Freeze-In of FIMP Dark Matter

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Outline of Talk

I. Freeze-out of Weakly Interacting Massive Particles

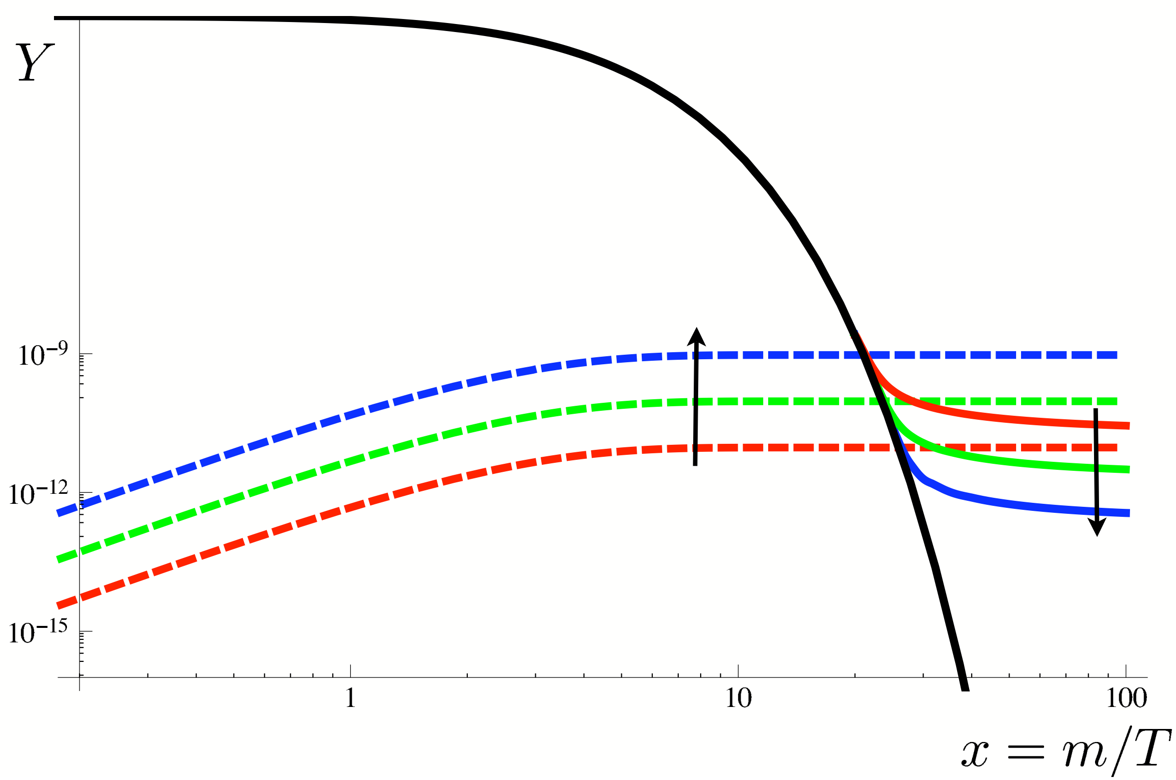
II. Freeze-In of Feebly Interacting Massive Particles
Hall, K.J., March-Russell, West

- The Freeze-In Process
- Comparison to super-WIMPs
- A Unified View of Freeze-In and Freeze-Out
- Detectability
- Candidate Particles

III. Conclusions on FIMPs IV. News of the Spite Plateau and the Lithium Problem V. Advertising IDM2010: 'Identification of Dark Matter' 26.7.-30.7. in Montpellier

Freeze-Out of Dark Matter

- need some dark matter particle X stabilizing symmetry (parity)
- annihilation reactions at $X + \bar{X} \rightarrow standard\, model\, particles$ freeze out at some $T \lesssim m_X$ and $n_X \ll T^3$



Virtues of Freeze-Out Production of Dark Matter

minimalistic assumptions as well as accelerator testability

- thermodynamic and chemical equilbrium at freeze-out

  seemingly reasonable assumption since typically $t_{equ}/t_{Hubble} \ll 1$

- $\Omega h^2 \approx 0.1 \left(\frac{\sigma v}{3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}}\right)^{-1}$ - required interactions in principle accelerator testable - in practice not that straightforward

reminiscent to conditions which led to the standard Big Bang nucleosynthesis model

The WIMP miracle

it is known that due to apparent violation of unitarity of the SM new physics is required at the TeV scale

a TeV-mass scale particle has $\sigma v \sim 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ give/or take $\sim$ two orders of magnitude

Question:

Is freeze-out of dark matter the ONLY *accelerator testable dark matter production mechanisim in thermodynamic equilibrium conditions ?*

No !

FIMP Dark Matter

imagine a particle X which is so feebly interacting with the plasma (in TE) that it will never reach equilibrium abundance

call it FIMP $\equiv$
"Feebly Interacting Massive Particle"

take interaction $\mathcal{L} \sim \lambda X B_1 B_2$ with $\lambda \ll 1$ where B_1 and B_2 are bath particles

the plasma produces it in attempting to attain equilibrium via $B_1 \to B_2 + X$ decay production

production per Hubble time

$$\Delta n_X / s \sim \frac{n_{B_1} \Gamma_{B_1 \to B_2 + X} t_H}{s}$$

$$\sim \frac{g_{B_1} T^3 \lambda^2 m_{B_1} M_{pl} / T^2}{g T^3}$$

$$\sim \frac{g_{B_1} \lambda^2 m_{B_1} M_{pl}}{g T^2}$$

prod. infrared dominated !!!

$$\to \Omega_X \sim \frac{g_{B_1}}{g} \lambda^2 M_{pl} \frac{m_X}{m_{B_1}}$$

Difference to super-WIMPs

- super-WIMPs as gravitinos or axinos are also very weakly interacting
- $\Delta n_G/s \sim n^2 \sigma v t_H/s \sim g^2 M_{pl} T \sigma v$ with $\sigma \sim 1/M_{pl}^2$ for weak mass scale gravitino, for example
- $\rightarrow$ their production is ultraviolet dominated and reheat temperature T dependent

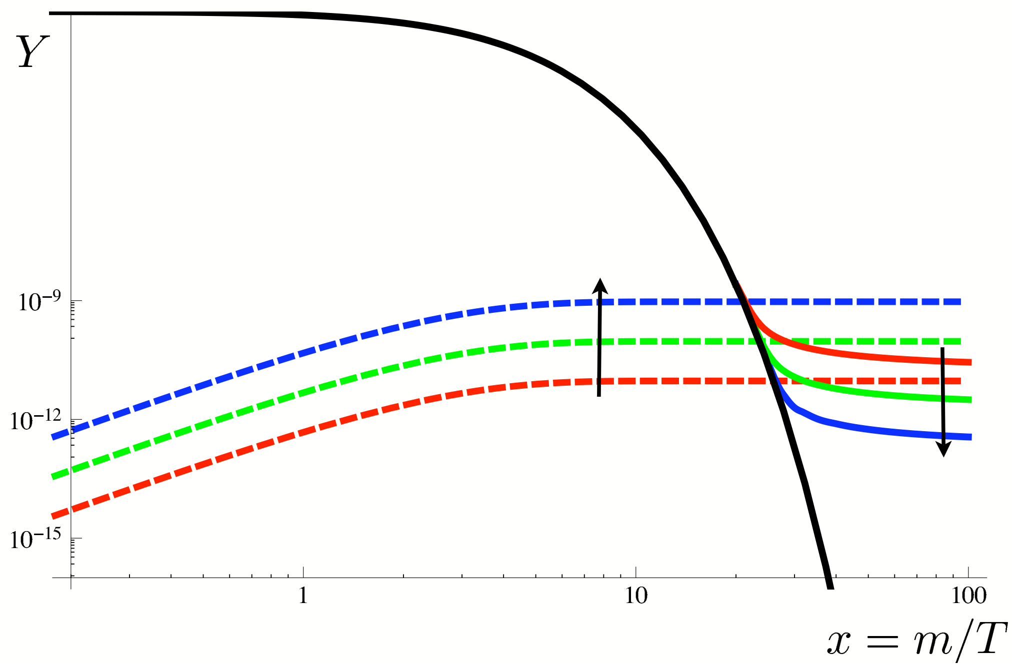
reheat temperature essentially non-testable in accelerators –

requires detailed information of the inflaton sector

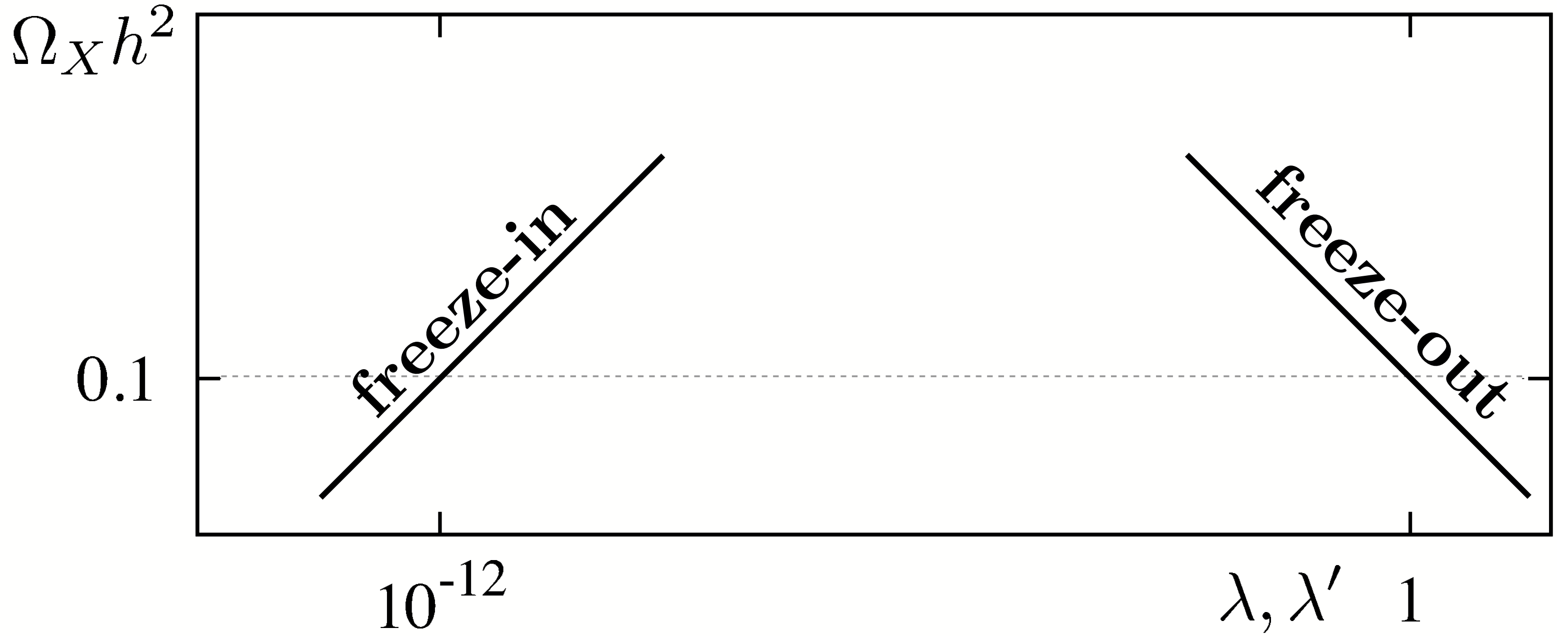
difference between super-WIMPs and FIMPs is renormalizability *of interaction*

Freeze-In of Dark Matter

- production reactions $B_1 \to X + B_2$ become inefficient at $T \lesssim m_{B_1}$ freezing-in (thawing-in) the dark matter abundance at $n_X \ll T^3$



- production goes up with interaction strength


$\Omega_X h^2$
0.1
freeze-in
freeze-out
10^{-12}
λ, λ' 1

Required Interaction Strength

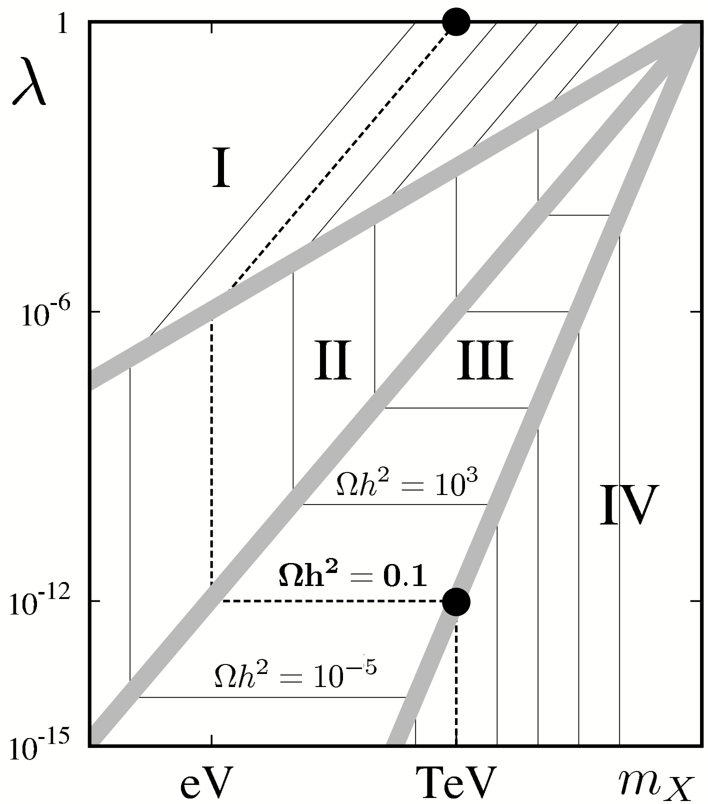
$$\lambda \simeq 1.5 \times 10^{-12} \left(\frac{m_X}{m_{B_1}}\right)^{1/2} \left(\frac{g_*(m_X)}{10^2}\right)^{3/4} \left(\frac{1}{g_{bath}}\right)^{1/2}$$

this is close to $M_{\rm EW}/M_{\rm GUT} \sim 10^{-13}$

$g_{bath} \gg 1$ possible

A Unified View of Freeze-In and Freeze-Out

$\mathcal{L} \sim \lambda X B_1 B_2$ and $M_x \sim M_{B_1}$

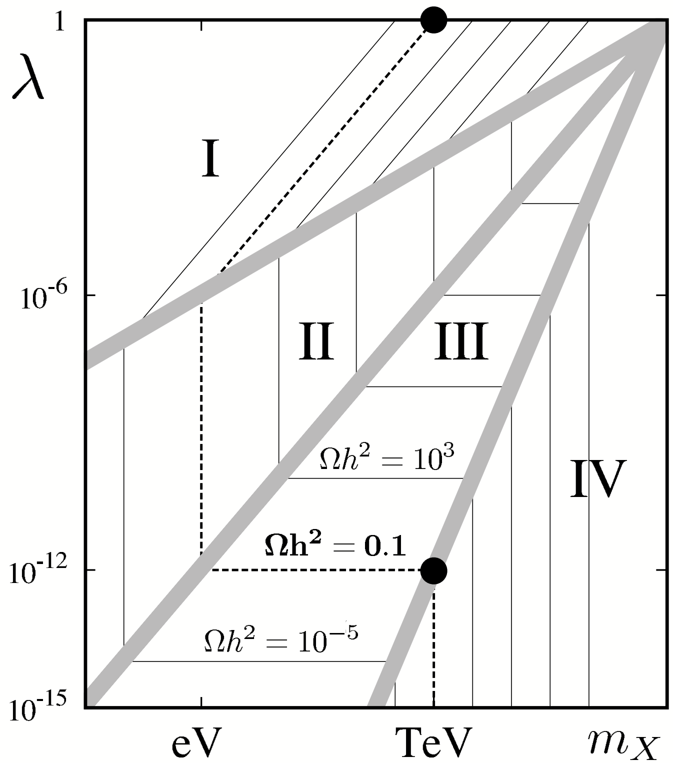


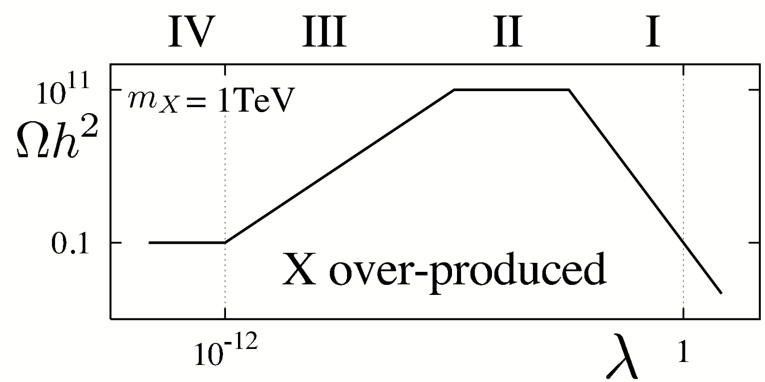
freeze-in completes the lower half of the diagram

Region I: Coupling λ of X to thermal bath strong enough such that equilibrium $\sim T^3$ density will be attained and at $T < m_X$ $n_X \ll T^3$ will be frozen out $\rightarrow$ non-relativistic freeze-out Region II: Coupling λ of X to thermal bath strong enough such that equilibrium $\sim T^3$ density will be attained – however when $T < m_X$ no further reduction $\rightarrow$ relativistic freeze-out Region III: Coupling to thermal bath **NOT** strong enough to attain equilibrium density $\sim T^3$ – freeze-in – abundance of X dominated by freeze-in Region IV: Coupling to thermal bath **NOT** strong enough to attain equilibrium density $\sim T^3$ – freeze-in – abundance of X dominated by freeze-out of bath particles and subsequent decay

A Unified View of Freeze-In and Freeze-Out

$\mathcal{L} \sim \lambda X B_1 B_2$ and $M_x \sim M_{B_1}$

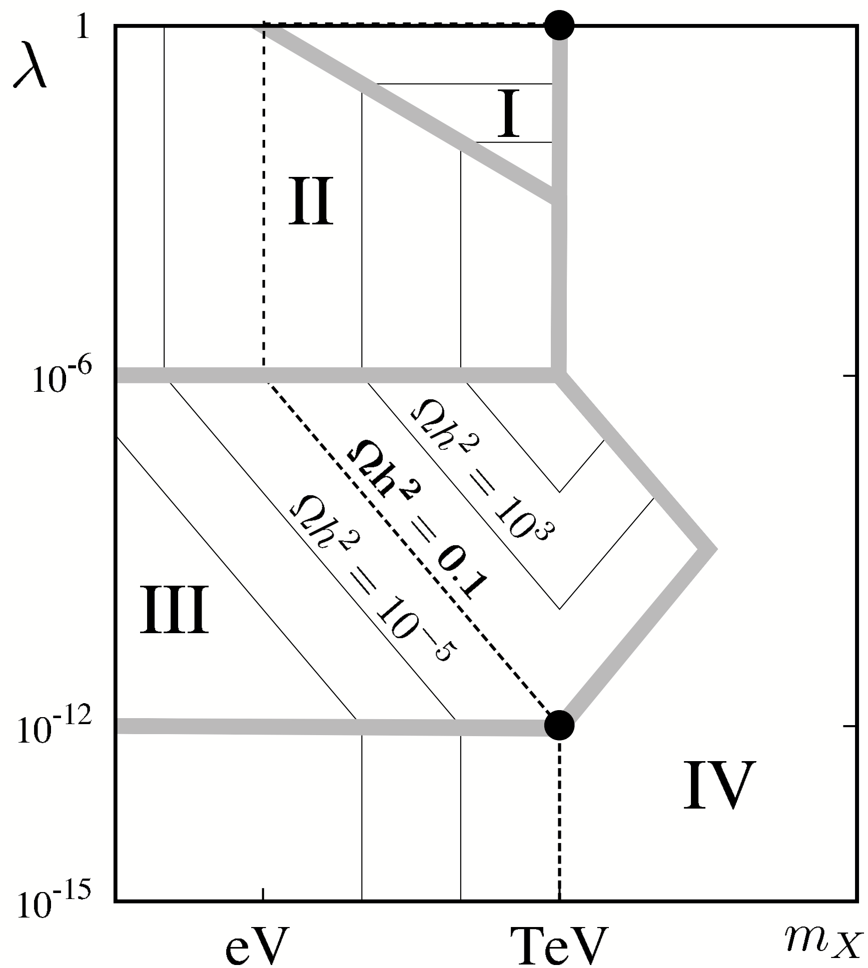




freeze-in completes the lower half of the diagram

Another Phase Diagram

$\mathcal{L} \sim \lambda X B_1 B_2$ and $M_{B_1} \sim 1$ TeV



Detectability of FIMPs ?

Production via $B_1 \longrightarrow B_2 + X$

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

$$\tau_{B_1} = 7.7 \times 10^{-3} \text{sec}$$

$$g_{B_1} \left(\frac{m_X}{100\,\text{GeV}}\right) \left(\frac{300\,\text{GeV}}{m_{B_1}}\right)^2 \left(\frac{10^2}{g_*(m_{B_1})}\right)^{3/2} \left(\frac{\Omega_X h^2}{0.011}\right)^{-1}$$

direct test of production mechanism in lab !!!!!

Why not $2 \to 2$ Production dominant ?

in case production via $B_1 + B_2 \to B_3 + X$ dominates, the Ω_X-τ_B correlation may be lost

however, $B_1 + B_2 \to B_3 + X$ production

$$\frac{dY_X}{dT} \approx \frac{3\lambda^2 T^2 m_X}{128\pi^5} \frac{K_1(m_X/T)}{SH}$$

is always phase space suppressed compared to $B_1 \to B_2 + X$ production

$$\frac{dY_X}{dT} \approx \frac{\lambda^2 m_{B_1}^3}{16\pi^3} \frac{K_1(m_{B_1}/T)}{SH}$$

Production of Dark Matter via Freeze-In of FIMPs

so far, have assumed FIMP is the dark matter particle

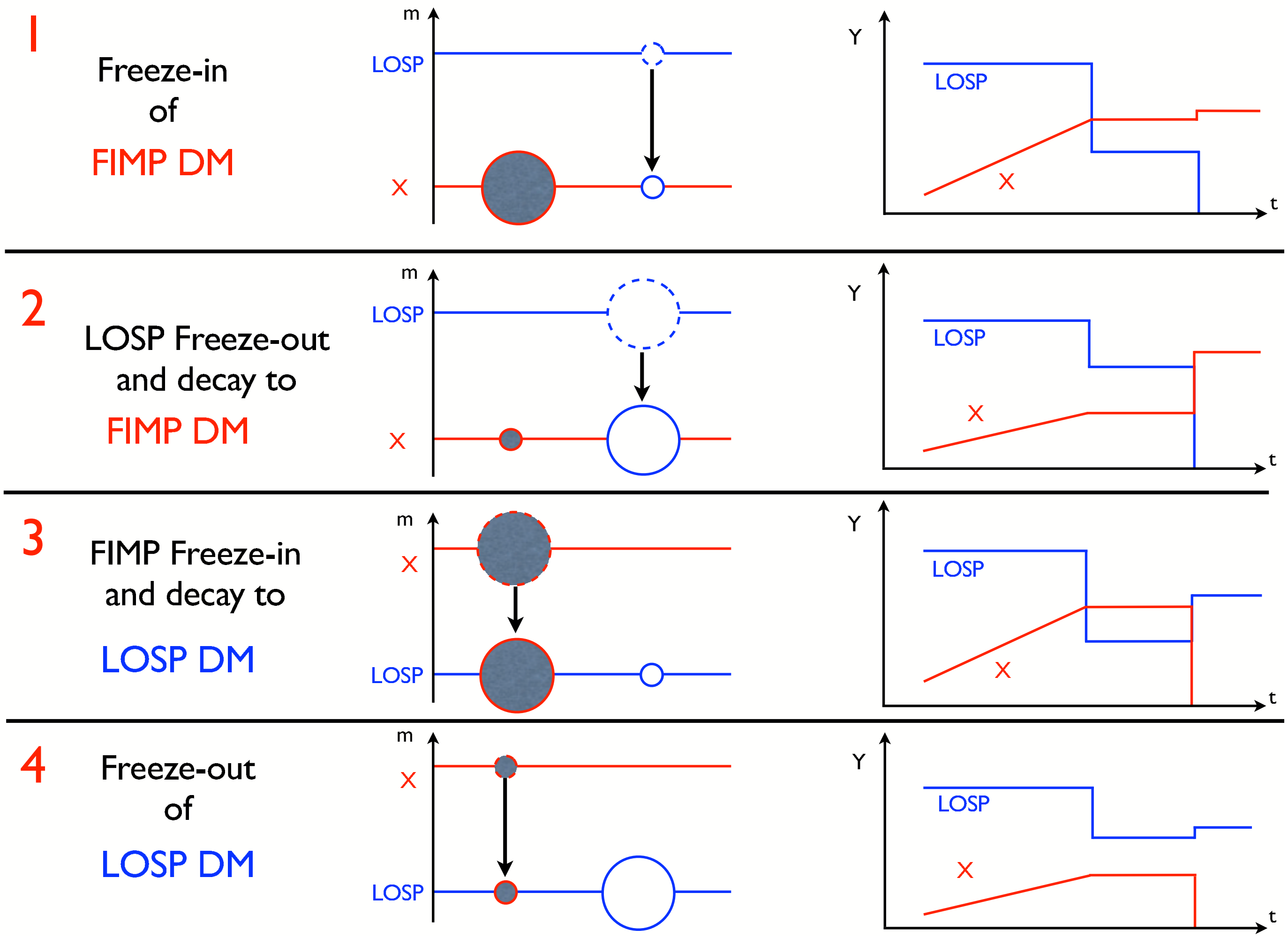
- need some (at least approximate) symmetry which stabilizes the dark matter particle, call it parity
- the standard model particles have positive parity
- the dark matter particle and other yet undiscovered particles have negative parity, stabilizing them towards decay into standard model particles

LOSP $\equiv$ "Lightest Observable Sector Particle" which carries negative parity

$m_{\rm LOSP} < m_{\rm FIMP}$ is possible $\rightarrow$ the **LOSP may be the dark matter particle**

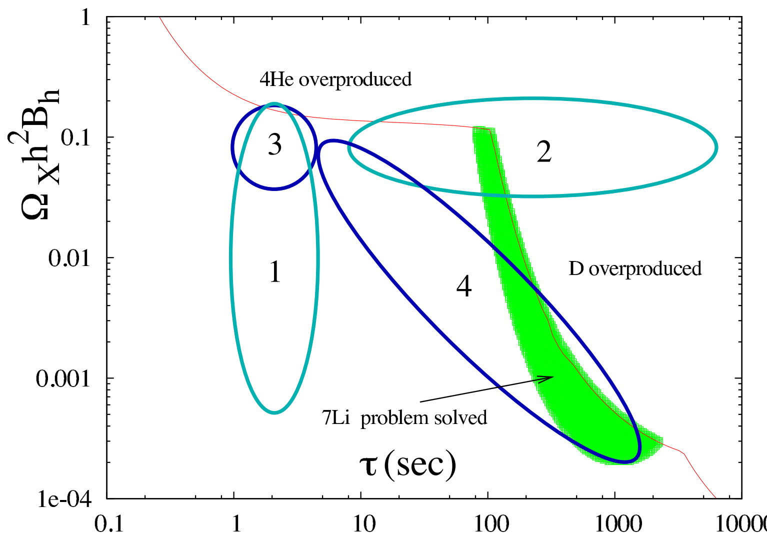
- FIMPs are produced by inverse decays, e.g. $B + {\rm LOSP} \rightarrow {\rm FIMP}$, which decay into LOSPs after LOSP freeze-out
- the LOSP self-annihilation cross section can be large

Four possibilities



LOSP/FIMP Decays during BBN ?

- two-body decay:
  $\tau \sim 10^{-2}\,\text{sec}\,(\Omega_X h^2/0.1)^{-1} g_{B_1}$
- for $\Omega_X h^2 \sim 0.1$ and $g_{B_1} \sim 1$
  $\rightarrow$ no effect
- three-body decay:
  $\tau \sim 3\text{sec}\, g^{-2}\,(\Omega_X h^2/0.1)^{-1} g_{B_1}$
- possible effect, especially when
  $\Omega_X h^2 < 0.1$ and/or $g_{B_1} \gg 1$
- three-body decay, for example, when
  LOSP *not* directly coupled to FIMP



Candidate Particles

- Moduli determining soft SUSY breaking parameters

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

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

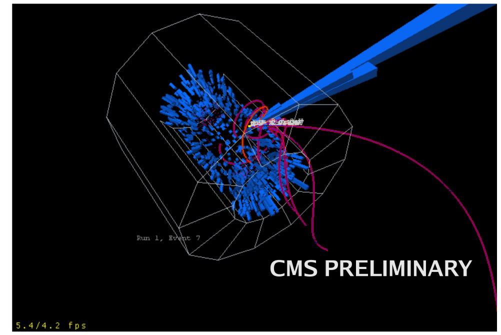
- Dirac Neutrinos within weak scale supersymmetry

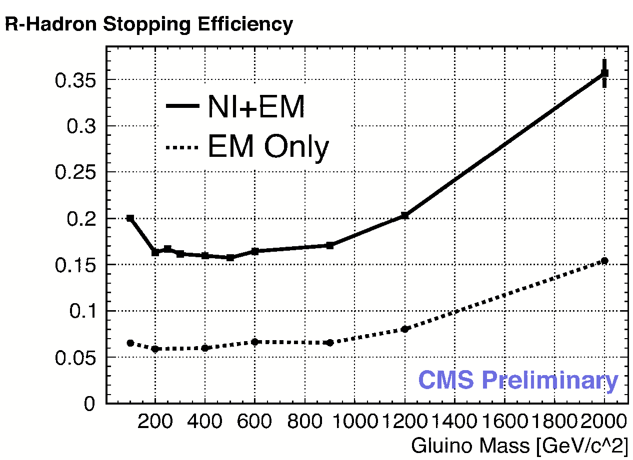
$$\lambda\, LNH_u,$$

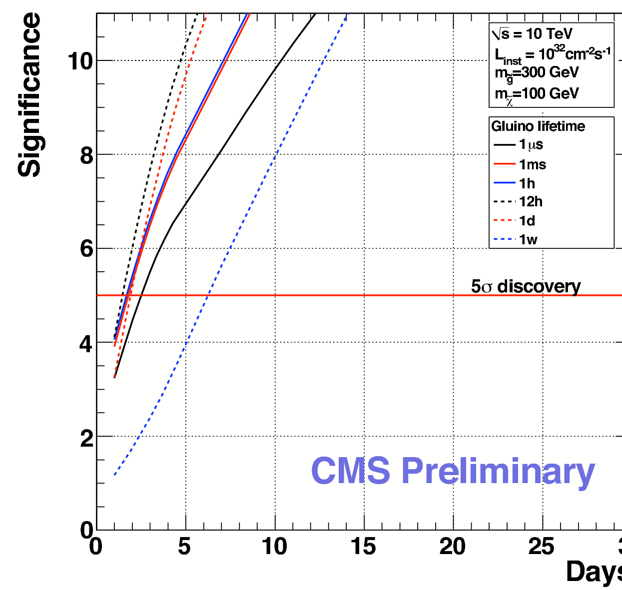
- $\lambda \sim 10^{-13}$ for observed neutrino masses !! Right-handed sneutrino close to perfect candidate for FIMP (cf. Asaka *et al.* 06,07)

A CMS Experiment to find metastable particles

- consider FIMP *is* the dark matter
- in case, the LOSP is charged and/or strongly interacting, it may be stopped in the CMS detector (inner HCL region)
- decay of such stopped particles are easily seen in "beam-off" periods (only background cosmic rays)







- "sensitivity" to $\tau_X \sim 10^{-6}\mathrm{sec} - 10^{5}\mathrm{sec}$

How to convince oneself that FIMPs constitute the dark matter ?

- the LOSP is charged and/or strongly interacting, *NOT* a neutralino
- it is metastable
- its life time falls is in the right ballpark to fulfill the $\tau_{\rm LOSP} \gtrsim 10^{-2} {\rm sec}\, m_X/m_{LOSP}$ relationship

FIMPs as dark matter is **a very** plausible scenario

how to really convince oneself

- one may determine $m_{\rm LOSP}$ and $m_{\rm X} \sim m_{\rm LOSP}$ from kinematics
- the $\tau_{\rm LOSP}$-Ω_X relationship is consistent with/close to the WMAP value

Summary

- dark matter production via freeze-out may occur in (plausible) thermodynamic equilibrium conditions, is UV insensitive, and accelerator testable !
- when looking at other dark matter production mechanism with such attributes one is led to the process of freeze-in
- in fact, freeze-in and freeze-out may be unified in a dark matter *interaction strength - mass* diagram
- candidate particles for *Feebly Interacting Massive Particles* as required in freeze-in do exist, in fact, the required interaction strength $\lambda \lesssim 10^{-12}$ is suggestive
- freeze-in production may lead to a simple testable correlation between the life time of a new fundamental metastable particle and the abundance of the dark matter