Probing dark matter through cosmic-ray anti-nuclei

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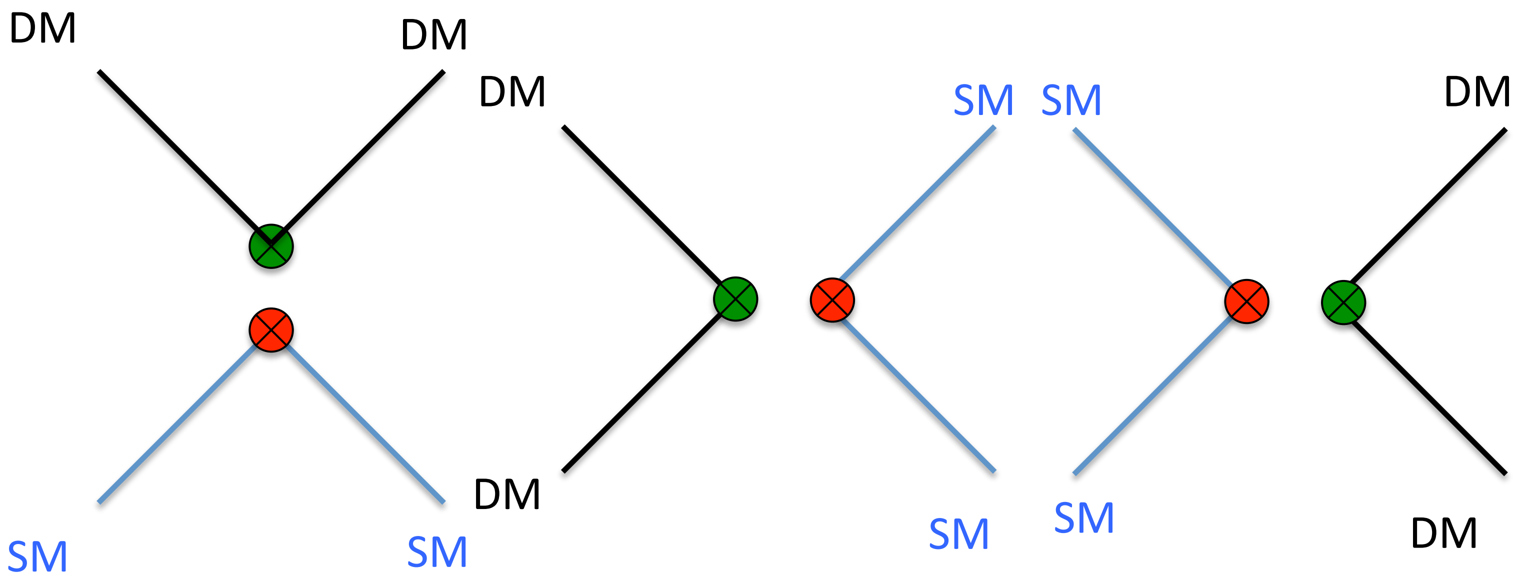
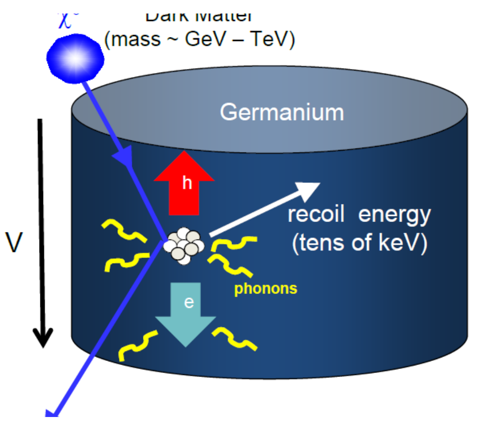
Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612, JCAP 1906 (2019) 06, 004

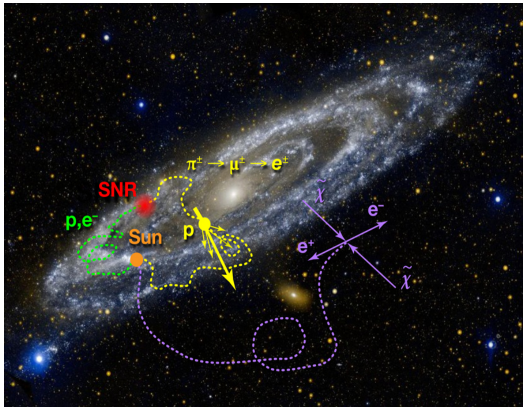
Detecting the non-gravitational interaction of DM

DM may interact with SM particles (weakly)

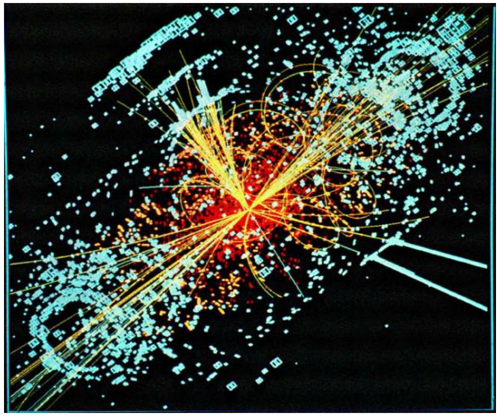




Direct searches

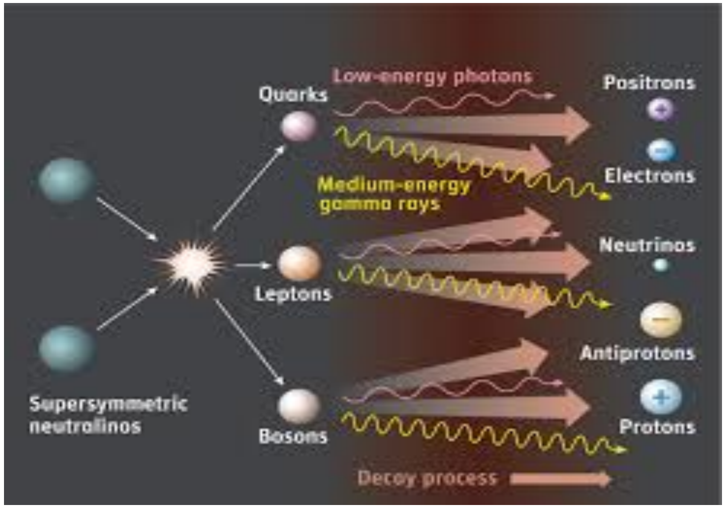


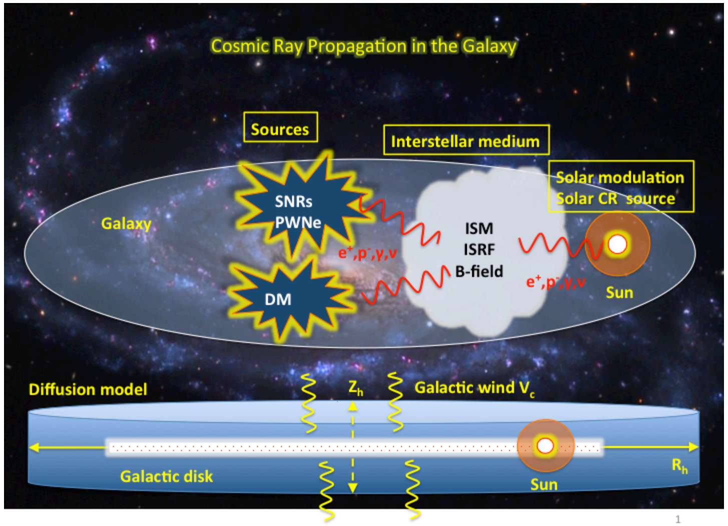
Indirect searches



Collider searches

DM indirect detections





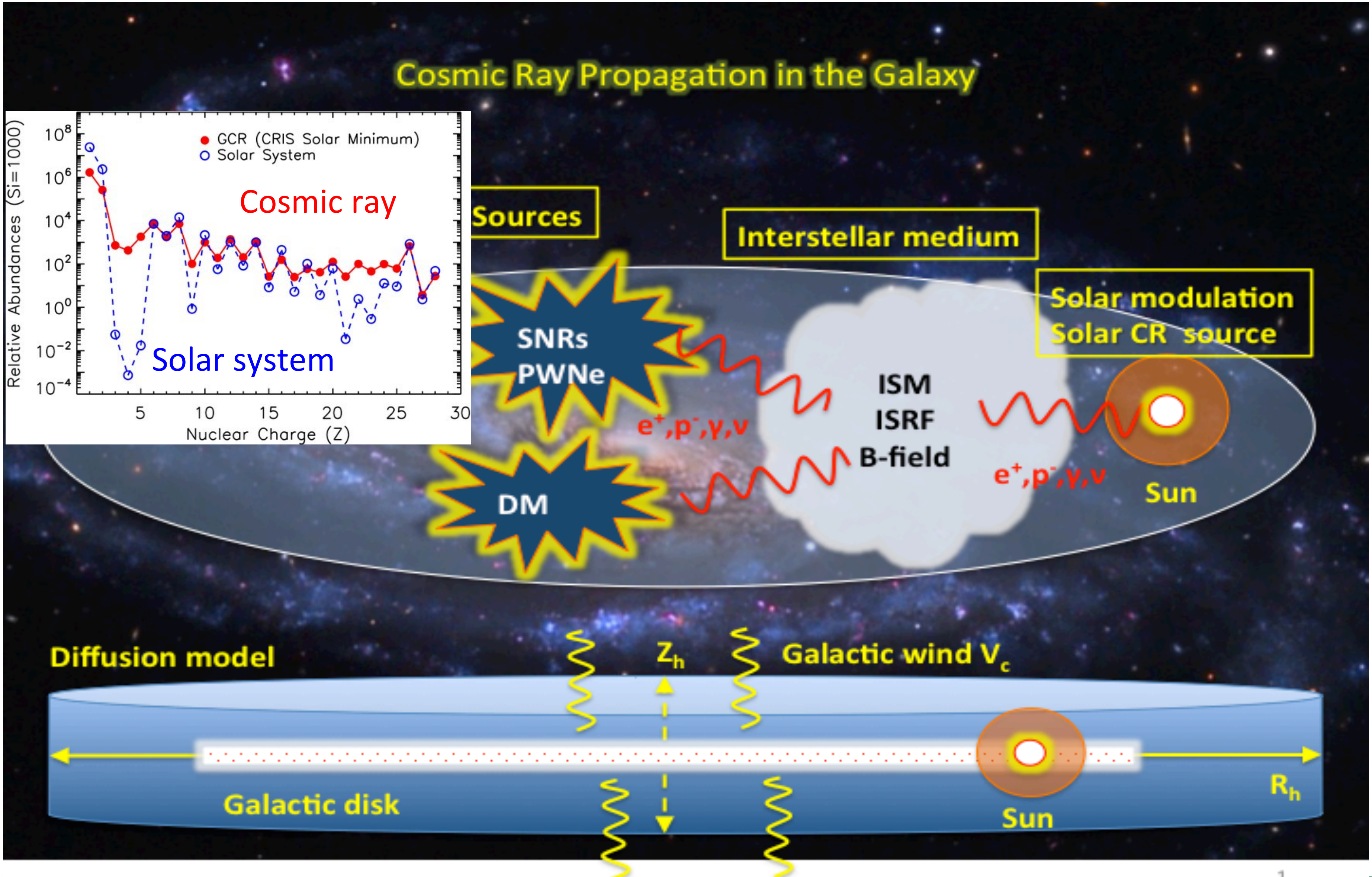
Advantages

- Probe DM annihilation, test the WIMP scenario
- Tiny signals enhanced by huge volume of the DM halo
- Many observables: CR leptons, hadrons, photons in multi-wave lengths. *Both* energy spectra and morphology
- Already place stringent constraints on DM

Difficulties

- Hard to distinguish DM “signal” from “background”
- Information lost of charged CRs (after propagation)
  - spectrum change du to E-dependent propagation,
  - convection, re-acceleration, E-loss
  - anisotropic source -->almost isotropic signals
- Significant uncertainties in theoretical predictions
  - models of CR propagation,
  - distributions of ISM,
  - interaction cross sections,
  - Solar modulation

Propagation of CR in the Galaxy



Cosmic-ray transportation equation

$$\frac{\partial\psi}{\partial t} = \nabla(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + q(\mathbf{r},p),$$

diffusion
convection
E-loss
reaccelaration
spallation
decay
source

Sources of CRs

- Primary sources from SNR, pulsars
- Primary sources from WIMP
- Secondary source from CR fragmentation

Processes in Propagation

- Diffusion (random B field)
- Convection (galactic wind)
- Reacceleration (turbulence)
- Energy loss: Ionization, IC, Synchrotron, bremsstrahlung
- Fragmentation (inelastic scattering)
- Radioactive decay (unstable species)

Solar modulation

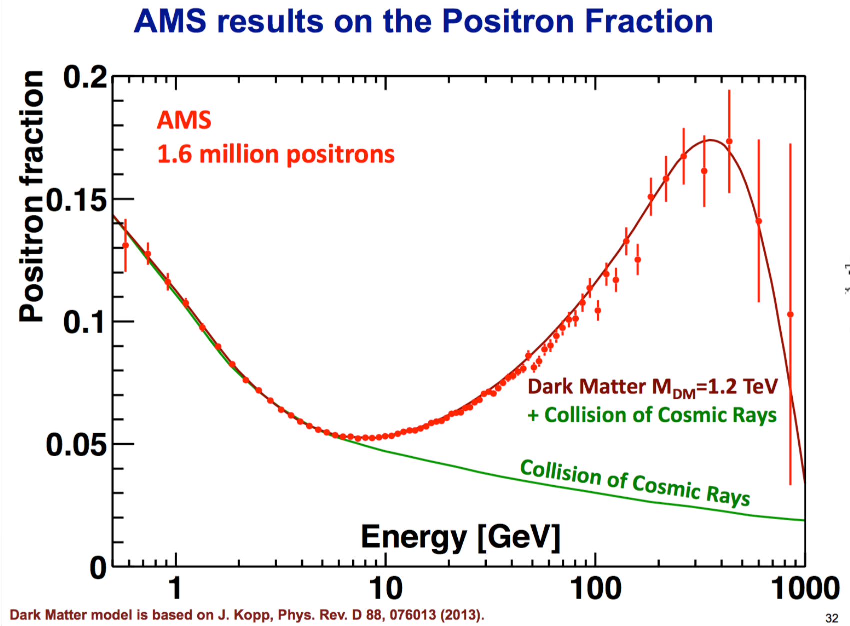
Uncertainties

- Distribution of primary sources
- Parameters in the diffusion equation
- Cross sections for nuclei fragmentation
- Distribution of B field
- Distribution of gas

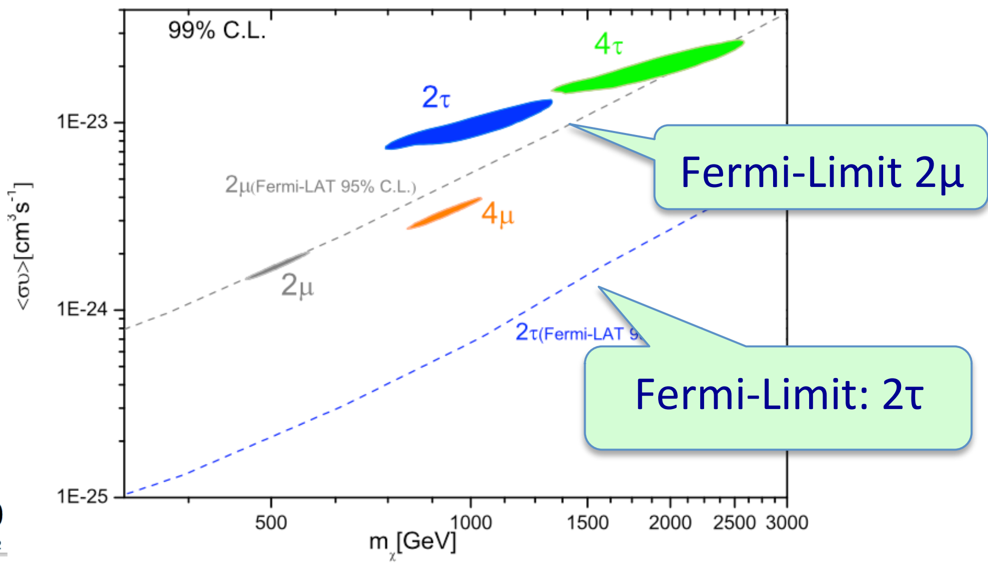
Approaches

- Semi-analytical:two-zone diffusion model.
- Numerical solution using realistic astrophysical data. GALPROP/Dragon code

The CR positron anomaly and its implications



H.B.Jin, Y.L.Wu, YFZ,1410.0171,JCAP



Fermi-LAT,1503.0264

Implications for DM annihilation

- large annihilation cross-section ~100-1000 times larger than that favored by DM thermal relic density.
- annihilate/decay dominantly to leptons, *not* quarks

Difficulties for thermal DM

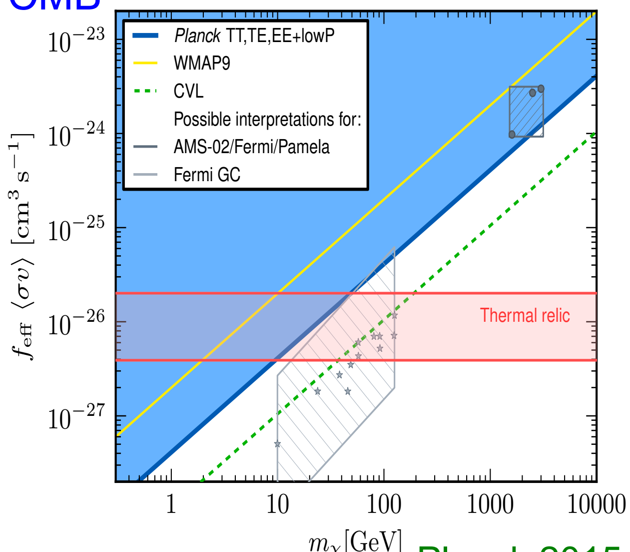
- Require velocity-dependent cross-section
  - Sommerfeld enhancement
  - Annihilation through narrow resonance

Constraints from gamma-rays

- Strong correlation with gamma-ray signals
  - FSR photons from all charged leptons
  - photons from μ, τ decays
  - Photons from hadronic (π^0) decays

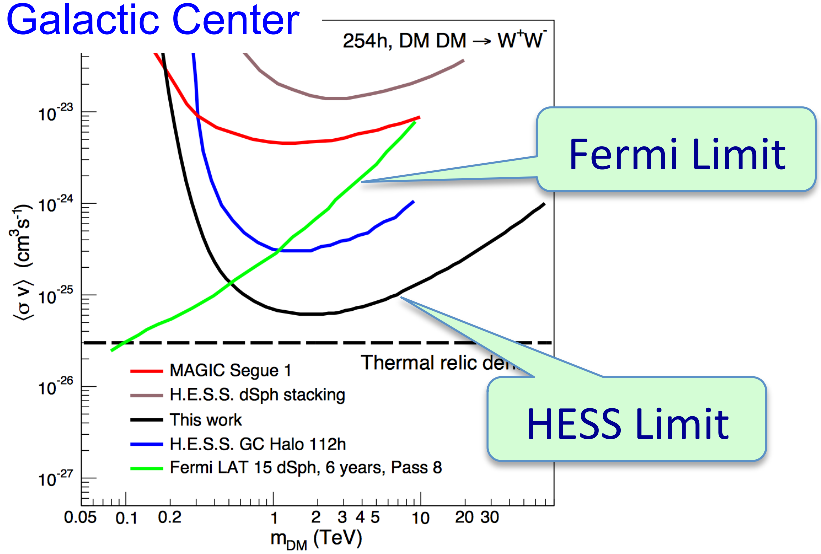
Stringent constraints on DM interpretations

CMB



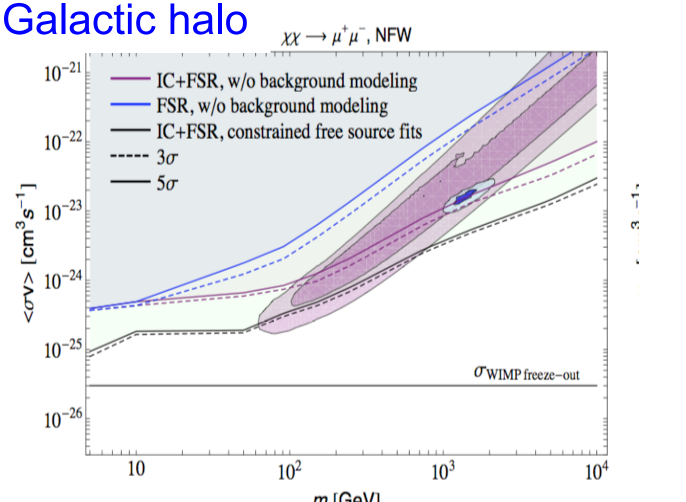
Planck 2015

Galactic Center



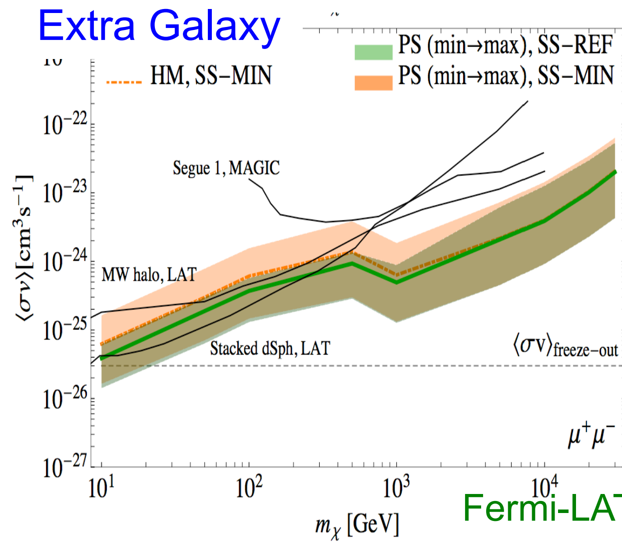
HESS 2016

Galactic halo



Fermi-LAT, 1205.6467

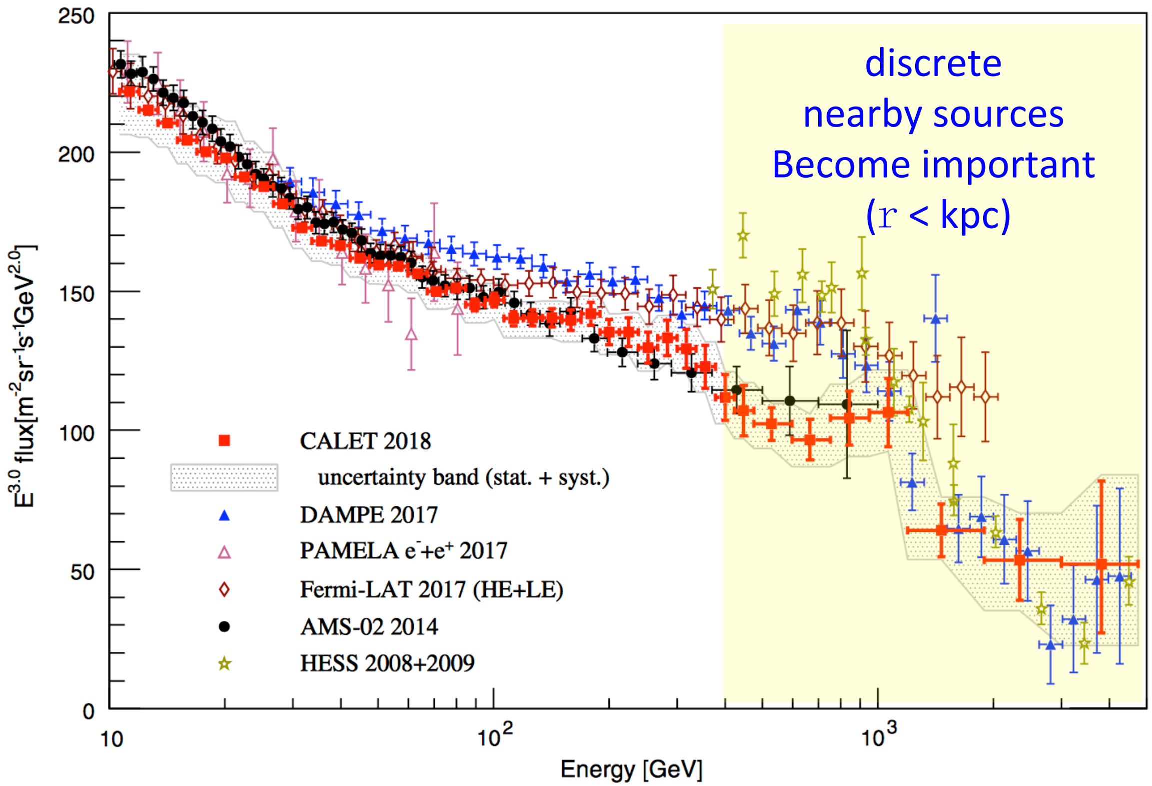
Extra Galaxy

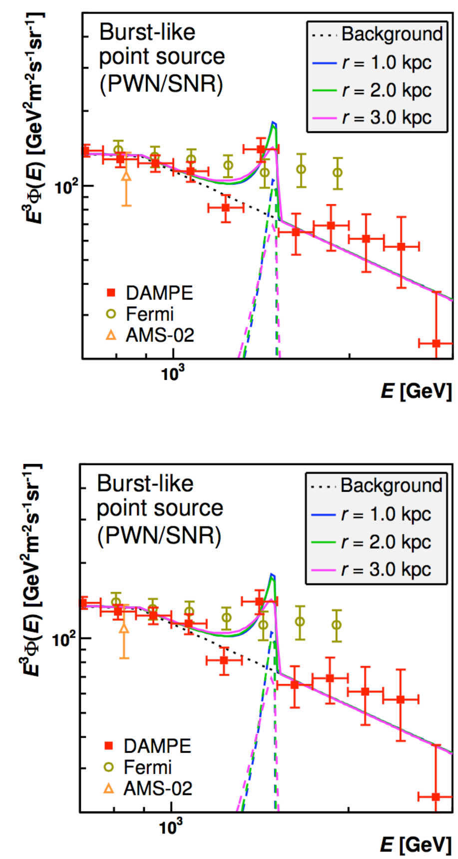


Fermi-LAT, 1501.05464

CR all-electron flux

Fermi-LAT, AMS-02, CALET, “DAMPE (悟空)”, not in full agreement

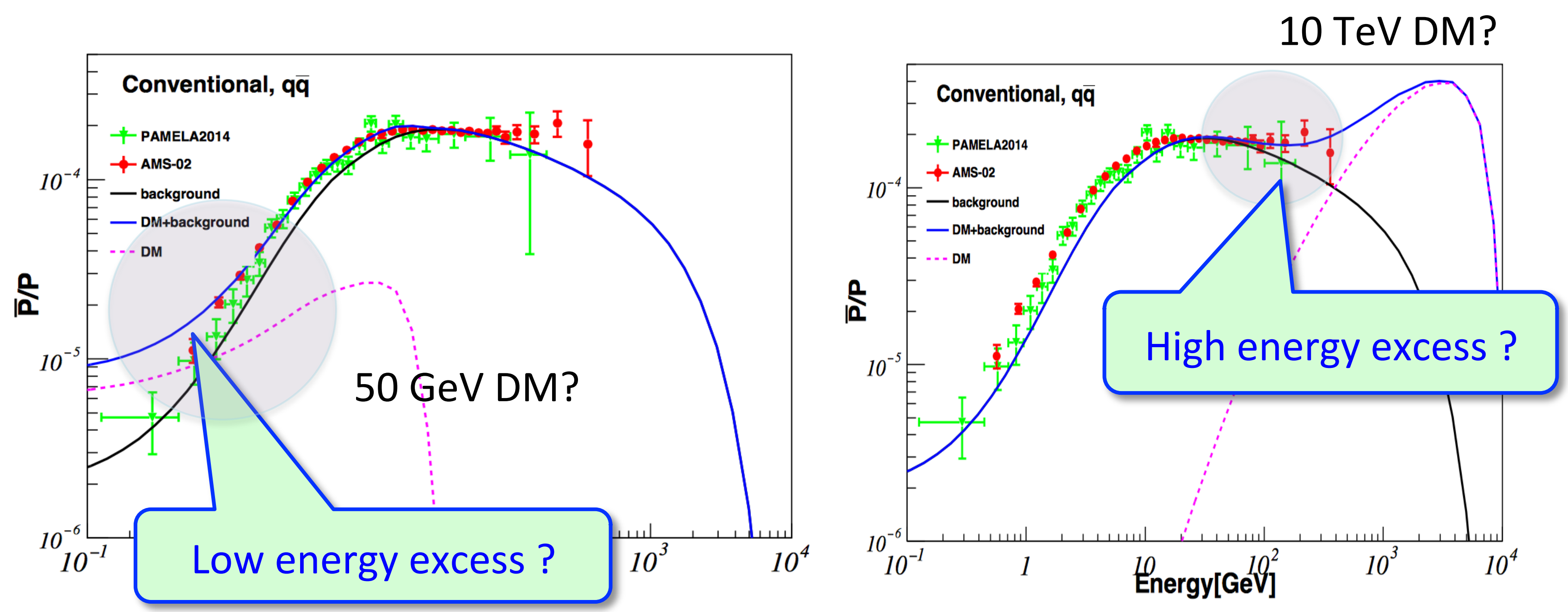




DAMPE “excess”?

X.J.Huang, W.H.Zhang, Y.L.Wu, YFZ, arXiv:1712.00005,PRD(R)

Possible excesses and DM interpretations



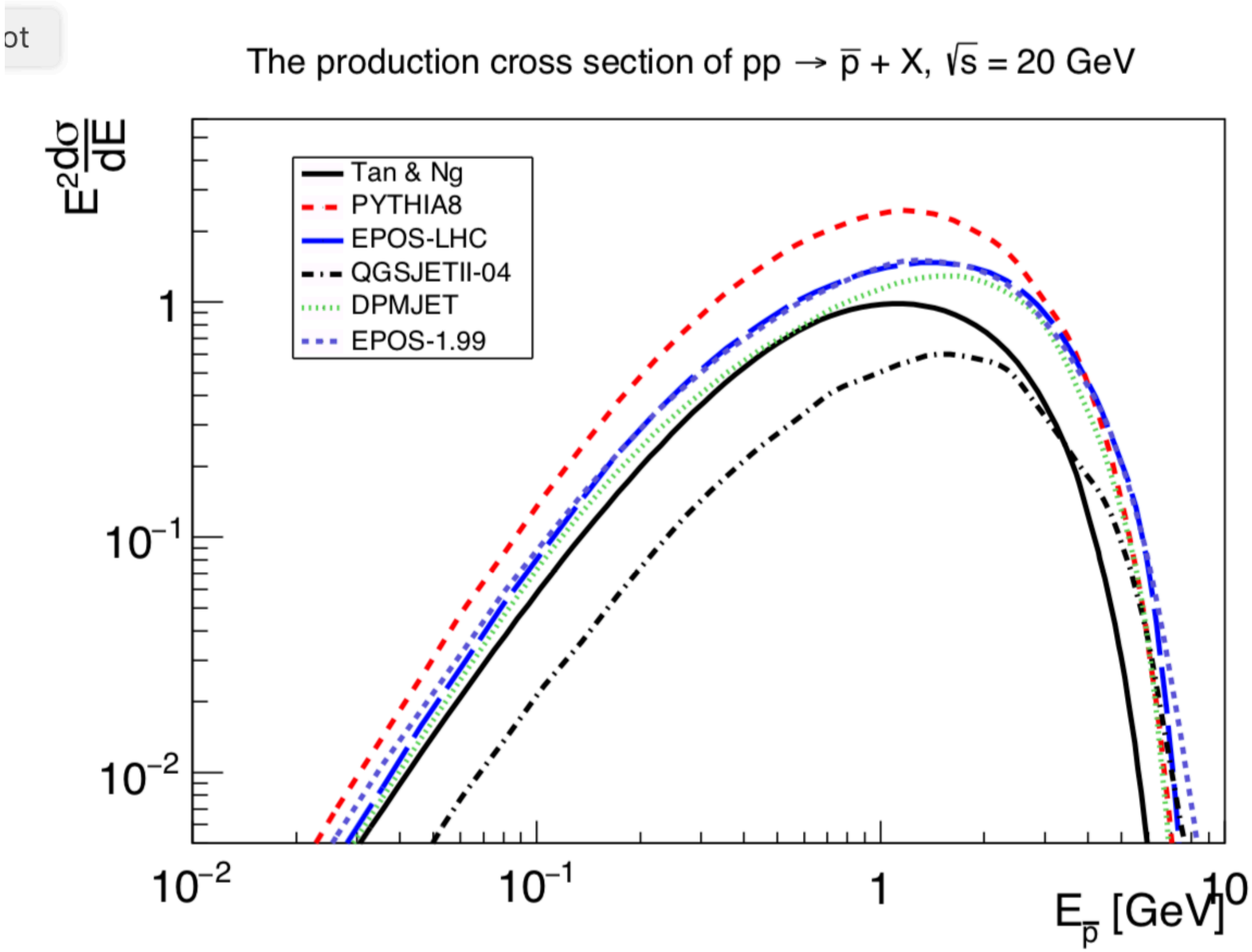
H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD

Low-energy excess: 40-50 GeV DM to 2b, thermal cross section, consistent with GC
High-energy excess: 10 TeV DM annihilation into 2W, 2b, boost factor ~10-100

Giesen, 1504.04276; Ibe 1504.05554;
Hamaguchi, 1404.05937; Lin, 1504.07230
Chen, 1504.07848; Chen,1505.00134

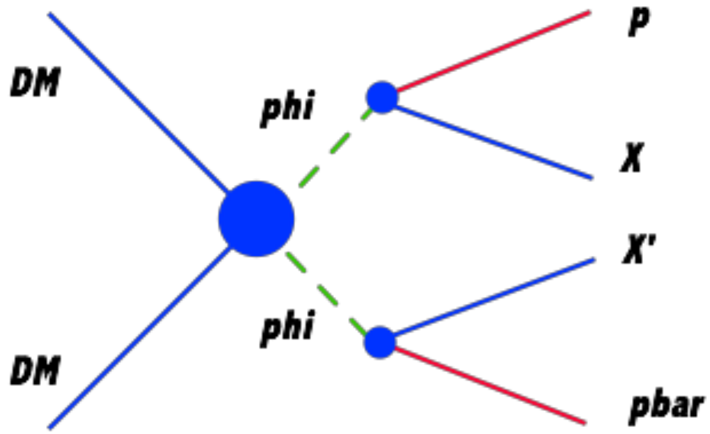
Low-energy “excess”: theoretical uncertainties

Uncertainties in antiproton production cross sections



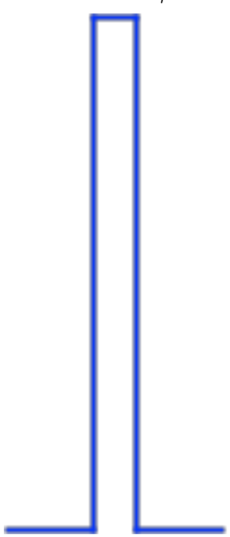
Other uncertainties: diffusion models, solar modulation,

High-energy “excess ”: origins of a sharp spectrum



Lorentz boost for finite ϵ_0

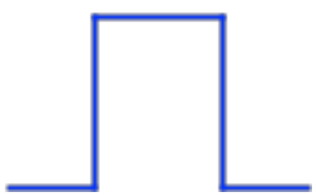
When $\phi \approx 2m_p$ small β'



Lorentz Boost

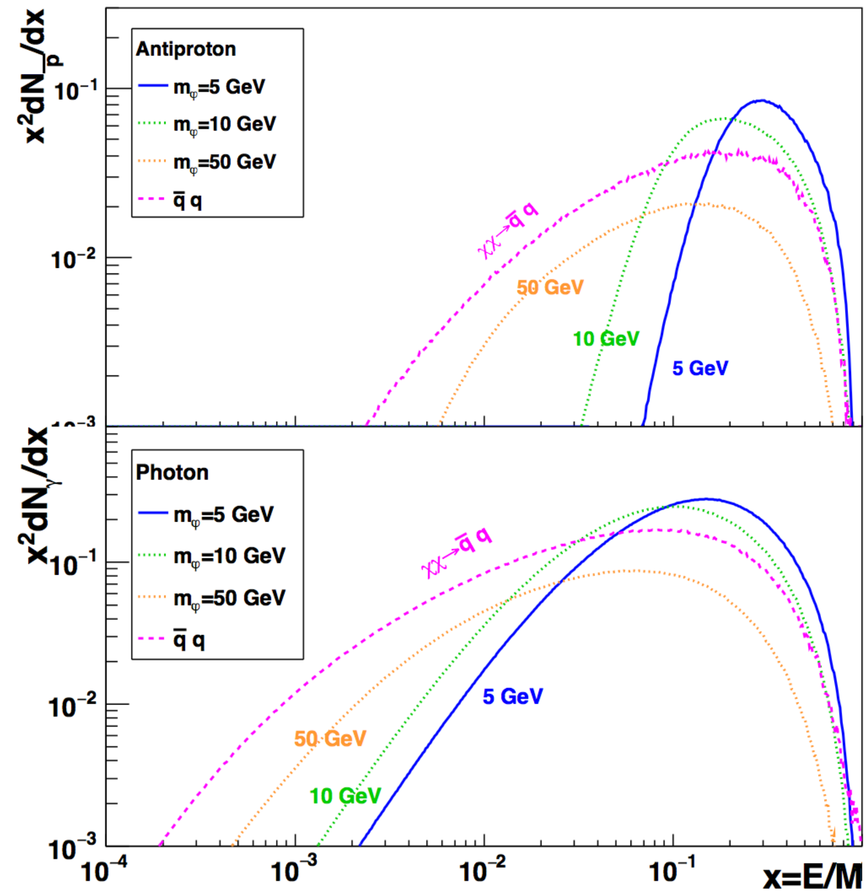
$$E = \gamma_B E'$$

$$\Delta E/E = 2\beta_B \beta'$$



ϕ rest-frame DM CM frame

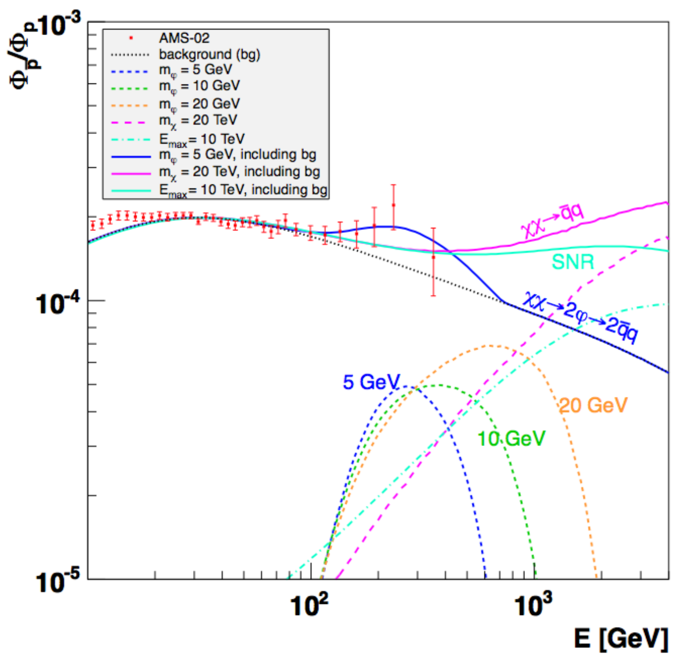
In the case with light mediators, sharp antiproton spectral can arise in the threshold limit



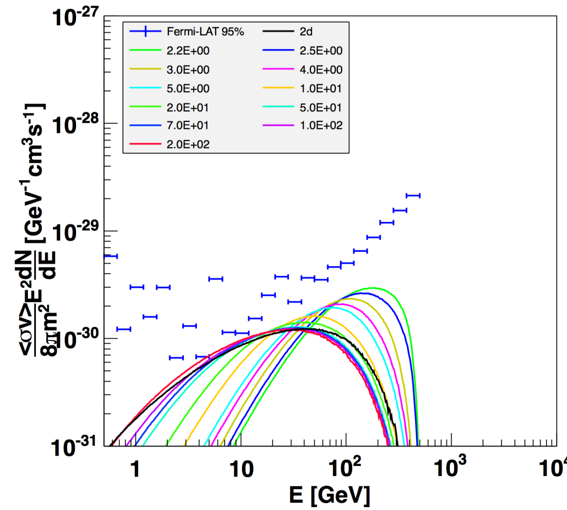
Huang, Wei, Wu ,YFZ, Zhang,1611.01983,PRD

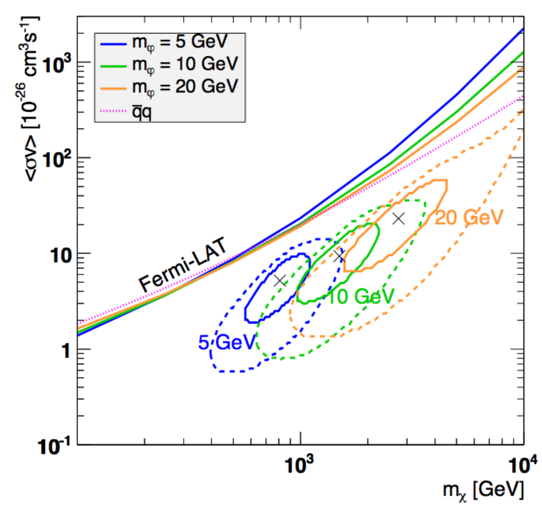
Sharp spectrum possible in four-body final sates

Light mediator scenario can explain the structure without violating the Fermi gamma-ray limits



Fermi gamma-ray limits



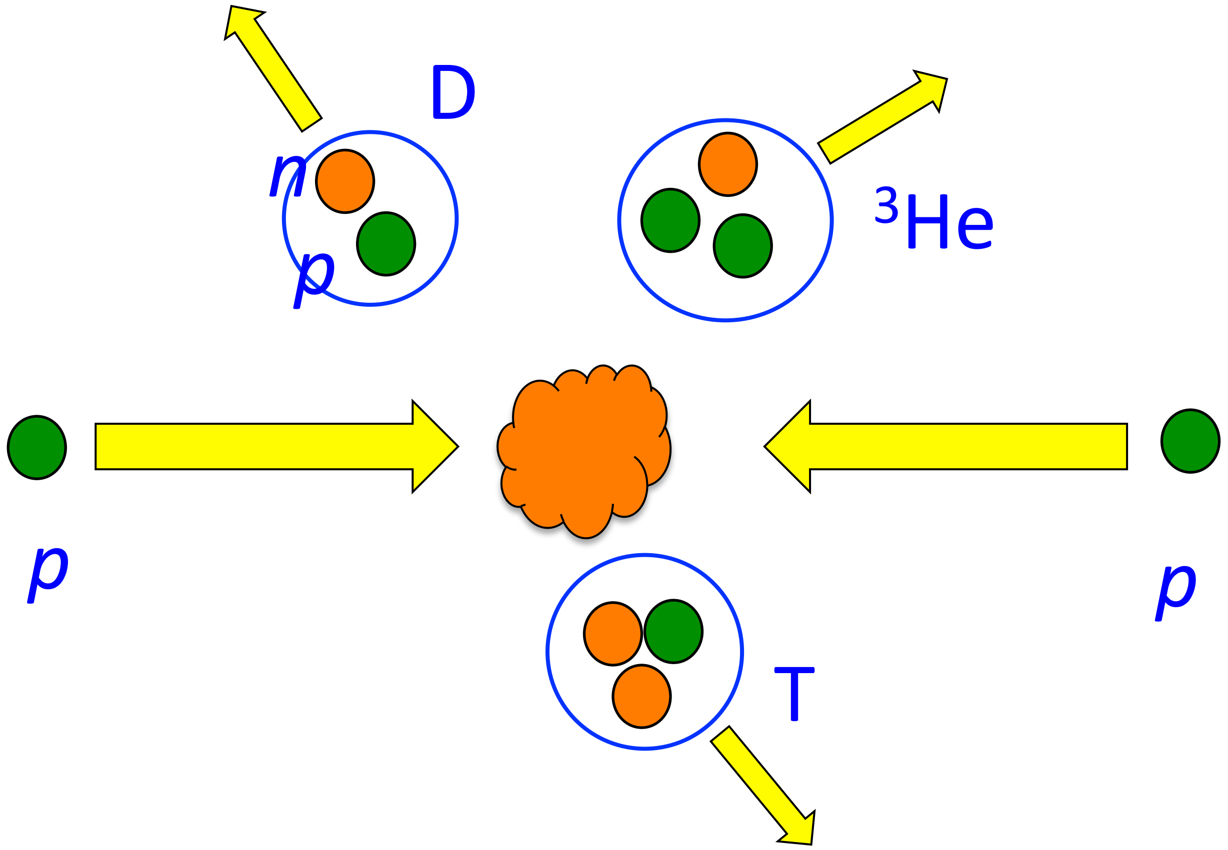


Favored DM mass ~800 GeV with thermal cross section

	Model	m_χ[GeV]	$\langle\sigma v\rangle(\eta)$	κ	χ^2	TS
A	MIN	765^{+167}_{-153}	$18.6^{+10.7}_{-8.0}$	1.12±0.01	12.5	11.6
	MED	808^{+184}_{-165}	$5.18^{+3.04}_{-2.37}$	1.13±0.01	13.8	9.0
	MAX	826^{+185}_{-168}	$2.29^{+1.31}_{-1.06}$	1.13±0.01	15.5	8.5
B	MIN	20000	1200±410	1.12±0.01	15.5	8.6
	MED	20000	291±123	1.13±0.01	17.2	5.6
	MAX	20000	117±54	1.12±0.01	19.3	4.7
C	MIN	–	(0.262±0.103)	1.08±0.02	17.6	6.5
	MED	–	(0.195±0.104)	1.10±0.02	19.2	3.5
	MAX	–	$(0.172^{+0.104}_{-0.105})$	1.10±0.02	21.4	2.7

Huang, Wei, Wu ,YFZ, Zhang,1611.01983,PRD

Formation of CR heavy anti-nuclei



High production threshold: $17m_p$ (antideuteron), $31m_p$ (antihelium) for fixed targets

heavy anti-nuclei

Spectra feature of secondary anti-nuclei

- Highly boosted after production

  production threshold: $17m_p$ (antideuteron), $31m_p$ (antihelium)

  low binding energy → less energy loss

  leave a low-energy window (<GeV) for exotic contributions

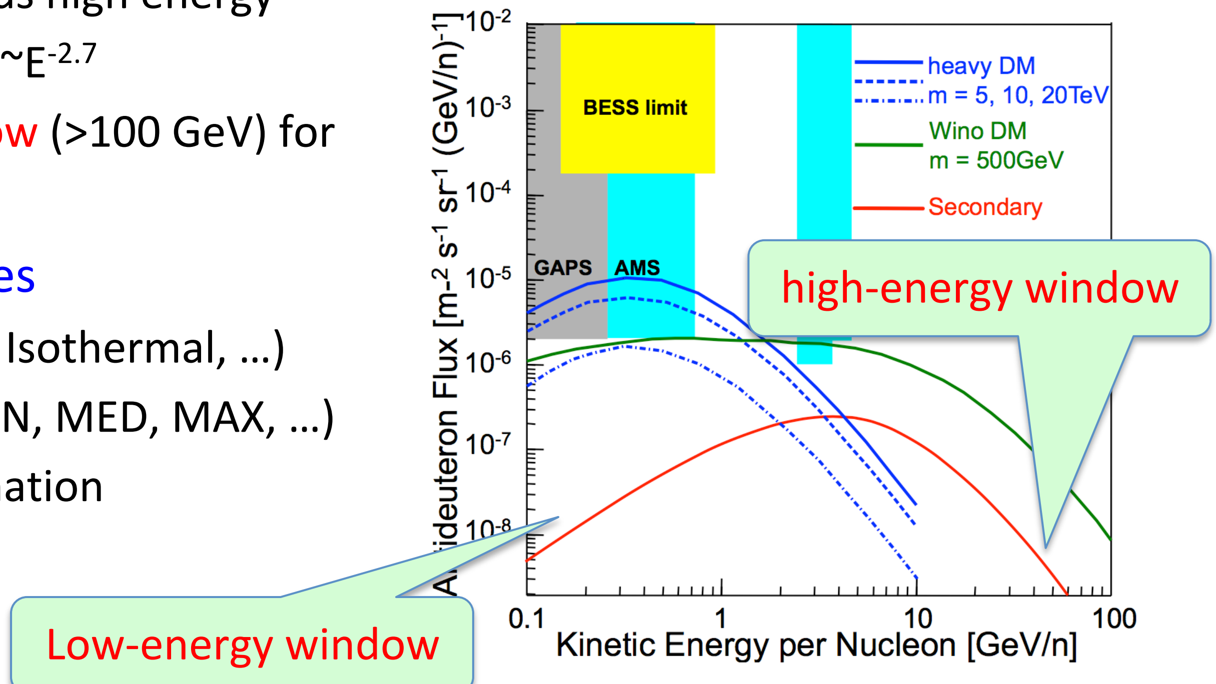
- Low production rate towards high energy

  fast falling of primary CRs ~$E^{-2.7}$

  leave a high-energy window (>100 GeV) for exotic contributions

Major source of uncertainties

- DM profiles (NFW, Einasto, Isothermal, …)
- CR propagation models (MIN, MED, MAX, …)
- Models for anti-nuclei formation
  - potential models
  - coalescence models
  - thermal models

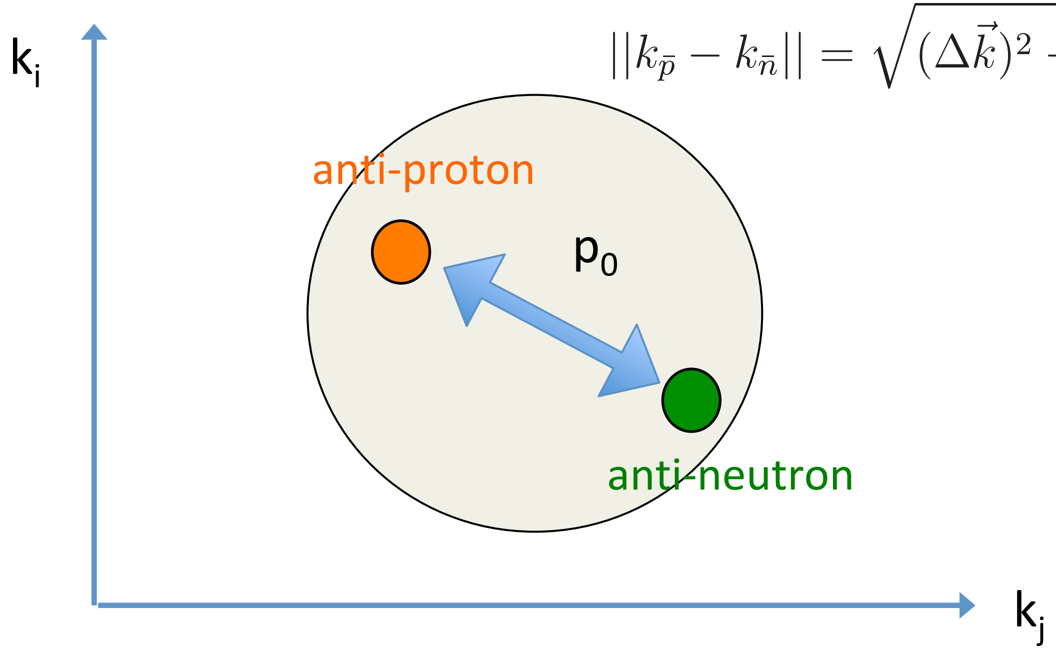


Aramaki, etal, 1505.07785

Formation of CR heavy anti-nuclei: the coalescence model

The coalescence model: the case of A=2

$$||k_{\bar{p}} - k_{\bar{n}}|| = \sqrt{(\Delta\vec{k})^2 - (\Delta E)^2} < p_0^{\overline{\mathrm{D}}},$$



- no dynamics (phase-space model)
- extremely simple, only one parameter p_0
- coalescence rate ~ $p_0^{3(A-1)}$

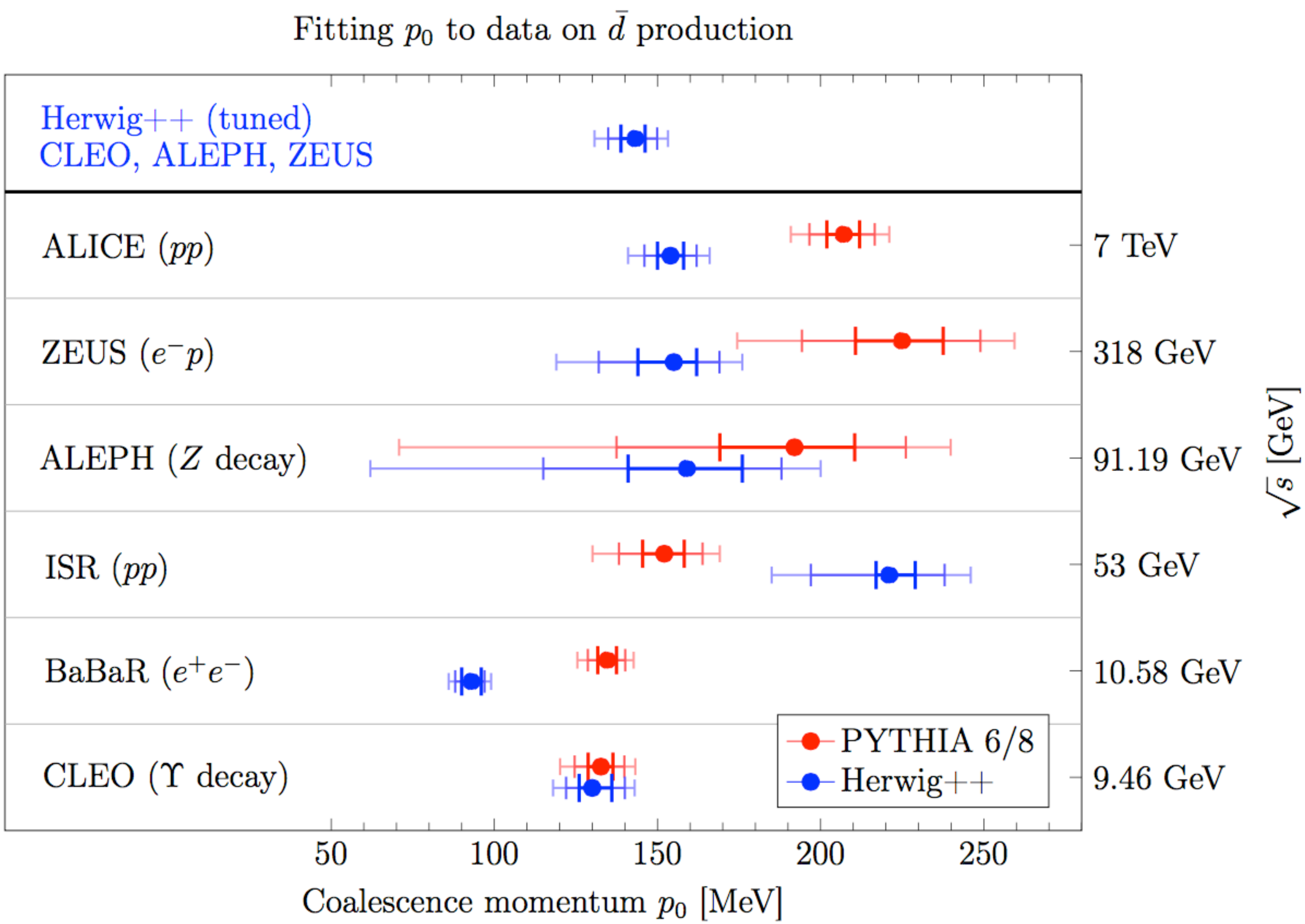
Energy spectrum

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6}\frac{m_{\bar{d}}}{m_{\bar{n}}m_{\bar{p}}}\frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}}\frac{dN_{\bar{n}}}{dT_{\bar{n}}}\frac{dN_{\bar{p}}}{dT_{\bar{p}}},$$

Caution: correlations are significant !

Formation of CR heavy anti-nuclei: the coalescence model

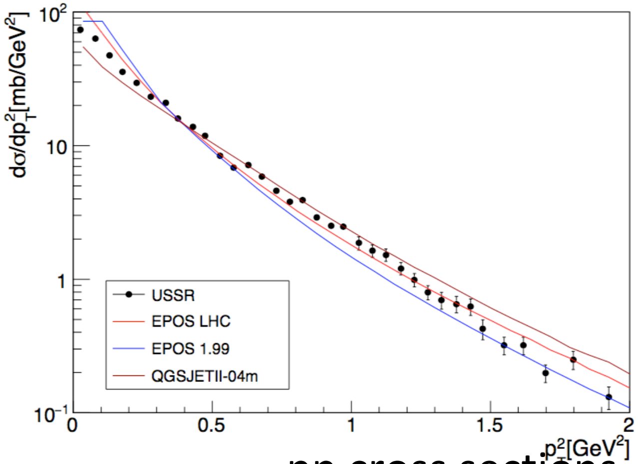
Determination of p^0 for anti-deuteron



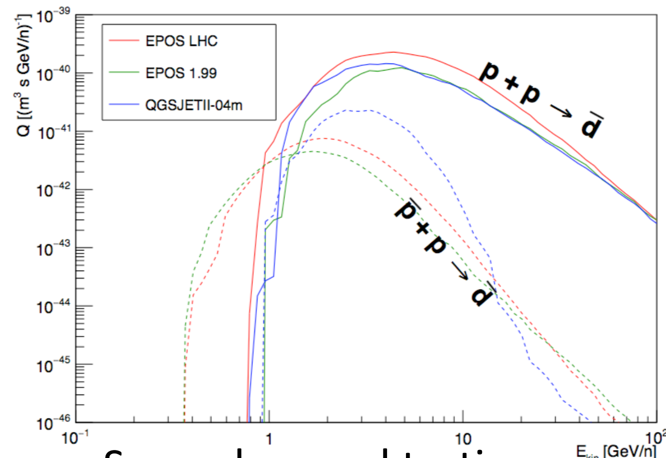
The scale of $p_0 \sim$ 100-200 MeV

Aramaki, etal, 1505.07785

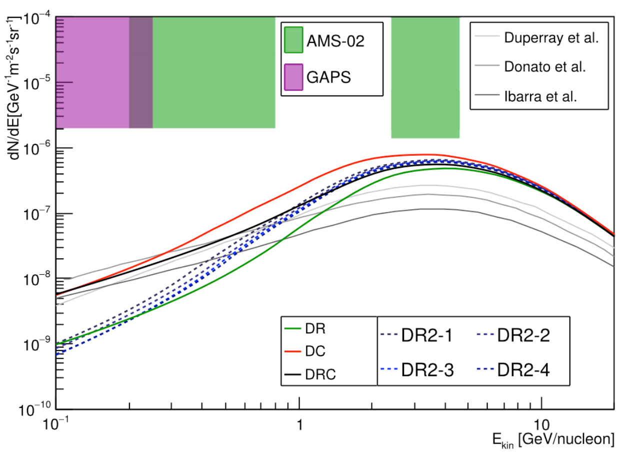
CR anti-deuteron and maximal DM contribution



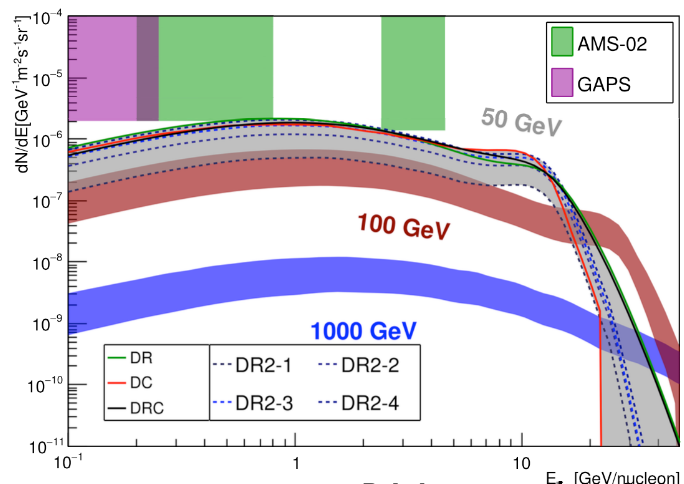
pp cross sections



Secondary and tertiary sources



backgrounds



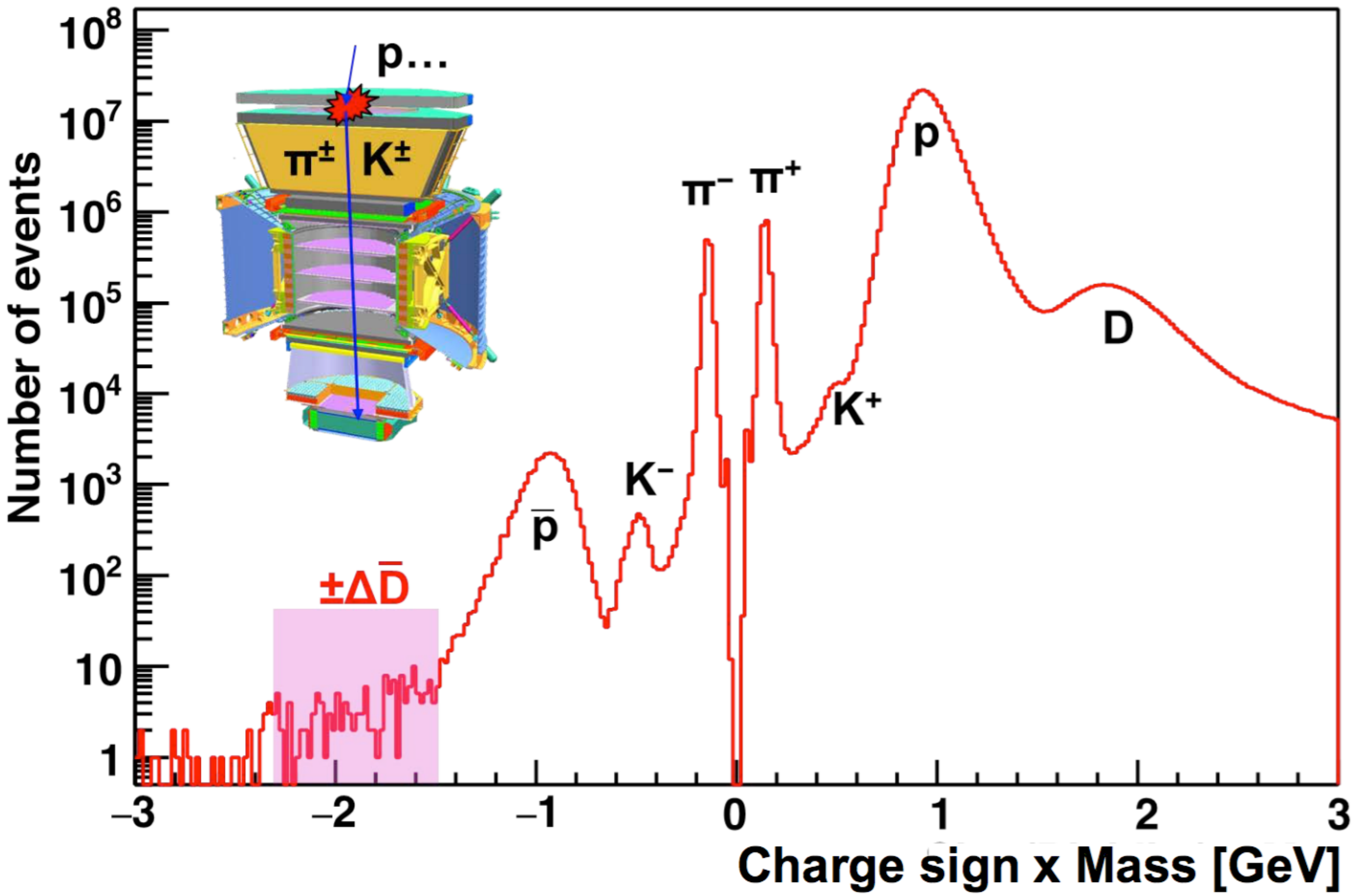
DM contributions

DM induced antideuteron flux can be reach by AMS-02 and GAPS

S.J. Lin et al, 1801.00997

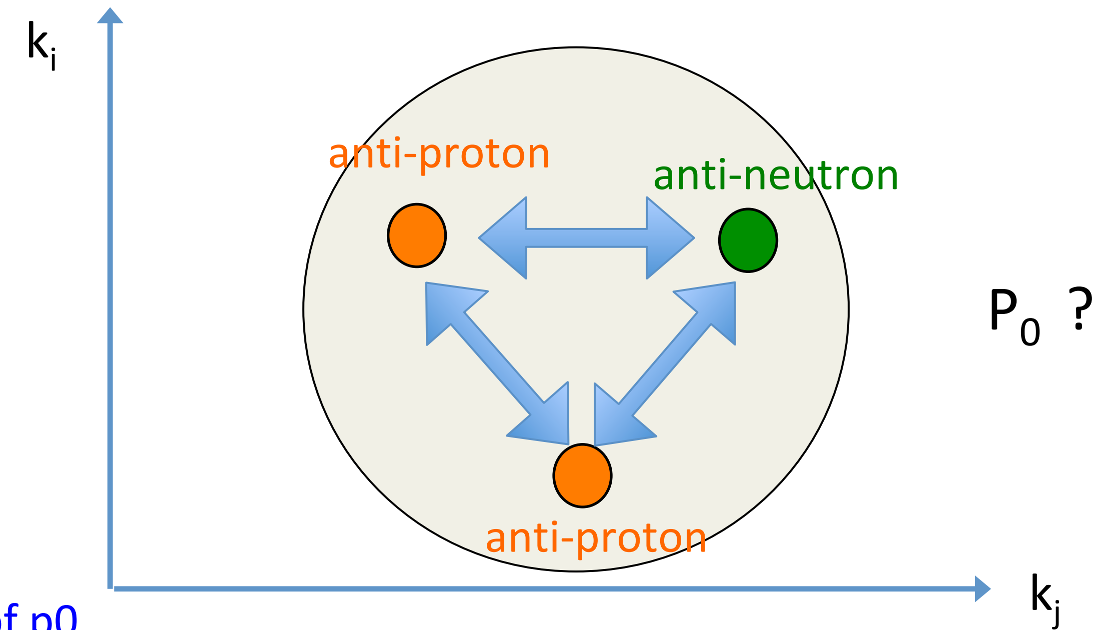
Current status of anti-deuteron detection

AM02 (2016)



Formation of CR heavy anti-nuclei: the coalescence model

The coalescence model: the case of A=3



Definitions of p0

- minimal circle

$$d_{\rm circ} = \frac{l_1 l_2 l_3}{\sqrt{(l_1+l_2+l_3)(-l_1+l_2+l_3)(l_1-l_2+l_3)(l_1+l_2-l_3)}} < p_0^{\overline{\rm He}}.$$

- absolute difference for all relative momenta

$$||k_i - k_j|| < p_0^{\overline{\rm He}}, \qquad (i \neq j).$$

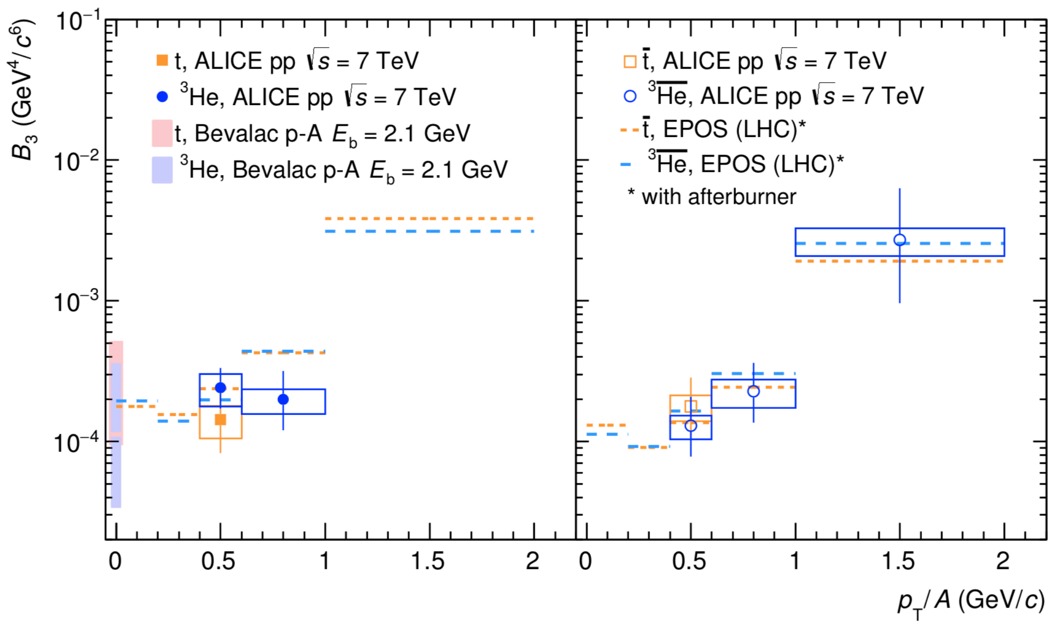
Coalescence momentum of anti-Helium

Indirect approaches

- Use the relation between nuclei: $p_{0A}^{\overline{\mathrm{He}}} = \langle p_0^{\mathrm{He}}/p_0^{\mathrm{D}} \rangle \, p_0^{\bar{\mathrm{D}}} = 1.28 \, p_0^{\bar{\mathrm{D}}} = 0.246 \pm 0.038 \ \mathrm{GeV}.$
- Use binding energy: $p_{0B}^{\overline{\mathrm{He}}} = \sqrt{E_b^{3\overline{\mathrm{He}}}/E_b^{\bar{\mathrm{D}}}} \, p_0^{\bar{\mathrm{D}}} = 0.357 \pm 0.059 \ \mathrm{GeV}.$

Direct approaches

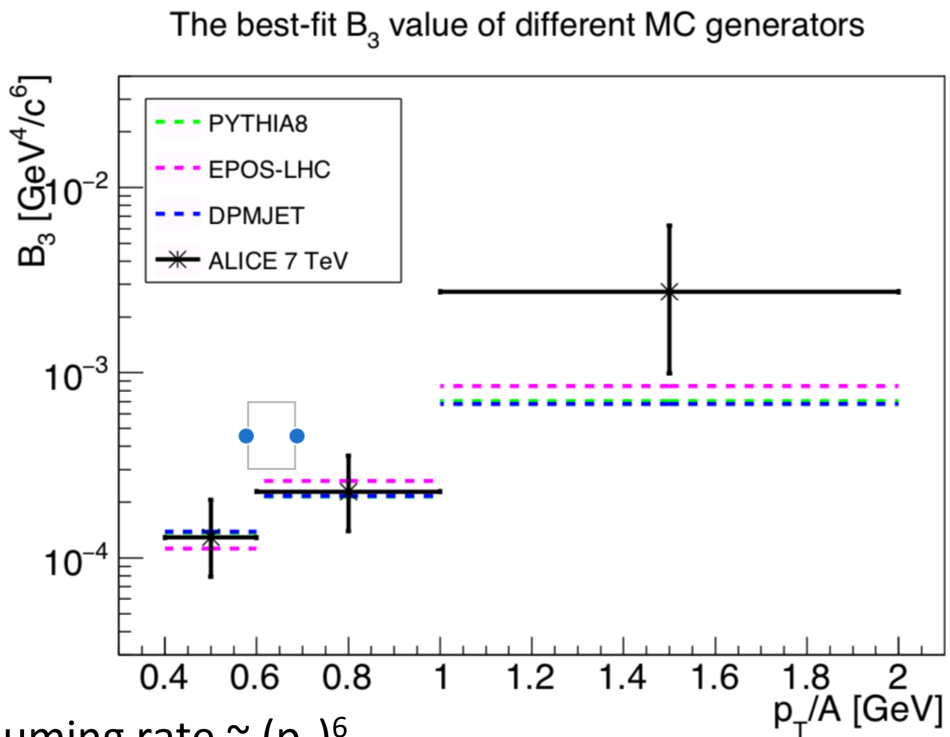
- Use Exp. data (e.g. ALICE, STAR)



ALICE, 1709.08522 (assuming rate ~ $(p_0)^6$)

Coalescence parameters determined from ALICE data

Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612

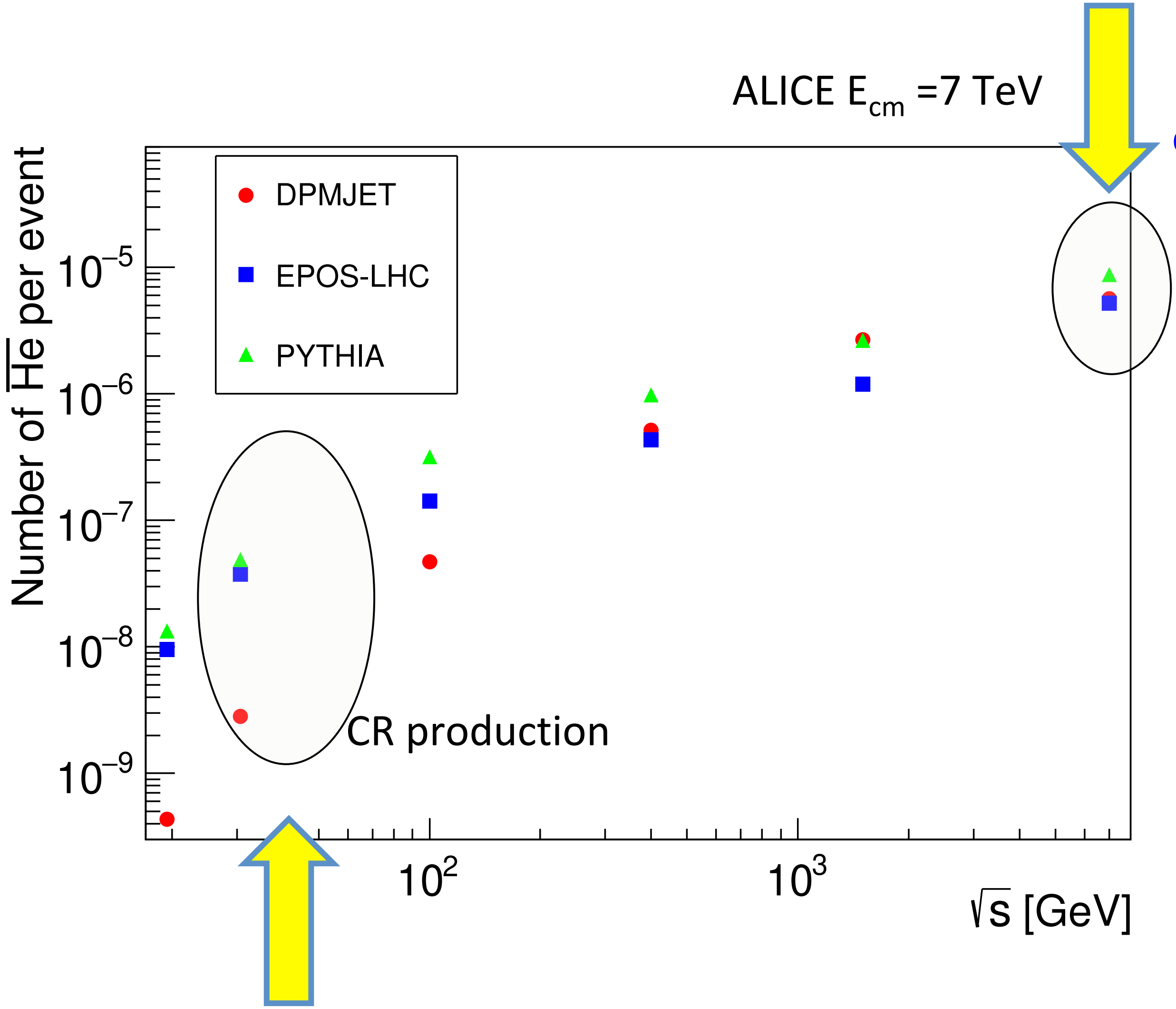


Typically O(10^{11}) event simulations required for each MC-generator

Without assuming rate ~ $(p_0)^6$

MC generators:	PYTHIA 8.2	EPOS-LHC	DPMJET-III
$p_0^{\overline{\mathrm{He}}}$ (MeV)	224^{+12}_{-16} (254 ± 14)	227^{+11}_{-16} (254 ± 14)	212^{+10}_{-13}
$p_0^{\bar{\mathrm{T}}}$ (MeV)	234^{+17}_{-29} (266 ± 22)	245^{+17}_{-30} (268 ± 22)	222^{+16}_{-26}

Significant uncertainties arise when extrapolating to low energies

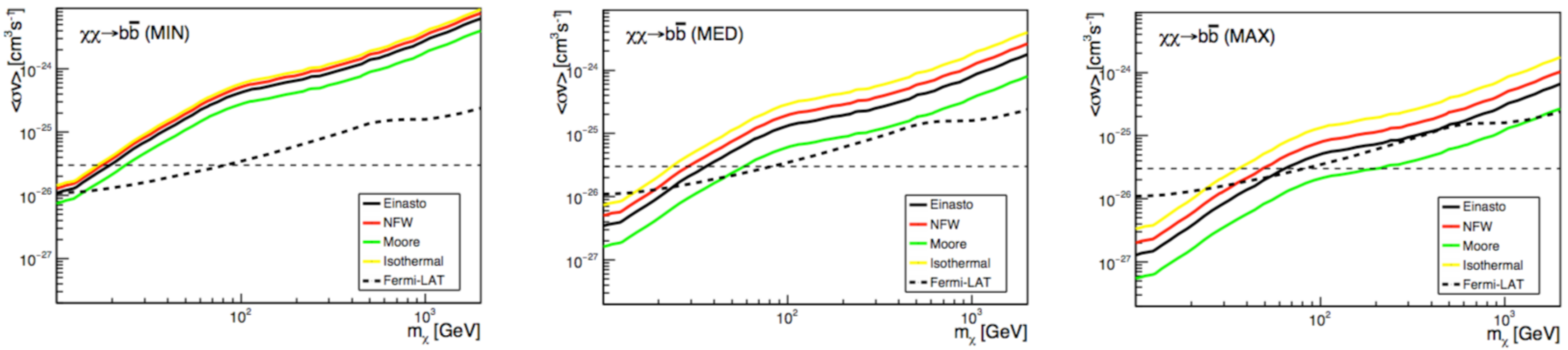


collider production

energy scale relevant to CR anti-helium production

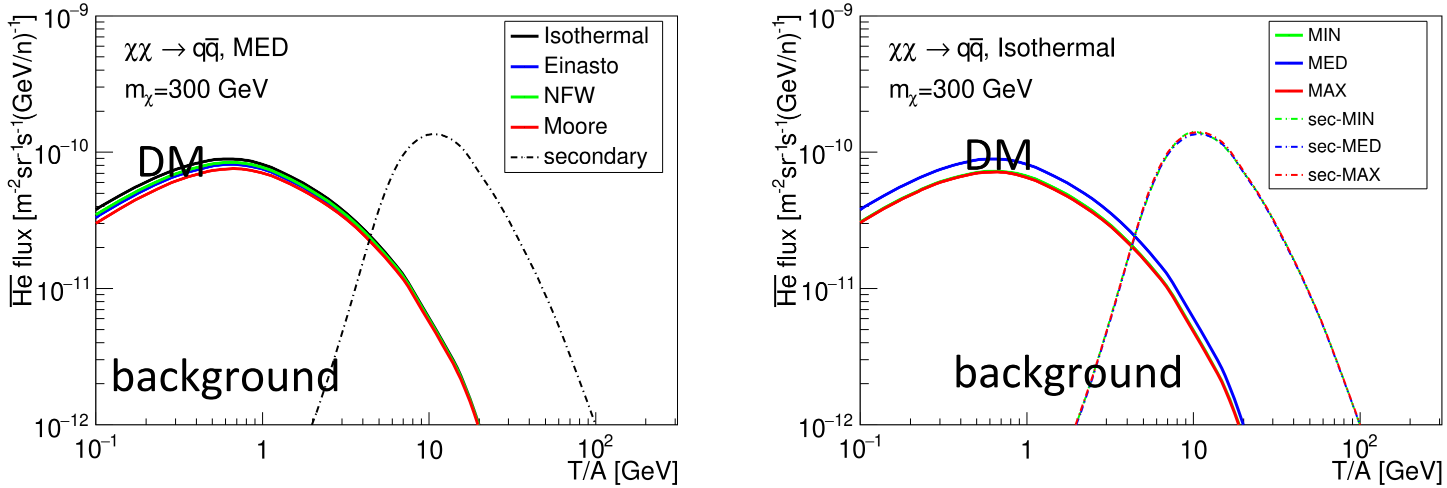
Using the limits derived from antiproton data

Importance of using antiproton limits for predicting anti-nuclei



Advantages:

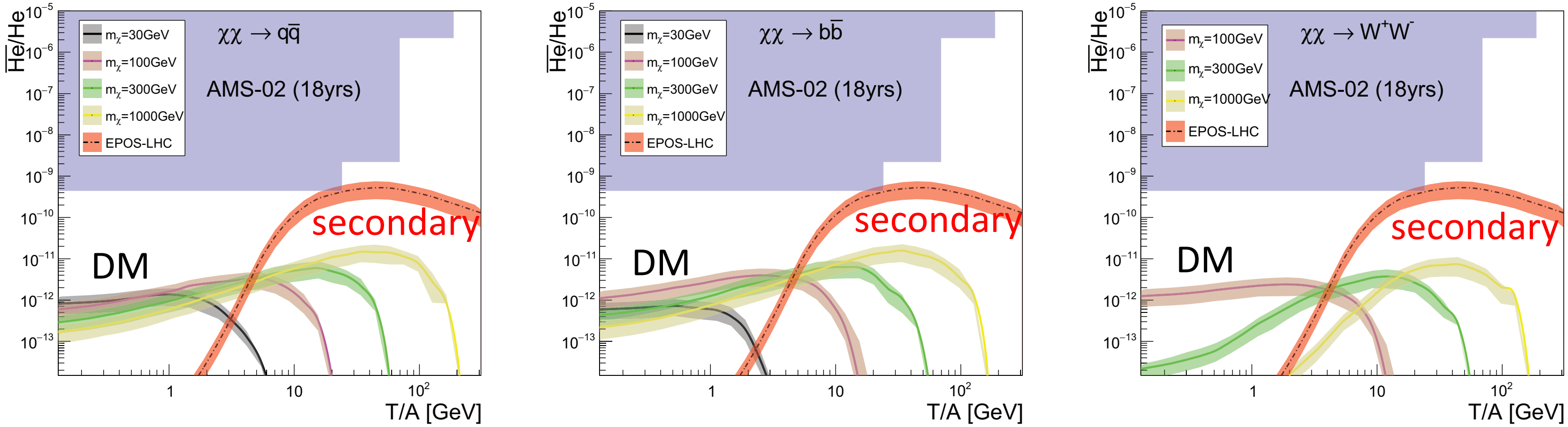
DM profile (also propagation) dependence **cancels out** in deriving the anti-helium limits



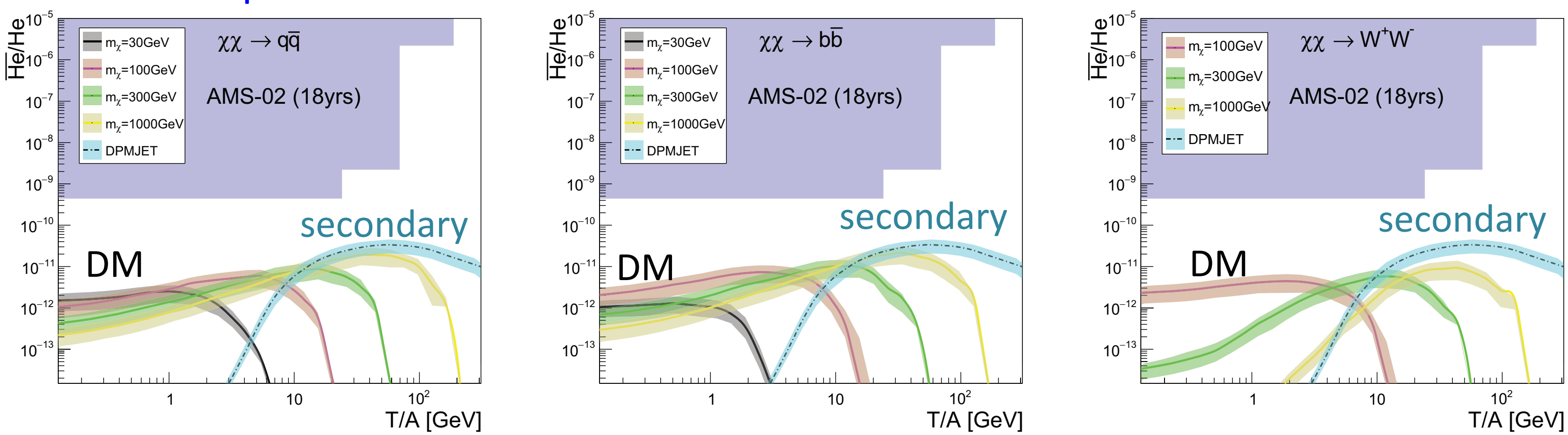
Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612

Projected maximal anti-helium flux @AMS-02

EPOS-LHC based predictions

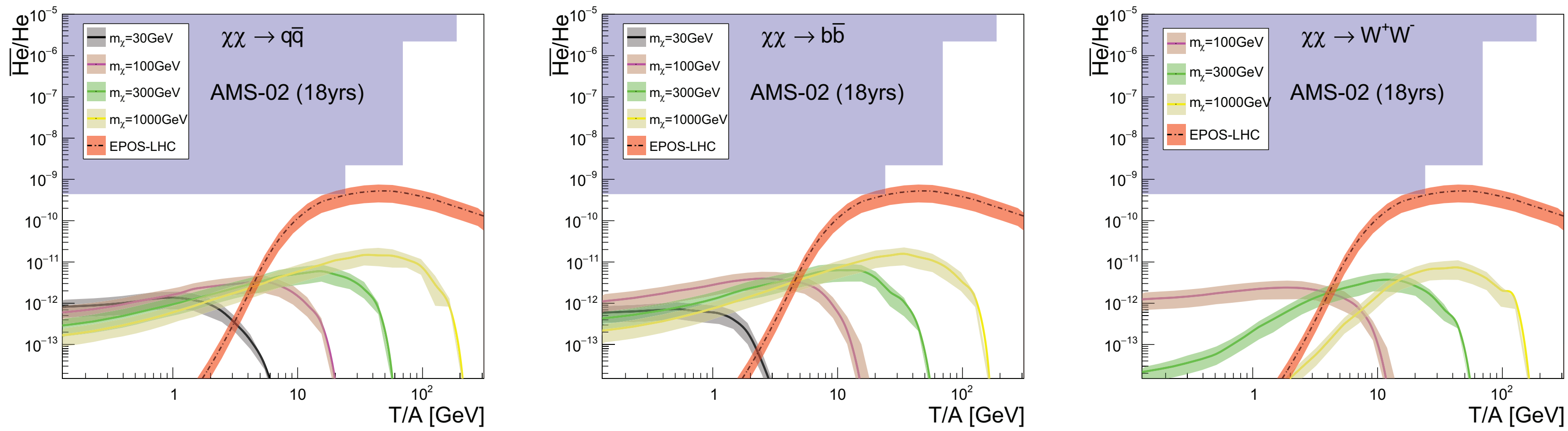


DPMJET based predictions



The most optimistic case for antihelium@AMS-02

The most optimistic case (using EPOS-LHC)

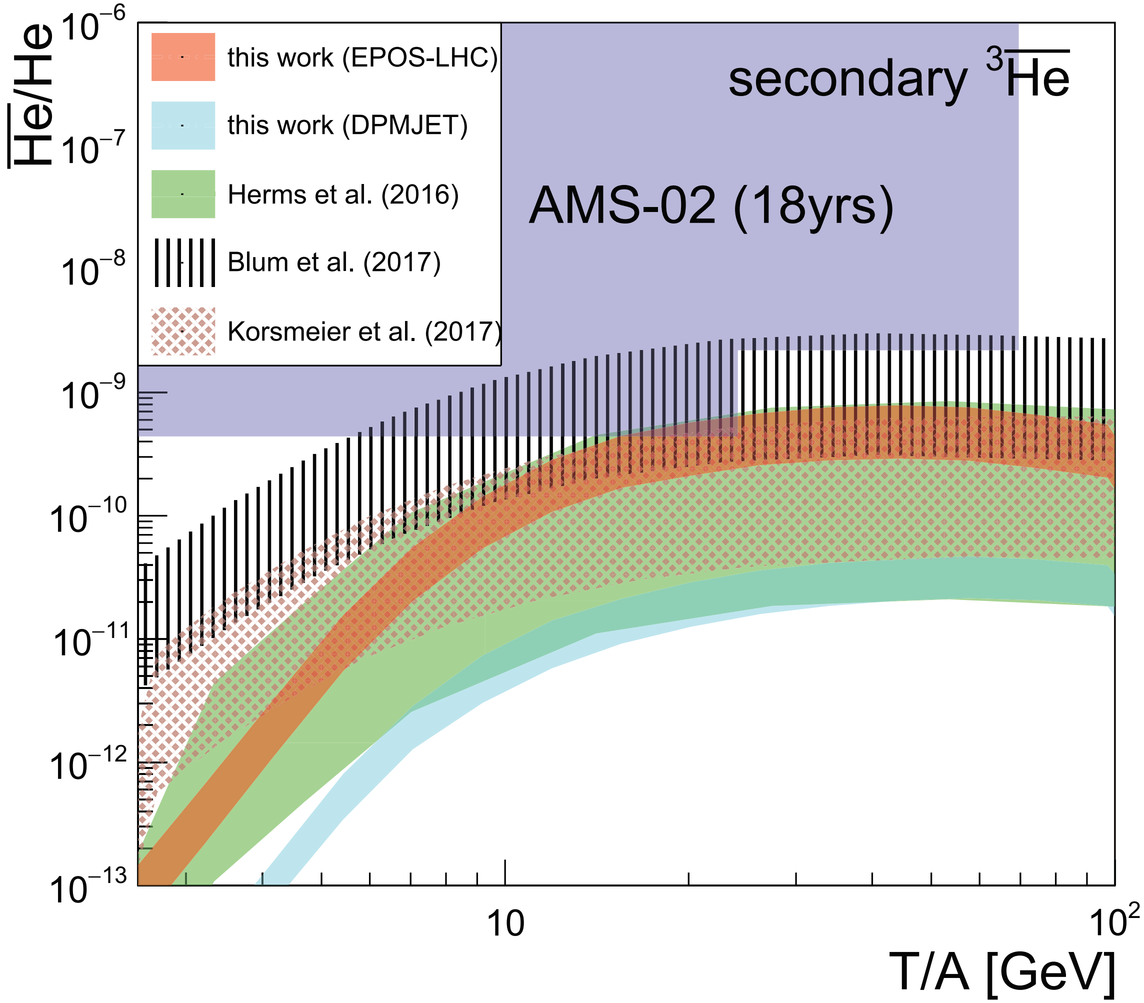


Expected anti-helium events (after 18 yrs of data collecting)

	m_χ (GeV)	$\chi\chi \to q\bar{q}$	$\chi\chi \to b\bar{b}$	$\chi\chi \to W^+W^-$
DM	30	$0.084^{+0.038}_{-0.040}$ $(0.153^{+0.070}_{-0.073})$	$0.041^{+0.020}_{-0.018}$ $(0.073^{+0.036}_{-0.032})$	—
	100	$0.153^{+0.065}_{-0.072}$ $(0.269^{+0.114}_{-0.127})$	$0.227^{+0.107}_{-0.103}$ $(0.419^{+0.198}_{-0.190})$	$0.164^{+0.077}_{-0.076}$ $(0.304^{+0.143}_{-0.141})$
	300	$0.122^{+0.055}_{-0.056}$ $(0.179^{+0.081}_{-0.082})$	$0.160^{+0.074}_{-0.074}$ $(0.256^{+0.118}_{-0.118})$	$0.054^{+0.025}_{-0.025}$ $(0.084^{+0.039}_{-0.039})$
	1000	$0.106^{+0.048}_{-0.048}$ $(0.138^{+0.063}_{-0.063})$	$0.131^{+0.058}_{-0.061}$ $(0.179^{+0.079}_{-0.083})$	$0.015^{+0.007}_{-0.007}$ $(0.019^{+0.009}_{-0.009})$
Secondary		$0.986^{+0.437}_{-0.455}$ $(0.054^{+0.021}_{-0.021})$		

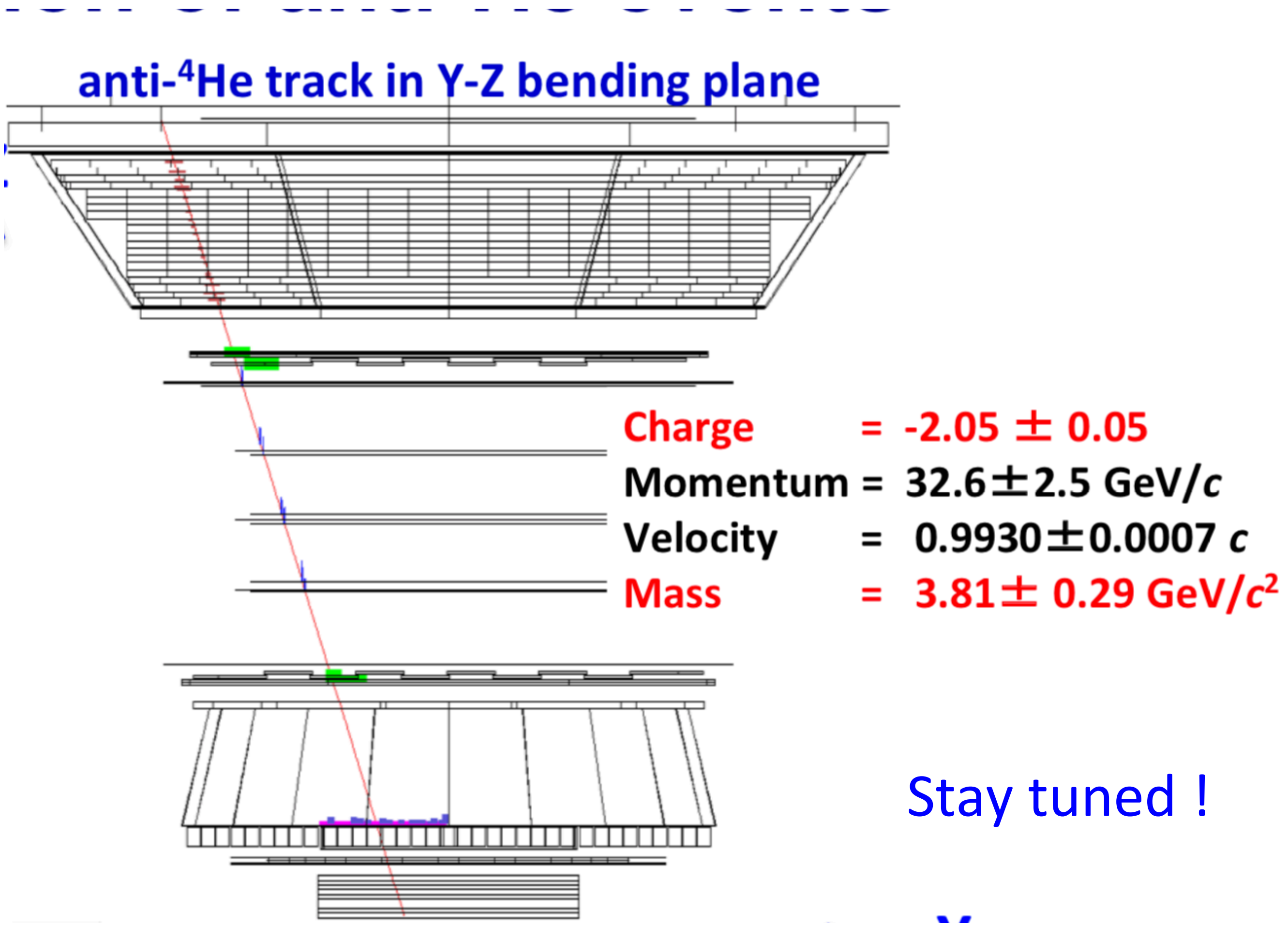
The expected anti-helium events is O(1), dominated by backgrounds NOT DM annihilation

Comparison with previous analysis



preliminary anti-Helium candidate events at AMS-02

AMS-02 so far find 8 anti-helium candidate events with 2 coincide with anti-helium-4



Stay tuned !

Thank you for your attention !