Aspen

February, 2011

Freeze-In of Dark Matter

and

Long-Lived States at the LHC

Lawrence Hall
University of California, Berkeley

LJH, Karsten Jedamsik, John March-Russell and Stephen West, arXiv:0911.1120 — Freeze-In - General Idea

Cliff Cheung, Gilly Elor, LJH, and Piyush Kumar arXiv:1010.0022, arXiv:1010.0024 — Hidden Sector Freeze-In

LJH, John March-Russell and Stephen West, arXiv:1010.0245 — Asymmetric Freeze-In

Cliff Cheung, Gilly Elor, LJH to appear — Freeze-In of Gravitinos

Testing Origin of Dark Matter at LHC

- Initial thermal state

- Relic abundance from calculable mechanism

- LHC measurements allow a prediction of $\Omega_D h^2$

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  No dependence on unknown UV physics: T_R , η, initial conditions, ...

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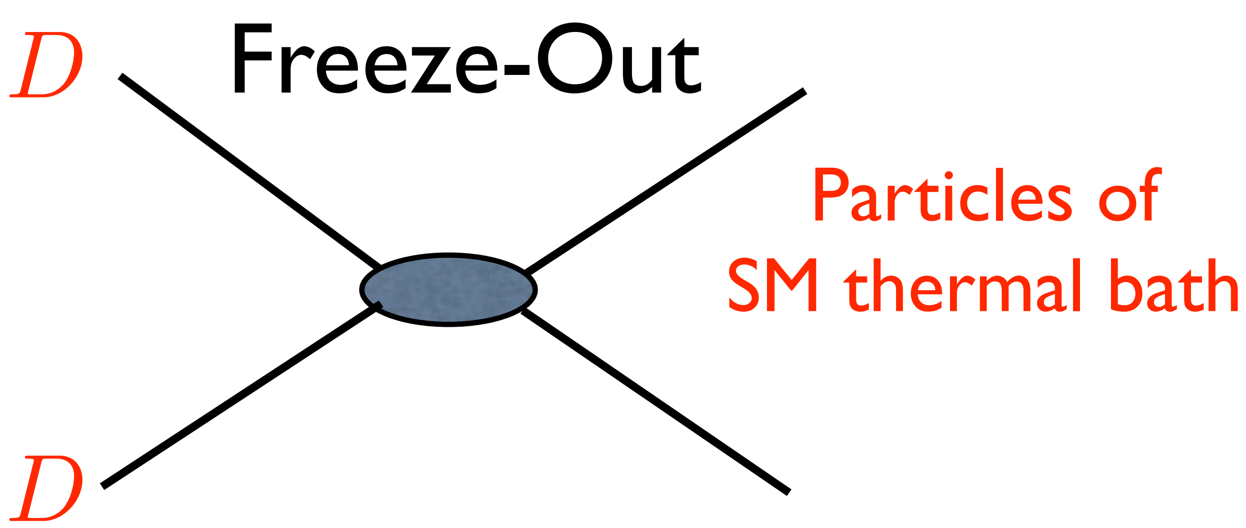

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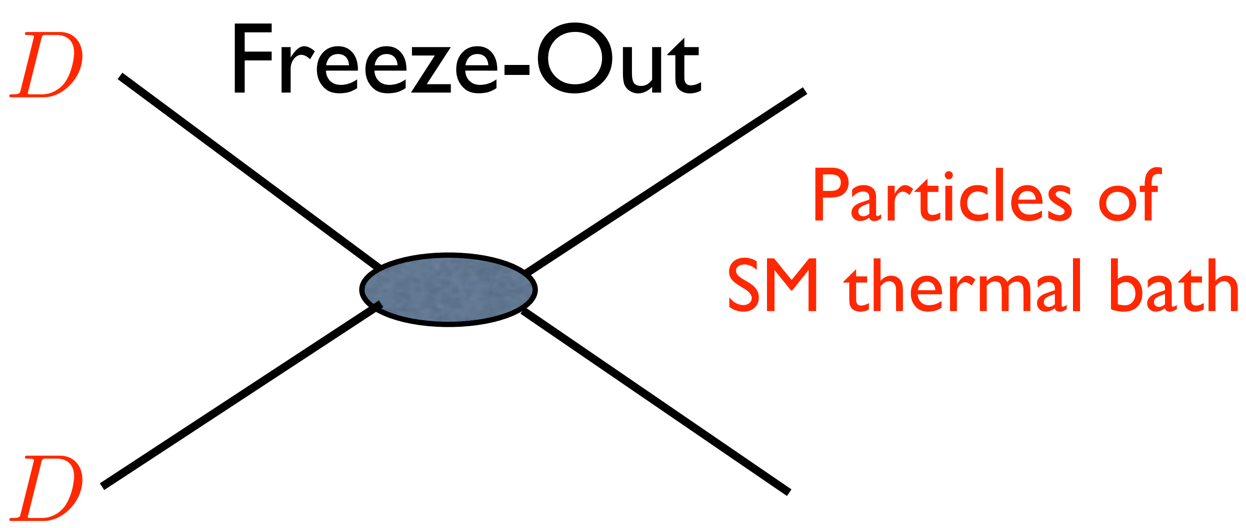

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$$\Omega_D h^2 = (\#)\,\frac{1}{\langle \sigma v \rangle}$$

A WIMP miracle?

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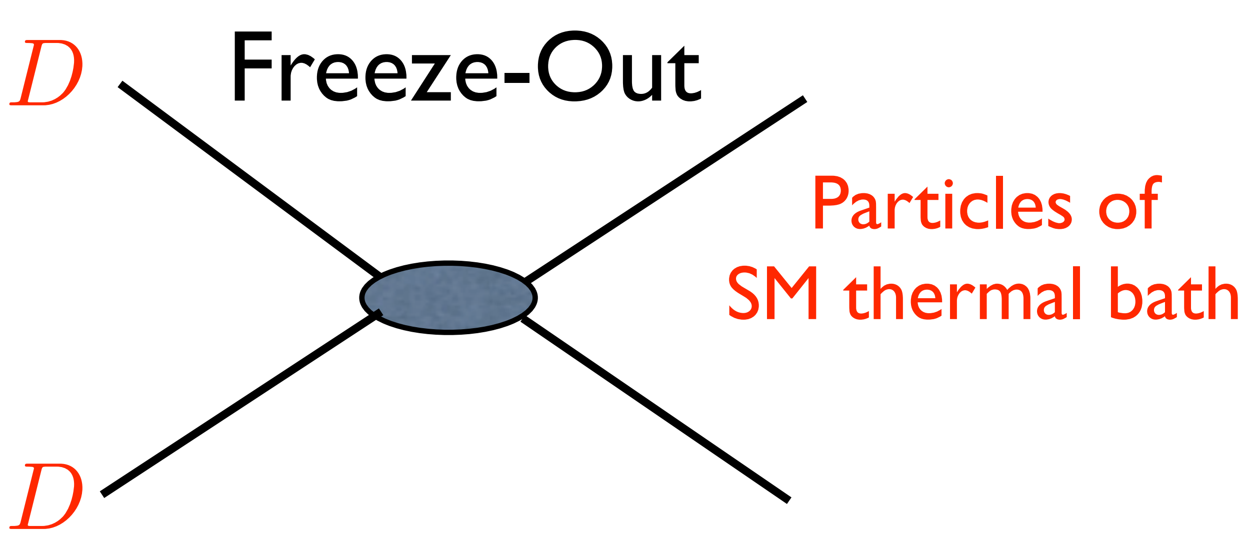

Alternative Mechanism??

- LHC measurements allow a prediction of $\Omega_D h^2$

$$\Omega_D h^2 = (\#)\,\frac{1}{\langle \sigma v \rangle}$$

A WIMP miracle?

Generic Test from New Physics at the Weak Scale??

Thermal Properties of DM at $T \sim v$

Three possibilities

1. Part of Standard Model thermal bath — WIMPs

2. Not part of a thermal bath — FIMPs

3. Part of a hidden sector thermal bath — Hidden Sector DM

Both 2 and 3 allow an IR dominated production mechanism that may be tested at LHC

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$$\Omega_D h^2 = (\#)\,\frac{1}{\langle \sigma v \rangle} \quad \Longrightarrow \quad \boxed{\Omega_D h^2 = (\#)\,\frac{1}{\tau}}$$

Aspects of Freeze-In:

(I) The Mechanism and Prediction

(II) Supersymmetric Models and LHC Signals

(III) Asymmetric Freeze-In

(IV) Freeze-In of Gravitino Dark Matter

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(IV) Freeze-In of Gravitino Dark Matter

Earlier work:

ϕ_S	McDonald ph/0106249	
$\tilde{\nu}_R$	Asaka, Ishiwata, Moroi ph/0512118	
ν_R	Kusenko ph/0609081	
...		

I'll stress general behavior

(I) The Freeze-In Mechanism

❈ Initial Condition

FIMP DM:

Visible sector thermal bath T		X

Hidden DM:

Visible sector thermal bath T		Hidden sector thermal bath $T' \ll T$ X

(I) The Freeze-In Mechanism

- Initial Condition

FIMP DM: | Visible sector thermal bath T | X

Hidden DM: | Visible sector thermal bath T | Hidden sector thermal bath $T' \ll T$ X

- Stabilizing Symmetry

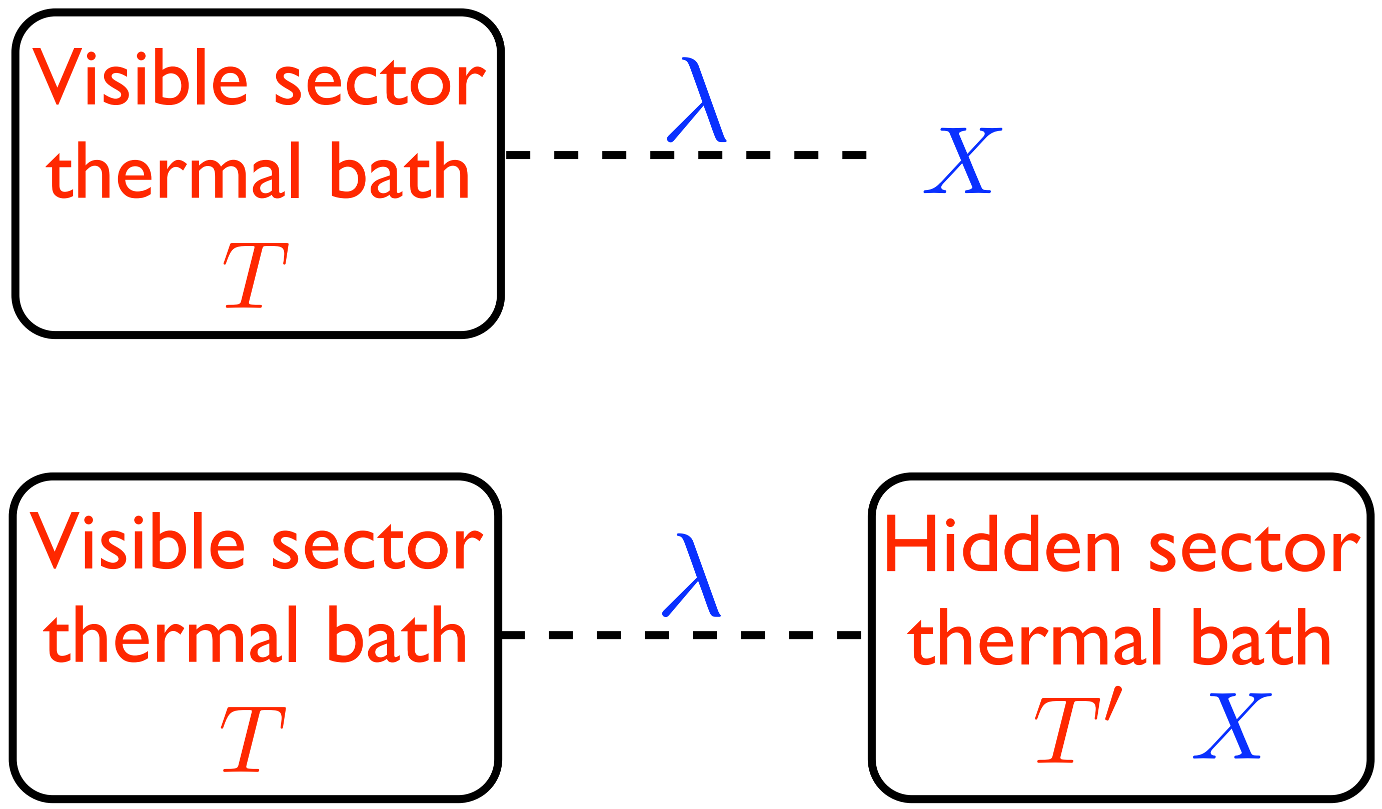
Carried by: $\{$ some visible sector particles
DM, X, which stabilized

eg R-parity in susy; LSP is FIMP or Hidden DM, visible sector contains LOSP

The "Connector" Interaction

- FIMP DM:

Hidden DM:



eg d=4

$$10^{-13} < \lambda < 10^{-6}$$

The "Connector" Interaction

- FIMP DM:

  Visible sector thermal bath T --- λ --- X

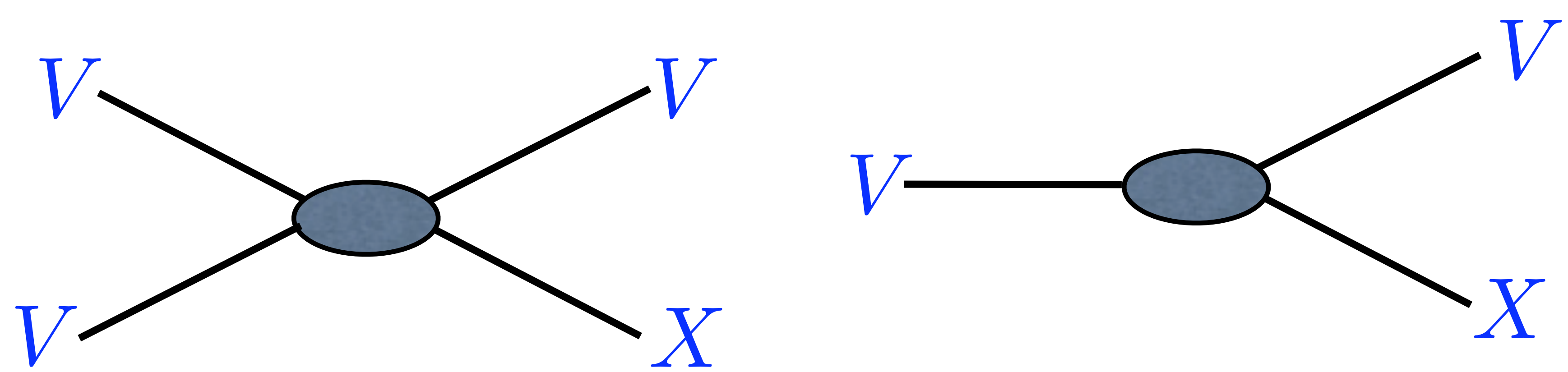
  eg d=4

  $$10^{-13} < \lambda < 10^{-6}$$

- Hidden DM:

  Visible sector thermal bath T --- λ --- Hidden sector thermal bath T' X

- Allows X production



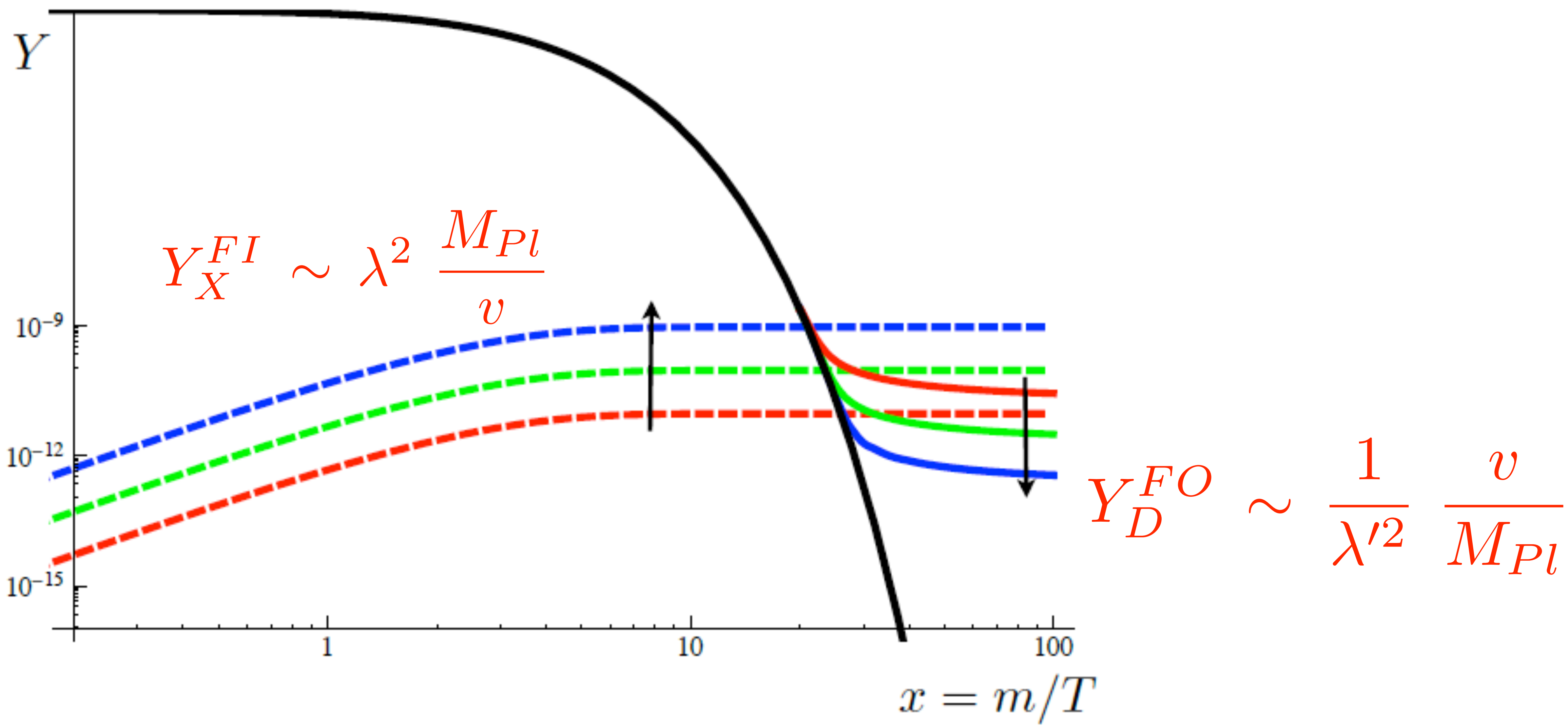
- Dimensional analysis

$$Y_X(T) \sim \lambda^2 \, \frac{M_{Pl}}{T}$$

- IR dominated; cutoff by masses

$$\boxed{Y_X \sim \lambda^2 \, \frac{M_{Pl}}{v}}$$

Heading "In" and "Out" of Equilibrium



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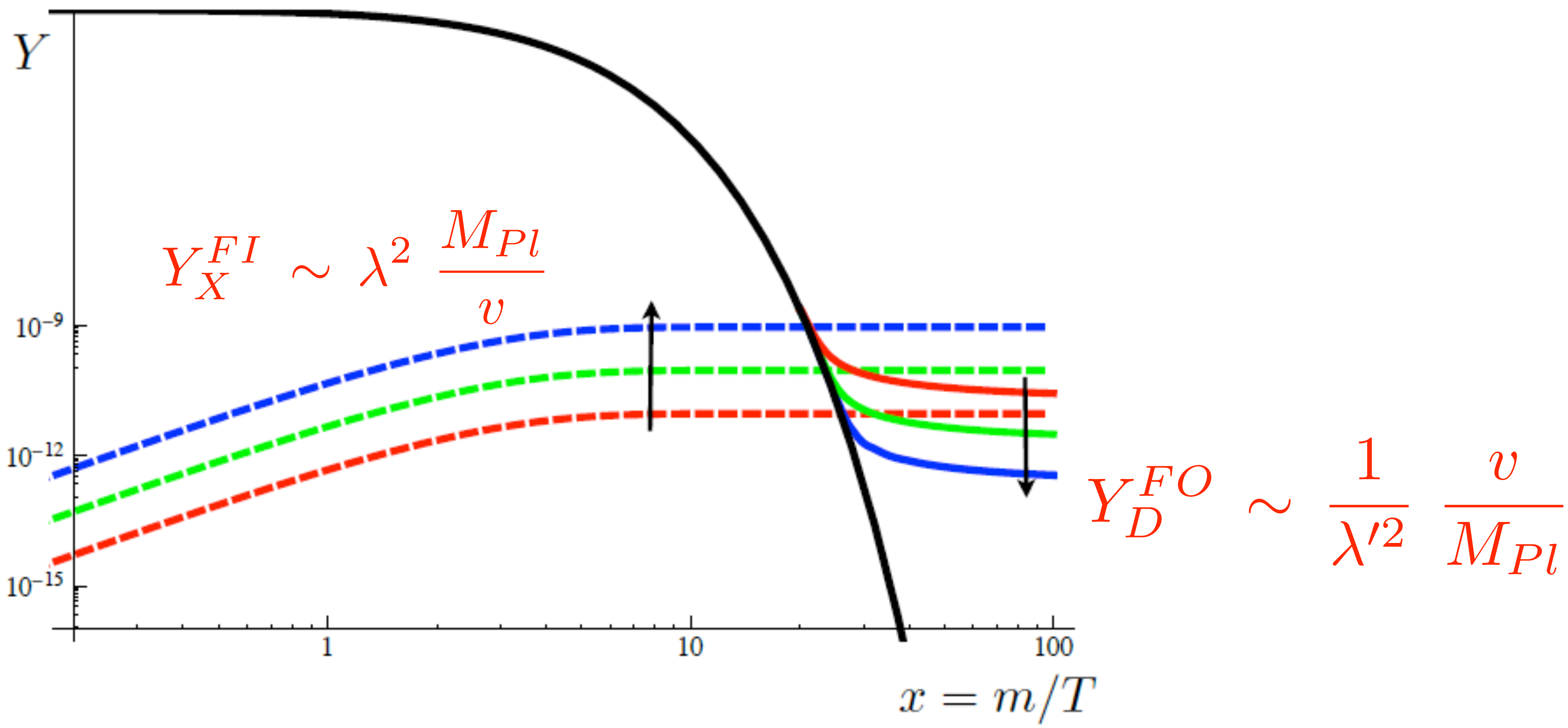

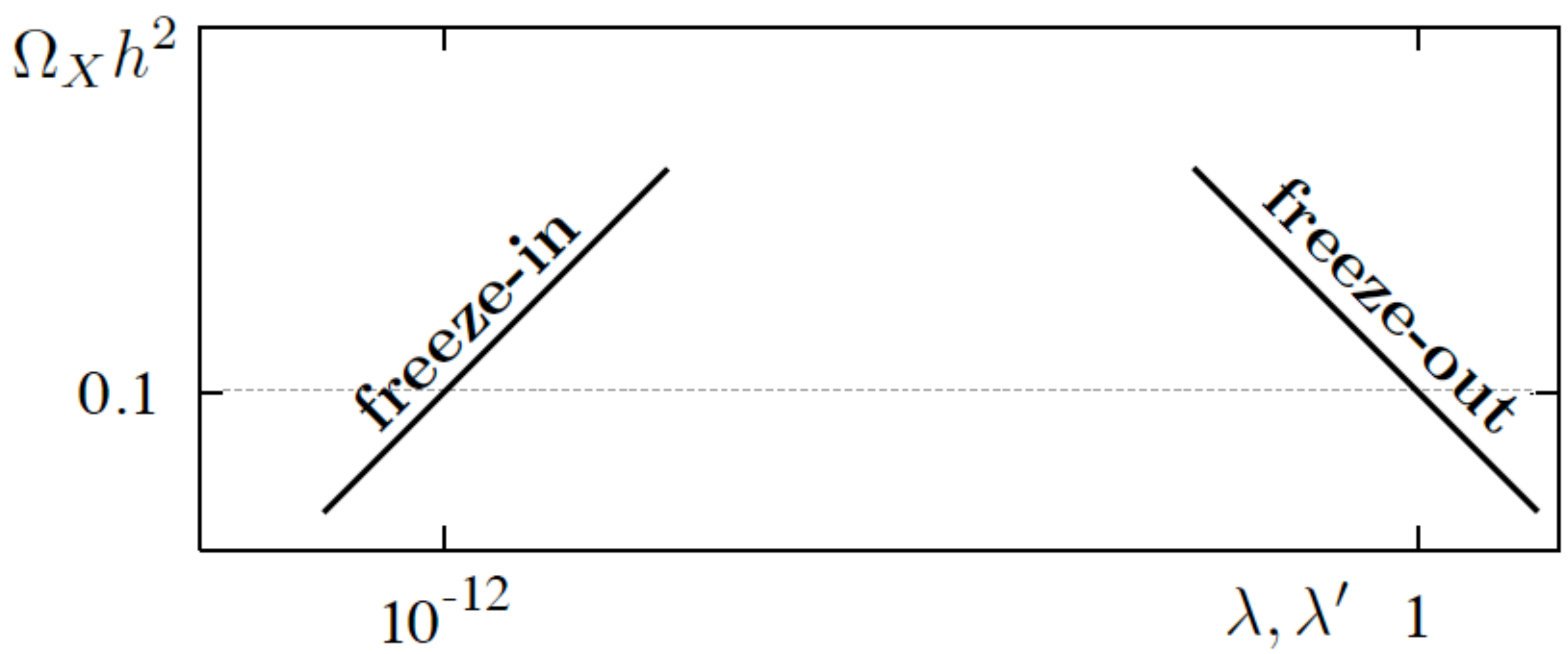

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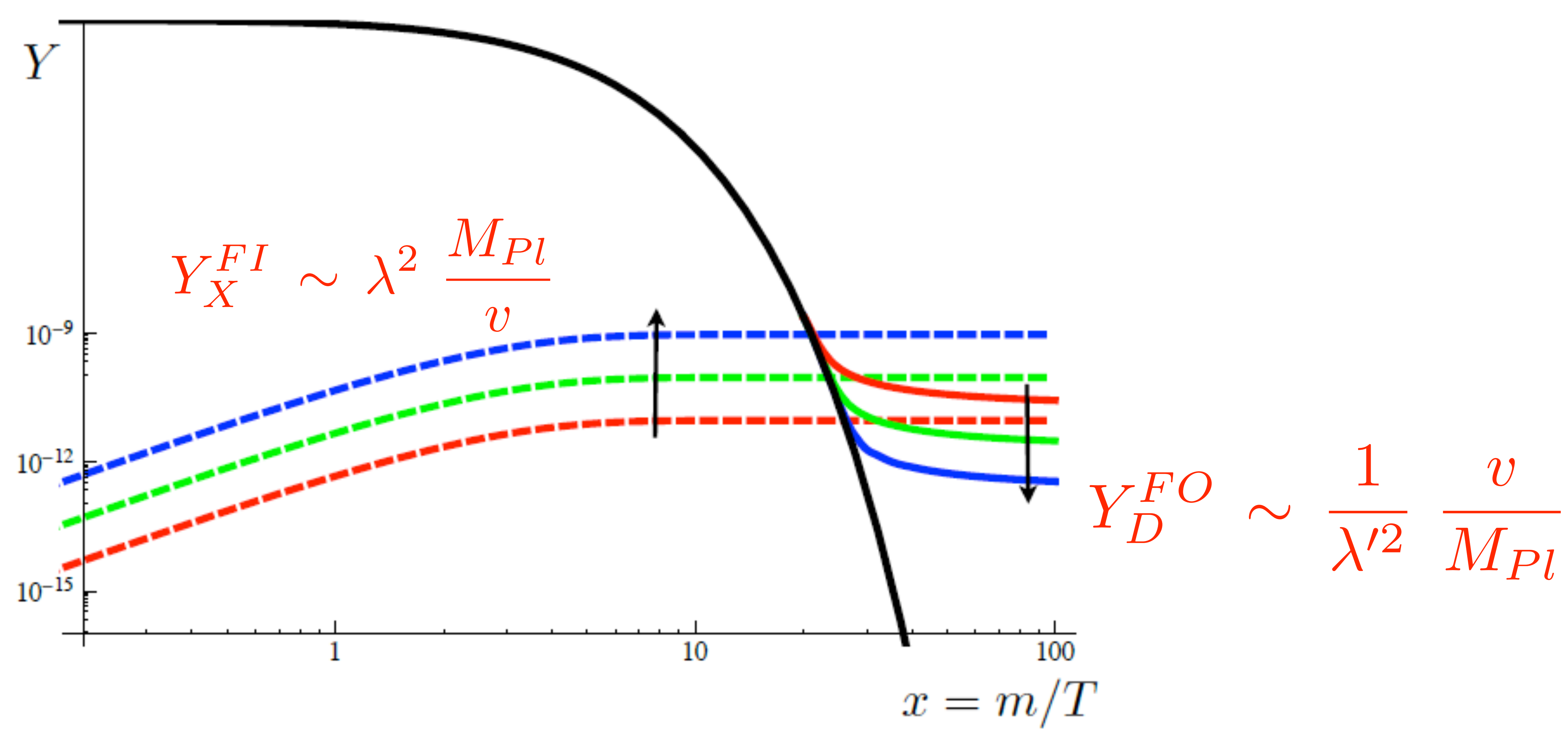

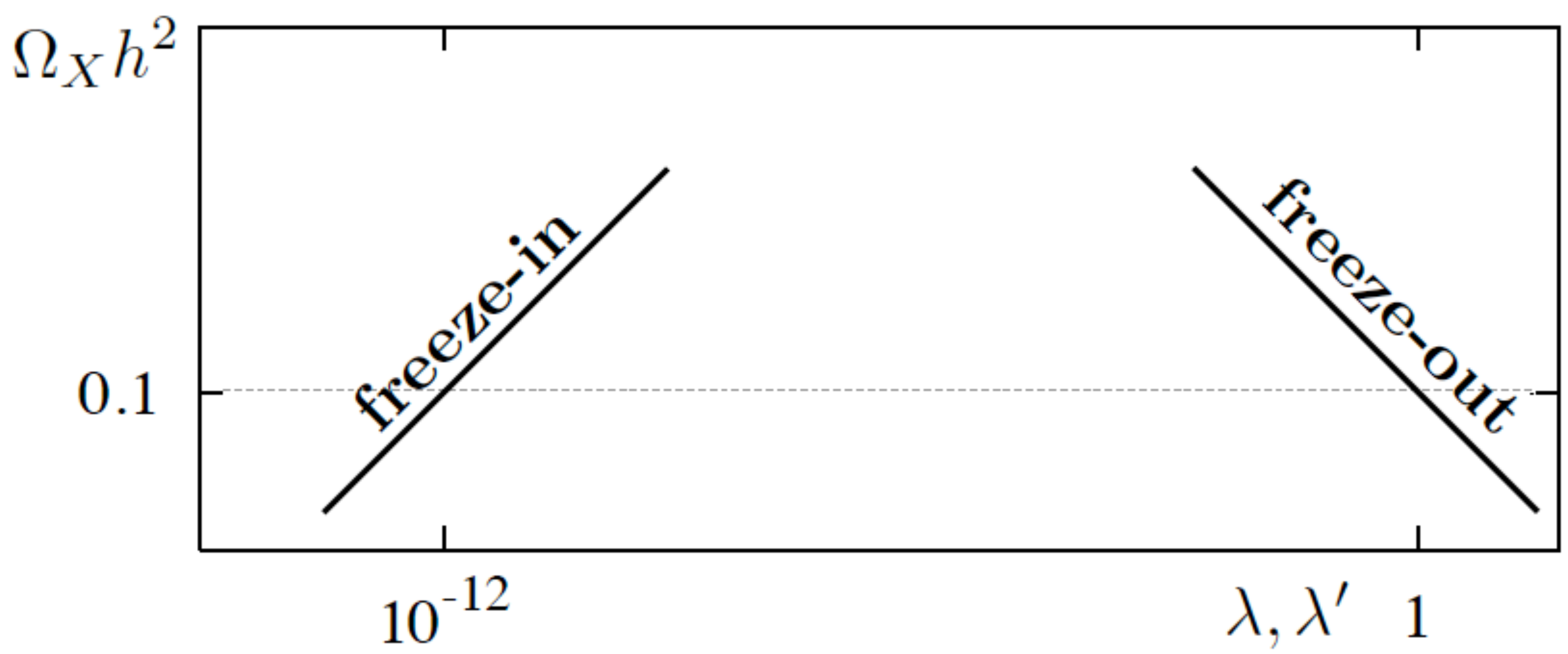

Two Thermal Mechanisms!!

The Lifetime Prediction

- Freeze-in production of X — Decays typically beat scattering $V \to X \ldots$

  Dominated by era $T \sim m_V$

- Giving abundance $$Y_{FI} = \frac{1.64\, g_V}{g_*^{3/2}} \; \frac{\Gamma_V\, M_{Pl}}{m_V^2}$$

  and lifetime

$$\boxed{\tau_V \;=\; 7.7 \times 10^{-3}\mathrm{s}\;\; g_V \left(\frac{m_X}{100\,\mathrm{GeV}}\right) \left(\frac{300\,\mathrm{GeV}}{m_V}\right)^2 \left(\frac{10^2}{g_*}\right)^{3/2}}$$

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- Applies to both FIMP and Hidden DM

- Applies to connector interaction of any dimension

- Completely general for any decay-dominated FI??   No -- later

- Susy theories: V is the LOSP: $(\tilde{\chi}^\pm, \tilde{l}^\pm, \ldots)$

II

Supersymmetric Models and LHC Signals

FI from Many Visible Particles

$$V \to X \quad \Longrightarrow \quad V_i \to X$$

$$Y_{FI} \sim M_{Pl} \frac{\Gamma_V}{m_V^2} \quad \Longrightarrow \quad Y_{FI} \sim M_{Pl} \sum_i \frac{\Gamma_i}{m_i^2}$$

Can only measure Γ_{LOSP}

Lose $\tau(\Omega h^2)$ relation??

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Can only measure Γ_{LOSP}

Lose $\tau(\Omega h^2)$ relation??

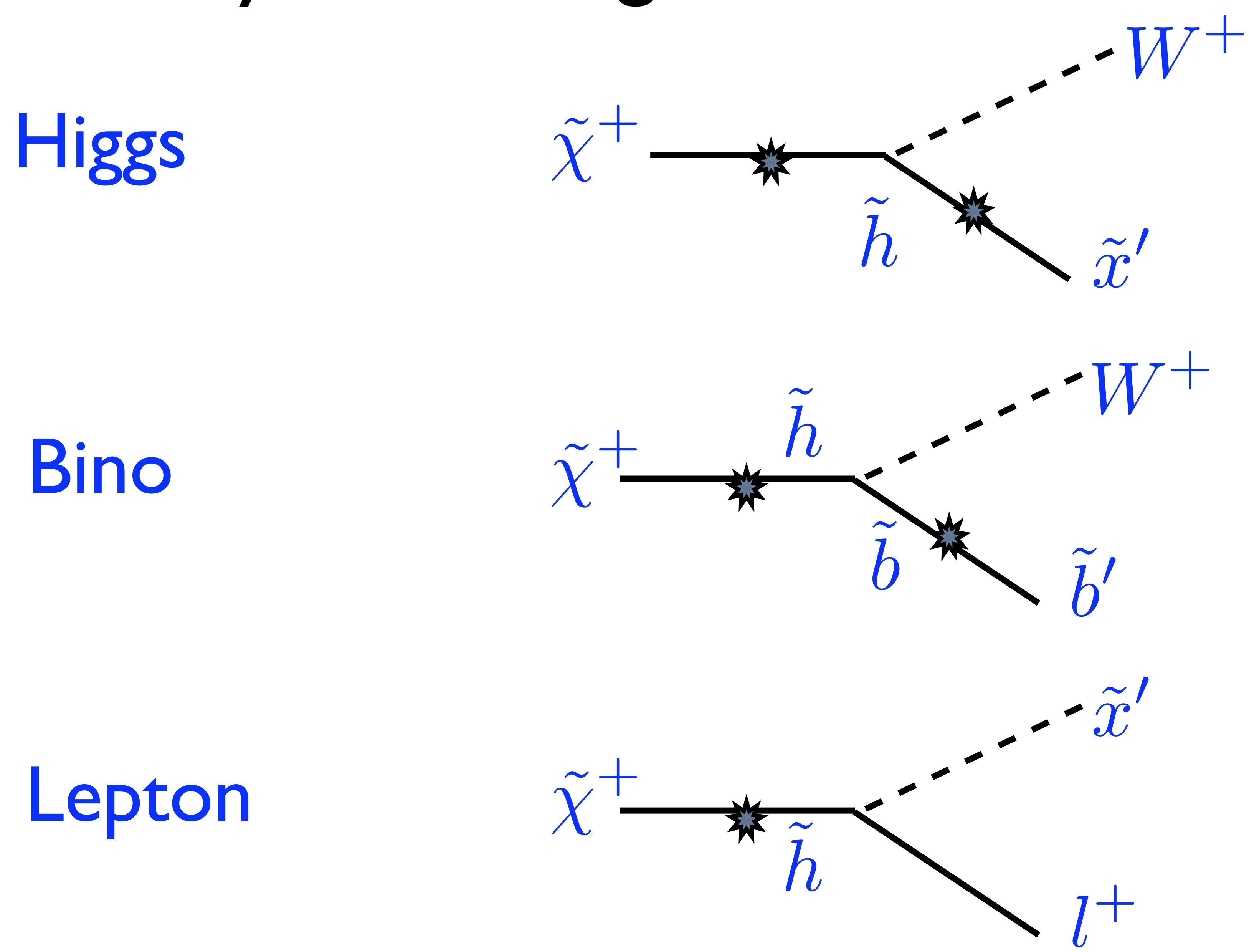
- $\frac{\Gamma_i}{m_i^2} \propto \frac{1}{m_i}$ Dominated by m_{LOSP} IR domination!

- Simple model with just one coupling parameter λ

Three d=4 Connector Interactions

			DM
❈	Higgs	$\lambda\, H_u H_d X'$	$\tilde{x}'$
❈	Bino	$\lambda\, B^\alpha\, B'_\alpha$	$\tilde{b}'$
❈	Lepton	$\lambda\, L H_u X'$	$\tilde{x}'$

Decays of Chargino LOSP



Reconstructing the Cosmology: $\tilde{l}^-$ LOSP

- LHC Discovers $\tilde{l}^-$ LOSP $\left\{ \begin{array}{l} m = 200\,\mathrm{GeV} \\ \tilde{l}^- \to l^- + \mathrm{missing} \end{array} \right.$ $\quad \tau = 0.1\,\mathrm{sec}$

  reconstruction gives $\quad m_{X'} = 100\,\mathrm{GeV}$

- Not FO&D: $Y_{FO}(\tilde{l}^-)$ too small

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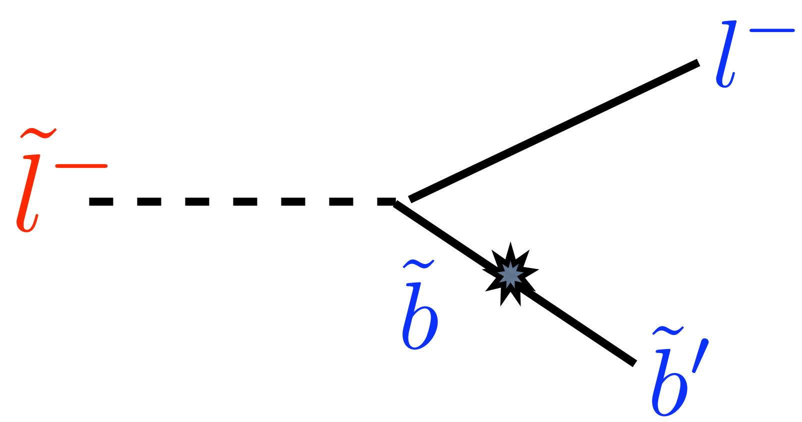
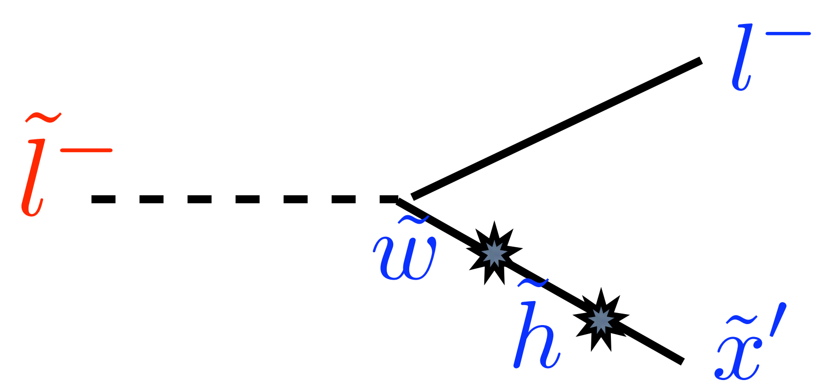
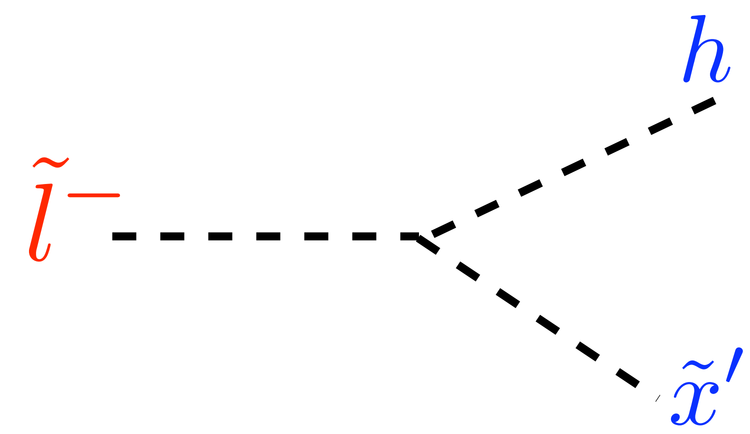


Bino Portal



Higgs Portal



Lepton Portal

Correct signal; but FI from $\quad \tilde{l}^- \to l^- + \tilde{x}' \quad$ gives $\quad \Omega_{\tilde{x}'} = 10^{-2}$

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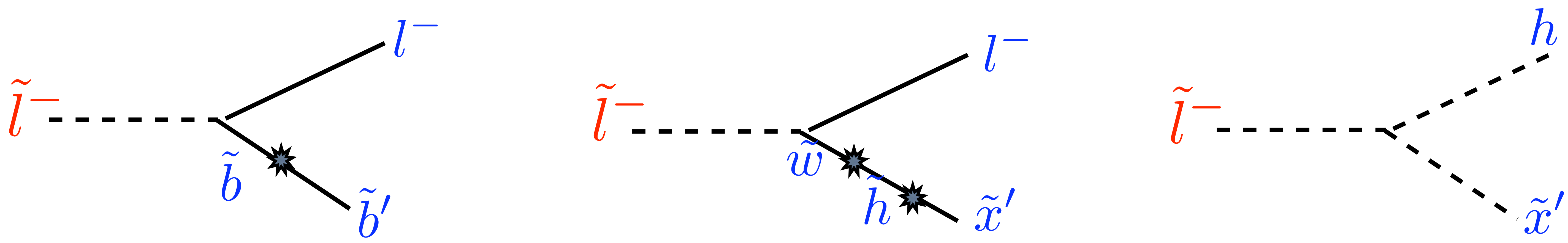
- 

Bino Portal Higgs Portal Lepton Portal

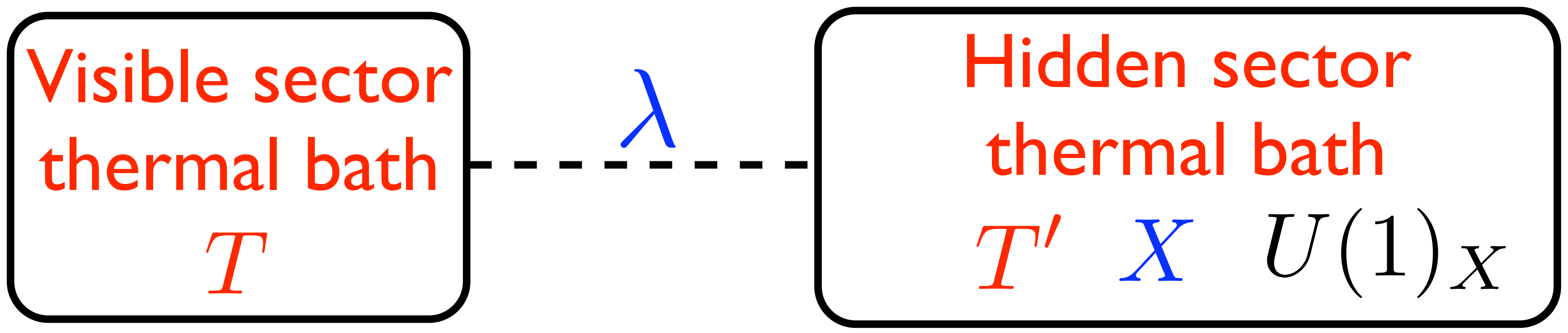
Correct signal; but FI from $\tilde{l}^- \to l^- + \tilde{x}'$ gives $\Omega_{\tilde{x}'} = 10^{-2}$

- Measure other superpartner masses and compute FI abundance from $\tilde{q} \to q\,\tilde{x}', \;\ldots$ $\Omega_{\tilde{x}'} = 0.11 \;\; ??$

III

Asymmetric Freeze-In

$\mathcal{A}\ U(1)_X$ Symmetry in Hidden Sector

❊ 

❊ V has multiple decay modes

$$V \longrightarrow f_1 \qquad \text{(no X)}$$

$$V \longrightarrow f_2 \qquad \text{(contains X)}$$

❊ Non-Thermal: $T' \neq T$
leading to an X asymmetry

$$\varepsilon = \frac{\Gamma(V \to X) - \Gamma(\bar{V} \to \bar{X})}{\Gamma(V \to X) + \Gamma(\bar{V} \to \bar{X})}$$

A $U(1)_X$ Symmetry in Hidden Sector

- Visible sector thermal bath T - - - - λ - - - - Hidden sector thermal bath T' X $U(1)_X$

- V has multiple decay modes

  $V \longrightarrow f_1$ (no X)

  $V \longrightarrow f_2$ (contains X)

- Non-Thermal: $T' \neq T$

  leading to an X asymmetry

  $$\varepsilon = \frac{\Gamma(V \to X) - \Gamma(\bar{V} \to \bar{X})}{\Gamma(V \to X) + \Gamma(\bar{V} \to \bar{X})}$$

- A large symmetric Y_X is annihilated away by a large $\langle \sigma v \rangle'$, leaving

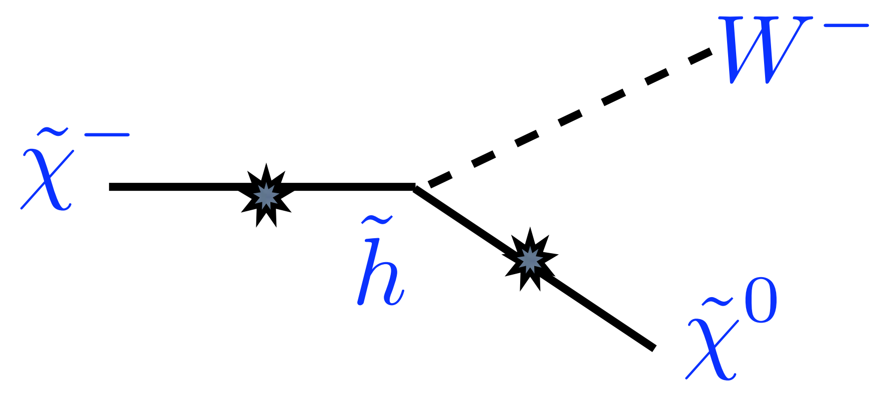
  $$\boxed{\begin{aligned} \eta_X &= \epsilon Y_X \\ \tau_V &= 7.7 \times 10^{-3} \epsilon \ \ \mathrm{s} \end{aligned}}$$

  requiring

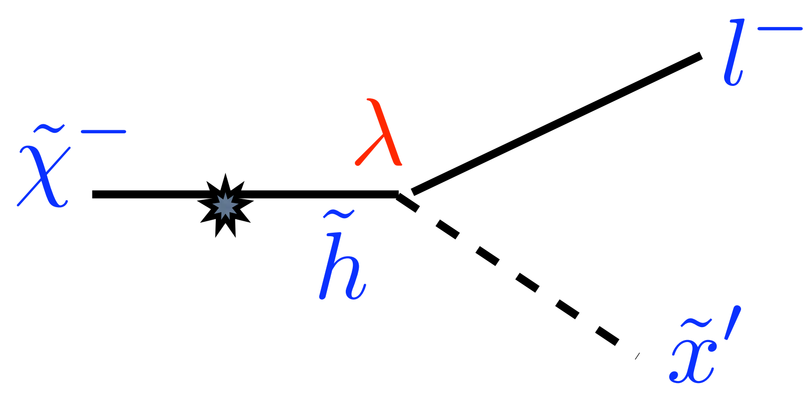
- If $B - L + X$ conserved, simultaneous generation of η_B !!

Asymmetric Freeze-In via $\lambda\, L H_u X'$.

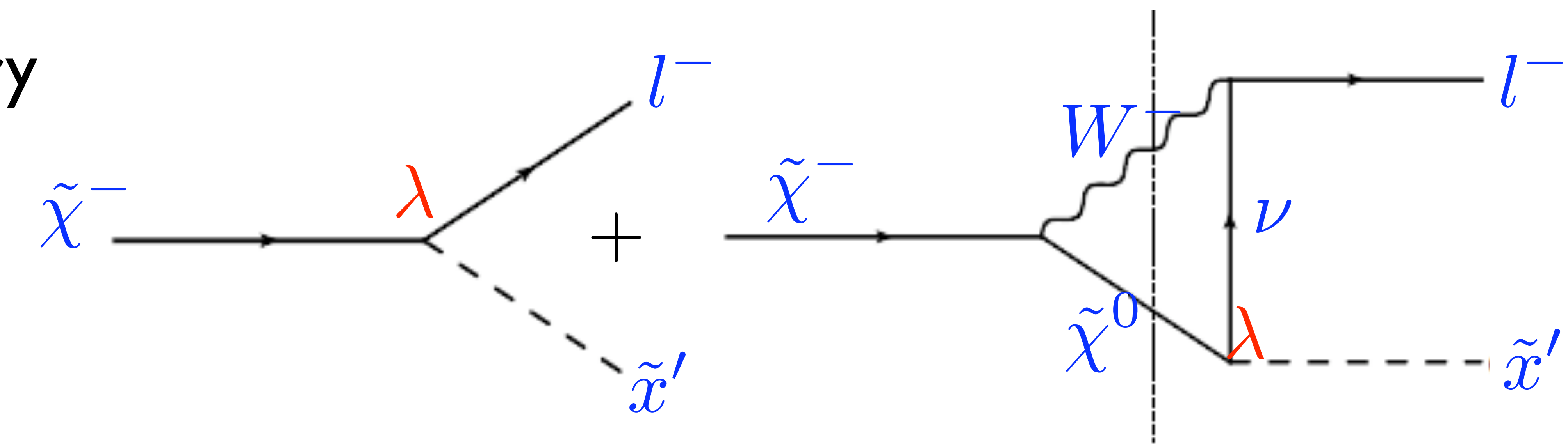
- Non-LOSP $\tilde{\chi}^-$ have fast decays



- They also have slow decays that contribute to FI of $\tilde{x}'$ via $\lambda\, L H_u X'$



- At one-loop an asymmetry is generated in the FI



- $\lambda\, L H_u X'$ conserves $B - L + X$ $\Rightarrow$ $\eta_{B-L} = -\eta_X$

- Sphalerons re-process the lepton asymmetry to give $\eta_B = \dfrac{28}{79} f(\tilde{m}_i)\, \eta_X$ $\Rightarrow$ $\boxed{m_X = 1.6\, f \,\mathrm{GeV}}$

DM Re-construction from LOSP lifetime

$$\tau(\tilde{\chi}^- \to l^- \, \tilde{x}') = 1.4 \times 10^{-8}\mathrm{s} \left(\frac{\varepsilon}{10^{-5}}\right) \left(\frac{m_X}{2\,\mathrm{GeV}}\right) \left(\frac{200\,\mathrm{GeV}}{m_{\tilde{\chi}^+}}\right)^2 \left(\frac{10^2}{g_*}\right)^{3/2}$$

- $\tilde{\chi}^-$ has fast decay $\tilde{\chi}^- \to W^- \, \tilde{\chi}^0$

- Must relate $\tau(\tilde{\chi}^- \to l^- \, \tilde{x}')$ to LOSP lifetime. eg for $\tilde{l}^-$ LOSP

$$\tau(\tilde{l}^- \to h \, \tilde{x}') = r \left(\frac{m_{\tilde{\chi}^-}}{m_{\tilde{l}^-}}\right) \tau(\tilde{\chi}^- \to l^- \, \tilde{x}')$$

susy mixing angles, etc

Must measure: LOSP lifetime
susy spectrum
CP violating phases

IV

Freeze-In

of

Gravitino Dark Matter

Cosmological Bounds on Gravitinos

All susy theories contain $\tilde{G}$:

interactions: $$\frac{1}{m_{3/2} M_{Pl}} \tilde{G} \left(m_{\tilde{q}}^2 \, q \tilde{q}^* + m_{\tilde{g}} \, \tilde{g} \sigma^{\mu\nu} G_{\mu\nu} + ... \right)$$

mass: $$\mathrm{eV} < m_{3/2} < 100 \, \mathrm{TeV}$$

Over much of mass range $\tilde{G}$ is LSP!

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Cosmological constraints on the light stable gravitino

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Department of Physics, Tohoku University, Sendai 980, Japan

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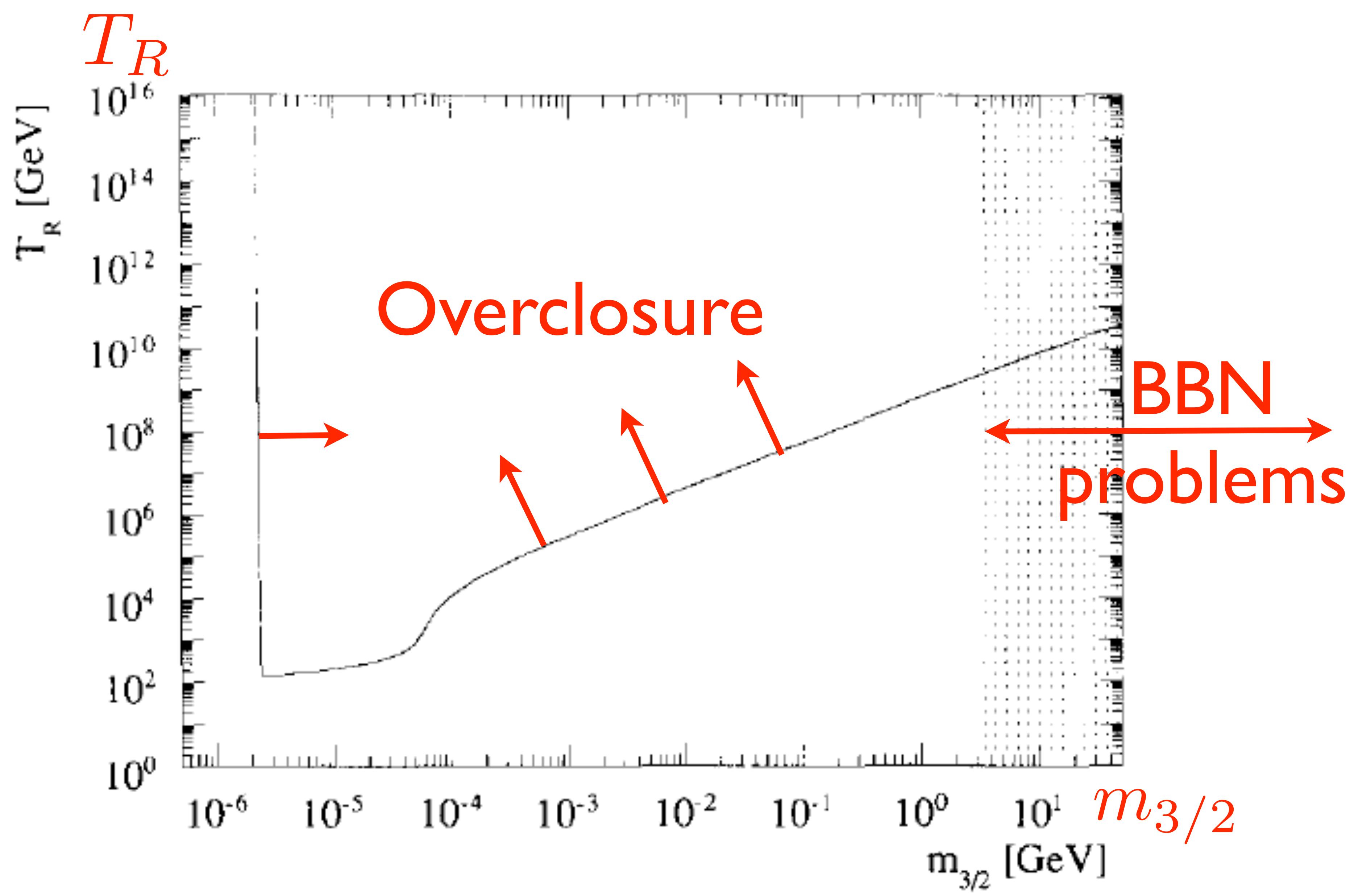

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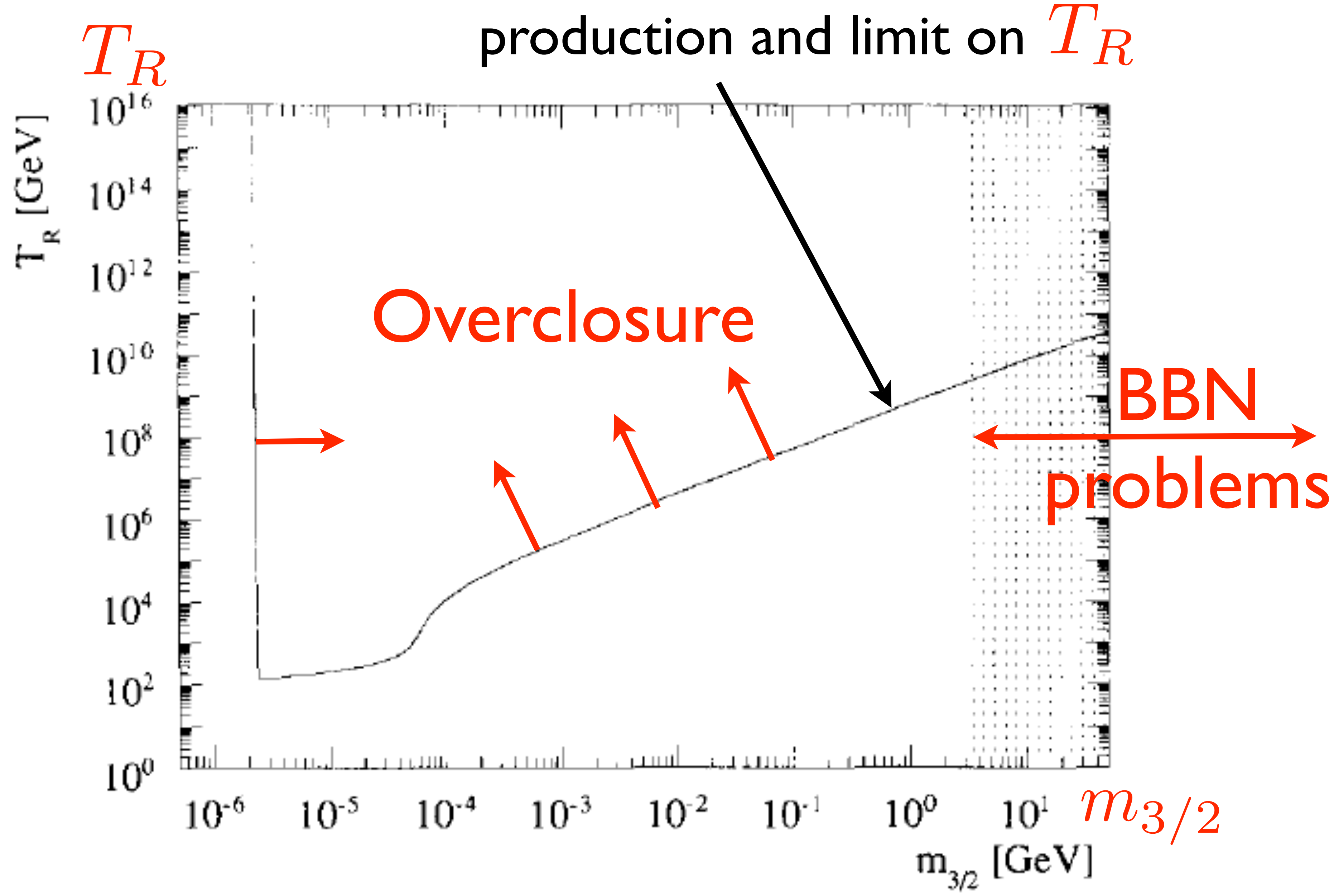
Much effort: UV sensitive scattering production and limit on T_R



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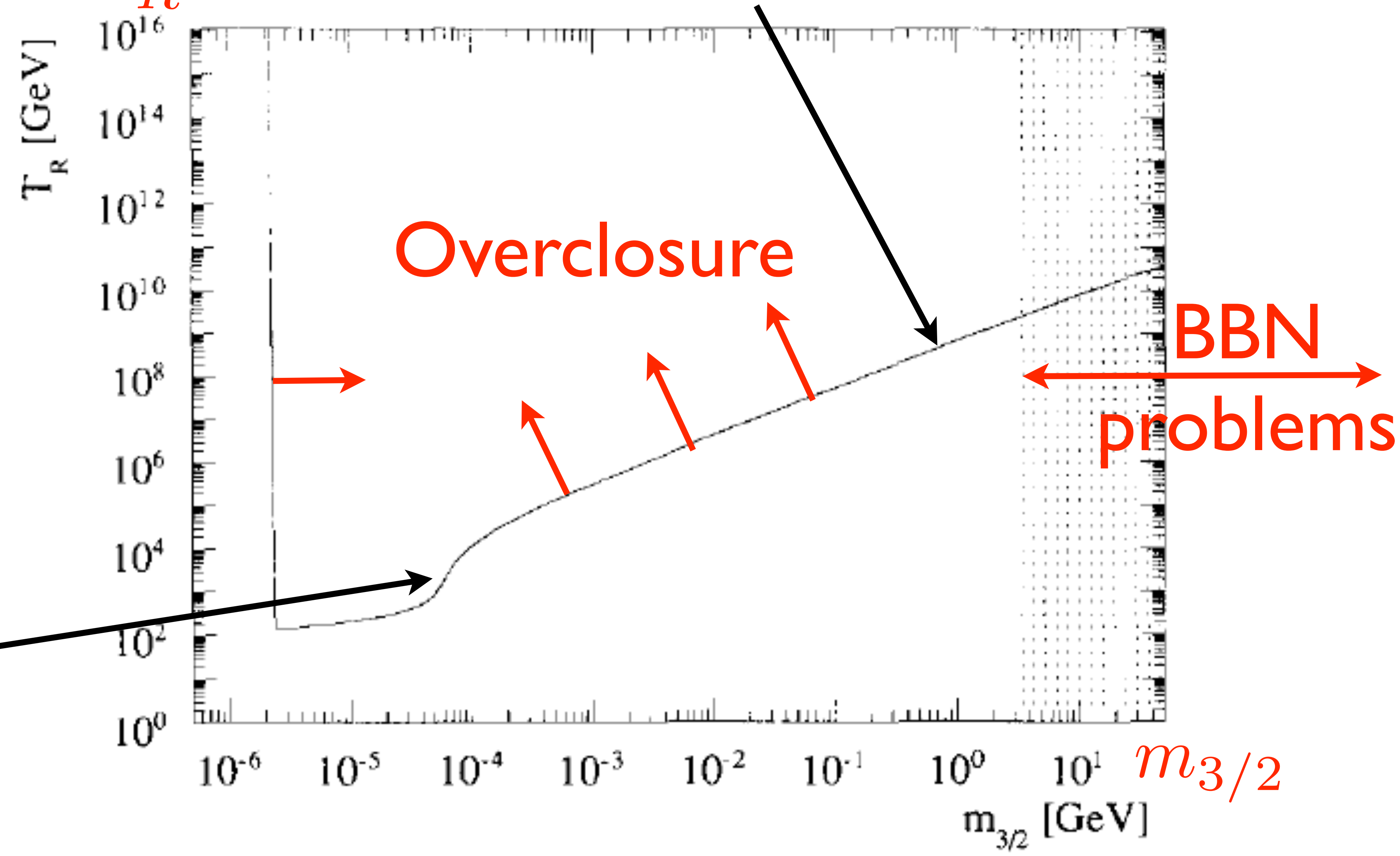


What's going on here?

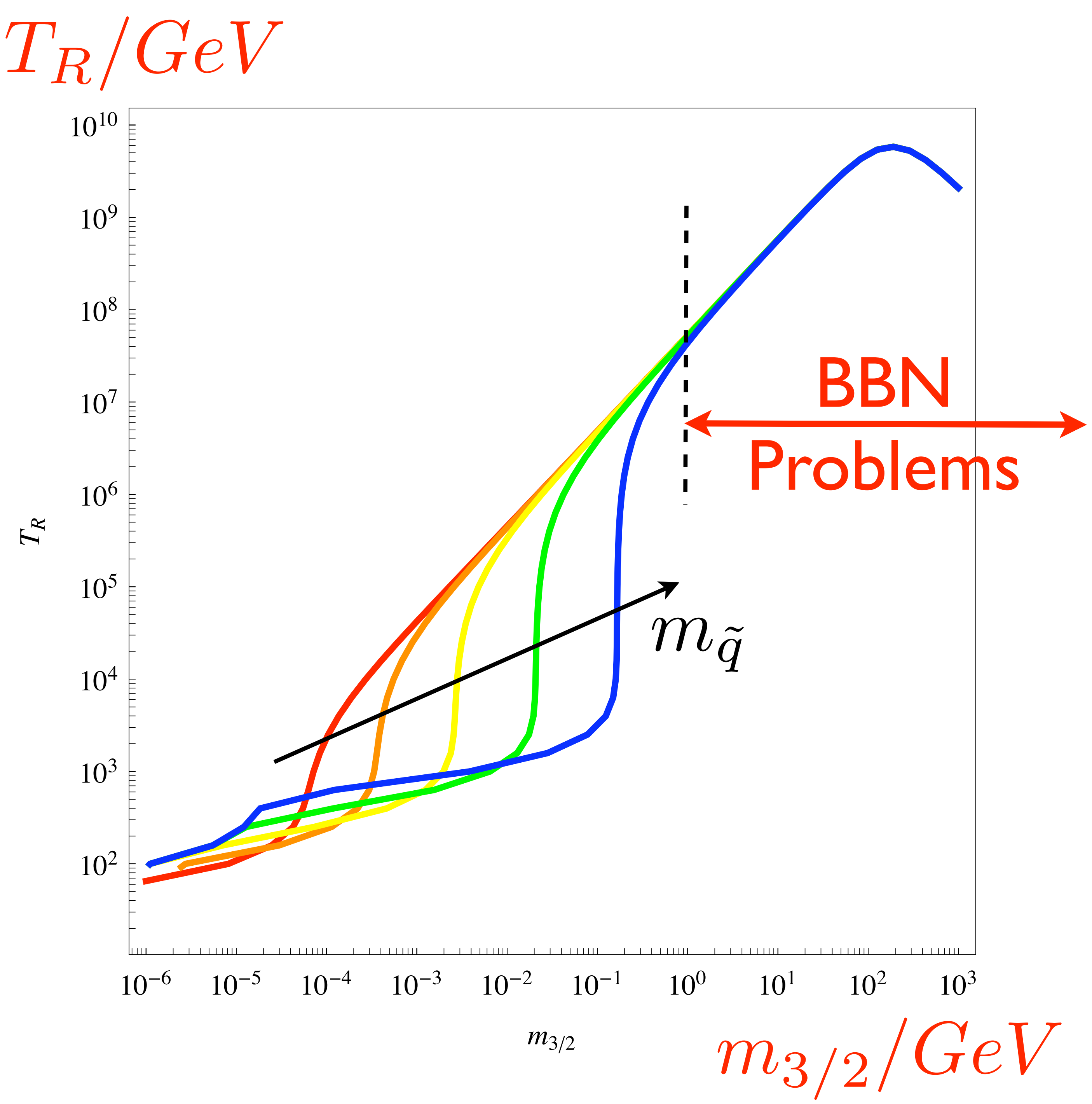
Gravitino DM from Freeze-In

$$\tilde{q} \to q\,\tilde{G}$$

$$\tilde{g} \to g\,\tilde{G}$$

$$\tilde{l} \to l\,\tilde{G}$$

$$Y_{3/2} \propto \frac{1}{m_{3/2}^2} \sum_i g_i\, \tilde{m}_i^3$$



Occurs over a large fraction of the allowed T_R

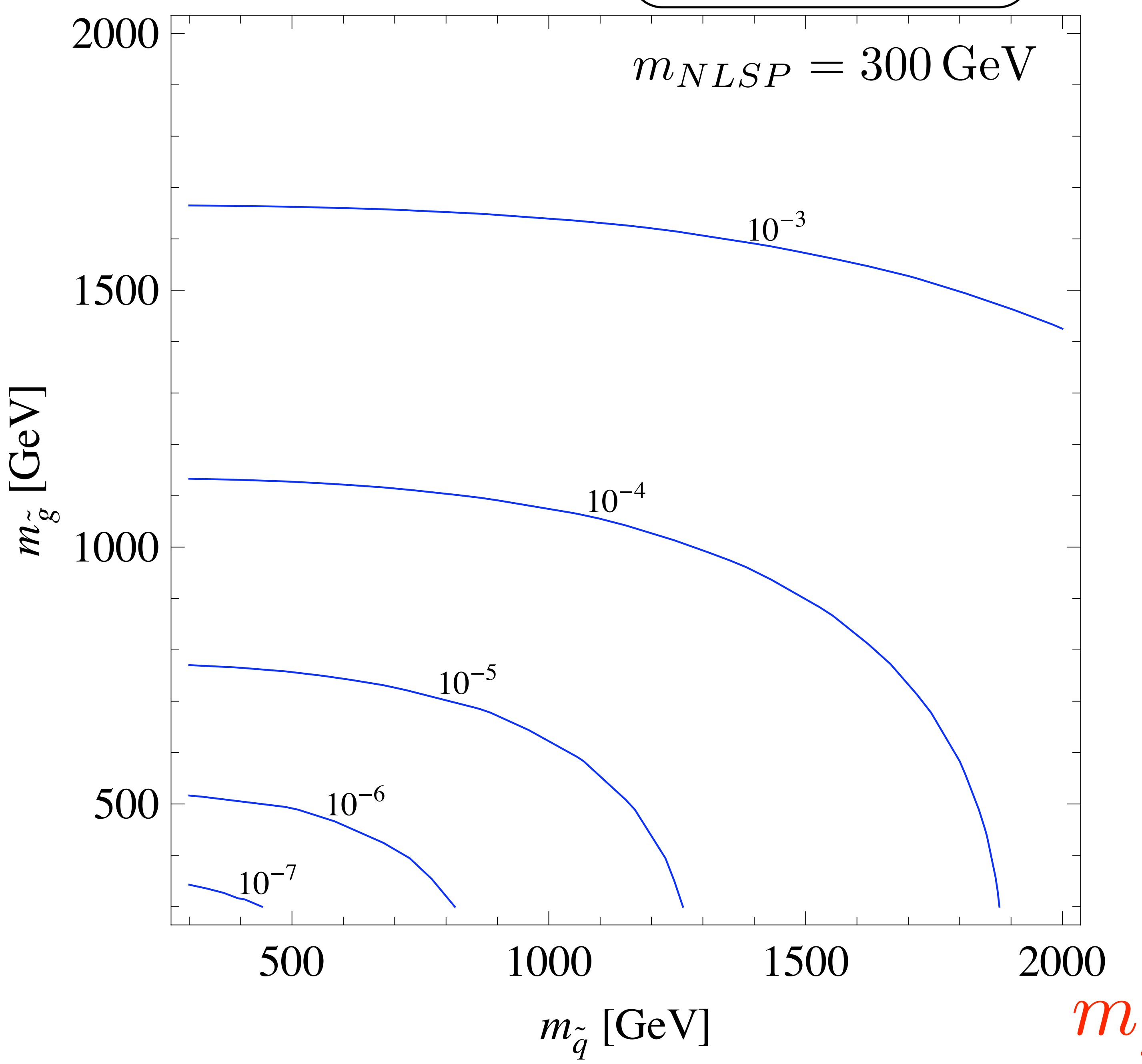
LHC Reconstruction of Gravitino DM

$\Omega\, h^2\, (\tilde{m}_i, m_{3/2})$ independent of T_R determines $m_{3/2}$

Allowing calculation of $\tau_{NLSP}\, (\tilde{m}_i)$

$m_{\tilde{q}}$

$\boxed{\tau_{NLSP}/\mathrm{sec}}$



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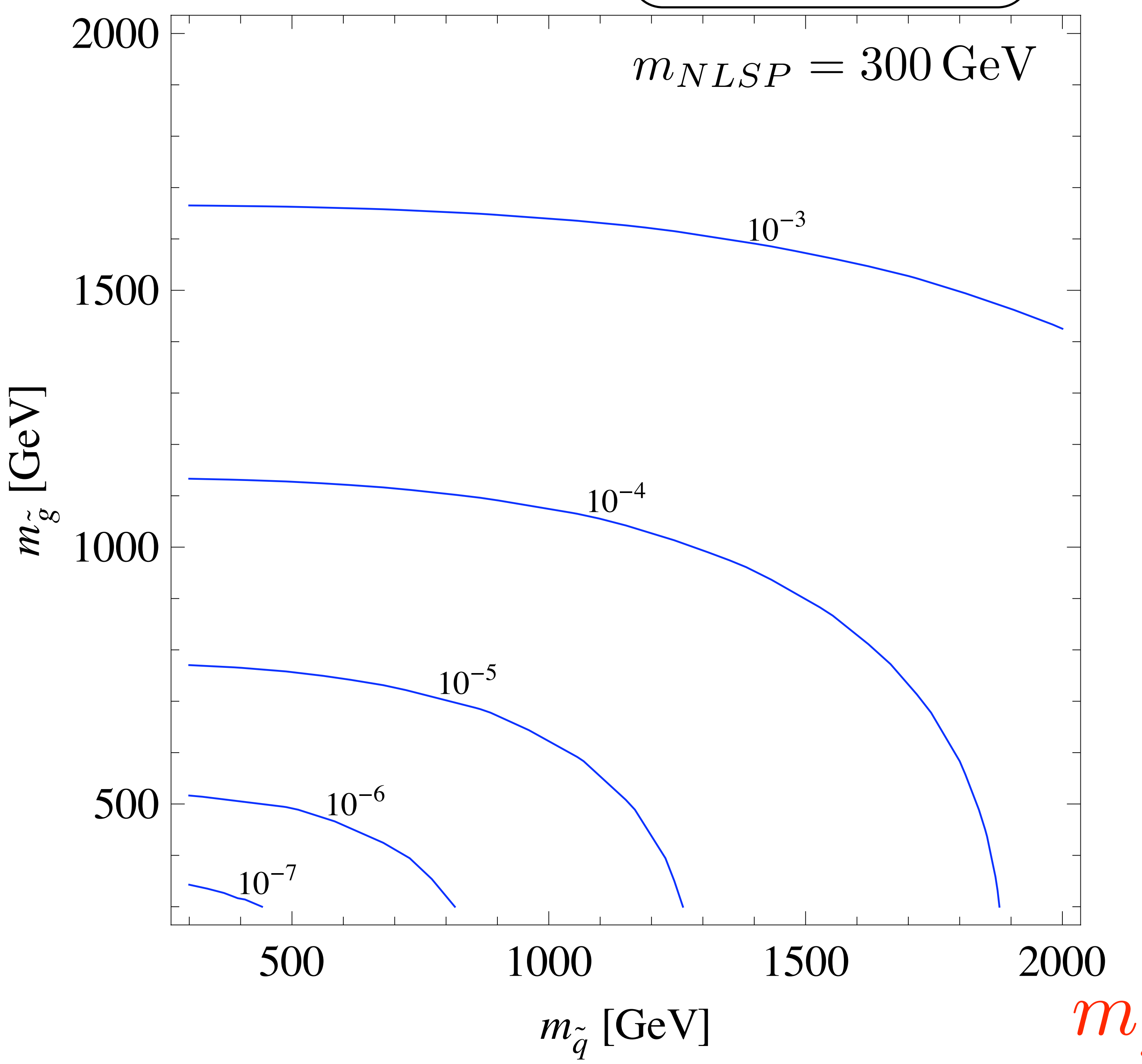

$m_{\tilde{g}}$

eg $\tilde{l} \to l\,\tilde{G}$

$$c\tau \;\sim\; (10^2\text{–}10^6)\,\left(\frac{300\,\mathrm{GeV}}{m_{\tilde{l}}}\right)^5 \;\mathrm{meters}$$

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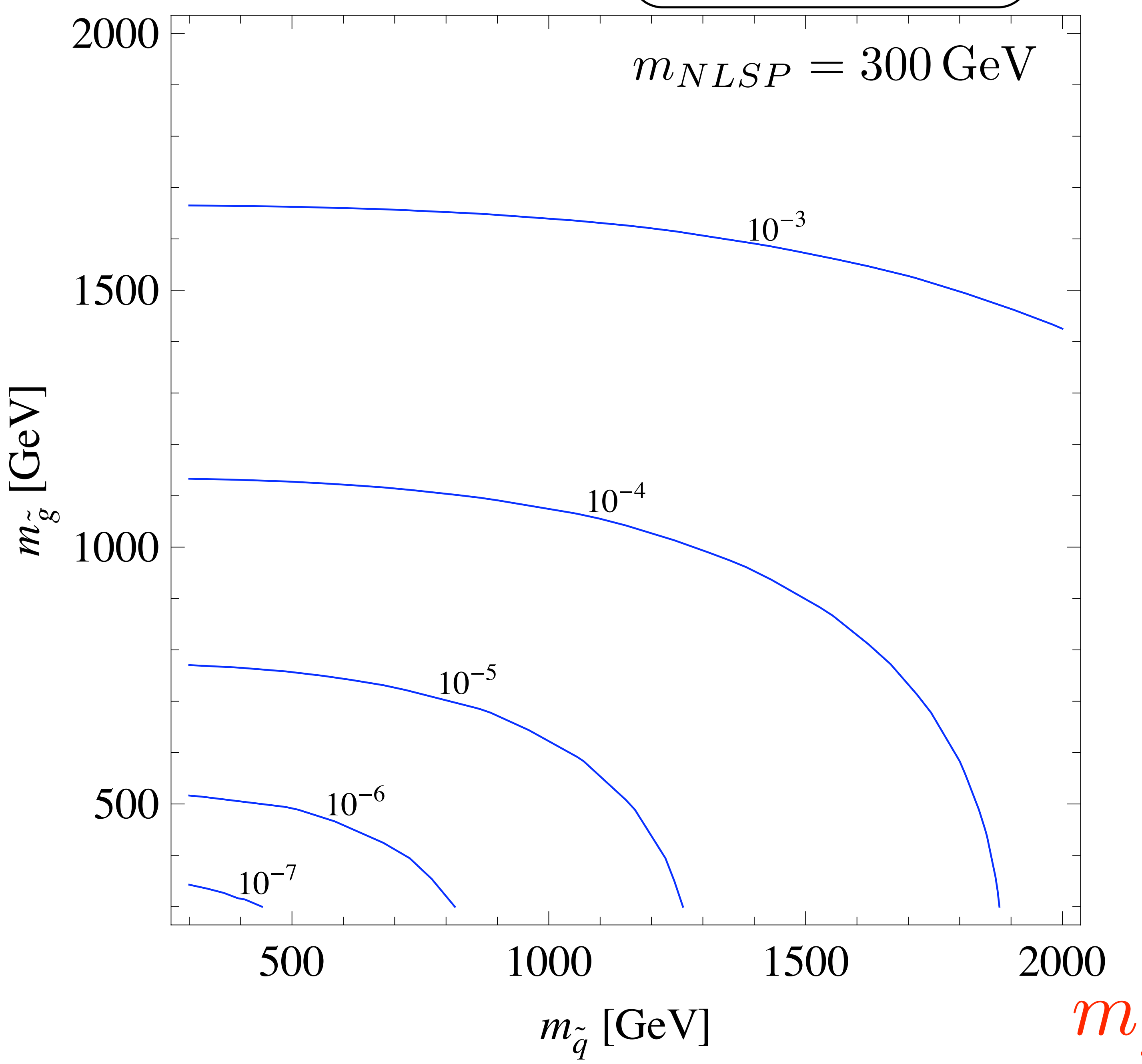

$m_{\tilde{g}}$

eg $\tilde{l} \rightarrow l\, \tilde{G}$

$$c\tau \;\sim\; (10^2\text{–}10^6)\left(\frac{300\,\mathrm{GeV}}{m_{\tilde{l}}}\right)^5 \;\mathrm{meters}$$

LHC directly measures
the cosmological production process!

Conclusions

There are 2 thermal production mechanisms with

- Initial state: particles with thermal distributions (m_i)
- Production IR dominated at $T \sim v$ (independent of $T_R, \eta, \ldots$)
- Measurements at LHC may allow a prediction of $\Omega_D h^2$

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Freeze-Out

$$\langle \sigma v \rangle = \frac{10^{-4}}{(200\,\mathrm{GeV})^2}$$

Freeze-In

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Freeze-Out

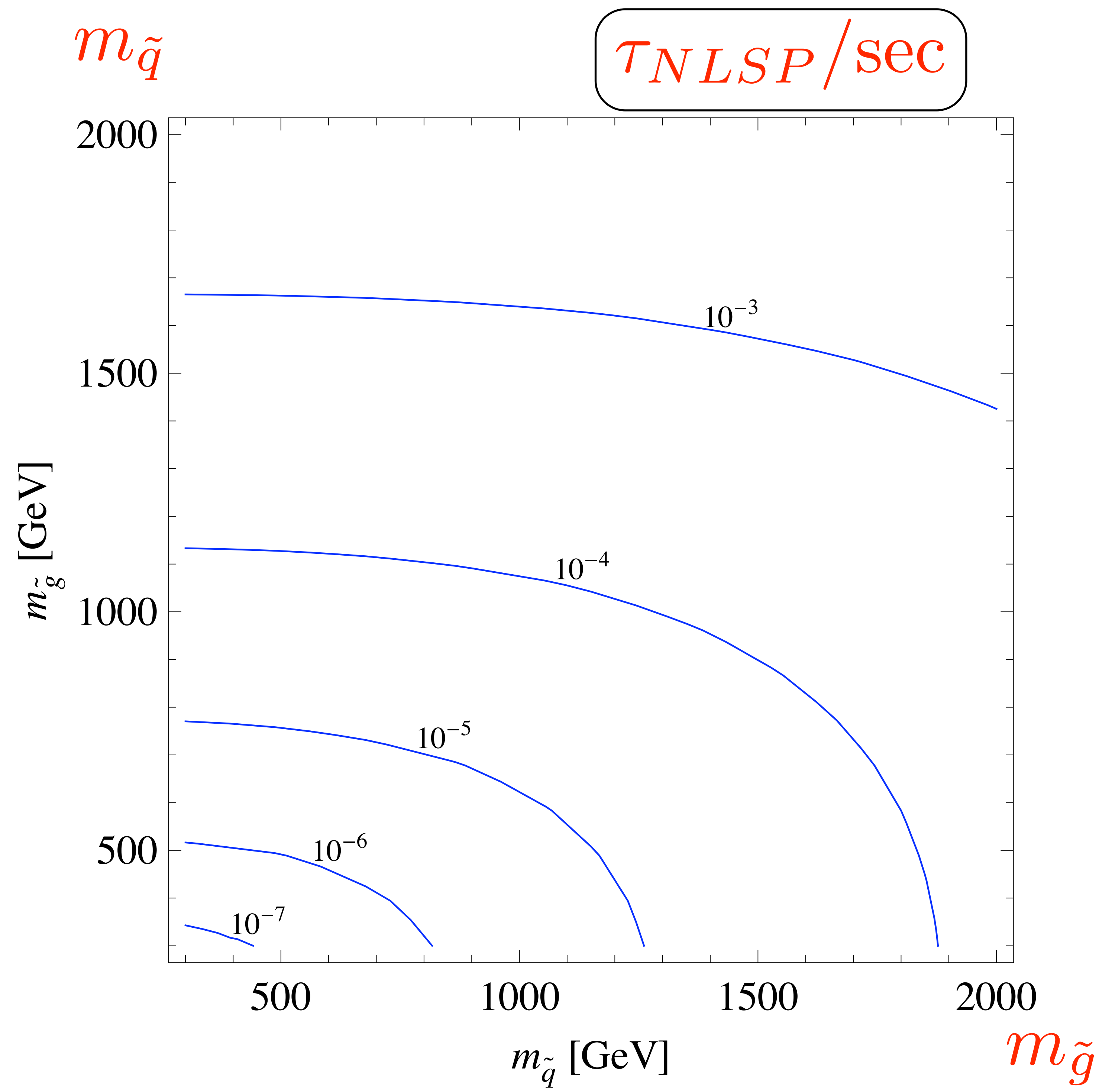
$$\langle \sigma v \rangle = \frac{10^{-4}}{(200\,\text{GeV})^2}$$

Freeze-In

$$\boxed{\tau_{LOSP} = 7.7 \times 10^{-3}\text{s}\;\, g_{LOSP} \left(\frac{m_X}{100\,\text{GeV}} \right) \left(\frac{300\,\text{GeV}}{m_{LOSP}} \right)^2 \left(\frac{10^2}{g_*} \right)^{3/2}}$$

- Only FI has an asymmetric version $\times\ \epsilon$

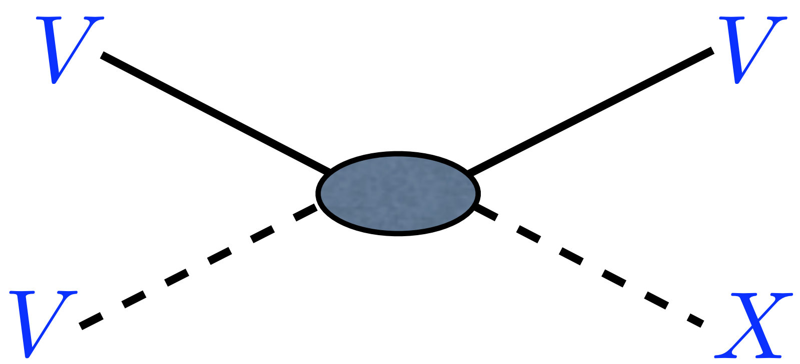
Gravitinos from Freeze-In make Superb Susy DM Candidate



Higher Dimensional Operators and UV Sensitivity

- d=5

$$\frac{1}{M_*} VVVX$$



$$Y_X \sim \frac{M_{Pl} T}{M_*^2}$$

Decays typically dominate only if $T_R < 20\,\mathrm{TeV}$

Higher Dimensional Operators and UV Sensitivity

- d=5

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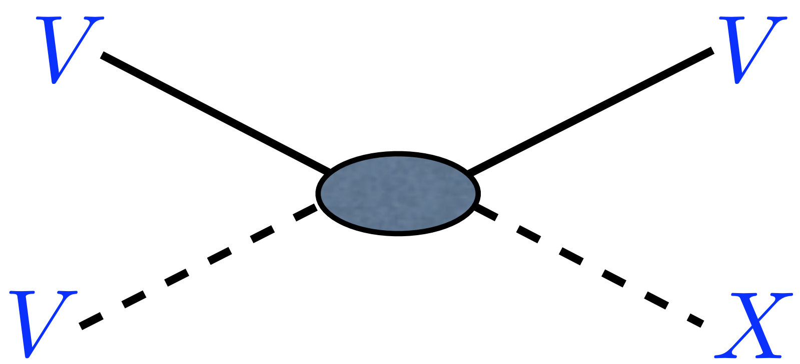


$$Y_X \sim \frac{M_{Pl} T}{M_*^2}$$

Decays typically dominate only if $T_R < 20\,\mathrm{TeV}$

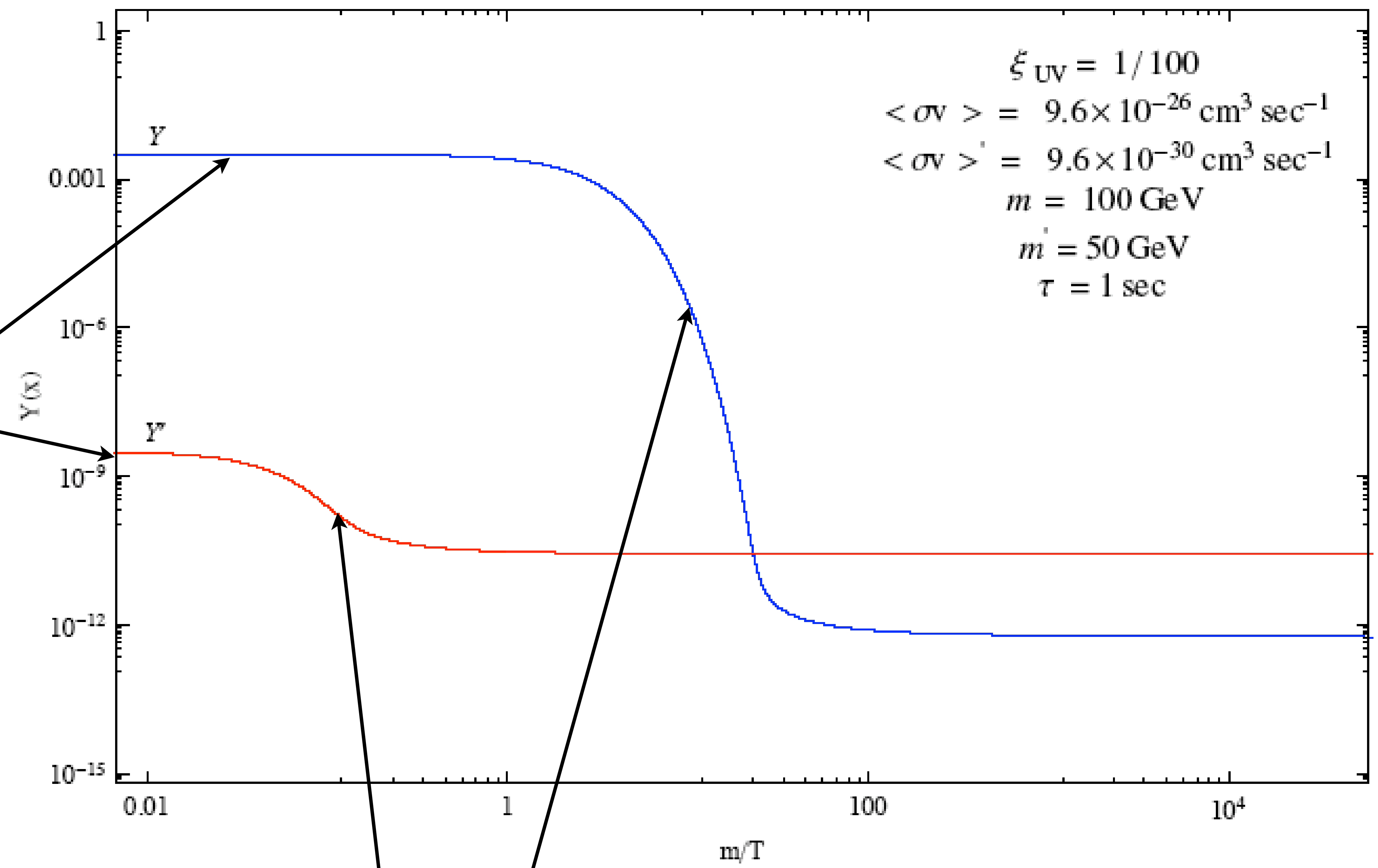
- Consider a universal small portal coupling λ

$$\lambda\, O_4 + \frac{\lambda}{M_*} O_5$$

IR domination by O_4 if $\boxed{T_R < \frac{M_*^2}{m}}$

eg $\quad M_* \sim 10^9\,\mathrm{GeV}$, $\; m \sim v \sim 200\,\mathrm{GeV}$ $\;\Longrightarrow\;$ $T_R < 10^{16}\,\mathrm{GeV}$

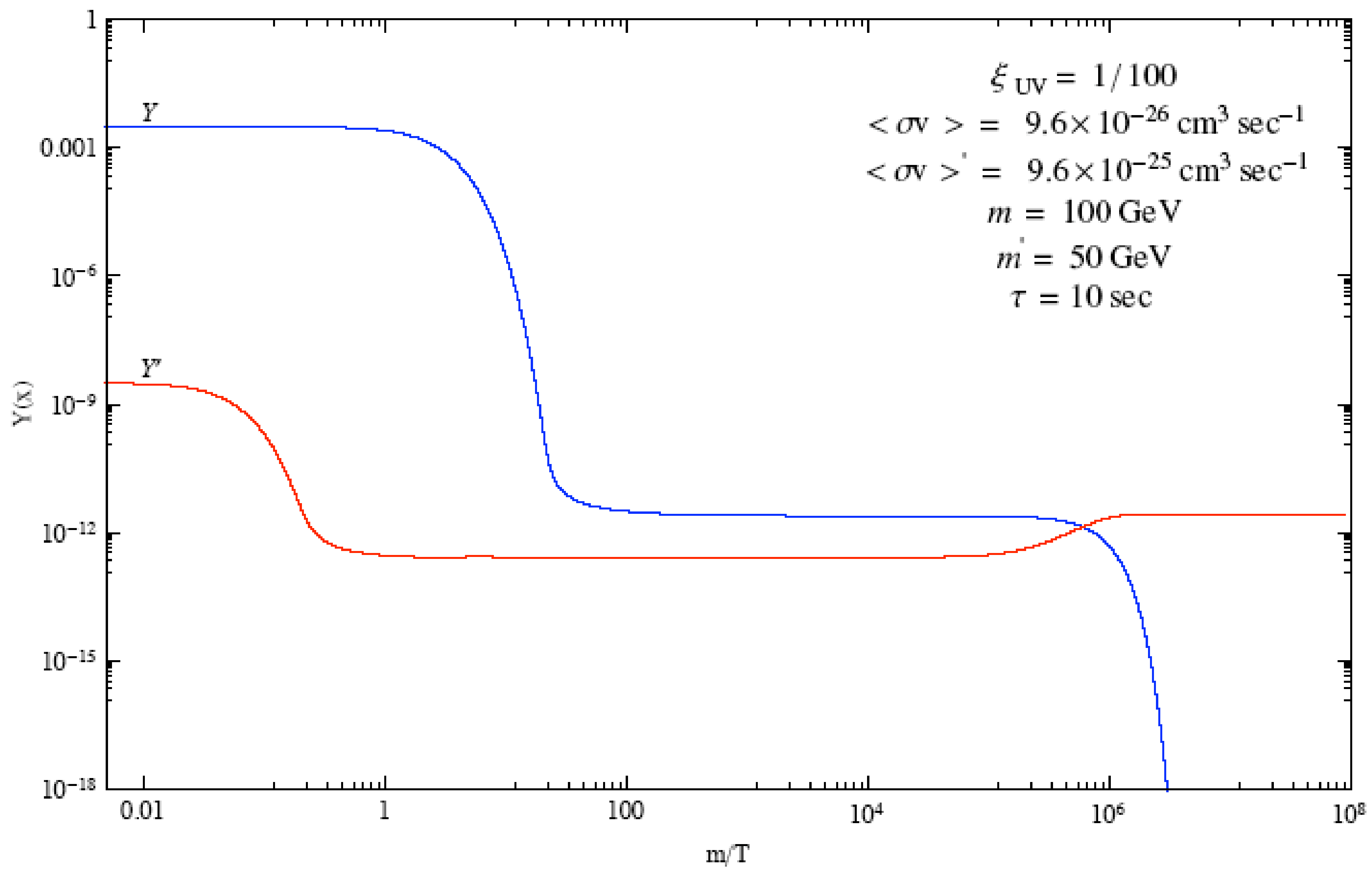
Yield Plots: FO and FO'



$T' \ll T$

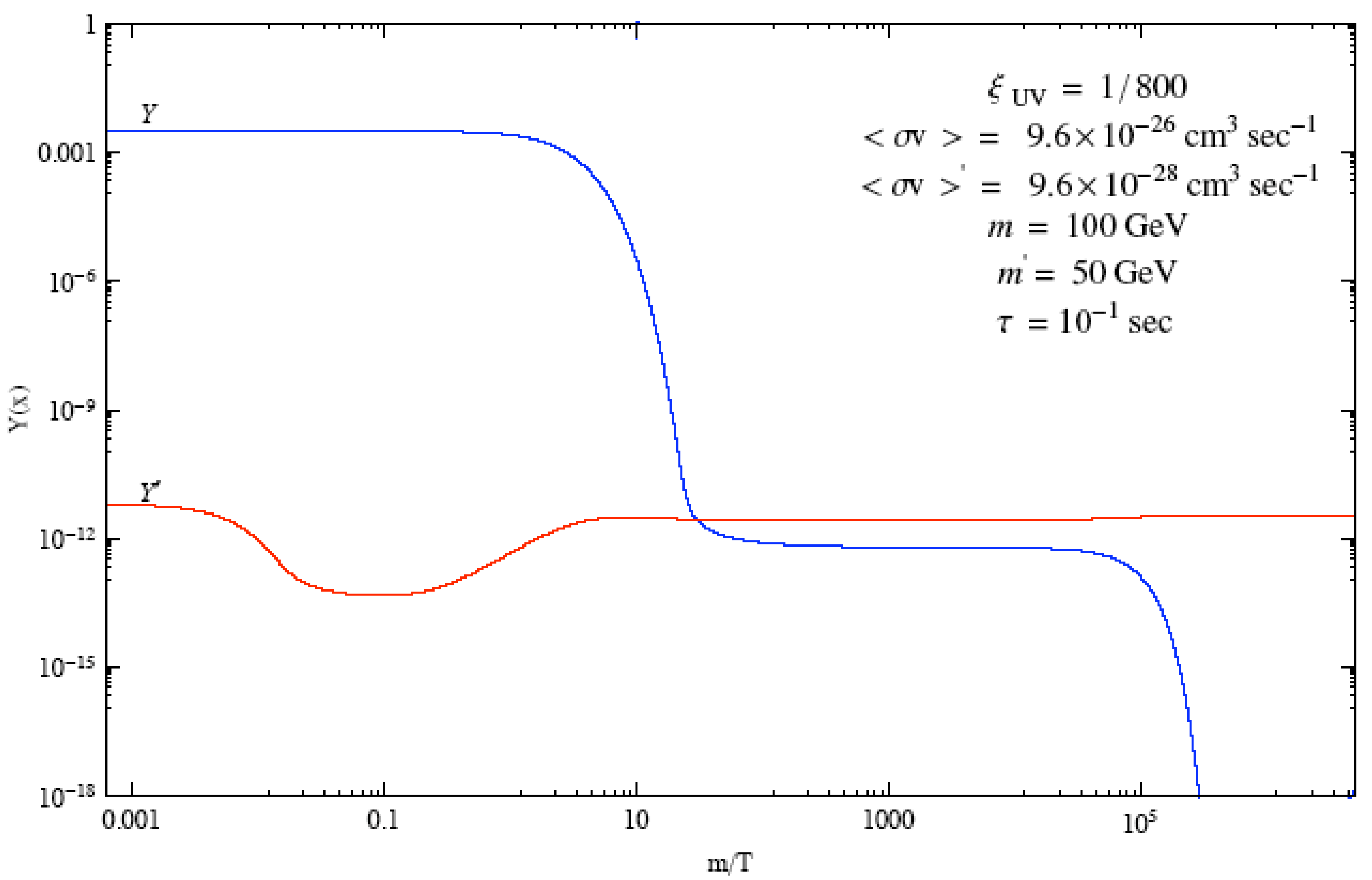
$\langle \sigma v \rangle' \ll \langle \sigma v \rangle$ ⟹ FO$'$ wins

Yield Plots: FO and Decay; FI



Freeze-Out and Decay of LOSP wins

Increase Γ by factor 100



Freeze-In wins