FIMP Dark Matter

FIMP = Frozen-In Massive Particle, or
Feebly-Interacting Massive Particle

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JHEP 1003, 080 (2010) with Lawrence Hall, Karsten Jedamzik and Stephen West and works in progress

- Quite generally, residual DM (X) density is due to a departure from equilibrium

- Usually assumed to be *freeze-out* where X starts with full T^3 density but interactions cannot maintain Boltzmann-suppressed X equilibrium density

- Freeze-out dominates our thinking about DM candidates, detection, and collider pheno

There exists an equally motivated, calculable, and testable mechanism of DM genesis, where interactions too weak to ever bring X to equilibrium: *freeze-in*

Basic Mechanism

- Suppose exists a FIMP, X, only very weakly coupled to the SM thermal bath via some renormalizable interaction

- Assume negligible initial X abundance

- As universe evolves X particles are produced from collisions or decays of bath particles, B_i , but at rate that is always suppressed by the small coupling

during a Hubble time at era $T \gg m$, the yield is

$$Y_{FI}(T) \sim \lambda^2 \, \frac{M_{Pl}}{T} \begin{cases} 1 & \longleftarrow \Delta L = \lambda X B_1 B_2 B_3 \\ \frac{m^2}{T^2} & \longleftarrow \Delta L = \lambda X B_1 B_2 \end{cases}$$

(m is mass of heaviest particle in vertex)

Process is always IR dominated

- Dominant production occurs at $T \sim m$, since at lower T there is an exponential suppression resulting from necessity of involving a particle of mass $m > T$

- Hence for all renormalisable interactions get X yield

$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m} \right)$$

Note: For non-renormalizable interactions FI is dominated by UV contributions (for large-enough reheat temperature) and so not calculable from IR theory alone, just like gravitinos in usual case

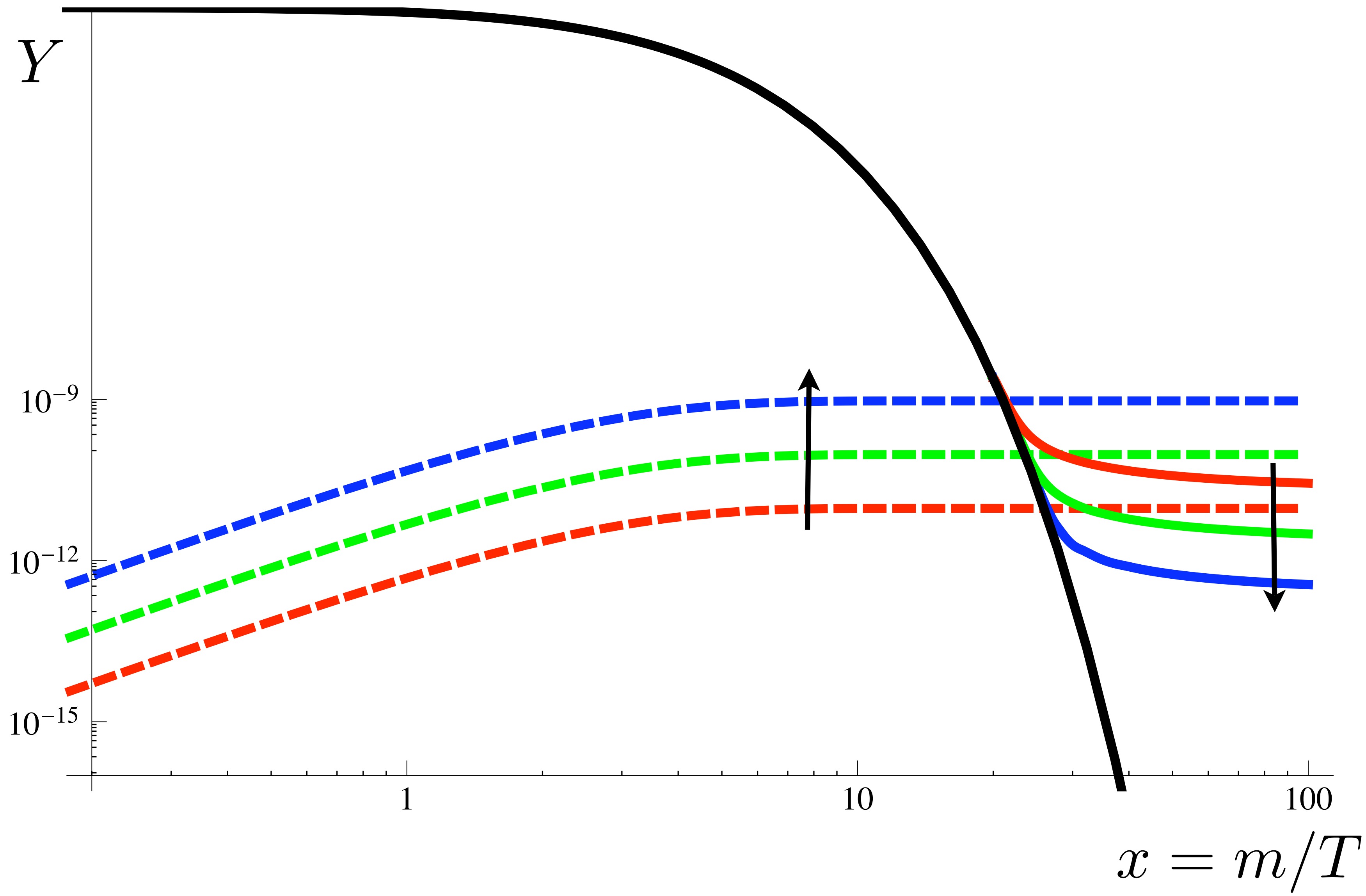
Freeze-in is the 'opposite' process to traditional freeze-out:

For increasing interaction strength

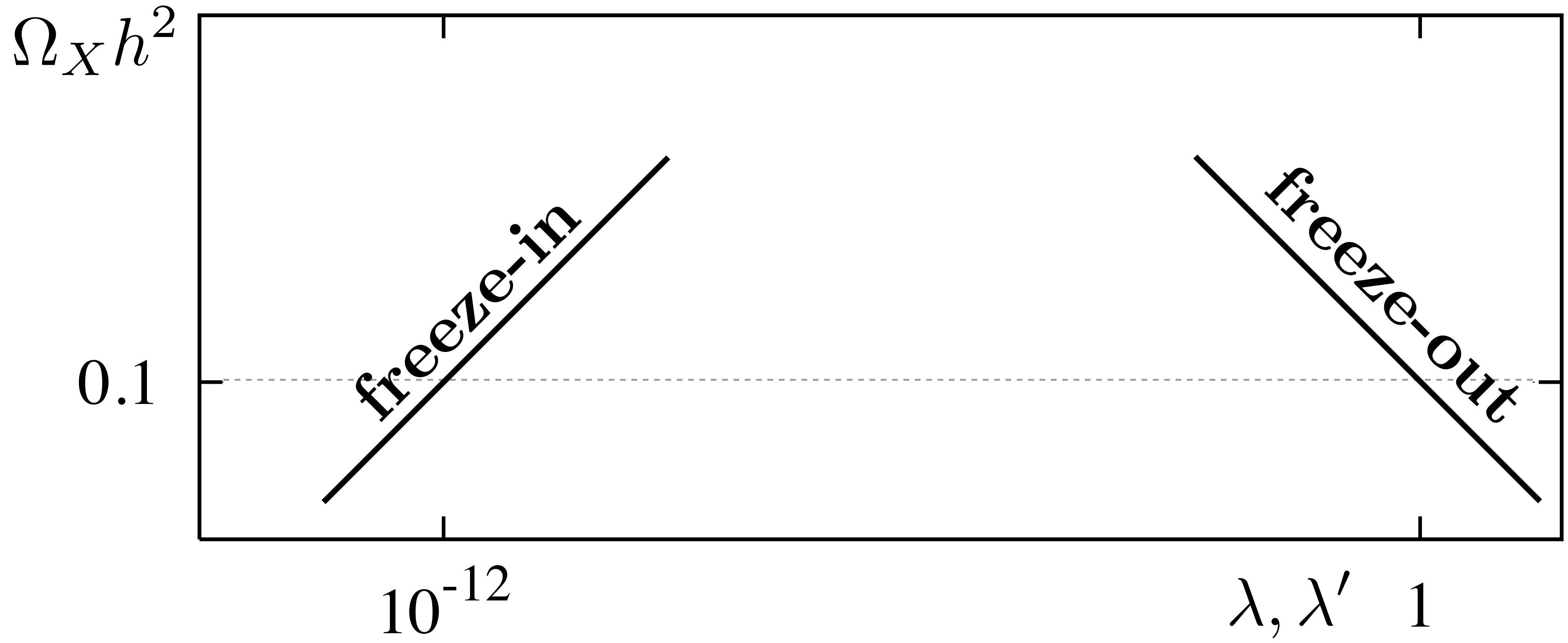
$$\begin{aligned} Y_{FO} &\sim \frac{1}{\sigma v M_{Pl}\, m'} \\ &\sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \end{aligned} \qquad\qquad Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m}\right)$$

or as a function of the time of FO (resp. FI) $t_m \sim M_{Pl}/m^2$

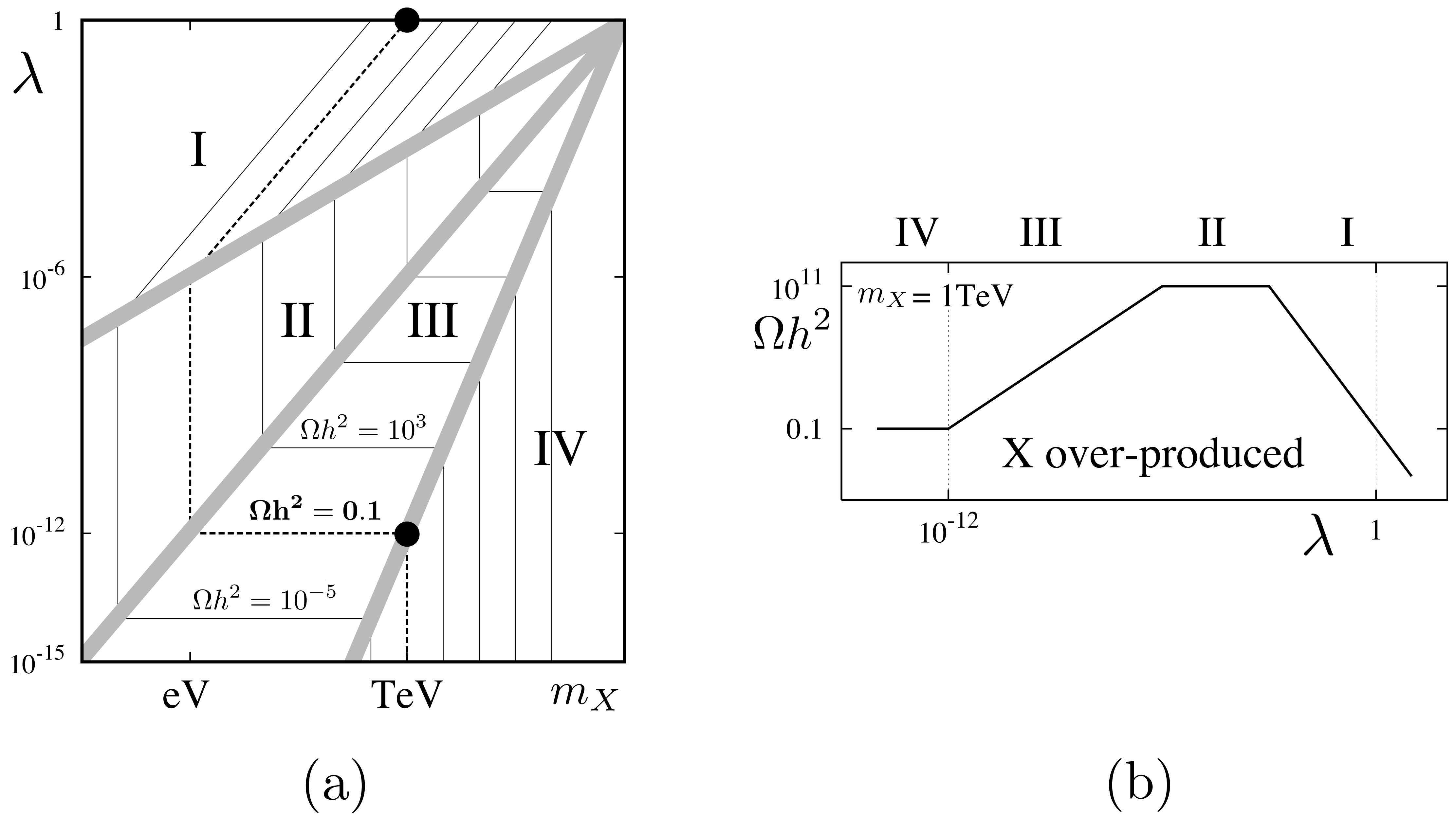
$$Y_{FO} \sim \frac{1}{\lambda'^2\, m' t_{m'}} \qquad\qquad Y_{FI} \sim \lambda^2\, m t_m$$



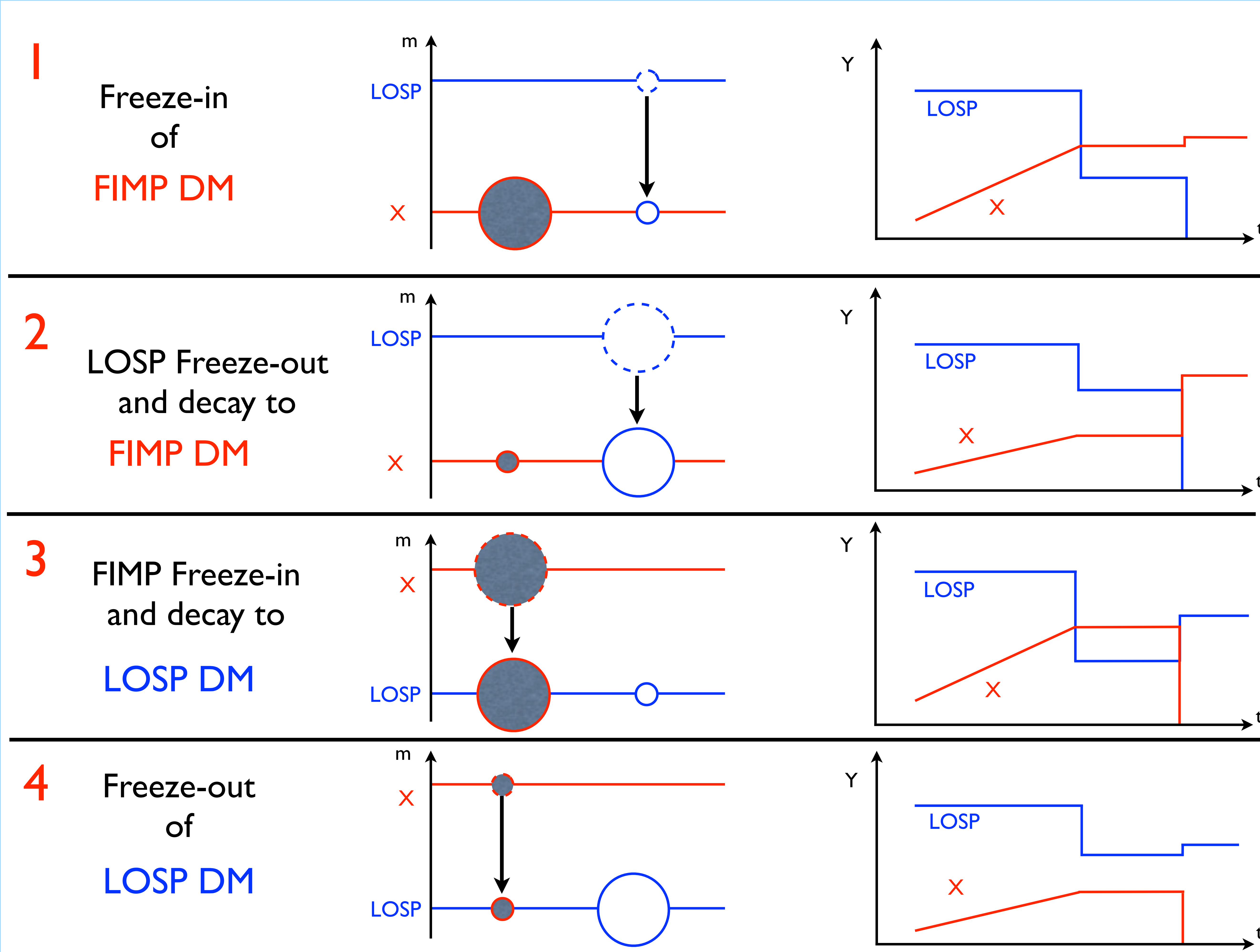
Evolution of the relic yields for freeze-out (solid coloured) and freeze-in via Yukawa interaction (dashed coloured). Arrows indicate effect of increasing coupling strength for the two processes.



Schematic of relic abundances due to FI and FO as function of coupling strength. Connection of FI and FO yield behaviours to one another is model-dependent: There exist ``abundance phase diagrams" of DM yield depending upon strength and type of DM-thermal bath interaction and DM mass



Abundance diagram with Ωh^2 contours as function of Yukawa λ and m_X:
I: $\lambda^2 > \sqrt{m_X/M_{Pl}}$; X undergoes conventional FO.
II: $m_X/m_{Pl} < \lambda^2 < \sqrt{m_X/M_{Pl}}$; X decouples from bath with yield $Y_X \sim 1$.
III: $m_X/m_{Pl} > \lambda^2 > (m_X/M_{Pl})^2$; $Y_X < 1$ and FI dominates.
IV: $\lambda < (m_X/M_{Pl})$; DM arises from ψ_1 FO and then decay to $X + \psi_2$.



1
Freeze-in of FIMP DM
m
LOSP
X
Y
LOSP
X
t
2
LOSP Freeze-out and decay to FIMP DM
m
LOSP
X
Y
LOSP
X
t
3
FIMP Freeze-in and decay to LOSP DM
m
X
LOSP
Y
LOSP
X
t
4
Freeze-out of LOSP DM
m
X
LOSP
Y
LOSP
X
t

Abundance Calculations

- First consider case 1 where FIMP X is the DM particle itself

- Suppose coupling $\Delta L = \lambda X B_1 B_2$ with $m_{B_1} > m_{B_2} + m_X$ then dominant FI process is via decays $B_1 \to B_2 X$

Boltzmann eqn:

$$
\begin{aligned}
\dot{n}_X + 3Hn_X &= \int \prod_i d\Pi_i \ \delta^4\left(\sum p_i\right)\left[|M|^2_{B_1 \to B_2 X} f_{B_1}(1 \pm f_{B_2})(1 \pm f_X) - \text{inverse}\right] \\
&\approx 2g_{B_1} \int d\Pi_{B_1} \Gamma_{B_1} m_{B_1} f_{B_1} \\
&= g_{B_1} \int \frac{d^3 p_{B_1}}{(2\pi)^3} \frac{f_{B_1} \Gamma_{B_1}}{\gamma_{B_1}}
\end{aligned}
$$

Can do integrals and using $Y \equiv n/S$ and $\dot{T} \approx -HT$ leads to

$$Y_X \approx \int_{T_{min}}^{T_{max}} \frac{g_{B_1} m_{B_1}^2 \Gamma_{B_1}}{2\pi^2} \frac{K_1(m_{B_1}/T)}{SH} dT$$
$$\approx \frac{135\, g_{B_1}}{8\pi^3 (1.66) g_*^S \sqrt{g_*^\rho}} \left(\frac{M_{Pl} \Gamma_{B_1}}{m_{B_1}^2} \right)$$

$$\boxed{\Omega_X h^2 \approx \frac{1.09 \times 10^{27} g_{B_1}}{g_*^S \sqrt{g_*^\rho}} \frac{m_X \Gamma_{B_1}}{m_{B_1}^2}}$$

Corresponding interaction strength for observed DM density

$$\lambda \simeq 1.5 \times 10^{-13} \left(\frac{m_B}{m_X} \right)^{1/2} \left(\frac{g_*}{10^2} \right)^{3/4} \left(\frac{g_{bath}}{10^2} \right)^{-1/2}$$

(Will soon see that naturally expect such couplings to arise...)

Due to small coupling, automatically get long-lived LOSP states at LHC (displaced decays, & out-of-time decay of stopped LOSP's if charged)

$$\tau_{B_1} = 7.7 \times 10^{-3}\mathrm{sec}\ \ g_{B_1} \left(\frac{m_X}{100\,\mathrm{GeV}}\right) \left(\frac{300\,\mathrm{GeV}}{m_{B_1}}\right)^2 \left(\frac{10^2}{g_*}\right)^{3/2}$$

direct test of production mechanism at LHC!

Such measurements well within capability of LHC, cf. in particular CMS studies

Even if LOSP is neutral so leading decay to X invisible, sub-dominant 3- or 4-body decays involve charged SM states and allow measurement of lifetime and X mass

Similarly for $m_X > m_{B_1} + m_{B_2}$ (so case 3: FIMP decays to B_1LOSP give DM density)

$$\Omega_{B_1} h^2 \approx \frac{1.09 \times 10^{27}}{g_*^S \sqrt{g_*^\rho}} \frac{m_{B_1} \Gamma_X}{m_X^2}$$

Here assumed :

- the FI contribution from decays of X dominates the conventional FO abundance of B_1

- the decay $X \to B_1 B_2$ occurs at a time after the FO of B_1 so that the density does not get reprocessed (this naturally so for weak scale masses)

Origin of Small Coupling

The 'WIMP miracle' is that for $m' \sim v$ and $\lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

gives the observed value of $\Omega_{DM}h^2$

The 'FIMP miracle' is that for $m \sim v$ and $\lambda \sim v/M_{Pl}$

$$Y_{FI} \sim \lambda^2\left(\frac{M_{Pl}}{m}\right) \sim \frac{v}{M_{Pl}}$$

Suggests that FIMPs occur where small couplings arise at linear order in the weak scale

Prime candidates:

- moduli of the SUSY-breaking sector giving MSSM soft terms

$$m^2\left(1+\frac{T}{M}\right)(\phi^\dagger\phi+h^\dagger h) \qquad \mu B\left(1+\frac{T}{M}\right)h^2 \qquad Ay\left(1+\frac{T}{M}\right)\phi^2 h$$

$$m_{\tilde g}\left(1+\frac{T}{M}\right)\tilde g\tilde g \qquad \mu y\left(1+\frac{T}{M}\right)\phi^2 h^* \qquad \mu\left(1+\frac{T}{M}\right)\tilde h\tilde h,$$

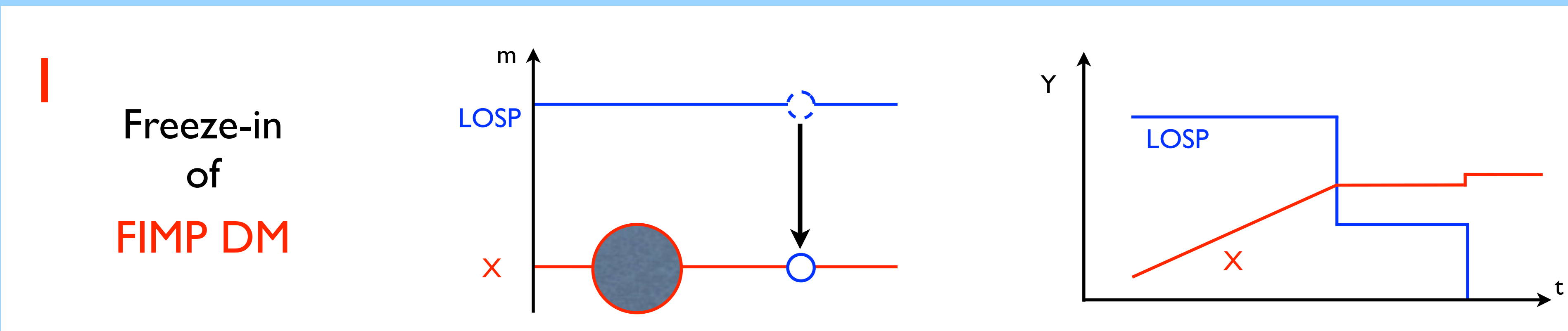
- similarly for the modulini

$$\mu\,\frac{\tilde T}{M}\,\tilde h h \qquad \frac{m_{susy}}{M}\,\tilde T(q\tilde q^\dagger, l\tilde l^\dagger, \tilde h h^\dagger)$$

For $M \sim M_{GUT}$ (natural value of compactification scale in realistic string theories) give renormalizable couplings $\lambda \sim 10^{-13}$

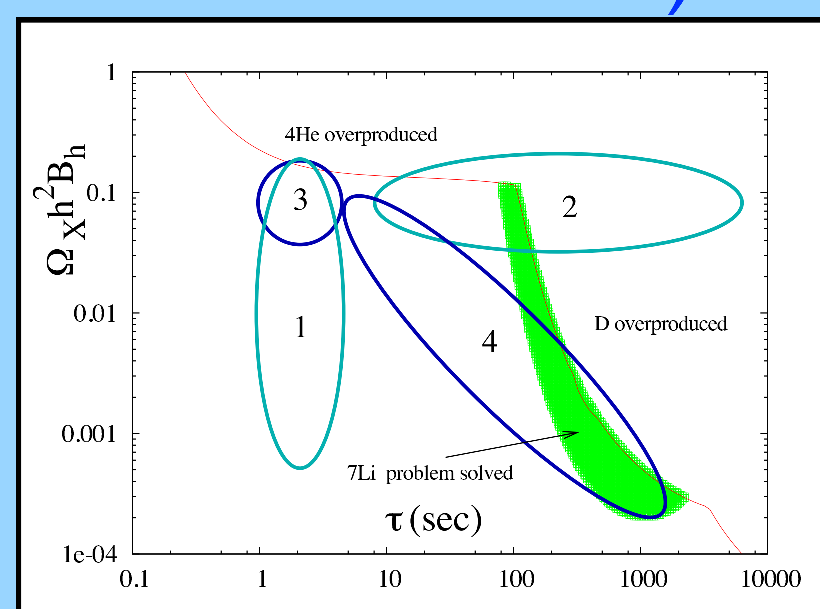
Experimental/Observational Consequences

A rich set of possibilities in all 4 cases. Very briefly, eg,...

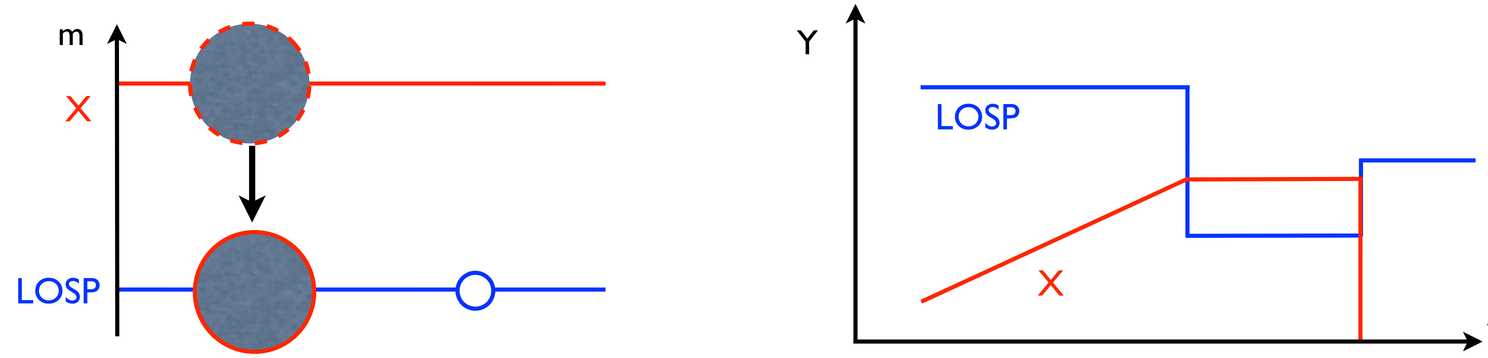


• Late decay of (possibly charged of coloured) MSSM LOSP at LHC.   Usual MSSM dis-favoured regions now allowed

• If 3- or 4-body decays dominate (for kinematic reasons) then MeV-era BBN-altering decays possible



3 FIMP Freeze-in and decay to LOSP DM



- Enhanced indirect detection signals of DM (as LOSP FO density has to be less than conventional value)

- If 3- or 4-body decays dominate (for kinematic reasons) then MeV-era BBN-altering decays of X possible

Final comment:

Have assumed throughout that FIMP is close to weak-scale. For WIMPs this must be so as unitarity limits size of annihilation cross-section

For FIMPs completely different:

DM with relic abundance Y and mass m leads to temperature for matter-rad'n equality of parametric form $T_e \sim Ym$

Remarkably for FI this is independent of mass

$$T_{e,FI} \sim \lambda^2 M_{Pl}$$

Calculable thermal production of superheavy FIMP DM possible

FIMPs and Freeze-In might rule!