GeV-Scale Thermal WIMPs: Not Even Slightly Dead

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In collaboration with
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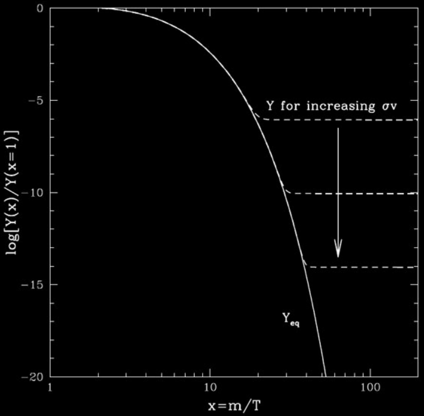
The Reign of WIMPs

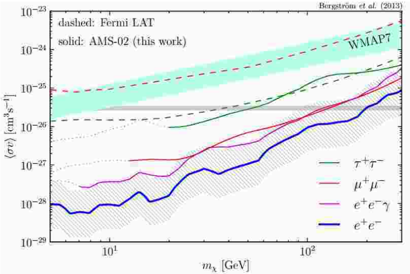
Dark matter landscape has long been dominated by WIMPs.

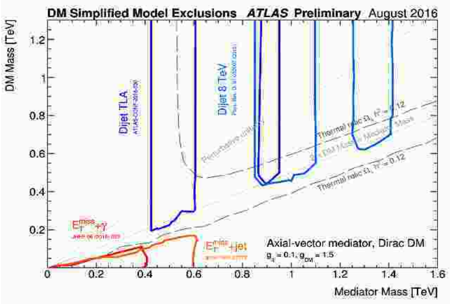
- Abundance is determined by its weak-scale annihilation rate

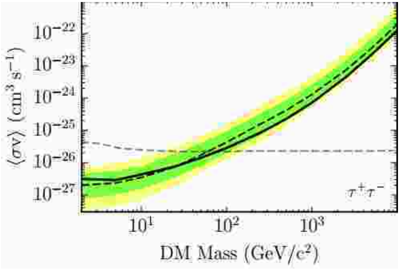
$$\Omega_\chi h^2 \approx 0.12 \times \frac{2.2 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

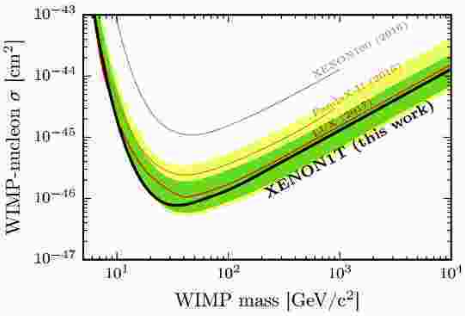
- Couplings too (small) large $\Rightarrow$ (over) under produce
- Implies mass $\sim$1 keV to $\sim$100 TeV
- Well motivated by theory and experiment

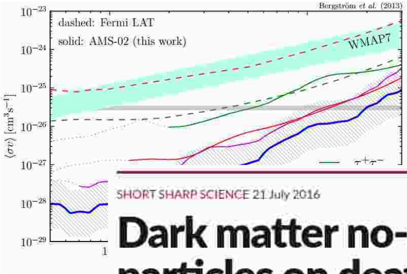


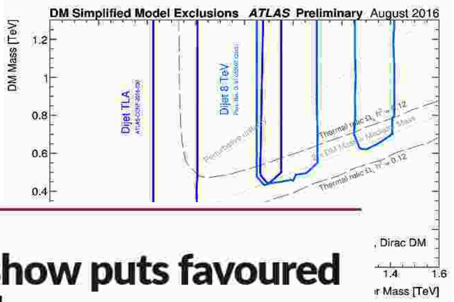

Bergström et al. (2013)
dashed: Fermi LAT
solid: AMS-02 (this work)
WMAP7
$\tau^+\tau^-$
$\mu^+\mu^-$
$e^+e^-\gamma$
e^+e^-
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
m_χ [GeV]


DM Simplified Model Exclusions ATLAS Preliminary August 2016
DM Mass [TeV]
Mediator Mass [TeV]
Dijet TLA
Dijet 8 TeV
Perturbative unitarity
Thermal relic $\Omega_c h^2 = 0.12$
$E_T^{miss}+\gamma$
$E_T^{miss}+jet$
Axial-vector mediator, Dirac DM
$g_q = 0.1, g_{DM} = 1.5$


$\langle \sigma v \rangle$ (cm^3 s^{-1})
$\tau^+\tau^-$
DM Mass (GeV/c^2)

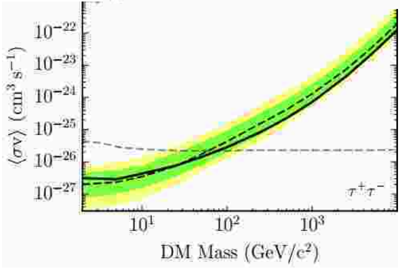

WIMP-nucleon σ [cm^2]
XENON100 (2016)
PandaX-II (2016)
LUX (2017)
XENON1T (this work)
WIMP mass [GeV/c^2]

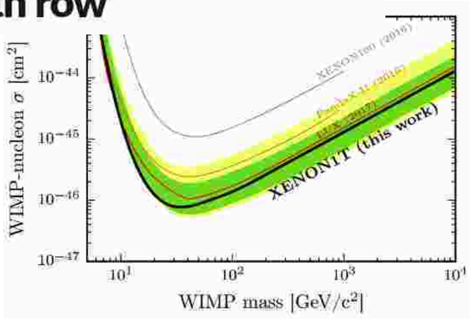


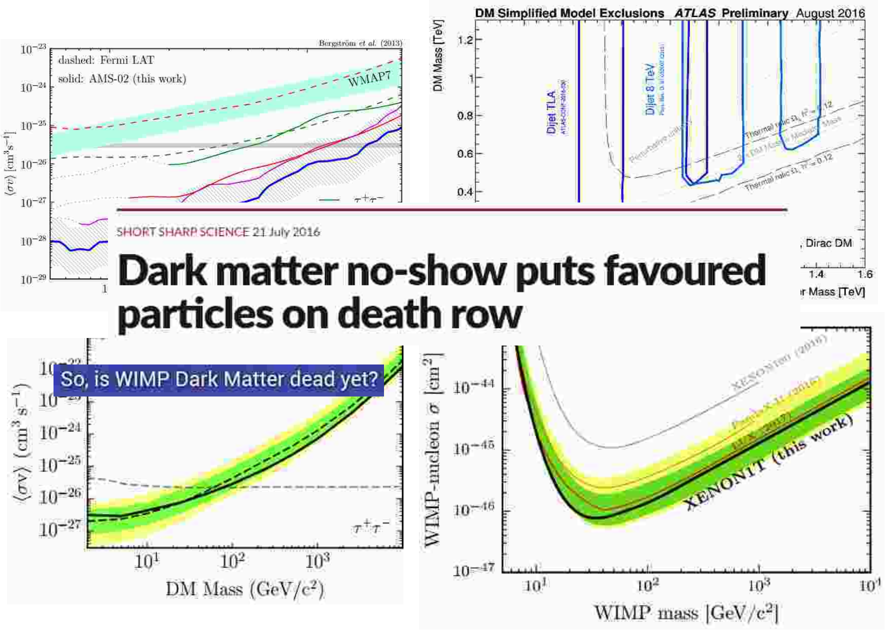


SHORT SHARP SCIENCE 21 July 2016

Dark matter no-show puts favoured particles on death row







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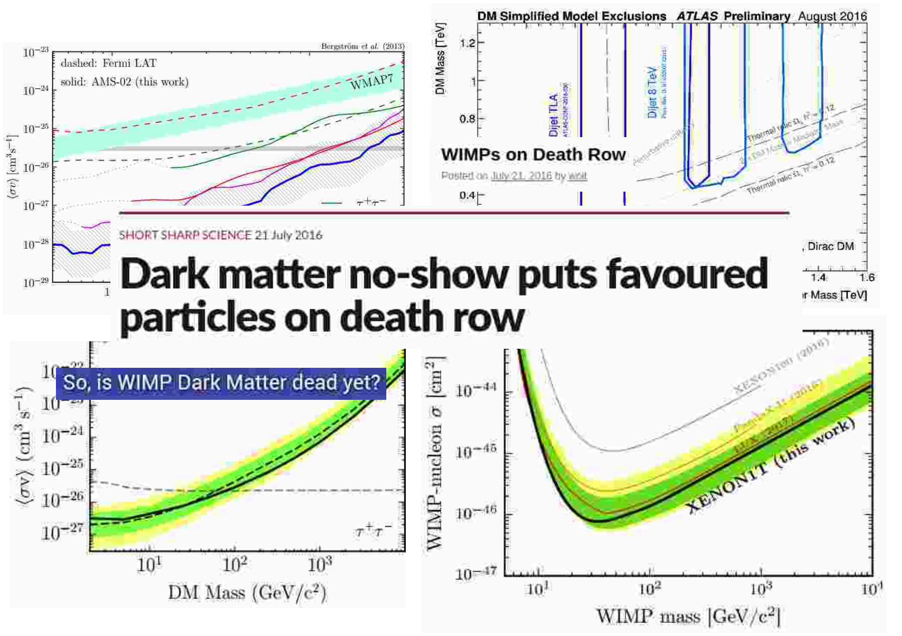

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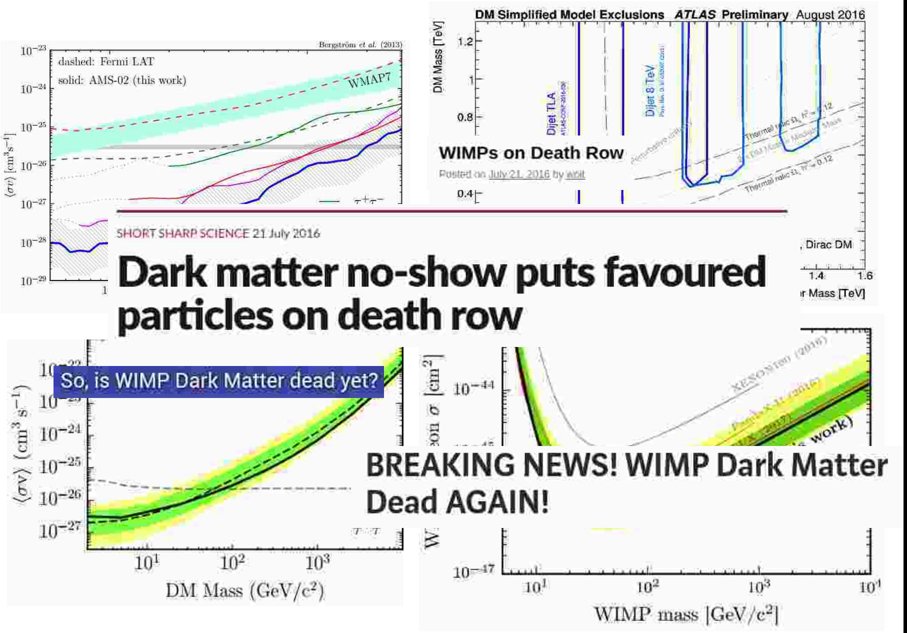
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DM Mass (GeV/c²)
BREAKING NEWS! WIMP Dark Matter Dead AGAIN!
WIMP mass [GeV/c²]

Annihilation scale as decisive test

- Scattering (direct detection) and production (colliders):
  there is not a well-defined scale because only some of the branching ratios or aspects of the interaction are being considered.

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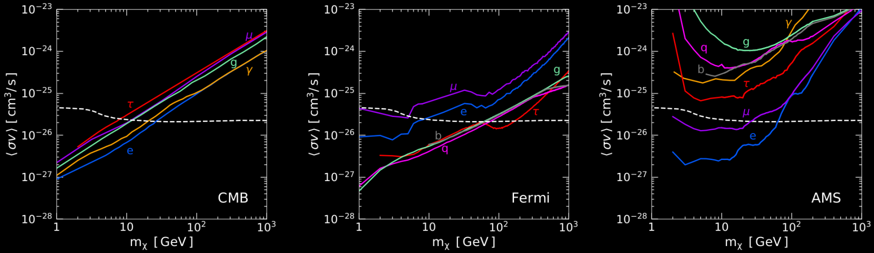
- Scattering (direct detection) and production (colliders): there is not a well-defined scale because only some of the branching ratios or aspects of the interaction are being considered.

- 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, which sets a well-defined scale for the total cross section.



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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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.

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

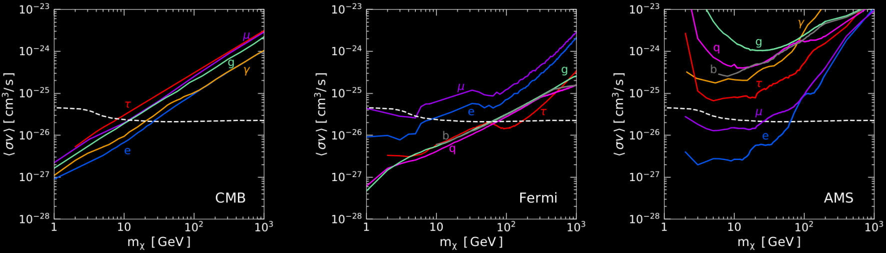
We perform the first calculation of the model-independent upper limit on the thermal WIMP cross section from data.

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

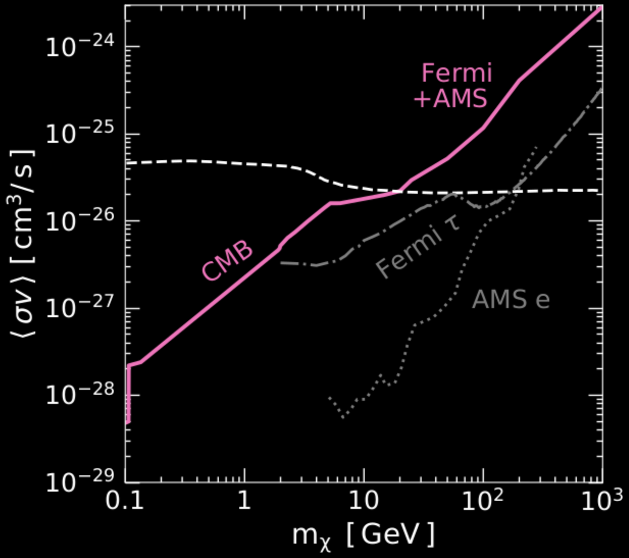
Method

- Consider most generic and accessible cases: $2 \to 2$ 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

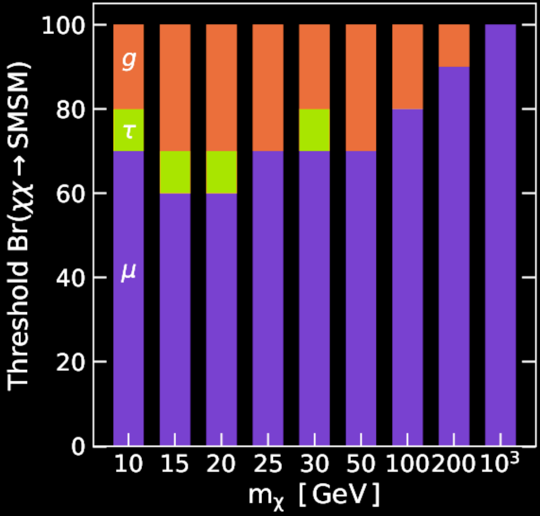
Total Annihilation Cross Section Limit?



Total Annihilation Cross Section Limit



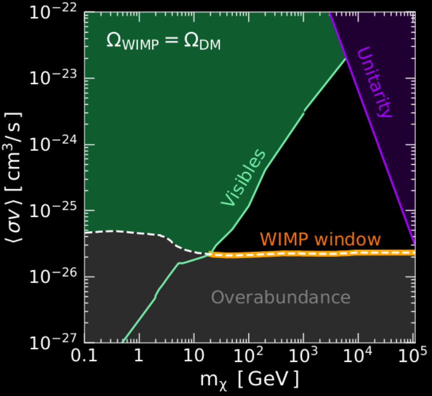
Threshold Exclusion Branching Fractions

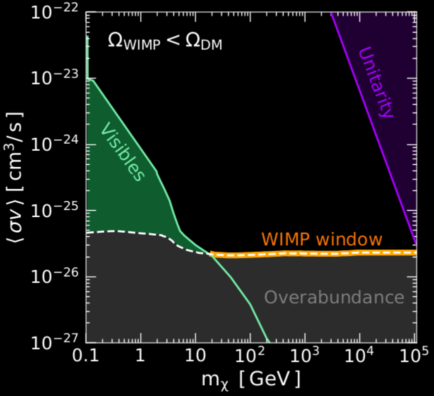


Implications for DM models

- Any DM below $\sim$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 $\sim$6 years of data

AMS:

- Constraints based on shorter exposure time, $\sim$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 $\sim$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

Back up slides

Cosmic-Ray Propagation

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

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

where D is the spatial diffusion coefficient, parametrized as

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

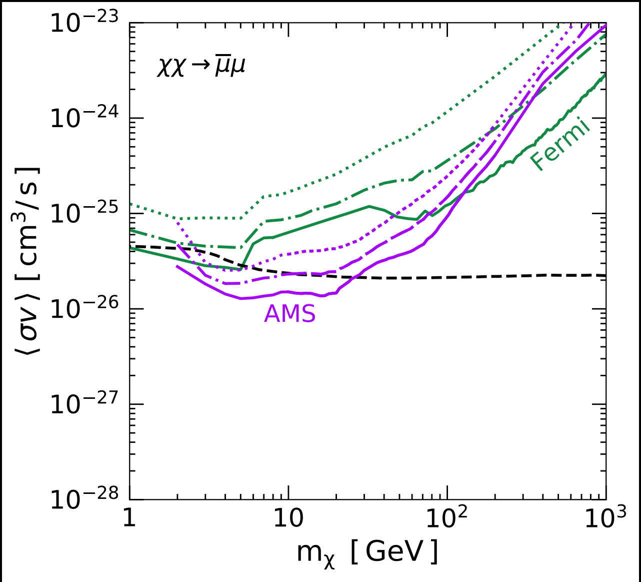
where $\rho = p/(Ze)$ is the rigidity of the charged particle with $Z = 1$ for electrons and positrons. The diffusion is normalized by D_0 at the rigidity $\rho_0 = 4$ GV. We assume the diffusion zone is axisymmetric with thickness $2z_t$.

$$Q_\chi(p, r, z) = \frac{\rho_\chi^2(r) \langle \sigma v \rangle}{2 m_\chi^2} \sum_f Br_f \frac{dN^f}{dE} .$$

Cosmic-Ray Propagation

- Model parameters: $z_t = 4$ kpc, $D_0 = 2.7 \times 10^{28}$ cm^2/s, $\delta = 0.6$
- Take the local DM density to be the maximally conservative $\rho = 0.25$ GeV/cm^3, with an NFW profile.
- Set the magnetic field at the Sun to be $B_\odot = 8.9\,\mu$G, which means that the local radiation field and magnetic field energy density is 3.1 eV/cm^3. Higher than the common conservative value of 2.6 eV/cm^3
- 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.

Statistics



$\chi\chi \to \overline{\mu}\mu$
Fermi
AMS
$\langle \sigma v \rangle$ [cm^3/s]
m_χ [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
1
10
10^2
10^3

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 $e^{\pm}/\gamma$ 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 $e^{\pm}/\gamma$ 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.

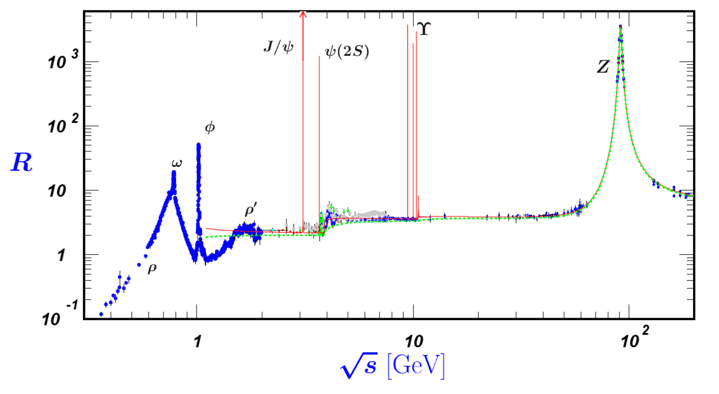
Escape Models

- 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 prefered types of models, or which aspects of annihilation are priority to improve

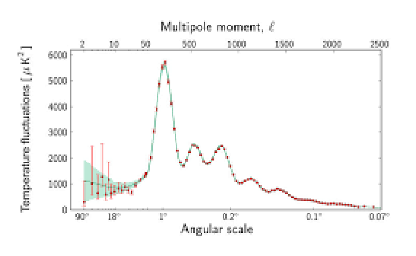
Below 5 GeV

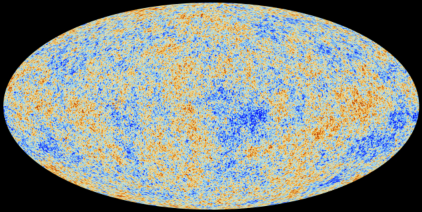


R
10^3
10^2
10
1
10^{-1}
1
10
10^2
$\sqrt{s}$ [GeV]
J/ψ
$\psi(2S)$
Υ
Z
ϕ
ω
ρ'
ρ

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.





Sub-dominant WIMP content

Ann cross section and the density are often considered as independent, and are related to the astrophysical flux F as

$$F = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int \rho_\chi^2 d\ell, \tag{1}$$

where ρ_χ is the DM density, and ℓ is the line of sight. The upper limit is obtained from upper limits on F, i.e.,

$$\langle \sigma v \rangle < \langle \sigma v_{\rm limit} \rangle \equiv F \, \frac{8\pi m_\chi^2}{\int \rho_\chi^2 d\ell}. \tag{2}$$

Sub-dominant WIMP content

For sub-dominant WIMP DM, if the WIMP density is completely determined by the annihilation cross section, they are no longer independent, as

$$\rho_{\rm WIMP}\langle\sigma v_{\rm WIMP}\rangle = \rho_\chi\langle\sigma v_\chi\rangle, \tag{3}$$

where $\langle\sigma v_\chi\rangle \sim 3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ is the thermal relic cross section. The annihilation flux from the sub-dominant WIMP is then

$$\begin{aligned} F &= \frac{\langle\sigma v_{\rm WIMP}\rangle}{8\pi m_\chi^2}\int \rho_{\rm WIMP}^2\, d\ell \\ &= \frac{\langle\sigma v_{\rm WIMP}\rangle}{8\pi m_\chi^2}\int \left(\frac{\sigma v_\chi \rho_\chi}{\langle\sigma v_{\rm WIMP}\rangle}\right)^2 d\ell \\ &= \frac{\langle\sigma v_\chi\rangle^2}{\langle\sigma v_{\rm WIMP}\rangle}\frac{1}{8\pi m_\chi^2}\int \rho_\chi^2\, d\ell. \end{aligned} \tag{4}$$

Therefore, an upper limit on the flux implies

$$\frac{\langle\sigma v_\chi\rangle^2}{\langle\sigma v_{\rm WIMP}\rangle} < \langle\sigma v_{\rm limit}\rangle, \tag{5}$$

Limits on Ionizing Particles

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

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

determines the strength of the CMB limit.

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

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

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

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

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,

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

  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 $B_\odot = 8.9\,\mu$G at the Sun
- Take largest value of the solar modulation potential, $\Phi = 0.6$ GV, measured for AMS during its data-taking period
- The local DM density is in range $\rho = [0.25, 0.7]$ GeV/cm^3. Take lowest density of $\rho = 0.25$ GeV/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 ($\lesssim 50$ GeV).
    - not one of the key threshold channels; the weakest channels from each experiment are what set the combined limit

Fit to Data

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

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

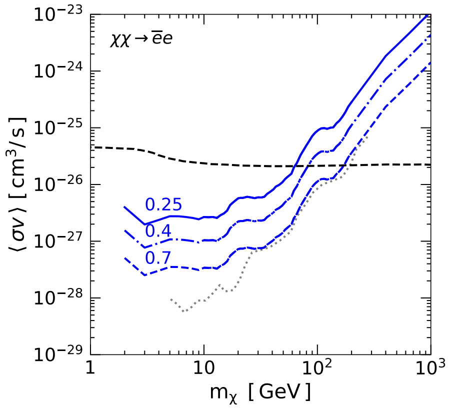
where $\theta = \{\theta^1, \theta^2, ..., \theta^n\}$ are parameters in the best fit polynomial function, and the $\chi^2(\theta)$ is given by

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

- 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

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

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