

GEV-SCALE THERMAL WIMPS: NOT EVEN SLIGHTLY DEAD

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IN COLLABORATION WITH

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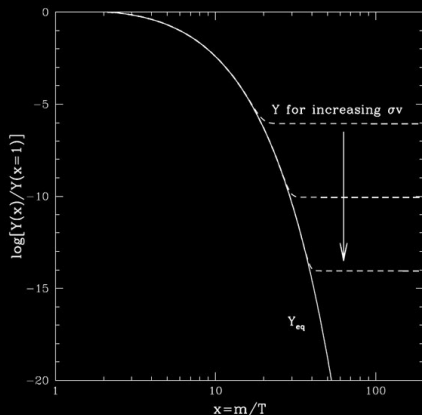
THE REIGN OF WIMPS

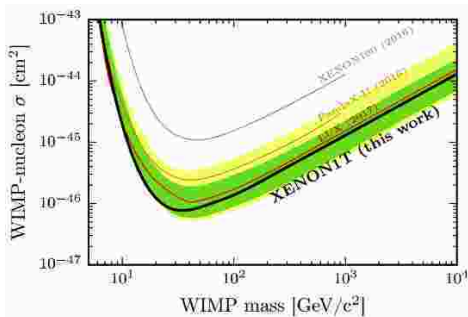
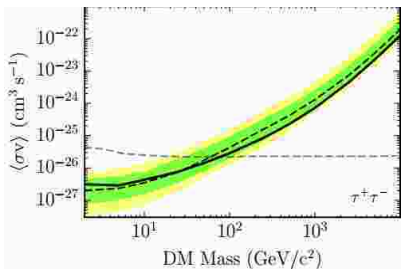
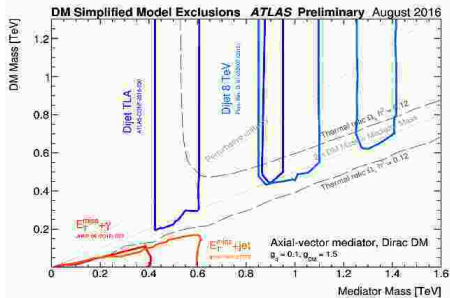
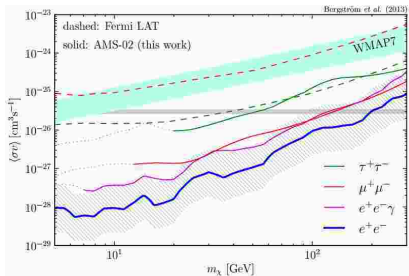
Dark matter landscape has long been dominated by WIMPs.

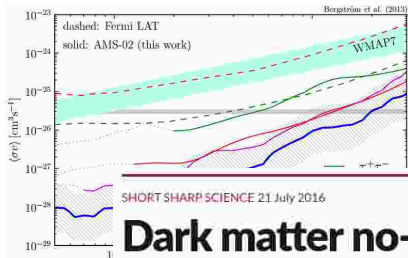
- Abundance is determined by its weak-scale annihilation rate

$$\Omega_{\chi} h^2 \approx 0.12 \times \frac{2.2 \times 10^{-26} \text{ cm}^3/\text{s}}{\langle \sigma v \rangle}$$

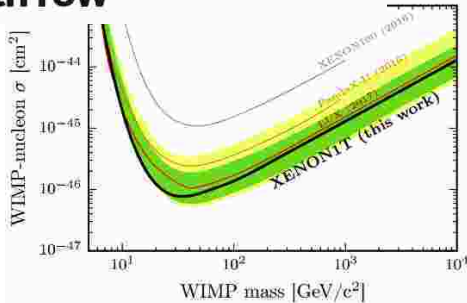
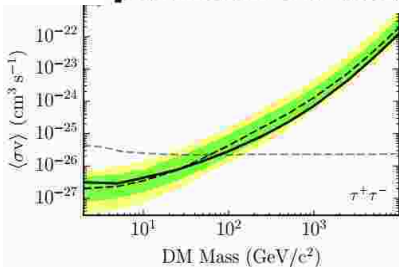
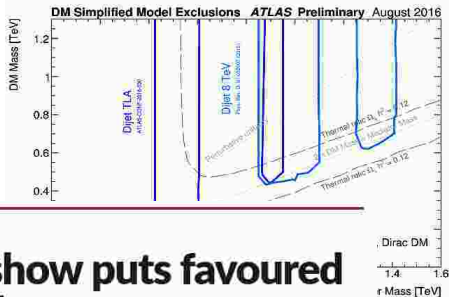
- Well motivated by theory and experiment

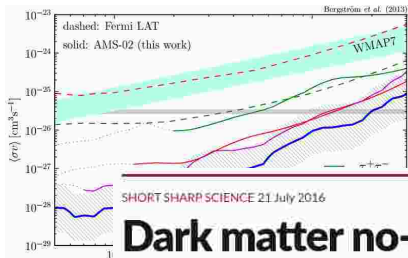




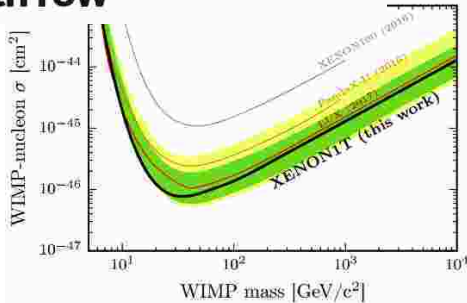
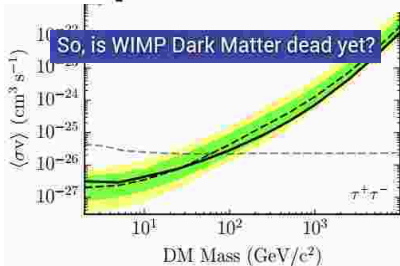
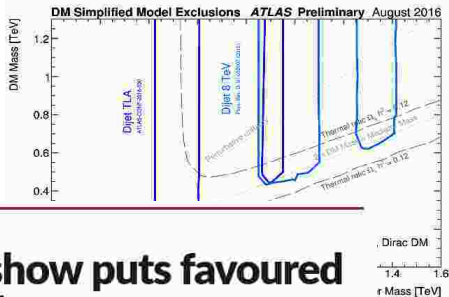


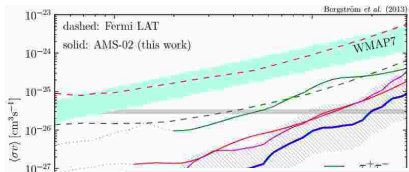
Dark matter no-show puts favoured particles on death row





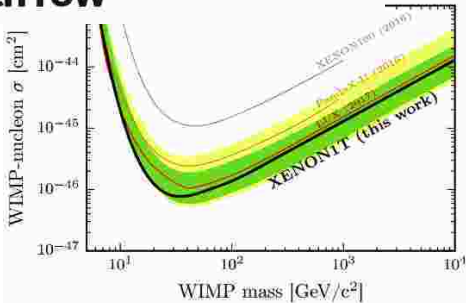
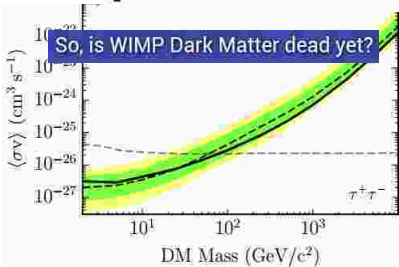
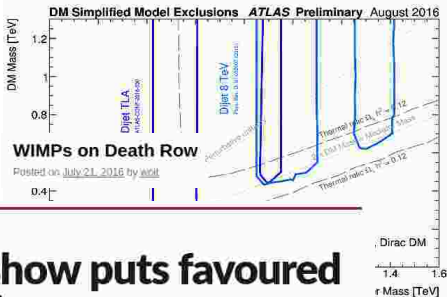
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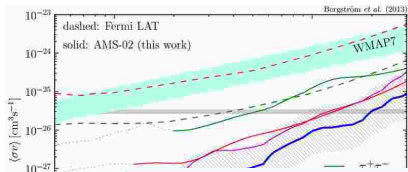




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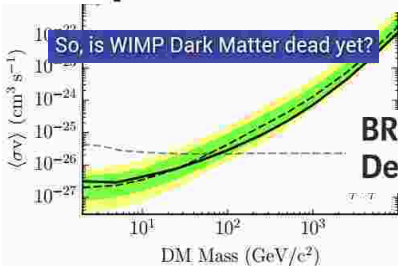
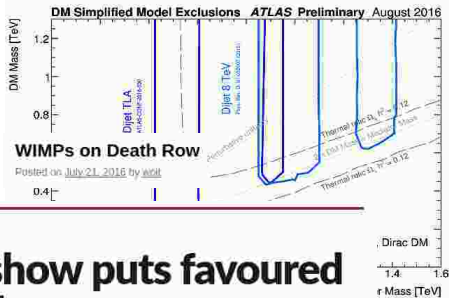
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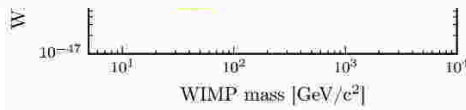


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Dark matter no-show puts favoured particles on death row



BREAKING NEWS! WIMP Dark Matter Dead AGAIN!

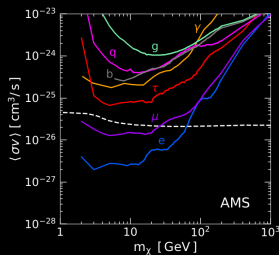
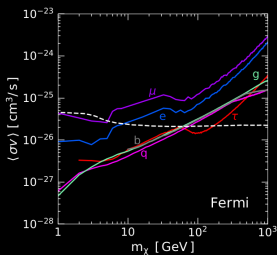
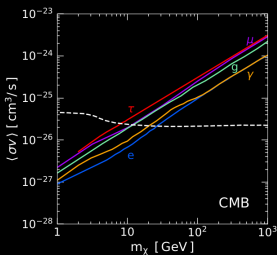


ANNIHILATION SCALE AS DECISIVE TEST

- Scattering (direct detection) and production (colliders):
there is no well-defined scale.

ANNIHILATION SCALE AS DECISIVE TEST

- Scattering (direct detection) and production (colliders): there is no well-defined scale.
- The most decisive way to test thermal WIMPs is through their annihilation products, as this exactly goes to their most fundamental feature: being annihilation relics



MODEL INDEPENDENT EXCLUSION

Is there a largely model-independent lower limit on the mass of thermal relic dark matter?

Branching fractions of DM must add to 100 percent.

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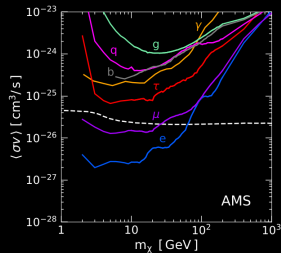
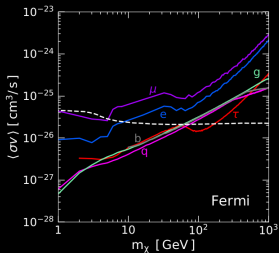
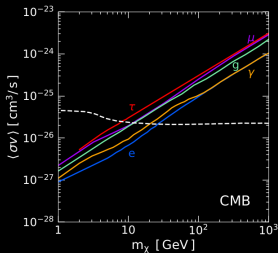
If no composite spectrum provides a limit above the thermal relic line, that mass must be excluded.

We perform the first calculation of the model-independent upper limit on the thermal WIMP cross section from data.

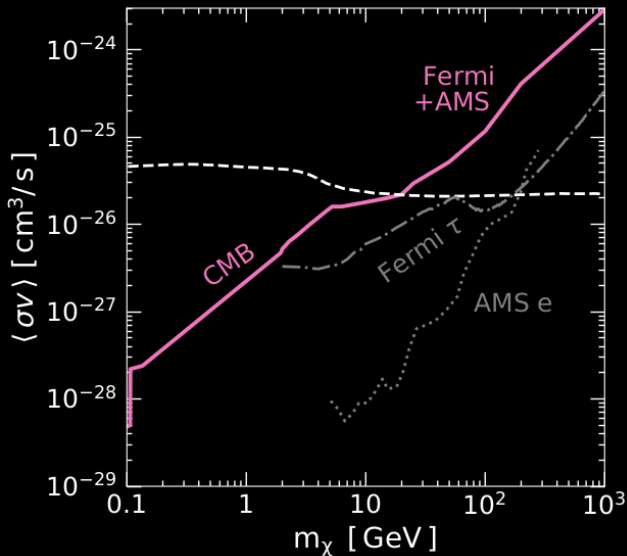
If energy disappears in one channel, it must reappear in another. Combining limits from these experiments exploits complementary strengths.

- Consider most generic and accessible cases: $2 \rightarrow 2$ s -wave annihilation to visible products
- Increase DM mass in increments through the thermal window
- Scan over all branching fractions to kinematically allowed final states
- Check all composite energy spectra against all limits, if no composition satisfies all limits, increase mass again
- Note this is not linear scaling of individual limits

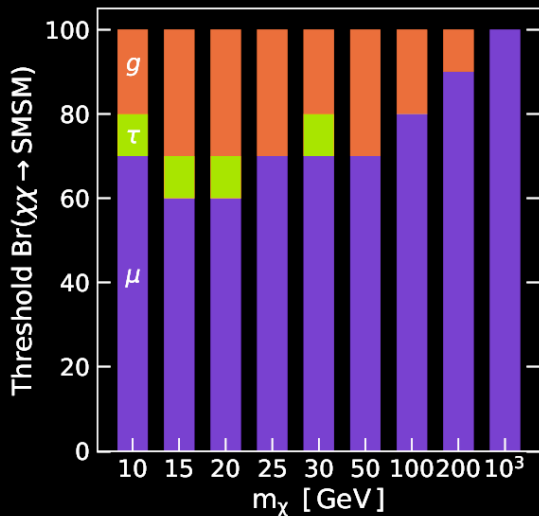
TOTAL ANNIHILATION CROSS SECTION LIMIT?



TOTAL ANNIHILATION CROSS SECTION LIMIT



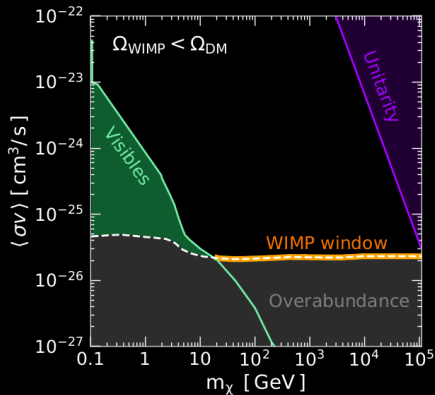
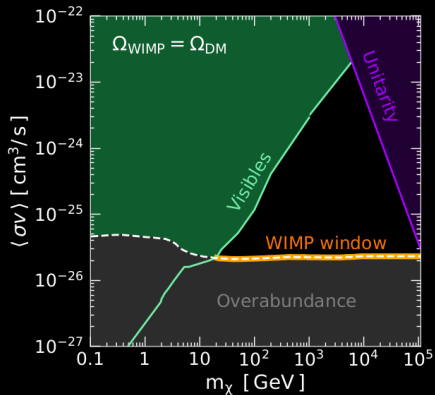
THRESHOLD EXCLUSION BRANCHING FRACTIONS



IMPLICATIONS FOR DM MODELS

- Any DM below ~ 20 GeV must be non-generic
- Muons least constrained
 - ▶ Possible in leptophilic DM models
- Covers models with suppressed collider or DD signals, i.e. velocity or momentum suppression, or cancellation between diagrams
- Strength of the limit below the relic line can also be used to set a bound on sub-dominant WIMP content
 - ▶ Cross section is no longer restricted to be thermal.

THE WIMP WINDOW



TOWARDS CLOSING THE WIMP WINDOW

FERMI:

- Relies on finding new dwarfs, closer to Earth
 - ▶ pre-DES: optimistic, order of magnitude improvement
- Otherwise, sensitivity $\sim \sqrt{t}$, existing constraints use ~ 6 years of data

AMS:

- Constraints based on shorter exposure time, ~ 2.5 years of data
- Understanding CR background/propagation uncertainties better could make constraints much stronger

PLANCK:

- Future CMB experiment could do factor \sim few better
- Fundamental bound of cosmic variance

CTA+IACT:

- H.E.S.S., VERITAS, MAGIC, HAWC aid eventually closing up to unitarity limit

CONCLUSION AND OUTLOOK

- Annihilation products most decisive way to test thermal WIMPs, sets well-defined scale for total cross section.
- Considered most generic, most accessible cases
- Generic GeV WIMP not even slightly dead
 - ▶ Conservative limit: the model-independent lower limit on the mass is ~ 20 GeV
 - ▶ At lower masses, can constrain subdominant fraction
- CTA, which is claimed decisive for masses over ~ 100 GeV, simply won't be able to address the lower mass range
 - ▶ Before saying WIMPs are dead, we need to probe this mass range!
- Improvements promising in near future

Cosmic-Ray Propagation

The evolution of the number density N_i of injected electrons and positrons is given by the diffusion equation,

$$\begin{aligned} \frac{\partial N_i}{\partial t} &= \vec{\nabla} \cdot (D \vec{\nabla}) N_i + \frac{\partial}{\partial p} (\dot{p}) N_i + Q_i(p, r, z) \\ &+ \sum_{j>i} \beta n_{\text{gas}}(r, z) \sigma_{ji} N_j - \beta n_{\text{gas}} \sigma_i^{\text{in}}(E_k) N_i, \end{aligned}$$

where D is the spatial diffusion coefficient, parametrized as

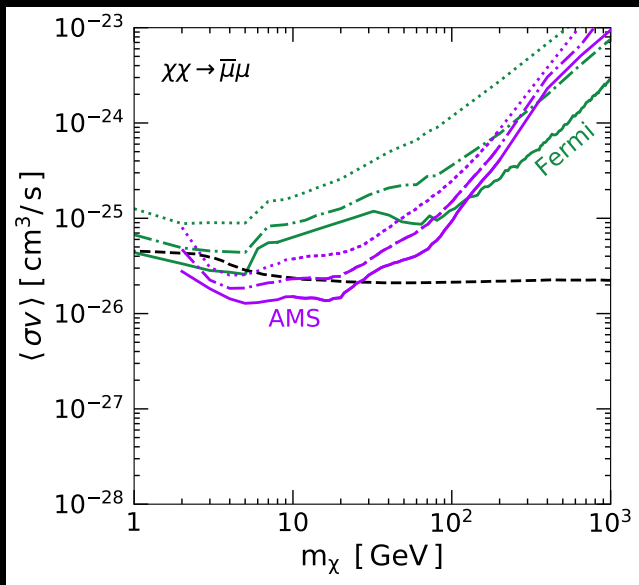
$$D(\rho, r, z) = D_0 e^{|z|/z_t} \left(\frac{\rho}{\rho_0} \right)^\delta,$$

where $\rho = p/(Ze)$ is the rigidity of the charged particle with $Z = 1$ for electrons and positrons. The diffusion is normalized by D_0 at the rigidity $\rho_0 = 4$ GV. We assume the diffusion zone is axisymmetric with thickness $2z_t$.

$$Q_X(p, r, z) = \frac{\rho_X^2(r) \langle \sigma v \rangle}{2m_X^2} \sum_f Br_f \frac{dN^f}{dE}.$$

Cosmic-Ray Propagation

- Model parameters: $z_t = 4$ kpc, $D_0 = 2.7 \times 10^{28}$ cm²/s, $\delta = 0.6$
- Take the local DM density to be the maximally conservative $\rho = 0.25$ GeV/cm³, with an NFW profile.
- Set the magnetic field at the Sun to be $B_\odot = 8.9$ μ G, which means that the local radiation field and magnetic field energy density is 3.1 eV/cm³. Higher than the common conservative value of 2.6 eV/cm³
- As such, different choices of the other propagation parameters do not appreciably change the results.
- The most substantial energy-loss for charged cosmic rays below about 10 GeV is due to solar modulation. The largest measured value of 0.6 GV is taken, we and employ the force-field approximation, which is valid for positron fluxes.



Energy Injection Fractions: Below 5 GeV

- There is no reason to expect this argument to break down for DM masses below 5 GeV, but need to be careful close to a hadronic resonance.
- For hadronic final states, we furthermore expect that the energy of the produced photons/electrons will peak no lower than a $\mathcal{O}(1)$ fraction of the pion mass
- Likewise, muon decays will typically produce electrons with $\mathcal{O}(10 - 100)$ MeV energies.
- Robustly expect that for DM masses between ~ 100 MeV and 5 GeV, at least 25% of the DM rest energy should go into producing photons, electrons and positrons with energies above 5 MeV.
- Even though PYTHIA has additional uncertainty in this regime, we can use this estimate to set a strong constraint on light DM annihilation.

Energy Injection Fractions: Below 5 GeV

- For e^\pm/γ energies above 5 MeV, the minimum value of f_{eff} is 0.32. Thus we expect f_{eff} for any 2-body SM final state other than neutrinos to exceed $f_{\text{min}} = 0.25 \times 0.32 \approx 0.08$ for DM masses in the 100 MeV - 5 GeV window
- Min f_{eff} value for DM masses above 5 GeV is 0.12 for the same set of channels; realistically all the e^\pm/γ will not be concentrated at the energies that minimize f_{eff} .
- Conservative f_{min} implies

$$\langle \sigma v \rangle < 2.6 \times 10^{-26} \text{cm}^3/\text{s}$$

for DM below 5 GeV. Excludes s -wave thermal relic cross section in this mass range.

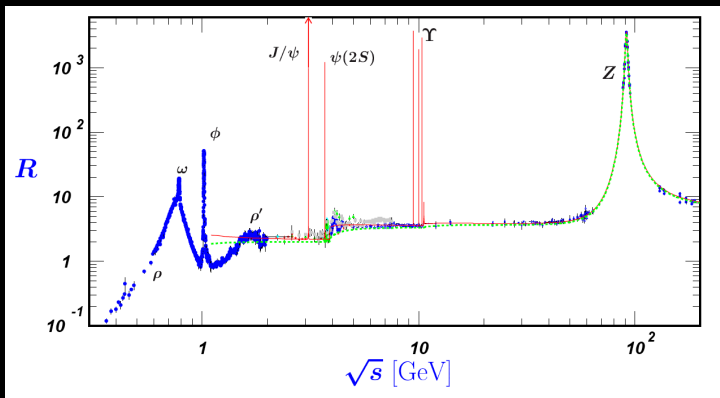
Escape Models

- Coannihilations
- Annihilations to W, Z, H : scattering through suppressed loops
- Suppressed scattering by powers of velocity or momentum
- Early matter domination, late-time reheating, extra particles
- Hidden sectors

Any extra caveat required tells us something about the WIMP

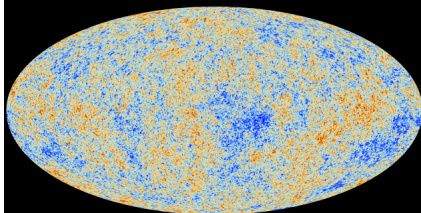
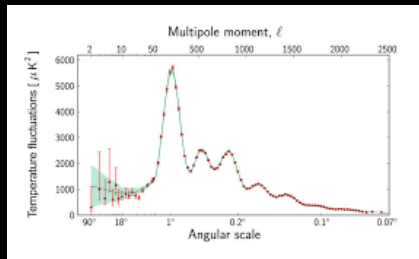
- Can point us in direction of preferred types of models, or which aspects of annihilation are priority to improve

Below 5 GeV



Energy Injection from Annihilating DM

- Anisotropies of the CMB provide powerful insight to physical processes present during the cosmic dark ages
- Any injection of ionizing particles modifies the ionization history of hydrogen and helium gas, perturbing CMB anisotropies
- Measurements provide robust constraints on production of ionizing particles
 - ▶ Most sensitive measurements to date are by *Planck*, superseding earlier measurements by WMAP.



Limits on Ionizing Particles

The annihilation power p_{ann} of DM to electromagnetic (EM) products,

$$p_{\text{ann}} = f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi},$$

determines the strength of the CMB limit.

Calculate the weighted efficiency factor f_{eff} by integrating energy spectra from PYTHIA over the $f_{\text{eff}}(E)$ curves calculated in Slatyer (2015),

$$f_{\text{eff}}(m_\chi) = \frac{1}{2m_\chi} \int_0^{m_\chi} \left(f_{\text{eff}}^e \frac{dN}{dE_e} + f_{\text{eff}}^\gamma \frac{dN}{dE_\gamma} \right) E dE.$$

From *Planck* data, the 95% C.L. limit on p_{ann} is

$$f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi} < 4.1 \times 10^{-28} \text{ cm}^3/\text{s}/\text{GeV}.$$

Fermi-LAT Dwarf Spheroidal Limits

- Dwarf spheroidal Galaxies of the Milky Way are one of the best DM signal targets, as according to kinematic data they are DM dense with low background
- Fermi has searched for excess gamma-rays. Strongest limits on DM to any photon rich final states, such as gamma-ray lines or hadronic final states.
- To set limits on photons from mixed final states, we consider nominal set of 45 dwarf galaxies.
- For each of these dwarf galaxies, *Fermi* provides the likelihood curves as a function of the integrated energy flux,

$$\Phi_E = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \left[\int_{E_{\min}}^{E_{\max}} E \frac{dN}{dE} dE \right] J_i,$$

Fermi-LAT Dwarf Spheroidal Limits

- Obtain the full likelihood $\mathcal{L}_i(\mu|\mathcal{D}_i)$ by multiplying the likelihoods for each for the 45 dwarfs together. The uncertainty in the J -factor is included as a nuisance parameter on the global likelihood, modifying the likelihood,

$$\begin{aligned}\tilde{\mathcal{L}}_i(\mu, J_i|\mathcal{D}_i) &= \mathcal{L}_i(\mu|\mathcal{D}_i) \\ &\times \frac{1}{\ln(10)J_i\sqrt{2\pi}\sigma_i} e^{-\left(\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right)^2/2\sigma_i^2}\end{aligned}$$

as per the profile likelihood method. Use J -factors provided by Fermi for a NFW profile.

- Likelihood is maximized, upper limit placed on the annihilation cross section at 95% C.L.

AMS-02 Limits

- We employ high energy losses, conservative choice for magnetic fields, of $B_{\odot} = 8.9 \mu\text{G}$ at the Sun
- Take largest value of the solar modulation potential, $\Phi = 0.6 \text{ GV}$, measured for AMS during its data-taking period
- The local DM density is in range $\rho = [0.25, 0.7] \text{ GeV}/\text{cm}^3$. Take lowest density of $\rho = 0.25 \text{ GeV}/\text{cm}^3$. Most dramatic impact on the limit — other choices such as propagation model, or choice of DM halo profile, have subdominant effect on our result
- AMS reports limits on b -quarks from their antiproton dataset, stronger stronger than *Fermi* at low masses ($\lesssim 50 \text{ GeV}$).
 - ▶ not one of the key threshold channels; the weakest channels from each experiment are what set the combined limit

- To set the limit we perform a likelihood ratio test, where the likelihood function is

$$\mathcal{L}(\theta) = \exp(-\chi^2(\theta)/2),$$

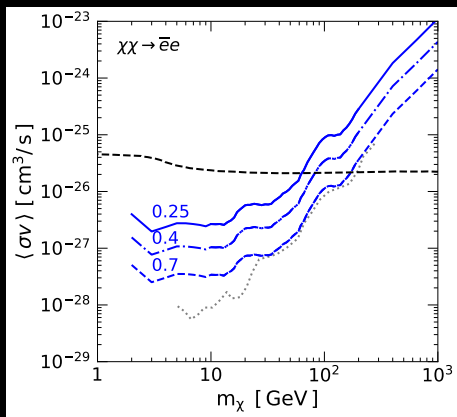
where $\theta = \{\theta^1, \theta^2, \dots, \theta^n\}$ are parameters in the best fit polynomial function, and the $\chi^2(\theta)$ is given by

$$\chi^2(\theta) = \sum_i \frac{(f_i^{th}(\theta) - f_i^{data})^2}{\sigma_i^2},$$

- Allow the parameters of the function to float within 30% of their best fit values without DM, and increase the DM signal normalization until the functional fit of the background plus signal to the data produces

$$\chi_{DM}^2 = \chi^2 + 2.71.$$

AMS-02 Limits: Conservative!



- Orders of magnitude more conservative in our limit compared to the literature
- Max solar modulation
- Large magnetic fields, large energy losses
- Minimum local DM density