Astrophysical background of cosmic-ray antinuclei

Astrophysical VS nuclear uncertainties

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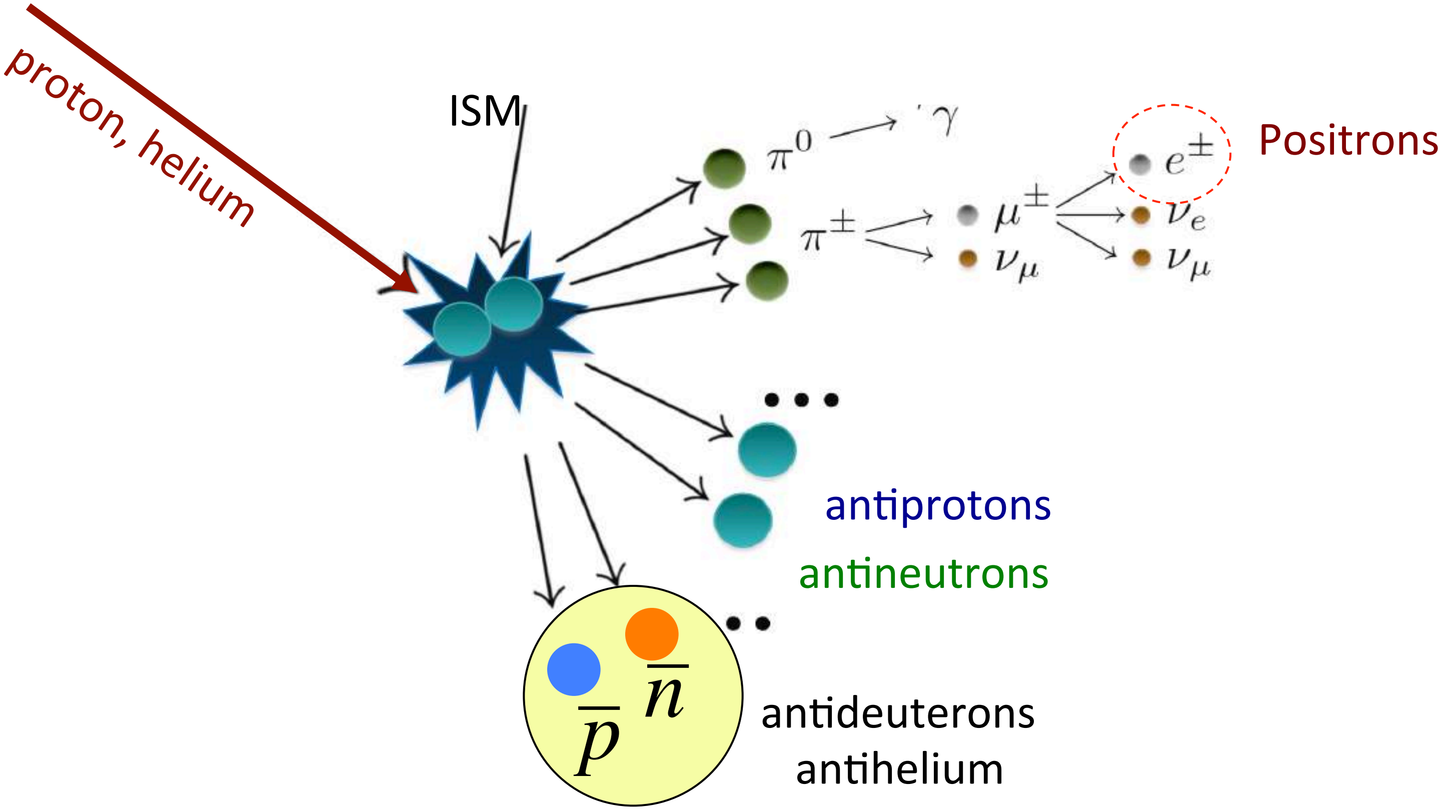
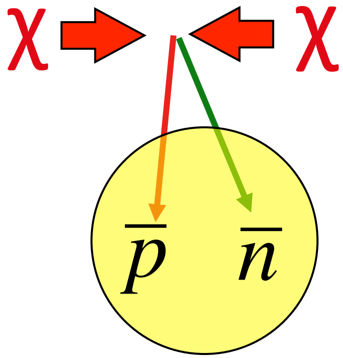
Perugia University & INFN
XSCR@CERN 29.03.2017

Astrophysical antimatter background

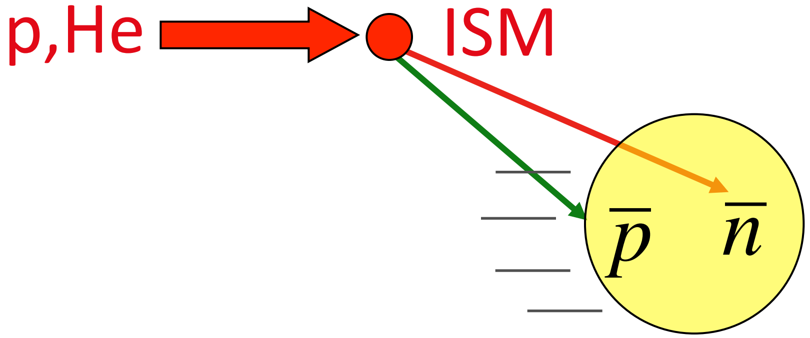


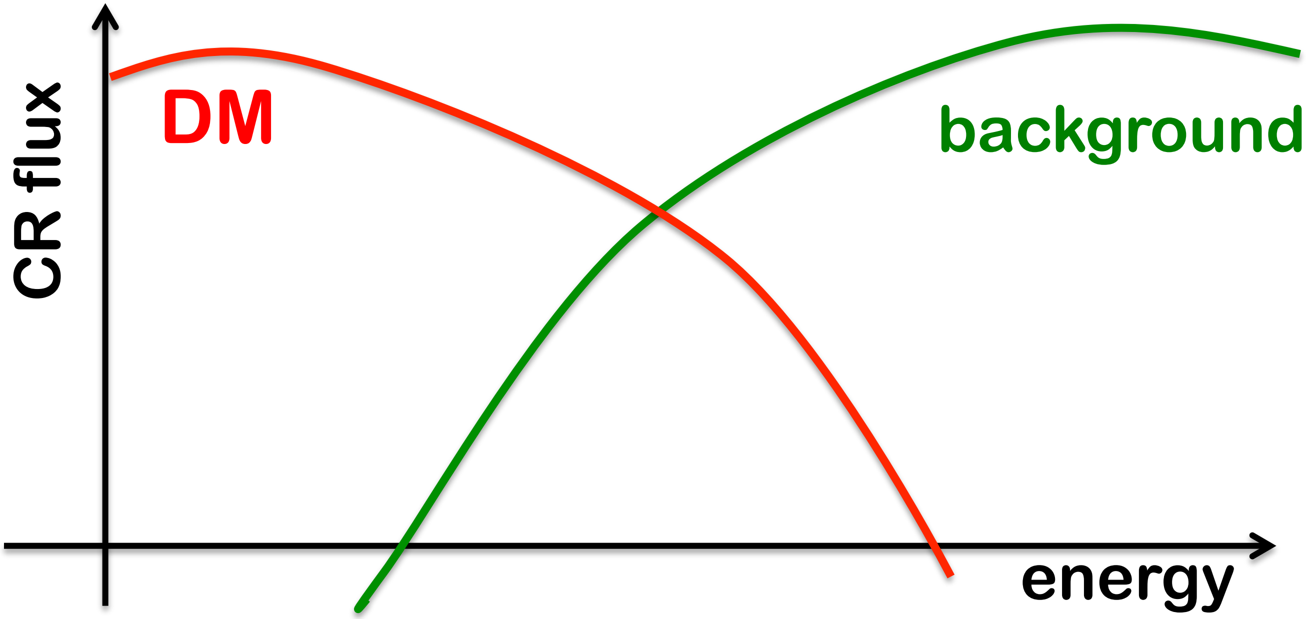
DM signal and background

Antideuteron from dark matter



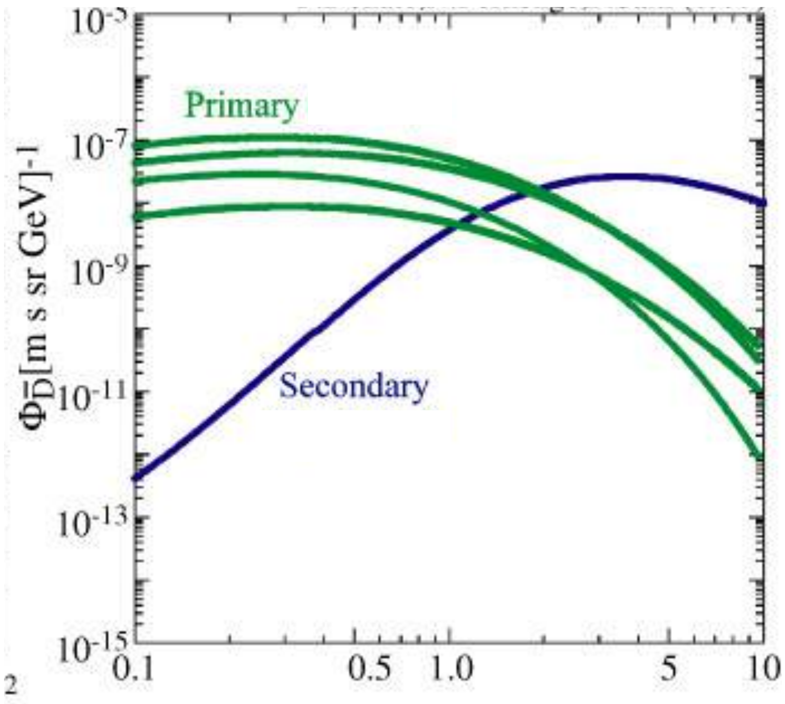
Secondary antideuteron production



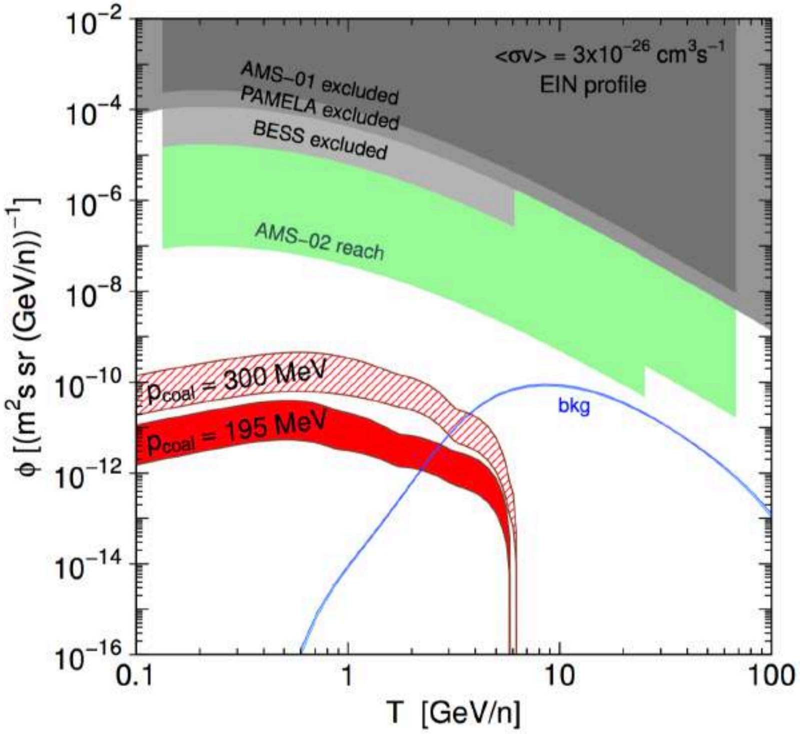


Indirect search of dark matter

Donato, Fornengo, Maurin 2008



Cirelli et al. 2014



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

Weak flux intensity, of both signal and background

Astrophysical antimatter background

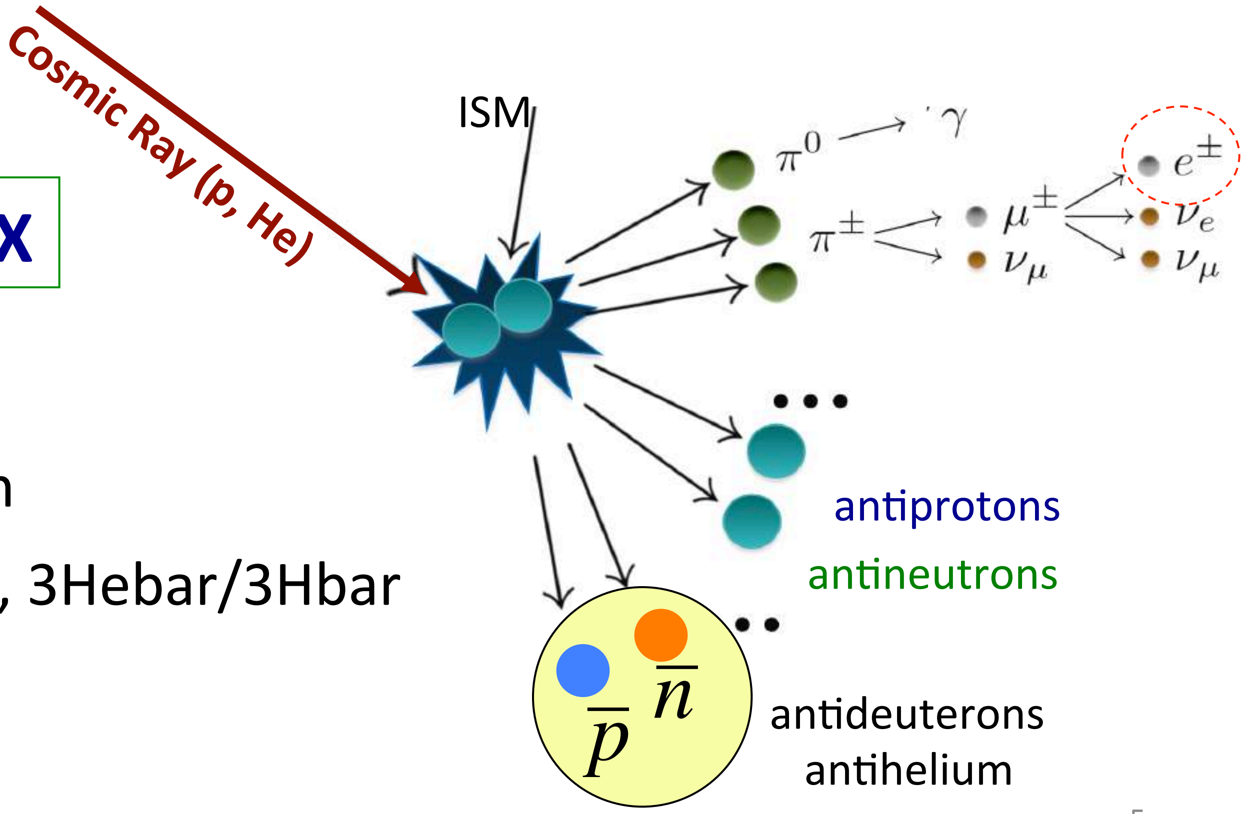
$$Q^{sec}_{\bar{A}}(E) \approx \frac{4\pi}{c} \sum_{CR} \sum_{ISM} \int_{E_{Th}}^{\infty} n_{ISM} \frac{d\sigma^{ISM}_{CR+ISM \rightarrow \bar{A}}}{dE'}(E,E') J_{CR}(E') dE'$$

CR + ISM → Abar + X

CR = proton, alpha

ISM = hydrogen, helium

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



Astrophysical antimatter background

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

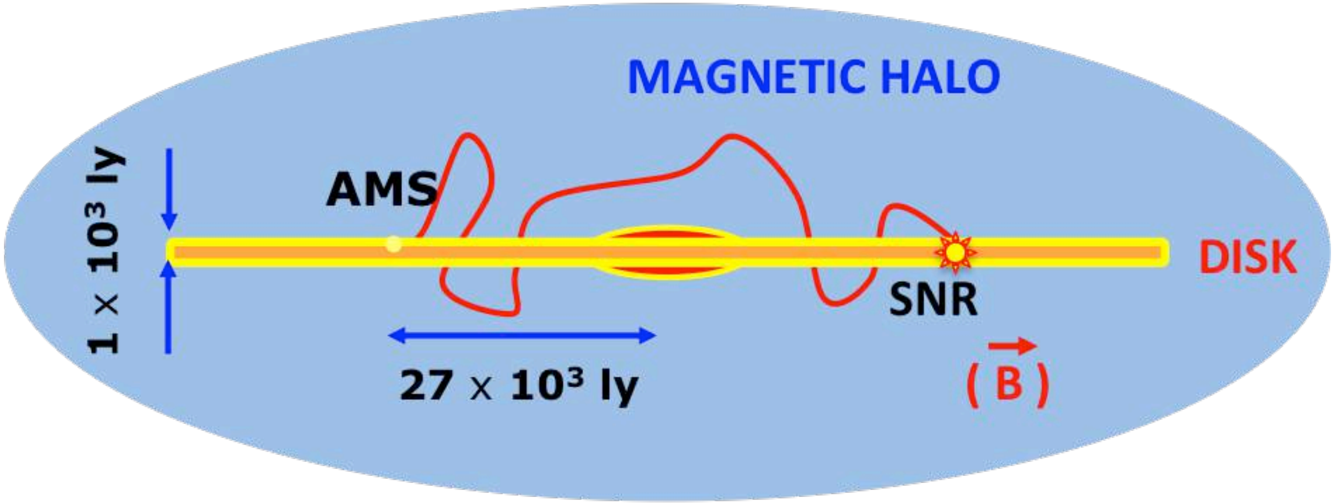
Propagation in the Galaxy:
diffusive transport,
energy loss/gain
nuclear spallation

$$J^{LIS}_{\bar{A}}(E)$$

Solar modulation in the Heliosphere:
diffusion, advection, drift

$$J^{TOA}_{\bar{A}}(E)$$

→ **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.

Uncertainties from primary CR spectra

Related to our knowledge of primary spectra, proton and helium, that produce antinuclei via collision with the gas

Before

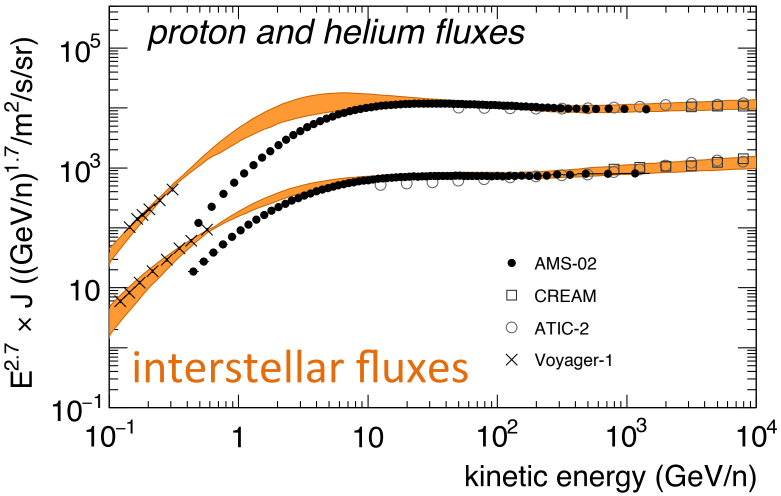
- Universal power-law parameterization assumed. Same spectra for proton and He.
- ➢ Tightly constrained with proton data at O(100 GeV) energy scale

After

- 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.

Take home messages

- ✓ Uncertainties on primary CRs are related to both injection and transport physics.
- ✓ These uncertainties were underestimated in the past due to too simple assumptions
- ✓ These uncertainties are sub-dominant at all energies, in comparison to other uncertainties



Uncertainties in CR transport in Galaxy

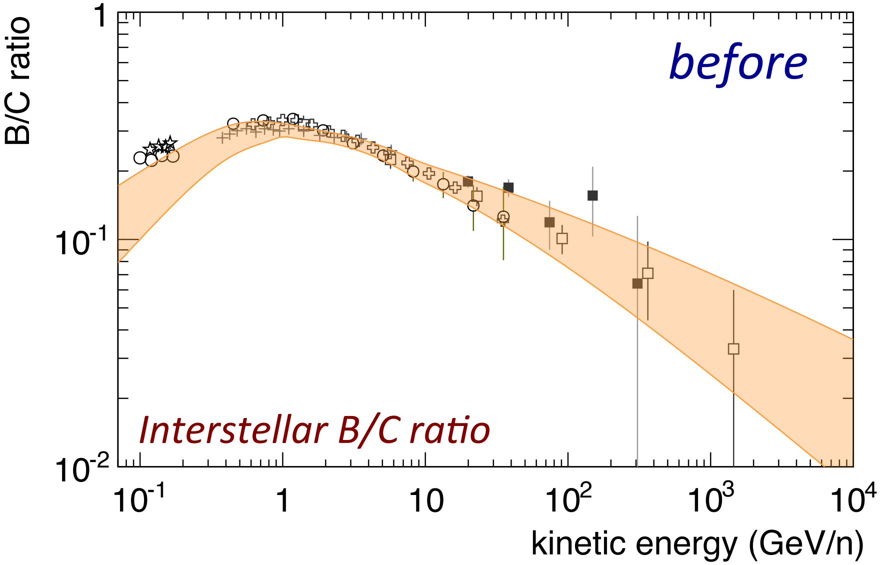
Related to our knowledge of CR transport parameters: B/C ratio

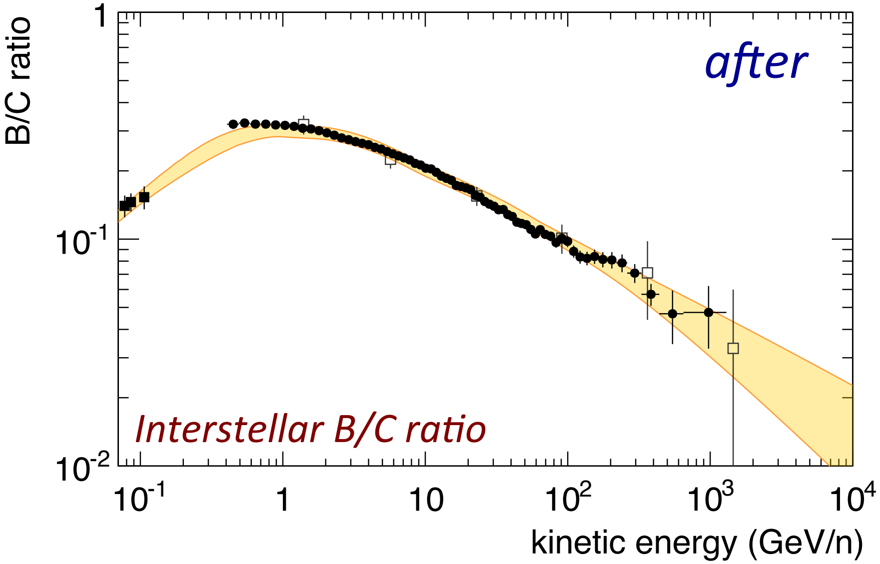
Pre – AMS & Voyager-1

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

Post – AMS & Voyager-1

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





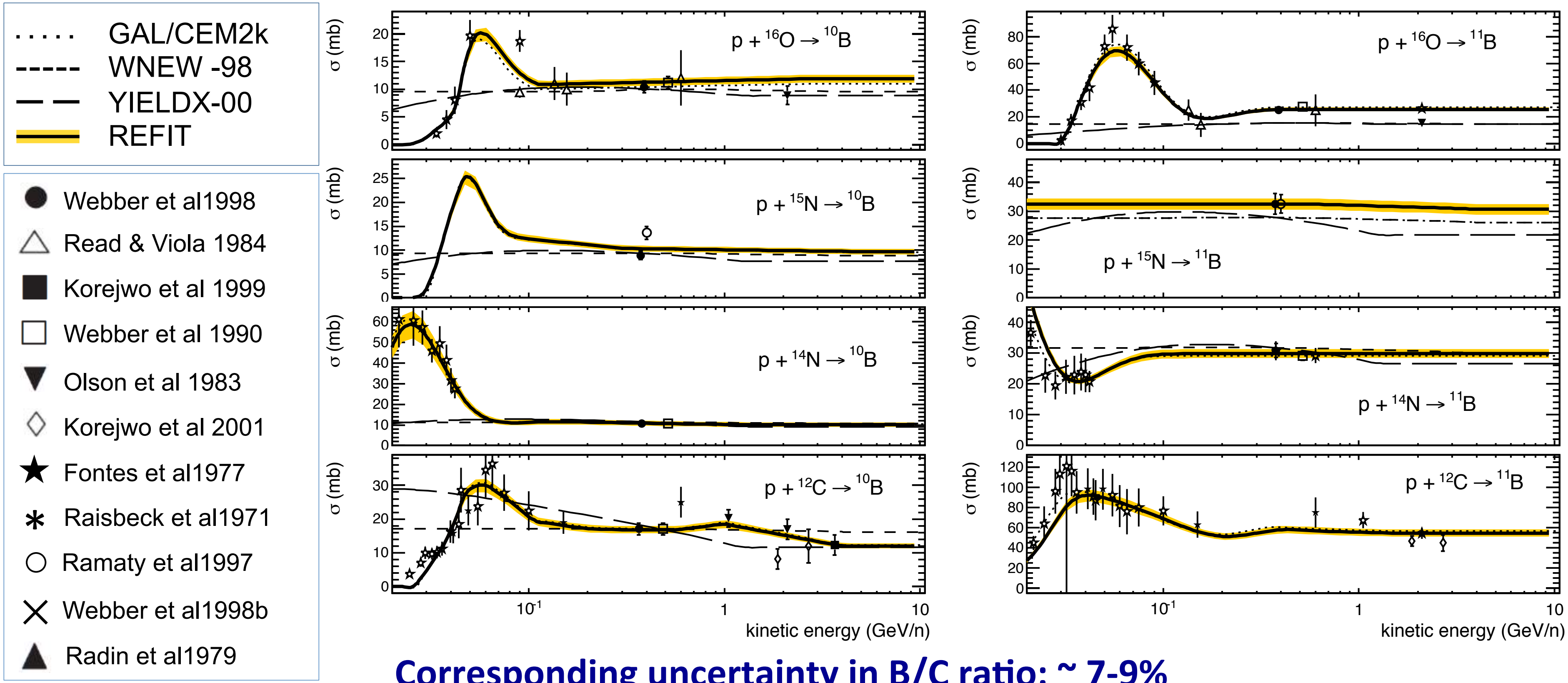
Uncertainties in CR transport in Galaxy

- Nuclear fragmentation XSs for CNO(p,X)B.
- Data collected in ~1970's – early 2000. Available at E = 20MeV/n – 10GeV/n
- Semi-empirical parametrizations: Webber 98 + Sielberberg & Tsao 2000 + GALPROP

- **Yellow bands: our error evaluation from re-fit:**

Based on GALPROP-XS, see NT 1509.05776

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



Corresponding uncertainty in B/C ratio: ~ 7-9%

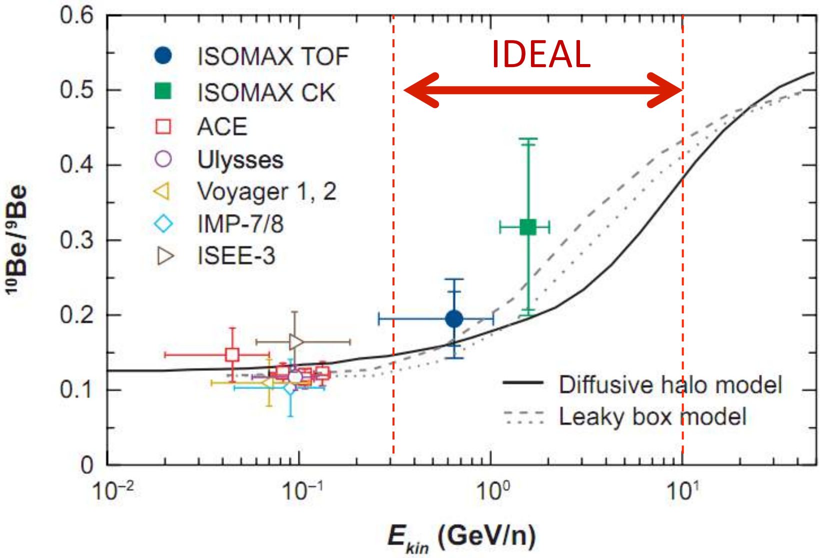
(Astrophysical uncertainties: K_0/L degeneracy

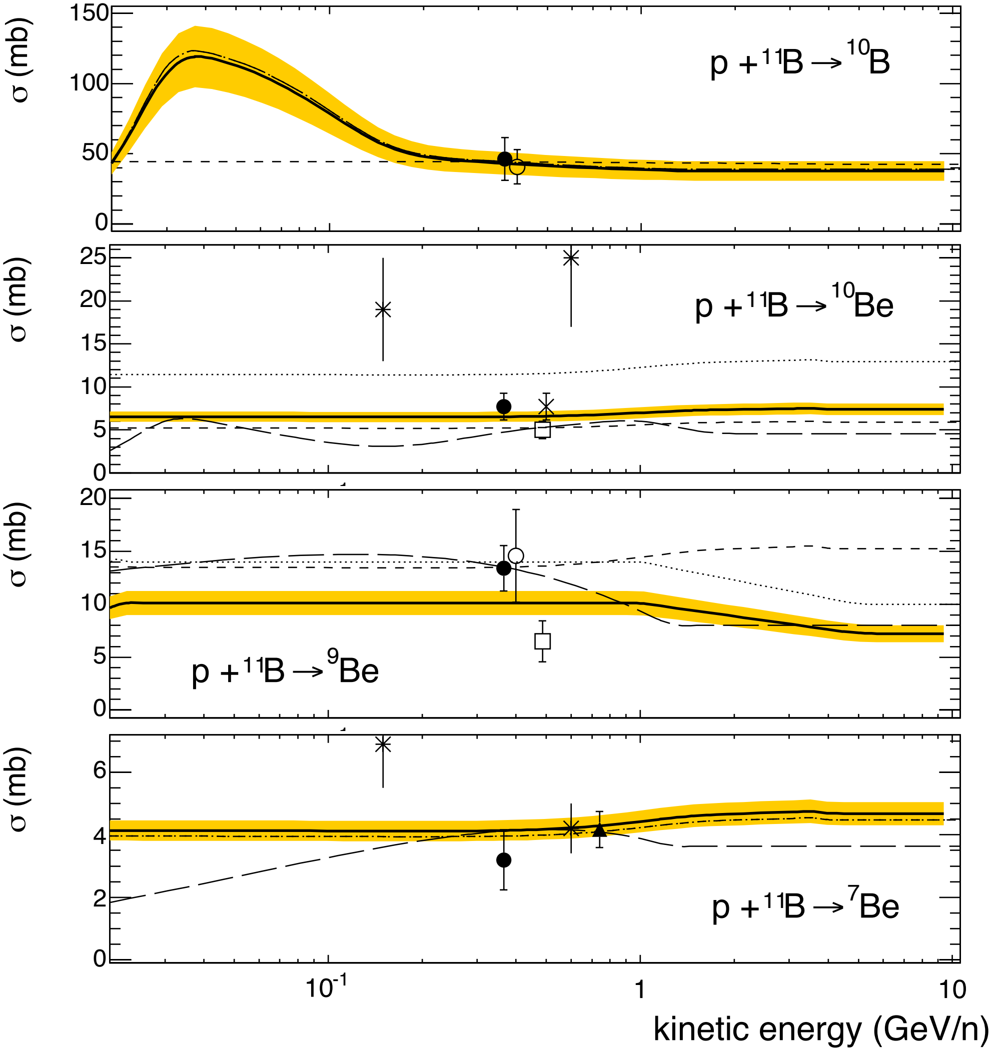
This degeneracy can be lifted with CR data on 10Be/9Be ratio

Very important for modeling the DM signal from annihilations in the halo

- *Lack of CR data on 10Be isotope*
- *Lack of XS data on 10Be production*

See. NT 1509.05776



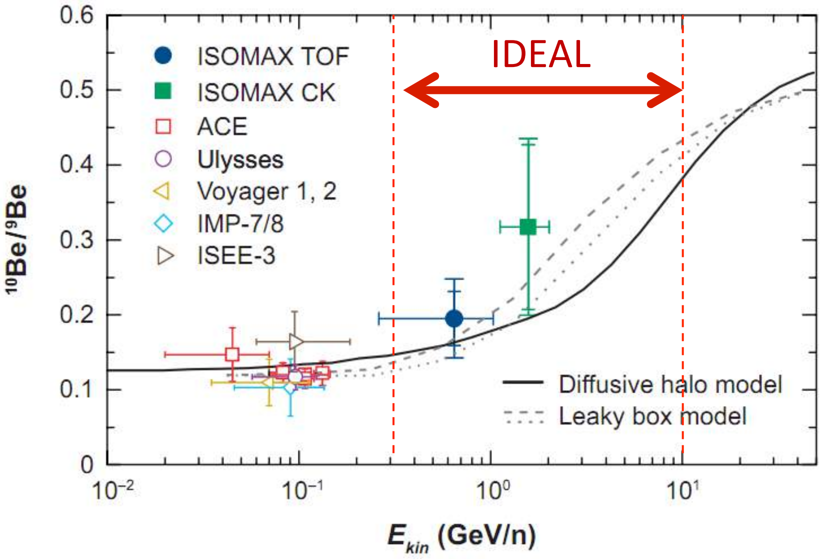


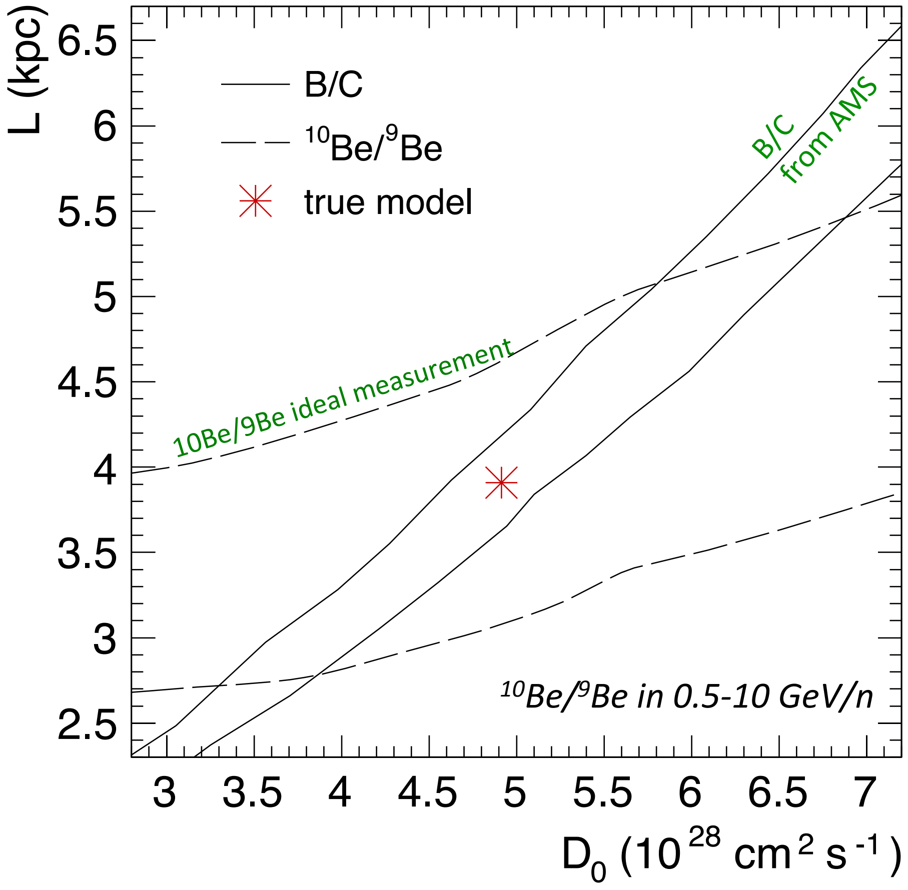
Astrophysical uncertainties: K_0/L degeneracy

This degeneracy can be lifted with CR data on 10Be/9Be ratio

- ✓ *Very important for the propagation of DM signal in the halo.*
- ✓ *Critically affected by beryllium-10 production cross-sections*
- ✓ ***Less important for secondary production calculations***

See. NT 1509.05776





Uncertainties in Solar modulation

Historical limiting factors

- Mis-knowledge of **LIS**
- Degeneracy between **solar-modulation** and **transport** parameters
- Simplicistic modeling approach based on FFA + direct fits to CR data.

Recent milestones & developments

- 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

1. Uncertainty from to spatial diffusion of CRs in the Heliosphere

From CR data and NM rates -> time series of ϕ(t) and uncertainties δϕ(t) ~ 40 MV.

Diffusion coefficient normalization $K(t) \sim \frac{V_{SW} d}{3\phi(t)}$ → antinuclei fluxes & uncertainty

2. Uncertainty from charge-sign (X solar-polarity) dependent drift effects

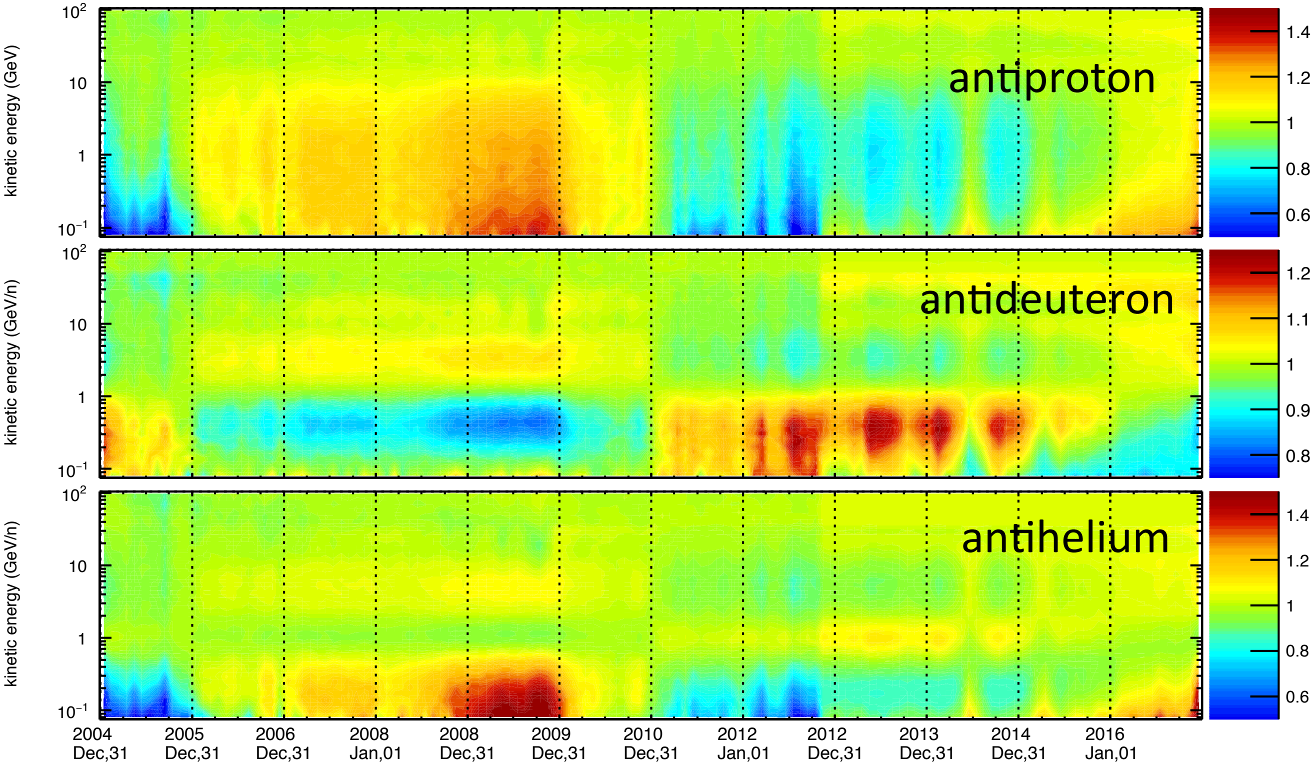
Calculation of antinuclei fluxes $J(t,E)$ and their charge-conjugated fluxes $\bar{J}(t,E)$

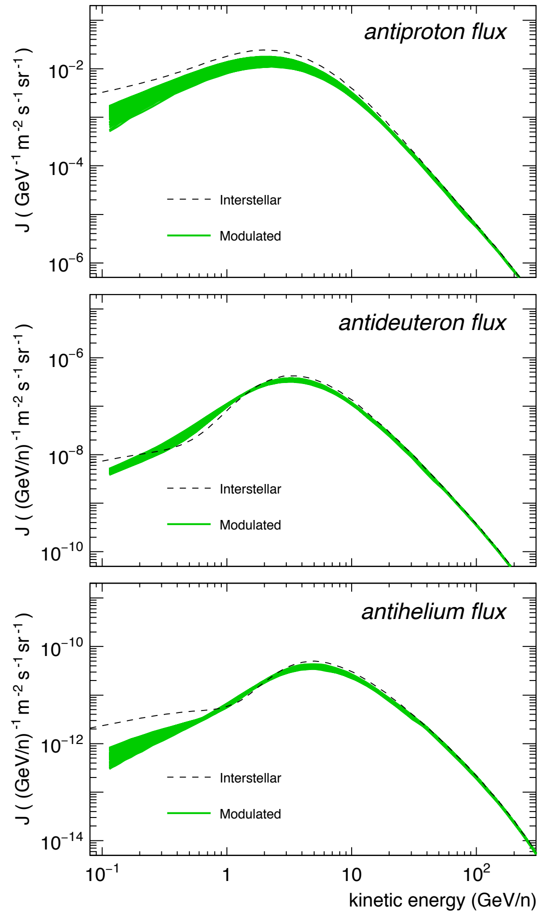
Evaluation of asymmetry parameter A(t,E) → Flux uncertainty $\delta J(E) = \langle J(E) \rangle \times \langle A(E) \rangle_{\Delta T}$

Uncertainties in Solar modulation

Flux variation V(t,E) of antinuclei as function of energy and time

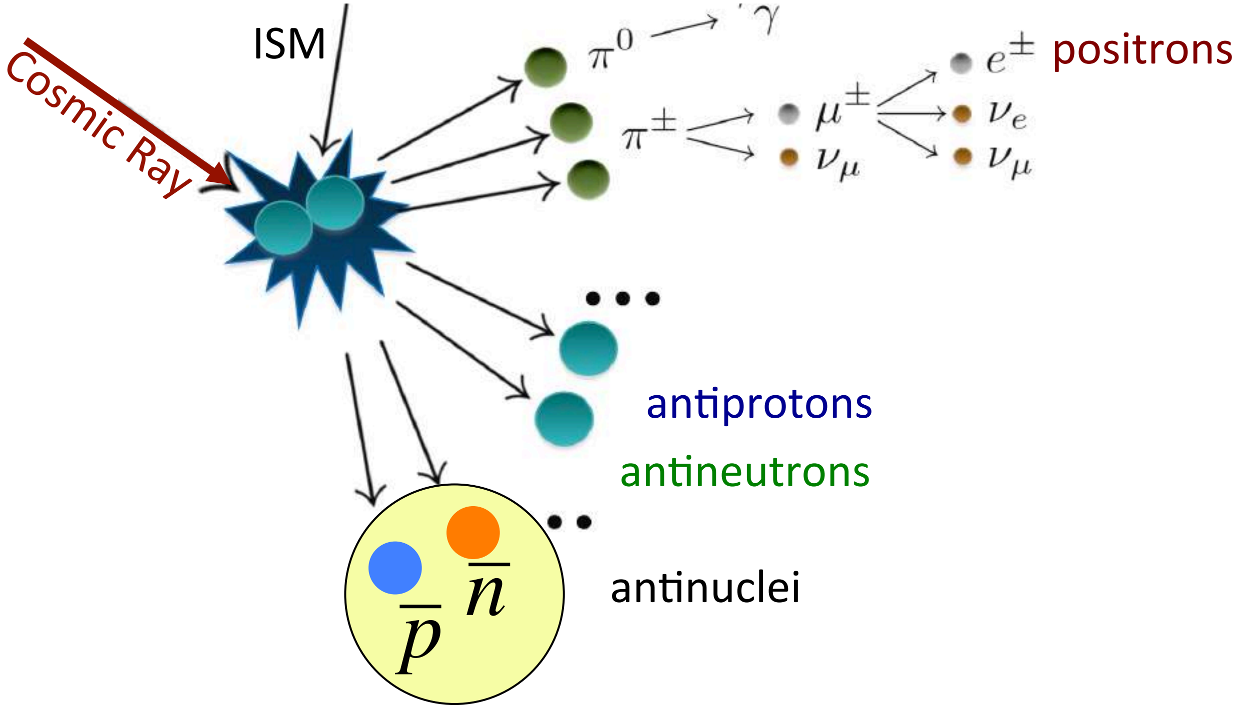
$$V(t,E)=J(t,E)/\langle J(t,E)\rangle_{\Delta T}$$





- ✓ Solar modulation do not provoke strong variation in antinuclei.
- ✓ Charge (xPolarity) - sign dependence must be accounted

Nuclear uncertainties



Production of anti-nucleons (nbar, dbar)

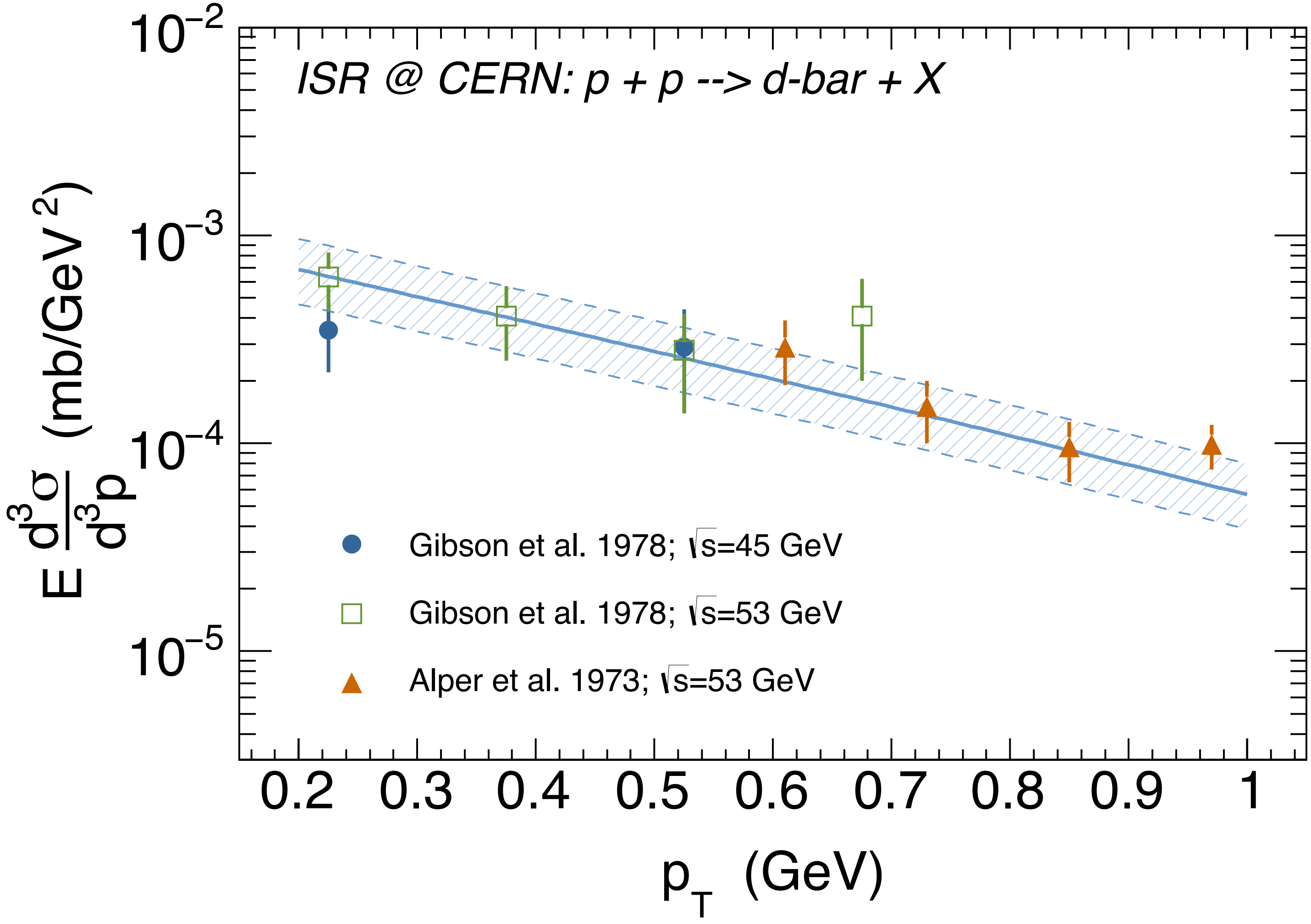
- New data, new parameterizations and MC-based calculations are now available.
- We tested many of them in Feng et al. 1610.06182 [QGSJET-II, EPOS-LHC, EPOS-1.99, SYBILL]
- We use *Di Mauro et al. 2014* thanks to its simplicity. We set nbar/pbar > 1.

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, pbar+H, pbar+He + tertiary
- **2H-bar** {nbar+pbar}, 3**H-bar** {nbar+nbar+pbar} **3He-bar** {nbar+pbar+pbar}

Antideuteron: nuclear coalescence & uncertainties

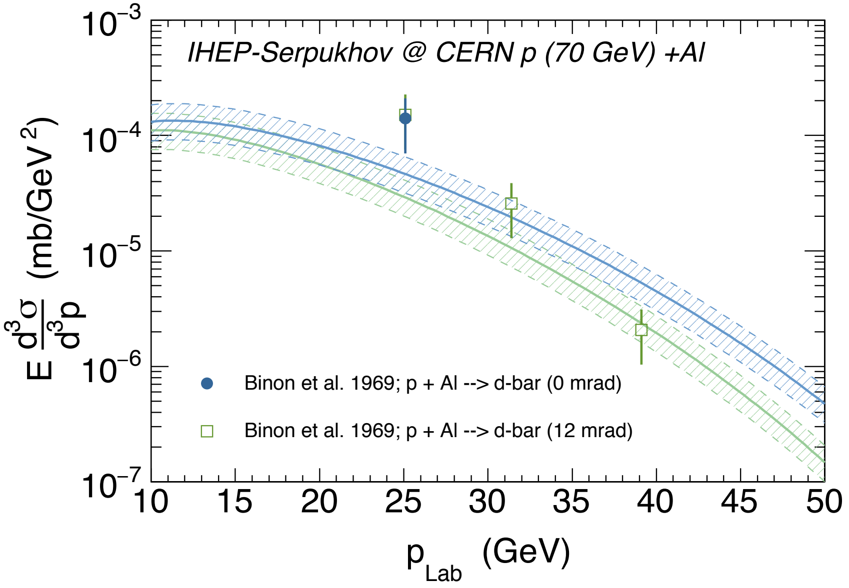
- ✓ Same accelerator data since ~1972: p+p , p+Be, p+Al @CERN
- ✓ New semi-parameterizations, new tuning efforts with MC-generators
- ✓ **Coalescence momentum is constrained with 12% uncertainty**

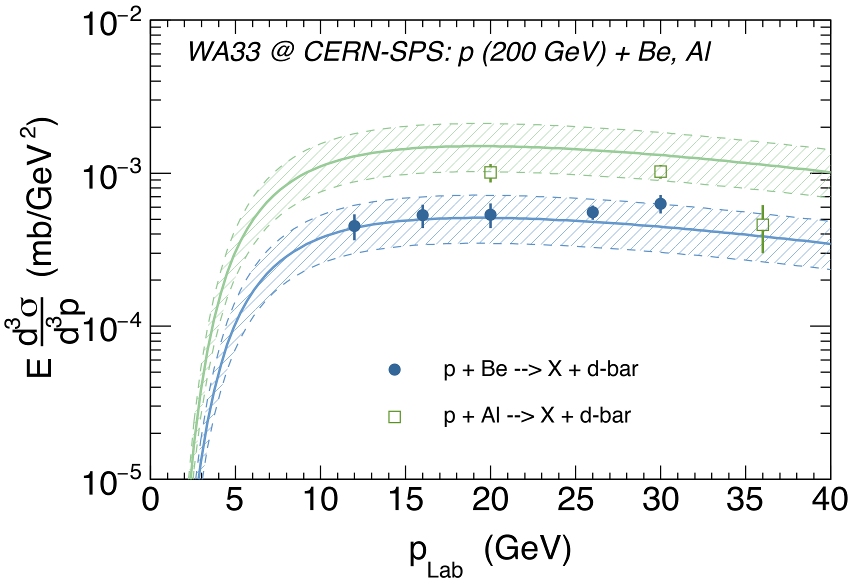


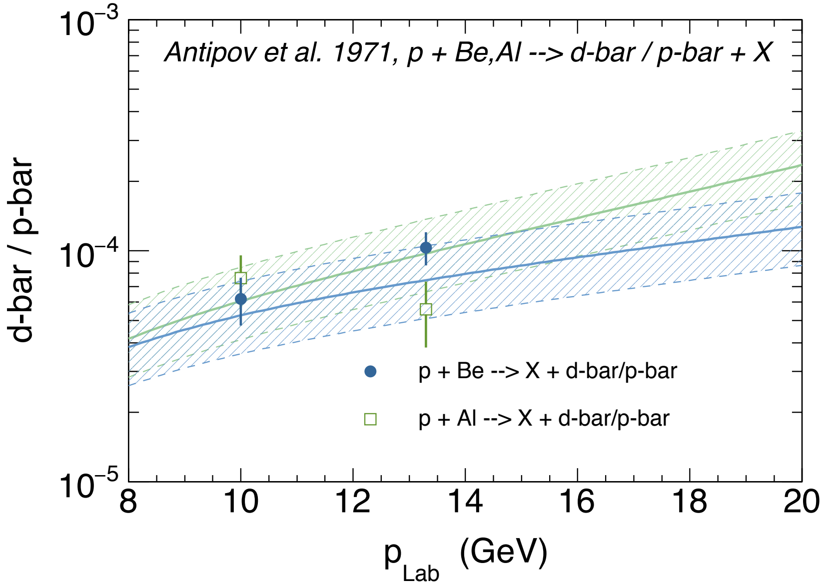
A. Oliva & NT 2017, improved coalescence model

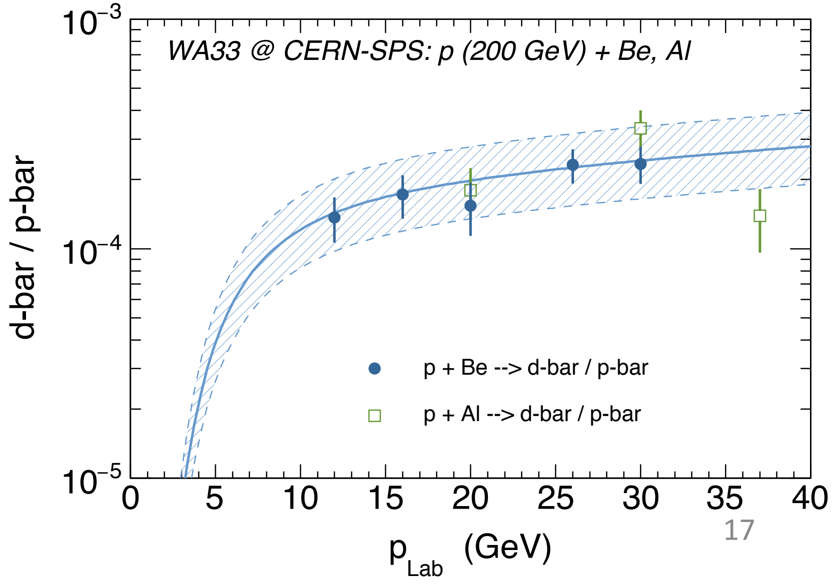
Antideuteron: nuclear coalescence & uncertainties

Many data are on p+Be or p+Al. Use of XS ratio pbar/nbar to cancel out target factors.



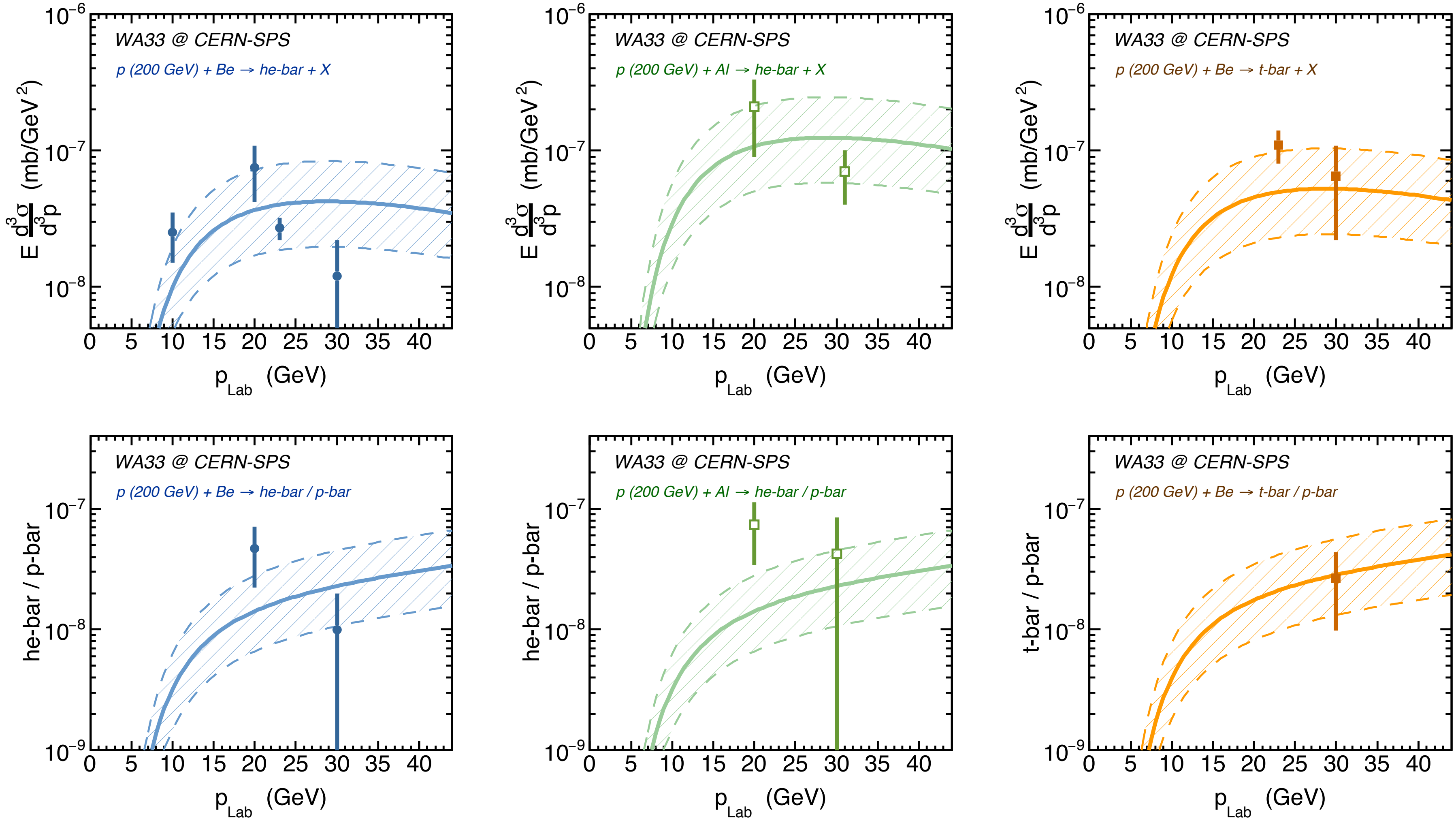






Antihelium: nuclear coalescence & uncertainties

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

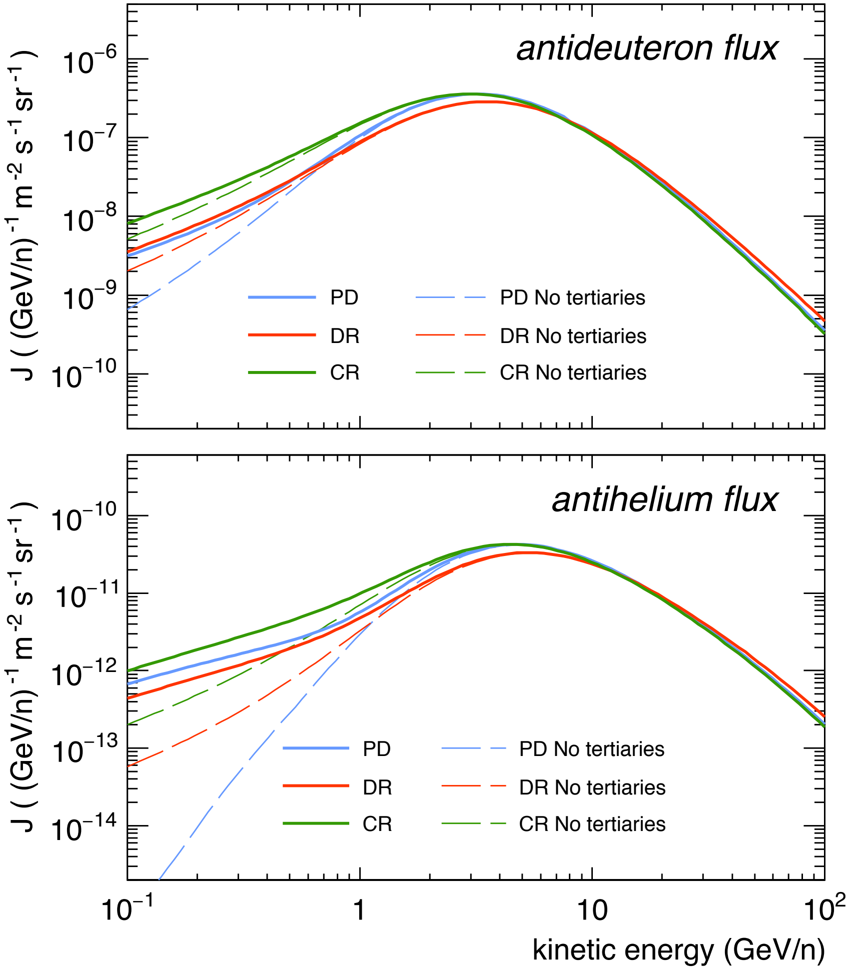
Dashed: fluxes w/o tertiary production.

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

Solid: tertiary production accounted.

- D-bar: NAR-XS from Duperray 2005. Tertiary spectra dN/dT' ~ 1/T (Tan&Ng 83)
- HEBAR: assumed same BR as DBAR.

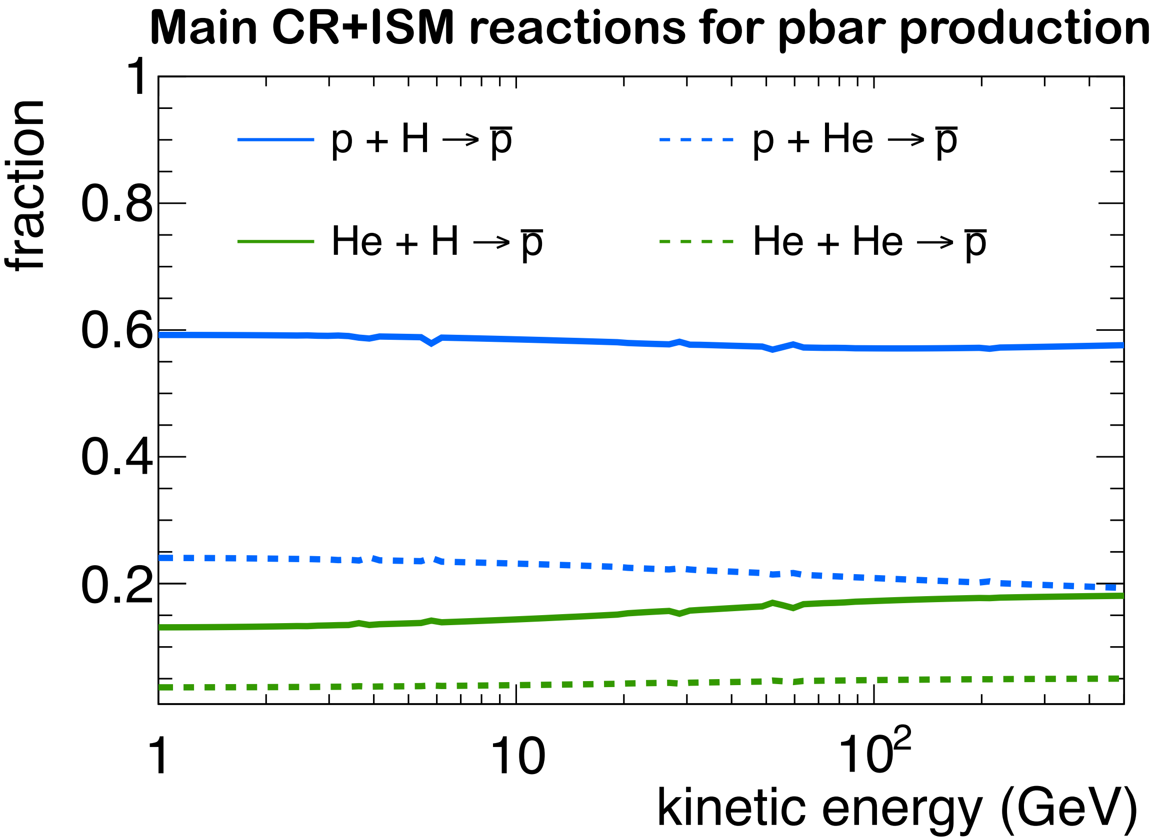
- ✓ Smoother sub-GeV/n flux, less sensitive to propagation loss/gain effects.
- ✓ Large uncertainty in tertiary production.



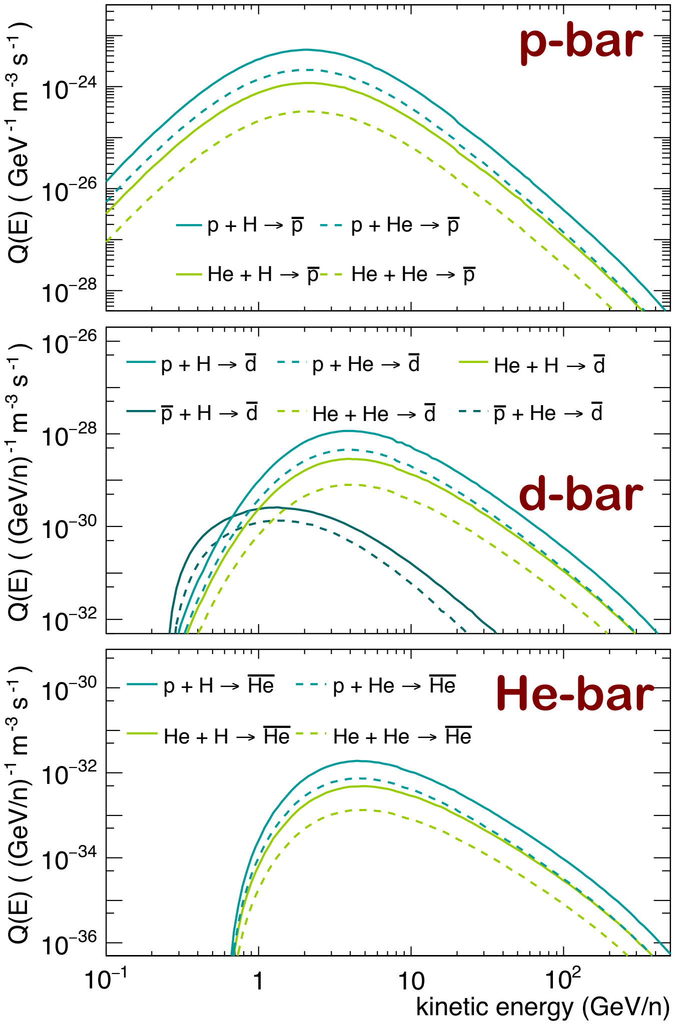
Take home messages

1) The sub-GeV region is appreciably influenced by tertiary production processes.
2) Accounting for tertiary processes mitigates the uncertainties in LE propagation

Secondary source spectra: main CR+ISM reactions



Main CR+ISM reactions for pbar production



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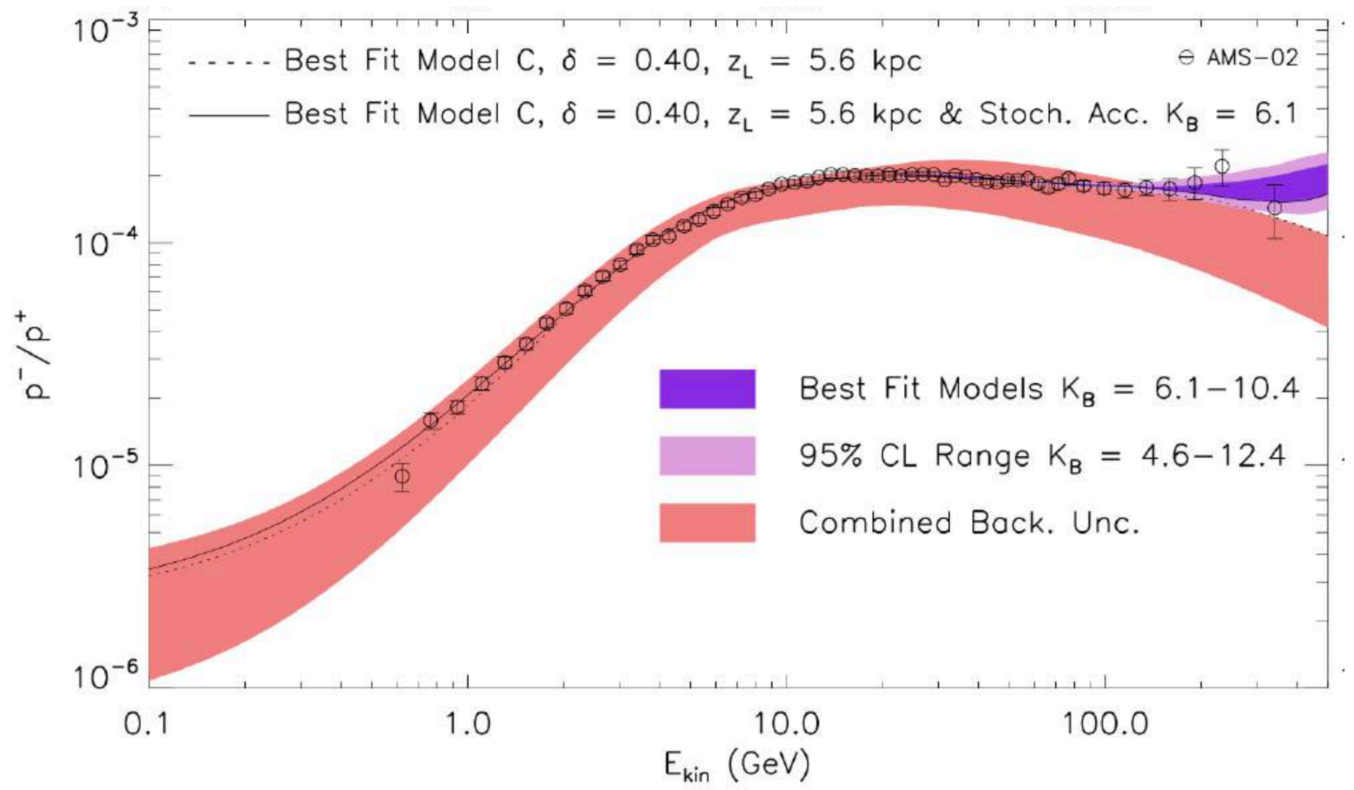
Antinuclei from supernova remnants?



Cholis & Hooper 1701.04406
Pbar/P “excess” explained by SNR production and acceleration of antiprotons...?

Antinuclei from supernova remnants?

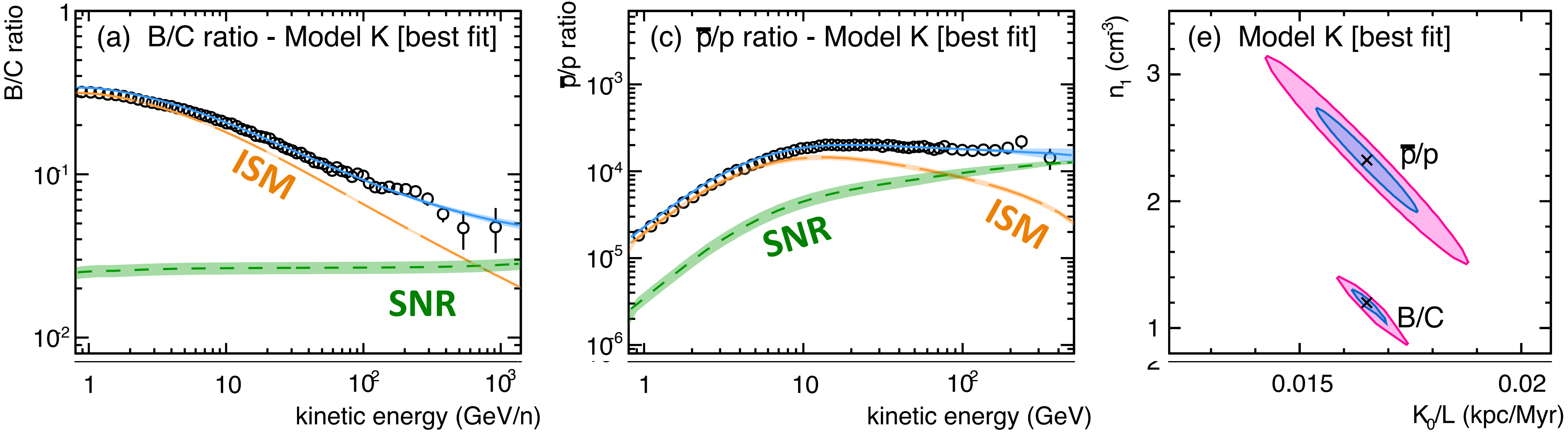
The B/C ratio gives tight constraints on SNR production of Boron nuclei

→ Evidence for SNR-induced boron compoents, consistent with expectations

→ Not to explain a flat pbar/p ratio

B/C driven fit

pbar/p driven fit



?

1) Yes, some antinuclei are likely produced in SNRs

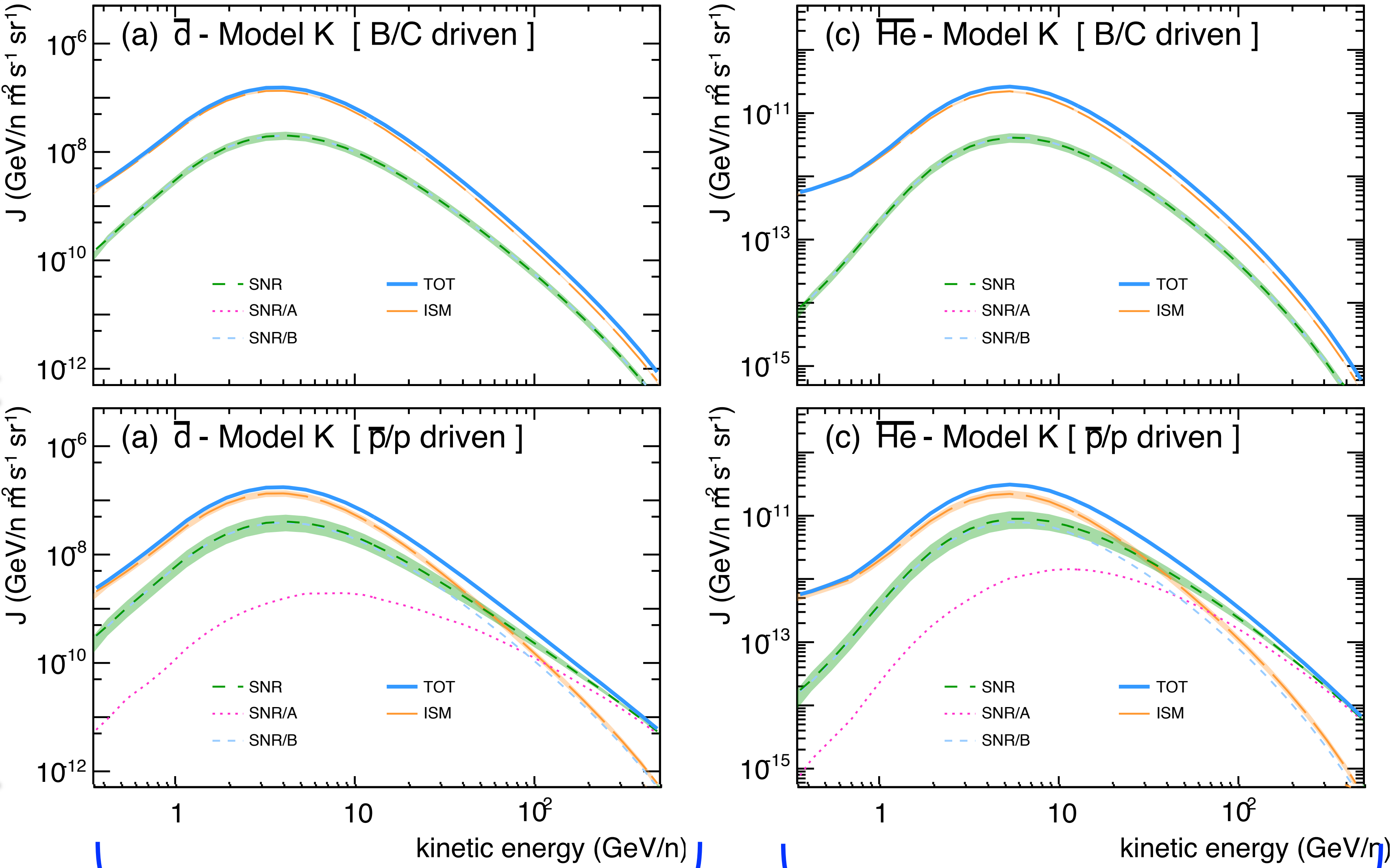
2) From B/C -> SNR production is subdominant w.r.t. ISM production

Dbar & Hebar from supernova remnants

The B/C ratio provides tighly bounds to SNR components

B/C driven

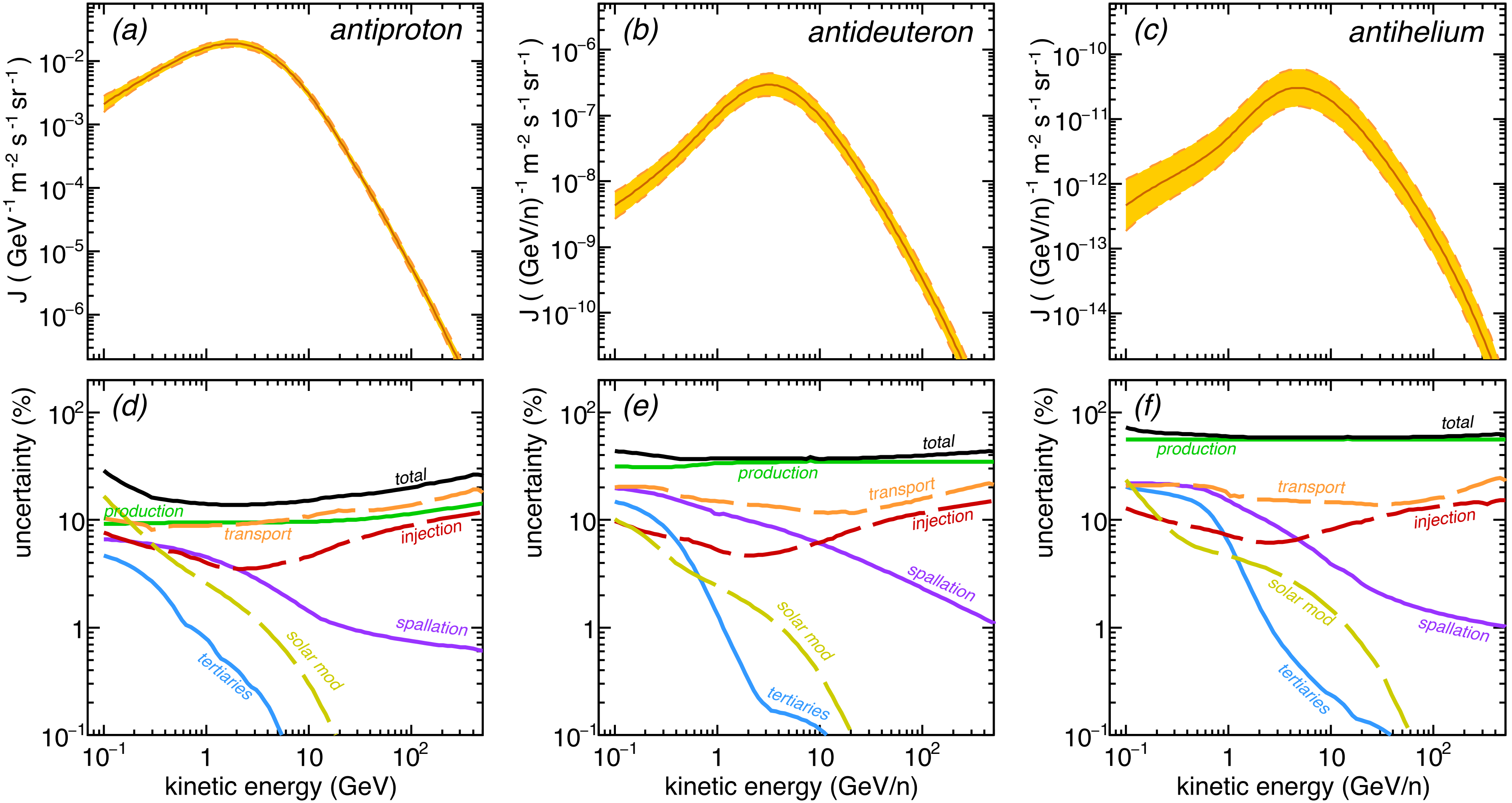
pbar/p driven



antideuteron

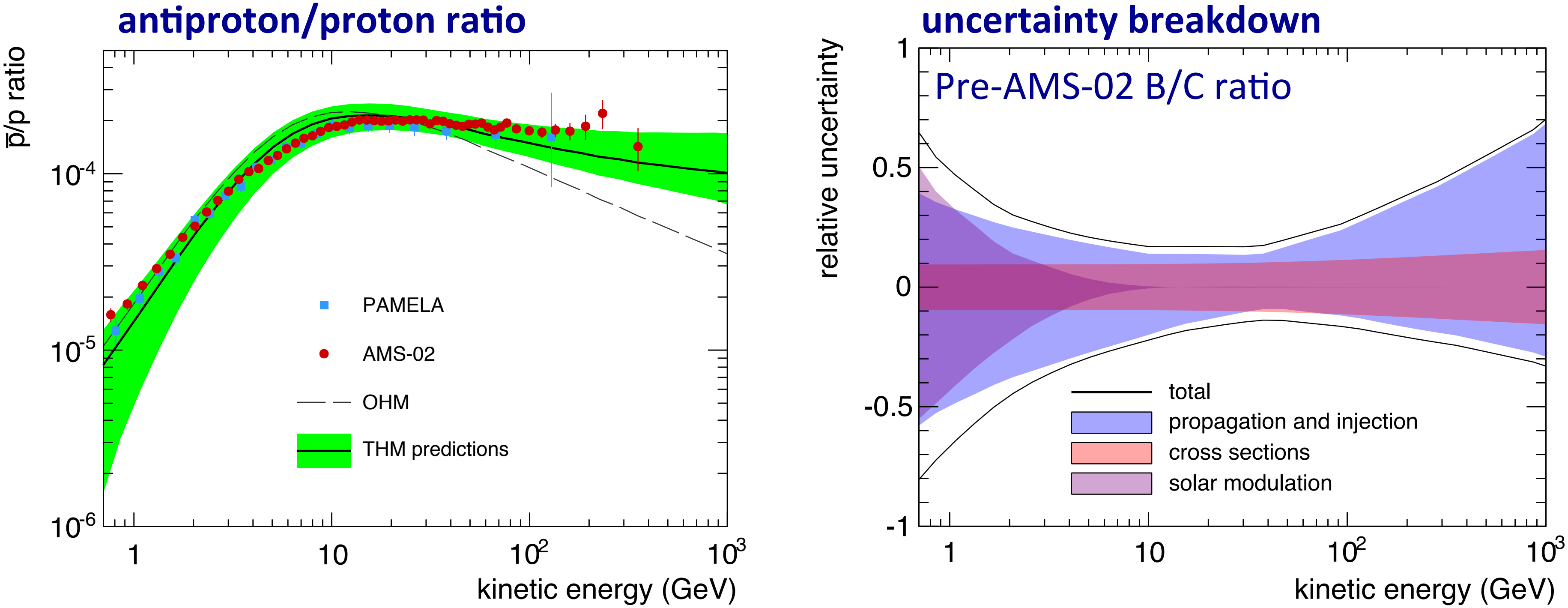
antihelium

Full uncertainty breakdown of CR antinuclei



This breakdown is somewhat artificial, because most of uncertainty contributions are correlated each others. Nonetheless it tells us which physical problems should be investigated in order to improve the estimation of the astrophysical background

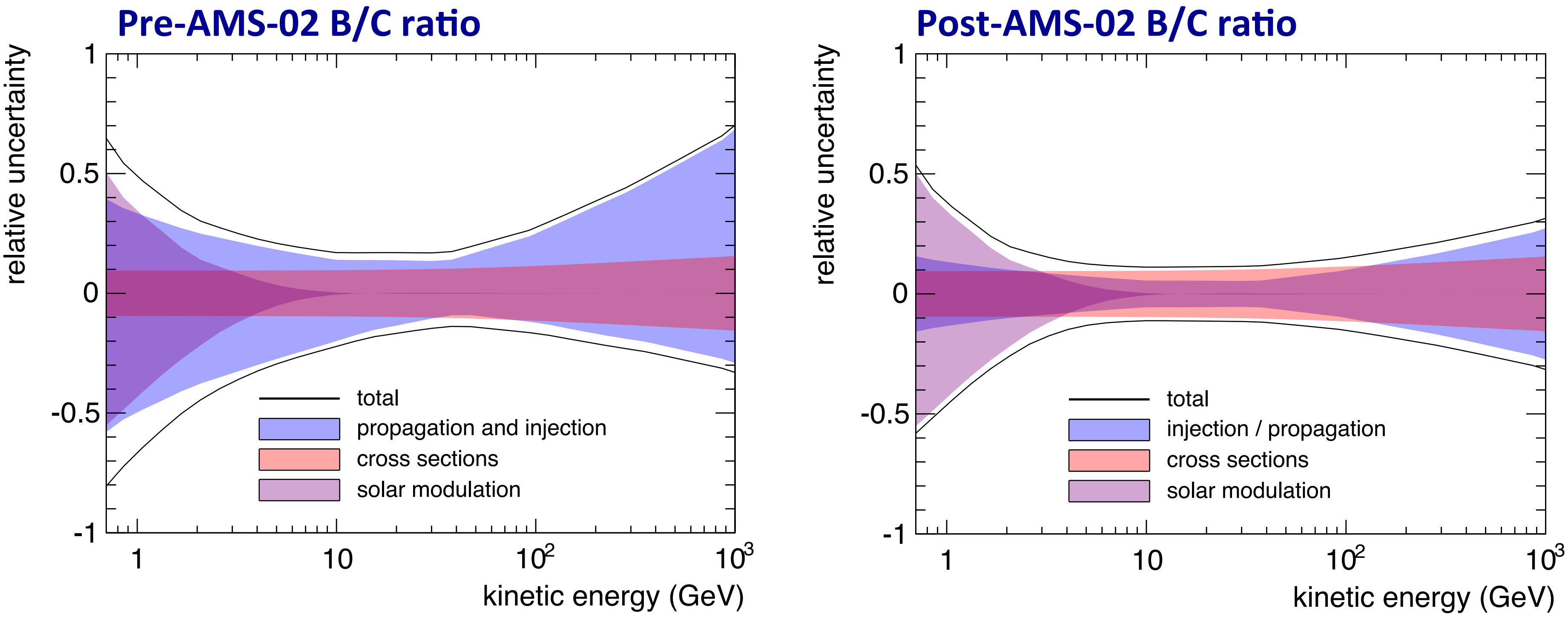
Astrophysical antiproton background


antiproton/proton ratio

uncertainty breakdown

J. Feng et al. 2016 1610.06182 : antiproton/proton ratio + uncertainty breakdown

Astrophysical antiproton background



J. Feng et al. 2016 1610.06182 : Antiproton/proton ratio + uncertainty breakdown

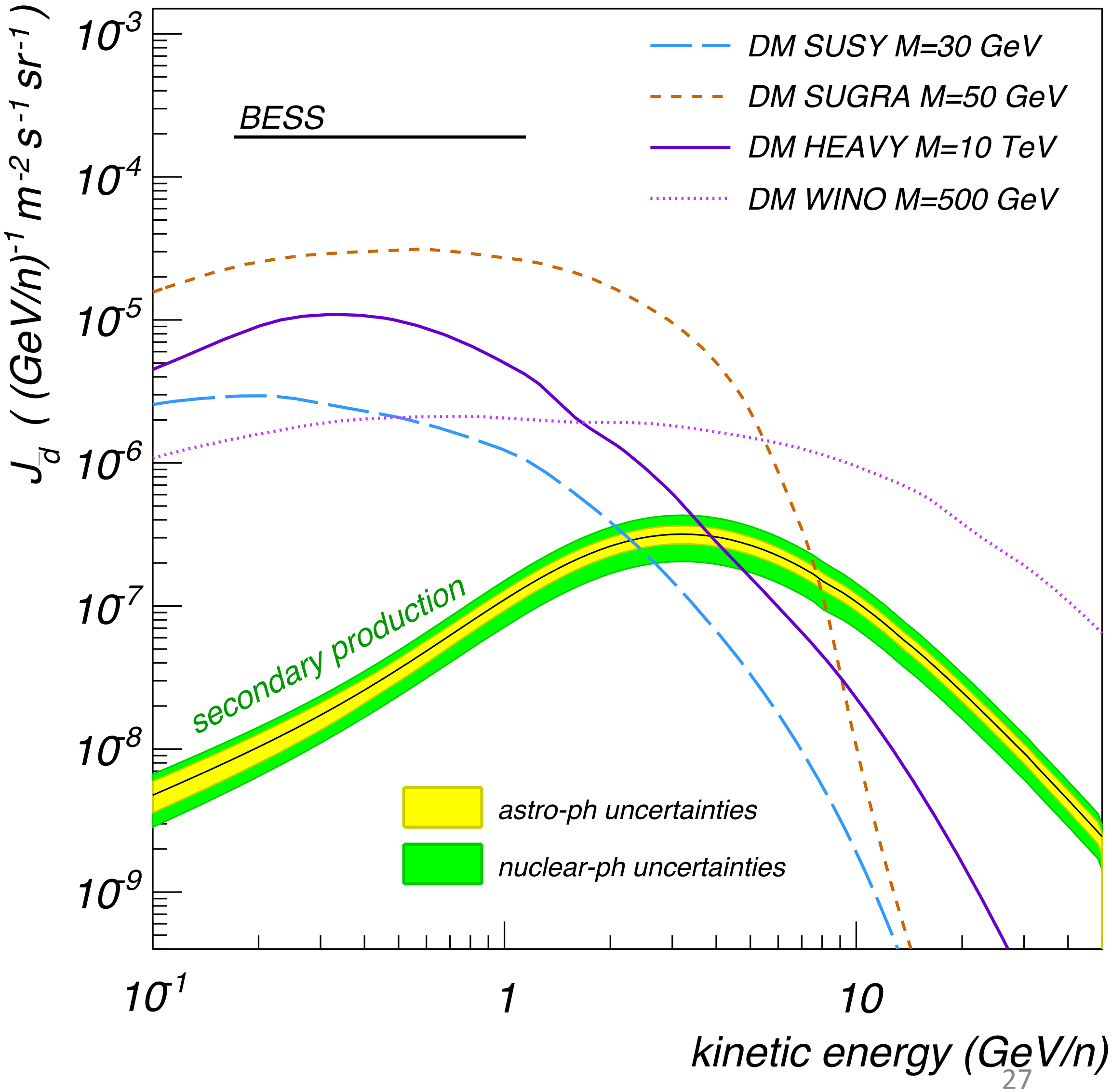
Updates on astrophysical uncertainties using new B/C data from AMS-02

Astrophysical antideuteron background

Updated uncertainties astrophysical + nuclear

Some optimistic DM annihilation models from Aramaki et al. 2016 Phys. Rept

- ✓ Uncertinties in calculations are dominated by nuclear coalescence.
- ✓ For a vaste class of DM models, the large signal/BG ratio offers promising discovery potential.



Astrophysical antihelium background

Updated uncertainties astrophysical + nuclear

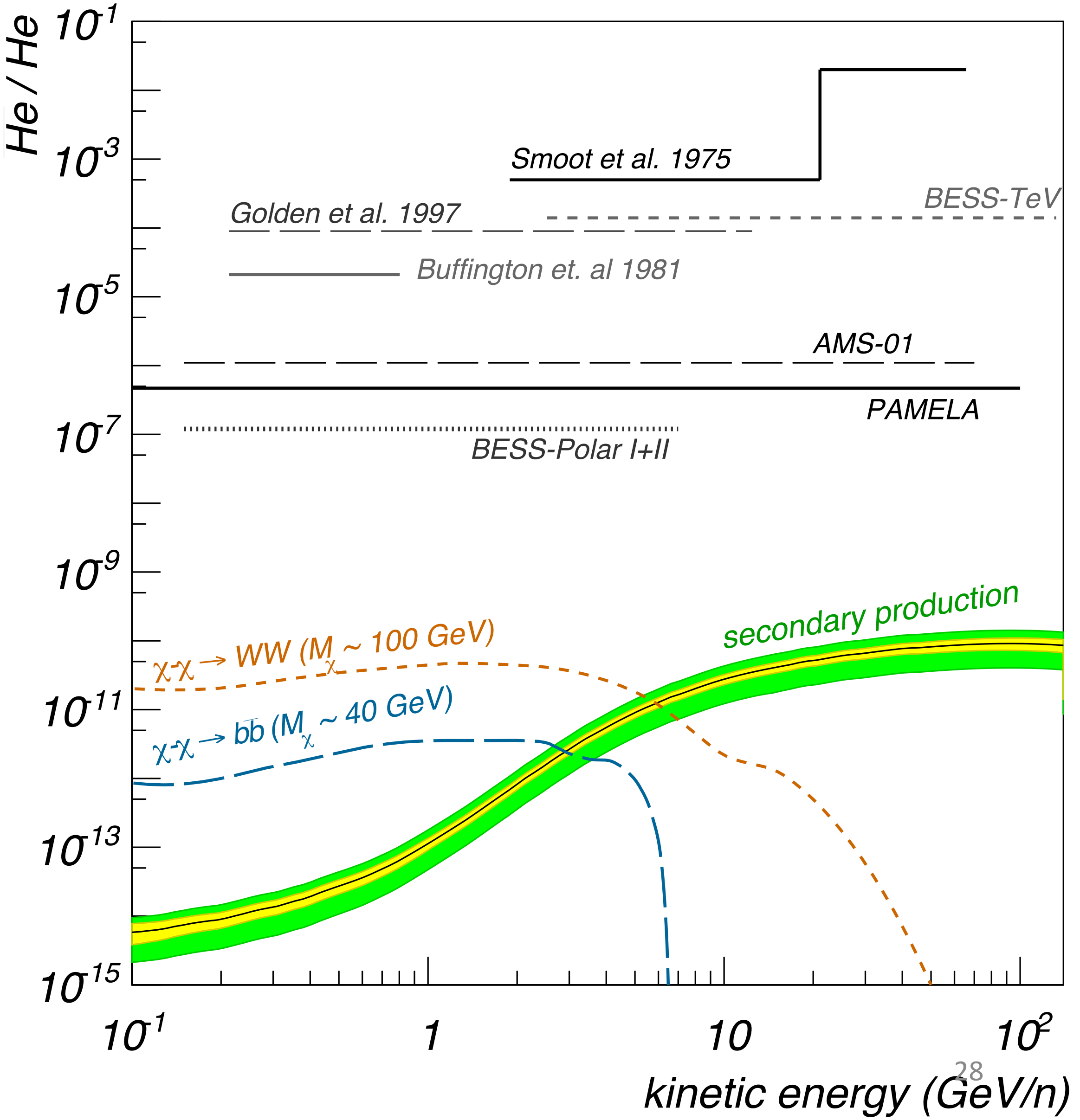
DM-DM annihilation models

- b-bbar, Cirelli et al. 2014
- WW, Carlson et al. 2014

✓ The current experimental sensitivity is far from the background level.

✓ Model uncertainties are strongly dominated by the coalescence mechanism.

✓ The sub-GeV He-bar flux is populated by tertiary particles: *NAR-XS unknown*



Some conclusions

All sources of uncertainties in have been review

- CR TRANSPORT

- New B/C data from AMS-02 and Voyager-1 pose tight constraints on CR transport.
- Cross-section uncertainties in Boron production
- Evidence for production in SNR. No big impact in secondary antinuclei.
- Diffusion/Halo (K/L) degeneracy limited by both CR and XS data.

- SOLAR MODULATION

- Uncertainty so far were over-estimated or mis-estimated

- PRIMARY CR – RELATED UNCERTAINTIES

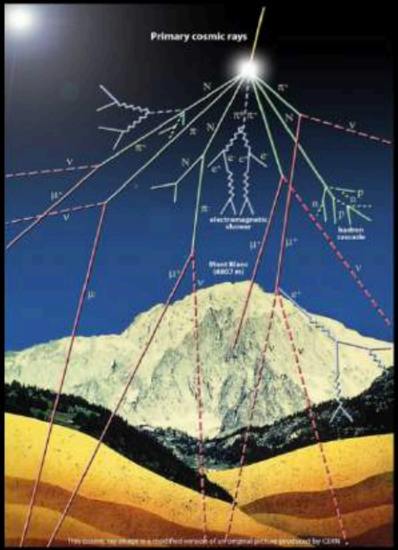
- Subdominant, but likely underestimated in many previous works

- NUCLEAR UNCERTAINTIES

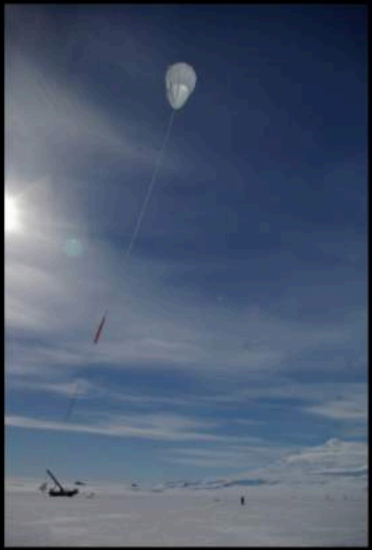
- Production XSs are the dominating uncertainties for all anti-nuclei pbar, dbar, hebar
- Antiprotons: limiting factor for the interpretation of AMS-02 data.
- Need of data on **p+He** or **He+H** and data and **anti-neutron** production.
- Dbar and He-bar: XS measurements needed. Role of tertiary poorly known.
- However, the astrophysical BG is far below the experimental sensitivity…

1. Introduction: experimental milestones

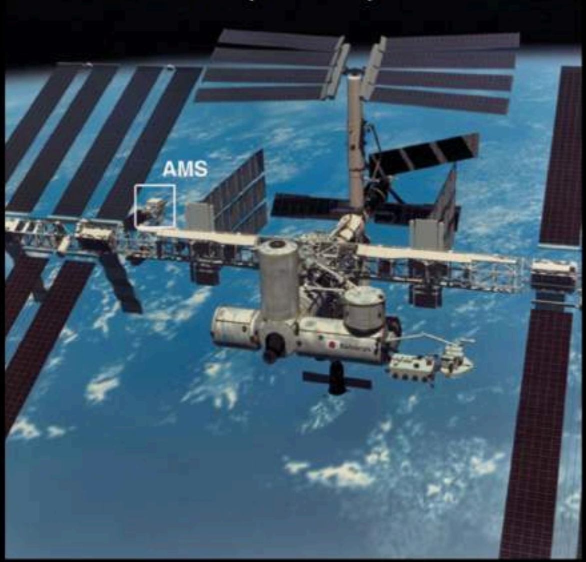
Mountain altitude < 5 km

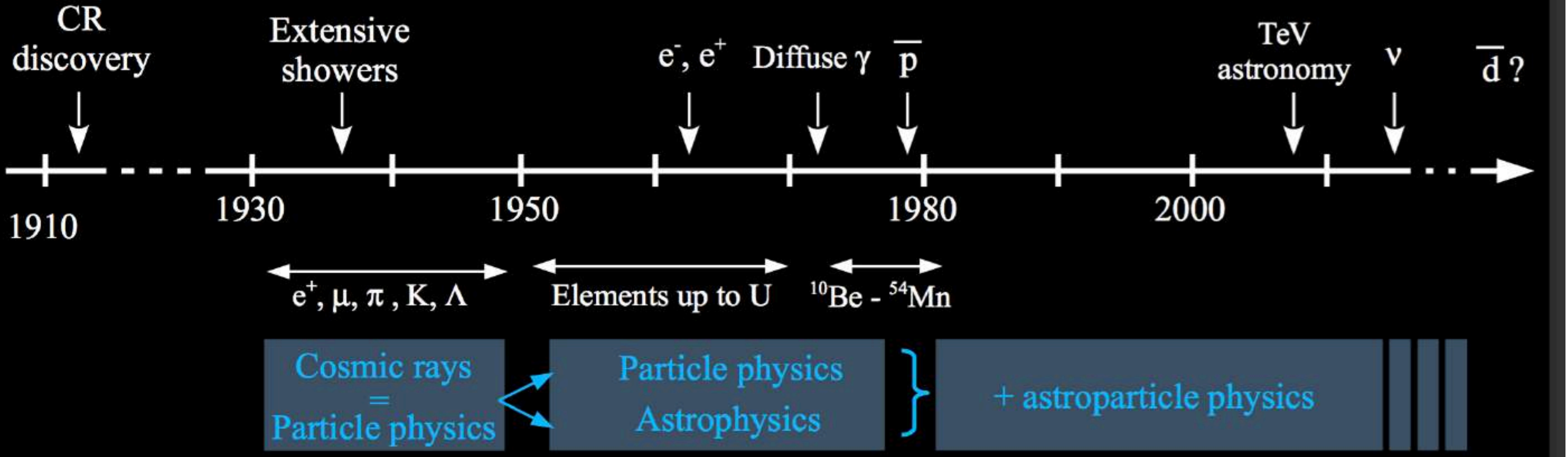


CREAM balloon ~ 40 km



AMS-02 (on ISS) ~ 300 km





CR discovery

Extensive showers

e^-, e^+

Diffuse γ

$\bar{p}$

TeV astronomy

ν

$\bar{d}$?

1910

1930

1950

1980

2000

e^+, μ, π, K, Λ

Elements up to U

^{10}Be - ^{54}Mn

Cosmic rays = Particle physics

Particle physics

Astrophysics

+ astroparticle physics

D. Maurin, talk at XSCRC2017, 29/03/2017