Title: Baryogenesis from WIMPs

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Abstract: We propose a robust, unified framework, in which the similar baryon and dark matter cosmic abundances both arise from the physics of weakly interacting massive particles (WIMPs), with the rough quantitative success of the so-called â€œWIMP miracleâ€•. In particular the baryon asymmetry arises from the decay of a meta-stable WIMP after its thermal freezeout at or below the weak scale. A minimal model and its embedding in R-parity violating (RPV) natural SUSY are studied as examples. The new mechanism saves RPV SUSY from the potential crisis of washing out primordial baryon asymmetry. We also consider the embedding of this idea in RPV split SUSY, where the mechanism works within the minimal model, and independently motivates the mini-split scale. Phenomenological implications for the LHC and precision tests are discussed.

# Baryogenesis from WIMPs

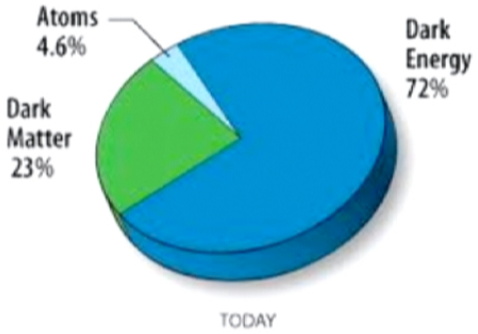
Yanou Cui
University of Maryland

- Phys.Rev.D, 87,11603 (arXiv:1212.2973), YC and Raman Sundrum
- arxiv:1309.2952,YC

# Baryon, Dark Matter

Accurate measurements of cosmic microwave background

Cosmic Pie Chart:

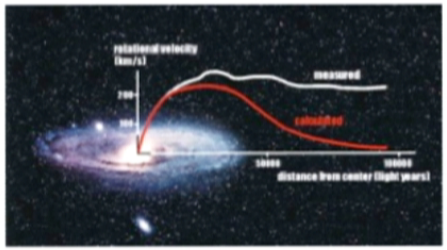



- Focus of this talk:

Baryon (atomic matter) $\Omega_B \approx 4\%$

& Dark matter

$\Omega_{DM} \approx 23\%$




& Coincidence/Similarity: $\Omega_{DM} \sim \Omega_B$

# Dark matter

- **Dark matter:** Stable, neutral,

  $\notin$ Standard Model particles ⇒ New physics!?

- **Origin of masses:** Higgs mechanism, Planck-electroweak Hierarchy problem

  ⇒ New physics at weak scale ( ~ TeV )

  ⇒ **Paradigm: WIMP dark matter**

  **(Weakly Interacting Massive Particle)**

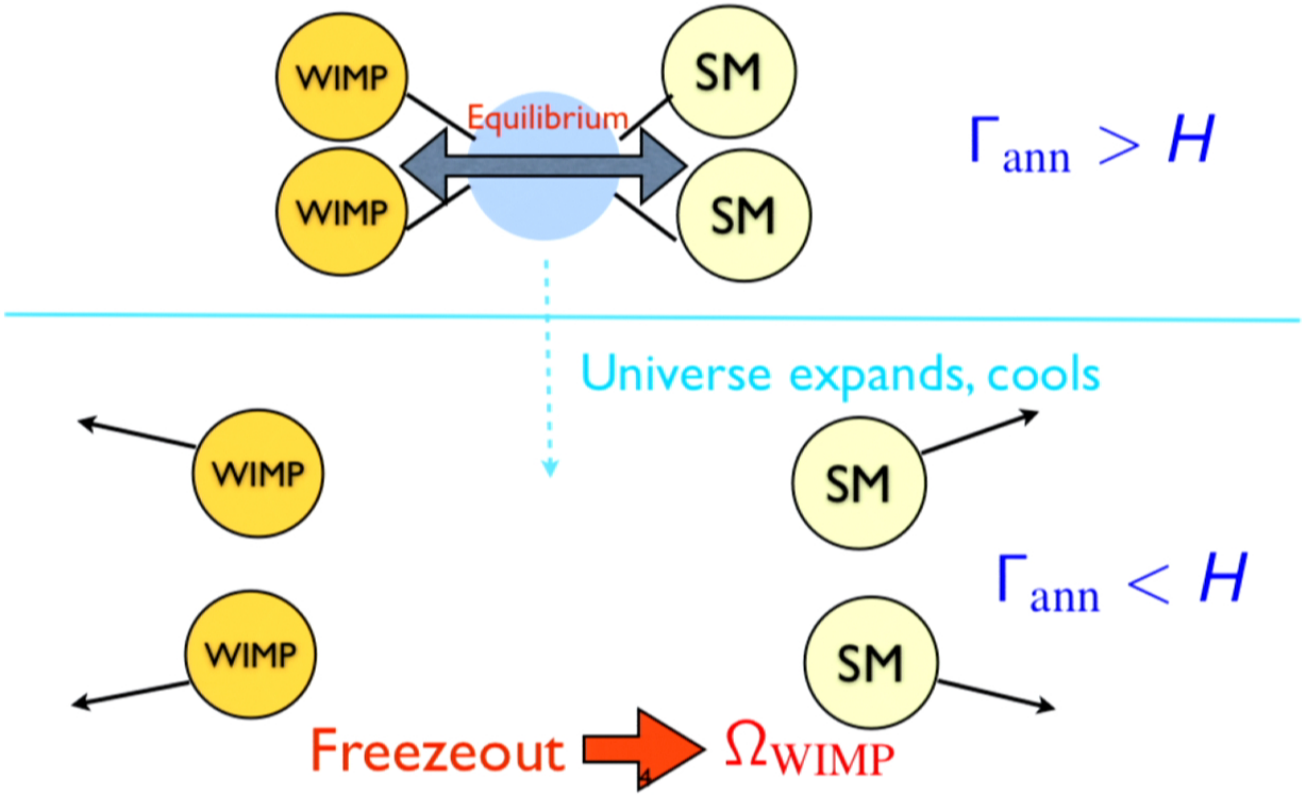
  Well motivated candidates, experimentally detectable

  Ex.: Neutralino LSP in SUSY

# Relic abundance of WIMP DM

## (general, independent of SUSY)

- Thermal freezeout of WIMP DM:



# WIMP Miracle

-- Crude quantitative success of WIMP DM in general

- A thermal WIMP $\chi$ freezes out around $T_f \sim \frac{1}{20} m_\chi$,

$$\Omega_\chi \simeq 0.1 \frac{\alpha^2_{\rm weak}/({\rm TeV})^2}{\langle \sigma_{\rm A} v \rangle}$$

$$\simeq 0.1 \left(\frac{g_{\rm weak}}{g_\chi}\right)^4 \left(\frac{m^4_{\rm med}}{m^2_\chi \cdot {\rm TeV}^2}\right)$$

⇒ Can readily fit $\Omega_{\rm DM} \approx 23\%$, **WIMP miracle!**

Remarkable quantitative success, but **NOT PRECISE**: natural **range** up to $g_\chi$, $m_{\rm med}$ etc.

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# Baryons $\Omega_B \approx 5\%$

Asymmetric abundance: $B$ **excess** over $\bar{B}$

$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

## Baryogenesis: intricate, puzzling

- (Necessary) *Sakharov conditions*: ~~$CP$~~, ~~$\not{B}$~~, out of equilibrium
- Suppress *"washout effect"*: persistent $\not{B}$ interactions ($B \to \bar{B}$) during/after baryogenesis, threat to Baryogenesis efficiency!
- **When? How?** various mechanisms:

  GUT baryogenesis, leptogenesis, EW sphalerons... (typically $T \gtrsim T_{EW}$ )

**RECAP:** $\Omega_B$ , $\Omega_{DM}$ apparently from separate mechanisms, at separate scales...

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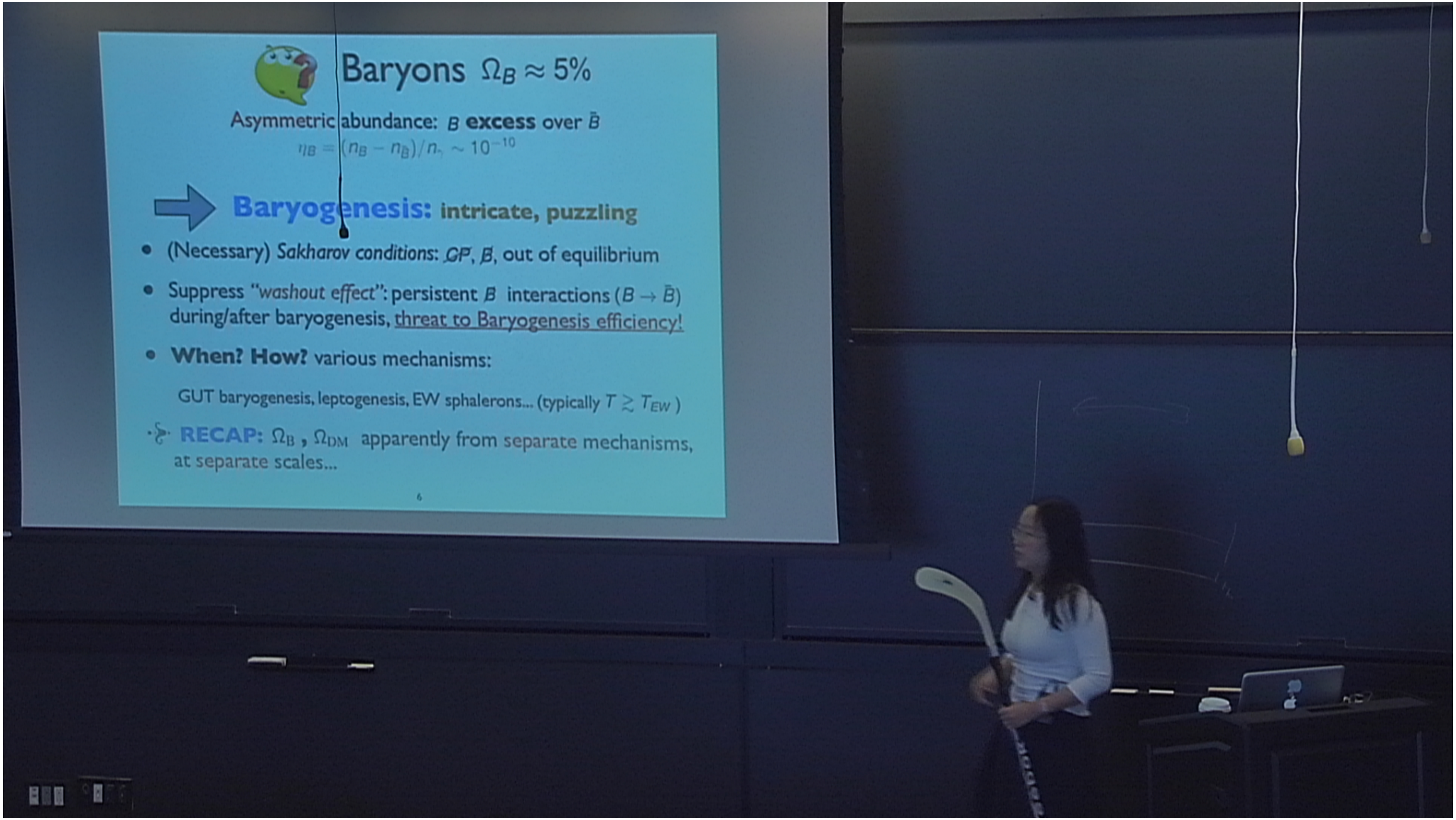
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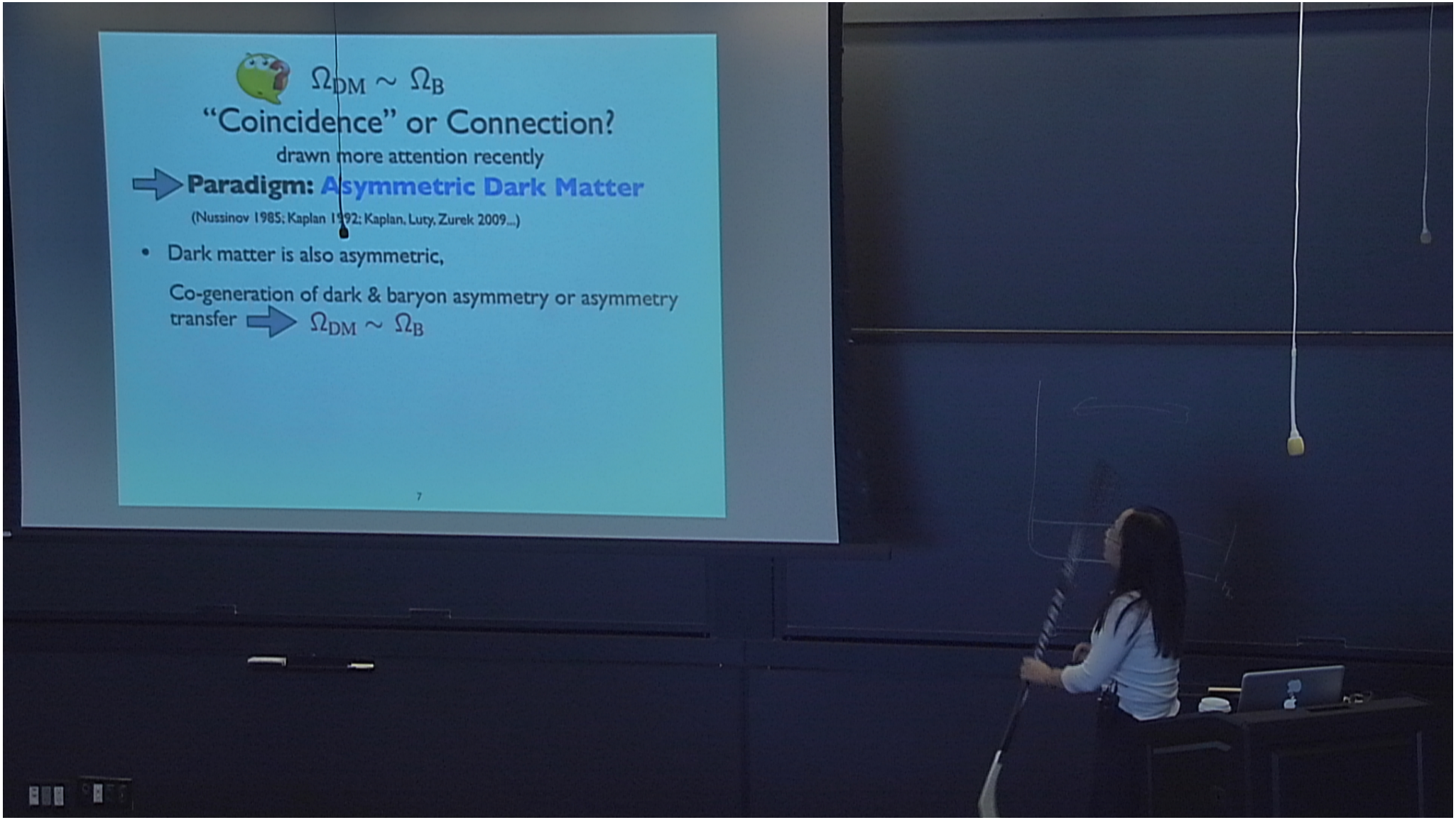
$\Omega_{DM} \sim \Omega_B$
"Coincidence" or Connection?
drawn more attention recently
Paradigm: Asymmetric Dark Matter
(Nussinov 1985; Kaplan 1992; Kaplan, Luty, Zurek 2009...)
• Dark matter is also asymmetric,
Co-generation of dark & baryon asymmetry or asymmetry transfer
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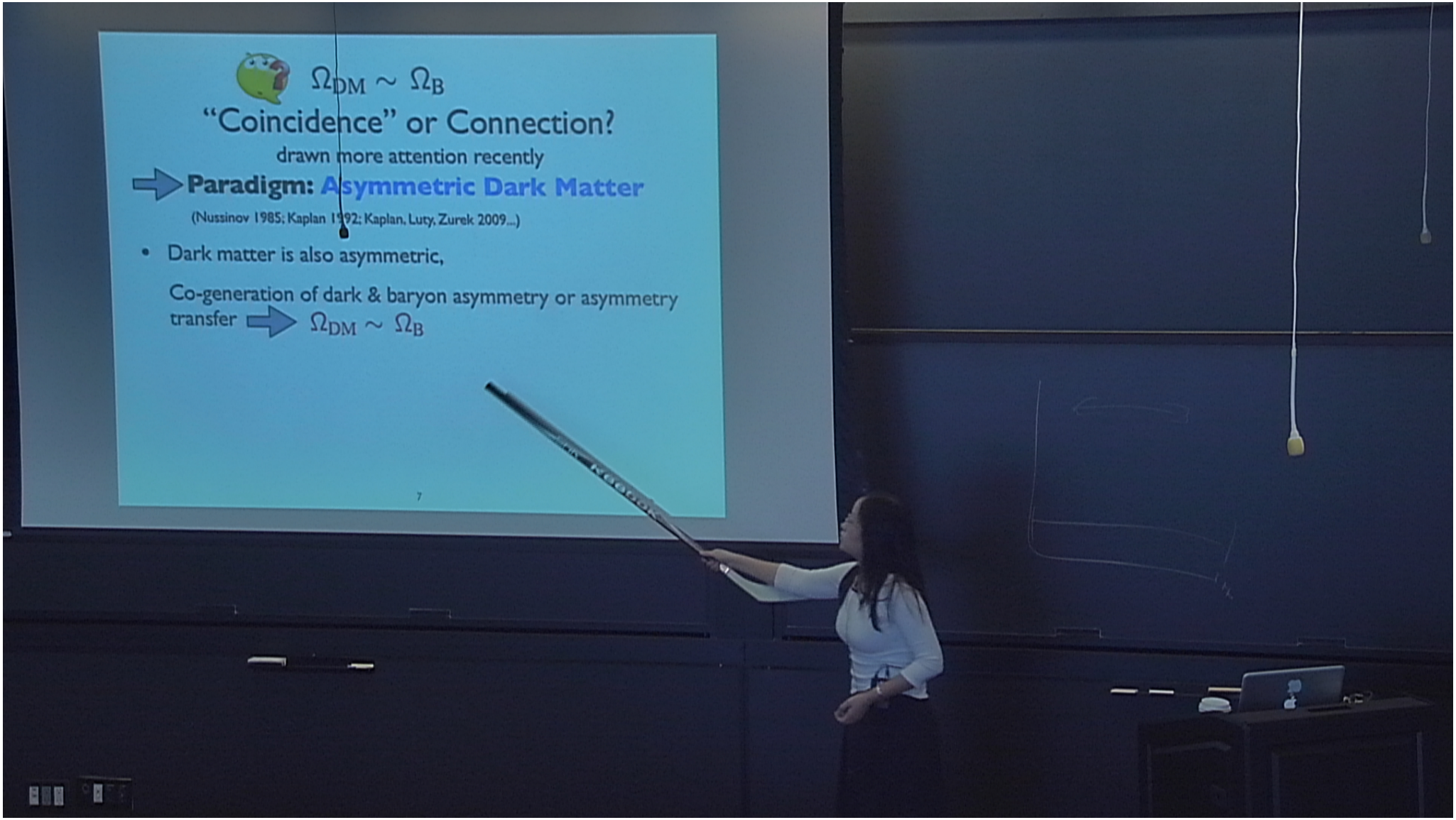
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# Summary: scorecard of existing paradigms

| | $\Omega_{DM}$ | $\Omega_B$ | $\Omega_B \sim \Omega_{DM}$ |
|---|---|---|---|
| WIMP Miracle DM | ✓⁻ | ✗ | ✗ |
| Baryogenesis | ✗ | ✓⁻⁻ | ✗ |
| Asymmetric DM | ✗ | ✗ | ✓⁻ |
| **?unified paradigm?** | ✓⁻ | ✓⁻ | ✓⁻ |

✓⁻ : readily at right ballpark of observation, yet NOT PRECISE

✓⁻⁻ : can FIT observed value, but no typical ballpark of prediction

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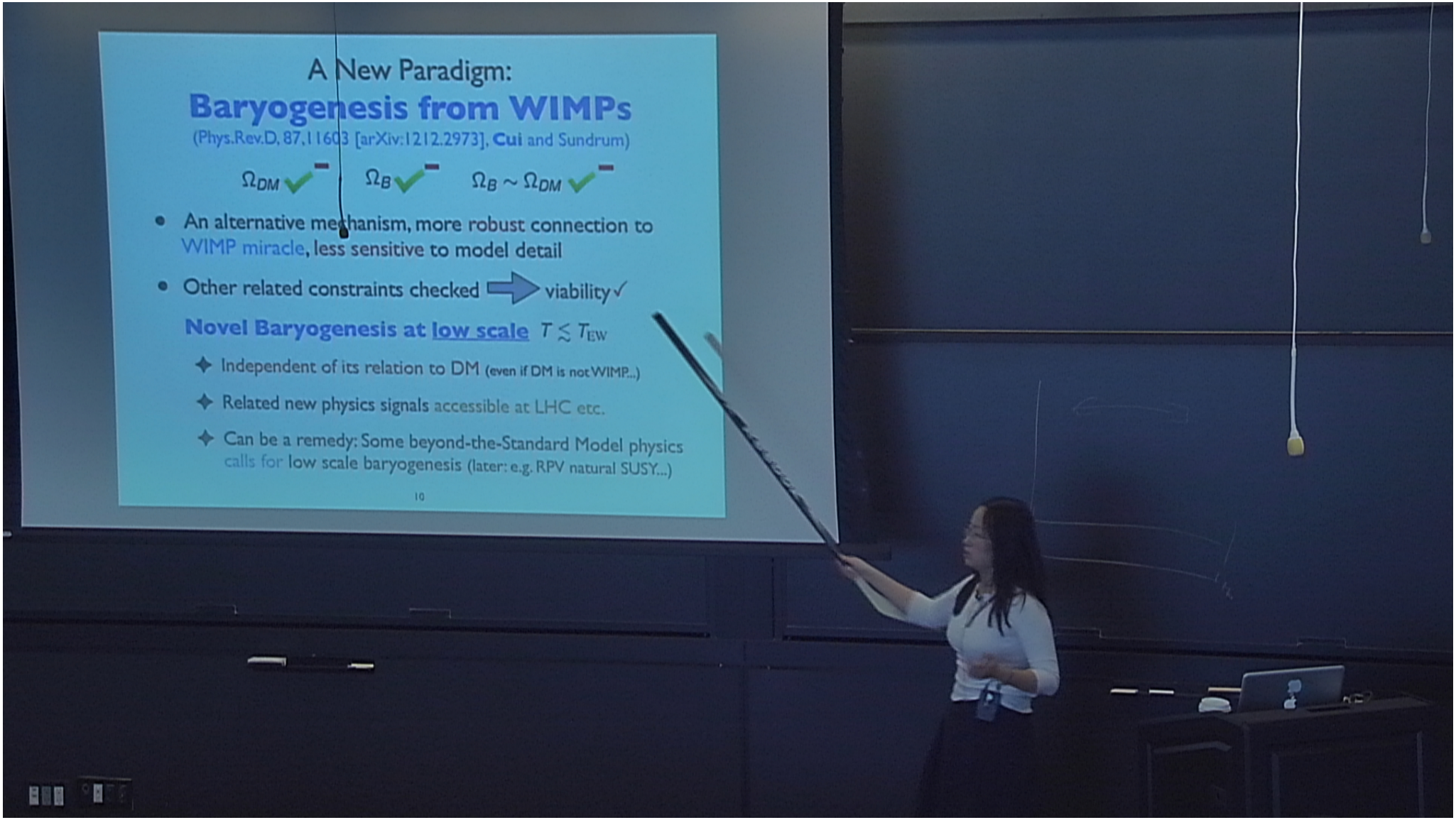
# The goal and challenge for getting

$\Omega_{DM}$ ✓ − $\Omega_B$ ✓ − $\Omega_B \sim \Omega_{DM}$ ✓ −

➡ WIMP miracle + $\Omega_{DM} \sim \Omega_B$ in a natural way

A few attempts made, only very recently, but all have sensitivity to model detail (washout, long lifetime...), tuning

- McDonald, Phys. Rev. D 83, 083509 (2011)
- **Cui**, Randall and Shuve, JHEP1204, 075 (2012): novel baryogenesis triggered by WIMP DM annihilation around freeze-out time
- Davidson and Elmer, JHEP1210, 148 (2012)


A New Paradigm:
Baryogenesis from WIMPs
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$\Omega_{DM}$ ✓ $\Omega_B$ ✓ $\Omega_B \sim \Omega_{DM}$ ✓
An alternative mechanism, more robust connection to WIMP miracle, less sensitive to model detail
Other related constraints checked → viability ✓
Novel Baryogenesis at low scale $T \lesssim T_{EW}$
Independent of its relation to DM (even if DM is not WIMP...)
Related new physics signals accessible at LHC etc.
Can be a remedy: Some beyond-the-Standard Model physics calls for low scale baryogenesis (later: e.g. RPV natural SUSY...)
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# A New Paradigm:

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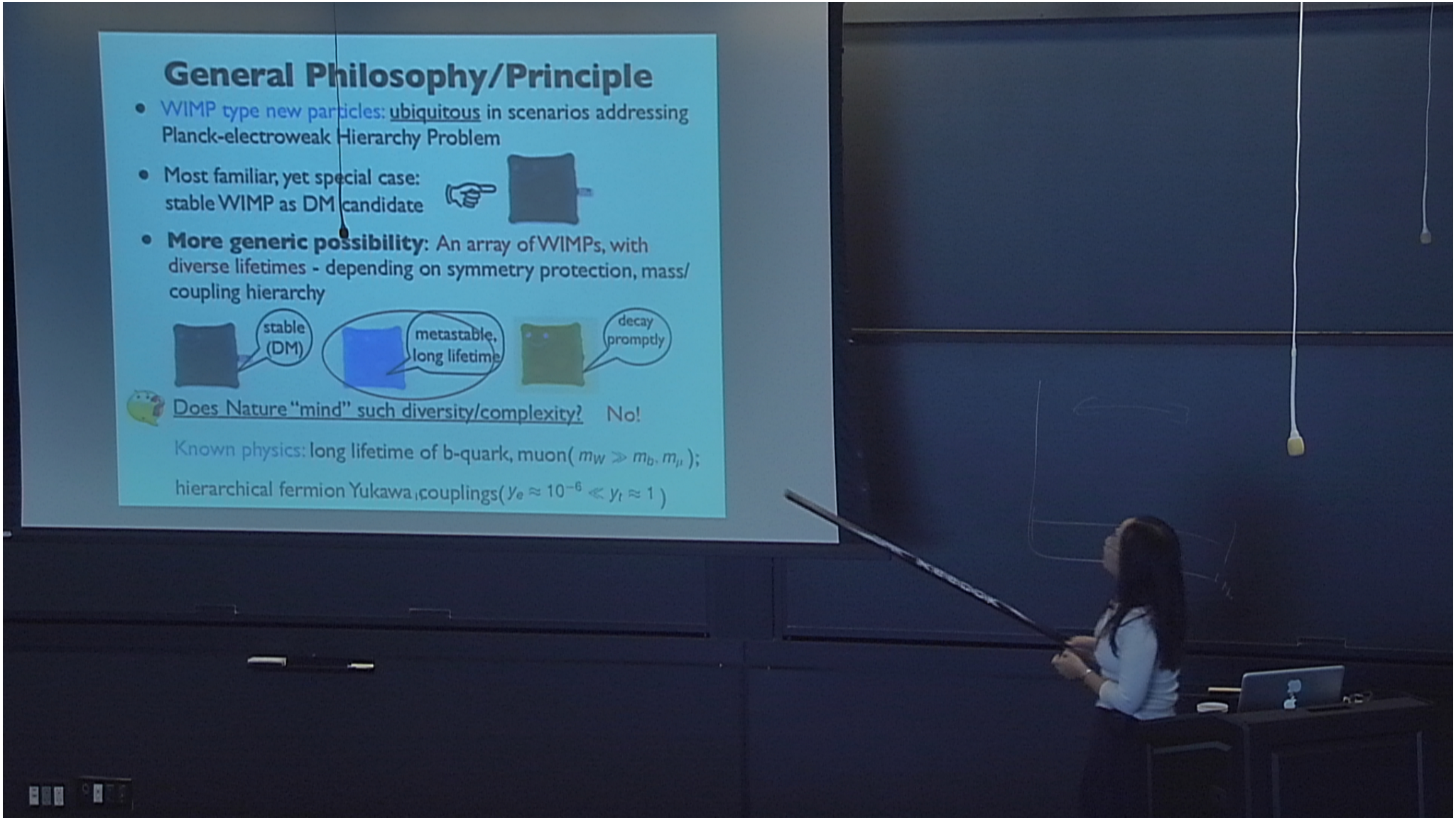
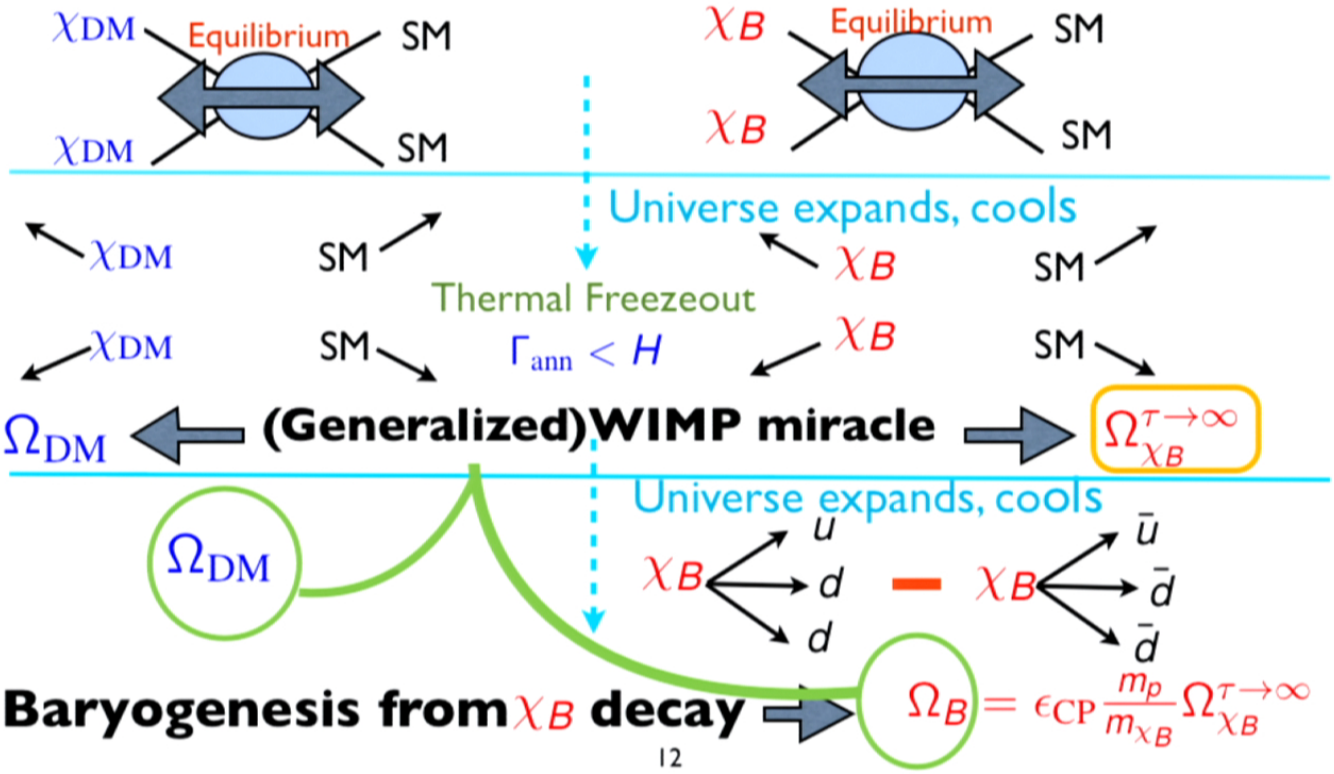

General Philosophy/Principle
WIMP type new particles: ubiquitous in scenarios addressing Planck-electroweak Hierarchy Problem
Most familiar, yet special case: stable WIMP as DM candidate
More generic possibility: An array of WIMPs, with diverse lifetimes - depending on symmetry protection, mass/coupling hierarchy
stable (DM)
metastable, long lifetime
decay promptly
Does Nature "mind" such diversity/complexity? No!
Known physics: long lifetime of b-quark, muon( $m_W \gg m_b, m_\mu$ );
hierarchical fermion Yukawa couplings( $y_e \approx 10^{-6} \ll y_t \approx 1$ )

Assume a stable WIMP $\chi_{DM}$ as DM;

In addition, a metastable WIMP $\chi_B$ as baryon parent:

$\chi_B$ : $\not{B}, \not{CP}$ decay after thermal freezeout ⇒ Baryogenesis

- **Cosmic evolution of the two WIMPs:**



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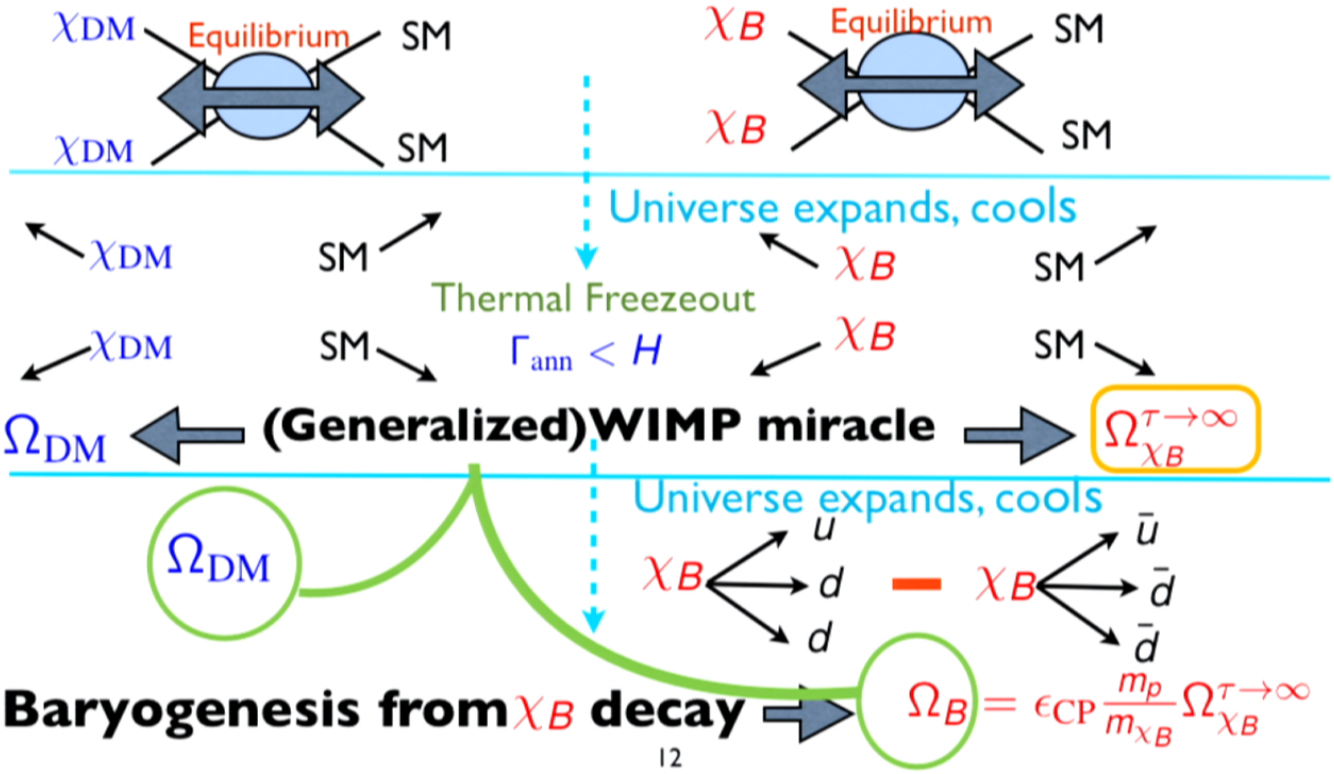

# Central Result:

## Generalized WIMP Miracle

$$\Omega_{\rm DM} \sim \Omega_B = \epsilon_{\rm CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau\to\infty}$$

- **Robustness**: insensitive to precise long-lifetime $\tau$
- Caveat: washout processes ($B \to \bar{B}$) needs to be suppressed to avoid extra reduction on $\Omega_B$, ⇒ Easy to realize (later...)
- Extra factor $\epsilon_{\rm CP} \frac{m_p}{m_{\chi_B}} \sim 10^{-4} - 10^{-3}$ (large CPV at 1-loop: $\epsilon_{\rm CP} \sim 1 - 10\%$) compensation factor from $\Omega_{\chi_B}^{\tau\to\infty} \sim 10^2 - 10^3$ to get $\frac{\Omega_B}{\Omega_{\rm DM}} \sim O(0.1)$ ,
- Easy to accommodate by different masses/couplings associated with $\chi_{\rm DM}$ and $\chi_B$ ($\chi_B$ : a "weaker" WIMP)

⇒ **Recall: WIMP miracle is a rough guideline!**

$$\Omega_\chi \simeq 0.1 \frac{\alpha_{\rm weak}^2/({\rm TeV})^2}{\langle\sigma_{\rm A} v\rangle} \simeq 0.1 \left(\frac{g_{\rm weak}}{g_\chi}\right)^4 \left(\frac{m_{\rm med}^4}{m_\chi^2 \cdot {\rm TeV}^2}\right)$$

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# Outline

- General formulation
- A minimal model, constraints/viability
- Embedding in $\not{B}$ "natural SUSY"
- Embedding in RPV Mini-Split SUSY
- Outlook

# General Formulation

- A thermal WIMP $\chi$ freezes out when $\Gamma_{\rm ann} \simeq H$

$$T_f \simeq m_\chi \left[\ln\left(0.038(g/g_*^{1/2}) m_\chi M_{\rm pl}\langle\sigma_{\rm A} v\rangle\right)\right]^{-1} \sim \frac{1}{20} m_\chi$$

Co-moving density: $Y_\chi(T_{\rm f}) = \dfrac{n_\chi^{\rm eq}(T_{\rm f})}{s(T_{\rm f})} \simeq 3.8 \dfrac{g_*^{1/2}}{g_{*s}} \dfrac{m_\chi}{T_{\rm f}} \left(m_\chi M_{\rm pl}\langle\sigma_{\rm A} v\rangle\right)^{-1}$

*If $\chi$ is stable, $Y_\chi(T_{\rm f}) \simeq Y_\chi(T_0)$*, relic density today:

$$\Omega_\chi \;=\; \frac{m_\chi Y_\chi(T_{\rm f}) s_0}{\rho_0} \simeq 0.1 \frac{\alpha_{\rm weak}^2/({\rm TeV})^2}{\langle\sigma_{\rm A} v\rangle}$$

- **Consider <u>two</u> species of WIMPs :**

★ Stable WIMP DM $\chi_{\rm DM}$ : $\Omega_\chi \equiv \Omega_{\rm DM} \approx 27\%$ (WIMP miracle)

★ Metastable WIMP (baryon parent) $\chi_B$: ~~$CP$~~, ~~$B$~~ decay at

$T_{\rm D} < T_{\rm f}$ , $Y_{\chi_B}(T_{\rm f}) \equiv Y_{\chi_B}^{\rm ini}$ ⇒ <u>initial condition</u> for baryogenesis

# Baryogenesis from late decay of WIMP $\chi_B$

- Assume well separated scales: $1\ \mathrm{MeV} \sim T_{\mathrm{BBN}} < T_{\mathrm{D}} < T_{\mathrm{f}}$

→ Freeze-out and baryogensis as decoupled processes, retain conventional success of BBN

- Solving Boltzmann equations, co-moving baryon density today:

$$Y_B(0) = \epsilon_{\mathrm{CP}} \int_0^{T_{\mathrm{D}}} \frac{dY_{\chi_B}}{dT} \exp\left( - \int_0^{T} \frac{\Gamma_{\mathrm{W}}(T')}{H(T')} \frac{dT'}{T'} \right) dT$$

$\epsilon_{\mathrm{CP}}$: CP asymmetry in $\chi_B$ decay, $\Gamma_{\mathrm{W}}$: the rate of $\not{B}$ washout processes

- **Weak washout:** $\Gamma_{\mathrm{W}} < H$

→ $$Y_B(0) \simeq \epsilon_{\mathrm{CP}} Y_{\chi_B}(T_{\mathrm{f}}), \quad \Omega_B(0) = \epsilon_{\mathrm{CP}} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau \to \infty} \sim \Omega_{\mathrm{DM}}$$

# Minimal Model: setup

We add to the Standard Model (SM) Lagrangian( $\not{B}$ )(complex couplings)

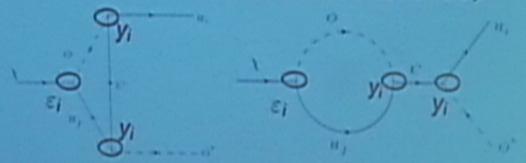
$$\begin{aligned}\Delta\mathcal{L} &= \lambda_{ij}\phi d_i d_j + \varepsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 \\ &+ \alpha \chi^2 S + \beta |H|^2 S + M_S^2 S^2 + \text{h.c.}\end{aligned}$$

- $\phi$: di-quark scalar with same SM gauge charge as u-quark
- $\chi, \psi$: SM singlet Majorana fermions.
  $\chi \equiv \chi_B$, the WIMP parent for baryogenesis.
- $\varepsilon_i \ll 1$: formal small parameter(small breaking of a $\chi$-parity symmetry)
  ⇒ long-lived $\chi$ $(\chi \to u\phi^*)$
- Singlet scalar $S$ : mediates WIMP annihilation $\chi\chi \to \text{SM}$

**Incorporate DM?** + $\chi_{\text{DM}}$ singlet, interactions analogous to $\chi$, except for exact $\chi_{\text{DM}}$-parity ⇒ $\varepsilon_{\text{DM}} = 0$

# Minimal Model: Baryogenesis

- Out-of-equilibrium decay $\chi \to \phi^* u$ ($\phi^* \to dd$) with $\Delta B = 1, \epsilon_{CP} \neq 0$
- CP asymmetry: $\epsilon_{CP} \equiv \frac{\Gamma(\chi \to \phi^* u) - \Gamma(\chi \to \phi \bar{u})}{\Gamma(\chi \to \phi^* u) + \Gamma(\chi \to \phi \bar{u})}$ from interference between tree-level and $\psi$-mediated loop diagrams:




Compute $\epsilon_{CP}$ (close analogy to leptogenesis), e.g. for $M_\phi > M_\chi$:

$$\epsilon_{CP} \simeq \frac{1}{8\pi} \frac{1}{\sum_i |\varepsilon_i|^2} Im\left\{ \left( \sum_i \varepsilon_i y_i^* \right)^2 \right\} \frac{M_\chi}{M_\phi}$$

⇒ To maximize CP asymmetry: $\varepsilon_i \ll y_i \sim 1$

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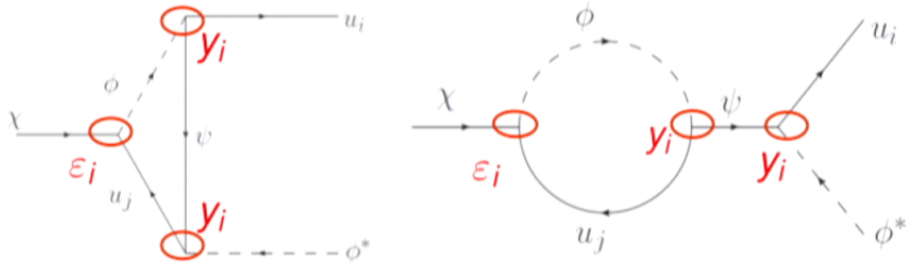


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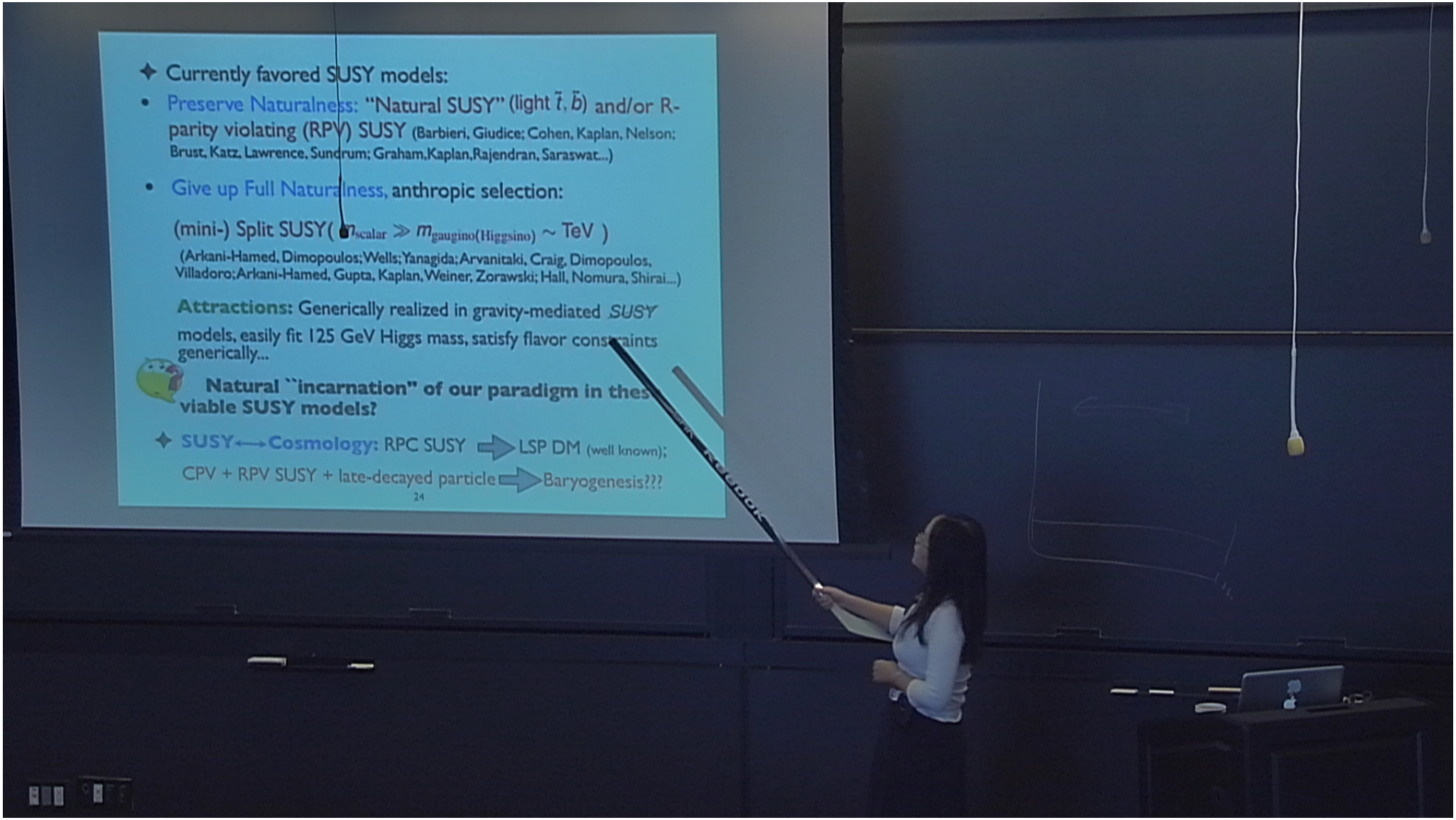
# Summary/Implications of the constraints

- Assume all new fields have weak scale masses,

  Precision constraints ⇒ New couplings involving first two generation quarks (e.g. $\lambda_{ij}$ for $\phi d_i d_j$ (i,j=1,2)) need to be suppressed

- **Simple, natural Solution:** Third-generation dominated pattern, new fields couple mostly to b, t (just like Higgs!), with "CKM-like mixing" suppressions to light quarks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• Give up Full Naturalness, anthropic selection:
(mini-) Split SUSY( $m_{\text{scalar}} \gg m_{\text{gaugino(Higgsino)}} \sim$ TeV )
(Arkani-Hamed, Dimopoulos;Wells;Yanagida;Arvanitaki, Craig, Dimopoulos, Villadoro;Arkani-Hamed, Gupta, Kaplan,Weiner, Zorawski; Hall, Nomura, Shirai...)
Attractions: Generically realized in gravity-mediated SUSY models, easily fit 125 GeV Higgs mass, satisfy flavor constraints generically...
Natural ``incarnation" of our paradigm in thes
viable SUSY models?
✦ SUSY⟷Cosmology: RPC SUSY ⇨ LSP DM (well known);
CPV + RPV SUSY + late-decayed particle ⇨ Baryogenesis???
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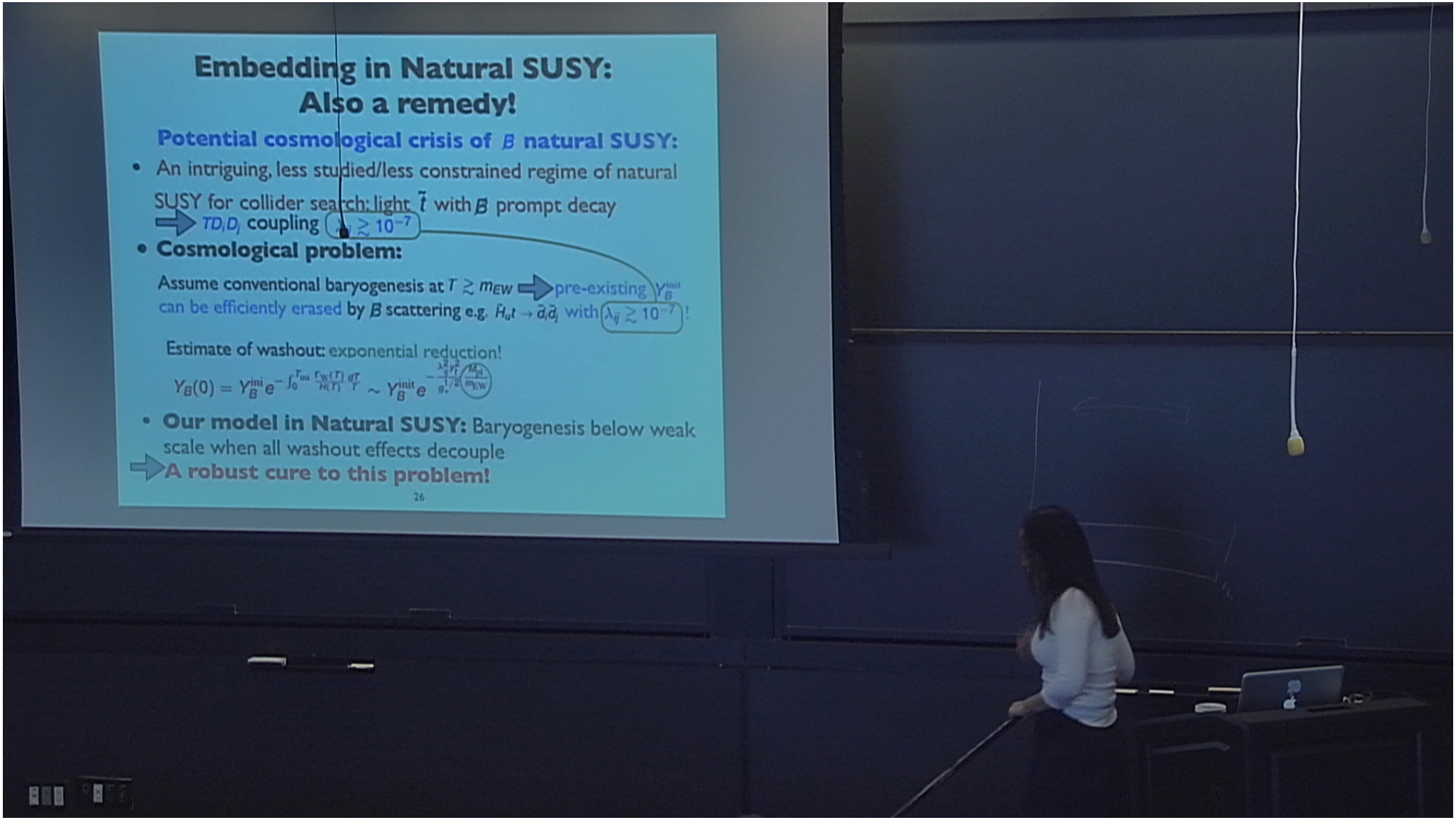
Embedding in Natural SUSY:
Also a remedy!
Potential cosmological crisis of B natural SUSY:
• An intriguing, less studied/less constrained regime of natural SUSY for collider search: light $\tilde{t}$ with B prompt decay
$TD_iD_j$ coupling $\lambda_{ij} \gtrsim 10^{-7}$
• Cosmological problem:
Assume conventional baryogenesis at $T \gtrsim m_{EW}$ pre-existing $Y_B^{init}$
can be efficiently erased by B scattering e.g. $\tilde{H}_u t \to \bar{d}_i \bar{d}_j$ with $\lambda_{ij} \gtrsim 10^{-7}$!
Estimate of washout: exponential reduction!
$Y_B(0) = Y_B^{ini} e^{-\int_0^{T_{ini}} \frac{\Gamma_W(T)}{H(T)} \frac{dT}{T}} \sim Y_B^{init} e^{-\frac{\lambda_B^2 y_t^2}{g_*^{1/2}} \left(\frac{M_{pl}}{m_{EW}}\right)}$
• Our model in Natural SUSY: Baryogenesis below weak scale when all washout effects decouple
A robust cure to this problem!
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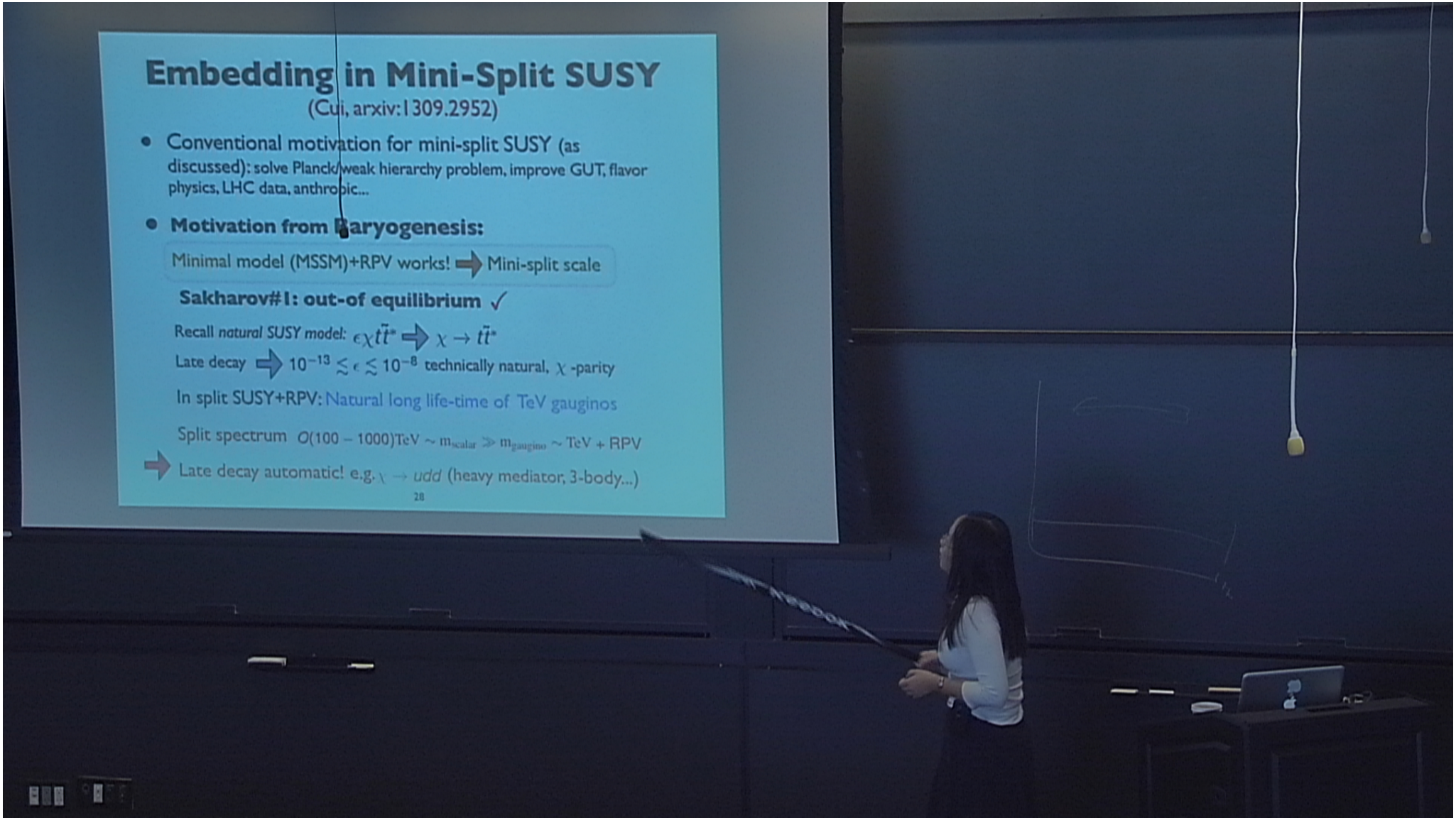
Embedding in Mini-Split SUSY
(Cui, arxiv:1309.2952)
Conventional motivation for mini-split SUSY (as discussed): solve Planck/weak hierarchy problem, improve GUT, flavor physics, LHC data, anthropic...
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Late decay $10^{-13} \lesssim \epsilon \lesssim 10^{-8}$ technically natural, $\chi$ -parity
In split SUSY+RPV: Natural long life-time of TeV gauginos
Split spectrum $O(100-1000)\text{TeV} \sim m_{\text{scalar}} \gg m_{\text{gaugino}} \sim \text{TeV} + \text{RPV}$
Late decay automatic! e.g. $\chi \to udd$ (heavy mediator, 3-body...)
28

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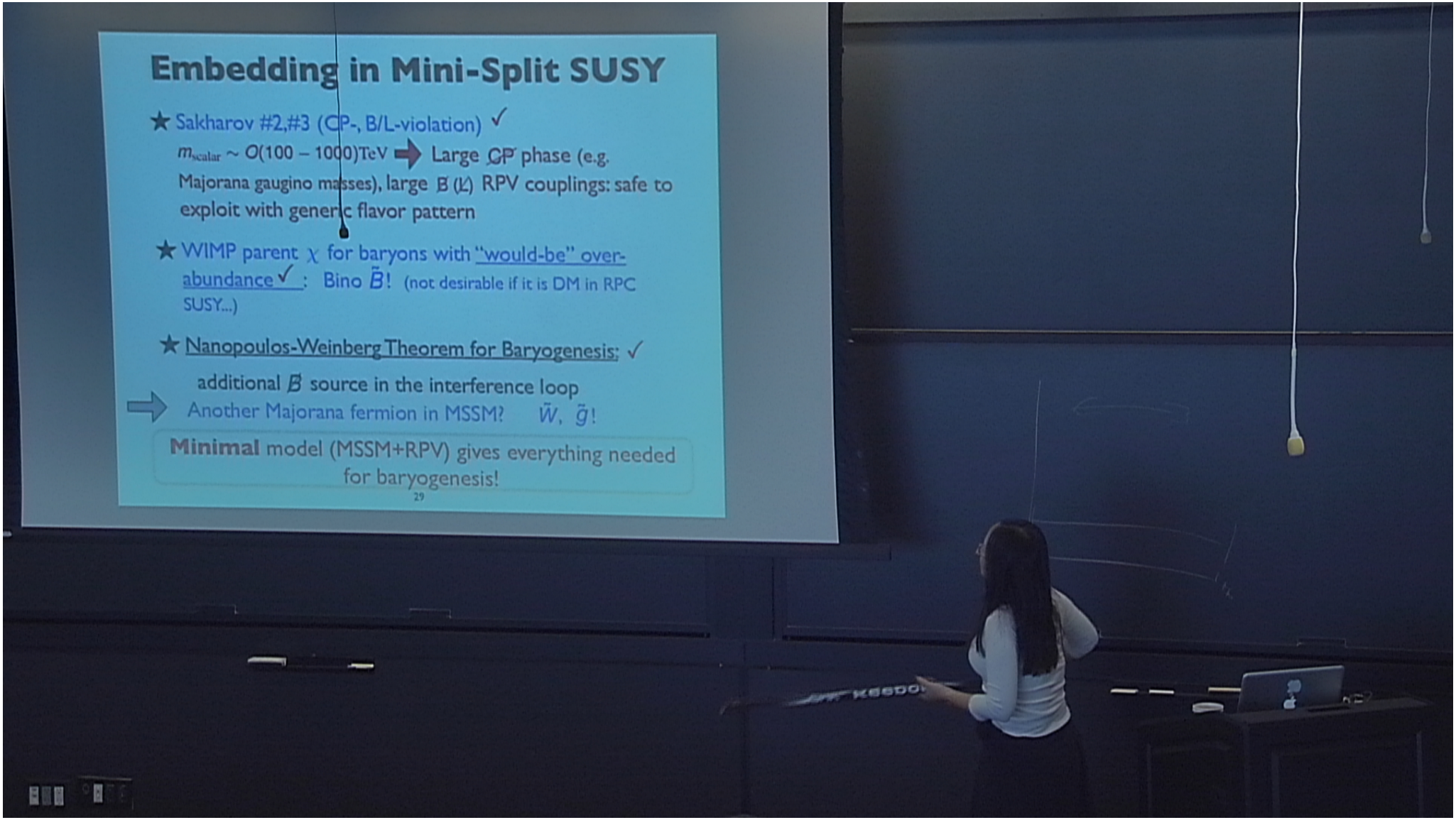
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$m_{scalar}$ ~ O(100 – 1000)TeV ➡ Large CP phase (e.g. Majorana gaugino masses), large B (L) RPV couplings: safe to exploit with generic flavor pattern
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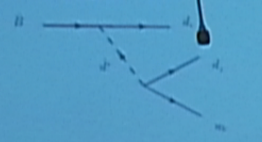
## Model-I: Baryogenesis with light gluino

- Tree-level decays:

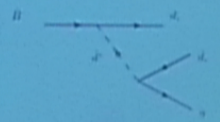
B-violating decay (baryogenesis):



(a)

$$\Gamma_{\tilde{B},\not B} = \frac{(\sqrt{2}\lambda'' Y_d g_1)^2}{512\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 18$$

B-conserving decay (competing):



(b)

$$\Gamma_{\tilde{B}\to udd\bar{\nu}} = \frac{(Y_d g_1 g_3)^2}{1024\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 3$$

$\not B$ decay dominates/comparable with $\lambda'' \gtrsim O(0.1)$.

-- viable for generic flavor structure, with $m_0 \gtrsim 100 - 1000$ TeV

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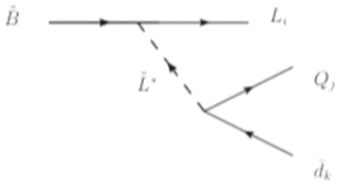
# Model-II: Leptogenesis with light wino

- Tree level decays:

L-violating decay (leptogenesis):




(a)

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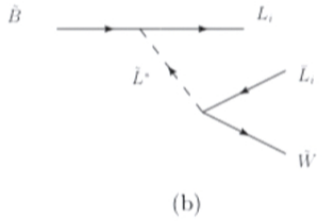
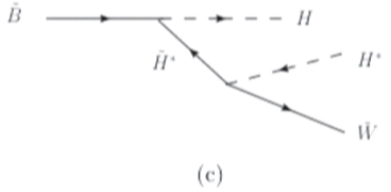



(b)




(c)

$$\Gamma_{\tilde{B},\not{L}} = \frac{(\sqrt{2}\lambda' Y_L g_1)^2}{512\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 27 \qquad \Gamma_{\tilde{B}\to L\bar{L}\tilde{W}} = \frac{(Y_L g_1 g_2)^2}{3072\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 3 \qquad \Gamma_{\tilde{B}\to H^* H\tilde{W}} = \frac{(Y_H g_1 g_2)^2}{384\pi^3}\frac{m_{\tilde{B}}^3}{\mu^2}$$

$\not{L}$ decay dominates/comparable, with $\mu \gg m_0$ and $\lambda' \gtrsim O(0.1)$.

$\mu$-term: *supersymmetric* mass parameter, in general can be different from both $m_0$ and $m_{\text{gaugino}}$; large $\mu$ : exempt from the "$\mu$ -problem", innocuous for phenomenology (Arkani-hamed et.al 2012)

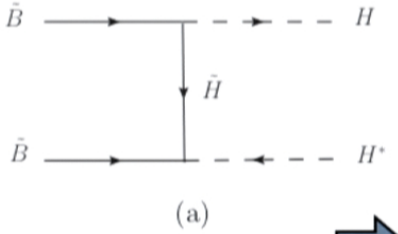
# Computation of $\Omega_{\Delta B}$

- Recall general prediction for baryon asymmetry:

$$\Omega_{\Delta B} = \epsilon_{\rm CP} \frac{m_p}{m_{\chi B}} \Omega_{\chi B}^{\tau \to \infty} \quad \text{(with negligible washout)} \qquad \epsilon_{CP} \checkmark \qquad \Omega_{\tilde{B}}^{\tau \to \infty}$$

- Thermal annihilation of $\tilde{B}$ ➡ would-be Relic abundance $\Omega_{\tilde{B}}^{\tau \to \infty}$

Leading process with small/moderate $\mu$ :



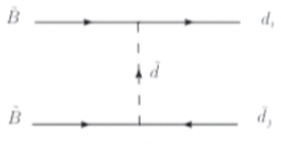
(a)

$$\sigma_{HH^*}(s) = \frac{g_1^4}{32\pi} \frac{s - 4M_1^2}{s\sqrt{1 - 4M_1^2/s}} \frac{1}{\mu^2}$$

$$\langle \sigma_{HH^*} v \rangle = \frac{1}{8M_1^4 T K_2^2(M_1/T)} \int_{4M_1^2}^{\infty} ds \sigma_{HH^*}(s)(s - 4M_1^2)\sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right)$$

➡ $\Omega_{\Delta B} \sim 10^{-2} \left(\frac{m_{\tilde{B}}}{1\ \text{TeV}}\right) \left(\frac{\mu}{10 m_0}\right)^2$ need $\mu \gtrsim 10 m_0$

Other processes, dominate at $\mu \to \infty$ :



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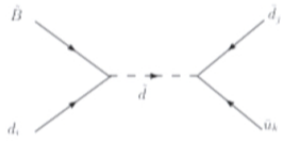

(c)

$$\langle \sigma_{\tilde{B}(\tilde{d}_i)} v \rangle \simeq \frac{\xi^2}{10\pi} \frac{M_1^2}{m_s^4} \left[5 \frac{K_4(M_1/T)}{K_2(M_1/T)} + 1\right]$$

# Embedding in Mini-Split SUSY

- **Phenomenology**
  - Constraints from low energy experiments:

$n - \bar{n}$ oscillation, neutron EDM, $K_0 - \bar{K}_0$ mixing... ✓ $(m_0 \gtrsim 100 - 1000\ \mathrm{TeV})$

  - Search for long-lived $\tilde{B}$, $\tilde{W}$, $\tilde{g}$ with RPV decay at LHC

(with strong cosmological motivation!)

*Displaced vertex; better reach at higher energy upgrade (33TeV, 100TeV...) for multi-TeV baryon parent (gluino, wino can be light), CP asymmetry measurement*

(work in preparation, YC and B.Shuve)

# Conclusions

- Our simple, robust mechanism realizes the challenging goal: $\Omega_{DM}$ ✓ $\Omega_B$ ✓ $\Omega_B \sim \Omega_{DM}$ ✓
- Unique low scale baryogensis mechanism independent of DM story: WIMP miracle predicts right ball park of $\Omega_B$
- Natural embedding in $\not{B}$ Natural SUSY, also a remedy to a potential cosmological problem
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# Outlook

- New particle physics related to EW hierarchy problem

(Appeals: motivated theories, LHC search...)

New cosmology

- Conventional focus: WIMP DM (e.g. RPC SUSY)
- New Perspective: Baryogenesis from metastable WIMP decay (e.g. RPV SUSY)

*Exciting possibility:*

Test the cosmological origin of matter (cosmology frontier) at energy frontier - current-day colliders (LHC), intensity frontier - improved low energy experiments ( $n - \bar{n}$ oscillation, flavor physics...)!

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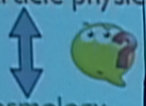

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