Galactic cosmic ray propagation and cross sections

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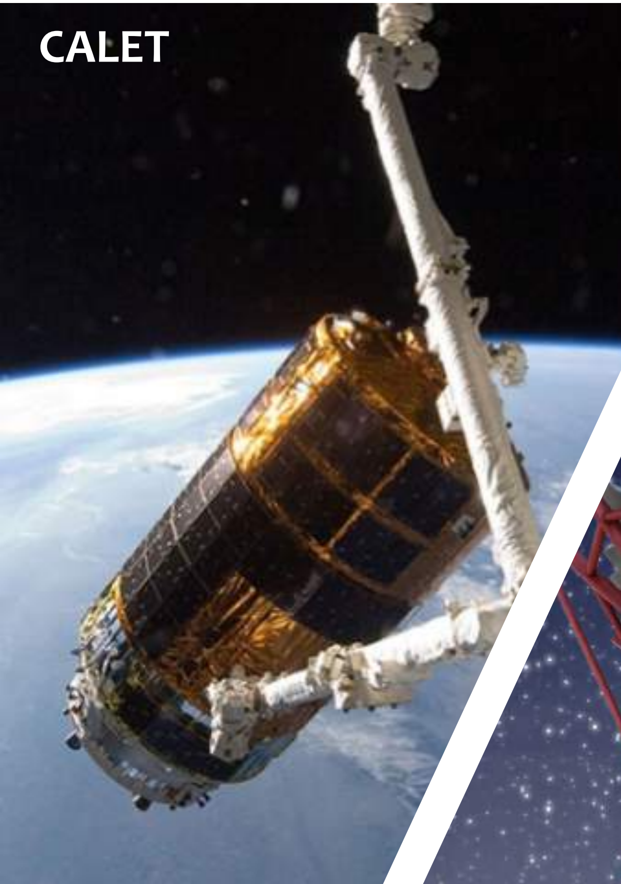
Università di Perugia / C.R.I.S.P. ASI-UniPG 2019-2-HH.0


DAMPE


VOYAGER


FERMI


AMS-02, PAMELA


CALET


CTA, HESS, MAGIC

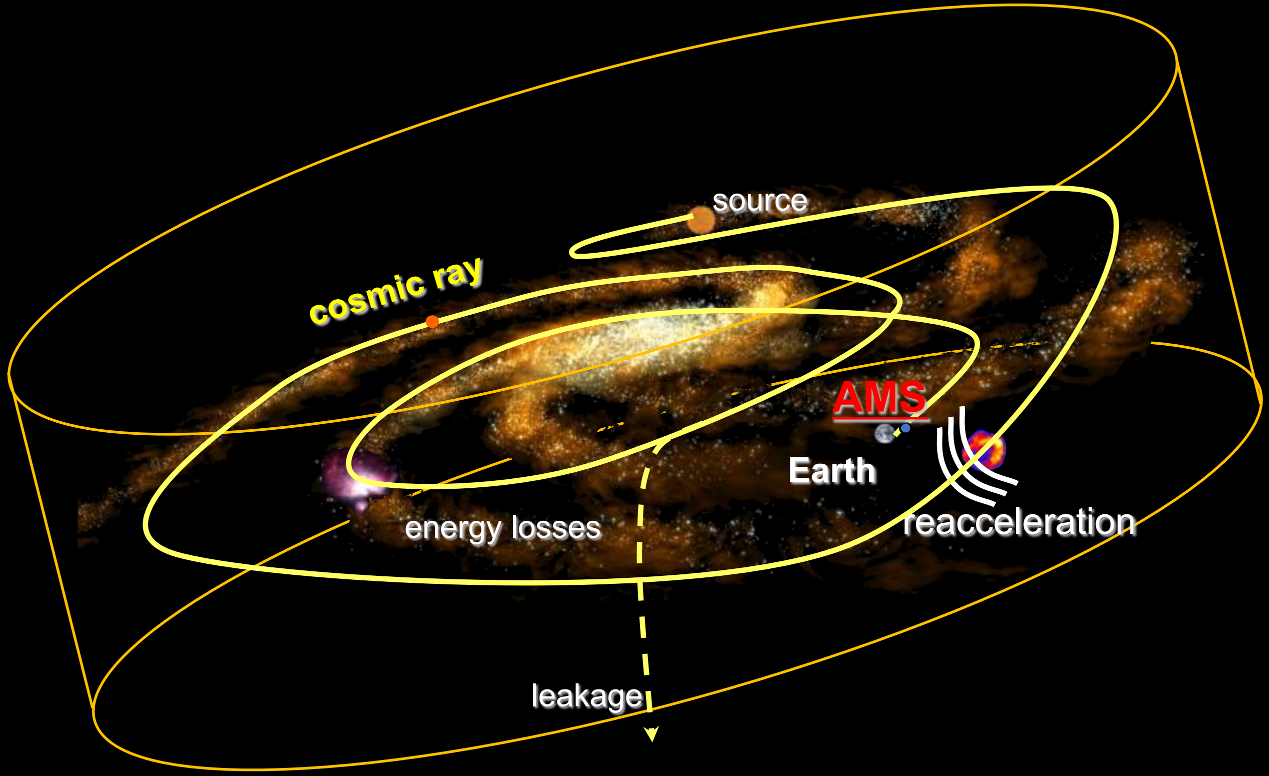
a golden age of new cosmic ray measurements

The physical picture

General paradigm based on three pillars [established mechanisms]

- Shock acceleration in SNRs: origin of primary CRS (p, C-N-O, Fe)
- Diffusive transport in interstellar (& interplanetary) magnetic turbulence
- Collisions with ISM gas → production of secondaries (Li-Be-B, antimatter)

The concrete realizations are often based on simplifying assumptions pertaining e.g. dimensionality, homogeneity, isotropy, stationarity, linearity…



The physical picture

Transport equation:

$$\frac{\partial\psi}{\partial t} = Q + \nabla\cdot(K\nabla\psi) + \frac{\partial}{\partial R}R^2K_R\frac{\partial}{\partial R}\frac{1}{R^2}\psi - \frac{\partial}{\partial R}\left[\dot{R}\psi\right] - \Gamma_t\psi$$

CR density

Source

Spatial diffusion

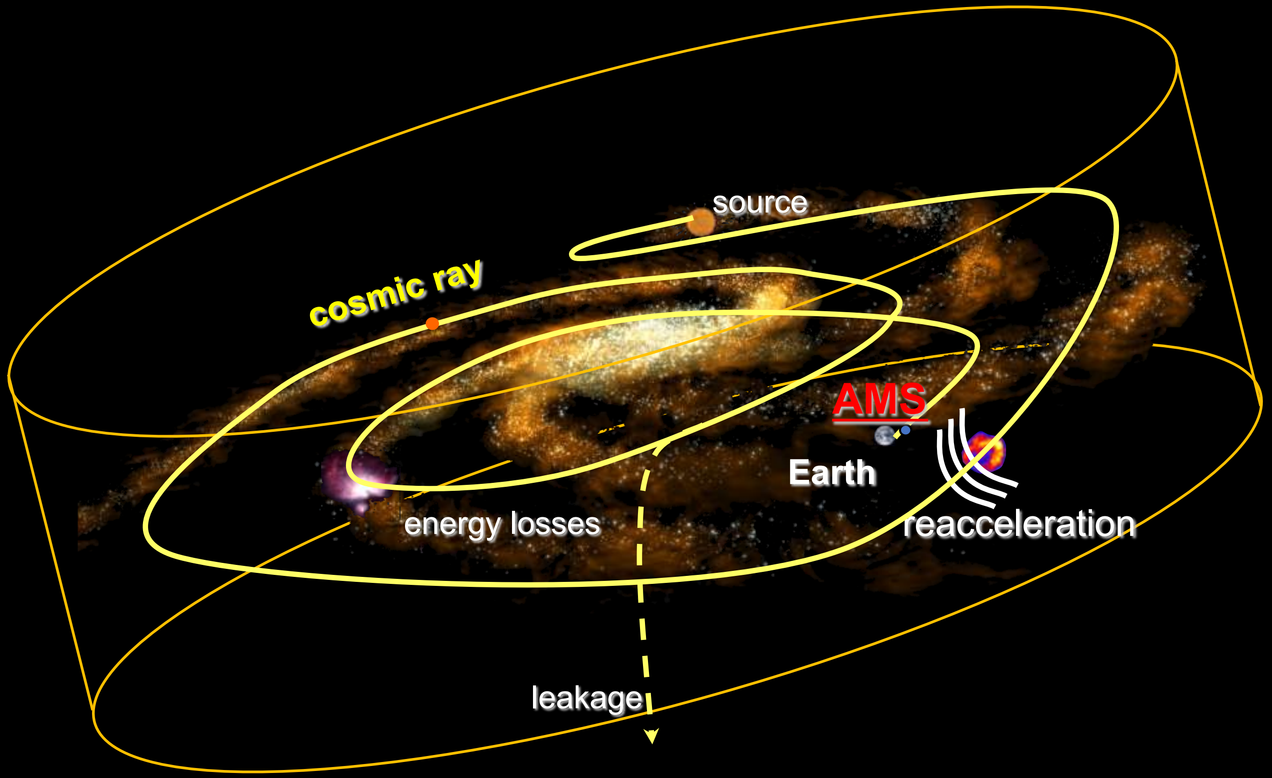
Reacceleration (rigidity diffusion)

Losses

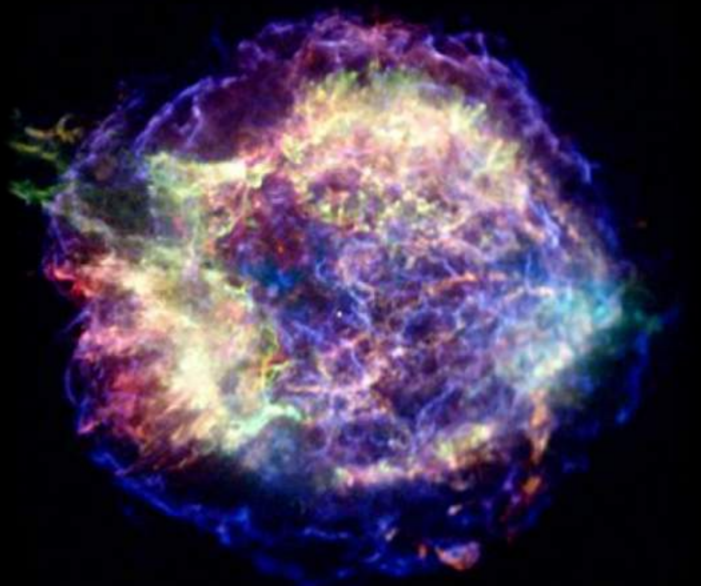
Decay or destruction

Steady-state $\partial\psi/\partial t \equiv 0$

Boundary conditions $\psi(\Omega) \equiv 0$

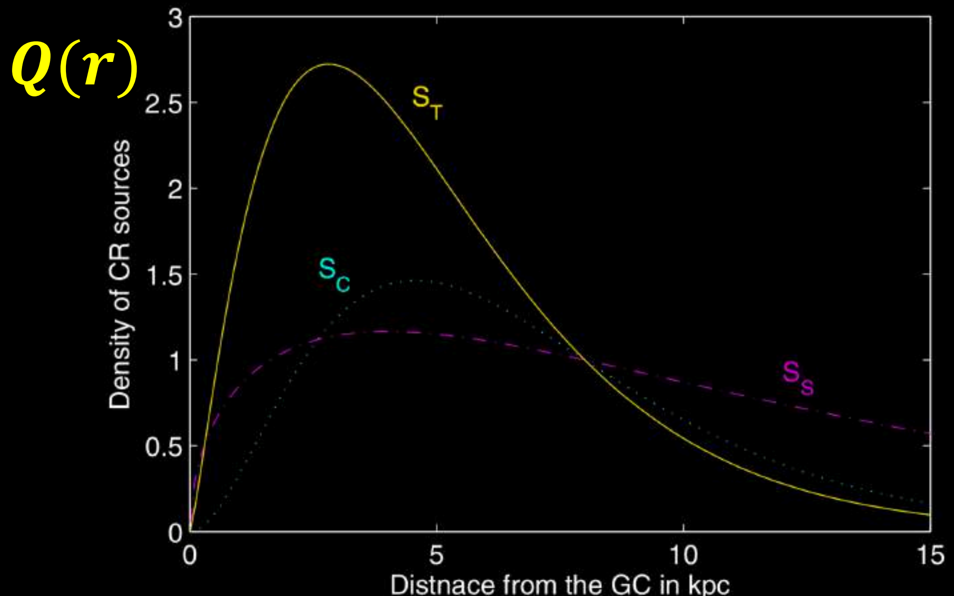


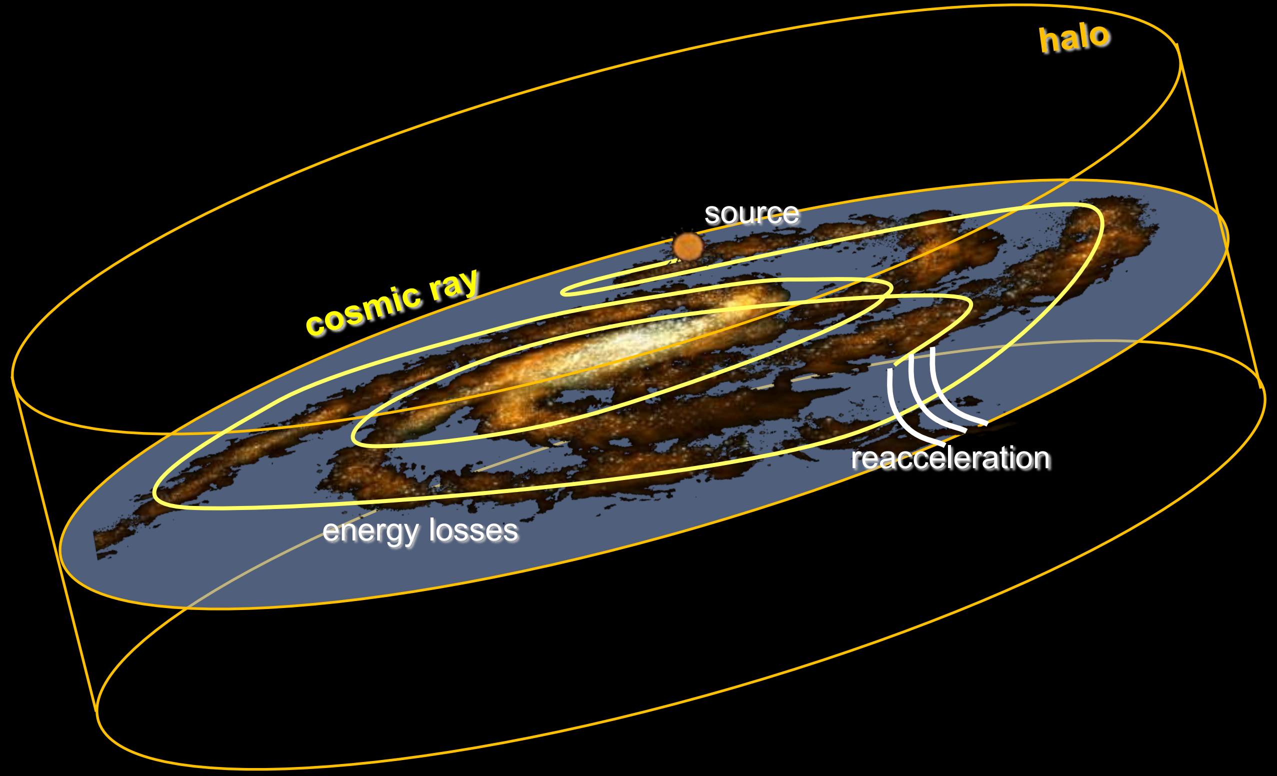
Primary sources and acceleration



Supernova remnants: shockwaves generated by SN explosions

- SNRs are known CR factories. PeV acceleration observed in GC
- Monstly on the Galactic disk. Average SN rate ~3/century.
- They also inject turbulence in the ISM!





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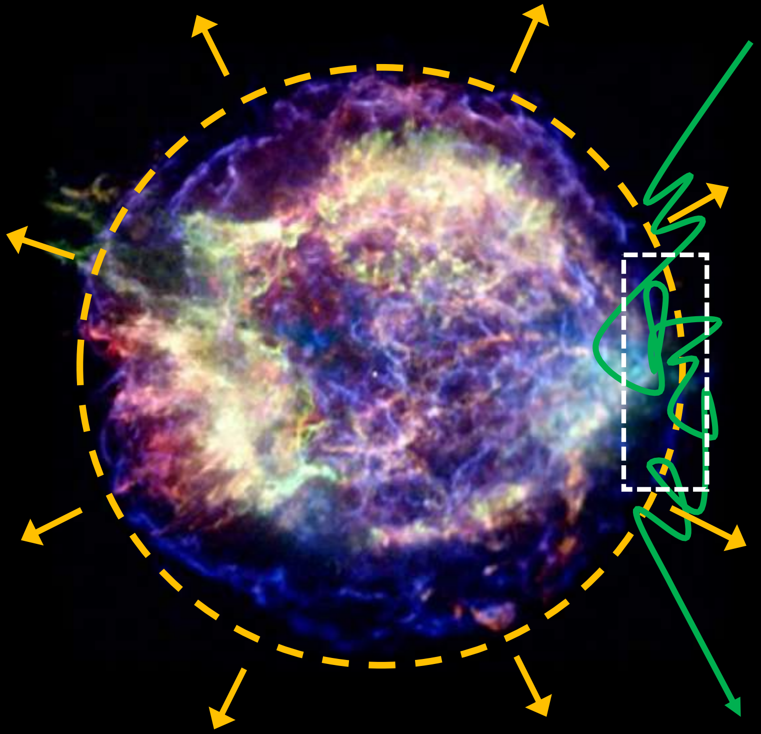

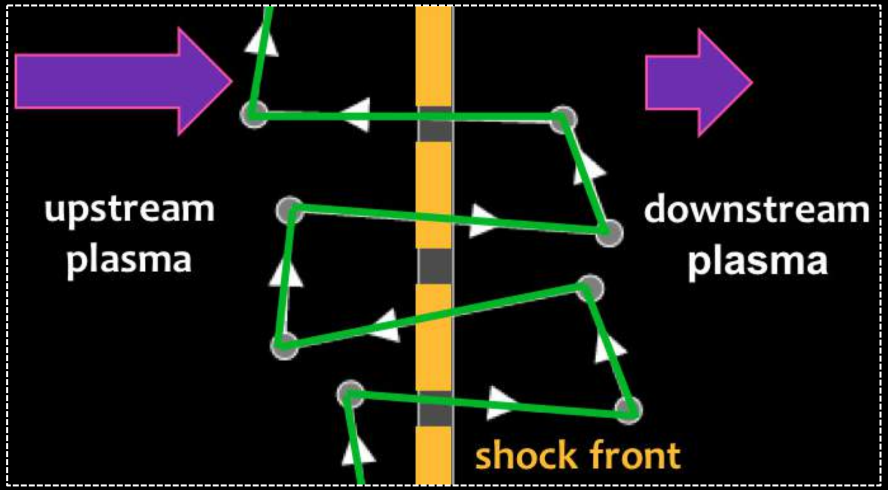

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Linear diffusive shock acceleration theory (DSA)

→ Power law energy spectrum of CRs injected in the ISM

$$Q(R) \propto Y \, (R/R_0)^{-\nu}$$

$\nu \approx 2$ injection index for linear DSA planar shocks

$Y =$ SNR composition factors $\approx$ ISM abundances

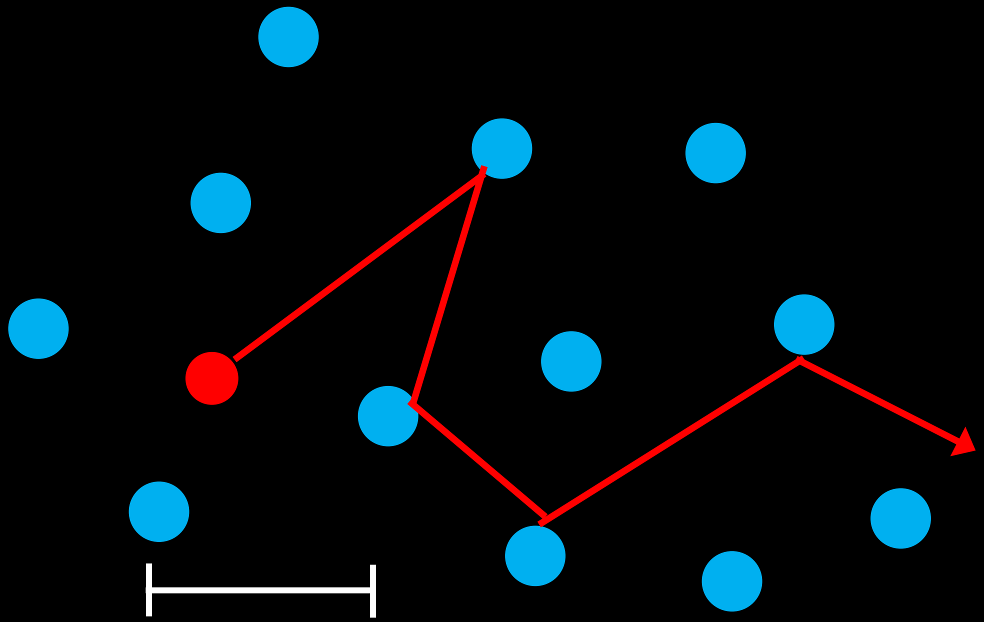
Bell 1978, Ostriker&Blandford 1978, Krimskii 1977

Diffusive Transport

Erratic motion of CRs through small-scale irregularities of the B-field

Related to the spectrum of interstellar turbulence, the “big power law in the sky”

$$K = \frac{1}{3} v\lambda$$

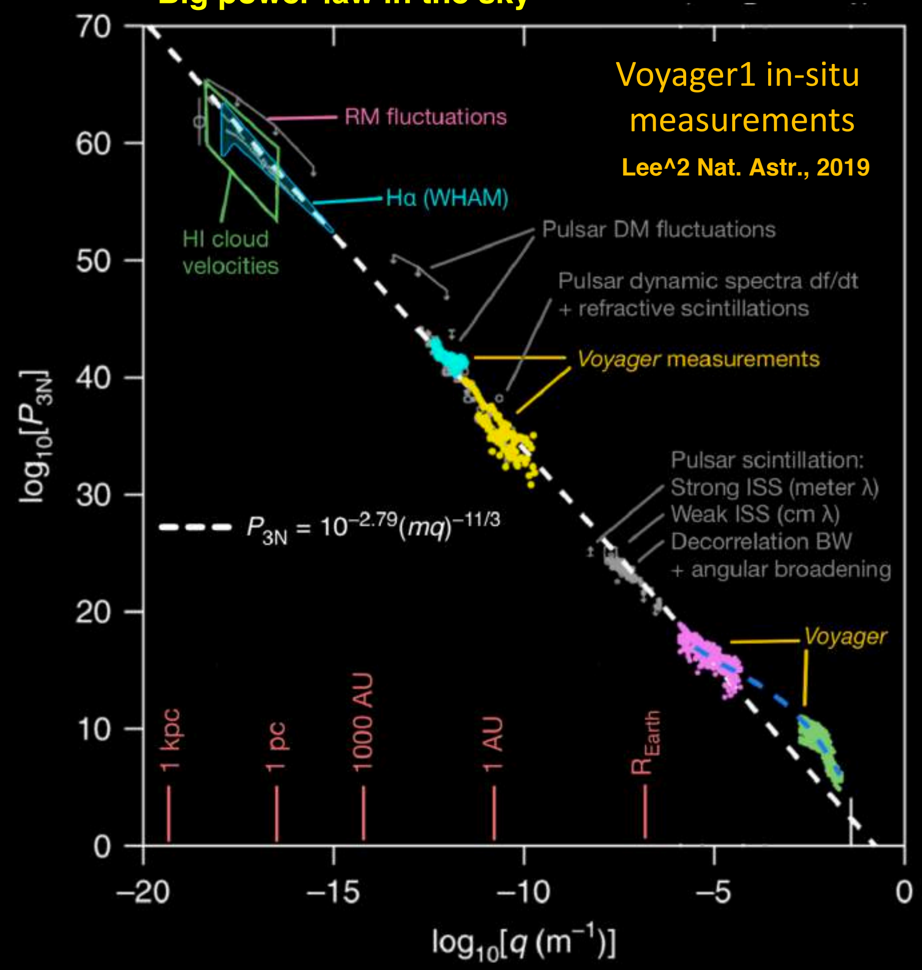


$\lambda \sim 1\,pc$

$K \sim kpc^2/Myr$

$K \propto \beta R^{1/3}$

Big power-law in the sky



Voyager1 in-situ measurements

Lee^2 Nat. Astr., 2019

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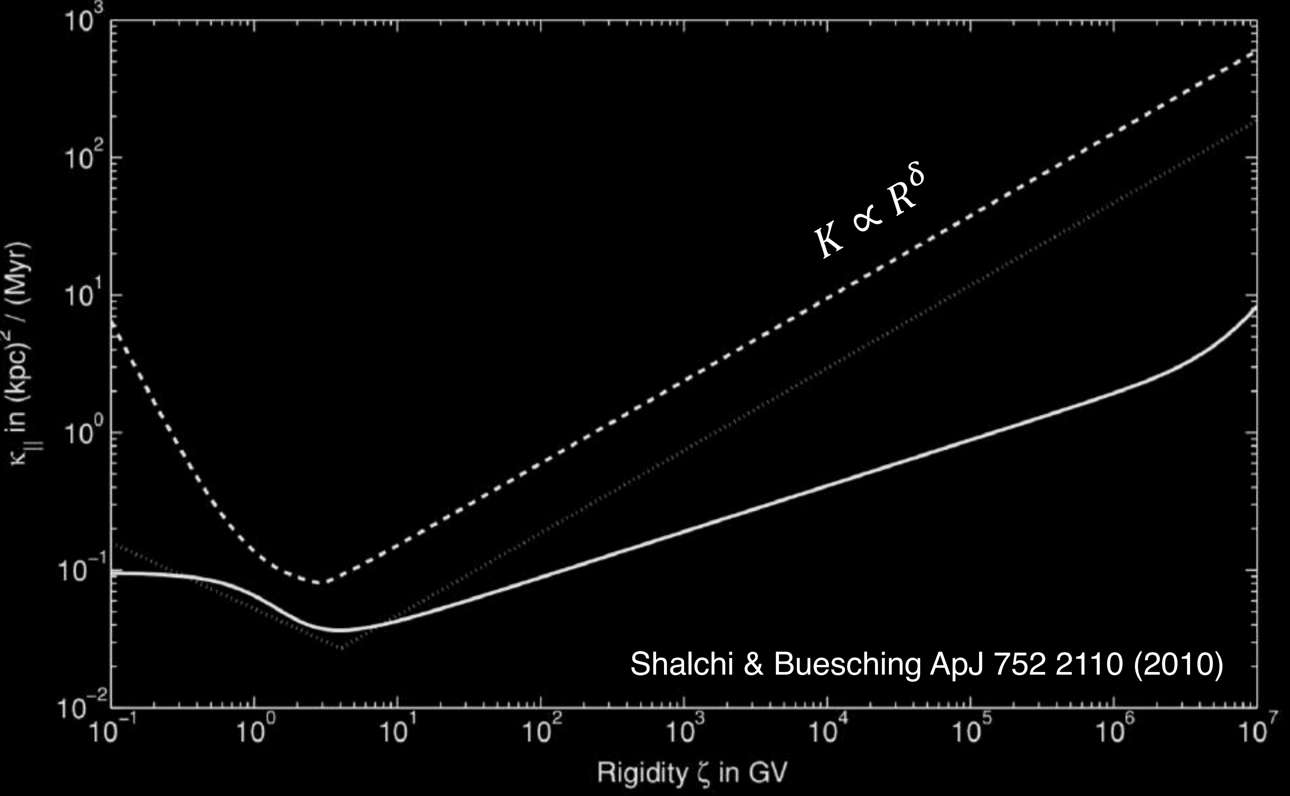

Shalchi & Buesching ApJ 752 2110 (2010)

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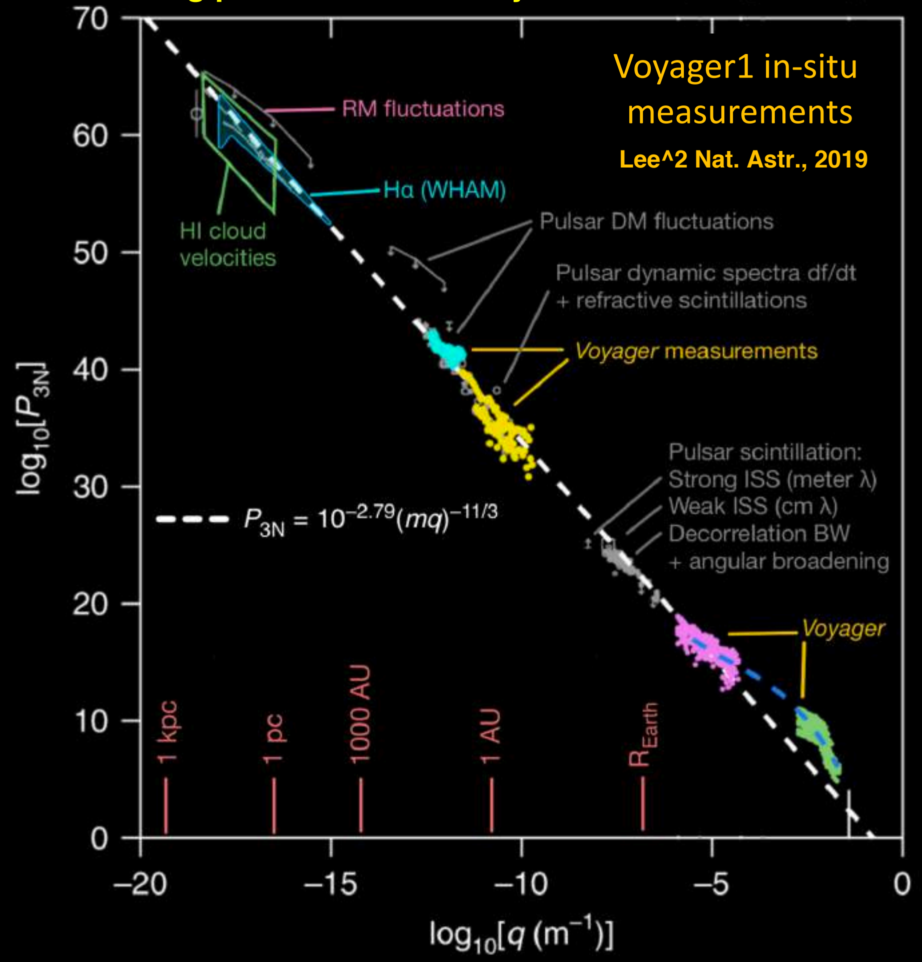

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Losses

Decay or destruction

Source

CR density

Spatial diffusion

$$K = K_0 \beta (R/R_0)^{\delta}$$

Spectral index $\delta \sim 0.3 - 0.5$

Reacceleration

$$K_R \propto R^2 v_A^2 / K$$

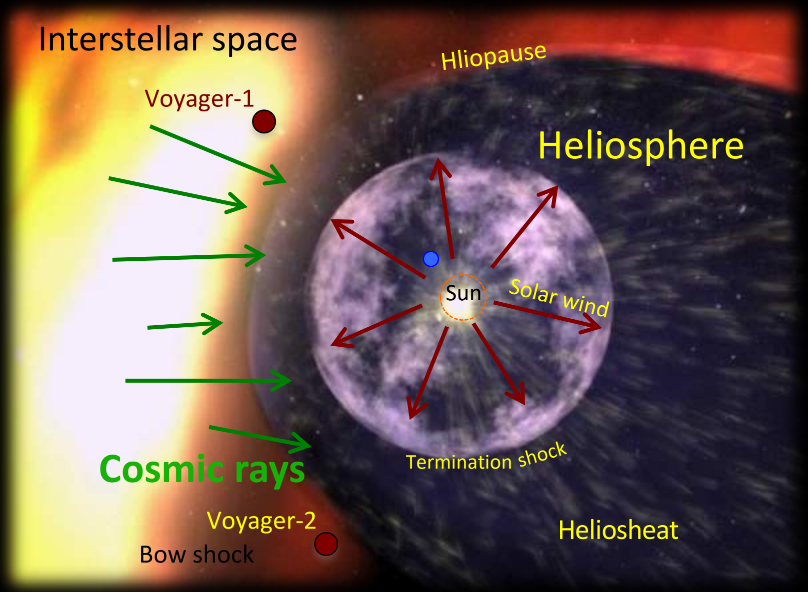
Alfven waves of speed v_A

$v_A = B_0/\sqrt{4\pi\rho} \sim 7\ km/s$

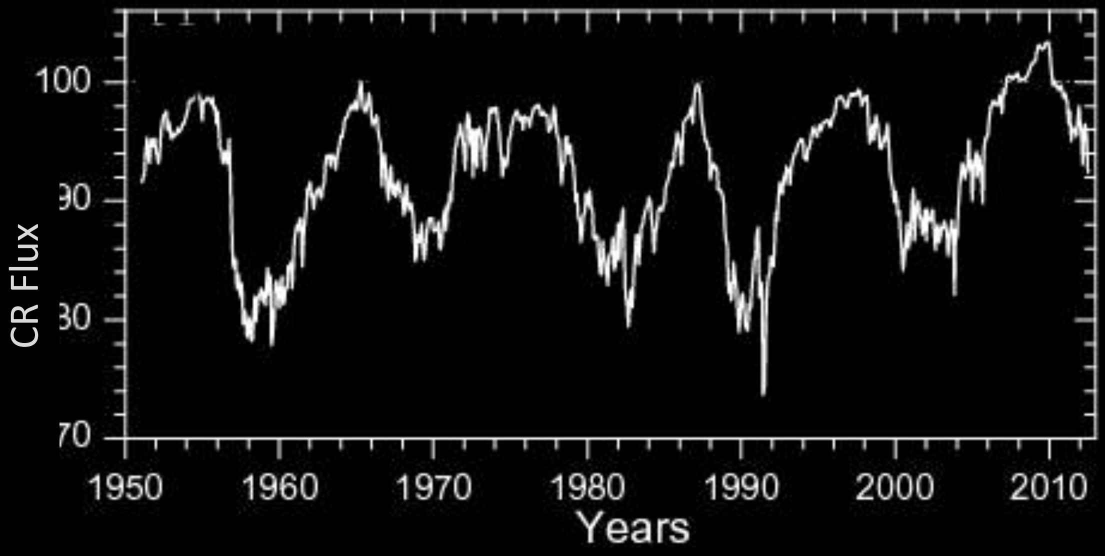
Diffusive-convective Transport in Heliosphere

All measurements on Galactic cosmic rays are made inside the heliosphere (with the remarkable exception of Voyager-1 and Voyager-2)

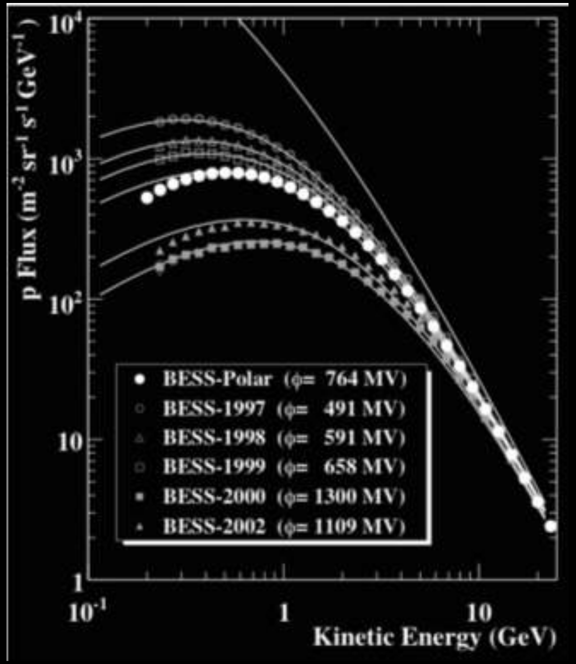
When CRs enter the heliosphere, they interact with the magnetized solar wind
-> Transport processes: diffusion, convection, cooling, drift



Quasi-11-yr temporal dependence of the CR flux

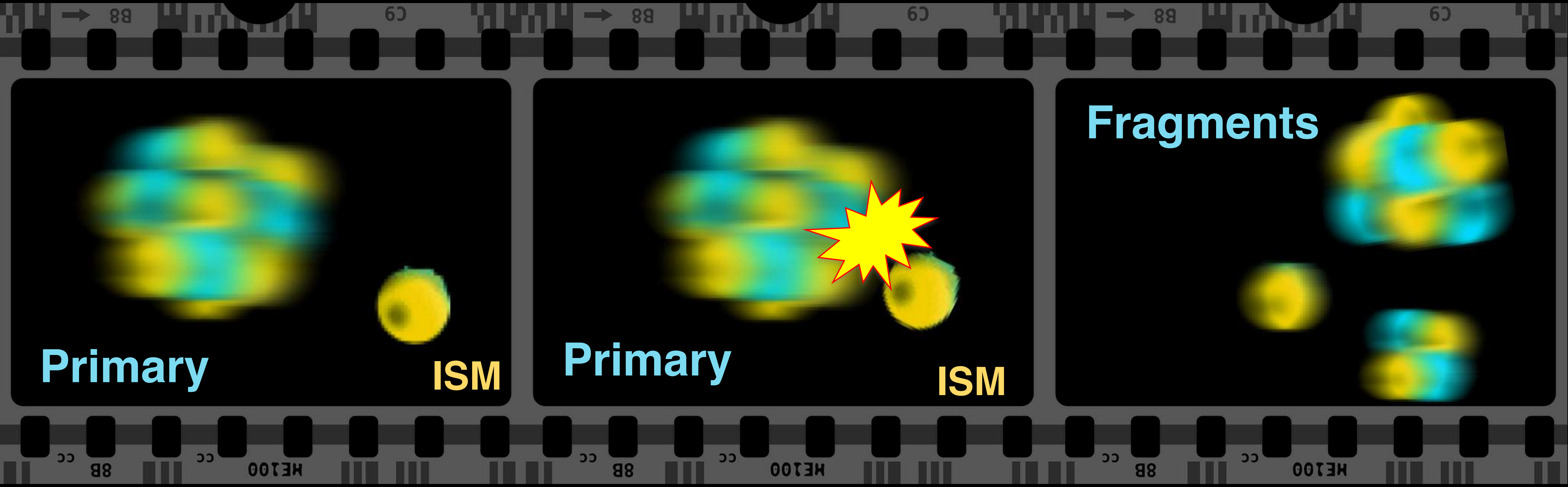


Modulation of CR energy spectra



Collisions

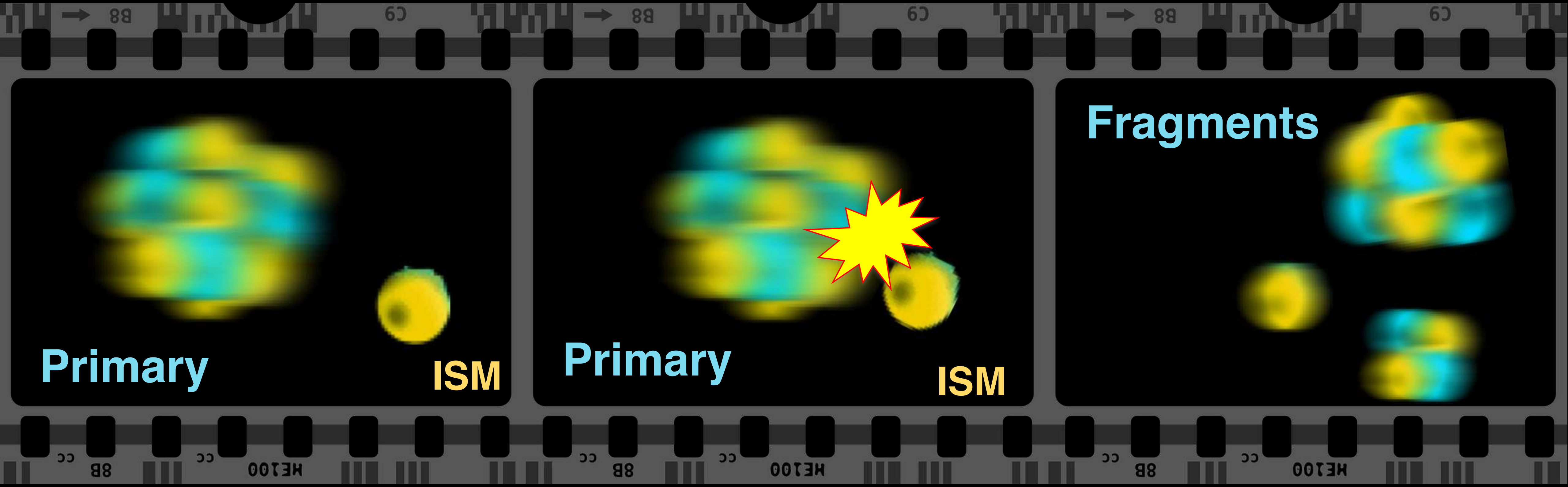
$$Q_j^{sec}(E) = \sum_{ism}\sum_{k} n^{ism}\,\beta_k\,c \int_{E_k} \psi_k(E_k)\,\frac{d\sigma_{k\to j}^{ism}}{dE}(E,E_k)\,dE_k$$



Collisions

two-component ISM + straight-ahead

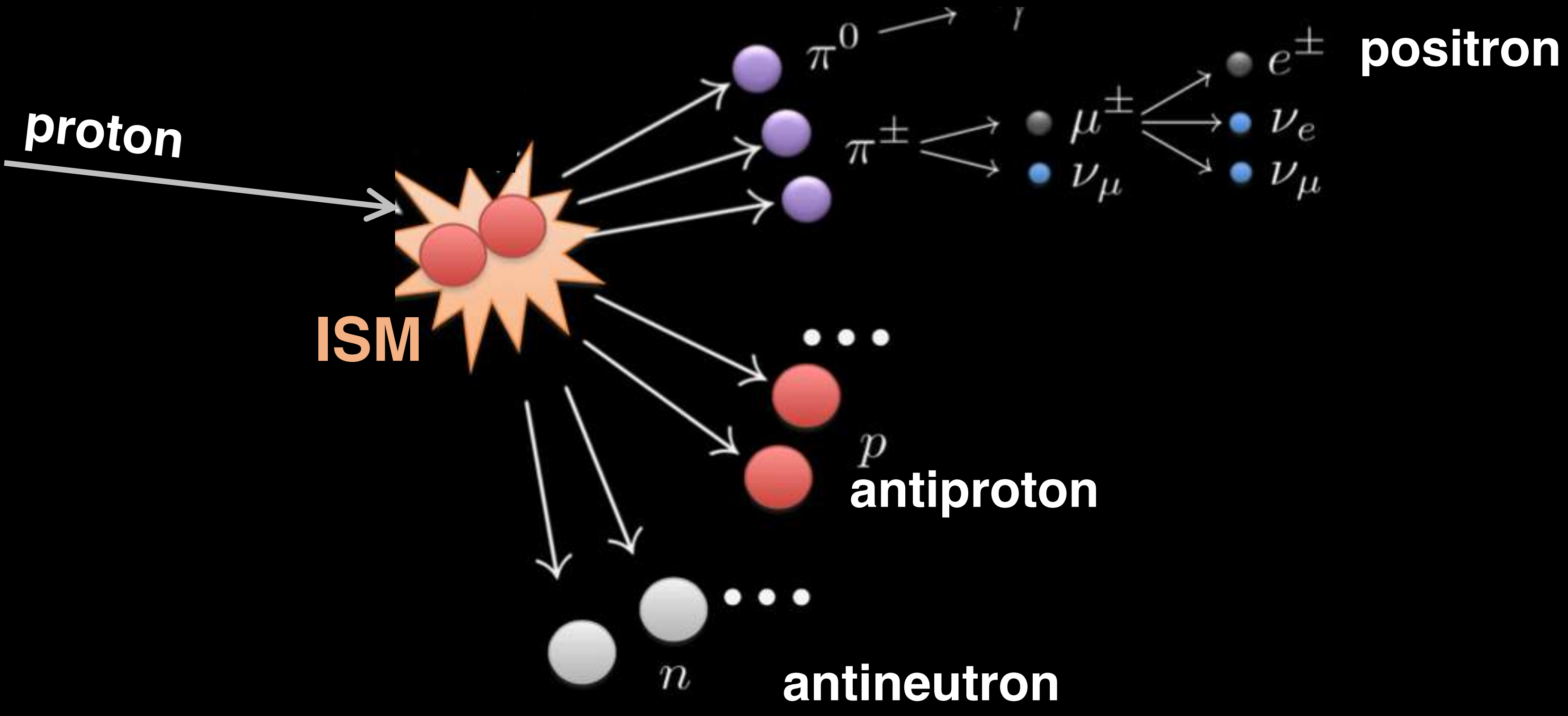
$$Q_j^{sec}(E) = \sum_k \left\{ n^H \beta_k c \boxed{\sigma^H_{k\to j}(E)} + n^{He} \beta_k c \boxed{\sigma^{He}_{k\to j}(E)} \right\} \boxed{N_k(E)}$$



Collisions

Antimatter:

$$Q_j^{sec}(E) = \sum_{ism} \sum_{k} n^{ism}\, \beta_k\, c \int_{E_k} \psi_k(E_k)\, \frac{d\sigma_{k \to j}^{ism}}{dE}(E, E_k)\, dE_k$$



positron

proton

ISM

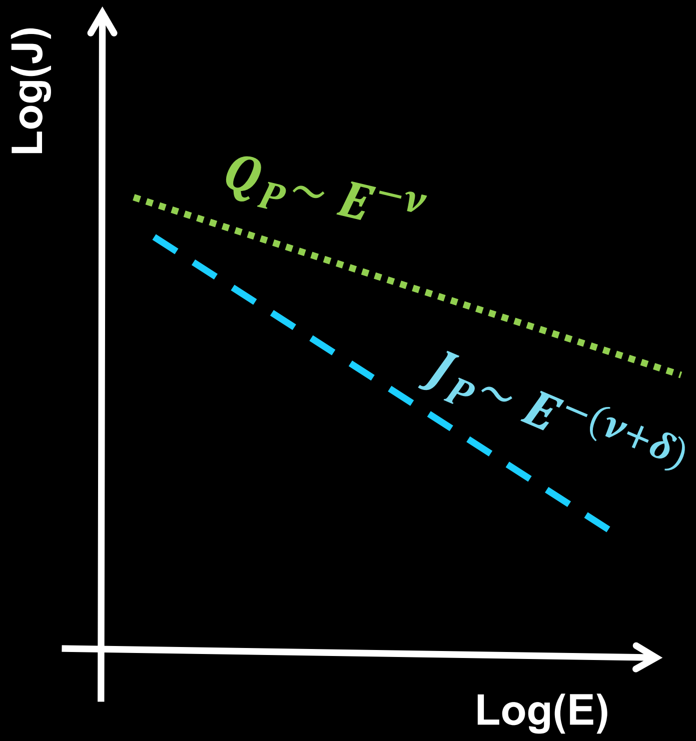
antiproton

antineutron

Basic predictions: primary & secondary CRs

$$J_P(E) \approx \frac{Q_P(E)}{K(E)/L} \propto E^{-(\nu+\delta)}$$

(H, He, C-N-O, Fe…)



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$$J_P(E) \approx \frac{Q_P(E)}{K(E)/L} \propto E^{-(\nu+\delta)}$$

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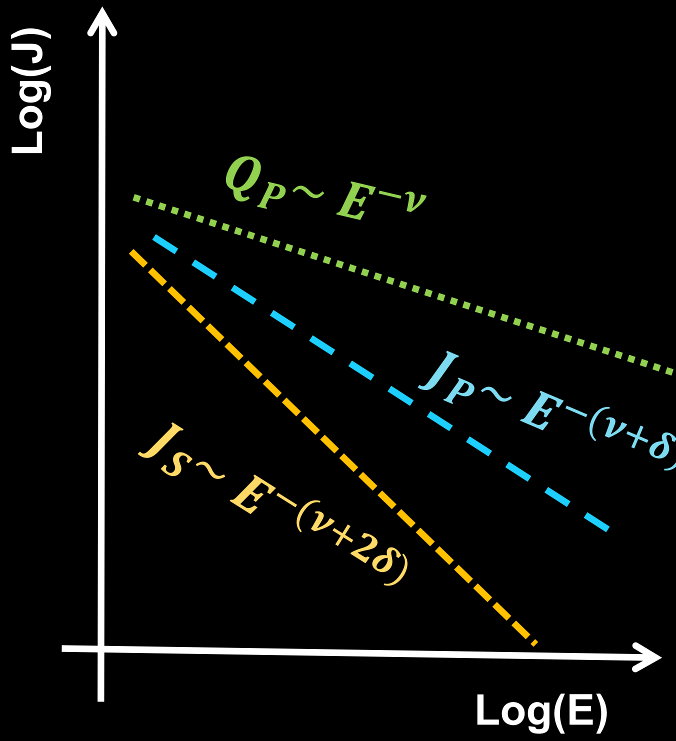
$$J_S(E) \approx \frac{Q_S(E)}{K(E)/L} \propto \frac{J_P(E)\,\sigma_{P\to S}(E)}{K(E)/L} \propto E^{-(\nu+2\delta)}$$

(2H, 3He, Li-Be-B…)



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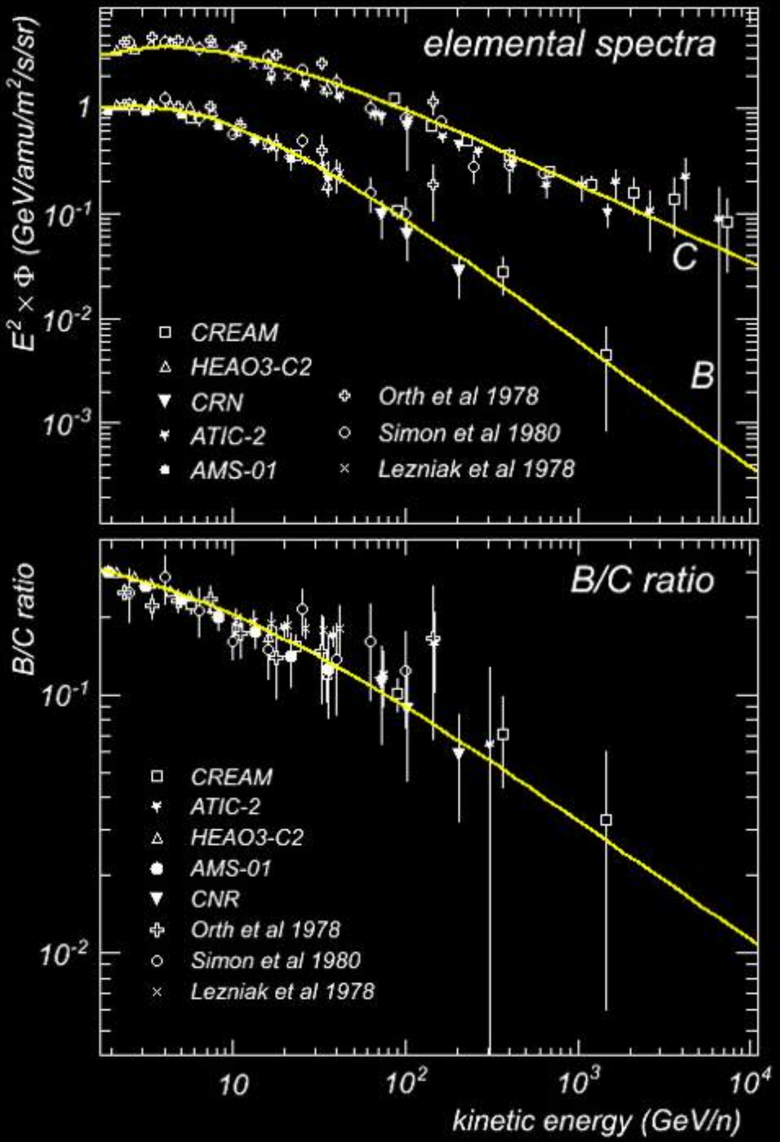
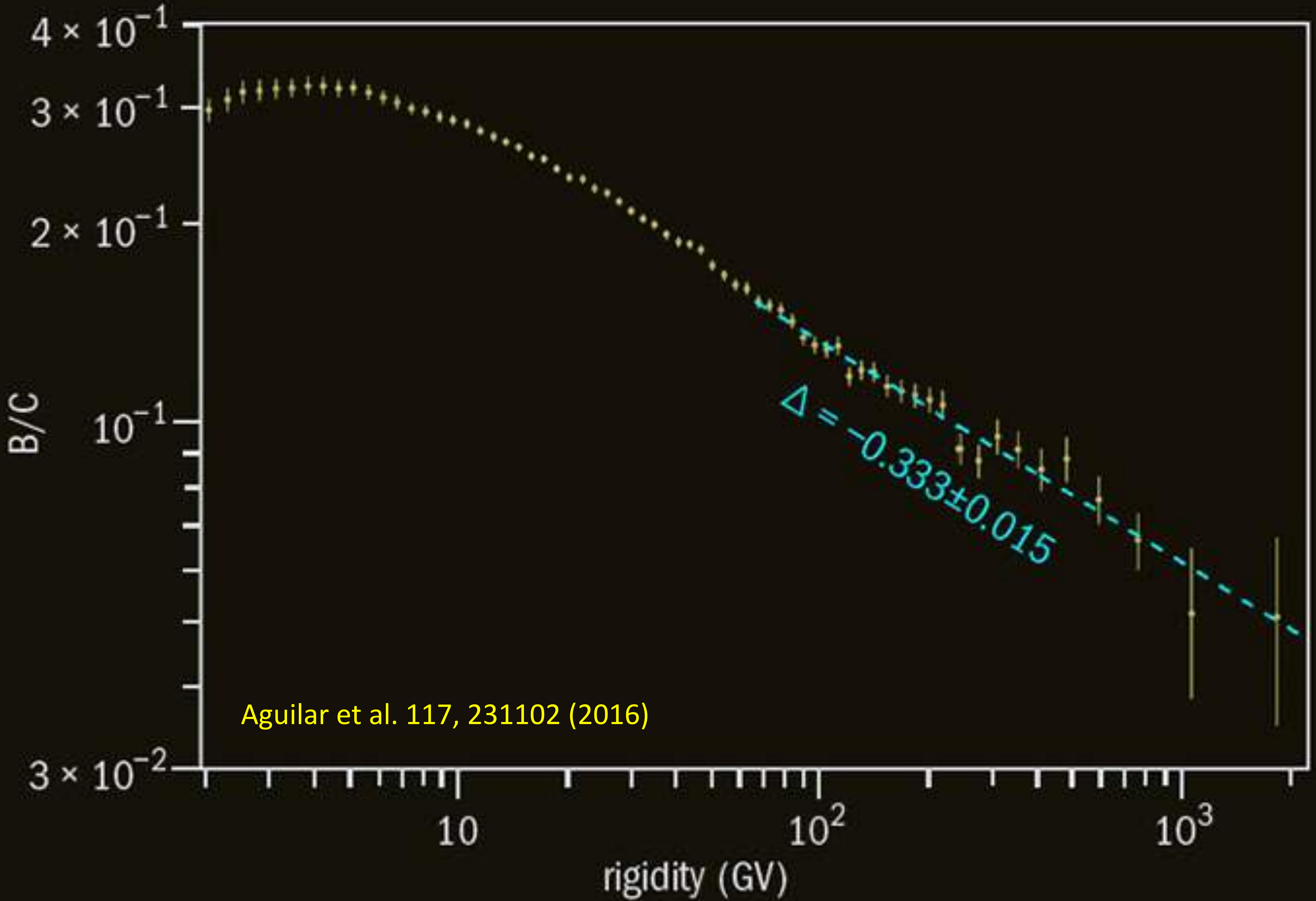
Secondary/primary ratios, e.g. B/C

$$B/C \propto \frac{L}{K_0} R^{-\delta}$$



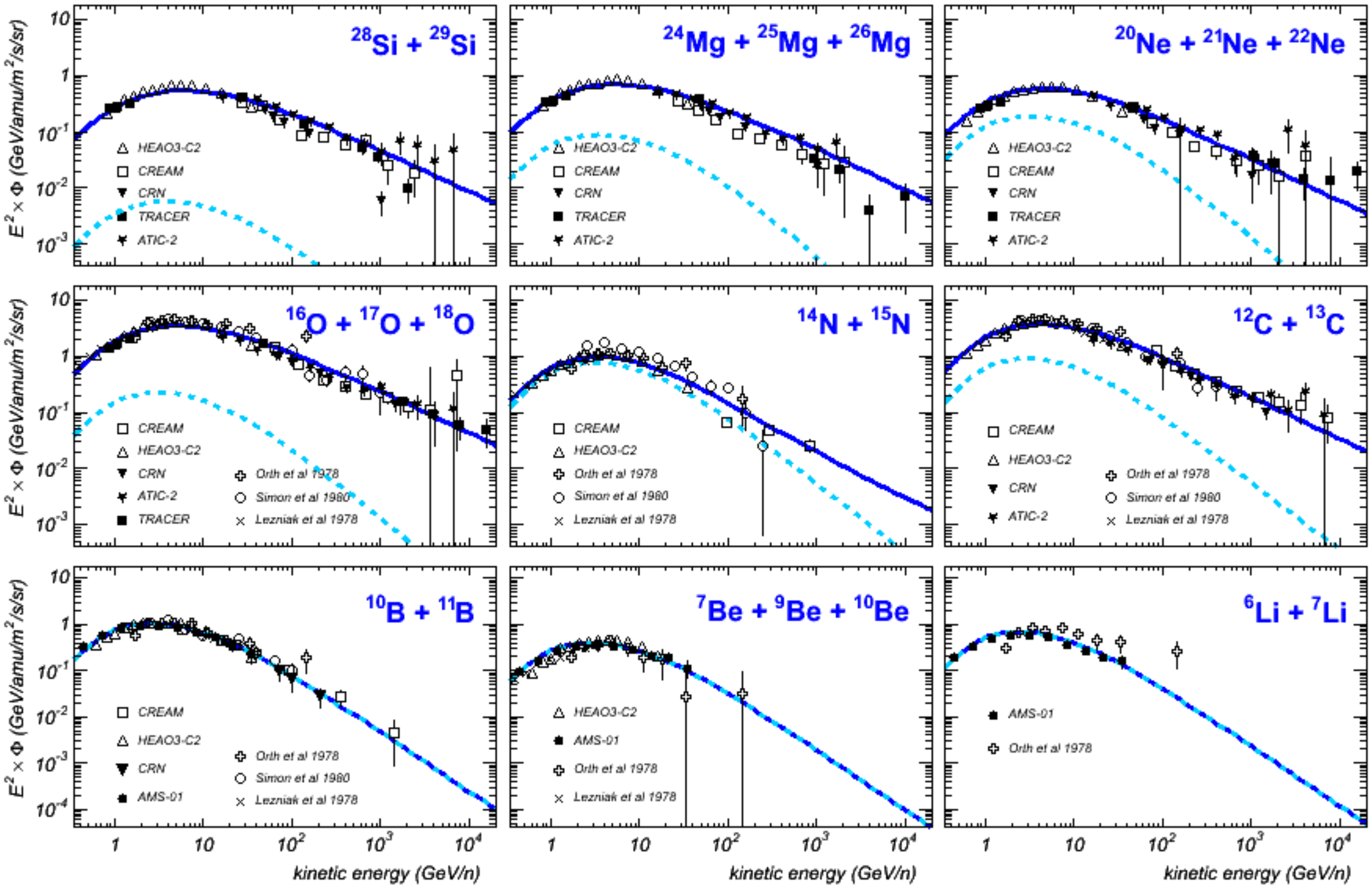


Aguilar et al. 117, 231102 (2016)

Basic predictions: primary & secondary CRs

total elemental spectra – secondary component

NT & Donato A&A 2012 [1203.6094]



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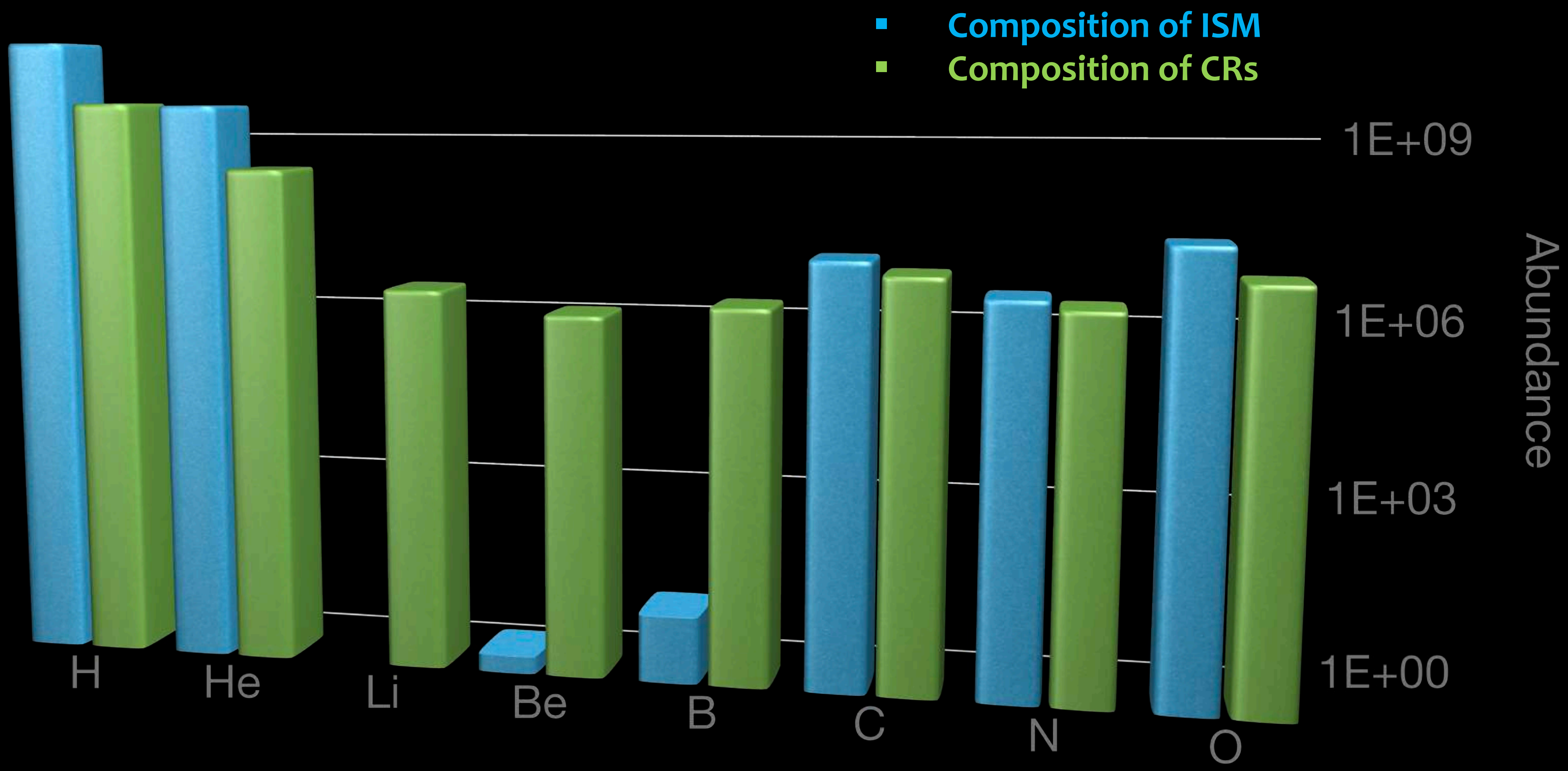


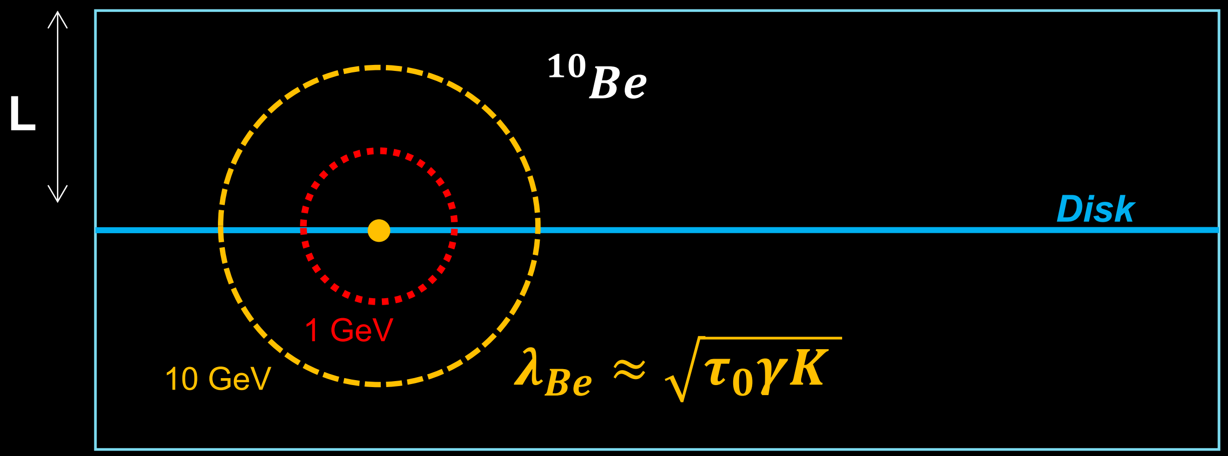
Parameter degeneracy & radioactive Be

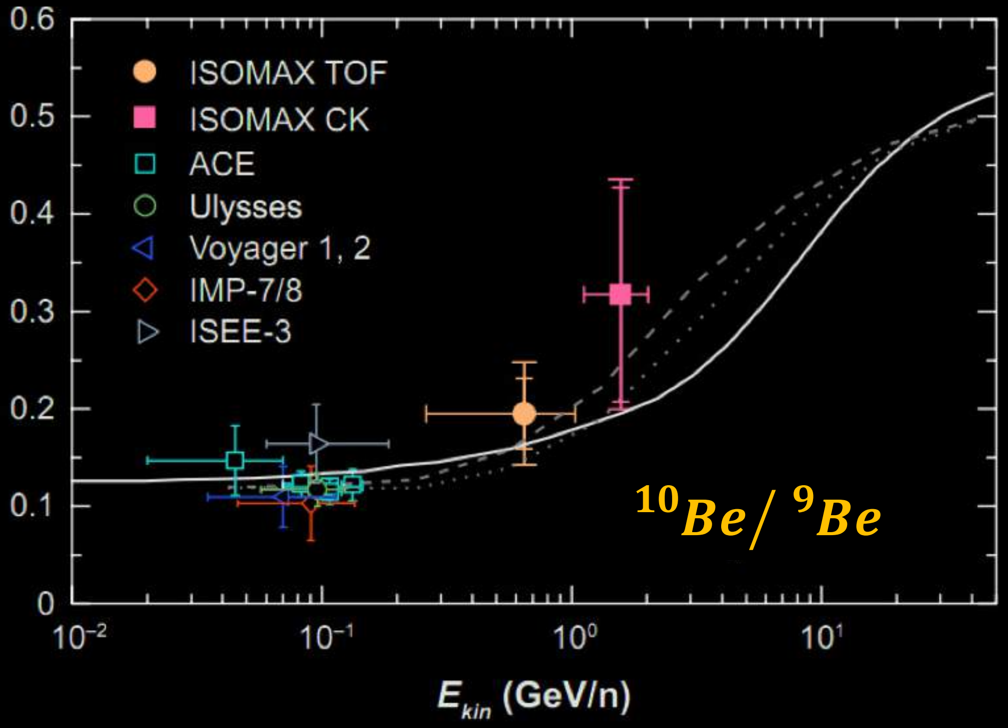
$$J_P \approx \frac{Y_P}{K_0/L} R^{-(\nu+\delta)} \qquad B/C \propto \frac{L}{K_0} R^{-\delta} \qquad {}^{10}Be/{}^{9}Be \propto \frac{\sqrt{K_0}}{L}$$

Source composition

obtain source spectral index *ν*

resolve K and halo height L





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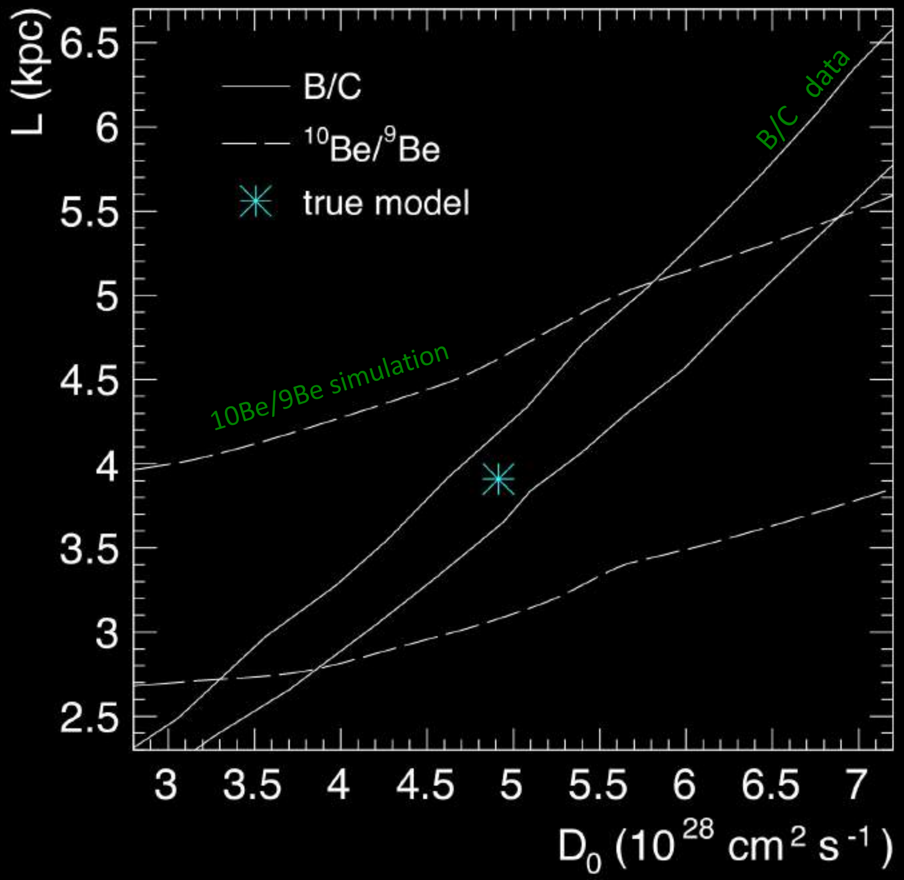

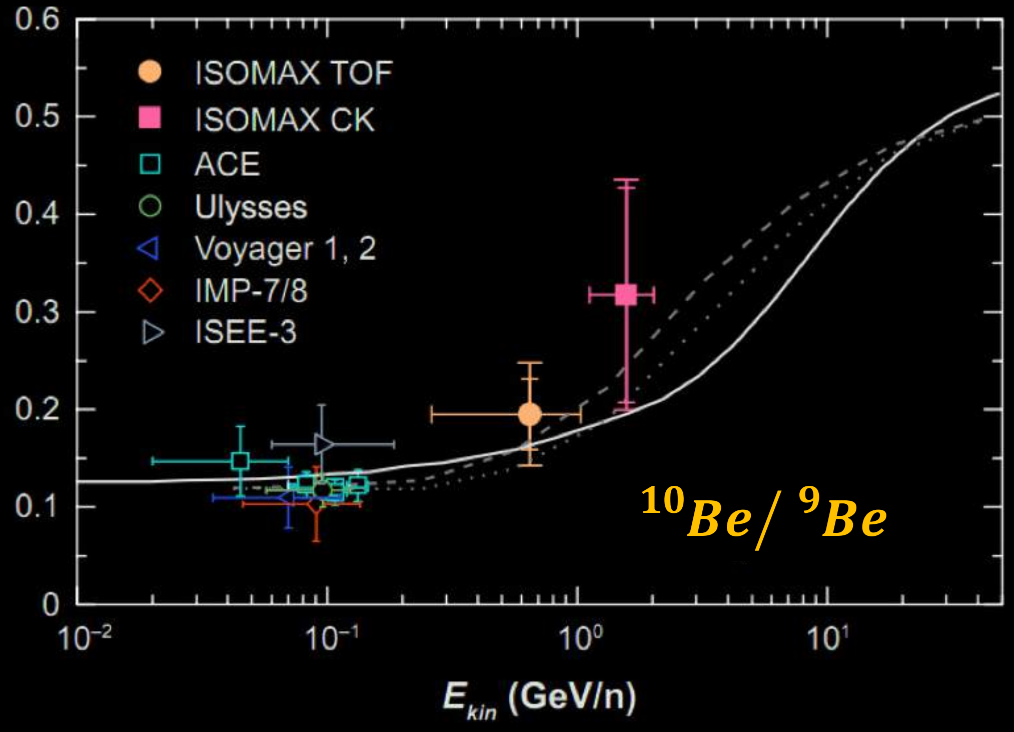

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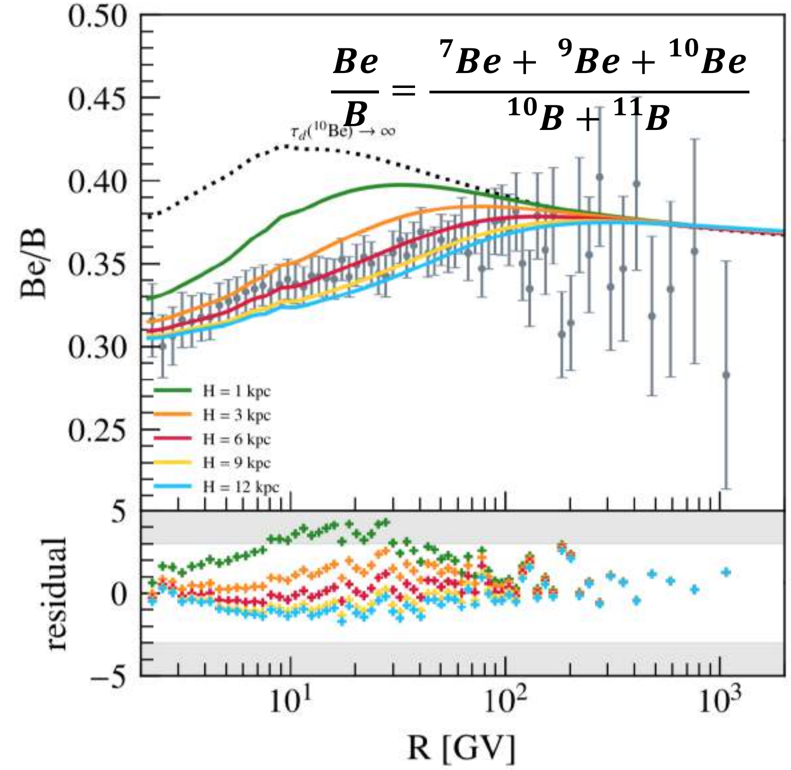
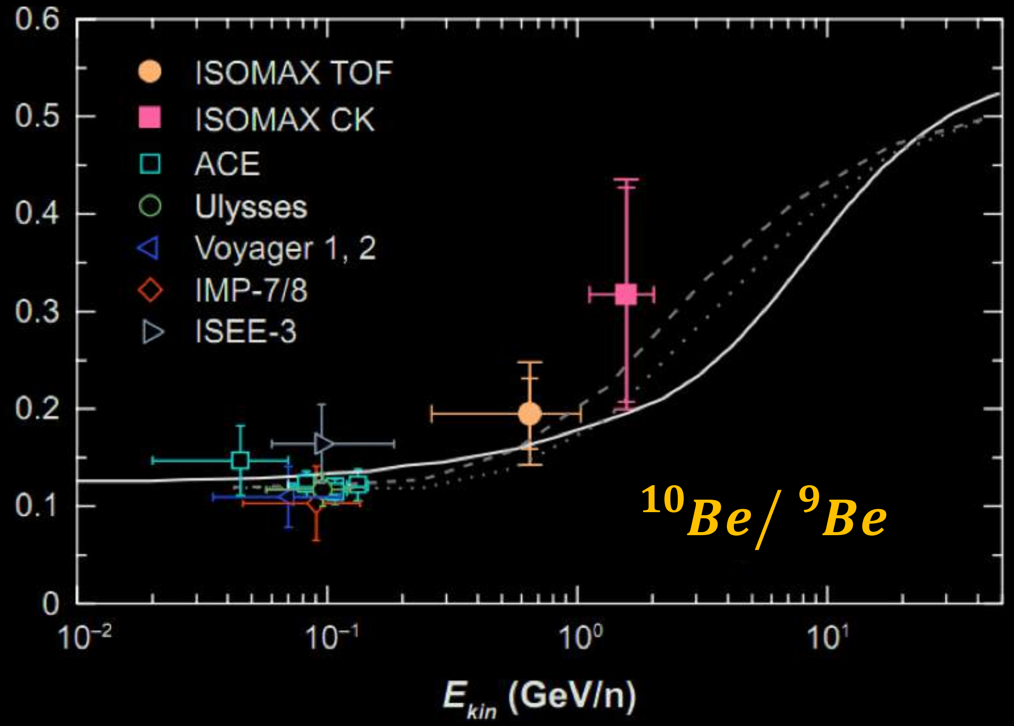
resolve K and
halo height L

Elemental Be/B ratio



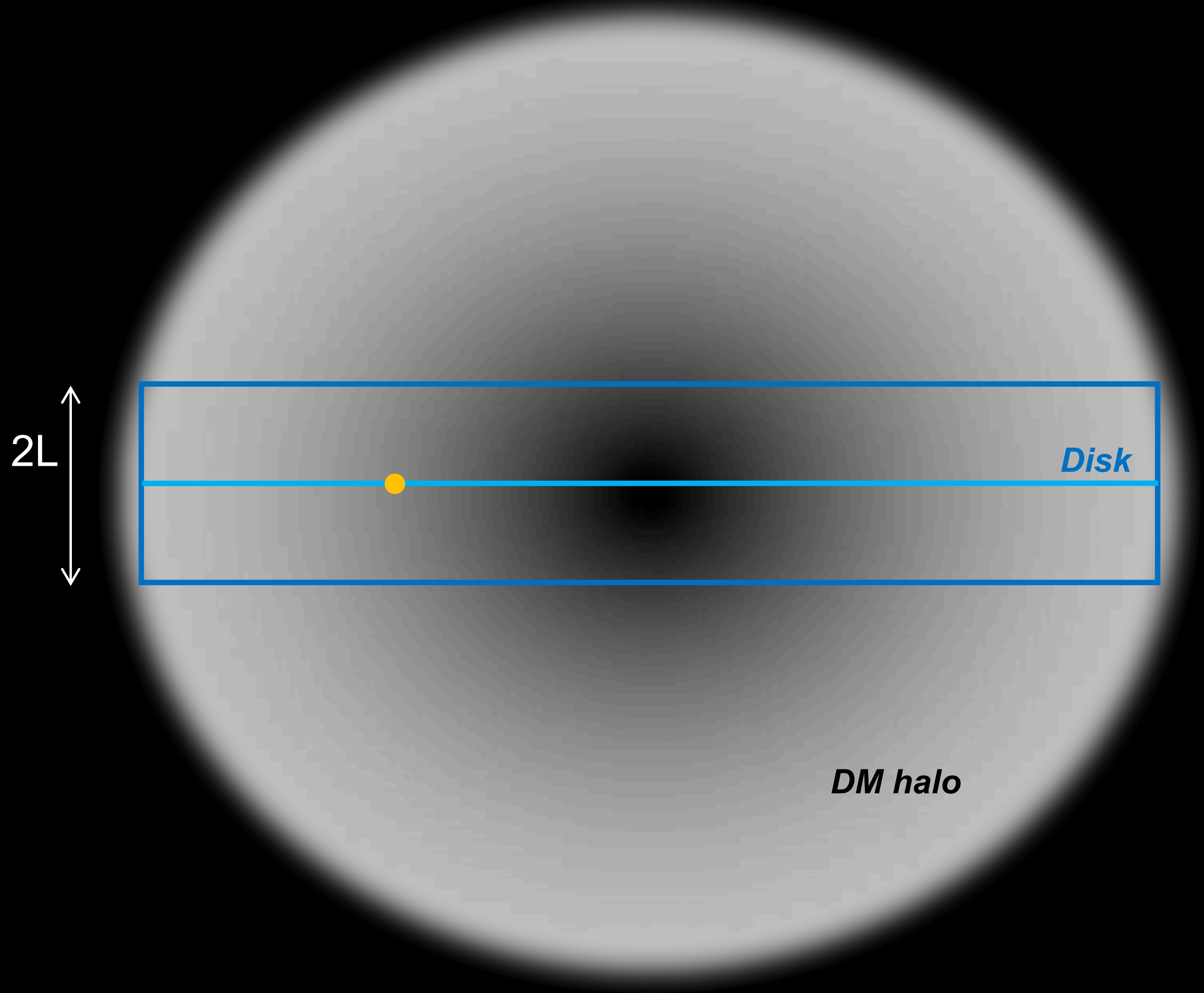
$$\frac{Be}{B} = \frac{{}^{7}Be + {}^{9}Be + {}^{10}Be}{{}^{10}B + {}^{11}B}$$

Evoli+ 1910.04113



The importance of breaking the K_0/L degeneracy

>> Talk by M. Cirelli

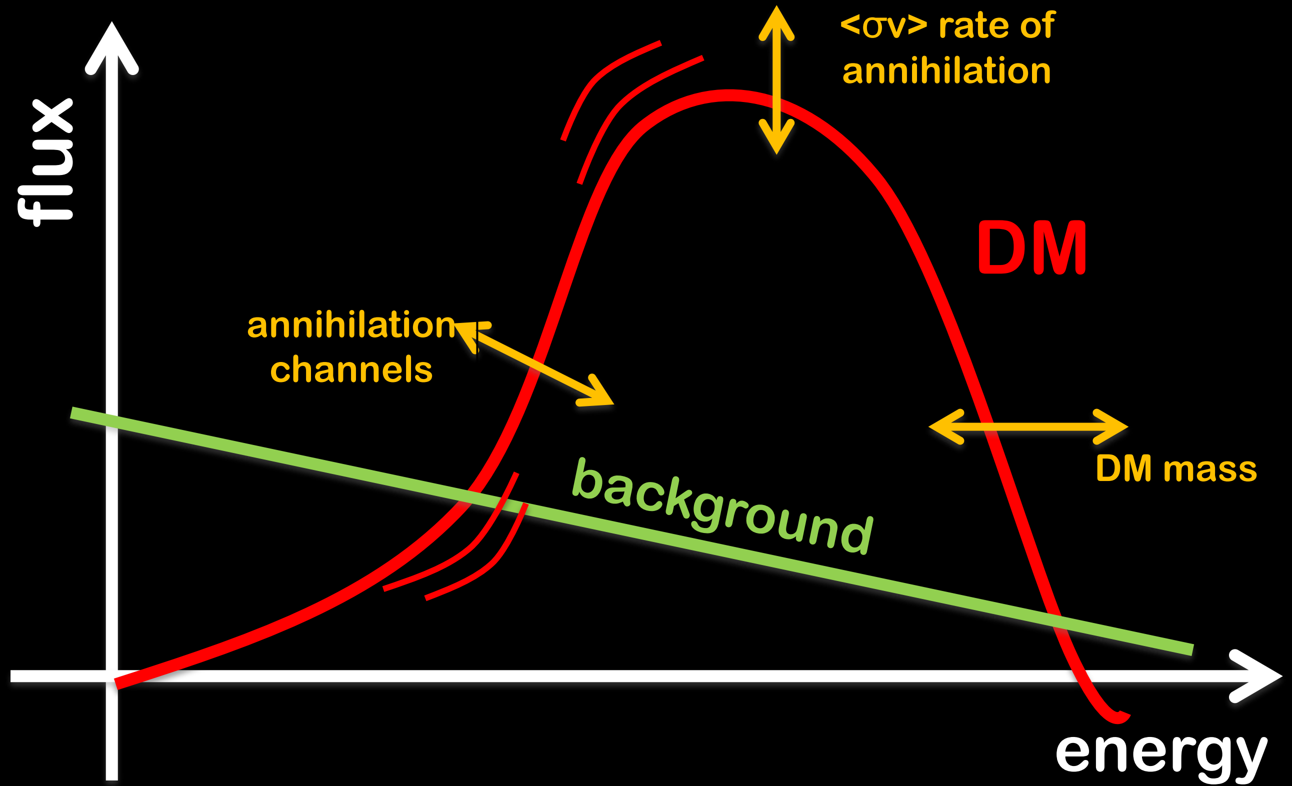


The L parameter sets how much signal from DM annihilation is injected in the confinement region

The importance of breaking the K_0/L degeneracy

>> Talk by M. Cirelli

$$\chi + \chi \longrightarrow (\ldots) \longrightarrow e^{\pm}, \overline{p}, \overline{d}, \overline{He}$$



The L parameter sets how much signal from DM annihilation is injected in the confinement region

Nuclear fragmentation and Li-Be-B production

$$Q_f^{sec}(E) = \sum_p \{ n^H \beta_p c \boxed{\sigma^H_{p\to f}(E)} + n^{He} \beta_p c \boxed{\sigma^{He}_{p\to f}(E)} \} \psi_p(E)$$

Even under straight-ahead, there is a huge number of XSs, i.e., combinations of projectile, fragment s, target ISM, and energy dependence.

$$\sigma^t_{p\to f}(E)$$

WNEW, YIELDX: Semi-empirical parametric formulae, with assumed factorized forms

$$\sigma^t_{p\to f}(E) = \sigma_0(\mathrm{Z_p}, \mathrm{Z_f}) \times F_1(Z_f, Z_p, E) \times F_2(Z_p, A_p, Z_f, A_f) \times F_3(A_t, Z_t)$$

GALPROP: use individual fits channel-by-channel (for H-target). Use semiempirical formulae for unmeasured channels (and some F_3 factor for all reactions involving He target). Assume constant high-energy dependence (like WNEW & YIELDX) at unmeasured energies.

Nuclear fragmentation and Li-Be-B production

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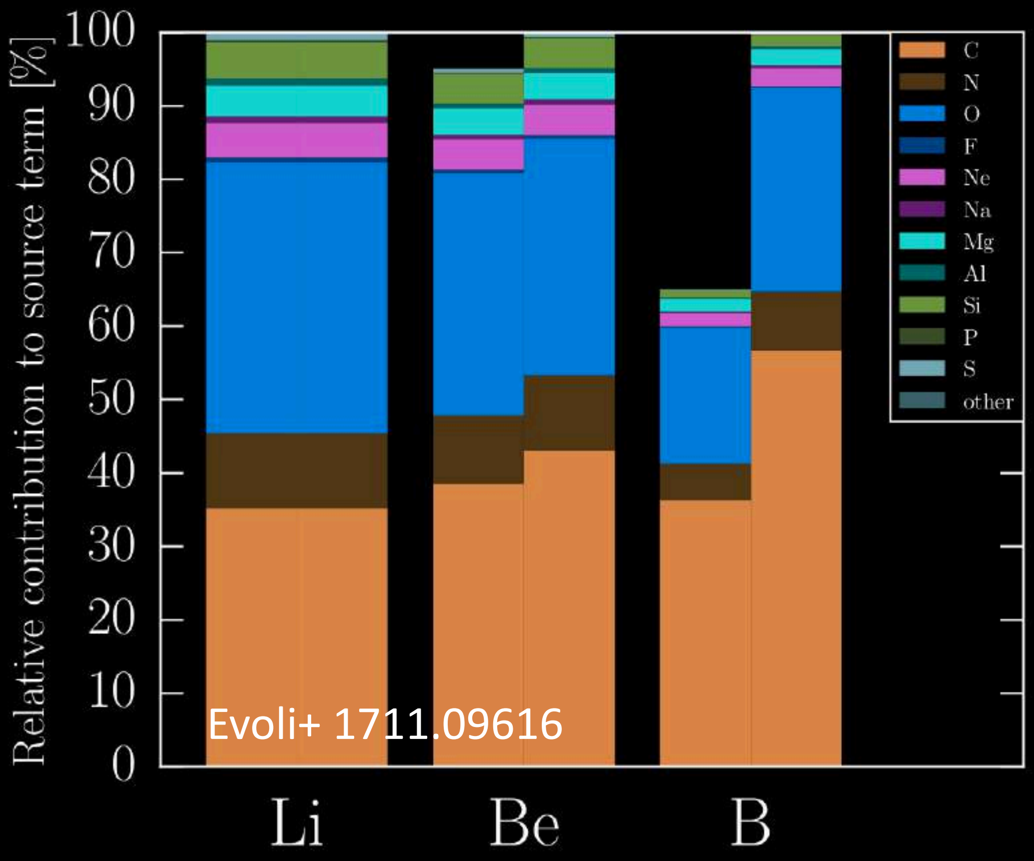
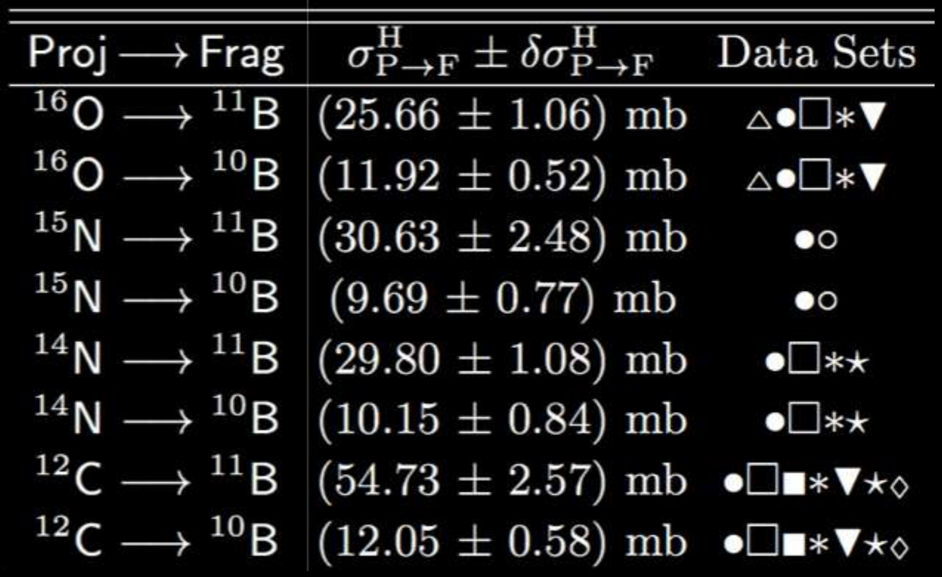


Evoli+ 1711.09616



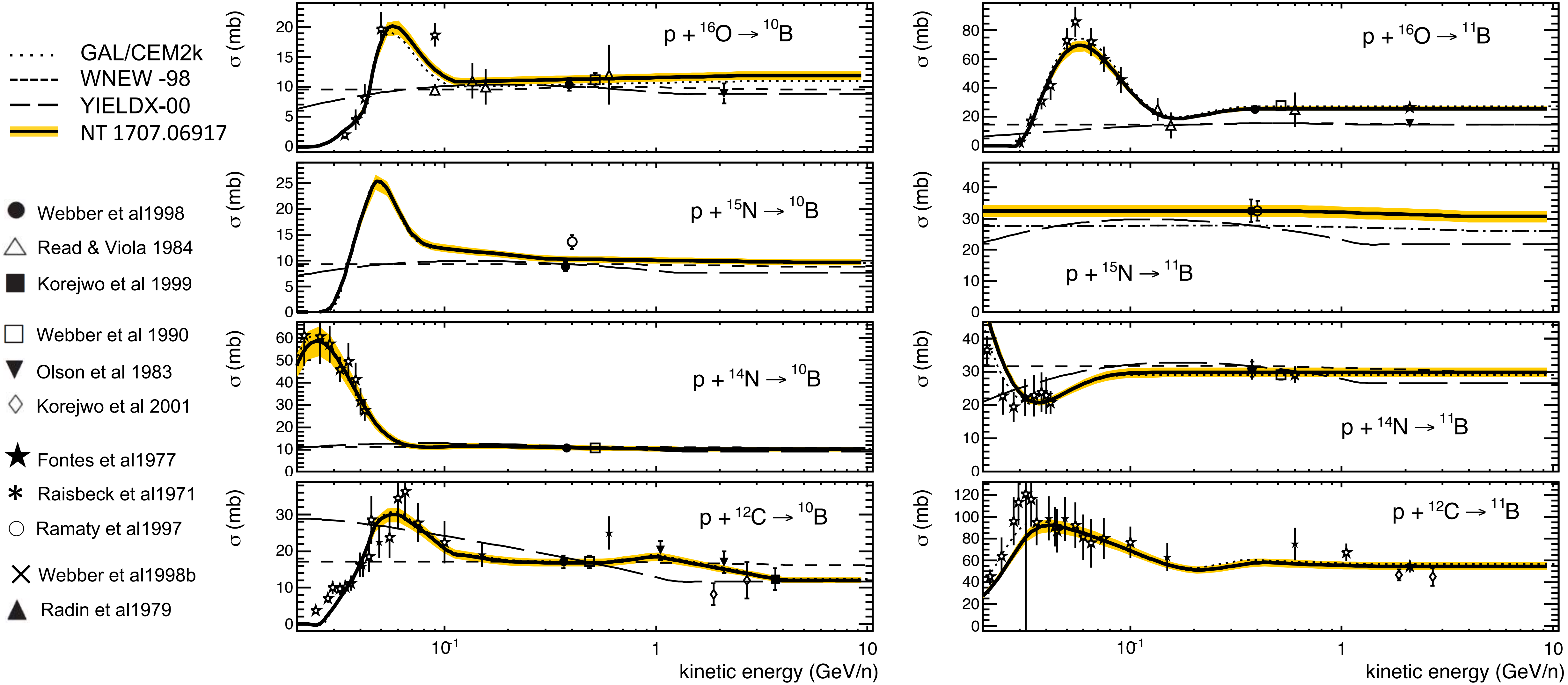
Proj ⟶ Frag	$\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}} \pm \delta\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}}$	Data Sets
^{16}O ⟶ ^{11}B	(25.66 ± 1.06) mb	△●☐∗▼
^{16}O ⟶ ^{10}B	(11.92 ± 0.52) mb	△●☐∗▼
^{15}N ⟶ ^{11}B	(30.63 ± 2.48) mb	●○
^{15}N ⟶ ^{10}B	(9.69 ± 0.77) mb	●○
^{14}N ⟶ ^{11}B	(29.80 ± 1.08) mb	●☐∗⋆
^{14}N ⟶ ^{10}B	(10.15 ± 0.84) mb	●☐∗⋆
^{12}C ⟶ ^{11}B	(54.73 ± 2.57) mb	●☐■∗▼⋆◇
^{12}C ⟶ ^{10}B	(12.05 ± 0.58) mb	●☐■∗▼⋆◇

…

NT 1509.05776

Boron production cross-sections and uncertainties

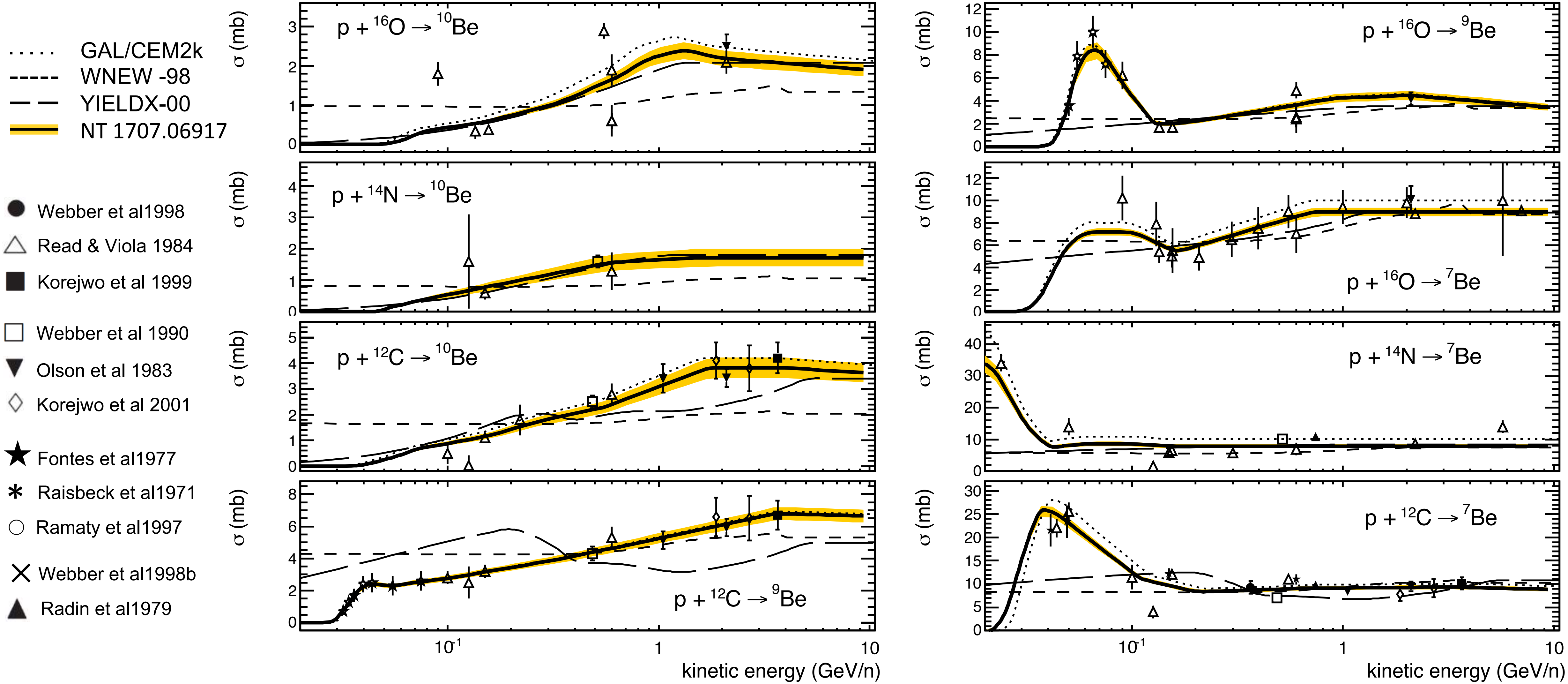
XS data and formulae for 10B and 11B production from C-N-O collisions off hydrogen



[From NT 1509.05776. See also Genolini+ 1803.04686, Evoli+ 1711.09616, NT 1707.06917]

Beryllium production cross-sections and uncertainties

XS data and formulae for 7Be, 9Be and 10Be production from C-N-O collisions off hydrogen



[From NT 1509.05776. See also Genolini+ 1803.04686, Evoli+ 1711.09616, NT 1707.06917]

“Tertiary” reaction channels

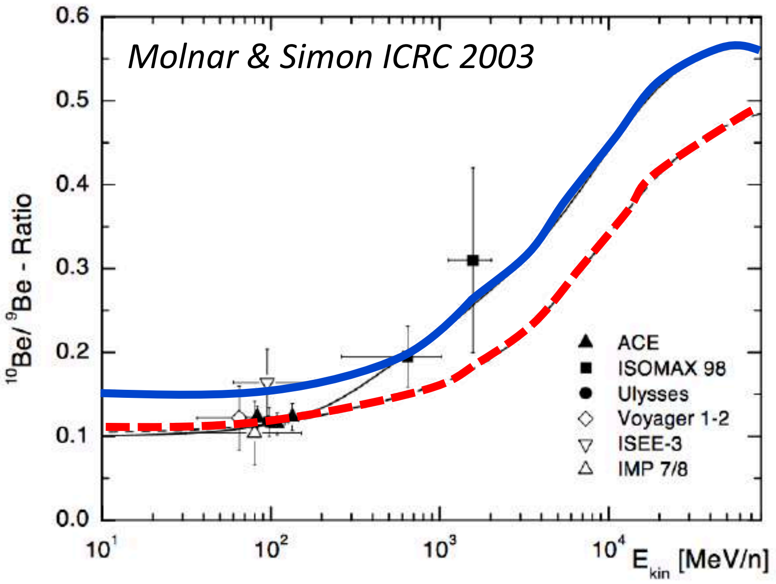
A large fraction of Li-Be progenitors are socondary isotopes Be-B

Important to precisely model the Li & Be fluxes

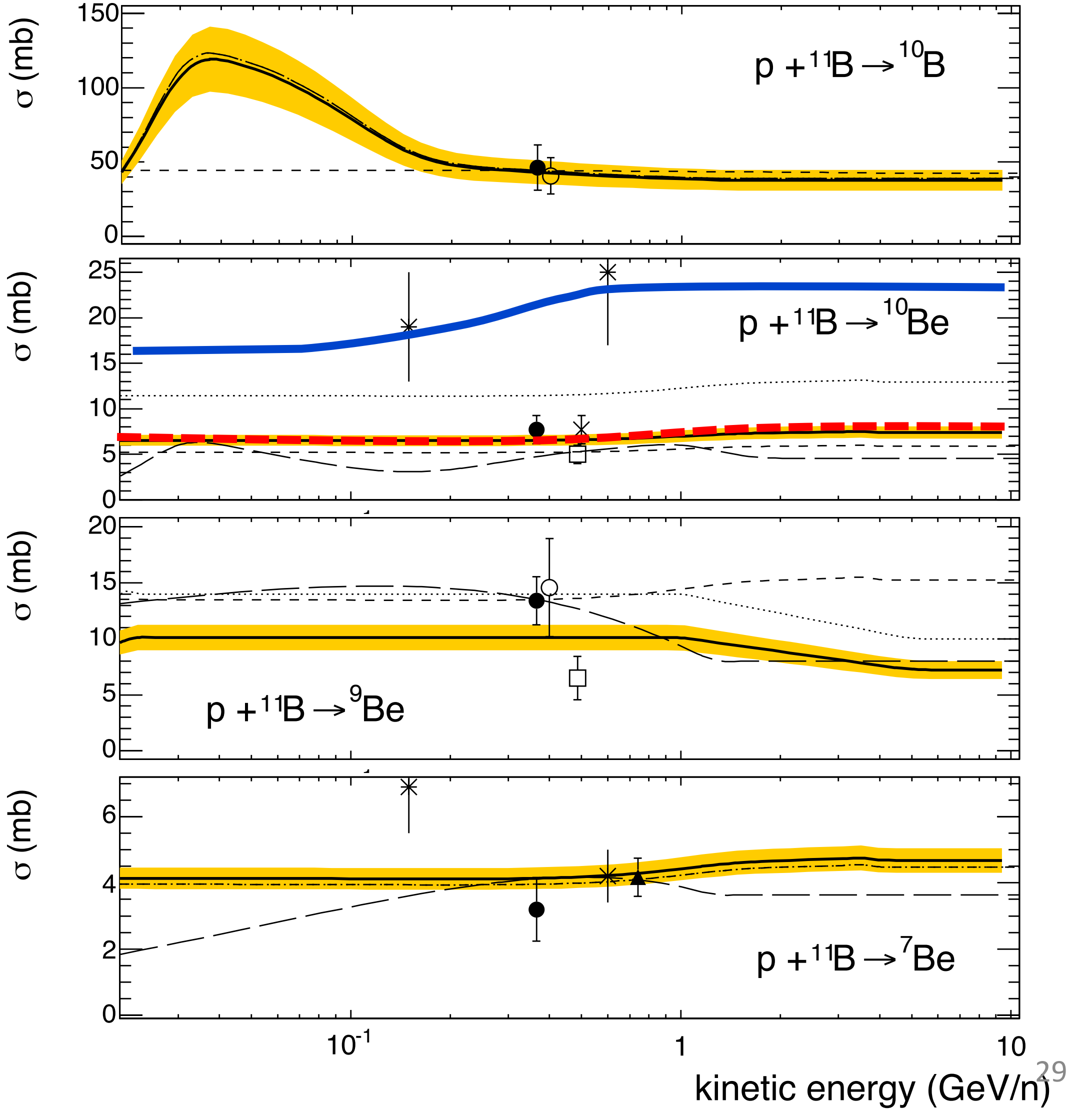
Essential to correctly interpret 10Be/9Be data

- ➢ *Lack of CR data on 10Be isotope*
- ➢ *Lack of XS data on 10Be production*

Very important for modeling the
DM signal from annihilations in the halo



NT 1509.05776



Multi-step and “virtual” reaction channels

Short-lived “ghost” nuclei

^{12}C+ISM ---> ^{11}B

^{12}C+ISM ---> ^{11}C* --->^{11}B

^{4}He+ISM ---> ^{3}H* --->^{3}He

Long-lived intermediate nuclei

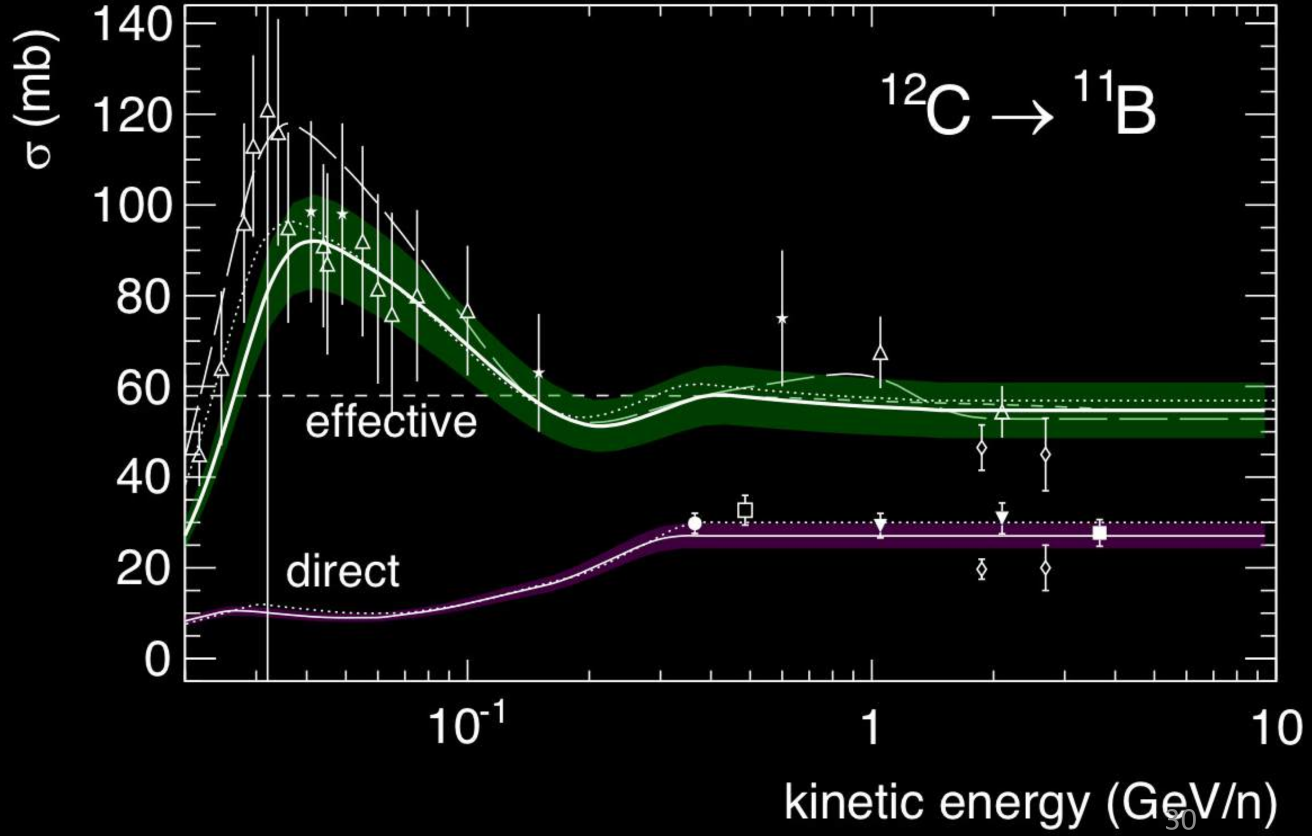
^{12}C+ISM ---> ^{10}Be --->^{10}B + e- + v

Stable intermediate nuclei

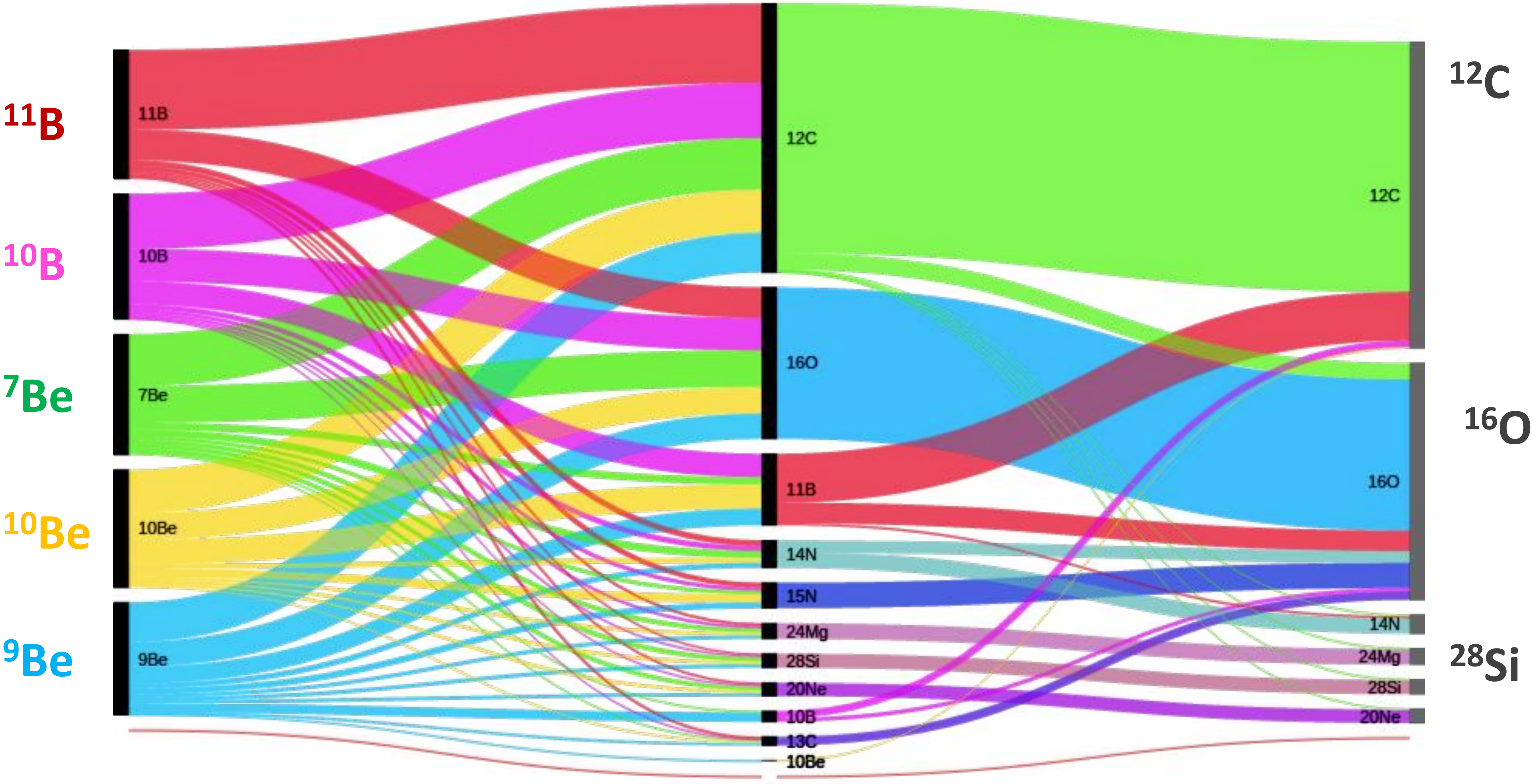
^{16}O+ISM ---> ^{12}C +ISM --->^{7}Be

^{12}C+ISM ---> ^{11}B +ISM --->^{7}Be

$$\sigma_{p\to f}^{eff} = \sigma_{p\to f}^{direct} + \sum_{g} \{\sigma_{p\to g} \times BR_{g\to f}\}$$



Multi-step cosmic ray fragmentation



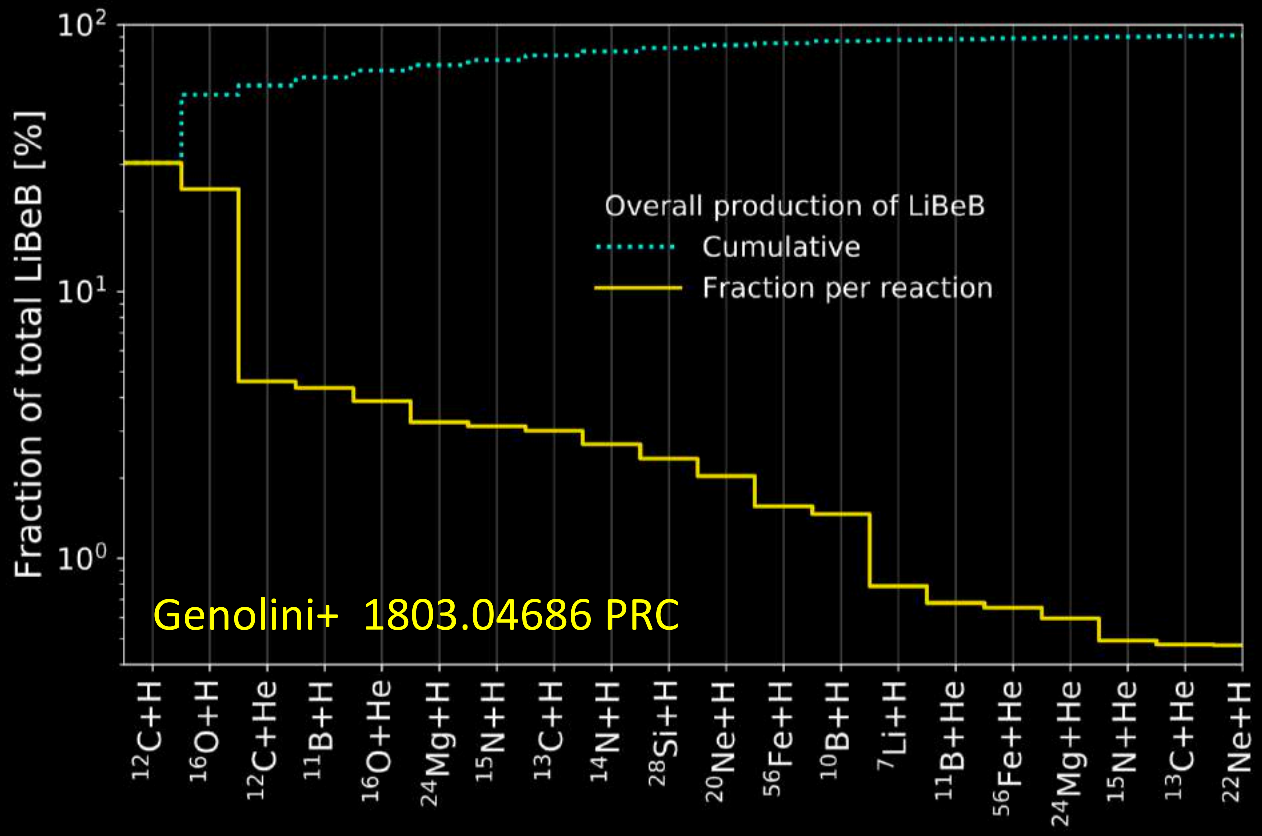
secondary

From NT 1707.06917

primary

Importance of target composition

Interstellar gas: 90% hydrogen and 10% helium.
XS Data: mostly off hydrogen -> semiempirical models are made for H targets.
He target -> rescaling factor F=F(E,A,Z) from Ferrando 1998. Typically F~1.3-2.0



Genolini+ 1803.04686 PRC

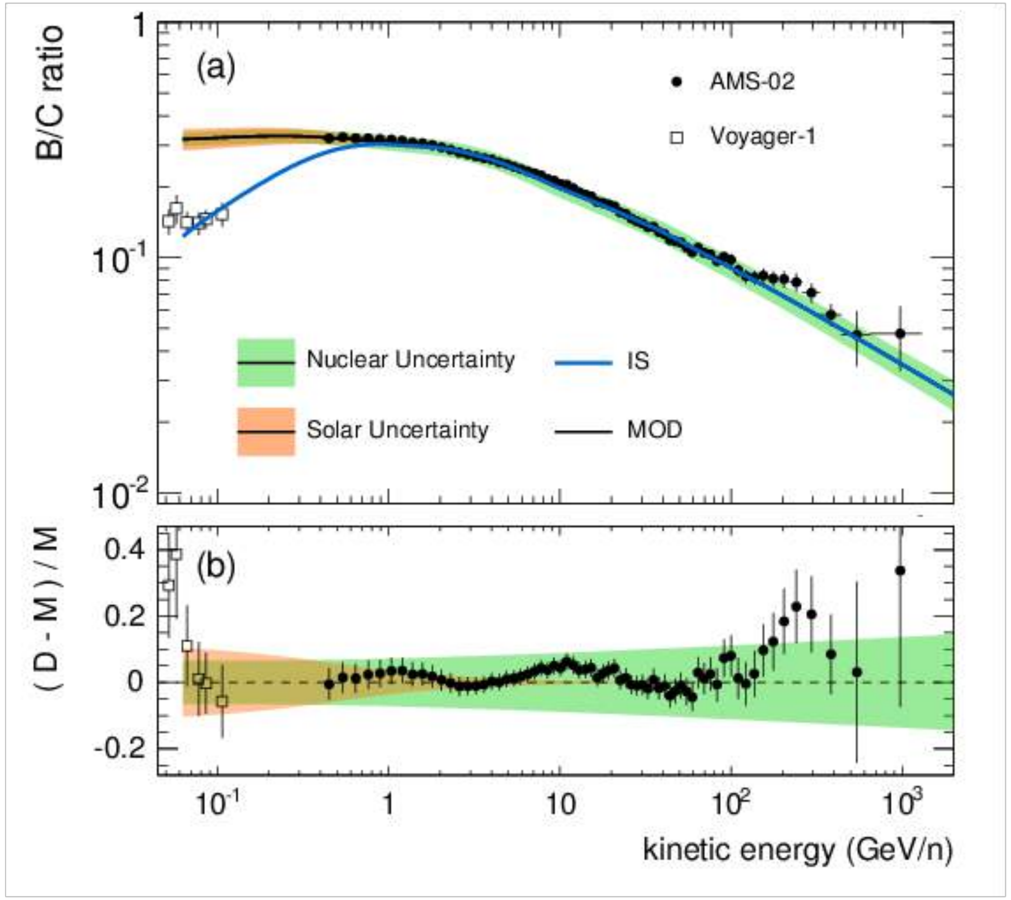
Li-Be-B production ranking

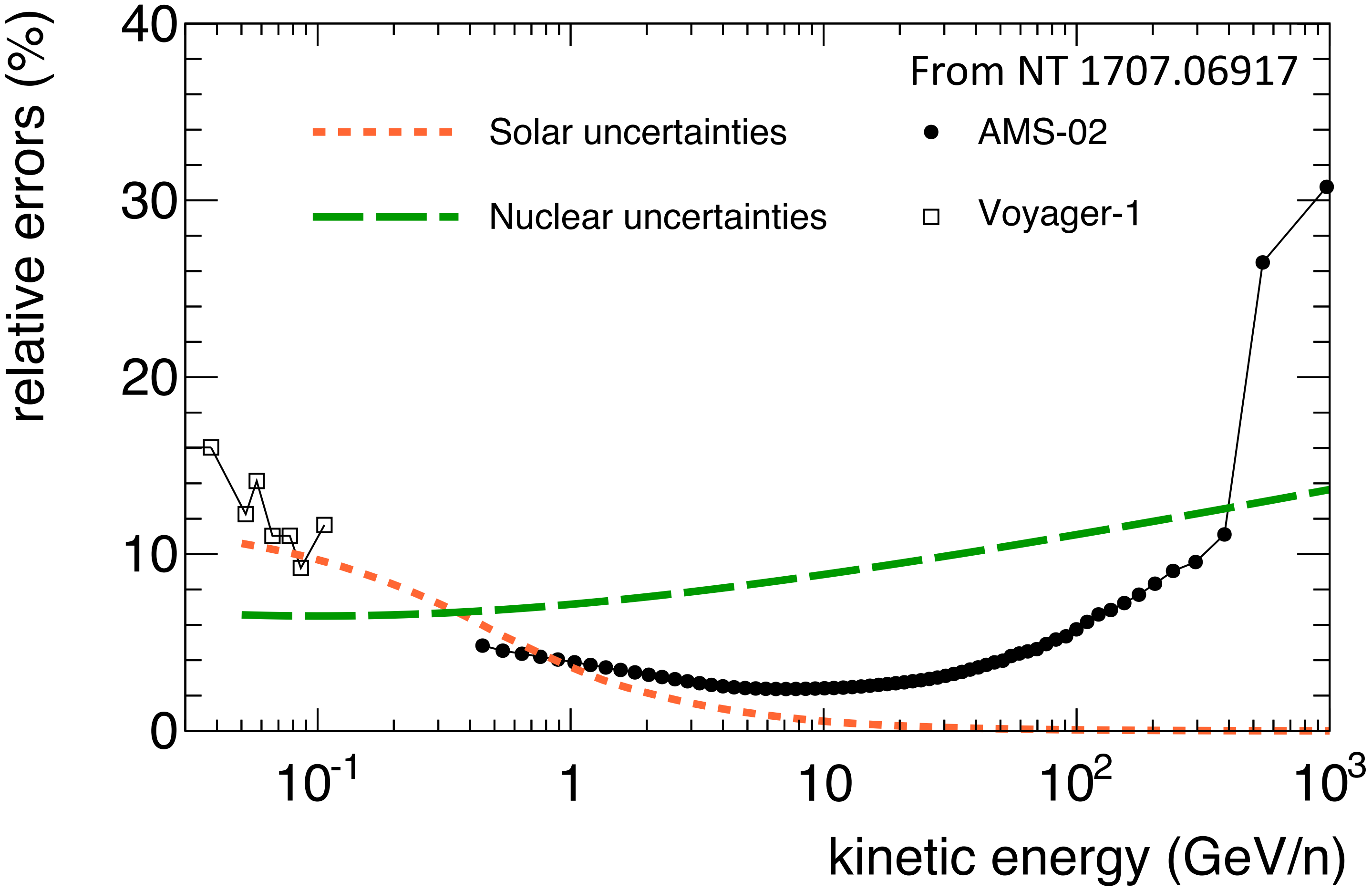
^{12}C + H	**30 %**	[>> Genolini's talk]
^{16}O + H	**22 %**	
^{12}C + He	**5 %**	
^{11}B + H	**5 %**	
^{16}O + He	**4 %**	

-> subdominant but appreciable

Nuclear uncertainties in the B/C ratio

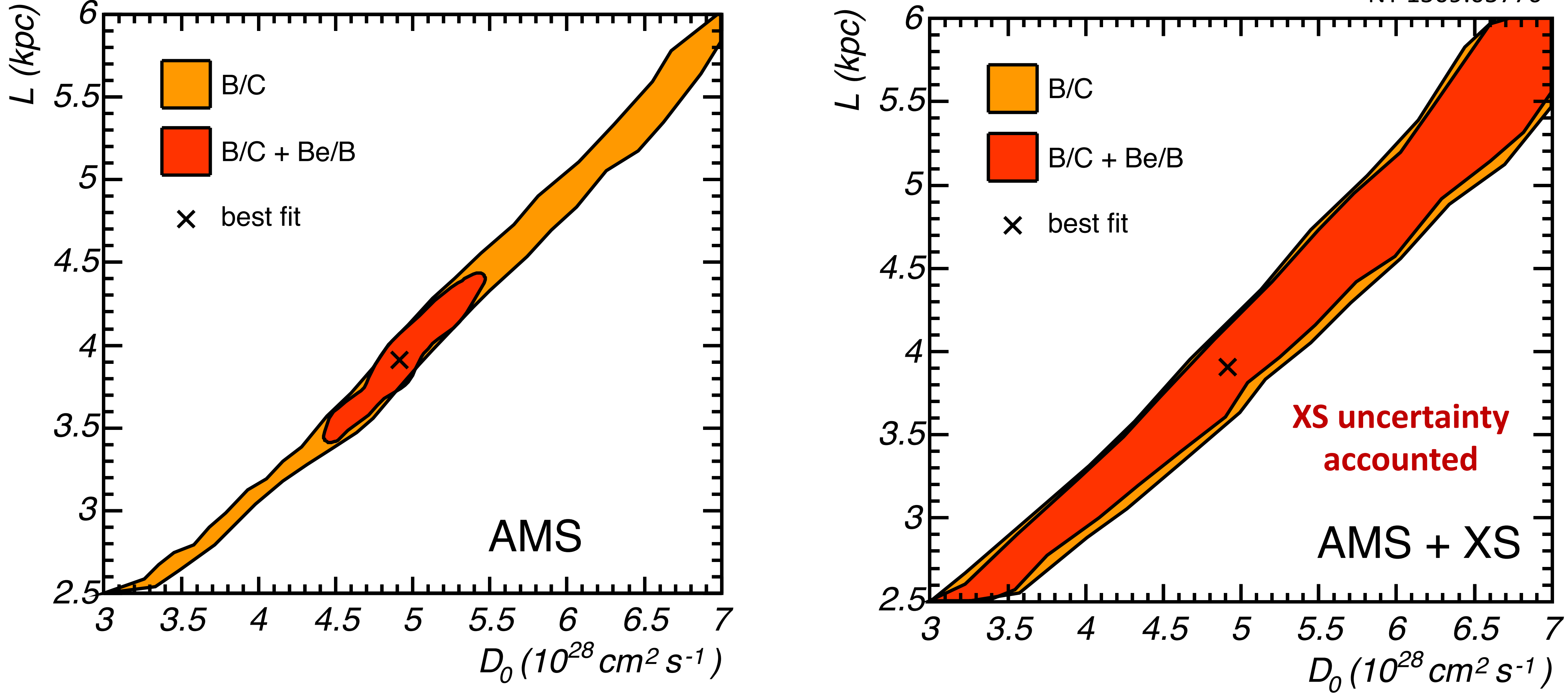
- ✓ **Crosss-section uncertainties are dominating at 0.5 – 500 GeV/n energies**
- ✓ **Accounting for bin-to-bin correlation would mitigate the problem**





Impact of cross-section uncertainties

Combined data on B/C and Be/B ratios



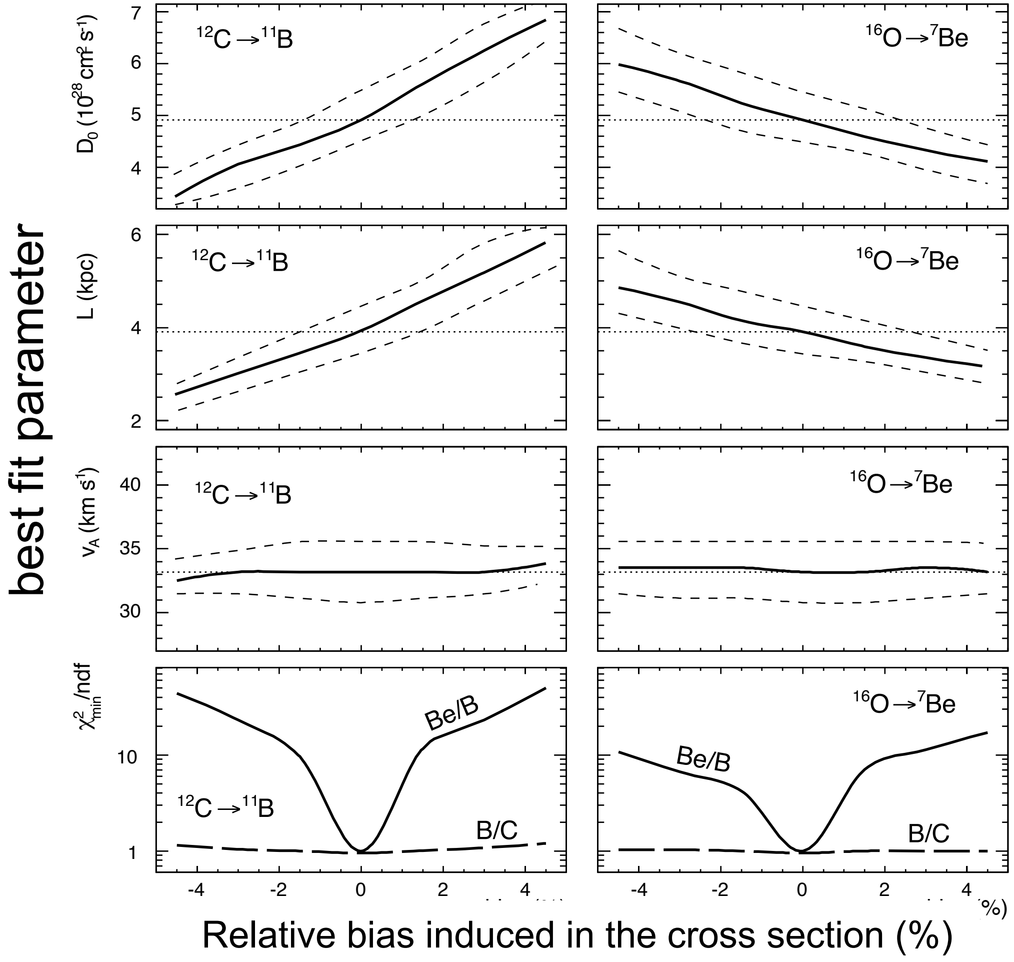
NT 1509.05776

- ✓ **Left: Combined (and precise) data on B/C and Be/B ratios can lift the L-K degeneracy**
- ✓ **Right: Uncertaintes in Be and B production cross-sections restore the degeneracy**

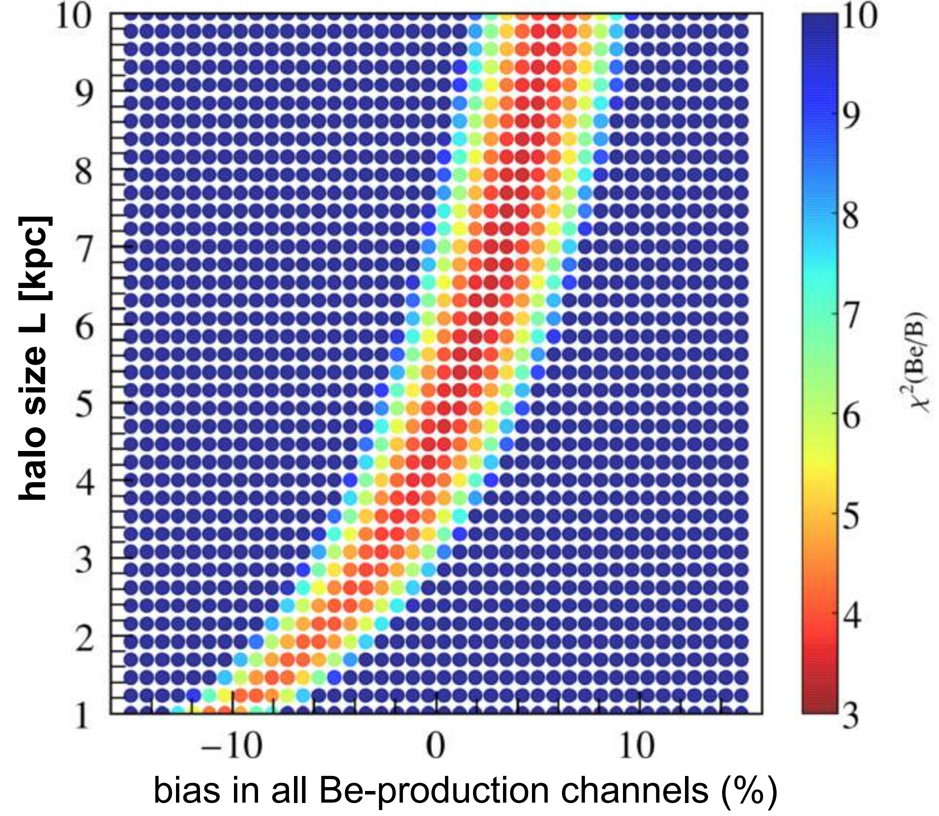
Impact of cross-section uncertainties

Systematic bias in individual XS channels

NT 1509.05776 **12C -> 11B** **16O -> 7Be**

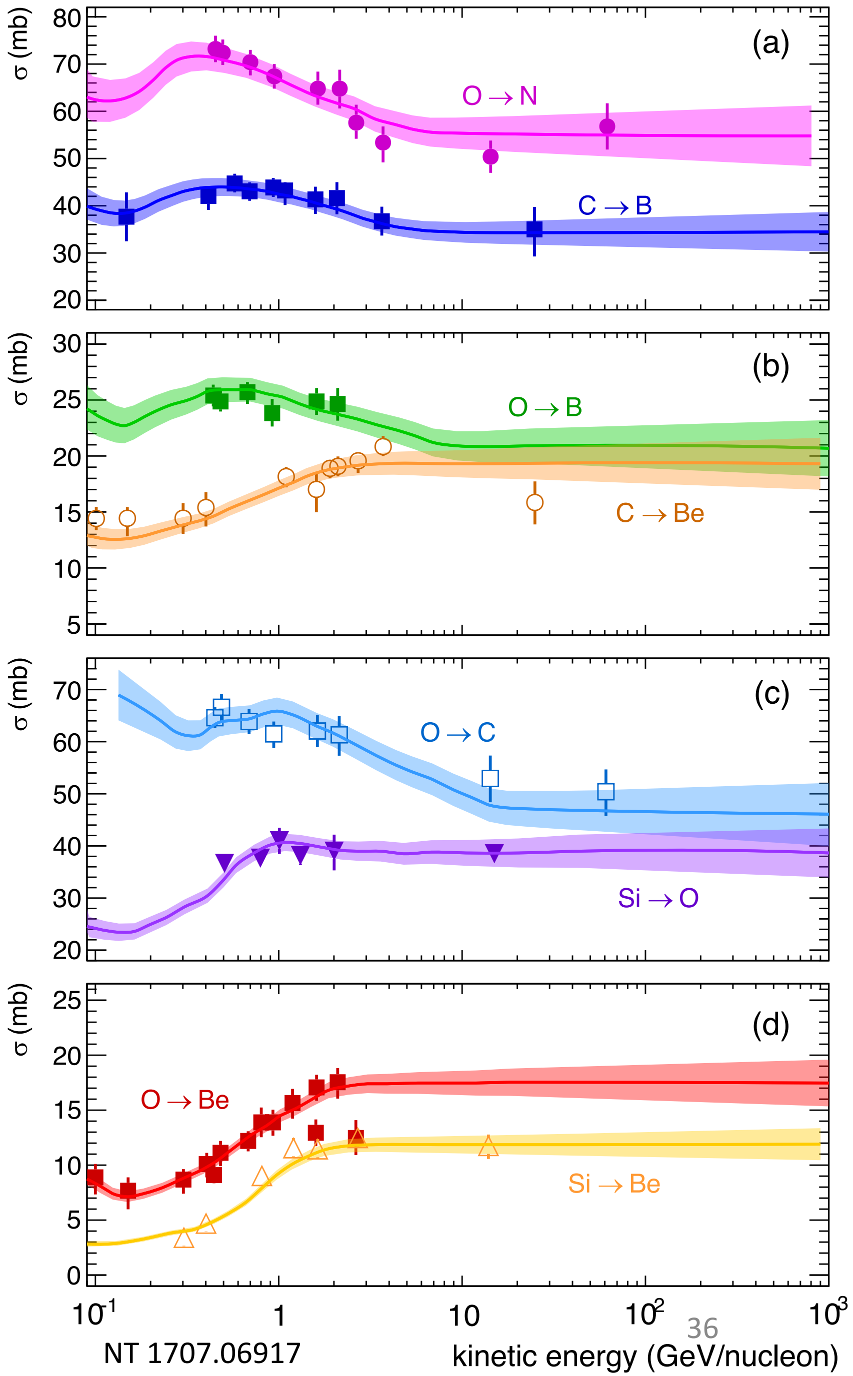


Evoli+ 1910.04113



- ✓ **Undetected biases in individual XS channels cause parameter mis-determination**
- ✓ **Large XS biases could be detected in <u>secondary/secondary ratios</u>**

Potential bias: energy dependence



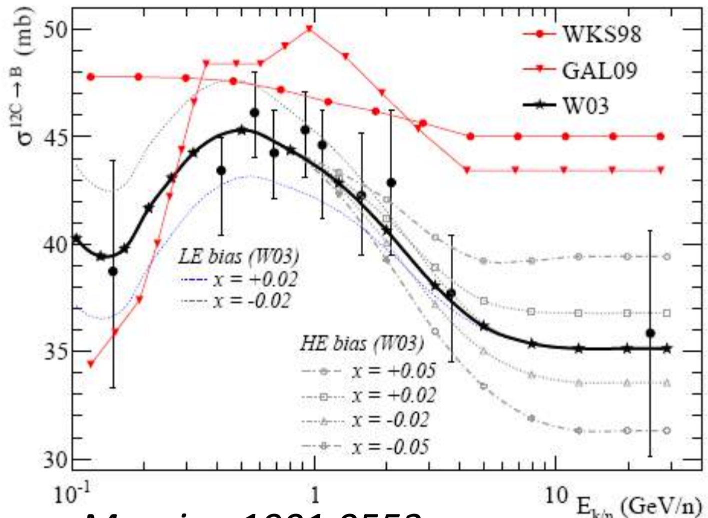
NT 1707.06917

E-dependence in XSs may cause bias in the determination of propagation parameters, e.g. diffusion index [Maurin+ A&A 2010]

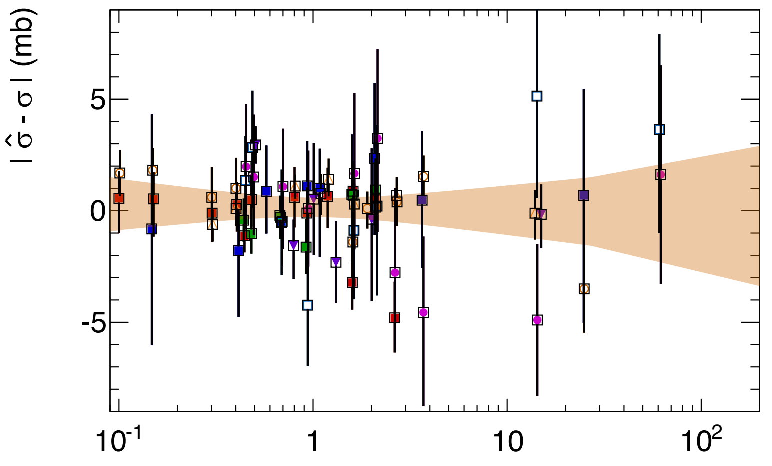
Lack of high-energy data in isotopically-resolved XS

It is important to understand and constrain the energy dependence of XSs at GeV – multi-TeV scale

Total inelastic and charge-changing XSs (only Z-resolved) can provide constraints on the energy dependence of partial XS



Maurin+ 1001.0553



NT 1707.06917

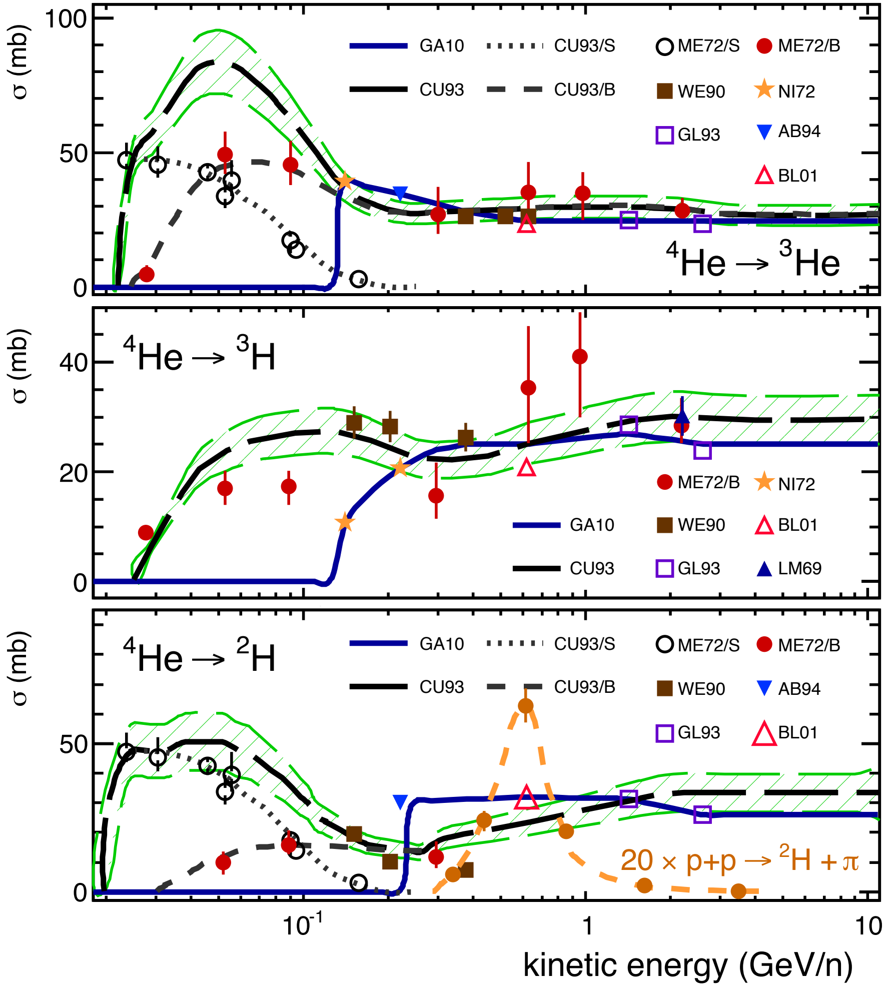
Cross sections for H-He isotopes

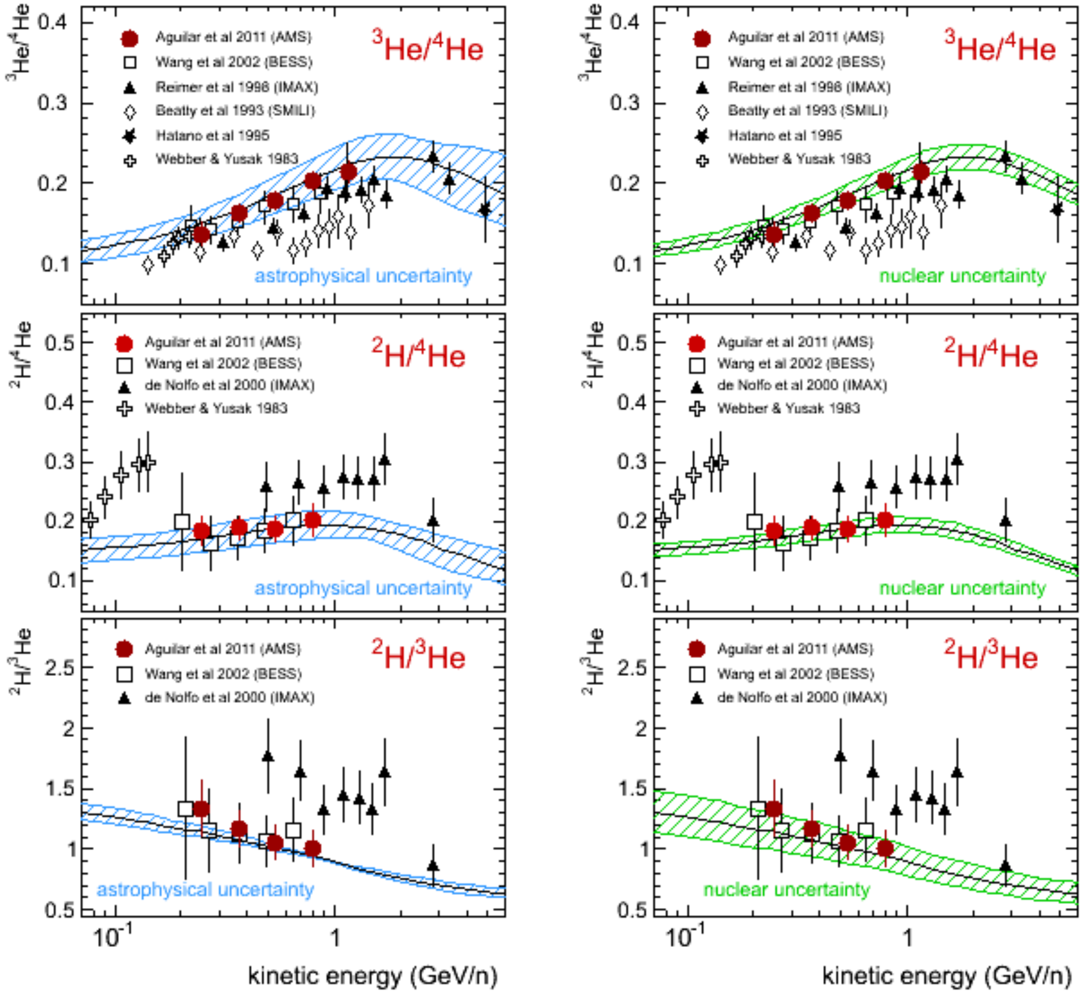
The CR quartet
^{1}H-^{2}H-^{3}He-^{4}He

- ✓ **Several nuclear data up to few GeV/n. No data above 10 GeV/n (QGSJET used)**
- ✓ **New 3He/4He ratio from AMS. To be compared with B/C ratio**

[>> A. Oliva talk]

[NT 1210.7355. See also Coste+ 1108.4349]





Cross sections for H-He isotopes

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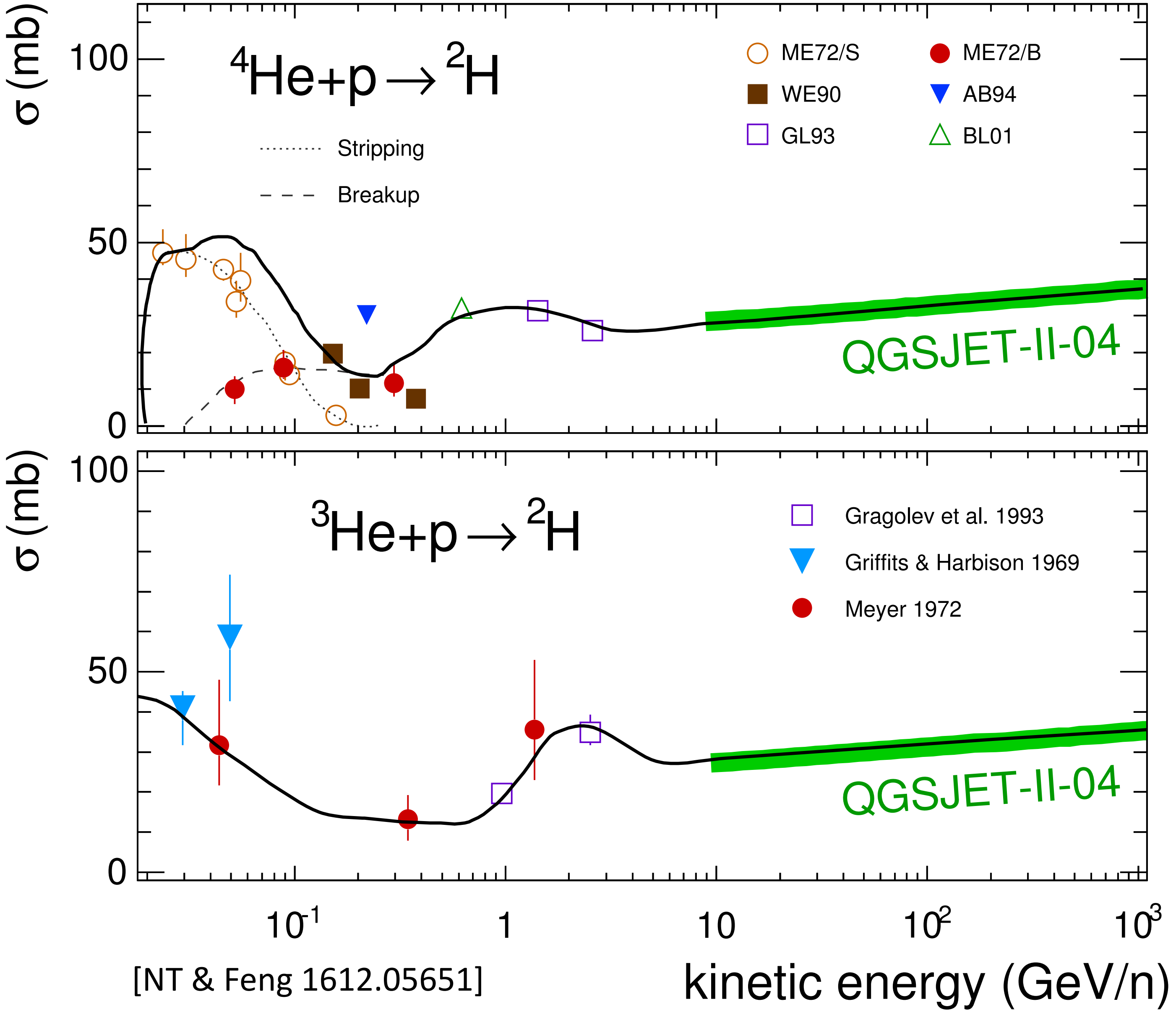

[NT & Feng 1612.05651]

High energy extrapolation with hadronic generator QGSJET-II-04. The XS is increasing with energy

Challenged by the data

Recent CR data at high energies (multi-GeV to multi-TeV)
are revealing several "anomalies", i.e., unexpected features

- **Positron** excess: evidence for extra source of HE leptons [PAMELA, Fermi, AMS]
- **Antiprotons**: hints of excess at ~20 GeV. Flat pbar/p ratio at ~50-500 GeV [AMS]

- Spectral **hardening** at R~300 GV in **primary** fluxes [PAMELA, CREAM, AMS]
- Spectral **softening** at R~10-TeV in the **proton** flux [DAMPE, CREAM]
- Spectral **hardening** at R~300 GV in **secondary/primary** ratios [AMS]
- Non universality of CR spectral indices (**p/He anomaly**) [CREAM, PAMELA, AMS]
- Diffuse **γ-ray** hardening towards Galactic Centre & GeV excess [FERMI]

➢ **Time to relax the several simplifying assumptions in the models, e.g. linearity, homogeneity, stationarity, isotropy**

➢ **Need for better control of all (astro)physical inputs of CR models such as to approach the precision of new measurements**

Some conclusions – considerations and questions

The link between laboratory data and XSs inside CR models is not straightforward

Uncertainties in Boron production (~10%) are larger than those in B/C data (~2% from AMS-02). The impact of XS uncertainty in CR propagation is not straightforward.

All data on isotopic XS are below ~5 GeV. At high energies, secondary/primary diagnostic tools rely on extrapolation (constant XSs) from semiempirical formulae.

Uncertainties in Be production cause mis-determination of CR diffusion parameters. Especially if Be/B is used in place of 10Be/9Be. Need data for some reactions e.g. 11B->10Be

Combined sets of sec/pri or sec/sec ratios can help to 'keep under control' the XSs. Inconsistencies among these ratios may reveal the presence of bias in some XS reactions.

Lack of XS data for light-nuclei off He target. Non-negligible ISM component with Z>1 is.

Can we rely on straight-ahead approximation, within the precision of AMS-02 nuclear data?

Can we rely on usual formulae for inelastic XSs, e.g. for heavy or fragile elements?