

Gauge Symmetry Stabilization of the Dark Matter Particles

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Purpose of the talk

introduction on various ways to stabilize DM from gauge symmetries and
some of the many phenomenological implications this may induce

recent work: DM from the center of SU(N)

DM stability

→ $\tau_{DM} > \tau_U \sim 10^{18} \text{ sec}$

$\tau_{DM} \gtrsim 10^{26-28} \text{ sec}$ ← in most models not to produce
 $e^+, \bar{p}, \gamma, \nu, \dots$ fluxes larger than observed

→ could be due to simple discrete Z_2 or global $U(1)$ symmetry but likely
behind the stability of DM there is something more fundamental

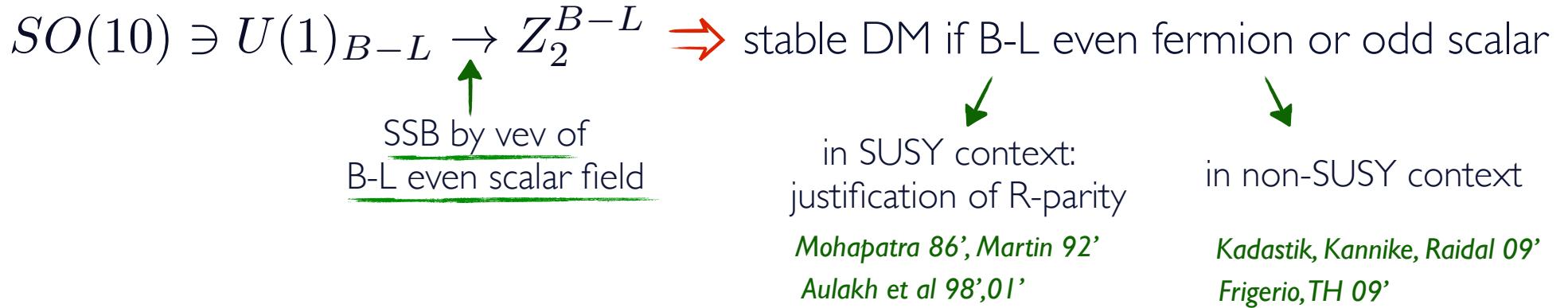
example of the SM: 4 stable particles:

- lightest ν : Lorentz invariance
- γ : massless: due to $U(1)_{EM}$ gauge symmetry
- e^- : lightest particle charged under $U(1)_{EM}$ gauge symmetry
- p^+ : accidental baryon number conservation: due to SM gauge symmetries
 $SU(3)_c, \dots$

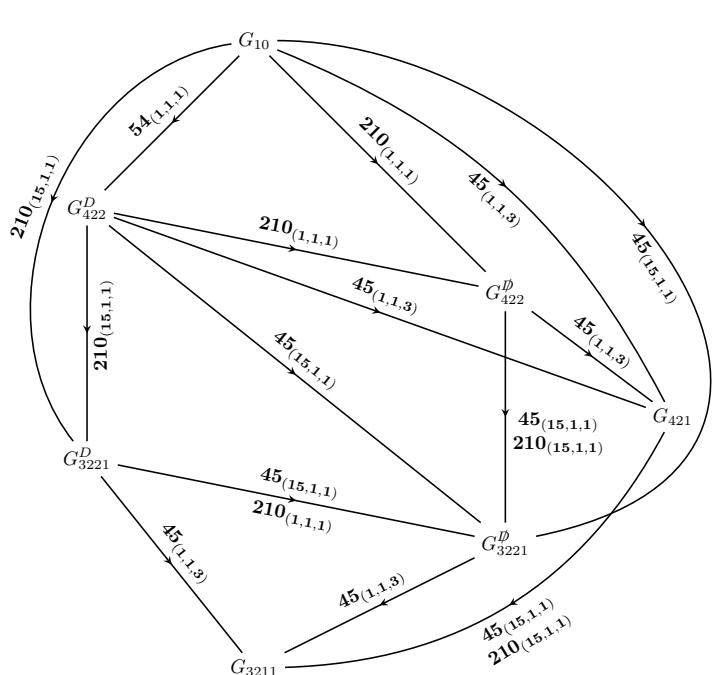
⇒ could DM be stable due to gauge symmetries too?

DM stability: UV or IR problem??
Visible or hidden sector dynamics??

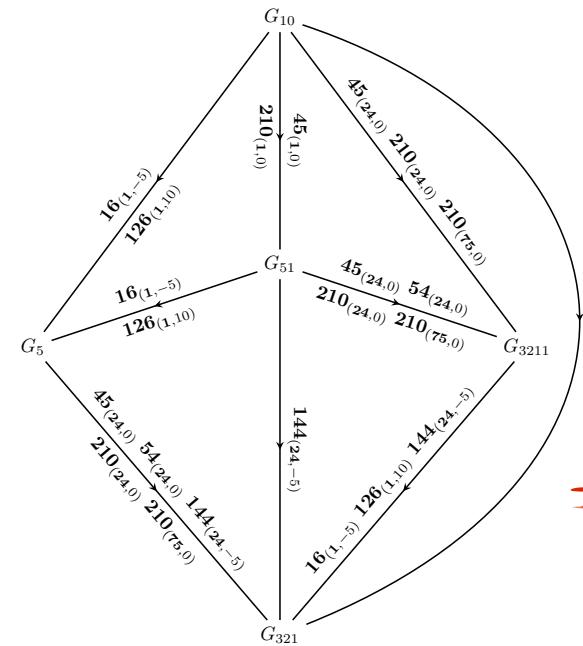
DM stability: UV origin well motivated example: $SO(10)$ GUT



recent systematic determination of all DM possibilities along all $SO(10)$ breaking paths:



TH, Heeck, Tytgat, 18'



(Repres. ≤ 210)

specific phenomenologies
DM low scale partners
from the same multiplet, ...
light Z' , ...

DM stability: IR explanation from gauge symmetries under which SM particles are charged: "visible sector models"

- "Minimal DM": a $SU(2)_L$ fermion quintuplet on top of SM and nothing else

no renormalizable or dim-5 interactions destabilizing it
quintuplet neutral component is a DM candidate

Cirelli, Fornengo, Strumia 07', ...

- Low $U(1)_{B-L}$ breaking scale models

-

DM stability from gauge symmetries under which SM particles are singlets

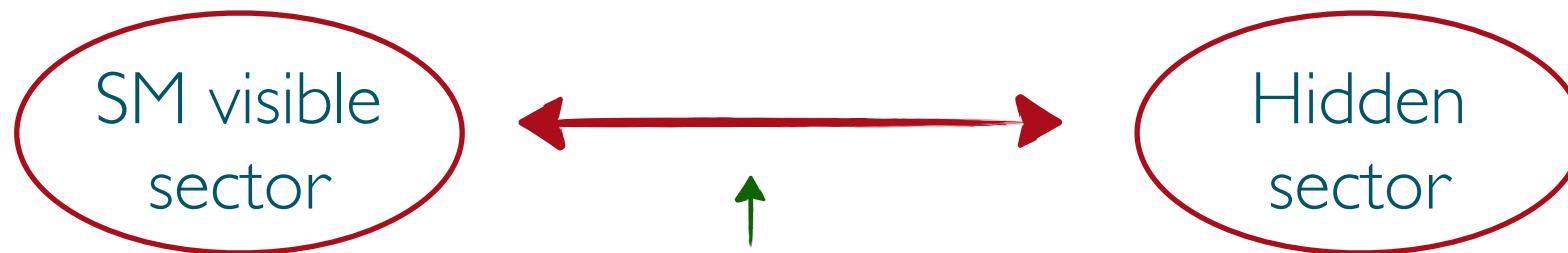
“hidden sector models”

Prototype model of hidden sector fermion DM: secluded $U(1)$



lightest fermion charged under an extra unbroken $U(1)'$

Feldman, Kors, Nath 06'
Pospelov, Ritz, Voloshin 07'



kinetic mixing portal

$$\mathcal{L} \ni -\frac{\epsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu}$$

a QED' structure:
a $U(1)'$ gauge symmetry
with DM the lightest particle
charged under it: a fermion e'

$$\mathcal{L} \ni \bar{\psi}' (i \not{D}' - m_{\psi'}) \psi'$$

→ 3 parameters: $m_{DM}, \alpha', \epsilon$

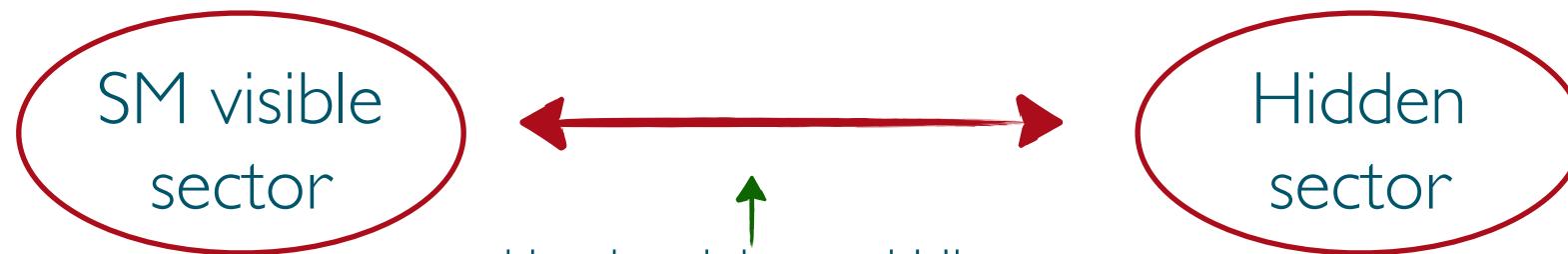
$$\alpha' \equiv \frac{e'^2}{4\pi}$$

Prototype model of hidden sector fermion DM: secluded $U(1)$



lightest fermion charged under an extra broken $U(1)'$

Feldman, Kors, Nath 06'
Pospelov, Ritz, Voloshin 08'



kinetic mixing and Higgs
portals

$$\mathcal{L} \ni -\frac{\epsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu} - \lambda_m H^\dagger H \phi^\dagger \phi$$

$$\alpha' \equiv \frac{e'^2}{4\pi}$$

a massive QED' structure:
a $U(1)'$ gauge sym. spontaneously
broken by a scalar field ϕ with
with DM the lightest particle charged
under it: a fermion e'

$$\mathcal{L} \ni \bar{\psi}' (i \not{D}' - m_{\psi'}) \psi'$$

$$-\mu^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2$$

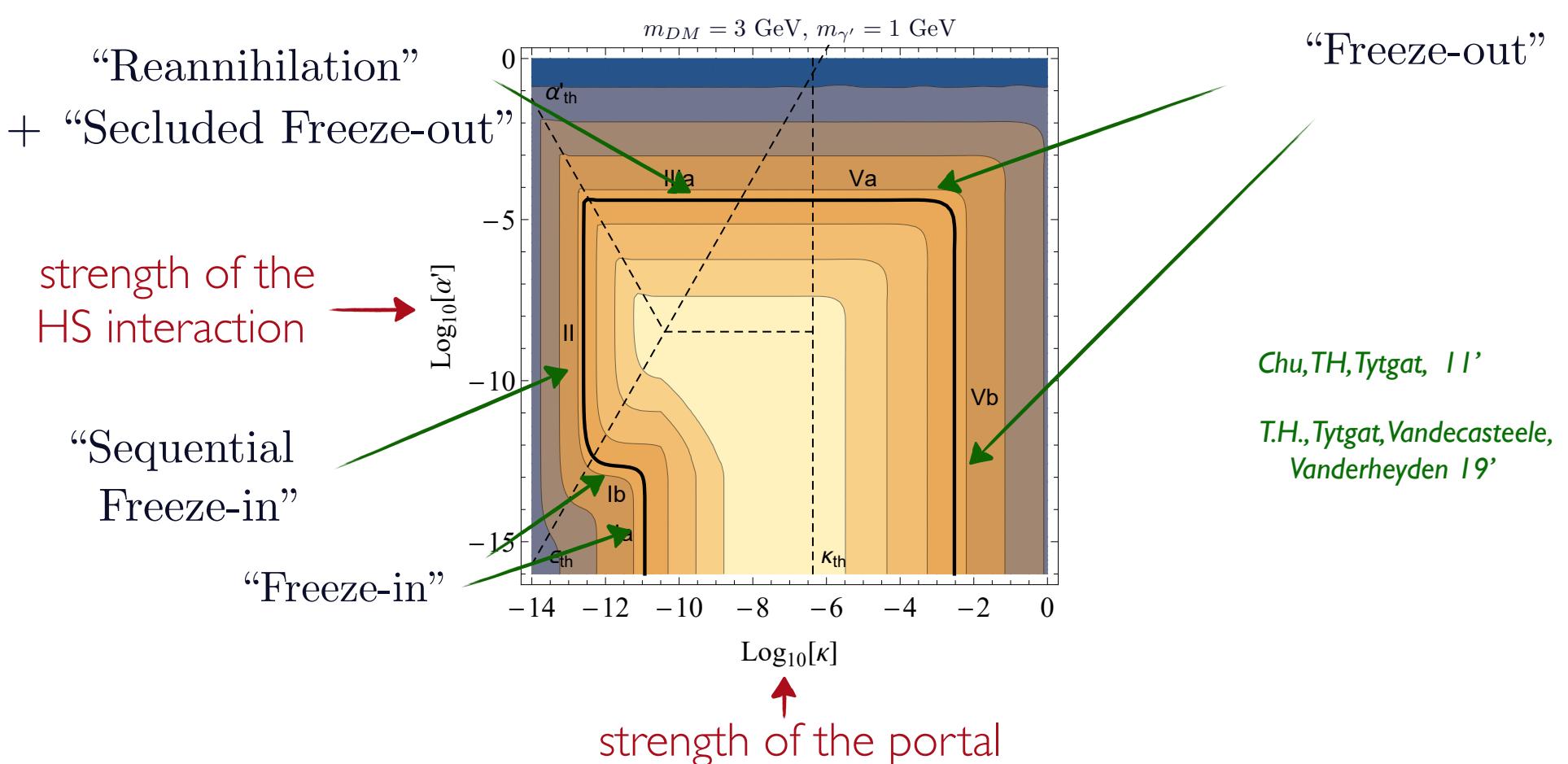
→ 6 parameters: $m_{DM}, \alpha', \epsilon, v_\phi, m_\phi, \lambda_m$

Prototype model of hidden sector fermion DM: secluded $U(1)$

huge phenomenology:

- relic density: secluded scenario: DM-SM interaction not necessarily large

5 dynamical basic ways to account for the observed relic density

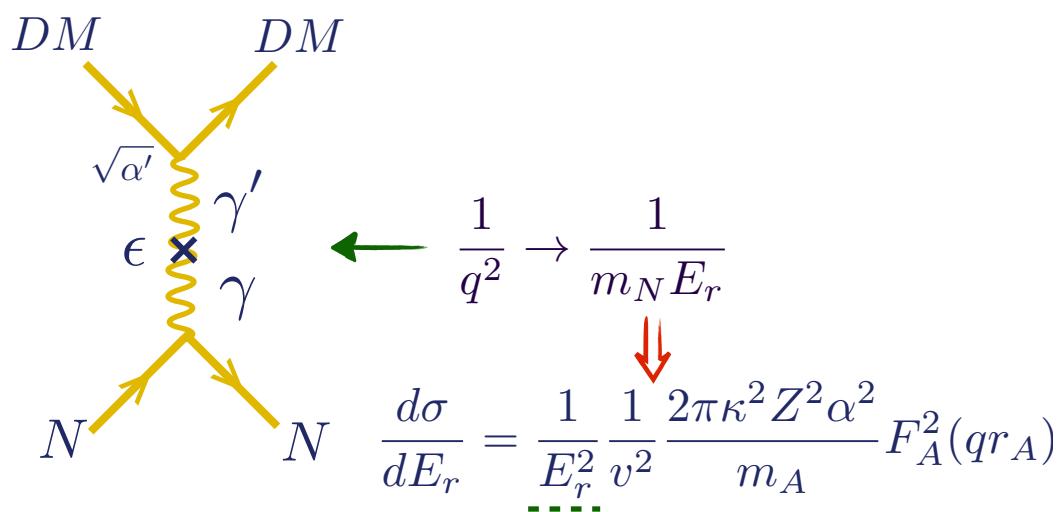


Prototype model of hidden sector fermion DM: secluded $U(1)$



huge phenomenology:

- endless phenomenology related to presence of massless or light dark photon
- direct detection: boosted t-channel exchange of dark photon

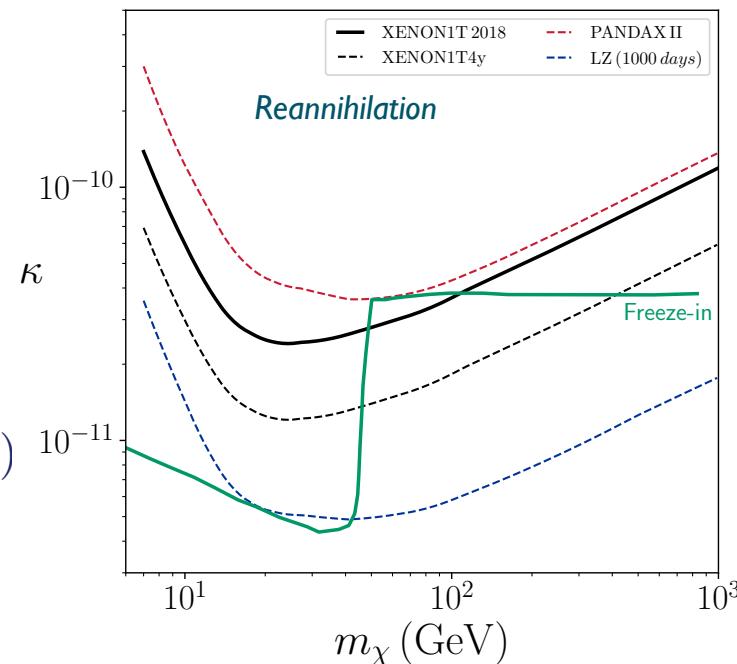


Chu, TH, Tytgat II,
Essig II'

$E_r \sim \text{few KeV}$

↓
huge enhancement
↓

direct detection sensitive
to very small κ values



T.H., M.Tytgat,
Vandecasteele,
Vanderheyden,
[arXiv:1807.05022](https://arxiv.org/abs/1807.05022)

⇒ freeze-in scenario already probed by Xenon-1T for $45 \text{ GeV} < m_{DM} < 100 \text{ GeV}$
LZ will probe it for $15 \text{ GeV} < m_{DM} < 4 \text{ TeV}$
freeze-out, secluded freeze-out, reannihilation already largely probed

Prototype model of hidden sector fermion DM: secluded $U(1)$

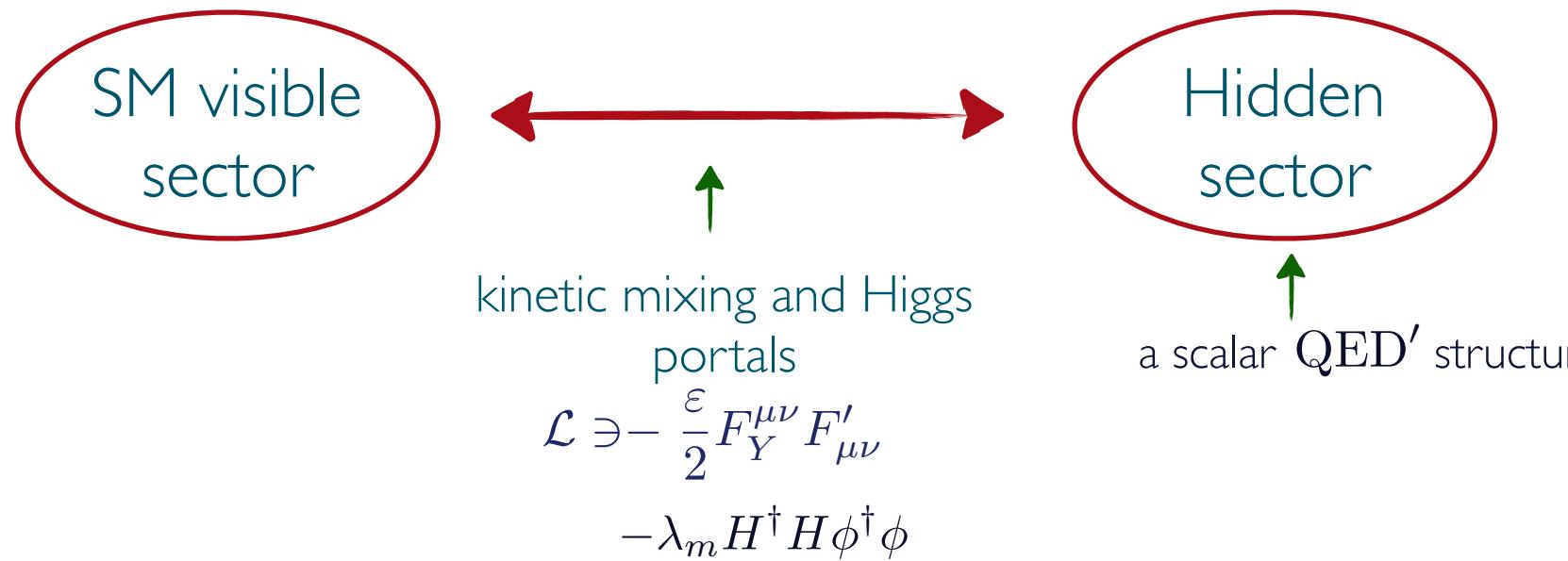


- huge phenomenology:
 - endless phenomenology related to presence of massless or light dark photon
 - boosted DM self interaction by dark photon induced Sommerfeld effect
 - small scale anomalies
 - long range force effects for massless case: DM halo formation, galactic shielding, ...
*Feng, Kaplinghat, Tu, Yu 09'; Feng, Tu, Yu 09'
Agashe, Cyr-Racine, Randall, Scholtz 17'*
 - cosmological constraints
Ackerman, Buckley, Carroll, Kamionkowski 09'; Feng, Kaplinghat, Tu, Yu 09'; Feng, Tu, Yu 09', ...
 - many more particle physics and astrophysical dark photon effects, ...
 - associated to the DM stabilization mechanism a lot of specific phenomenology!

Prototype model of hidden sector scalar DM: secluded $U(1)$

Feng, Kaplinghat, Tu, Yu 09', ...

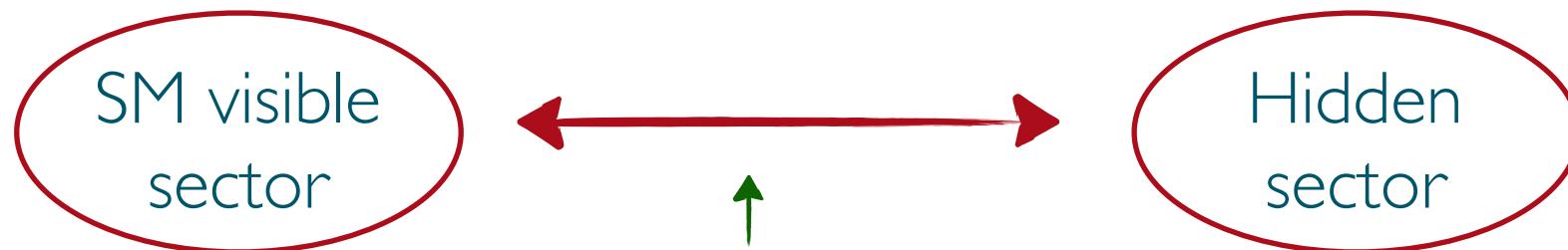
lightest scalar charged under an extra unbroken $U(1)'$



⇒ 6 parameters: $m_{DM}, \alpha', \epsilon, m_\phi, \lambda_\phi, \lambda_m$

Prototype model of hidden sector scalar DM: secluded $U(1)$

lightest scalar charged under an extra broken $U(1)'$



kinetic mixing and Higgs
portals

$$\mathcal{L} \ni -\frac{\varepsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu}$$

$$-\lambda_{m_1} H^\dagger H \phi_1^\dagger \phi_1$$

$$-\lambda_{m_2} H^\dagger H \phi_2^\dagger \phi_2$$



a scalar QED' structure with
2 charged scalars:

example: SSB of $U(1)'$ from
vev of ϕ_1 which has charge 2
+ ϕ_2 with charge 1: stable

⇒ 10 parameters: $m_{DM}, \alpha', \epsilon, v_\phi, m_{\phi_2}, \lambda_{\phi_2}, \lambda_{m_1}, \lambda_{m_2}, \lambda_{12}, \lambda'_{12}$

⇒ similar phenomenology + specific scalar phenomenology

Prototype model of hidden sector spin-1 DM

→ abelian? ← SM + a gauge $U(1)'$ spontaneously broken by a single charged scalar → perfectly viable spin-1 Z' DM model

T.H. 08', Lebedev, Lee, Mambrini 11'

→ but only if no $F'_{\mu\nu} F_Y^{\mu\nu}$ kinetic mixing

↑
requires an extra charge conjugation symmetry

→ non-abelian? ← no-kinetic mixing

→ minimal model: "Hidden vector DM"

T.H. 08'

Hidden vector DM: DM from accidental custodial symmetry

T.H. 08'

a $SU(2)_X$ gauge sym. + a scalar doublet ϕ

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu a}F_{\mu\nu}^a + (D^\mu\phi)^\dagger(D_\mu\phi) - \mu_\phi^2\phi^\dagger\phi - \lambda_\phi(\phi^\dagger\phi)^2$$

↓ ϕ gets a vev

3 massive gauge bosons V_i + a real scalar η

$$m_V = \frac{g_\phi v_\phi}{2}$$
$$m_\eta = \sqrt{2\lambda_\phi} v_\phi$$

↙ degenerate and stable due to residual accidental $SO(3)_c$ custodial sym.

(V_1, V_2, V_3) : triplet

η : singlet

+ communication with SM through Higgs portal $\mathcal{L} \ni -\lambda_m H^\dagger H \phi^\dagger \phi$

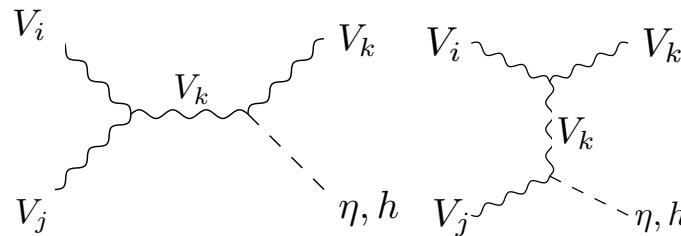
→ DM made of non-abelian gauge bosons with specific phenomenology

↙ with 4 parameters: $m_{DM}, g_D, m_\eta, \lambda_m$ ← DM mass and gauge sym.
breaking scale: same scale

Hidden vector specific phenomenology

T.H. 08', T.H., Tytgat 09', Arina, TH, Ibarra, Weniger 10'
D'Eramo, Thaler 10'

non-abelian gauge symmetry \Rightarrow DM semi-annihilations



today's semi-annih. of DM in the galactic center:
mono-chromatic flux of boosted DM: a "DM-line"
search in ν telescopes

Agashe, Cui, Necib, Thaler 14'

so far only a SuperK specific search

SuperKamiokande 18'

Hidden vector specific phenomenology

→ DM stable from accidental custodial symmetry: could be destabilized in the UV
as for the proton protected by accidental baryon number conservation

but spin-1 DM:

no destabilizing $SO(3)_c$ breaking dim-5 operator

only dim-6 operator: give a DM lifetime of order experimental

$$\frac{1}{\Lambda_{UV}^2} D_\mu \phi^\dagger D_\nu \phi F_Y^{\mu\nu}$$

$$\frac{1}{\Lambda_{UV}^2} \phi^\dagger F_{\mu\nu}^a \frac{\tau_a}{2} \phi F_Y^{\mu\nu}$$

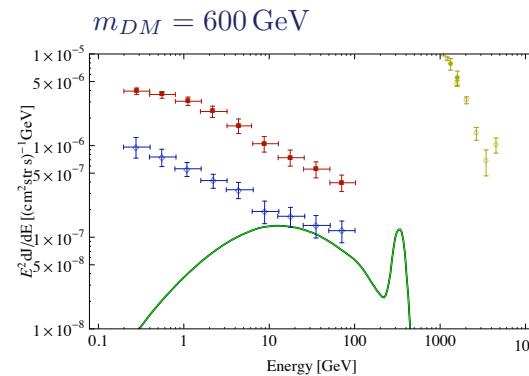
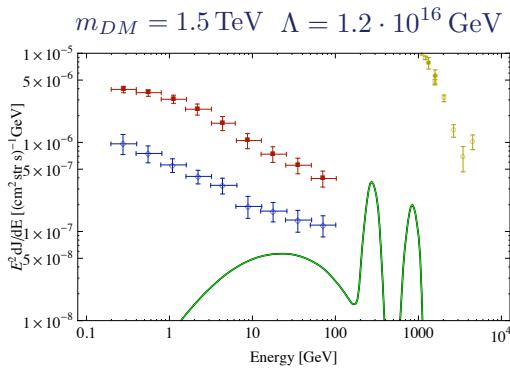
sensitivity if $m_{DM} \sim \text{TeV}$ and $\Lambda_{UV} \sim M_{GUT}$



2-body decay to a photon + X



intense γ -lines



Arina, TH, Ibarra, Weniger 10'

Stable DM in non-abelian confined frameworks

→ a minimal model with gauge-scalar dynamics:

hidden vector $SU(2)_X$ model in its confined phase

T.H.Tytgat 09'

if no SSB: $SU(2)_X$ confines at Λ_X scale

but accidental custodial sym. remains exact



the lightest boundstate transforming non trivially under $SO(3)_c$ is stable

→ confined phase - SSB phase duality:

Fradkin, Shenker 79'
t'Hooft 98'

SSB spectrum of
elementary states



spectrum of confined
bound states

η : singlet

(V_1, V_2, V_3) : triplet

$S \equiv \phi^\dagger \phi$: singlet

$V \equiv \phi^\dagger D_\mu \phi$: triplet



DM spin-1 triplet



DM spin-1 triplet
(multi-TeV)

Stable DM in non-abelian confined frameworks



a minimal model with pure gauge dynamics: hidden sector glueball DM

Faraggi, Pospelov 00'

Soni, Zhang 16'

- relic density from $3 \rightarrow 2$ processes
- DM self-interactions
- truly hidden sector DM: communication with the SM only
 - through gravity or higher dim. operators
 - ...

Gauge-scalar dynamics DM models: generalization to higher representations, higher groups, more multiplets,...

→ $SU(2)_X$ model with a real scalar triplet instead of doublet:

Baek, Ko, Park 13'

$SU(2)_X \rightarrow U(1)_{T_3^X}$: a dark photon + 2 stable massive gauge bosons

charged under conserved T_3^X
no custodial sym.

→ $SU(3)_X$ with 2 scalar fundamental representations

Gross, Lebedev, Mambrini 15'
Arcadi et al 16'

→ $SU(N)_X, SO(N)_X, Sp(N)_X$ with a single scalar 1 or 2 index representation

Buttazzo, Di Luzio, Landini, Strumia, Teresi 19'
Buttazzo, et al 20'

2 general messages: - stable particles come out of many of these cases, sometimes viable for DM

→ from remnant gauge or accidental global symmetries

- in many case a gauge $U(1)$ remains unbroken: charged DM with extra radiation

A very recent non-abelian setup:

DM from the center of $SU(N)$

Frigerio, Grinbaum-Yamamoto, TH, arXiv:2212.11918

DM from the center of $SU(N)$: basic simple idea

→ $SU(N)$ has a center subgroup: Z_N ← "N-ality"

each irreducible representation with n upper and m lower indices has Z_N charge equal to $n - m \pmod{N}$

$SU(2)$

fundamental: 2 : Φ^i ($i = 1, 2$) : Z_2 charge 1 : $\Phi^i \rightarrow e^{i\pi} \cdot \Phi^i$

adjoint: 3 : Φ_j^i ($i, j = 1, 2$) : Z_2 charge 0 : $\Phi_j^i \rightarrow \Phi_j^i$

$SU(3)$

fundamental: 3 : Φ^i ($i = 1, 2, 3$) : Z_3 charge 1 : $\Phi^i \rightarrow e^{i2\pi/3} \cdot \Phi^i$

anti-fundamental: $\bar{3}$: Φ_i ($i = 1, 2, 3$) : Z_3 charge -1 : $\Phi_i \rightarrow e^{-i2\pi/3} \cdot \Phi_i$

2-index symmetric: 6 : Φ^{ij} ($i, j = 1, 2, 3$) : Z_3 charge 2 : $\Phi^{ij} \rightarrow e^{i4\pi/3} \cdot \Phi^{ij}$

adjoint: 8 : Φ_j^i ($i, j = 1, 2, 3$) : Z_3 charge 0 : $\Phi_j^i \rightarrow \Phi_j^i$

3-index symmetric: 10 : Φ^{ijk} ($i, j, k = 1, 2, 3$) : Z_3 charge 0 : $\Phi^{ijk} \rightarrow \Phi^{ijk}$

⇒ if $SU(N)$ broken by a scalar Z_N singlet representation, the lightest component of any non singlet representation will be stable

2 minimal implementations:

→ $SU(2)$ implementation: broken by the adjoint $3 \equiv \Phi_j^i \Rightarrow Z_2$ unbroken
+ a fundamental scalar $2 \equiv \chi^i$: DM

→ $SU(3)$ implementation: broken by the $10 \equiv \Phi^{i,j,k} \Rightarrow Z_3$ unbroken
+ a fundamental scalar $3 \equiv \chi^i$: DM

DM from the center of $SU(2)$

→ $SU(2)$ implementation: broken by the adjoint $3 \equiv \Phi_j^i \Rightarrow Z_2$ unbroken
+ a fundamental scalar $2 \equiv \chi^i$: DM

Phenomenological main consequences:

I) gauge boson spectrum: $SU(2) \rightarrow U(1)_{T_3}$

$$V(\Phi) = -\frac{\mu^2}{2}\Phi^{ij}\Phi_{ji} + \frac{\lambda}{4}(\Phi^{ij}\Phi_{ji})^2$$

$$\langle \Phi^{ij}\Phi_{ji} \rangle = \mu^2/\lambda \equiv v_D^2$$

$$V_{portal} = \left(\lambda_{\chi H} \chi^i \tilde{\chi}_i + \frac{1}{2} \lambda_{\Phi H} \Phi^{ij} \Phi_{ji} \right) H^\dagger H$$

the T_3 neutral component in the $3, \rho$, takes a vev and is unstable (through Higgs portal)

from eating both other components of the $3, 2$ gauge bosons gets massive, W_D

the third gauge boson remains massless: dark photon \Rightarrow extra radiation

DM from the center of $SU(2)$

→ $SU(2)$ implementation: broken by the adjoint $3 \equiv \Phi_j^i \Rightarrow Z_2$ unbroken
+ a fundamental scalar $2 \equiv \chi^i$: DM

Phenomenological main consequences:

$$V(\Phi, \chi) = -\kappa \chi^i \Phi_{ij} \tilde{\chi}^j + \frac{1}{2} \lambda_{\chi\Phi} (\Phi^{ij} \Phi_{ji}) (\chi^i \tilde{\chi}_i)$$

2) χ^1 mixes with χ^{2*} and χ^2 mixes with χ^{1*} to form 2 mass eigenstates

$$\chi^+ = \cos \theta \chi^1 + \sin \theta \chi^{2*} \quad T_3 = 1/2 \quad T_3^\chi = 1/2$$

$$\chi^- = \cos \theta \chi^2 - \sin \theta \chi^{1*} \quad T_3 = -1/2 \quad T_3^\chi = 1/2$$

in the mass eigenstate basis there is an accidental global symmetry $U(1)_\chi$ under which χ^+ and χ^- have same charge \Rightarrow given that W_D^\pm have $T_3 = \pm 1$, $T_3^\chi = 0$ the only possible decays are $W_D^\pm \rightarrow \chi^\pm (\chi^\mp)^*$ or $\chi^+ \rightarrow \chi^- W_D^+$ ($m_{\chi^+} > m_{\chi^-}$)

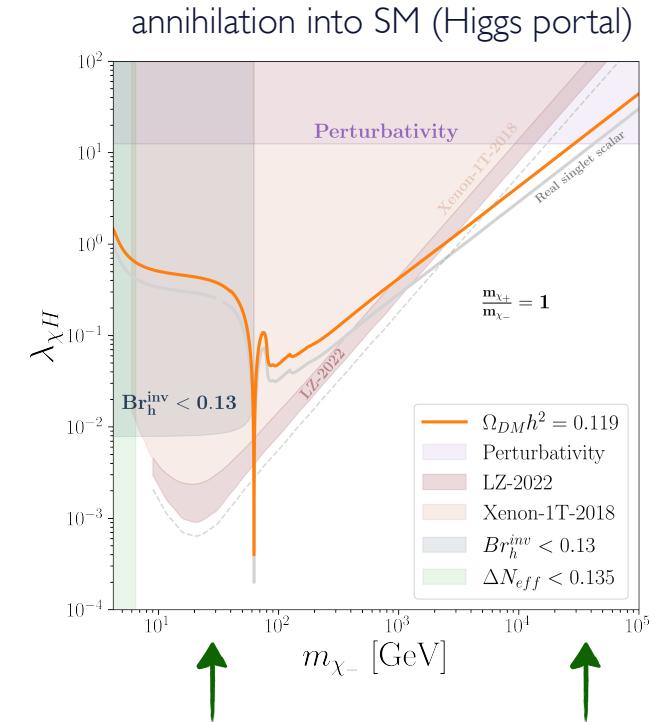
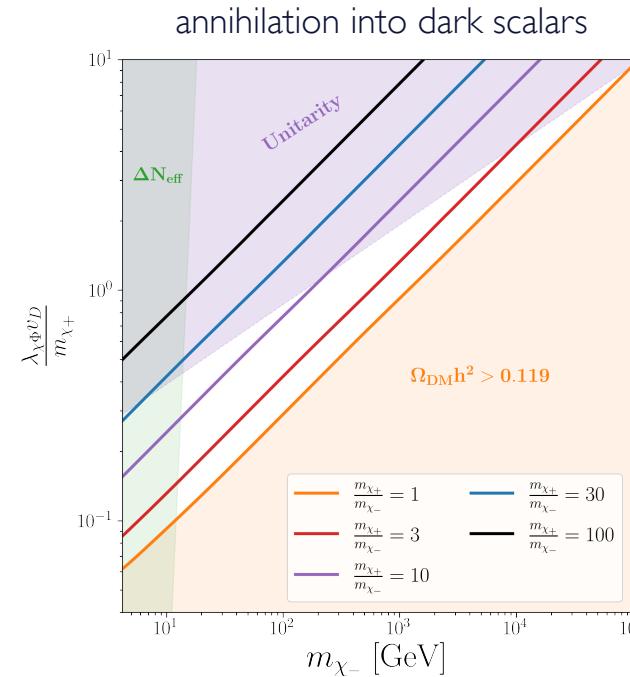
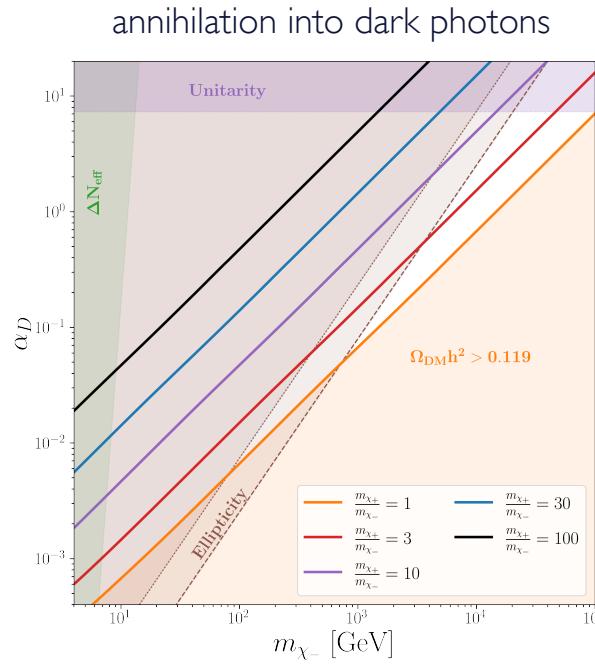
- multicomponent DM:
- DM content A: χ_- and χ_+ , for $m_{\chi_+} + m_{\chi_-} < m_{W_D}$
 - DM content B: χ_- , χ_+ and W_D , for $m_{\chi_+} - m_{\chi_-} \leq m_{W_D} \leq m_{\chi_+} + m_{\chi_-}$
 - DM content C: χ_- and W_D , for $m_{W_D} < m_{\chi_+} - m_{\chi_-}$

DM from the center of $SU(2)$

→ $SU(2)$ implementation: broken by the adjoint $3 \equiv \Phi_j^i \rightarrow Z_2$ unbroken
+ a fundamental scalar $2 \equiv \chi^i$: DM

Phenomenological main consequences:

3) many ways to account for the DM relic density



+ non-freeze-out DM production regimes,
DM self-interaction, long range force,
Higgs portal phenomenology, ...

specific Higgs portal scenario with 2 DM states
annihilating through the same Higgs portal

DM from the center of $SU(3)$

→ $SU(3)$ implementation: broken by the adjoint $10 \equiv \Phi^{i,j,k}$ $\Rightarrow Z_3$ unbroken
 + a fundamental scalar $3 \equiv \chi^i$: DM

Complex interesting vacuum structure

$$\begin{aligned} V(\Phi) = & -\mu^2 \Phi_{ijk}^* \Phi^{ijk} + \lambda \left(\Phi_{ijk}^* \Phi^{ijk} \right)^2 + \delta \Phi^{i_1 j_1 k_1} \Phi_{i_1 j_1 k_2}^* \Phi^{i_2 j_2 k_2} \Phi_{i_2 j_2 k_1}^* \\ & + \left(\eta \epsilon_{i_1 i_2 i_3} \epsilon_{j_1 j_2 j_3} \Phi^{i_1 j_1 k_1} \Phi^{i_2 j_2 k_2} \Phi^{i_3 j_3 k_3} \Phi_{k_1 k_2 k_3}^* + h.c. \right) \\ & + \left(\sigma \epsilon_{i_1 j_2 k_3} \epsilon_{i_4 j_1 k_2} \epsilon_{i_3 j_4 k_1} \epsilon_{i_2 j_3 k_4} \Phi^{i_1 j_1 k_1} \Phi^{i_2 j_2 k_2} \Phi^{i_3 j_3 k_3} \Phi^{i_4 j_4 k_4} + h.c. \right) \end{aligned}$$

in the limit $\eta, \sigma \rightarrow 0$ the vacuum has flat directions beyond the Goldstone boson ones..

for $\eta, \sigma \neq 0$ and for a large fraction of the parameter space the minimum is in

$$\underline{\underline{\langle \Phi^{123} \rangle \equiv v_D \neq 0}} \quad \underline{\underline{\langle \Phi^{ijk} \rangle = 0 \text{ if } i = j \text{ or } i = k \text{ or } j = k}}$$

→ accidental symmetry S_3 : any permutation of i, j, k

DM from the center of $SU(3)$

→ $SU(3)$ implementation: broken by the adjoint $10 \equiv \Phi^{i,j,k}$ $\Rightarrow Z_3$ unbroken
+ a fundamental scalar $3 \equiv \chi^i$: DM

3 phenomenological consequences:

I) 2 massless dark photons

$$SU(3) \rightarrow U(1)_3 \times U(1)_8$$

\uparrow

$$\langle \Phi^{123} \rangle \equiv v_D \neq 0$$

← allowed by BBN and CMB extra radiation constraints
soon to be seen or excluded!

2 dark photons: undistinguishable: same mass and same gauge coupling

\uparrow

they are in a doublet of accidental S_3

⇒ a “4-component photon” + 6 massive degenerate gauge bosons

\uparrow

in a complex triplet of accidental S_3

DM from the center of $SU(3)$

→ $SU(3)$ implementation: broken by the adjoint $10 \equiv \Phi^{i,j,k}$ $\Rightarrow Z_3$ unbroken
+ a fundamental scalar $3 \equiv \chi^i$: DM

3 phenomenological consequences:

2) Degenerate DM mass spectrum:

the 3 components of the fundamental repres. $3 \equiv \chi^i$ are degenerate and stable: DM

in a triplet of accidental symmetry S_3 Z_3



DM from the center of $SU(3)$

→ $SU(3)$ implementation: broken by the adjoint $10 \equiv \Phi^{i,j,k}$ $\Rightarrow Z_3$ unbroken
+ a fundamental scalar $3 \equiv \chi^i$: DM

3 phenomenological consequences:

3) Semi-annihilations:

$$V(\Phi, \chi) = (\kappa \Phi^{ijk} \chi_i^* \chi_j^* \chi_k^* + h.c.) + \lambda_{\chi\Phi} (\Phi^{ijk} \Phi_{ijk}^*) (\chi^i \chi_i^*) + \lambda'_{\chi\Phi} \chi_i^* \Phi^{ijk} \Phi_{jkl}^* \chi^l$$



tri-linear DM interactions from tri-ality: $\chi^i \chi^j \rightarrow \chi^k X \quad X = h, \rho, \gamma_3, \gamma_8, \dots$

there is an all regime where semi-annihilation into SM Higgs boson are dominant:

$\chi^i \chi^j \rightarrow \chi^k h$ from κ interaction large + Higgs portal $\lambda_{\Phi H} H^\dagger H \Phi^\dagger \Phi$

$\langle \sigma_{\chi^i \chi^j \rightarrow \chi^k h} v \rangle$ fixed by freeze-out relic density

prediction of a "DM-line" from GC with predicted intensity and energy

$$E_\chi = (5m_\chi^2 - m_h^2)/(4m_\chi) \quad E_h = (3m_\chi^2 + m_h^2)/(4m_\chi)$$

possible observation in neutrino telescopes

DM from the center of $SU(3)$

→ $SU(3)$ implementation: broken by the adjoint $10 \equiv \Phi^{i,j,k}$ $\Rightarrow Z_3$ unbroken
+ a fundamental scalar $3 \equiv \chi^i$: DM

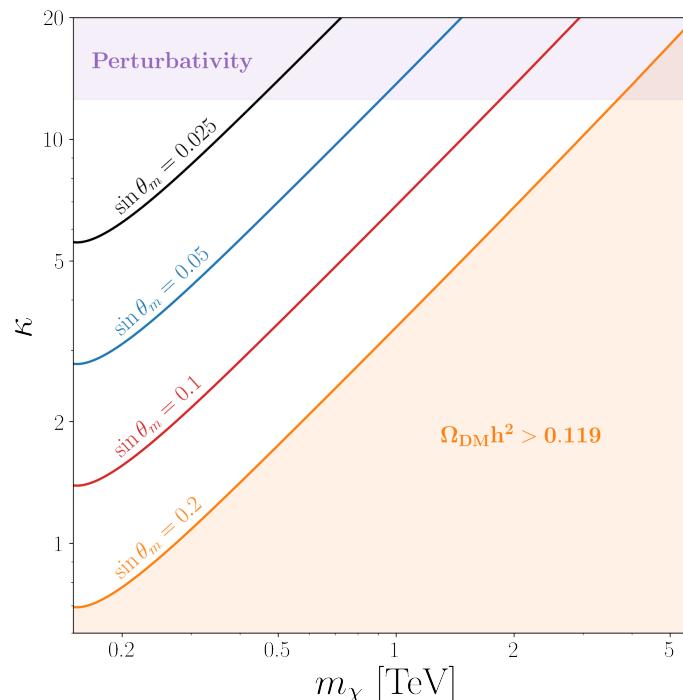
3 phenomenological consequences:

3) Semi-annihilations: $\chi^i \chi^j \rightarrow \chi^k h$

$$E_\chi = (5m_\chi^2 - m_h^2)/(4m_\chi)$$

$$E_h = (3m_\chi^2 + m_h^2)/(4m_\chi).$$

values of κ leading to the observed relic density through semi-annihilations:



Outline

A large variety of simple stabilization mechanisms exist based on new gauge symmetries

Very rich and diverse associated specific phenomenology

- several associated basic DM production regimes
- associated dark radiation
- residual accidental global symmetries (continuous or discrete), especially in
non-abelian case



- DM slow decay indirect detection phenomenology (intense γ -line)
- semi-annihilations: "DM-line"
- multi-component DM
- DM direct detection (boosted signal)
- generic DM self-interactions
- low scale DM partners from same multiplet
- Monopoles
- confined non-abelian structures
- ...

