On Symmetric/Asymmetric Light Dark Matter

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Exploring Low-Mass Dark Matter Candidates
PITT PACC, 11/16/2011

Motivations

- Traditionally, we focus on O(100 GeV) dark matter.
- Hints for light dark matter

  DAMA, CoGeNT, CRESST (10 GeV); Dan Hooper`s talk; 511 keV gamma rays (MeV)

- Challenges for light DM models (1MeV-10GeV)

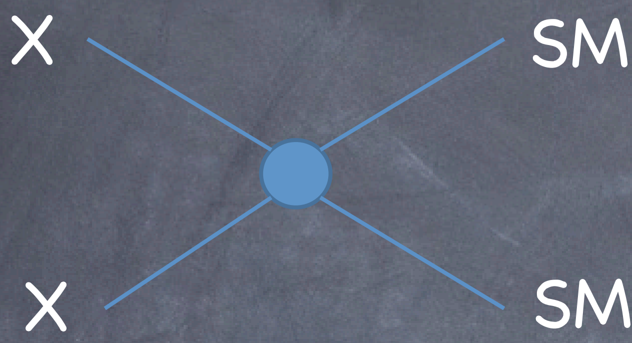
  CMB constraints; Collider constraints

- In this talk, we will examine cosmological, astrophysical and collider constraints on light DM.
- Ways to evade these bounds.

Outline

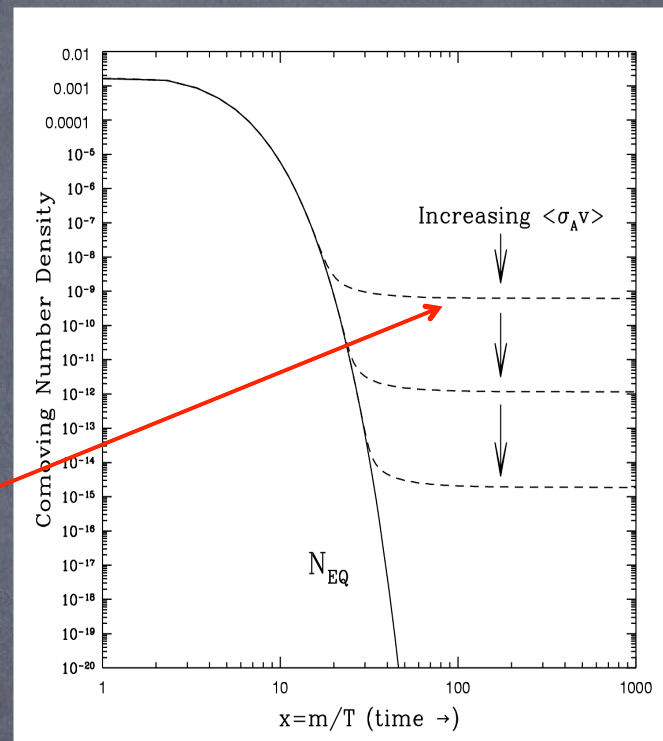
- Theoretical models: usual thermal WIMP and asymmetric DM
- The CMB and collider constraints; light DM prefers light mediators
- DM halo shape constrains on mediator mass
- Implications for direct detection

Theory: Thermal WIMP

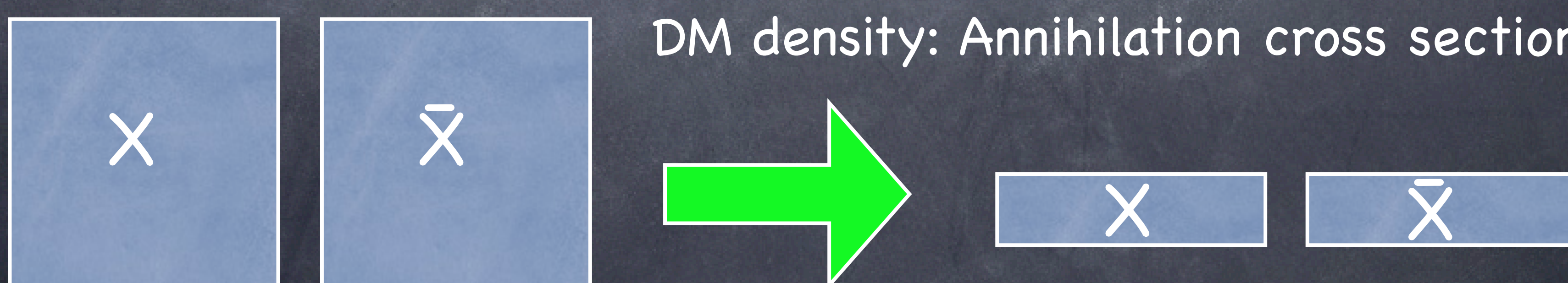


$$\Omega_X \simeq 0.23 \left(\frac{3.0 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle} \right)$$

(DM has zero chemical potential)



DM density: Annihilation cross section

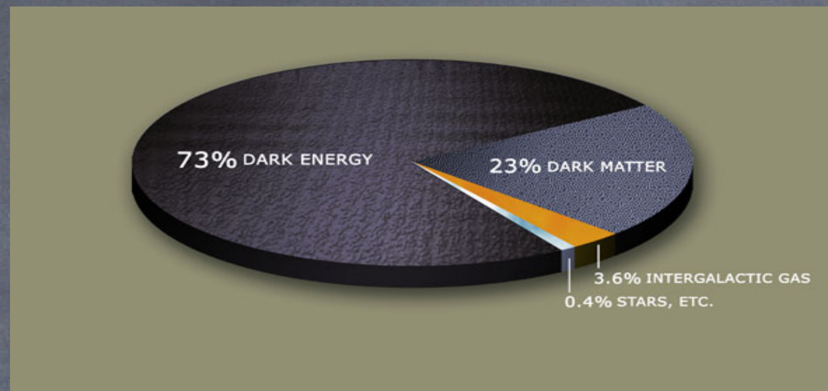


Early Universe

Late Universe

Theory: Asymmetric DM

Nussinov (1985); Kaplan (1992); Hooper, March-Russell, West (2004); Kaplan, Luty, Zurek (2009)...

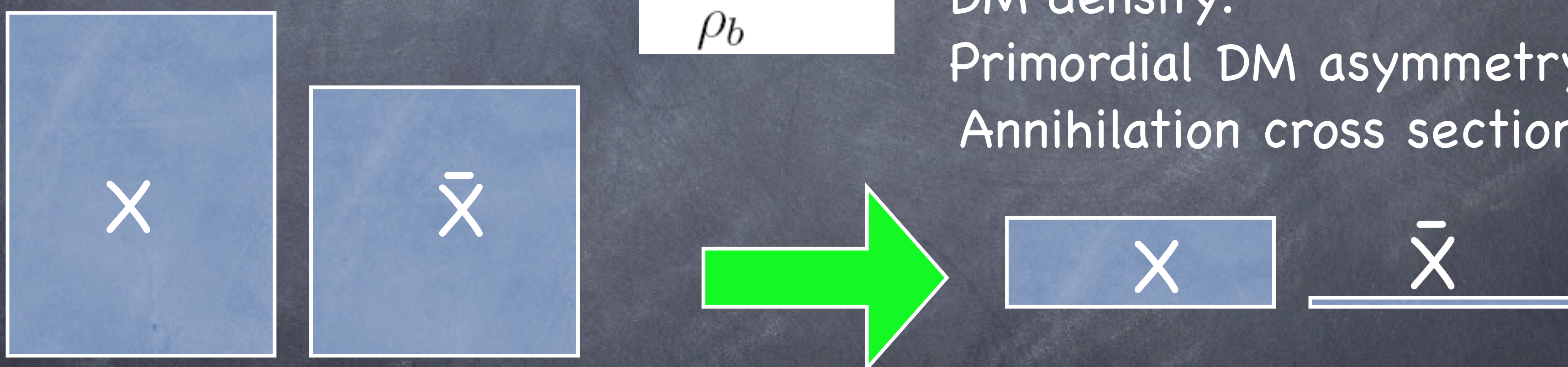


Mass

$$(\Omega_{DM}/\Omega_b)m_p$$
$$\simeq 5\ \mathrm{GeV}$$

$$\frac{\rho_{DM}}{\rho_b} \approx 5$$

DM density:
Primordial DM asymmetry
Annihilation cross section



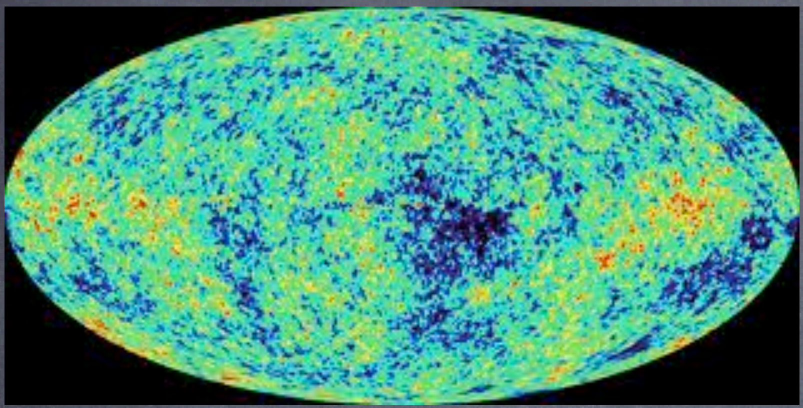
Early Universe

Late Universe

Anti-DM is negligible now! Look for accumulation

McDermott, HBY, Zurek (2011); Zentner, Hearin (2011)

CMB Constraints



Energy deposition from DM annihilation at z~1000

- Ionize atoms
- Distort CMB power spectra

$$\frac{dE}{dtdV} = \rho_c^2 \Omega_{\rm CDM}^2 (1+z)^6 f \frac{\langle \sigma v \rangle_{CMB}}{m_X}$$

$f \sim 1\ (e^{\pm}); f \sim 0.2(\mathrm{q}^{\pm})$

$f \sim 0(\nu)$

WMAP7 95% C.L.

$$f \frac{\langle \sigma v \rangle_{CMB}}{m_X} < \frac{2.42 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\mathrm{GeV}}$$

Galli, Iocco, Bertone, Melchiorri (2011)

For symmetric DM

$$\Omega_X \simeq 0.23 \left(\frac{3.0 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\rm ann} v_{\rm rel} \rangle} \right)$$

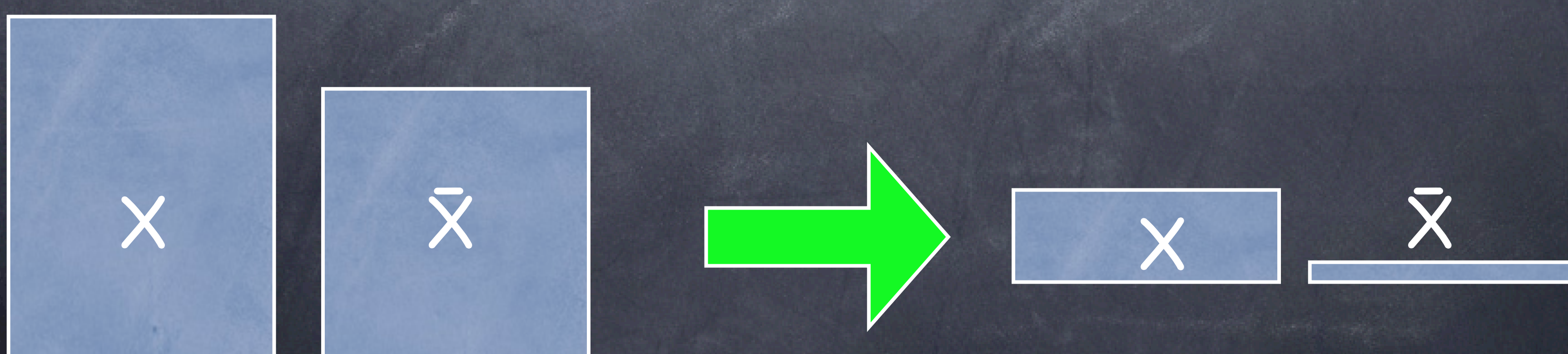
Evade CMB constraints

Symmetric DM

- Annihilate to neutrinos
- Annihilation cross section is p-wave suppressed

$$\langle \sigma v \rangle_{CMB} \simeq (v_{CMB}/v_f)^2 \langle \sigma v \rangle_f \,, \; v_{CMB} \sim 10^{-8}, \; v_f \sim 0.3$$

Asymmetric DM



Asymmetric Case

Lin, Zurek, HBY (2011)

- The present anti-DM to DM ratio

$$r = \frac{n_{\bar{X}}}{n_X}(\infty) \simeq \exp\left[-\eta_X \langle \sigma v \rangle 0.264 m_{pl} m_X \sqrt{g_*}/x_f\right]$$

primordial DM asymmetry

- CMB constraints for ADM

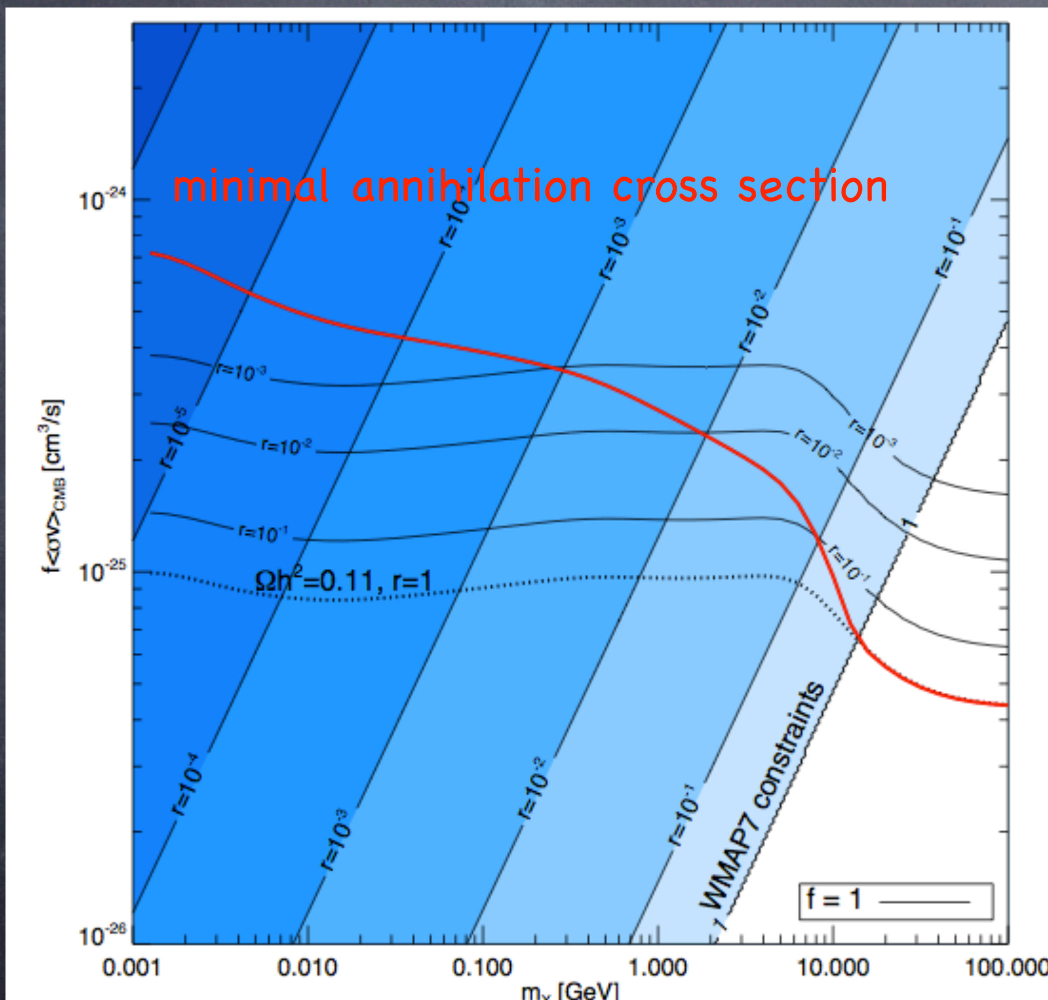
$$\eta_X \simeq \frac{\Omega_{\rm CDM}}{m_X}\frac{\rho_c}{s_0} \text{ if } r \ll 1$$

$$\frac{2r}{(1+r)^2} f \frac{\langle \sigma v \rangle}{m_X} < \frac{2.42 \times 10^{-27}\ {\rm cm}^3/{\rm s}}{\rm GeV}$$

- The anti-DM to DM ratio is exponentially suppressed by the annihilation cross section, so does the energy injection rate.

- In the ADM scenario, the CMB bounds set a minimal annihilation cross section.

CMB Bounds in ADM

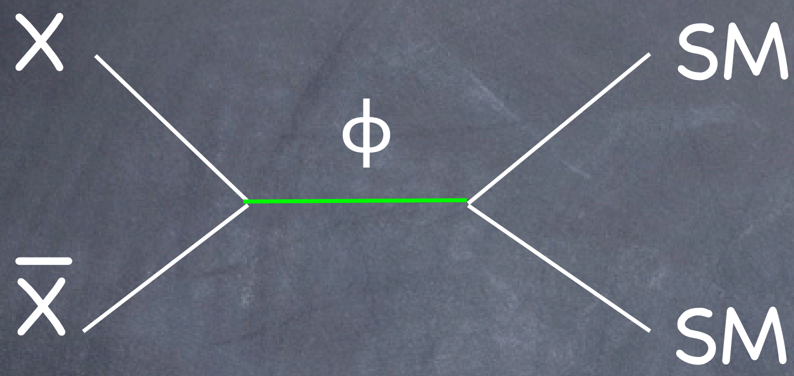


Lin, Zurek, HBY (2011)

- ADM can avoid CMB constraints rather naturally.
- Large annihilation cross section

How to get large <σv> ?

Achieving Large $\langle \sigma v \rangle$



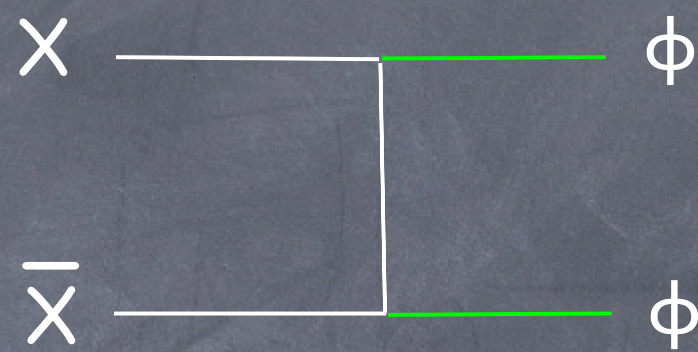
$$m_X < m_\phi$$

- Collider constraints

$$m_\phi \gg p \sim \mathcal{O}(100\ \mathrm{GeV})$$

$$m_\phi \ll p \sim \mathcal{O}(100\ \mathrm{GeV})$$

Mono-jet+missing energy



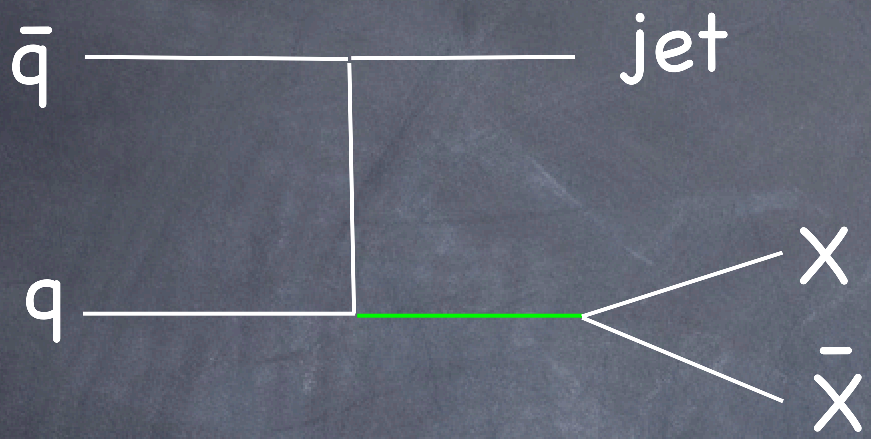
$$m_X > m_\phi$$

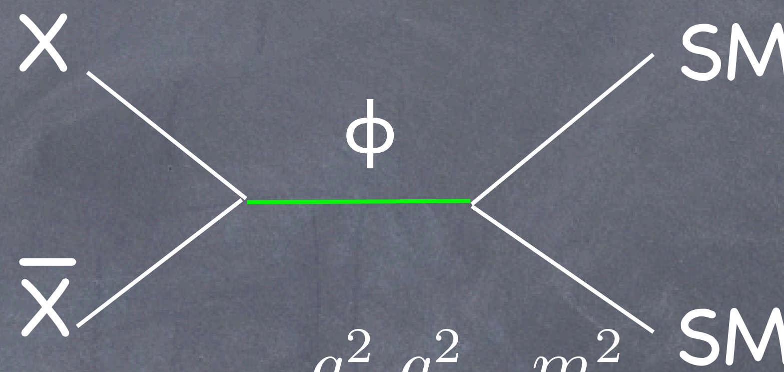
- No collider constraints

ϕ mass? Couple to the SM?

Astrophysical/Cosmological constraints

A Simple Argument





$$\langle \sigma v \rangle \sim \frac{g_X^2 g_{SM}^2 m_X^2}{m_\phi^4}$$

$$m_\phi \gg p_T \sim \mathcal{O}(100\ \mathrm{GeV})$$

$$\sigma_C \sim \frac{g_X^2 g_{SM}^2 p^2}{m_\phi^4} \sim \langle \sigma v \rangle \frac{p^2}{m_X^2}$$

Strong constraints

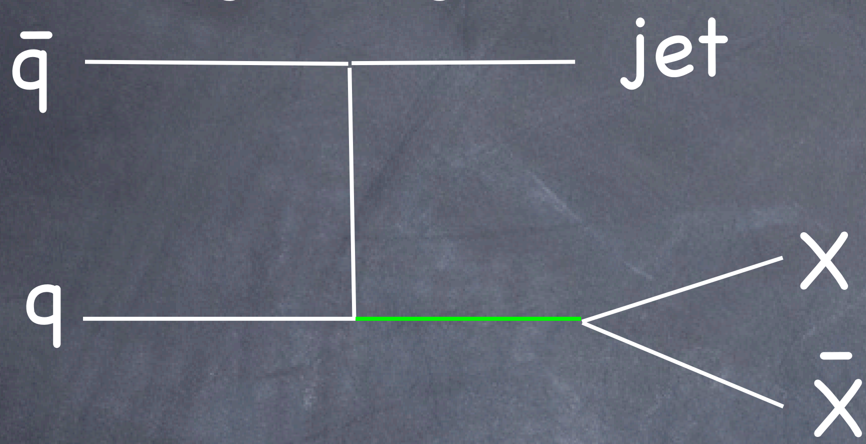
$$m_\phi \ll p \sim \mathcal{O}(100\ \mathrm{GeV})$$

$$\sigma_C \sim \frac{g_X^2 g_{SM}^2}{p^2} \sim \langle \sigma v \rangle \frac{m_\phi^4}{p^2 m_X^2}$$

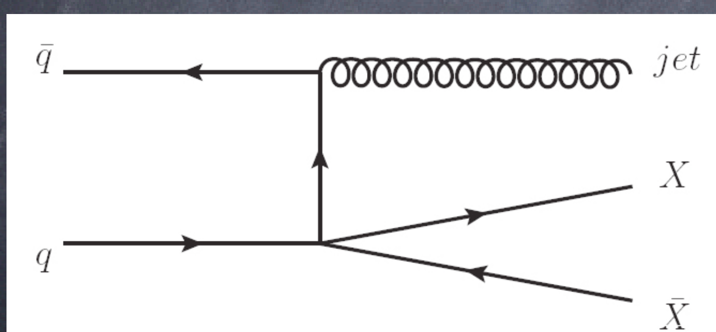
Weak

An Effective Theory

missing energy+mono-jet



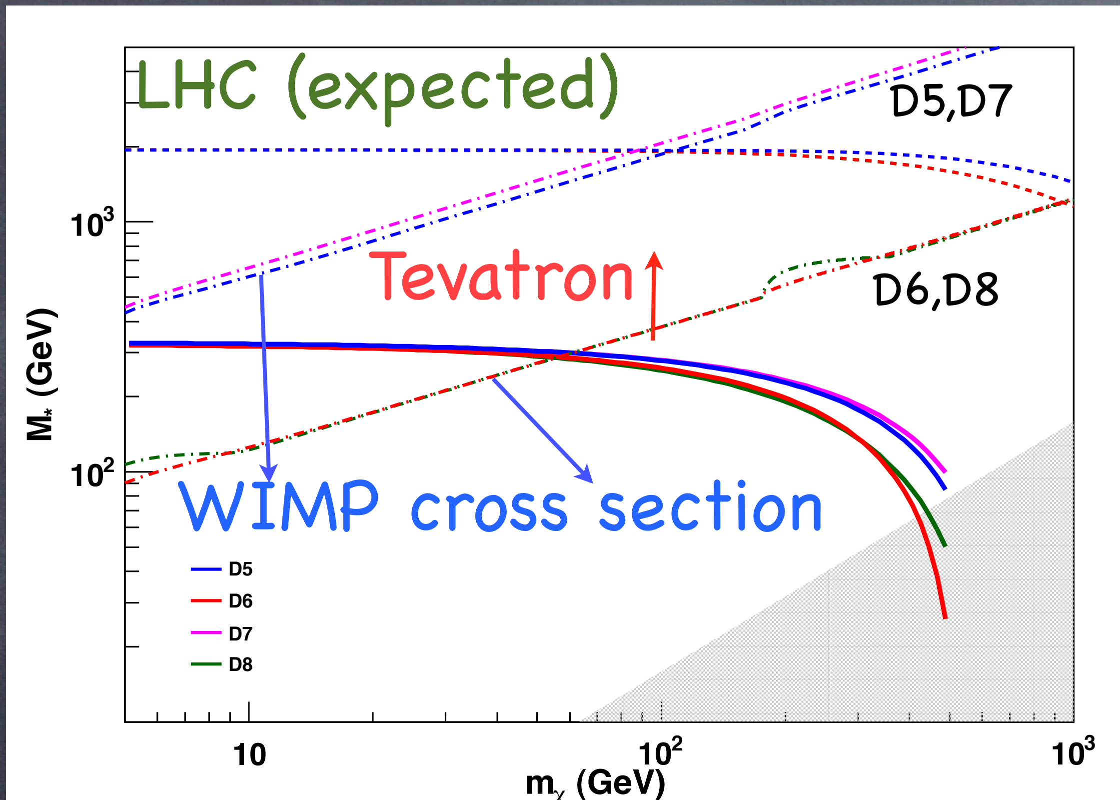
$$m_\phi \gg p \sim \mathcal{O}(100\ \text{GeV})$$



Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman, Ibe, Rajarama, Shepherd, Tait, HBY (2010)

Tevatron Constraints



Goodman, Ibe, Rajarama, Shepherd, Tait, HBY (2010)

$$m_\phi \gg p \sim \mathcal{O}(100\ \text{GeV})$$

Name	Operator	Coefficient
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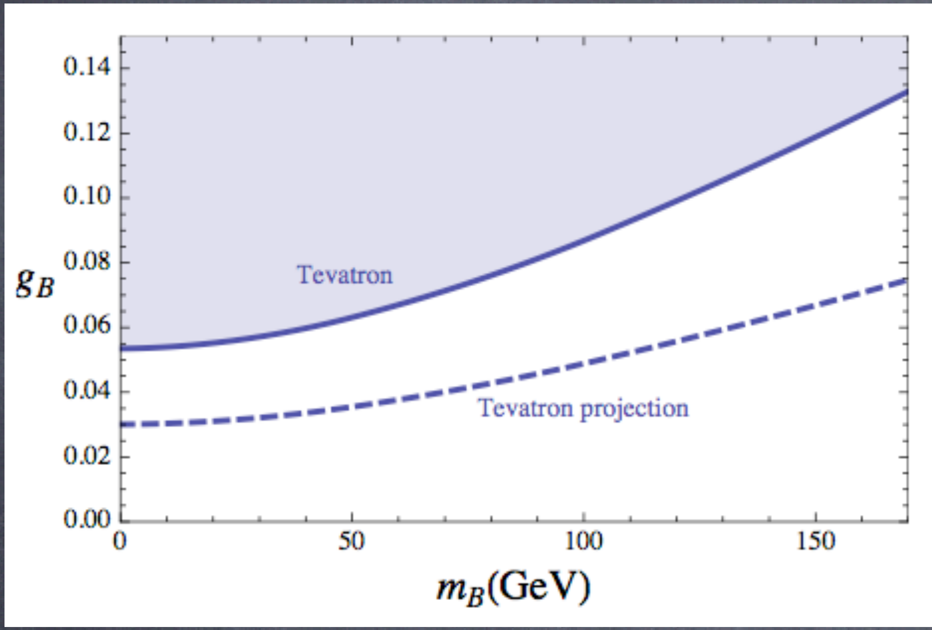
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	~~$\bar\chi\chi\bar q\gamma^5 q$~~	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	~~$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$~~	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	~~$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$~~	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta} q$	i/M_*^2
D11	~~$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$~~	$\alpha_s/4M_*^3$
D12	~~$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$~~	$i\alpha_s/4M_*^3$
D13	~~$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$~~	$i\alpha_s/4M_*^3$
D14	~~$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$~~	$\alpha_s/4M_*^3$

Lighter Mediator Case

Graesser, Shoemaker, Vecchi (2011)

$$m_\phi \ll p \sim \mathcal{O}(100 \text{ GeV})$$



$$g_{SM} = \frac{g_B}{3} < 0.015$$

$$BR(\phi \to X\bar{X}) = 1$$

If not

$$g_{SM} \to g_{SM}/\sqrt{BR}$$

$$m_\phi \lesssim 13 \text{ GeV} \left(\frac{\alpha_X}{10^{-1}}\right)^{1/4} \left(\frac{10^{-25} \text{ cm}^3/\text{s}}{\langle\sigma v\rangle}\right)^{1/4} \left(\frac{m_X}{1 \text{ GeV}}\right)^{1/2}$$

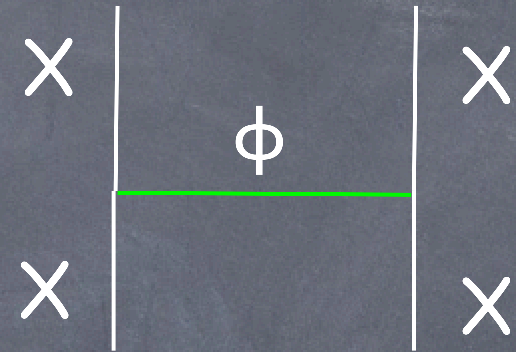
Lin, HBY, Zurek (2011)

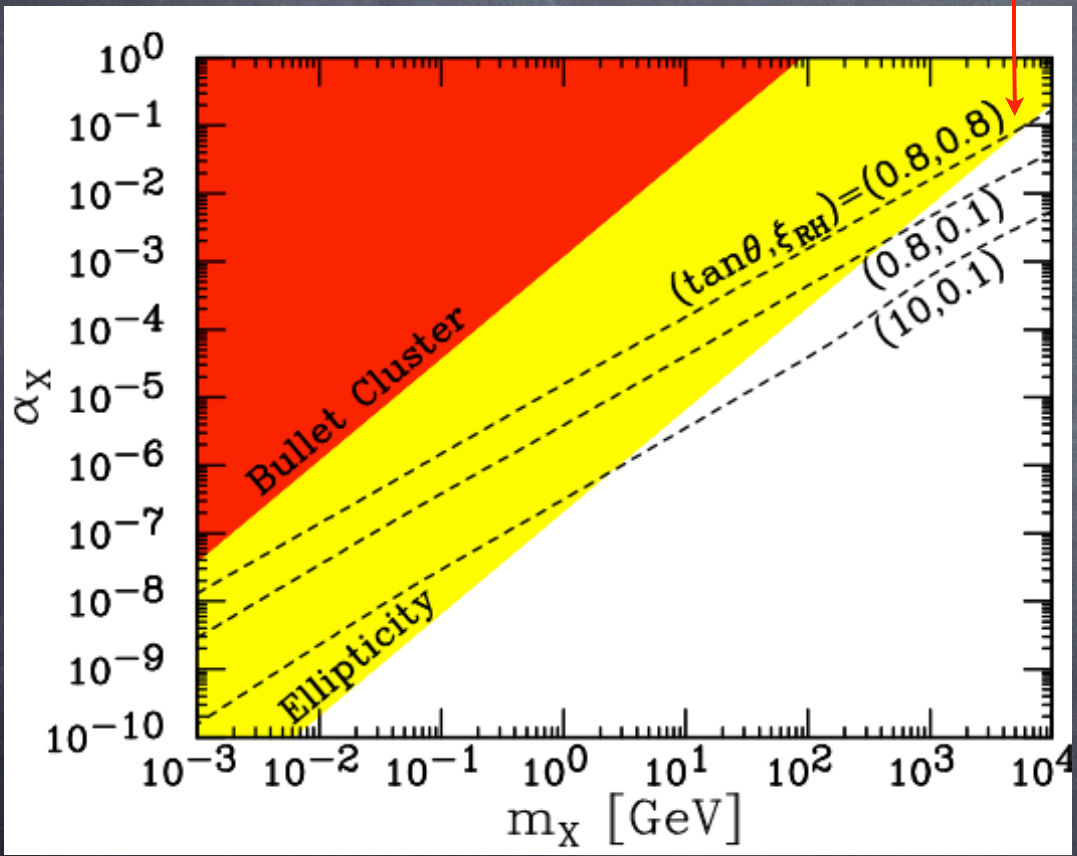
$$m_X < m_\phi \ll p \sim \mathcal{O}(100 \text{ GeV})$$ OK

$$m_X > m_\phi \ ?$$

How light can ϕ be?

If ϕ is nearly massless, DM mass has to be O(1 TeV).

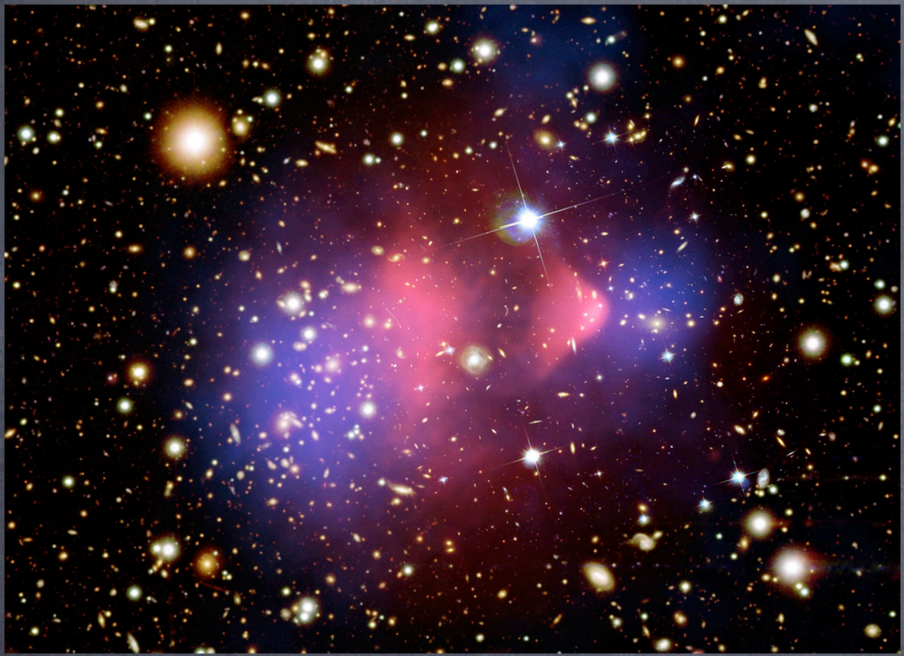


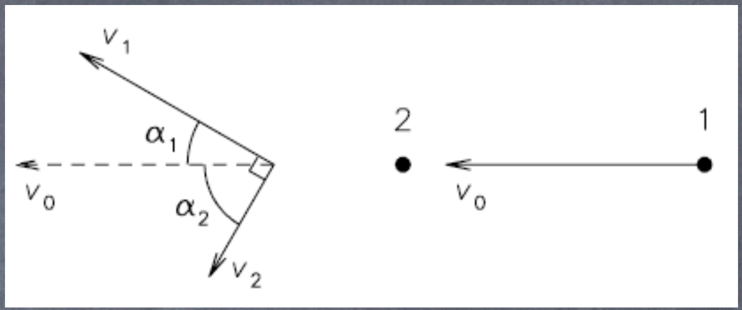


- The mediator can lead to DM self-interactions.
- Constraints on DM self-interactions: the Bullet Cluster DM halo shapes

Feng, Kaplinghat, Tu, HBY (2009)

The Bullet Cluster





$$\frac{\sigma_{XX}}{m_X} < 1 \ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

$$= 1.8 \times 10^{-24} \ \frac{\mathrm{cm}^2}{\mathrm{GeV}}$$

Markevitch, Gonzalez, Clowe, Vikhlinin, David, Forman, Jones, Murray, Tucker (2003)

Ellipticity of DM Halos

- If DM self-interactions are strong enough to create O(1) velocity change, they can erase the anisotropy of the DM velocity dispersion and create spherical halos.
- There are elliptical galaxies and clusters.
- We consider the well-studied, nearby (about 25 Mpc away) elliptical galaxy NGC720.

$$\overline{v_r^2} \simeq (240\ \mathrm{km/s})^2,\ \rho_X \simeq 4\ \mathrm{GeV/cm}^3$$

Feng, Kaplinghat, Tu, HBY (2009); Feng, Kaplinghat, HBY (2009);

Ellipticity of DM Halos

- We consider the rate to create O(1) velocity change

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

- Determine the coefficient by comparing with simulation.

$$\Gamma_k^{-1} > 10^{10} \text{ years}$$

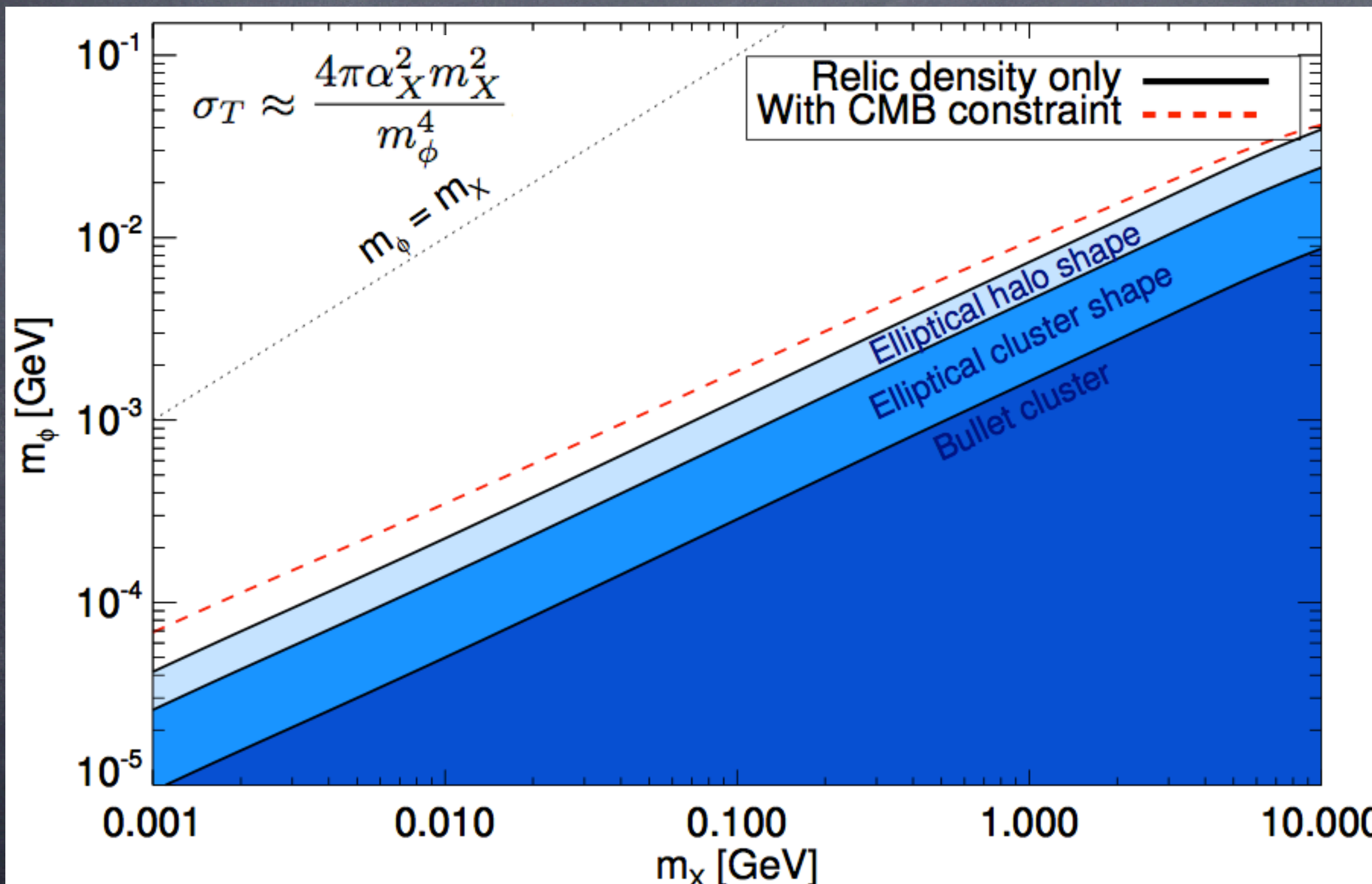
$$\frac{\sigma_{XX}}{m_X} < 2.4 \times 10^{-3} \ \frac{\text{cm}^2}{\text{g}} = 4.4 \times 10^{-27} \ \frac{\text{cm}^2}{\text{GeV}}$$

- About two orders of magnitude stronger than the bound from the Bullet Cluster.

Feng, Kaplinghat, HBY (2009); Lin, HBY, Zurek (2011)

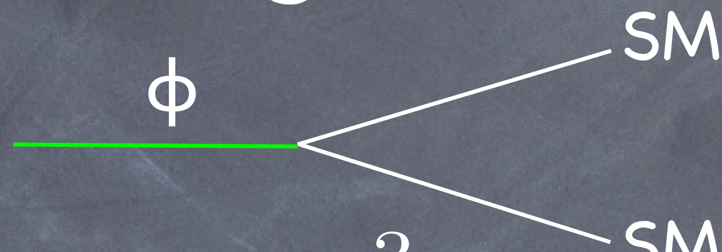
Lower Mass Bounds on ϕ

Lin, HBY, Zurek (2011)



For DM mass 1 MeV-10 GeV, ϕ mass > 40 KeV-40 MeV

Cosmology of Massive ϕ



g_{SM}?

- Dark sector thermalizes with the SM sector

$$\Gamma_\phi > H(T \simeq m_X) \qquad g_{SM} > 8 \times 10^{-8}$$

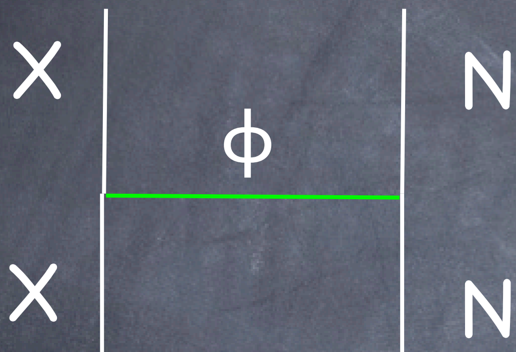
Inverse decay keeps ϕ in thermal equilibrium.

- Decay before BBN; Two sectors evolve differently

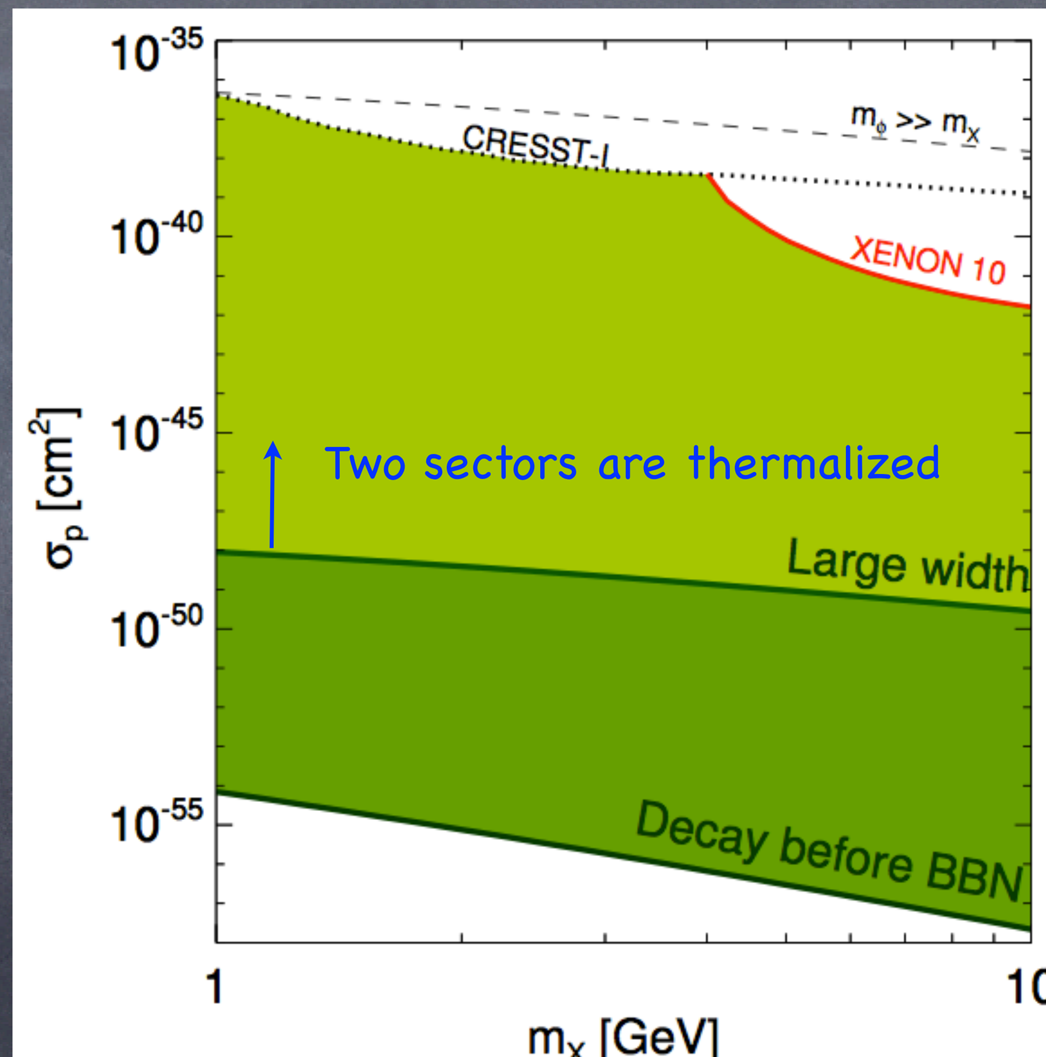
$$\Gamma_\phi > \frac{1}{0.01 - 1\ \mathrm{s}} \qquad g_{SM} > 10^{-11}$$

Direct Detection

Assume a vector ϕ



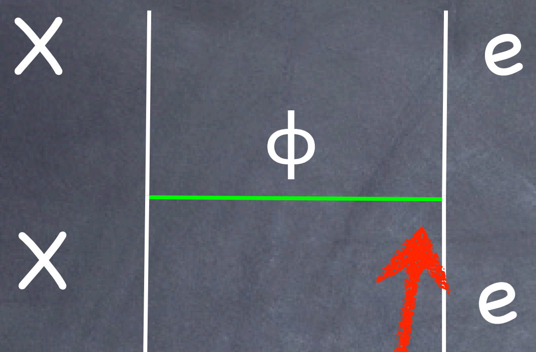
Lin, HBY, Zurek (2011)



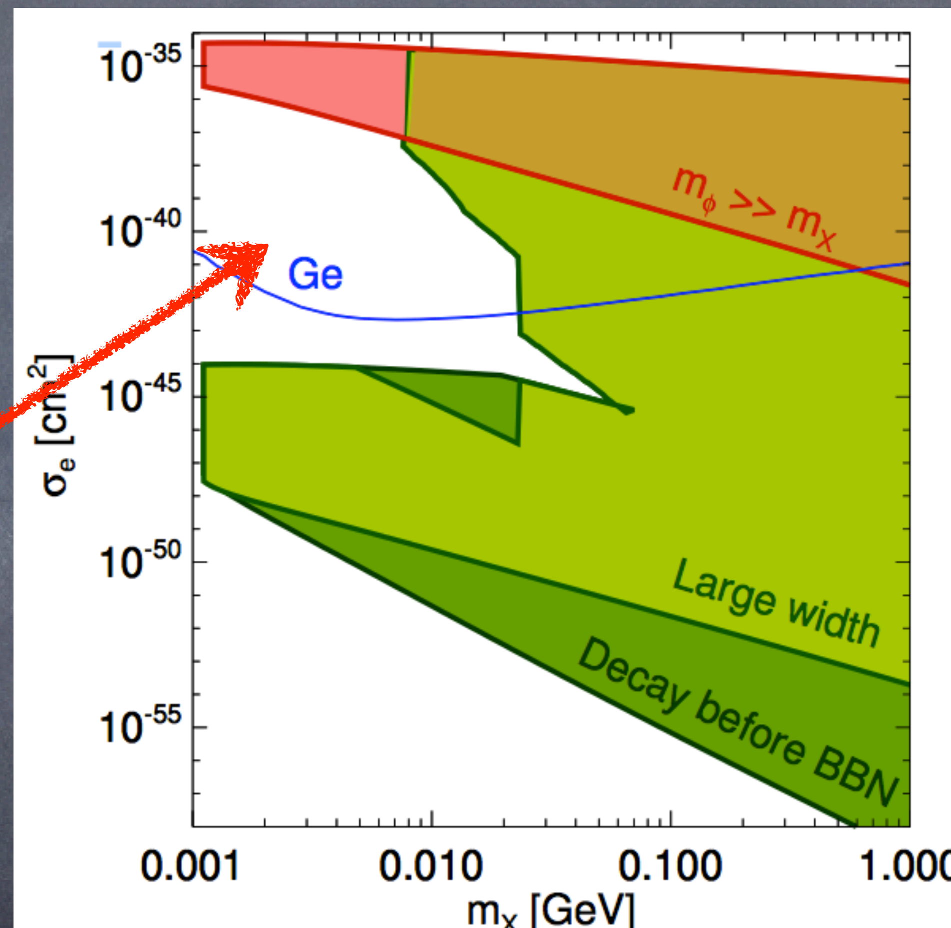
- Consistent with all constraints
- Wide range!
- Neutrino background?

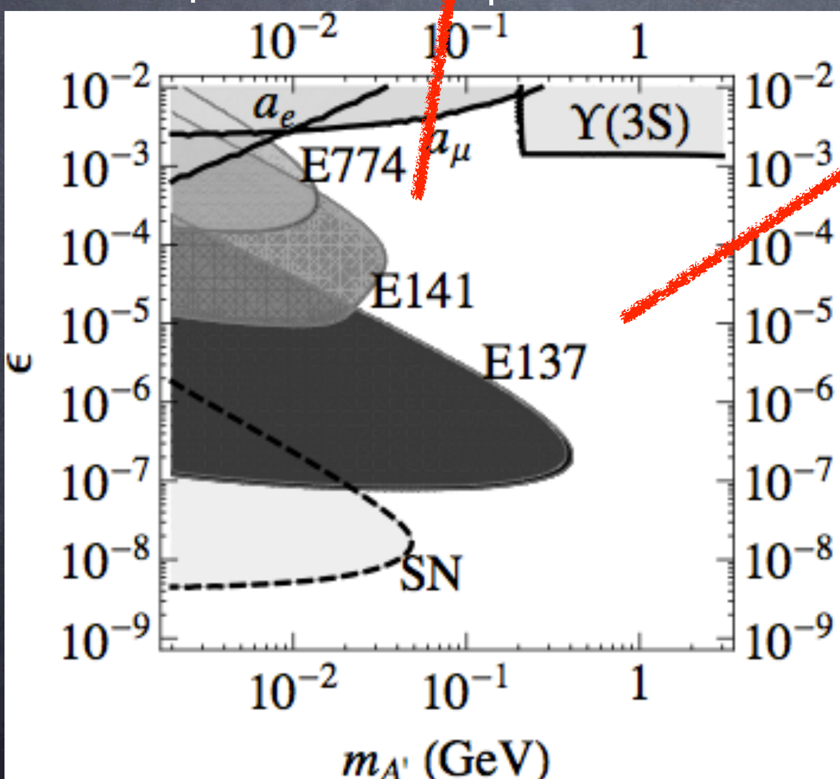
Strigari (2009)

Electron Scattering



Lin, HBY, Zurek (2011)





Ge line: Essig, Mardon, Volansky (2011)

Bjorken, Essig, Schuster, Toro (2009)

Summary

- Many constraints become relevant if DM is light.
- ADM can avoid CMB bounds quite naturally.
- Light DM prefers to have light mediators to avoid collider constraints.