Nuclei and antinuclei production in cosmic rays

Cross-sections and uncertainties for cosmic-ray propagation

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Astrophysical antimatter background

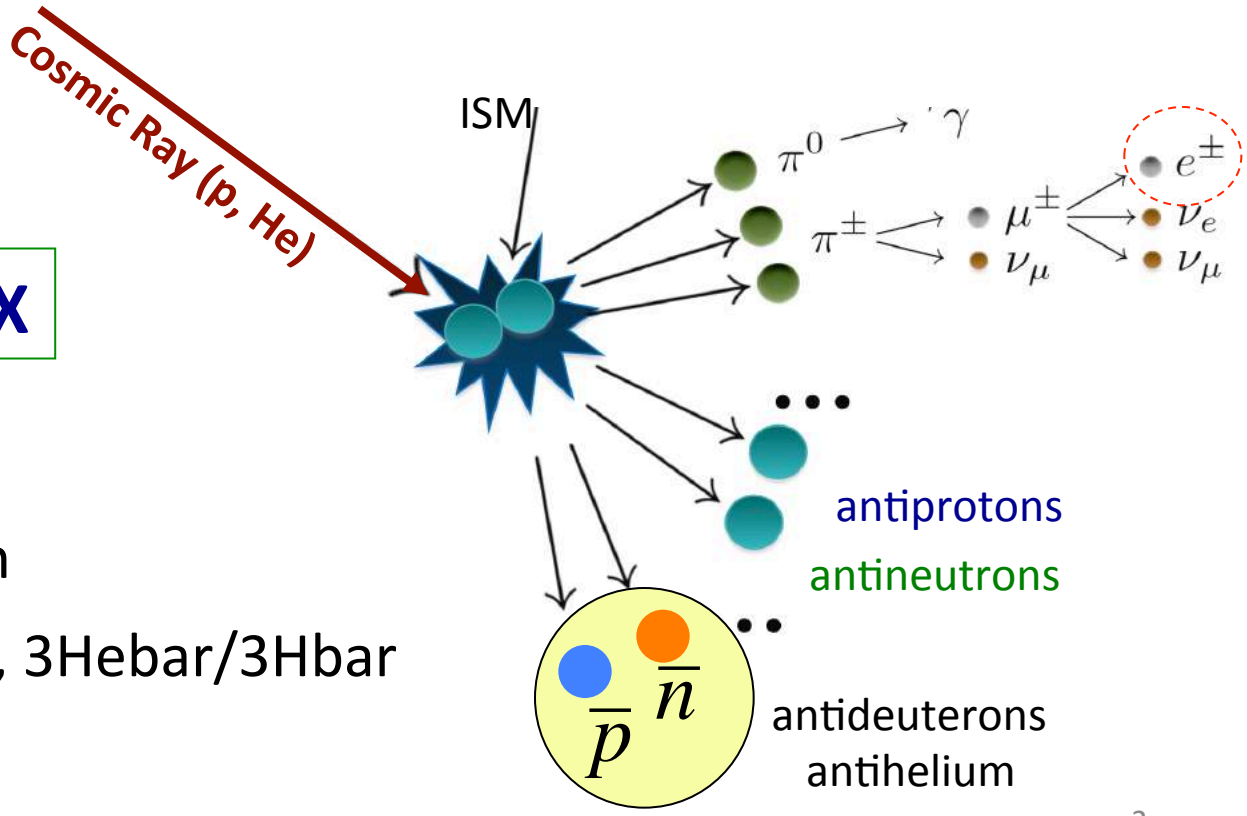
$$Q_{\bar{A}}^{sec}(E) \approx \frac{4\pi}{c} \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} n_{ISM} \frac{d\sigma_{CR+ISM \to \bar{A}}^{ISM}}{dE'}(E, E') J_{CR}(E') dE'$$

CR + ISM → Abar + X

CR = proton, alpha

ISM = hydrogen, helium

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



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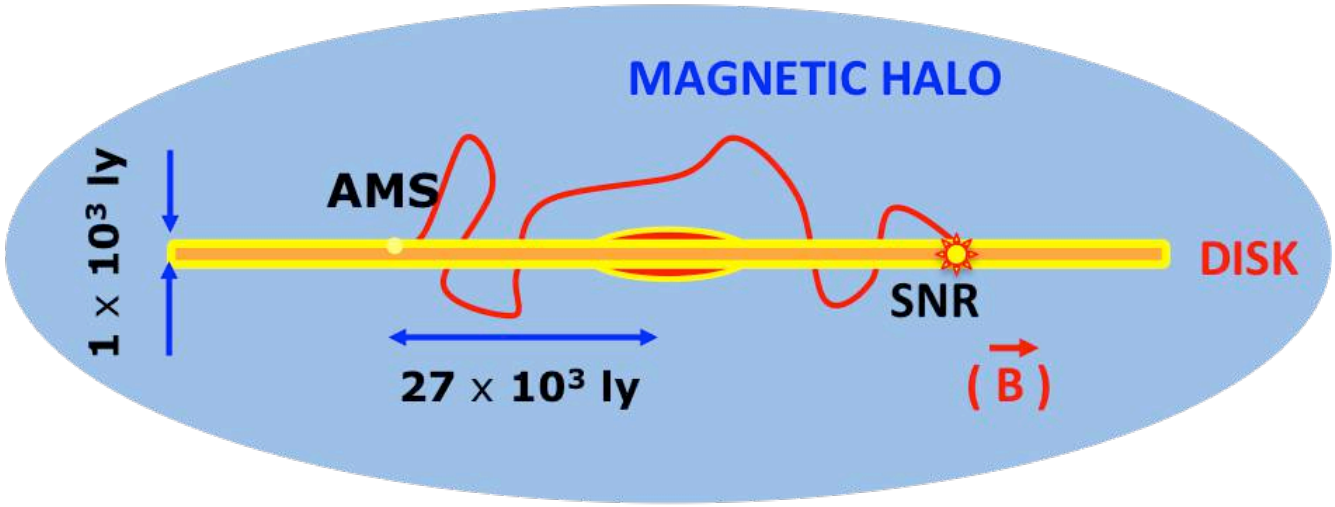
Propagation in the Galaxy:
diffusive transport,
energy loss/gain
nuclear spallation

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

Solar modulation in the Heliosphere:
diffusion, advection, drift

$$J_{\bar{A}}^{TOA}(E)$$ → **Dectection :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.

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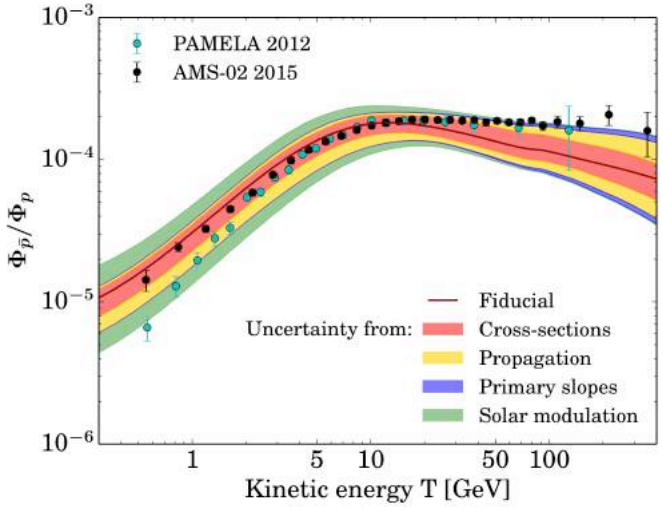
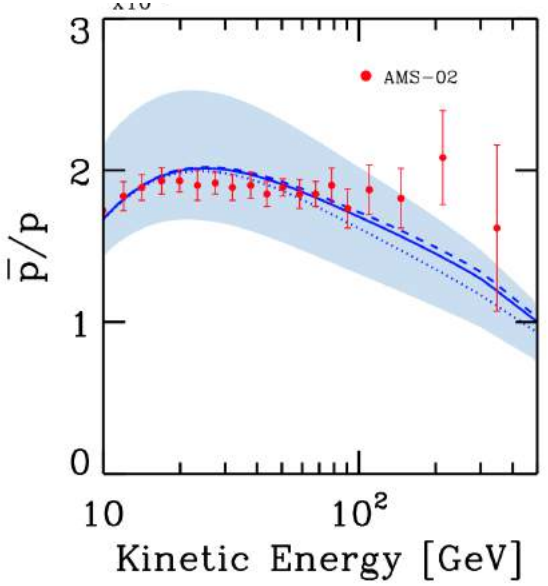
Antiprotons: any excess in the AMS data?

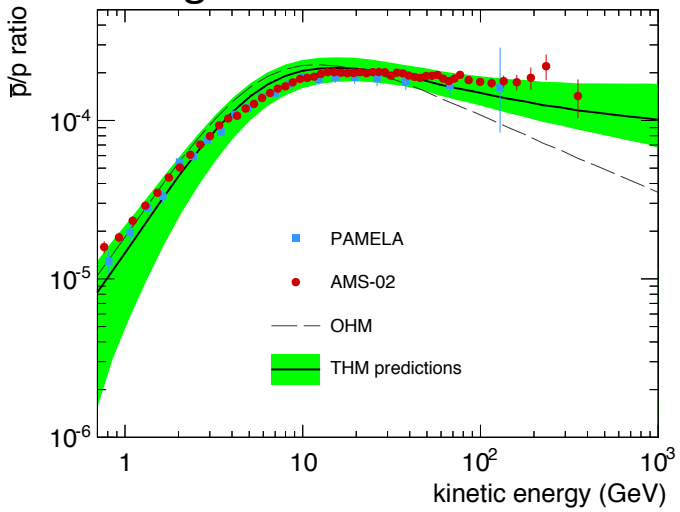
Giesen et al. 1504.04276



Evoli et al. 1504.05175



Feng et al. 1610.06182



- ✓ **No clear excess**
- ✓ **No clear agreement**

Antiprotons: any excess in the AMS data?

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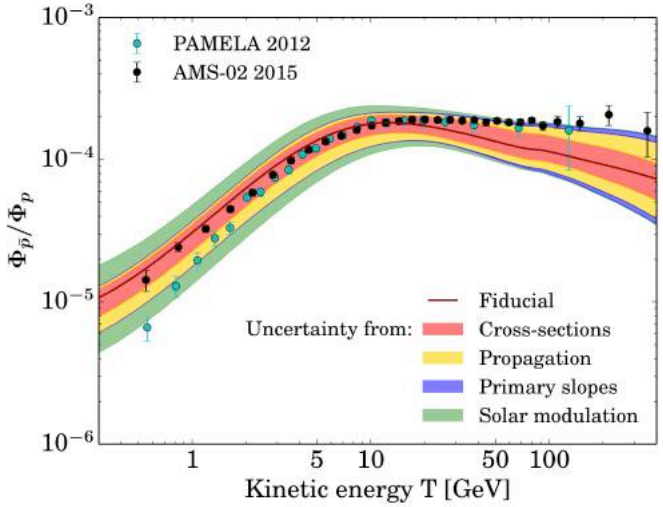

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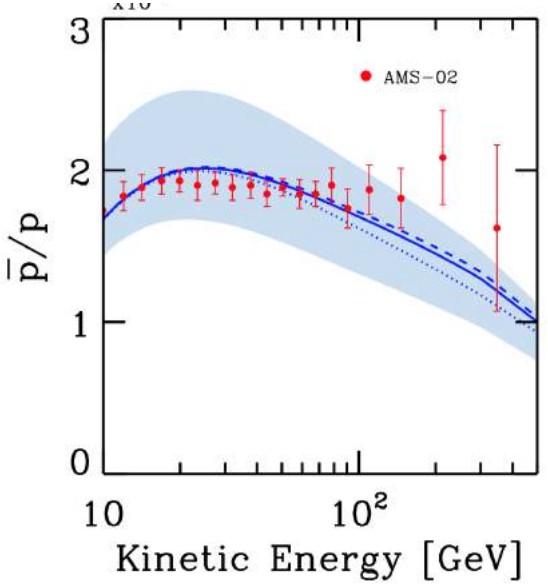

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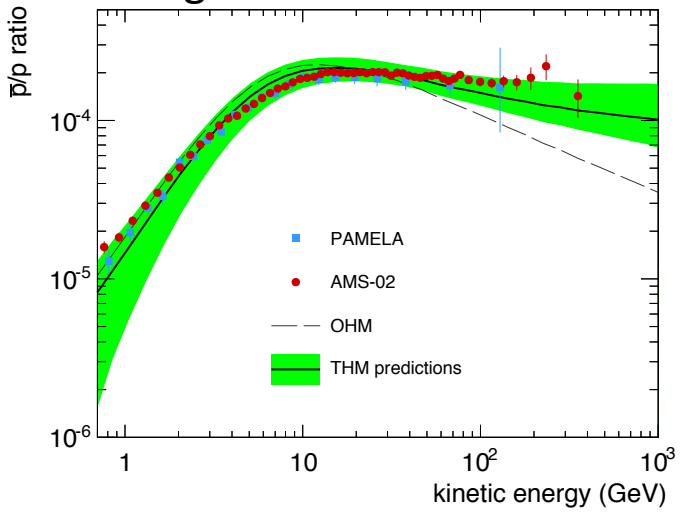
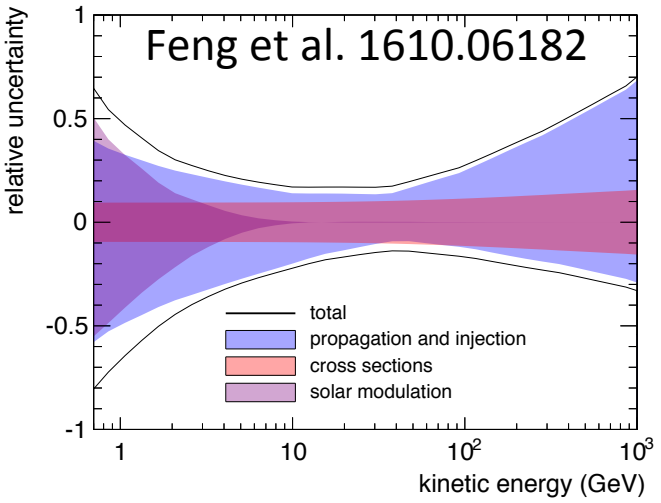
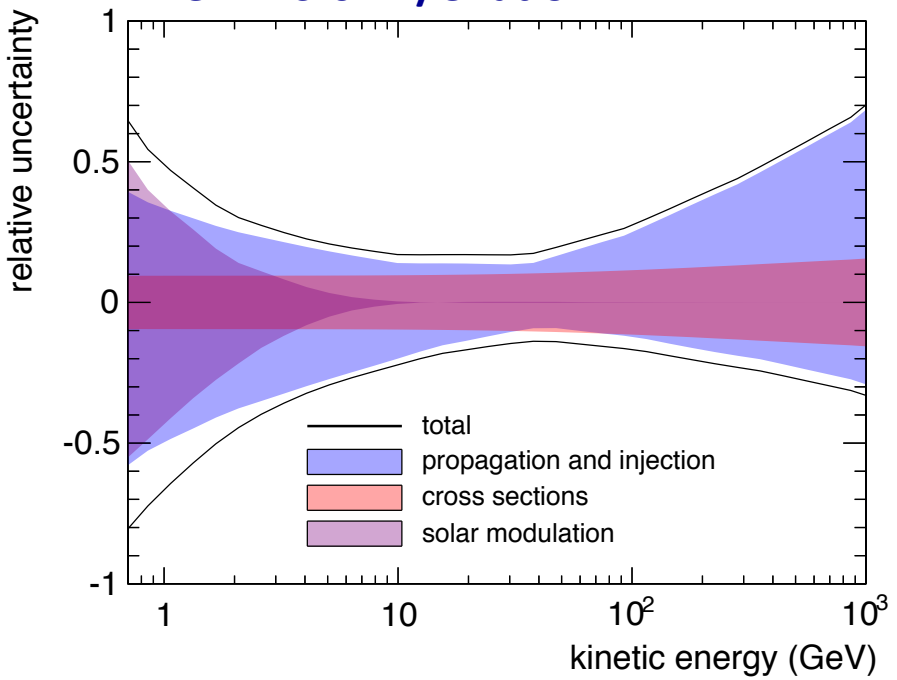




Astrophysical antiproton background

Pre-AMS-02 B/C ratio



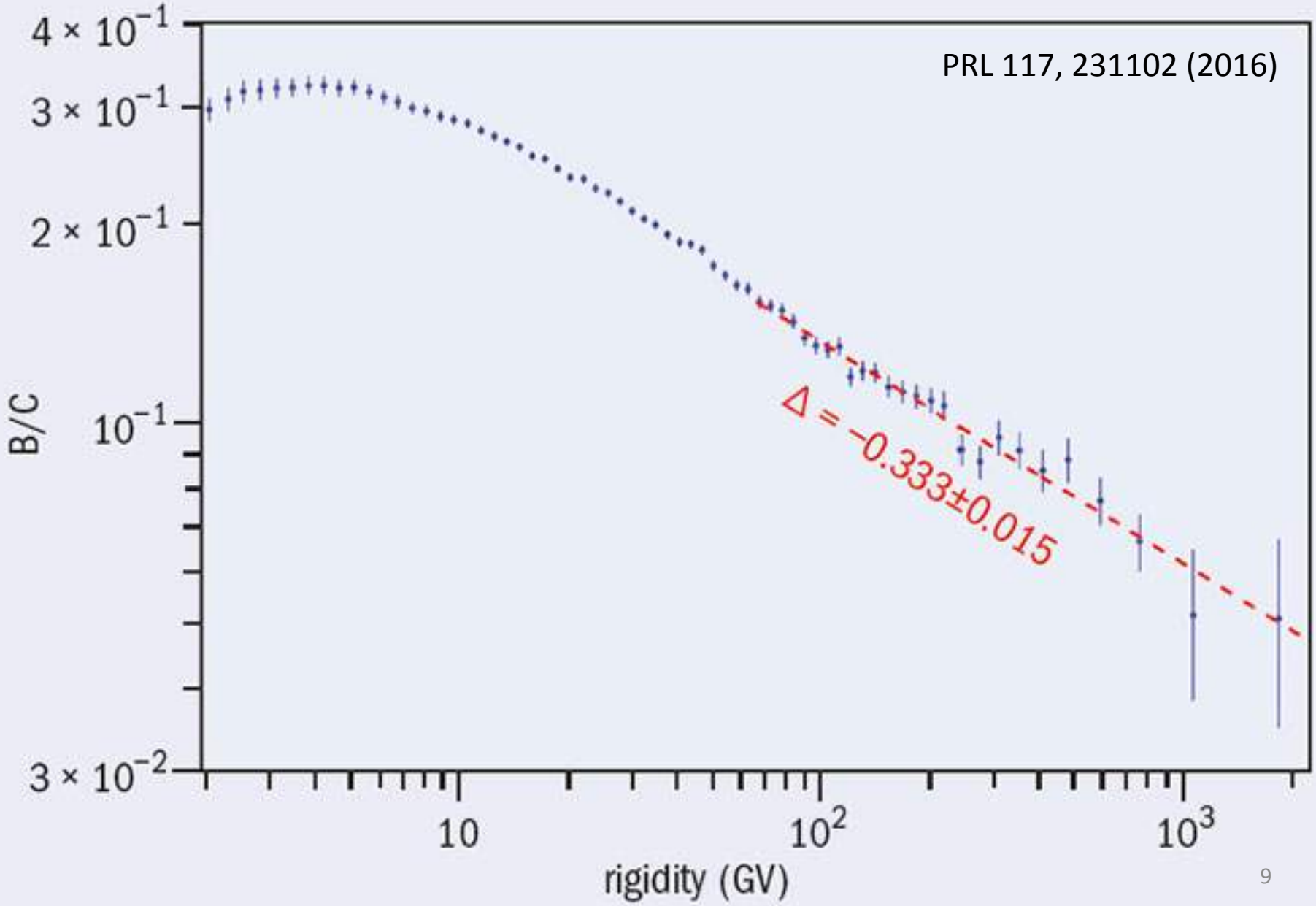
J. Feng et al. 2016 [1610.06182]
Uncertainties on pbar/p ratio

"Uncertainty in CR propagation can be stongly reduced with Precise B/C data at GeV − TeV"

(October 2016)

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

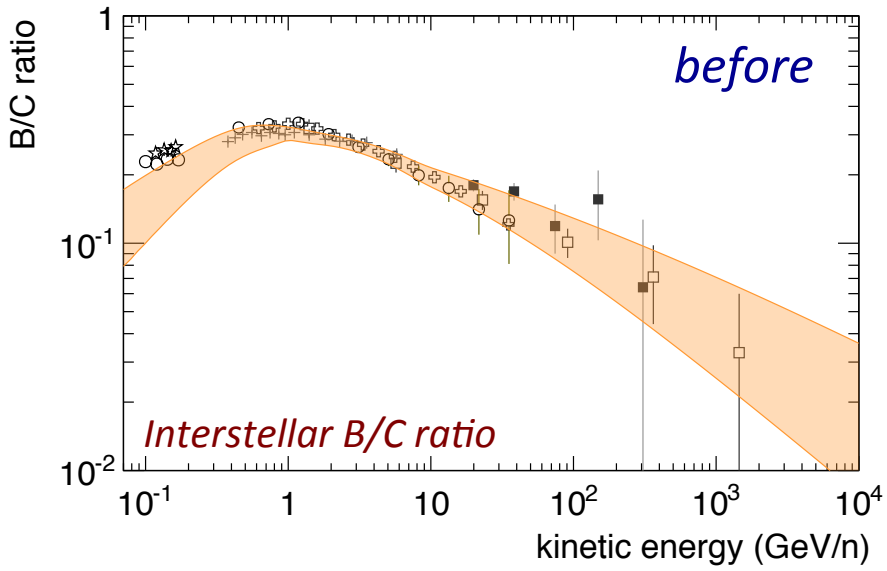
November 2016 : B/C ratio from AMS

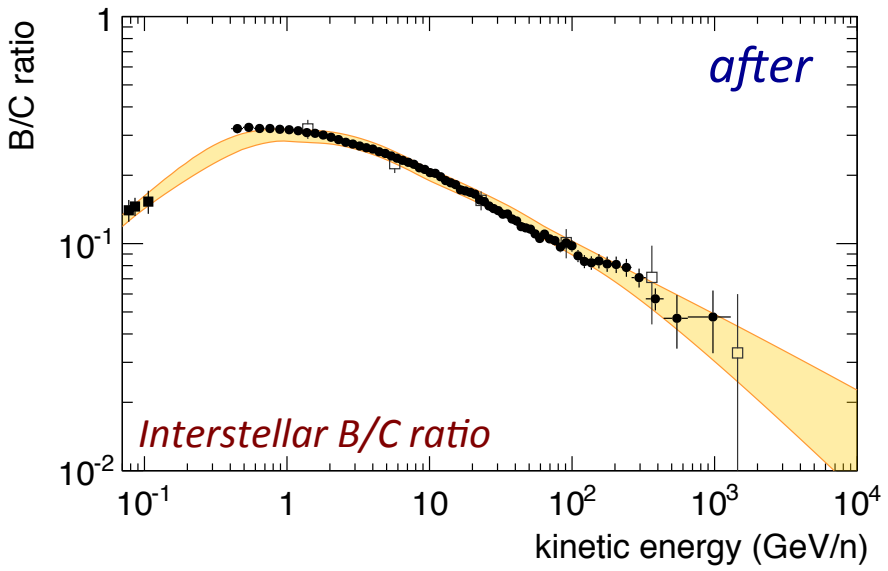


Uncertainties in CR transport in Galaxy

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

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





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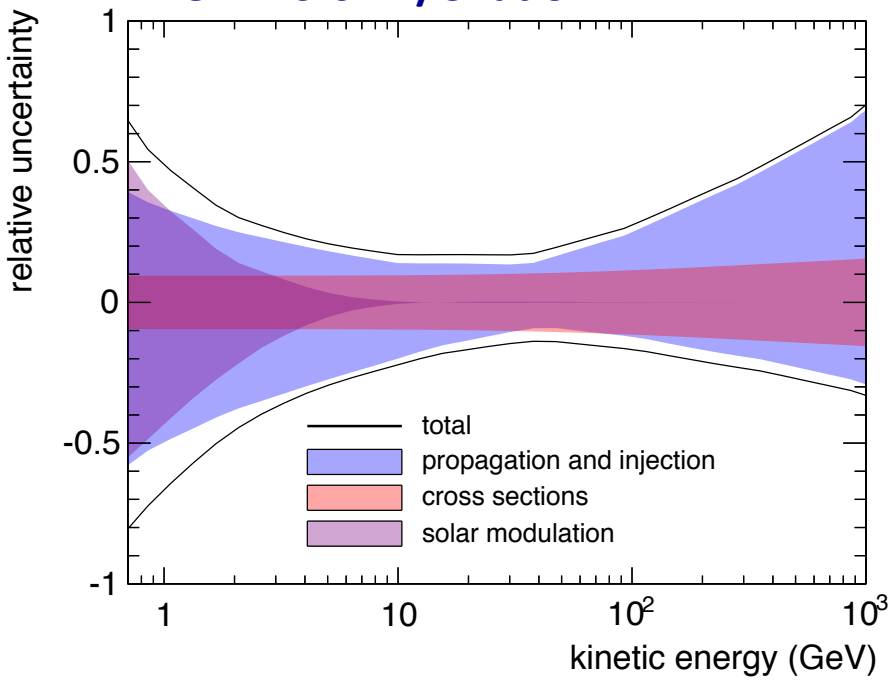

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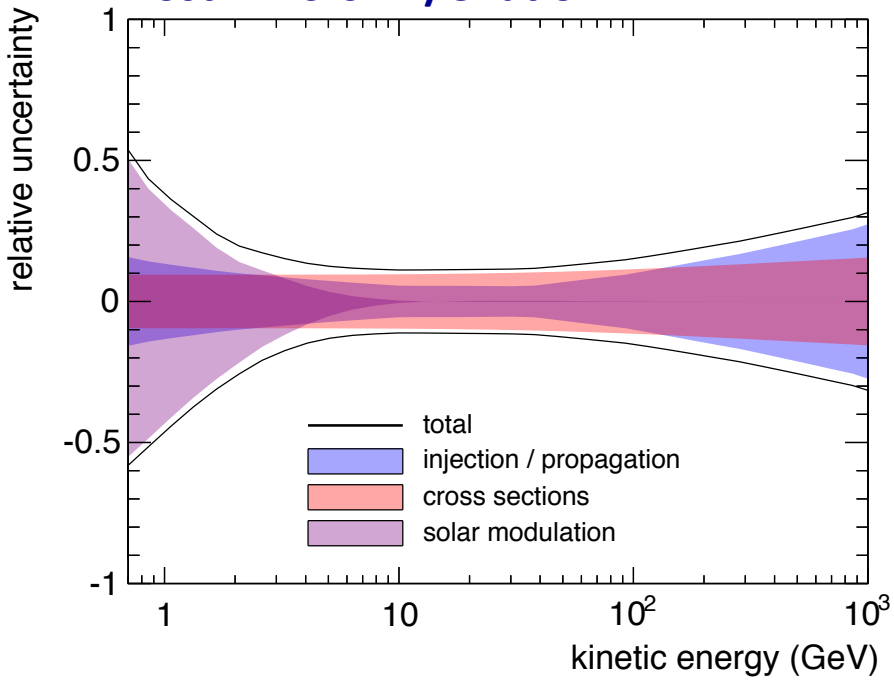
Post-AMS-02 B/C ratio



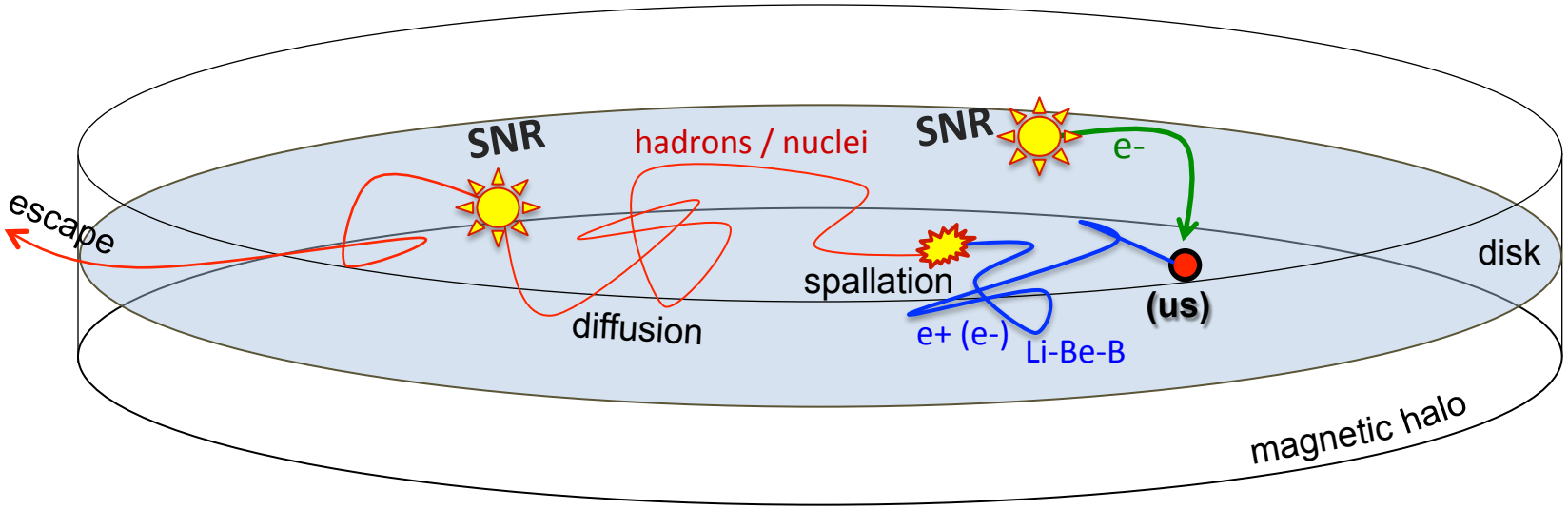
Improved propagation uncertainty after using B/C data from AMS

- ✓ *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.*

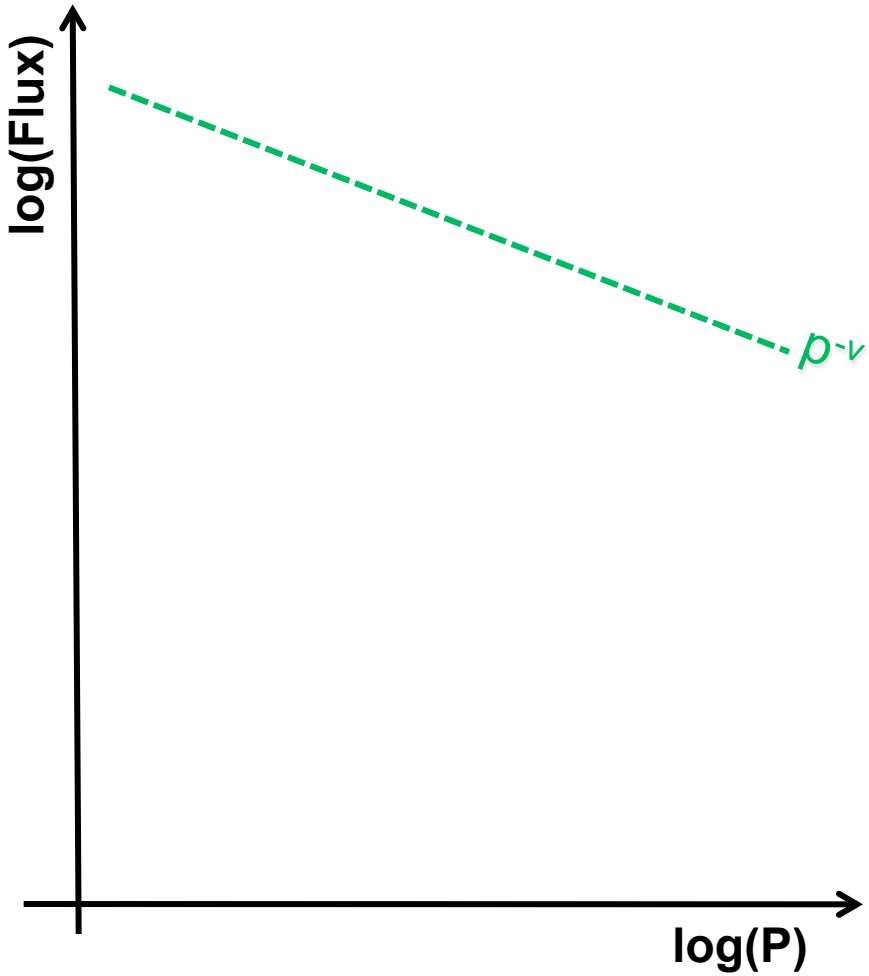


Pillars

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



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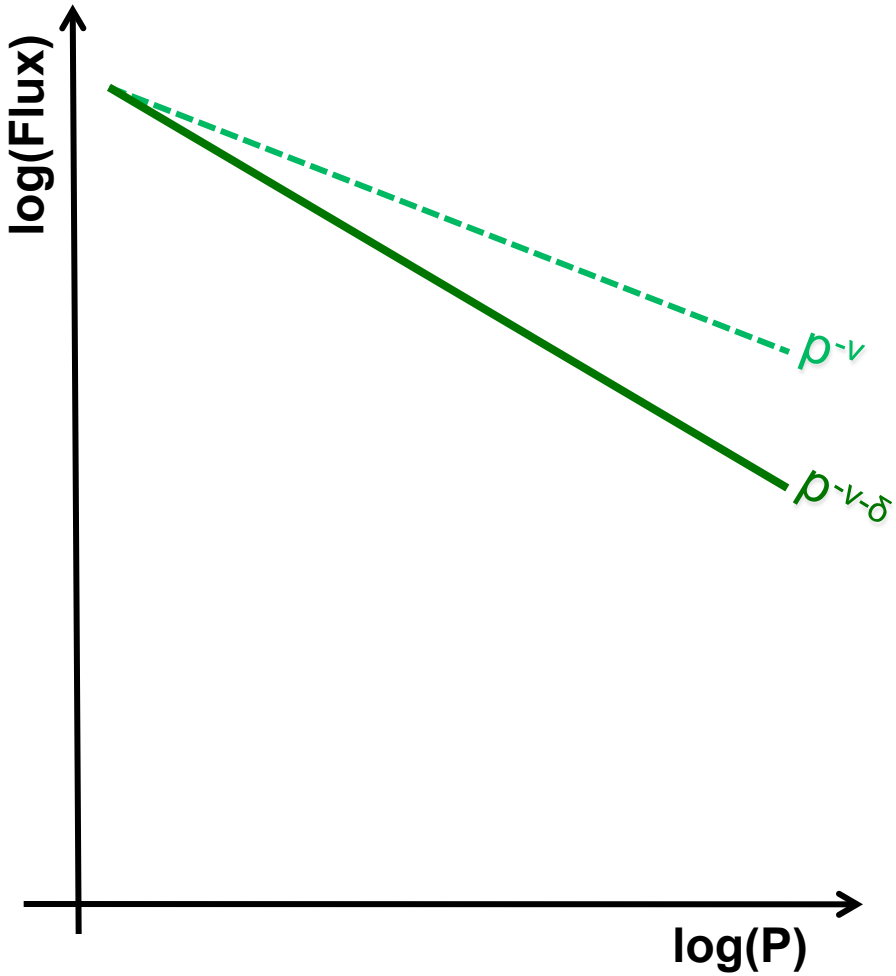
Prmaries at equilibrium: $n(p) \sim p^{-\nu-\delta}$

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



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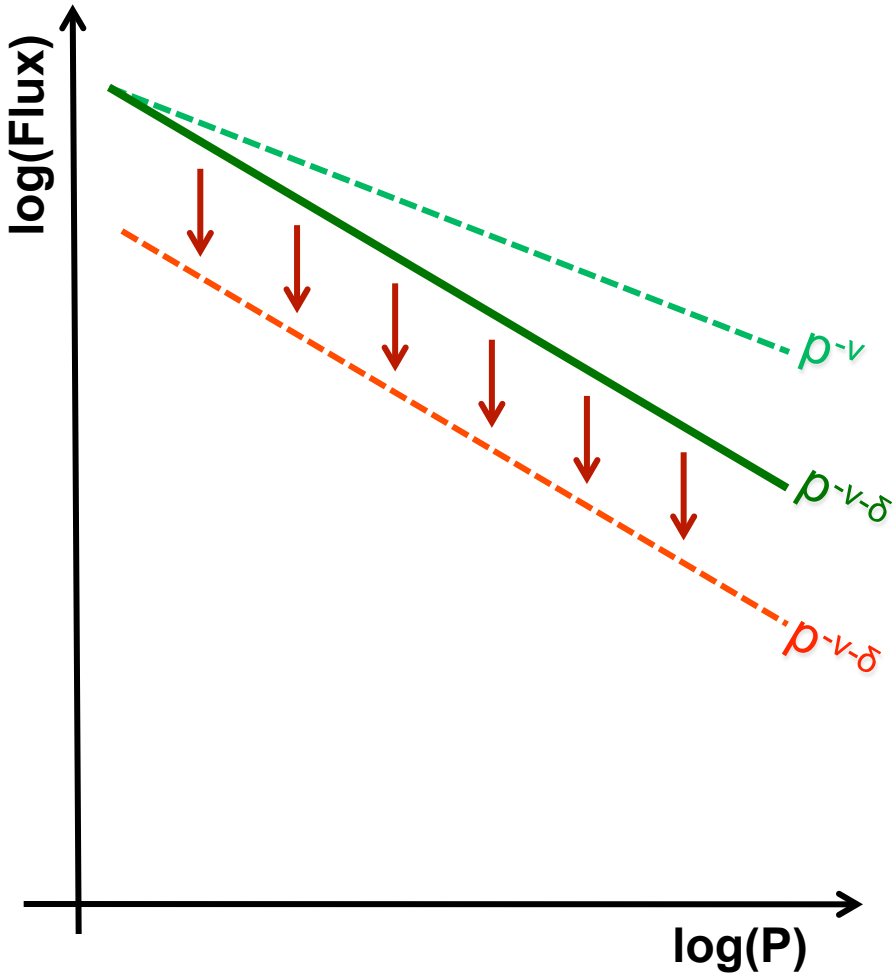

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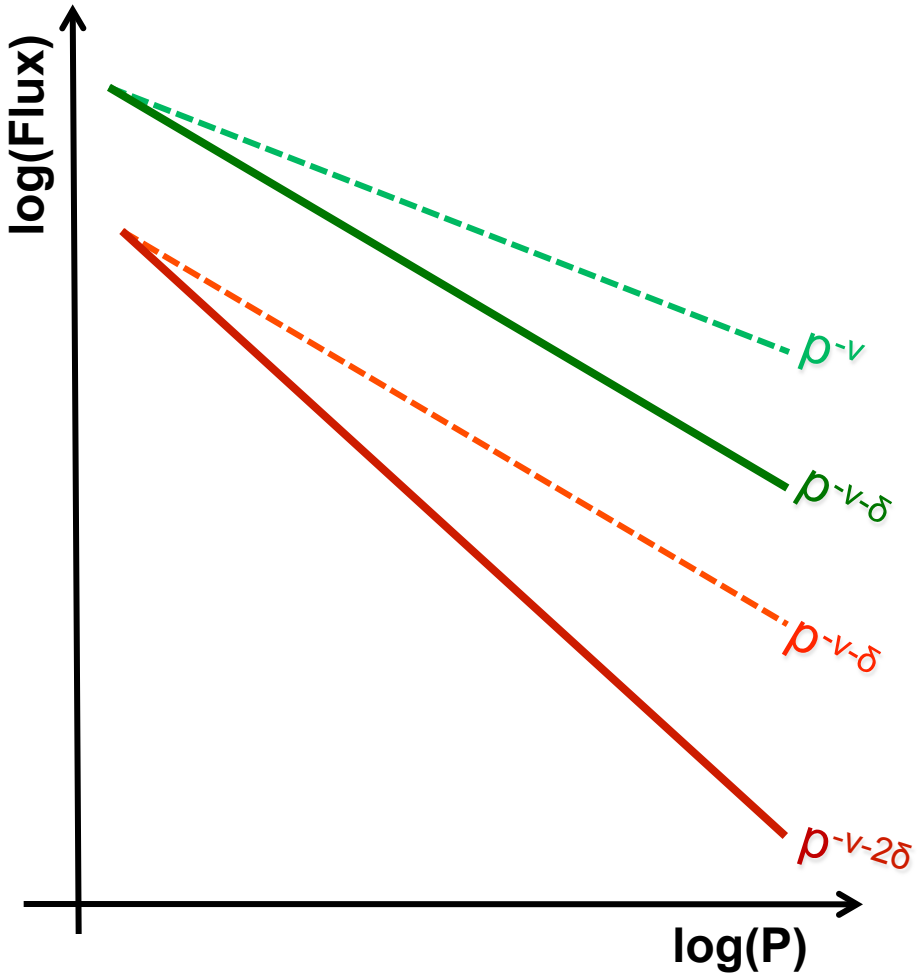

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Secondaries from spallation at equilibrium: $n(p) \sim p^{-\nu-2\delta}$

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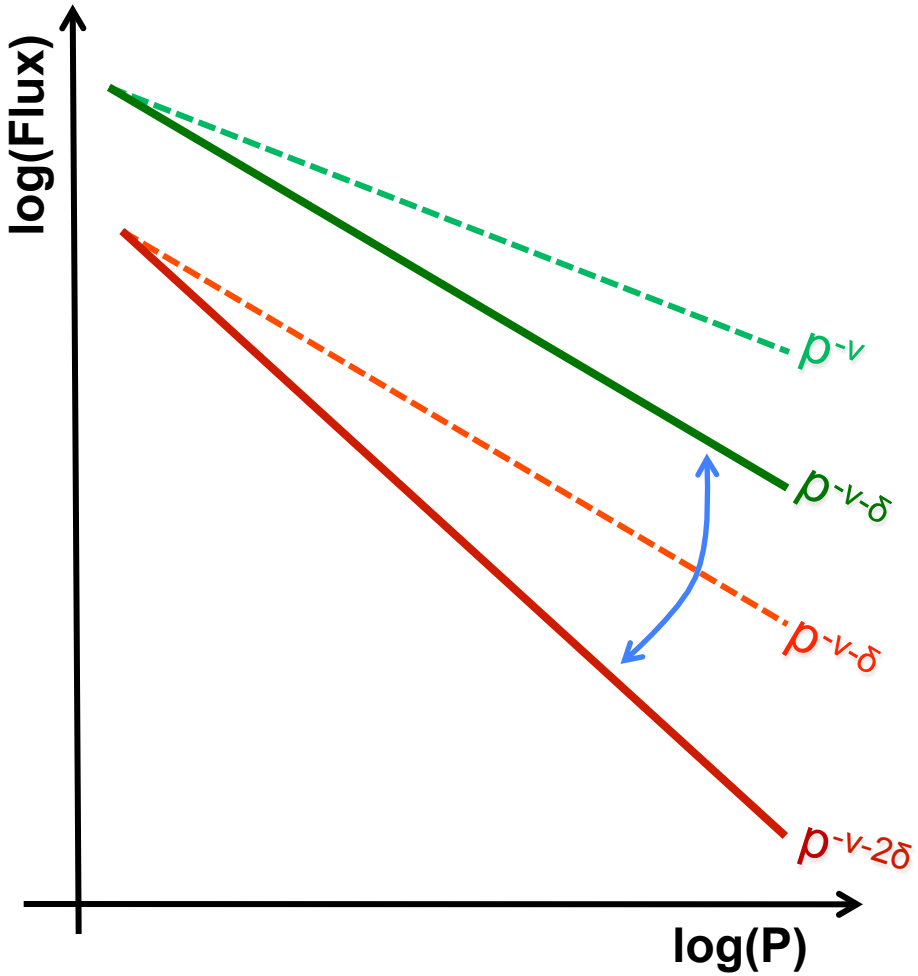
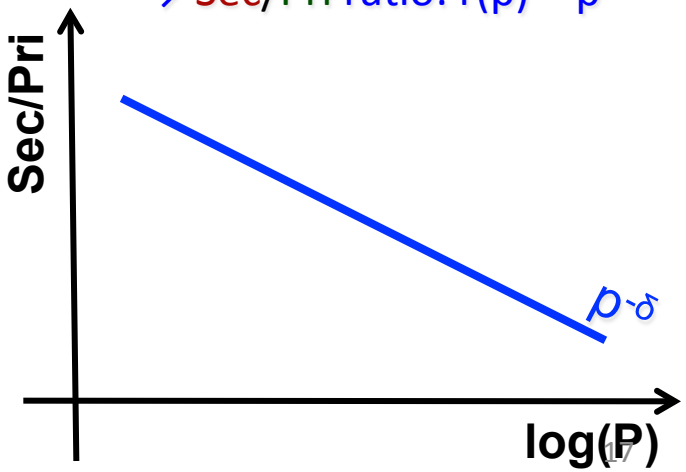
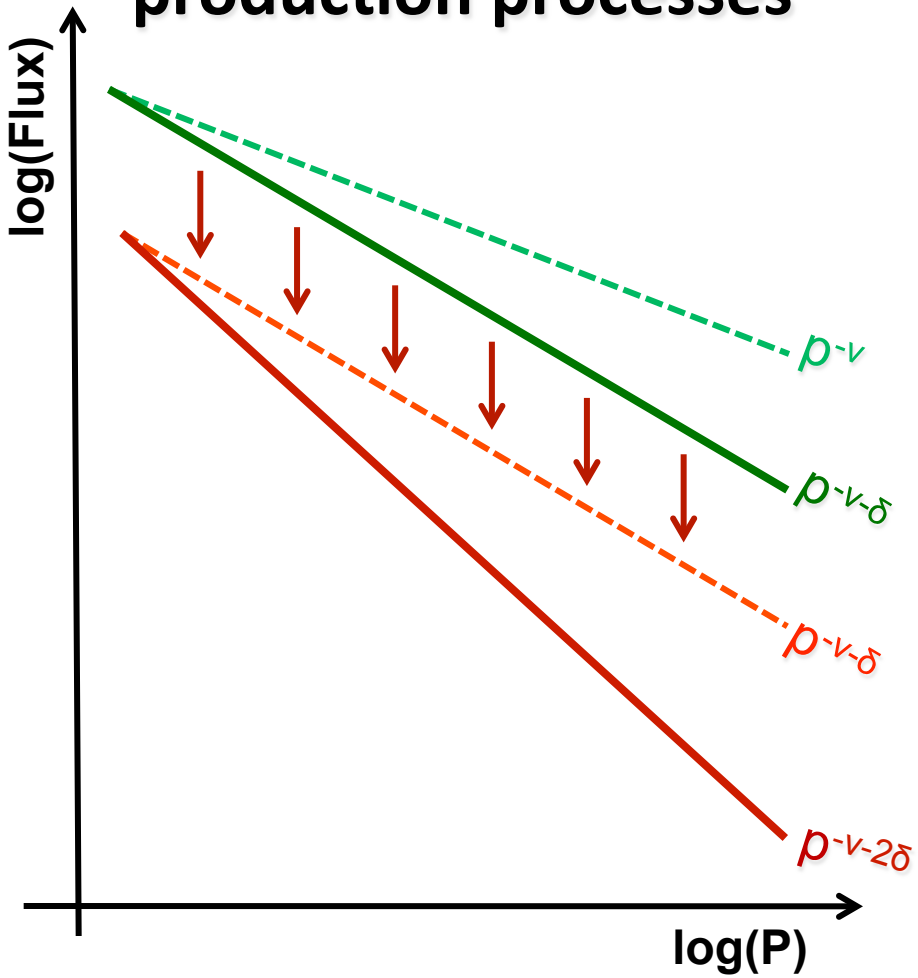


→ Sec/Pri ratio: $r(p) \sim p^{-\delta}$



What makes the B/C ratio

Pri + ISM -> Sec + X production processes



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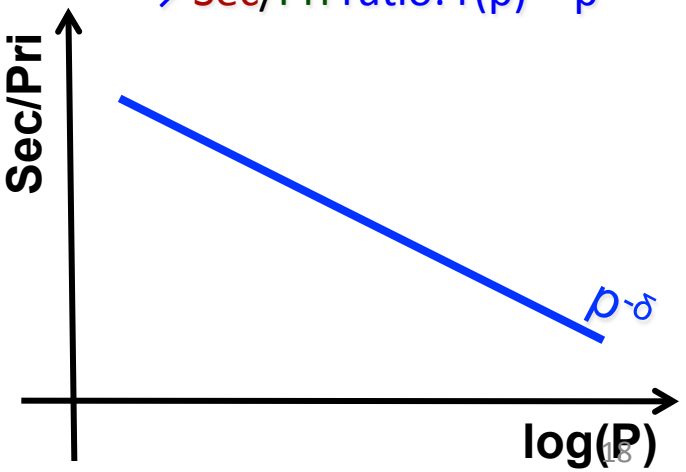
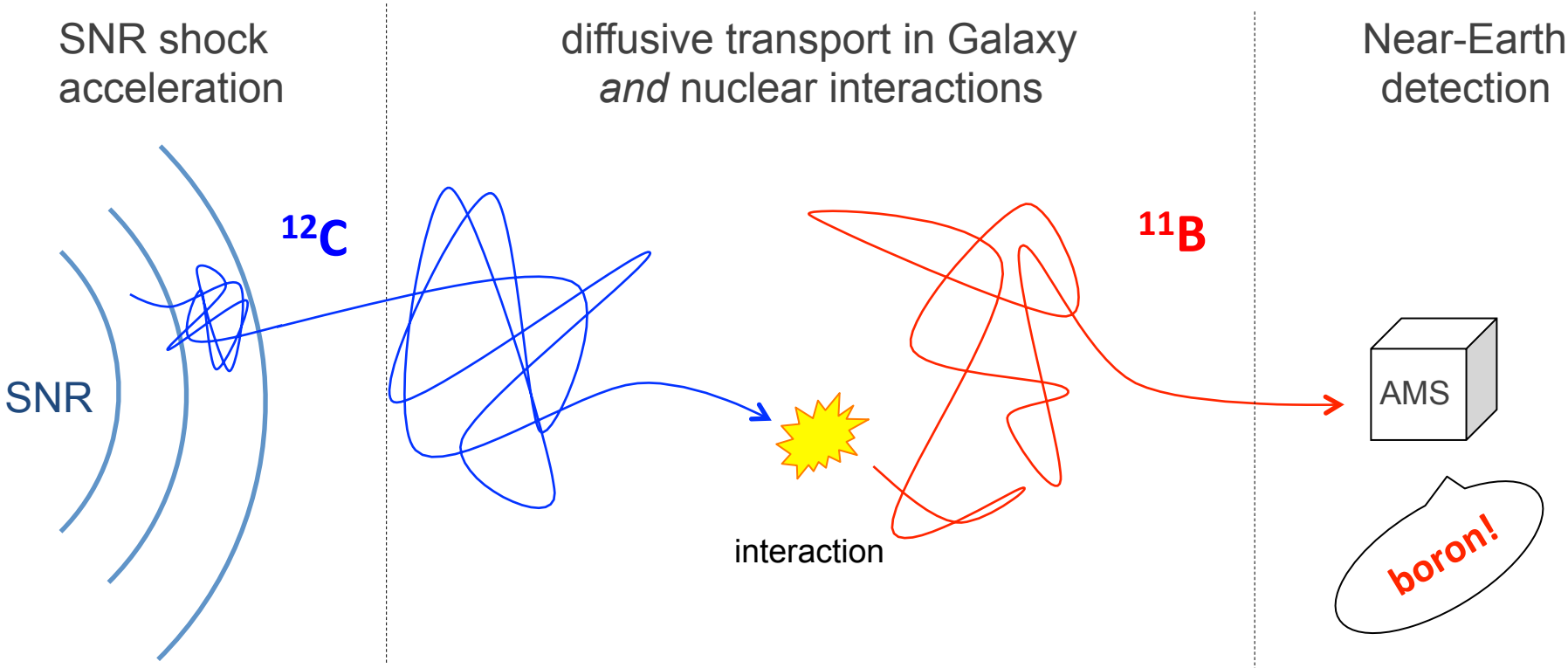
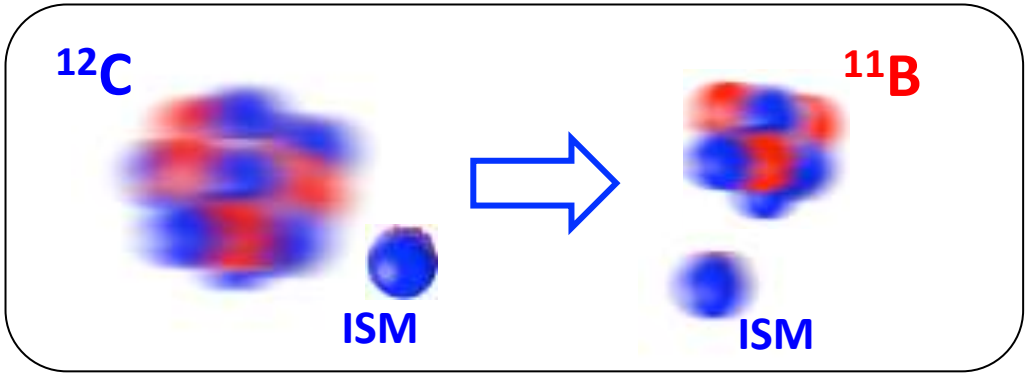


The physical picture



^{12}C+ISM ---> ^{10,11}B
^{16}O+ISM ---> ^{10,11}B
^{15}N+ISM ---> ^{10,11}B
^{28}Si+ISM ---> ^{10,11}B



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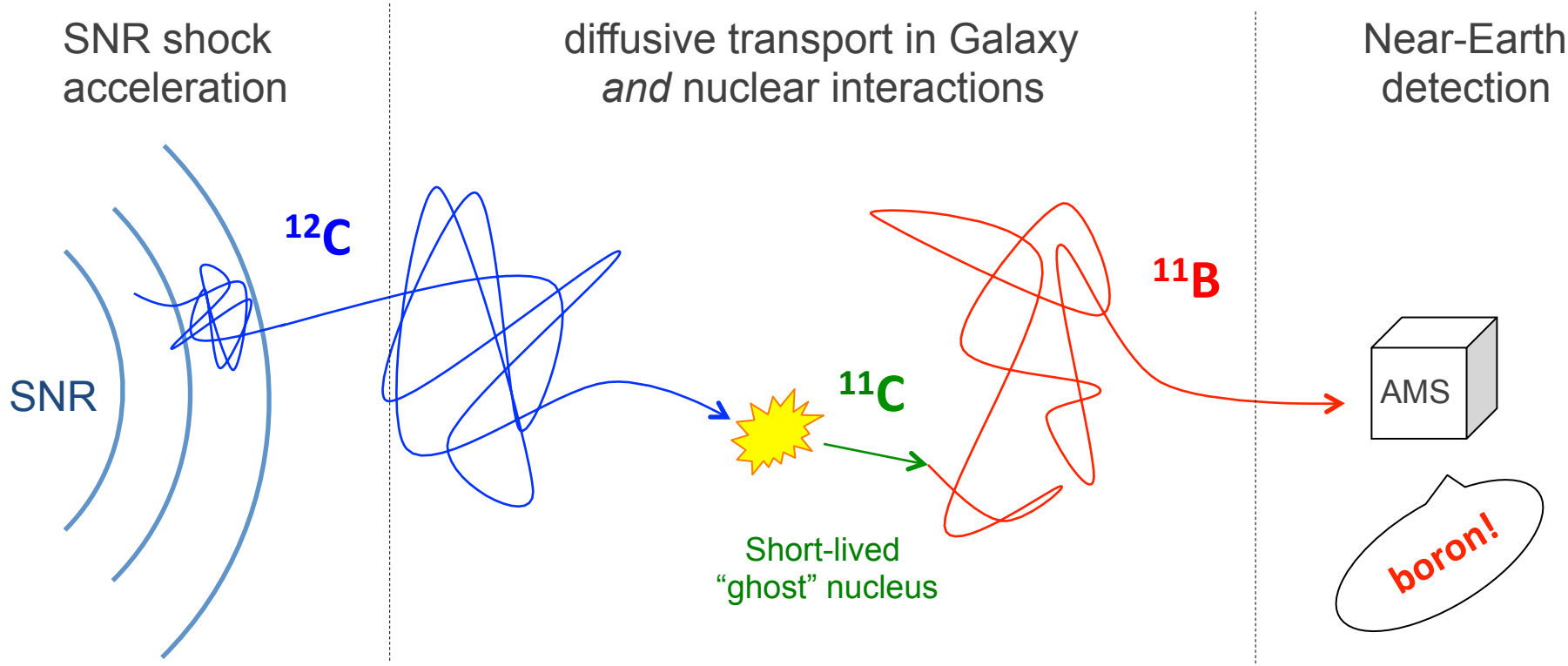
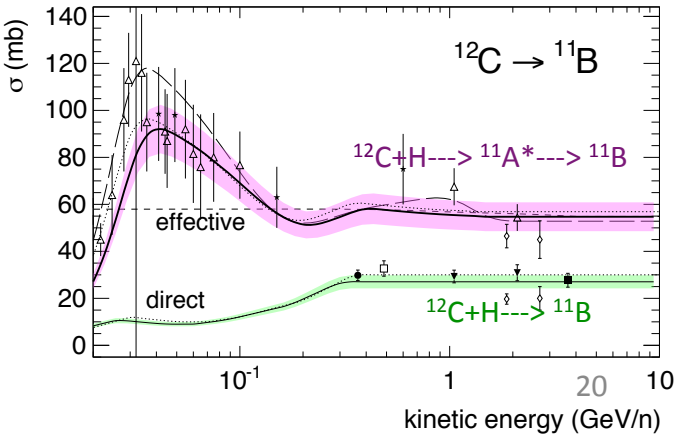


- Act as virtual particles for CR propagation
- Effective (cumulative) cross-sections used

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

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



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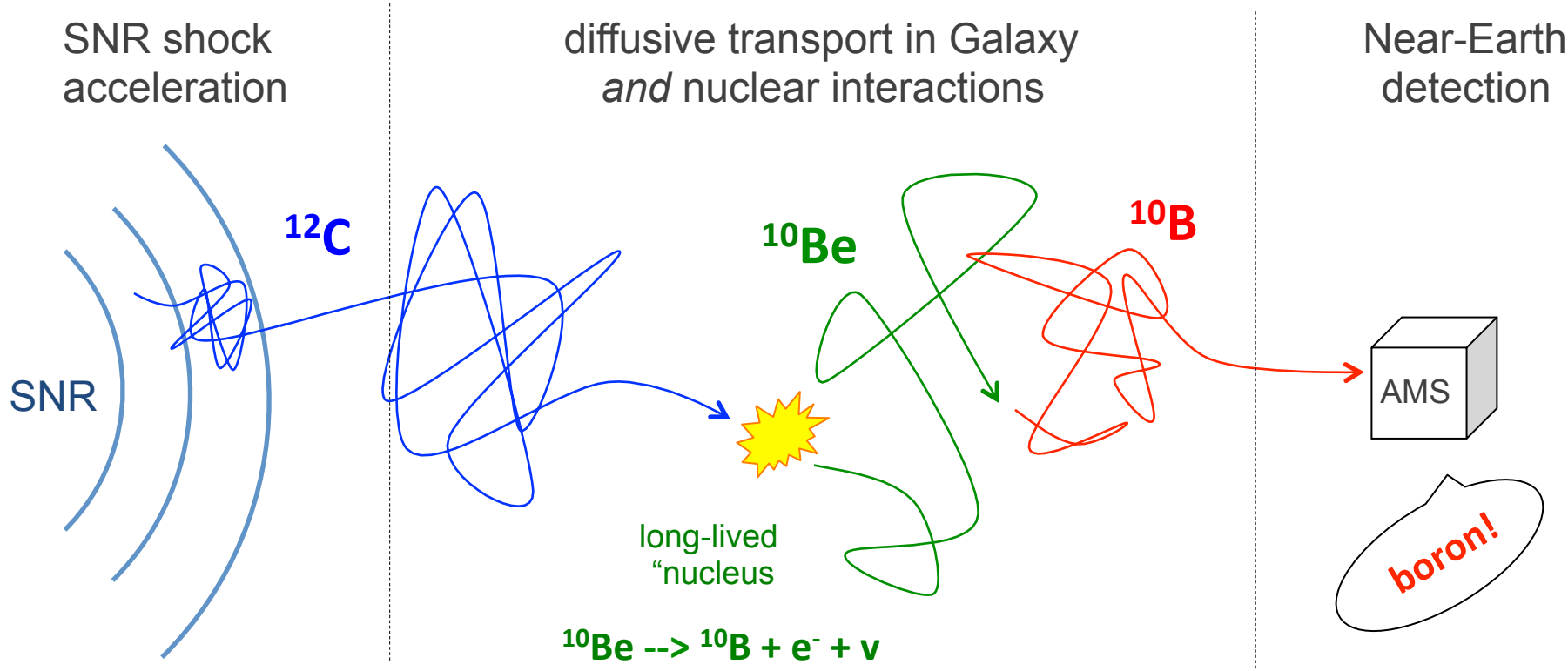
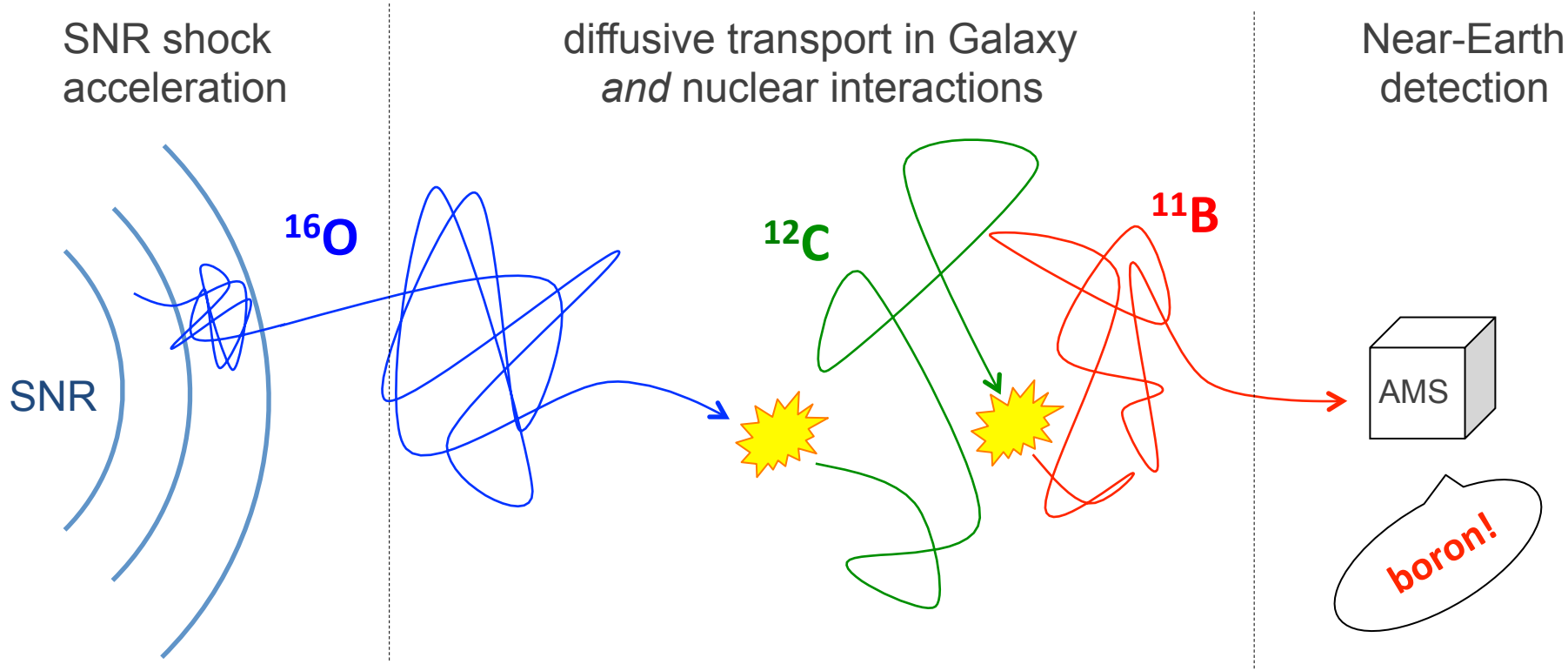


- Long-lived (or stable) intermediate nuclei
- CR propagation must be accounted
- Multi-step nature of fragmentation

Radioactive with T~1.5Myr

The physical picture



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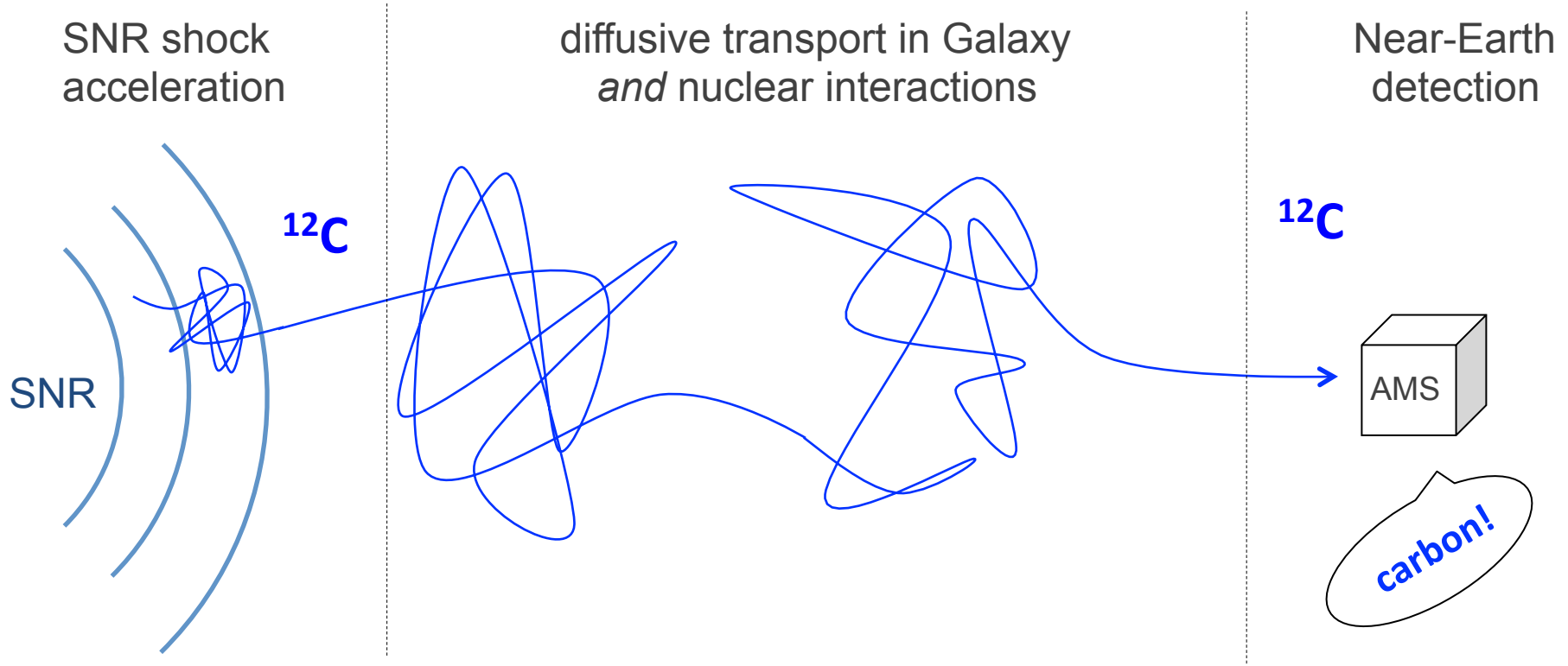
- CR propagation must be accounted
- Multi-step nature of fragmentation

Stable, interacting again with the gas

The physical picture



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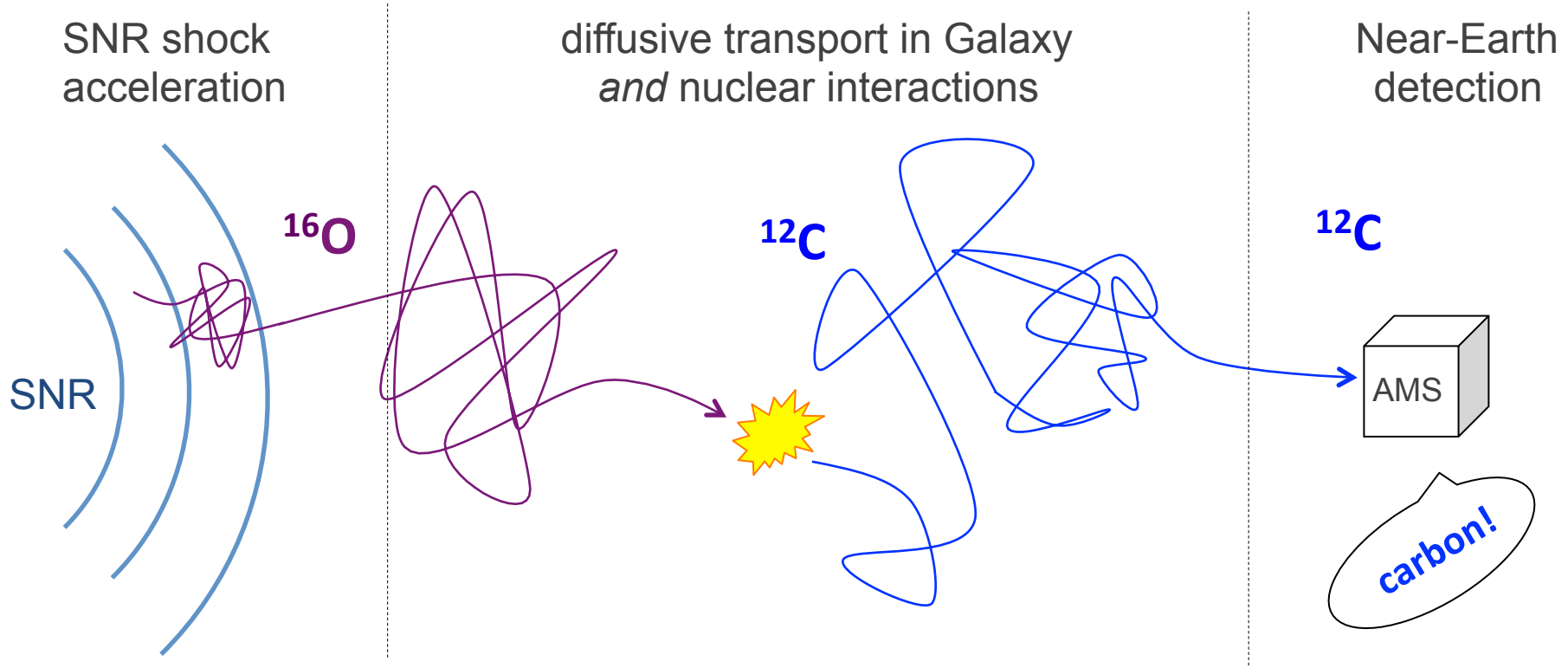

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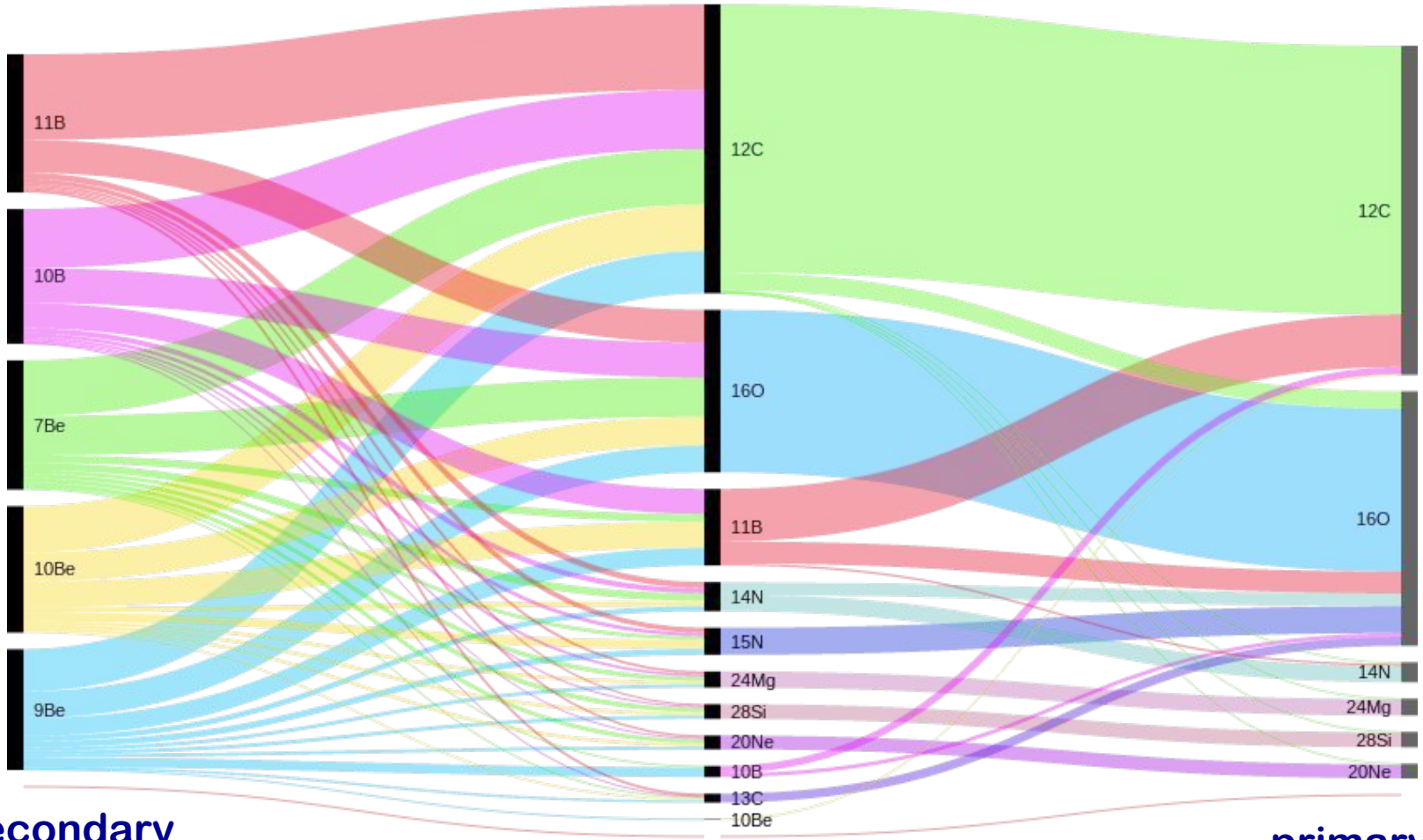
- Multi-step nature of fragmentation

Multi-step cosmic ray fragmentation

alluvial diagram of fragmentation reactions

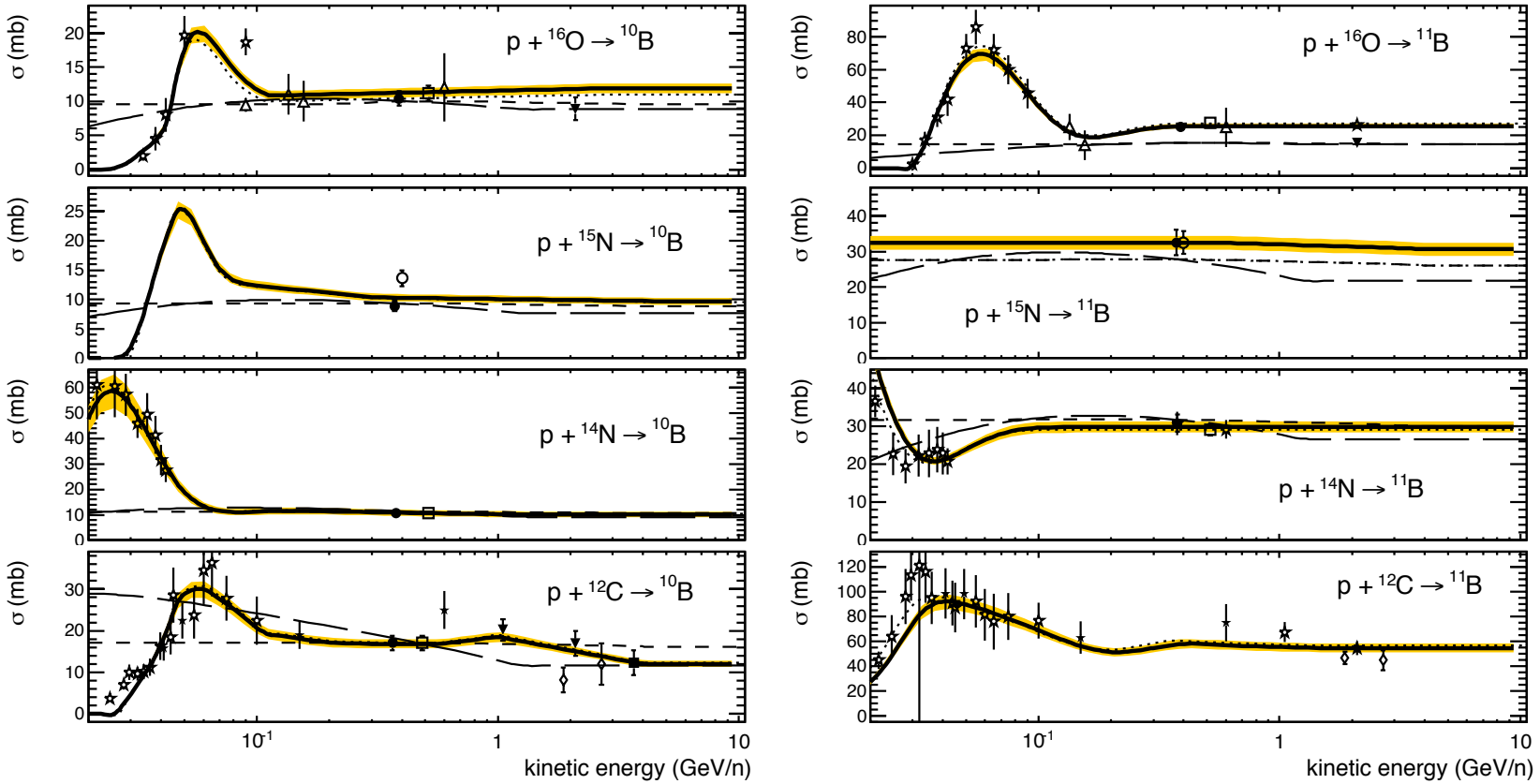


From NT 1707.06917

Uncertainties in CR transport in Galaxy

Refit normalization and energy scale $\sigma^{H}_{CNO\to B}(E) = a \cdot \sigma^{G}_{CNO\to B}(b \cdot E)$

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 · Webber et al1998b · WNEW -98

Korejwo et al 1999 · Korejwo et al 2001 · Ramaty et al1997 · Radin et al1979 · YIELDX-00

REFIT

Uncertainties in CR transport in Galaxy

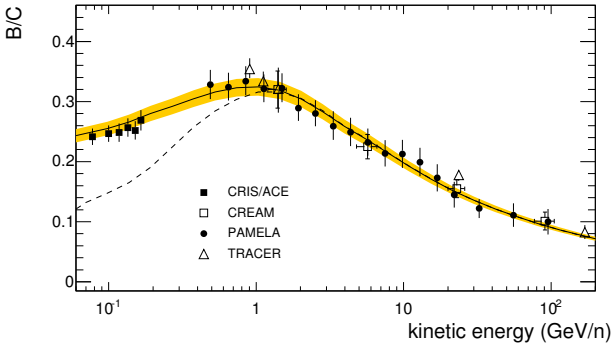
Impact of cross-section uncertainties in CR propagation parameters

Toy simulation for AMS-02 [NT 1509.05776]

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

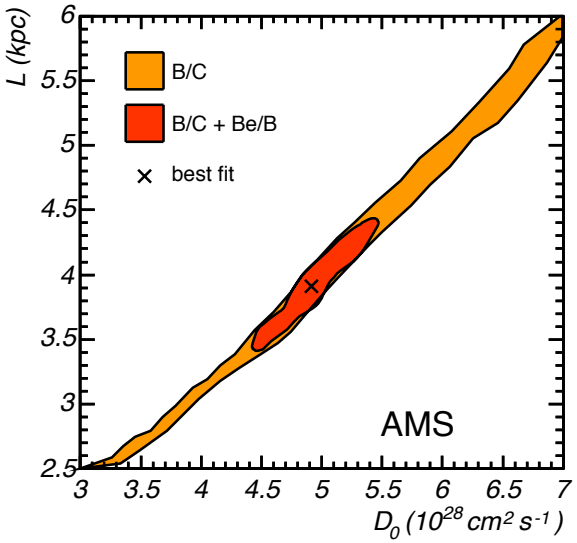
L = half-size of magnetic halo

D = normalization of diffusion coefficient



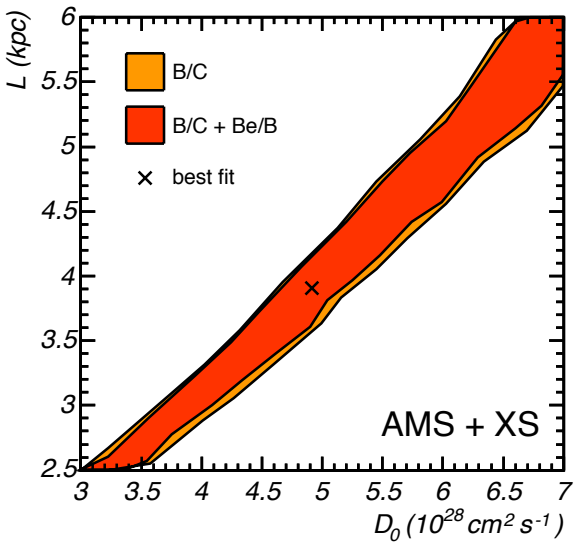
Precise B/C+Be/B data

-> degeneracy resolved!



XS errors accounted

-> degeneracy restored!

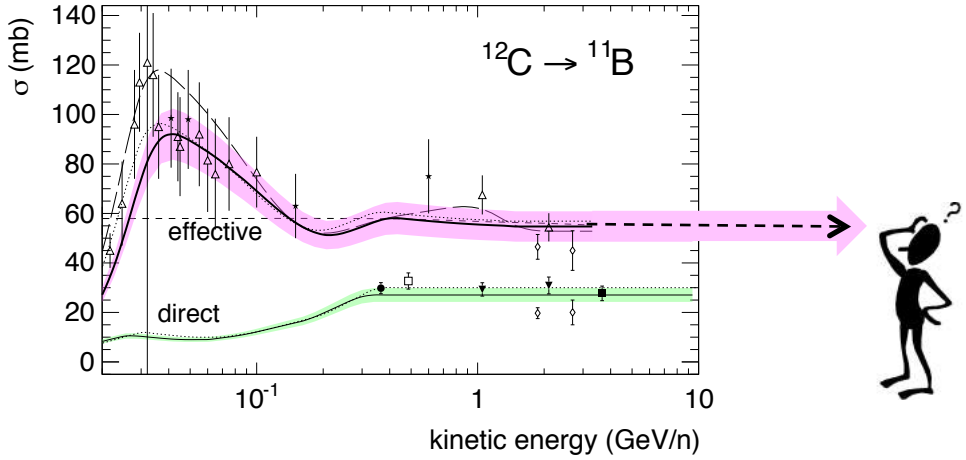


The determination of key parameters is plagued by uncertainties in XS data

Energy-dependent bias?

In semi-empirical formulae, all XS's are assumed energy independent at E >> 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

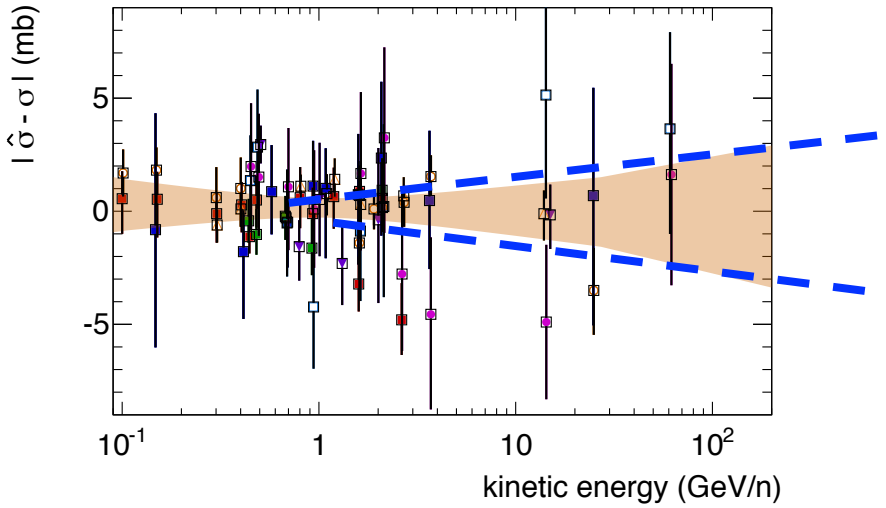
Energy-dependent bias?

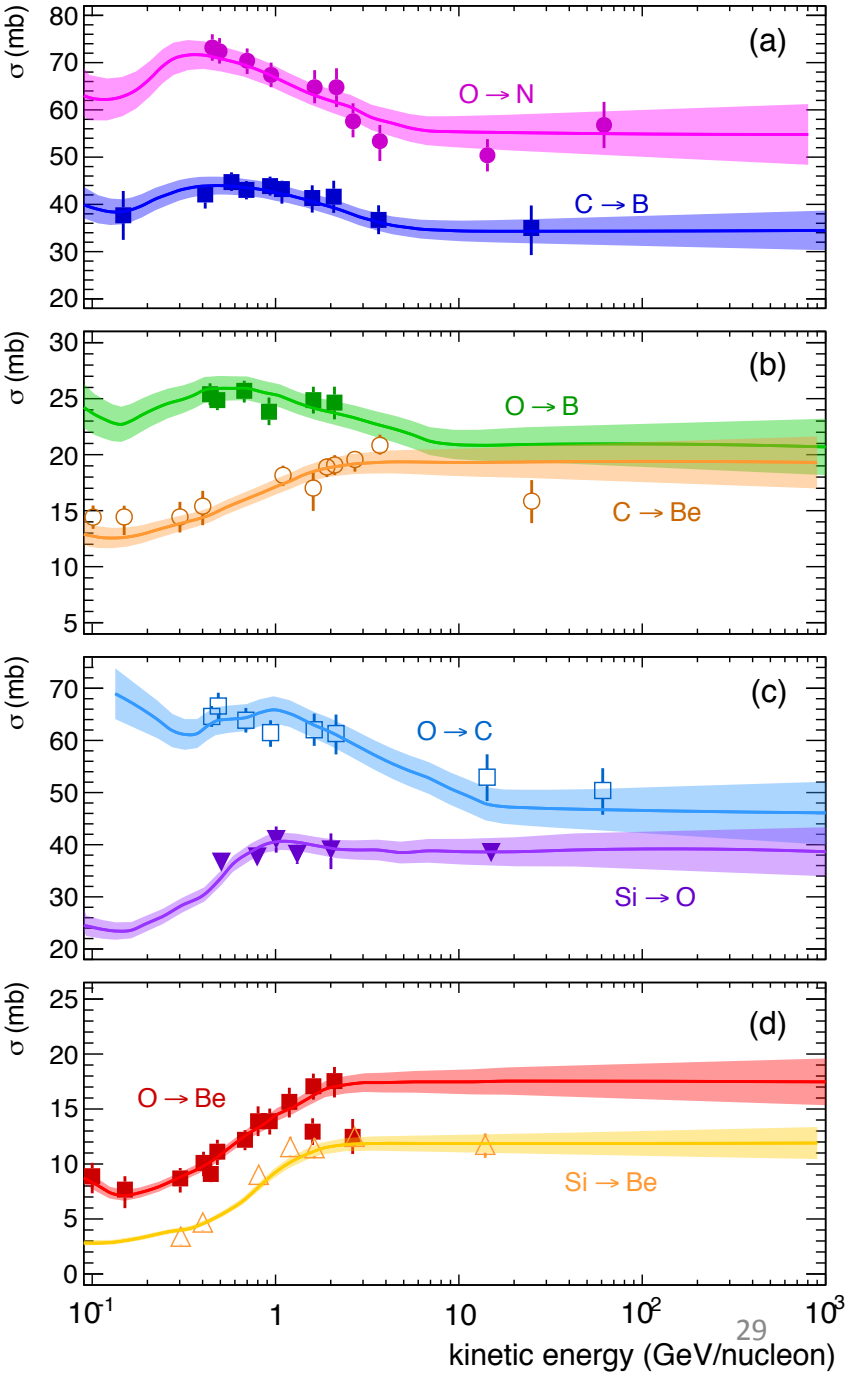
A possible approach: [NT 1707.06917]

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

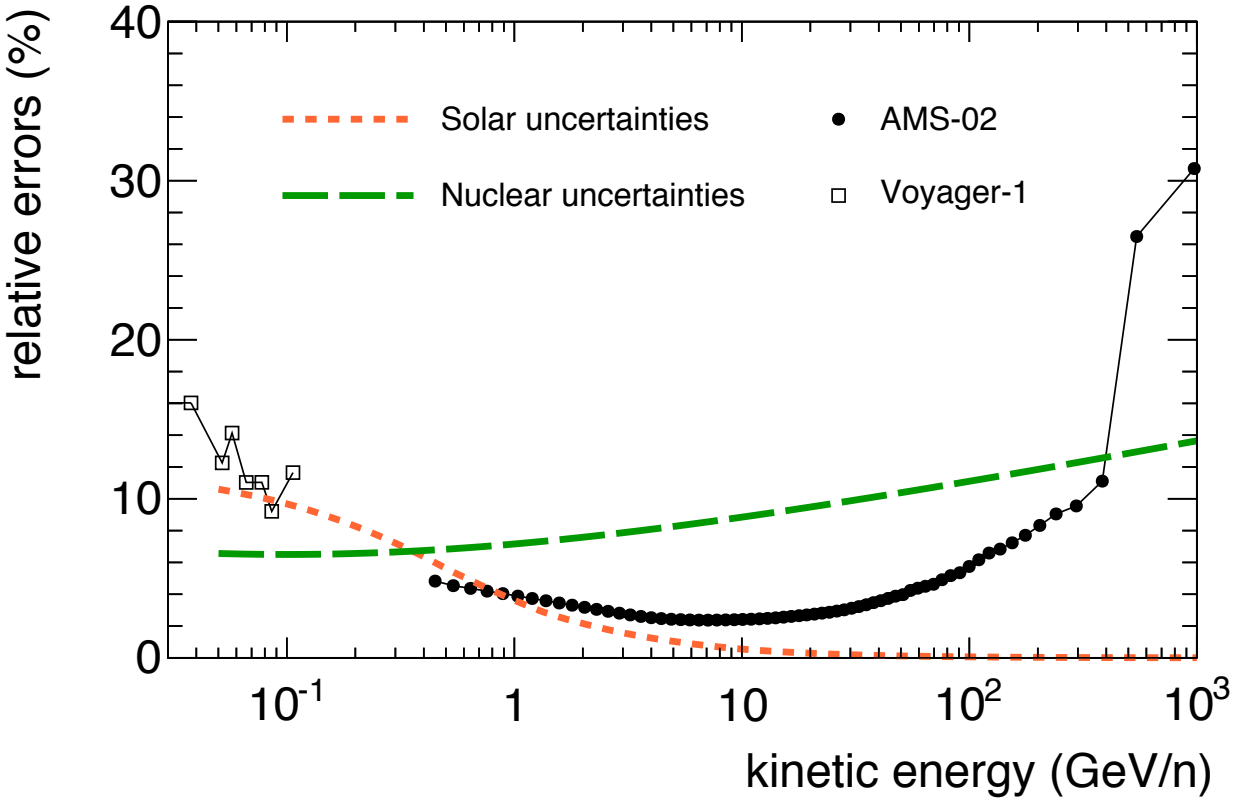
Assume common E-depependent bias

--> XS uncertainty at high-energy





Model uncertainties on B/C ratio



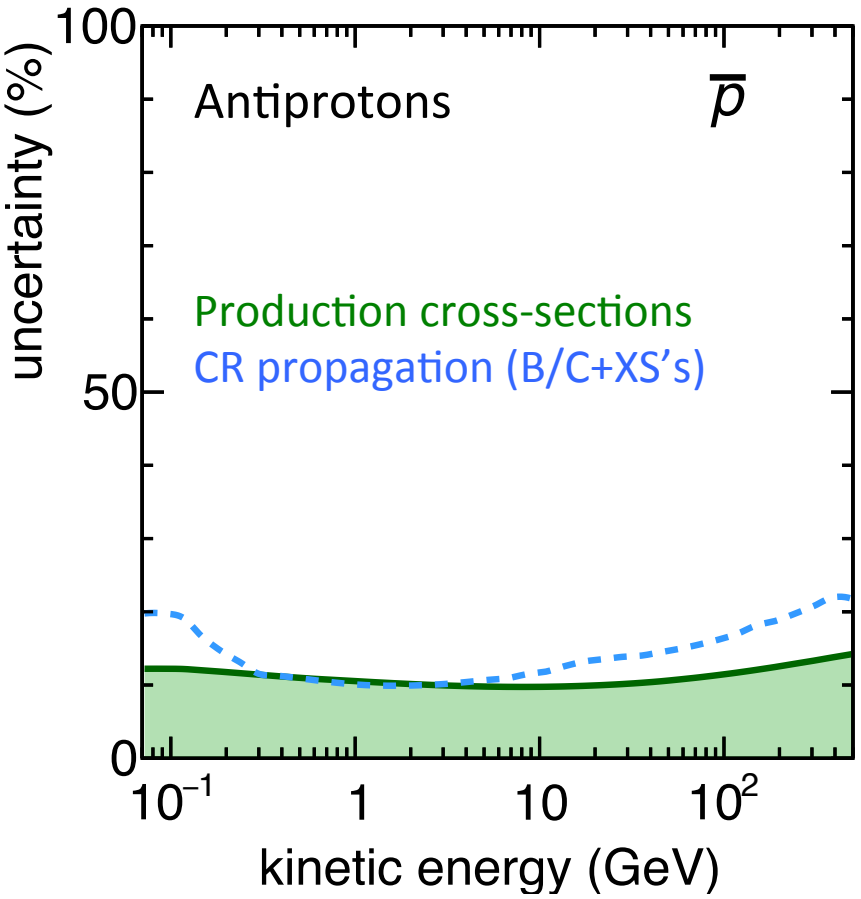
- **Esperimental errors in the AMS-02 B/C ratio**

  ~ 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

Uncertinties on secondary antiprotons



Uncertainties in Cosmi-ray propagation still relevant

once cross-section errors in Boron production are accounted

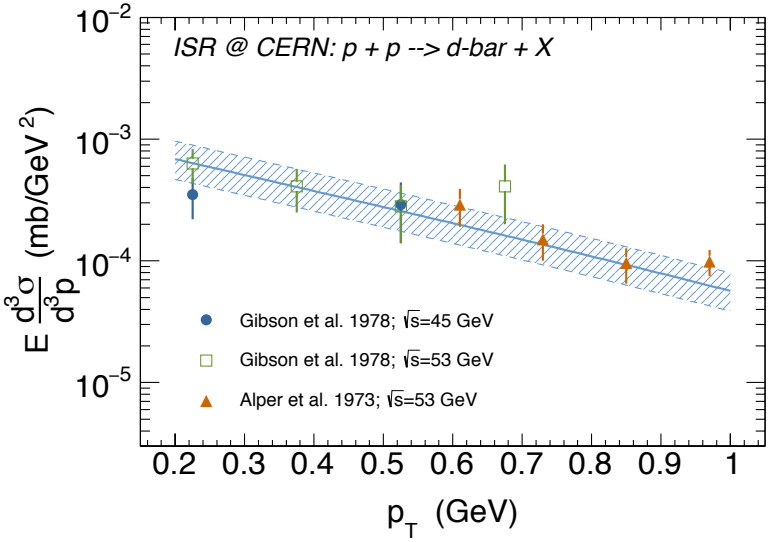
- ✓ Uncertainties from cross-sections -> using comparisons between MC generators and data
- ✓ Uncertainties from CR propagation -> using two-zone propagation model and B/C data

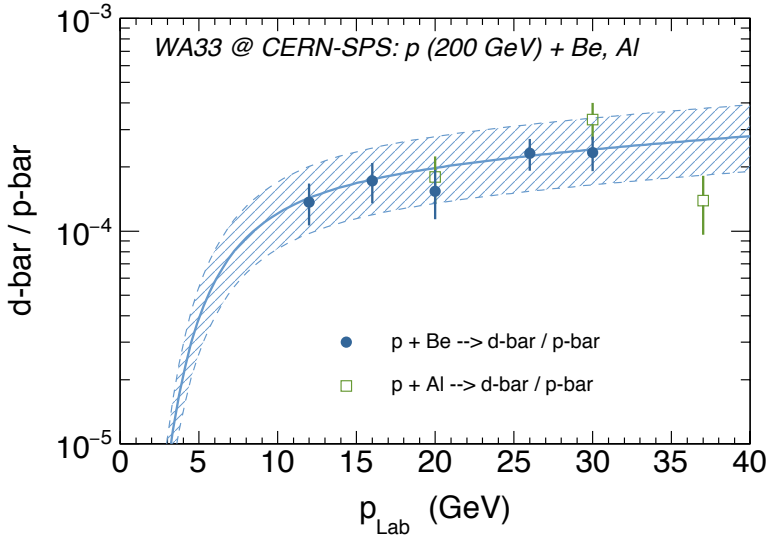
Calculations for anti-nuclei

Antideuterons: Nuclear coalescence

- ✓ Analytical model for pbar & nbar production [based on Di Mauro et al. 2014 PRD]
- ✓ Antineutron enhancement factor [k~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

$$E_{\bar{A}}\frac{d^3N_{\bar{N}}}{dp^3_{\bar{A}}} = B_{\bar{A}} \times \left(E_p \frac{d^3N_p}{dp^3_p}\right)^Z \times \left(E_n \frac{d^3N_n}{dp^3_n}\right)^{A-Z}$$





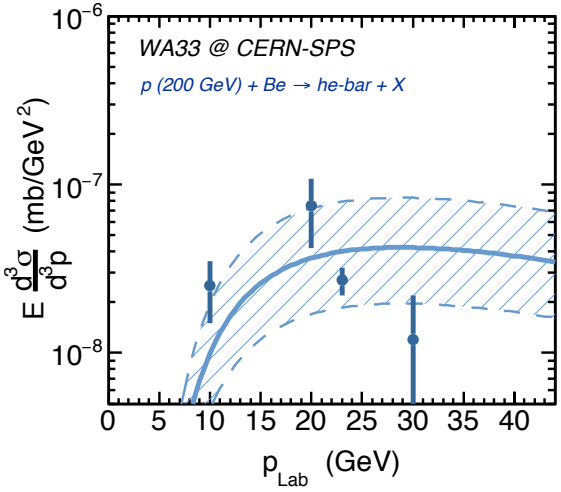
Data on p+p, p+Be , p+Al. Use of XS ratio pbar/nbar to cancel out target factors

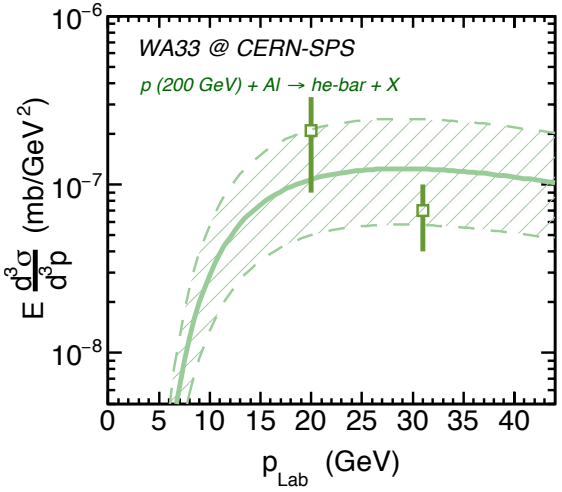
[A. Oliva & NT 2017 1707.06918]

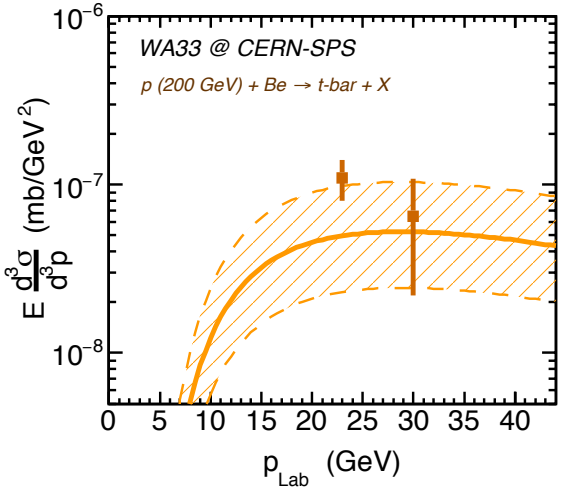
Anti-helium & anti-tritium

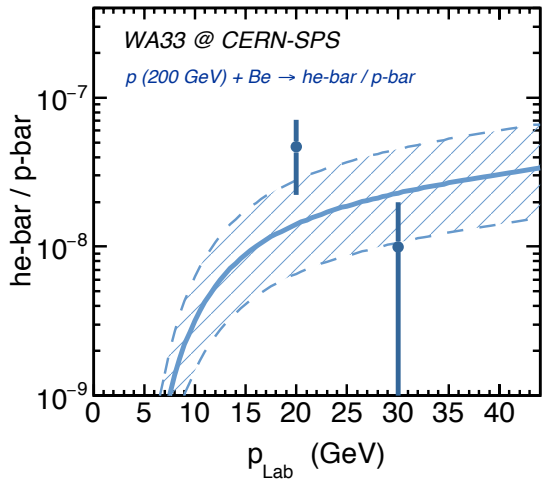
Measurements are very scarce --> poor constraints.

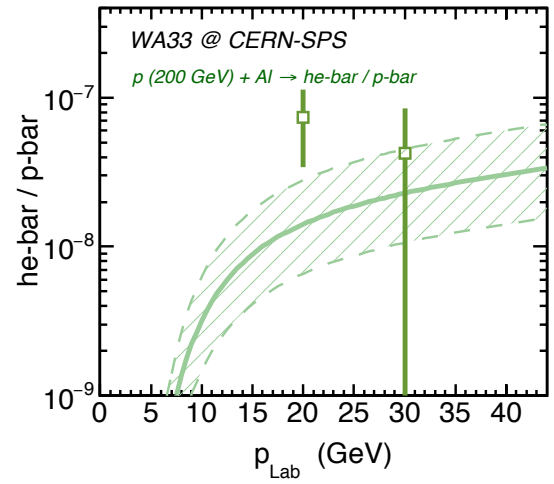
Using the same coalescence momentum of D-bar, we get a reasonable description

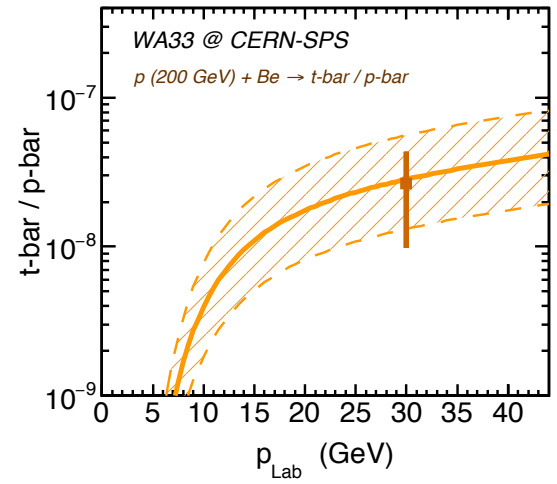








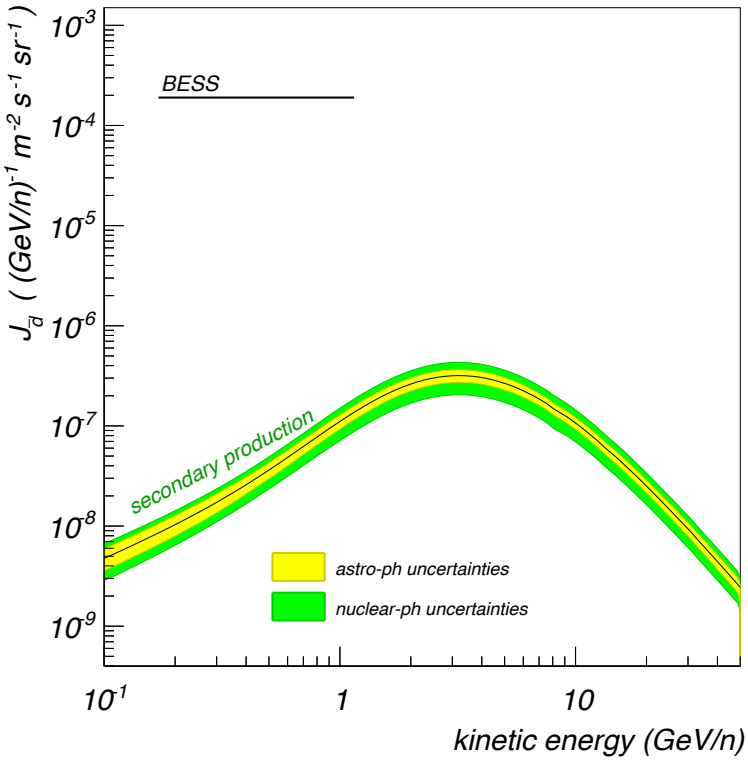


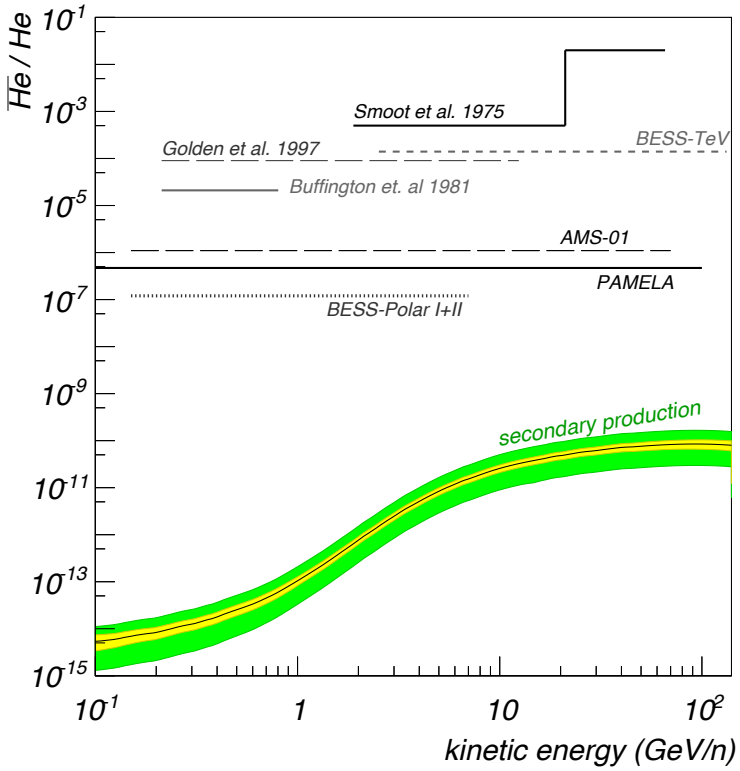


[A. Oliva & NT 2017 1707.06918]

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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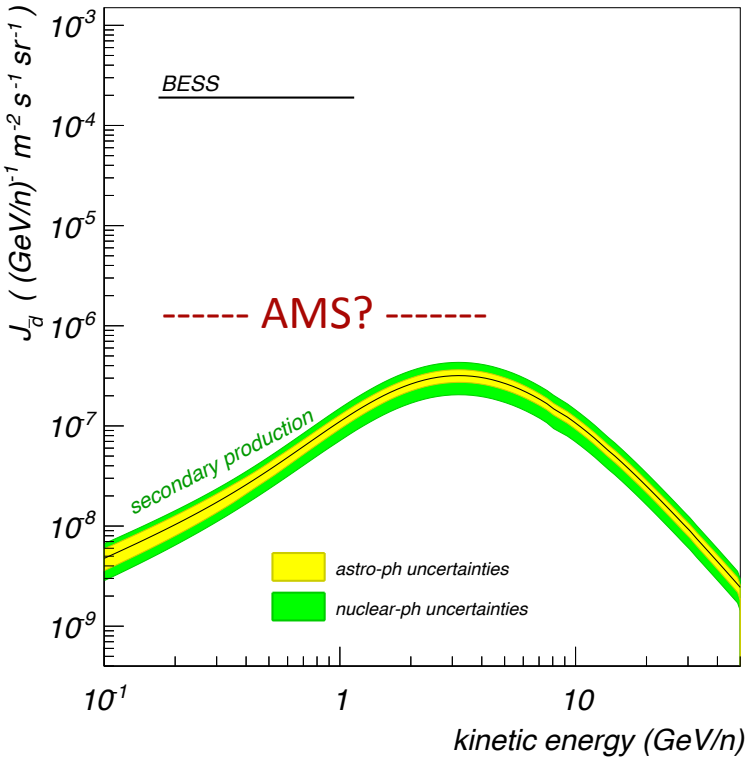
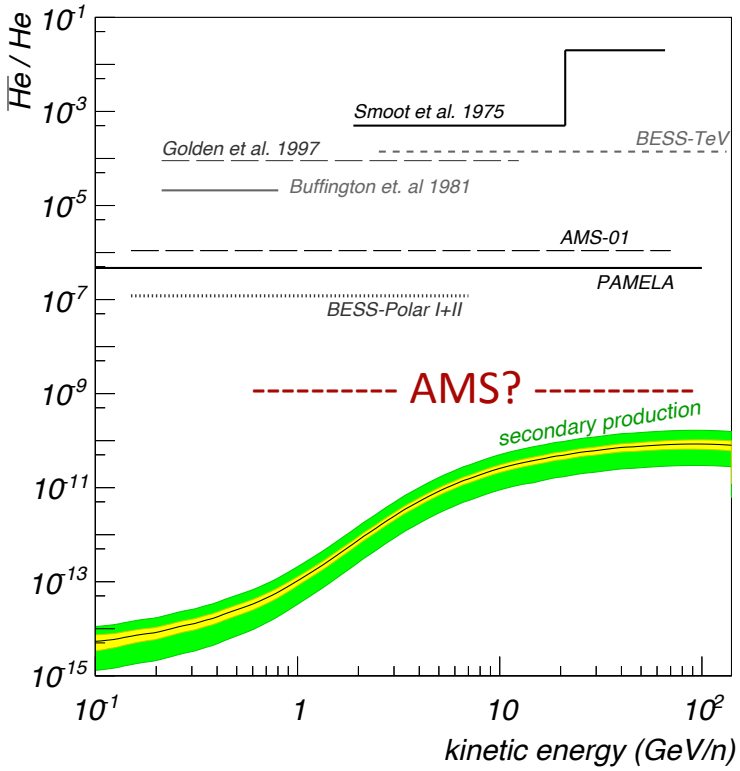
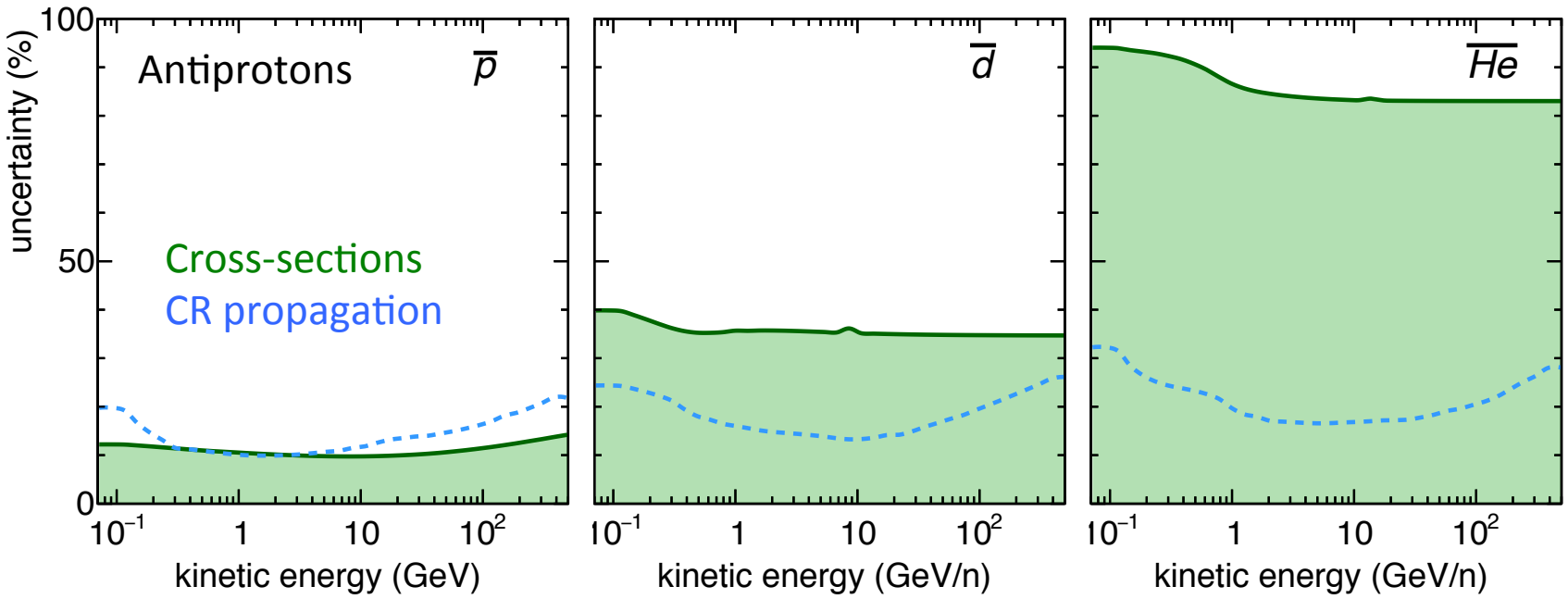




Propagation VS cross-section uncertainties



Reduce nuclear uncertainties

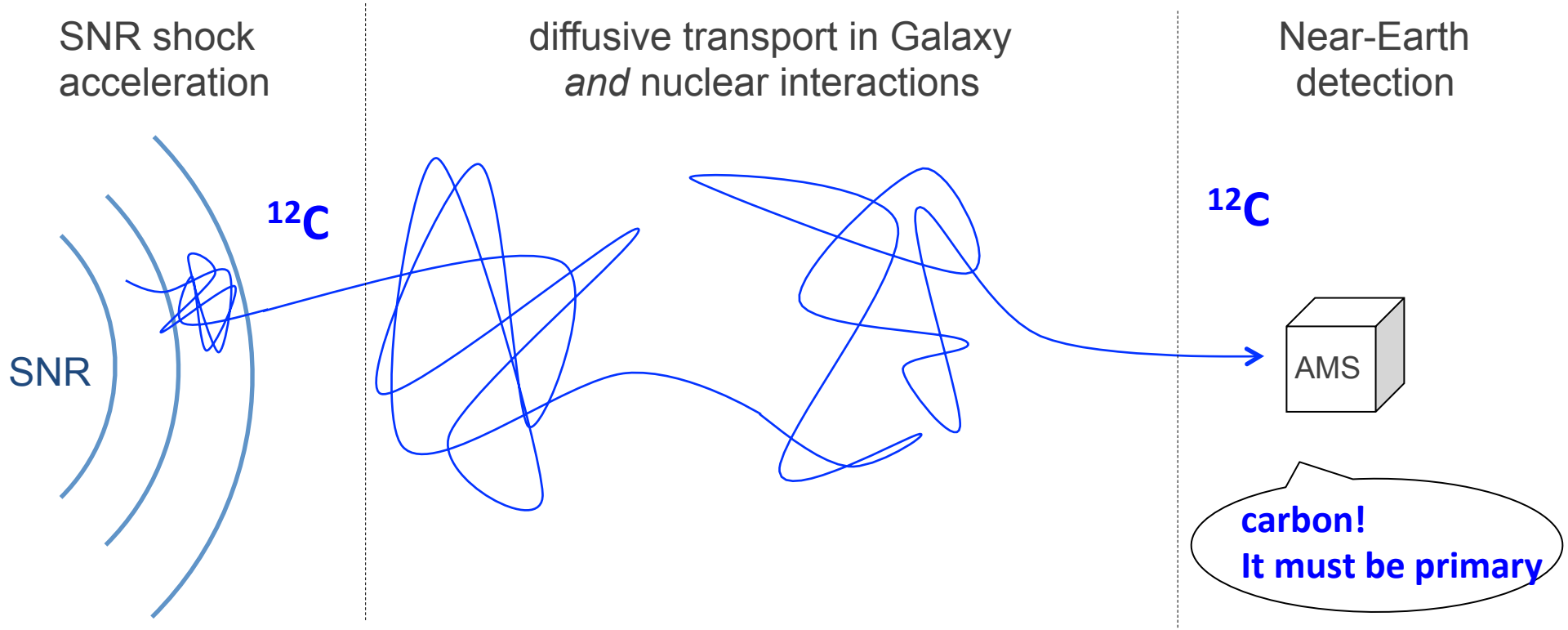
- Laboratory data on p+p or p+HE collisions
- Improve calculations or MC generators

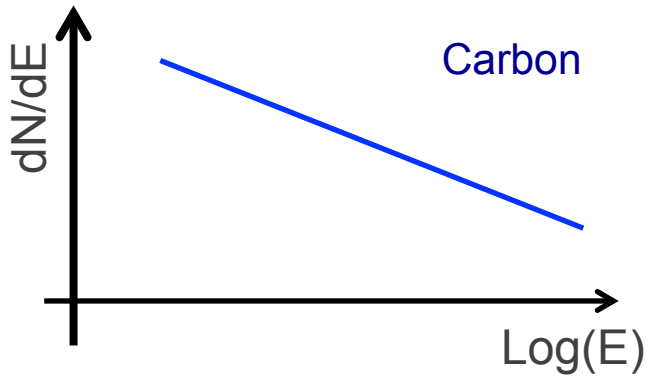
Reduce CR propagation uncertainties

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

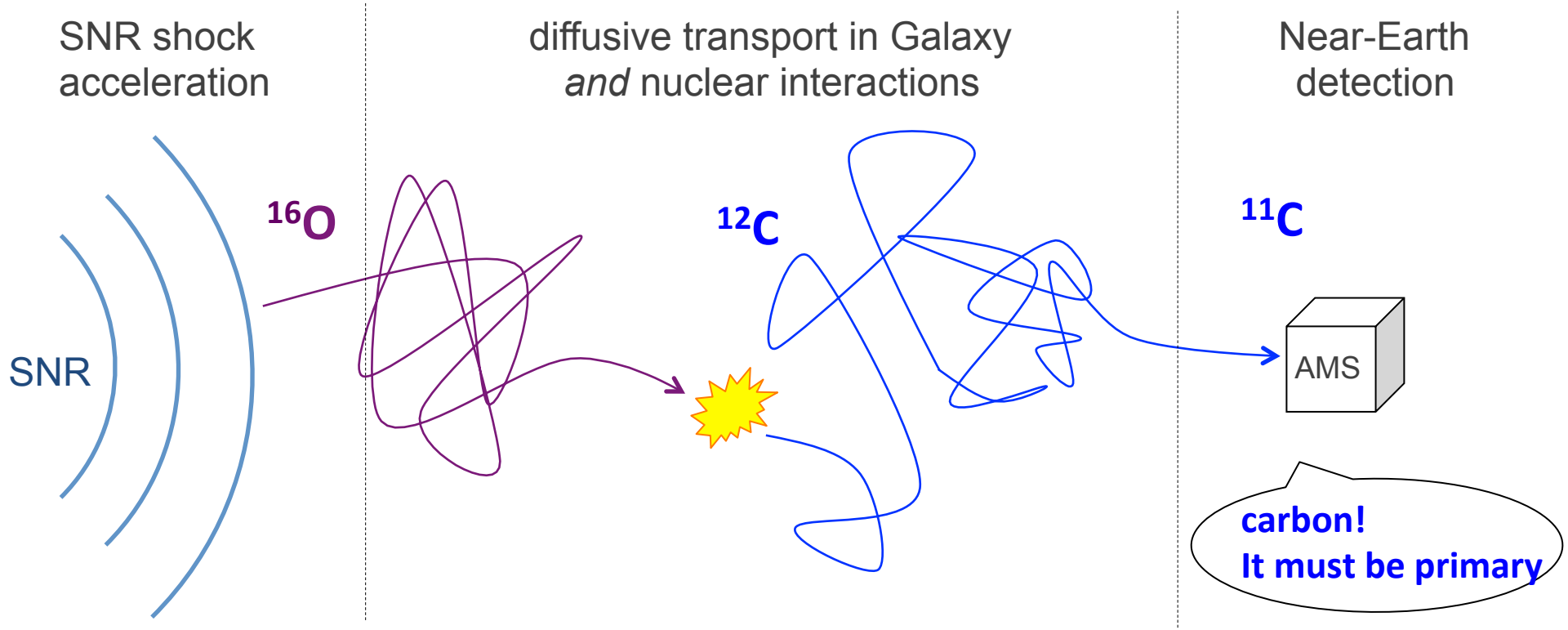
Shock accelerated secondaries

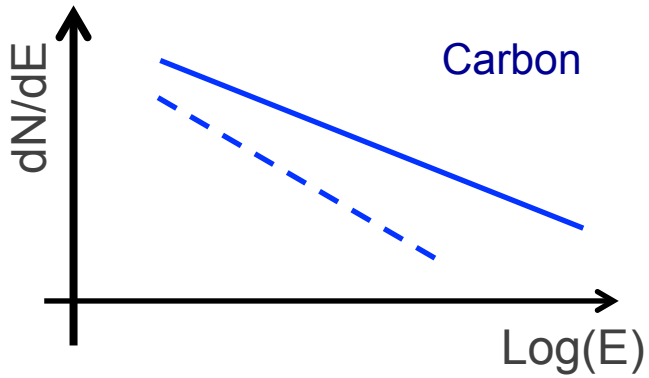
The physical picture



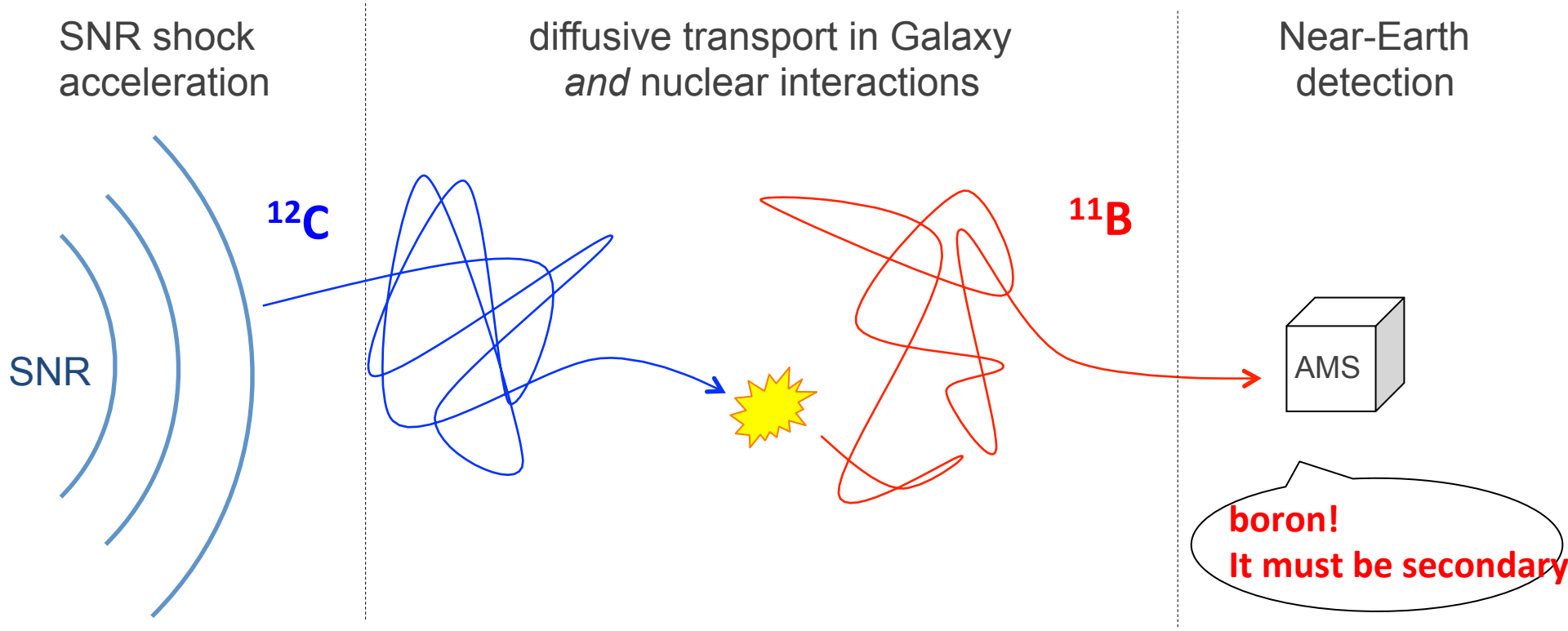


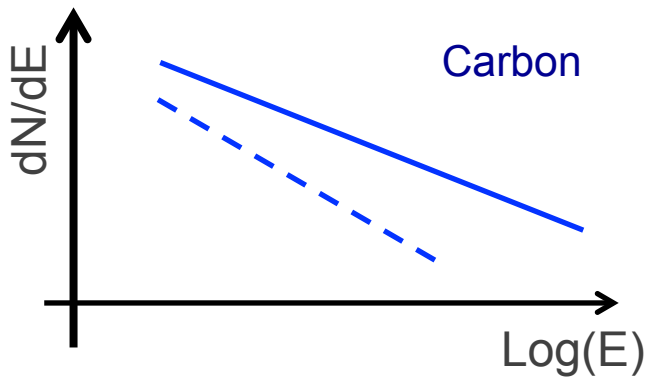
The physical picture

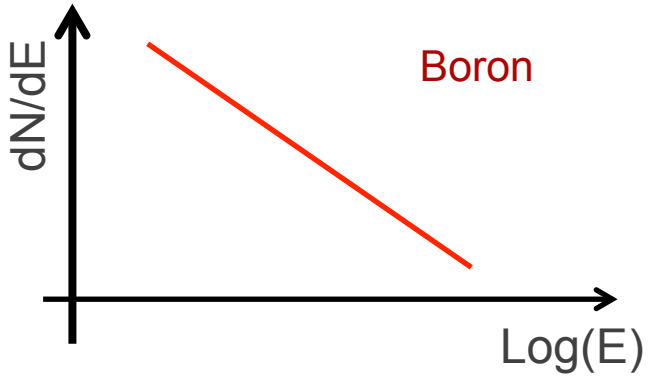




The physical picture







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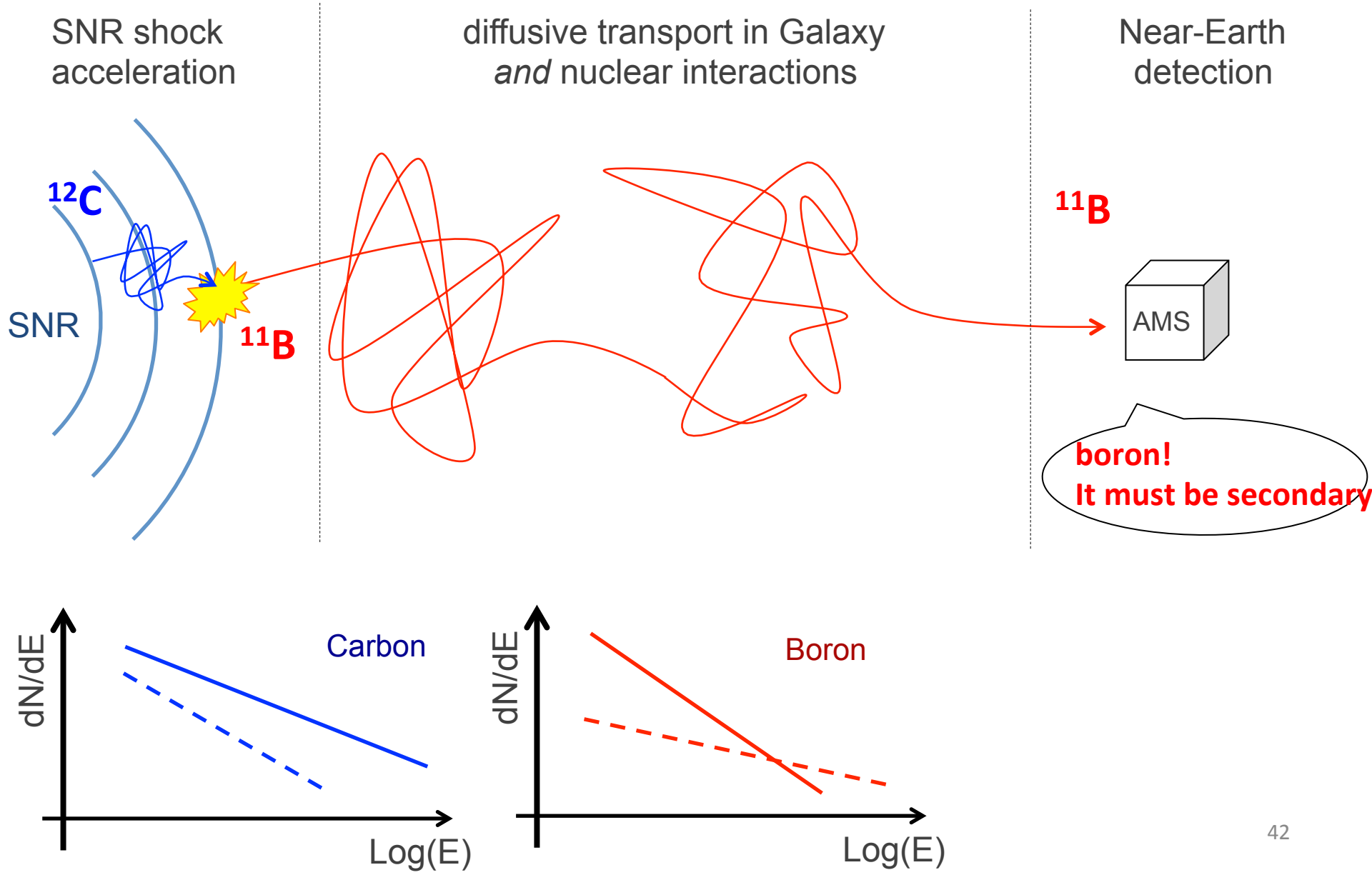

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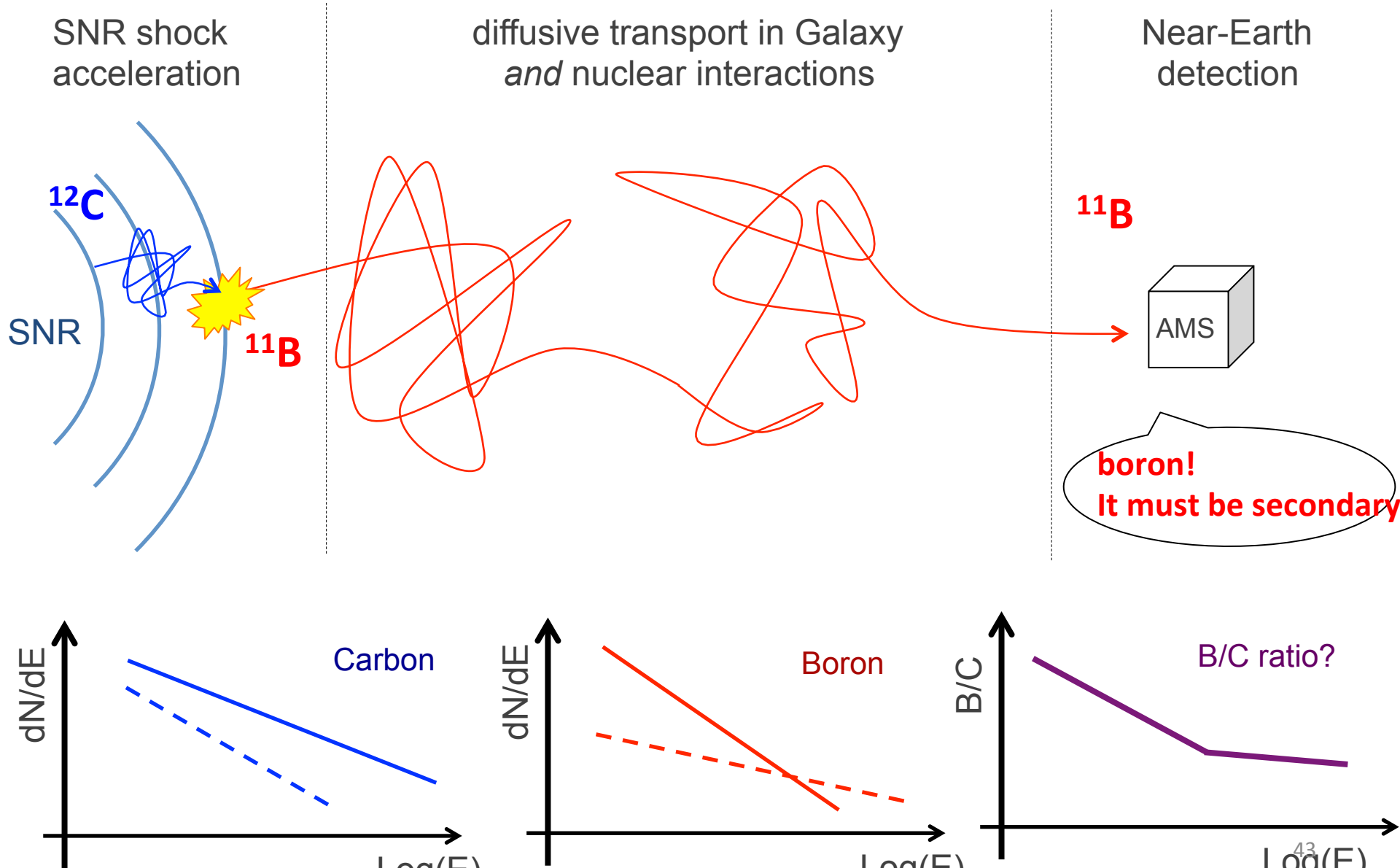

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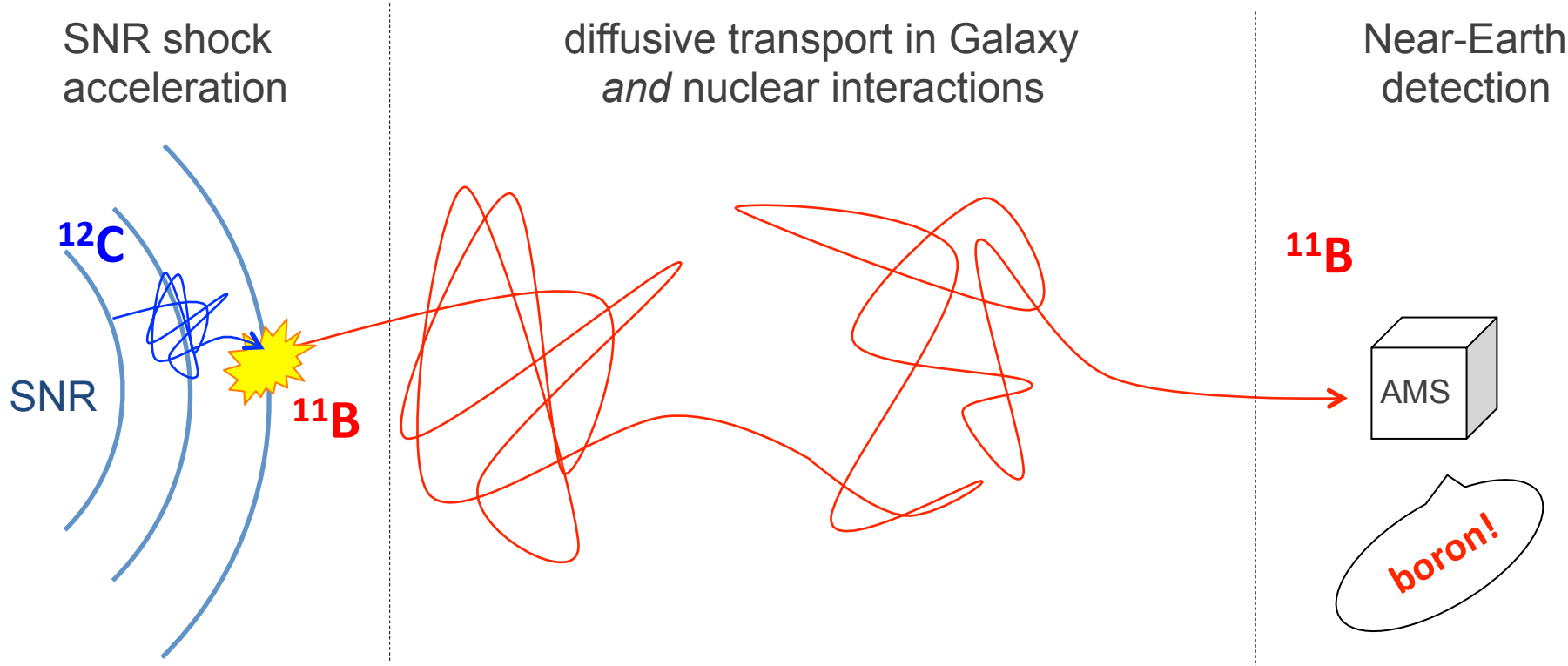
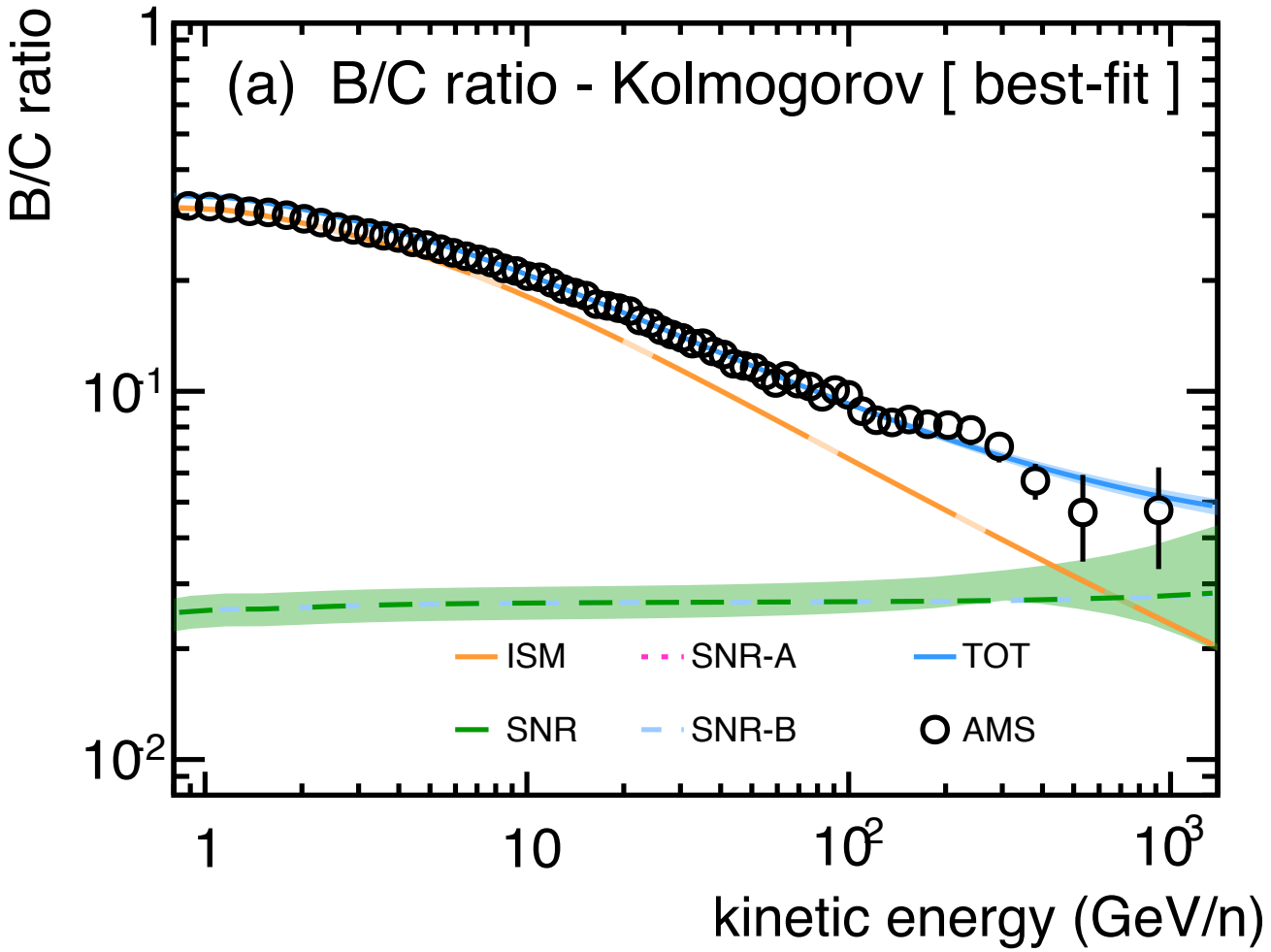


Fermi acceleration at SNR shocks *with interactions*

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

Shock accelerated B/C ratio

NT & Oliva 1707.06915

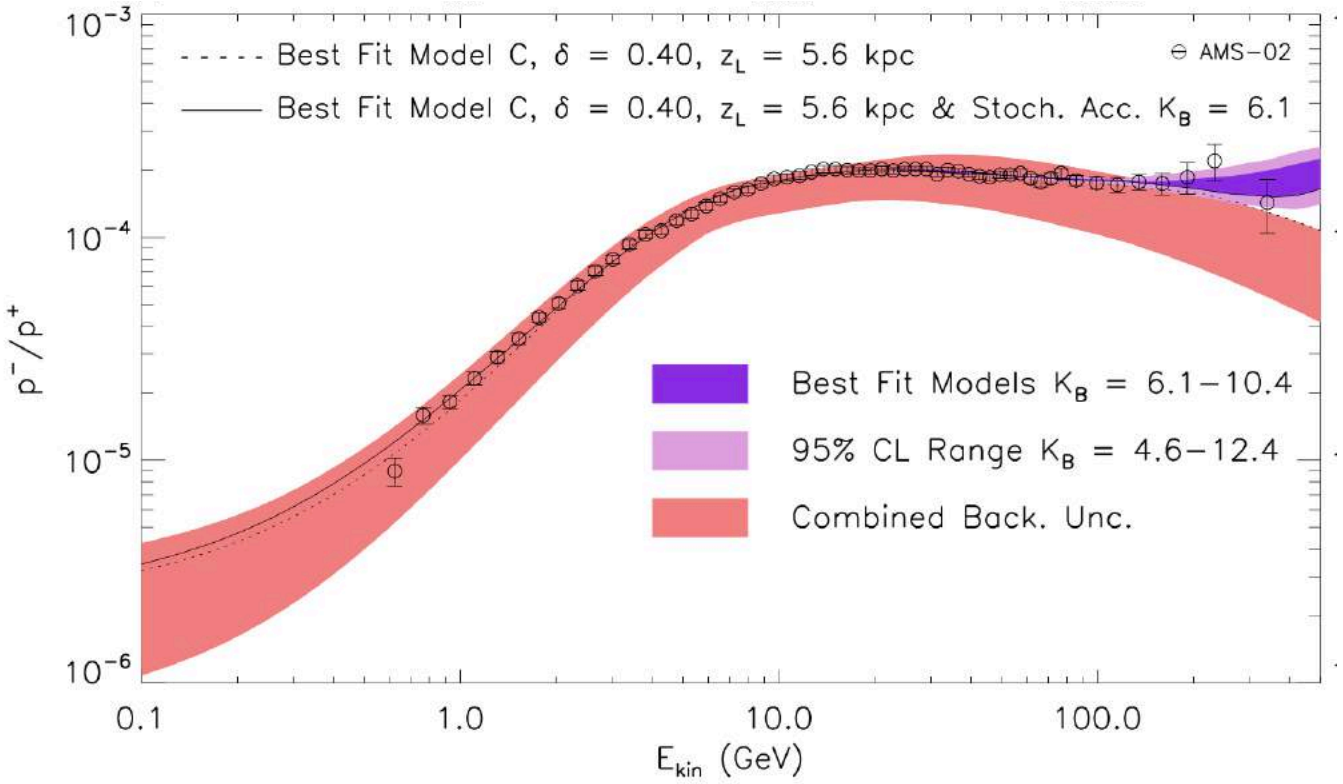


→ B/C ratio well described

→ Evidence for SNR accelerated Boron

Shock accelerated antiprotons

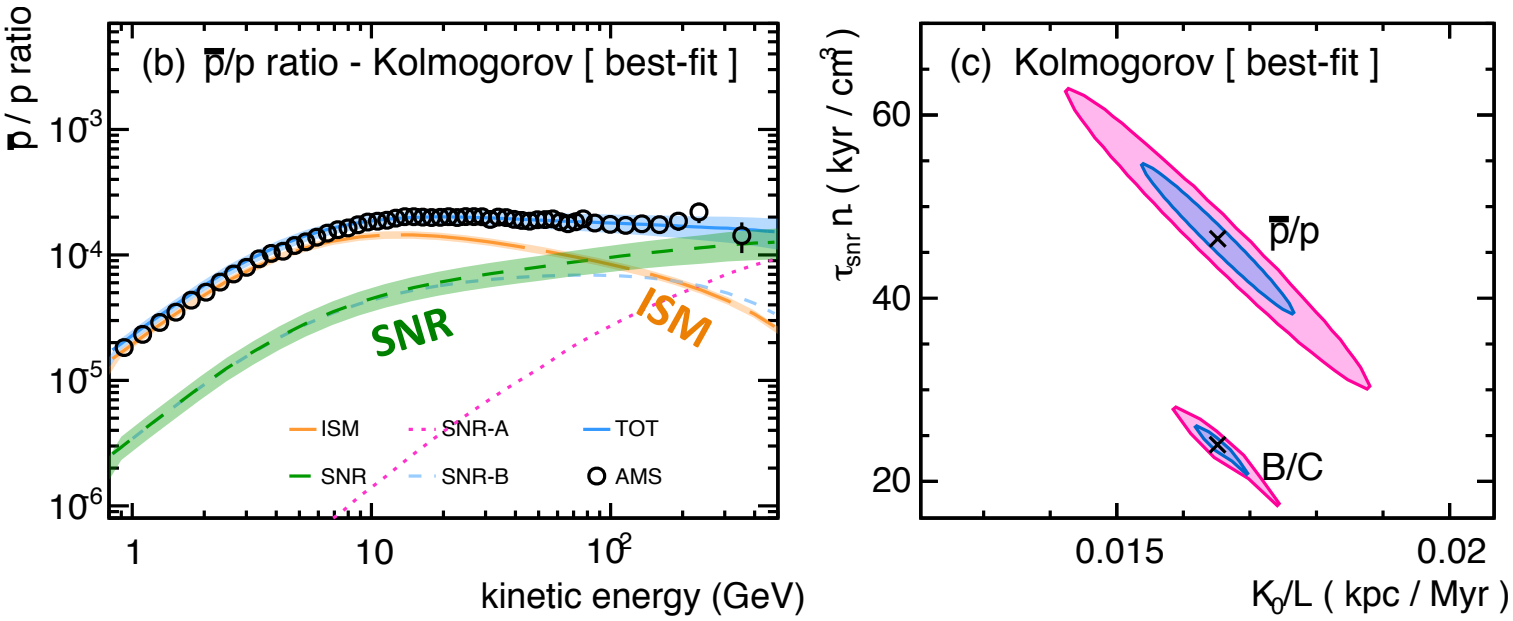
[Cholis, Hooper, Linden 1701.04406]



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

Shock accelerated anti-protons

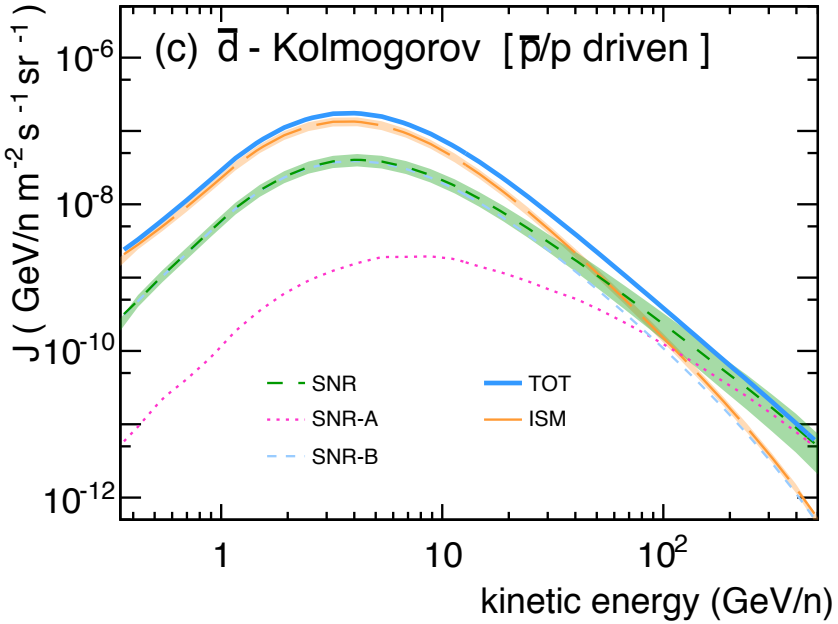
NT & Oliva 1707.06915

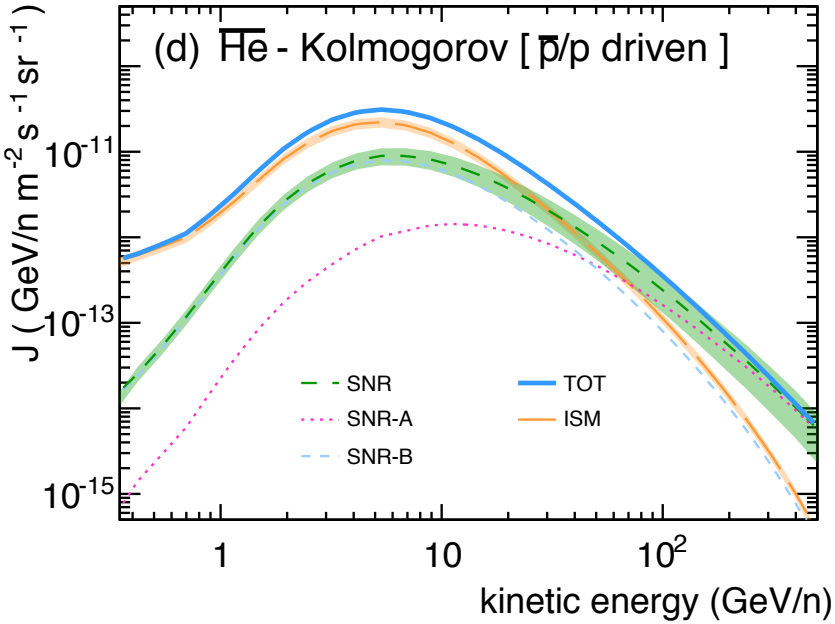


- ✓ Good fits to antiproton/proton ratio
- • Still inconsistent description of both B/C & pbar/p ratios

Shock accelerated anti-nuclei

NT & Oliva 1707.06915





- ✓ Pbar/p- driven model: upper limit to SNR accelerated antinuclei
- ✓ At E>>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

Nicola Tomassetti
Perugia University & INFN
27 July.2017 - Geneva