Production and Acceleration of Anti-Nuclei in Supernova Shockwaves

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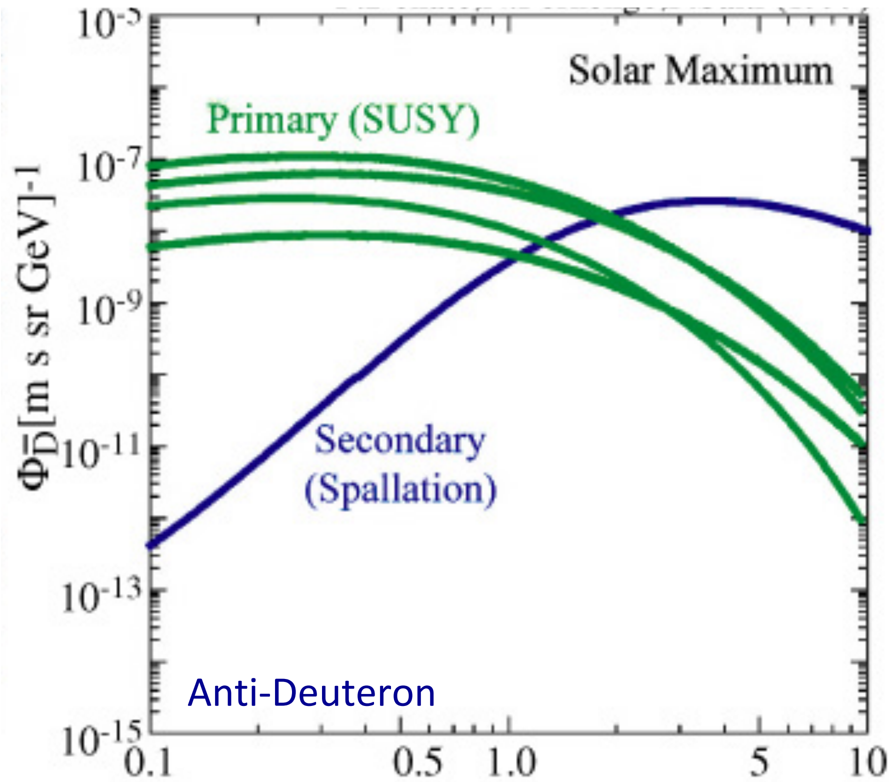
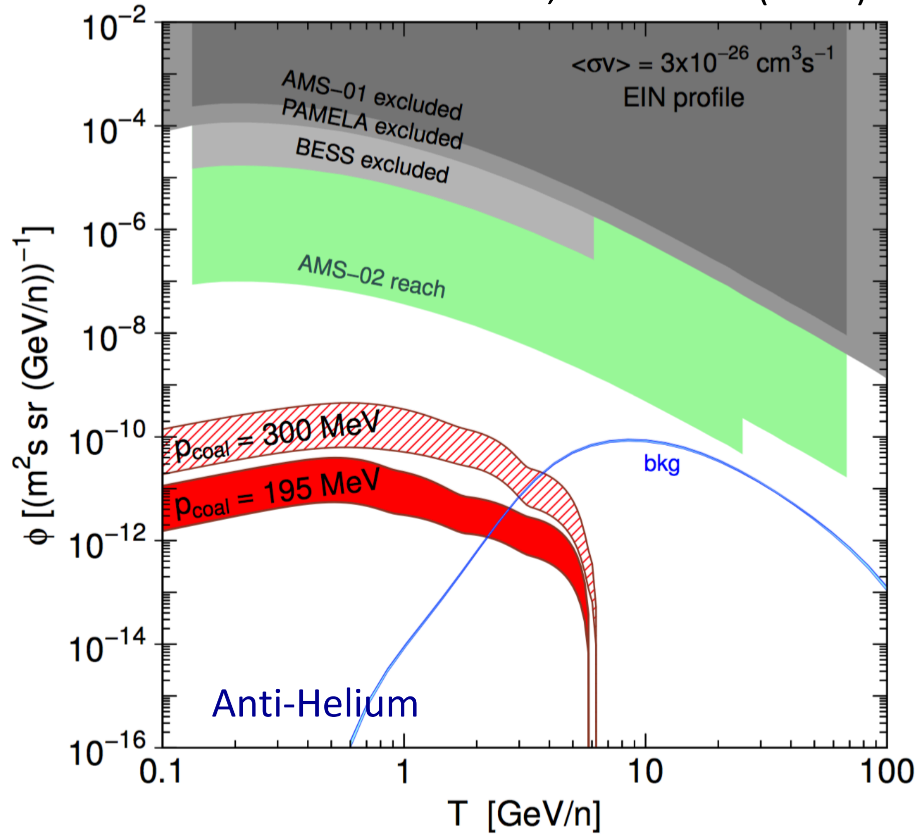
Indirect Search of Dark Matter with Anti-Nuclei

F. Donato et al., Phys. Rev. D 78 (2008)



Cirelli et al., JHEP 1408 (2014)

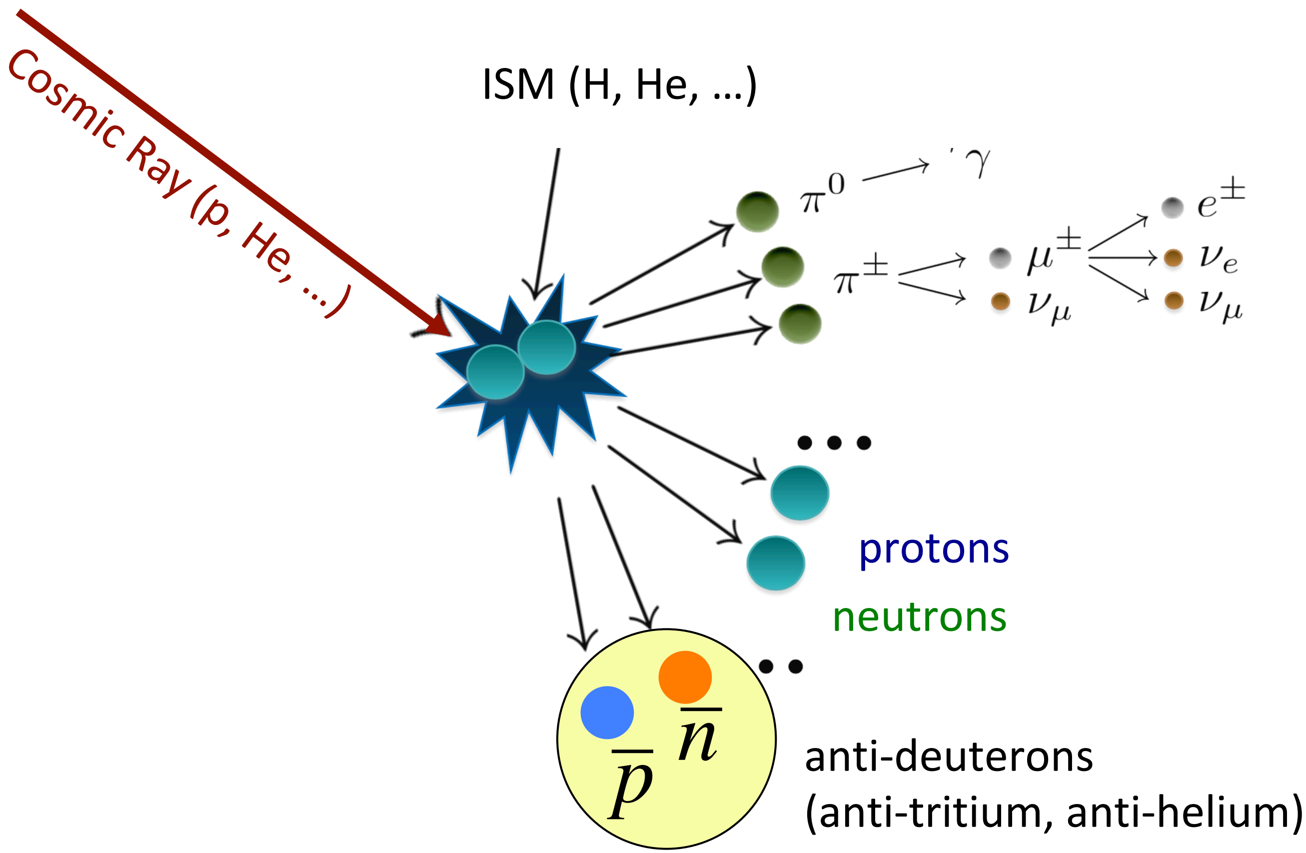


+ Promising signal/background ratio for a vast class of DM candidates

– Weak flux intensity, of both signal and background

Astrophysical Anti-Nuclei Background

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



Astrophysical Anti-Nuclei Background

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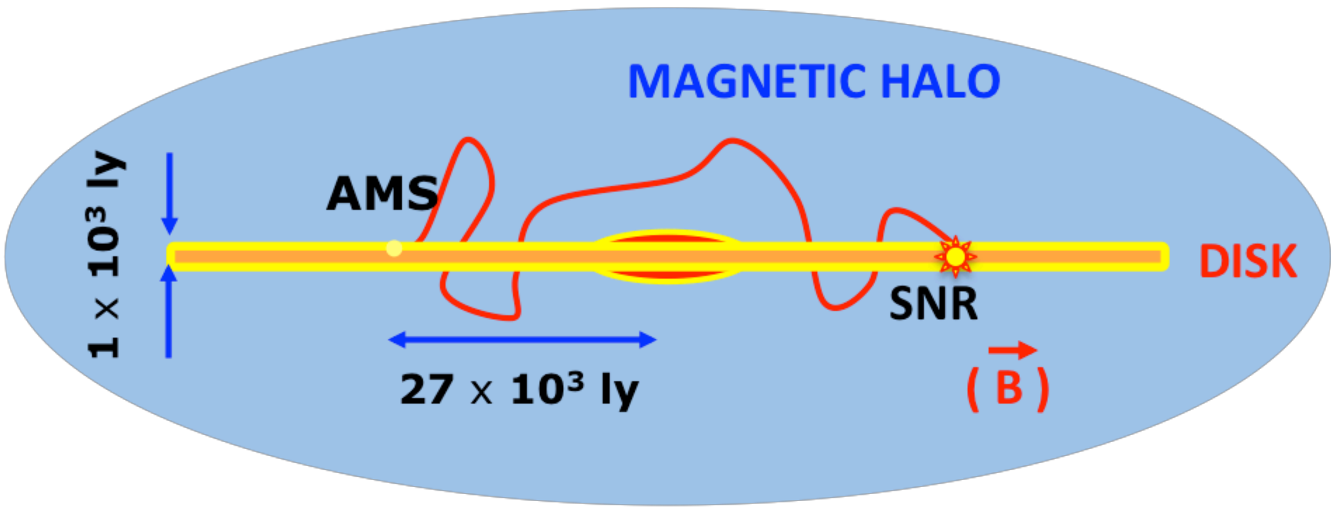
Propagation
in the Galaxy:
diffusive transport,
energy loss/gain
nuclear spallation



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

Solar modulation
in the Heliosphere:
diffusion, advection, drift

$$J_{\bar{A}}^{TOA}(E)$$ → **Detection**

Astrophysical and Nuclear Uncertainties

Main source of uncertainties in astrophysical BG calculations:

1) **PRIMARY CRs** – 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.

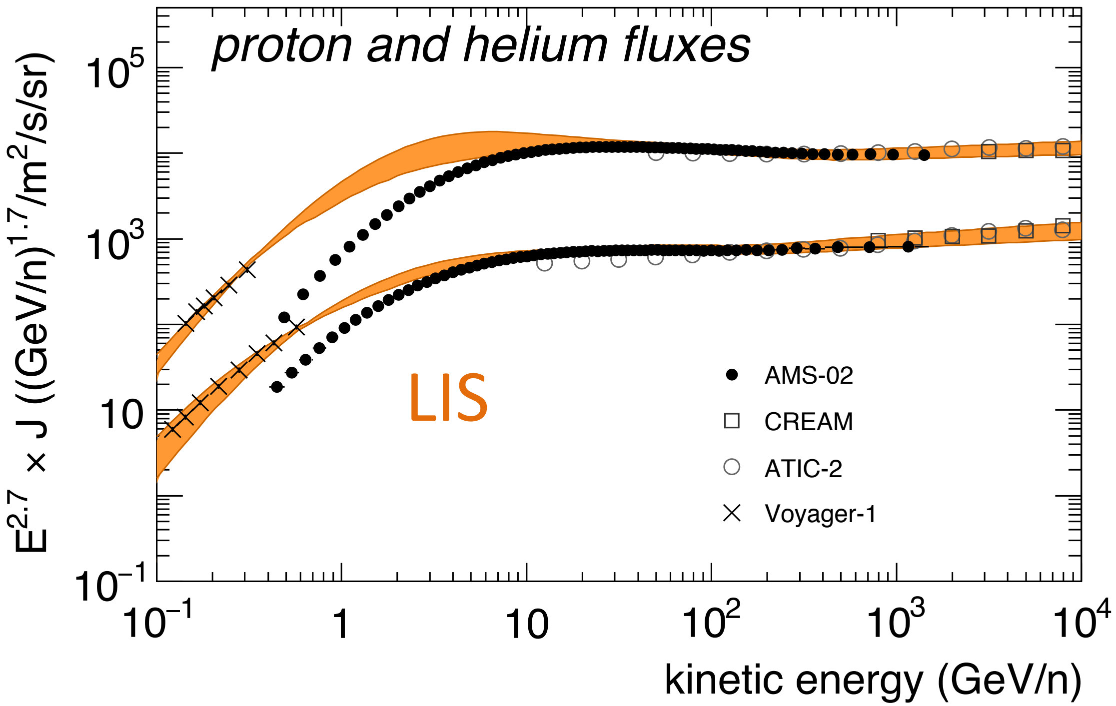
Uncertainties from Primary CR Spectra

Before PAMELA & AMS-02

- Universal power-law parameterization assumed. Same spectra for proton and He.
- Tightly constrained with proton data at O(100 GeV) energy scale.

After PAMELA & AMS-02

- Different spectra for proton and He nuclei + change in slope at ~300 GeV .
- Multi-TeV scale data essential. Increasing importance of helium at high-energy.
- Origin of spectral anomalies must be understood.



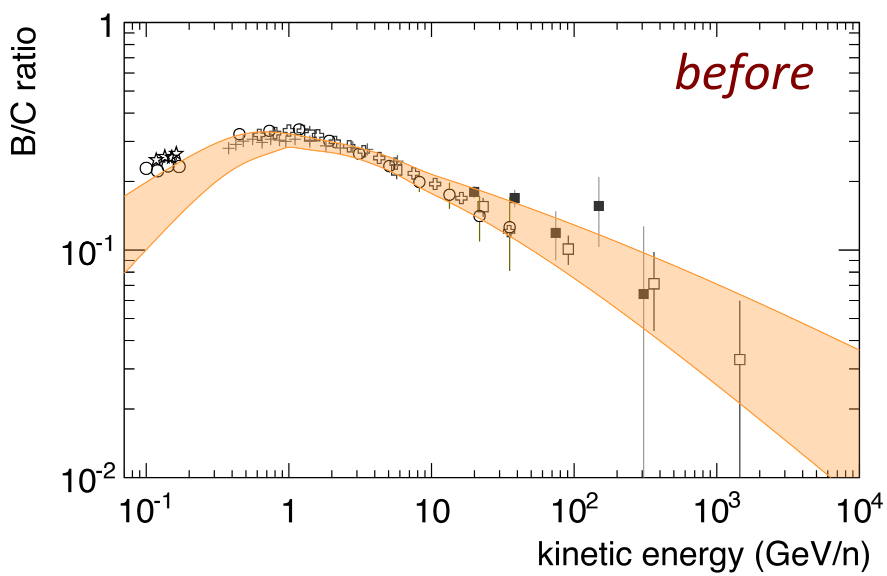
Uncertainties from CR Transport (I)

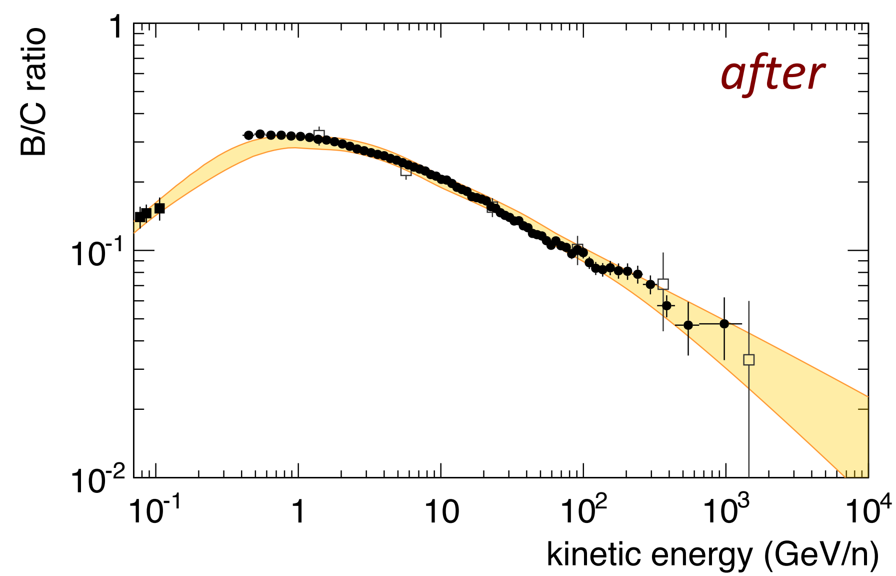
Before Voyager-1 & AMS-02

- Unclear B/C behavior at high energy. Poor constraints to high-energy transport.
- Strong degeneracy at low-energy (transport + solar modulation).

After Voyager-1 & AMS-02

- AMS-02 + PAMELA + Voyager-1 data become available.
- Tight constraints on CR diffusion.
- Increasing importance of XS uncertainties for boron production.
- Halo-Diffusion K/L degeneracy still unbroken.

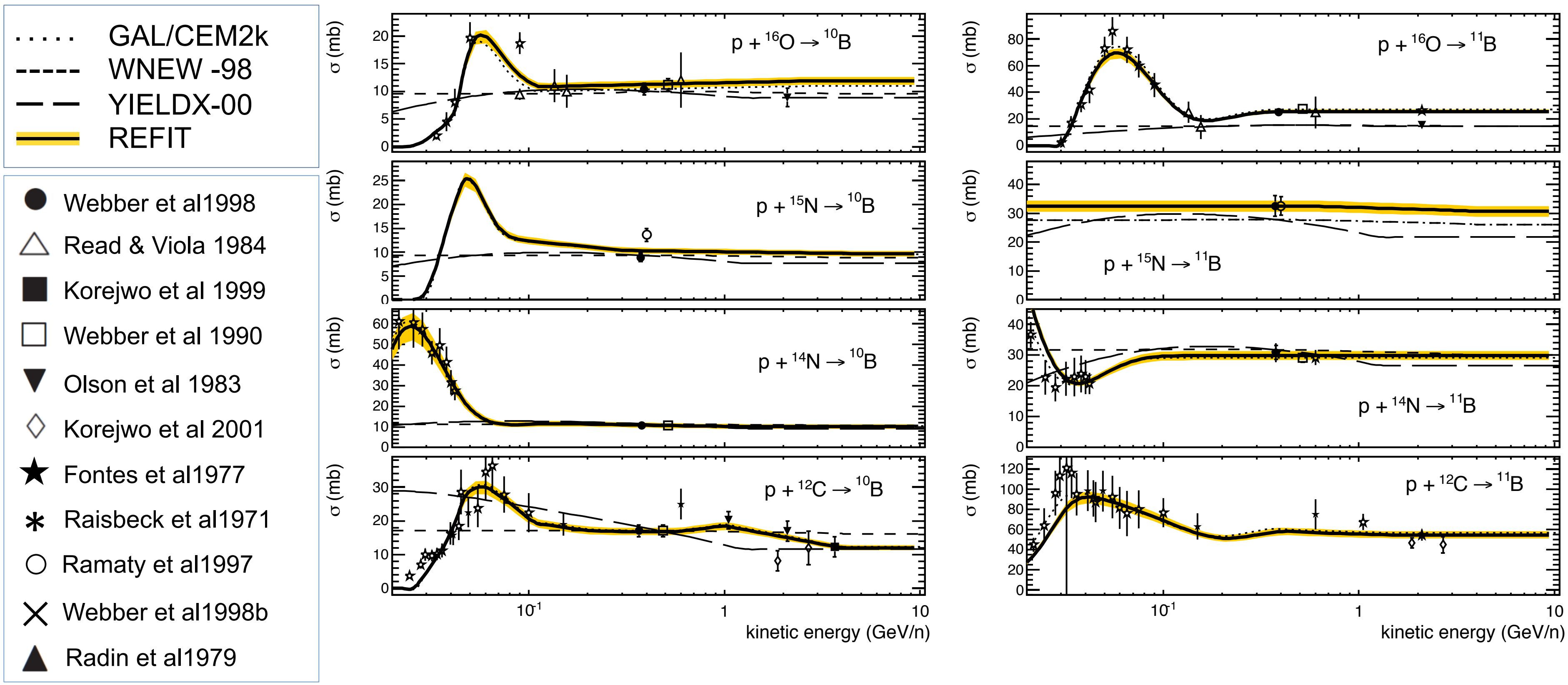




Using a two halo model as in J. Feng et al., Phys. Rev. D 94 (2016).

Uncertainties from CR Transport (II)

- Nuclear fragmentation XSs for CNO(p,X)B.
- Data collected in ~1970's – early 2000. Available at E = 20MeV/n – 10GeV/n.
- Semi-empirical parameterizations: Webber '98 + Sielberberg & Tsao 2000 + GALPROP.
- Using XS from N. Tomassetti, Phys. Rev. C 92 (2015).

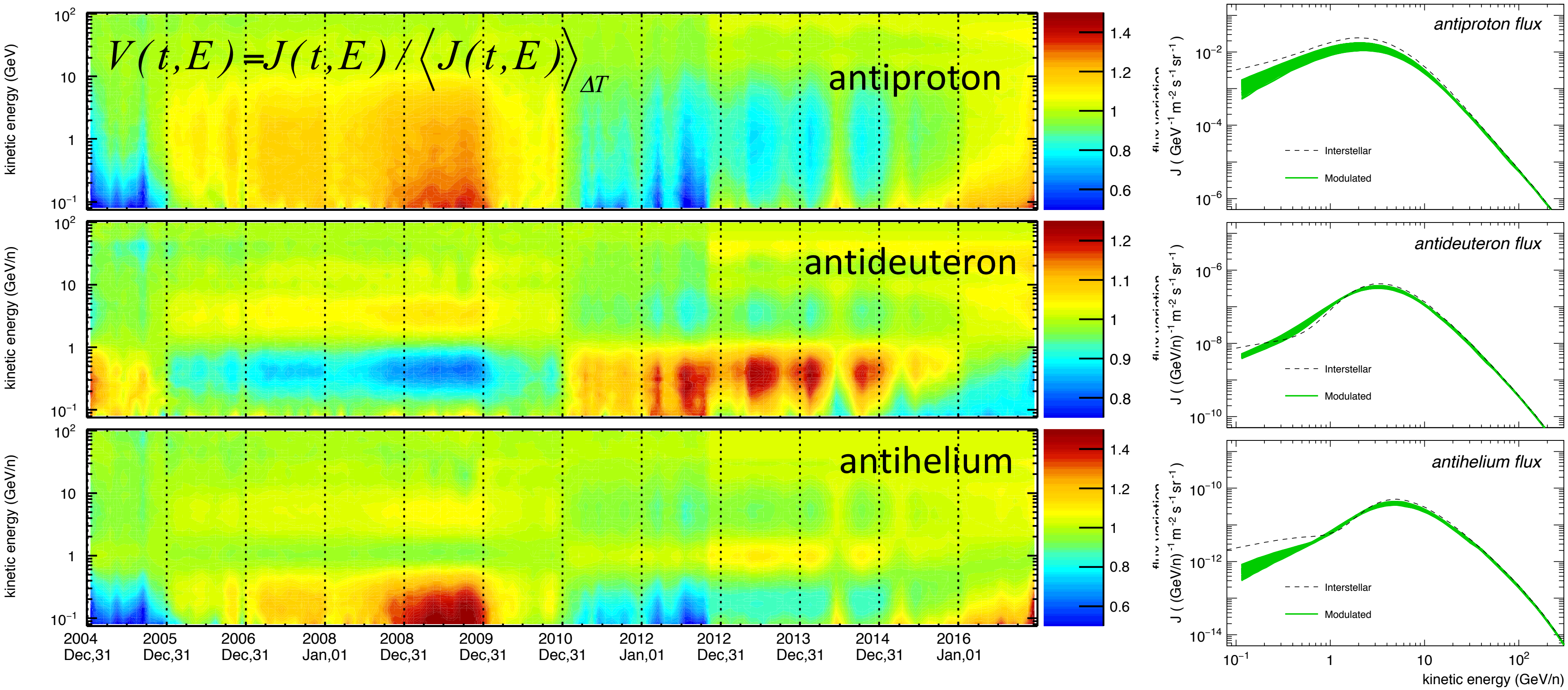


Uncertainty on the B/C ratio of 7-9%.
Limiting factor in the interpretation of other secondary species.

Uncertainties from Solar Modulation

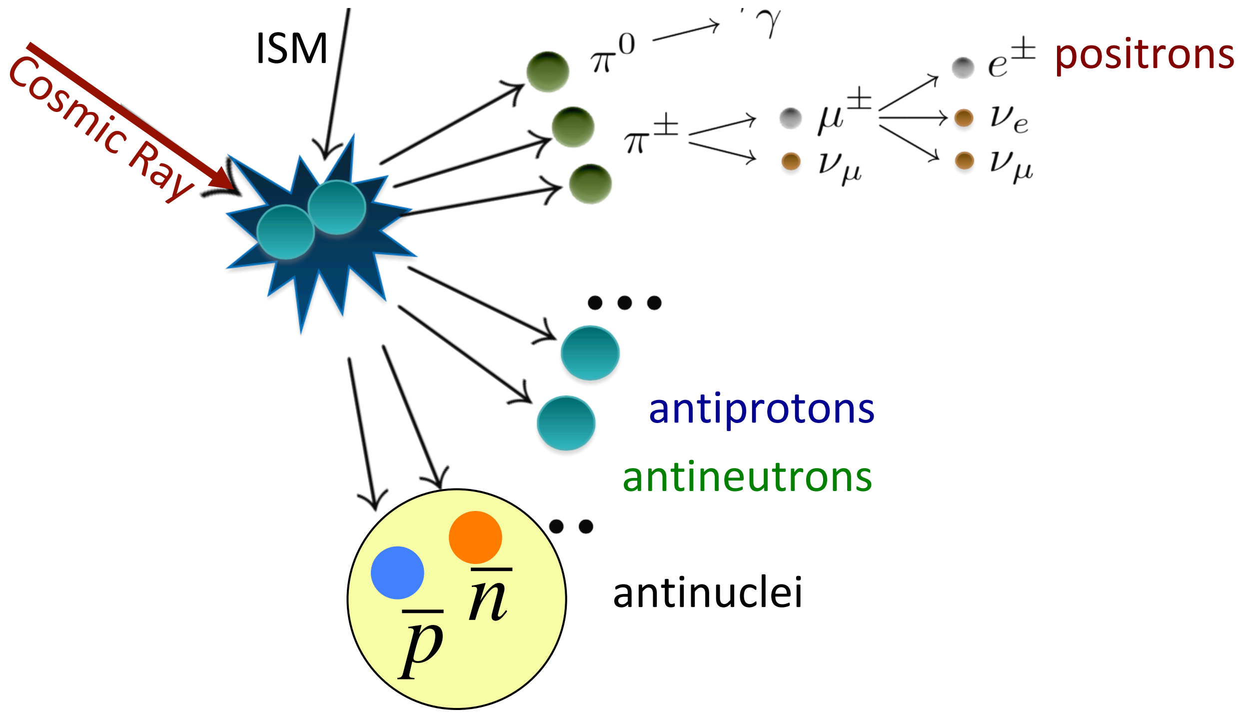
Recent Milestones

- Voyager-1: **interstellar data** on CR proton, helium, all-electron.
- AMS & PAMELA: continuous **time-series** of multichannel solar-modulated fluxes.
- Development & availability of numerical models w/ **charge-sign** dependent effects.



Use SOLARPROP (Kappl et al., CPC 207 (2016)) and derive uncertainty from NM.
Derive additional uncertainty from the charge-conjugate flux.

Uncertainties from Production



Production of anti-nucleons

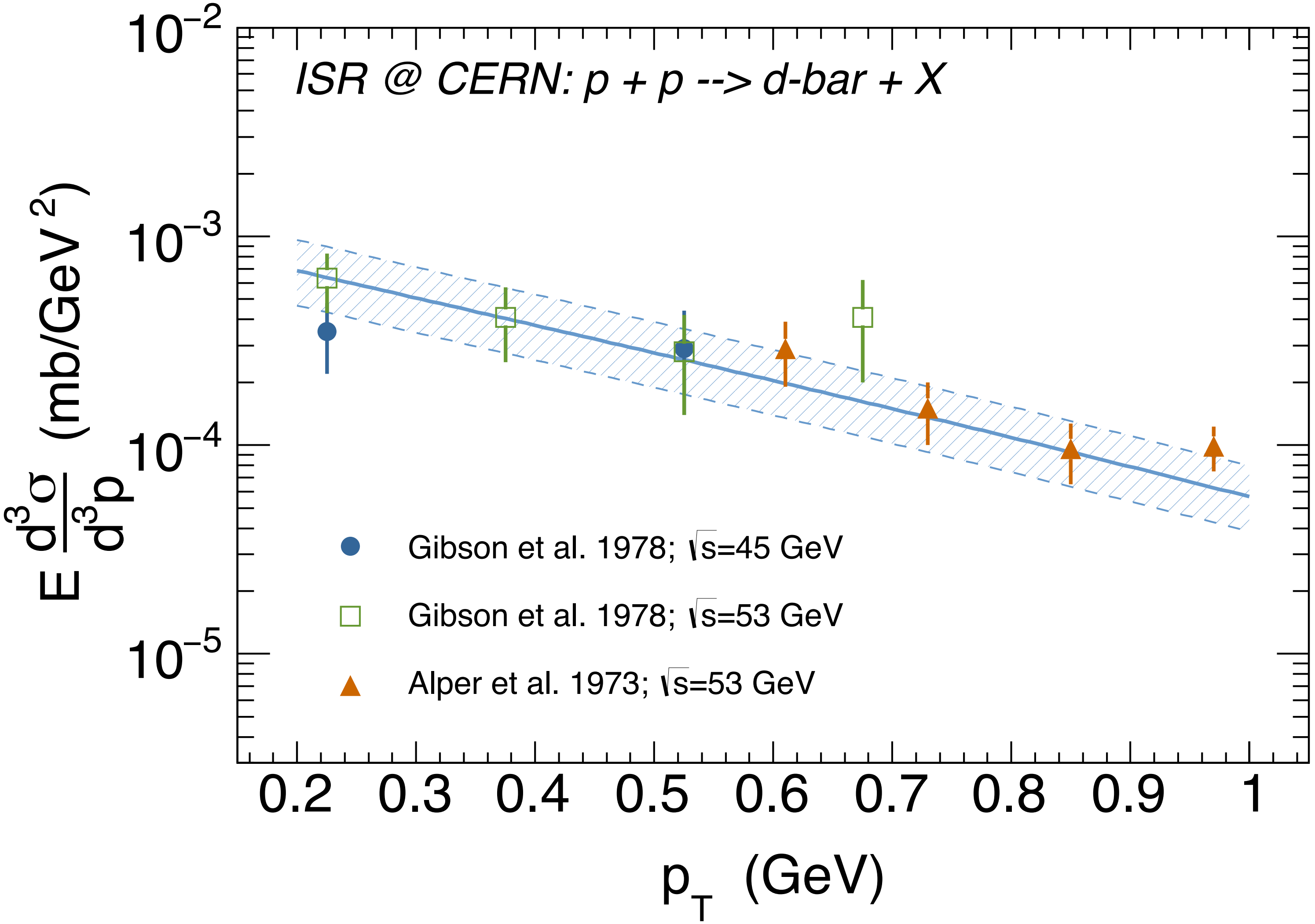
- New data, new parameterizations and MC-based calculations are now available.
- We tested many of them in J. Feng et al., Phys. Rev. D 94 (2016). [QGSJET-II, EPOS-LHC, …]
- We choose to use M. Di Mauro et al., Phys. Rev. D 90 (2014). We set n-bar/p-bar > 1.

Production of A>1 antinuclei

- Improved coalescence model for antinuclei, allowing for different nbar/pbar production.
- Collisions p+H, p+He, He+H, He+He, p-bar+H, p-bar+He + tertiary
- 2H-bar {nbar+pbar}, 3H-bar {nbar+nbar+pbar} 3He-bar {nbar+pbar+pbar}

Anti-Deuteron: Nuclear Coalescence & Uncertainties

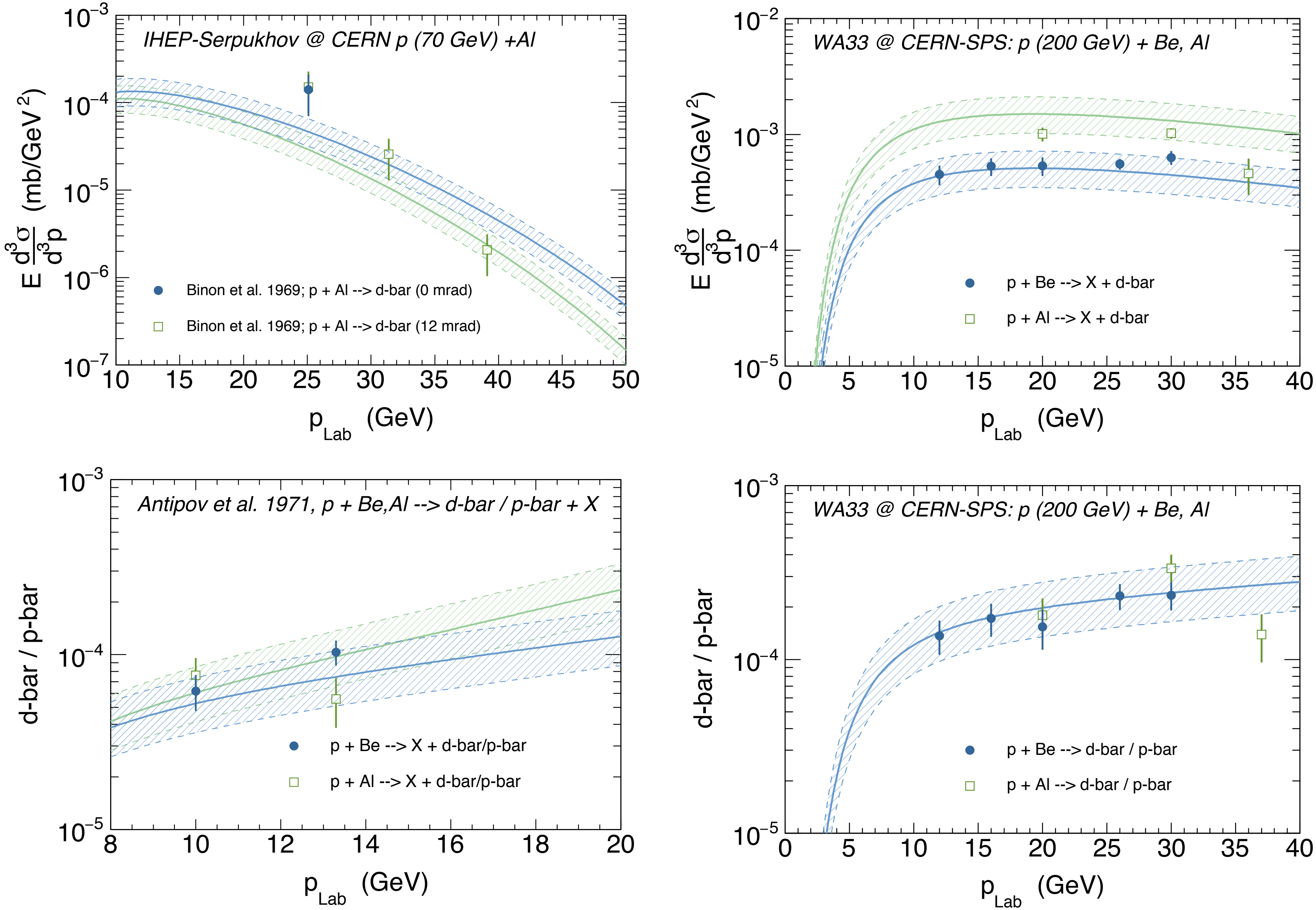
Use accelerator data since ~ 1972: p+p , p+Be, p+Al @CERN



Coalescence momentum is constrained with 12% uncertainty

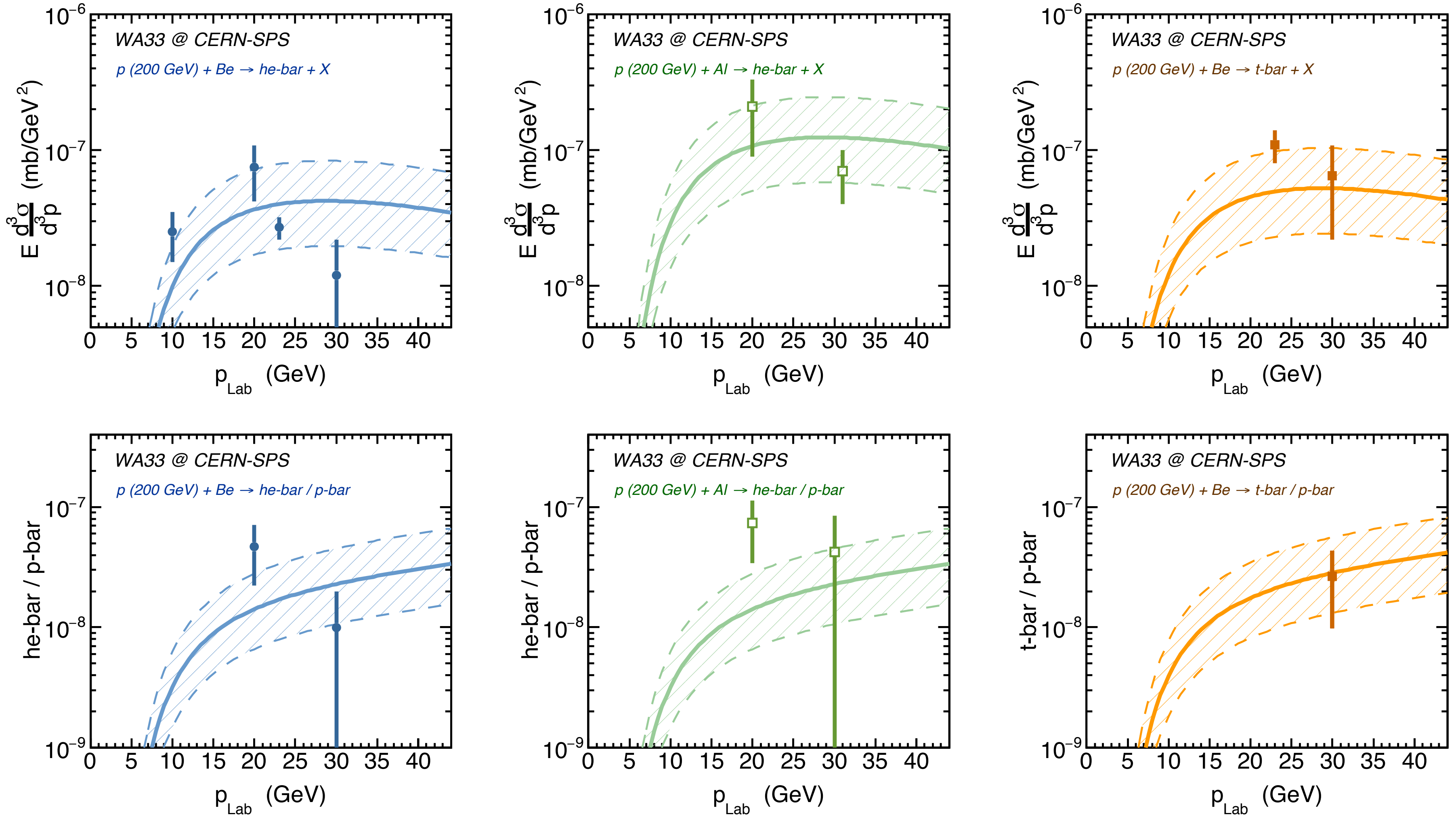
Anti-Deuteron: Nuclear Coalescence & Uncertainties

Many data are on p+Be or p+Al. Use of XS ratio d-bar/p-bar to cancel out common factors.



Anti-Helium: Nuclear Coalescence & Uncertainties

He-bar and T-bar production measurements are very scarce → poor constraints.
Using the same coalescence momentum of d-bar, we get a reasonable description.



The importance of being tertiary

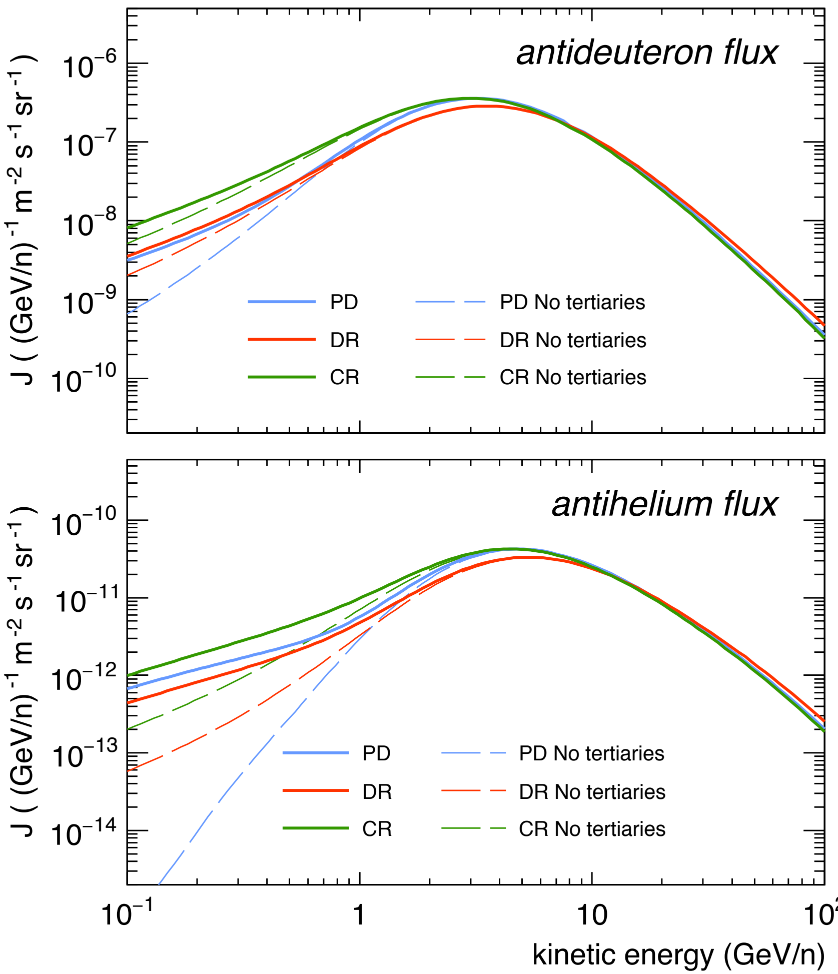
NAR $\bar{A} + ISM \rightarrow \bar{A}' + X$

Dashed: fluxes w/o tertiary production.

- Sharp low-energy depletion in PD models.
- Significant effect of reacceleration and convection (in shaping low-energy flux).

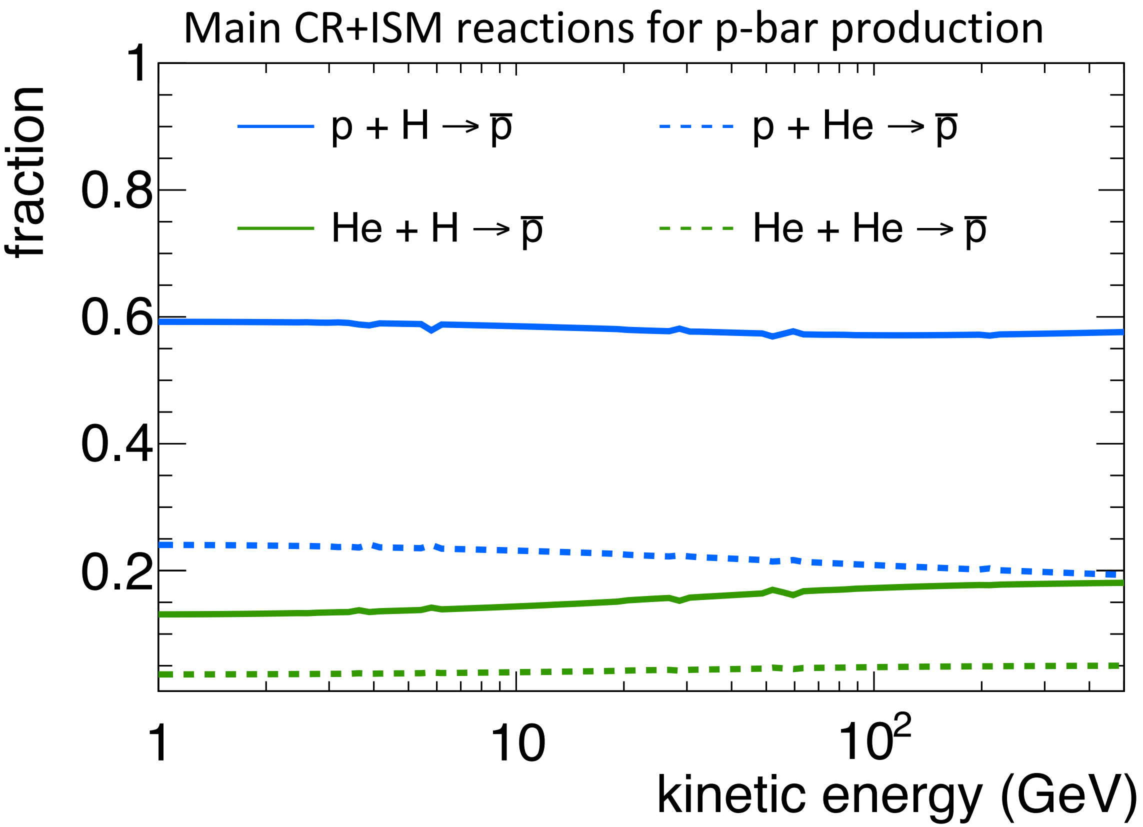
Solid: tertiary production accounted.

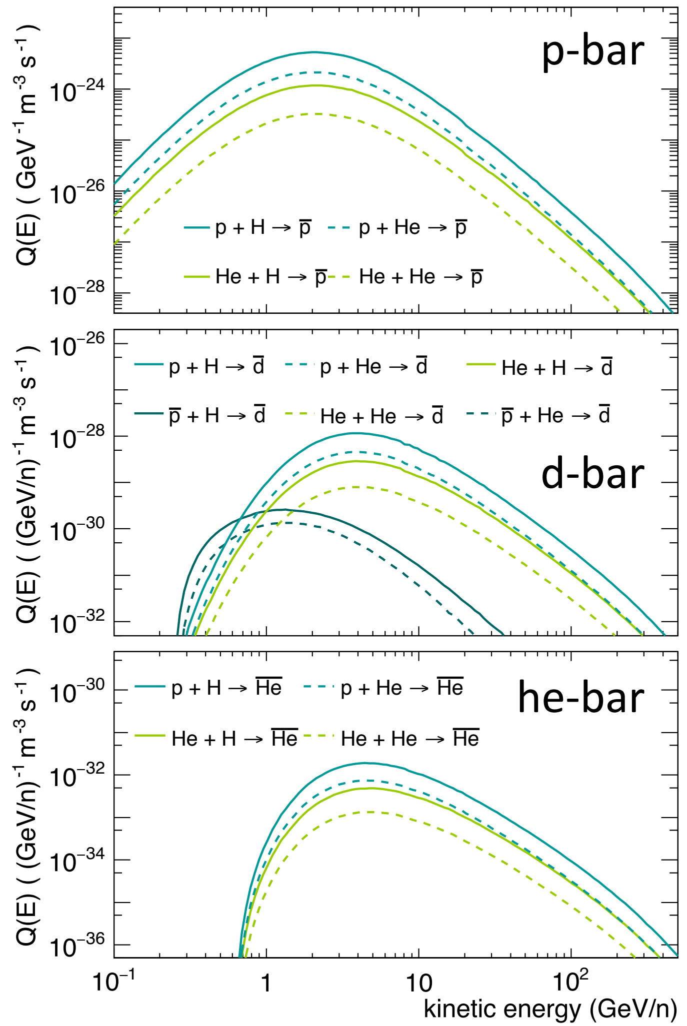
- anti-deuteron: from Duperray et al., Phys. Rev. D 71 (2005).
- anti-helium: assumed same BR as d-bar (→ not known).
- Smoother sub-GeV/n flux, less sensitive to propagation loss/gain effects.
- Large uncertainty in tertiary production.



The sub-GeV region is appreciably influenced by tertiary production processes.

CR+ISM Secondary Source Spectra



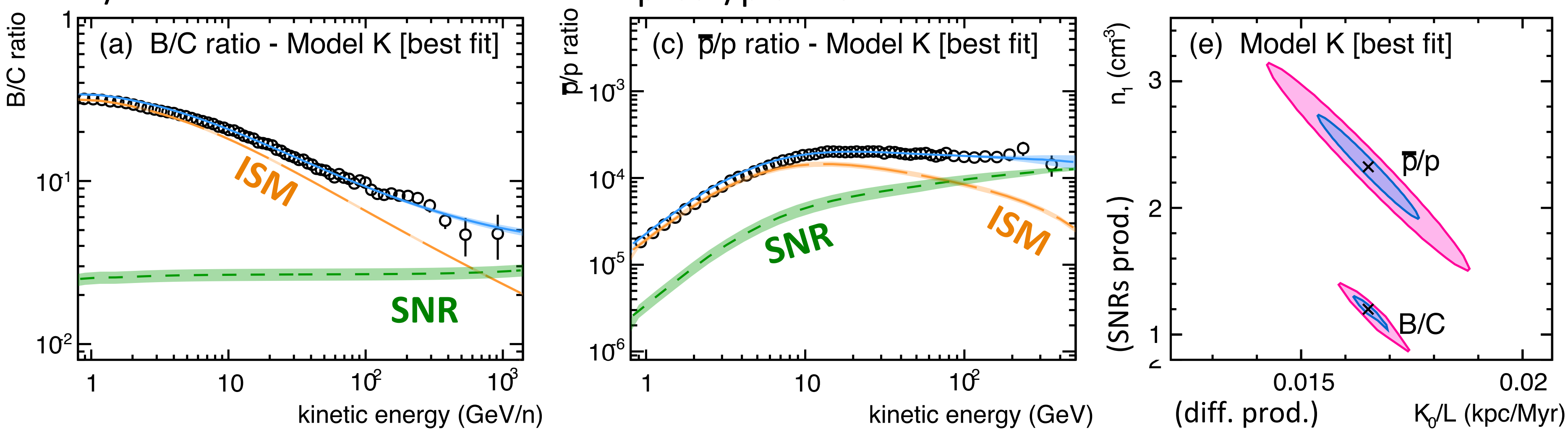


Anti-Nuclei from Supernova Remnants

Using approach of N. Tomassetti et al., Astroph. J. Lett. 835 (2017) [DSA theory].

B/C driven fit

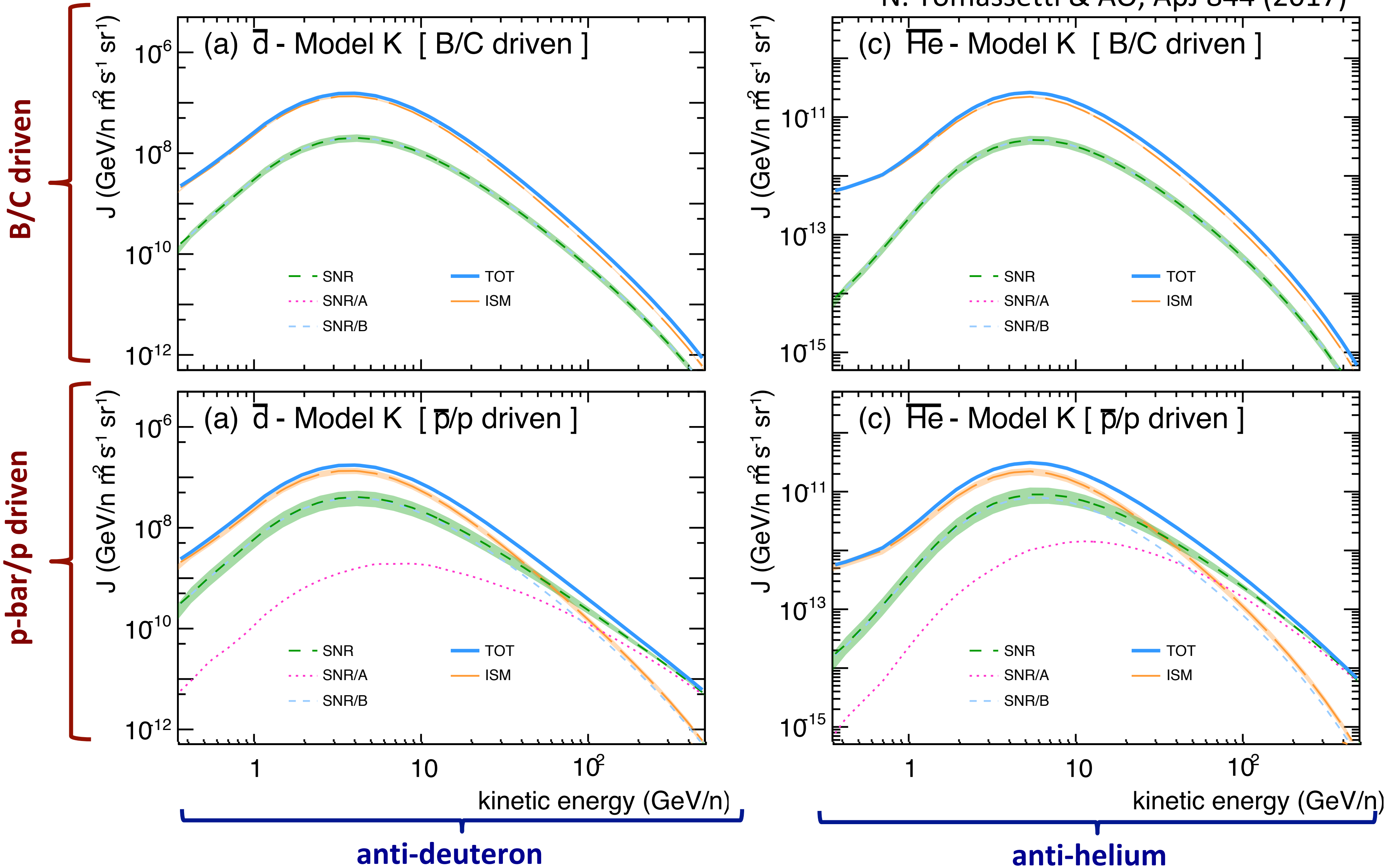
p-bar/p driven fit



The B/C ratio gives tight constraints on SNR production of Boron nuclei.
Evidence for SNR-induced Boron components.
SNR production is subdominant w.r.t. ISM production.
Inconsistency between B/C and p-bar/p driven fits.

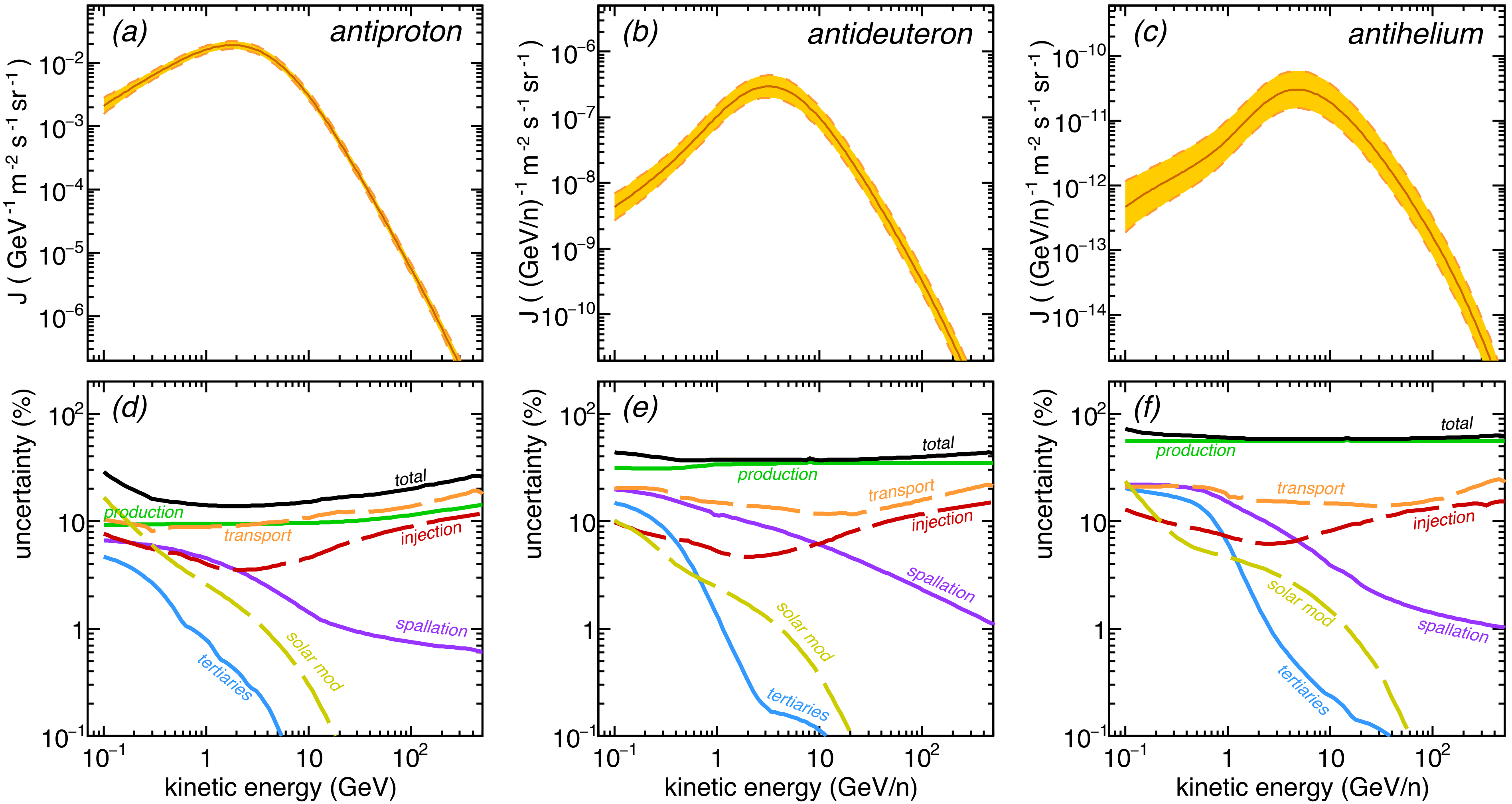
Anti-Nuclei from Supernova Remnants

N. Tomassetti & AO, ApJ 844 (2017)



p-bar/p scenario predicts higher SNRs contribution (predicted B/C too high).
However, similar prediction of total flux in the two scenarios.

Full Uncertainty Breakdown of CR Anti-Nuclei



→ a bit of caution, errors are correlated.

Uncertinties in calculations are dominated by nuclear coalescence.

Conclusions

Astrophysical background to anti-nuclei in CRs have been calculated including error analysis on **primary CRs fluxes, CR transport, solar modulation, anti-nuclei production, spallation, tertiary re-scattering component.**

Some observations:
→ New B/C data from AMS-02 and Voyager-1 pose tight constraints on CR transport.
→ Important cross-section uncertainties in Boron production (→ Li, Be?).
→ Production in SNR included. No big impact in secondary anti-nuclei.
→ Production XSs are the dominating uncertainties for all anti-nuclei.
→ Anti-deuterons and anti-helium: XS measurements needed. Tertiary poorly known.

Remark:
This work should be updated.
→ Not included recent measurements LHCb p+He→p-bar, SHINE p+p→p-bar, ALICE p+p→d-bar, t-bar, he-bar. Expected to lower the anti-nuclei production uncertainty.
→ Impact of different parameterization of p-bar production cross section (M.W. Winkler JCAP02 (2017), …) still to be evaluated.
→ Impact of new coalescence parameterizations (D. M. Gomez-Coral et al., Phys Rev. D 98 (2018)) still to be evaluated.