Asymmetric Dark Matter (Part II)--Constraints

Hai-Bo Yu
University of Michigan, Ann Arbor

DMUH11

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Outline

- Collider constraints on ADM-SM coupling

  Tevatron, LEP; LHC

- ADM accumulation in stars

  the Sun; neutron stars

- Elliptical DM halo shape constraints on ADM self-interactions

ADM Relic Density

Early Universe | Late Universe

- We require $T_\mu > T_f(X) > T_f(\bar{X})$

  $\mu/T_\mu \sim 1$, μ is the chemical potential

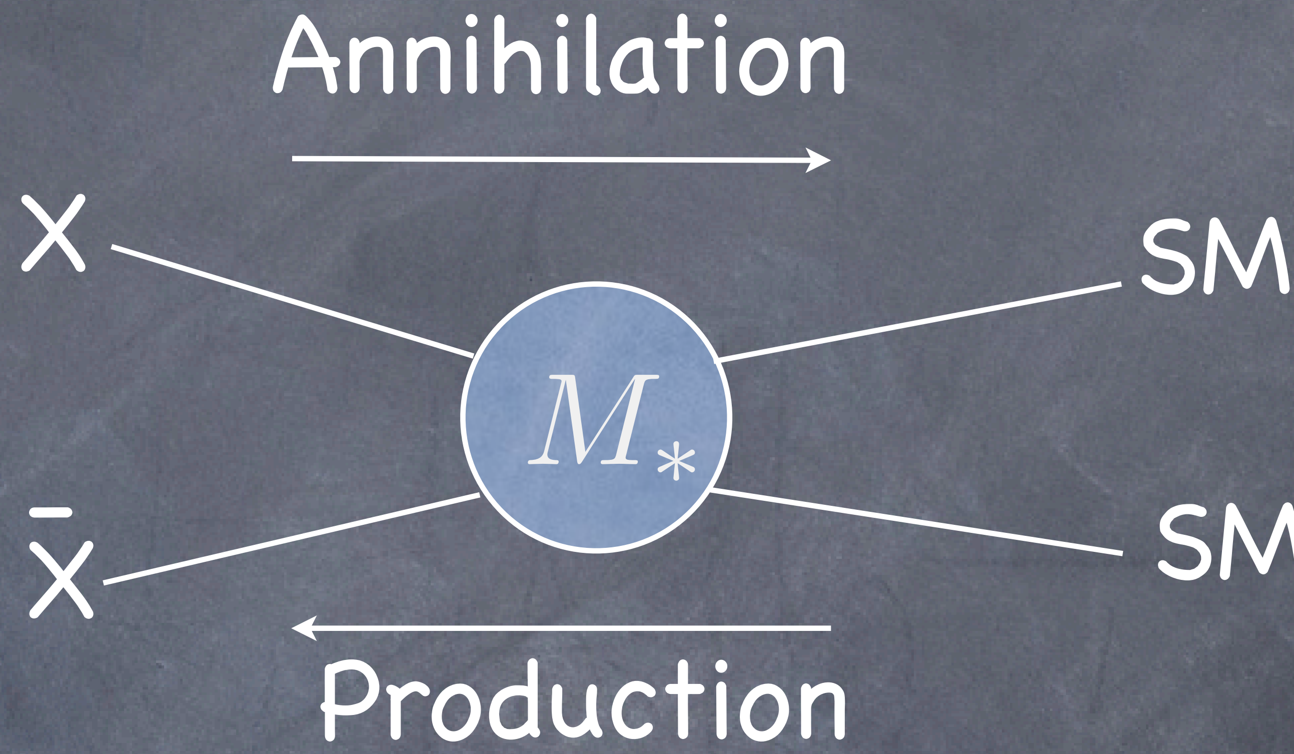
- If $\eta_X \sim \eta_B$ $\langle\sigma v\rangle \gtrsim \sigma_{WIMP} \sim 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

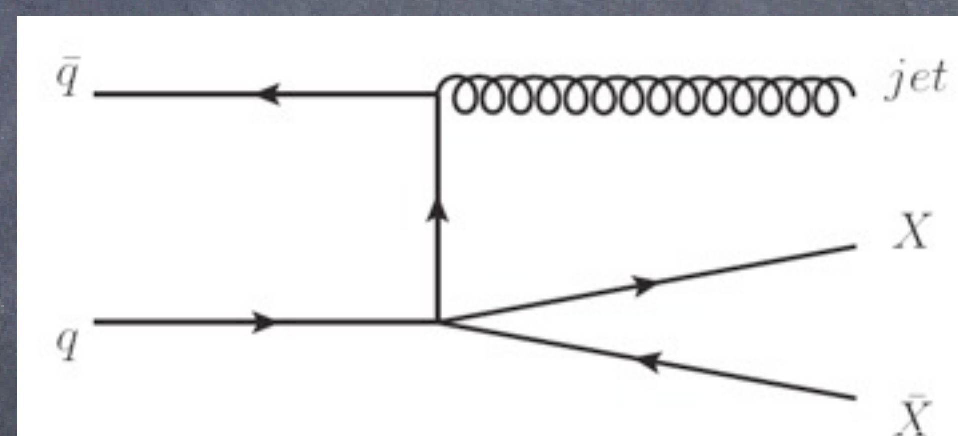
- Annihilate to hidden sector particles

- Annihilate to SM particles

Couple to Quarks/Gluons

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$



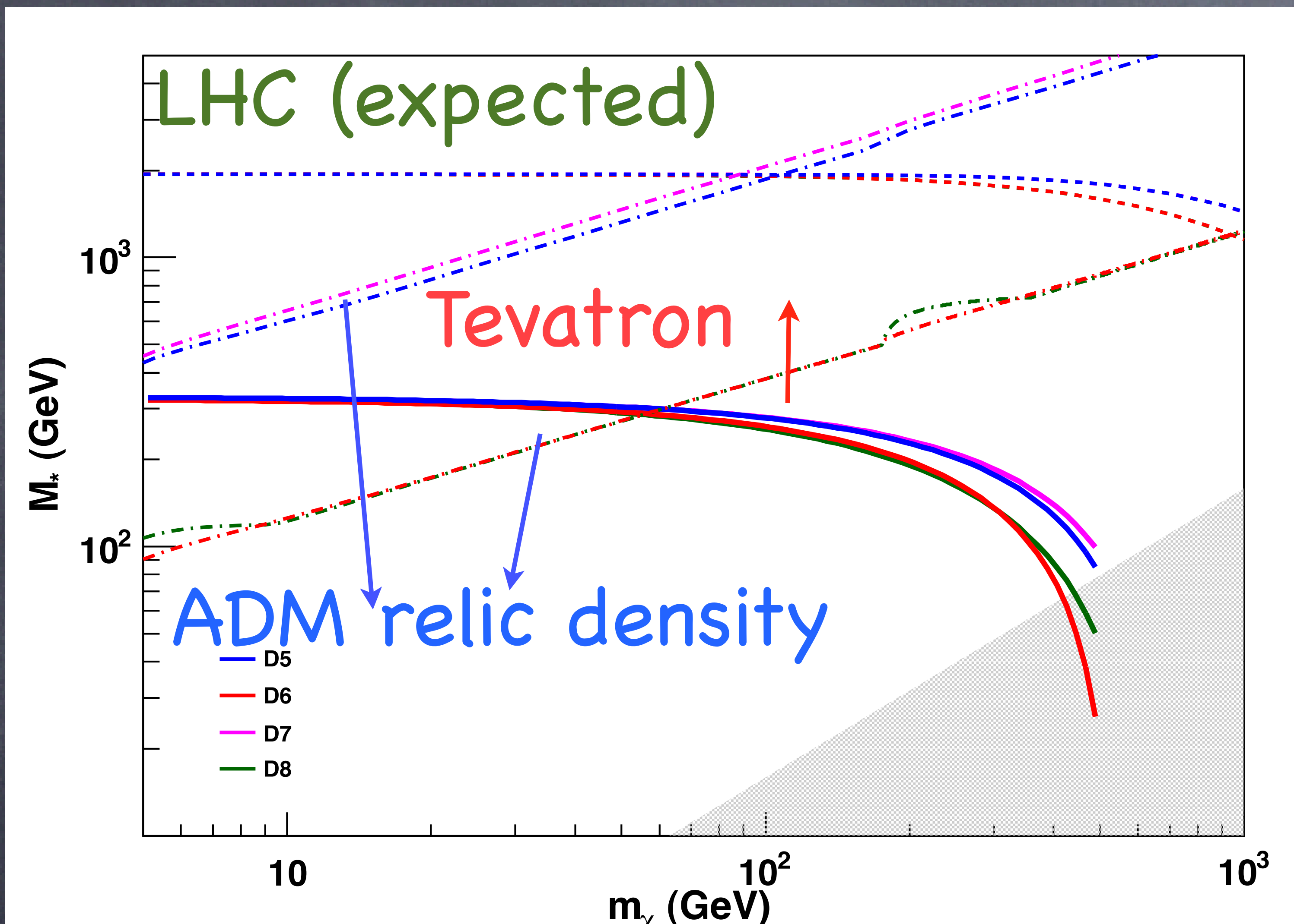


missing energy
+mono-jet

The cutoff scale determines both collider signals and annihilation cross section.

Goodman, Ibe, Rajarama, Shepherd, Tait, HBY (2010); Bai, Fox, Harnik (2010)

Constraints from Tevatron



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

- Only a few operators are allowed.
- For light ADM, the tension is stringent.
- P-wave cross section can avoid CMB constraints, but not colliders!

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	~~$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$~~	$\alpha_s/4M_*^3$

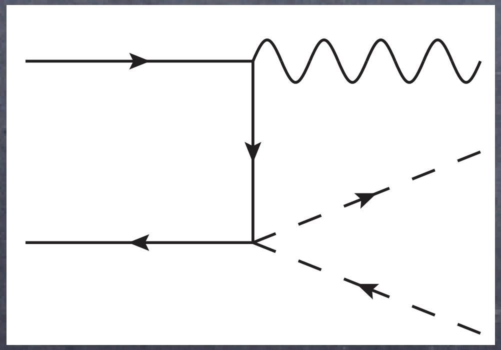
Couple to Leptons

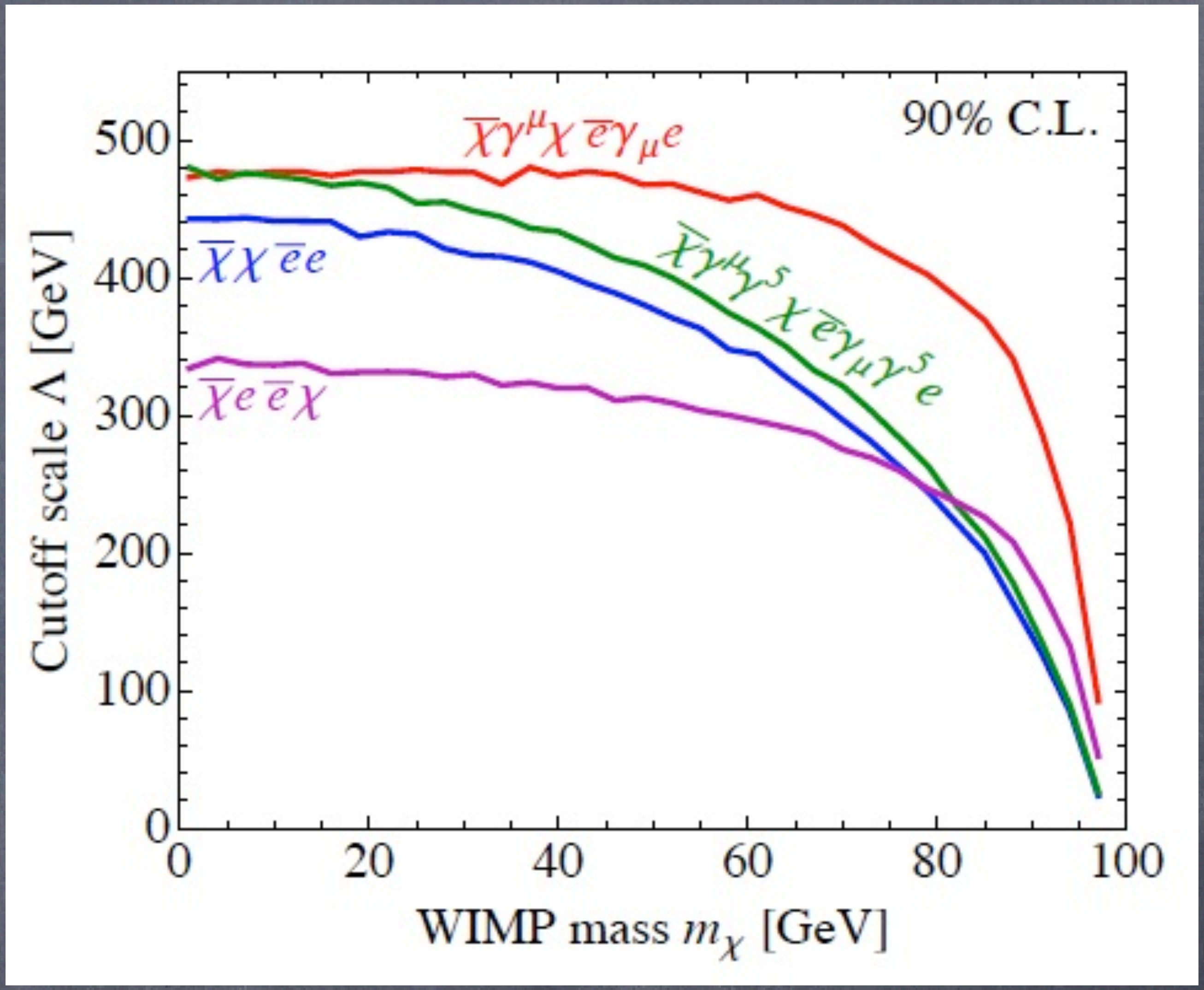
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2},$$

$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2},$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2},$$

$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2},$$



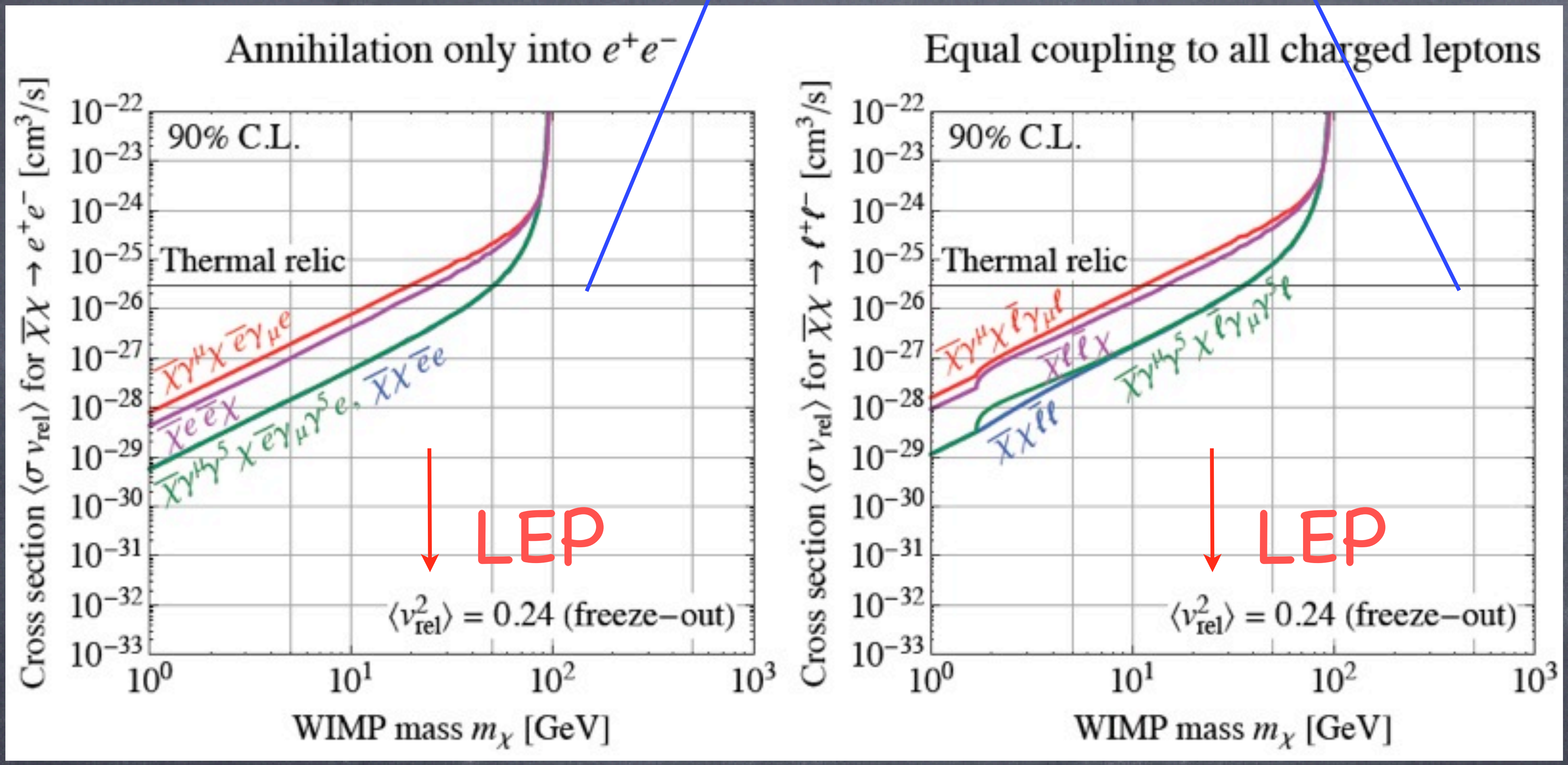


Fox, Harnik, Kopp, Tsai (2011)

- Missing energy+mono-photon

LEP Constraints

Deplete the symmetric component



Fox, Harnik, Kopp, Tsai (2011)

- Tevatron and LEP set strong constraints on ADM-SM coupling.
- LHC will tell us more.

ADM Accumulation

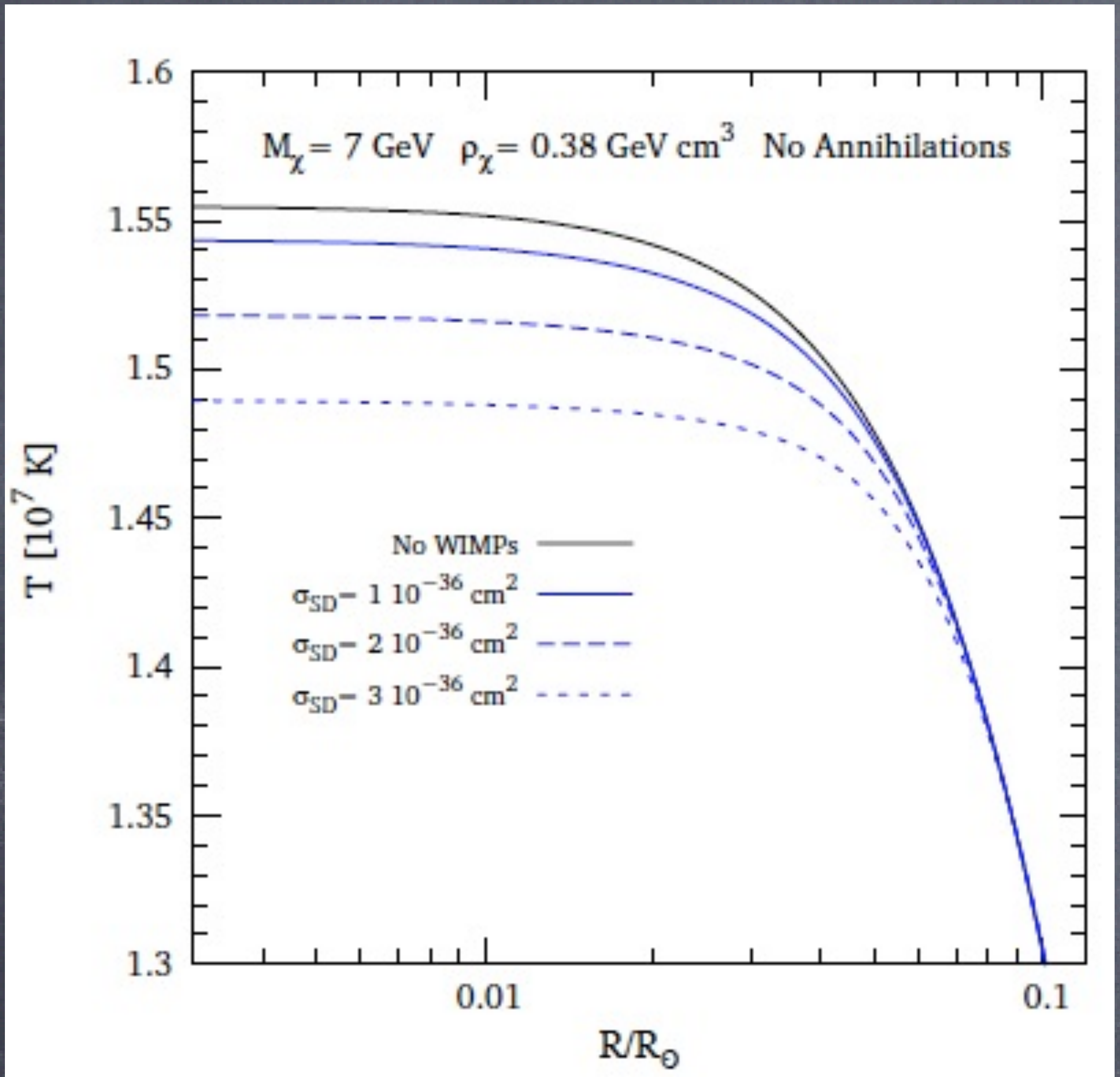
- Typically, there are no annihilation signals. Look for ADM accumulation.
- Accumulation in the Sun.

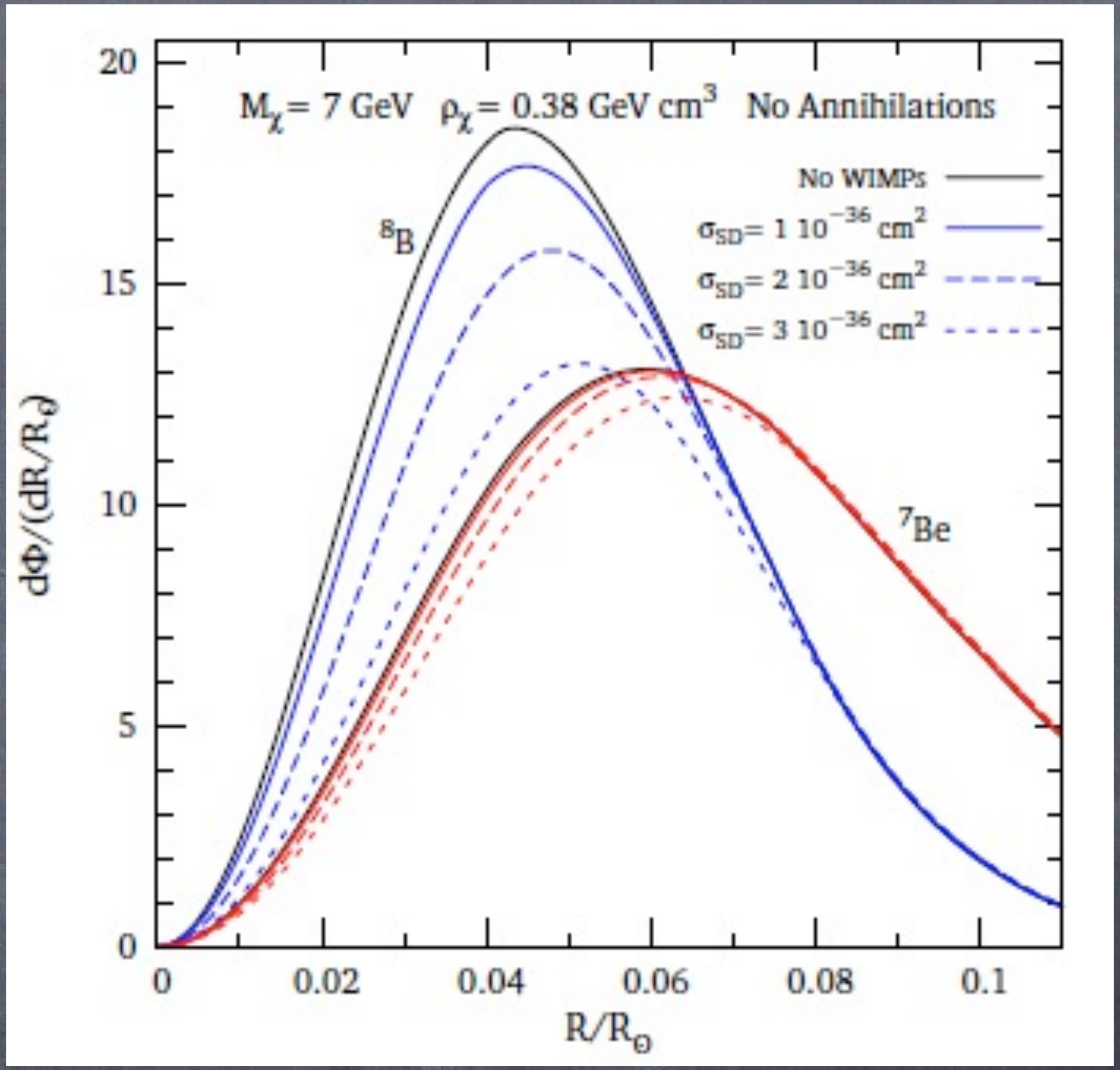
  Frandsen, Sarkar (2010); Cumberbatch, Guzik, Silk, Watson, West (2010); Taoso, Iocco, Meynet, Bertone, Eggenberger (2010)

- Accumulation in neutron stars.

  Goodman, Nussinov (1989); McDermott, HBY, Zurek (2011); Kouvaris, Tinyakov (2011); Lavallaz, Fairbairn (2010);

ADM in the Sun





Taoso, Iocco, Meynet, Bertone, Eggenberger (2010)

- Captured ADM particles transport heat and reduce the solar temperature.
- The neutrino production rate is sensitive to the solar temperature.

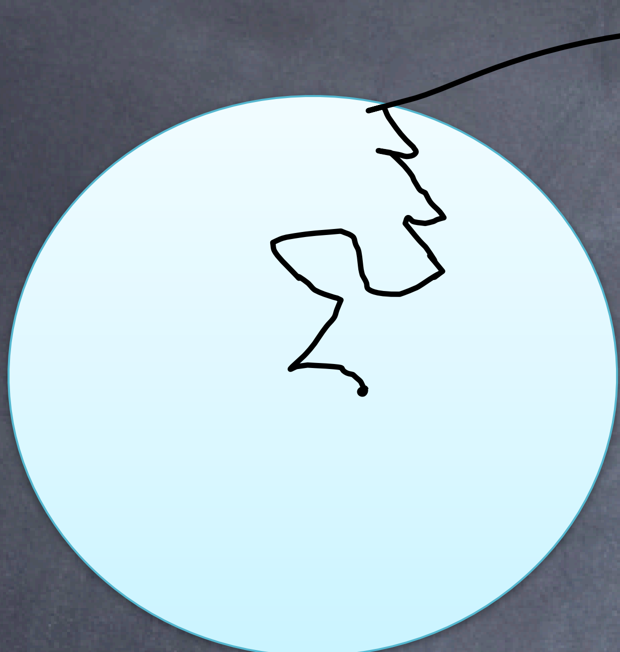
Basics of Neutron stars

- Mass: $\sim 10^{57}$ protons ~ 1.4 Solar Mass
- Density: $\sim 1.4 \times 10^{3}\ \mathrm{kg/m^3}$ $\sim 10^{18}\ \mathrm{kg/m^3}$
- Escape V: $\sim 2 \times 10^{-3} c$ $\sim 0.6c$
- Temperature: $\sim 1.6 \times 10^{7}\ \mathrm{K}$ $\sim 10^{5} - 10^{6}\ \mathrm{K}$

Advantages: high capture rate; fast thermalization; Bose-Einstein condensate (Bosonic ADM)

These captured ADM particles may form a mini **black hole** at the neutron star center.

ADM in a Neutron Star



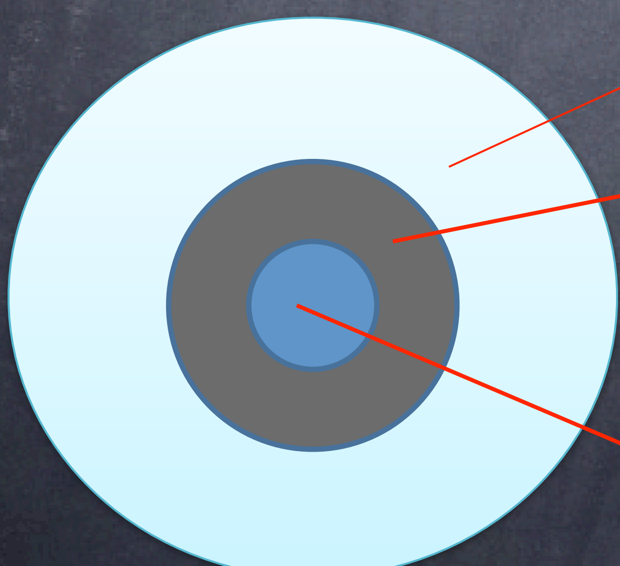
Capture (Step 1)

$$N_X \simeq 2.3 \times 10^{44} \left(\frac{100\ \mathrm{GeV}}{m_X}\right)\left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm^3}}\right)\left(\frac{\sigma_{XB}}{2.1\times 10^{-45}\ \mathrm{cm^2}}\right)\left(\frac{t}{10^{10}\ \mathrm{years}}\right)$$

Thermalization (Step 2)

$$t_{th} \simeq 0.054\ \mathrm{years}\left(\frac{m_X}{100\ \mathrm{GeV}}\right)^2\left(\frac{2.1\times 10^{-45}\ \mathrm{cm^2}}{\sigma_n}\right)\left(\frac{10^5\ \mathrm{K}}{T}\right)$$

$R_n = 10.6\ \mathrm{km}$ typical neutron star radius



ADM in the thermal state

$$24\ \mathrm{cm}\left(\frac{T}{10^5\ K}\cdot\frac{100\ \mathrm{GeV}}{m_X}\right)^{1/2}$$

ADM in the BEC state

$$1.5\times 10^{-5}\ \mathrm{cm}\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^{1/2}$$

Self-gravitation (Step 3)

$$\frac{3N_X m_X}{4\pi r^3} > \rho_B$$

Without a BEC

$$N_{self} \simeq 4.8\times 10^{41}\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^{5/2}\left(\frac{T}{10^5\ \mathrm{K}}\right)^{3/2}$$

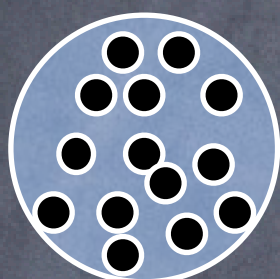
With a BEC

$$1.0\times 10^{23}\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^{5/2}$$

Chandrasekhar Limit

Beyond this limit, the system can collapse to a black hole.

- Fermions: gravity VS. Fermi pressure



$$E \sim -\frac{GNm^2}{R} + \frac{N^{1/3}}{R}$$

$$N_{Cha}^{fermion} \sim \left(\frac{M_{pl}}{m}\right)^3 \sim 1.8 \times 10^{51} \left(\frac{100\ \mathrm{GeV}}{m}\right)^3$$

- Bosons: gravity VS. zero point energy

$$E \sim -\frac{GNm^2}{R} + \frac{1}{R}$$

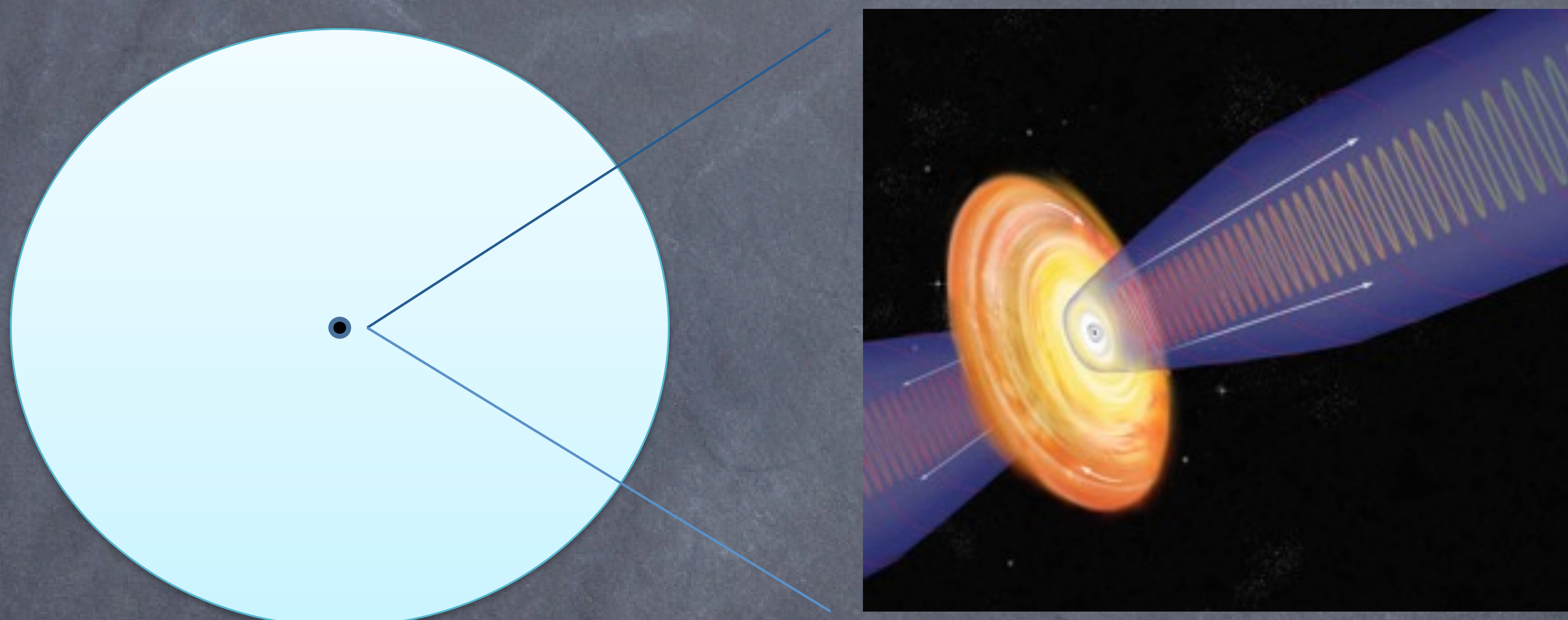
$$N_{Cha}^{boson} \sim \left(\frac{M_{pl}}{m}\right)^2 \sim 1.5 \times 10^{34} \left(\frac{100\ \mathrm{GeV}}{m}\right)^2$$

NOTE

$$N_X \simeq 2.3 \times 10^{44} \left(\frac{100\ \mathrm{GeV}}{m_X}\right) \left(\frac{\rho_X}{10^3\ \mathrm{GeV/cm^3}}\right) \left(\frac{\sigma_{XB}}{2.1 \times 10^{-45}\ \mathrm{cm}^2}\right) \left(\frac{t}{10^{10}\ \mathrm{years}}\right)$$

Minimal Black Holes

$$N_X > N_{self} > N_{Cha}^{boson}$$



$$\frac{dM_{BH}}{dt} \simeq 4\pi\lambda_s \left(\frac{GM_{BH}}{v_s^2}\right)^2 \rho_B v_s - \frac{1}{15360\pi G^2 M_{BH}^2}$$

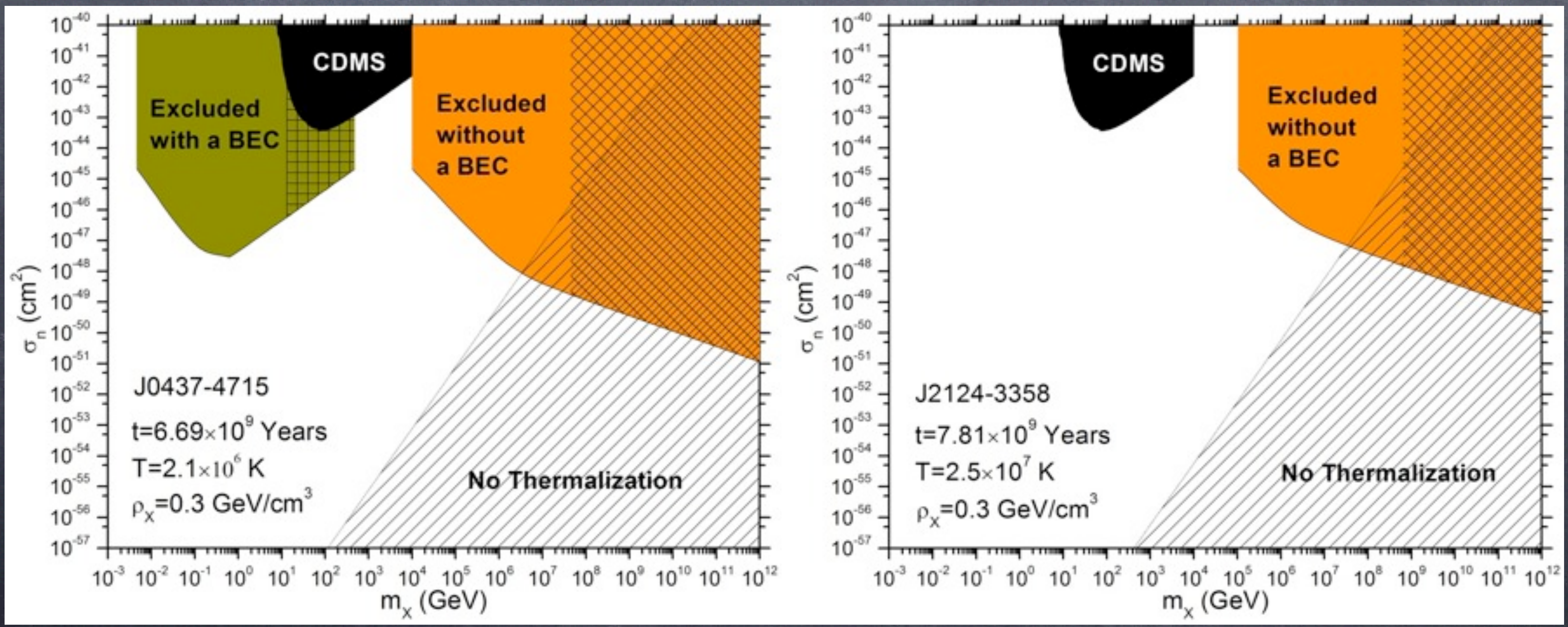
Baryon accretion   Hawking radiation

Hawking wins if the initial black hole mass is less than

$$M_{BH}^{crit} \simeq 1.2 \times 10^{37}\ \mathrm{GeV}$$

Nearby Old Pulsars

- But we see many very old pulsars! We can derive a bound on the ADM-neutron scattering cross section.



Ways to avoid this bound?

DM Self-interactions

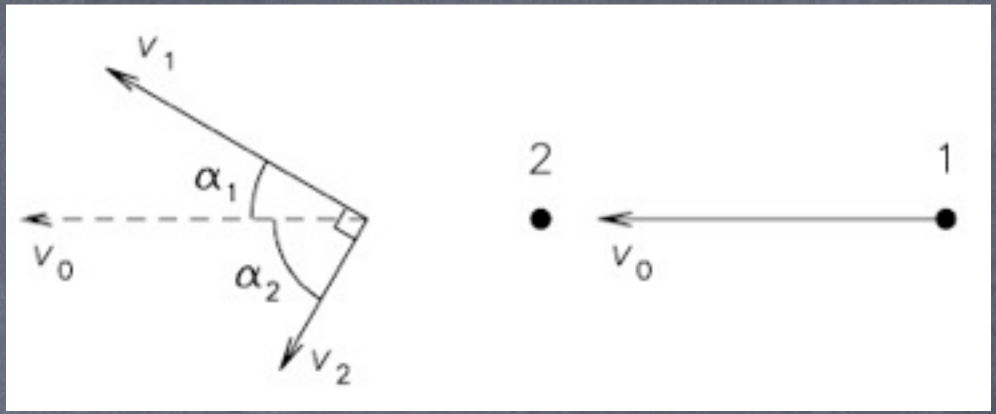
- Self-interacting DM Spergel, Steinhardt (1999); Dave, Spergel, Steinhardt, Wandelt (2000)
- contact interactions Spergel, Steinhardt (1999); Recent ADM models, see Mads` talk
- mediated by massless mediators

  Feng, Tu, HBY (2008); Ackerman, Buckley, Carroll, Kamionkowski (2008); Feng, Kaplinghat, Tu, HBY (2009)
- mediated by light massive mediators

  Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009); Loeb, Weiner (2010)

Bullet Cluster

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



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

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

initial suggestion

$$\frac{\sigma_{XX}}{m_X} \sim 1 - 100\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

simulation

$$\frac{\sigma_{XX}}{m_X} \sim 0.5 - 5\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

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.

$$v_0 \simeq 340 \text{ km/s}, \ \rho_X \simeq 4 \text{ GeV/cm}^3$$

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.

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

$$\frac{\sigma_{XX}}{m_X} < 2 \times 10^{-3} \ \frac{\text{cm}^2}{\text{g}} = 3.6 \times 10^{-27} \ \frac{\text{cm}^2}{\text{GeV}}$$

- About 3 orders of magnitude stronger than constrains from the Bullet Cluster.

Feng, Kaplinghat, HBY (2009)

Summary

- Colliders excludes many ways in which the ADM symmetric component can annihilate away.
- We can use stars to probe ADM.
- The ellipticity of DM halos put (the) strong (est?) constraints on DM self-interactions.