From accelerator measurements to particle astrophysics results

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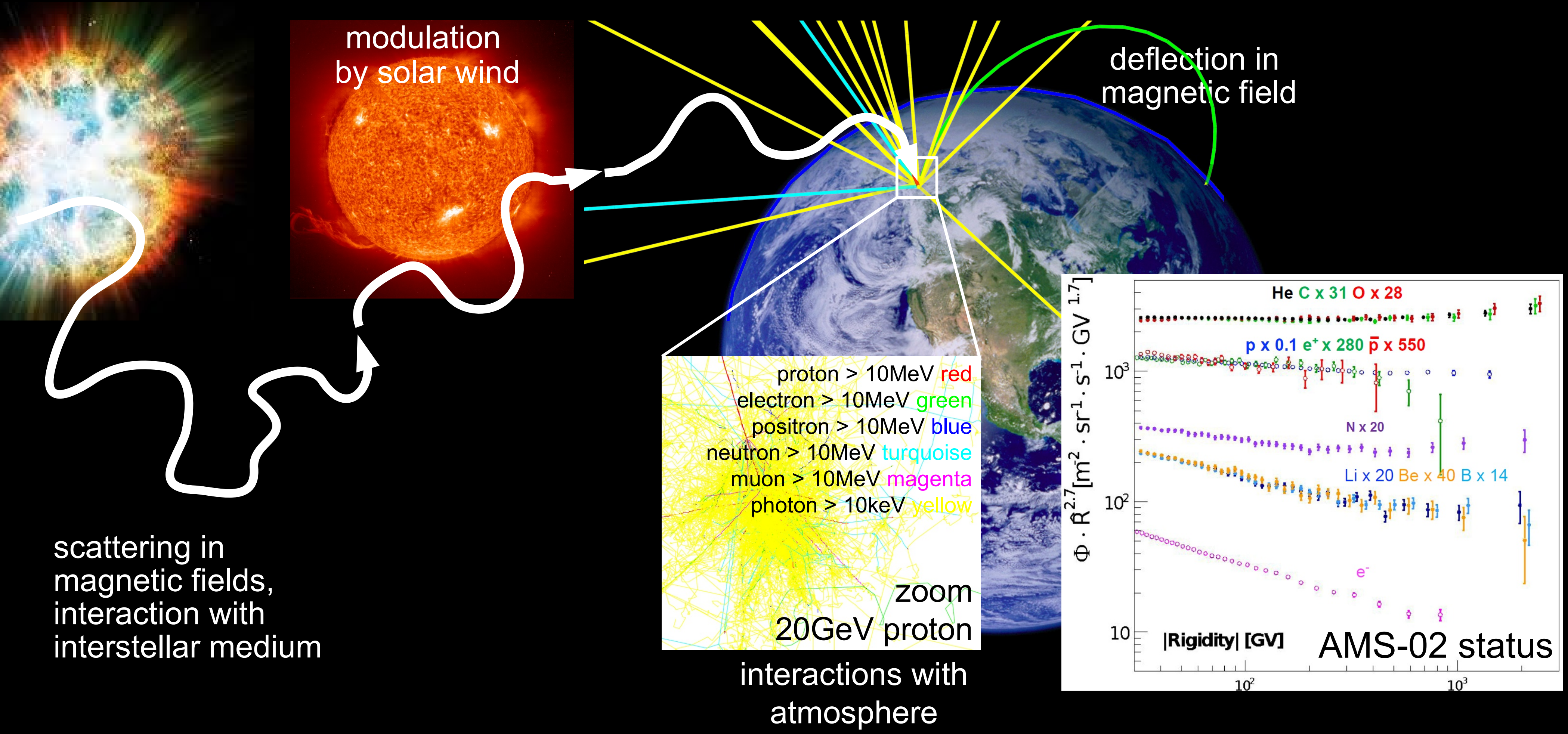
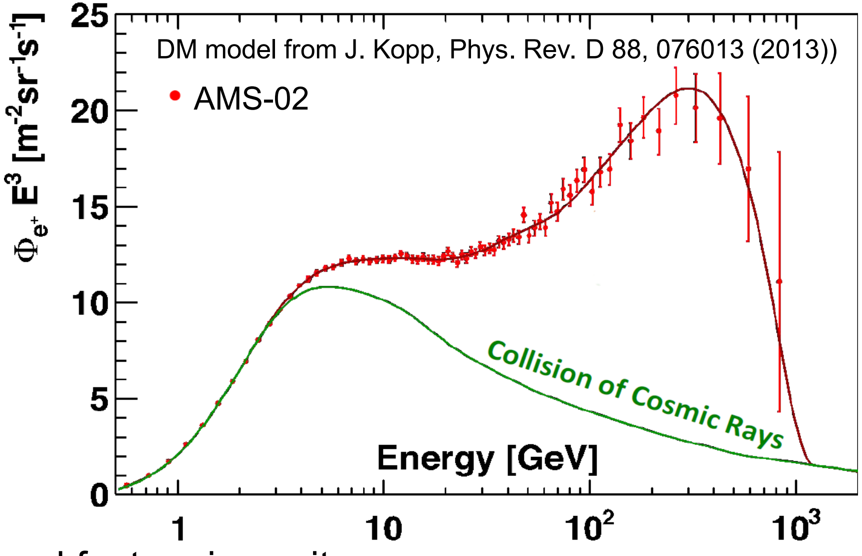
Cosmic rays as messengers

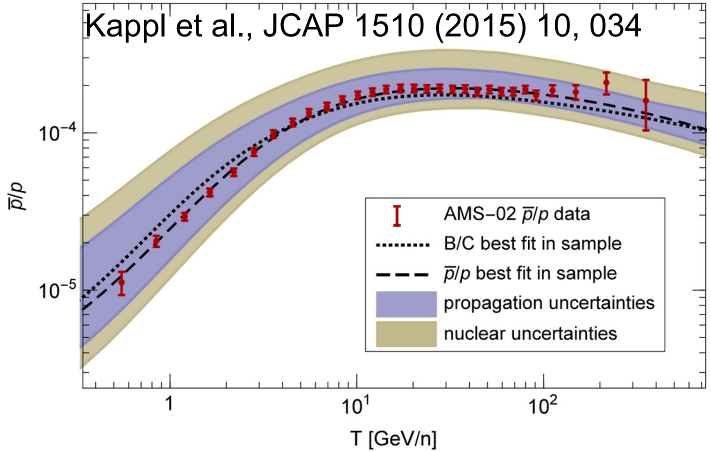


Dark matter signal in cosmic rays?

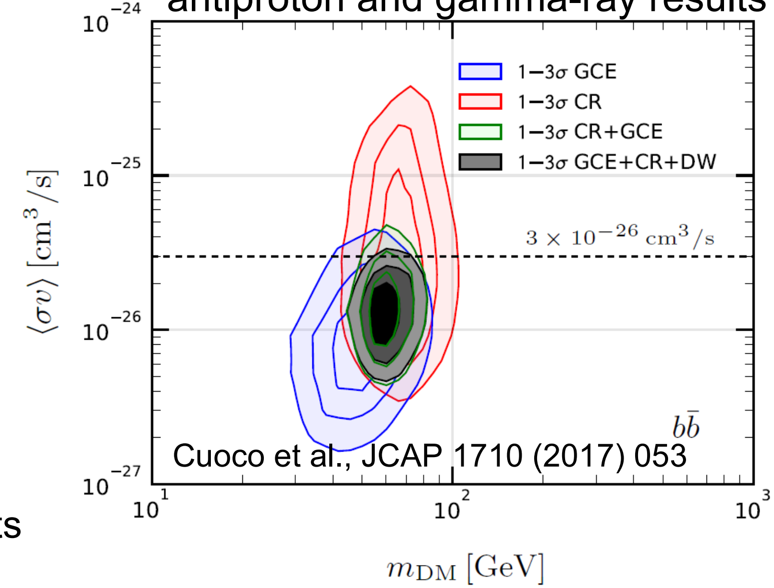
positron



antiproton



antiproton and gamma-ray results

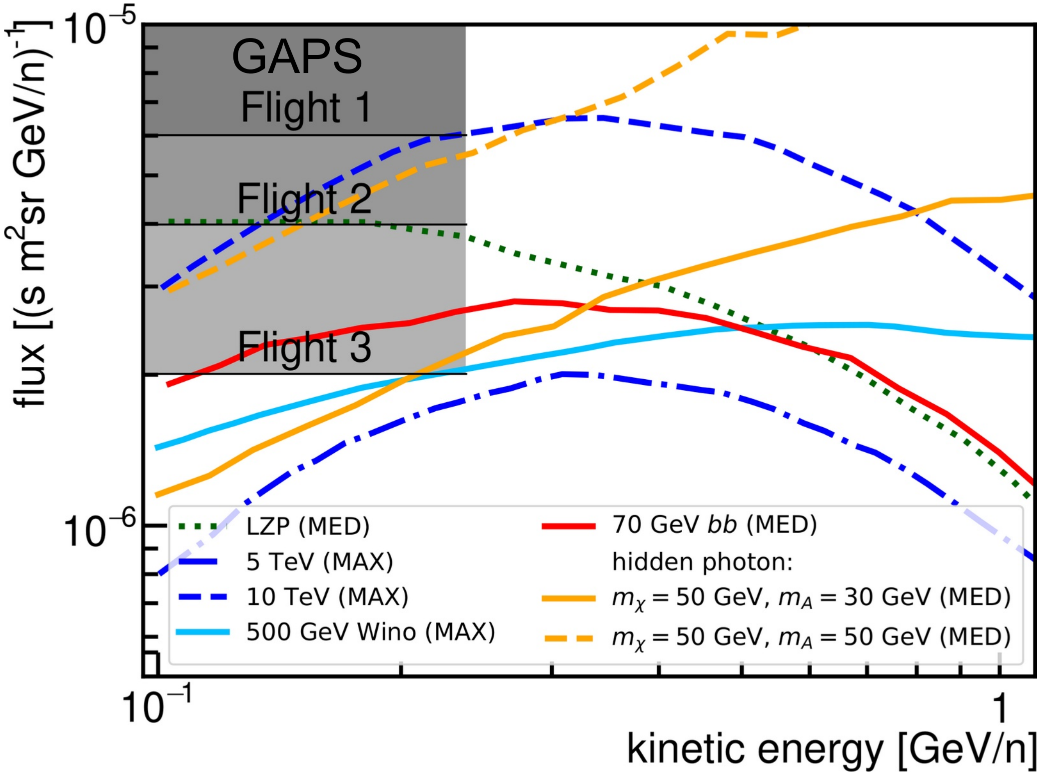


- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - **dark matter annihilation**
- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 80GeV DM particle?

- understanding astrophysical background is a challenge better constraints on cosmic-ray propagation and astrophysical production are needed

Antideuterons as a probe of dark matter

- Antideuterons sensitive to a **wide range of dark matter models**, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and γ-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Dark photons
  - Heavy DM models with Sommerfeld enhancement
  - Primordial black holes (antiprotons)



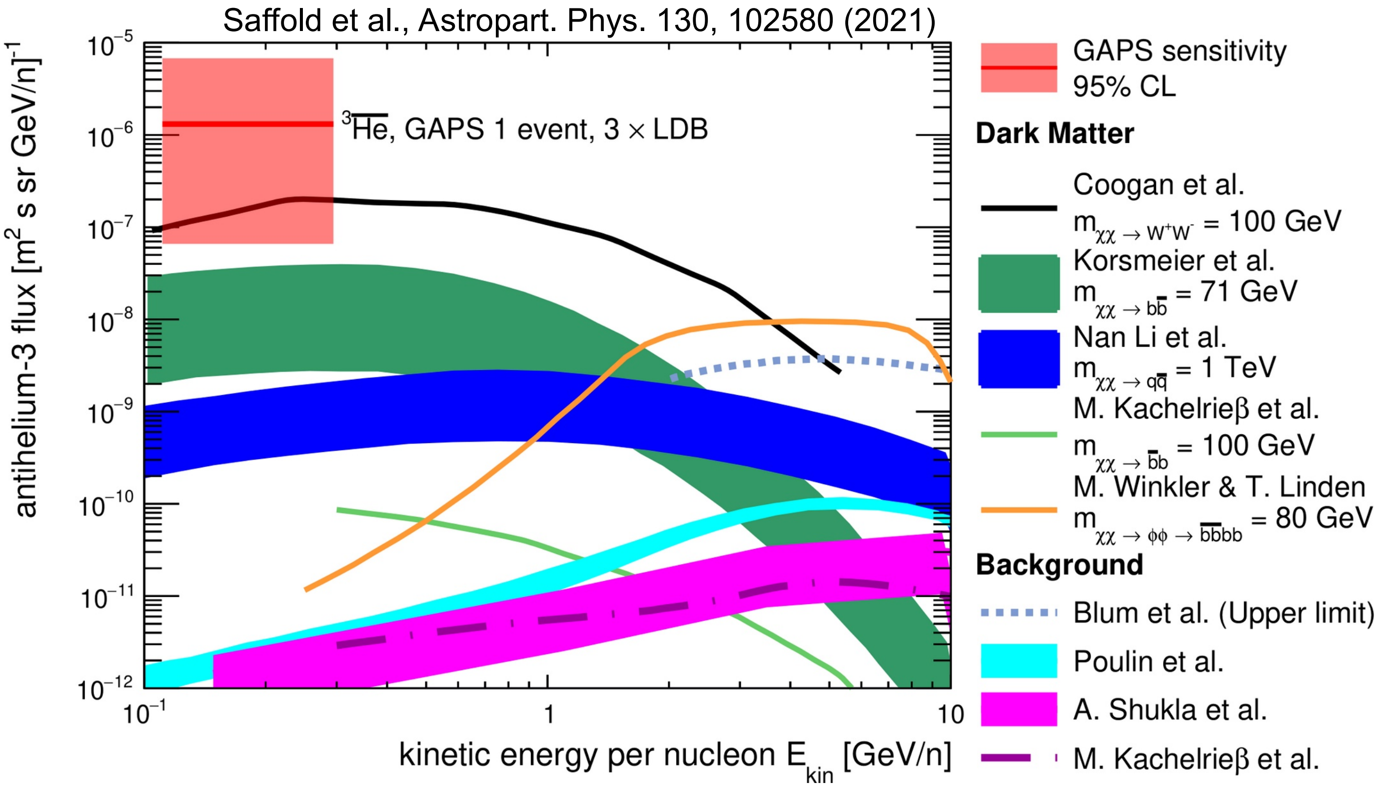
Antideuterons are an important unexplored indirect detection technique!

Cosmic-ray antihelium

- AMS-02 reported that **several $\overline{He}$ candidate events have been observed**
  → interpretations are actively ongoing

- Antiproton and antihelium both constrain antideuterons
  → no explanation of antihelium should overproduce antiprotons and antideuterons

- **Possible antihelium candidate explanations include:**
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc

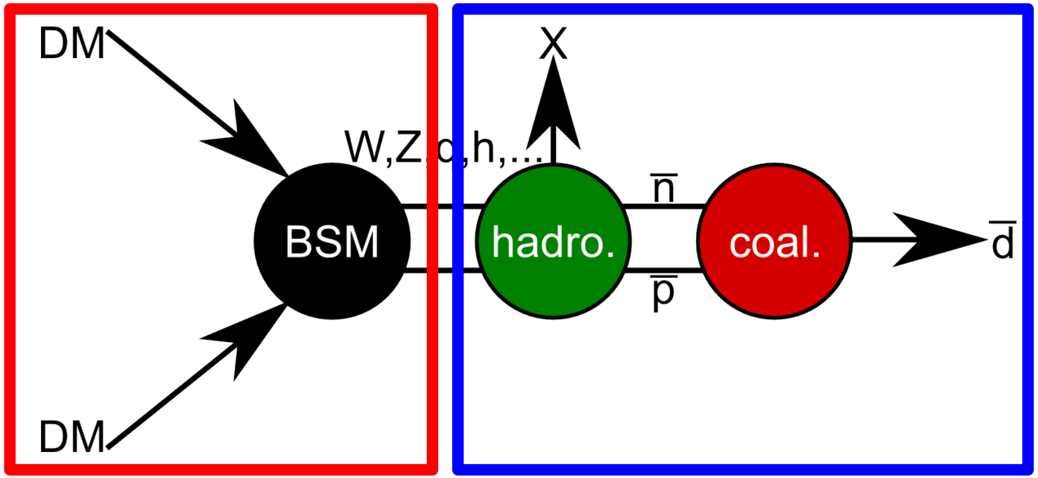


Finding low-energy antihelium would be truly revolutionary new physics

Uncertainties

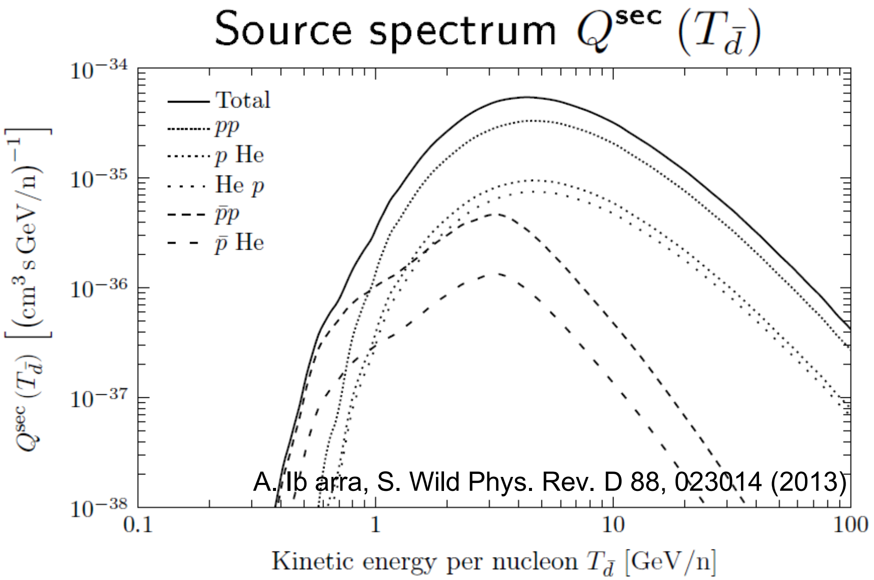
- **Cosmic-ray propagation**:
  - Important constraint for antinuclei flux from dark matter annihilations is the Galactic halo size, which directly scales the observable flux
  - Fits of cosmic-ray nuclei data are very important to constrain cosmic-ray propagation models (e.g., Li/C, Li/O, Be/C, Be/O, B/C, B/O)
  - Inelastic interactions of antinuclei in the Galaxy
- **Antinuclei formation** process breaks the degeneracy of antinuclei with antiprotons. Different approaches exist:
  - Coalescence: $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if relative momentum is small compared to coalescence momentum p_0
  - Wigner-function based, semi-classical model has been developed (M. Kachelrieß et al., Eur. Phys. J. A 56, 4 (2020)
  - Thermal model: Antinuclei directly formed at hadronization stage
- **Measurements of relevant primary cosmic ray and interstellar medium cross sections are important**

(Anti)deuteron formation: coalescence



dark matter

conventional production (e.g., p+ISM) & dark matter



- $\bar{d}$ can be formed by an $\bar{p}$-$\bar{n}$ pair if coalescence momentum p_0 is small

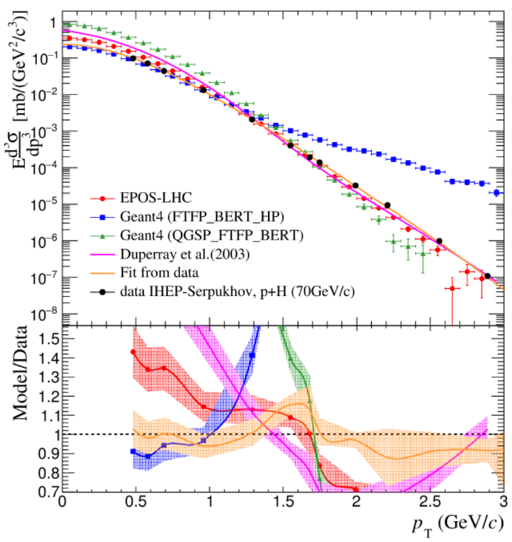
$$\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_p \frac{d^3 N_p}{dp_p^3}\right)\left(\gamma_n \frac{d^3 N_n}{dp_n^3}\right)$$

- use an event-by-event coalescence approach with hadronic generators

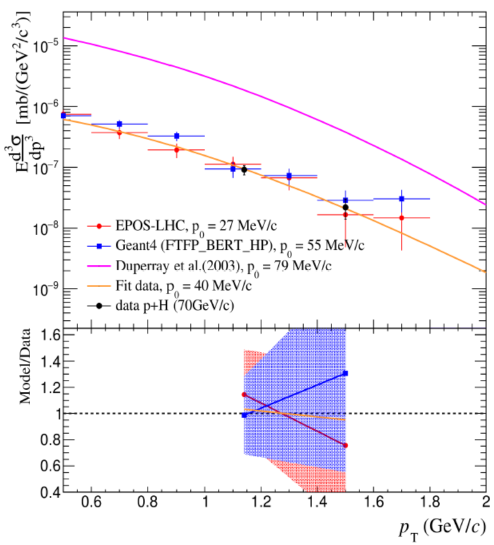
Coalescence modeling

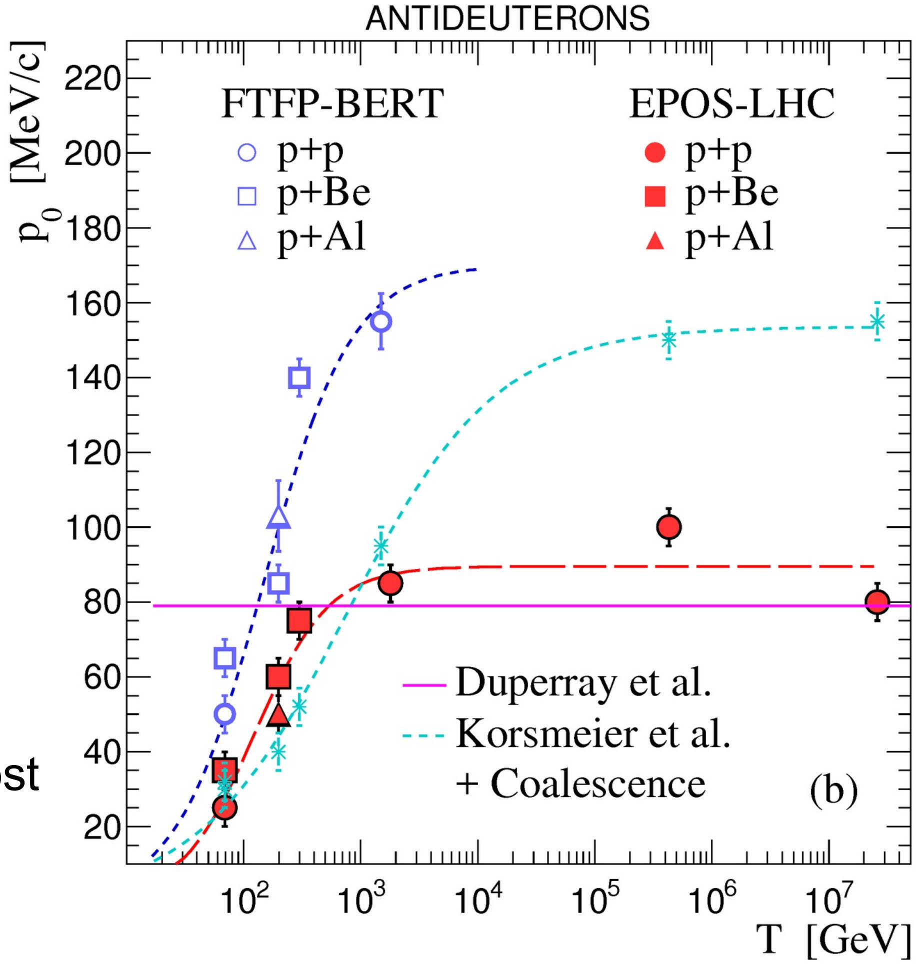
D. Gomez-Coral et al., Phys Rev D 98, 023012 (2018)

Antiprotons



Antideuterons





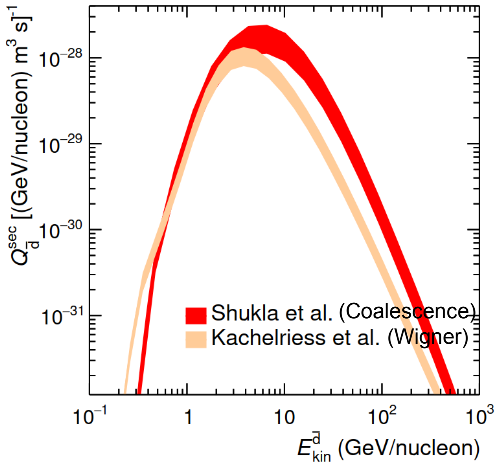
- find p_0 for each data set where antiproton and antideuteron results exist
- p_0 show strong energy depedence in the range most important for cosmic rays
- **more high-statistics data needed to constrain antinuclei formation models**

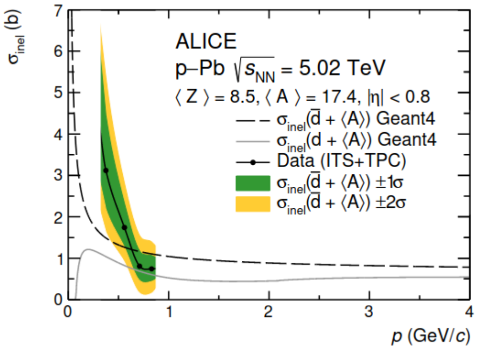
From production to flux at Earth

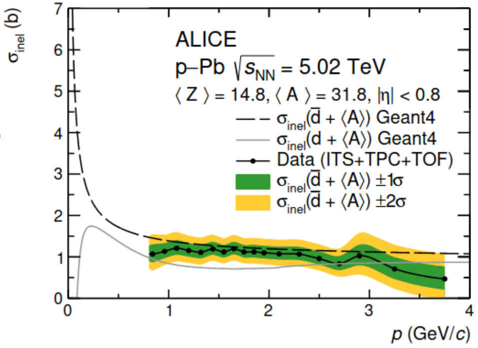
Šerkšnytė et al., Phys. Rev. D 105, 083021 (2022)

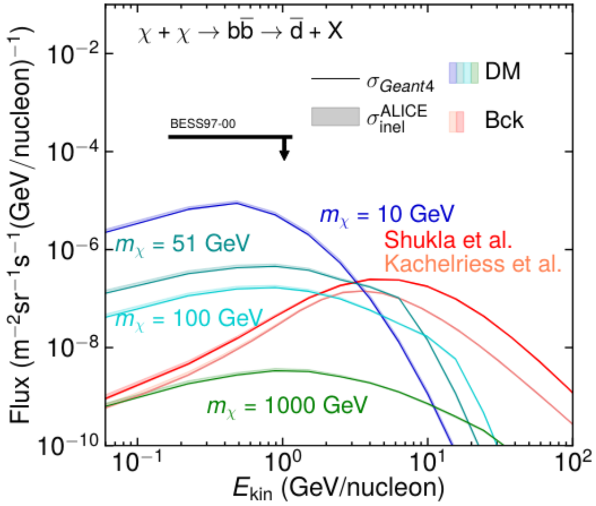
Propagation equation:

$$\frac{\partial\psi}{\partial t} = Q(\boldsymbol{r},p) + \mathbf{div}(D_{\rm xx}\mathbf{grad}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{\rm pp}\frac{\partial}{\partial p}\frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi\frac{{\rm d}p}{{\rm d}t} - \frac{p}{3}(\mathbf{div}\cdot\boldsymbol{V})\psi\right] - \frac{\psi}{\tau},$$





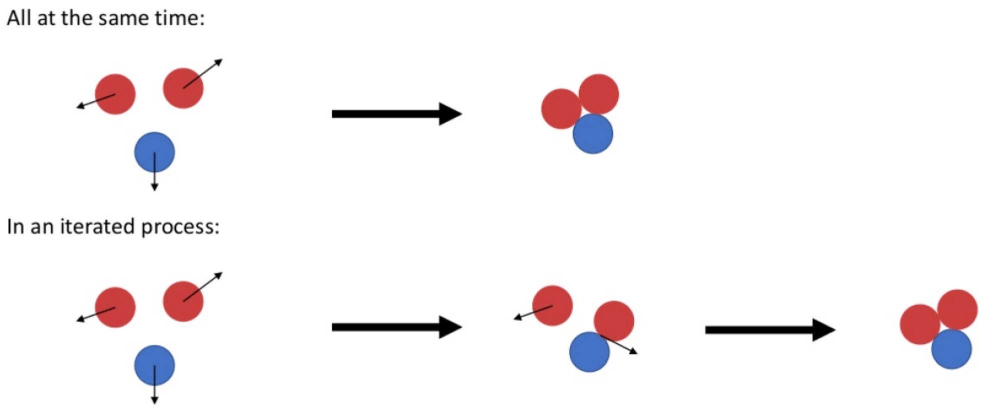




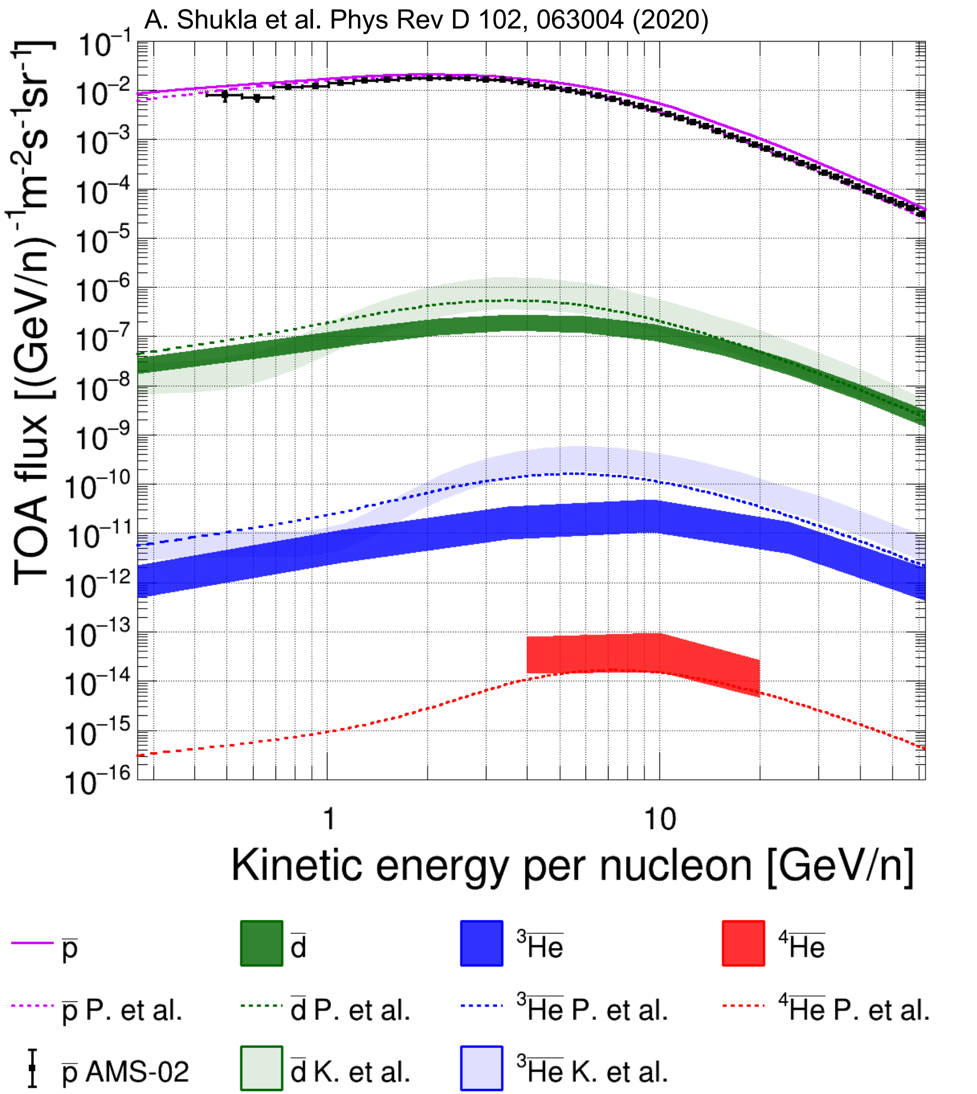
Antideuteron flux at the top of the atmosphere

- D_{xx}, V, and D_{pp} are the spatial diffusion coefficient, the convection velocity, and the diffusive re-acceleration coefficient, respectively.
- ψ/τ accounts for particles lost via decay, fragmentation and inelastic interactions in the Galaxy

Antihelium coalescence



- expanded modified MC coalescence model to merging multiple antinucleons from p-p interactions
  → requires quite a bit of computing power (~**5,000 years**, every additional antinucleon is about a factor of 1,000 suppressed → thanks UH HPC, OSG)
- use the p_0 behavior from antideuterons
- Very good agreement with ALICE antihelium-3 data (p-p at √s=7TeV)

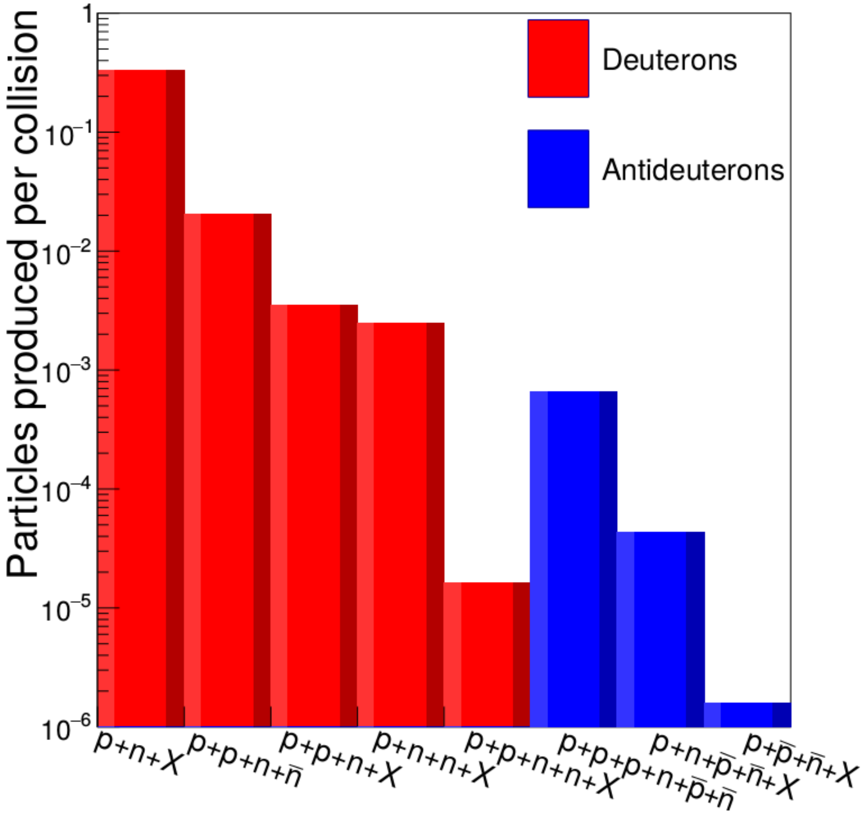


Issues of the coalescence model

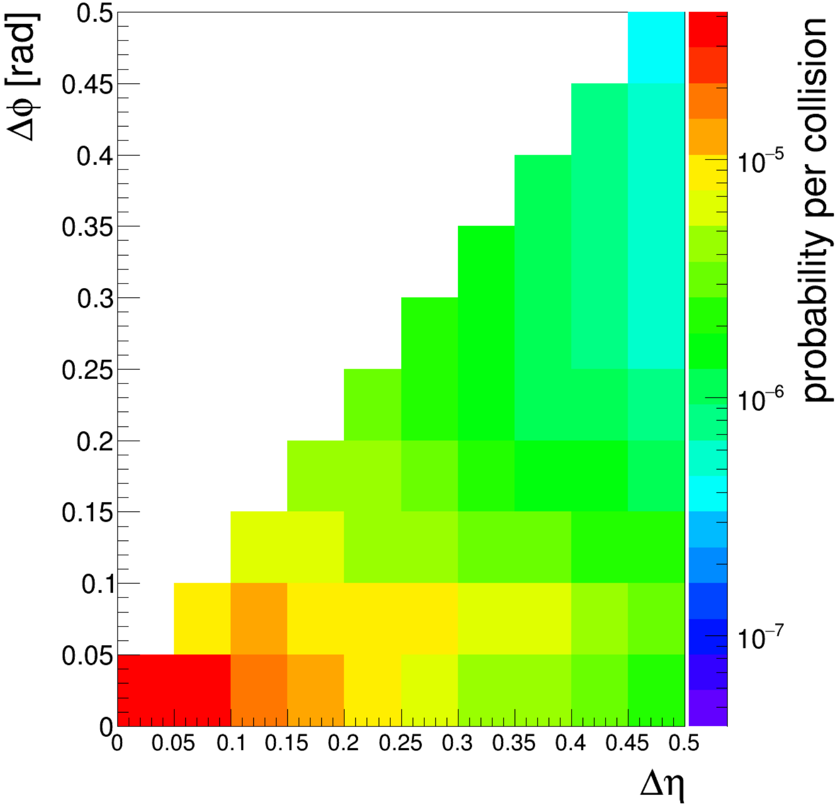
- **phase space** for ion production depends on the available energy in the formation interaction
- highly sensitive to **two-particle correlations** between the participating (anti)nucleons
- (anti)neutron spectra are challenging to access experimentally, potential asymmetries should be evaluated
- hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of p_0
- **spin** is not considered
- not a QM model
- generators not really tuned for antiparticle production
  → use dedicated antiproton, deuteron, and antideuteron data

Example for needed measurements

EPOS-LHC for p-p at 158GeV/c



Predicted production of nucleons



Angular correlation of p-p pairs within a radius of *Δp*=100MeV/*c*

Tune hadronic generators with more information on nucleon correlations

Future measurements

- NA61/SHINE at CERN SPS:
  - Fixed target experiment
  - High statistics $\overline{p}$ studies → Shukla: Identified hadron spectra in high-statistics p+p collisions at 158 GeV/c (POS-OTH-02)
  - C-p fragmentation cross section measurements
  - Deuteron production cross section, d/p ratio
  - Antiparticle correlation studies

- LHCb at LHC:
  - Antideuteron production in heavy hadron decays and in fixed-target collisions
  - Antihelium-3 from antilambda-b decays

- ALICE at LHC
  - Antinuclei production
  - Antinuclei inelastic cross sections

- AMBER at CERN SPS (upgraded COMPASS):
  - Fixed target experiment
  - High-statistics antiproton production cross section measurements

Summary

- Ideal range for relevant cosmic-ray antinuclei cross section studies is p_{lab}=100-500GeV/c for *pp*
- Nuclei production measurements from various experiments and at a broad range of energies are already used
- Antiproton cross section uncertainties in the energy range of AMS-02 are at the level of 10–20%, with higher uncertainties for lower energies
- Full QM model for antinuclei formation needs to be further developed and validated
- More measurements are upcoming by many different experiments
- Reviews: Doetinchem et al., JCAP08 035 (2020), Snowmass21: arXiv 2201.00925

(Additional measurements needed for understanding of primary cosmic rays and positrons)