Dark matter from dark gauge groups

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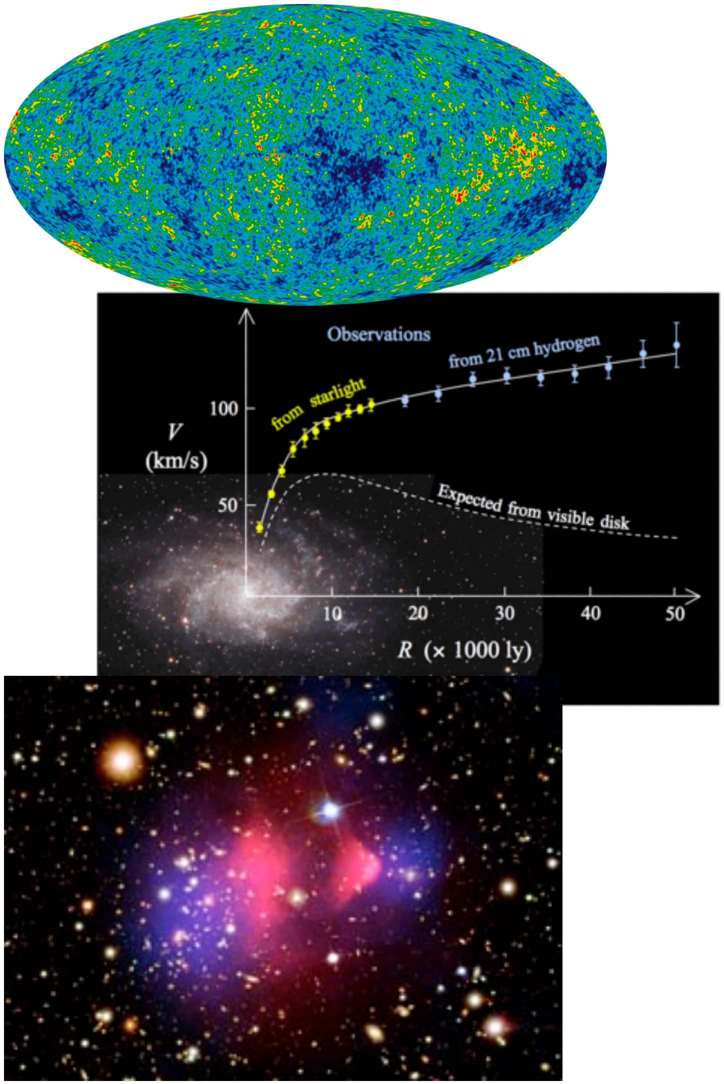
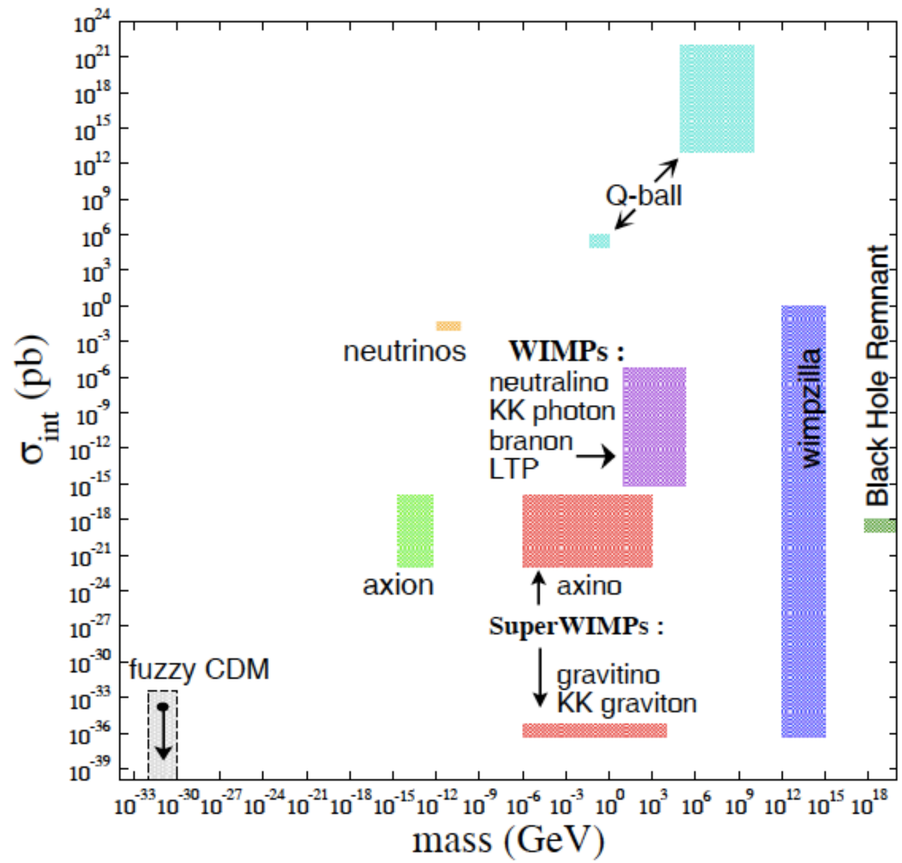
based on work in collaboration with G. Arcadi, O. Lebedev, Y. Mambrini, S. Pokorski, T. Toma

We know DM exists:



....but we have no clue what kind of particle(s) DM consists of:

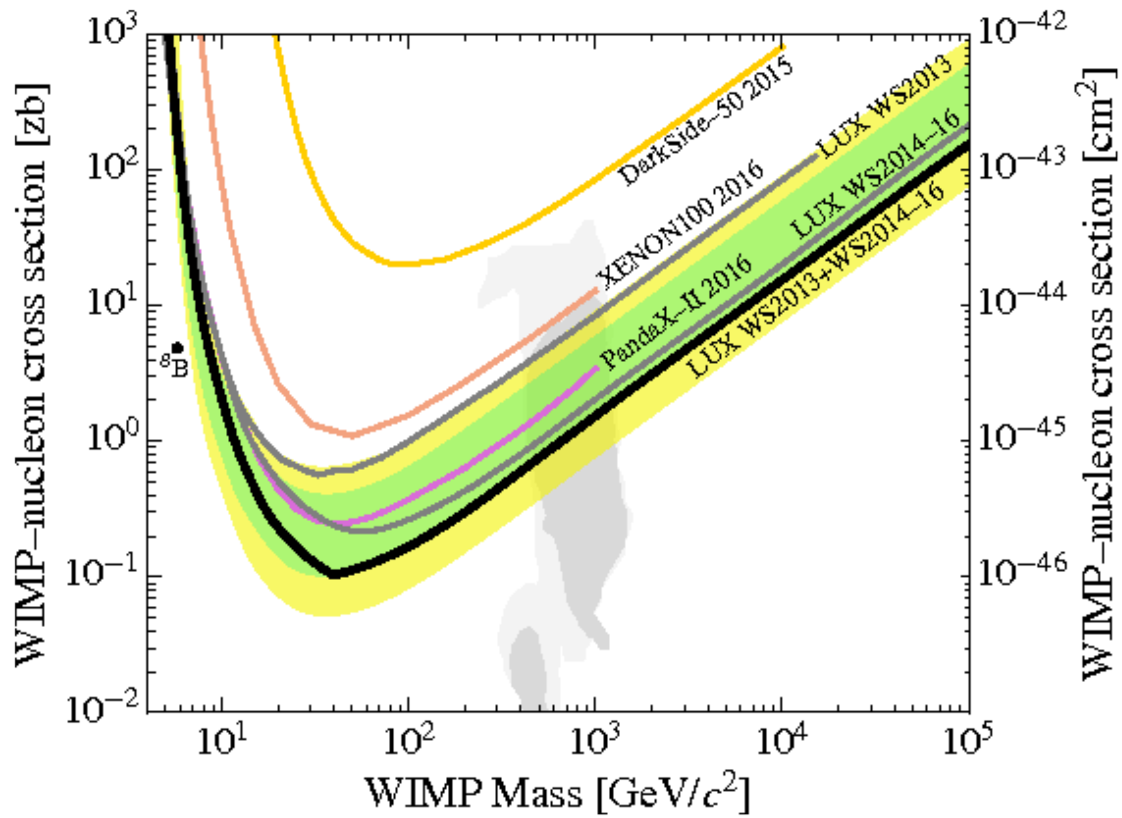


[figure taken from E.-K. Park, contribution to DMSAG report, July 18, 2007]

why WIMPs are popular

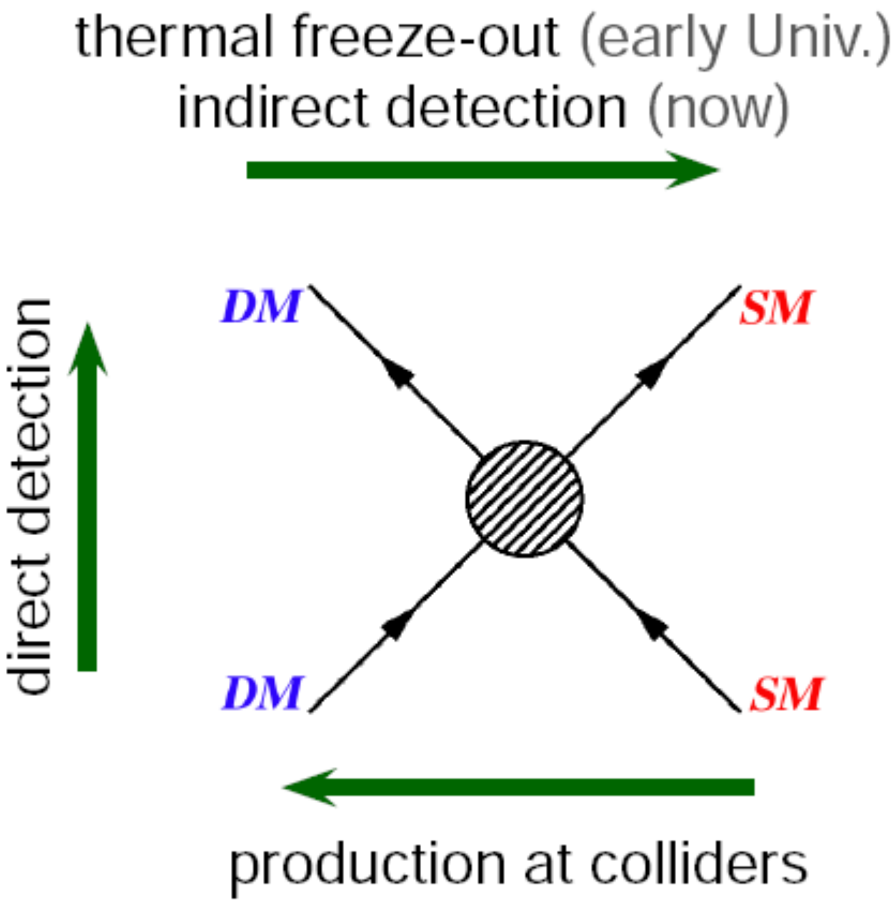
- The WIMP miracle
→ link to TeV scale BSM physics

- Huge efforts to search for WIMPs in direct detection experiments



[LUX, 1608.07648]

why simple WIMP DM models are under pressure

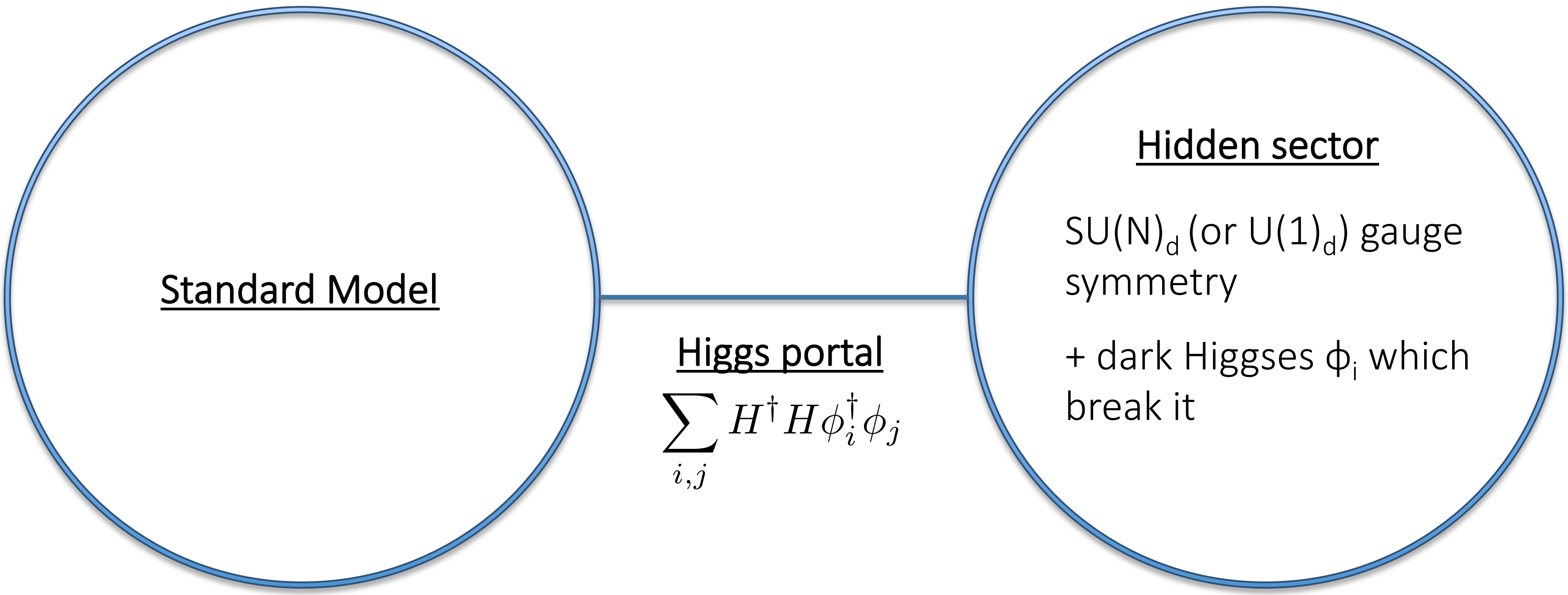


[image: www.mpi-hd.mpg.de/lin/research_DM.en.html]

- Reason for tension in simplest models:
  DD limits require small coupling
  → small <σ v>
  → WIMPs overabundant due to
  $\Omega \propto 1/\langle \sigma v \rangle$

- Need to break the `crossing relation', e.g. by:
  - resonant DM annihilation
  - additional annihilation channels into the dark sector
  - cancellation among different direct detection diagrams
  - ...

WIMP DM from hidden gauge groups



plan for the rest of the talk:

① why the massive gauge fields are stable

② three ways to naturally reconcile direct detection limits and relic abundance

stability of U(1)$_d$ vector dark matter

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

complex scalar

A_μ is stable due to charge-conjugation symmetry

$$Z_2: \begin{cases} \phi \to \phi^* \\ A_\mu \to -A_\mu \end{cases}$$

[Lebedev,Lee,Mambrini, 2011]

stability of SU(2)$_d$ vector dark matter

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}\sum_{a=1}^{3} F^a_{\mu\nu} F^{a\mu\nu} + |D_\mu \phi|^2 - V(\phi)$$

↖ SU(2)$_d$ doublet

$A^a_\mu \rightarrow -A^a_\mu$ is not a symmetry, due to triple gauge boson vertex

stability of SU(2)$_d$ vector dark matter

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↖ SU(2)$_d$ doublet

- since the generators are $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$

charge conjugation acts as $Z_2: \begin{cases} \phi \to \phi^* \\ A^1_\mu \to -A^1_\mu \\ A^3_\mu \to -A^3_\mu \end{cases}$

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- there is another Z_2: $\begin{cases} A^1_\mu \to -A^1_\mu \\ A^2_\mu \to -A^2_\mu \end{cases}$

which can be shown to be a remnant of SU(N)$_d$ gauge symmetry

[CG, Lebedev, Mambrini, 2015]

stability of $SU(2)_d$ vector dark matter

$$\mathcal{L}_{\rm dark} = -\frac{1}{4}\sum_{a=1}^{3} F^a_{\mu\nu}F^{a\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

↖ $SU(2)_d$ doublet

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which can be shown to be a remnant of $SU(N)_d$ gauge symmetry

[CG, Lebedev, Mambrini, 2015]

- this $Z_2 \times Z_2$ ensures stability of the three A^a_μ;

it enlarges to a custodial SO(3) → the A^a_μ have same masses

[Hambye, 2008]

stability of $SU(N\geq3)_d$ vector dark matter

[CG, Lebedev, Mambrini, 2015]

- $SU(N\geq3)_d$ broken completely by N-1 dark Higgs N-plets

- N(N-1)/2 physical CP-even scalars
  N(N-3)/2+1 `` CP-odd ``

- assuming CP invariance, obtain $Z_2 \times Z_2$ symmetry,
  as in the $SU(2)_d$ case
  ($Z_2 \times Z_2$ is part of a global $U(1) \times Z_2$)

- DM: two degenerate vectors + { one slightly lighter vector or one CP-odd scalar }

plan for the rest of the talk:

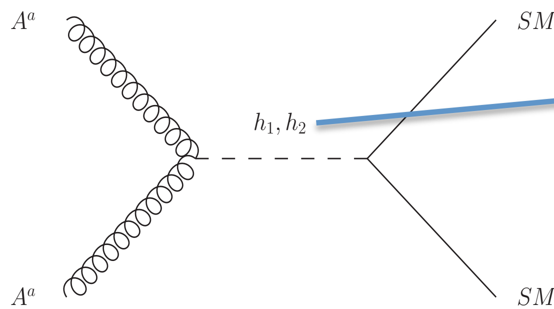
① why the massive gauge fields are stable

② three ways to naturally reconcile direct detection limits and relic abundance

a) DM annihilation via (broad) resonances

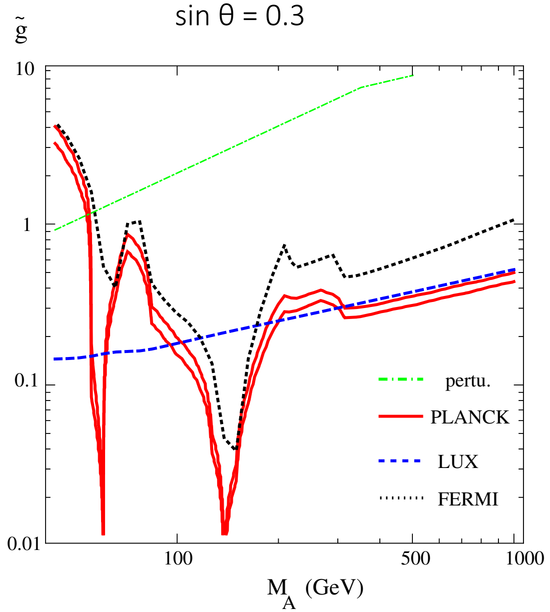
[CG, Lebedev, Mambrini, 2015]

DM annihilation via s-channel Higgses:

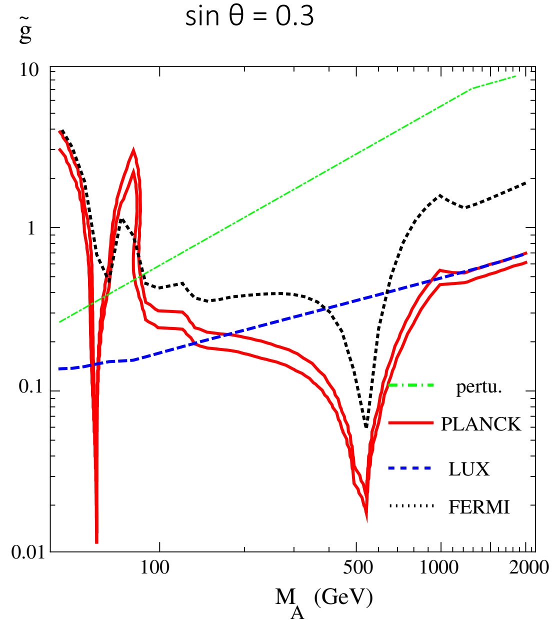


h_1, h_2: mass eigenstates of dark Higgs and $SU(2)_L$-Higgs, with mixing sin θ

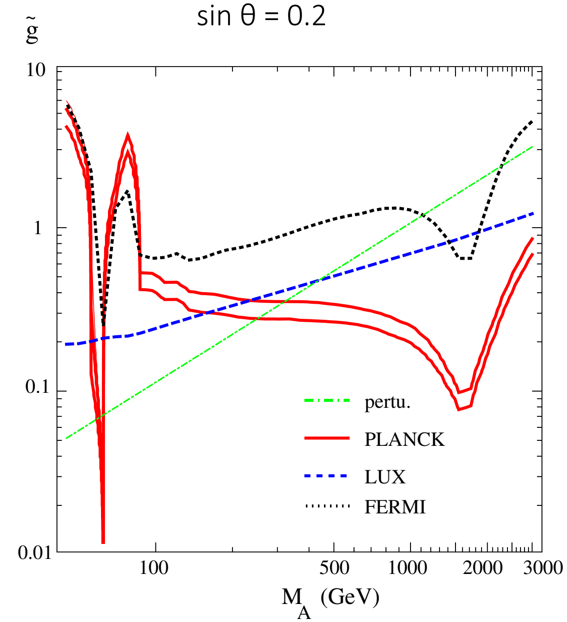
m_{h2} = 280 GeV
sin θ = 0.3



m_{h2} = 1 TeV
sin θ = 0.3



m_{h2} = 3 TeV
sin θ = 0.2

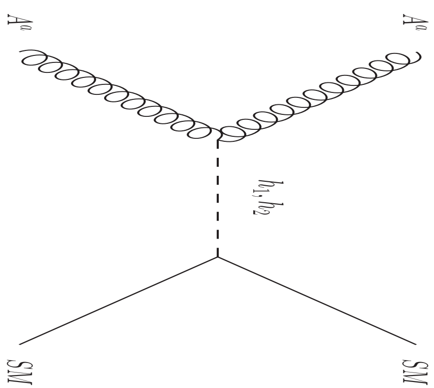


b) DM annihilation mostly into hidden sector

- The basic mechanism is known as <u>secluded DM</u>: [Pospolov, Ritz, Voloshin, 2007]
  DM annihilation into dark sector states may provide an efficient extra annihilation channel. This breaks the correlation between DD and annihilation cross section.

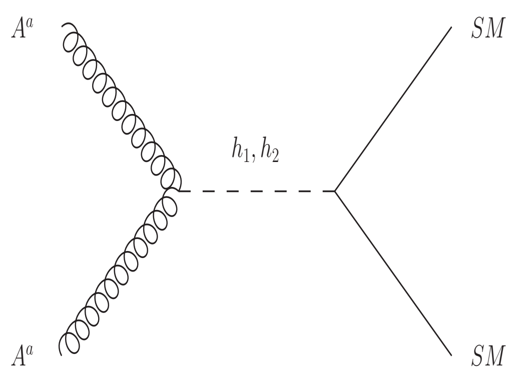
- The scalar sector of spontaneously broken hidden gauge groups automatically contains such dark sector states into which DM may annihilate: the hidden sector scalars.

direct detection

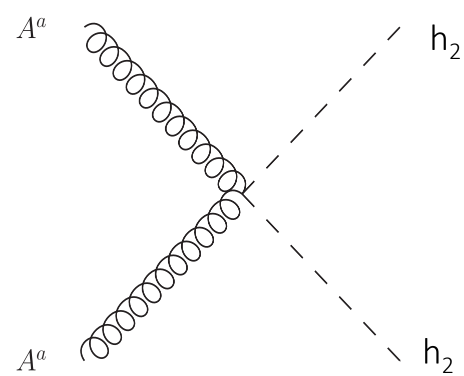


~ sin θ cos θ

DM annihilation



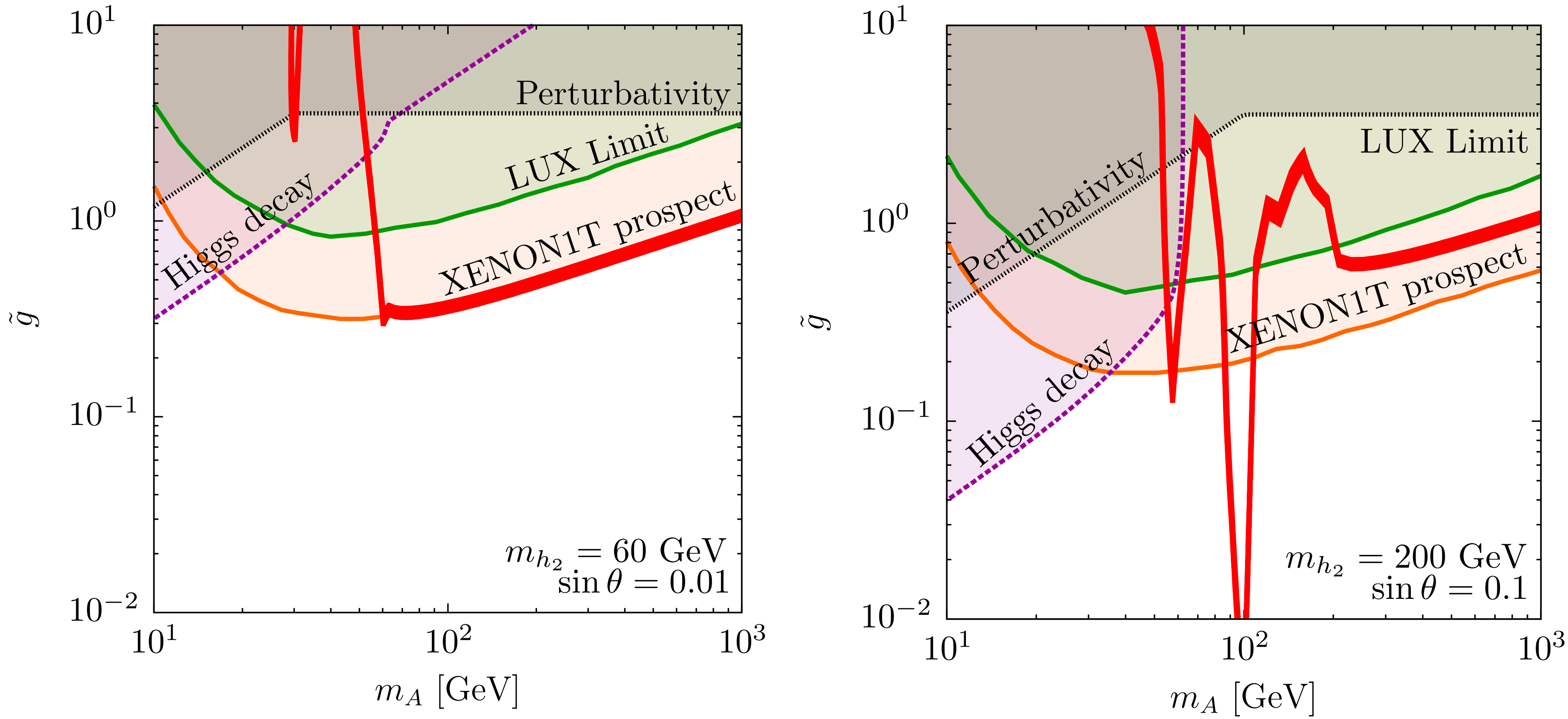
~ sin θ cos θ



no sin θ suppression!

b) DM annihilation mostly into hidden sector

[Arcadi,CG,Lebedev,Pokorski,Toma; 2016]

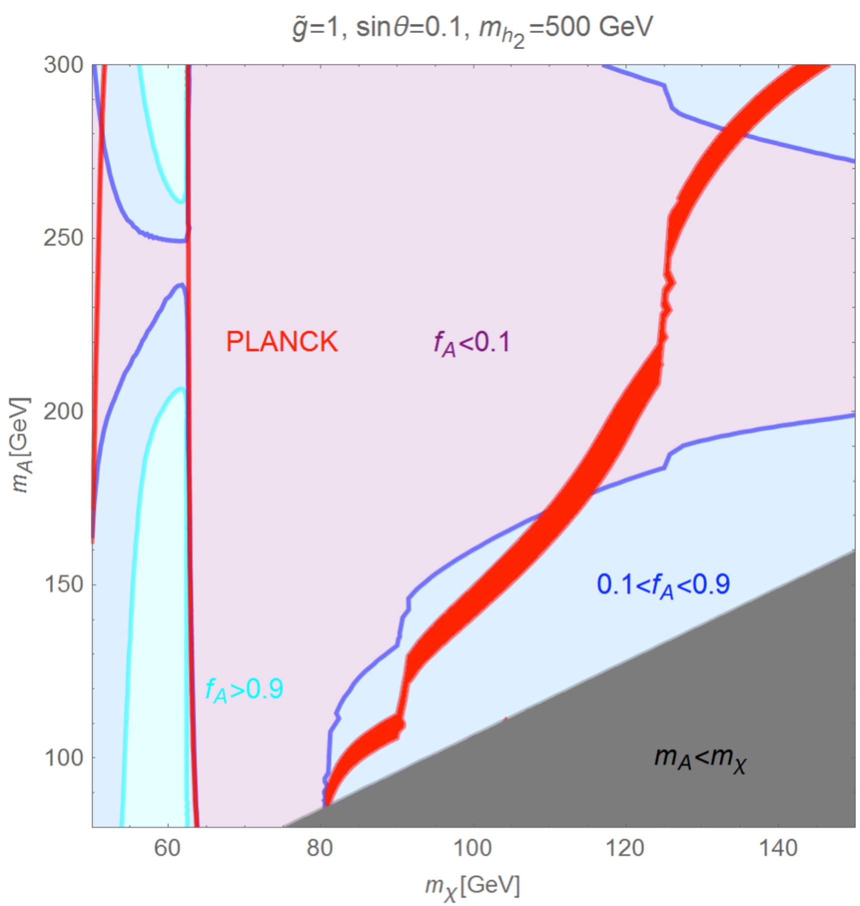


- The coupling required to obtain the correct relic abundance drops dramatically as soon as the dark annihilation channel opens up.
- The smaller sin θ is, the stronger this effect is.

c) cancellation among direct detection diagrams

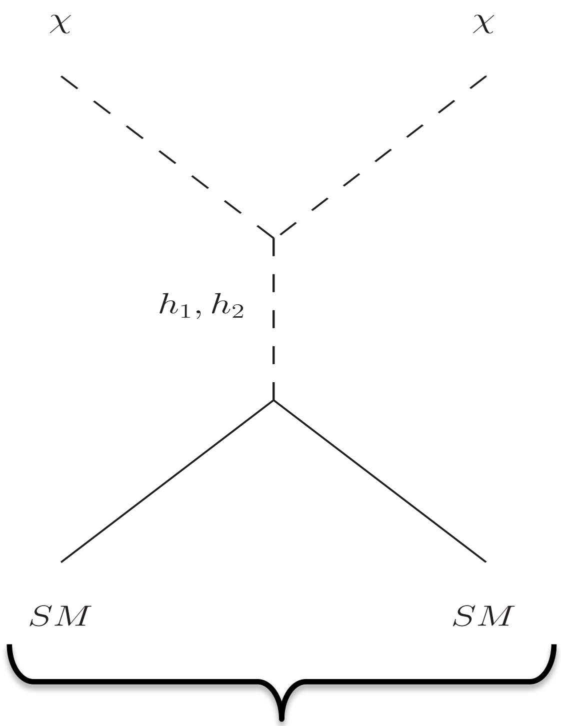
[Arcadi,CG,Lebedev,Mambrini,Pokorski,Toma; 2016]

- for $SU(N\geq3)_d$ DM can consist of vectors and a CP-odd scalar χ
- Both components may be dominant, depending on parameters:

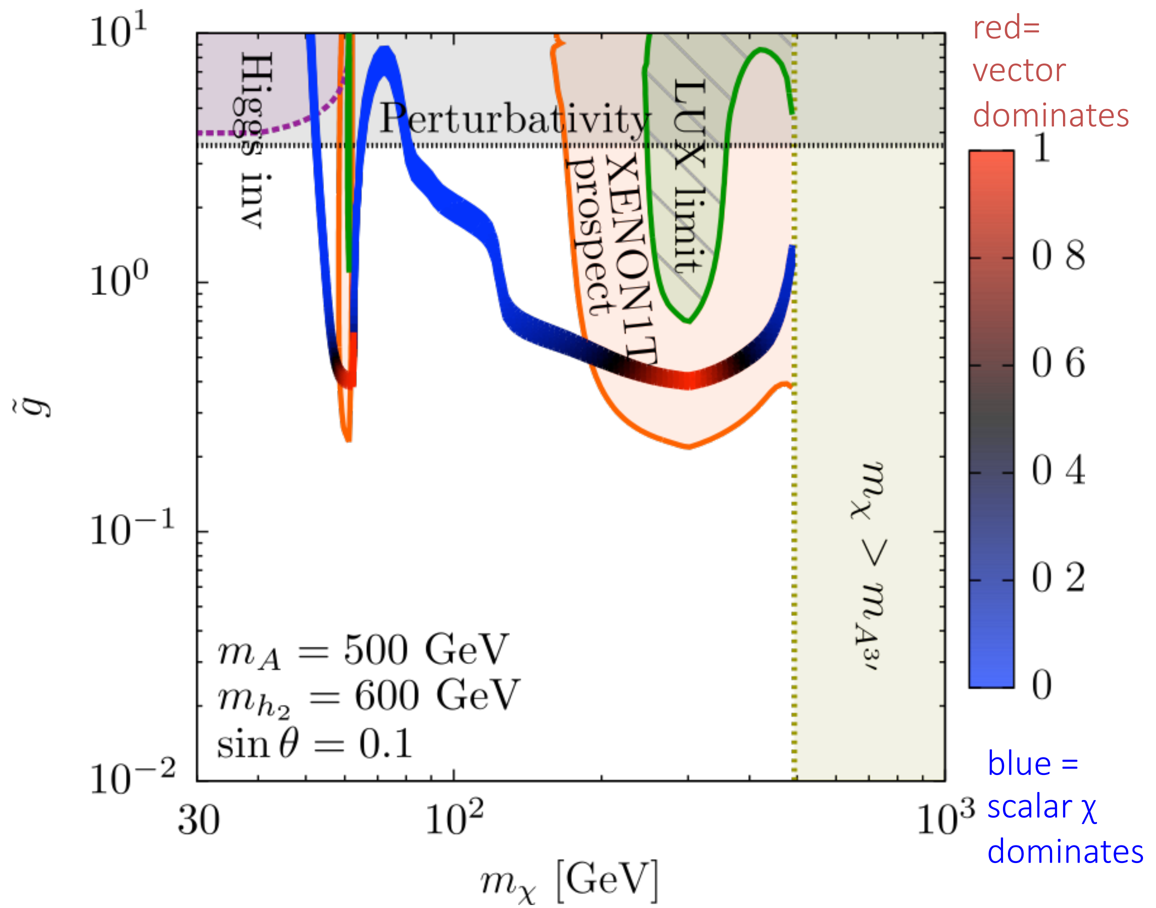


- shown: relative contribution of vector DM to total DM: $f_A=\Omega_A/\Omega_{total}$
- since, very roughly, $\Omega_{total} \propto 1/\langle\sigma v\rangle_A + 1/\langle\sigma v\rangle_\chi$ component with smaller $\langle\sigma v\rangle$ dominates
- this explains e.g. behaviour when one of the components annihilates resonantly

c) cancellation among direct detection diagrams

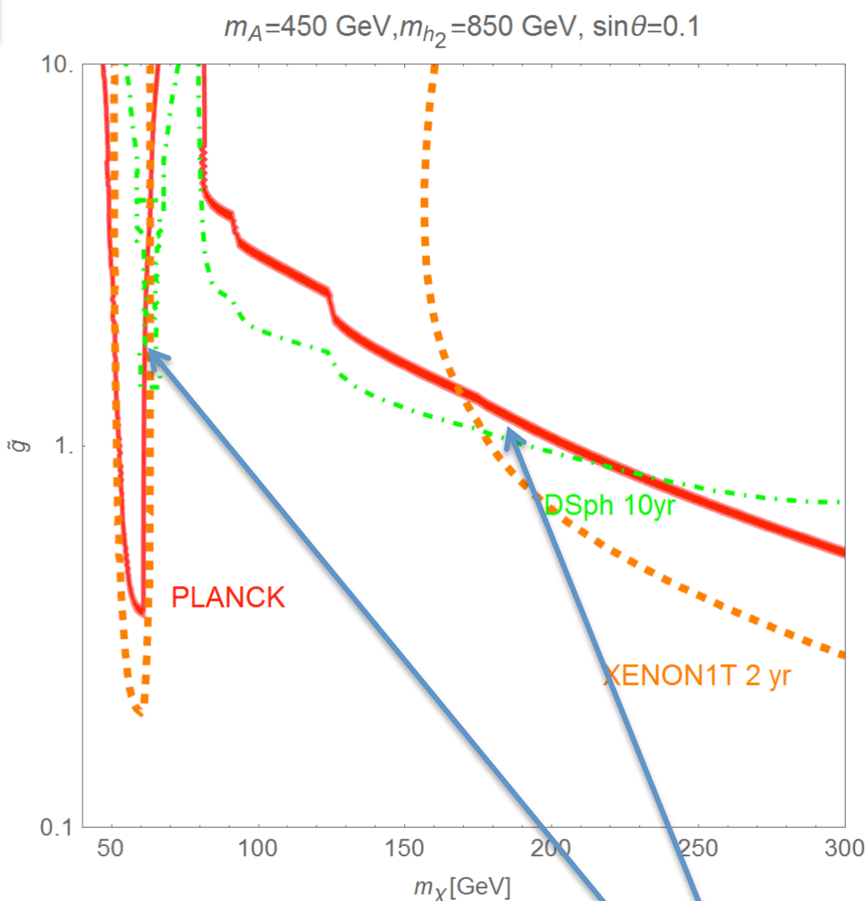


couplings lead to exact tree-level cancellation in scattering of χ-DM on nuclei, independently of the mass of h_2



→ WIMPs can be completely invisible in direct detection

side remark:
in the mixed scalar-vector DM case, one might be able to see one DM component in indirect detection and the other in direct detection



basic point:

- χ is invisible in DD, but might be observable in ID (if its DM fraction is large enough)
- on the other hand: vector component could be visible in DD, but is hardly visible in ID because main annihilation (often) into dark sector (A A → χ χ)

two regions where testing this scenario might be possible with future data

Summary

- Gauge fields of a spontaneously broken dark $SU(N)_d$ are viable DM candidates
- Stability of DM is due to a $Z_2 \times Z_2$ symmetry that automatically arises for minimal CP-conserving Higgs sectors
- Several ways to reconcile relic abundance and direct detection limits:
  - annihilation via (broad) resonances
  - annihilation dominantly into dark sector
  - cancellation among direct detection diagram