Ann Arbor
Michigan

October, 2010

Freeze-In of Weak-Scale Dark Matter

Lawrence Hall
University of California, Berkeley

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

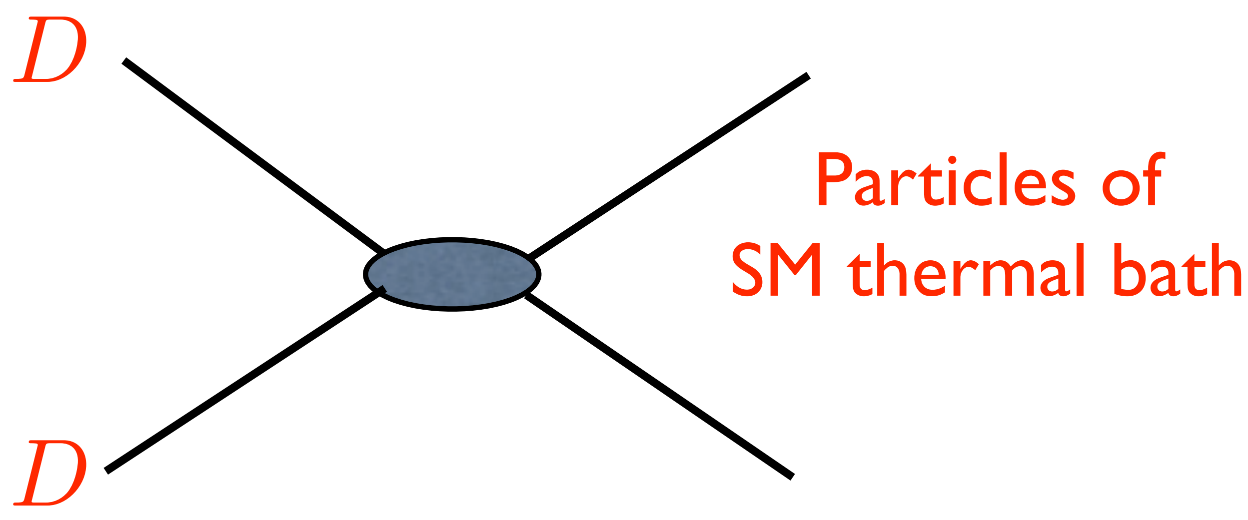
Cliff Cheung, Gilly Elor, LJH, and Piyush Kumar arXiv:1010.0022 — Hidden Sector Freeze-In: I) Cosmology

Cliff Cheung, Gilly Elor, LJH, and Piyush Kumar arXiv:1010.0024 — Hidden Sector Freeze-In: II) LHC Signals

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

Features of Freeze-Out

- Relic abundance arises from calculable mechanism



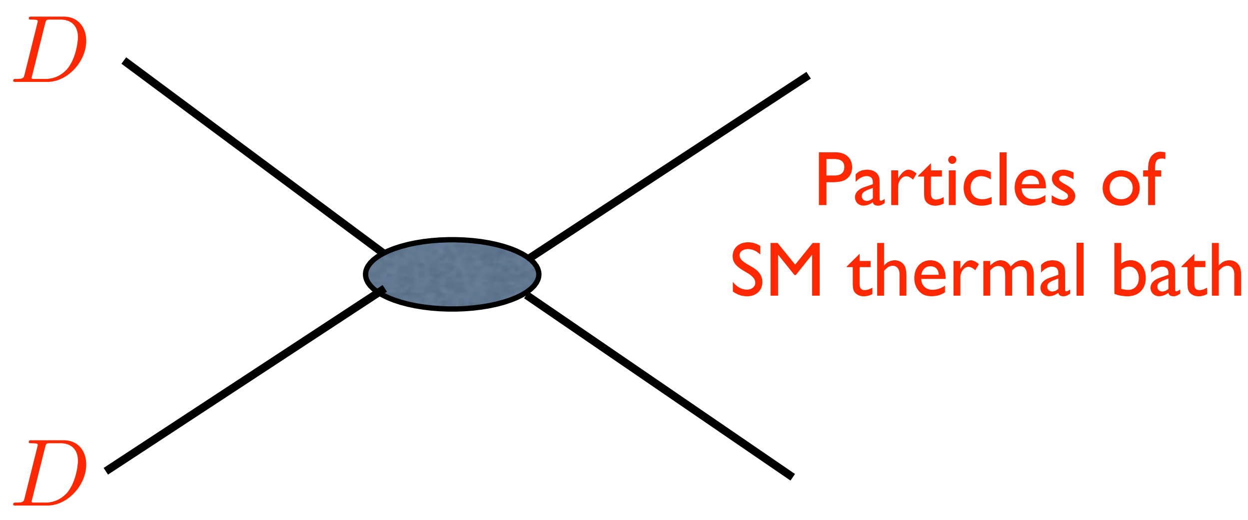
- Initial thermal state, IR dominated → No dependence on unknown UV physics: T_R, initial conditions, ...

- Measurements at LHC may allow a prediction of $\Omega_D h^2$

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

Features of Freeze-Out

- Relic abundance arises from calculable mechanism



- Initial thermal state, IR dominated $\Longrightarrow$ No dependence on unknown UV physics: T_R, initial conditions, ...

- Measurements at LHC may allow a prediction of $\Omega_D h^2$

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

A WIMP miracle?

Seek Alternative Mechanism

- Initial state: particles with thermal distributions (m_i)

- Production is IR dominated -- ie occurs at $T \sim m_i$

  $\Longrightarrow$ No sensitivity to initial conditions: $T_R, \eta, ...$

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

  $\Longrightarrow$ $m_i \lesssim v$ New Physics at the Weak Scale

Seek Alternative Mechanism

- Initial state: particles with thermal distributions (m_i)

- Production is IR dominated -- ie occurs at $T \sim m_i$

  ⟹ No sensitivity to initial conditions: $T_R, \eta, \ldots$

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

  ⟹ $m_i \lesssim v$ New Physics at the Weak Scale

Drop $T_{eq} \sim v^2/M_{Pl}$; Stress LHC tests

Thermal Properties of DM at T ~ v

Three possibilities

1. Part of SM 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

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

Aspects of Freeze-In:

(I) The Mechanism and Prediction

(II) General Frameworks and Features

(III) Supersymmetric Models and LHC Signals

Aspects of Freeze-In:

(I) The Mechanism and Prediction

(II) General Frameworks and Features

(III) Supersymmetric Models and LHC Signals

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

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

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 Portal Coupling

- FIMP DM:

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

  eg d=4

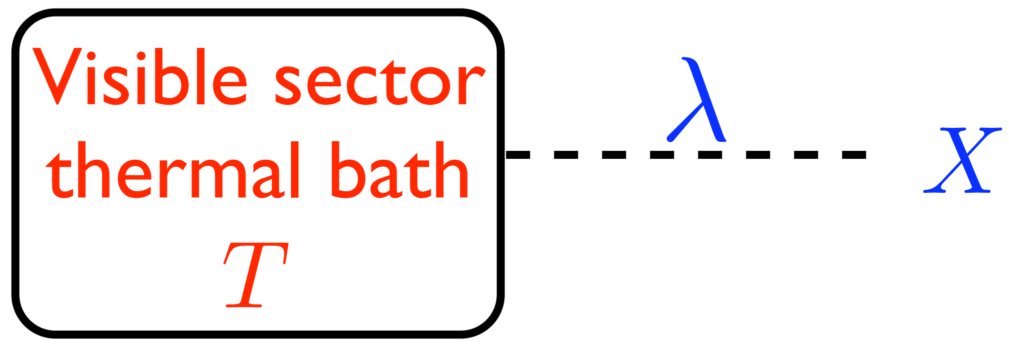
  $10^{-13} < \lambda < 10^{-6}$

  Hidden DM:

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

The Portal Coupling

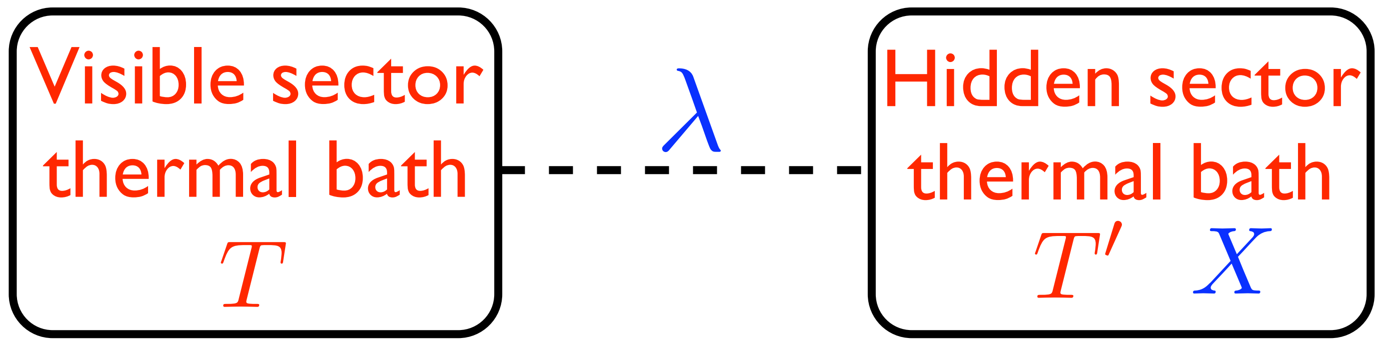
- FIMP DM:



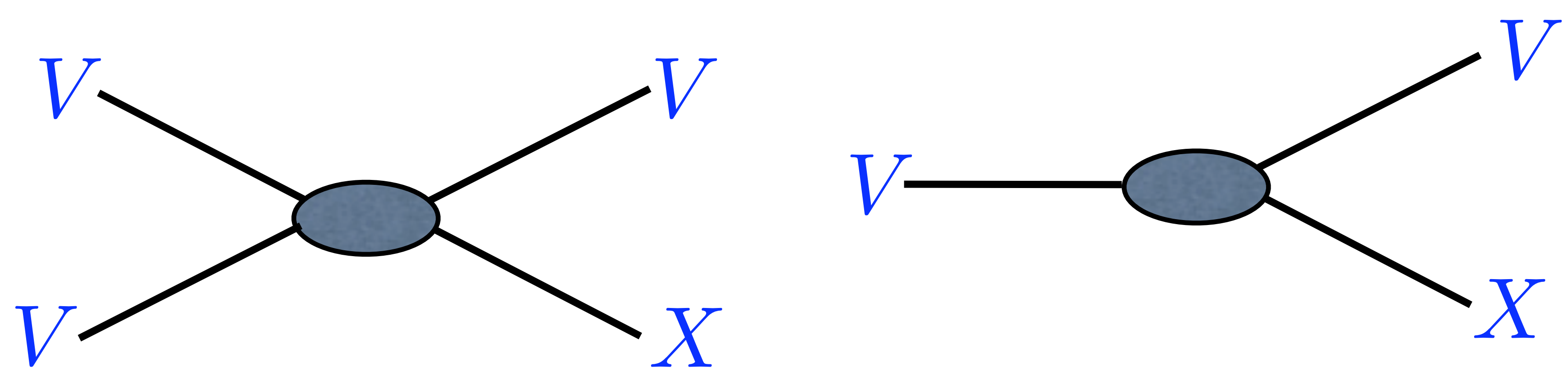
eg d=4

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

Hidden DM:



- Allows X production



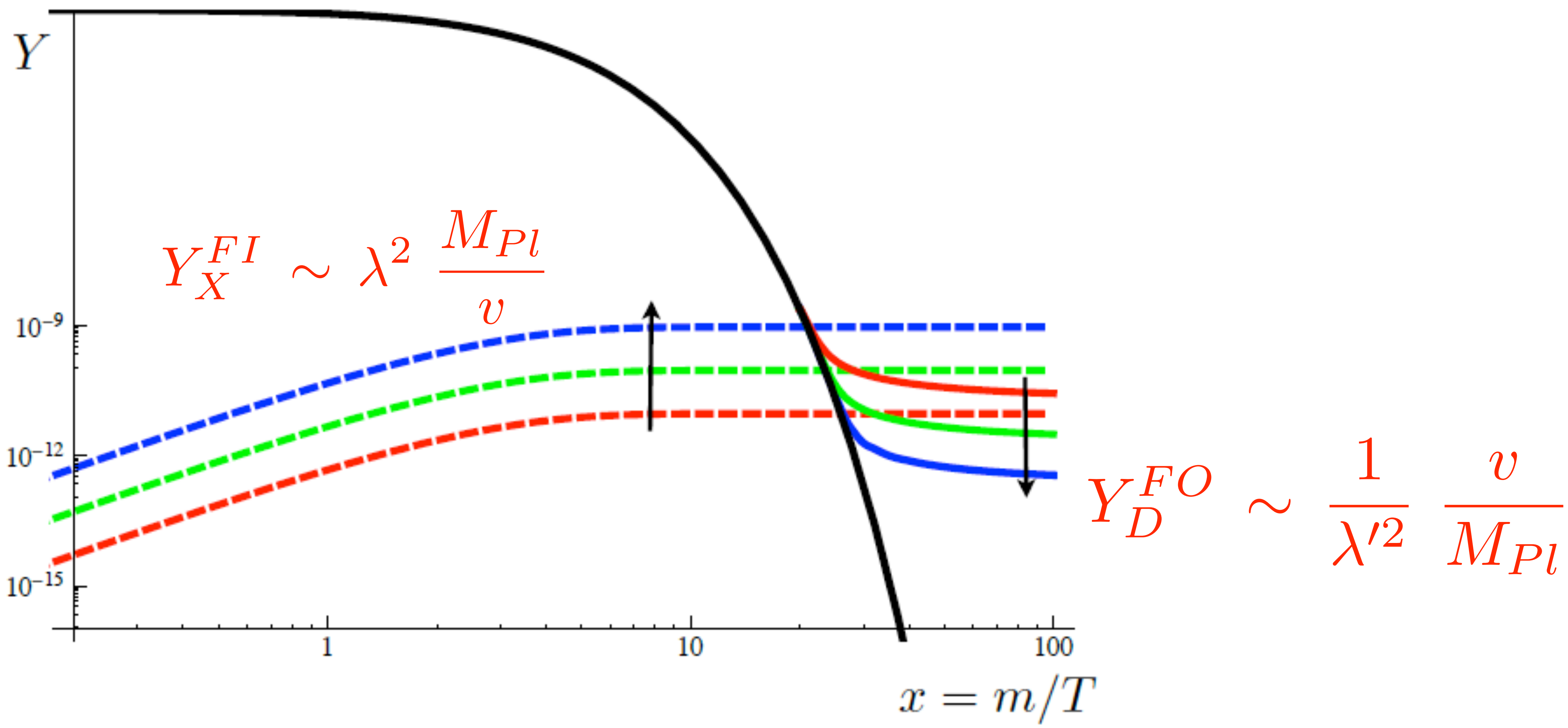
- Dimensional analysis

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

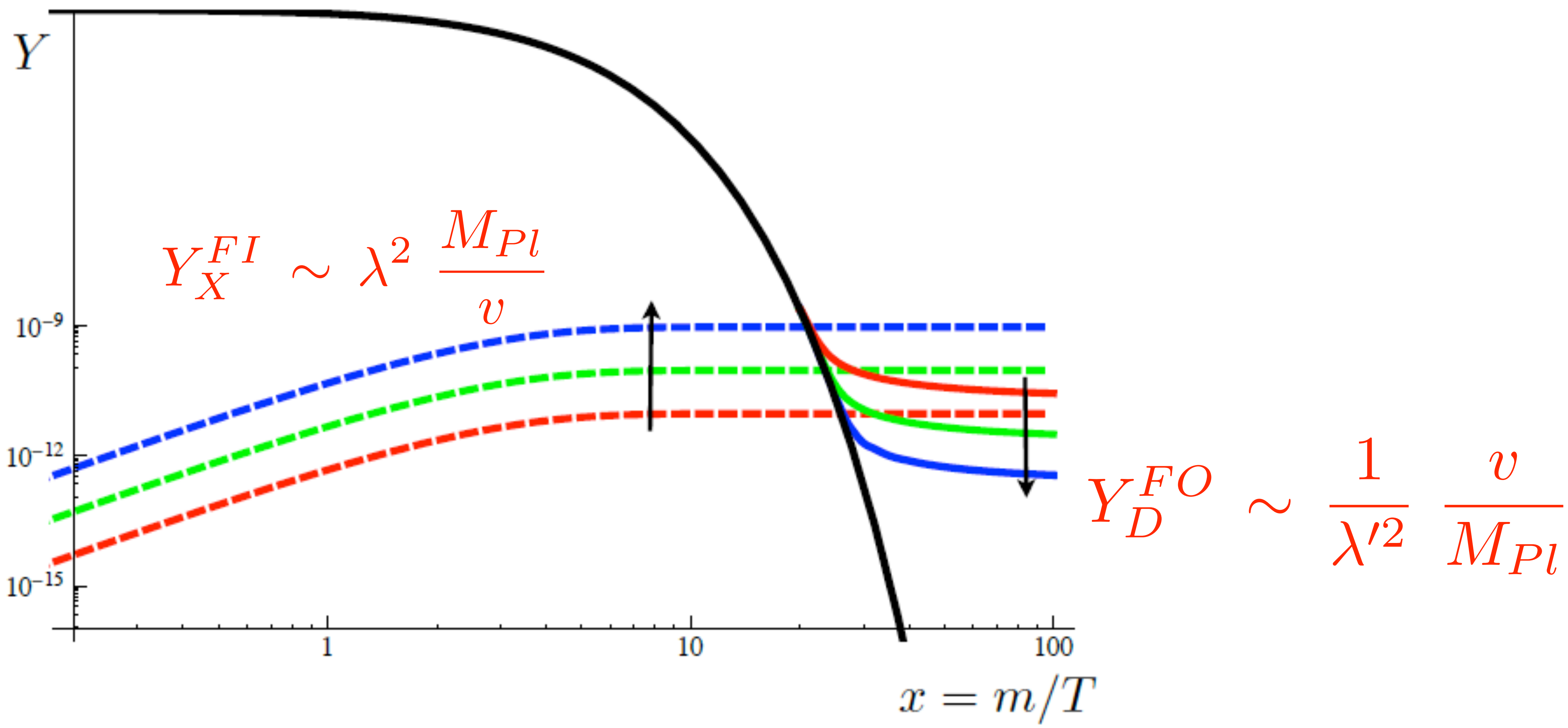
- IR dominated; cutoff by masses

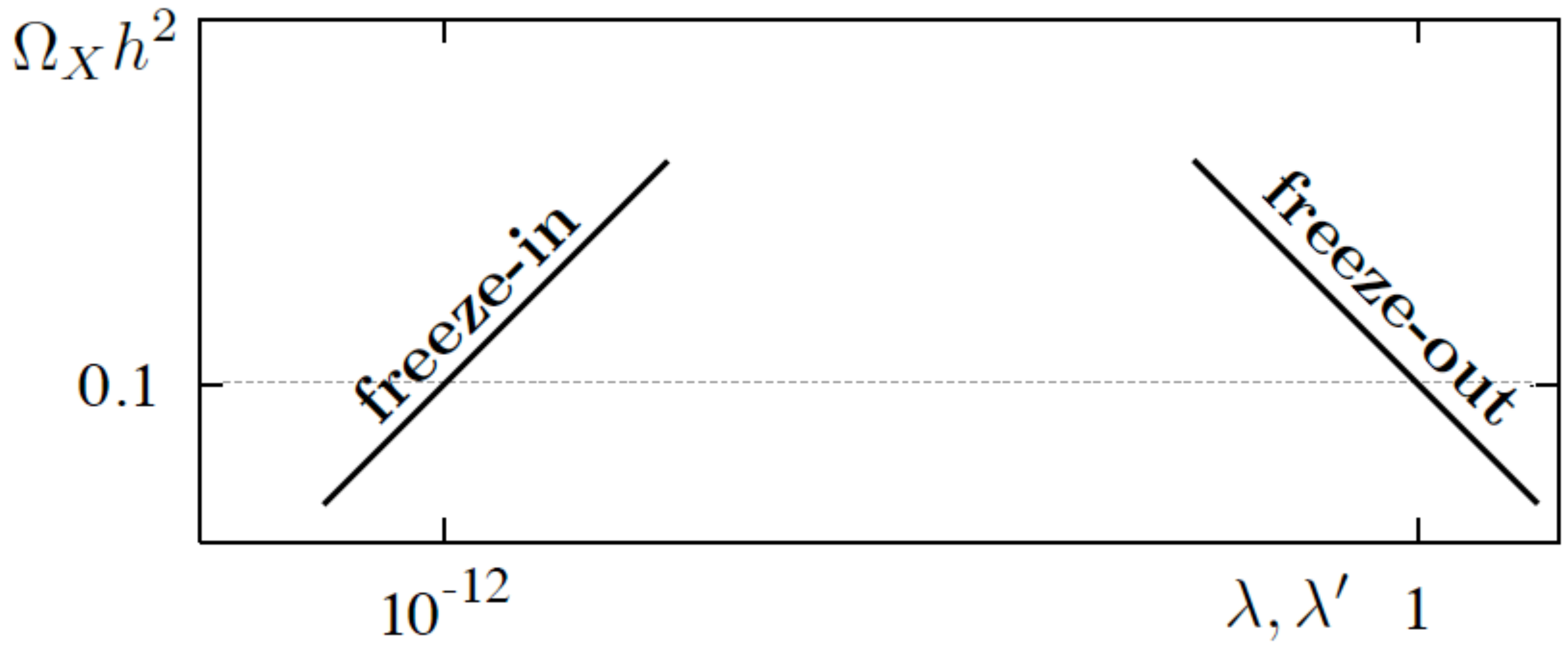
$$\boxed{Y_X \sim \lambda^2 \frac{M_{Pl}}{v}}$$

Heading "In" and "Out" of Equilibrium

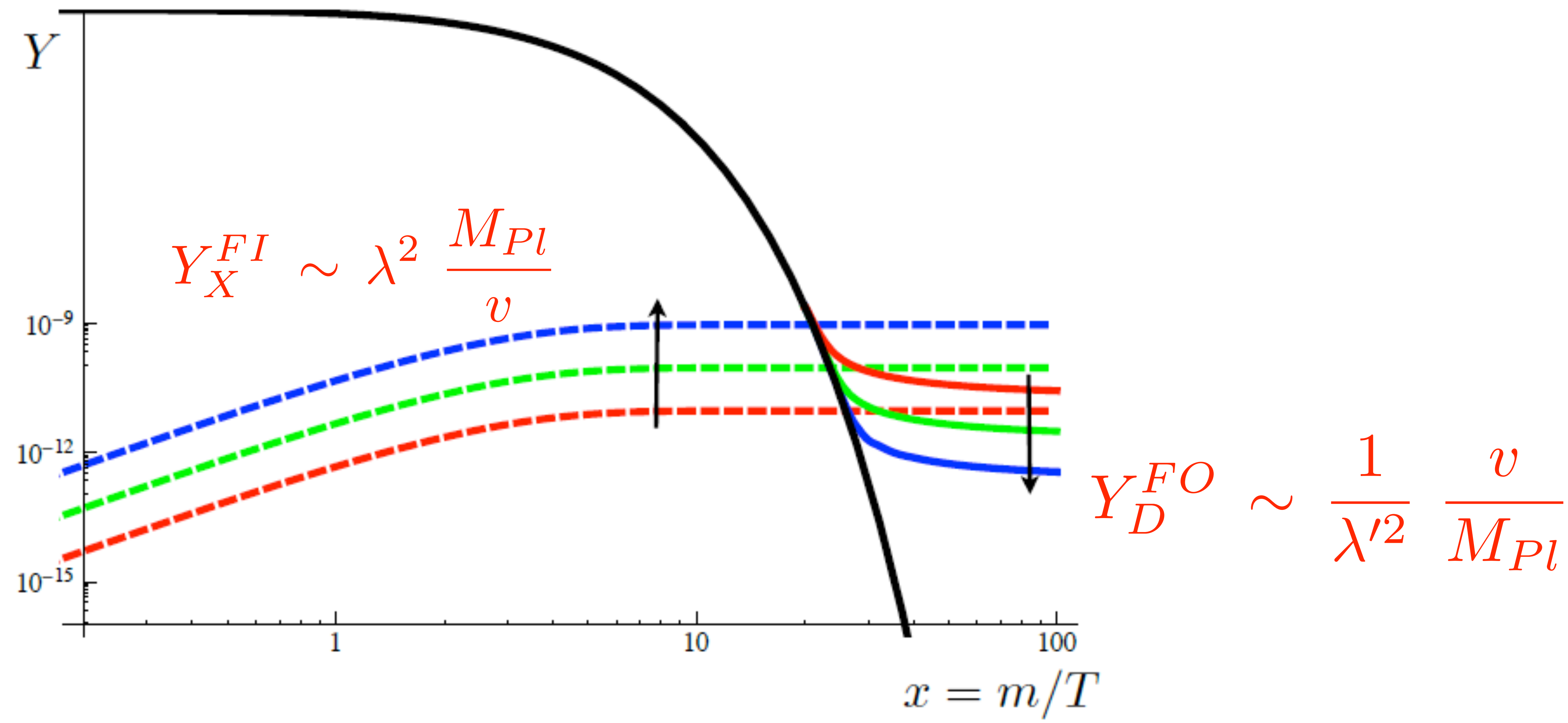


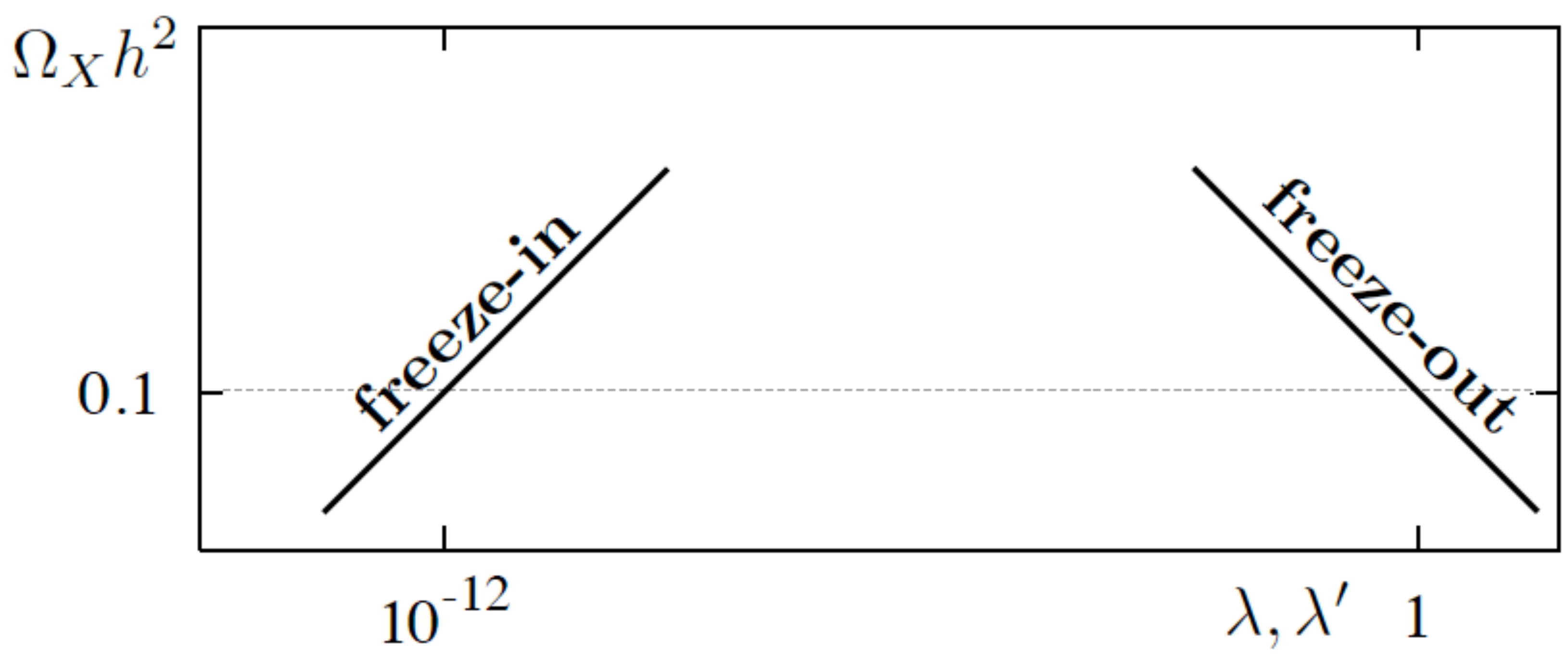
Heading "In" and "Out" of Equilibrium





Heading "In" and "Out" of Equilibrium





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

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

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

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

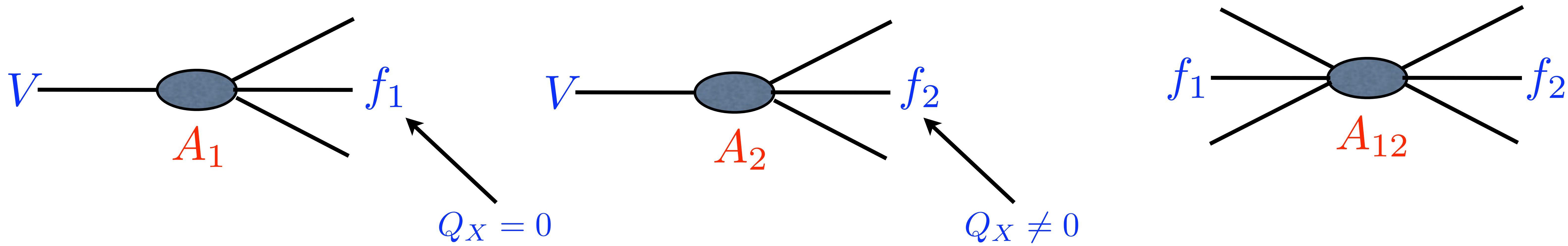
- Applies to both FIMP and Hidden DM,

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

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

Asymmetric Freeze-In

- Hidden sector with a global $U(1)_X$
- V has multiple decay modes

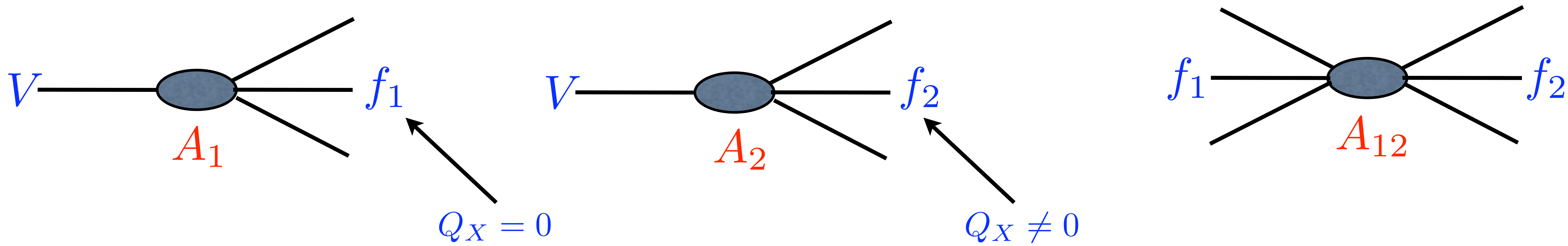


- Non-Thermal: $T' \neq T$ leading to an X asymmetry

$$\varepsilon = \frac{\Gamma(V \to X) - \Gamma(\bar{V} \to \bar{X})}{\Gamma(V \to X) + \Gamma(\bar{V} \to \bar{X})} \simeq \frac{1}{16\pi} \frac{Im\, A_1 A_2^* A_{12}}{|A_2|^2}$$

Asymmetric Freeze-In

- Hidden sector with a global $U(1)_X$
- V has multiple decay modes



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

$$\varepsilon = \frac{\Gamma(V \to X) - \Gamma(\bar{V} \to \bar{X})}{\Gamma(V \to X) + \Gamma(\bar{V} \to \bar{X})} \simeq \frac{1}{16\pi} \frac{Im\, A_1 A_2^* A_{12}}{|A_2|^2}$$

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

requiring

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

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

II Frameworks and Features of Freeze-In

"Phase Diagrams" for FIMP DM

- Allow d=4 coupling λ of X to thermal bath to vary over *many* orders of magnitude

- 4 production mechanisms for X

I Freeze-Out of X

II Relativistic Decoupling

FIMP DM $\left\{ \begin{array}{l} \text{III Freeze-In} \\ \text{IV Freeze-Out and Decay of LOSP} \end{array} \right.$

λ increasing upward ($\uparrow \lambda$)

“Phase Diagrams” for FIMP DM

❈ Allow d=4 coupling λ of X to thermal bath to vary over *many* orders of magnitude

❈ 4 production mechanisms for X

I Freeze-Out of X

II Relativistic Decoupling

FIMP DM { III Freeze-In

IV Freeze-Out and Decay of LOSP

$\uparrow \lambda$

❈ Choose simple models

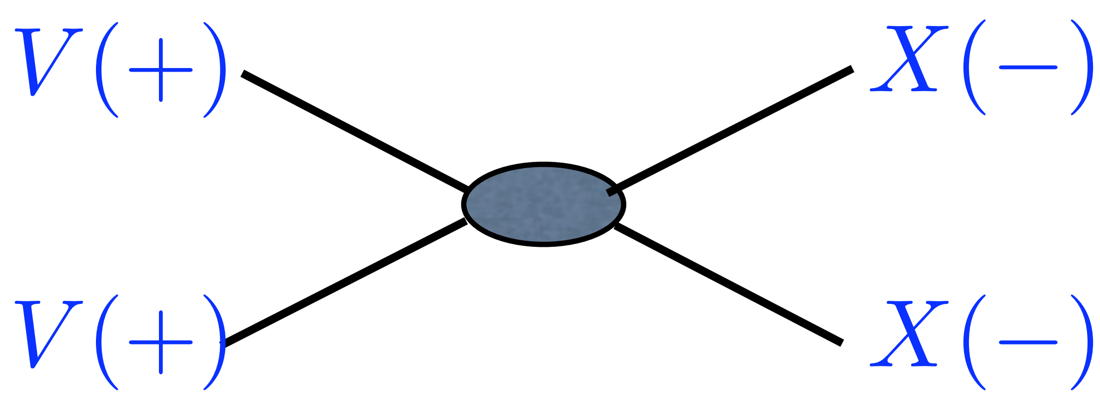
Scan over parameter space

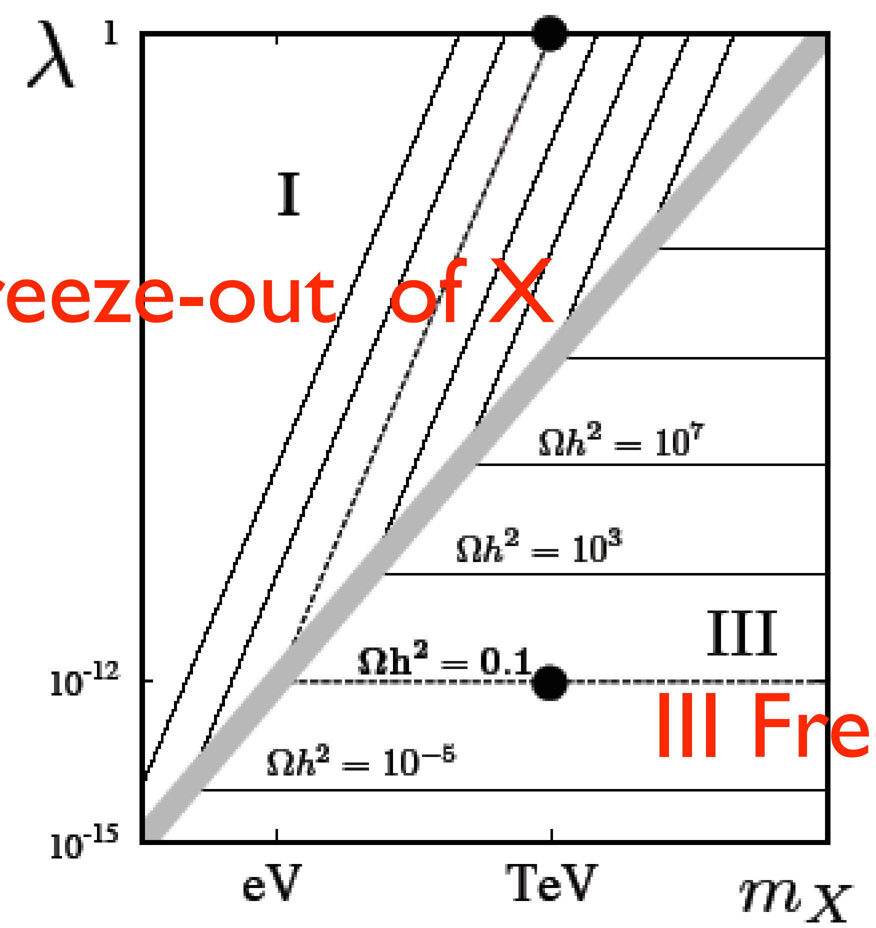
Determine regions where each production mechanism dominates

Quartic Scalar Interaction

$$\lambda\, V^\dagger V\, X^\dagger X$$

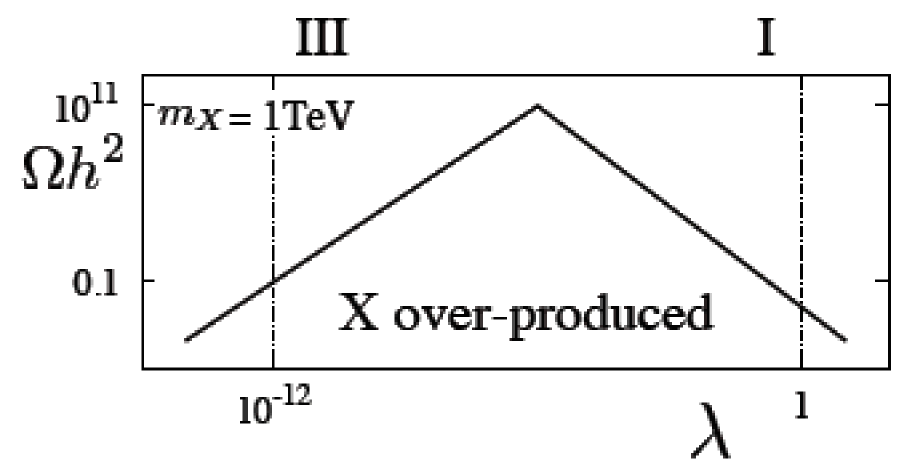
$$m_X > m_{V_+}$$





I Freeze-out of X

III Freeze-In

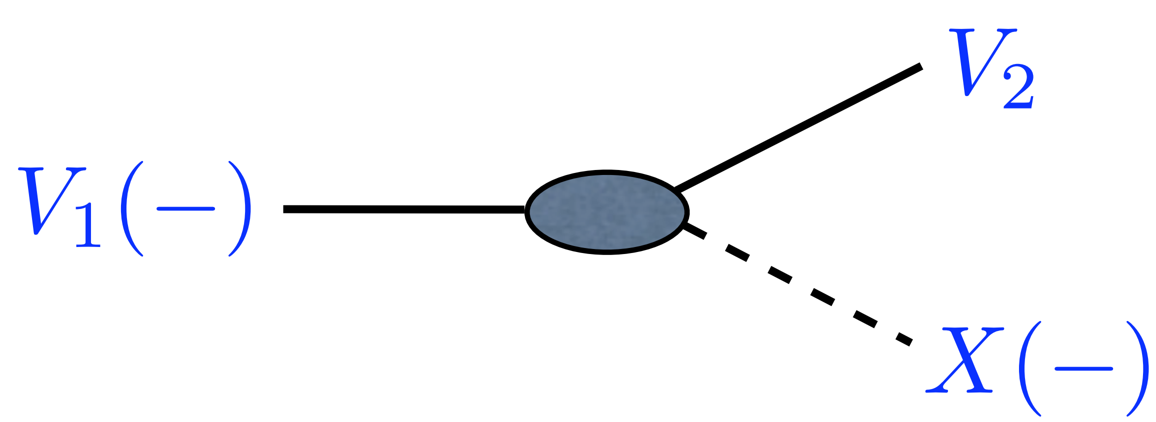


Yukawa Coupling

$$\lambda\,(V_1 V_2)\,X$$

$$m_2 \ll m_X < m_1$$

m_X, m_1 comparable

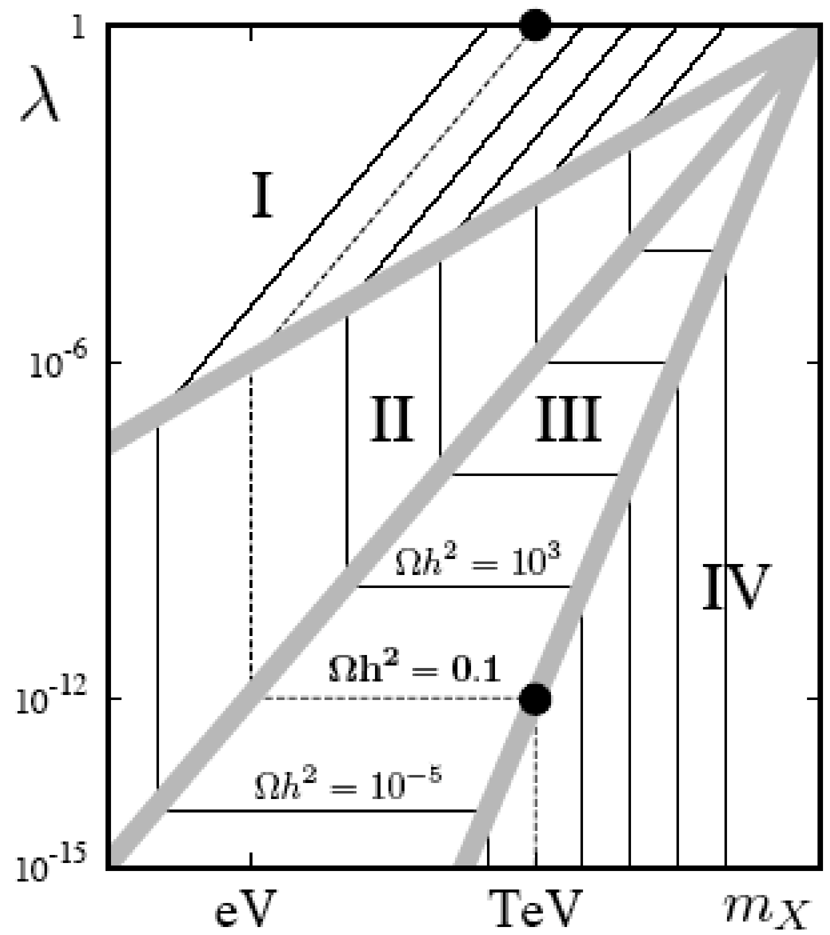


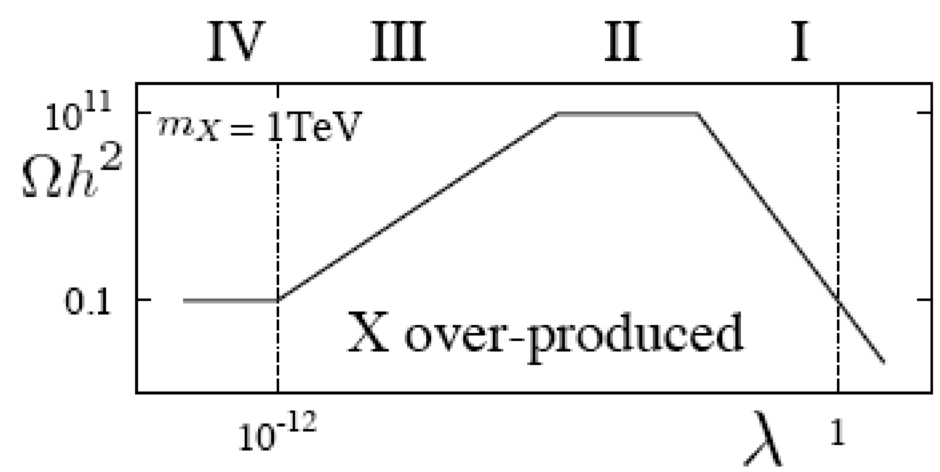
I Freeze-Out of X

II Relativistic Decoupling

III Freeze-In

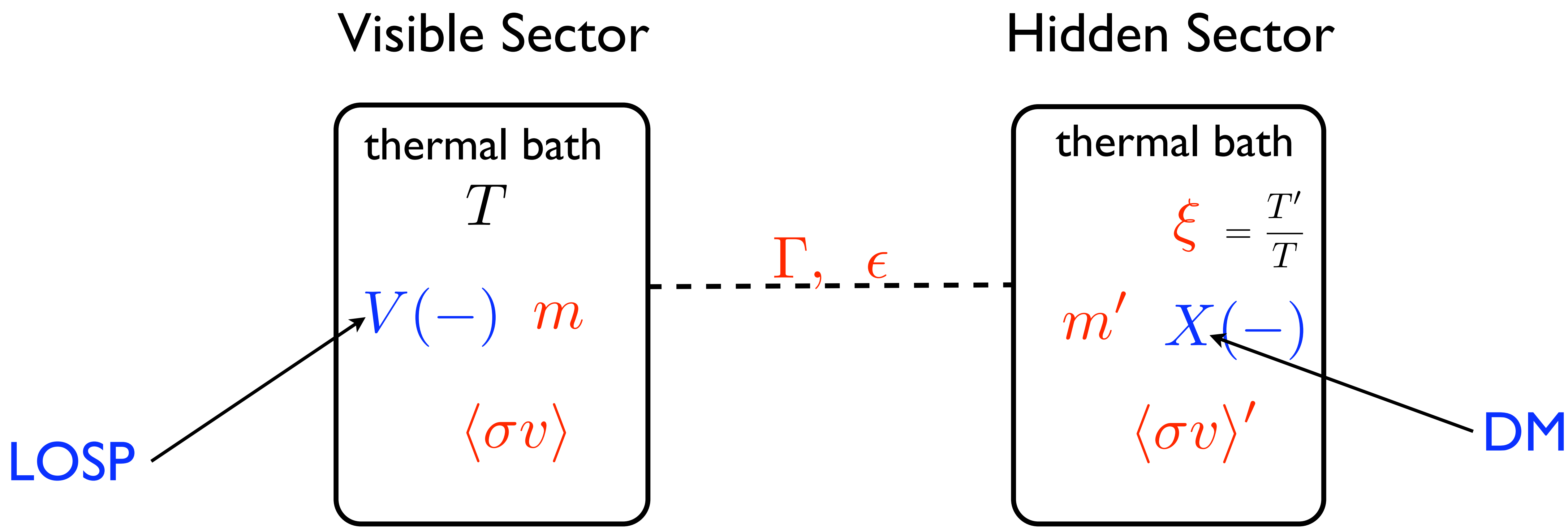
IV Freeze-Out and Decay of LOSP





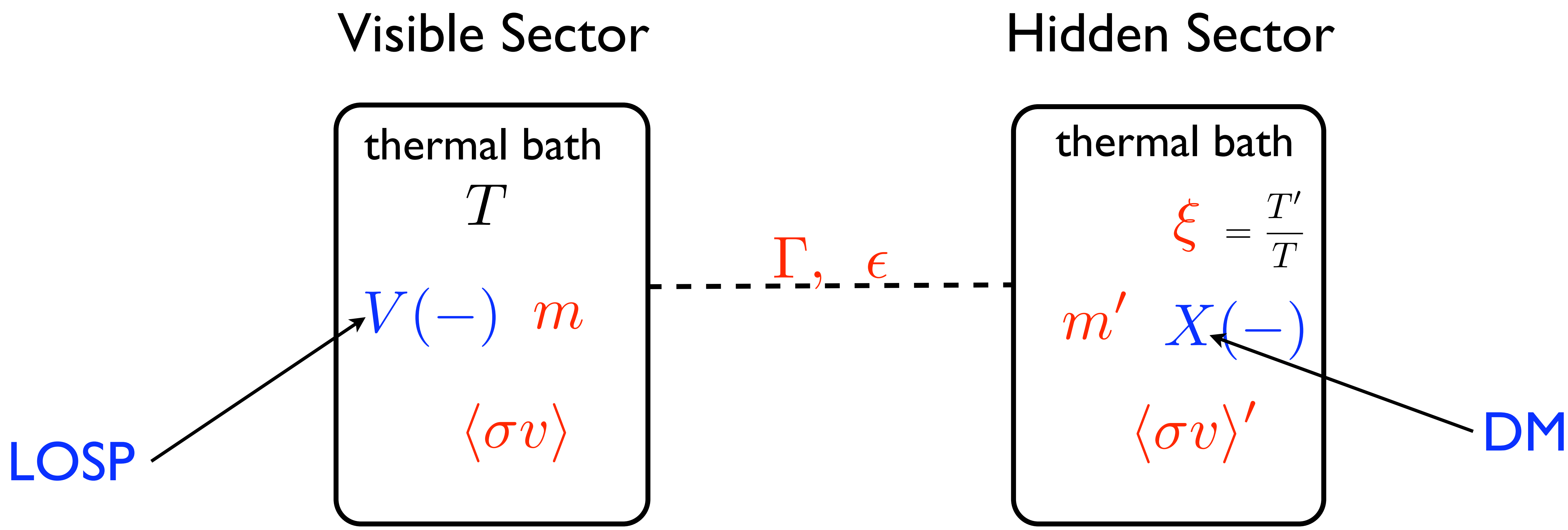
Hidden Sector DM

Attempt model independent approach



Hidden Sector DM

Attempt model independent approach

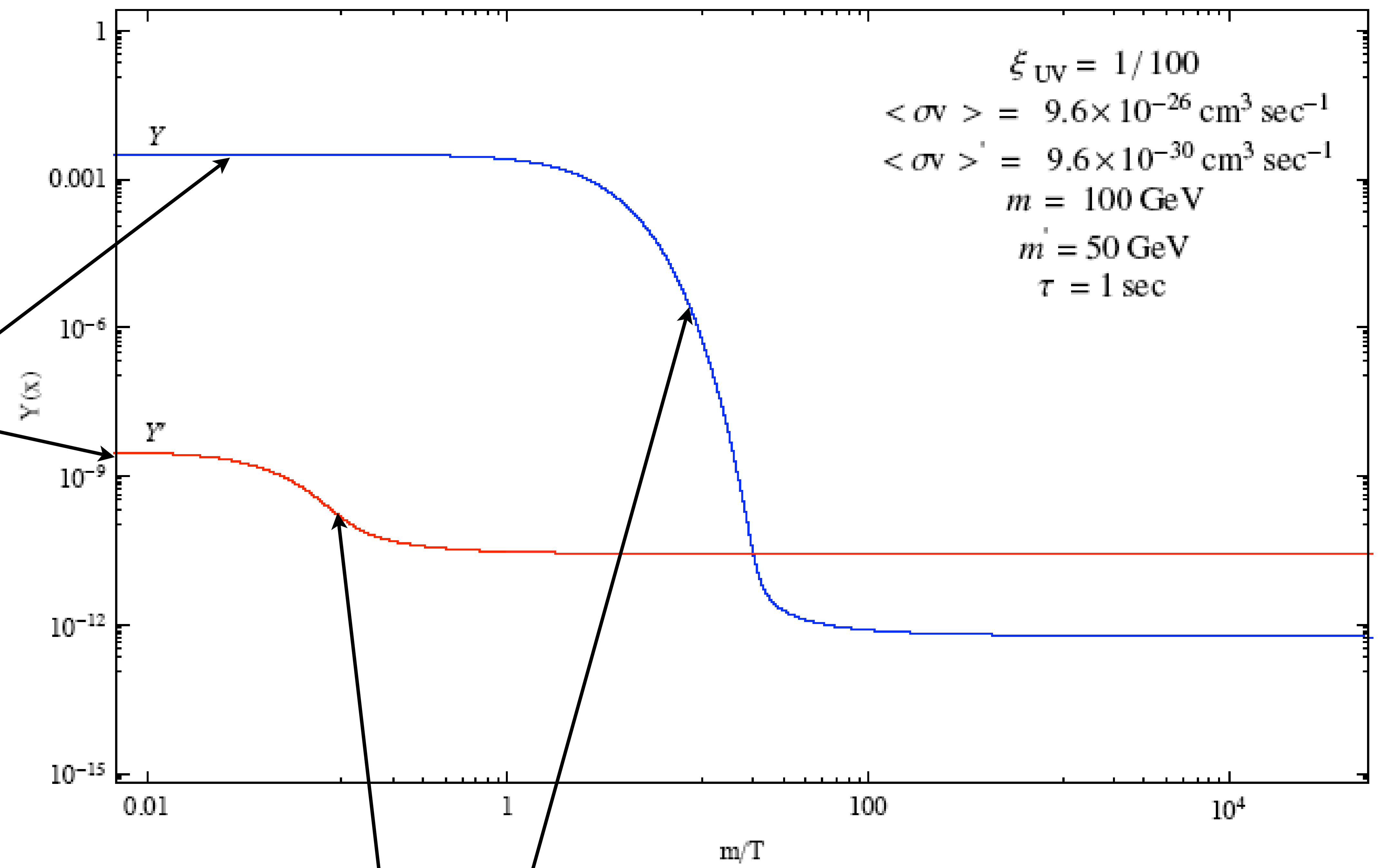


Phase Diagram is 7 dimensional!

What are the possible production mechanisms?

Yield Plots: FO and FO'

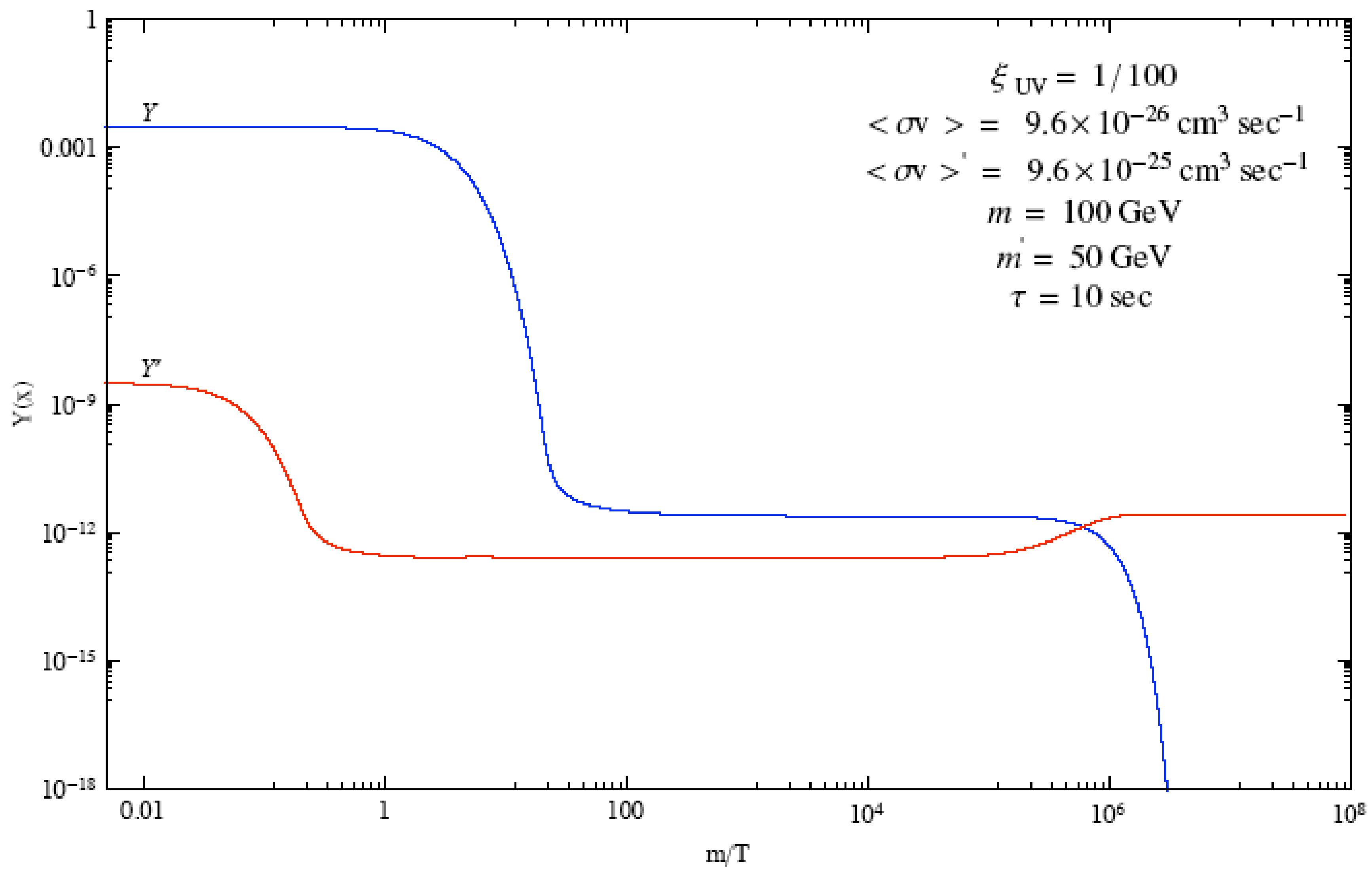
$T' \ll T$



$\langle\sigma v\rangle' \ll \langle\sigma v\rangle$

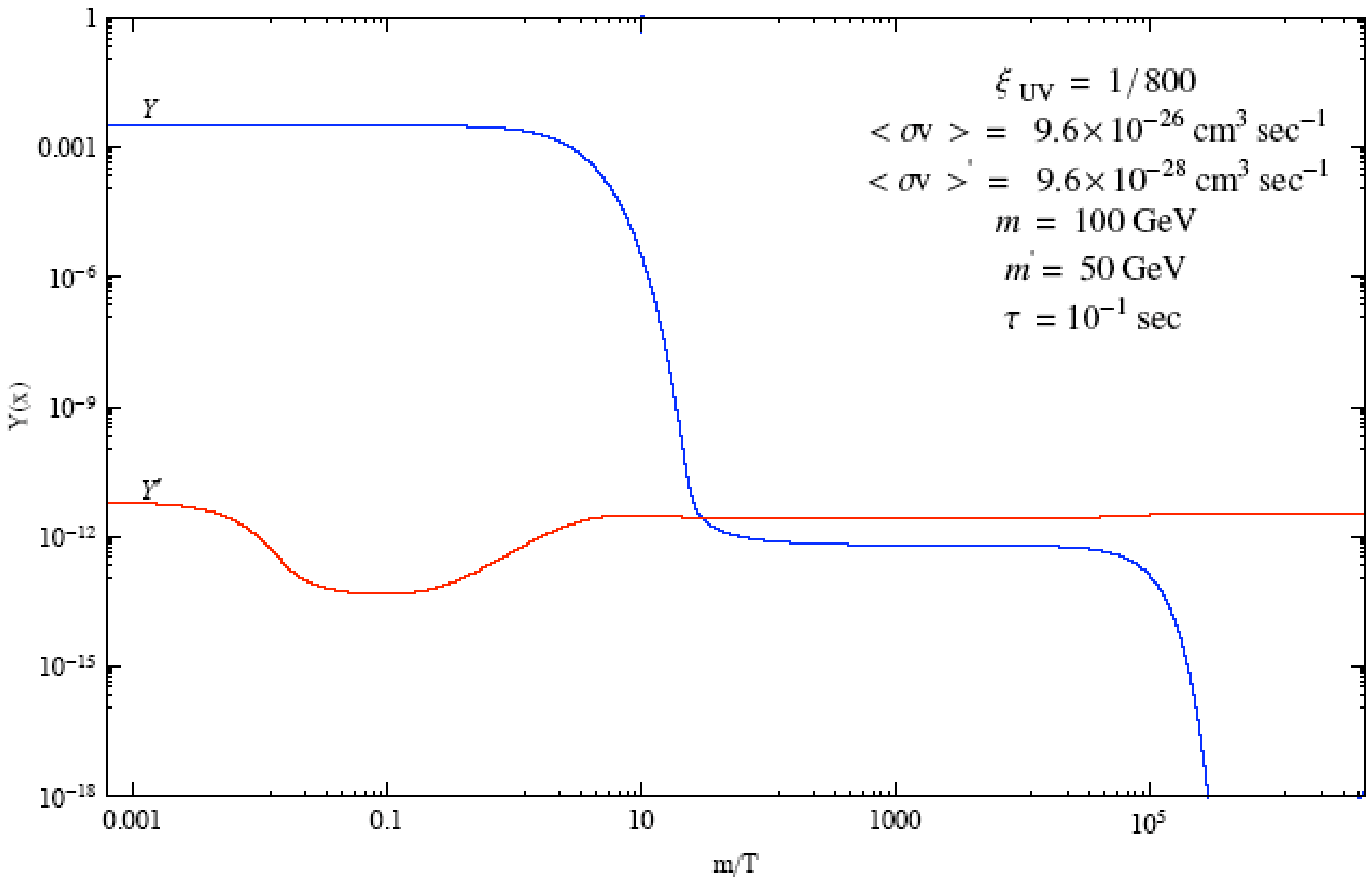
FO$'$ wins

Yield Plots: FO and Decay; FI



Freeze-Out and Decay of LOSP wins

Increase Γ by factor 100



Freeze-In wins

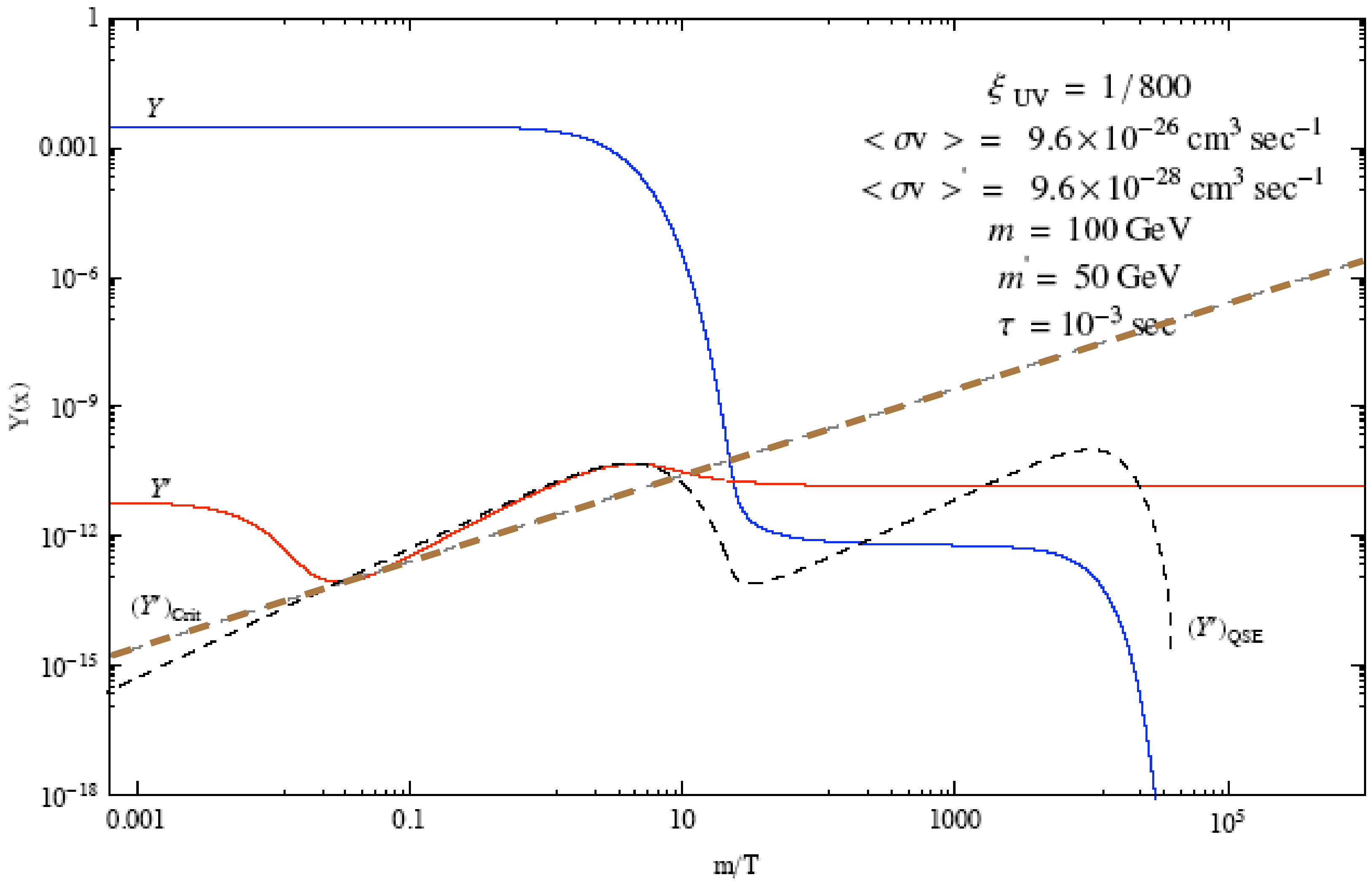
Yield Plots: Re-Annihilation

If Y' is increased above a critical value

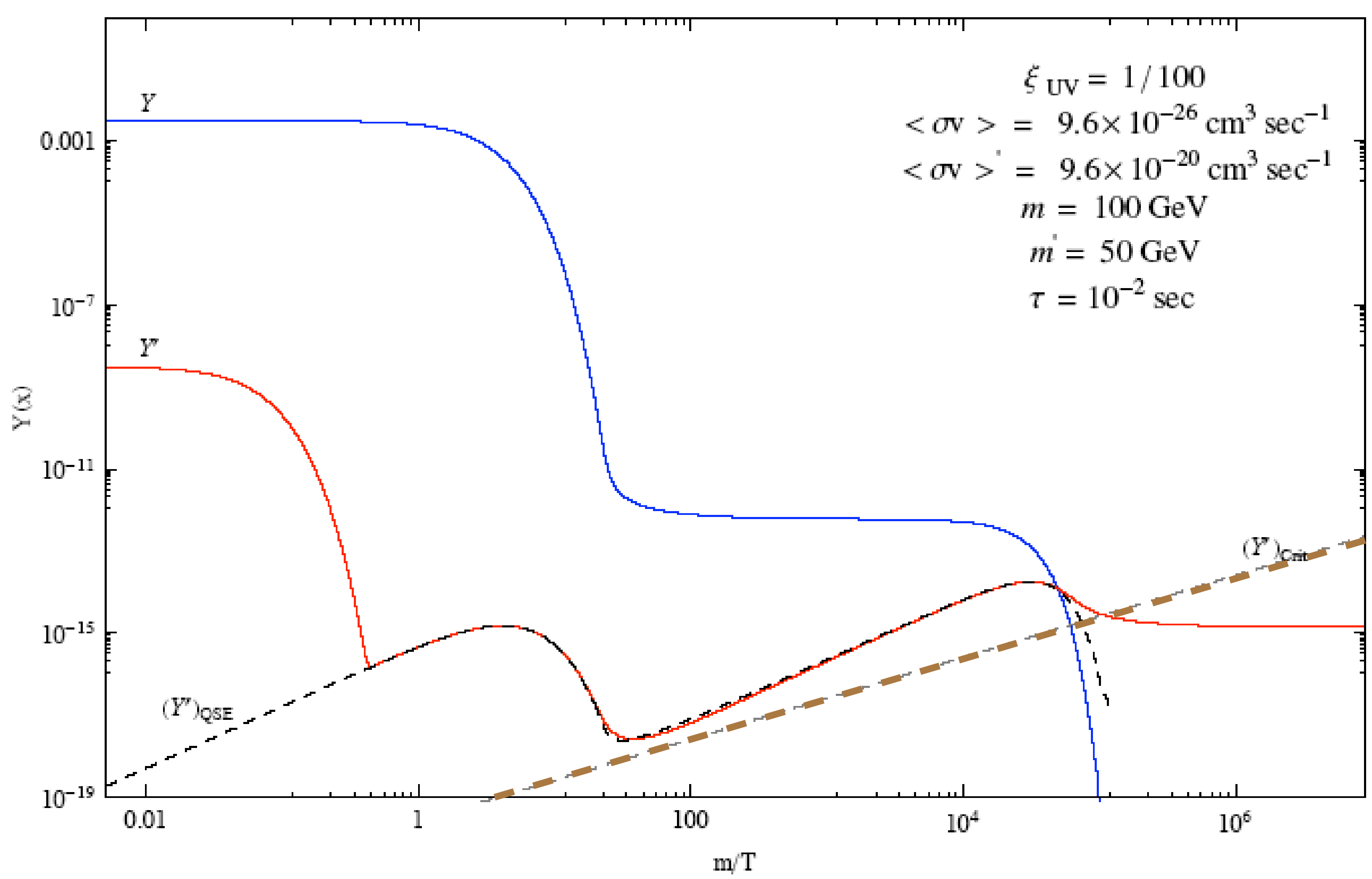
XX annihilations restart, and Y' hits a quasi-static equilibrium

Y' is determined by $\langle \sigma v \rangle'$ and may emerge

After FI

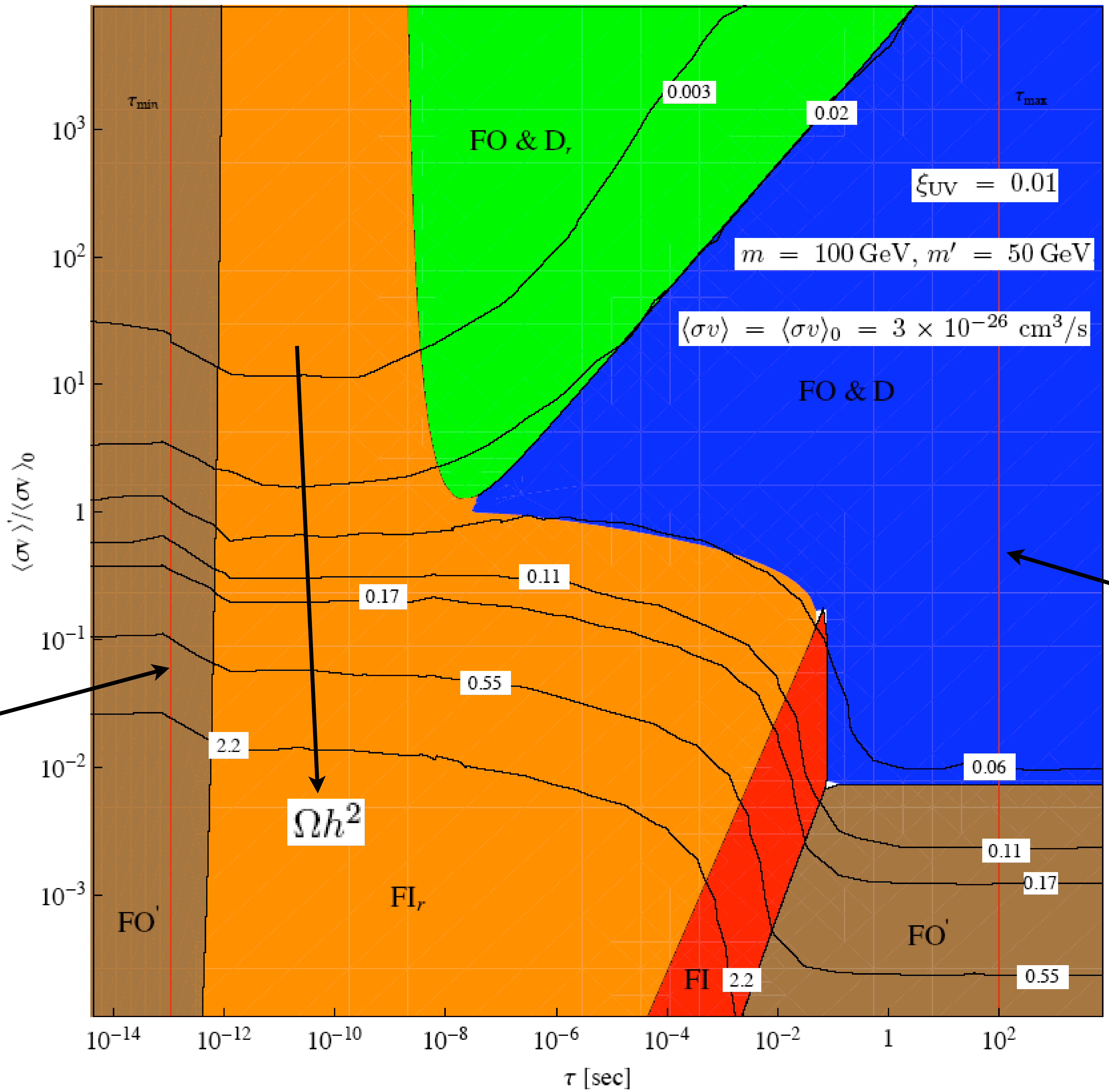


After FO and Decay



Phase Diagram for Hidden DM

$\epsilon = 0$

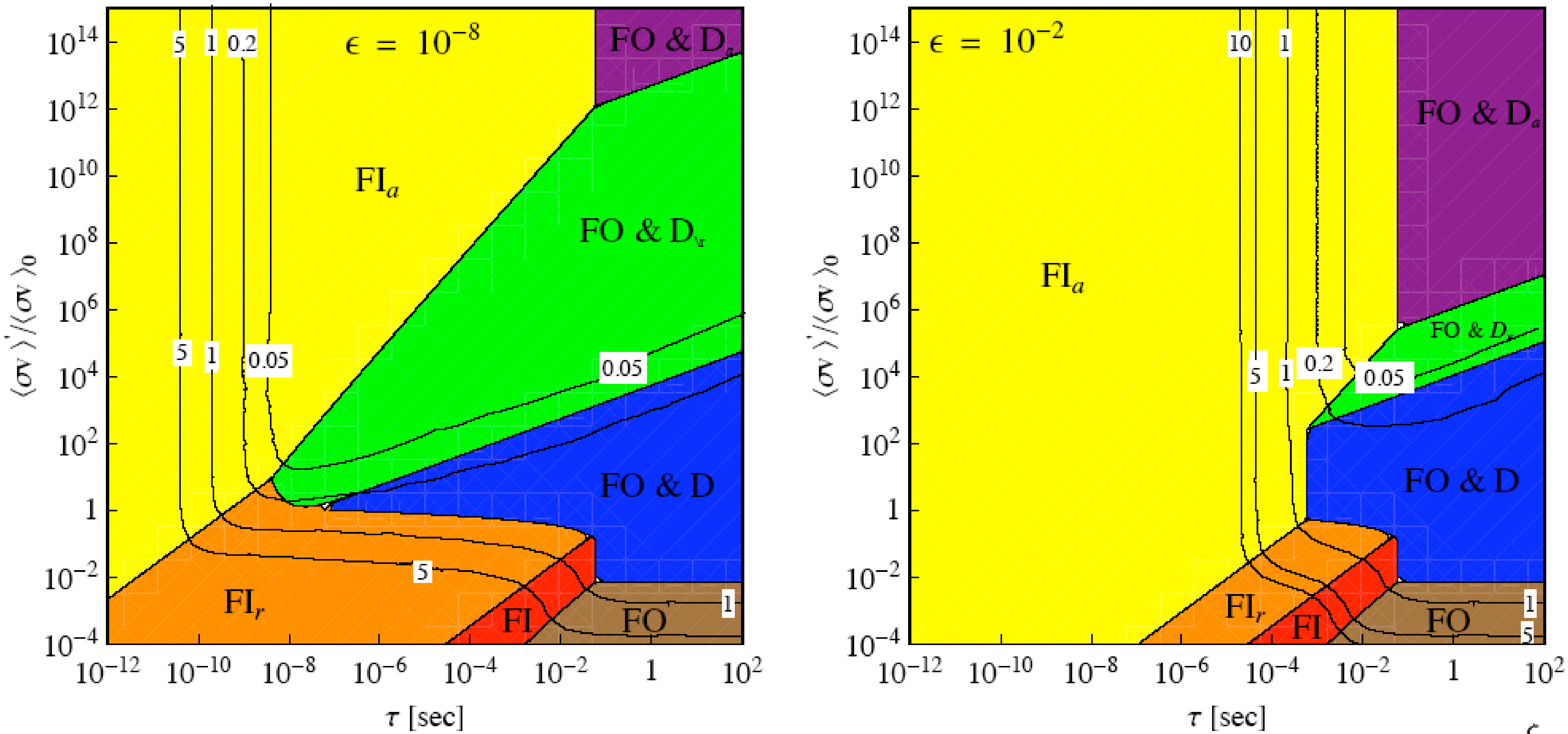


Sectors equilibrate

BBN concerns

Including Asymmetries

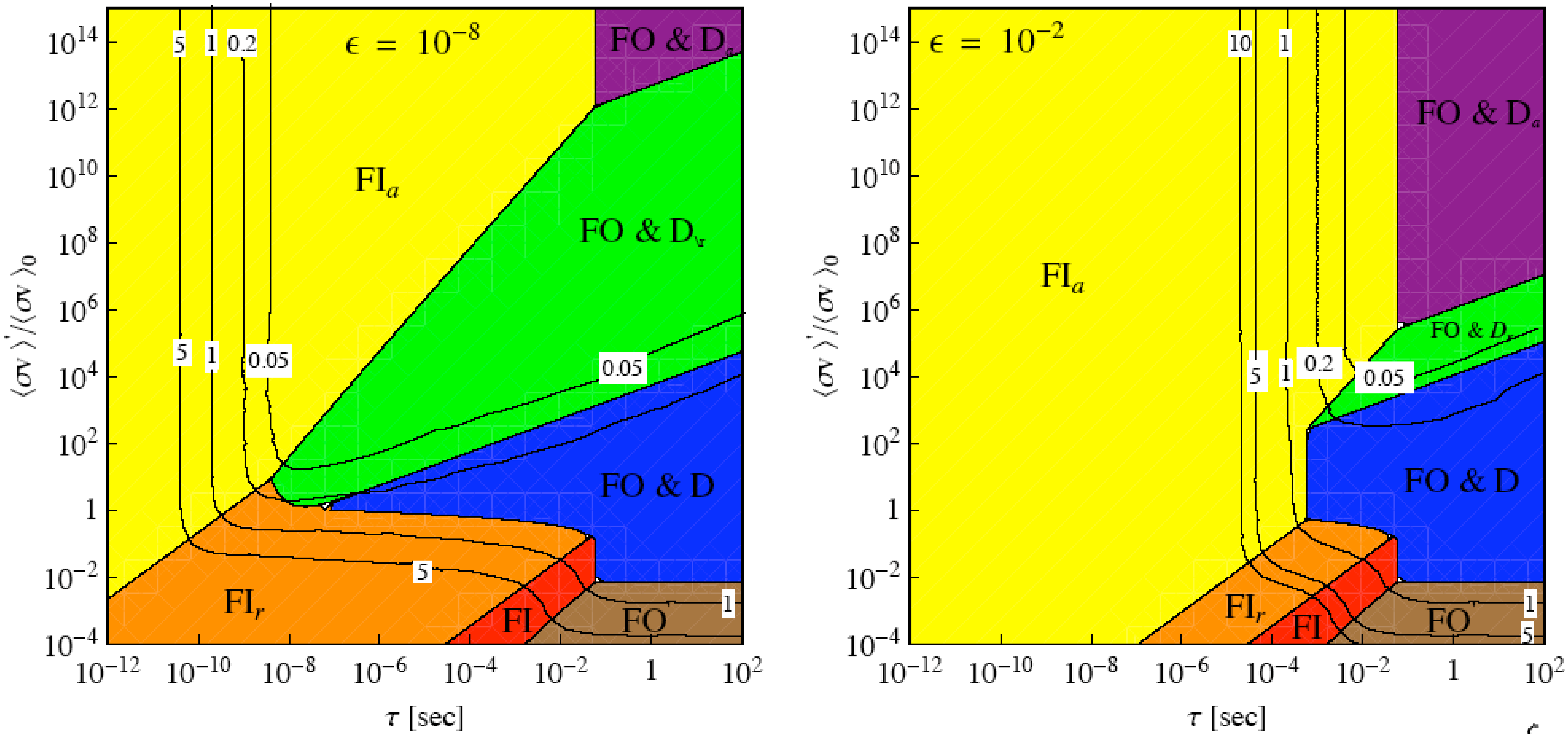
$\epsilon = 10^{-8}$ $\epsilon = 10^{-2}$



$$\xi_{\rm UV} = 0.01$$
$$m = 100\,{\rm GeV},\ m' = 50\,{\rm GeV}$$
$$\langle\sigma v\rangle = \langle\sigma v\rangle_0 = 3\times10^{-26}\ {\rm cm^3/s}$$

Including Asymmetries

$\epsilon = 10^{-8}$ $\epsilon = 10^{-2}$



$\xi_{UV} = 0.01$

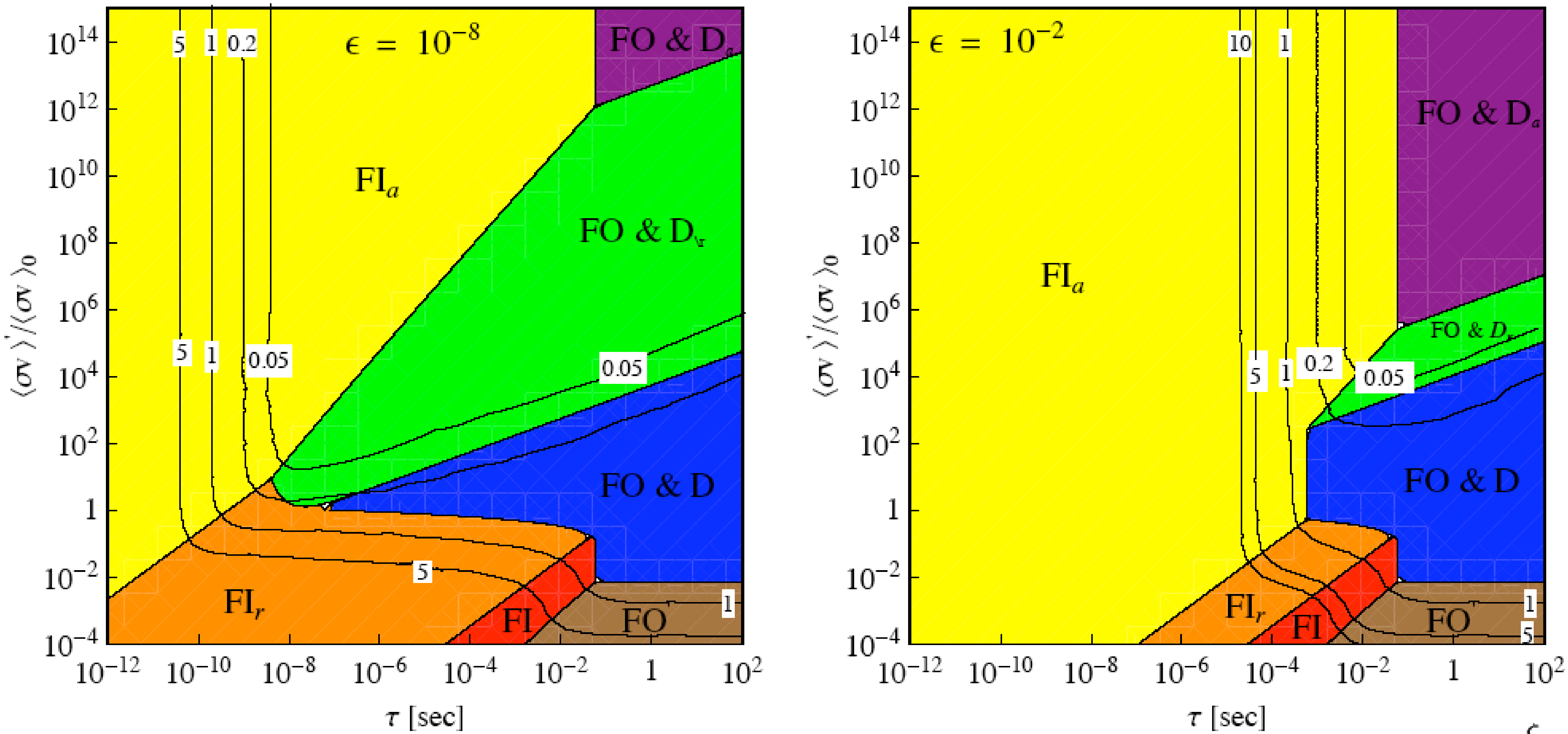
$m = 100\,\mathrm{GeV},\ m' = 50\,\mathrm{GeV}$

$\langle\sigma v\rangle = \langle\sigma v\rangle_0 = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

- Asymmetric FO&D requires large τ and huge $\langle\sigma v\rangle'$

Including Asymmetries

$\epsilon = 10^{-8}$ $\epsilon = 10^{-2}$

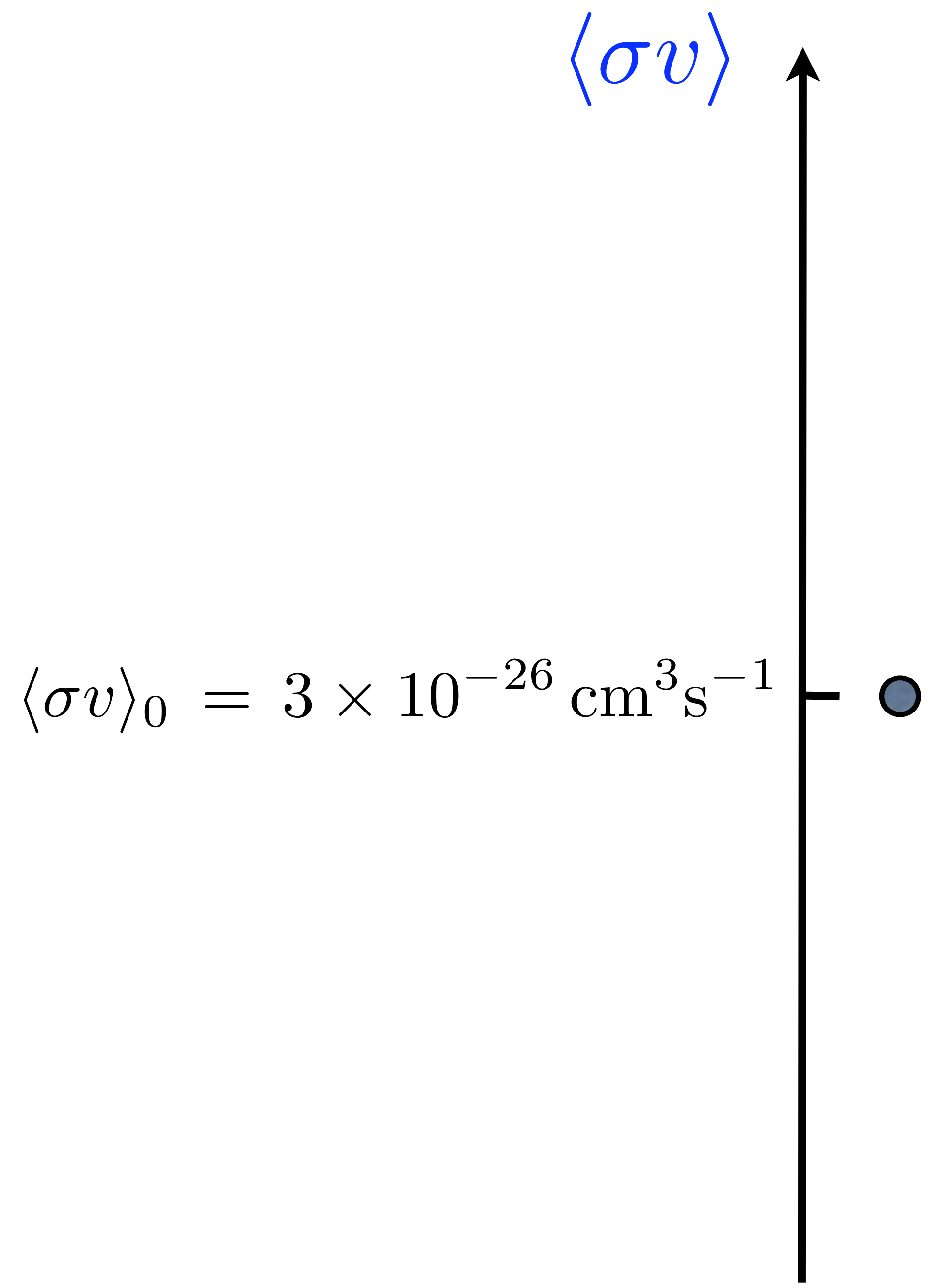


$$\xi_{UV} = 0.01$$
$$m = 100\,\mathrm{GeV},\ m' = 50\,\mathrm{GeV}$$
$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 = 3 \times 10^{-26}\ \mathrm{cm^3/s}$$

- Asymmetric FO&D requires large τ and huge $\langle \sigma v \rangle'$
- Asymmetric FI dominates over a very wide range of interesting $(\tau, \langle \sigma v \rangle')$

One Sector Cosmology with $\Omega h^2 = 0.11$

FO:



Two Sector Cosmologies with $\Omega h^2 = 0.11$

Sample over unknown parameters

$10^{-5} < \langle \sigma v \rangle' / \langle \sigma v \rangle_0, < 10^5$

$10^{-3} < \xi < 10^{-1}$

$10^{-8} < \epsilon < 10^{-3}$

$10 \text{ GeV} < m < 1 \text{ TeV}$

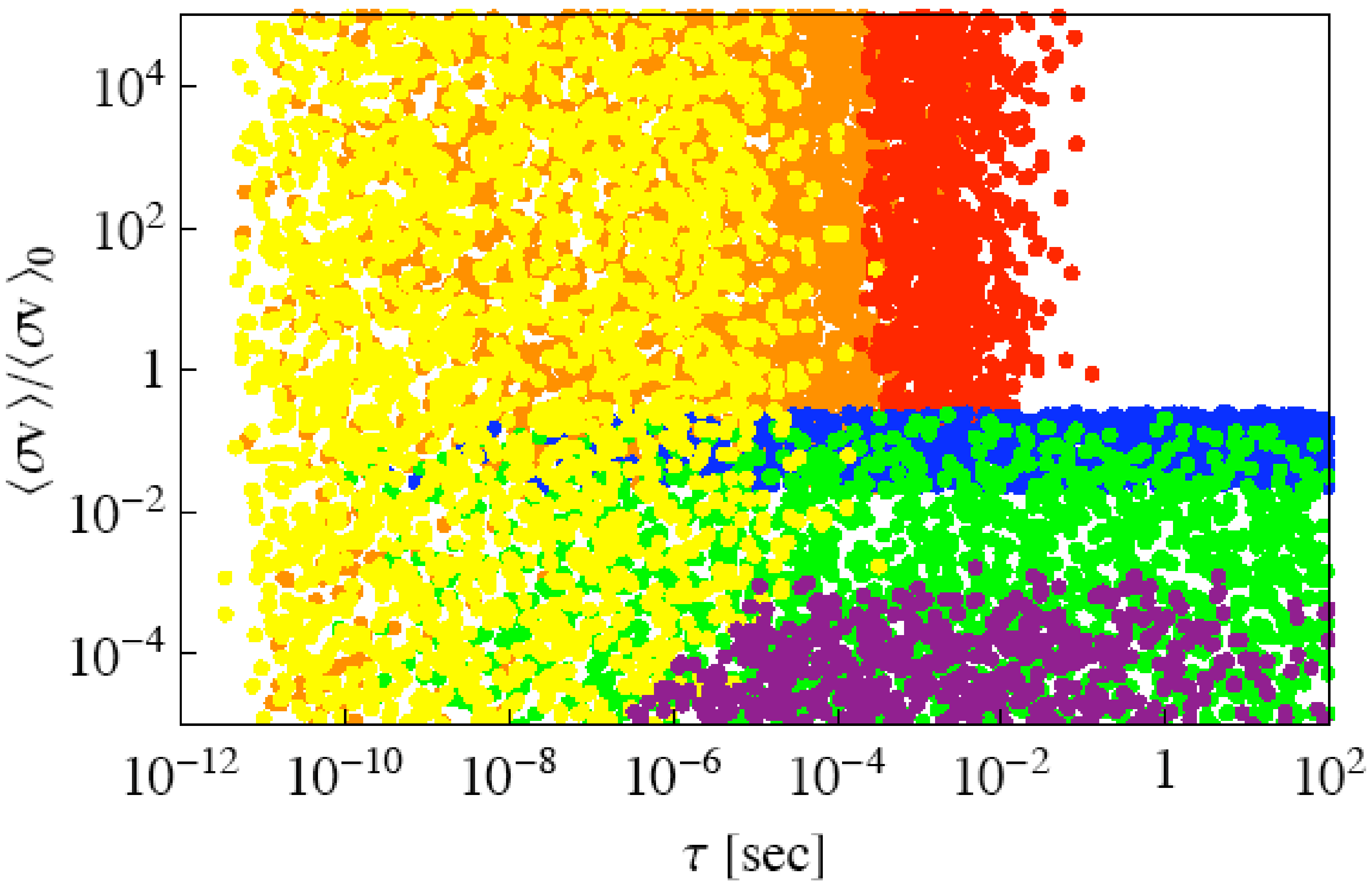
$1/20 < m'/m < 1/2$

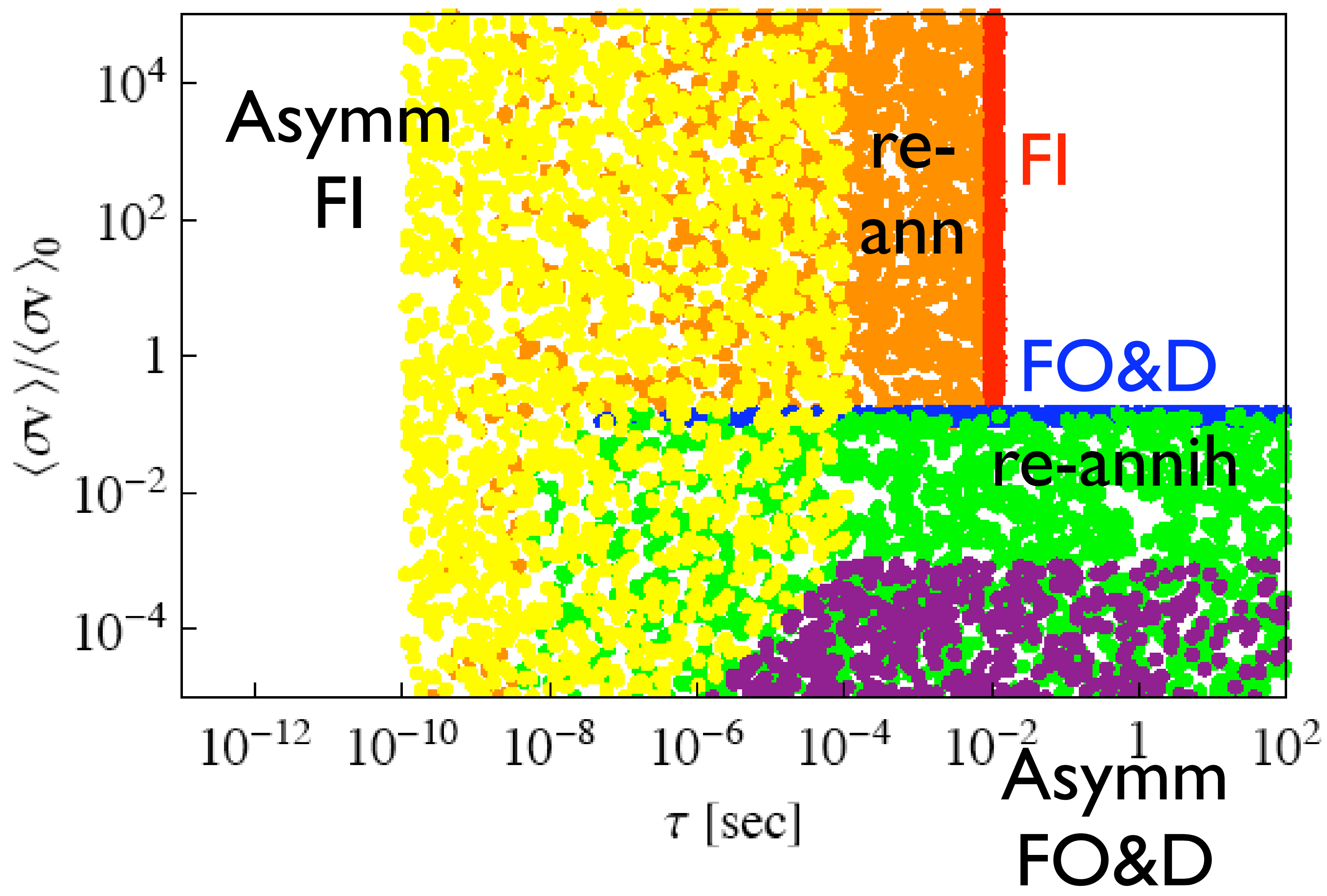
Measure

Masses

$m = 100 \text{ GeV}$

$1/4 < m'/m < 1/3$





Two Sector Cosmologies with $\Omega h^2 = 0.11$

Sample over unknown parameters

$$10^{-5} < \langle \sigma v \rangle' / \langle \sigma v \rangle_0, < 10^5$$

$$10^{-3} < \xi < 10^{-1}$$

$$10^{-8} < \epsilon < 10^{-3}$$

$10 \text{ GeV} < m < 1 \text{ TeV}$

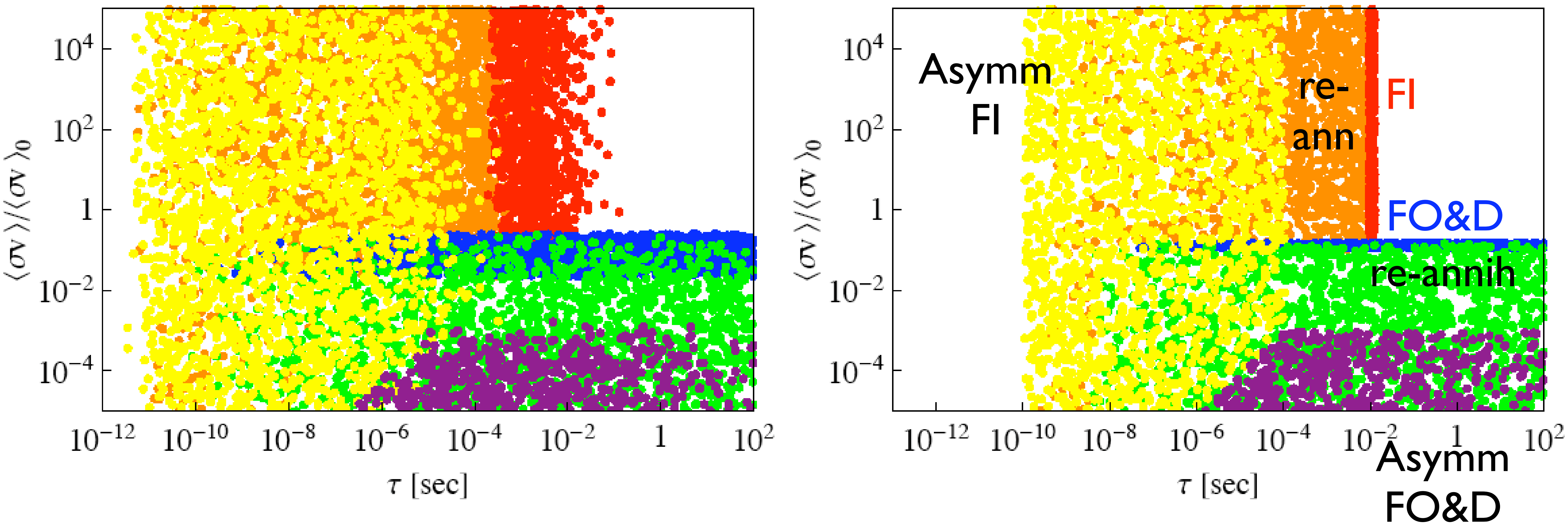
$1/20 < m'/m < 1/2$

Measure

Masses

$m = 100 \text{ GeV}$

$1/4 < m'/m < 1/3$



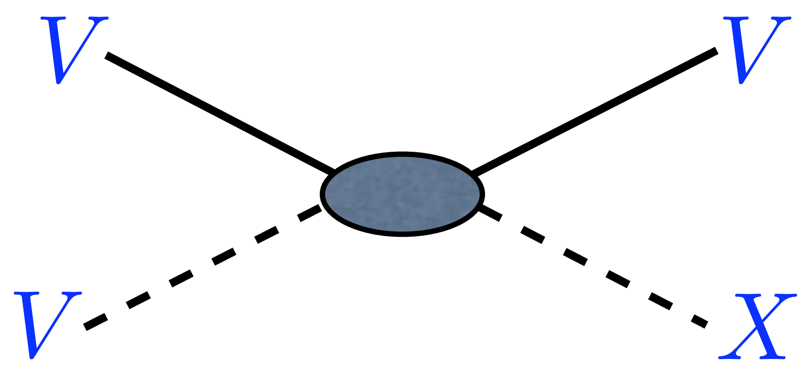
FI and FO&D cosmologies can be reconstructed

Can ϵ be measured?

Higher Dimensional Operators and UV Sensitivity

- d=5

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



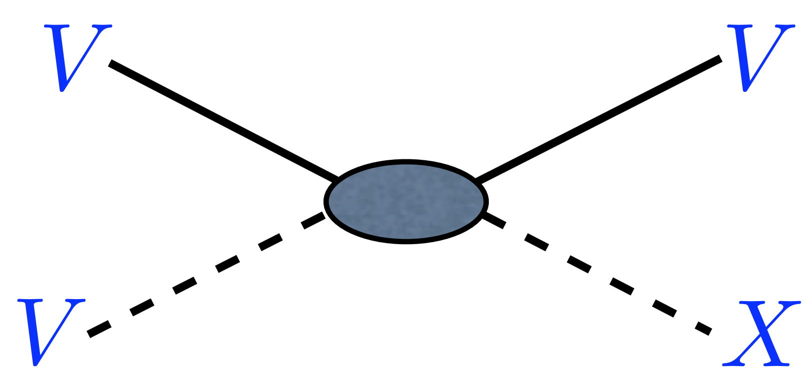
$$Y_X \sim \frac{M_{Pl} T}{M_*^2}$$

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

Higher Dimensional Operators and UV Sensitivity

- d=5

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



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

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

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??

FI from Many Visible Particles

$V \to X$ ⟹ $V_i \to X$

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

Can only measure Γ_{LOSP} Lose $\tau(\Omega h^2)$ relation??

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

- Simple model with just one coupling parameter λ

III

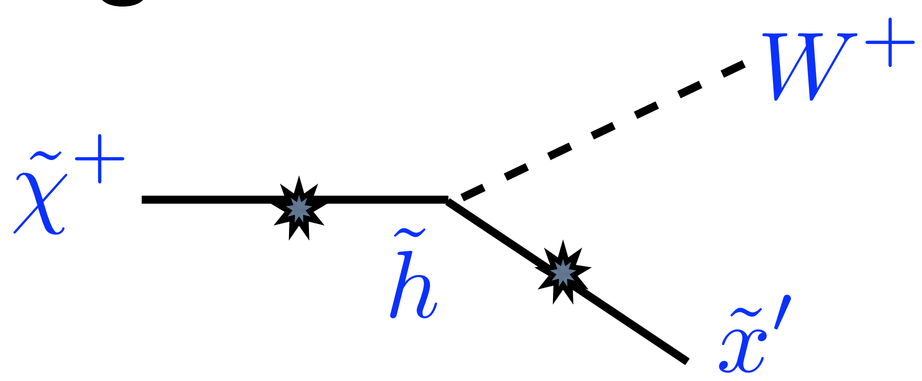
Supersymmetric Models and LHC Signals

Three d=4 Portals

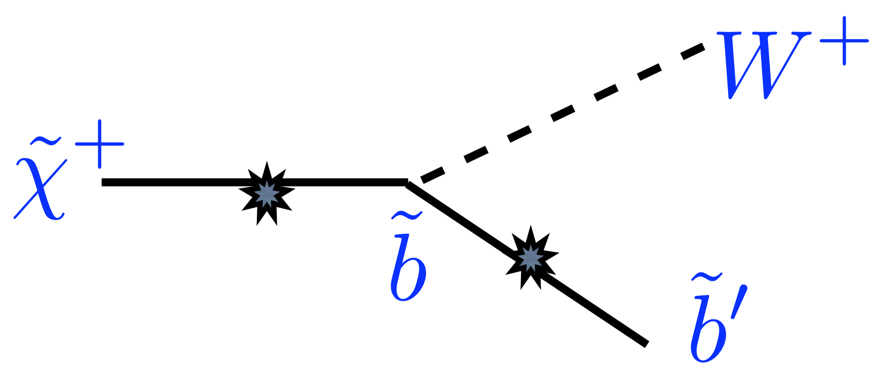
			DM
❉	Higgs Portal	$\lambda\, H_u H_d X'$	$\tilde{x}'$
❉	Bino Portal	$\lambda\, B^\alpha\, B'_\alpha$	$\tilde{b}'$
❉	Lepton Portal	$\lambda\, L H_u X'$	$\tilde{x}'$

Decays of Chargino LOSP

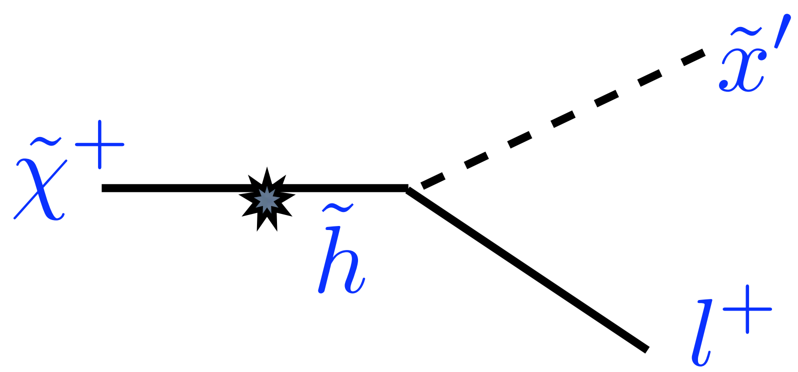
Higgs Portal



Bino Portal



Lepton Portal



Three d=4 Portals

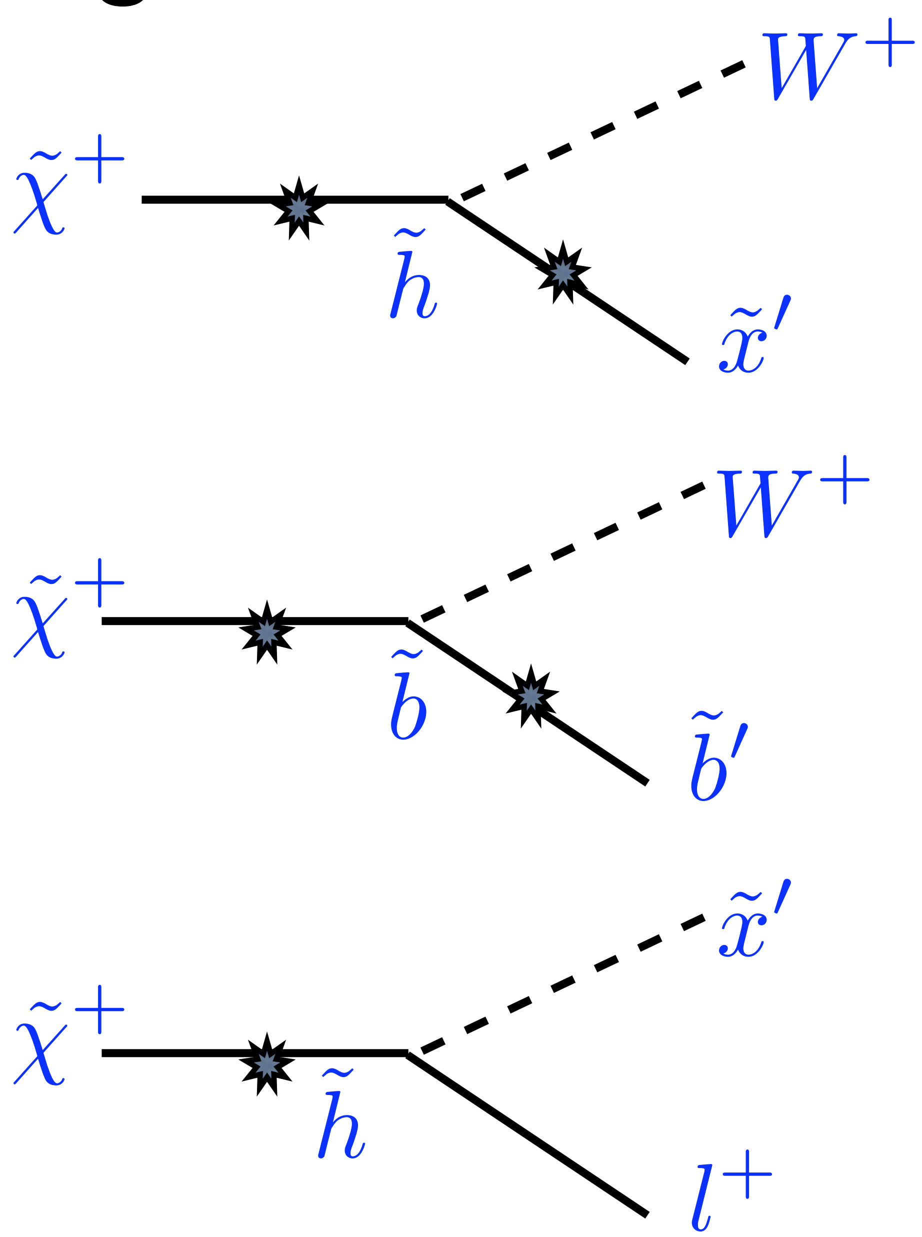
			DM
❈	Higgs Portal	$\lambda\, H_u H_d X'$	$\tilde{x}'$
❈	Bino Portal	$\lambda\, B^\alpha\, B'_\alpha$	$\tilde{b}'$
❈	Lepton Portal	$\lambda\, L H_u X'$	$\tilde{x}'$

Decays of Chargino LOSP

Higgs Portal

Bino Portal

Lepton Portal



FI				
	Higgs Portal: $H_u H_d X'$		Bino Portal: $B^\alpha X'_\alpha$	
LOSP	Decay	k	Decay	k
$\tilde{g}$	$\tilde{g} \to qq\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{h}\tilde{q}q} \frac{m^4}{m^4_{\tilde{q}}}$	$\tilde{g} \to qq\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{1q} \frac{m^4}{m^4_{\tilde{q}}}$
$\tilde{\nu}$	$\tilde{\nu} \to \ell^\pm(h^\mp, W^\mp)\tilde{x}'$ $\tilde{\nu} \to \tilde{\nu}\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{\tilde{h}\tilde{\nu}\ell} \frac{m^2}{m^2_{\tilde{h}}}(1, g_2^2)$ $g^2_{\tilde{h}\tilde{\nu}\nu}$	$\tilde{\nu} \to \ell^\pm(h^\mp, W^\mp)\tilde{x}'$ $\nu \to \nu\tilde{x}'$	$\frac{1}{(4\pi)^2} g^2_{1h} g^2_{\tilde{h}\tilde{\nu}\ell} \frac{m^2}{m^2_{\tilde{h}}}(1, g_2^2)$ $g^2_{1\nu}$
$\tilde{q}$	$\tilde{q} \to q\tilde{x}'$ $\tilde{q} \to q(h^{0,\pm}, W^{0,\pm})\tilde{x}'$	$g^2_{\tilde{h}\tilde{q}q}$ $\frac{1}{(4\pi)^2} g^2_{\tilde{h}\tilde{q}q} \frac{m^2}{m^2_{\tilde{h}}}(1, g_2^2)$	$\tilde{q} \to q\tilde{x}'$ $\tilde{q} \to q(h^{0,\pm}, W^{0,\pm})\tilde{x}'$	g^2_{1q} $\frac{1}{(4\pi)^2} g^2_{1h} g^2_{\tilde{h}\tilde{q}q} \frac{m^2}{m^2_{\tilde{h}}}(1, g_2^2)$
$\tilde{\chi}^\pm$	$\tilde{\chi}^\pm \to (h^\pm, W^\pm)\tilde{x}'$ $\tilde{\chi}^\pm \to \ell^\pm \nu \tilde{x}'$	$g_2^2(\theta^2_{\tilde{\chi}\tilde{w}}, \theta^2_{\tilde{\chi}\tilde{h}})$ $\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\nu} g^2_{\tilde{h}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\chi}^\pm \to (h^\pm, W^\pm)\tilde{x}'$ $\tilde{\chi}^\pm \to \ell^\pm \nu \tilde{x}'$	$g^2_{1h}(\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{w}})$ $\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\nu} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$
$\tilde{\chi}_0$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$ $\tilde{\chi}_0 \to y'\tilde{y}'$ $\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2$ $\theta^2_{\tilde{\chi}\tilde{h}} \lambda'^2$ $\frac{1}{(4\pi)^2} g^2_{\tilde{\chi}\tilde{\ell}\ell} g^2_{\tilde{h}\tilde{\ell}\ell} \frac{m^4}{m^4_{\tilde{l}}}$	$\tilde{\chi}_0 \to (h^0, Z)\tilde{x}'$ $\tilde{\chi}_0 \to y'\tilde{y}'$ $\tilde{\chi}_0 \to \ell^+\ell^-\tilde{x}'$	$\theta^2_{\tilde{\chi}\tilde{h}}\, g^2_{1h}, \theta^2_{\tilde{\chi}\tilde{h}} g_2^2 g^2_{1h}$ $\theta^2_{\tilde{\chi}\tilde{b}} g'^2$ $\frac{1}{(4\pi)^2} g^2_{\chi\tilde{\ell}\ell} g^2_{1\ell} \frac{m^4}{m^4_{\tilde{l}}}$
$\tilde{\ell}^\pm$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{\tilde{h}\tilde{\ell}\ell}$	$\tilde{\ell}^\pm \to \ell^\pm \tilde{x}'$	$g^2_{1\ell}$

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

- LHC Discovers $\tilde{l}^-$ LOSP $\left\{ \begin{array}{l} m = 200\,\mathrm{GeV} \\ \tilde{l}^- \to l^- + \text{missing} \qquad \tau = 0.1\,\mathrm{sec} \\ \text{reconstruction gives} \qquad m_{X'} = 100\,\mathrm{GeV} \end{array} \right.$

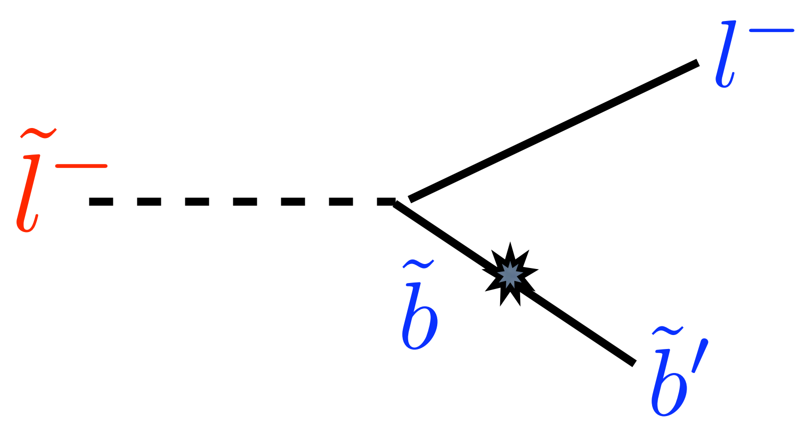
- Not FO&D: $Y_{FO}(\tilde{l}^-)$ too small

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

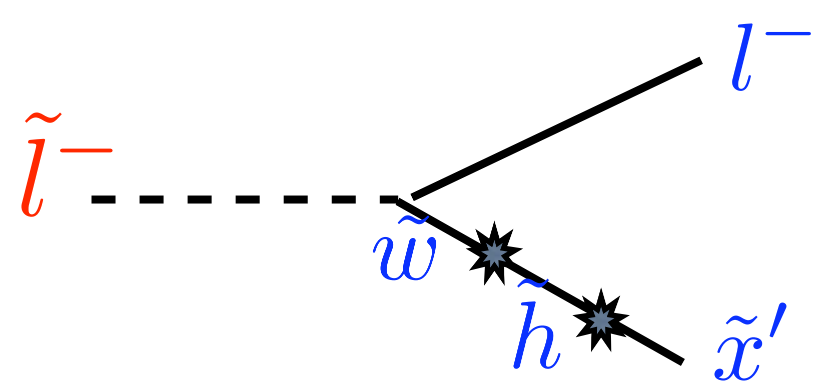
- LHC Discovers $\tilde{l}^-$ LOSP $\left\{ \begin{array}{l} m \;=\; 200\,\mathrm{GeV} \\ \tilde{l}^- \;\to\; l^- + \mathrm{missing} \end{array} \right.$

  reconstruction gives $\tau \;=\; 0.1\,\mathrm{sec}$, $m_{X'} \;=\; 100\,\mathrm{GeV}$

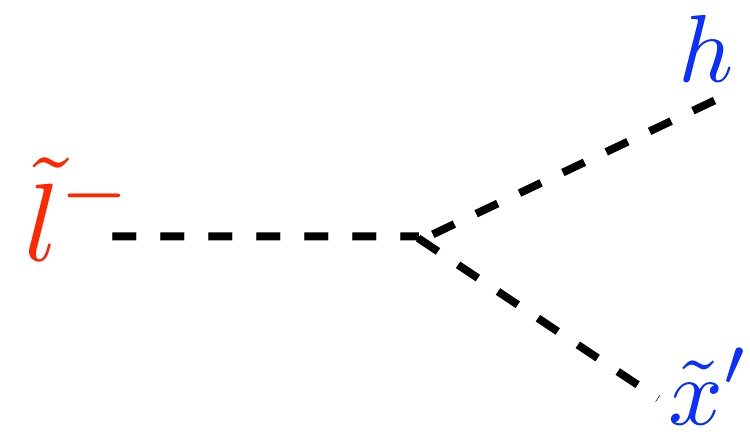
- Not FO&D: $Y_{FO}(\tilde{l}^-)$ too small

- 

Bino Portal



Higgs Portal



Lepton Portal

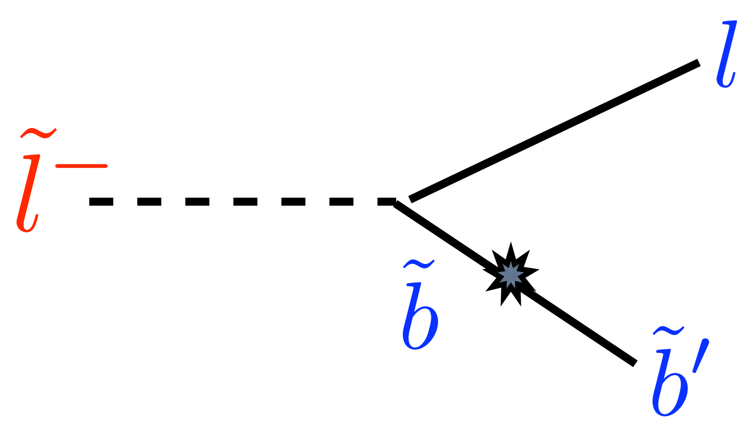
Correct signal; but FI from $\tilde{l}^- \to l^- + \tilde{x}'$ gives $\Omega_{\tilde{x}'} = 10^{-2}$

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

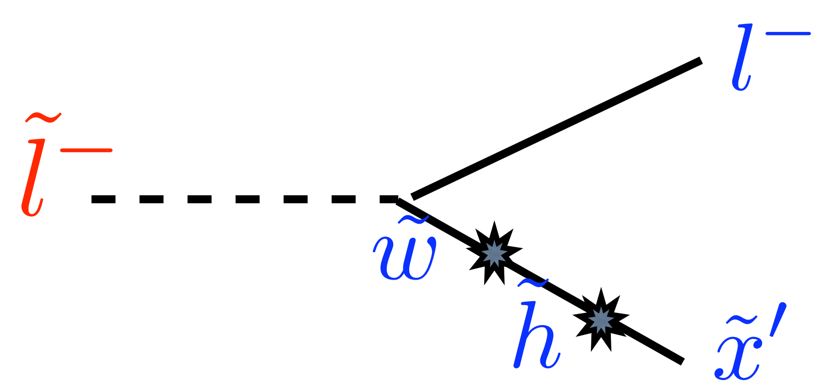
- LHC Discovers $\tilde{l}^-$ LOSP $\left\{ \begin{array}{l} m \;=\; 200\,\mathrm{GeV} \\ \tilde{l}^- \;\rightarrow\; l^- + \mathrm{missing} \end{array} \right.$

  reconstruction gives $\quad \tau \;=\; 0.1\,\mathrm{sec}$, $\quad m_{X'} \;=\; 100\,\mathrm{GeV}$

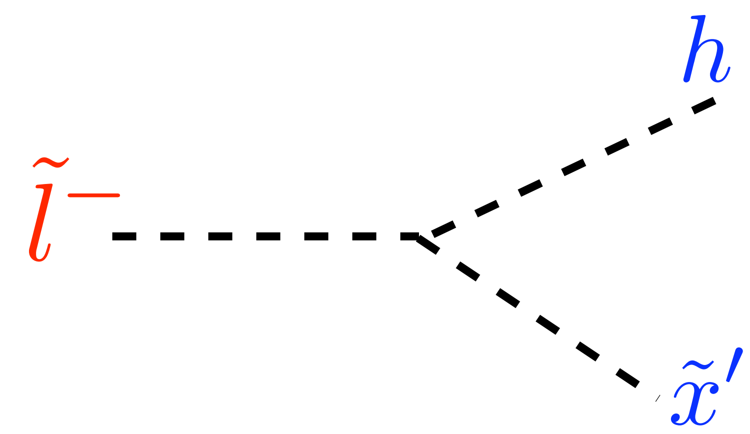
- Not FO&D: $Y_{FO}(\tilde{l}^-)$ too small

- 

Bino Portal



Higgs Portal



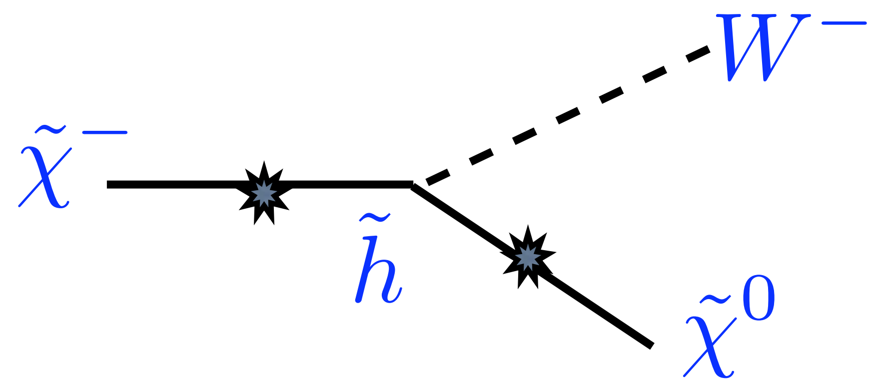
Lepton Portal

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

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

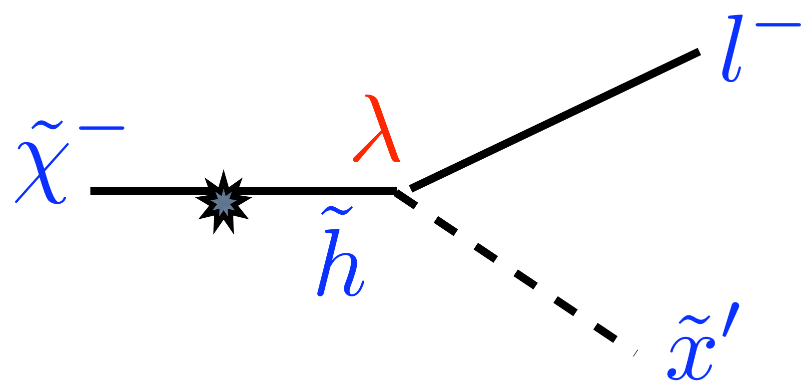
Asymmetric Freeze-In Via the Lepton Portal

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



A_1

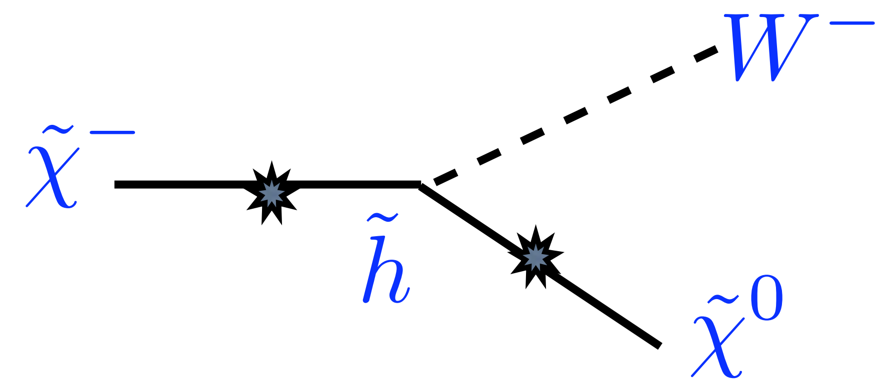
- They also have slow decays that contribute to FI of $\tilde{x}'$ via $\lambda L H_u X'$



A_2

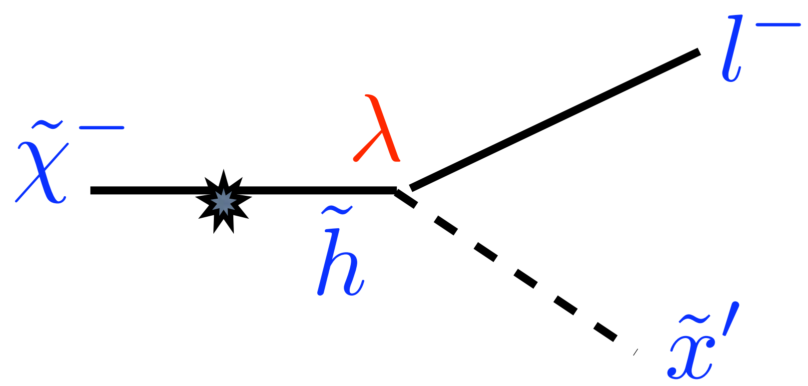
Asymmetric Freeze-In Via the Lepton Portal

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



A_1

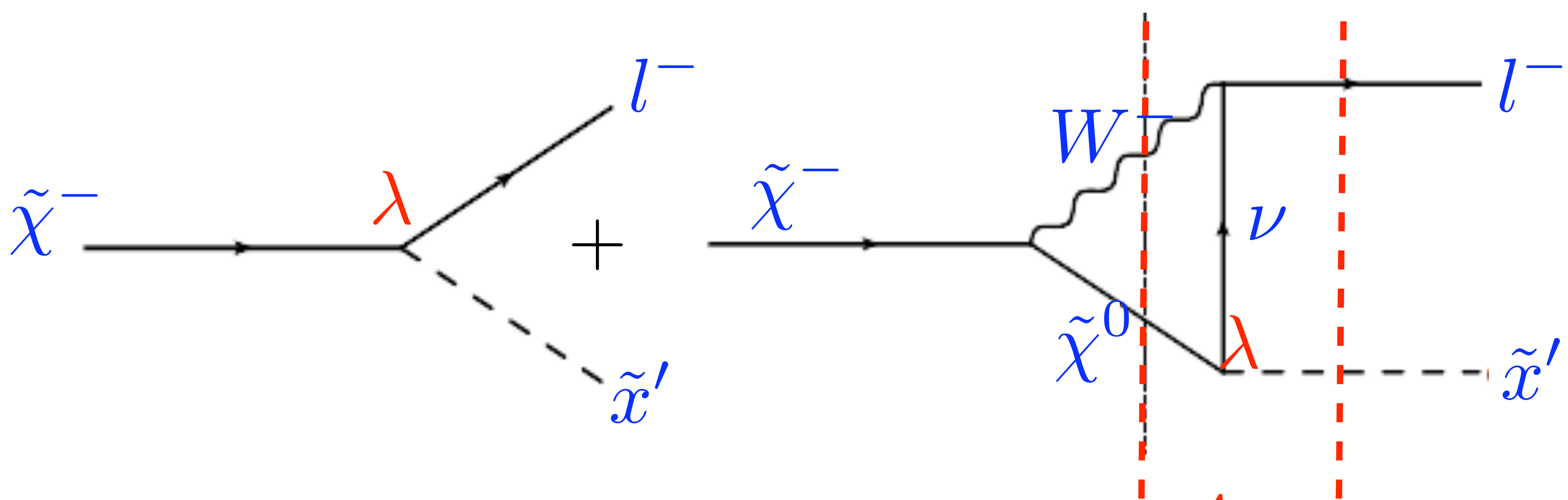
- They also have slow decays that contribute to FI of $\tilde{x}'$ via $\lambda\, L H_u X'$



A_2

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

$$\epsilon = \frac{\Gamma(\tilde{\chi}^- \to l^-) - \Gamma(\tilde{\chi}^+ \to l^+)}{\Gamma(\tilde{\chi}^- \to l^-) + \Gamma(\tilde{\chi}^+ \to l^+)} \simeq \frac{1}{16\pi} \frac{Im\ A_1 A_2^* A_{12}}{|A_2|^2}$$



A_{12}

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

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

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

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

Re-construction from LOSP lifetime

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

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

Re-construction from LOSP lifetime

$$\tau(\tilde{\chi}^- \to l^- \tilde{x}') = 1.4 \times 10^{-8}\mathrm{s} \left(\frac{\varepsilon}{10^{-5}}\right) \left(\frac{m_X}{2\,\mathrm{GeV}}\right) \left(\frac{200\,\mathrm{GeV}}{m_{\tilde{\chi}^+}}\right)^2 \left(\frac{10^2}{g_*}\right)^{3/2} (1 + NL)$$

contribution to asymmetric FI from other non-LOSPs

* $\tilde{\chi}^-$ 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

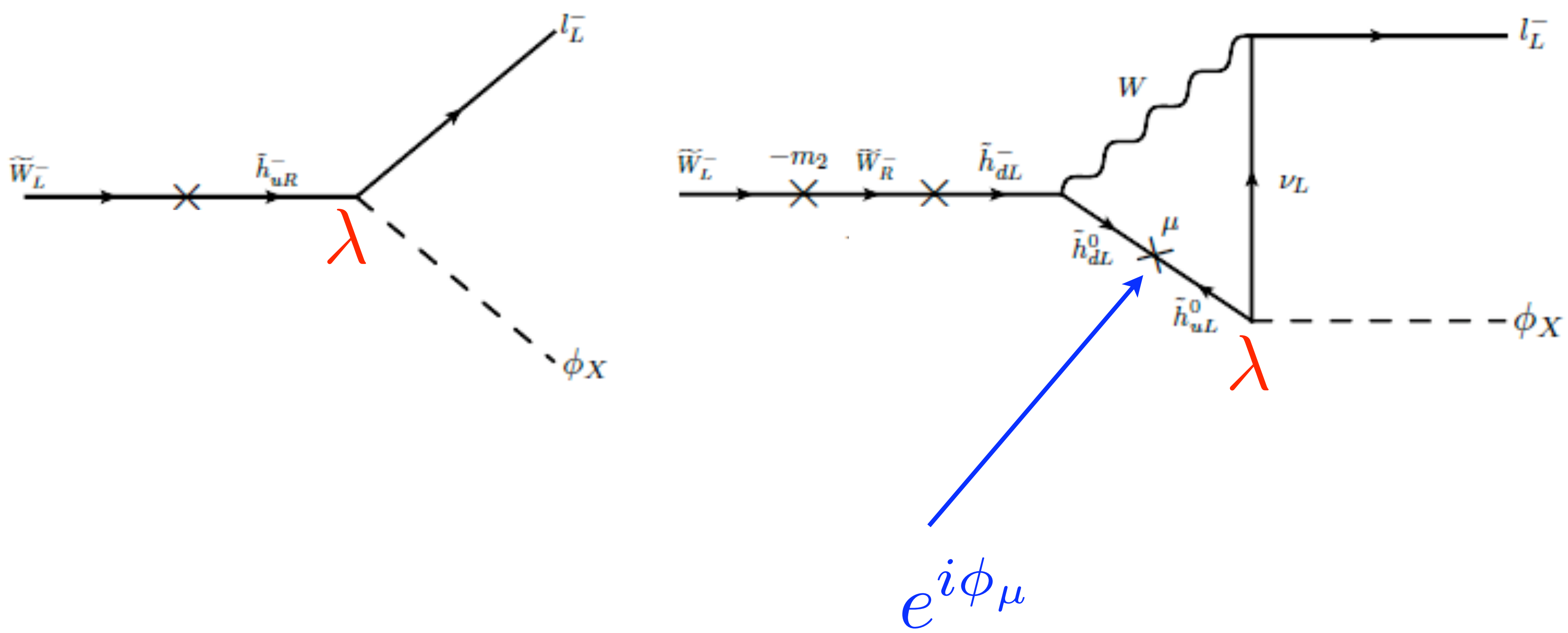
CP violating phases

CP Violation from MSSM Soft Phases

- $\lambda \, L H_u X'$ make λ real by rotating X'

  Phase must come from visible sector

- eg. take $\tilde{\chi}^-$ to be wino-like



- ϕ_μ could be measured by precision spectroscopy at ILC, or via discovery of EDMs

- $$\epsilon = \frac{g^2}{16\pi} f(M_1, M_2, \mu, \tan\beta) \sin\phi_\mu$$

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 $T_R,\ \eta, \dots$)
- Measurements at LHC may allow a prediction of $\Omega_D h^2$

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 $\Omega_D h^2$

Freeze-Out

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

Freeze-In

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

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

A WIMP Miracle?

- Observations require

$$\langle \sigma v \rangle_0 \sim 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

- Dimensional analysis using the weak scale

$$\langle \sigma v \rangle \sim \frac{1}{v^2} \sim 3 \times 10^{-22}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

10^4 off

- Annihilation via heavy virtual state

$$\langle \sigma v \rangle \sim g^4 \frac{m_D^2}{m_V^4} \sim 3 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1} \left(\frac{g}{0.3}\right)^4 \left(\frac{m_D}{100\,\mathrm{GeV}}\right)^2 \left(\frac{400\,\mathrm{GeV}}{m_V}\right)^4$$

Looks good, but allowing a factor 5 variation in each of $g,\ m_D,\ m_V$ 10^7 spread

- More predictive within a particular model --
  WIMP DM in MSSM is pushed into corners