Constraining annihilating Dark Matter with the Cosmic Microwave Background

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Based on arXiv:1303.xxxx [hep-ph],
with **Laura Lopez-Honorez** (Vrije U. Brussels),
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Outline

1. Why Annihilating Dark Matter?
2. Why the CMB?
3. DM vs CMB
4. Analysis and Results
5. Conclusions

I. Why Dark Matter

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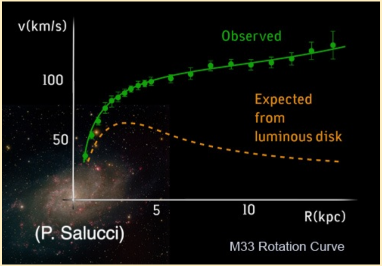
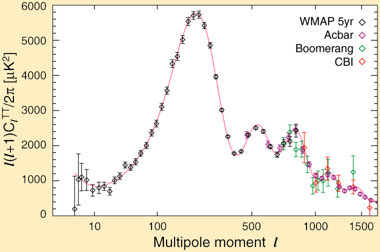
1970's: Ruben et al. find that rotation curves of gases in **galaxies** are too fast for visible mass



(an incomplete list of) further evidence

Cosmic microwave background (**CMB**) observations imply a large non-baryonic matter component to account for acoustic oscillations.



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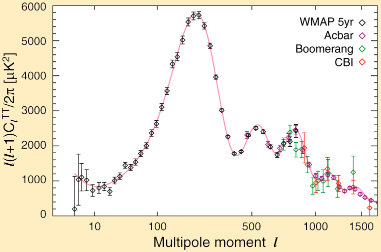
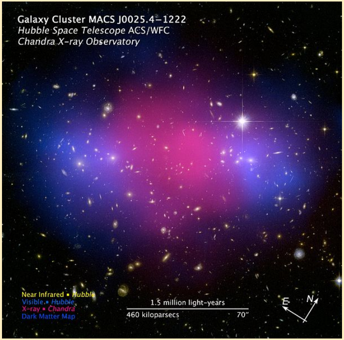


Gravitational lensing, in particular of colliding clusters implies separate baryonic and lensing components.



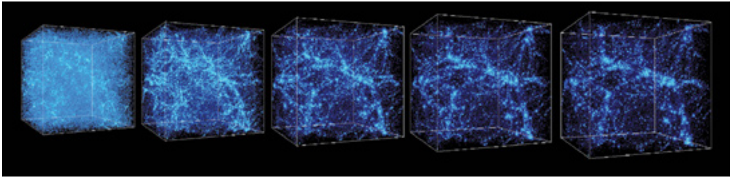
(image: not the bullet cluster!)

What is dark matter?

From gravity, we know it must have

- Galaxies + CMB: very **small self-interaction** cross-section (to form "fluffy" structures);
- CMB, lensing: Very **small interaction with the SM** ;
- CMB, LSS: Massive enough to be **non-relativistic** (CDM) or **mildly relativisitic** (WDM) at decoupling;
- Abundance (where $\Omega_i = \rho_i/\rho_c$):

$$\Rightarrow \frac{\Omega_{DM}}{\Omega_{SM}} = \frac{0.111h^{-2}}{0.0226h^{-2}} = 4.9$$



Particle nature: the WIMP miracle

Freeze-out abundance ($\rho_{DM} \simeq \rho_{SM}$) depends on the **self-annihilation** rate. To get the proper abundance of DM today, we need a self-annihilation cross-section:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

...which is about the same cross-section as processes interacting via the **electroweak force**.

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Whatever the channel, a thermal origin implies ongoing interaction between WIMPs, from decoupling to the present-day halos.

Could we see such a signature?

what do we know about DM's particle properties?

- **Direct detection** experiments search for nuclear recoils caused by DM-SM collisions
- **Collider searches** (i.e. LHC) look for missing energy from collisions
- **Indirect searches** give us a multitude of opportunities:
  - Direct annihilation signals: dwarf galaxies, the GC (e.g. Fermi line)
  - Diffuse gamma rays
  - Neutrinos from the sun
  - Intergalactic heating
  - Excess antimatter (positrons, anti-deuterons, etc.)
  - the CMB...

II: The Cosmic Microwave Background

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- At high temperatures, the photons and baryons are tightly coupled.
- As expansion forces the fluid to cool, hydrogen recombines. Once $T \sim 0.1 \times 13.6$ eV, photons can no longer excite H atoms. They **decouple**, streaming away until the present.

CMB photons

- **Hot**, overdense regions emit higher-energy photons
- However, these are **redshifted** by the gravitational potential they escape (**Sachs-Wolfe** effect)
- Photons are further **doppler** shifted due to their relative motion
- **Integrated Sachs-Wolfe** causes further red/blue shifting.

$$\Theta|_{\mathrm{obs}} = \underbrace{(\Theta_0 + \psi)|_{\mathrm{dec}}}_{\mathrm{SW}} + \underbrace{\hat{n} \cdot \vec{v}_{\mathrm{b}}|_{\mathrm{dec}}}_{\mathrm{Doppler}} + \underbrace{\int_{\eta_{\mathrm{dec}}}^{\eta_0} d\eta \, (\phi' + \psi')}_{\mathrm{ISW}}$$

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CMB photons have a **long way** to travel from last scattering. What if there's an extra source of energy along the way from DM? Will it increase their chance of rescattering? **Can we detect it?**

III. Energy deposition into the IGM from annihilating DM

The energy injected into the IGM is quite straightforward

$$\left(\frac{dE}{dVdt}\right)_{\rm injected} = m_\chi n_\chi(z)^2\langle\sigma v\rangle$$
$$= (1+z)^6(\Omega_{DM}\rho_c)^2\frac{\langle\sigma v\rangle}{m_\chi},$$

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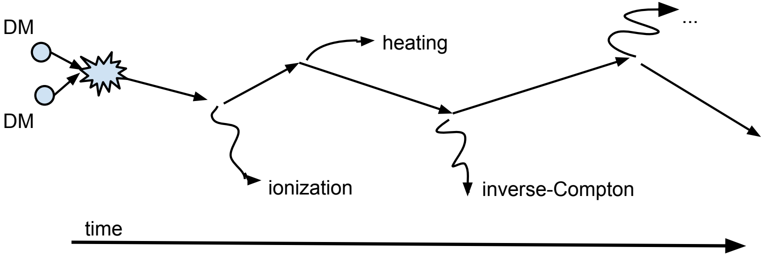
Deposited energy is a different story

- Final-sate invisible particles (*e.g.* neutrinos) do not heat the IGM
- Deposition efficiency will depend on the transparency of the IGM to the daughter particles i at each redshift z and energy E_i.
- Heating and ionization are due to electromagnetic processes. Therefore the final states that matter are electrons, positrons and photons.

Energy deposition into the IGM

Proper calculation of the deposition efficiency

1. At a given redshift z, calculate the final-state spectrum dN_i/dE_i for $i = \{e^+, e^-, \gamma\}$
2. Calculate the energy loss to (inverse) Compton scattering, Coulomb scattering, (photo) ionization or pair-production for each species.
3. Step forward to the next value of z, given the new $E_i = E_{i,0} - E(z)'dz$, including loss to IGM and to redshift.
4. Repeat.



Energy deposition into the IGM

From this process, one can build a transfer matrix $T_i(z', z, E_i)$ (*Slatyer 2012*) which gives the fraction of the initial energy E_i **injected** at redshift z' that is **deposited** into the IGM at redshift z. Then we can rewrite our previous equation:

$$\left(\frac{dE}{dVdt}\right)_{\rm deposited} = f(z, m_\chi)(1+z)^6(\Omega_{DM}\rho_c)^2\frac{\langle \sigma v\rangle}{m_\chi}, \quad (1)$$

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where

$$f(z, m_\chi) = \frac{\sum_i \int dz' \frac{(1+z')^2}{H(z')} \int T_i(z', z, E_i) E_i \frac{dN}{dE_i} dE_i}{\frac{(1+z)^3}{H(z)} \sum_i \int E \frac{dN_i}{\mathrm{d}E_i}(m_\chi) dE_i}$$

Numerator: properly computed energy deposition.
Denominator: normalization to (1).

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Time $\leftrightarrow$ redshift;
Injected energy spectrum from annihilation;
Physics of the intergalactic medium.

Energy deposition into the IGM

The energy deposition efficiency depends on *energy* and *redshift*

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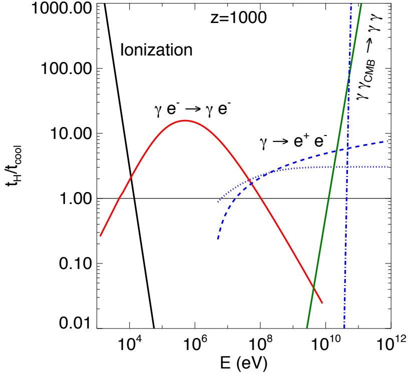

Slatyer et al. 2009

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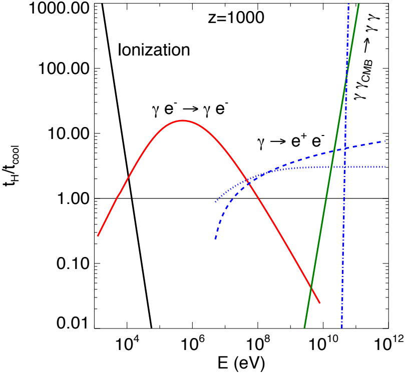

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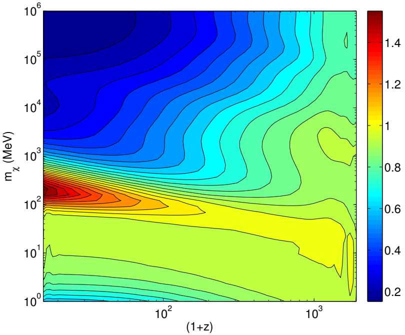

$f(z, m_\chi)$

Energy injection effect on CMB photons

Extra deposited energy causes **heating** and **ionization**:

$$\frac{dT_{\rm m}}{dz} = -\frac{1}{(1+z)H(z)}\frac{2}{3k_B}\frac{g_{\rm h}(z)}{N_{\rm H}(z)[1+f_{\rm He}+X_{\rm e}]}\left(\frac{dE}{dtdV}\right)_{\rm deposited} ;$$

$$\frac{dN_{\rm 1s}^{\rm H\,I}}{dz} = \frac{1}{(1+z)H(z)}\frac{1}{N_{\rm H}(z)[1+f_{\rm He}]}\frac{\tilde{g}_{\rm ion}^{\rm H}(z)}{E_{\rm ion}^{\rm H\,I}}\left(\frac{dE}{dtdV}\right)_{\rm deposited} ;$$

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$f_{\rm He}$	Helium fraction;
$E_{\rm ion}^i$	Ionization potential;
$g_h, g_{\rm ion}^i$	heating and ionization efficiencies.

Early Times: The ionization floor

- Dark matter annihilation rate is proportional to $(1+z)^6$, which leads to a dependence of
$$\sqrt{1+z} \quad (2)$$
for the heating and ionization rates. Therefore dominates in the early Universe. Around $z = 1100$, the extra energy injection has the effect of **delaying recombination**.

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- This can be disentangled by late-time effects.

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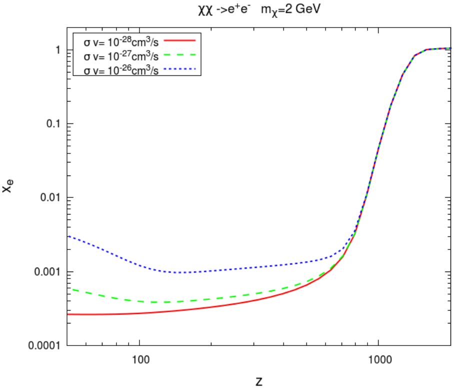

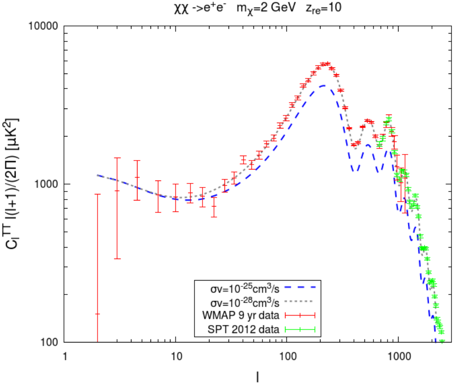

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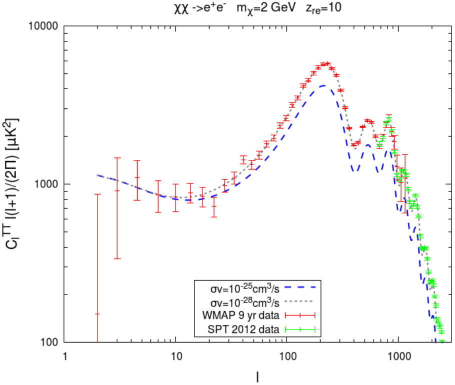
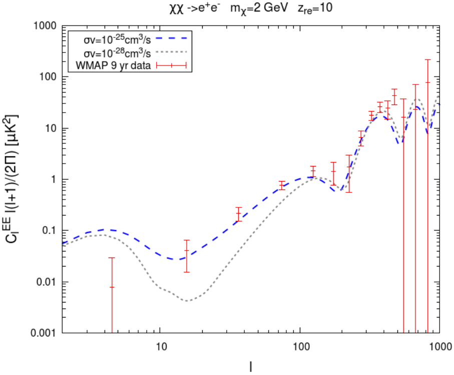
- Affect the reionization history, which changes the **polarization** spectrum. Rescattering at low redshift:
  - Decreases polarization (as well as temperature) correlations on small scales (large l)
  - Increases polarization correlations on large scales ($l \sim 2 - 200$) since only certain polarizations are rescattered toward us (like the sky).

Late times



Temperature



polarization

Late times: the influence of Halos

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$$n^2 \propto \int \mathrm{d}M \frac{\mathrm{d}N_{halos}}{\mathrm{d}M}(z, M)\tilde{g}(c_\Delta(M,z))\frac{M\Delta\rho_c(z)}{3}.$$

- $\frac{\mathrm{d}N_{halos}}{\mathrm{d}M}(z, M)$: halo mass function
- $\tilde{g}(c_\Delta(M,z))\frac{M\Delta\rho_c(z)}{3}$: enhancement of individual halos of mass M. Computed by integrating over an NFW profile:

$$\int_0^{r_\Delta} dr\, 4\pi r^2\, \rho^2_{\mathrm{NFW}}(r) = \tilde{g}(c_\Delta)\, \frac{M\,\Delta\,\rho_c(z)}{3};$$

$$\rho_{\mathrm{NFW}}(r) = \rho_s\, \frac{4}{(r/r_s)\,(1+r/r_s)^2}$$

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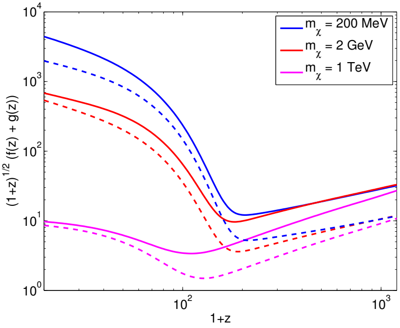
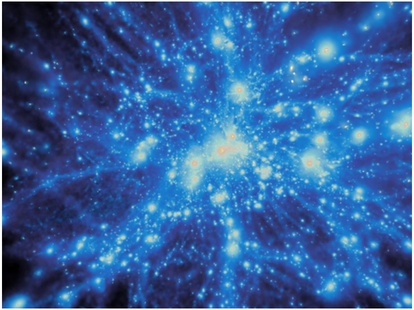
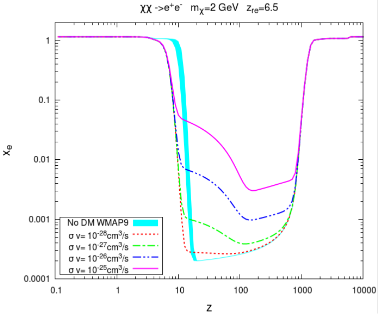
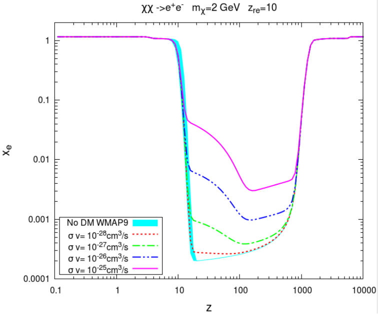
For the halo mass function $\frac{\mathrm{d}N_{halos}}{\mathrm{d}M}(z, M)$, we use a parametrization of the results from the Multidark (BigBolshoi) simulation:





Full effect on the ionization history





IV: Analysis

To properly constrain the DM cross-section, we perform a full Monte-Carlo for each m_χ over:

Ω_b	the baryonic content of the Universe;
Ω_{CDM}	the dark matter content of the Universe;
z_{reio}	the time of reionization;
n_s	the scalar spectral index;
A_s	he primordial power spectrum;
$\langle \sigma v \rangle$	the DM self-annihilation cross-section.

For the numerics, we use CAMB, CosmoRec with CosmoMC for the Monte-Carlo.

This allows us to extract 2σ (95% c.l.) constraints on the thermally-averaged cross-section.

Analysis

We use the following data:

- Nine-year WMAP CMB data;
- South Pole Telescope (Dec. 2012) CMB data;
- BAO measurements from BOSS DR9, LRG (DR7) 6dF Galaxy Survey and WiggleZ (different redshifts);
- Hubble Space Telescope (constraints on H_0).

...and nuisance parameters:

- Sunyaev–Zel'dovich contribution A_{SZ};
- Amplitude of clustered point-source contribution A_C;
- Amplitude of Poisson-distributed point sources A_P.

The Model

We consider two channels of self-annihilating dark matter:

$$\chi\chi \rightarrow e^+e^-$$

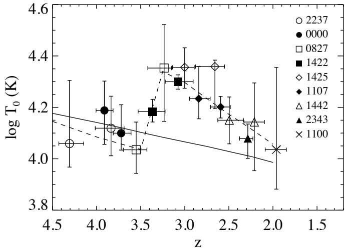
and

$$\chi\chi \rightarrow \mu^+\mu^-$$

These "leptophilic" channels will be the **most constrained**, since IGM heating is an **electromagnetic** process. Also interesting because they have been invoked to explain "anomalies" observed by PAMELA (high-E e^+), INTEGRAL (low-E e^+) and ARCADE (excess diffuse radio from synchrotron).
For many more channels see *e.g.* estimates by Cline & Scott 2013.

Further constraints: T_{IGM}

The matter temperature of the intergalactic medium at redshifts $2 - 5$ has been measured by Ly-α observations:



Schaye et al. 2000

This can be used (*e.g. Cirelli et al 2009*) to constrain the amount of energy injected by DM.

Further constraints: the Gunn-Peterson observations

Lyman-α observations also tell us that:

- At $z \gtrsim 6$, the universe was not yet fully ionized ($X_H \geqslant 10^{-3}$)
- By $z = 5.5$, reionization was nearly complete ($X_H \leqslant 10^{-4}$)

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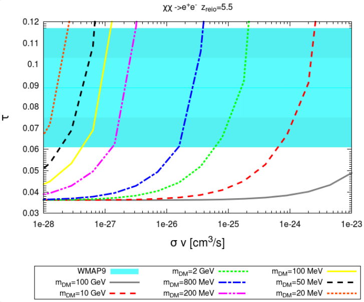
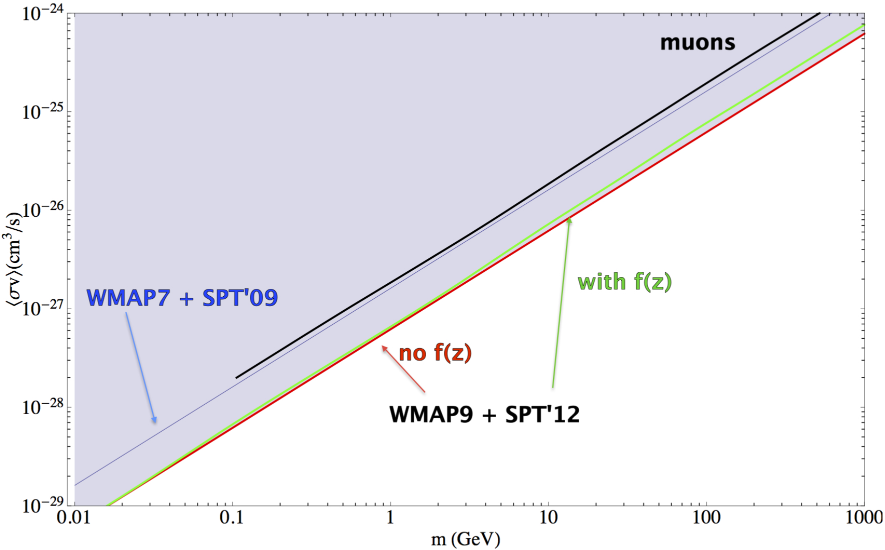
- This is in **conflict** with WMAP measurements of the reionization optical depth τ, which favour $z_{\rm reio} \sim 10$.
- However, annihilating dark matter can increase τ, bringing WMAP and Gunn-Peterson observations back into agreement! (see *e.g. Lesgourgues 2012*)
- Unfortunately, the values of $\langle \sigma v \rangle$ required to do so are, we will see, **badly excluded**

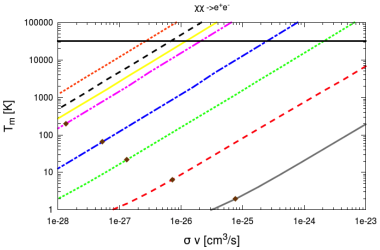


Results

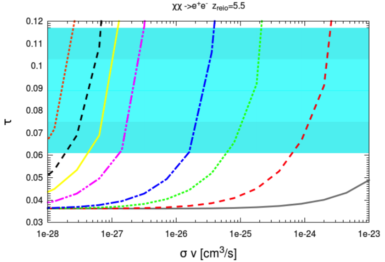


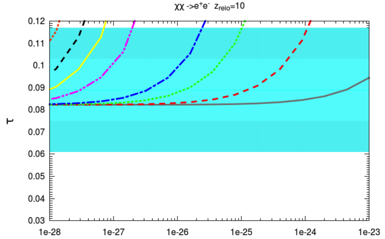
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
$\langle\sigma v\rangle(\mathrm{cm}^3/\mathrm{s})$
0.01
0.1
1
10
100
1000
m (GeV)
muons
WMAP7 + SPT'09
with f(z)
no f(z)
WMAP9 + SPT'12

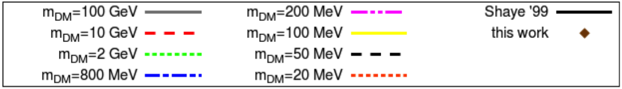
Results: T_m and τ (Top: $z_{\rm reio} = 5.5$; Bottom: $z_{\rm reio} = 10$)



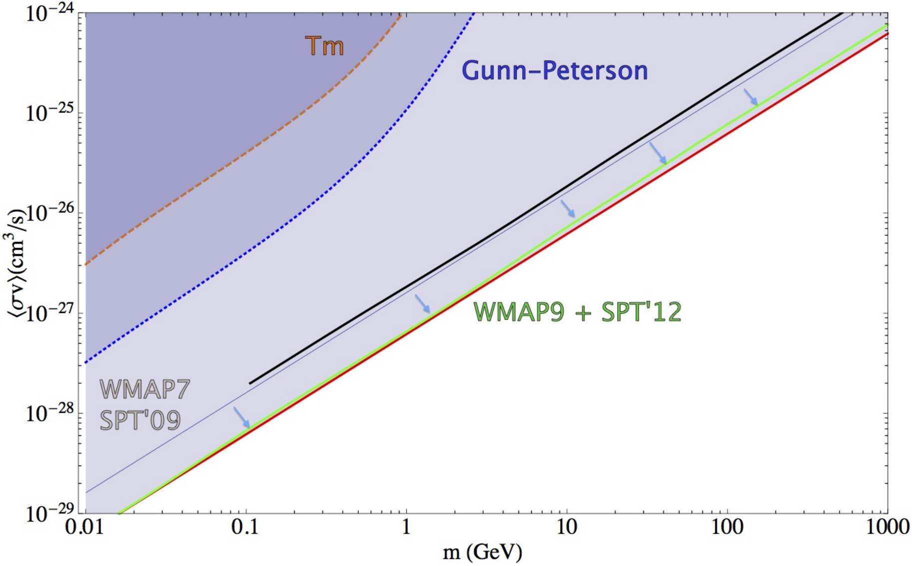
(T from reionization not included)







Results: all together



Results: Salient points

- Improvement by a factor of ~ 3 over WMAP7/SPT'09 bounds.
- T_m, Gunn-Peterson bounds less constraining than CMB temperature and polarization data
- This means that early universe (broadening of last scattering surface) effects dominate over late-time (halo formation) effects
- Gunn-Peterson and WMAP cannot be brought back into agreement by using allowed $(m_\chi, \langle \sigma v \rangle)$ combinations.

V. Conclusions

- We have explored the effect of annihilating dark matter on the CMB temperature and polarization power spectra.
- We have included a full description of time- and energy-dependent deposition of DM energy into the IGM.
- Improved constraints by using CMB (WMAP9 + SPT), Ly-α (T and τ) and BAO surveys.
- Excluded annihilating $\chi\chi \to e^+e^-$ with the thermal abundance cross-section for $m_\chi \lesssim 30$ GeV.
- Ibid. for $\chi\chi \to \mu^+\mu^-$ for $m_\chi \lesssim 10$ GeV.
- t minus 1 week for Planck data: let's see what they have in store for us!

Priors

Parameter	Prior
$\Omega_b h^2$	$0.005 \to 0.1$
$\Omega_c h^2$	$0.01 \to 0.99$
Θ_s	$0.5 \to 10$
$z_{\rm reio}$	$6 \to 12$
n_s	$0.5 \to 1.5$
$\ln(10^{10} A_s)$	$2.7 \to 4$
$\langle \sigma v \rangle / (3 \cdot 10^{-26} cm^3/s)$	$10^{-5} \to 10^{2.5}$

Table: *Uniform priors for the cosmological parameters considered here.*

halo mass function