17th Marcel Grossmann Meeting

7-12 July 2024

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

Sarah Recchia

INAF Brera(Merate)

Overview

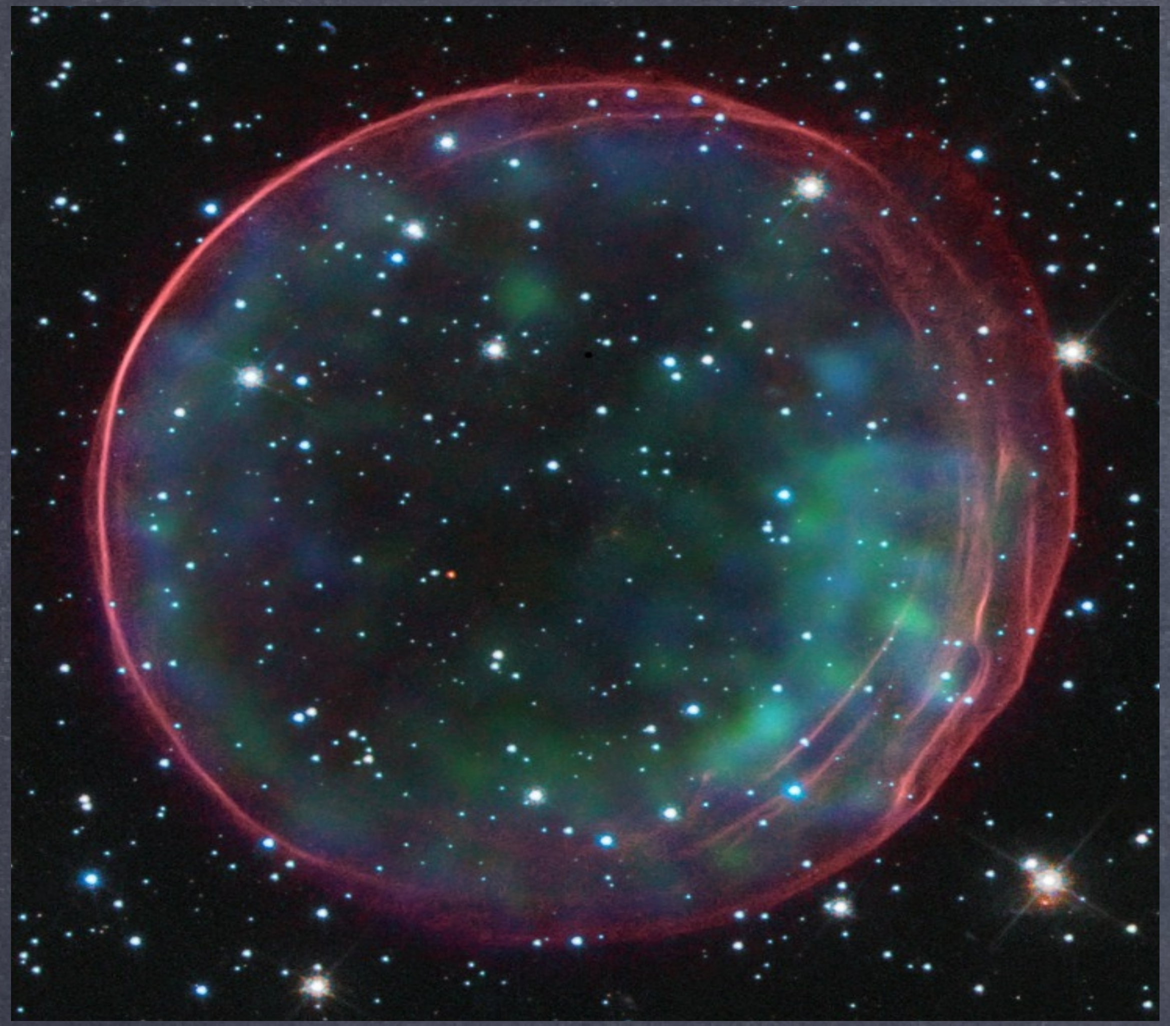
Recchia & Gabici (2023)

- 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

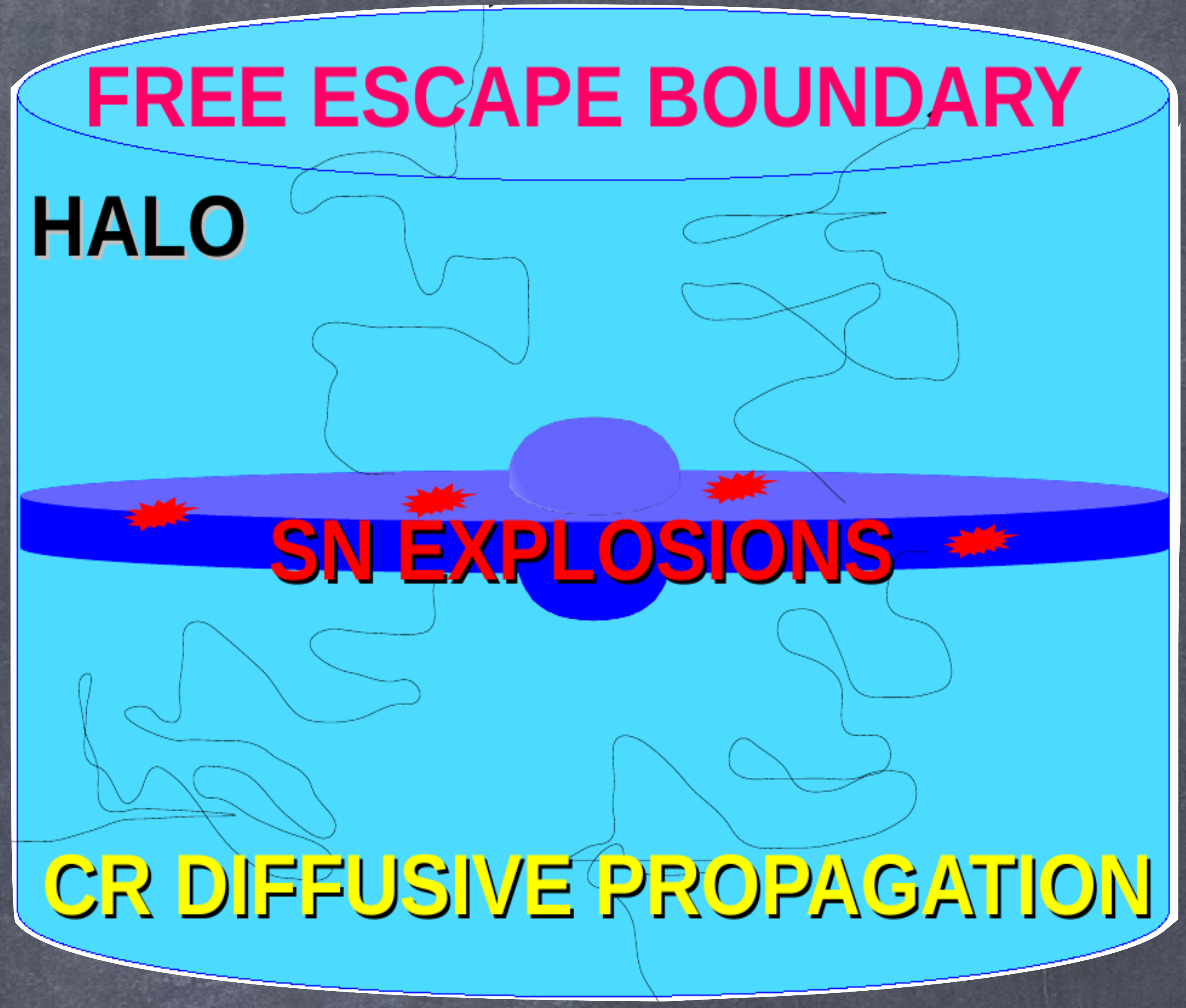
CRs in a nutshell - SNR paradigm

~ 10% of SNR power



Equilibrium

$N_{CR} \propto Q_{CR}/D \propto E^{-2.7}$



diffusive shock acceleration

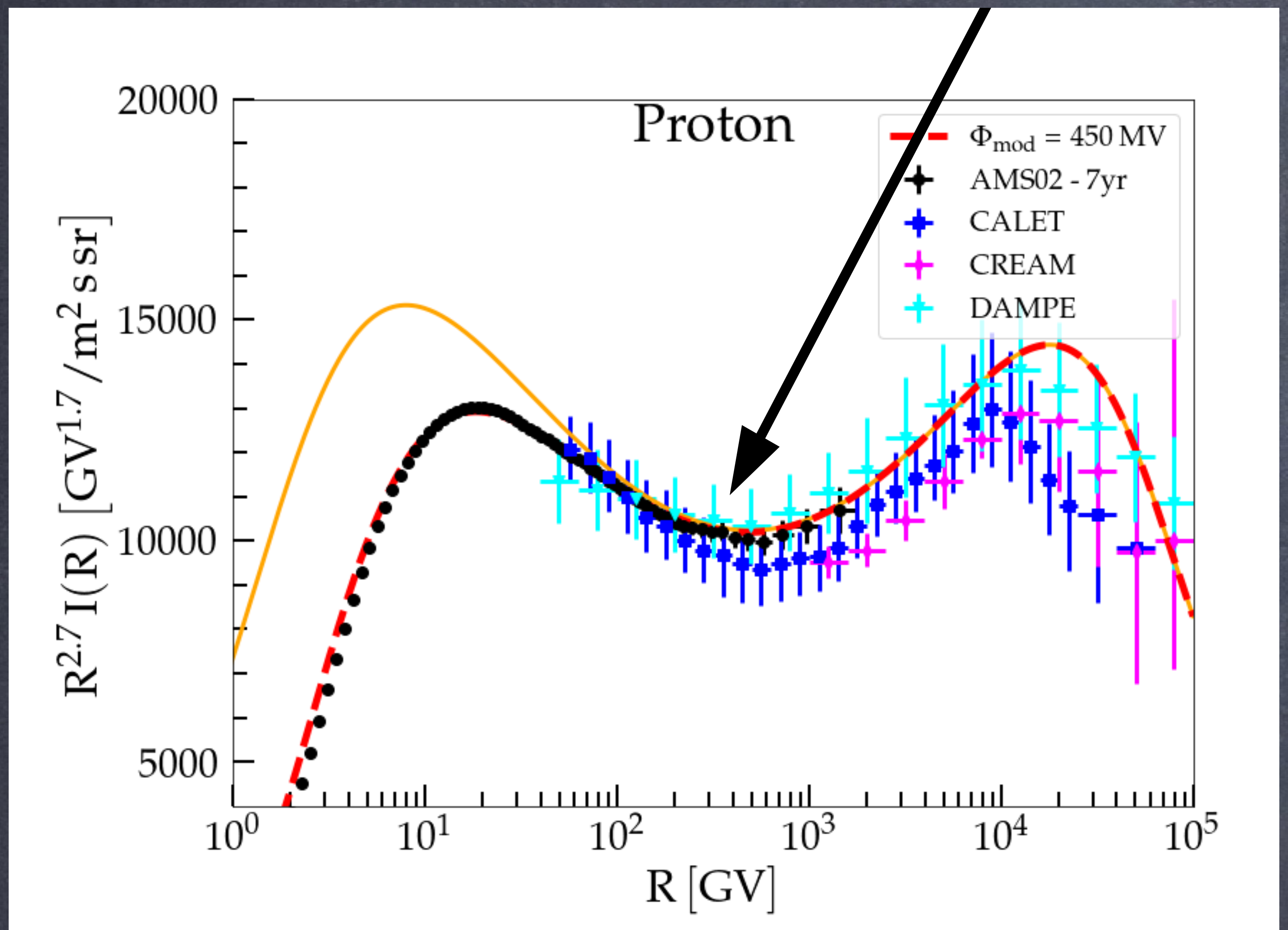
- power-law spectrum $Q_{CR} \propto E^{-2}$
- rigidity dependent $R \propto p/Z$
- protons to the knee? $\approx 3\,\mathrm{PeV}$

Galactic propagation

- B/C, unstable isotopes...
- grammage, energy-dependent escape
- $D(E) \propto E^{0.3-0.7}$, H ~ few kpc

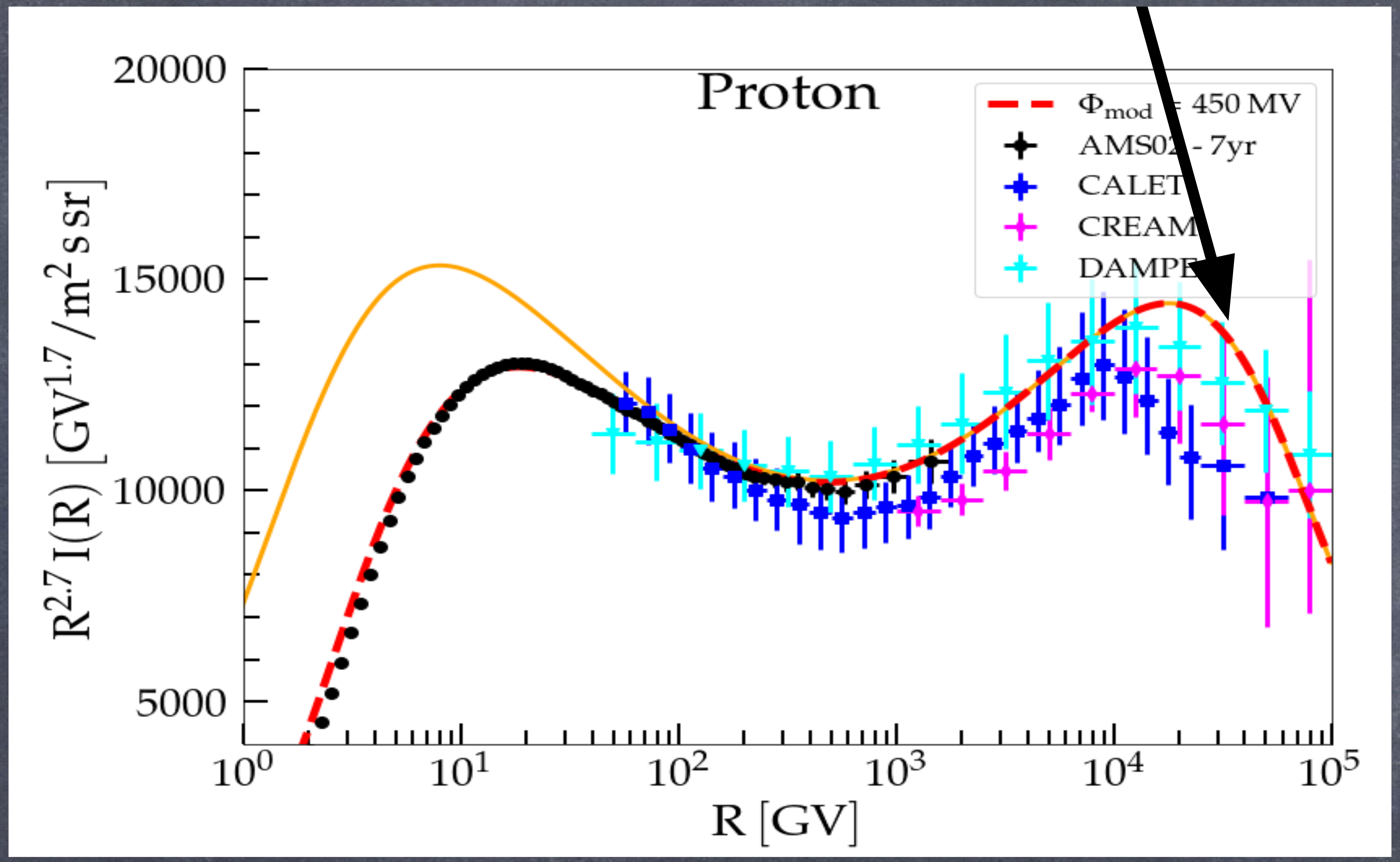
Breaks in GV-PV range

~ 300 GV



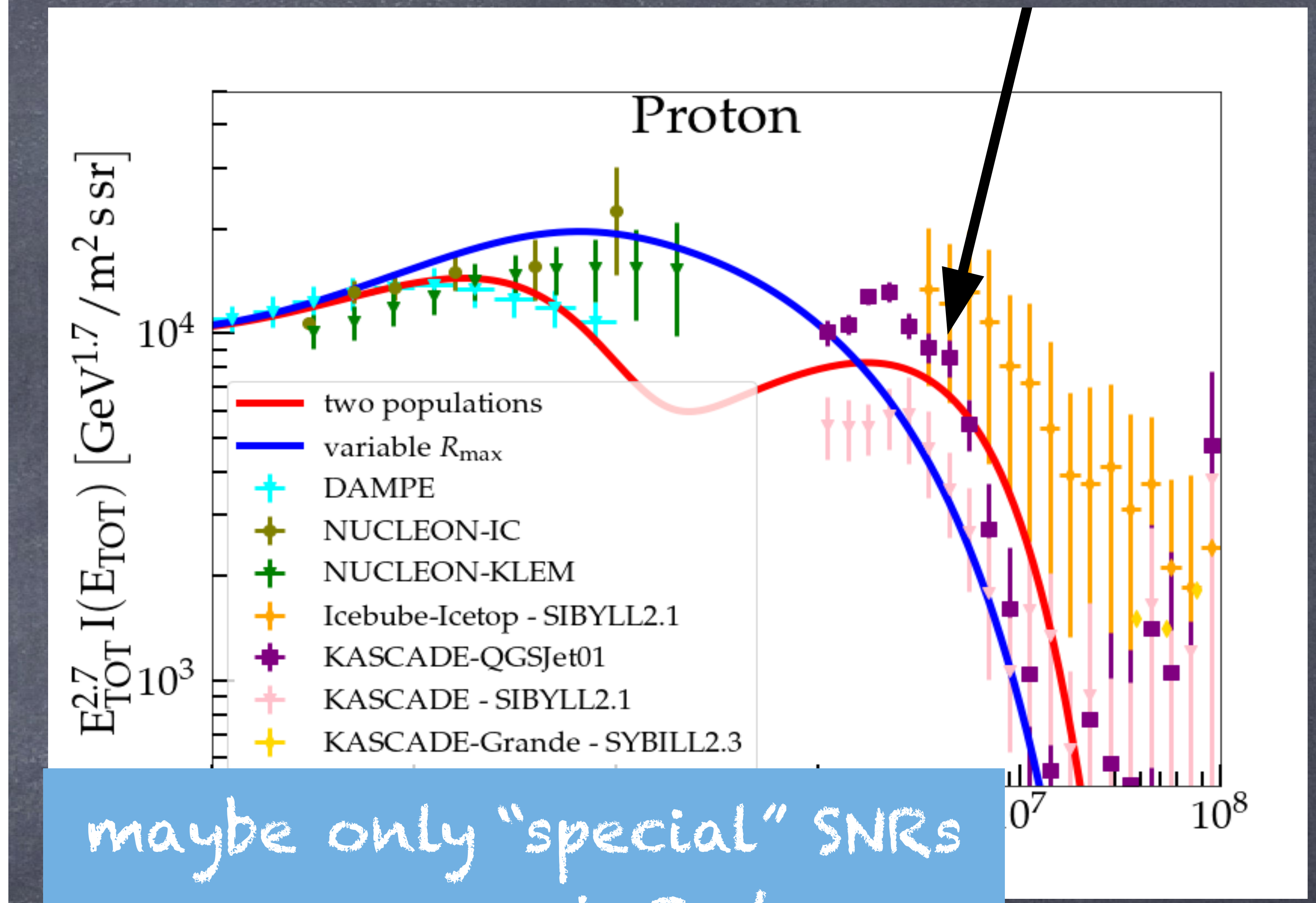
- hardening by ~ 0.1
- confirmed in secondary nuclei, by ~ 0.2
- change in propagation

"Dampe" ~ 15 TV



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

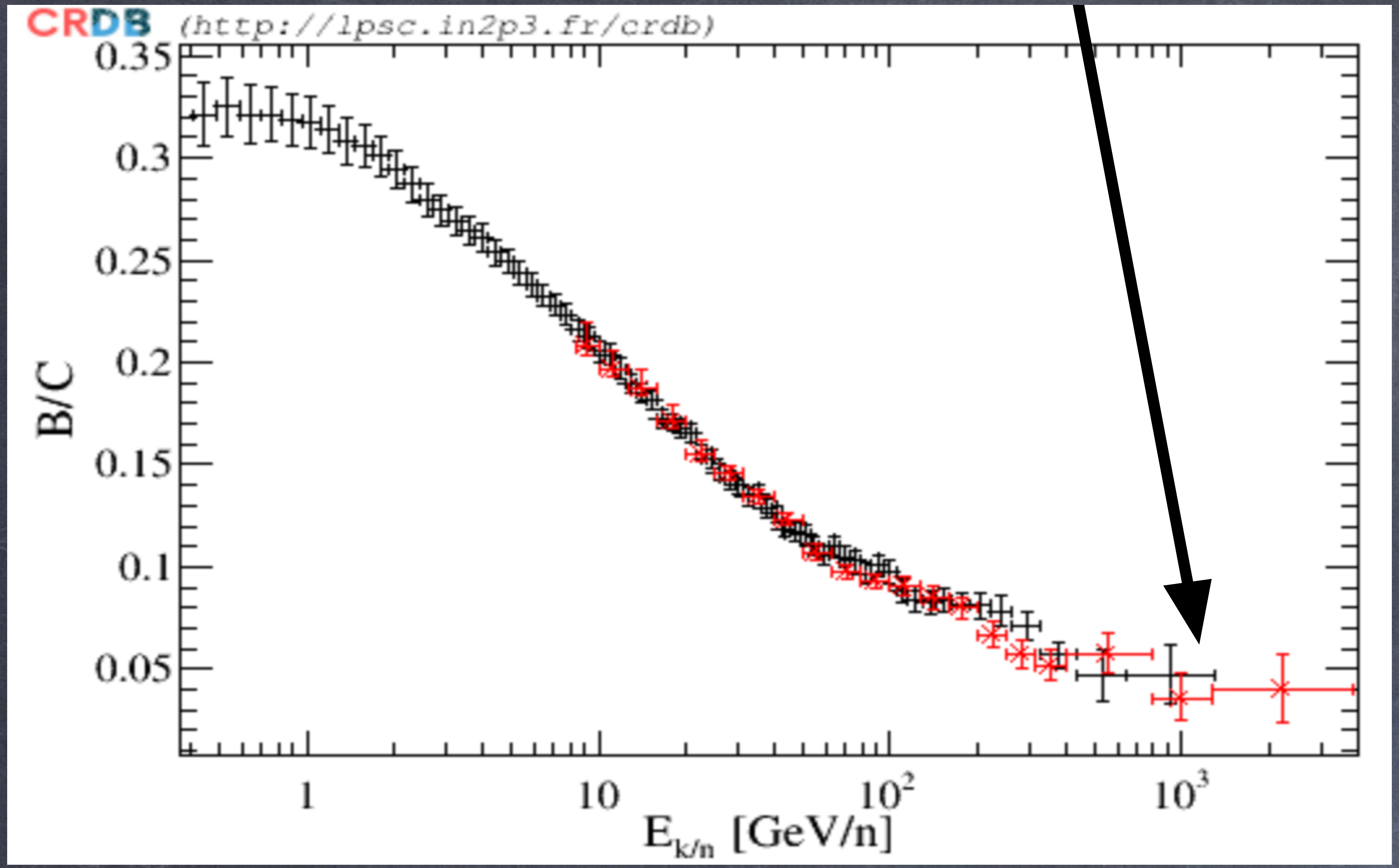
"Knee" ~ 3 PV

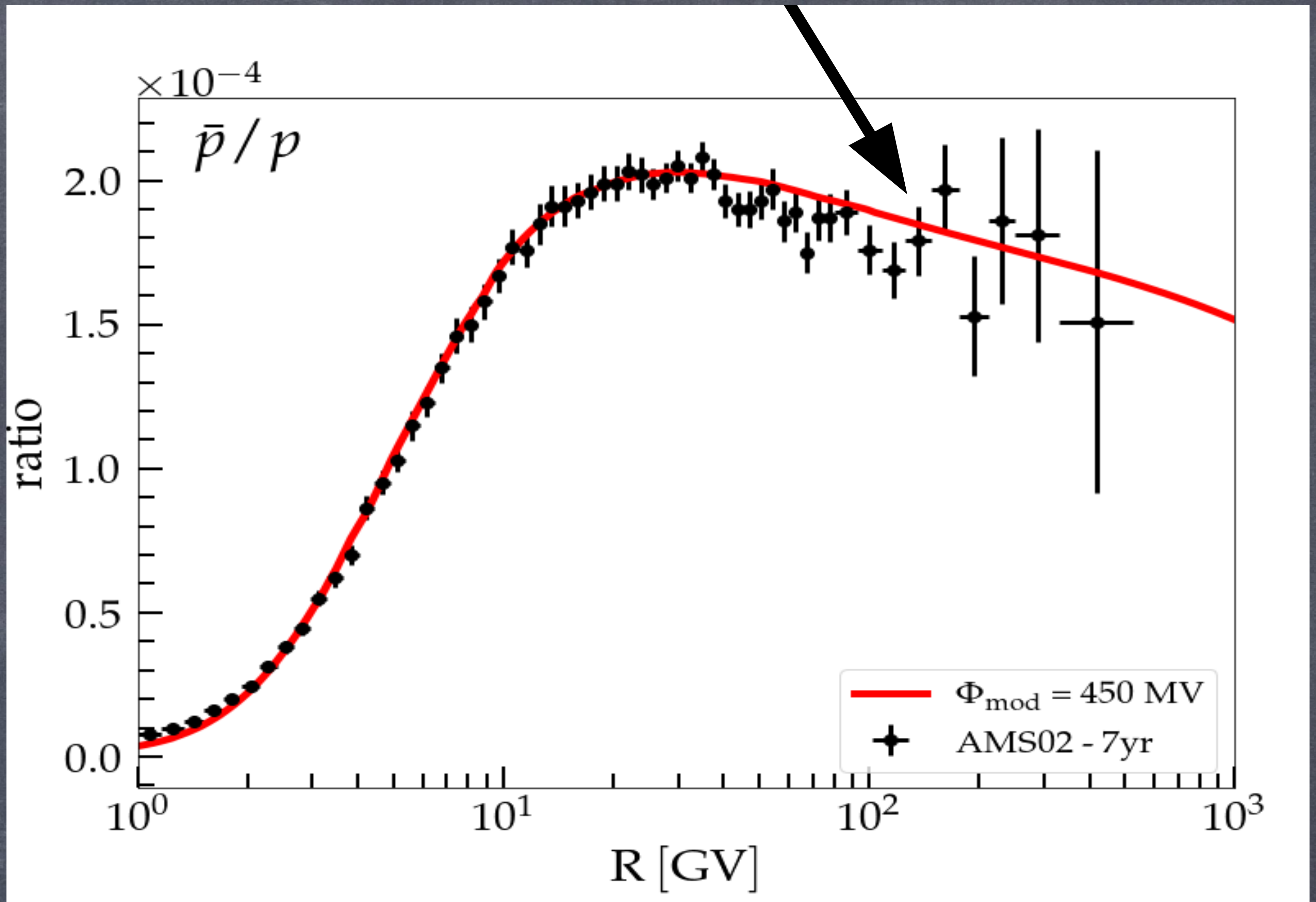


maybe only "special" SNRs can reach PeV

- 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)

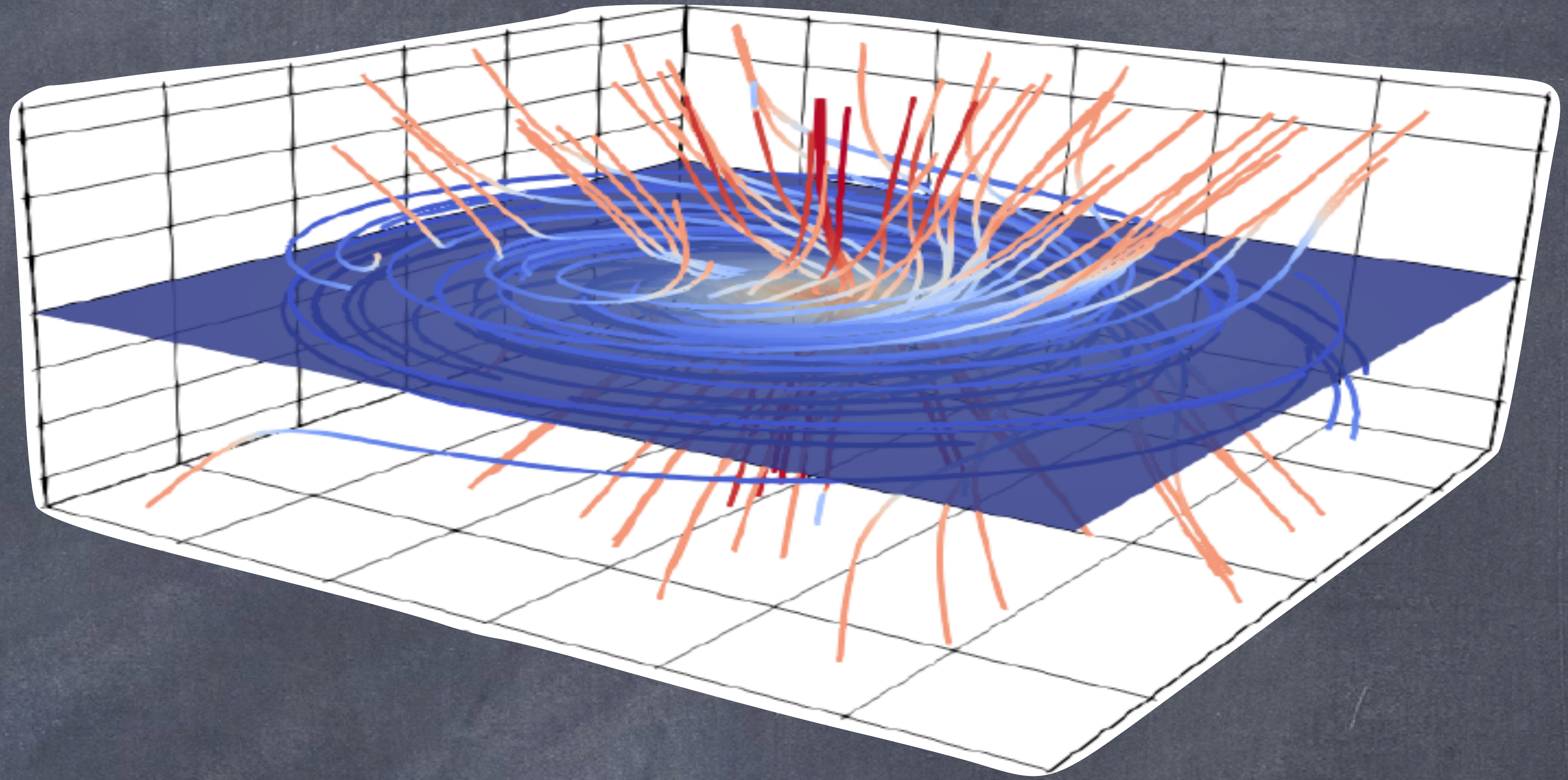
D'Angelo et al. (2016)

Recchia et al. (2022)

Alternative framework
CR data ~ GV- PV

Alternative framework - CR data ~ GV- PV

Recchia & Gabici (2023)



CR propagation in disk

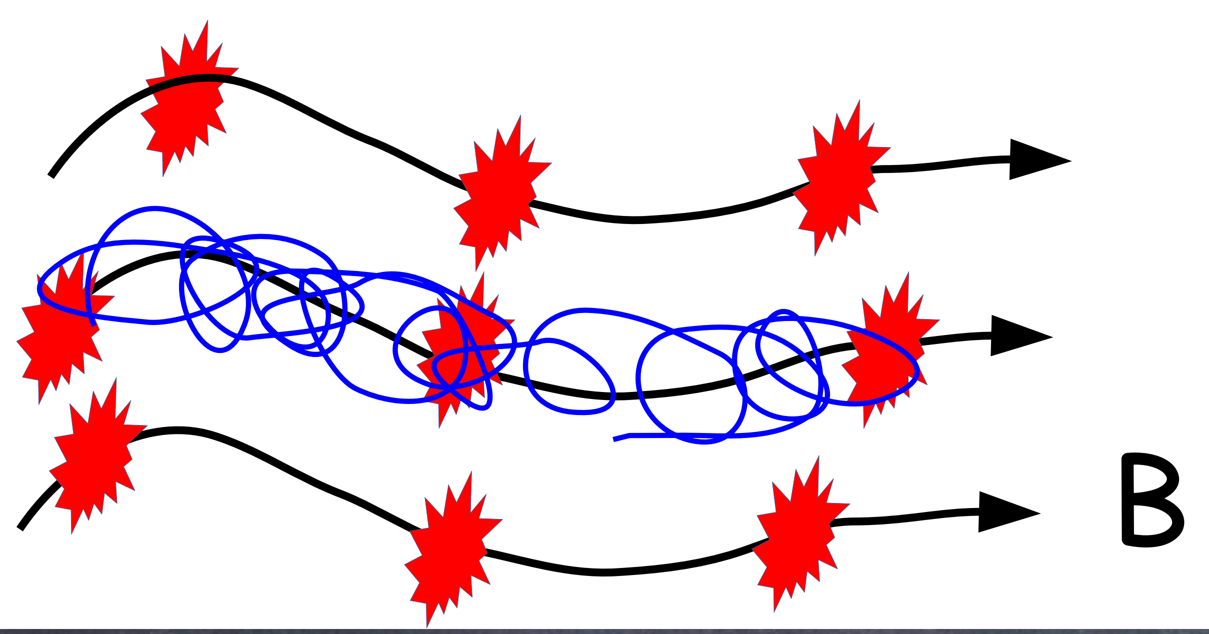
- weak scattering along B (along Galactic plane) damping/anisotropic cascade
- energy-independent perp. transport
- typical diffusion D(E) in Galactic halo
- role of disk emerges above ~ TV

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

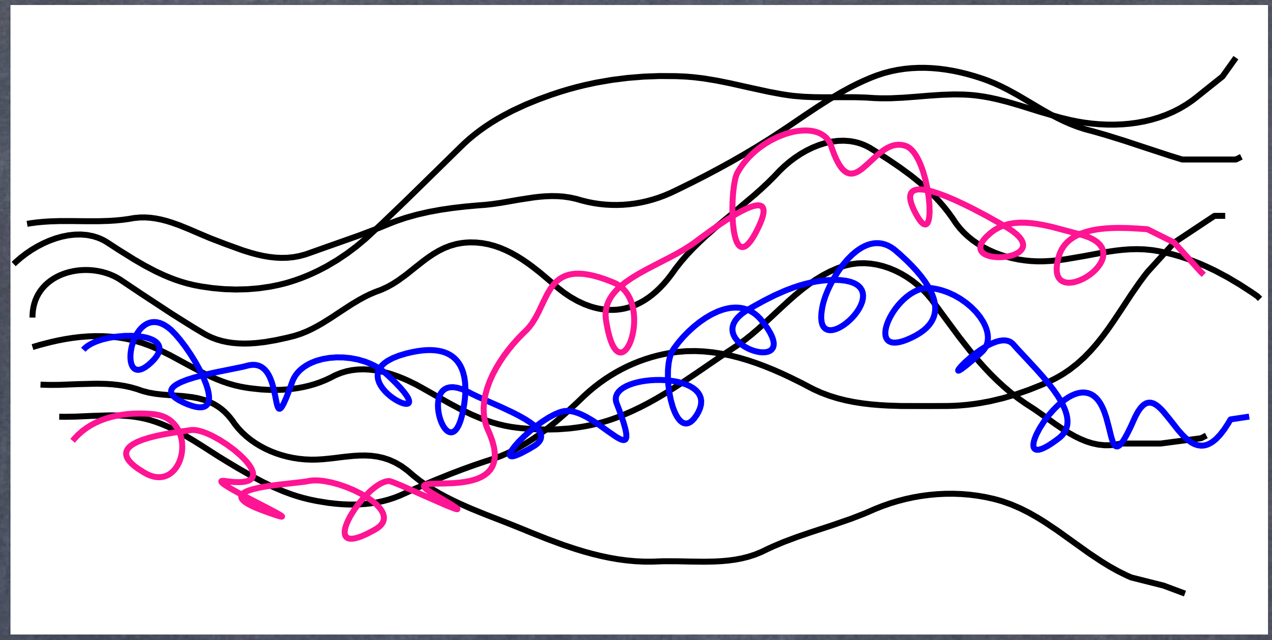
CR transport in (very) short

parallel diffusion



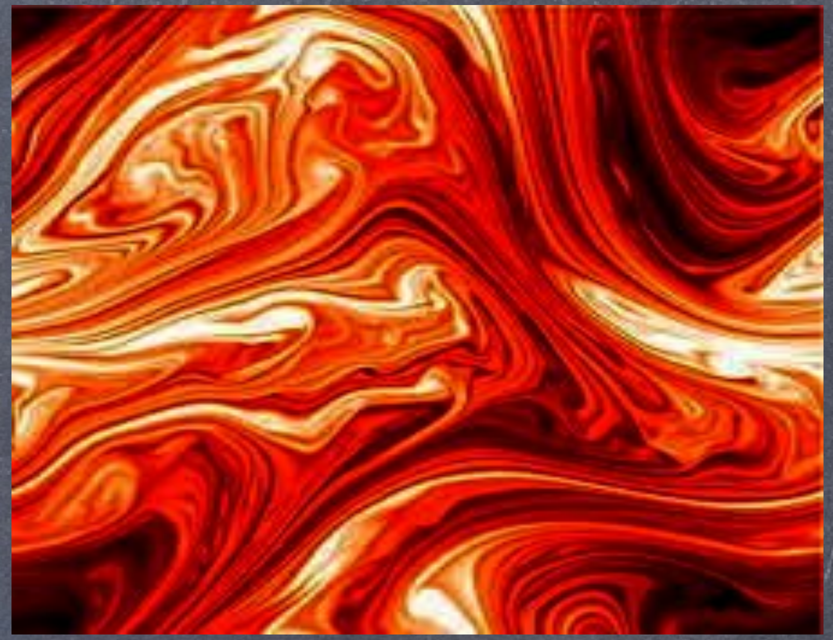
- CR gyromotion
- scattering off waves
- $k \sim 1/r_L$ (resonance)
- scattering mean free path $\lambda_{\rm mfp}$
- $D_{\parallel}(E) \propto \lambda_{\rm mfp}$

perp. transport



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

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 $D_{\|}$ ⟶ $\lambda_{\rm mfp} \gtrsim L_{\rm coh}$
  - 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

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

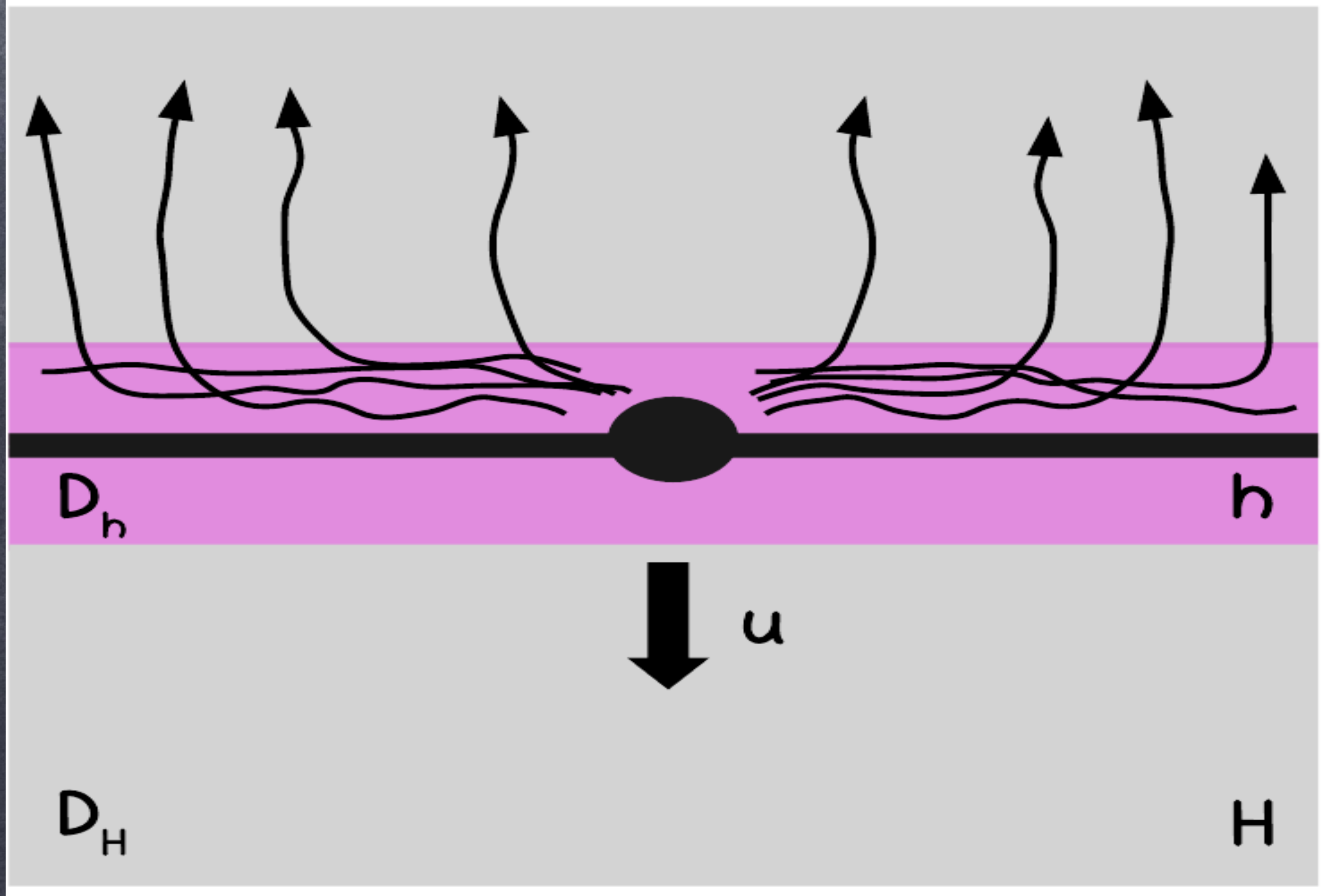
Alternative framework
CR data ~ GV- PV

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

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

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

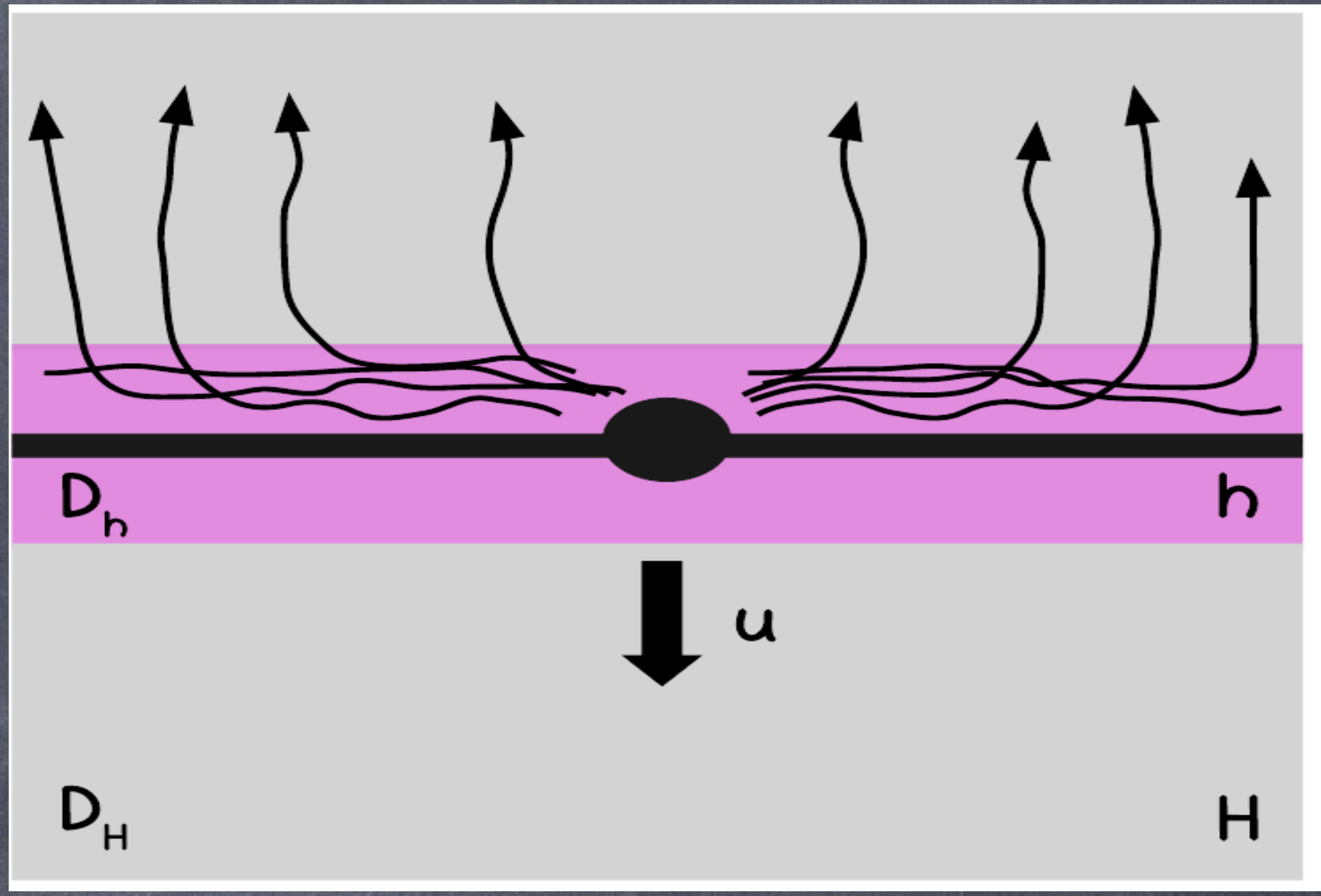


Analytic solution of the CR transport

flux of stable nuclei VS E_{kin}/n

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

$$\begin{cases} Q_{\alpha,\mathrm{src}} \equiv c A p^2 q_{0\alpha} & \text{inj. sources} \\ Q_{\alpha,\mathrm{spall}} \equiv \sum_{\beta>\alpha} v(E_k) \sigma_{\beta\alpha}(E_k) I_\beta(E_k) & \text{inj. spallation} \end{cases}$$



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

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

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

diffusion in disk
constant in E

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

smooth transition

$$R^* = \left[80\,\frac{H}{4\,\mathrm{kpc}}\,\frac{h}{150\,\mathrm{pc}}\,\frac{D_m}{\mathrm{pc}}\,\frac{10^{28}\mathrm{cm}^2/\mathrm{s}}{D_0}\right]^{1/\delta}\ \mathrm{GV}.$$

≈ 6 TV	$(\delta = 0.5)$
≈ 2 TV	$(\delta = 0.6)$
≈ 500 GV	$(\delta = 0.7)$
≈ 200 GV	$(\delta = 0.8)$

Analytic solution of the CR transport

residence time in disk

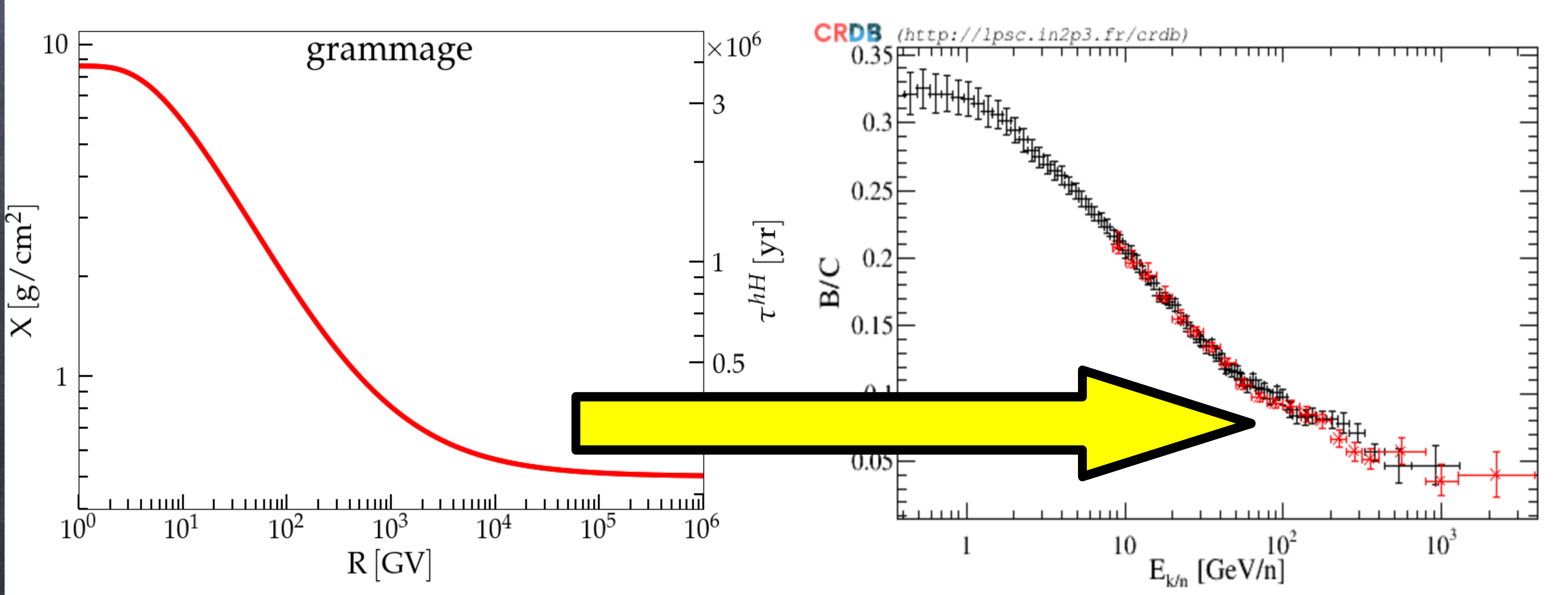
$$\tau_\alpha^{hH} \equiv \frac{h^2}{D_h} + \frac{h\,H}{D_H}\,\frac{1-\exp^{-\frac{u\,H}{D_H}}}{\frac{u\,H}{D_H}}.$$

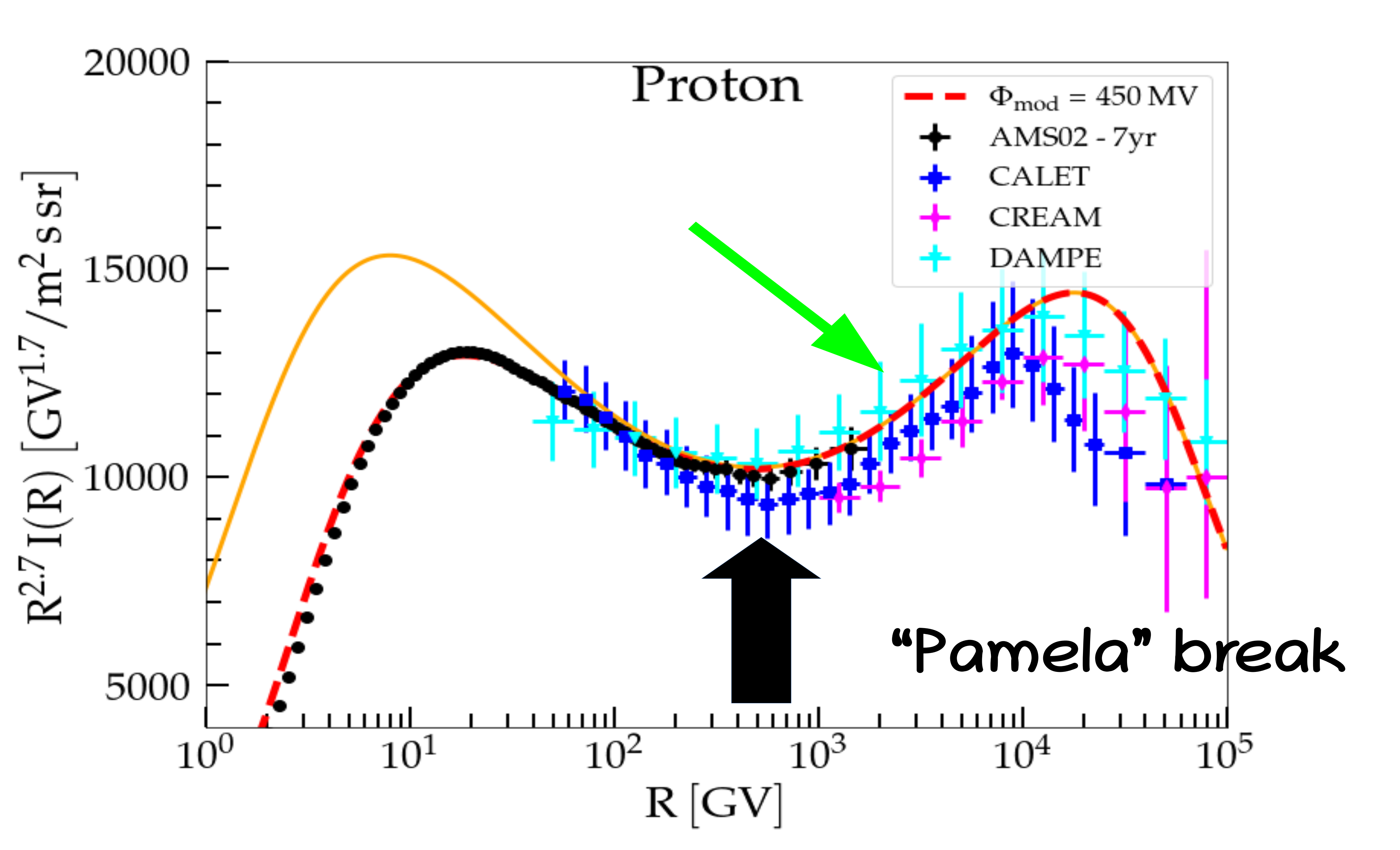
repeated crossings of disk induced by diffusion in halo
decreases with E due to $D_H \sim E^{0.7}$

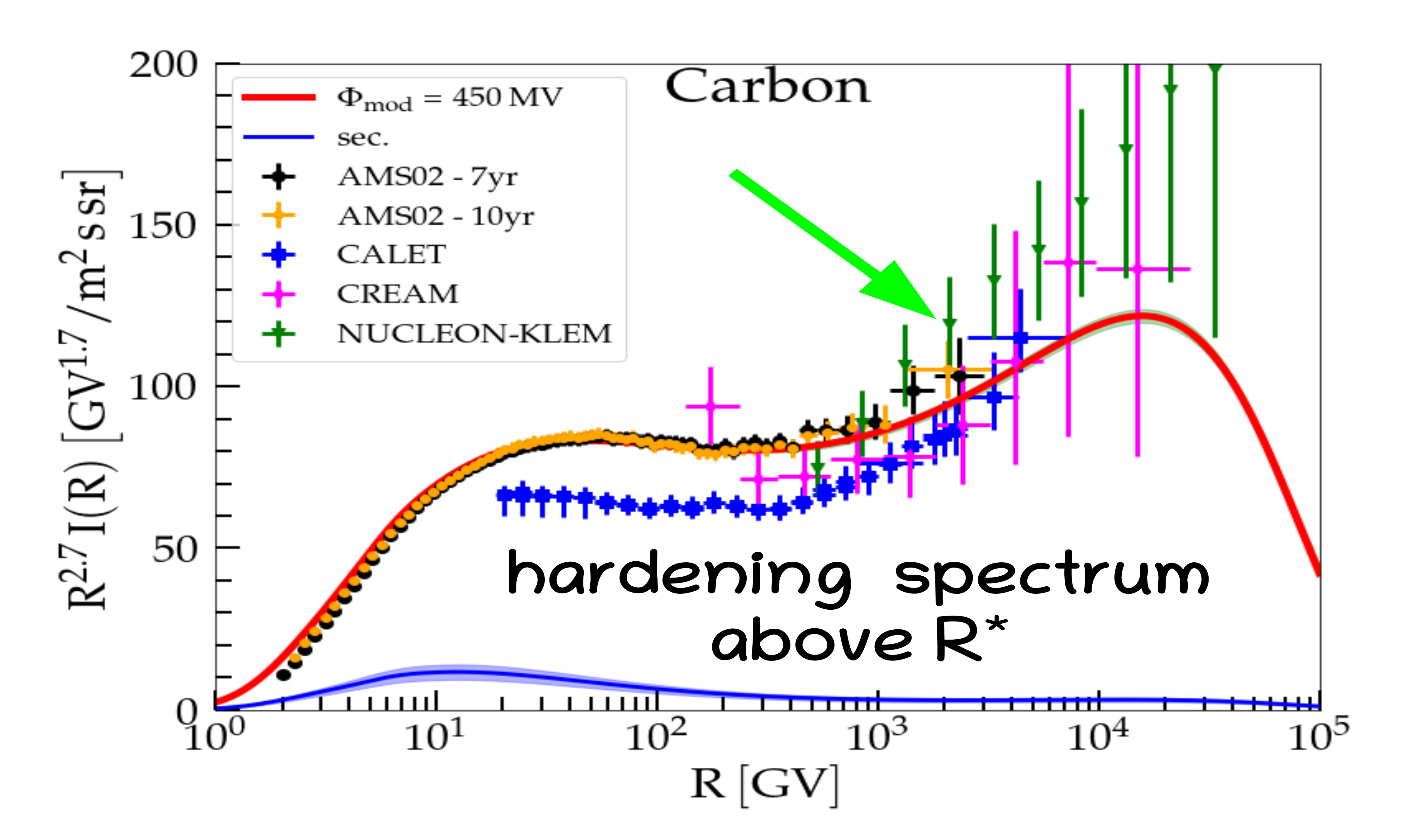
diffusion in disk
constant in E

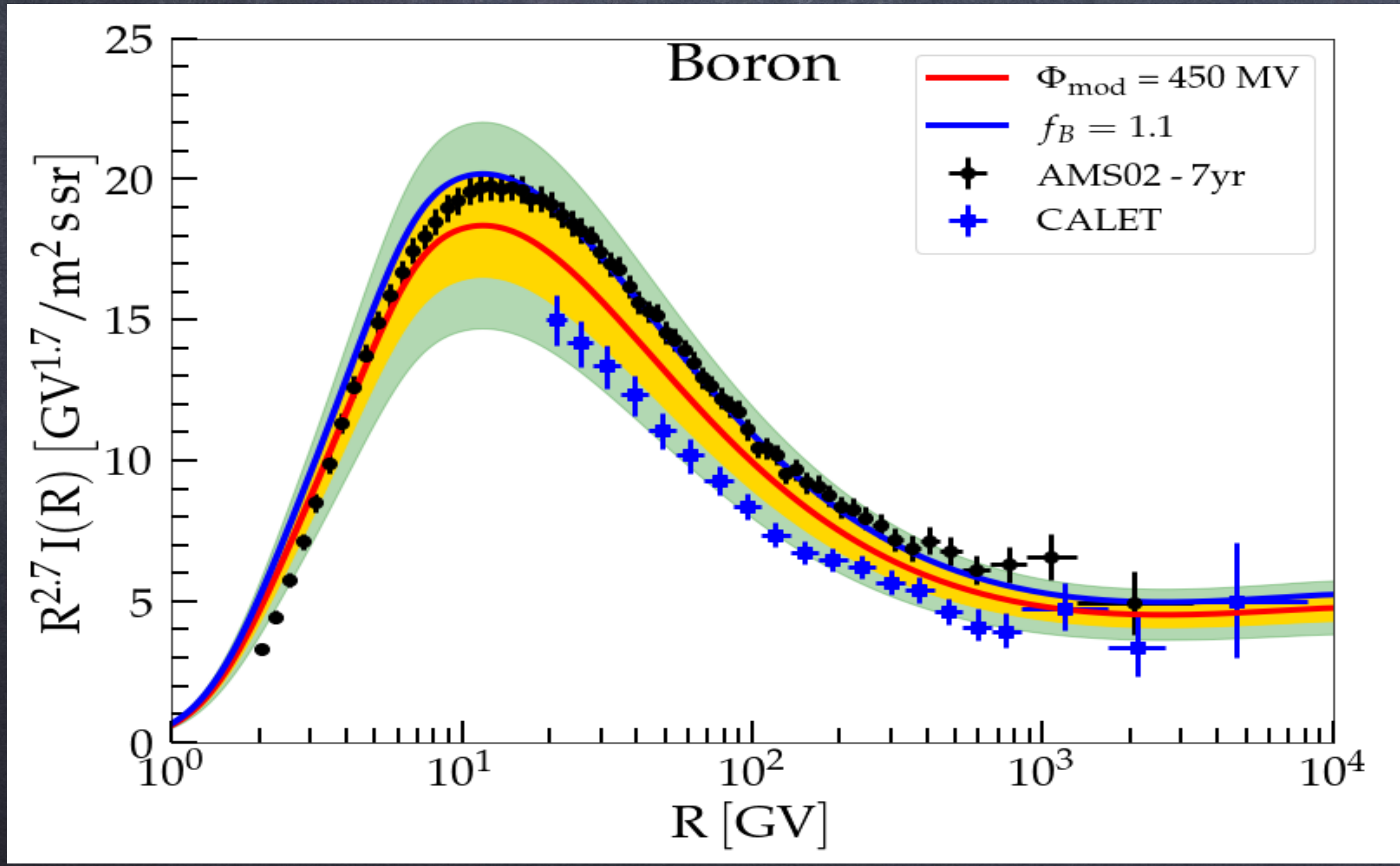
$$\tau_d^{\min} \sim \frac{h^2}{D_{\mathrm{eff},\perp}} \approx 2\times10^5 \left(\frac{h}{150\,\mathrm{pc}}\right)^2 \left(\frac{\mathrm{pc}}{D_m}\right) \mathrm{yr},$$

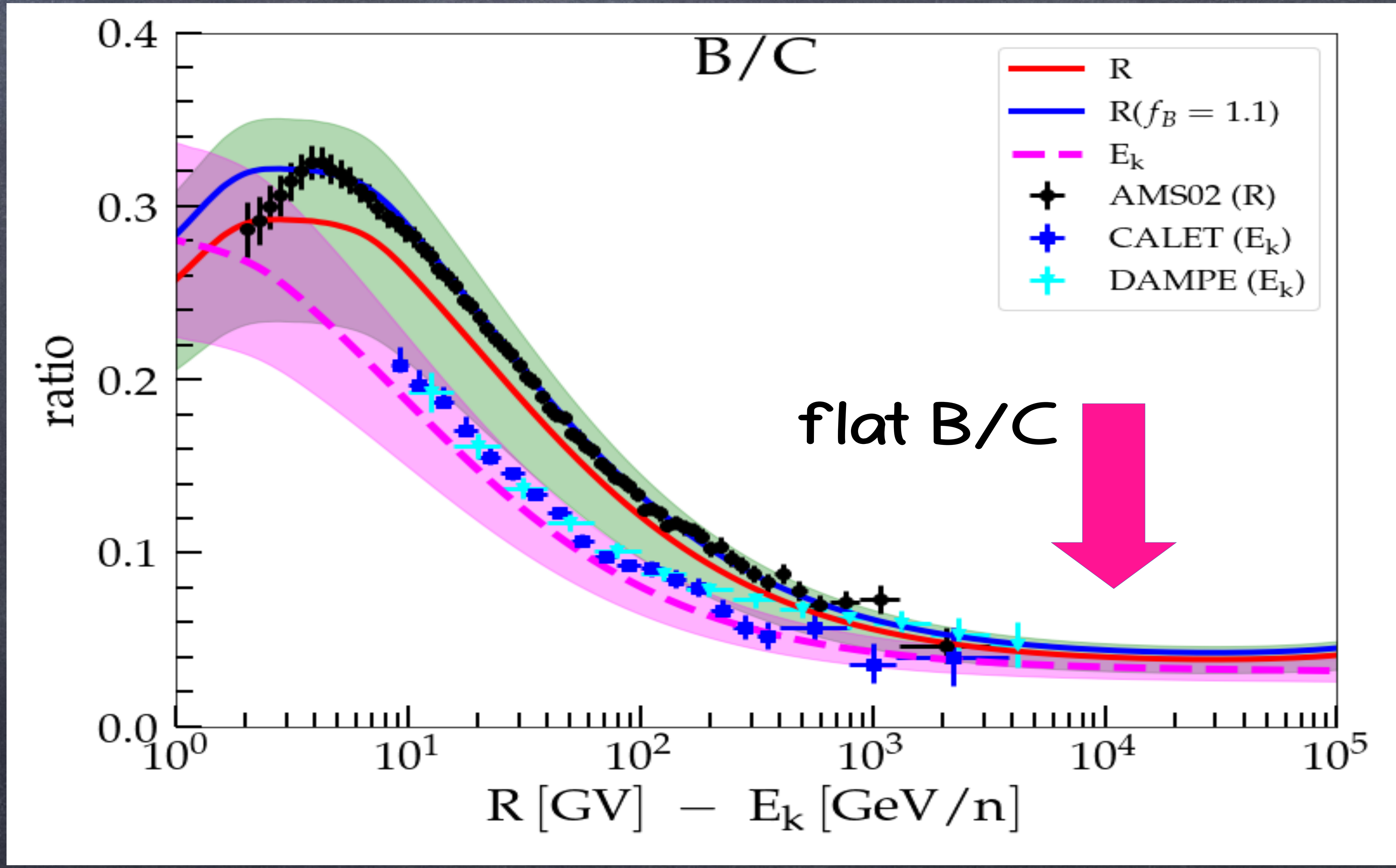
$$X_{\min} \approx 0.4\, n_d \left(\frac{h}{150\,\mathrm{pc}}\right)^2 \left(\frac{\mathrm{pc}}{D_m}\right) \mathrm{g/cm^2}.$$



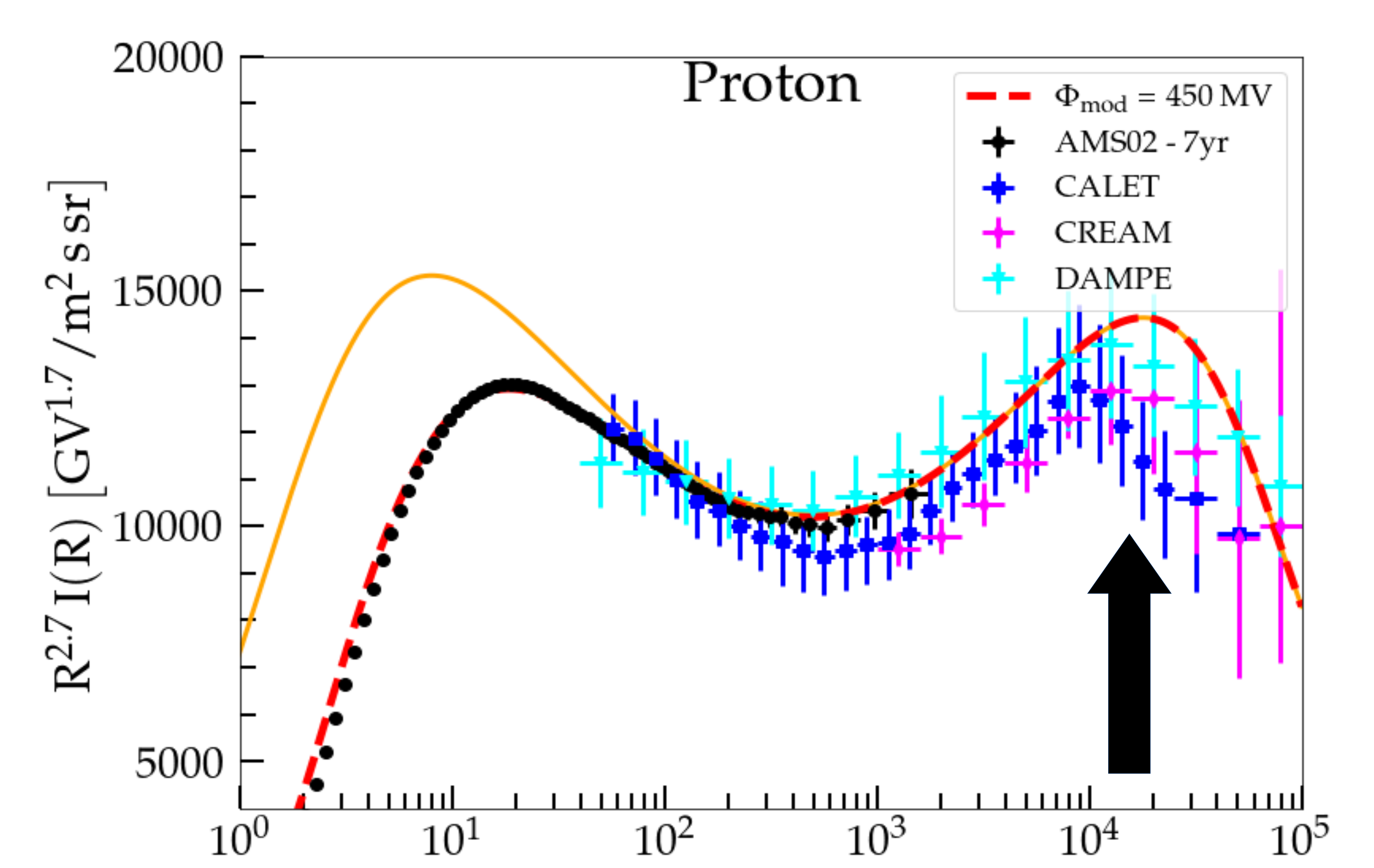

Proton
Φ_{mod} = 450 MV
AMS02 - 7yr
CALET
CREAM
DAMPE
"Pamela" break
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]

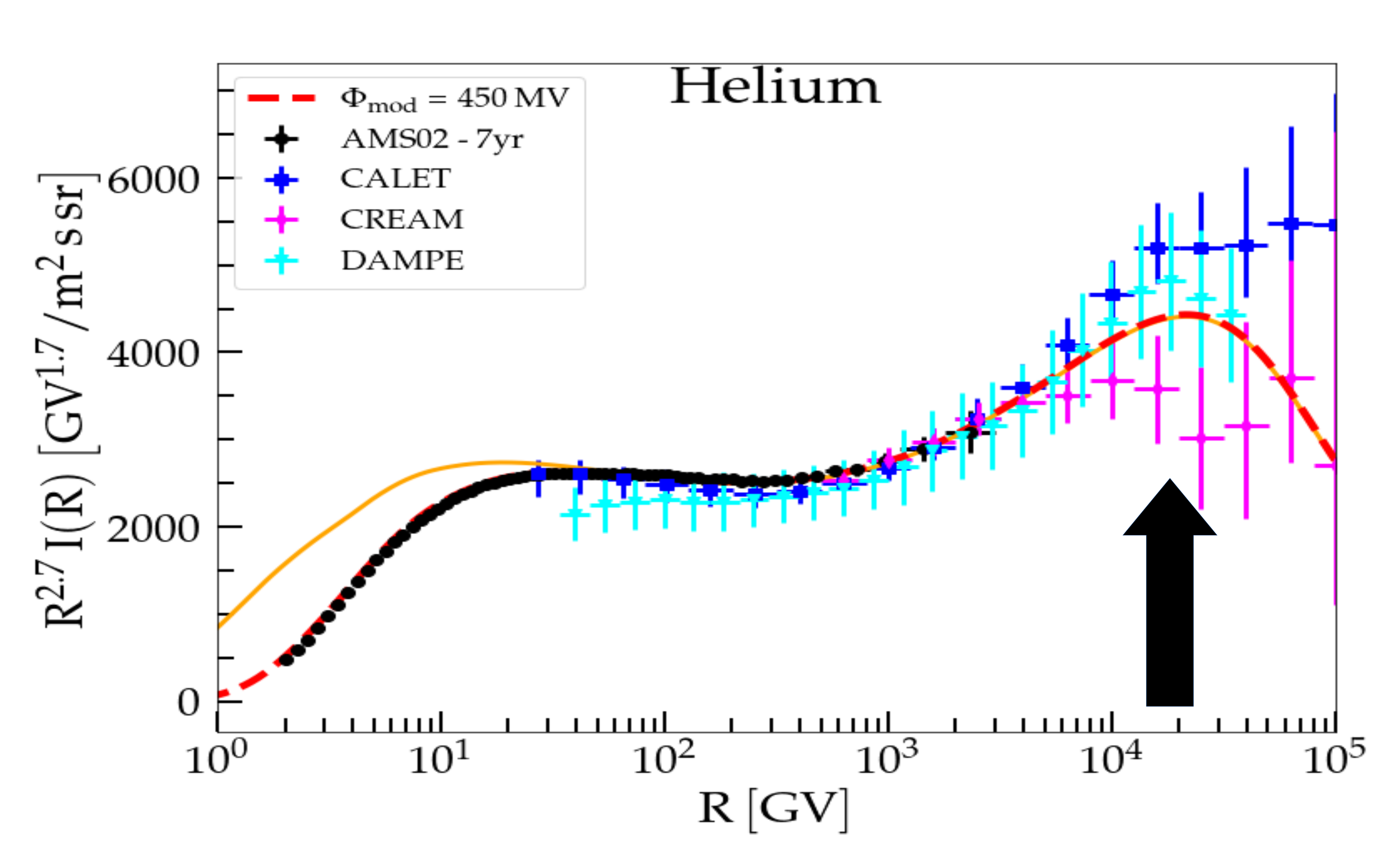

Carbon
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
AMS02 - 10yr
CALET
CREAM
NUCLEON-KLEM
hardening spectrum
above R*
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]

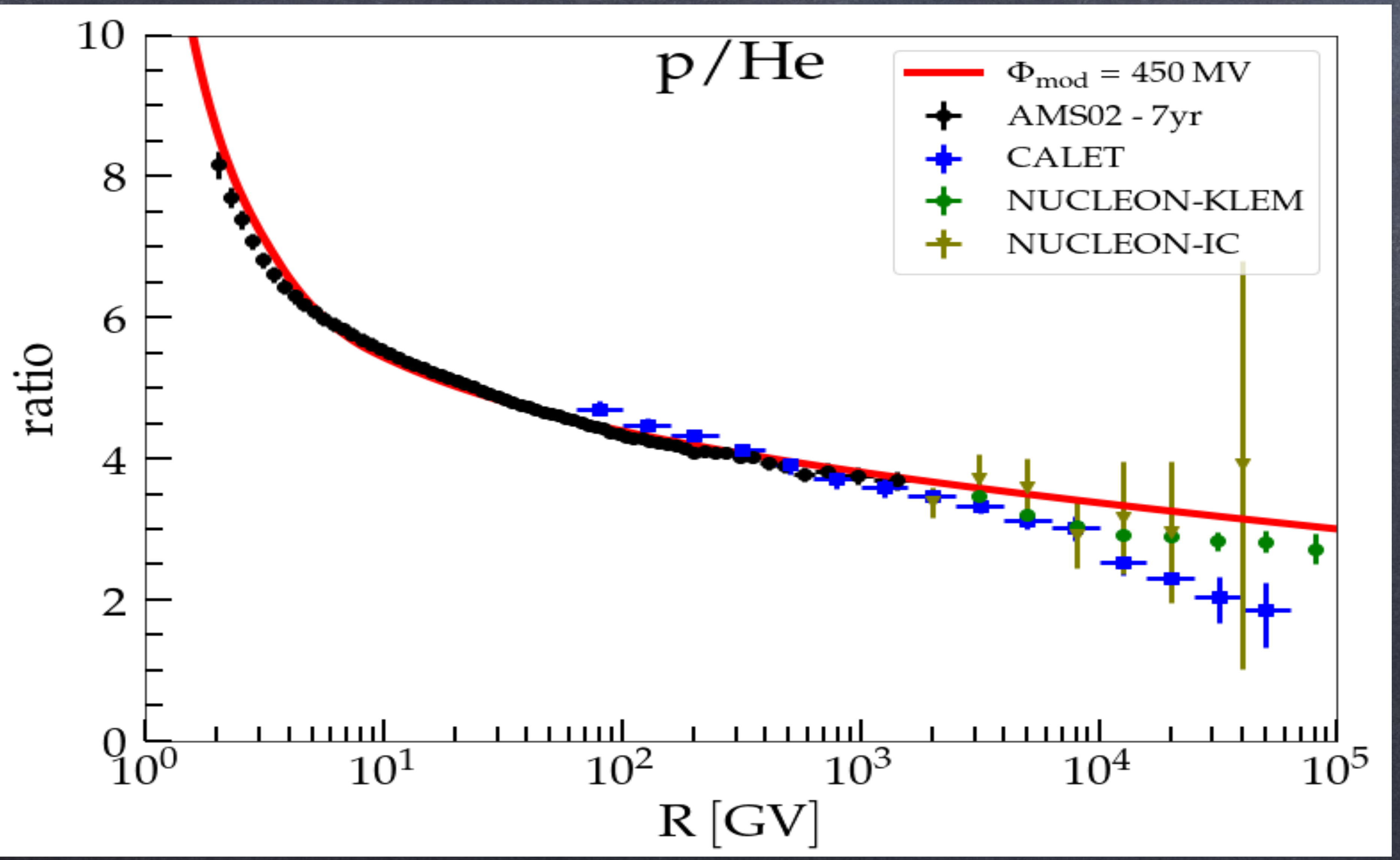

Boron
Φ_{mod} = 450 MV
$f_B = 1.1$
AMS02 - 7yr
CALET
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]


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"

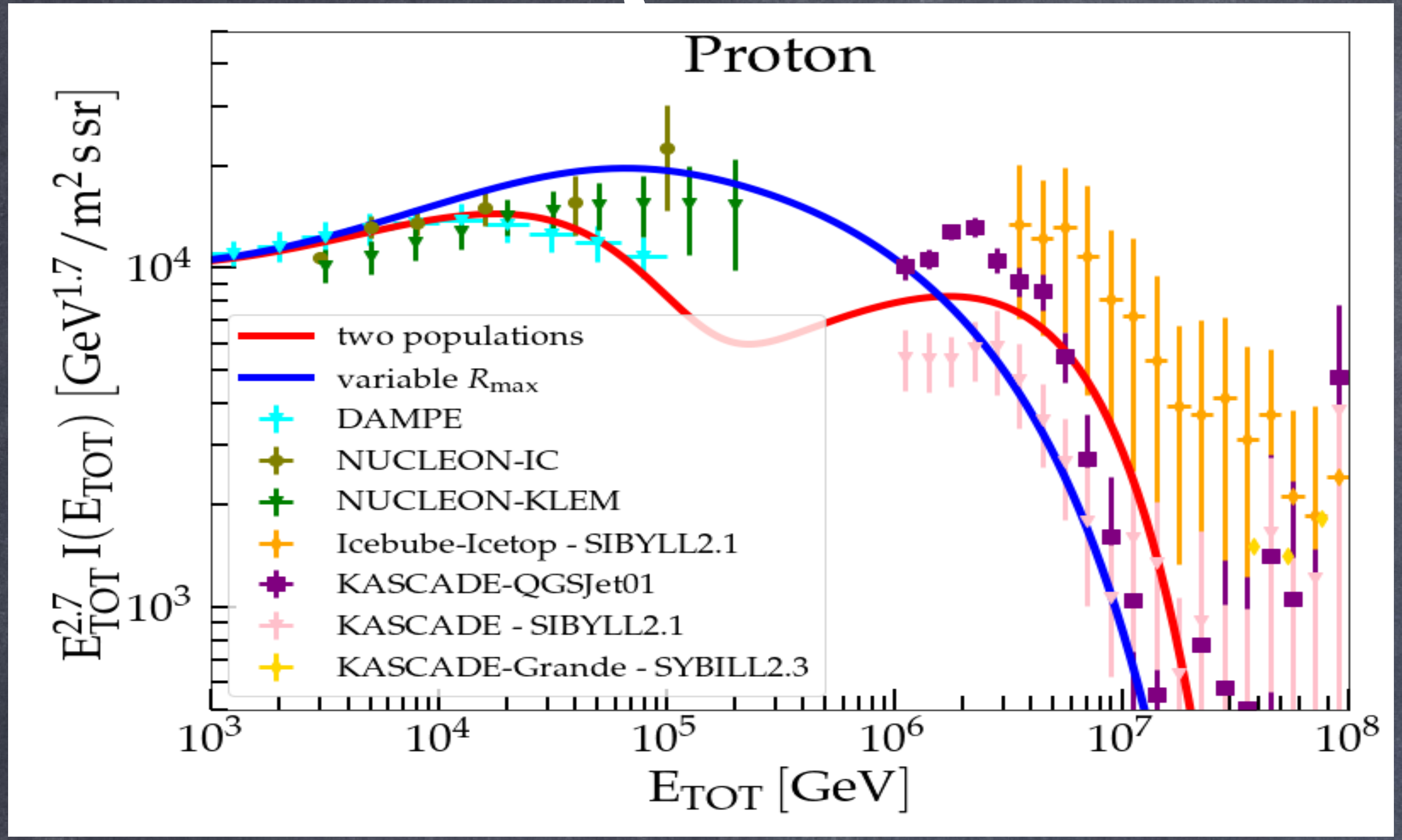


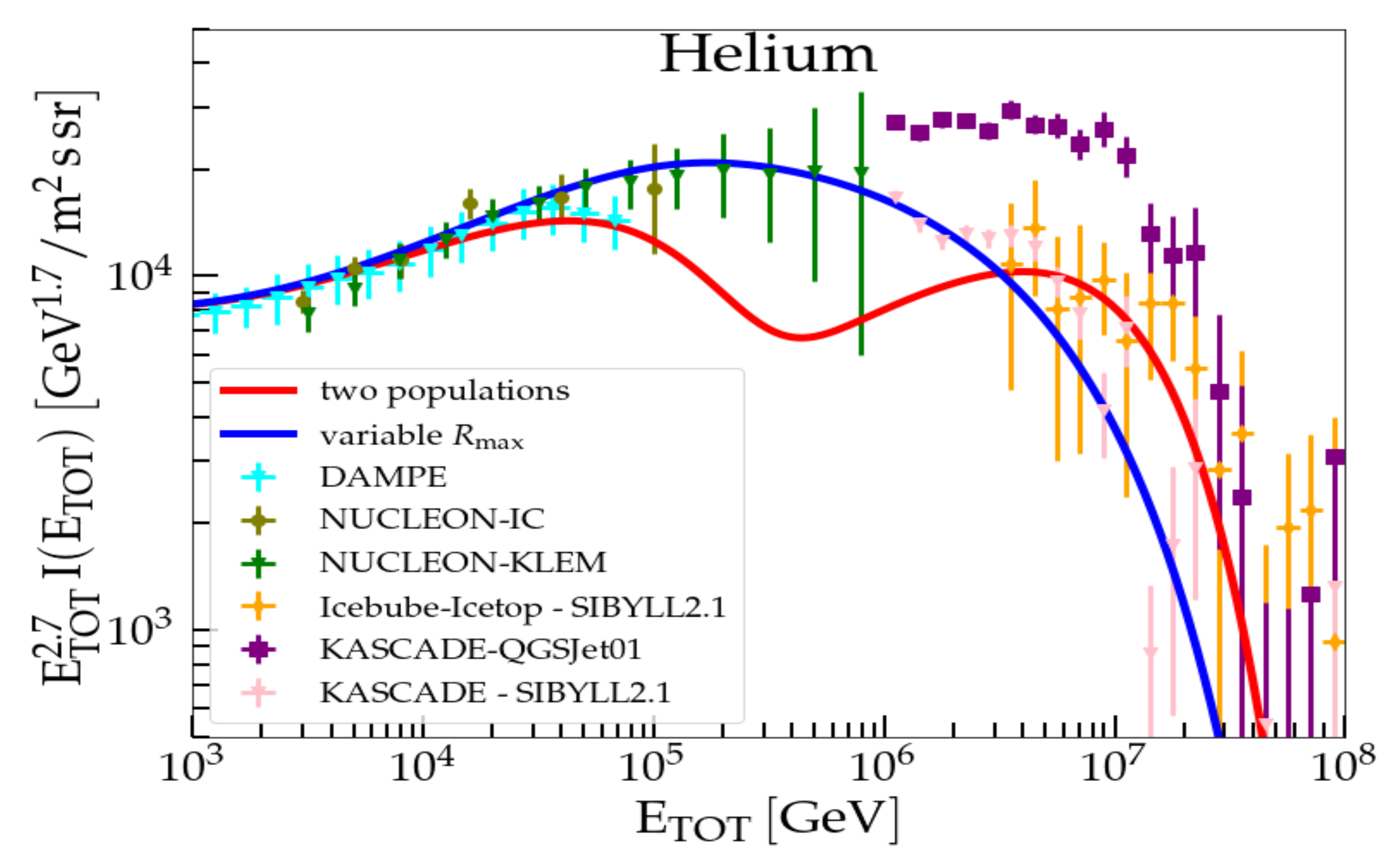




gaseous disk				
n_d 1 cm^{-3}	f_{He} 0.1	h_d 150 pc	R_d 15 kpc	
Galactic disk (GD)				
h 150 pc	L_c 10 pc	b^2 0.4	D_m 1 pc	L_{RR} 50 – 100 pc
Galactic halo (GH)				
H 4 kpc	D_0 10^{28} cm^2/s	δ 0.7	u 40 km/s	
bulk of SNRs				
γ_p 4.35	γ_{He} 4.30	γ_n 4.33	R_{max}^{bulk} 50 TV	
PeV sources				
γ_p 4.35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

"Dampe" break and the "knee"

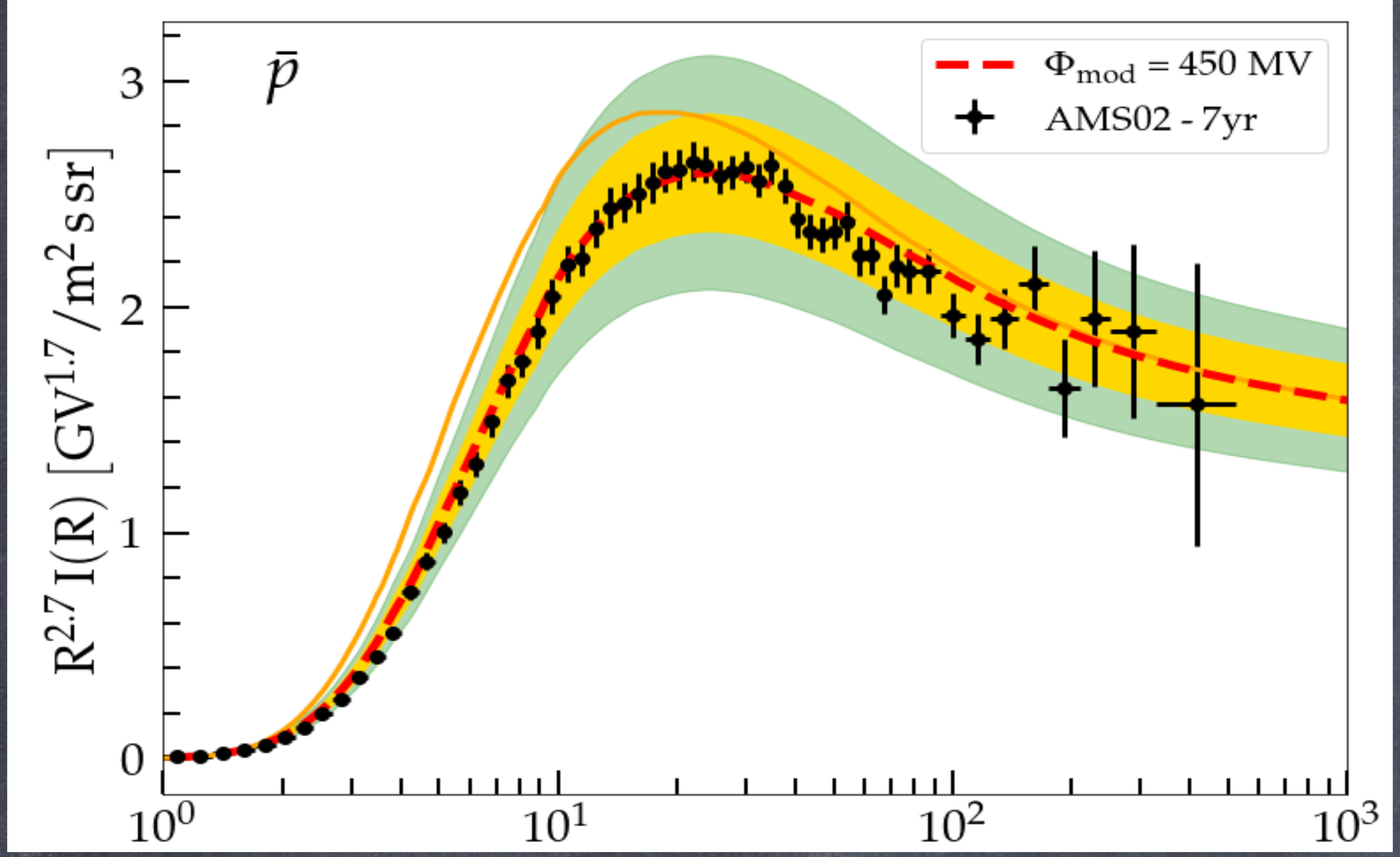


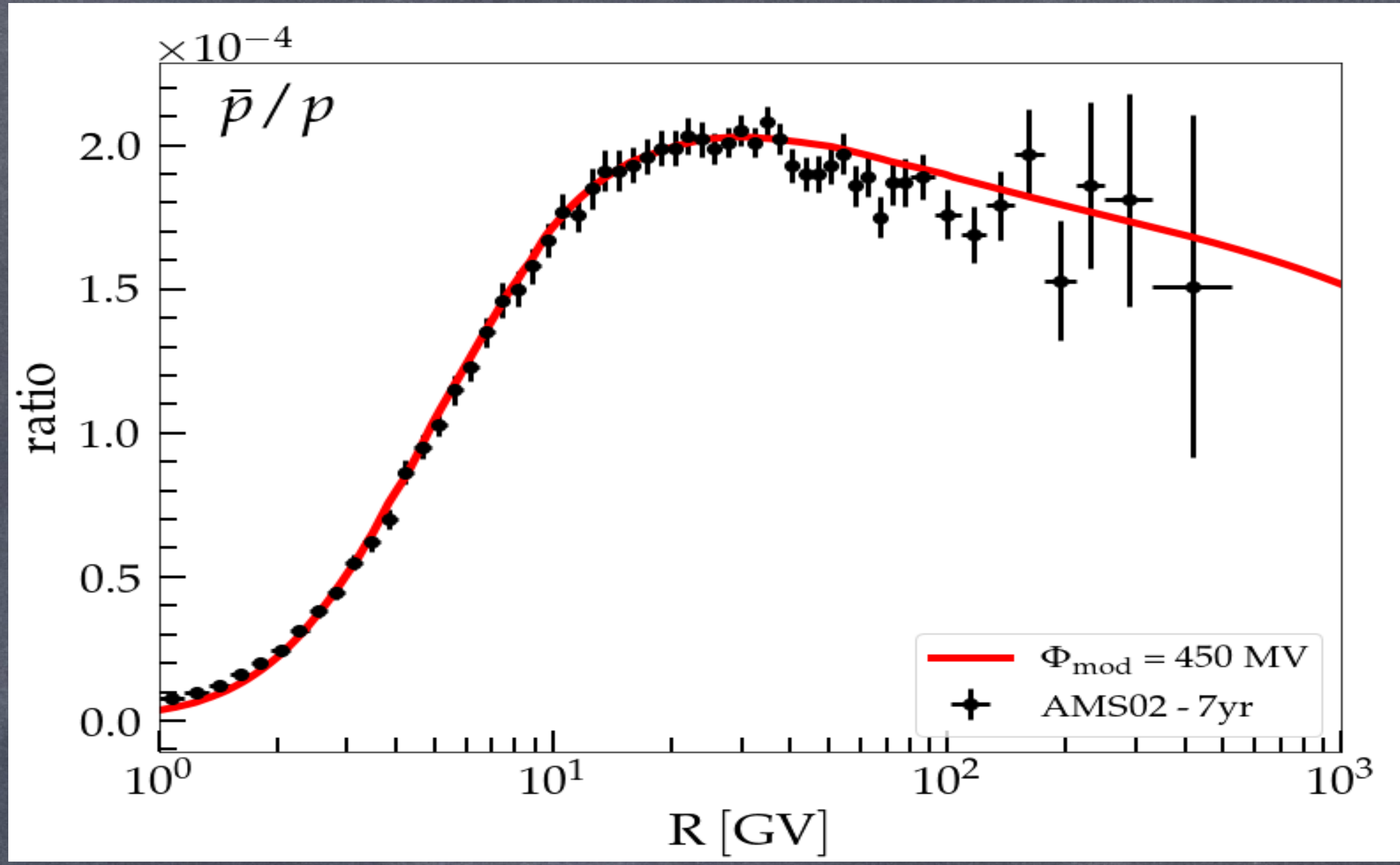


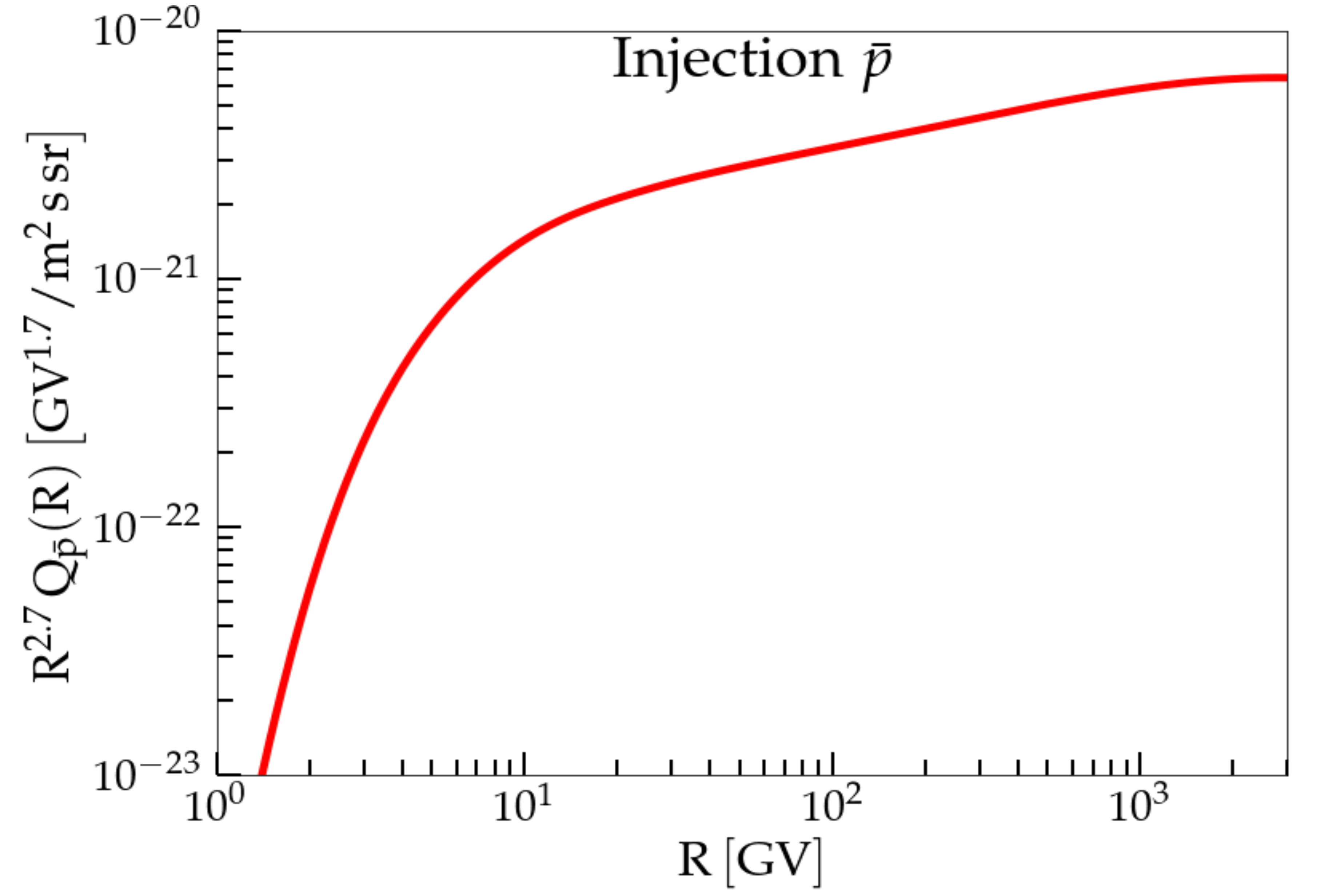
- special SNRs, star clusters
- ...
- ~ 10-20% of typical CR source luminosity
- more in agreement with theory

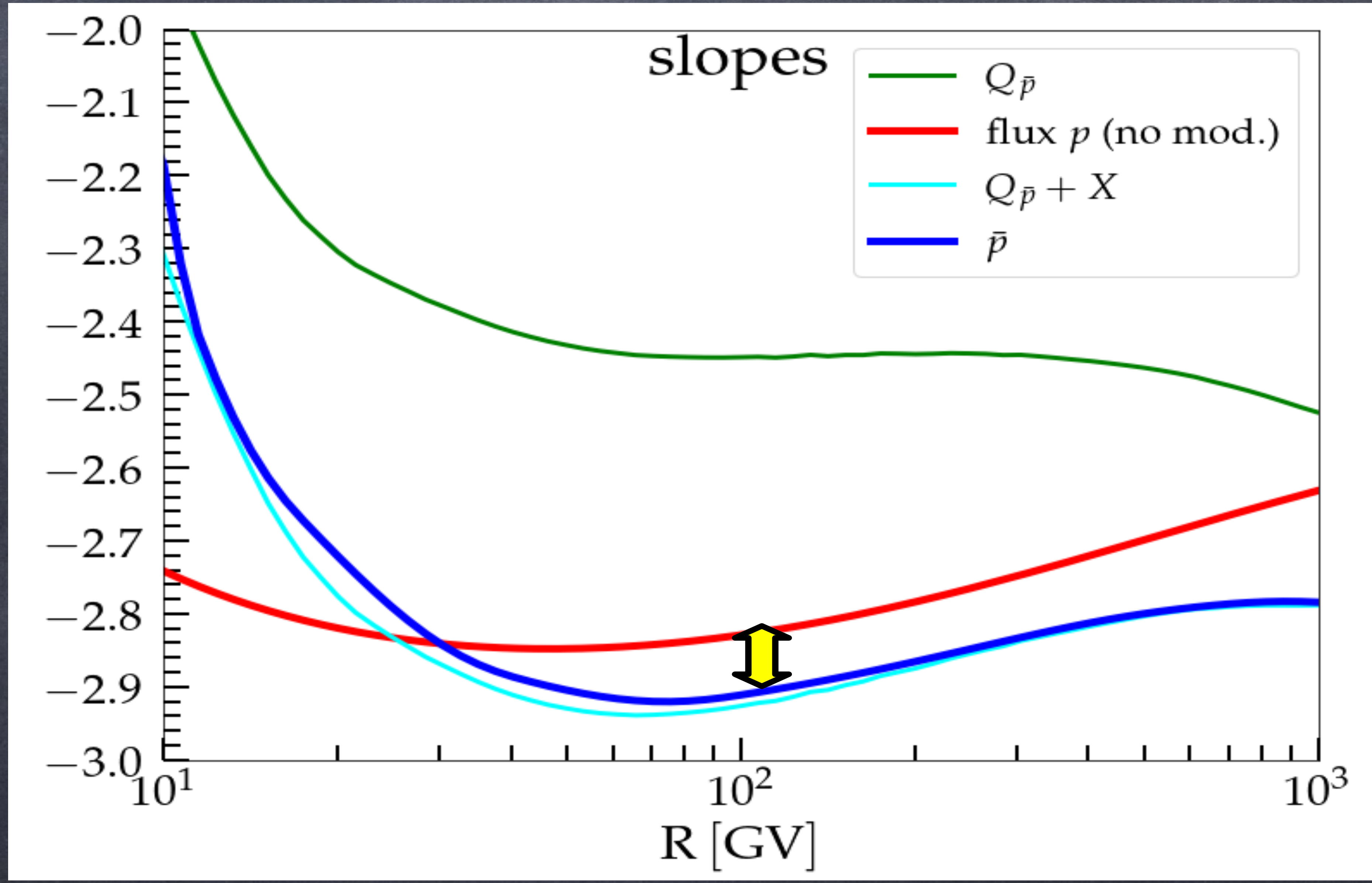
		gaseous disk		
n_d	f_{He}	h_d	R_d	
1 cm^{-3}	0.1	150 pc	15 kpc	
		Galactic disk (GD)		
h	L_c	b^2	D_m	L_{RR}
150 pc	10 pc	0.4	1 pc	50 − 100 pc
		Galactic halo (GH)		
H	D_0	δ	u	
4 kpc	10^{28} cm^2/s	0.7	40 km/s	
		bulk of SNRs		
γ_p	γ_{He}	γ_n	R_{max}^{bulk}	
4.35	4.30	4.33	50 TV	
		PeV sources		
γ_p	γ_{He}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

Antiprotons









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...

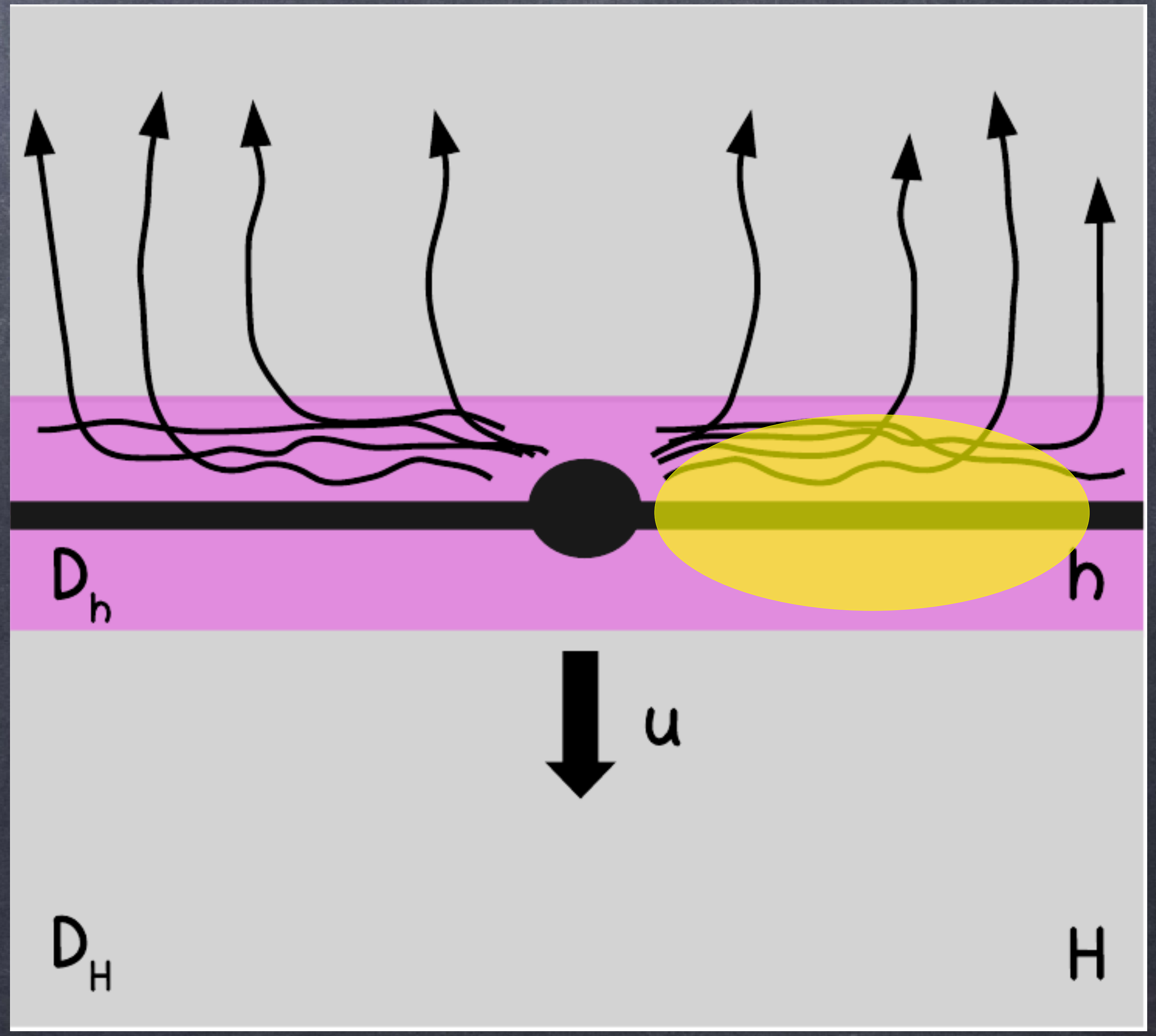
Anisotropy...

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

crucial test

average number of contributing sources at VHE

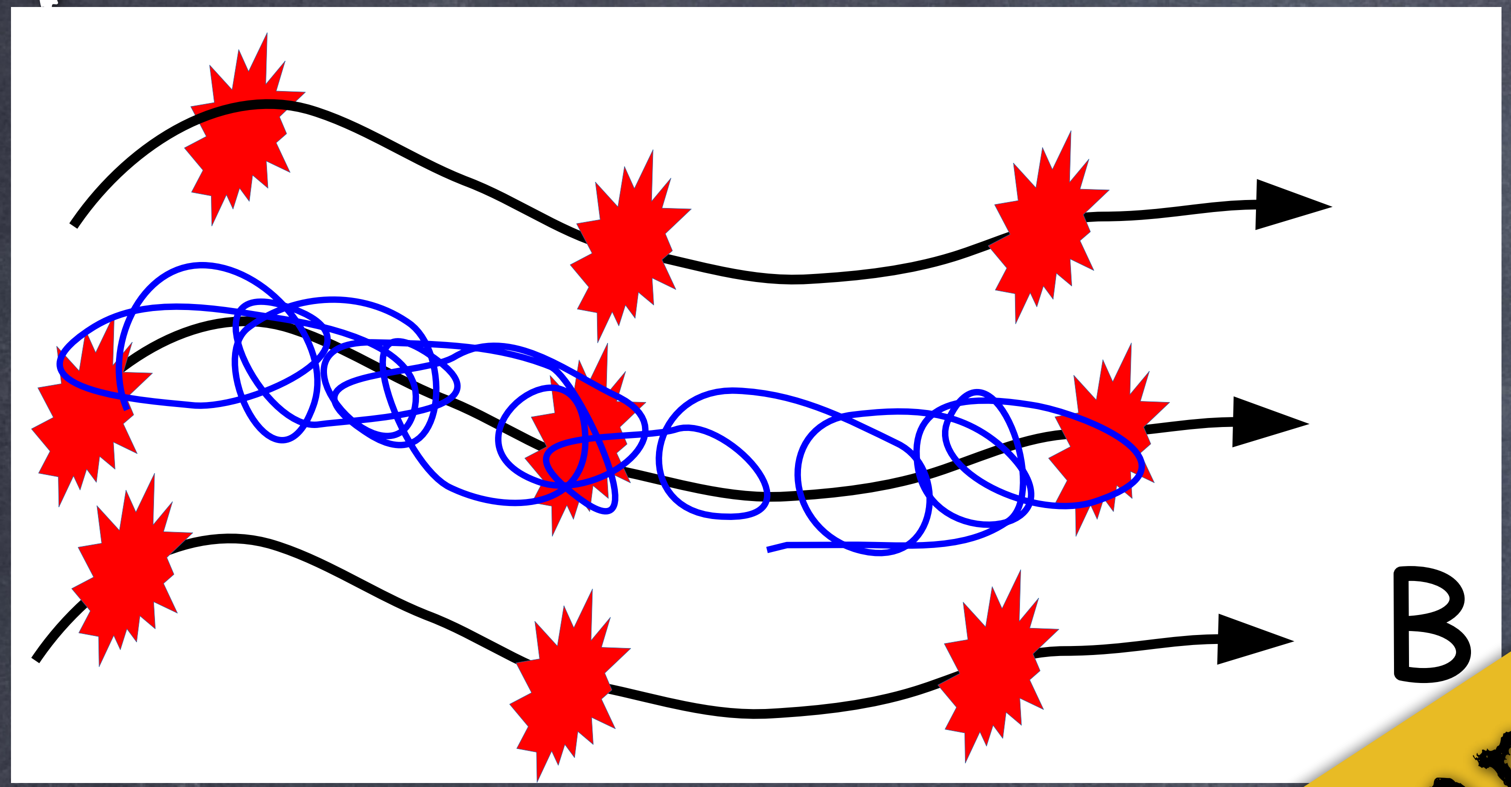
$$\langle N_{\rm PV}\rangle \approx 10\left(\frac{\xi_{\rm PV}}{0.15}\right)\left(\frac{\nu_{\rm SNe}}{1/30\,{\rm yr}}\right)\left(\frac{h}{150\,{\rm pc}}\right)^2\left(\frac{\rm pc}{D_m}\right)\left(\frac{d}{\rm kpc}\right)^2,$$



Thank You

Parallel CR transport

parallel diffusion

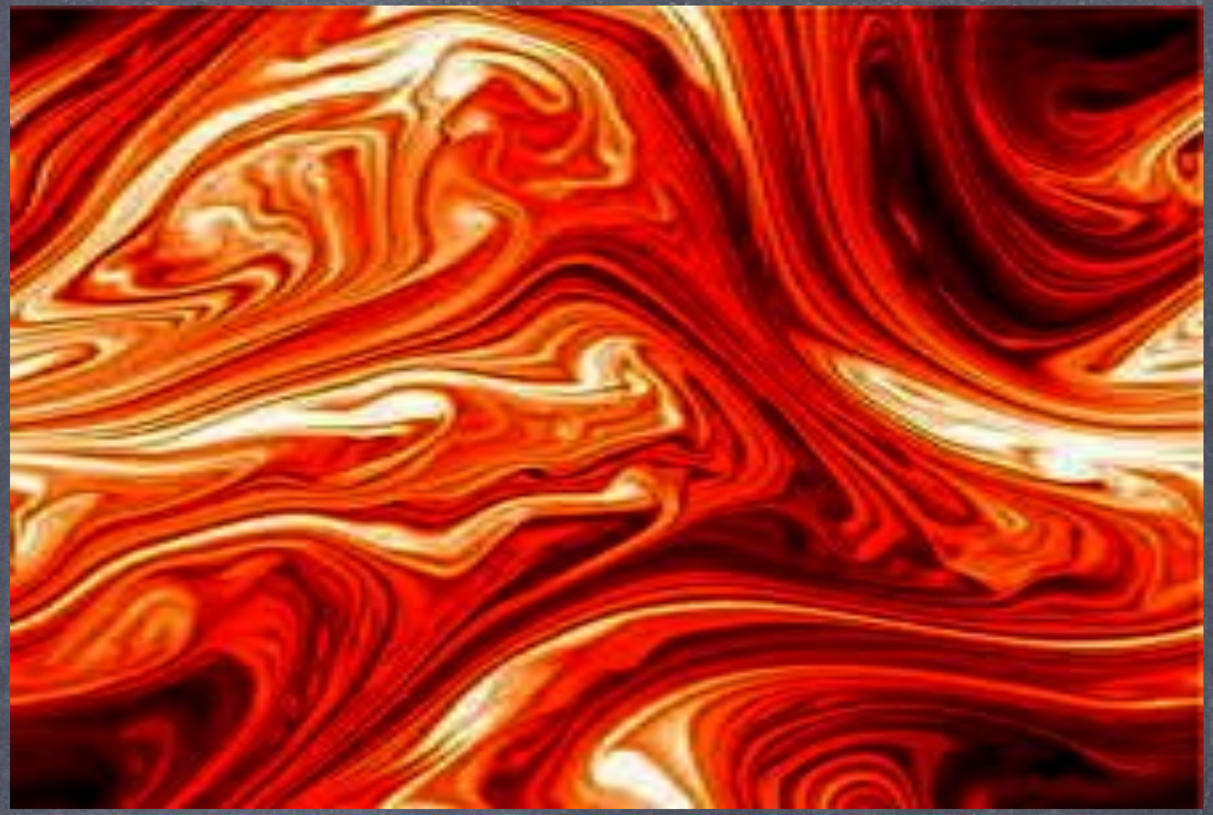


(parallel) diffusion coefficient

$$D_{||}(E) \propto \lambda_{\rm mfp} \propto E^{\delta}$$

- CR gyromotion
- scattering off waves
- mean-free path $\lambda_{\rm mfp}$
- $k \sim 1/r_L$ (resonance)

MHD turbulence



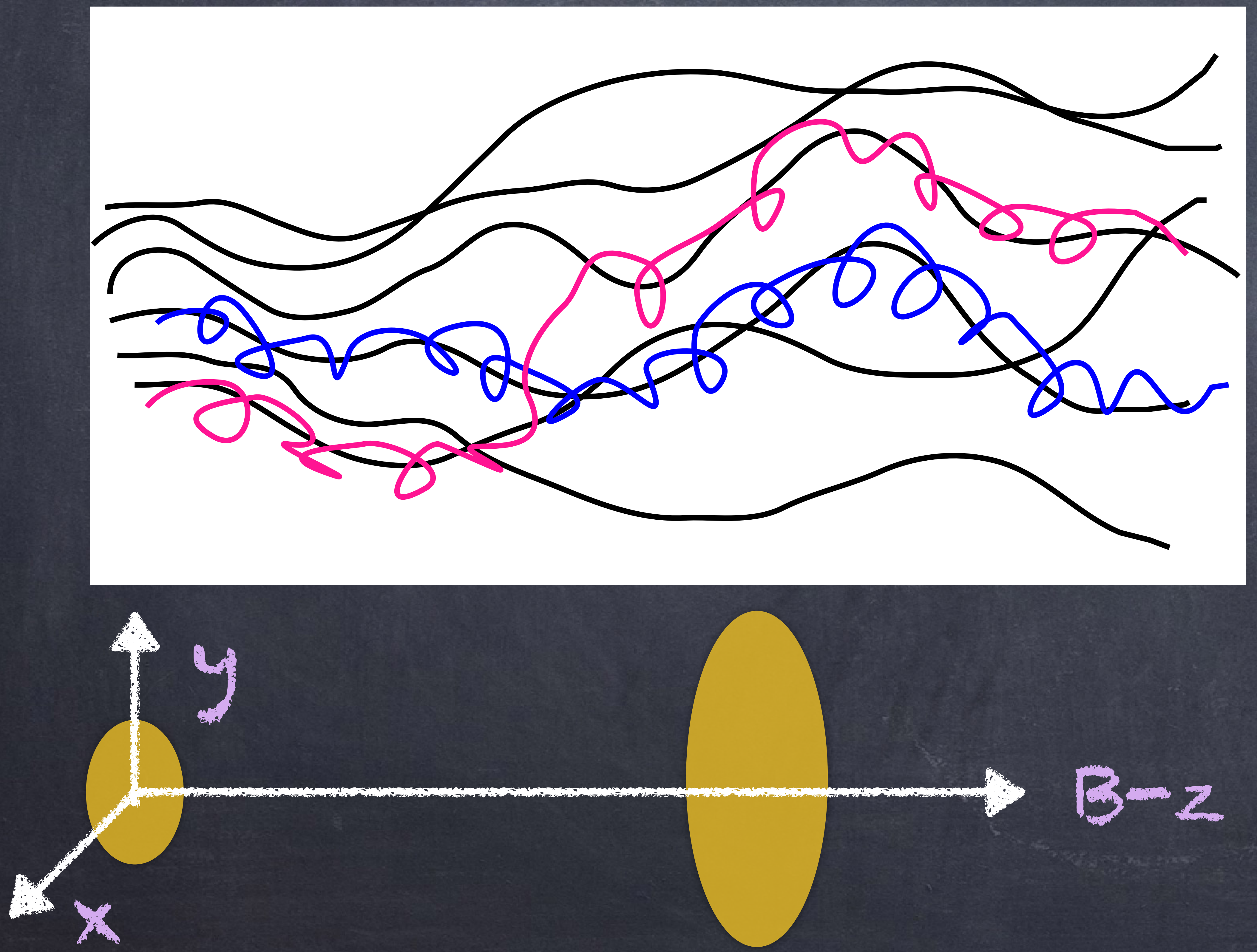
- source injection (10s pc)
- cascade to $k \sim 1/r_L$?
- damping?

Mertsch (2020) - review turbulence & transport

Perpendicular CR transport

Shalchi (2020) - review perp. Transport

perpendicular diffusion



- field line random walk (FLRW)
  - turbulent motion of field lines
  - large-scale ($\gg r_L$) turbulence

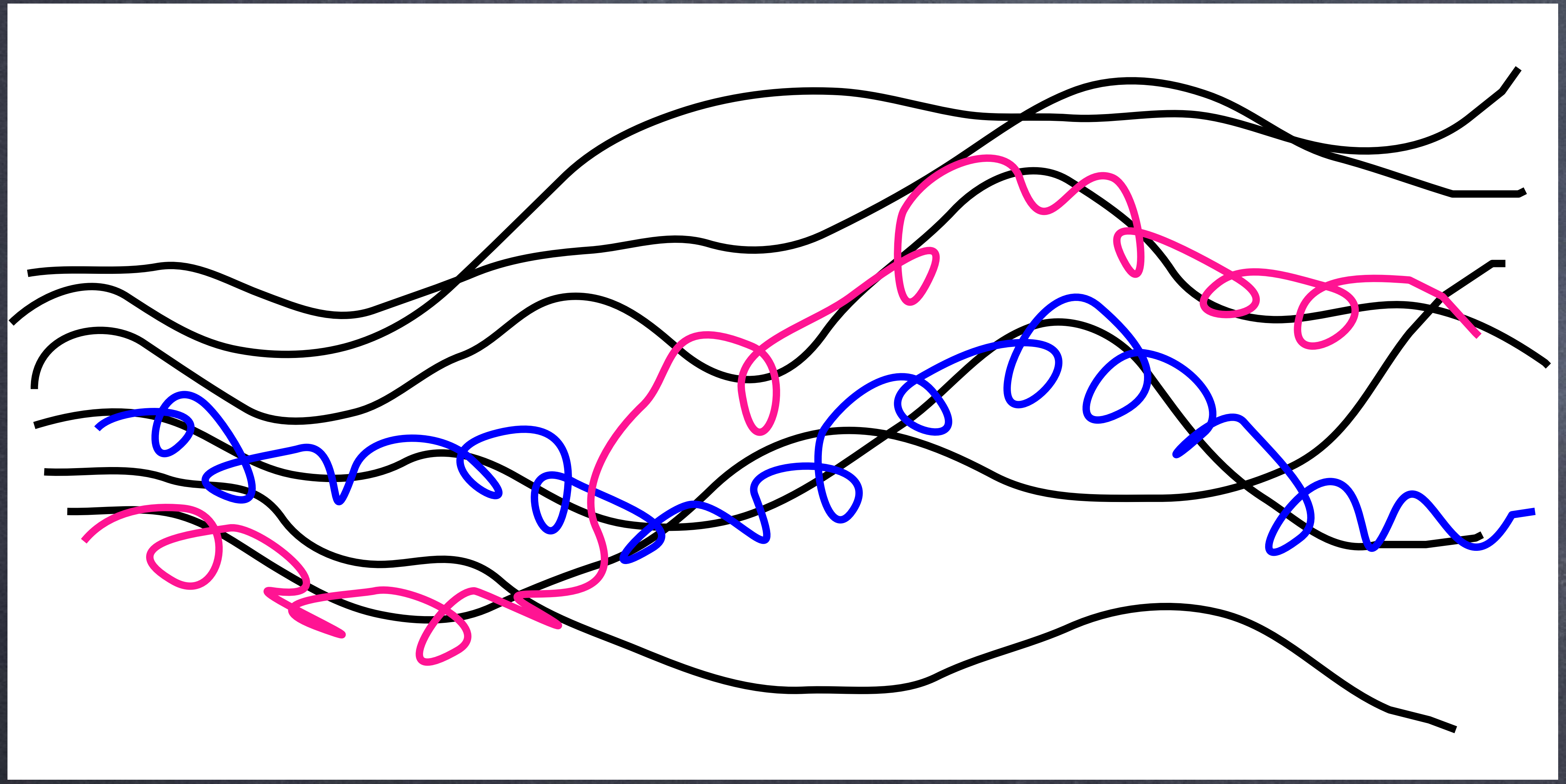
$$\langle (x - x_0)^2 \rangle = \langle (y - y_0)^2 \rangle = 2 D_m z.$$

$$D_m = \left(\frac{\delta B}{B_0}\right)^2 \frac{L_c}{4} = 0.25 \left(\frac{b^2}{0.1}\right)\left(\frac{L_c}{10\,\mathrm{pc}}\right) \mathrm{pc},$$

Perpendicular CR transport

Shalchi (2020) - review perp. Transport

perpendicular diffusion



- field line walk (FLRW)
  - turbulent motion of field lines
  - large-scale ($\gg r_L$) turbulence
- Small-scale perp. diffusion
  - CRs jump between field lines
  - scattering, drifts...

⟶ LARGE-SCALE PERPENDICULAR DIFFUSION

$D_\perp(E) \lesssim D_\parallel(E)$

Perp. diffusion: weak scattering limit

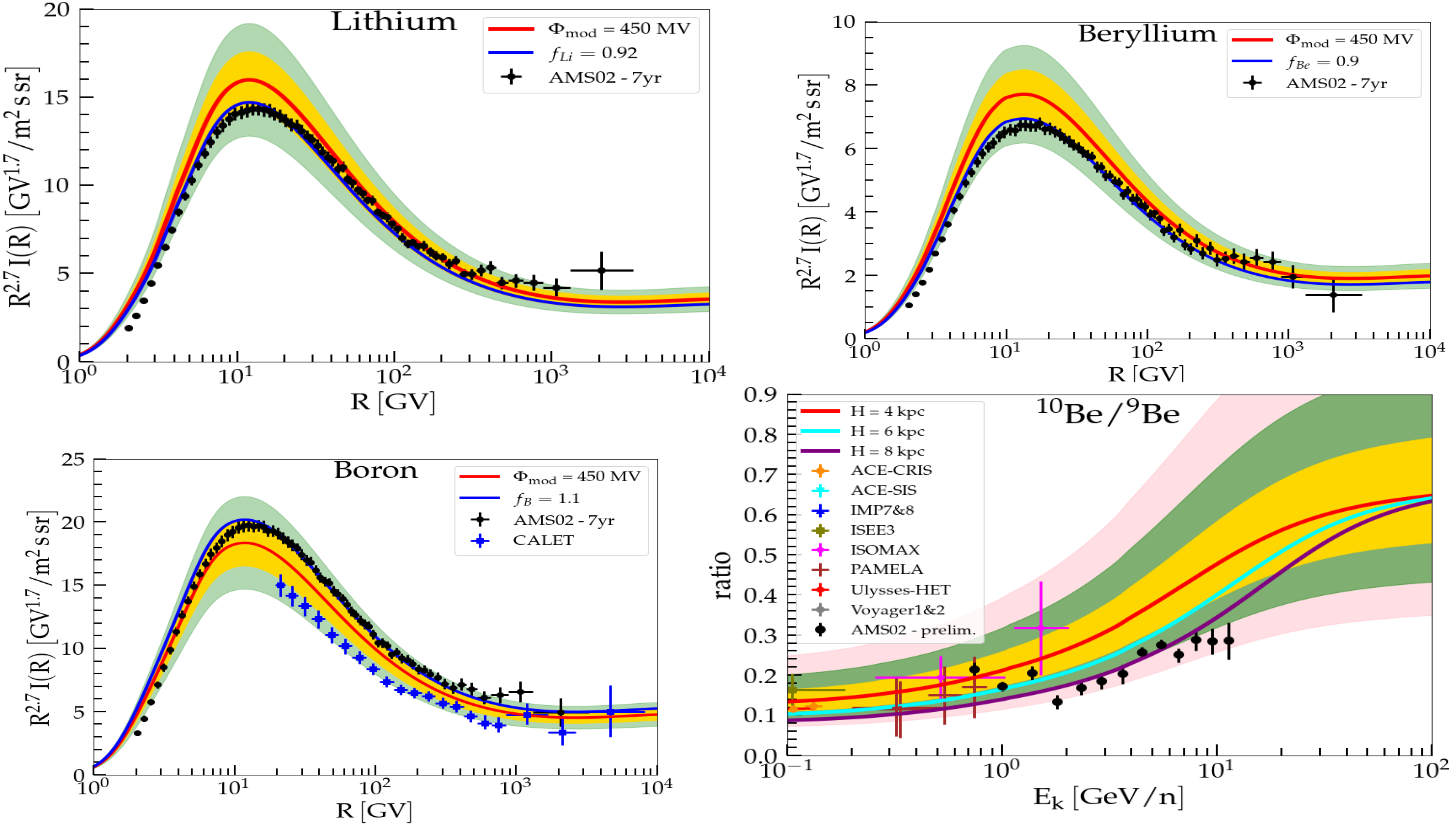
Rechester & Rosenbluth 1978 | Chandran 2000 | Snodin et al. (2022) | Pezzi & Blasi (2024)

- weak scattering ALONG field lines + FLRW
  - $\lambda_{\rm mfp} \gtrsim L_{\rm RR}$
  - $L_{RR} \gtrsim L_{\rm coh}$ ---> trajectory decorrelates from initial field line
  - $L_{\rm RR}$ statistically independent random step
  - within $L_{\rm coh}$, $z(t) \sim v\,t$

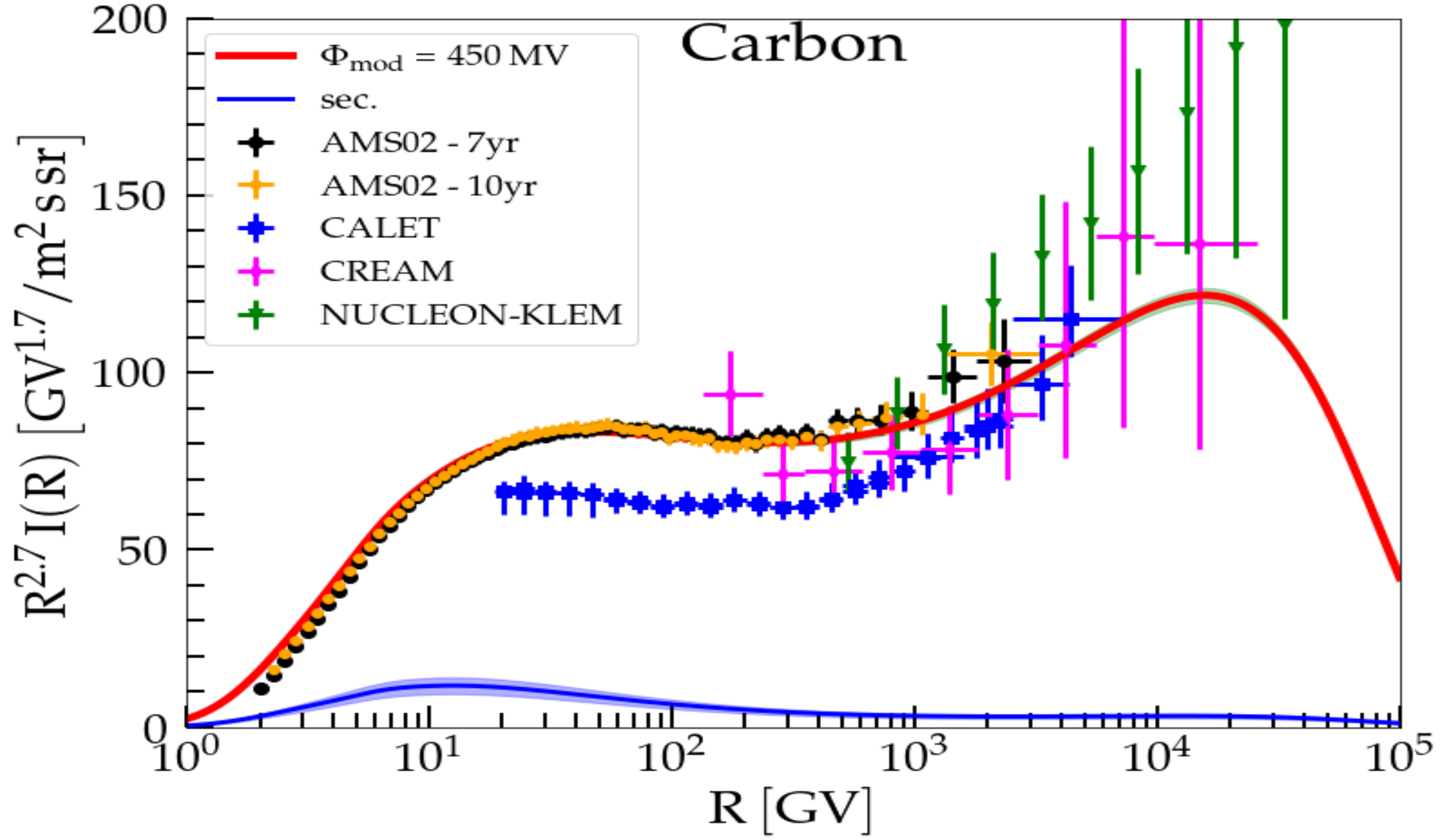
$$\langle (x - x_0)^2 \rangle = \langle (y - y_0)^2 \rangle = 2D_m z.$$

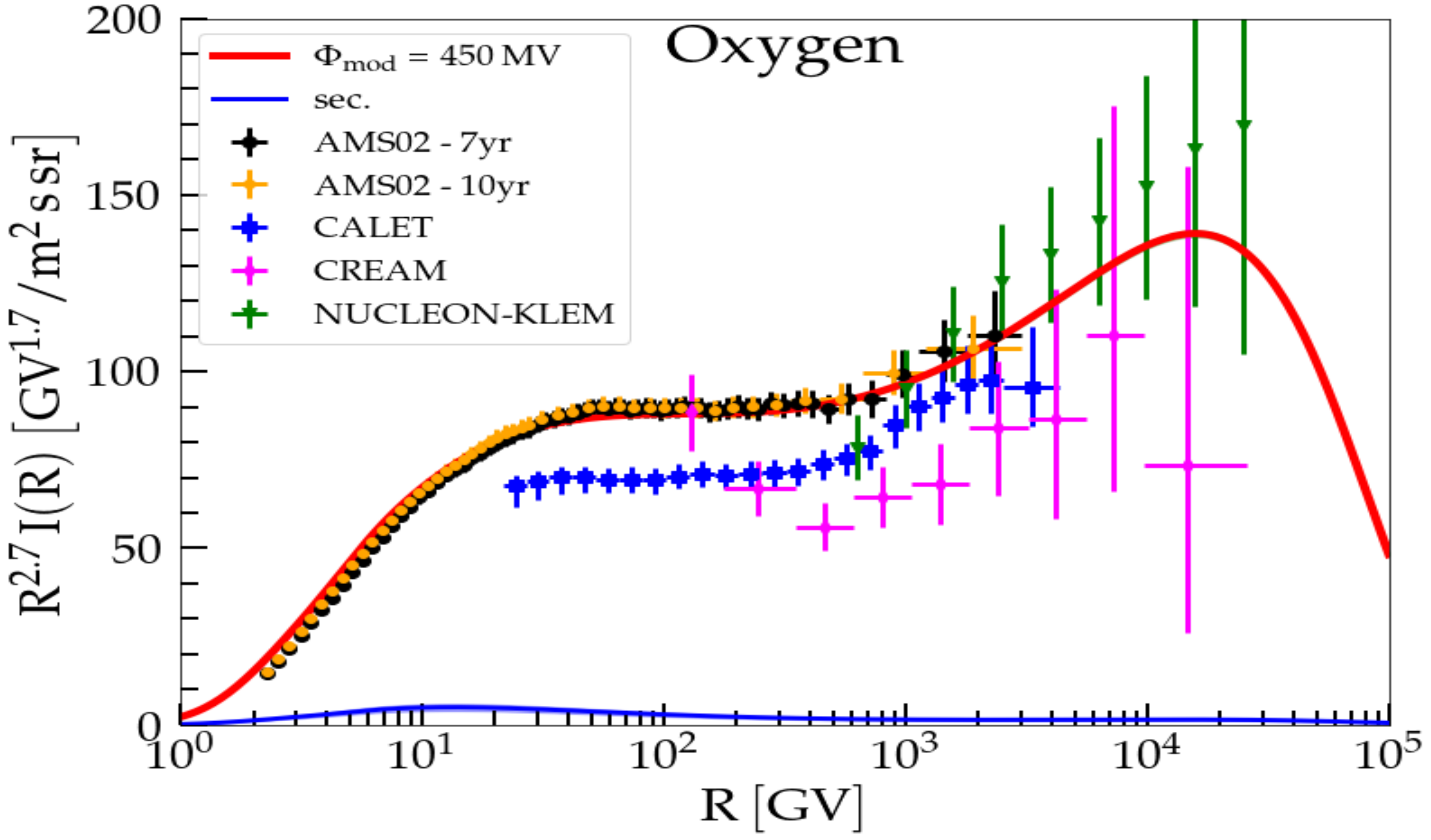
$$\begin{cases} (\Delta R)^2 = 2D_m L_{RR} \\ \Delta t = \dfrac{L_{RR}}{v} \end{cases}$$

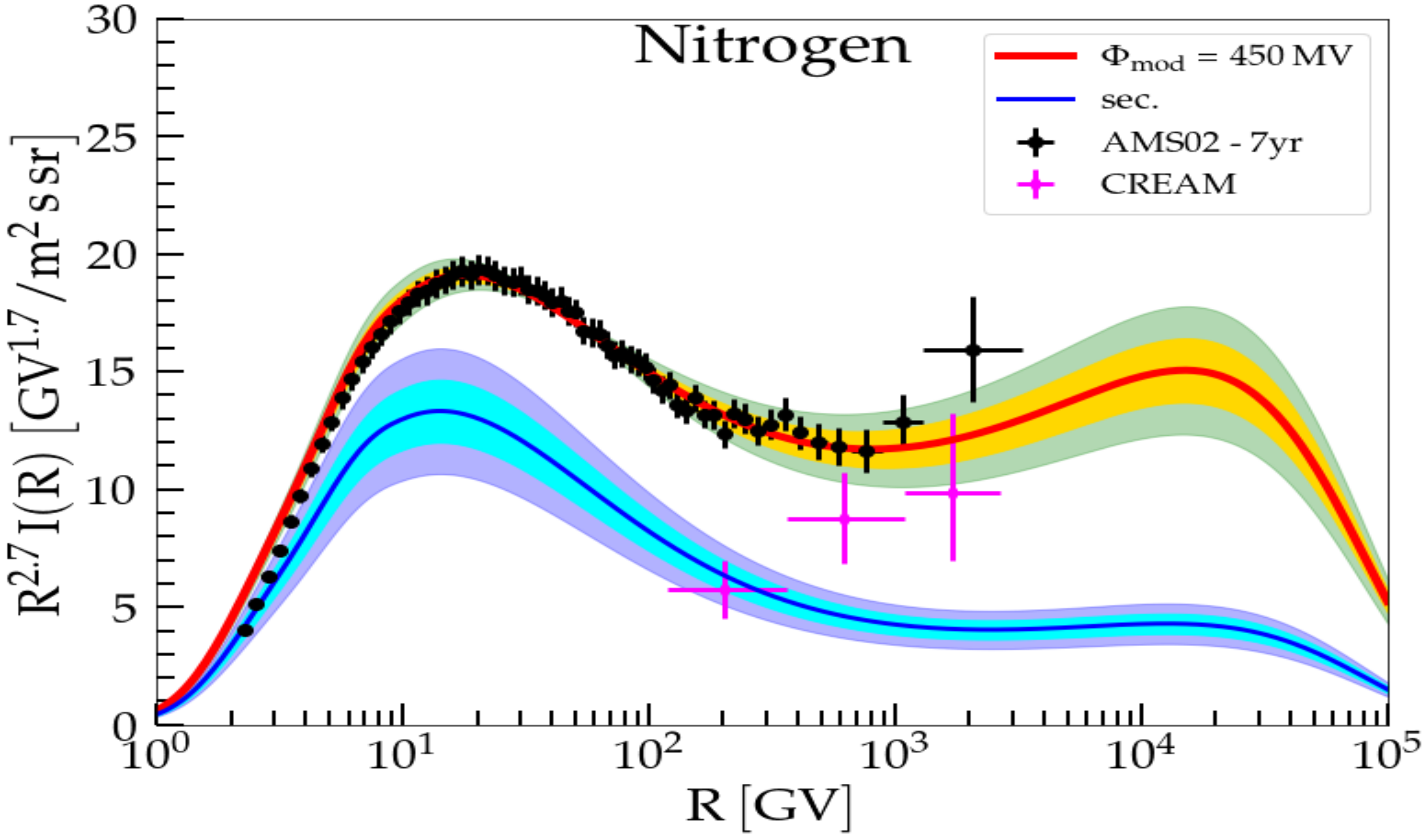
- perpendicular diffusion becomes energy-independent
  - $D_\perp = \dfrac{1}{2}\dfrac{(\Delta R)^2}{\Delta t}$ ⟹ $D_m v \approx 3 \times 10^{28} \left(\dfrac{D_m}{\rm pc}\right) {\rm cm}^2/{\rm s},$
  - (ΔR) rms perp. displacement during each random step $L_{\rm RR}$

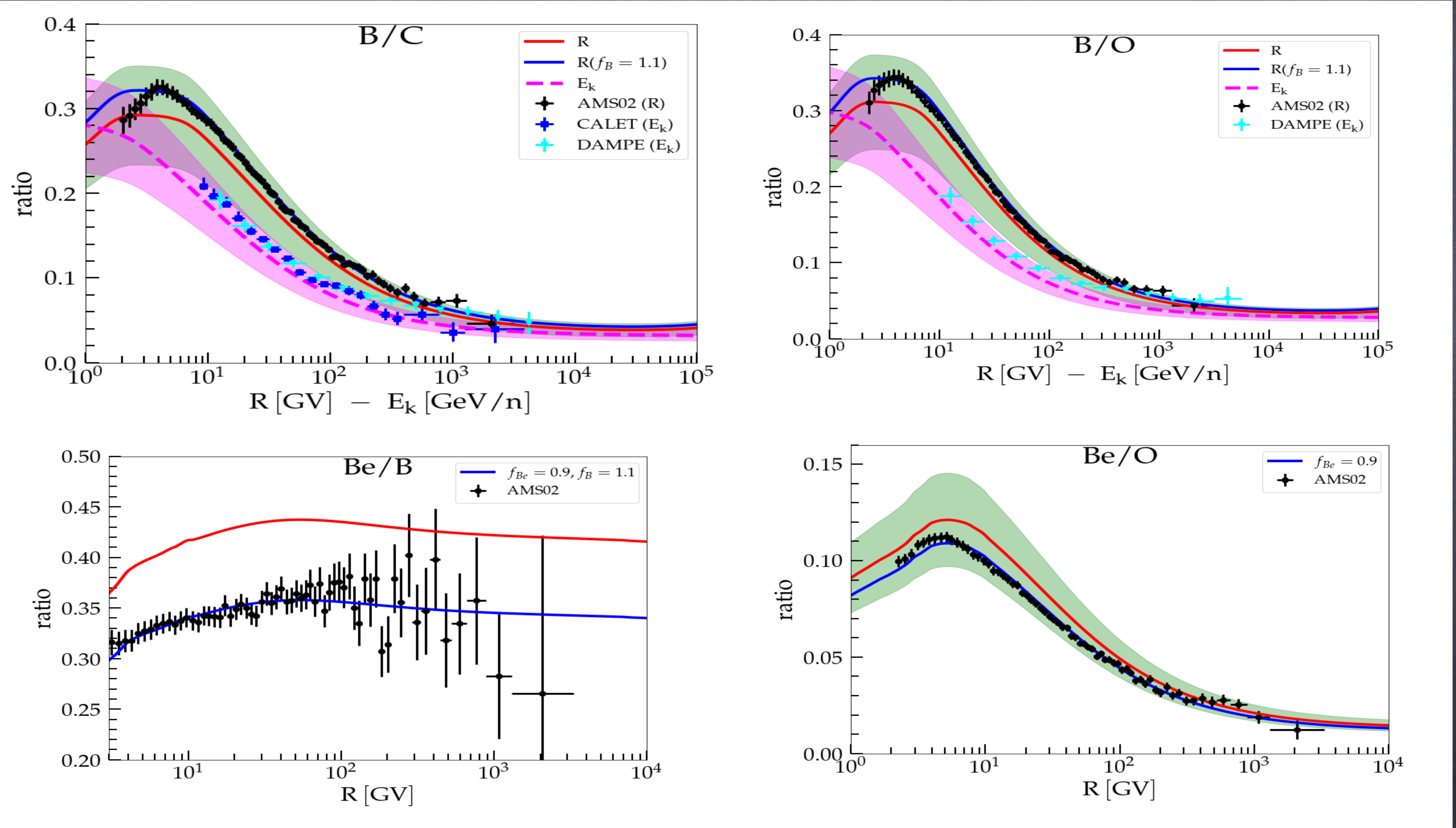


Lithium
Φ_{mod} = 450 MV
f_{Li} = 0.92
AMS02 - 7yr
$R^{2.7} I(R)$ [$GV^{1.7}/m^2 s sr$]
R [GV]
Beryllium
Φ_{mod} = 450 MV
f_{Be} = 0.9
AMS02 - 7yr
$R^{2.7} I(R)$ [$GV^{1.7}/m^2 s sr$]
R [GV]
Boron
Φ_{mod} = 450 MV
f_B = 1.1
AMS02 - 7yr
CALET
$R^{2.7} I(R)$ [$GV^{1.7}/m^2 s sr$]
R [GV]
$^{10}Be/^{9}Be$
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
E_k [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]
200
150
100
50
0
10^0
10^1
10^2
10^3
10^4
10^5


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]
200
150
100
50
0
10^0
10^1
10^2
10^3
10^4
10^5


Nitrogen
Φ_{mod} = 450 MV
sec.
AMS02 - 7yr
CREAM
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]
30
25
20
15
10
5
0
10^0
10^1
10^2
10^3
10^4
10^5


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]