Freeze-in

2018 Workshop on the
Standard Model and Beyond

Corfu, Greece

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LPTHE - Paris

Outline

· Freeze-in: General framework and practical computations

· A bit of model-building: Clockworking FIMPs

· Signatures of freeze-in

· Summary and outlook

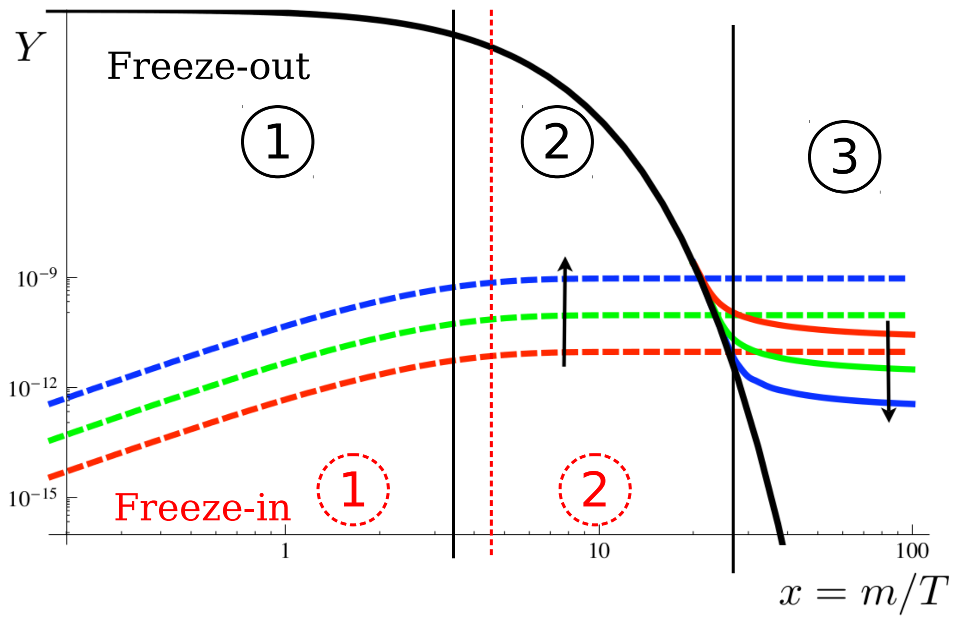
Based on:

- G. Bélanger, F. Boudjema, A.G., A. Pukhov, B. Zaldivar, arXiv:1801.03509
- A. G. *et al*, contribution in arXiv:1803.10379
- A.G., K. Mohan, D. Sengupta, arXiv:1807.06642
- A.G. *et al*, arXiv:1809.XXXXX

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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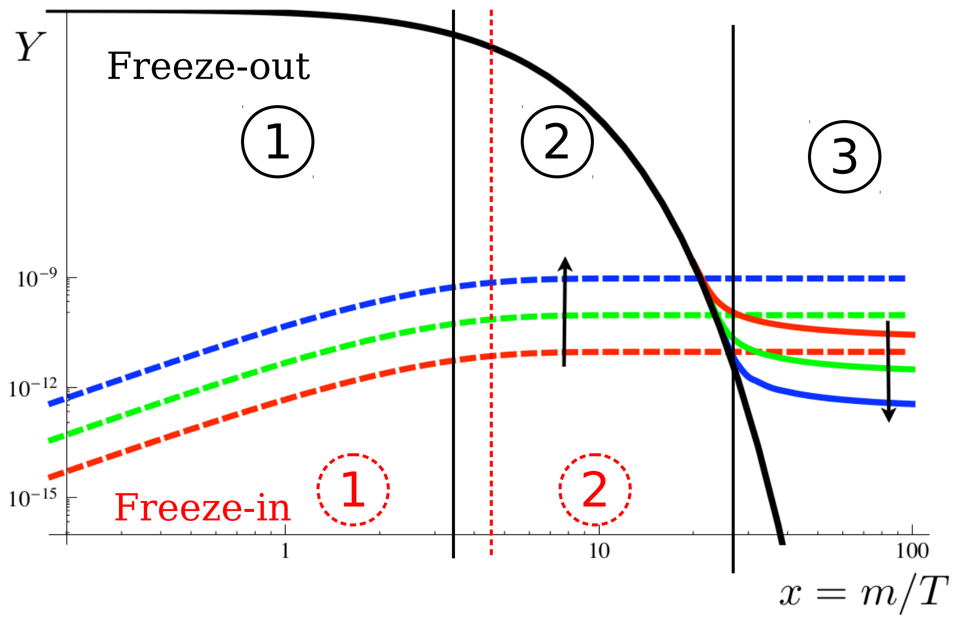

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$$\mathcal{N}(in \to out) = \int \prod_{i=in} \left(\frac{d^3 p_i}{(2\pi)^3 2E_i} f_i \right) \prod_{j=out} \left(\frac{d^3 p_j}{(2\pi)^3 2E_j} (1 \mp f_j) \right) \times (2\pi)^4 \delta^4 (\sum_{i=in} P_i - \sum_{j=out} P_j) C_{in} |\mathcal{M}|^2$$

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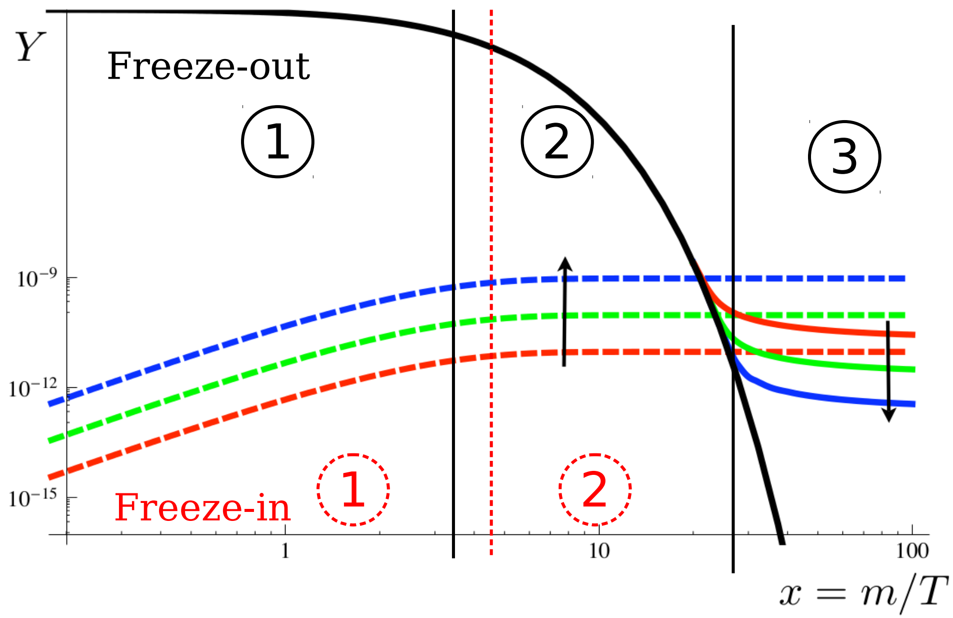

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1. DM produced from decays/annihilations of other particles.
2. DM production disfavoured → Abundance freezes-in

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 (exc. coannihilations/late decays).

· FI: their decays can dominate DM production.

Need to track the evolution of heavier states.

In equilibrium? Relics? FIMPs?

Need dedicated Boltzmann eqs

Relevant temperature:

· FO: around $m_\chi/20$.

· FI: several possibilities ($m_\chi/3$, $m_{\rm parent}/3$, T_R or higher), depending on nature of underlying theory.

- Statistics/early Universe physics can become important.

- Phase transitions may occur *after* DM production.

Automatising freeze-in calculations

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.

Boost activity in

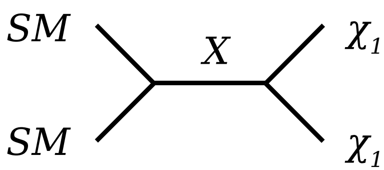
· Model-building: what types of ("well-motivated") models can accommodate freeze-in?

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

Model-building issues

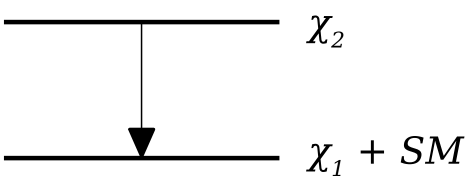
What kind of models can accommodate successful freeze-in? Let's have a look at the necessary couplings:

Annihilation:



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

Decay:



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

How can we justify such small numbers?

Two main ways so far:

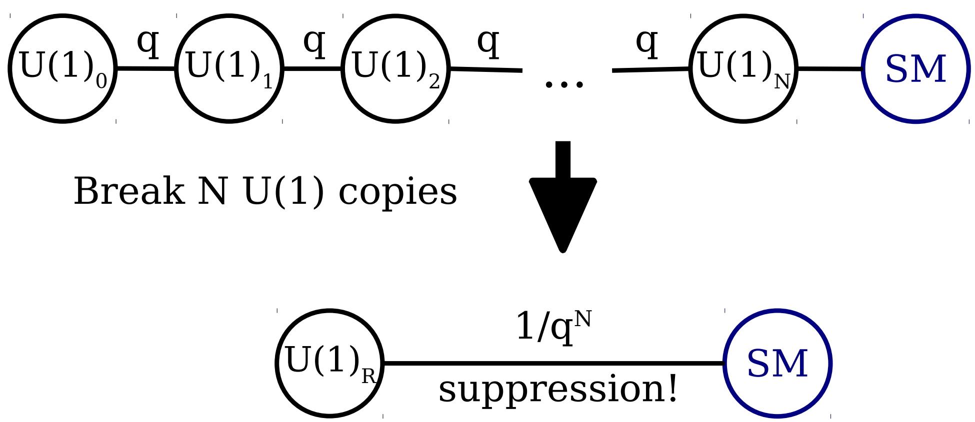
- Scale suppression
  - *e.g.* gravitino – not the topic of this talk
- Symmetries
  - More coming up

Symmetries: Clockworking FIMPs

A. G., K. Mohan, D. Sengupta, arXiv:1807.06642

The Clockwork mechanism was 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 :

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

Similar setup considered in arXiv:1709.04105

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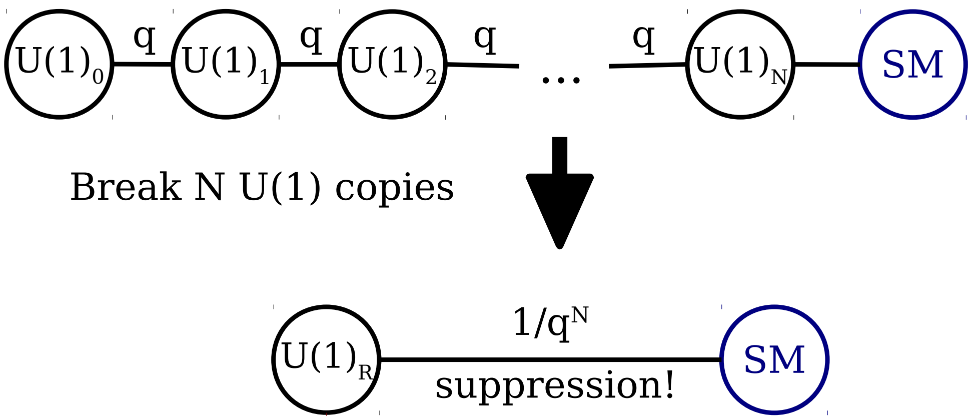

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In the original construction: zero mode strictly massless.

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Allows FIMP mass adjustment

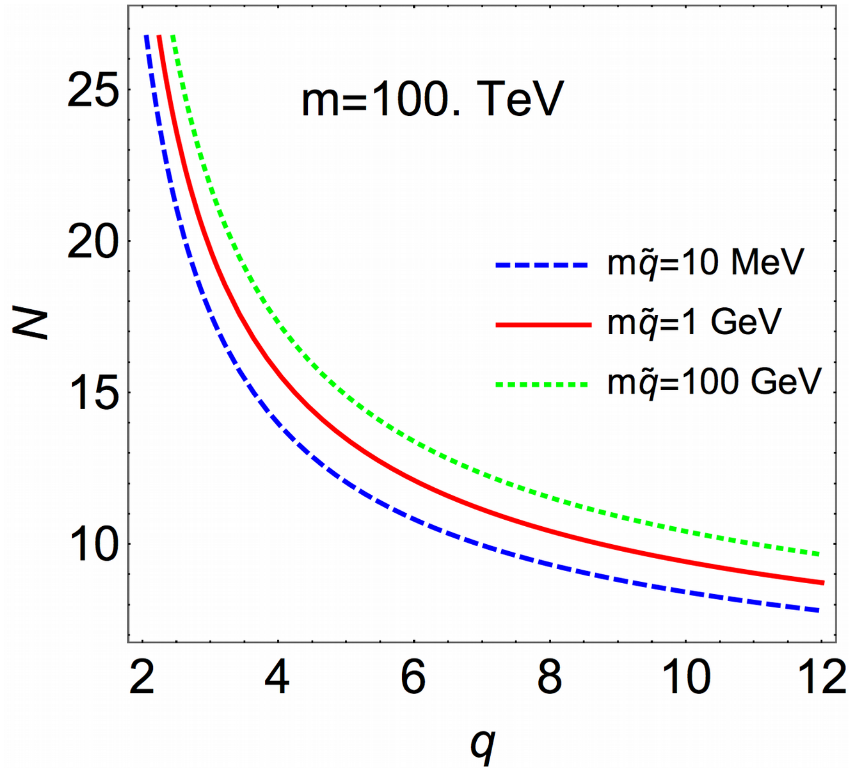
Example: a fermion Clockwork FIMP

A. G., K. Mohan, D. Sengupta, arXiv:1807.06642

Consider Lagrangian as :

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

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



· Proof of principle: the 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.

NB: 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!

NB: 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

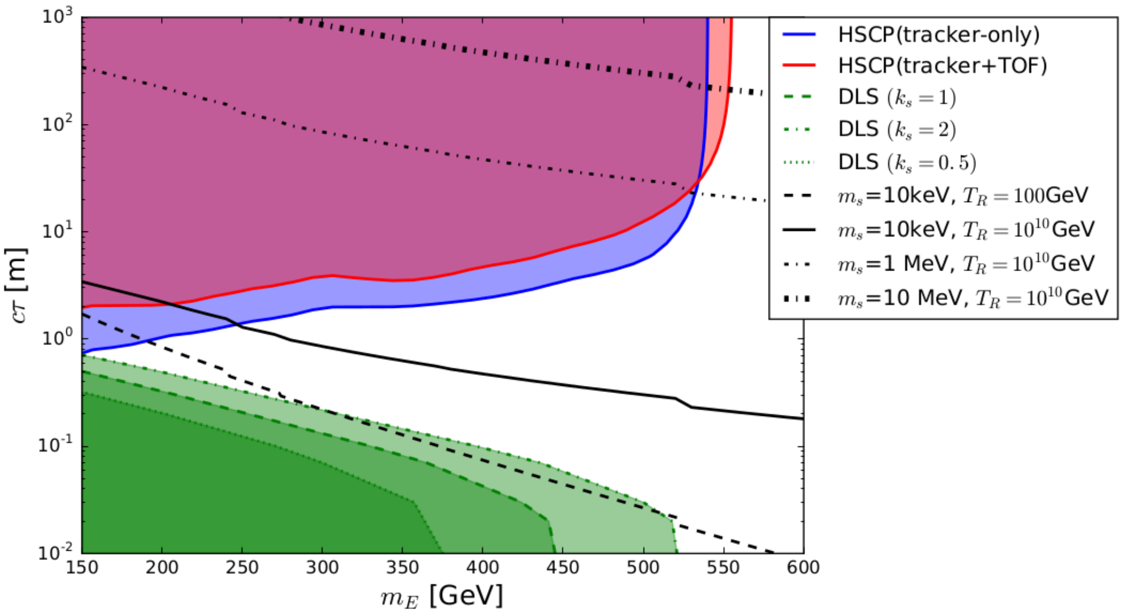
If DM warm/self-interacting

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 Z_2-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 production suppressed, but can Drell-Yan – produce the heavy electron.



Two possible signatures in this case :

· Searches for Heavy Stable Charged Particles (if τ > 10 ns).

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

A. G. *et al*, arXiv:1809.XXXXX: Extend framework to include jets

A. G. *et al*, contribution in arXiv:1803.10379, arXiv:1809.XXXXX

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 involving small couplings, it may have numerous different experimental signatures (cosmology, astrophysics, intensity frontier, colliders).

· 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 freeze-in DM abundance in generic BSM models.

Have fun with it!

· Still several open questions. One I'm particularly interested in: what if a phase transition occurs during DM production?

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

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

Calculable analytically

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

S contains all the stat. mech. information