Freeze-in

14th International Workshop on
the Dark Side of the Universe

LAPTh – Annecy

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LPTHE - Paris

Outline

· Freeze-in: General framework and practical computations

· A bit of model-building: Clockworking FIMPs

· (Some) signatures of freeze-in

· Summary and outlook

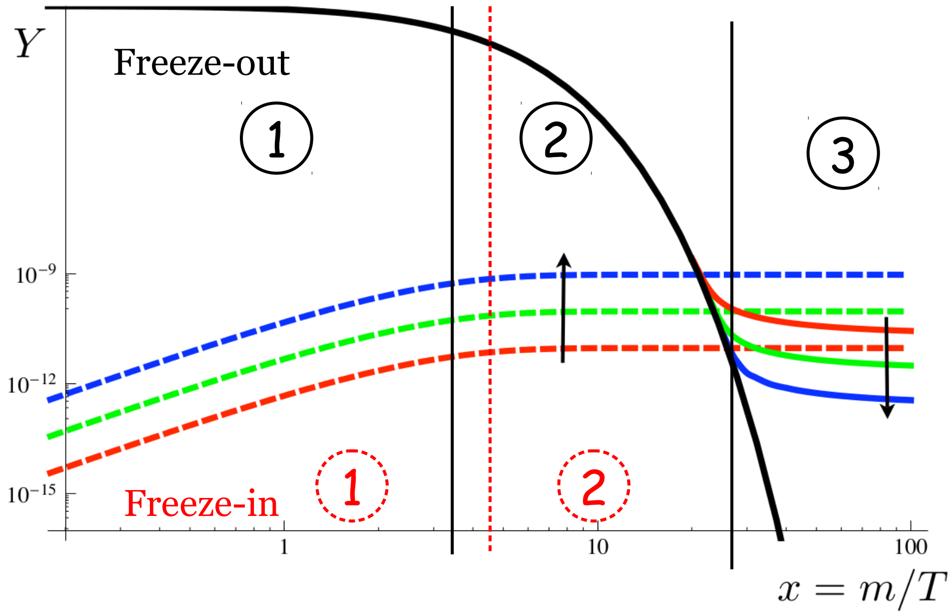
Based on:

- G. Bélanger, F. Boudjema, A.G., A. Pukhov, B. Zaldivar, arXiv:1801.03509
- A. G. *et al*, contribution in 1803.10379
- A.G., K. Mohan, D. Sengupta, 1807.xxxxx
- A.G., *et al, in preparation*

Freeze-in: general idea

arXiv:hep-ph/0106249
arXiv:0911.1120
arXiv:1706.07442...

Tweaked from, arXiv:0911.1120



Two basic premises :

- DM interacts *very* weakly with the SM.
- DM has a negligible initial density.

Assume that in reaction $A \to B$, ξ_A/ξ_B particles of type χ are destroyed/created. Integrated Boltzmann equation :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B} (\xi_B - \xi_A)\mathcal{N}(A \to B)$$

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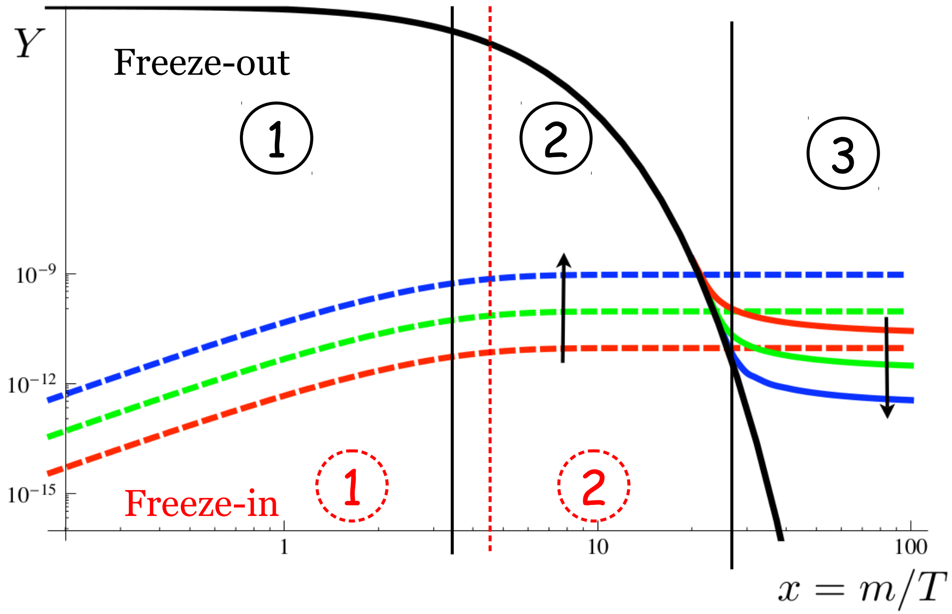

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① DM produced from decays/annihilations of other particles.

② DM production disfavoured → Abundance freeze-in

Freeze-in vs freeze-out

Naively, the freeze-in BE is simpler than the freeze-out one. However :

Initial conditions:

- FO: equilibrium erases all memory.
- FI: Ωh^2 depends on the initial conditions.

Heavier particles:

- FO: pretty irrelevant (modulo coannihilations/late decays).
- FI: their decays can be the dominant DM production mechanism.

Need to track the evolution of heavier states.

In equilibrium? Relics? FIMPs?

Dedicated Boltzmann eqs ←

Relevant temperature:

- FO: around $m_\chi/20$.
- FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on DM production channel and on nature of underlying theory.

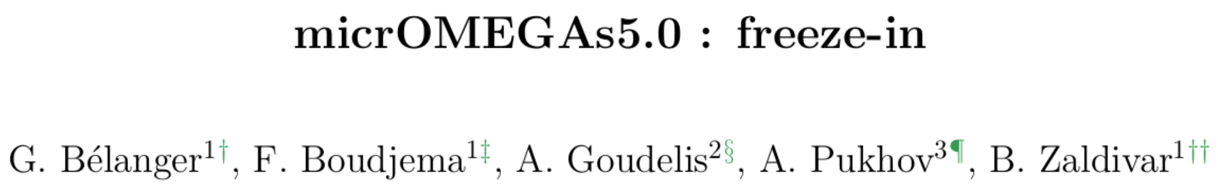
- Statistics can become important. So can very early Universe physics.

- Easily above *e.g.* T_{EWSB} → Phase transitions may occur *after* DM production.

DM density calculations in freeze-in scenarios

Given the previous subtleties and the potentially large number of contributing processes, freeze-in calculations can get tricky.

· Until recently, no publicly available computational tools:



micrOMEGAs5.0 : freeze-in

G. Bélanger[1†], F. Boudjema[1‡], A. Goudelis[2§], A. Pukhov[3¶], B. Zaldivar[1††]

arXiv:1801.03509

→ Can compute the freeze-in DM abundance in fairly generic BSM scenarios: scattering, decays of heavier bath particles/FIMPs/relics.

Hopefully will boost activity in

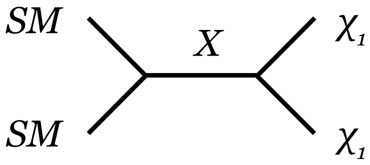
· Model-building: what types of (“well-motivated”) models can accommodate freeze-in?

· Phenomenology: what are the “standard” signatures of freeze-in scenarios?

Model-building issues

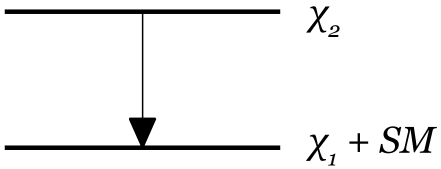
What kind of couplings do we need for successful freeze-in?

Annihilation:



- Requires $\lambda_1 \lambda_2 \sim 10^{-10}$ - 10^{-12}

Decay:



- Requires $\lambda \sim 10^{-13}$ x $(m_{\chi 2}/m_{\chi 1})^{1/2}$

How can we justify such small numbers?

Two main ways so far:

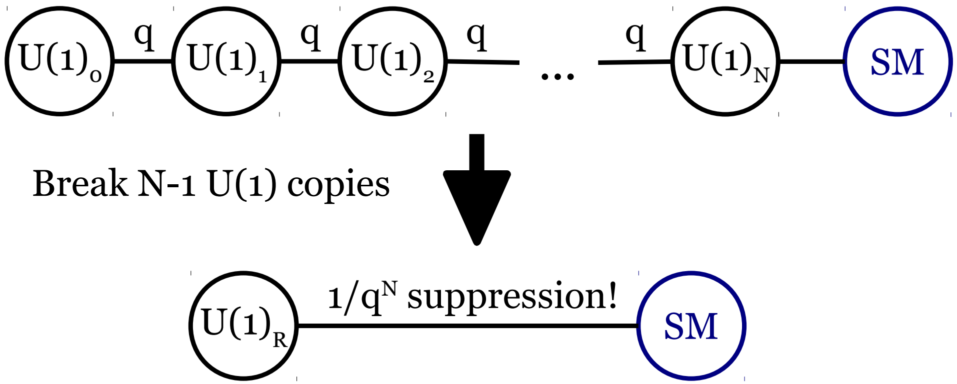
- Scale suppression
  - UV-dominated, *cf* talks by Y. Mambrini, K. Olive, D. Chowdhury
- Symmetries
  - Potentially IR-dominated

Symmetry approach: Clockworking FIMPs

A. G., K. Mohan, D. Sengupta, arXiv:1807.xxxxx

The Clockwork mechanism was initially introduced to address completely different issues. Has found many more applications (inflation, neutrinos, flavour, axions...).

arXiv:1511.01827, 1511.00132, 1610.07962...



- Clockwork FIMP approach: DM – SM coupling protected *e.g.* by Goldstone or chiral symmetry.

- A Scalar Clockwork FIMP :

$$\mathcal{L}_{sFIMP} = \underbrace{\mathcal{L}_{kin} - \frac{1}{2}\sum_{i,j=0}^{N} \phi_i M_{ij}^2 \phi^j - \frac{m^2}{24 f^2}\sum_{i,j=0}^{N} (\phi_i \tilde{M}_{ij}^2 \phi^j)^2 - \kappa |H^\dagger H| \phi_n^2}_{} + \sum_{i=0}^{n} \frac{t^2}{2} \phi_i^2$$

Similar setup considered in arXiv:1709.04105 ◀

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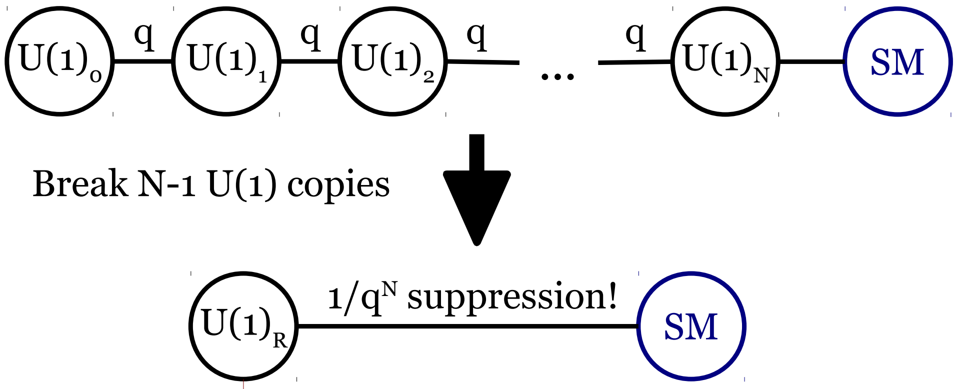

- Clockwork FIMP approach: DM – SM coupling protected *e.g.* by Goldstone or chiral symmetry.

In the original construction: zero mode strictly massless.

- A Scalar Clockwork FIMP :

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Example: a fermion Clockwork FIMP

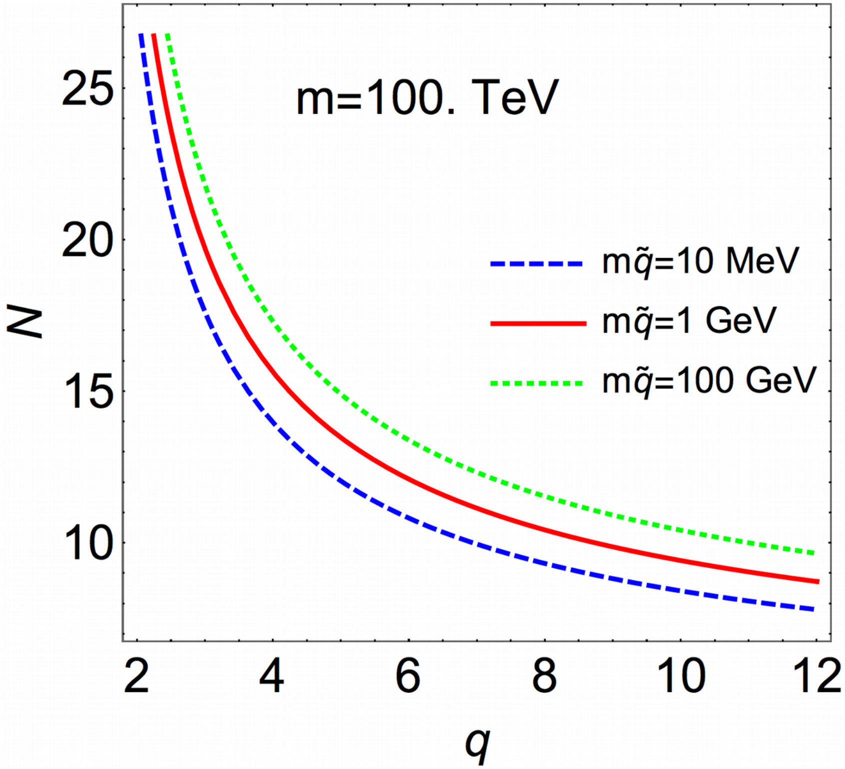
A. G., K. Mohan, D. Sengupta, arXiv:1807.xxxxx

Consider Lagrangian as :

$$\mathcal{L}_{fFIMP} = \mathcal{L}_{kin} - m\sum_{i=0}^{N-1}(\bar{\psi}_{L,j}\psi_{R,j} - q\bar{\psi}_{L,j}\psi_{R,j+1} + \mathrm{h.c}) - \frac{\mathrm{M_L}}{2}\sum_{\mathrm{i=0}}^{\mathrm{N-1}}(\bar{\psi}^{\mathrm{c}}_{\mathrm{L,i}}\psi_{\mathrm{L,i}}) - \frac{\mathrm{M_R}}{2}\sum_{\mathrm{i=0}}^{\mathrm{N}}(\bar{\psi}^{\mathrm{c}}_{\mathrm{R,i}}\psi_{\mathrm{R,i}})$$

$$+ i\bar{L}DL + i\bar{R}DR + M_D(\bar{L}R) + Y\bar{L}\tilde{H}\psi_{R,N} + \ \mathrm{h.c}$$

- $\psi_{L/R}$: CW sector chiral fermions
- L/R: (**1**, **2**, **−1/2**) VL leptons



· Proof of principle: Clockwork mechanism can be used to construct freeze-in models.

· CW gears + VL fermions have un-suppressed couplings → thermalise with the SM.

· For chosen parameter values freeze-in dominated by decays of CW gears + VL fermions into DM + SM.

This is not a universal feature.

Other constructions possible, can have observable signals.

Freeze-in phenomenology

Can we test freeze-in? Certainly not in full generality, but

There are actually numerous handles!

Arguably, both remarks also apply to freeze-out

If there are heavier particles in the spectrum

Primordial nucleosynthesis

Long lifetimes

Displaced vertices/ kinked tracks

Shorter lifetimes, requires tweaking.
More relevant arXiv:1705.09292

Charged track searches @ LHC

Long lifetimes, charged parent

Structure formation (Lyman-α)

Long lifetimes

Mono-X searches @ LHC + new experiments

Long lifetimes, neutral parent, *cf e.g.* arXiv:1806.07396

Otherwise

Direct/Indirect detection

In very special limits

Structure formation

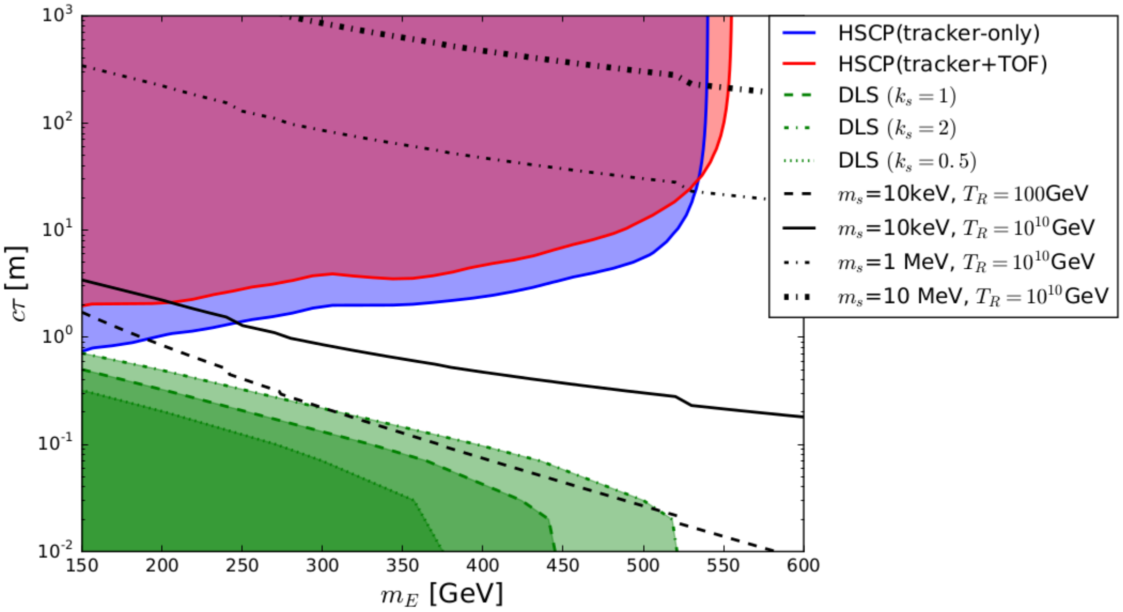
If DM warm/self-interacting

An example @ the LHC

Consider an extension of the SM by a real singlet scalar *s* and a VL fermion *E* transforming as (**1**, **1**, **-1**) under SU(3)xSU(2)xU(1), both Z2-odd.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + (\partial_\mu s)(\partial^\mu s) + \frac{\mu_s^2}{2} s^2 - \frac{\lambda_s}{4} s^4 - \lambda_{hs} s^2 \left(H^\dagger H\right)$$
$$+ i\left(\bar{E}_L D E_L + \bar{E}_R D E_R\right) - \left(m_E \bar{E}_L E_R + y_{sEe} s \bar{E}_L e_R + \text{h.c.}\right)$$

Direct FIMP pair-production suppressed, but can Drell-Yan - produce the heavy electron.



Two possible signatures in this case :

· Searches for Heavy Stable Charged Particles (if $\tau > 10$ ns).

· Searches for displaced leptons/tracks with kinks (if $\tau < 10$ ns).

A. G. *et al, in progress*:
Extend framework to include jets

A. G. *et al*, contribution in arXiv:1803.10379

Outlook

· Freeze-in is a well-established alternative mechanism to explain the dark matter abundance in the Universe relying on (effectively) feebly interacting particles.

· It can be implemented in many (simple or sophisticated) extensions of the SM.

· Despite the fact that it involves small couplings, it may have numerous different experimental signatures (cosmology, astrophysics, intensity frontier, colliders). For the most, the relevant studies are still at an embryonic stage.

· Although freeze-in has picked up a lot of momentum, a systematic exploration of models and signatures is still missing.

· micrOMEGAs 5 can compute the DM abundance according to the freeze-in mechanism.

Have fun with it!

· Still several open questions. One I'm particularly interested in: what if DM production occurs before the E/W phase transition?

Reminder: dark matter relic density

The dark matter yield (comoving number density) $Y_\chi = n_\chi/s$ is computed as

$$Y_\chi^0 = \int_{T_0}^{T_R} \frac{dT}{T\overline{H}(T)s(T)} \left(\mathcal{N}(bath \to \chi X) + 2\mathcal{N}(bath \to \chi\chi)\right)$$

where $\overline{H}(T) = \dfrac{H(T)}{1 + \frac{1}{3}\frac{d\ln(h_{\mathrm{eff}}(T))}{d\ln T}}$

The dark matter relic density is computed as

$$\Omega h^2 = \frac{m_\chi Y_\chi^0 s_0 h^2}{\rho_c}$$

Decay rate in a medium

Consider the decay of a particle *Y* into two particles a, b in the early Universe. The number of decays per unit space-time volume is

$$\mathcal{N}(Y \to a, b) = \int \frac{d^3p_Y}{(2\pi)^3 2E_Y} \frac{d^3p_a}{(2\pi)^3 2E_a} \frac{d^3p_b}{(2\pi)^3 2E_b} f_Y (1 \mp f_a)(1 \mp f_b) \\ \times (2\pi)^4 \delta(P_Y - P_a - P_b) |\mathcal{M}|^2 \ .$$

Replacing $f_Y(p_Y) \longrightarrow (2\pi)^3 \delta^3(\vec{p} - \vec{p}_Y)/g_1$ we get :

$$G_{Y \to a,b} = \frac{1}{2E_Y} \int \frac{d^3p_a}{(2\pi)^3 2E_a} \frac{d^3p_b}{(2\pi)^3 2E_b} (1 \mp f_a)(1 \mp f_b) \\ \times (2\pi)^4 \delta(P_Y - P_a - P_b) \overline{|\mathcal{M}|}^2$$

Decay rate of *Y* in the medium created by *a*, *b*

Defining : $$S\,(p/T, x_Y, x_a, x_b, \eta_a, \eta_b) = \frac{1}{2} \int_{-1}^{1} dc_\theta \frac{e^{E_Y^{\rm CF}/T}}{(e^{E_a^{\rm CF}/T} - \eta_a)(e^{E_b^{\rm CF}/T} - \eta_b)}$$

Calculable analytically

We obtain : $$G_{Y \to a,b} = \frac{m_Y \Gamma_{Y \to a,b}}{E_Y^{\rm CF}} S\,(p/T, x_Y, x_a, x_b, \eta_a, \eta_b)$$

S contains all the stat. mech. information