GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

GAMMA RAYS FROM STAR CLUSTERS AND IMPLICATIONS FOR GALACTIC COSMIC RAYS

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TOSCA 2024

Why did the community get interested in SC?

We do not find the PeVatrons yet and yet we detect PeV CRs...
Maybe SC can be PeVatrons?

Even if SNR were the main sources of CR, yet most of them are in SC...
Maybe SC can be main contributors to the CR flux?

Recall the anomaly in $^{22}Ne/^{20}Ne$

Finally we did detect SC in VHE gamma rays, **what does this tell us?**

Ultimately, does the detection of high energy gamma rays imply that SC are important CR sources?

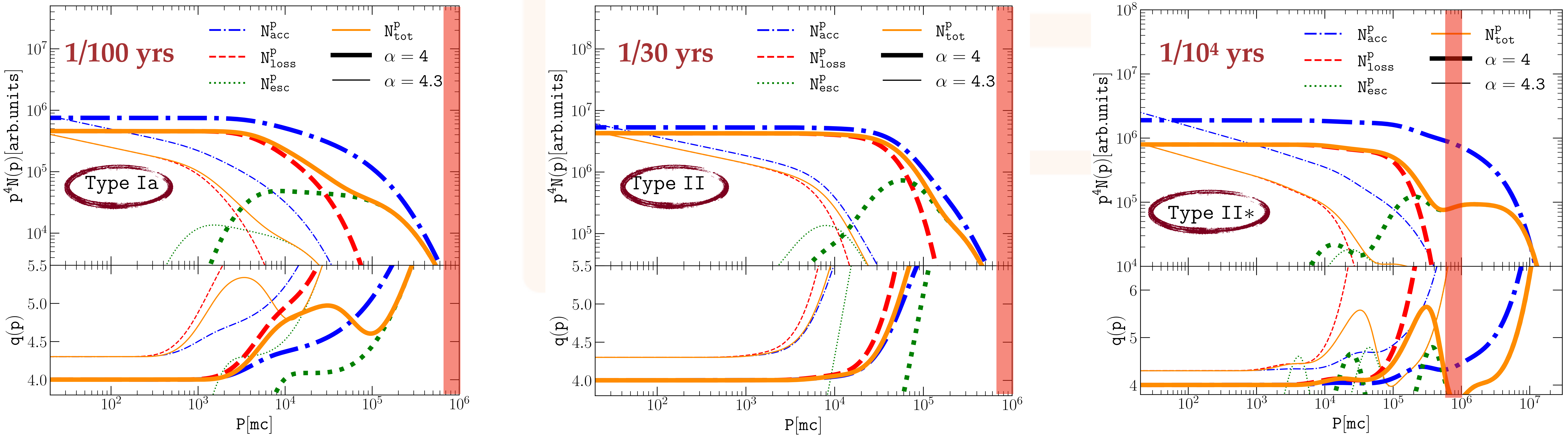
Why are SNRs are not PeVatrons?

SNRs can accelerate particles to "decent" energies only if CRs can self-confine themselves close to the shock

The fastest instability to do so is the non-resonant hybrid instability

But even in the presence of this phenomenon... what happens is shown below...

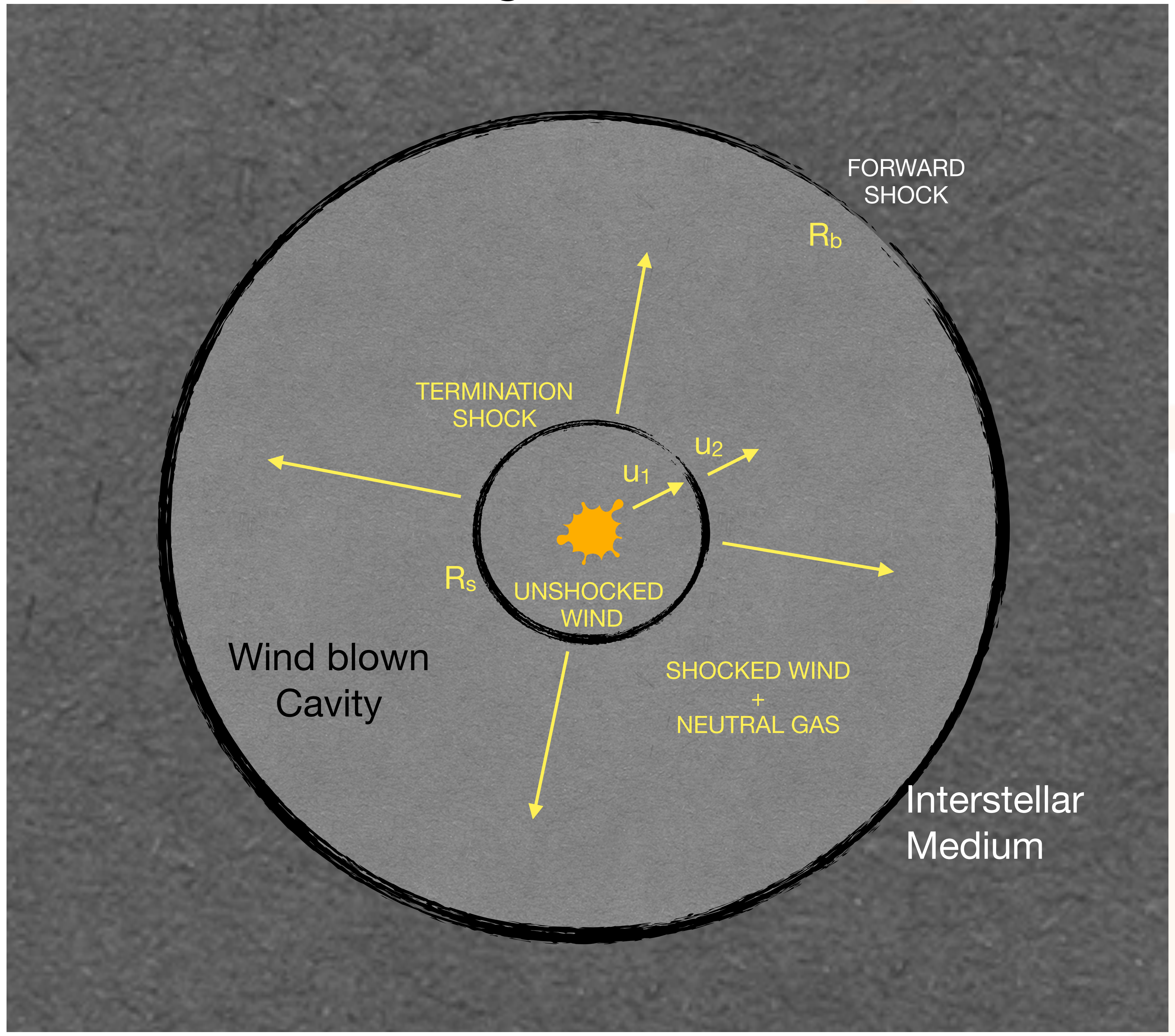
The problem is that even this instability is insufficient to confine for long enough particles UPSTREAM of the shock!



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

The bubble for compact clusters

PB & Morlino 2023



If the cluster is sufficiently compact the collective wind of the stars in the core may excavate a bubble with an outer boundary (forward shock) and a termination shock at a distance that is fixed by dynamics

$$R_s = 24.3 \dot{M}_{-4}^{3/10} v_8^{1/10} \rho_{10}^{-3/10} t_{10}^{2/5} \text{pc}$$

$$R_b(t) = 139 \rho_{10}^{-1/5} \dot{M}_{-4}^{1/5} v_8^{2/5} t_{10}^{3/5} \text{pc}$$

In the wind region the plasma velocity is constant, hence the density drops as $1/r^2$

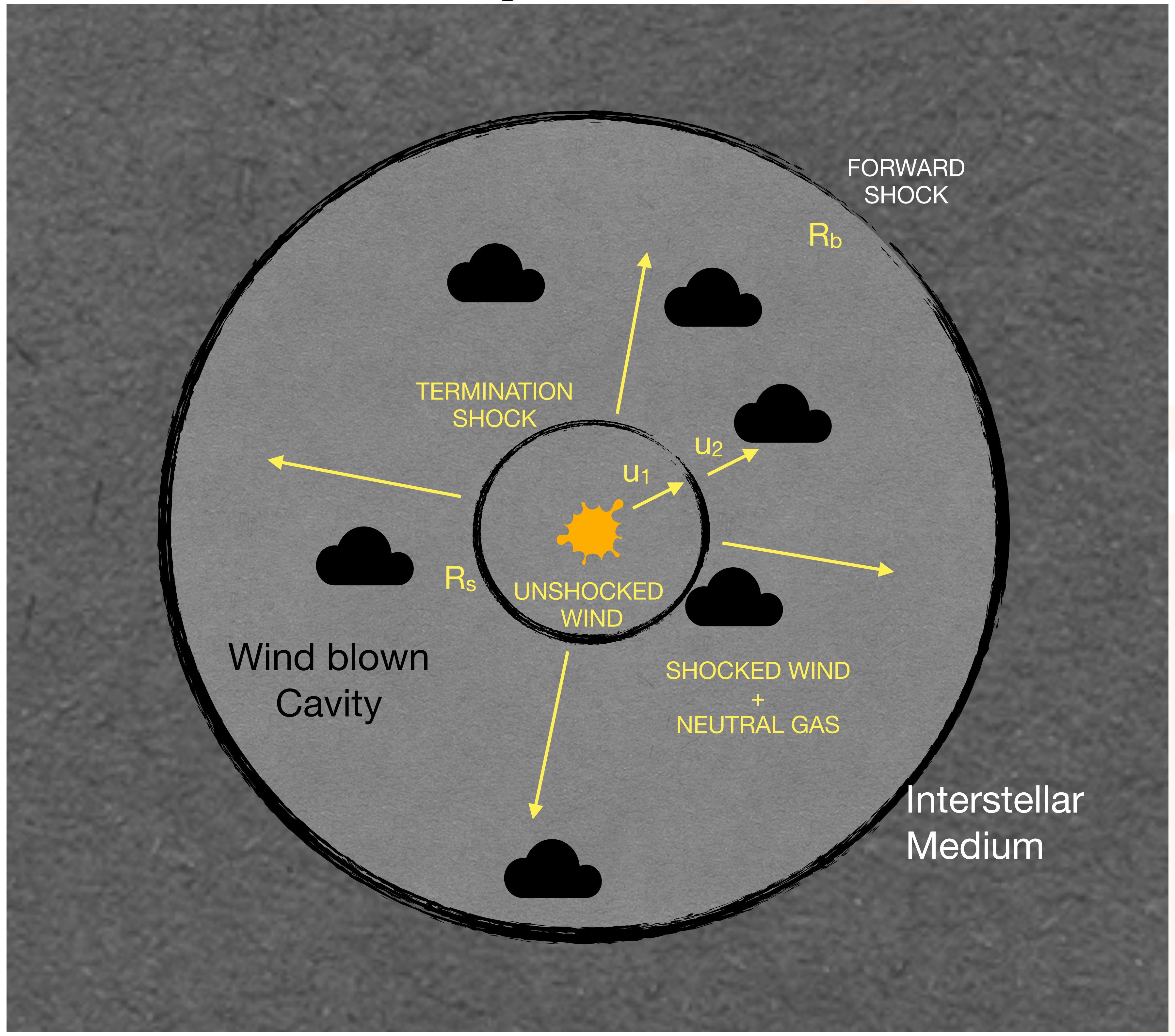
$$\rho_w(r) = \frac{\dot{M}}{4\pi r^2 v_w}, r > R_c$$

In the downstream of the termination shock, the gas density is constant and the velocity drops as $1/r^2$

$$\rho_{w,d} = 4\rho_w(R_s) \qquad v_{w,d} = \frac{v_w}{4}\left(\frac{r}{R_s}\right)^{-2}$$

The bubble for compact clusters

PB & Morlino 2023



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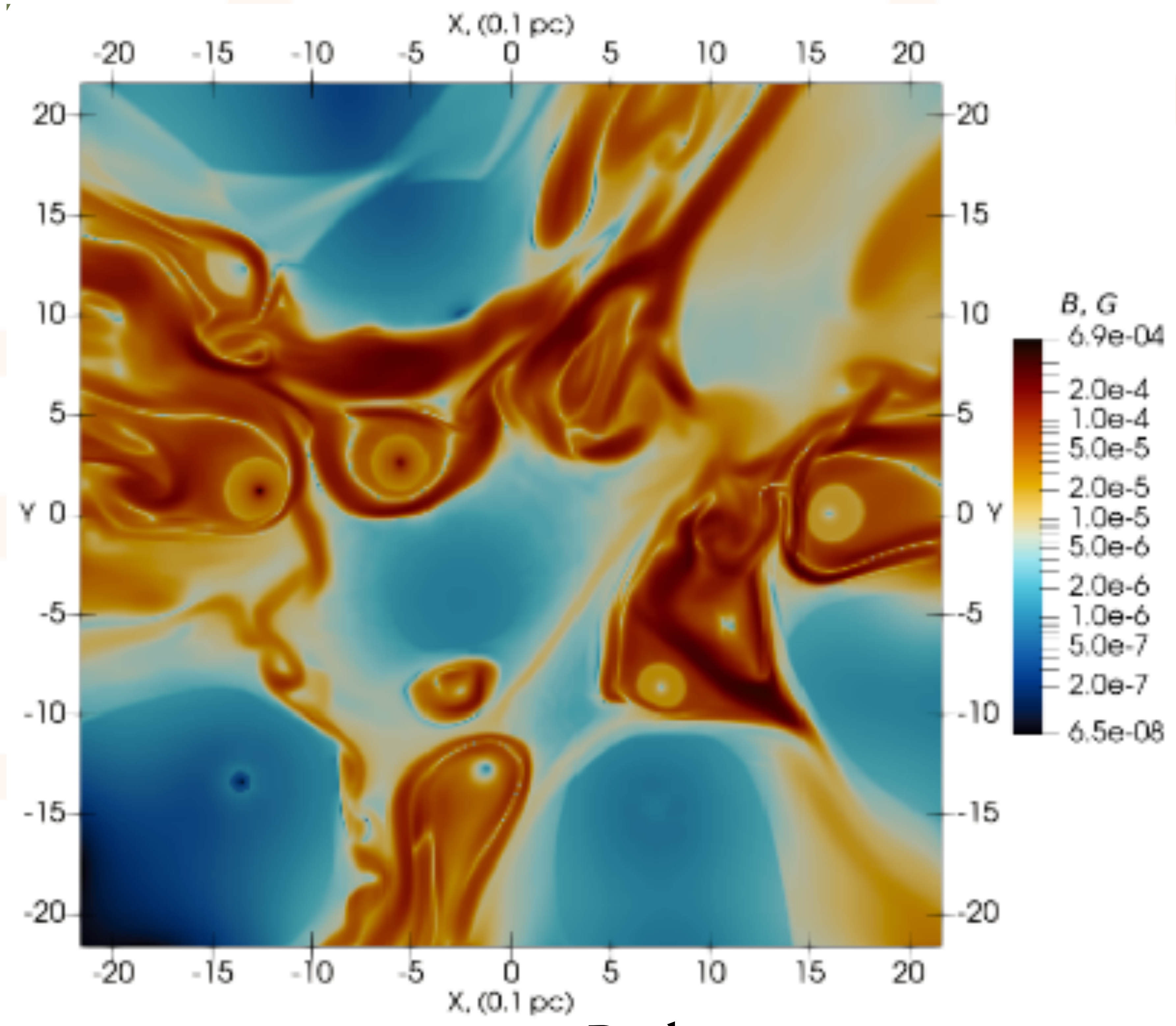
Particle acceleration at the Termination Shock

- The TS is expected to be rather strong, M>>1
- The collision between winds in the core and in the wind region is expected to transform some fraction η_B of the kinetic energy of the wind to MHD turbulence... at the shock:

$$B(R_s) = 7.4\, \eta_B^{1/2} \dot{M}_{-4}^{1/5} v_8^{2/5} \rho_{10}^{3/10} t_{10}^{-2/5}\ \mu\mathrm{G}$$

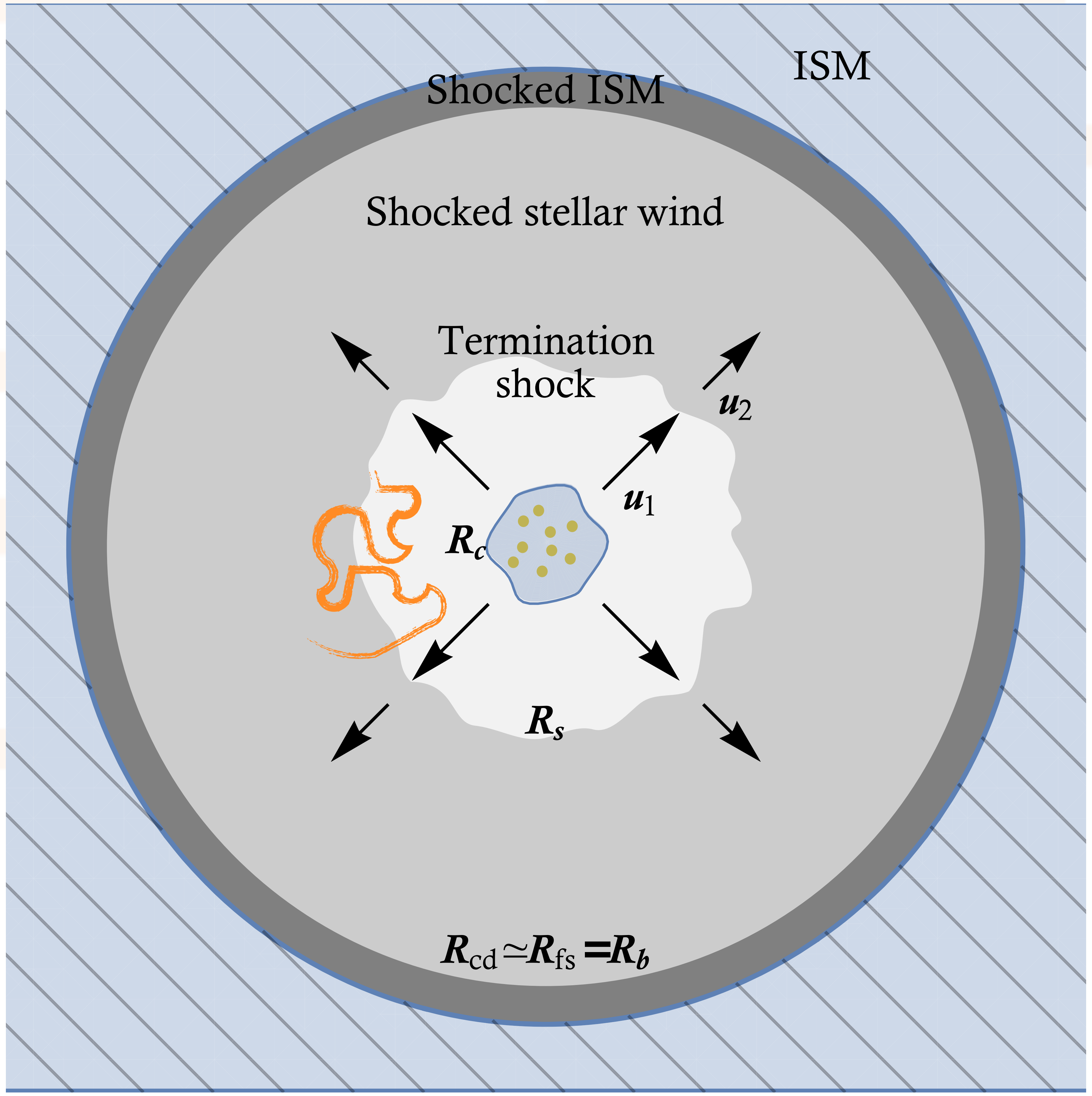
- While the magnetic energy is expected to be injected at some large scale, the resulting diffusion coefficient depends on the MHD cascade to small scales
- One can study different cases (Kolmogorov, Kraichnan, Bohm), non particularly compelling...some less credible than others
- Intermittency can make the effective D(E) more dependent upon quantities other than the spectrum (Lemoine 2024)
- For parameters typical of star clusters, self-generation is not expected to play an important role



Badmaev+2022

Particle acceleration at the Termination Shock

- The TS behaves as a standard spherical Newtonian shock
- While the main limitation to particle acceleration at a shock is usually due to escape from upstream, here the upstream is closed! All particles remain inside
- Transport equation needs to be solved accounting for the spherical symmetry
- Particles with low energies probe the region very close to the shock surface (weak effect of sphericity) —> standard power law spectrum
- Higher energy particles move farther from the shock and feel gradually lower effective plasma speed due to sphericity —> gradually steeper spectrum
- How spectrum approaches p_{max} depends on D(E) more than for a standard planar shock or an expanding spherical shock (Morlino+21)

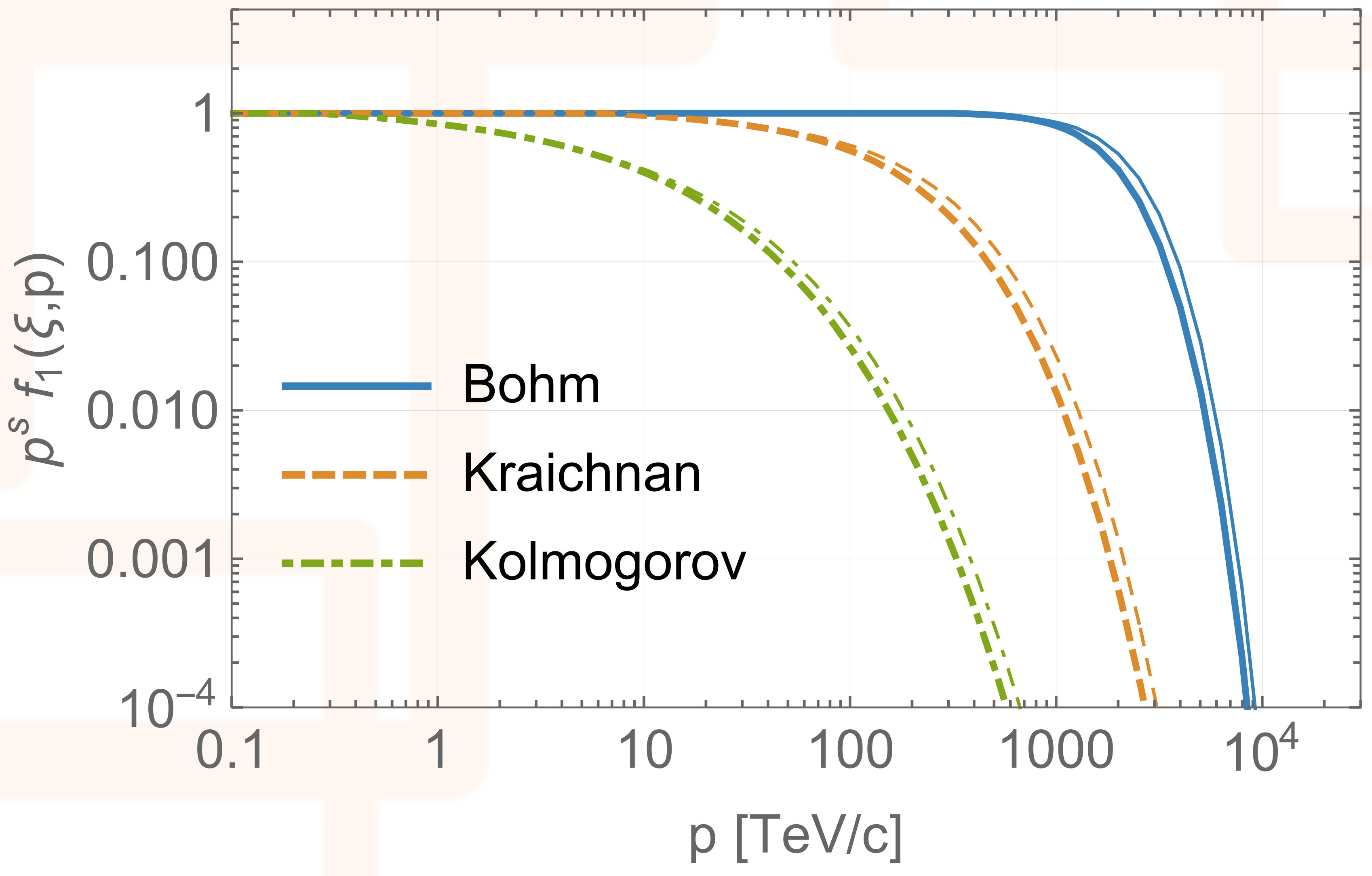


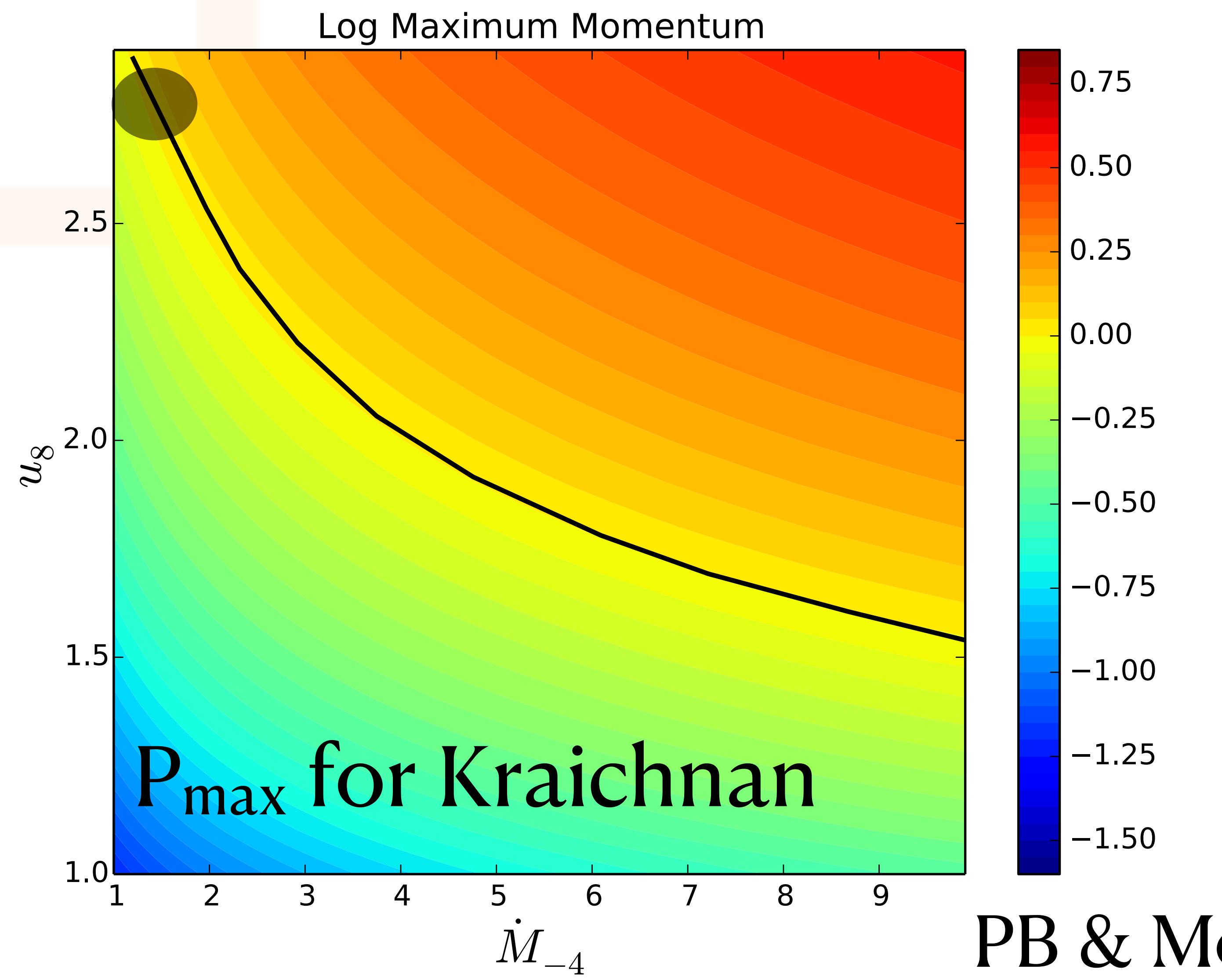
Morlino+2021

Particle acceleration at the Termination Shock

- If a few percent of the wind kinetic energy is channeled into MHD turbulence —> diffusivity in the bubble reduced by 2-3 orders of magnitude wrt ISM
- Maximum energy determined by the size of the confinement region ~ R_s
- **Easily p_{max}~PeV but for Kraichnan and Kolmogorov turbulence, substantial suppression at $p \ll p_{max}$**
- Recall that Bohm diffusion corresponds to equal power on all scales, unjustified unless for self-generation with a p^{-4} spectrum (not the case here)
- **The effective maximum energy much smaller than the nominal value**
- This seems confirmed by what we see in gamma rays!

Morlino+2021





PB & Morlino2023

Particle acceleration at the Termination Shock

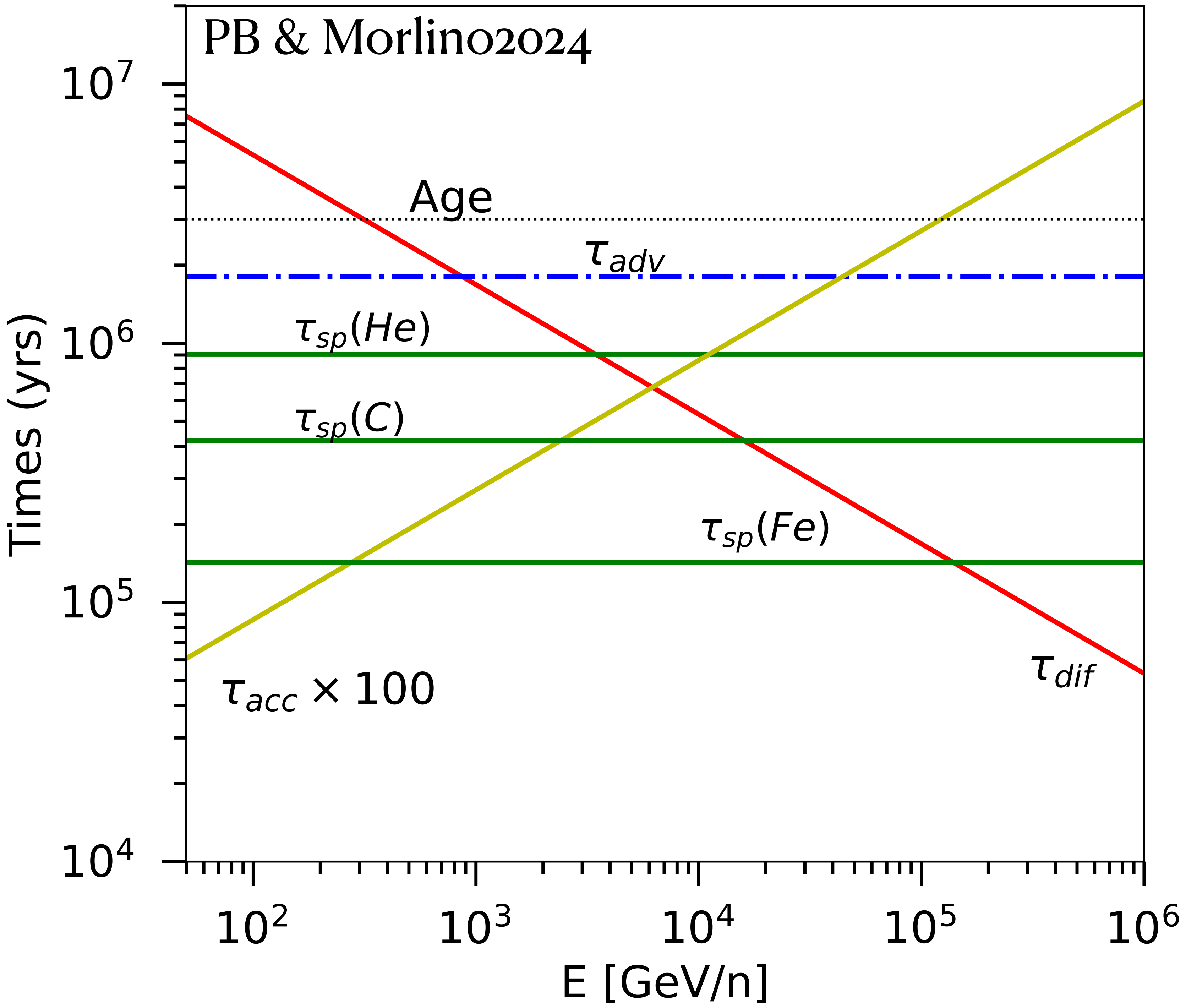
- The transport of particles in the bubble, including acceleration at the TS is described by:

$$\frac{\partial}{\partial r}\left[\tilde{u}r^2 N - r^2 D\frac{\partial N}{\partial r}\right] = E\frac{\partial N}{\partial E}\left[\frac{1}{3}\frac{\mathrm{d}(\tilde{u}r^2)}{\mathrm{d}r} - r^2\frac{b}{E}\right] + N\left[\frac{1}{3}\frac{\mathrm{d}(\tilde{u}r^2)}{\mathrm{d}r} - r^2 b'\right]$$

For protons $b(E,r) = c\dot{p}$

$$\frac{\partial}{\partial r}\left[\tilde{u}r^2 N_\alpha - r^2 D\frac{\partial N_\alpha}{\partial r}\right] = E\frac{\partial N_\alpha}{\partial E}\frac{1}{3}\frac{\mathrm{d}(\tilde{u}r^2)}{\mathrm{d}r} + \frac{1}{3}\frac{\mathrm{d}(\tilde{u}r^2)}{\mathrm{d}r}N_\alpha - \frac{N_\alpha}{\tau_{\mathrm{sp},\alpha}} + \sum_{\alpha'>\alpha}\frac{N_{\alpha'}}{\tau_{\mathrm{sp},\alpha'\to\alpha}}$$

For nuclei



$$\tau_{\mathrm{adv}} = \int_{R_s}^{R_b}\frac{dr}{u(r)} = \frac{1}{3}\frac{R_b}{u_2}\left(\frac{R_b}{R_s}\right)^2\left[1-\left(\frac{R_s}{R_b}\right)^3\right]$$

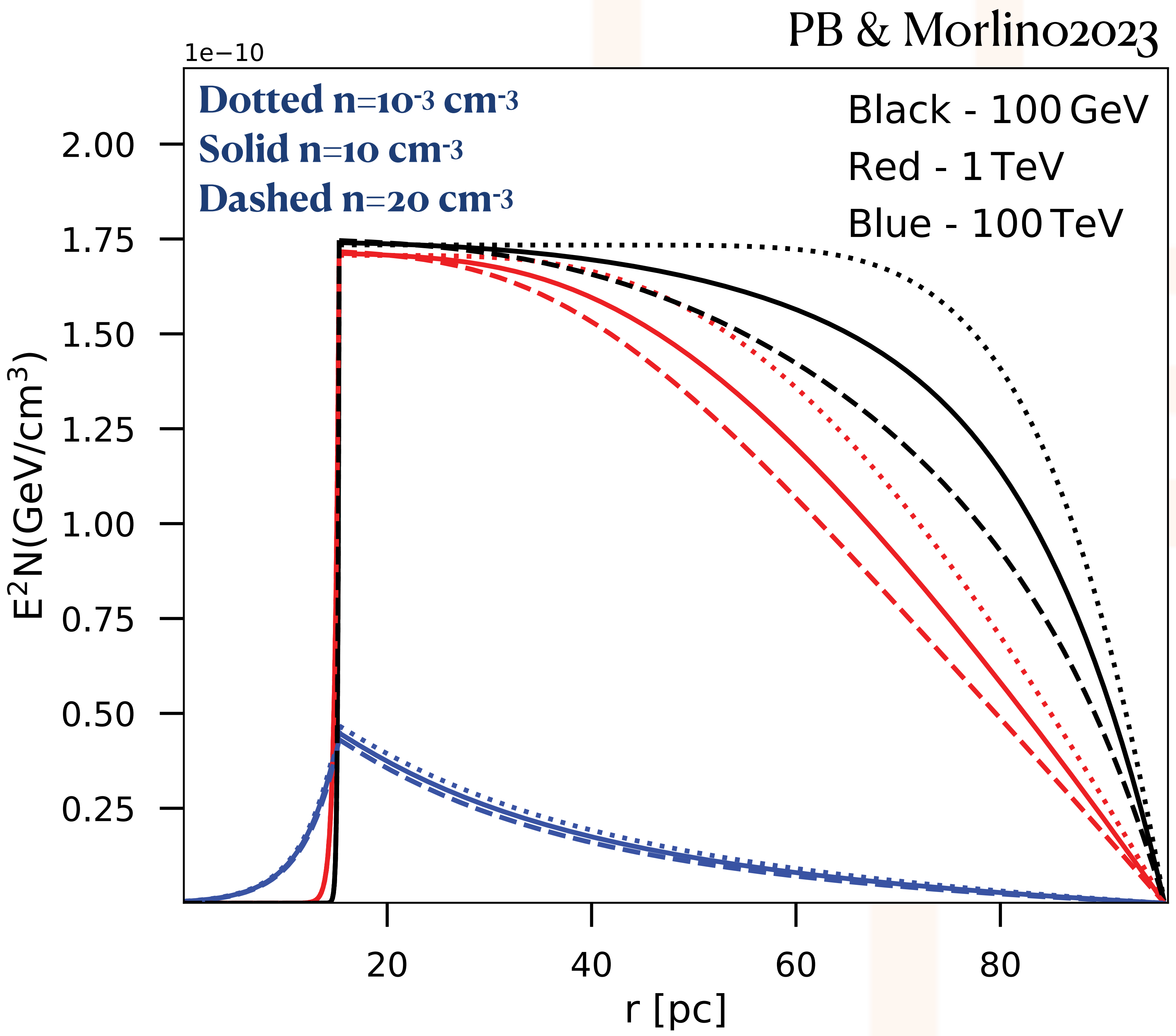
The advection time as well as the time scales for spallation and for diffusion at higher E are shorter than the age —> stationary solution OK

The spectrum of H only marginally affected by pp energy losses

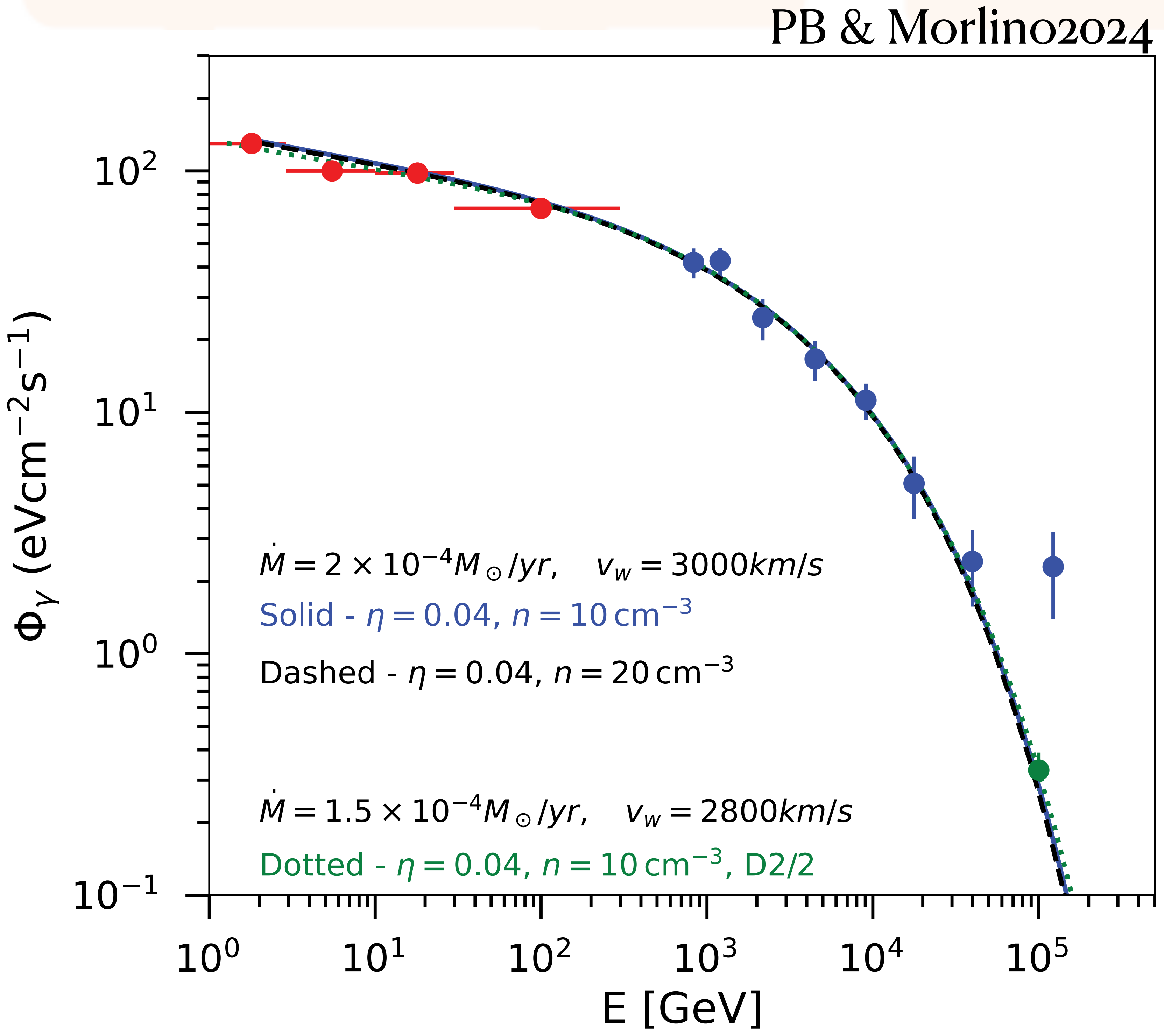
The spectrum of He sizeably changed by spallation, with production of ^{3}He

Nuclei heavier than He severely affected

Acceleration of H and gamma ray emission

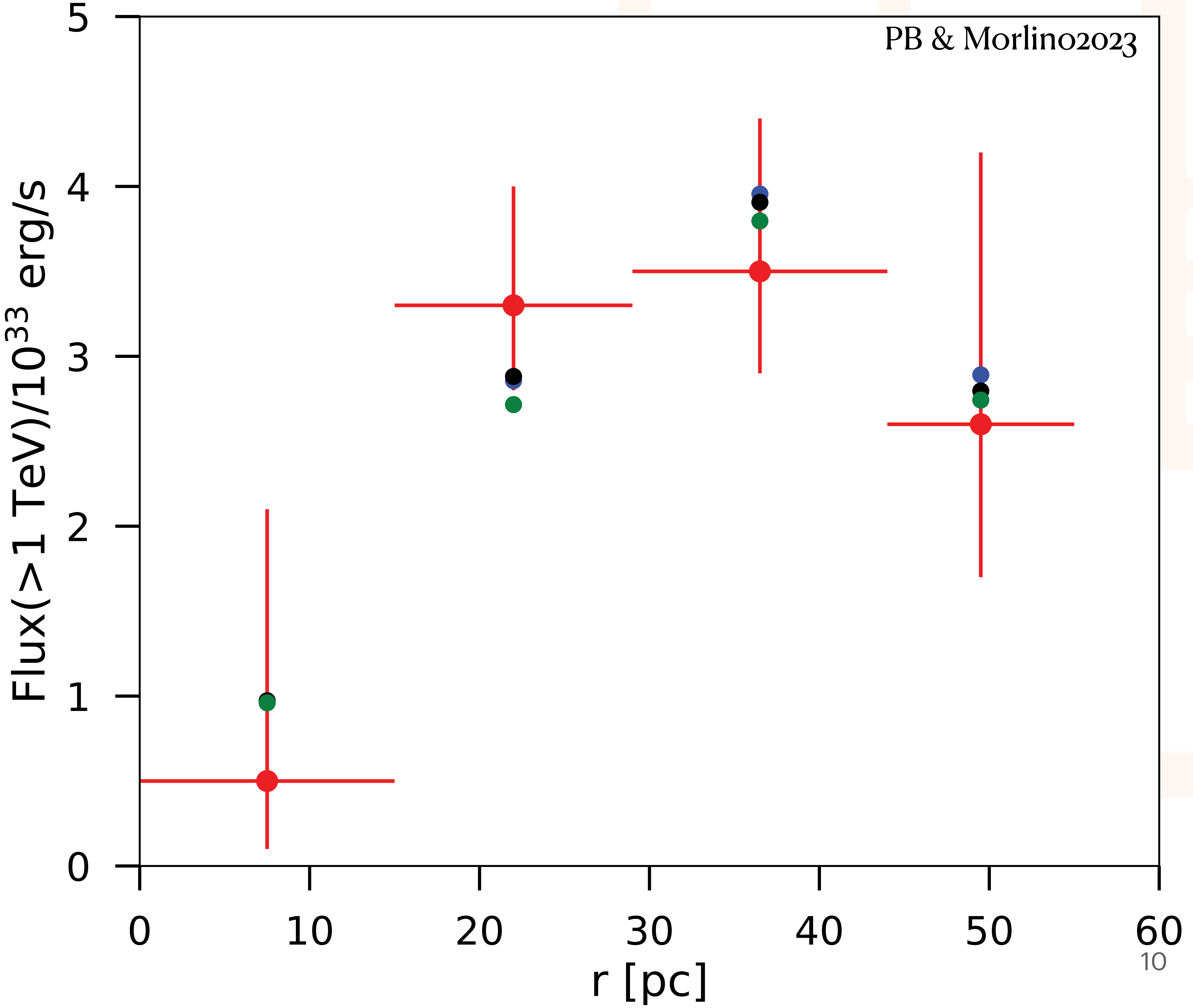


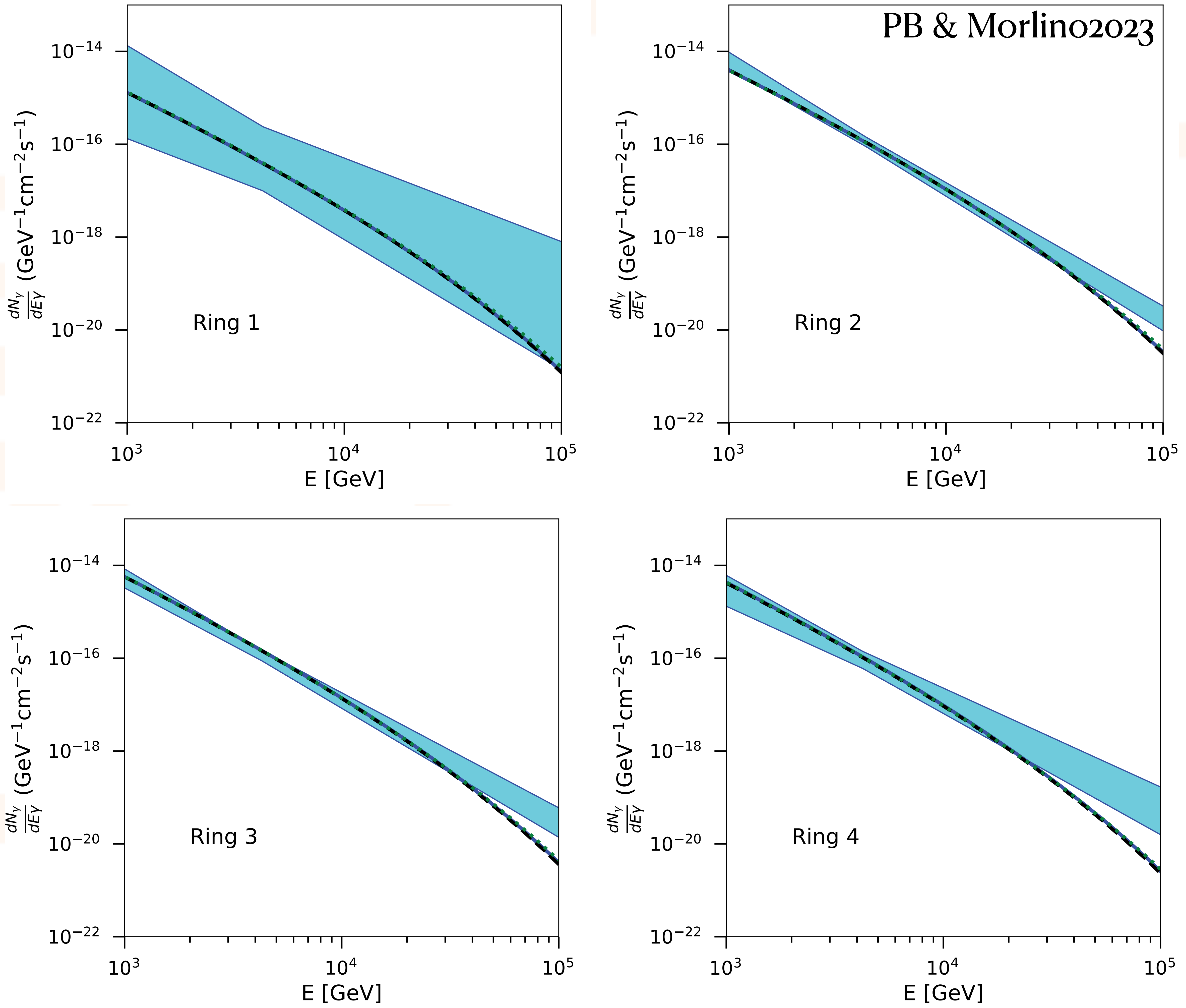
For low energy particles, the effect of energy losses is that of changing the spatial distribution of particles downstream of the TS



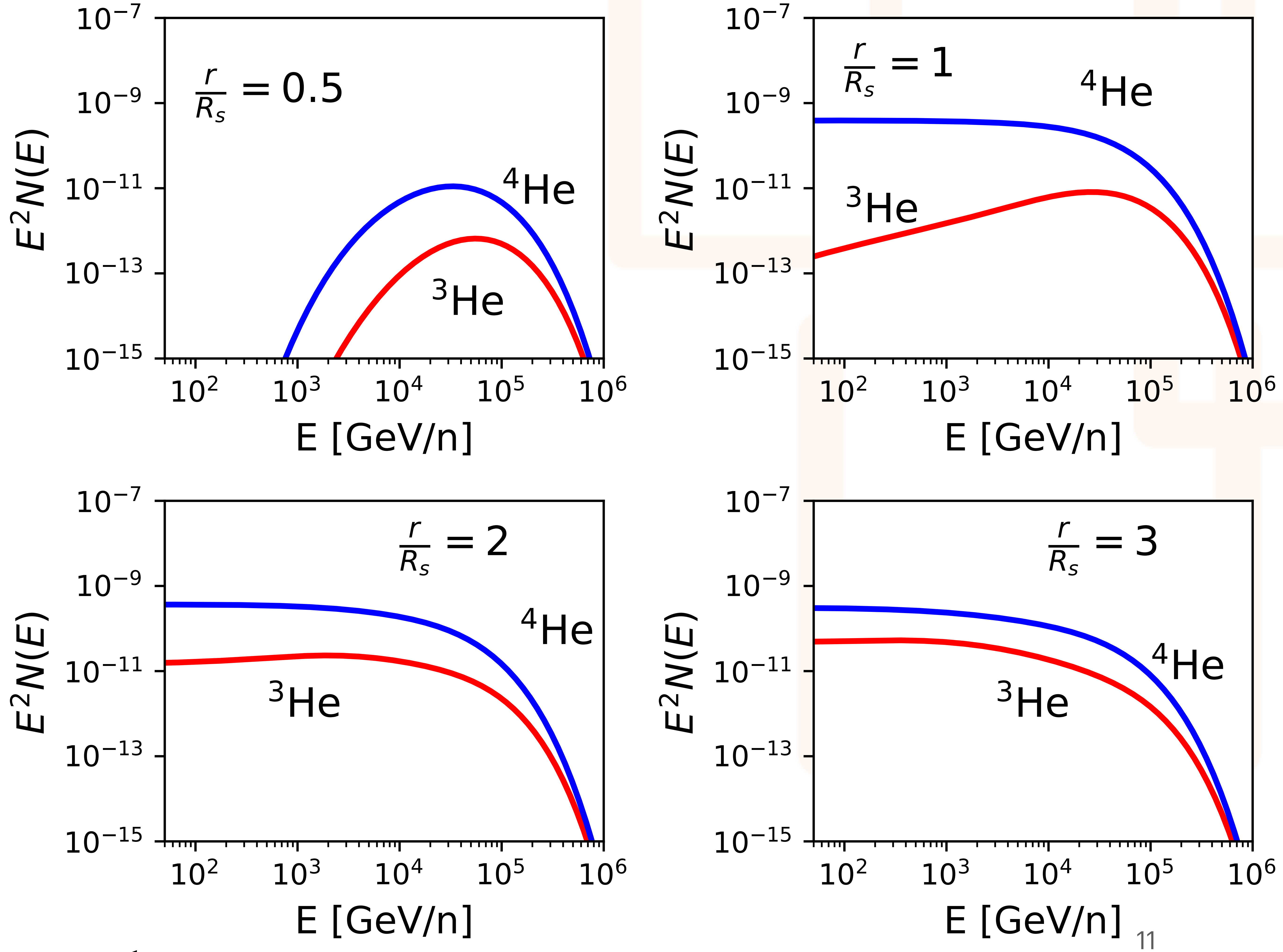
Fitting to the Fermi+HAWC (2 degrees) data, for the nominal density n=10 cm^{-3}, requires either loss rates and speed slightly larger than normally assumed, or additional production of turbulence downstream

Acceleration of H and gamma ray emission





Acceleration of nuclei



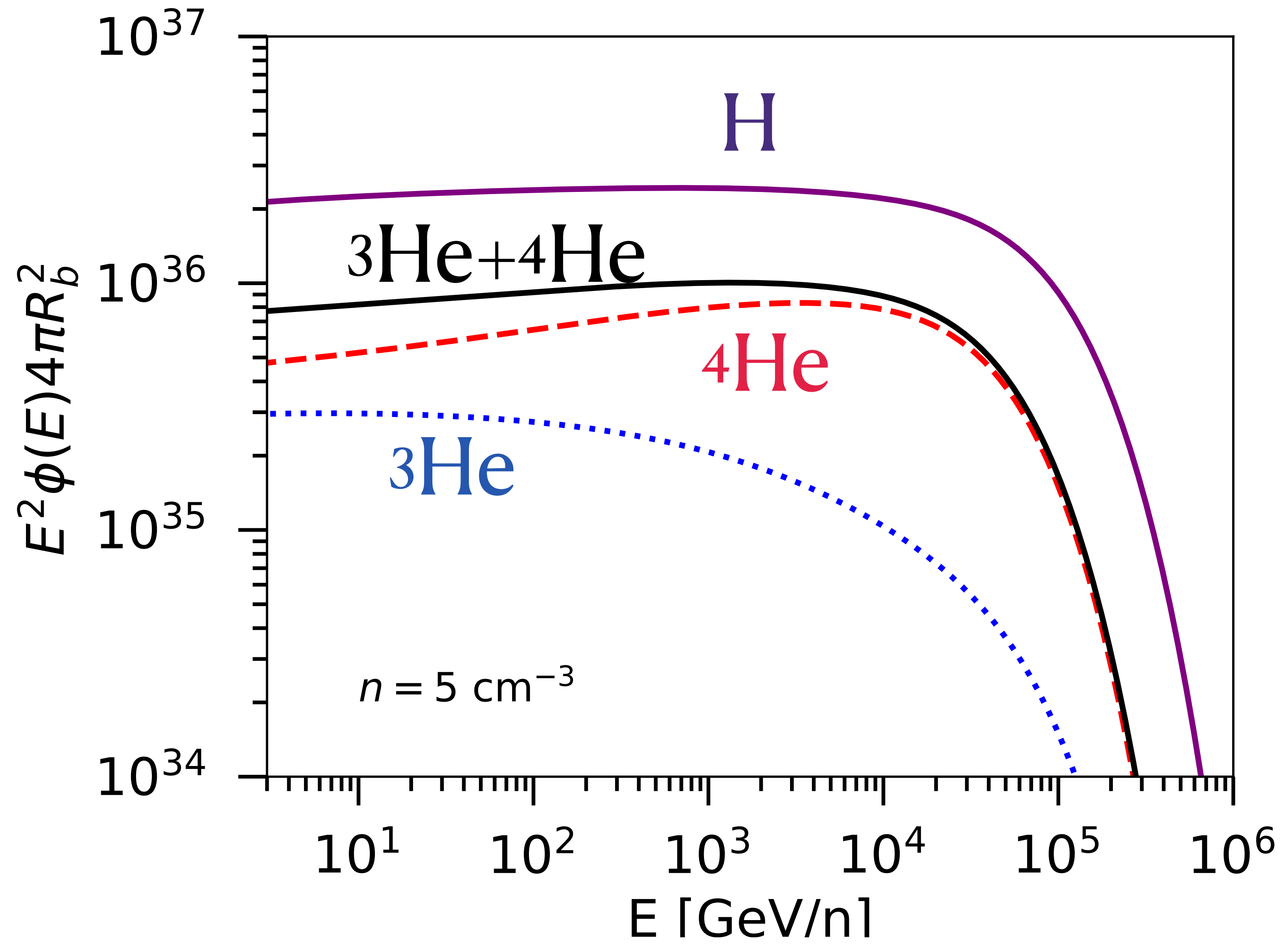
- We assume that ^{3}He is mainly produced as spallation reaction of ^{4}He
- ^{3}He produced upstream of the TS is advected back onto the shock and gets reaccelerated
- Both ^{3}He and ^{4}He suffer spallation downstream of the termination shock
- The spectrum of the escaping particles at the edge of the bubble is given as

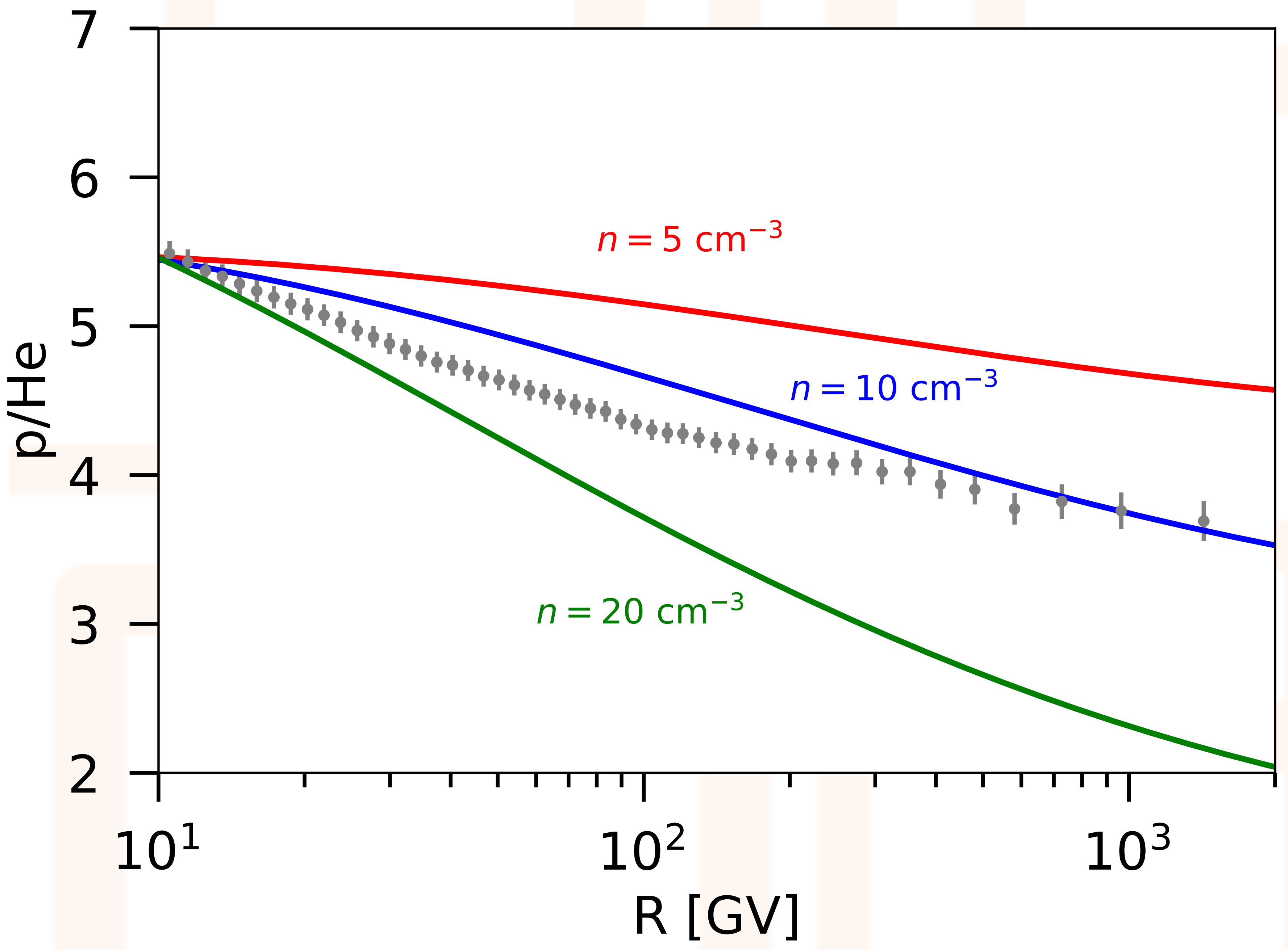
$$\Phi(E) = -D_2(E)\frac{\partial N_2(E,r)}{\partial r}\Big|_{r=R_b}$$

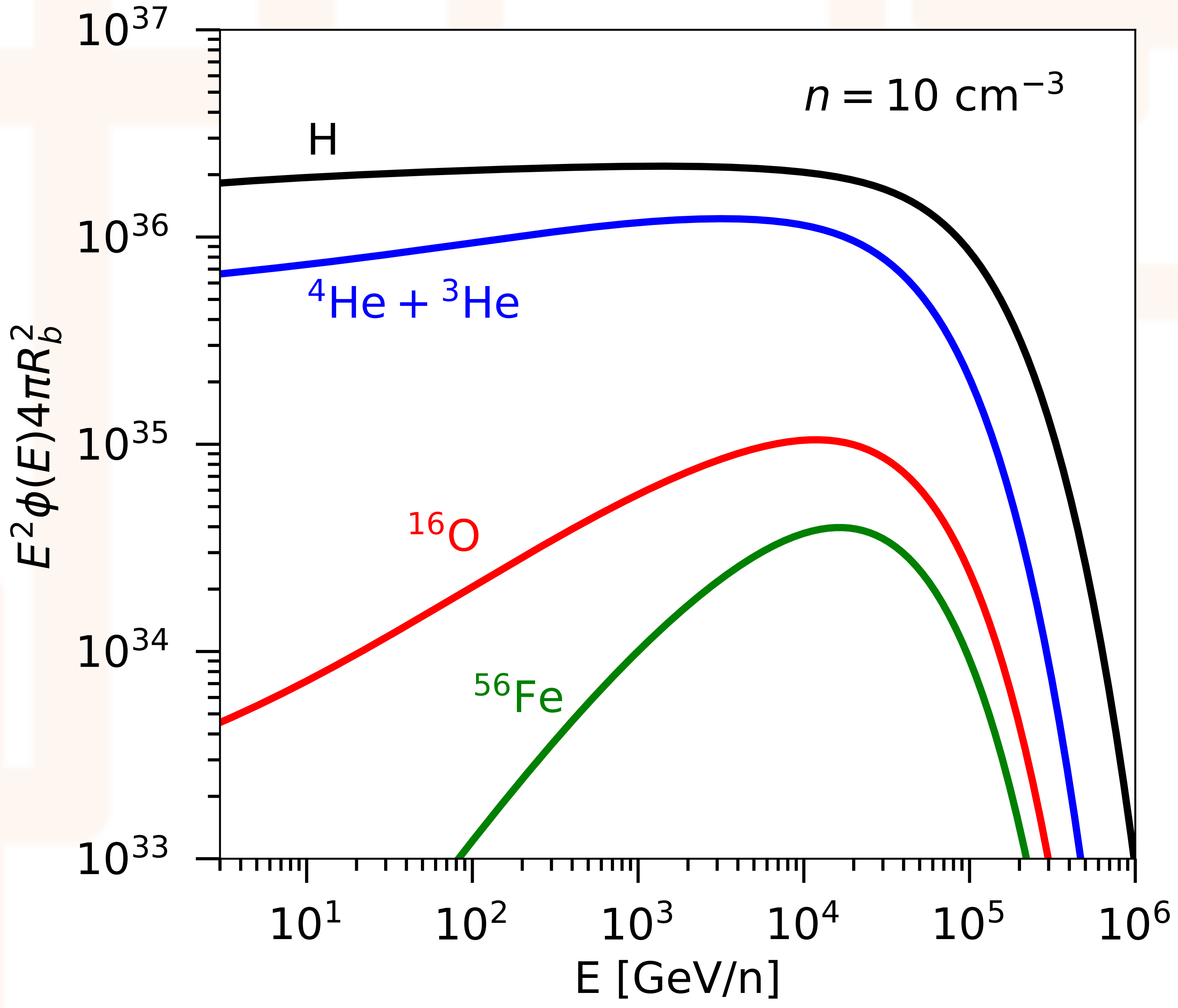
The role of spallation of He nuclei is that of changing the ratio H/He injected into the ISM

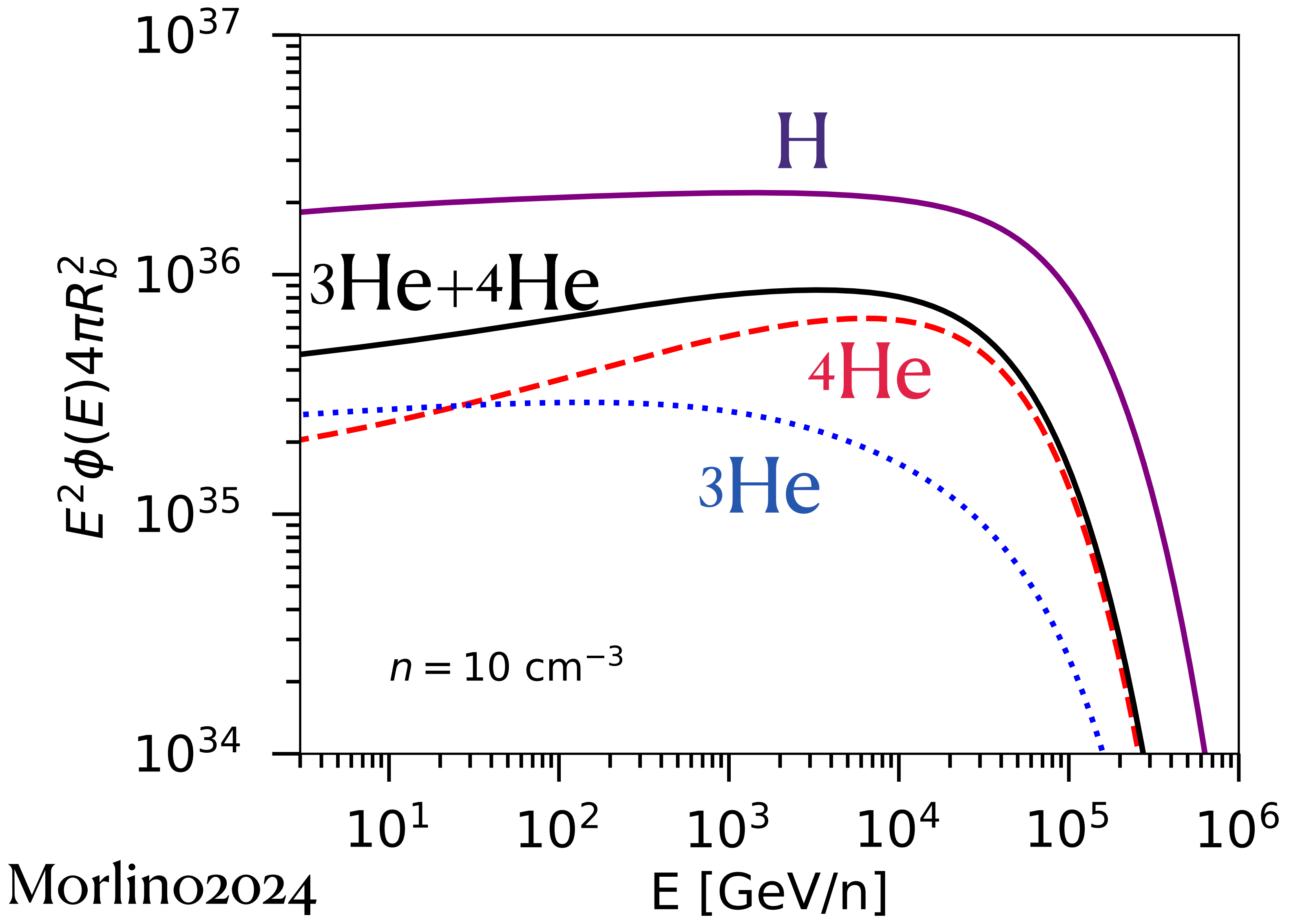
PB & Morlino2024

The H/He ratio and heavier nuclei







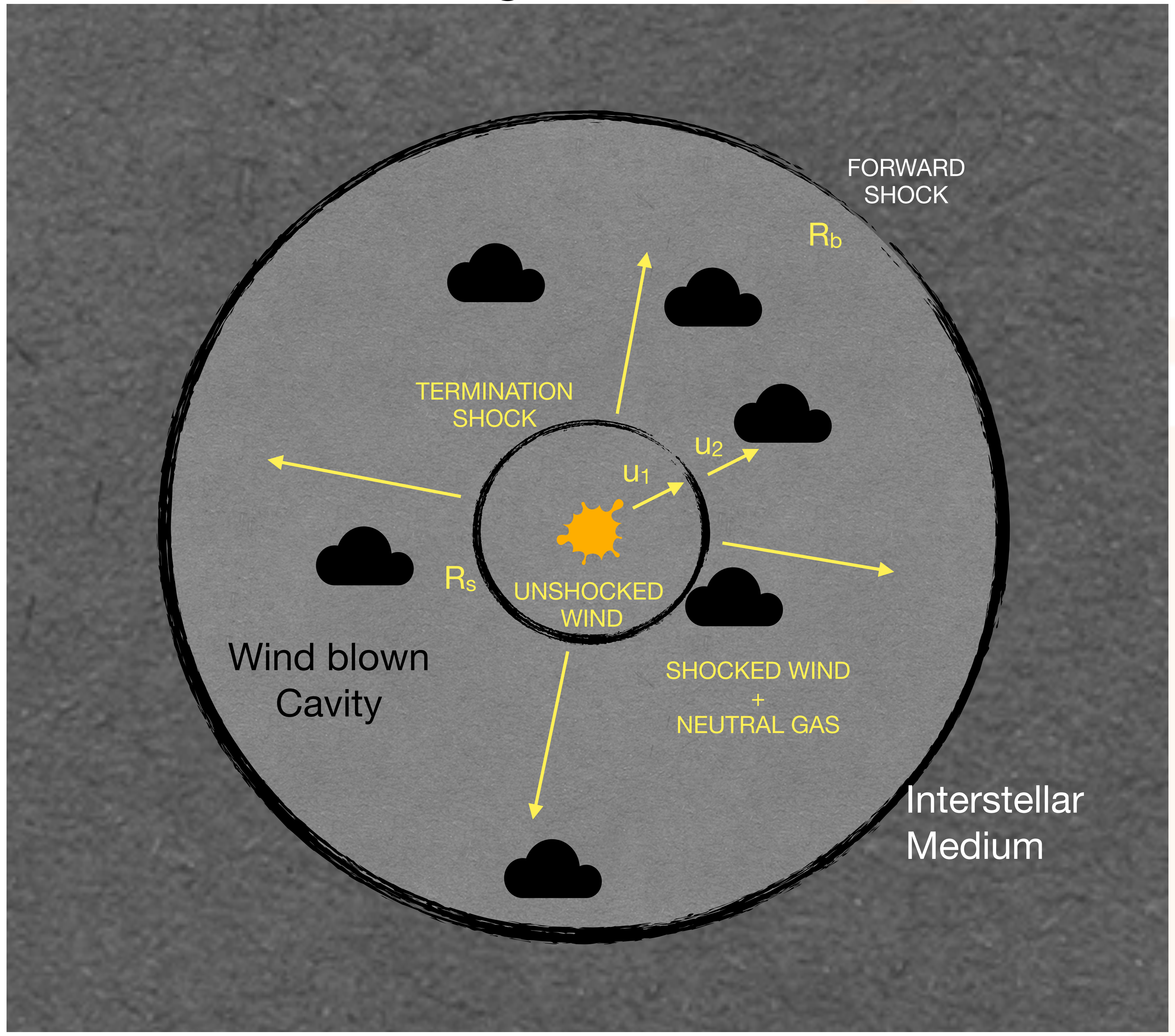


PB & Morlino2024

- The spectrum of escaping (total) He is harder than that of protons
- The ratio H/He is easily comparable with the observed one
- This result is obtained with the same values of the gas density inferred in other ways and compatible with gamma ray observations
- But the price to pay is to destroy nuclei heavier than He

Limitations of spherical symmetry

PB & Morlino 2023



- It may be argued that the cold gas is not distributed homogeneously but in clouds — what is the effect on spallation?
- The assumption of mean density works fine in terms of gamma ray emission

$$\frac{4\pi}{3} R_b^3 \, n \, m_p = N_{\rm cl} M_{\rm cl} = N_{\rm cl} \frac{4\pi}{3} R_{\rm cl}^3 \, n_{\rm cl} \, m_p \;\Rightarrow\; N_{\rm cl} = \frac{n}{n_{\rm cl}} \left(\frac{R_b}{R_{\rm cl}}\right)^3$$

- For typical values of parameters, the typical distance between two clumps is d~4 $R_{\rm cl}$
- The time required to cover such a distance by diffusion is

$$\tau_c = \frac{d^2}{6D(E)} = 16 \frac{R_{\rm cl}^2}{6D(E)} = 16 \left(\frac{R_{\rm cl}}{R_b}\right)^2 \frac{\tau_{\rm dif}(E)}{\tau_{\rm adv}} \tau_{\rm adv}$$

- This is shorter than both advection and diffusion time in the bubble —> particles cross numerous clumps while escaping
- As long as the number of clumps traversed is >>1 the assumption of mean density makes sense and we can introduce a mean grammage in the bubble

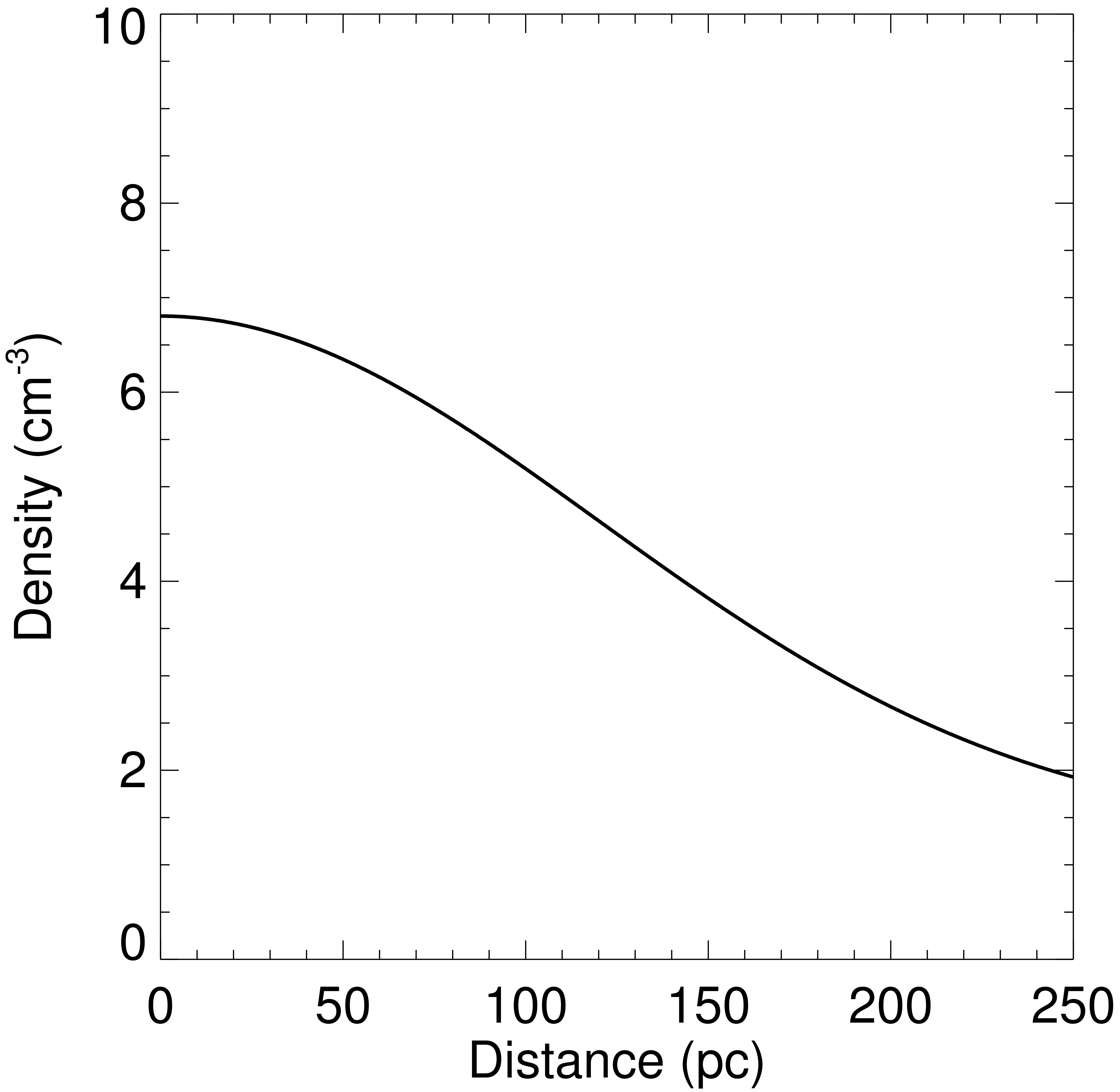
$$X(E) = n \, c \, m_p \, \tau_{\rm esc}$$

General implications of gamma rays from SC for CR

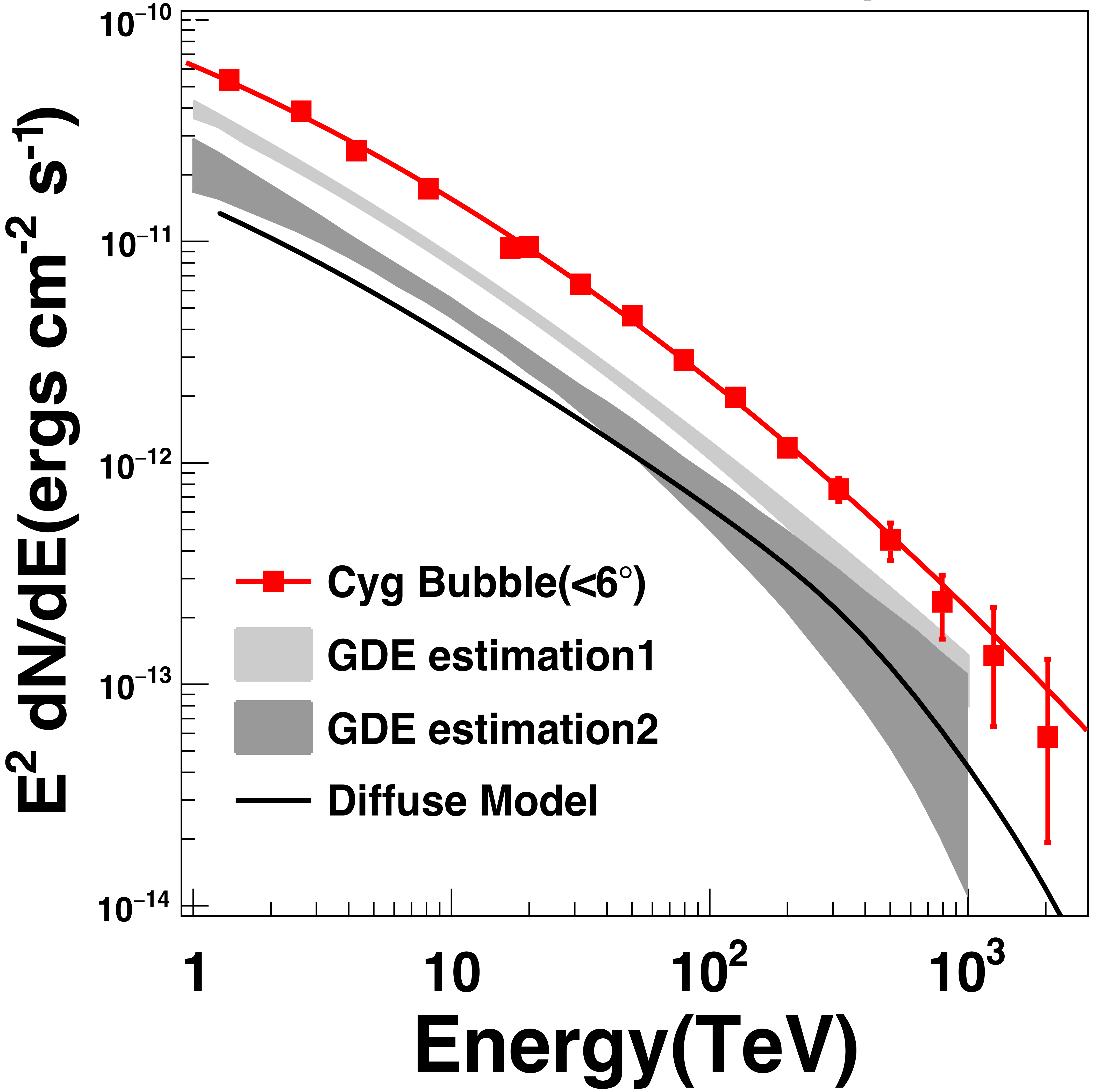
- The results presented above suggest that with the standard values of the gas density inferred from observations of clouds in the region of the Cygnus cocoon, the grammage felt by CR while escaping must be **~50 g cm^{-2} >> Galactic Grammage!!!**
- **This would have dramatic implications for the origin of CRs if at least a fraction of them are produced in star clusters that resemble the Cygnus cocoon**
- One might wonder whether this implication can somehow be weakened, for instance changing the acceleration efficiency or even the whole scenario of particle acceleration in star clusters
- Here I will consider two very different models and explore the question: **what do these two models imply in terms of the LHAASO data at E_γ>1 TeV from Cygnus?**

CR are accelerated in the center by a continuous source and diffuse outward	CR are accelerated at the Termination Shock and produce gamma on their way out

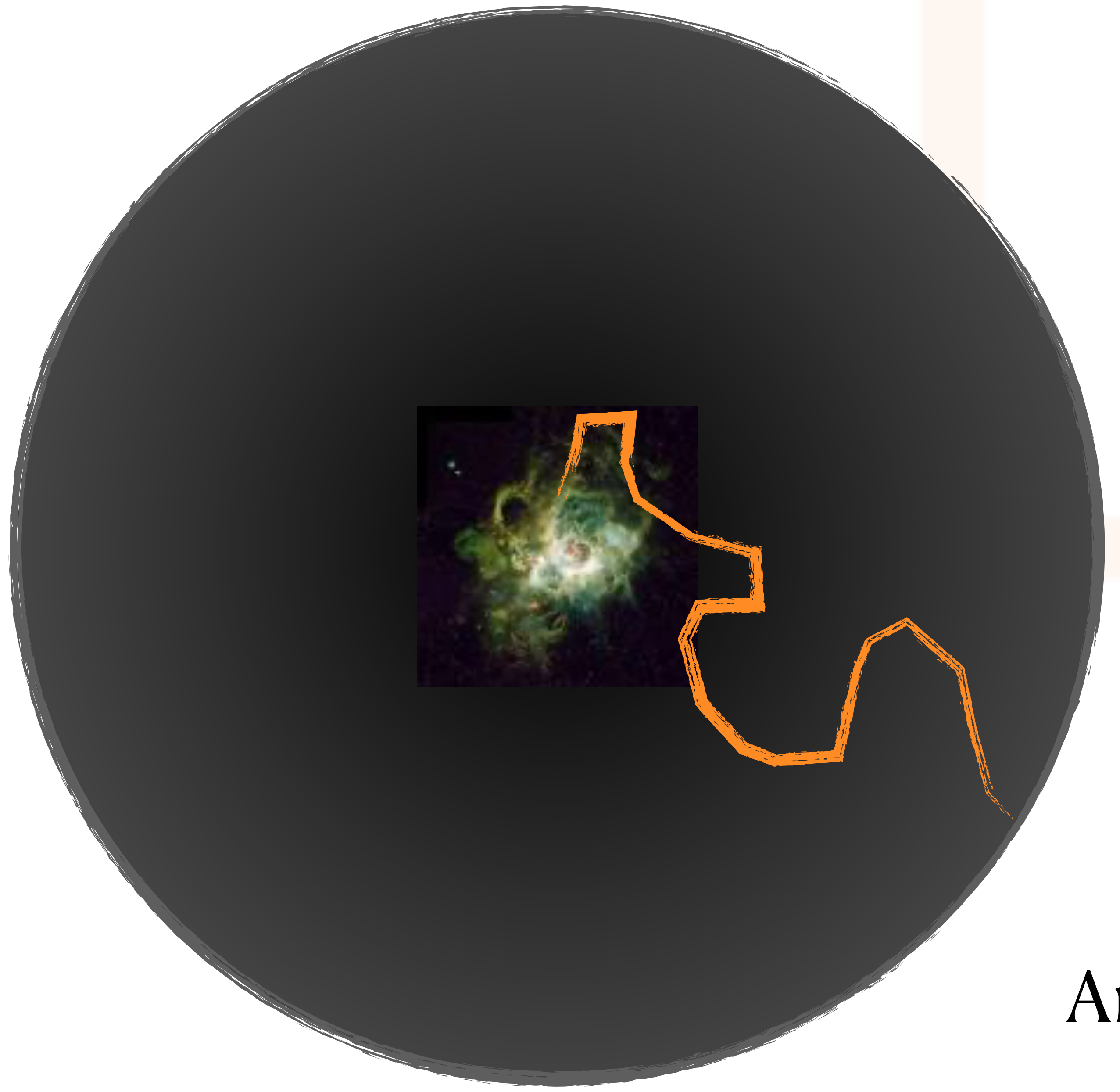
General implications of gamma rays from SC for CR



LHAASO 2024



Model 1: diffusion from a central source



$$n_{CR}(r,E) = \frac{Q(E)}{4\pi r D(E)}$$

Density of CR at distance r

$$J_\gamma(E_\gamma)dE_\gamma = n_{CR}(E)dE n_{gas} c\sigma_{pp}$$

Simple scaling relation good enough with $E_\gamma=\eta E$

$$E_\gamma^2\Phi_\gamma(E_\gamma) = \int_0^{R_b} dr \frac{r^2}{d^2}\xi_{CR}\frac{L_{SC}(\alpha-2)}{4\pi r D(E)}\eta^{\alpha-1}\left(\frac{E_\gamma}{m_p}\right)^{-\alpha+2}\times n_{gas}c\sigma_{pp} = \xi_{CR}\frac{L_{SC}(\alpha-2)}{4\pi d^2 D(E)}\eta^{\alpha-1}\left(\frac{E_\gamma}{m_p}\right)^{-\alpha+2}\frac{R_b^2}{2}n_{gas}c\sigma_{pp}$$

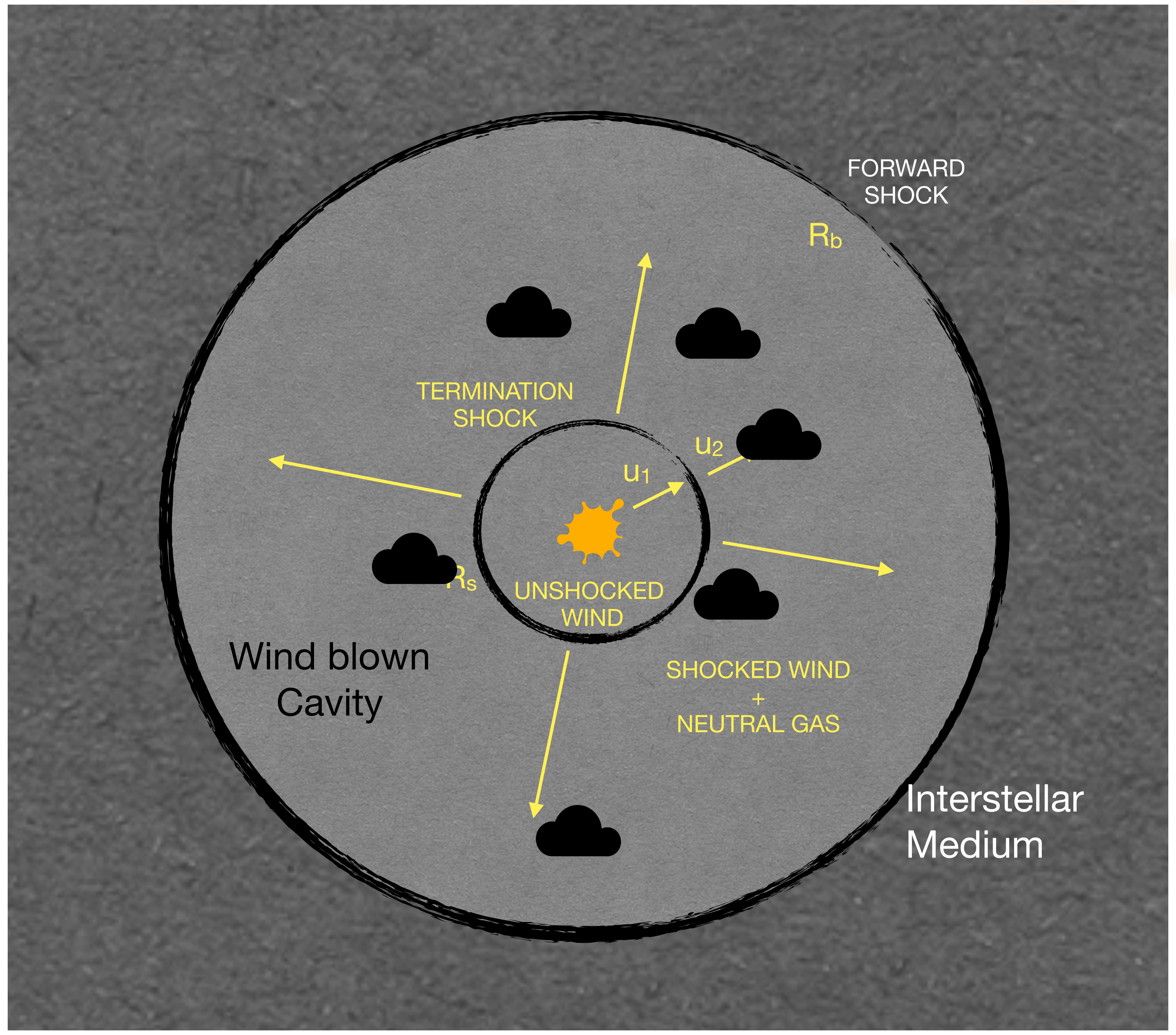
And introducing the grammage: $X(E) = n_{gas}m_p c\tau_b(E) = n_{gas}m_p c\frac{R_b^2}{6D(E)}$

$$E_\gamma^2\Phi_\gamma(E_\gamma) = \frac{3\xi_{CR}L_{SC}(\alpha-2)\eta^{\alpha-1}}{4\pi d^2}\left(\frac{E_\gamma}{m_p}\right)^{-\alpha+2}\frac{X(E)}{X_{cr}}$$

$$X_{cr} = m_p/\sigma_{pp}$$

The expected gamma ray emission at a given energy can be estimated as only function of the grammage X(E) in the bubble and the conversion efficiency of the SC luminosity L_{SC} to CR

Model 2: Acceleration at the TS



Most gamma rays are produced downstream of the termination shock

The spectrum of particles accelerated at the TS can be written easily by assuming the conversion of a fraction of the kinetic energy of the wind is converted to CR

$$n_{CR}(E) = \xi_{CR} \frac{\dot{M} v_w (\alpha - 2)}{4\pi R_{sh}^2 (m_p c^2)^2} \left(\frac{E}{m_p}\right)^{-\alpha}$$

If we assume that this density remains constant downstream we maximise the gamma ray flux

$$E_\gamma^2 \Phi_\gamma(E_\gamma) = \frac{\xi_{CR} \dot{M} v_w (\alpha - 2)}{4\pi R_{sh}^2} \eta^{\alpha-1} \left(\frac{E_\gamma}{m_p}\right)^{-\alpha+2} \frac{R_b^3}{3d^2} n_{gas} c \sigma_{pp}$$

$$\tau_{adv} \approx \frac{4}{3} \frac{R_{sh}}{v_w} \left(\frac{R_b}{R_{sh}}\right)^3$$

$$E_\gamma^2 \Phi_\gamma(E_\gamma) = \frac{2\xi_{CR} L_w (\alpha - 2)\eta^{\alpha-1}}{4\pi d^2} \left(\frac{E_\gamma}{m_p}\right)^{-\alpha+2} \frac{X(E)}{X_{cr}}$$

$$X(E) = n_{gas} m_p c \tau_{adv}$$

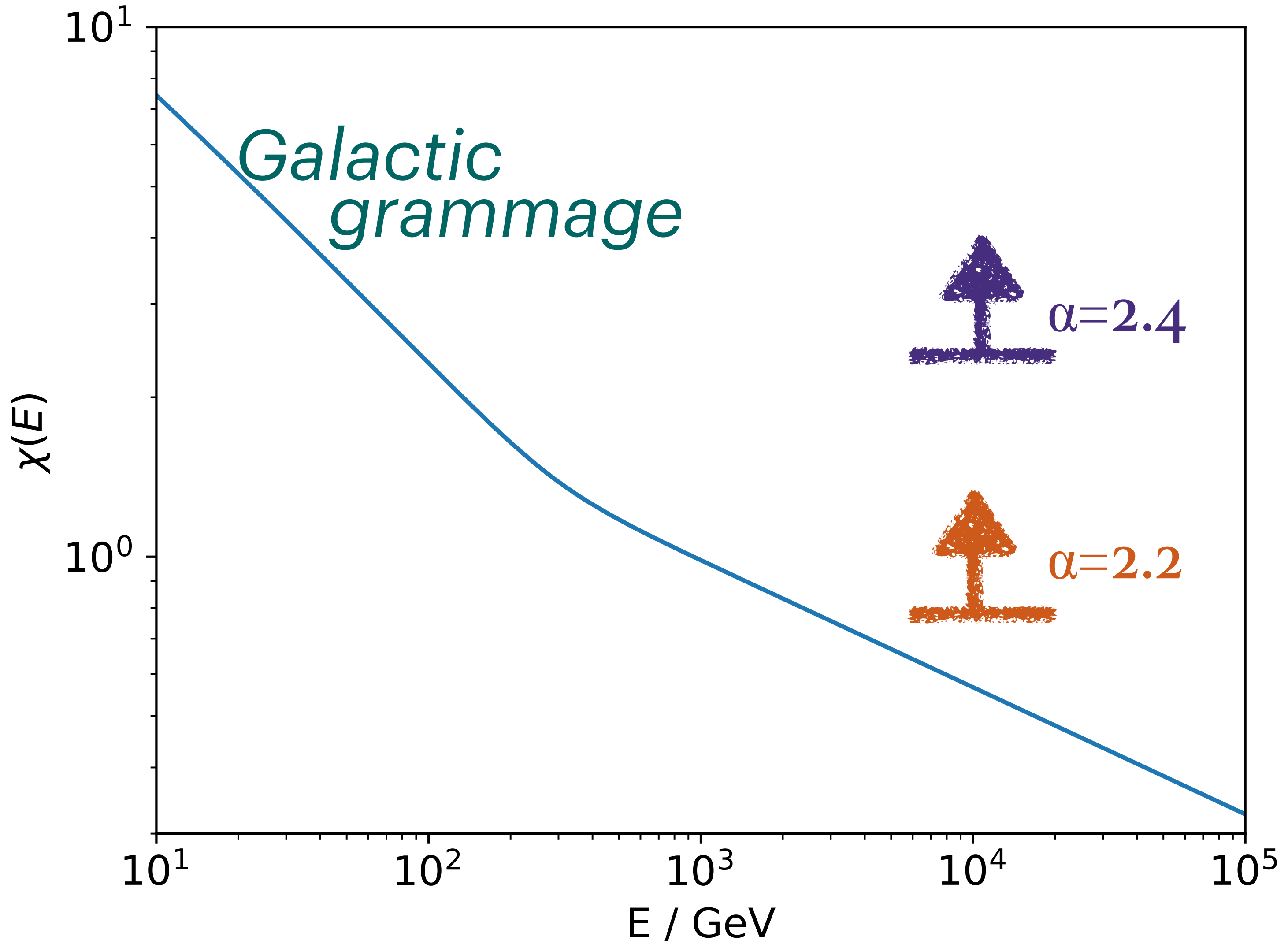
Lower limits to the grammage in the Cygnus cocoon

Model 1

$$X(E=10TeV) \gtrsim 0.8 L_{39}^{-1}\,\mathrm{g\,cm^{-2}} \text{ for } \alpha = 2.2$$

$$X(E=10TeV) \gtrsim 2.5 L_{39}^{-1}\,\mathrm{g\,cm^{-2}} \text{ for } \alpha = 2.4$$

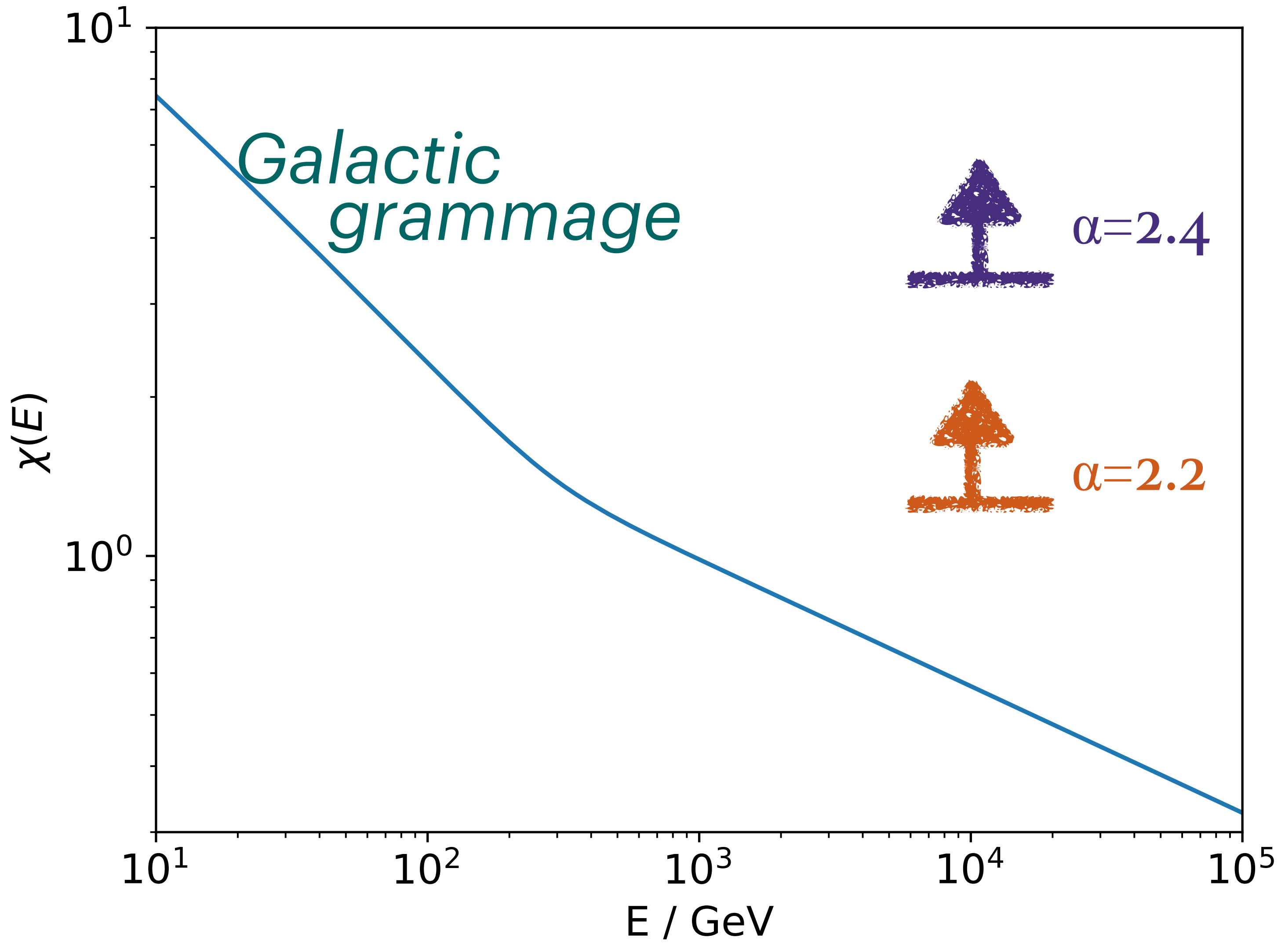
PB 2024



Model 2

$$X(E=10TeV) \gtrsim 1.2 L_{w,39}^{-1}\,\mathrm{g\,cm^{-2}} \text{ for } \alpha = 2.2$$

$$X(E=10TeV) \gtrsim 3.3 L_{w,39}^{-1}\,\mathrm{g\,cm^{-2}} \text{ for } \alpha = 2.4$$



The case of Westerlund 1

Model 1

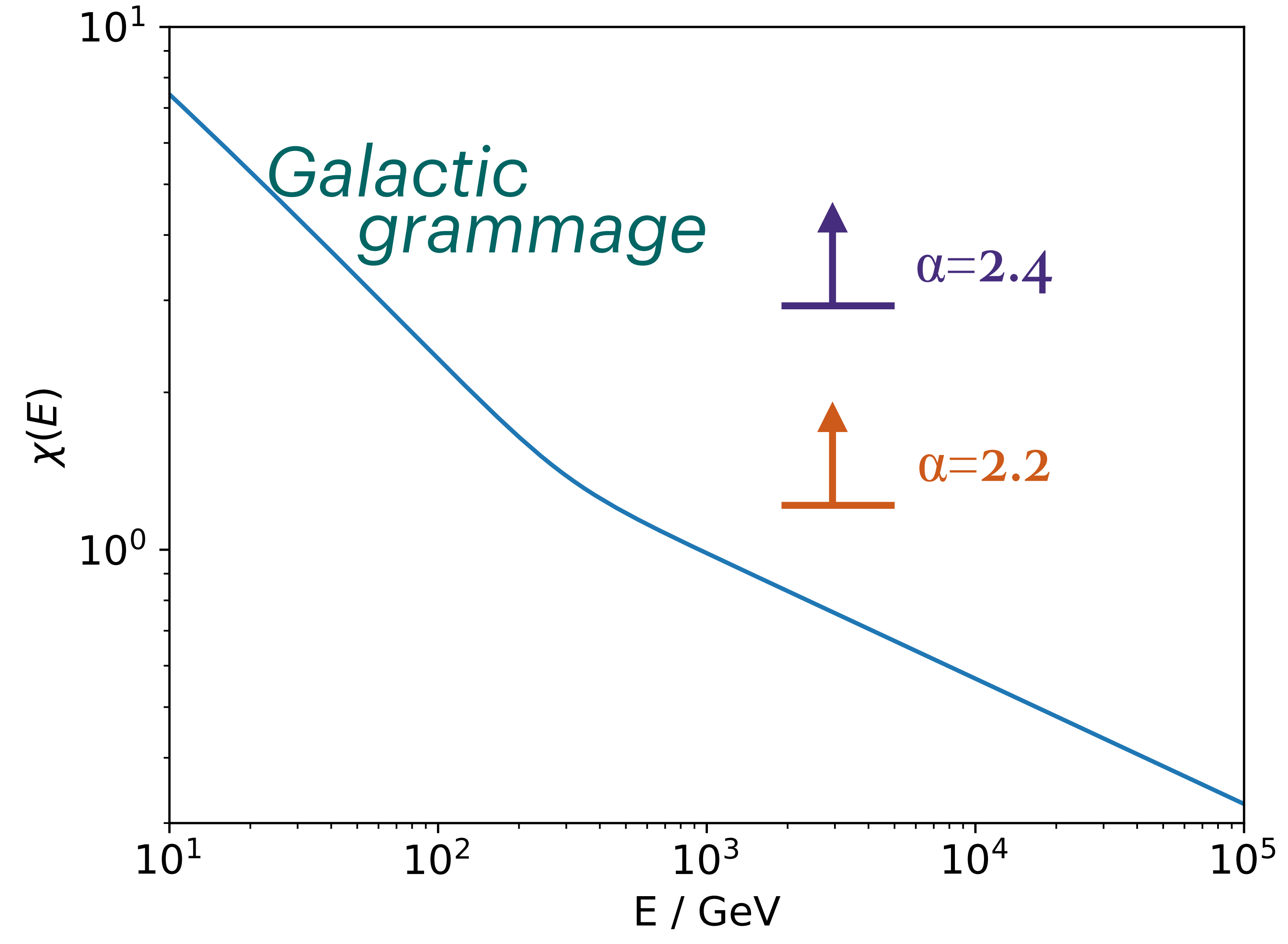
$$X(E = 3TeV) \gtrsim 1.2 \text{ g cm}^{-2}\text{L}_{39}^{-1} \qquad \alpha = 2.2$$

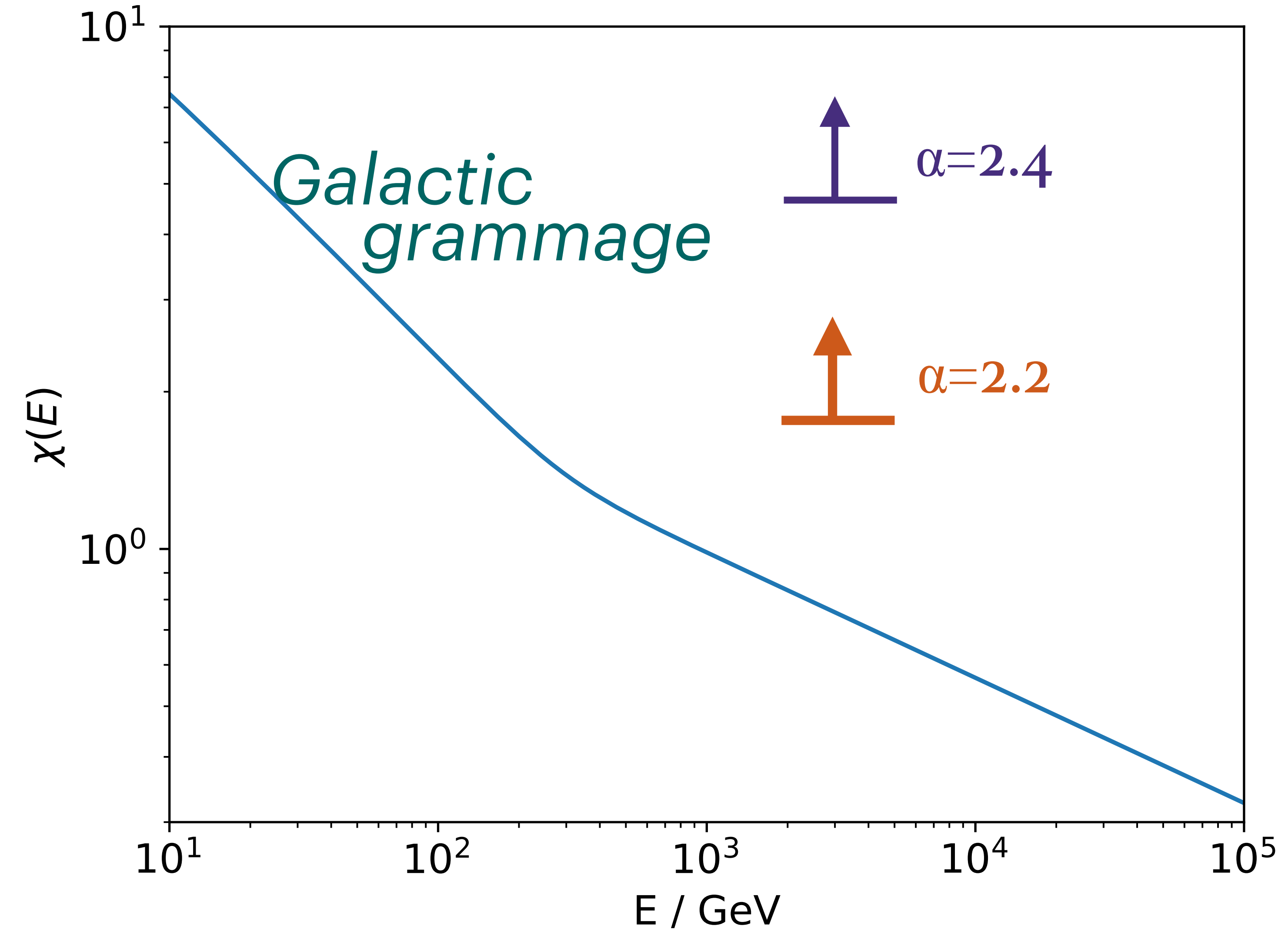
$$X(E = 3TeV) \gtrsim 2.9 \text{ g cm}^{-2}\text{L}_{39}^{-1} \qquad \alpha = 2.4$$

Model 2

$$X(E = 3TeV) \gtrsim 1.8 \text{ g cm}^{-2}\text{L}_{39}^{-1} \qquad \alpha = 2.2$$

$$X(E = 3TeV) \gtrsim 4.6 \text{ g cm}^{-2}\text{L}_{39}^{-1} \qquad \alpha = 2.4$$





Lower limits to the grammage in the cocoon

- Independent of the specific model of CR transport in the bubble, the detection of gamma ray emission with $E_\gamma > 1$ TeV by LHAASO implies a lower limit on the grammage

- This lower limit is already in excess of the Galactic grammage at the same energy

- How this extends to lower energies depends on Model 1 or 2 (more severe for Model 1)

If the gamma ray emission detected from Cygnus is a common phenomenon, and this is all but guaranteed clearly, then

1. Either Star Clusters do not contribute but a small fraction of Galactic cosmic rays
2. ...or if they do, then a major revision of the transport of cosmic rays on Galactic scales is required... including the production and decay of both stable and unstable secondaries (e.g. ^{10}Be, ^{26}Al, ...)
3. In alternative the gamma ray emission we see is not of hadronic origin, but then it means that most measurements of the density carried out are not to be trusted!

Leptonic models of the gamma ray emission

- At least for Westerlund 1 it has been proposed that the gamma ray emission is due to ICS of leptons (Harer et al 2023)

- In general these models require low magnetic fields (lower than for hadronic models) to limit energy losses

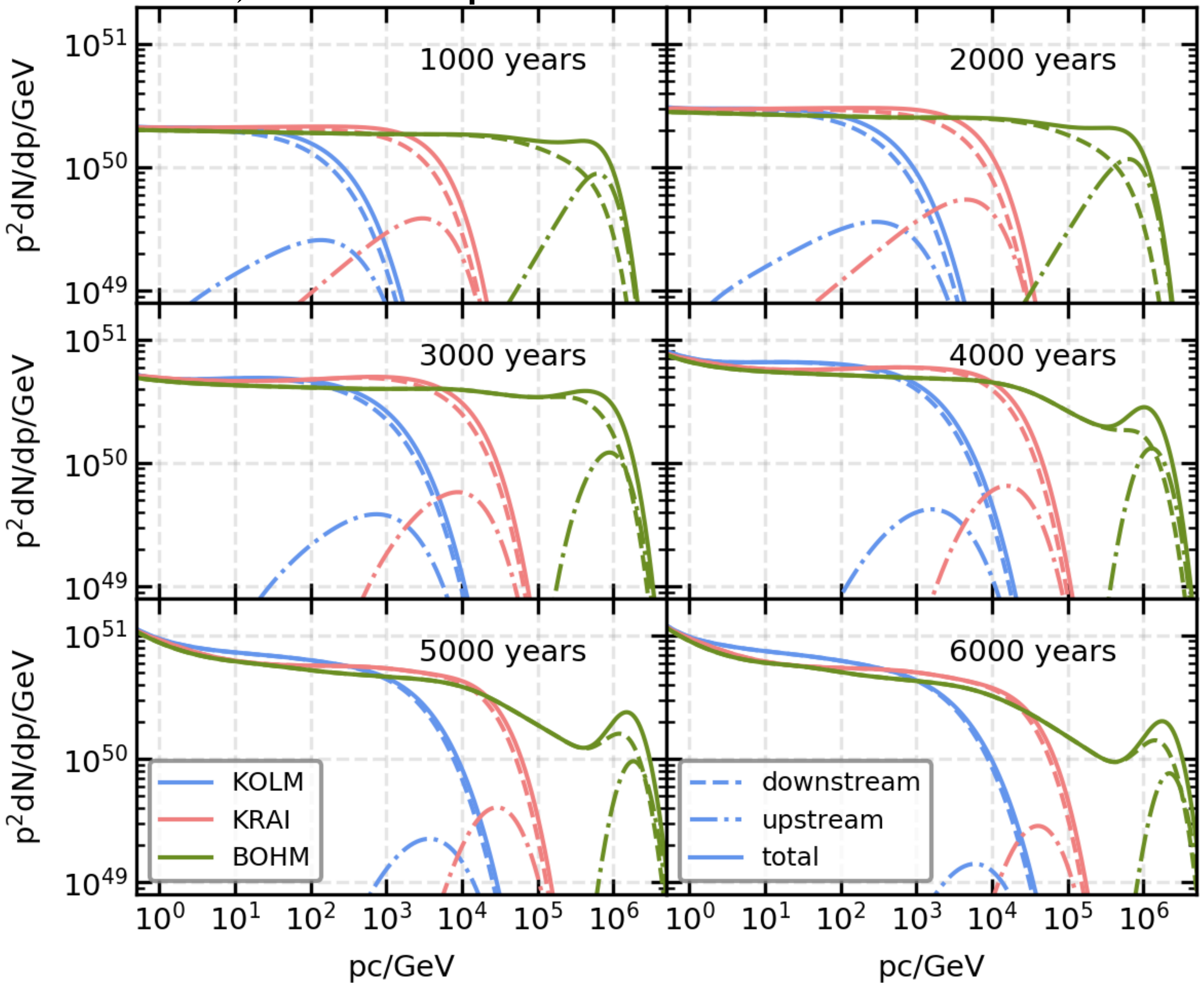
- But the small fields lead to lower maximum energies of accelerated particles (for electrons about 200 TeV) even for Bohm diffusion

- Either way, for hadronic or leptonic interpretation of the gamma ray emission, it seems that star clusters as sources of CR especially at the knee, raise many doubts

- The issue of SN explosions in star clusters might circumvent some of these issues, but not all...

SN explosions inside a SC

Sushch, PB & Brose 2024



We ran simulations of the evolution of a SN shock in the environment of the bubble excavated by the collective wind

As expected, the cutoff in thespectrum of accelerated particles at the SN shock depends strongly on the D(E)

If to use the turbulence already existing in the wind in which the SN shock moves, E_{max} fails to reach PeV

Bohm diffusion might be justified if turbulence is self-generated, and in that case E_{max} approaches PeV

But it is unlikely to have the right conditions for streaming instability in the bubble

If the gas in the SC is the one we inferred above, we have exactly the same problems raised above: the grammage accumulated in the SC is too large

Conclusions

- SC were proposed as possible sources of PeV Galactic CR, but the effective maximum energy is quite lower than PeV (gamma ray emission confirms that E_{max}<PeV)
- If gamma rays are generally of hadronic origin, ξ_{CR}=0.5%, hence negligible contribution to the CR flux, including at PeV energies
- On the other hand, for Cygnus, gamma ray morphology and spectrum agrees well with a hadronic interpretation —> the low ξ_{CR} leads to requiring a large grammage
- This large grammage reflects in a nice difference between H and He spectra, but…
- The price to pay is that nuclei are all destroyed and the transport on Galactic scales requires major revision
- We are left with a conundrum: a) Star clusters do now appreciably contribute to CR flux, or b) the gamma ray emission is not of hadronic origin —> perhaps larger CR contribution from less bright SC, but in this case hardly important at PeV