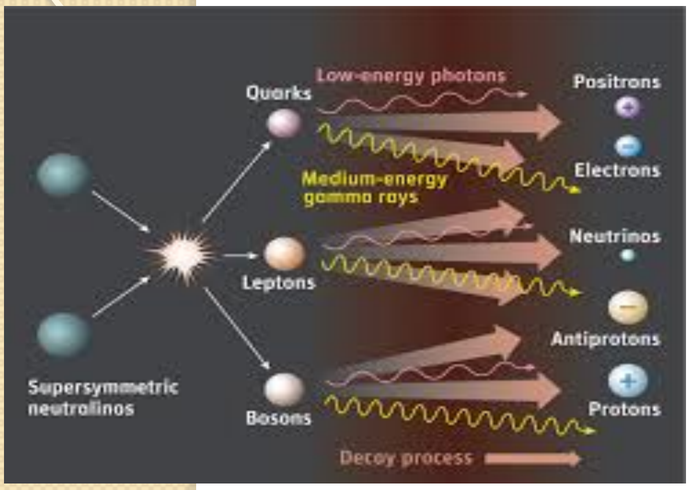
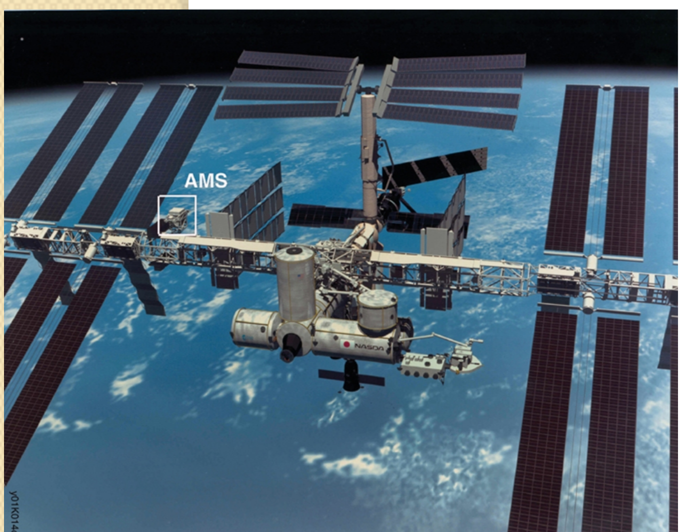
Outline

- Introduction
- DM annihilation through light mediators
  - Hierarchical limit
  - Non-hierarchical case
- A possible excess at 300 GeV in AMS-02 pbar data
  - DM annihilation: direct ann. or with mediators
  - SNR contributions
- Results
  - Fit results and model comparison
  - Constraints from dSphs
- Conclusions

DM indirect searches





Advantages

- can probe DM annihilation/decay, important to understand the origin of DM density.
- tiny signals enhanced by huge volume of the DM halo
- can probe *both* energy spectral and morphology
  - line vs. continuum,
  - peaky vs. featureless power law,
  - extended signal in space vs. point-like source.

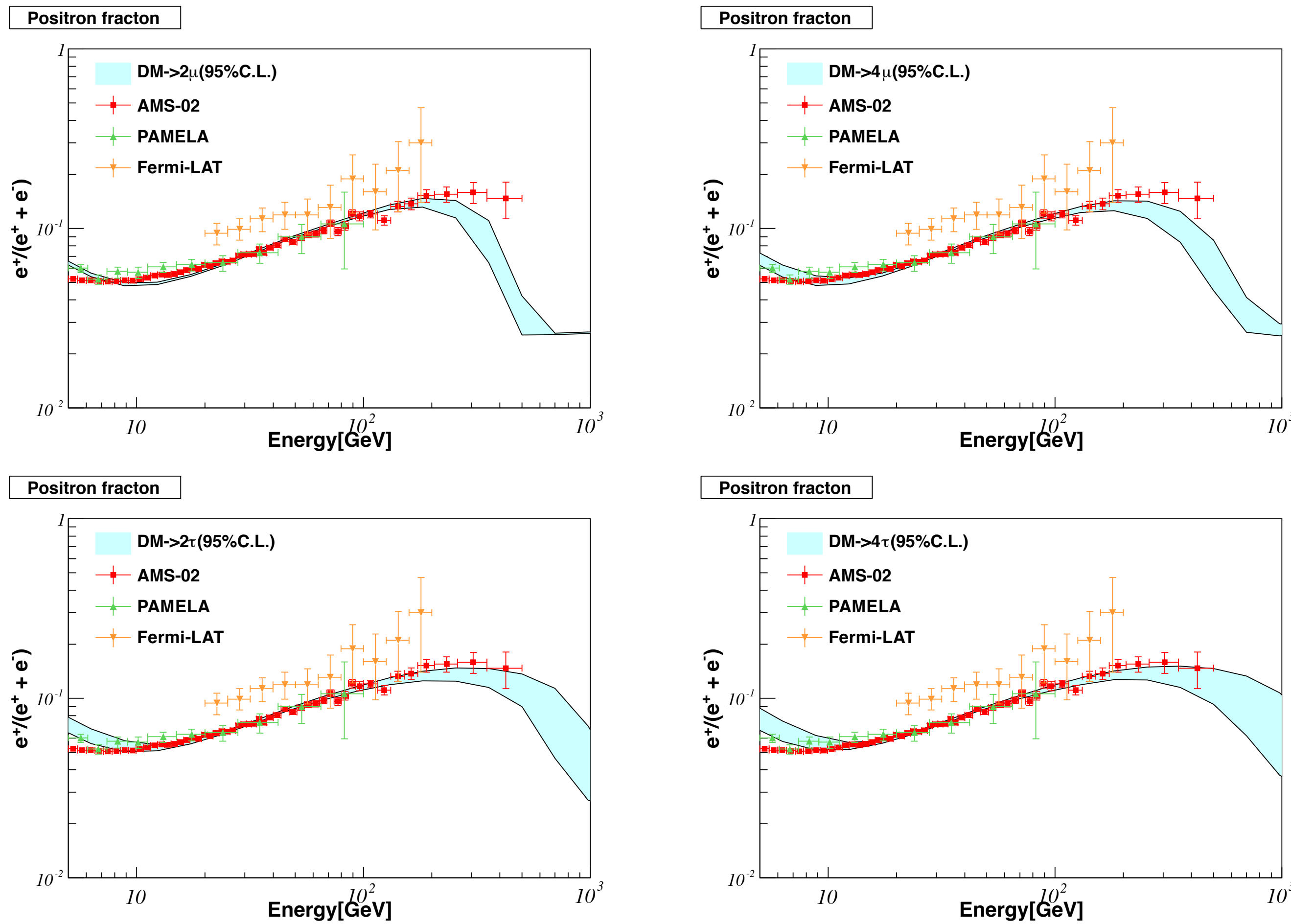
Challenges

- always difficult to distinguish from astrophysical backgrounds ("backgrounds" not well undstood)
- Information loss during propagation
  - spectrum change du to E-dependent propagation, convection, re-acceleration, E-loss
  - anisotropic source -->isotropic signals
- Large uncertainties in theoretical predictions

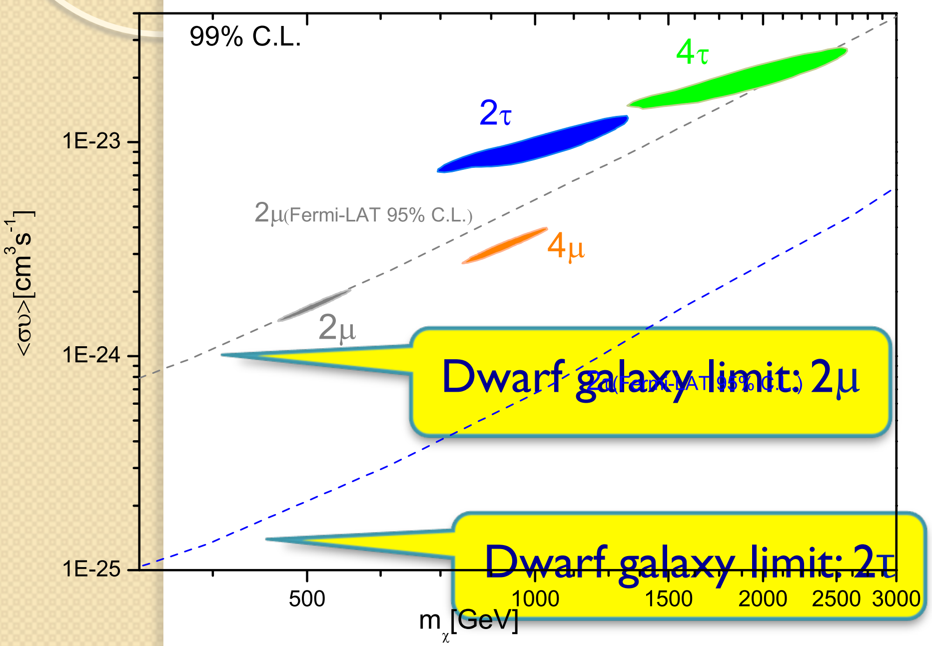
  origin/propagation of CRs, Solar modulation,

  hadronic interaction cross sections low energies

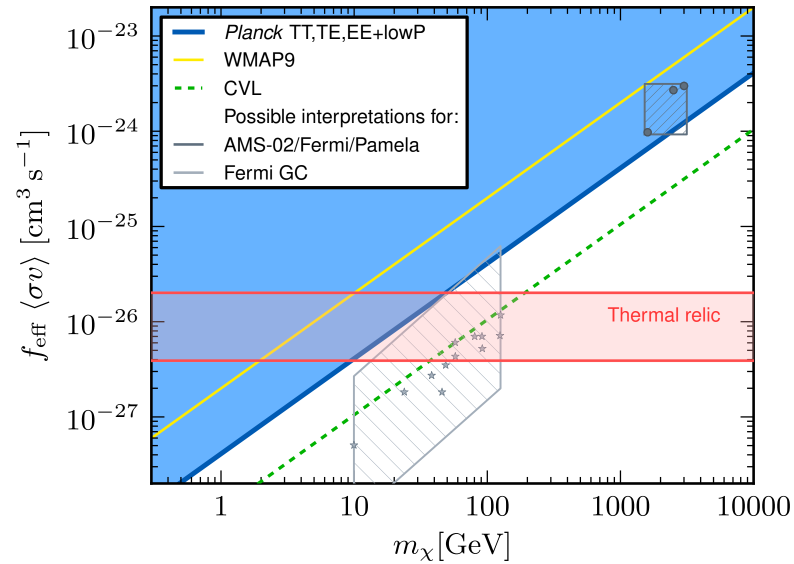
AMS-02 electrons: DM explanations



Constraints from gamma rays



Fermi limits from dSphs

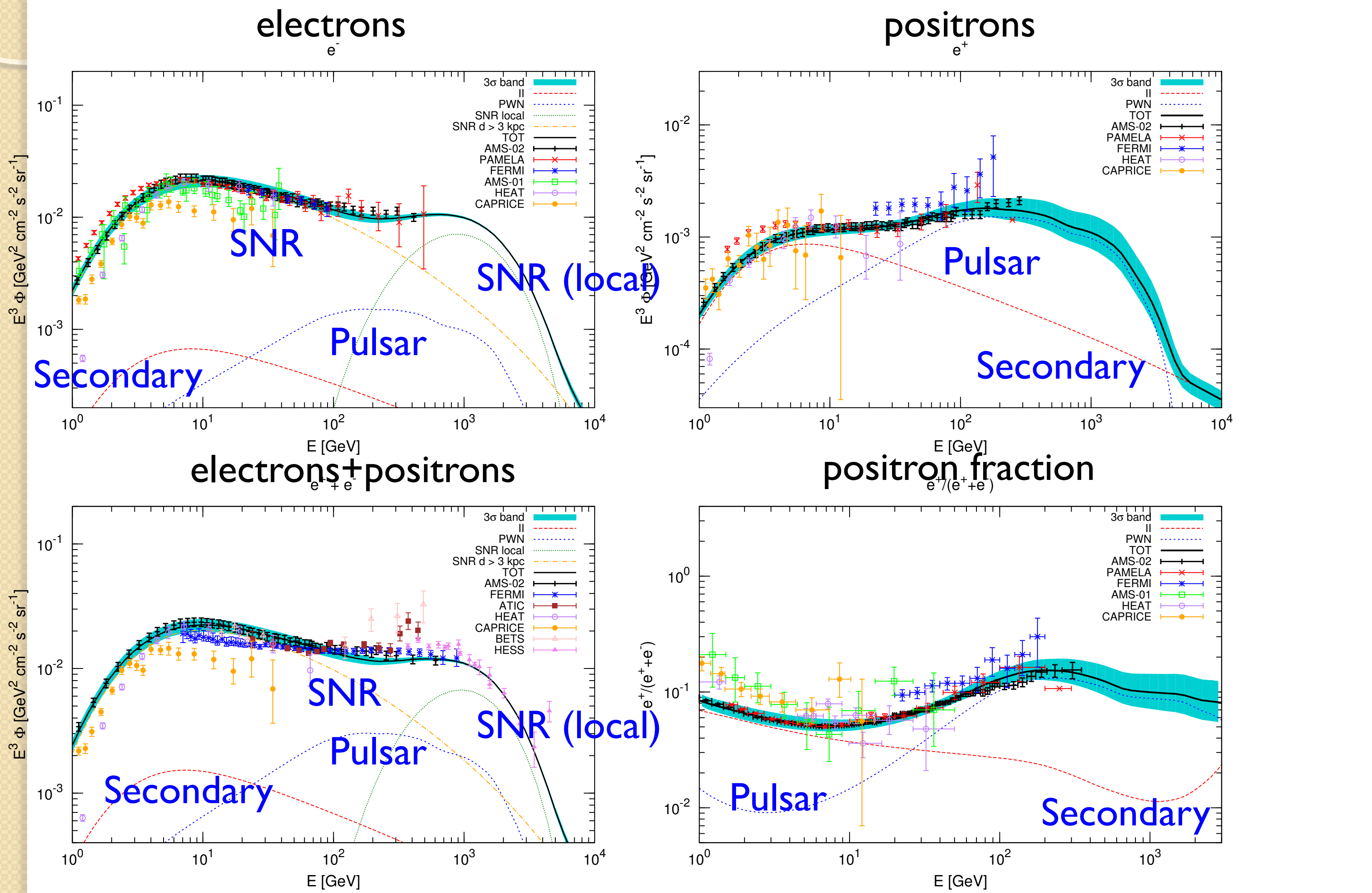


PLANK limits

Only DM annihilating into muon-final states are consistent with the dSphs limit

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

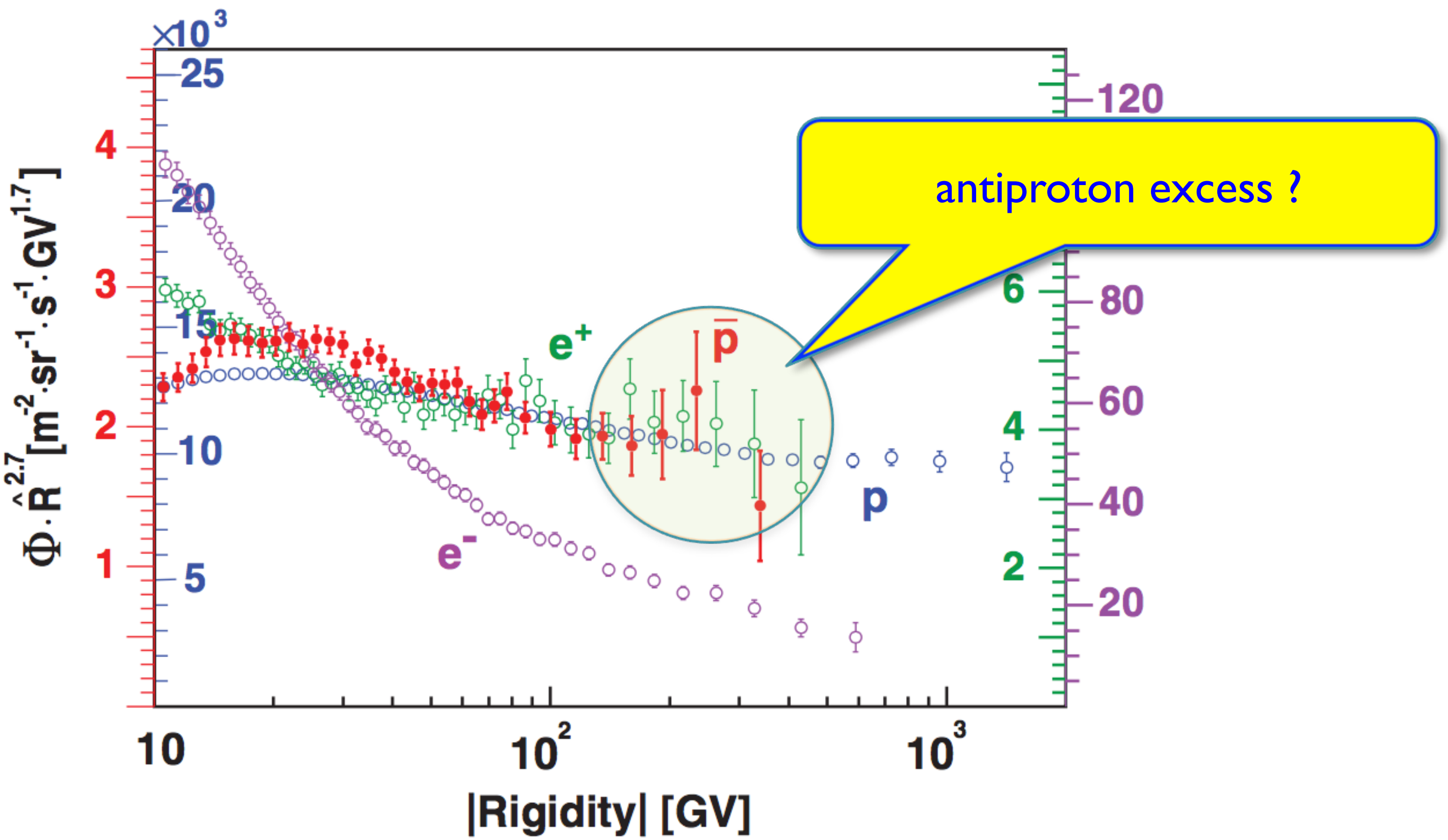
AMS-02 electrons: astrophysical explanations



Mauro etal, 1402.0321

AMS-02 antiprotons: 2016

PRL **117,** 091103 (2016) PHYSICAL REV

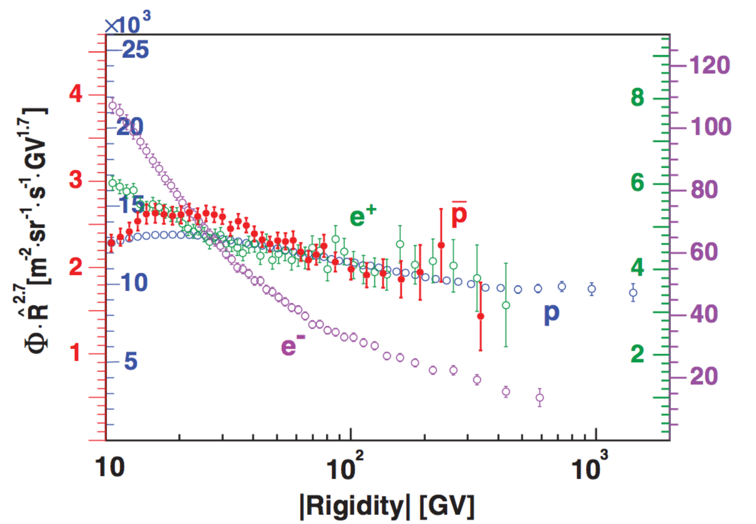


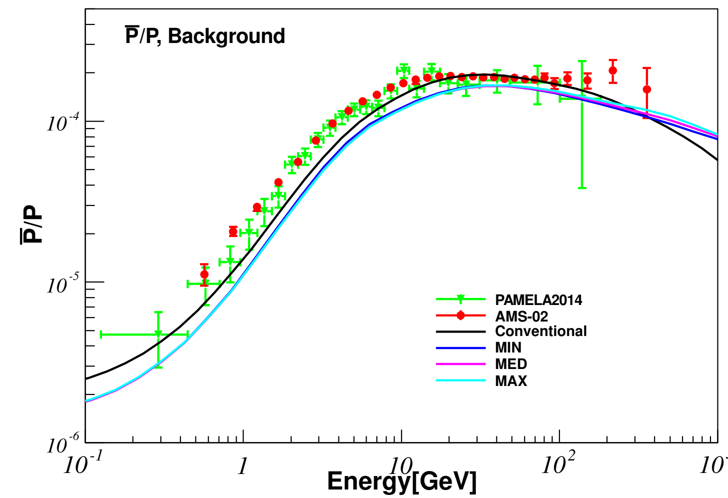
AMS—02 Collaboration

AMS-02 antiproton data

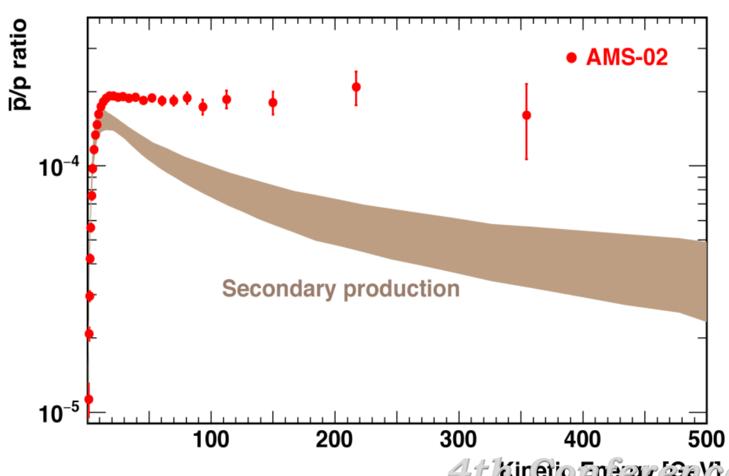
H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD

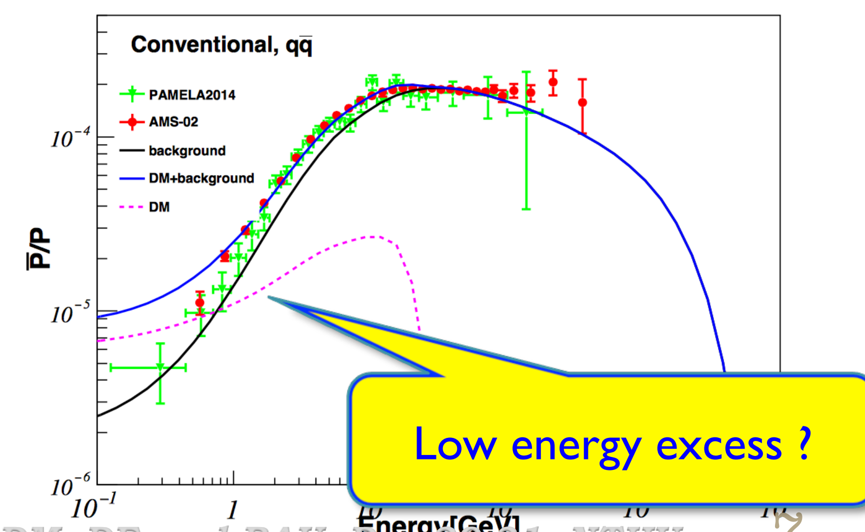
PRL **117,** 091103 (2016) PHYSICAL REV

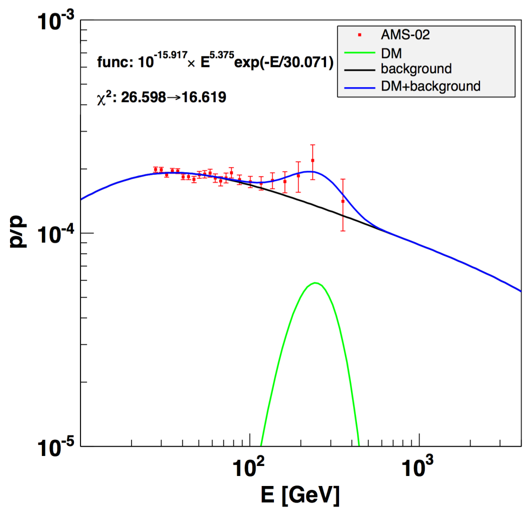


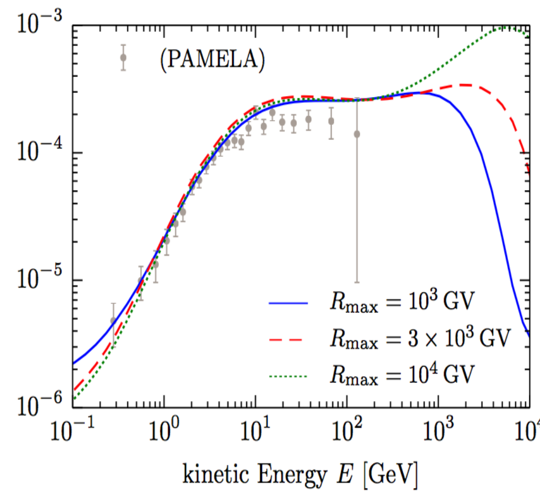


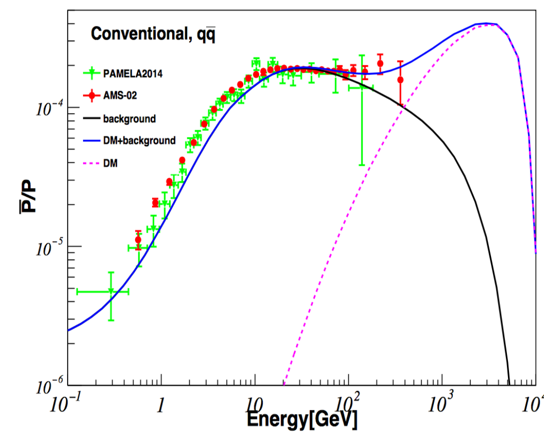
AMS p̄/p results and modeling











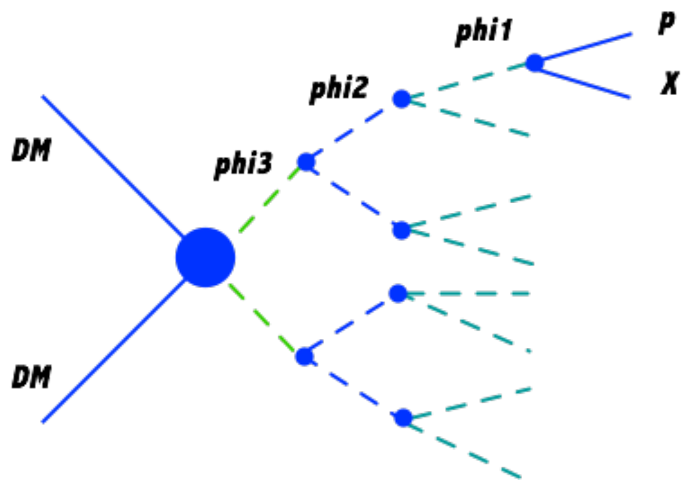
Implications

- The spectral feature can be well-fitted with a power law spectrum with a cut off, typical significance 2.5—3 sigma.
- Pulsars are unlikely to produce energetic antiprotons.
- SNRs can produce secondary antiprotons but with a flat (or smooth rising) spectrum.
- DM direct annihilation (DMDM→f fbar→pbar +X) predicts a broad bump, too smooth to explain the excess in a narrow energy range.

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

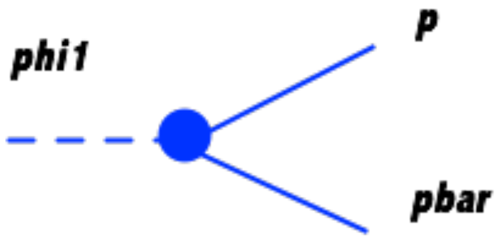
$$\frac{d\tilde{N}_\psi}{dx_1} = \int_{-1}^{1} d\cos\theta \int_{\epsilon_0}^{1} dx_0 \, \frac{d\tilde{N}_\psi}{dx_0}\, \delta\left(2x_1 - x_0 - \cos\theta\sqrt{x_0^2 - \epsilon_0^2}\sqrt{1-\epsilon_1^2}\right),$$

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 $\varepsilon_0 \ll \varepsilon_1 \ll \varepsilon_2 \dots$



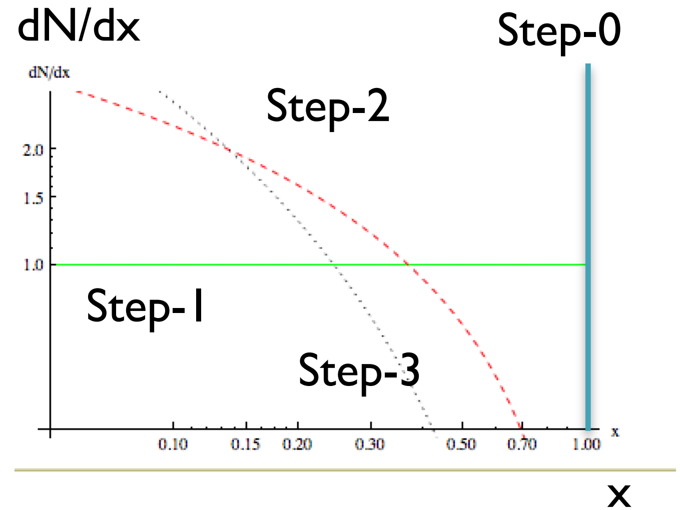
$$\frac{d\tilde{N}_\psi}{dx_1} = \int_{x_1}^{1} \frac{dx_0}{x_0} \frac{d\tilde{N}_\psi}{dx_0} + \mathcal{O}(\epsilon_i^2),$$

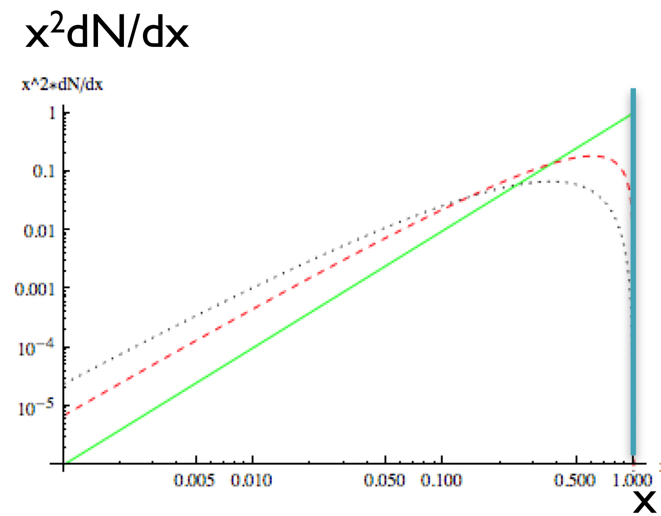
$$\text{Step-0:} \quad \frac{dN}{dx_0} = \delta(1 - x_0)$$

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

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

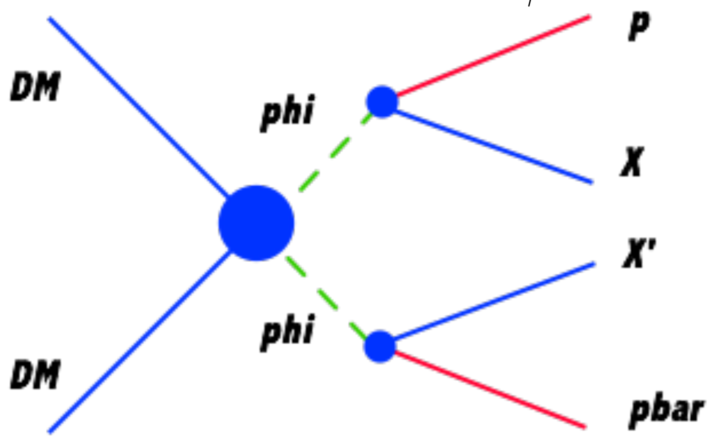
$$\text{Step-n:} \quad \frac{dN}{dx_n} = \frac{1}{(n-1)!} \left(\ln \frac{1}{x_n} \right)^{n-1}$$

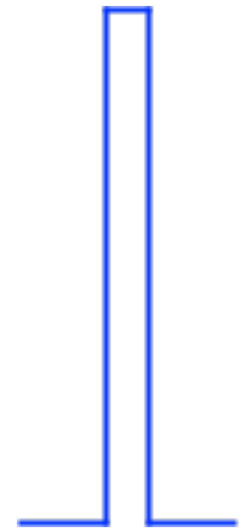




Non-hierarchical case

small β'



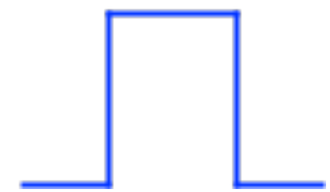


phi rest-frame

Lorentz Boost

$$E = \gamma_B E'$$

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



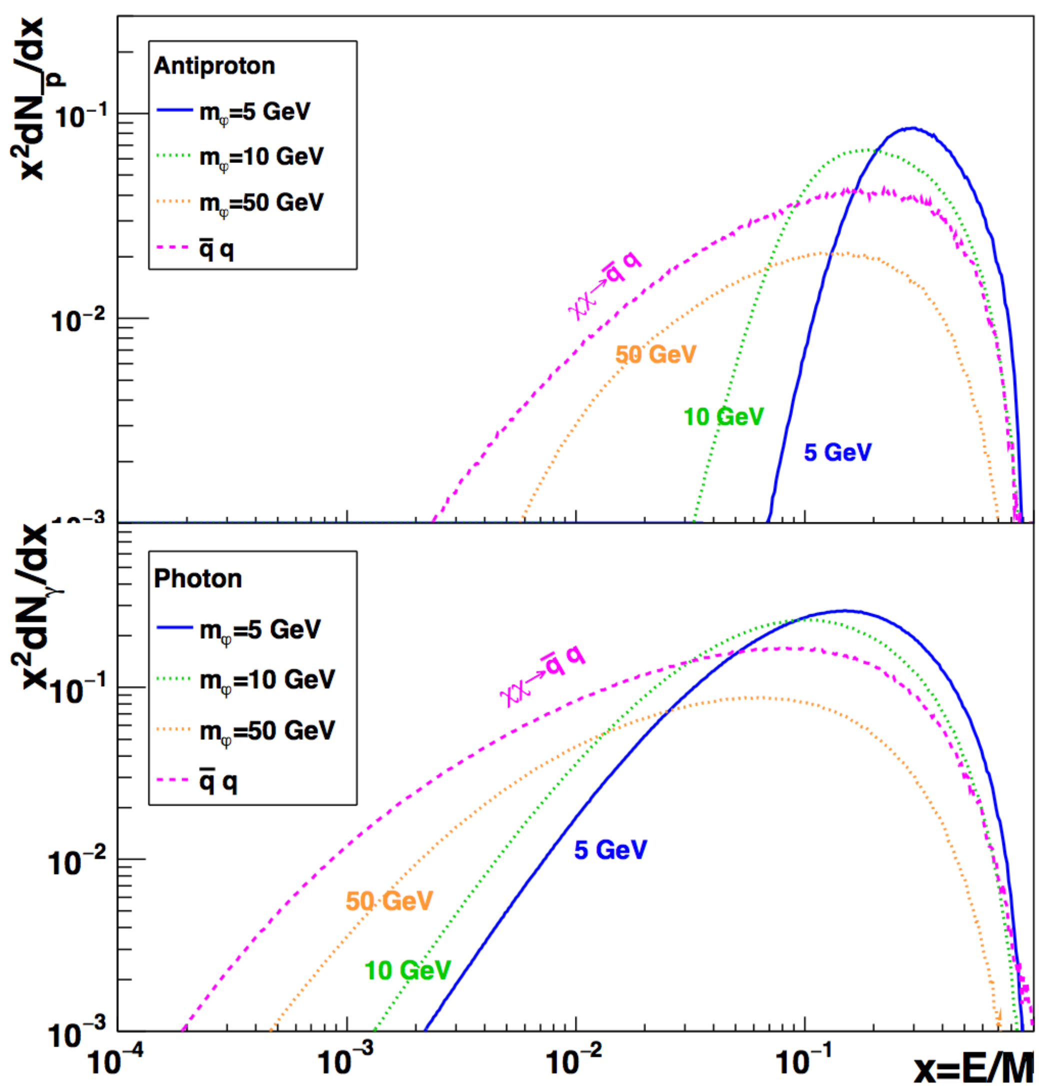
DM CM frame

When $\phi \approx 2m_p$

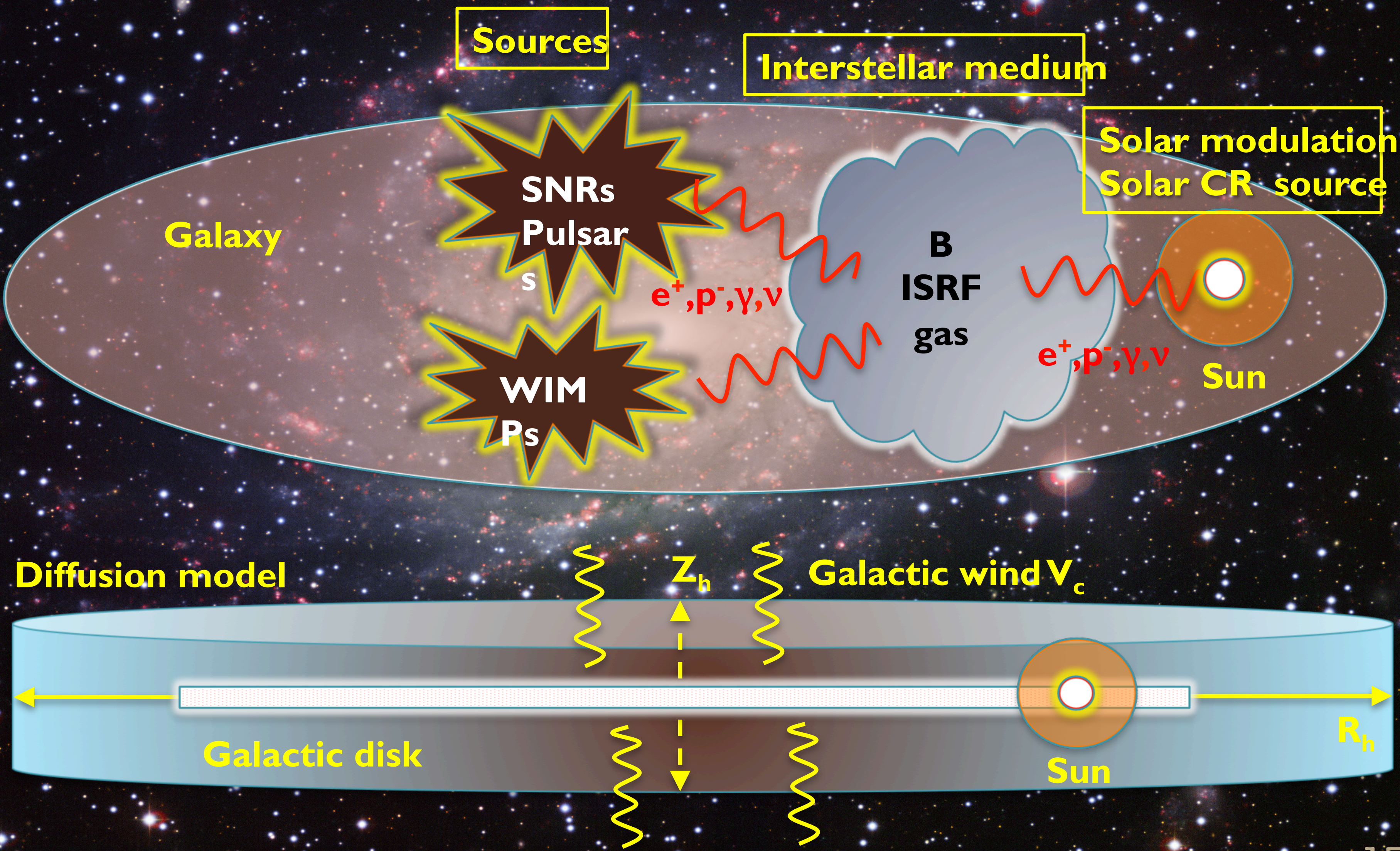
Lorentz boost for finite ϵ_0

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

Narrow bump antiproton spectra



propagation of CRs



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

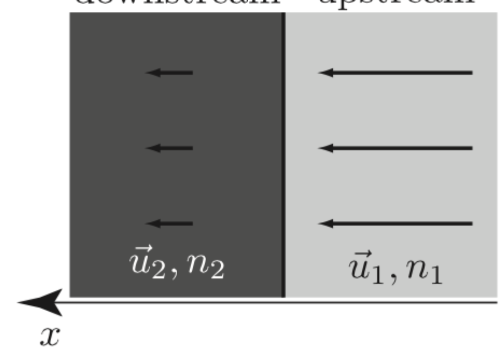
Approaches

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

Antiprotons from SNRs

- Antiprotons can be generated from pp inelastic scatterings

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



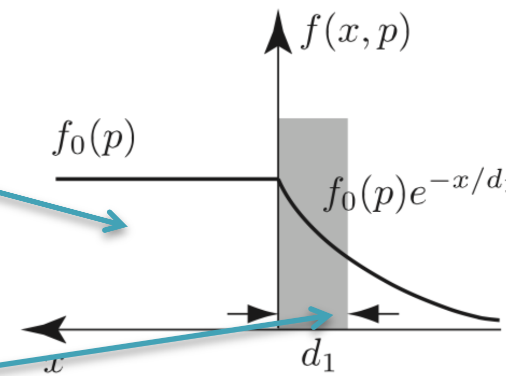
- Antiprotons accelerated by the shock-wave and propagate in the same way as protons

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

$$\mathcal{A}(E) = \gamma \left(\frac{1}{\xi} + r^2 \right) \times$$

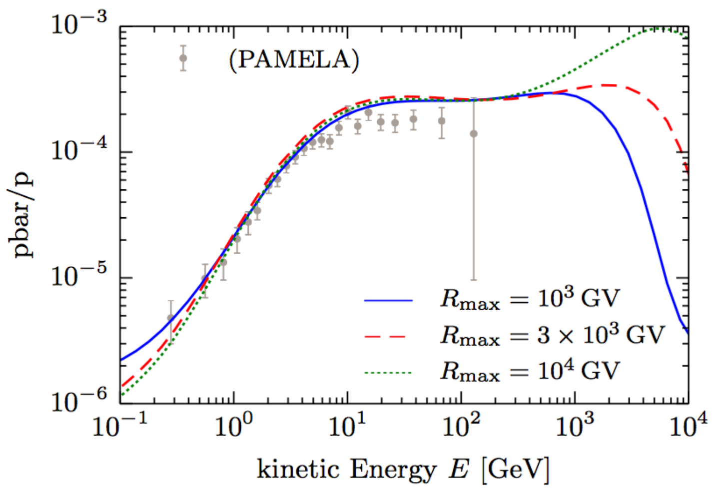
$$\times \int_m^E \mathrm{d}\omega\, \omega^{\gamma-3} \frac{D_1(\omega)}{u_1^2} \int_\omega^{E_{\max}} \mathrm{d}\mathcal{E}\, \mathcal{E}^{2-\gamma}\, \sigma_{p\bar{p}}(\mathcal{E}, \omega)\,,$$

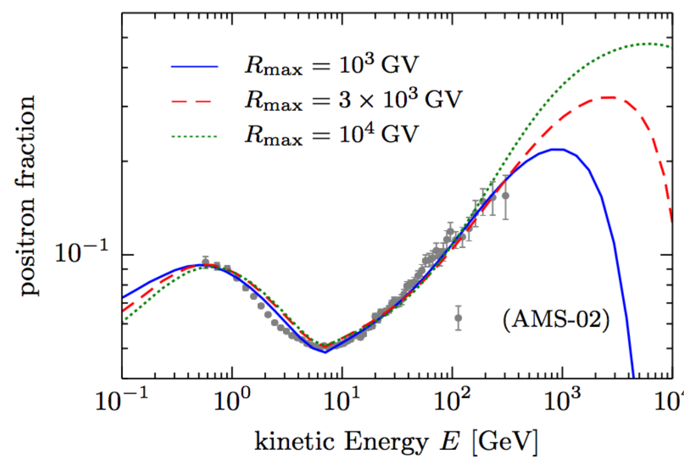
$$\mathcal{B}(E) = \frac{\tau_{SN}\, r}{2\, E^{2-\gamma}} \int_E^{E_{\max}} \mathrm{d}\mathcal{E}\, \mathcal{E}^{2-\gamma}\, \sigma_{p\bar{p}}(\mathcal{E}, E)\,.$$



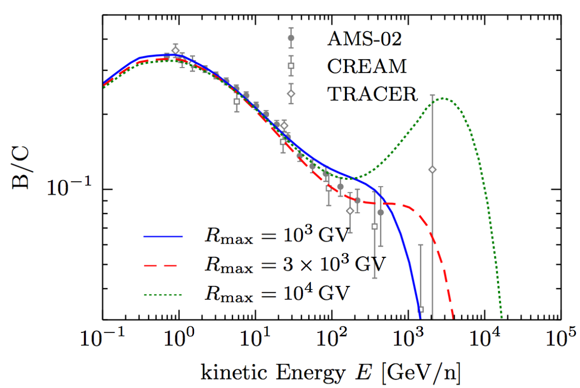
Diffusion coefficient inside SNRs

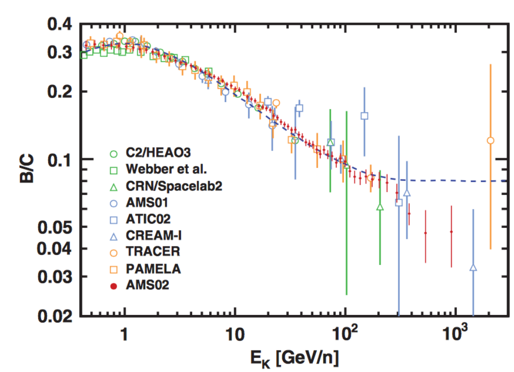
$$D_1(E) = \left(\frac{\lambda_c\, c}{3\, \mathcal{F}} \right) \left(\frac{E}{e\, B\, \lambda_c} \right)^{2-\beta}\,,$$





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





Fit to the AMS-02 antiproton data

- Three antiproton source models considered
  - A) DM annihilation through light (5GeV) mediators
  - B) DM annihilation directly into two quarks
  - C) antiprotons generated by SNRs (E_{max}=10 TeV)

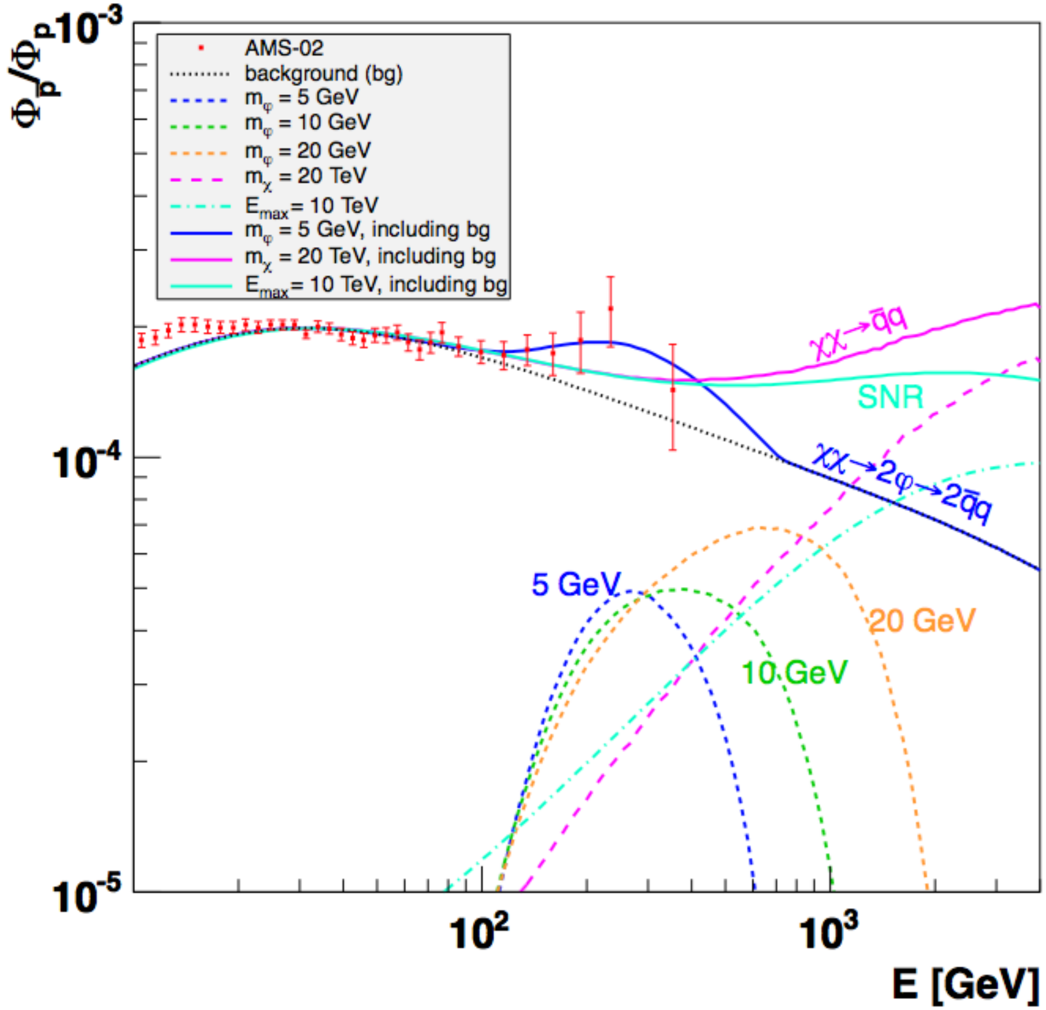
- Three propagation models (MIN, MED, MAX)
- DM profile: Einasto profile
- The DM mass and cross sections are set free
- Injection spectrum generated by Pythia 8 (low energy issu)
- Background normalization allowed to float freely
- chi^2 analysis for AMS-02 data above 20 GeV
- Solar modulation considered with potential phi=500 MV.

Results

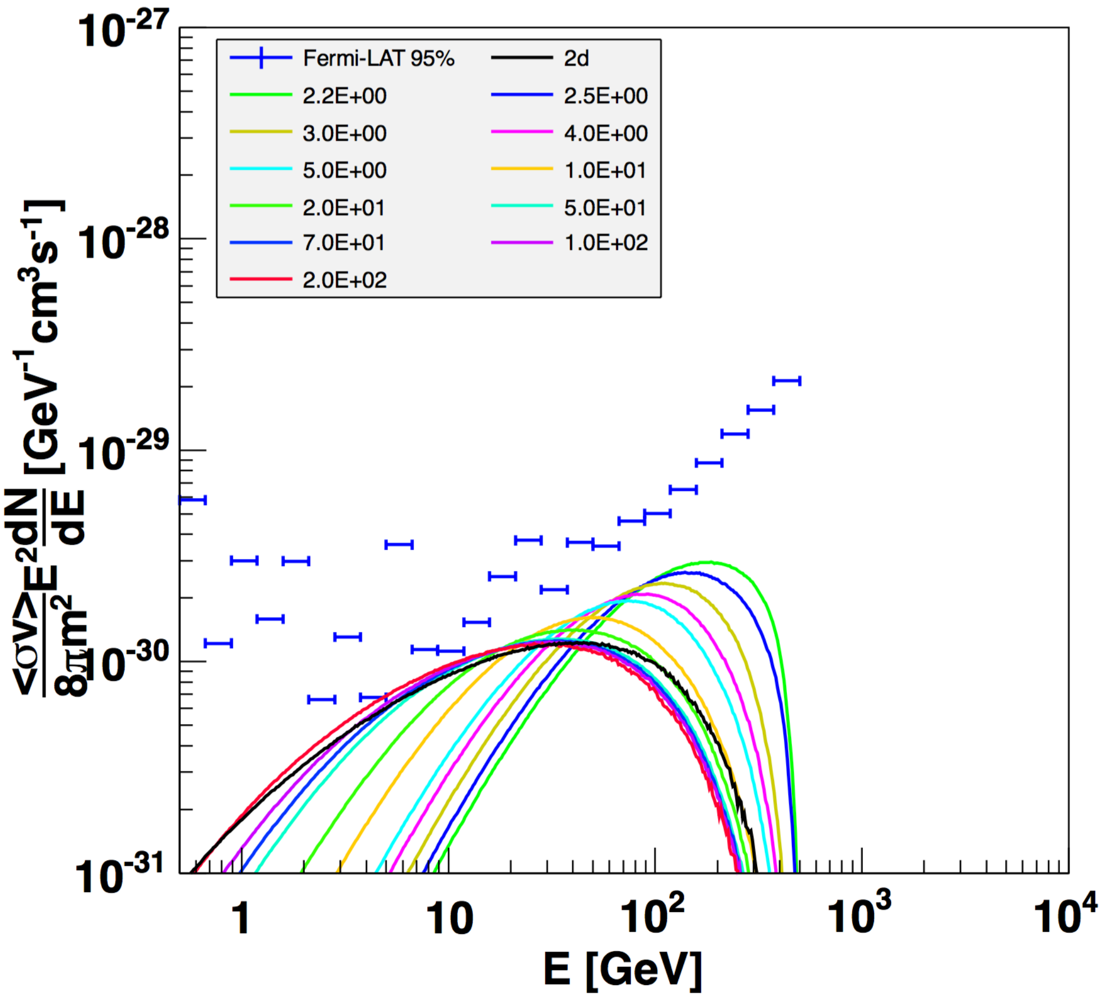
	Model	m_χ[GeV]	$\langle\sigma v\rangle(\eta)$	κ	χ^2	TS
A	MIN	765^{+167}_{-153}	$18.6^{+10.7}_{-8.0}$	1.12±0.01	12.5	11.6
	MED	808^{+184}_{-165}	$5.18^{+3.04}_{-2.37}$	1.13±0.01	13.8	9.0
	MAX	826^{+185}_{-168}	$2.29^{+1.31}_{-1.06}$	1.13±0.01	15.5	8.5
B	MIN	20000	1200±410	1.12±0.01	15.5	8.6
	MED	20000	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

- Model A (DM annihilation through light mediators) is favoured
- Best fit DM mass ~800 GeV,
  cross section compatible with thermal value

Comparing three models

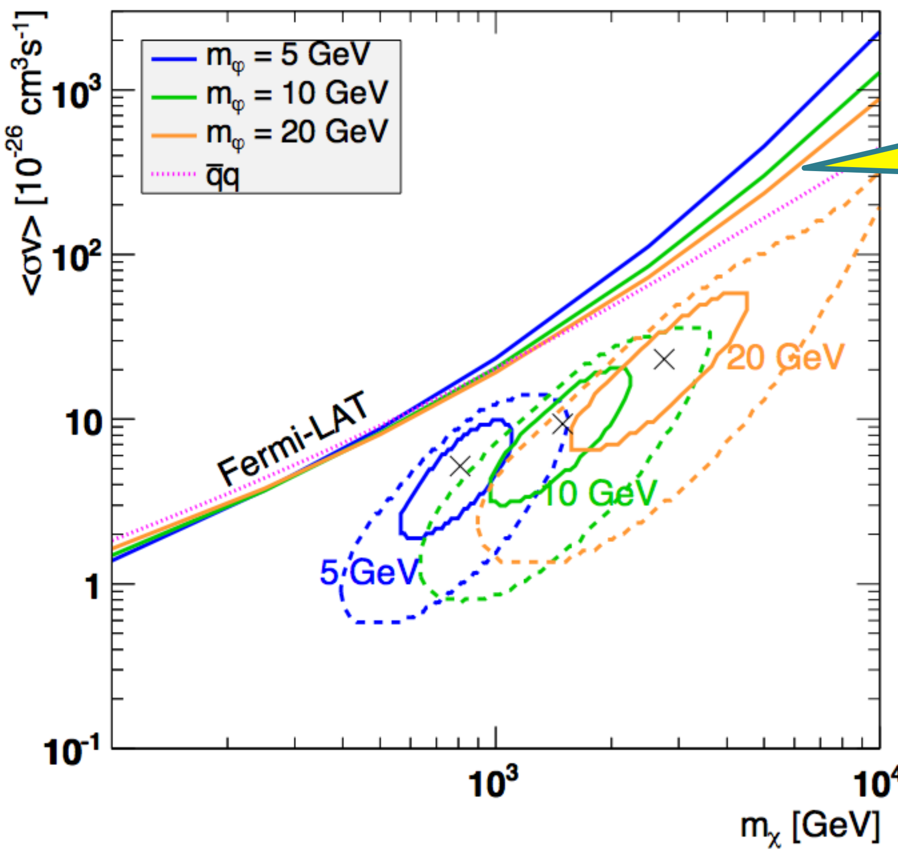


Limits from dwarf galaxies



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

Limits from dwarf galaxies



Weaker limits for light mediators

DM (with mediators) interpretation is consistent with the limits from dSphs

Conclusions

- DM annihilation through light mediator can leads to different energy spectral features of CR antiprotons
- When the mass of the mediator is close to the antiproton production threshold (~2mp), a shape spectral bump appears
- The current AMS-02 antiproton data show a hint of excess: a rise in 100-260 GeV, followed by a drop of 30% in 260-450 GeV, with a significance 2.5-3 sigma.
- Such an "excess", if confirmed, will not favor SNR explanation and DM direct annihilation into SM quarks
- DM annihilation through light mediator (5 GeV or less) can provide an consistent explanation.