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

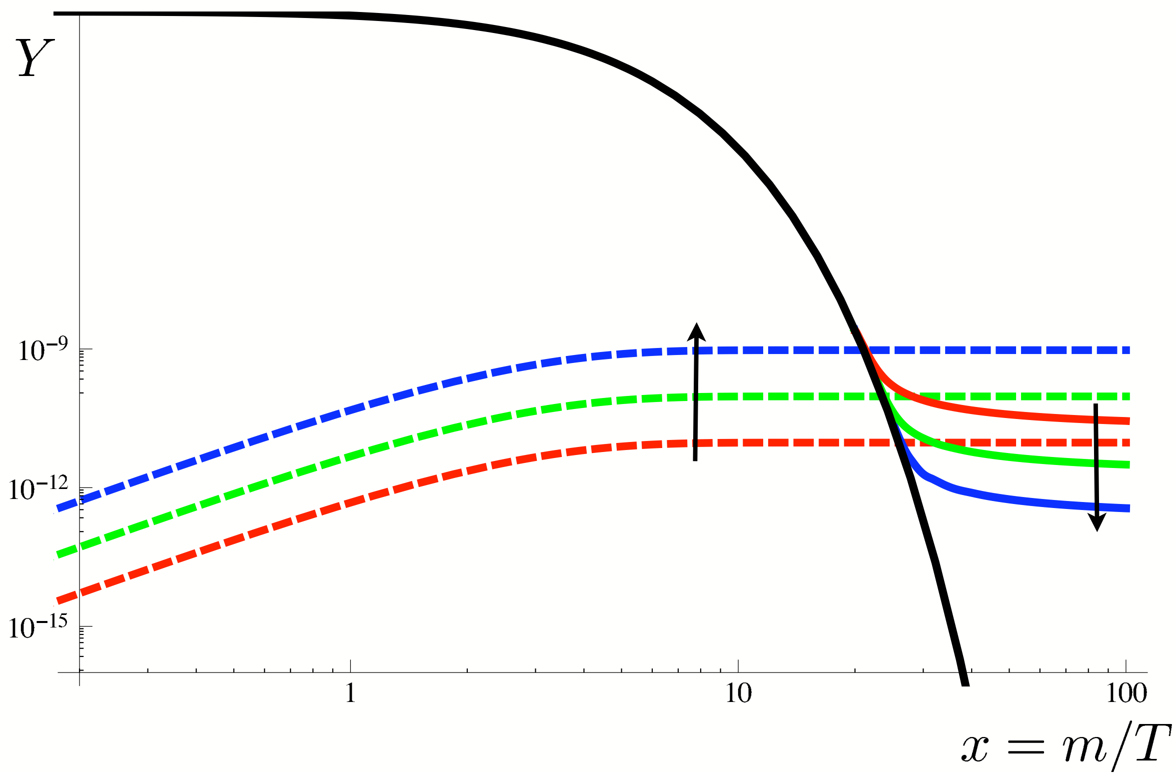
Hall, K.J., March-Russell, West

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

III. Conclusions

Freeze-Out of Dark Matter

- need some dark matter particle X stabilizing symmetry (parity)
- annihilation reactions at $X + \bar{X} \to standard\, model\, particles$ 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 shortly before 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
- WIMP-"miracle": the required interaction strength is reached roughly at the electroweak scale where new physics is expected

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

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

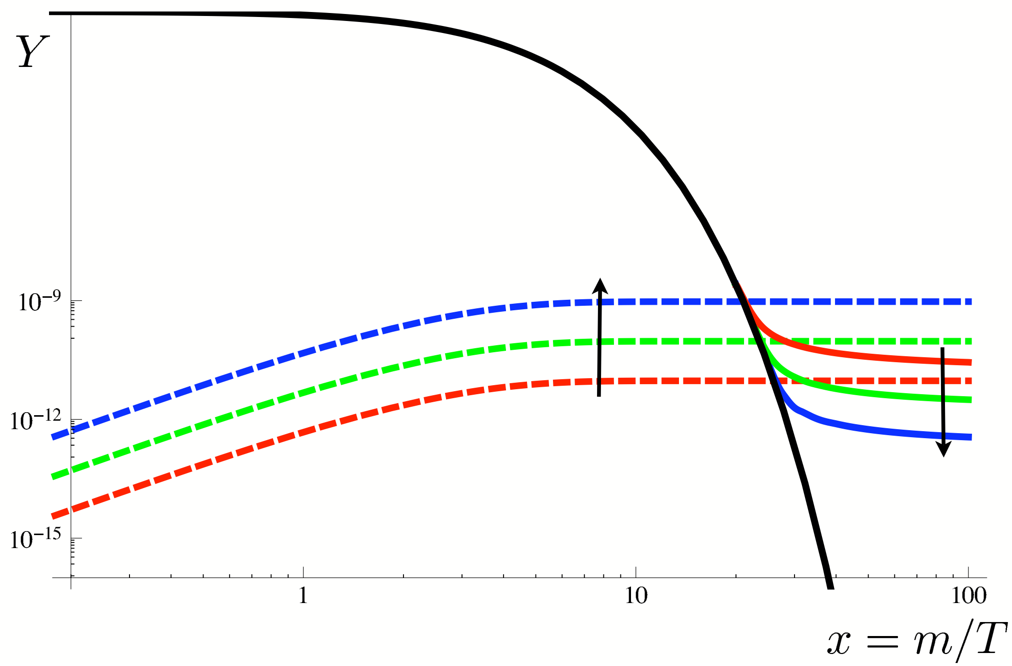
reheat temperature essentially non-testable in accelerators –

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

Required Interaction Strength

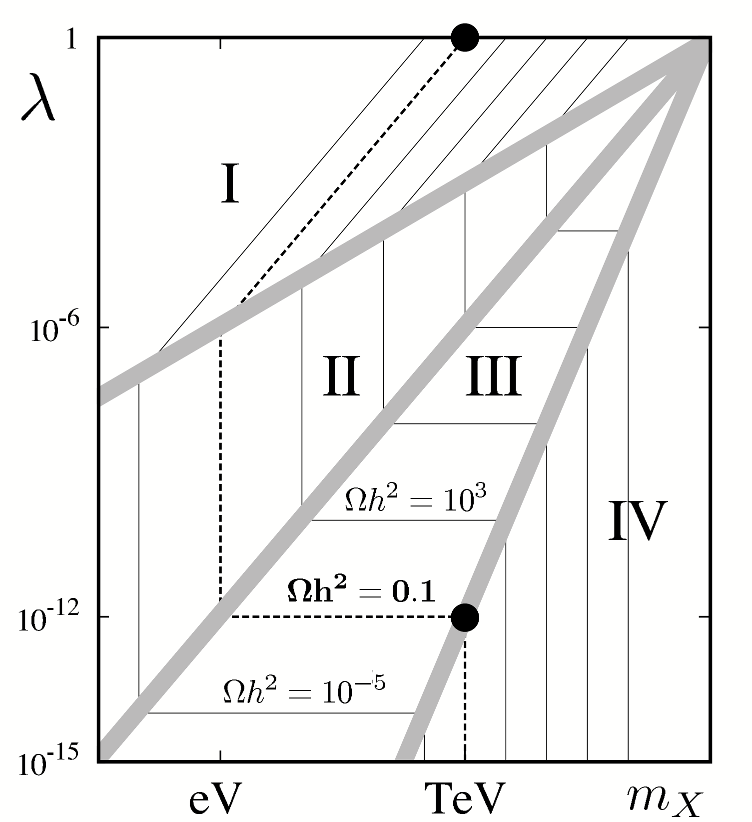
$$\lambda \simeq 1.5 \times 10^{-12} \left(\frac{m_X}{m_{B_1}}\right)^{1/2} \left(\frac{g_*(m_X)}{10^2}\right)^{3/4} \left(\frac{1}{g_{bath}}\right)^{1/2}$$

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 $M_x \lesssim M_{B_1}$

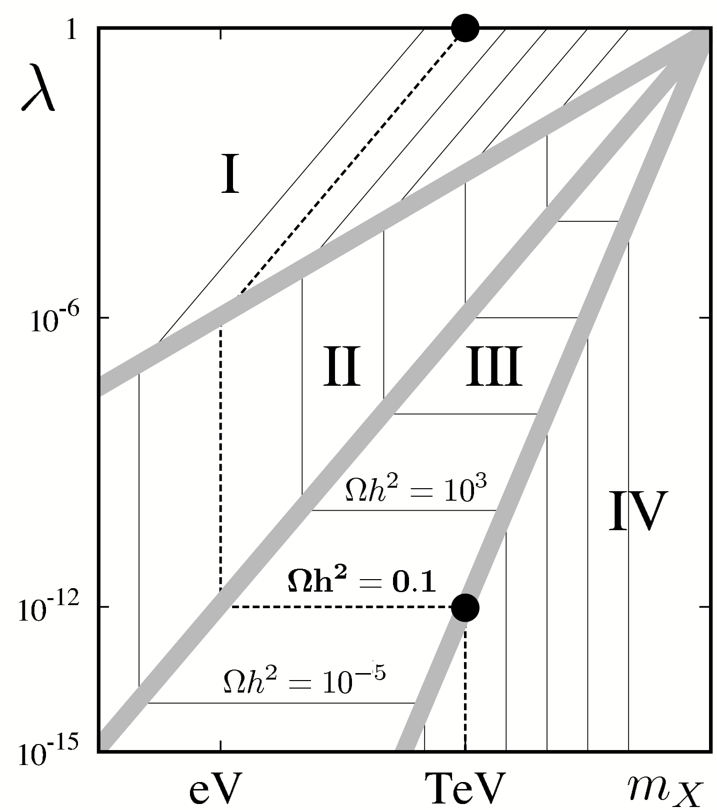


Region I: Coupling λ of X to thermal bath strong enough such that equilibrium $\sim T^3$ density will be attained and at $T < m_X$ $n_X \ll T^3$ will be frozen out $\rightarrow$ non-relativistic freeze-out

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

A Unified View of Freeze-In and Freeze-Out

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



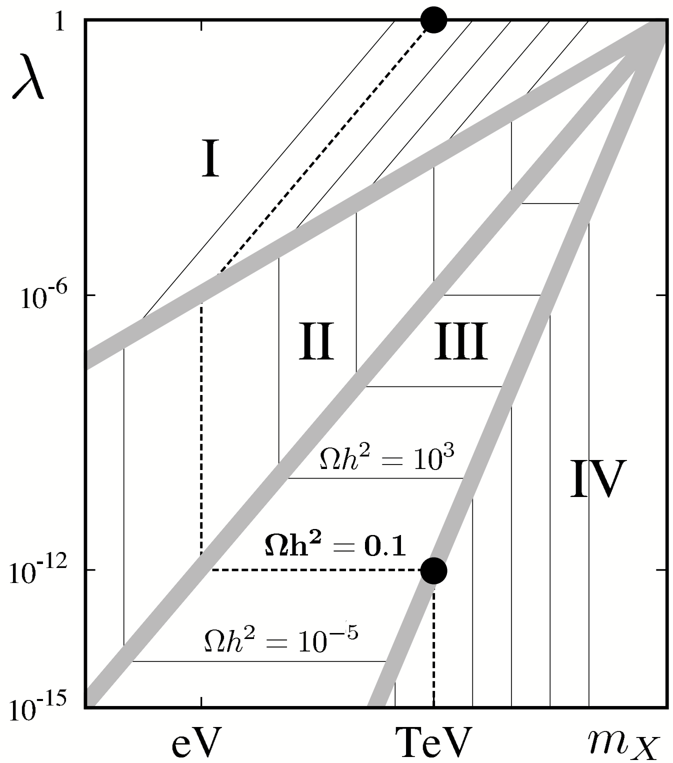
Region III: Coupling to thermal bath **NOT** strong enough to attain equilibrium density $\sim T^3$ – freeze-in – abundance of X dominated by freeze-in

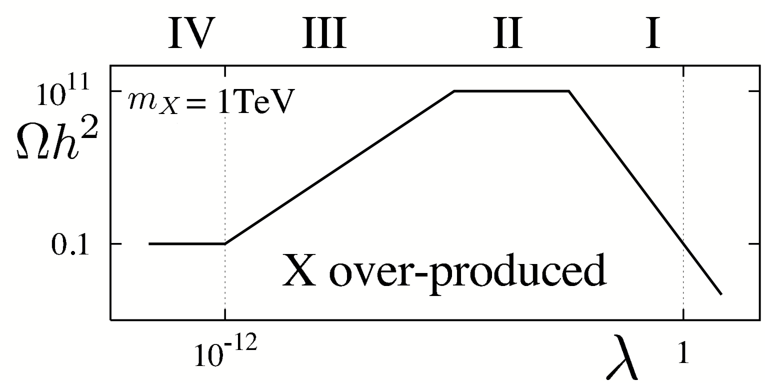
Region IV: Coupling to thermal bath **NOT** strong enough to attain equilibrium density $\sim T^3$ – freeze-in – abundance of X dominated by freeze-out of bath particles B and subsequent decay to X

freeze-in completes the lower half of the diagram

A Unified View of Freeze-In and Freeze-Out

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





freeze-in completes the lower half of the diagram

Detectability of FIMPs ?

Production via $B_1 \to B_2 + X$

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

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

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

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

Production of Dark Matter via Freeze-In of FIMPs

so far, have assumed FIMP is the dark matter particle

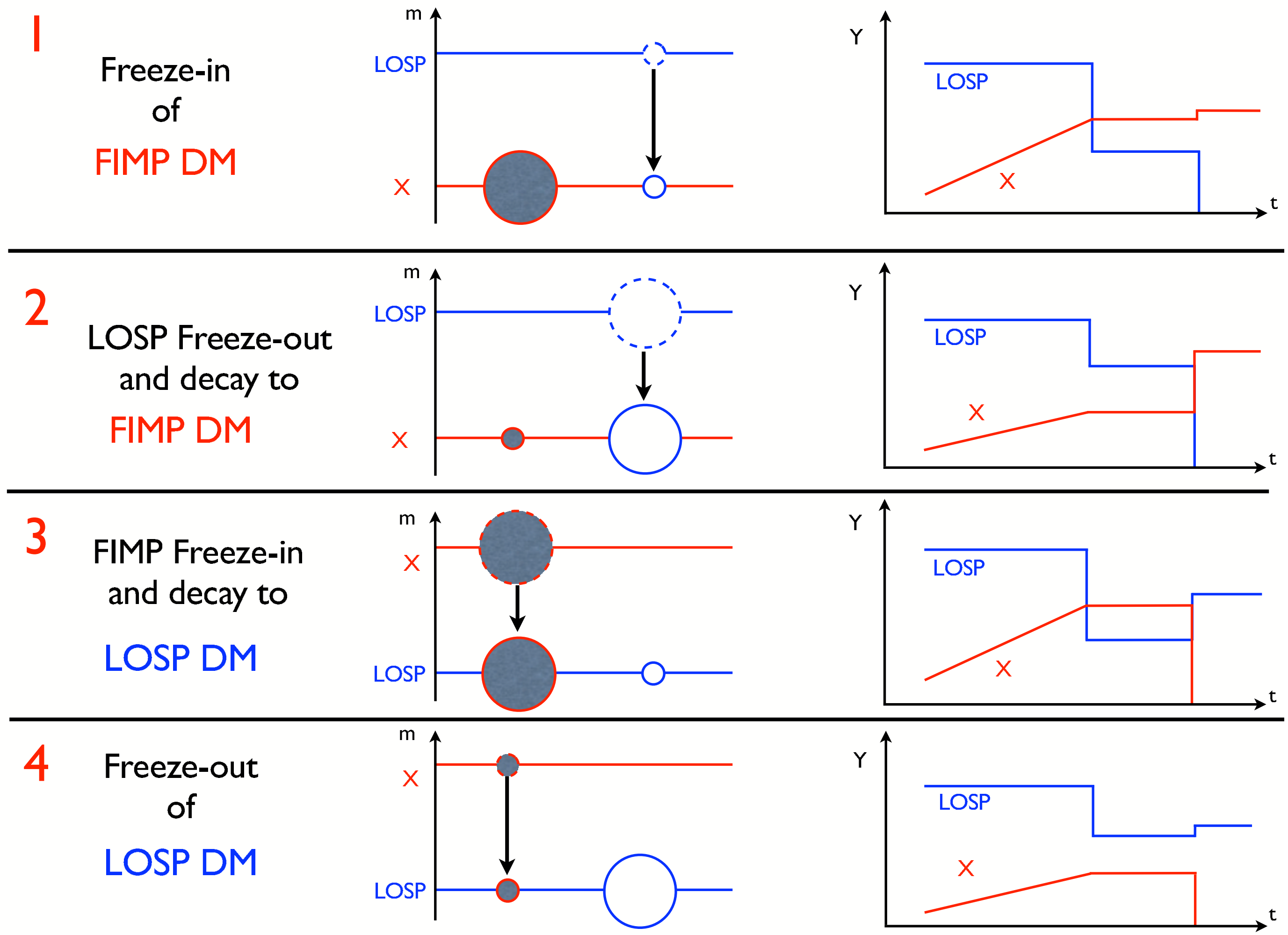
- need some (at least approximate) symmetry which stabilizes the dark matter particle, call it parity
- the standard model particles have positive parity
- the dark matter particle and other yet undiscovered particles have negative parity, stabilizing them towards decay into standard model particles

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



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)

LOSP/FIMP Decays during BBN ?

- two-body decay:
  $\tau \sim 10^{-2}\,\mathrm{sec}\,(\Omega_X h^2/0.1)^{-1} g_{B_1}$
- for $\Omega_X h^2 \sim 0.1$ and $g_{B_1} \sim 1$
  $\rightarrow$ no effect
- three-body decay:
  $\tau \sim 3\mathrm{sec}\,g^{-2}\,(\Omega_X h^2/0.1)^{-1} g_{B_1}$
- 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

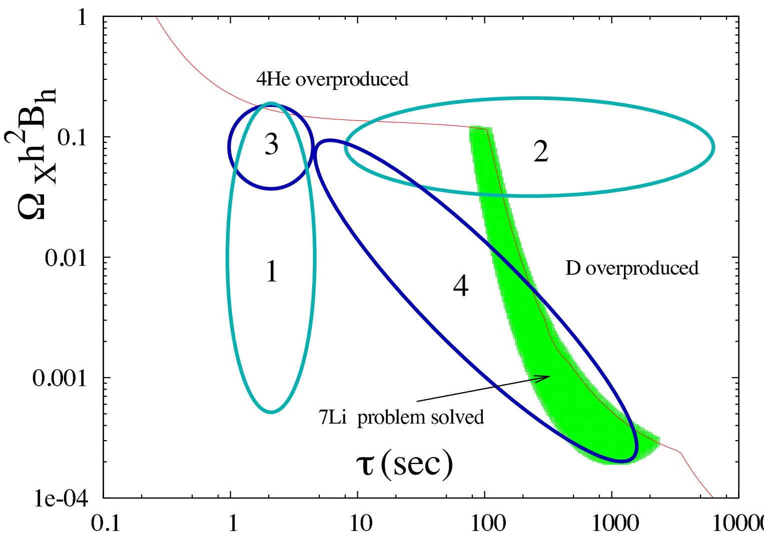


figure assumes LOSP/FIMP three-body decays but production of FIMPs via two-body (inverse) decays

LHC Experiments to find metastable particles

Both, Atlas and CMS, are searching for metastable particle decays .... as of January 31, CMS has a *hint* of a $\sim 700\mathrm{GeV}$ "heavy stable charged particle" ...

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 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

LOSP/FIMP Decays during BBN ?

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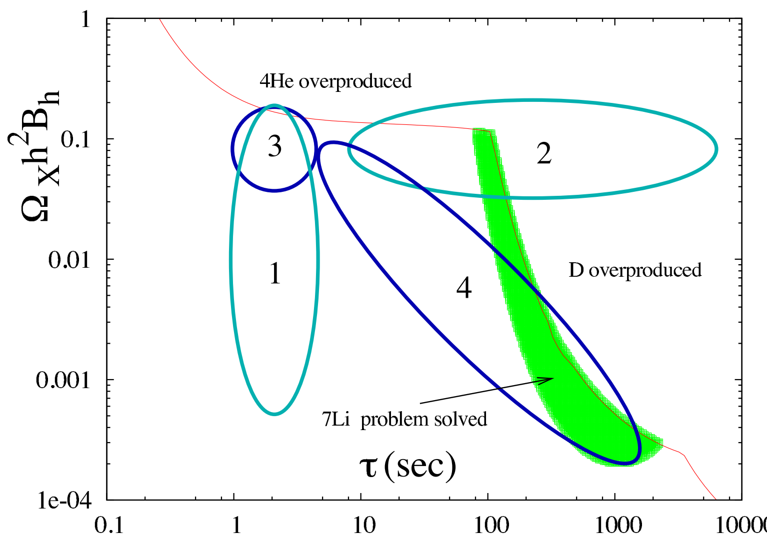

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