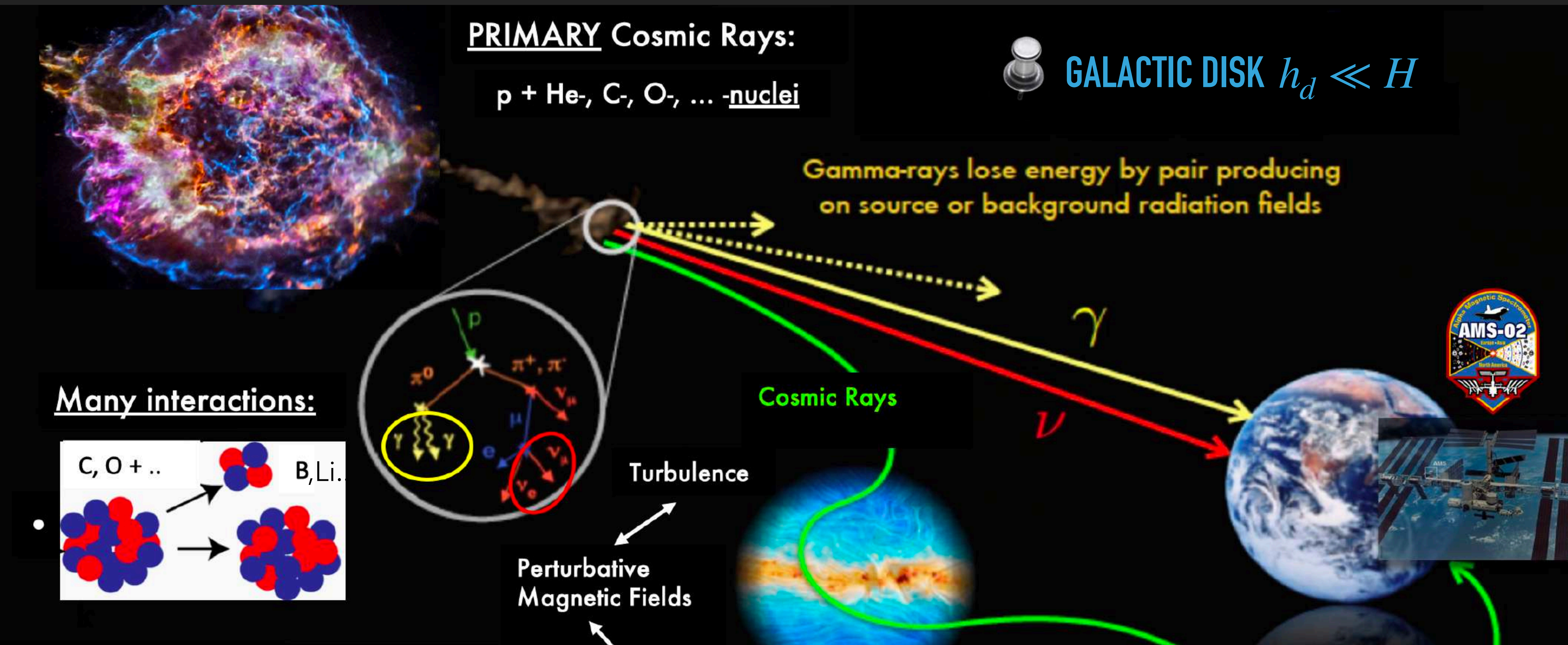
INSTITUT D'ASTROPHYSIQUE DE PARIS
Unité mixte de recherche 7095 IAP CNRS - Sorbonne Université

PHYSICS and ASTROPHYSICS of COSMIC RAYS

OHP Saint Michel l'Observatoire, France

EFFECTS OF REACCELERATION AND SOURCE GRAMMAGE ON SECONDARY COSMIC RAYS SPECTRA

28/11/19 - Virginia Bresci



GALACTIC DISK $h_d \ll H$

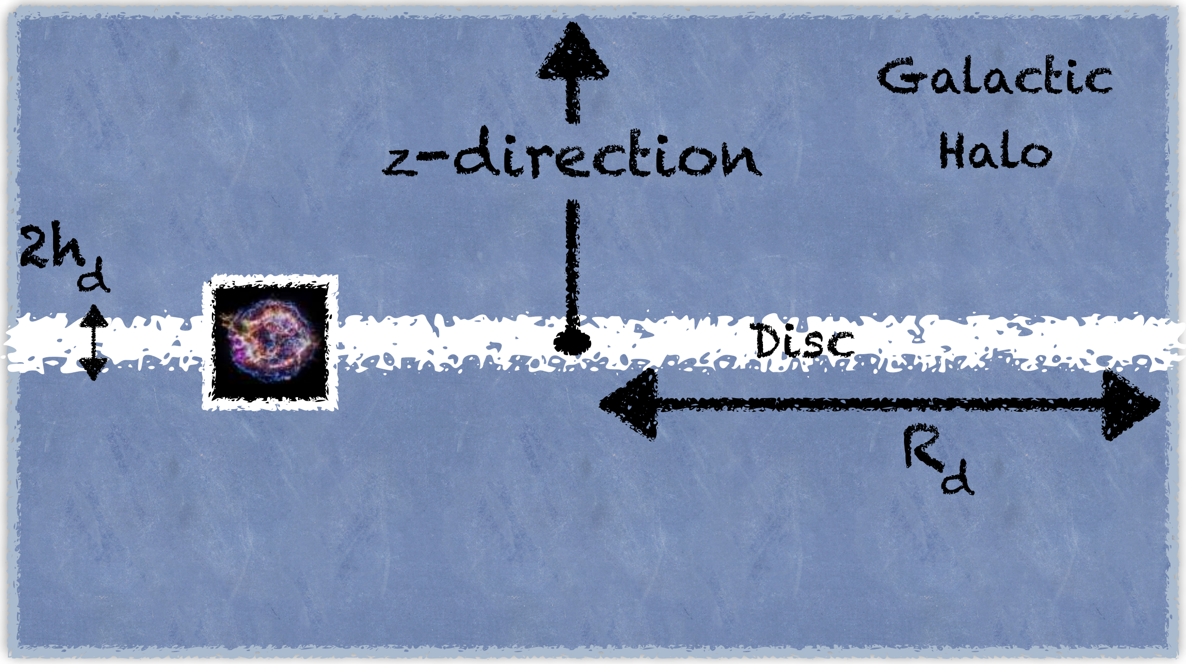
GALACTIC HALO $n_H \ll n_d$

THE TRANSPORT EQUATION

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{I_\alpha}{\partial z}\right] + v_A \frac{\partial I_\alpha}{\partial z} + 2h_d n_d v_\alpha \sigma_\alpha I_\alpha \,\delta(z) -$$

$$-\frac{2}{3} v_A A_\alpha p^3 \frac{\partial F_\alpha}{\partial p}\delta(z) + 2h_d \delta(z) \frac{\partial}{\partial p}\left[\left(\frac{dp}{dt}\right)_{\alpha,\mathrm{Ion.}} I_\alpha\right] =$$

$$= A_\alpha p^2 Q_\alpha(p)\delta(z)$$



…What experiments really measure:

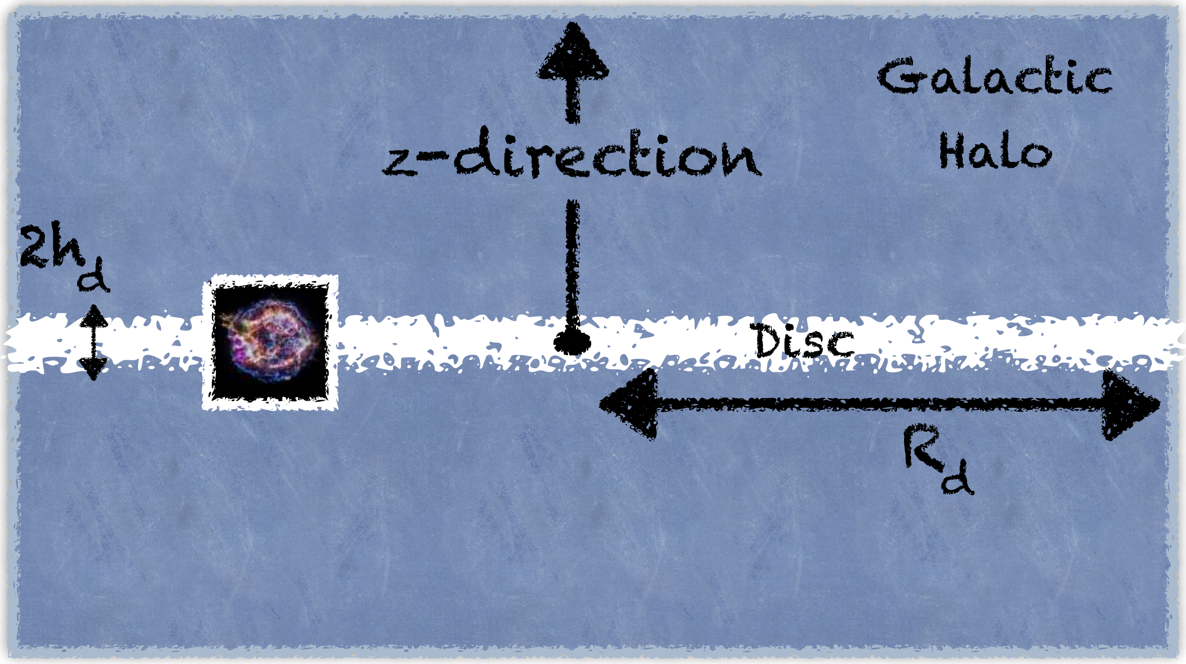
$$I_\alpha(z, E_k) dE_k = v_\alpha(p) F_\alpha(z, p) p^2 dp$$

Spatial Diffusion

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{I_\alpha}{\partial z}\right] \quad + v_A \frac{\partial I_\alpha}{\partial z} + 2h_d n_d v_\alpha \sigma_\alpha I_\alpha \,\delta(z) -$$

$$-\frac{2}{3} v_A A_\alpha p^3 \frac{\partial F_\alpha}{\partial p} \delta(z) + 2h_d \delta(z) \frac{\partial}{\partial p}\left[\left(\frac{dp}{dt}\right)_{\alpha,\mathrm{Ion.}} I_\alpha\right] =$$

$$= A_\alpha p^2 Q_\alpha(p) \delta(z)$$



…What experiments really measure:

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Advection

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{I_\alpha}{\partial z}\right] + v_A \frac{\partial I_\alpha}{\partial z} + 2h_d n_d v_\alpha \sigma_\alpha I_\alpha \delta(z) -$$

$$-\frac{2}{3} v_A A_\alpha p^3 \frac{\partial F_\alpha}{\partial p} \delta(z) + 2h_d \delta(z) \frac{\partial}{\partial p}\left[\left(\frac{dp}{dt}\right)_{\alpha,\mathrm{Ion.}} I_\alpha\right] =$$

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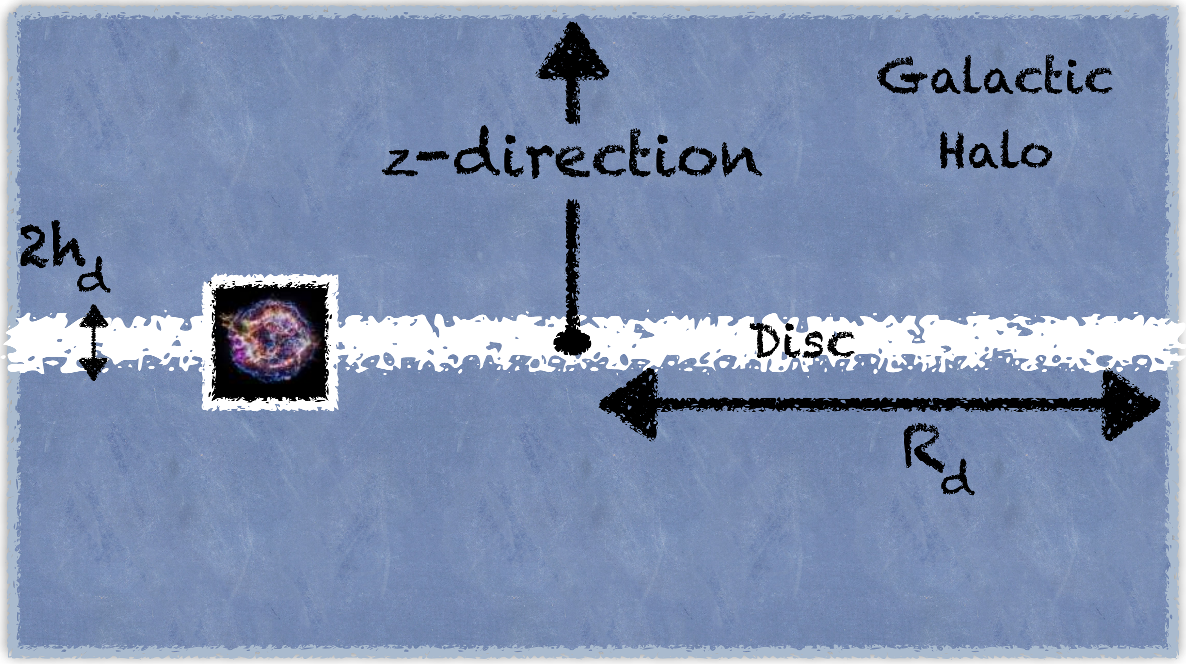


…What experiments really measure:

$$I_\alpha(z, E_k) dE_k = v_\alpha(p) F_\alpha(z, p) p^2 dp$$

Spallation reactions

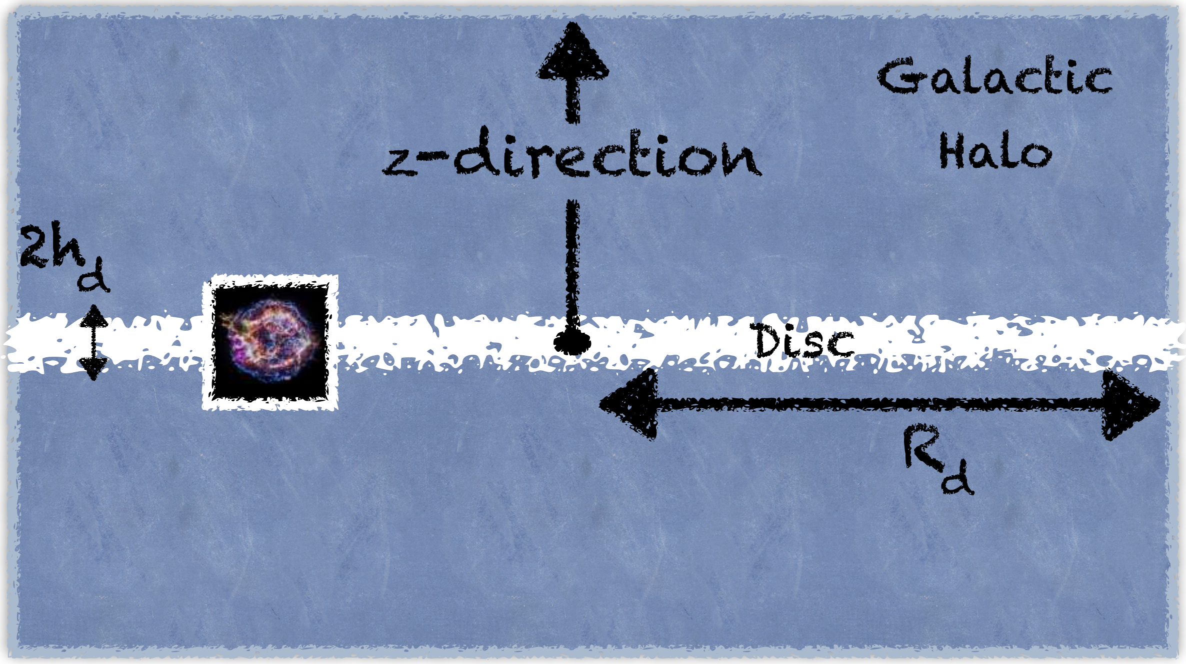
$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{I_\alpha}{\partial z}\right] + v_A \frac{\partial I_\alpha}{\partial z} \quad + 2h_d n_d v_\alpha \sigma_\alpha I_\alpha \, \delta(z) -$$

$$-\frac{2}{3} v_A A_\alpha p^3 \frac{\partial F_\alpha}{\partial p} \delta(z) + 2h_d \delta(z) \frac{\partial}{\partial p} \left[\left(\frac{dp}{dt} \right)_{\alpha,\mathrm{Ion.}} I_\alpha \right] =$$

Adiabatic expansion

Ionization of the medium

$$= A_\alpha p^2 Q_\alpha(p) \delta(z)$$



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Source term

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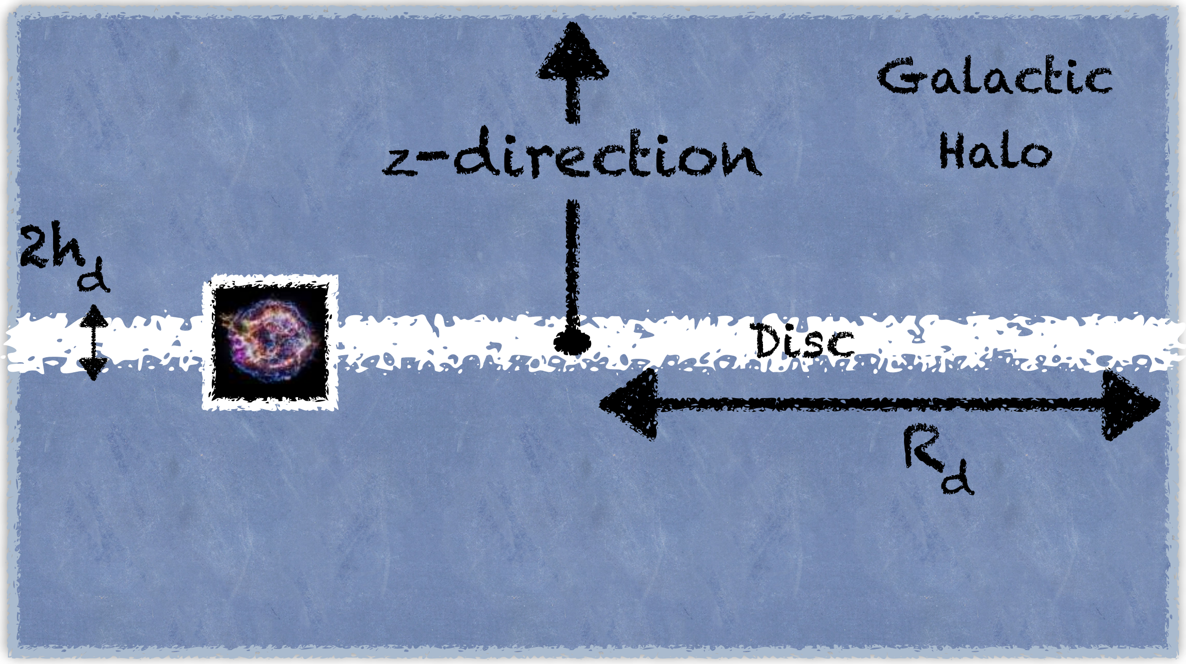
$$I_\alpha(z, E_k) dE_k = v_\alpha(p) F_\alpha(z, p) p^2 dp$$



SOURCE TERM

Primary nuclei

$$\frac{\partial}{\partial z}\left[D(p)\frac{\partial f(z,p)}{\partial z}\right] - u\frac{\partial f(z,p)}{\partial z} +$$

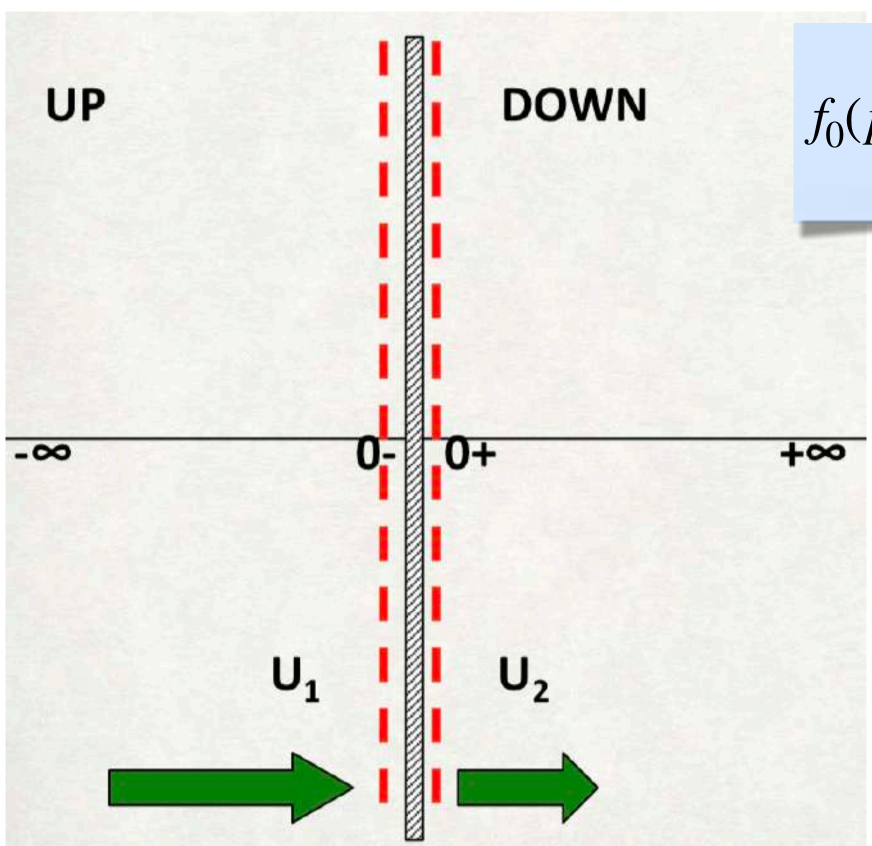
Diffusion

Advection

$$+\frac{1}{3}\left(\frac{du}{dz}\right) p \frac{\partial f(z,p)}{\partial p} + \eta \frac{n_1 u_1}{4\pi p_{\rm inj}^2}\,\delta(p-p_{\rm inj})\,\delta(z) = 0$$

Compression

Injection at the shock surface



$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s}$$

- ☑ Power law in momentum, slope s=3r/(r-1) depends ONLY on the compression ratio r=u1/u2 -> 4
- ☑ No dependence upon diffusion

Secondary CRs

Created in interactions between primaries - ISM:

Nuclei

$$A_\alpha p^2 Q_\alpha(p) = \sum_{\alpha'>\alpha} 2h_d n_d v_{\alpha'}(E_k)\sigma_{\alpha'\alpha} I_{\alpha',0}(E_k)$$

Antiparticles

$$p^2 Q_{\bar p} = 2h_d v_{\bar p} n_{d,j}\int_{E_{\rm th}}^{+\infty} dE_{k,\alpha'} I_{\alpha',0}(E_{k,\alpha'})\frac{d\sigma_{\alpha',j}}{dE_{k,\bar p}}$$

$$-\frac{\partial}{\partial z}\left[D_\alpha \frac{I_\alpha}{\partial z}\right] + \cancel{v_A \frac{\partial I_\alpha}{\partial z}} + \cancel{2h_d n_d v_\alpha \sigma_\alpha I_\alpha}\,\delta(z) - \frac{2}{3}\cancel{v_A A_\alpha p^3 \frac{\partial F_\alpha}{\partial p}}\,\delta(z) + 2h_d\delta(z)\frac{\partial}{\partial p}\left[\cancel{\left(\frac{dp}{dt}\right)}_{\alpha,\mathrm{Ion.}} I_\alpha\right] =$$

$$= A_\alpha p^2 Q_\alpha(p)\delta(z)$$

Primary CRs

- $D_\alpha \propto E_k^\delta$
- $p^2 Q_\alpha \propto E_k^{-s'}$

Secondary CRs

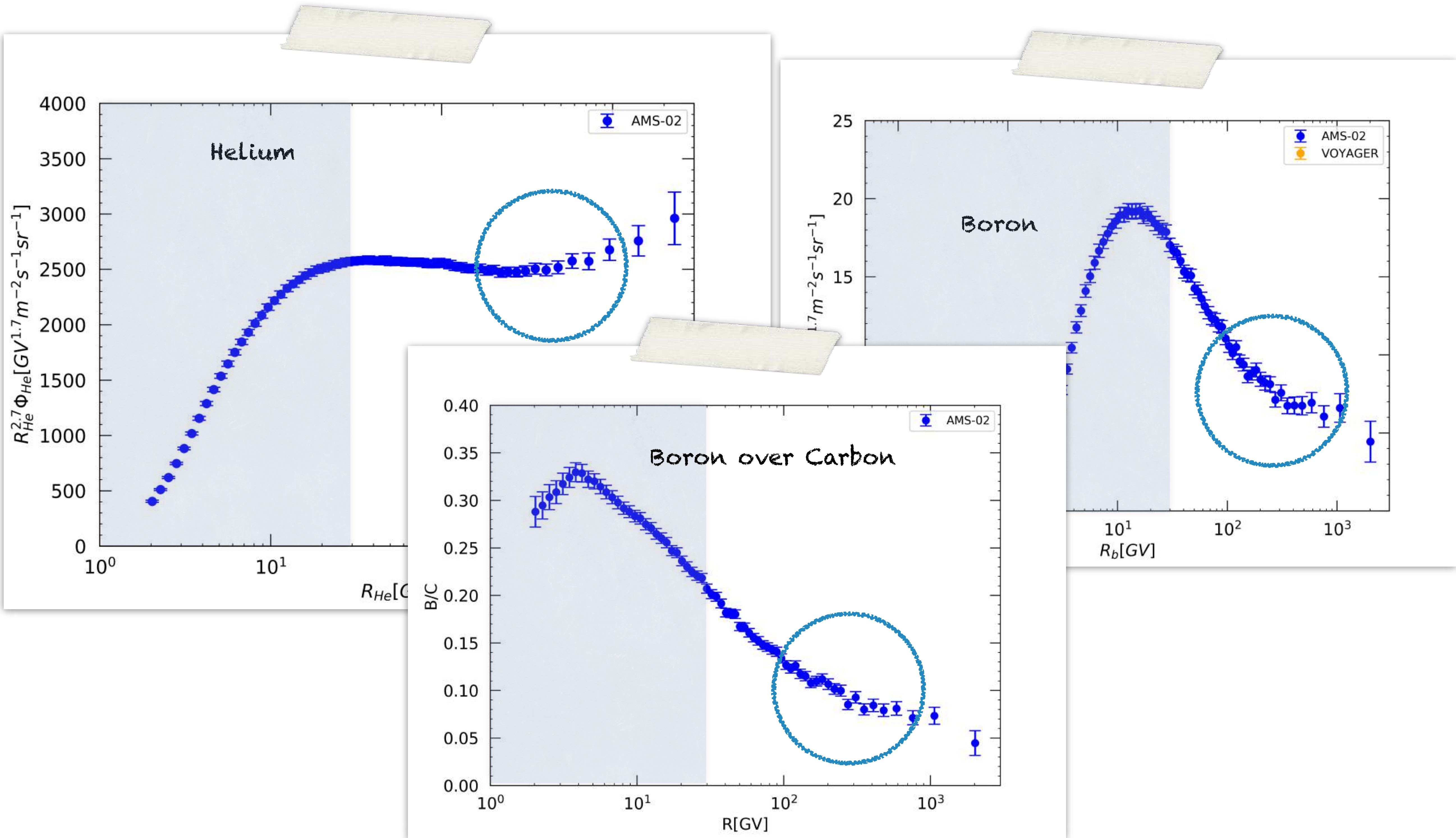
- $D_\alpha \propto E_k^\delta$
- $p^2 Q_{\alpha'} \propto I_\alpha(E_k) \propto E_k^{-s'-\delta}$

Secondary to Primary (nuclei) Ratios:

$$\frac{I_{\alpha'}(E_k)}{I_\alpha(E_k)} \propto X_\alpha(E_k) \propto E_k^{-\delta}$$

"GRAMMAGE"

RECENT AMS-02 OBSERVATIONS



NON-LINEAR EFFECTS

- Super-Alfvenic streaming of cosmic rays ⟶ instability ⟶ growth of Alfvén waves (e.g. Blasi+ 2012 PRL 109,061101)

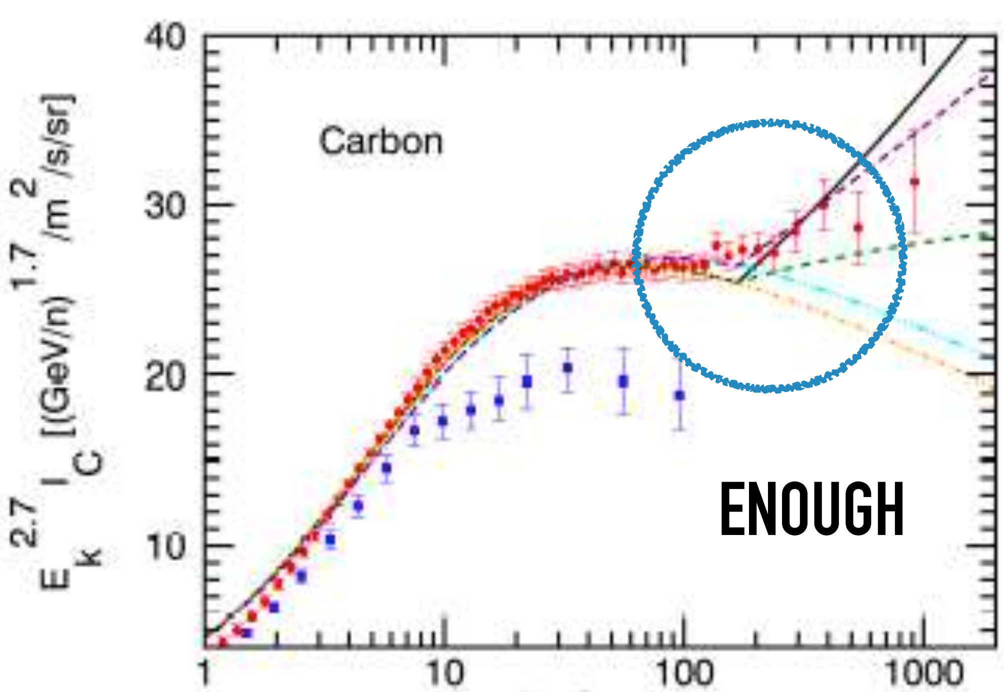
- Transition from this regime to Galactic turbulence generates a break in the diffusion coefficient just around ~200 GV :

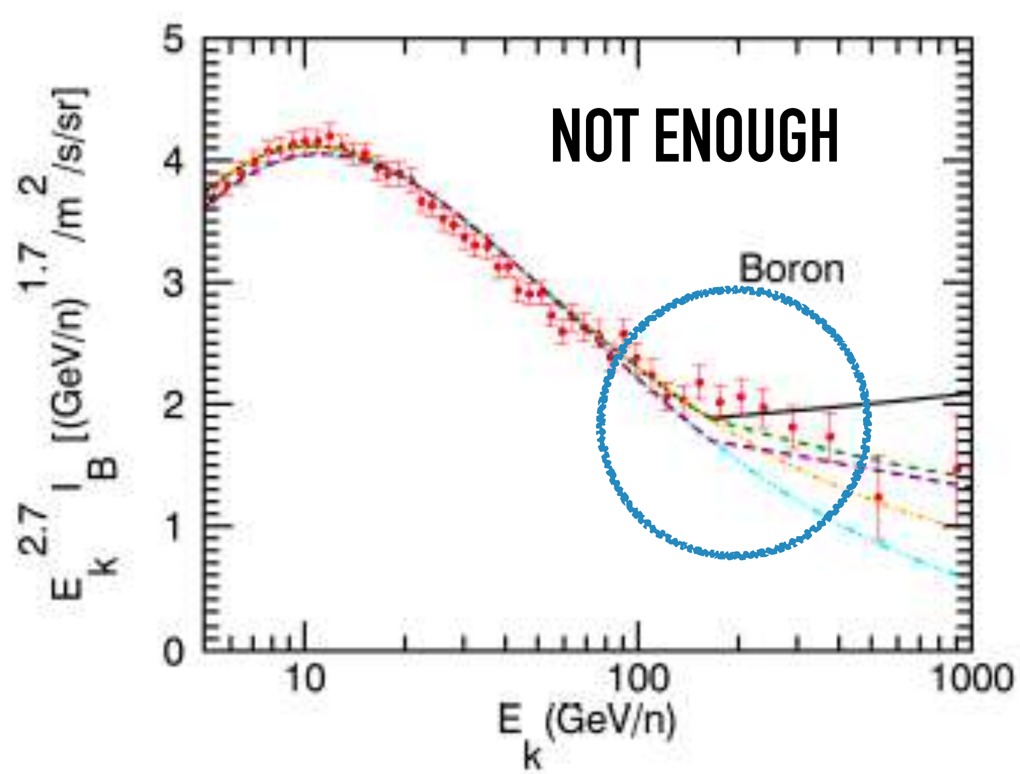
$$D(R) = \begin{cases} D_0 \text{ if } \mathrm{R} < \mathrm{R}_0 \\ D_0 \left(\frac{R}{R_0}\right)^{\delta_1} \text{if } \mathrm{R}_0 \leq \mathrm{R} \leq \mathrm{R}_1 \\ D_0 \left(\frac{R_1}{R_0}\right)^{\delta_1} \left(\frac{R}{R_1}\right)^{\delta_2} \text{if } \mathrm{R} \geq \mathrm{R}_1. \end{cases}$$

PURPLE VS CYAN LINE:

$\delta_1 = \delta_2$

$\delta_1 \neq \delta_2$





(Blasi 2017)

The same shock waves at supernovae explosions that accelerate primary CRs in the first place are expected to pick up and re-energize any other charged particle in the upstream above the threshold of injection

DIFFERENT BOUNDARY CONDITION:

$$f(-\infty, p) = g(p)$$

SOURCE TERM NOW ?

$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} + s\int_{p_0}^{p}\frac{dp'}{p'}\left(\frac{p'}{p}\right)^{s} g(p')$$

$$\boxed{A_\alpha p^2 Q_\alpha(p) = A_\alpha p^2 f_0(p)\frac{V_{\rm SN}\mathscr{R}_{\rm SN}}{\pi R_d^2}}$$

AS BEFORE..
(NOT FOR SECONDARIES)

..RE-ACCELERATION TERM
(EVERYONE)

A. REACCELERATION EFFECT:

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AS BEFORE..
(NOT FOR SECONDARIES)

..RE-ACCELERATION TERM
(EVERYONE)

- Distribution of SNRs that CRs found in the Galactic disk as a function of their radius in the S-T phase

$$P\left(r_{\mathrm{SN}}\right) dr_{\mathrm{SN}} = K_P \frac{dt(r_{\mathrm{SN}})}{T_{\mathrm{Max}}} \; ; \qquad T_{Max} \approx 3 \times 10^4 \, \mathrm{yr}$$

- Maximum energy cut-off

$$E_{\mathrm{Max}}(t) \approx 100 \left(\frac{t}{t_{\mathrm{ST}}} \right)^{-\frac{4}{5}} \mathrm{TeV} \; = 100 \left(\frac{r_{\mathrm{SN}}}{r_{\mathrm{ST}}} \right)^{-2} \mathrm{TeV}$$

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$$e^{-p/p_{Max}(r_{SN})}$$

$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\mathrm{inj}}^3}\left(\frac{p}{p_{\mathrm{inj}}}\right)^{-s} + s\int_{p_0}^{p}\frac{dp'}{p'}\left(\frac{p'}{p}\right)^{s} I^{(i-1)}(p') \times$$

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AVERAGE VOLUME

$$\bar{V}_{\rm SN} = \int_{r_{\rm ST}}^{r_{\rm Max}} P(r_{\rm SN}) \frac{4}{3} \pi r_{\rm SN}^3 dr_{\rm SN} = \frac{20}{33} \pi \frac{r_{\rm Max}^{11/2} - r_{\rm ST}^{11/2}}{r_{\rm Max}^{5/2} - r_{\rm ST}^{5/2}}$$

- Distribution of SNRs that CRs found in the Galactic disk as a function of their radius in the S-T phase

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Particles up to $E_k \sim$ TeV/n are typically confined for a time $T_{\rm SN} \approx 3 \times 10^4$ yr inside the sources

A non-negligible production of secondaries might come from interactions occurring inside the SNR **BEFORE** the escape of primaries:

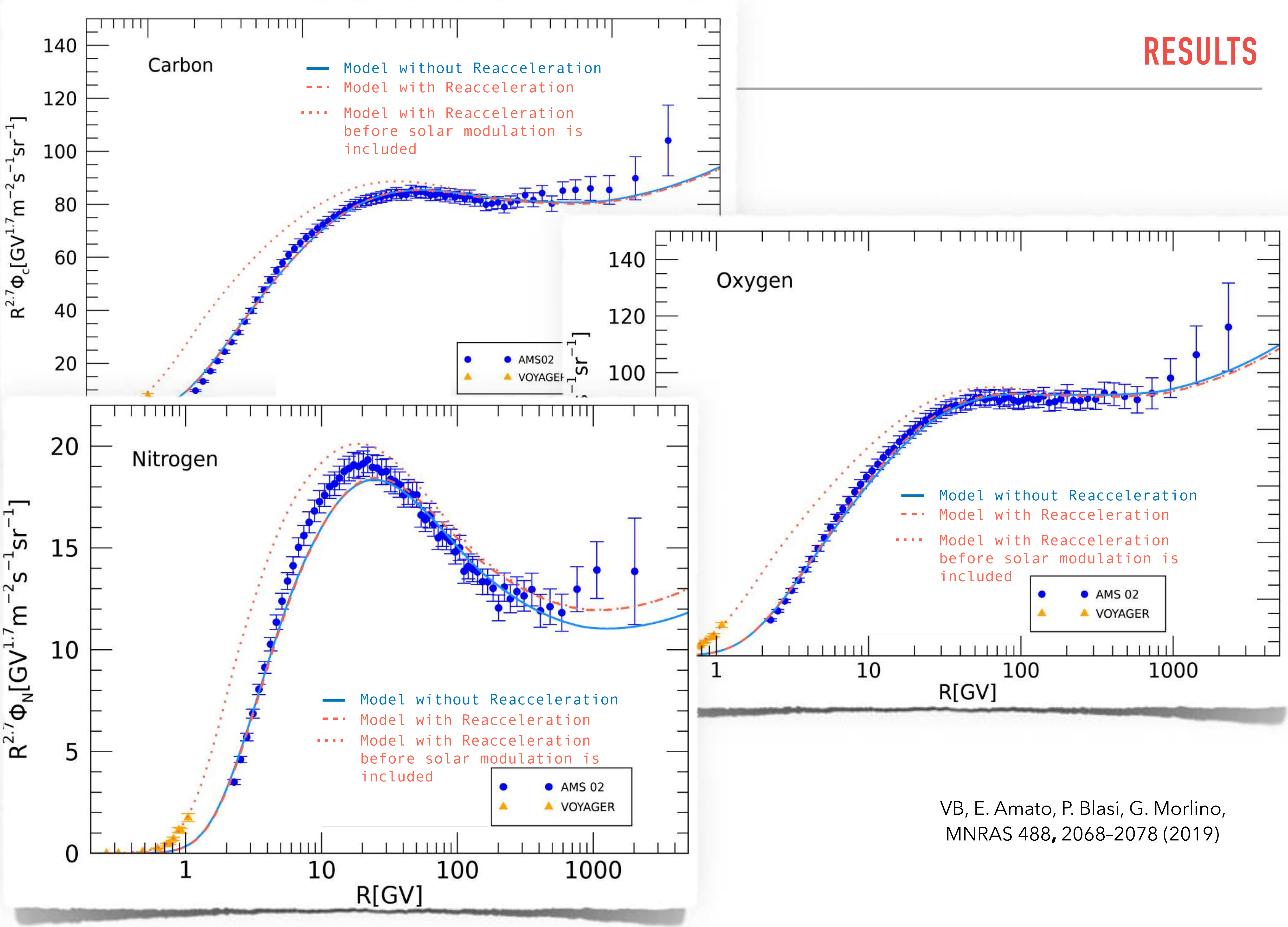
CONTRIBUTION FROM PRIMARY PARTICLES THAT ARE STILL LOCATED INSIDE THE SOURCES

$$Q_{src,\alpha} = v_\alpha\, r(s)\, n_{\rm src,\it j}\, \frac{s V_{\rm SN} T_{\rm SN} \mathscr{R}}{\pi R_d^2} \times$$
$$\times A_{\alpha'} K_{\alpha'} \int_{E_{\rm th}}^{+\infty} dE'_{k,\alpha'} \frac{d\sigma_{\alpha',j}}{dE_{k,\alpha}} \left(\frac{p'(E'_{k,\alpha'})}{p_{{\rm inj},\alpha'}} \right)^{2-s}$$

NB: for spallation processes $\frac{d\sigma_{\alpha',j}}{dE_{k,\alpha}} \equiv \sigma_{\alpha,\alpha'}\, \delta(E'_{k,\alpha'} - E_{k,\alpha})$

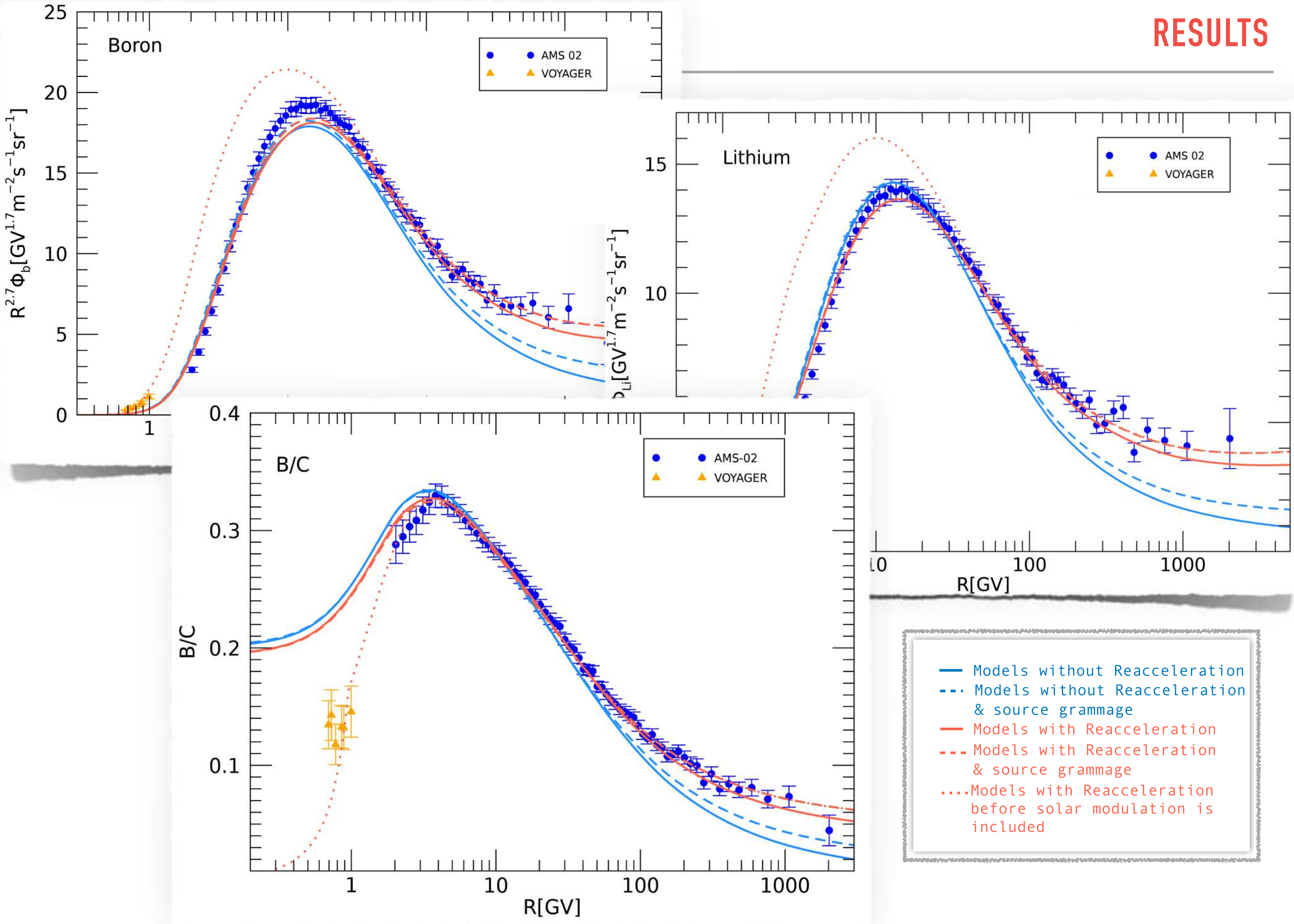
RESULTS

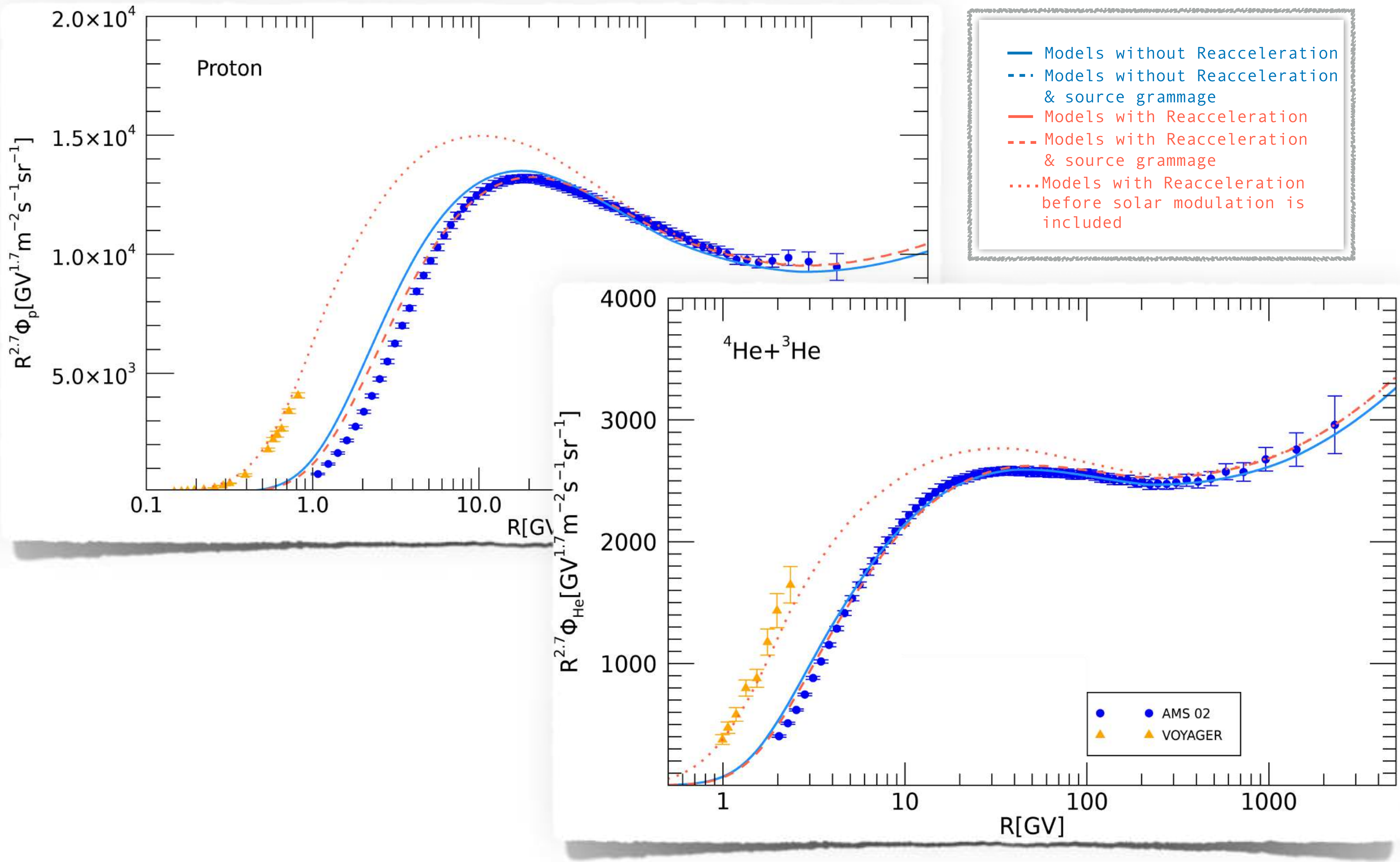
RESULTS



VB, E. Amato, P. Blasi, G. Morlino,
MNRAS 488, 2068–2078 (2019)

RESULTS


Boron
AMS 02
VOYAGER
$R^{2.7}\Phi_b[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
Lithium
AMS 02
VOYAGER
$\Phi_{Li}[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
R[GV]
B/C
AMS-02
VOYAGER
B/C
R[GV]
Models without Reacceleration
Models without Reacceleration & source grammage
Models with Reacceleration
Models with Reacceleration & source grammage
Models with Reacceleration before solar modulation is included



Proton
$R^{2.7}\Phi_p[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
R[GV]
$^4He+^3He$
$R^{2.7}\Phi_{He}[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
R[GV]
AMS 02
VOYAGER
Models without Reacceleration
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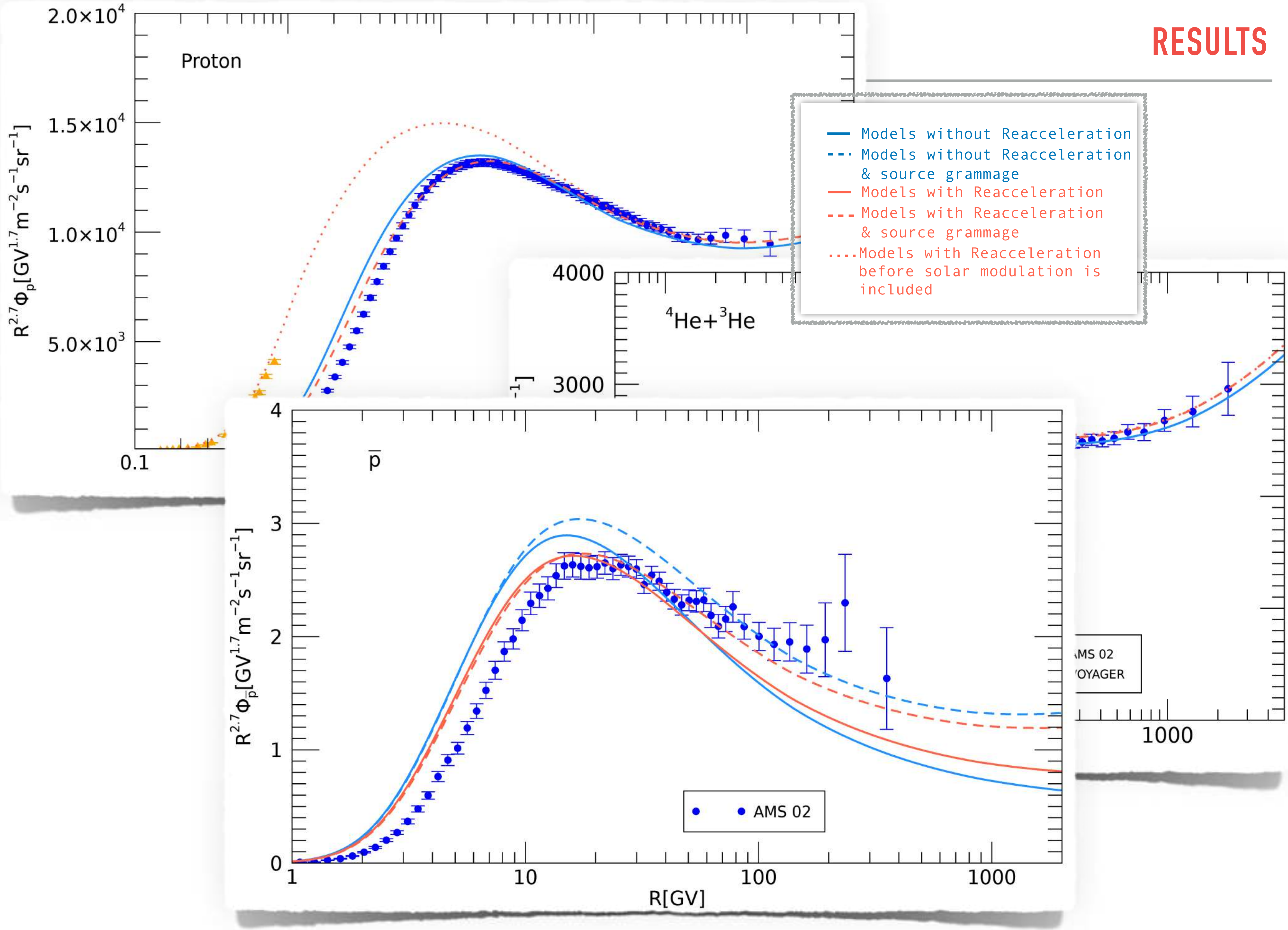
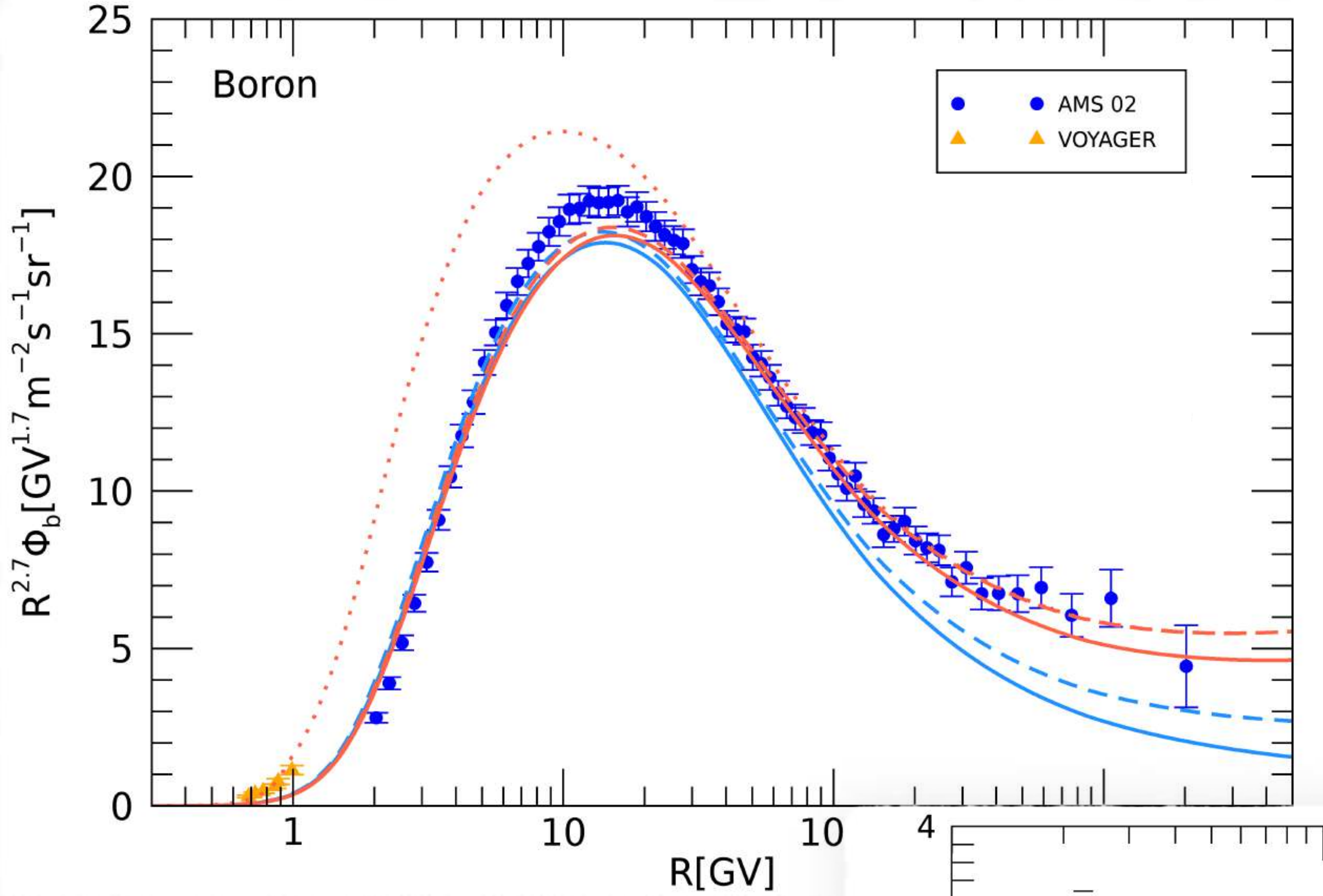
RESULTS

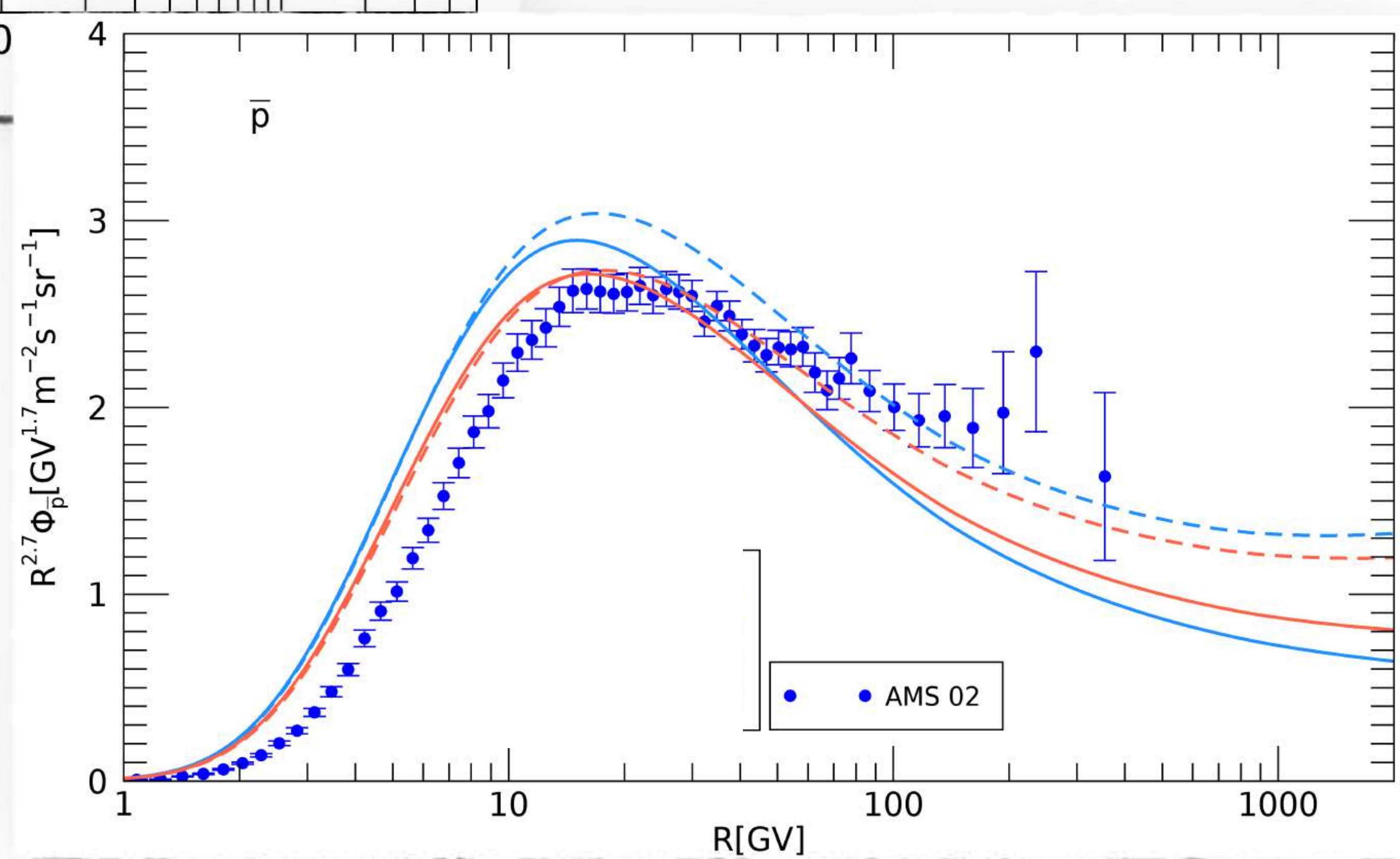


Proton
$R^{2.7}\Phi_p[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
0.1
Models without Reacceleration
Models without Reacceleration & source grammage
Models with Reacceleration
Models with Reacceleration & source grammage
Models with Reacceleration before solar modulation is included
$^4He+^3He$
4000
3000
1000
AMS 02
VOYAGER
$\bar{p}$
$R^{2.7}\Phi_{\bar{p}}[GV^{1.7}m^{-2}s^{-1}sr^{-1}]$
0
1
2
3
4
1
10
100
1000
R[GV]
AMS 02

RESULTS



Models without Reacceleration
Models without Reacceleration & source grammage
Models with Reacceleration
Models with Reacceleration & source grammage
Models with Reacceleration before solar modulation is included



… REACCELERATION & GRAMMAGE INSIDE SOURCES allow us to well-reproduce the spectra of CNO, p, He and B/C, B, Li, pbar without requiring alternative descriptions of CRs transport