Well-tempered next-to-minimal dark matter

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Motivation: WIMPs

Observation:

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

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“WIMP miracle”

A closer look

Does this back-of-an-envelope survive when doing a proper calculation?

No — in fact we're $1-2$ orders of magnitude short of a miracle:

- 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 $\mathrm{SU}(2) \times \mathrm{U}(1)$ singlet.

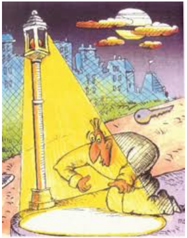
This talk's WIMP

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!



This talk’s WIMP

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.

A familiar example

Split SUSY with somewhat heavy higgsinos and $M_1 < M_2$.
DM is mostly bino (singlet), mixing with wino (3-plet) through dimension-5 operator

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

where $\phi =$ SM-like Higgs doublet.

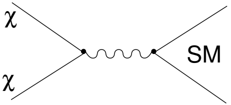
Example of a "well-tempered neutralino" → e.g. Arkani-Hamed/Delgado/Giudice '06
Pheno details: e.g. → Rolbiecki/Sakurai '15, Nagata/Otono/Shirai '15

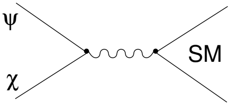
Features:

- Rather small direct detection cross section (small mixing angle in MSSM, no Z coupling to either bino or wino)
- Tiny indirect detection cross section (DM mostly singlet)

Relic density

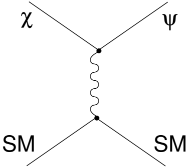
Somewhat under-appreciated fact: Coannihilation can be very efficient in reducing the DM relic density even when DM coupling to SM is tiny.



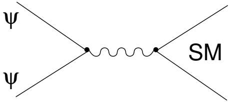


can be small

provided that χ remains in equilibrium via



and that



is efficient.

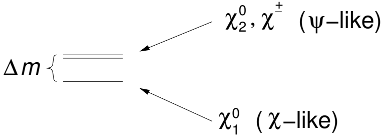
Annihilation of ψ efficiently depletes χ, even if $\psi - \chi$ mixing angle is $\ll 1$.

→ Bharucha/FB/Ruffault '17, D'Agnolo/Pappadopulo/Ruderman '17, Garny/Heisig/Lülf/Vogl '17

First case study: SU(2) triplets

→ See also talk by A. Filimonova on Wednesday (pseudoscalar coupling)

Particle content: one charged and two neutral fermions

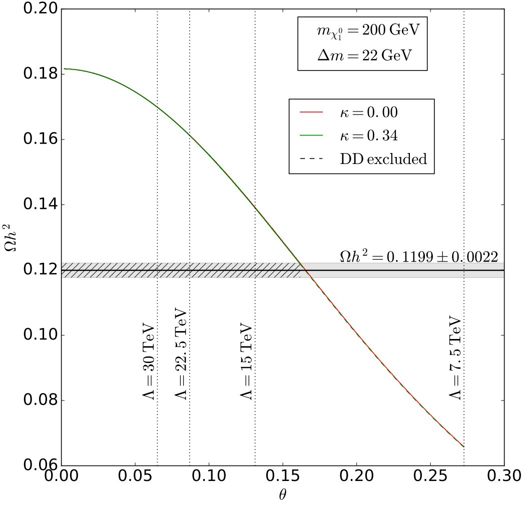


Interactions of χ_1^0 with SM mainly through two operators:

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

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

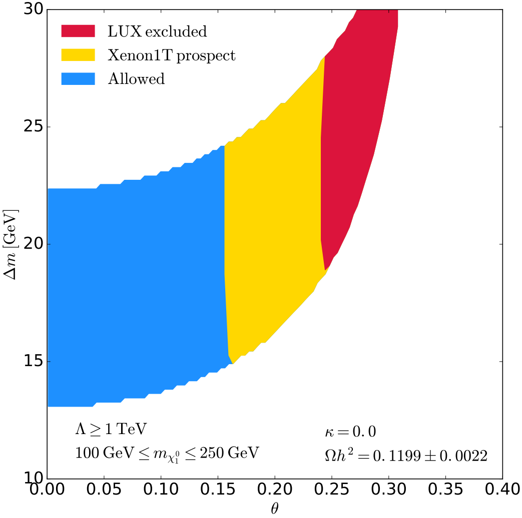
First case study: SU(2) triplets



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

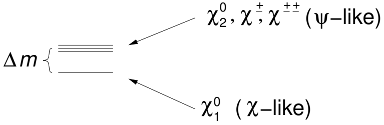
First case study: SU(2) triplets

For $\kappa = 0$:



Second case study: SU(2) quintuplets

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

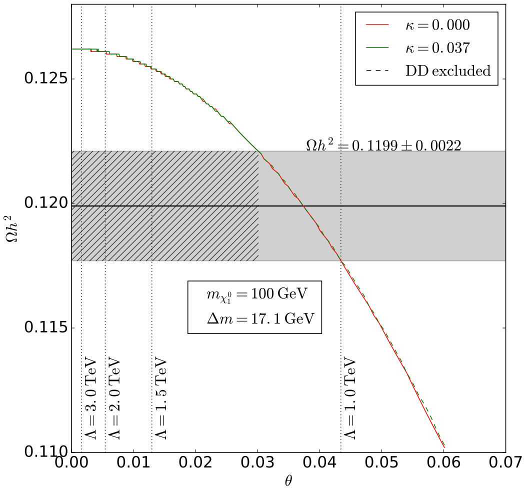


- Doubly charged state ⇒ potentially characteristic signatures at LHC (long-lived)
- Mixing operator is now dimension 7:

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

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

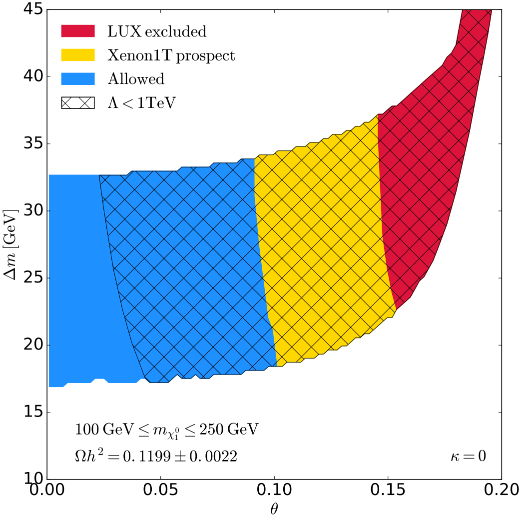
Second case study: SU(2) quintuplets



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

For $\kappa = 0$:



On quadruplets

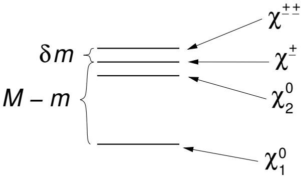
The quadruplet (isospin 3/2) case is more complicated because

- we now need a Dirac fermion $(\psi, \overline{\psi})$
- one doubly charged, two singly charged mass eigenstates
- three neutral mass eigenstates ⇒ 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 → FB/Bharucha/Ruffault '17

Collider phenomenology: Displaced leptons

Zoom in on the quintuplet mass spectrum:



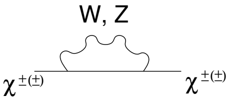
where

$$\delta m = \delta m^{\text{(tree)}} + \delta m^{\text{(1-loop)}}$$

Source for $\delta m^{\text{(tree)}}$ is dimension-7 operator:

$$\frac{1}{\Lambda^3}\underbrace{C^{ABC}}_{\text{tot. symmetric}}\psi_A\psi_B(\phi^\dagger\phi\phi^\dagger\phi)_C \qquad \Rightarrow \qquad \left|\delta m^{\text{(tree)}}\right| \lesssim \text{few 100 MeV}$$

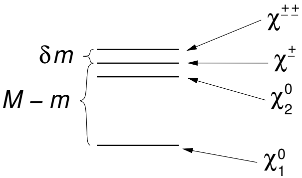
Source for $\delta m^{\text{1-loop}}$ are electroweak loops:



$$\Rightarrow \qquad \delta m^{\text{(one-loop)}} \approx 500\text{ MeV}$$

Collider phenomenology: Displaced leptons

Zoom in on the quintuplet mass spectrum:



Numerically: $M - m \approx 15 - 50$ GeV (coannihilation), $\delta m \approx$ few 100 MeV.

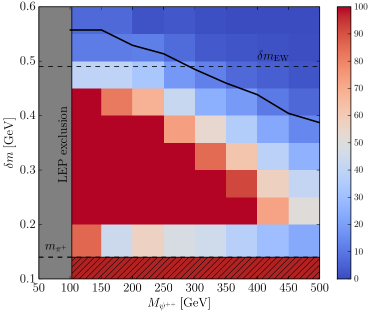
Typical $\chi^{\pm\pm}$ decay:

$$\chi^{\pm\pm} \to \chi^{\pm}(\to \chi_1^0 \ell^{\pm} \nu_\ell)\pi^{\pm}$$

- Decay into singly-charged $\chi^{\pm}$ and pion via off-shell W is only open 2-body mode. Pion too soft to be seen.
- Small mass splitting $\delta m \Rightarrow$ small phase space $\Rightarrow$ macroscopic decay length ≈ 0.5 mm
- Lepton from subsequent $\chi^{\pm}$ decay will be displaced.

Collider phenomenology: Displaced leptons

- CMS has published searches for displaced OS leptons at 8 TeV → PRL 114 (2015) 6 and 13 TeV → CMS-PAS-EXO-16-022
- 8 TeV analysis gives better constraints because of looser lepton p_T cuts (At 13 TeV, hard cuts to completely remove heavy flavour backgrounds)
- Exclusion (black curve) as a function of M and δm:



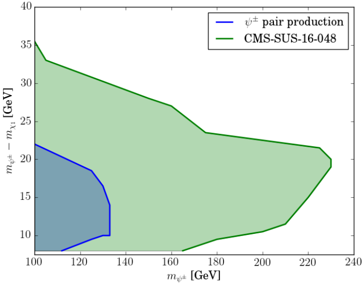
Collider phenomenology: Soft dileptons

Triplet model usually doesn't have long-lived states)

Instead: Low-momentum OS lepton pairs

Search for compressed SUSY neutralino-chargino pair production
→ CMS-PAS-SUS-16-048 allows to constrain triplet model. Exclusion depends on preferred χ_2 decay mode:

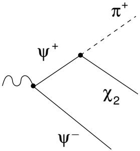
- green curve: CMS analysis, assuming $\chi_2\psi^\pm$ production with $\chi_2 \rightarrow \chi_1 Z^*$
- blue curve: recast for $\psi^+\psi^-$ production if $\chi_2 \rightarrow \chi_1 h^*$ (no leptons)

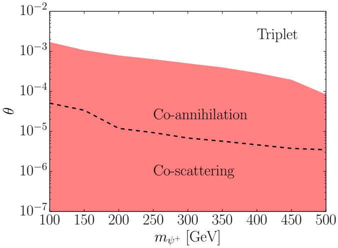


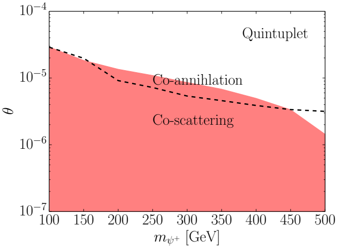
Collider phenomenology: Disappearing tracks

For very small mixing angles $\lesssim 10^{-3}$ between singlet χ and *n*-plet ψ: singly-charged ψ^+ decays into χ_2 (ψ-like) rather than directly into χ_1 (χ-like).

Mass degeneracy in *n*-plet sector ⇒ long-lived ψ^+ ⇒ disappearing track







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.
- LUX already very constraining, Xenon1T even more.
- Collider signatures:
    - Displaced leptons in quintuplet model
    - Soft dileptons in triplet model (weaker constraints)
    - Disappearing tracks in both (if mixing angle small)