Freeze-in and long-lived particles at the LHC

HEP-2019, NCSR Demokritos

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Outline

· Reminder: thermal freeze-out

· Freeze-in and Feebly Interacting Massive Particles (FIMPs)

· Collider probes of frozen-in dark matter

· Summary and outlook

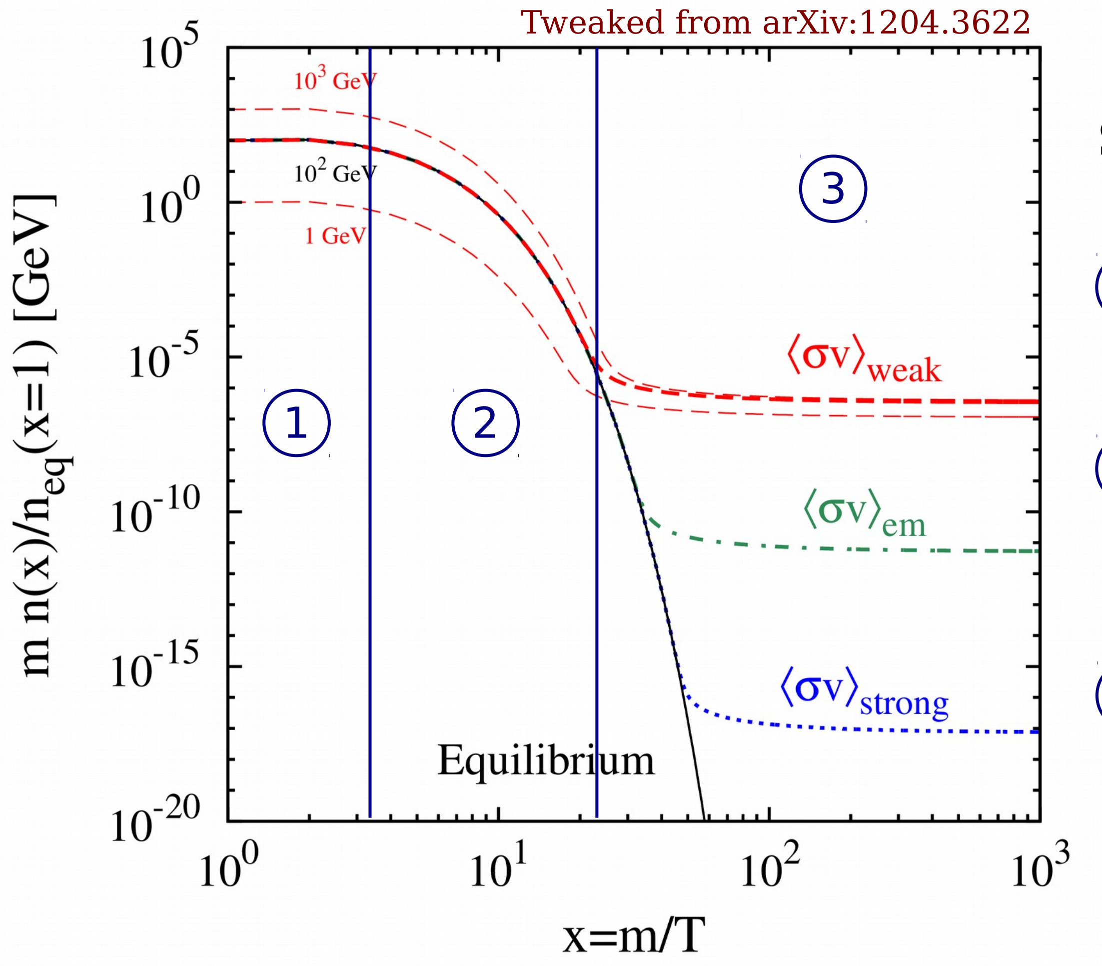
Based on:

· micrOMEGAs 5: G. Bélanger *et al*, arXiv:1801.03509
· Model-building: A. G. *et al*, arXiv:1807.06642
· Phenomenology: G. Bélanger *et al*, arXiv:1811.05478

Short reminder:
Thermal freeze-out

Freeze-out: the standard result

Assume strong enough DM-SM interactions → the two sectors in equilibrium.



Schematically:

1 DM + DM ↔ SM + SM efficient in both directions.

2 DM + DM ← SM + SM disfavoured, DM partly annihilates away following equilibrium distribution.

3 $n_{\rm DM} <\sigma v> < H$: Equilibrium lost → Freeze-out.

Same picture even if we started from a zero initial density

As long as interactions strong enough

Freeze-in

Freeze-in: general idea

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

Two basic premises :

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

Assume that reaction $A \rightarrow B$ destroys/creates ξ_A/ξ_B particles of type χ :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B} (\underbrace{\xi_B}_{\text{DM production term}} - \underbrace{\xi_A}_{\text{DM depletion term}}) \mathcal{N}(A \rightarrow B)$$

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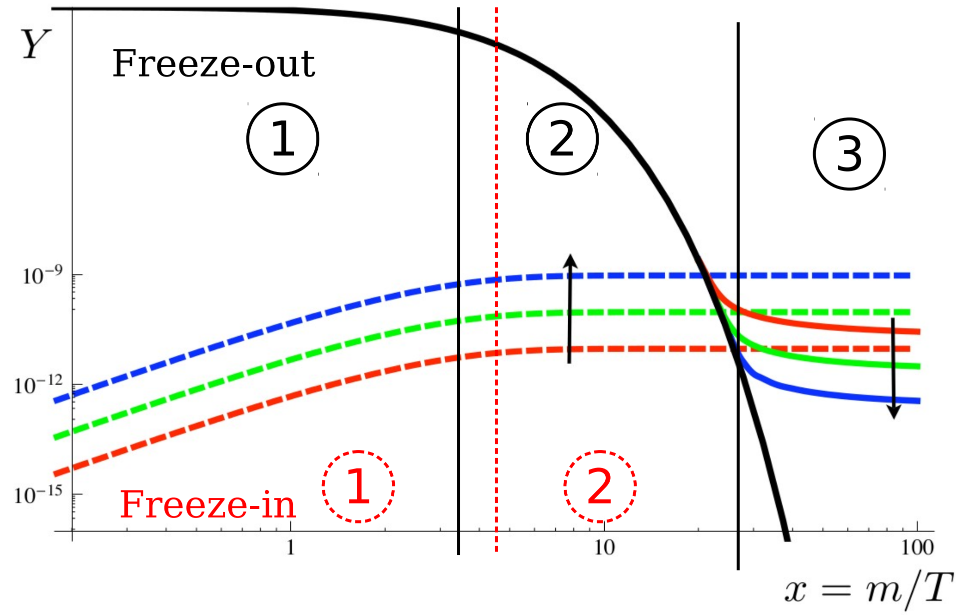
Rate for $1+2 \to 3+4$ scales as $n_1\, n_2 <\sigma v>$

No DM depletion, only consider processses with $\xi_A = 0$

Freeze-in: result

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

Tweaked from arXiv:0911.1120



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1 DM produced from decays/annihilations of other particles.

2 DM production disfavoured → Abundance freezes-in

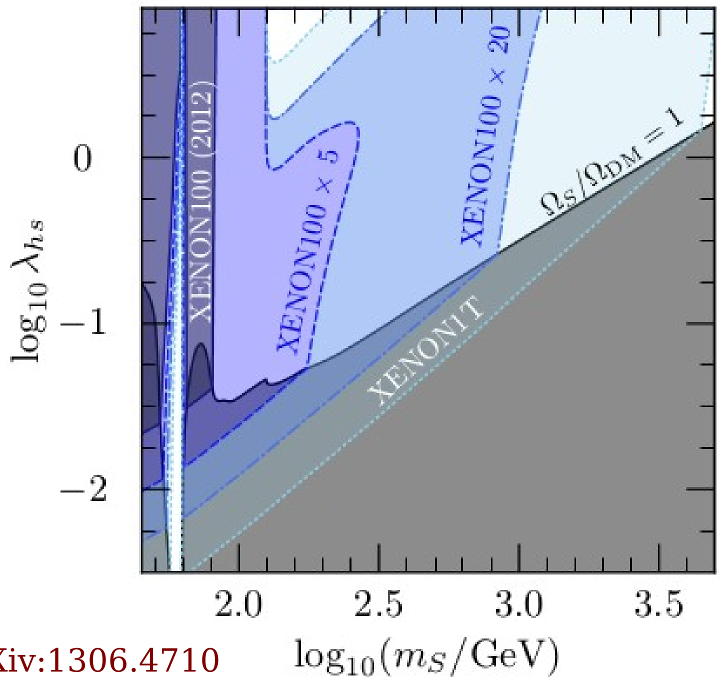
Freeze-in
@ colliders

FIMPs and standard DM searches

Perhaps the simplest freeze-in model: SM + a singlet scalar field

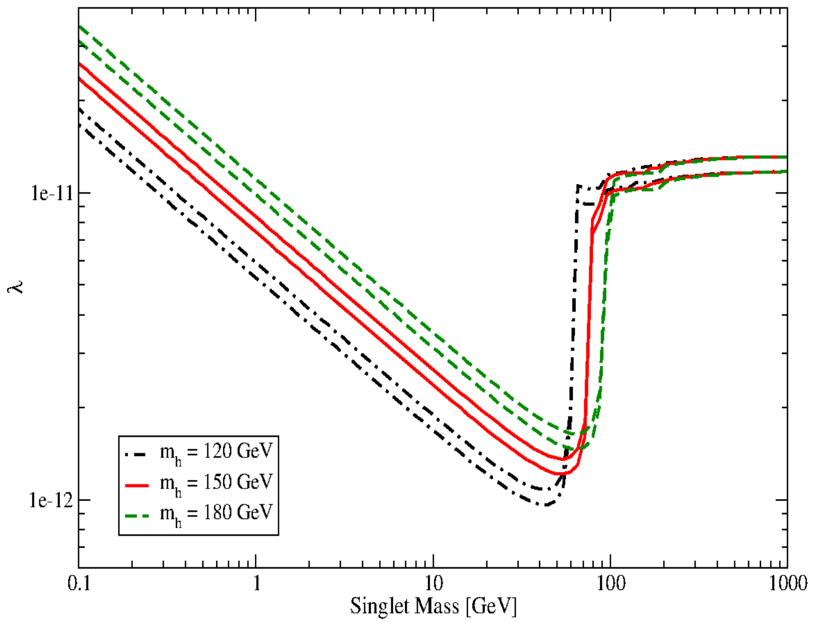
$$V = \frac{\mu_S^2}{2} S^2 + \frac{\lambda_{hs}}{2} S^2 |H|^2$$

WIMP regime



arXiv:1306.4710

FIMP regime



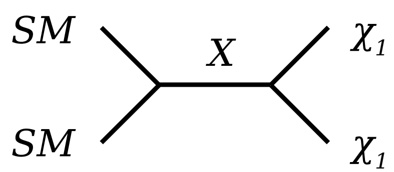
arXiv:1105.1654

Typically, FIMPs lie orders of magnitude below DD/ID/LHC sensitivity

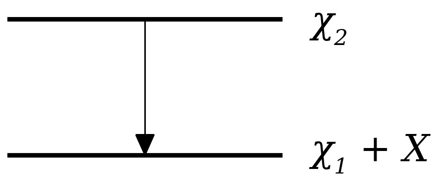
Then, how to probe freeze-in?

Freeze-in requires DM particles to be (effectively) feebly coupled to the SM.

Annihilation:



Decay:



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

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

But not all other BSM particles need to be so

· Some of the particles that mediate its interactions could even be strongly coupled with the Standard Model.

The Higgs boson is pretty strongly coupled to some SM particles (the LHC discovered it), but the singlet scalar model is a perfectly viable freeze-in scenario!

· Such particles could be produced copiously at colliders.

Freeze-in with a charged parent

Consider an extension of the SM by a Z_2-odd real singlet scalar s (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion F (parent).

contribution in arXiv:1803.10379
and arXiv:1811.05478

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\,(iD)\,F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F} \left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

Distinguish three cases:

- f = $\{e,\mu,\tau\}$ → F transforms as (**1, 1, -1**)
  "Heavy lepton"
- f = $\{u,c,t\}$ → F transforms as (**3, 1, -2/3**)
  "Heavy *u*-quark"
- f = $\{d,s,b\}$ → F transforms as (**3, 1, 1/3**)
  "Heavy *d*-quark"

Parent particle lifetime

Assuming that DM is mostly populated by F decays, we can relate the relic abundance with the parent particle lifetime:

$$c\tau \approx 4.5\,\mathrm{m}\,\xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\; x^3 K_1(x)}{3\pi/2}\right]$$

$$\Downarrow$$

Freeze-in favours long lifetimes, unless

- Dark matter is very light
- The reheating temperature is low

This brings us into the realm of long-lived particle searches

Signatures at the LHC

So what are the model's signatures at the LHC?

· First of all, production through :

- Drell-Yan (lepton model)
- Drell-Yan +QCD (quark model)

· Several search strategies, depending on the lifetime of the parent particle, i.e. which part of the detector it mostly decays at (if at all).

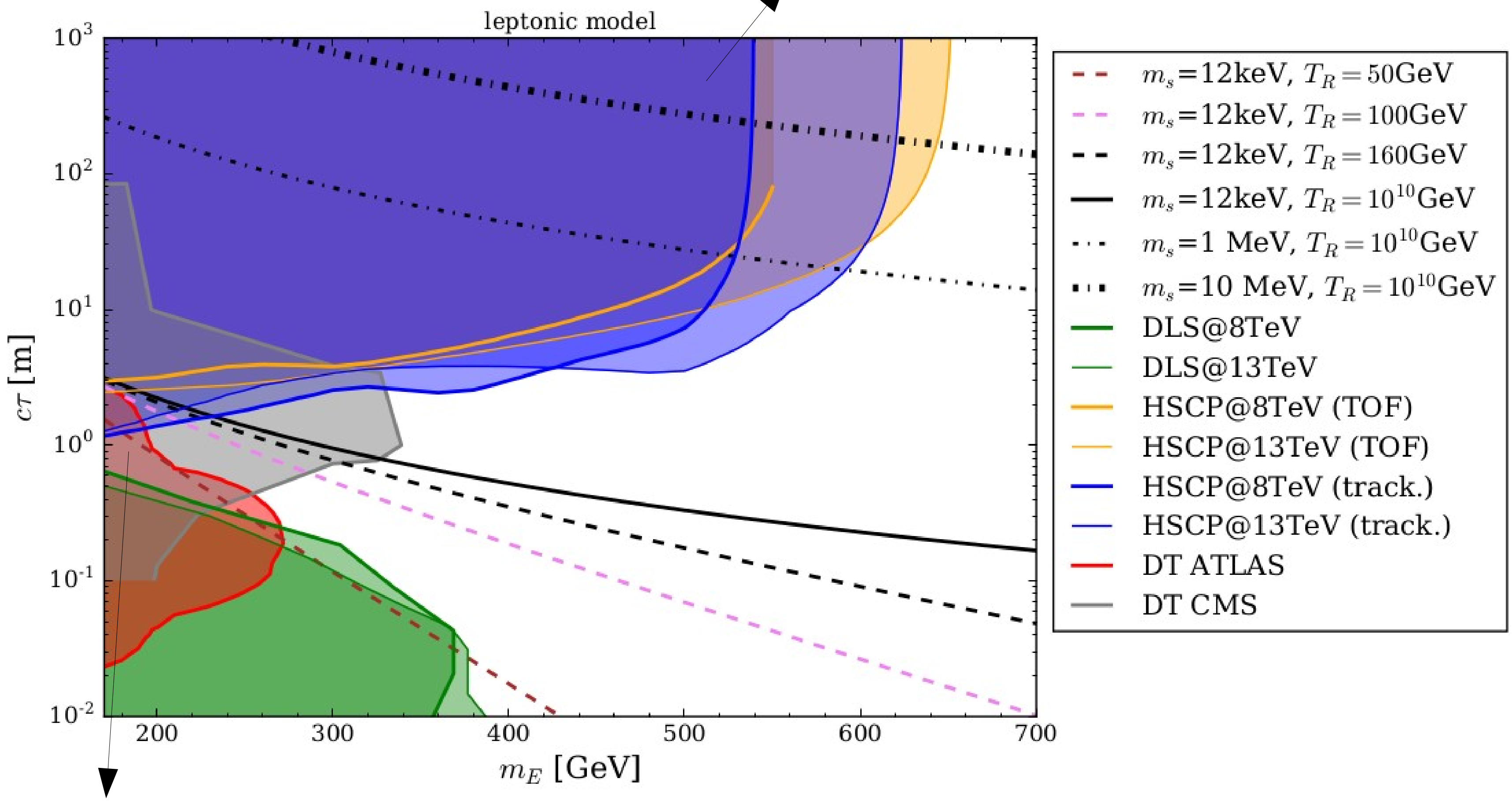
Long lifetimes → **Heavy Stable Charged Particles (HSCPs)**

Intermediate lifetimes (for lepton model) → **Disappearing/kinked tracks**

Short lifetimes → **Displaced leptons/vertices**

Results: lepton model

HSCP: Tracker + TOF analysis more powerful for larger lifetimes, tracker-only for shorter ones.

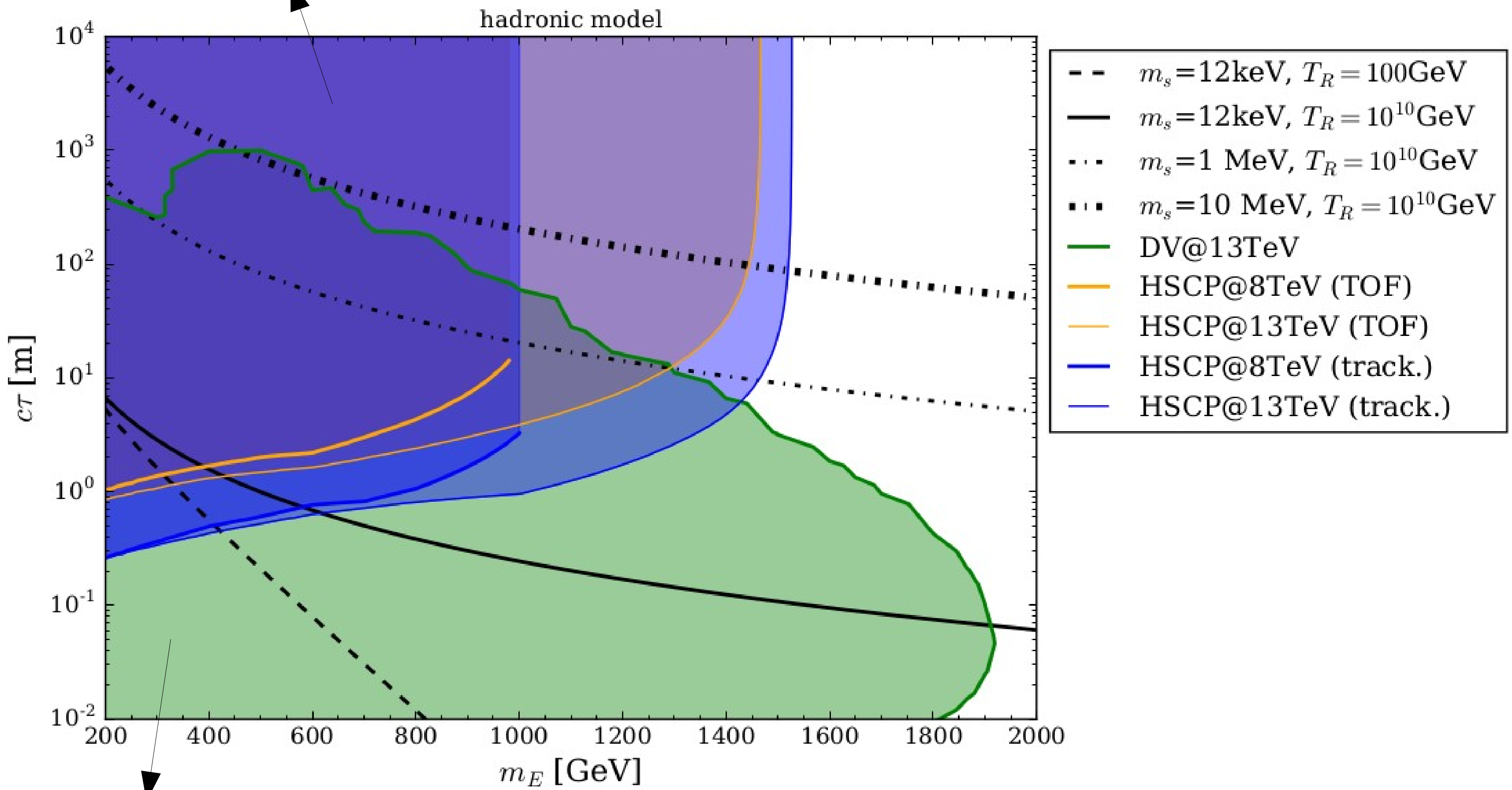


DT: Order-of-magnitude difference in peak sensitivity between ATLAS/CMS

More accurate estimates require extensive input from EXP collaborations

Results: quark model

HSCP: Tracker-only analysis always more powerful, neutral R-hadrons fail tracker + TOF selection.



DV: Impressive reach as high as $c\tau_F \sim 100$ m

Clear complementarity between different LHC searches

Summary

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

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

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

· Despite involving such tiny couplings, freeze-in models can have many different experimental signatures, notably at the LHC.

· We proposed a set of simple such models that provide motivation and can be used as benchmarks for numerous long-lived particle searches at the LHC.

Additional material

A leitmotiv for dark matter models ?

We know a few main things about dark matter :

· It gravitates

· It doesn't interact (much) with photons

· Its abundance within ΛCDM cosmology

· Some "excluded hypersurfaces" in a "parameter space" characterised by, *e.g.*

How many species of DM "particles" exist

Which other particles each DM species interacts with

Their masses, spins and CP properties

Their masses, spins and CP properties

The nature and strength of the interactions between these sectors

Can we explain the observed DM abundance in the Universe?

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 $m_\chi/20$.

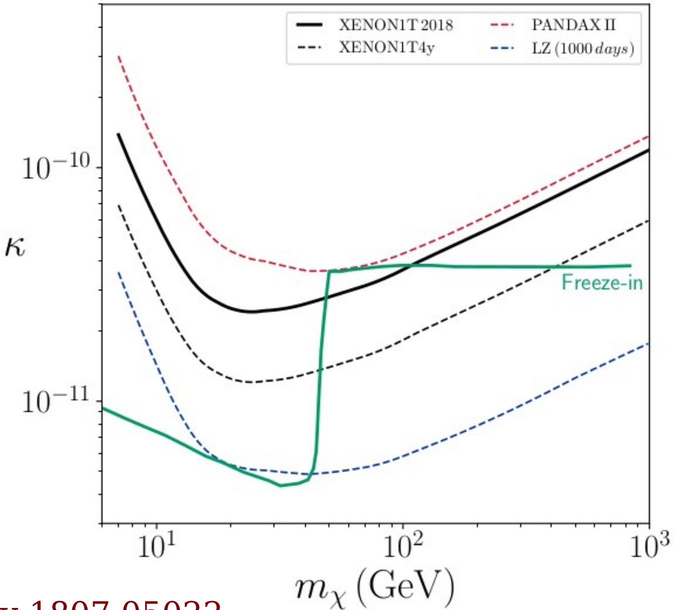
· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on nature of underlying theory.

- Statistics/early Universe physics can become important.

When conventional searches work

Actually, there are two cases in which conventional searches *can* probe freeze-in scenarios

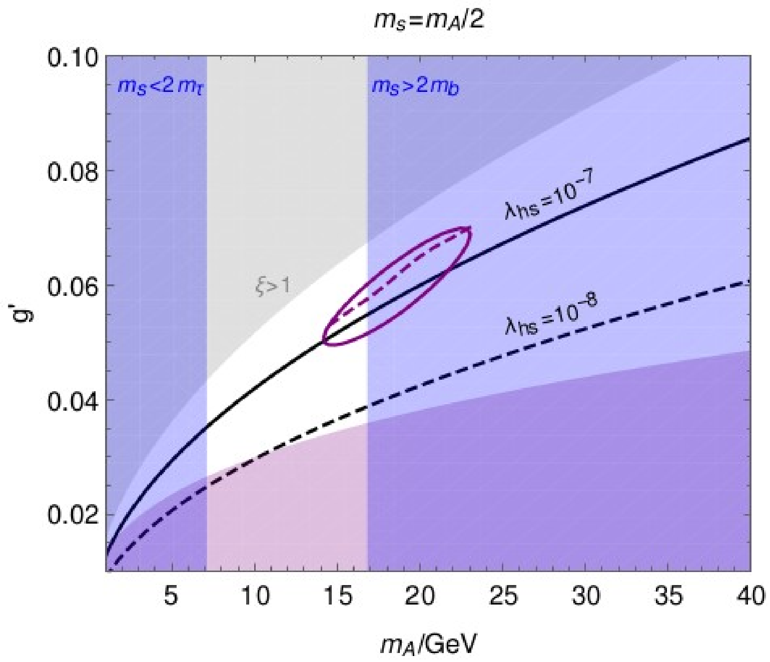
Direct detection w/ light mediator



arXiv:1807.05022

$\sigma_{\chi n} \propto 1/E_r^2$ ⟶ $\sigma_{\chi n}$ enhanced

Indirect detection w/ dark freeze-out from freeze-in



Can even explain GC excess

Interesting possibilities, but in the general case DD/ID impossible

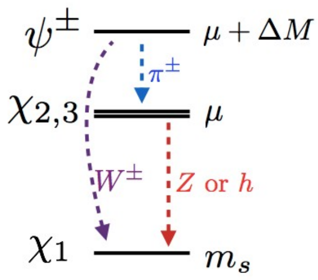
Another example: singlet-doublet model

Consider the singlet-doublet fermion model: SM + 2 Weyl (**2, ±1/2**) fermions ψ_u, ψ_d + a (**1, 0**) fermion ψ_s

arXiv:hep-ph/0510064

$$-\mathcal{L} \supset \mu\ \psi_d \cdot \psi_u + y_d\ \psi_d \cdot H\,\psi_s + y_u\ H^\dagger \psi_u\,\psi_s + \frac{1}{2} m_s\ \psi_s \psi_s + h.c.$$

· DM can be *e.g.* produced through



arXiv:1805.04423

· Collider signatures:

- ψ± decays (disappearing tracks)
- displaced h/Z + MET
- Promptly (although: not for freeze-in)
- Mono-X (large decay lengths)

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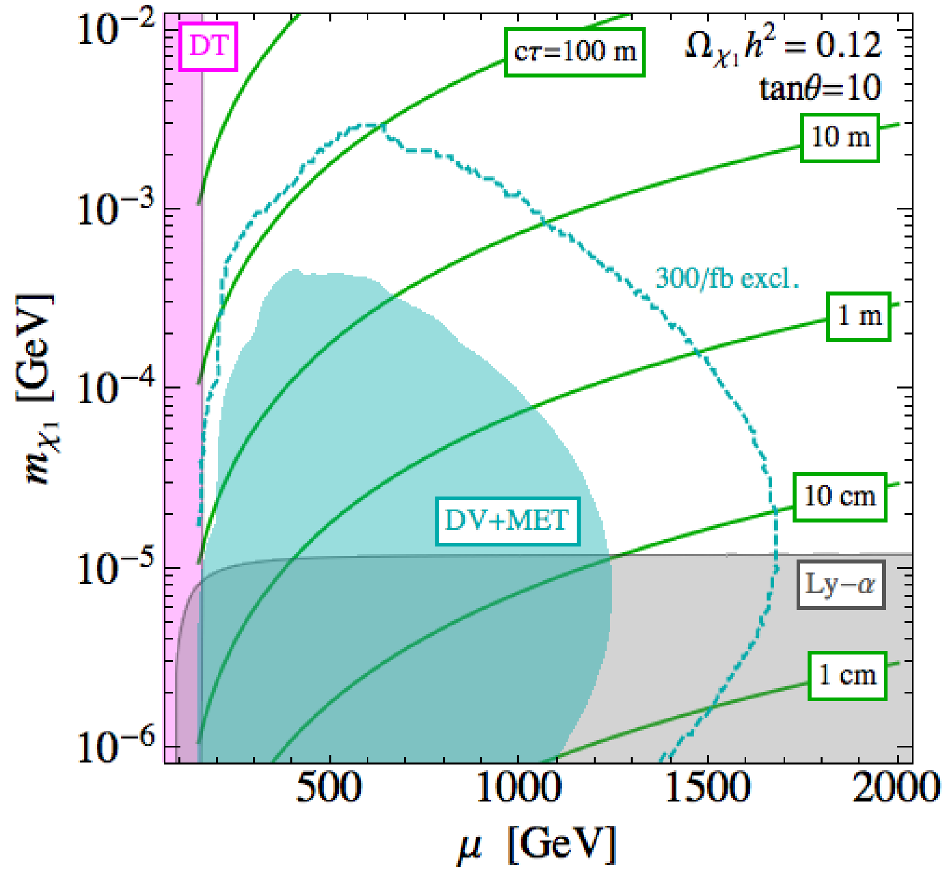
Consider the singlet-doublet fermion model: SM + 2 Weyl (**2, ±1/2**) fermions ψ_u, ψ_d + a (**1, 0**) fermion ψ_s

arXiv:hep-ph/0510064

$$-\mathcal{L} \supset \mu\ \psi_d \cdot \psi_u + y_d\ \psi_d \cdot H\, \psi_s + y_u\ H^\dagger \psi_u\, \psi_s + \frac{1}{2} m_s\ \psi_s \psi_s + h.c.$$

arXiv:1805.04423

· Combination of all constraints :



Non-LLP constraints: earth-bound

Focus on the first two models (heavy lepton, heavy u-quark).

Heavy lepton model

- LEP2: $m_F > 104$ GeV

  Actually slightly weaker, depending on lifetime

- No EWPT constraints

  arXiv:1404.4398

- Muon lifetime: $\mu \to ess$

  Checked, irrelevant

- LFV processes, in particular $\mu \to e\gamma$

$$Br(\mu \to e\gamma) \sim \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3m_F^4 (16\pi)^2} \sim 10^{-46}$$

i.e. tiny

Heavy quark model

- Direct collider bounds subleading

  Require prompt jets

- Running of α_s : $m_F >$ few hundred GeV

- Rare decays, e.g. $K^+ \to \pi^+ ss$

  NA62 can reach down to $y_s \sim 10^{-5}$

- Meson mixing: similarly to $\mu \to e\gamma$, tiny

Globally: still lots of room for interesting phenomenology

HSCP searches

General idea: look for a “heavy muon” or “heavy hadron”.

Heavy lepton model

· Some V-L leptons survive through the tracker and leave an ionising track

Different than SM e/μ

· If they also survive past the muon chambers, one can measure their time-of-flight (TOF)

Typically larger than for μ’s

· Two analyses: tracker-only, tracker + TOF

Heavy quark model

· V-L quarks will hadronize and give rise to charged and neutral hadrons (“*R-hadrons*”)

· Limit depends on number of produced charged hadrons

Hadronisation as in arXiv:1305.0491

· Interactions in the calorimeter may cause R-hadrons to flip charge
→ neutral R-hadrons may appear

Disappearing tracks (lepton model)

General idea:

· The heavy leptons F are produced promptly → they leave a track in the tracker.

· A theorist's view: if F decays before the end of the tracker, we'd observe a "kinked" track.

· But the outgoing lepton can typically *not* be reconstructed.

→ Experimentally, the track "disappears"

Non-trivial to assess how often the track *actually* disappears, here assume it always does so → limits rather aggressive

· Limits will differ from one experiment to the other: different hardware.

e.g. as of Run 2 ATLAS can reconstruct tracks as short as 12 cm, while CMS ~25 cm

Displaced leptons/vertices

Heavy lepton model

· For shorter F lifetimes, the SM lepton track can be reconstructed

· Look for displaced opposite-charge $e+\mu$ (one of each/event)

· Note: in principle possible to reconstruct both $c\tau_F$ and m_F.

→ Assuming s is all of DM, for a given m_s we can infer T_R

Interesting implications for EW baryo/leptogenesis

Heavy quark model

· Look for displaced jets + MET

· Performing the analysis from scratch requires very sophisticated detector simulation

→ Instead use parametrised efficiencies provided by ATLAS

An interplay with baryo/leptogenesis ?

An upshot:

· In E/W baryogenesis and leptogenesis, the reheating temperature must in general be larger than both the EW phase transition temperature (T_{EW}~160 GeV) and the sphaleron freeze-out one (T^*~132 GeV).

· Assume s makes up all of dark matter.

If it doesn't, argument even stronger!

· Assume we manage to measure $c\tau_F$ and $m_F \rightarrow$ 2 free parameters: m_s and T_R.

· Difficult to access $m_s \rightarrow$ take the lowest value allowed from Lyman-α.

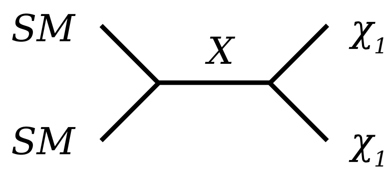
If it's heavier, argument even stronger!

If measurements point to $T_R < T_{EW}$, T^*, we can falsify baryogenesis models that rely on efficient sphaleron transitions

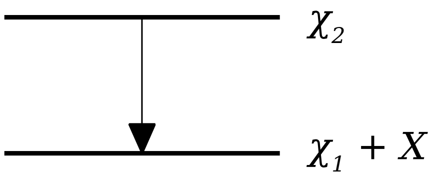
Model-building issues

What do freeze-in models look like? Let's have a look at the necessary couplings:

Annihilation:



Decay:



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

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

Somewhat "unnatural"?

Such small numbers:

Scale suppression

e.g. gravitino, arXiv:1103.4394

Symmetries

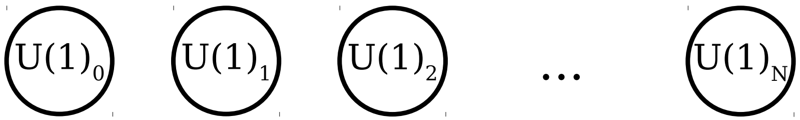
e.g. Clockwork, arXiv:1709.04105, 1807.06642

The Clockwork mechanism

arXiv:1511.01827, 1511.00132, 1610.07962...

- Introduce a global $U(1)^{N+1}$ symmetry, spontaneously broken at some scale f

→ Below f: N+1 massless Goldstones



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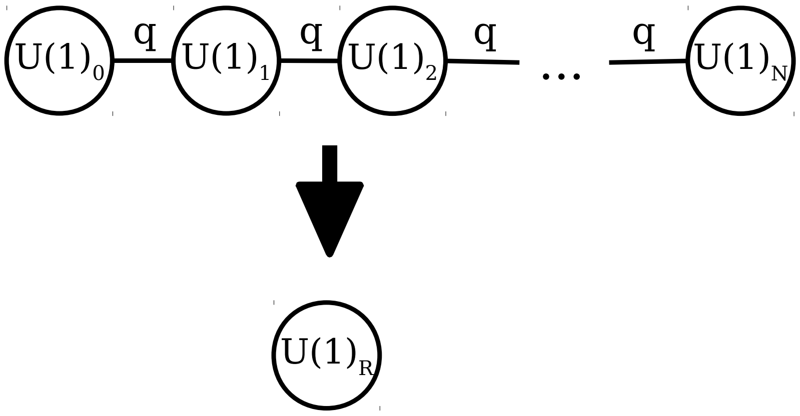
- Further break $U(1)^{N+1}$ symmetry by introducing N mass parameters m^2

  → One massless Goldstone left



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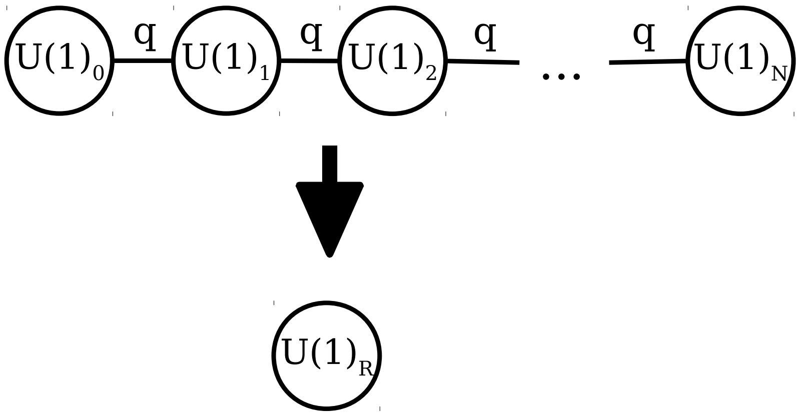

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· For $m^2 < f^2$: $$\mathcal{L}_{SCW} = -\frac{1}{2}\sum_{j=0}^{N} \partial_\mu \phi_j^\dagger \partial^\mu \phi_j - \left(\frac{1}{2}\sum_{i,j=0}^{N} \phi_i M_{ij}^2 \phi^j + \frac{m^2}{24 f^2} \sum_{i,j=0}^{N} (\phi_i M_{ij}^2 \phi^j)^2 + \mathcal{O}(\phi^6) \right)$$

· Diagonalising the (“*tridiagonal*”) mass matrix, we obtain:

$$m_{a_0}^2 = 0, \quad m_{a_k}^2 = \lambda_k m^2; \quad \lambda_k = q^2 + 1 - 2q\cos\frac{k\pi}{N+1}$$

$$O_{j0} = \frac{\mathcal{N}_0}{q^j}, \; O_{jk} = \mathcal{N}_k \left[q \sin\frac{jk\pi}{N+1} - \sin\frac{(j+1)k\pi}{N+1} \right]; \quad \mathcal{N}_0 = \sqrt{\frac{q^2-1}{q^2-q^{-2N}}}, \quad \mathcal{N}_K = \sqrt{\frac{2}{(N+1)\lambda_k}}$$

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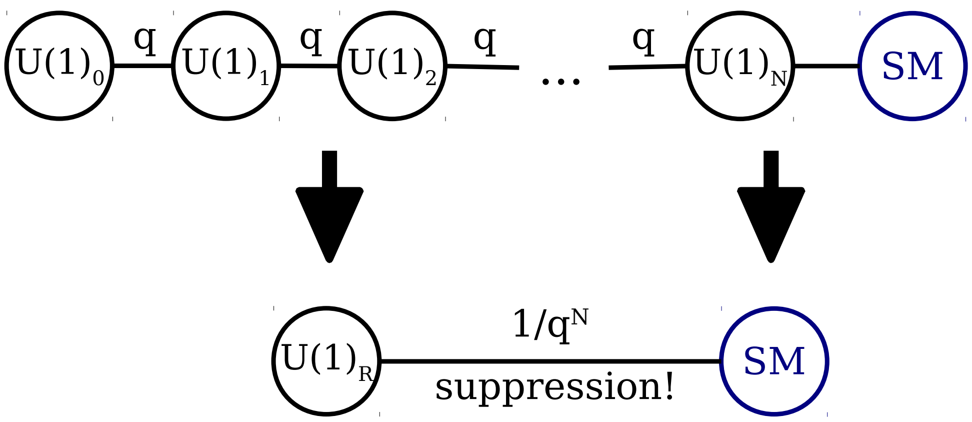

- The crucial point for us: if we couple some physics to the N-th site, its interactions with the zero mode scale as $1/q^N$

  → For a sufficiently large number of scalars we can achieve a massive suppression

Can we exploit this feature to build a freeze-in model starting from $O(1)$ couplings?

A scalar Clockwork FIMP

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

- Start from the original Clockwork Lagrangian and couple the N-th site to the SM through the Higgs portal interaction.

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

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- Before EWSB, the zero mode is massless. After EWSB, it acquires a tiny, clockwork-suppressed mass.

For successful freeze-in, typically sub-keV → Excluded

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- Add an additional mass term for all sites → Now can control the zero mode mass.

In arXiv:1709.04105 only to the N-th site → MeV mass

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- Huge number of processes from zero mode/gear quartic interactions.

Computationally untractable

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Computationally untractable

- Deform quartic piece of the scalar potential to eliminate them.

Note: Just a computational limitation!

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

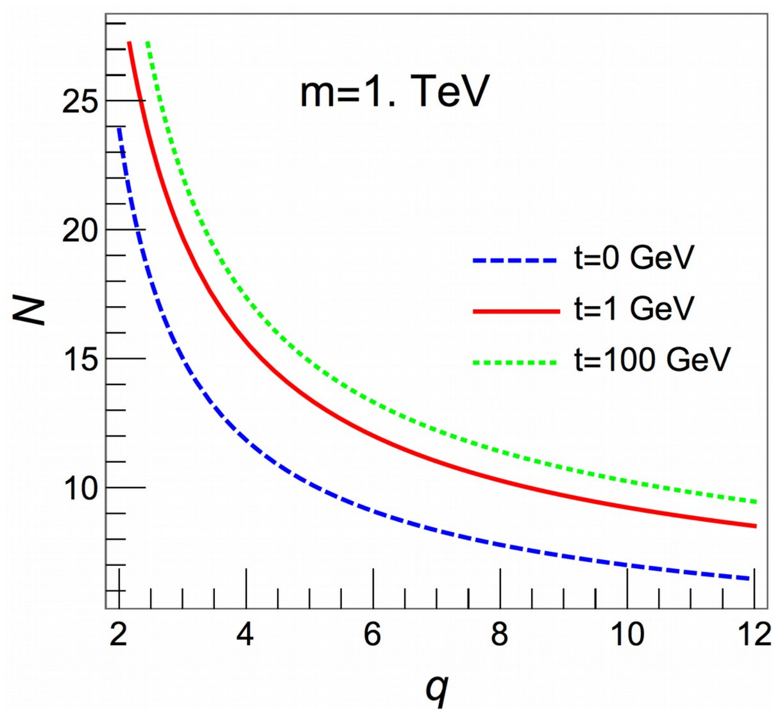
NB: Now includes t-terms

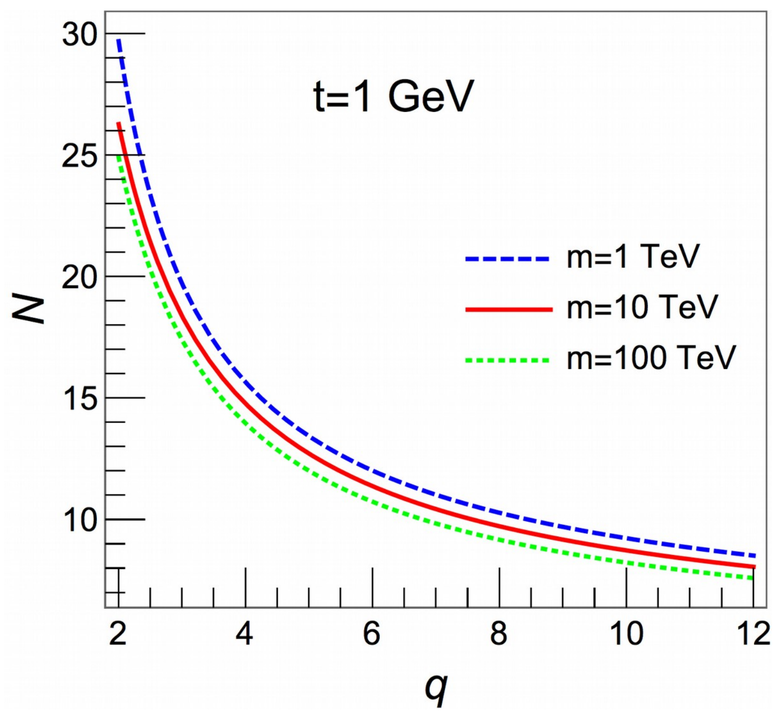
$$\left(\tilde{M}_{ij} \equiv M_{ij} + \kappa v^2 \delta_{iN}\delta_{jN}\right)$$

A scalar Clockwork FIMP - Results

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

Combinations of (q,N) for which we can obtain correct freeze-in:





· Higgs portal set to 1

· t=0: DM mass generated entirely from Higgs portal (DM too light)

· For these parameter choices, DM abundance dominated by gear decays $a_i \rightarrow a_0 + h$

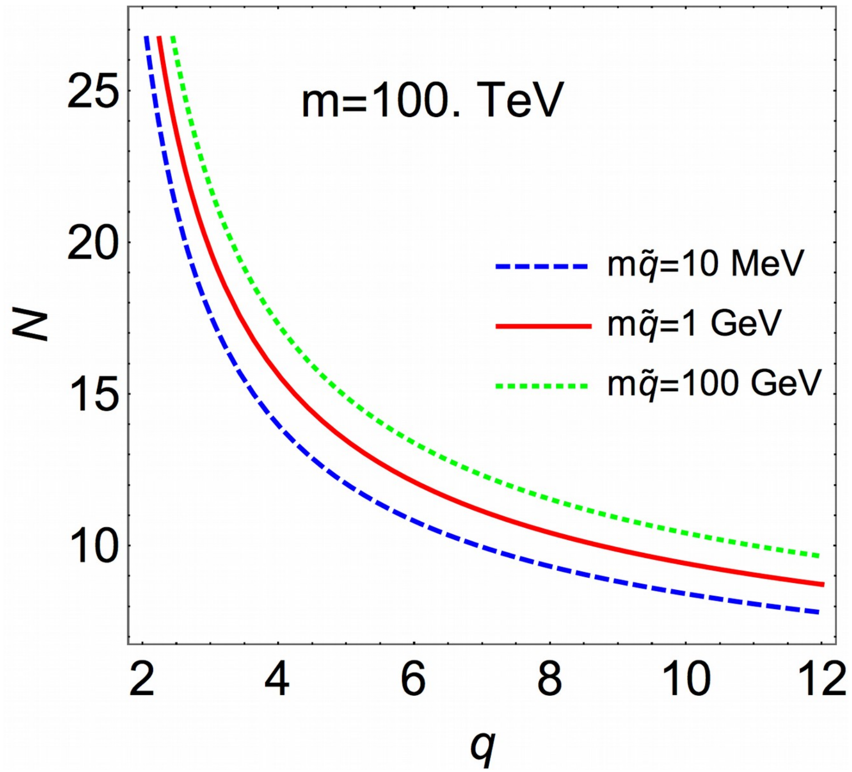
A fermion Clockwork FIMP

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

A similar game can be played for a fermionic Clockwork sector

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

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



· Clockwork sector set heavy to avoid mixing between gears and V-L leptons → no interactions involving gauge bosons.

Again, just a computational issue

· Dominated by decays of CW gears and V-L fermions into DM + SM.

Proof of principle: the Clockwork mechanism can be used to build viable freeze-in models