The Symposium of Ultra-High-Energy Gamma Rays from Supernova Remnants and the Origin of Galactic Cosmic Rays

February 26 to March 2, 2026
Yuxi CHINA

Supernova Remnants as the Main Sources of Galactic Cosmic Rays

Insights from Spectral Features

Sarah Recchia (IFJ-PAN - Krakow)

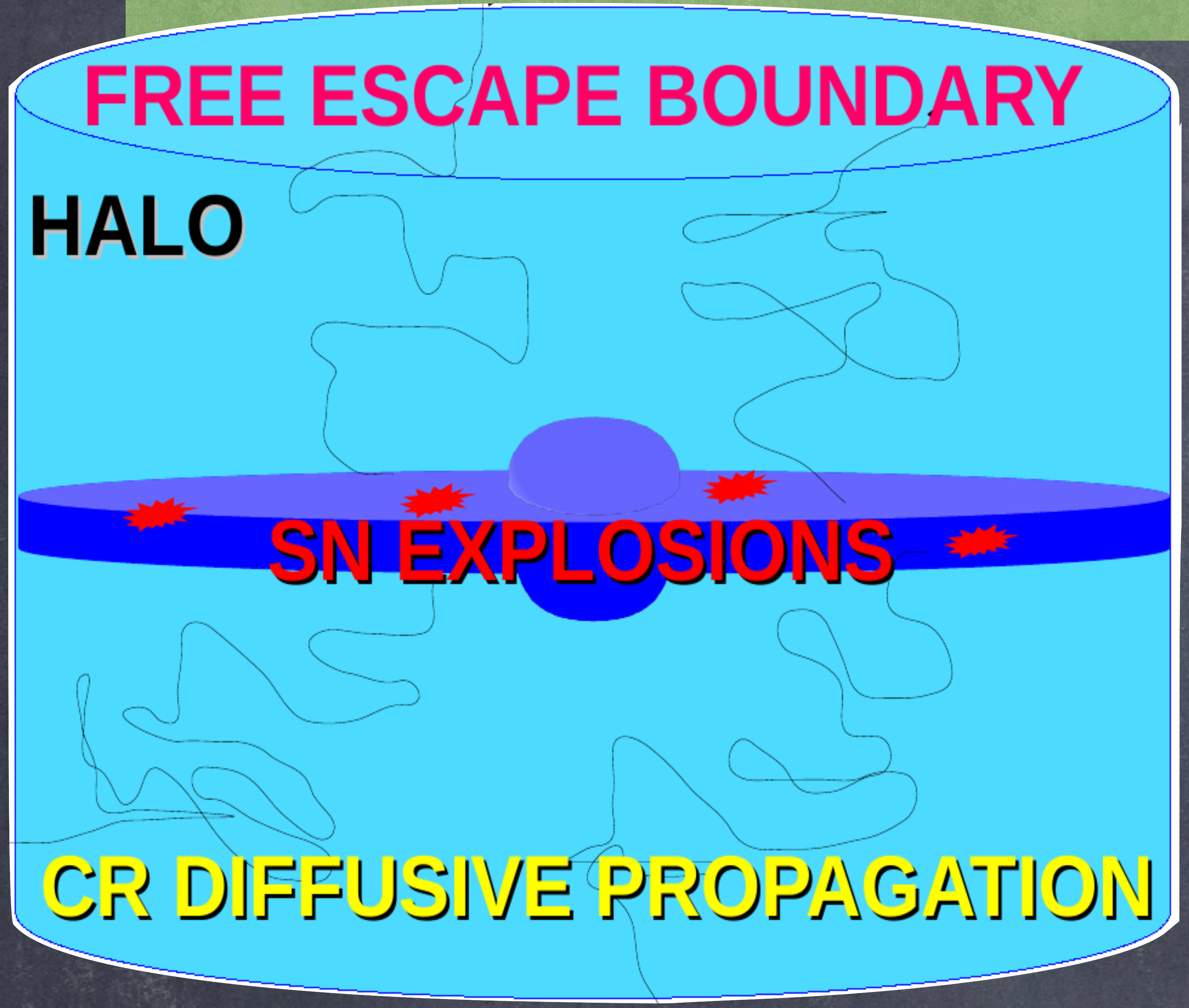
Overview

Recchia & Gabici (2024)

- Where do SNRs reach?
- CR propagate in kpc-scale magnetized halo
- what about propagation in the Galactic disk?
  Several issues ... turbulence ... damping
- spectral features in the CR data GeV - PeV - new results
- anisotropic transport - disk could dominate transport > TeV
- SUB-class of PeVatrons

CR spectrum:
data and main paradigm

CRs in a nutshell - SNR paradigm



diffusive propagation in HALO

- kpc-scale magnetized halo as
- repeated crossings of the disk -> secondaries
- B/C, unstable isotopes...
- grammage, energy-dependent escape
- $D(E) \propto E^{0.3-0.7}$

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

diffusive shock acceleration

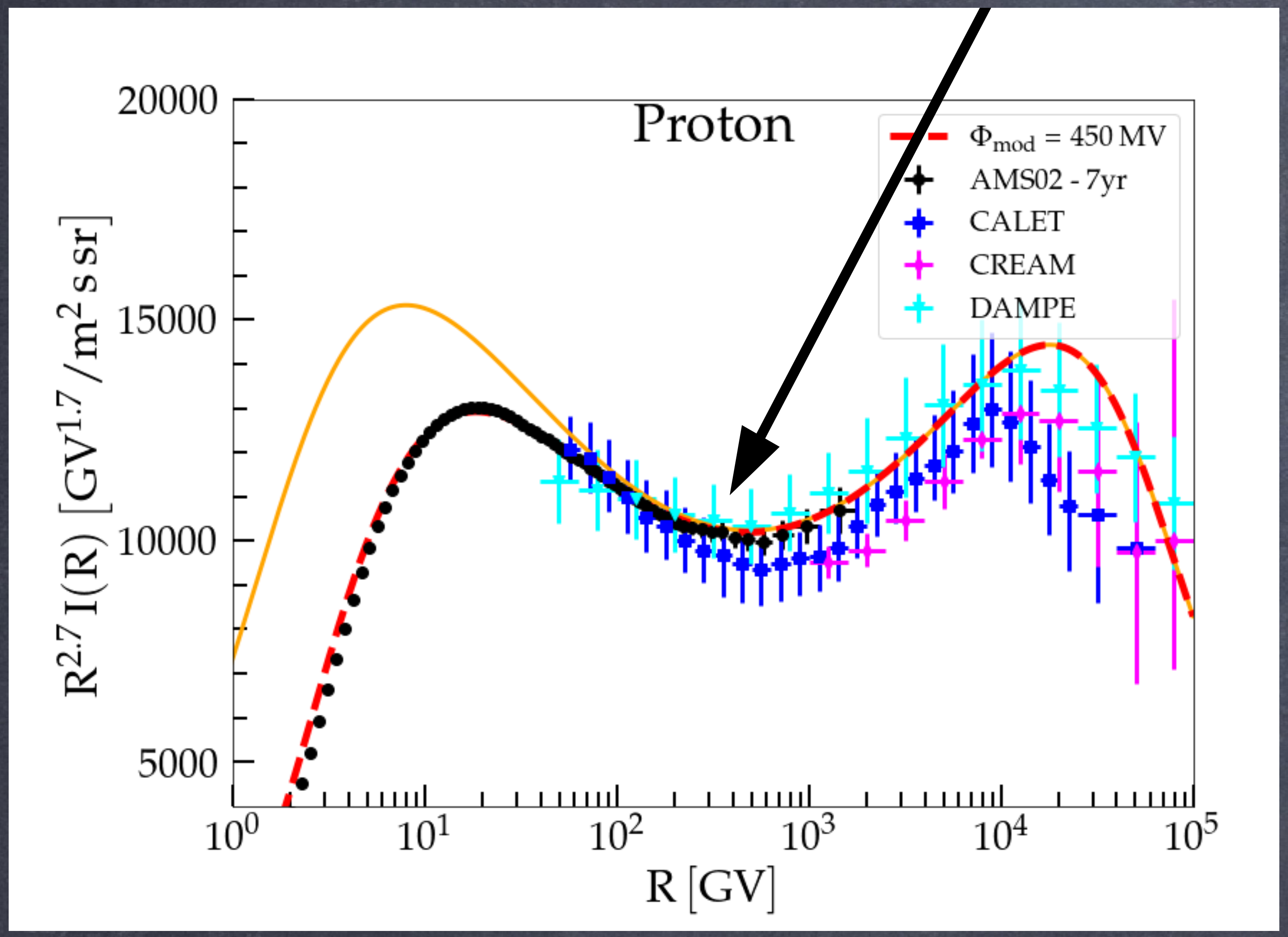
- ~ 10% of SNR power
- power-law spectrum $Q_{\rm CR} \propto E^{-2}$
- protons to the knee? $\approx 3\,\mathrm{PeV}$

?? where is the limit of SNRs ??

?? what is the role of the disk ??

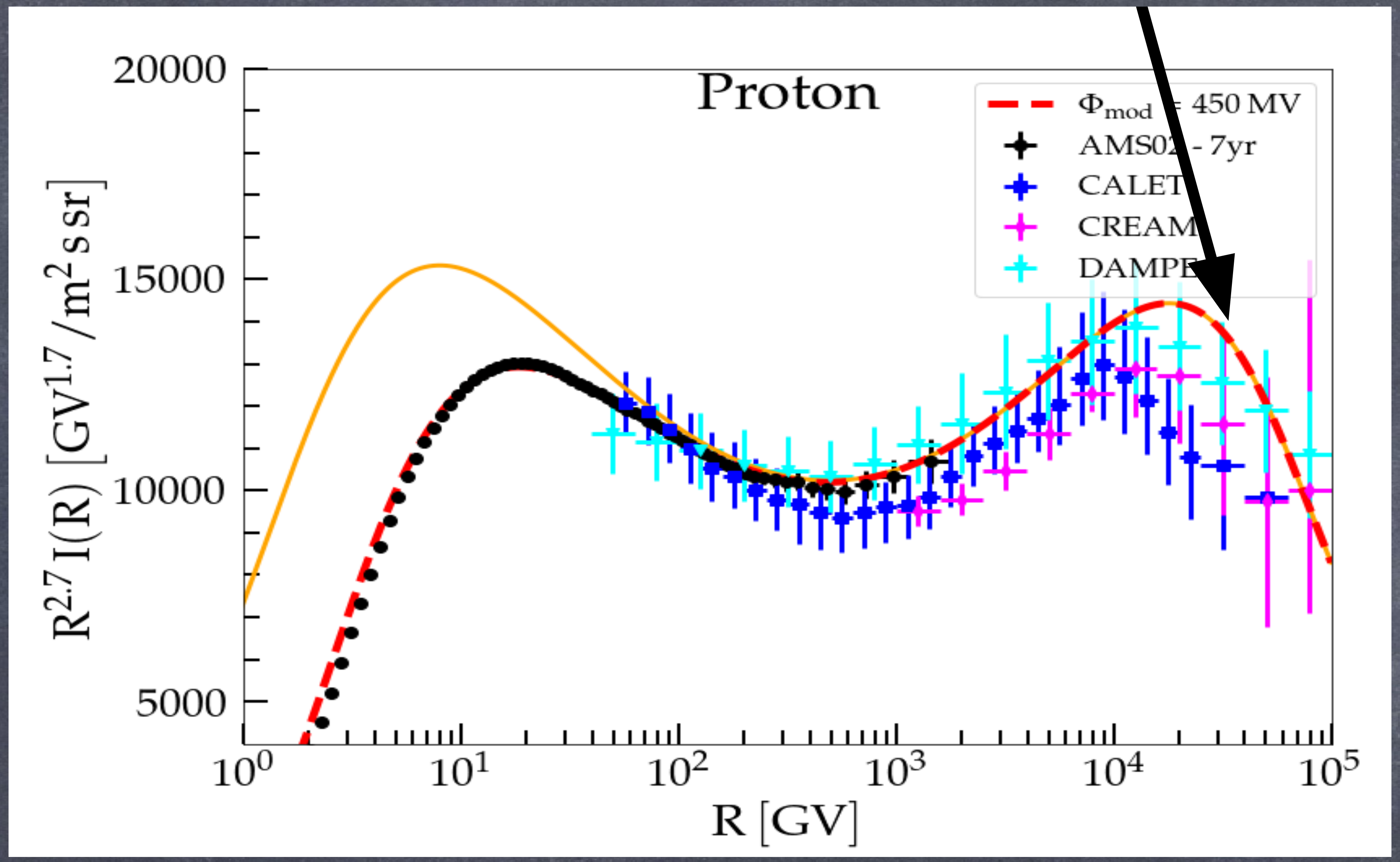
Breaks in GV-PV range

~ 300 GV



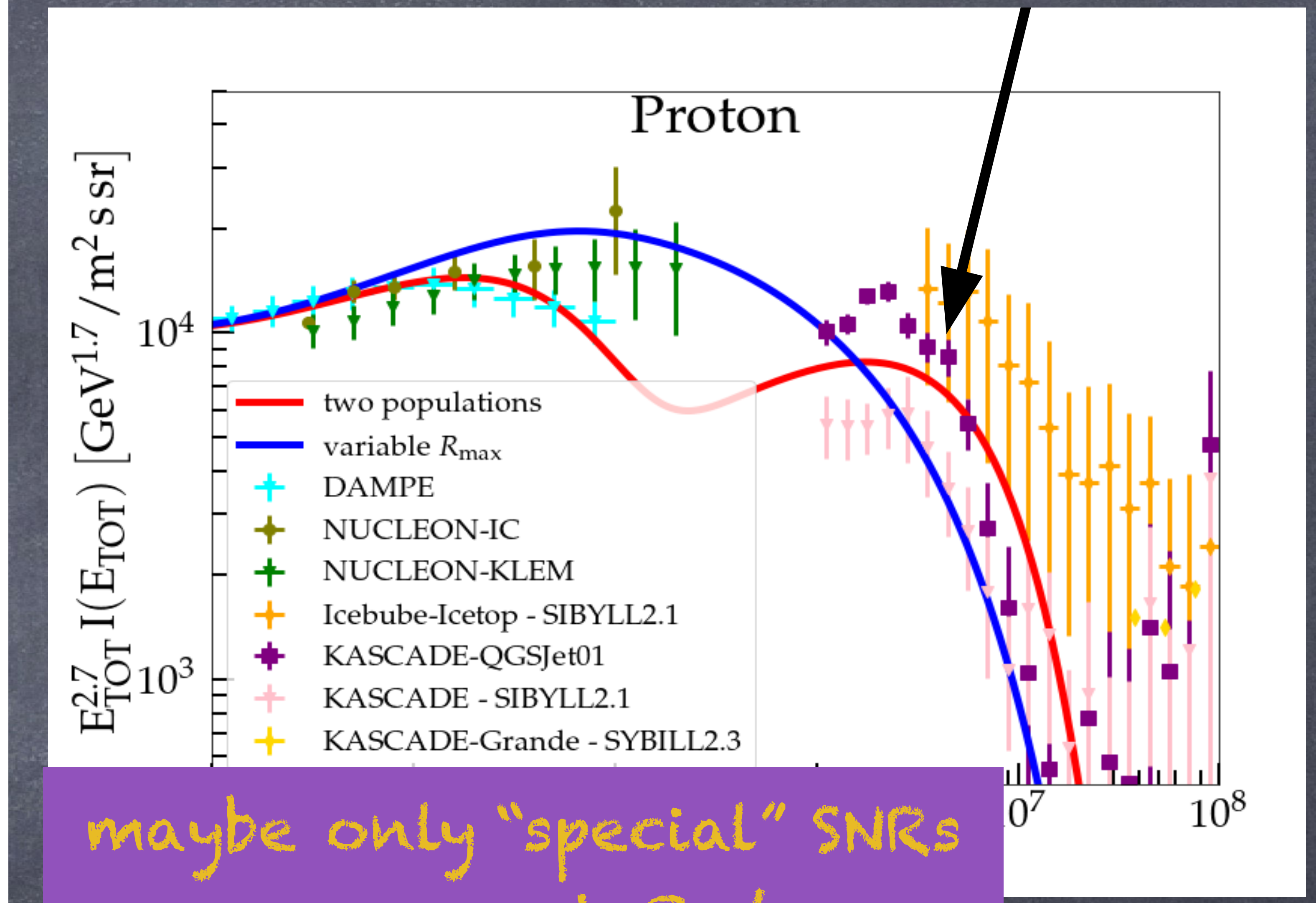
- hardening by ~ 0.1
- confirmed in secondary nuclei, by ~ 0.2
- change in propagation

"Dampe" ~ 15 TV



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

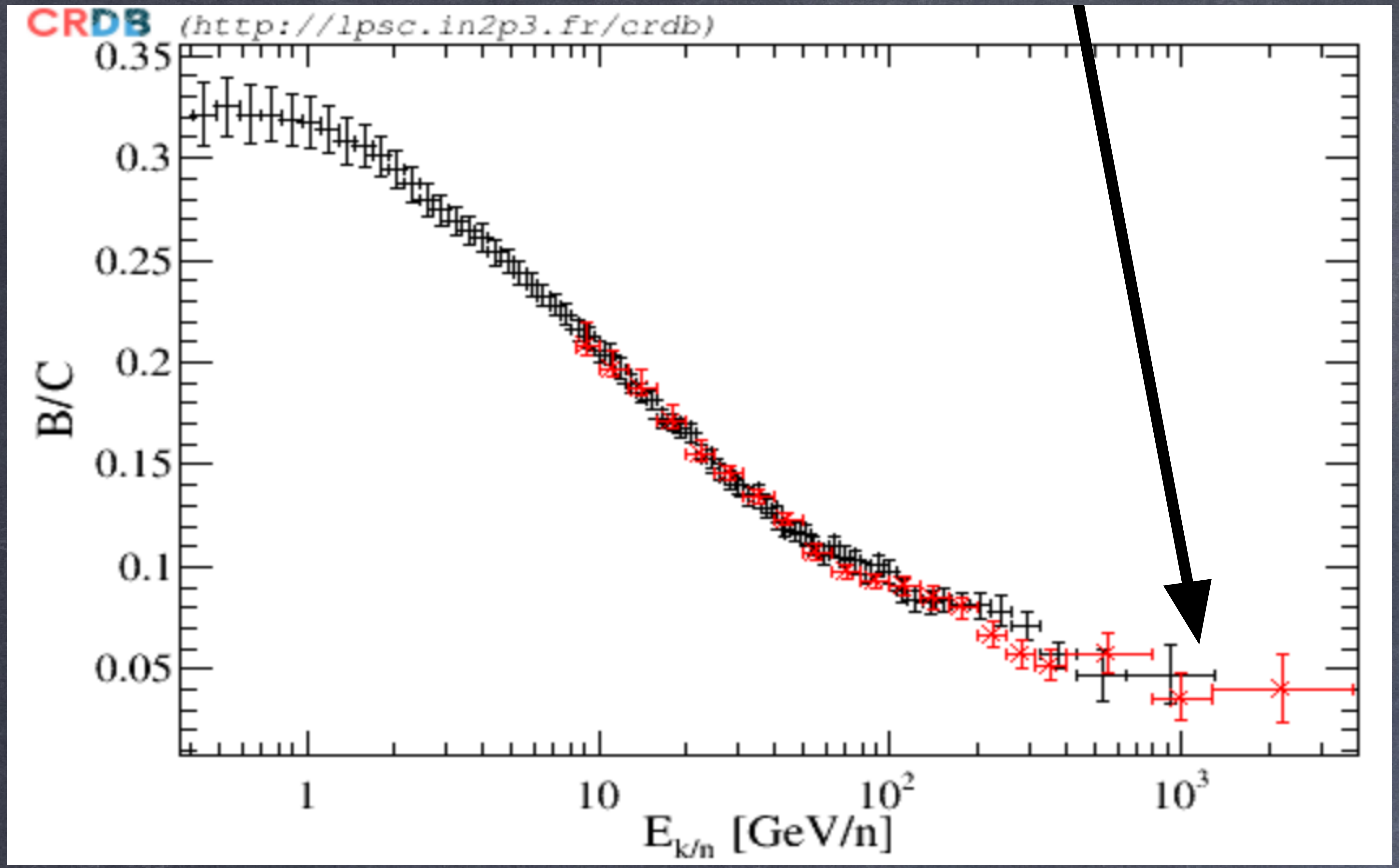
"Knee" ~ 3 PV

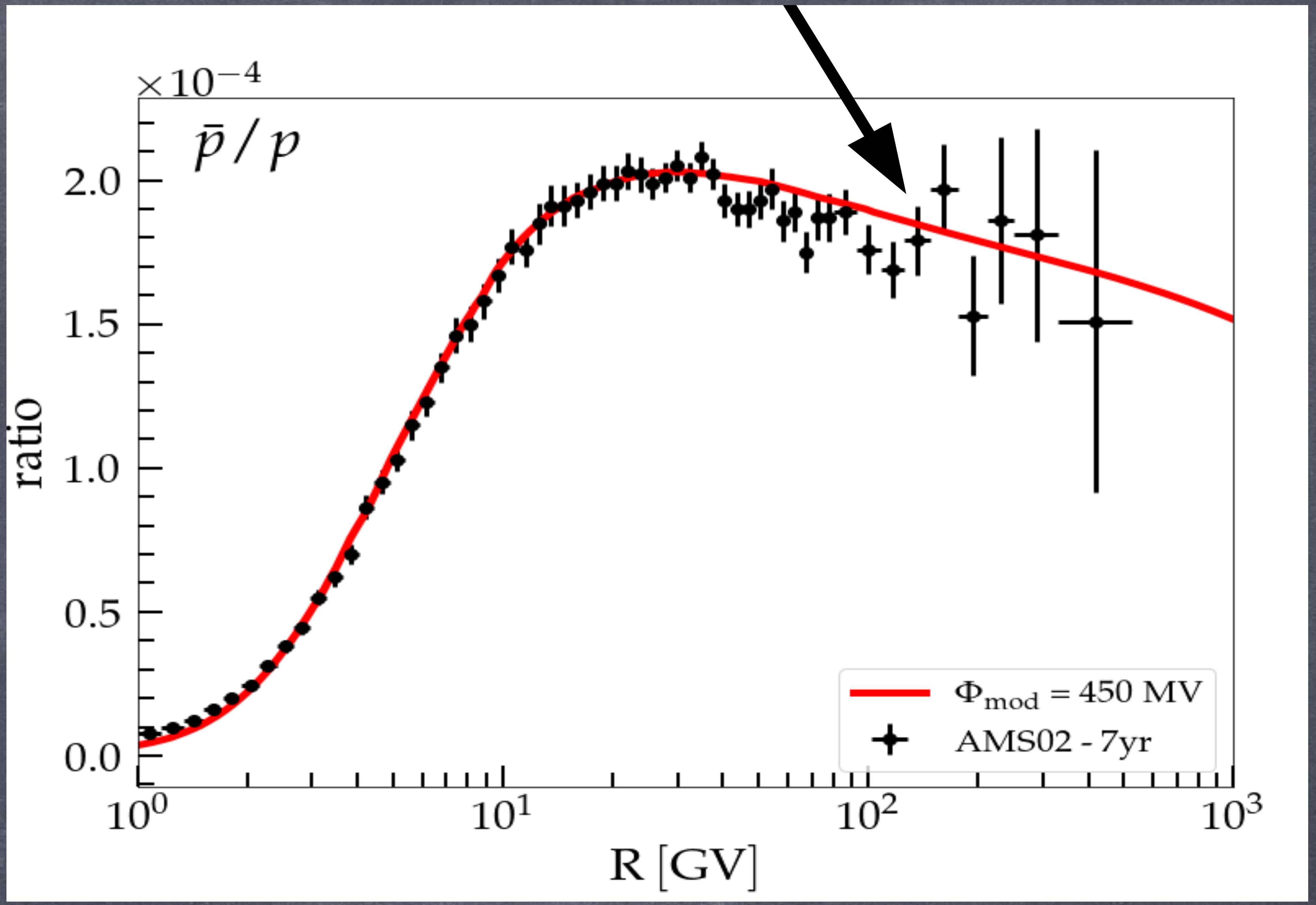


maybe only "special" SNRs can reach PeV

- 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)

What about propagation in the Galactic disk?

The Galactic disk

turbulence & damping

- scattering in disk debated Skilling (1971)
- many sources of turbulence BUT …
- which is effective at scattering? (anisotropic cascade of Alfvén waves …)
- other modes?
- self-generation only up to few 100s GeV…
- effective damping (ion-neutral, turbulent damping, …)

SHOULD WE BOTHER?

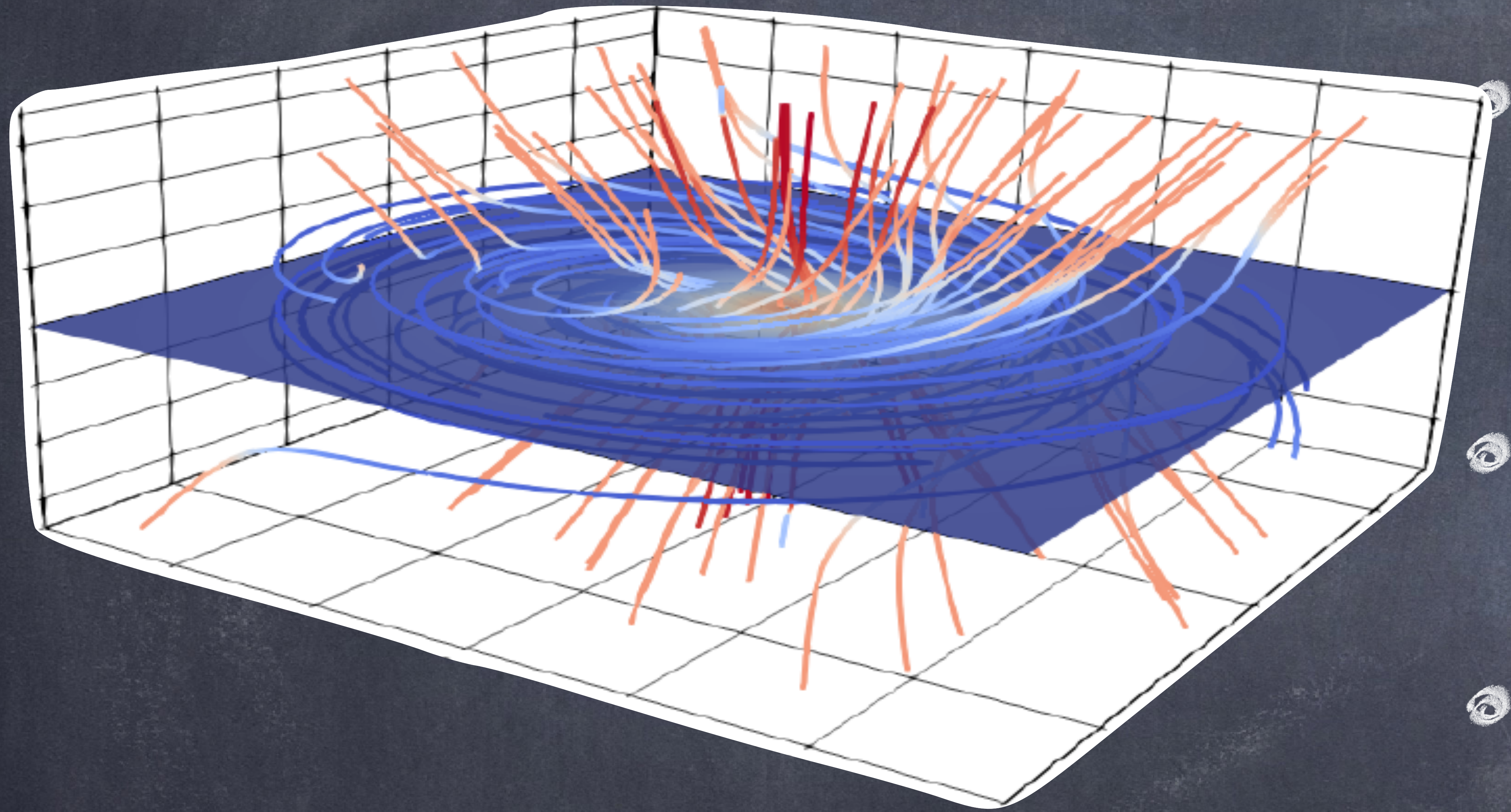
- propagation in the disk is often ignored
- just a passive target for secondary production
- 10s time smaller than the halo…

Recchia et al (2022)

MAYBE YES…

The Galactic disk

Recchia & Gabici (2024)



- IN THE DISK - field lines mostly along GP
- IN THE HALO - field lines mostly perp to GP
- to ESCAPE CRs need cross the disk mostly perpendicular to the field lines ...
- dependence on Galactocentric distance

Cerri et al. (2017)

DISK : weak scattering + perpendicular transport

HALO : typical energy dependent isotropic diffusion, D(E)

Perpendicular diffusion: weak scattering limit

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

Shalchi (2020) - review perp. Transport

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

Casse et al. (2002)

(Kadomtsev & Pogutse (1979)
Kirk et al. (1996)

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

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

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

?? where is the limit of SNRs ??

Alternative framework
CR data ~ GV- PV

Recchia & Gabici (2024)

CR propagation in the halo

- effective scatterning
- typical (isotropic) diffusion D(E)
- $D(E) \sim 10^{28}$ cm^2/s E$^{0.7}$
- + advection away from the disk

CR propagation in disk

- weak scattering along B (GP)
- $D_\perp \sim D_m c$ [energy-independent]
- injection/spallation

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

Model of CR transport in the disk-halo

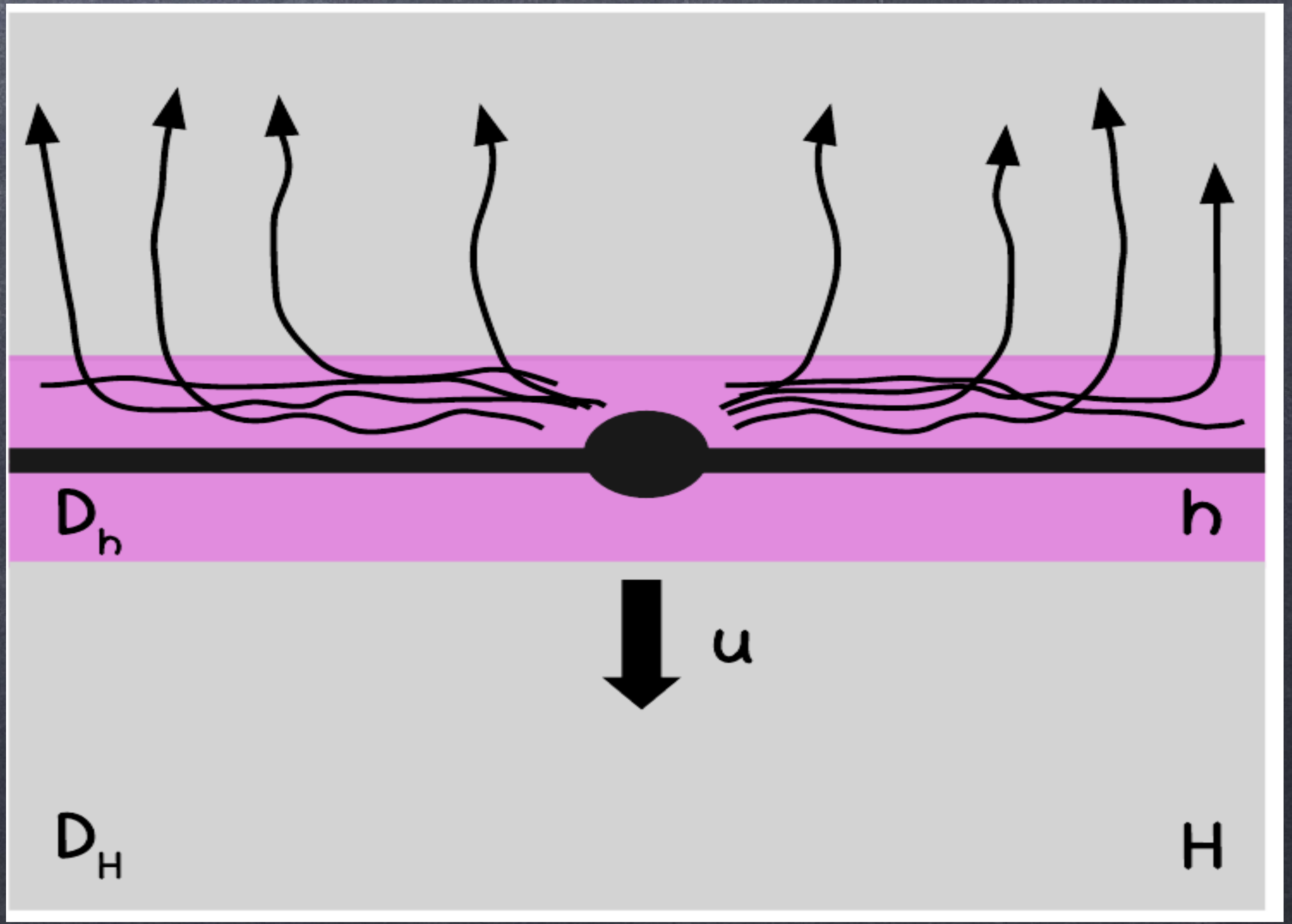
- "slab model"
- prop. only depends on distance from the disk
- continuous and homogeneous injection (no source granularity)
- steady-state solution

... ok if small inhomogeneity along the GP

... if many sources contribute

... NEED FOR ANISOTROPIC DIFFUSION (AT HE...)

... approach may break (more on that later)



Analytic solution of the CR transport

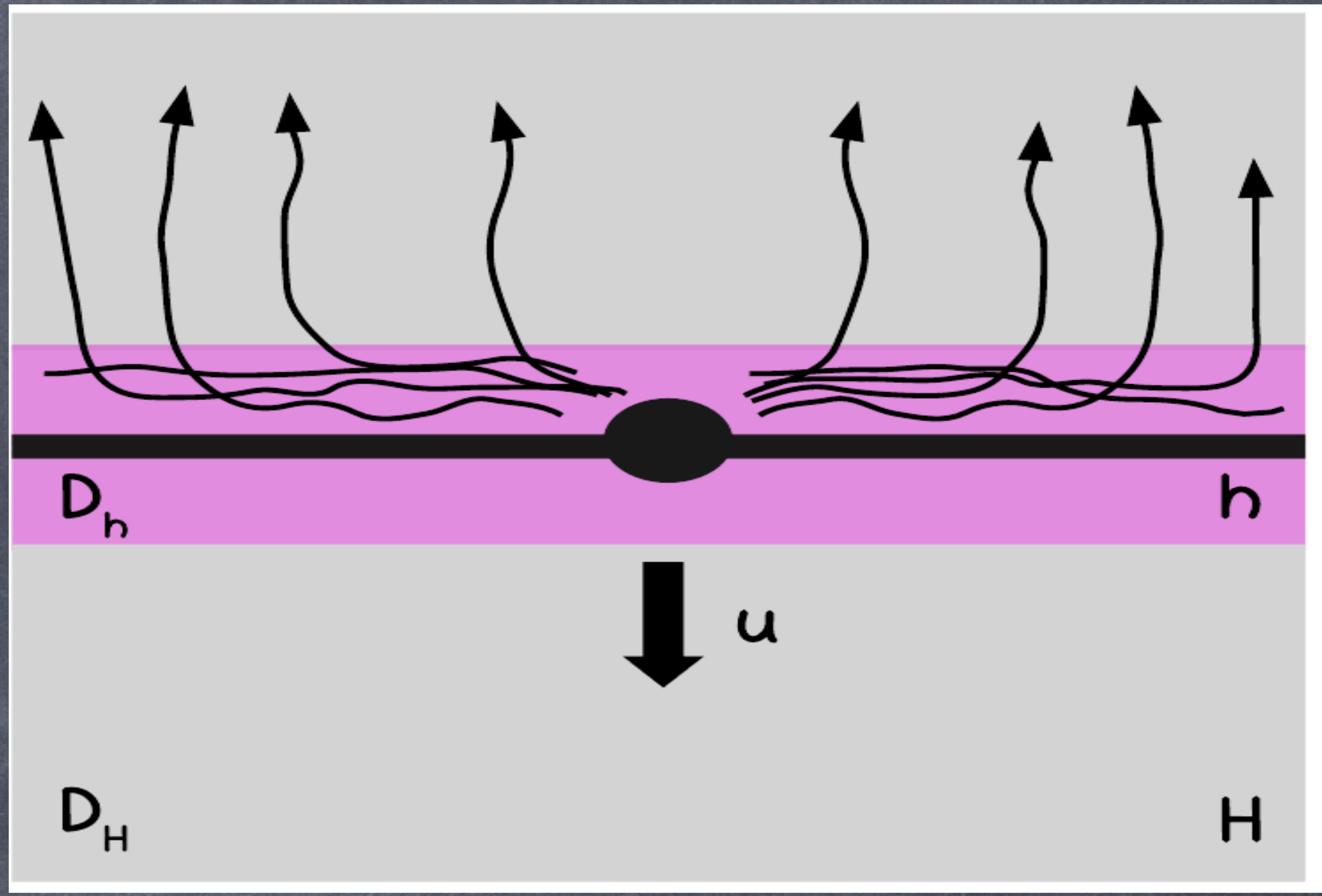
flux of stable nuclei VS E_{kin}/n

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

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

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

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

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	$(\delta = 0.8)$

diffusion in disk
constant in E

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

Analytic solution of the CR transport

residence time in disk

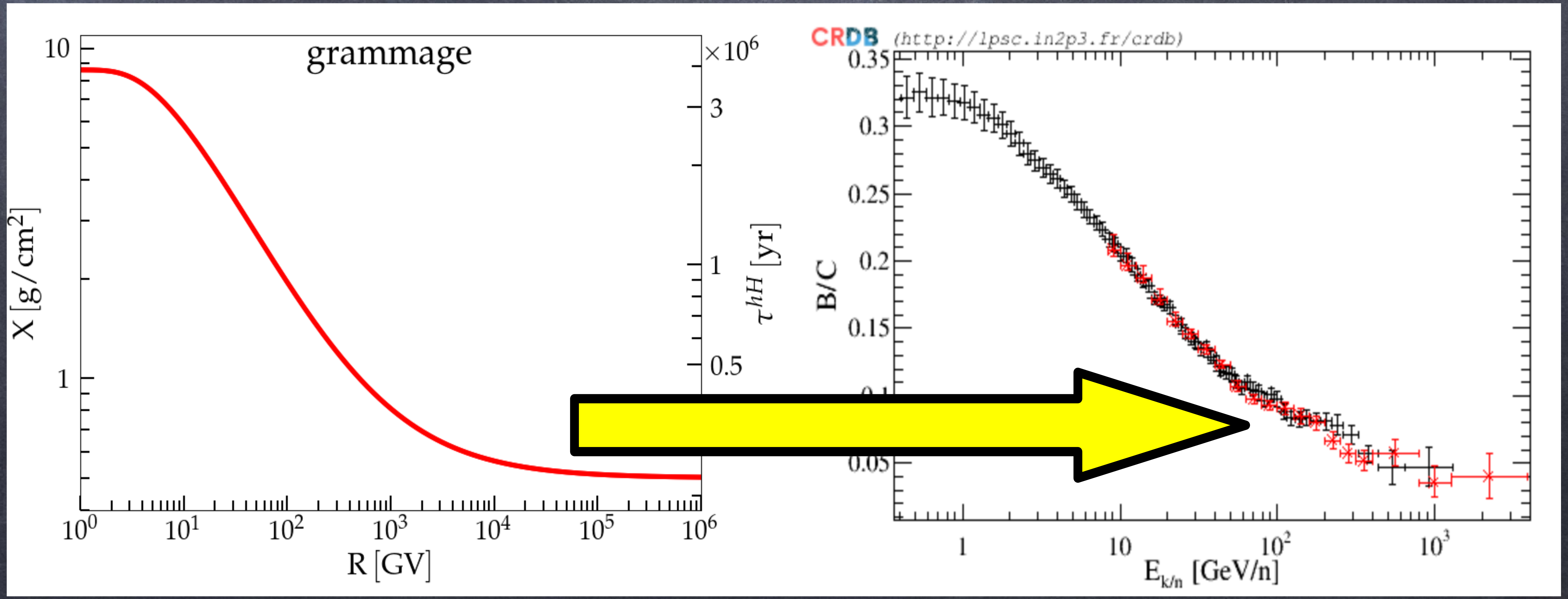
$$\tau_\alpha^{hH} \equiv \frac{h^2}{D_h} + \frac{h\,H}{D_H}\,\frac{1-\exp^{-\frac{u\,H}{D_H}}}{\frac{u\,H}{D_H}}.$$

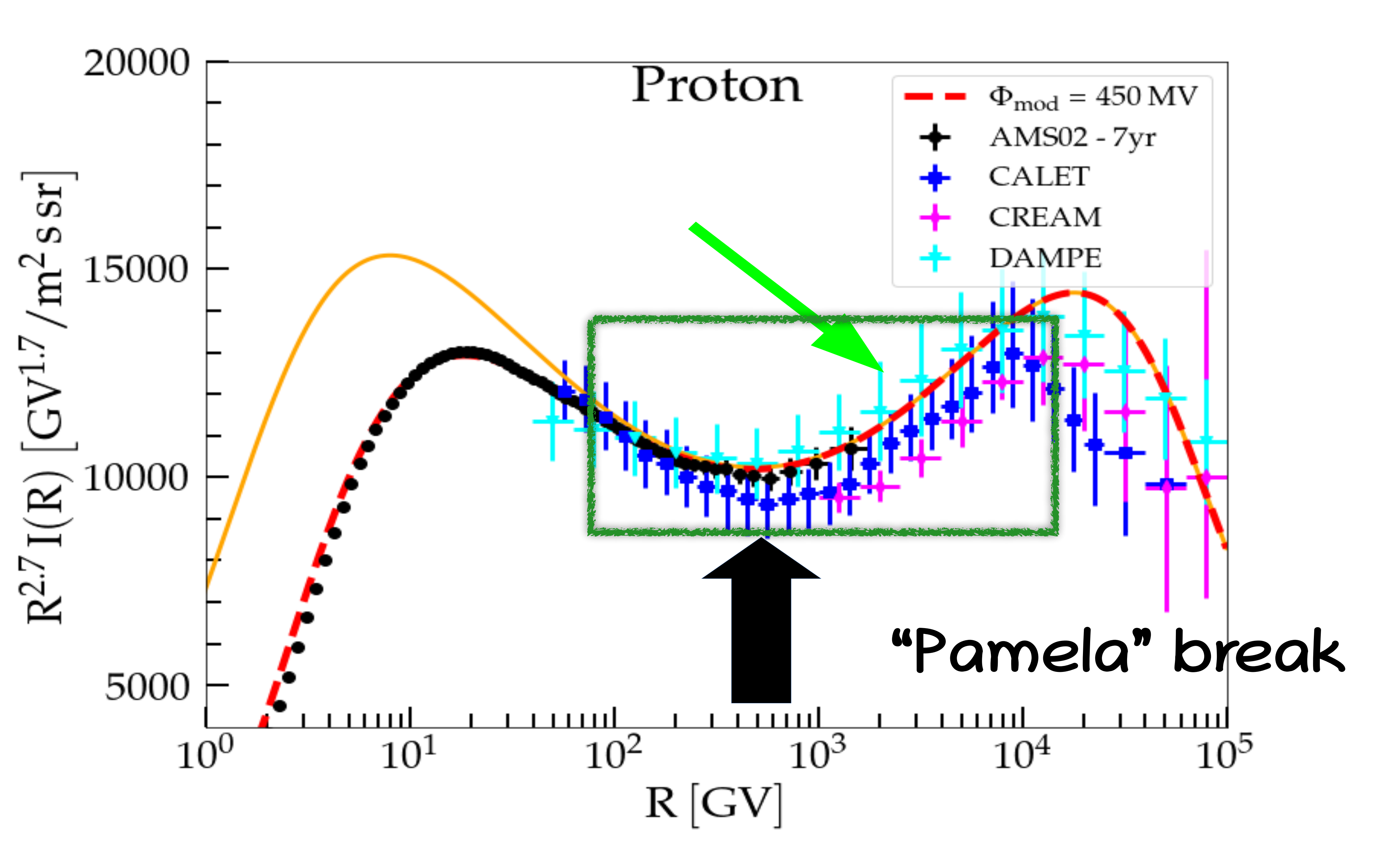
repeated crossings of disk induced by diffusion in halo
decreases with E due to $D_H \sim E^{0.7}$

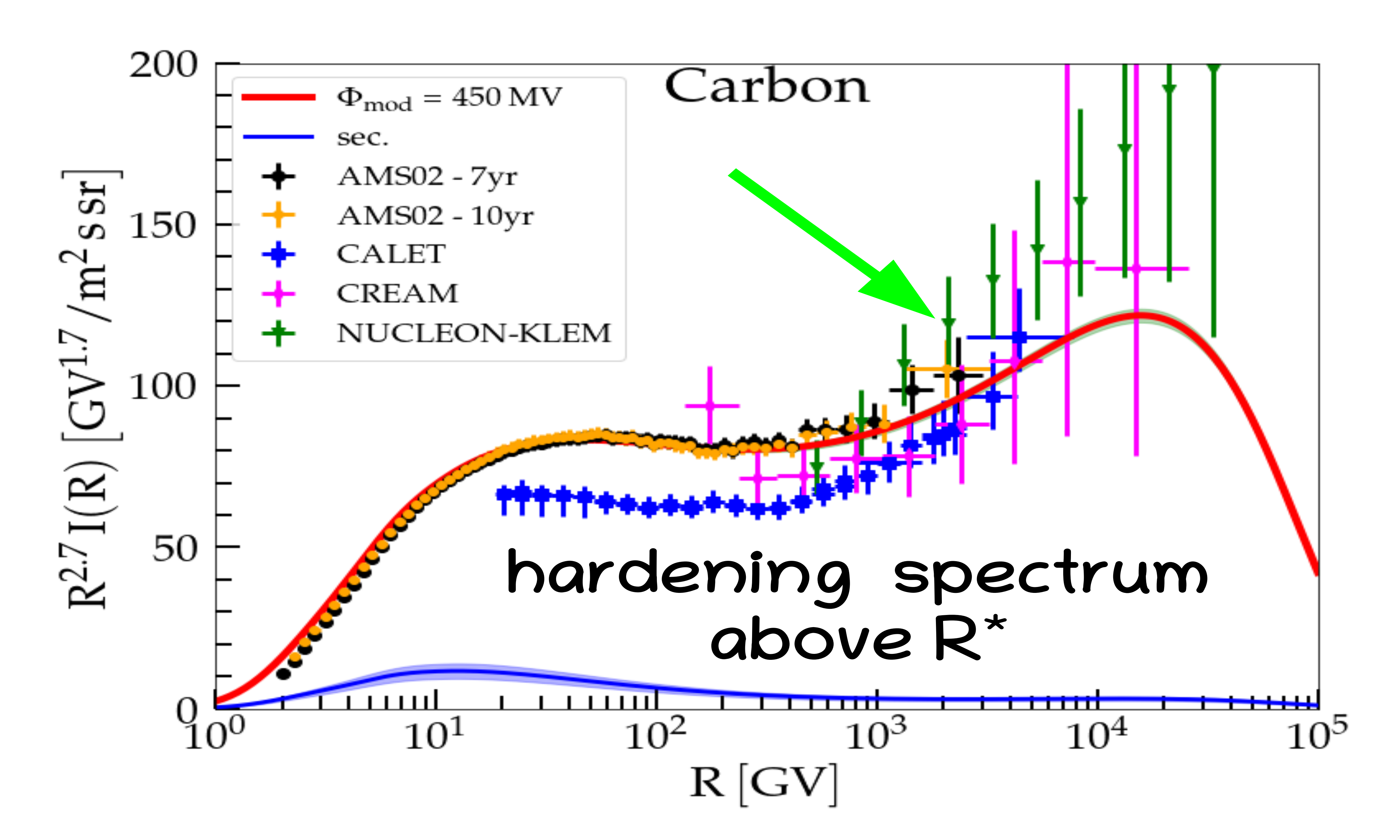
diffusion in disk
constant in E

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

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

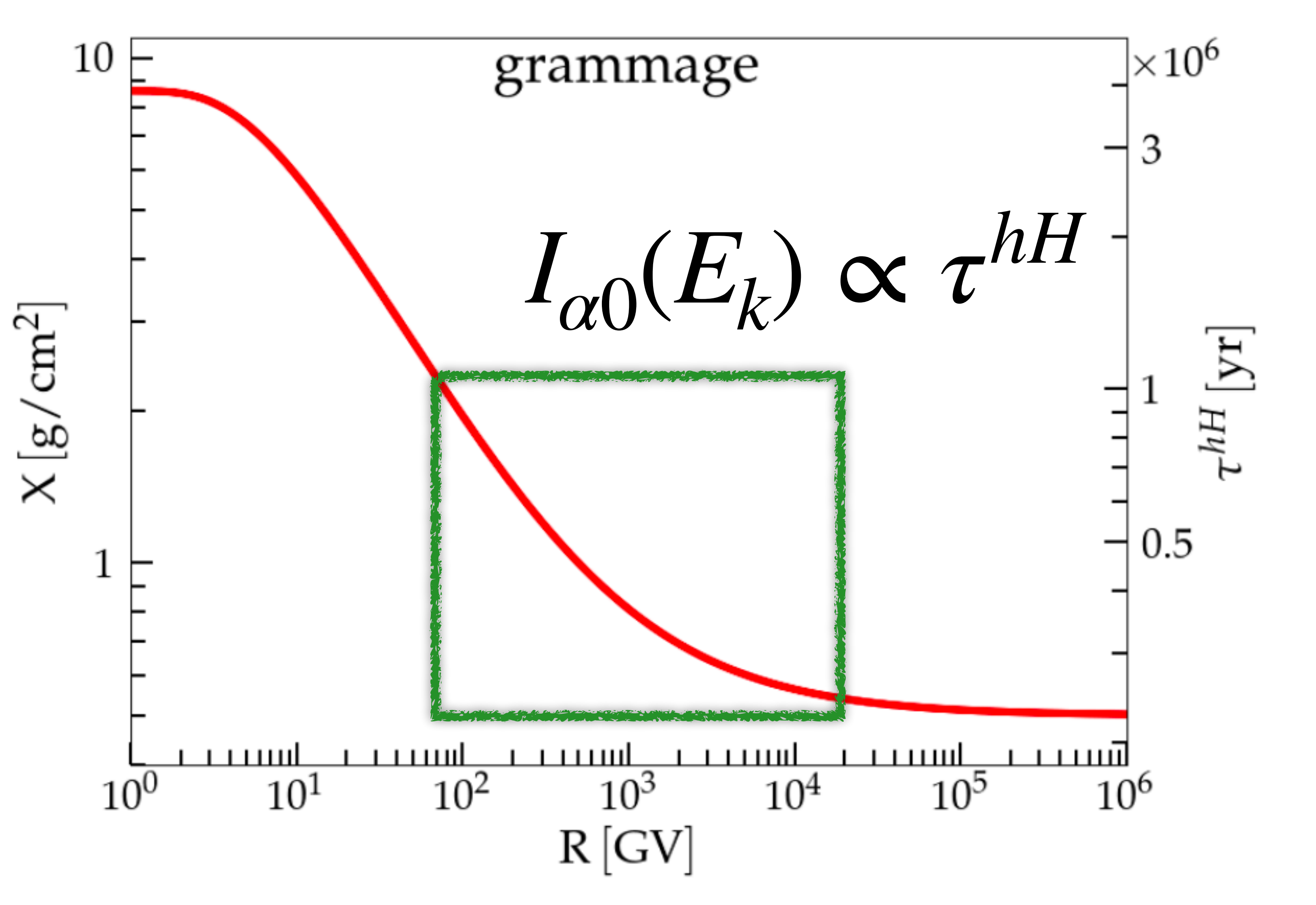






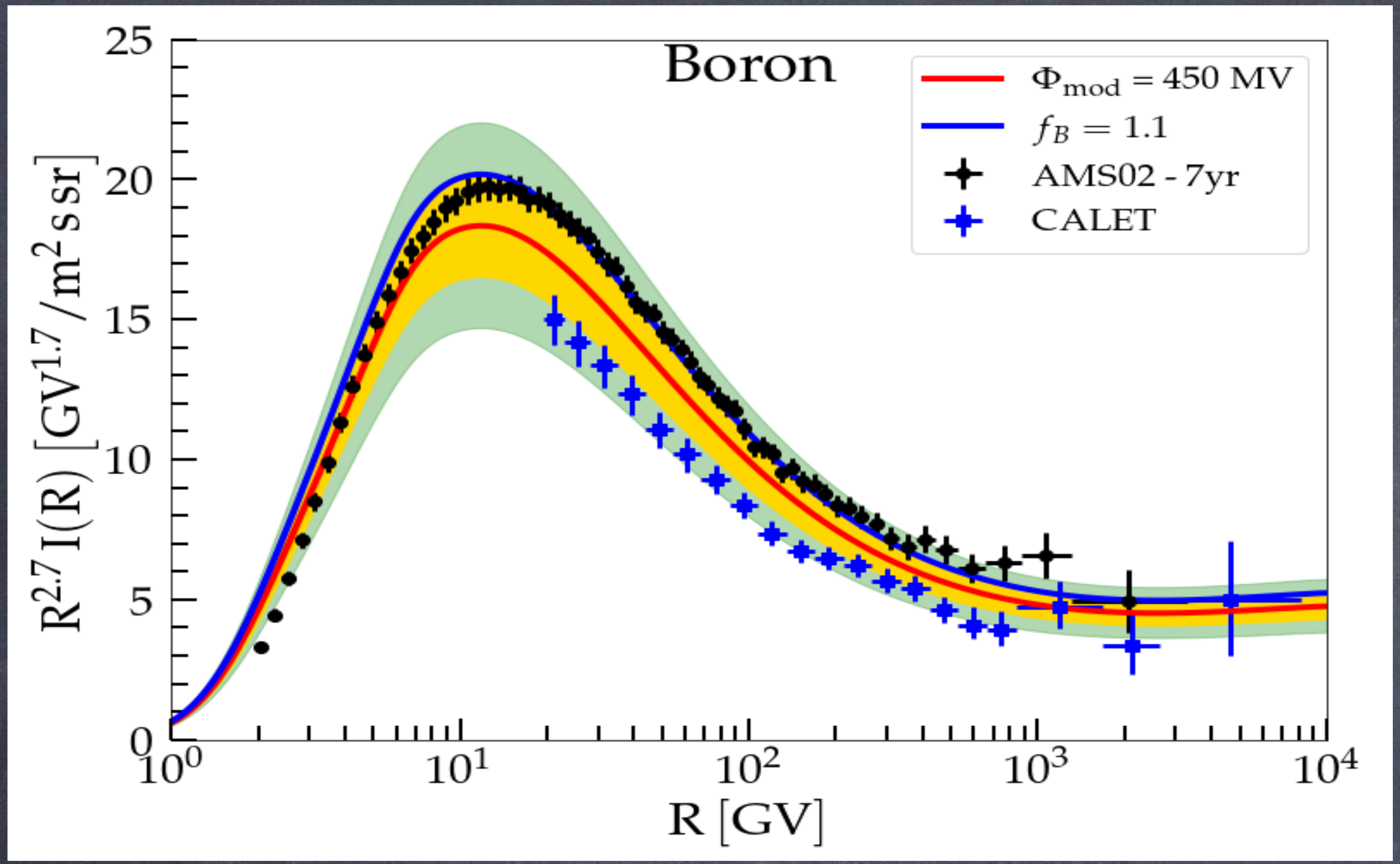
Above ~ 10s GeV

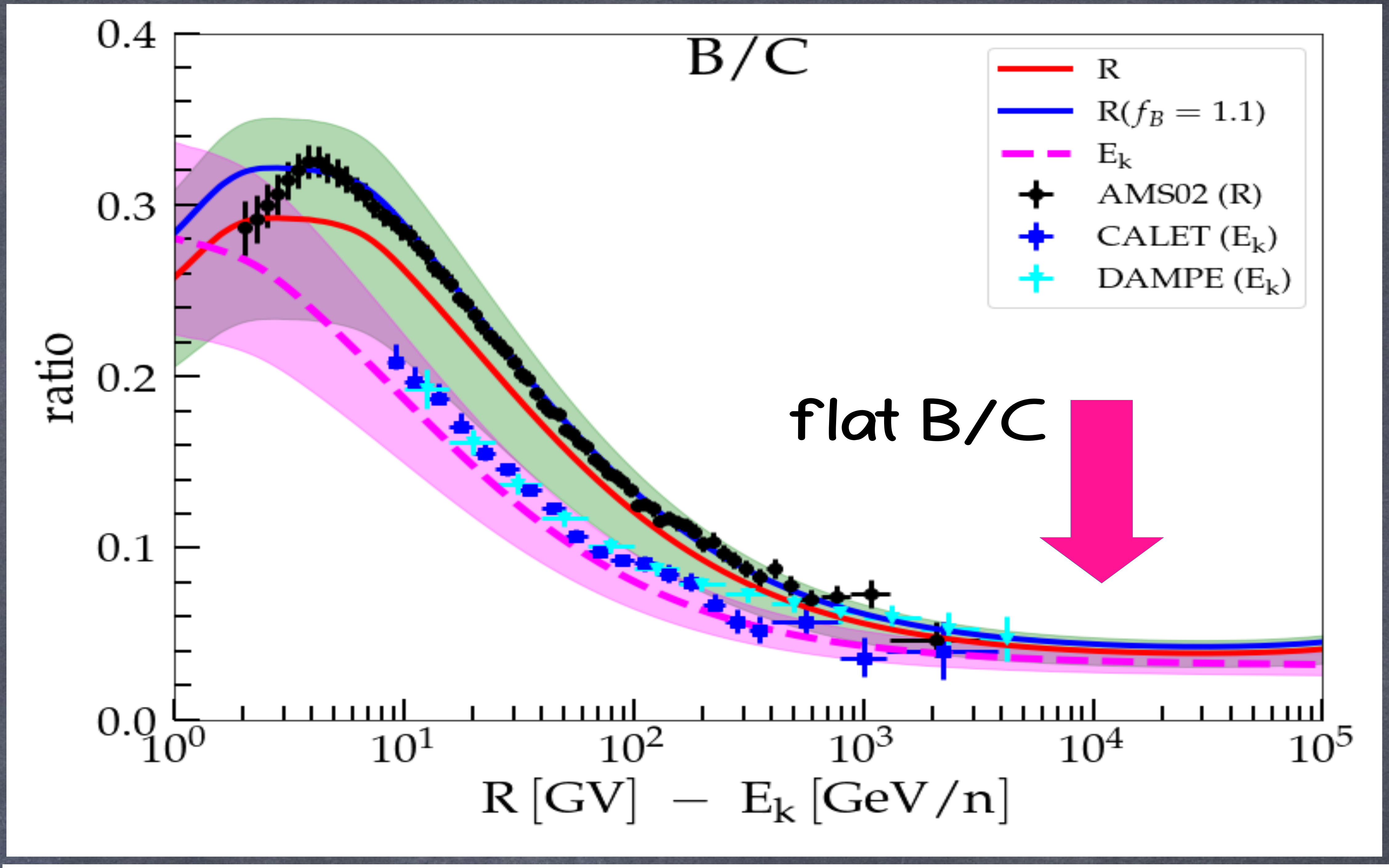
smooth transition halo -> disk



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

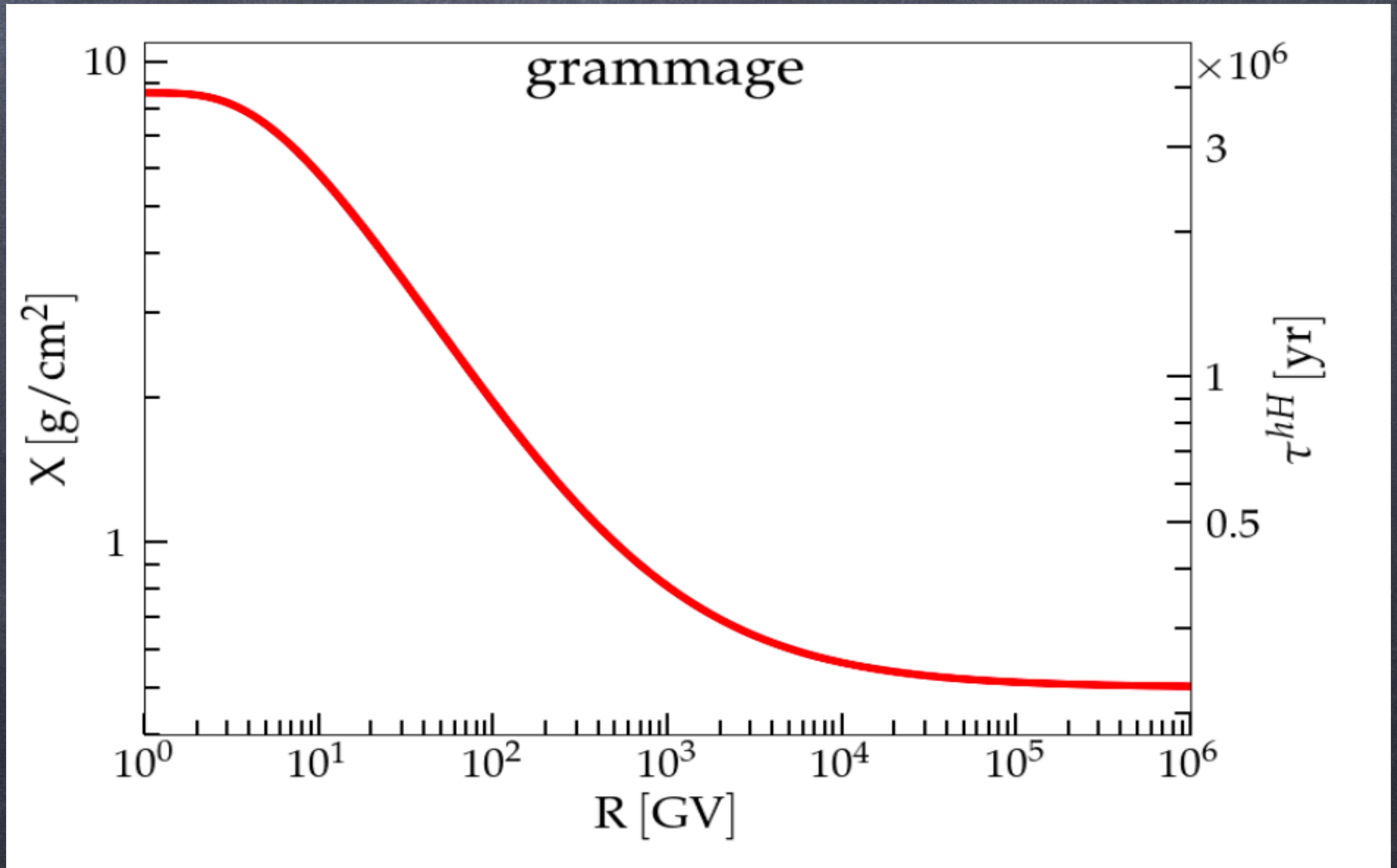
$\approx$ 6 TV ($\delta = 0.5$)
$\approx$ 2 TV ($\delta = 0.6$)
$\approx$ 500 GV ($\delta = 0.7$)
$\approx$ 200 GV ($\delta = 0.8$)





clear prediction of a flat

B/C above ~ 10 TeV



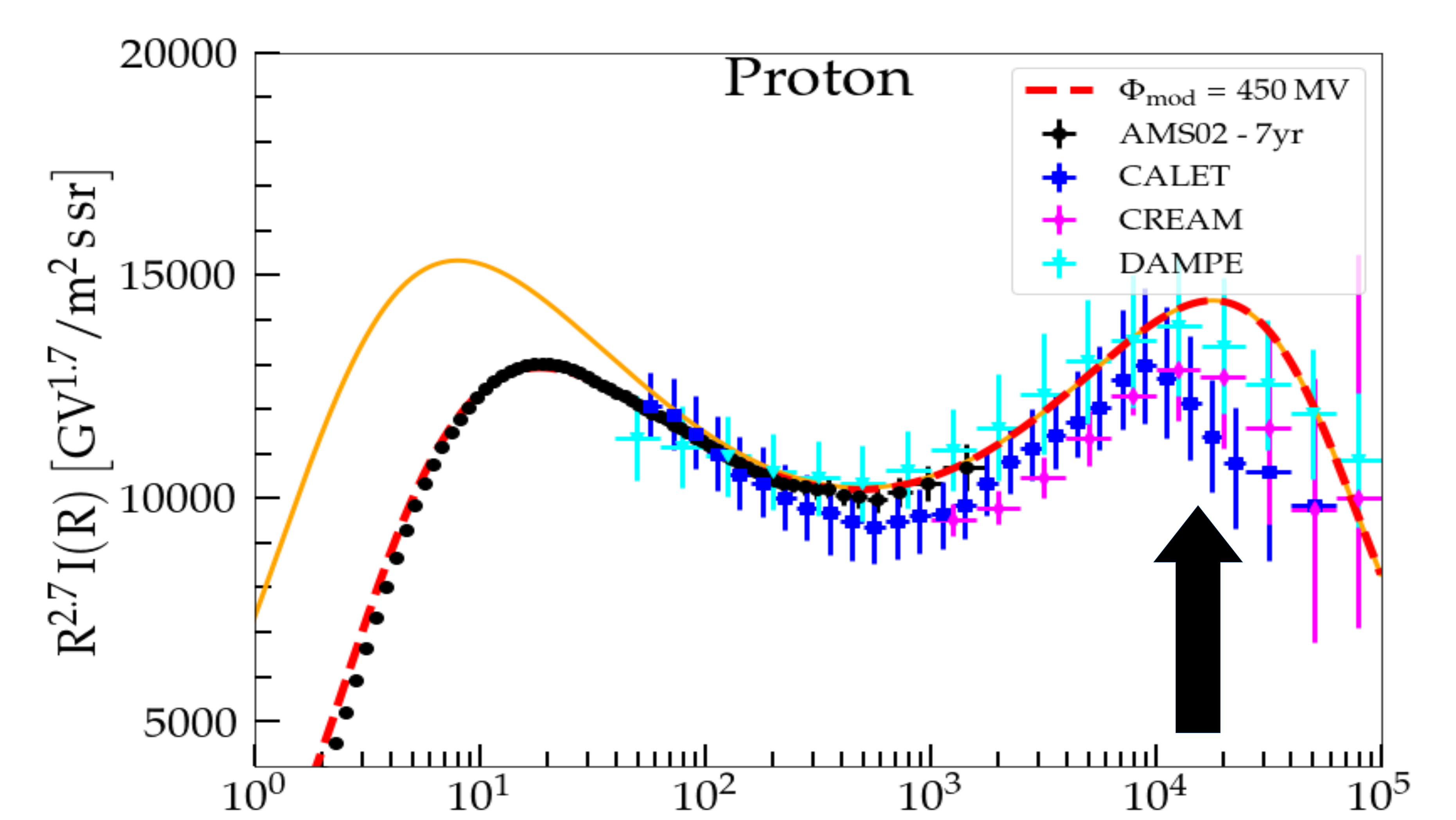
hints from current data but

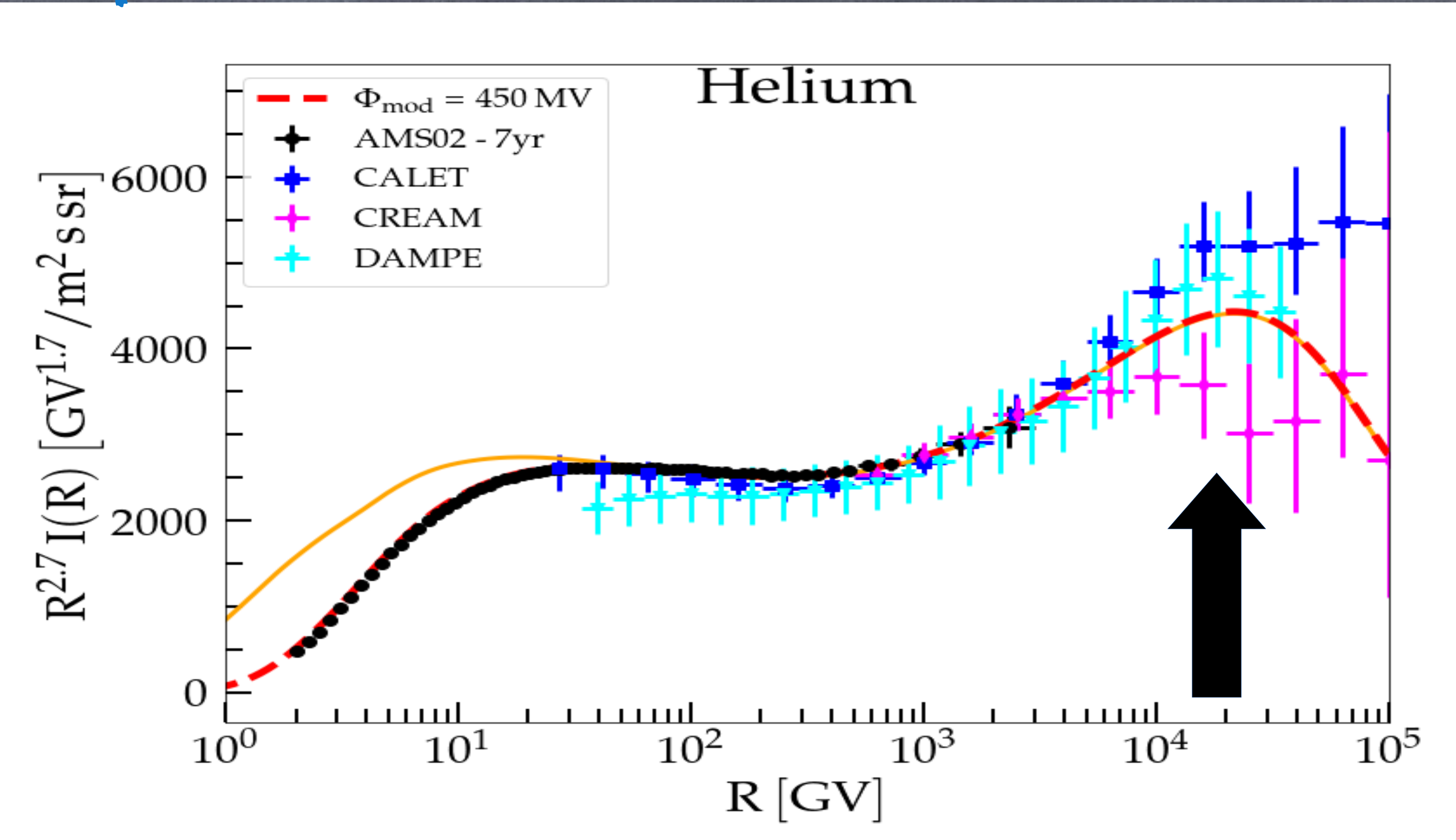
need measurements at higher energy

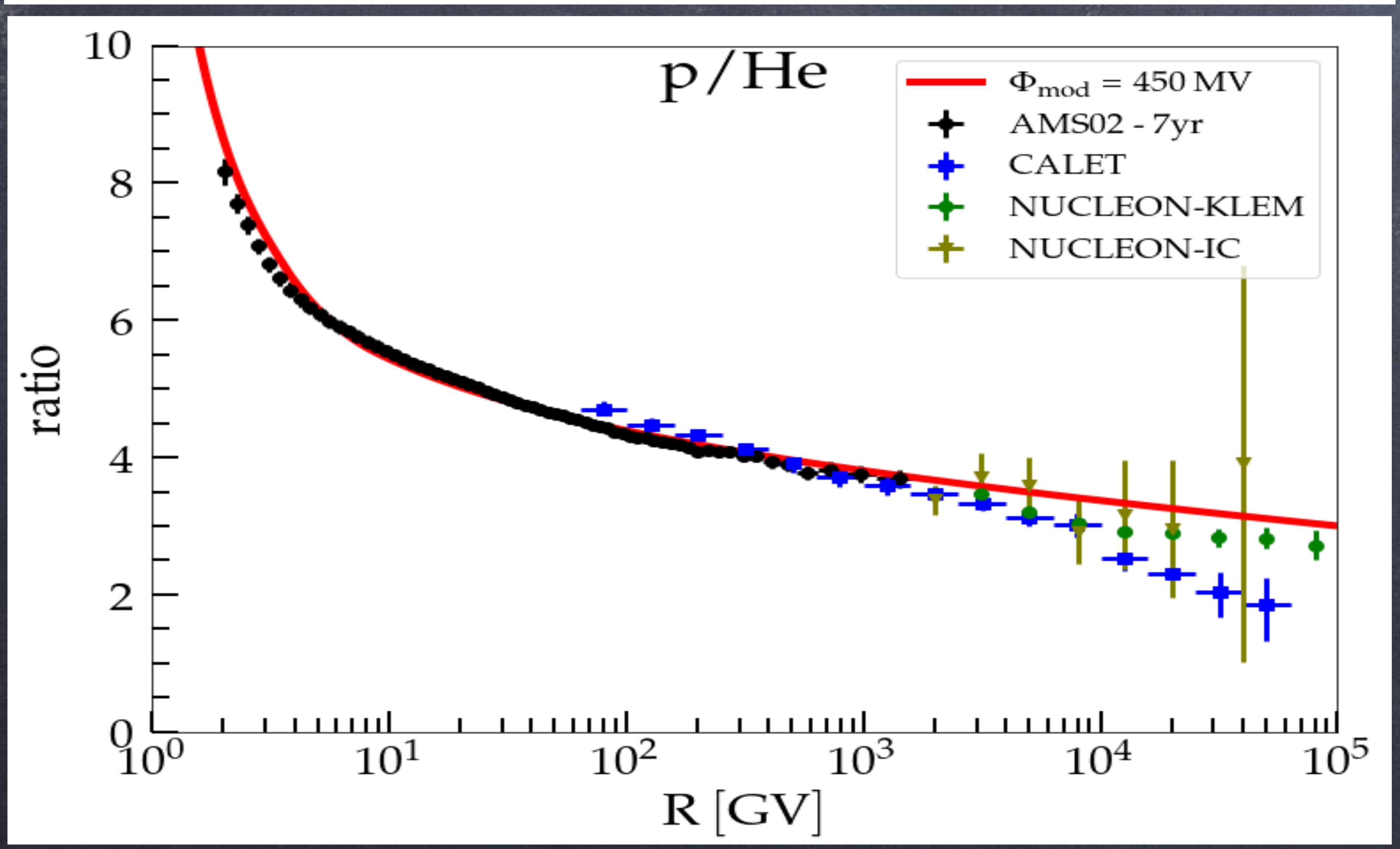
... difficult

"Dampe" break and the "knee"

MOST sources (SNRs) only accelerate up to 10s-100 TeV



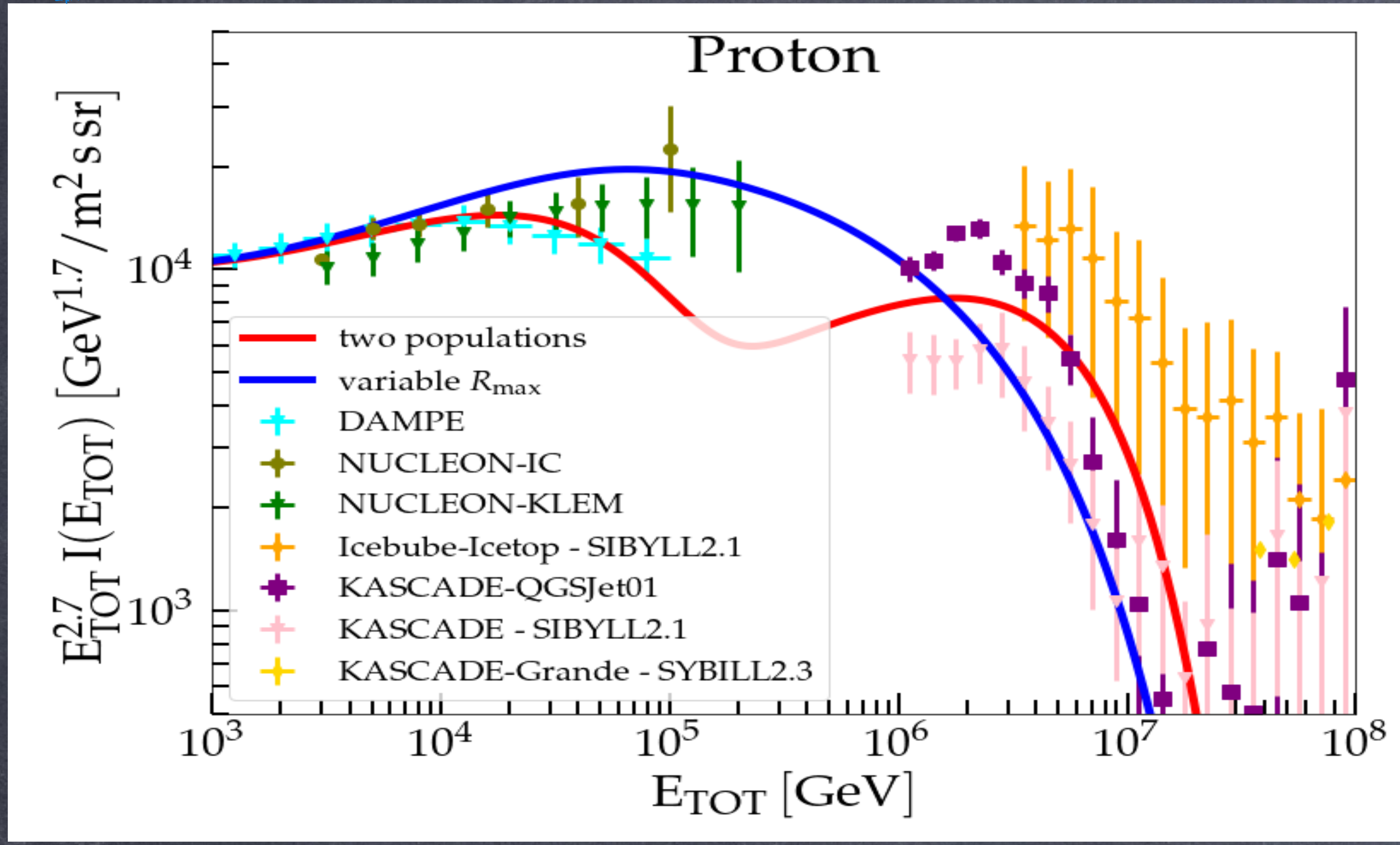


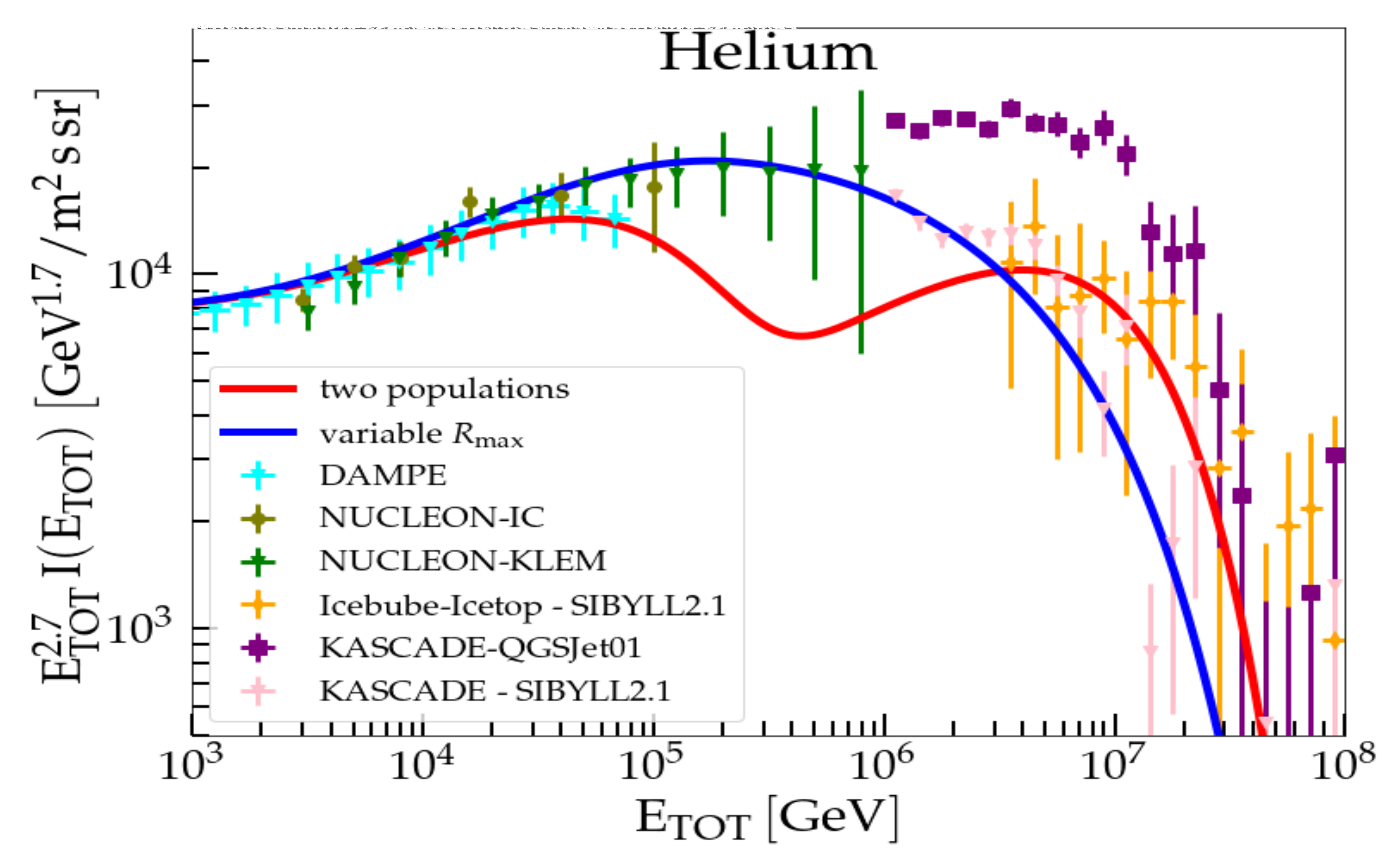


gaseous disk				
n_d	f_{He}	h_d	R_d	
1 cm^{-3}	0.1	150 pc	15 kpc	
Galactic disk (GD)				
h	L_c	b^2	D_m	L_{RR}
150 pc	10 pc	0.4	1 pc	50 − 100 pc
Galactic halo (GH)				
H	D_0	δ	u	
4 kpc	10^{28} cm^2/s	0.7	40 km/s	
bulk of SNRs				
γ_p	γ_{He}	γ_n	R_{max}^{bulk}	
4.35	4.30	4.33	50 TV	
PeV sources				
γ_p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

only a FRACTION of sources are PeVatrons





- 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
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CAVEATS

Caveats: back on "slab" model

... ok if small inhomogeneity along the GP
... if many sources contribute
...

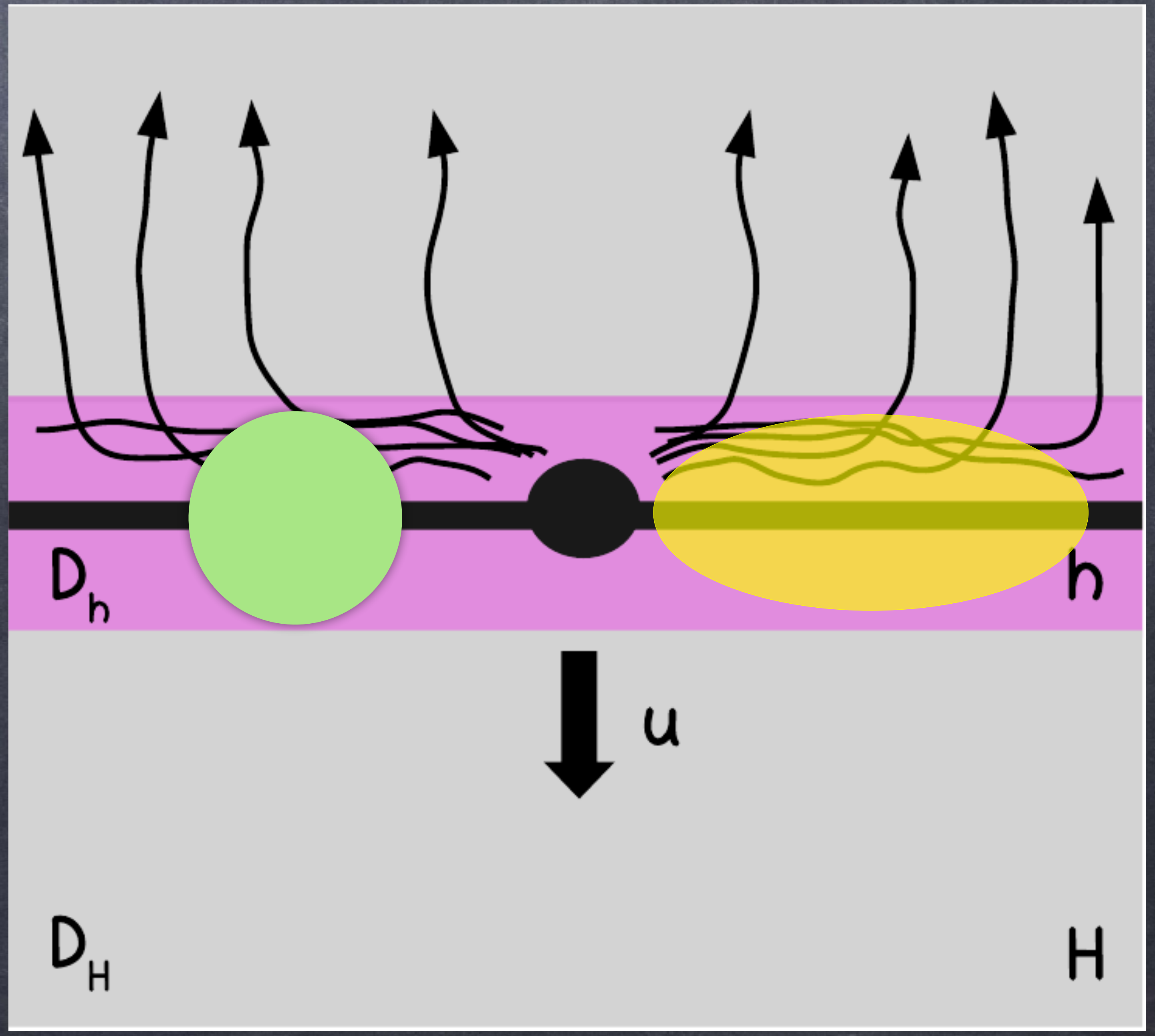
HALO : D(E) ---> $\lambda_{\rm mfp}(E)$

$$R_H^{\rm mfp} = \left[12\times10^3 \frac{H}{4\,{\rm kpc}} \frac{10^{28}{\rm cm^2/s}}{D_0}\right]^{1/\delta} \;{\rm GV}.$$

≈ 150 PV	$(\delta = 0.5)$
≈ 6 PV	$(\delta = 0.6)$
≈ 700 TV	$(\delta = 0.7)$
≈ 100 TV	$(\delta = 0.8)$.

... mfp becomes larger than H
... not come back to disk

maximum distance for sources?

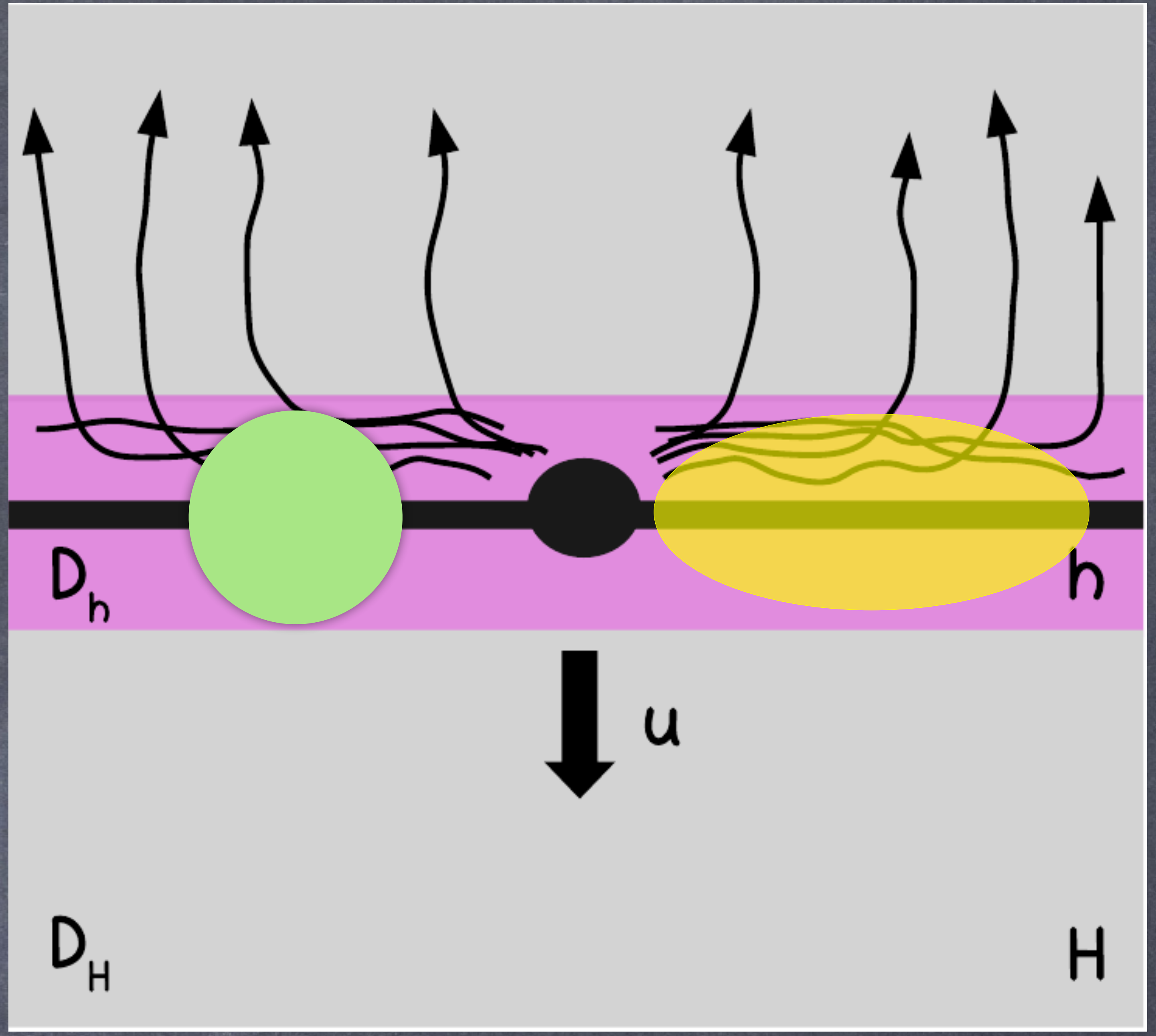


Caveats: back on "slab" model

maximum distance for sources?

... with isotropic D particles only from d~h
... very short horizon of 100-150 pc

... with anisotropic D much larger horizon



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

$$D_{\|} \sim L_c v$$

$$D_{\perp} \sim D_m v$$

... with isotropic diffusion in disk the slab approximation would badly break down at a few 100s TeV

... need to assume anisotropic diffusion to make it work (at least in principle) at high energies

Caveats: back on "slab" model

CR anisotropy

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

average number of contributing sources at VHE

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

tests & applications

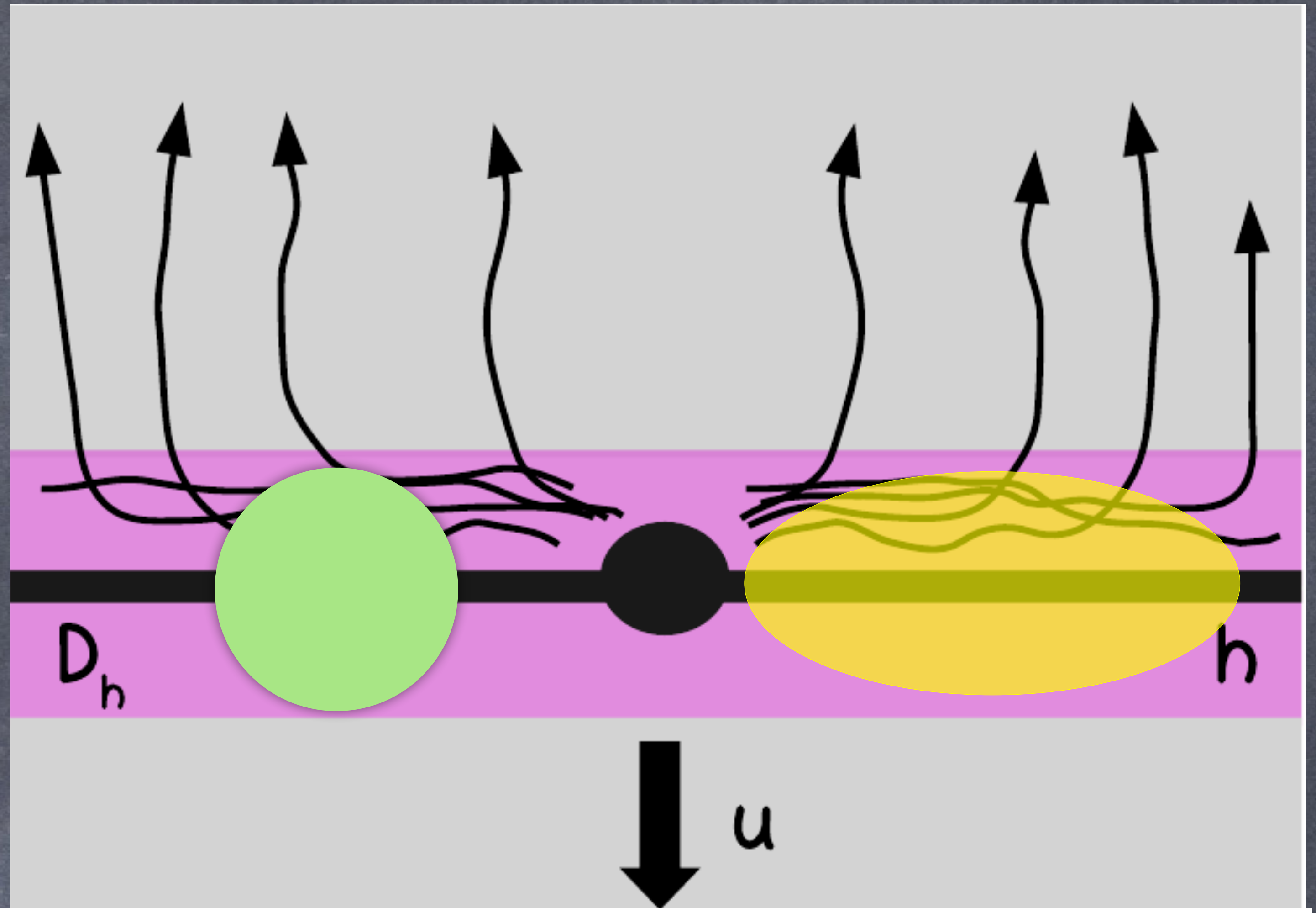
Multi-TeV electrons

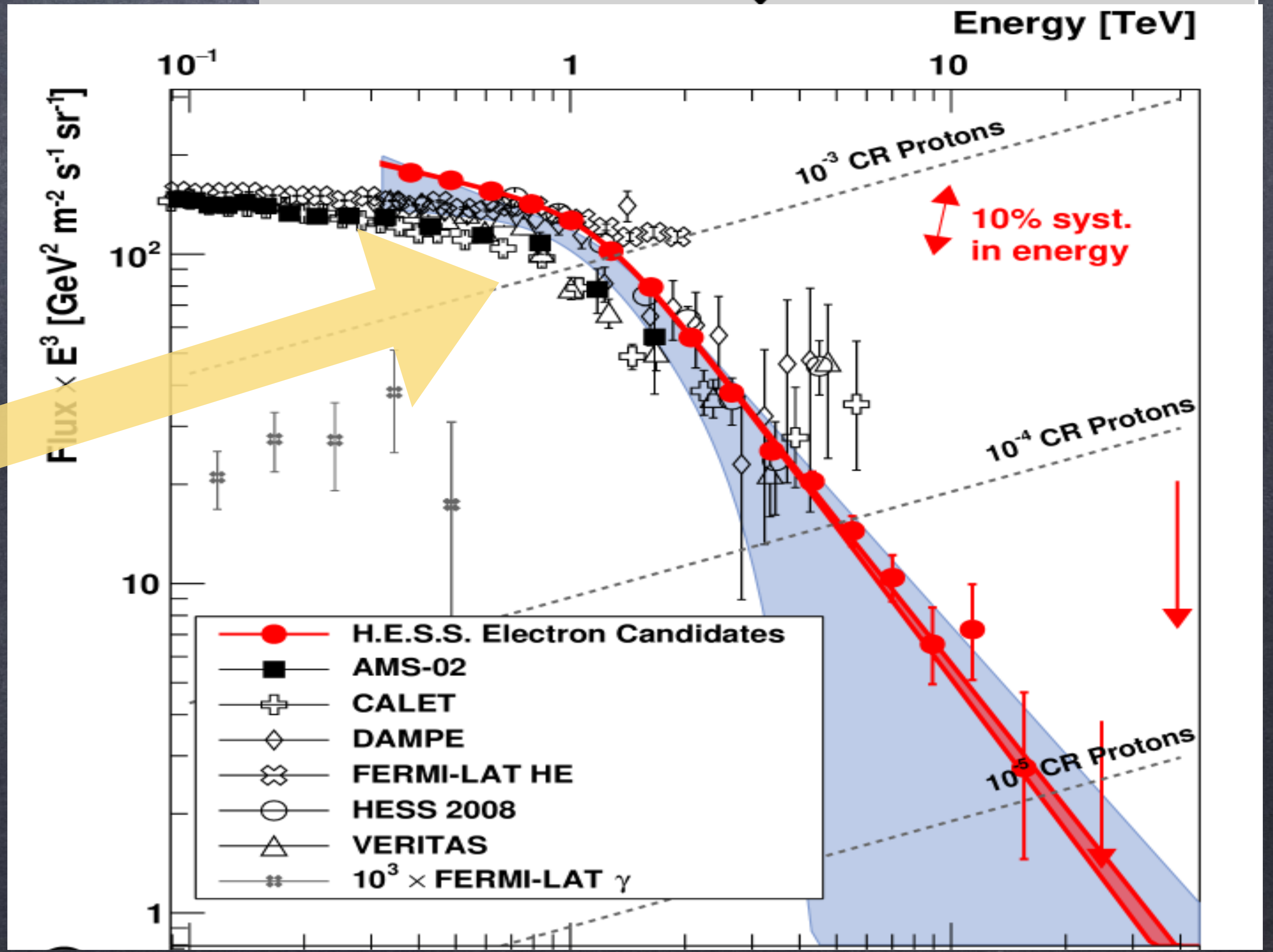
$$\tau_d^{\rm min} \sim \frac{h^2}{D_{{\rm eff},\perp}} \approx 2\times10^5\left(\frac{h}{150\,{\rm pc}}\right)^2\left(\frac{\rm pc}{D_m}\right)\,{\rm yr},$$

$d_{\|} \propto E^{-1/2}$

$$\tau_{\rm loss}(E) \approx 10^5\,{\rm yr}\left(\frac{\rm TeV}{\rm E}\right)$$

calorimetric disk





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 50-100 TV
- Only a fraction of sources reach PeV

- possible to explain features in CR spectra in GV-PV range
  - without breaks in injection or propagation
  - need discussion on physical setup

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 ... is the effect at the same level?

tests & applications

... new data DAMPE & LHAASO

... CR Anisotropy

... multi-TeV electrons

Thank You

Analytic solution of the CR transport

a few comments on parameters

gaseous disk				
n_d	f_{He}	h_d	R_d	
$1\,cm^{-3}$	0.1	150 pc	15 kpc	
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- [for a given nucleous]
  same slope for BULK and PeV sources
- but need different slopes for p, He, nuclei
  [same problem of previous studies...]
- no breaks in diffusion in halo and disk
- no attempt for a fitting procedure - no best-fit parameters

A comment on source grammage

secondaries are also produced in/around sources —> flattening B/C

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

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

- sec. produced at shock and leave accelerator —> same spectrum as primaries
- sec. produced at shock and re-accelerated —> spectrum harder than secondaries
- sec. produced in the source proximity —> spectrum steeper than primaries
- effect must be there but not clear its E-dependent relevance
- anyway should be included in more refined models

...time-dependent Emax ?

... for how long acceleration ?

... res. time in/around sources?

Perp. diffusion: weak scattering limit

Rechester & Rosenbluth 1978 | Chandran 2000

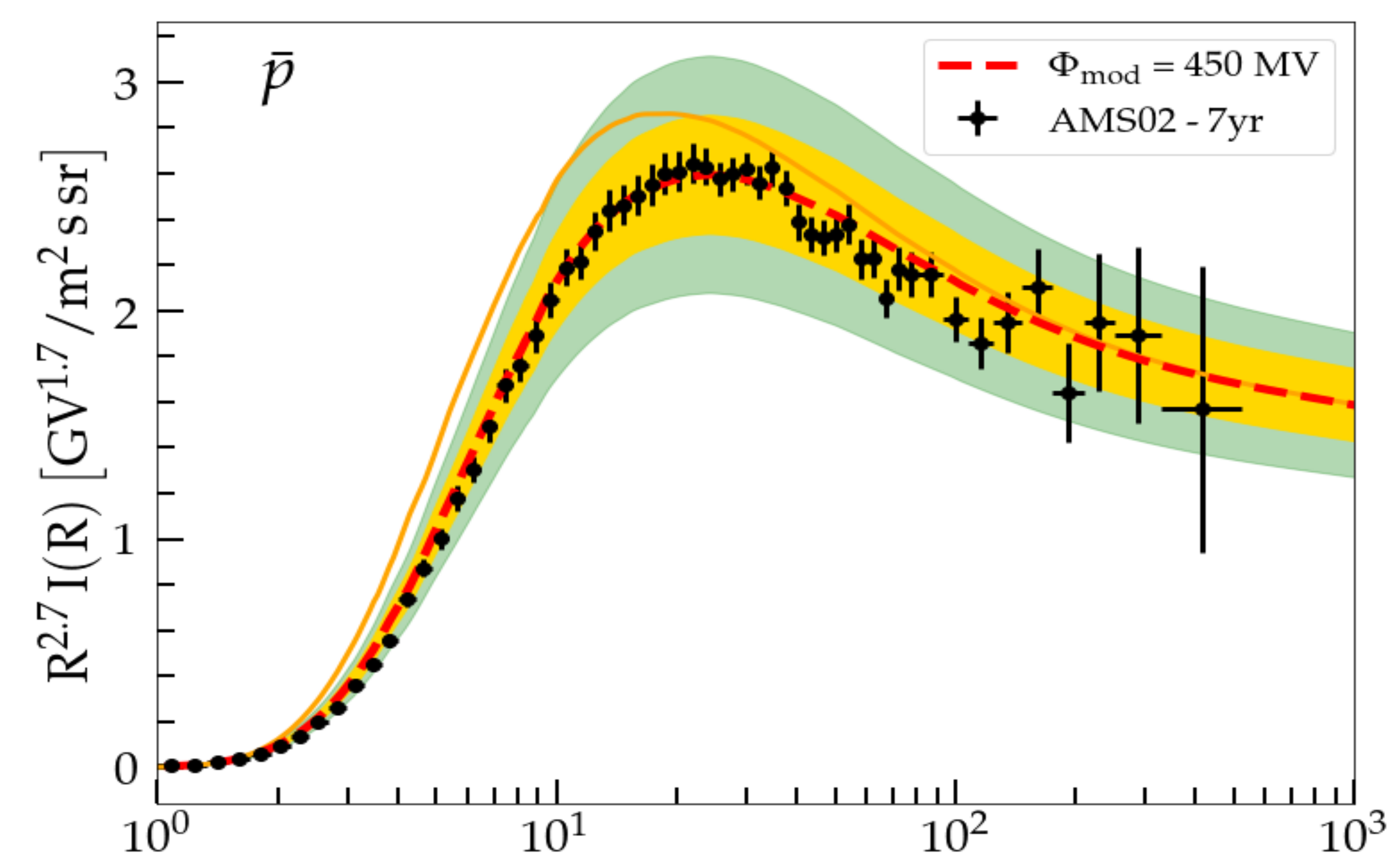
- weak scattering ALONG field lines + FLRW
  - $\lambda_{\rm mfp} \gtrsim L_{\rm RR}$
  - $L_{RR} \gtrsim L_{\rm coh}$ ⟶ trajectory decorrelates from initial field line
  - $L_{\rm RR}$ statistically independent random step
  - within $L_{\rm coh}$, $z(t) \sim v\,t$

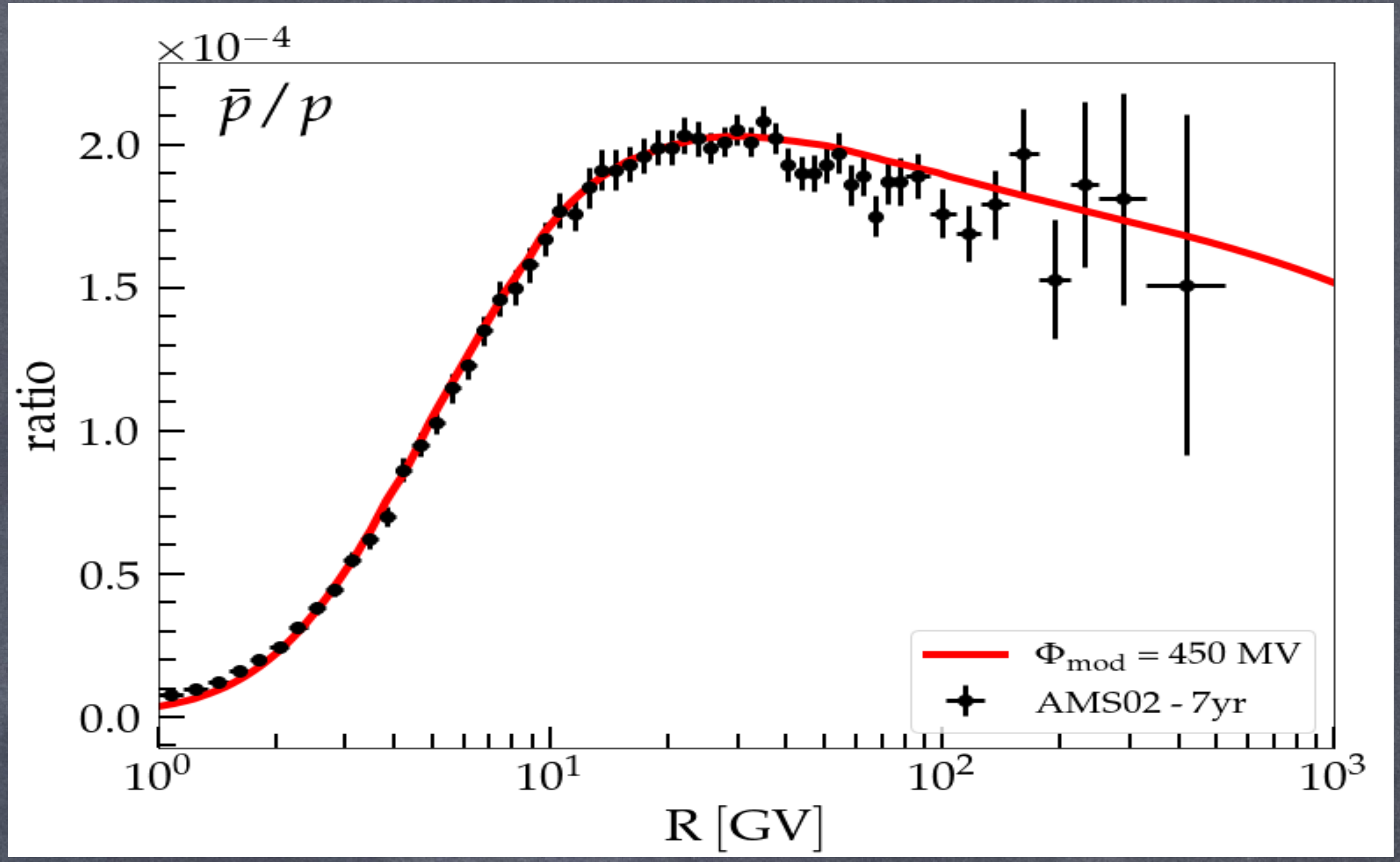
$$\langle (x-x_0)^2 \rangle = \langle (y-y_0)^2 \rangle = 2D_m z.$$

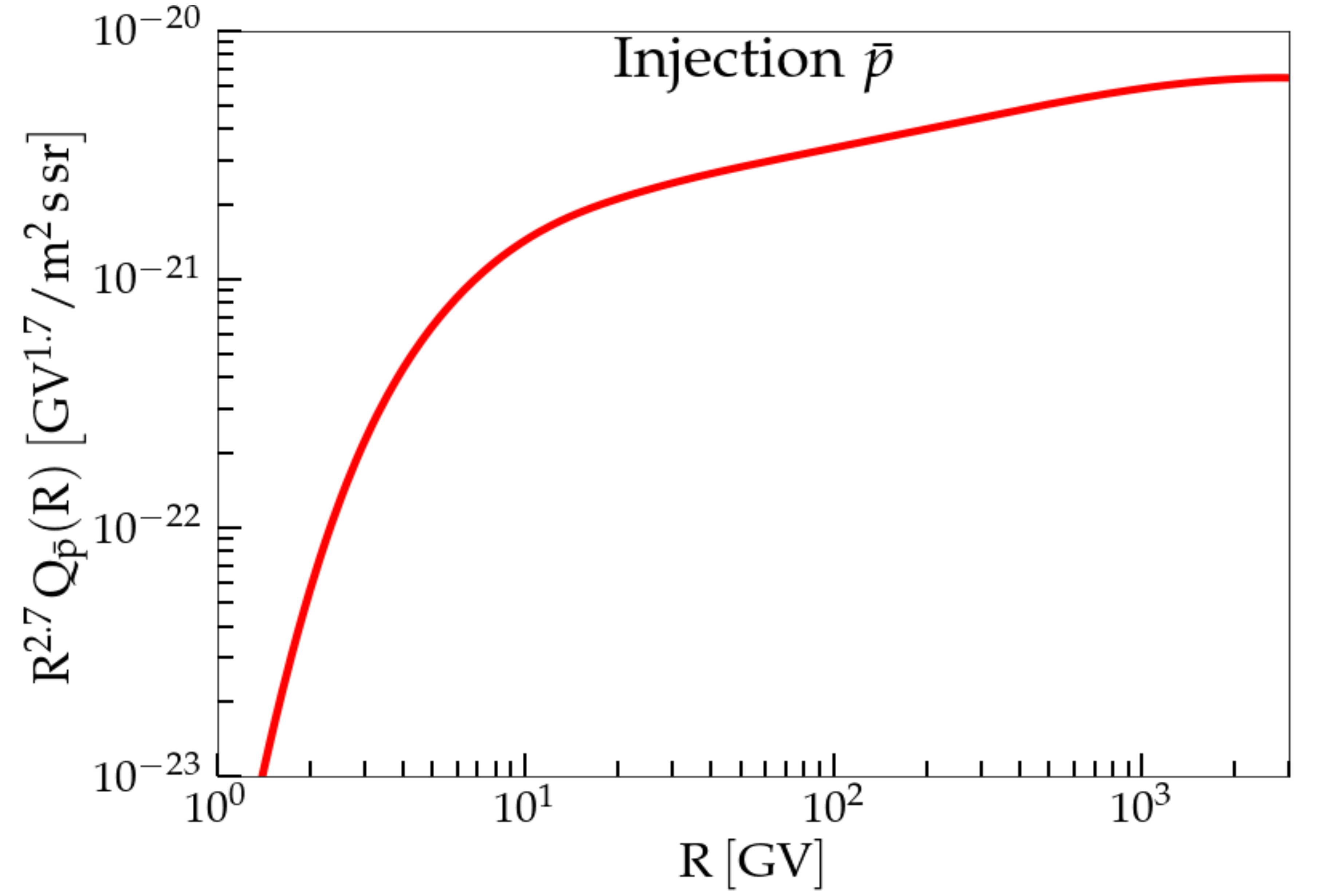
$$\begin{cases} (\Delta R)^2 = 2D_m L_{RR} \\ \Delta t = \dfrac{L_{RR}}{v} \end{cases}$$

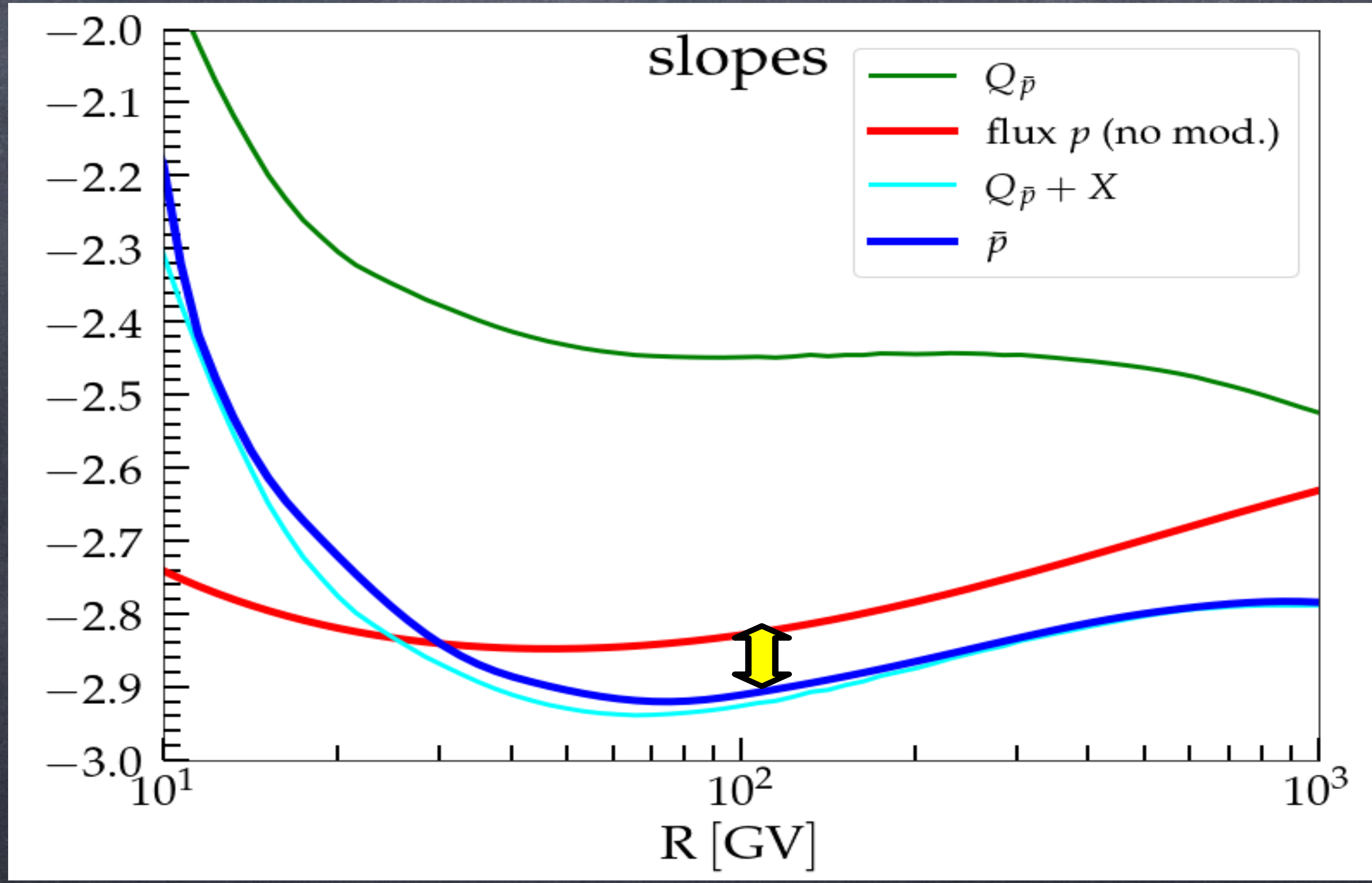
- perpendicular diffusion becomes energy-independent
  - $D_\perp = \dfrac{1}{2}\dfrac{(\Delta R)^2}{\Delta t}$ ⟹ $D_m v \approx 3 \times 10^{28} \left(\dfrac{D_m}{\rm pc}\right) {\rm cm}^2/{\rm s},$
  - (ΔR) rms perp. displacement during each random step $L_{\rm RR}$

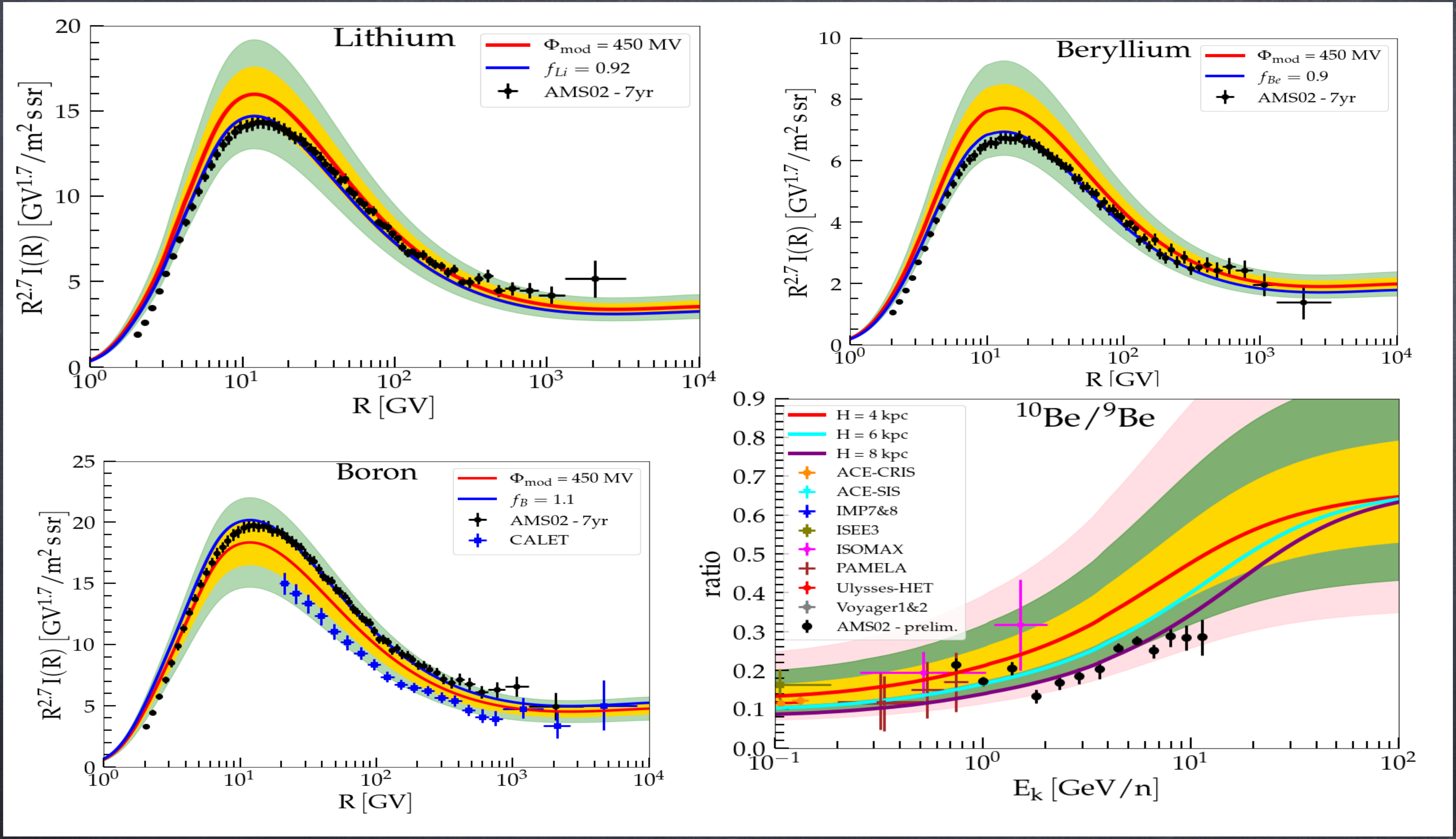
Antiprotons

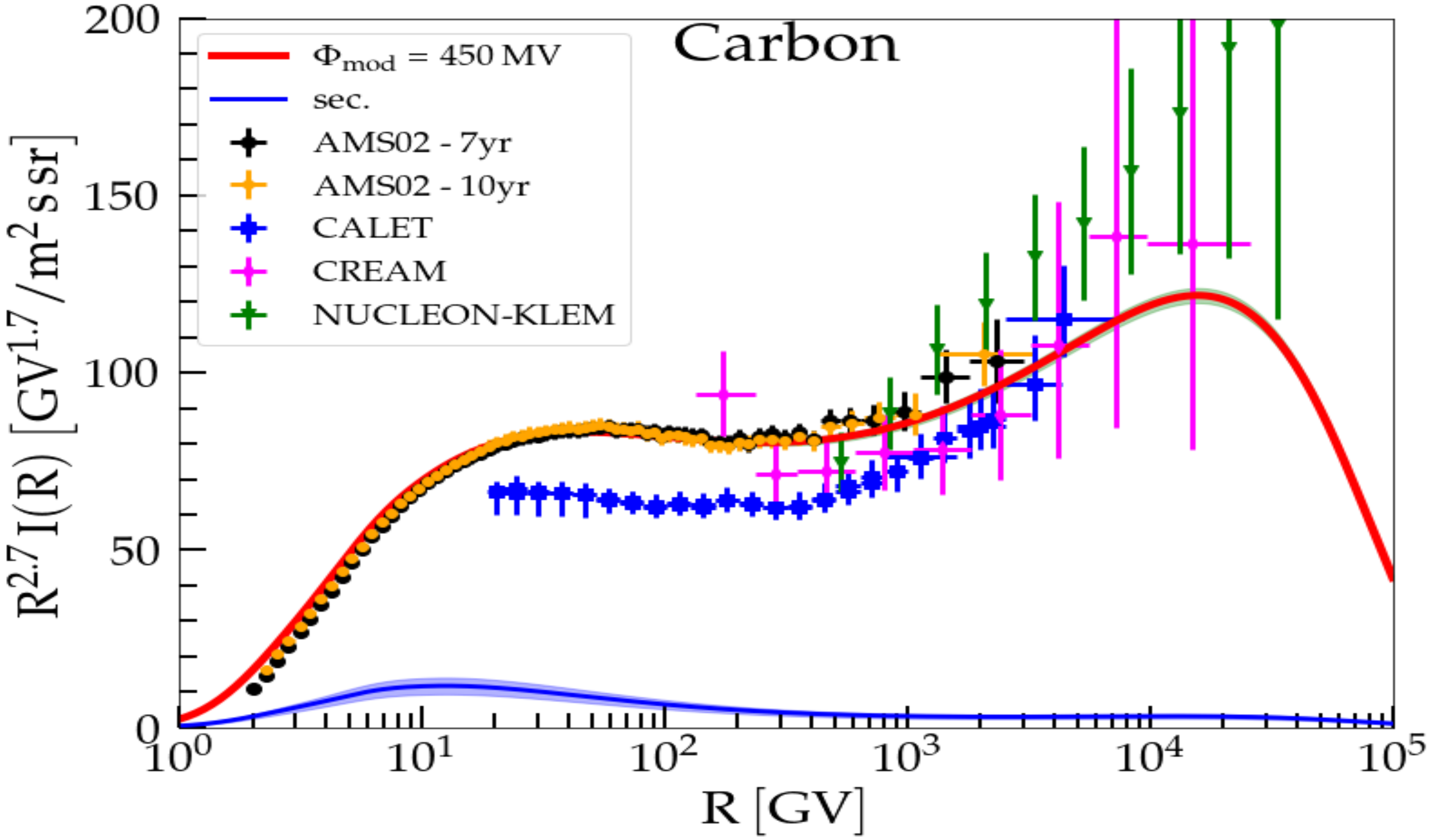


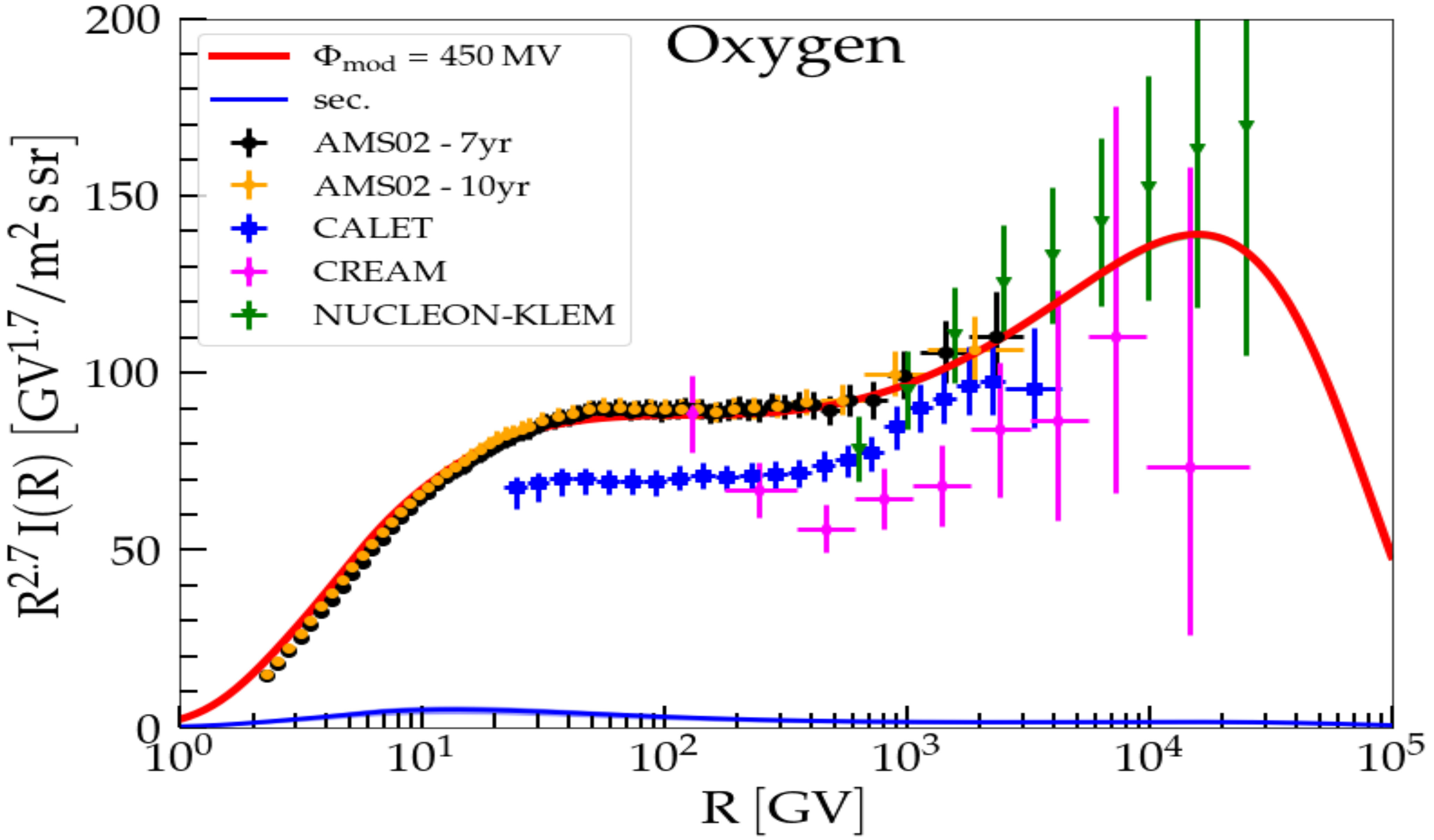


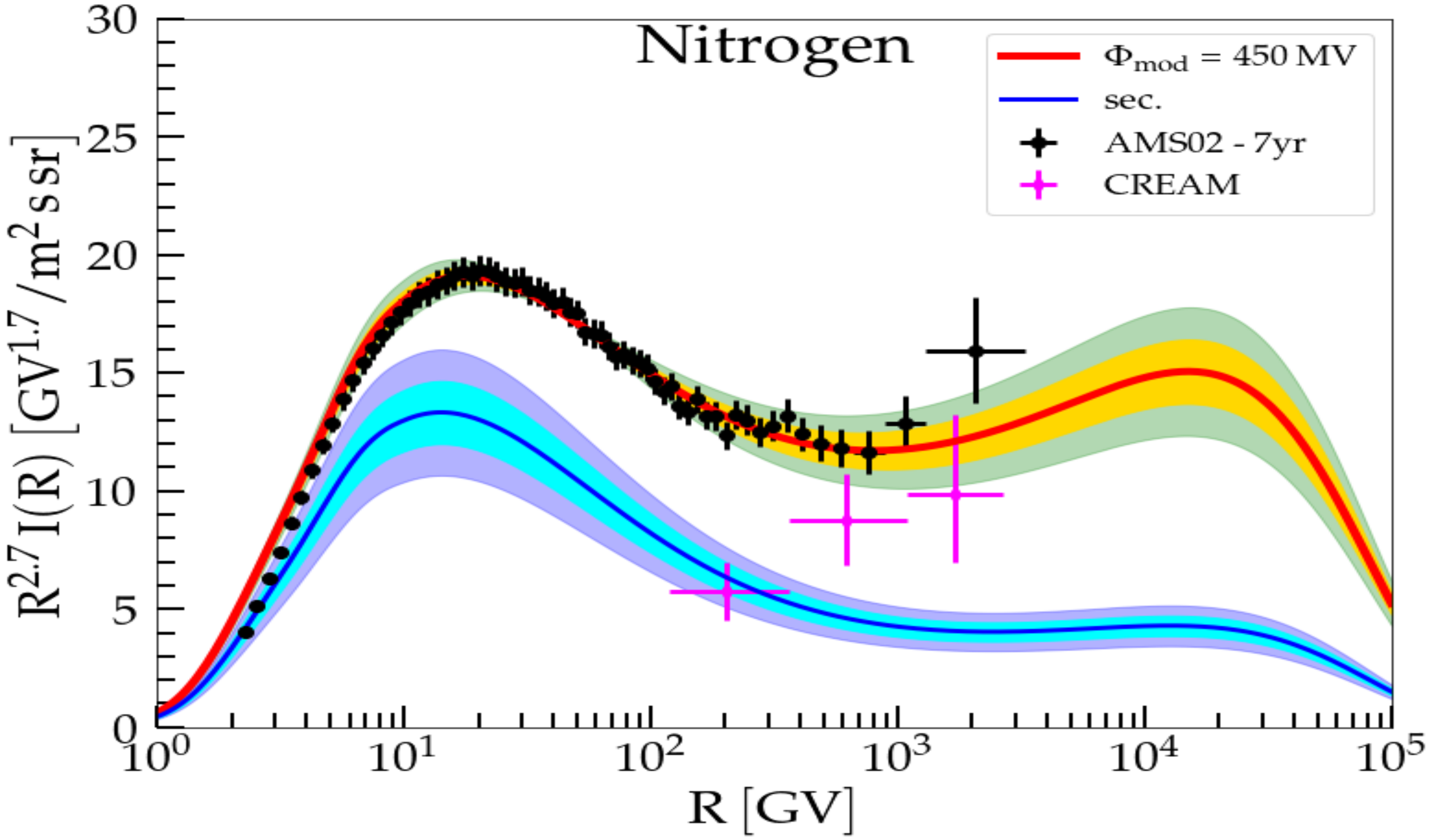


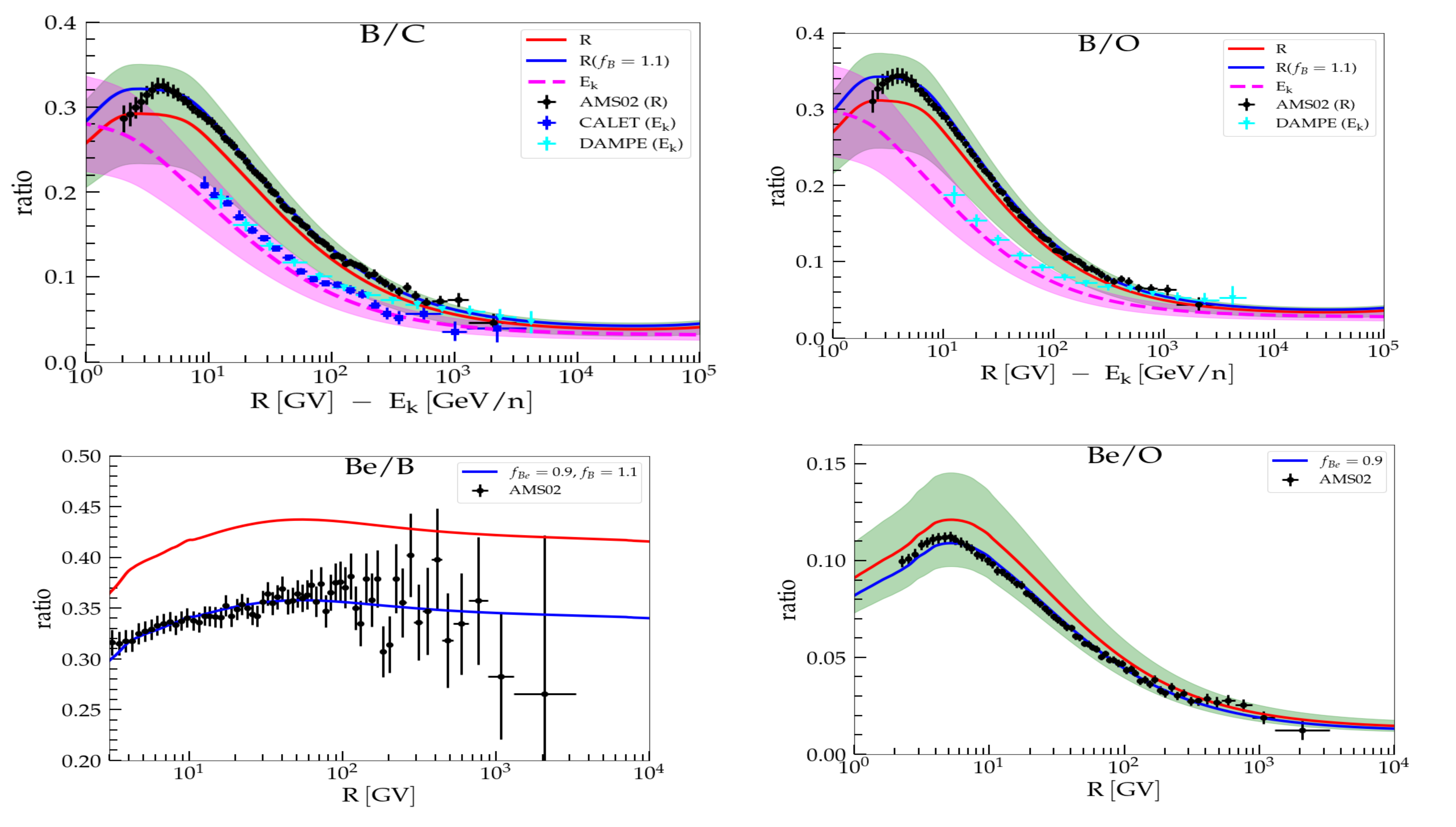



Lithium
$\Phi_{mod} = 450$ MV
$f_{Li} = 0.92$
AMS02 - 7yr
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]
Beryllium
$\Phi_{mod} = 450$ MV
$f_{Be} = 0.9$
AMS02 - 7yr
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [GV]
Boron
$\Phi_{mod} = 450$ MV
$f_B = 1.1$
AMS02 - 7yr
CALET
$R^{2.7} I(R)$ [$GV^{1.7}/m^2$ s sr]
R [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]


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]