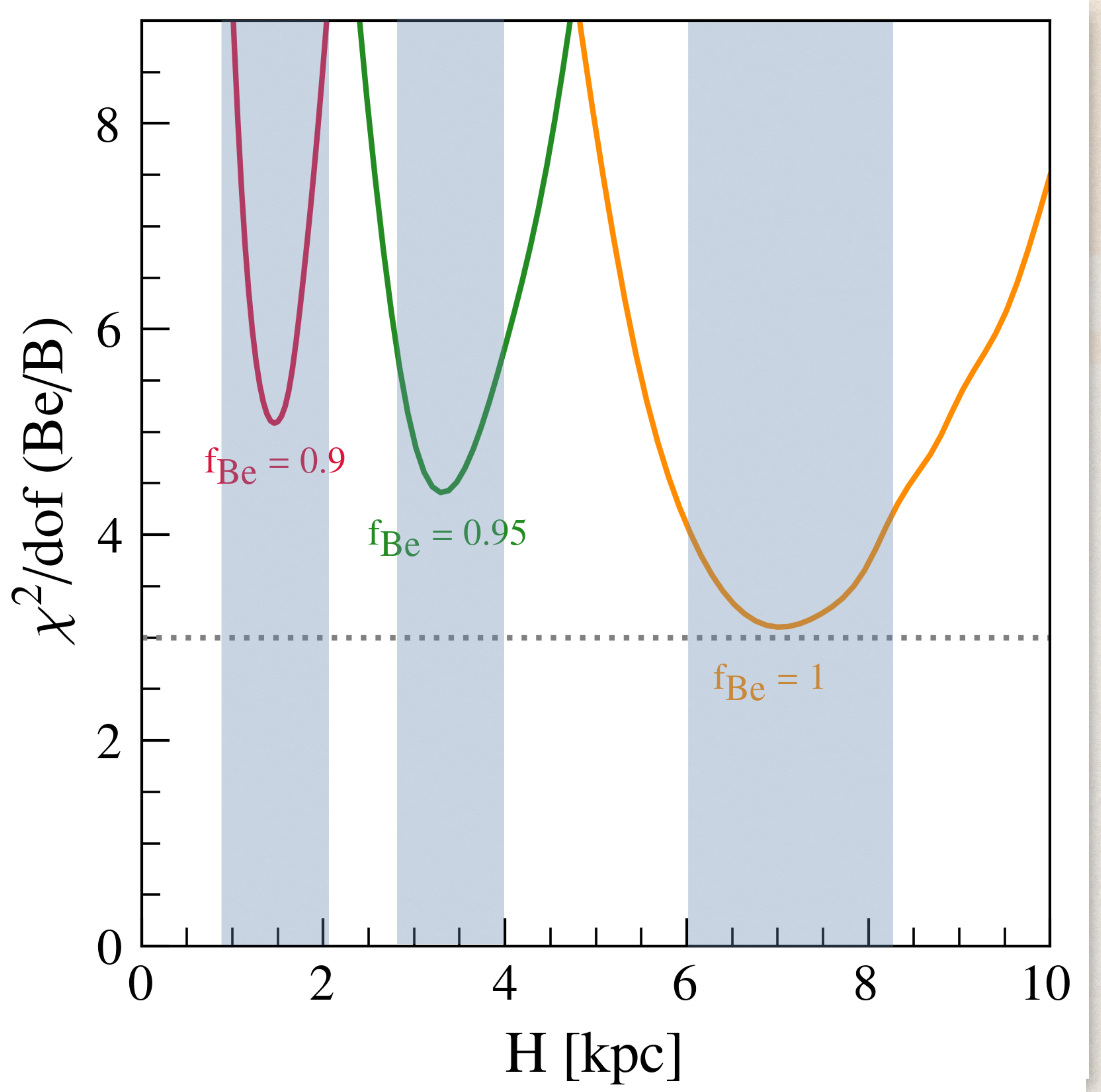


Evoli et al. 2020

Change in D(E) from what to what?

- **Short answer: we do not know**
- At R<1000 TV CR can be self-confined through resonant streaming instability
- At R>1000 TV they have to rely upon pre-existing turbulence but…
    - *Alfvenic turbulence develops anisotropy*
    - *Fast modes isotropic but possibly damped*
    - *No easy way to a smooth transition from low to high energies* (Kempski+2021)

Diffusion at high energies

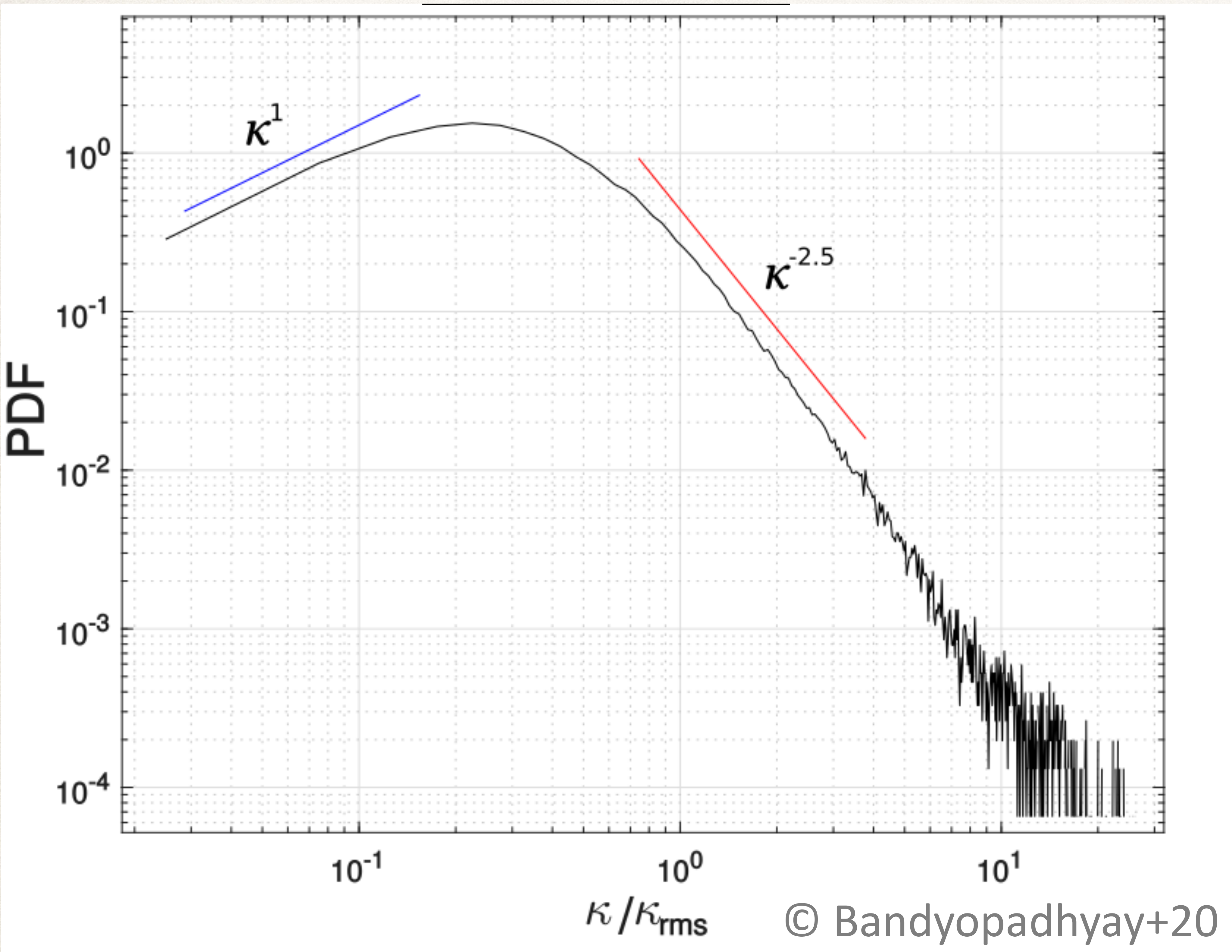
◆ Many investigations of the scattering processes as due to mirrors (Lazarian & Xu 2021), intermittency (Lemoine 2024, Kempski+2024), resonances, … FLRW (Pezzi & PB 2024, Recchia & Gabici 2024)

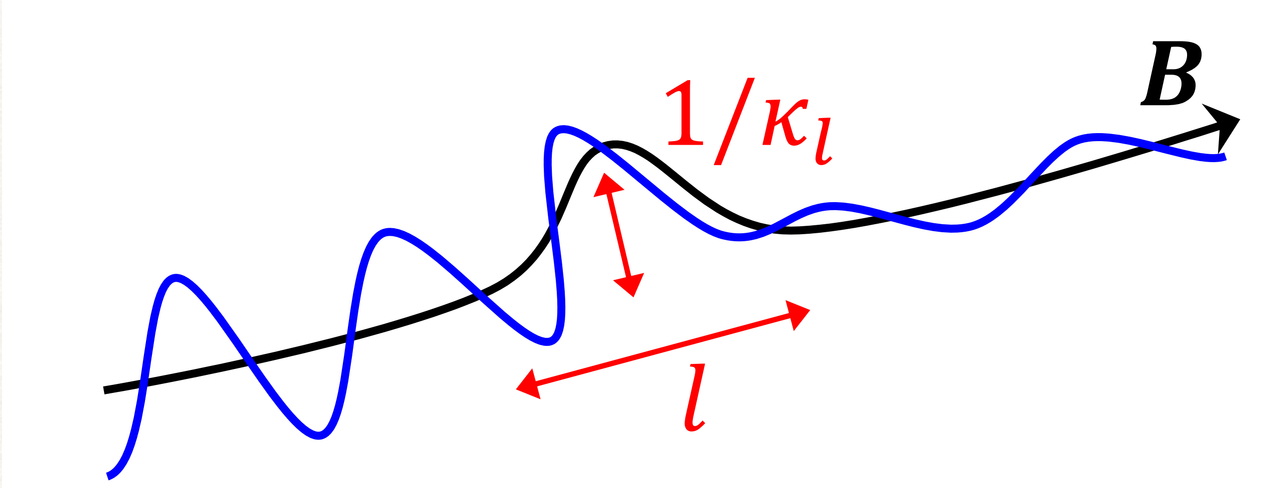
◆ In general, D(E) in MHD turbulence strongly depends upon conditions in the plasma (plasma β, $\delta B/B$, anisotropy…) but…

◆ The rather new picture of scattering as due to curvature in intermittent MHD turbulence (Lemoine 2024, Kempski+2024) appears very promising (though only $\delta B/B >> 1$)

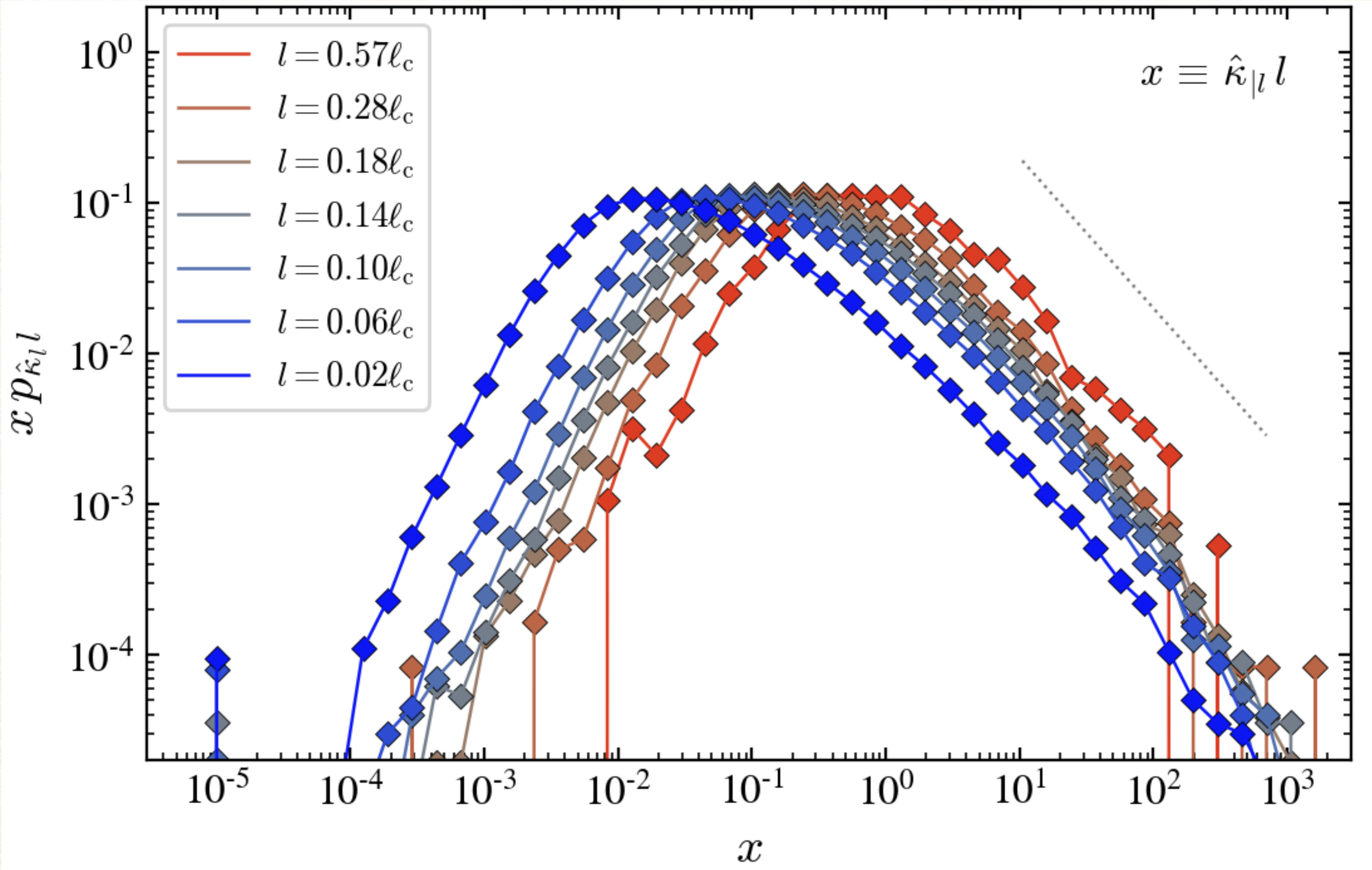
CR transport in intermittent turbulence

Lemoine 2024





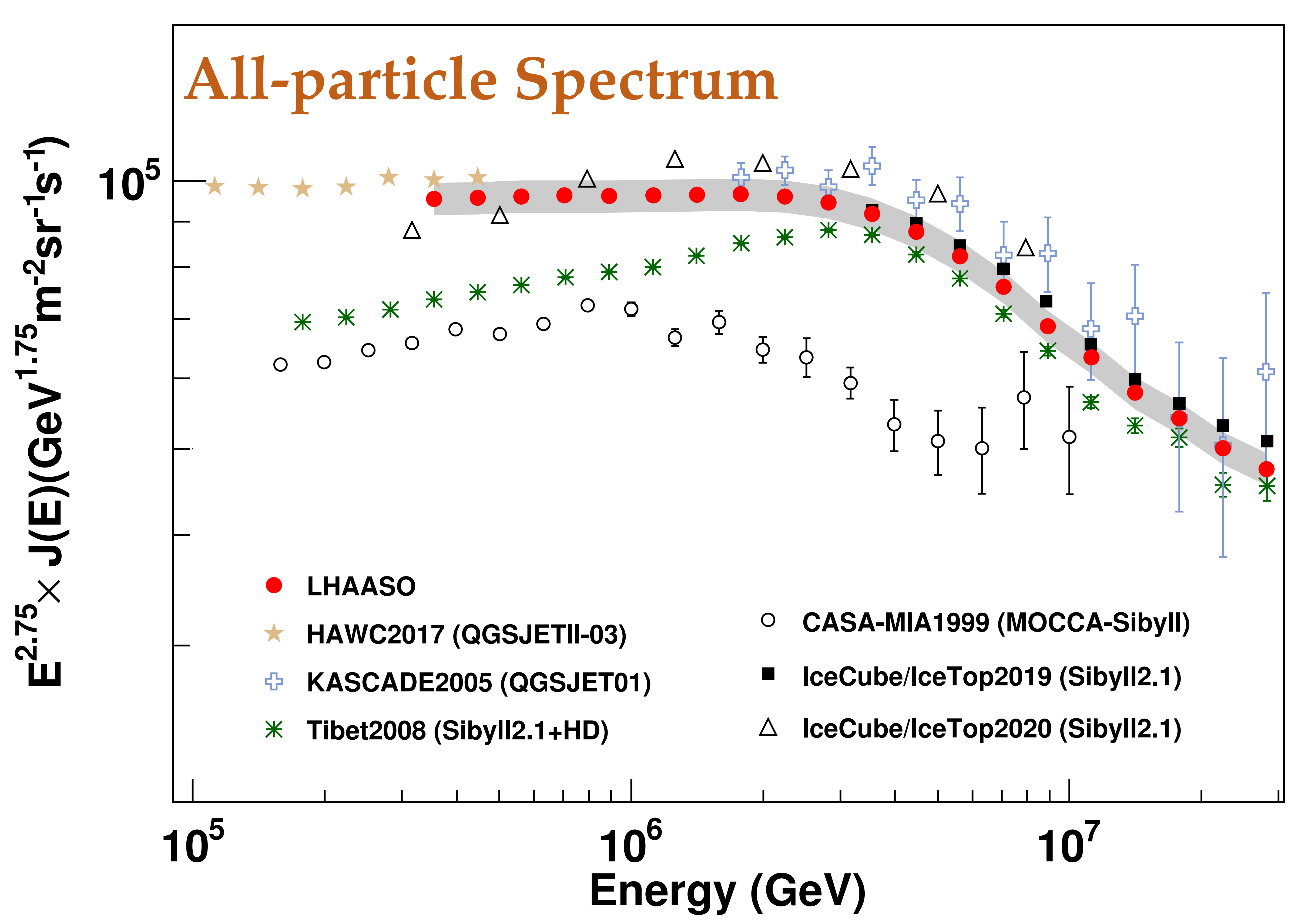
$$\lambda_s \sim \ell_c^{0.7}\, r_g^{0.3}$$

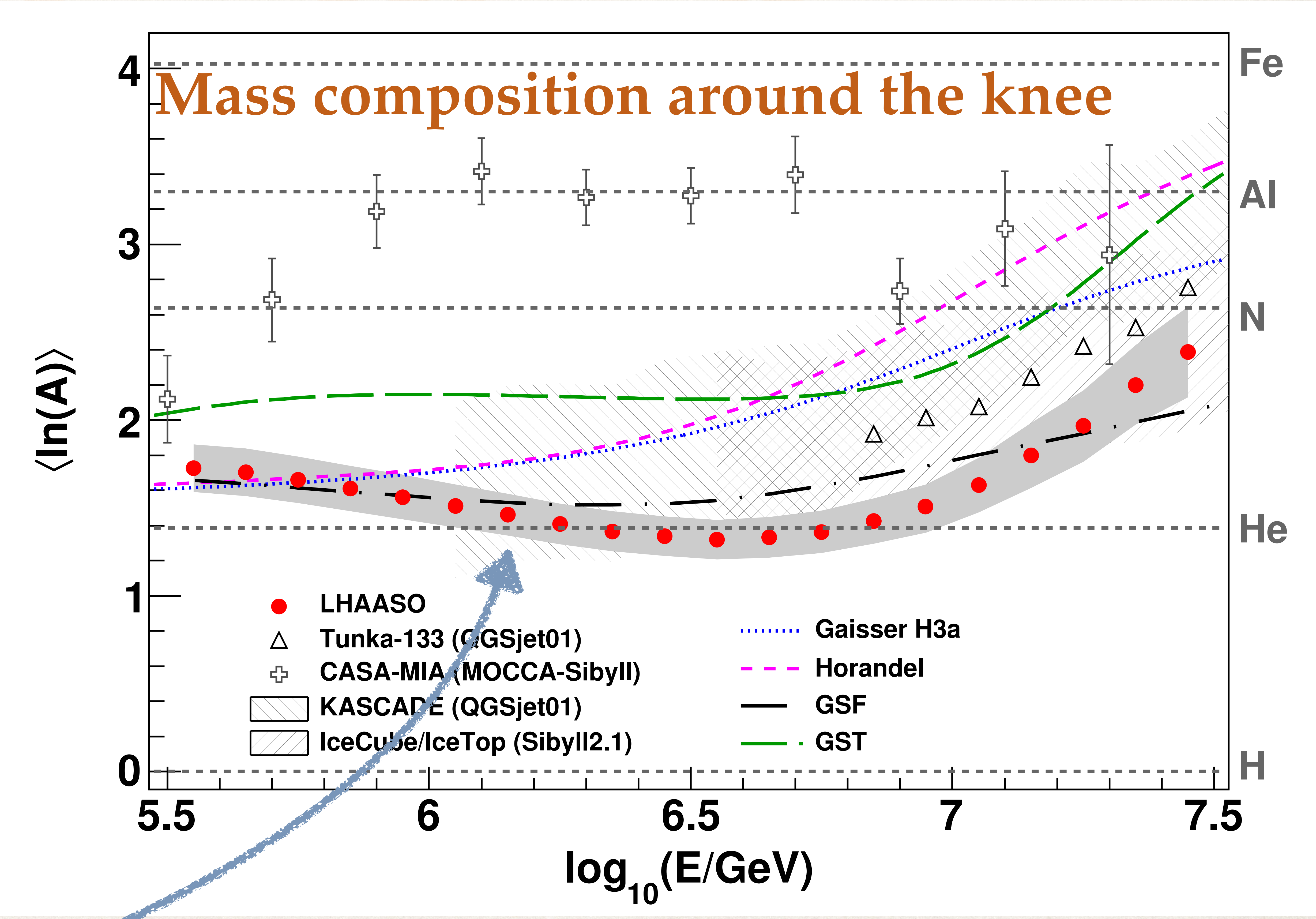


Scattering length with the same scaling on l_c and energy as would be expected for a Kolmogorov spectrum, but no connection with such a case

The result basically derives from the non-Gaussian statistics of curvatures in MHD turbulence

LHAASO Knee

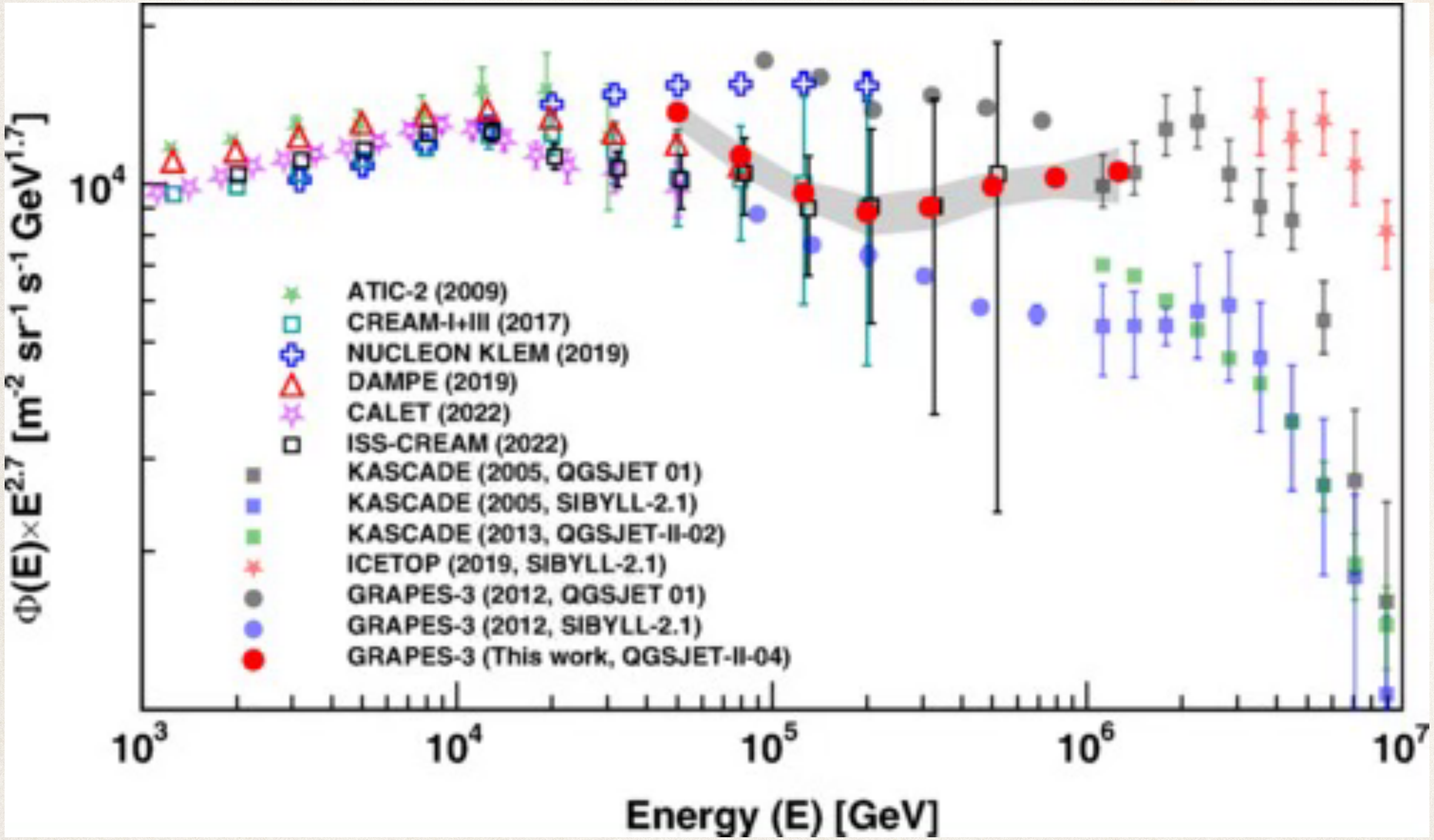




Hint of different classes of sources with different E_{max}?

Cao et al. 2024

A picture that starts taking shape…



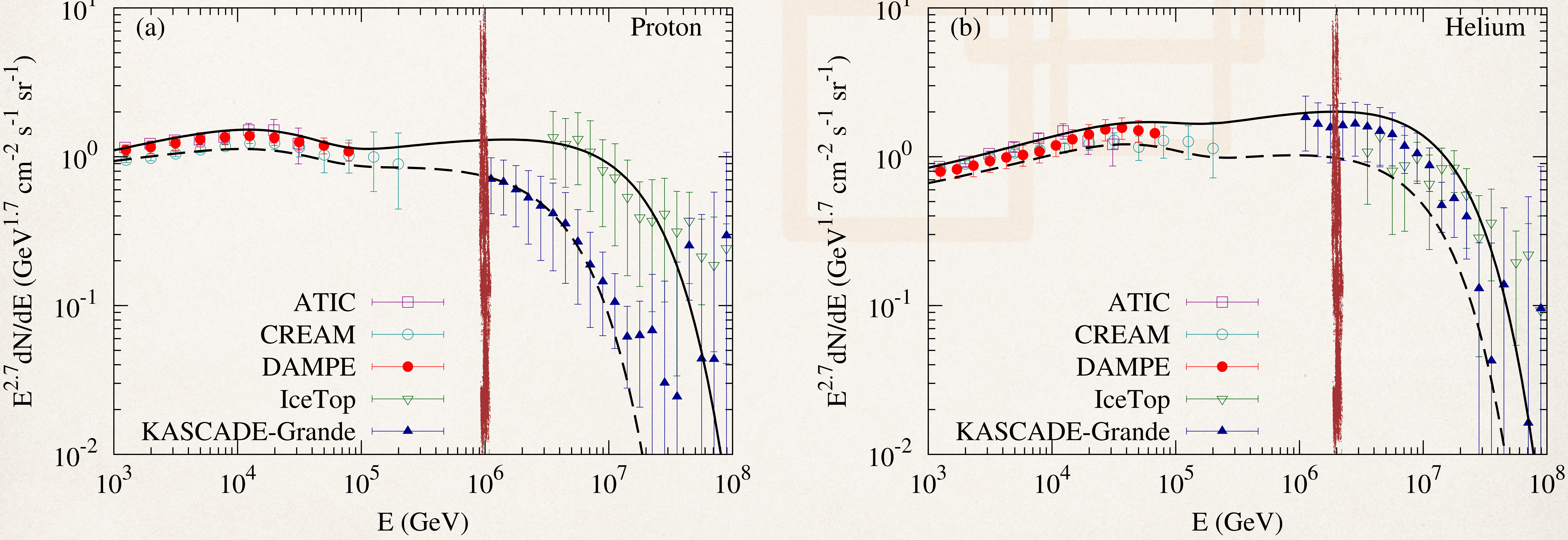
Varsi et al. 2024

The DAMPE bump connects well with the GRAPES measurement of the spectrum at higher energies

Given the strength of the effect it seems unlikely that we are looking at a fluctuation

A new population of sources with higher E_{max}?

Knee Pain

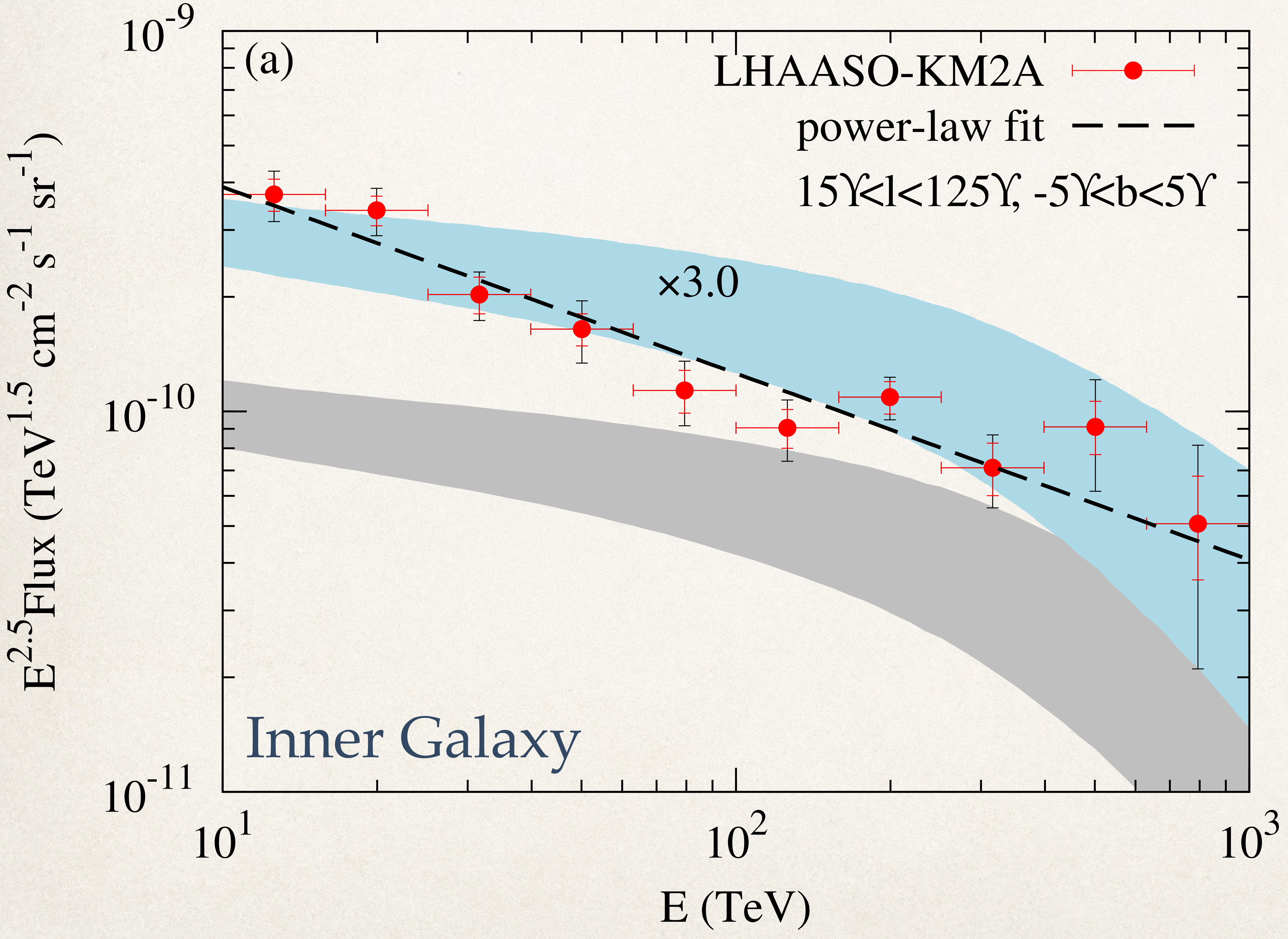


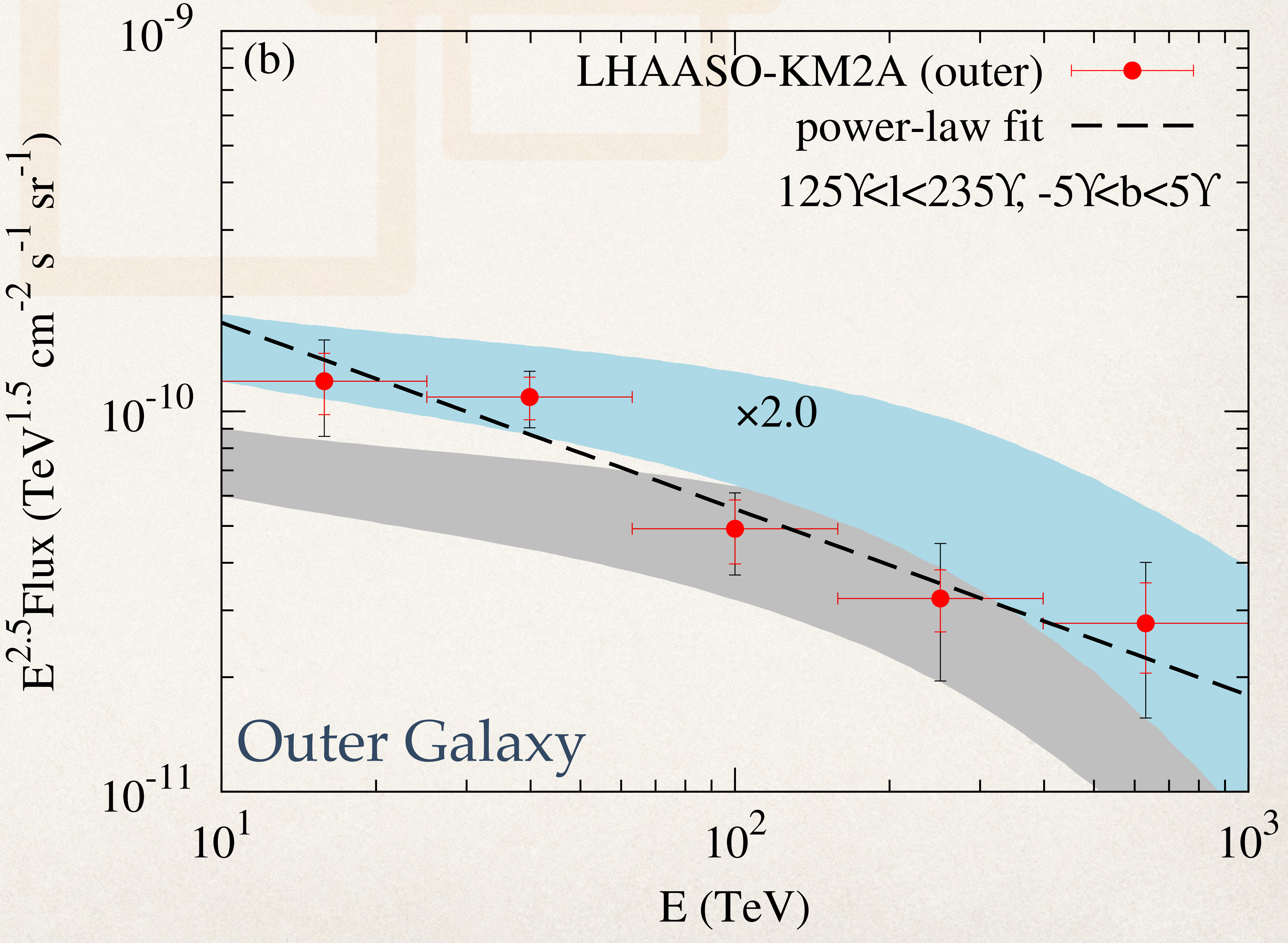
The uncertainty in the position of the proton knee has serious implications on the description of the transition to extra-Galactic CRs

Diffuse gamma rays and neutrinos:

Diffuse emission or sources?

Cao et al. 2023





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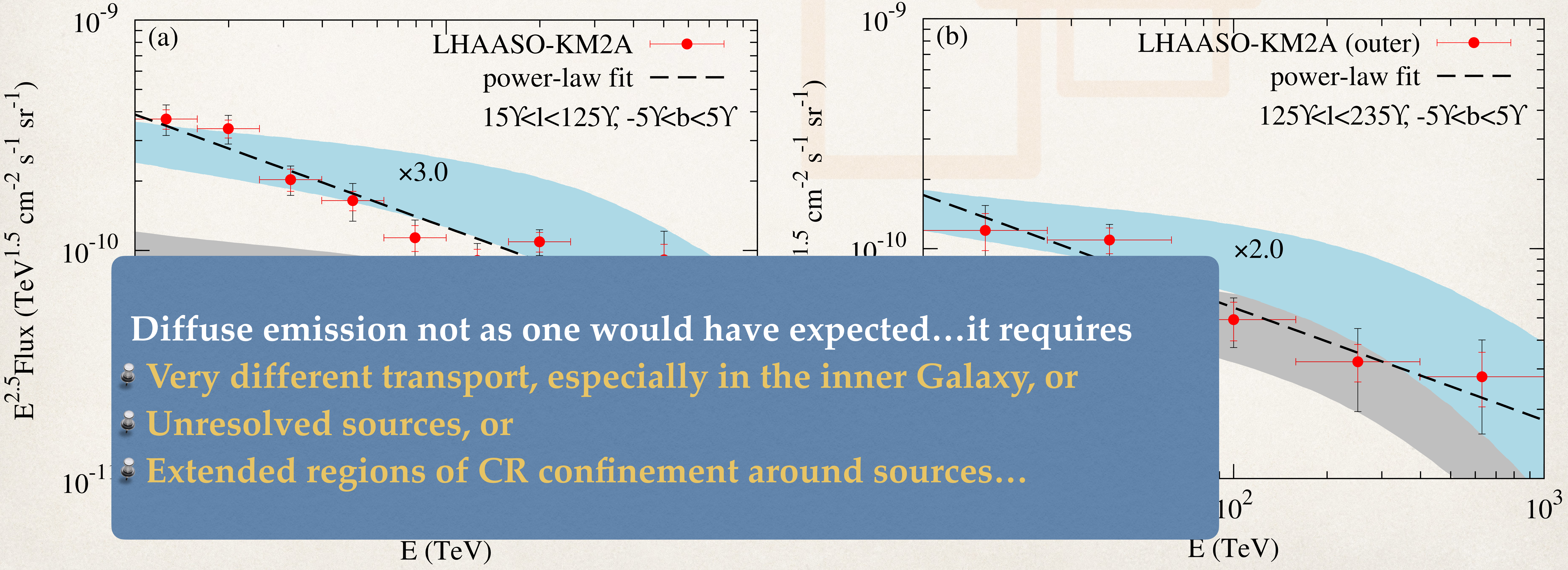
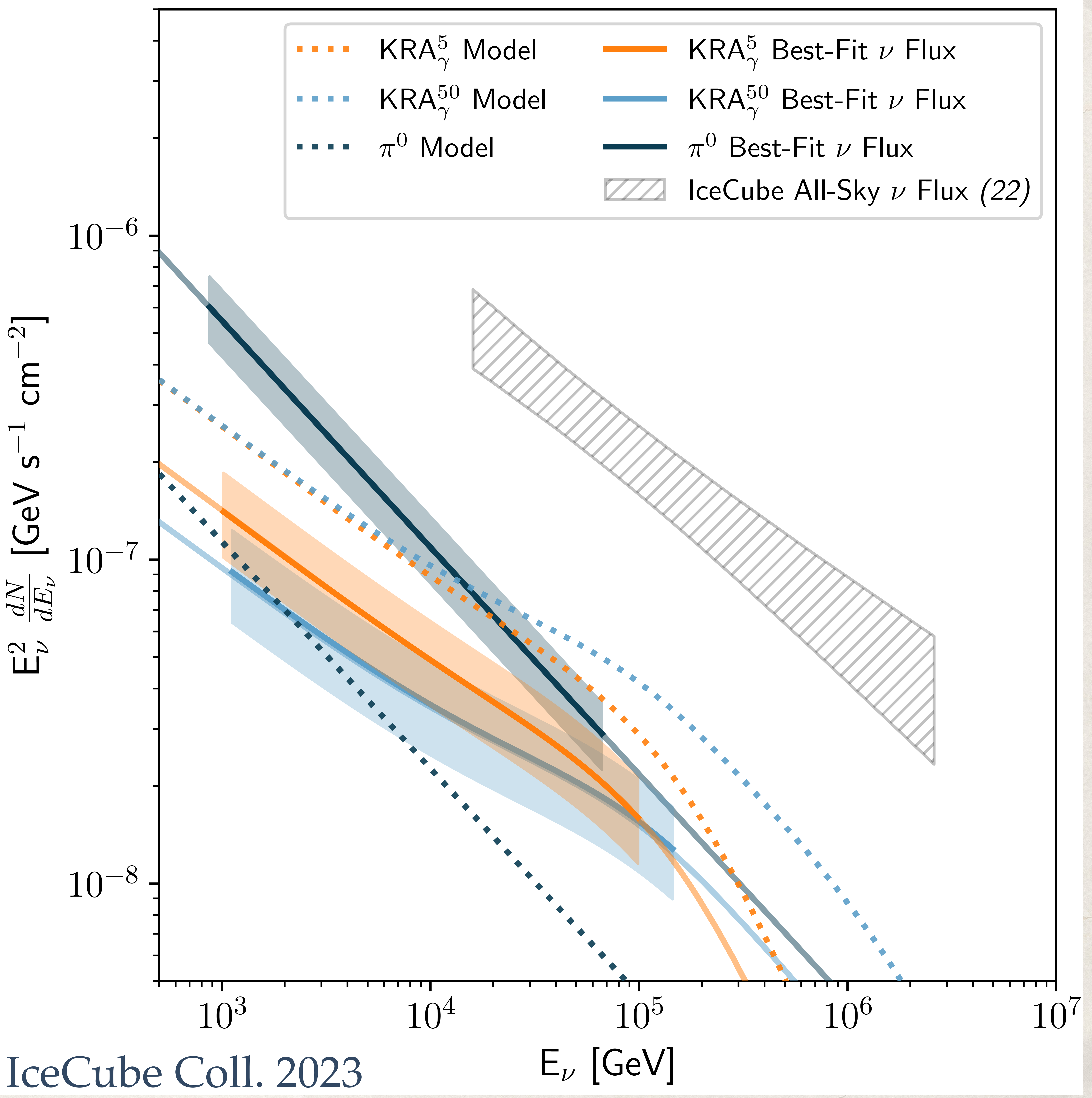


Diffuse emission not as one would have expected…it requires

- **Very different transport, especially in the inner Galaxy, or**
- **Unresolved sources, or**
- **Extended regions of CR confinement around sources…**

Similar considerations from neutrinos



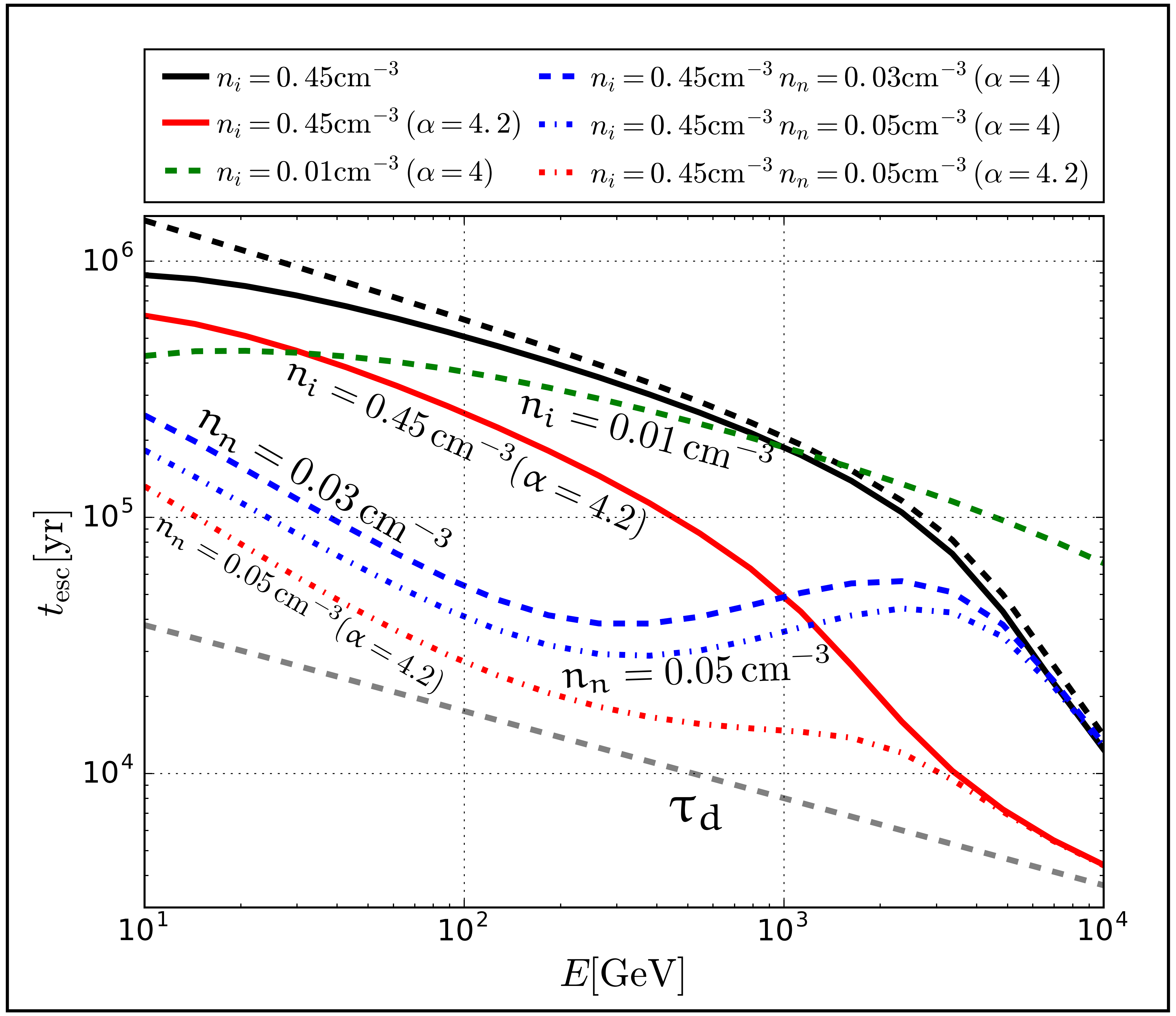
IceCube Coll. 2023

Self-Confinement Near a SNR

The regions around sources have the strongest CR densities and density gradients, which lead to self-confinement, due to streaming instability. The diffuse gamma ray emission due to the overlap of these regions reflects this (D'Angelo+2018)

D'Angelo, PB, Amato 2016, 2018

Nava+2016, Recchia+, 2023



THE PHENOMENON IS REGULATED AND SHAPED BY DAMPING, ESPECIALLY NLLD

Regions of smaller density in which molecular clouds are embedded set the best situation in which the confinement time is the longest and interactions occur in the cloud (Bao, PB & Chen 2024)

Grammage near the source

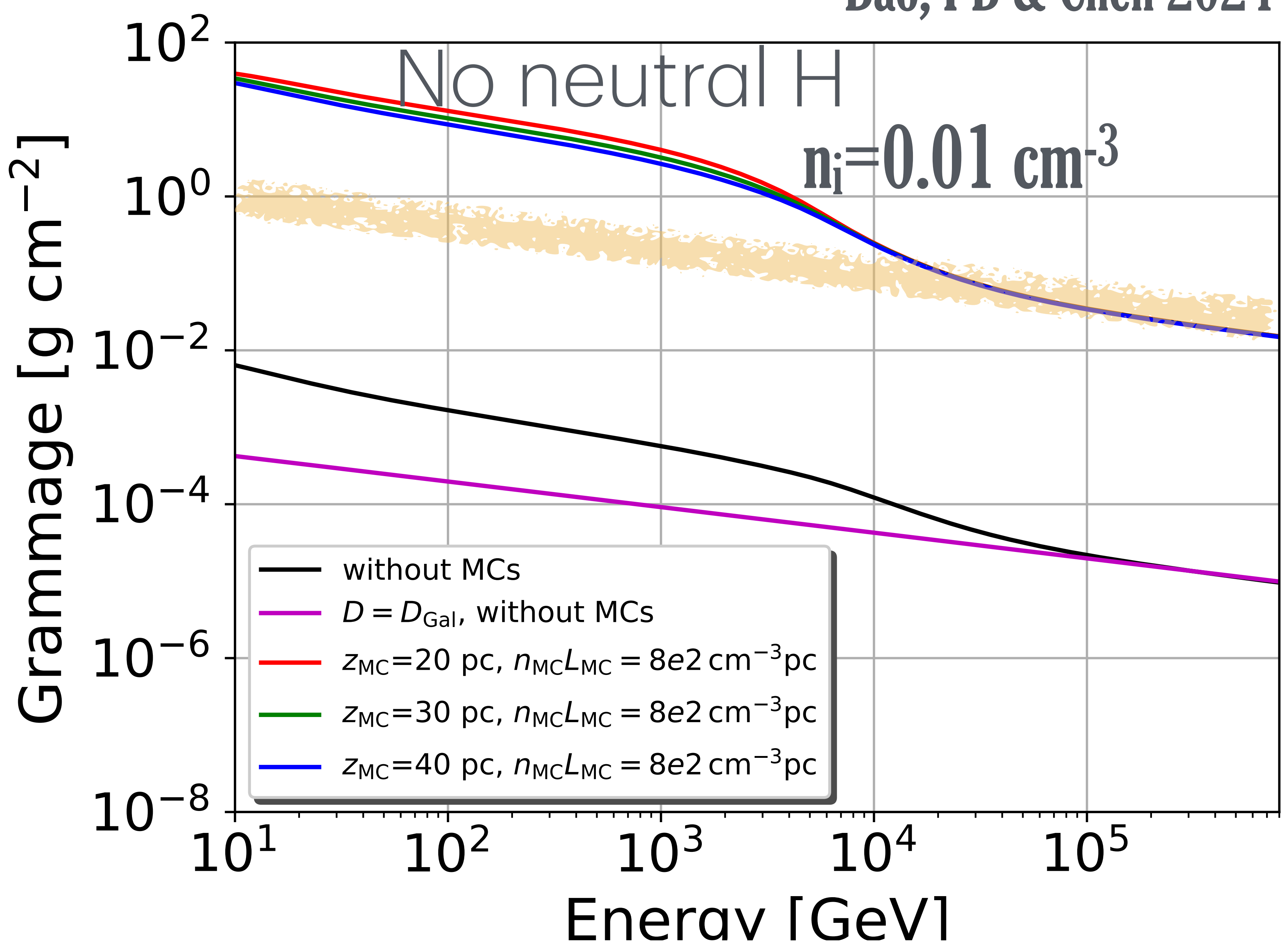
The grammage near a source, due to self-confinement, depends on conditions (level of ionisation, coherence length)

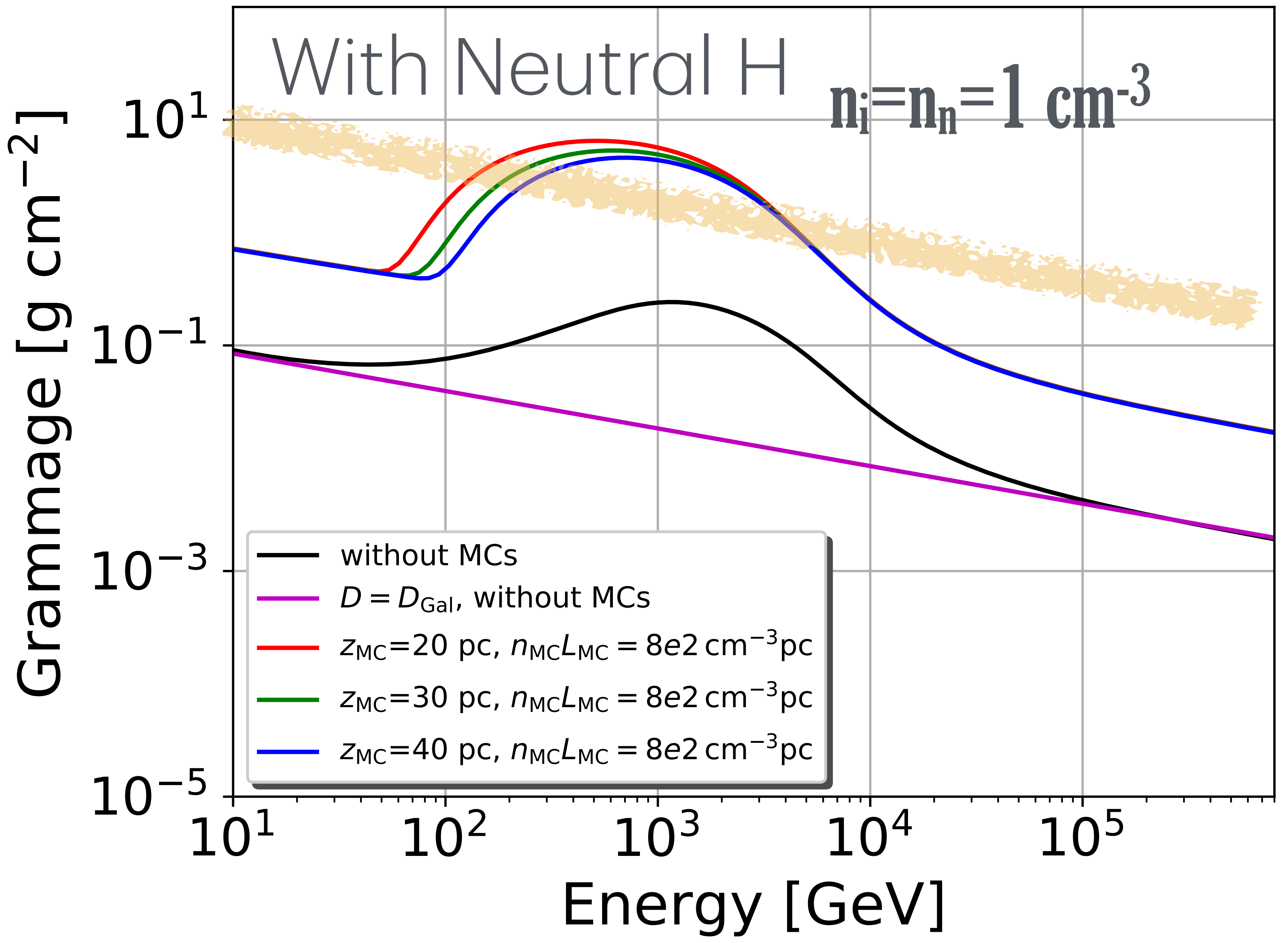
Most importantly it depends upon the presence of molecular clouds in the neighbourhood of a source

…but it is clear that it is not a phenomenon that we can ignore at a time in which measurements of the grammage are made at percent level

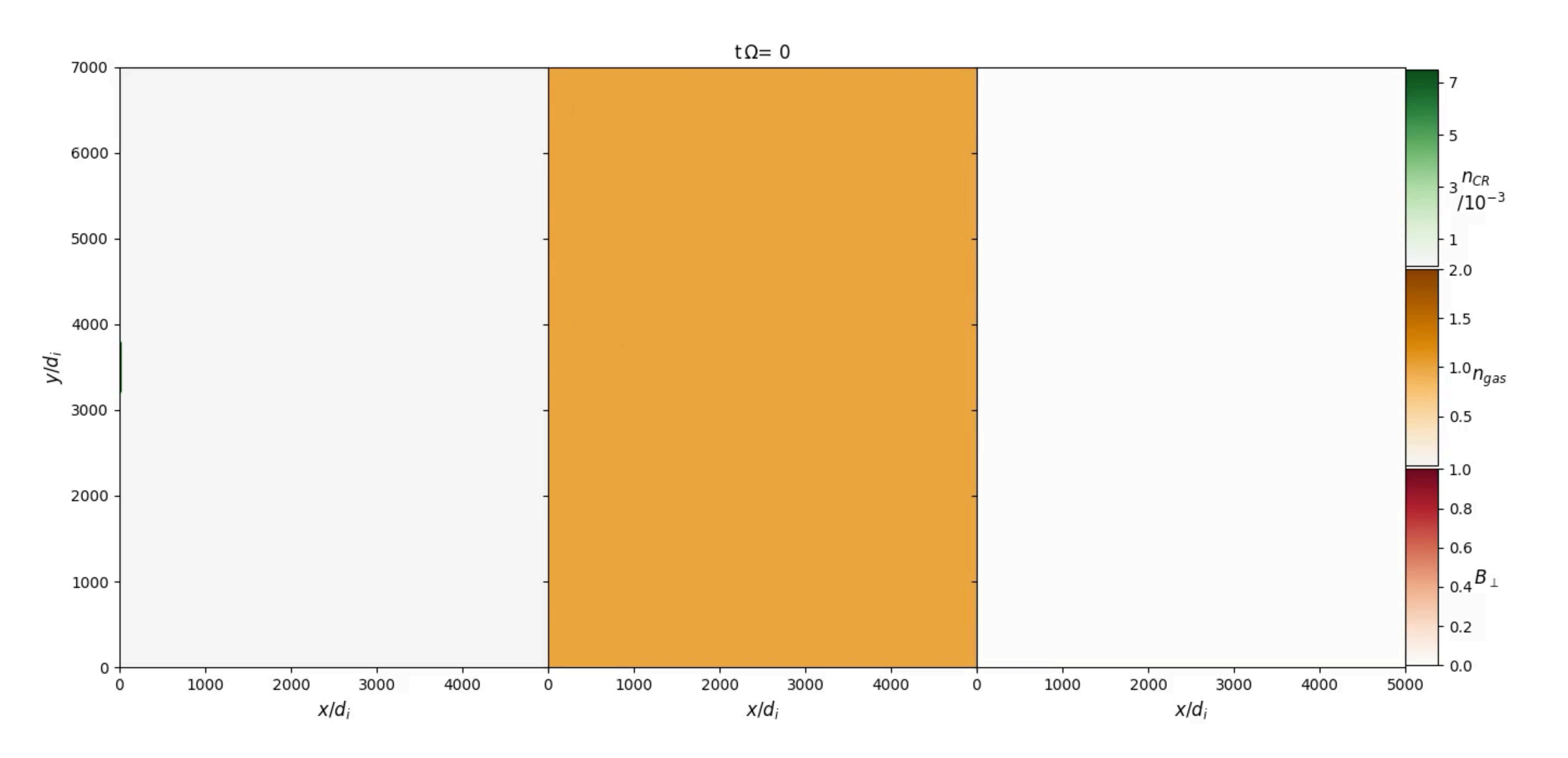
… and at a time in which the diffuse fluxes of gamma rays and neutrinos hint at some possible anomalous behaviour

Bao, PB & Chen 2024





Regions of reduced diffusivity around young SNRs



Schroer+, 2021, 2022

For young SNRs the current density can be sufficient to excite a non-resonant instability, which induces self-confinement

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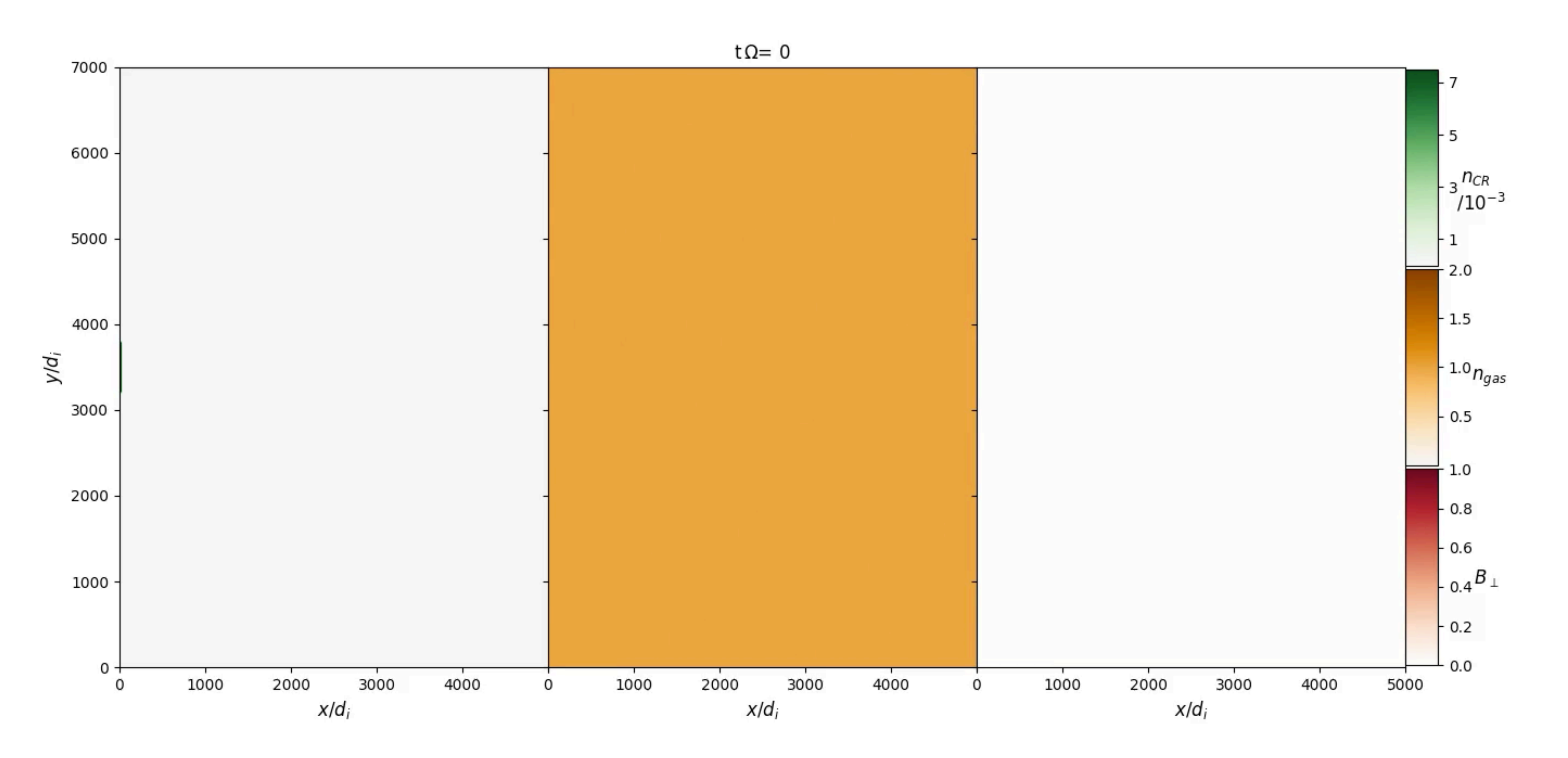

Schroer+, 2021, 2022

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Where are PeVatrons?

Definition of a PeVatron: "*A PeVatron is a source that is able to accelerate particles with a spectrum that shows a substantial suppression with respect to its low energy power law extrapolation in the region of PeV energies*"

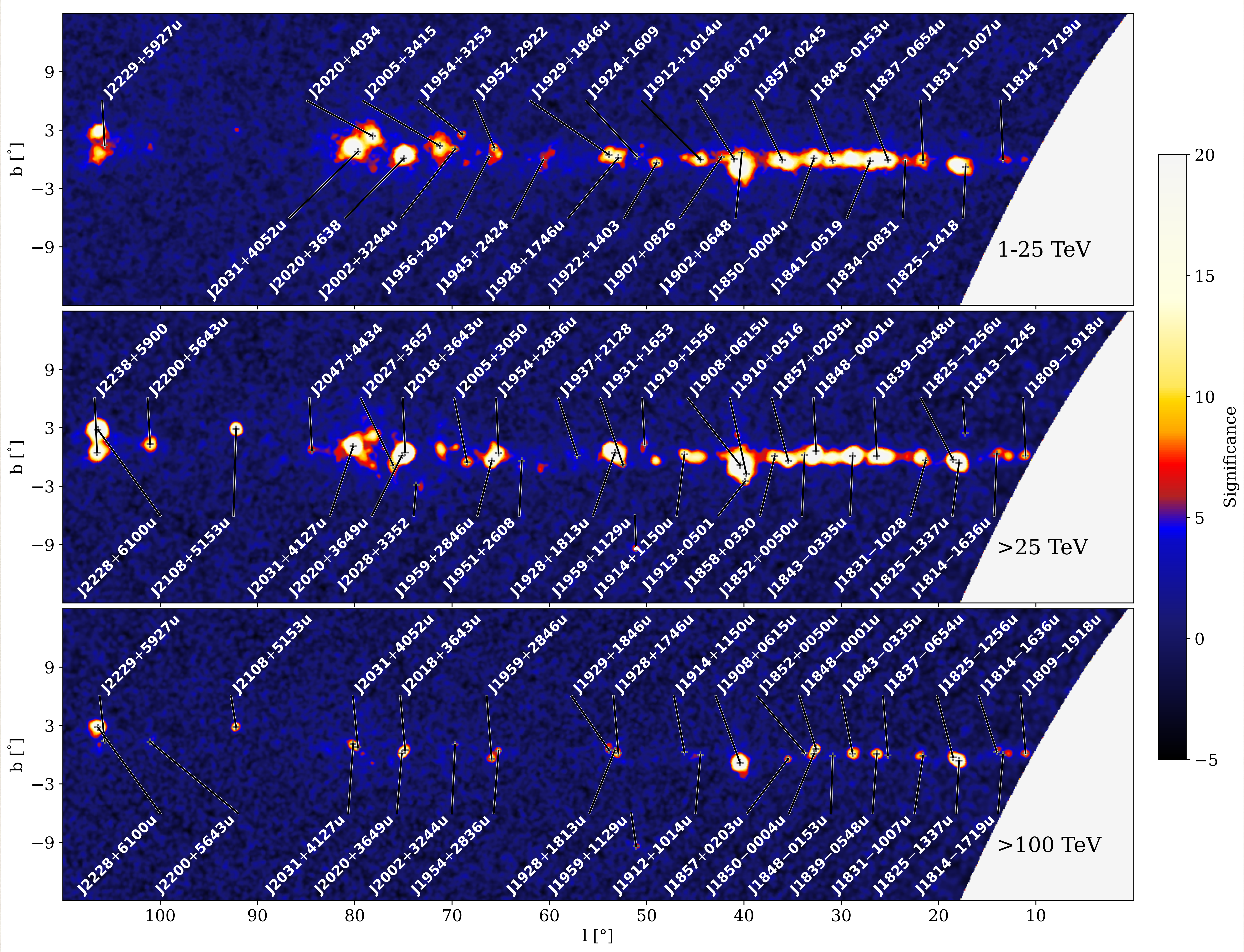
It follows that a PeVatron would show a hard (slope ~2) power law gamma ray spectrum with a suppression in the region of hundreds of TeV

These are the sources that we have been looking for as sources of Galactic cosmic rays

It can be argued that if SNRs are PeVatrons, we did not figure out how they can be so…

Direct detection of PeVatrons?

Cao et al. 2024 *"The First LHAASO Catalog of Gamma-Ray Sources"*

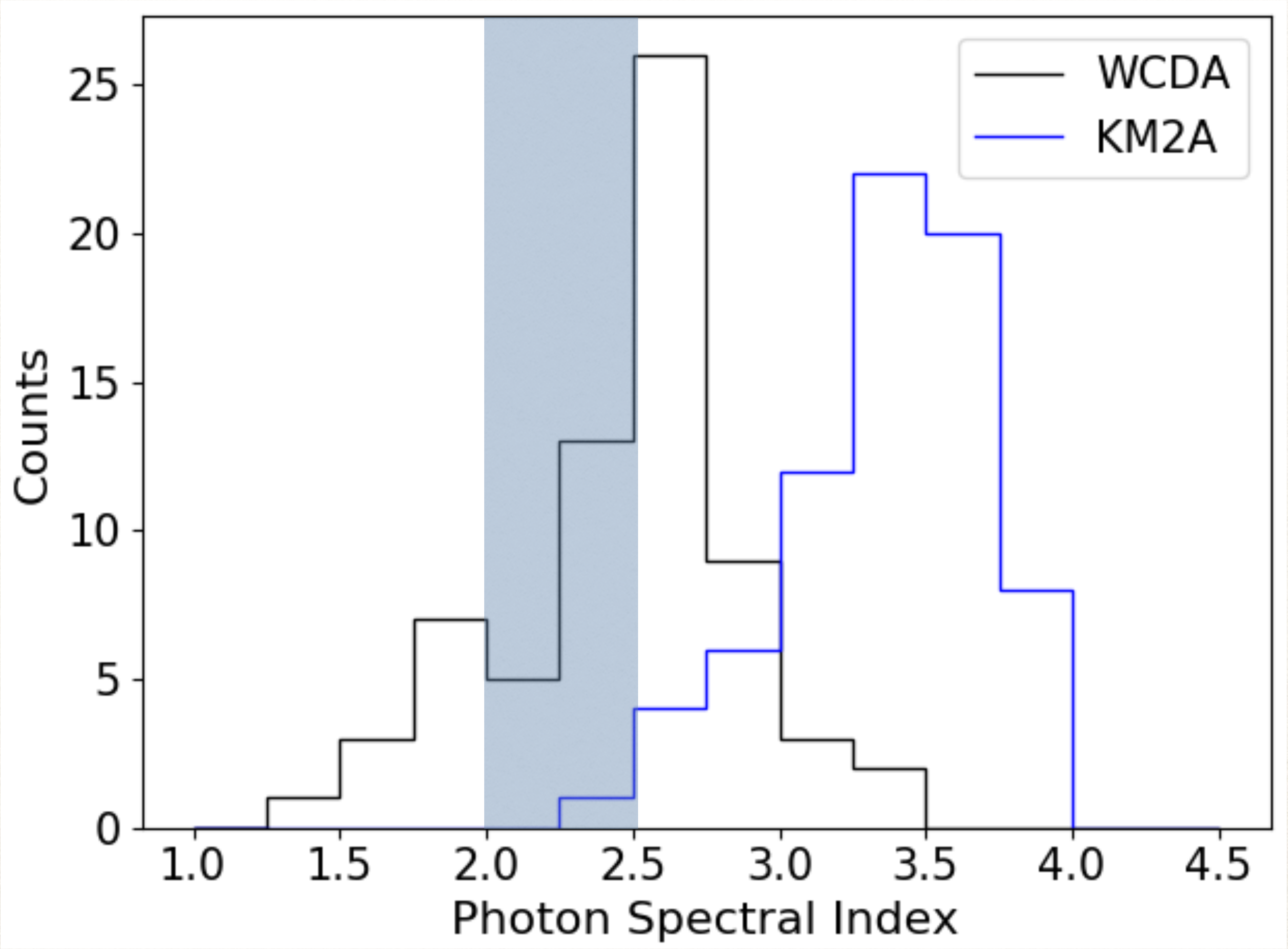


- For the first time, LHAASO is providing us with the unique opportunity to answer the question "***which sources are responsible for PeV CR?***"
- Currently **43 sources** with gamma rays with E>100 TeV detected at 4σ
- Of these **22 sources** have significance >7σ
- Of these, for sure some are well known pulsar wind nebulae, which means that the emission is most likely of leptonic origin (electron-positron pairs)
- Among PWNe one is the well known Crab Nebula, the only PeVatron known for sure, BUT the PeV particles are leptons

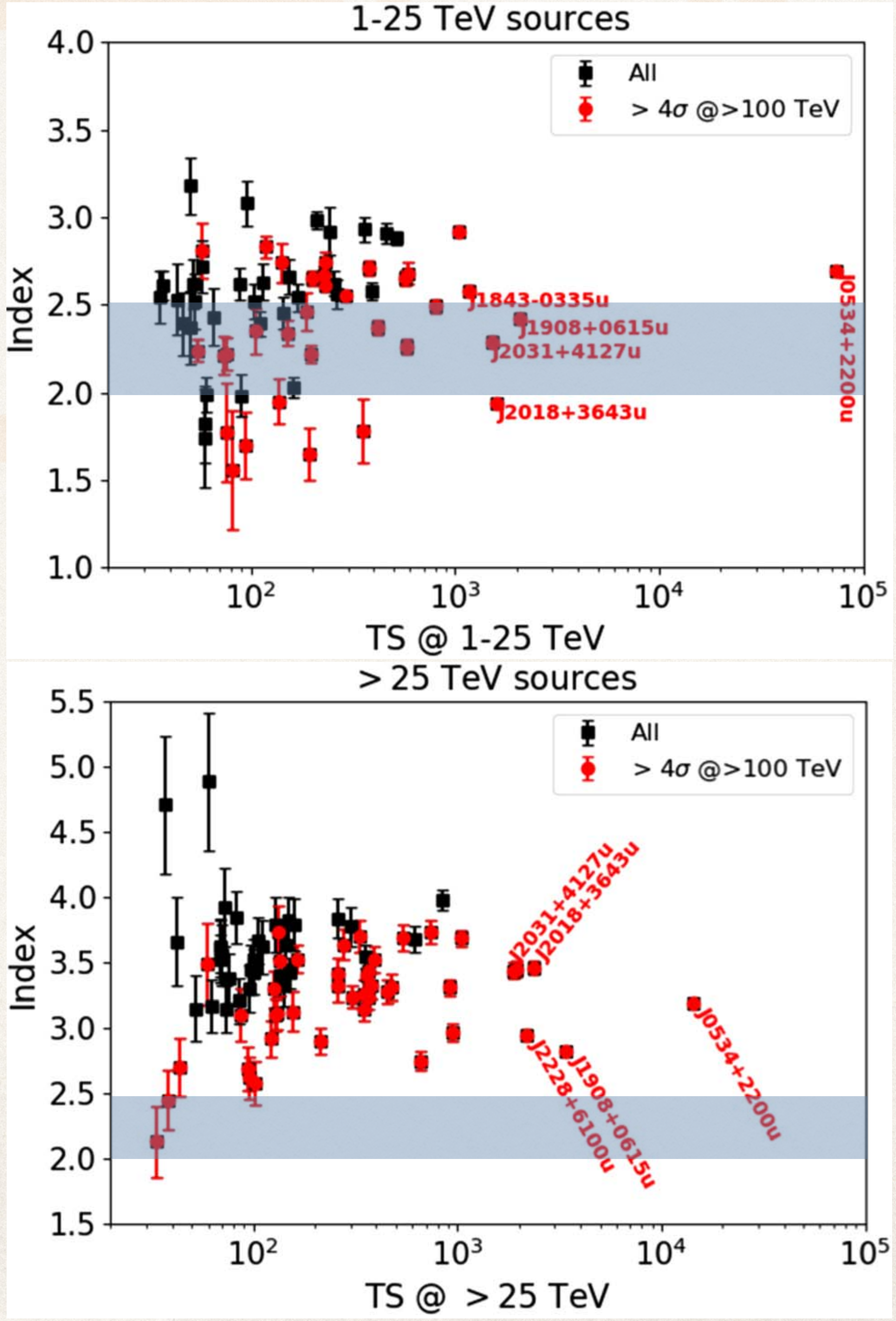
Direct detection of PeVatrons?

Cao et al. 2024 *"The First LHAASO Catalog of Gamma-Ray Sources"*

- At 1-25 TeV many detected sources with slope consistent ~2-2.5
- At higher energies, slope ≥3, cutoff region?
- For >100 TeV only a couple of sources with slope~2-2.5, no clear association yet



Adapted from Cao et al. 2024



Particle Acceleration to PeV

In astrophysical plasma, the high conductivity forces electric fields to be short-circuited (**no large scale electric fields**, with few exceptions)

Magnetic fields do not do work on charged particles, hence the energy of the particles cannot change

The only electric fields allowed are of induced origin (**magnetic fields in motion**)

That is why fast moving plasmas (violent phenomena) both ensure high total energetics and high induced electric fields

The best conditions for acceleration are the regions where dissipation occurs, typically involving COLLISIONLESS SHOCKS (**see talk by Caprioli**)

A plethora of non-linear effects in DSA

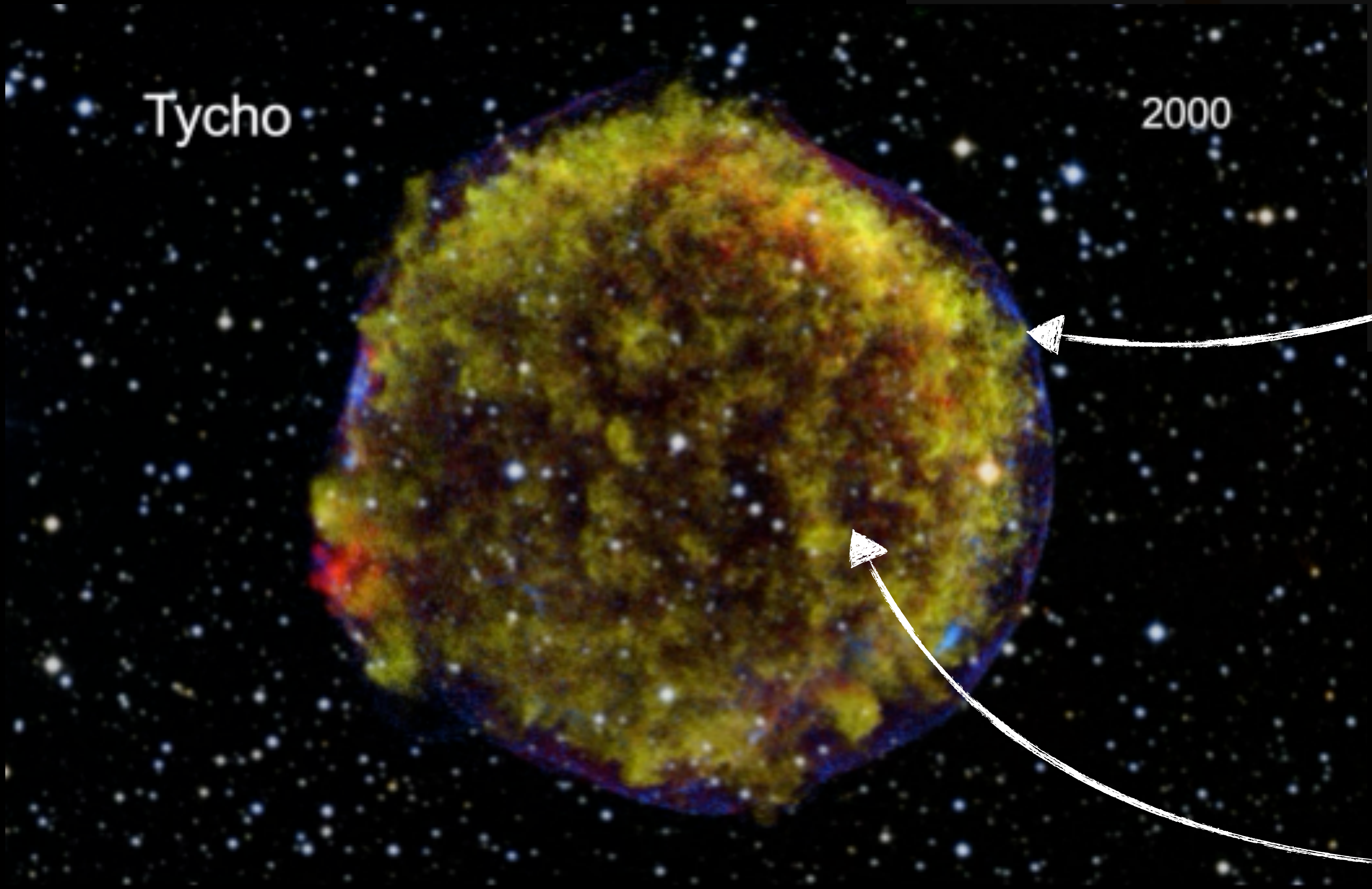
See talk by D. Caprioli

- Efficient CR acceleration strongly modifies the dynamics of the plasma motion ahead of the shock —> **modified spectrum**

- Efficient CR acceleration leads to magnetic field amplification —> **higher energies through more effective scattering**

- Higher B fields mean larger speed of scattering centres —> **modified (steeper) spectrum** [Caprioli, Haggerty & PB 2020]

X-ray Observation of the Shock —> Large B



The purple filaments are X-ray emission of non-thermal origin, namely caused by **synchrotron emission** of high energy accelerated electrons

The very thin thickness (~0.01 pc) allows us to determine the magnetic field in that region — **about 300 μG**, hundreds of time larger than it should be [see e.g. Vink 2012]

$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

$$B \approx 100\ \mu\mathrm{Gauss}$$

$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \mathrm{TeV} \qquad \nu_{max} \approx 0.2\ u_8^2\ \mathrm{keV}$$

Soft X-rays due to line emission of thermal origin from the Ejecta

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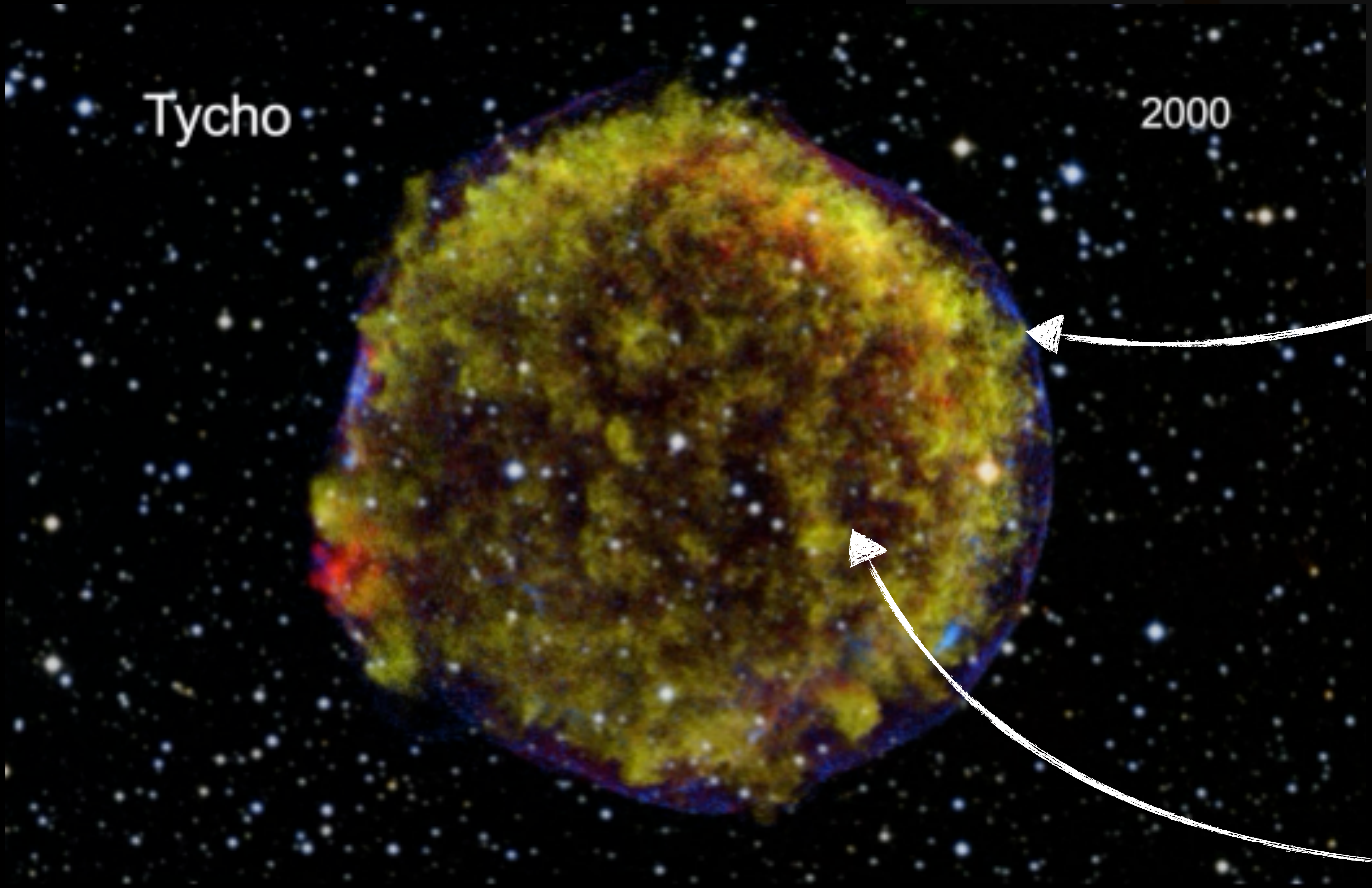

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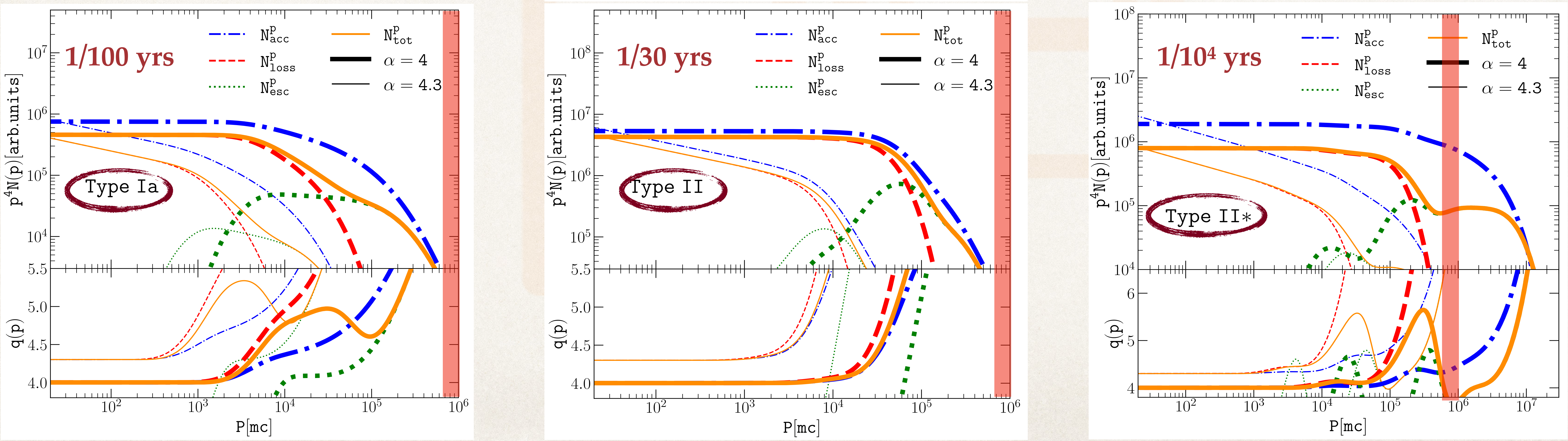
CONSIDERATIONS ON SNRs AS PEVATRONS

- EVEN IN THE PRESENCE OF EFFICIENT CR INDUCED STREAMING INSTABILITY (Bell 2004), THE CORRESPONDING SCATTERING IS TOO SLOW TO REACH PeV ENERGIES IN STANDARD SNR (Bell+2013, Schure+2013, Schure+2014)
- THERE ARE SEVERAL CLASSES OF SNR WITH DIFFERENT E_{MAX}...
- ONLY VERY LUMINOUS, RARE SNR MIGHT BE ABLE TO REACH THESE VERY HIGH ENERGIES



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

Star Clusters as PeVatrons?

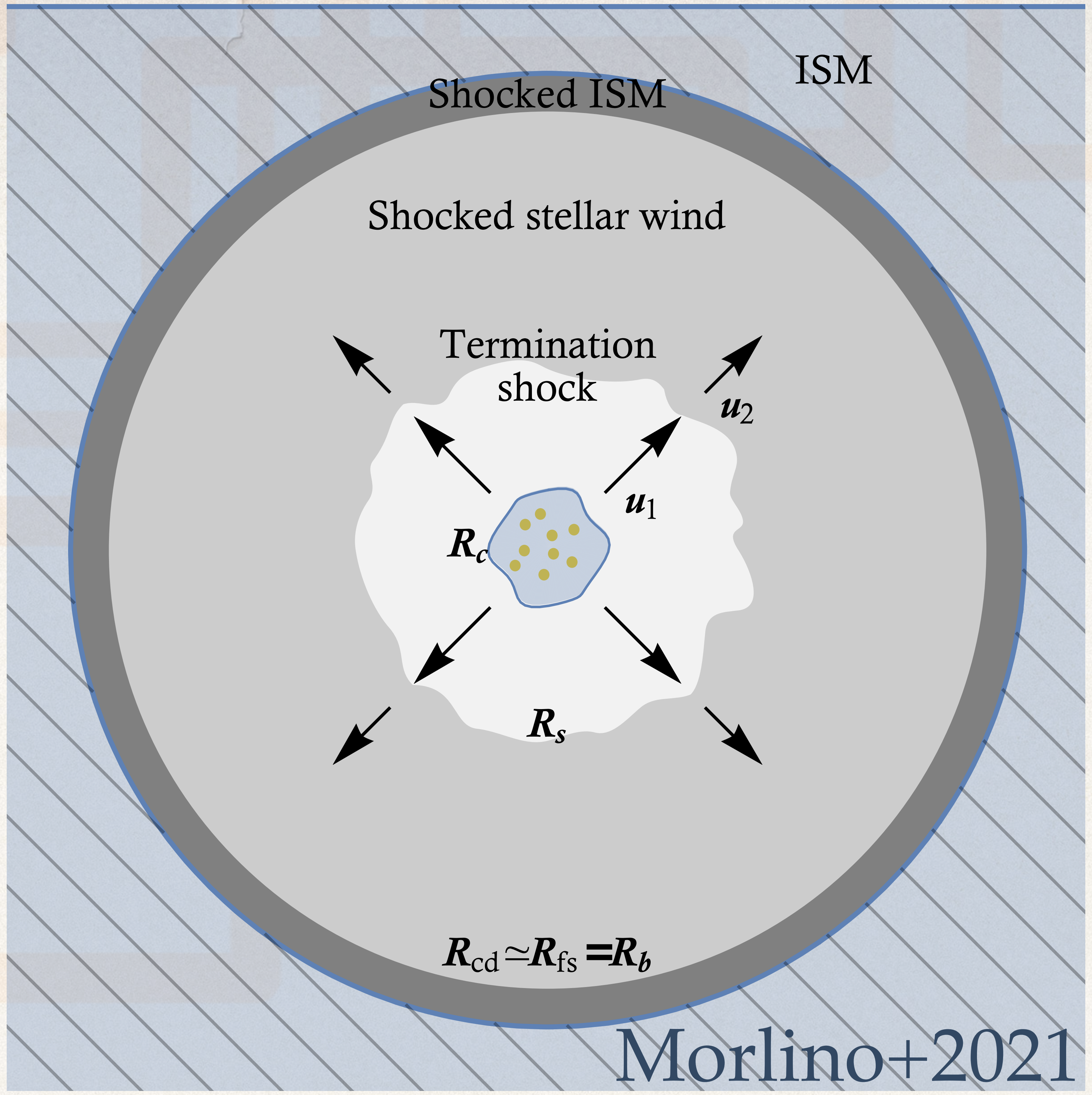
See Talk by G. Morlino

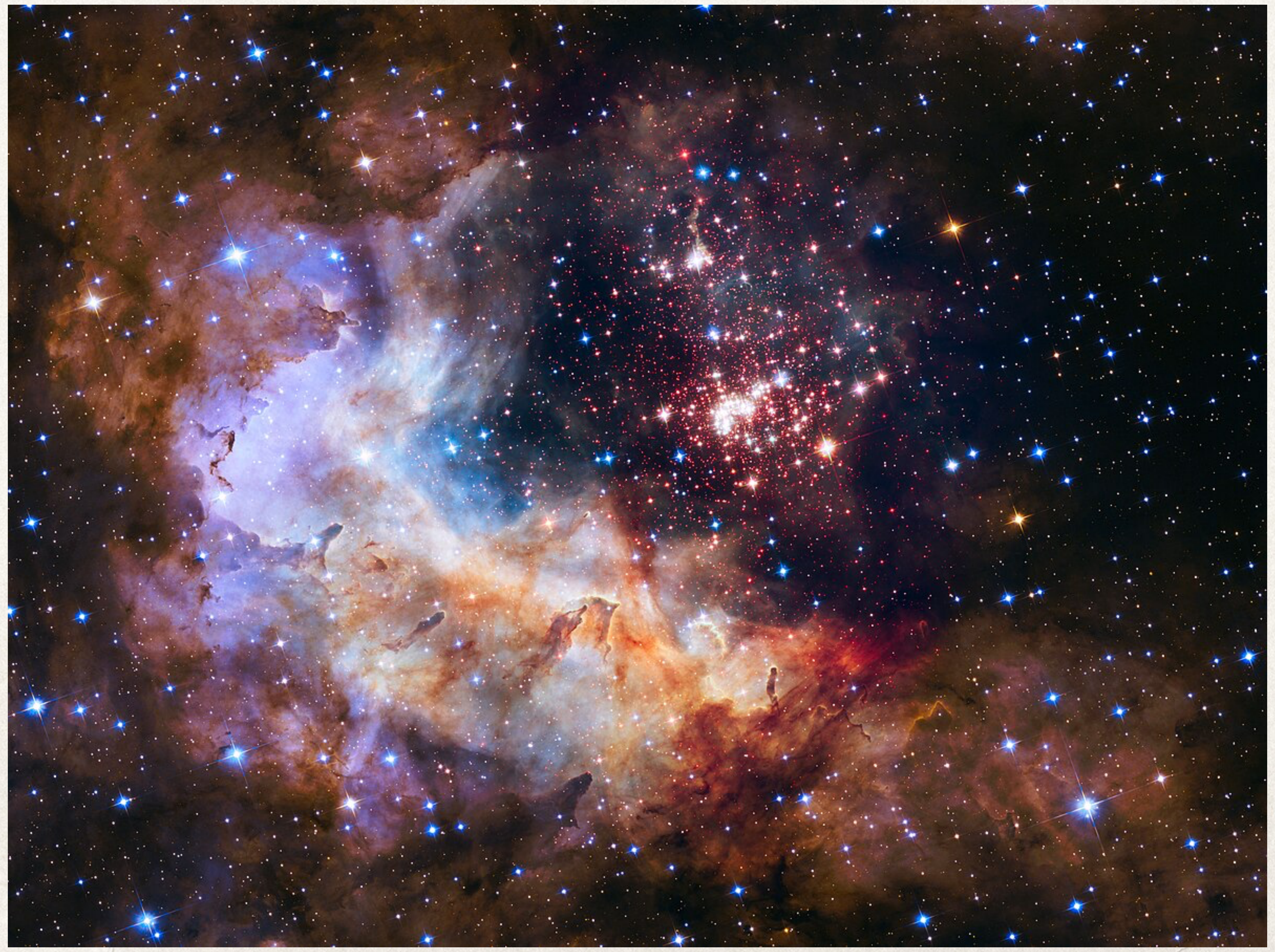
- Particle Acceleration at a stagnating termination shock of the collective wind of the cluster (wind speed 2000-3000 km/s)

- Often times evoked to explain the 22Ne anomaly and also because most young massive stars are embedded in SC

- Gamma ray emission from selected SC has measured by Fermi, HAWC, LHAASO… great target for γ-ray telescopes as LHAASO (spectrum, morphology, …)

- The main gamma ray emission is produced in the scattering of CR with molecular gas in the downstream of the termination shock



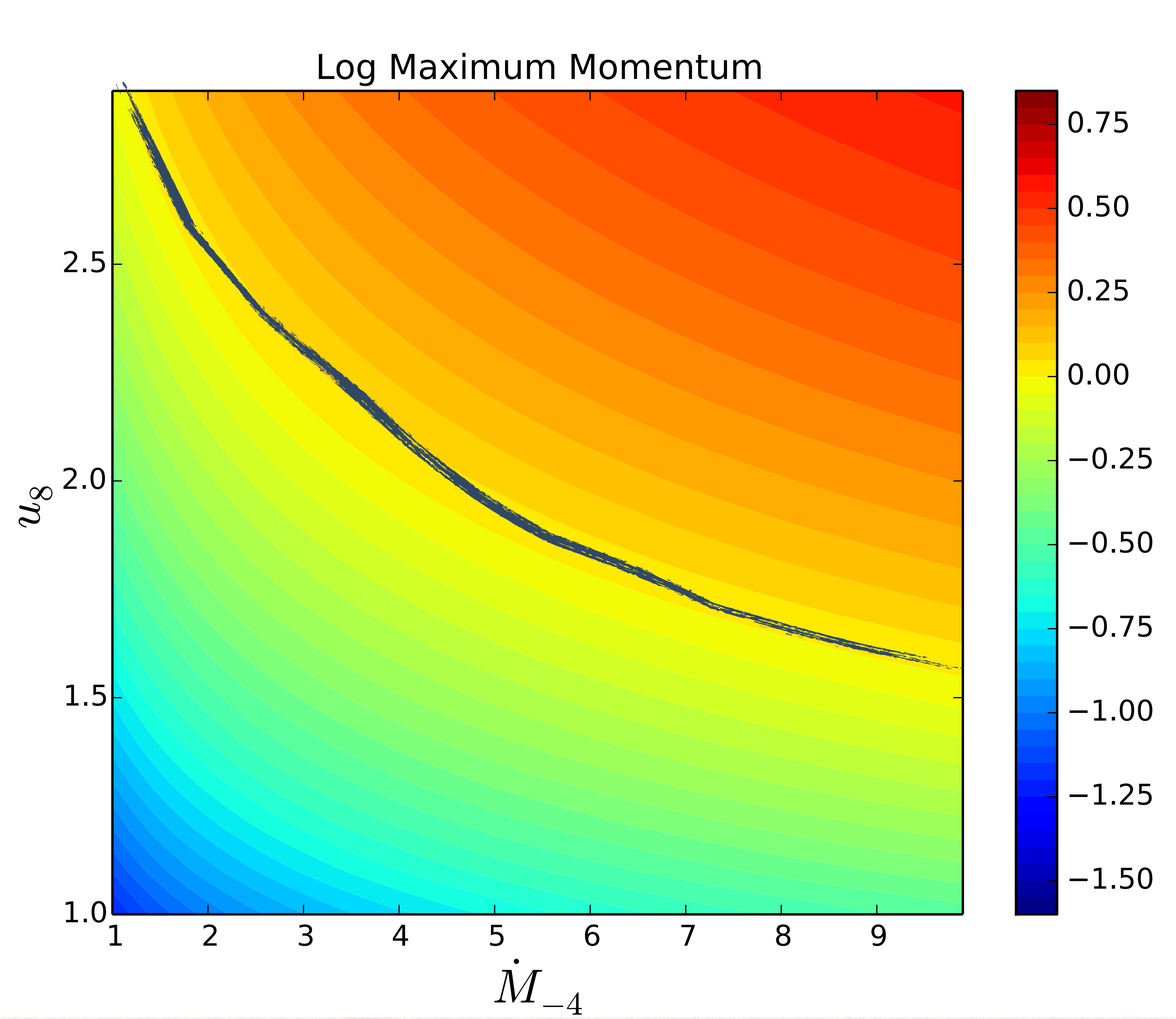


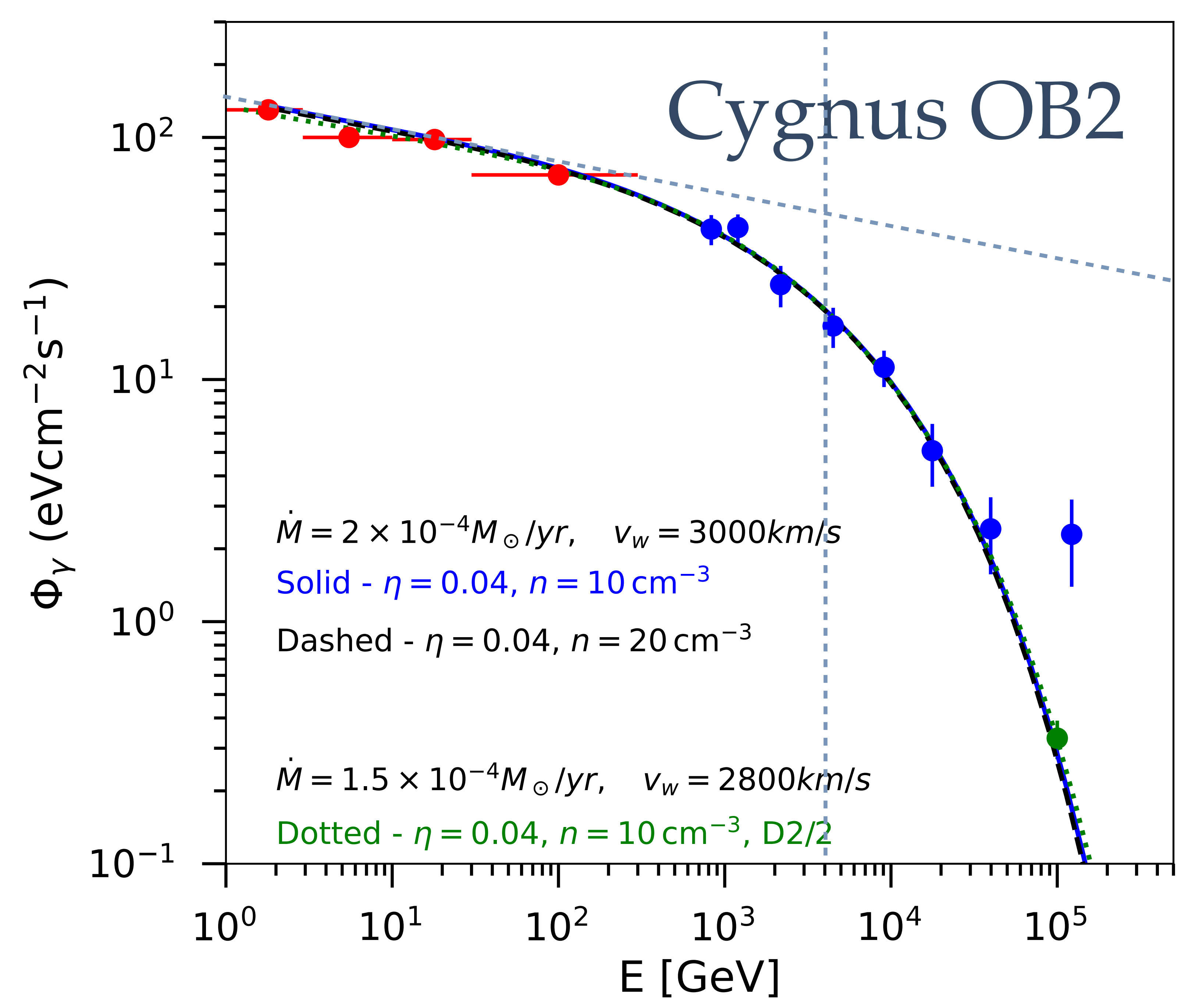
Star Clusters as PeVatrons?

- The approximate spherical geometry is ideal for particle acceleration (the upstream in inside!)

- But leads to a slow rollover that does not allow to reach very high effective maximum energy

- For the brightest Cygnus OB2, the maximum energy is appreciably below the knee





PB&Morlino 2023

Star Clusters as PeVatrons?

- While in young, compact star clusters, there has not been enough time for SN explosions, this is not the case for star clusters older than a few Myr

- For SN explosions in the outskirts of the core, the maximum energy remains <PeV (Sushch, PB & Brose, in prep.)

- For SN explosions inside the core, the situation might be better but requires more investigation

Summary [1]

- **The spectrum of primaries and secondary nuclei shows breaks that signal new pieces of physics:**
  - The 200 GV break associated with transport (transition from self-generation to what?)
  - The DAMPE feature at 20 TeV likely identifying the end of a class of sources (type Ia?)
  - GRAPES suggests the H spectrum keeps going at E>20 TeV toward the knee…(made of what?)
- **The positron ratio expected to drop … but it rises (pulsars?)**
- **The observed diffuse γ-ray and ν emission much higher than expected**
  - Did we mess up transport in the inner Galaxy?
  - Did we miss large extended sources (e.g. star clusters)? or unresolved sources?
  - Could CR be self-confined near sources for much longer than naively estimated

Summary [2]

- **SNR long suggested to be PeVatrons, except that:**
  - ☑ We did not find any evidence… probably because we did not have SN explosions in the last 30 years (E_{max})?
  - ☑ …but also searches of high energy emission around SNRs did not reveal any evidence for PeV particles
  - ☑ Theoretically, SNRs of Type Ia and II are NOT expected to be PeVatrons… so which ones? Very rare, perhaps transrelativistic SNRs?
- **Star clusters as PeVatrons?**
  - ☑ Gamma ray emission does not show evidence for E_{max}=PeV in Cygnus, although γ-rays @1.4 PeV from LHAASO!
  - ☑ Perhaps particle acceleration in SNR in the core of a cluster? to be explored better…

Summary [3]

- **Shaking pillars of transport?**
  - ☑ The rise of the positron ratio has stimulated the revival of the Nested Leaky Box (NLB) model (Cowsik & Wilson 1975; Cowsik&Madziwa-Nussinov 2016) (B produced around the sources, positrons and antiprotons produced in the ISM)
  - ☑ These models struggle to explain many things (beryllium, breaks in the B/C and primaries, etc) but should be credited for attracting attention on transport around sources
  - ☑ It is certainly true that CR can accumulate a fraction of the grammage due to self-confinement… or inside sources… beware when comparing with %level measurements
  - ☑ At least in the case of TeV halos we have evidence that regions of reduced diffusivity around sources do exist