A WIMPy Baryogenesis Miracle

Baryogenesis via WIMP annihilation

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Outline

- Motivation: WIMP miracle and dark matter/baryon ratio
- Review of baryogenesis
- Example: WIMPy leptogenesis
- WIMP annihilation to quarks
- Constraints and detection prospects

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- Our models incorporate both observations
  1. **Dark matter abundance:** Established by thermal freeze-out according to the WIMP miracle
  2. **Dark matter/baryon ratio:** Dark matter annihilation generates a baryon asymmetry
     - ⋆ Connection between the dark and visible sector abundances

- For a model incorporating the WIMP miracle in baryogenesis in a different way than WIMPy baryogenesis, see McDonald, 1009.3227 and 1108.4653

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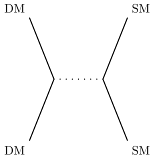

- Relic abundance inversely proportional to annihilation cross section

$$\Omega_{\mathrm{WIMP}} \approx \Omega_{\mathrm{DM}} \frac{1 \text{ pb}}{\langle \sigma_{\mathrm{ann}}\, v \rangle}$$

Motivation: dark matter/baryon ratio

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  - Baryonic matter abundance is determined by a matter-antimatter asymmetry
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- Models accounting for the dark matter/baryon ratio typically ignore the WIMP miracle
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  - Both dark matter and baryons have their origin in a primordial excess of matter over antimatter
- Can we have some features of symmetric dark matter while also establishing a connection between the dark matter and baryon abundances?

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- **WIMPy baryogenesis:**
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- WIMPy baryogenesis is nice because it
  - Ties all dark matter and baryogenesis physics to the weak scale
    - Possible weak scale origin of new fields and couplings?
  - Gives indirect detection signals of conventional symmetric WIMP dark matter
  - Incorporates baryogenesis by annihilation, which has often been overlooked
    - Proposed by Bento, Berezhiani 2001; Gu, Sarkar 2009

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- All three conditions are satisfied in the Standard Model **but**
  - CP violation not big enough (suppressed by 12 Yukawa couplings $\sim 10^{-20}$)
  - Phase transition not first order

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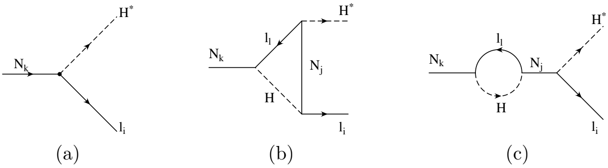
2. *CP violation:* CP-violating phases in y_ν
3. *Departure from equilibrium:* N decays out of equilibrium

- If we only considered tree level diagram, CP phases disappear with $|\mathcal{M}|^2$
  - Need to consider interference of tree and loop diagrams



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- Two necessary components:
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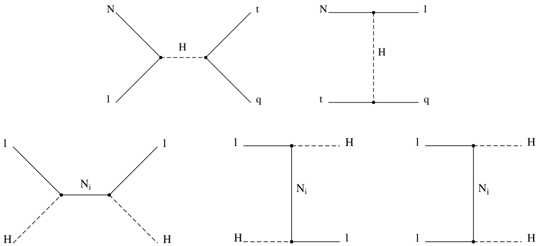
  2. **Washout** scatterings must go out of equilibrium



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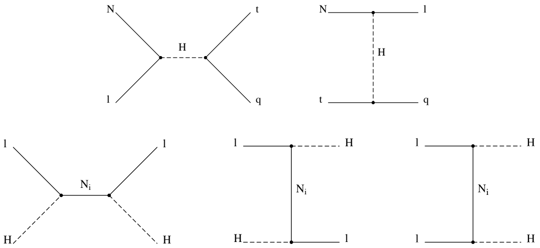

- Asymmetry proportional to number of decays that happen **after** washout freezes out (at $T \ll m_{N1}$)
  - N_1 lifetime longer than Hubble time at $T = m_{N1}$ ($\Gamma_{N1} < H(m_{N1})$)

WIMPy leptogenesis

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     - ★ For $T < m_{\rm DM}$, have net dark matter annihilation
     - ★ Need washout to go out of equilibrium
     - ★ **Final asymmetry proportional to DM relic density when washout freezes out**
- How can washout go out of equilibrium sufficiently early?
  - ▸ One of lepton-number-carrying fields is heavy **or** washout cross section much smaller than annihilation cross section

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- Lepton asymmetry transferred to baryon asymmetry by sphalerons
  - Sphalerons ineffective after electroweak phase transition ($T_{\rm c} \sim 100$ GeV)
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- Singlet fermion dark matter X
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- New field ψ
  - ψ is a doublet with hypercharge $+1/2$
  - To allow the widest possible range of masses, take ψ to be vectorlike

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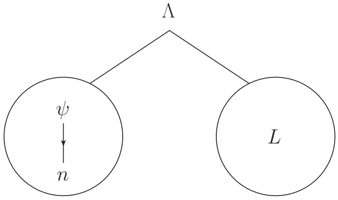
- Two possible solutions:
  1. Two sectors with separately preserved asymmetries
     - ⋆ Simplest ψ decay: $\psi \to H\, n$, where n is a singlet
  2. ψ decays with $\mathrm{U}(1)$-violating couplings

WIMPy leptogenesis: model



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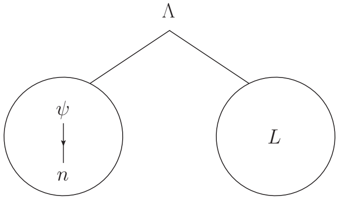

- Also want dark matter stability
- **Minimal solution:** Z_4 symmetry
  - Charge of $X = i$
  - Charge of $\psi = -1$
  - Charge of SM fields $= +1$
- Since X has a Z_4 charge, it must be *Dirac*

WIMPy leptogenesis: model

- **A minimal "complete" model:**
  - We choose the simplest UV completion: effective operator arises from exchange of pseudoscalars S_α

$$\mathcal{L} \supset \frac{i}{2}(\lambda_{X\alpha}\, X^2 + \lambda'_{X\alpha}\, \bar{X}^2) S_\alpha + i\lambda_{L\alpha}\, L\psi S_\alpha + \mathrm{h.c.}$$

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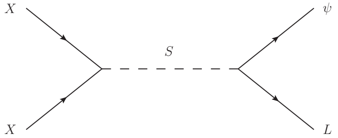
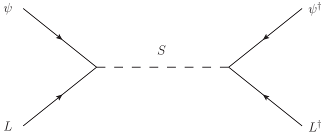
- Annihilation and washout scatterings:





$$\sigma_{\mathrm{ann}} \sim |\lambda_X|^2\, |\lambda_L|^2 \qquad \sigma_{\mathrm{washout}} \sim |\lambda_L|^4$$

WIMPy leptogenesis: Sakharov conditions

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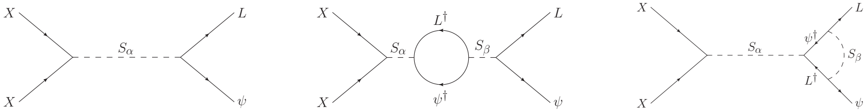
2. CP violation:
   - CP phases in couplings λ_X, λ_L
   - Interference of tree and loop diagrams



- Must have at least two generations of S for non-zero CP phase in amplitude

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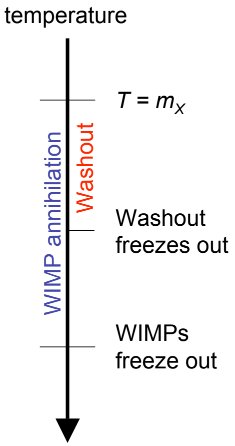
3. Departure from thermal equilibrium?

- Asymmetry generated while DM annihilates
- Washout eliminates asymmetry as it accumulates
- Need to have washout freeze out during era of rapid WIMP annihilation



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- At $z \gg 1$, X and lepton asymmetry (ΔL) go *out of equilibrium*
  - Determines WIMP relic abundance and baryon asymmetry

WIMPy leptogenesis: WIMP evolution

- Evolution of Y_X and $Y_{\Delta L}$:

Boltzmann equations:

$$\frac{dY_a}{dz} = -\frac{(2\pi)^4}{z\,H(z)\,s(z)} \int d\Pi_a\, d\Pi_b\, d\Pi_c\, d\Pi_d\, |\mathcal{M}_{ab\to cd}|^2 \delta^4(\sum p)(f_a f_b - f_c f_d)$$

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  - Drives Y_X to equilibrium value when scattering is rapid
  - Proportional to the *square* of the X distribution

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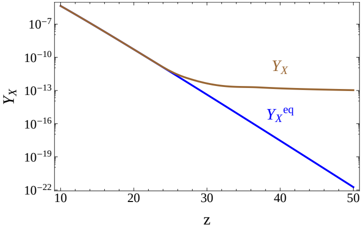
$$\frac{dY_X}{dz} \sim -\langle \sigma_{XX\to L\psi}\, v\rangle \left[Y_X^2 - (Y_X^{\mathrm{eq}})^2\right]$$

- If the baryon asymmetry is small, there is no back-reaction on Y_X

WIMPy leptogenesis: asymmetry

- We get the conventional WIMP equation
  - $Y_X(z = \infty) \sim 1/\langle \sigma_{XX \to L\psi}\, v \rangle$



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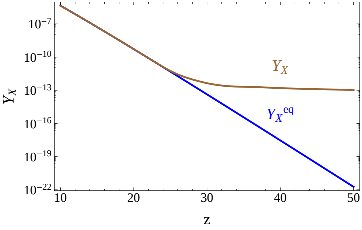

- For $z > 1$, we want $dY_X/dz \approx dY_X^{\rm eq}/dz$ if X tracks its equilibrium distribution
  - This implies a departure of X from thermal equilibrium!
  - Integrating the deviation from equilibrium over z gives ΔY_X, the total number of DM particles annihilated

WIMPy leptogenesis: lepton asymmetry evolution

- Lepton asymmetry evolution:
  - Two important terms:
    - ⋆ Asymmetry generation by XX annihilation (proportional to fractional asymmetry per annihilation ϵ)
    - ⋆ Asymmetry depletion by $L\psi \to L^\dagger \psi^\dagger$

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$$\frac{dY_{\Delta L}}{dz} \sim +\epsilon \times (\text{WIMP ann. rate}) - Y_{\Delta L} \times (\text{washout rate})$$

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  - Two important terms:
    - ⋆ Asymmetry generation by XX annihilation (proportional to fractional asymmetry per annihilation ϵ)
    - ⋆ Asymmetry depletion by $L\psi \to L^\dagger \psi^\dagger$

$$\frac{dY_{\Delta L}}{dz} \sim +\epsilon \times (\text{WIMP ann. rate}) - Y_{\Delta L} \times (\text{washout rate})$$

$$\sim -\epsilon \frac{dY_X}{dz} - Y_{\Delta L} \langle \sigma_{L\psi \to L^\dagger \psi^\dagger} v \rangle Y_L^{\text{eq}} Y_\psi^{\text{eq}}$$

WIMPy leptogenesis: asymmetry

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$$Y_{\Delta L}(z) \sim \frac{\text{generation rate}}{\text{washout rate}} \sim \frac{1}{\langle \sigma_{L\psi \to L^\dagger \psi^\dagger} \, v \rangle \, Y_L^{\rm eq} \, Y_\psi^{\rm eq}} \left(-\epsilon \, \frac{dY_X}{dz} \right)$$

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    - Too small for observed baryon asymmetry
  - **Late times:** define z_0 as the time when washout processes freeze out
    - We're left with the equation

$$\frac{dY_{\Delta L}}{dz} \sim -\epsilon \frac{dY_X}{dz} \qquad (z > z_0)$$

WIMPy leptogenesis: asymmetry

$$Y_{\Delta L}(\infty) \approx \epsilon \left[Y_X(z_0) - Y_X(\infty) \right]$$

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- If washout freezes out before WIMP freeze-out, $Y_X(z_0) \gg Y_X(\infty)$, and **asymmetry is proportional to dark matter number at time of washout freeze-out**

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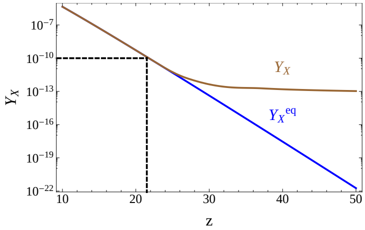

- Washout must freeze out before annihilations cease
- Washout freezes out when washout rate $\lesssim$ Hubble scale
- Washout rate $\sim \langle \sigma_{L\psi \to L^\dagger \psi^\dagger}\, v\rangle\, Y_L^{eq}\, Y_\psi^{eq}$

$$Y_{\Delta L} \sim 10^{-10} \text{ and } \epsilon < 1 \quad \Rightarrow \quad z_0 \lesssim 20$$

WIMPy leptogenesis: asymmetry

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  1. Heavy m_ψ so that $Y_\psi^{\rm eq}$ is exponentially suppressed
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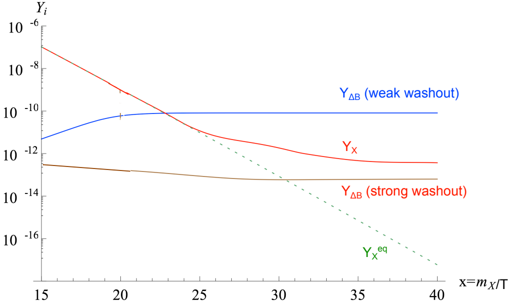

- Washout freezes out before WIMPs $\to$ **weak washout**
- Washout freezes out after WIMPs $\to$ **strong washout**

WIMPy leptogenesis

Recap so far:

- Baryogenesis through WIMP annihilation is possible if
  - Annihilation occurs through L-violating coupling
  - Non-zero CP phases in L-violating coupling
- Need washout to freeze out while WIMP annihilation is still active
- WIMPs described by *equilibrium* distribution during this time!

Numerical results

- CP-violating factor: fractional asymmetry generated by each annihilation

$$\epsilon = \frac{\sigma(XX \to \psi_i L_i) - \sigma(XX \to \psi_i^\dagger L_i^\dagger)}{\sigma(XX \to \psi_i L_i) + \sigma(XX \to \psi_i^\dagger L_i^\dagger)}$$

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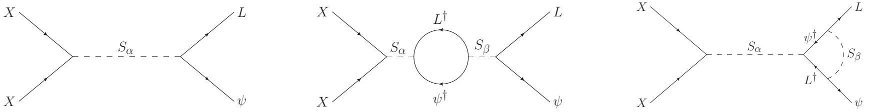
- Many free parameters! Make assumptions to include minimal ingredients, simplify analysis:
  - Only one flavour of lepton relevant for WIMPy leptogenesis
  - Annihilation through the lightest scalar S_1 is dominant
  - Phases are large

Numerical results



- With these assumptions:

$$\epsilon \sim -\frac{1}{4\pi}\frac{\mathrm{Im}(\lambda_{L1}^2\lambda_{L2}^{*2})}{|\lambda_{L1}^2|}\frac{(2m_X)^2}{m_{S2}^2} f\left(\frac{m_\psi}{2m_X}\right)$$

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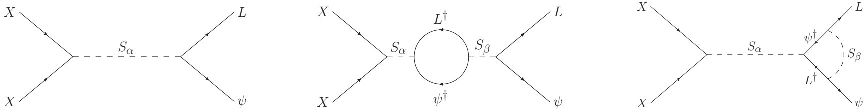

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$$|\epsilon| \lesssim \frac{2\lambda_{L1}^2 m_X^2}{3\pi\sqrt{5} m_{S1}^2} f\left(\frac{m_\psi}{2m_X}\right)$$

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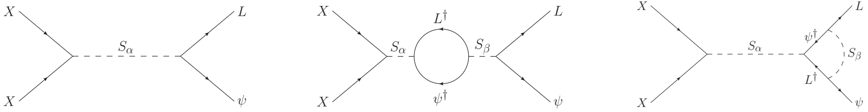

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- Masses and couplings of heavy S_α contribute only indirectly through loop effects to ϵ
  - **Use ϵ as a free parameter, subject to bound**

Numerical results: masses

- 6 parameters: m_X, m_ψ, m_S, λ_X, λ_L, and ϵ
- Show masses for which WIMPy leptogenesis gives correct relic density and asymmetry with perturbative couplings λ_L, λ_X, and ϵ

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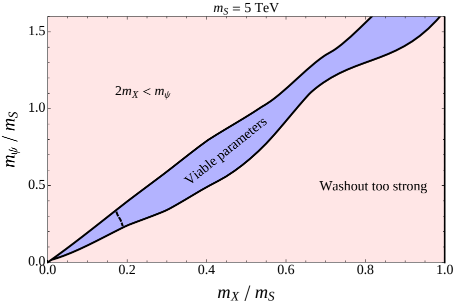

- X and ψ mass constrained to lie close together (within $m_\psi \sim 1 - 2m_X$)

- $m_S = 5$ TeV
- Asymmetry should be generated before sphalerons decouple $\Rightarrow m_X \gtrsim$ TeV
  - Dashed line in figure for Standard Model electroweak phase transition

Numerical results: couplings

- Choose points in middle of parameter space:
  - $m_S = 5$ TeV for both plots

Numerical results: couplings

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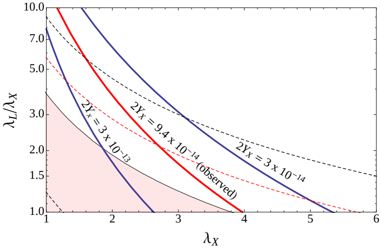
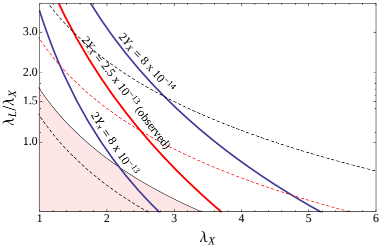
  - $m_S = 5$ TeV for both plots

- $m_X = 4.25$ TeV, $m_\psi = 7.5$ TeV, and $\epsilon = 0.075$



- $m_X = 1.5$ TeV, $m_\psi = 2.25$ TeV, and $\epsilon = 0.0075$



- Solid lines: X relic abundance
- Dotted lines: baryon asymmetry (from top, $Y_{\Delta B} = 3 \times 10^{-11}$, 8.85×10^{-11}, 3×10^{-10})
- Shaded region inconsistent with assumptions

Numerical results

- Constructed a concrete model of leptogenesis through WIMP annihilation
- Get correct WIMP relic density and baryon asymmetry with:
  - All masses $\mathcal{O}(\mathrm{TeV})$
  - All couplings $\gtrsim 1$
  - Sufficiently large asymmetry in region with $m_X \sim m_\psi$
- Limitation: $T_{\mathrm{lepto}} > T_{\mathrm{electroweak}}$

Annihilation to quarks

- Consider model similar to leptogenesis
  - WIMP annihilation to up quark $\bar{u}$; ψ is colour triplet with charge $+2/3$

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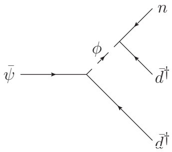

- ψ decays through operator $\bar{\psi}\bar{d}\bar{d}n/\Lambda^2$ to quarks, singlet n
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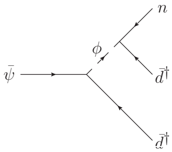

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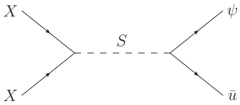
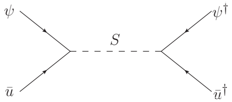
$$\Delta\mathcal{L} = +\frac{i}{2}\left(\lambda_{X\alpha}X^2 + \lambda'_{X\alpha}\bar{X}^2\right)S_\alpha + i\lambda_{B\,\alpha i}\,S_\alpha\bar{u}_i\psi_i + \text{h.c.}$$





$\sigma_{\text{ann}} \sim |\lambda_X|^2\,|\lambda_B|^2$

$\sigma_{\text{washout}} \sim |\lambda_B|^4$

Annihilation to quarks: numerical results

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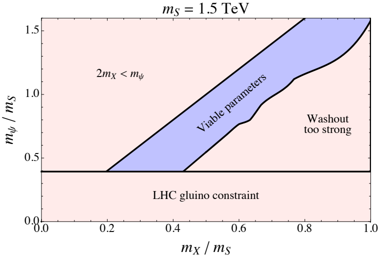
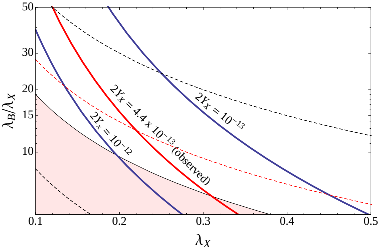
$m_S = 1.5$ TeV



$m_S = 1.5$ TeV, $m_X = 0.9$ TeV,
$m_\psi = 1.3$ TeV, $\epsilon = 0.075$



Constraints and signals

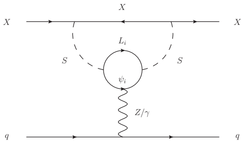
- We consider (briefly) the three most important constraints/observable effects:

1. Direct detection
2. Indirect detection
3. Colliders

Constraints and signals: direct detection

Annihilation to leptons:

- Only couples to nucleons through 2-loop moment
- Cross section too small



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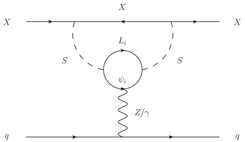
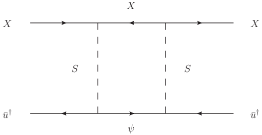


Annihilation to quarks:

- Couples at one-loop:

$$\sigma_{X-N} \sim \frac{1}{16\pi}\left(\frac{\lambda_B^2\lambda_X^2}{16\pi^2}\right)^2 \frac{\mu^2}{m_X^4}$$



- Benchmark points:
  1. $m_X = 4.25$ TeV, $m_\psi = 7.25$ TeV, $m_S = 5$ TeV, $\lambda_X = 2.7$ and $\lambda_B = 4.5$: $\sigma_{X-N} \approx 1 \times 10^{-44}\ \mathrm{cm}^2$
  2. $m_X = 0.9$ TeV, $m_\psi = 1.2$ TeV, $m_S = 1.5$ TeV, $\lambda_X = 0.22$ and $\lambda_B = 2.8$: $\sigma_{X-N} \approx 4 \times 10^{-46}\ \mathrm{cm}^2$

Constraints and signals: indirect detection

- Both scenarios annihilate to quarks
- Best prospect for indirect detection: antideuterons
  - Very low astrophysical backgrounds at low energies
  - Donato, Fornengo, Salati 2000; Baer, Profumo 2005; Cui, Mason, Randall 2010

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Annihilation to leptons:

- $XX \to W^{\pm}$, h
- Hadronization in boosted frame
- Mass constraint reach $\mathcal{O}(100\ \mathrm{GeV})$

Annihilation to quarks:

- $XX \to$ color-connected $\bar{u}\bar{d}\bar{d}$
- Some hadronization in rest frame
- Low-energy antideuterons!
- Can exclude up to $m_X \sim$ TeV

Constraints and signals: colliders

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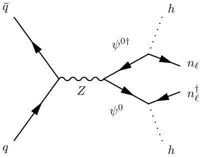

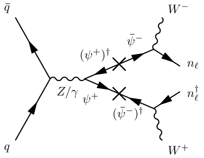

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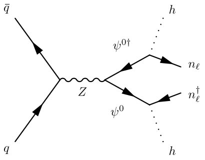

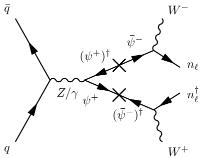

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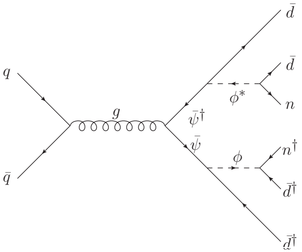
  - $\tilde{\chi}^\pm \to W^\pm \, \tilde{\chi}^0 \to jj \, \tilde{\chi}^0$
- LHC not yet sensitive to electroweak production
  - May be able to find in targeted searches: b-tagging, reconstruct Higgs mass

Constraints and signals: colliders

Annihilation to quarks:

Constraints and signals: colliders

Annihilation to quarks:



$$\mathcal{L} \supset \lambda_i\, \bar{\psi}_i\, \bar{d}_i\, \phi^* + \lambda_i'\, \phi\, \bar{d}_i\, n_i$$

- Gluino-like topology with different group theory factors
- $4j + \not{E}_{\mathrm{T}}$ final state
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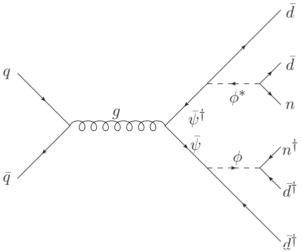

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- LHC should test m_ψ up to ~ 2 TeV at $100 \ \mathrm{fb}^{-1}$

Conclusions

- WIMPy baryogenesis: WIMP annihilations can generate a baryon asymmetry
- Can get correct relic density and baryon asymmetry with $\sim$ TeV masses, $\mathcal{O}(1)$ couplings
  - Need $m_X \sim m_\psi$
- Baryon asymmetry generated at weak scale (directly or via leptogenesis)
- Examined possible signals at the LHC and in dark matter detection experiments

Back-up slides

Back-up slides

WIMPy leptogenesis: Boltzmann equations

Evolution of the asymmetry in one **component** of the L doublet:

$$\frac{H(m_X)}{z}\frac{dY_X}{dz} = -4s\langle\sigma_{XX\to L_i\psi_i}v\rangle[Y_X^2-(Y_X^{\rm eq})^2] - 2s\epsilon_X\frac{\xi\,Y_{\Delta L_i}}{Y_\gamma}\langle\sigma_{XX\to L_i\psi_i}v\rangle(Y_X^{\rm eq})^2$$
$$-{\rm Br}_X^2\langle\Gamma_S\rangle Y_S^{\rm eq}\left(\frac{Y_X}{Y_X^{\rm eq}}\right)^2 + {\rm Br}_X\langle\Gamma_S\rangle\left(Y_S - {\rm Br}_L\,Y_S^{\rm eq}\right) - \epsilon\frac{\xi\,Y_{\Delta L_i}}{2Y_\gamma}{\rm Br}_X{\rm Br}_L\langle\Gamma_S\rangle Y_S^{\rm eq}$$

$$\frac{H(m_X)}{z}\frac{dY_S}{dz} = -\langle\Gamma_S\rangle Y_S + \langle\Gamma_S\rangle Y_S^{\rm eq}\left[{\rm Br}_L + {\rm Br}_X\left(\frac{Y_X}{Y_X^{\rm eq}}\right)^2\right]$$

$$\frac{H(m_X)}{z\,\eta}\frac{dY_{\Delta L_i}}{dz} = \frac{\epsilon_S}{2}{\rm Br}_L\langle\Gamma_S\rangle\left[Y_S + Y_S^{\rm eq}\left(1-2{\rm Br}_L - {\rm Br}_X\left[1+\frac{Y_X^2}{(Y_X^{\rm eq})^2}\right]\right)\right] + 2s\,\epsilon_X\langle\sigma_{XX\leftrightarrow L_i\psi_i}v\rangle\left[Y_X^2 \right.$$
$$-\frac{\xi\,Y_{\Delta L_i}}{Y_\gamma}\left[s\,\langle\sigma_{XX\leftrightarrow L_i\psi_i}v\rangle(Y_X^{\rm eq})^2 + 2s[\langle\sigma_{L_i\psi_i\leftrightarrow L_i^\dagger\psi_i^\dagger}v\rangle + \langle\sigma^{(i\neq j)}_{L_i\psi_i\leftrightarrow L_j^\dagger\psi_j^\dagger}v\rangle]Y_L^{\rm eq}Y_\psi^{\rm eq}\right.$$
$$-\frac{2\xi\,Y_{\Delta L_i}}{Y_\gamma}s\,\langle\sigma_{L_i\psi_j\leftrightarrow L_j^\dagger\psi_i^\dagger}v\rangle Y_L^{\rm eq}Y_\psi^{\rm eq}$$
$$-\frac{\xi\,Y_{\Delta L_i}}{Y_\gamma}\left[s\,\langle\sigma_{X\psi_i\leftrightarrow XL_i^\dagger}v\rangle Y_X Y_\psi^{\rm eq} + 2s\,\langle\sigma_{\psi_i\psi_i\leftrightarrow L_i^\dagger L_i^\dagger}v\rangle(Y_\psi^{\rm eq})^2 + 2s\,\langle\sigma^{(i\neq j)}_{\psi_i\psi_j\leftrightarrow L_i^\dagger L_j^\dagger}\right.$$
$$+\frac{\epsilon^2\,\xi\,Y_{\Delta L_i}}{4Y_\gamma}{\rm Br}_L^2\langle\Gamma_S\rangle Y_S^{\rm eq}$$

Back-up slides: chemical potential relations

1. The ψ mass: $\mu_\psi = -\mu_{\bar{\psi}}$.
2. The $\mathrm{SU}(2)$ sphalerons: $3\mu_Q + \mu_L = 0$.
3. The up quark Yukawa: $\mu_Q + \mu_H - \mu_u = 0$.
4. The down quark Yukawa: $\mu_Q - \mu_H - \mu_d = 0$.
5. The lepton Yukawa: $\mu_L - \mu_H - \mu_E = 0$.
6. The ψ Yukawa: $\mu_\psi - \mu_H + \mu_\chi = 0$.
7. Hypercharge conservation:
   $\mu_Q + 2\mu_u - \mu_d - \mu_L - \mu_E + (\mu_\psi - \mu_{\bar{\psi}}) \times (n_\psi^{\mathrm{eq}}/n_\gamma^{\mathrm{eq}}) + 2\mu_H/3 = 0$.
8. Conservation of generalized $B + \psi - L - \chi$ symmetry:
   $2\mu_Q + \mu_u + \mu_d - 2\mu_L - \mu_E - \mu_\chi + 2(\mu_\psi - \mu_{\bar{\psi}}) \times (n_\psi^{\mathrm{eq}}/n_\gamma^{\mathrm{eq}}) = 0$.

Back-up slides: chemical potential solutions

$$
\begin{aligned}
\mu_Q &= -\frac{1}{3}\,\mu_L, \\
\mu_u &= \frac{5-19r}{21+84r}\,\mu_L, \\
\mu_d &= -\frac{19+37r}{21+84r}\,\mu_L, \\
\mu_E &= \frac{3+25r}{7+28r}\,\mu_L, \\
\mu_H &= \frac{4+3r}{7+28r}\,\mu_L, \\
\mu_\chi &= -\frac{79-9r}{21+84r}\,\mu_L \\
\mu_\psi &= \frac{13}{3+12r}\,\mu_L,
\end{aligned}
$$

WIMPy leptogenesis: other interactions

- How do **other** interactions change our results?
- Assume that we have accounted for all lepton number violation, but there are new **lepton-number-preserving** DM annihilation modes

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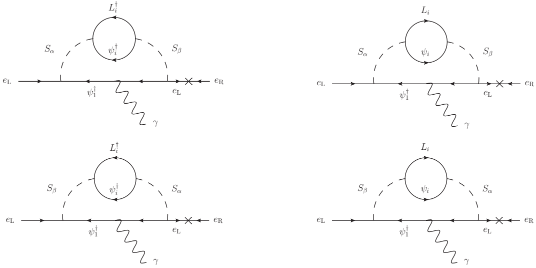
Suppression of asymmetry:

- Fraction of annihilations generating an asymmetry if $1/\alpha$, so $Y_{\Delta B} \to Y_{\Delta B}/\alpha$
- Maximum allowed ϵ is smaller because λ_L is smaller: $\epsilon \to \epsilon/\sqrt{\alpha}$

Constraints and signals: EDMs

- Expect large CP phases to contribute to EDMs $\rightarrow$ CP problem
- New physics couples only to either LH **or** RH fields
  - Loops are helicity-preserving, so equal number of λ and λ^* insertions



$$\frac{d}{e} \sim \sum_i \mathrm{Im}(\lambda_{\alpha 1}\lambda_{\alpha\, i}\lambda^*_{\beta 1}\lambda^*_{\beta i} + \lambda_{\alpha 1}\lambda^*_{\alpha\, i}\lambda_{\beta 1}\lambda^*_{\beta i} + \mathrm{c.c}) = 0$$

- Vanishes when summed over permutations of internal lines!
  - No CP problem $\rightarrow$ $d/e < 10^{-30}$ $\mathrm{e \cdot cm}$