Cosmic-ray antiprotons and dark matter

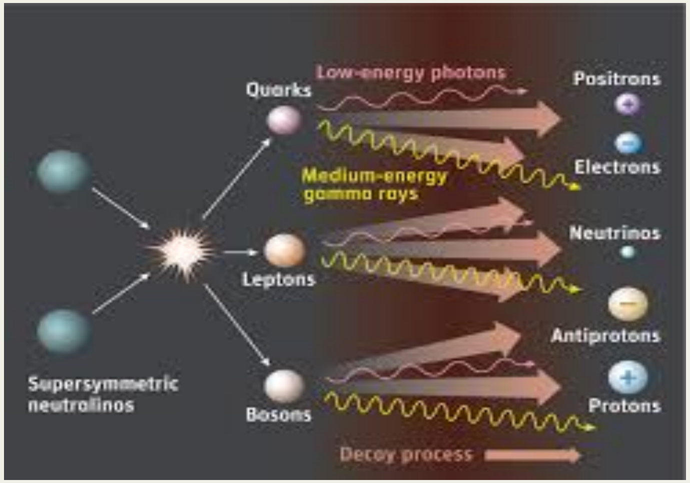
Yu-Feng Zhou

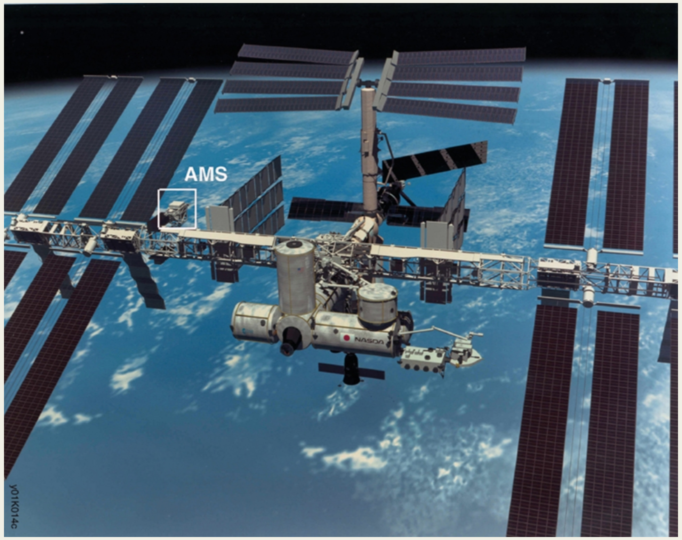
Institute of Theoretical Physics,
Chinese Academy of Sciences

X.J.Huang, Y.L.Wu, YFZ, Phys.Rev.D95 (2017), 06301, [arXiv:1611.01983]
H.B.Jin, Y.L.Wu, YFZ, Phys.Rev. D92 (2015) 5, 055027 [arXiv:1504.04601]
H.B.Jin, Y.L.Wu, YFZ, JCAP 1509 (2015) 09, 049 [arXiv:1410.0171]

2017.07.13, DSU2017, KAIST, Daejeon

Overview: DM indirect searches





Advantages

- Can probe DM annihilation/decay, important to understand the origin of DM.
- 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 can be measured

Challenges

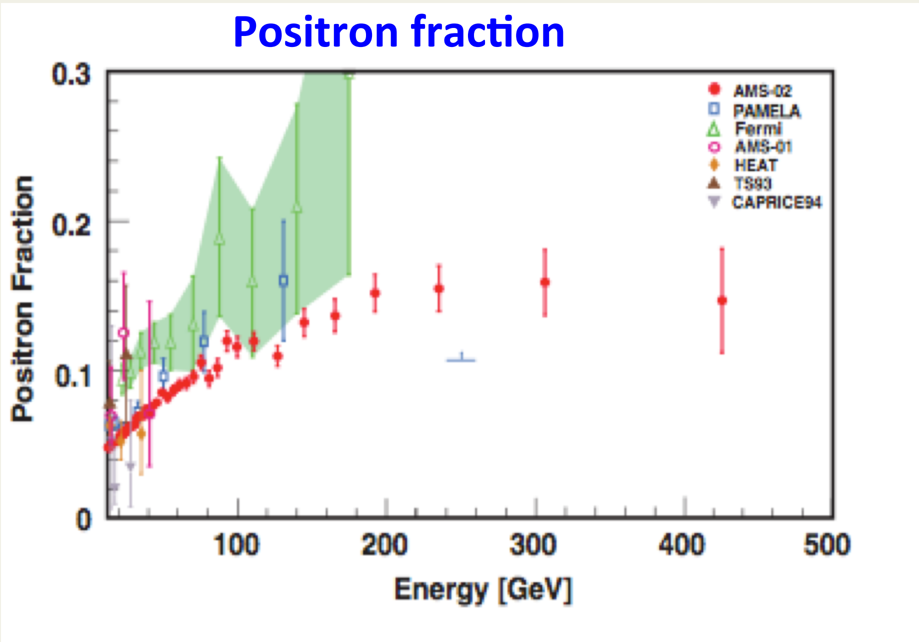
- "backgrounds" not well understood, difficult to distinguish "signal" and "background"
- Information loss after propagation (for charged CRs)

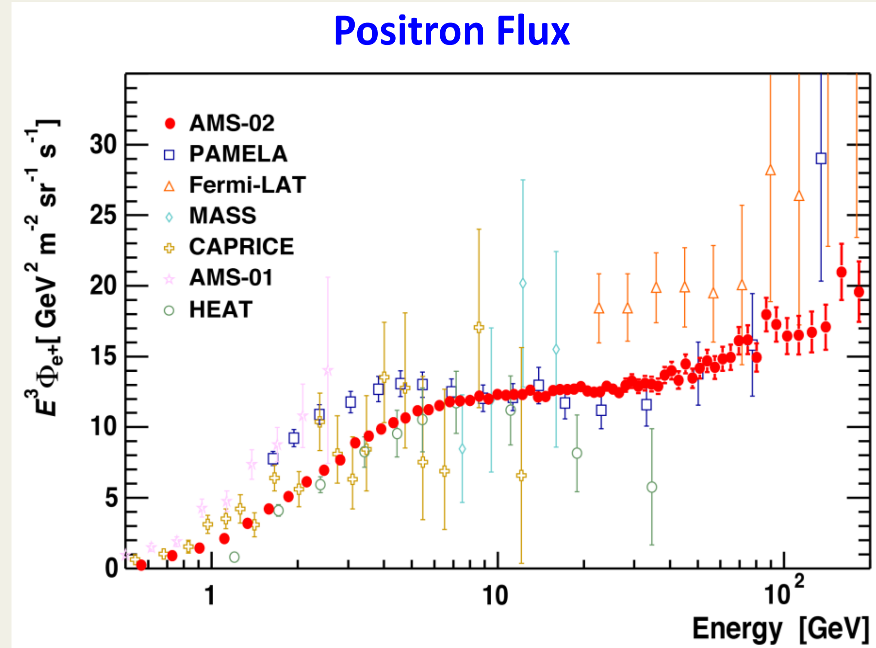
  - spectrum change du to E-dependent propagation, convection, re-acceleration, E-loss

  - anisotropic source -->almost isotropic signals
- Significant uncertainties in theoretical predictions

  e.g. model of CR propagation, distribution of ISM, interaction cross sections, Solar modulation

CR positron anomaly



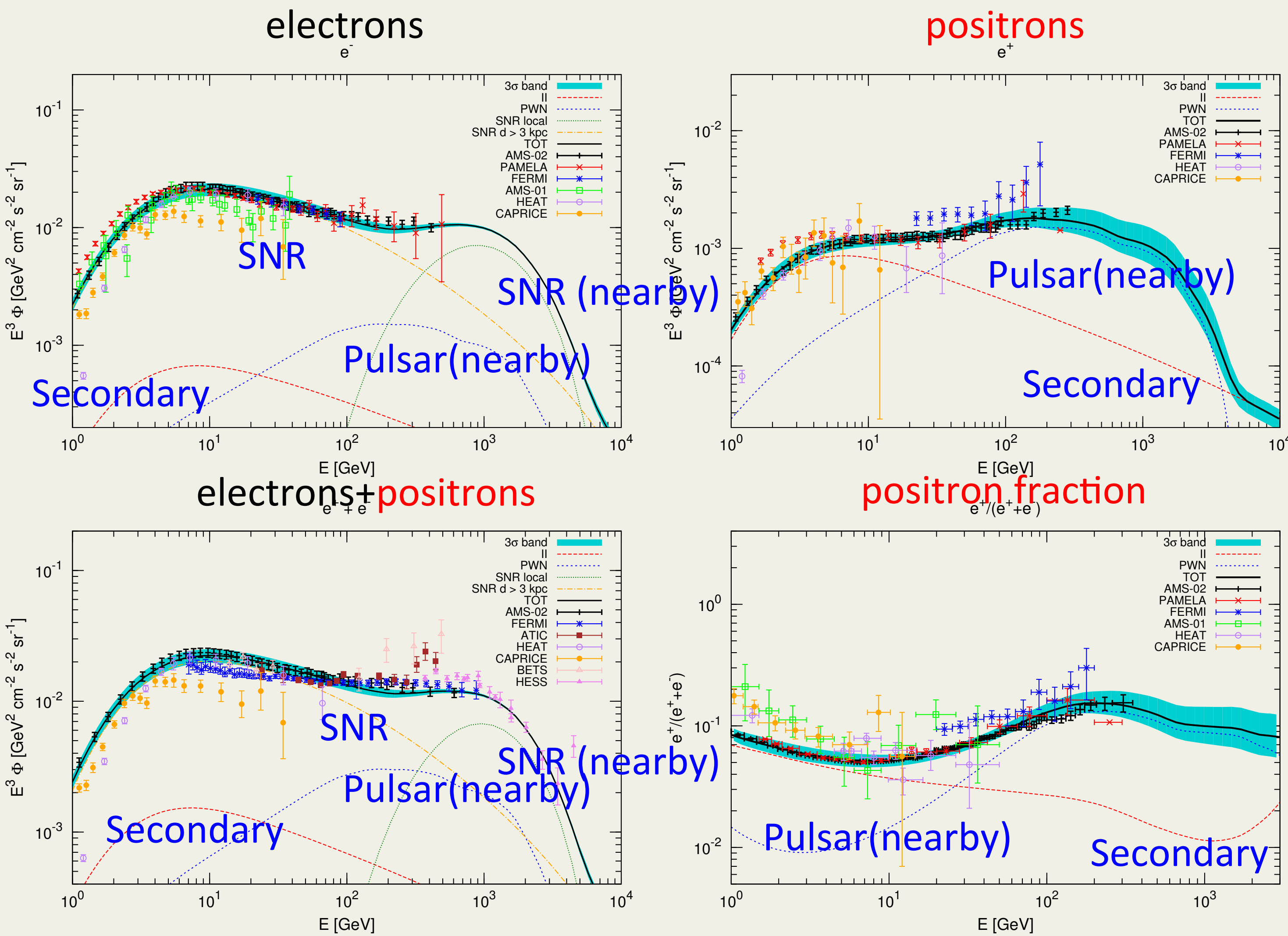


AMS-02 Phys.Rev.Lett. 113 (2014) 121102

A rise in positron fraction (flux) is well-established (PAMELA, Fermi-LAT, AMS-02)

- Viable explanations: PWN, SNR, DM and unconventional secondary sources
- Models with modified propagation constrained by AMS-02 B/C data
- Upper limits on dipole anisotropies not stringent enough to distinguish DM and astrophysical (PWNe, SNRs) sources
- Ferm-LAT gamma-ray data (also Planck) strongly disfavor DM annihilation with or w/o Sommerfeld Enhancement

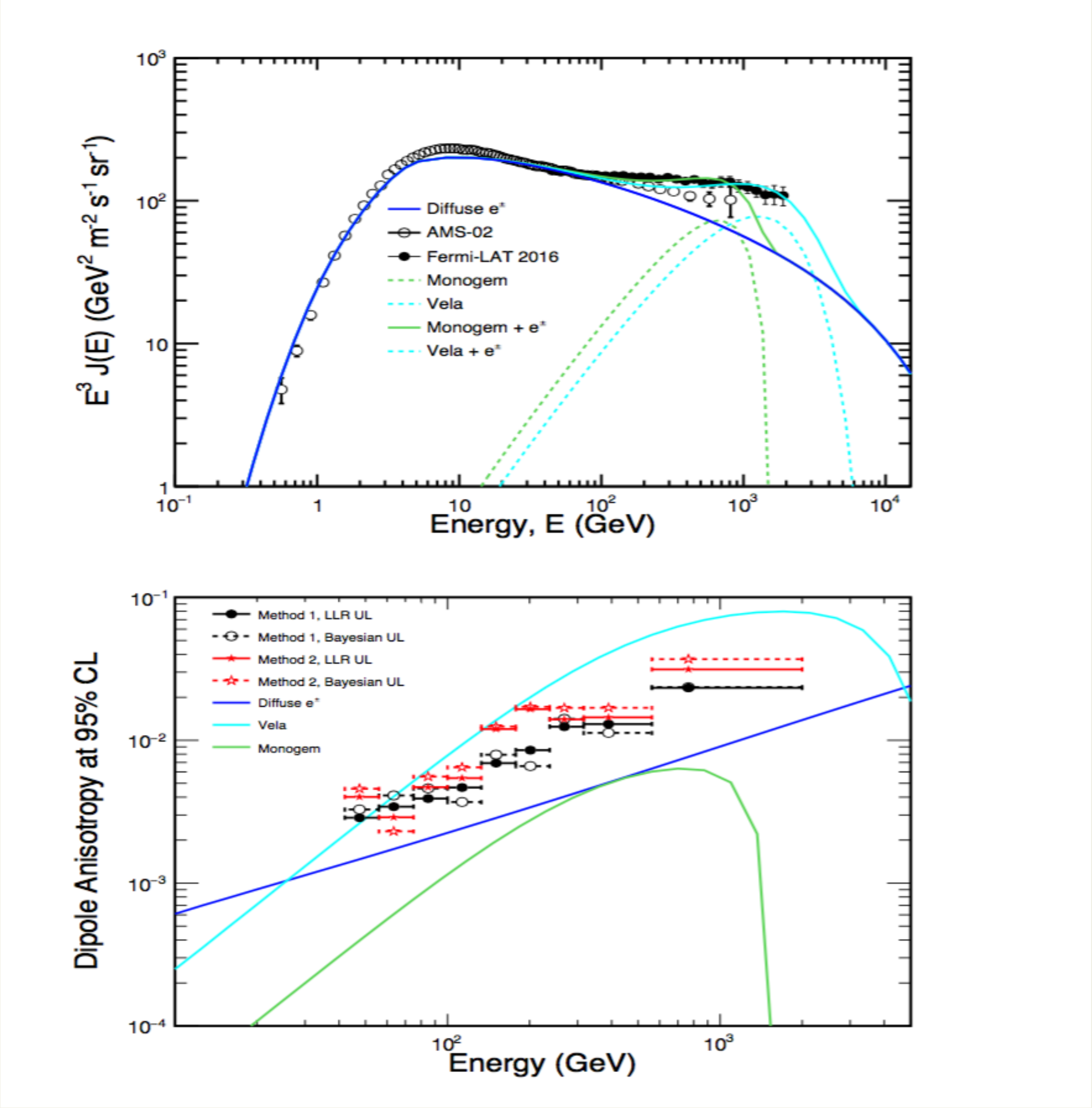
Multiple astrophysical sources can account for both positron and electron spectra



Nearby source can generate significant anisotropy

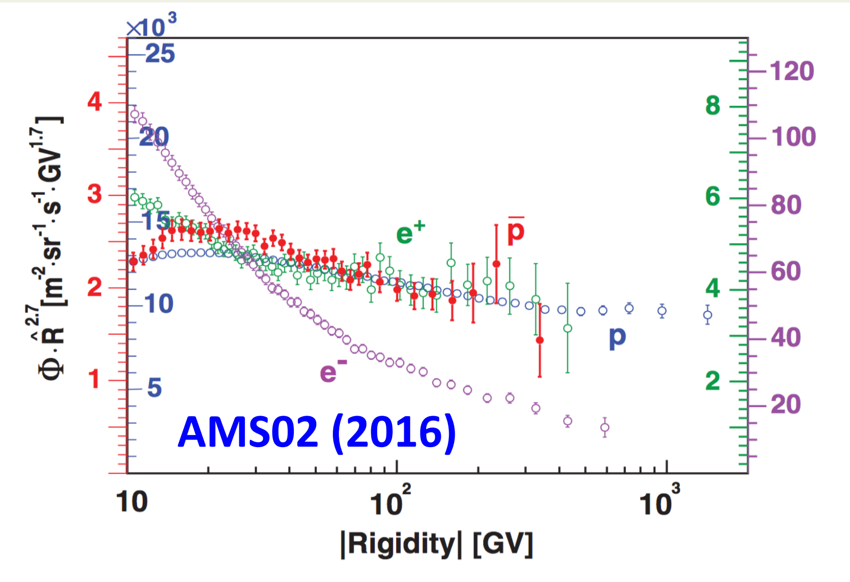
Mauro etal, 1402.0321

Ferm-LAT limits on anisotropy



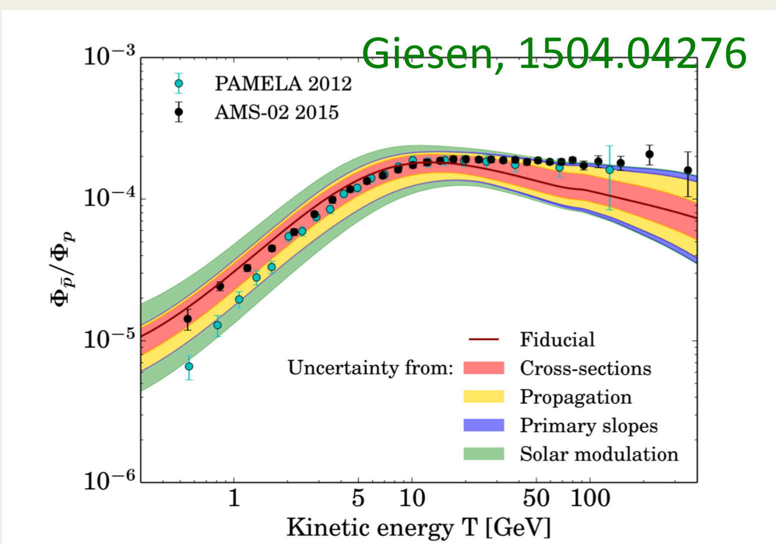
Fermi-LAT,1703.01073

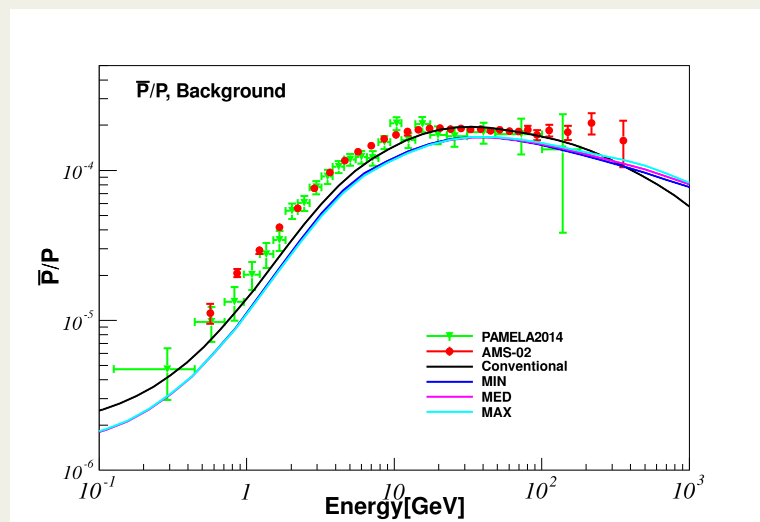
High-energy antiprotons



CR antiprotons

- AMS-02 data roughly consistent with background
- PWNe unlikely to contribute
- SNRs still possible source
- Cooling is less important , compared with CR electrons.
- More sensitive to propagation parameters and DM profile





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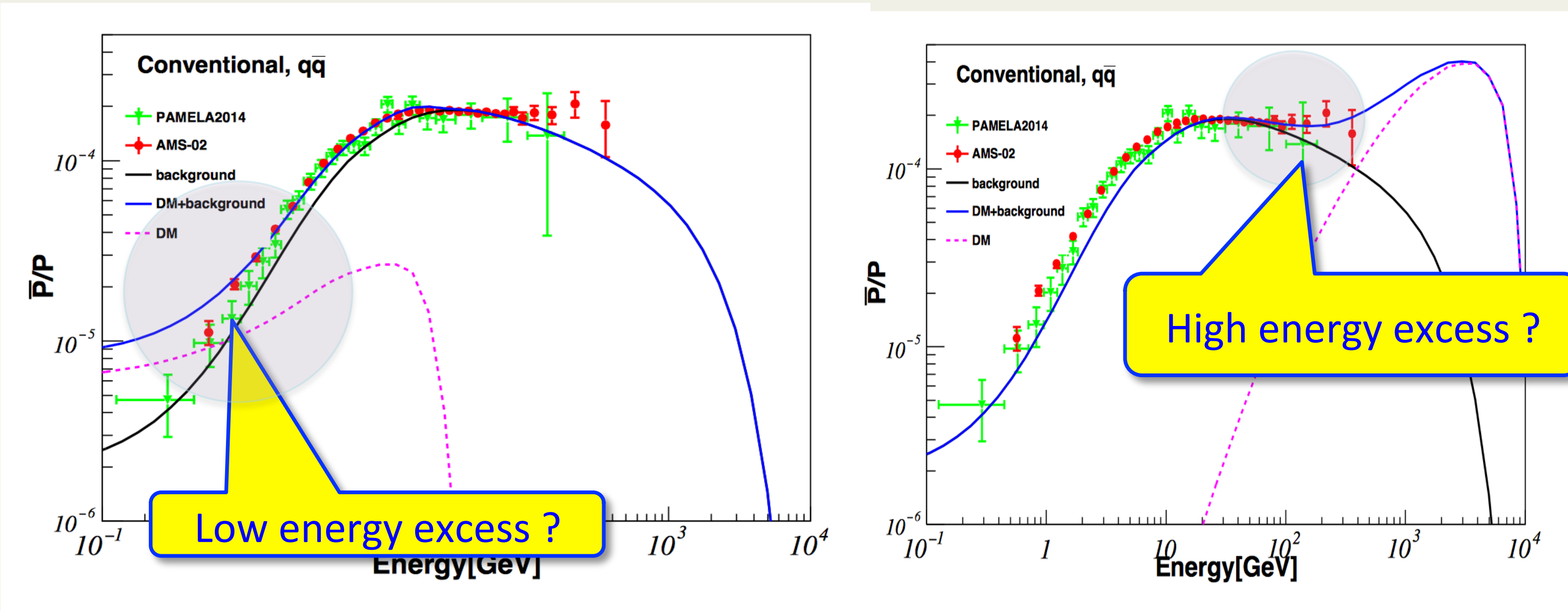
Possible excess and DM interpretation



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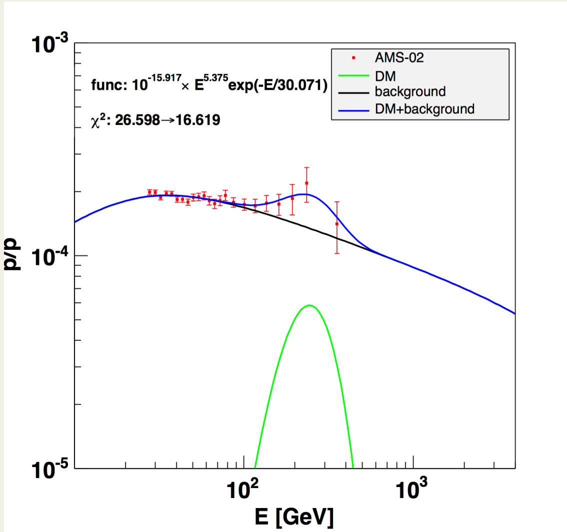
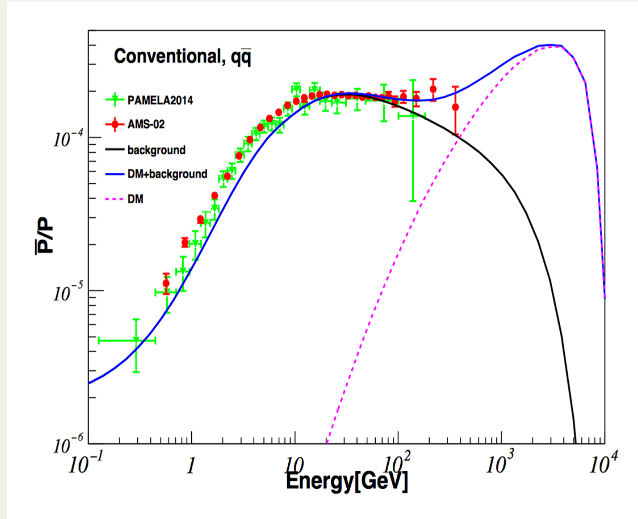
Low energy excess: 40-50 GeV DM to 2b, thermal cross section, consistent with GC γ excess
High energy excess: 10 TeV DM annihilation into 2W, 2b, boost factor ~10-100

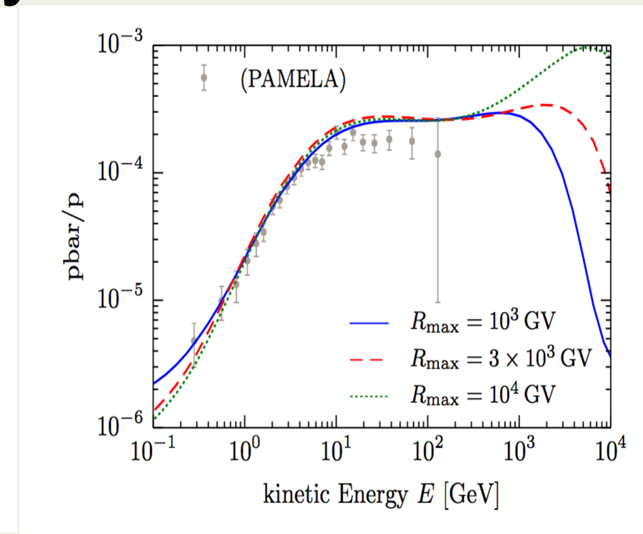
Giesen, 1504.04276; Ibe 1504.05554;
Hamaguchi, 1404.05937; Lin, 1504.07230
Chen, 1504.07848; Chen,1505.00134

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

The possible high-energy excess







Power law with cut off

DM →2q

SNR

Implications

1. The spectral feature can be well-fitted with a power law spectrum with a cut off, typical significance ~3 sigma.
2. DM direct annihilation (DMDM→f fbar→pbar +X) predicts a broad bump, too smooth to explain the excess in a narrow energy range.
3. SNRs can produce secondary antiprotons but with a flat (or smooth rising) spectrum.

For DM interpretation, propagation is one of the major source of uncertainty

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, reaccelaration, E-loss, 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

Determine the propagation models

Observables

1) Secondary/Primary

- B/C and sub-Fe(Sc+V+Ti)/Fe

  sensitive to combination D_0/Z_h

2) Radioactive species (cosmic clock)

- $^{10}Be/^{9}Be$, $^{36}Cl/Cl$, $^{26}Al/^{27}Al$

  sensitive to diffusive halo size

3) Stable primaries

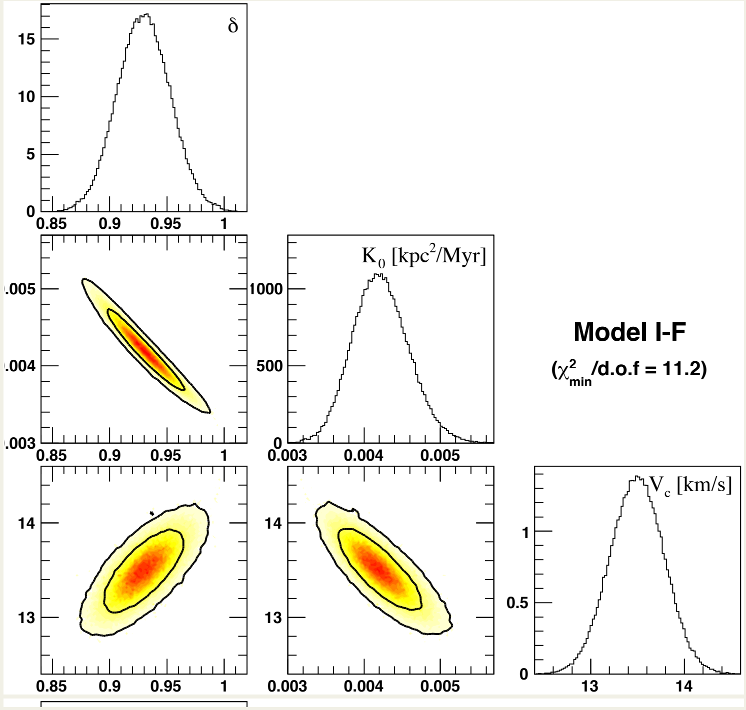
- Proton and electron fluxes

  sensitive to primary sources

Trotta, etal, arXiv:1011.0037

Degeneracies between parameters

1. D_0 / Z_h, most relevant for DM
2. $\delta + \gamma_{p2} = 2.7$
3. V_a scales as $(D_0)^{1/2}$



Maurin, etal, astro-ph/0212111

Constraining the propagation model using AMS-02 data

Standard approach: B/C+ $^{10}Be/^{9}Be$

pros: B/C source independent, only constrain D_0/Z_h,

^{10}Be: τ_{Be10} =1.4 Myr, sensitive to D_0 only, break the D_0/Z_h degeneracy

corns: lower precision $^{10}Be/^{9}Be$ data (from ACE, ISOMAX)

data come from different exps., different solar activity periods,

Alternative approach: B/C + Proton

- B/C + Proton forms a complete set for determining all the propagation parameters.
- Both have been measured by AMS-02
  - Very precisely measured
  - Avoiding combination of syst. errors in different experiments
  - All data from the same period, easy to model solar modulation effects

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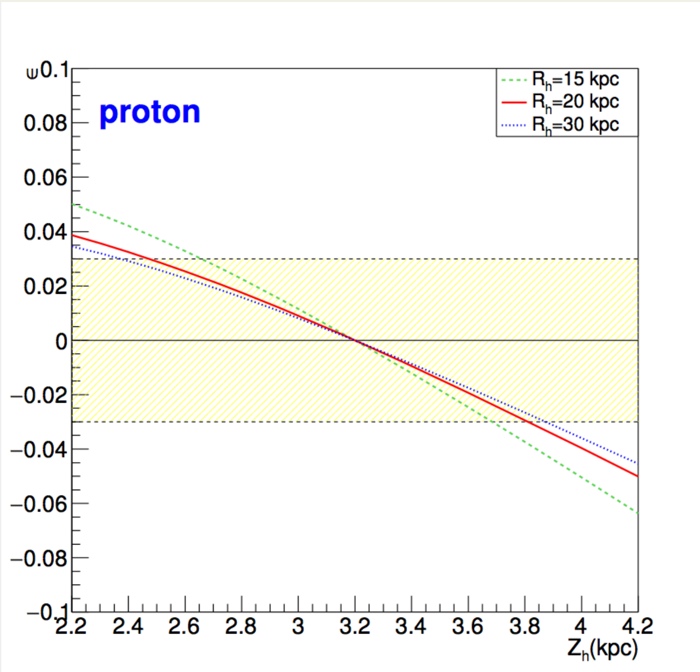
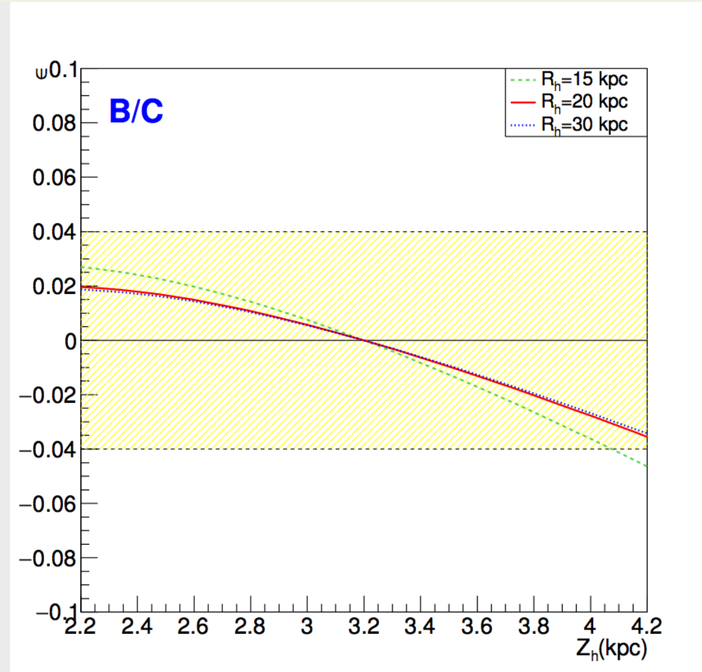
Proton flux breaks the D_0/Z_h degeneracy in 2D diffusion model

Relative change with Z_h for fixed D_0/Z_h





Analytic solution in 2D two-zone model

$$\psi_i(0) = \frac{2hq_i}{V_c + 2h/\tau_f + D_{xx}S_i\coth(S_iZ_h/2)},$$

$$S_i^2 = \frac{V_c^2}{D_{xx}^2} + \frac{4}{D_{xx}\tau_r} + \frac{4\zeta_i^2}{R_h^2}.$$

Breaking term

$$D_{xx}S_i\coth(S_iZ_h/2) \approx \left(\frac{D_{xx}}{Z_h}\right)\left(2 + \frac{V_c^2Z_h^2}{6D_{xx}^2} + \frac{2Z_h^2}{3D_{xx}\tau_r} + \boxed{\frac{2Z_h^2}{3R_h^2}\zeta_i^2}\right).$$

D0/Zh degeneracy is broken in stable CR fluxes

- For proton ~5%, data err ~3%
- For B/C ~2%, data error ~4%

Thus

- B/C determines D0/Zh
- Proton flux determines Zh

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Results

(using data from AMS02, ICRC2013)

Trotta, 1011.0037
Fit B/C+$^{10}Be/^{9}Be$

Quantity	Prior range	Best-fit value	Posterior mean and Standard deviation	Posterior 95% range	Ref. [23]
Z_h(kpc)	[1, 11]	3.2	3.3±0.6	[2.1, 4.6]	5.4±1.4
D_0/Z_h	[1, 3]	2.02	2.00±0.07	[1.82, 2.18]	(1.54±0.48)
δ	[0.1, 0.6]	0.29	0.29±0.01	[0.27, 0.32]	0.31±0.02
$V_a(\mathrm{km} \cdot \mathrm{s}^{-1})$	[20, 70]	44.7	44.6±1.2	[41.3, 47.5]	38.4±2.1
γ_{p1}	[1.5, 2.1]	1.79	1.78±0.01	[1.75, 1.81]	1.92±0.04
γ_{p2}	[2.2,2.6]	2.46	2.45±0.01	[2.43,2.47]	2.38±0.04

D_0/Z_h is precisely determined (err <5%)

$$\frac{D_0}{Z_h} = (2.00 \pm 0.07)\ \mathrm{cm^2 s^{-1} kpc^{-1}}.$$

A lower Z_h favored

$$Z_h = 3.3 \pm 0.6\mathrm{kpc}$$

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Correlations between parameters

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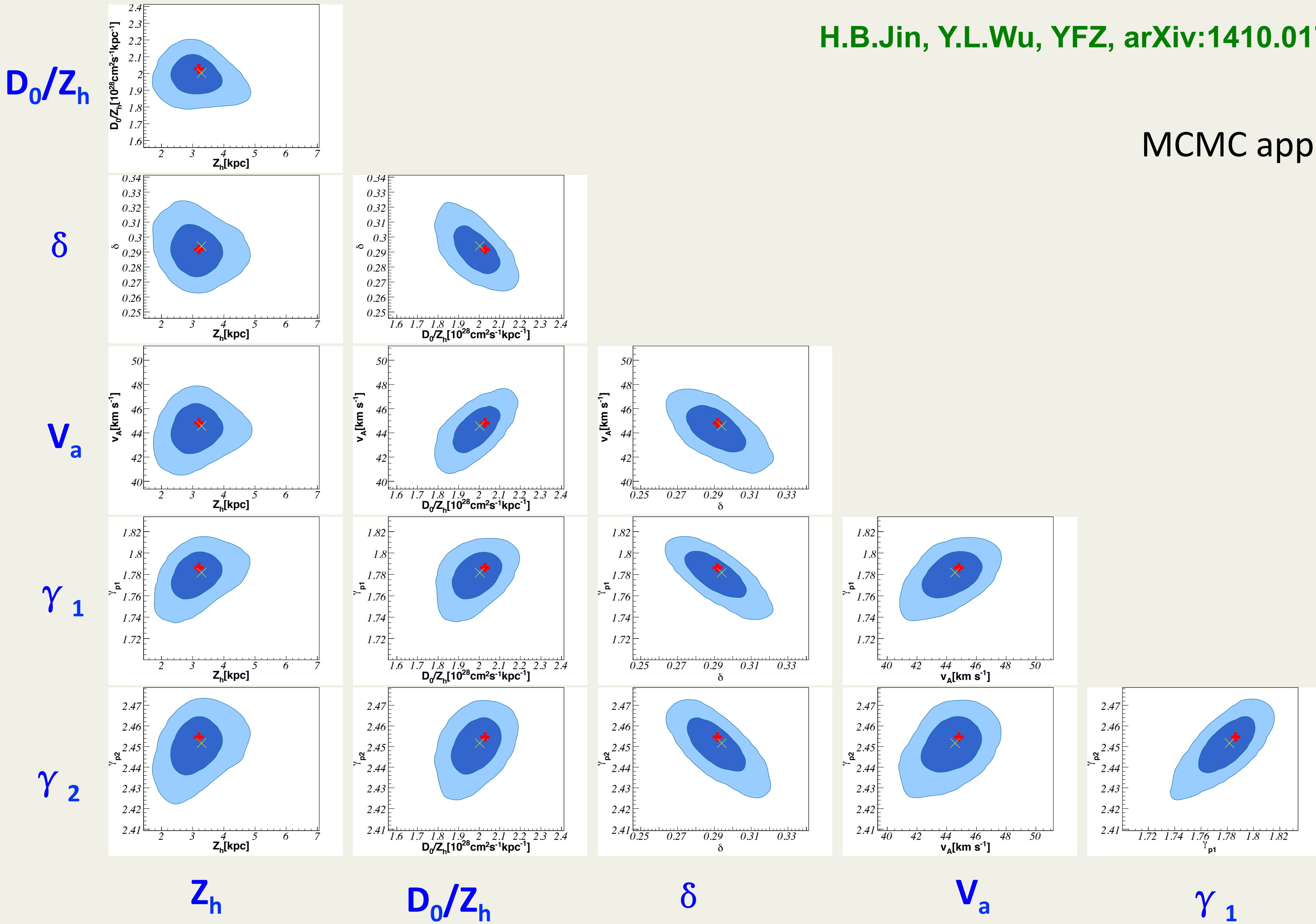
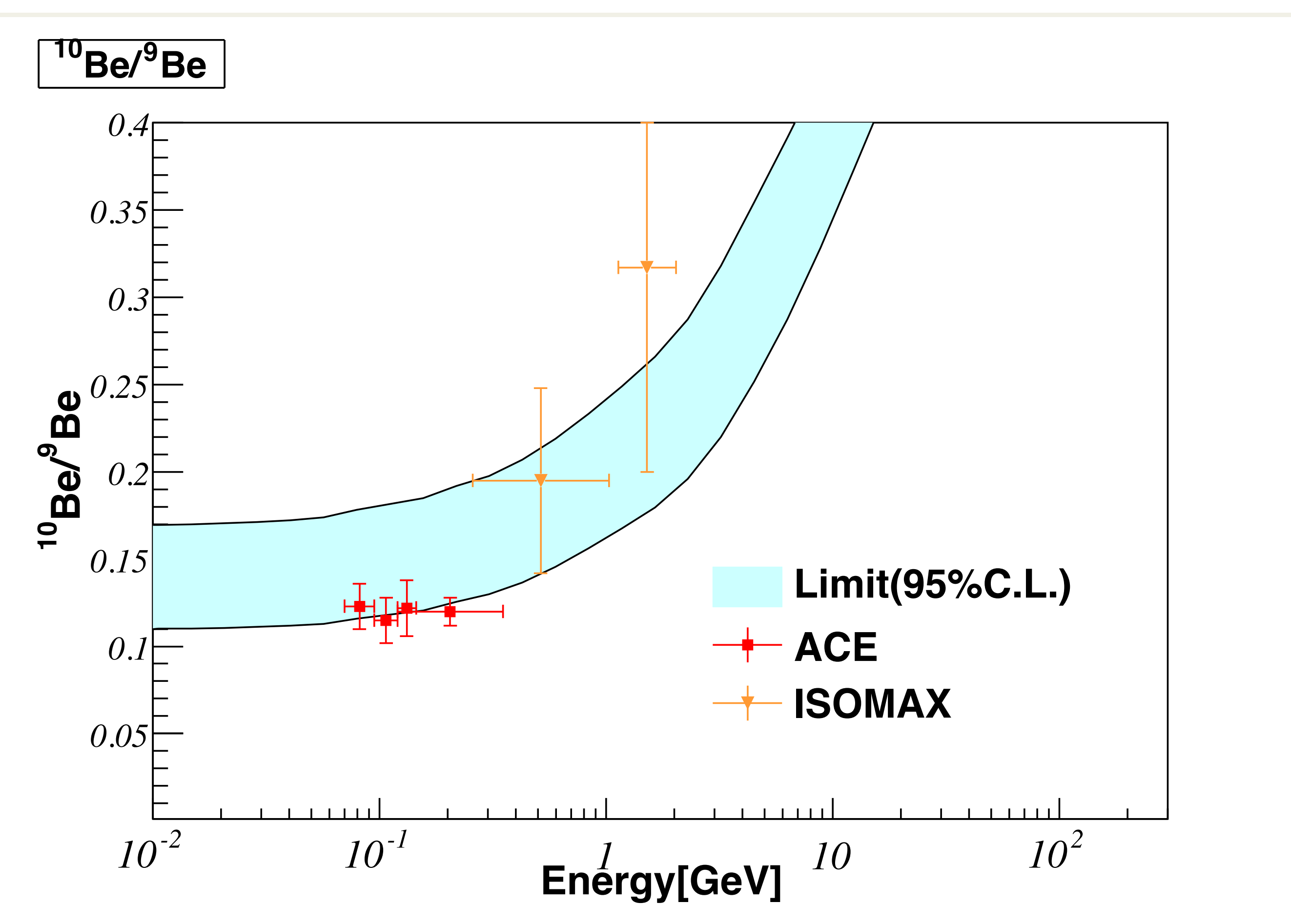
MCMC approach



Prediction for $^{10}Be/^{9}Be$ consistent with data



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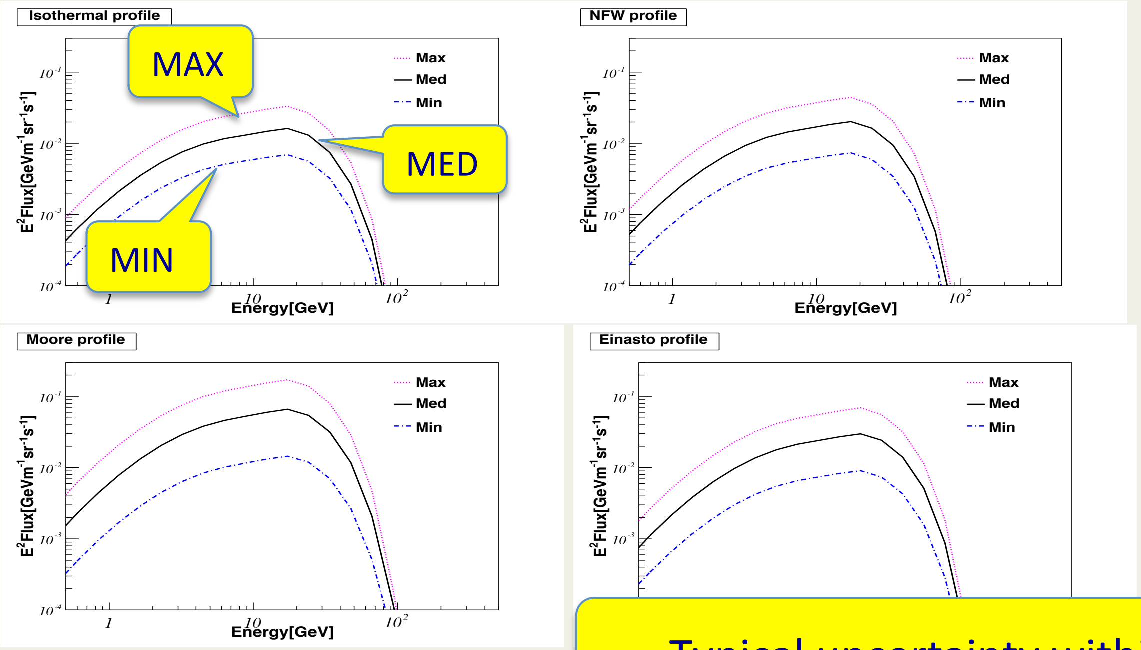
The "MIN", "MED", "MAX" models in Galprop framework



Typical uncertainty within a factor of five

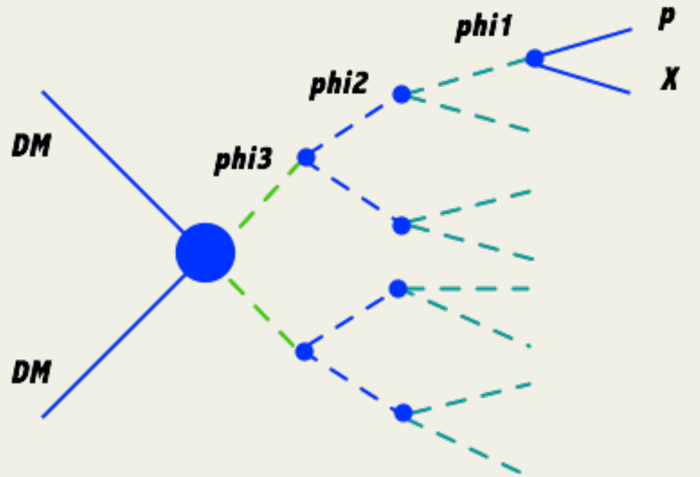
model	R(kpc)	Z_h(kpc)	D_0	ρ_0	δ_1/δ_2	V_a(km/s)	ρ_s	γ_{p1}/γ_{p2}
Conventional	20	4.0	5.75	4.0	0.34/0.34	36.0	9.0	1.82/2.36
MIN	20	1.8	3.53	4.0	0.3/0.3	42.7	10.0	1.75/2.44
MED	20	3.2	6.50	4.0	0.29/0.29	44.8	10.0	1.79/2.45
MAX	20	6.0	10.6	4.0	0.29/0.29	43.4	10.0	1.81/2.46

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

Spectral feature of DM annihilation through light mediators

DM cascade annihilation

$$\chi\chi \to 2\phi_n \to 2^2\phi_{n-1}\cdots \to 2^n\phi_1(\phi_1 \to \psi + X)$$



$$x_0 = \frac{2E_0}{m_1}, \qquad \epsilon_0 = \frac{2m_\psi}{m_1},$$

$$x_1 = \frac{2E_1}{m_2}, \qquad \epsilon_1 = \frac{2m_1}{m_2}.$$

Lorentz boost

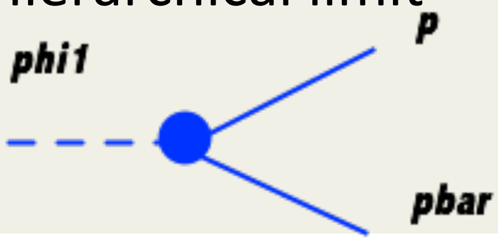
$$\frac{d\tilde{N}_\psi}{dx_1} = \int_{-1}^{1} d\cos\theta \int_{\epsilon_0}^{1} dx_0 \, \frac{d\tilde{N}_\psi}{dx_0}\, \delta\left(2x_1 - x_0 - \cos\theta\sqrt{x_0^2 - \epsilon_0^2}\sqrt{1-\epsilon_1^2}\right),$$

Large hierarchy limit $\varepsilon_0 \ll \varepsilon_1 \ll \varepsilon_2 \ldots$

$$\frac{d\tilde{N}_\psi}{dx_n} = \int_{x_n}^{1} \frac{dx_{n-1}}{x_{n-1}} \frac{d\tilde{N}_\psi}{dx_{n-1}} + \mathcal{O}(\epsilon_i^2),$$

Hierarchical limits

- Hierarchical limit $\varepsilon_0 \ll \varepsilon_1 \ll \varepsilon_2 \ldots$



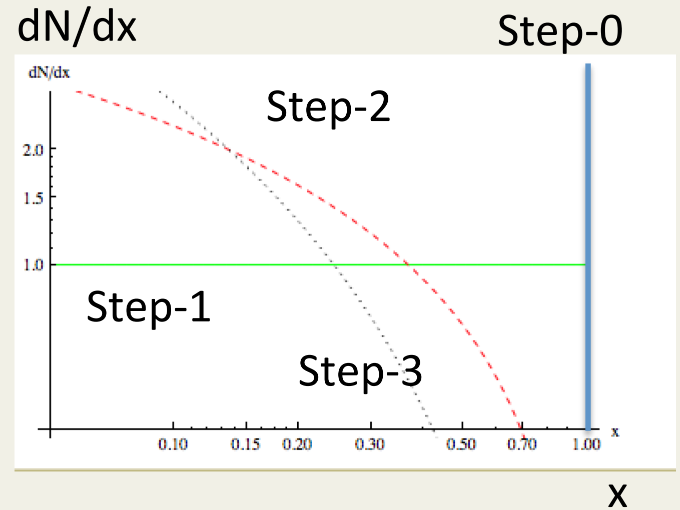
$$\frac{d\tilde{N}_\psi}{dx_1} = \int_{x_1}^{1} \frac{dx_0}{x_0} \frac{d\tilde{N}_\psi}{dx_0} + \mathcal{O}(\epsilon_i^2),$$

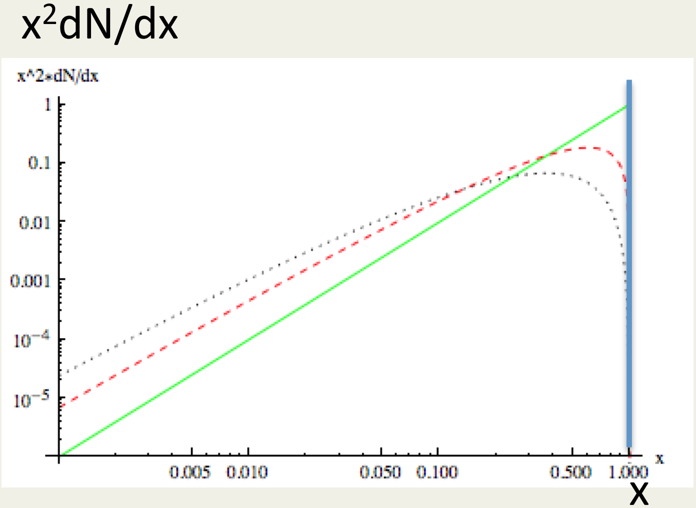
$$\text{Step-0:} \quad \frac{dN}{dx_0} = \delta(1 - x_0)$$

$$\text{Step-1:} \quad \frac{dN}{dx_1} = 1$$

$$\text{Step-2:} \quad \frac{dN}{dx_2} = \ln\frac{1}{x_2}$$

$$\text{Step-n:} \quad \frac{dN}{dx_n} = \frac{1}{(n-1)!}\left(\ln\frac{1}{x_n}\right)^{n-1}$$





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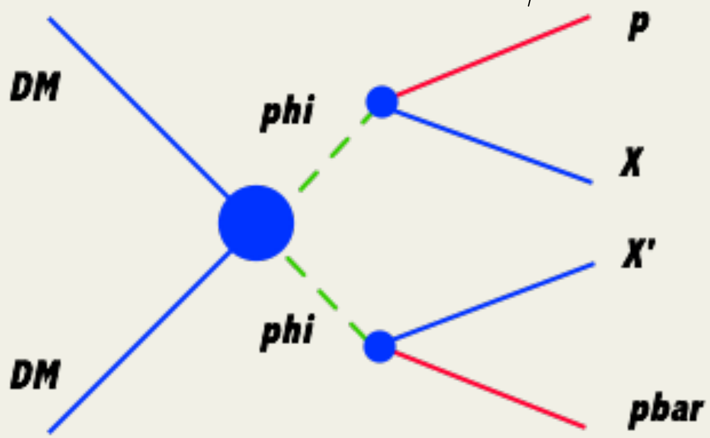
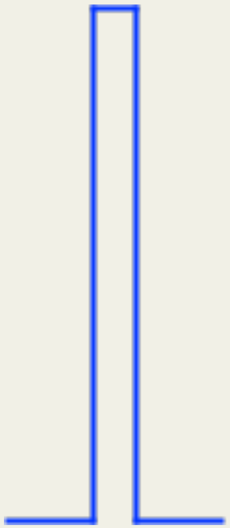
Non-hierarchical case

small β'



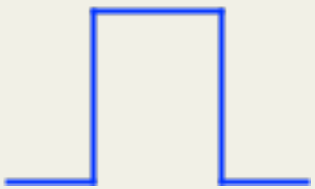


phi rest-frame

Lorentz Boost

$$E = \gamma_B E'$$

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



DM CM frame

When $\phi \approx 2m_p$

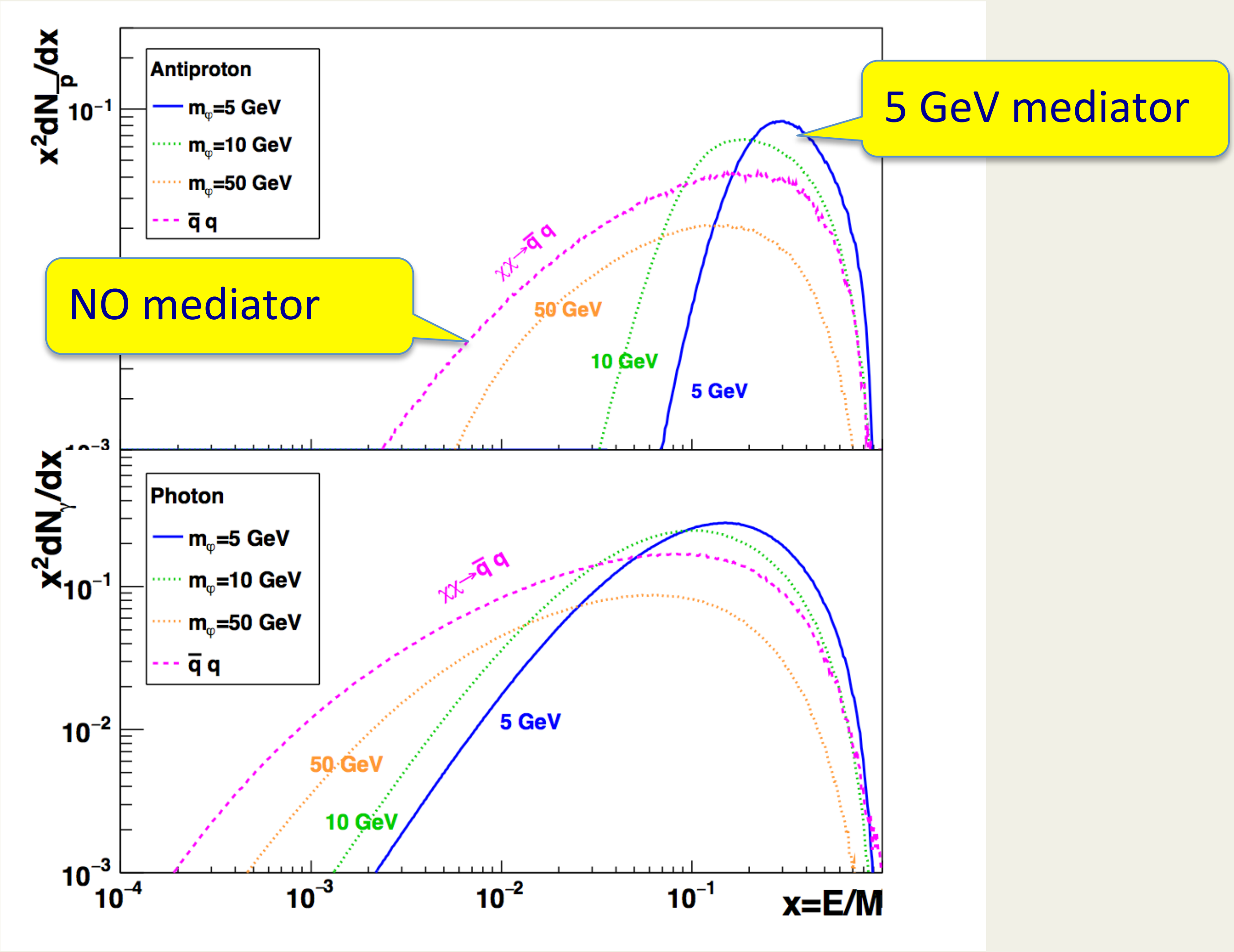
Lorentz boost for finite ϵ_0

$$\frac{dN(x)}{dx} = 2\int_{a(x)}^{b(x)} dx' \frac{1}{\sqrt{1-\varepsilon_1^2}\sqrt{x'^2-\varepsilon_0^2}} \frac{dN(x')}{dx'},$$

$$a(x) = x_- \text{ and } b(x) = \min\{1, x_+\}$$

$$x_\pm = 2(x \pm \sqrt{(1-\varepsilon_1^2)(x^2-\varepsilon_1^2\varepsilon_0^2/4)})/\varepsilon_1^2.$$

Sharp antiproton energy spectra



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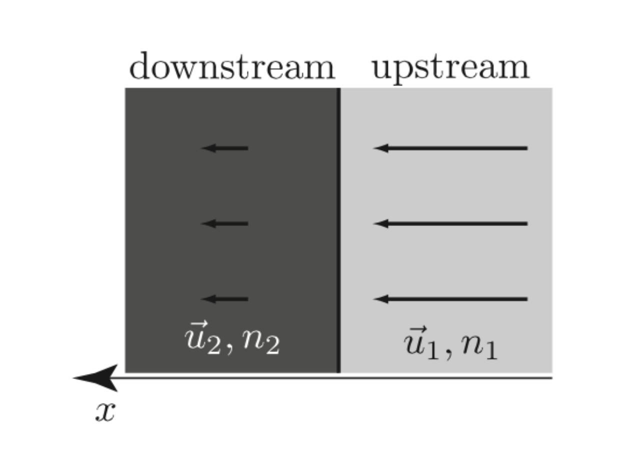
Secondary antiproton from inside SNR

- Antiprotons can be generated from pp inelastic scatterings

$$Q_{\bar{p}}(E) \simeq 2 \int_E^{E_{\max}} \mathrm{d}\mathcal{E} N_{CR}(\mathcal{E}) \sigma_{p\bar{p}}(\mathcal{E}, E) n_{gas}\, c\,,$$

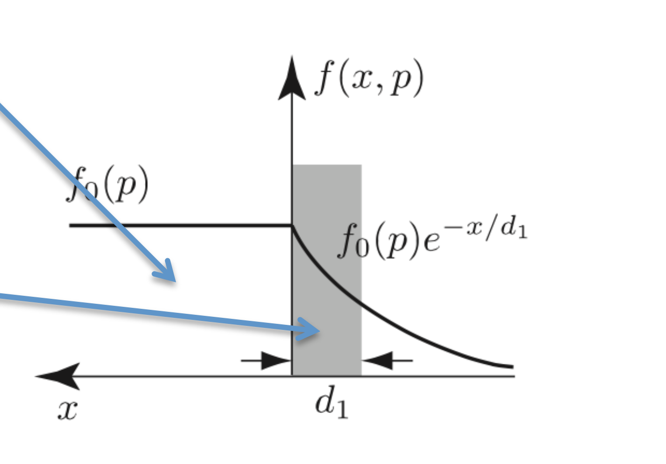


- Antiprotons accelerated by the shock-wave and propagate in the same way as protons

$$\frac{J_{\bar{p},SNRs}(E)}{J_p(E)} \simeq 2\, n_1\, c\, [\mathcal{A}(E) + \mathcal{B}(E)]$$

$$\mathcal{A}(E) = \gamma \left(\frac{1}{\xi} + r^2 \right) \times$$
$$\times \int_m^E \mathrm{d}\omega\, \omega^{\gamma-3} \frac{D_1(\omega)}{u_1^2} \int_\omega^{E_{\max}} \mathrm{d}\mathcal{E}\, \mathcal{E}^{2-\gamma}\, \sigma_{p\bar{p}}(\mathcal{E}, \omega)\,,$$

$$\mathcal{B}(E) = \frac{\tau_{SN}\, r}{2\, E^{2-\gamma}} \int_E^{E_{\max}} \mathrm{d}\mathcal{E}\, \mathcal{E}^{2-\gamma}\, \sigma_{p\bar{p}}(\mathcal{E}, E)\,.$$

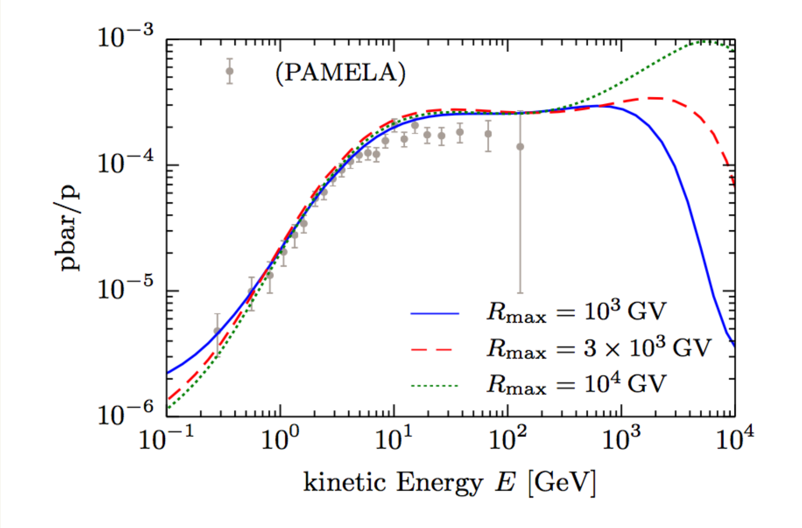


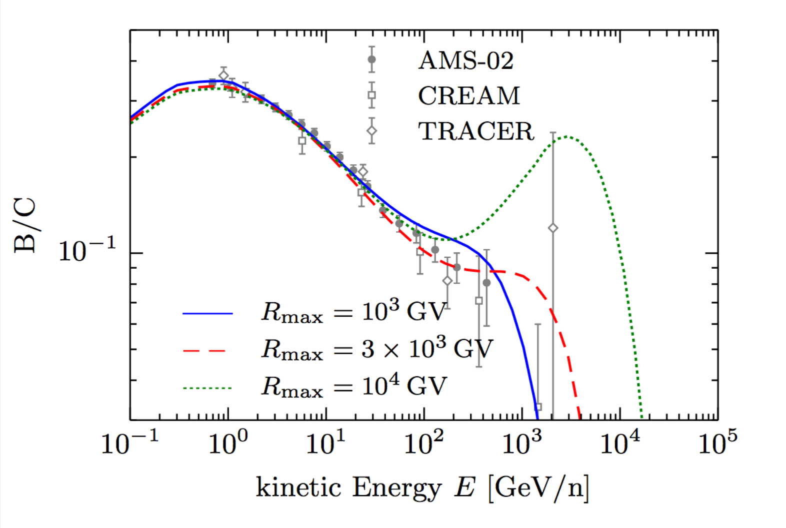
Diffusion coefficient inside SNRs

$$D_1(E) = \left(\frac{\lambda_c\, c}{3\, \mathcal{F}} \right) \left(\frac{E}{e\, B\, \lambda_c} \right)^{2-\beta},$$

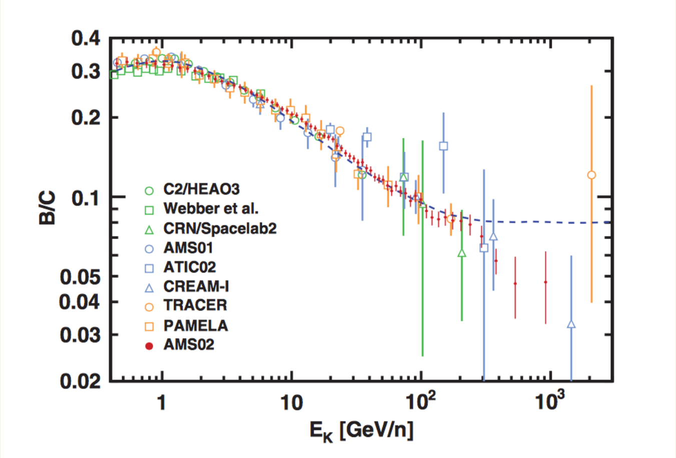
P. Blasi and P. D. Serpico, 0904.0871.
P. Mertsch and S. Sarkar, 0905.3152

Spectral feature of SNR antiproton





SNRs can in principle explain the rising of both the positrons and antiprotons, but also over predicts in B/C



Mertsch, Sarkar, 0905.3152
Mertsch, Sarkar, 1402.0855

Global fits in the three scenarios

	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

A: DM → 2b with 5 GeV mediators, **B:** DM → 2b directly **C:** antiproton from inside of SNR

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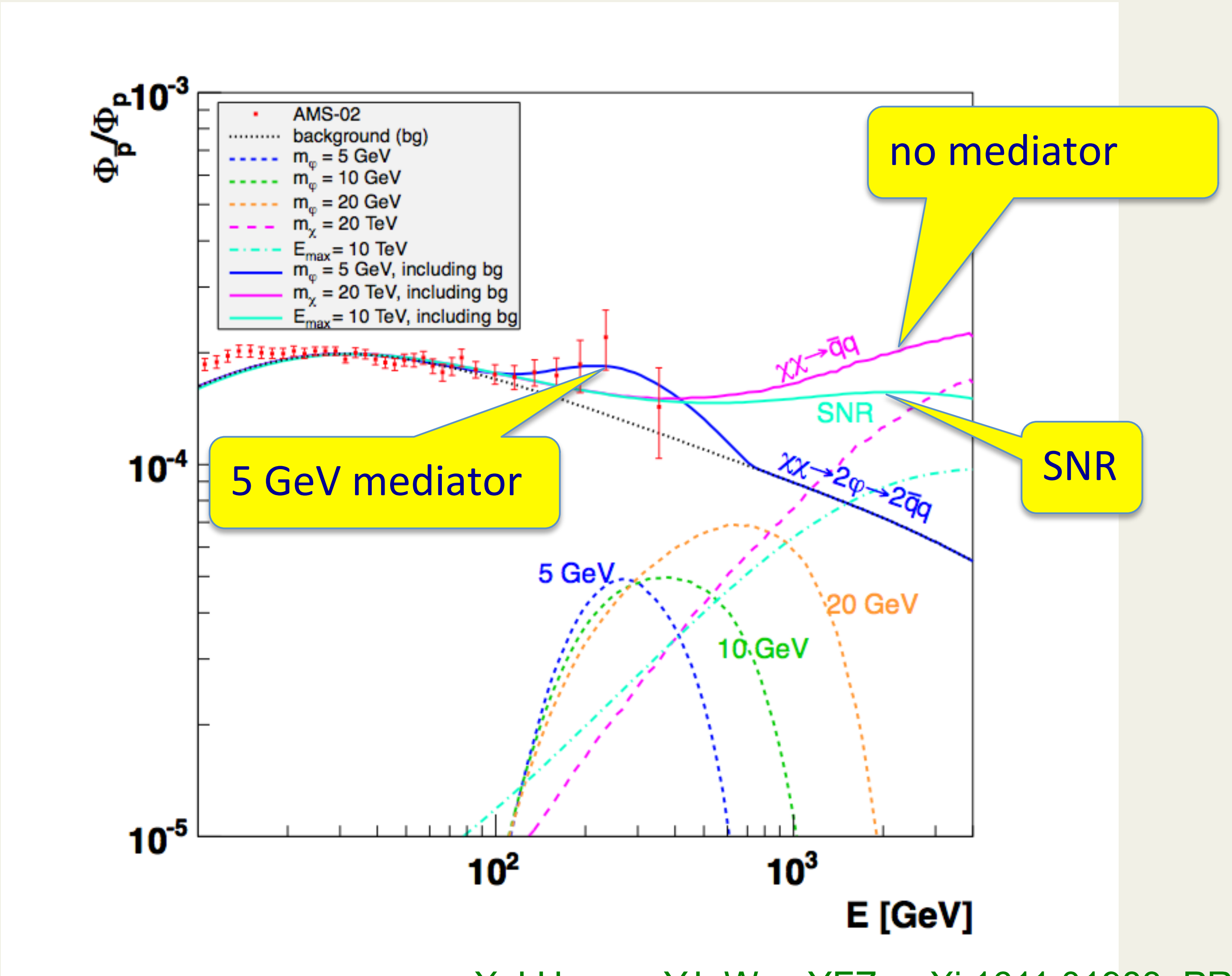
Comparing DM and SNR explanations



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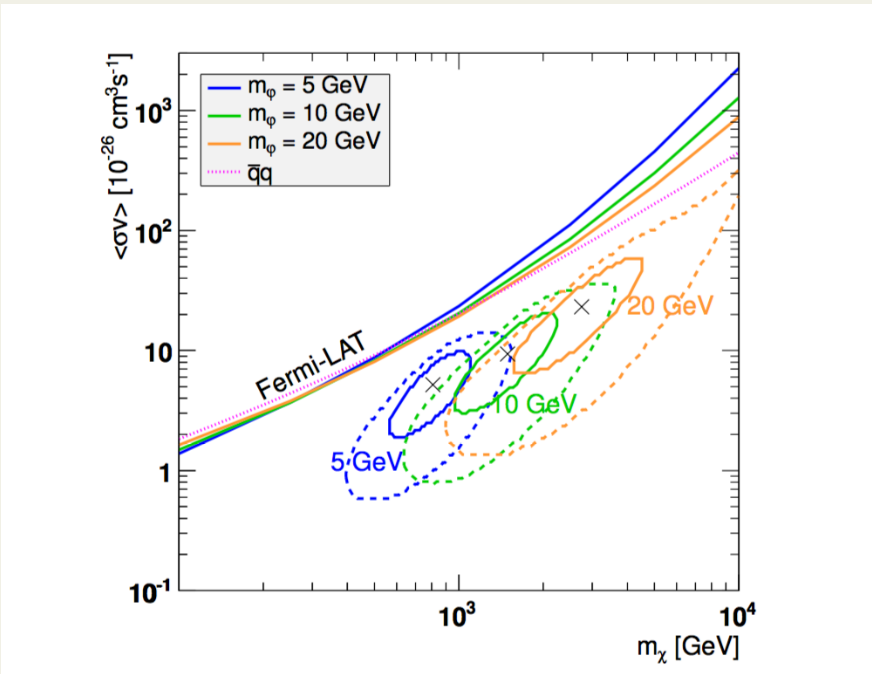
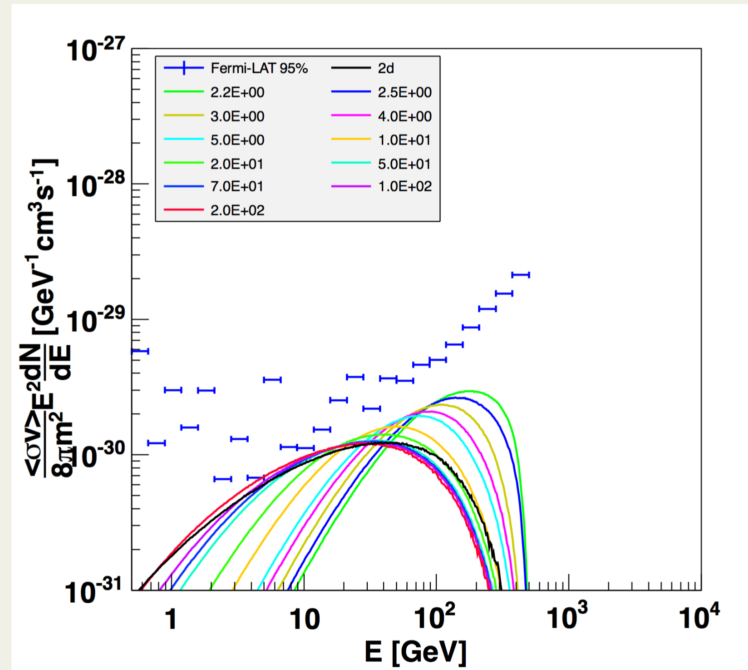
Limits from dwarf galaxies





Fermi-LAT sets limits per energy bin, sensitive to the spectral shape

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Conclusions

- CR antiprotons is a very important probe of new sources participating strong interactions.
- The AMS-02 data show hint of a structure at high energy region (~300 GeV).
- CR antiproton flux are sensitive to propagation models. The cosmic ray propagation models can be determined by the AMS-02 data on B/C and proton flux.
- DM particle annihilation through light mediators (around p-pbar production threshold) can generate a spectral structure consistent with the AMS-02 data.

Thank you!