Well-tempered n-plet dark matter

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Motivation: WIMPs

Observation:

EW-scale mass + EW-scale cross section
$\Rightarrow$ thermal relic density $\Omega h^2 \approx 0.1$ = observed value

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"WIMP miracle"

Motivation: WIMPs

A closer look:

To match the observed relic density

- a thermal higgsino needs $m = 1.1$ TeV $\gg m_Z$
- a thermal wino needs $m = 2.5$ TeV $\gg m_Z$
- minimal DM (fermionic 5-plet or scalar 7-plet) needs $m \approx 10$ TeV $\ggg m_Z$
- ...

A WIMP with generic electroweak quantum numbers and a mass of ~ 100 GeV has a too large annihilation cross section.

A WIMP which is within kinematic reach of LHC is necessarily mostly $SU(2) \times U(1)$ singlet.

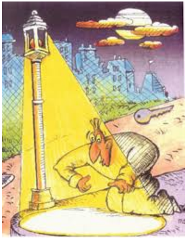
Motivation: WIMPs

Assumptions for this talk:

- DM = mostly SU(2) × U(1) singlet
- Some admixture of non-singlet state for right relic density from coannihilation
- Mass of order 100 GeV to be within LHC reach

Q: Why should nature care about LHC discovery potential?

A: She might not — but we do!



Motivation: WIMPs

Further assumptions:

- DM is a fermion
- Stabilized by $\mathbb{Z}_2$
- Sub-TeV particle content is minimal
- We don't consider EW doublets
  $\rightarrow$ extensive literature on well-tempered bino-higgsino and its non-SUSY version

Dark matter is a singlet fermion χ mixing with an n-plet fermion ψ ($n \geq 3$) through higher-dimensional operators.

States inducing the mixing live at scales $\gtrsim$ TeV $\Rightarrow$ mostly irrelevant for LHC if carrying only EW charges.

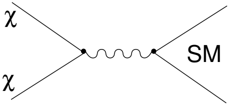
Familiar example: Split SUSY with somewhat heavy higgsinos and $M_1 < M_2$. DM is mostly bino, mixing with wino through dimension-5 operator

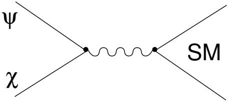
$$\mathcal{L}_{\text{mix}} = \frac{\tilde{g}_u \tilde{g}'_d + \tilde{g}_d \tilde{g}'_u}{\mu} \, \phi^\dagger \tau^a \phi \, \widetilde{W}^a \, \widetilde{B}$$

$\rightarrow$ e.g. Arkani-Hamed/Delgado/Giudice '06

Relic density

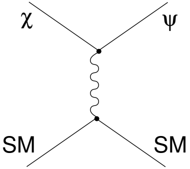
Somewhat under-appreciated fact: Coannihilation can be very efficient in reducing the DM relic density even when DM coupling to SM is tiny.



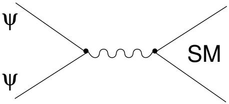


can be small

provided that χ remains in equilibrium via



and that

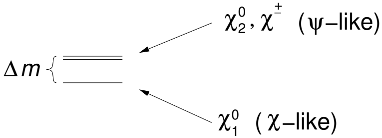


is efficient.

Annihilation of ψ efficiently depletes χ density,
even if $\psi - \chi$ mixing angle is $\ll 1$.

First case study: SU(2) triplets

Particle content: one charged and two neutral fermions

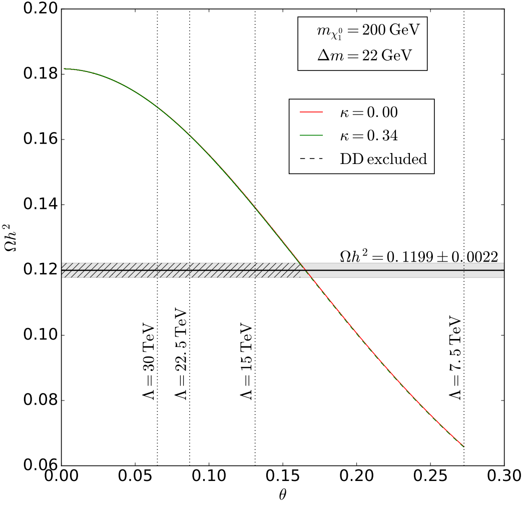


Interactions of χ_1^0 with SM mainly through two operators:

$$\mathcal{L} = \frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \frac{\lambda}{\Lambda}\phi^\dagger\tau^a\phi\,\psi^a\chi + \text{h.c.}$$

ϕ = SM Higgs; Λ = cutoff scale.
Wilson coefficients κ, λ both contribute to DM annihilation ($\Rightarrow$ thermal relic density) and DM-nucleus scattering ($\Rightarrow$ direct detection).
Trade λ for mixing angle $\theta = \frac{\lambda}{\Lambda}\frac{v^2}{\Delta m}$

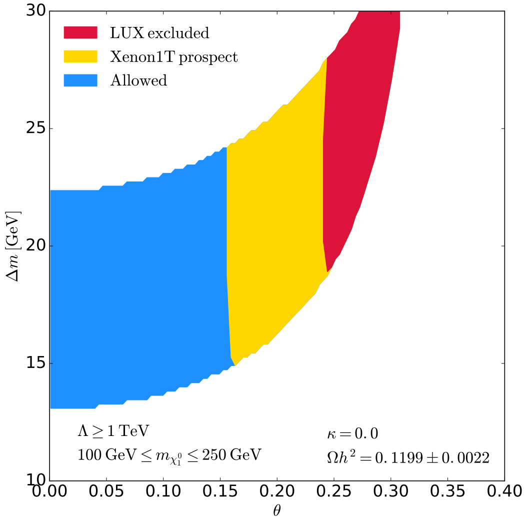
First case study: SU(2) triplets



Any κ large enough to influence relic density significantly is ruled out by direct detection.

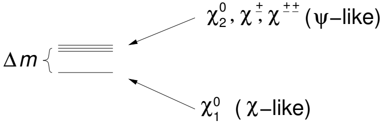
First case study: SU(2) triplets

For $\kappa = 0$:



Second case study: SU(2) quintuplets

Particle content: one doubly charged, one singly charged and two neutral fermions

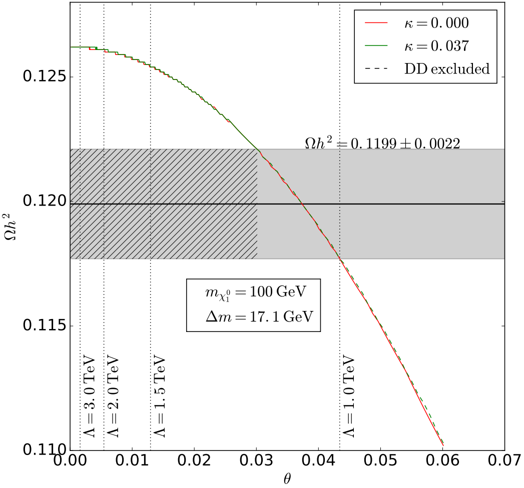


- Doubly charged state ⇒ potentially characteristic signatures at LHC (long-lived)
- Mixing operator is now dimension 7:

$$\frac{\lambda}{\Lambda^3}\phi^{\dagger i}\phi_j\phi^{\dagger k}\phi_\ell \; C_{A\,ik}^{j\ell}\psi^A\chi + \text{h.c.}$$

⇒ mixing angles small for reasonable cutoff scale ($\Lambda \gtrsim$ TeV)

Second case study: SU(2) quintuplets



Similar to triplet case. Mass parameters need some tuning. Wilson coefficient κ for dimension-5 operator $\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi$ already tightly constrained by direct detection.

First case study: SU(2) quintuplets

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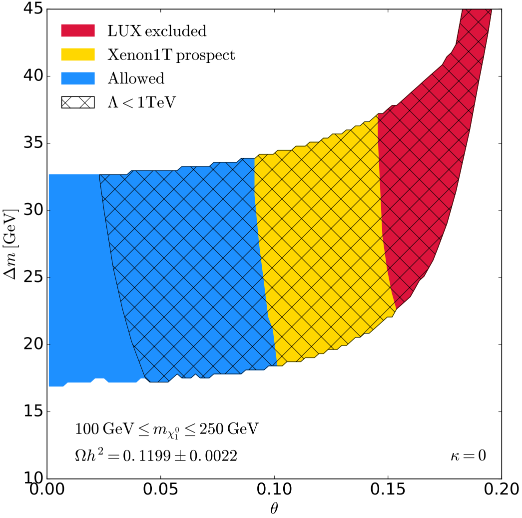

On quadruplets

The quadruplet (isospin 3/2) case is more complicated because

- we now need a Dirac fermion $(\psi, \overline{\psi})$
- one doubly charged, two singly charged mass eigenstates
- three neutral mass eigenstates $\Rightarrow$ two relevant neutral mixing angles
- spectrum depends on additional Wilson coefficients inducing non-universal mass splittings in the ψ sector
- proliferation of parameters

Result of our analysis: Qualitatively similar conclusions as for triplet/quintuplet case $\rightarrow$ FB/Bharucha/Ruffault '17

Conclusions

- Dark matter could be a mixed singlet-n-plet with an EW-scale mass.
- Effective theory. Mixing induced by higher-dimensional operators.
- Simplest example: Well-tempered bino-wino in split SUSY.
- More interesting for colliders: Singlet-quintuplet (doubly charged states).
- LUX already very constraining, even more so with Xenon1T.
- Collider phenomenology: under investigation.