Production and propagation of secondary antinuclei in the Galaxy

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Production of Cosmic Rays (CRs) in the Galaxy

- Primaries: produced by astrophysical sources (SNEs, SNRs, Pulsars)

- Secondaries: produced by inelastic collisions between primary CRs and interstellar medium (ISM) or by decay of unstable nuclei

  - Tertiaries: produced by contributions from energy losses in inelastic collisions between secondary CRs and ISM

Energy Spectrum

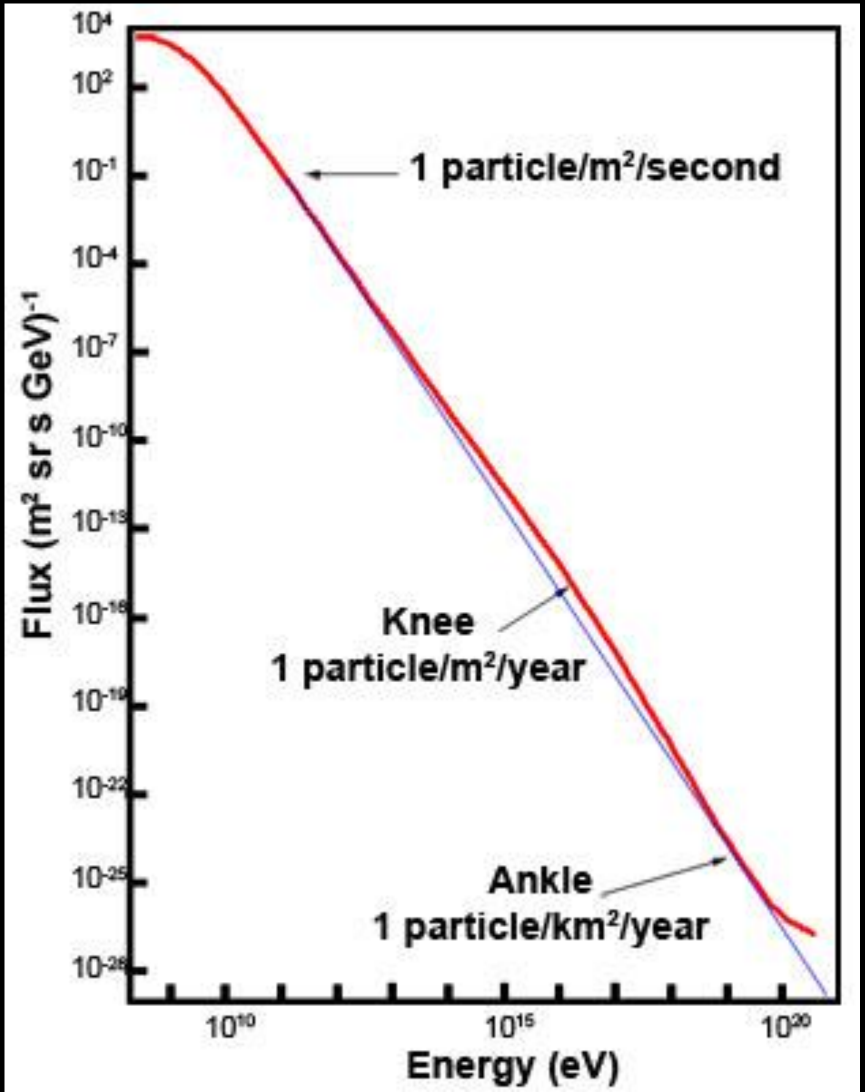


Image taken from:

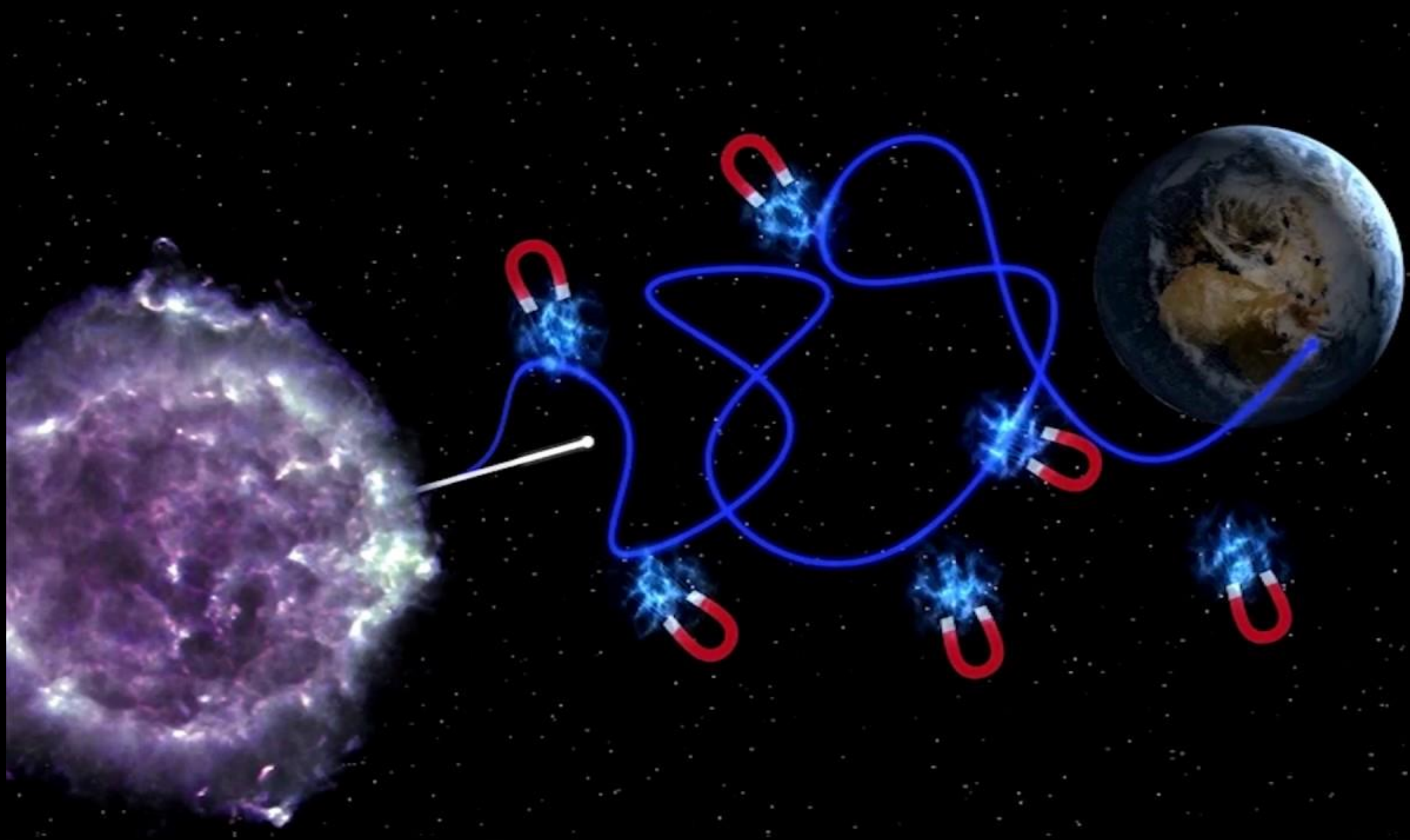
*https://astronomy.swin.edu.au/cosmos/C/Cosmic+Ray+Energies

Transport of galactic CRs

- Accelerated in SNEs and SNRs, CRs diffuse in the ISM of the Galaxy

- The travel is dominated by magnetic fields in the Galaxy

- Scape time is longer than travel time through the Galaxy



The transport equation

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions…)

diffusion $$+ \vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$

convection
(Galactic wind)

diffusive reacceleration
(diffusion in the momentum space)
$$+ \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

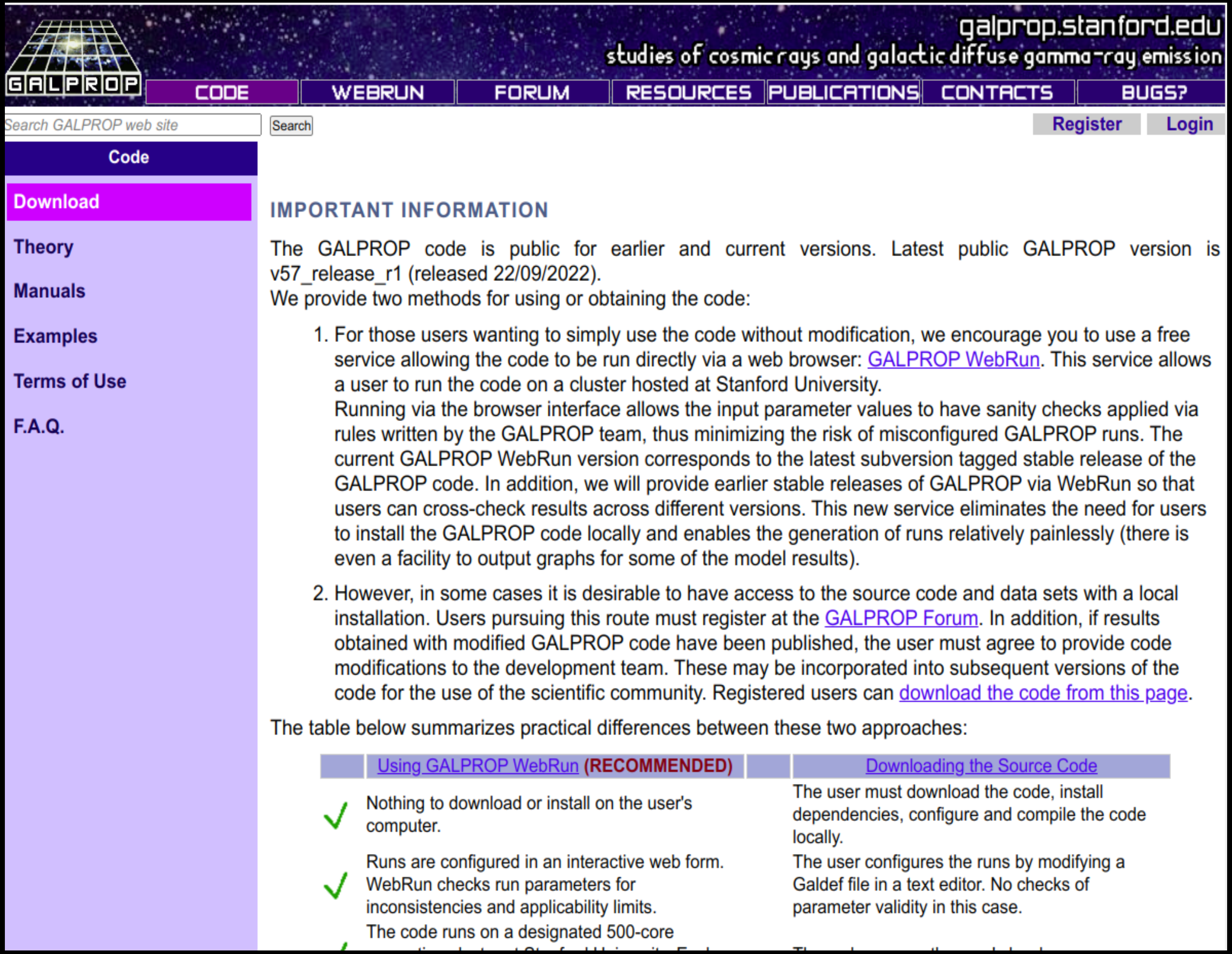
E-loss $$- \frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$

fragmentation $$- \frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

+ boundary conditions

ψ(r,p,t) – density per total momentum

GALPROP v.57



galprop.stanford.edu
studies of cosmic rays and galactic diffuse gamma-ray emission

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Code

- Download
- Theory
- Manuals
- Examples
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IMPORTANT INFORMATION

The GALPROP code is public for earlier and current versions. Latest public GALPROP version is v57_release_r1 (released 22/09/2022).
We provide two methods for using or obtaining the code:

1. For those users wanting to simply use the code without modification, we encourage you to use a free service allowing the code to be run directly via a web browser: GALPROP WebRun. This service allows a user to run the code on a cluster hosted at Stanford University.
Running via the browser interface allows the input parameter values to have sanity checks applied via rules written by the GALPROP team, thus minimizing the risk of misconfigured GALPROP runs. The current GALPROP WebRun version corresponds to the latest subversion tagged stable release of the GALPROP code. In addition, we will provide earlier stable releases of GALPROP via WebRun so that users can cross-check results across different versions. This new service eliminates the need for users to install the GALPROP code locally and enables the generation of runs relatively painlessly (there is even a facility to output graphs for some of the model results).
2. However, in some cases it is desirable to have access to the source code and data sets with a local installation. Users pursuing this route must register at the GALPROP Forum. In addition, if results obtained with modified GALPROP code have been published, the user must agree to provide code modifications to the development team. These may be incorporated into subsequent versions of the code for the use of the scientific community. Registered users can download the code from this page.

The table below summarizes practical differences between these two approaches:

	Using GALPROP WebRun **(RECOMMENDED)**		Downloading the Source Code
✓	Nothing to download or install on the user's computer.		The user must download the code, install dependencies, configure and compile the code locally.
✓	Runs are configured in an interactive web form. WebRun checks run parameters for inconsistencies and applicability limits.		The user configures the runs by modifying a Galdef file in a text editor. No checks of parameter validity in this case.
✓	The code runs on a designated 500-core		

- Solve the transport equation numerically

- Updated nuclei fragmentation cross sections

- New CRs source distributions

The GALPROP Cosmic-ray Propagation and Nonthermal Emissions Framework: Release v57. T. A. Porter et al 2022 ApJS 262 30

Parameters

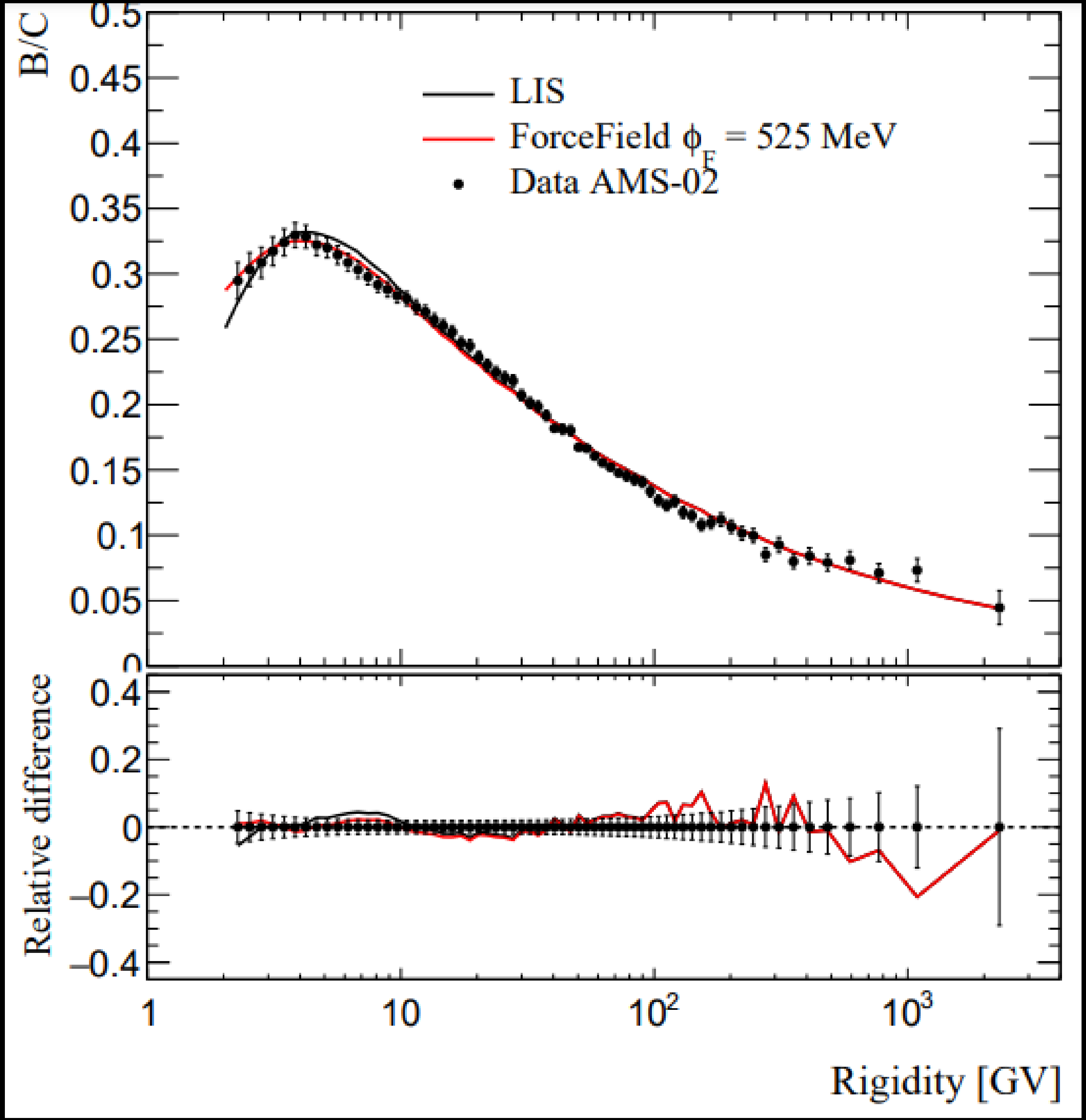
- Based on adjusted simulation parameters by Boschini et al

Parameter	Best value	Error	Units
r	20.0	0.6	kpc
z	4.0	0.6	kpc
D_0	4.3×10^{28}	0.7	$\frac{cm^2}{s}$
δ^a	0.415	0.025	
v_{Alf}	30.0	3.0	$\frac{km}{s}$
$\frac{dv_{conv}}{dz}$	9.8	0.8	$\frac{km}{s}$

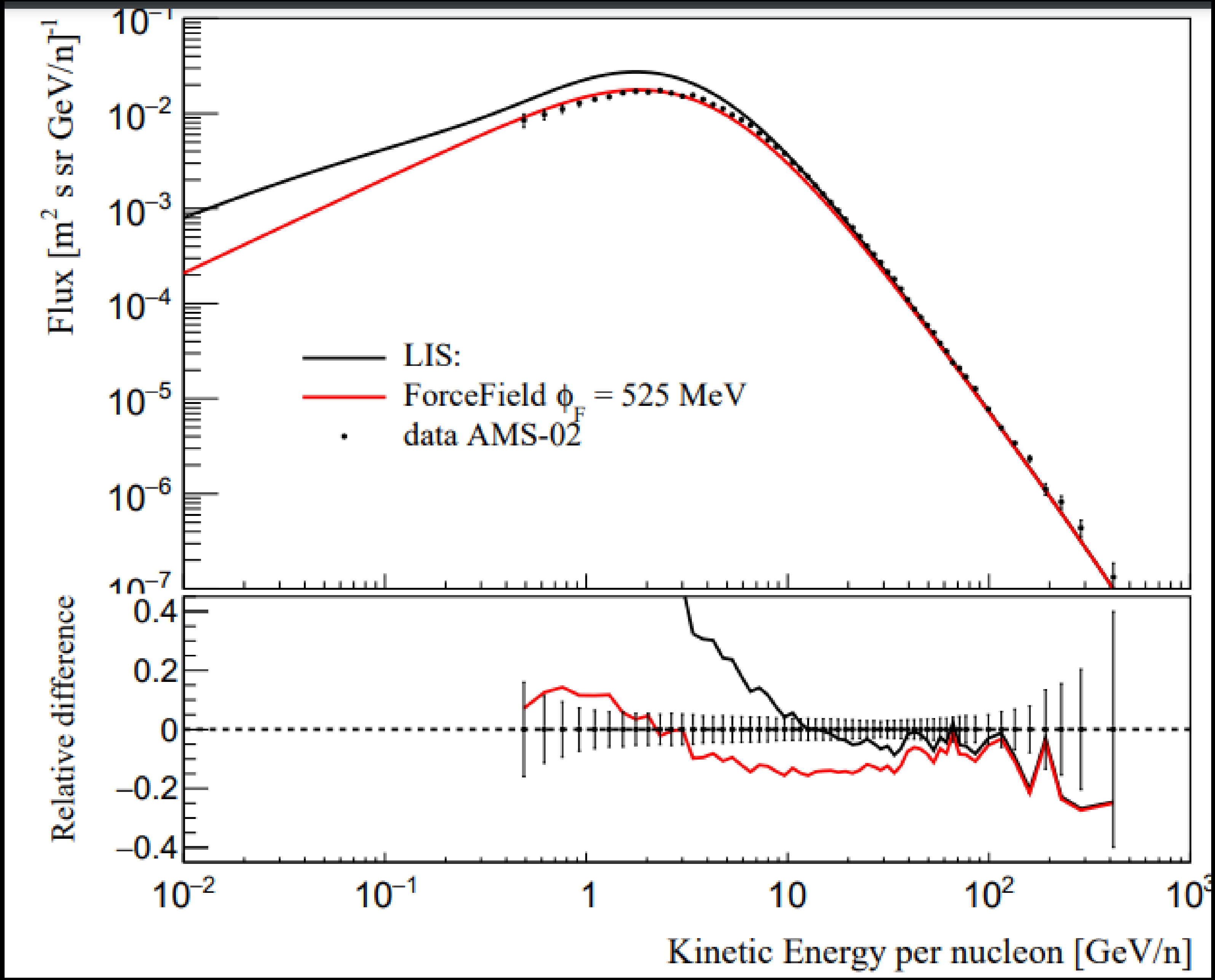
Boschini, M. J., "Inference of the Local Interstellar Spectra of Cosmic-Ray Nuclei Z ≤ 28 with the GALPROP-HELMOD Framework", The Astrophysical Journal Supplement Series, vol. 250, no. 2, IOP, 2020. doi:10.3847/1538-4365/aba901

Verifications

- Ratio $\frac{B}{C}$



• Flux $\bar{p}$



Flux [m^2 s sr GeV/n]$^{-1}$
LIS:
ForceField ϕ_F = 525 MeV
data AMS-02
Relative difference
Kinetic Energy per nucleon [GeV/n]

Antinuclei production

- Light antinuclei has also been detected in cosmic rays

- In a Universe dominated by matter, the production of antinuclei could only be possible in nuclear interactions of cosmic rays with the interstellar medium:

  “Secondary production”

Coalescence Model

The model postulates that for any close enough pair pn or $\bar{p}\bar{n}$ in phase space they can coalesce to produce an d and $\bar{d}$ so on:

$$p + p \longrightarrow p + \bar{p} + n + \bar{n} + p + \bar{p} + p + p + n + \bar{n}$$

$$\bar{d}$$

$$^{3}\overline{He}$$

$$^{4}\overline{He}$$

$$coalescence \quad \therefore$$

$$\swarrow$$

$$^{12}\bar{C}$$

- Analytical approach

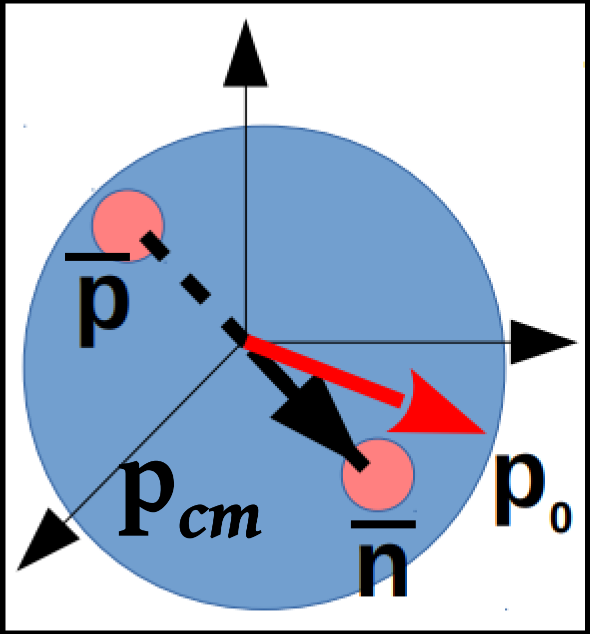
In this way, $\bar{d}$ spectrum is given by

$$\gamma_{\bar{d}} \frac{\mathrm{d}^3 N_{\bar{d}}}{\mathrm{d}p_{\bar{d}}^3} = \frac{4\pi}{3} p_0^3 \left(\gamma_{\bar{p}} \frac{\mathrm{d}^3 N_{\bar{p}}}{\mathrm{d}p_{\bar{p}}^3} \right) \left(\gamma_{\bar{n}} \frac{\mathrm{d}^3 N_{\bar{n}}}{\mathrm{d}p_{\bar{n}}^3} \right)$$

p_0 is determined trough fittimg to experimental data

Antinuclei production simulation

- Collisions are simulated with **Monte Carlo** (MC) generators, to produce $\bar{p}\bar{n}$ pairs.



- $\bar{d}$ are created from the pairs **event by event** (EPOS-LHC, QGSJETII-04, SYBILL 2.1)
- The results from simulations are compared to data (CERN-ALICE, CERN-ISR, CERN-SPS, SERPUKHOV)
- p_0 is determined from this comparison:

$$p_0 = p_0(E_k) \approx 80MeV$$

Source term

- Primary production: SNEs, SNRs, etc.
- Secondary production: secondary source term can be written as

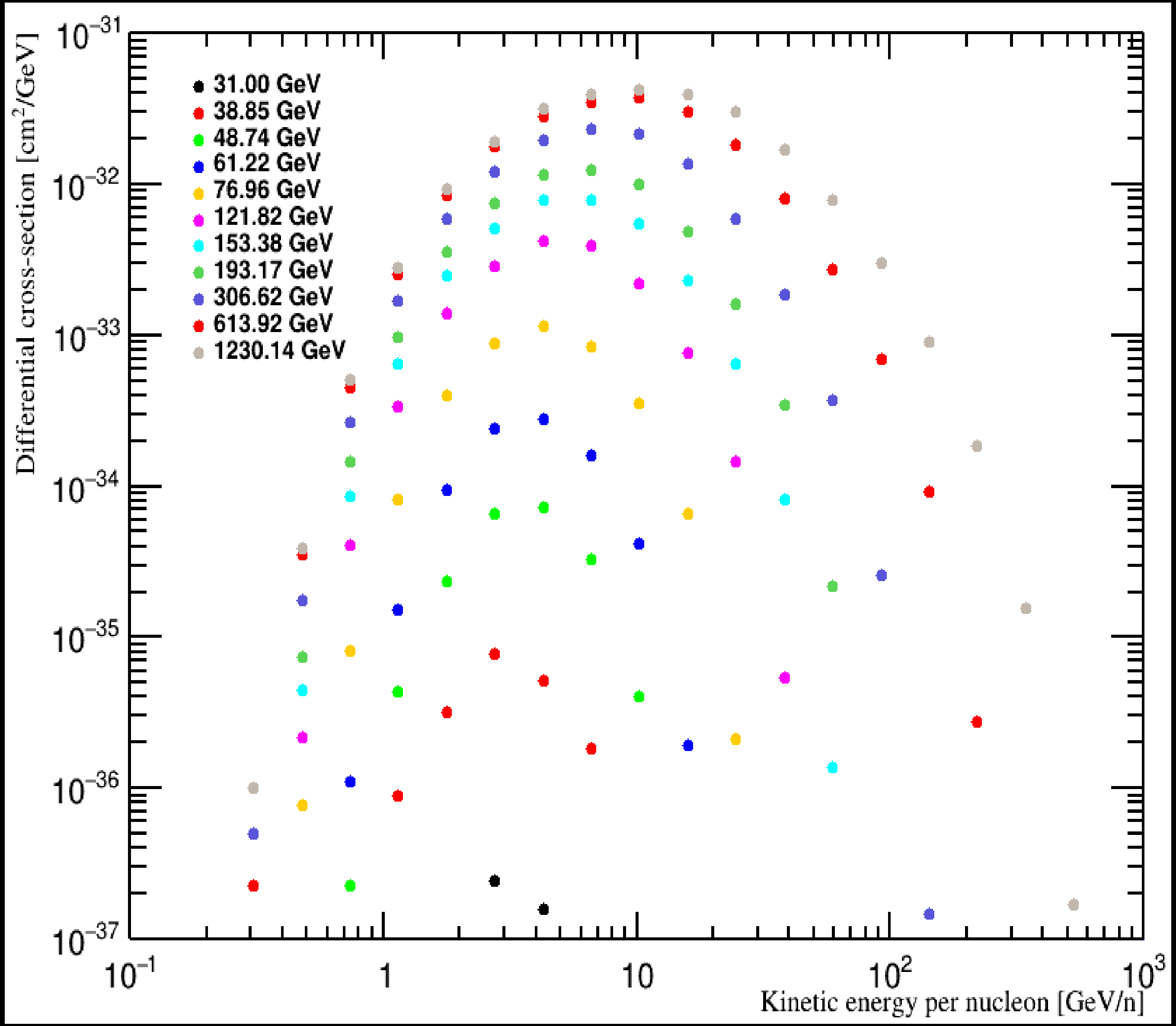
$$Q^{\rm sec}(T_{\bar{N}}, \boldsymbol{r}) = \sum_{i\in\{p,{\rm He},\bar{p}\}} \sum_{j\in\{p,{\rm He}\}} 4\pi n_j(\boldsymbol{r}) \int_{T^{(i,j)}_{\bar{N},\rm min}}^{\infty} {\rm d}T_i \frac{{\rm d}\sigma_{i,j}(T_i, T_{\bar{N}})}{{\rm d}T_{\bar{N}}} \Phi_i(T_i, \boldsymbol{r})$$

The index *i* corresponds to the incident particles while the index *j* corresponds to the particles of the ISM.

- Convolution of differential cross section and the incident flux

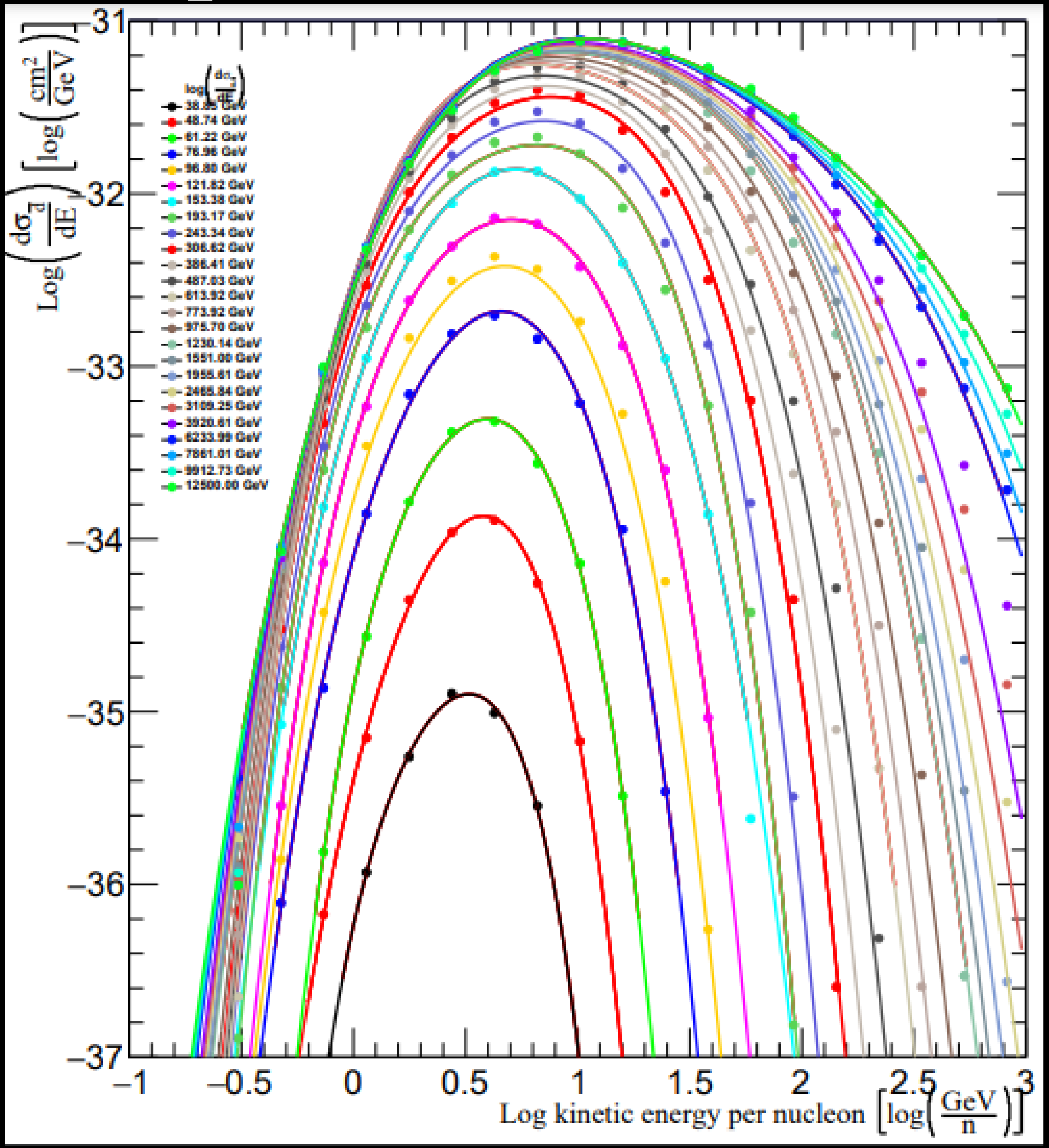
$\bar{d}$ Production cross sections

The data generated by Monte Carlo + event-by-event afterburner reported by Shukla et al were fitted to a polynomial

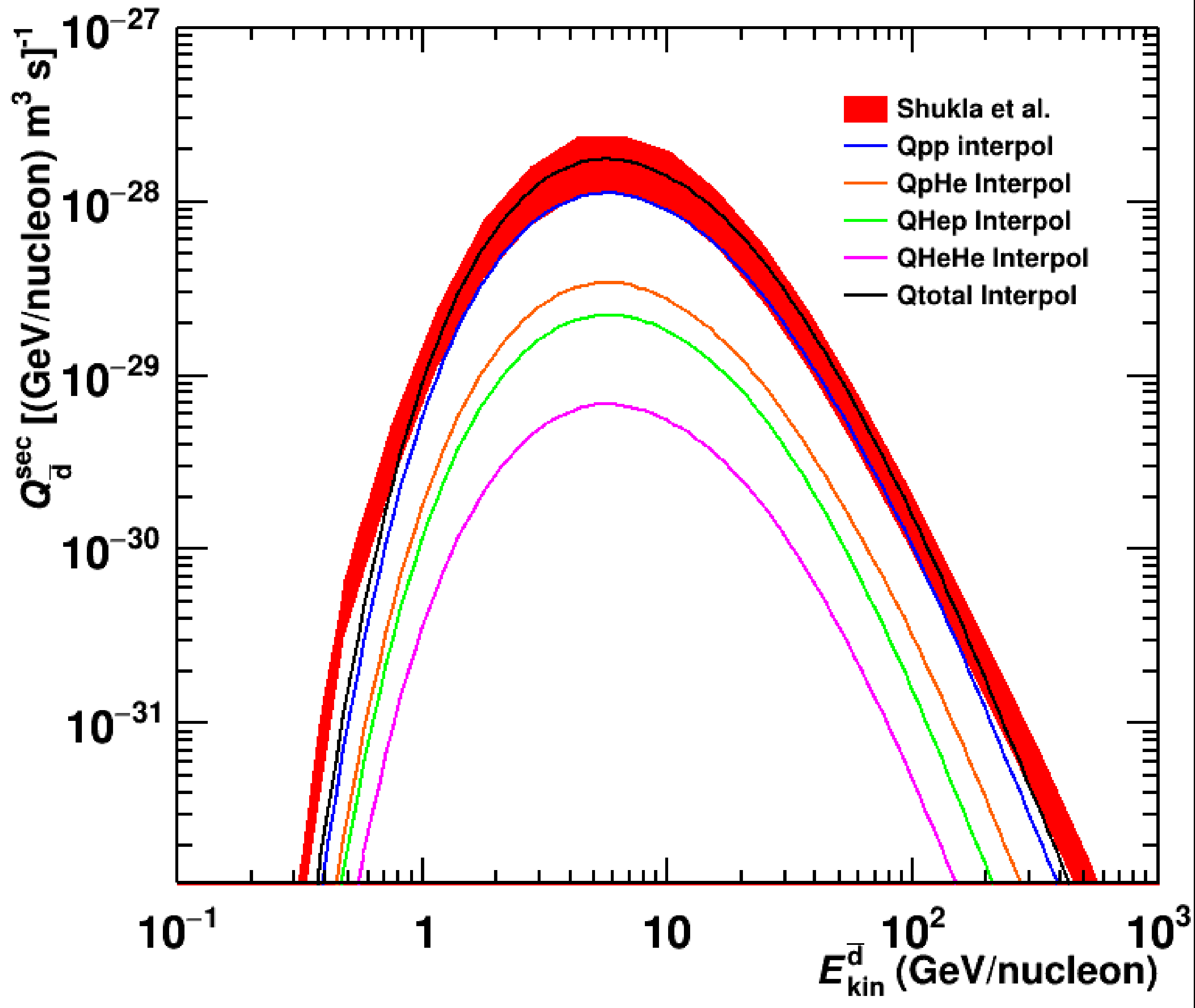


*Shukla, A., Datta, A., von Doetinchem, P., Gomez-Coral, D.-M., and Kanitz, C., “Large-scale simulations of antihelium production in cosmic-ray interactions”, Physical Review, vol. 102, no. 6, APS, 2020.

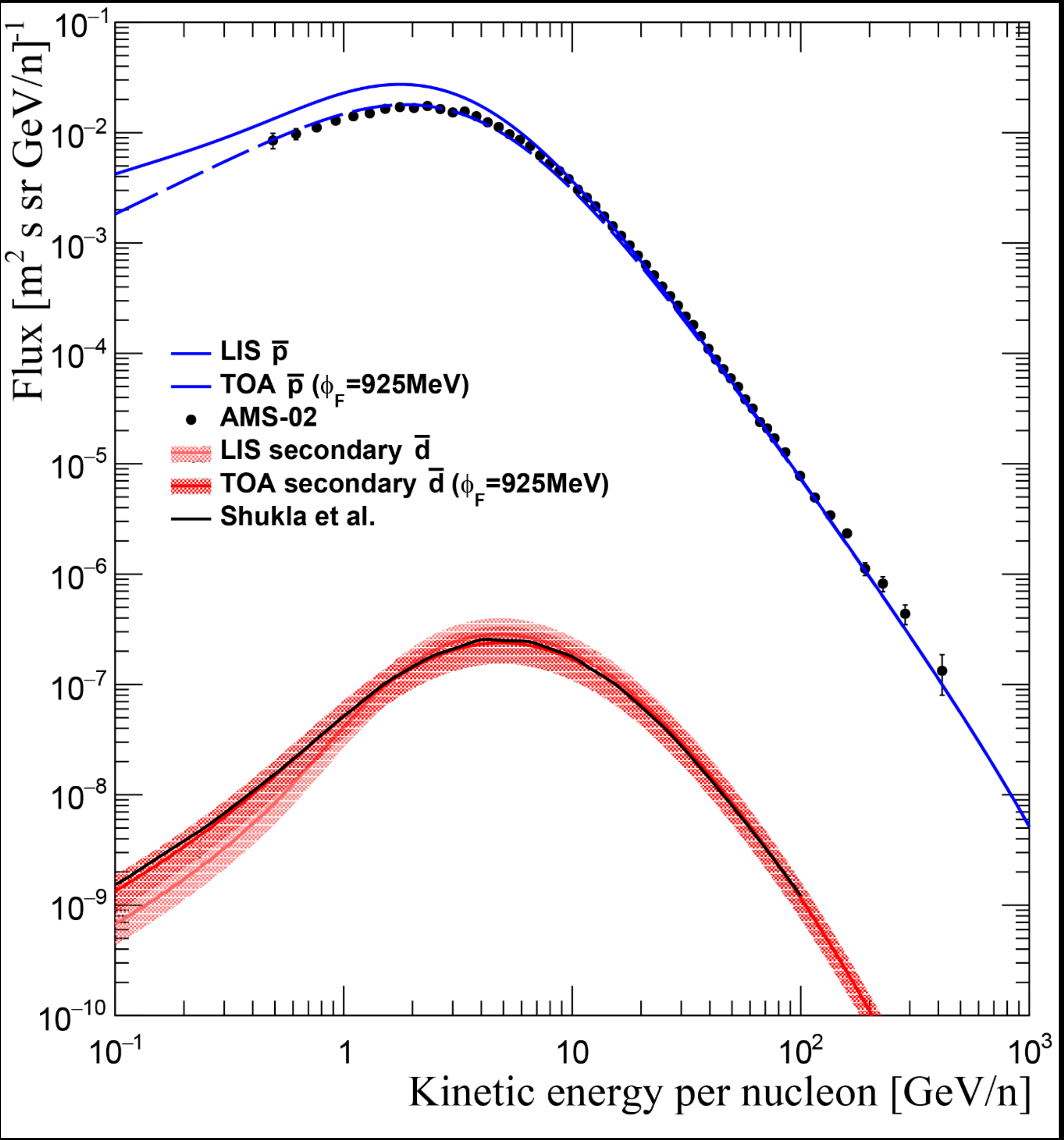
Cross sections interpolation



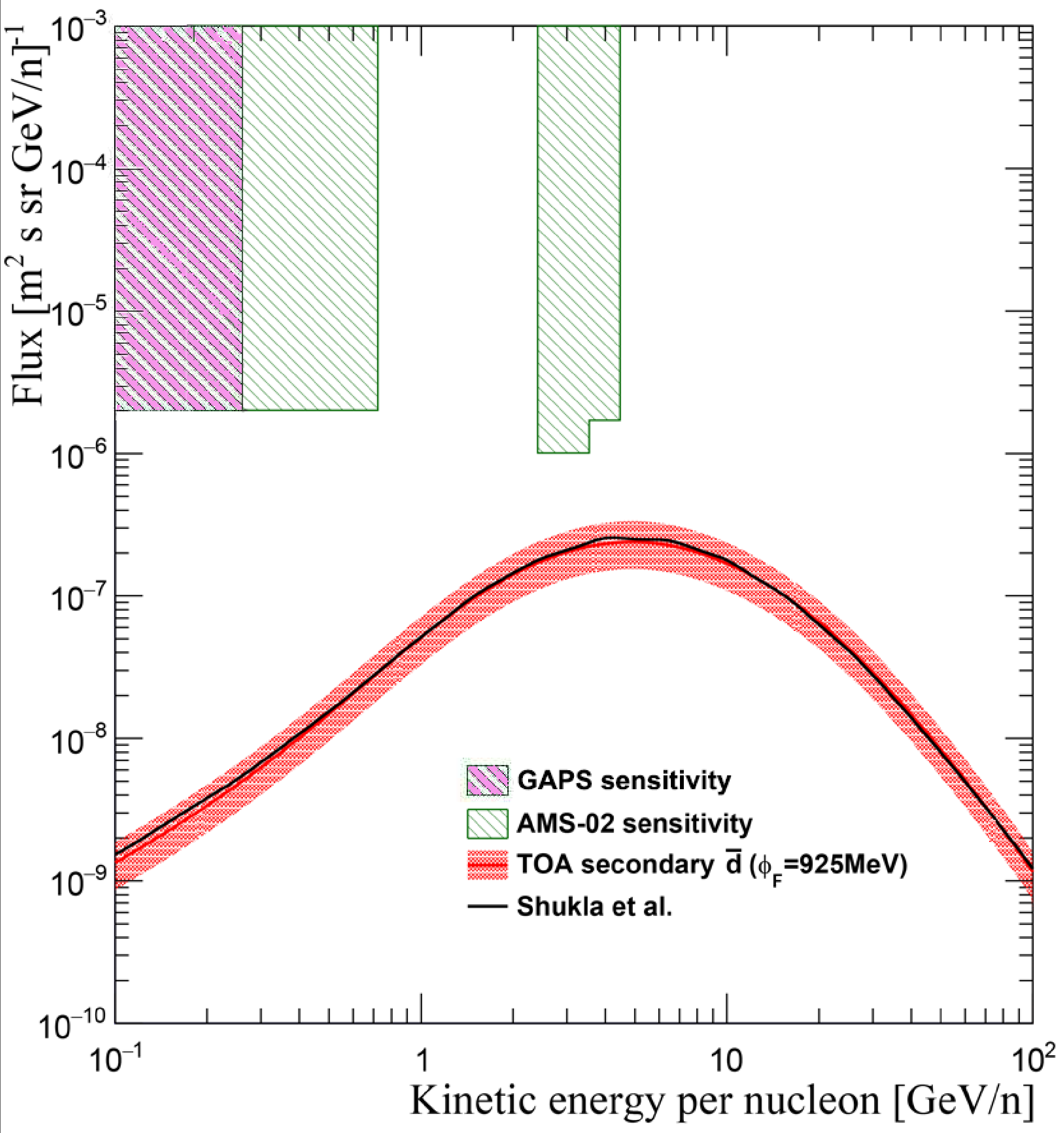
$\bar{d}$ source term



Expected $\bar{d}$ flux



Search of $\bar{d}$



Conclusions

- The latest Galprop v.57 was validated using the ratio B/C and $\bar{p}$ flux measurements, comparing to AMS-02 data
- An interpolation of cross sections was performed, based on Monte Carlo simulations realized by Shukla et al
- An update of the antideuteron flux was performed showing that it is at least one order of magnitude below the sensitivity of AMS-02 reported by the literature

Thank you!