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INAF
ISTITUTO NAZIONALE DI ASTROFISICA

On the origin of the spectral features observed in the cosmic ray spectrum

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Overview

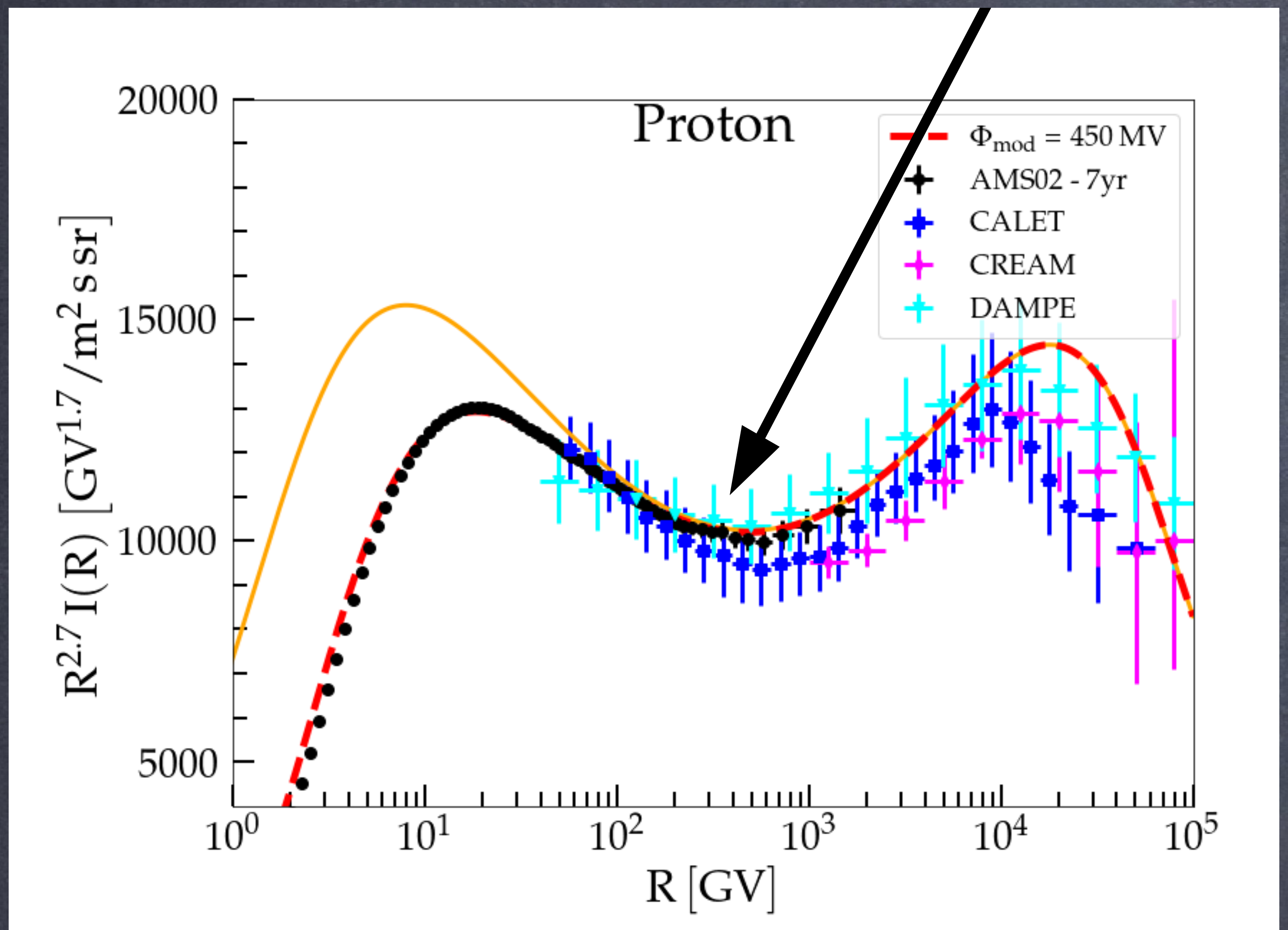
Recchia & Gabici (2023)

- Spectral features in the CR data - new results
- GeV - PeV
- how to interpret features - propagation, sources ... ?
- CRs up to ~ TeV - propagation and grammage CRs
- multi TV - PV range - sources and maximum energy
- microphysics of CR transport ? Galactic PeVatrons?

Breaks in the CR spectrum

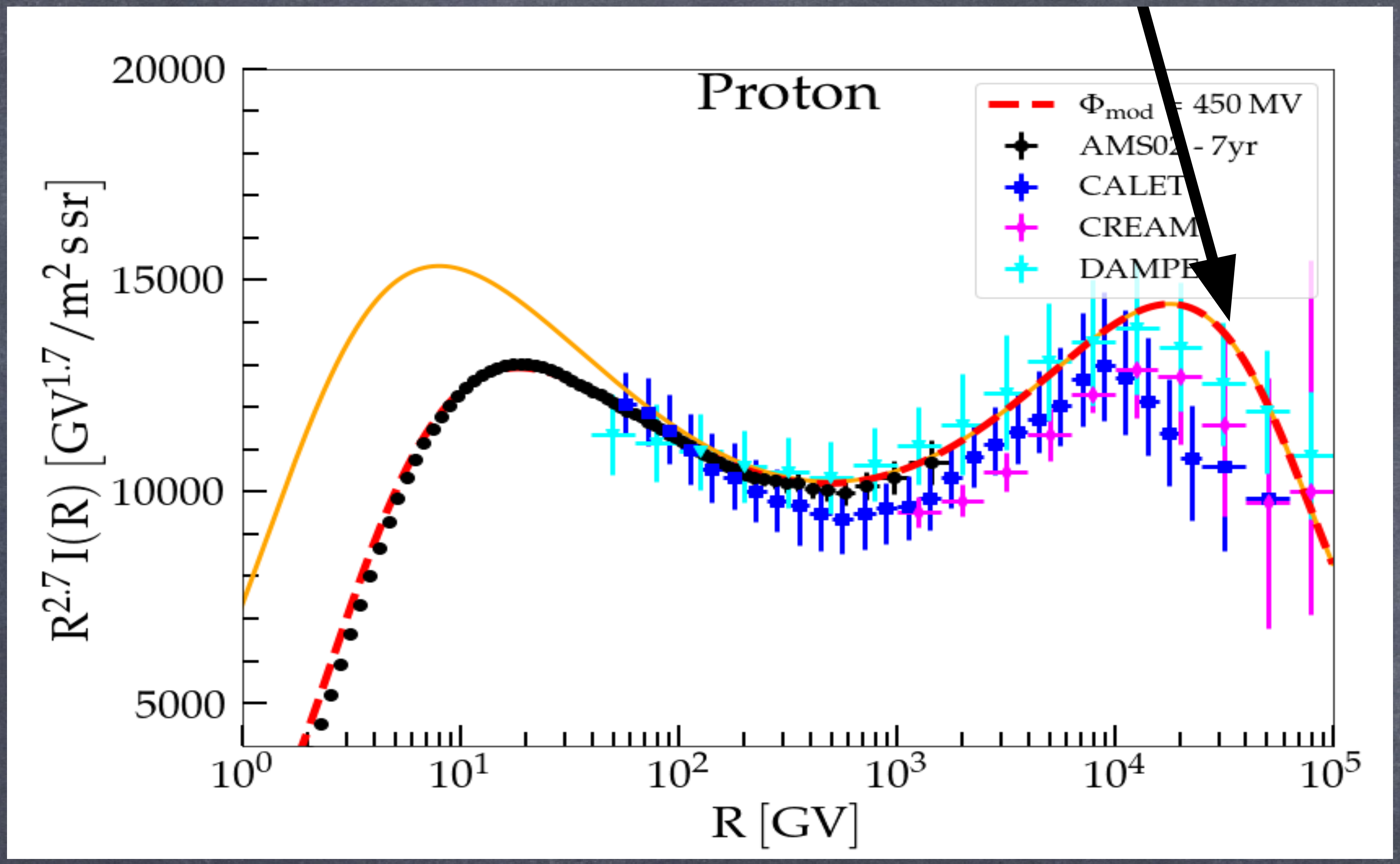
Breaks in GV-PV range

~ 300 GV



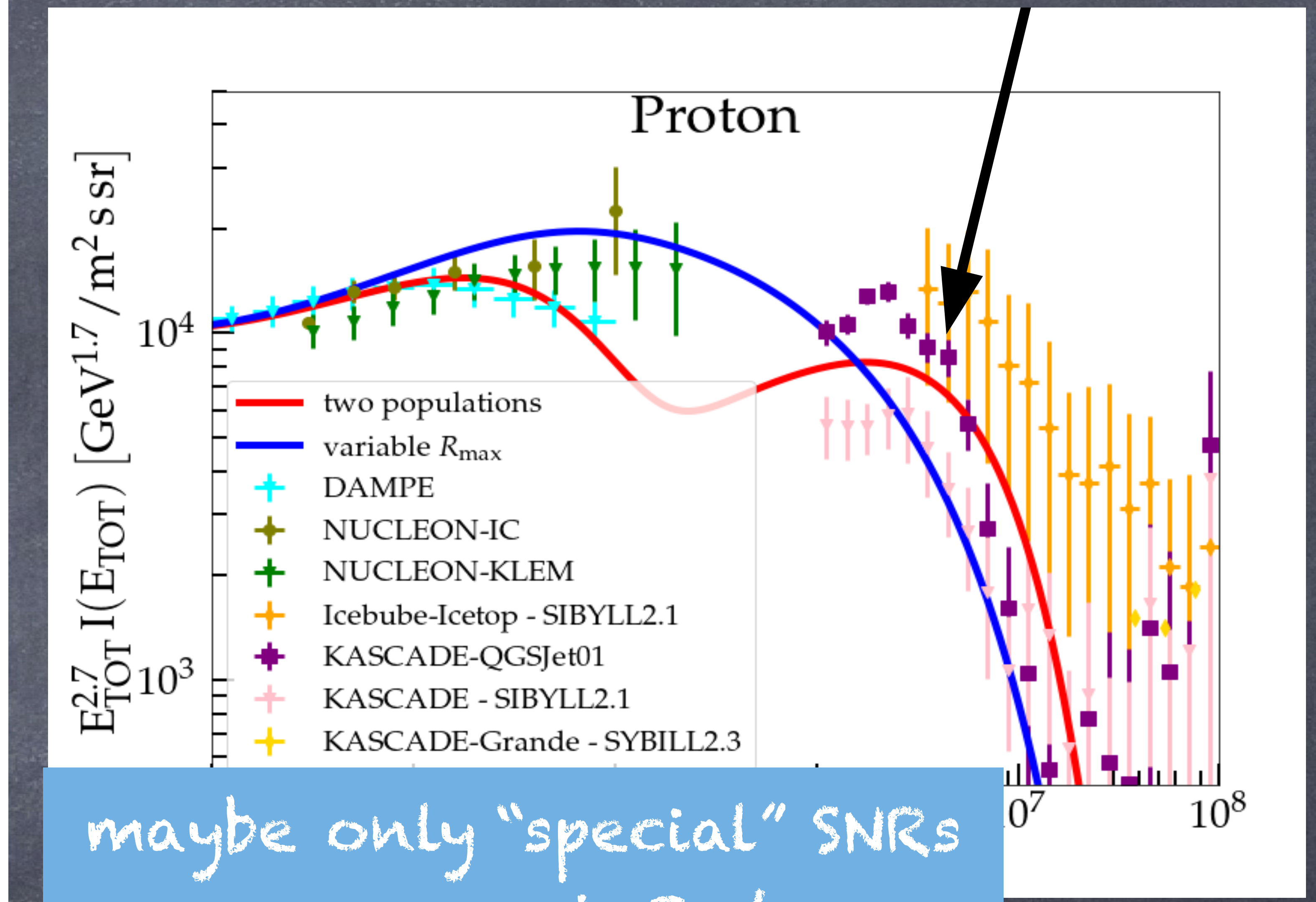
- hardening by ~ 0.1
- confirmed in secondary nuclei, by ~ 0.2
- change in propagation

"Dampe" ~ 15 TV



- local source? (most popular in literature)
- "Special" sources
- features of acceleration?
- change in propagation?

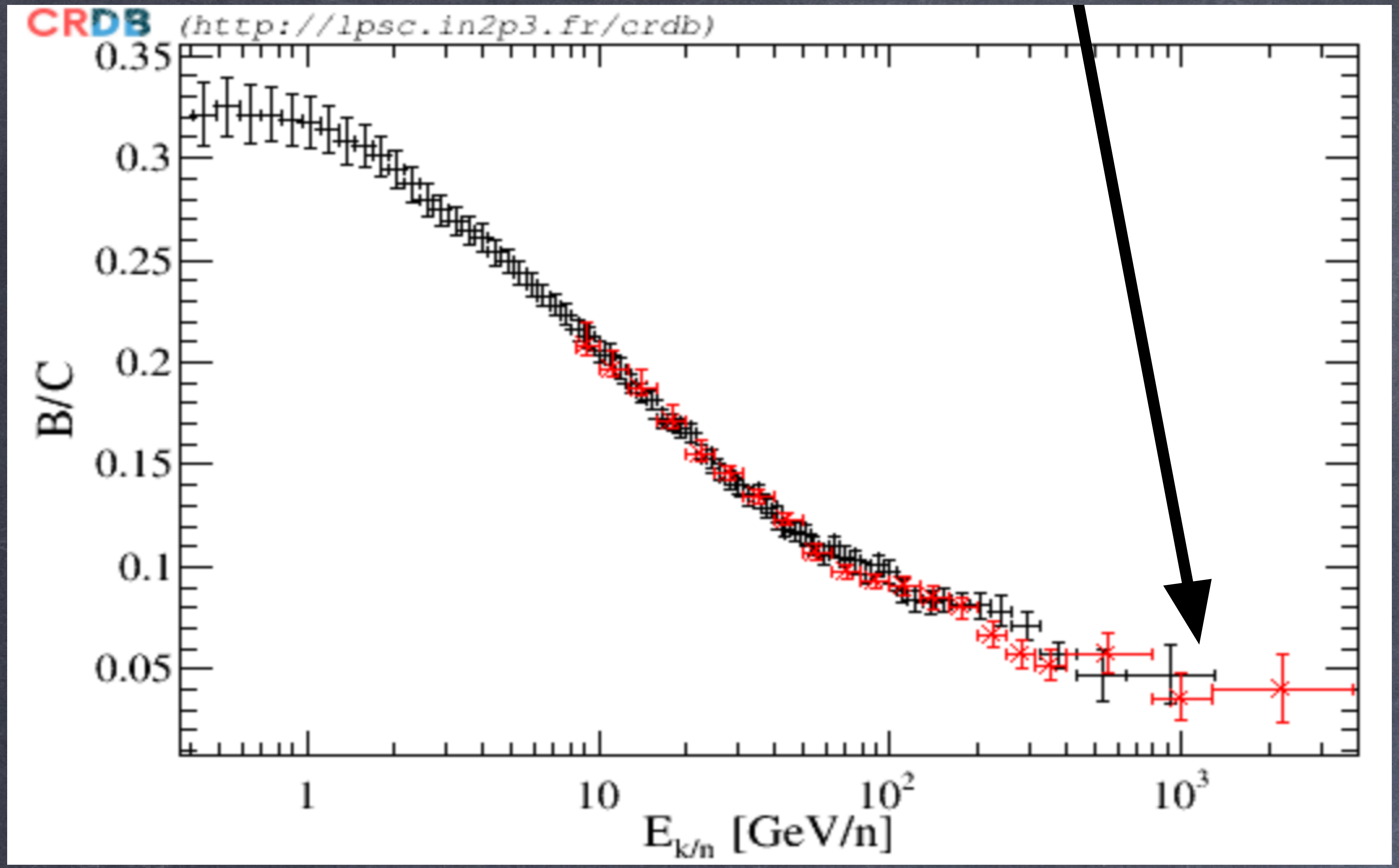
"Knee" ~ 3 PV

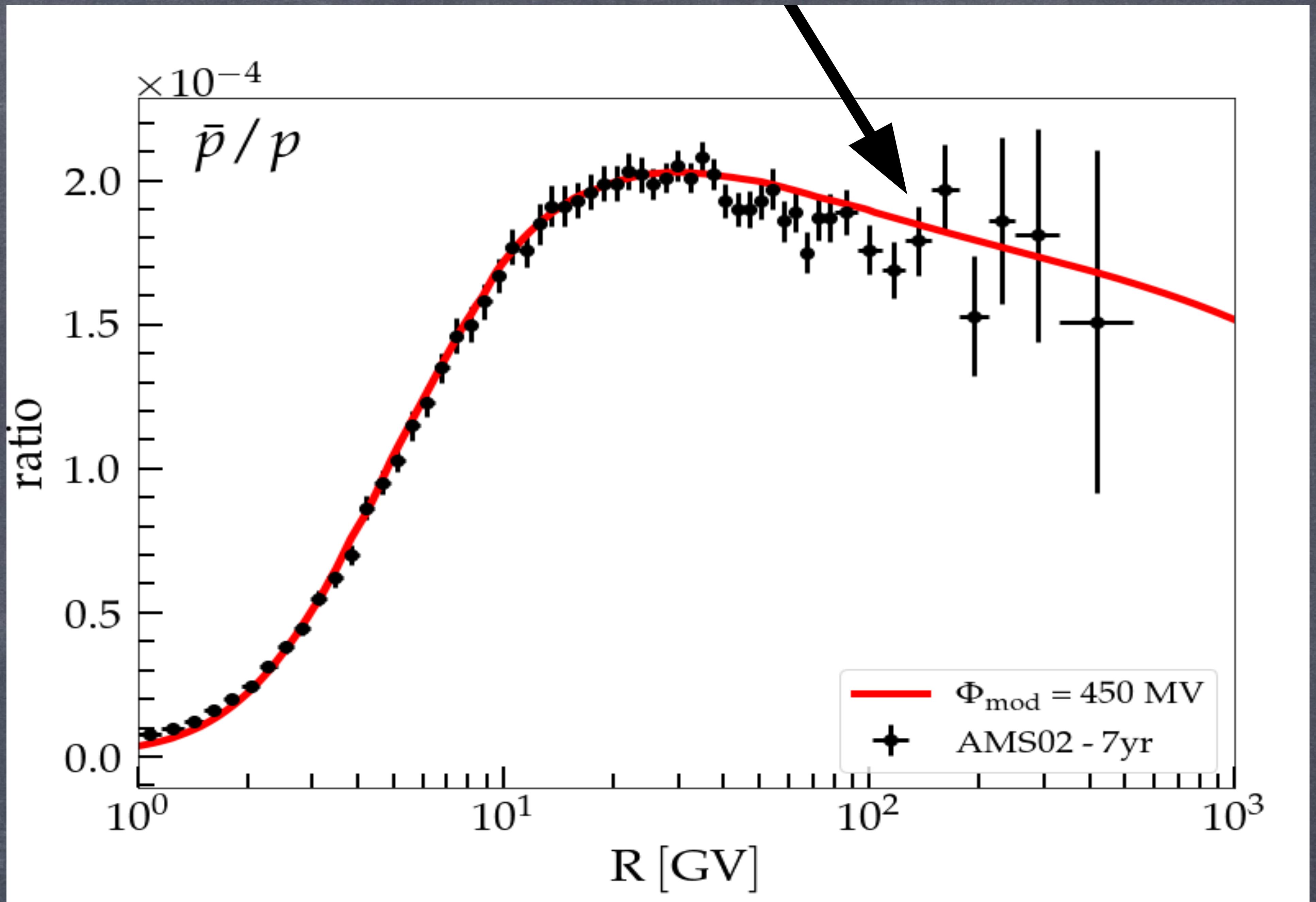


maybe only "special" SNRs can reach PeV

- most SNRs accelerate up to ~ 3xZ PeV ?
- overlap of Emax of different species
- difficult for current theories

Hardening of B/C at ~ TeV/n & pbar/p





- explained by flatter D(R) above ~ 300 GV ?
- where is the grammage accumulated? role of sources?
- secondaries produced at/nearby accelerators?
- effect of sources is unavoidable but not clear if enough

Tomassetti & Donato (2012)

Bresci et al. 2019

Mertsch et al. (2021)

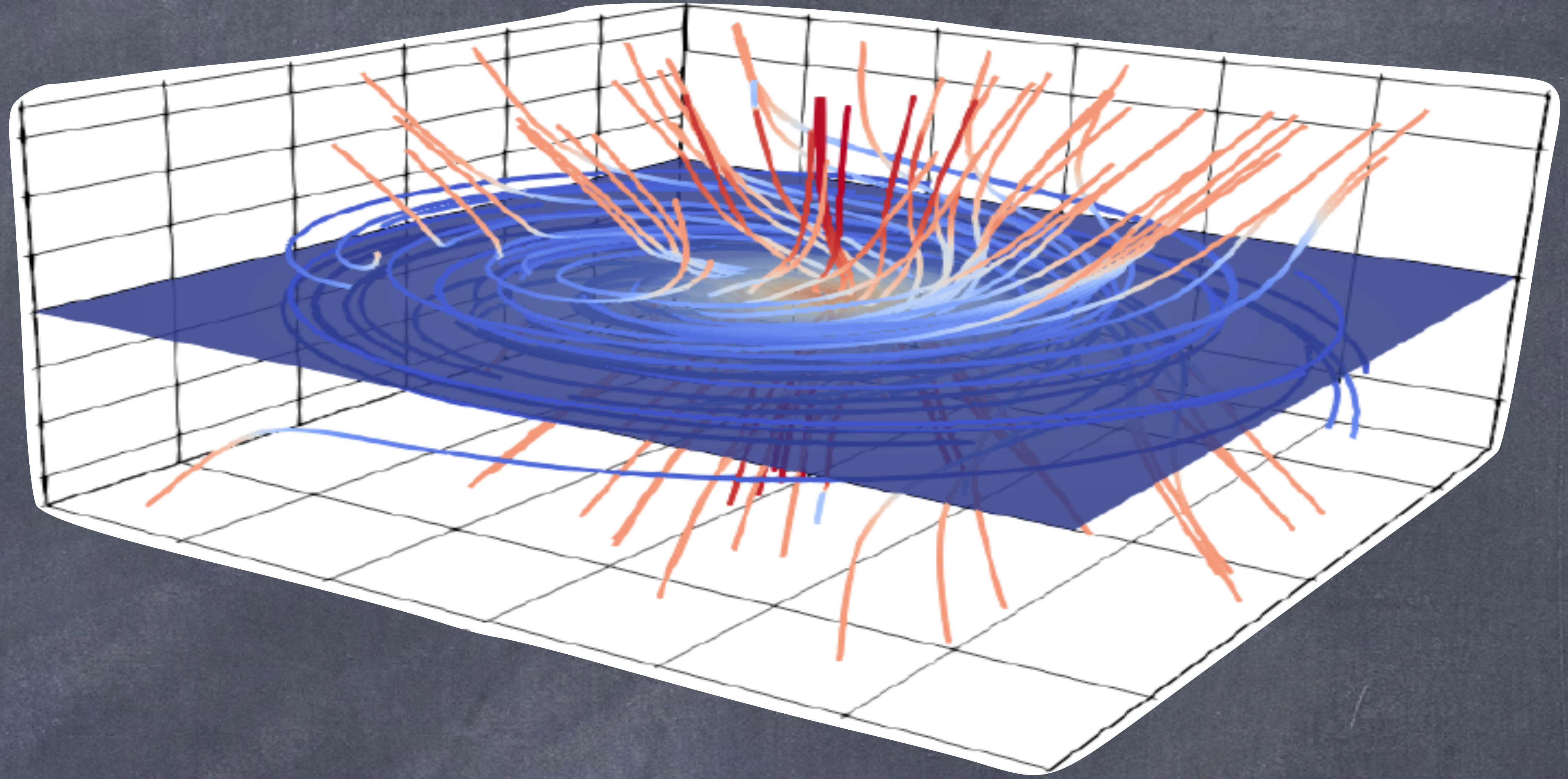
D'Angelo et al. (2016)

Recchia et al. (2022)

Alternative framework
CR data ~ GV- PV

Alternative framework - CR data ~ GV- PV

Recchia & Gabici (2023)



CR propagation in disk

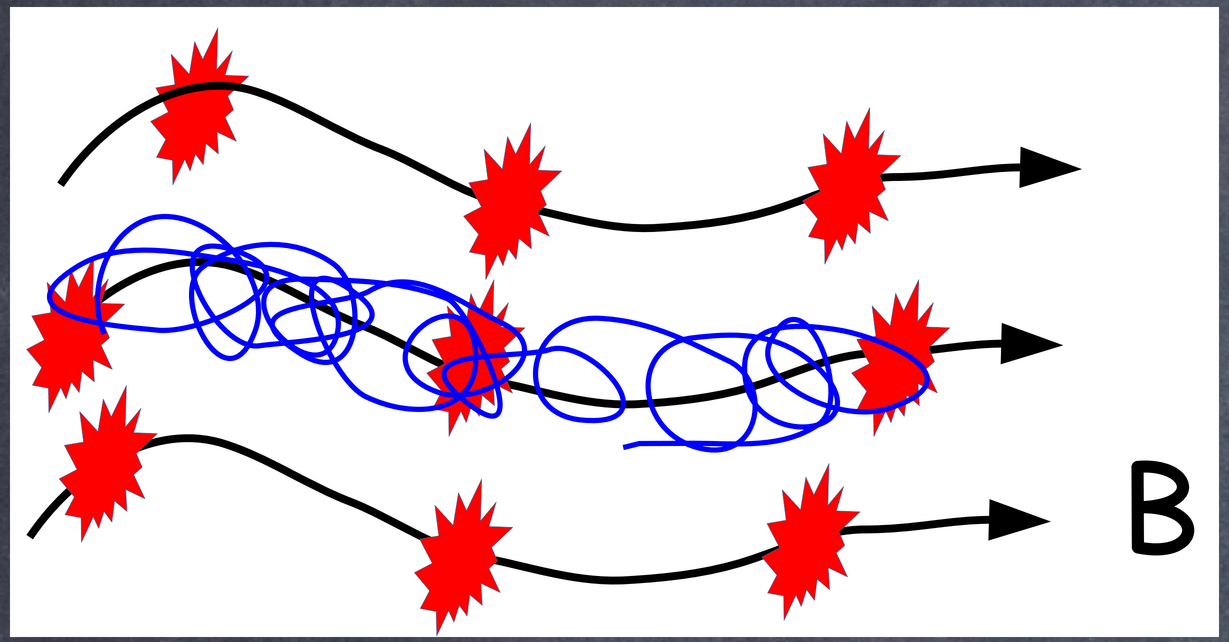
- weak scattering along B
  (along Galactic plane)
  damping/anisotropic cascade
- energy-independent perp. transport
- typical diffusion D(E)
  in Galactic halo
- role of disk emerges above ~ TV

Emax of "typical" SNRs

- "Dampe break"
  Emax of typical SNRs (~ 50 TV)
- "special" sources can reach the "knee" (~10-15% luminosity)
- easier with current theories

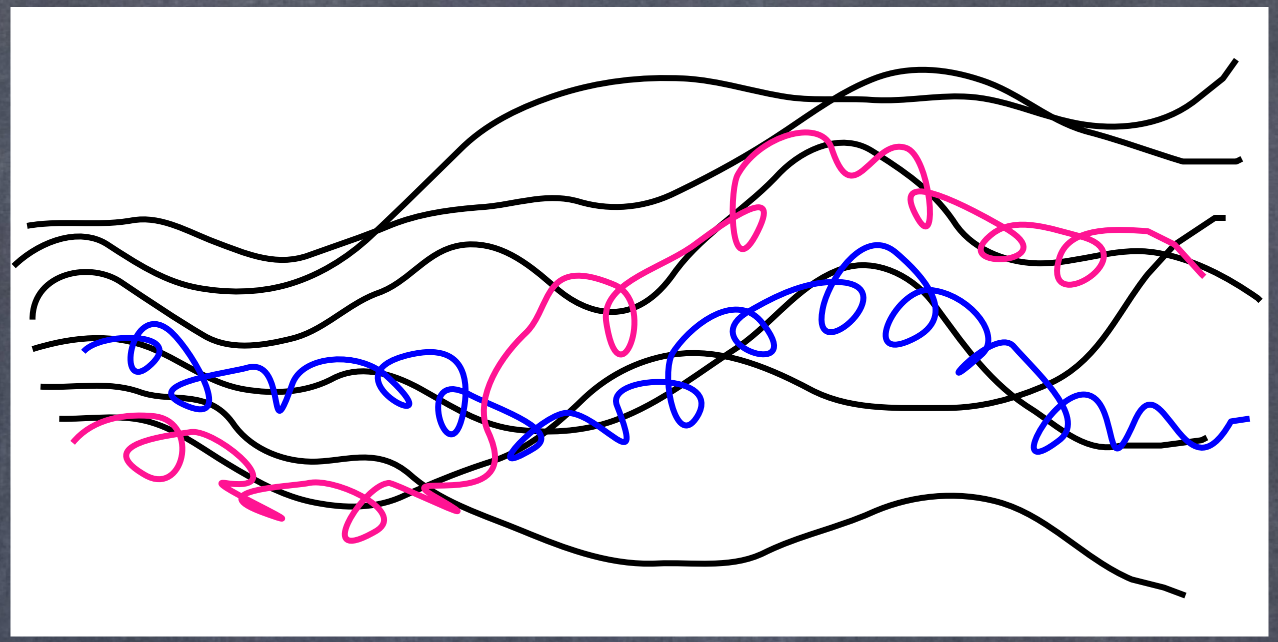
CR transport in (very) short

parallel diffusion



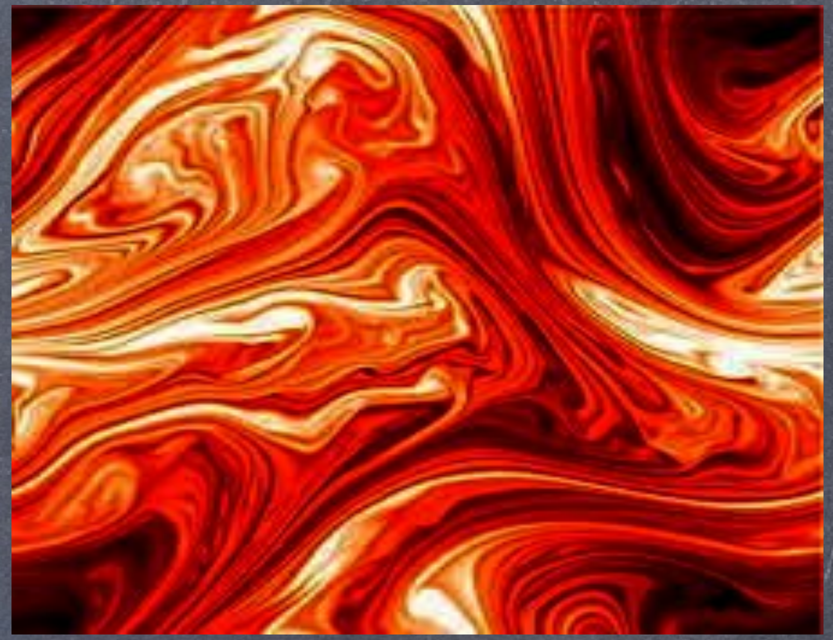
- CR gyromotion
- scattering off waves
- $k \sim 1/r_L$ (resonance)
- scattering mean free path λ_{mfp}
- $D_{\|}(E) \propto \lambda_{\mathrm{mfp}}$

perp. transport



- field line random walk
- CR jump between lines
- large-scale perp diffusion
- $D_{\perp}(E) \lesssim D_{\|}(E)$

MHD turbulence



- source injection (10s pc)
- cascade to $k \sim 1/r_L$?
- damping?
- Produced by CRs ?

Mertsch 2020 - review turbulence & transport

Shalchi 2020 - review perp. Transport

Perpendicular diffusion: weak scattering limit

Rechester & Rosenbluth 1978 | Chandran 2000 | Snodin et al. (2022) | Pezzi & Blasi (2024)

- weak scattering ALONG field lines
  - scattering along B is inefficient (damping, "wrong" cascade...)
  - large $D_{\parallel}$ ⟶ $\lambda_{\rm mfp} \gtrsim L_{\rm coh}$
  - within $L_{\rm coh}$, $z(t) \sim v\,t$

- diffusive motion of field lines
  - D_m [length] ⟶ field line diffusion coefficient
  - large scale turbulence ($\gg r_L$)
  - $D_{\perp}$ becomes energy-independent

$$D_m v \approx 3 \times 10^{28} \left(\frac{D_m}{\rm pc}\right) {\rm cm}^2/{\rm s},$$

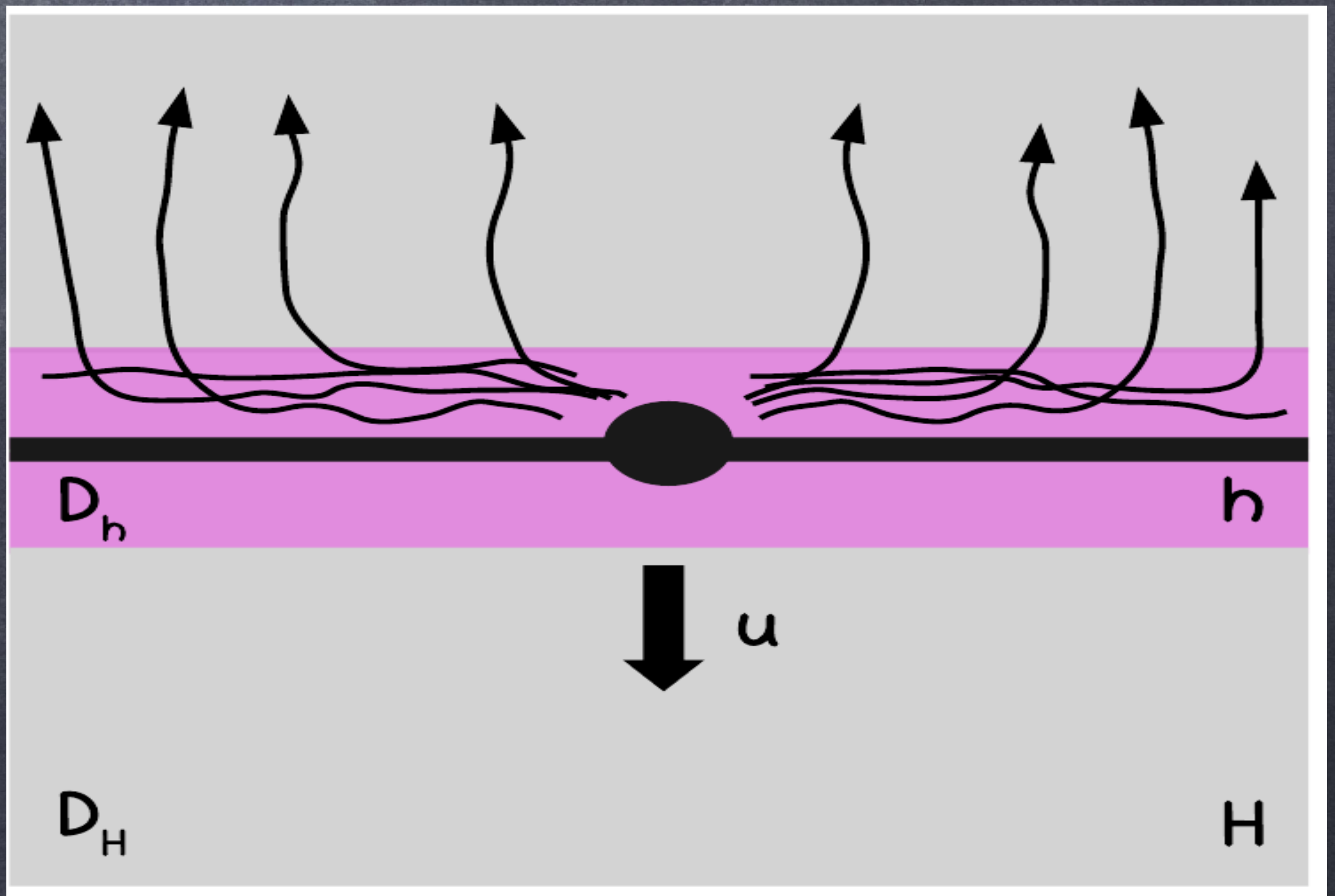
Alternative framework
CR data ~ GV- PV

Model of CR transport in the disk-halo

- Galactic disk
  - field lines mostly along the GP
  - weak scattering along B0 (along GP)
  - injection/spallation in thin gaseous disk

$$D_m v \approx 3 \times 10^{28} \left(\frac{D_m}{\mathrm{pc}}\right) \mathrm{cm}^2/\mathrm{s},$$

- Galactic halo
  - $D(E) \sim 10^{28}\,\mathrm{cm}^2/\mathrm{s}\ \mathrm{E}^{0.7}$
  - advection away from disk
  - size H~4kpc



Analytic solution of the CR transport

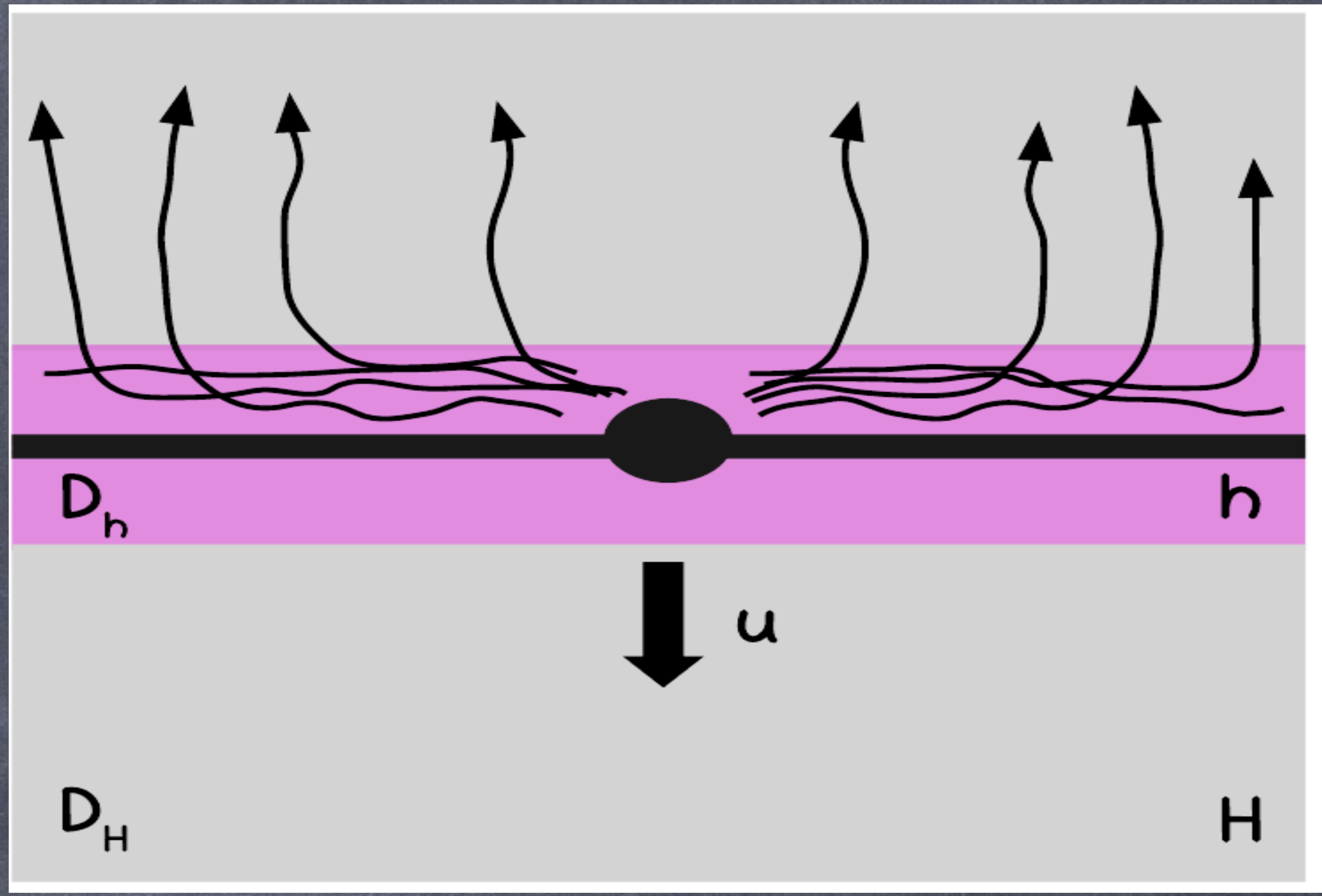
flux of stable nuclei VS E_{kin}/n

$$I_{\alpha 0}(E_k) = \frac{\tau_\alpha^{hH}}{1 + n_d \frac{h_d}{h} v(E_k)\sigma_\alpha \tau_\alpha^{hH}} \times \left[\frac{1}{2h} Q_{\alpha,\mathrm{src}} + n_d \frac{h_d}{h} Q_{\alpha,\mathrm{spall}}\right]$$

$$\begin{cases} Q_{\alpha,\mathrm{src}} \equiv cAp^2 q_{0\alpha} \\ Q_{\alpha,\mathrm{spall}} \equiv \sum_{\beta>\alpha} v(E_k)\sigma_{\beta\alpha}(E_k) I_\beta(E_k) \end{cases}$$

inj. sources

inj. spallation



$$\tau_\alpha^{hH} \equiv \frac{h^2}{D_h} + \frac{h\,H}{D_H} \frac{1 - \exp^{-\frac{uH}{D_H}}}{\frac{uH}{D_H}}.$$

residence time in disk

$$X_\alpha(E_k) = \left(n_d \frac{h_d}{h}\right) \mu v(E_k) \tau_\alpha^{hH},$$

grammage

$$\frac{n_s}{n_p} \sim \frac{\sigma_s X}{\mu m_p}$$

$$X = \mu m_p c\, n_d\, \tau_d$$

Analytic solution of the CR transport

residence time in disk

$$\tau_\alpha^{hH} \equiv \frac{h^2}{D_h} + \frac{h\,H}{D_H}\,\frac{1-\exp^{-\frac{u\,H}{D_H}}}{\frac{u\,H}{D_H}}.$$

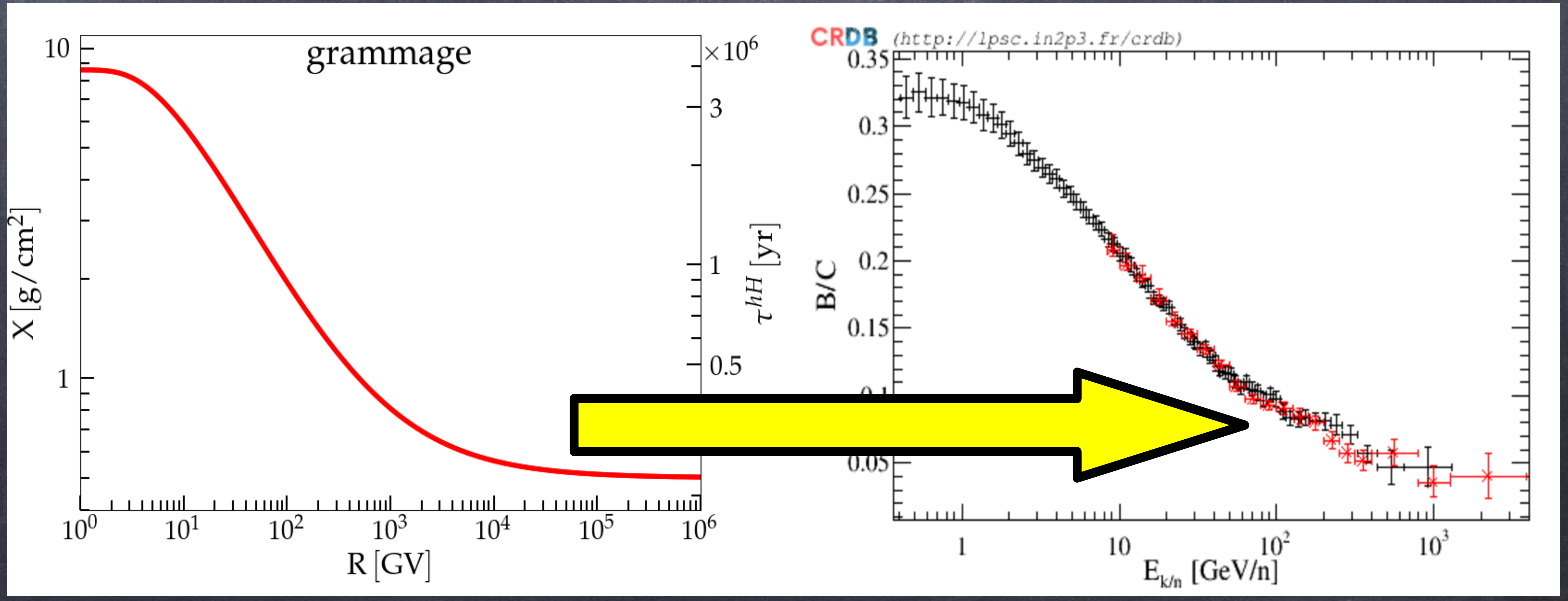
repeated crossings of disk induced by diffusion in halo
decreases with E due to $D_H \sim E^{0.7}$

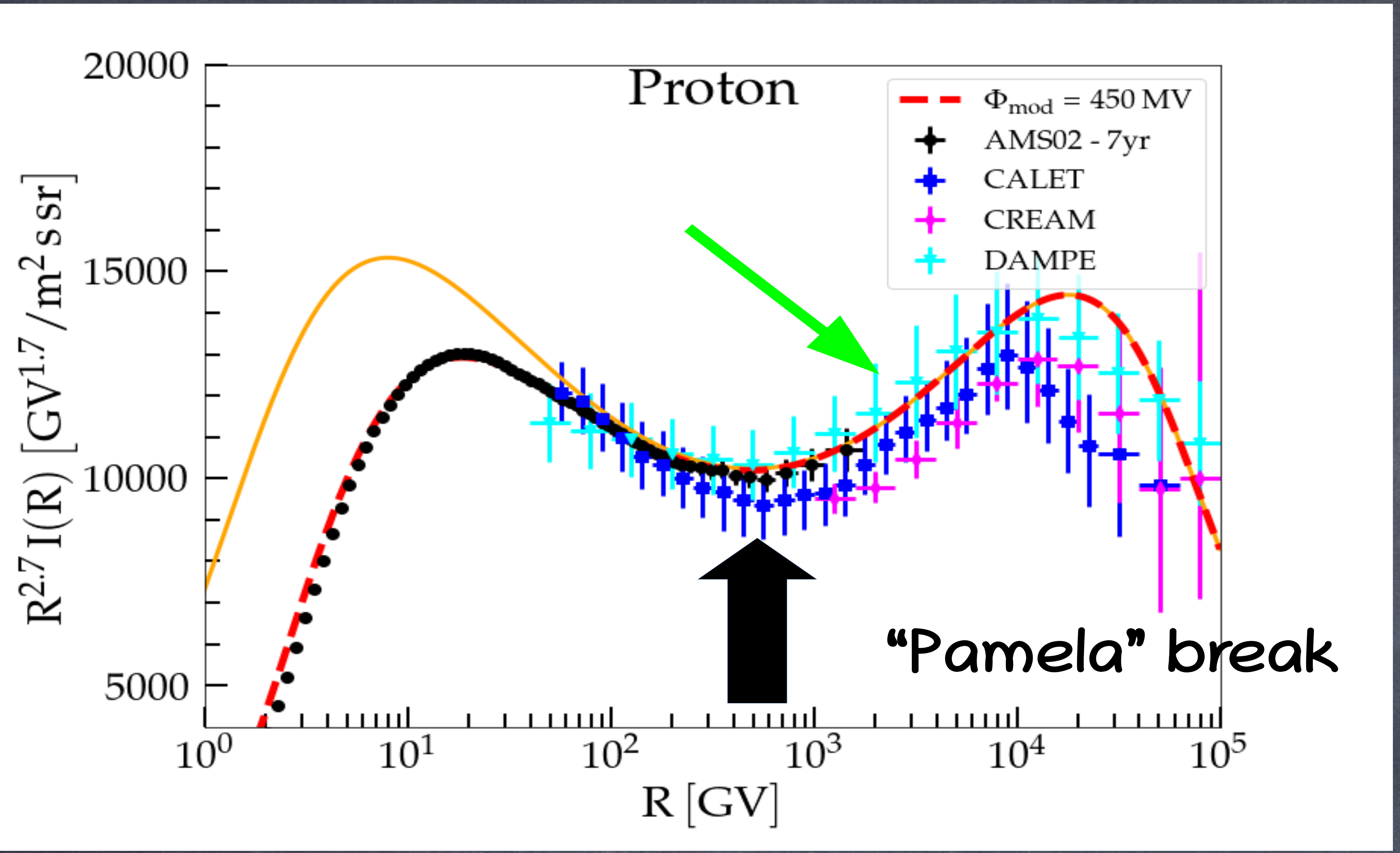
diffusion in disk
constant in E

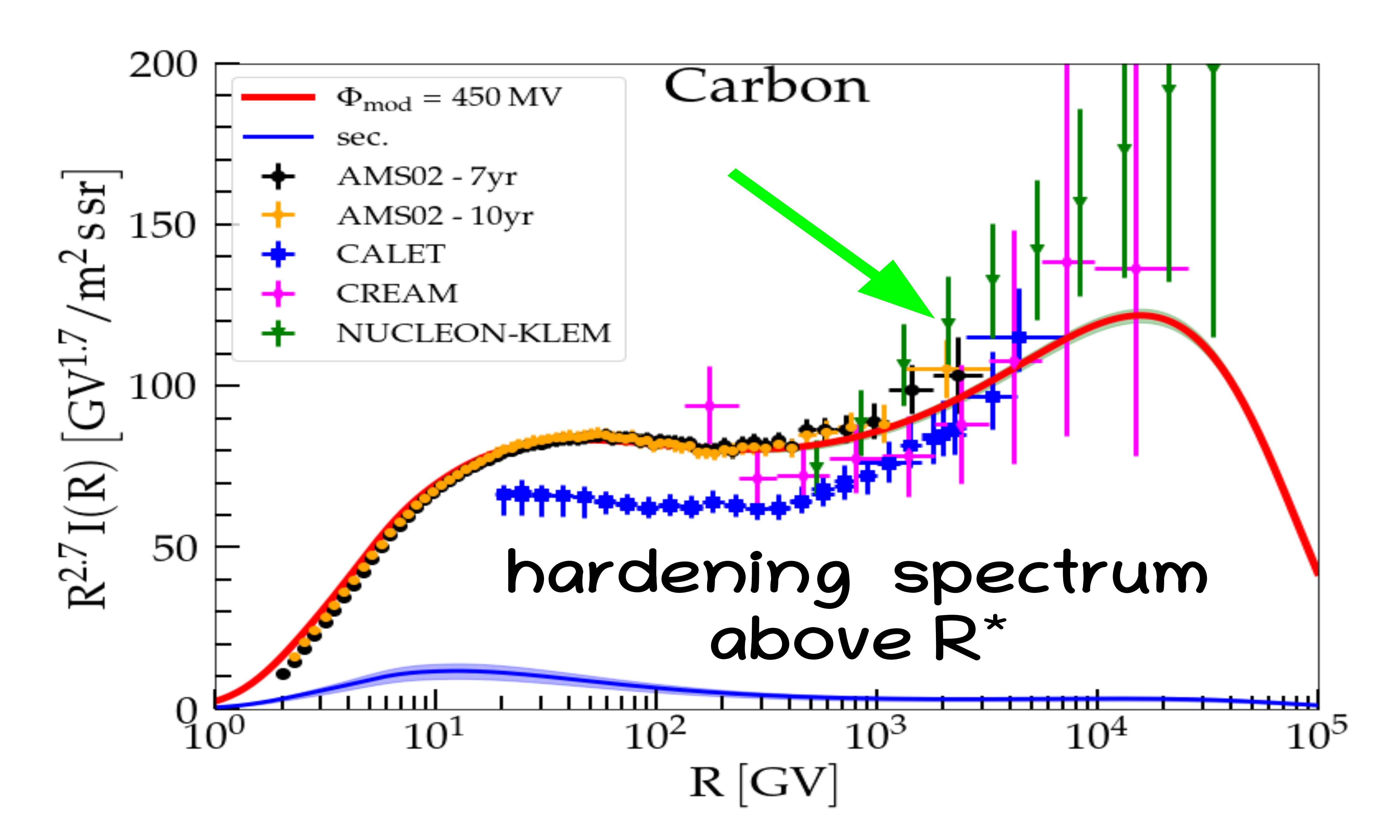
$$\tau_d^{\min} \sim \frac{h^2}{D_{\mathrm{eff},\perp}} \approx 2\times 10^5 \left(\frac{h}{150\,\mathrm{pc}}\right)^2 \left(\frac{\mathrm{pc}}{D_m}\right) \mathrm{yr},$$

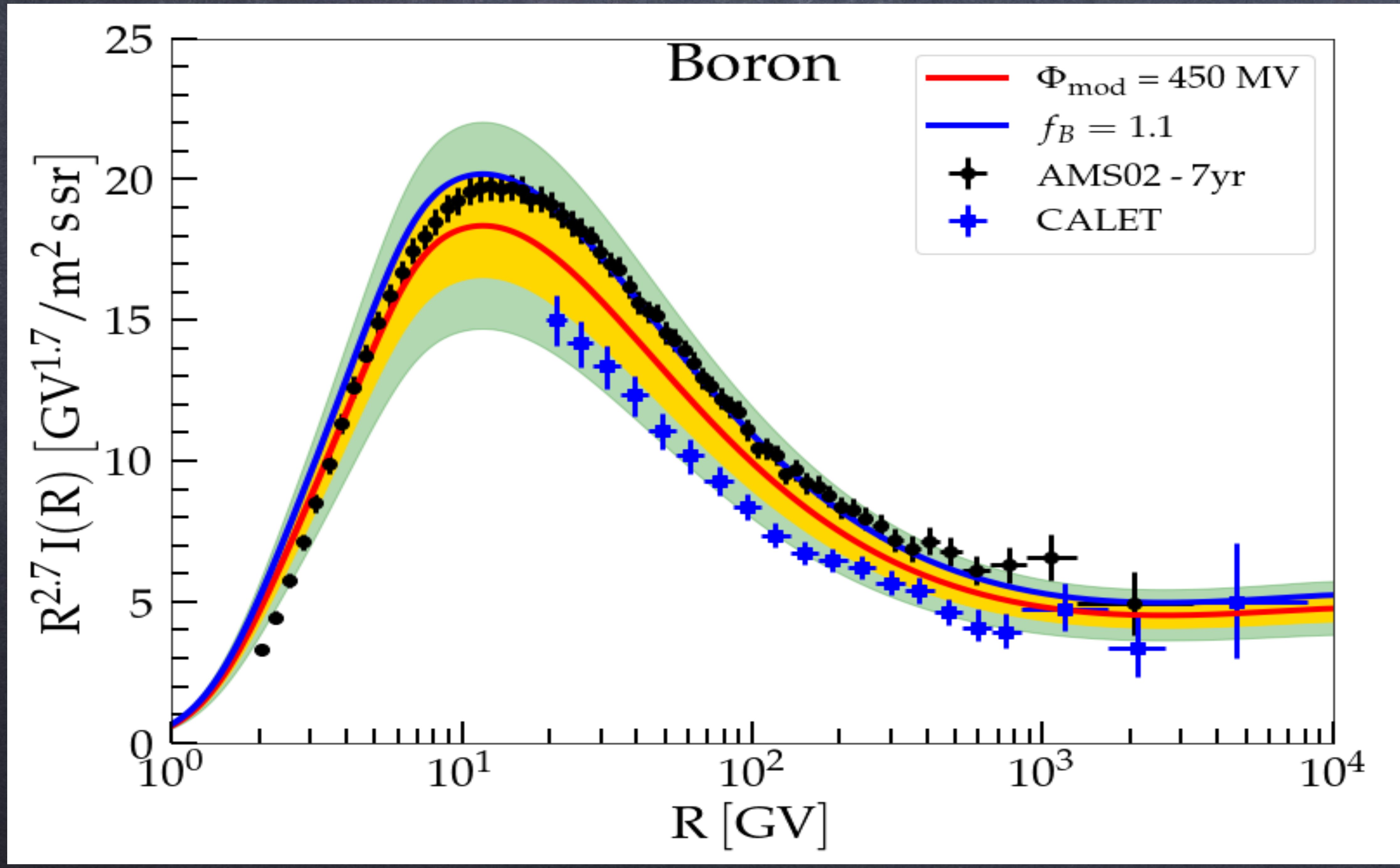
$$X_{\min} \approx 0.4\, n_d \left(\frac{h}{150\,\mathrm{pc}}\right)^2 \left(\frac{\mathrm{pc}}{D_m}\right) \mathrm{g/cm^2}.$$

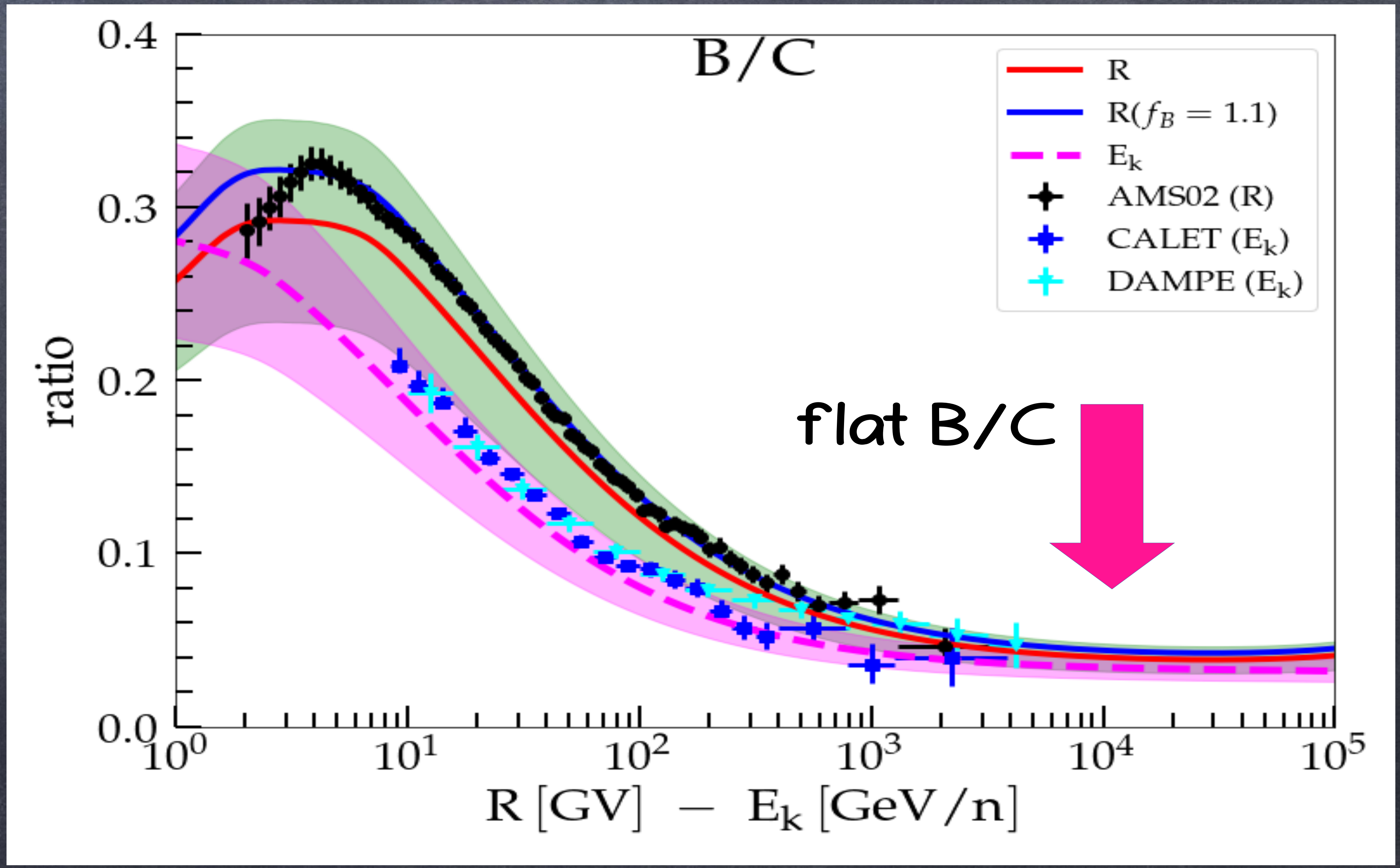
smooth transition



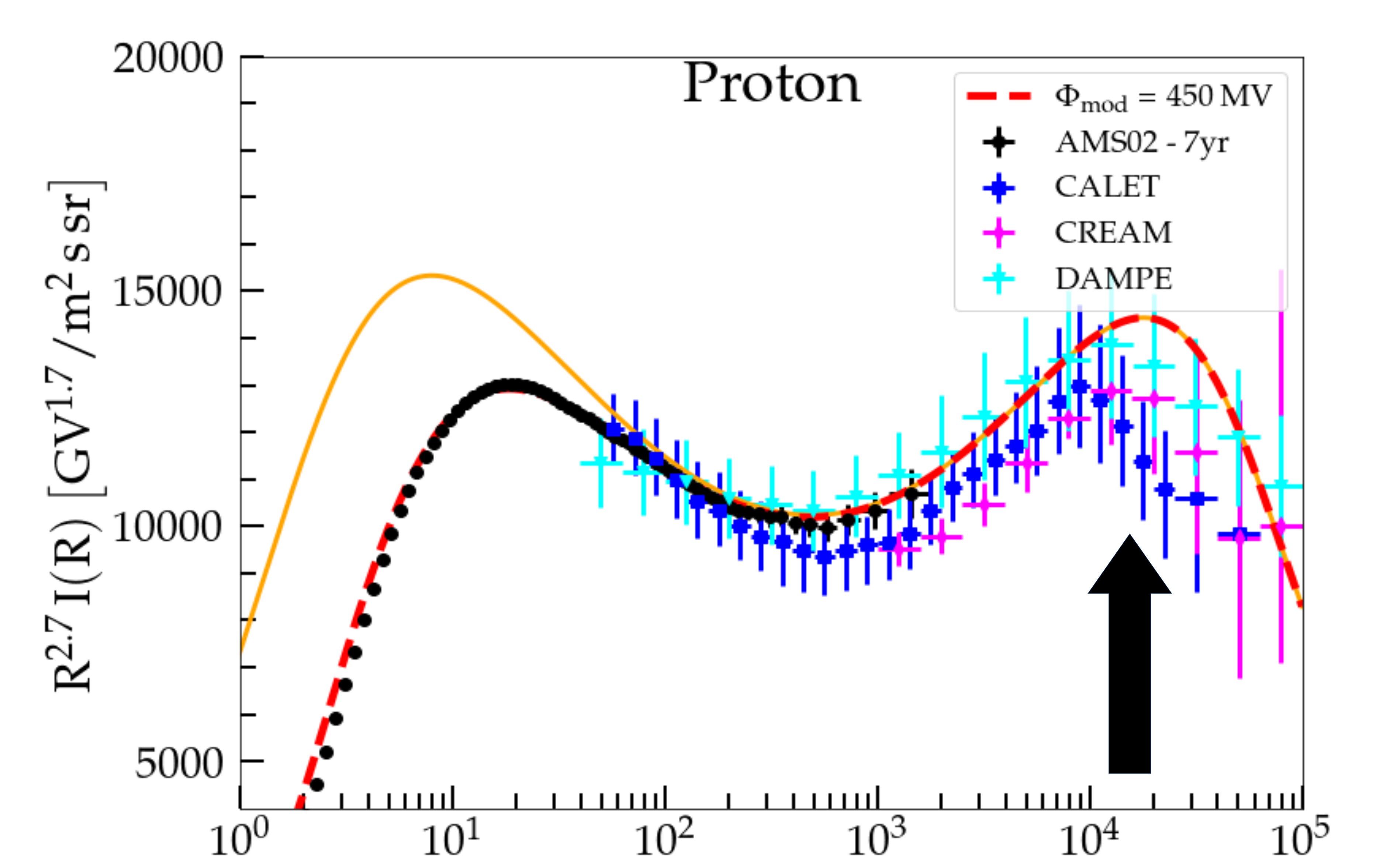

Proton
Φ_{mod} = 450 MV
AMS02 - 7yr
CALET
CREAM
DAMPE
"Pamela" break
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]

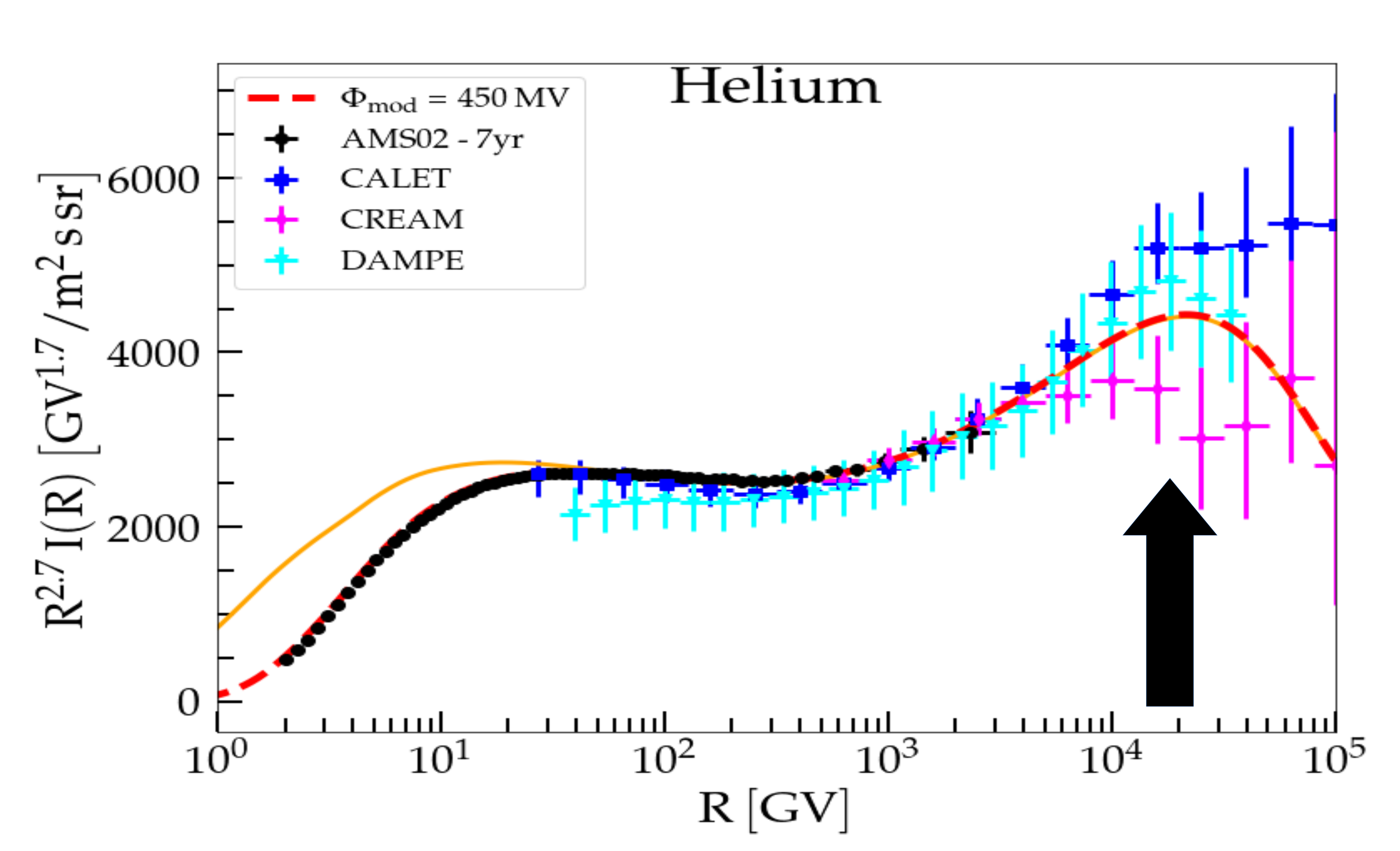

Carbon
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
AMS02 - 10yr
CALET
CREAM
NUCLEON-KLEM
hardening spectrum
above R*
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]

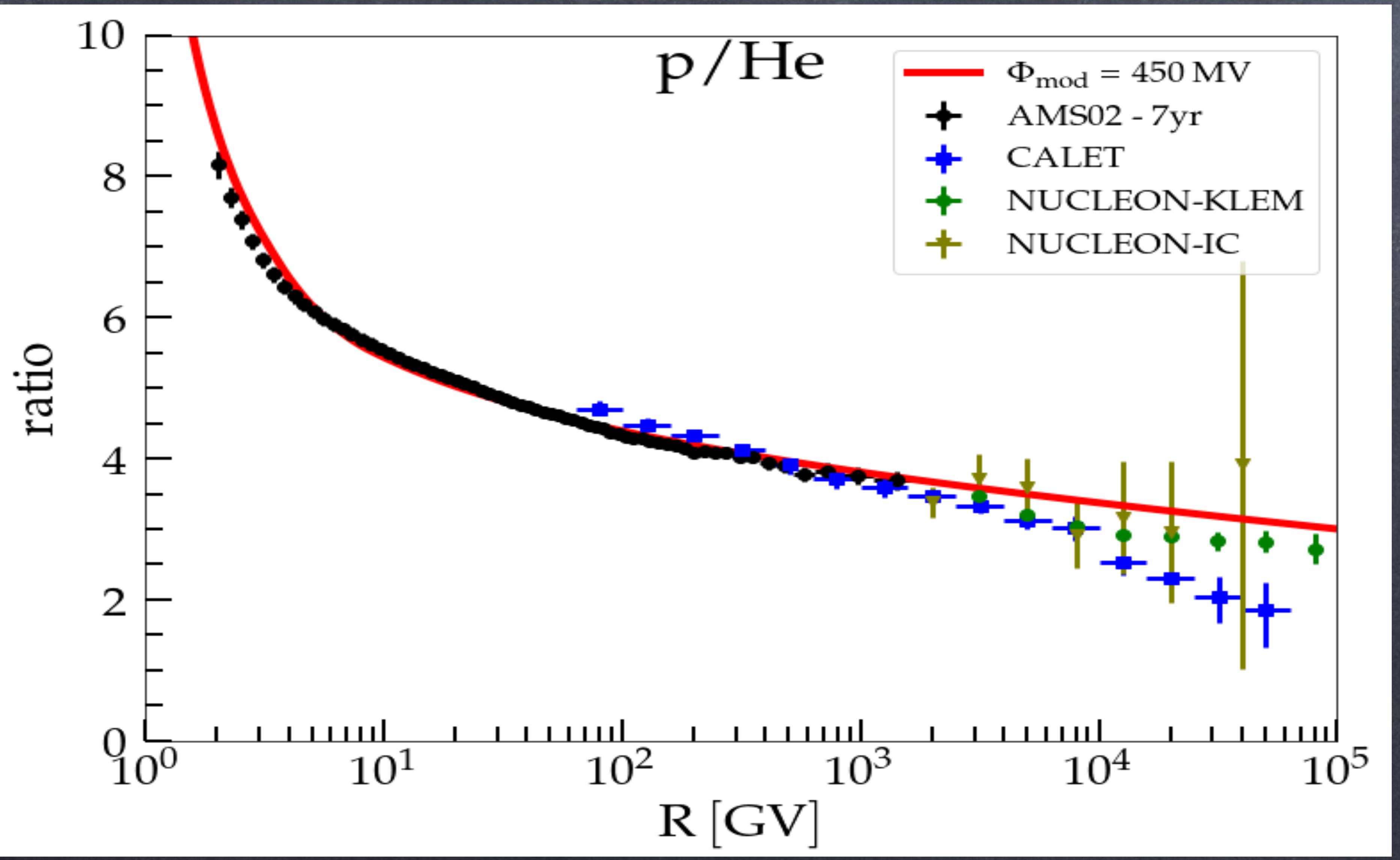

Boron
Φ_{mod} = 450 MV
$f_B = 1.1$
AMS02 - 7yr
CALET
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]


B/C
R
R($f_B = 1.1$)
E_k
AMS02 (R)
CALET (E_k)
DAMPE (E_k)
flat B/C
ratio
R [GV] — E_k [GeV/n]

"Dampe" break and the "knee"

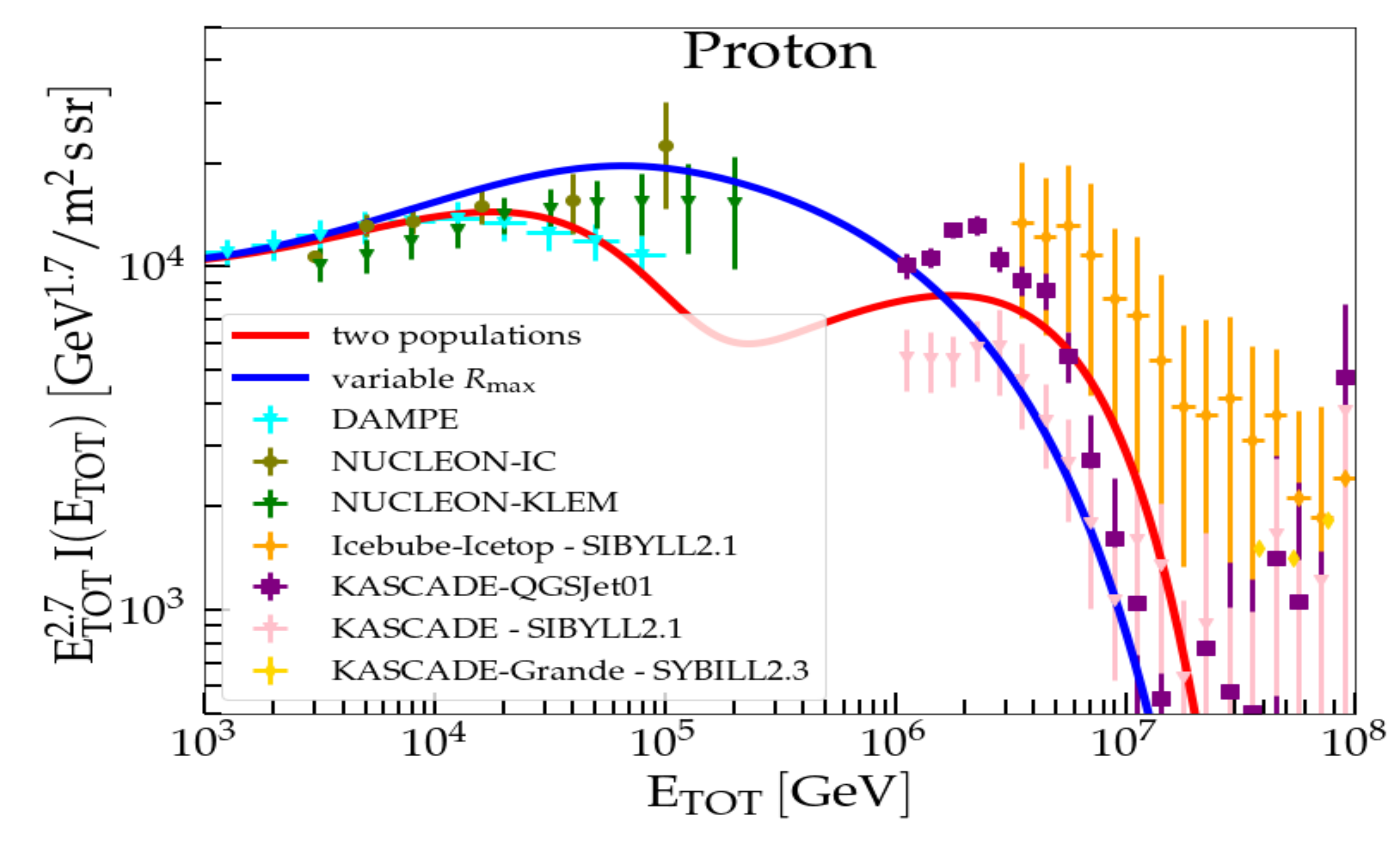


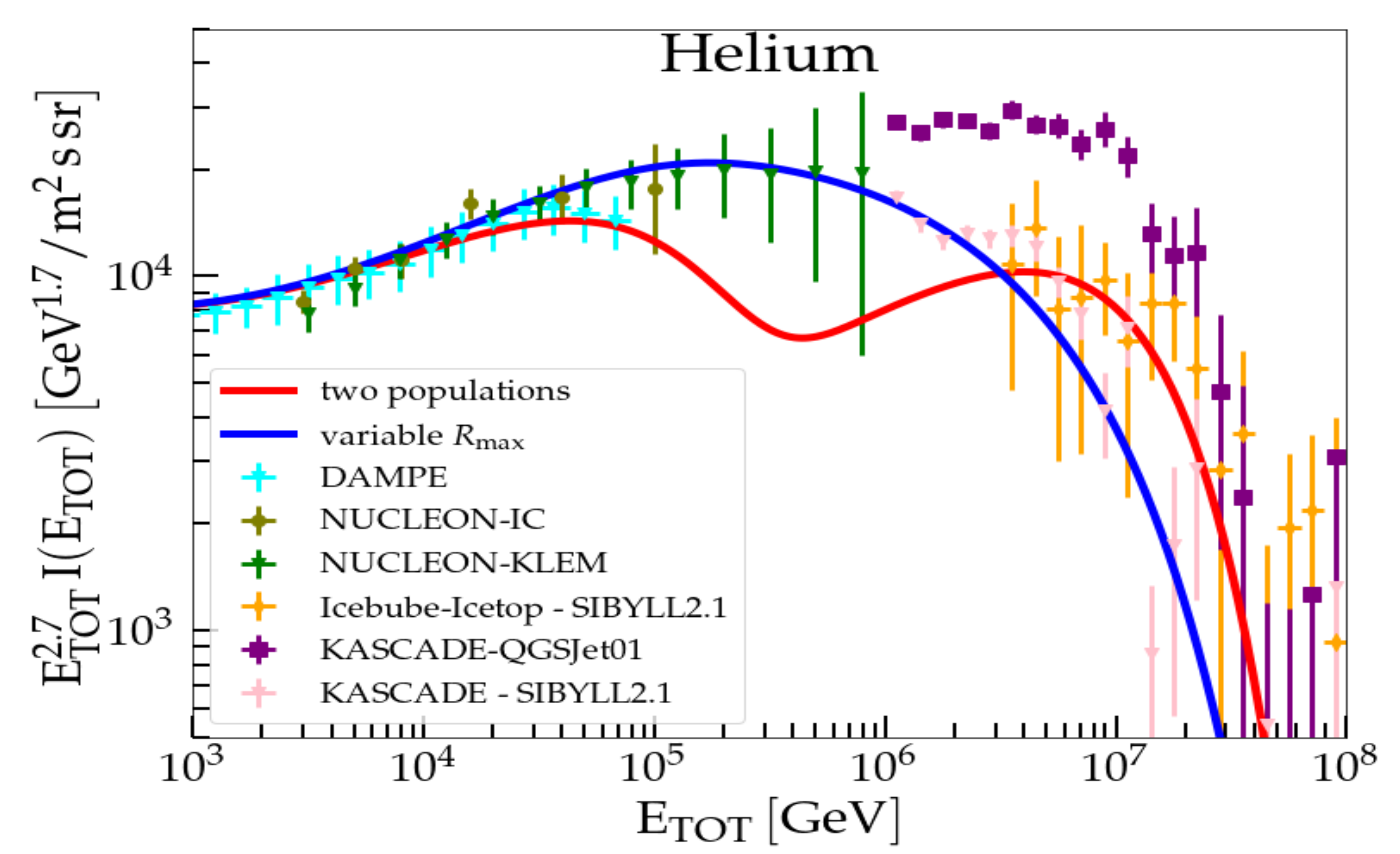




gaseous disk				
n_d	f_{He}	h_d	R_d	
1 cm^{-3}	0.1	150 pc	15 kpc	
Galactic disk (GD)				
h	L_c	b^2	D_m	L_{RR}
150 pc	10 pc	0.4	1 pc	50 – 100 pc
Galactic halo (GH)				
H	D_0	δ	u	
4 kpc	10^{28} cm^2/s	0.7	40 km/s	
bulk of SNRs				
γ_p	γ_{He}	γ_n	R_{max}^{bulk}	
4.35	4.30	4.33	50 TV	
PeV sources				
γ_p	γ_{He}	γ_n	R_{max}^{PeV}	ϵ_{bulk}^{PeV}
4.35	4.30	4.33	5 PV	0.15

"Dampe" break and the "knee"





- special SNRs, star clusters
- ...
- ~ 10-20% of typical CR source luminosity
- more in agreement with theory

gaseous disk				
n_d	f_{He}	h_d	R_d	
1 cm^{-3}	0.1	150 pc	15 kpc	
Galactic disk (GD)				
h	L_c	b^2	D_m	L_{RR}
150 pc	10 pc	0.4	1 pc	50 − 100 pc
Galactic halo (GH)				
H	D_0	δ	u	
4 kpc	10^{28} cm^2/s	0.7	40 km/s	
bulk of SNRs				
γ_p	γ_{He}	γ_n	R^{bulk}_{max}	
4.35	4.30	4.33	50 TV	
PeV sources				
γ_p	γ_{He}	γ_n	R^{PeV}_{max}	ϵ^{PeV}_{bulk}
4.35	4.30	4.33	5 PV	0.15

summary & caveats/perspectives

- in Galactic disk weak scattering + field lines along GP
  - can lead to energy-independent diffusion perp. to GP
  - effect appears at $R \gtrsim TV$
- Emax of bulk SNRs ~ to 50 TV only a fraction of sources reach
- possible to explain features in CR spectra in GV-PV range
  - without breaks in injection or propagation
  - physically motivated scenario
    (but need cross-check with dedicated theory/simulations)

summary & caveats/perspectives

Caveats...

- nuclei data at multi-TV have large uncertainties
- uncertainties in spallation cross-section and chains
- need for better understanding of turbulence/propagation
- acceleration and PeVatrons?
- include source grammage? Check leptons...

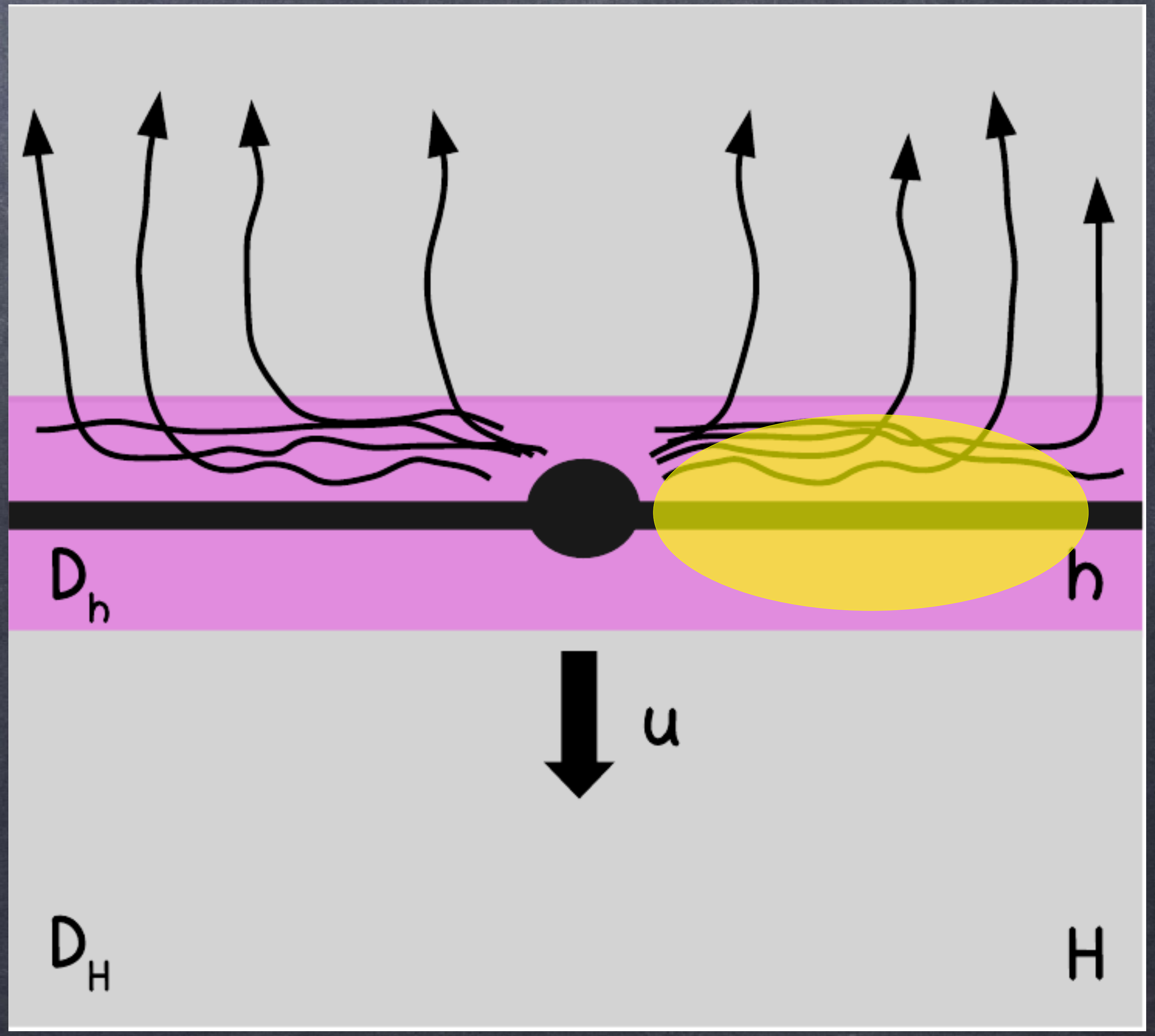
Anisotropy...

$$d_{\parallel} \sim D_{\parallel}/D_{\perp}\, h \approx 1 - 2\,\mathrm{kpc}$$

average number of contributing sources at VHE

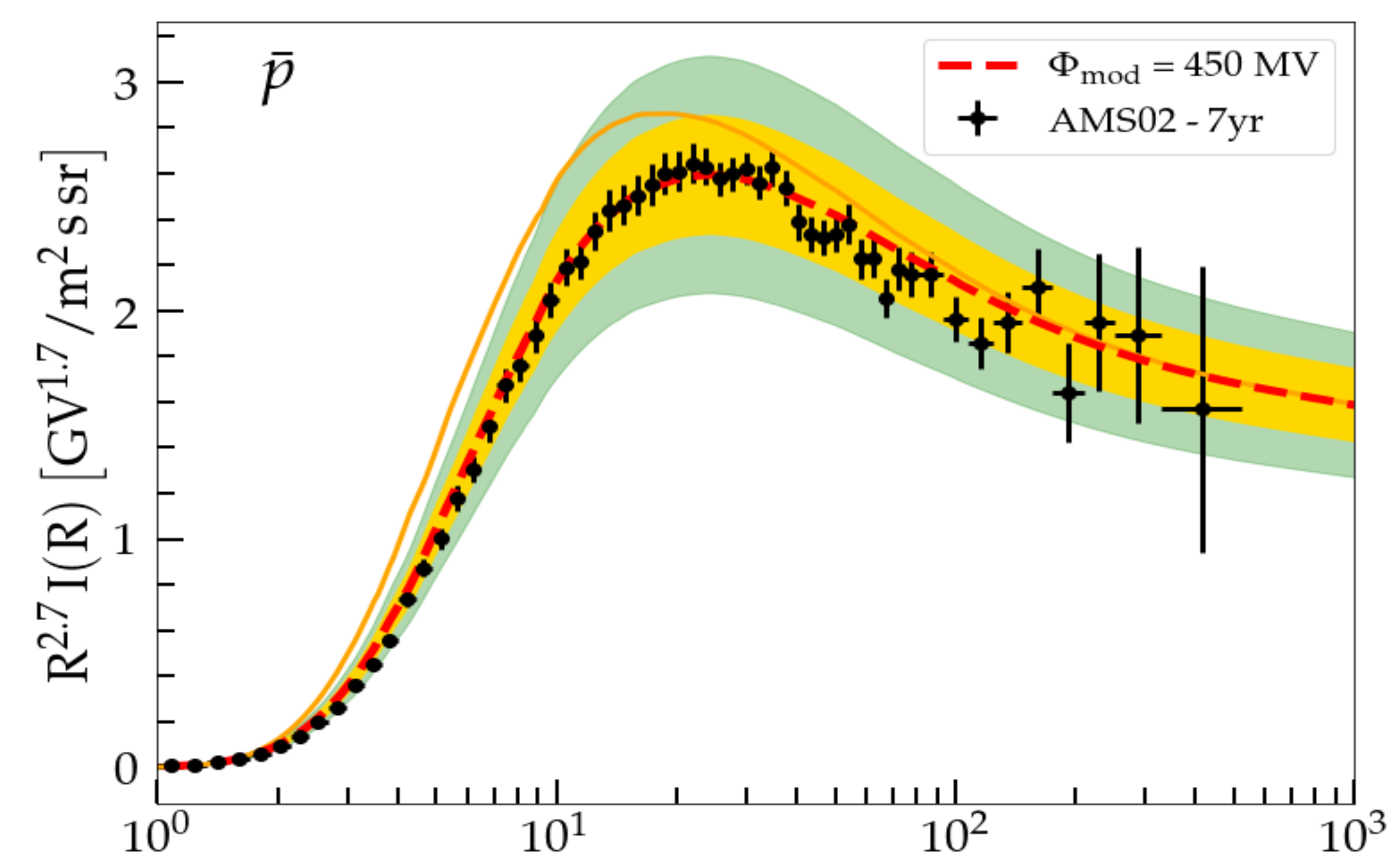
$$\langle N_{\rm PV}\rangle \approx 10 \left(\frac{\xi_{\rm PV}}{0.15}\right)\left(\frac{\nu_{\rm SNe}}{1/30\,{\rm yr}}\right)\left(\frac{h}{150\,{\rm pc}}\right)^2\left(\frac{\rm pc}{D_m}\right)\left(\frac{d}{\rm kpc}\right)^2,$$

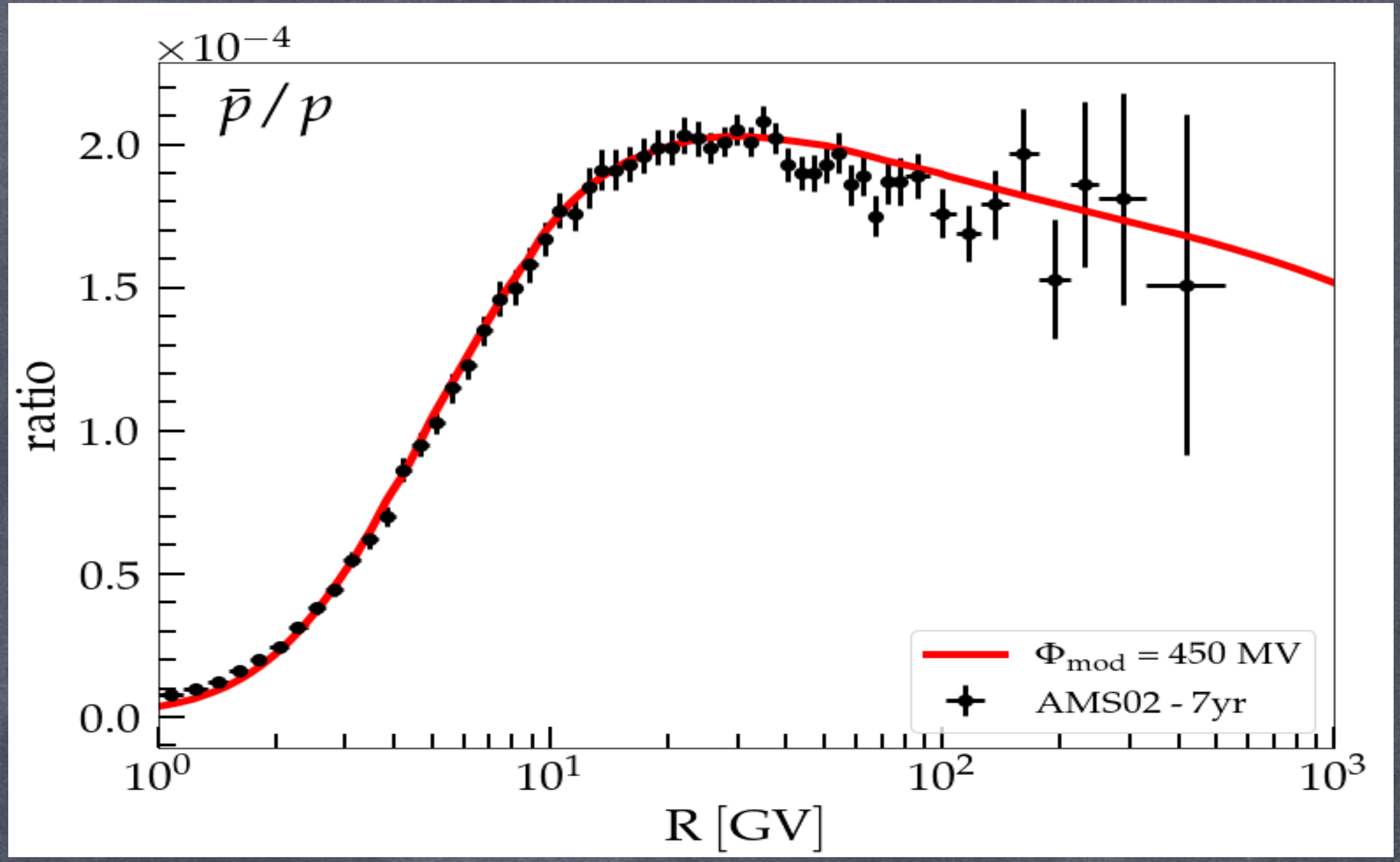
crucial test

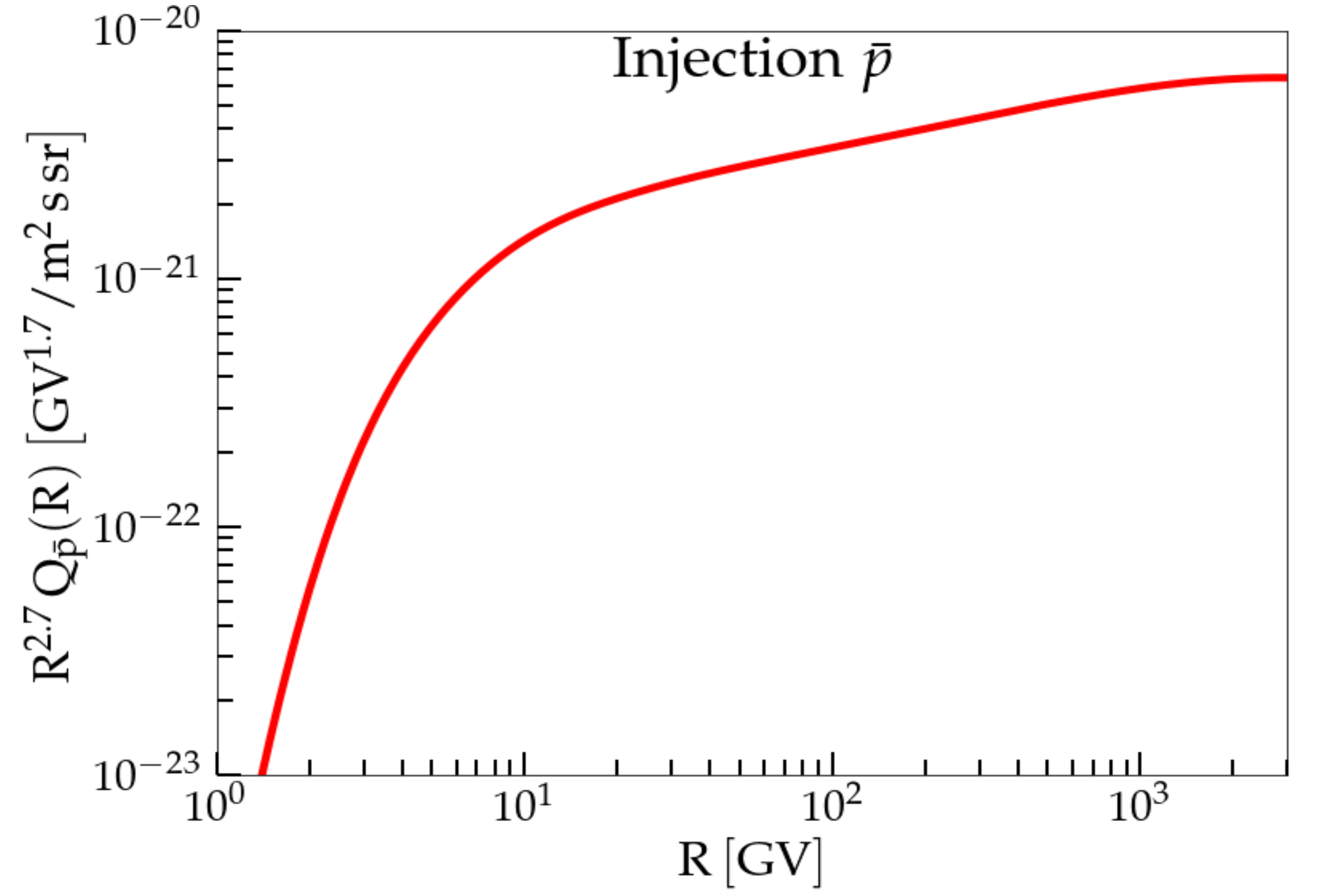


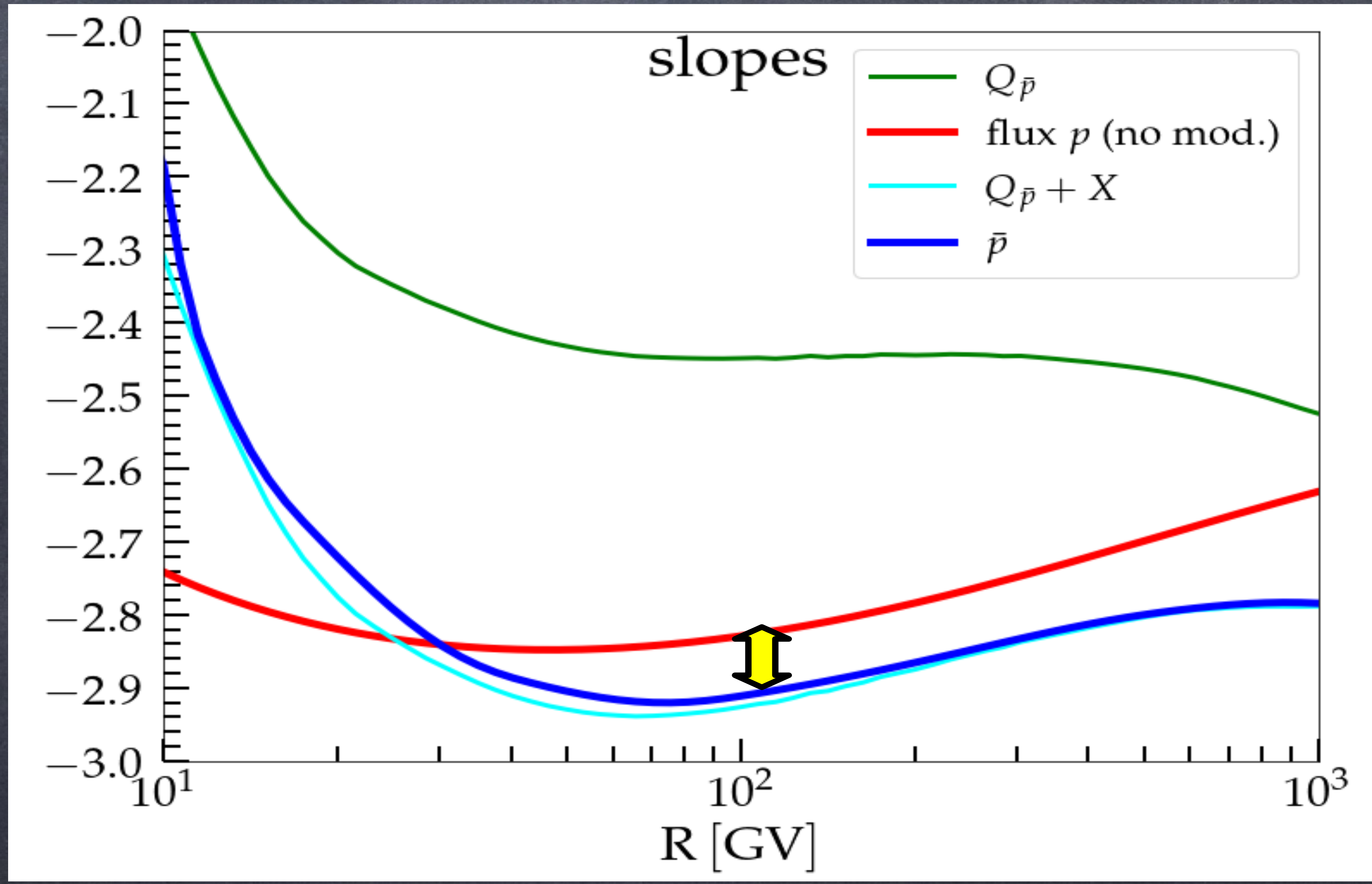
Thank You

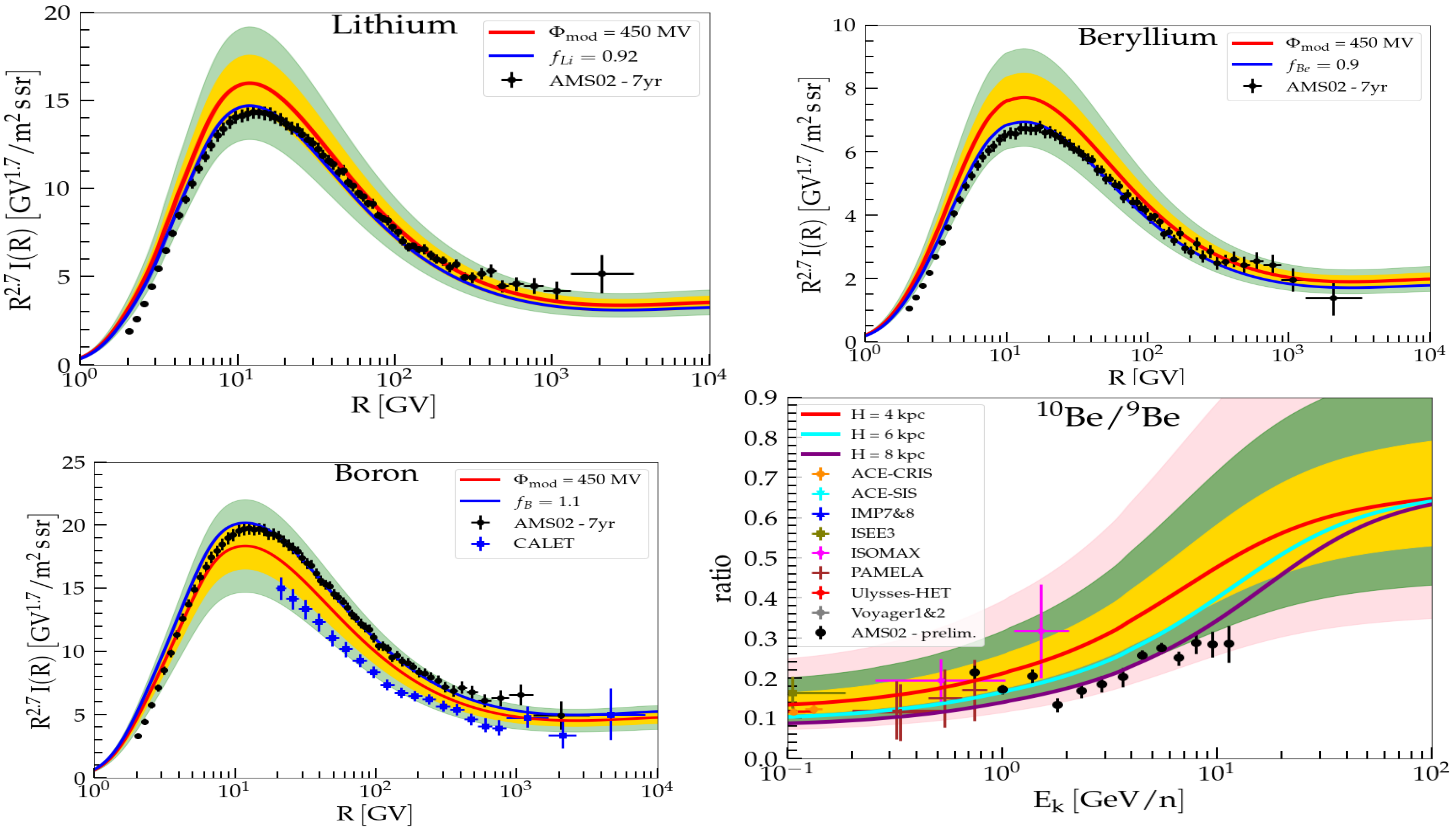
Antiprotons



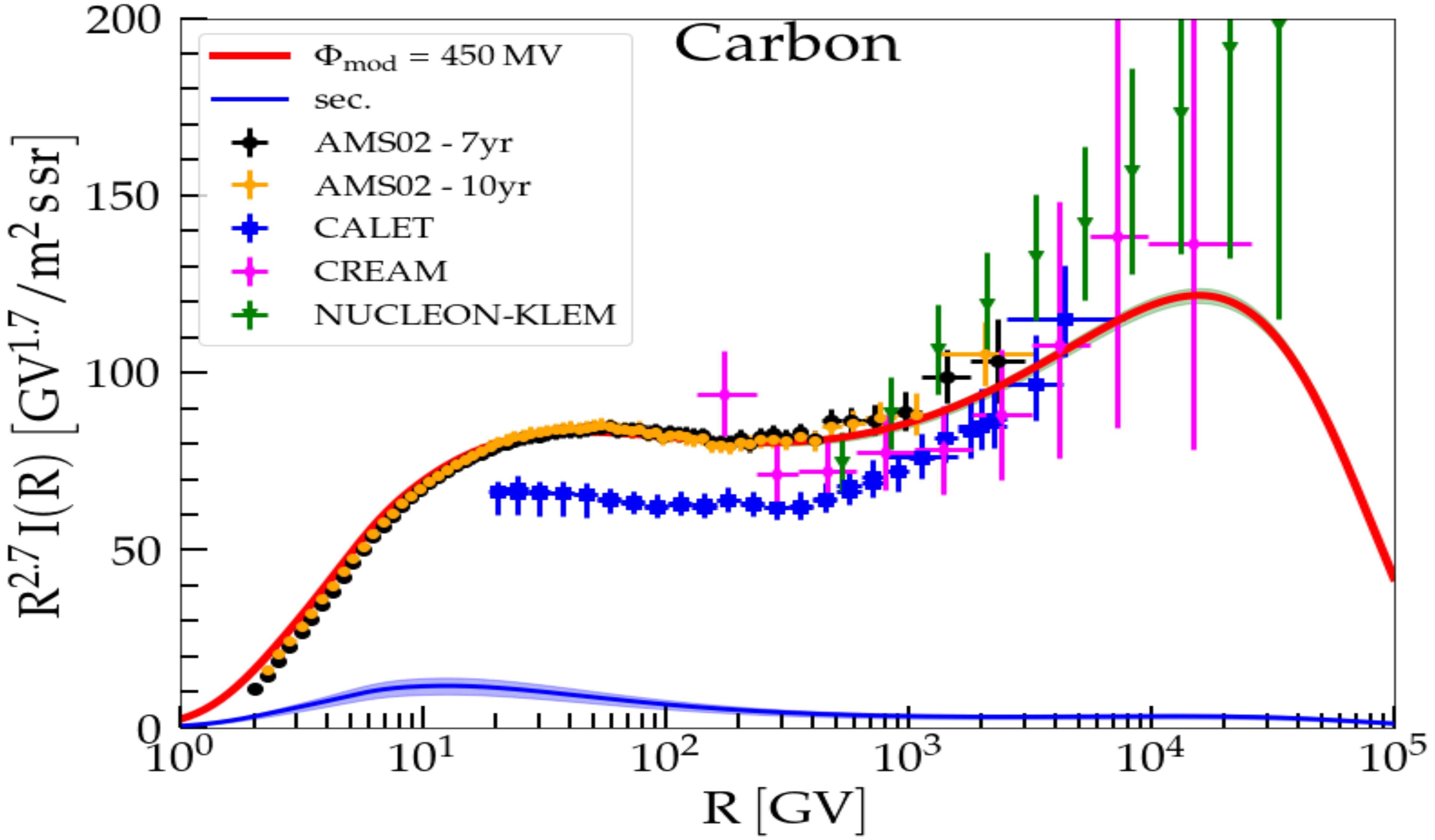




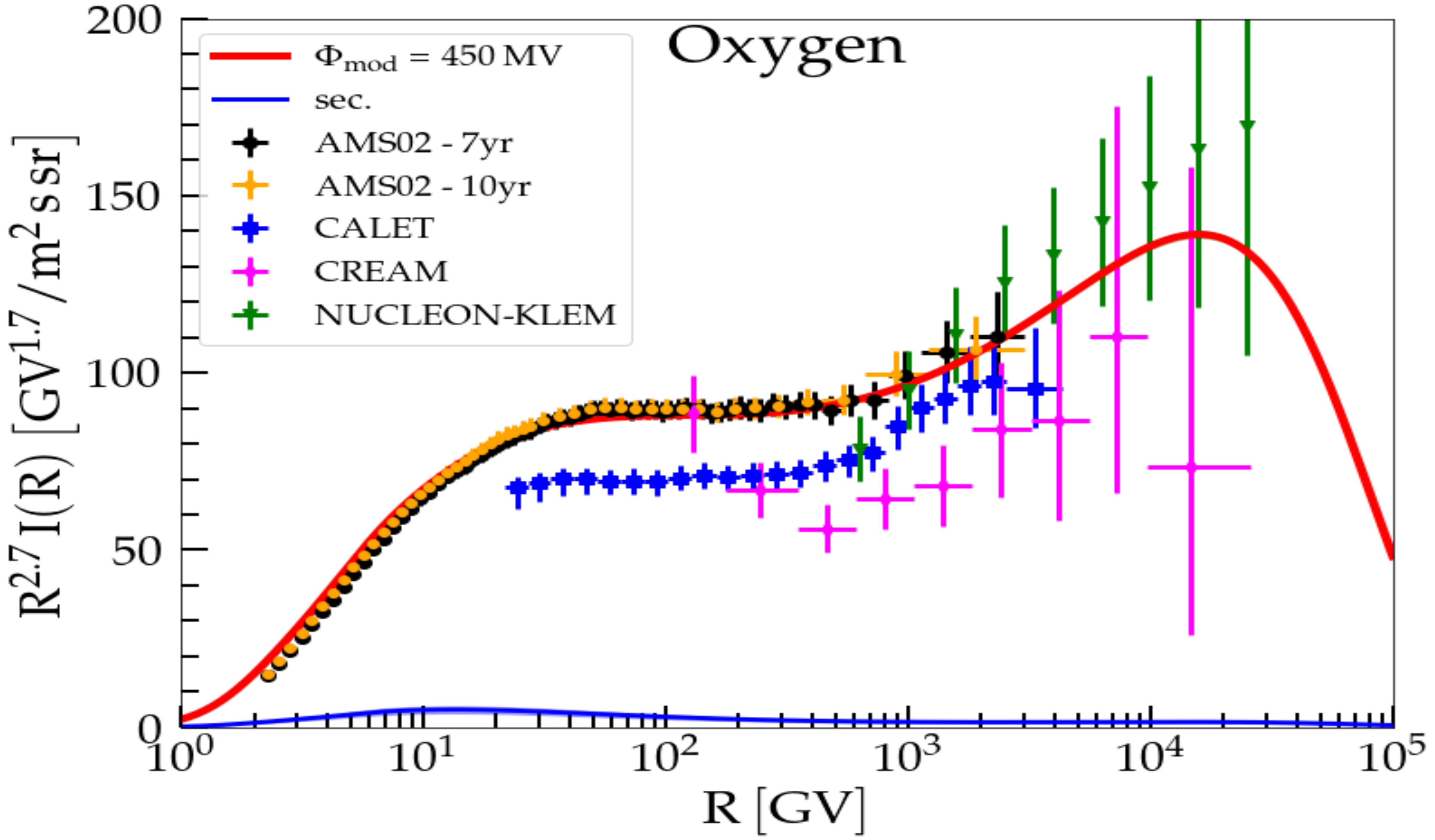




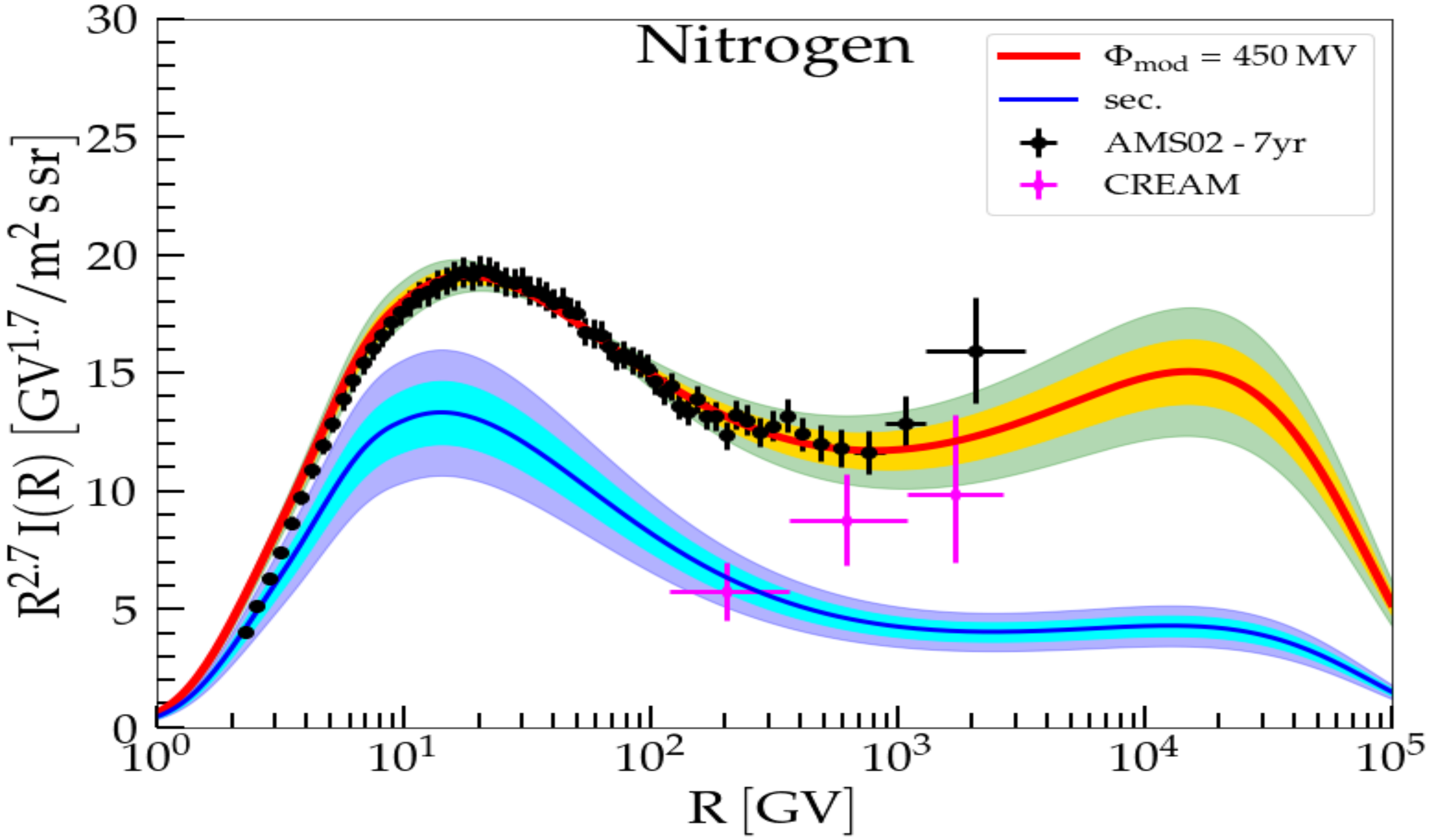
Lithium
Φmod = 450 MV
fLi = 0.92
AMS02 - 7yr
R^2.7 I(R) [GV^1.7/m^2 s sr]
R [GV]
Beryllium
Φmod = 450 MV
fBe = 0.9
AMS02 - 7yr
R^2.7 I(R) [GV^1.7/m^2 s sr]
R [GV]
Boron
Φmod = 450 MV
fB = 1.1
AMS02 - 7yr
CALET
R^2.7 I(R) [GV^1.7/m^2 s sr]
R [GV]
10Be/9Be
H = 4 kpc
H = 6 kpc
H = 8 kpc
ACE-CRIS
ACE-SIS
IMP7&8
ISEE3
ISOMAX
PAMELA
Ulysses-HET
Voyager1&2
AMS02 - prelim.
ratio
Ek [GeV/n]



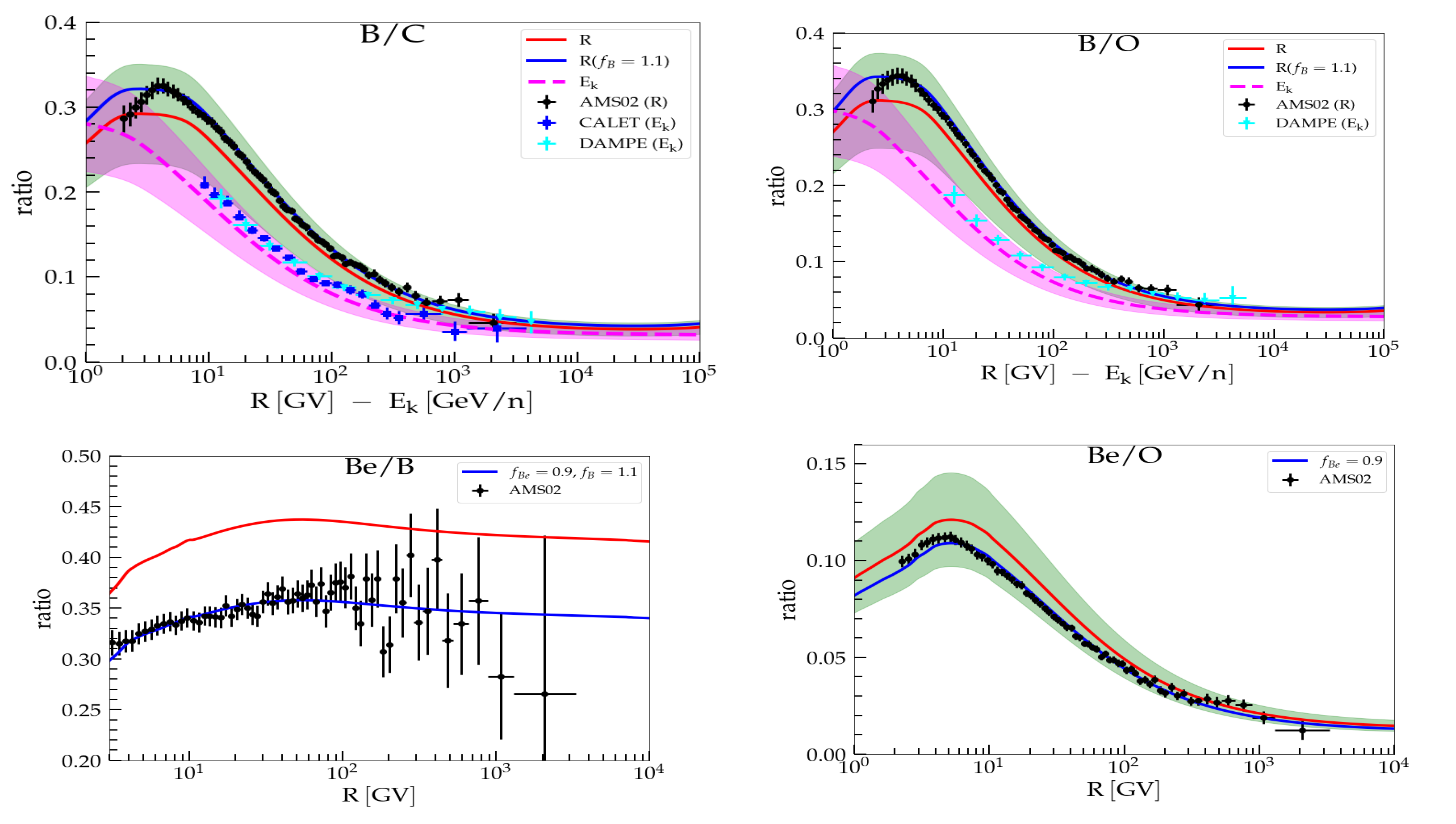
Carbon
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
AMS02 - 10yr
CALET
CREAM
NUCLEON-KLEM
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]



Oxygen
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
AMS02 - 10yr
CALET
CREAM
NUCLEON-KLEM
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]



Nitrogen
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
CREAM
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]



B/C
R
R($f_B = 1.1$)
E_k
AMS02 (R)
CALET (E_k)
DAMPE (E_k)
ratio
R [GV] — E_k [GeV/n]
B/O
R
R($f_B = 1.1$)
E_k
AMS02 (R)
DAMPE (E_k)
ratio
R [GV] — E_k [GeV/n]
Be/B
$f_{Be} = 0.9, f_B = 1.1$
AMS02
ratio
R [GV]
Be/O
$f_{Be} = 0.9$
AMS02
ratio
R [GV]