Gauged U(1) clockwork

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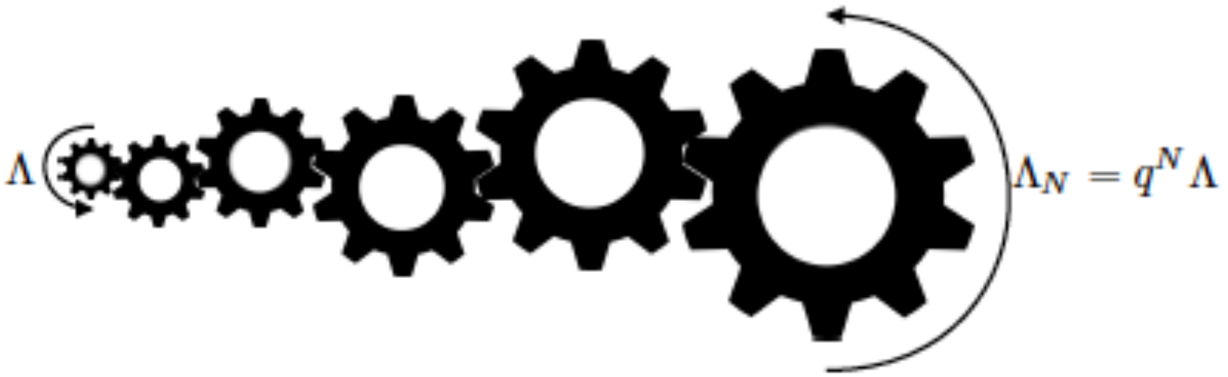
Outline

- Introduction & motivation
- Gauged U(1) clockwork
- Examples: DM mediator, B-meson decays
- Conclusions

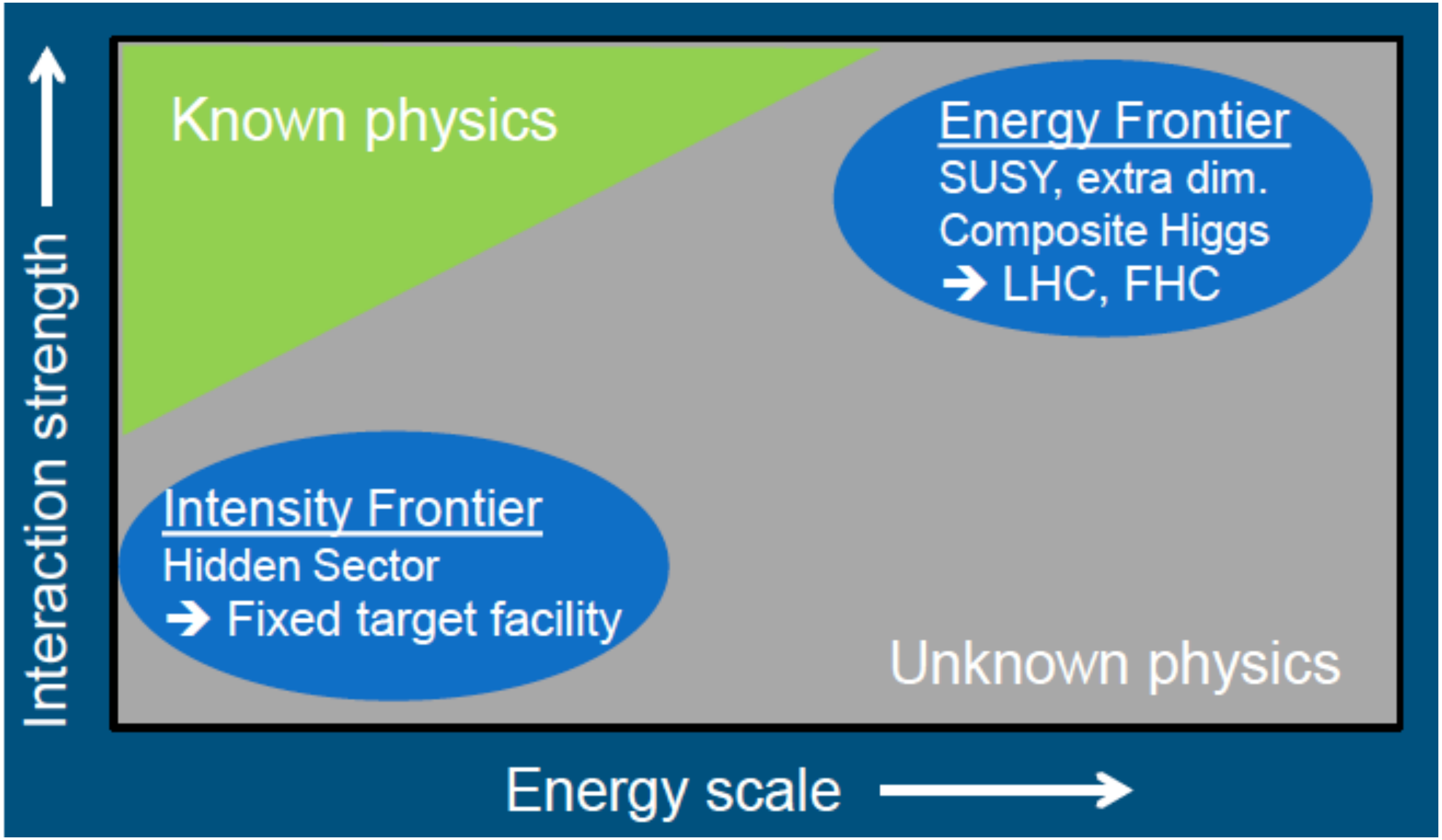


Taken from Giudice, McCollough

Intensity vs energy frontiers

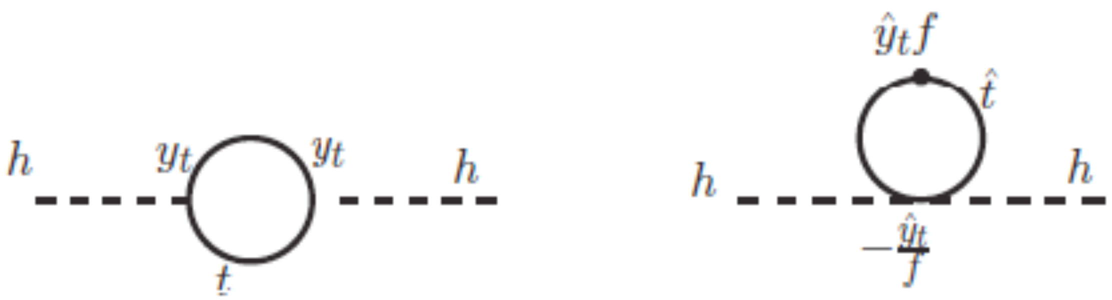
- Complementary direct probes for new physics with light particles or heavy particles.

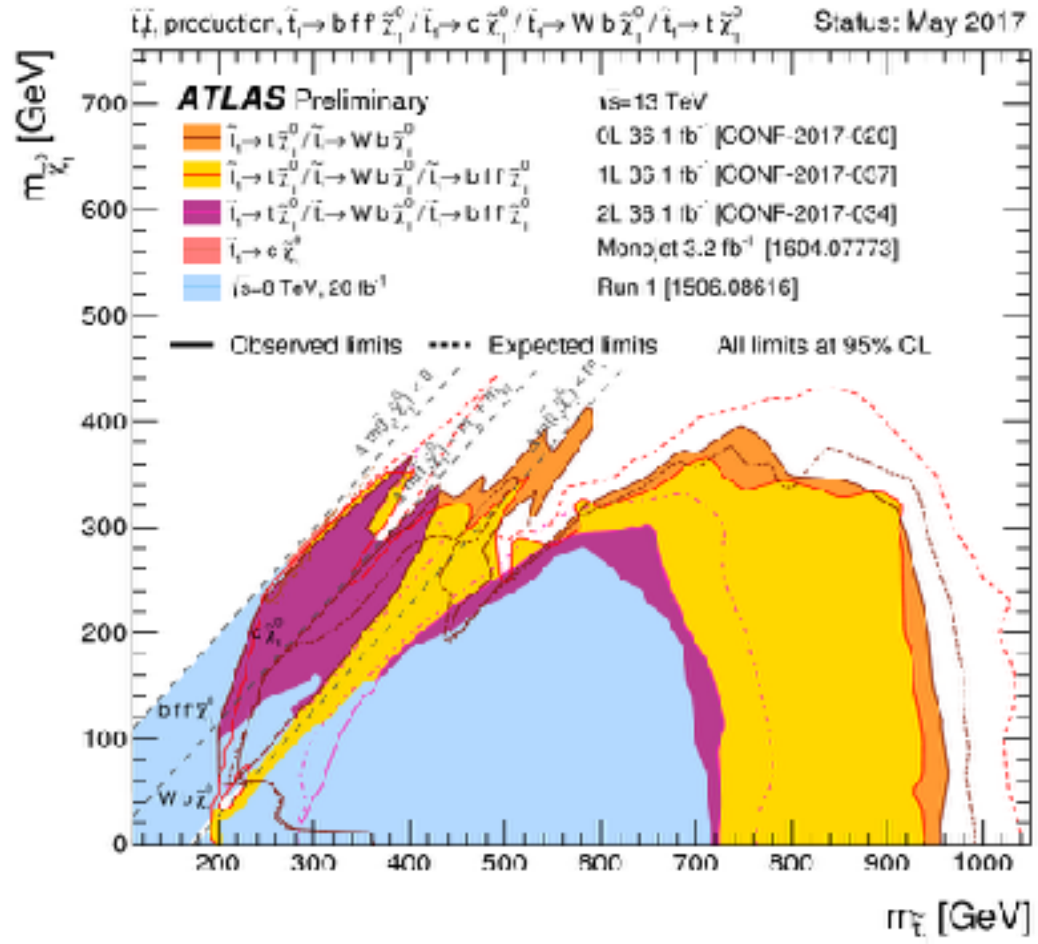
[SHiP physics case, 1504.04855]



New physics at weak scales

- Two hierarchically different masses:
  Planck scale vs weak scale in SM + GR.
- New symmetry protects Higgs mass against large quantum corrections and predicts new particles with sizable couplings at weak scale.





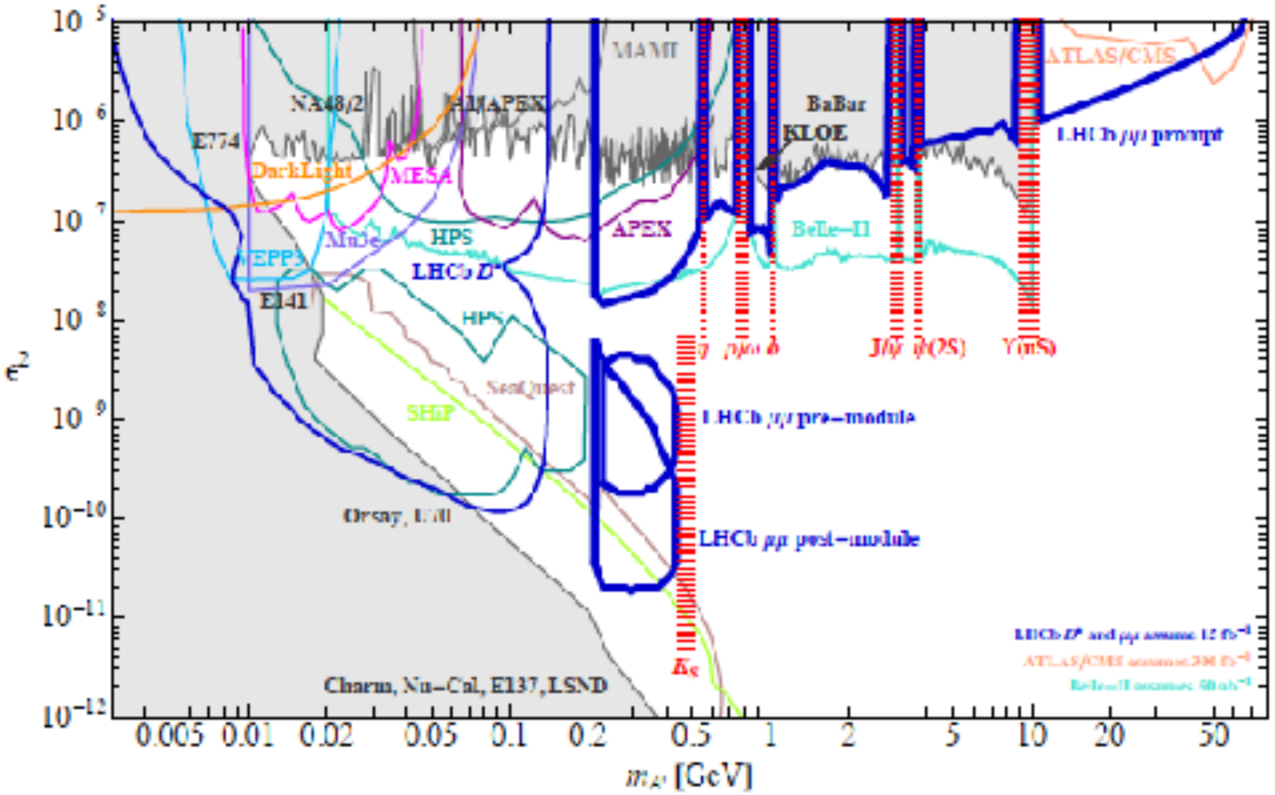
- No direct hint yet for new physics at weak scales.

New physics below weak scale

- QCD axion, sterile neutrinos, new long-range force, self-interacting dark matter, etc.
- New particles could be produced at low-energy experiments, such as ADMX, Belle-II, SHiP, etc.
- How new physics couples so weakly to the SM?
- Portal models: Higgs, Z', neutrino, axion, etc

$$|H|^2\mathcal{O}_{\rm new}, \qquad F_{\mu\nu}F'^{\mu\nu},$$

$$N\mathcal{O}_{\rm new} \qquad a_{\rm ALP}\,F_{\mu\nu}F^{\mu\nu}, \cdots$$



[Ilten et al, 2016]

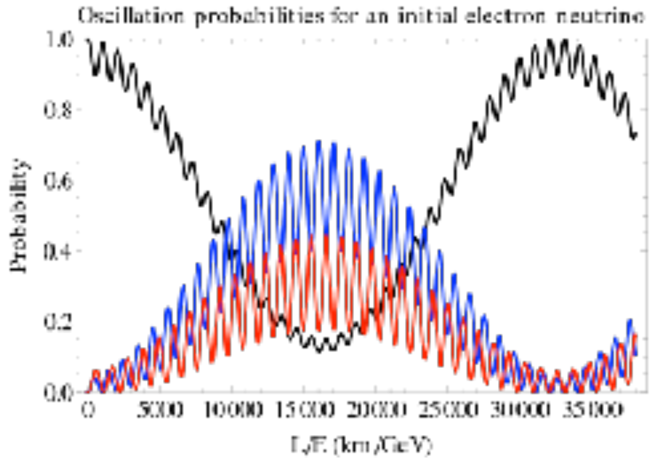
Flavors of the SM

- The quark mixing in the SM well parametrized and no FCNC at tree level due to GIM mechanism.

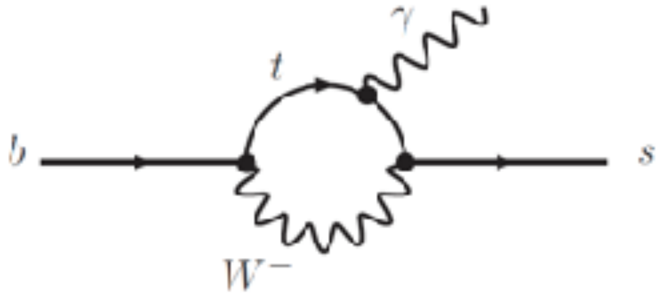
$$\frac{-g}{\sqrt{2}}(u_L, c_L, t_L)\gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

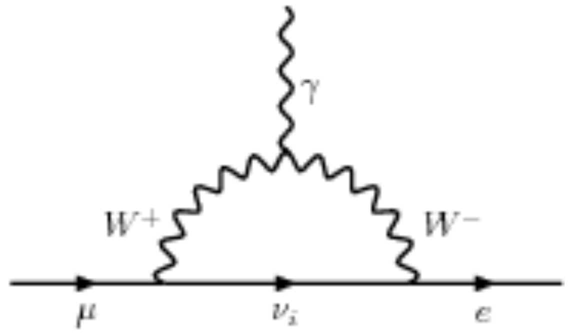
- But, we don't know the origin of neutrino masses and flavor structure.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Flavor violation is a precise probe of new physics at high scales, complementary to direct searches at the LHC



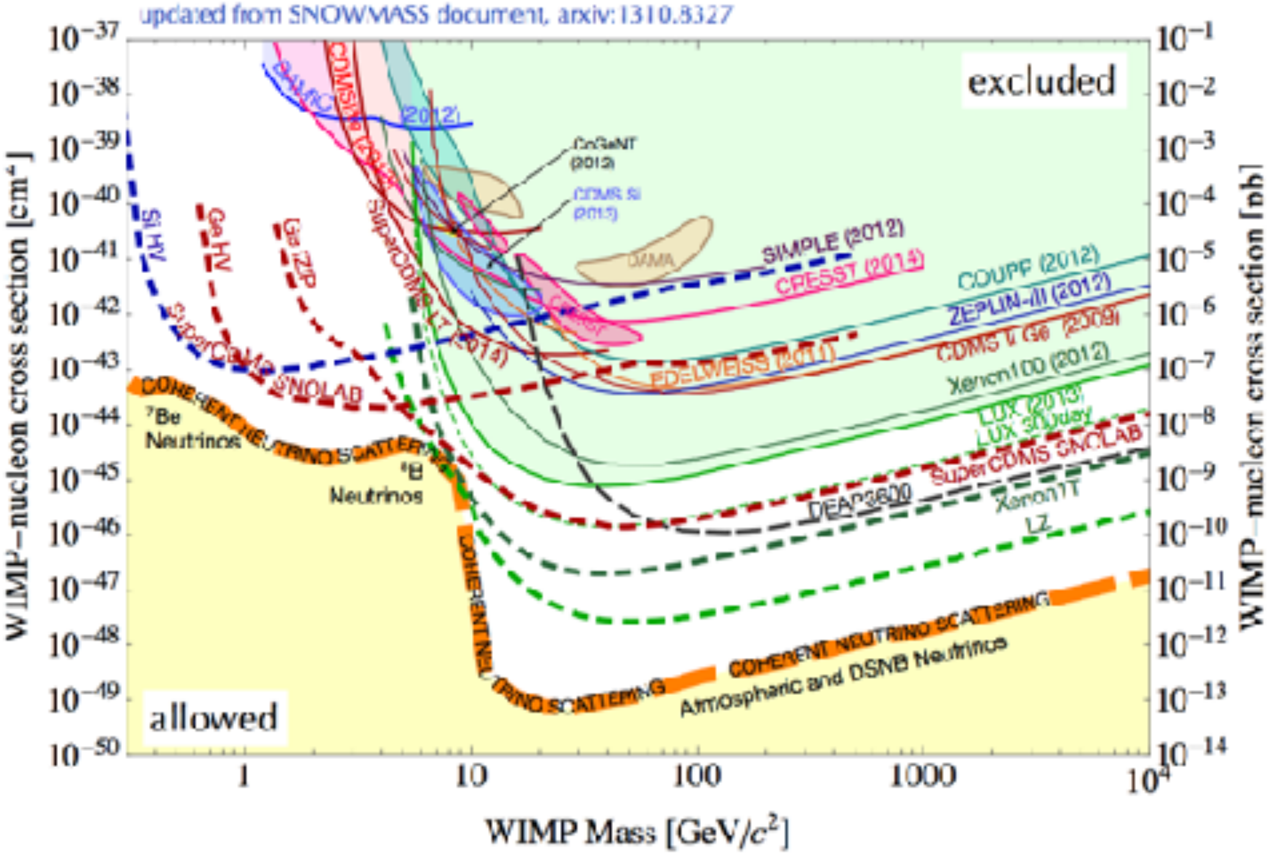


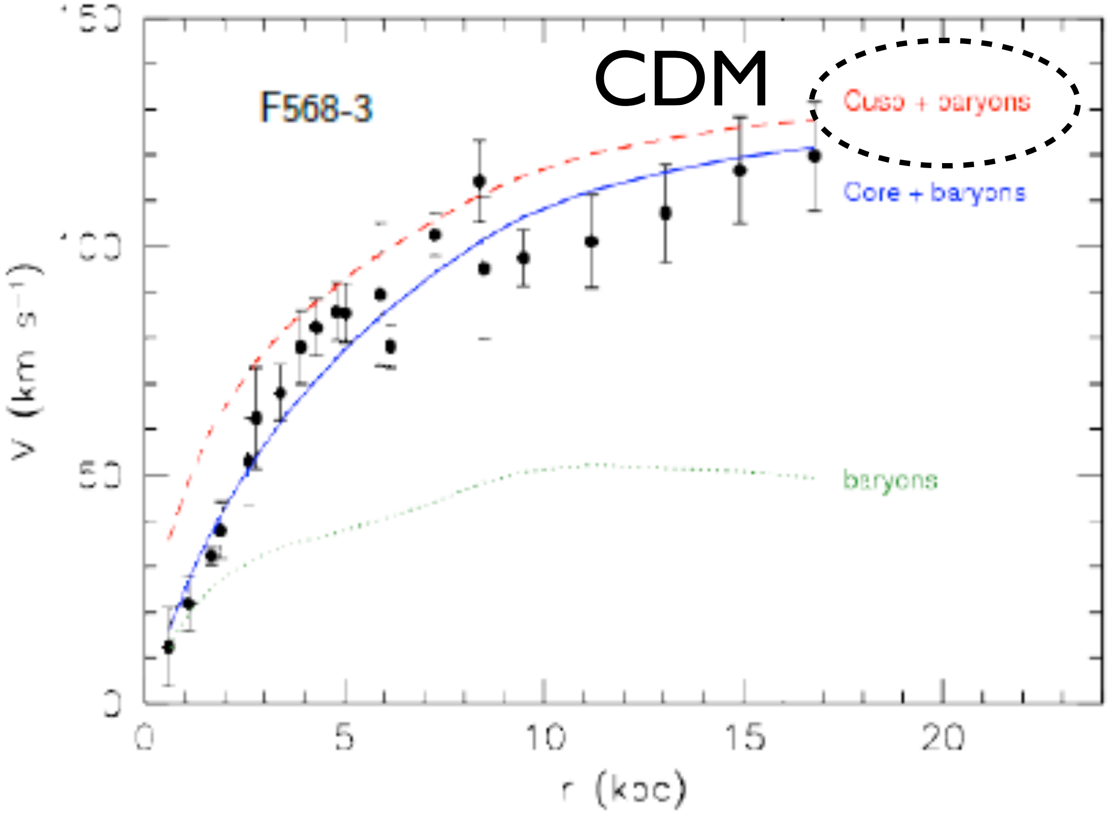
Beyond WIMP DM

- Various evidences for dark matter from galaxy rotation curves, CMB, and gravitational lensing, etc.

- No direct evidence for WIMP DM → light or heavy?

- Simulation with CDM (cusp) overshoots galaxy rotation curves. (small-scale problems) → self-interacting DM?



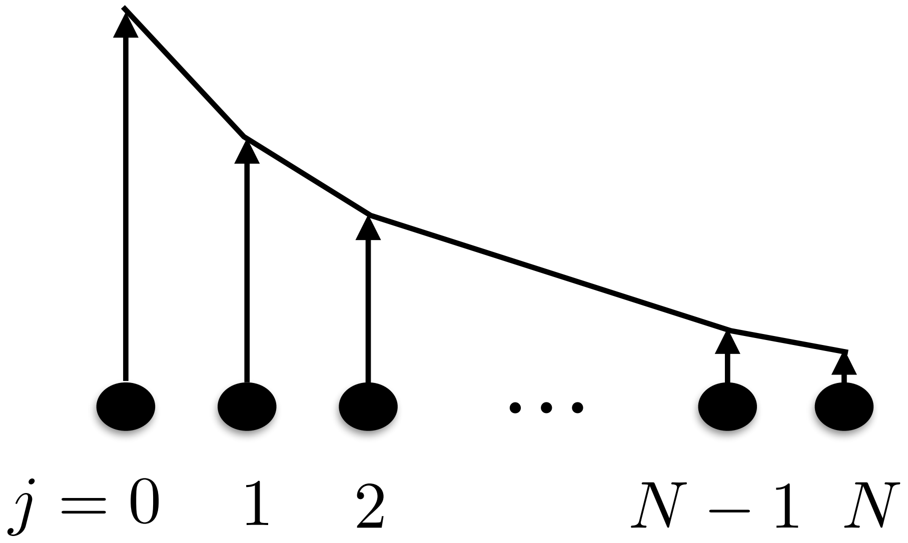


Clockwork mechanism

- Multiple copies of symmetries are broken down to one symmetry by nearest neighbor interactions.

$$\mathcal{L} = \frac{1}{2}\sum_{j=0}^{N} \partial_\mu \phi_j \partial^\mu \phi_j - \frac{m^2}{2}\sum_{j=0}^{N-1} (\phi_j - q\phi_{j+1})^2,$$

$$M_\phi^2 = \ m^2 \begin{pmatrix} 1 & -q & 0 & \cdots & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix} .$$



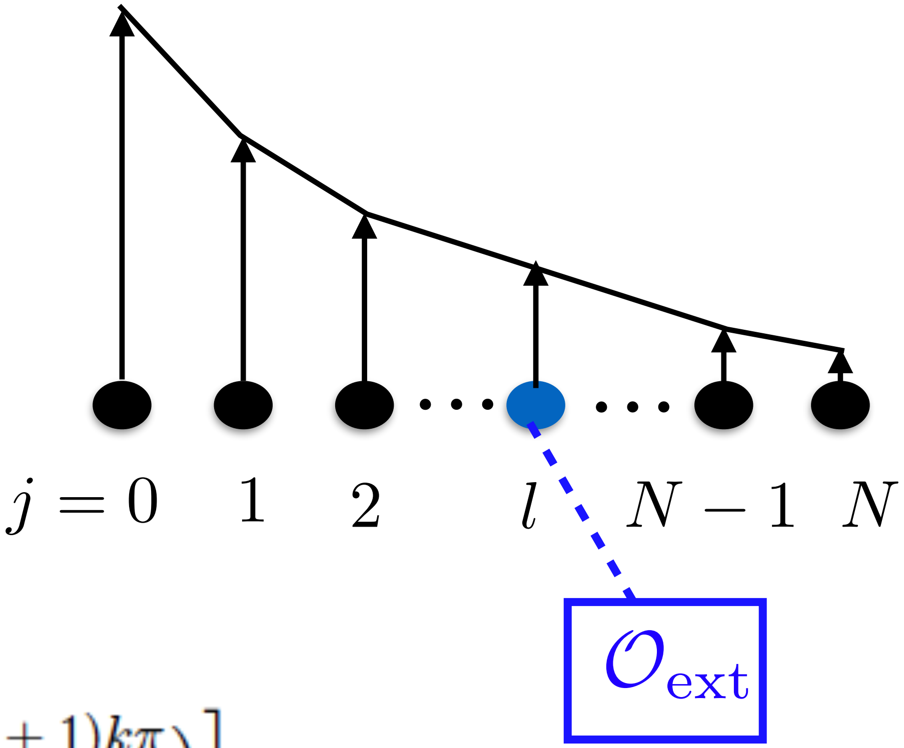
⇨ Zero mode: $\phi_N = \frac{1}{q}\phi_{N-1} = \cdots = \frac{1}{q^N}\phi_0$

$\left\{ \right.$ localized at j=0 for q>1 by $1/q^j \sim e^{-jka}$;

mass protected by remaining symmetry, $\phi_j \to \phi_j + \frac{c}{q_j}$.

Effective couplings

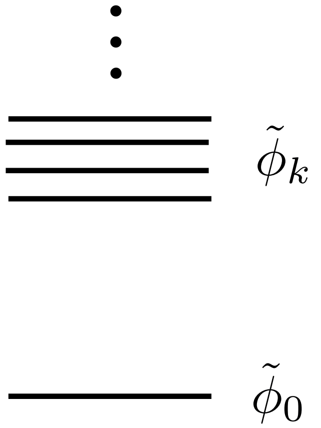
- Effective couplings of massless mode depend on the locations of external fields.



$$\mathcal{L}_{\text{int}} = \phi_l \mathcal{O}_{\text{ext}},$$

$$\phi_l(x) = \underline{\frac{N_0}{q^l}\,\tilde{\phi}_0(x)} + \underline{\sum_{k=1}^{N} a_{lk}\tilde{\phi}_k(x)}.$$

"zero mode" "massive"



$$\begin{cases} a_{jk} = N_k\left[q\sin\left(\frac{jk\pi}{N+1}\right) - \sin\left(\frac{(j+1)k\pi}{N+1}\right)\right], \\ M_k^2 = m^2\left(1+q^2-2q\cos\frac{k\pi}{N+1}\right) \end{cases}$$

[Kaplan, Rattazzi, 2015]

e.g. QCD axion: $\mathcal{O}_{\text{ext}} = \frac{1}{f_{\text{QCD}}} G_{\mu\nu}\tilde{G}^{\mu\nu}\ :\quad l = N$

⇒ $\mathcal{L}_{\text{eff}} = \frac{1}{f_{\text{eff}}}\tilde{\phi}_0 G_{\mu\nu}\tilde{G}^{\mu\nu},\quad f_{\text{eff}} = q^N f_{\text{QCD}} \gg f_{\text{QCD}}.$

Large effective decay constant

UV-complete scalar CW

- Continuum limit: $\phi(x,y) = \phi_j(x),\ y = ja\,,(y = \pi R \equiv Na)$

$$\mathcal{L} = \frac{1}{2}\sum_{j=0}^{N} \partial_\mu \phi_j \partial^\mu \phi_j - \frac{m^2}{2}\sum_{j=0}^{N-1} (\phi_j - q\phi_{j+1})^2,$$

$$\Longrightarrow \qquad \mathcal{L} = \int_0^{\pi R} dy \left[\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}(\partial_y \phi + k\phi)^2\right]$$

$a \to 0,\ m \to \infty;$

$m\,a \to 1, q \to 1.$

$a:$ lattice distance

$$+\int dy\, \delta(y - \pi R)\, \phi\, \mathcal{O}_{\rm ext}$$

[Giudice, McCollough, 2016]

- 5d dilaton background: $\chi = e^{ky}\phi\ , \quad S = -ky$ “dilaton"

$$\mathcal{L}_{5d} = \int_0^{\pi R} dy\, e^{S}\left[\frac{1}{2}\partial_M \chi \partial^M \chi\right] + \int dy\, \delta(y - \pi R) e^{\frac{1}{2}S}\, \chi\, \mathcal{O}_{\rm ext}\,,$$

$$\Longrightarrow \qquad \phi_0 \sim \boxed{e^{-ky}}, \qquad \phi_n \sim \cos\frac{ny}{R} - \frac{kR}{n}\sin\frac{ny}{R}, \qquad m_n^2 = \boxed{k^2 + \frac{n^2}{R^2}}$$

KK reduction “zero mode” “massive” KK mass

Applications & generalization

- Axion-like scalars

[Nilles, Kim, Peloso, 2014;
Choi, Im, 2015; Kaplan, Rattazzi, 2015]

$$V = \Lambda_1^4 \sum_{j=0}^{N-1} \cos\left(\frac{\phi_j}{f} - q\,\frac{\phi_{j+1}}{f}\right) + \Lambda_2^4 \cos\left(\frac{\phi_N}{f} + \delta\right), \quad \Lambda_1 \gg \Lambda_2$$

⇨ $$V_{\rm eff} = \Lambda_2^4 \cos\left(\frac{\tilde{\phi}_0}{f_{\rm eff}} + \delta\right), \quad f_{\rm eff} = q^N f.$$

See also K. Choi's talk!

- Fields with other spins

[Giudice, McCollough, 2016]

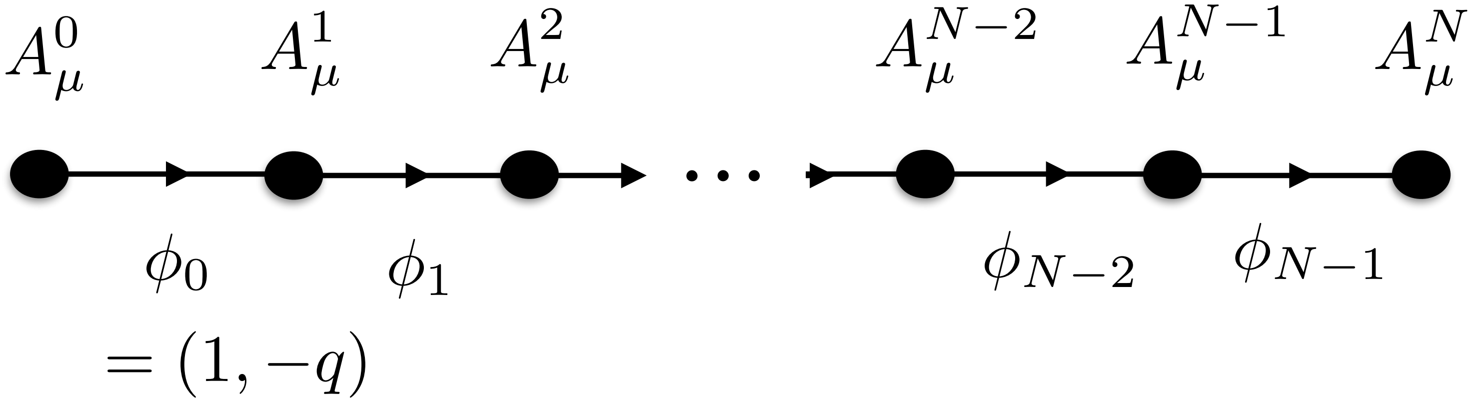
Fermion clockwork	e.g. neutrino masses
Tensor clockwork	spin-2 graviton
Vector clockwork	⇨ topic of this talk!

Gauged U(1) clockwork

- N+1 local U(1)'s broken down to U(1) by link fields:

$$U(1)_0 \times U(1)_1 \times \cdots \times U(1)_N \to U(1)$$

[HML, 2017]



$$\langle \phi_i \rangle = \frac{1}{\sqrt{2}} f \quad \Longrightarrow \quad \mathcal{L}_{\rm gauge} = -\sum_{j=0}^{N-1} \frac{1}{2} g^2 f^2 \left(A^j_\mu - q A^{j+1}_\mu \right)^2 .$$

- Similar localization of massless mode at j=0 for q>1.
- Each U(1) gauge boson is expanded as

$$A^j_\mu(x) = \frac{N_0}{q^j}\, \tilde{A}^0_\mu(x) + \sum_{k=1}^{N} a_{jk} \tilde{A}^j_\mu(x).$$

Couplings to external fields

- Fermion interactions

$$\mathcal{L}_{\text{fermion}} = i\bar{\psi}\gamma^{\mu}\Big(\partial_{\mu} + ig(v_{\psi} + a_{\psi}\gamma^{5})A^{l}_{\mu}(x)\Big)\psi(x)$$

⇨ $$\mathcal{L}_{\text{f,int}} = -g\bar{\psi}(x)\gamma^{\mu}(v_{\psi} + a_{\psi}\gamma^{5})\psi(x)\left(\underline{\frac{N_0}{q^l}\tilde{A}^{0}_{\mu}(x)} + \sum_{k=1}^{N} a_{lk}\tilde{A}^{k}_{\mu}(x)\right).$$

“milicharge” effective couplings

- Boson interactions

$$\mathcal{L}_{\text{scalar}} = \left|\partial_{\mu}\phi + igA^{l}_{\mu}(x)\phi\right|^{2} - V(\phi)$$

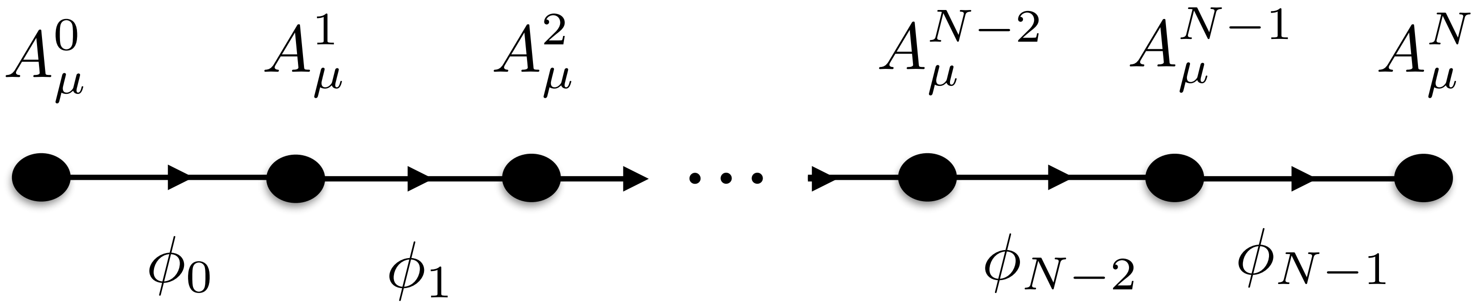
⇨ $$\langle\phi\rangle = \tfrac{1}{\sqrt{2}}v_{\phi} \ll f \ : \quad \underline{M_0^2 \approx \frac{g^2 N_0^2}{q^{2l}}\, v_{\phi}^2}$$

Remaining U(1) gauge boson has a naturally small mass due to extra Higgs field with milicharge.

UV-complete U(1) CW

- 5d kinetic term for Higgs requires new link fields S$_j$.

$(=(1,-q-1,q))$



$$\mathcal{L} = -\sum_{j=0}^{N}\frac{1}{4}F^j_{\mu\nu}F^{j\mu\nu} - \sum_{j=0}^{N-1}\left[(D_\mu\phi_j)^\dagger D^\mu\phi_j + m_0^2\left|\phi_j - \omega^{-1}\,S_j\phi_{j+1}\right|^2 + V(\phi_j)\right]$$

$$\left(V(\phi_j) = -\tilde{m}^2|\phi_j|^2 + \tilde{\lambda}|\phi_j|^4\right)$$

$$\mathcal{L}_{\text{Higgs}} = -\sum_{j=0}^{N-1}\Big(\frac{1}{2}(\partial_\mu h_j)^2 + \frac{1}{2}m_0^2|h_j - h_{j+1}|^2$$
$$+\frac{1}{2}g^2(f+h_j)^2\Big(A^j_\mu - qA^{j+1}_\mu + \frac{1}{gf}\partial_\mu\pi_j\Big)^2 + V(f+h_j)\Big).$$

$$\langle S_j\rangle = \omega \ll f$$

$$\langle\phi_j\rangle = \frac{1}{\sqrt{2}}(f+h_j)e^{i\pi_j/f}$$

- 5d limit is U(1) with dilaton coupling + decoupled Higgs.

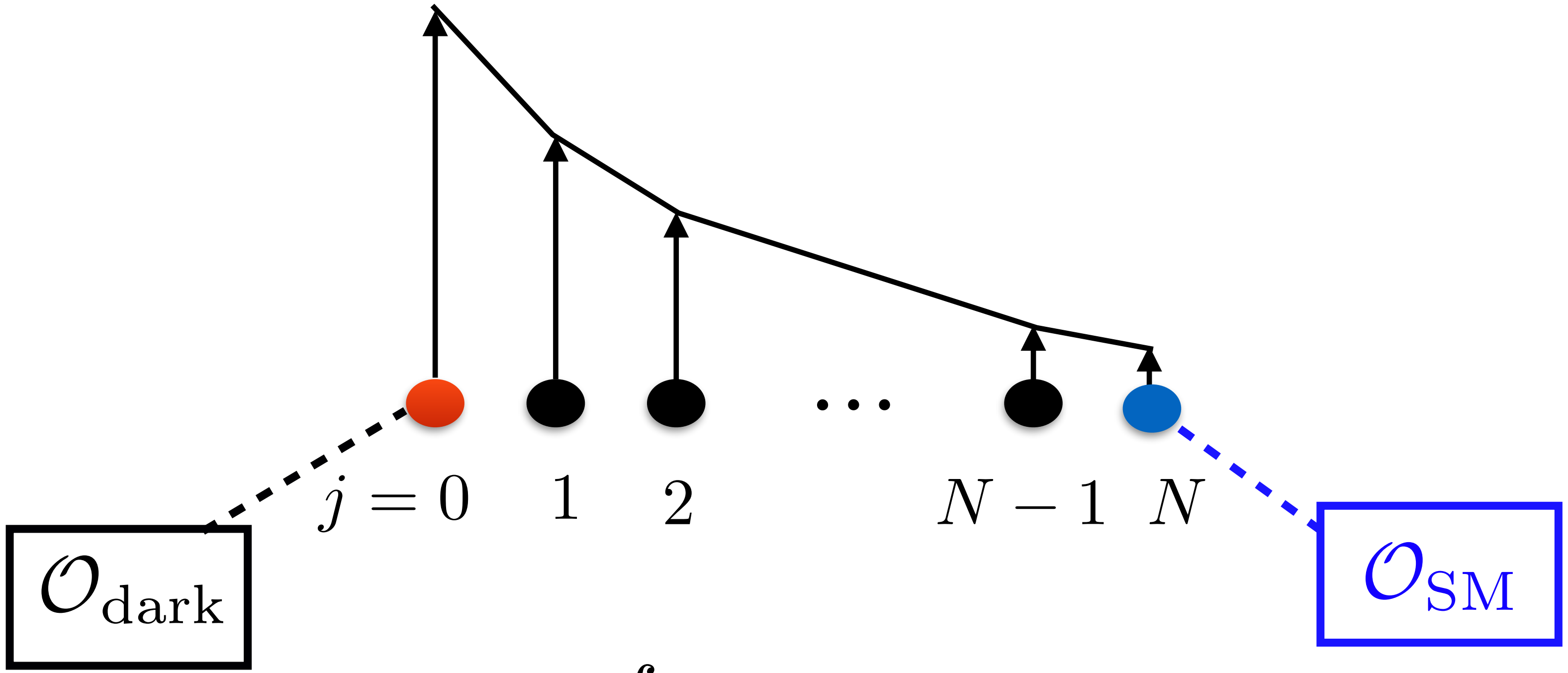
$$a, \tilde{\lambda} \to 0$$
$$f, m_0 \to \infty$$
$$m_0 a = 1 \text{ and and } \tilde{\lambda}f^2 \text{ finite}$$

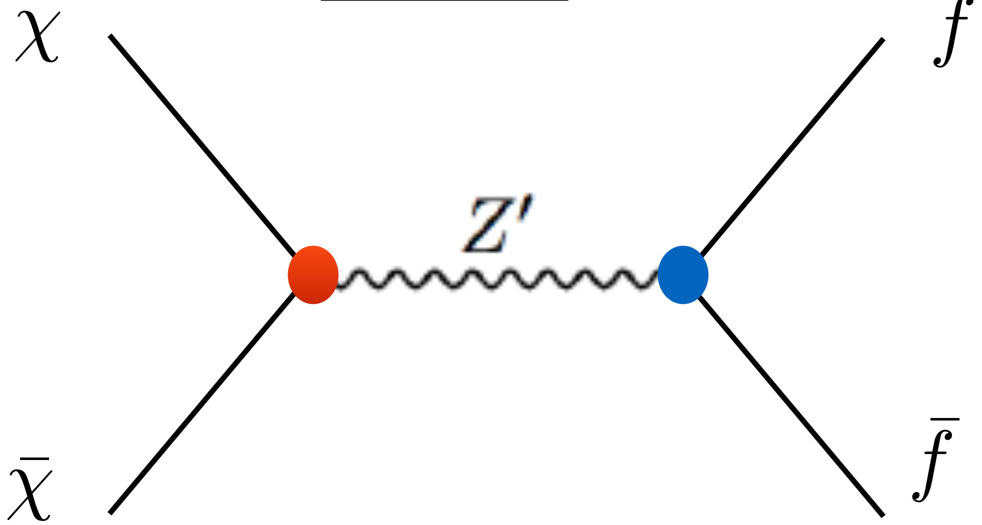
$$\mathcal{L}_{5d} = \int_0^{\pi R} dy\, e^S\left[-\frac{1}{4}F_{MN}F^{MN}\right] - \int_0^{\pi R} dy\left[\frac{1}{2}(\partial_M h)^2 + \frac{1}{2}\tilde{m}_h^2 h^2\right]$$

U(1)' as dark matter mediator

- Clockwork for an anomaly-free U(1) has interactions to dark matter χ at j=0 and SM fermions *f* at j=N.

$$\mathcal{L}_{Z'} = \underline{-q_\chi g_{Z'}\bar{\chi}\gamma^\mu\chi A^0_\mu} - \underline{q_f q_{Z'}\bar{f}\gamma^\mu f A^N_\mu}$$

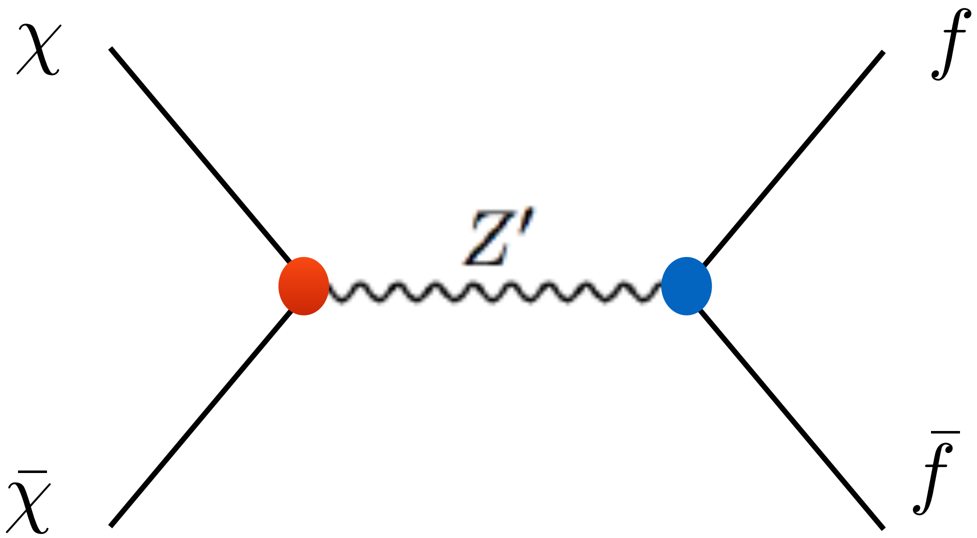




$$\mathcal{M} \sim q_f^2 q_\chi^2 g_{Z'}^4 \left[\frac{N_0^2/q^N}{4m_\chi^2 - M_0^2 + i\Gamma_0 M_0} + \sum_{k=1}^{N} \frac{a_{0k}a_{Nk}}{4m_\chi^2 - M_k^2 + i\Gamma_k M_k}\right]$$

U(1)' as dark matter mediator

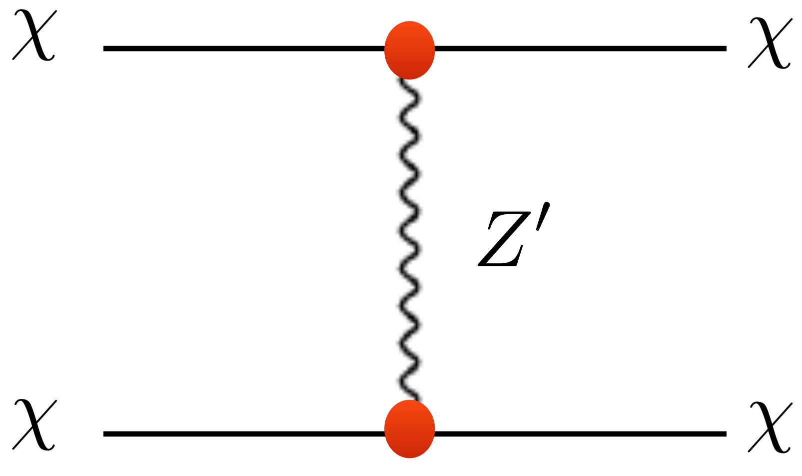
DM annihilation



$$\langle\sigma v\rangle_{\chi\bar{\chi}\to f\bar{f}} = \frac{q_f^2 q_\chi^2 g_{Z'}^4}{2\pi}(m_f^2+2m_\chi^2)\sqrt{1-\frac{m_f^2}{m_\chi^2}} \times \left|\frac{\boxed{e^{-2k\pi R}}}{M_0^2}+\frac{F_1(k\pi R)}{k^2}\right|^2$$

"suppressed"

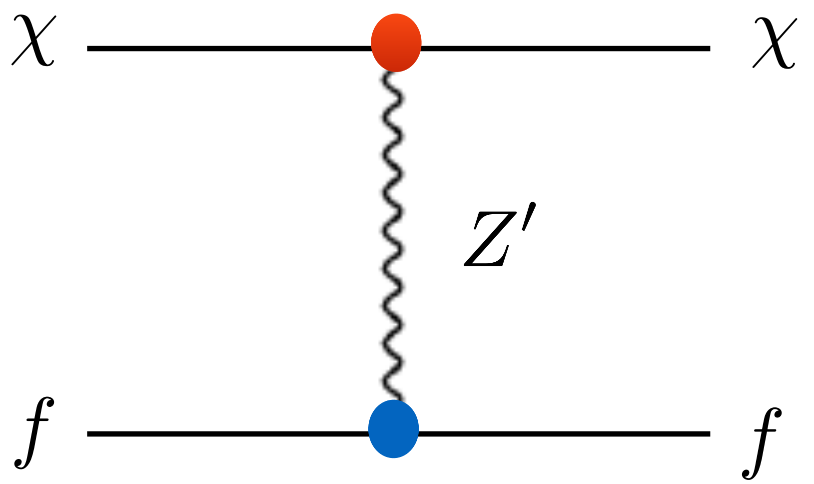
DM self-scattering



$$\sigma_{\chi\chi\to\chi\chi} = \frac{q_\chi^4 g_{Z'}^4 m_\chi^2}{4\pi}\left|\frac{1}{M_0^2}+\frac{F_2(k\pi R)}{k^2}\right|^2$$

large self-scattering

DM-nucleon scattering



$$\sigma_{\chi N} = \frac{\mu^2}{\pi A^2}\Big(Zf_p+(A-Z)f_n\Big)^2$$

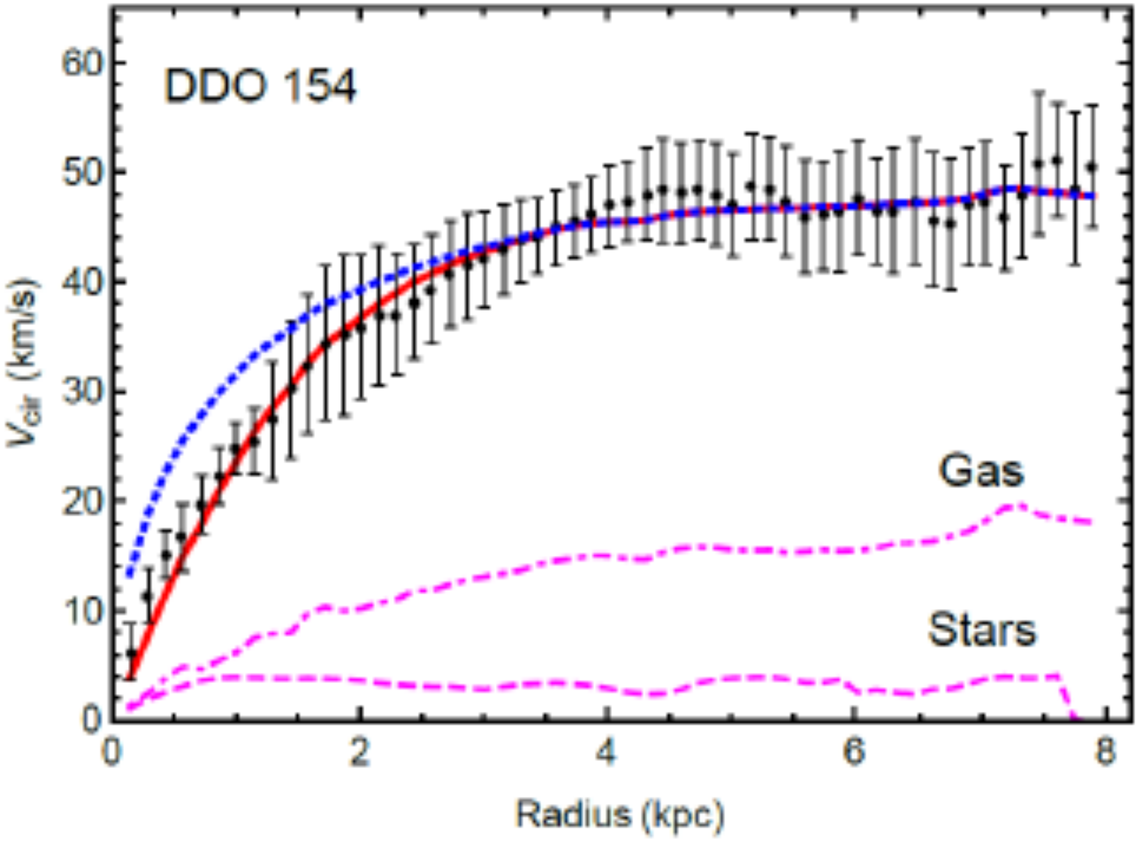
$$f_{p,n} = c_{p,n}q_\chi g_{Z'}^2\left|\frac{\boxed{e^{-2k\pi R}}}{M_0^2}+\frac{F_1(k\pi R)}{k^2}\right|$$

"suppressed"

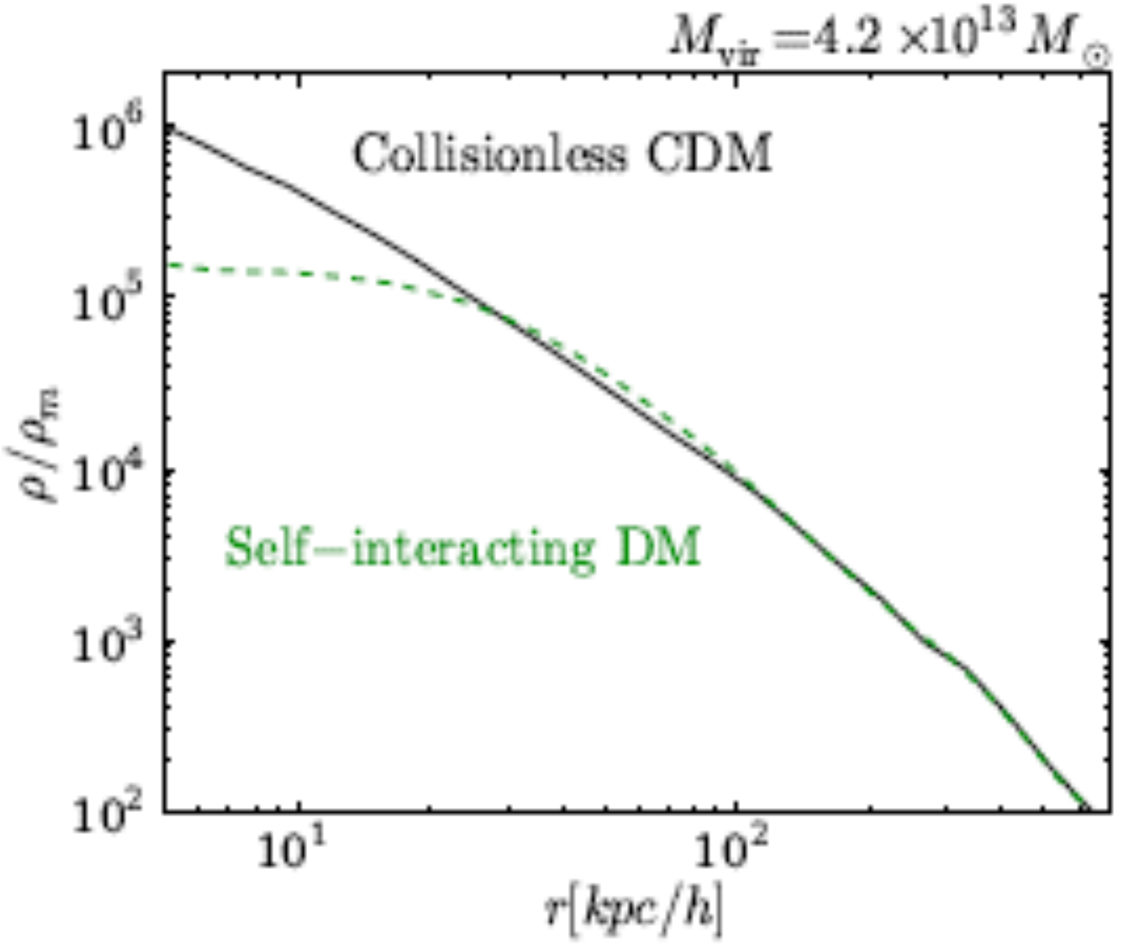
$$F_1(x) = \frac{\sinh x - x\cosh x}{4\sinh^2 x}, \qquad F_2(x) = \frac{\sinh x\cosh x - x}{4\sinh^2 x}.$$

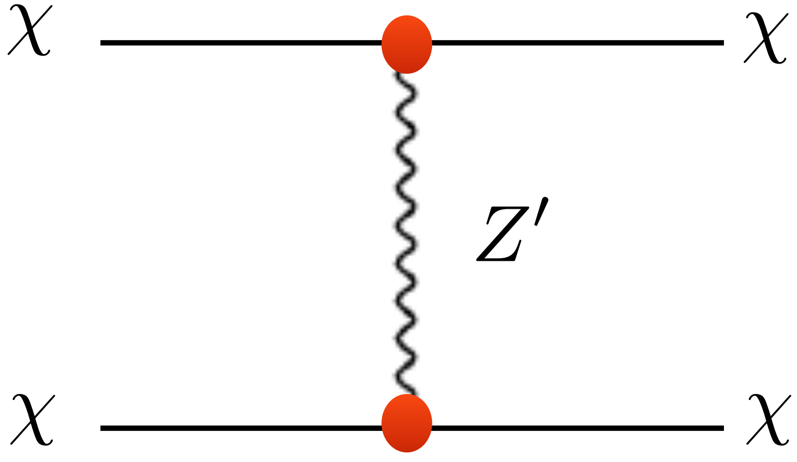
$$\ll 1, \quad x \gg 1 \qquad\qquad \approx \frac{1}{4}, \quad x \gg 1$$

Self-interacting dark matter



[Tulin, Yu, 2017]





self-scattering

- DM self-interactions can solve small-scale problems at galaxies.

$$\sigma_{\text{self}}/m_{\text{DM}} = 0.1 - 10\,\text{cm}^2/\text{g}$$

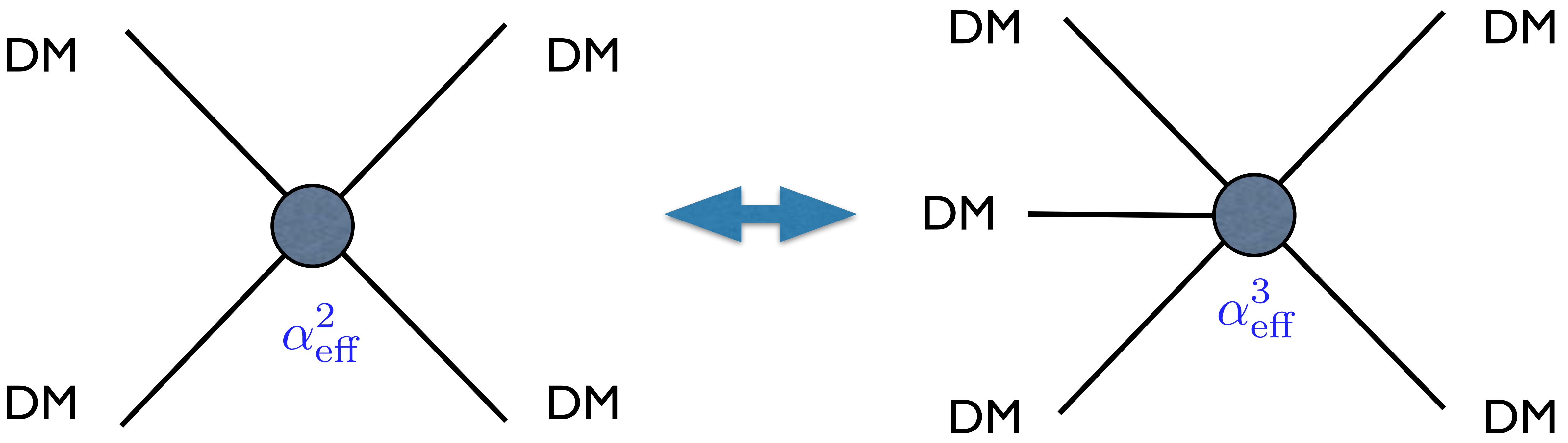
→ sub-GeV dark matter or Sommerfeld effects

SIMP mechanism

- Self-scattering vs 3→2 annihilation

[Carlson,Machacek, Hall (1992);
Hochberg et al(2014);
S-M Choi, HML (2015)]

Number-changing DM self-interactions



$$\sigma_{\rm self} = \frac{\alpha_{\rm eff}^2}{m_{\rm DM}^2} = 0.1\,{\rm b}\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)$$

$$\langle \sigma_{\rm eff} v\rangle = n_{\rm DM}\langle \sigma v^2\rangle$$
$$= R\,\sigma_{\rm self} = 10^{-12}\,{\rm b}$$

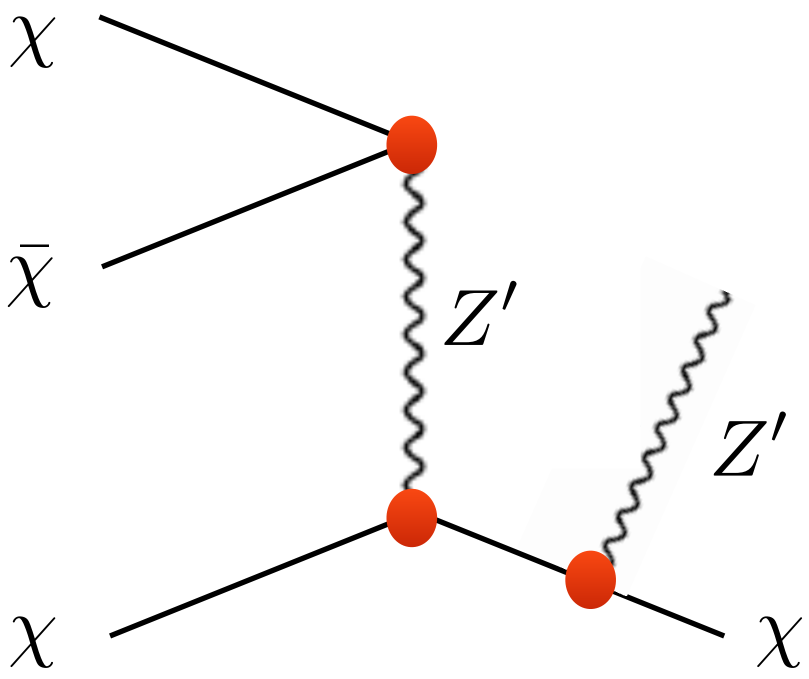
$$R = \frac{g_{\rm DM}\alpha_{\rm eff}}{(2\pi)^{3/2}}\,x_f^{-3/2}\,e^{-x_f}$$

Boltzmann-suppressed
small annihilation

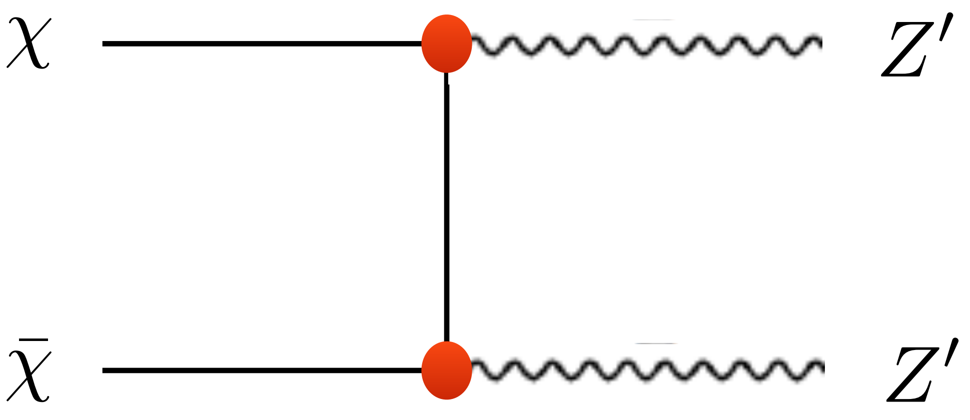
Relic density: $\alpha_{\rm eff} \sim 3\left(\frac{m_{\rm DM}}{100\,{\rm MeV}}\right)$

Strongly Interacting
Massive Particles (SIMP)

U(1)'-mediated dark matter



3→2 process
(cf. J. Cline et al, 1702.07716)

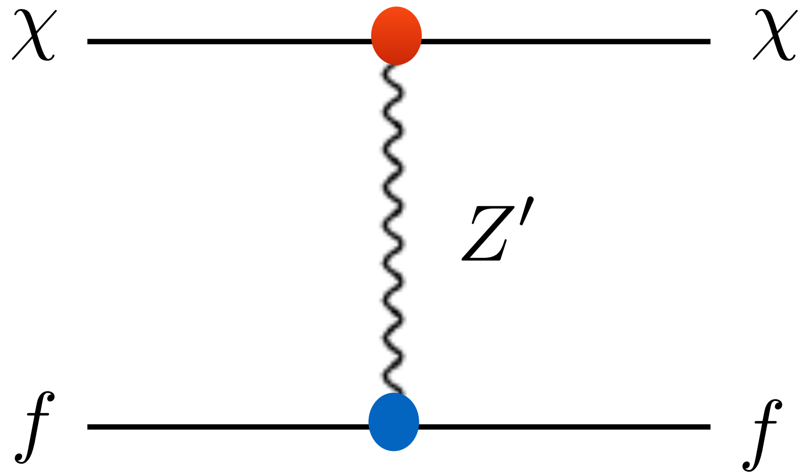


forbidden channels

$m_\chi < m_{Z'}$

⇒ Large self-interaction & thermal freeze-out.

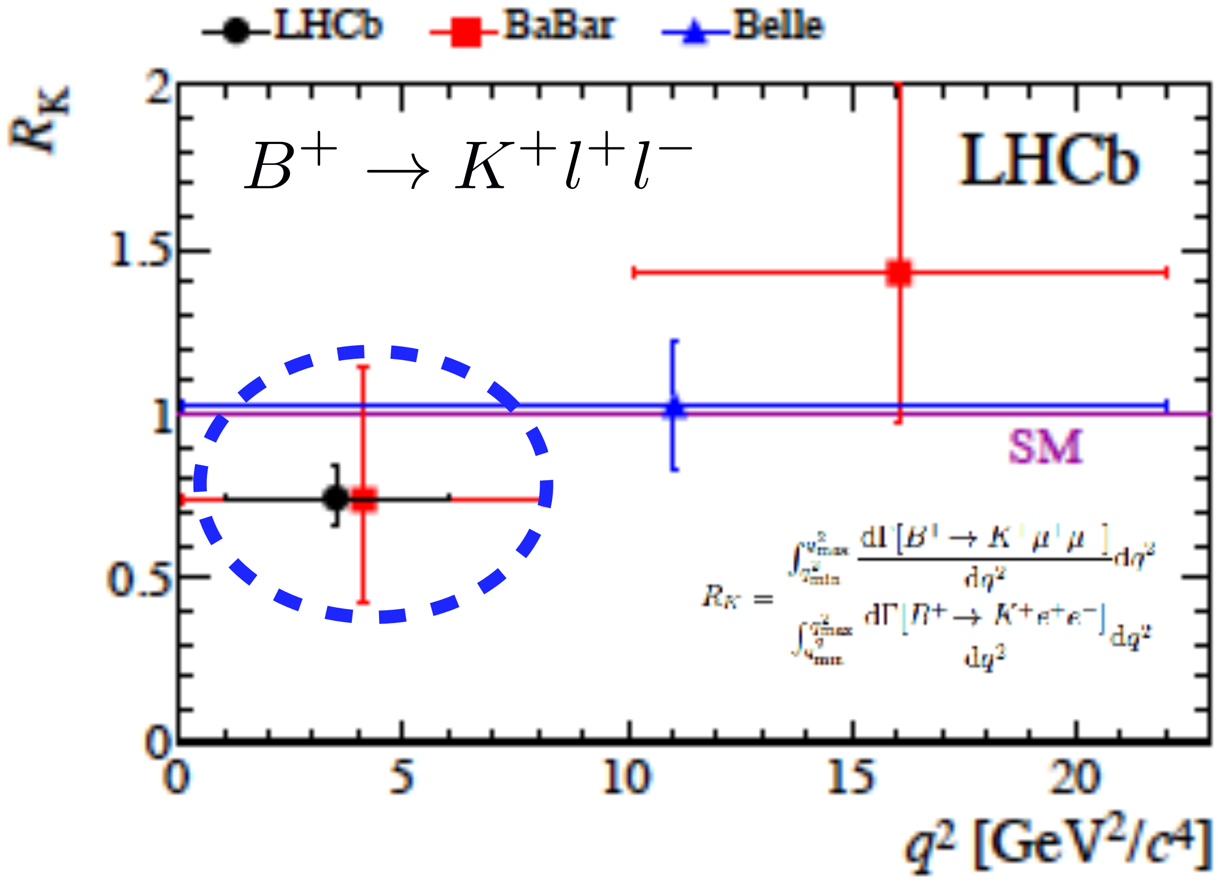
[S.-M. Choi, Y.-J. Kang, HML, 2016]



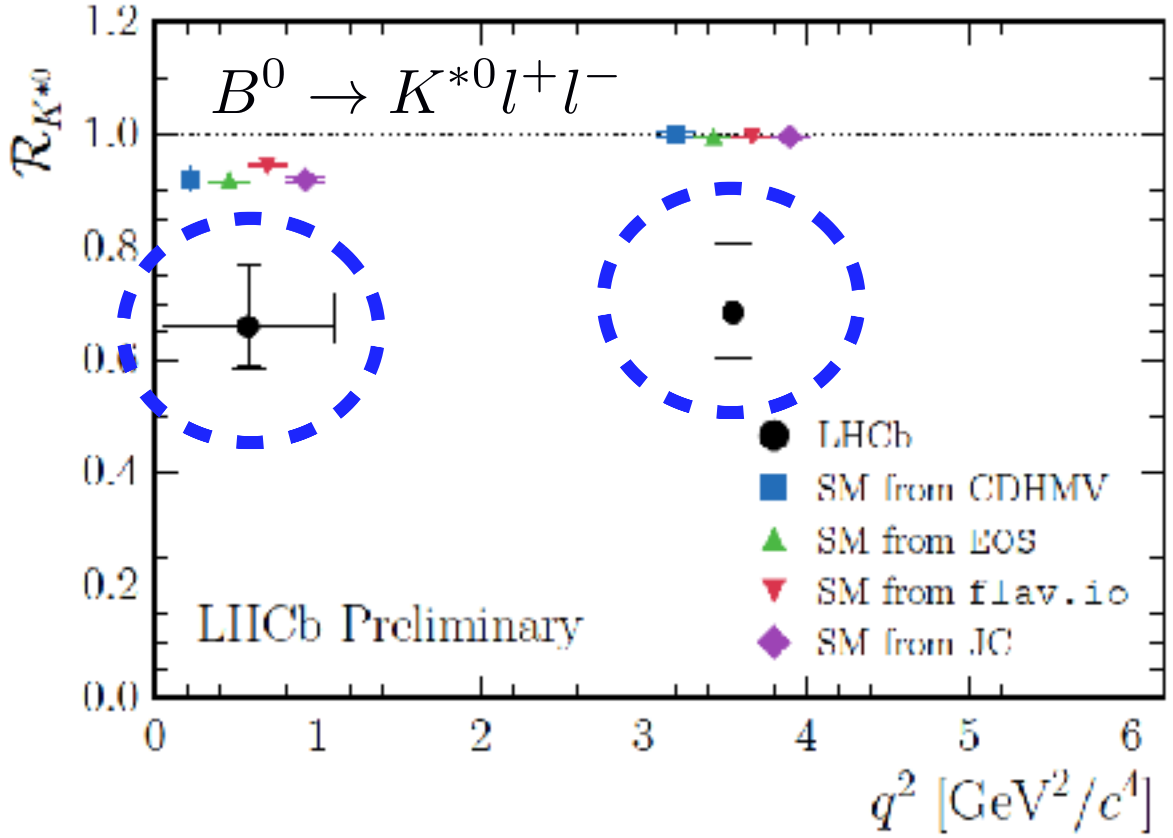
2→2 scattering
for kinetic equilibrium
& DM-electron scattering

B-meson decays from U(1)'

- B-meson 2-3σ anomalies at LHCb might hint at violation of lepton flavor universality.



[June 24, 2014]



[April 18, 2017]

Minimal choice for bottom quark and non-LFU:

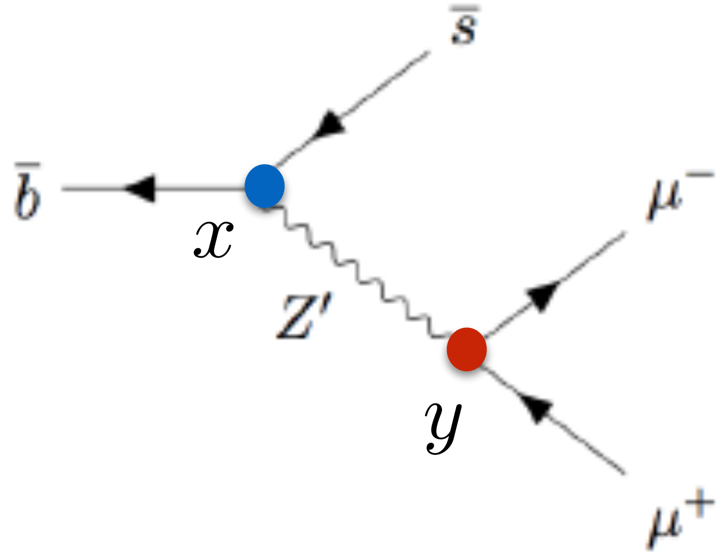
$U(1)_{B_3-L_3}$ + lepton flavor mixing
[Alonso et al, 2017]

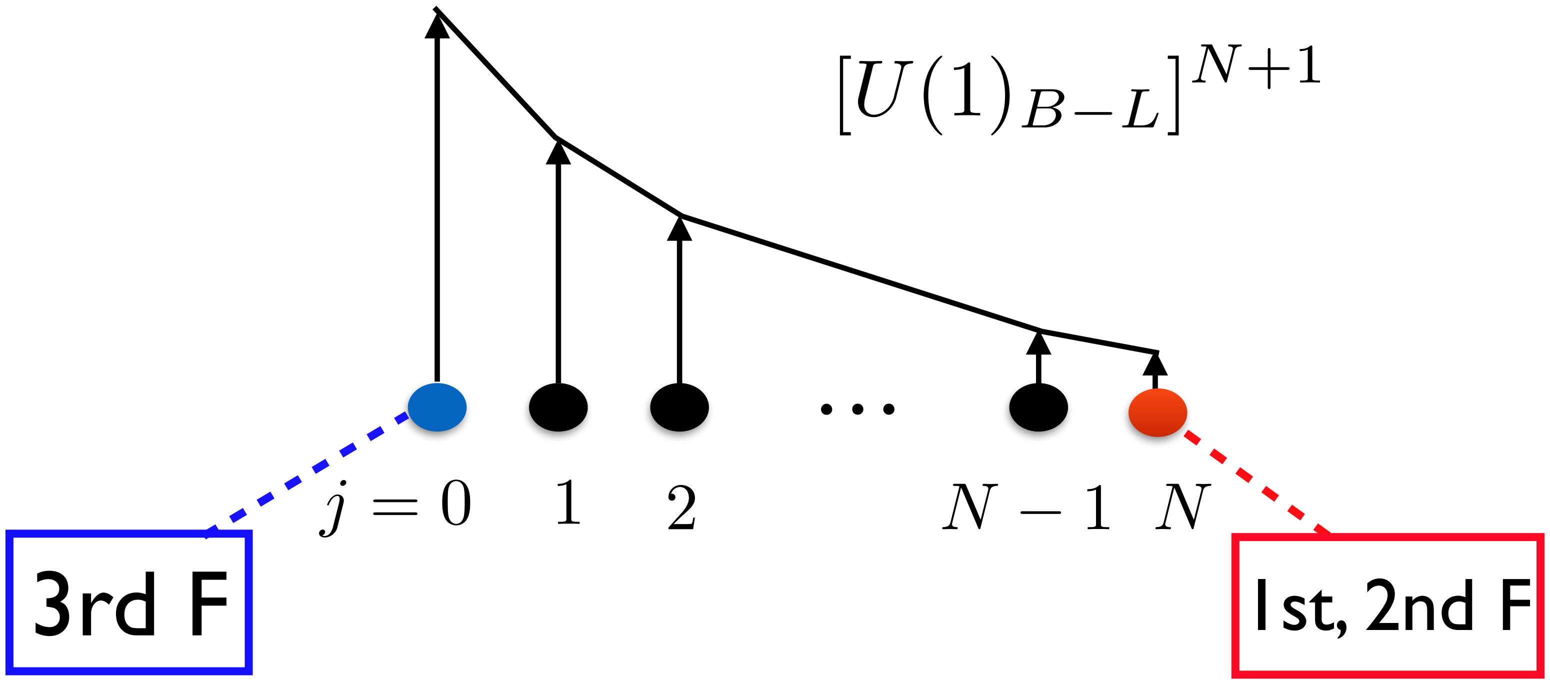
or mixing with $U(1)_{L_\mu - L_\tau}$
[Bian, Choi, Kang, HML, 2017]

U(1)' clockwork & B-decays

- U(1)$_{\text{B-L}}$ clockwork with first two families and third family localized at different sites.

➡ Effective family-dependent B-L: $U(1)_{B_3-L_3}$





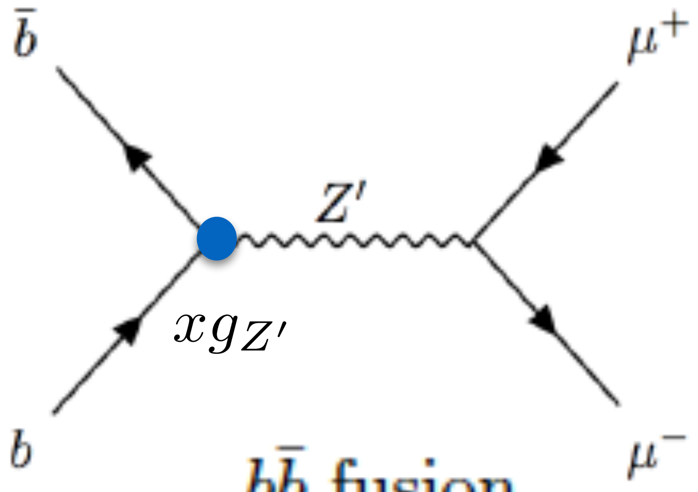
$$\Delta\mathcal{H}_{\text{eff},\bar{b}\to\bar{s}\mu^+\mu^-} = -\frac{4G_F}{\sqrt{2}}V_{ts}^*V_{tb}\frac{\alpha_{em}}{4\pi}C_9^{\mu,\text{NP}}\mathcal{O}_9^{\mu}, \qquad C_9^{\mu,\text{NP}} = -\frac{8xy\pi^2\alpha_{Z'}}{3\alpha_{\text{em}}}\left(\frac{v}{m_{Z'}}\right)^2$$

B-meson G-fit: $C_9^{\mu,\text{NP}} = -1.10$ ➡ $\boxed{m_{Z'} = \left(xy\frac{\alpha_{Z'}}{\alpha_{\text{em}}}\right)^{1/2} 1.2\,\text{TeV}.}$

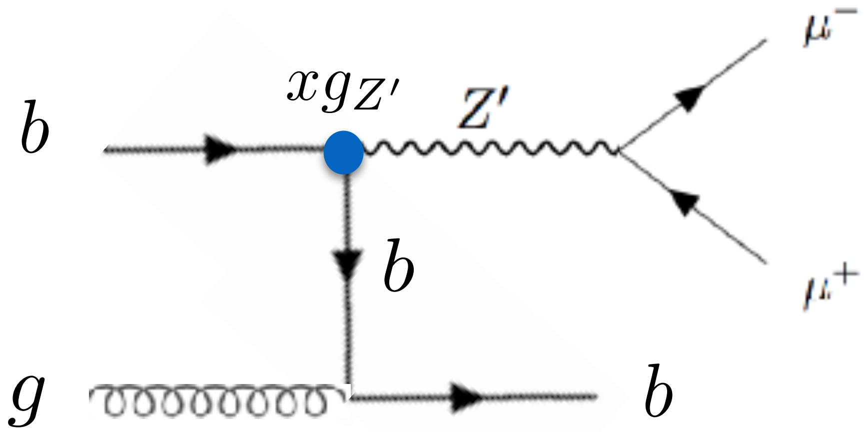
[Crivellin et al, 2017]

Model constraints

- LHC dimuon searches: MadGraph5_aMC@NLO + NN23LO1

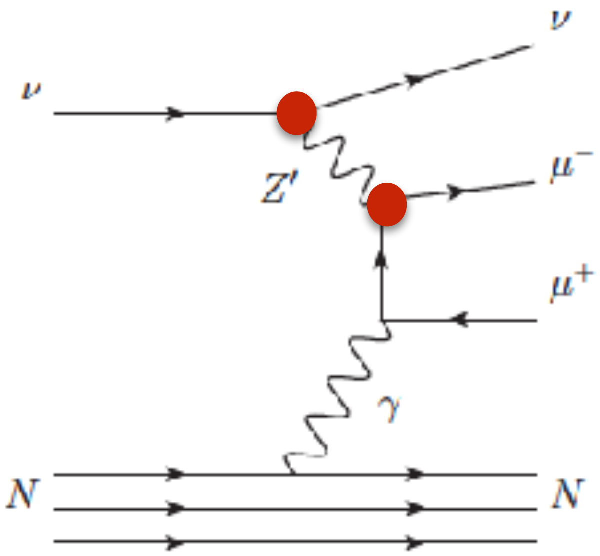


$b\bar{b}$ fusion



$pp \to Z'j$, and $pp \to Z'jj$.

- Neutrino trident production (CHARM-II, CCFR, NuTeV)



$$\frac{\sigma}{\sigma_{\rm SM}} \simeq \frac{1+(1+4s_W^2+2y^2g_{Z'}^2v^2/m_{Z'}^2)^2}{1+(1+4s_W^2)^2}$$

$$< 1.45(2\sigma)$$

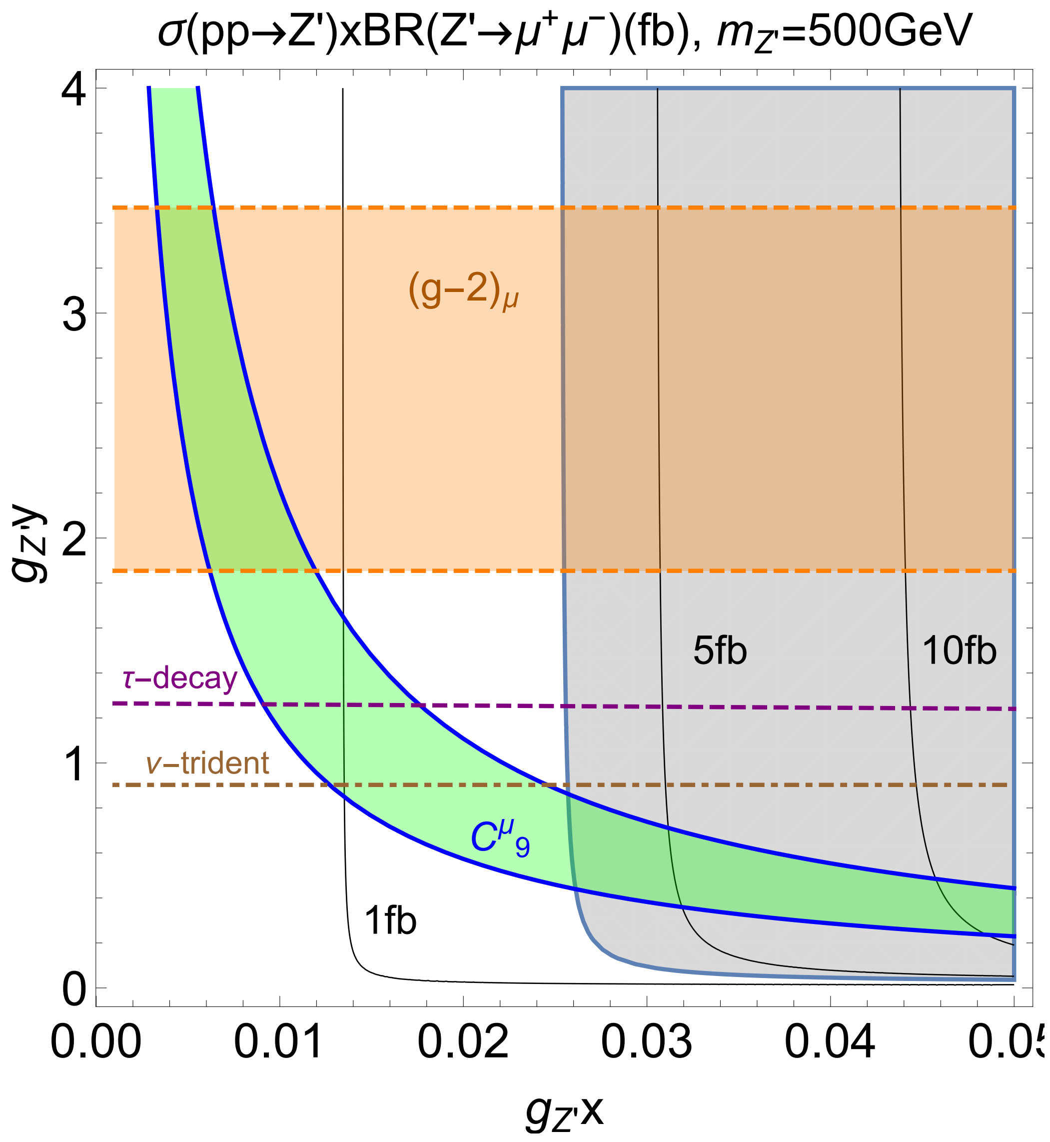
$$\Rightarrow \quad \frac{m_{Z'}}{yg_{Z'}} > 554\,{\rm GeV}.$$

cf. similar bounds from tau decay.

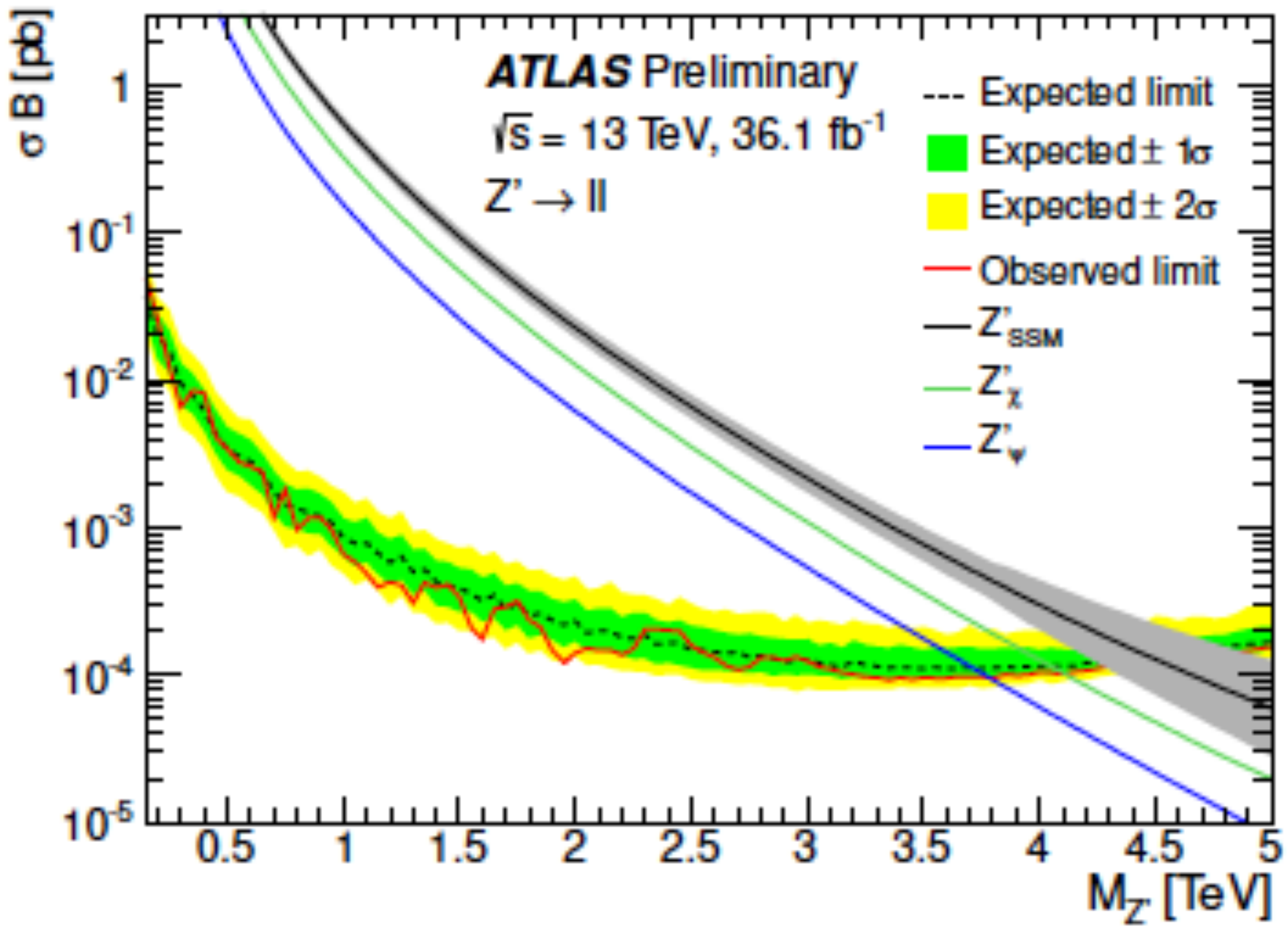
Parameter space

[Bian, Choi, Kang, HML, 2017]

Lepton couplings



Quark couplings



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- LHC dimuon and tau decay/neutrino scattering are complementary in constraining B/L charges.

Conclusions

- Clockwork mechanism can explain effective small or large couplings due to the localization of fields, without a hierarchy of couplings.
- Scalar clockwork based on shift symmetry might allows for a common existence of QCD and large effective decay constants for axion.
- Gauged U(1) clockwork provides a mechanism to generate hierarchical gauge couplings, identified with a 5d massless U(1) with dilaton background.
- We showed examples with DM mediators and flavor-dependent U(1)’ for B-meson anomalis.