Asymmetric Dark Matter

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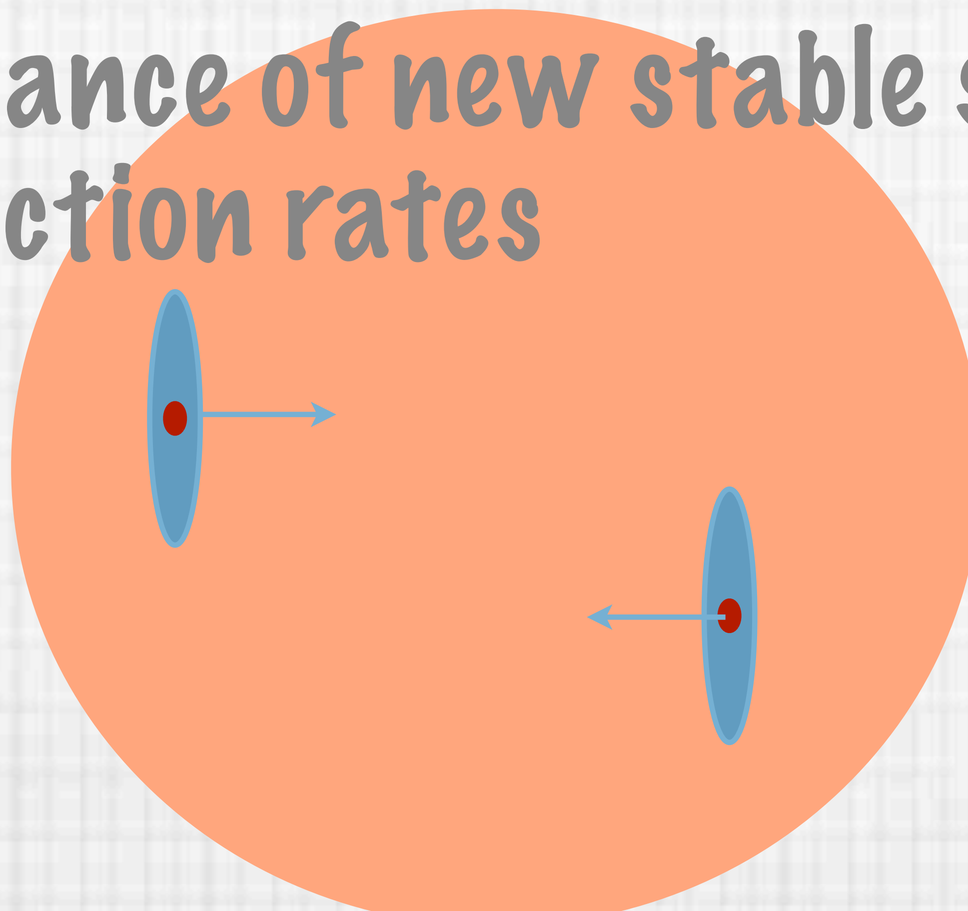
Baryon and DM Number Related?

* Accidental, or dynamically related?

Why the Weak Scale is Compelling

- New scale, 100's GeV set by SM
- Abundance of new stable states set by interaction rates



Measured by WMAP + LSS

$$\Gamma = n\sigma v = H$$

Why a weak scale WIMP?

* Magic thermal cross-section
* Annihilation cross-section sets abundance

$$\Omega h^2 \approx \frac{2 \times 10^{-10} \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$$

$$\sigma v \approx \frac{g^4}{1\ \mathrm{TeV}^2} \approx 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

$$\Omega_c h^2 = 0.114 \pm 0.003$$

* Same cross-section sets size of indirect detection signals

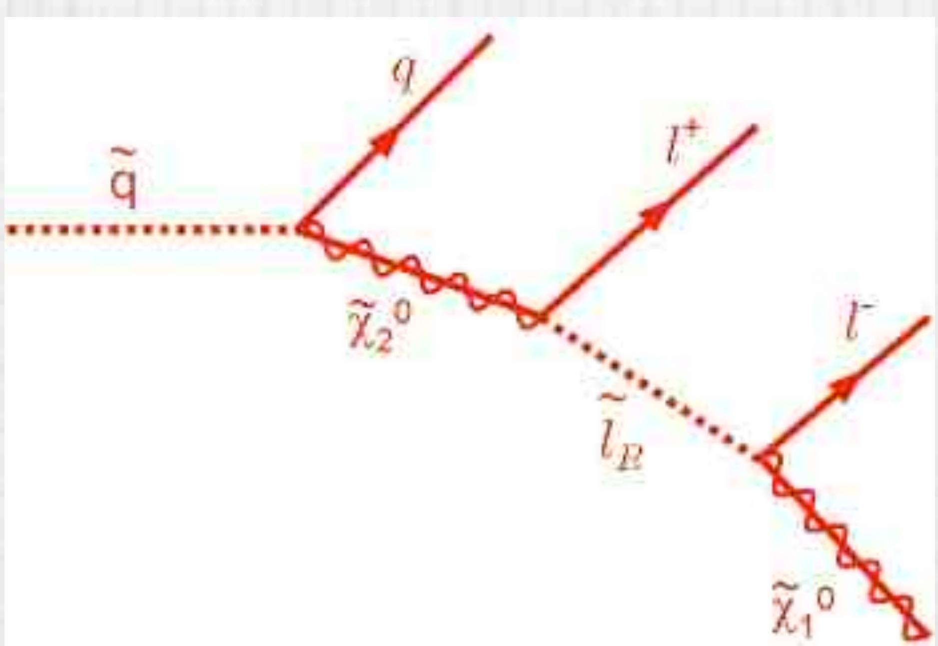
SUSY produces such a candidate

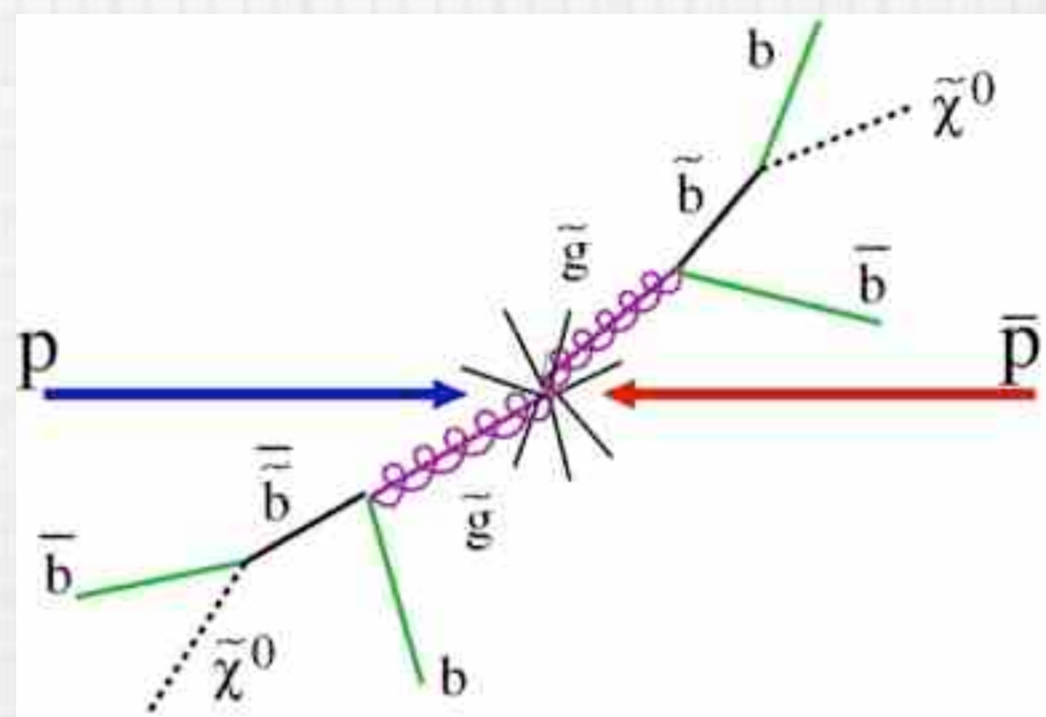
* SUSY + R-parity

$$\tilde{\nu} \qquad \tilde{B},\ \tilde{W}_3,\ \tilde{H}$$

$$\tilde{\chi}$$

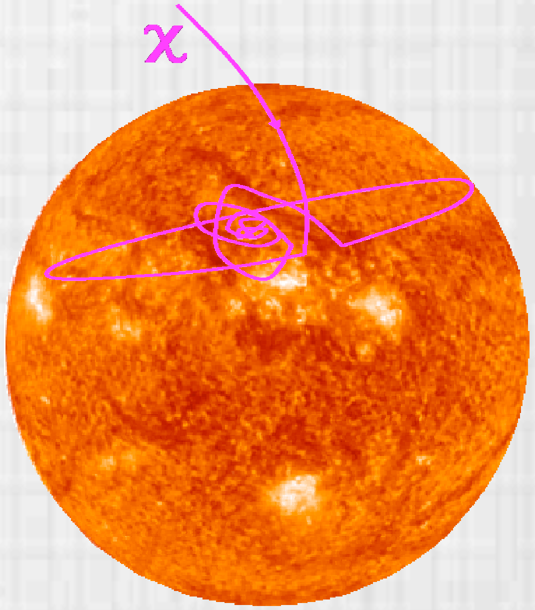
* Production and decay at colliders





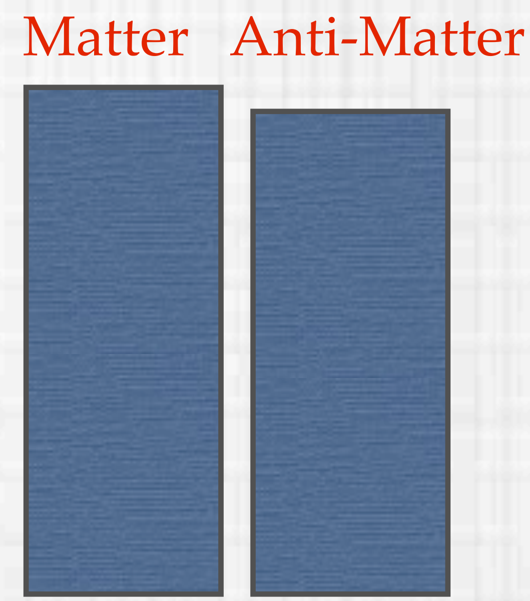
Leading DM Candidates ....

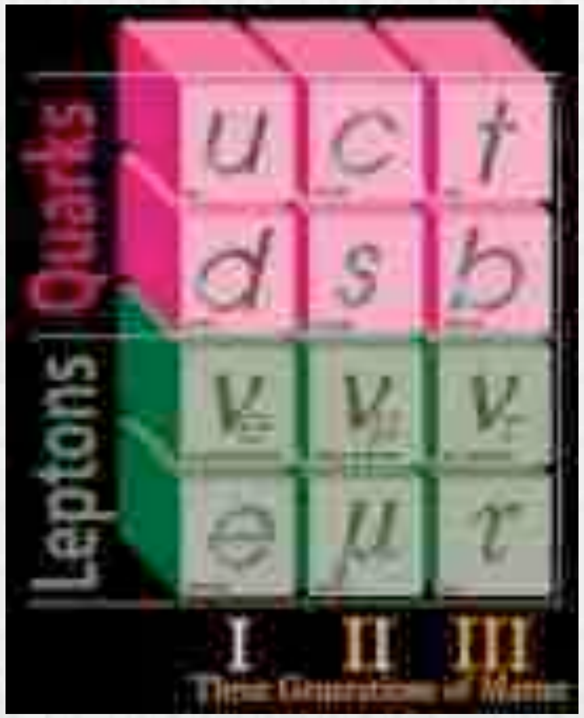
* ... have very particular properties
  * DM typically its own anti-particle
    * Sets indirect detection prospects
    * Relic density considerations
    * Cosmological constraints



Extremely different from the visible sector

- Baryons are not their own antiparticles
  - Have chemical potentials that set the abundance
- Large annihilation cross-sections
- Complex dynamics, multiple forces and multiple mass scales





Relating DM to the Baryon Asymmetry

In standard picture, DM abundance set by thermal freezeout,

$$\Gamma_{ann} \lesssim H$$

What if instead set by baryon density?

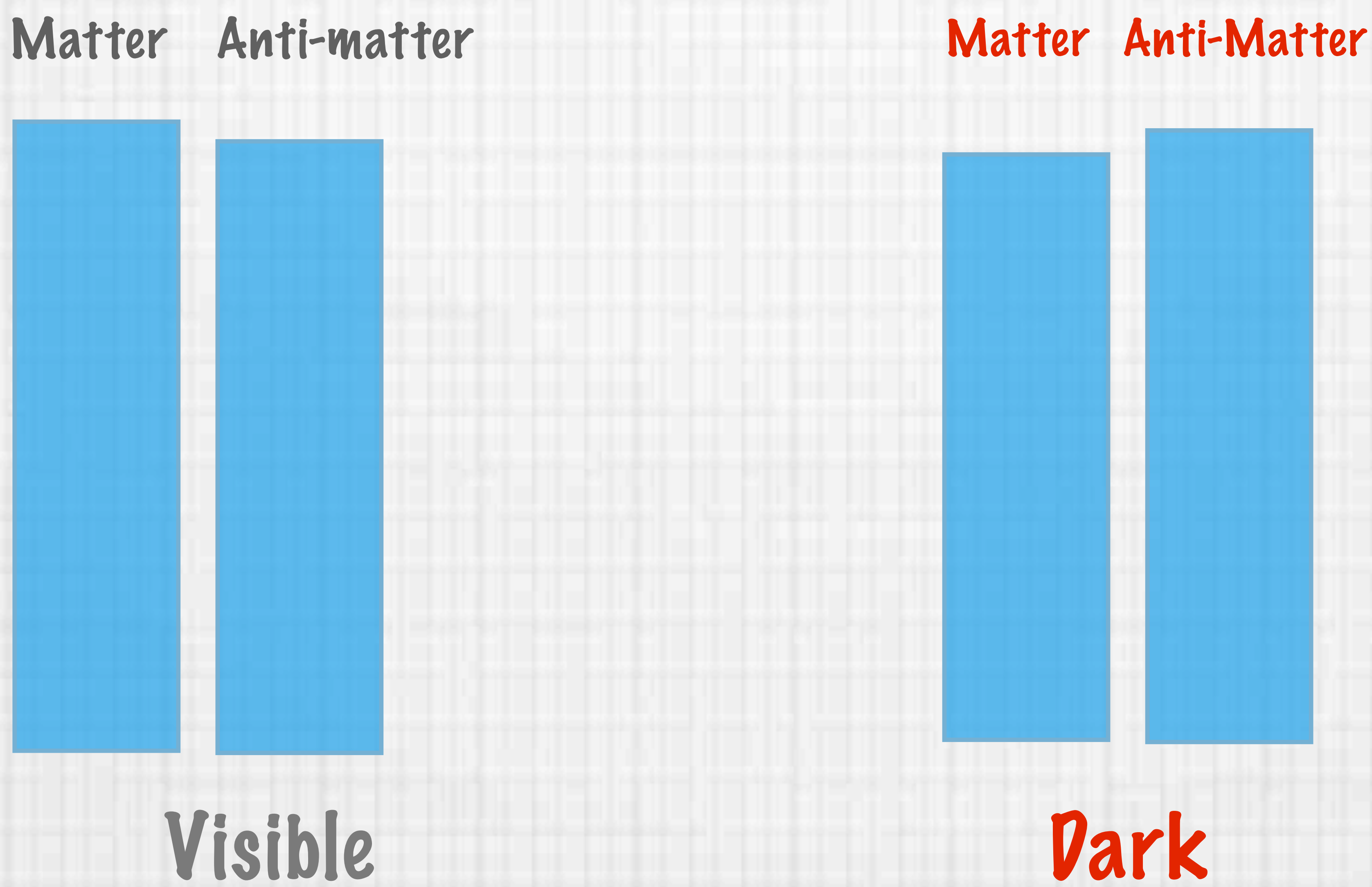
Experimentally, $\Omega_{DM} \approx 5\Omega_b$

Find mechanism $n_{DM} \approx n_b$

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

Nussinov, S.M. Barr, D.B. Kaplan

Asymmetric Dark Matter

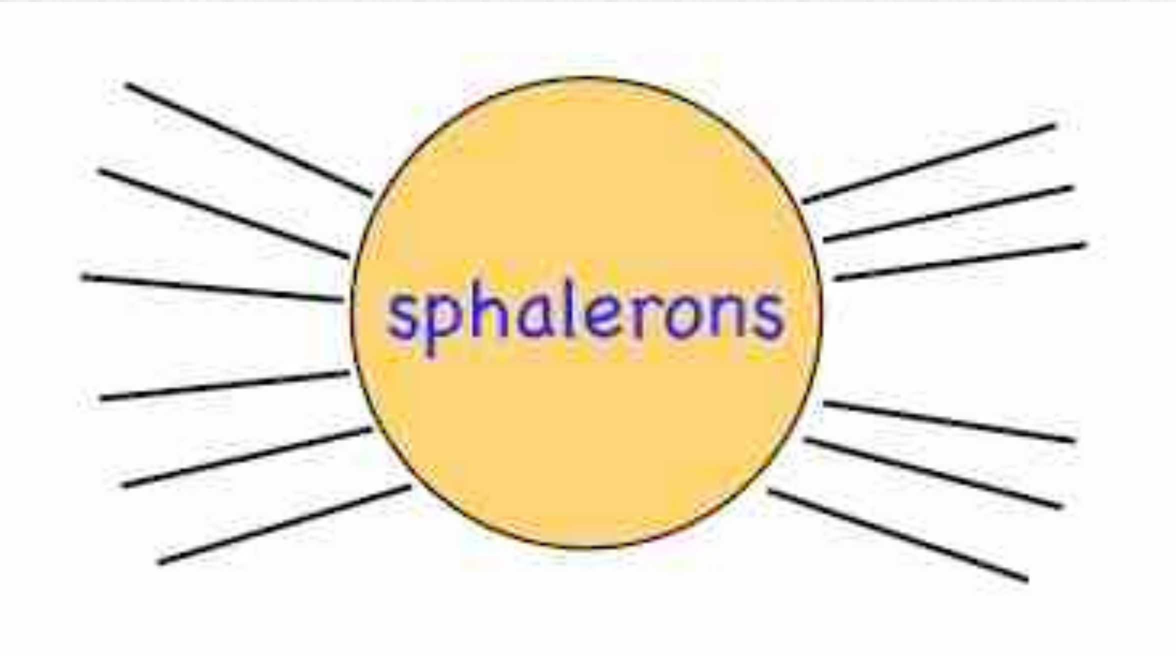


Relating DM to the baryon asymmetry

* First models used EW sphalerons to transfer the asymmetry S. Barr (1992) and D. B. Kaplan (1993)

DM number anomalous under SU(2)

DM carries EW quantum numbers



Visible sector

* These models no longer work because a) DM cannot be > 45 GeV b) coupling to the Z rules them out

Relating DM to the baryon asymmetry

* The dark matter can be heavier if it becomes non-relativistic just as B or L violating operators decouple

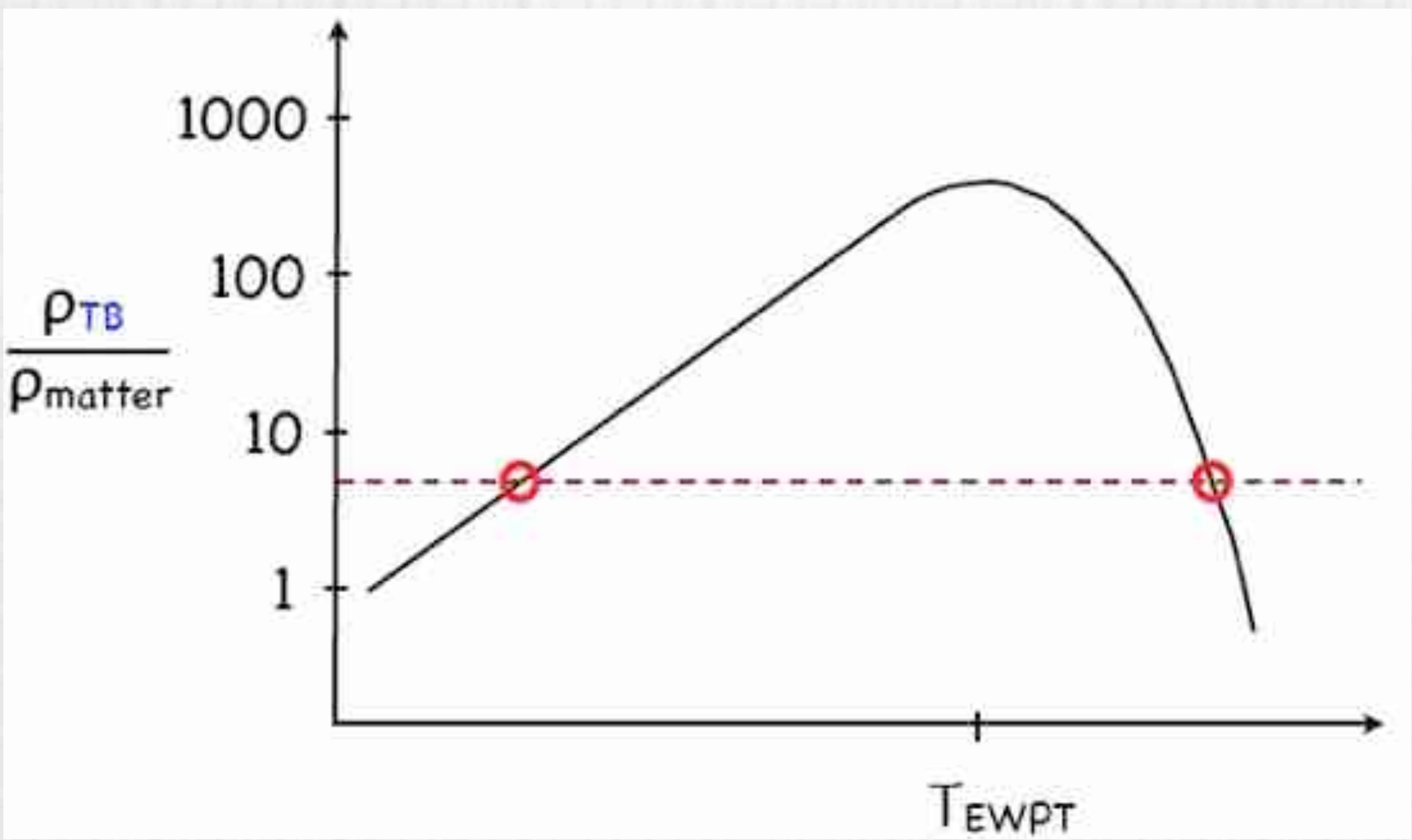
$$(n_X - n_{\bar{X}}) \sim (n_\ell - n_{\bar{\ell}})\, e^{-m_X/T_d}$$

$$\rho_{DM} = m_{DM} n_{DM}$$

* e.g. sphalerons transfer the asymmetry, mDM > Tsph

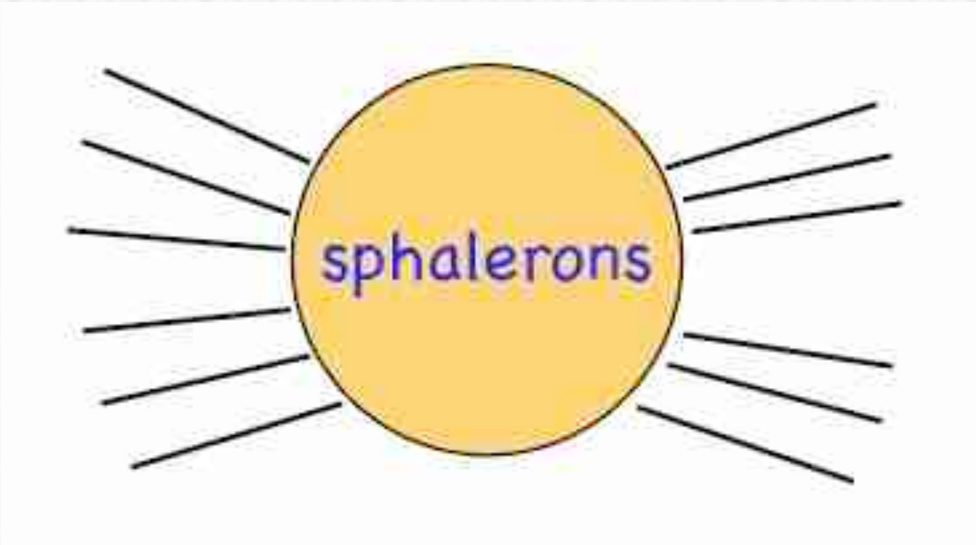
Relating DM to the baryon asymmetry

* The dark matter can be heavier if it becomes non-relativistic just as B or L violating operators decouple



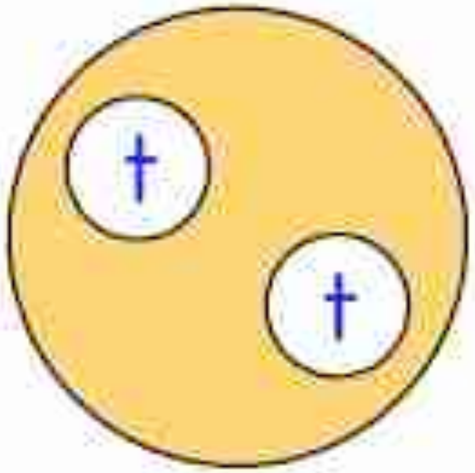
Technibaryon and Quirky dark matter

* Use sphalerons to transfer asymmetry



* First used in the context of technicolor, by Barr, Chivukula, Farhi
* Sphalerons mix SM fields carrying B,L with technifermions

Technicolor and technibaryons



Technifermions transform under SM

Technibaryon is gauge singlet (scalar or fermion)

TB number is accidental global symmetry, completely analogous to baryon number.

Difficulties with TB DM

* Couple inherently to Technicolor problems
* Difficult to get enough Boltzmann suppression: DM mass set by Higgs vev which is too small
* Must tune B and DM global charges
* Halo shape bounds problematic

A simple prescription: Asymmetric DM

Luty, Kaplan, KZ '09

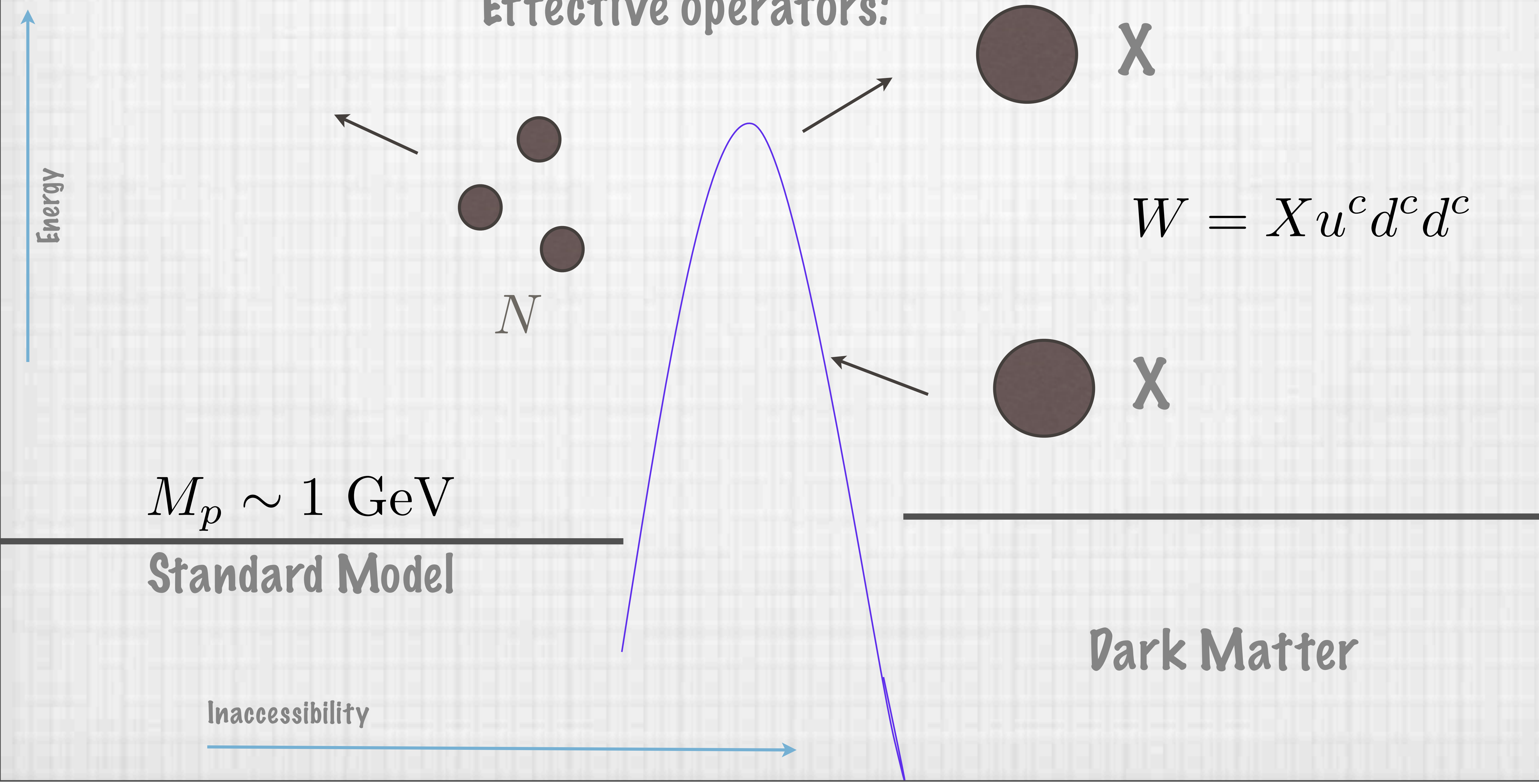
* Avoids the pitfalls of models which have their asymmetry related to the baryon asymmetry via EW quantum numbers
* Essential idea is to use higher dimension operators to transfer the asymmetry between sectors

Asymmetric DM

Luty, Kaplan, KZ '09

Integrate out heavy state
Effective operators:

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



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

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

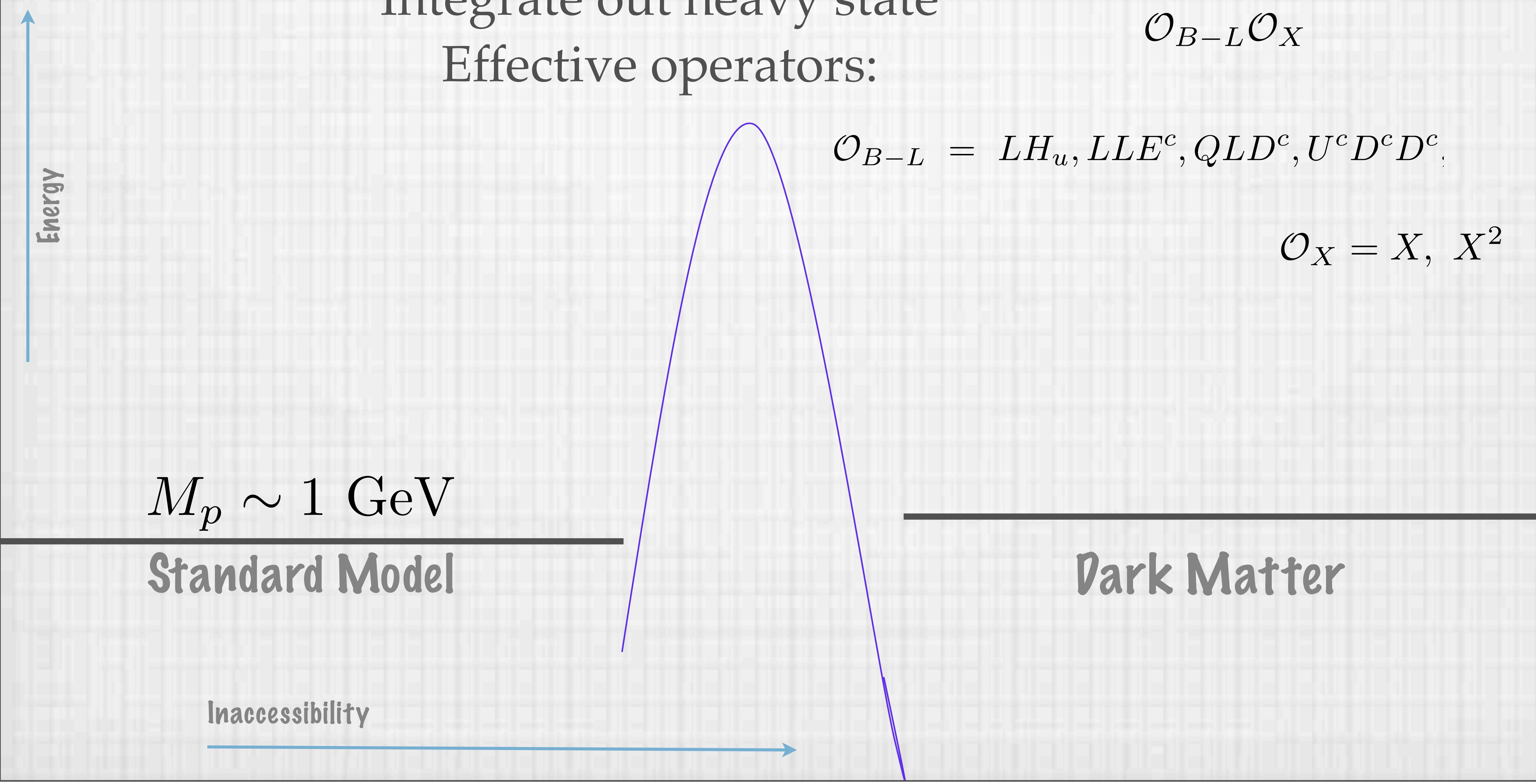
Asymmetric DM

Integrate out heavy state
Effective operators:

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

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

$$\mathcal{O}_X = X,\ X^2$$



Asymmetric DM

A model
One example, many possibilities

DM carries lepton or baryon number

$$W = \frac{X^2 LH}{M} \quad 2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$

Z2 symmetry to stabilize DM

1. Operator transfer lepton asymmetry to DM
2. Detailed calculation

DM carries lepton number L = 1/2

$$m_X \simeq 2.4 \text{ GeV} \frac{\Omega_{DM}}{\Omega_b} \simeq 11 \text{ GeV}$$

Asymmetric DM

A model

One example, many possibilities

DM carries lepton or baryon number

$$W = \frac{X^2 LH}{M}$$

Z2 symmetry to stabilize DM

3. Operator goes out of equilibrium before DM becomes non-relativistic, preventing XX -> nu nu, washing out asymmetry

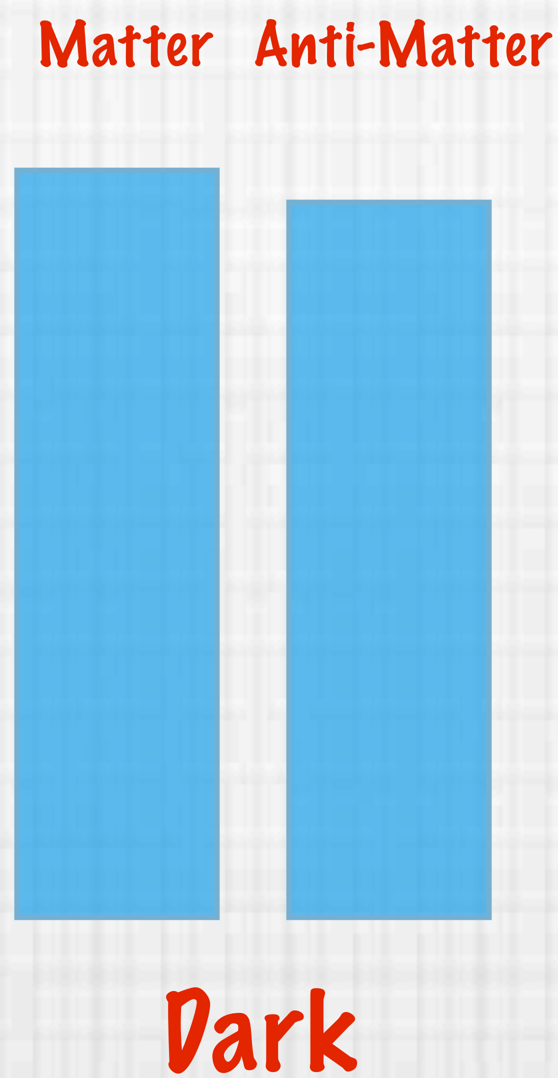
DM carries lepton number L = 1/2

4. Annihilate thermal abundance:

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

Annihilating thermal abundance

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



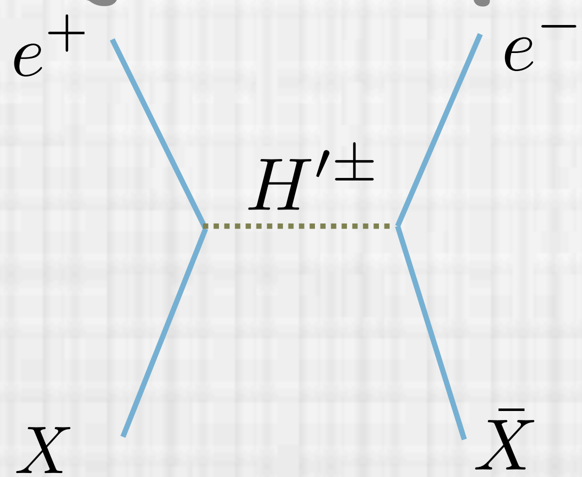
Annihilating thermal abundance

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

* Extra relativistic states (Goldstone)

$m_X \bar{X} X e^{ia/s}$ $\quad s < 200\ \text{GeV}$ sufficient

* Through heavy mediators

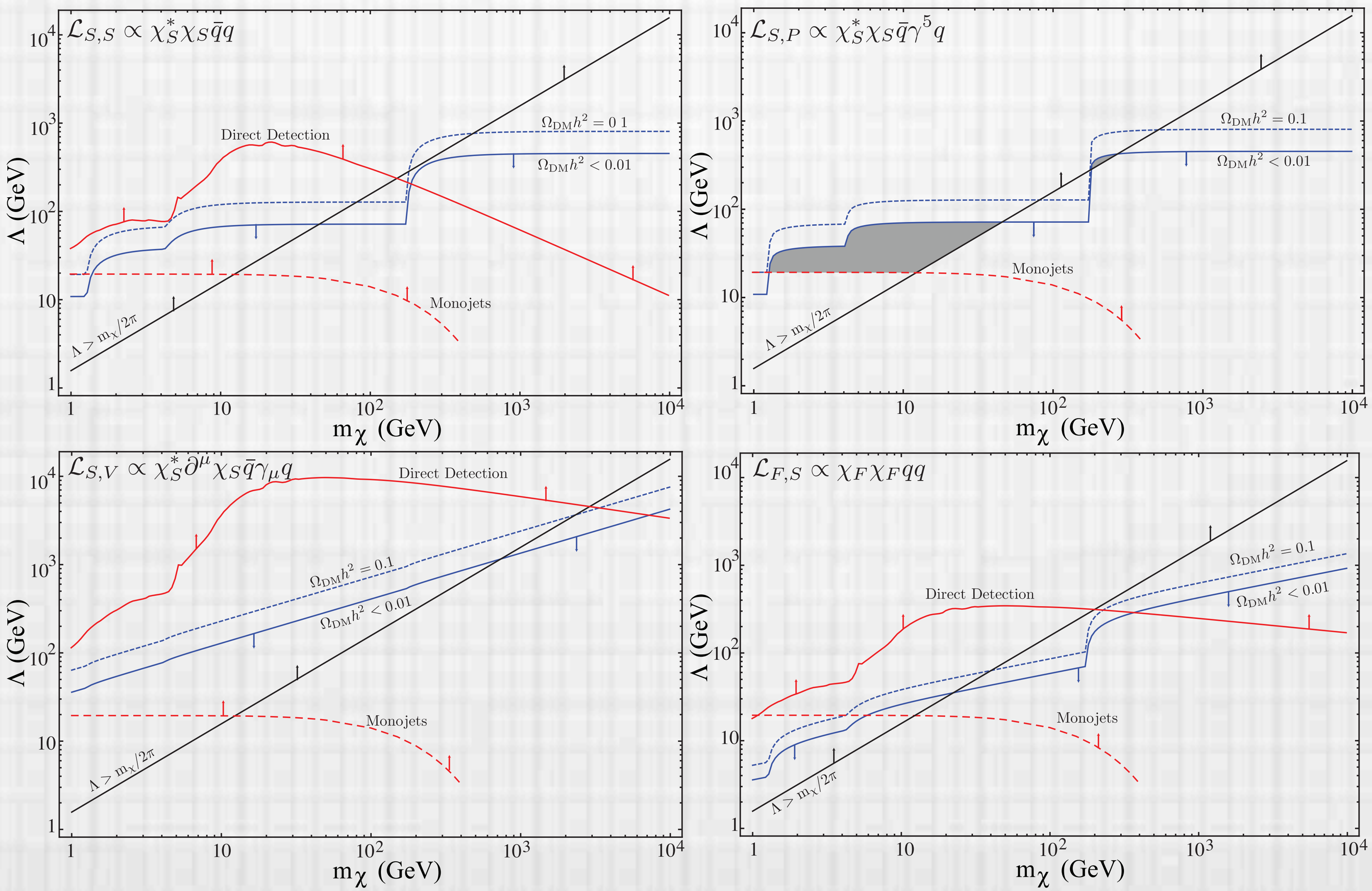


$$m_{H'}/y' \lesssim 200\ \text{GeV}$$

* Tight constraints!

Annihilating Thermal Abundance

* In general difficult to do via higher dimension operators

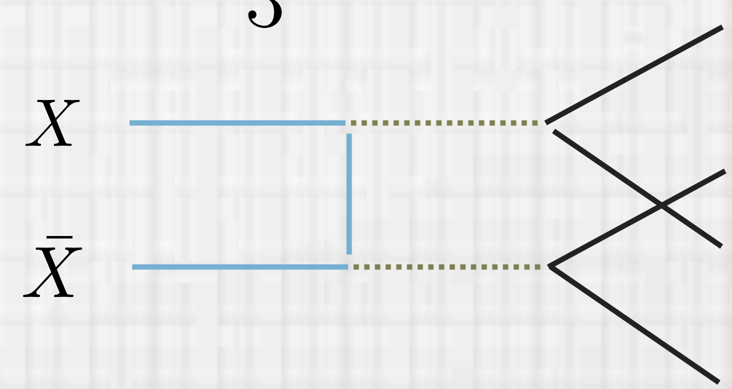


M. Buckley

Annihilating Thermal Abundance

- Alternative: light states that the DM can annihilate to that rapidly decay
- Much more robust!

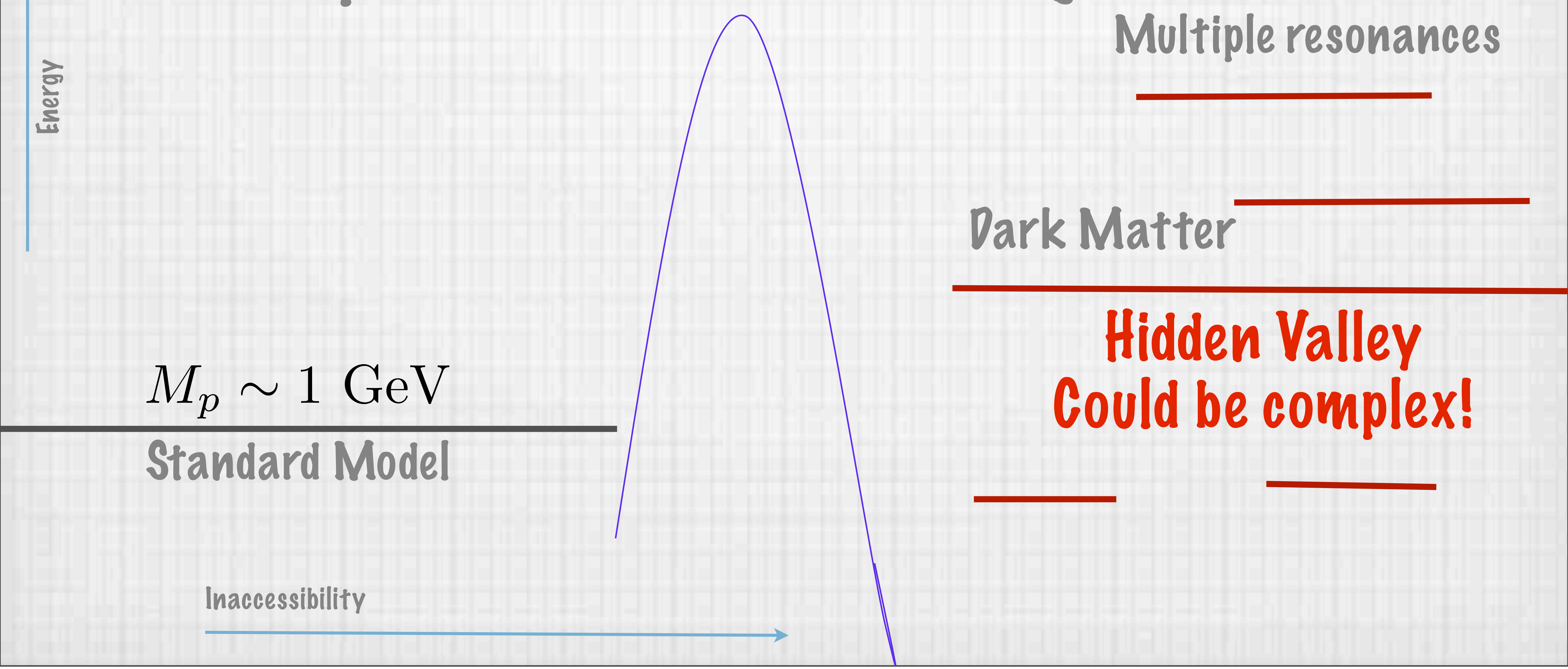
$$\Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3 .$$



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

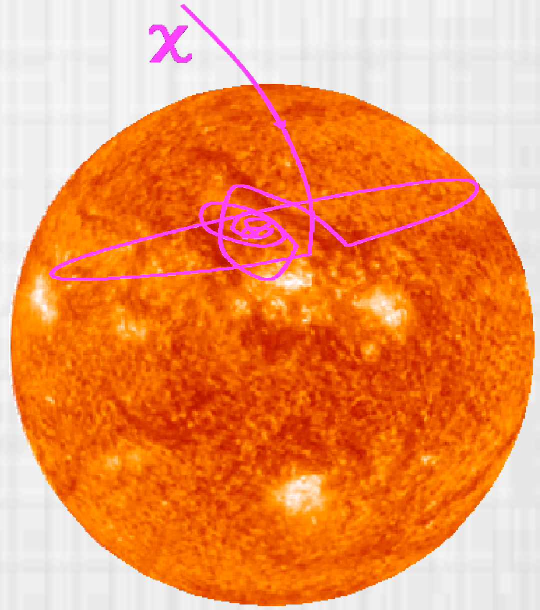
Summary

* The presence of the light DM states also implies the need for other light states



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!

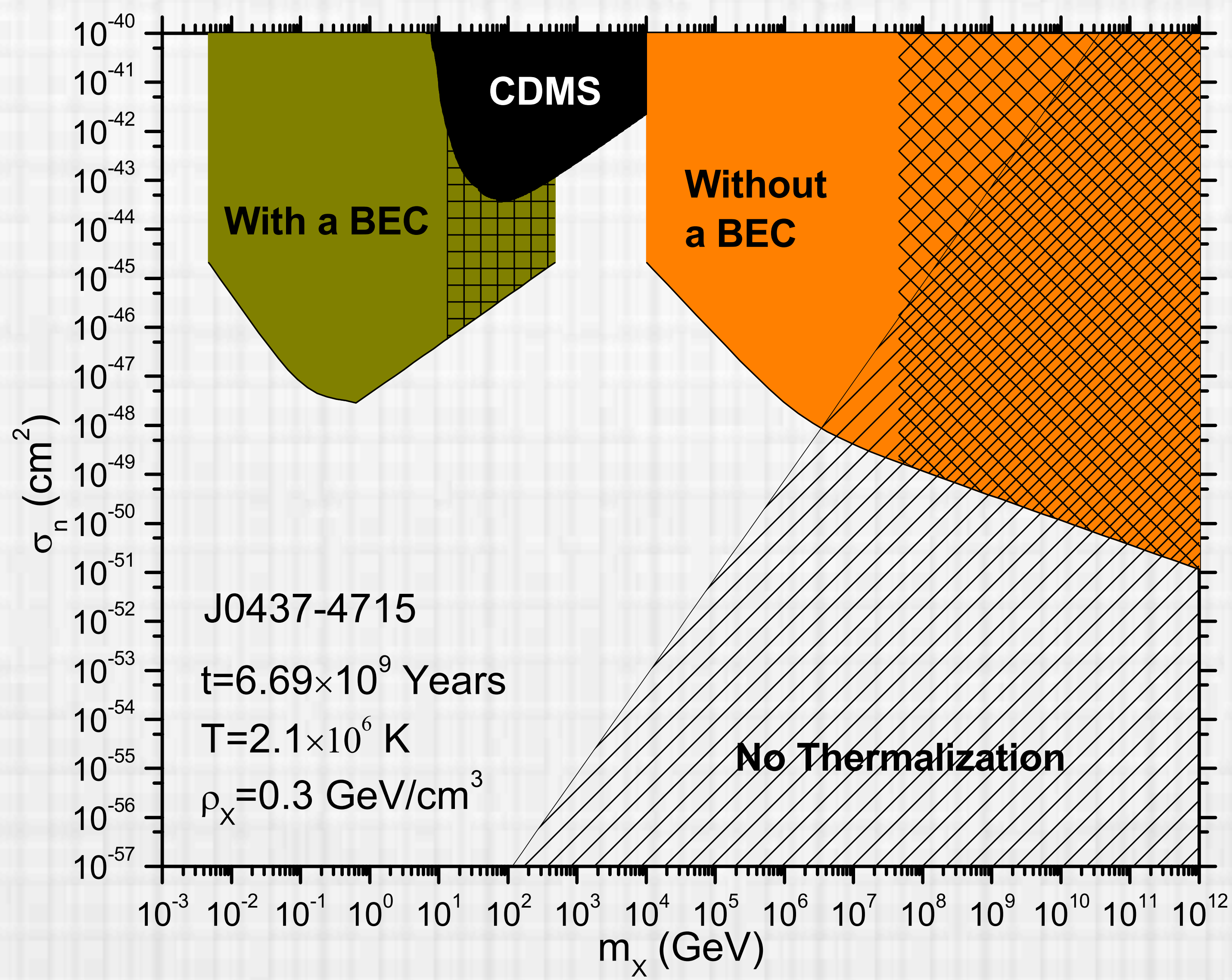


ADM, Black Hole and Neutron Stars

* 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!

ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ, '11



Seems to strongly constrain a scalar ADM explanation for CoGeNT!

Dark Sector Baryogenesis

* With DM sectors a possibility opens:
* Baryogenesis in the hidden sector?
* Opens a wide range of possibilities

Generate in dark sector then transfer = darkogenesis

Generate dark and visible asymmetries simultaneously = cogenesis

Cogenesis

Cheung, KZ '11

* Simultaneously generate a DM and baryon asymmetry
* Make use of Affleck-Dine mechanism
* ADM has operators of form:

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

* Breaks B-L, X, preserves B-L+X!

Cogenesis

* Drives non-zero <B-L> and <X>, but theory preserves B-L+X!
* --> $-n_{B-L} = n_X \neq 0.$
* Asymmetries generated simultaneously --> Cogenesis!

Cogenesis in the Early Universe

* Map onto simple mechanical analog: pseudo-particle in two 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 (AD) Cogenesis:
  * Stabilization: non-zero B-L and X vevs
  * Torque: non-zero angular momentum

Cosmology

* At low temperatures $U(1)_{B-L+X} \to U(1)_{B-L} \times U(1)_X$ since $\mathcal{O}_{B-L}\mathcal{O}_X$ decouples
* --> Two effective global symmetries + R-parity --> LXP and LSP stable
* Relic abundance set by baryon number divided by entropy density from inflaton decay:

$$\eta_B = \frac{n_B}{s} \sim \frac{n_B}{\rho_\chi / T_R}$$

1. Stabilization

* Hubble induced SUSY-breaking terms stabilize at non-zero <B-L>, <X>
* Usual mechanism: mass terms

$$\delta K = \frac{1}{M_p^2}\chi^\dagger\chi\phi^\dagger\phi$$

$$V_{\rm soft} \supset \sum_\phi (a_\phi m^2 + b_\phi H^2)|\phi|^2$$

Dine, Randall, Thomas

* New mechanism: A-terms

$$V_{\rm soft} \supset (fm + gH)\frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{d-4}}$$

2. Torque

* To see how this works, parameterize

$$\phi = r_\phi \exp i\,(q_{B-L,\phi}\theta_{B-L} + q_{X,\phi}\theta_X)$$

$$r_{B-L}^2 = \sum_\phi q_{B-L,\phi}^2 r_\phi^2$$

$$r_X^2 = \sum_\phi q_{X,\phi}^2 r_\phi^2.$$

* In this notation

$$\mathcal{L} = \frac{1}{2}(r_{B-L}^2\dot\theta_{B-L}^2 + r_X^2\dot\theta_X^2) - V(\theta_{B-L} - \theta_X)$$

* Then define according to conserved quantities:

$$\theta_\pm = \theta_{B-L} \pm \theta_X$$

Note θ_+ conserved!

2. Torque

* Note that the torque is exerted on θ_- only!
* Thus $n_{B-L} + n_X = 0.$ is conserved!
* The torque is exerted when fm = gH

$$V_{\rm soft} \supset (fm + gH)\frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{d-4}}.$$

Evolution of Asymmetry

* Can be solved numerically explicitly
* Parametrically set by <V>/H:

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{\theta}_-} = \frac{d}{dt}\left(n_{B-L} - n_X\right) = -\frac{\partial V}{\partial \theta_-}$$

Impulse approximation; evaluate at:

$$H \sim fm/g.$$

$$V_{\rm soft} \supset (fm + gH)\frac{\mathcal{O}_{B-L}\mathcal{O}_X}{M^{d-4}}$$

$$-n_{B-L} = n_X \sim \frac{\arg(f/g)\, g\, |\mathcal{O}_{B-L}|\, |\mathcal{O}_X|}{M^{d-4}}$$

* AD cogenesis ends when the field arrives at origin

Thermalization and Freeze-out

* For what values of re-heat temperature will the DM and visible sectors be in chemical or thermal equilibrium?

* Must be out of chemical equilibrium to prevent wash-out $W = \frac{QLD^c X}{M}$

$$T_D^{(d=5)} \sim 10^{14}\ \mathrm{GeV} \left(\frac{g_*}{200}\right)^{1/2} \left(\frac{M}{10^{15}\ \mathrm{GeV}}\right)^2$$

Thermalization and Freeze-out

* Marginal operators recouple at late times
* However, they do not wash-out the asymmetry if they recouple below EW phase transition $W = \lambda L H_u X$

$$T_D^{(d=4)} = 100 \text{ GeV} \left(\frac{200}{g_*}\right)^{1/2} \left(\frac{\lambda}{10^{-7}}\right)^2$$

Explicit Models

* $r_Q = r_L = r_{D^c}$ flat direction, i.e. QLD^cX

$$W = \frac{QLD^cX}{M}$$

* Full potential

$$V = \frac{r_Q^6}{8M^2} + \frac{3r_Q^4 r_X^2}{8M^2} + \frac{r_Q^3 r_X}{2M} fm \cos(\arg f - \theta_{B-L} + \theta_X) + \frac{r_Q^3 r_X}{2M} gH \cos(\arg g - \theta_{B-L} + \theta_X).$$

* At high temperatures, extremum at

$$r_Q^2 = r_X^2 = \frac{2gHM}{3}$$
$$\arg g - \theta_{B-L} + \theta_X = \pi$$

Yields

* Number density $-n_{B-L} = n_X \sim \arg(f/g)\, f^2 g\, m^2 M.$
* Baryon to entropy ratio: $\eta_B = \frac{n_B}{s} \sim \frac{n_B}{\rho_X / T_R}$
* Combine with constraint on reheat temperature to avoid gravitino problem

$$T_R \lesssim 10^{10}\ \mathrm{GeV}$$

* --> lower bound on M $M \gtrsim 10^{16}\ \mathrm{GeV}.$

Explicit Models

See also Hooper, March-Russell, West
Aoki, Kanemura, Seto

* Can choose leptonic flat direction instead $r_L = r_{H_u}$

$$W = \lambda L H_u X$$

* Full potential

$$V_{\rm soft} = (fm + gH)\lambda L H_u X$$

$$V = \frac{\lambda^2 r_L^4}{4} + \frac{\lambda^2 r_L^2 r_X^2}{2} + \frac{\lambda r_L^2 r_X f m \cos(\arg f - \theta_{B-L} + \theta_X)}{\sqrt{2}} + \frac{\lambda r_L^2 r_X g H \cos(\arg g - \theta_{B-L} + \theta_X)}{\sqrt{2}}$$

* Initial condition

$$r_L^2 = r_X^2 = \frac{g^2 H^2}{2\lambda^2}$$

$$\arg g - \theta_{B-L} + \theta_X = \pi$$

Yield

* Again puts a lower bound on the weakness of the interaction

$$-n_{B-L} = n_X \sim \frac{\arg(f/g)\, f^3 g\, m^3}{4\lambda^2}$$

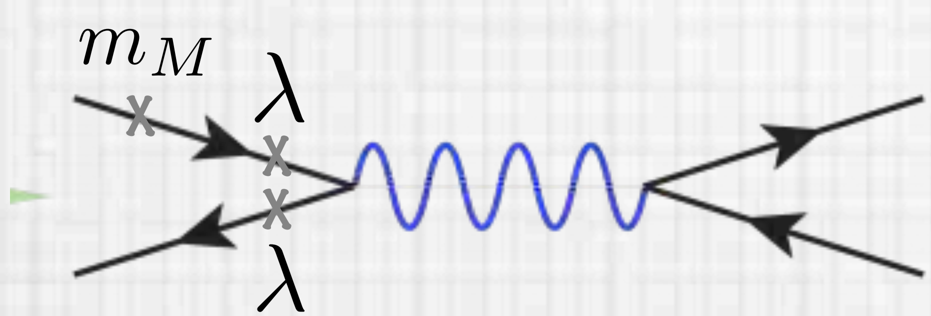
* Baryon to entropy ratio $\eta_B = \frac{n_B}{s} \sim \frac{n_B}{\rho_\chi / T_R}$
* Reheat constraint $T_R \lesssim 10^{10}\ \text{GeV}$
* --> $\lambda \lesssim 10^{-7}$

Neutrino Masses

* Note that the operator generates neutrino masses $W = \lambda L H_u X$
* Can take Dirac neutrino masses if $\lambda \sim 10^{-12}$
* We can accommodate Majorana neutrino masses if they are at the weak scale

Majorana Neutrino Masses

* Annihilations through Z boson are suppressed $\lambda \lesssim 10^{-7}$



$$\Gamma \sim \lambda^4 \frac{m_M^2 T^3}{m_Z^4}$$

Cool Collider Signatures

* Lightest Supersymmetric Partner Resides in the Hidden Sector!

$$W = \frac{QLD^cX}{M} \qquad W = \lambda L H_u X$$

$$M \gtrsim 10^{16}\ \mathrm{GeV}. \qquad \lambda \lesssim 10^{-7}$$

* --> Operators are weakly coupled
* --> Long lifetimes on collider timescales

$$\tilde{C} \to \ell \tilde{x} \qquad c\tau \sim 1\ \mathrm{cm} \times \left(\frac{100\ \mathrm{GeV}}{m}\right)\left(\frac{10^{-8}}{\lambda}\right)^2$$

Generating the GeV scale for ADM

Asymmetric DM

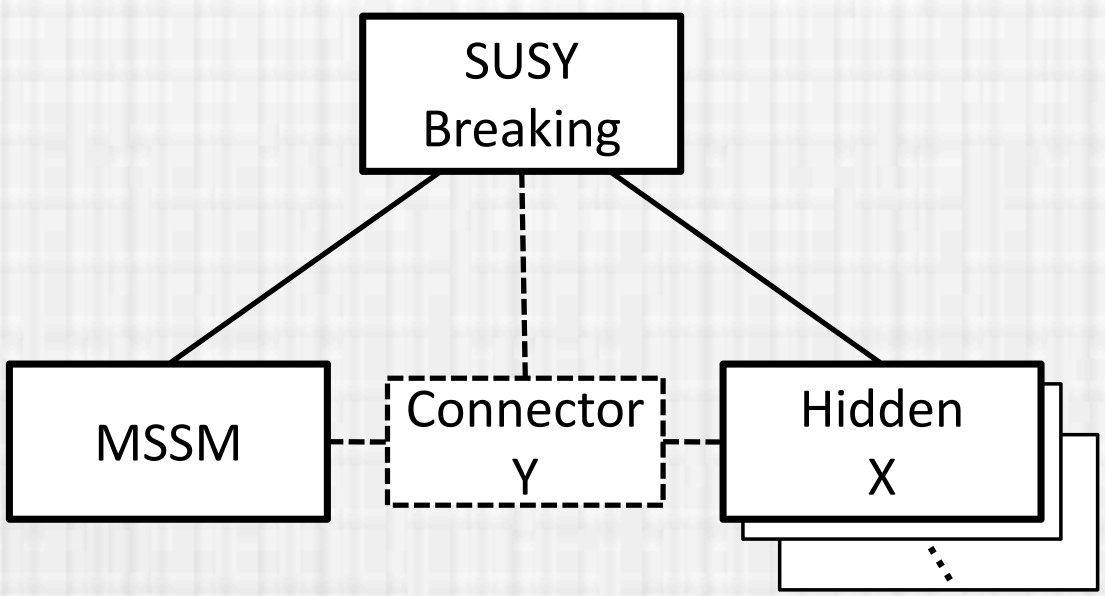
* Why the GeV scale for DM?
* How does one generate light higgses and massive gauge bosons in a hidden sector naturally?

GeV scale dark sectors and ADM

* Generate GeV scale dynamically
* Dark gauge bosons provide efficient annihilation mechanism

Naturally Light Hidden Sectors

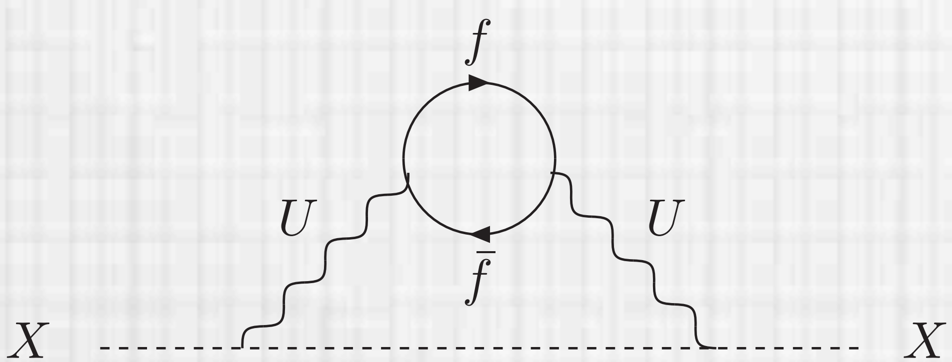
Communicate SUSY breaking more weakly to the hidden sector than the visible sector!



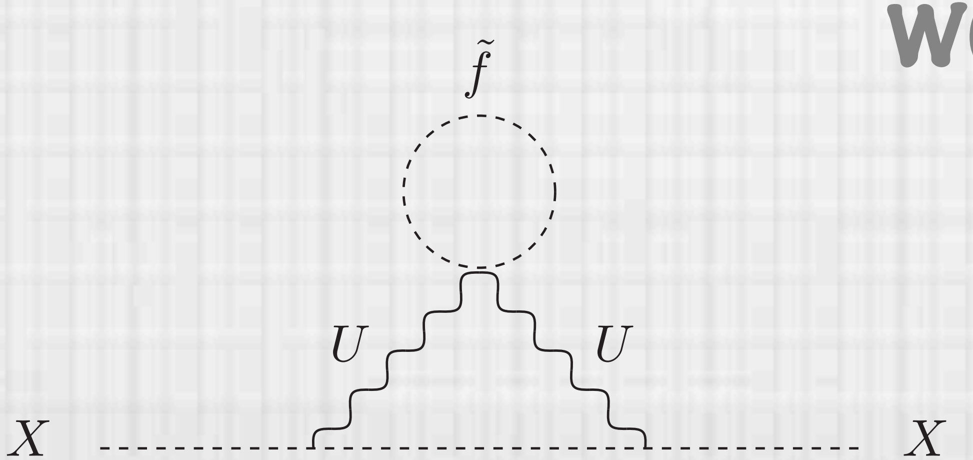
Feng and Kumar

Naturally Light Hidden Sectors

* Gauge mediation provides a natural framework for week communication of SUSY breaking to a hidden sector



weaker coupling to messengers --> smaller SUSY breaking masses

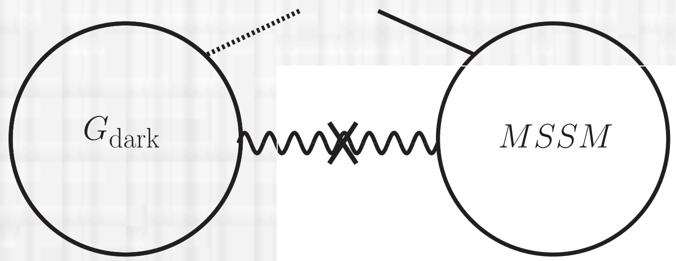


Hooper, KZ

via D- term kinetic mixing

Baumgart, Cheung, Ruderman, Wang, Yavin, '09

* One way to communicate small SUSY breaking is via kinetic mixing



Arkani-Hamed et al

$$V_{\rm gauge} = \frac{1}{2}D_Y^2 + \frac{1}{2}D_y^2 - \epsilon D_Y D_y + g_Y D_Y \sum_i Q_i |H_i|^2 + g_y D_y \sum_i q_i |h_i|^2$$

$$V_{\rm gauge} \supset \epsilon D_y \langle D_Y \rangle = \xi D_y$$

$$\xi = \epsilon \langle D_Y \rangle = \epsilon \frac{g_Y}{2} \cos 2\beta\, v^2$$

A Simple Model

DM = S/T!

Cohen, Phalen, Pierce, KZ

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

+ kinetic mixing

	S	T
$U(1)_X$	+1	-1
$U(1)_d$	+1	-1

* Potential

$$V = \lambda^2 |H'|^2 (|S|^2 + |T|^2) + \lambda^2 |S|^2 |T|^2 + \frac{g_d^2}{2}(-|T|^2 + |H'|^2 - \xi)^2$$

$$\xi = -\epsilon \frac{g_Y}{2} c_{2\beta} v^2$$

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

A Simple Model

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

Simply require $\lambda \gtrsim g_d$

A Simple Model

* S, T chiral sector in more detail

Stable by U(1)_X!
Asymmetric

* Efficient annihilation to dark higgs H' -- erases relic abundance

A Simple Model

* LSP is gravitino, but dark photino has long lifetime and could disrupt BBN

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

* Small relic abundance because of efficient annihilation to dark photon

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

Summary

* Asymmetric Dark Matter provides an alternative framework to weak scale freeze-out
* Does require a 1-particle extension of the SM + additional heavy state for mediation of chemical potentials

Summary

* An extension of the DM sector to multiple particles opens many possibilities for model building
  * Generation of baryon asymmetry at low scale
  * Dynamical generation of DM mass in the hidden sector

Summary

* Phenomenologically distinct both in terms of astrophysics and collider signatures
* Time to look beyond the MSSM?