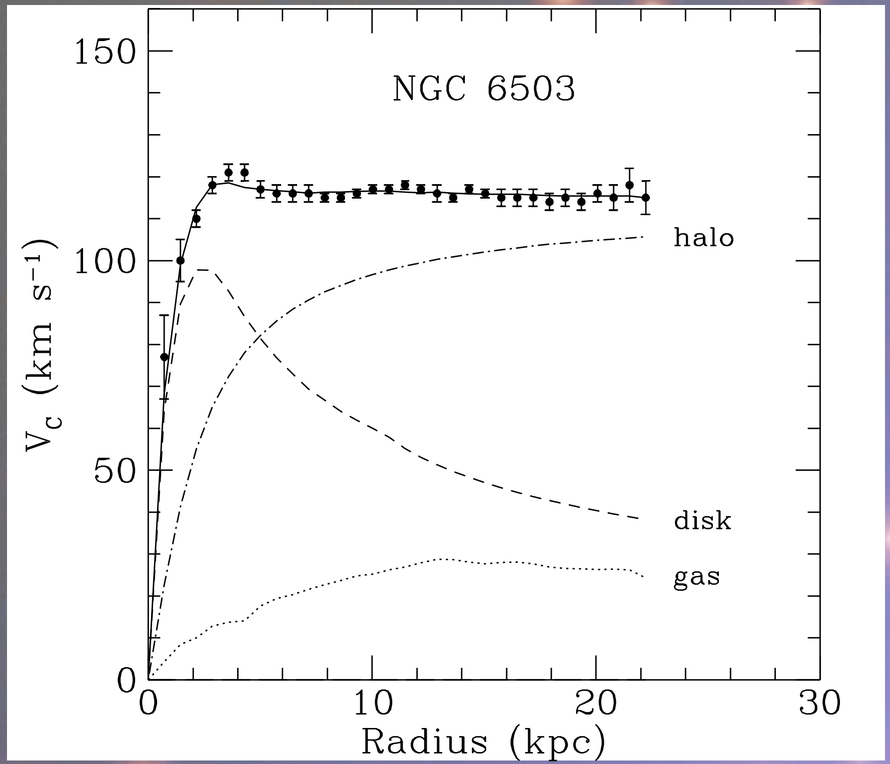
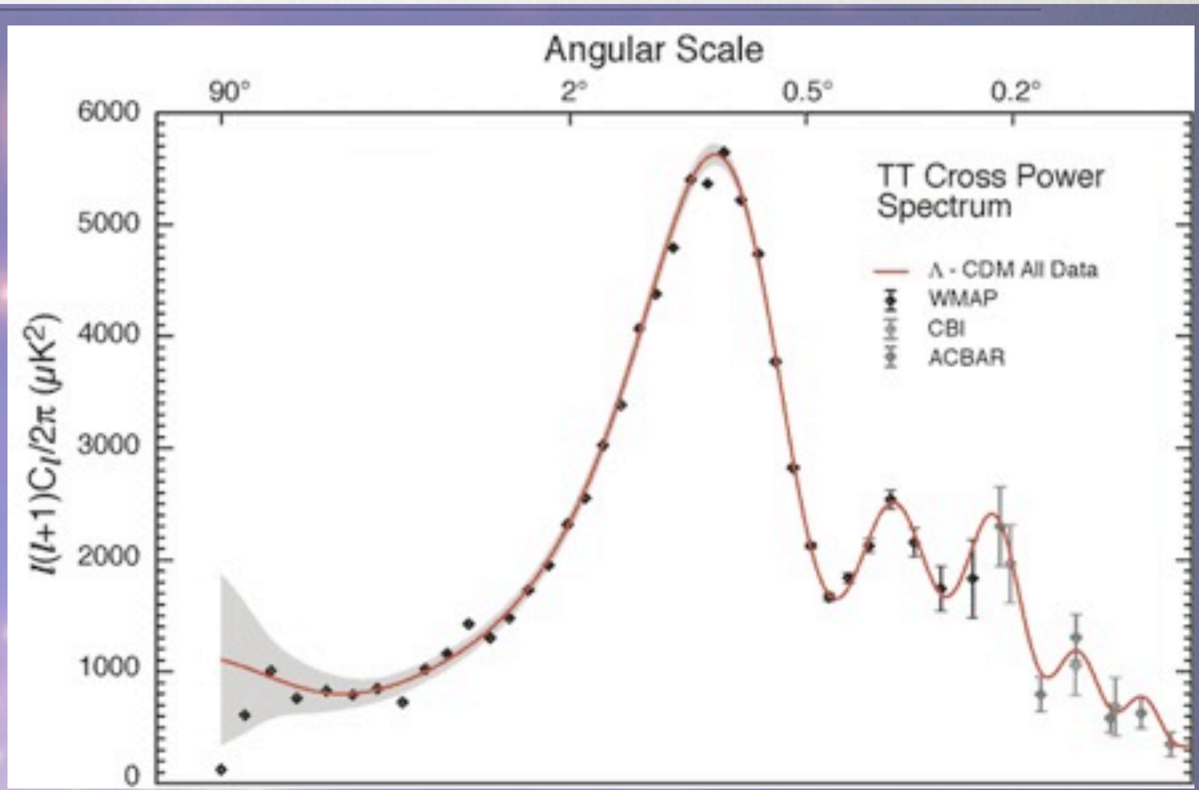
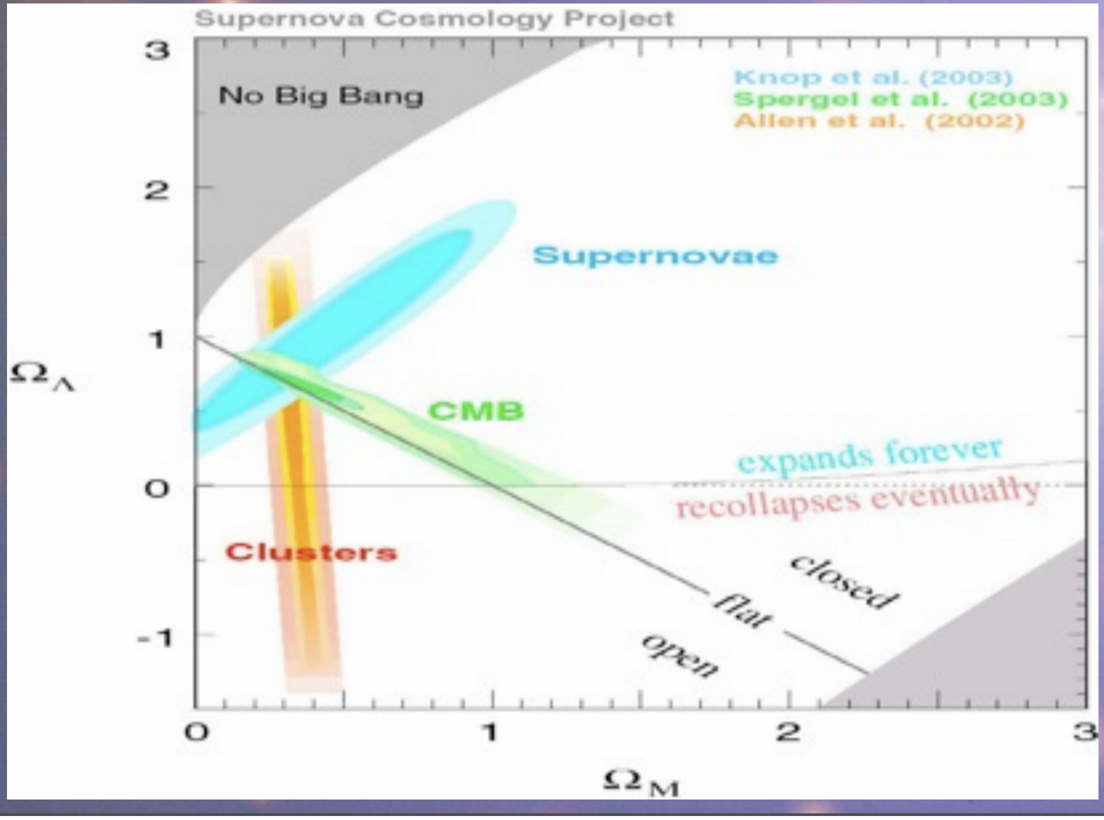
Asymmetric Dark Matter

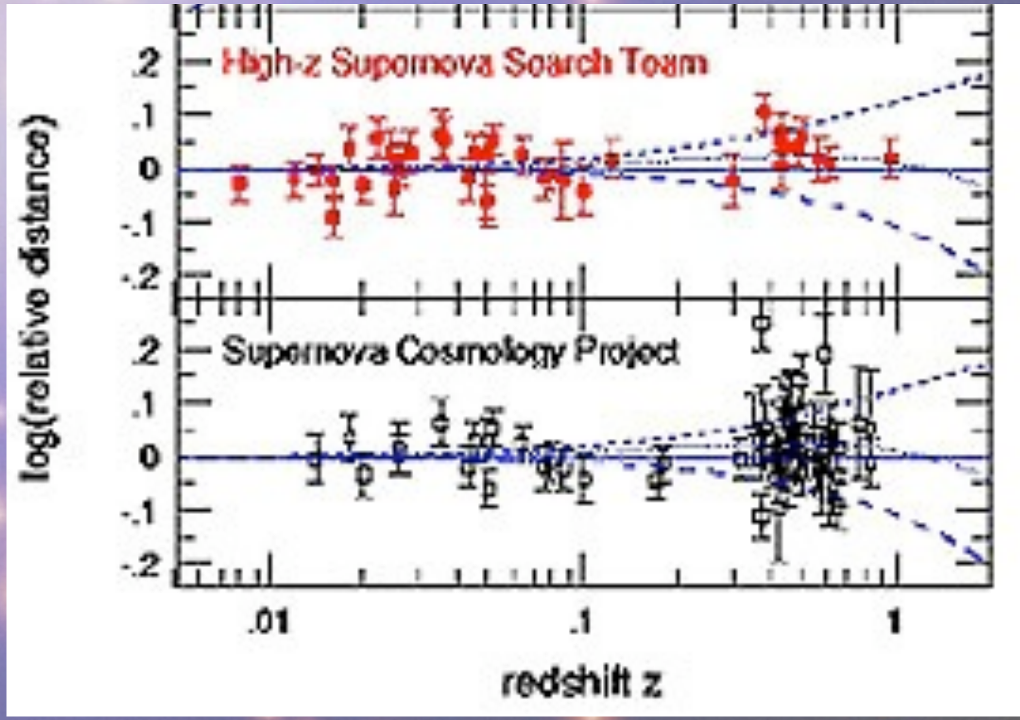
Kathryn M. Zurek
University of Michigan

Overwhelming Evidence for Dark Matter



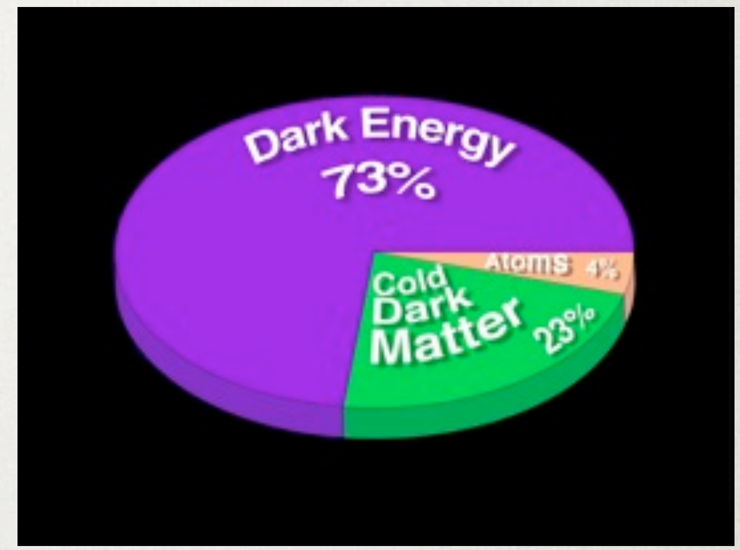


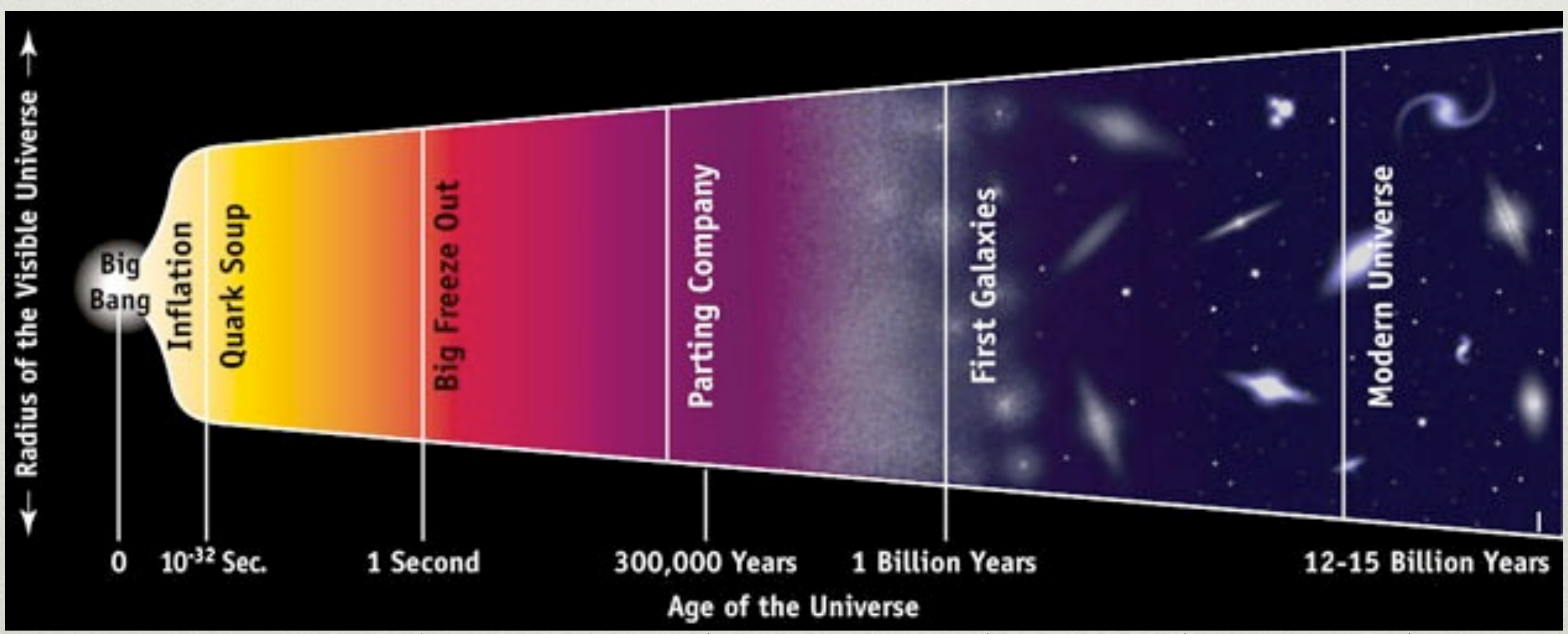




Evidence for DM Overwhelming

All evidence points toward





BBN (baryons)

CMB (curvature)

Supernovae (DE)

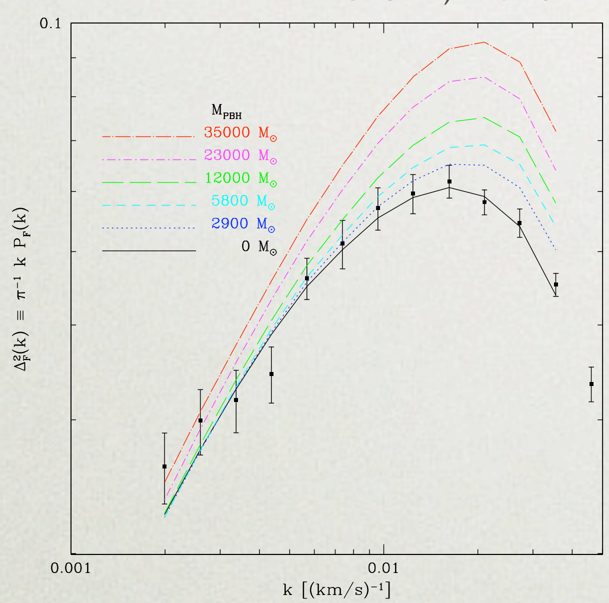
LSS (matter)

Galaxy curves (matter)

What do we know about DM?

- Not baryonic

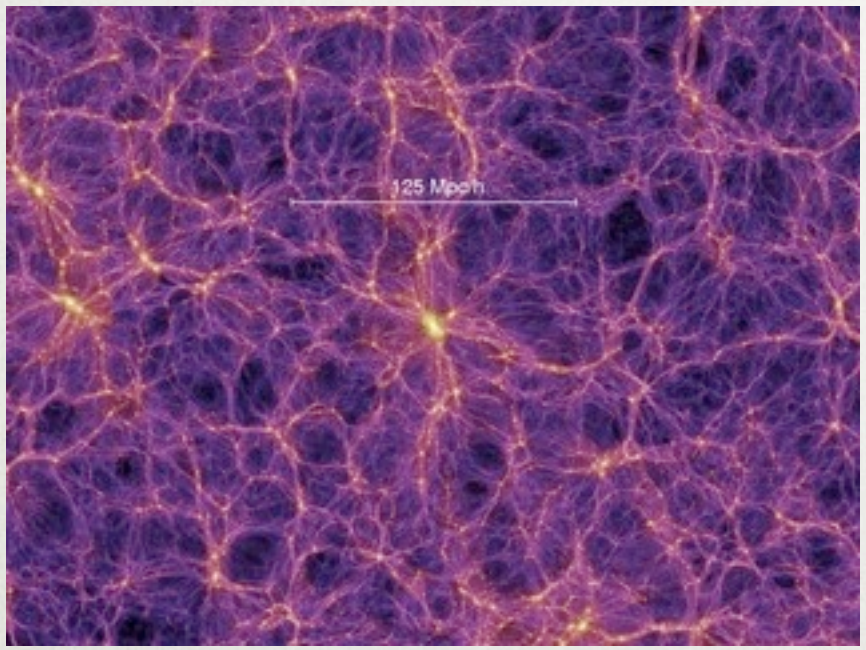
Afshordi, McDonald, Spergel



- Not modified gravity
- BBN --> not free baryons
- MACHO searches +Lya --> not bound baryons
- CMB + LSS + Bullet --> not neutrinos as DM

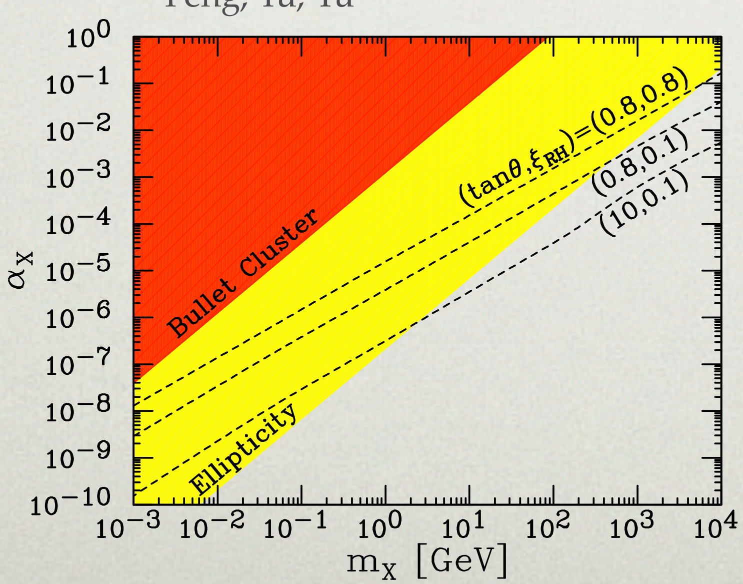
What do we know about DM?

- Cold



- CMB + LSS -- clustering properties

Feng, Tu, Yu

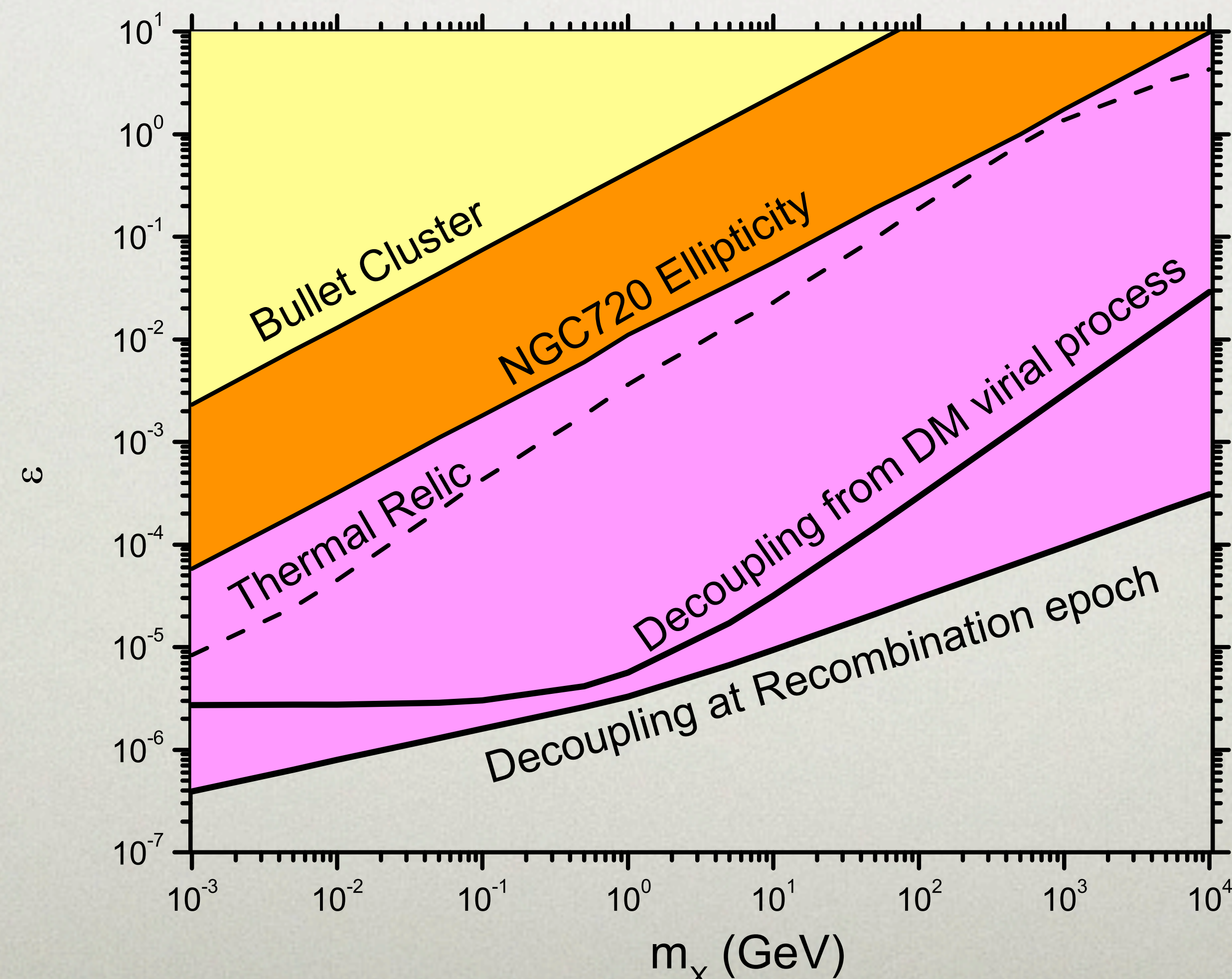


- Weakly interacting
- With us -- direct detection
- With itself -- halo shape bounds

How Dark is Dark Matter?

- Which probe is the most constraining?

$$\mathrm{d}\langle \delta p_X^2 \rangle/\mathrm{dt} = \sum_{b=e,p} n_b \int d^3 v_B d^3 v_X f(v_B) f(v_X) d\Omega_* \frac{d\sigma_{Xb}}{d\Omega_*} v_{\rm rel} \delta p_X^2$$



McDermott, Yu, KZ

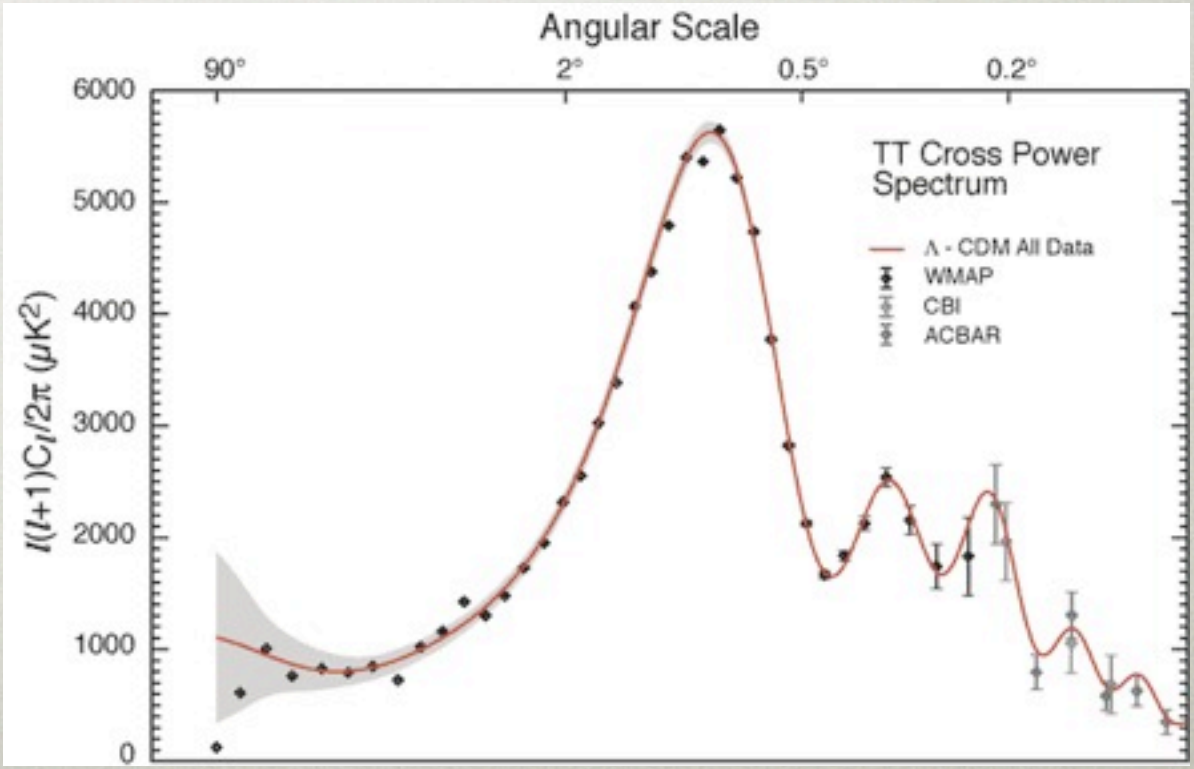
How Dark is Dark Matter?

- Coupling at CMB epoch is most constraining

$$\frac{\mathrm{d}\sigma_{XX}}{\mathrm{d}\Omega_*} = \frac{\alpha_{\mathrm{em}}^2 \epsilon^4}{m_X^2 v_{\mathrm{rel}}^4 \sin^4(\theta_*/2)}$$

$$\frac{\mathrm{d}\sigma_{Xb}}{\mathrm{d}\Omega_*} = \frac{\alpha_{\mathrm{em}}^2 \epsilon^2}{4\mu_b^2 v_{\mathrm{rel}}^4 \sin^4(\theta_*/2)}$$

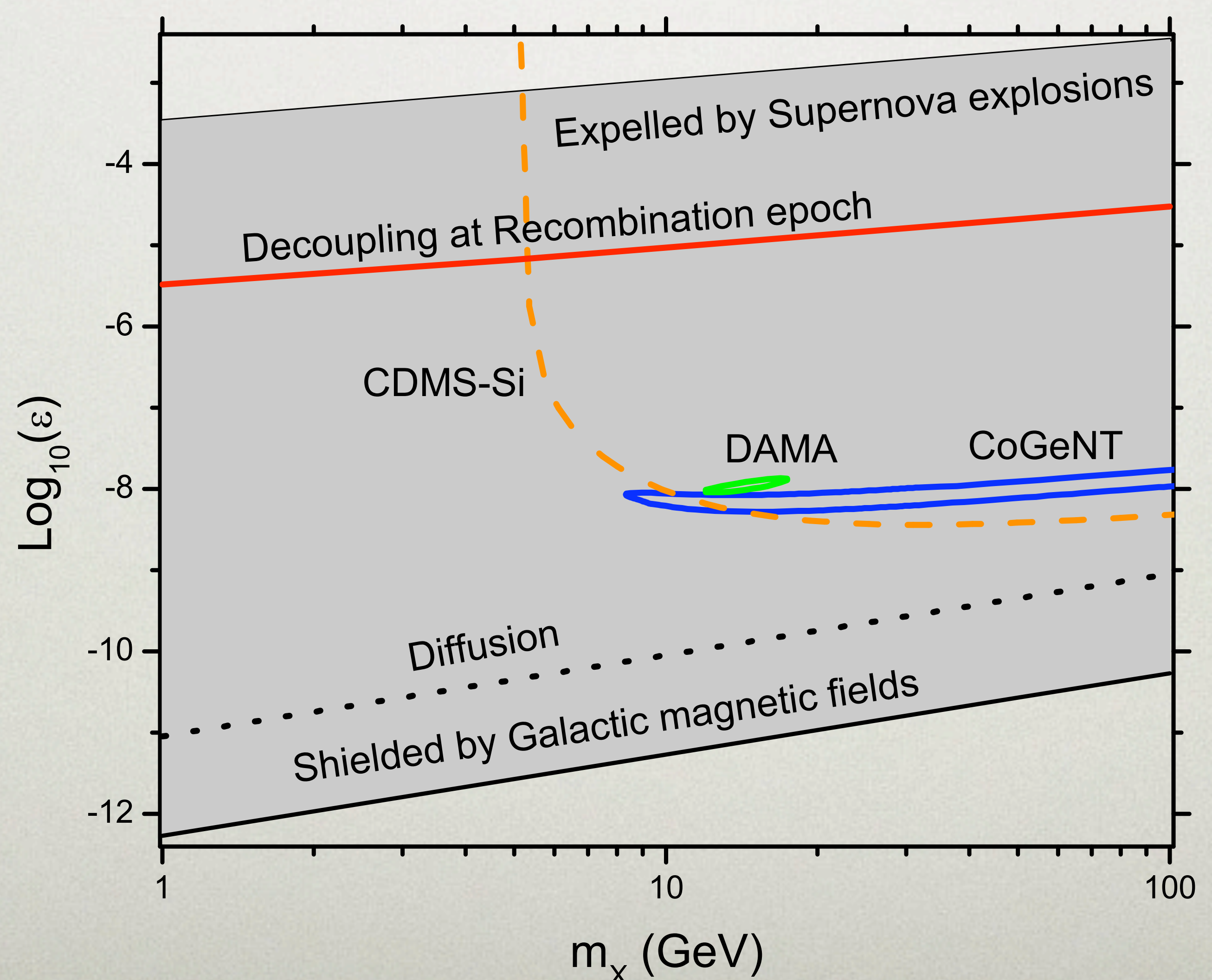
$$\frac{d\sigma}{d\Omega} \propto \frac{1}{v^4}!$$



How Dark is Dark Matter?

- Direct detection is also (potentially) highly constraining

McDermott, Yu, KZ



Theories of Dark Matter

- Axions

  - Solve Strong CP

  - Correct density of high scale axions via selection

- WIMPs

  - Naturally obtain correct density via freeze-out

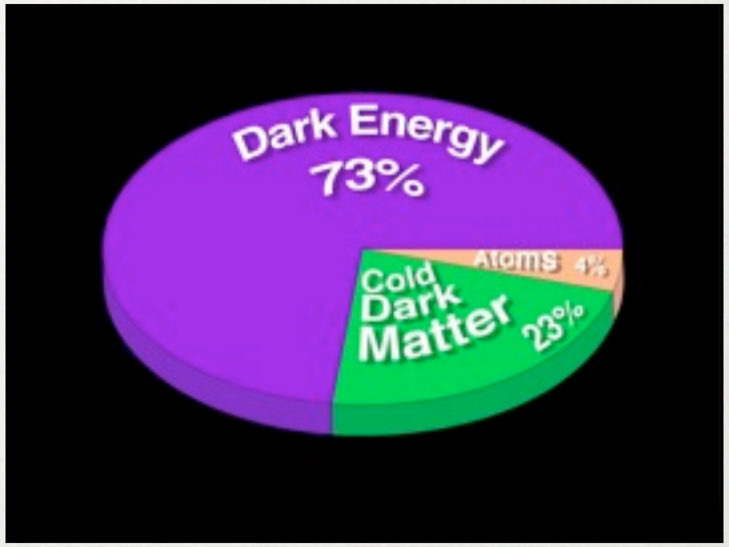
  - Connected to weak scale

- Chemical Potential Dark Matter

  - Naturally obtain correct density via chemical potential

  - Connected to weak scale

Baryon and DM Number Related?

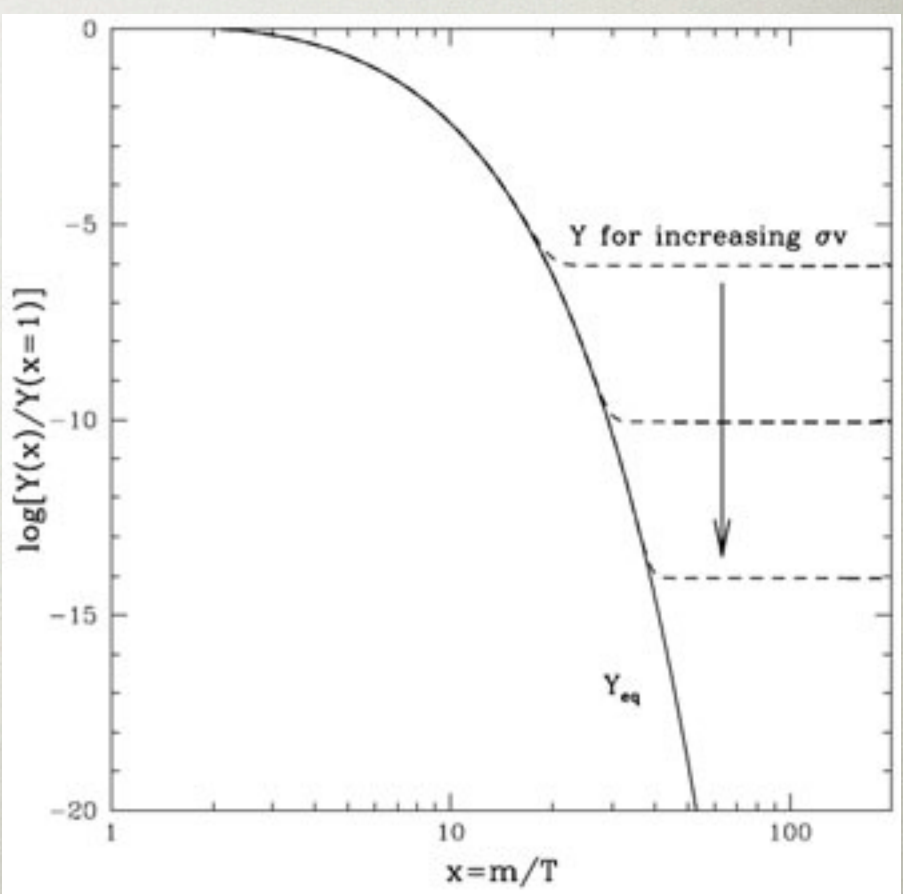


- Weak scale freeze-out

Measured by WMAP + LSS

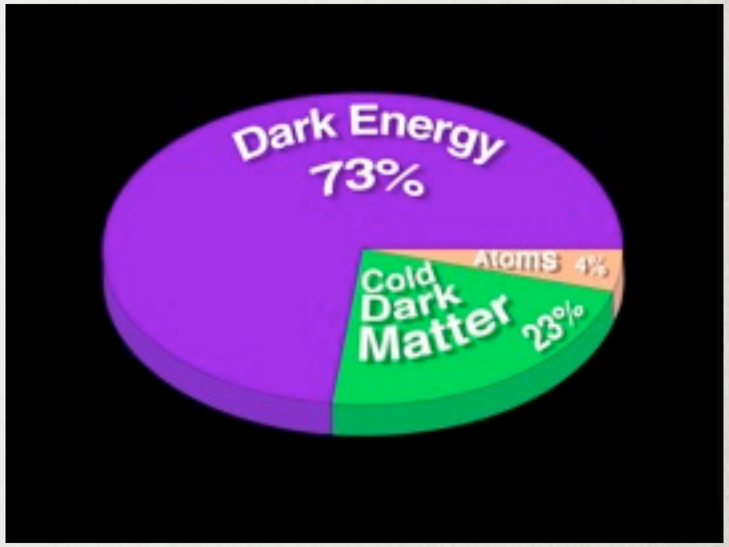
$$\Gamma = n\sigma v \overset{\swarrow}{=} H \quad \Longrightarrow \sigma \sim \frac{1}{(100\text{GeV})^2}$$

Kolb and Turner



- But why baryon and DM densities so close?

BARYON AND DM NUMBER RELATED?



- Accidental, or dynamically related?

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \approx 5m_p$

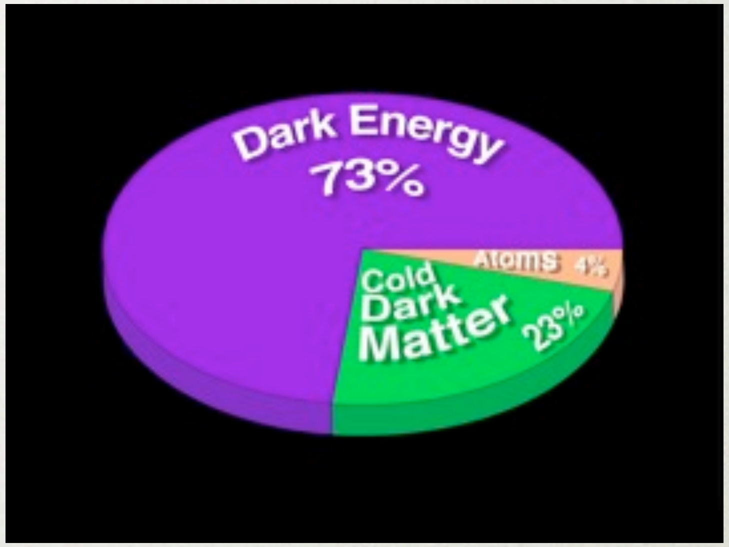
Nussinov,
Hall, Gelmini,
Barr, Chivukula, Farhi,
D.B. Kaplan

Chemical Potential Dark Matter

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

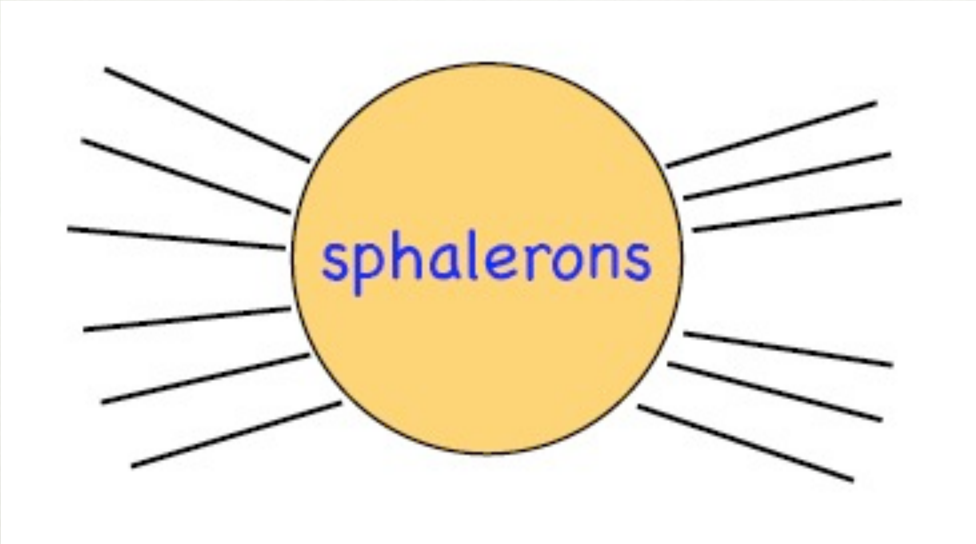
Mechanism $n_{DM} \approx n_b$

→ $m_{DM} \approx 5m_p$



Use EW sphalerons?

B, L



X

SU(2) carrying dark fields!

Barr, Chivukula, Farhi; D.B. Kaplan

Chemical Potential Dark Matter

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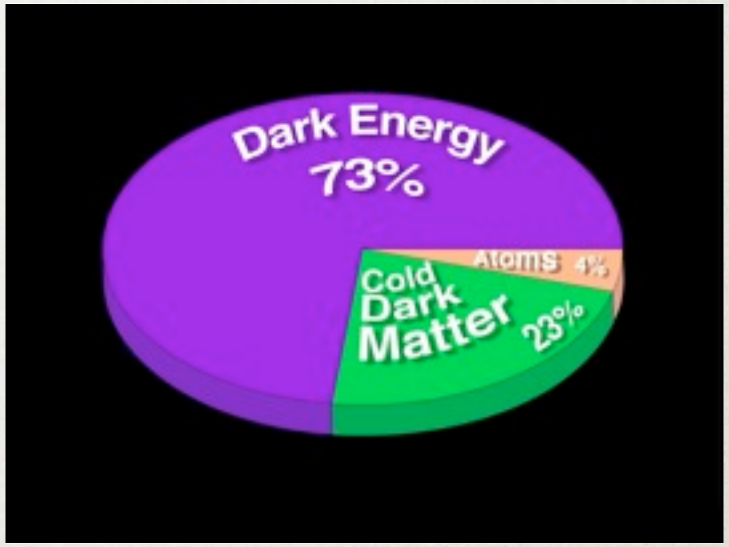
Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \approx 5m_p$



Use EW sphalerons?

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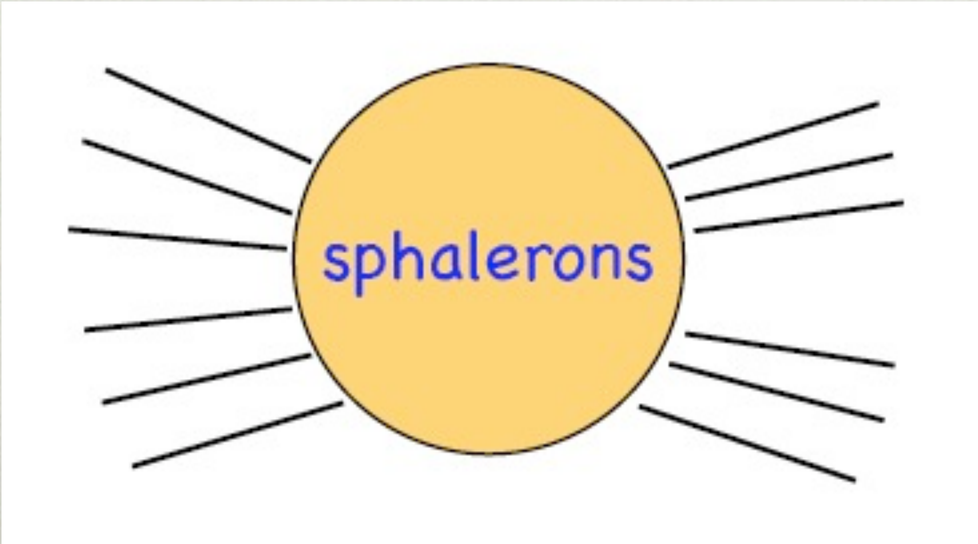


X

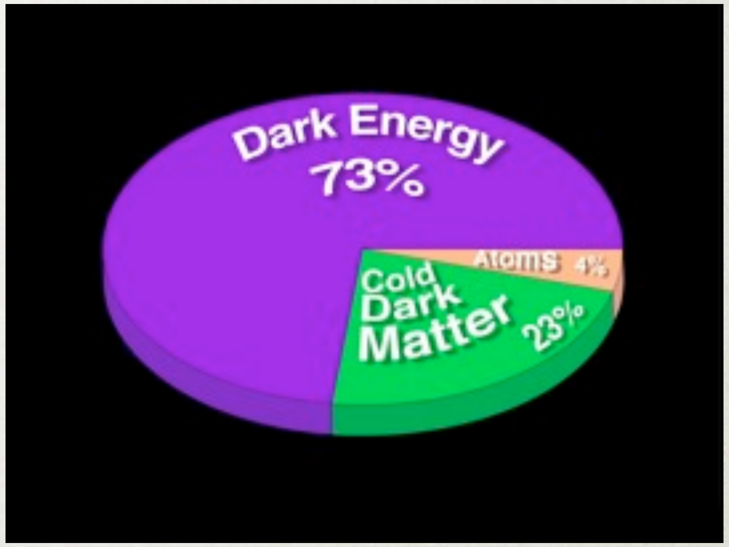
LEP and Precision EW tend to result in problematic models

A simple prescription: Asymmetric DM

Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Mechanism $n_{DM} \approx n_b$

$\Rightarrow$ $m_{DM} \approx 5m_p$



- Essential idea is to use higher dimension operators to transfer the asymmetry between sectors

Luty, Kaplan, KZ '09

- Avoid problems of precision EW

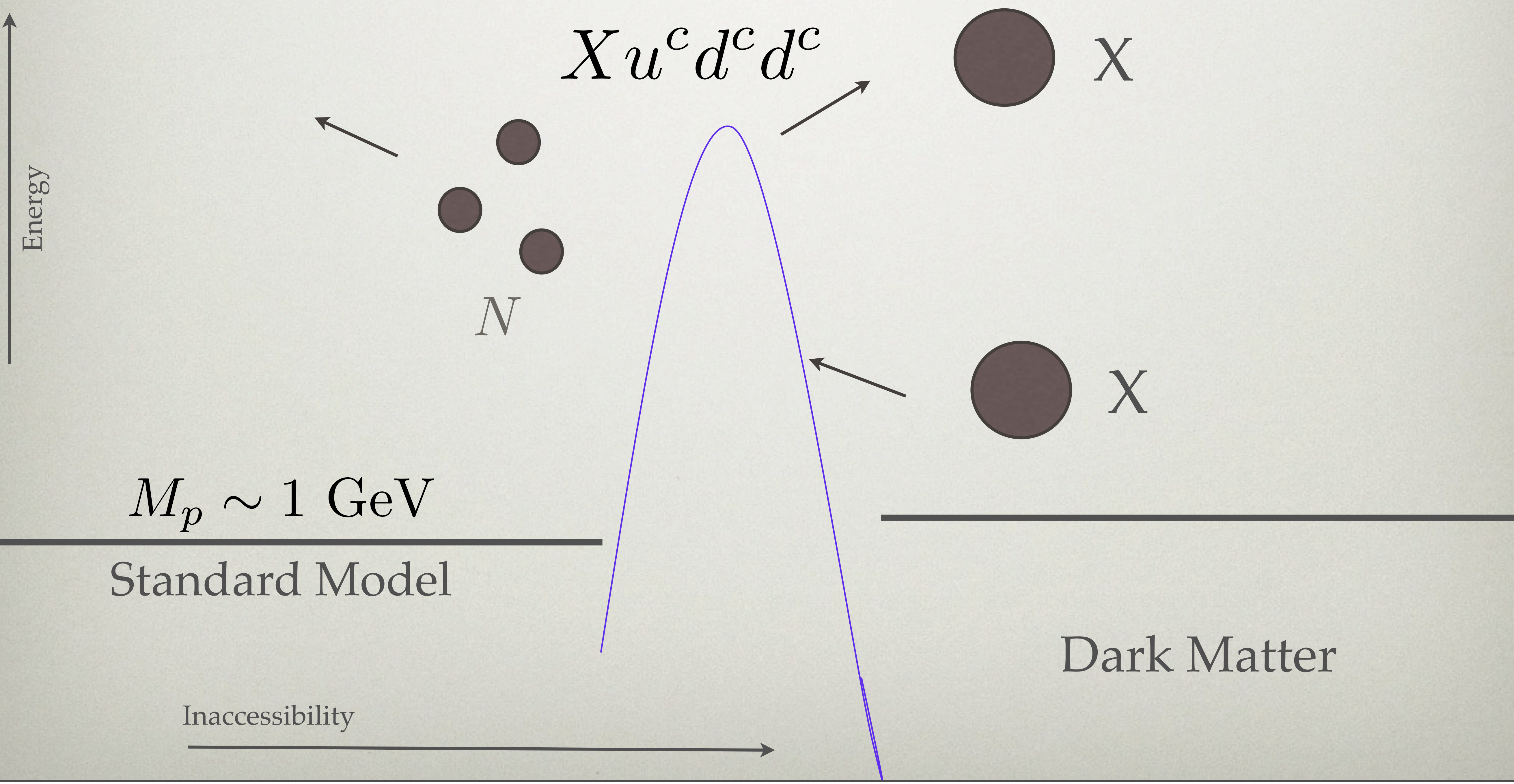
Asymmetric DM

Integrate out heavy state

Effective operators:

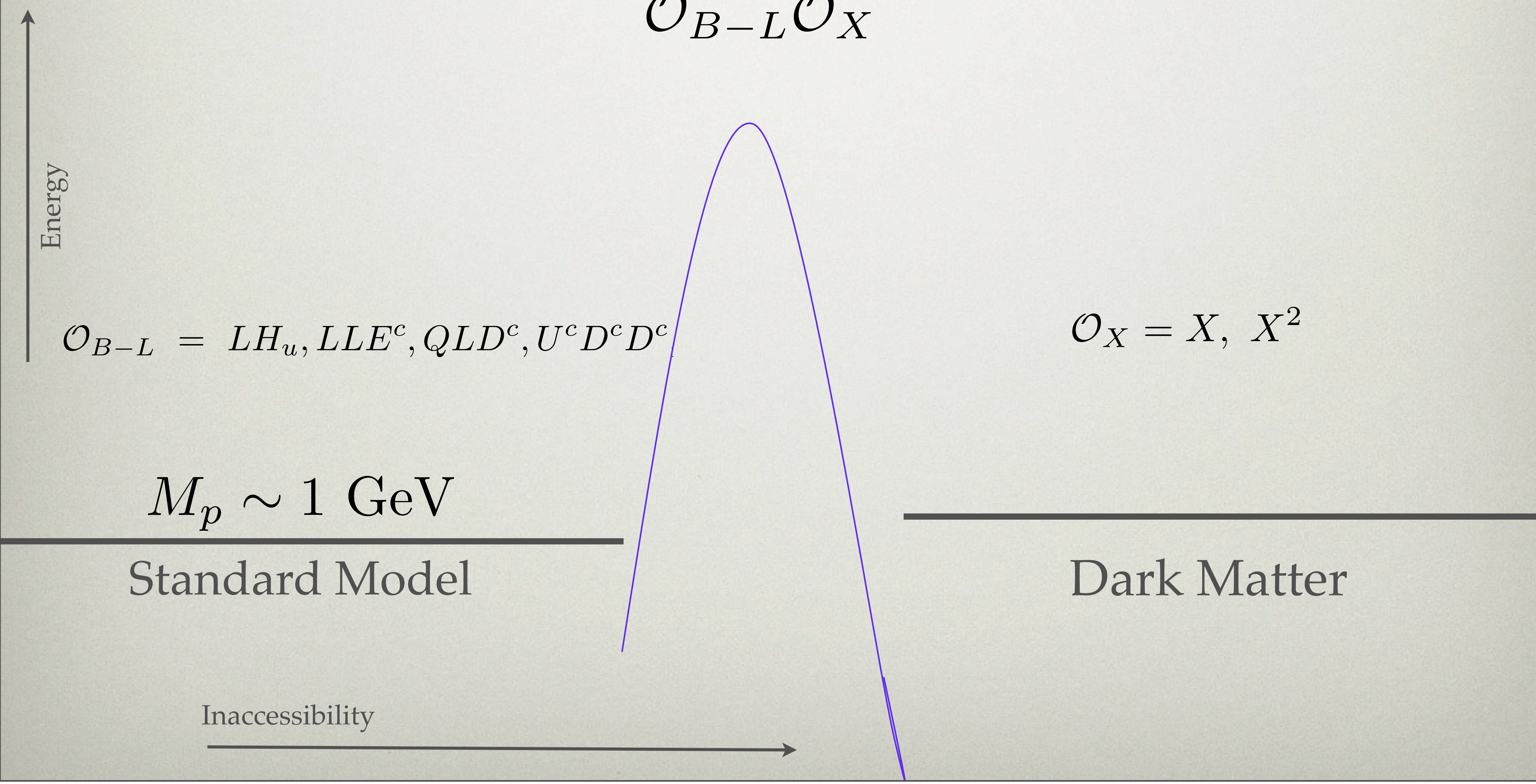
Luty, Kaplan, KZ '09

$$Xu^cd^cd^c$$



Asymmetric DM

$$\mathcal{O}_{B-L}\mathcal{O}_X$$



Asymmetric DM

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator

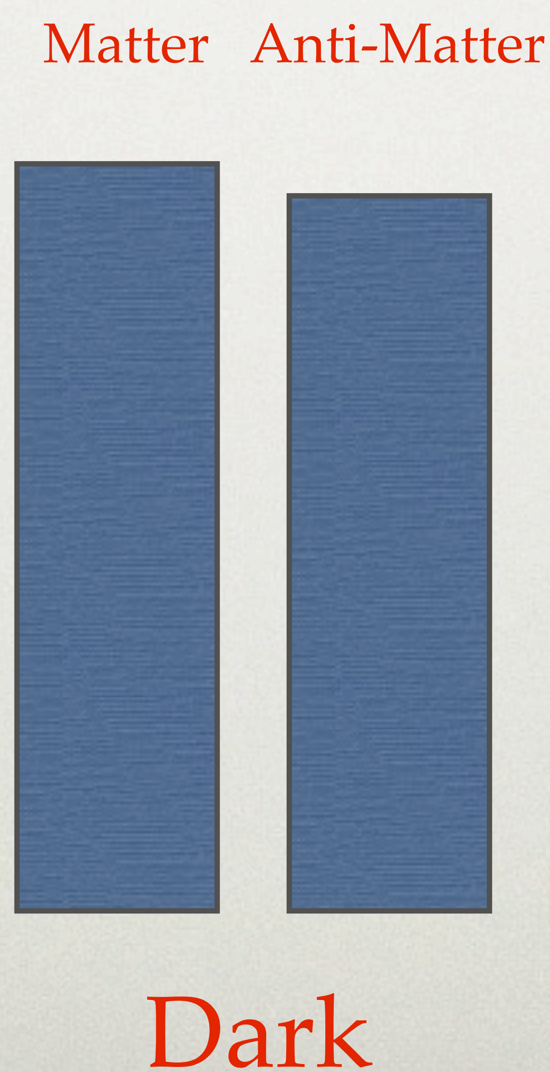
2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (Otherwise allows DM asymmetry to wash-out)

3. Annihilate away symmetric abundance of DM

$$n_X - n_{\bar{X}} \approx 10^{-10} n_X$$

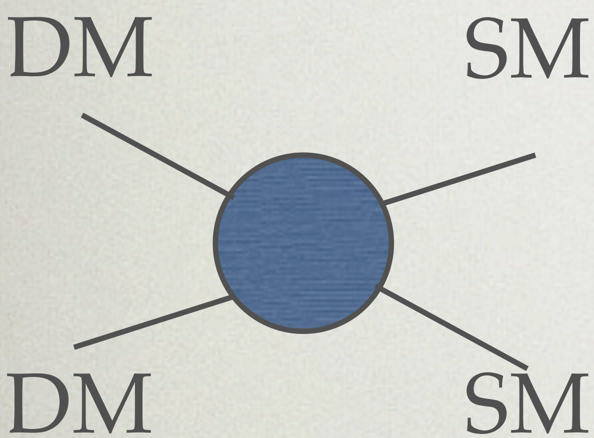
Annihilating thermal abundance

$$n_{DM} \sim T^3 \to 10^{-10} T^3$$

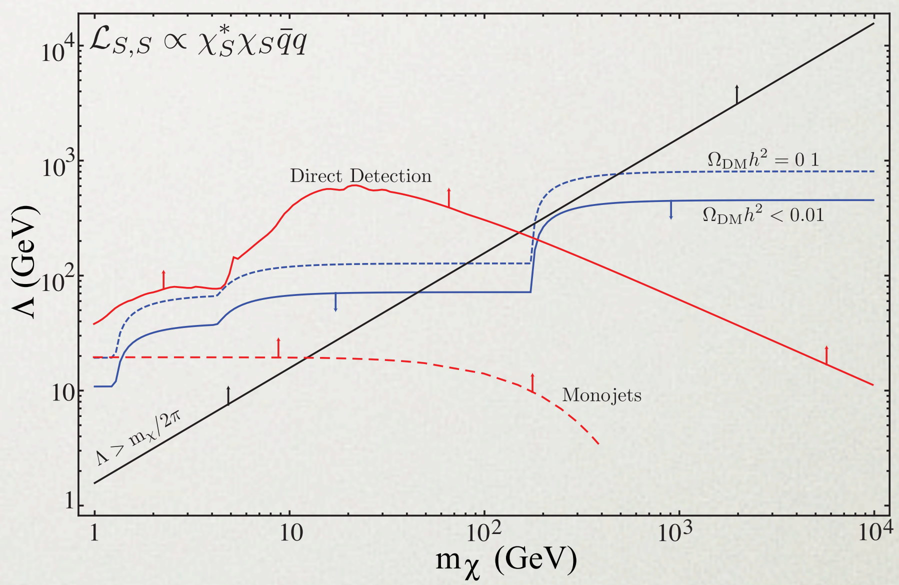


Annihilating thermal abundance

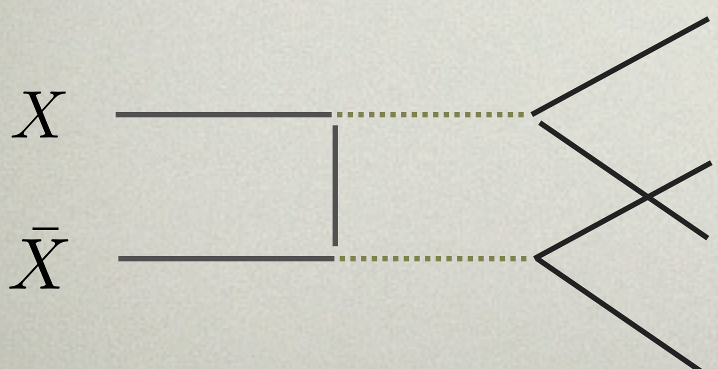
$$n_{DM} \sim T^3 \to 10^{-10} T^3$$



Buckley



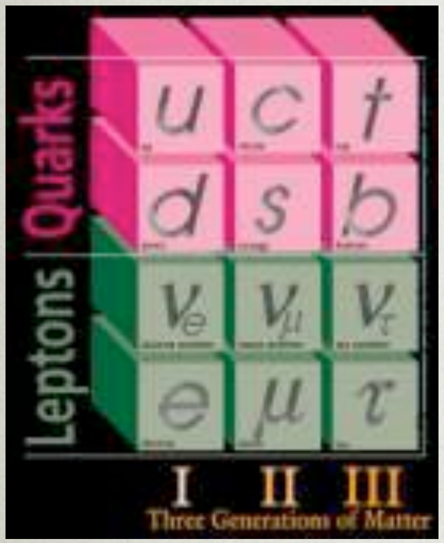
Robust alternative: annihilate to light states!

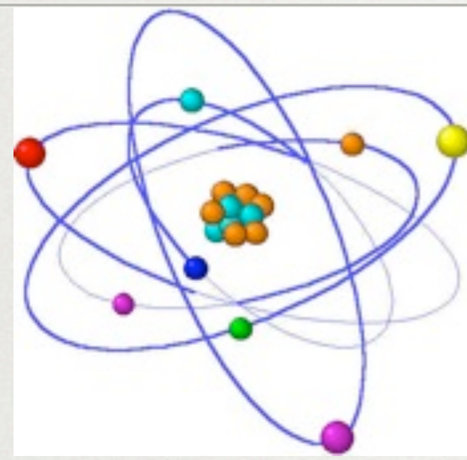


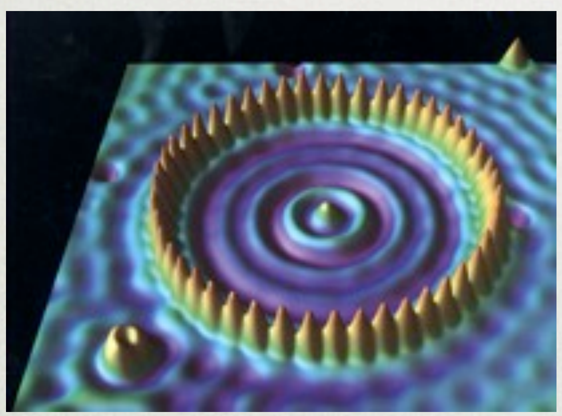
$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3 .$$

$$\Delta \mathcal{L}_{\rm e} = m_X \bar{X} X e^{ia/s} + \text{h.c.},$$

Many Examples of Asymmetric DM







Multiple resonances?

Could be complex

$M_p \sim 1$ GeV

Standard Model

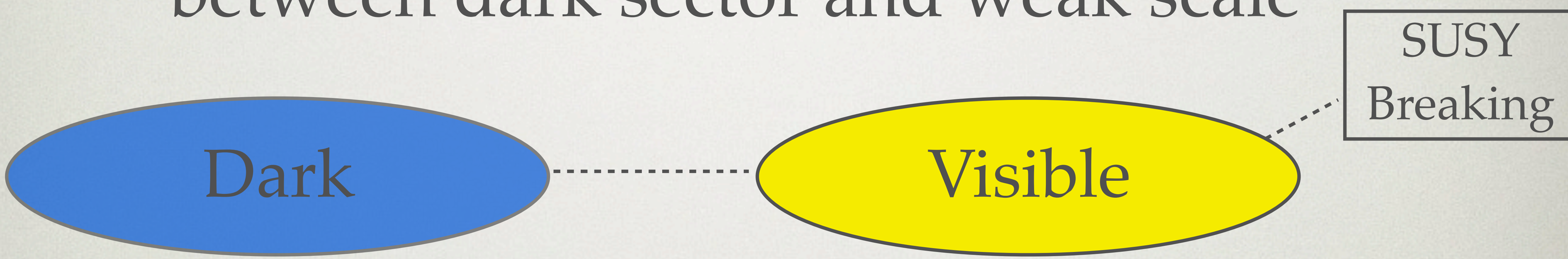
Dark forces and dark Higgs mechanism

Constructing ADM Sectors

- Difficult? Highly constrained? Predictive?
- Generate GeV scale dynamically
- Dark photon and dark Higgs provide efficient annihilation mechanism

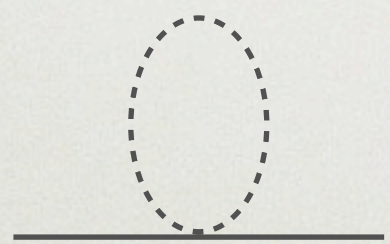
Dynamical Generation of "Low" Scale

- All that's needed is a weak coupling between dark sector and weak scale

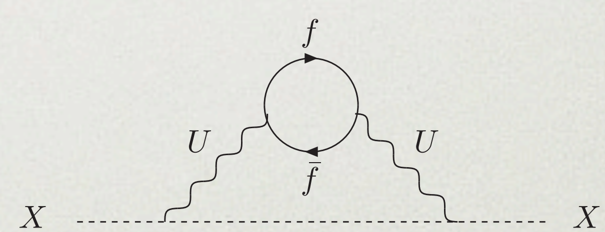


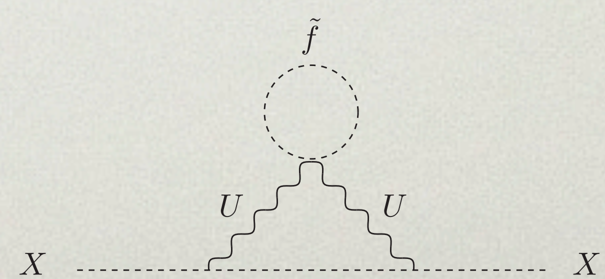
Yukawa

$$m_X^2 \simeq \frac{y^2 m_{SUSY}^2}{16\pi^2}$$



Nelson, Weiner '04
KZ '08





Hooper, KZ '08
Feng, Kumar '08
Arkani-Hamed, Finkbeiner, Slatyer, Weiner '08

Gauge

$$m_X^2 \simeq \frac{g_{vis}^2 g_X^2 m_{SUSY}^2}{16\pi^2}$$

$$\sigma v \simeq \frac{g_{vis}^2 g_X^2}{16\pi m_X^2}$$

Dynamical Generation of "Low" Scale

Cohen, Phalen, Pierce, KZ

$$W = \lambda S T H' + S^2 L H$$ + Kinetic Mixing

$U(1)_X$ +1 -1

$U(1)_d$ +1-1

Dynamical Generation of "Low" Scale

$$W = \lambda S T H' + S^2 L H$$ + Kinetic Mixing

$U(1)_X$ +1 -1

$U(1)_d$ +1-1

$$V = \frac{1}{2}\left(g_d(|T|^2 - |H'|^2) + \epsilon\langle D_Y\rangle\right)^2 + |\lambda|^2\left(|S|^2|H'|^2 + |S|^2|T|^2 + |T|^2|H'|^2\right)$$

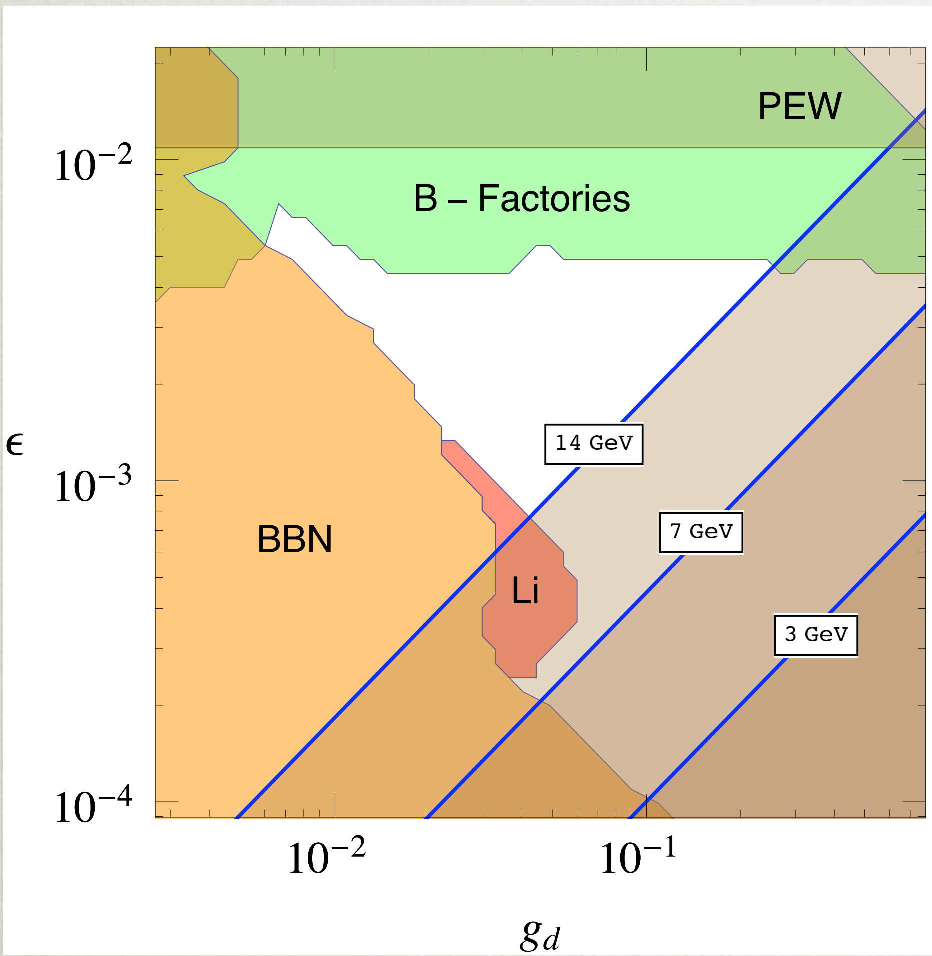
$$\langle D_Y\rangle \;=\; \frac{g_Y v^2 c_{2\beta}}{4}$$

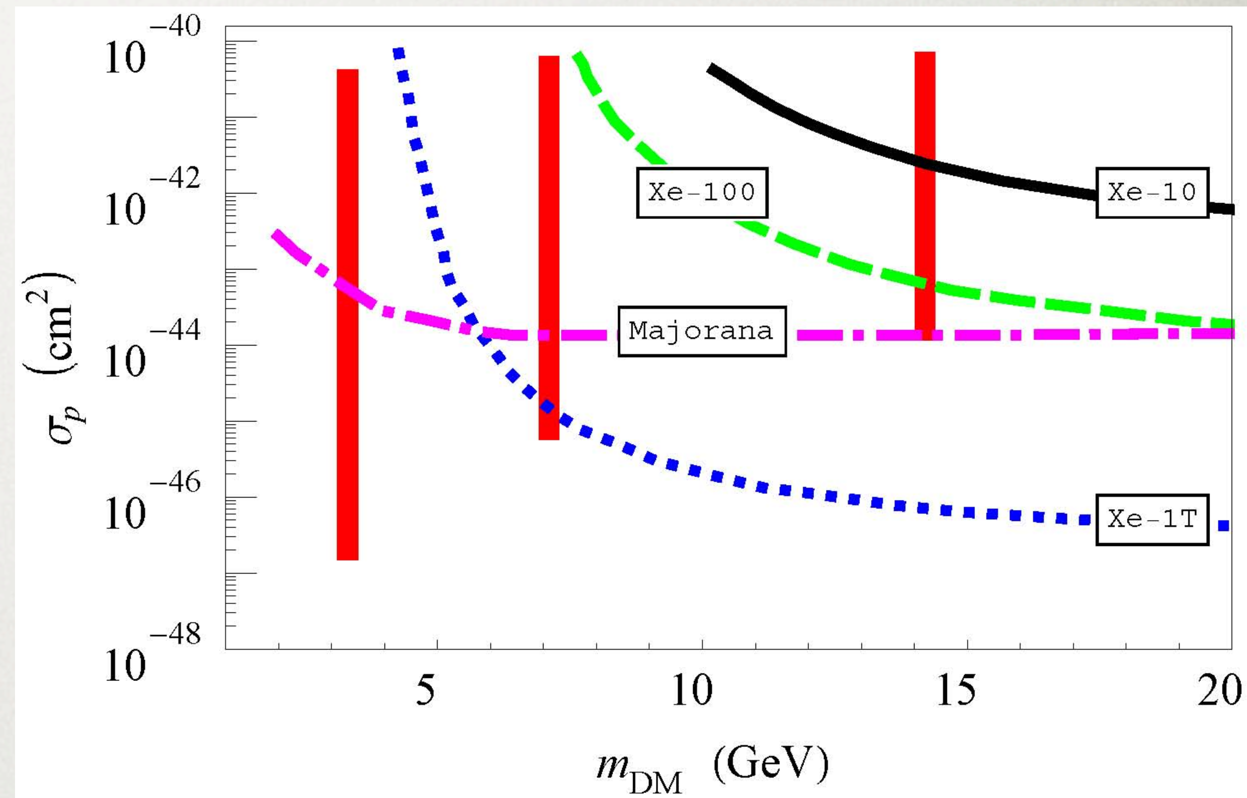
$$\langle S\rangle = \langle T\rangle = 0 \qquad \langle H'\rangle = \sqrt{\xi}$$

A Simple Model

- Unbroken global $U(1)_X$ --> stable sterile DM candidate
- Approximately supersymmetric; a workable spectrum

Destructive Power of Dark Photinos

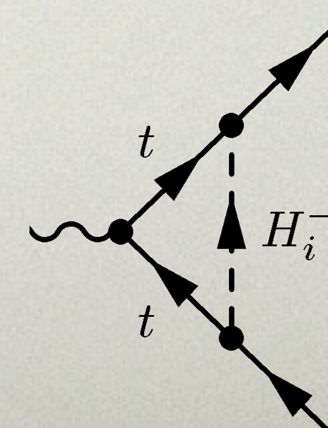




DM is singlet, but couples to dark photon via 1-loop

$$\tau(\tilde{\gamma}_d \to \gamma \tilde{G}) = 190 \text{ s} \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{\text{GeV}}{m_{\tilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{50 \text{ TeV}}\right)^4$$

$$\langle \sigma_{\tilde{\gamma}_d} v \rangle \simeq \frac{g_d^4}{16\pi m_{\tilde{\gamma}_d}^2} v_{f.o.} \simeq 7 \times 10^{-24} \text{cm}^3/\text{s} \left(\frac{g_d}{0.1}\right)^4 \left(\frac{1 \text{ GeV}}{m_{\tilde{\gamma}_d}}\right)^2 \left(\frac{v_{f.o.}}{0.3}\right)$$



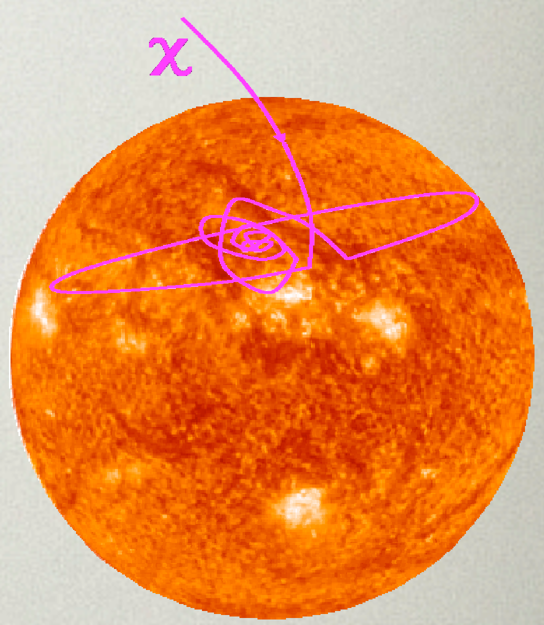
Many Questions Remain

- How to generate the asymmetry? Cheung, KZ '11
- How to dynamically generate DM mass and light states in hidden sector?
- Cosmological implications -- is the asymmetry erased? Impact on astrophysical objects? Tulin, Yu, KZ '12 McDermott, Yu, KZ, '11
- Direct and indirect detection of DM?

Lin, Yu, KZ, '11

Astrophysical Implications

- DM does not annihilate
- It can accumulate in the center of stars
- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!



ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ '11

- Scalar case can lead to BH formation
- DM continues to accumulate until there are enough that they self-gravitate
- OR, they first form Bose-Einstein condensate and then self-gravitate
- Once they self-gravitate, they can collapse to form a BH!

BH Formation W/O BEC

McDermott, Yu, KZ, '11

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

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

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

- Rapidly accumulate enough DM to exceed Chandrasekhar number
- Rapidly thermalize
- Then need to self-gravitate!

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

BH Formation W/BEC

- With BEC, DM becomes dense fast!

$$N_X^0 = N_X \left[1 - \left(\frac{T}{T_c}\right)^{3/2}\right] \simeq N_X - 1.0 \times 10^{36} \left(\frac{T}{10^5 \text{ K}}\right)^3 \qquad r_{BEC} = \left(\frac{3}{8\pi G m_X^2 \rho_B}\right)^{1/4} \simeq 1.5 \times 10^{-5} \text{ cm} \left(\frac{100 \text{ GeV}}{m_X}\right)^{1/2}$$

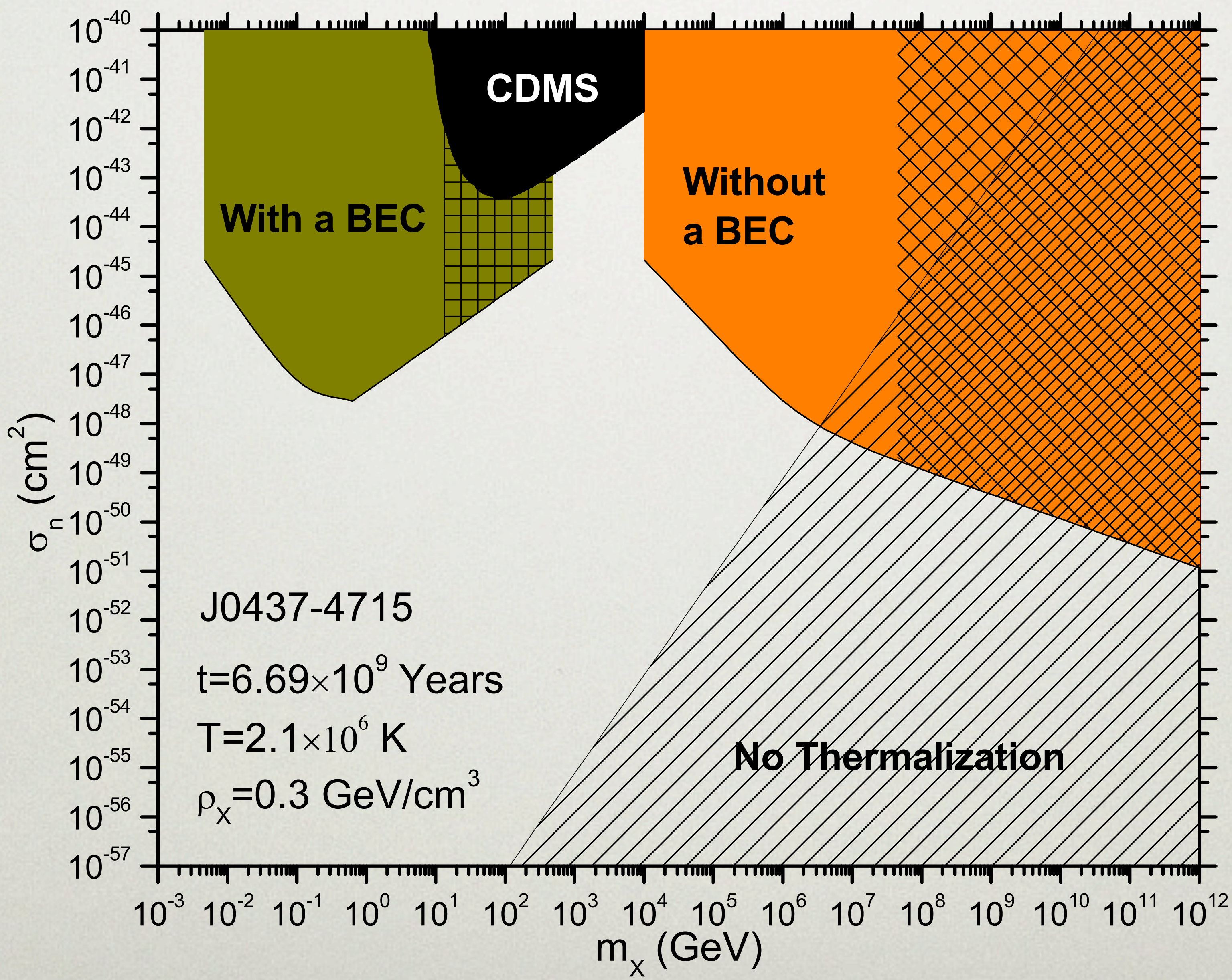
- Have to worry about evaporation

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

$$\left(\frac{dM_{BH}}{dt}\right)_{DM} \simeq 2.3 \times 10^{36} \text{ GeV/year} \left(\frac{\rho_X}{10^3 \text{ GeV/cm}^3}\right)\left(\frac{\sigma_{XB}}{2.1 \times 10^{-45} \text{ cm}^2}\right)$$

ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ, '11



Light Dark Matter

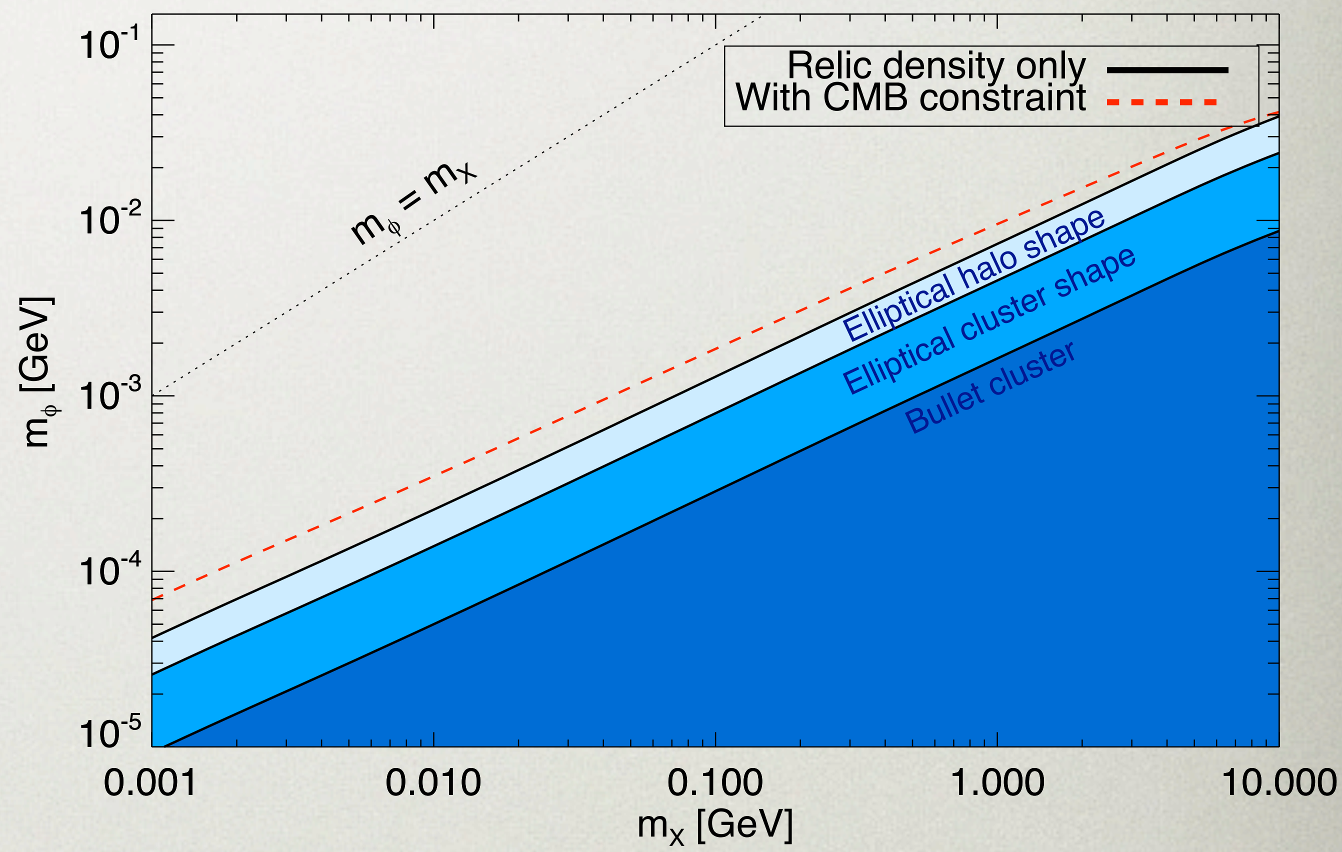
$$m_X < 10 \text{ GeV}$$

- What are the cosmological constraints?
- Assume thermalized hidden sector
  - Relic density + LHC
  - Halo shapes
  - CMB and ADM

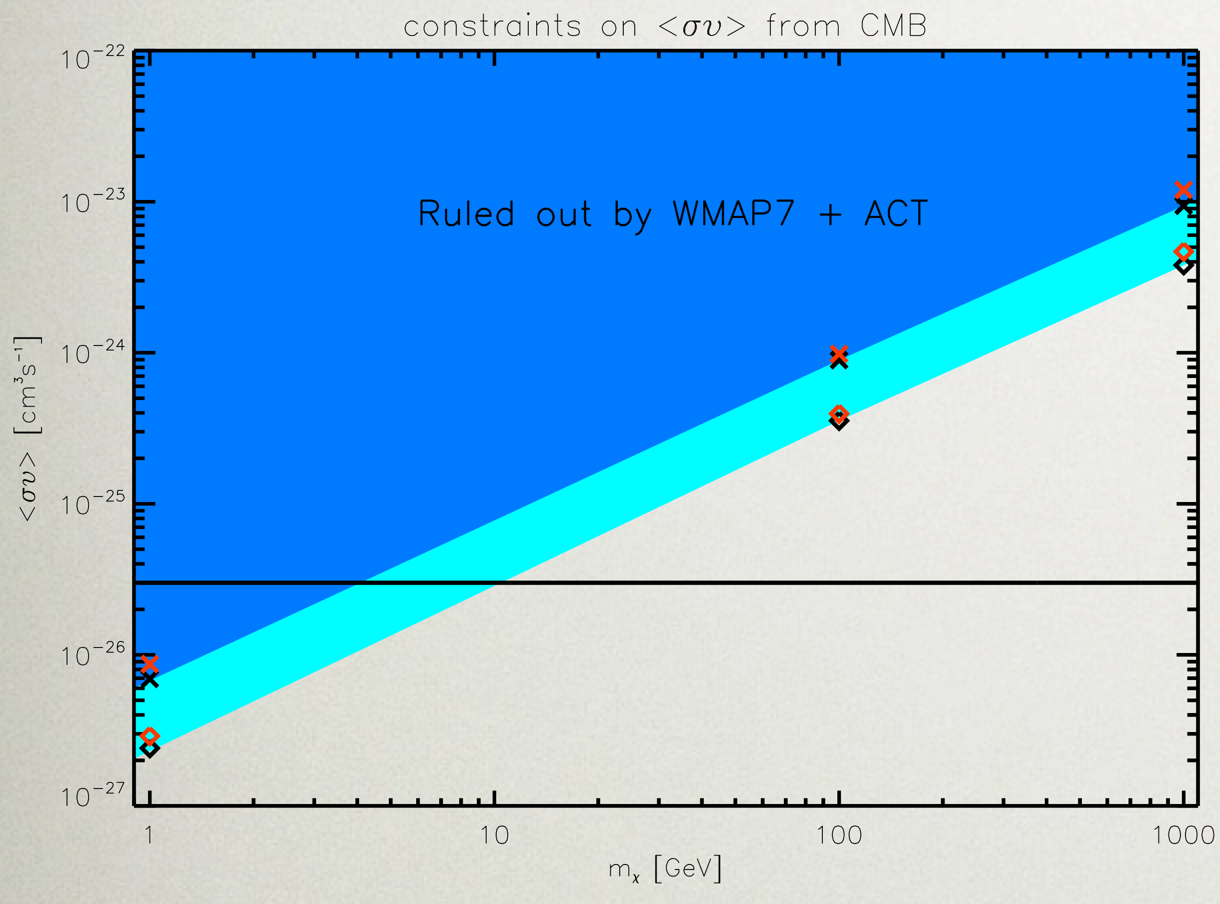
Halo Shapes

- Need new light states
- New light states can mediate scattering

Lin, Yu, KZ '11

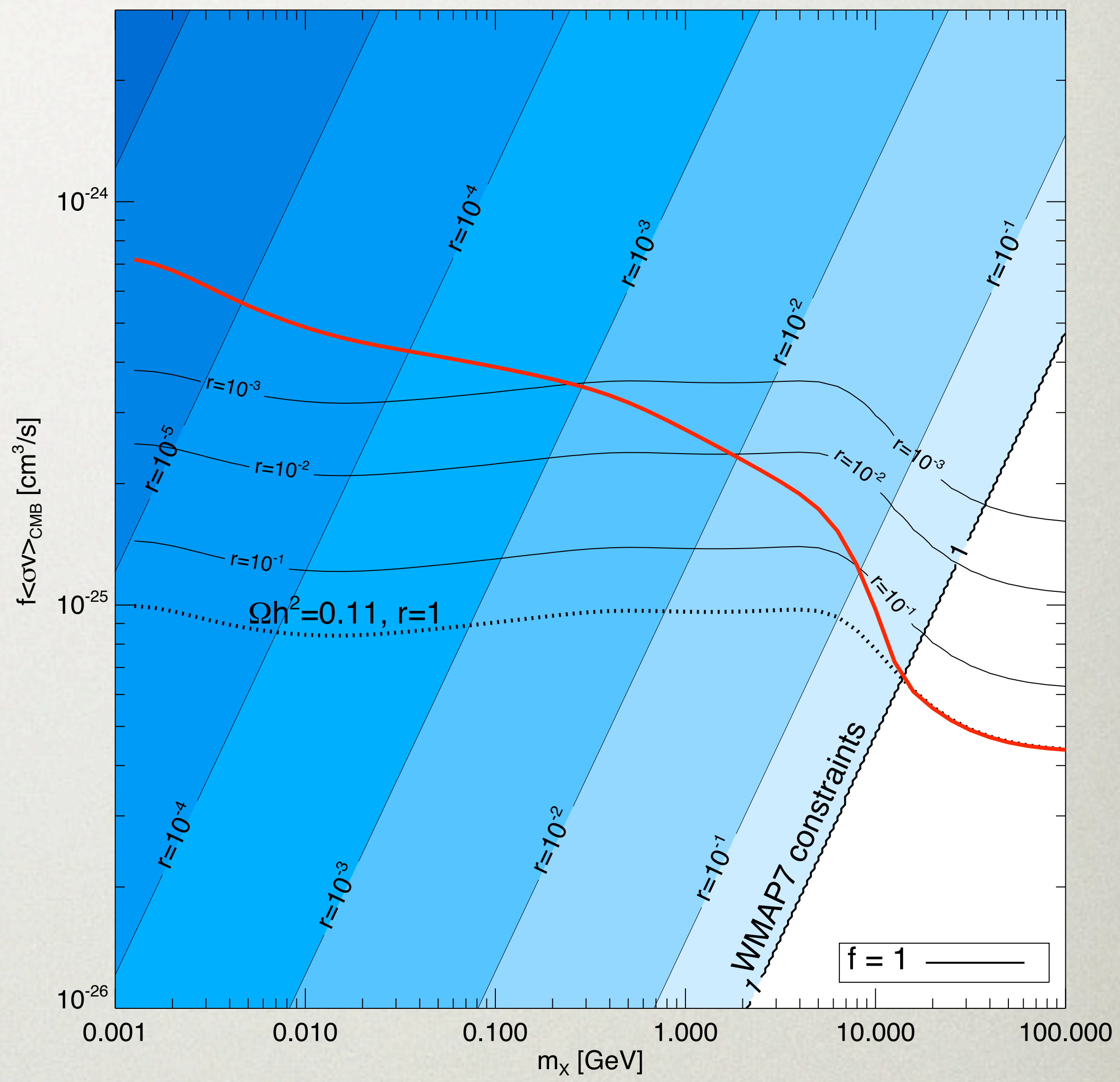


CMB: Light DM Prefers an Asymmetry



Bertone et al '11

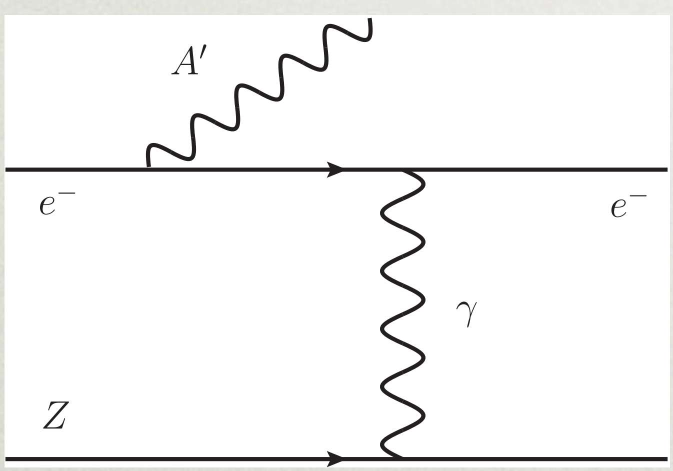
Lin, Yu, KZ '11

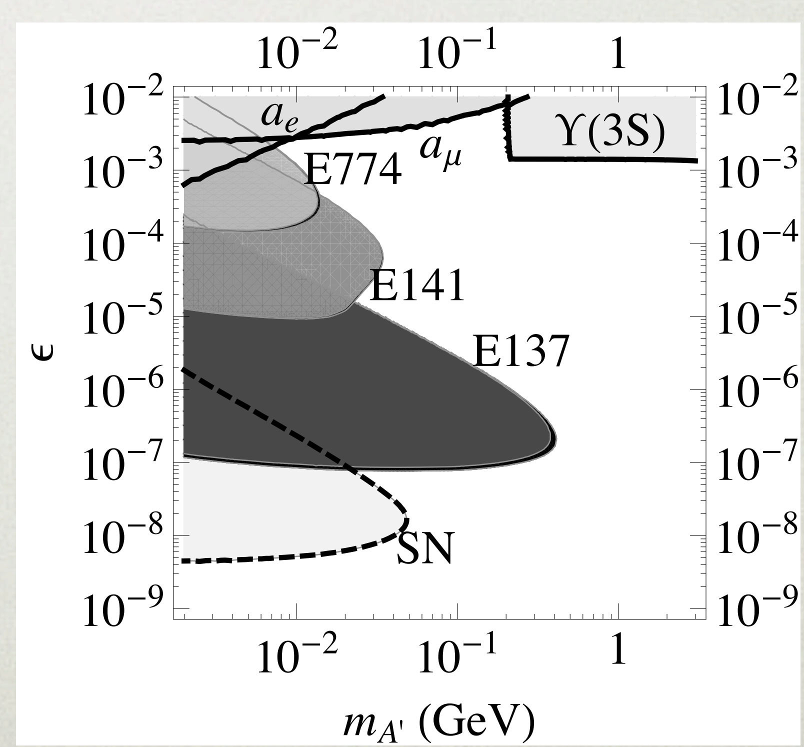


Direct Detection

- Couplings (freeze-out)
- Mediator masses (halo shapes)

Bjorken, Essig, Schuster, Toro





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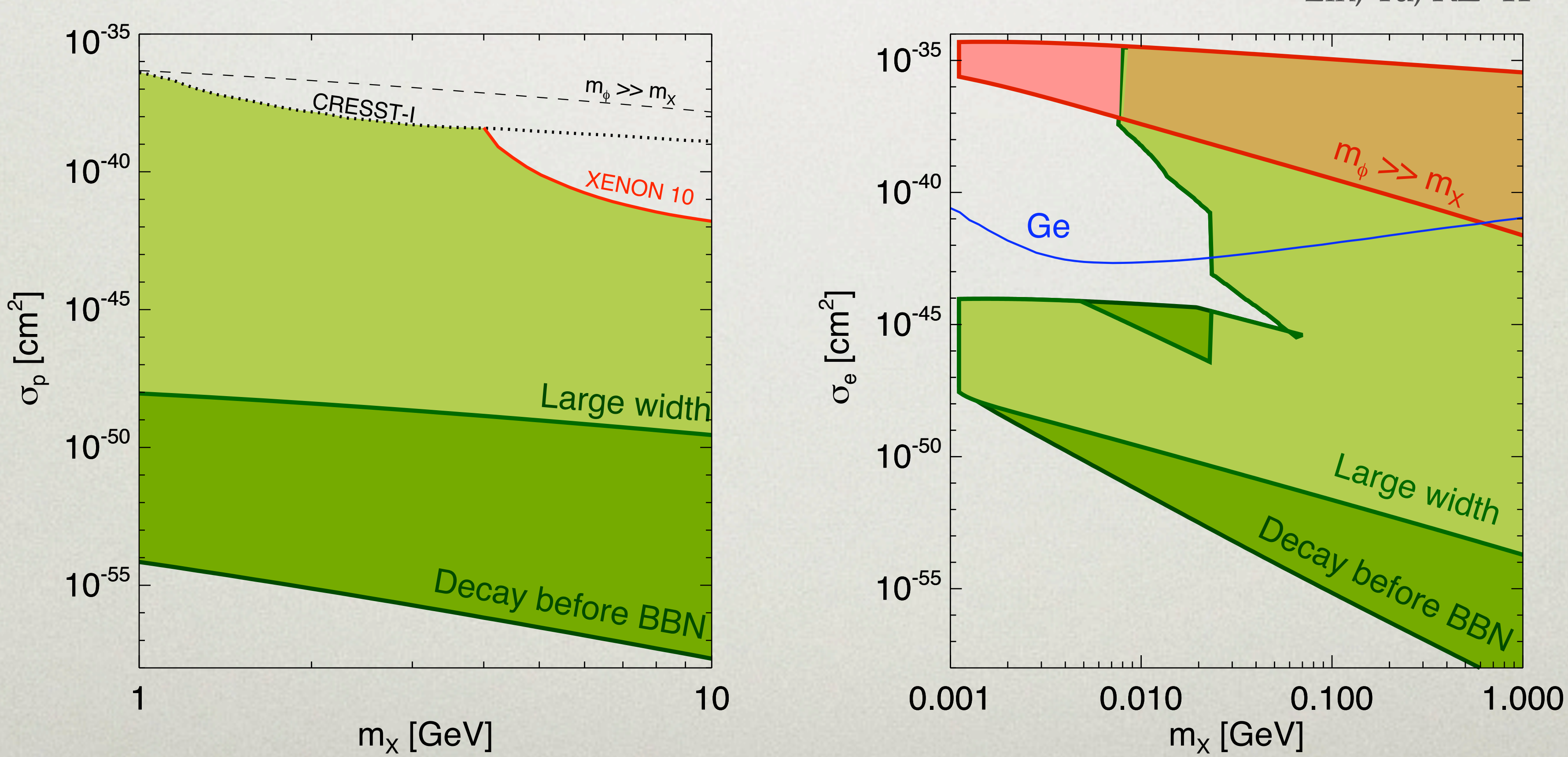
Lin, Yu, KZ '11



Oscillating ADM

- Any violation of X number can lead to dark - anti - dark oscillations, e.g. $m_M X^2$
- What are the conditions for this to happen?

Oscillation time scale $m_M > H$

Scattering time scale $\frac{dY_\beta}{dz} = \frac{z}{2} \langle P_{\alpha\to\beta}(t)\rangle \frac{\Gamma_\alpha}{H_1} (Y_\alpha - Y_\beta)$

- True results more subtle

Cohen, KZ '09
Falkowski, Rudermann, Volansky '10
Buckley, Profumo '11
Cirelli, Panci, Servant, Zaharijas '11

Boltzmann Eq from First Principles

Tulin, Yu, KZ '12

$$\frac{\partial \mathscr{F}_k}{\partial t} - Hk\,\frac{\partial \mathscr{F}_k}{\partial k} = -i\big[\mathcal{H}_k,\ \mathscr{F}_k\big] + C_k[\mathscr{F}]$$

Coherent oscillations

$$\begin{matrix} & X & X^C \end{matrix}$$

$$M = \begin{pmatrix} m_X & m_M \\ m_M & m_X \end{pmatrix}$$

$$\mathcal{H}_k = \sqrt{k^2 + M^2} = \omega_k\,\mathbb{1} + \frac{m_X \delta m}{\omega_k}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\delta m \sim m_M > H$$

Boltzmann Eq from First Principles

$$n \equiv (2s+1)\int \frac{d^3k}{(2\pi)^3}\,\mathscr{F}_k = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}\,, \quad \bar{n} \equiv (2s+1)\int \frac{d^3k}{(2\pi)^3}\,\bar{\mathscr{F}}_k = \begin{pmatrix} n_{22} & n_{12} \\ n_{21} & n_{11} \end{pmatrix}$$

$$\frac{\partial n}{\partial t} + 3Hn = -i\big[\mathcal{H}_0,\, n\big] - \frac{\Gamma_\pm}{2}\,\big[O_\pm,\,\big[O_\pm,\, n\big]\big] - \langle \sigma v\rangle_\pm\Big(\frac{1}{2}\big\{n,\, O_\pm\,\bar{n}\,O_\pm\big\} - n^2_{\rm eq}\Big)$$

Coherence broken only through flavor sensitive interactions

Boltzmann Eq from First Principles

$$n \equiv (2s+1)\int\frac{d^3k}{(2\pi)^3}\,\mathscr{F}_k = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}\,, \quad \bar{n} \equiv (2s+1)\int\frac{d^3k}{(2\pi)^3}\,\bar{\mathscr{F}}_k = \begin{pmatrix} n_{22} & n_{12} \\ n_{21} & n_{11} \end{pmatrix}$$

$$\frac{\partial n}{\partial t} + 3Hn = -i\big[\mathcal{H}_0,\, n\big] - \frac{\Gamma_\pm}{2}\,[O_\pm,\,[O_\pm,\,n]] - \langle\sigma v\rangle_\pm\Big(\frac{1}{2}\big\{n,\,O_\pm\,\bar{n}\,O_\pm\big\} - n_{\rm eq}^2\Big)$$

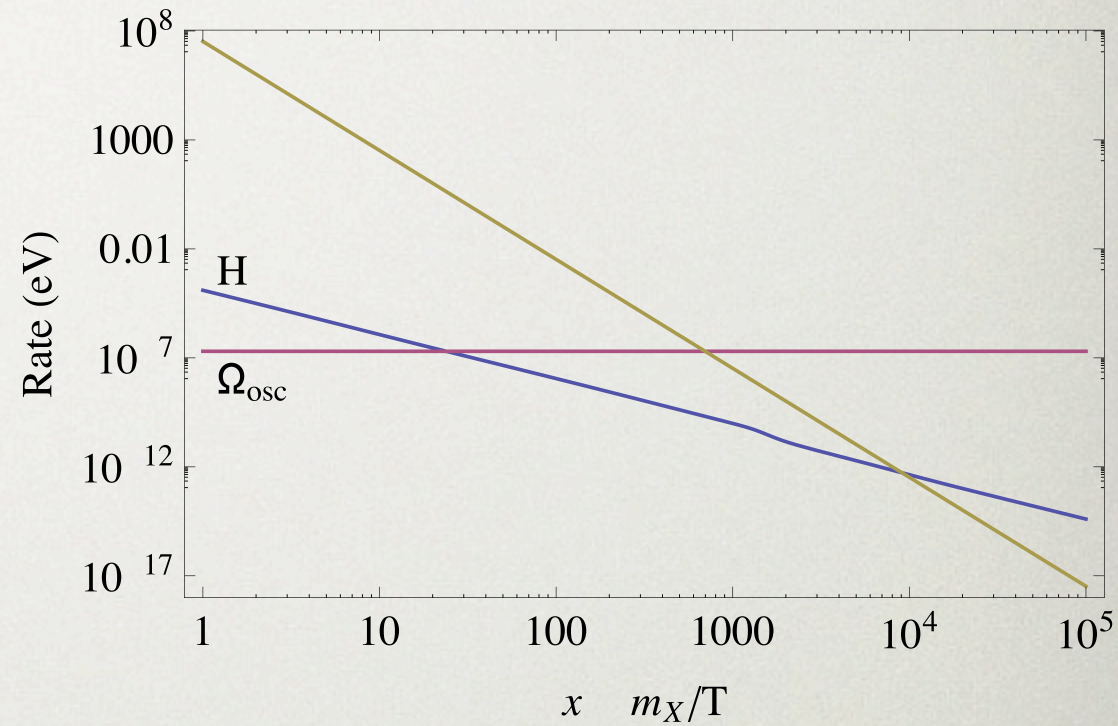
Only flavor blind interactions source annihilations:

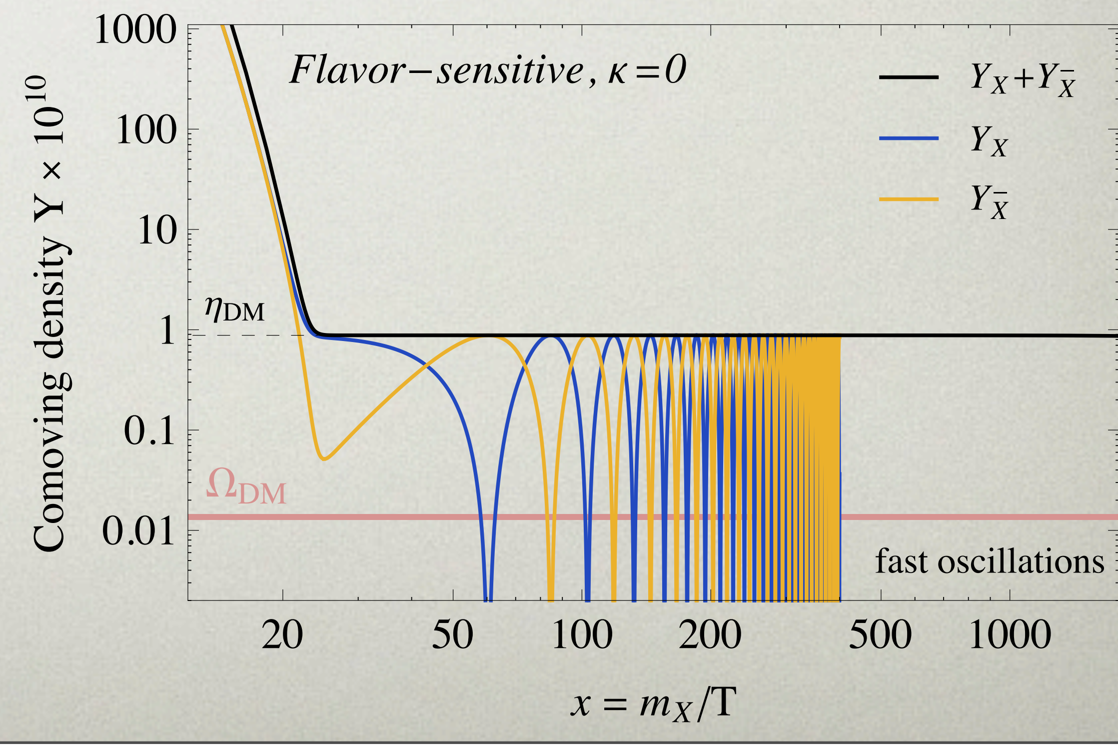
$$\frac{1}{2}\{Y,\,O_+\bar{Y}O_+\} = \begin{pmatrix} Y_{11}Y_{22}+Y_{12}Y_{21} & Y_{11}Y_{12}+Y_{12}Y_{22} \\ Y_{21}Y_{11}+Y_{22}Y_{21} & Y_{11}Y_{22}+Y_{12}Y_{21} \end{pmatrix}$$

$$\frac{1}{2}\{Y,\,O_-\bar{Y}O_-\} = \begin{pmatrix} Y_{11}Y_{22}-Y_{12}Y_{21} & 0 \\ 0 & Y_{11}Y_{22}-Y_{12}Y_{21} \end{pmatrix}$$

Numerical Results

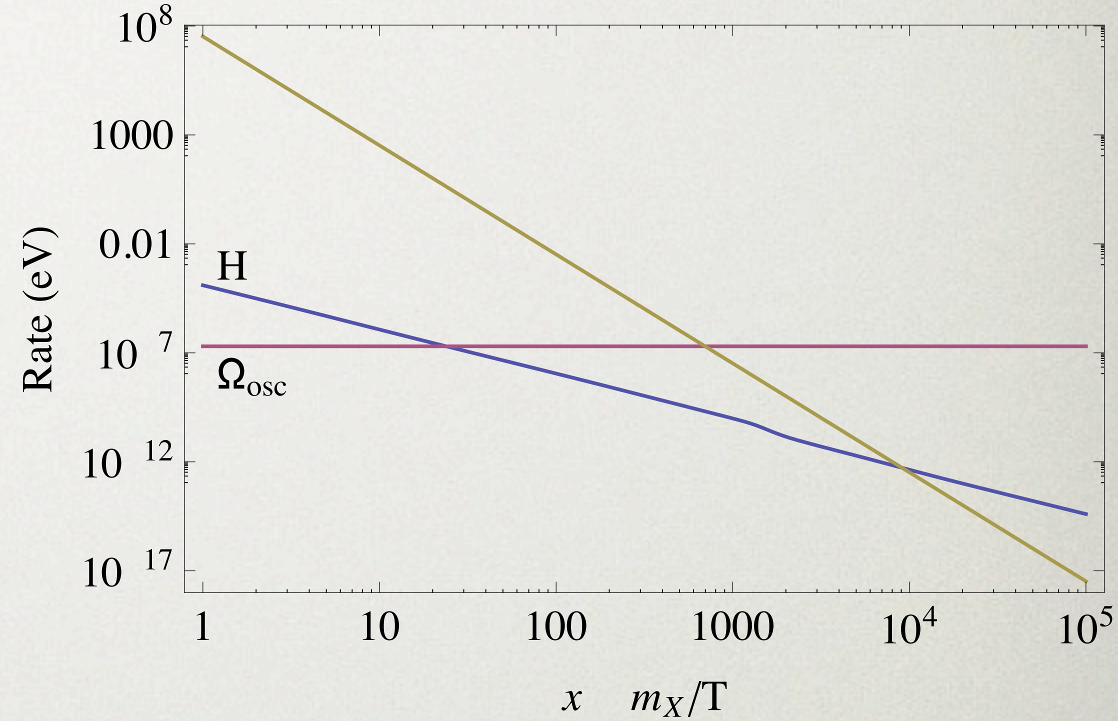
- Vector interactions
- But scattering off
- Oscillations turn on, no depletion of DM density

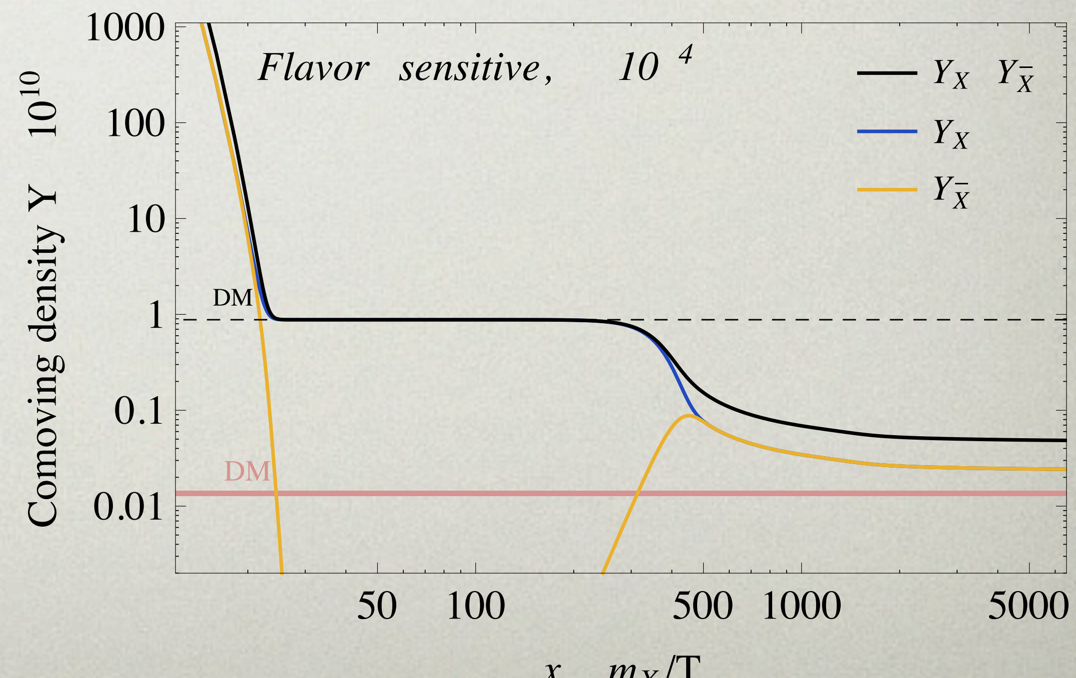




Numerical Results

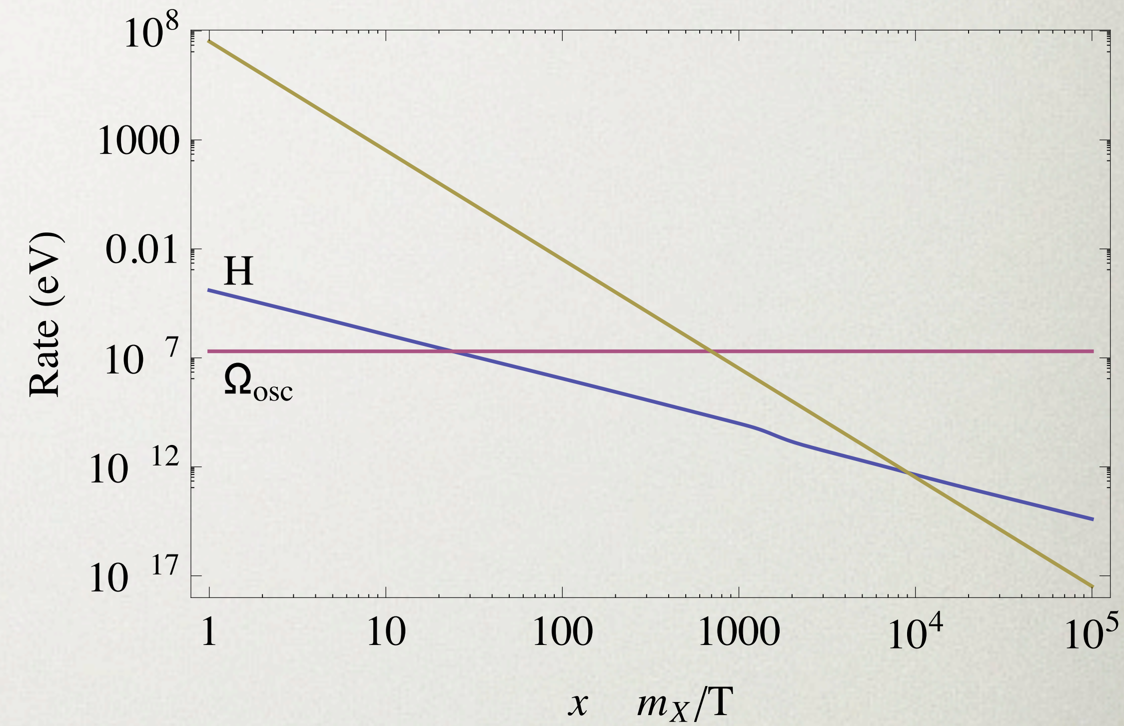
- Vector interactions
- Quantum Zeno prevents oscillation
- Scattering causes de-coherence and washout
- Washout when oscillations commence

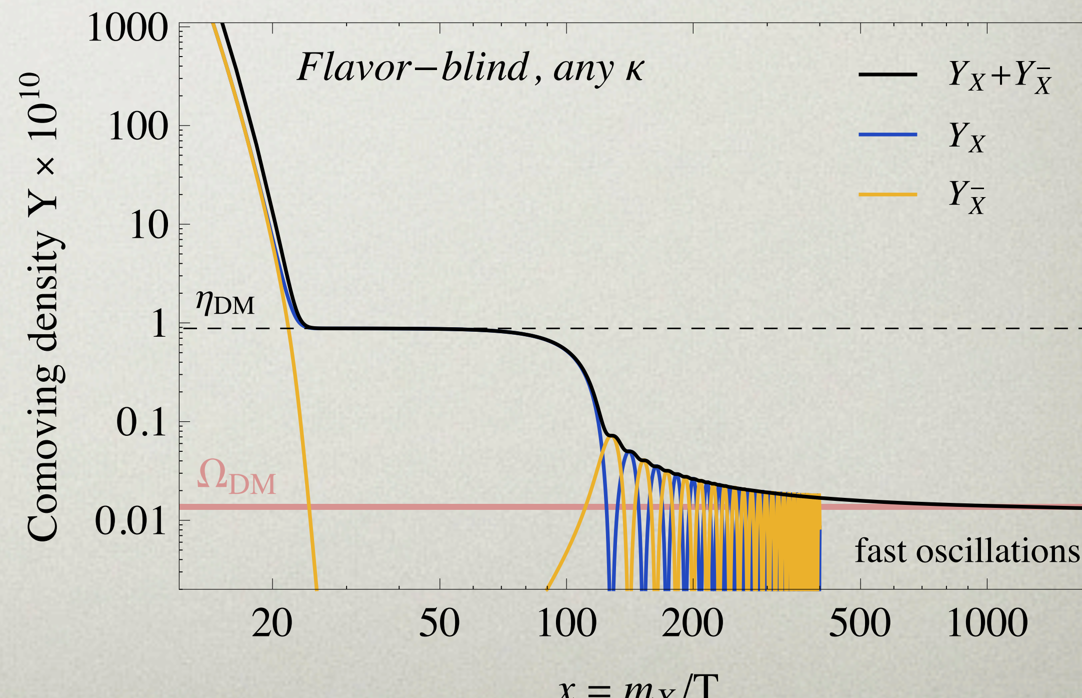




Numerical Results

- Scalar interactions
- Oscillations turn on
- Depletion continues as soon as oscillations commence

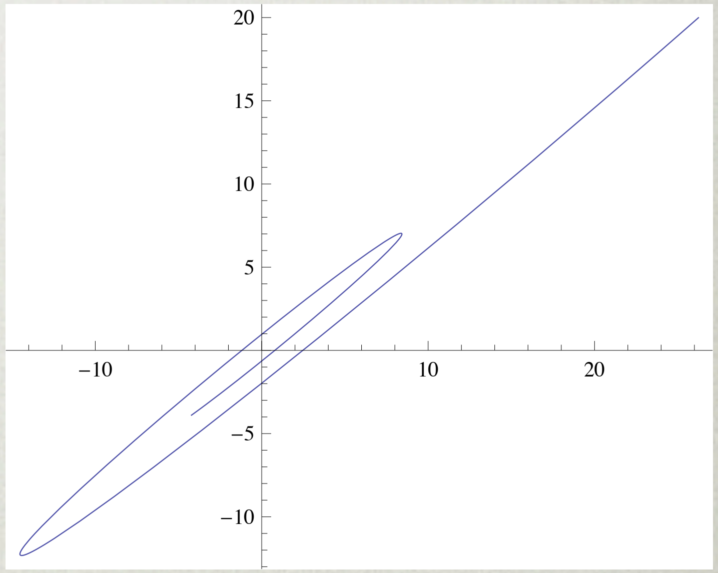




New Avenues for Baryogenesis

- B and DM number violation simultaneously
- Coupled oscillators
- Generates equal and opposite B and DM number -- cogenesis!

$$W = X u^c d^c d^c$$



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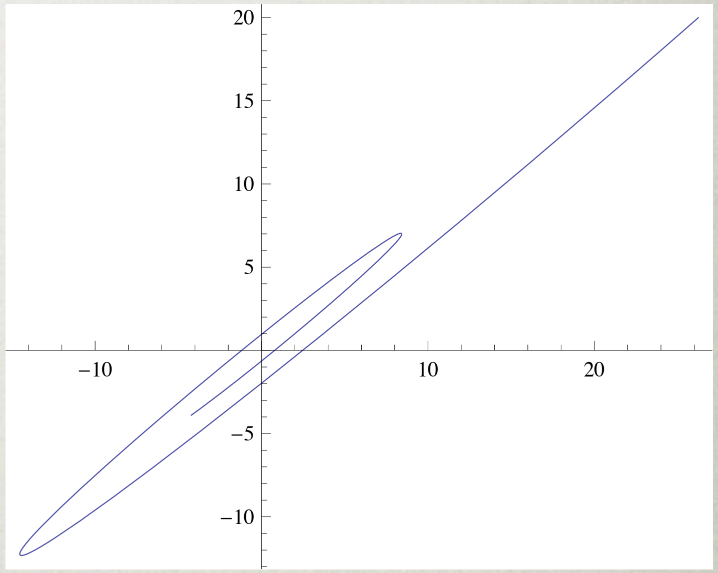
$$n_{B-L} = -n_X$$

Cogenesis in the Early Universe

- To see how it works, map to simple mechanical analog: pseudo-particle in 2-dimensions

$$\phi = \frac{1}{\sqrt{2}} r_\phi e^{i\theta_\phi}$$

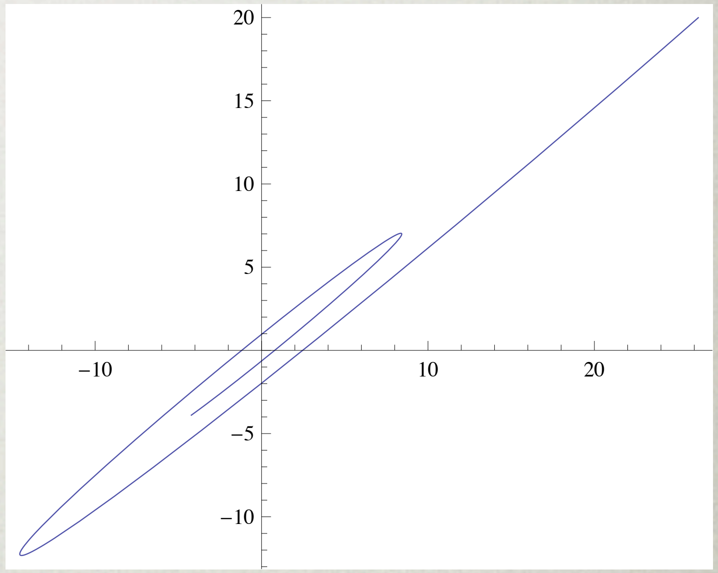
$$n_\phi = j^0 = i(\phi\dot{\phi}^\dagger - \phi^\dagger\dot{\phi}) = r_\phi^2\dot{\theta}_\phi$$



- B-L and X asymmetry: torque on mechanical analog

Cogenesis in the Early Universe

- Two ingredients for successful Affleck-Dine Cogenesis
  - Stabilization: non-zero B-L and X vevs
  - Torque: non-zero angular momentum



Cogenesis -- Natural for ADM!

$\mathcal{O}_{B-L} = LH_u, LLE^c, QLD^c, U^cD^cD^c$ $\mathcal{O}_X = X,\ X^2$

$$\mathcal{O}_{B-L}\mathcal{O}_X$$

- Affleck-Dine works by utilizing flat directions with non-zero <B-L>
- Note there is a symmetry $U(1)_{B-L+X}$ which generates $-n_{B-L} = n_X \neq 0$.
- At low temperature, symmetry breaks when $\mathcal{O}_{B-L}\mathcal{O}_X$ decouples, separately freezing in the asymmetries

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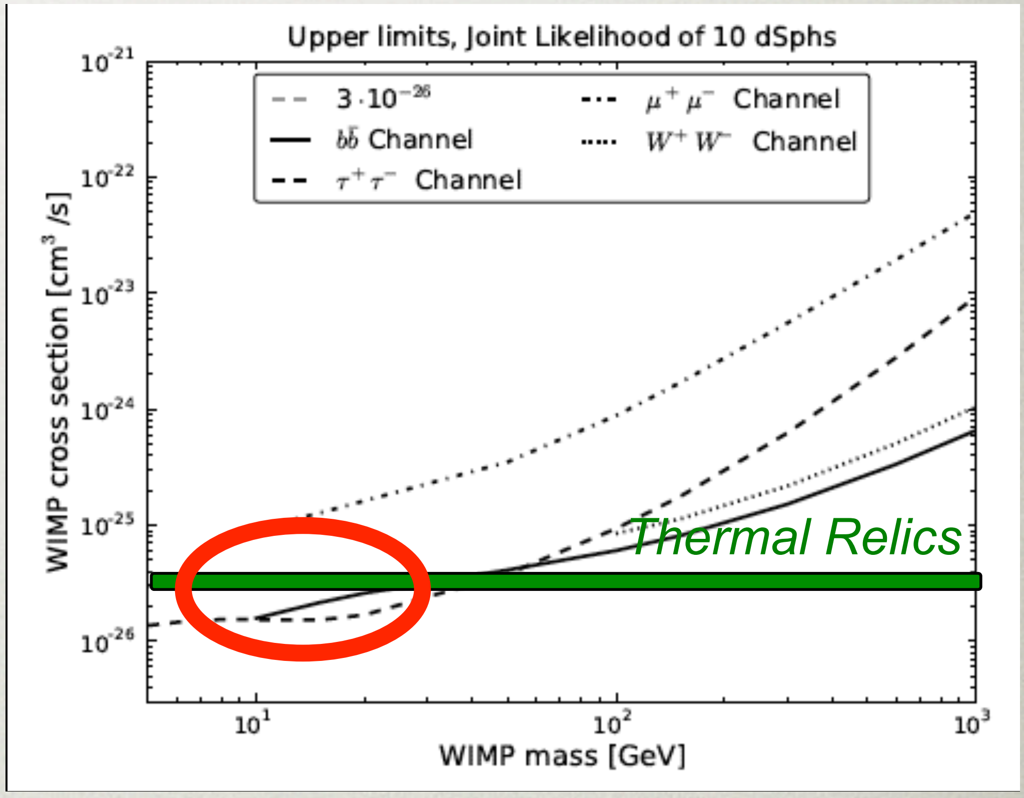
$$U(1)_{B-L+X} \to U(1)_{B-L} \times U(1)_X$$

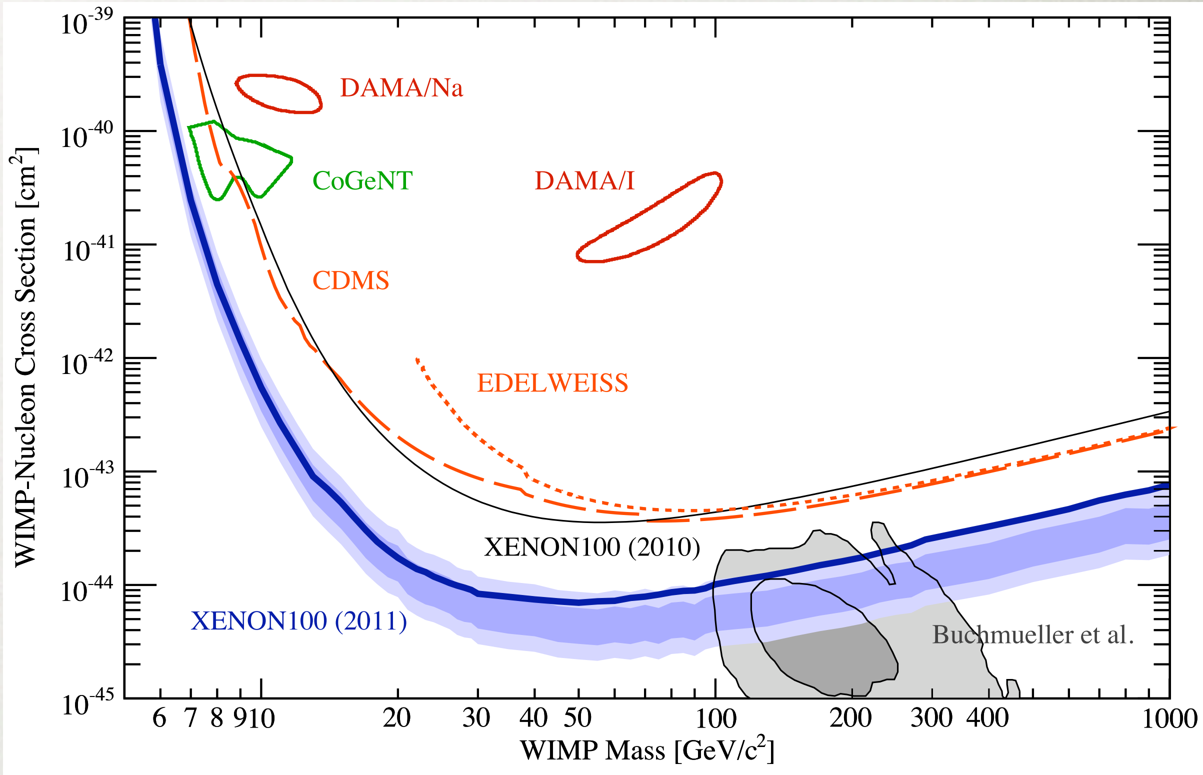
DM: Where are We?

- The Nature of the DM remains one of the most important open problems in physics
- It's an auspicious time
- Indirect detection -- approaching thermal cross-sections in some mass regions



DM: Where are We?

- Direct detection -- reaching the Higgs pole. Ton scale experiments should surpass it
- In a position to rule out or observe "standard" WIMP



$$\sigma_n \sim 10^{-45-46}\ \mathrm{cm}^2$$

DM:
Where are We?

- DM anomalies?
- Other candidates
- Asymmetric Dark Matter gives rise to a distinctive phenomenology to explore