

# *Production and Acceleration of Anti-Nuclei in Supernova Shockwaves*

*[based on N. Tomassetti and AO APJ Lett. 844 (2017)]*

*A. Oliva*

*Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy*

*LAN 2019,  
17/19/2019,  
Leiden, Holland*

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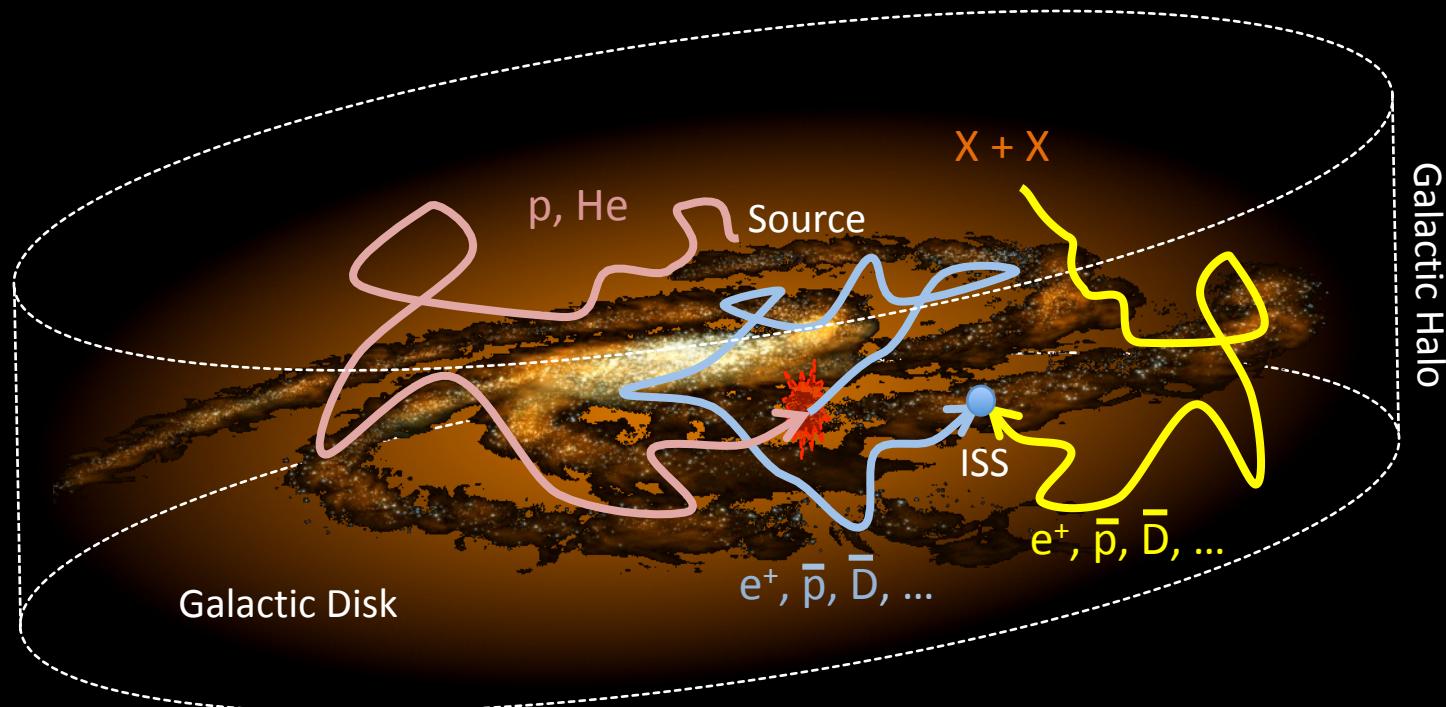
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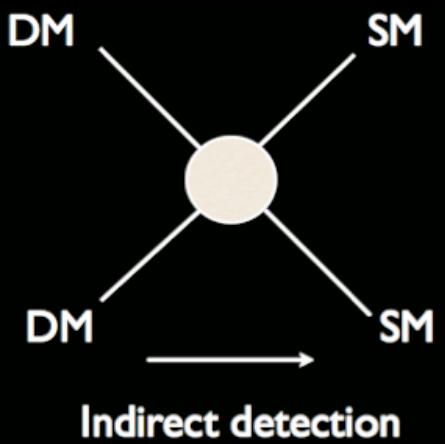
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# Indirect Search of Dark Matter with Anti-Nuclei

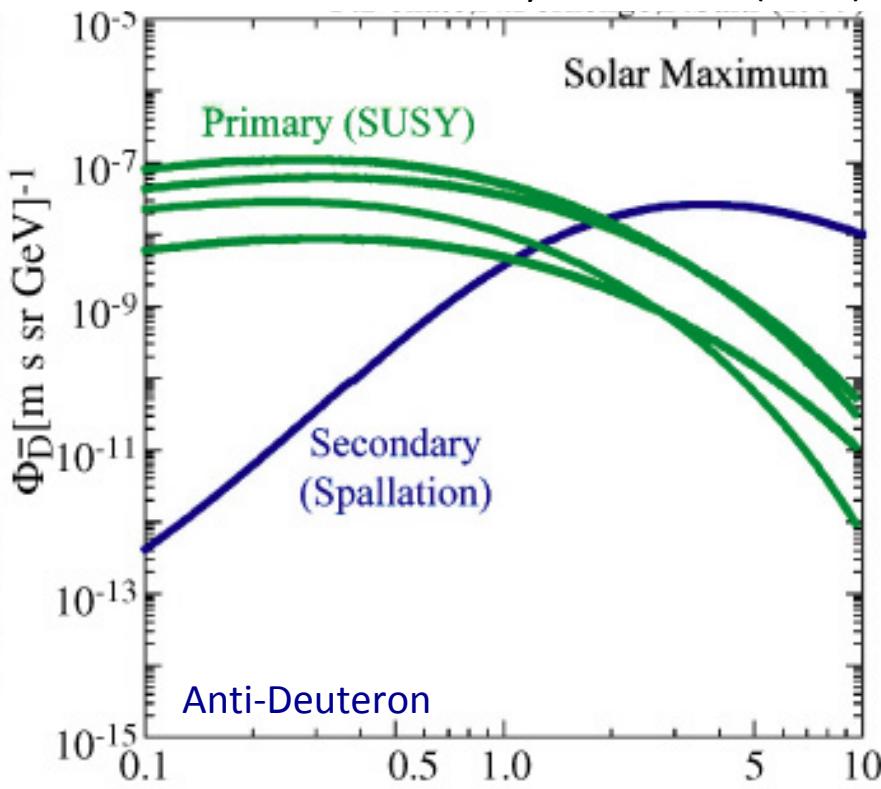


Collisions of dark matter particles (ex. neutralinos)  
may produce a signal of  $e^+, \bar{p}, \bar{D}, \dots$  that  
can be detected above the background from the  
collisions of primary CRs on interstellar medium

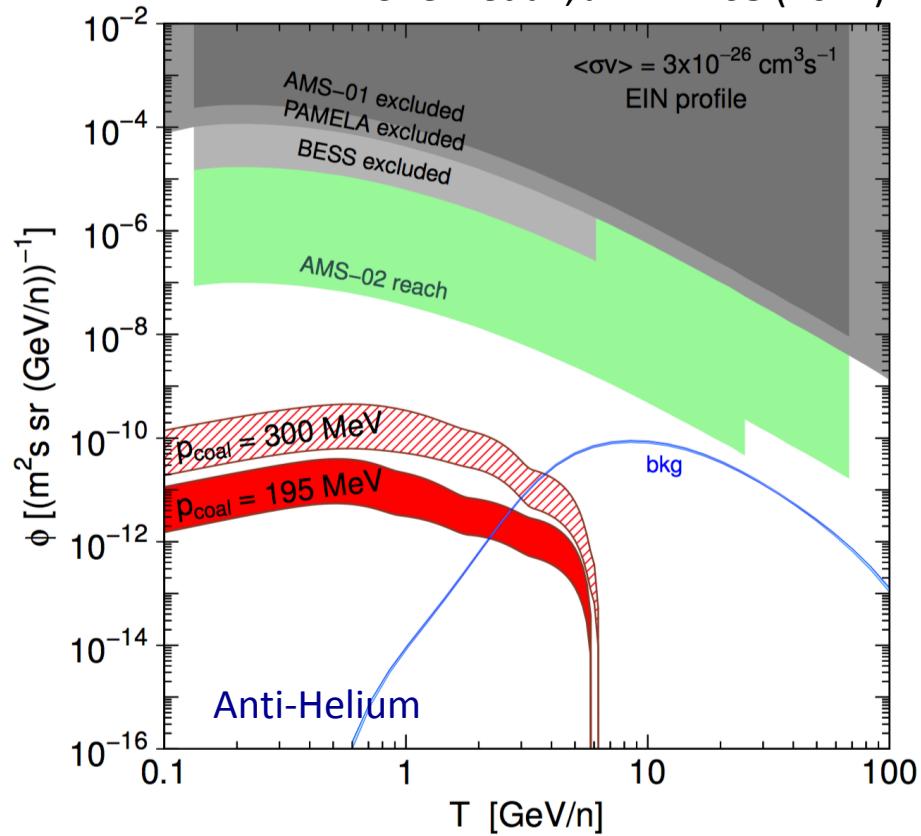


# Indirect Search of Dark Matter with Anti-Nuclei

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



M. Cirelli et al., JHEP **1408** (2014)

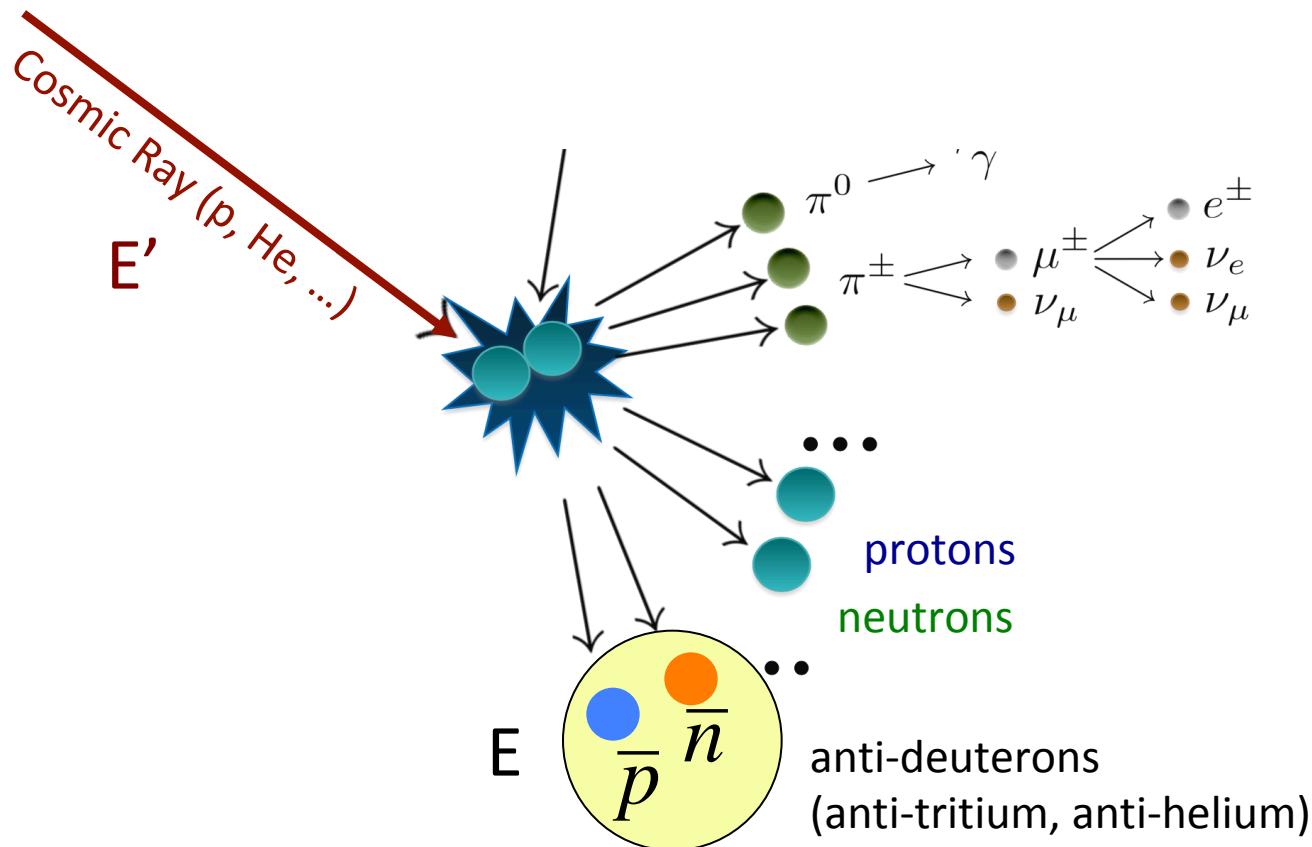


- + Promising signal/background ratio for a vast class of DM candidates (kinematic suppression of secondary production)
- Weak flux intensity, of both signal and background

# Astrophysical Anti-Nuclei Background

source term

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

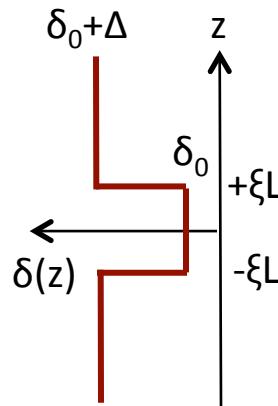


# Astrophysical Anti-Nuclei Background

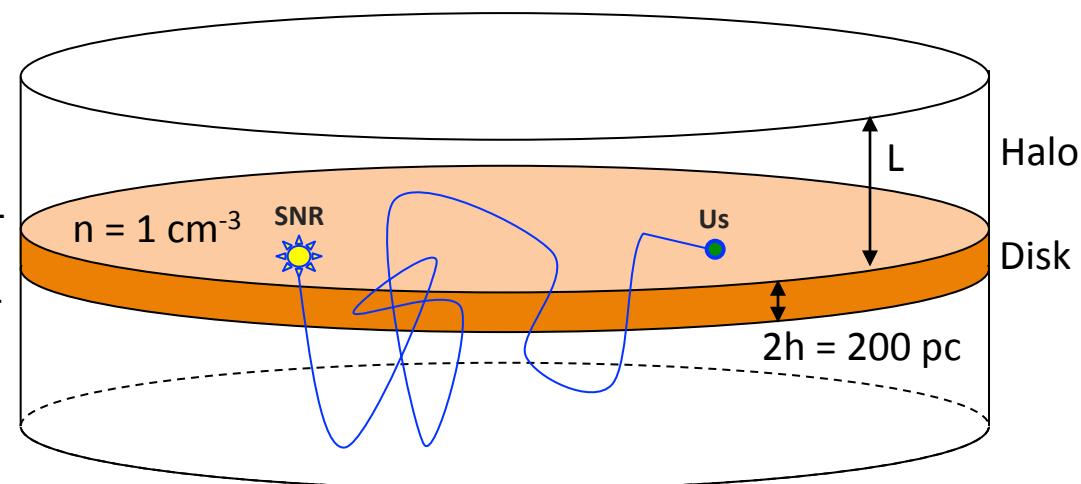
$$Q_{\bar{A}}^{sec}(E) \approx \frac{4\pi}{c} \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} n_{ISM} \frac{d\sigma_{CR+ISM \rightarrow \bar{A}}^{ISM}}{dE'}(E, E') J_{CR}(E') dE'$$

**Propagation  
in the Galaxy:**

diffusive transport,  
energy loss/gain  
nuclear spallation



Using **Two Halo Model** of diffusive propagation with diffusion coefficient  $K(R, z) = \beta K_0 (R/GV)^{\delta(z)}$



**Solar modulation  
in the Heliosphere:**

diffusion, advection, drift

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

Following J. Feng et al., Phys. Rev. D 94 (2016) we use  $L = 5 \text{ kpc}$ ,  $\xi = 0.1$ ,  $\Delta = 0.55$  and  $\delta_0 = 1/3$  (Kolmogorov-like), that provides good description of p, He and B/C.

# *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.

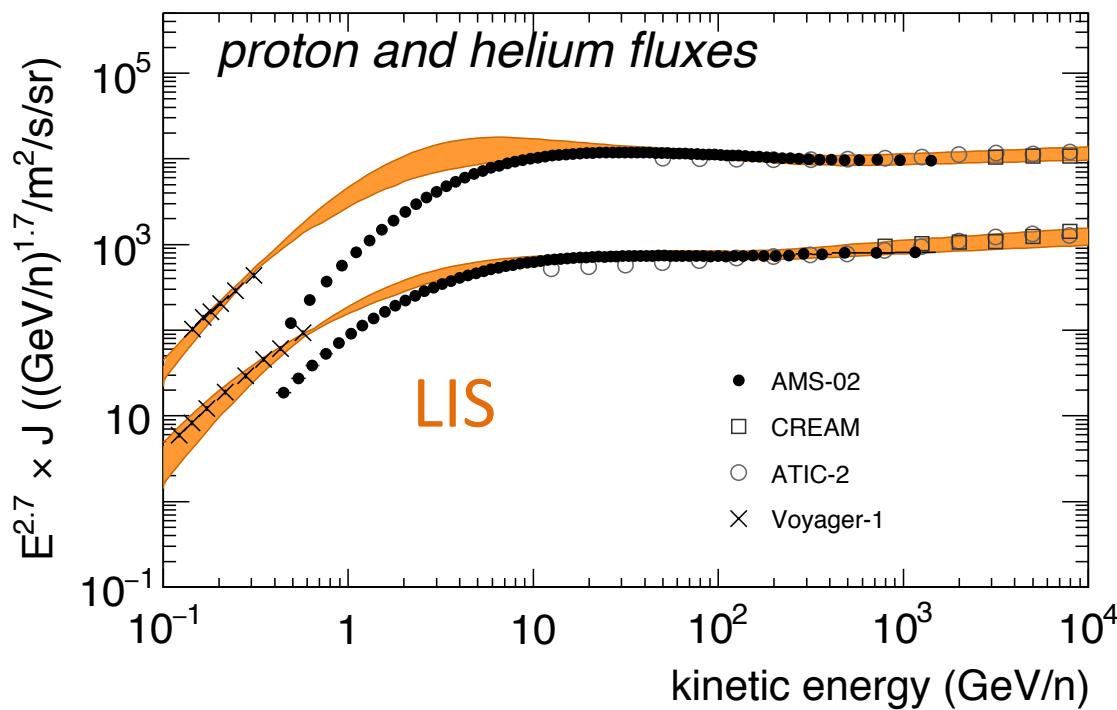
# *Uncertainties from Primary CR Spectra*

## 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 (DAMPE, CALET)

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



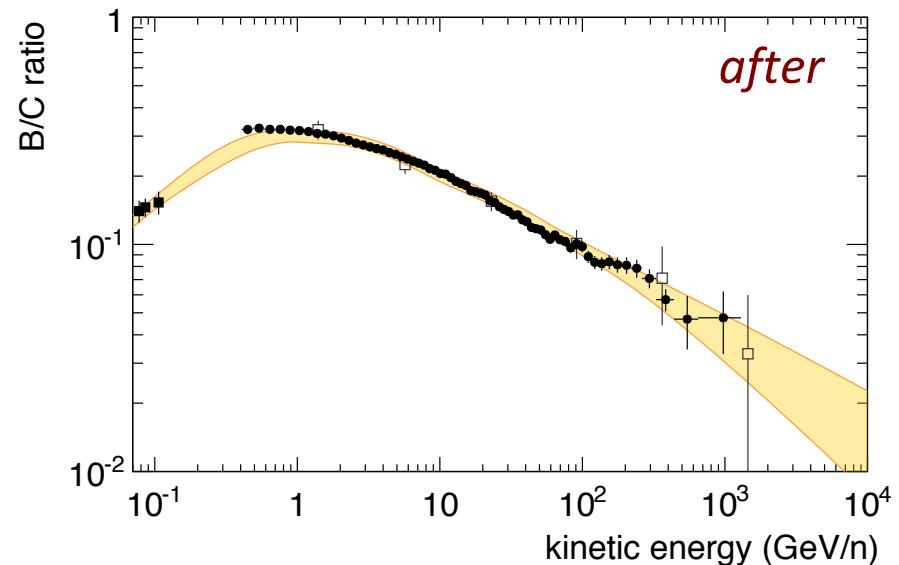
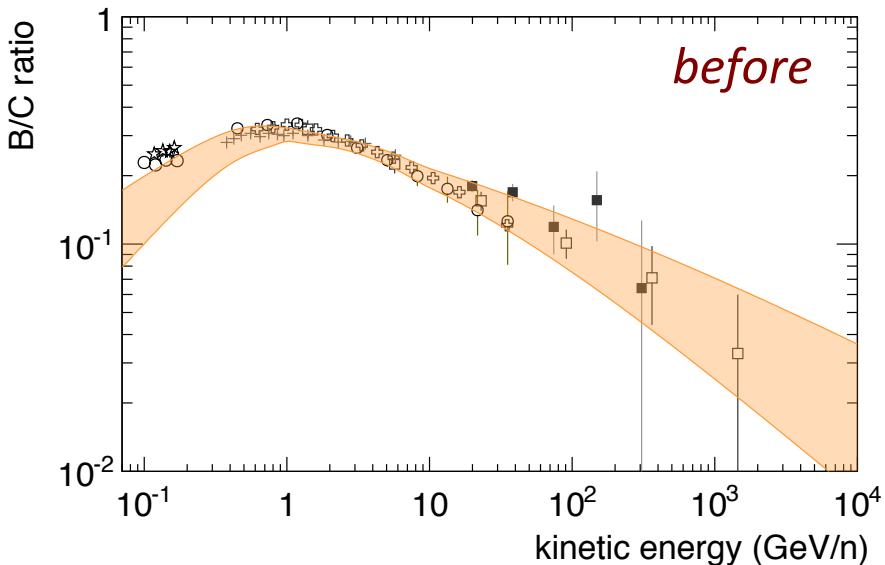
# *Uncertainties from CR Transport (I)*

## 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).

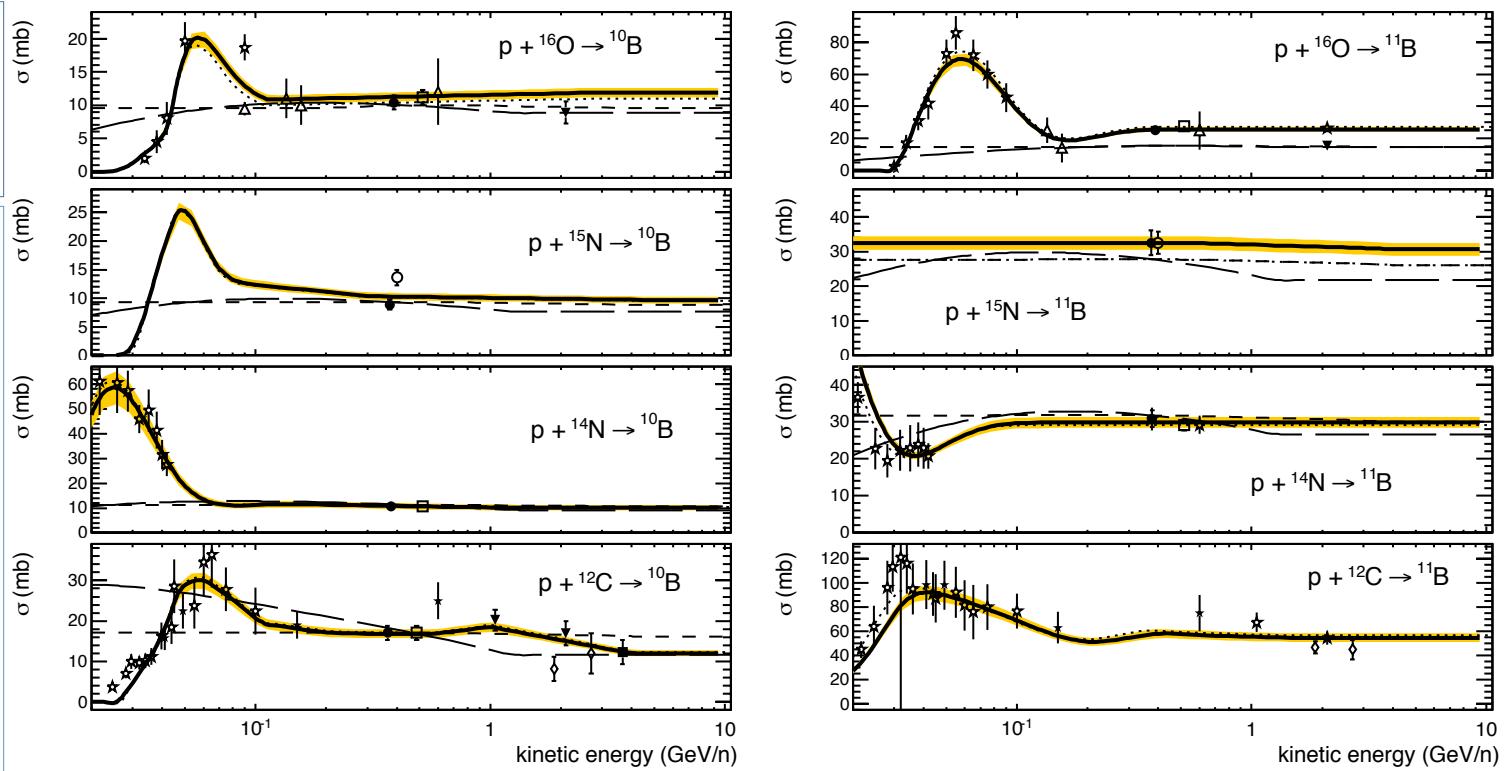
## After Voyager-1 & AMS-02

- AMS-02 + PAMELA + Voyager-1 data become available.
- Tight constraints on CR diffusion.
- Increasing importance of XS uncertainties for Boron production → Y. Génolini et al. Phys. Rev. C 98 (2018).
- Halo-Diffusion K/L degeneracy still unbroken.



# Uncertainties from CR Transport (II)

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



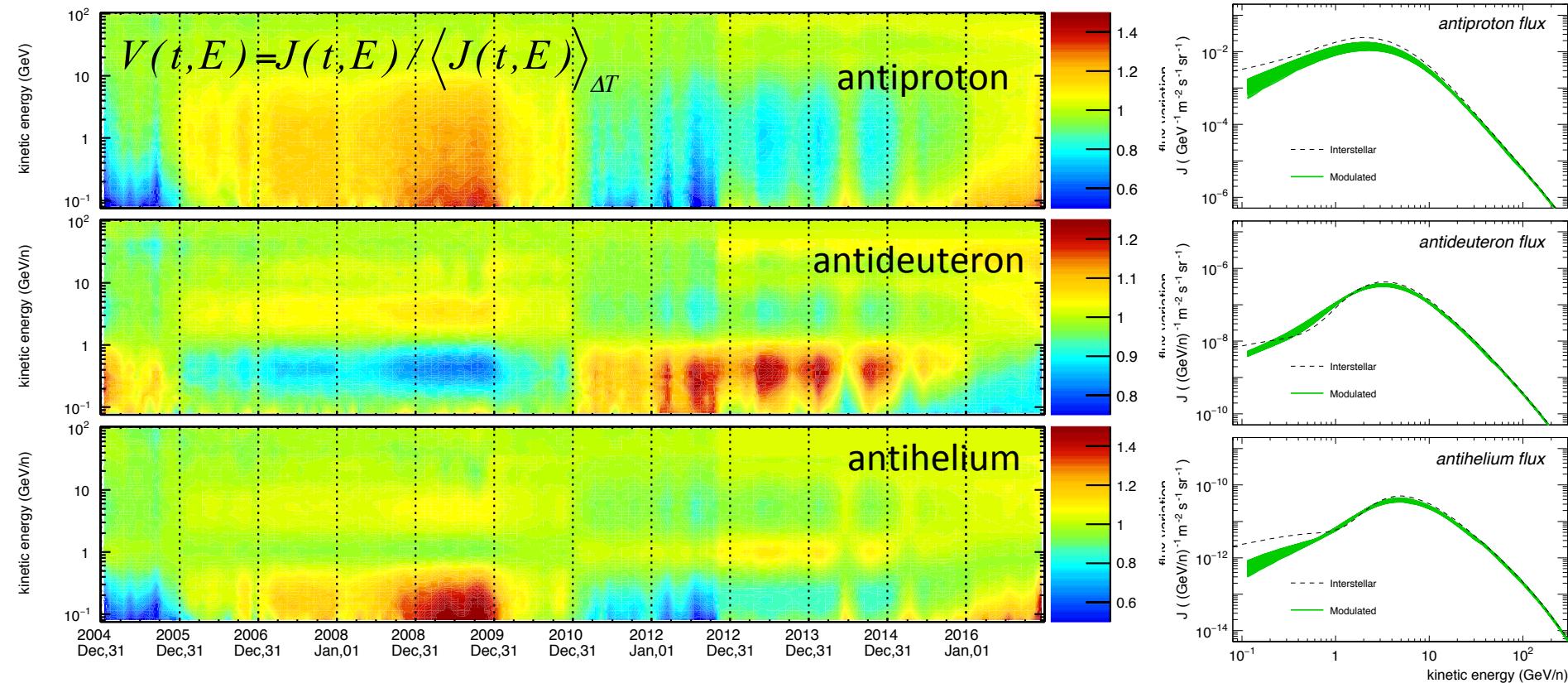
Uncertainty on the B/C ratio of 7-9%.

→ Limiting factor in the interpretation of other secondary species.

# Uncertainties from Solar Modulation

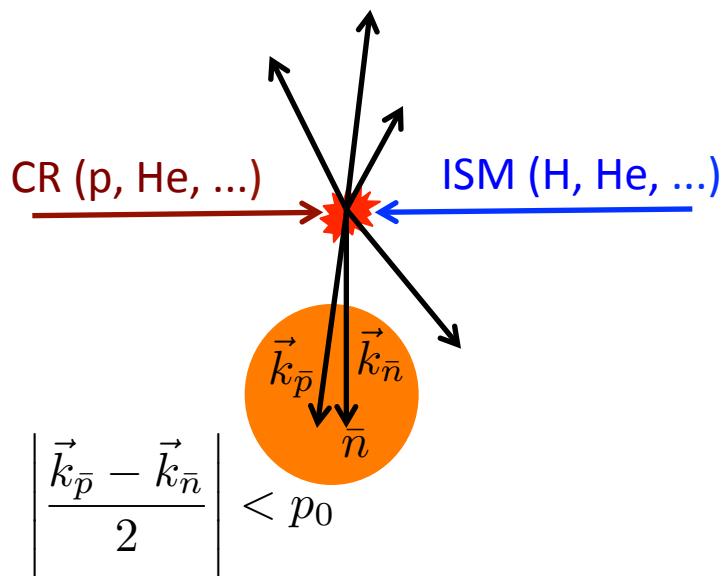
## Recent Milestones

- 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.



First tests of a stochastic solar propagation code. Derive uncertainty from NM.  
Derive additional uncertainty from the charge-conjugate flux.

# Uncertainties from Production



**Coalescence model** from  
P. Chardonnet et al. Phys. Lett. B **409** (1997)

$$E_{\bar{A}} \frac{d^3 N_{\bar{A}}}{dp_{\bar{A}}^3} = B_{\bar{A}} \left( E_{\bar{p}} \frac{d^3 N_{\bar{p}}}{dp_{\bar{p}}^3} \right)^Z \left( E_{\bar{n}} \frac{d^3 N_{\bar{n}}}{dp_{\bar{n}}^3} \right)^{A-Z}$$

$$B_{\bar{A}} = \frac{m_A}{m_p^Z m_n^{A-Z}} \left( \frac{4}{3} \pi p_0^3 \right)^{A-1}$$

## Anti-nucleon production

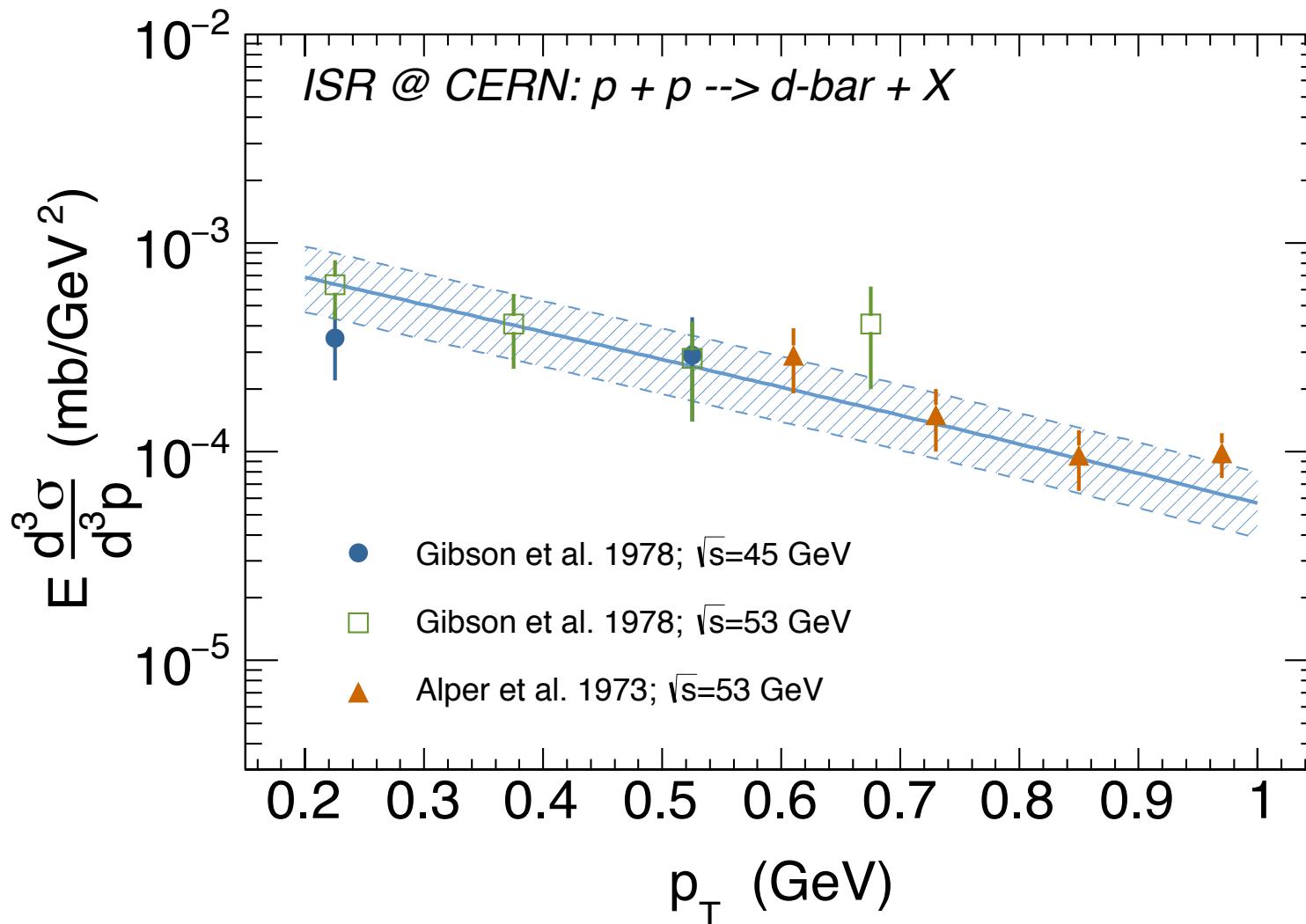
- Many parameterizations and MC-based calculations were available;
- We tested many in J. Feng et al., Phys. Rev. D **94** (2016) [QGSJET-II, EPOS-LHC, ...];
- We choose to use M. Di Mauro et al., Phys. Rev. D **90** (2014). We also set  $\bar{n}/\bar{p} > 1$ .

## A>1 anti-nuclei production and interactions ( ${}^2\bar{H}$ , ${}^3\bar{H}$ , ${}^3\bar{He}$ )

- Allow for different  $\bar{n}$  and  $\bar{p}$  production;
- Collisions (p,He)+(H,He) implemented as R.K. Tripathi et al., NIM B **117** (1996);
- Destruction of anti-nuclei, not-annihilating rescattering (NAR) and  $\bar{p}+(H,He) \rightarrow {}^2\bar{H}$  as in R. Duperray et al., Phys. Rev. D **71** (2005).

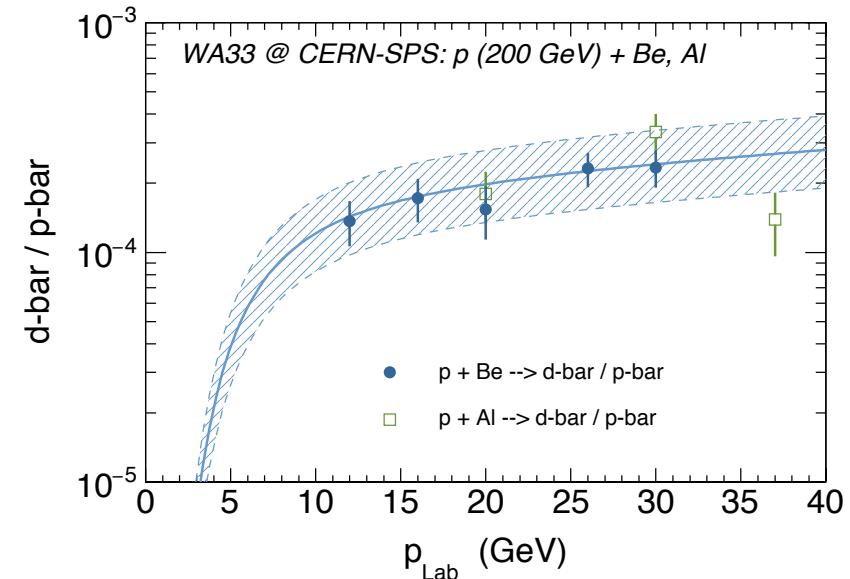
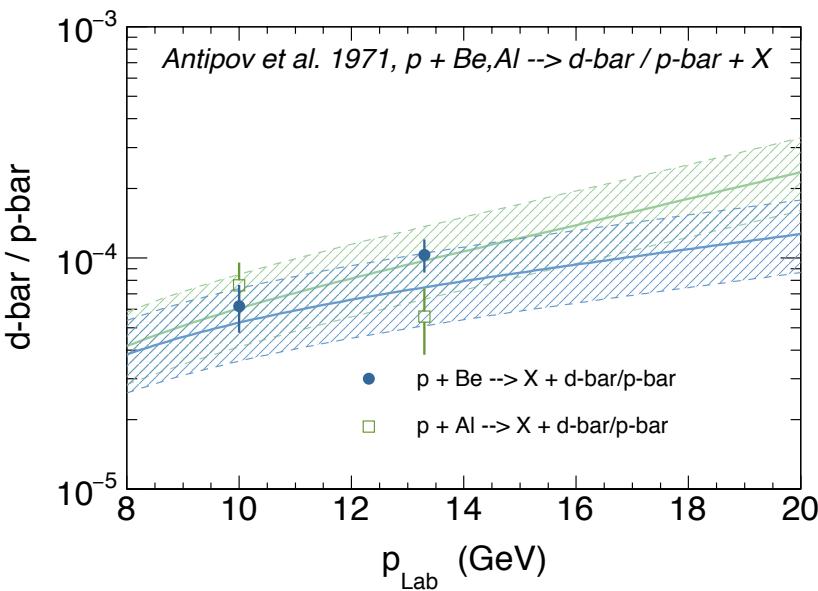
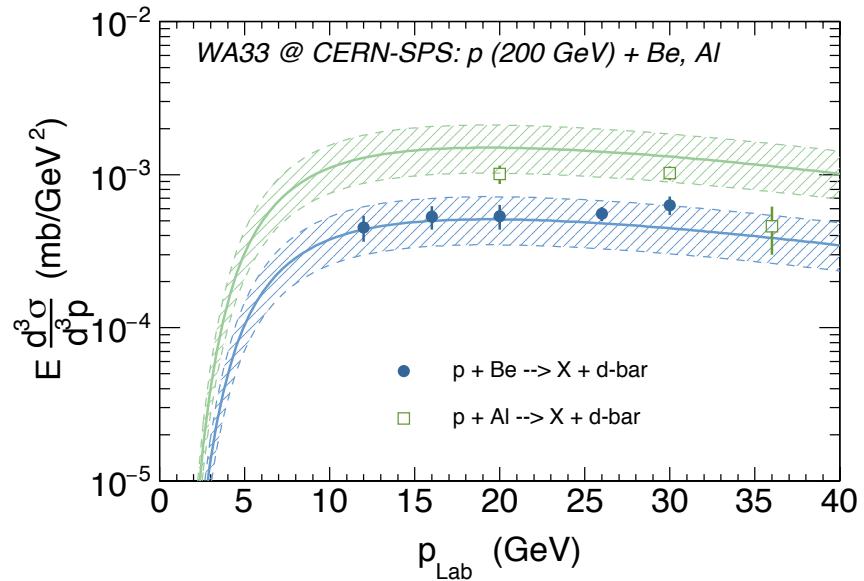
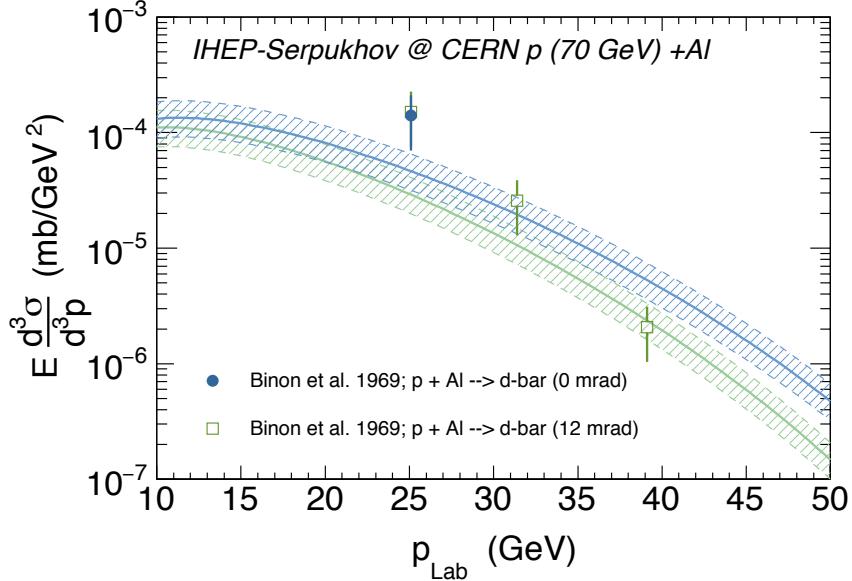
# *Uncertainties from Production: Anti-Deuteron (I)*

Use accelerator data since  $\sim 1972$ :  $p+p$ ,  $p+Be$ ,  $p+Al$  ISR@CERN



# *Uncertainties from Production: Anti-Deuteron (II)*

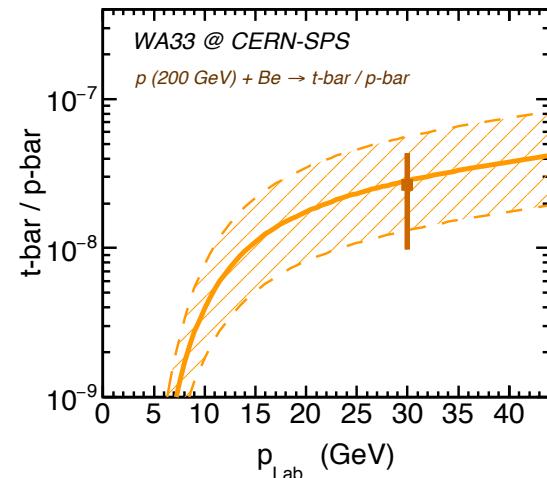
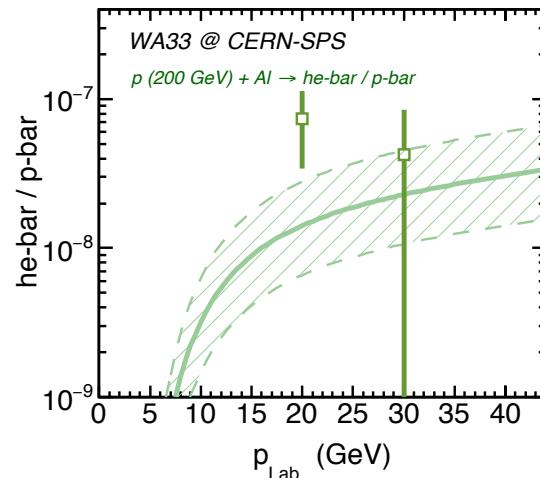
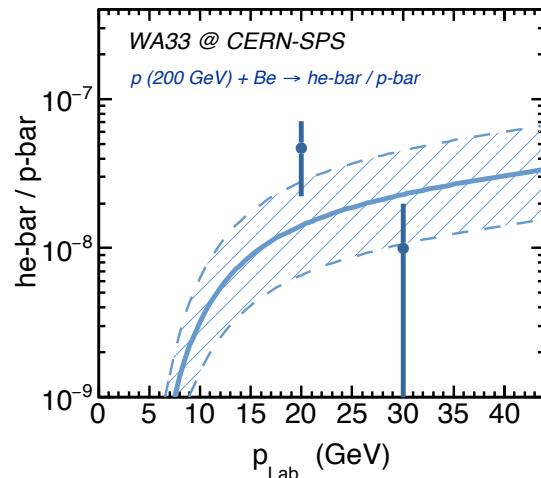
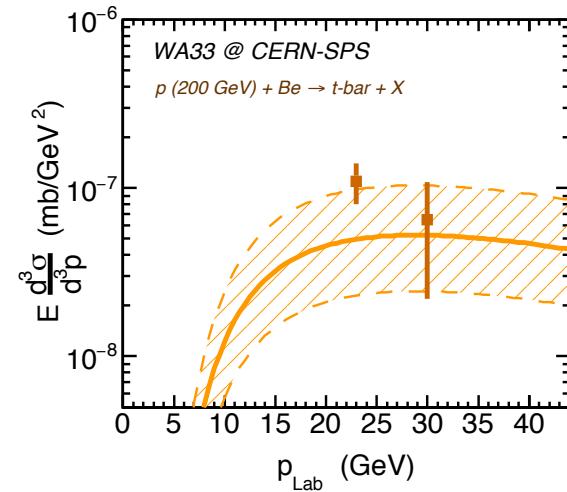
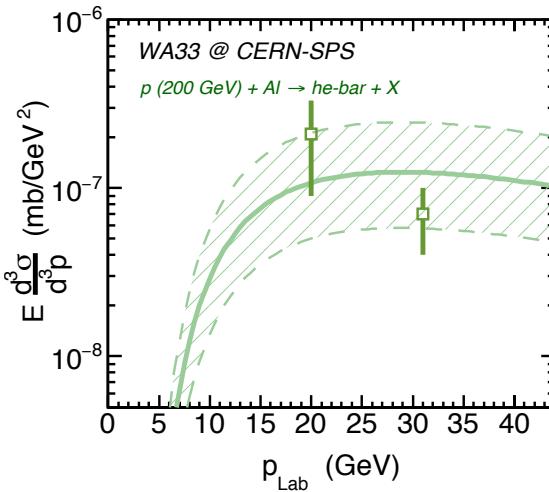
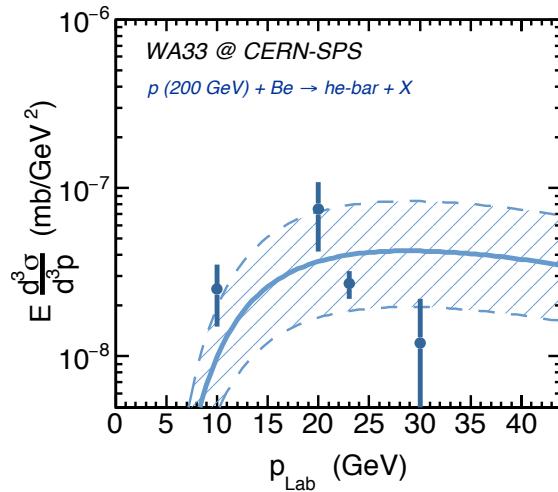
Many data are on p+Be or p+Al. Use of XS ratio  ${}^2\bar{H}/\bar{p}$  to cancel out common factors.



# *Uncertainties from Production: Anti-Helium*

${}^3\overline{\text{He}}$  and  ${}^3\overline{\text{H}}$  production measurements are very scarce  $\rightarrow$  poor constraints.

Using the same coalescence momentum for anti-deuteron we get a reasonable description.



# *Tertiary Component*

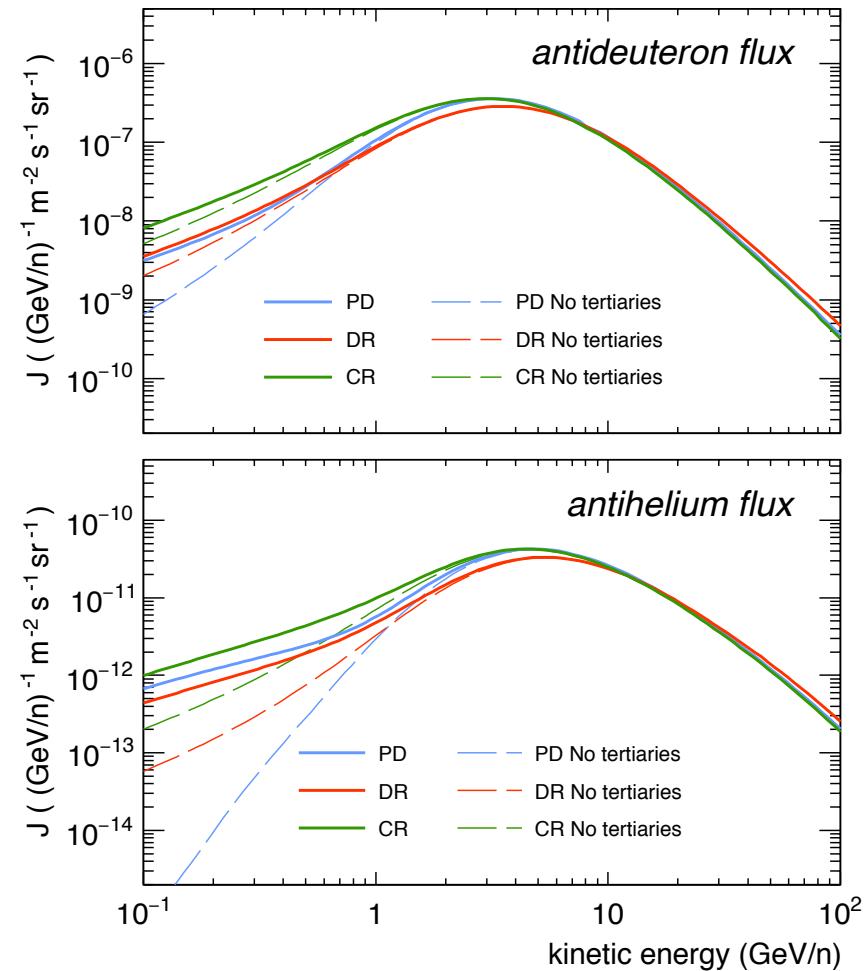


Dashed: fluxes w/o tertiary production.

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

Solid: tertiary production accounted.

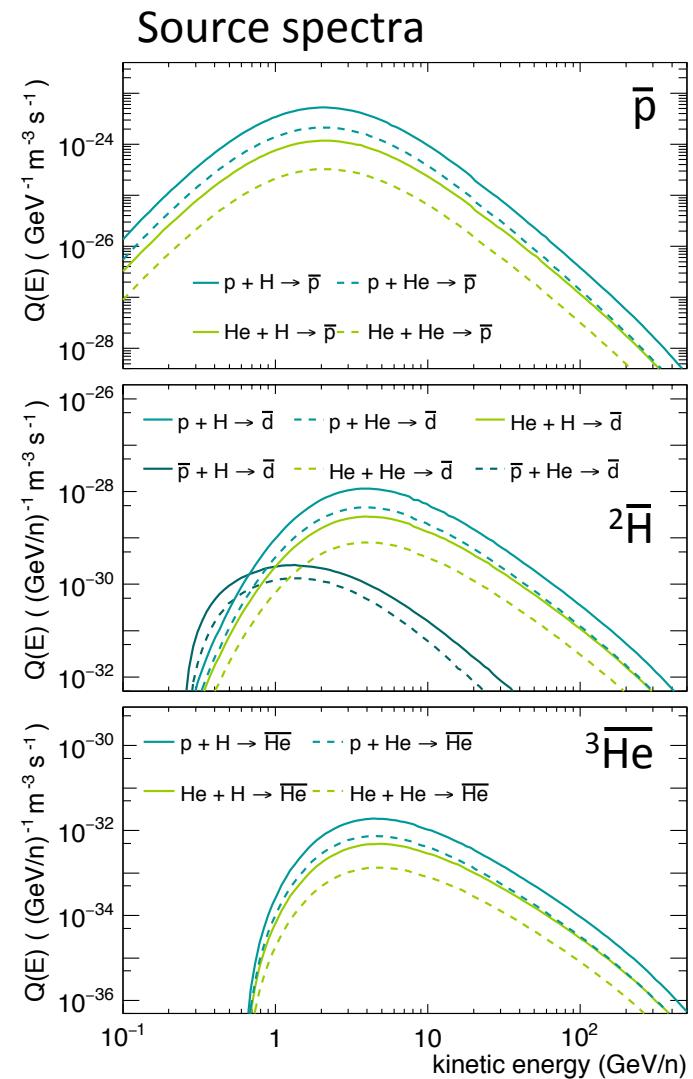
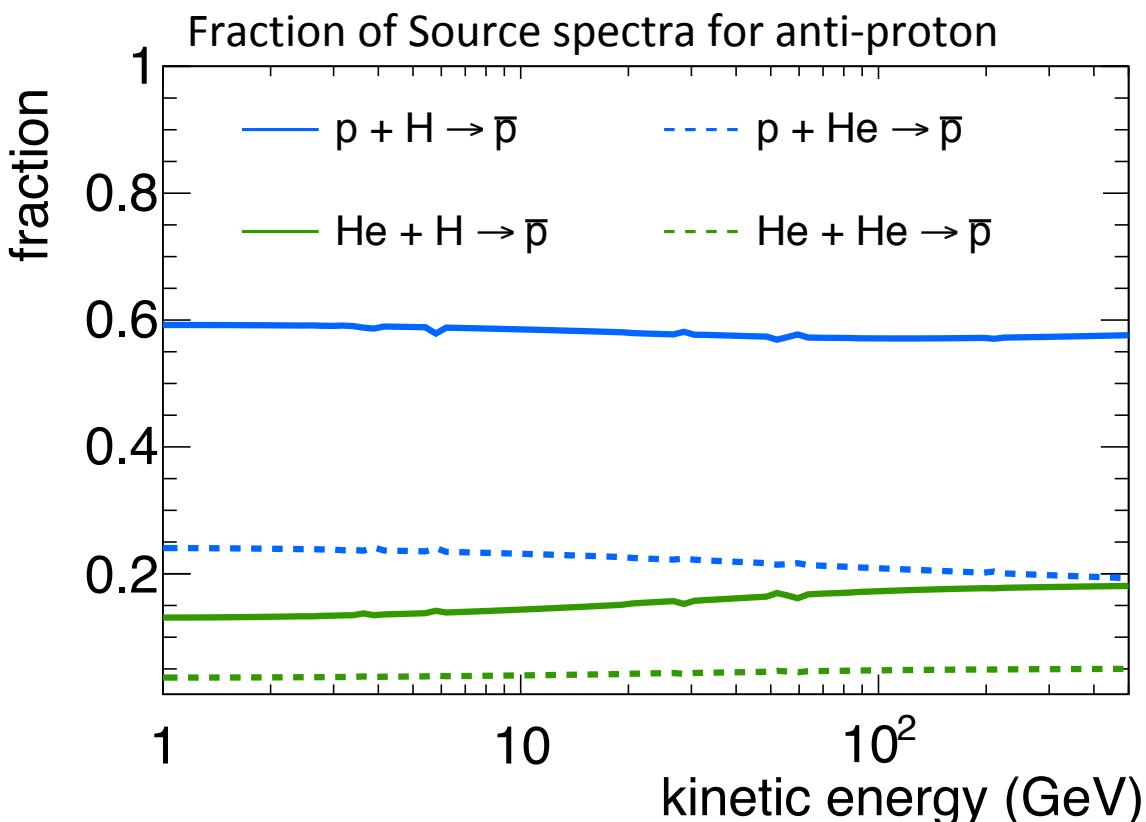
- **anti-deuteron:** from R. Duperray et al., Phys. Rev. D **71** (2005).
- **anti-helium:** assumed same BR as  $d\bar{}$  ( $\rightarrow$  not known).
- Smoother sub-GeV/n flux, less sensitive to propagation loss/gain effects.
- Large uncertainty in tertiary production.



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

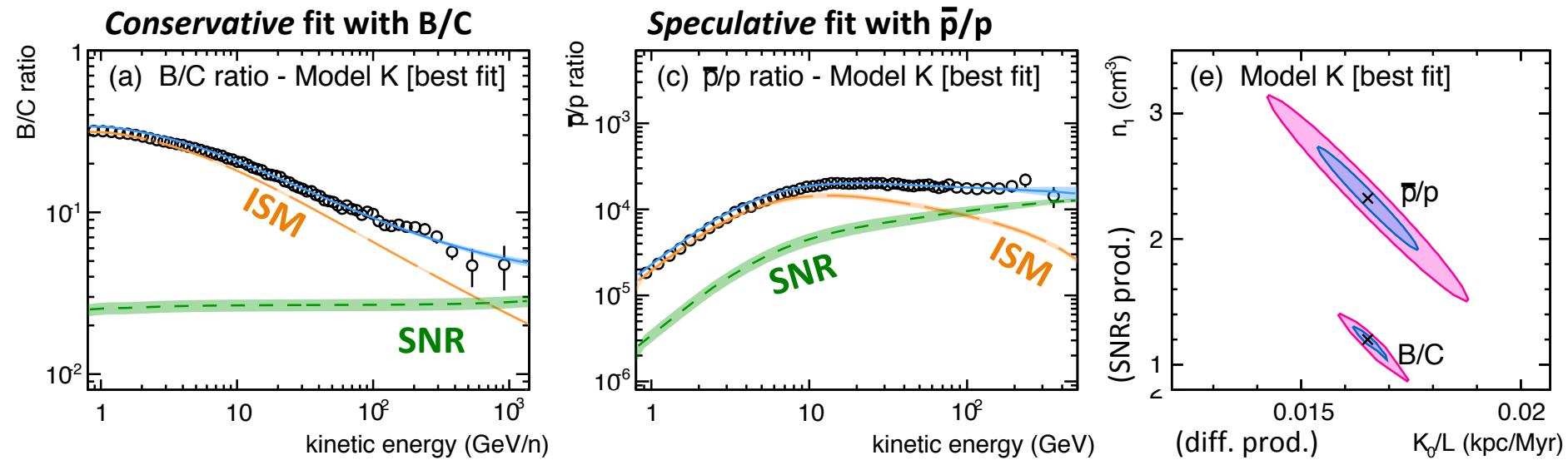
# *CR+ISM Secondary Source Spectra*

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



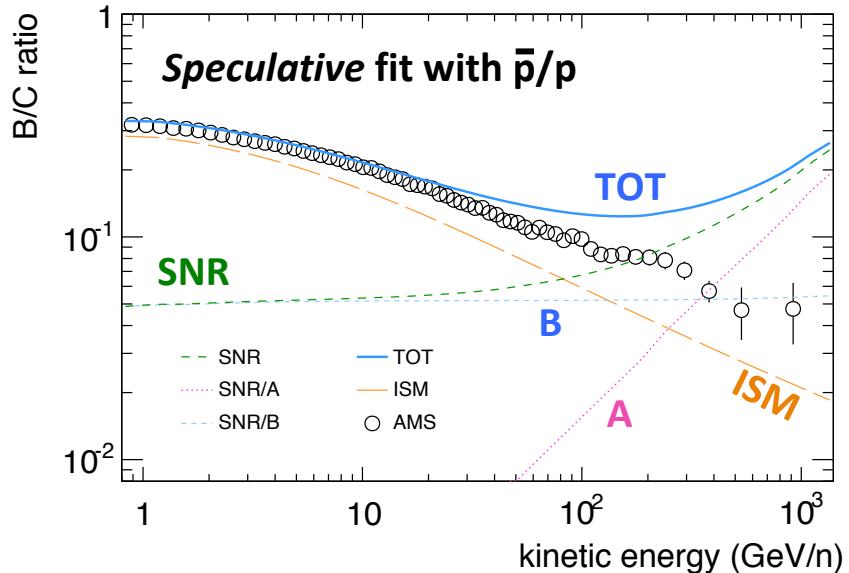
# Anti-Nuclei from Supernova Remnants

We include also SNR source terms A and B following P. Blasi and P.D. Serpico PRL 103 (2009) and others.



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.

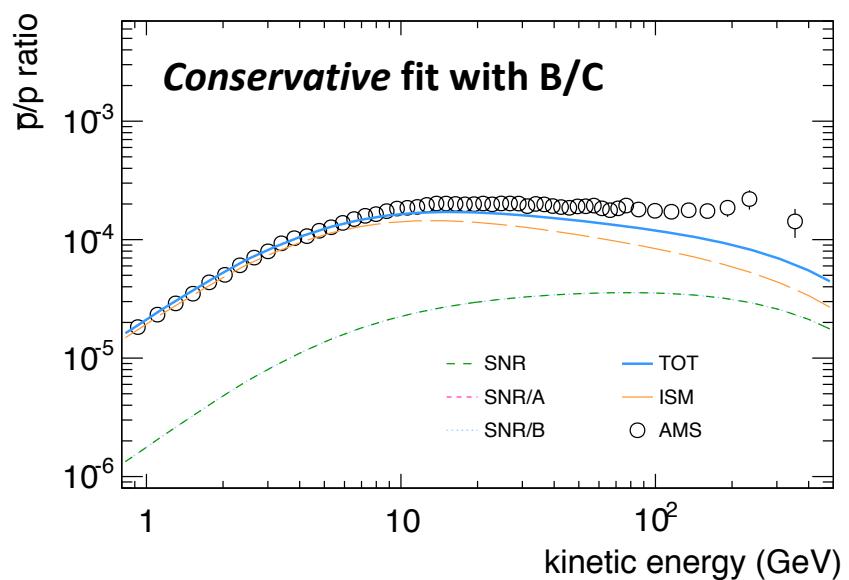
# *More on the Inconsistency between B/C and pbar/p*



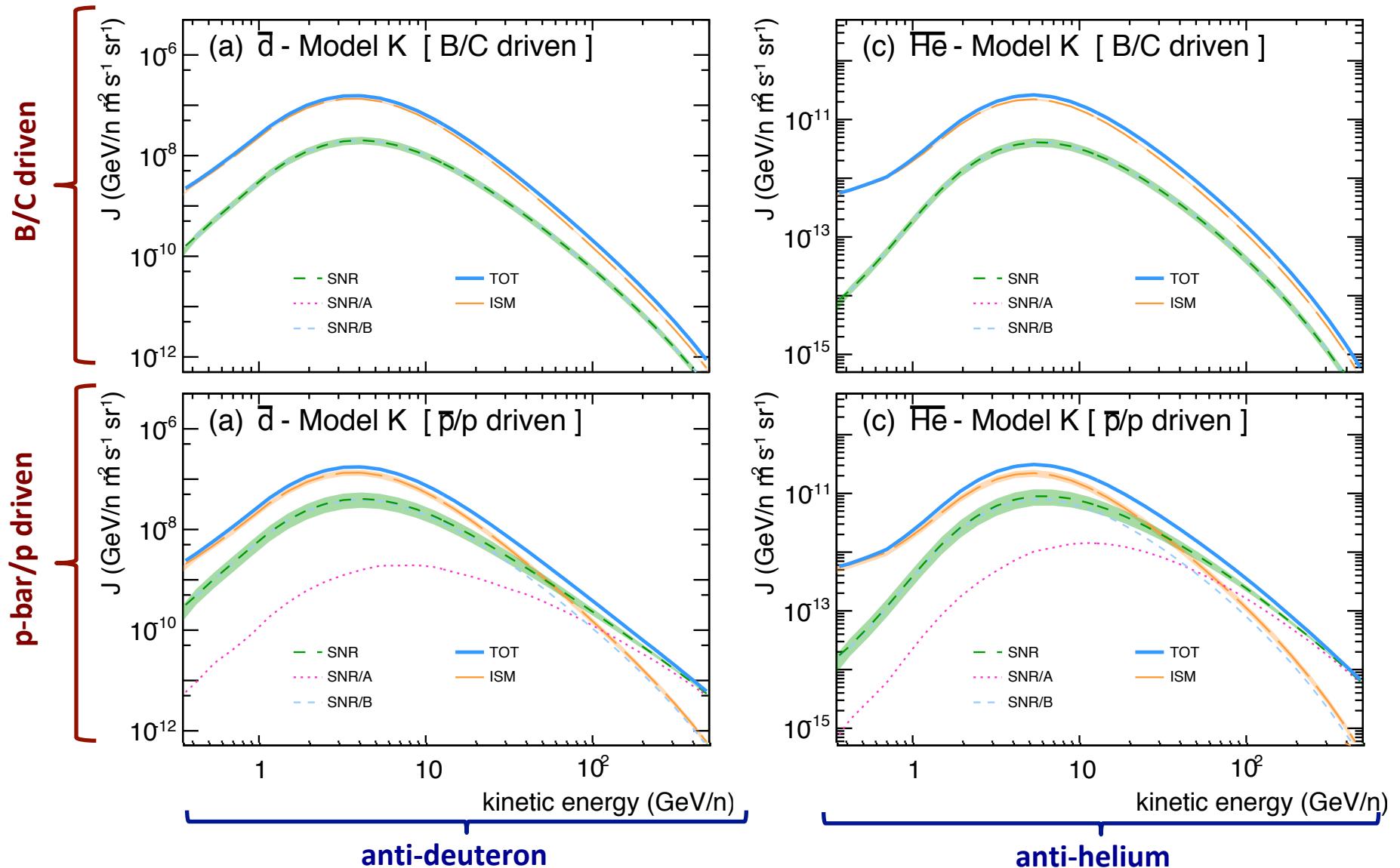
If the model is tuned using antiproton data, it strongly over-estimates the B/C ratio at high energy.

If the model is tuned using B/C data it under-predicts the antiprotons at high energy.

Note that the B/C ratio prefers a negligible SNR-A component.

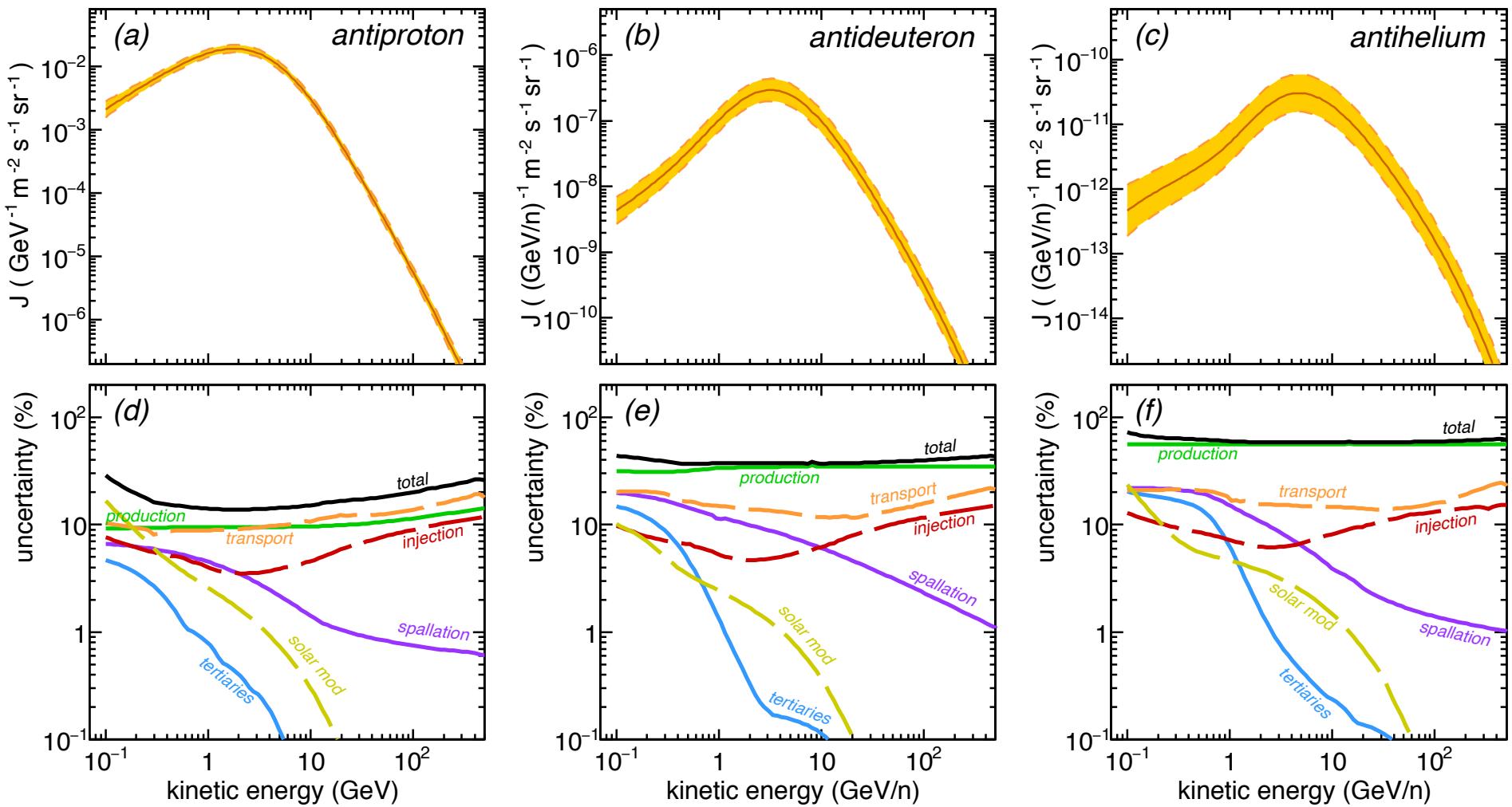


# Anti-Nuclei from Supernova Remnants



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

# Full Uncertainty Breakdown of CR Anti-Nuclei



→ a bit of caution, errors are correlated.

Uncertainties in calculations are dominated by production cross section.

# *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.
- 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.

*Remarks:*

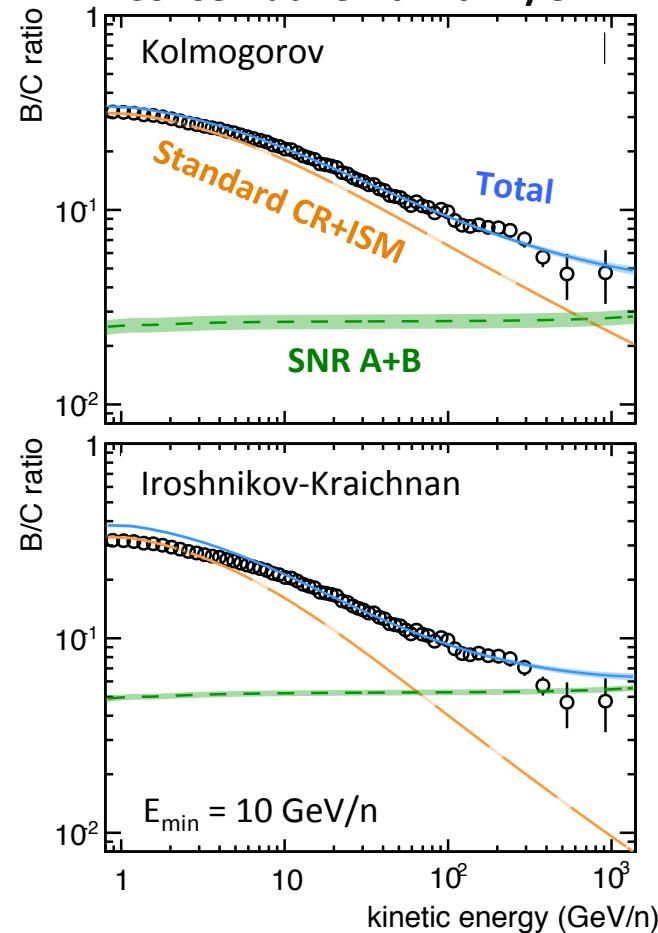
- Not included recent measurements: LHCb  $p+He \rightarrow p\bar{}$ , SHINE  $p+p \rightarrow p\bar{}$ , ALICE  $p+p \rightarrow d\bar{}$ ,  $t\bar{}$ ,  $he\bar{}$ . Expected to lower the anti-nuclei production uncertainty.
- Impact of different parameterization of  $p\bar{}$  production cross section (M.W. Winkler JCAP02 (2017), ...).
- Impact of new coalescence parameterizations (D. M. Gomez-Coral et al., Phys Rev. D 98 (2018)) still to be evaluated.
- improved solar modulation model.

# Anti-Nuclei from Supernova Remnants

We include also SNR source terms A and B following P. Blasi and P.D. Serpico PRL 103 (2009) and others.

Using two scenarios (Kolmogorov, Iroshnikov-Kraichnan) and fitting with three parameters regulating diffusion, SNR-A and SNR-B terms.

**Conservative fit with B/C**



**Speculative fit with  $\bar{p}/p$**

