WIMPS – how to hunt them and how to save them.

Felix Kahlhoefer
52nd Rencontres de Moriond
18-25 March 2017

HELMHOLTZ ASSOCIATION

DESY

What do we know?

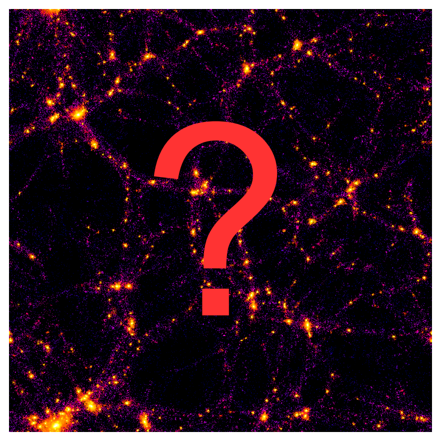
Cold white matter

Known

Hot dark matter

Known

Cold dark matter

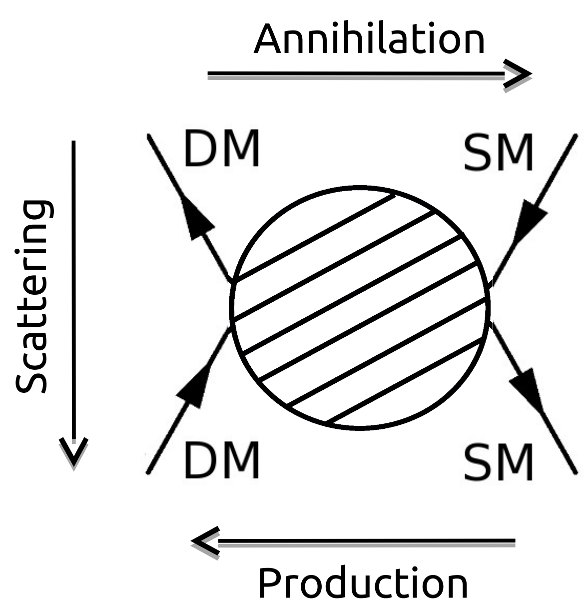


Unknown

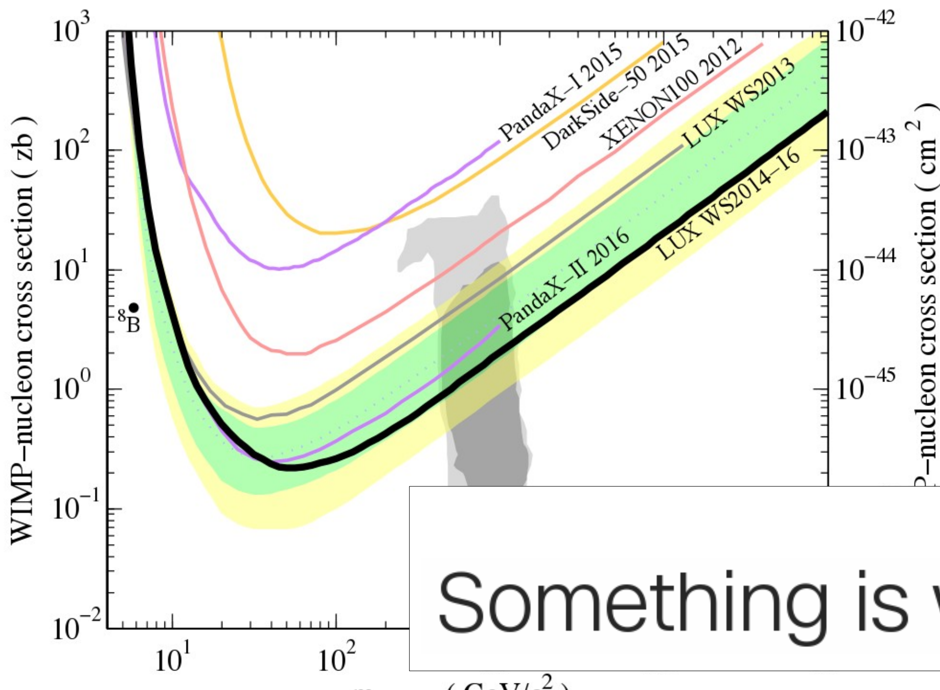
Weakly-interacting massive particles

- Thermal freeze-out is the most widely studied paradigm for DM production in the early Universe.
  Lee & Weinberg, 1977
- Basic idea: DM was in thermal equilibrium with SM states at high temperatures, then became non-relativistic and finally decoupled from the thermal bath.
- Such particles are called WIMPs, because the observed abundance is reproduced for a particle with weak interactions and weak-scale mass.
- WIMPs are also highly promising from an experimental point of view
  - The DM particle cannot be arbitrarily heavy.
  - Interactions with SM particles have to be sizeable.

There are many ways to test the WIMP paradigm!



Where are the WIMPs?



A number of experiments (LUX, PandaX, LHC, ...) have recently published results from various WIMPs searches without observing any significant excess over expected backgrounds.

CNN

Something is wrong with dark matter

SCIENTIFIC AMERICAN.

In the Dark about Dark Matter

Recent disappointments have physicists looking beyond WIMPs for dark matter particles

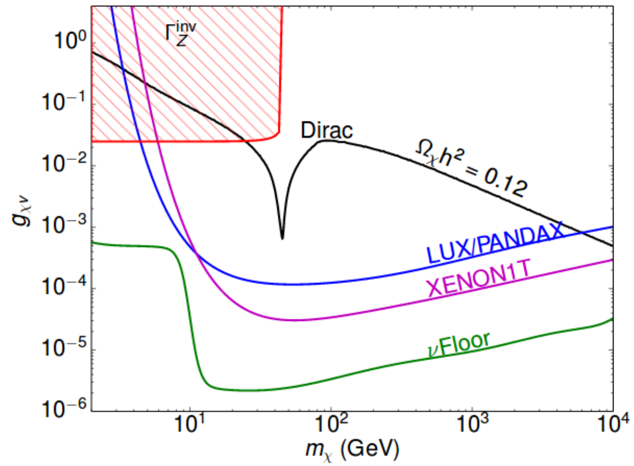
Are WIMPs in trouble?

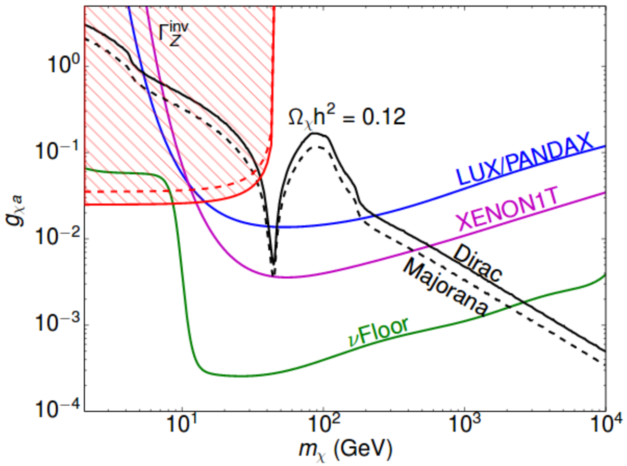
Does the WIMP need saving?

- Consider a DM particle interacting with the SM via Z exchange.

Escudero et al., arXiv:1609.09079

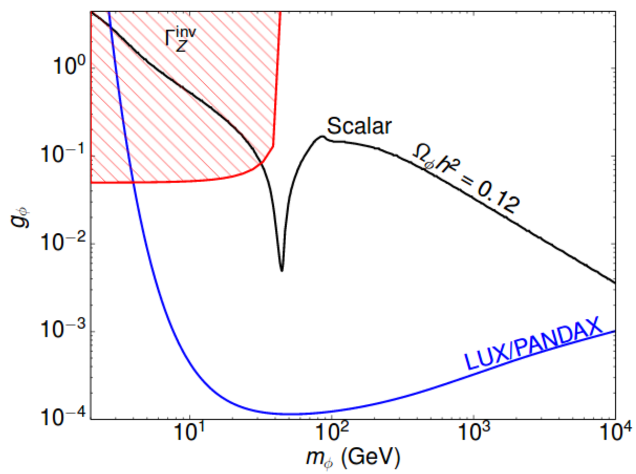
Spin 1/2 vector coupling

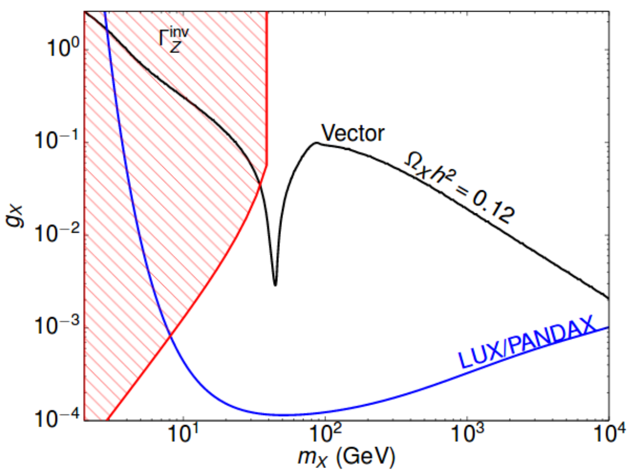




Spin 1/2 axial coupling

Spin 0





Spin 1

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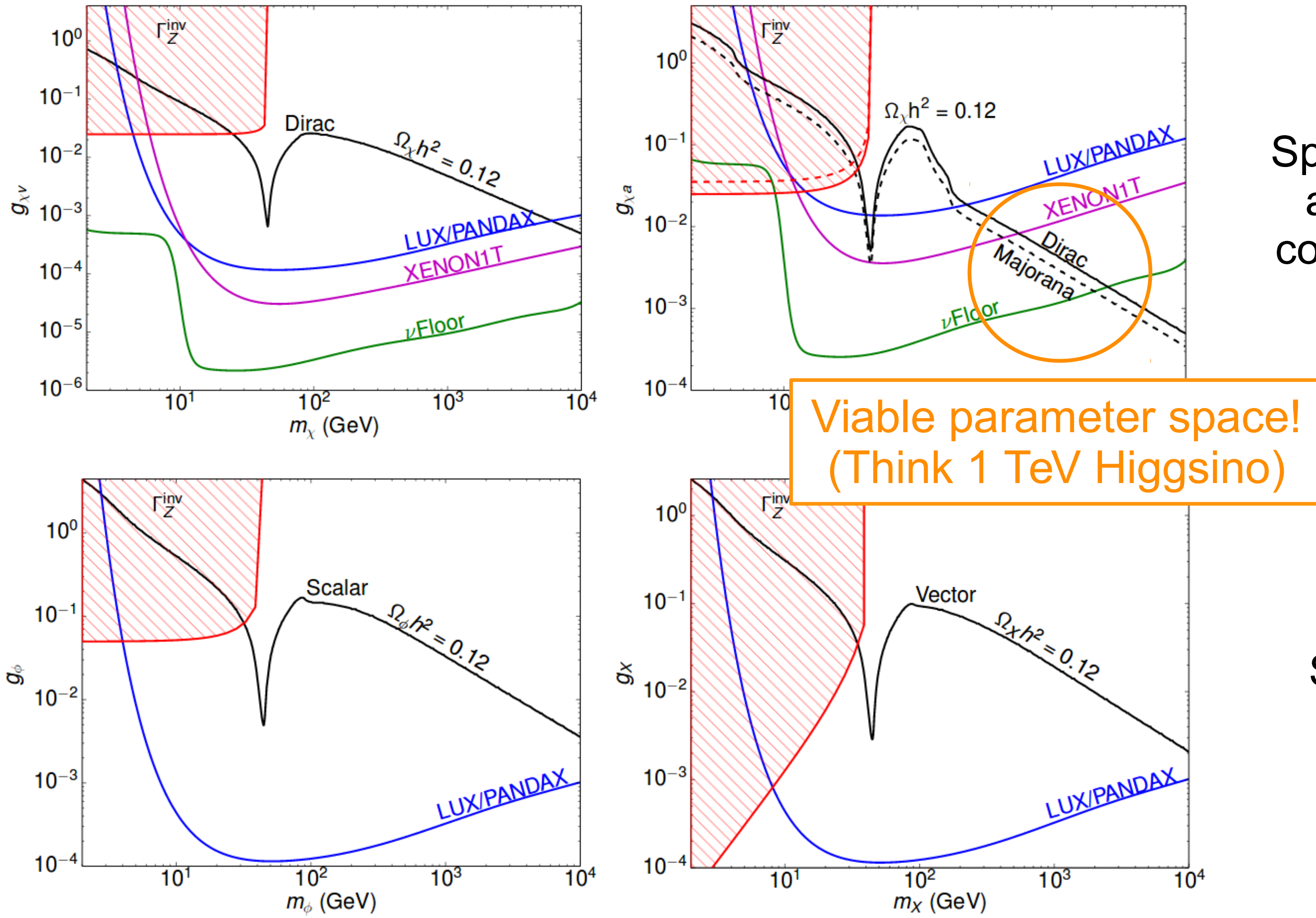


Spin 0

Spin 1

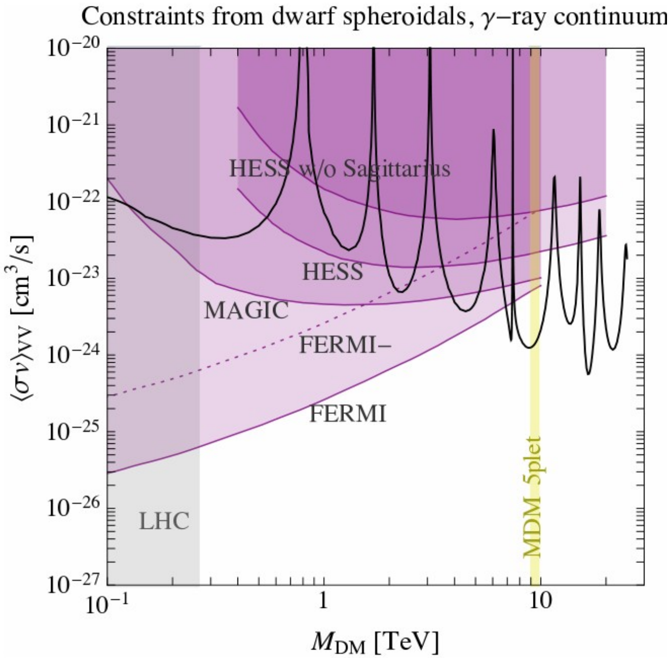
How about minimal dark matter?

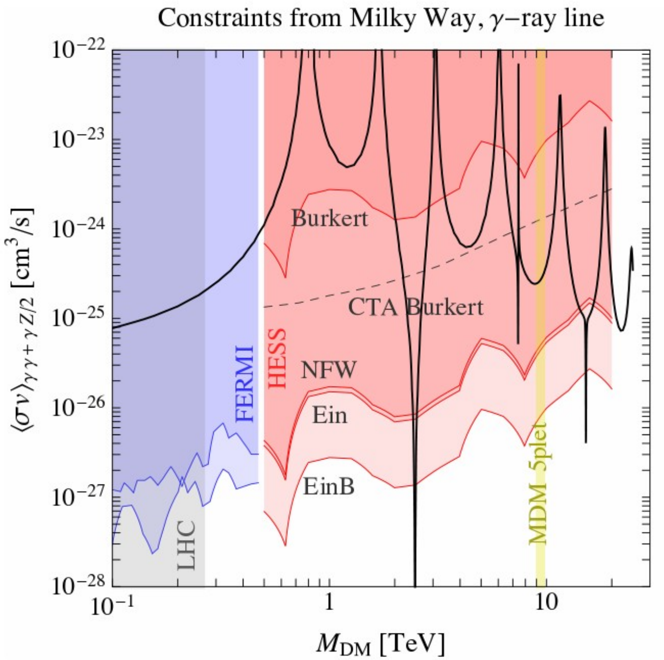
- Dark matter could still sit in a multiplet of $SU(2)_L$ provided the electromagnetically neutral state does not couple to the Z boson at tree-level (so-called minimal DM).

  Cirelli, Fornengo & Strumia, arXiv:hep-ph/0512090

- The most promising set-up (a ~10 TeV quintuplet with zero hypercharge) is potentially ruled out by γ-ray searches due to the large Sommerfeld enhancement.

  Cirelli et al., arXiv:1507.05519





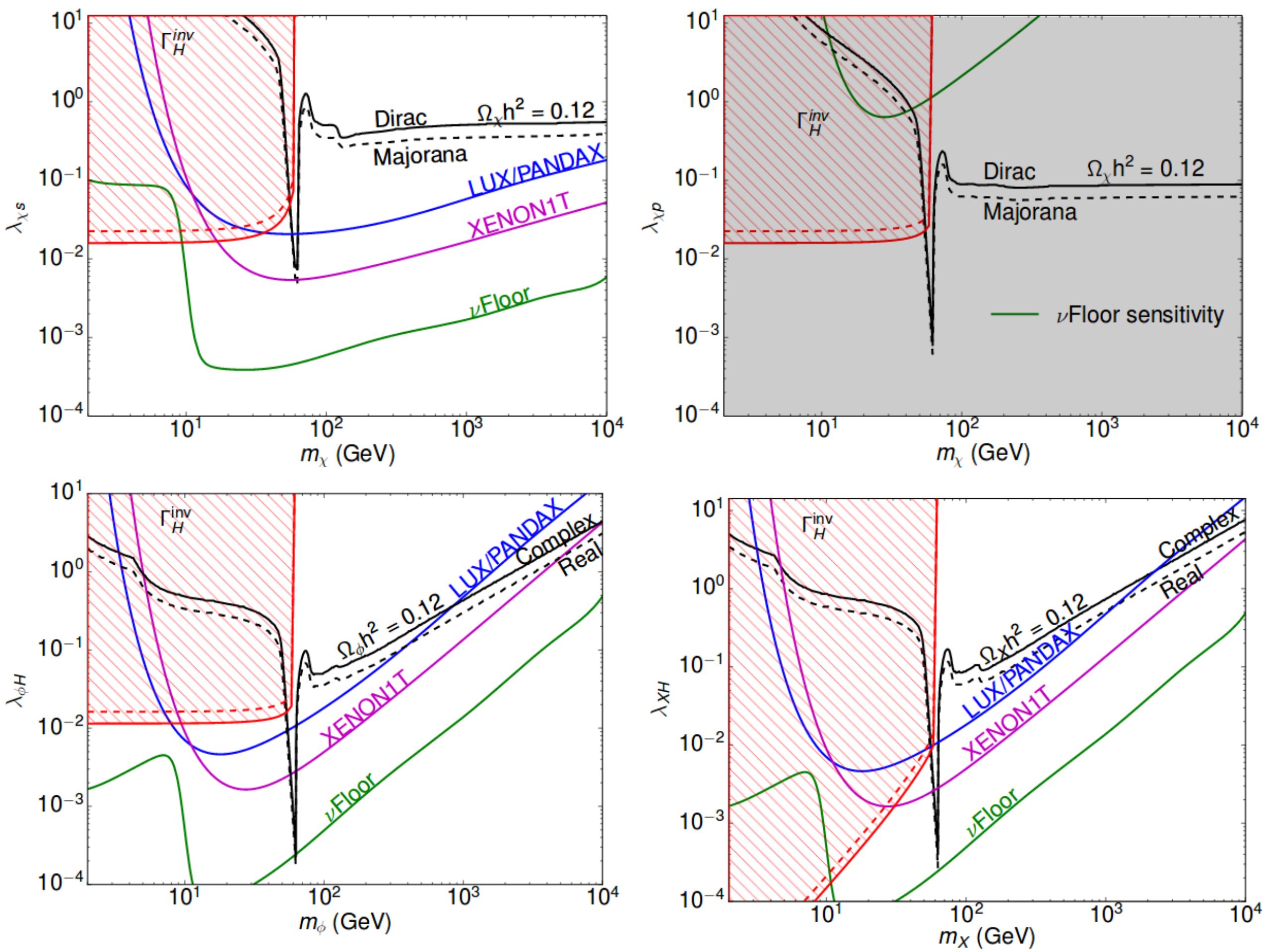
Does the WIMP need saving?

- Consider a DM particle interacting with the SM via BEH (Higgs) boson exchange.

Escudero et al., arXiv:1609.09079

Spin 1/2 scalar coupling

Spin 1/2 pseudoscalar coupling (violates CP)



Spin 0

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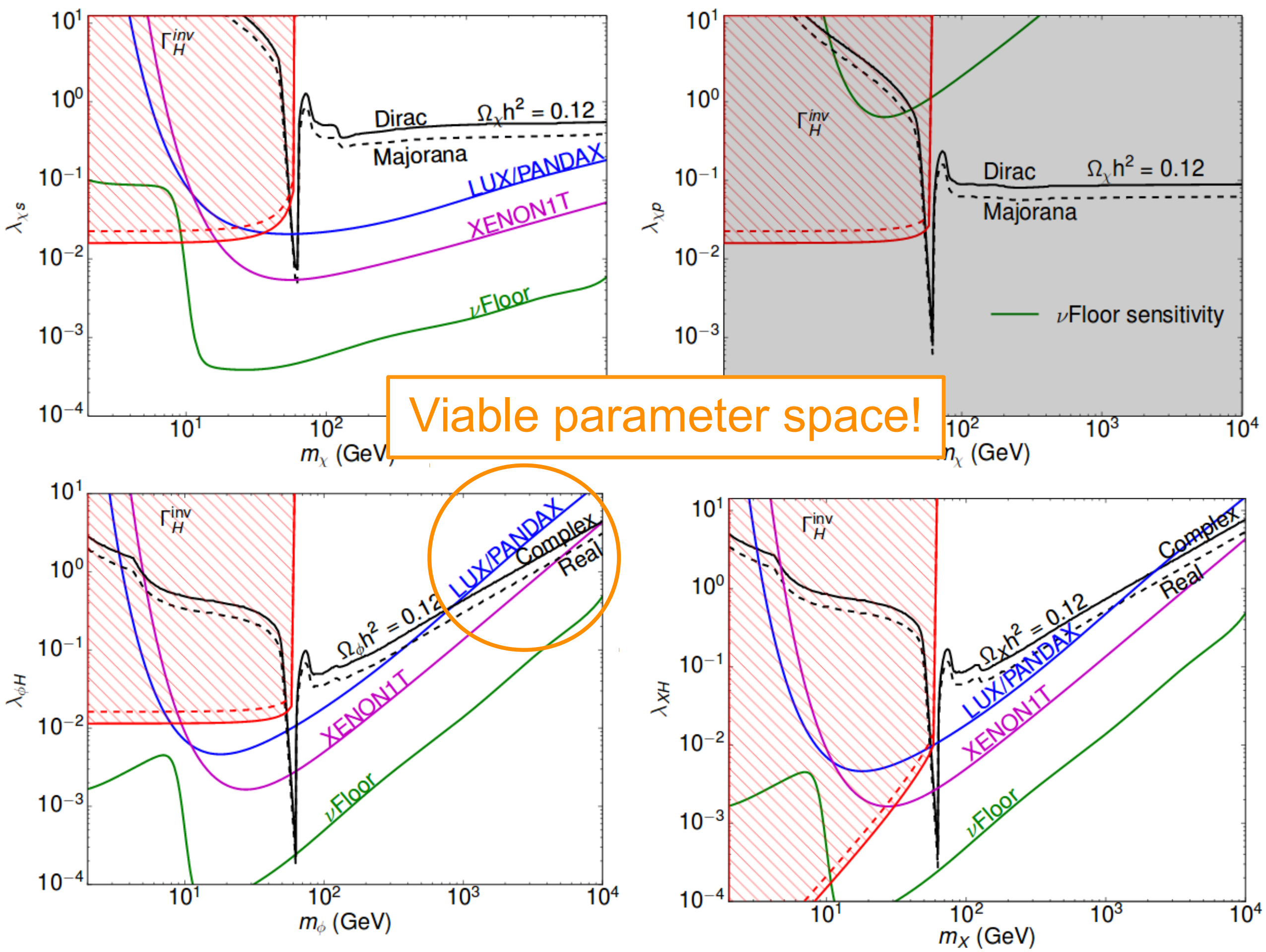


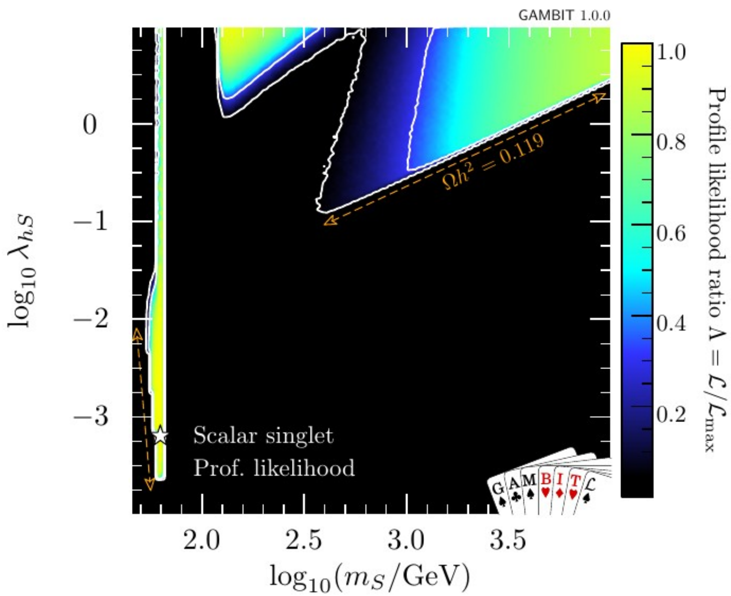
Spin 0

Spin 1

How about scalar singlets?

- A real scalar singlet coupled to the SM BEH boson is arguably the simplest realization of the WIMP idea.

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$



- The GAMBIT collaboration will soon publish a global analysis of this model (with constraints from direct and indirect searches and LHC).

Athron, FK et al., submitted to EPJC

- Intriguingly, the model is still viable and can account for all of the dark matter.

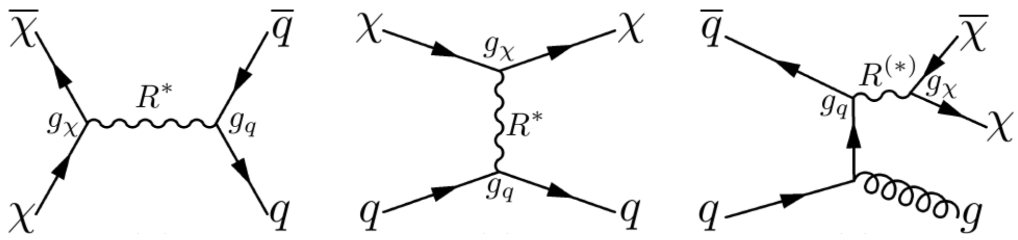
- For WIMP masses between 700 and 2000 GeV the contribution of the scalar singlet to the scalar potential stabilizes the electroweak vacuum all the way to the Planck scale.

FK & McDonald, arXiv:1507.03600

- Xenon1T will be able to test this mass range within the next few years and thereby probe one of the last remaining simple WIMP models.

New mediators

- Experiments are closing in on the WIMP idea, assuming that the DM particle interacts via Standard Model bosons.
- Possible conclusion: abandon the WIMP idea and focus on different DM candidates, such as axions or sterile neutrinos.
- However, the paradigm of thermal freeze-out is very general and does not require the DM particle to directly couple to any of the SM bosons.
- Instead, there may be a new mediator responsible for communicating the interactions of DM.



- This opens up new parameter space – but also leads to new constraints, for example from searches for dijet resonances..

Chala, FK et al., arXiv:1503.05916
Fairbairn, FK et al., arXiv:1605.07940

Models of new mediators

- Aim: combine information from searches for new mediators with results from DM searches to understand whether thermal freeze-out is still viable in this set-up.
- This will typically only be possible within the context of a specific DM model.
- At first sight: huge number of possibilities…
- However, we can eliminate a number of possibilities:
  - Strong direct detection constraints on spin-independent interactions: Focus on Majorana DM.
  - Strong LHC constraints on mediators coupling to leptons: Focus on quark couplings.
  - Respect the full gauge symmetry of the SM before electroweak symmetry breaking.

Mediators from a *U(1)'*

- An interesting example: a new *U(1)'* gauge group under which only quarks and the DM particle are charged.

- This gauge group is spontaneously broken by the vev of a SM singlet S, generating the Z' mass and the DM mass.

$$\mathcal{L}_\mathrm{DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g^A_\mathrm{DM} Z'^\mu \bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_\mathrm{DM}\bar{\psi}(P_L S + P_R S^*)\psi \,,$$

$$\mathcal{L}_S = \left[(\partial^\mu + i\, g_S\, Z'^\mu)S\right]^\dagger \left[(\partial_\mu + i\, g_S\, Z'_\mu)S\right] + \mu_s^2\, S^\dagger S - \lambda_s \left(S^\dagger S\right)^2$$

- The singlet mixes with the SM BEH boson and thus obtains couplings to the SM.

- The model therefore contains two possible dark mediators:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s \,,$$

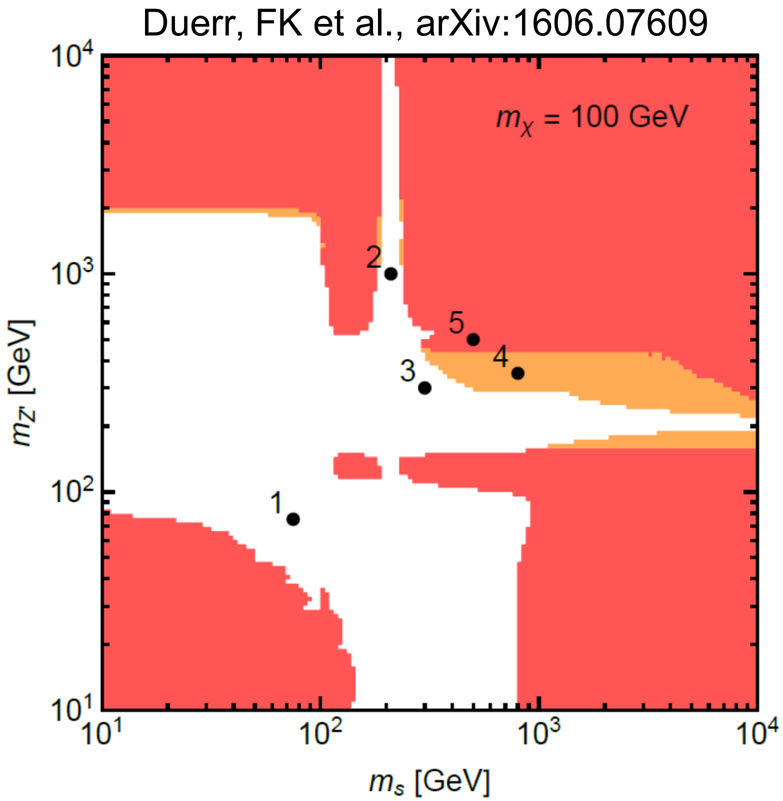
$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}q s\right)$$

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

FK et al., arXiv:1510.02110

Global scans

- For a given combination of the three masses, we can now scan over all coupling combinations to find parameter points compatible with the observed relic density and all experimental constraints.



Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

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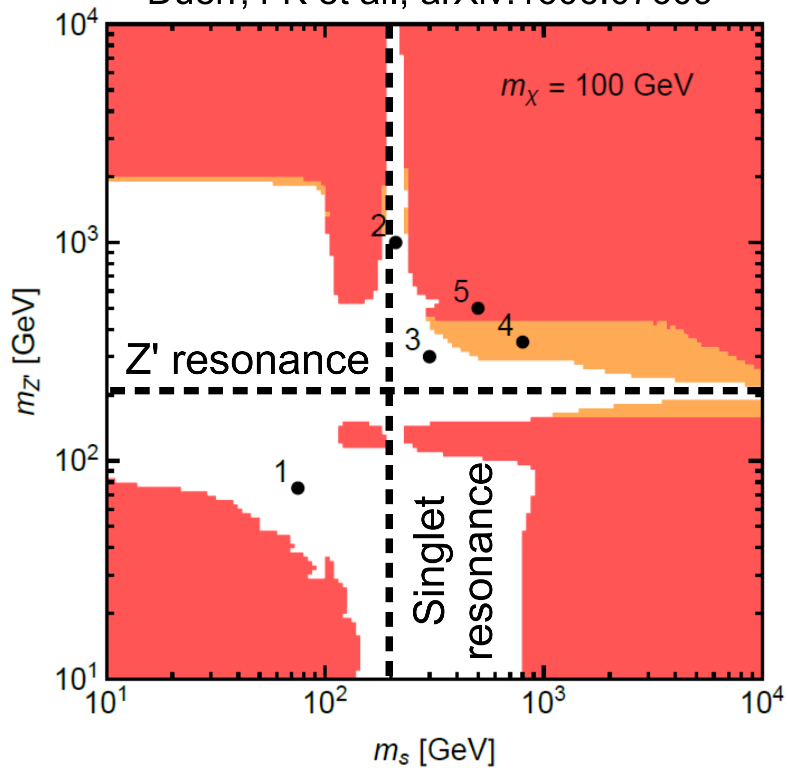
Duerr, FK et al., arXiv:1606.07609



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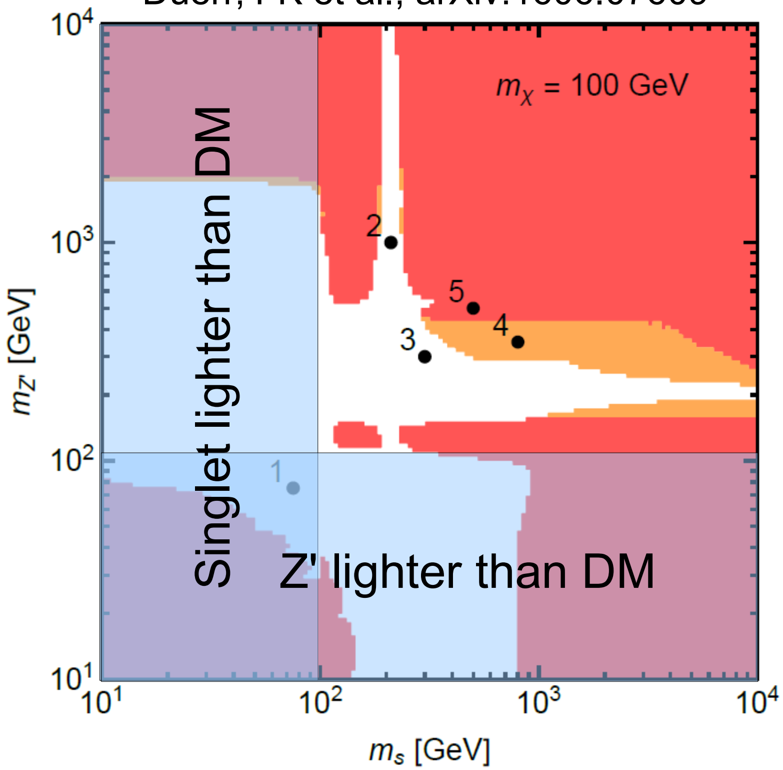

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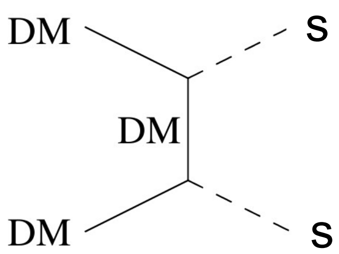
Saving WIMPs with new light states?

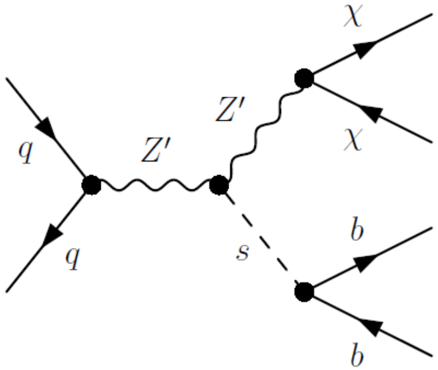
- If one of the mediators is lighter than the DM particle, a new final state for DM annihilation opens up:

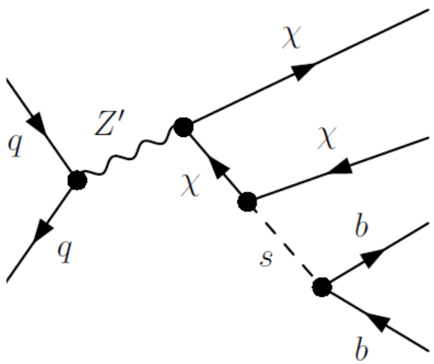


- Easily possible to reproduce the observed relic abundance.
- Should we still call this a WIMP? Secluded DM? Hidden sector freeze-out? …?
- Key point: experimental results disfavour simple WIMP models and prefer more complex dark sectors.
- Can we probe such a set-up experimentally?

Experimental signatures of complex dark sectors

- Consider DM coupled to a light scalar singlet with tiny mixing with the SM BEH boson.
- Although the singlet couples weakly to the SM, couplings within the dark sector must be large!
- If any of the dark sector states are produced at the LHC, they may emit singlet-strahlung (or dark-Higgs-strahlung)!

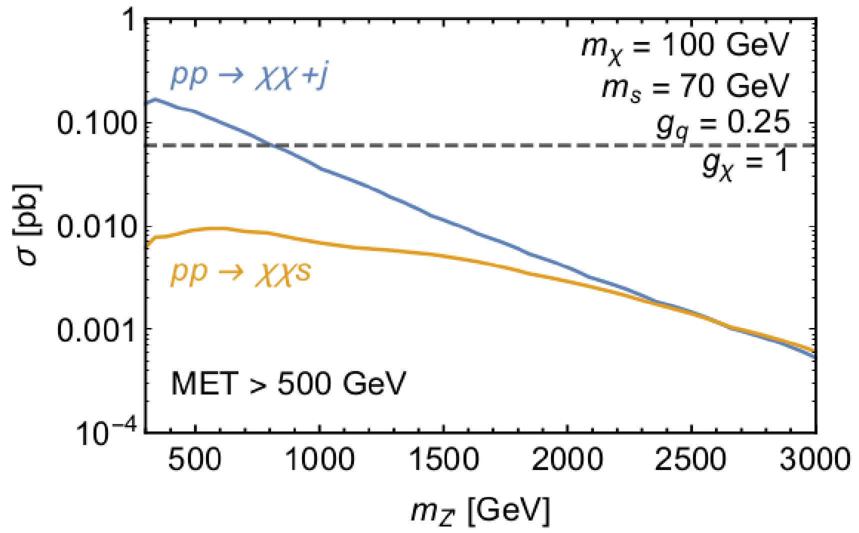




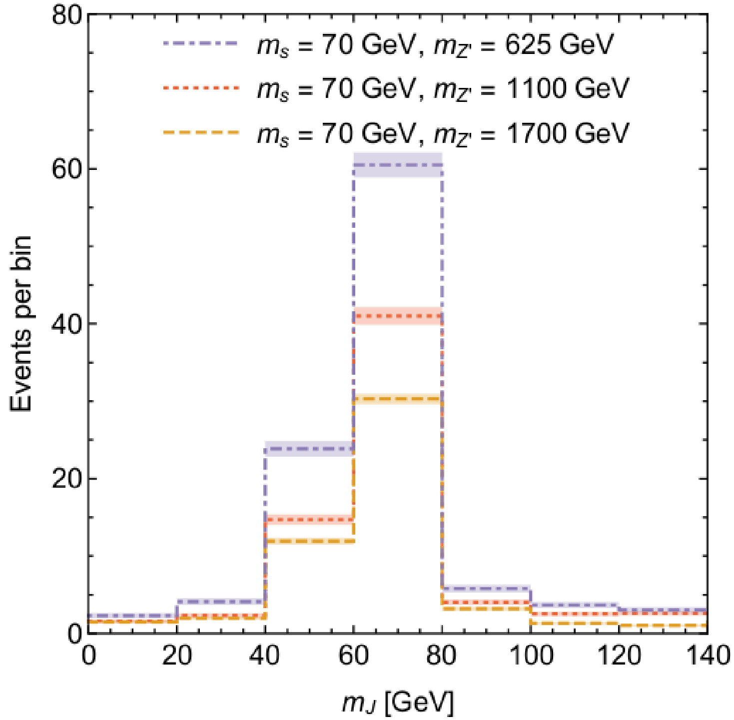
A dark Higgs at the LHC?

Thanks to Teppei Katori for the picture!

Hunting light singlets - predicted event rates



- For large Z' masses, the rate of (high-p_T) singlet-strahlung becomes comparable to the rate of QCD radiation from the initial state.



- We end up with a very characteristic signal: a fat jet containing two b-jets with an invariant mass close to the singlet mass in association with large amounts of MET.

Duerr, FK, et al., arXiv:1701.08780

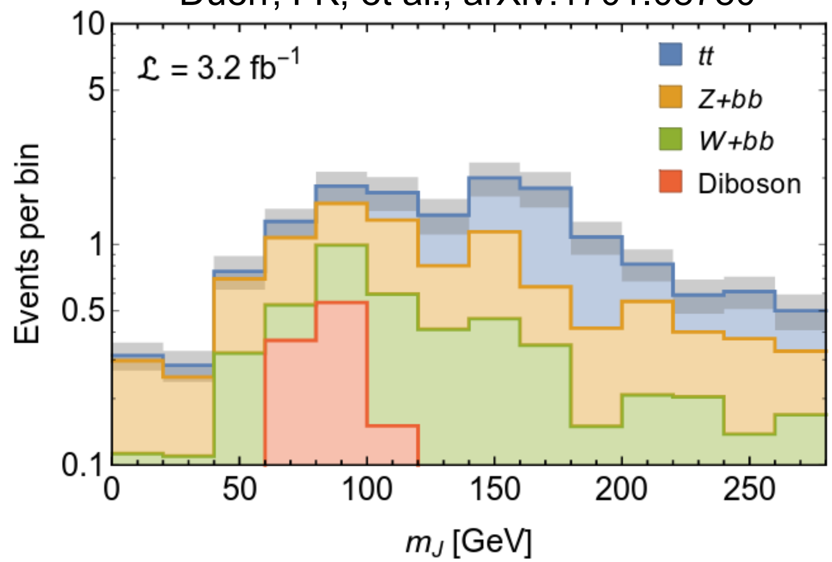
Hunting light singlets - predicted backgrounds

- Experimental searches are conceptually very similar to so-called mono-BEH-searches (or mono-Higgs-searches) – the difference is simply to consider general invariant masses of the fat jet.

- We adopt event selection criteria from ATLAS-CONF-2016-019.
  - Fat jet (R = 1 , pT > 250 GeV, η < 2) with two associated b-tagged track jets (R = 0.2, pT > 10 GeV, η < 2.5).
  - MET > 500 GeV, no isolated leptons (pT > 7 GeV, η < 2.5).

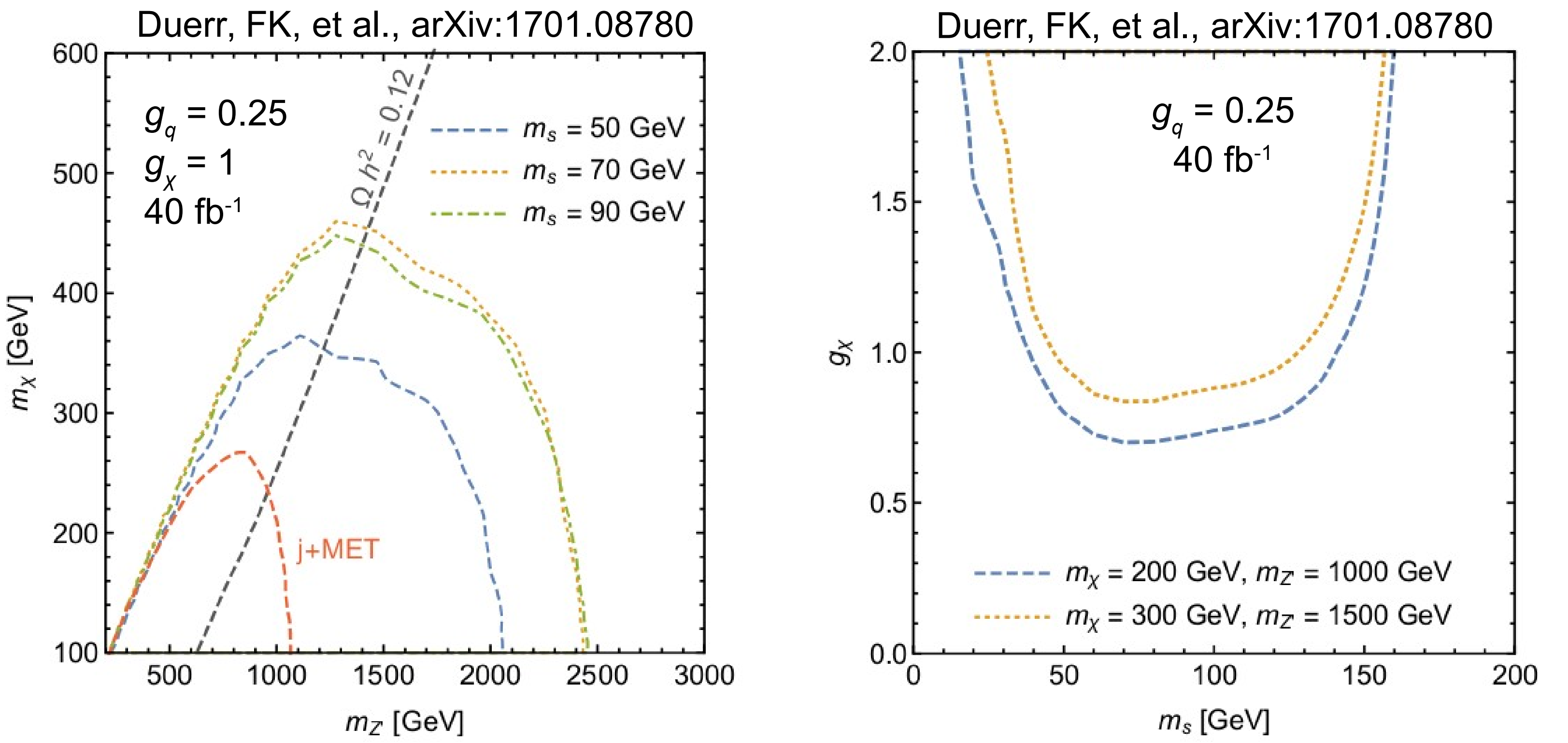
- Dominant backgrounds
  - V+bb for $m_s < m_h$.
  - tt for $m_s > m_h$.
  - Good agreement with ATLAS estimates after applying moderate rescaling factors.

Duerr, FK, et al., arXiv:1701.08780



Hunting light singlets - projected sensitivity

- The shape of the m_J distribution is very different for signal and background!
- These generalized mono-dark-Higgs-searches make it possible to probe dark sectors with a light singlet up to very large Z' masses.



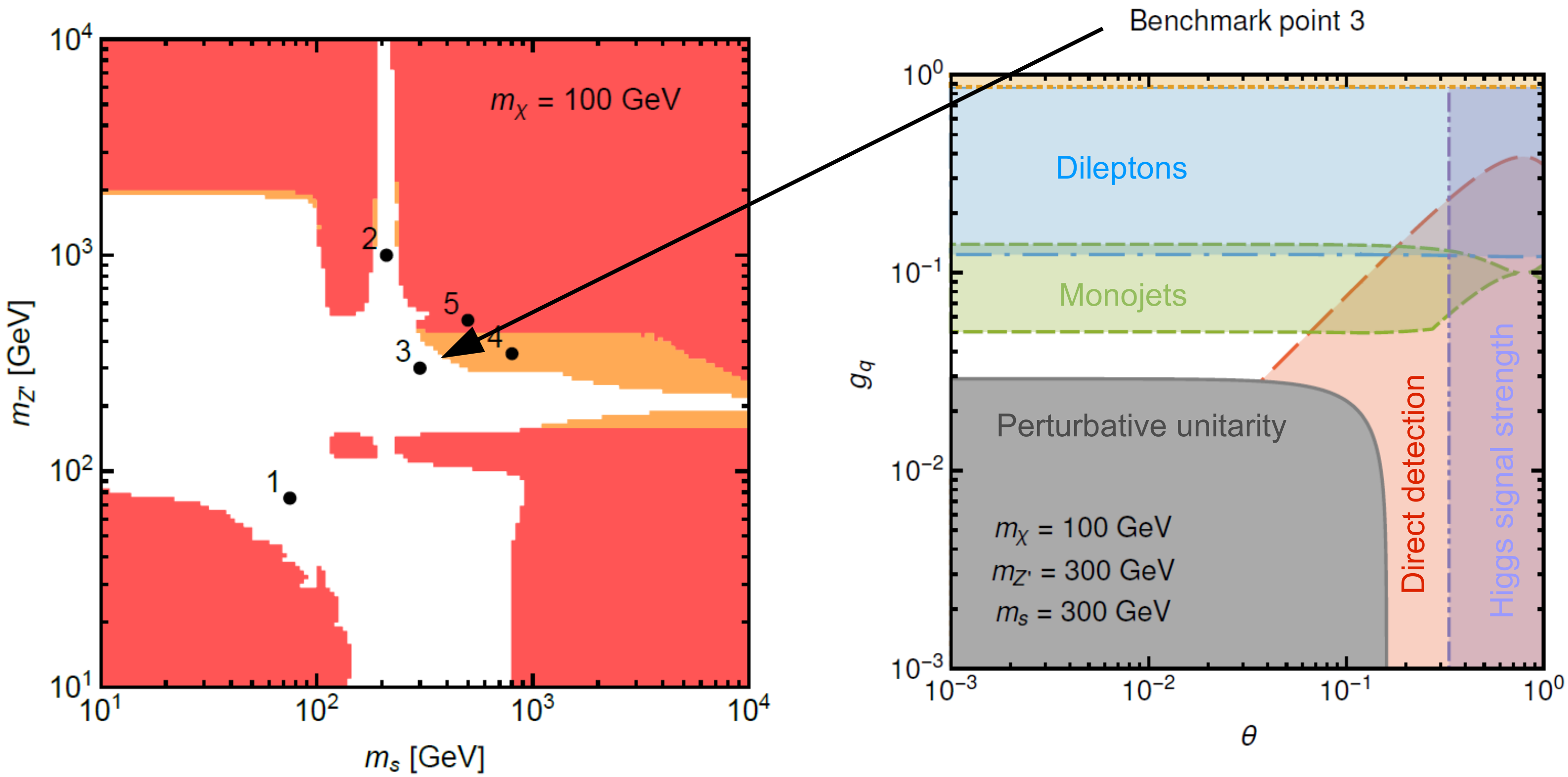
Conclusions

- The non-observation of new physics at the LHC and null results in direct DM searches put significant pressure on the WIMP idea (but scalar singlets still viable).
- A possible way forward: New mediators open up large new parameter space but also predict many new signatures (e.g. dijet resonances).
- Considering the case of new mediators from a broken U(1)' gauge group, we find significant experimental pressure on heavy mediators.
- Still, thermal freeze-out is perfectly viable if the dark sector has additional structure, for example if the additional singlet in the dark sector is light.
- Such models of secluded WIMPs can be probed experimentally, for example with LHC searches for boosted fat jets in association with missing transverse energy.

Backup

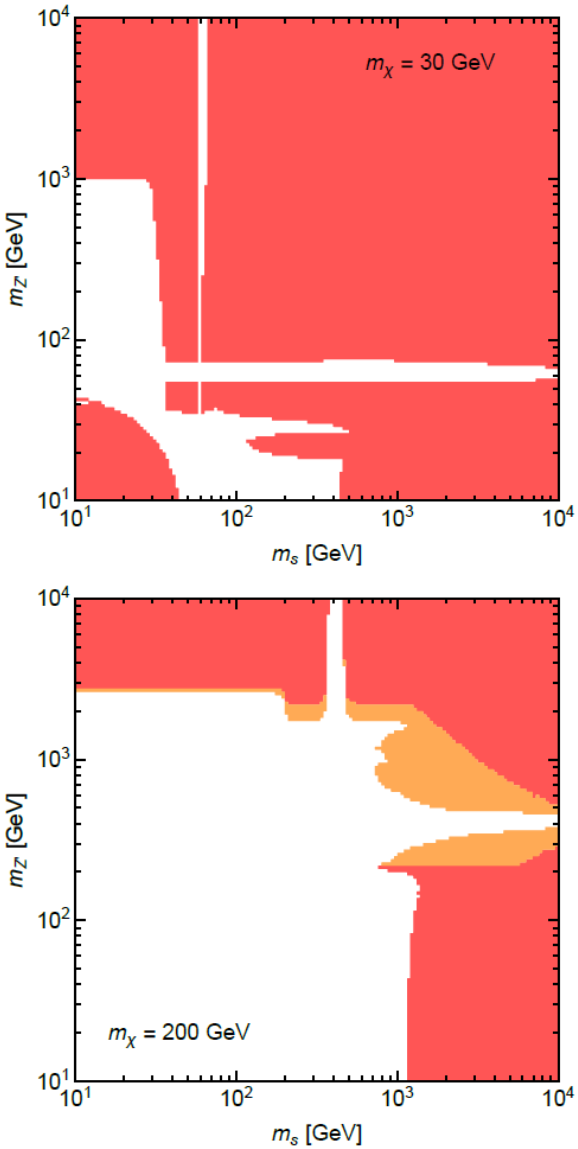
WIMPs via Z' exchange

- We also find viable parameter points where both the Z' and the singlet are heavier than the DM particle.



- Allowed parameter space for $g_q \sim 0.04$ and $\theta < 0.06$.

Global scans: Dependence on the DM mass



- For small DM masses the presence of an even lighter mediator (Z' or singlet) is essential!
- Models with two dark terminators are in fact excluded by indirect detection constraints for m_χ < 100 GeV.
- For larger DM masses, there is larger viable parameter space (we find allowed solutions up to $m_\chi \sim$ 50 TeV).

Hunting light singlets – relic density

- Rather than setting the dark sector coupling to a specific value, one can determine it from the requirement to reproduce the observed DM relic abundance.
- This approach leads to an exciting complementarity between mono-dark-Higgs searches and searches for dijet resonances.