Thermal Dark Matter and the Higgs

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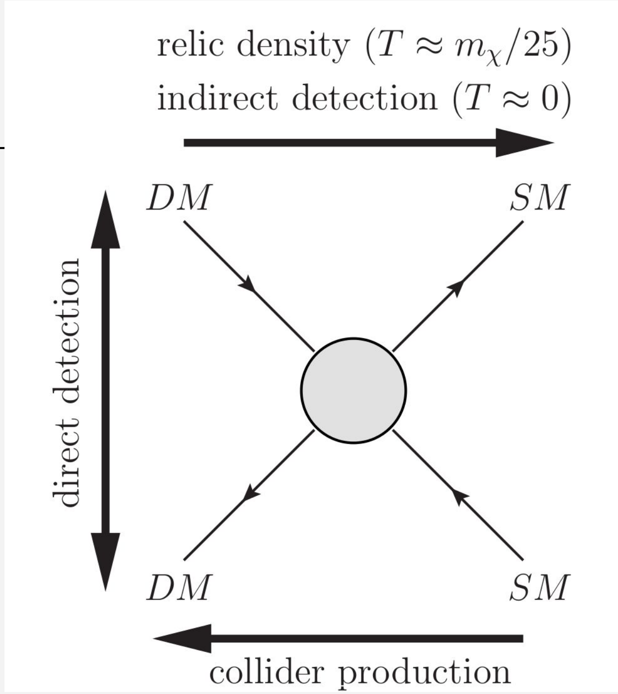
WIMP Dark Matter

Vanilla thermal production:

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ cm^3/s$

but direct detection limits are very strong

Production and direct detection cross-sections must be decoupled (unless $m_{DM} \gg 100$ GeV)



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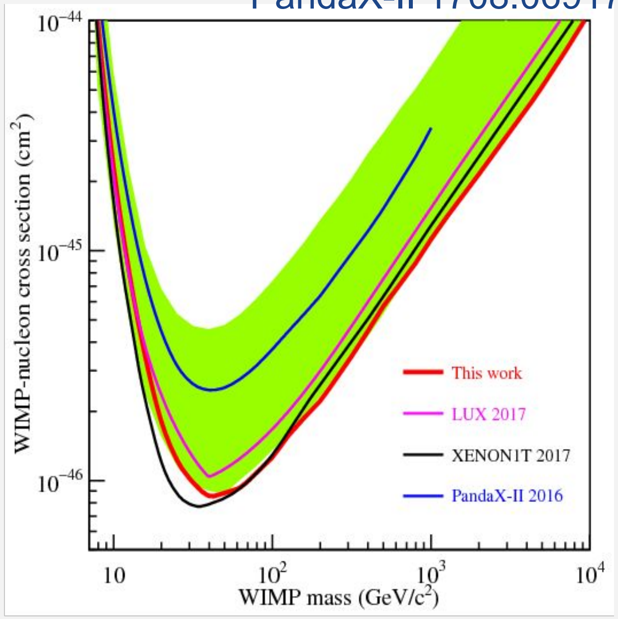

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Griest&Seckel, PRD 43, 3197 (1991)

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Both options require extended BSM sectors to supply either

- co-annihilation partners
- Multiple mediators allowing for destructive interference

Model-building

- Dark Matter candidate: Majorana fermion χ
- Type II 2 Higgs Doublet Model (2HDM) (H_u, H_d)
- Invoke a Z_3 symmetry under which all scalars/fermions transform as $\psi \to e^{2\pi i} \psi$ to forbid Majorana mass for χ
- Weak scale mass for χ can be obtained via the vacuum expectation value (vev) of an extra SM-singlet (complex) scalar S
  - Generates weak scale mass for χ if vev $\langle S \rangle$ from same mechanism as EWSB
  - S couples to SM only via mixing with neutral components of H_u, H_d after EWSB

Model-building

- Write down all operators to dimension $d \leq 6$ arising from integrating out a heavy $SU(2)$-doublet Dirac fermion

  (ignoring charged gauge boson interactions)

$$\mathcal{L} = -\delta \frac{\chi\chi}{\mu}(H_u \cdot H_d)\left(1 - \frac{\lambda \hat{S}}{\mu}\right) - \kappa S \chi\chi \left(1 + \xi \frac{H_d^\dagger H_d + H_u^\dagger H_u}{|\mu|^2}\right) + \text{h.c.}$$
$$+ \frac{\alpha}{|\mu|^2}\left\{\chi^\dagger H_u^\dagger \bar{\sigma}^\mu \left[i\partial_\mu - \frac{g_1}{s_W}(T_3 - Q s_W^2) Z_\mu\right](\chi H_u)\right.$$
$$\left. + \chi^\dagger H_d^\dagger \bar{\sigma}^\mu \left[i\partial_\mu - \frac{g_1}{s_W}(T_3 - Q s_W^2) Z_\mu\right](\chi H_d)\right\},$$

- DM mass $m_\chi = 2\kappa\langle S\rangle$
- Heavy $SU(2)$-doublet fermion mass: $\mu = \lambda\langle S\rangle$

Model phenomenology. Higgs sector

- Rotate scalars to Higgs basis

$$H^{\rm SM} = \sqrt{2}{\rm Re}\left(\sin\beta H_u^0 + \cos\beta H_d^0\right),$$ ← SM-like

$$G^0 = \sqrt{2}{\rm Im}\left(\sin\beta H_u^0 - \cos\beta H_d^0\right),$$ ← Neutral Goldstone (Z)

$$H^{\rm NSM} = \sqrt{2}{\rm Re}\left(\cos\beta H_u^0 - \sin\beta H_d^0\right),$$ ← MSSM-like scalar

$$A^{\rm NSM} = \sqrt{2}{\rm Im}\left(\cos\beta H_u^0 + \sin\beta H_d^0\right),$$ ← MSSM-like pseudoscalar

+ scalar (H^S) and pseudoscalar (A^S) from singlet

- 125 GeV Higgs pheno requires approximate alignment: $h_{125} \sim H^{\rm SM}$

Model phenomenology. DM

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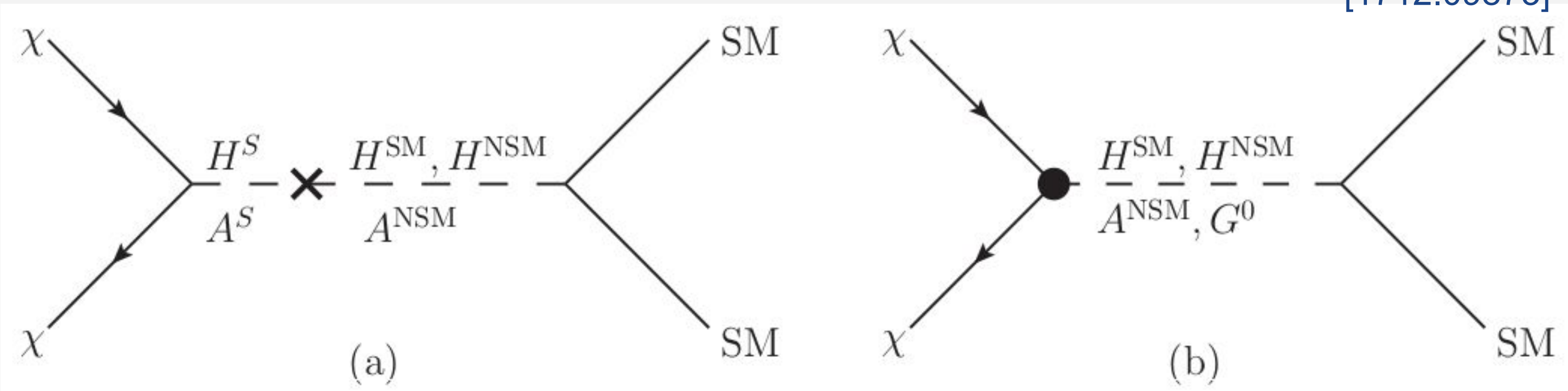
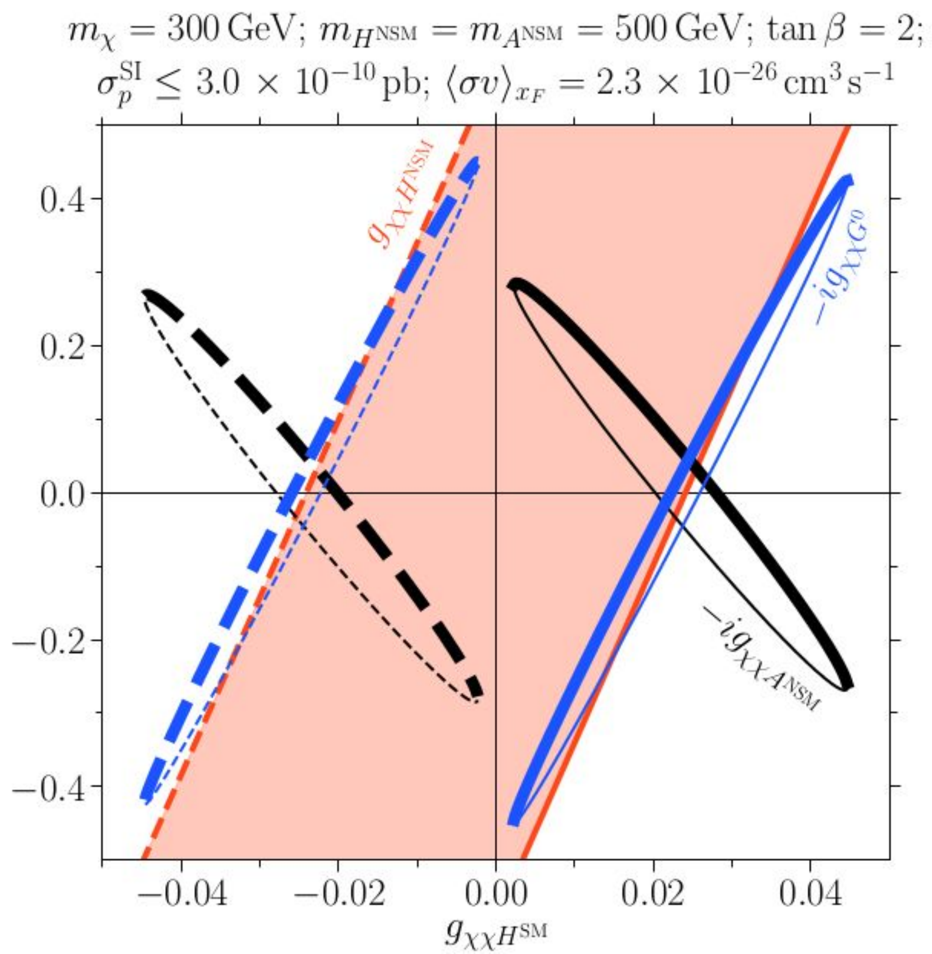
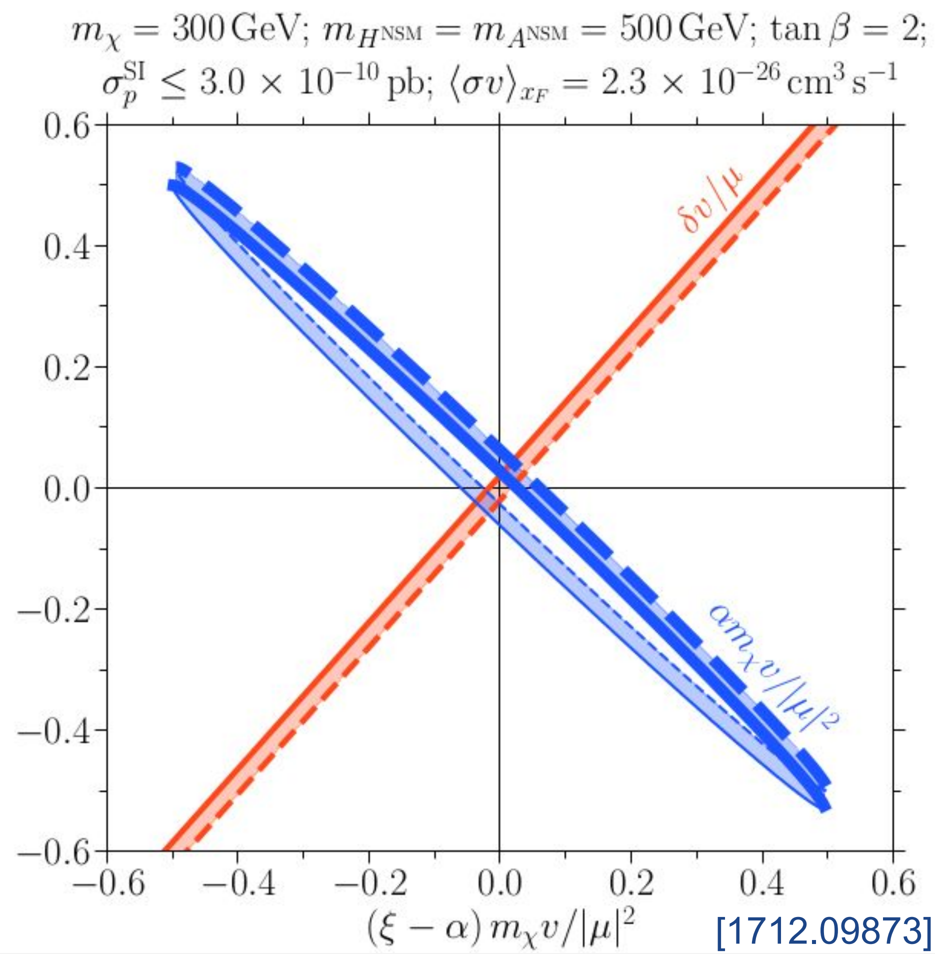


mixing $\qquad$ $d \geq 5$ operators

- Thermal production via
  - $\chi\chi \to q\bar{q}$ (important contribution from longitudinal Z/neutral Goldstone)
  - Usually small contributions from $\chi\chi \to h_i h_j$ / $h_i a_j$ / WW / ZZ
- SI Direct Detection mediated predominantly by CP-even Higgs bosons
  - EFT operators allow for blind spot where $g_{\chi\chi h} \to 0$
  - Presence of 3 CP-even Higgses allows for destructive interference

Model phenomenology. DM





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Example of allowed couplings / EFT parameters

(standard thermal production & current Direct Detection limits)

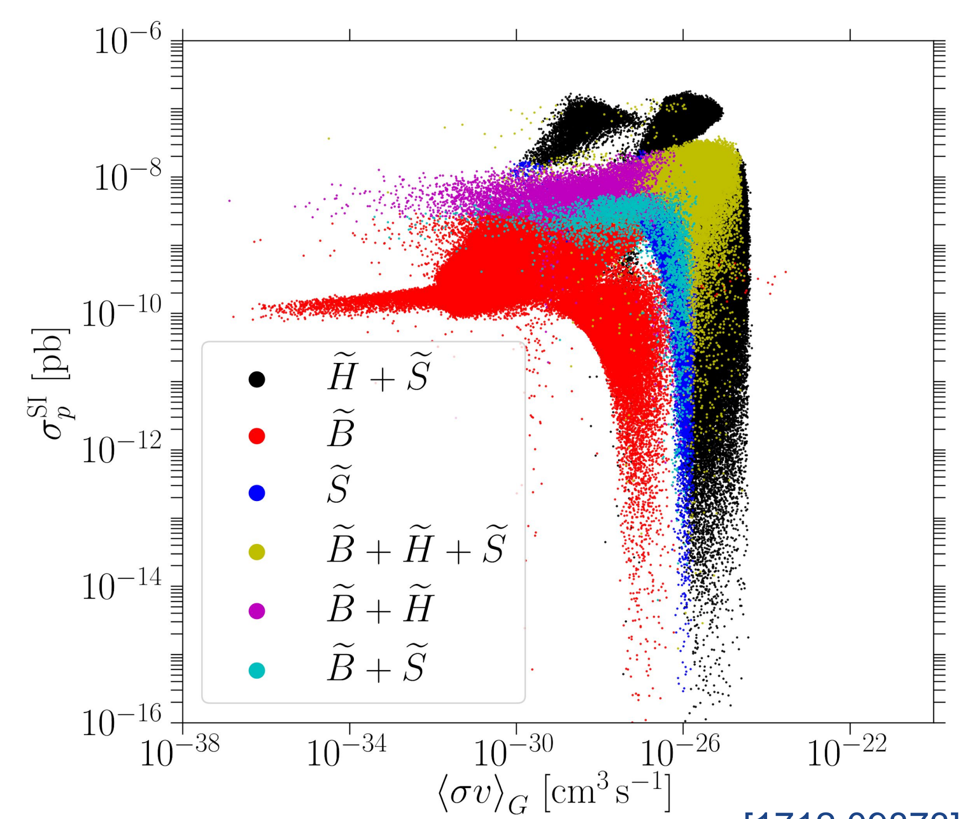
Does this really work? (aka UV completion)

(Z_3-invariant) Next to minimal Supersymmetric Standard Model (NMSSM)

- MSSM particle content + one extra SM-singlet chiral superfield
- Same Higgs sector as our model (2HDM+S)
- Fermionic component of singlet (‘singlino’) plays role of our DM candidate
- Mature numerical tools exist to study DM & collider phenomenology
- Besides the singlino, the NMSSM contains a second SM-singlet fermion, the bino
    - Smaller couplings to Higgs sector than singlino
    - EFT model can be extended in simple fashion to include bino

NMSSM: Singlino DM. Production

- predominantly vanilla thermal production dominated by annihilations into top quarks
- Longitudinal Z (neutral Goldstone mode) plays prominent role



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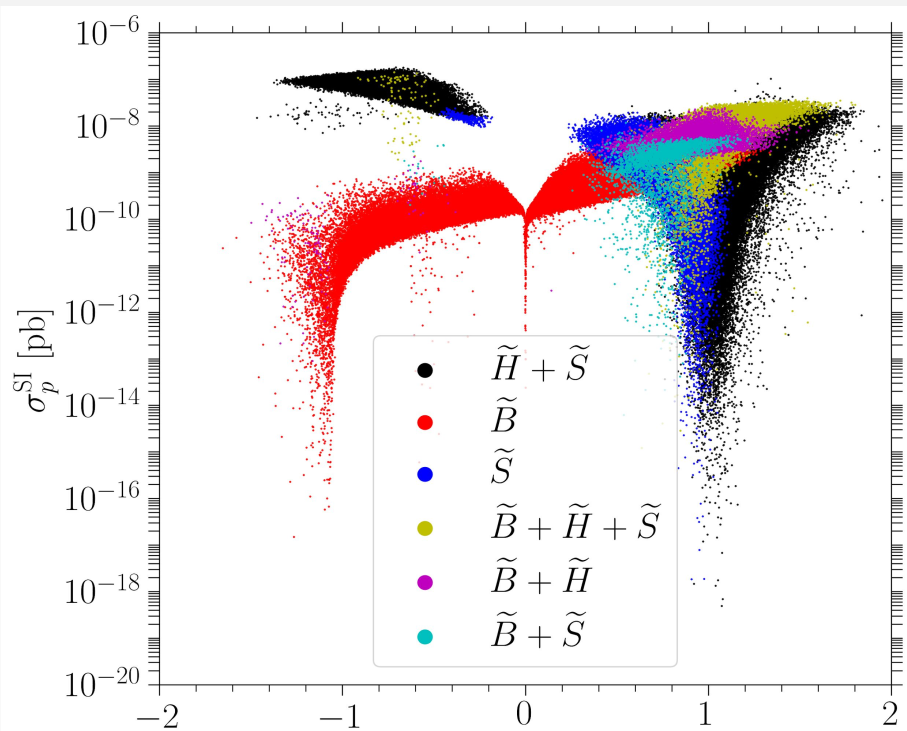
NMSSM: Singlino DM. Direct Detection

SI Direct Detection cross section suppressed by:

- Proximity to h_{125} blind spot (Cheung+ 1406.6372, Badziak+ 1512.02472)
- Destructive interference between CP-even Higgs mass eigenstates



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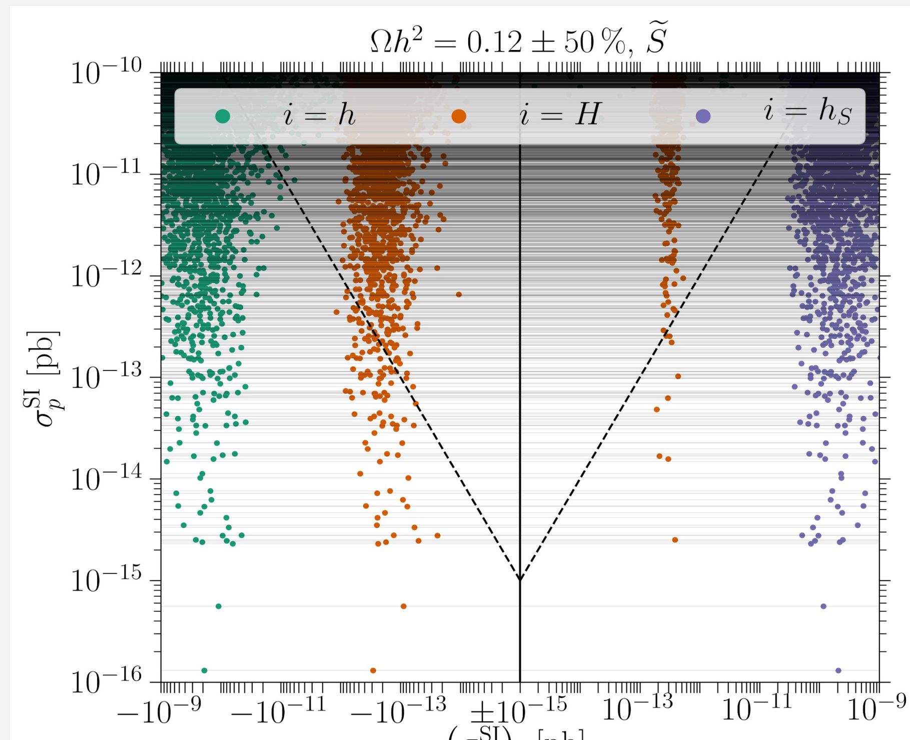

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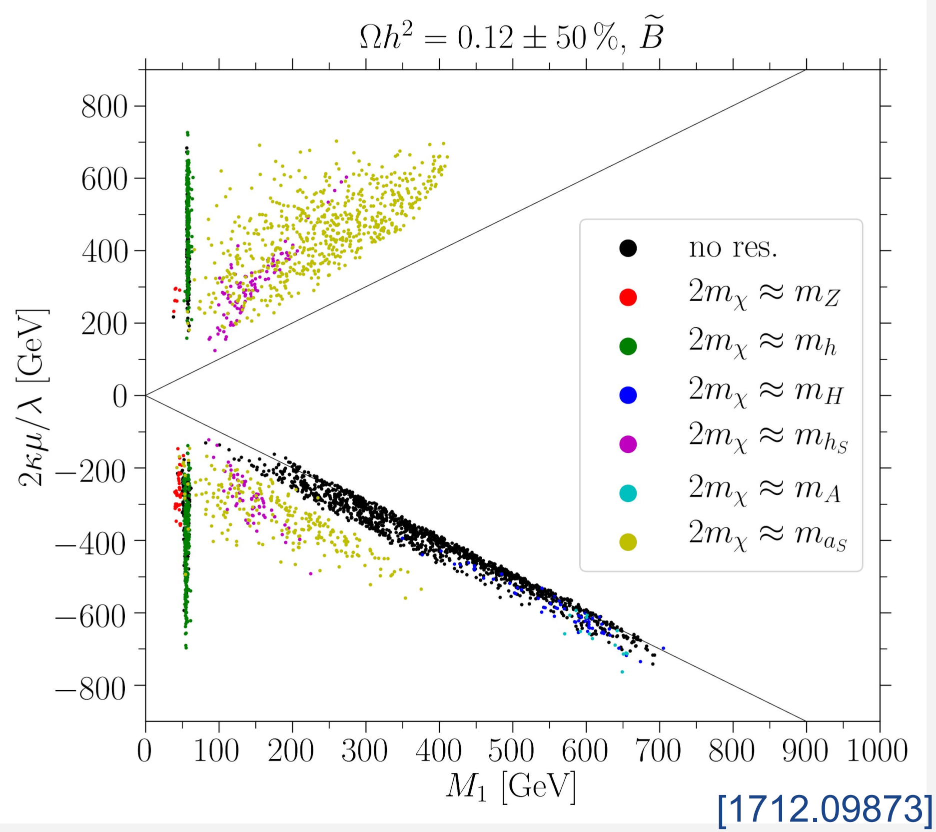
NMSSM: (new ‘well-tempered’) Bino DM

- Thermal production via co-annihilation with singlino
- SI Direct Detection cross section suppressed by h_{125} blind spot proximity



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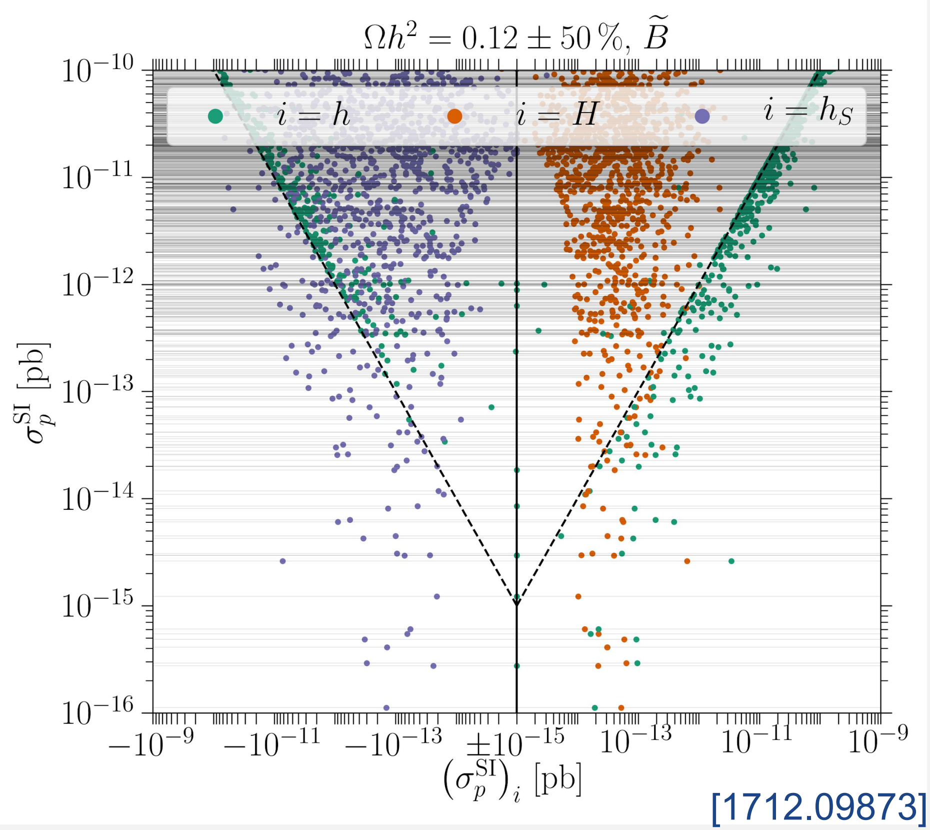

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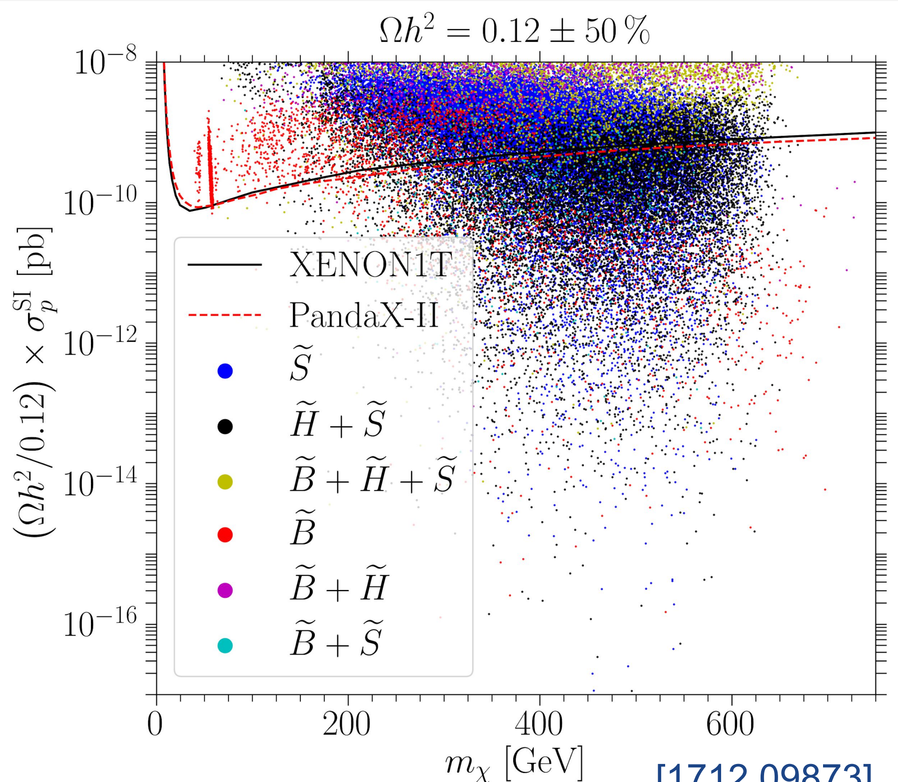
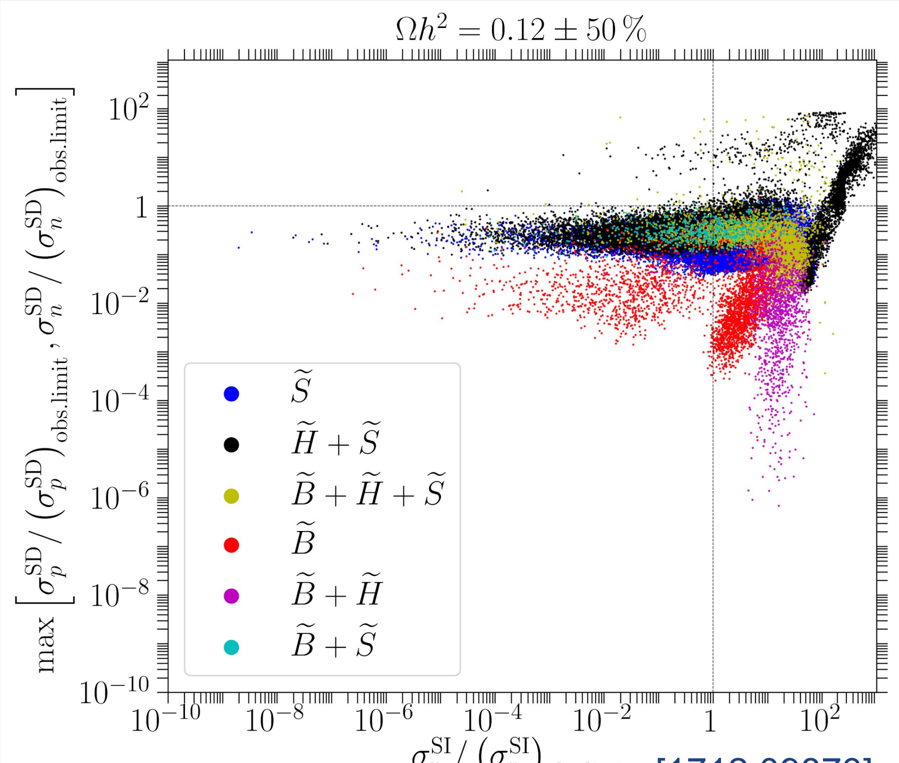
NMSSM: DM. Direct Detection Potential





- As yet, SI limits are much more relevant
- But, increasing sensitivity of SD experiments by ~ 2 orders of magnitude would probe most of the remaining parameter space!

Conclusions

- Stringent Direct Detection limits require decoupling of SI detection cross section and annihilation cross section
  - Either, one enhances the production cross-section by co-annihilation or resonant annihilation,
  - Or, one suppresses the SI detection cross section by destructive interference
- Qualitative features studied in Majorana DM + (2HDM+S) model
- Tested validity of results and extended numerical study in NMSSM
  - Singlino region: Vanilla thermal production (via the longitudinal Z), h_{125} blind spot + destructive interference for direct detection
  - New ‘well-tempered’ Bino region: co-annihilation with singlino for thermal production, blind-spot for direct detection
  - Both can be probed by SD experiments in near future!