Dark matter at the LHC

(WIMPs and beyond)

LHCP 2019 - Puebla, Mexico

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LPTHE - Jussieu

Outline

· Standard lore: thermal freeze-out (WIMPs)

· Alternative @ weaker coupling: conversion-driven freeze-out

· Alternative @ feeble coupling: freeze-in

· Summary and outlook

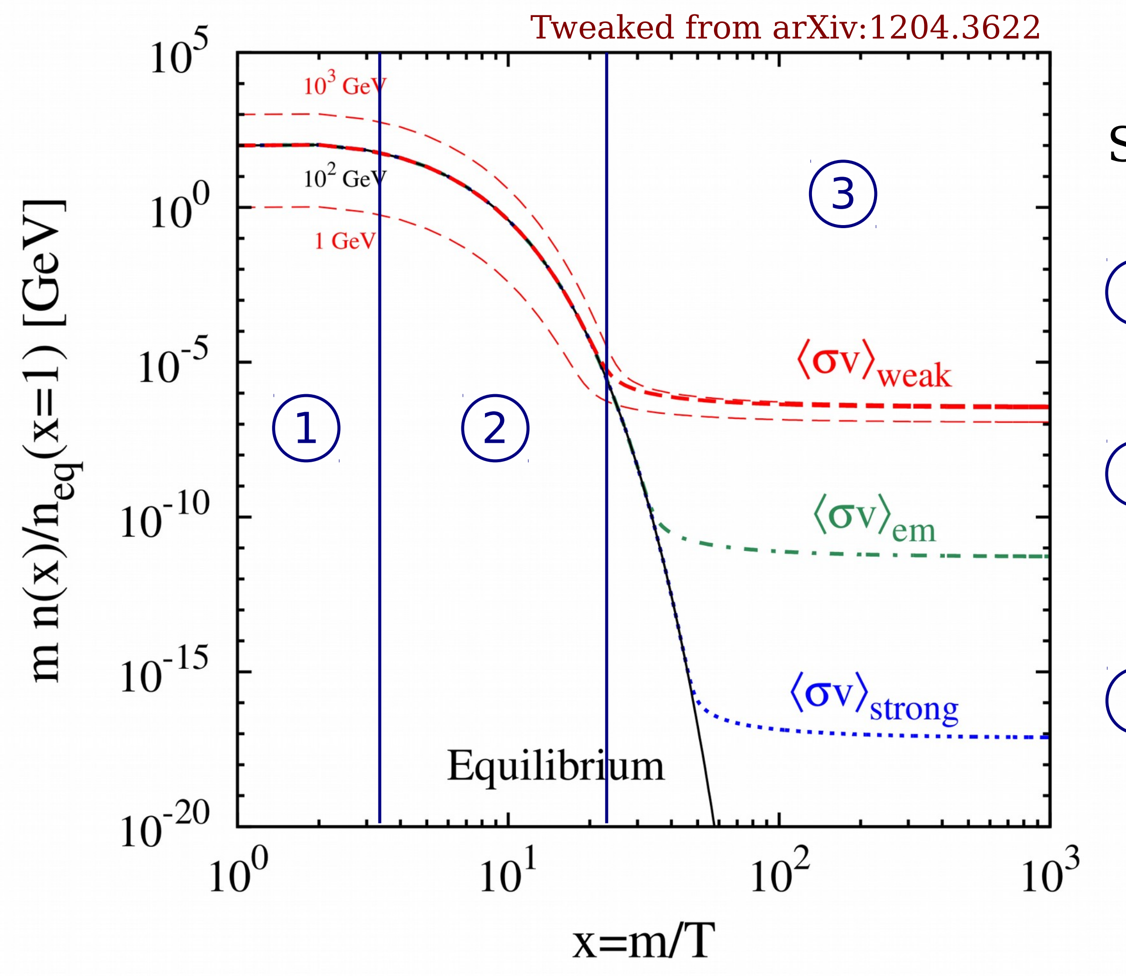
Cf also talks by:

· P. Foldenauer (Monday, Exotics)
· M. Borsato (Tuesday, Plenary)
· S-C Hsu (Tuesday, Plenary)
· A-G Delannoy Sotomator (Wednesday, Higgs)
· This session (Thursday, Exotics)
· This afternoon (Thursday, SUSY)

Strong-ish coupling:
Thermal freeze-out

Freeze-out: Main idea

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

Same picture even if we started from a zero initial density

As long as interactions strong enough

Freeze-out: LHC searches

Three main approaches

Direct DM (pair-) production

Fairly generic, not always the most powerful

Production in decay chains

Can be very powerful, but highly model-dependent

Mediator searches

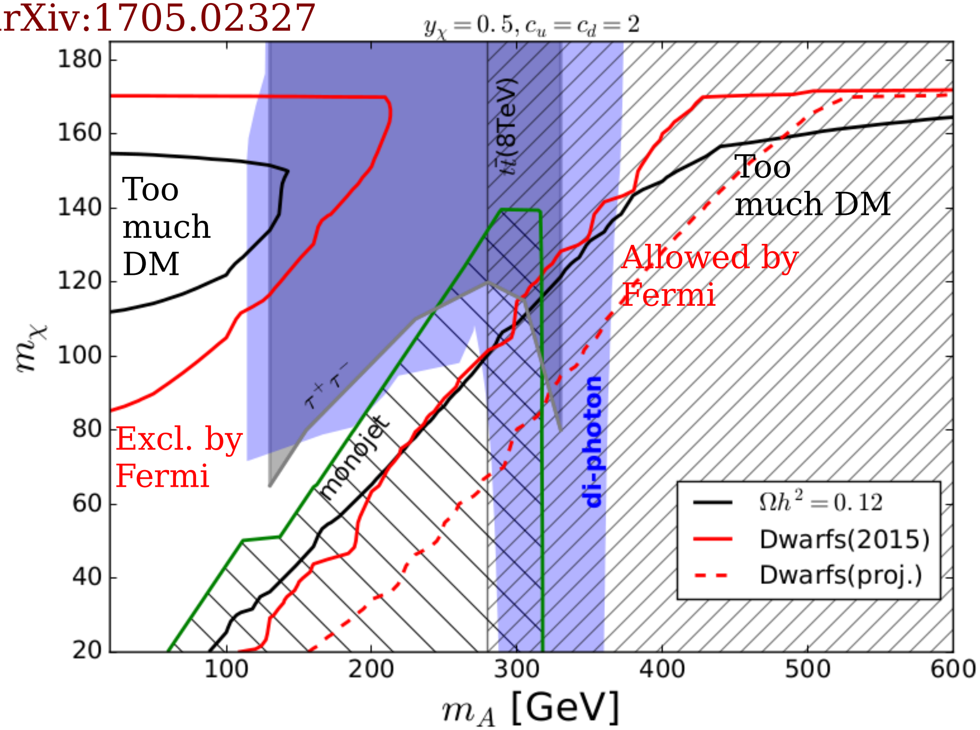
Can be very powerful, but we don't learn much about dark matter

Freeze-out: LHC searches

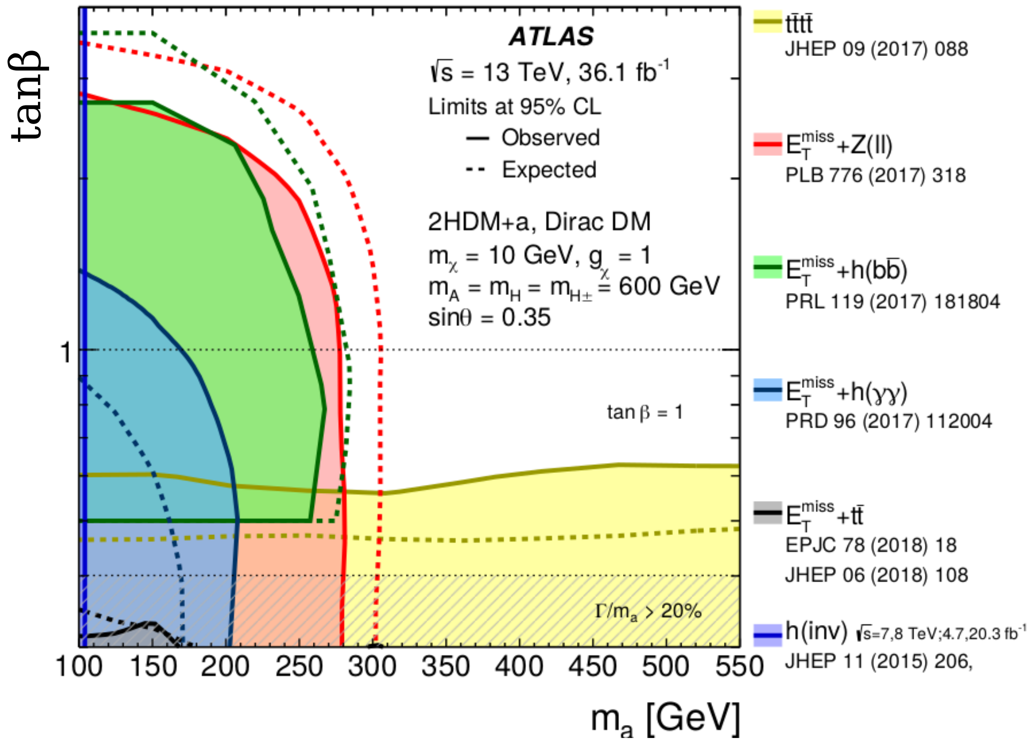
Three main approaches

Direct DM (pair-) production	Production in decay chains	Mediator searches

arXiv:1705.02327



arXiv:1903.01400



Dark matter and mediator searches are complementary

“Status of WIMPs”

Hard to summarize the status of ~30 years of model-building.

Q: Are mono-X searches obsolete?
A: No

E.g. valuable for light DM, but I can understand that EXPs find them boring

Q: Is thermal freeze-out more contrived?
A: Yes!

It’s no longer that trivial to write down a viable model with m_{DM}~$O(10^2)$ GeV

Q: Is thermal freeze-out excluded?
A: No

Can go to higher masses, coannihilation etc

Q: Will we manage to exclude it?
A: Not soon

But combination with DD/ID can make it even more unappealing

Q: Should we consider alternatives?
A: Yes!

Because they can be interesting

Because they are possible!

Weaker coupling:
Conversion-driven freeze-out

An alternative within freeze-out

For small enough mass splitting between DM and the heavier dark sector particles, DM can annihilate with and/or convert into them: whichever reaction freezes out first sets the DM abundance.

Coannihilation

· Annihilation freezes out first.

· Standard searches for compressed spectra + a bit of LLPs.

Conversion-driven freeze-out

· Conversion freezes out first.

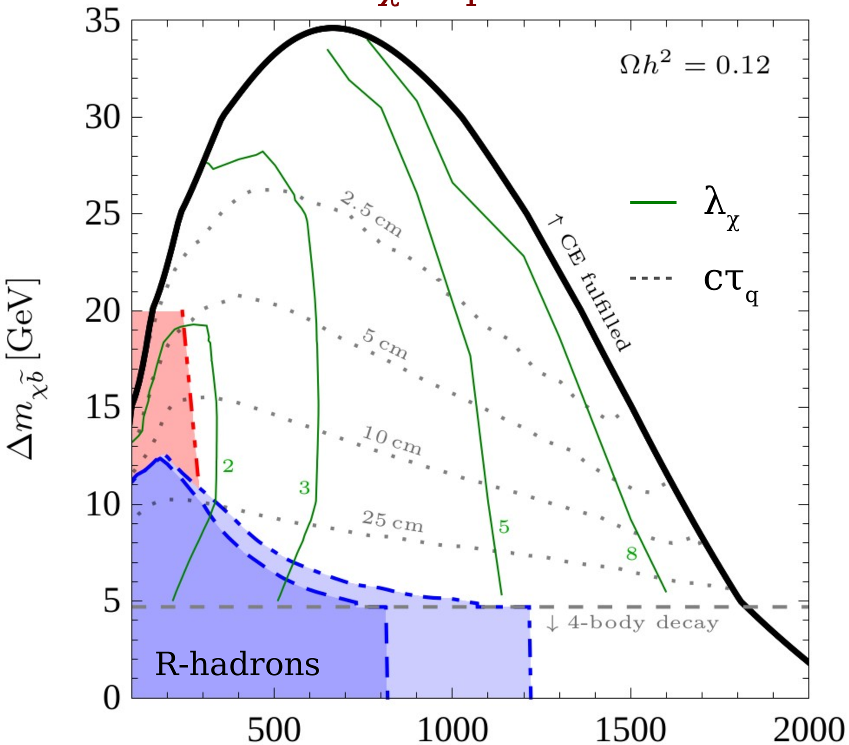
· Mostly searches for LLPs.

An alternative within freeze-out

For small enough mass splitting between DM and the heavier dark sector particles, DM can annihilate with and/or convert into them: whichever reaction freezes out first sets the DM abundance.

Coannihilation | **Conversion-driven freeze-out**

Model with "χ+squark"



arXiv:1705.09292 m_χ [GeV]

· Involves small, $\boldsymbol{O}(10^{-7})$ couplings between DM and the other dark particle → Typically leads to LLPs. Constraints from:

- Monojets
- R-hadron searches

· Actually, the mechanism can involve LLP's decaying into soft products + MET.

→ Can they be used as handles?

Partial signature overlap with freeze-in

Feeble coupling: Freeze-in

Freeze-in: main idea

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

Two basic premises :

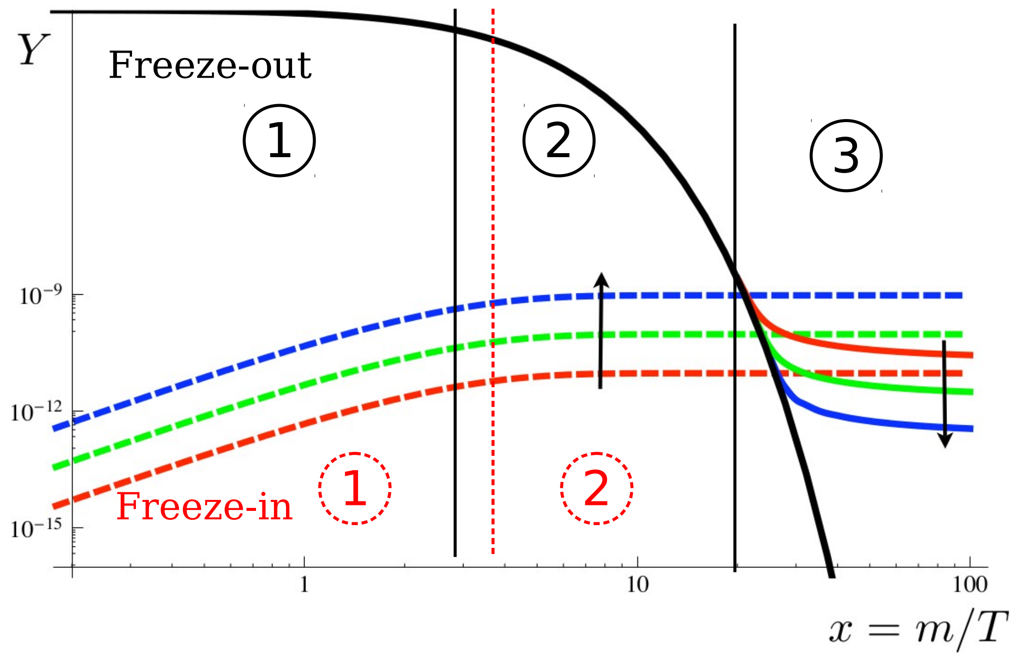
- DM interacts *very* weakly with the SM.
- DM has a negligible initial density.

DM annihilation rate scales as $n_\chi^2 \langle\sigma v\rangle$

⬇

→ DM-SM never in chemical equilibrium, DM doesn't annihilate

Tweaked from arXiv:0911.1120



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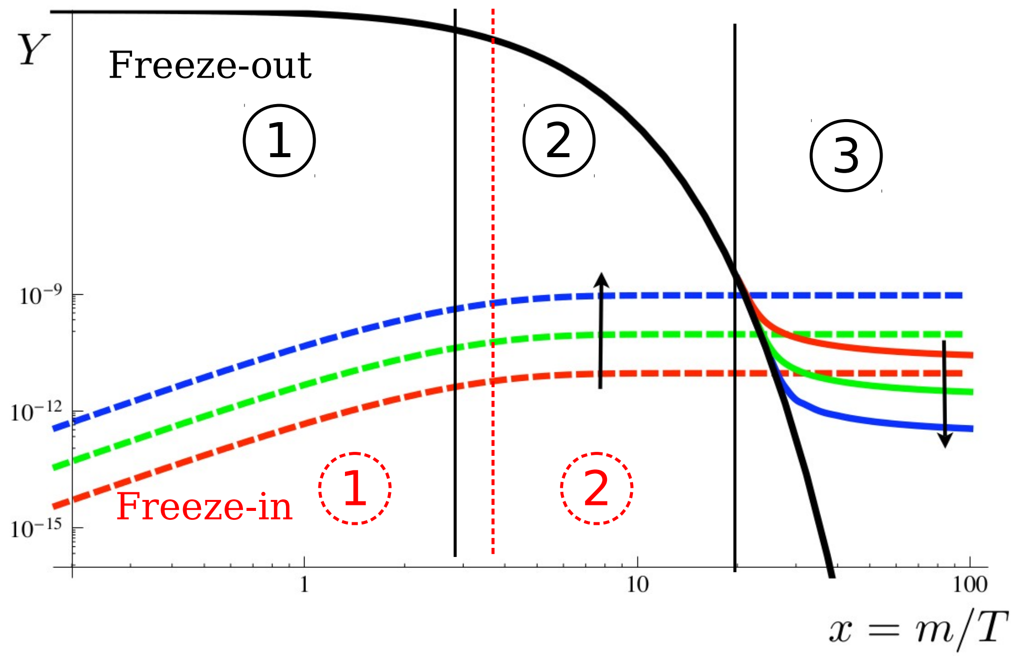

DM annihilation rate scales as $n_\chi^2 <\sigma v>$

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→ DM-SM never in chemical equilibrium, DM doesn't annihilate

For your freeze-in computational needs :

micrOMEGAs5.0 : freeze-in

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

arXiv:1801.03509

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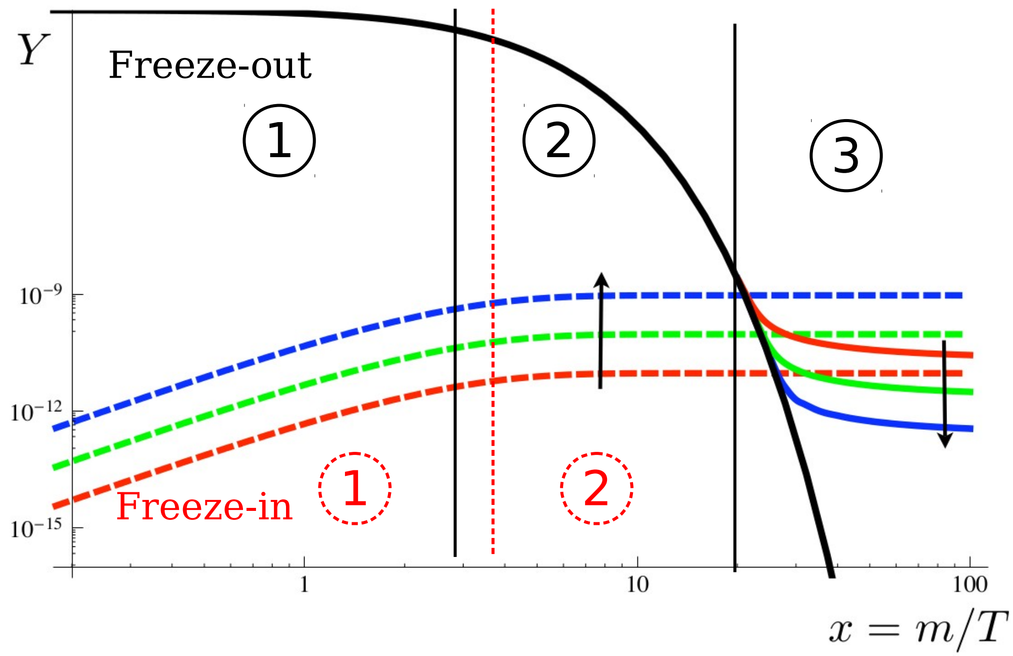
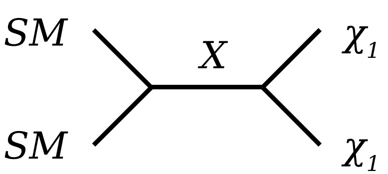
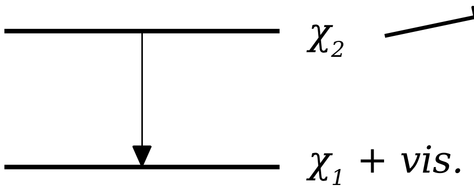


Annihilation:



Decay:



Can even be strongly coupled!

- Requires $\lambda_1\ \lambda_2 \sim 10^{-10}$ - 10^{-12}
- Requires $\lambda \sim 10^{-13}$ x $(m_{\chi 2}/m_{\chi 1})^{1/2}$

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

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

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:

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

↓

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?

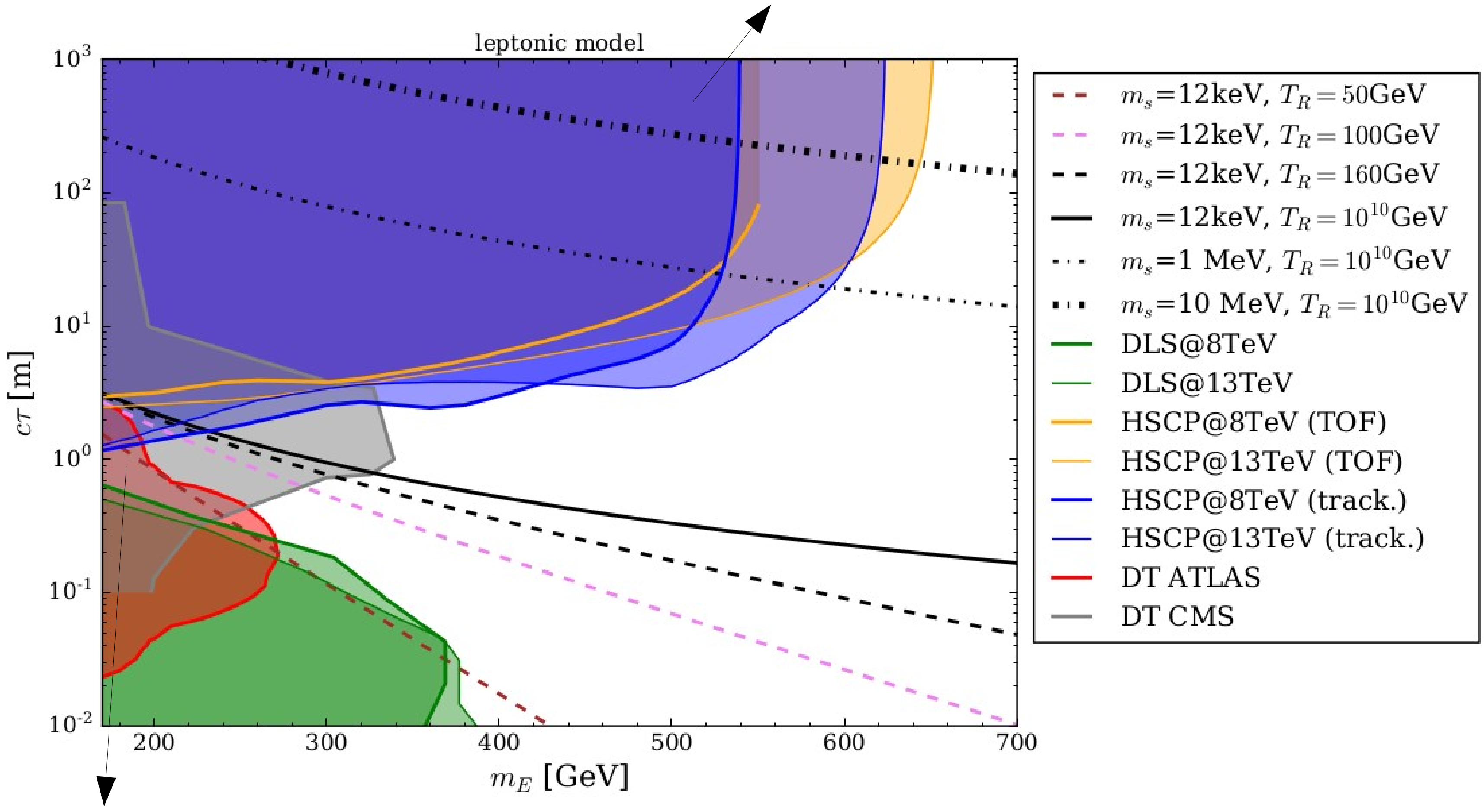
· First of all, production through :
- Drell-Yan (lepton model)
- Drell-Yan +QCD (quark model)

· 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.

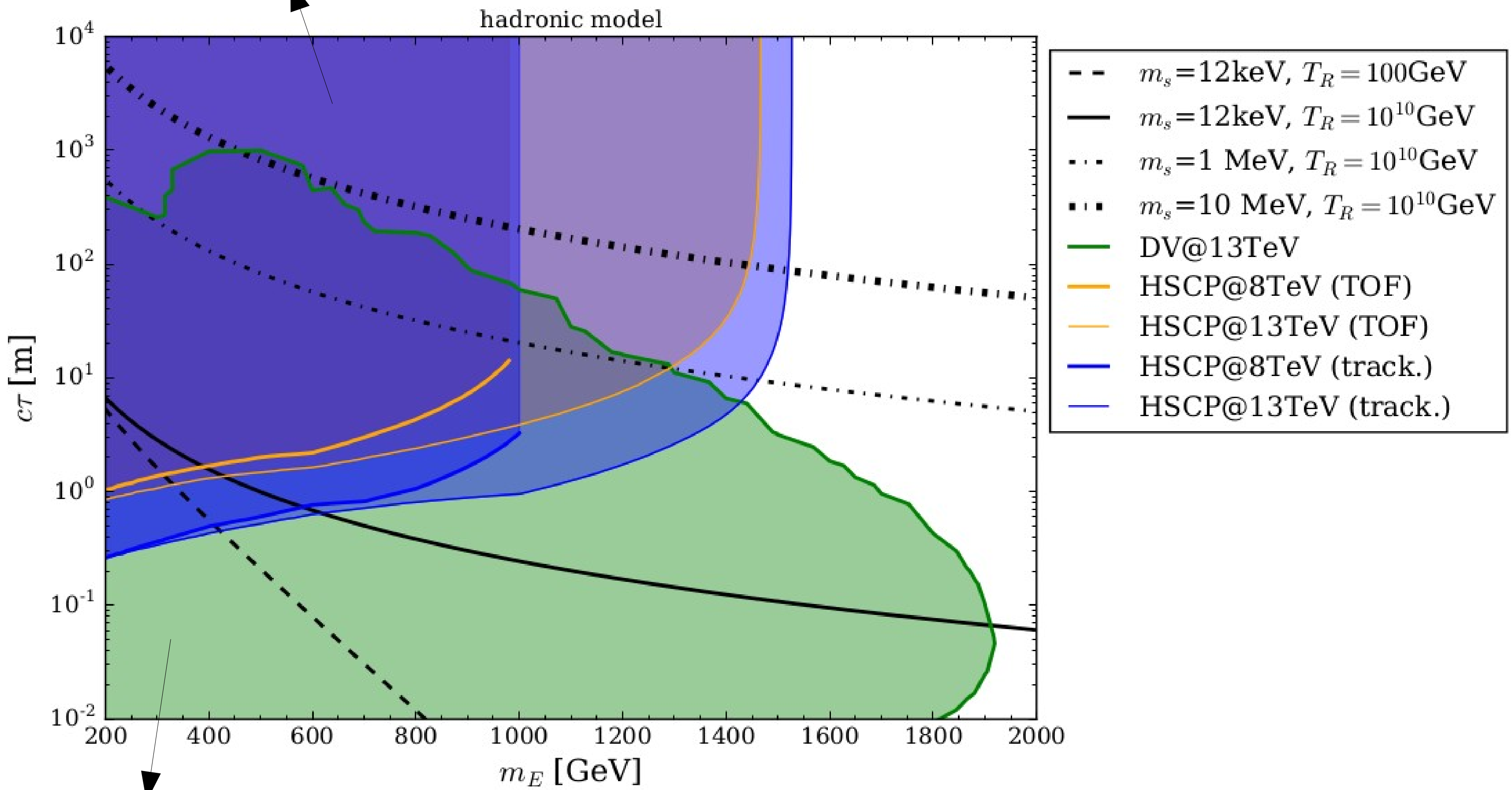


DT: Order-of-magnitude difference in peak sensitivity between ATLAS/CMS

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 and outlook

· WIMPs are definitely not excluded. But they're becoming increasingly contrived thanks to the combined efforts of DD/ID/Collider experiments.

· In light of this situation (but not only!), alternative possibilities for dark matter genesis are being explored within the dark matter community.

They are cosmologically and theoretically interesting

They give rise to new phenomenological signatures

· We focused on two such scenarios: conversion-driven freeze-out and freeze-in.

There are more possibilities, *e.g.* asymmetric dark matter.

· These scenarios naturally predict long-lived particles which can be copiously produced @ the LHC. They must be looked for.

Cosmology is still providing motivation for exciting searches at the LHC!

Additional material

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 $m_\chi/20$.

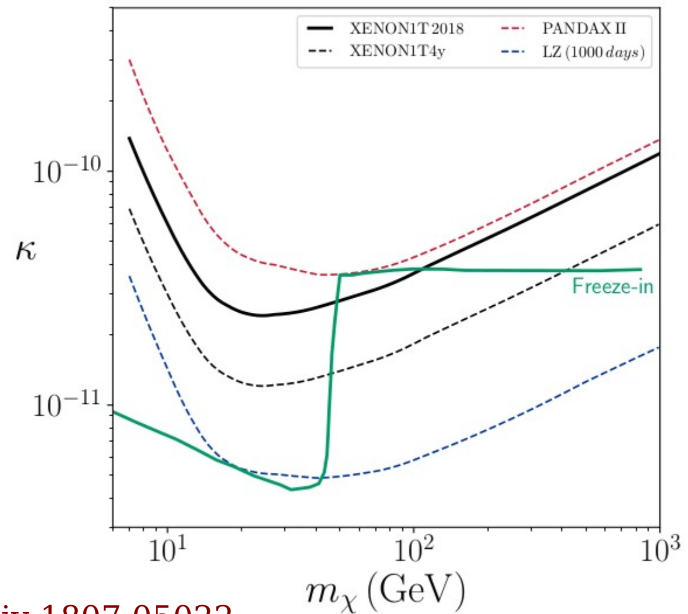
· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on nature of underlying theory.

- 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

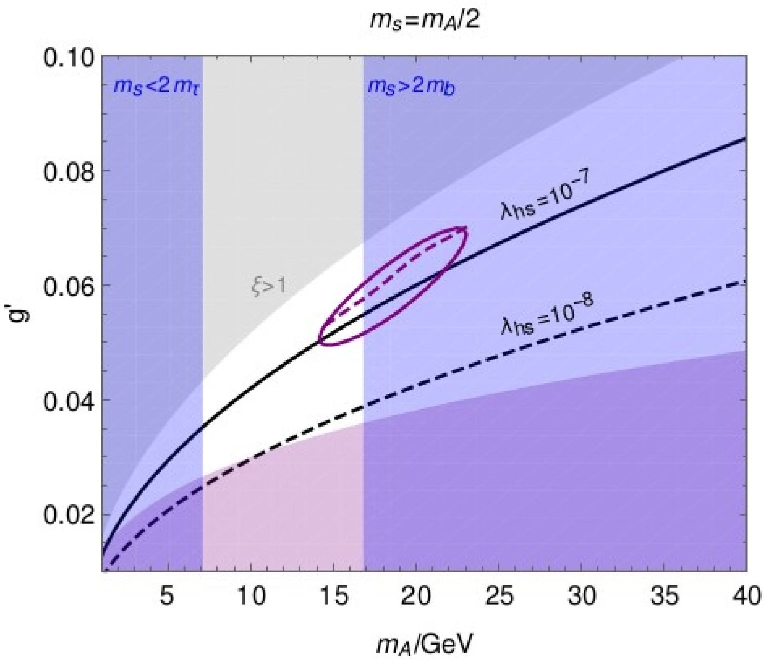
Direct detection w/ light mediator



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

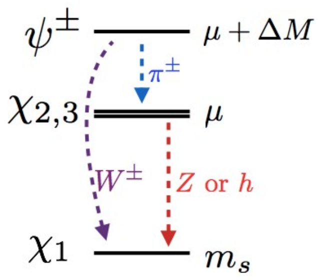
Another example: singlet-doublet model

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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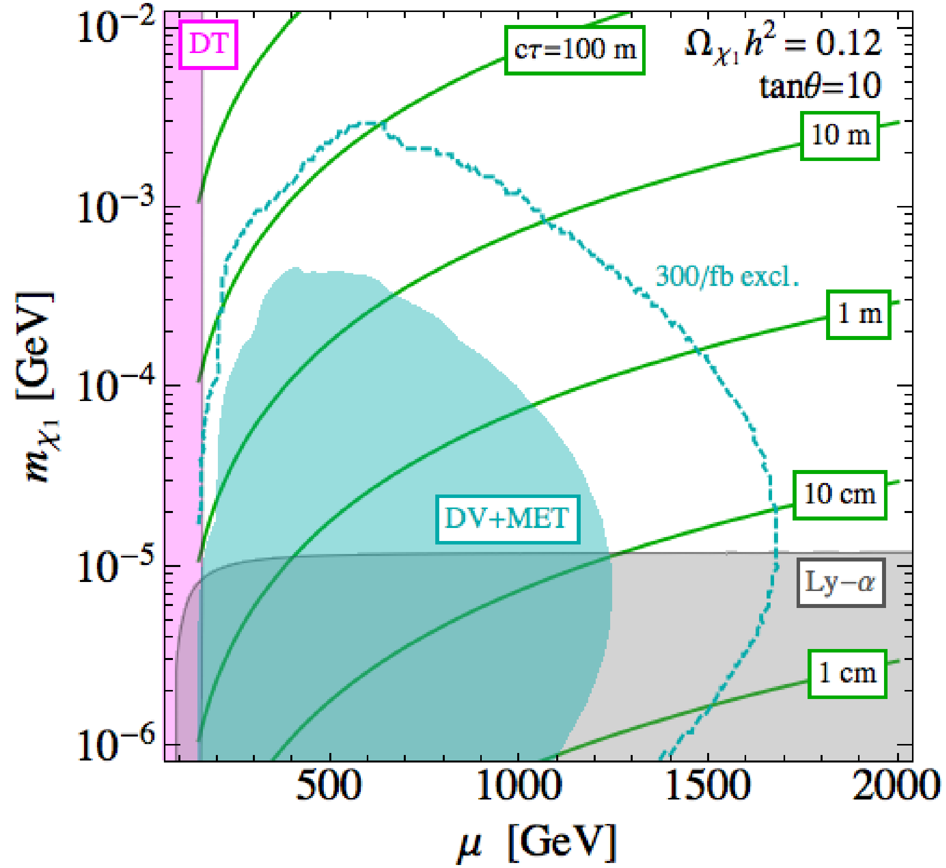
· Combination of all constraints :



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 $\mu \to e\gamma$

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

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

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!

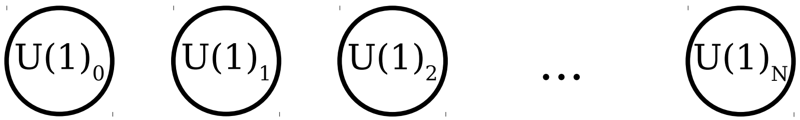
If measurements point to $T_R < T_{EW}$, T^*, we can falsify baryogenesis models that rely on efficient sphaleron transitions

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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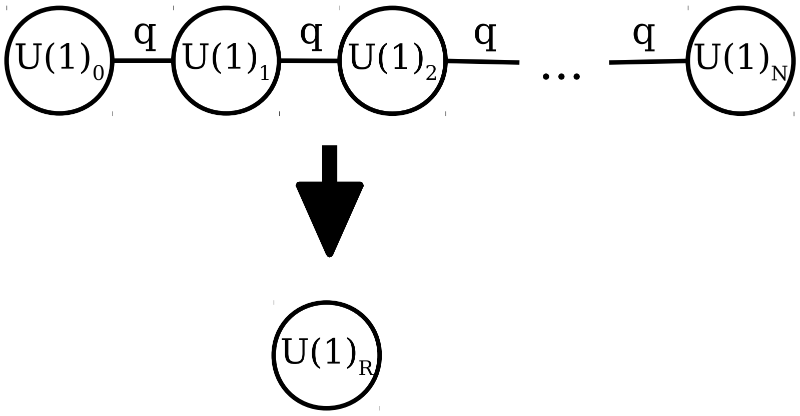
  → One massless Goldstone left



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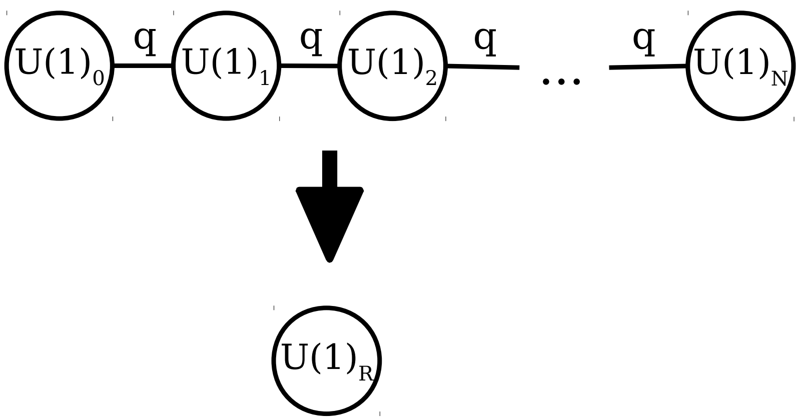

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· For $m^2 < f^2$: $\mathcal{L}_{SCW} = -\frac{1}{2}\sum_{j=0}^{N}\partial_\mu\phi_j^\dagger\partial^\mu\phi_j - \left(\frac{1}{2}\sum_{i,j=0}^{N}\phi_i M_{ij}^2\phi^j + \frac{m^2}{24f^2}\sum_{i,j=0}^{N}(\phi_i M_{ij}^2\phi^j)^2 + \mathcal{O}(\phi^6)\right)$

· 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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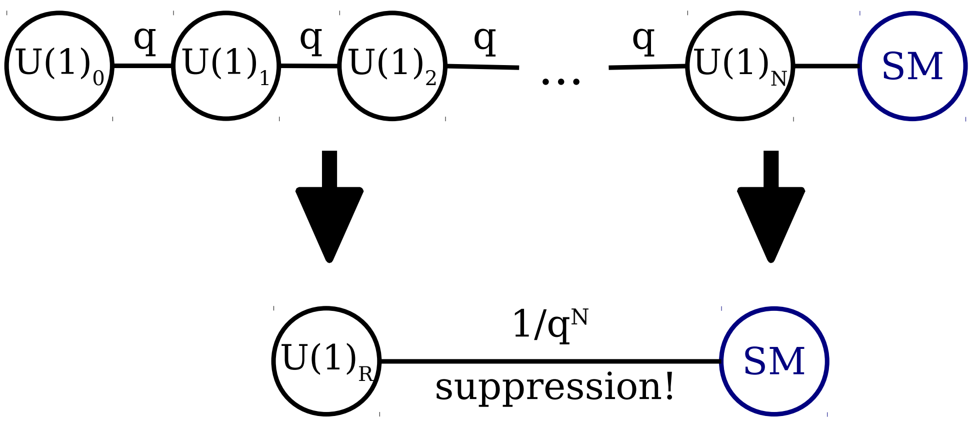

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  → One massless Goldstone left

- 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!

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

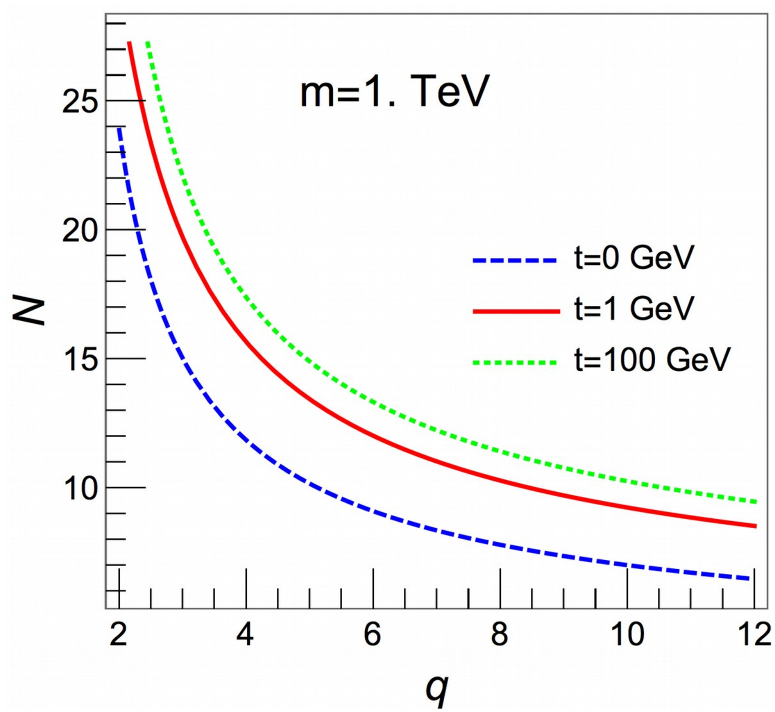
NB: Now includes t-terms

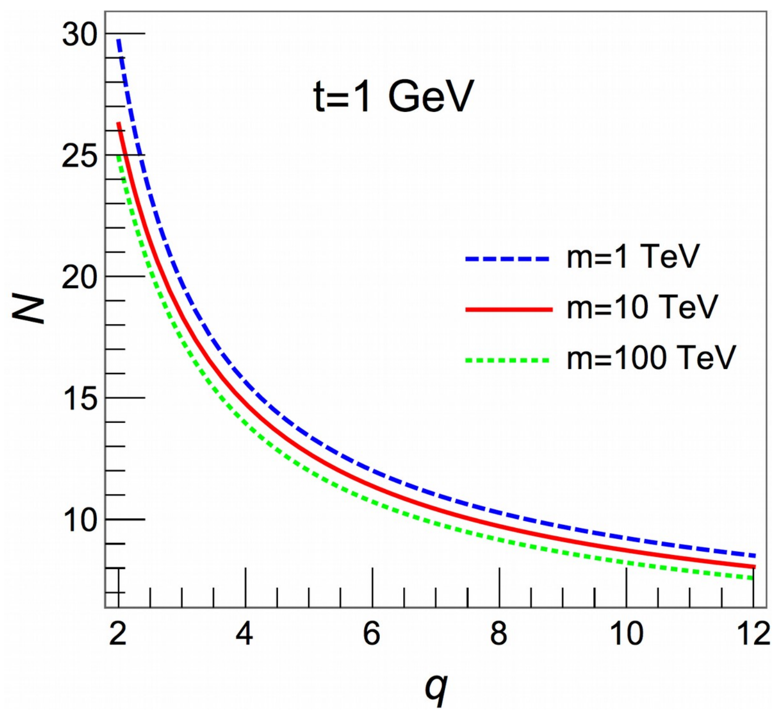
$$\left(\tilde{M}_{ij} \equiv M_{ij} + \kappa v^2 \delta_{iN}\delta_{jN}\right)$$

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 $a_i \rightarrow a_0 + h$

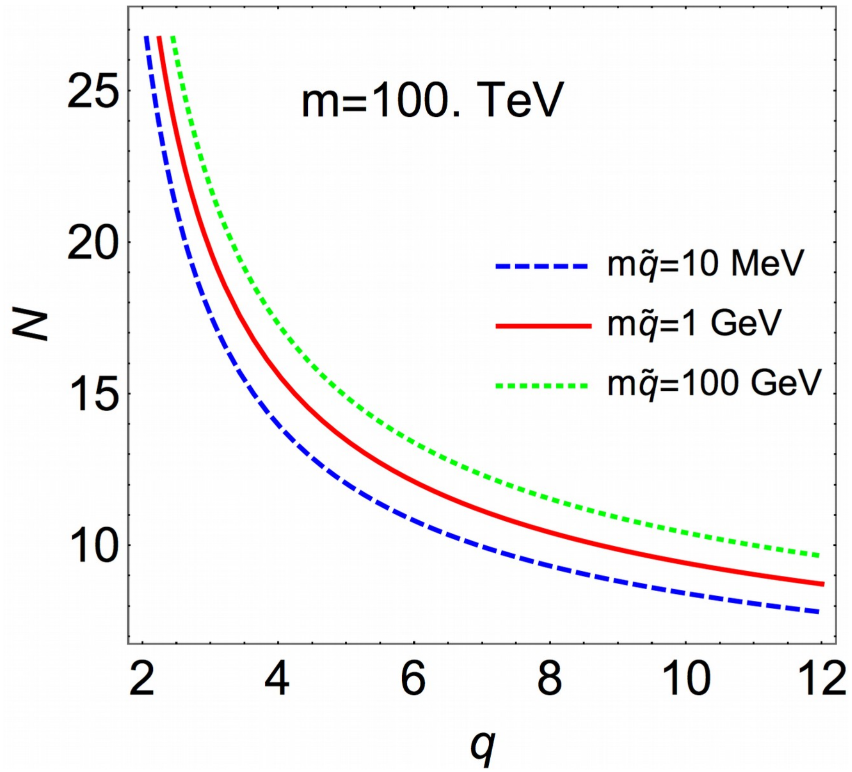
A fermion Clockwork FIMP

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.

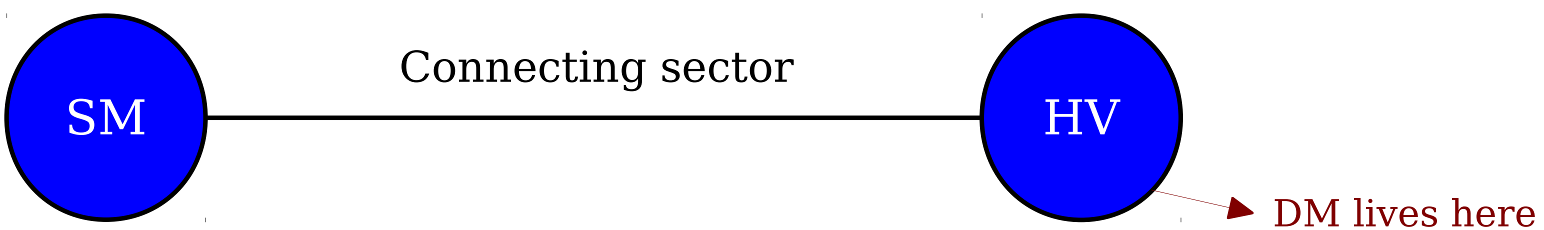
Proof of principle: the Clockwork mechanism can be used to build viable freeze-in models

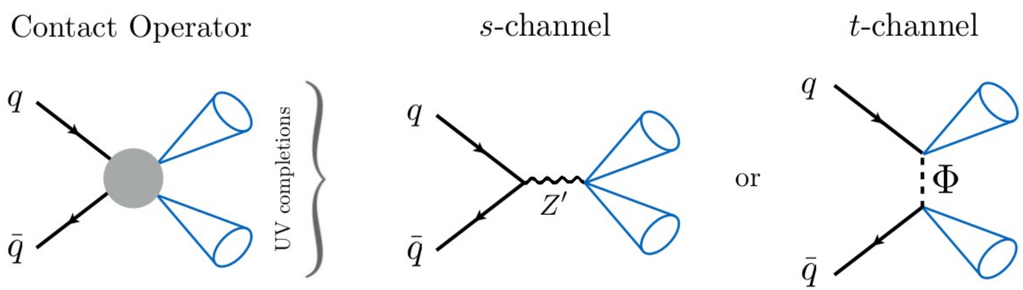
Asymmetric DM

Main idea: DM annihilates very efficiently, observed abundance due to initial asymmetry between DM and anti-DM (much like in the baryonic sector).

One class of realisations:

Hidden valley dark matter





Emergent jet signature