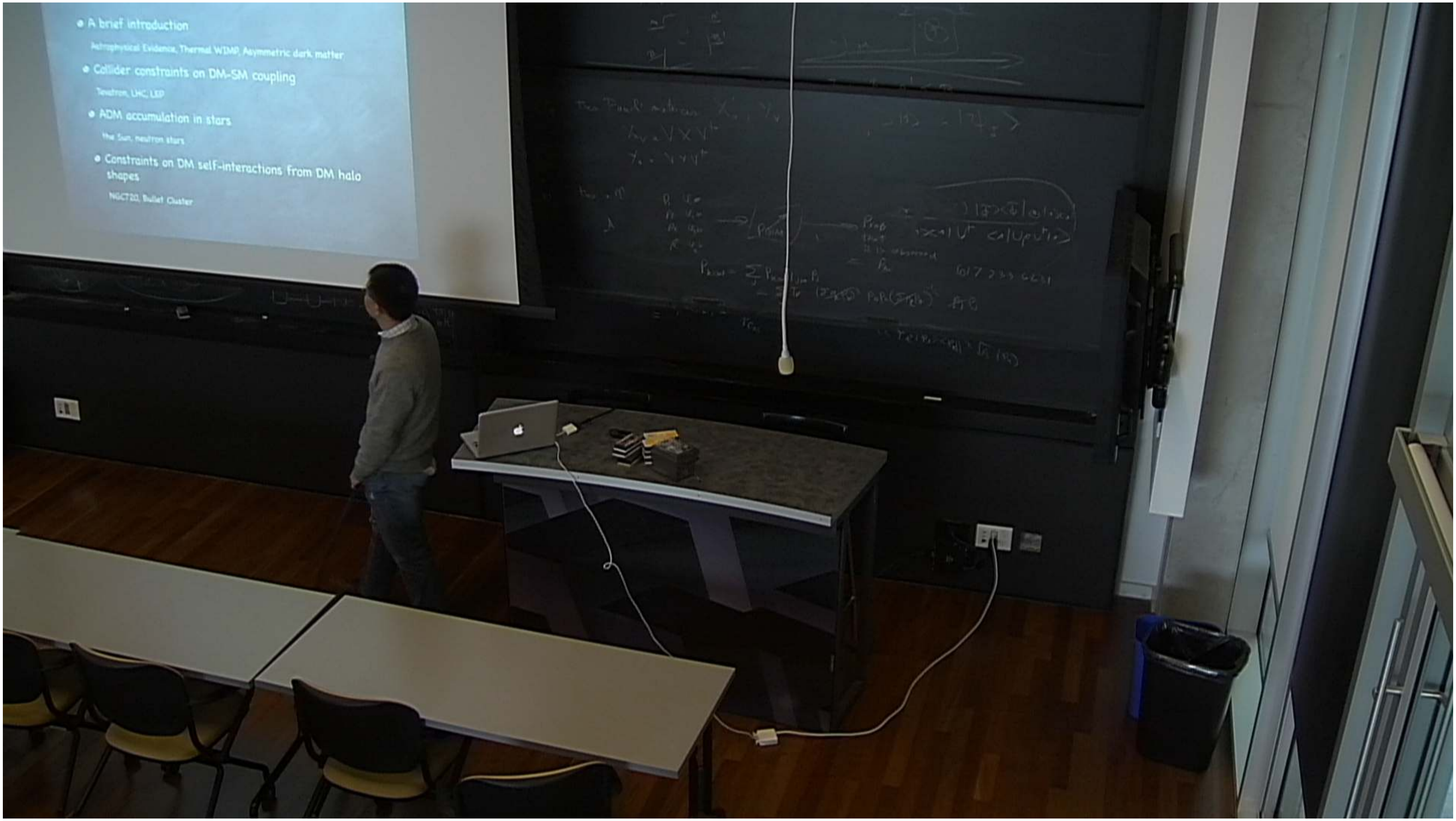
Title: Constraining Dark Matter

Date: Oct 18, 2011 12:30 PM

URL: http://pirsa.org/11100052

Abstract: In this talk, I will discuss constraints on dark matter (DM) from collider physics, neutron stars and DM halo shapes. Monojet plus missing energy searches at hardron colliders limit DM interactions with quarks and gluons, which provide a complementary probes of DM to direct detection. Stars can capture ambient DM particles. The captured scalar DM particles may form a Bose-Einstein condensate, leading to a black hole at the center of the host neutron star that eventually causes its destruction. The observation of old neutron stars exclude a wide range of the DM-neutron scattering cross-section for the scalar asymmetric DM. In various well-motivated models, DM has self-interactions which may leave imprints on galactic dynamics. I will discuss an upper bound on DM self-interaction cross section derived from elliptical DM halo shapes which is about two orders of magnitude stronger than the result from the Bullet Cluster.


A brief introduction
Astrophysical Evidence, Thermal WIMP, Asymmetric dark matter
Collider constraints on DM-SM coupling
Tevatron, LHC, LEP
ADM accumulation in stars
The Sun, neutron stars
Constraints on DM self-interactions from DM halo shapes
NGC720, Bullet Cluster

Outline

- A brief introduction

  Astrophysical Evidence, Thermal WIMP, Asymmetric dark matter

- Collider constraints on DM-SM coupling

  Tevatron, LHC, LEP

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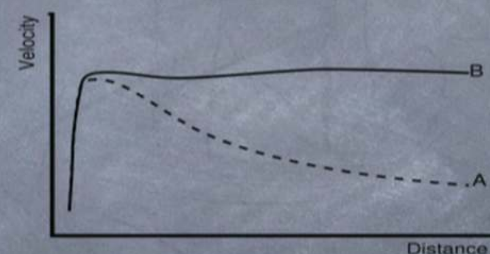
  the Sun, neutron stars

- Constraints on DM self-interactions from DM halo shapes

  NGC720, Bullet Cluster

Evidence For Dark Matter

- Rotation curves of galaxies



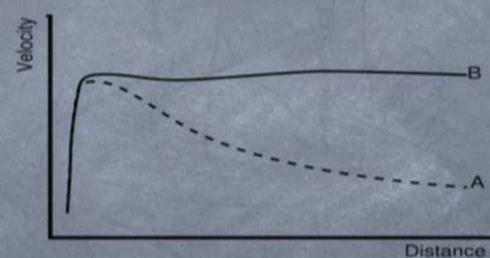
- Expect v drops beyond luminous region
- Find v is nearly a constant
- The discrepancy is resolved by dark matter

modify gravity?

Fritz Zwicky (1933)
Vera Rubin (1970)

Evidence For Dark Matter

- Rotation curves of galaxies



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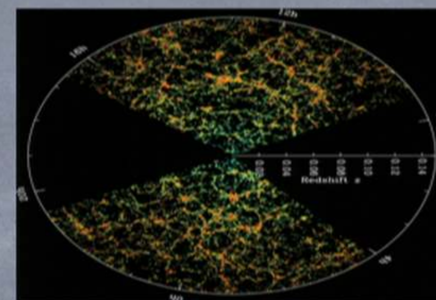
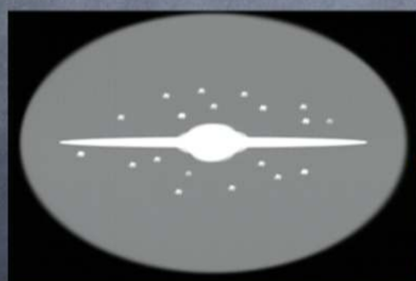
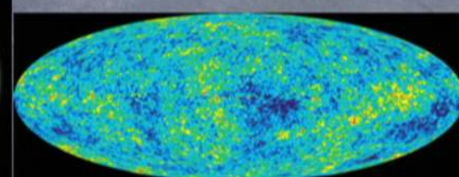
We Need Dark Matter

- Large structure formation
- Galaxy formation
- CMB
- Gravitational lensing...



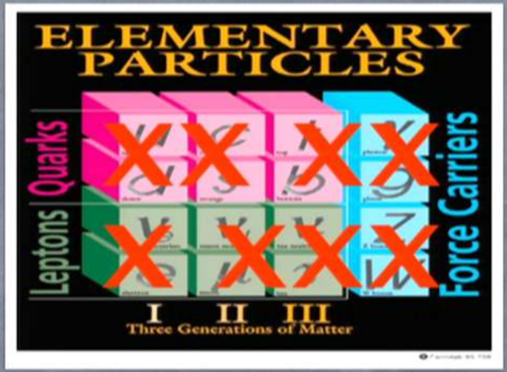


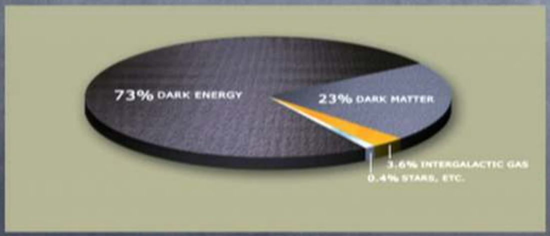


Known and Unknown

- Known properties

✓ Cold (Warm)
✓ Stable
✓ Non-baryonic
✓ Dark
✓ Density

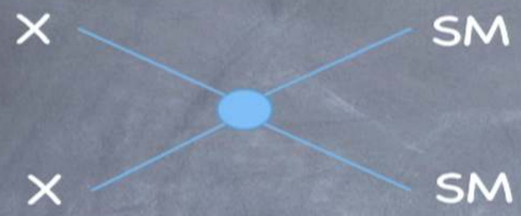




- Unknown properties

- Mass
- Spin
- Quantum Number

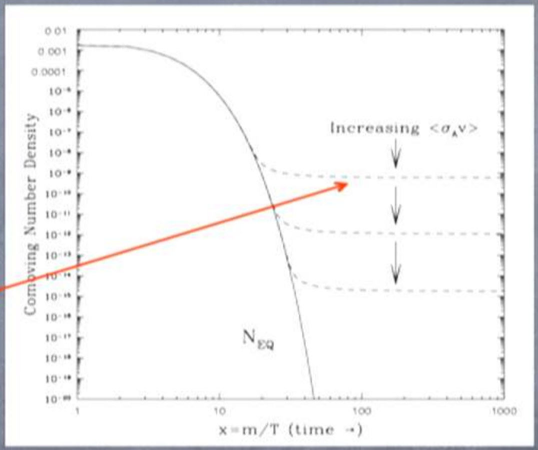
Theory: Thermal WIMP



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

(DM has zero chemical potential)

$$\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle \sim \frac{g_X^4}{m_X^2}$$

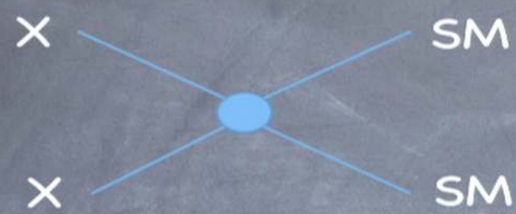


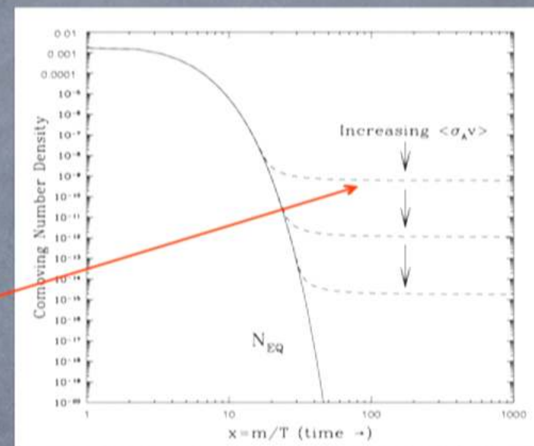
m_X ≈100 GeV, g_X ≈0.23 → Ω_X≈0.2

A remarkable coincidence:

Dark matter and weak scale new physics

Theory: Thermal WIMP





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$m_X \approx 100$ GeV, $g_X \approx 0.23 \rightarrow \Omega_X \approx 0.2$

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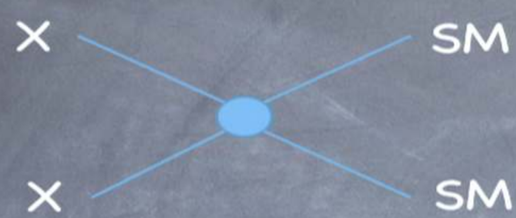
Theory: Asymmetric DM

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

- Some mechanism generates DM and anti-DM number asymmetry. It may connect to the baryon asymmetry.
- DM has a nonzero chemical potential. Usual thermal WIMP is the symmetric limit.
- DM is the Dirac fermion or complex scalar.

Nussinov (1985); Kaplan (1992); Kaplan, Luty, Zurek (2009); An, Chen, Mohapatra, Zhang (2009)...

Theory: Thermal WIMP



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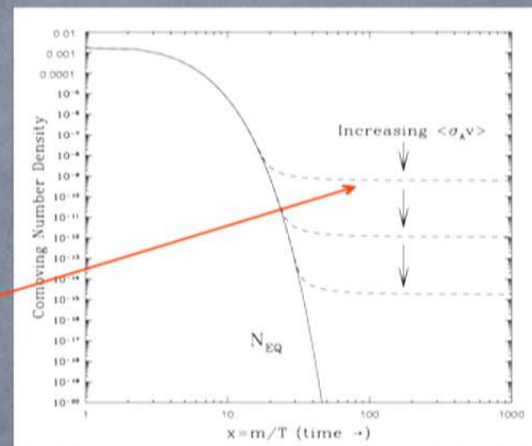

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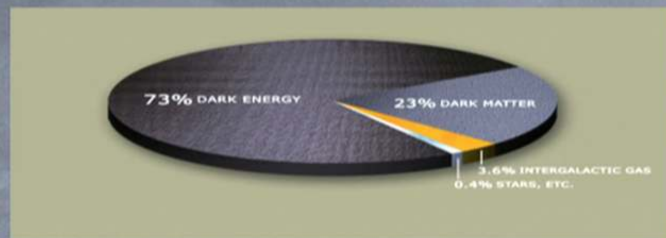

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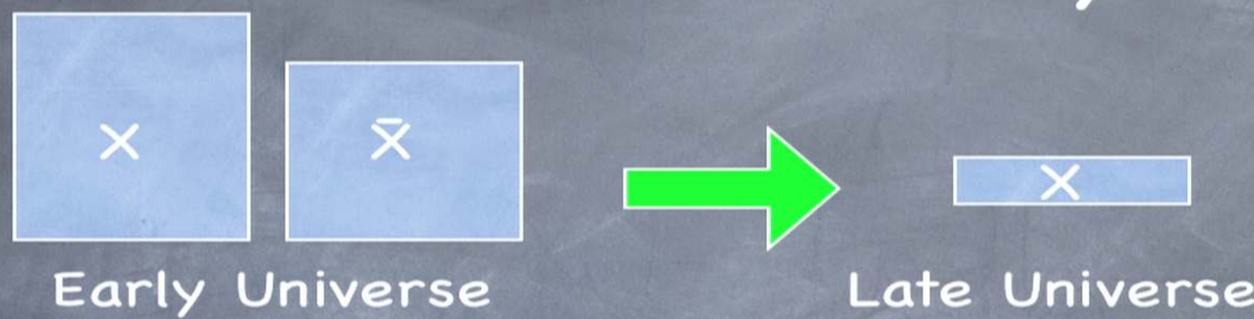
ADM Relic Density



- In the early Universe, T>>μ, both DM and anti-DM particles populate in the thermal bath.
- If $\eta_X \sim \eta_B \quad \langle \sigma v \rangle \gtrsim \sigma_{WIMP} \sim 6 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
- Annihilate to hidden sector particles
- Annihilate to SM particles (collider constraints!)

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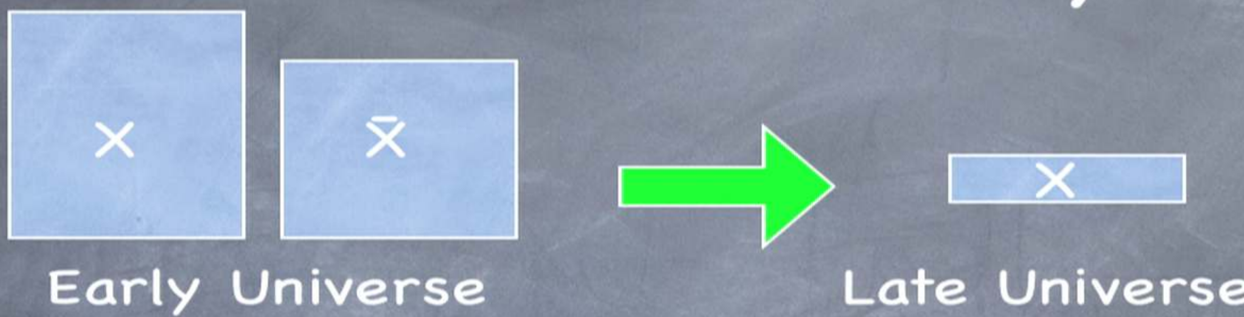

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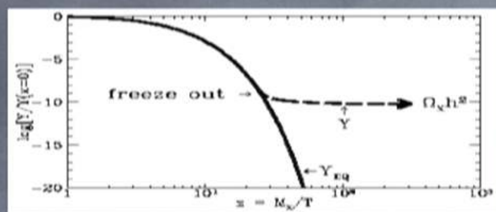
SDM VS. ADM



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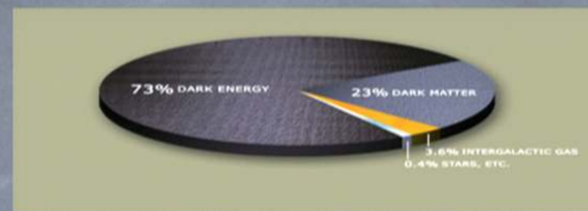

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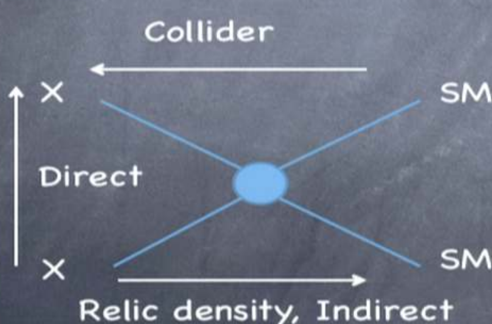

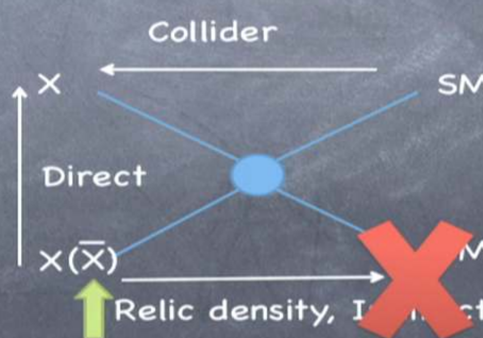

Negligible now! Look for accumulation

An Effective Theory Approach

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
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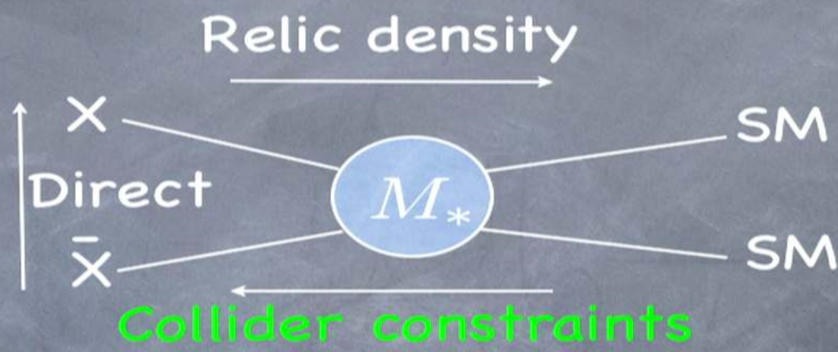

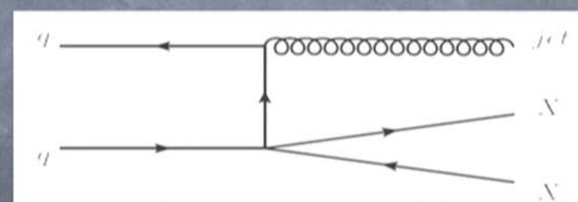

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The cutoff scale determines everything!

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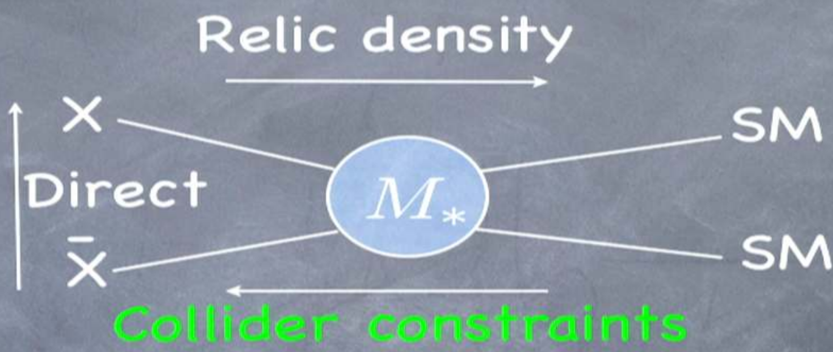

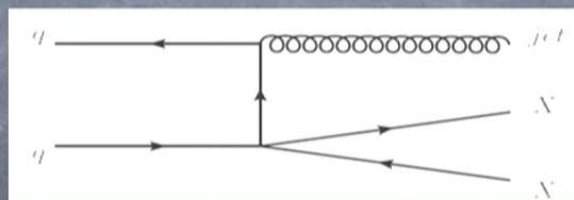

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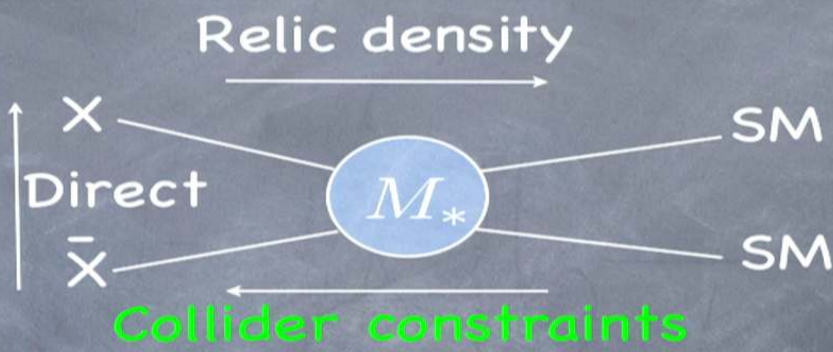

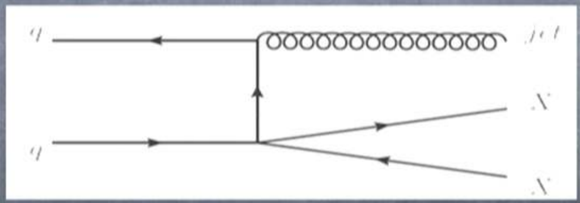

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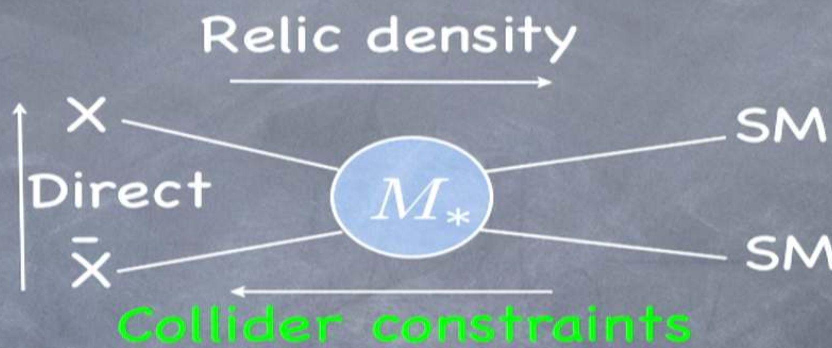

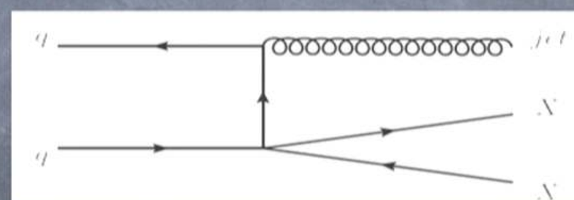

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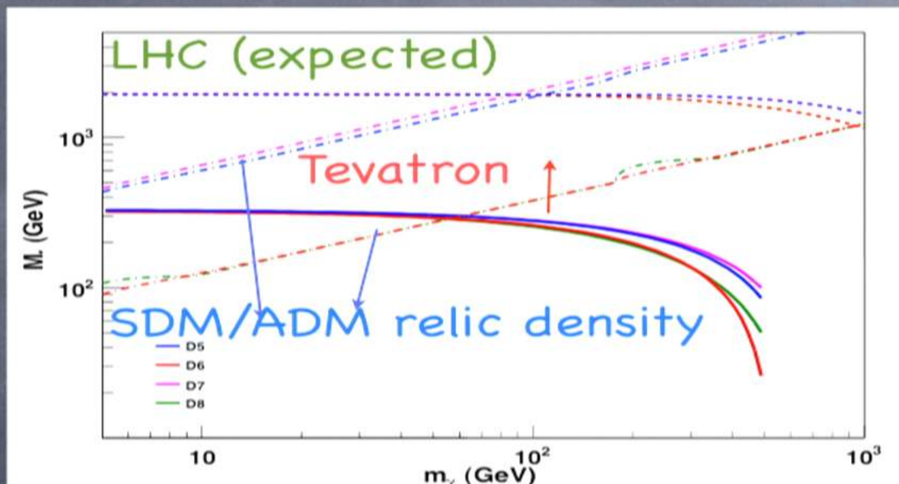
Relic Density VS. Tevatron



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

- ADM needs to deplete the symmetric component through annihilation
- Not easy for DM to have right relic density through these high dimensional operators

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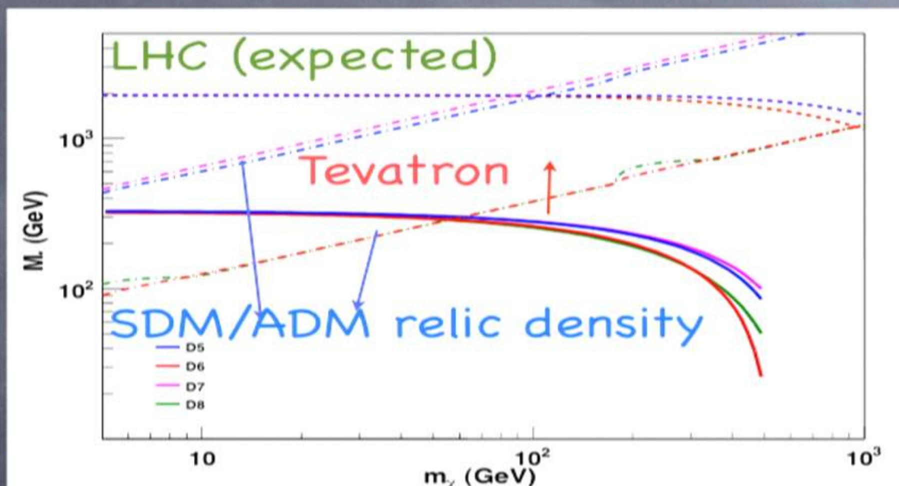
Relic Density VS. Tevatron



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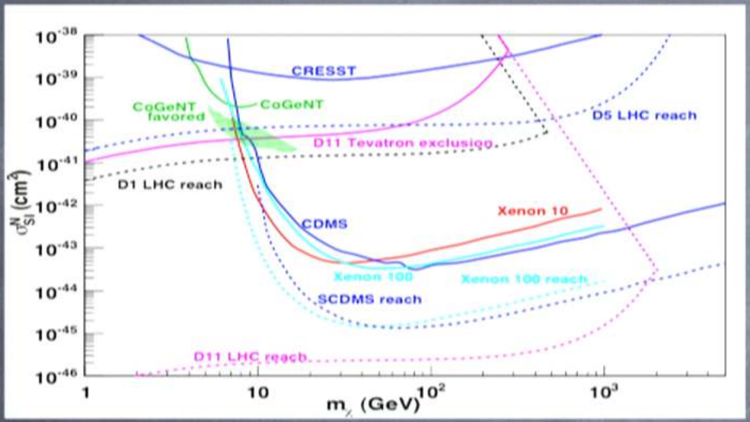
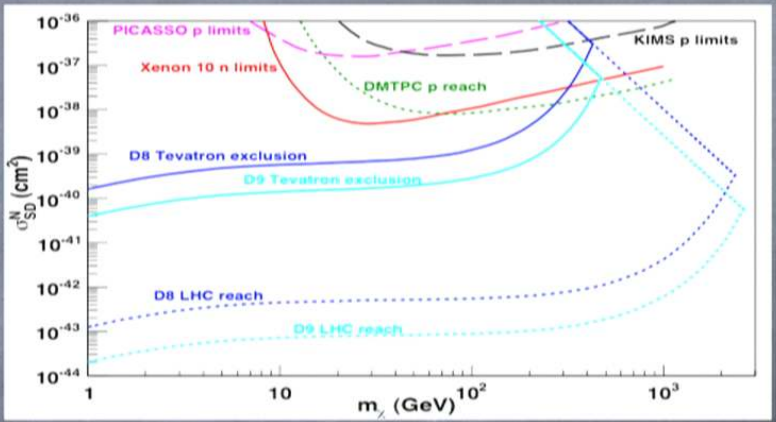
D13	~~$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$~~	$i\alpha_s/4M_*^3$
D14	~~$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$~~	$\alpha_s/4M_*^3$

Direct Detection VS. Tevatron



Spin-independent

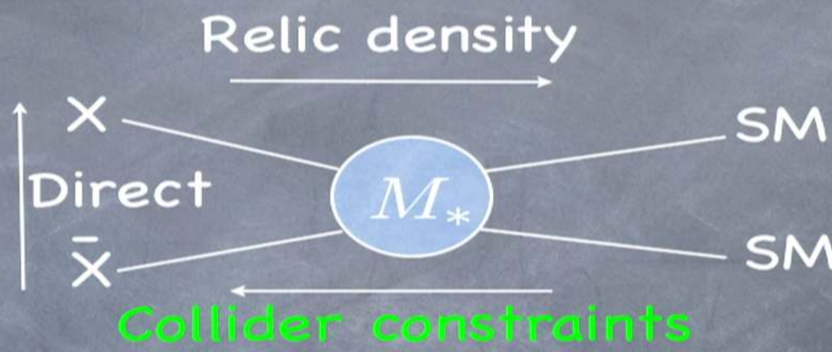


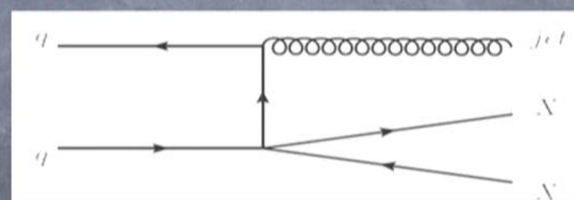
Spin-dependent

For some operators, colliders can do better!

An Effective Theory Approach

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



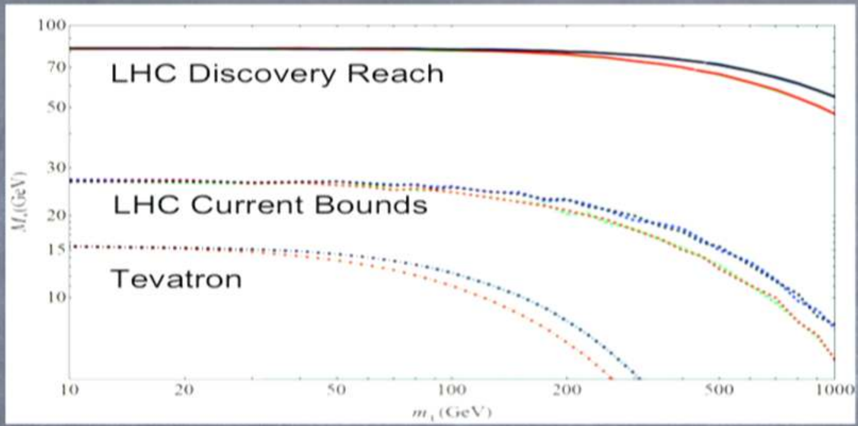


missing energy
+mono-jet

The cutoff scale determines everything!

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

LHC at 7 TeV

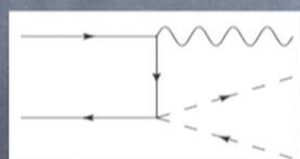


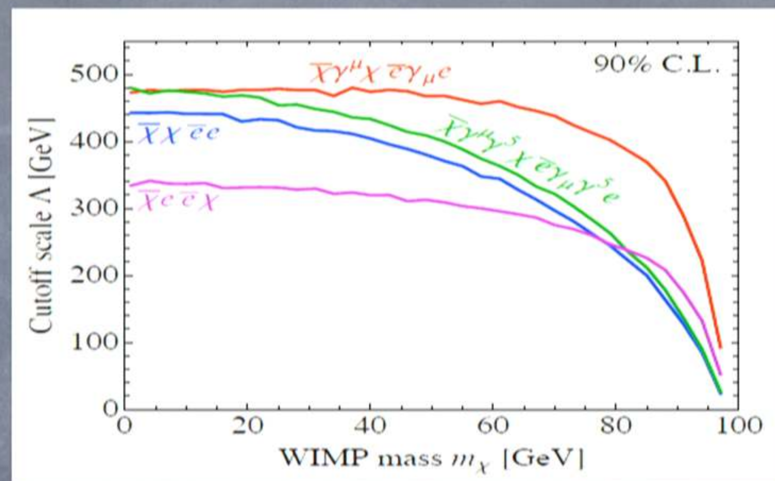
For D1,D2,D3,D4 operators

Rajaraman, Shepherd, Tait, Wijangco (2011)

Couple to Leptons

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



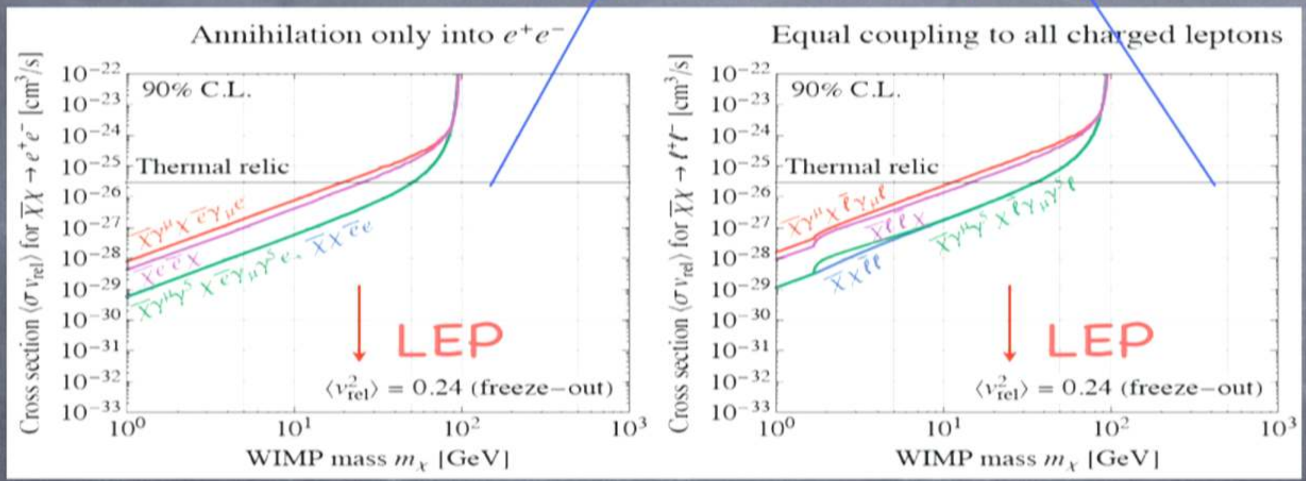


Fox, Harnik, Kopp, Tsai (2011)

- Missing energy+mono-photon

LEP Constraints

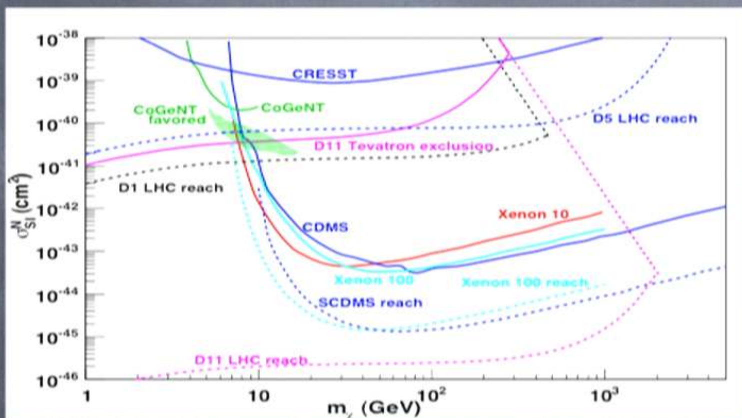
SDM/ADM relic density



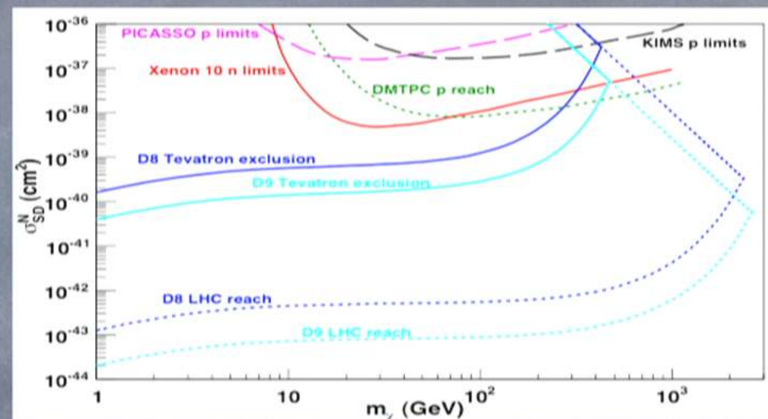
Fox, Harnik, Kopp, Tsai (2011)

- The Tevatron and LEP set strong constraints on DM-SM coupling.
- The light DM requires a light mediator with the mass much less than the transverse momentum O(100) GeV in colliders.

Direct Detection VS. Tevatron



Spin-independent



Spin-dependent

For some operators, colliders can do better!

ADM Accumulation

- Typically, there are no annihilation signals. Look for ADM accumulation.

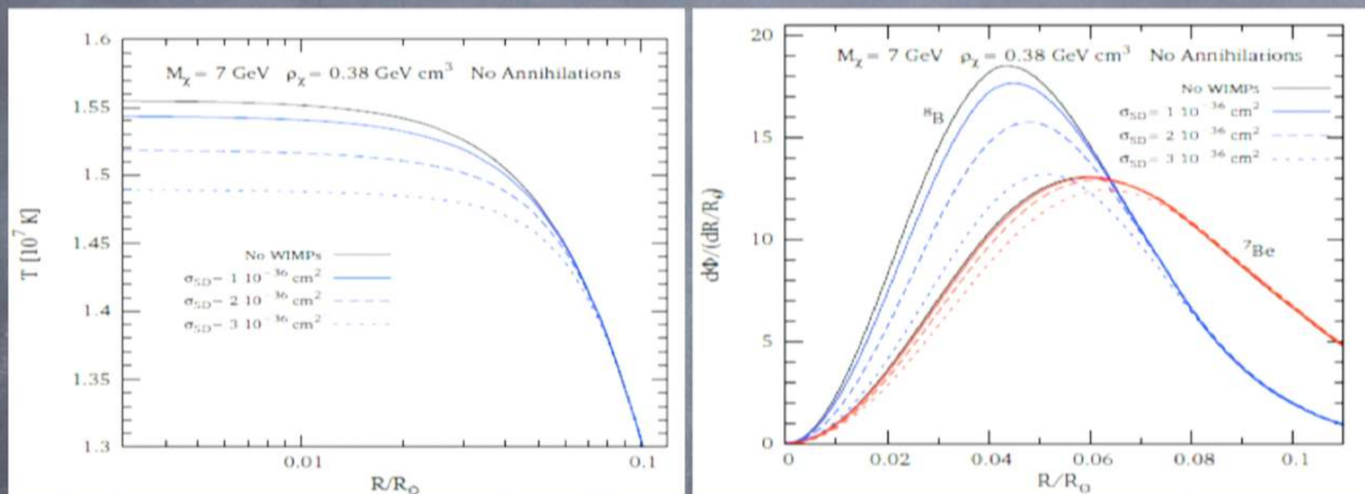
- Accumulation in the Sun.

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

- Accumulation in neutron stars.

  McDermott, HBY, Zurek (2011)

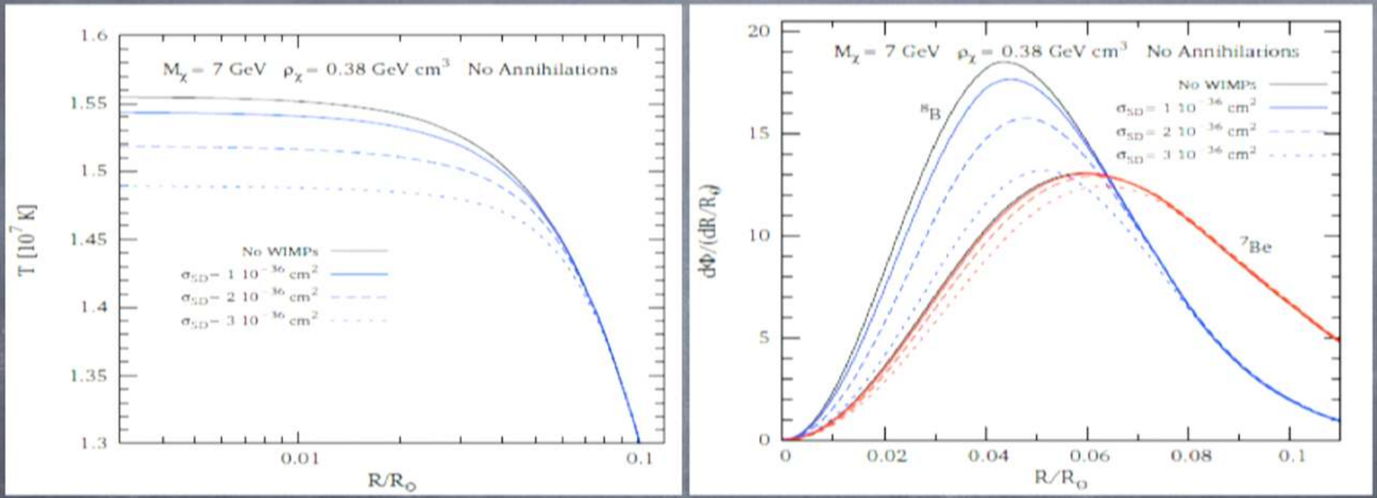
ADM in the Sun



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.

ADM in the Sun



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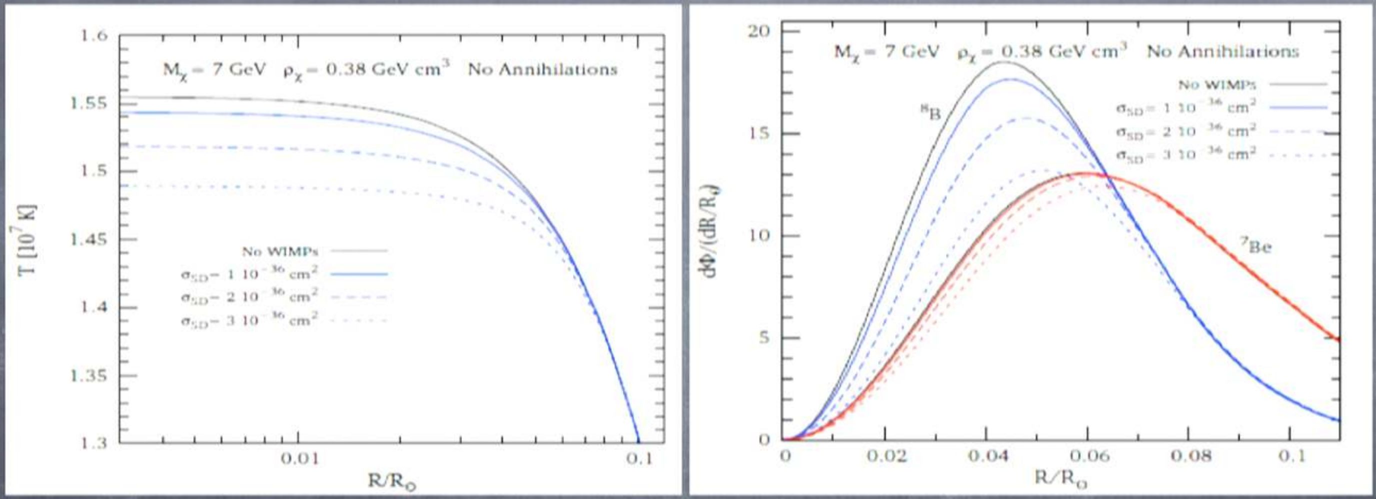
Basics of Neutron stars

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

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

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

ADM in the Sun



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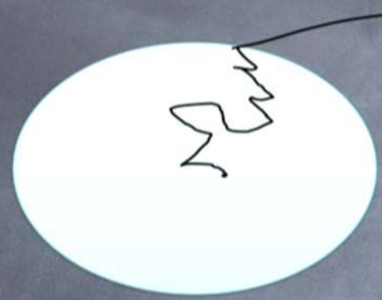


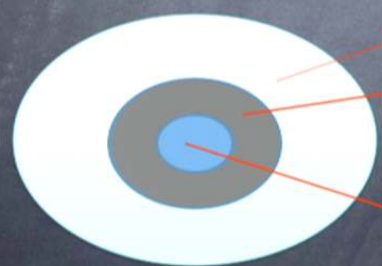
Capture (Step 1)

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

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)

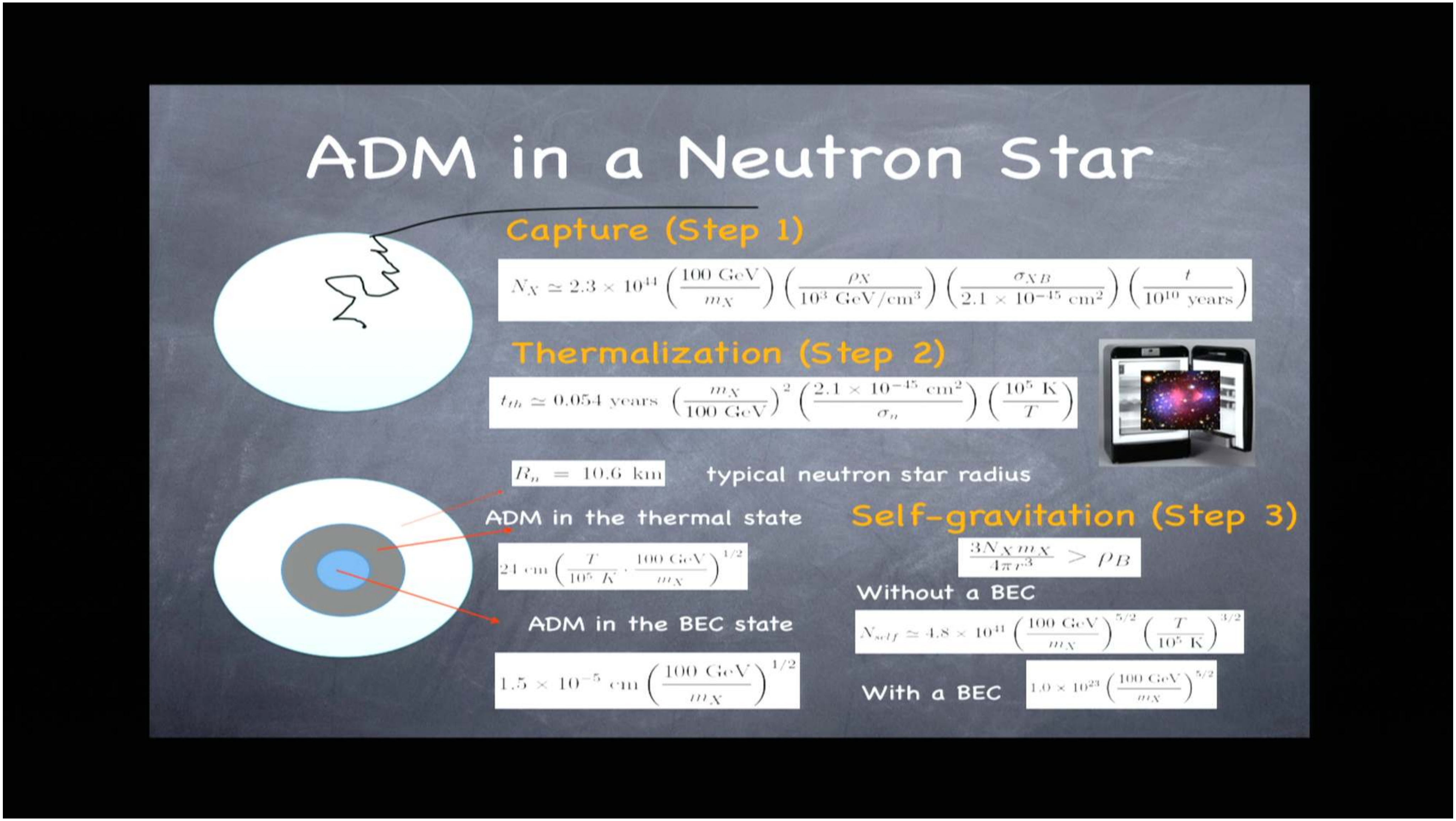
$$\frac{3N_X m_X}{4\pi r^3} > \rho_B$$

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

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


ADM in a Neutron Star
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typical neutron star radius
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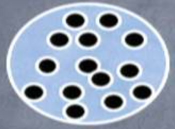
With a BEC
$1.0\times10^{23}\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^{5/2}$

Chandrasekhar Limit

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

- Fermions: gravity VS. Fermi pressure



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

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

- Bosons: gravity VS. zero point energy

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

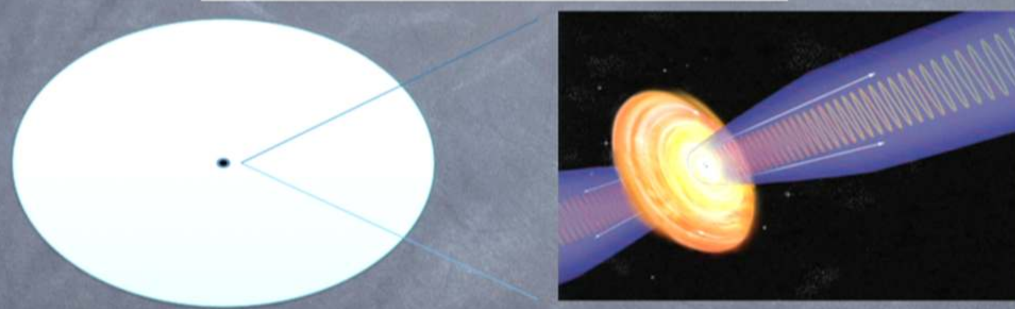
$$N_{Cha}^{boson} \sim \left(\frac{M_{pl}}{m}\right)^2 \sim 1.5 \times 10^{34} \left(\frac{100 \text{ GeV}}{m}\right)^2$$

NOTE

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

Minimal Black Holes

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



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

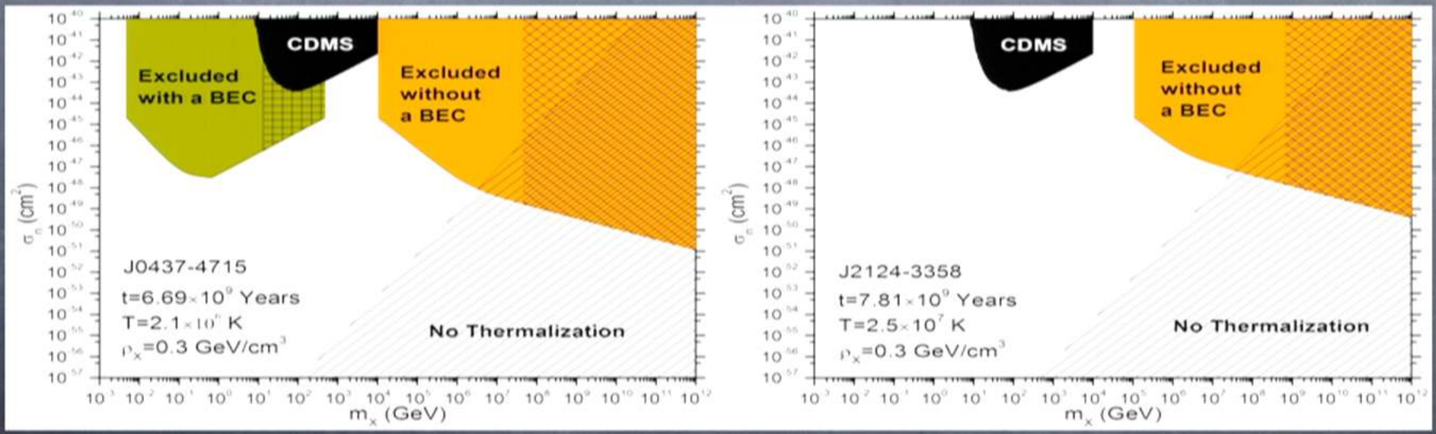
Baryon accretion   Hawking radiation

Hawking wins if the initial black hole mass is less than

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

Nearby Old Pulsars

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



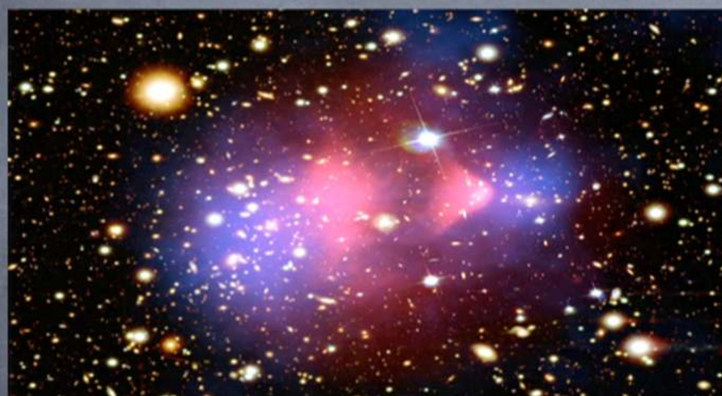
DM Self-interactions

- Self-interacting DM Spergel, Steinhardt (1999); Dave, Spergel, Steinhardt, Wandelt (2000)
- Contact interactions Spergel, Steinhardt (1999); Recent ADM models involving strong dynamics
- Mediated by massless mediators

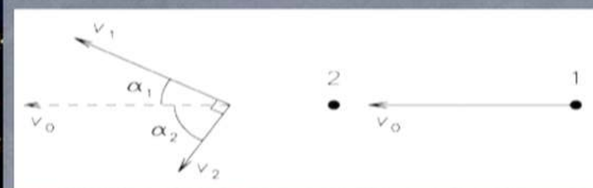
  Feng, Tu, HBY (2008); Ackerman, Buckley, Carroll, Kamionkowski (2008); Feng, Kaplinghat, Tu, HBY (2009)
- Mediated by light massive mediators

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

The 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.

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

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.

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

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

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

Feng, Kaplinghat, HBY (2009); Lin, HBY, Zurek (in preparation)

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Summary

- Colliders provide interesting constraints on DM-SM interactions.
- We can use stars to probe ADM.
- The ellipticity of DM halos puts a strong constraint on the DM self-interaction cross section.