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 equilibrium at freeze-out
  seemingly reasonable assumption since typically \( t_{\text{equ}}/t_{\text{Hubble}} \ll 1 \)

- \( \Omega h^2 \approx 0.1 \left( \frac{3 \times 10^{-26}\text{cm}^3\text{s}^{-1}}{\sigma v} \right)^{-1} \) - 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 $\sigma v \sim 3 \times 10^{-26} \text{cm}^3\text{s}^{-1}$ give/or take $\sim$ two orders of magnitude
Question:

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

No!
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 $B_1 \rightarrow B_2 + X$ decay production

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

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

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

prod. infrared dominated !!!

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

→ 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
production reactions $B_1 \rightarrow X + B_2$ 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 \( M_{EW}/M_{GUT} \sim 10^{-13} \)

\( g_{bath} \gg 1 \) possible
A Unified View of Freeze-In and Freeze-Out

\[ \mathcal{L} \sim \lambda X B_1 B_2 \text{ and } M_x \sim M_{B_1} \]

Region I: Coupling \( \lambda \) 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 \( \lambda \) 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

freeze-in completes the lower half of the diagram
A Unified View of Freeze-In and Freeze-Out

\[ \mathcal{L} \sim \lambda X B_1 B_2 \quad \text{and} \quad M_x \sim M_{B_1} \]

freeze-in completes the lower half of the diagram
Another Phase Diagram

\[ \mathcal{L} \sim \lambda X B_1 B_2 \text{ and } M_{B_1} \sim 1 \text{ TeV} \]
Detectability of FIMPs?

Production via $B_1 \rightarrow B_2 + X$

$$\Omega_X h^2 \approx \frac{1.09 \times 10^{27} g_{B_1}}{g^s_\ast \sqrt{g^p_\ast}} \frac{m_X \Gamma_{B_1}}{m_{B_1}^2}$$

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

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

direct test of production mechanism in lab

!!!!!!
Why not $2 \rightarrow 2$ Production dominant?

in case production via $B_1 + B_2 \rightarrow B_3 + X$ dominates, the $\Omega_{X^{-}\tau_B}$ correlation may be lost

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

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

\[ \text{LOSP} \equiv "\text{Lightest Observable Sector Particle}" \] which carries negative parity

\[ m_{\text{LOSP}} < m_{\text{FIMP}} \] is possible \( \rightarrow \) the LOSP may be the dark matter particle

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

1. Freeze-in of FIMP DM

2. LOSP Freeze-out and decay to FIMP DM

3. FIMP Freeze-in and decay to LOSP DM

4. Freeze-out of LOSP DM
LOS/FIMP Decays during BBN?

- two-body decay:
  \[ \tau \sim 10^{-2} \text{ sec} \left( \Omega_X h^2 / 0.1 \right)^{-1} g_{B_1} \]
  for \( \Omega_X h^2 \sim 0.1 \) and \( g_{B_1} \sim 1 \)
  \( \rightarrow \) no effect

- three-body decay:
  \[ \tau \sim 3 \text{ sec} g^{-2} \left( \Omega_X h^2 / 0.1 \right)^{-1} g_{B_1} \]
  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

\[ m^2 \left( 1 + \frac{T}{M} \right) (\phi^\dagger \phi + h^\dagger h) \]
\[ \mu B \left( 1 + \frac{T}{M} \right) h^2 \]
\[ A y \left( 1 + \frac{T}{M} \right) \phi^2 h \]
\[ m_\tilde{g} \left( 1 + \frac{T}{M} \right) \tilde{g} \tilde{g} \]
\[ \mu y \left( 1 + \frac{T}{M} \right) \phi^2 h^* \]
\[ \mu \left( 1 + \frac{T}{M} \right) \tilde{h} \tilde{h}, \]

- Dirac Neutrinos within weak scale supersymmetry

\[ \lambda L N H_u, \]

- \( \lambda \sim 10^{-13} \) 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 $\tau_X \sim 10^{-6}\text{ sec} - 10^5\text{ sec}$
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 \( \tau_{\text{LOSP}} \gtrsim 10^{-2} \text{ sec} \frac{m_X}{m_{\text{LOSP}}} \) relationship

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

how to really convince oneself

- one may determine \( m_{\text{LOSP}} \) and \( m_X \sim m_{\text{LOSP}} \) from kinematics
- the \( \tau_{\text{LOSP}} - \Omega_X \) 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