Title: On Symmetric and Asymmetric Light Dark Matter

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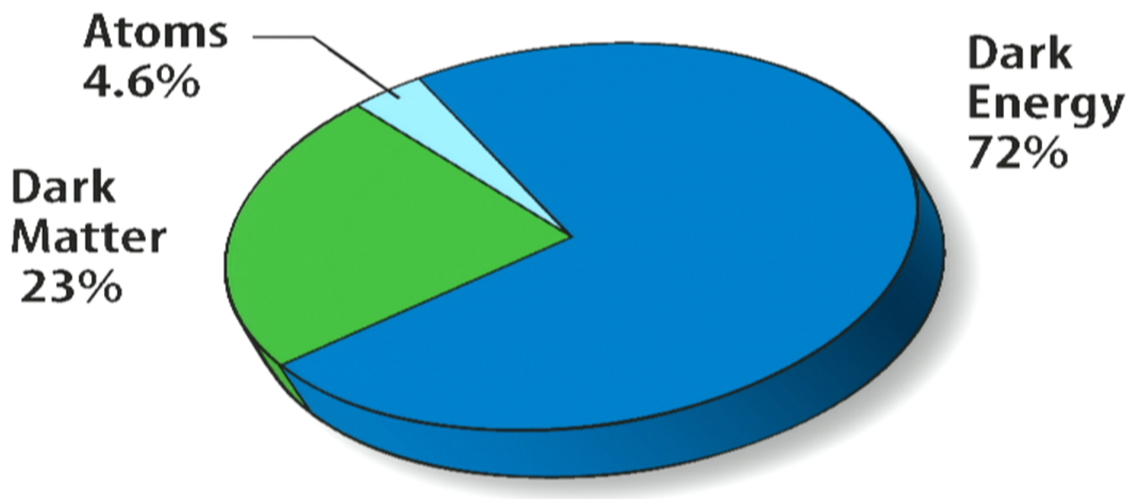
Abstract: I will discuss cosmological, astrophysical and collider constraints on thermal dark matter with mass in the range 1 MeV to 10 GeV. CMB observations can be evaded if the DM relic density is sufficiently asymmetric, while collider constraints generally require sufficiently light mediators. These light mediators can give rise to significant DM self-interactions, and I will describe bounds on such interactions from dark matter halo shapes. Finally, I will describe how these constraints map onto the parameter space of DM-electron and DM-nucleon scattering cross sections for direct detection.

There is a lot of dark matter

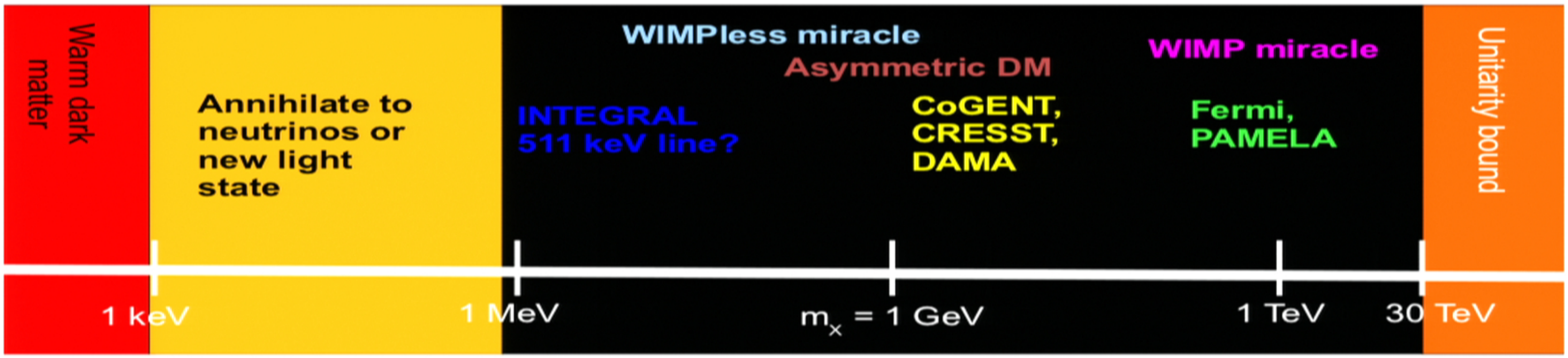


Questions: what is it? what is the origin of energy density and/or why is it 23%?

Wide range of experimental searches for wide range of dark matter models, though focus on WIMP

Light dark matter

"light" dark matter: $1\ \mathrm{MeV} \lesssim m_X \lesssim 10\ \mathrm{GeV}$



interesting phenomenology, not as well studied as WIMP

Symmetric and asymmetric light DM

- Dark matter (fermion): $X, \bar{X}$
- Mediator: ϕ_μ
- For simplicity, focus on mediator lighter than DM, $m_\phi < m_X$.
  (Different constraints are more important for $m_\phi > m_X$)
- Dark sector coupling g_X, mediator-SM coupling g_f:

$$\mathcal{L}_V = g_X \bar{X} \gamma^\mu X \phi_\mu + g_f \bar{f} \gamma^\mu f \phi_\mu + m_\phi^2 \phi^\mu \phi_\mu$$

- Assume thermal equilibrium in the early universe
- (Conserved) number asymmetry η_X, interpolate between symmetric and ADM

Symmetric and asymmetric light DM

Relic density depends on annihilation cross section $\langle\sigma v\rangle = \frac{\pi\alpha_X^2}{m_X^4}$ and number asymmetry η_X

Symmetric limit ($n_X = n_{\bar{X}}$):

$$\Omega_{\rm CDM} \approx 0.22 \frac{6 \times 10^{-26}\mathbf{cm}^3/\mathbf{s}}{\langle\sigma v\rangle}$$

Asymmetric limit (assume $n_X \gg n_{\bar{X}}$):

$$\Omega_{\rm CDM} \approx m_X \eta_X \frac{s_0}{\rho_c}$$

can explain why $\Omega_X/\Omega_b \approx 6$ if $\eta_X = \eta_B$ and $m_X \approx 6$ GeV.
Models: transfer operator, cogenesis, technibaryon dark matter...

Symmetric and asymmetric light DM

Freezeout happens when annihilation rate is too slow compared to expansion

Symmetric case: number density drops exponentially when $T \lesssim m_X$. If $\eta_X \neq 0$, (comoving) number density of asymmetric component is constant. Generally:

$$\Omega_{\rm CDM} \approx m_X \eta_X \frac{s_0}{\rho_c} \quad \text{(+ symmetric thermal abundance)}$$

symmetric part is exponentially suppressed,

$$r_\infty \equiv \frac{n_{\bar{X}}}{n_X} \simeq \exp\left(-m_X \eta_X \langle \sigma v \rangle \frac{0.264 M_{\rm pl}\sqrt{g_*}}{x_f}\right)$$

$$\Omega_X = \frac{1}{1-r_\infty} \frac{\eta_X m_X s_0}{\rho_c}, \quad \Omega_{\bar{X}} = \frac{r_\infty}{1-r_\infty} \frac{\eta_X m_X s_0}{\rho_c}$$

Talk outline

1. CMB constraints on annihilation cross section
2. Halo shape constraints on DM self-interaction
3. Direct detection of light dark matter

CMB Constraints

1. robust prediction/constraint on DM annihilation
   — doesn't depend on late-time astrophysics
   — can derive general, model-independent bounds
   — degeneracies with cosmological parameters
2. strong constraint on light DM, power $\propto 1/m_X$
   — will improve by up to factor of 10 with Planck data
3. implies minimum annihilation cross section for ADM, and thus minimum coupling α_X

Note: bounds apply for both heavy and light mediator

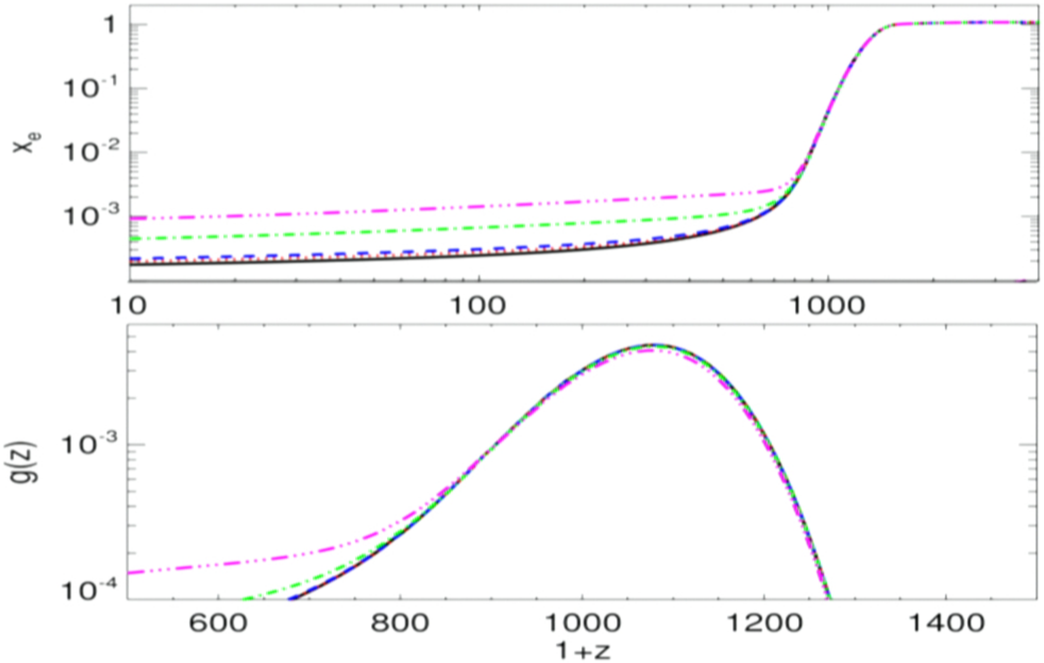
Effect of DM annihilation on CMB

CMB is sensitive to ionization history of universe, and thus measures energy injection from DM annihilation

- Universe became transparent around redshift 1100 (photons and electrons stopped scattering)
- Residual fraction of atoms still ionized
- DM annihilation increases residual ionization fraction

(Chen and Kamionkowski, Padmanabhan and Finkbeiner)

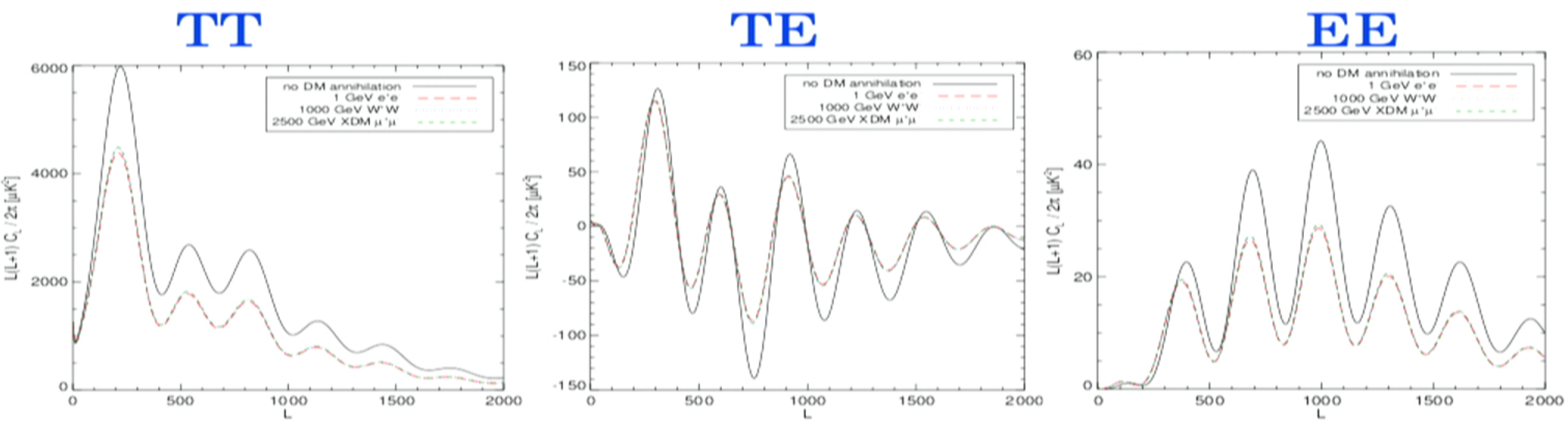
Effect of DM annihilation on CMB



Surface of last scattering is broader

Effect on CMB temperature (T), polarization (E) anisotropies

Correlations suppressed - damping of modes



Constrained by WMAP, polarization important for Planck

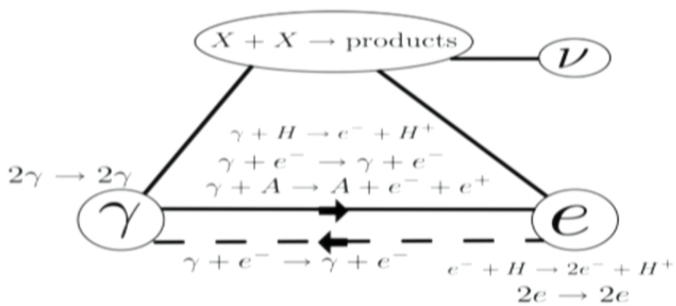
Rate of energy deposited by DM

Symmetric case:

$$p_{\rm ann}(z) = f(z)\frac{\langle\sigma v\rangle}{m_X}$$

$f(z)$ - **"efficiency", effective** $f \approx$ **0.2 -0.9**

- **neutrinos interact weakly**
- **some photons just redshift**

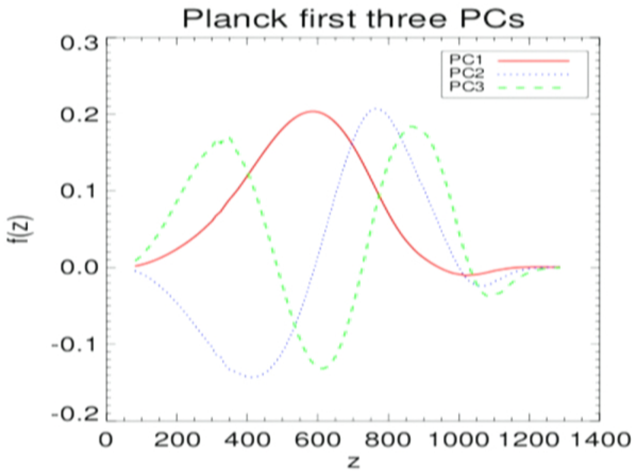


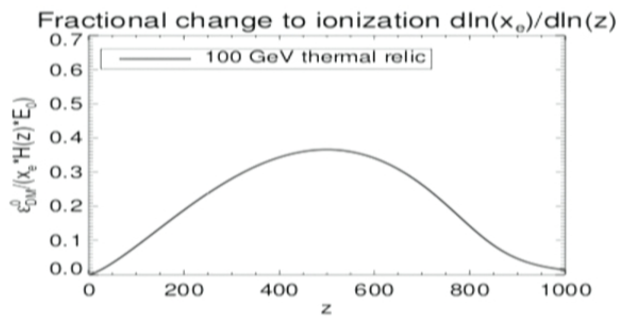
EM cascade: effect on CMB isn't very sensitive to spectrum of annihilation products, only total energy

Aside: more general treatment of problem

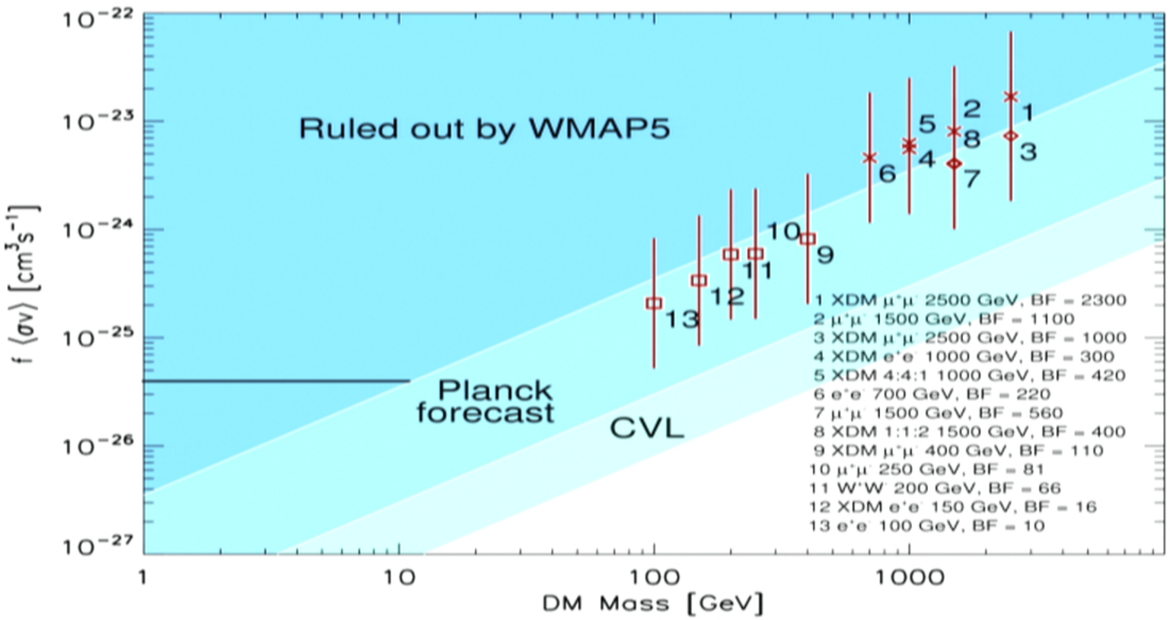
Finkbeiner, Galli, Lin, Slatyer 2011:

- "universal" $p_{\rm ann}(z) \propto e_{\rm WIMP}(z)$ for most WIMP models
- up to 3 parameters can describe general $p_{\rm ann}(z) = \sum_i \varepsilon_i e_i(z)$ for Planck





Constraints - symmetric case



Interesting constraints on: light ($m_X < 10$ GeV) dark matter, Sommerfeld-enhanced dark matter models
Galli et al. 2009, Slatyer et al. 2009

Rate of energy deposited by DM

Symmetric:

$$p_{\rm ann}(z) = f(z)\frac{\langle \sigma v\rangle}{m_X}$$

Asymmetric:

$$p_{\rm ann}(z) = \frac{2r_\infty}{(1+r_\infty)^2} f(z)\frac{\langle \sigma v\rangle}{m_X}$$

Exponentially suppressed symmetric (thermal) component

$$r_\infty \equiv \frac{n_{\bar{X}}}{n_X} \simeq \exp\left(-m_X \eta_X \langle \sigma v\rangle \frac{0.264 M_{\rm pl}\sqrt{g_*}}{x_f}\right)$$

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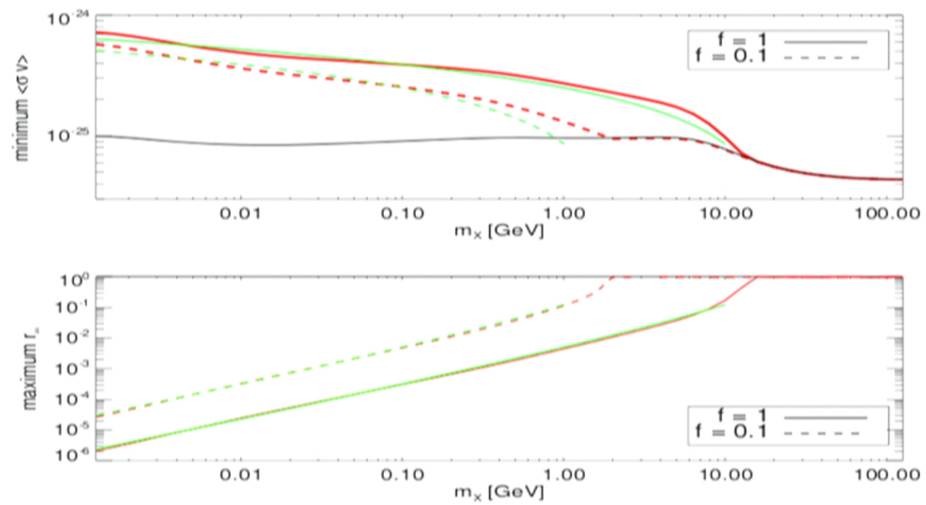
Minimum $\langle\sigma v\rangle$ for efficient annihilation of symmetric component

$$\langle\sigma v\rangle \gtrsim 5\times 10^{-26}\ \mathrm{cm^3/s}\ \ln\left(\frac{40f\ \mathrm{GeV}}{m_X}\right),\quad m_X \lesssim f\times 10\mathrm{GeV}$$



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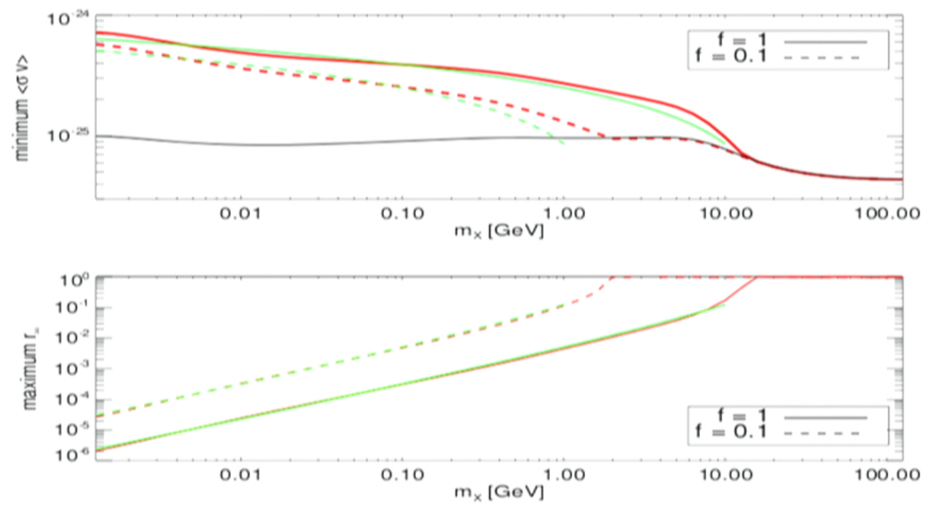

Summary of CMB constraints

- robust limits on DM annihilation through its effect on ionization history
- important for light DM (unless p-wave)
- light mediator: $\langle \sigma v \rangle = \frac{\pi \alpha_X^2}{m_X^4}$
- CMB limits imply minimum hidden sector coupling α_X

Light mediators means more DM self-scattering

- self-interactions affect DM halo shapes (ellipticity, cores)
- XX elastic scattering cross section (weighted by momentum transfer):

$$\sigma_T \approx \frac{4\pi\alpha_X^2 m_X^2}{m_\phi^4}$$

- bound on σ_T implies lower limit on m_ϕ

Physical effects of DM self-interactions

- Heat conduction in DM halos, transfer of kinetic energy between outer and inner parts
  – formation of cores (vs. cusps in ΛCDM)
  – lead to more isotropic halos (vs. elliptical)
- Spergel-Steinhardt: can improve agreement with observations of dwarf galaxies (but also constrained by other observations)

Assume hard-sphere scattering (justify later).

Velocity-dependent scattering: Loeb and Weiner 2011.

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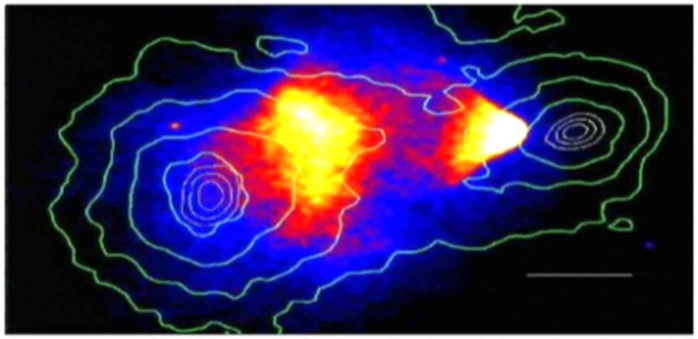
Bullet Cluster



Markevitch et al. 2003:

$$\sigma_T \lesssim 2 \times 10^{-24}\ \mathrm{cm}^2 \left(\frac{m_X}{1\ \mathrm{GeV}}\right)$$

Analytic estimate: $\frac{\Sigma_s}{m_X}\sigma_T \lesssim 1$ or $\frac{\rho}{m_X}\sigma_T v_{col} \lesssim 1/t_{col}$

Parameters:
$t_{col} \approx l_s/v_{col}, l_s \approx 100$ **kpc**, $v_{col} \approx 4000$ **km/s**, $\rho_s \approx .4\mathrm{GeV}/$**cm**^{3}

Supported by simulations of merger (Randall et al. 2007)

Elliptical DM cluster

Miralda-Escude 2001:

$$\sigma_T \lesssim 3 \times 10^{-26}\ \mathrm{cm}^2 \left(\frac{m_X}{1\ \mathrm{GeV}}\right)$$

Analytic estimate:

$$\Gamma_k = \int d^3v_1 d^3v_2 f(v_1) f(v_2) (n_X v_{\mathbf{rel}} \sigma_T)(v_{\mathbf{rel}}^2 / v_0^2) \propto n_X \sigma_T v_0$$

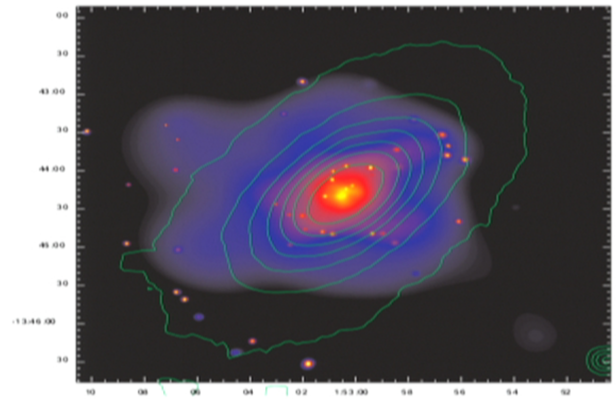
Parameters of galaxy cluster at around $r \approx 70$ kpc:

$$\rho_X \sim 1\mathrm{GeV}/\mathbf{cm}^3, v_0 \sim 1000\mathbf{km/s}$$

Supported by cosmological simulations in Yoshida et al. 2001

Elliptical DM halo

Elliptical Galaxy NGC720:
(Feng Kaplinghat Yu 2009.)



$$\sigma_T \lesssim 8 \times 10^{-27}\ \mathrm{cm}^2 \left(\frac{m_X}{1\ \mathrm{GeV}}\right)$$

see also: Buote et al. 2002,
Humphrey et al. 2006

Parameters of halo at around $r \approx 5$ kpc:

$$\rho_X \sim 4\ \mathrm{GeV/cm}^3, v_0 \sim 300\mathbf{km/s}$$

Warnings:

- Deriving bounds from one (special?) case
- Need simulations

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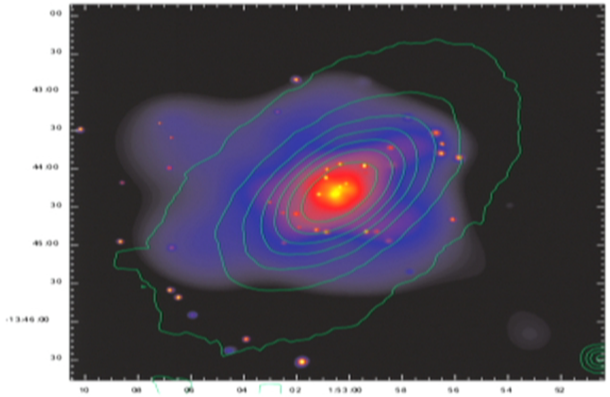

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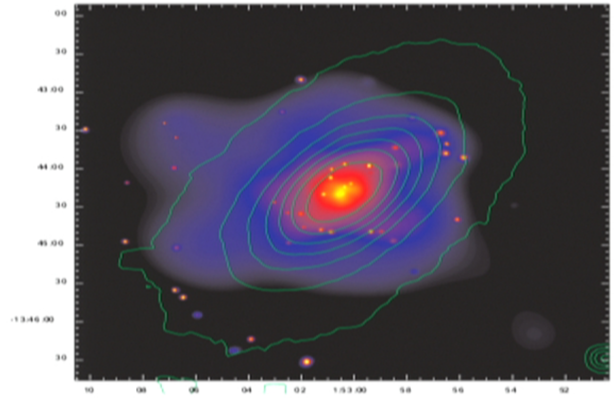

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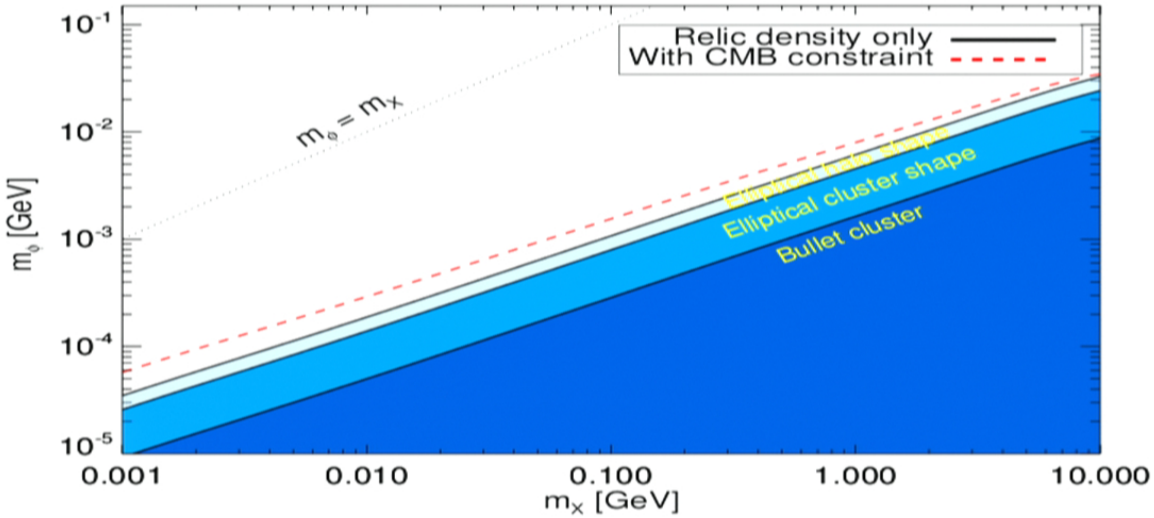
Halo shapes: lower bound on m_ϕ



NGC720: $m_\phi \gtrsim 10\ \mathrm{MeV} \left(\frac{\langle \sigma v \rangle}{10^{-25}\mathrm{cm}^3/\mathrm{s}}\right)^{1/4} \left(\frac{m_X}{\mathrm{GeV}}\right)^{3/4}$

(For this m_ϕ, assumption of short range interaction self-consistent.)

Talk outline

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2. Halo shape constraints on DM self-interaction
3. Direct detection of light dark matter

Direct detection of light dark matter

- Combine CMB, halo shape constraints (plus a few more) to derive range of direct detection cross sections
- Kinematics suggests two cases:
  - Electron scattering, 1 MeV $\lesssim m_X \lesssim$ 1 GeV
  - Nucleon scattering, 1 GeV $\lesssim m_X \lesssim$ 10 GeV

Focus on asymmetric dark matter (because of CMB bounds)

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Nucleon (spin-independent) scattering

$$\sigma_n = 4\alpha_X (3g_q)^2 \frac{\mu_n^2}{m_\phi^4}$$

- Upper bound
  – $\sigma_n = \frac{4\mu_n^2}{\sqrt{4\pi m_X}} \sqrt{\frac{\sigma_T}{m_X}} \left(\frac{3g_q}{m_\phi}\right)^2$
  – for kinetic mixing, upper bound on g_q/m_ϕ from muon anomalous magnetic moment
  – $\sigma_n \lesssim \times 10^{-34}$ cm^2
- Lower bound
  – minimum α_X from CMB
  – require $m_\phi < m_X$
  – minimum g_q from decay of ϕ by BBN
- "Large width"
  – minimum g_q from requiring hidden and dark sectors in thermal equilibrium

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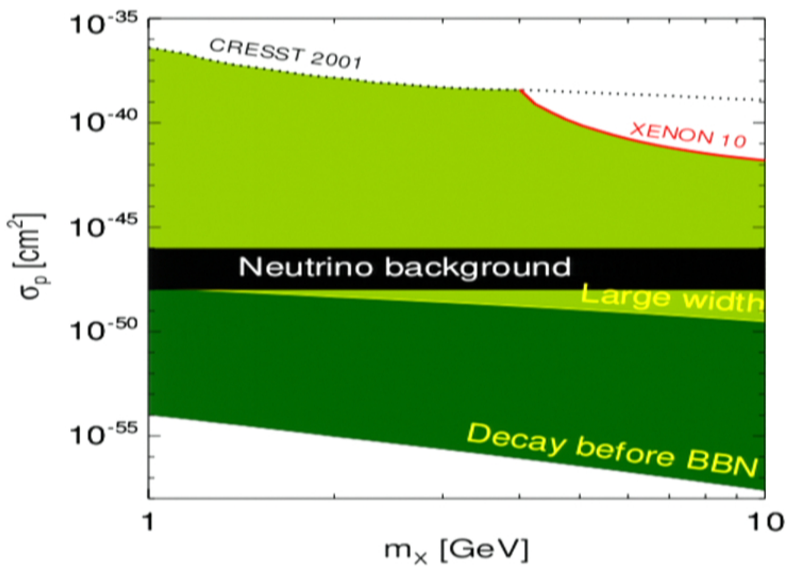
  – **minimum g_q from requiring hidden and dark sectors in thermal equilibrium**

Nucleon scattering

Upper bound is mostly irrelevant because of experimental constraints, lower bound is far below detection (neutrino background).



Electron scattering

$$1\ \text{MeV} \lesssim m_X \lesssim 1\ \text{GeV}$$

$$\sigma_e = 4\alpha_X (g_e)^2 \frac{\mu_n^2}{m_\phi^4}$$

Ionization from DM-electron scattering could be detected, single electron detection with Xe or Ge? (Essig, Mardon, Volansky 2011)

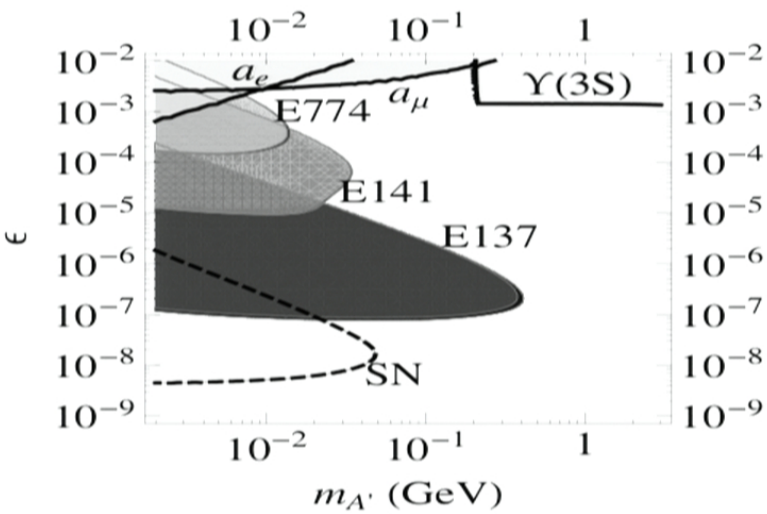
- Upper bound: halo shape, electron anomalous magnetic moment
- Lower bound: CMB bounds, mediator decay before BBN

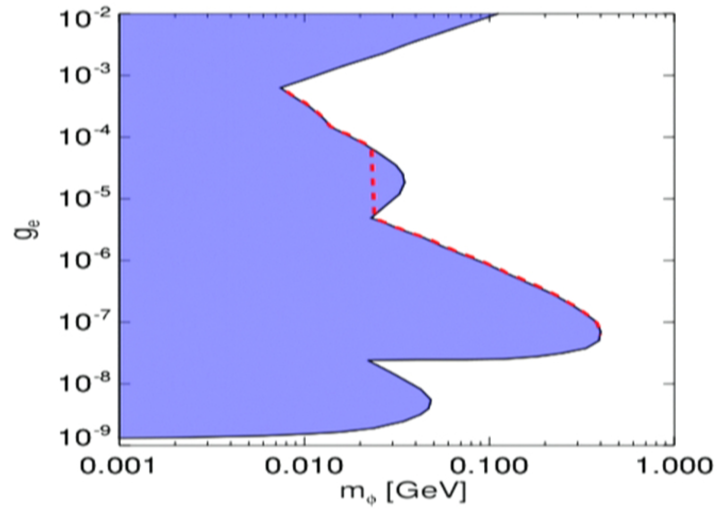
Also require $m_\phi > 2m_e$.

However, there are other strong constraints on light gauge bosons. (Loophole: unless they can decay to new very light states.)

Constraints on dark gauge bosons

Parameter space: (electron) coupling, mediator mass



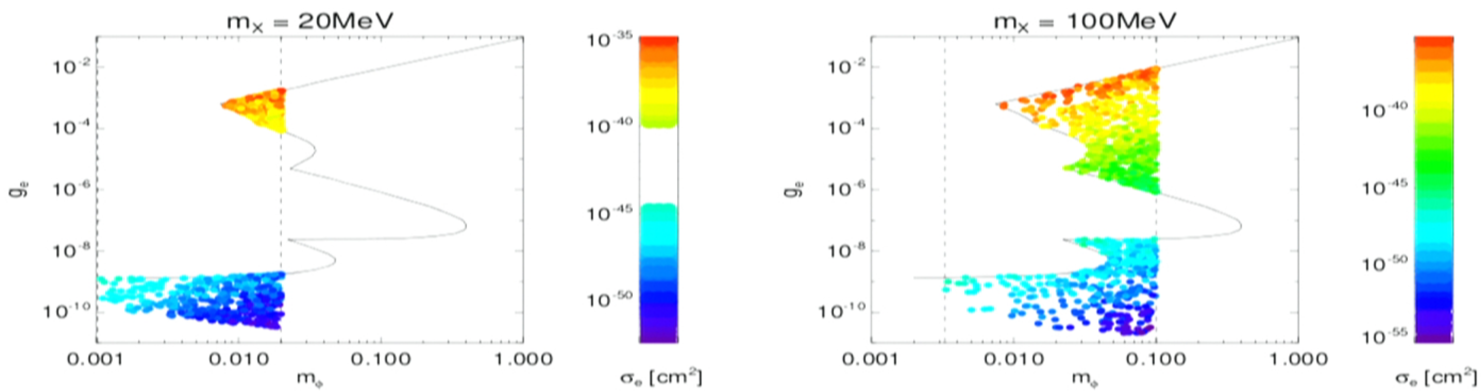


Left: Bjorken, Essig, Schuster, Toro 2009

We use constraints from: SN cooling, beam dump, electron anomalous magnetic moment.

Constraints on dark gauge bosons

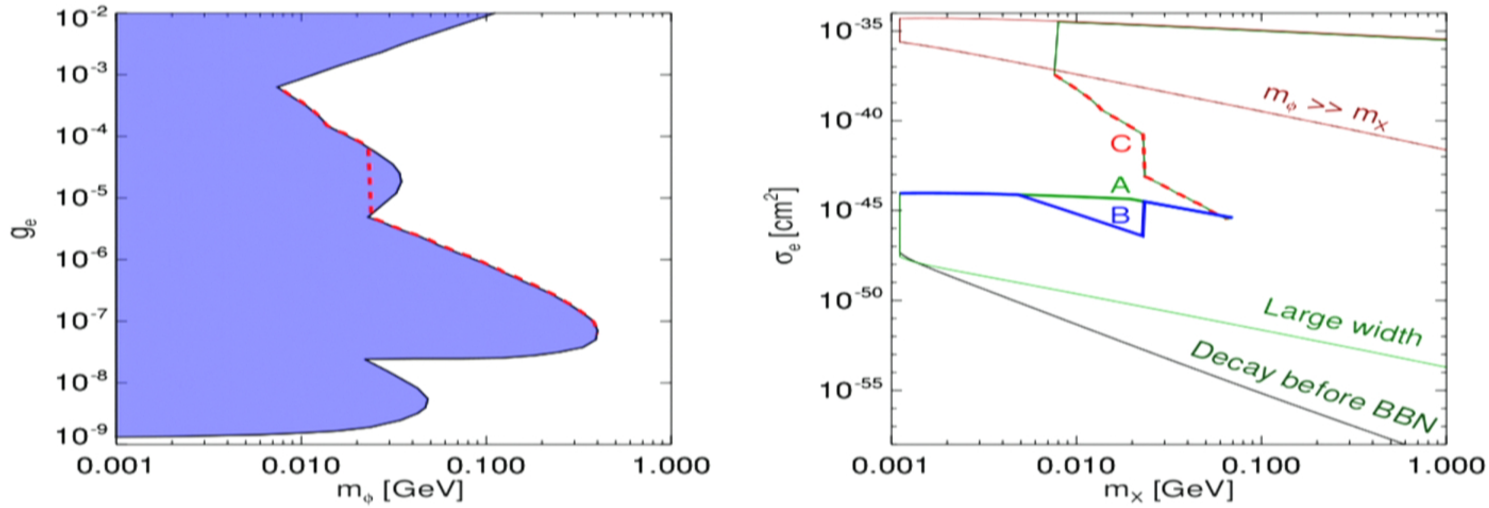
Scan over parameter space of (α_X, g_e, m_ϕ) subject to constraints.



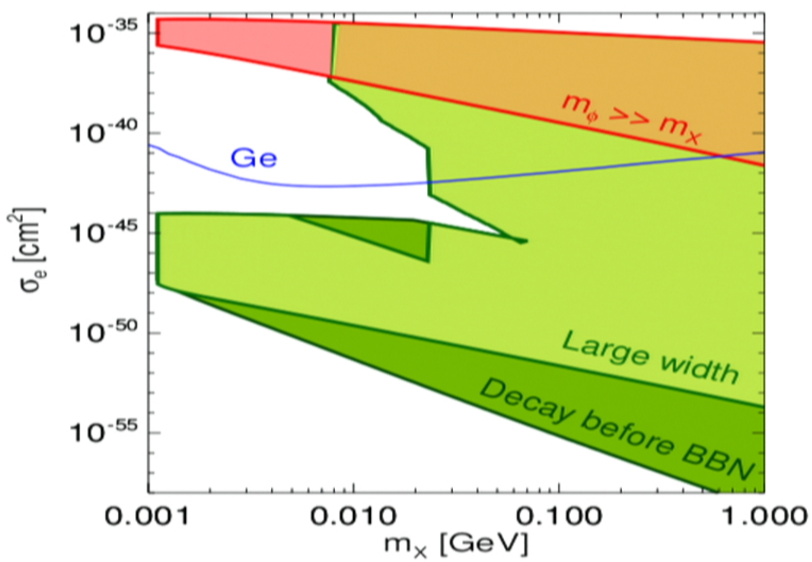
Color of point: size of direct detection cross section σ_e. For a fixed m_X, not all σ_e are accessible.

Constraints on dark gauge bosons

Constraints in (g_e, m_ϕ) map onto allowed (σ_e, m_X):



Electron scattering - direct detection



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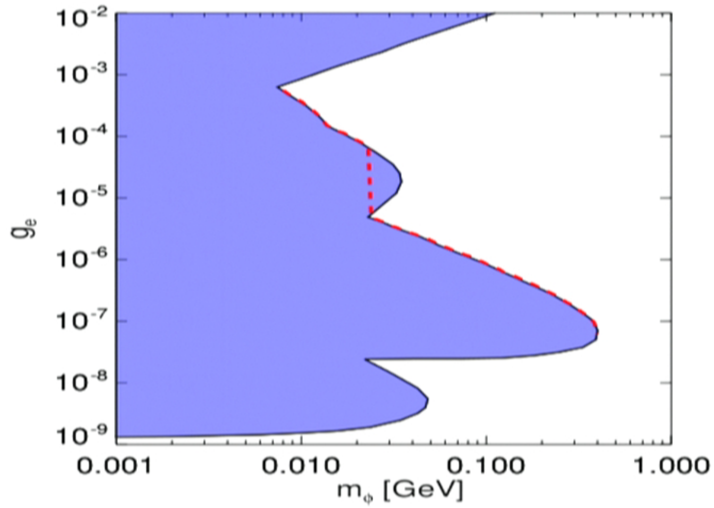
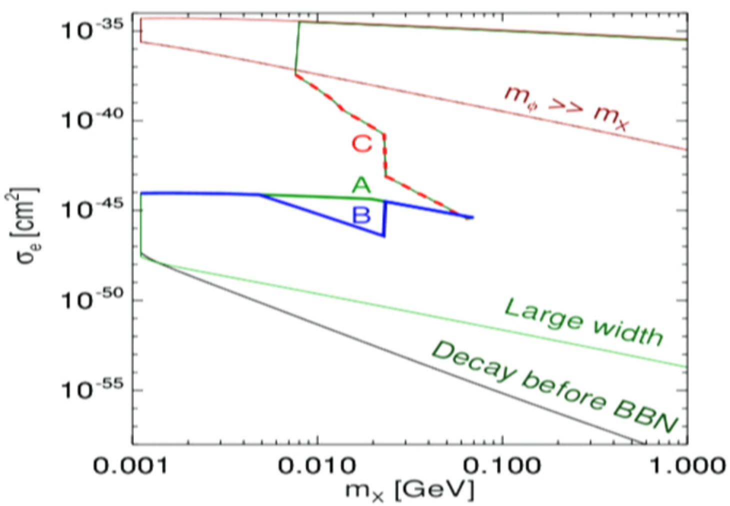




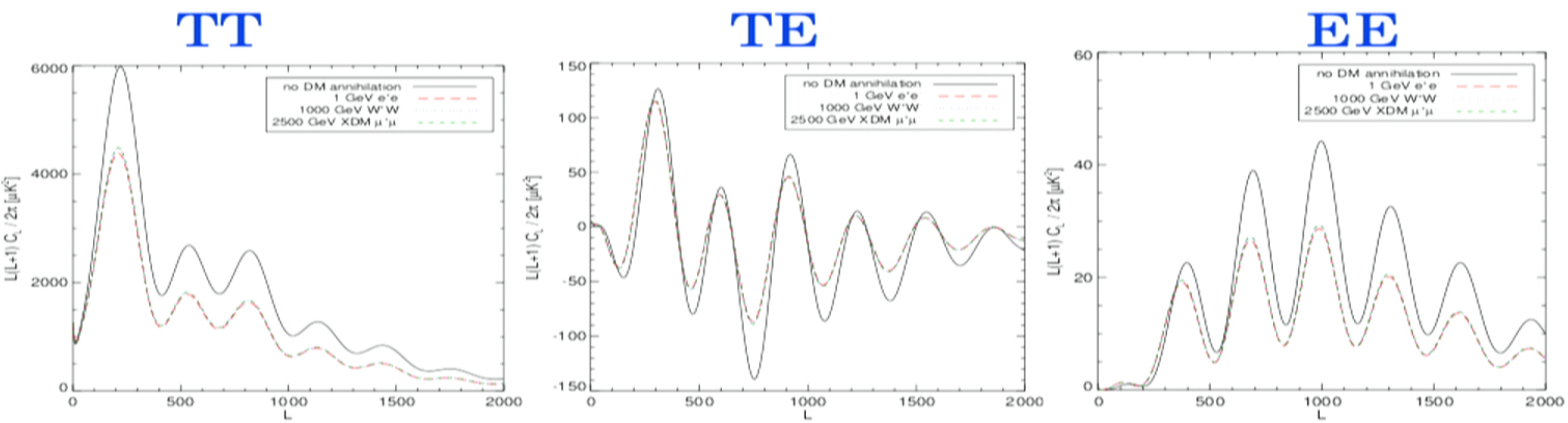
Symmetric and Asymmetric Light Dark Matter, Conclusions

m_X =1 MeV to 10 GeV (with light mediators)

- CMB bounds on energy injection from DM annihilation
- Self-interaction bounds from halo shapes limit m_ϕ
- Direct detection cross sections: wide range
  - nucleon scattering
  - electron scattering

Effect on CMB temperature (T), polarization (E) anisotropies

Correlations suppressed - damping of modes



Constrained by WMAP, polarization important for Planck