Minimal dark matter in SU(5) grand unification

Takashi Toma (Kanazawa U.)

KEK-PH @ KEK
19th Feb. 2025

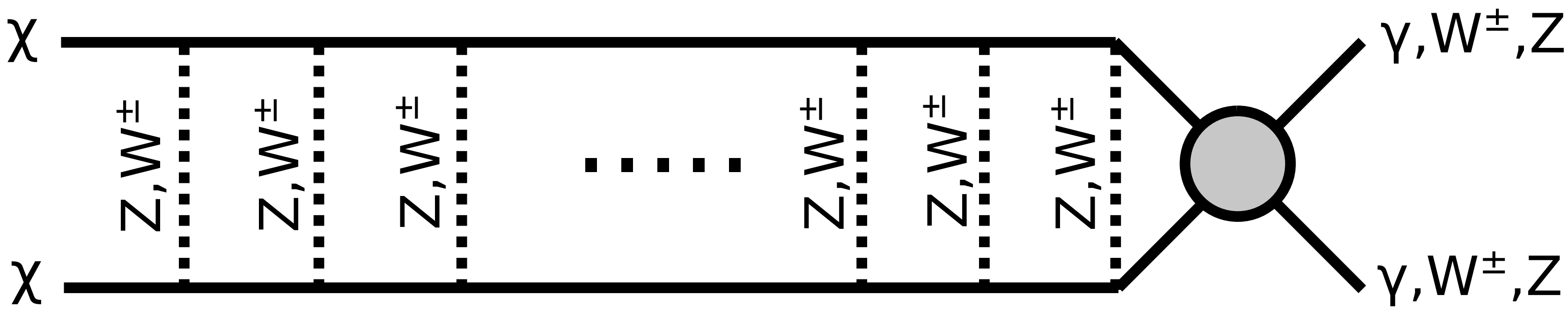
Based on arXiv: 2412.19660 [hep-ph]

Minimal dark matter

M. Cirelli et al., Nucl.Phys.B (2005) [hep-ph/0512090]
Farina et al., JHEP (2013) [arxiv:1303.7244]

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	σ_{SI} in 10^{-46} cm^2
5	0	1/2	stable	$4.4 \to 14$	166	1.0 ± 0.2
7	0	0	stable	$8 \to 25$	166	4 ± 1

- Lagrangian: $\mathcal{L} = \frac{1}{2}\overline{\chi}\left(i\not{D} - M_5\right)\chi$ or $\mathcal{L} = \frac{1}{2}\left(D_\mu\chi\right)^*\left(D^\mu\chi\right) - \frac{1}{2}M_7\chi^2$
- No other interactions $\Rightarrow$ χ^0 is stabilized
  (Thermal relic via by $\chi\chi \to$ gauge bosons, mass $M_5 \sim$ 14 TeV)
- Sommerfeld enhancement and bound state formation

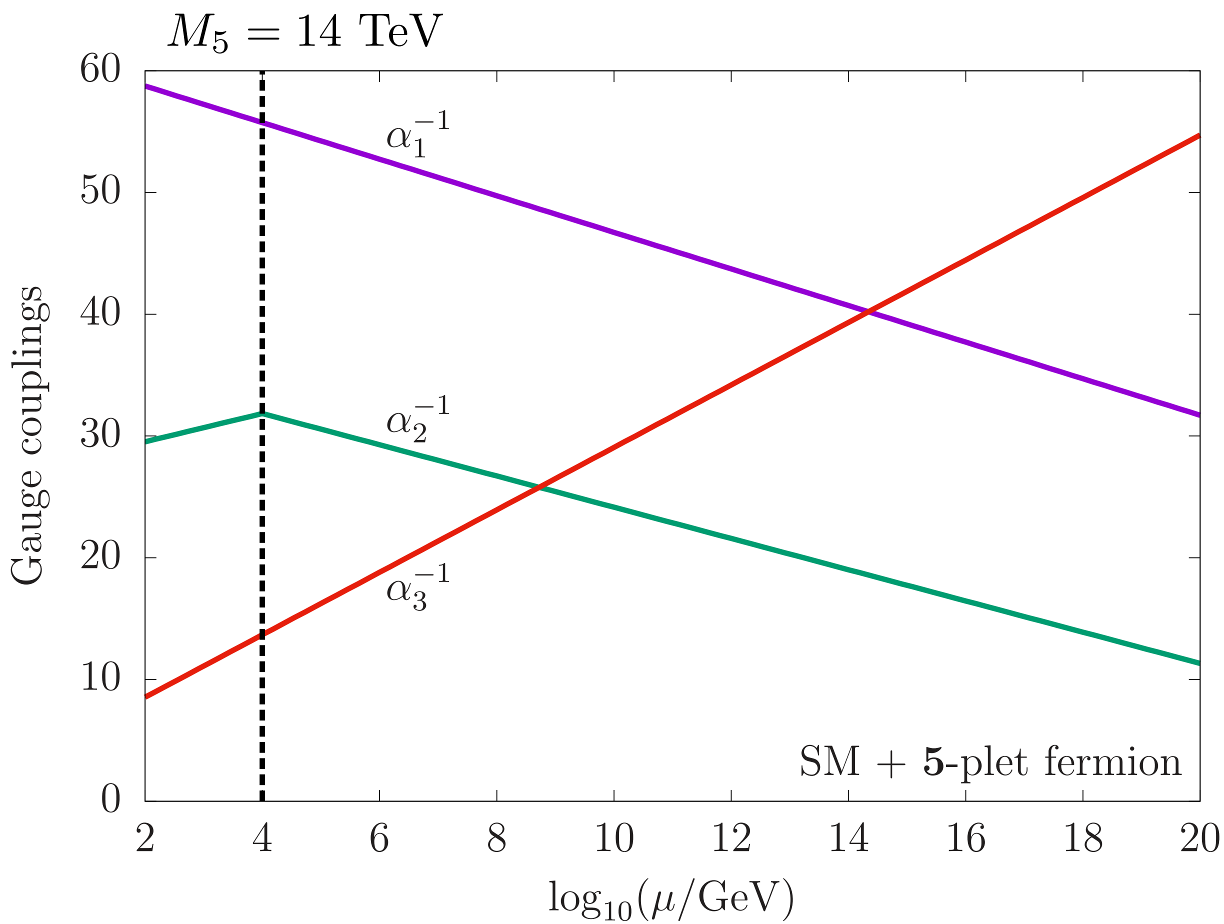


Motivation

- **Fermionic MDM can achieve gauge coupling unification?**
- Big change of the running at $\mu = M_5$
  $\Rightarrow$ need to add colored fields with non-zero Y, but singlet for $SU(2)_L$.

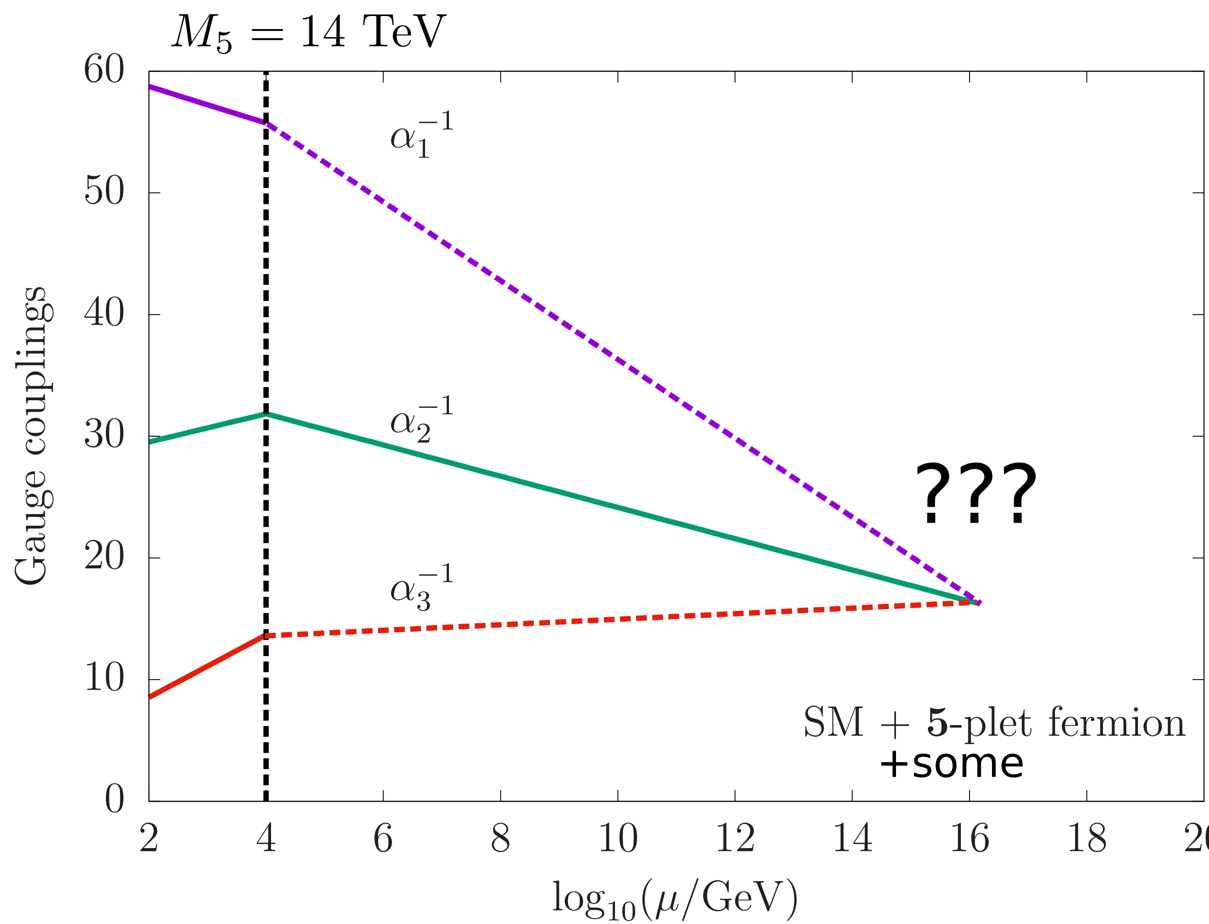
Assumptions (Requirements)

- No additional scale other than $\mathcal{O}(10)$ TeV
- No Landau pole up to Planck scale
- Extra fields have to be embedded in SU(5).
  $\Rightarrow$ possible reps. are limited. $\mathbf{5}$-plet $\subset \mathbf{200}$



MDM in SU(5)

- $\mathbf{200} = (\mathbf{6},\mathbf{3})_{-5/3} + (\mathbf{15},\mathbf{2})_{-5/6} + (\mathbf{3},\mathbf{4})_{-5/6} + (\mathbf{3},\mathbf{2})_{-5/6}$
  $+(\mathbf{27},\mathbf{1})_0 + (\mathbf{8},\mathbf{3})_0 + (\mathbf{8},\mathbf{1})_0 + (\mathbf{1},\mathbf{5})_0 + (\mathbf{1},\mathbf{3})_0 + (\mathbf{1},\mathbf{1})_0$
  $+(\overline{\mathbf{6}},\mathbf{3})_{5/3} + (\overline{\mathbf{15}},\mathbf{2})_{5/6} + (\overline{\mathbf{3}},\mathbf{4})_{5/6} + (\overline{\mathbf{3}},\mathbf{2})_{5/6}$
- Only $(\mathbf{1},\mathbf{5})_0$ is light.
- Other states cannot be light.
  Otherwise Landau pole for g_2 appears below Planck scale.

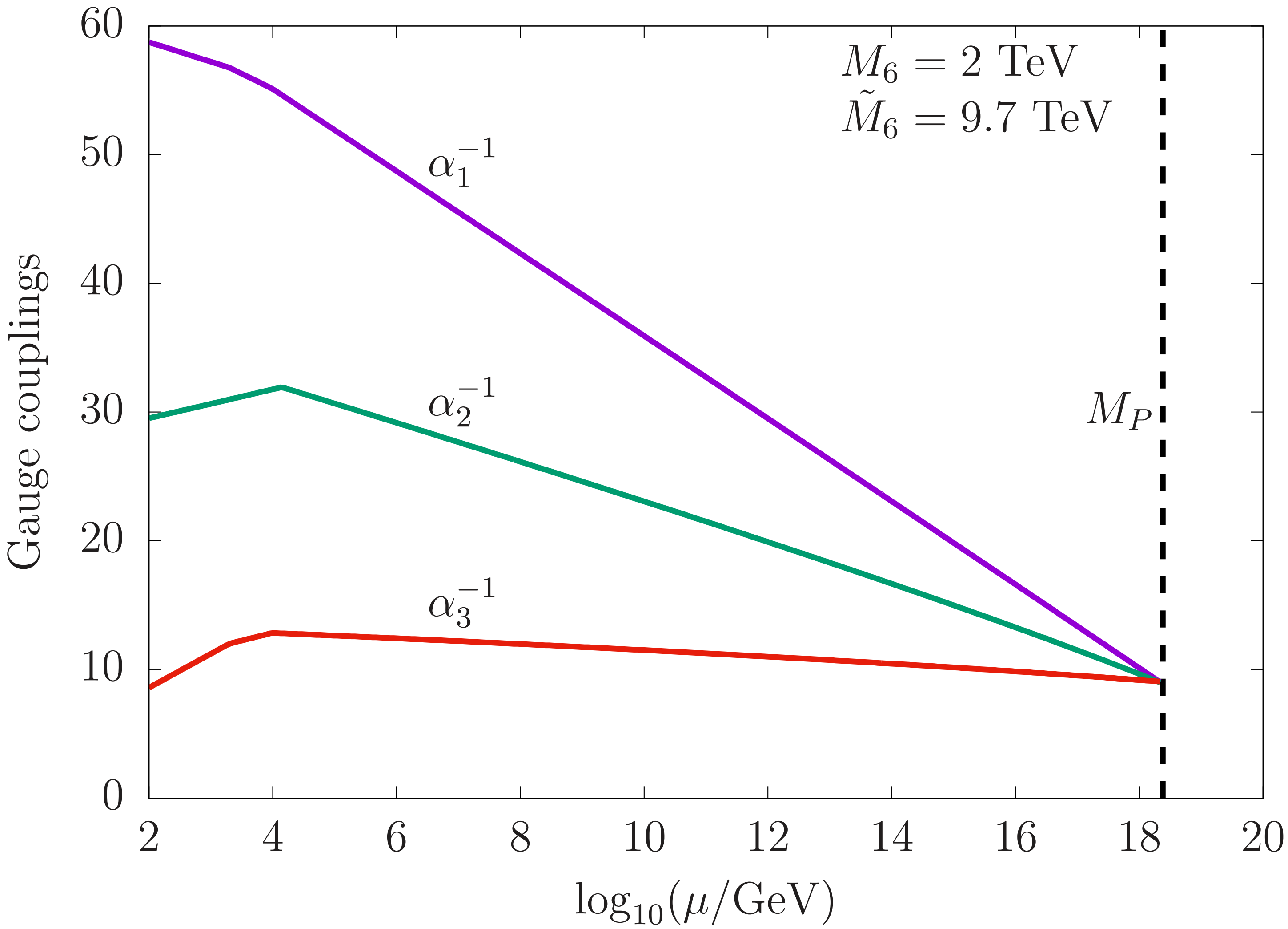


Rough estimate at one-loop level

N. Yamatsu, arXiv:1511.08771 (> 10000 pages)

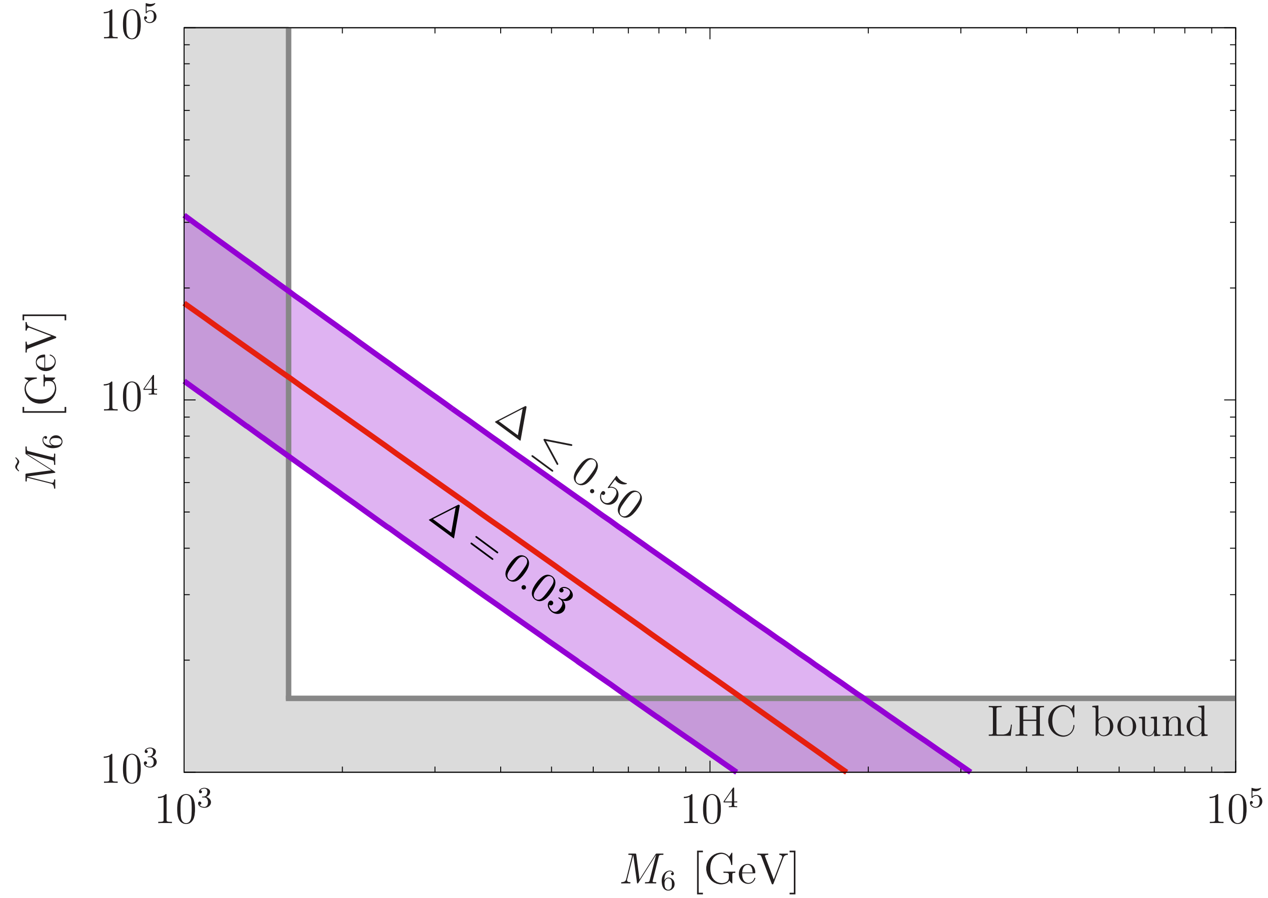
- β functions:
  $$\frac{dg_i}{dt} = \frac{b_i g_i^3}{(4\pi)^2} \text{ where } b_1 = \frac{41}{10},\ b_2 = -\frac{19}{6},\ b_3 = -7 \text{ in SM}$$
  and $\Delta b_2 = \frac{20}{3}$ from $\mathbf{5}$-plet MDM
- Requirement for gauge coupling unification ($g_1 = g_2 = g_3$ at $\mu = M_U$),
  $\Rightarrow -2.9 \lesssim \Delta b_1 - \Delta b_3 \lesssim -1.6$ (additional contribution)
- Look for possible states
  $(\mathbf{3},\mathbf{1})_{-1/3},\ (\overline{\mathbf{3}},\mathbf{1})_{1/3} \subset \mathbf{5}, \overline{\mathbf{5}},$ $\quad(\overline{\mathbf{3}},\mathbf{1})_{-2/3},\ (\mathbf{3},\mathbf{1})_{2/3} \subset \mathbf{10}, \overline{\mathbf{10}},$
  $(\mathbf{6},\mathbf{1})_{-2/3},\ (\overline{\mathbf{6}},\mathbf{1})_{2/3} \subset \mathbf{15}, \overline{\mathbf{15}},$ $\quad\cdots$
  If two pairs of $(\mathbf{6},\mathbf{1})_{-2/3},\ (\overline{\mathbf{6}},\mathbf{1})_{2/3}$ are added
  $\Rightarrow \Delta b_1 - \Delta b_3 = -\frac{12}{5} = -2.4 \Leftarrow$ likely to work
- Two-loop calculation

Gauge coupling unification



- Unification scale M_U is close to the reduced Planck scale M_P
- No proton decay, $\tau_p \gtrsim 10^{39}$yrs $\gg \tau_{\rm exp} = 10^{34}$yrs

Gauge coupling unification 2



- Define criterion of unification (complete unification if $\Delta = 0$)

$$\Delta(\mu) \equiv \sqrt{\Delta\alpha_{12}^{-2}(\mu) + \Delta\alpha_{23}^{-2}(\mu)}, \quad \Delta\alpha_{ij} = \alpha_i^{-1} - \alpha_j^{-1}$$

- 1.6 TeV $\lesssim M_6, \tilde{M}_6 \lesssim$ 20 TeV

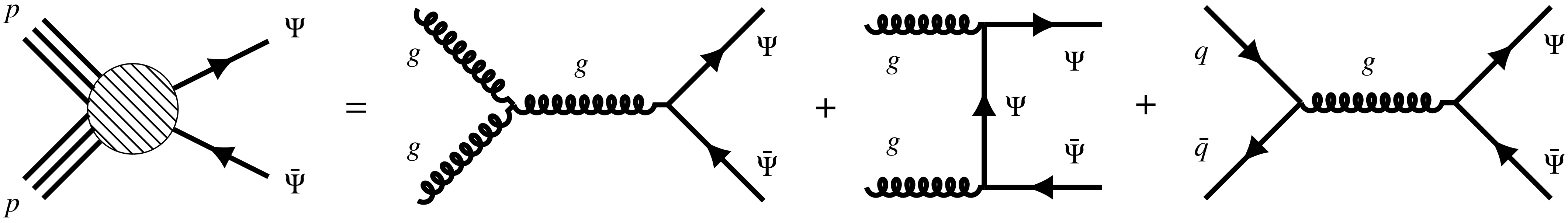
Mass splitting

- $\mathcal{L} = -\frac{M_{200}}{2}\mathbf{200}_F\mathbf{200}_F + \frac{Y_{200}}{2}\mathbf{24}_H\mathbf{200}_F\mathbf{200}_F$
- $\mathbf{5}$-plet:
  $M_{200} - Y_{200}\langle\mathbf{24}_H\rangle = 14$ TeV
  Other states:
  $M_{200} - C_i Y_{200}\langle\mathbf{24}_H\rangle \sim M_U$
- Same for $(\mathbf{15}, \overline{\mathbf{15}})$ pairs.
- Dimopoulos-Wilczek mech.
  $\rightarrow$ no fine-tuning?
  $(\mathbf{1},\mathbf{5})_0 \subset \mathbf{2640}$ in SO(10)

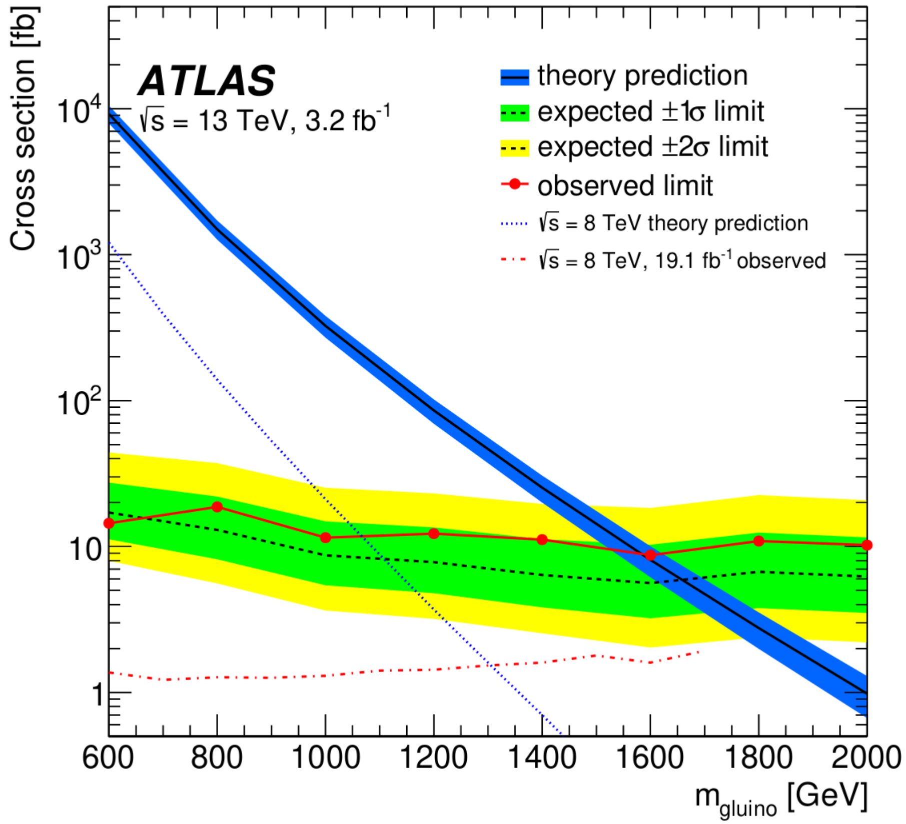
Representation			C_i
$\mathbf{24}_H$	$\mathbf{200}_F$	$\mathbf{200}_F$	
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{6},\mathbf{3})_{-5/3}$	$(\overline{\mathbf{6}},\mathbf{3})_{5/3}$	$1/6$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{15},\mathbf{2})_{-5/6}$	$(\overline{\mathbf{15}},\mathbf{2})_{5/6}$	$1/4$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{3},\mathbf{4})_{-5/6}$	$(\overline{\mathbf{3}},\mathbf{4})_{5/6}$	$-7/12$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{3},\mathbf{2})_{-5/6}$	$(\overline{\mathbf{3}},\mathbf{2})_{5/6}$	$-19/84$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{27},\mathbf{1})_0$	$(\mathbf{27},\mathbf{1})_0$	$2/3$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{8},\mathbf{3})_0$	$(\mathbf{8},\mathbf{3})_0$	$1/6$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{8},\mathbf{1})_0$	$(\mathbf{8},\mathbf{1})_0$	$1/14$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{5})_0$	$(\mathbf{1},\mathbf{5})_0$	1
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{3})_0$	$(\mathbf{1},\mathbf{3})_0$	$11/21$
$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_0$	$(\mathbf{1},\mathbf{1})_0$	$-2/7$
$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{2})_{5/6}$	$(\mathbf{3},\mathbf{2})_{-5/6}$	$-19/84$
$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{3}},\mathbf{4})_{5/6}$	$(\mathbf{3},\mathbf{4})_{-5/6}$	$-7/12$
$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{15}},\mathbf{2})_{5/6}$	$(\mathbf{15},\mathbf{2})_{-5/6}$	$1/4$
$(\mathbf{1},\mathbf{1})_0$	$(\overline{\mathbf{6}},\mathbf{3})_{5/3}$	$(\mathbf{6},\mathbf{3})_{-5/3}$	$1/6$

Exotic colored fermion search

Carpenter et al., arXiv:2110.11359, ATLAS Coll., arXiv: 1606.05129



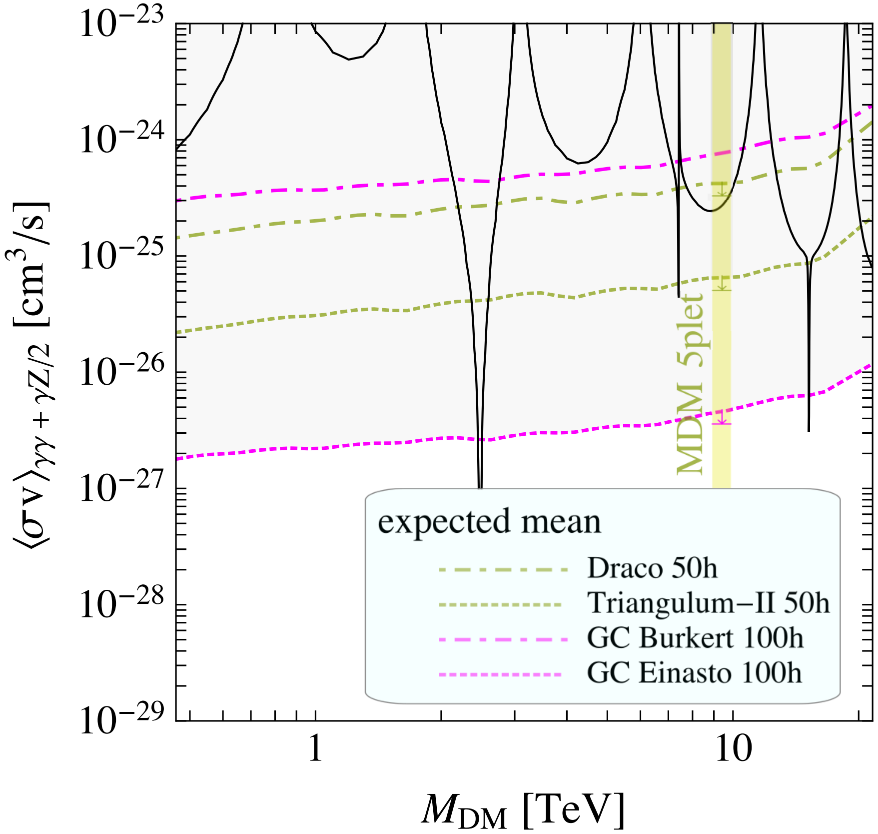
- $\Psi = (\mathbf{6},\mathbf{1})_{-2/3}$, $\overline{\Psi} = (\overline{\mathbf{6}},\mathbf{1})_{2/3}$
- Metastable sextet production at LHC
- Mass bound is 1.6 TeV for metastable gluino.
- R-hadrons are produced (bound state of Ψ, $\overline{\Psi}$ and quarks)
- Detectable via large ionization losses and slow propagation velocities

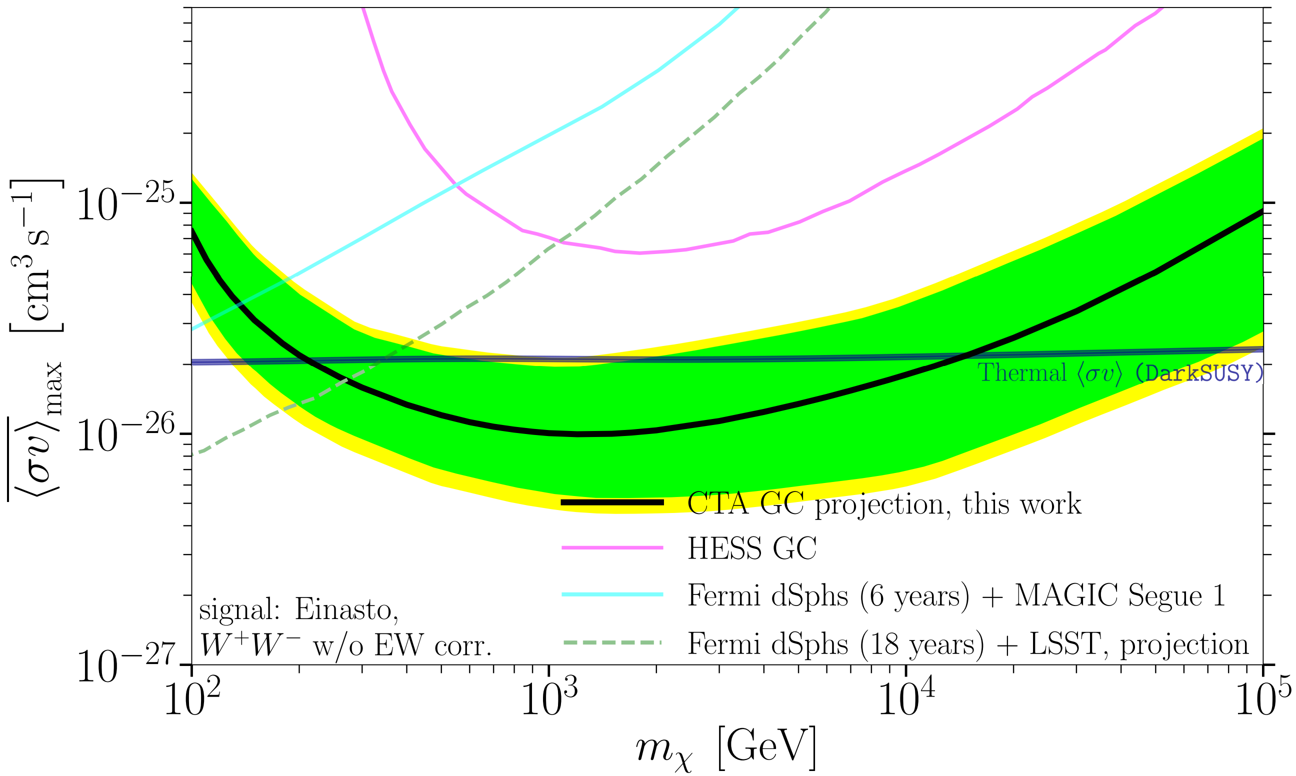


Gamma-ray search

Lefranc et al., arXiv:1608.00786, CTA Collaboration, arXiv:2007.16129

- CTA prospect (expected to start in 2026)
  Energy range: 20 GeV – 300 TeV
- Line (left) and continuum (right)

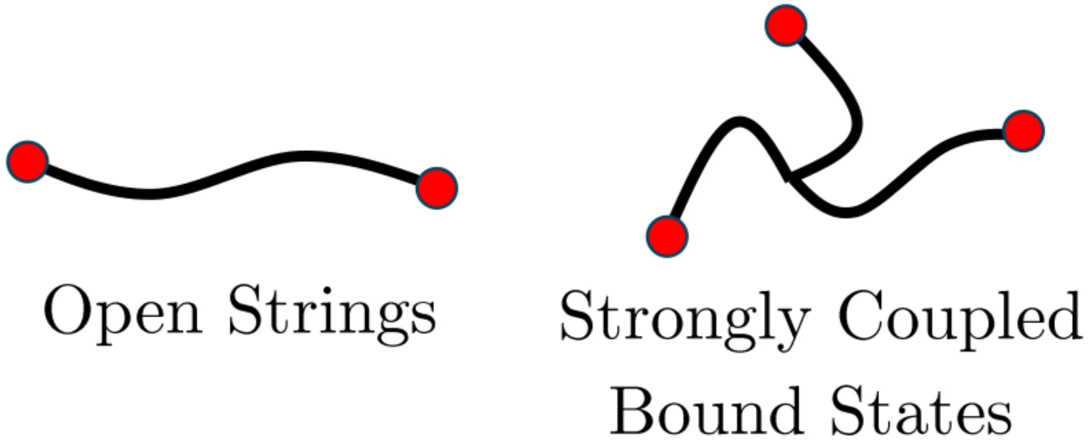




Implication to string theory

M. Baumgart et al., arXiv: 2412.13192

- String endpoints correspond to fundamental indices of gauge groups. Ex. symmetric $ij \Rightarrow$ adjoint
- Maximally three indices even if strongly coupled strings are considered.



- Any examples with four indices are not known so far, and such construction seems to be difficult.
- Isolation of high dimensional reps is also difficult.

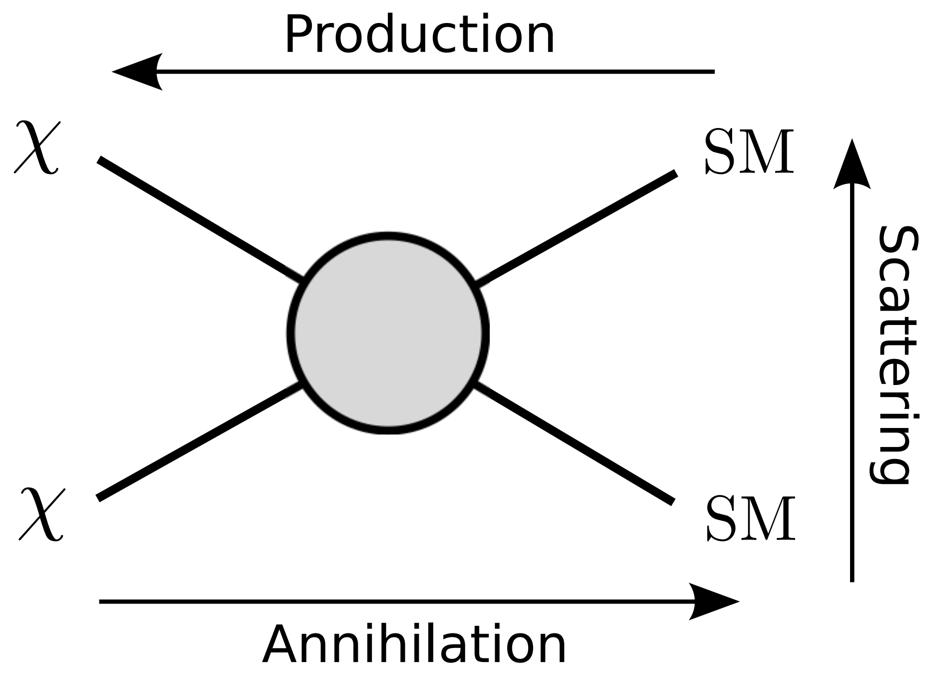
  $\Rightarrow$ Once $\mathbf{5}$-plet MDM with exotic colored fermions is experimentally confirmed, most of known string theories have to be falsified.

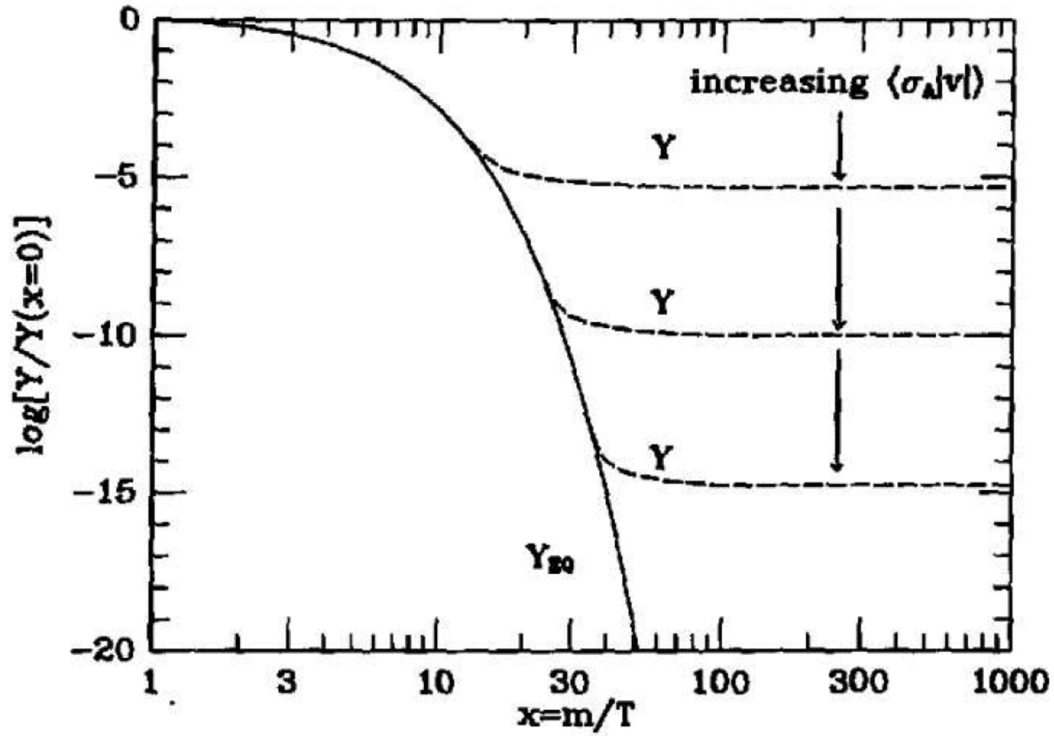
Summary

1. $\mathbf{5}$-plet MDM is phenomenologically promising DM candidate.
   The mass $=$ 14 TeV.
2. The model can accommodate gauge coupling unification at the reduced Planck scale by adding 2 pairs of SU$(3)_c$ $\mathbf{6}$-plet fermions.
3. The model can be tested via searching for the exotic $\mathbf{6}$-plet fermions at TeV scale, and MDM through gamma-ray observation.
4. If the isolated MDM is found by experiments, most of known string theories are excluded, and need to be modified.

Backup

Thermal dark matter

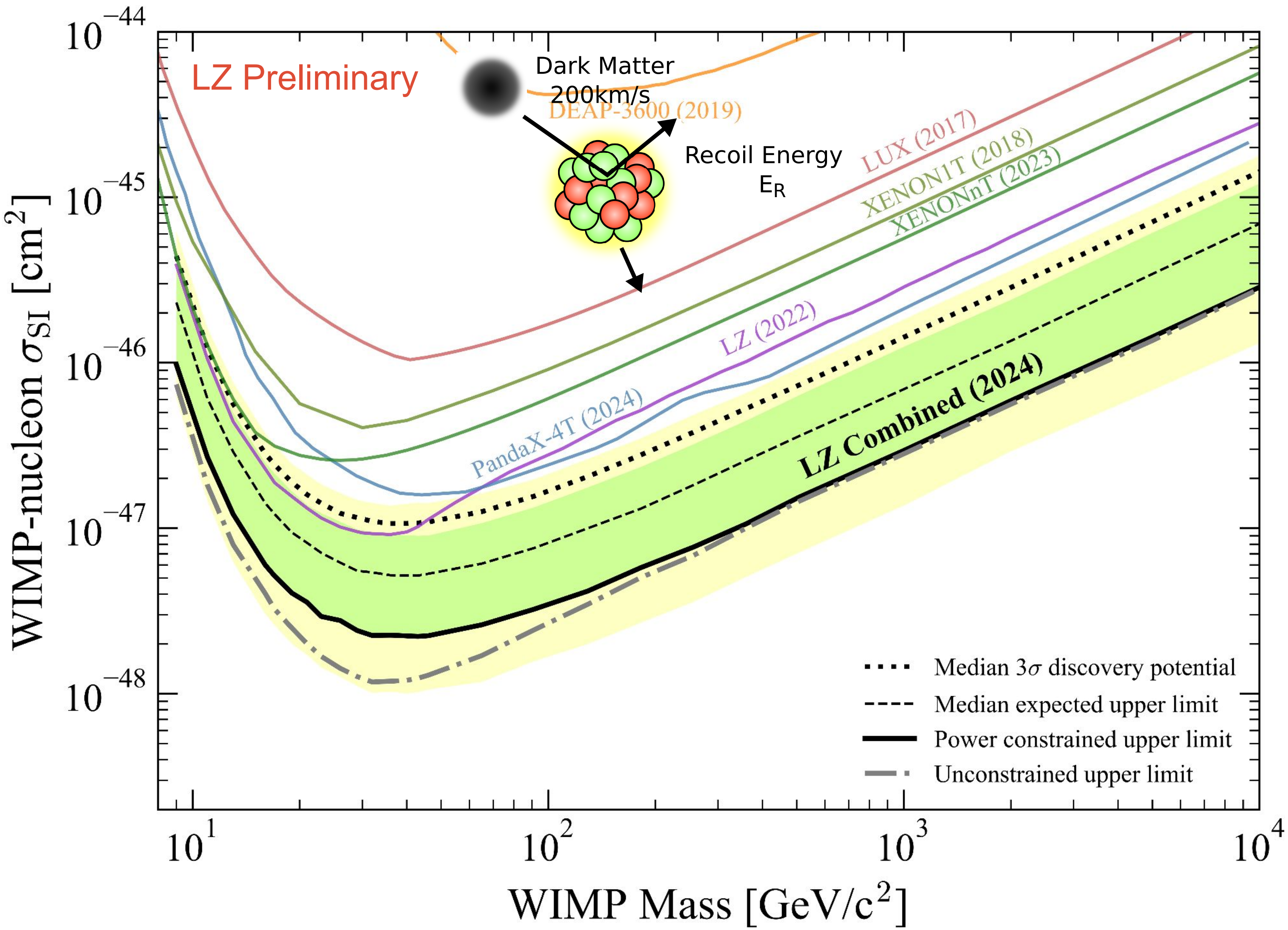


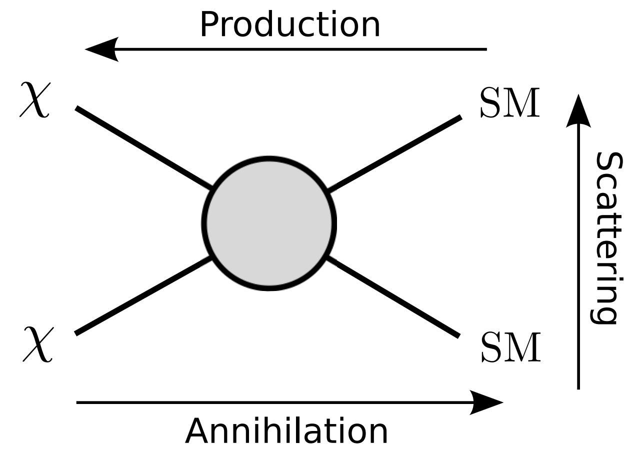


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

- Thermalized with SM particles in early universe.
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}$cm^3/s $\sim 10^{-36}$cm^2
  (only log dependent on DM mass)

Status of direct detection experiments





- $\Omega h^2 = 0.12$
  $\Leftrightarrow \sigma_{\rm el} \sim 10^{-36}$ cm^2
  ($\sigma_{\rm el} \lesssim 10^{-45}$ cm^2)
  (loop)

LZ talk @ TeVPA2024

- LZ gives the strongest bound 2.2×10^{-48} cm^2 at 43 GeV.