Uncertainties in Nuclear Data for Cosmic Ray Physics

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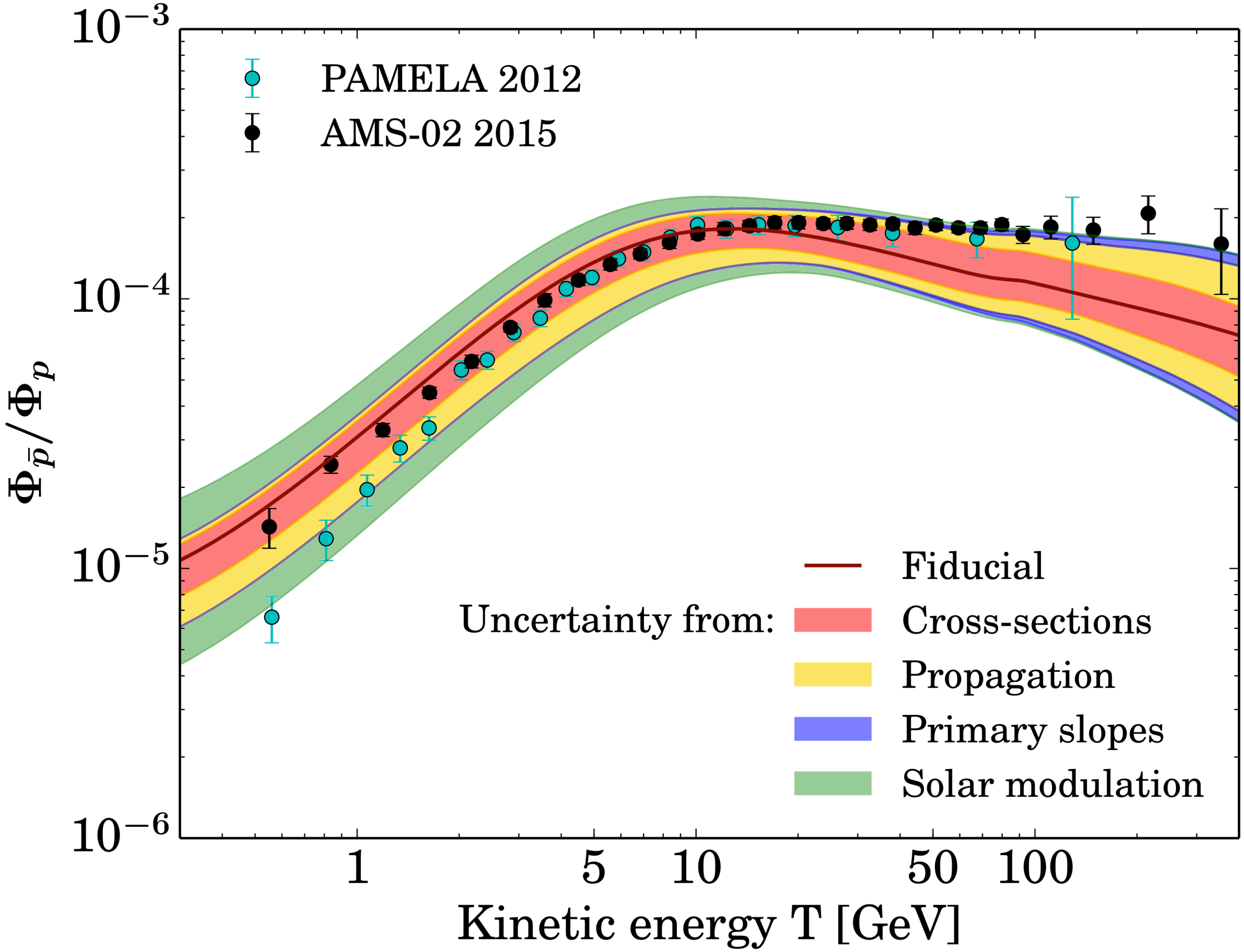
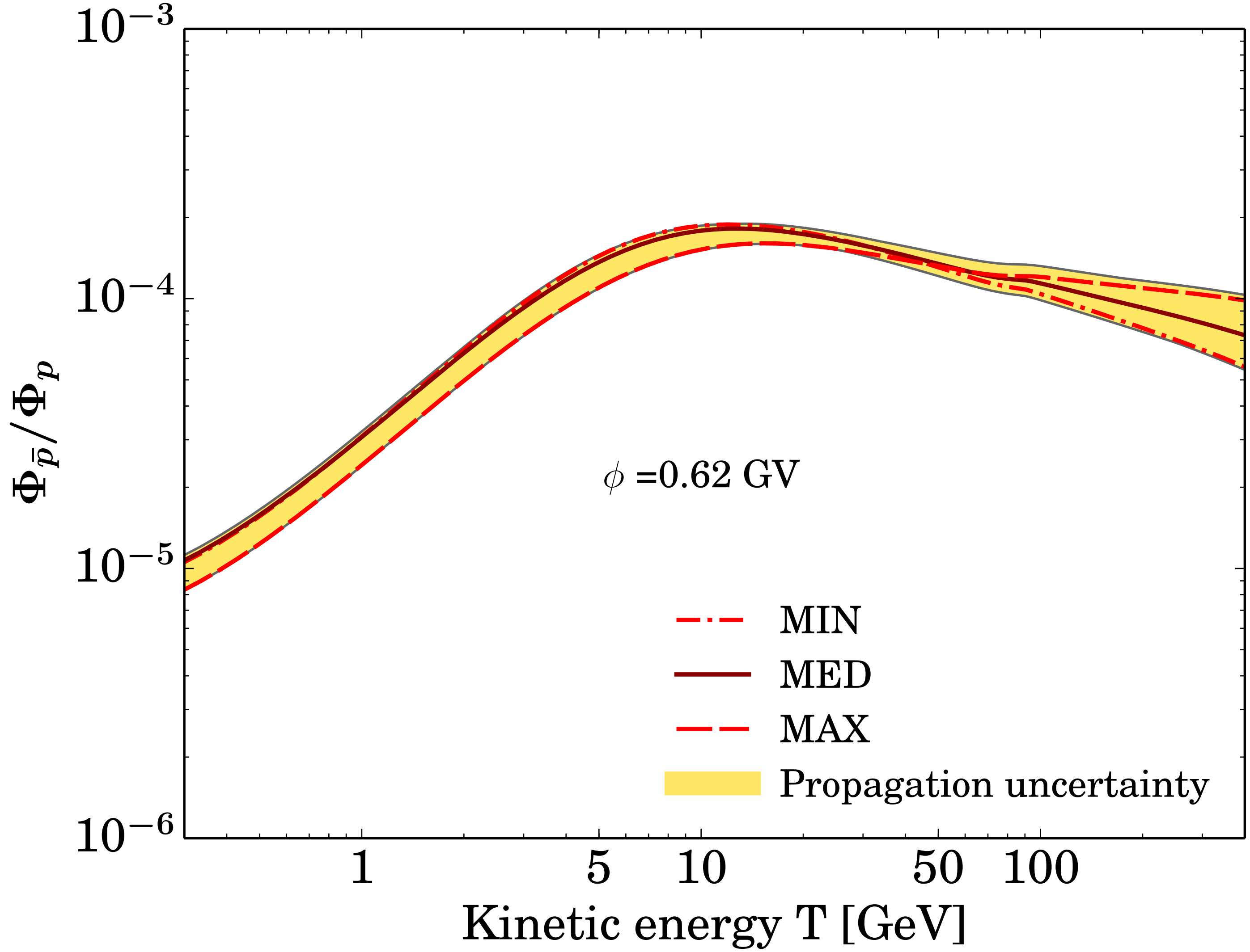
LPSC - CNRS / IN2P3 - Grenoble

p/He workshop - Torino - 6 July 2015

Physics case for CRs: antiproton/proton ratio



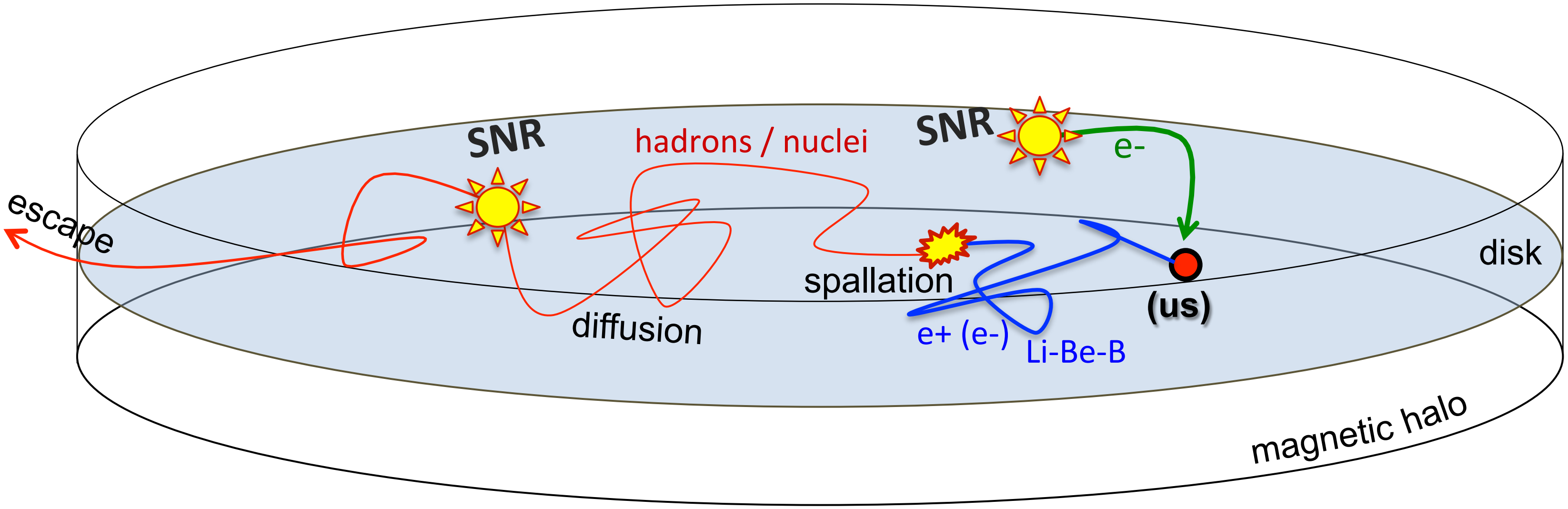
Uncertainty in “cosmic ray propagation”



Cosmic Ray Propagation

A LEADING THEORY [SNR PARADIGM] → phenomenological models

- ✓ *Supernova Remnant (SNR) origin via **diffusive shock acceleration** (DSA) mechanisms*
- ✓ ***Diffusive transport** off magnetic turbulence + **interactions** in the interstellar matter.*

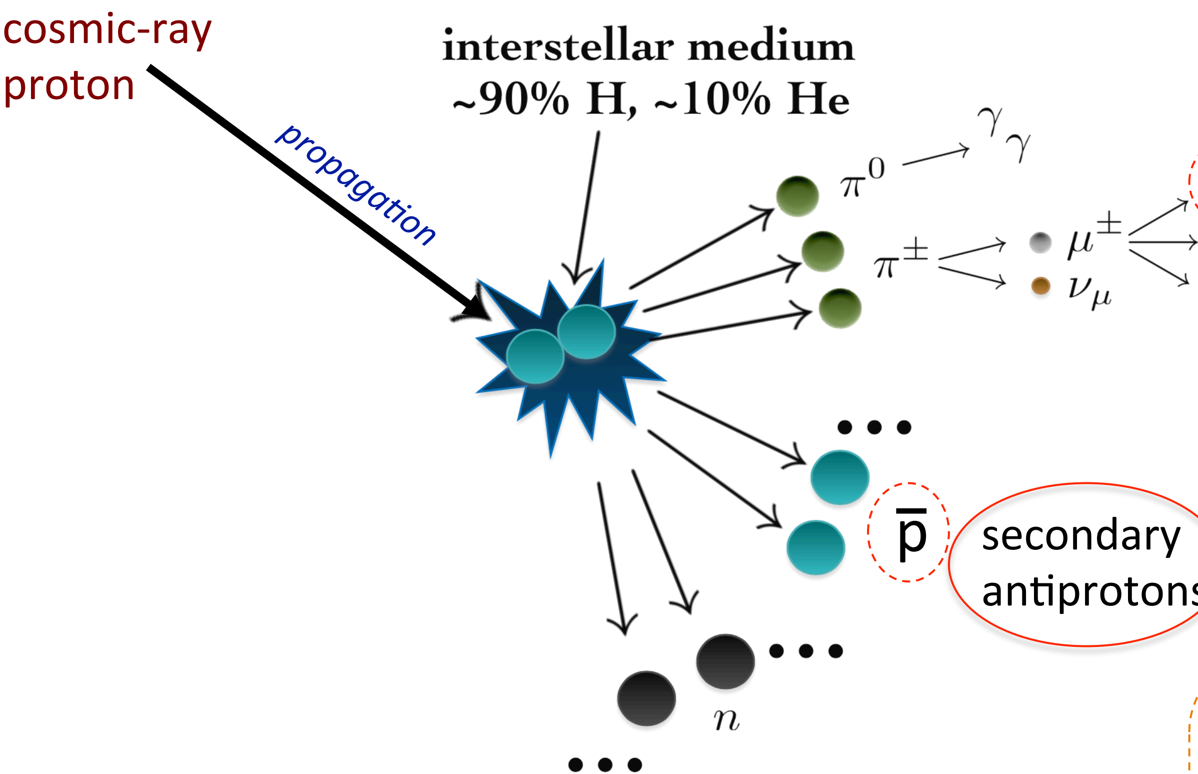


Basic pillars

1. *Diffusive Shock Accleration @SNRs: accounts for energetics & power-law spectra*
2. *Diffusion off magnetic turbulence: explain CR isotropy and large CR residence time*
3. *Interactions off ISM: account for Li-Be-B abundances & diffuse γ-ray emission*

Dark matter and CR propagation physics

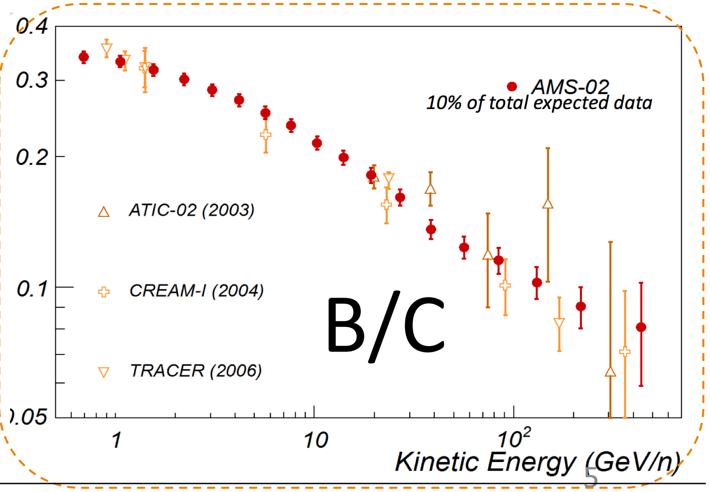
Secondary e+ production



secondary
positrons

secondary
antiprotons

B/C used to calibrate secondary production



Secondary nuclei production

CNO… Fe + ISM → Li, Be, **B**
B, Be + ISM → Li, **Be**

secondary
Li-Be-B

- ✓ **Background for the search of new physics**
- ✓ **Study of high-energy astrophysical processes**

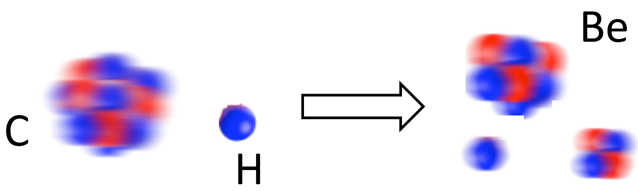
Cosmic Ray Nuclei

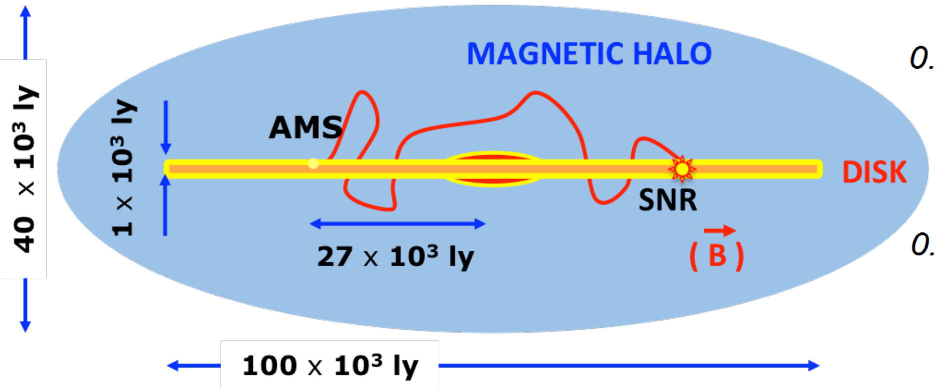
Secondary Li-Be-B nuclei: produced by high energy collisions of C-N-O, Si, Fe with the ISM.

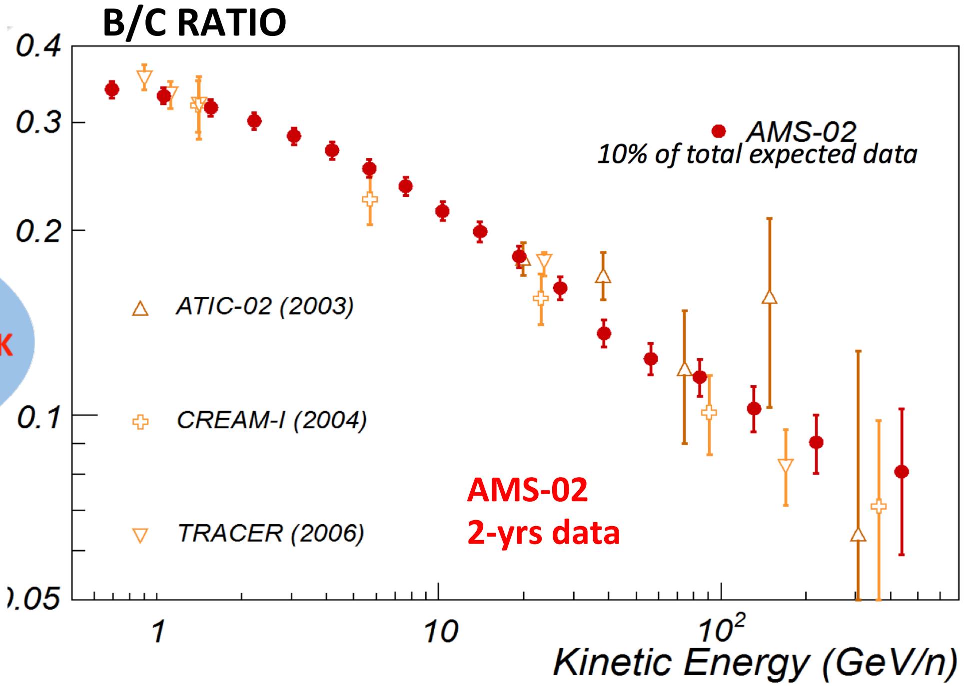
Sec/Pri ratios: fundamental quantities for modeling the processes of CR acceleration, propagation and interactions in the Galaxy.

CNO, Si, Fe + ISM → Li, **Be**, **B**

- ✓ **Background for the search of new physics**
- ✓ **Study of high-energy astrophysical processes**







Transport parameters

$\psi(\mathbf{r},p,t)$ – density per total momentum

$$\frac{\partial \psi}{\partial t} = q + \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi] + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \dot{p}\psi\right] - \Gamma_d\psi$$

spatial diffusion

$$D_{xx} = \beta D_0 (R/R_0)^{\delta}$$

energy gain

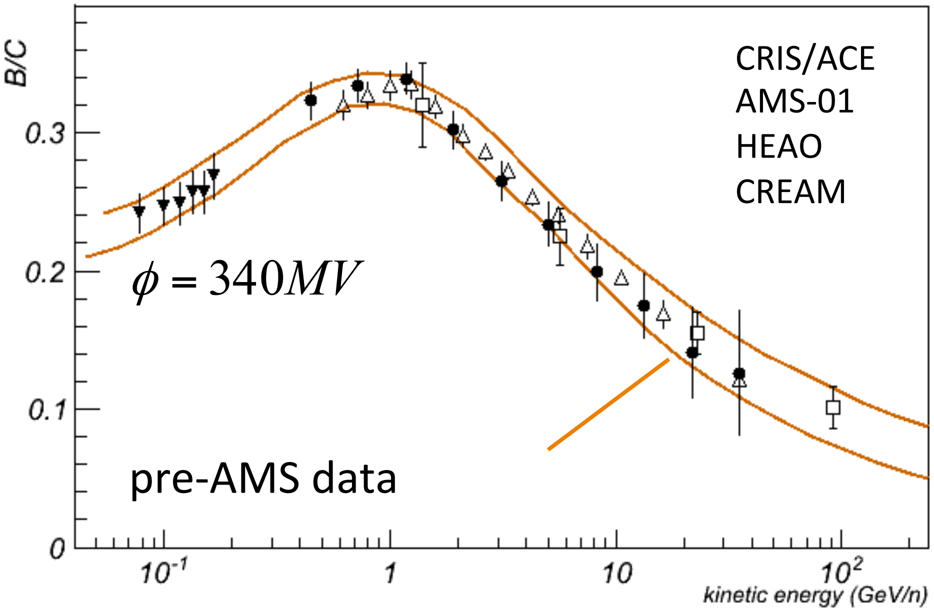
$$D_{pp} \propto V_a^2 / D_{xx}$$

Transport Parameters

Secondary nuclei are much sensitive to these processes.

Transport parameters D_0/L, δ and Va from the B/C

- *D_0/L = 0.038 ± 0.013 kpc/Myrs*
- *δ = 0.42 ± 0.15*
- *V_Alfvén = 40 ± 16 km/s*



steady state d/dt = 0

boundary conditions

$\psi(r=R_0, z=L) = 0$

Parameter degeneracy & physics observables

$$q \sim E^{-\alpha} \quad K \sim K_0 E^{\delta}$$

Primary spectra: α+δ

$$p \sim \frac{q_{pri}}{K/L} \propto E^{-(\alpha+\delta)}$$

p, He, C-N-O, Fe

Emitted from SNRs. Their source spectra are modified by diffusion

Sec/Pri ratios: δ, K_0/L

$$B/C \sim \frac{L}{D} q_{sp} \propto \frac{L}{D_0} E^{-\delta}$$

Li/C, B/C, F/Ne, Ti/Fe

Secondary nuclei are from spallation. Their production depends on D(E) and L.

Unstable/Stable sec: L

$$^{10}Be/^{9}Be \sim \sqrt{\tau / D_0}$$

^{10}Be/^{9}Be, ^{26}Al/^{27}Al

Unstable 10Be isotopes are not sensitive to the halo boundaries $\sqrt{\gamma\tau D(E)} << L$

- **Primary spectra:** → **α+δ degeneracy**

+

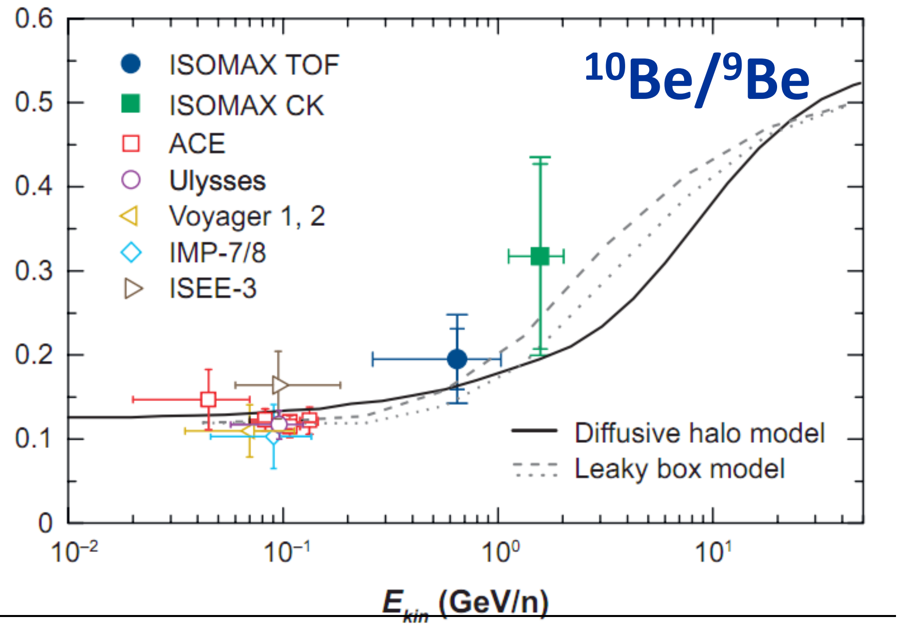
- **Sec/Pri ratios:** → **α+δ break**

  → **K_0/L degeneracy**

+

- **Unstable/Stable:** → **K_0/L break**

= α, δ, K_0, and L fully resolved



Parameter degeneracy & physics observables

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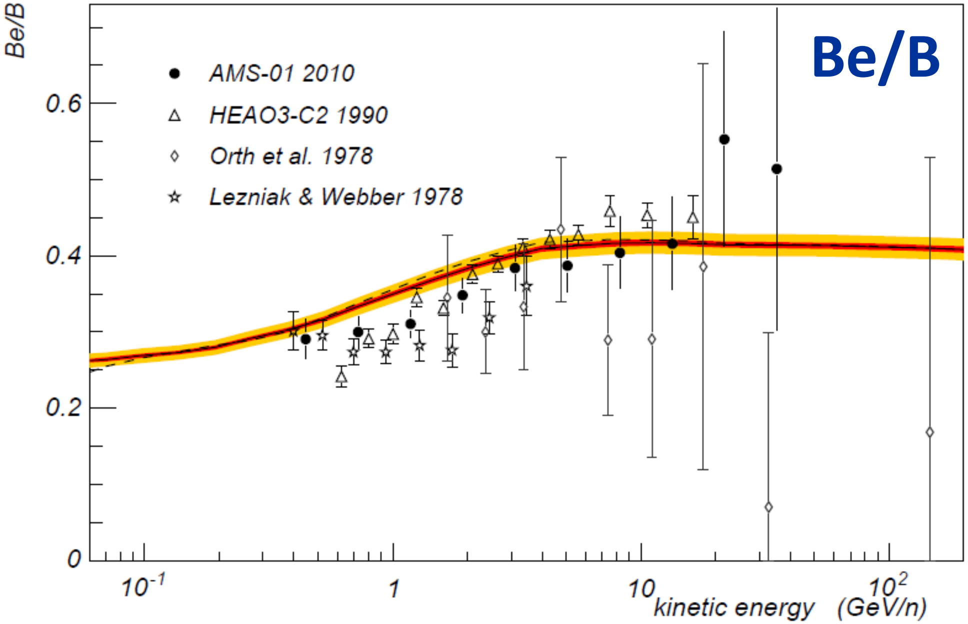
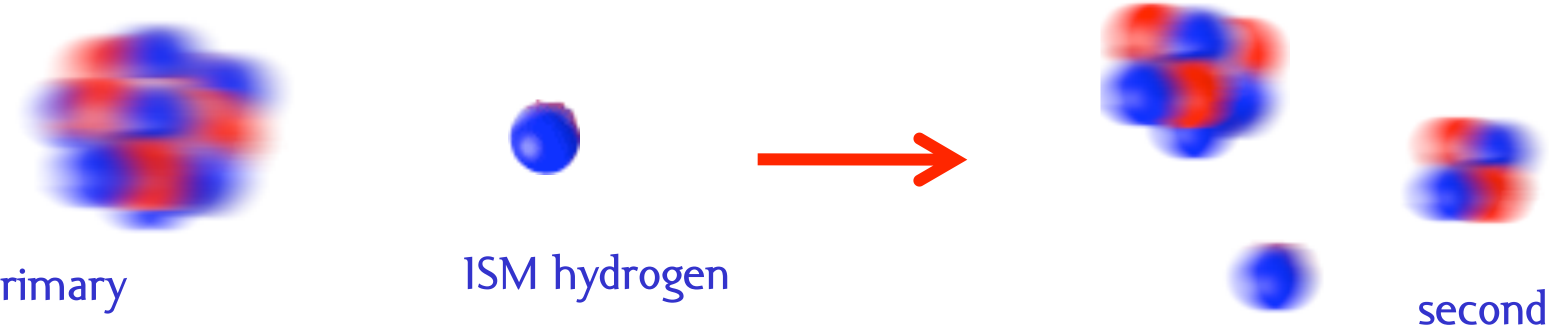
Decaying/Decayed elemental ratios

- The Be/B elemental ratio may replace the 10Be/9Be ratio.
- Be/B, maximize the effect of radioactive decay $^{10}Be \rightarrow {}^{10}B$
- No mass separation required



Cross-sections for secondary CR production



Primary Nucelus

ISM hydrogen

secondary fragments

$$\Gamma_{k\to j} = \beta_k c \sum_i \int_0^\infty n_i \boxed{\sigma^i_{k\to j}(E, E')} dE'$$

Straight-ahead approximation

$$\boxed{\Gamma_{k\to j} \sim \beta_k c \sum n_i \boxed{\sigma^i_{k\to j}(E)}}$$

Secondary production

$$\mathcal{S}/\mathcal{P} \sim \frac{\boxed{\Gamma_{p\to s}}}{2D/L + \boxed{\Gamma_s^{tot}}}$$

To extract the D/L ratio from Sec/Pri data, the rates Γ have to be precisely known.

- Secondary **production** rate (from nucleus k fragmenting into j)

$$\Gamma_{k\to j} = n_H \beta_k c \sigma^H_{k\to j} + n_{He} \beta_k c \sigma^{He}_{k\to j}$$

Hydrogen density in the galactic medium

Fragmentation cross section k+H->j

Helium density in the galactic medium

Fragmentation cross section k+He->j

Several fragmentation XS are involved. Some of them are poorly known.

- **Destruction** rate for nucleus j colliding with ISM matter or decaying

$$\Gamma_s^{tot} \quad \beta_j c \left(n_H \sigma^{tot}_{j,H} + n_{He} \sigma^{tot}_{j,He} \right) + \frac{1}{\gamma_j \tau_j}$$

total inelastic cross section k+H->anything

Few inelastic XS are involved (~50).
Experimentally better known.

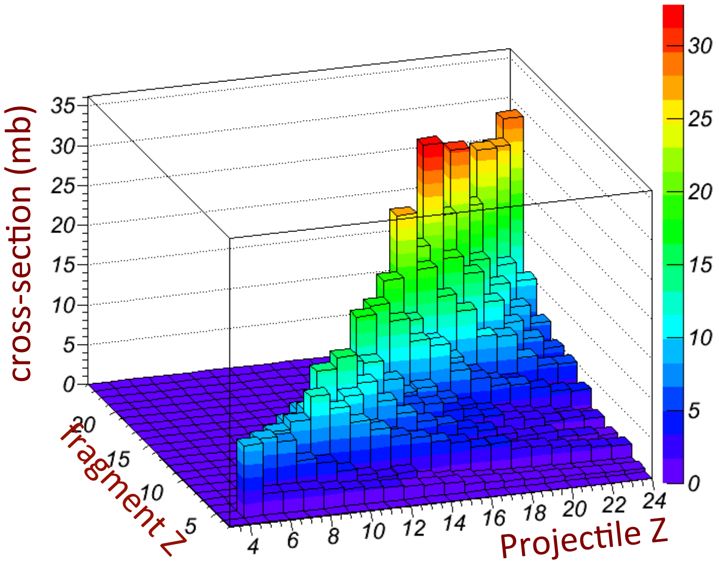
Cross-section re-determination

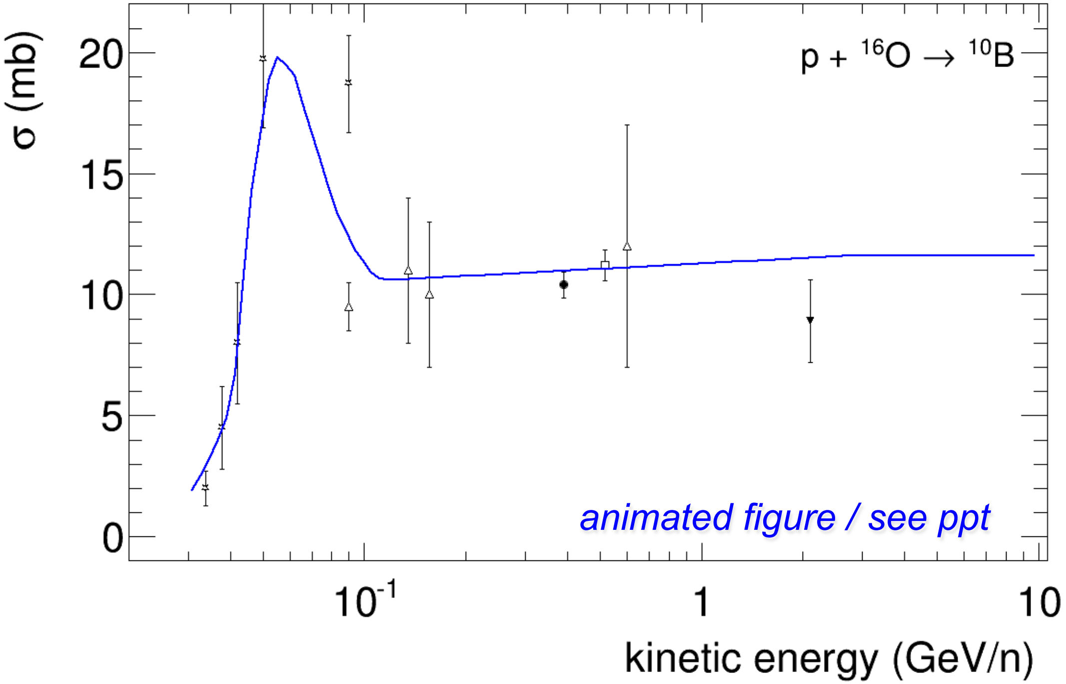
For several P->F reactions, the GALPROP cross-sections have been re-fitted as:

$$\sigma^{H}_{CNO\to B}(E) = a\cdot\sigma^{G}_{CNO\to B}(b\cdot E)$$

✓ New value – often close to original GALPROP XS's

✓ Uncertainty band: one-sigma constraints provided by the data

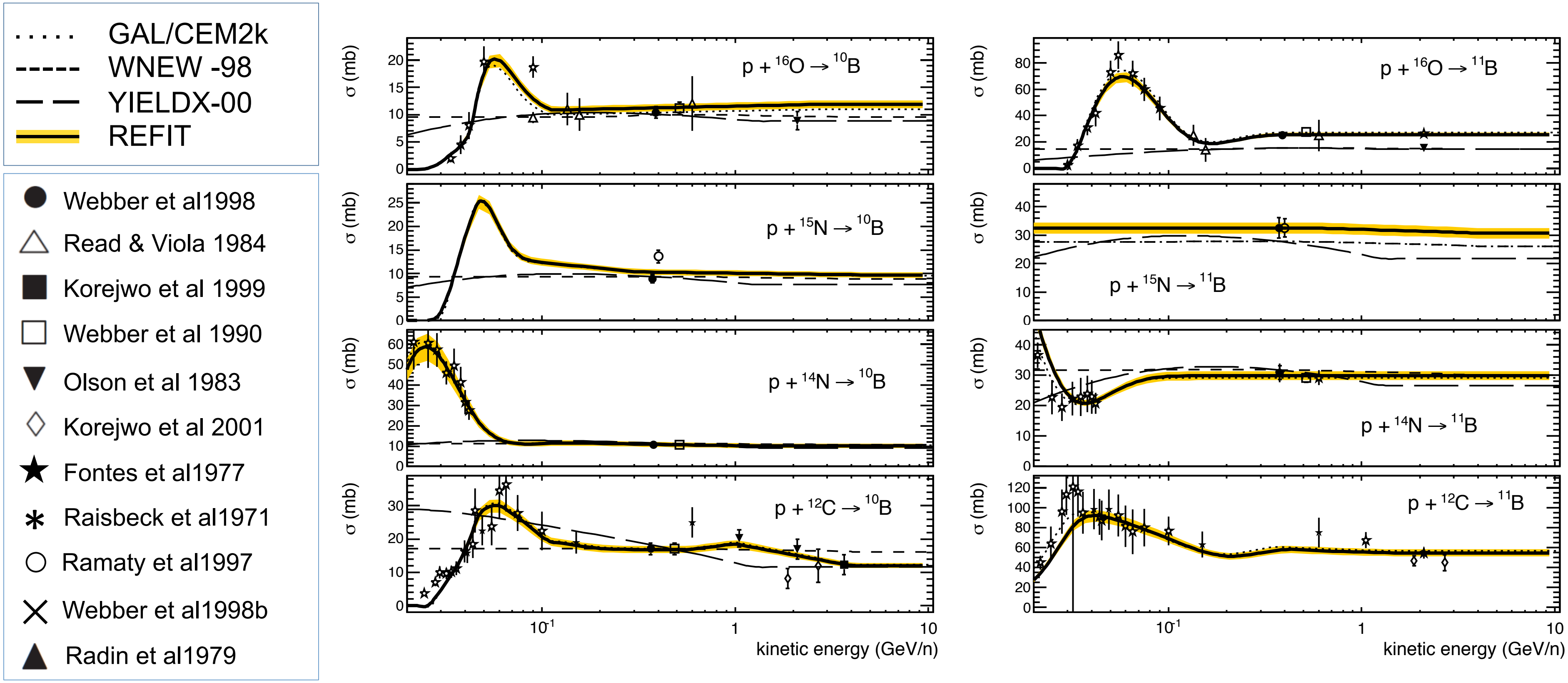




animated figure / see ppt

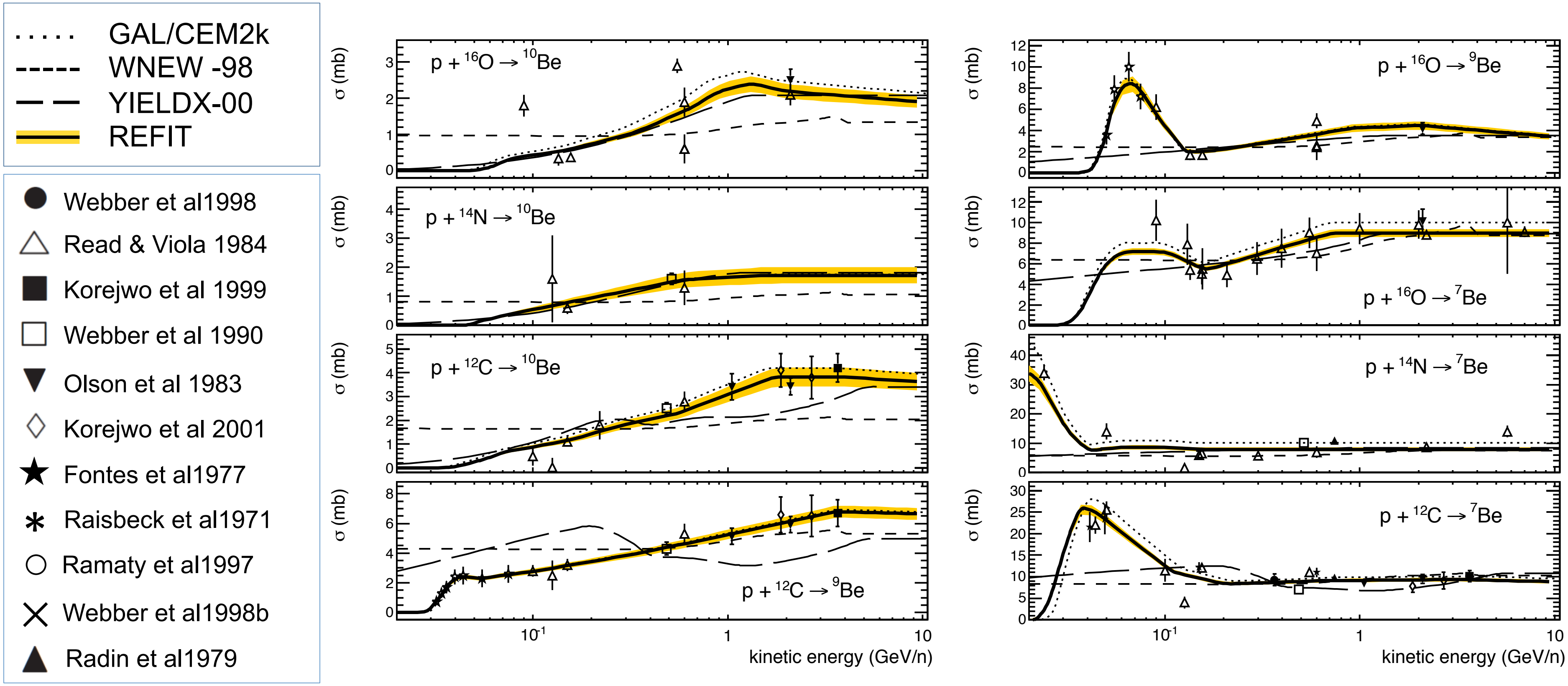
Boron production cross-sections

- Main fragmentation cross sections for CNO(p,X)B between 20MeV/n and 10GeV/n
- Data from various experiments between 1970’s and 2000.
- Formulae: Webber 98->2003. Sielberberg & Tsao 2000. GALPROP (CEM2k)
- Yellow bands: our error estimations after re-fit: $\sigma^{H}_{CNO\to B}(E) = a\cdot\sigma^{G}_{CNO\to B}(b\cdot E)$



Beryllium production cross-sections

- Main fragmentation cross sections for CNO(p,X)Be between 20MeV/n and 10GeV/n
- Data from various experiments between 1970's and 2000.
- Formulae: Webber 98->2003. Sielberberg & Tsao 2000. GALPROP (CEM2k)
- Yellow bands: our error estimations after re-fit: $\sigma^{H}_{CNO\to Be}(E) = a\cdot\sigma^{G}_{CNO\to Be}(b\cdot E)$



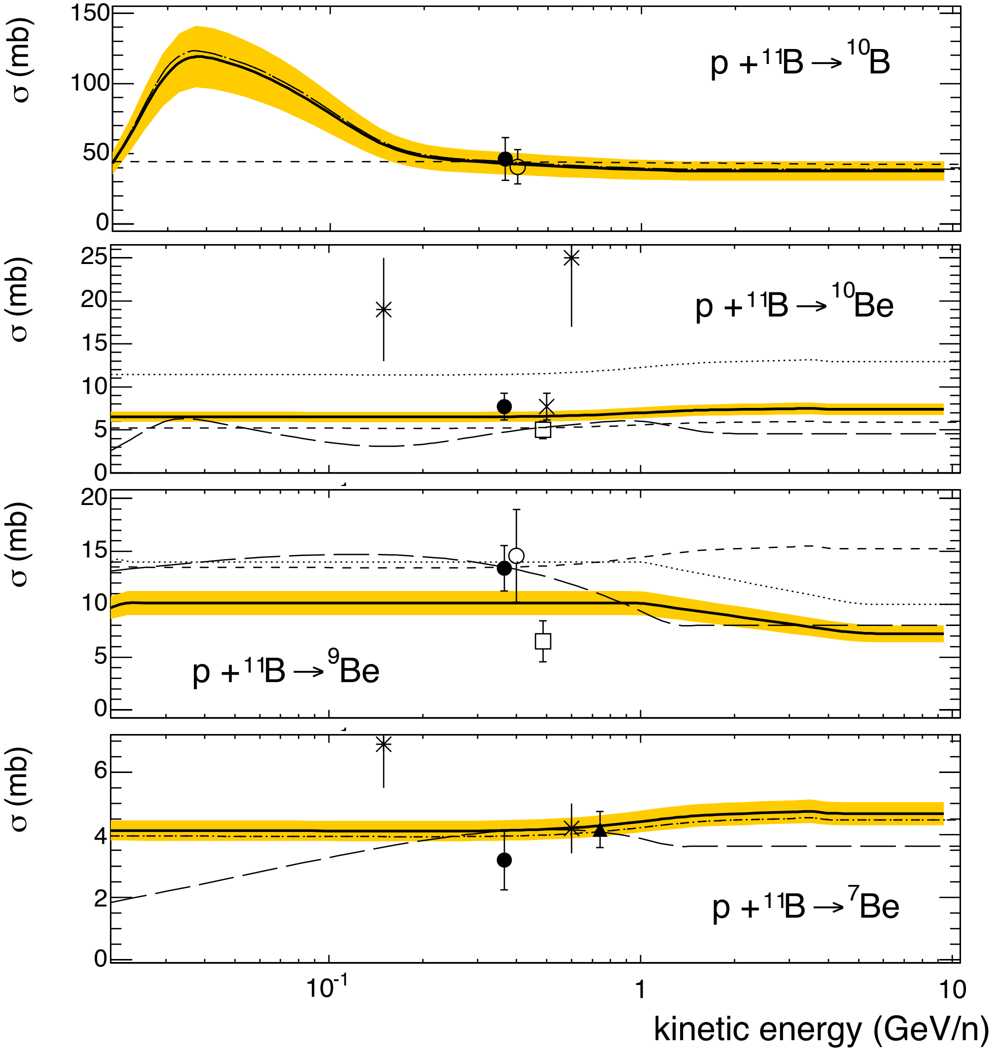
Cross-sections for “tertiary” reactions

- Secondary nuclei Be,B may also fragment in Li,Be,B.
- B(p,X)Be reactions poorly known. Relevant contribution on Be production.

$$\sigma^{H}_{B\rightarrow Be}(E) = a\cdot\sigma^{G}_{B\rightarrow Be}(b\cdot E)$$

····· GAL/CEM2k
----- WNEW -98
— — YIELDX-00
▬ REFIT

● Webber et al1998
△ Read & Viola 1984
■ Korejwo et al 1999
□ Webber et al 1990
▼ Olson et al 1983
◇ Korejwo et al 2001
★ Fontes et al1977
∗ Raisbeck et al1971
○ Ramaty et al1997
× Webber et al1998b
▲ Radin et al1979



Production cross sections – summary @ 10 GeV/n

Proj ⟶ Frag	GALPROP	WNEW	YIELDX	$\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}} \pm \delta\sigma^{\mathrm{H}}_{\mathrm{P}\to\mathrm{F}}$	Data Sets	$F_{\alpha/p}$	$\sigma^{\mathrm{He}}_{\mathrm{P}\to\mathrm{F}} \pm \delta\sigma^{\mathrm{He}}_{\mathrm{P}\to\mathrm{F}}$
^{16}O ⟶ ^{11}B	27.34 mb	14.57 mb	14.41 mb	(25.66 ± 1.06) mb	△●□∗▼	1.34	(34.37 ± 1.43) mb
^{16}O ⟶ ^{10}B	11.00 mb	9.52 mb	8.81 mb	(11.92 ± 0.52) mb	△●□∗▼	1.34	(15.97 ± 0.70) mb
^{15}N ⟶ ^{11}B	26.12 mb	26.12 mb	21.71 mb	(30.63 ± 2.48) mb	●○	1.31	(40.04 ± 3.24) mb
^{15}N ⟶ ^{10}B	9.56 mb	8.81 mb	7.63 mb	(9.69 ± 0.77) mb	●○	1.31	(12.66 ± 1.01) mb
^{14}N ⟶ ^{11}B	29.22 mb	29.98 mb	26.66 mb	(29.80 ± 1.08) mb	●□∗★	1.21	(35.94 ± 1.30) mb
^{14}N ⟶ ^{10}B	10.44 mb	10.64 mb	9.18 mb	(10.15 ± 0.84) mb	●□∗★	1.21	(12.24 ± 1.01) mb
^{12}C ⟶ ^{11}B	56.88 mb	54.86 mb	52.83 mb	(54.73 ± 2.57) mb	●□■∗▼★◊	1.29	(70.50 ± 3.32) mb
^{12}C ⟶ ^{10}B	12.30 mb	16.21 mb	11.59 mb	(12.05 ± 0.58) mb	●□■∗▼★◊	1.29	(15.52 ± 0.74) mb
^{16}O ⟶ ^{10}Be	2.14 mb	1.34 mb	2.07 mb	(1.90 ± 0.13) mb	△▼	1.47	(2.79 ± 0.19) mb
^{16}O ⟶ ^{9}Be	3.48 mb	3.35 mb	3.51 mb	(3.40 ± 0.22) mb	△∗▼	1.47	(4.99 ± 0.32) mb
^{16}O ⟶ ^{7}Be	10.00 mb	8.75 mb	8.92 mb	(8.97 ± 0.29) mb	△▼	1.47	(13.16 ± 0.42) mb
^{14}N ⟶ ^{10}Be	1.75 mb	1.06 mb	1.81 mb	(1.73 ± 0.21) mb	△□	1.43	(2.47 ± 0.30) mb
^{14}N ⟶ ^{7}Be	10.10 mb	7.46 mb	8.47 mb	(7.90 ± 0.47) mb	△▲□	1.43	(11.29 ± 0.67) mb
^{12}C ⟶ ^{10}Be	3.94 mb	2.05 mb	3.41 mb	(3.61 ± 0.27) mb	△□■▼◊	1.41	(5.07 ± 0.38) mb
^{12}C ⟶ ^{9}Be	6.76 mb	5.31 mb	4.98 mb	(6.63 ± 0.29) mb	△□■∗▼◊▲	1.41	(9.32 ± 0.41) mb
^{12}C ⟶ ^{7}Be	9.58 mb	10.32 mb	10.76 mb	(8.88 ± 0.30) mb	△●□■▼★◊	1.41	(12.48 ± 0.42) mb
^{11}B ⟶ ^{10}B	38.91 mb	42.58 mb	38.91 mb	(37.83 ± 9.25) mb	●○	1.29	(48.63 ± 11.89) mb
^{11}B ⟶ ^{10}Be	12.95 mb	5.90 mb	4.56 mb	(6.52 ± 1.04) mb	●□	1.40	(9.14 ± 1.46) mb
^{11}B ⟶ ^{9}Be	10.00 mb	15.27 mb	8.01 mb	(7.22 ± 1.08) mb	△●	1.40	(10.13 ± 1.51) mb
^{11}B ⟶ ^{7}Be	4.48 mb	4.48 mb	3.63 mb	(4.31 ± 0.60) mb	●□○	1.40	(6.05 ± 0.85) mb

Cross section uncertainties – impact in CR calculation

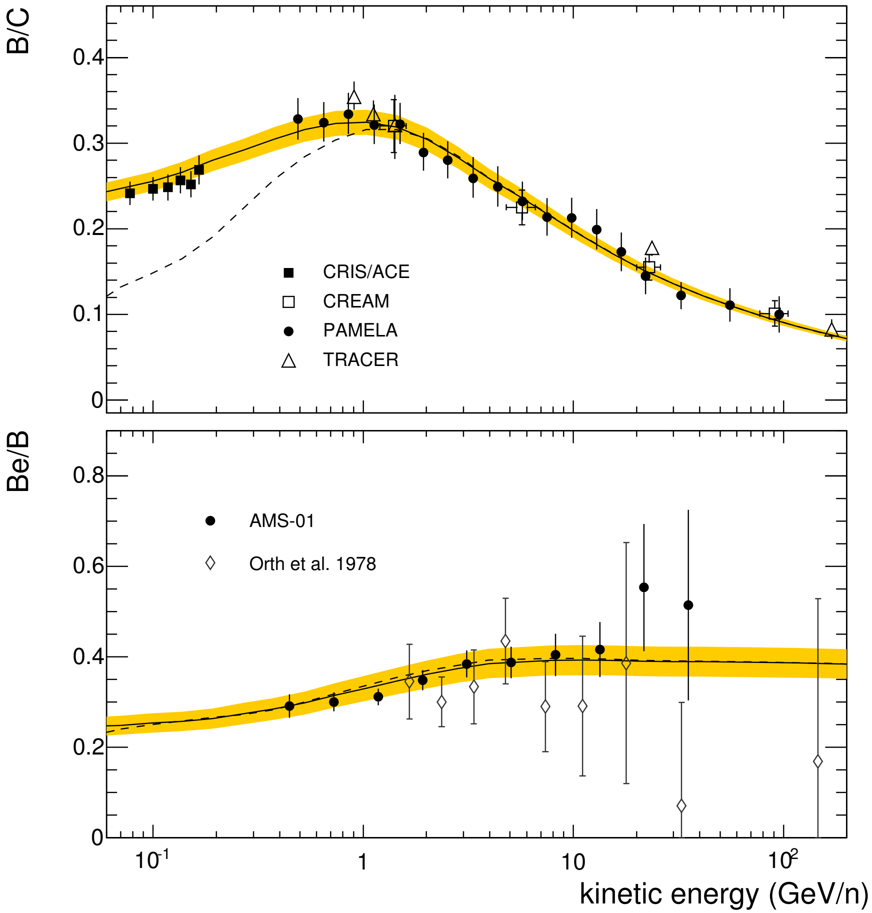
Reference model setting

Parameter	Name	Ref. Value
Injection index	ν_1	1.80
Injection index	ν_2	2.38
Rigidity break	R_B [GV]	9
Ref. rigidity	R_0 [GV]	4
Diffusion coeff.	D_0 [10^{28}cm^2 s^{-1}]	5.04
Diffusion slope	δ	0.38
Halo height	L [kpc]	3.9
Halo radius	r_{max} [kpc]	30
Alfvén speed	v_A [km s^{-1}]	33
Modulation potential	ϕ [MV]	550

Cross sections errors can be translated into errors in the B/C and Be/B ratios predicted. For secondaries:

$$\left(\delta q_j^{\text{sec}}\right)^2 = c \sum_i n_i \sum_k \beta_k \psi_k \left(\delta\sigma^i_{k\to j}\right)^2$$

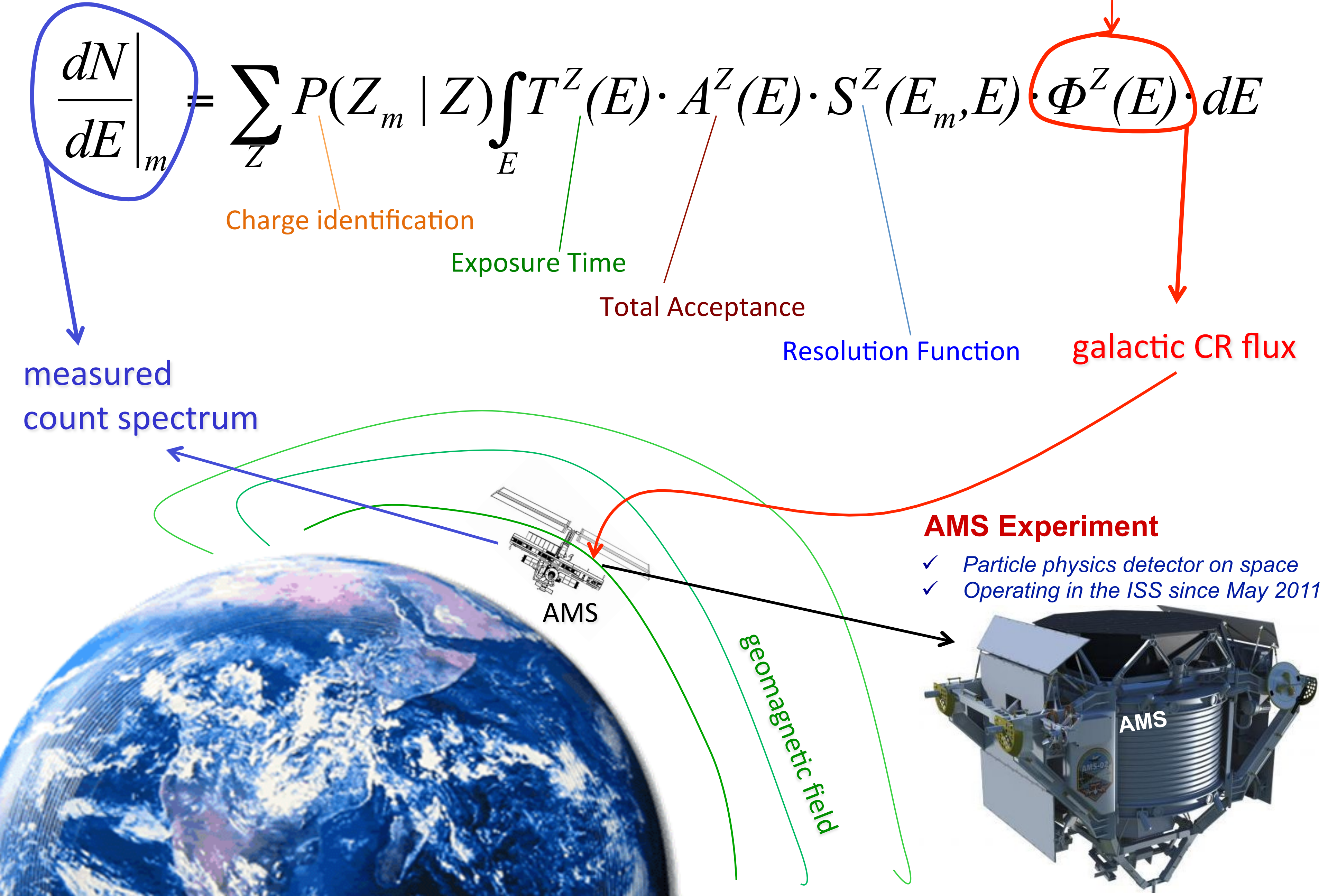
These errors affect the constraining power of B/C and Be/B ratios in determining the transport parameters



At present, errors on CR data seem to be of the same level of nuclear uncertainties

What about **future AMS** data?

Modeling the AMS performance



propagation model

$$\left.\frac{dN}{dE}\right|_m = \sum_Z P(Z_m \mid Z)\int_E T^Z(E)\cdot A^Z(E)\cdot S^Z(E_m,E)\cdot \Phi^Z(E)\cdot dE$$

Charge identification

Exposure Time

Total Acceptance

Resolution Function

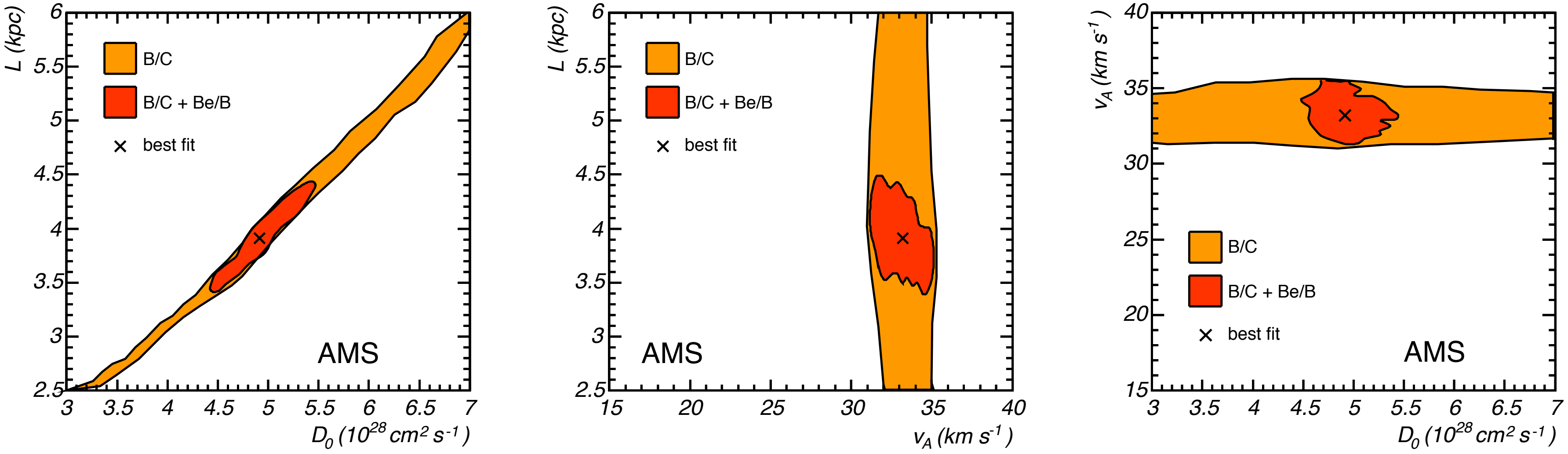
galactic CR flux

measured
count spectrum

AMS Experiment

- ✓ *Particle physics detector on space*
- ✓ *Operating in the ISS since May 2011*

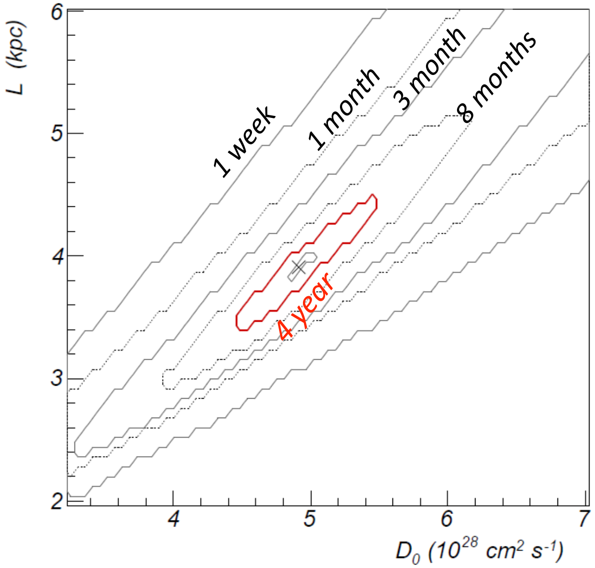
AMS Sensitivity to CR propagation parameters



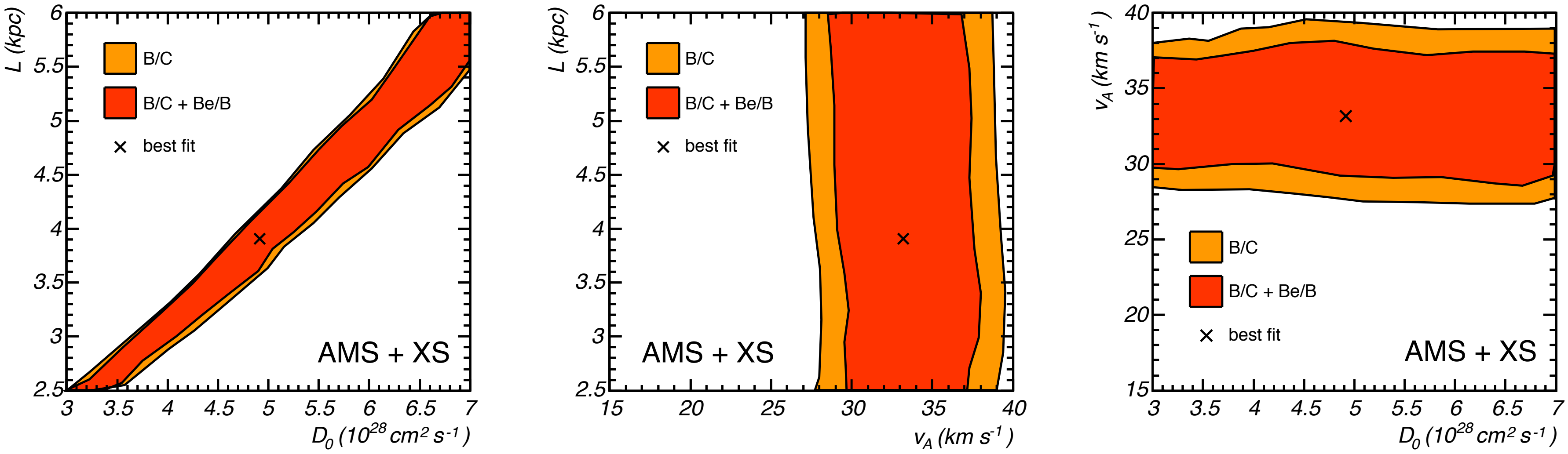
Orange area: one sigma contour regions, from AMS mock data on the **B/C ratio**
→ The **D/L** degeneracy is apparent.

Red area: one sigma contour regions from simultaneous AMS mock data on **B/C and Be/B**
→ **The D/L degeneracy is broken**

Star: true model (corresponding to best-fit model)



AMS Sensitivity to CR propagation parameters



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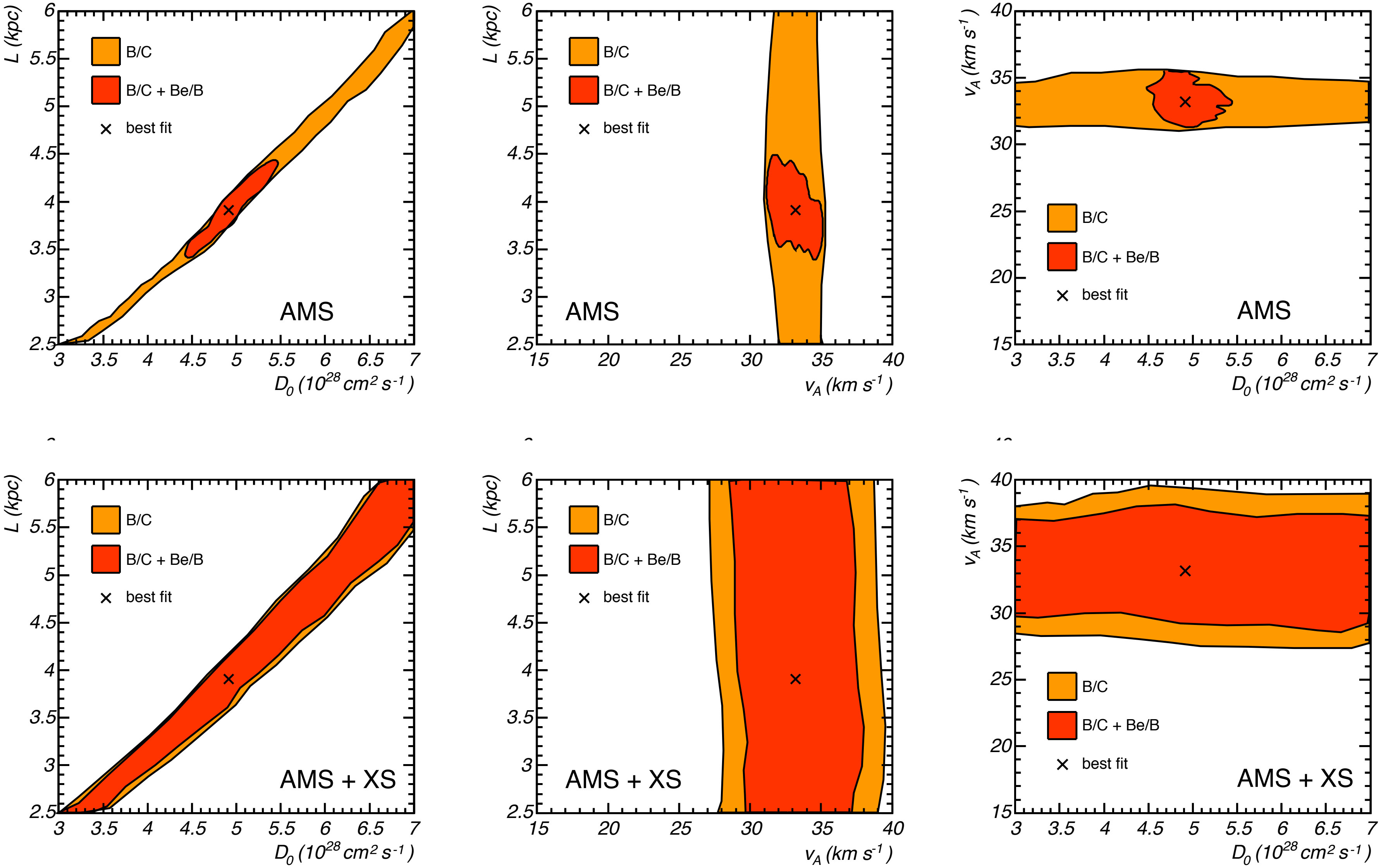
Star: true model (corresponding to best-fit model)

Nuclear uncertainties are now accounted

After accounting for nuclear uncertainties the D/L degeneracy remains unresolved

AMS Sensitivity to CR propagation parameters



Systematic Biases in Cross Sections Data

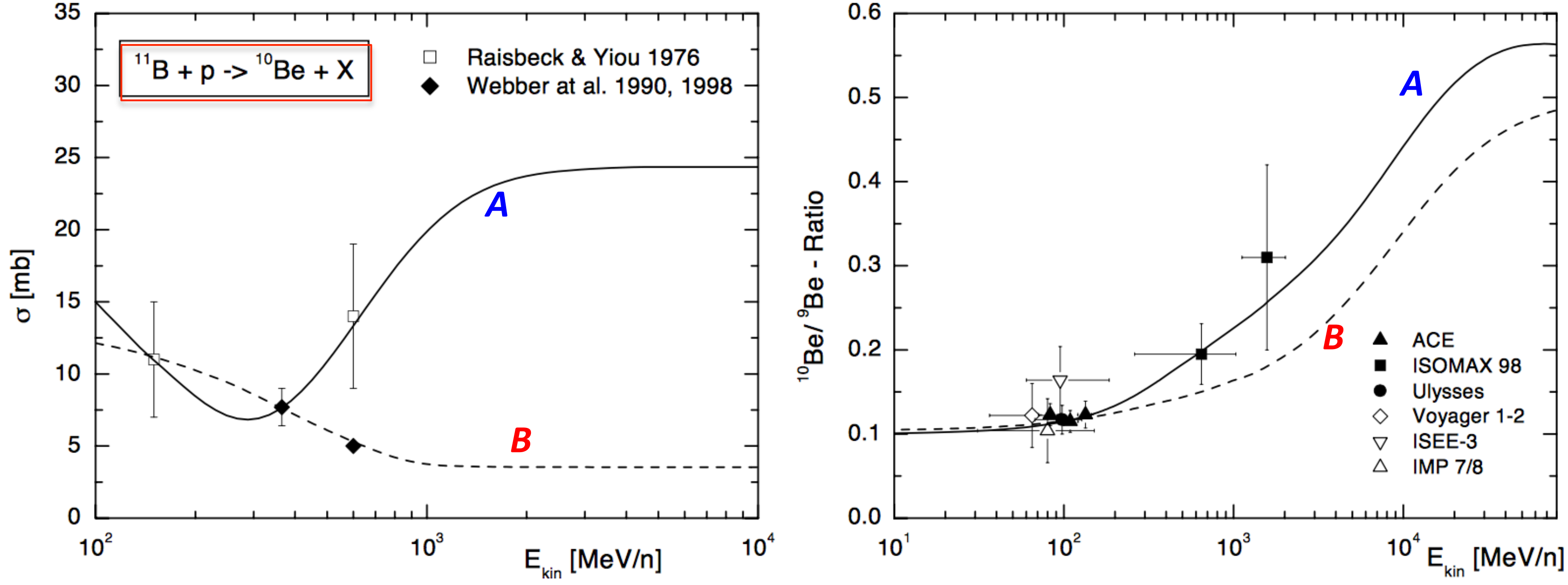
Large errors/bias in single cross-section reactions:

- **Break** correspondence between **best** model and **best-fit** model

→ **mis-**predictions of the ratios B/C or Be/B.

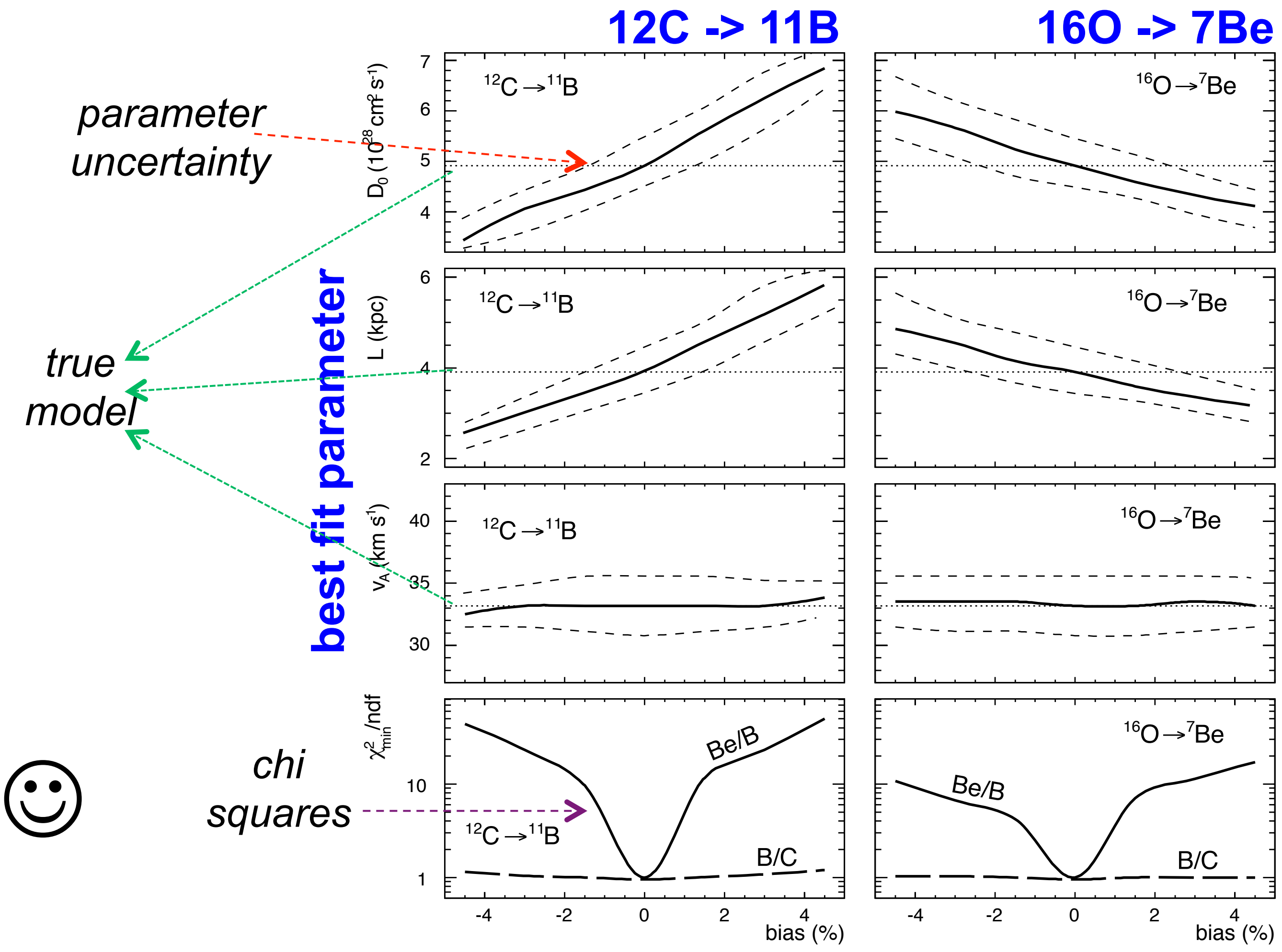
→ **mis-**determination of CR transport parameters

An example: 11B → 10Be reactions [Hams et al 2004; Molnar & Simon 2003]



Systematic Biases in Cross Sections Data

- Introduce bias in the cross-section normalization
- Generated a biased reference model -> new AMS predictions for B/C + Be/B
- Re-apply the parameter reconstruction, with the unbiased model



12C -> 11B

16O -> 7Be

parameter uncertainty

true model

chi squares

best fit parameter

bias induced in the cross section (%)

Parameter mis-determination caused by bias ☹

Large chi2 from the Be/B at high energy ☺

Independent on CR propagation effects

Conclusions

- ✓ From AMS expected capabilities, the combination of the B/C+Be/B can in principle break the D/L degeneracy and precisely measure the CR transport parameters L and D.

- ✓ Once the nuclear uncertainties are accounted in the model prediction, the D/L degeneracy remains largely unresolved.

- ✓ Large systematic bias in the main production channels (e.g. 12C->11B) may well lead to a parameter mis-determination.

- ✓ The presence of biases can be detected by AMS using Be/B at high-energy (E>10 GeV/n) or secondary-to-secondary ratios of stable species.

- ✓ The Be/B ratio give little information on the CR transport. Isotopically resolved data (10Be) are better for propagation studies.

New challenges for everybody

✓ **For CR propagation physicists**

Use independent strategies (and observables) to infer the CR parameters.
For **L/D degeneracy**: heavy nuclei propagation; low-energy leptons; radio emission

✓ **For CR experiments (AMS)**

Along with Be/B, feasibility studies for **10Be/9Be** at 1 – 10 GeV/n.
A ~5% of systematic error would be a great progress.
Other elemental ratios can be considered be Al/Mg or Cr/Ar

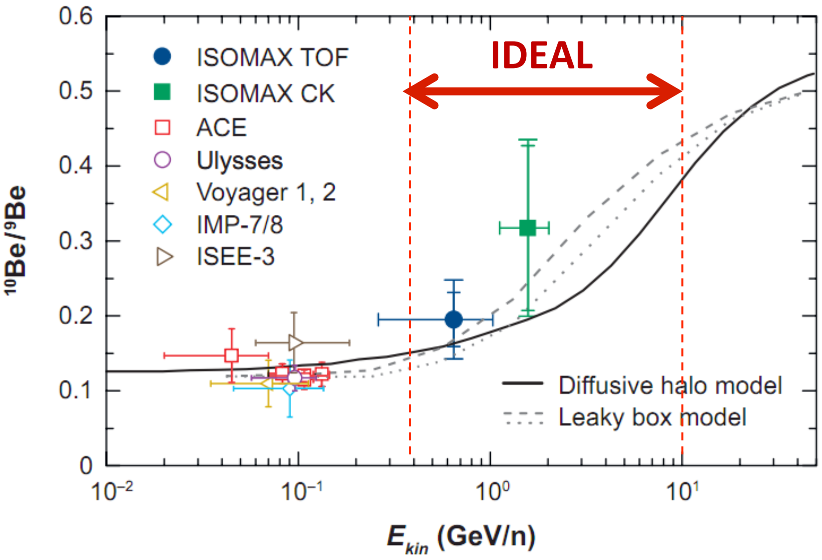
✓ **For nuclear physicists**

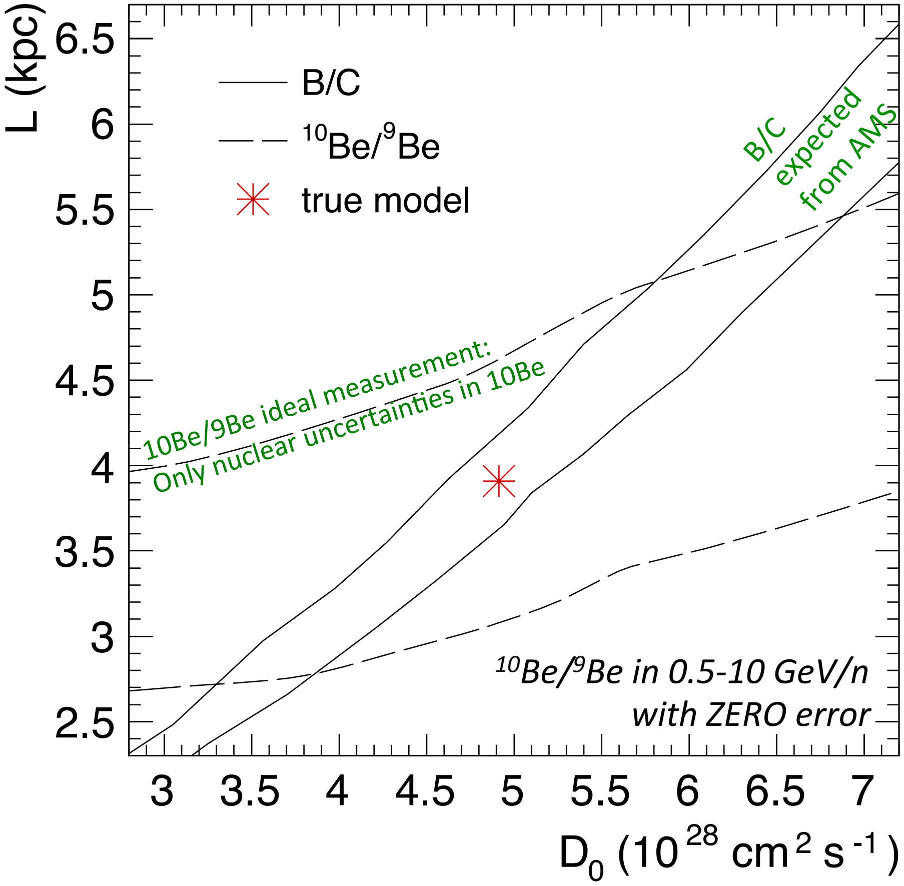
Better data on **Li-Be-B production** in p+N and α+N reactions.
In particular, beryllium. More in particular, tertiary reaction 11B->10Be.

backup

Ideal 10Be/9Be measurement

Assumed:
-NO-errors in 10Be/9Be at 0.5-10 GeV/n
- Only nuclear uncertainties to 10Be.
The D/L degeneration is (poorly) lifted.

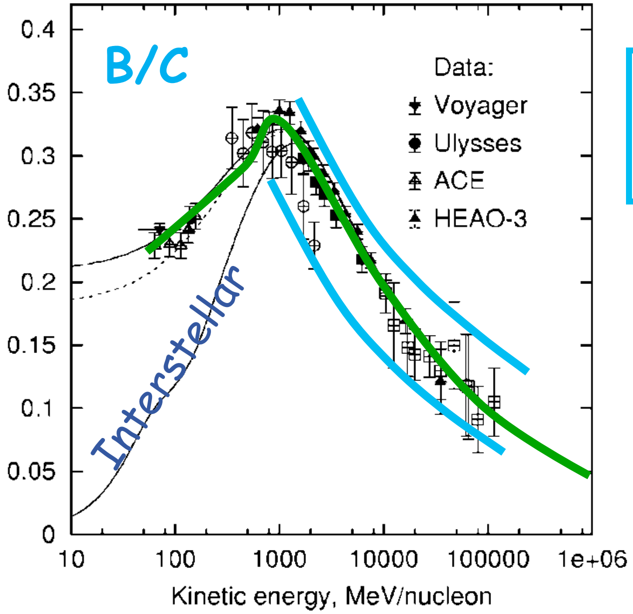


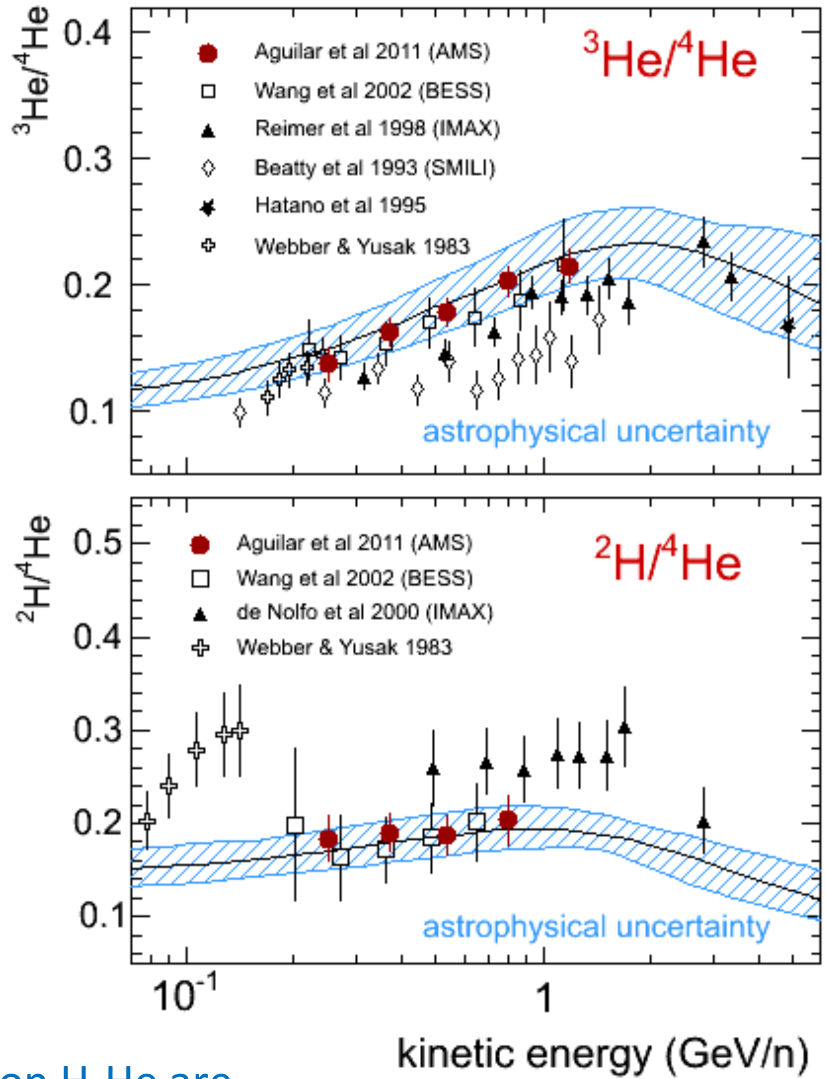


^{2}H/^{4}He and ^{3}He/^{4}He Ratios: Propagation

Shaded bands:
From models consistent with the B/C ratio after a parameter scan.

Key parameters:
- δ: diffusion coefficient index
- D_0/L: diffusion coeff. / halo eight
- Va: Alfvenic speed





NB: AMS data on H-He are consistent and competitive.

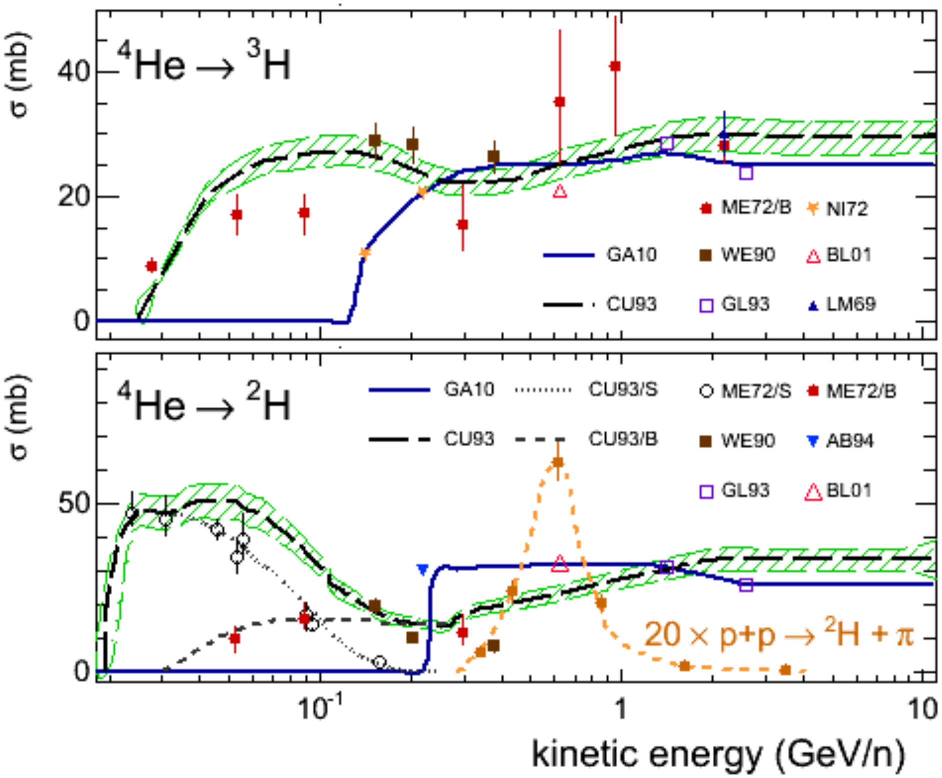
$^{2}H/^{3}He$ Ratio: Model Check

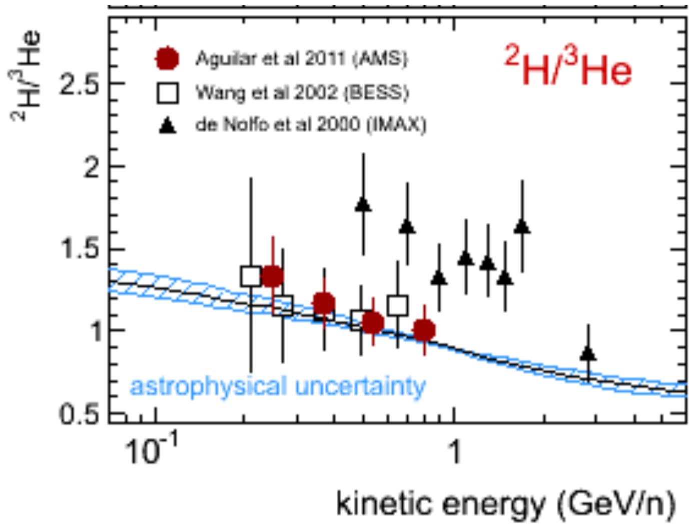
Cross section uncertainties in the main production channels.

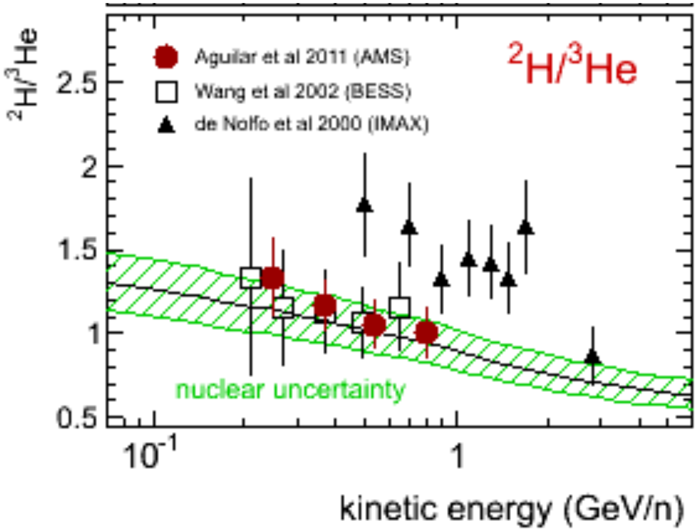
→Intrinsic uncertainties model predictions

→Mis-determination of the transport parameters

- model consistency check: **sec/sec ratios**







2H/3He ratio is almost insensitive to CR transport parameters.

Other aspects

Destruction?

Measured with better precisions.
Less impact in light-nuclei propagation
Used: Tripathi et al 1999.

Helium target?

Adopted Ferrando 1989. No data to test it.
Typical He/H factor is ~1.2-1.4
Typical He fraction in ISM: 10%
-> Expected to contribute at ~15% in the flux.
Same relative uncertainty as H assumed.

Straight ahead?

Assumed to be valid.
Proven at O(%) accuracy for LiBeB (Kneller 2003)
With the expected AMS precision, it probably needs to be re-investigated.

(High-)Energy dependence?

All XS's assumed FLAT above few ~GeV/n
No data at E >10 GeV/n to test it.
Possible impact on delta parameter