Searching for Anti-Nuclei in Cosmic-Ray with the Dark Matter Particle Explorer

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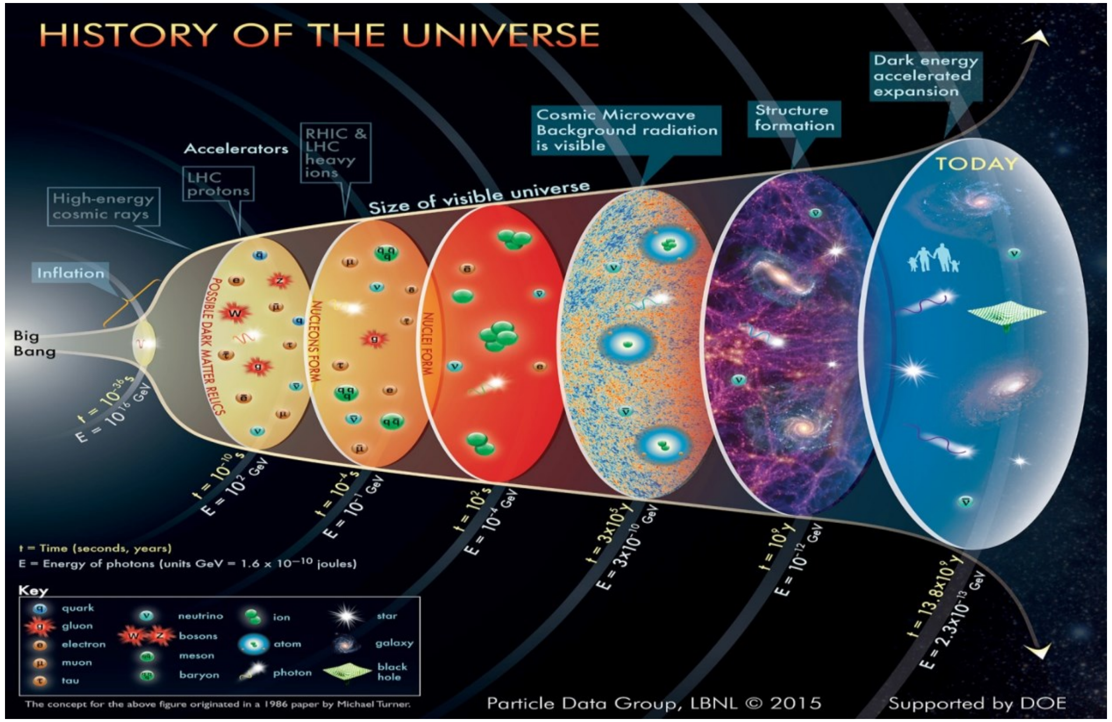
Outline

- Motivation
- Dark Matter Particle Explorer
- Searching anti-deuteron with DAMPE
- Summary
- Backup(Dark Matter in Antiproton Cosmic Rays)

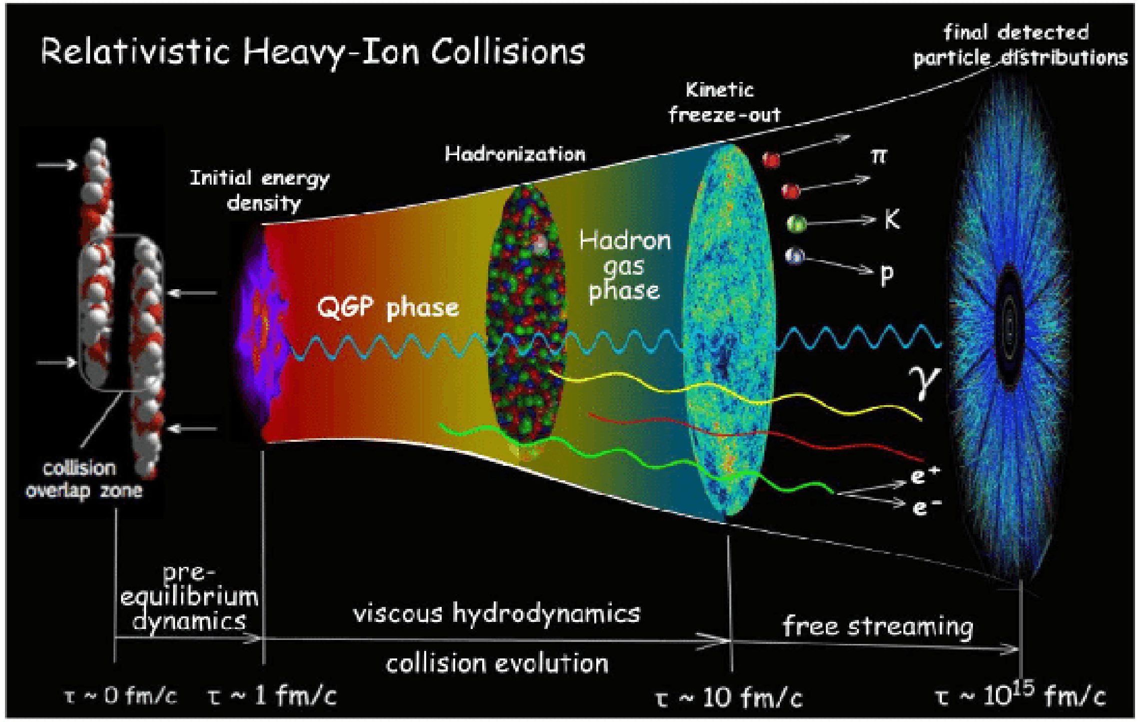
Motivation

One of the greatest challenges in physics: asymmetry between matter and antimatter

Big Bang of Universe

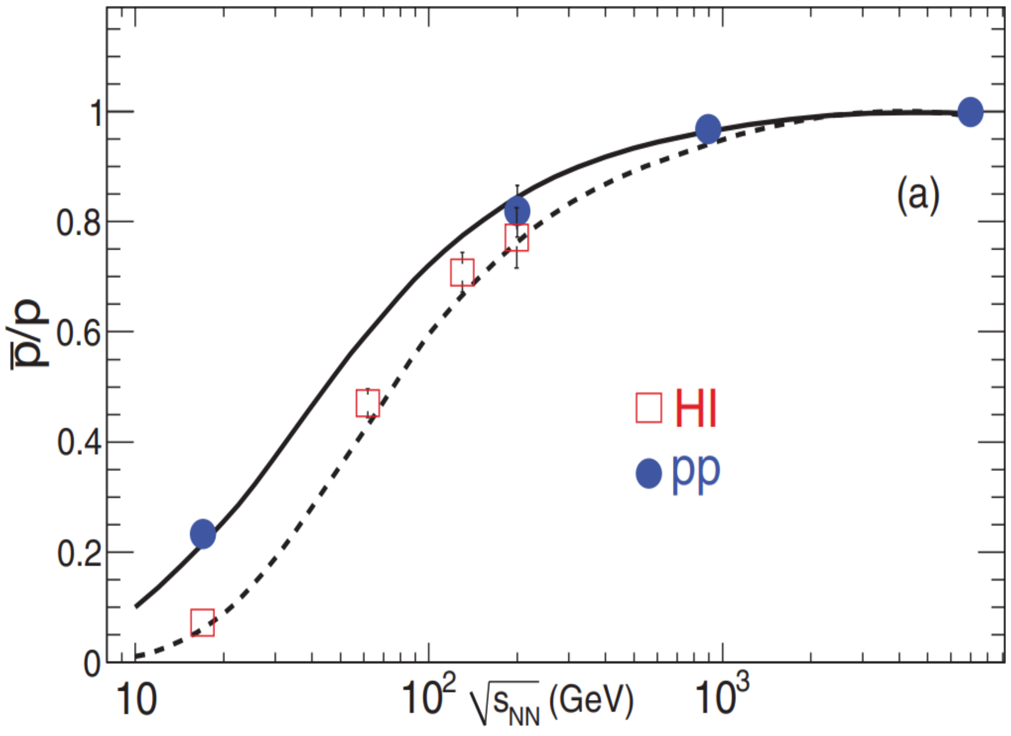


Little Bang of HICs

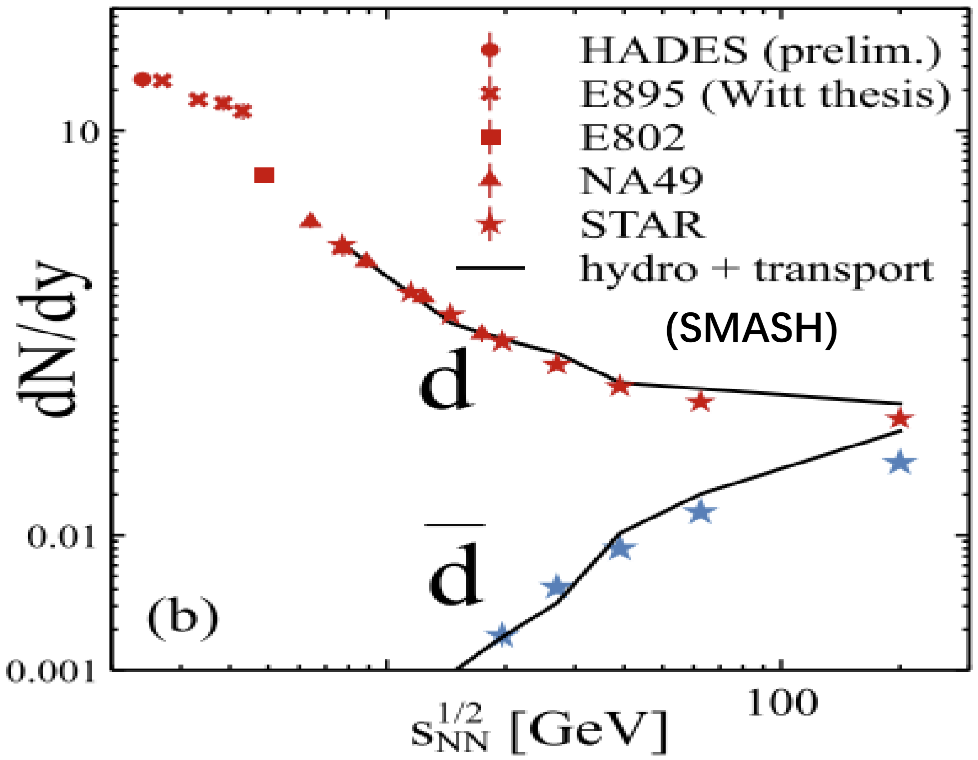


Motivation

Anti-proton and Anti-deuteron production in pp/AA collision



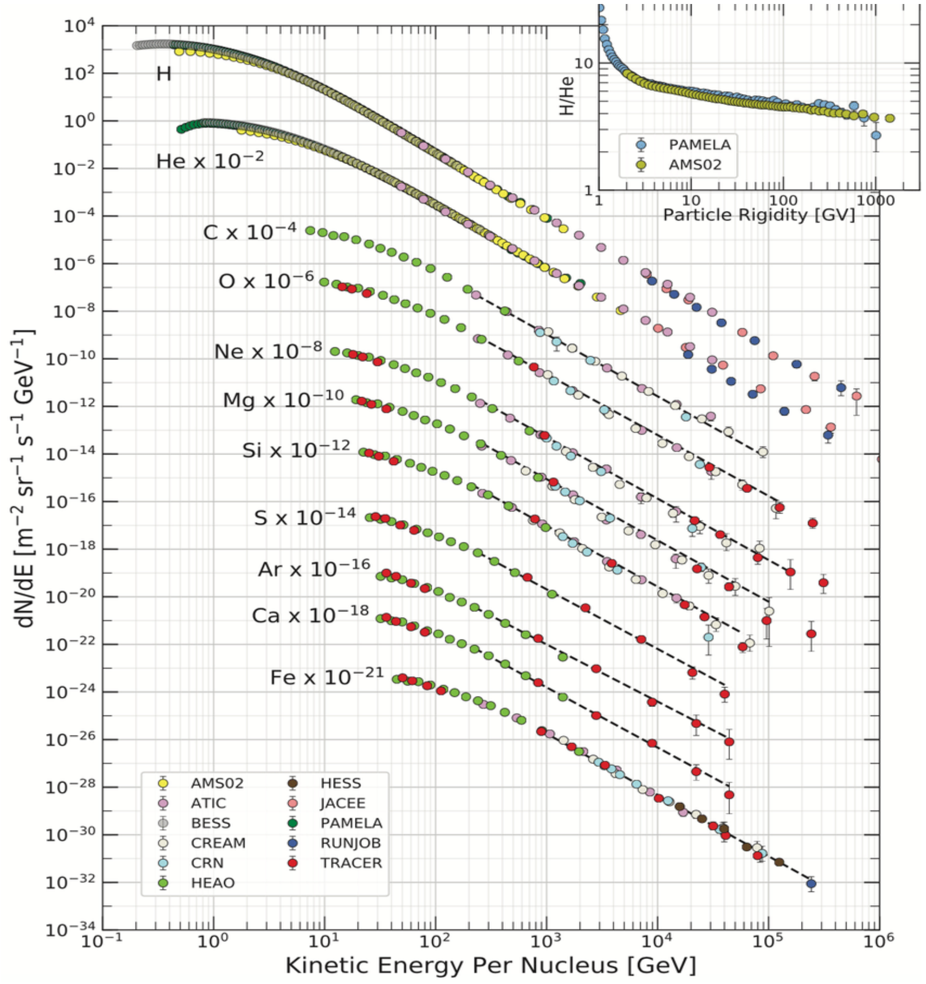
PHYSICAL REVIEW C 84, 054916 (2011)



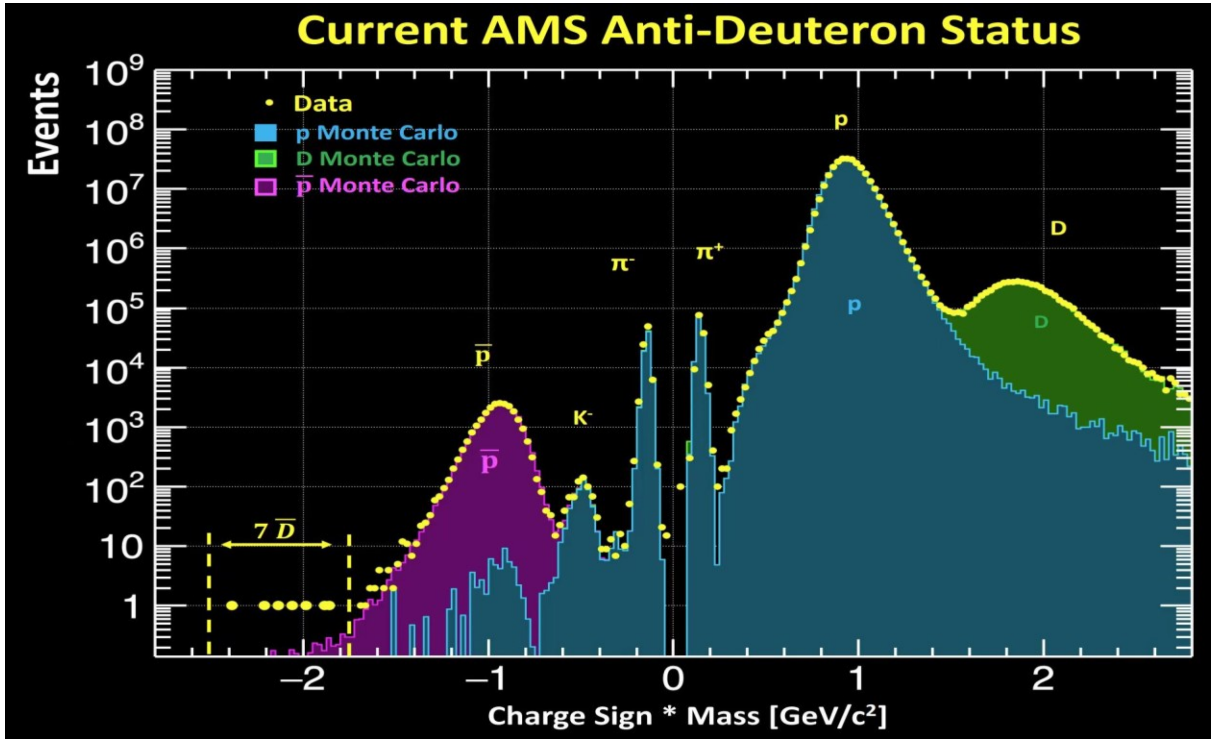
OLIINYCHENKO, PRC,103, 034913 (2021)

Motivation

Cosmic-ray flux



So far, no anti-deuteron has been observed in cosmic-ray



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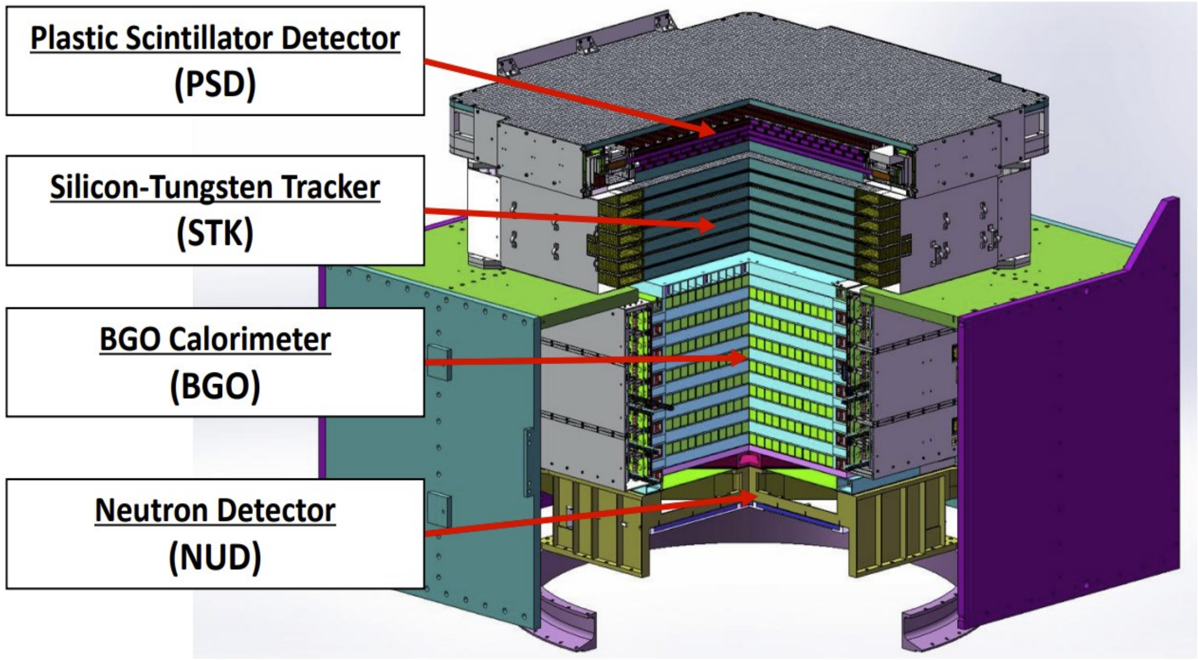
Dark Matter Particle Explorer (DAMPE)

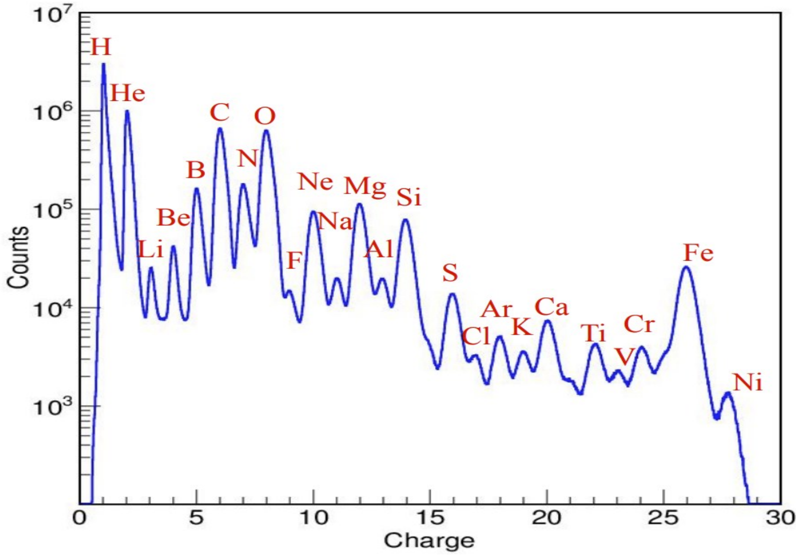
Dampe a big dE/dx-E telescope in space



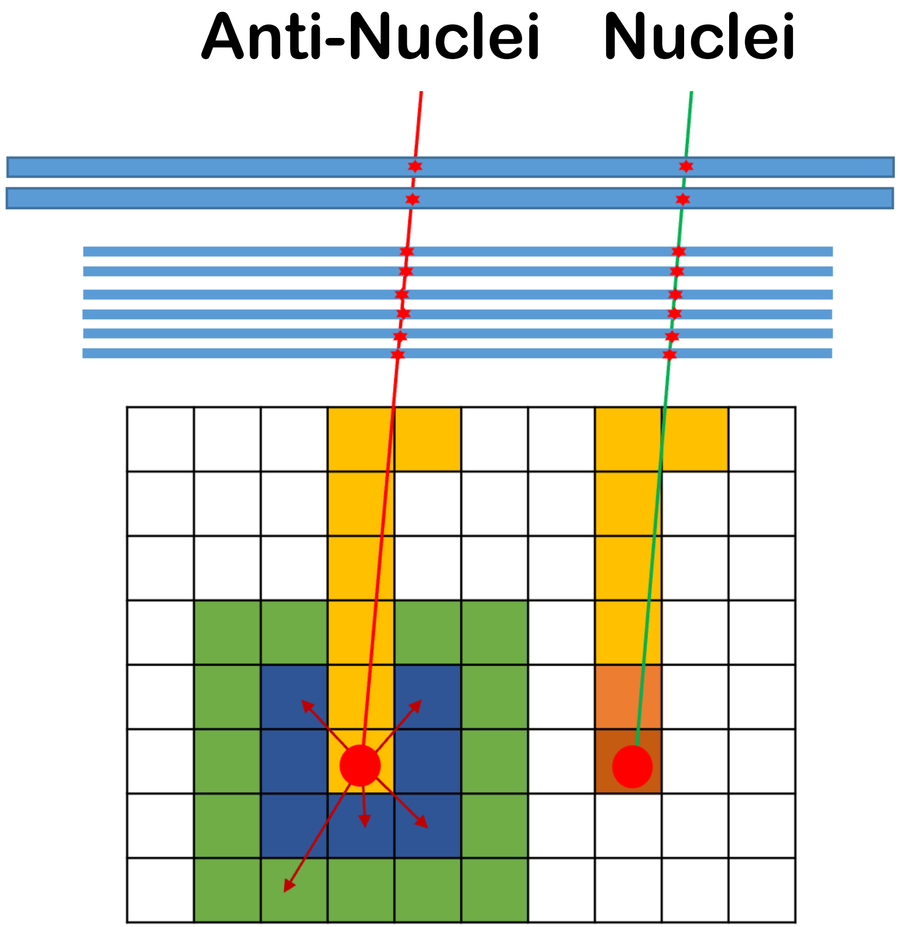
- Charge measurement (dE/dx in PSD, STK and BGO)
- Pair production and precise tracking (STK and BGO)
- Precise energy measurement (BGO bars)
- Hadron rejection (BGO and neutron detector)

dE/dx: PSD & STK
E: BGO Calorimeter

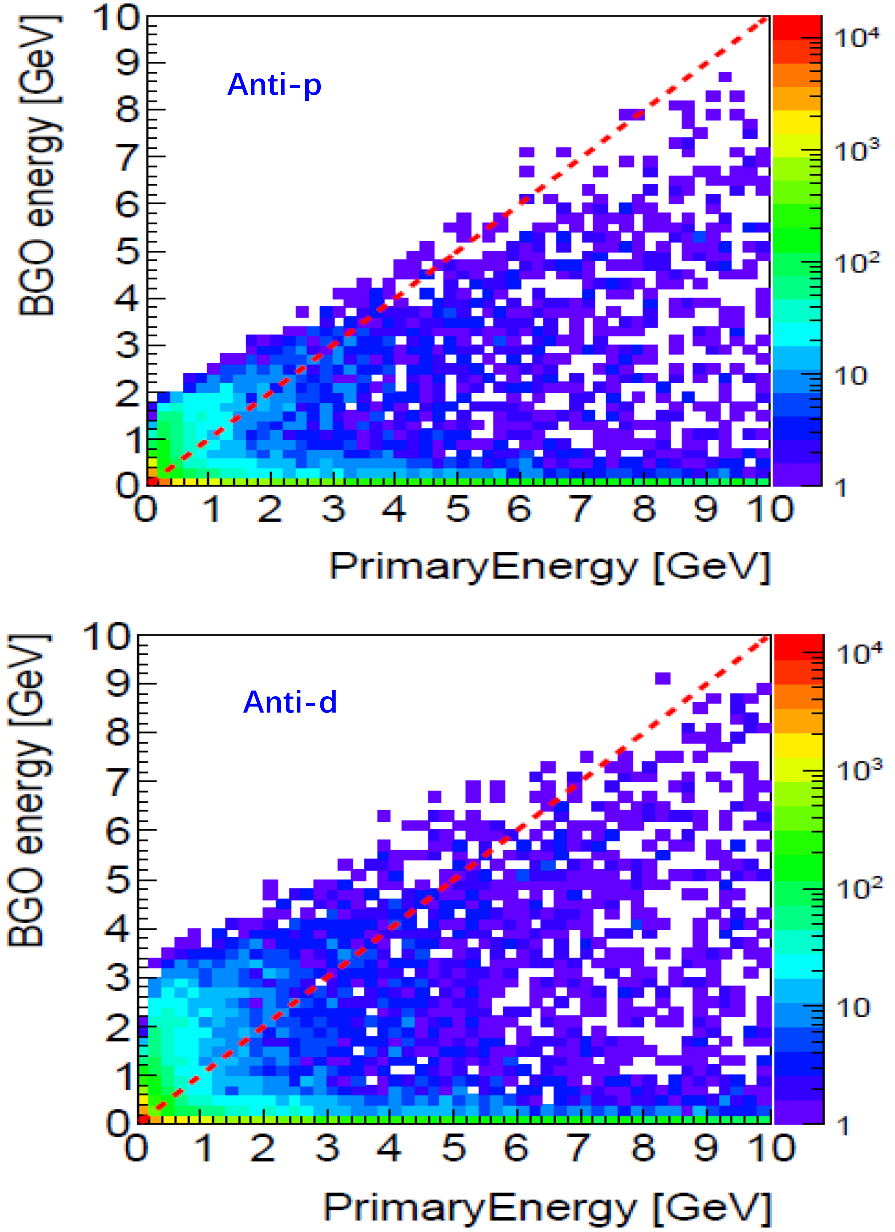
Charge measurement by the PSD



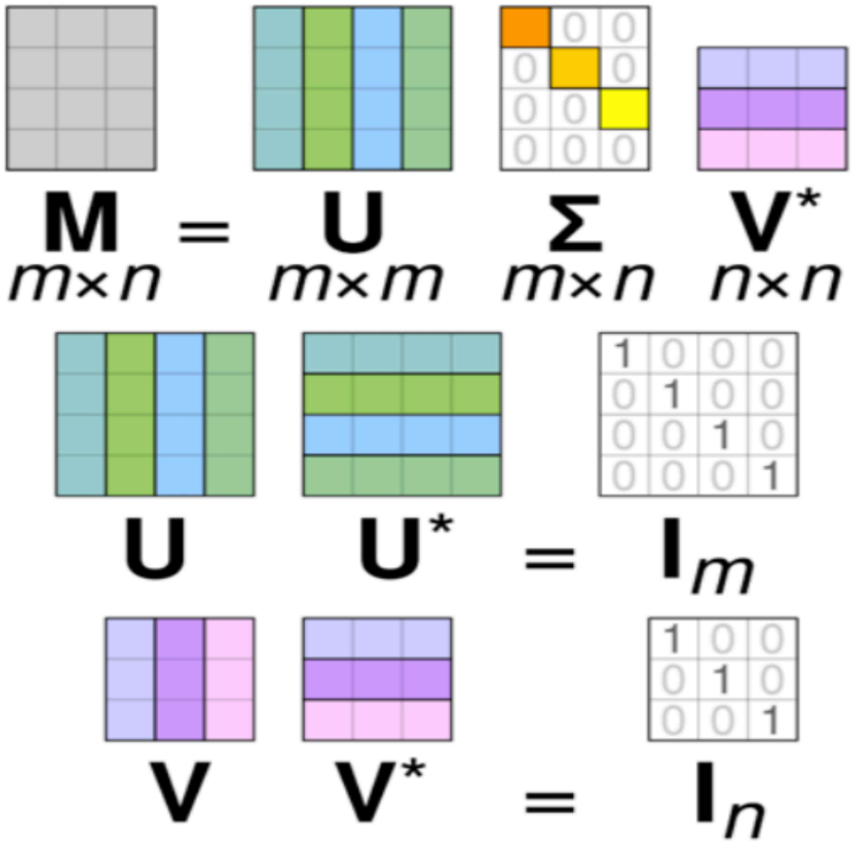
Basic idea for low-energy anti-nuclei



Additional energy release due to matter-antimatter annihilation



PCA (Principal component analysis)



Singular value decomposition finds the eigenvectors of the covariance matrix.

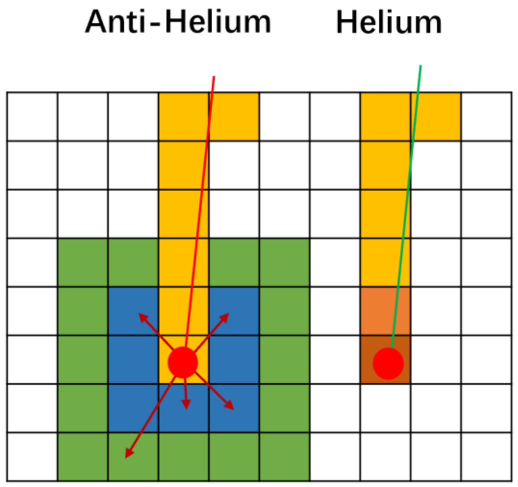
Find the direction corresponding to the largest eigenvector of the covariance matrix.

Tool：sklearn.decomposition.PCA

$$X'_{m,k} = X_{(m,n)} \cdot R_{(n,k)}$$

reducing from m-dimensional space to k-dimensional space.

PCA machine learning method

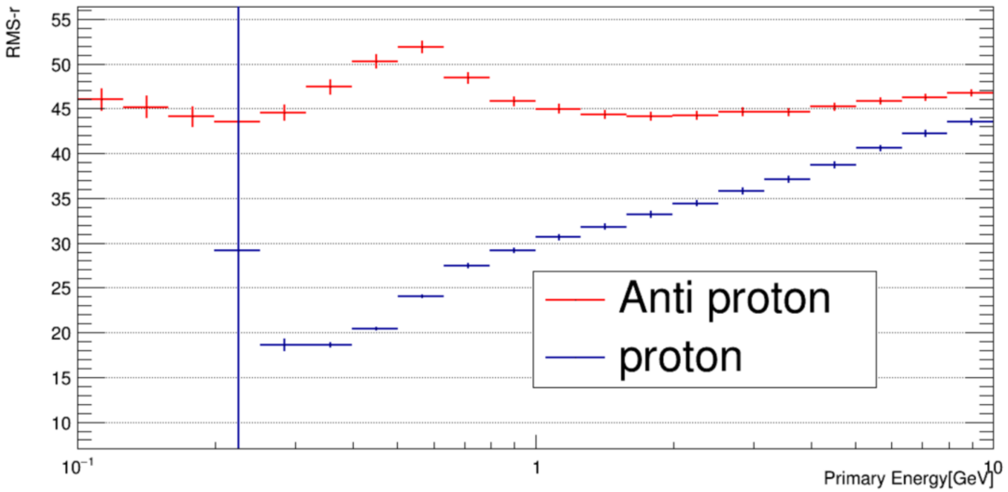


$$\mathrm{RMS}_r = \sqrt{\sum_{j=1}^{N} E_j \times D_j^2 / E_{\mathrm{total}}},$$

$$\mathrm{RMS}_i = \sqrt{\frac{\sum_{j=1}^{22} E_{ij} \times (d_{ij} - d_i^{\mathrm{cog}})^2}{\sum_{j=1}^{22} E_{ij}}}, \quad i=0,\ \ldots,\ 13,$$

PCA variables:

1) EBGO_Total
2) EBGO_max
3) STKQ
4) PSDQ
5) EC1 (Blue)
6) EC2 (Green)
7) nEC1
8) nEC2
9) EMax/Ebgo
10) EC1/Ebgo
11) EC2/Ebgo
12) EC1/EMax
13) EC2/EMax
14) EC1/EC2

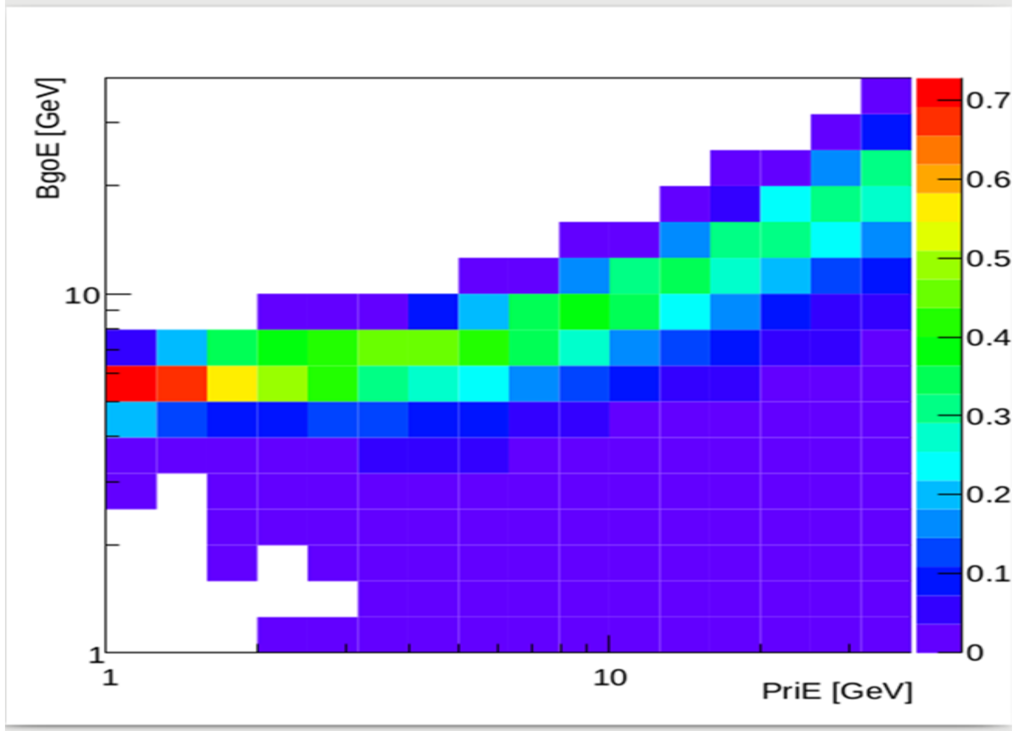


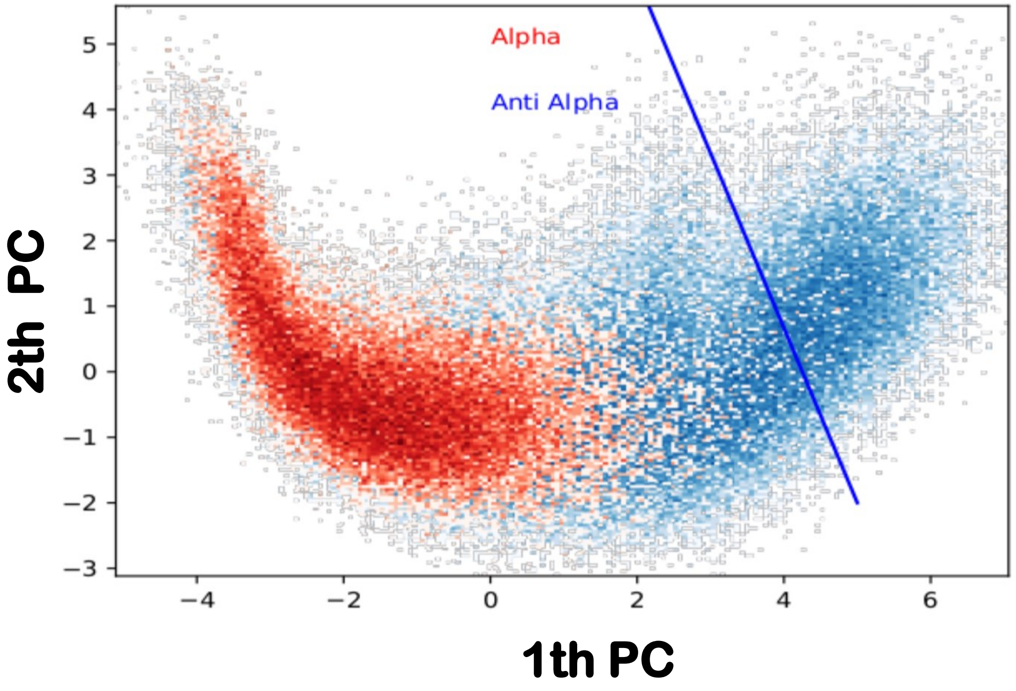
$$\mathrm{RMS}_i' = \mathrm{RMS}_i \times (\cos\theta)^\gamma \times \alpha_i$$
$$F_i' = F_i \times \beta_i,$$
$$\mathrm{EC1}' = \mathrm{EC1} \times \zeta,$$

...... **Extract characteristic variables**

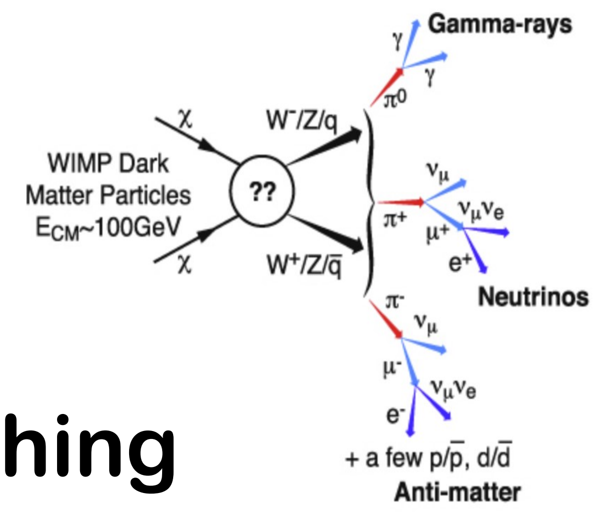
Very-Preliminary results

Energy response matrix





Summary



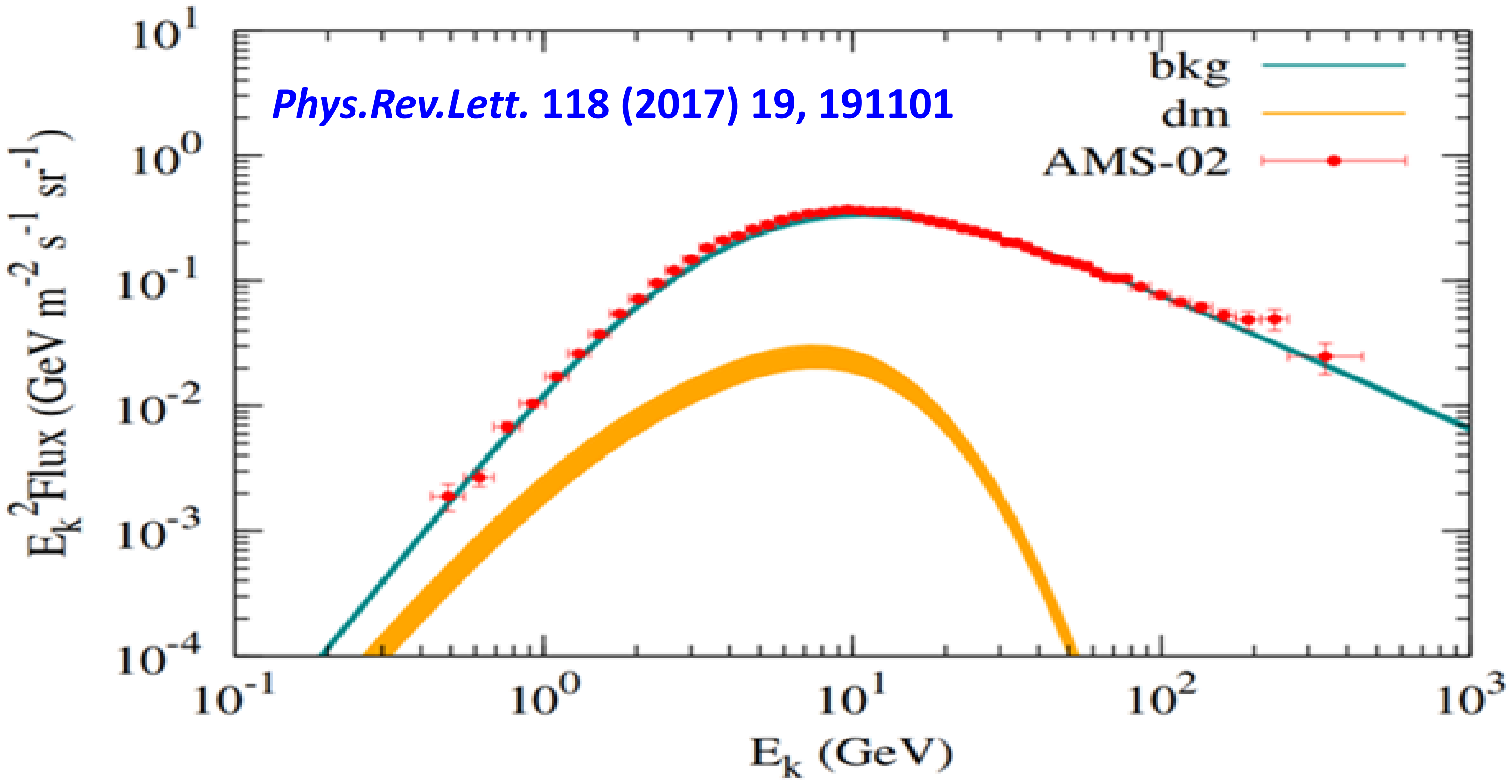
- Anti-matters searching in cosmic-ray
  - ➢ The cluster formation mechanism
  - ➢ Important input for dark matter searching

- DAMPE is a largest ΔE-E detector in space

- PCA based machine learning method for searching anti-d and anti-^{4}He in cosmic-ray is on-going

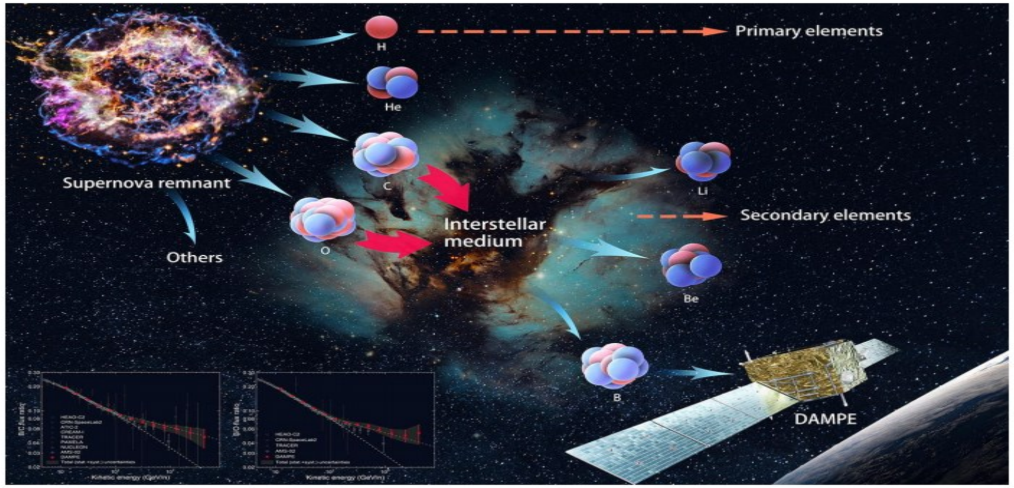
Backup
(Dark Matter in Antiproton Cosmic Rays)

Anti-Proton Spectrum



Anti-Proton annihilation energy relative lower, it`s hard to identify $p\bar{p}$.

Cosmic Ray Propagation



$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$

sources (SNR, nuclear reactions...)

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

convection (Galactic wind)

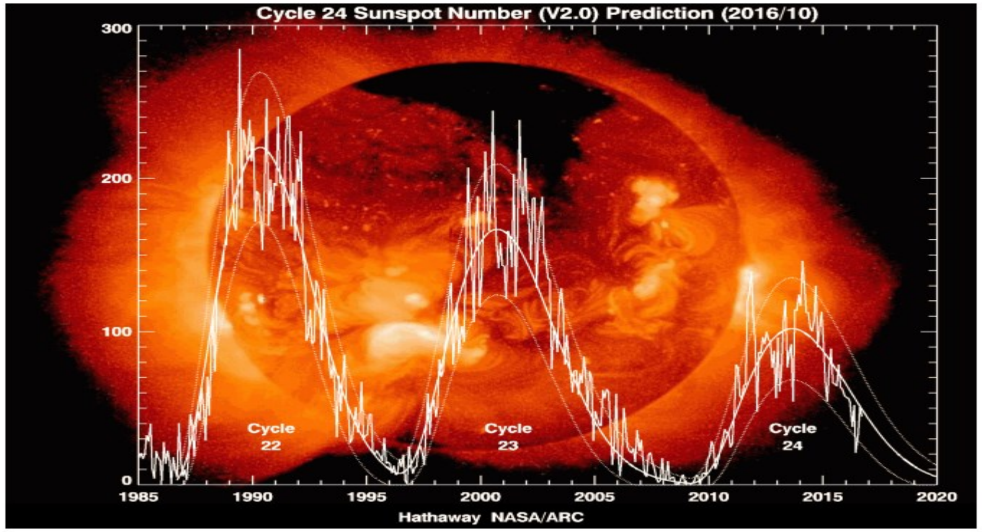
diffusive reacceleration (diffusion in the momentum space) $+\frac{\partial}{\partial p}\left[p^{2}D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^{2}}\right]$

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

$\psi(r,p,t)$ – density per total momentum

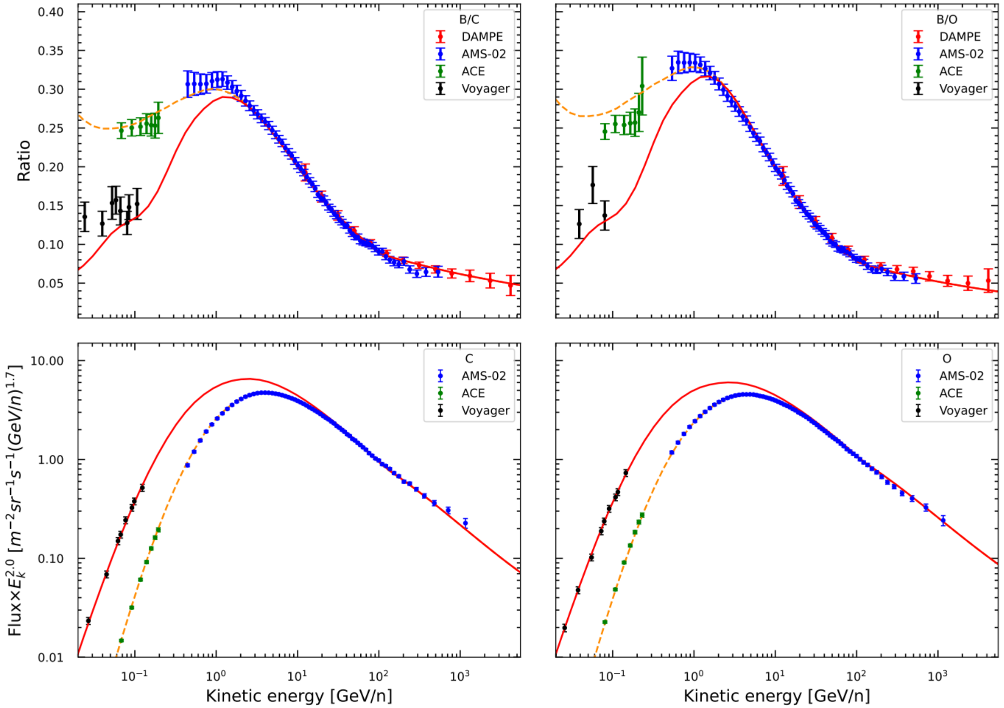


力场近似：

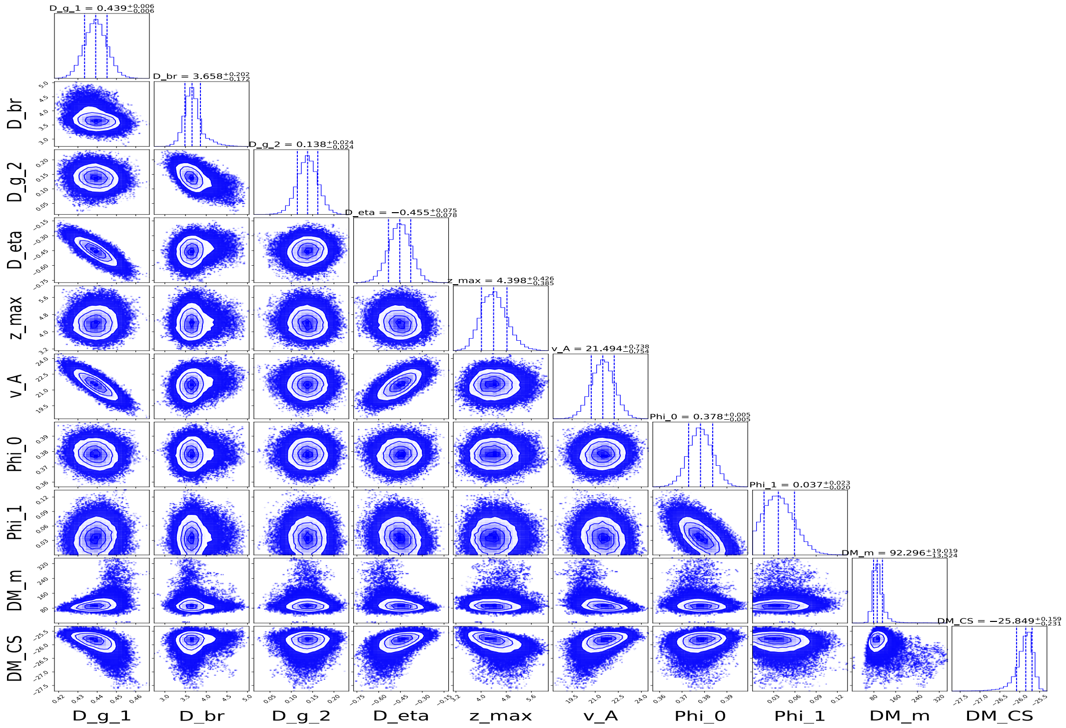
$$J^{\mathrm{TOA}}(E) = J^{\mathrm{LIS}}(E+\Phi)\times\frac{E(E+2m_p)}{(E+\Phi)(E+\Phi+2m_p)}$$

E :动能、m_p :质子静止质量。

Solve Cosmic ray Propagation Equation



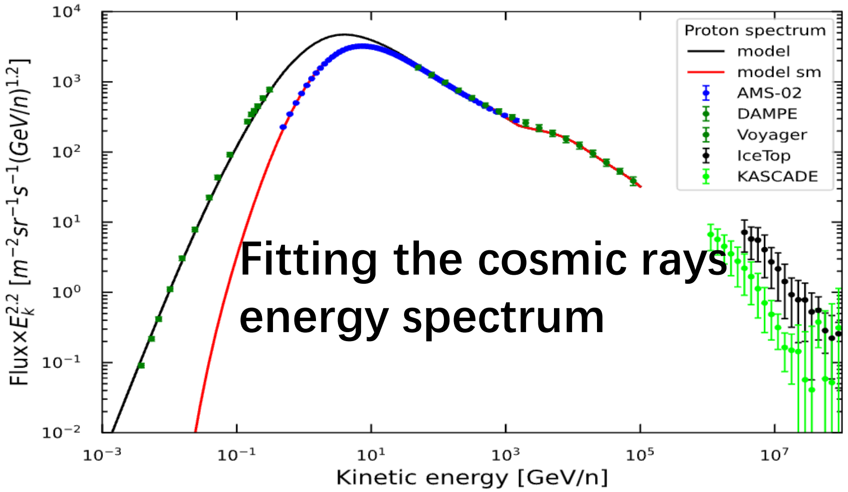
Galprop + MCMC
Global Fitting all cosmic ray spectrum.

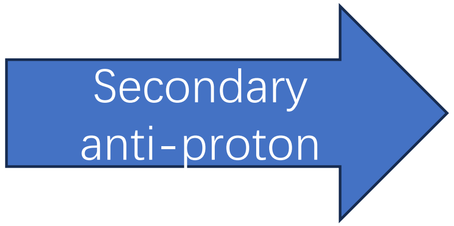


The distribution of cosmic rays propagation

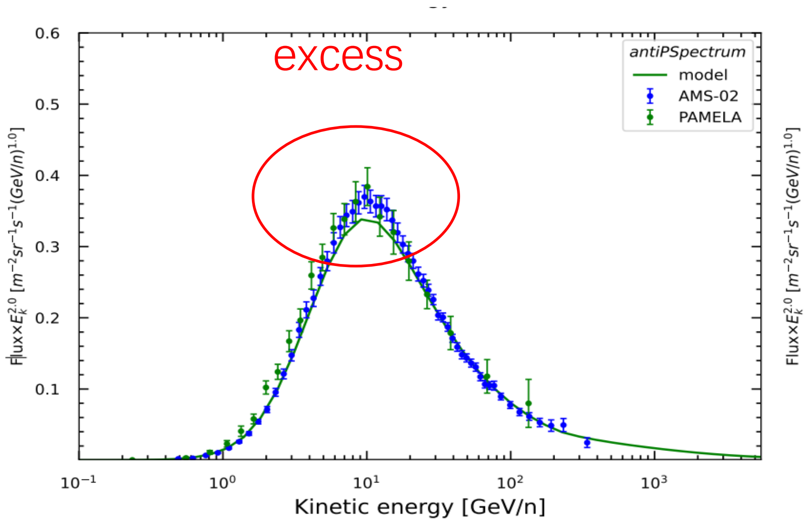
We find solar modulation and propagation module does not affect the excess of anti-proton

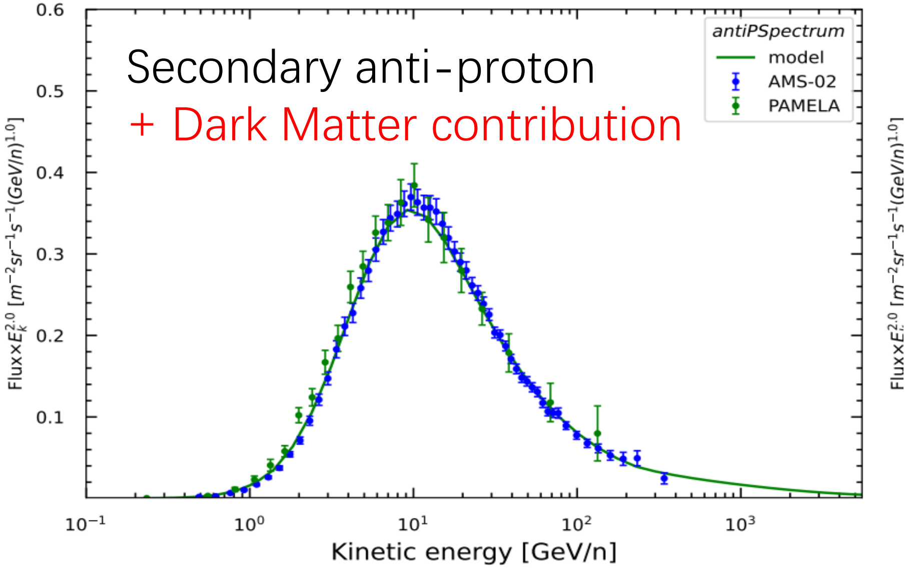
Anti-Proton excess

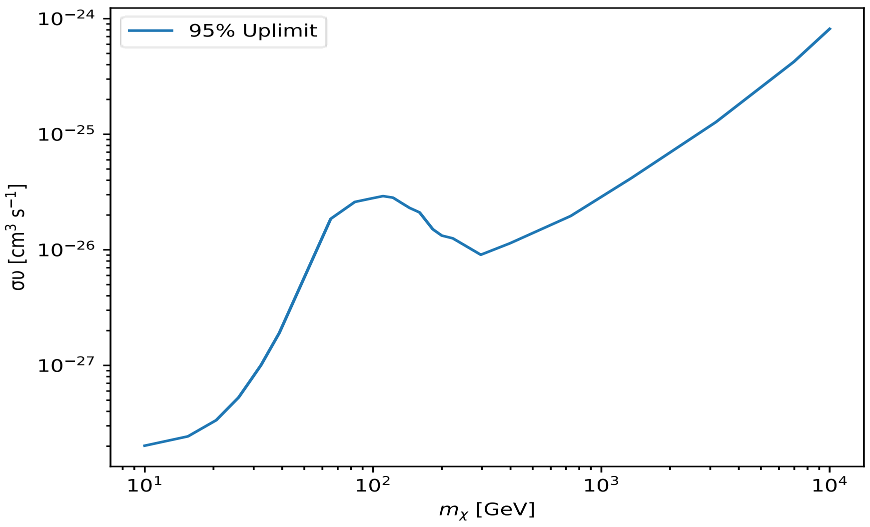




nuclei-nuclei collision

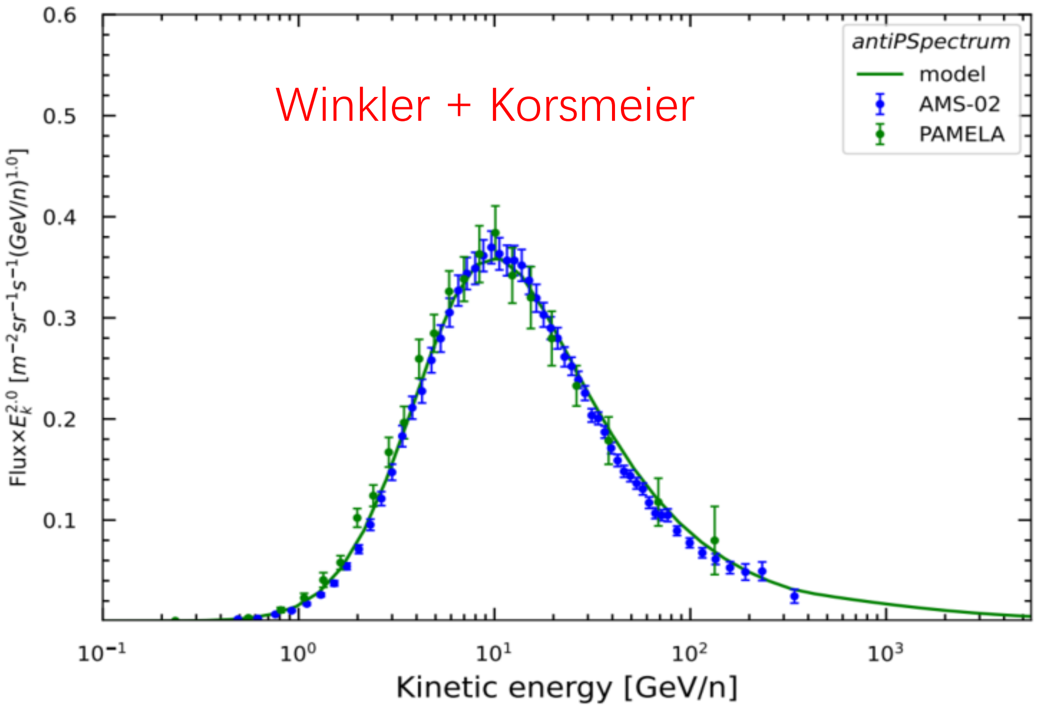


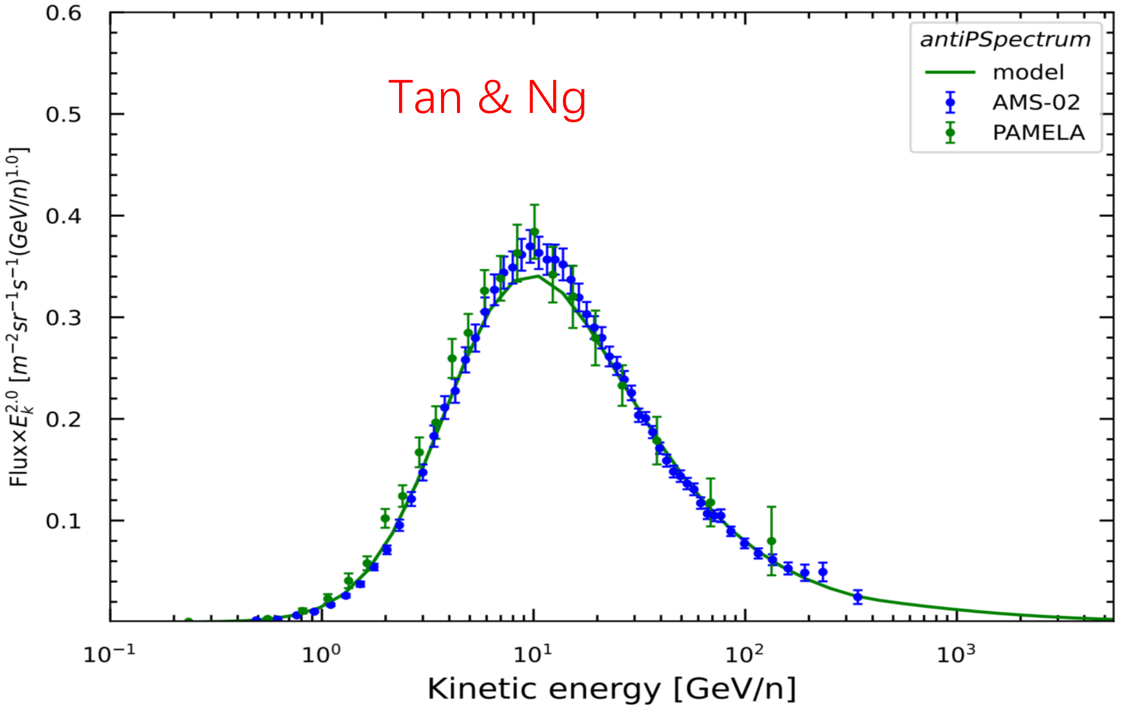




The 95% credible upper limits of the DM annihilation cross section

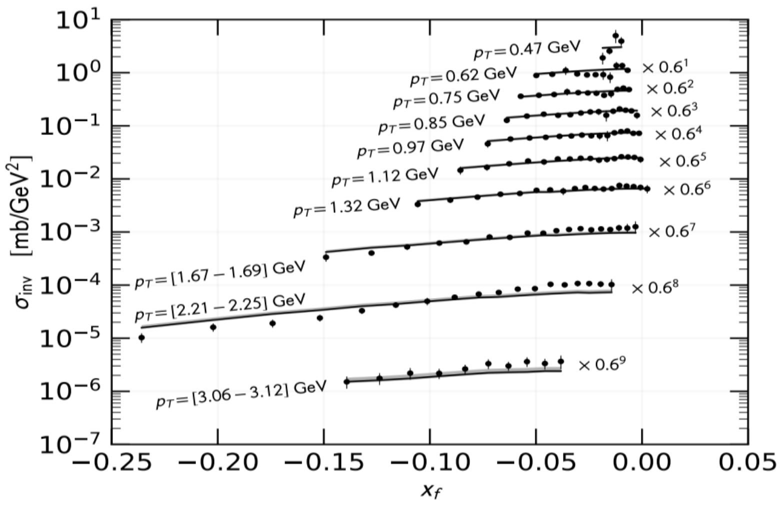
Different nuclei-nuclei collision Cros-section





Collision affect the flux of secondary cosmic ray antiprotons.
However, W-K models does not need dark matter contribution, but the predictions are higher than the measurements in both the low-energy and high-energy regions.

Nucleus-Nucleus collision cross section

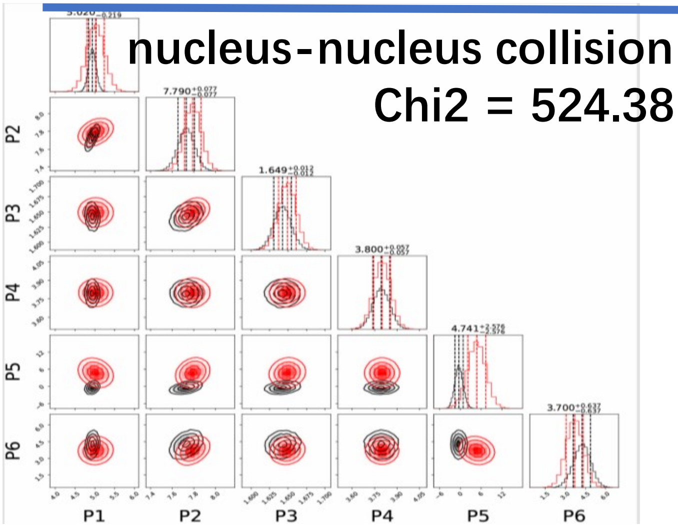


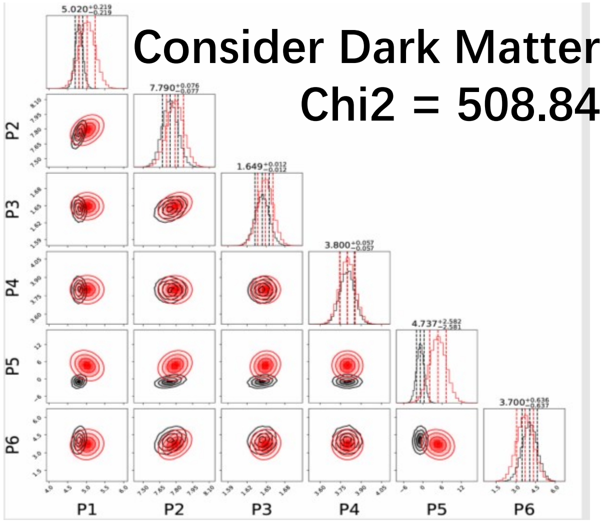
$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in} R\, C_1 (1 - x_{\rm R})^{C_2} \times \left[1 + \frac{X}{\rm GeV}(m_T - m_p)\right]^{\frac{-1}{C_3 X}},$$

here $m_T = \sqrt{p_T^2 + m_p^2}$. The factor

$$R = \begin{cases} 1 & \sqrt{s} \geq 10\,\mathrm{GeV} \\ \left[1 + C_5\left(10 - \frac{\sqrt{s}}{\rm GeV}\right)^5\right] \times \exp\left[C_6\left(10 - \frac{\sqrt{s}}{\rm GeV}\right)^2 \times (x_{\rm R} - x_{R,\min})^2\right] & \text{elsewhere} \end{cases}$$

- ✓ Parametrized Differential N-N collision Cross Section
- ✓ C5 is a normalization parameters in low energy.
- ✓ C1 is normalization parameters for all energy range.





The uncertainty in nucleon-nucleon collision cross-sections can explain the excess of cosmic ray antiprotons. However, the confidence level for the existence of dark matter remains at 3.5σ. Therefore, more precise nucleon-nucleon collision cross-sections will help understand whether there is indeed dark matter in cosmic ray antiprotons.