Next-to-minimal dark matter

Felix Brümmer

1703.00370, with A. Bharucha and R. Ruffault
1804.02357, with A. Bharucha and N. Desai
and work in progress

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The summary to start with

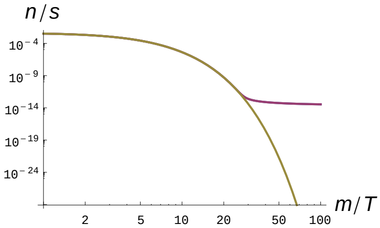
What I want to show in this talk:

- Sub-TeV WIMPs are still alive…
- …even the Original WIMP$^{\text{TM}}$ = the MSSM neutralino
- The LHC will further constrain them using long-lived particle searches
- More outlandish models give more outlandish signatures

What is a WIMP?

This talk's definition:

- A WIMP is a thermal relic.
- At large temperatures it is in thermal equilibrium. At temperatures $T \lesssim m$ its number density decreases exponentially due to scattering processes.
- At temperatures $T \lesssim T_{\text{freeze-out}}$ these processes become inefficient and its number density becomes constant.



- WI = "weakly interacting". We take as part of the definition: DM abundance generated by electroweak processes.

WIMPs

First possibility: DM itself carries electroweak quantum numbers.

E.g. generic MSSM neutralino:

$$\chi_1^0 = \alpha\,\widetilde{H}_u^0 + \beta\,\widetilde{H}_d^0 + \gamma\,\widetilde{B} + \delta\,\widetilde{W}^0$$

This is largely ruled out below a TeV by direct detection → see e.g. Krall&Reece '17

Some remaining options:

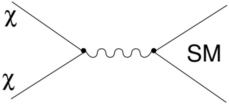
- mostly-bino χ_1^0 coannihilating with sleptons, or annihilating via Z- or Higgs funnel → e.g. GAMBIT collaboration '18
- pseudo-Dirac higgsino, $m_{\chi_1^0} = 1.1$ TeV → A. Delgado's talk
- pure wino, $m = 2.5$ TeV (but under pressure from indirect detection)
- SU(2) 5-plet fermion, $m_5 \approx 10$ TeV
- SU(2) 7-plet scalar, $m_7 \approx 25$ TeV
- ...

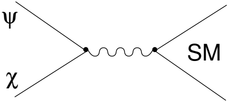
(first three items: SUSY; last two items: MDM)

WIMPs

Second possibility: DM χ does not interact much with the EW sector but remains in equilibrium by scattering with some particle ψ which does.

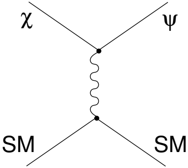
This will be the case for most of this talk's WIMPs. Specifically:



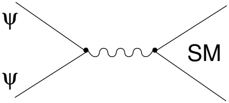


can be small

provided that χ remains in equilibrium via conversion



and that



is efficient.

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

The case of marginally efficient conversion processes is especially interesting

$\rightarrow$ D'Agnolo/Pappadopulo/Ruderman '17, Garny/Heisig/Lülf/Vogl '17

Next-to-minimal dark matter

For the purposes of this talk:

- DM χ is mostly a Majorana singlet
- Stabilized by $\mathbb{Z}_2$
- Coannihilation partner ψ is a $\mathbb{Z}_2$-odd fermionic *n*-plet of SU(2)
- Sub-TeV particle content is minimal: there is only ψ and χ
- We don't consider SU(2) doublets (mostly ruled out by direct detection anyway) $\rightarrow$ 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 $\Rightarrow$ 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

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

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

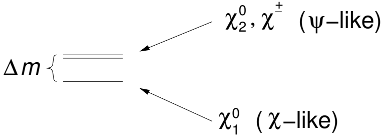
Features:

- 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)

First case study: SU(2) triplets

$\rightarrow$ See also talk by A. Filimonova

Particle content: one charged and two neutral fermions

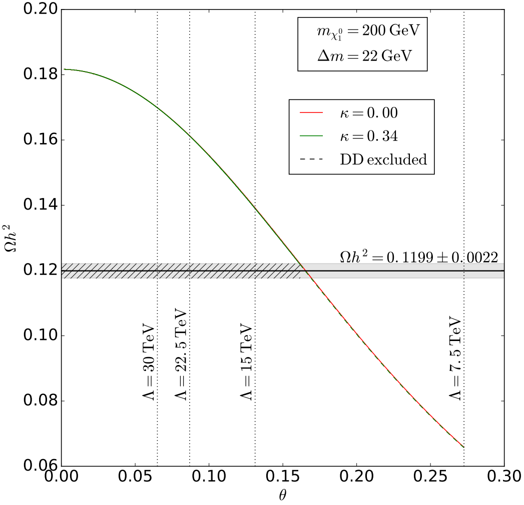


Interactions of χ_1^0 with SM mainly through two operators:

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

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 $\theta = \frac{\lambda}{\Lambda}\frac{v^2}{\Delta m}$

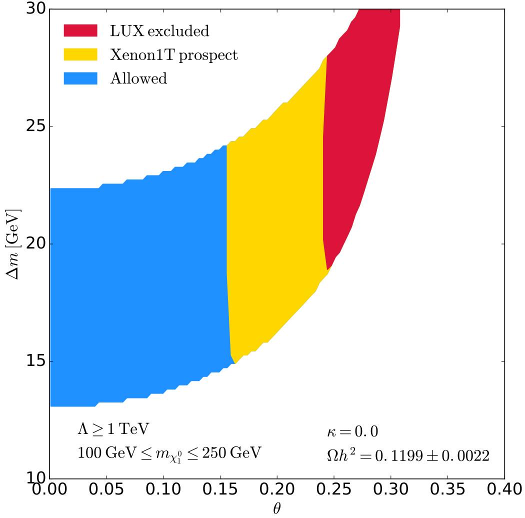
First case study: SU(2) triplets



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

First case study: SU(2) triplets

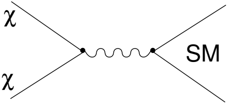
For $\kappa = 0$:

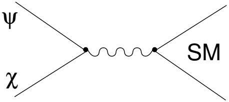


SU(2) triplets at (really) small mixing angle

How far away can the cutoff scale Λ be?

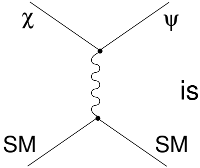
Remember: we don't need





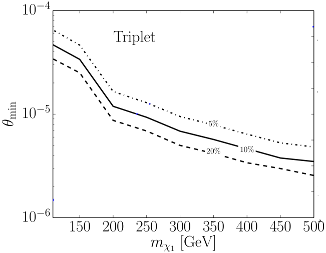
($\propto \theta^2$, doubly Boltzmann-suppressed)

provided that



is effective ($\propto \theta^2$, singly Boltzmann-suppressed)

Still the case for surprisingly small θ:

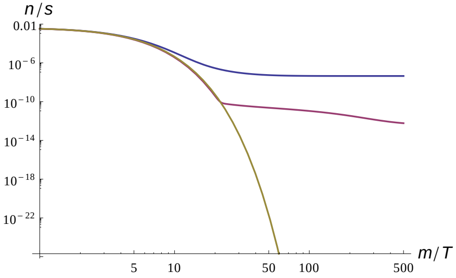


SU(2) triplets at (really) small mixing angle

At even smaller mixing: Relic density no longer determined by ψ annihilations freezing out but by χ SM $\rightarrow$ ψ SM conversion rate dropping below Hubble rate

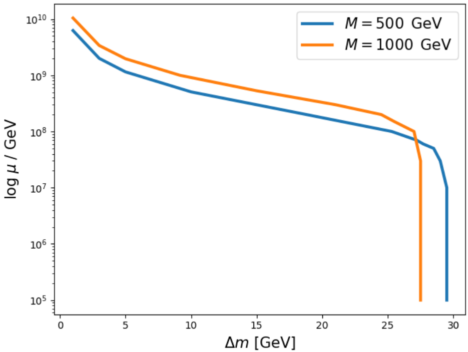
$\rightarrow$ D'Agnolo/Pappadopulo/Ruderman '17, Garny/Heisig/Lülf/Vogl '17

- "Effective number density" formalism used by standard codes no longer applicable: need to solve full Boltzmann equations, including conversion terms
- DM number density departs from equilibrium earlier $\Rightarrow$ increased Ωh^2
- Can compensate (to some extent) by varying Δm
- "Conversion-driven freeze-out", "Coscattering"



χ abundance, ψ abundance, equilibrium

Special case: Split SUSY at (really) large μ

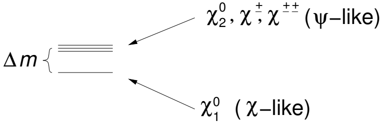


$\tan\beta = 1$ $\quad \Omega h^2 = 0.12 \quad \Delta m \equiv m_{\chi_1^\pm} - m_{\chi_1^0}$

- Coannhilation phase: $\Delta m \approx$ const.
- Coscattering phase at large $\mu \gtrsim 10^7$ GeV

Second case study: SU(2) quintuplets

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

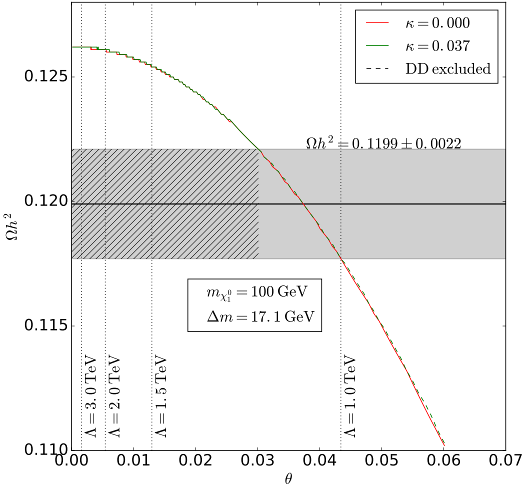


- Doubly charged state $\Rightarrow$ potentially characteristic signatures at LHC (long-lived)
- Mixing operator is now dimension 7:

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

$\Rightarrow$ mixing angles guaranteed to be small for cutoff scale $\Lambda \gtrsim$ TeV

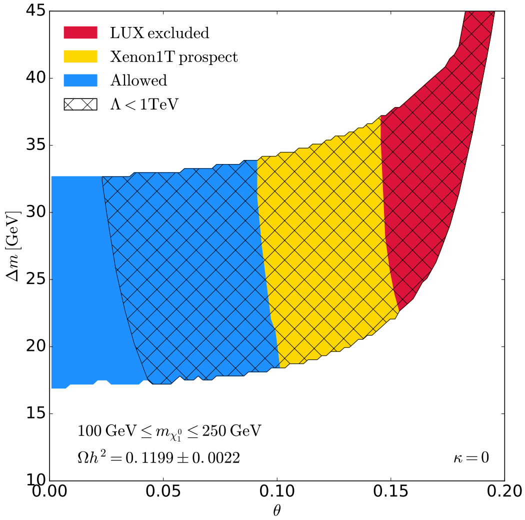
Second case study: SU(2) quintuplets



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

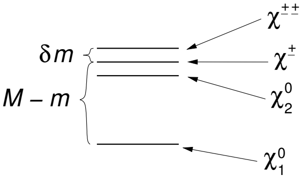
The quadruplet (isospin 3/2) case is more complicated because

- we now need a Dirac fermion $(\psi, \overline{\psi})$
- one doubly charged, two singly charged mass eigenstates
- three neutral mass eigenstates $\Rightarrow$ 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

Collider phenomenology: Displaced leptons

Zoom in on the quintuplet mass spectrum:



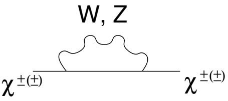
where

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

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

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

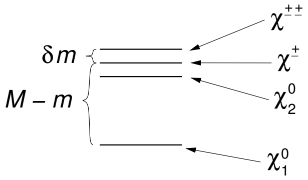
Source for $\delta m^{\text{1-loop}}$ are electroweak loops:



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

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.

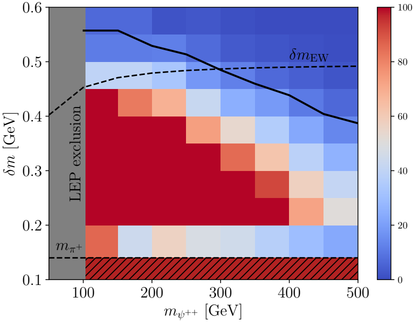
Typical $\chi^{\pm\pm}$ decay:

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

- 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:



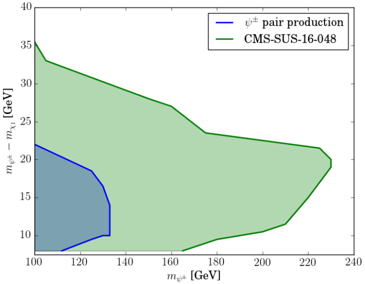
Collider phenomenology: Soft dileptons

Triplet model doesn't have long-lived states except at very small θ

Instead: Low-momentum OS lepton pairs

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

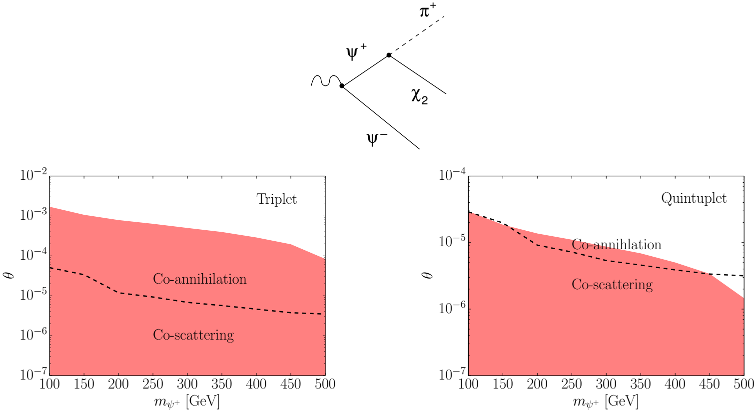
- green curve: CMS analysis, assuming $\chi_2\psi^\pm$ production with $\chi_2 \rightarrow \chi_1 Z^*$
- blue curve: recast for $\psi^+\psi^-$ production if $\chi_2 \rightarrow \chi_1 h^*$ (no leptons)



Collider phenomenology: Disappearing tracks

For small mixing angles $\theta \lesssim 10^{-3}$: 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. “Phase diagram” for neutralino dark matter.
- LUX already very constraining, Xenon1T even more. But at small mixing, DD constraints go away.
- Collider signatures:
  - Displaced leptons in quintuplet model
  - Soft dileptons in triplet model (weaker constraints)
  - Disappearing tracks in both (if mixing angle small)
  - A 500 GeV bino-like neutralino is not excluded if it coannihilates/coscatters with a wino-like chargino and neutralino. If it coscatters, the chargino will soon be found in disappearing track searches.