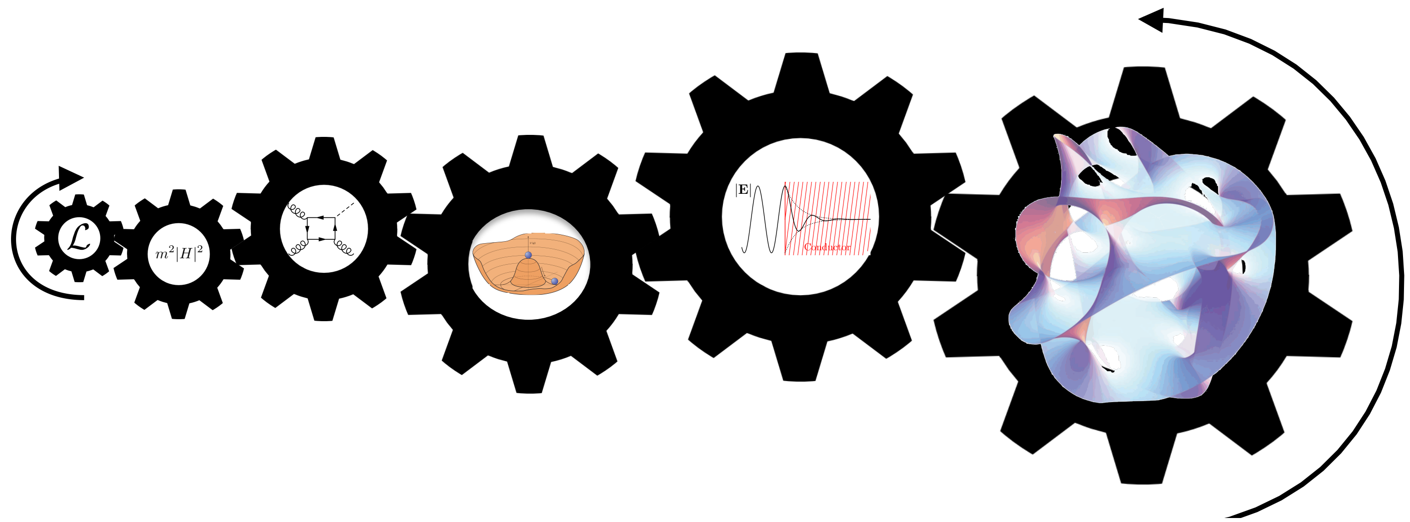
Clockworking FIMPS



Dipan Sengupta

Based on

A.Goudelis (LPTHE,Paris), K. Mohan (MSU, U.S.A)

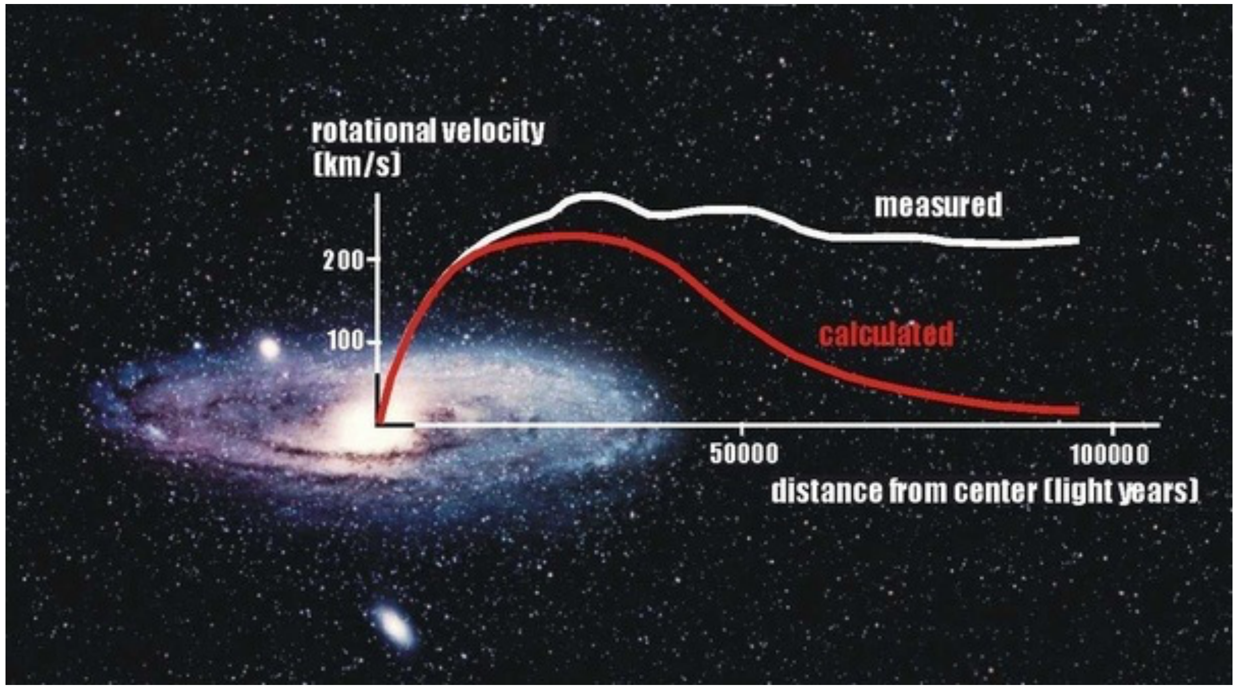
arXiv: 1807.06442, JHEP-xxxx

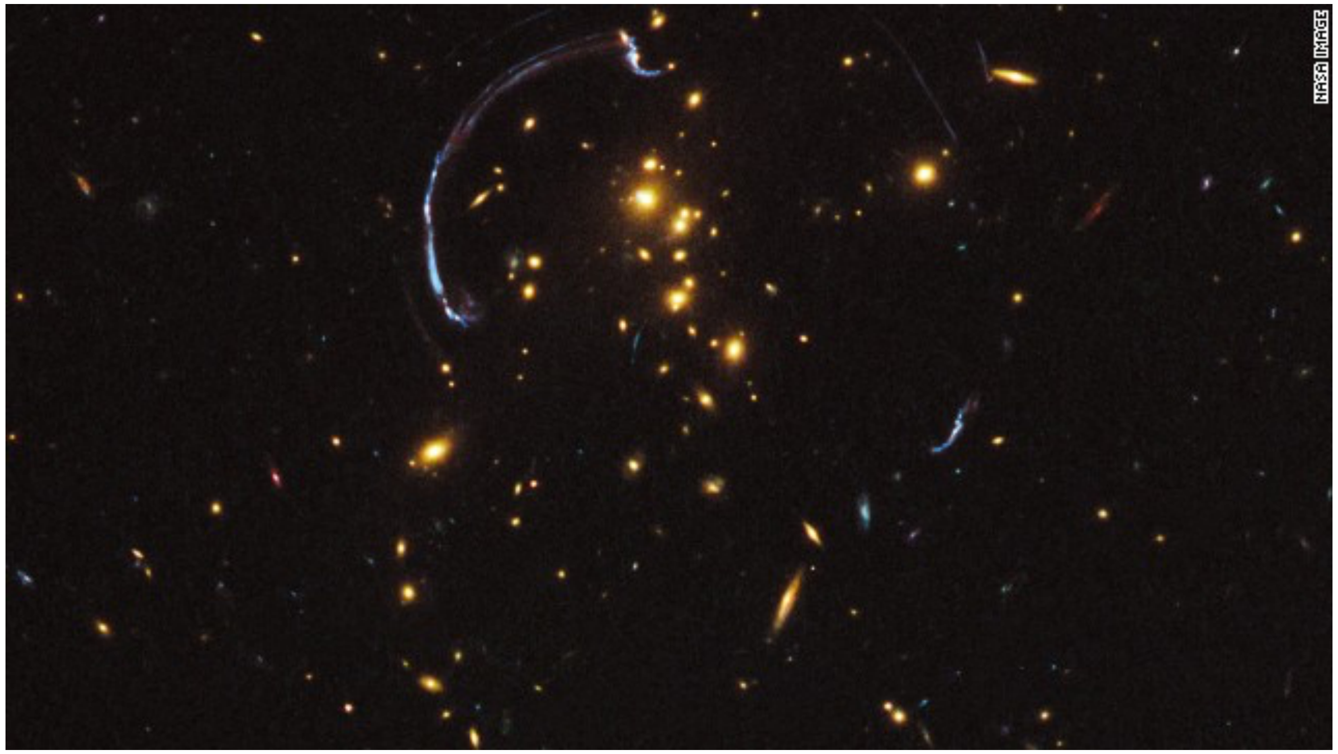
MICHIGAN STATE
UNIVERSITY

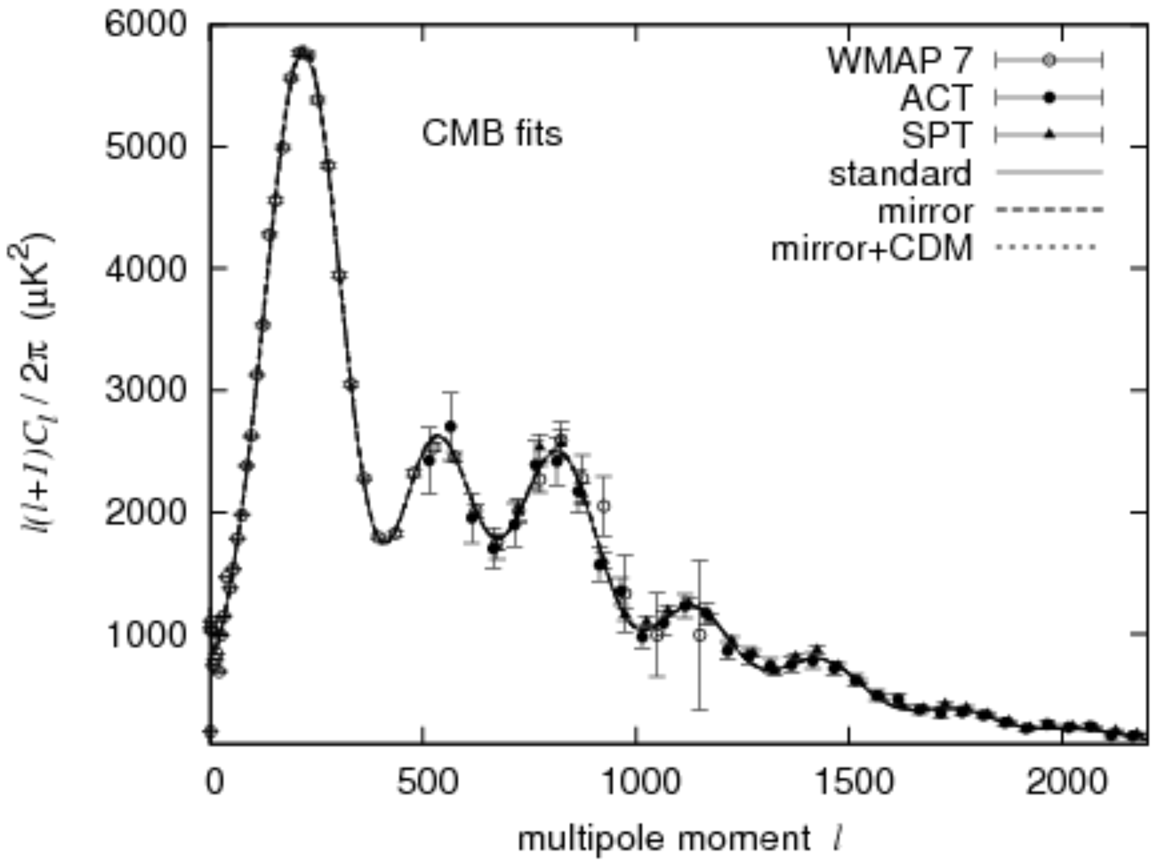
Plan of this talk

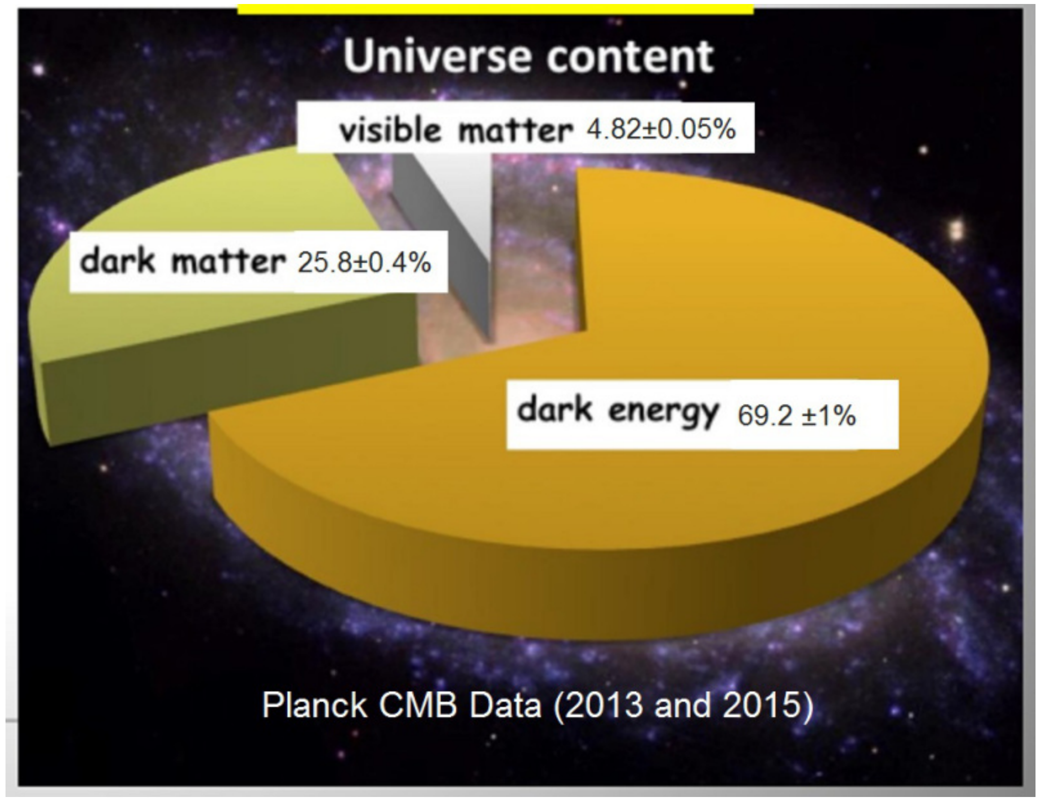
- Revisiting Freeze-out.
- A general introduction to Freeze-in.
- Hierarchy problem and clockworks
- Introduction to the clockwork set up
- Clockwork scalars and fermions.
- Models of scalar and fermionic FIMPs.

DM : Evidence



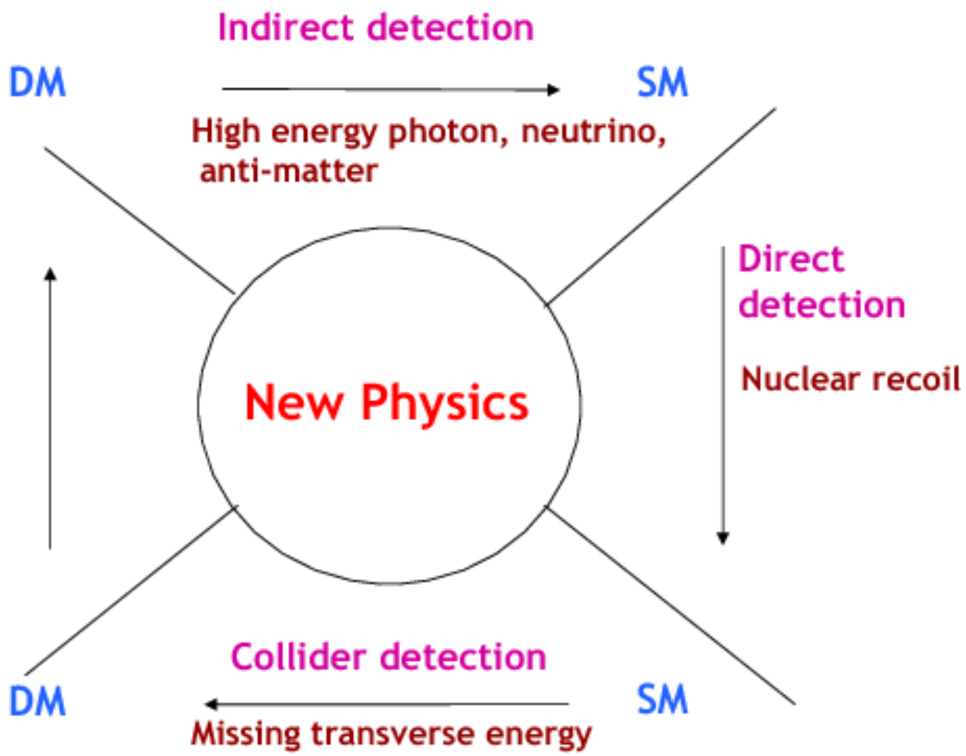






$$\Omega h^2|_{\rm exp} = 0.1188 \pm 0.0010$$

Weakly Interacting Massive Particle(WIMPs)



DM in thermal equilibrium with bath particles in early universe

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi =< \sigma v > [n_\chi^2 - n_{eq}^2]$$

→ **Boltzmann equation for DM**

$$\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle (x) = \frac{4x}{K_2(x)^2} \int_1^{+\infty} d\bar{s} \quad \sqrt{\bar{s}} \cdot (\bar{s} - 1) \cdot K_1(2x\sqrt{\bar{s}}) \cdot \sigma_{\text{ann}}$$

$$x \equiv \frac{M_X}{T}$$

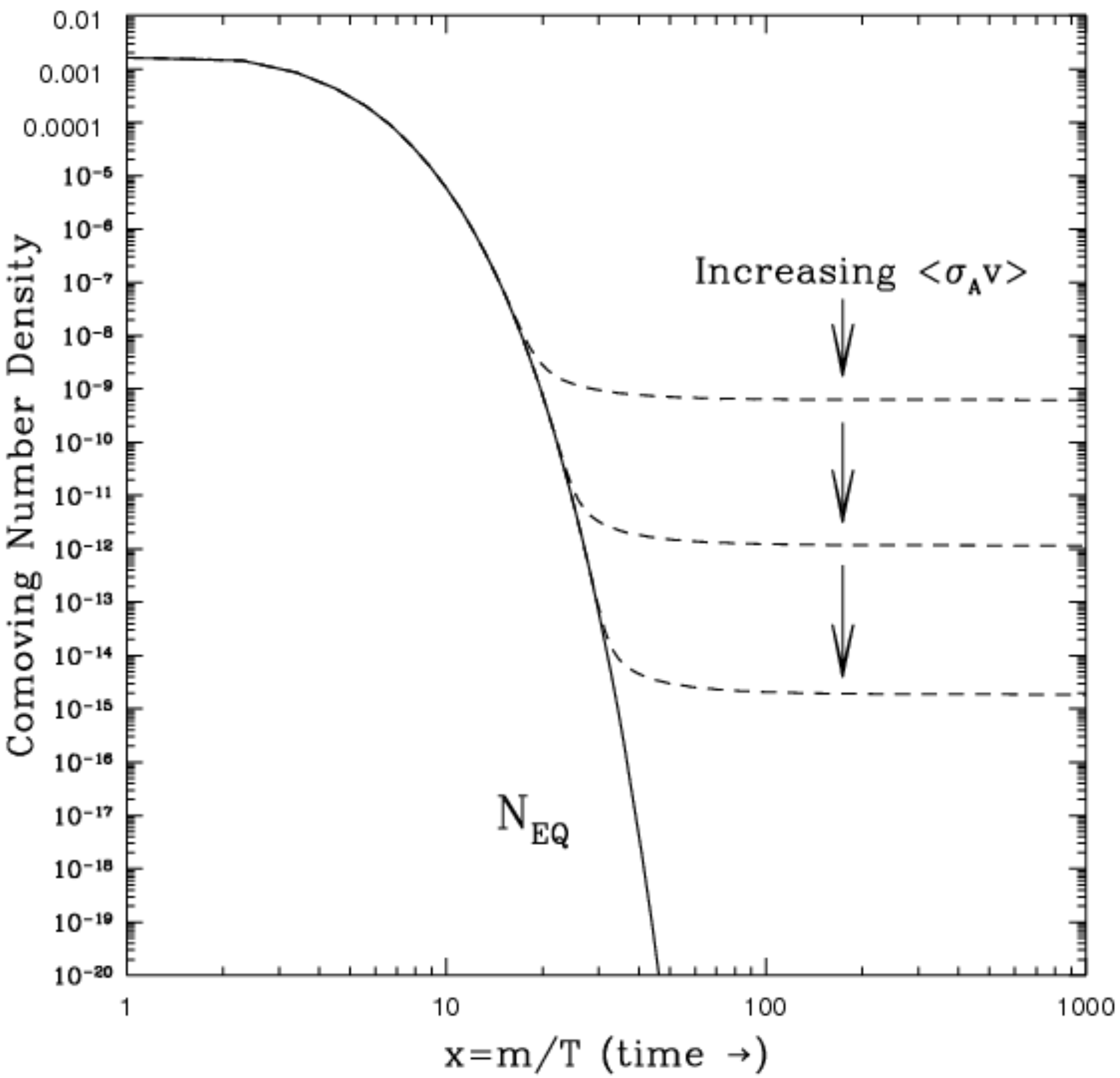
$$\Omega_X \equiv \frac{\rho_{X,0}}{\rho_{\text{crit},0}}$$
$$= \frac{M_X n_{X,0}}{3M_{\text{pl}}^2 H_0^2} = \frac{M_X N_{X,0} s_0}{3M_{\text{pl}}^2 H_0^2} = M_X N_X^\infty \frac{s_0}{3M_{\text{pl}}^2 H_0^2}$$

$$\Omega_\chi h^2 = 0.1 \frac{x_f}{28} \frac{\sqrt{g_{eff}}}{10} \frac{2.10^{-26} cm^3 s^{-1}}{< \sigma_{\chi\chi} v_{ann} >}$$

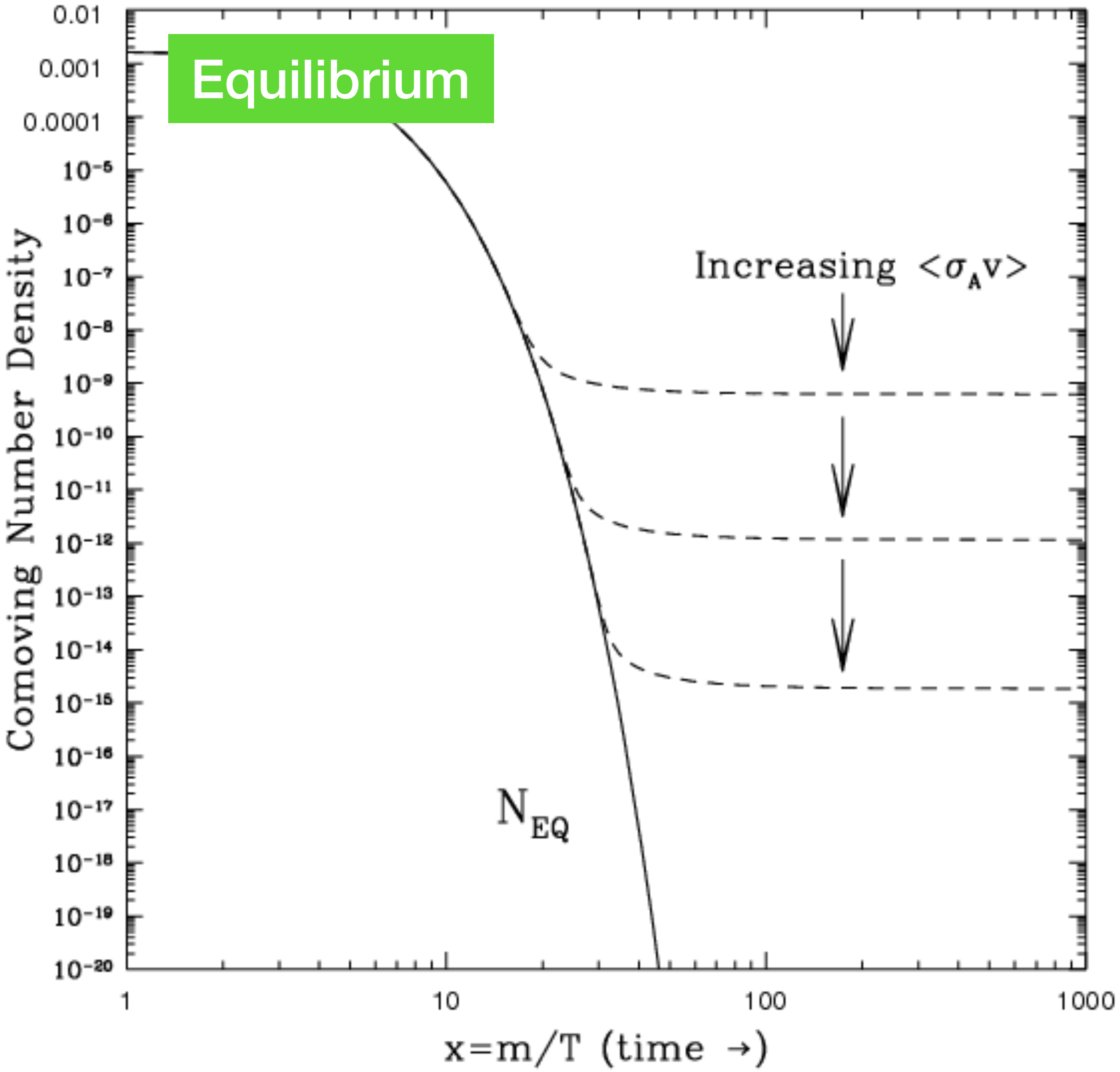
Interaction Strength : Weak Scale -> A BSM theory that also solves Hierarchy problem

Weakly Interacting Massive Particle

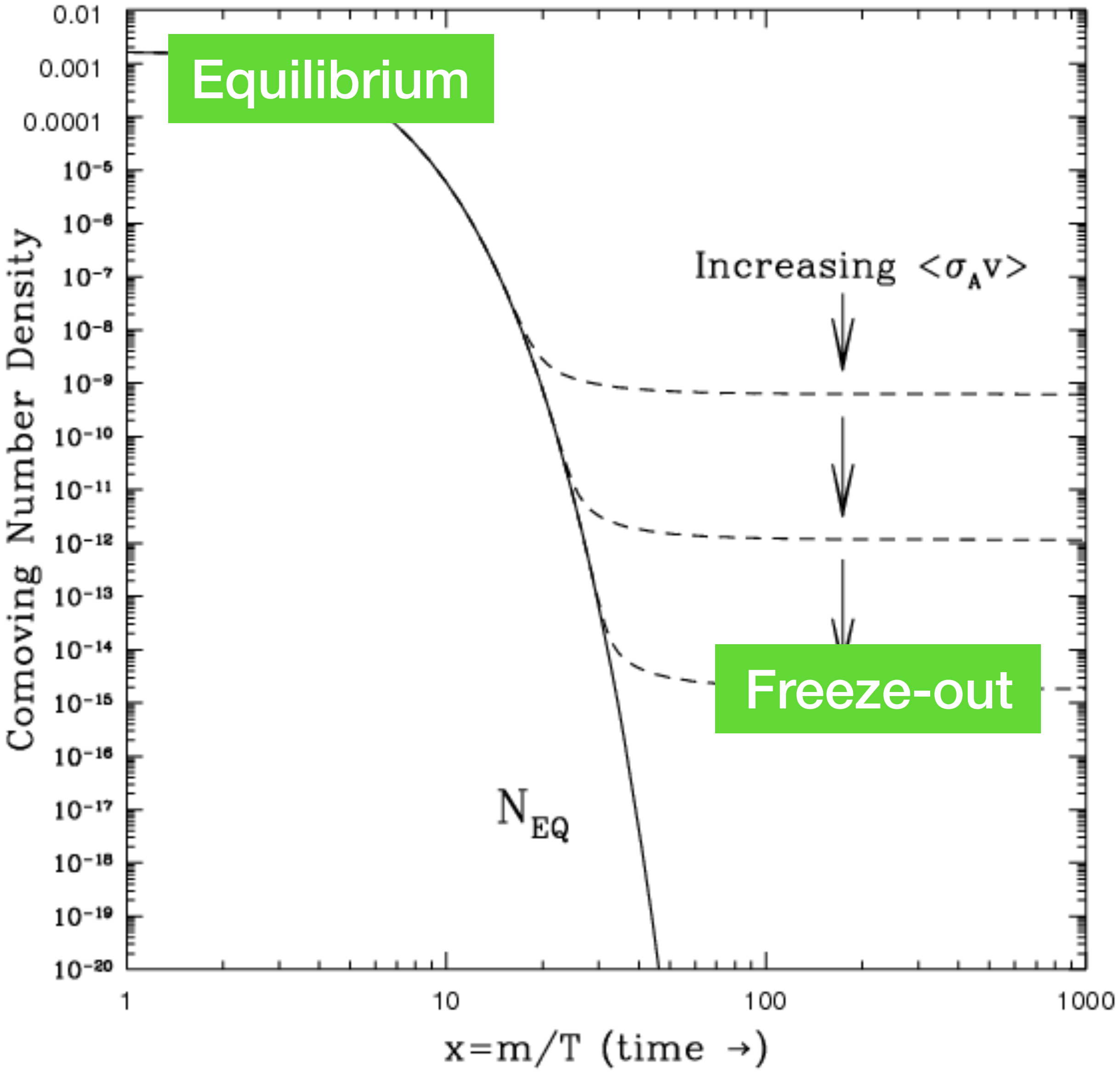
Weakly Interacting Massive Particle



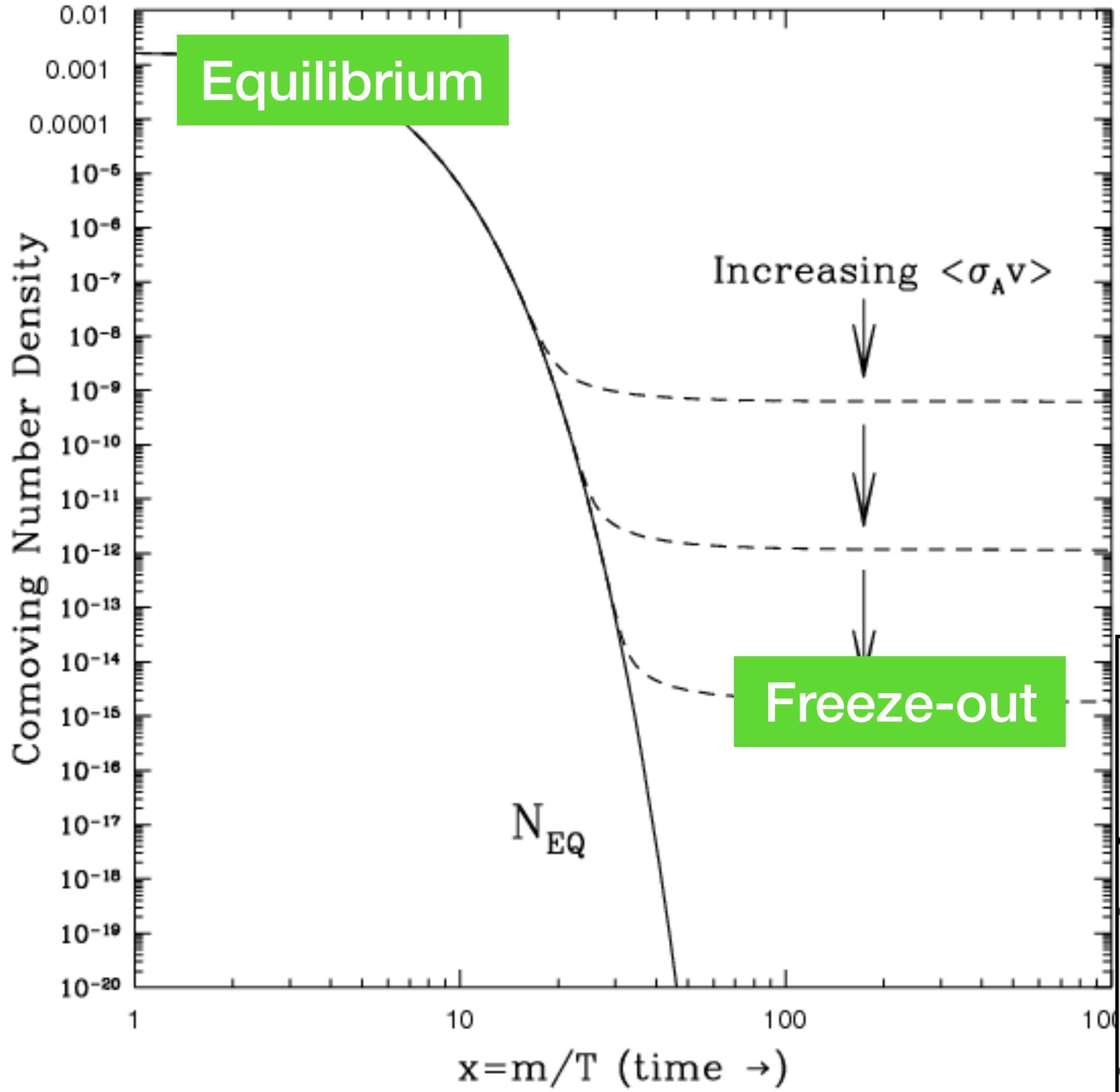
Weakly Interacting Massive Particle

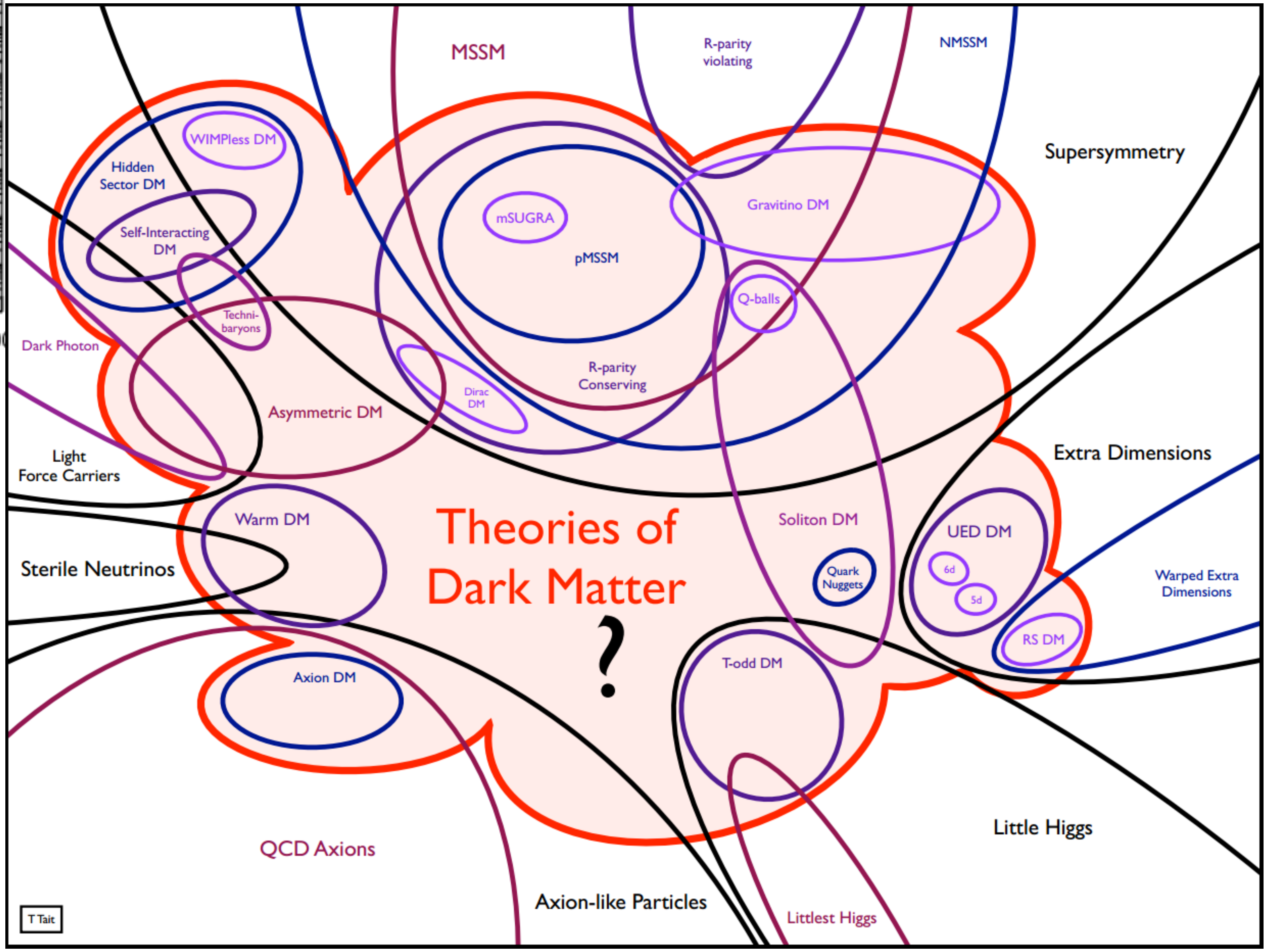


Weakly Interacting Massive Particle

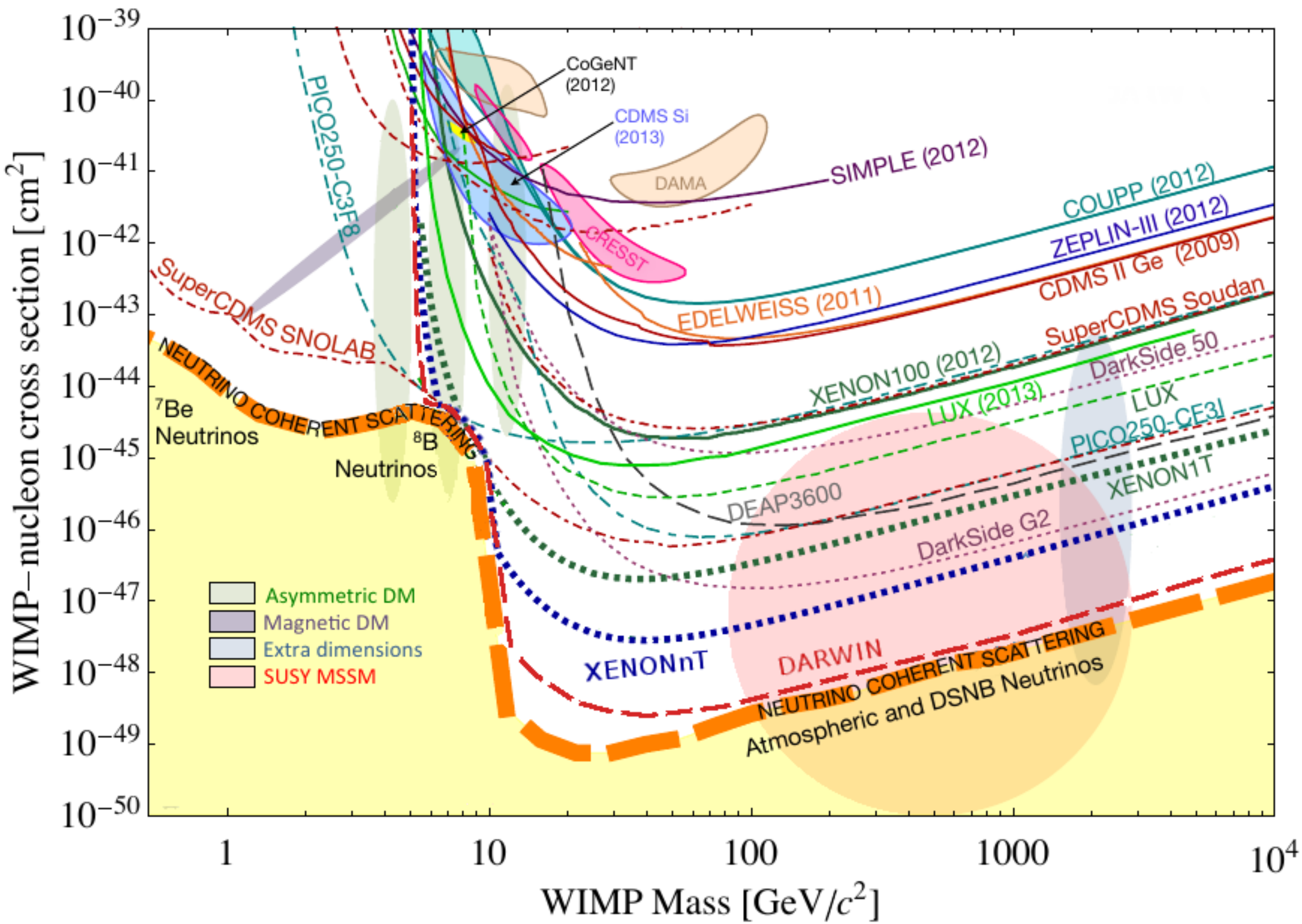


Weakly Interacting Massive Particle





Status of WIMPY DM : Doomsday or not ?

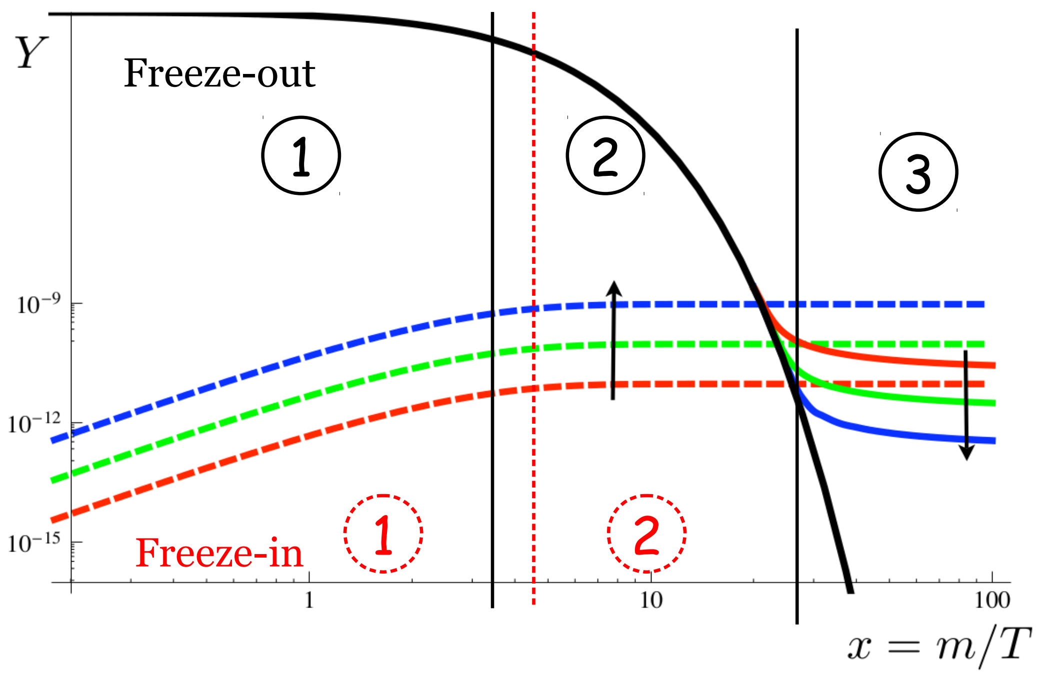


Alternative ideas ?

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 $A \rightarrow B$, ξ_A/ξ_B particles of type χ are destroyed/created. Integrated Boltzmann equation :

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

1 DM produced from decays/annihilations of other particles.

2 DM production disfavoured → Abundance freeze-in

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

Freeze-In Dark Matter/ Feebly Interacting massive particles

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.

Relevant temperature:

· FO: around $m_\chi/20$.

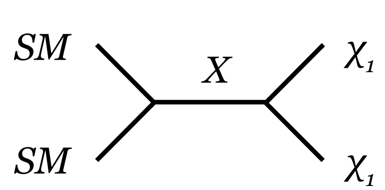
· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on DM production channel and on nature of underlying theory.

- Statistics can become important. So can very early Universe physics.
- Easily above *e.g.* T_{EWSB} → Phase transitions may occur *after* DM production

Model-building issues

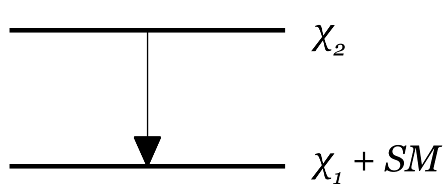
What kind of couplings do we need for successful freeze-in?

Annihilation:



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

Decay:



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

Freeze-In Dark Matter/ Feebly Interacting massive particles

$\lambda X B_1 B_2$

$B_1 \rightarrow B_2 X.$ → **DM candidate**

Exponentially small coupling required

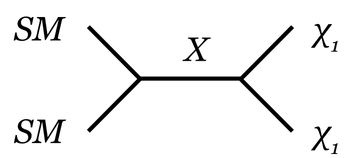
$$\Omega_X h^2|_{tot} \approx \frac{1.09 \times 10^{27}}{g_*^S \sqrt{g_*^\rho}} m_X \sum_i \frac{g_{B_i} \Gamma_{B_i}}{m_{B_i}^2}$$

$$\lambda \simeq 1.5 \times 10^{-13} \left(\frac{m_B}{m_X}\right)^{1/2} \left(\frac{g_*(m_B)}{10^2}\right)^{3/4} \left(\frac{g_{bath}}{10^2}\right)^{-1/2}.$$

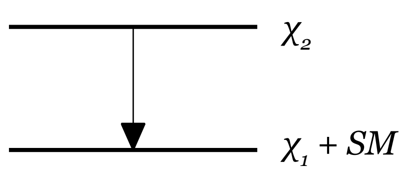
Model-building issues

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

Annihilation:



Decay:



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

· 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
- Symmetries

The idea of "Clockwork"-ing

What's the clockwork mechanism?

- **clockwork mechanism** $\rightarrow$ an elegant and economical way to generate **tiny numbers**/large hierarchies X with only $\mathcal{O}(1)$ **couplings** and $\mathcal{N} \sim \log X$ **fields**
- Originally introduced in the context of relaxation models, to solve technical issues present in these [Choi, Im, '15; Kaplan, Rattazzi, '15]
- Then realized as a **framework** for model building: [Giudice, McCullough, '16]
  - low-scale invisible axions [Giudice, McCullough, '16; Farina, Pappadopulo, Rompineve, Tesi, '16;
  - **hierarchy problem** [Giudice, McCullough, '16; Giudice, McCullough, Katz, Torre, Urbano, '17;
  - inflation [Kehagias, Riotto, '16; . . .]
  - neutrino physics Ibarra, Kushwaha, Vempati, '17; . . .]
  - UV/EFT relation [Craig, Garcia Garcia, Sutherland, '17; Giudice, McCullough, '17]
  - supergravity [Kehagias, Riotto, '17; Antoniadis, Delgado, Markou, Pokorski, '17]
  - **collider pheno** and cosmology [Giudice, McCullough, Katz, Torre, Urbano, '17;

Criticisms : Works only for abelian theories
Continuum solutions only for special cases
UV completions are tricky to find

See criticism by,
Craig, Garcia, Sutherland

The idea of “Clockwork”-ing

How the clockwork works (made easy)

Based on the simple observation that:

$1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad \ldots \quad \times \quad 1/2$ can **easily** be **tiny**

Use a **chain** of N fields

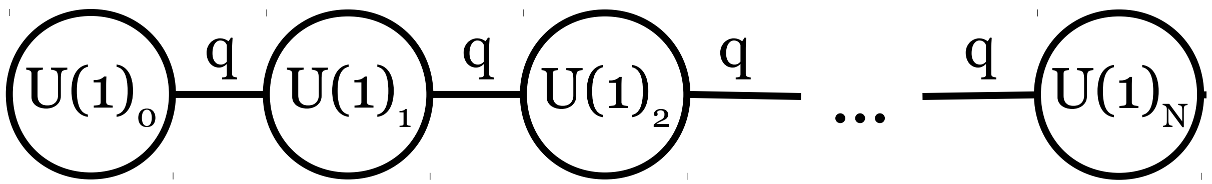
$$\phi_0 \;\overset{1/q}{\text{\_\_\_\_}}\; \phi_1 \;\overset{1/q}{\text{\_\_\_\_}}\; \phi_2 \;\overset{1/q}{\text{\_\_\_\_}}\; \phi_3 \;\overset{1/q}{\text{\_\_\_\_}}\; \ldots \;\overset{1/q}{\text{\_\_\_\_}}\; \phi_{\mathcal{N}} \;\text{\_\_\_\_}\; \mathbf{SM}$$

For **fermions** use chiral symmetries

$$R_0 \;\overset{m}{\text{\_\_\_}}\; \underbrace{L_1 \quad R_1}_{qm} \;\overset{m}{\text{\_\_\_}}\; \underbrace{L_2 \quad R_2}_{qm} \;\overset{m}{\text{\_\_\_}}\; \underbrace{L_3 \quad R_3}_{qm} \;\overset{m}{\text{\_\_\_}}\; \ldots \;\overset{m}{\text{\_\_\_}}\; \underbrace{L_{\mathcal{N}} \quad R_{\mathcal{N}}}_{qm} \;\text{\_\_\_}\; L_{SM}$$

light $N \approx R_0 \quad \Longrightarrow \quad N — L_{SM} \sim \mathbf{1/q}^{\mathcal{N}}$

A clockwork scalar



N+1 copies of U(1) global symmetry in theory space spontaneously broken down to a single U(1) at a scale f

Below f, N+1 massless Goldstones

$$U_j = e^{i\phi_j/f} \qquad j = 0, ..., N$$

Introduce N “soft” mass parameters $\boxed{m_i^2}$ that break this symmetry explicitly

$\downarrow$

Background of N spurion fields

Nearest neighbor interactions

$$\boxed{Q_i = \delta_{ij} - q\delta_{i,j+1} \quad , q > 1}$$

Non-diagonal charges

The unbroken generator

$$\boxed{\mathcal{Q} = \sum_{j=0}^{N} \frac{Q_j}{q^j}}$$

A clockwork scalar

Low energy effective lagrangian

$$\mathcal{L} = -\frac{f^2}{2}\sum_{j=0}^{N}\partial_\mu U_j^\dagger\,\partial^\mu U_j + \frac{m^2 f^2}{2}\sum_{j=0}^{N-1}\left(U_j^\dagger\,U_{j+1}^q + \text{h.c.}\right)$$

$$\mathcal{L}_{SCW} = -\frac{1}{2}\sum_{j=0}^{N}\partial_\mu\phi_j^\dagger\partial^\mu\phi_j + \sum_{j=0}^{N-1}\frac{m^2}{2}(\phi_j - q\phi_{j+1})^2 + \sum_{j=0}^{N-1}\frac{m^2}{24f^2}(\phi_j - q\phi_{j+1})^4 + \mathcal{O}(\phi_6)$$

$$\begin{aligned} V(\phi) &= \sum_{j=0}^{N-1}\frac{m^2}{2}(\phi_j - q\phi_{j+1})^2 + \sum_{j=0}^{N-1}\frac{m^2}{24f^2}(\phi_j - q\phi_{j+1})^4 + \mathcal{O}(\phi_6) \\ &= \frac{1}{2}\sum_{i,j=0}^{N}\phi_i M_{ij}^2\phi^j + \frac{m^2}{24f^2}\sum_{i,j=0}^{N}(\phi_i M_{ij}^2\phi^j)^2 + \mathcal{O}(\phi_6) \end{aligned}$$

See A.G, K.M, D.S 1807.06642 for analytic diagonalization

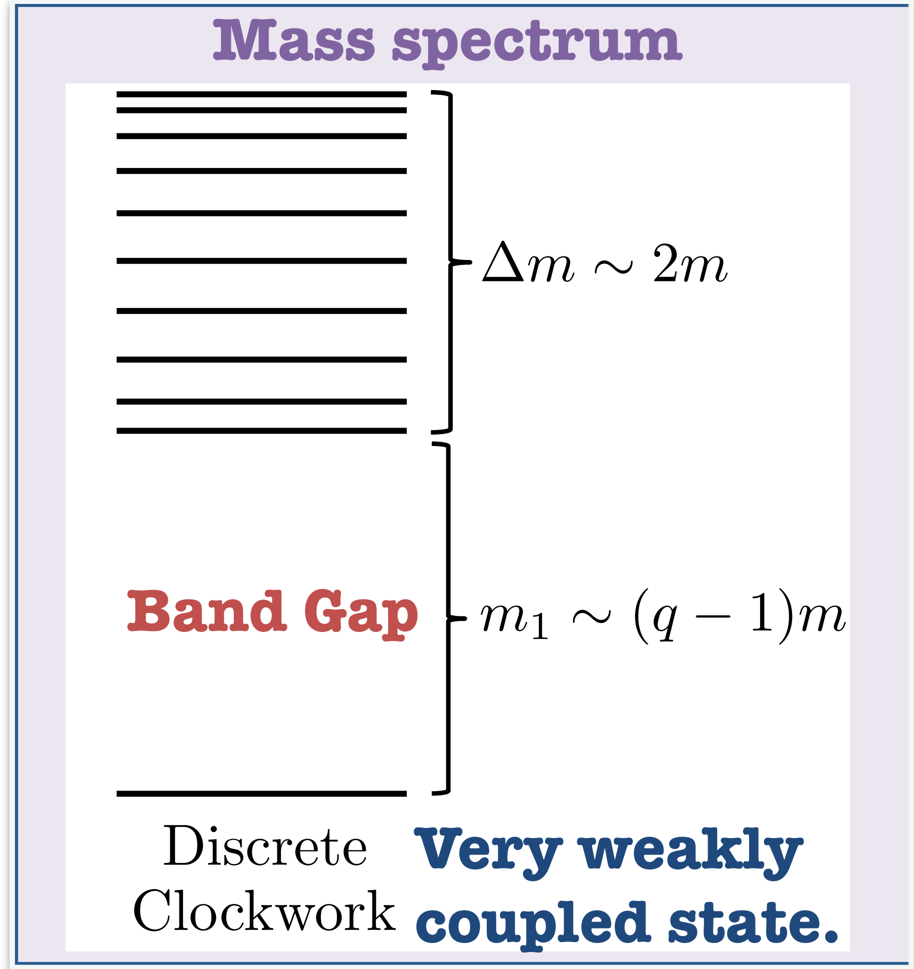
A clockwork scalar

$$\mathcal{L} = \frac{\pi_N}{16\pi^2 f} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\mathcal{L} = \frac{1}{16\pi^2} G_{\mu\nu}\widetilde{G}^{\mu\nu}\left(\frac{a_0}{f_0} - \sum_{k=1}^{N}(-)^k \frac{a_k}{f_k}\right)$$

$$f_0 \equiv \frac{f q^N}{\mathcal{N}_0}, \qquad f_k \equiv \frac{f}{\mathcal{N}_k \; q \; \sin\frac{k\pi}{N+1}}.$$

The clockwork axion



UV completions →

- **Parallels with RS/LED scenarios**
- **Continuum version : Linear dilaton set up.**
- **Low energy version of Little String Theory.**
- **Some interesting background geometries in the continuum**

- a well-defined continuum limit exists and selects either
  - massless field in curved **clockwork** metric $ds^2 = e^{\frac{4}{3}ky}(dx^2 + dy^2)$ [Giudice, McCullough, '16]

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

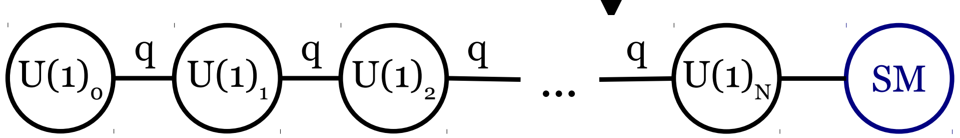
arXiv:1511.01827, 1511.00132, 1610.07962...

Clockworking a scalar FIMP

A model of scalar FIMP

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

Diagonal mass term for every site



SM coupled to the nth site

Expand the gears in the basis of Eigen-states

Identify the zero mode as the FIMP candidate

Clockworking a scalar FIMP

$$\mathcal{L}_{int} = \kappa|H^\dagger H|\phi_n^2$$
$$= \kappa \sum_{j=0,k=0}^{n} O_{kl}O_{jm}a_k a_l(v^2+2vh+h^2)/2$$

$$\phi_i\tilde{M}_{ij}\phi_j = \phi_i M_{ij}\phi_j + \kappa v^2\delta_{in}\delta_{jn}\phi_n\phi_n$$

Modified mass matrix

FIMP mass suppressed by clockwork ~ 1 keV
(close to the warm DM)

How to raise the mass ?

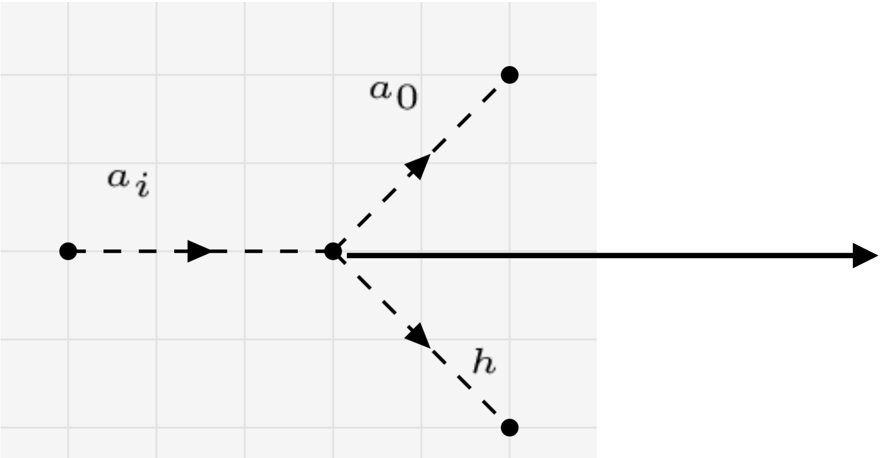
Add a diagonal mass term $\sum_{i=0}^{N}\frac{t^2}{2}\phi_i^2$

$$M_t = m\cdot\begin{bmatrix} 1+t^2/m^2 & -q & 0 & \dots & 0 & 0 \\ -q & 1+q^2+t^2/m^2 & -q & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1+q^2+t^2/m^2 & -q \\ 0 & 0 & 0 & \dots & -q & q^2+t^2/m^2 \end{bmatrix}_{(n+1)\times(n+1)}$$

Diagonal mass term unsuppressed by clockwork $\longrightarrow$ Adds a mass term to the zero mode without spoiling the clockwork mechanism

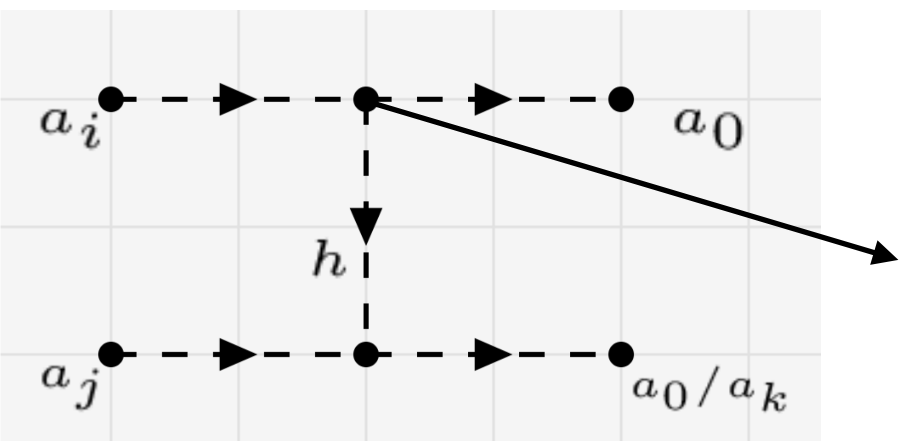
Spurion transformation under $t^2 f^2(U^{q_j\dagger} + h.c)$

FIMP production

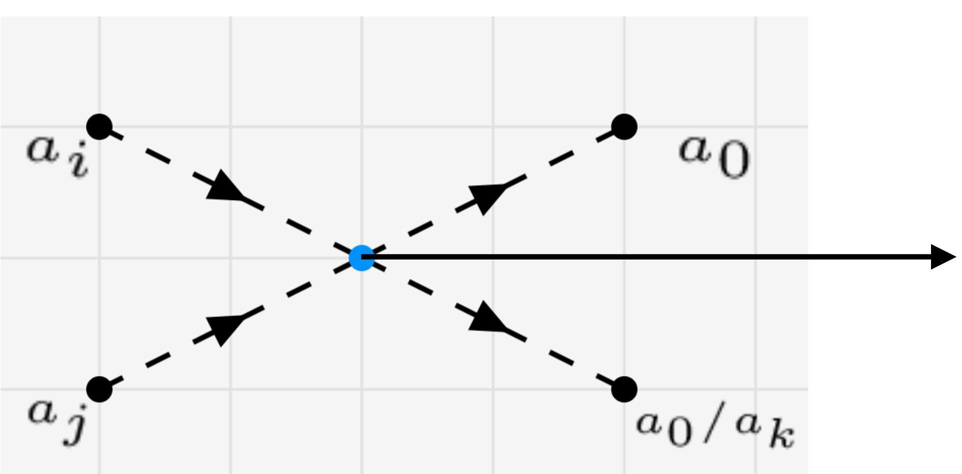


$$\frac{\kappa}{q^n} O_{jn}$$

Dominant process

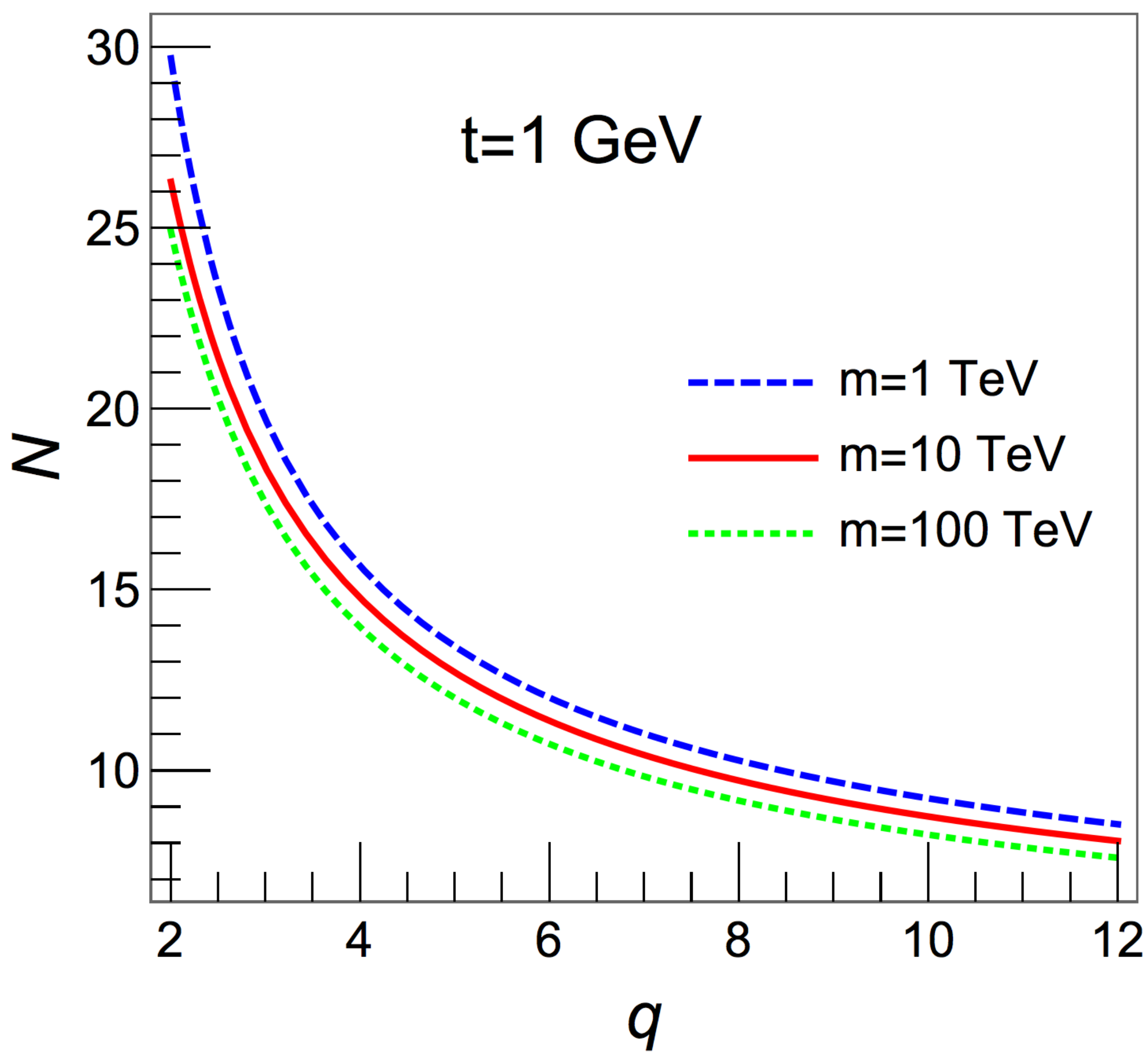


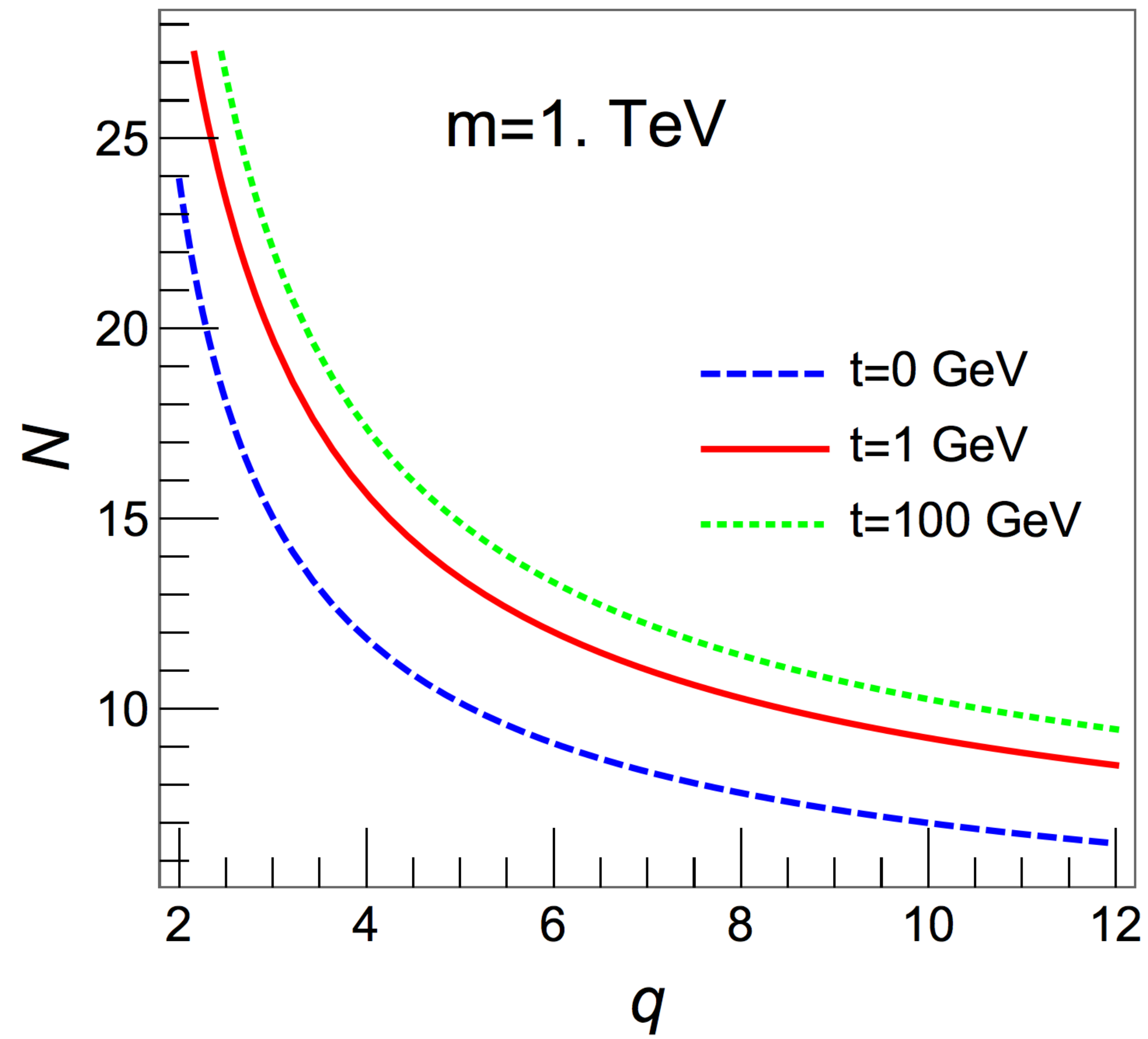
$$\frac{\kappa}{q^n} O_{jn}$$



$$\frac{\kappa}{q^n} O_{jn}$$

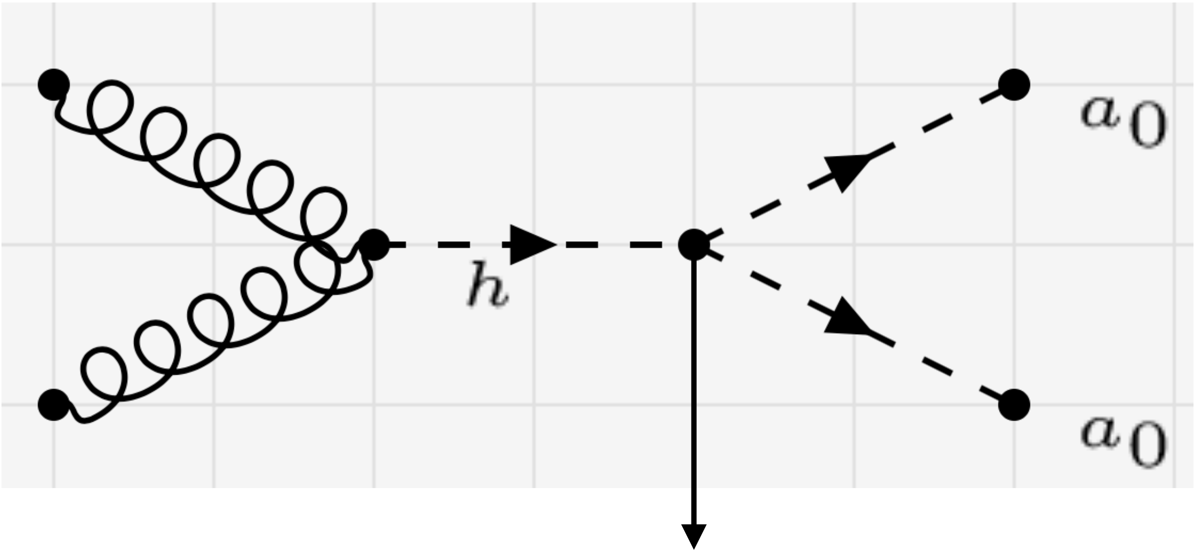
Clockworking a scalar FIMP

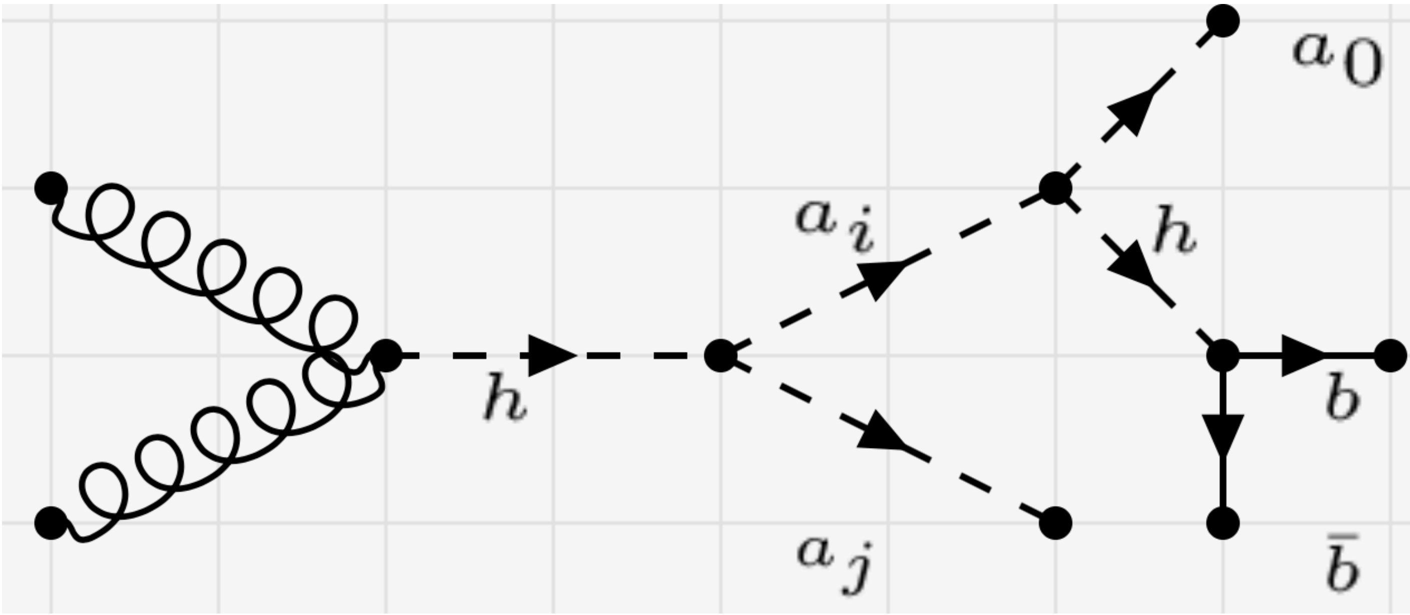




1807.06642 : A . Goudelis, K. Mohan and D.S

Phenomenology of the scalar FIMP



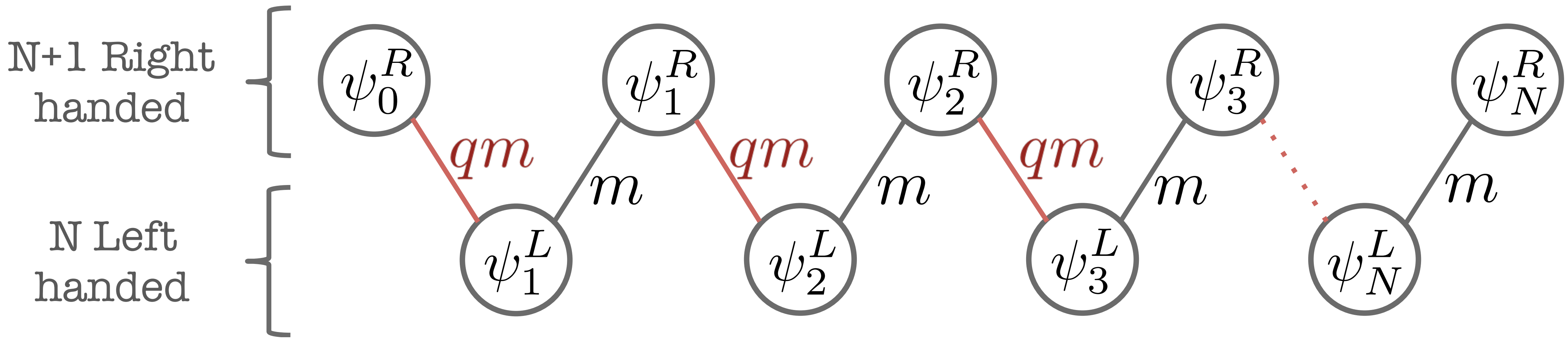


Tiny Invisible Width

Produce the higher gears with Order(1) coupling via off-shell Higgs

Displaced b-jets

A fermionic clockwork



$$
\begin{aligned}
\mathcal{L}_{FCW} &= \mathcal{L}_{kin} - m\sum_{i=0}^{N-1}(\bar{\psi}_{L,j}\psi_{R,j} - q\bar{\psi}_{L,j}\psi_{R,j+1} + h.c) - \frac{M_L}{2}\sum_{i=0}^{N-1}(\bar{\psi}^c_{L,i}\psi_{L,i}) - \frac{M_R}{2}\sum_{i=0}^{N}(\bar{\psi}^c_{R,i}\psi_{R,i}) \\
&= \mathcal{L}_{kin} - \frac{1}{2}(\bar{\Psi}^c\mathcal{M}\Psi + h.c) \qquad (12)
\end{aligned}
$$

N (N+1) copies of left (right) handed fermions

Majorana Mass terms

A.G, K.M, D.S 1807.06642 for analytic diagonalization

A fermionic FIMP

$$\boxed{\mathcal{L}_{fFIMP} = \mathcal{L}_{fcw} + i\bar{L}\not{D}L + i\bar{R}\not{D}R + M_D(\bar{L}R) + Y\bar{L}\tilde{H}\psi_{R,n} + \text{ h.c}}$$

$$L' = (l_1, l_2),\ R' = (r_1, r_2)$$

$$(SU(3), SU(2))_Y = (1,2)_{-1/2}$$

$$m_\nu = \begin{array}{c} \\ l_1 \\ r_1 \\ \chi_0 \\ \chi_1 \\ \chi_2 \\ \vdots \\ \chi_{2N} \end{array} \begin{array}{c} \begin{array}{cccccccc} l_1 & r_1 & \chi_0 & \chi_1 & \chi_2 & \cdots & \chi_{2n} \end{array} \\ \begin{pmatrix} 0 & M_D & vY_0 & vY_1 & vY_2 & \cdots & vY_{2N} \\ M_D & 0 & 0 & 0 & 0 & \cdots & 0 \\ vY_0 & 0 & M_0 & 0 & 0 & \cdots & 0 \\ vY_1 & 0 & 0 & M_1 & 0 & \cdots & 0 \\ vY_2 & 0 & 0 & 0 & M_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ vY_{2N} & 0 & 0 & 0 & 0 & \cdots & M_{2N} \end{pmatrix} \end{array}$$

$$Y_0 = Y(u_R)_N = \frac{1}{q^N}\sqrt{\frac{q^2-1}{q^2-q^{-2N}}}$$

$$Y_j = Y_{(N+j)} = \frac{Y}{\sqrt{2}}(U_R)_{Nj} = \sqrt{\frac{1}{(N+1)\lambda_j}}\left[q\sin\frac{Nj\pi}{N+1}\right], \quad j = 1, \ldots, N$$

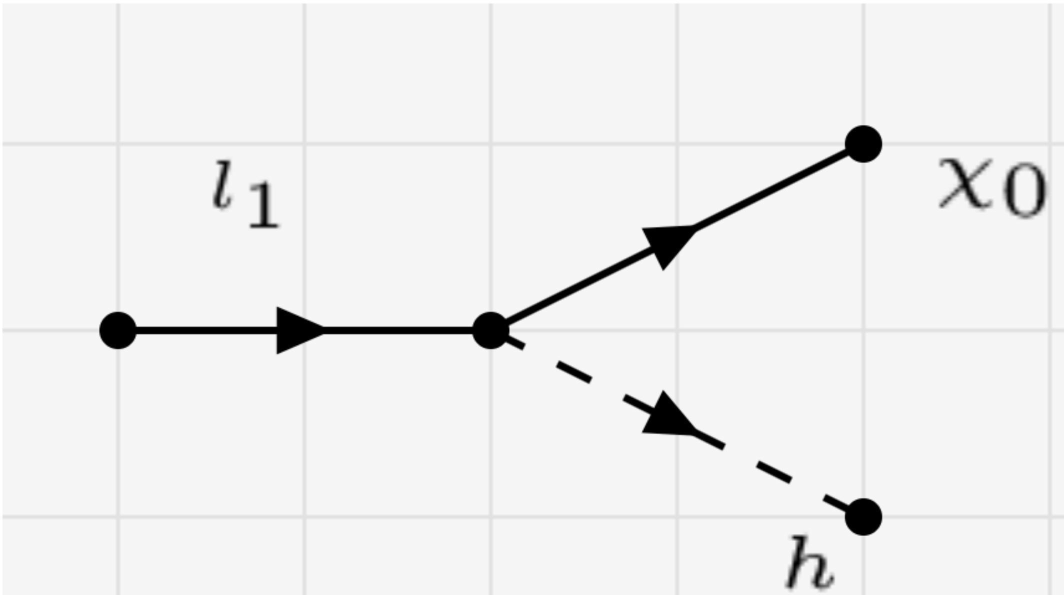
Work in the limit of $v/m \to 0$ $\quad \text{set } m = 100 \text{ TeV}$

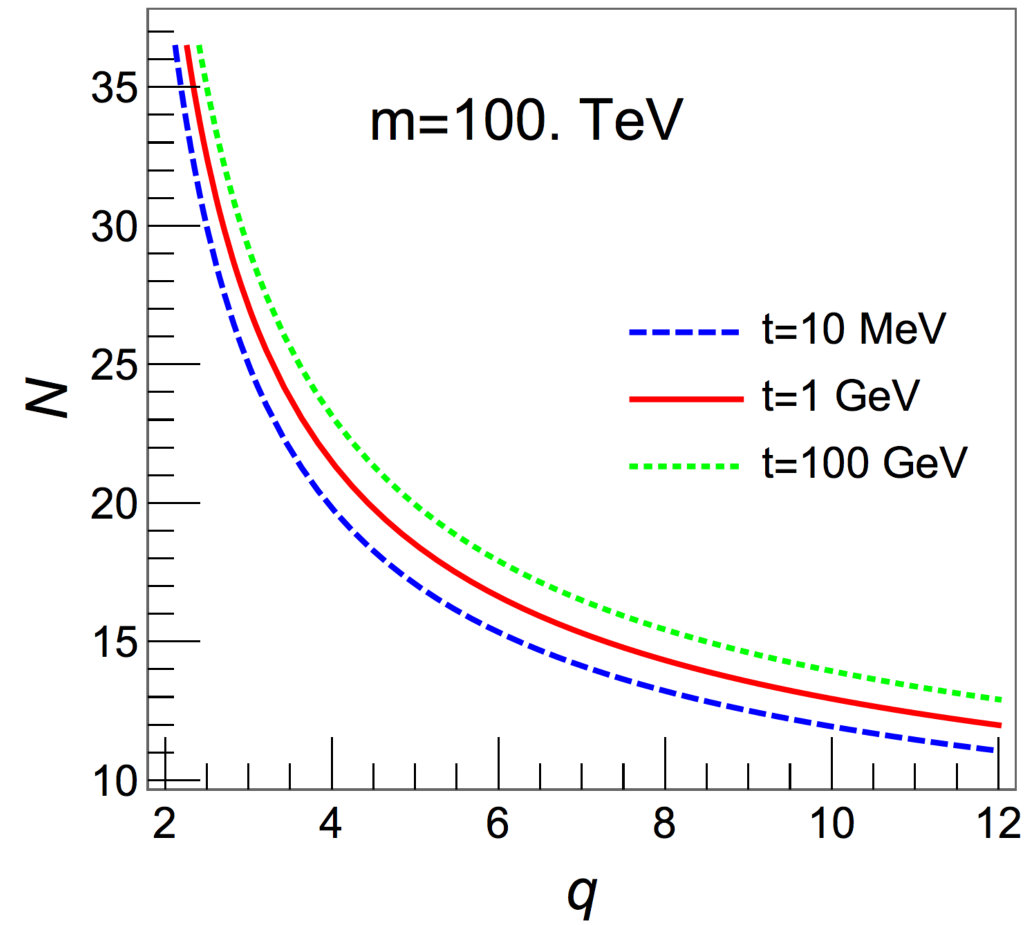
All off-diagonal entries except the Dirac mass vanish

Identify the zero mode fermion of the clockwork as the FIMP candidate

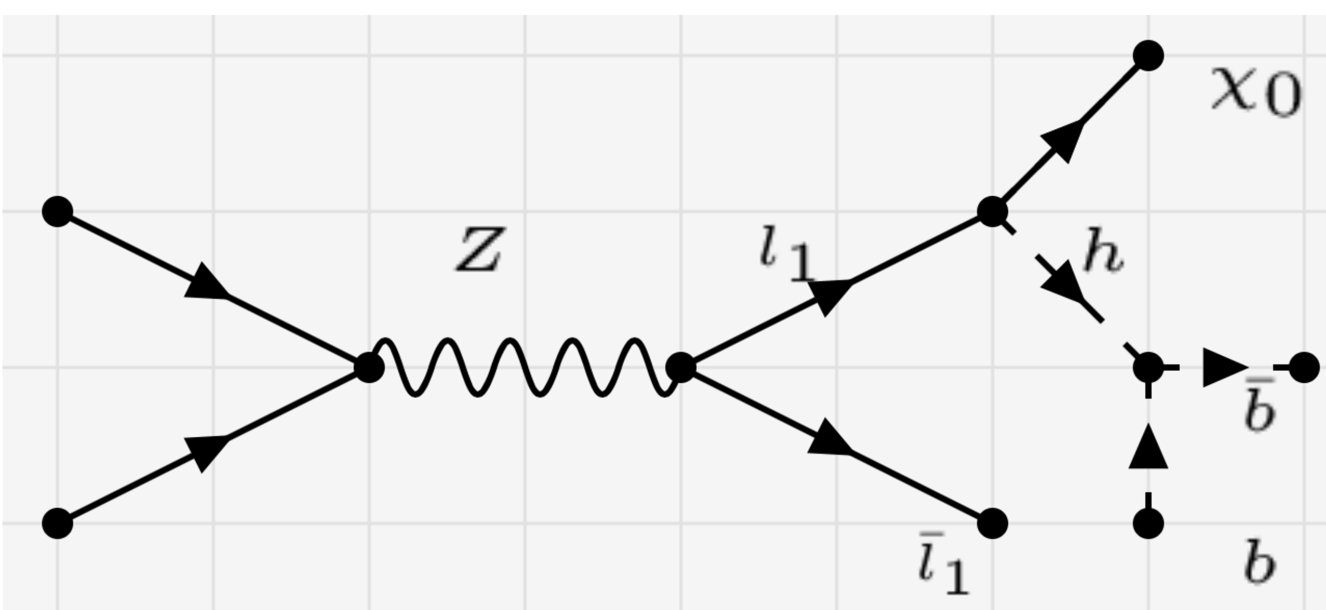
A fermionic clockwork

FIMP production





LHC pheno



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

Conclusion

- **Freeze -in dark matter scenarios are alternatives to WIMP freeze outs**
- **FIMPs are out of thermal equilibrium and require very small couplings**
- **A “natural” way to generate exponentially small couplings are Clockwork mechanisms**
- **Scalar and Fermionic clockwork freeze-in models are constructed and shown to be a viable set up.**
- **Such set ups also have long lived particles as a viable signature**

Conclusion

- Freeze -in dark matter scenarios are alternatives to WIMP freeze outs
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- A “natural” way to generate exponentially small couplings are Clockwork mechanisms
- Scalar and Fermionic clockwork freeze-in models are constructed and shown to be a viable set up.
- Such set ups also have long lived particles as a viable signature