

Nuclei and antinuclei production in cosmic rays

Cross-sections and uncertainties for cosmic-ray propagation



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27 July.2017 - Geneva

Astrophysical antimatter background

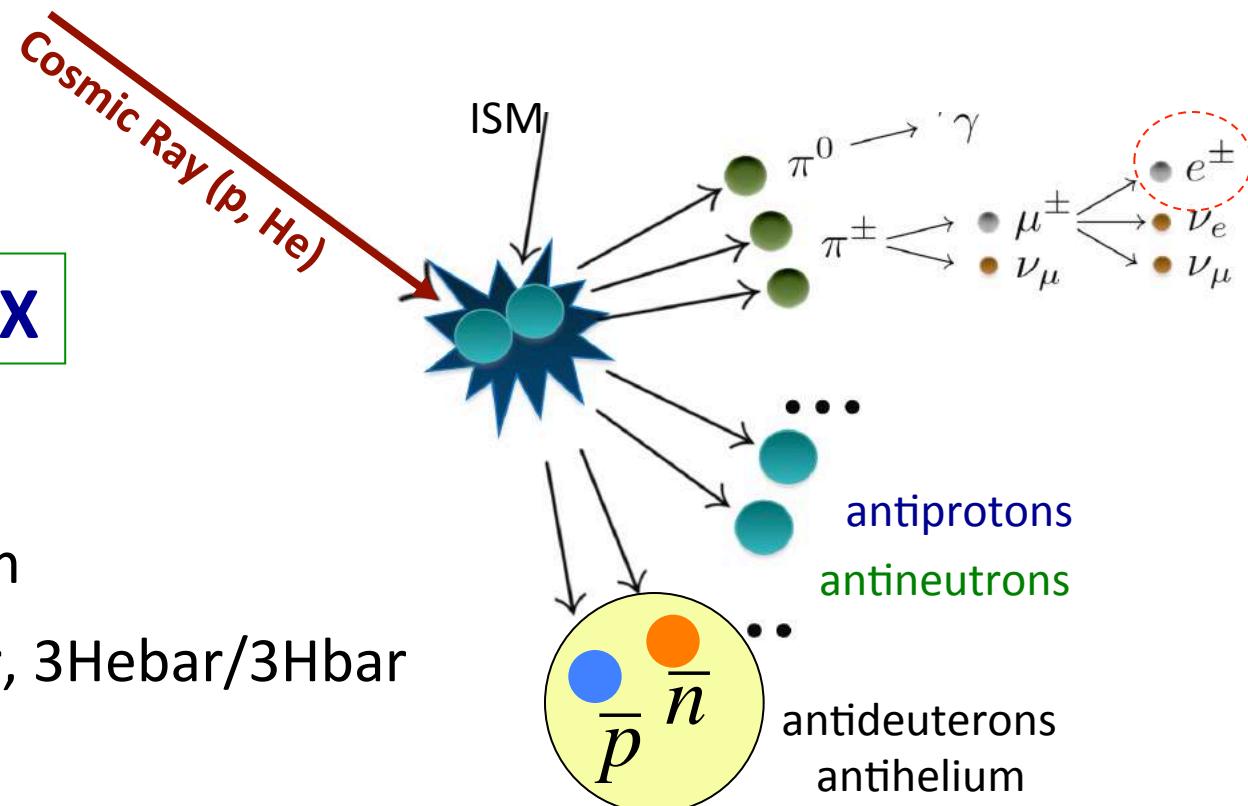
$$Q_{\bar{A}}^{sec}(E) \approx \frac{4\pi}{c} \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} n_{ISM} \boxed{\frac{d\sigma_{CR+ISM \rightarrow \bar{A}}^{ISM}}{dE'}(E, E')} J_{CR}(E') dE'$$

CR + ISM → Abar + X

CR = proton, alpha

ISM = hydrogen, helium

Abar = pbar/nbar, dbar, 3Hebar/3Hbar



Astrophysical antimatter background

$$Q_{\bar{A}}^{sec}(E) \approx \frac{4\pi}{c} \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} n_{ISM} \frac{d\sigma_{CR+ISM \rightarrow \bar{A}}^{ISM}}{dE'}(E, E') J_{CR}(E') dE'$$

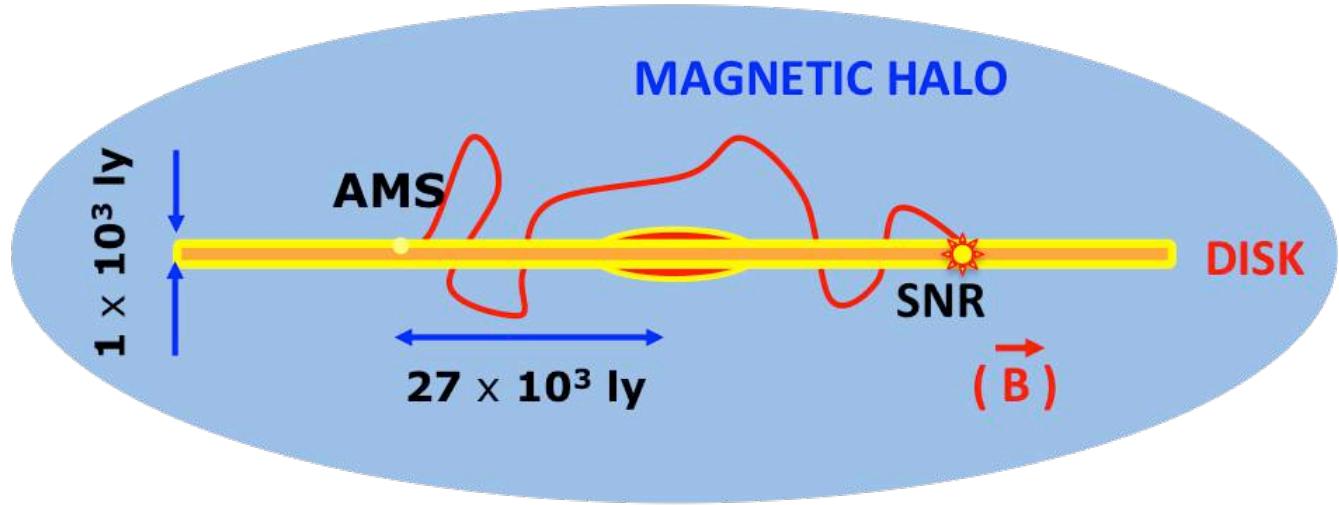
Propagation
in the Galaxy:

diffusive transport,
energy loss/gain
nuclear spallation

$$J_{\bar{A}}^{LIS}(E)$$

Solar modulation
in the Heliosphere:
diffusion, advection, drift

$$J_{\bar{A}}^{TOA}(E) \rightarrow \text{Detection : D}$$



Astrophysical and nuclear uncertainties

Main source of uncertainties in astrophysical BG calculations:

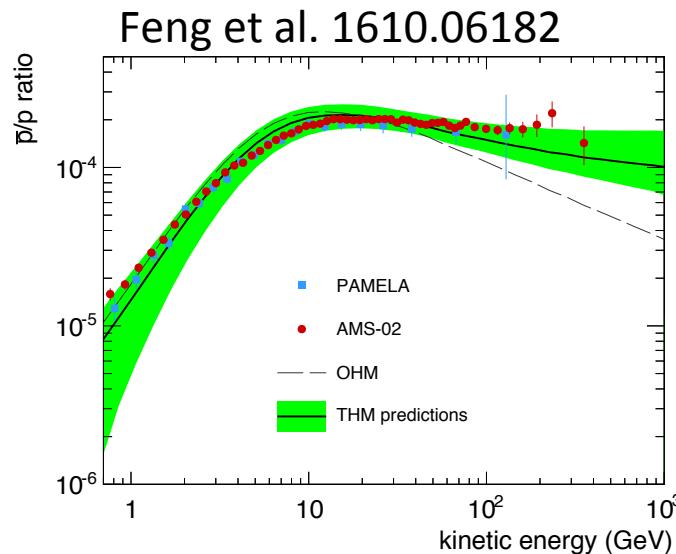
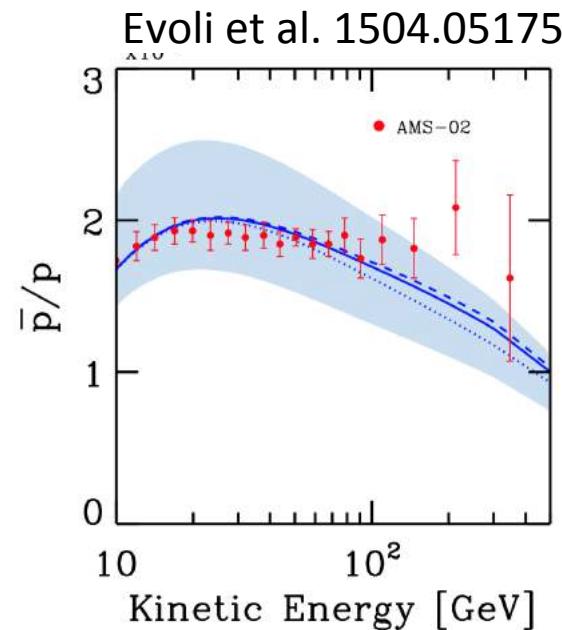
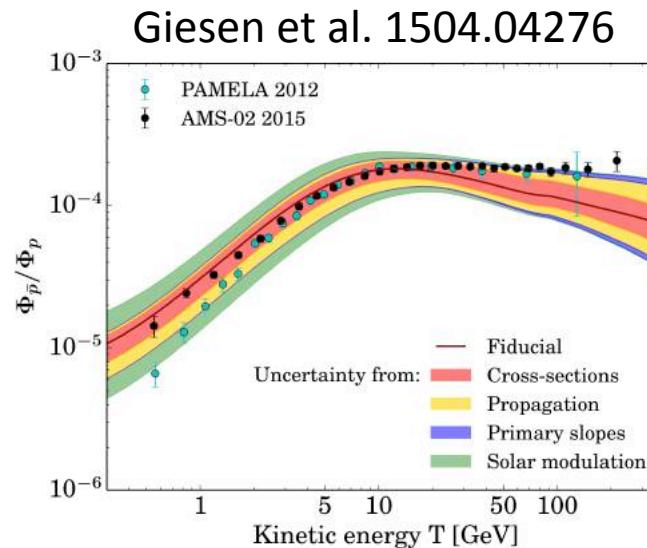
- 1) **PRIMARY CR - RELATED** – From our knowledge of primary CR fluxes. Related to our understanding of CR injection and acceleration.
- 2) **CR TRANSPORT IN GALAXY** – Arising from our knowledge of CR transport. Linked to the precision of the data on the B/C ratio and our ability to model it.
- 3) **SOLAR MODULATION IN HELIOSPHERE** – Uncertainties in CR diffusion in the heliosphere and charge-sign/polarity dependent effects.
- 4) **PRODUCTION** – cross-sections for anti-nucleon production and their coalescence into anti-nuclei. Several configurations of projectile-target-fragment-energy
- 5) **SPALLATION** – cross-sections for CR destructive (ANN) reactions in the ISM
- 6) **TERTIARY** – cross-sections for non-annihilating reactions and energy distribution of “tertiary” particles.

Astrophysical and nuclear uncertainties

Main source of uncertainties in astrophysical BG calculations:

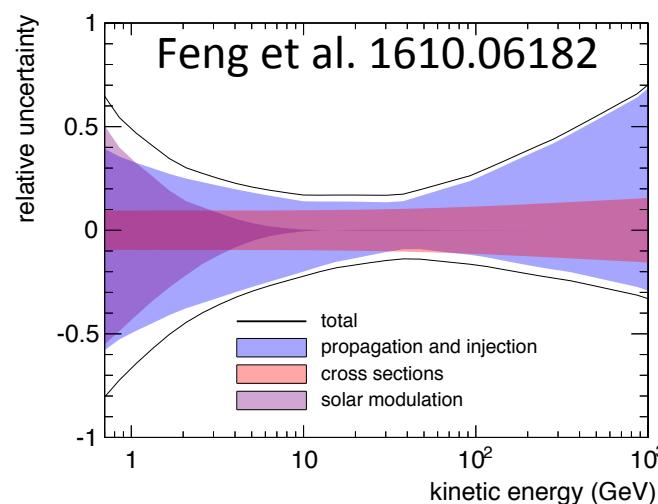
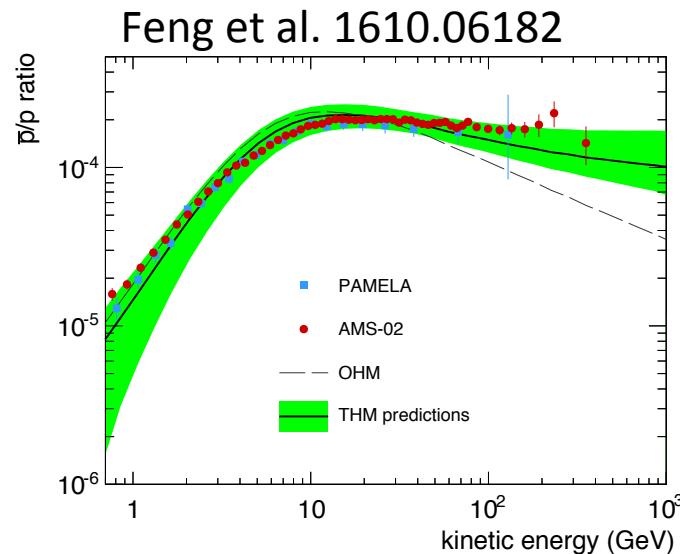
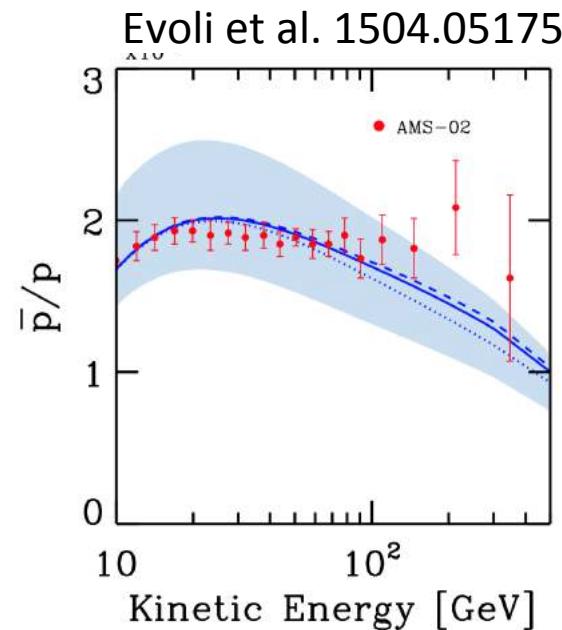
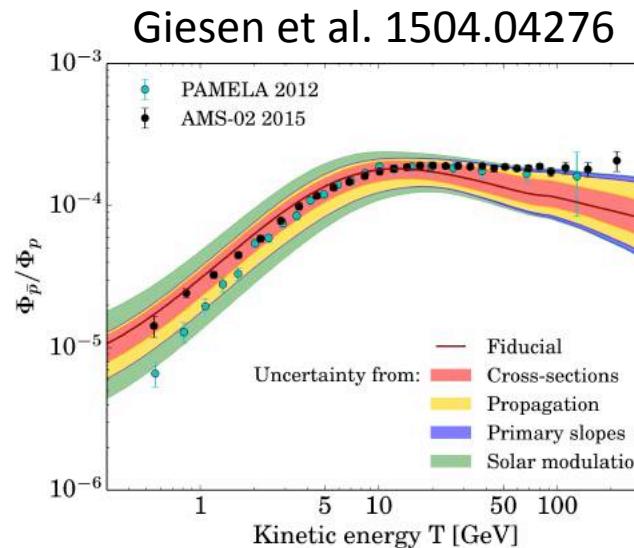
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Antiprotons: any excess in the AMS data?

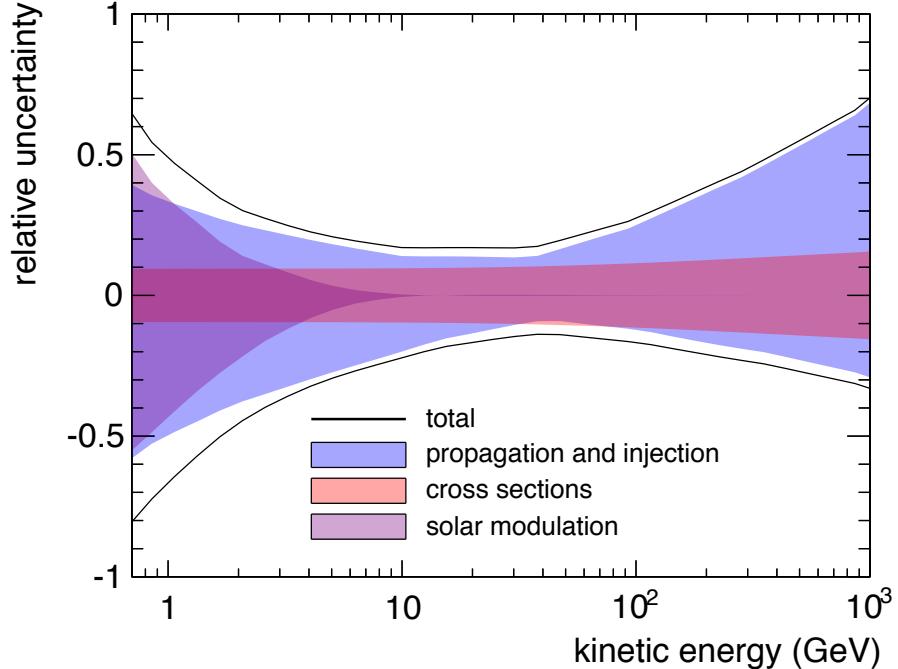


- ✓ No clear excess
- ✓ No clear agreement

Antiprotons: any excess in the AMS data?



Astrophysical antiproton background



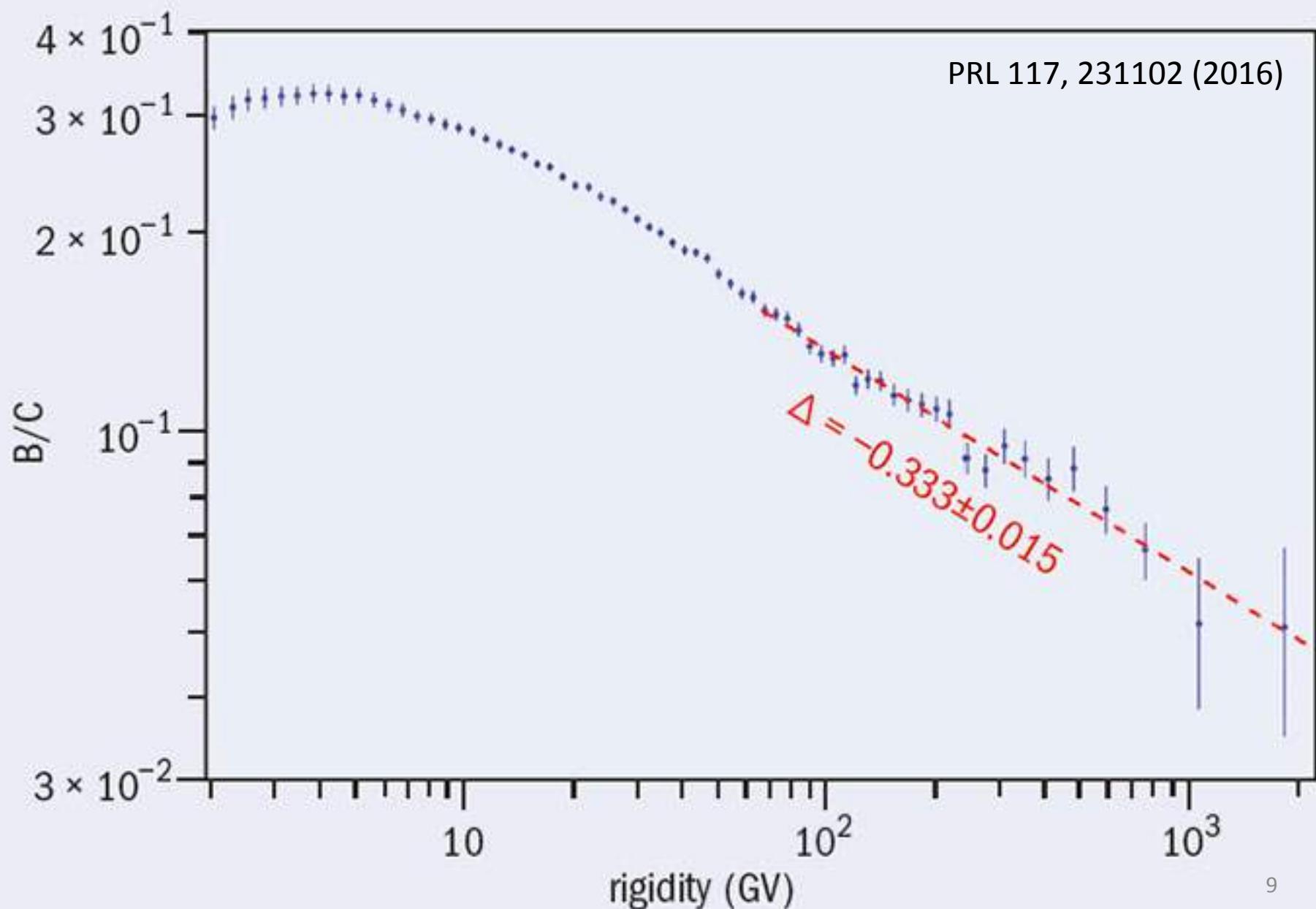
“Uncertainty in CR propagation
can be strongly reduced with
Precise B/C data at GeV – TeV”

(October 2016)

J. Feng et al. 2016 [1610.06182]
Uncertainties on pbar/p ratio

- ✓ *Uncertainties in antiproton production cross-sections -> comparisons MC generators -data*
- ✓ *Uncertainties in CR propagation -> from two-zone CR propagation model against B/C data*

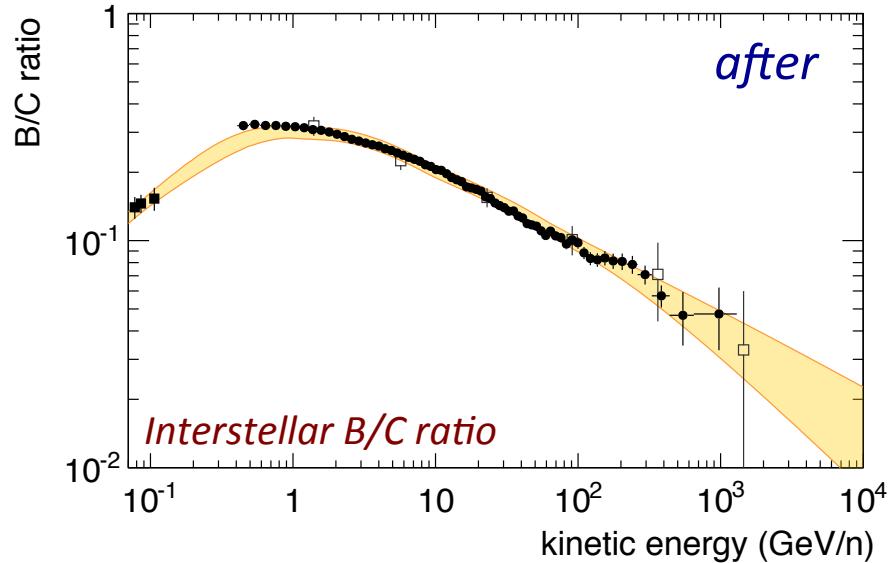
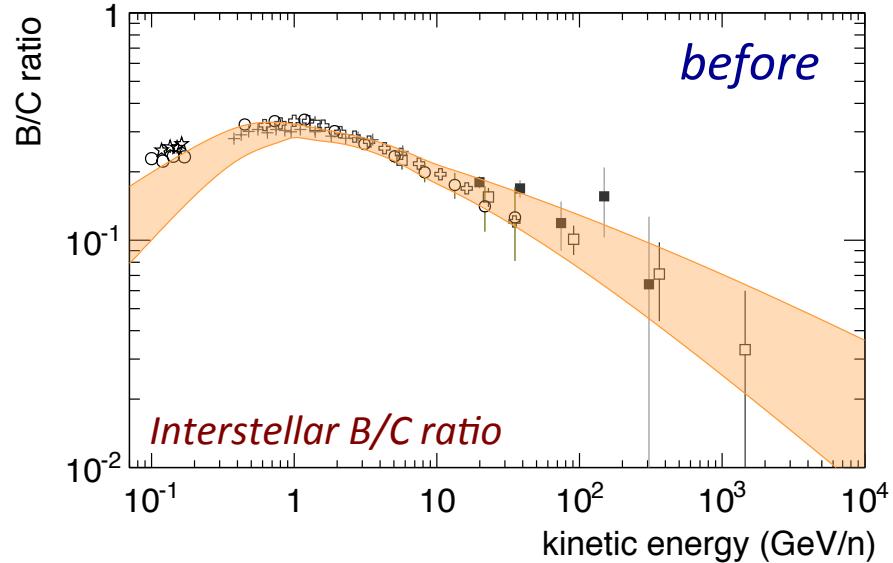
November 2016 : B/C ratio from AMS



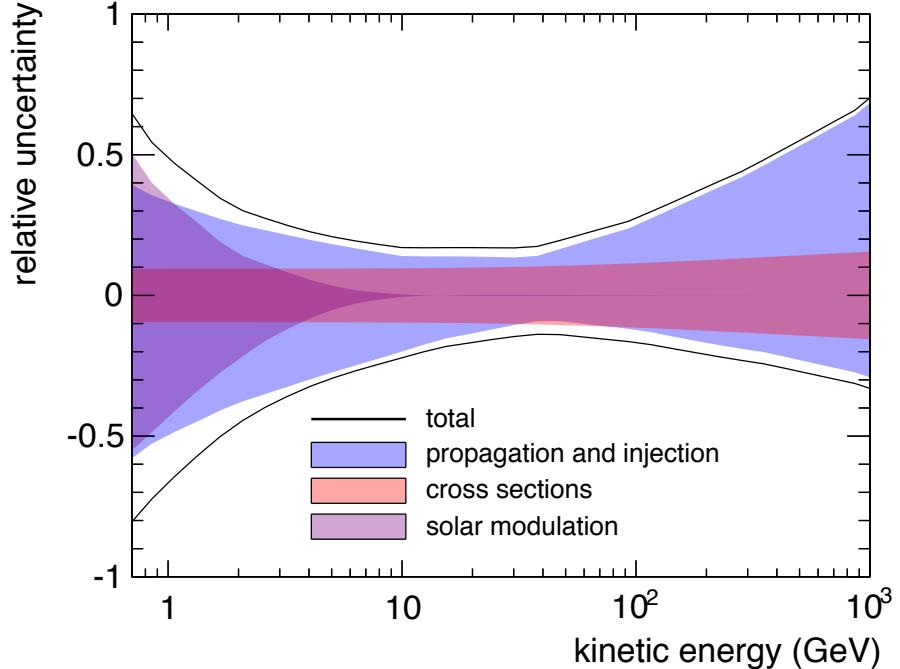
Uncertainties in CR transport in Galaxy

Related to our knowledge of CR transport parameters: B/C ratio

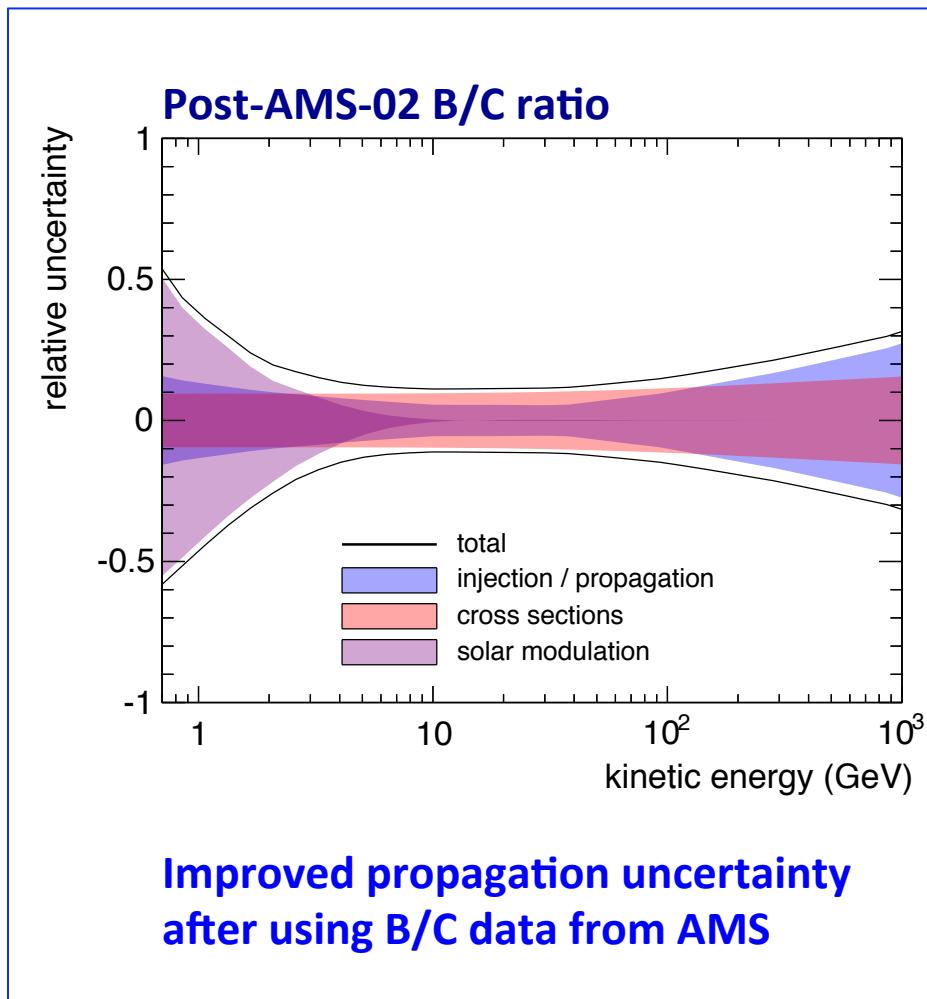
Substantial advance after **Voyager-1 & AMS-02**



Astrophysical antiproton background



J. Feng et al. 2016 [1610.06182]
Uncertainties on pbar/p ratio

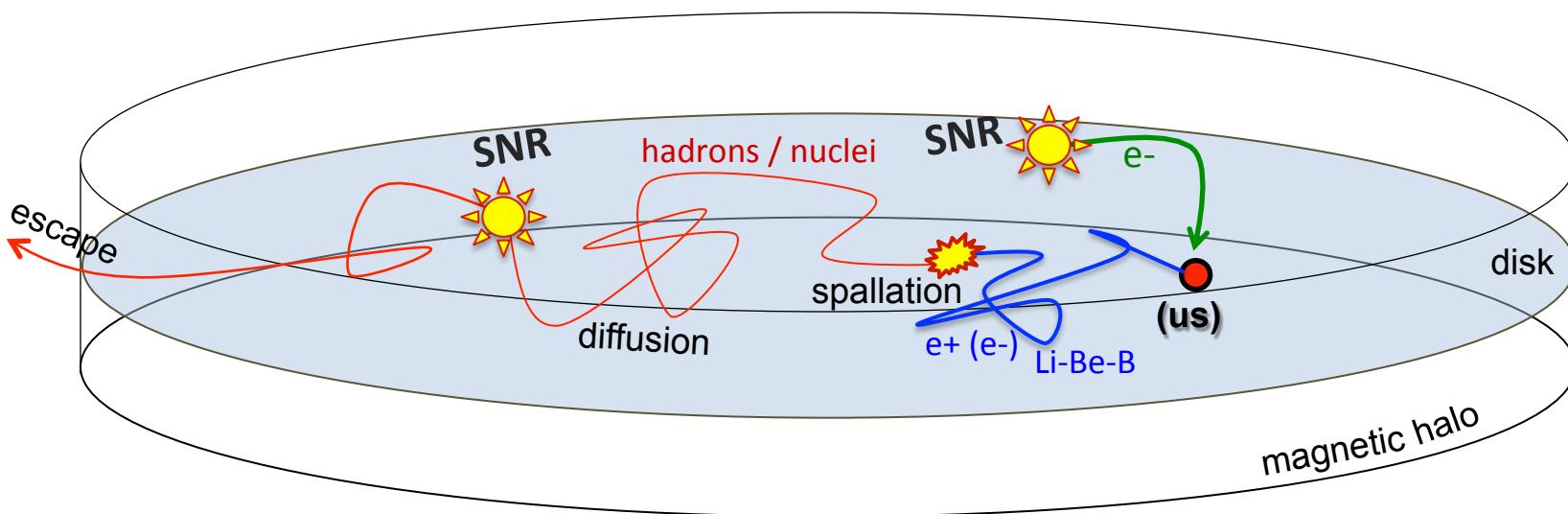


- ✓ New B/C data provides very tight constraints, BUT…
- Within this precision, it is critical to address systematic uncertainties in the model

What makes the B/C ratio: the physical picture

LEADING THEORY OF GCR [SNR PARADIGM]

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

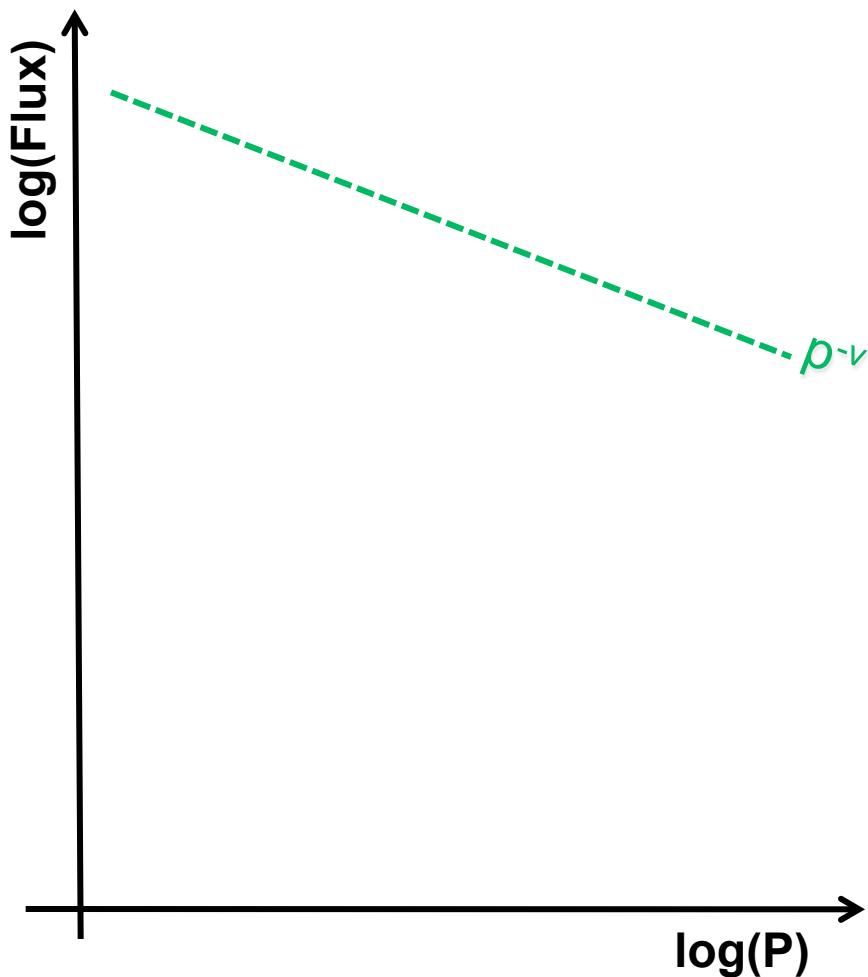


Pillars

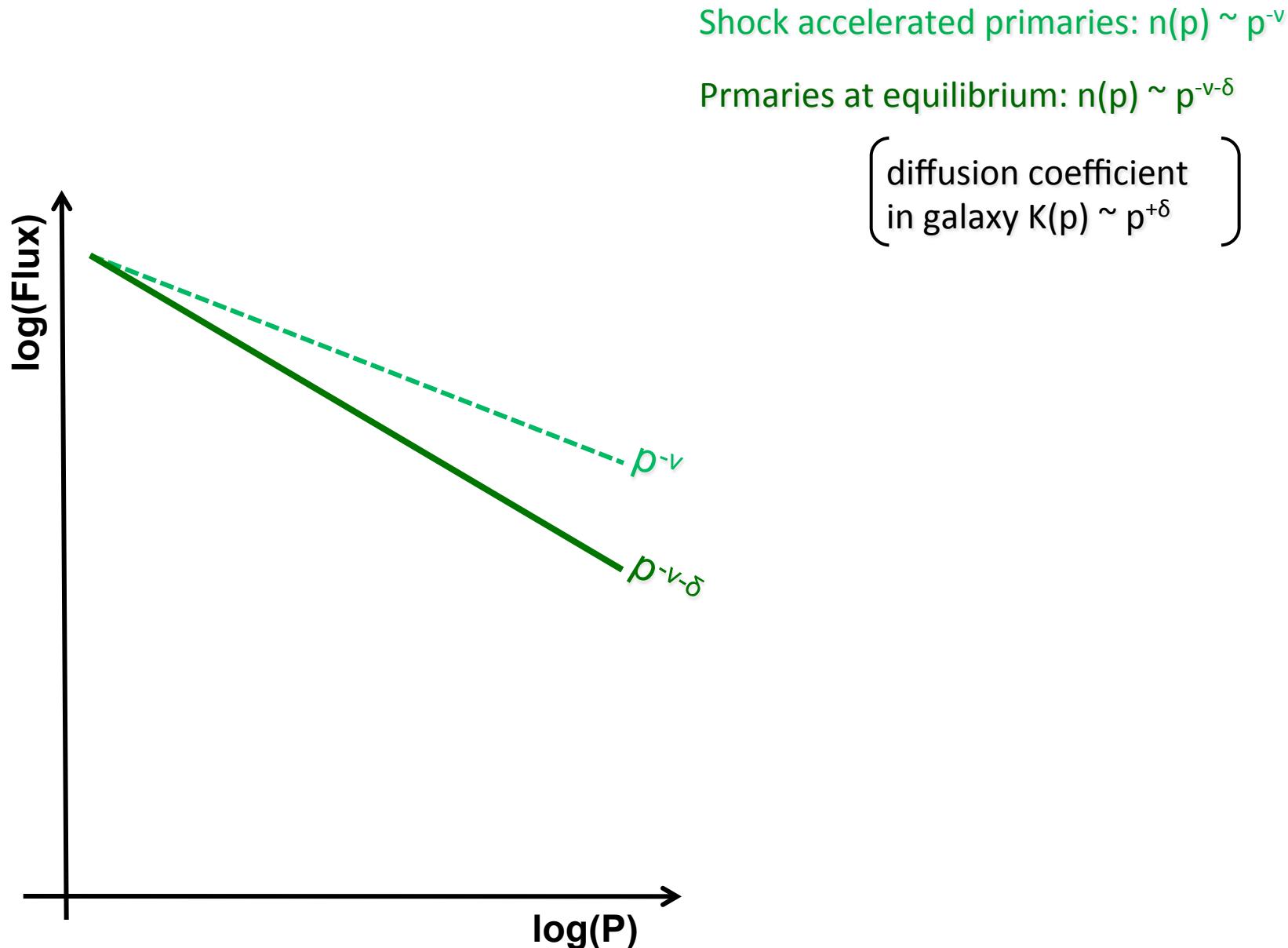
- DSA @SNR: accounts for energetics
- Diffusion: explain the high CR isotropy
- Interactions: account Li-Be-B abundance

What makes the B/C ratio

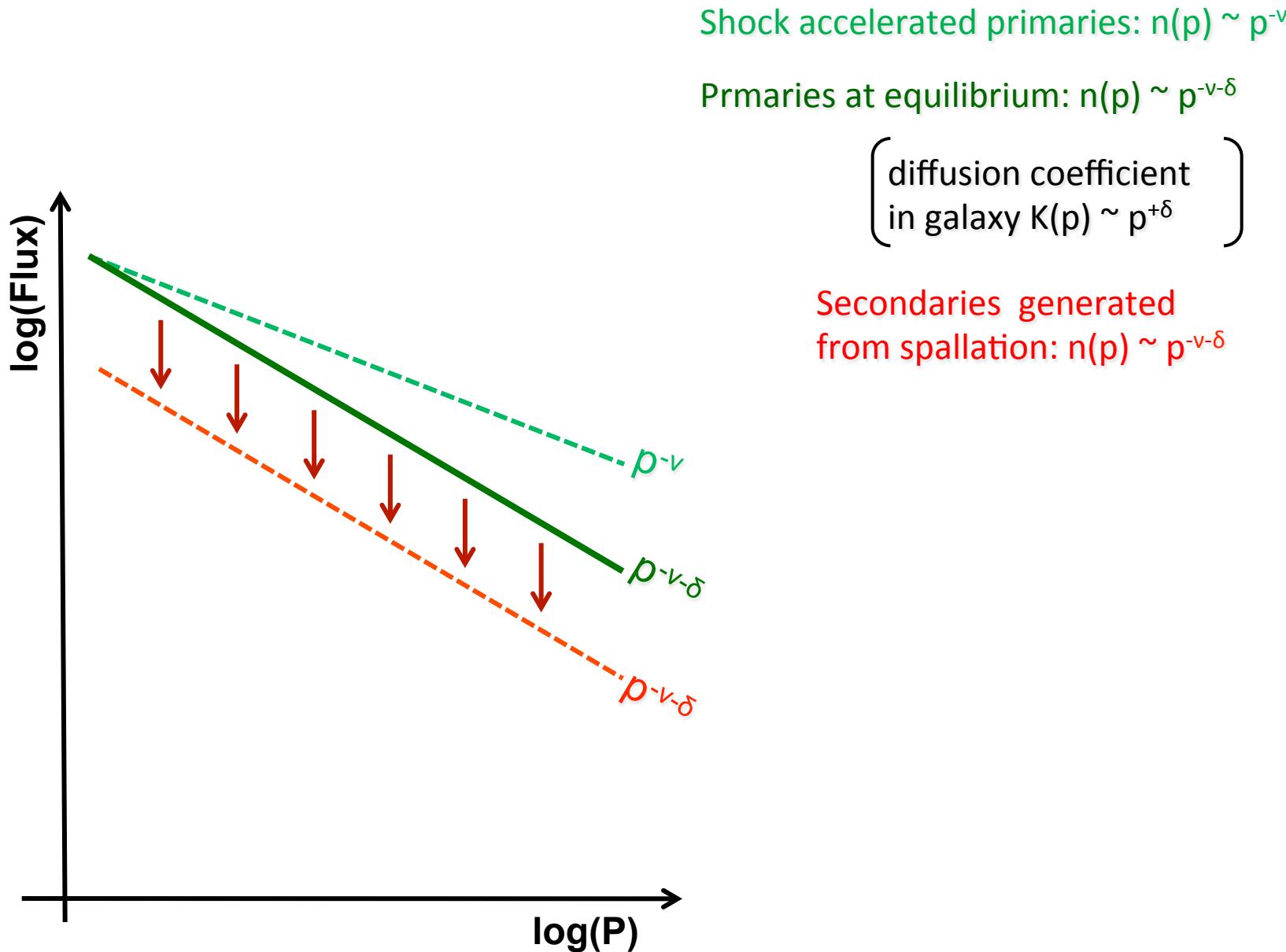
Shock accelerated primaries: $n(p) \sim p^{-\nu}$



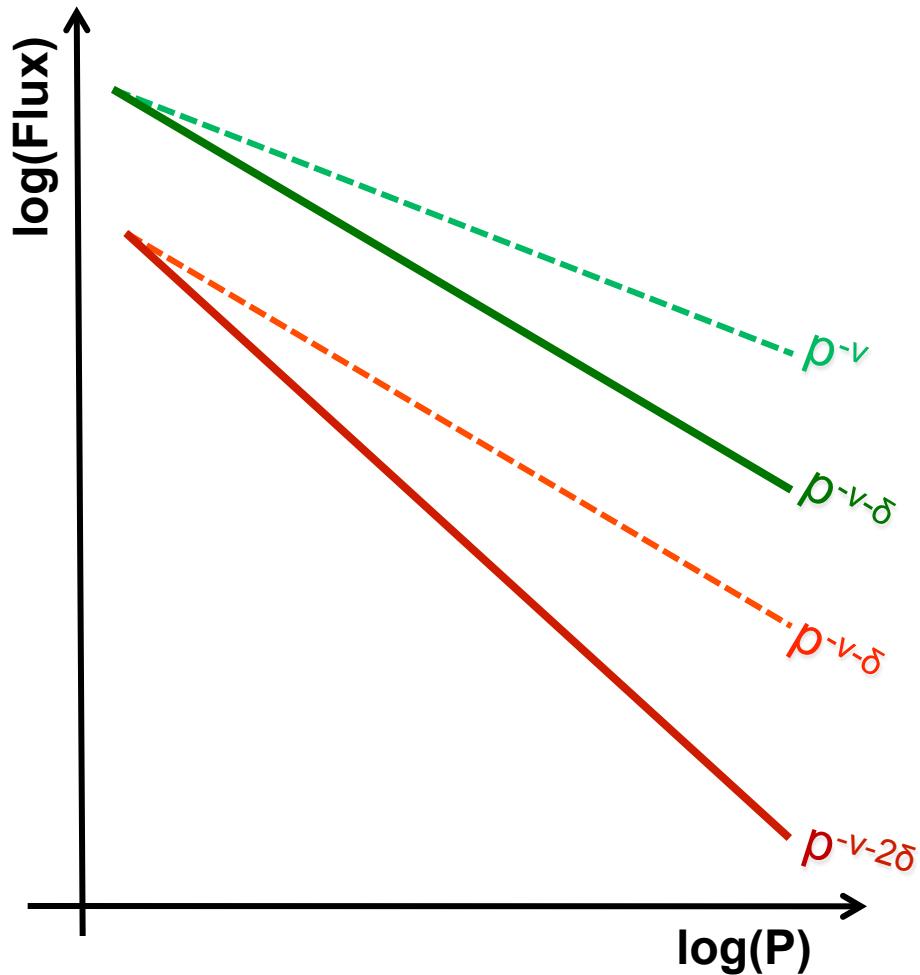
What makes the B/C ratio



What makes the B/C ratio



What makes the B/C ratio



Shock accelerated primaries: $n(p) \sim p^{-v}$

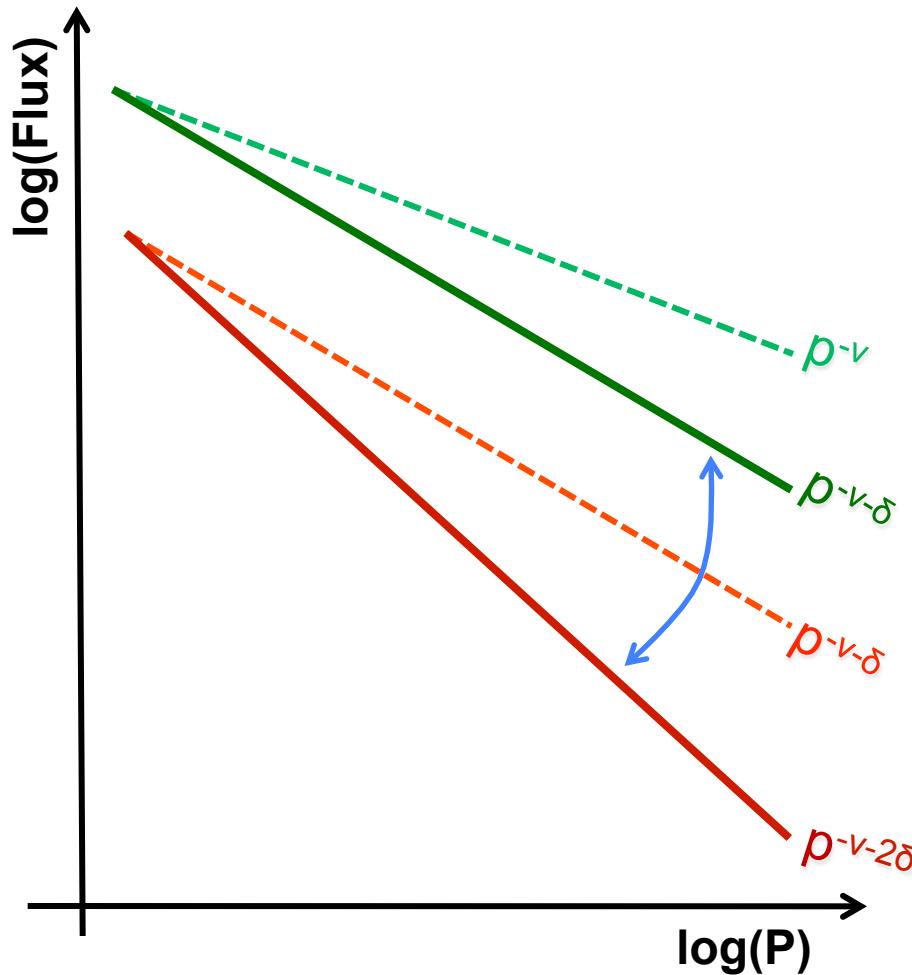
Prmaries at equilibrium: $n(p) \sim p^{-v-\delta}$

diffusion coefficient
in galaxy $K(p) \sim p^{+\delta}$

Secondaries generated
from spallation: $n(p) \sim p^{-v-\delta}$

Secondaries from spallation
at equilibrium: $n(p) \sim p^{-v-2\delta}$

What makes the B/C ratio



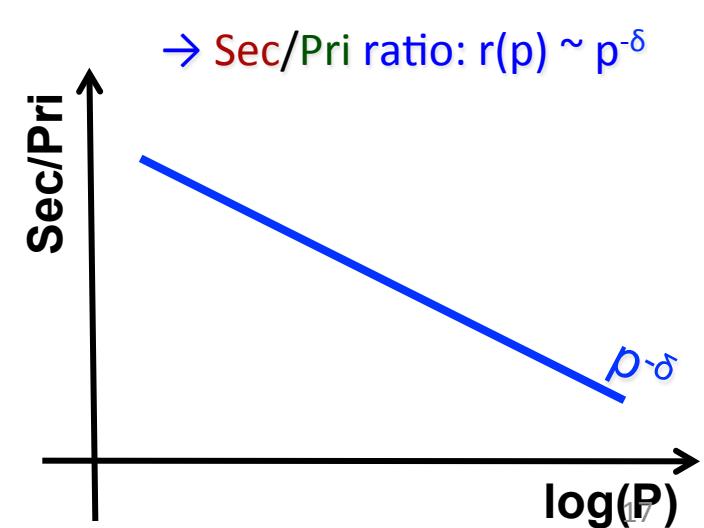
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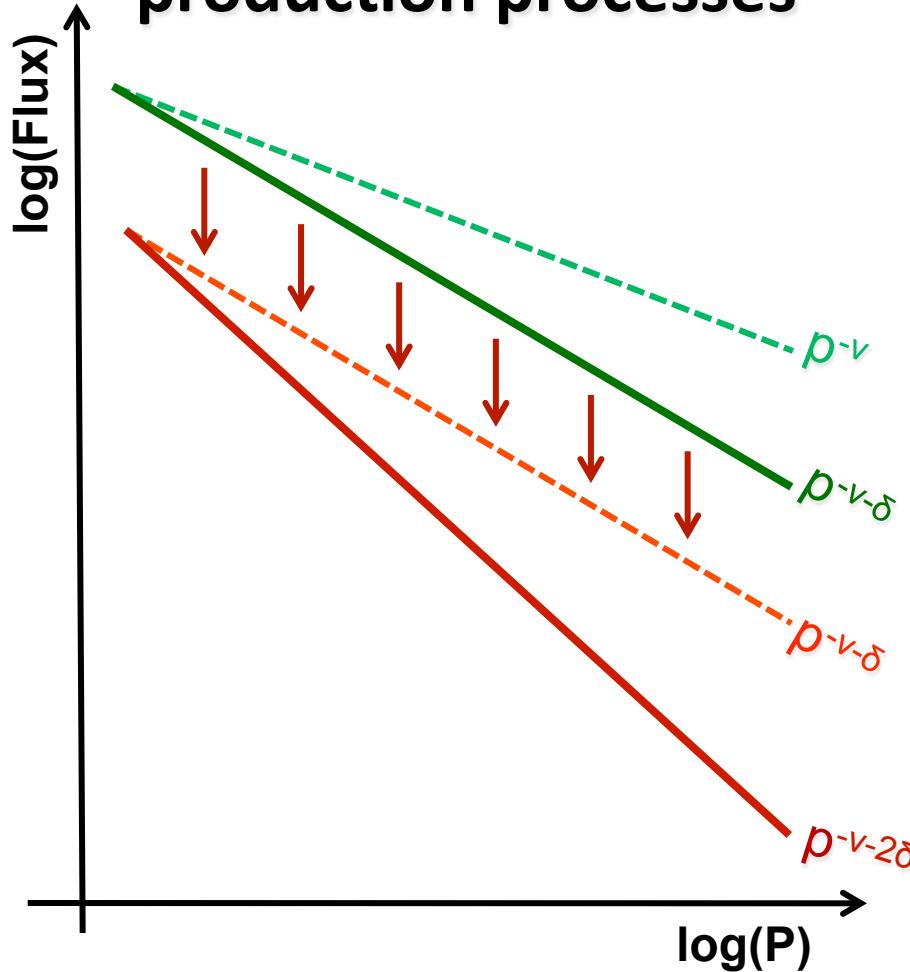
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What makes the B/C ratio

**Pri + ISM \rightarrow Sec + X
production processes**



Shock accelerated primaries: $n(p) \sim p^{-\nu}$

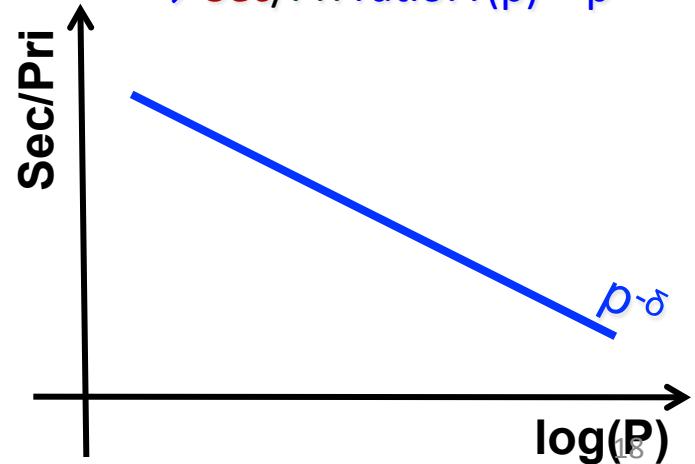
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Secondaries from spallation
at equilibrium: $n(p) \sim p^{-\nu-2\delta}$

\rightarrow Sec/Pri ratio: $r(p) \sim p^{-\delta}$

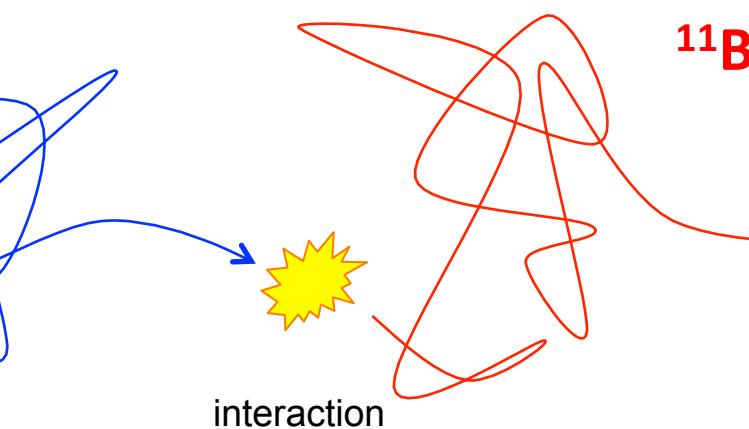


The physical picture

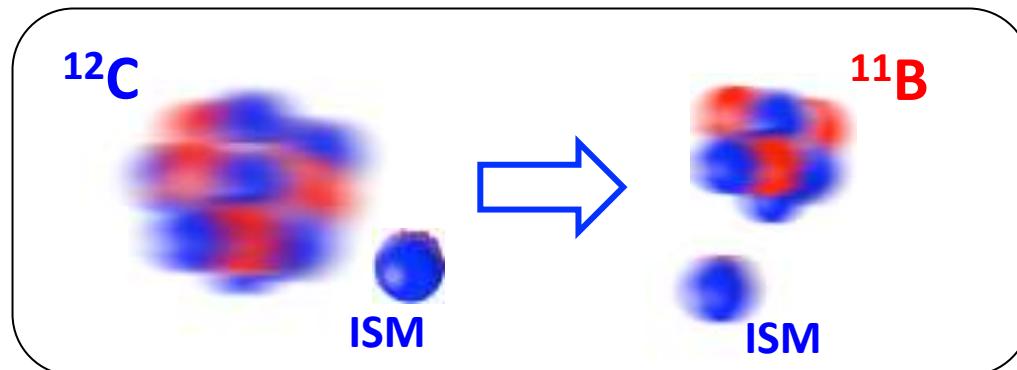
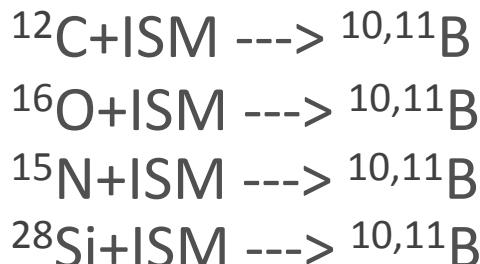
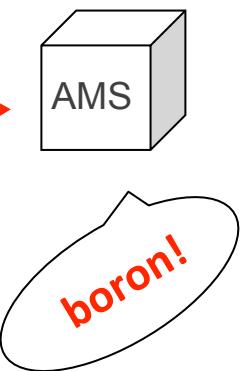
SNR shock acceleration



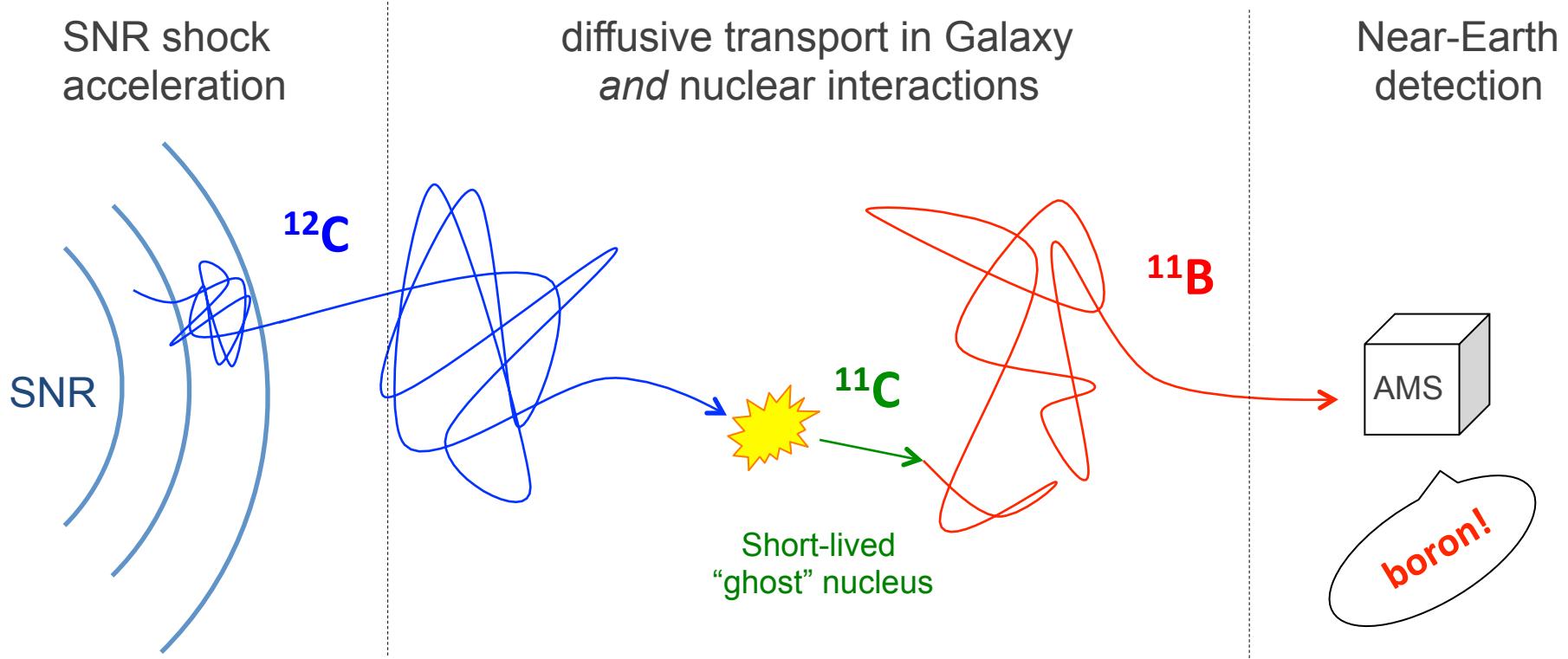
diffusive transport in Galaxy
and nuclear interactions



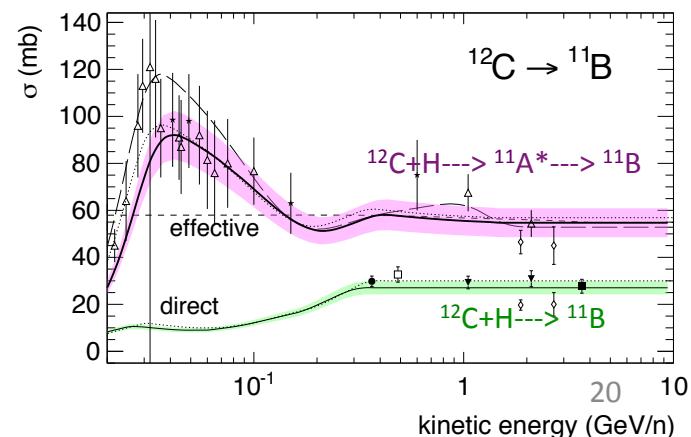
Near-Earth detection



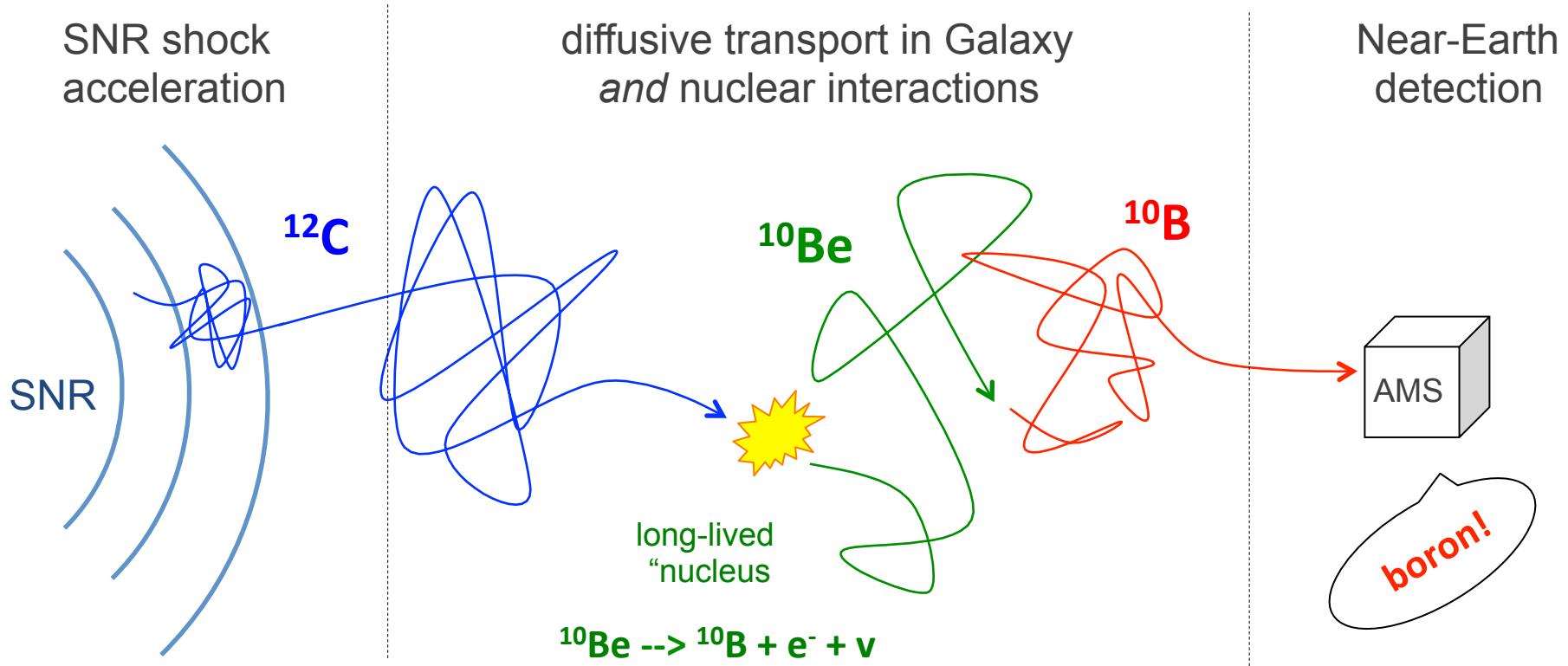
The physical picture



- Act as virtual particles for CR propagation
- Effective (cumulative) cross-sections used



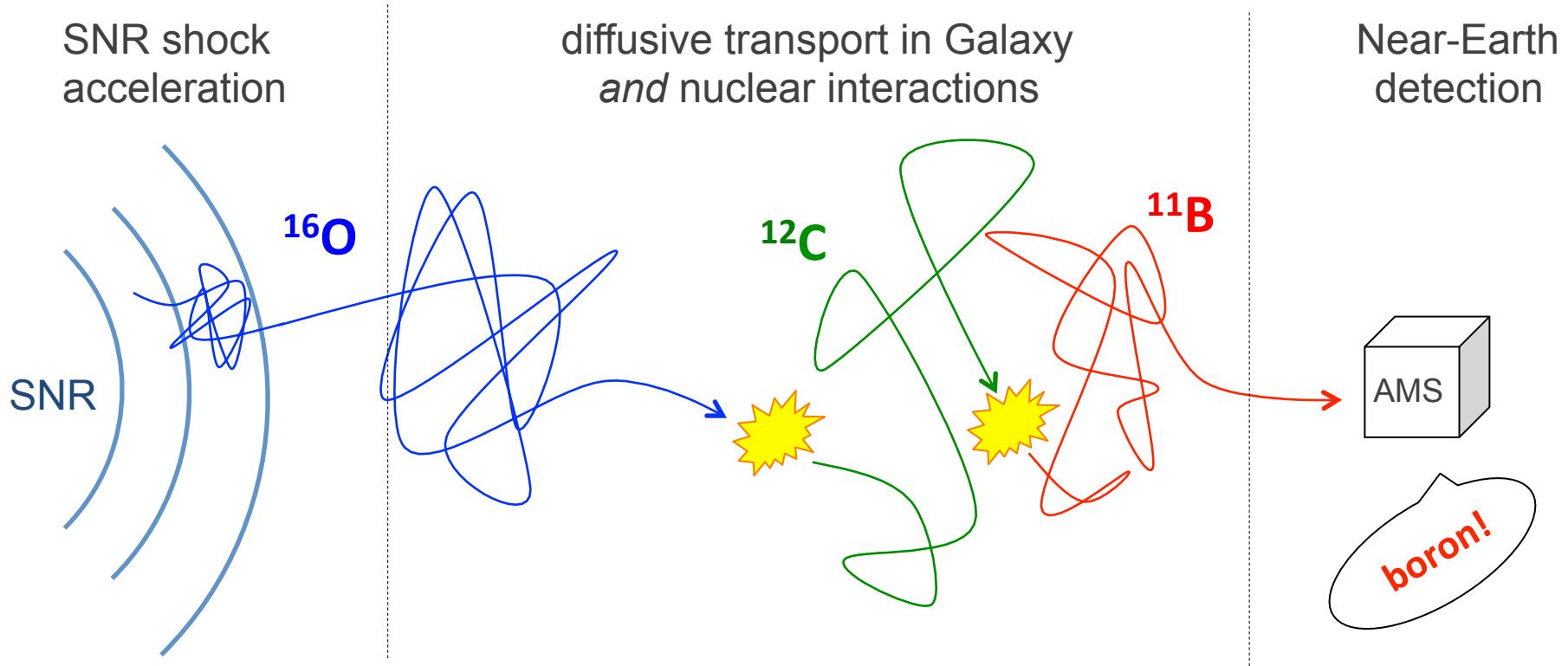
The physical picture



- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Radioactive
with $T \sim 1.5 \text{ Myr}$

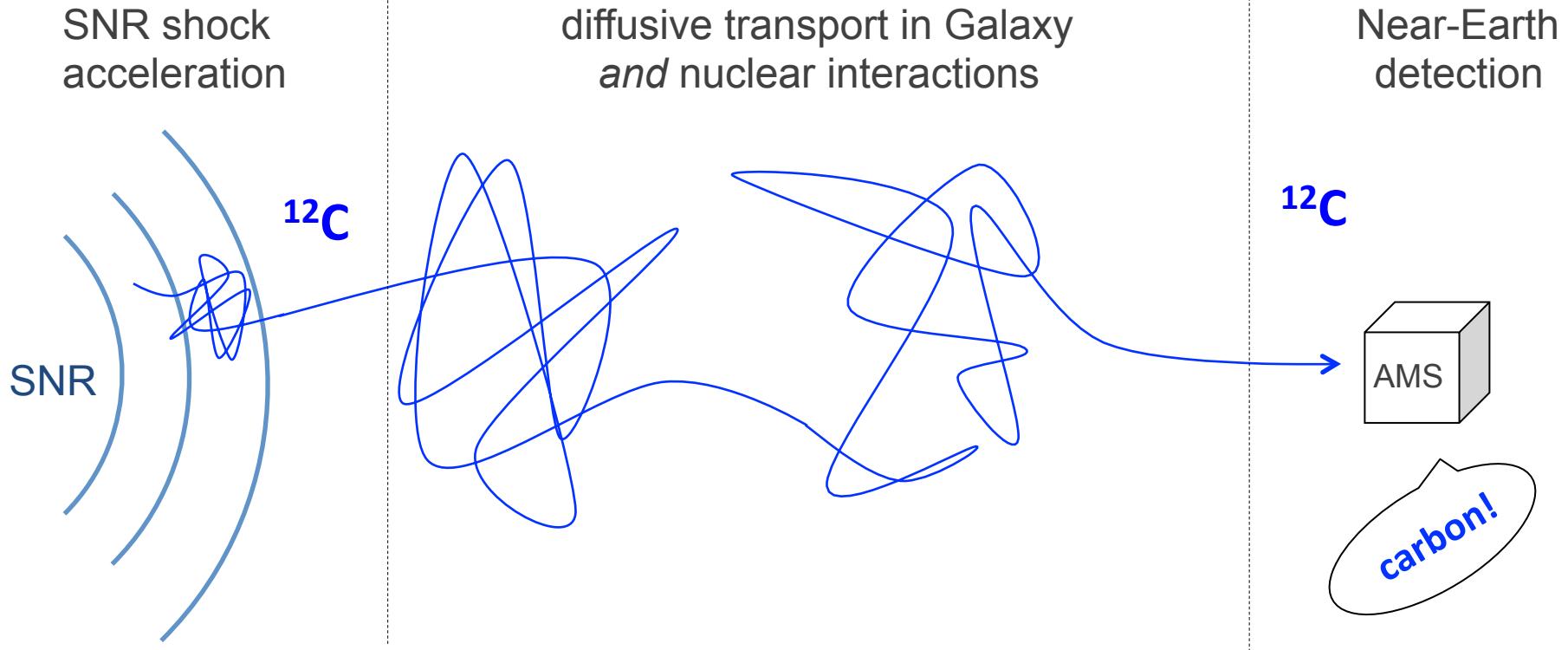
The physical picture



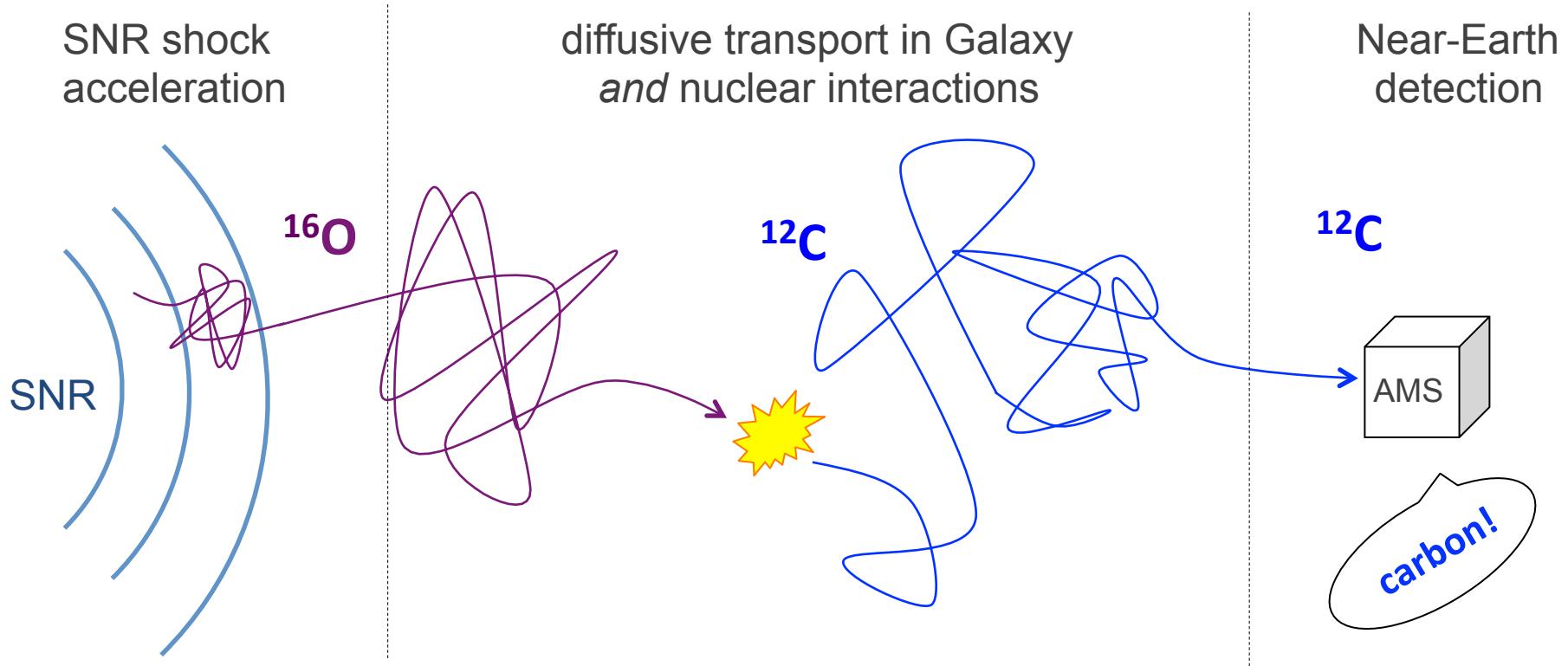
- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Stable, interacting
again with the gas

The physical picture



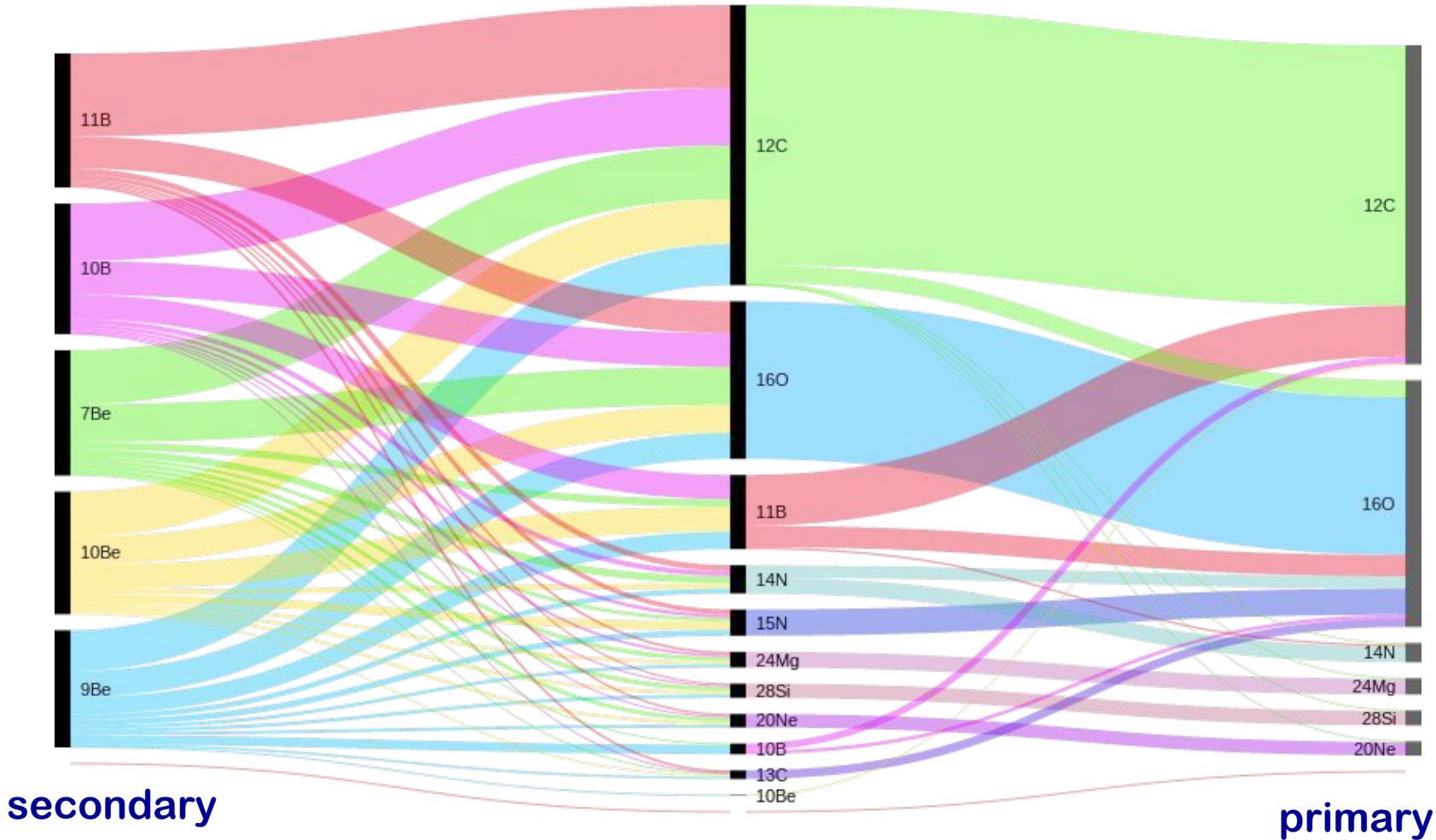
The physical picture



- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Multi-step cosmic ray fragmentation

alluvial diagram of fragmentation reactions



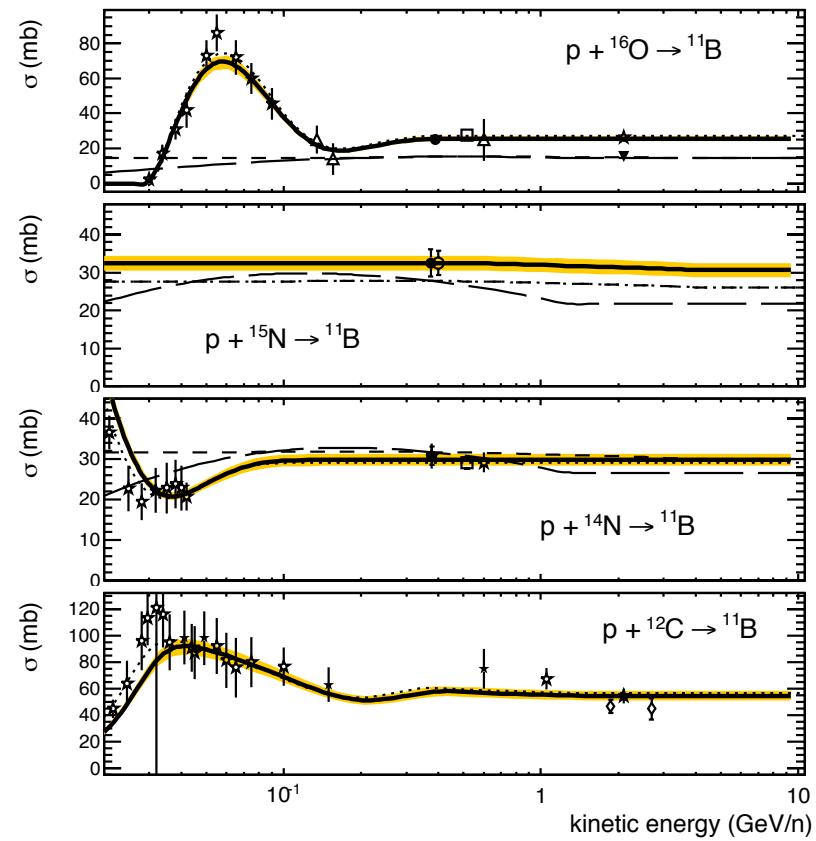
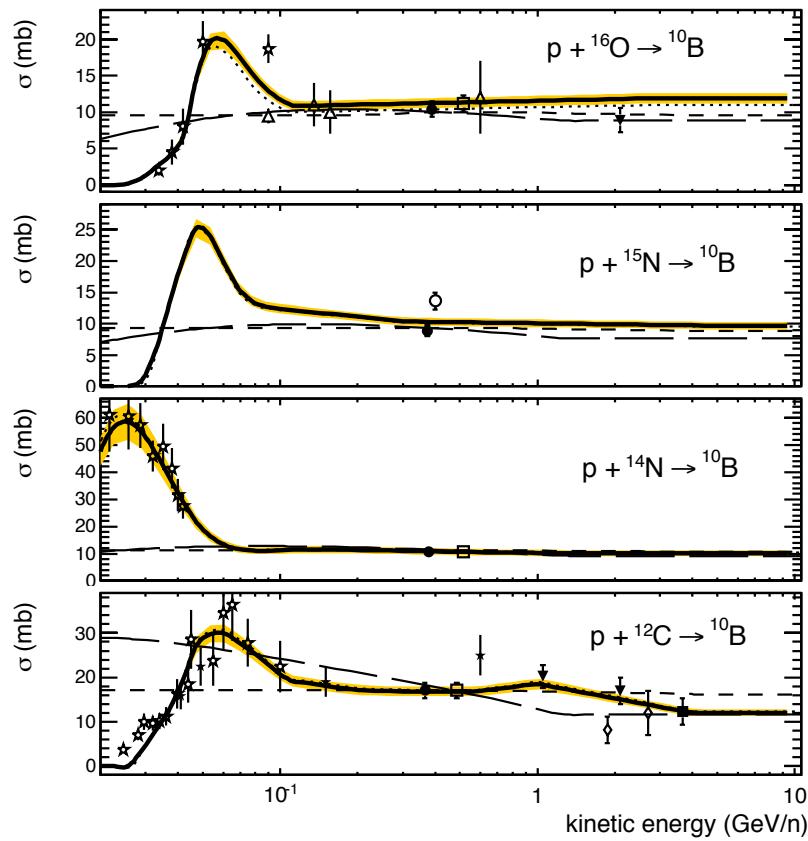
From NT 1707.06917

Uncertainties in CR transport in Galaxy

Refit normalization and energy scale

$$\sigma_{CNO \rightarrow B}^H(E) = a \cdot \sigma_{CNO \rightarrow B}^G(b \cdot E)$$

From NT 1509.05776



- | | | | |
|----------------------|----------------------|----------------------|-----------------|
| ● Webber et al1998 | □ Webber et al 1990 | ★ Fontes et al1977 | GAL/CEM2k |
| △ Read & Viola 1984 | ▼ Olson et al 1983 | * Raisbeck et al1971 | - - - WNEW -98 |
| ■ Korejwo et al 1999 | ◊ Korejwo et al 2001 | ○ Ramaty et al1997 | - - - YIELDX-00 |
| | | ▲ Radin et al1979 | — REFIT |

Uncertainties in CR transport in Galaxy

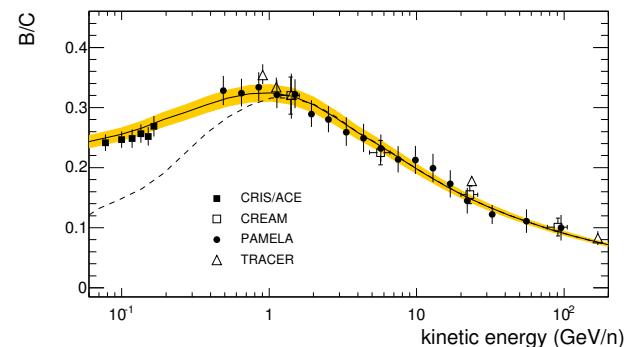
Impact of cross-section uncertainties in CR propagation parameters

Toy simulation for AMS-02 [NT 1509.05776]

B/C + Be/B measurements at 0.5-200 GeV/n

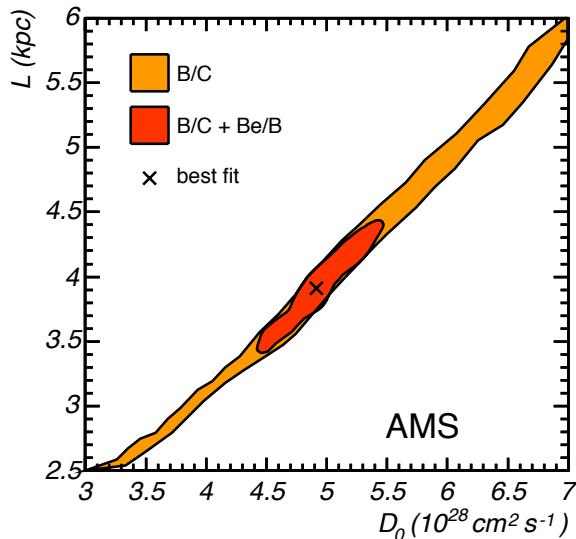
L = half-size of magnetic halo

D = normalization of diffusion coefficient



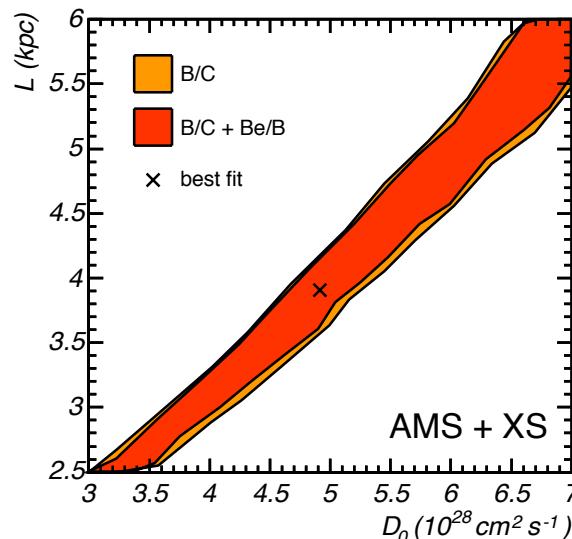
Precise B/C+Be/B data

-> degeneracy resolved!



XS errors accounted

-> degeneracy restored!

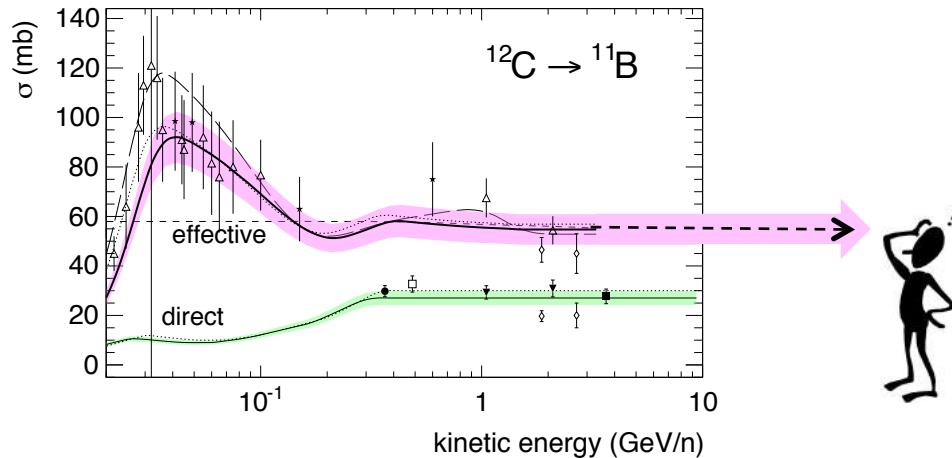


The determination of
key parameters is
plagued by
uncertainties in XS data

Energy-dependent bias?

In semi-empirical formulae, all XS's are assumed energy independent at $E \gg \text{GeV/n}$

Models of CR propagation relies on extrapolations to untested energies



Slope of B/C ratio <----> CR diffusion coefficient

Bias in XS energy-dependence → Bias in CR propagation



- No multi-GeV data to test energy-dependent bias
- No clear way to estimate XS uncertainties at high-energy



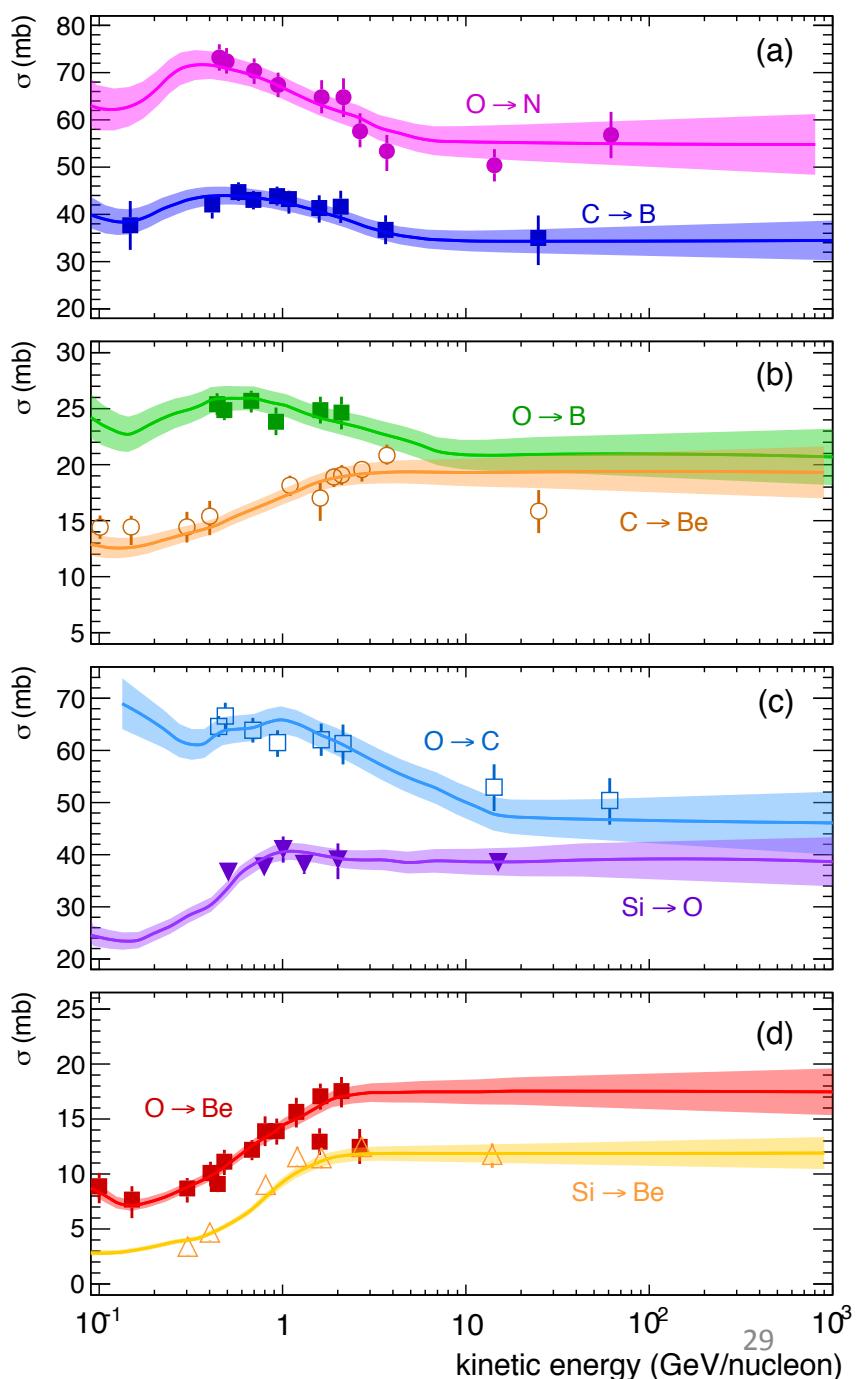
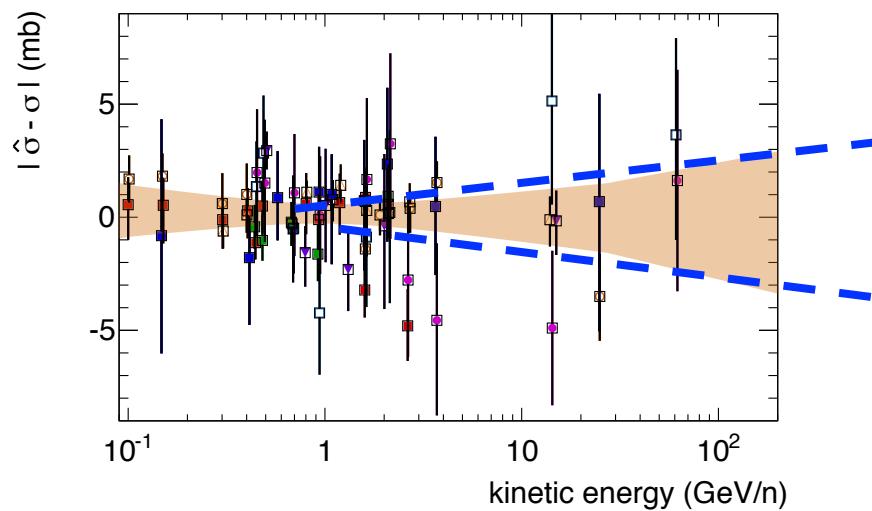
Energy-dependent bias?

A possible approach: [NT 1707.06917]

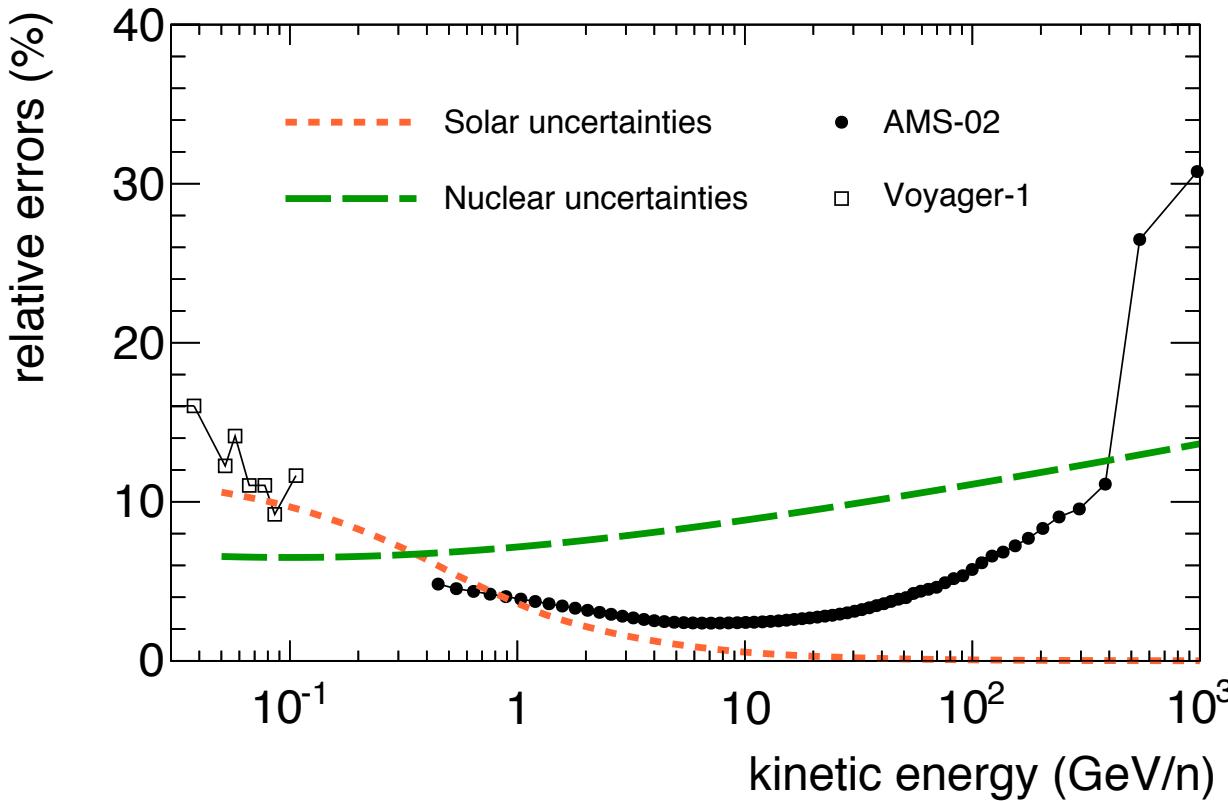
Use *charge-changing* reaction: up ~ 100 GeV

Assume common E-depependent bias

--> XS uncertainty at high-energy

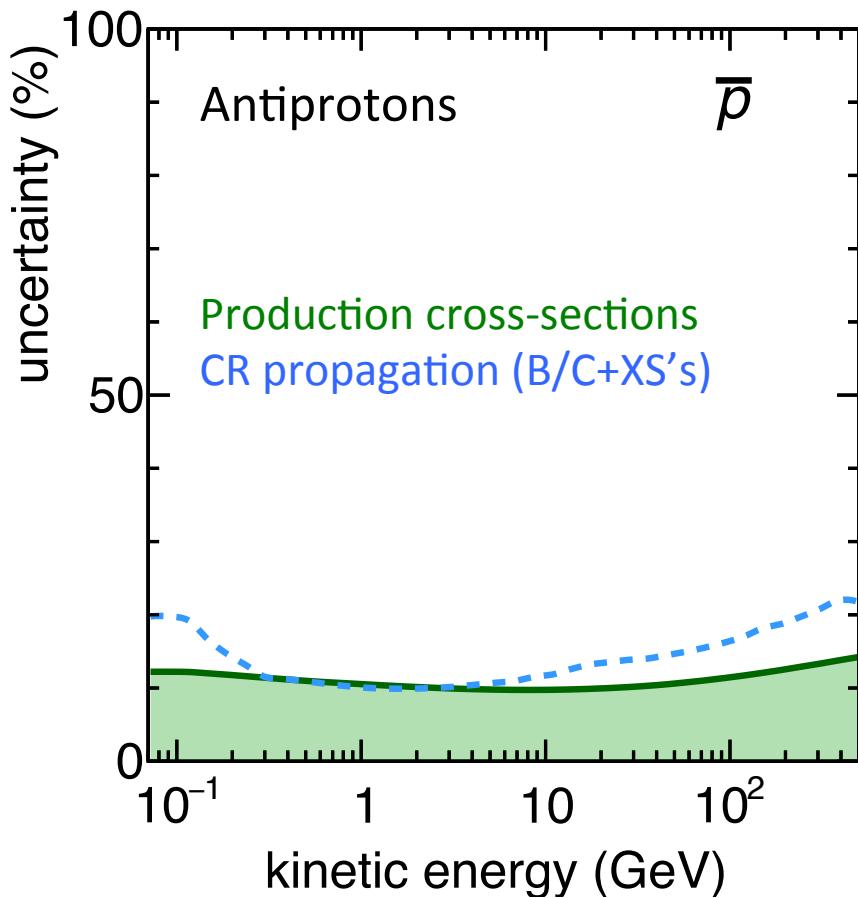


Model uncertainties on B/C ratio



- Experimental errors in the AMS-02 B/C ratio
 - ~ potential level of precision on which CR propagation can be understood
- Estimated uncertainties in boron production cross-sections
 - ~ dominating level of uncertainty at energy 0.5 – 500 GeV/n

Uncertainties on secondary antiprotons



Uncertainties in Cosmi-ray propagation still relevant
once cross-section errors in Boron production are accounted

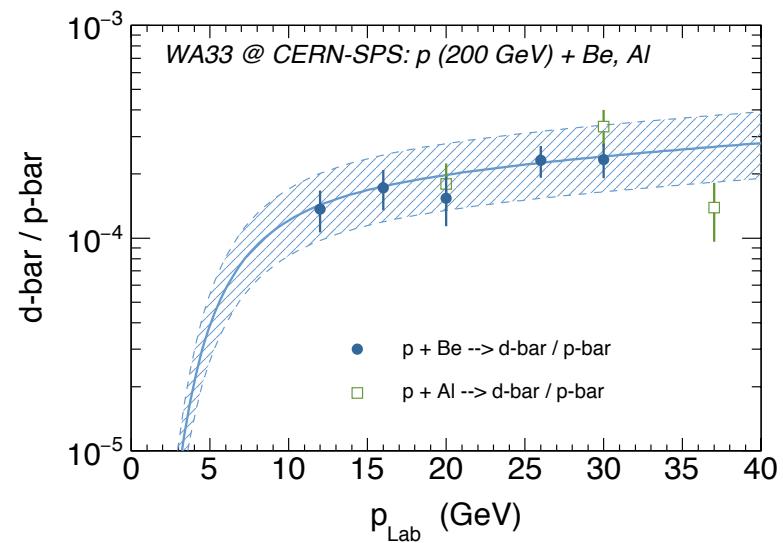
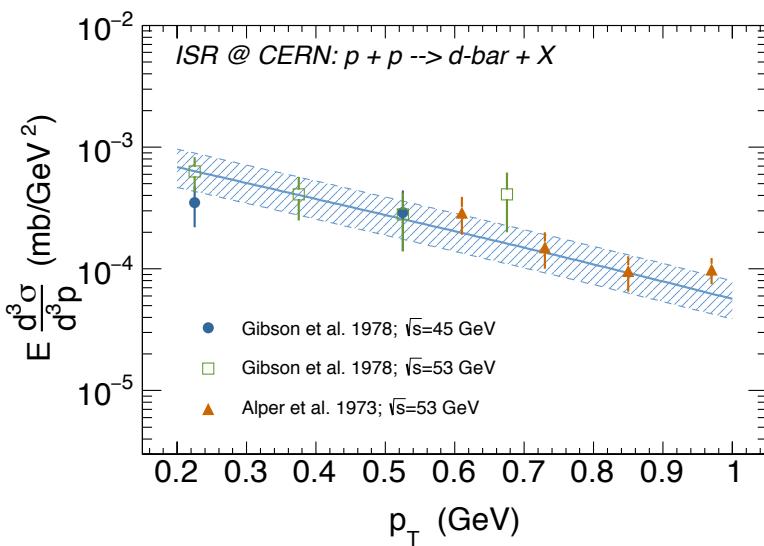
- ✓ Uncertainties from cross-sections -> using comparisons between MC generators and data
- ✓ Uncertainties from CR propagation -> using two-zone propagation model and B/C data

Calculations for anti-nuclei

Antideuterons: Nuclear coalescence

- ✓ Analytical model for pbar & nbar production [based on Di Mauro et al. 2014 PRD]
- ✓ Antineutron enhancement factor [$k \sim 1.3$] from NA49 [JCAP 10, 034 (2015)]
- ✓ Analytical model for nuclear coalescence [based on Chardonnet et al. PLB 409, 3 1997]
- ✓ Antideuteron production p+p data from ISR @ CERN -> constraints coalescence momentum

$$E_{\bar{A}} \frac{d^3 N_{\bar{N}}}{dp_{\bar{A}}^3} = B_{\bar{A}} \times \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^Z \times \left(E_n \frac{d^3 N_n}{dp_n^3} \right)^{A-Z}$$

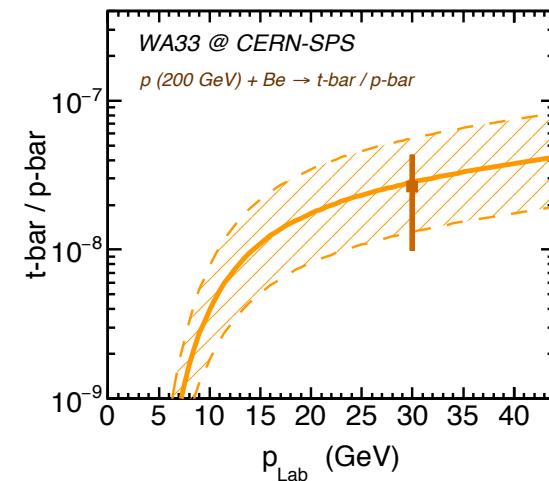
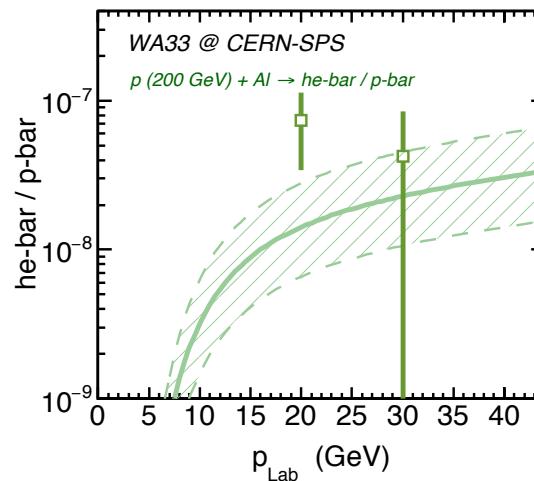
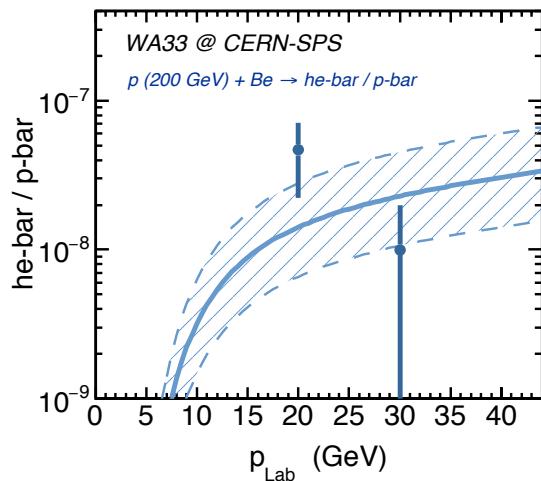
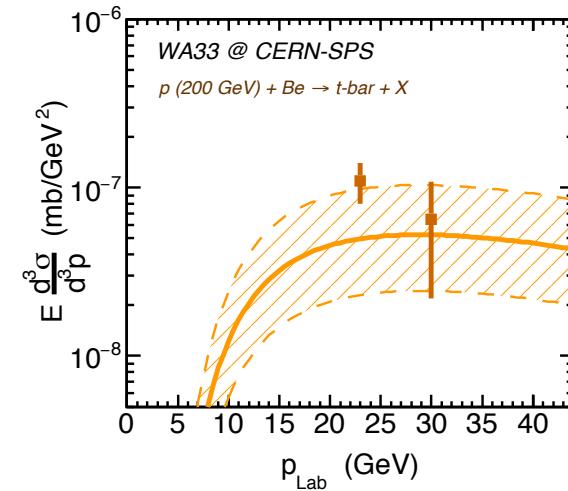
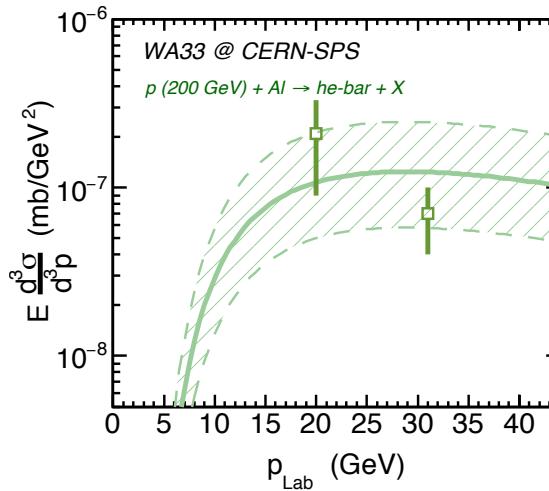
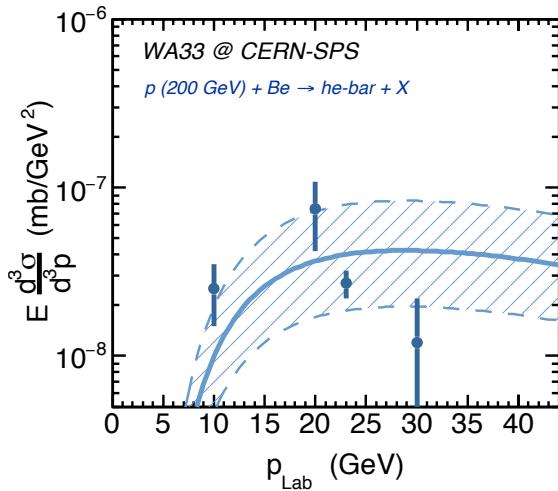


Data on $p+p$, $p+Be$, $p+Al$. Use of XS ratio $p\bar{b}ar/n\bar{b}ar$ to cancel out target factors

Anti-helium & anti-tritium

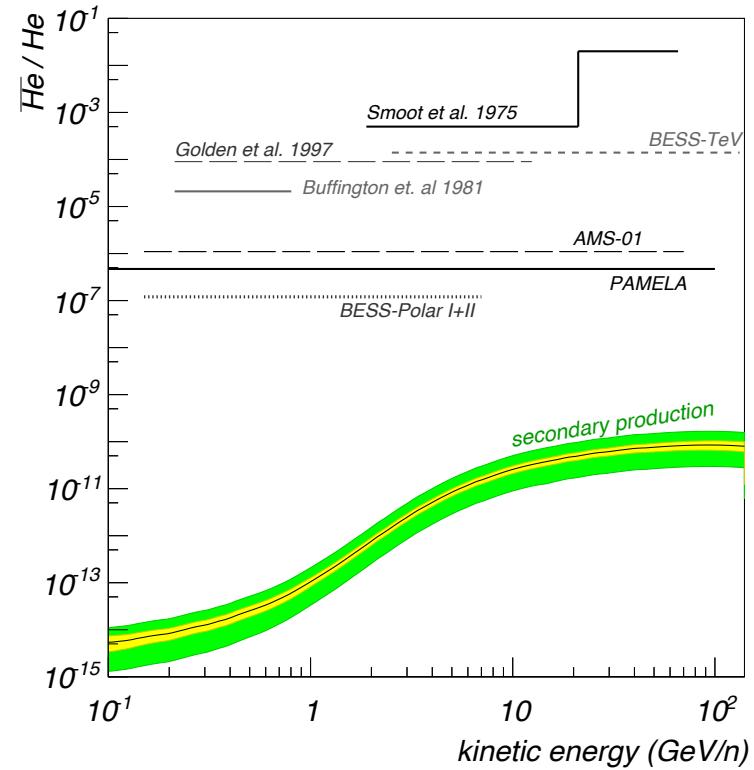
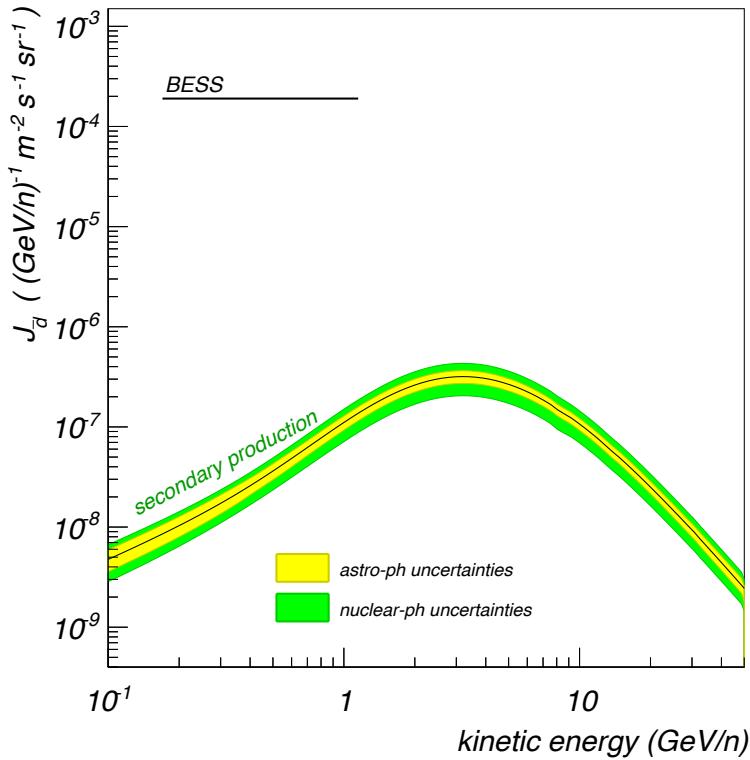
Measurements are very scarce --> poor constraints.

Using the same coalescence momentum of D-bar, we get a reasonable description



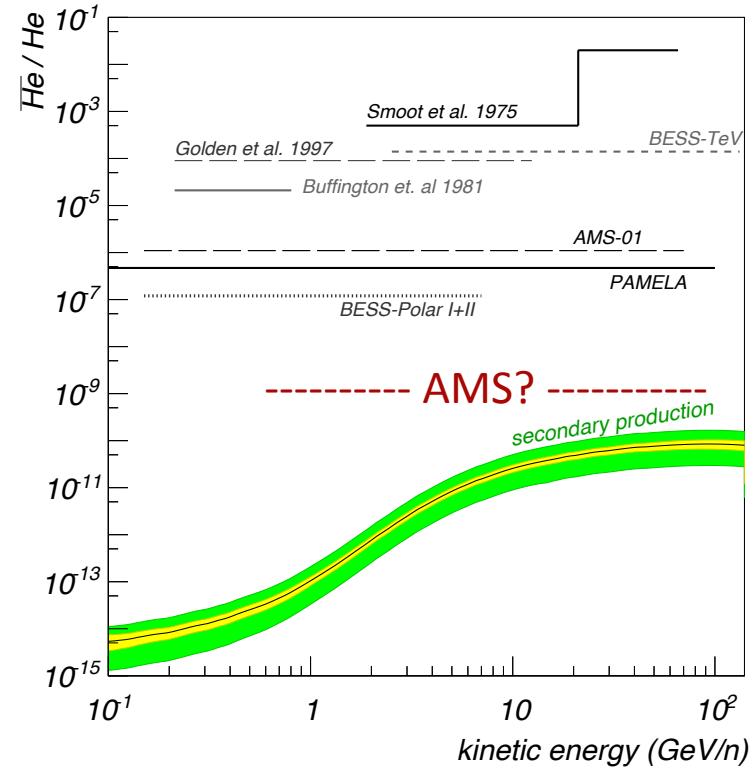
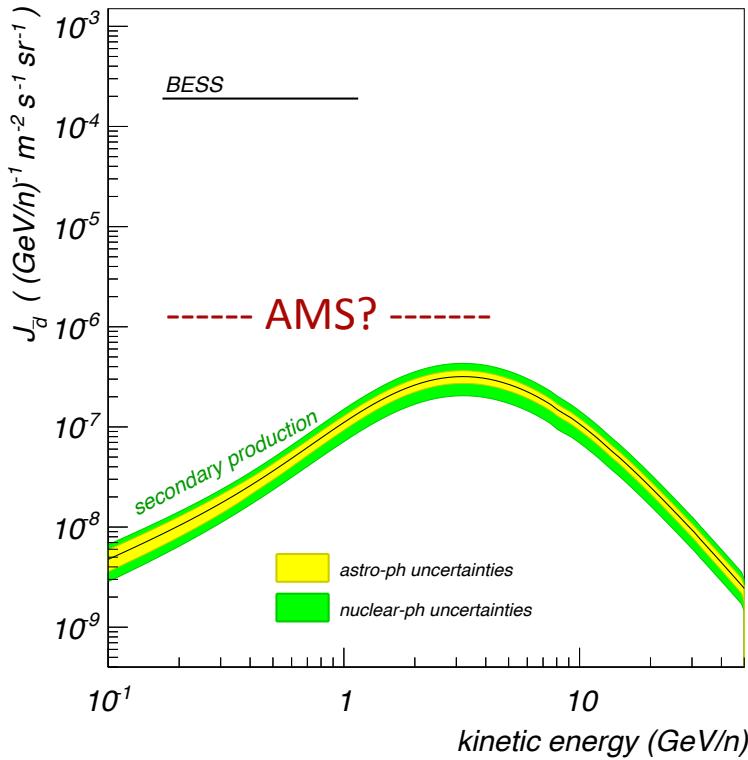
Astrophysical background of anti-nuclei

- ✓ The current experimental sensitivity is far from the background level.
- ✓ Model uncertainties are dominated by the coalescence mechanism.

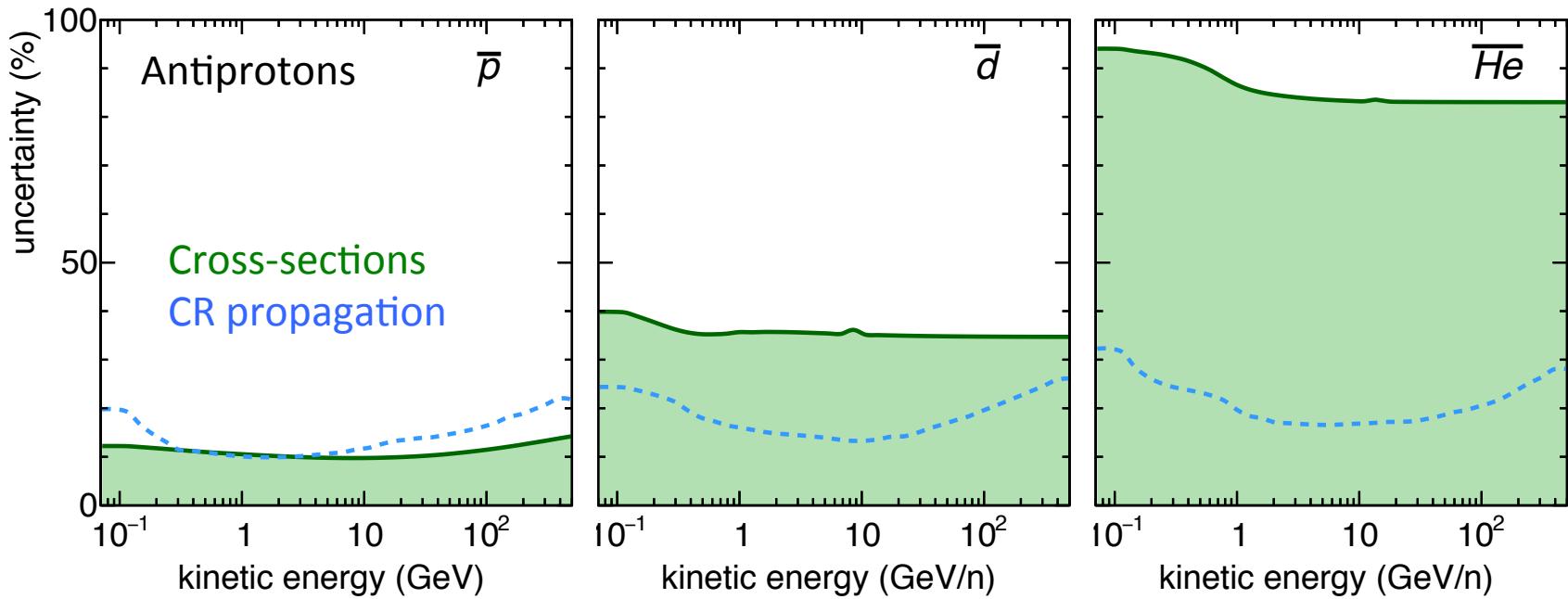


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Propagation VS cross-section uncertainties



Reduce nuclear uncertainties

- Laboratory data on p+p or p+HE collisions
- Improve calculations or MC generators

Reduce CR propagation uncertainties

- ✓ Precision data on B/C ratio up TeV/n
- Improve modeling starting from B/C ratio

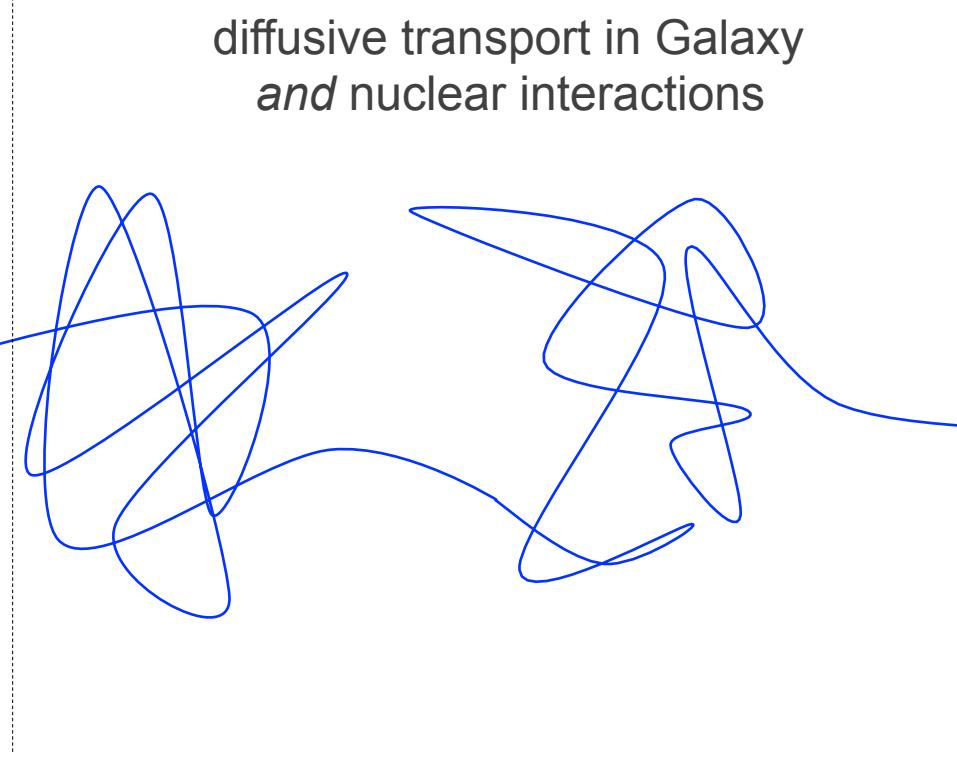
Shock accelerated secondaries

The physical picture

SNR shock
acceleration

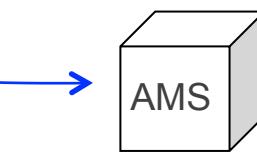


diffusive transport in Galaxy
and nuclear interactions

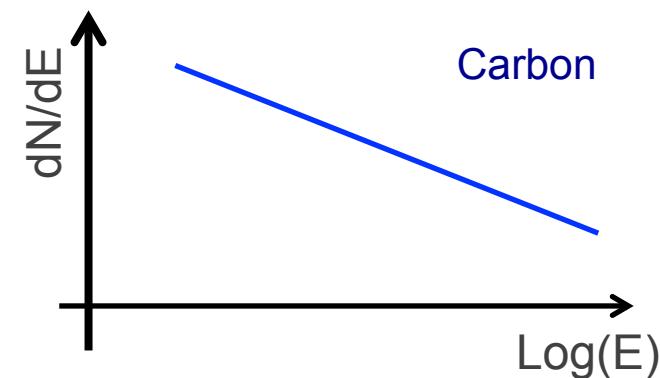


Near-Earth
detection

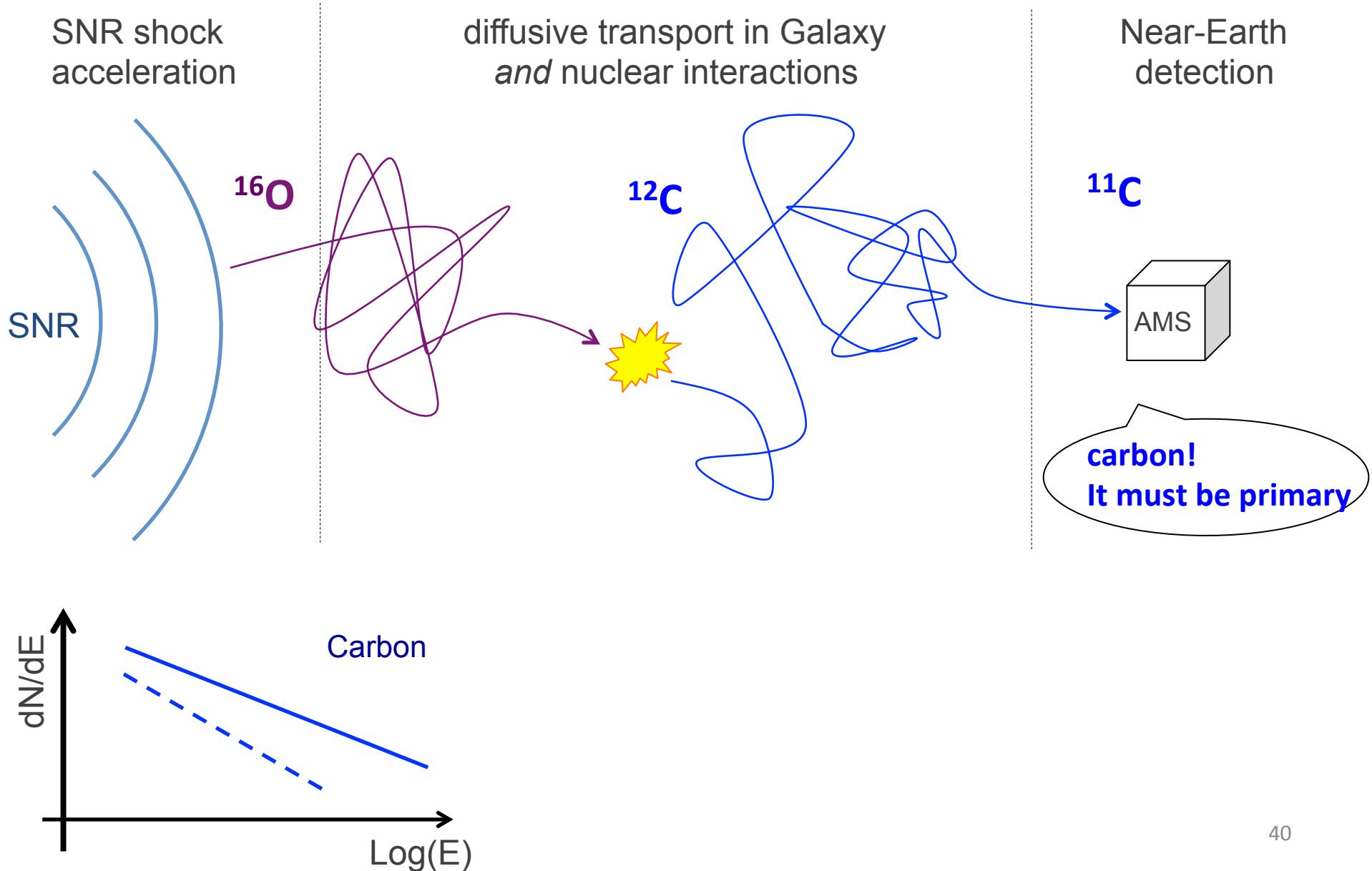
^{12}C



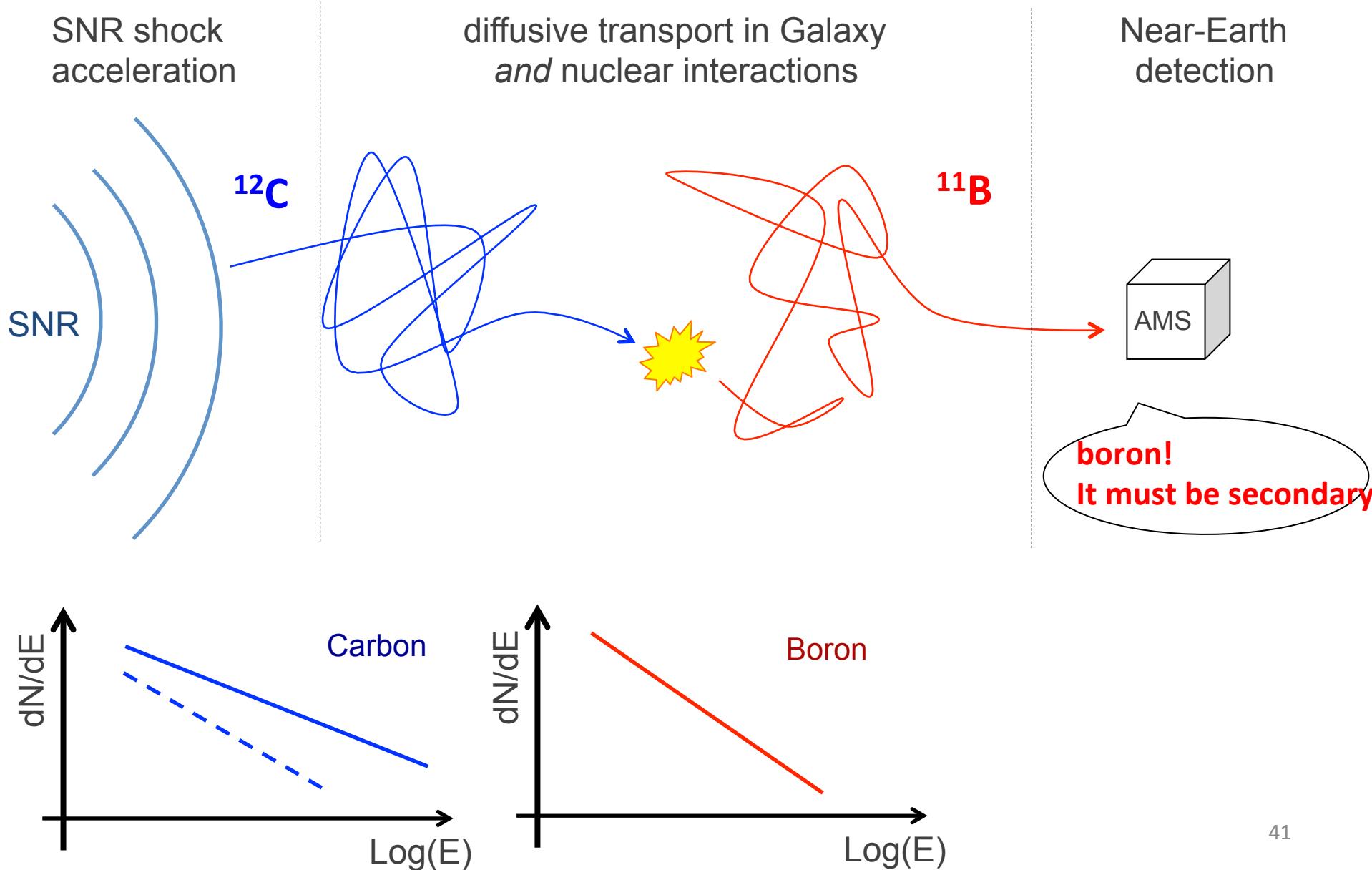
carbon!
It must be primary



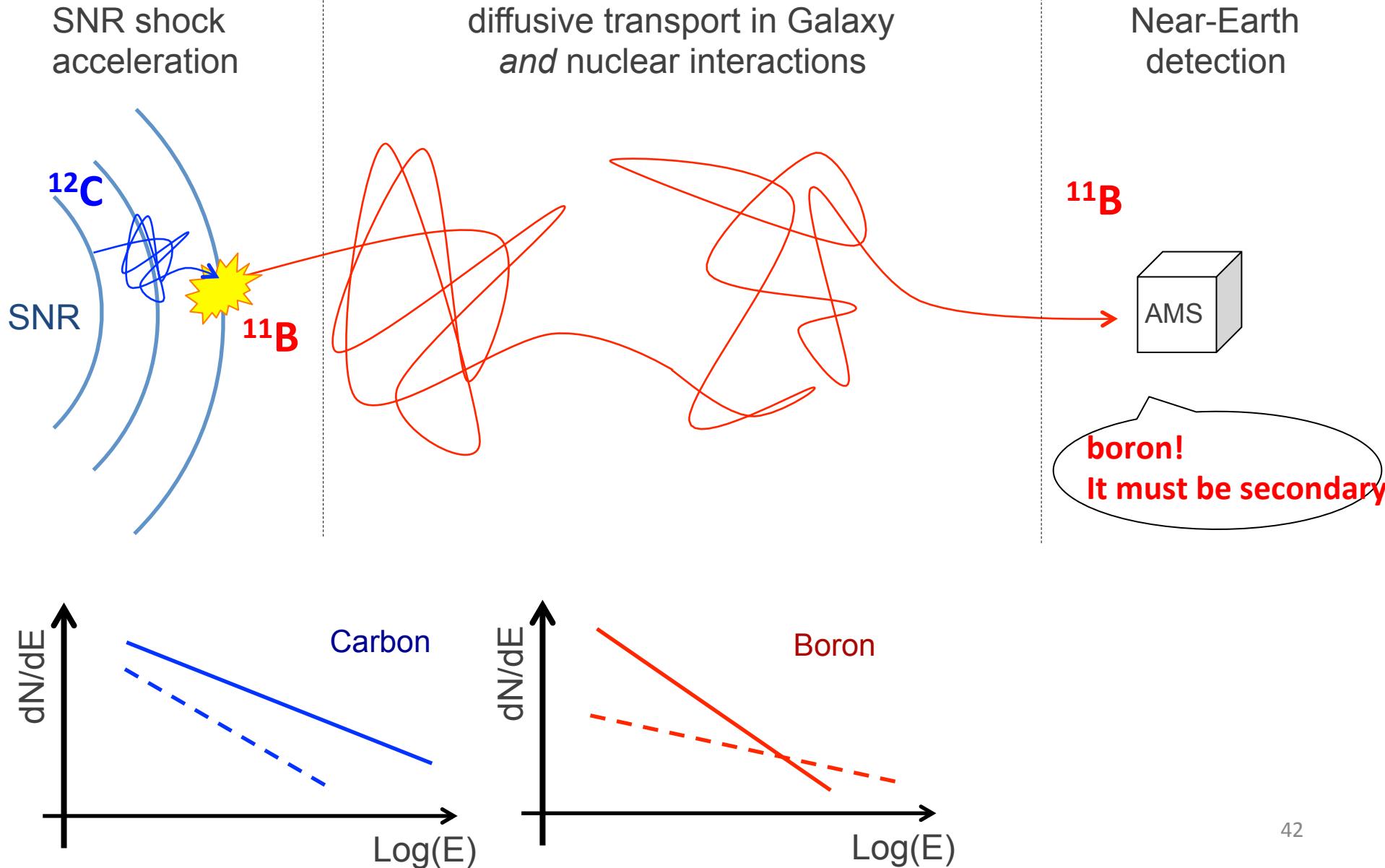
The physical picture



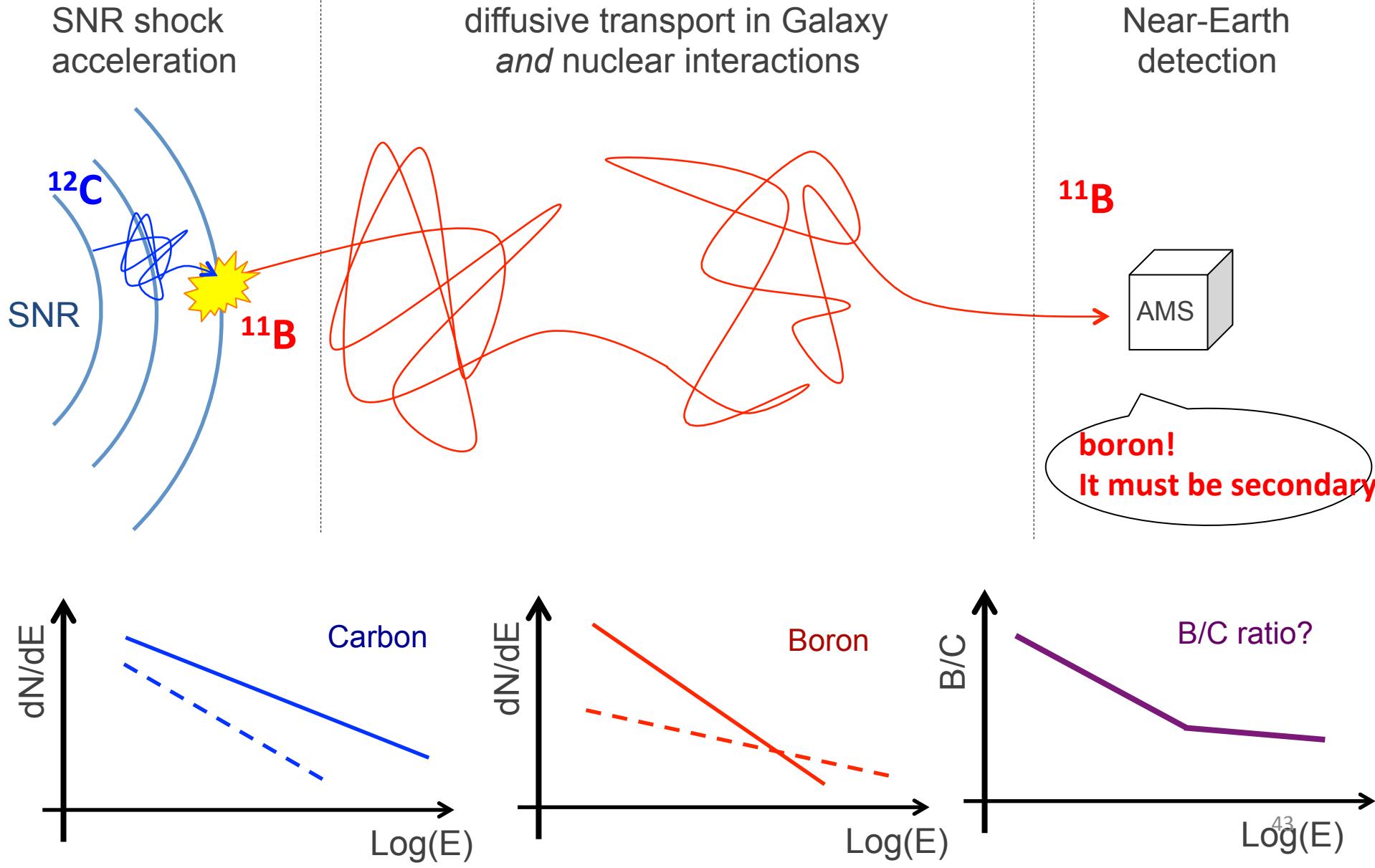
The physical picture



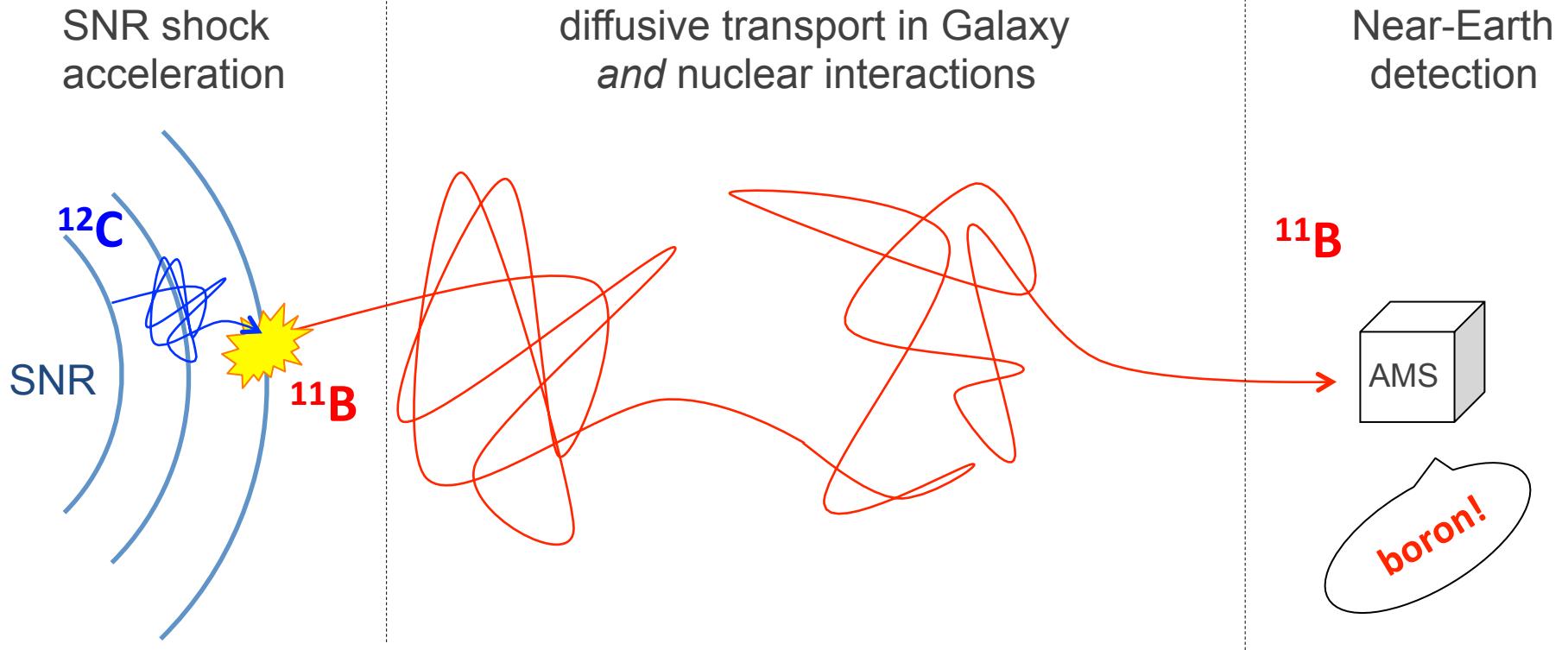
The physical picture



The physical picture



The physical picture

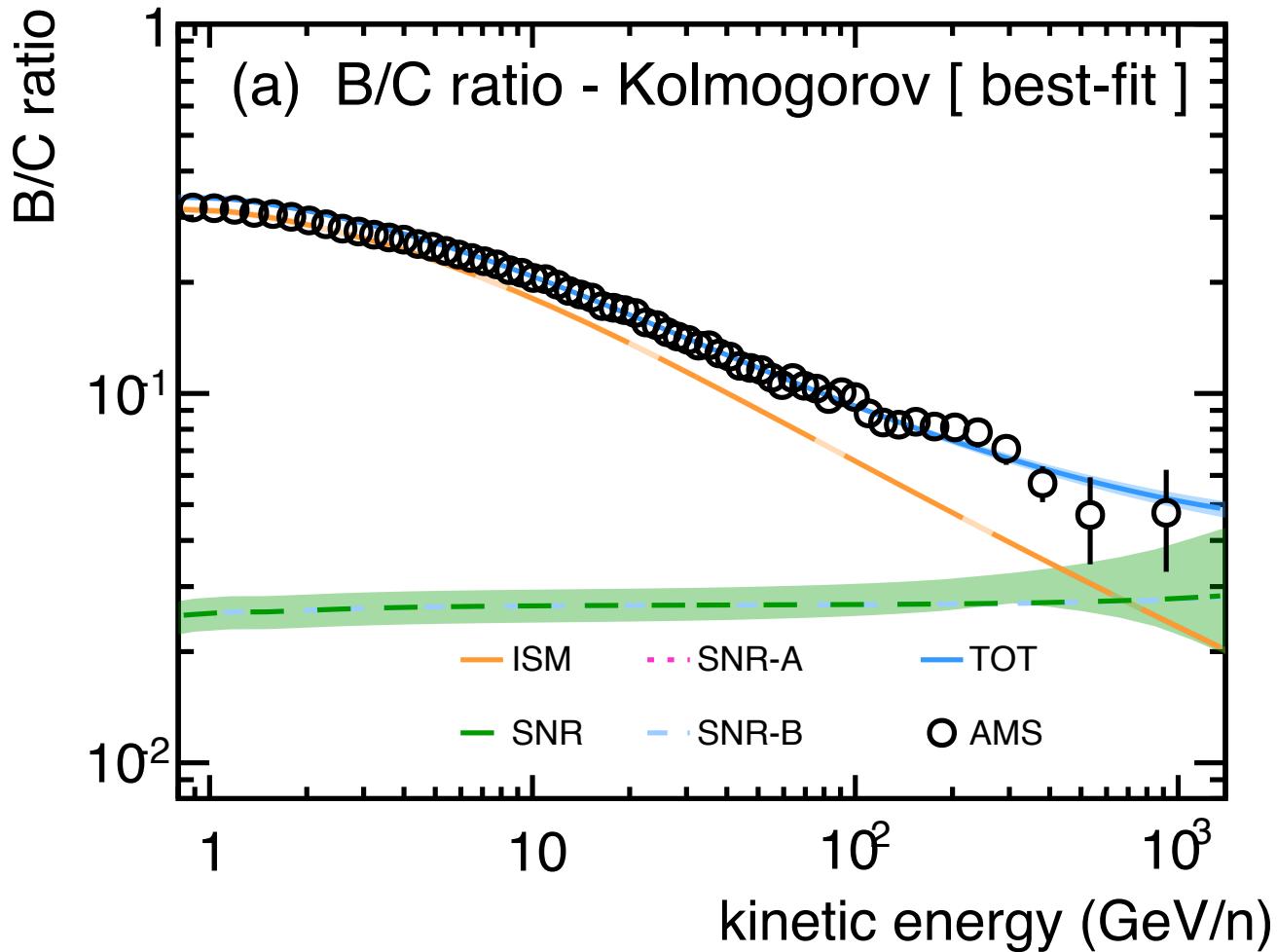


Fermi acceleration at SNR shocks *with interactions*

$$u \frac{\partial f}{\partial x} = D \frac{\partial^2 f}{\partial x^2} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f}{\partial p} - \boxed{\Gamma^{\text{tot}} f + Q}$$

Shock accelerated B/C ratio

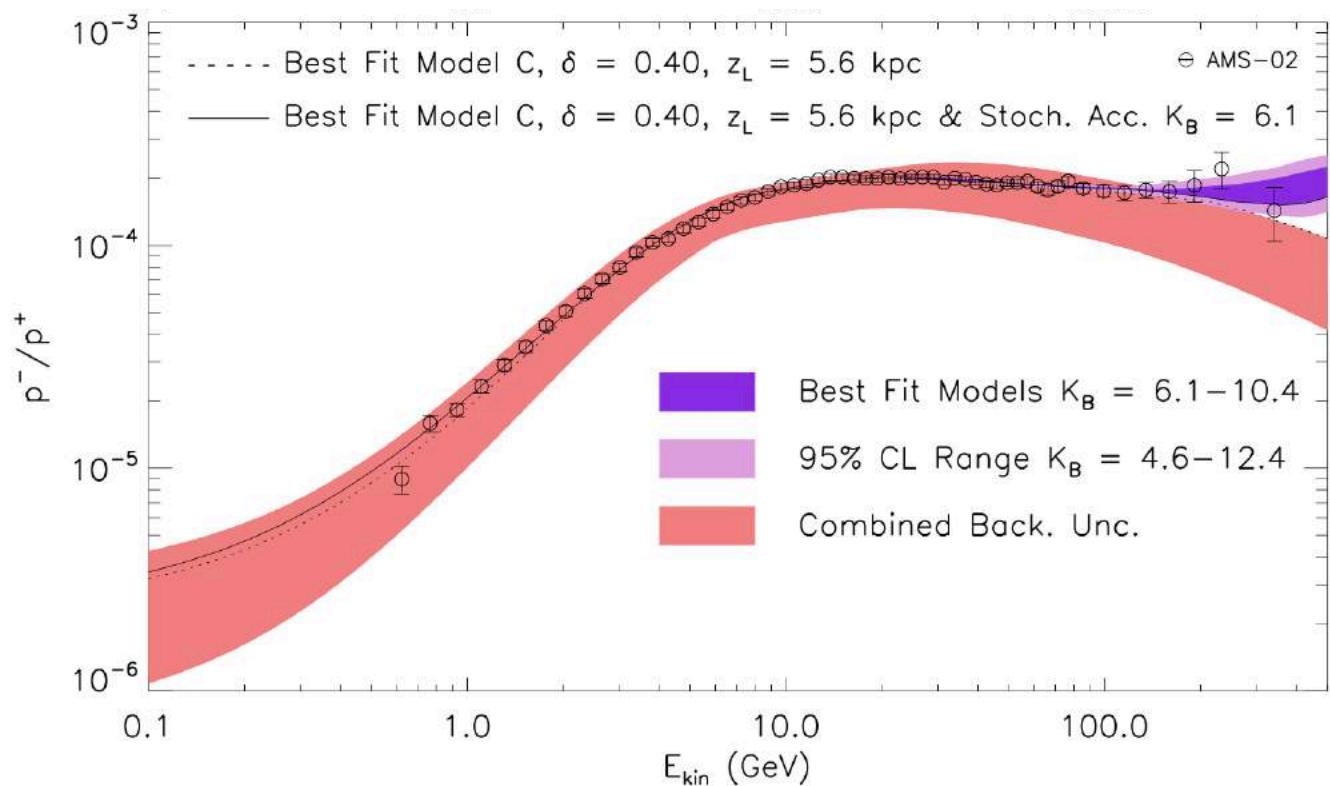
NT & Oliva 1707.06915



- B/C ratio well described
- Evidence for SNR accelerated Boron

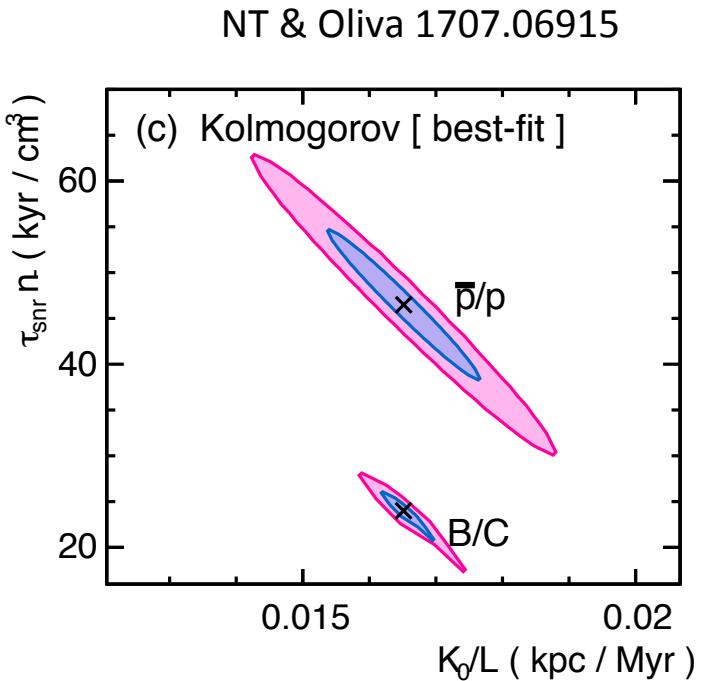
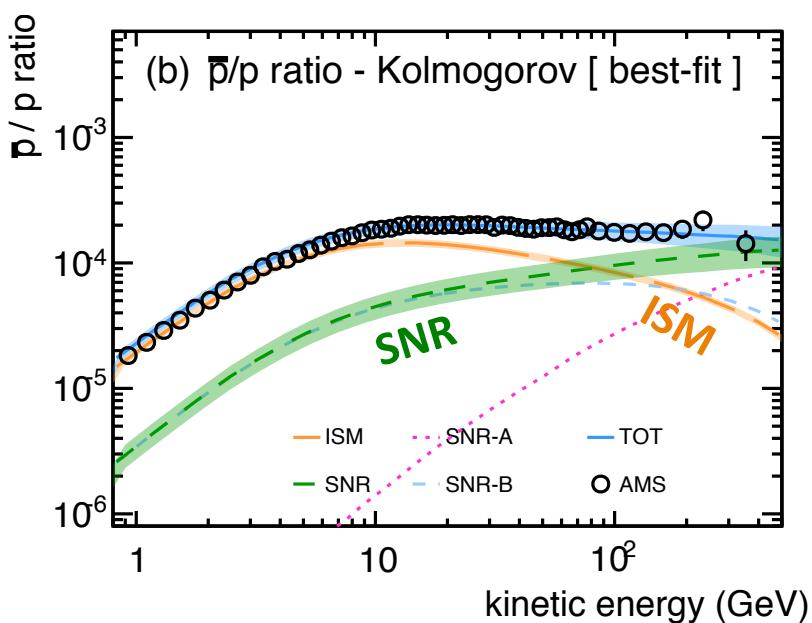
Shock accelerated antiprotons

[Cholis, Hooper, Linden 1701.04406]



Pbar/P “excess” explained by SNR production and acceleration of antiprotons...?

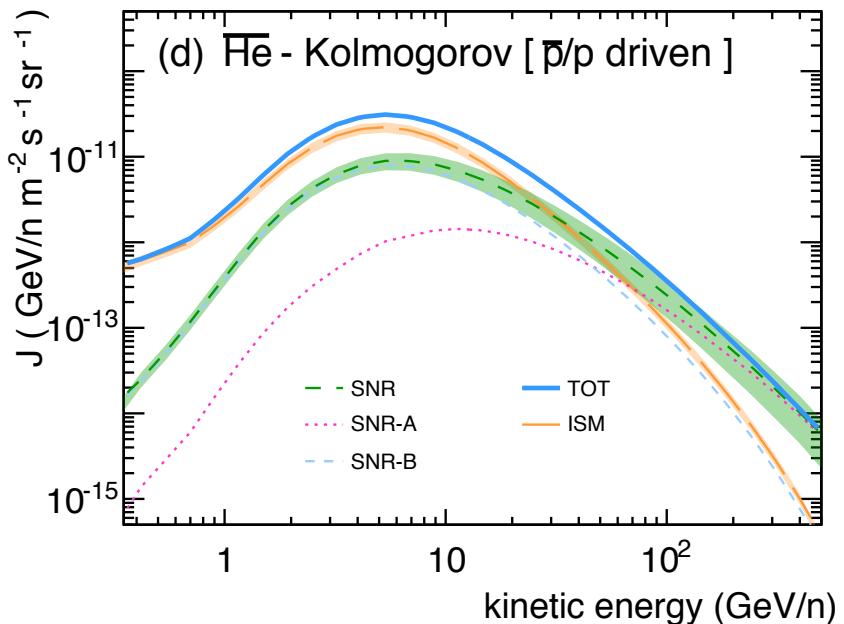
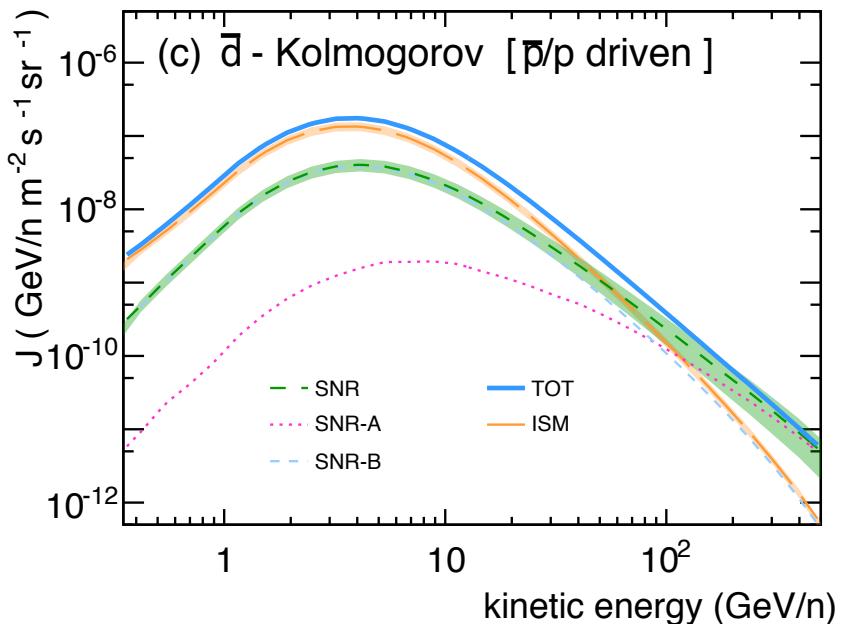
Shock accelerated anti-protons



- ✓ Good fits to antiproton/proton ratio
- Still inconsistent description of both B/C & pbar/p ratios

Shock accelerated anti-nuclei

NT & Oliva 1707.06915



- ✓ Pbar/p- driven model: upper limit to SNR accelerated antinuclei
- ✓ At $E \gg 10$ GeV, flux is dominated by shock accelerated antinuclei
- ✓ The low-energy region is unaffected by SNR production

Conclusions

It is unclear if antiprotons are consistent with astrophysical background

Need to improve models for antiproton/proton ratio in two directions:

- 1) XS data on antiproton production *and* improved parameterizations /MC generators
- 2) Better understanding of CR propagation:

- Advanced analysis based on B/C ratio to exploit the phenomenology
- Beyond standard diffusion models: data hint at new astrophysical processes
- Address model uncertainties: *fragmentation cross-sections for B-production*

Models of CR propagation rely on (extrapolations of)XS data collected in the 90's

From C. X. Chen et al., 1997 ApJ 479, 504-52 [Transport collaboration]

``With the shutdown of the LBL-Bevalac and the pending closure of the Saclay-Saturne accelerators, opportunities for obtaining cross-section measurements relevant to the interpretation of CR data are rapidly dwindling worldwide.

Thus, future experiments will rely heavily upon cross-section predictions, and it is important to update our formulae using data (...) to ensure that the solutions to some astrophysical problems are not dominated by cross-section inaccuracies rather than by CR measurements''.

Thank you

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