Title: A WIMPy Baryogenesis Miracle

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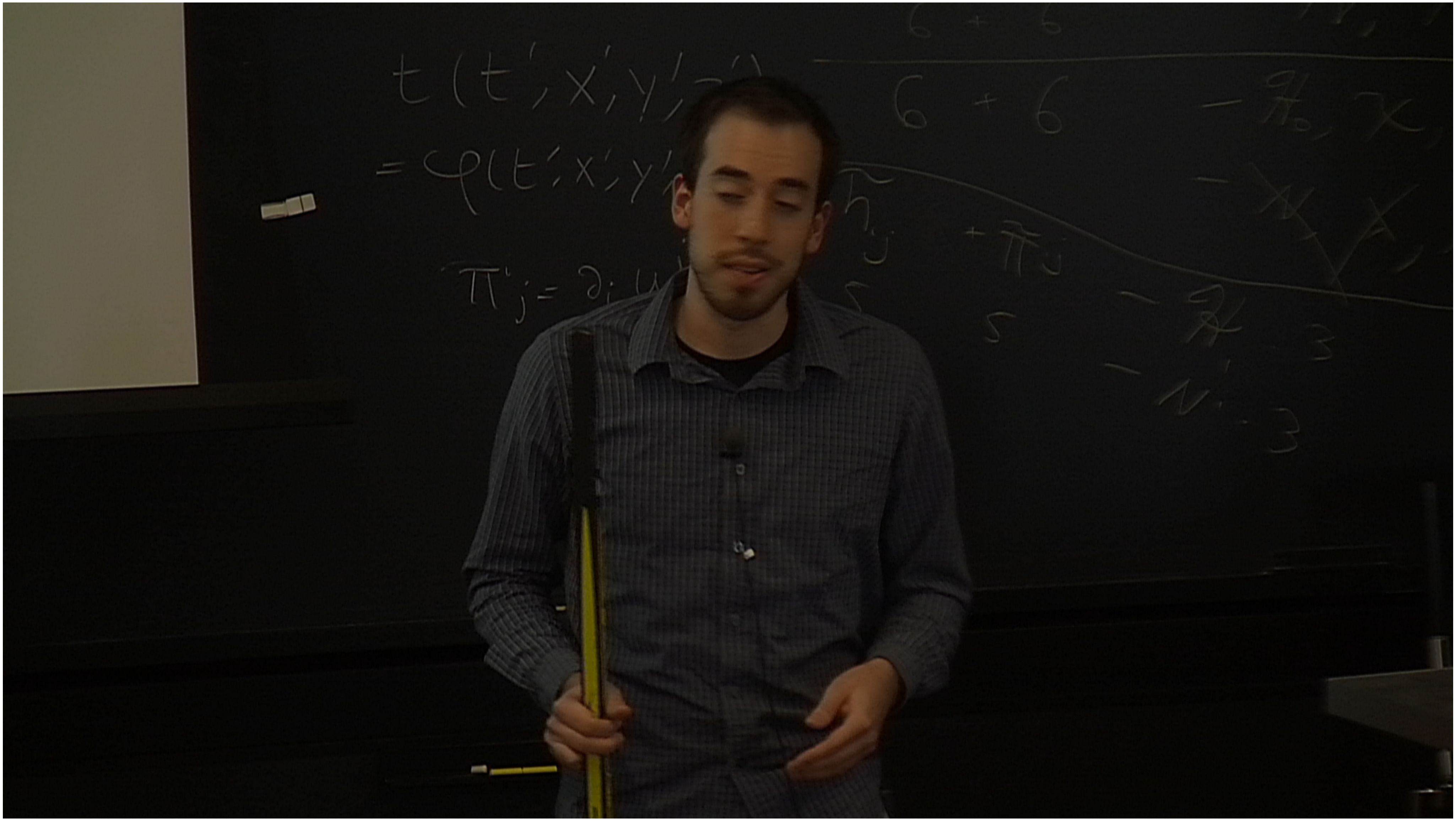
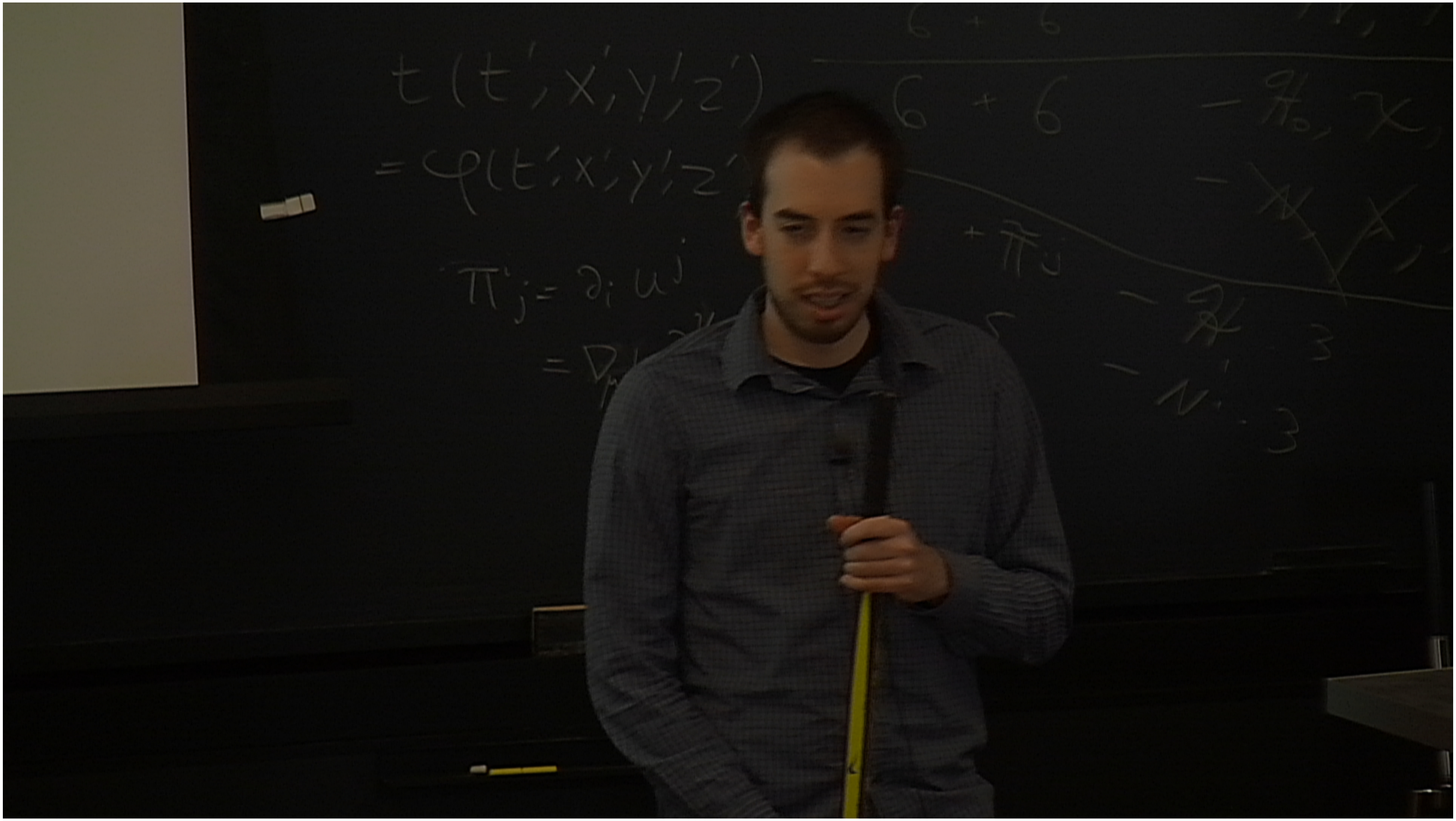
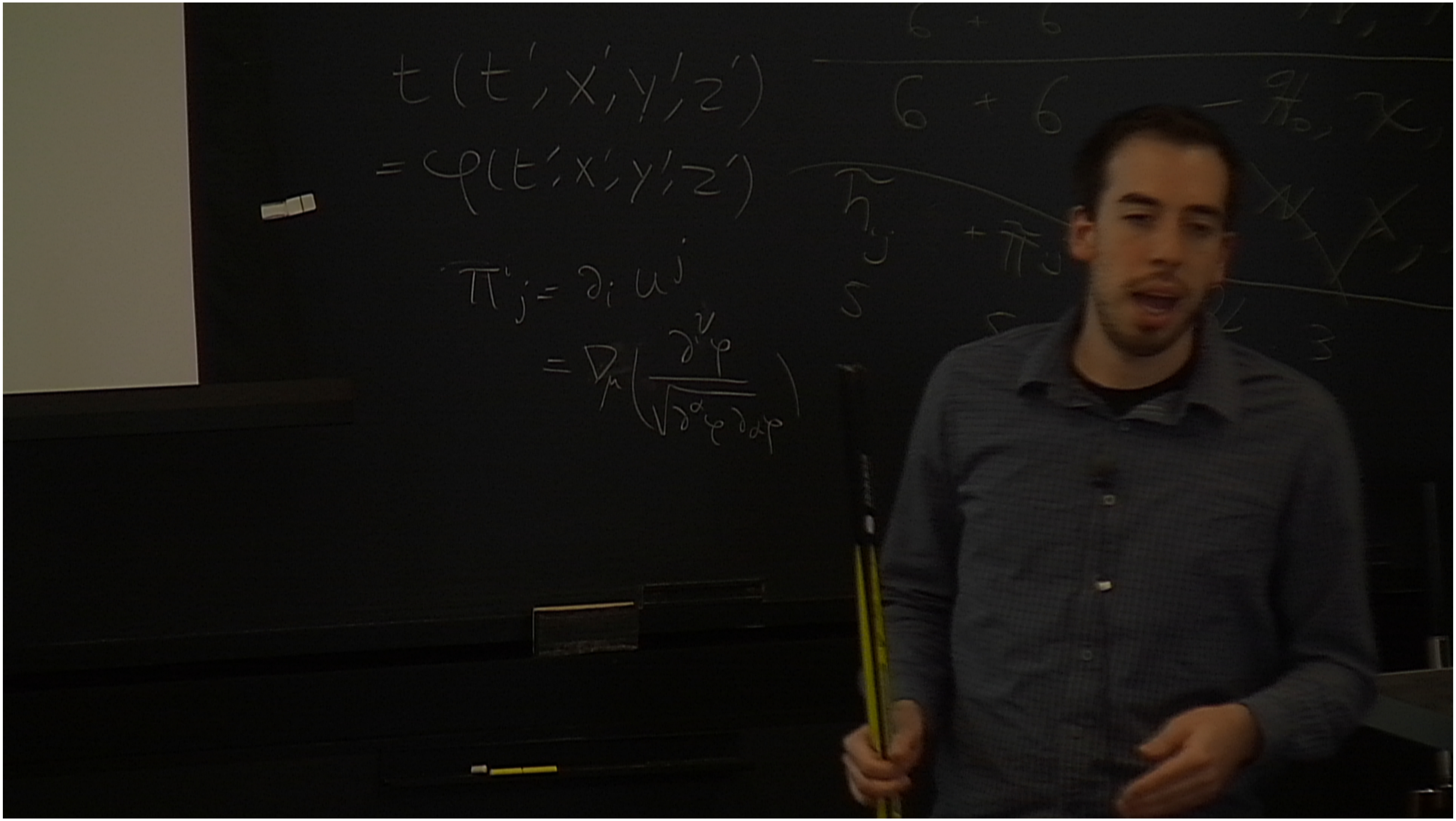
URL: http://pirsa.org/11110060

Abstract: We propose models of symmetric WIMP dark matter in which dark matter annihilations generate the baryon asymmetry. We call this mechanism "WIMPy baryogenesis". This provides a dynamical connection between the late-time abundances of both dark matter and baryons. We construct explicit models of leptogenesis and baryogenesis at the weak scale, and find the "miraculous" result that, for order one couplings and weak scale masses for any new fields, the baryon asymmetry and dark matter relic density from WIMPy baryogenesis match the observed values. We also discuss implications for the LHC and dark matter detection experiments.




t(t',x',y',z')
6 + 6


t(t', x', y', z')
= φ(t', x', y', z')
π^i_j = ∂_i u^j
= D_μ(∂^ν φ / √(∂^α φ ∂_α φ))
6 + 6

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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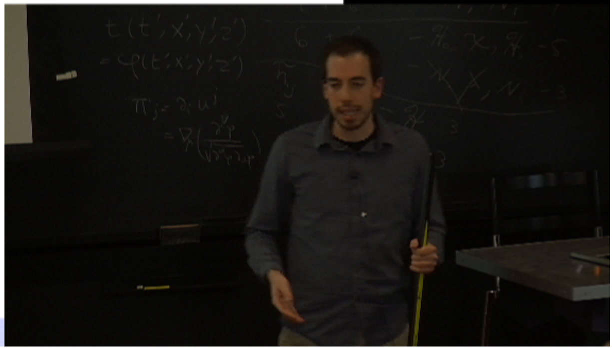


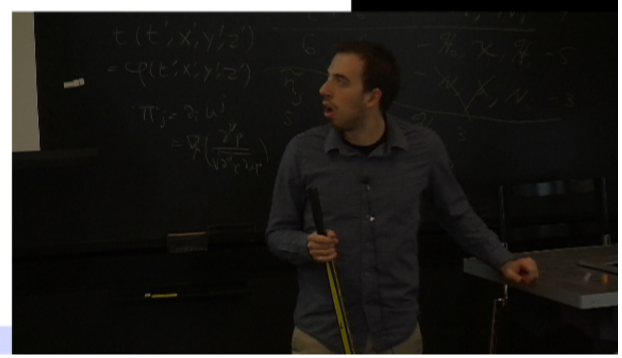
Motivation

- No conclusive evidence to date on the nature of the dark matter particle(s)

- Astrophysical observations hint at possible connections between dark and visible sectors

  1. **Dark matter abundance:** Observed abundance of dark matter is the same as thermal relic density of a particle with weak scale mass and couplings
     - ★ The WIMP miracle

  2. **Dark matter/baryon ratio:** $\Omega_{\mathrm{DM}} \approx 5\,\Omega_{\mathrm{baryon}}$



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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

Motivation: WIMP Miracle

- Consider a stable, weakly interacting massive particle (WIMP)
  - What happens as the universe expands and cools?

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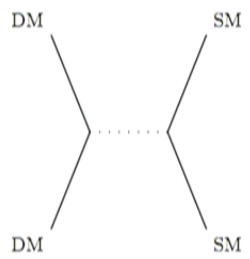
- At $T > m_{\text{WIMP}}$, all fields are in equilibrium
  - Dark matter (WIMP) $\leftrightarrow$ Standard Model (SM) scattering occur at equal rates
- Thermal freeze-out: for $T < m_{\text{WIMP}}$, SM fields are no longer energetic enough to annihilate into WIMPs
  - WIMP density depleted
  - WIMP particles eventually unable to find one another to annihilate



- Relic abundance inversely proportional to annihilation cross section

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

Motivation: dark matter/baryon ratio

- In WIMP miracle framework, $\Omega_{\rm DM} \sim \Omega_{\rm baryon}$ is a coincidence
  - Baryonic matter abundance is determined by a matter-antimatter asymmetry
  - In conventional WIMP picture, asymmetry generation and dark matter annihilation are independent processes
- Models accounting for the dark matter/baryon ratio typically ignore the WIMP miracle
  - Most common explanation is **asymmetric dark matter** (Nussinov 1985; Kaplan, Luty, Zurek 2009; ...)
  - 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?

Motivation: dark matter/baryon ratio

- **WIMPy baryogenesis:**
  - Conventional WIMP thermal relic (abundance given by WIMP miracle)
  - Baryon asymmetry generated by WIMP annihilation
- 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

Review of baryogenesis

- Three Sakharov conditions must be satisfied to generate an asymmetry
  1. Violation of baryon number
  2. Violation of C and CP symmetries
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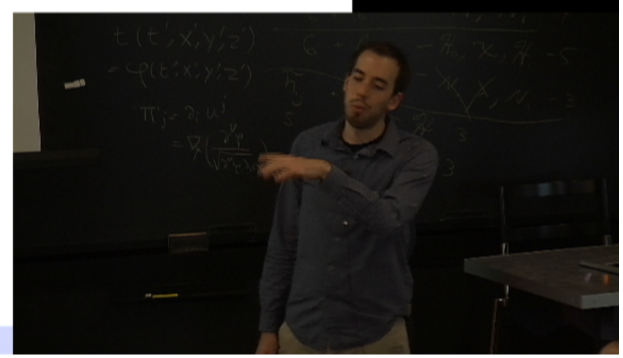

Review of baryogenesis

- Three Sakharov conditions must be satisfied to generate an asymmetry
  1. Violation of baryon number
  2. Violation of C and CP symmetries
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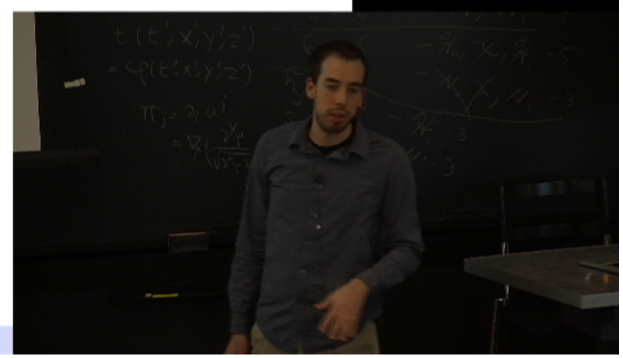
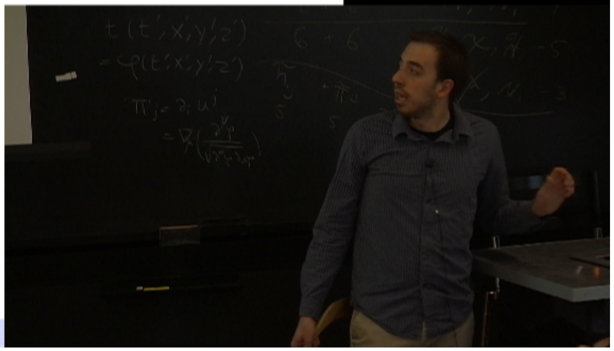
- All three conditions are satisfied in the Standard Model **but**
  - CP violation not big enough (suppressed by 12 Yukawa couplings $\sim 10^{-20}$)
  - Phase transition not first order



Review of baryogenesis

- Many possible mechanisms have been proposed from minimal extensions of the Standard Model
- **Example:** Leptogenesis through the decay of RH Majorana neutrinos
  - Review: Chen, hep-ph/0703087

$$\Delta\mathcal{L} = y_{\nu\, ij}\, L_i H N_j + M_{N\, i}\, N_i N_i \qquad\qquad m_\nu \sim \frac{y_\nu^2\, v^2}{M_N}$$



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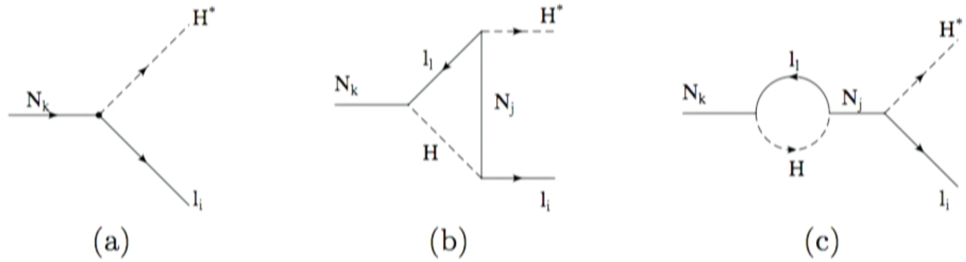
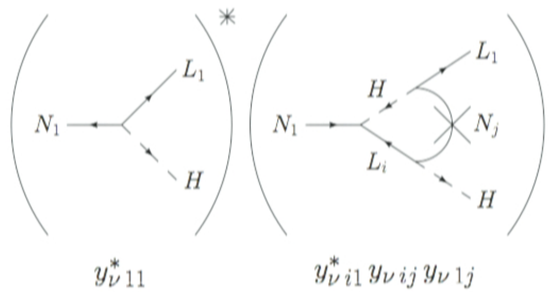
1. *B or L violation:* Majorana mass of RH neutrino violates L, lepton asymmetry transferred to B by sphalerons
2. *CP violation:* CP-violating phases in y_ν

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



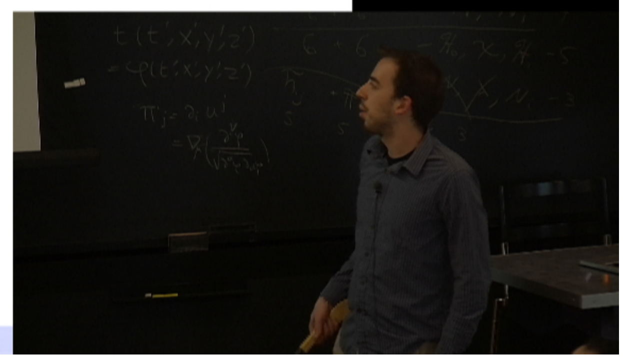
Review of baryogenesis: leptogenesis

- We look at the specific case $N_1 \to L_1\, H$
- CP violation gives a difference rate between $N_1 \to H L_1$ and $N_1 \to H^* L_1^\dagger$



- Define ϵ, the fractional asymmetry produced per decay to L

$$\epsilon \equiv \frac{\Gamma(N_1 \to H L_1) - \Gamma(N_1 \to H^* L_1^\dagger)}{\Gamma(N_1 \to H L_1) + \Gamma(N_1 \to H^* L_1^\dagger)}$$



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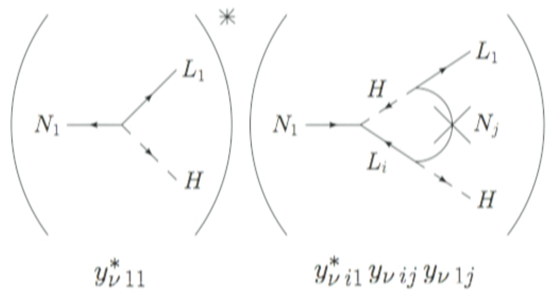

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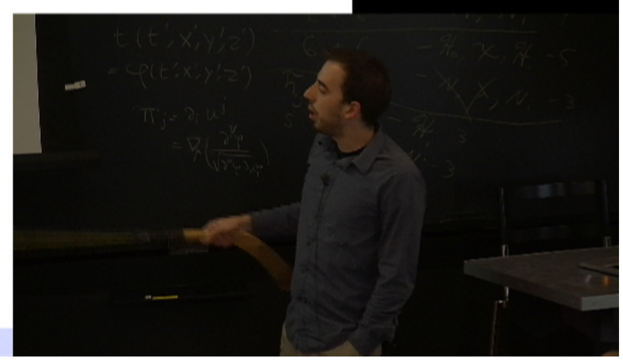
$$\sim \frac{\mathrm{Im}(y^*_{\nu\,11}\, y^*_{\nu\,i1}\, y_{\nu\,ij}\, y_{\nu\,1j})}{|y_{\nu\,11}|^2} \frac{m_{N1}}{m_{Ni}}$$



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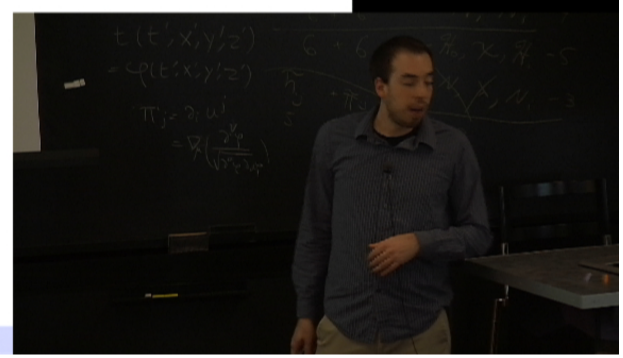

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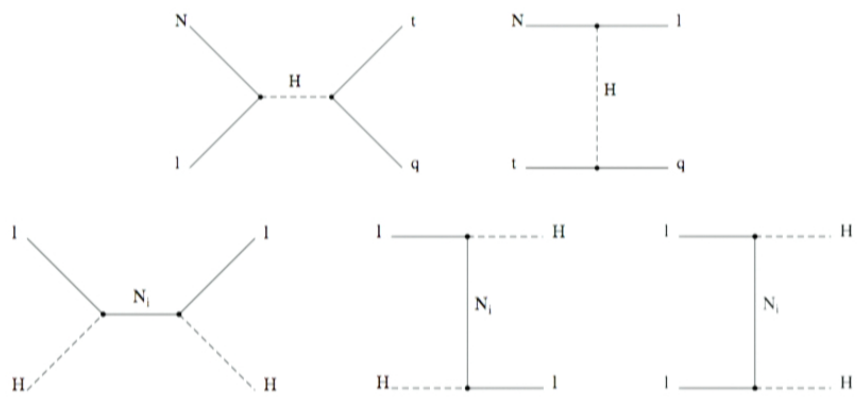
- Two necessary components:
    1. Cooling of universe results in net N decays
    2. **Washout** scatterings must go out of equilibrium



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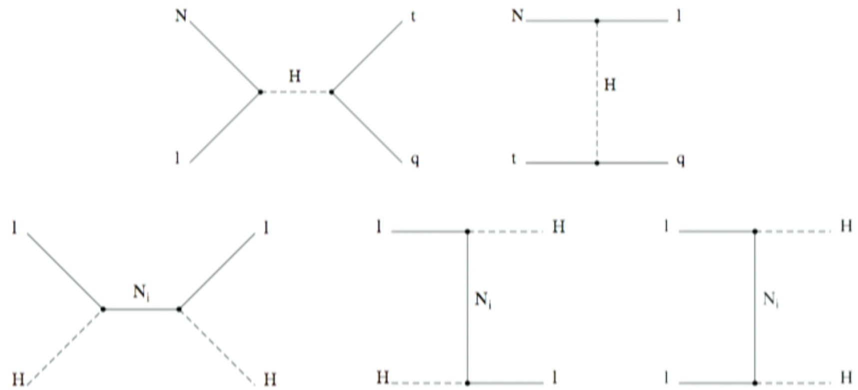

- Decays must occur **after** washout freezes out (at $T \ll m_{N1}$)
  - N_1 lifetime longer than Hubble time at $T = m_{N1}$

WIMPy leptogenesis

Overview of WIMPy leptogenesis

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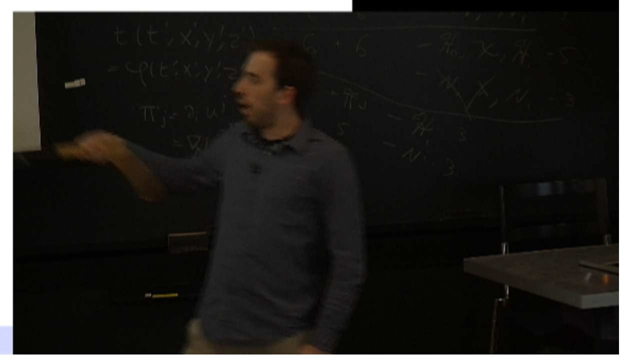
WIMPy leptogenesis: model

- Dark matter annihilates to leptons
- Lepton asymmetry transferred to baryon asymmetry by sphalerons
  - Sphalerons ineffective after electroweak phase transition ($T_c \sim 100$ GeV)
  - **Model-independent constraint:** $T_{\rm lepto} > T_{\rm electroweak} \rightarrow m_X \gtrsim {\rm TeV}$

Minimal set-up:

- Singlet fermion dark matter X
- Dark matter annihilates to lepton doublet field L
- Easiest way to break lepton number: only create one L through annihilation!



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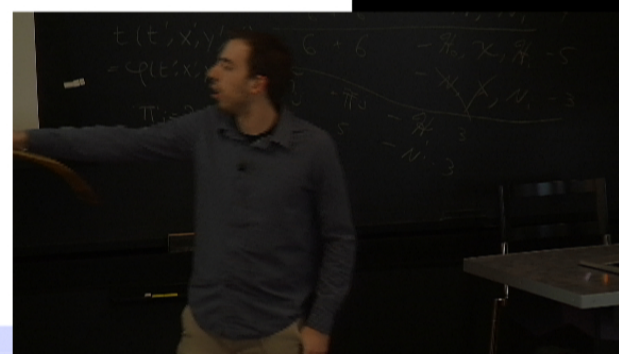

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- New field ψ
  - Gauge invariance $\rightarrow \psi$ is a doublet with hypercharge $+1/2$
  - To allow the widest possible range of masses, take ψ to be vectorlike

WIMPy leptogenesis: model

- What does this interaction tell us about the lepton asymmetry?

$$\Delta\mathcal{L} \sim \frac{1}{\Lambda^2} X^2 L \psi$$

- $\mathrm{U}(1)$ symmetry under which L, ψ oppositely charged
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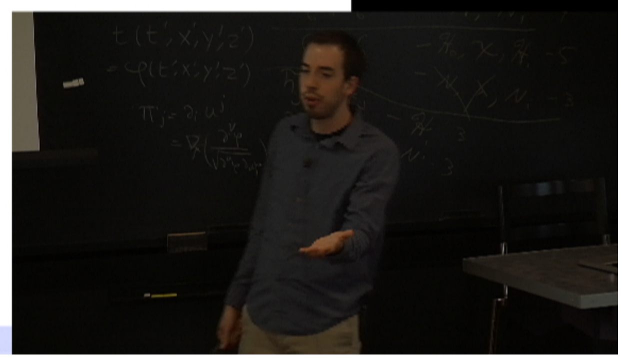
  - No **generalized** lepton asymmetry, but can get a **SM** lepton asymmetry



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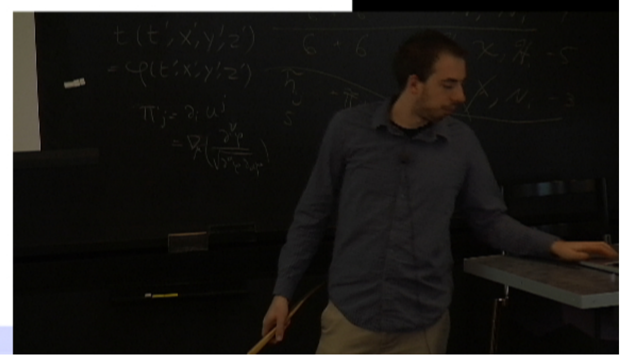

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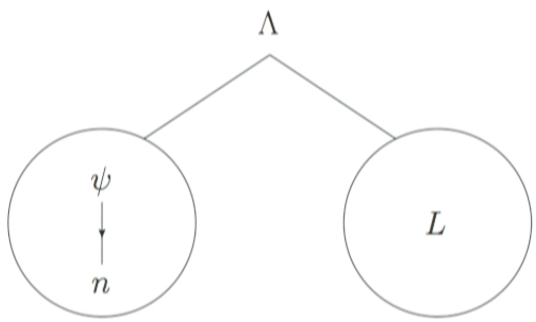
- Two possible solutions:
  1. Two sectors with separately preserved asymmetries
     - ⋆ Simplest ψ decay: $\psi \to H\, n$, where n is a singlet
  2. ψ decays with $\mathrm{U}(1)$-violating couplings

WIMPy leptogenesis: model



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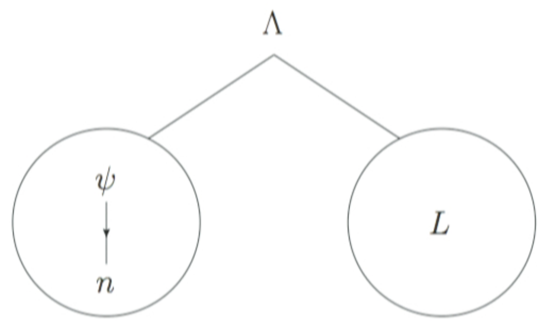
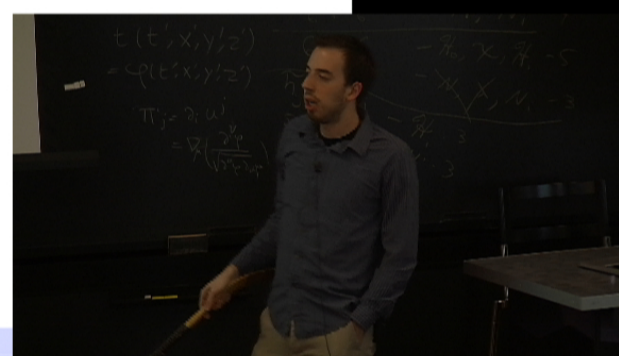


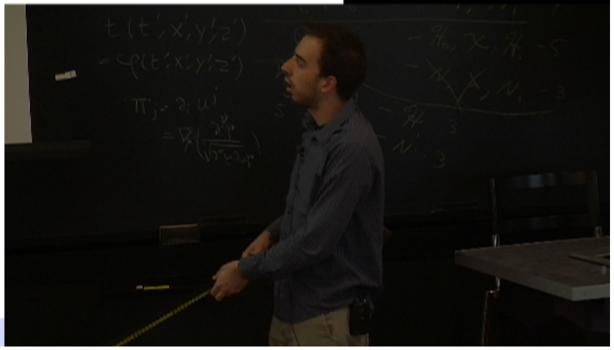
- Also want dark matter stability
- **Minimal solution:** Z_4 symmetry
  - Charge of $X = i$
  - Charge of $\psi = -1$
  - Charge of SM fields $= +1$
- Since X has a Z_4 charge, it must be *Dirac*



WIMPy leptogenesis: model

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

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



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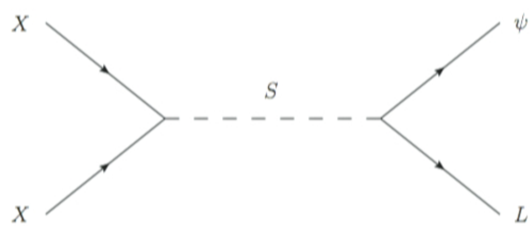
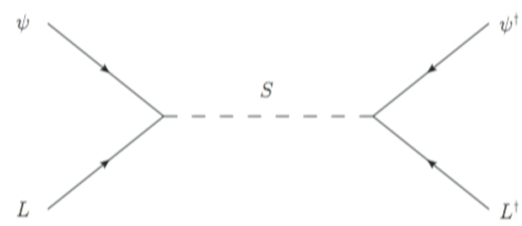
- Annihilation and washout scatterings:

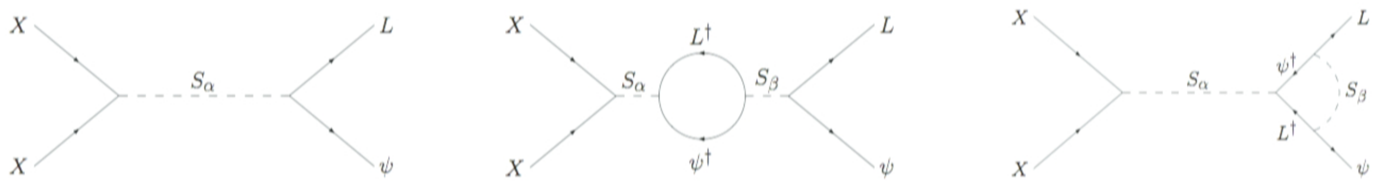




$$\sigma_{\text{ann}} \sim |\lambda_X|^2 |\lambda_L|^2 \qquad \sigma_{\text{washout}} \sim |\lambda_L|^4$$

WIMPy leptogenesis: Sakharov conditions

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

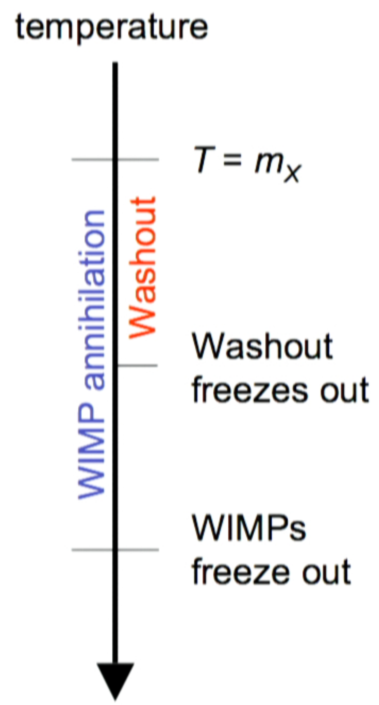


- Must have at least two generations of S for non-zero CP phase in amplitude

WIMPy leptogenesis: Sakharov conditions

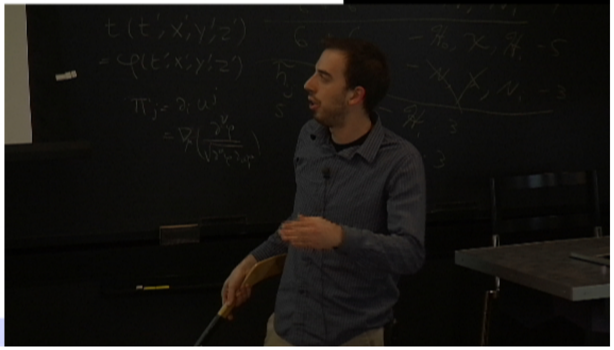
1. Baryon number violation ✓
2. CP violation ✓
3. Departure from thermal equilibrium?

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



WIMPy leptogenesis: evolution

- To determine the asymmetry and WIMP relic abundance, we need to know the evolution of particle abundances and of interaction rates
- Define dimensionless variables:
  - Inverse temperature, $z = m_X/T$
  - Number density per comoving volume, $Y_i(z) = n_i(z)/s(z)$ (s is entropy density)



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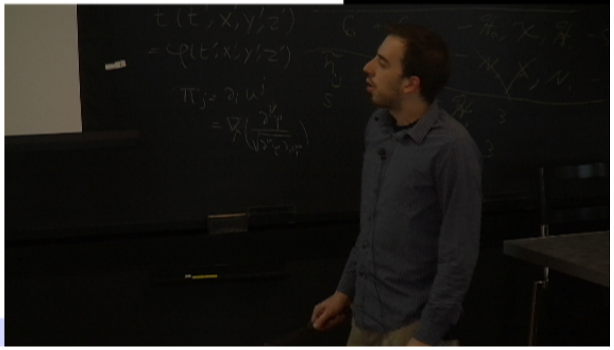
- Initially ($z \lesssim 1$), particles start in equilibrium and follow equilibrium distribution

$$Y_i^{\rm eq} \quad \sim \quad \text{constant} \qquad\qquad (z \ll 1)$$



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  - Number density per comoving volume, $Y_i(z) = n_i(z)/s(z)$ (s is entropy density)
- Initially ($z \lesssim 1$), particles start in equilibrium and follow equilibrium distribution

$$
\begin{aligned}
Y_i^{\mathrm{eq}} &\sim \text{constant} \qquad && (z \ll 1) \\
&\sim z^{3/2}\, e^{-z} && (z \gg 1)
\end{aligned}
$$

WIMPy leptogenesis: evolution

- To determine the asymmetry and WIMP relic abundance, we need to know the evolution of particle abundances and of interaction rates
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$$\begin{aligned} Y_i^{\mathrm{eq}} &\sim \text{constant} & (z \ll 1) \\ &\sim z^{3/2}\, e^{-z} & (z \gg 1) \end{aligned}$$

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

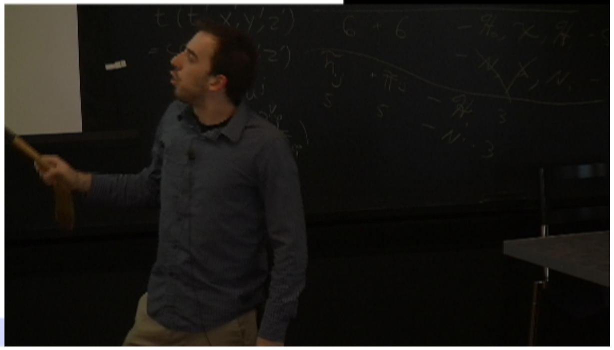
WIMPy leptogenesis: WIMP evolution

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

Boltzmann equations:

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

- Integral over phase space; f_i is phase space density of species i



B. Shuve (Harvard) A WIMPy Baryogenesis Miracle

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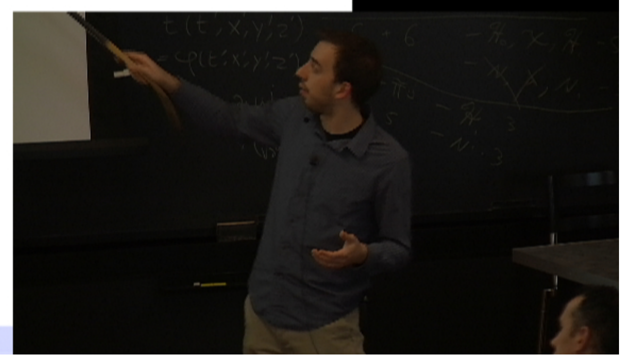

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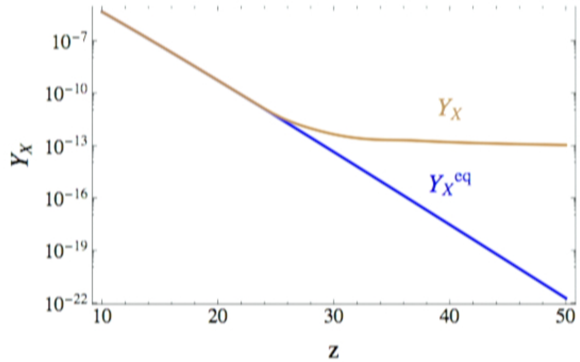
$$\frac{dY_X}{dz} \sim -\langle \sigma_{XX\to L\psi}\, v\rangle \left[Y_X^2 - (Y_X^{\rm eq})^2\right]$$

- 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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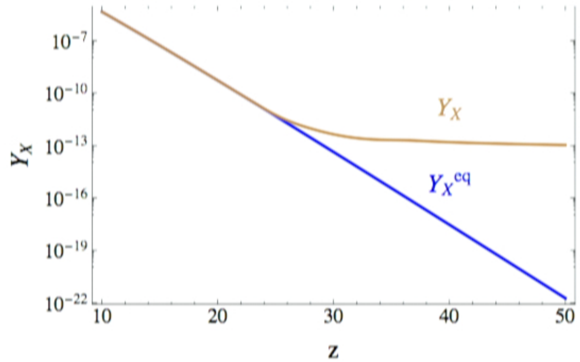

- For $z > 1$, we want $dY_X/dz \approx dY_X^{\rm eq}/dz$ if X tracks its equilibrium distribution
  - This implies a departure of X from thermal equilibrium!
  - Integrating the deviation from equilibrium over z gives ΔY_X, the total number of DM particles annihilated

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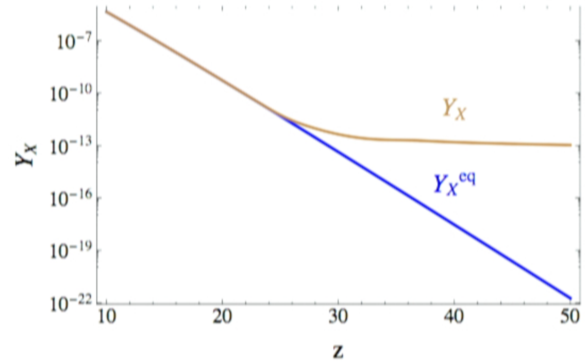

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  - Two important terms:
    - Asymmetry generation by XX annihilation (proportional to fractional asymmetry per annihilation ϵ)
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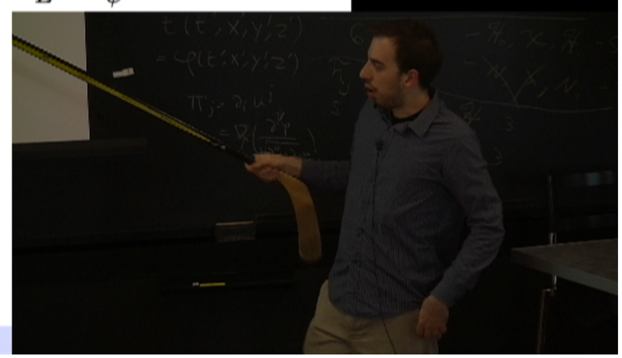
$$\begin{aligned}\frac{dY_{\Delta L}}{dz} &\sim +\epsilon \times (\text{WIMP ann. rate}) - Y_{\Delta L} \times (\text{washout rate}) \\ &\sim -\epsilon \frac{dY_X}{dz} \qquad\qquad\qquad - Y_{\Delta L} \langle \sigma_{L\psi \to L^\dagger \psi^\dagger} v \rangle Y_L^{\text{eq}} Y_\psi^{\text{eq}}\end{aligned}$$



WIMPy leptogenesis: asymmetry

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- While annihilation is occurring, there is competition between asymmetry generation and washout

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- While annihilation is occurring, there is competition between asymmetry generation and washout
  - **Early times:** there is an instantaneous steady-state solution found by balancing the rates of asymmetry creation and depletion

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

    dY_X/dz is decreasing, so asymmetry driven to very small values

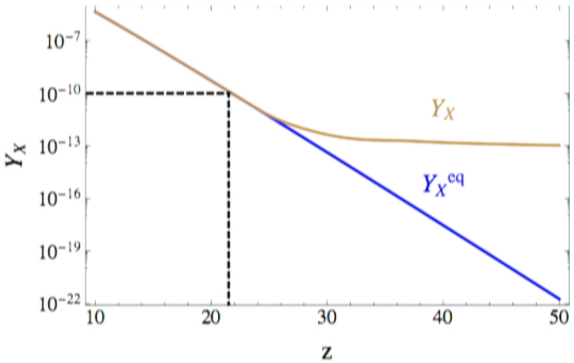
    - Too small for observed baryon asymmetry
  - **Late times:** define z_0 as the time when washout processes freeze out
    - We're left with the equation

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

WIMPy leptogenesis: asymmetry

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

- *Asymmetry proportional to change in X density* **after** *washout processes freeze out*
- 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



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

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

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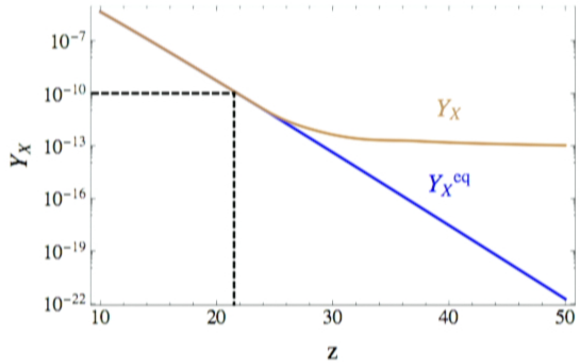

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- Two possibilities for successful baryogenesis:
  1. Heavy m_ψ so that $Y_\psi^{\rm eq}$ is exponentially suppressed
  2. $\langle \sigma_{XX \to L\psi} v \rangle \gg \langle \sigma_{L\psi \to L^\dagger \psi^\dagger} v \rangle$ $(\lambda_X \gg \lambda_L)$

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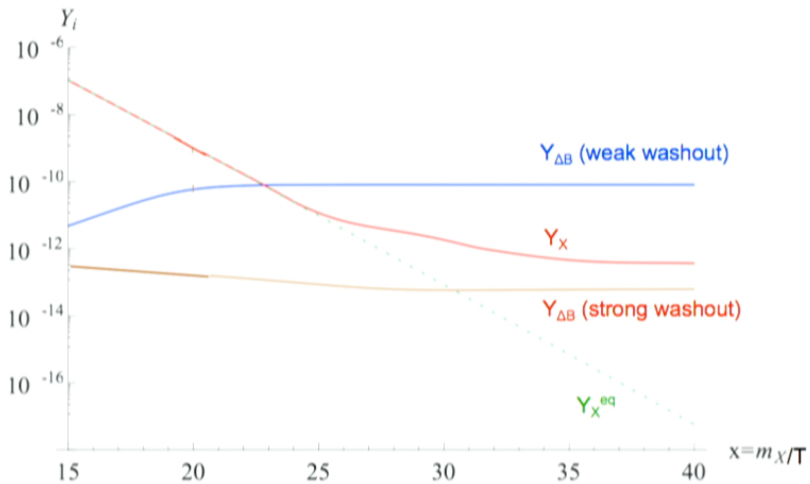
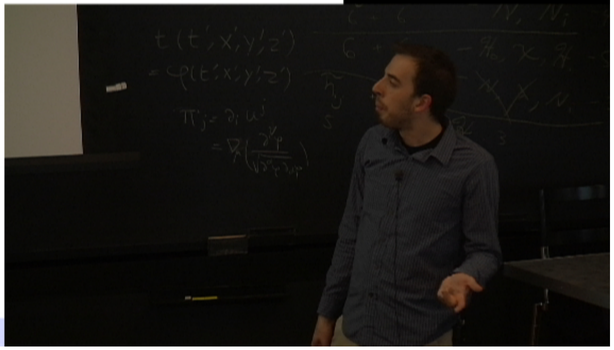


- Washout freezes out before WIMPs $\rightarrow$ **weak washout**
- Washout freezes out after WIMPs $\rightarrow$ **strong washout**

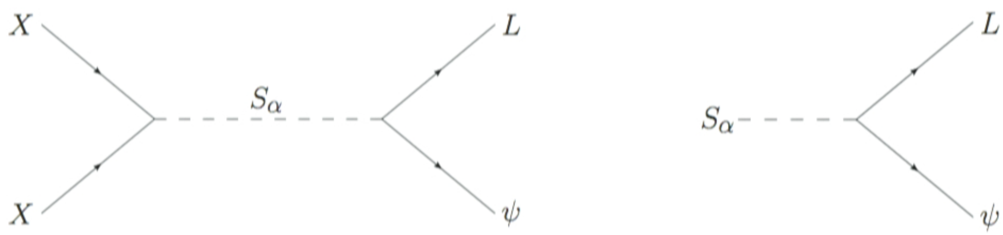
WIMPy leptogenesis

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!



WIMPy leptogenesis: Annihilation vs. decay



- We have asymmetry from S decay and XX annihilation
  - Which is bigger?

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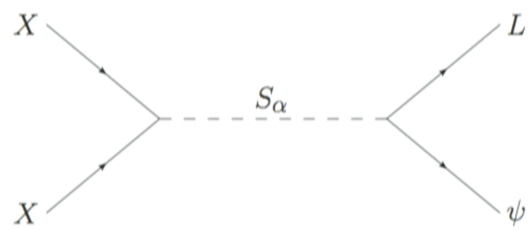

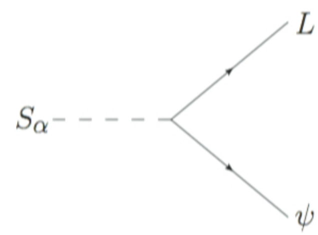

- We have asymmetry from S decay and XX annihilation
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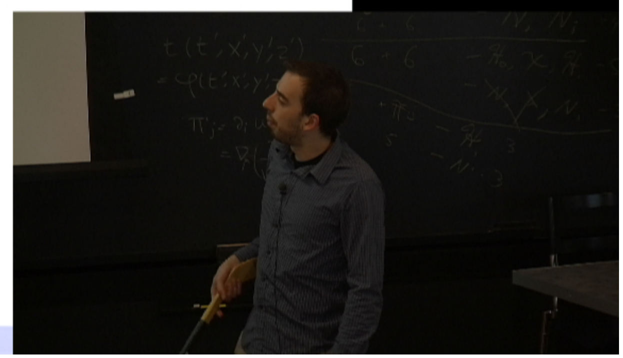
$$Y_{\Delta L}(\infty) \approx \epsilon_X \, Y_X(z_0) + \epsilon_S \, Y_S(z_0)$$



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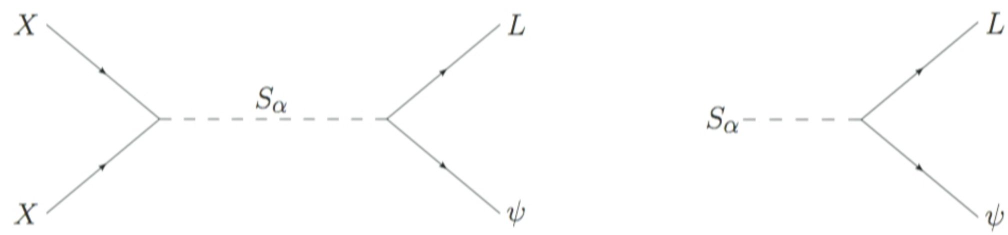

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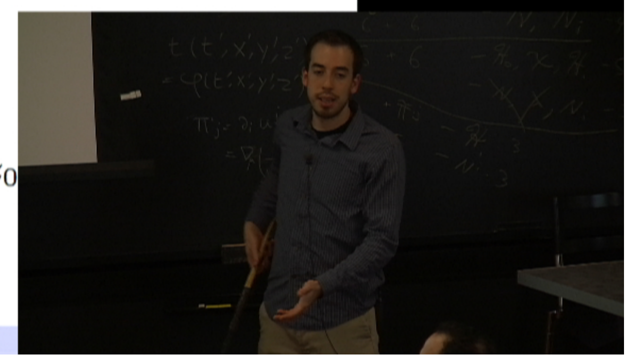
$$Y_{\Delta L}(\infty) \approx \epsilon_X Y_X(z_0) + \epsilon_S Y_S(z_0)$$

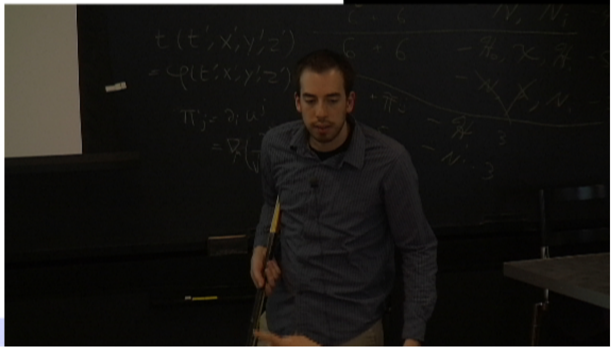
- Requirement for annihilation-dominated:
  - More X than S when washout freezes out: $Y_X(z_0) > Y_S(z_0$
  - $m_X < m_S$



WIMPy leptogenesis: CP-violation

- Define 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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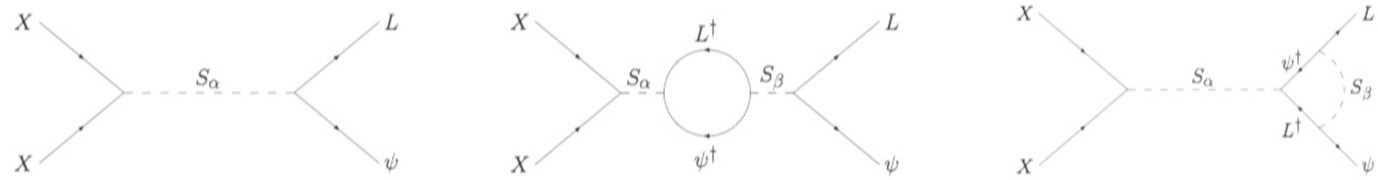
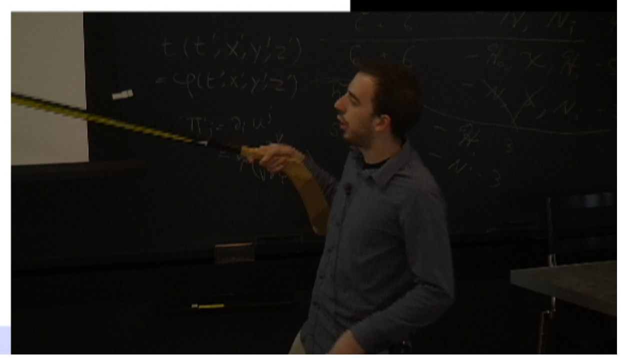


- With these assumptions:

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



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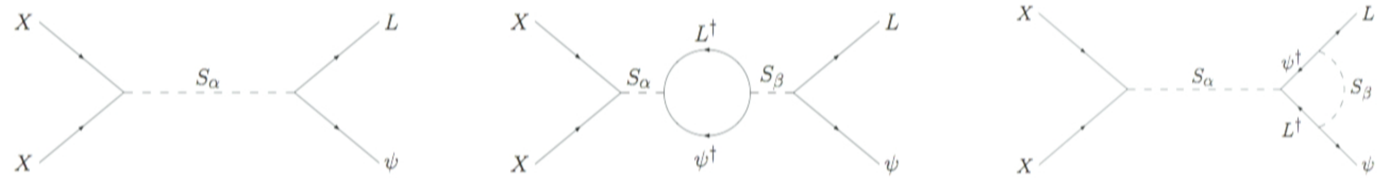

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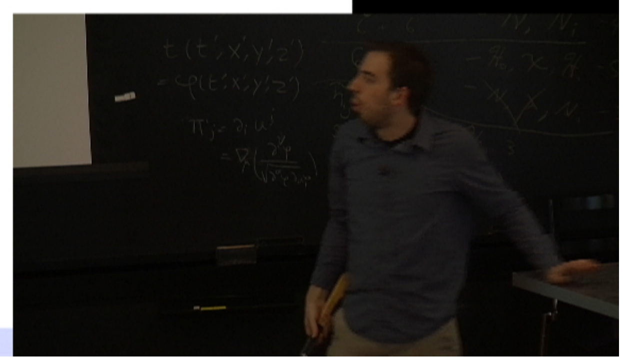

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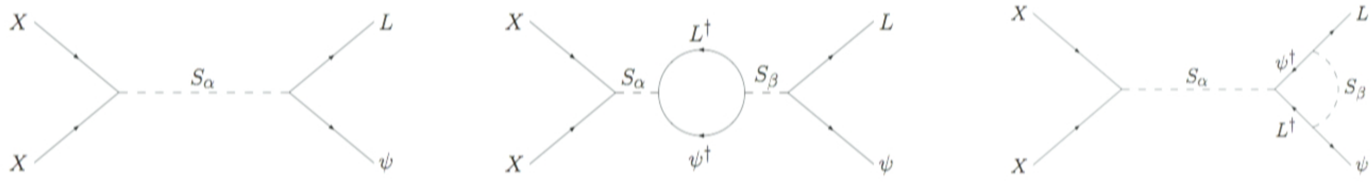

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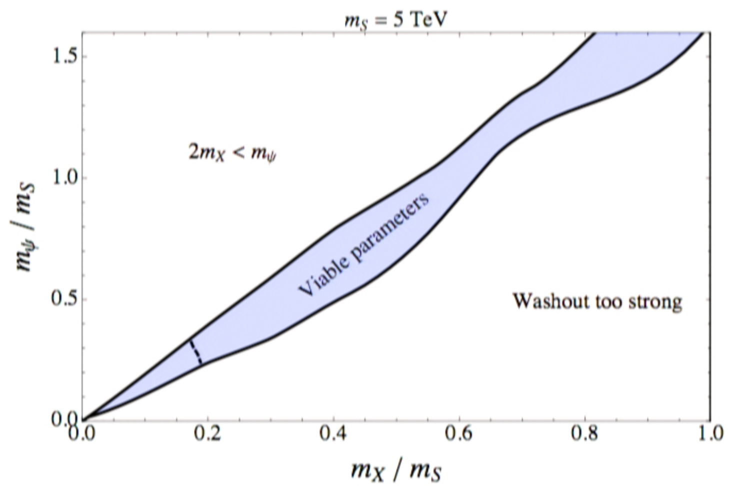
- Masses and couplings of heavy S_α contribute only indirectly through loop effects to ϵ
  - **Use ϵ as a free parameter, subject to bound**

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



- 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

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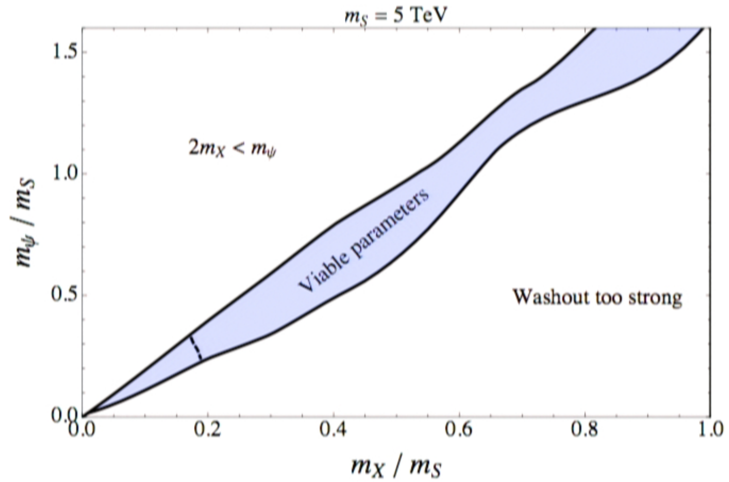

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- Choose points in middle of parameter space:
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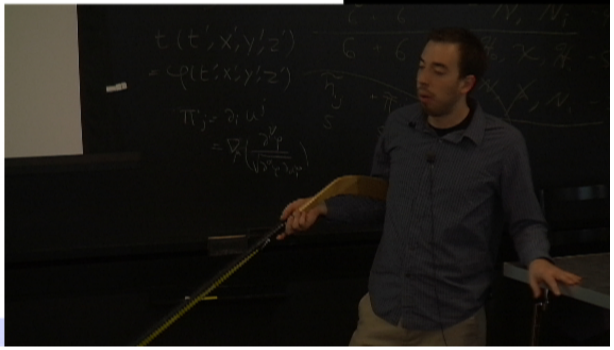
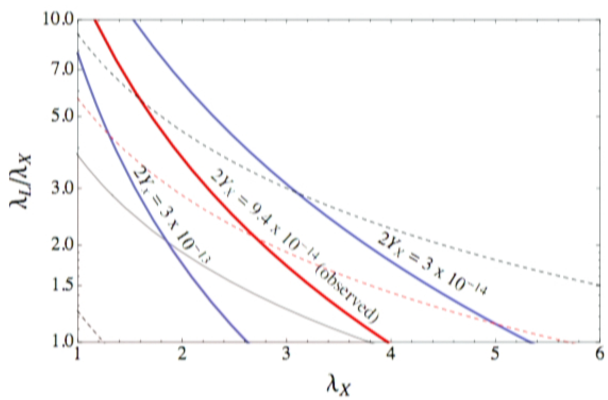


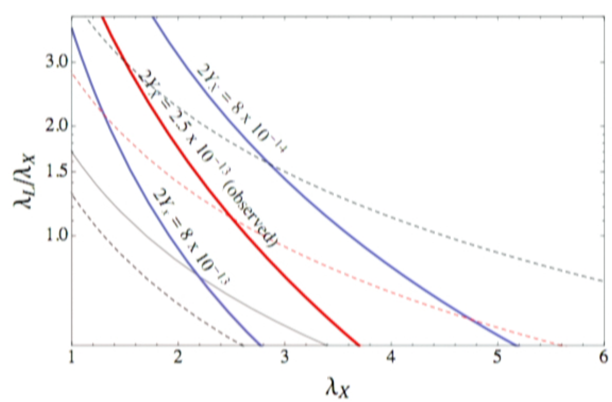
Numerical results: couplings

- Choose points in middle of parameter space:
  - $m_S = 5$ 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 $\epsilon = 0.0075$

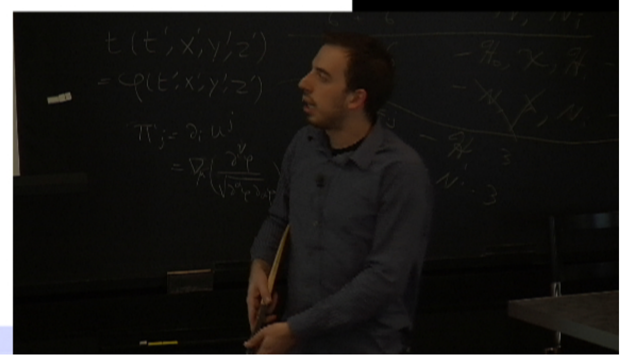




- Solid lines: X relic abundance
- Dotted lines: baryon asymmetry (from top, $Y_{\Delta B} = 3 \times 10^{-11}$, 8.85×10^{-11}, 3×10^{-10})
- Shaded region inconsistent with assumptions

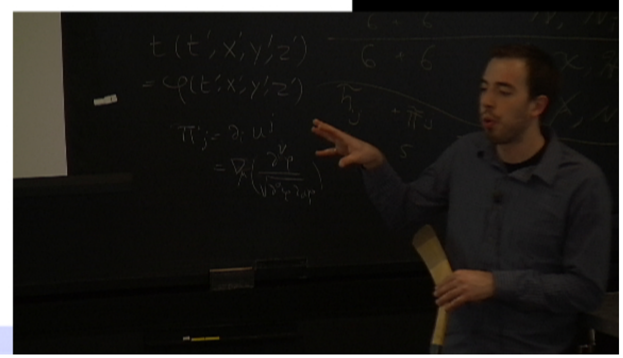
Numerical results

- 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 $\mathcal{O}(1)$
  - 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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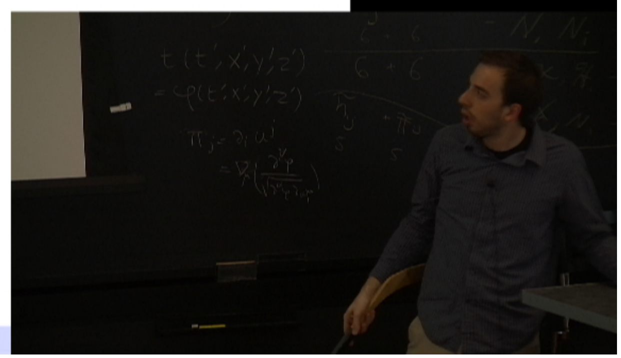

Annihilation to quarks

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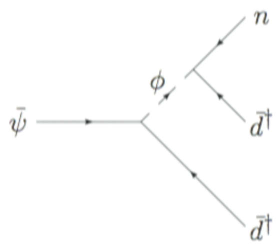
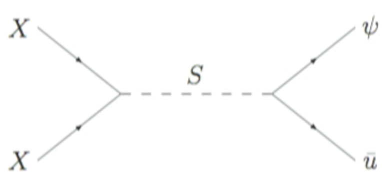
  - WIMP annihilation to up quark $\bar{u}$; ψ is colour triplet with charge $+2/3$
  - ψ can accumulate an asymmetry $\to$ allow ψ to decay



- ψ decays through operator $\bar{\psi}\bar{d}\bar{d}n/\Lambda^2$ to quarks, singlet n
  - ex. decay through coloured scalar ϕ

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



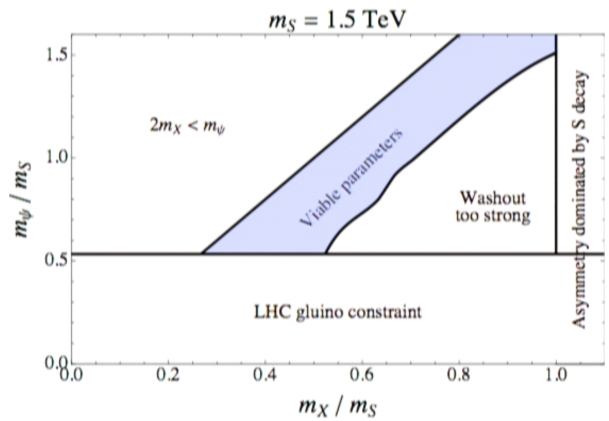
$\sigma_{\text{ann}} \sim |\lambda_X|^2\,|\lambda_B|^2$

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

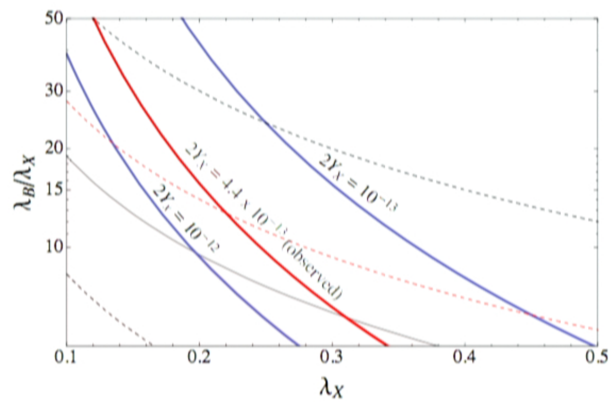
Annihilation to quarks: numerical results

- 6 parameters: m_X, m_ψ, m_S, λ_X, λ_B, and ϵ
- ψ is coloured $\to$ strong collider bounds!
  - $m_\psi \gtrsim 800$ GeV
  - $m_X \gtrsim 400$ GeV

$m_S = 1.5$ TeV

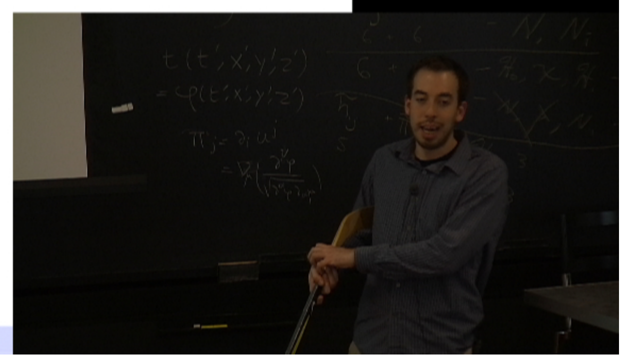


$m_S = 1.5$ TeV, $m_X = 0.9$ TeV,
$m_\psi = 1.3$ TeV, $\epsilon = 0.075$



Constraints and signals: colliders

- In general, phenomenology is model-dependent

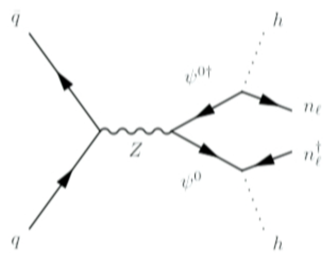


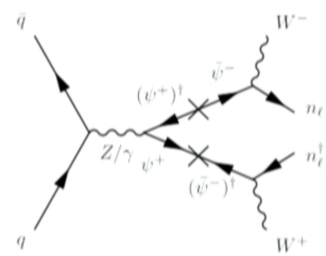
Constraints and signals: colliders

- In general, phenomenology is model-dependent
- In both scenarios we considered, ψ decays to gauge singlets
  - Expect signatures with missing energy (SUSY searches apply)

Leptogenesis:

$$\mathcal{L} \supset \lambda'_i \, \psi \, n \, H^\dagger$$





- Strongest bound comes from chargino searches at LEP ($m_\psi \gtrsim 100$ GeV)
  - $\tilde{\chi}^\pm \to W^\pm \, \tilde{\chi}^0 \to jj \, \tilde{\chi}^0$

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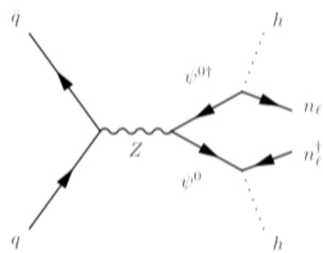

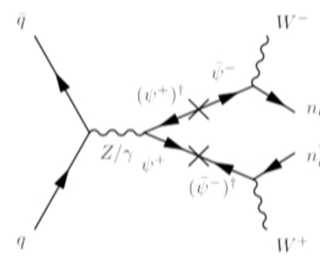

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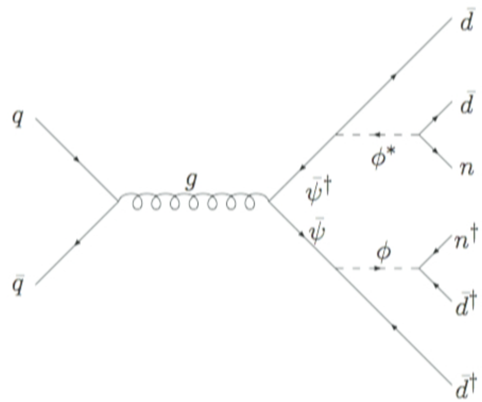
  - $\tilde{\chi}^\pm \to W^\pm \, \tilde{\chi}^0 \to jj \, \tilde{\chi}^0$
- LHC not yet sensitive to electroweak production
  - May be able to find in targeted searches: b-tagging, reconstruct Higgs mass

Constraints and signals: colliders

Annihilation to quarks:



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

- Gluino-like topology with different group theory factors
- $4j + \not{E}_{\mathrm{T}}$ final state
- Current LHC bound excludes $m_\psi \lesssim 800$ GeV

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

Constraints and signals: indirect detection

Annihilation to leptons:

- 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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- Mass constraint reach $\mathcal{O}(100\ \text{GeV})$

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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 $m_X \sim m_\psi$
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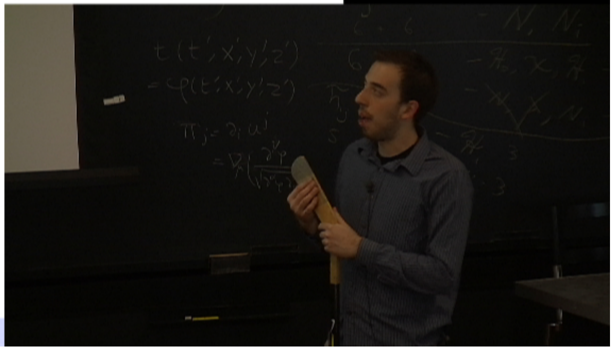

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