Vector Mediators in Dark Matter Direct Detection and at Colliders

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arXiv:1107.2118, arXiv:1204.XXXX

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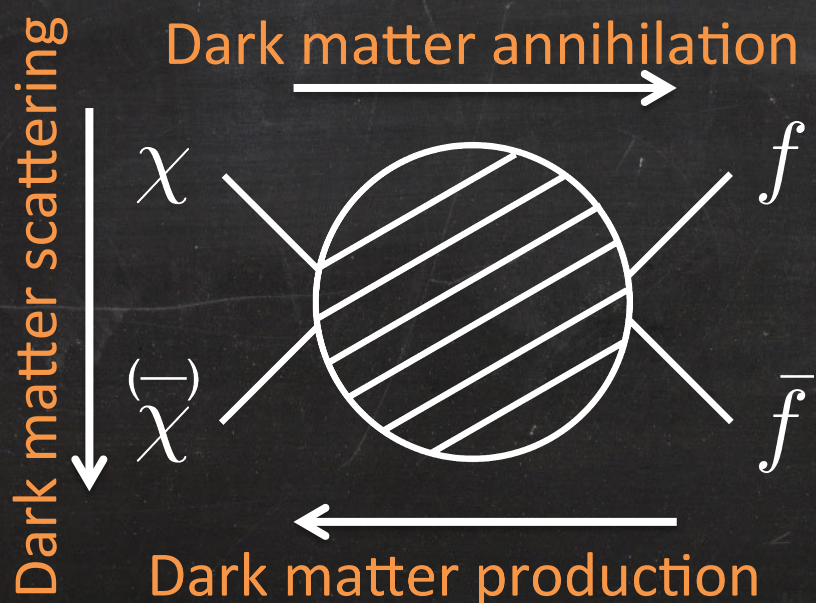
Outline

1. Introduction and Motivation
2. Discussion of different mediator masses
    - Very heavy mediators: $M_R \geq 4$ TeV
    - Heavy mediators: 100 GeV $\leq M_R \leq$ 4 TeV
    - Light mediators: 100 MeV $\leq M_R \leq$ 100 GeV
    - Very light mediators: $M_R \leq$ 100 MeV
3. Example: The dark Z'
4. Conclusions

Introduction

If dark matter scatters on nuclei to give a direct detection signal, we also expect other processes to give observable signatures



Experiments searching for these signatures can constrain the direct detection cross section

Introduction

Problem: Separation of scales

- Dark matter direct detection probes the non-relativistic limit ($v_{DM} \approx 10^{-3}$), while the LHC probes the TeV scale.
- To compare these two types of experiments, we need to know the mediator mass, its spin and its various couplings.
- In this talk: Focus on vector mediators (R).

Why vector mediators?

- Common assumption: spin-independent dark matter-nucleon interactions are mediated by scalar particles (such as the Higgs)
- This is the only option if dark matter is a Majorana fermion (for example the neutralino)
  - → Typically small couplings to light quarks
  - → Equal couplings to protons and neutrons: $f_n / f_p \approx 1$
  - → Very difficult to get large cross sections

Why vector mediators?

- If dark matter is a Dirac fermion or a complex scalar, spin-independent interactions can also be mediated by spin-1 particles (e.g. gauge bosons)
  - → Possibly large couplings to light quarks
  - → Large amount of freedom in f_n/f_p

Photon:	$f_p = 1, f_n = 0$
Z boson:	$f_p \approx 0, f_n = 1$
ρ meson:	$f_p \approx -f_n$

Very heavy mediators

$M_R \geq 4$ TeV

- Effective interactions remain valid at the LHC

$$\sigma(j + \text{MET}) \sim g_q^{\,2}\, g_\chi^{\,2} / M_R^{\,4} \sim \sigma_p$$

- We can directly compare LHC searches for dark matter to direct detection cross sections

See talks by A. Barr and S. Worm

- Typically, $\sigma_p \approx 10^{-42}\, g_q^{\,2}\, g_\chi^{\,2}\, (4 \text{ TeV} / M_R)^4 \text{ cm}^2$, so σ_p will be small unless couplings are close to the bounds from perturbativity and unitarity.

Shoemaker, Vecchi, arXiv:1112.5457

Fox, Harnik, Primulando, Yu, arXiv:1203.1662

Heavy mediators

$100\ \text{GeV} \leq M_R \leq 4\ \text{TeV}$

- LHC can produce the mediator on-shell

$$\sigma(j + \text{MET}) \sim \sigma(pp \rightarrow R + j) \times \text{BR}(R \rightarrow \text{invisible})$$

→ Monojet (and monophoton) cross sections depend on all possible decay channels of *R*

→ The connection to direct detection cross sections is more involved

Decay channels

R can decay into fermions, bosons

and new hidden sector states

$$\Gamma_R = \Gamma^{\chi\bar{\chi}} + \sum_q \Gamma^{q\bar{q}} + \sum_l \Gamma^{l\bar{l}} + \sum_\nu \Gamma^{\nu\bar{\nu}}$$

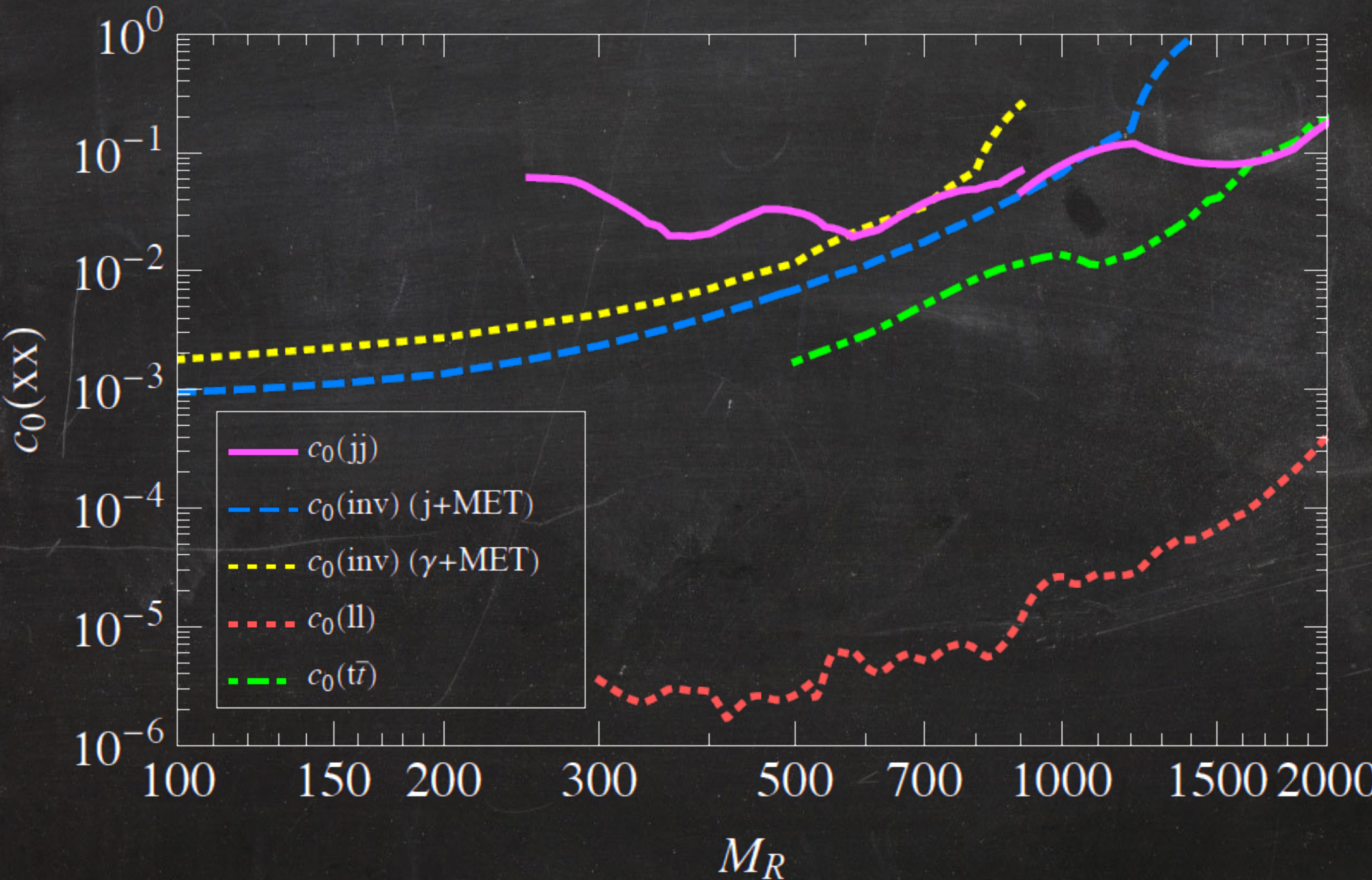
$$+ \Gamma^{W^+W^-} + \Gamma^{ZZ} + \Gamma^{\gamma Z} + \Gamma^{ZH}$$

$$+ \Gamma^{X}$$

All of these channels can be constrained by LHC data!

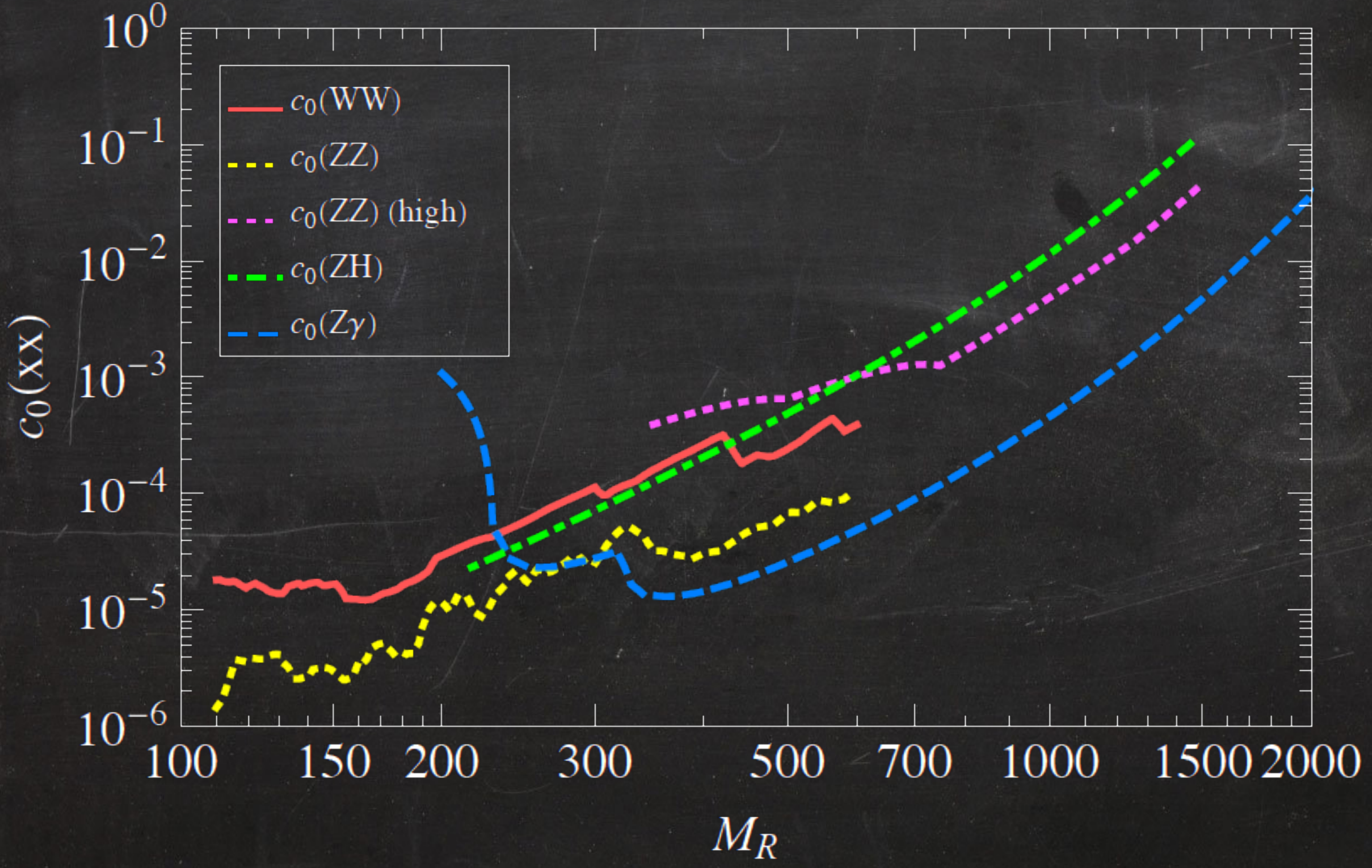
Constraints: Fermions

Define $c_0(xx) = g_q^{\,2} \times \mathrm{BR}(R \rightarrow xx)$



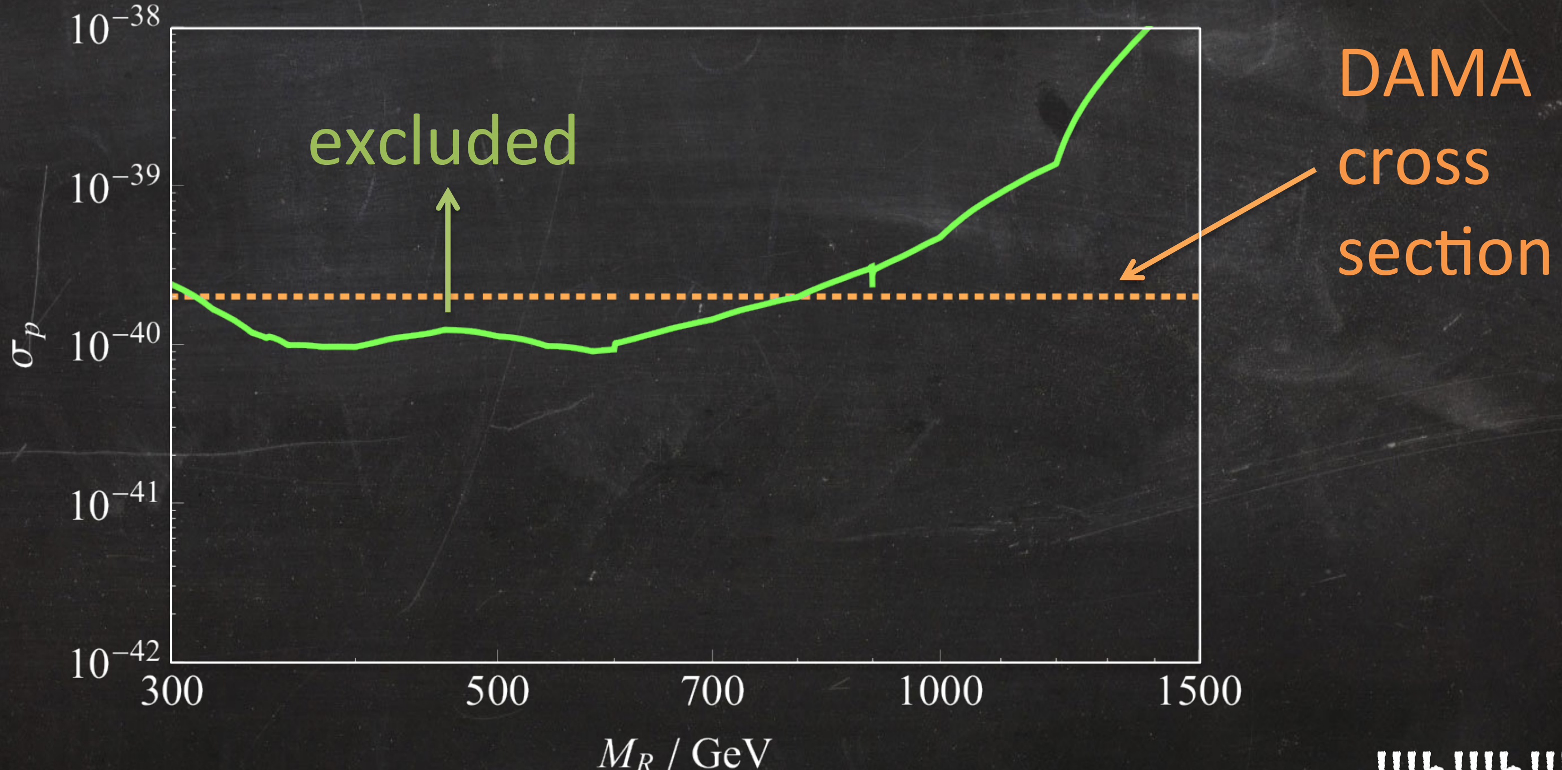
Constraints: Bosons

Define $c_0(xx) = g_q{}^2 \times \mathrm{BR}(R \to xx)$



Combined Constraints

$$\sigma_p \leq 108 \frac{\mu_{\chi n}^2 \Gamma_R^{\text{tot}}}{M_R^5} \text{BR}(R \to \text{inv}) g_q^2$$



Light mediators

$100\text{ MeV} \leq M_R \leq 100\text{ GeV}$

- Monojet and monophoton signals at the LHC are strongly suppressed
- More stringent constraints arise from
  - Electroweak precision tests
  - Muon $g - 2$
  - Atomic parity violation
  - Hadronic decays

Constrained by BaBar, Belle, BEPC and LHCb

Aranda, Carone, Phys.Lett. B443 (1998), 352–358
Chun, Park, Scopel, JHEP 1102 (2011), 100
Frandsen, F.K., Sarkar, Schmidt-Hoberg,JHEP 1109 (2011), 128

Very light mediators

$M_R \leq 100$ MeV

- Give rise to long-range forces

  → Modification of direct detection spectrum

  Fornengo, Panci, Regis, Phys.Rev. D84 (2011) 115002

  → Enhancement of dark matter self-interactions

  Buckley, Fox, Phys.Rev. D81 (2010) 083522
  Foot, arXiv:1110.2908

- Constraints from astrophysics and cosmology

  Boehm, Fayet, Nucl.Phys. B683 (2004) 219-263

Example: The dark Z′

- As an example we consider the case where *R* is the gauge boson of a new *U*(1) under which only the dark matter particle is charged

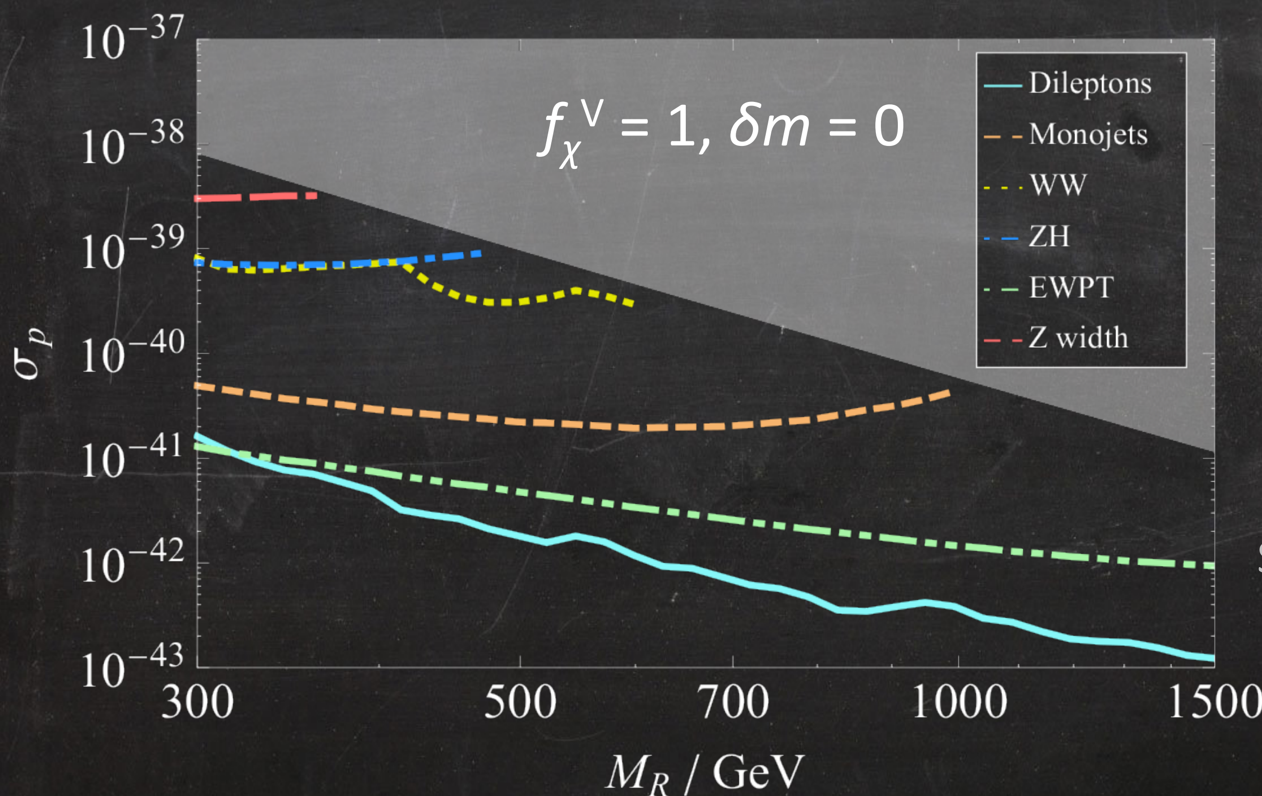
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m^2_{Z'} Z'_{\mu} Z'^{\mu}$$

$$- \frac{1}{2} \sin\epsilon \, B_{\mu\nu} Z'^{\mu\nu} + \delta m^2 Z_{\mu} Z'^{\mu}$$

K. Babu, C. F. Kolda, and J. March-Russell, Phys.Rev. D57 (1998), 6788–6792
Fox, Liu, Tucker-Smith, Weiner, Phys.Rev. D84 (2011) 115006
Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011), 128

Example: The dark Z′

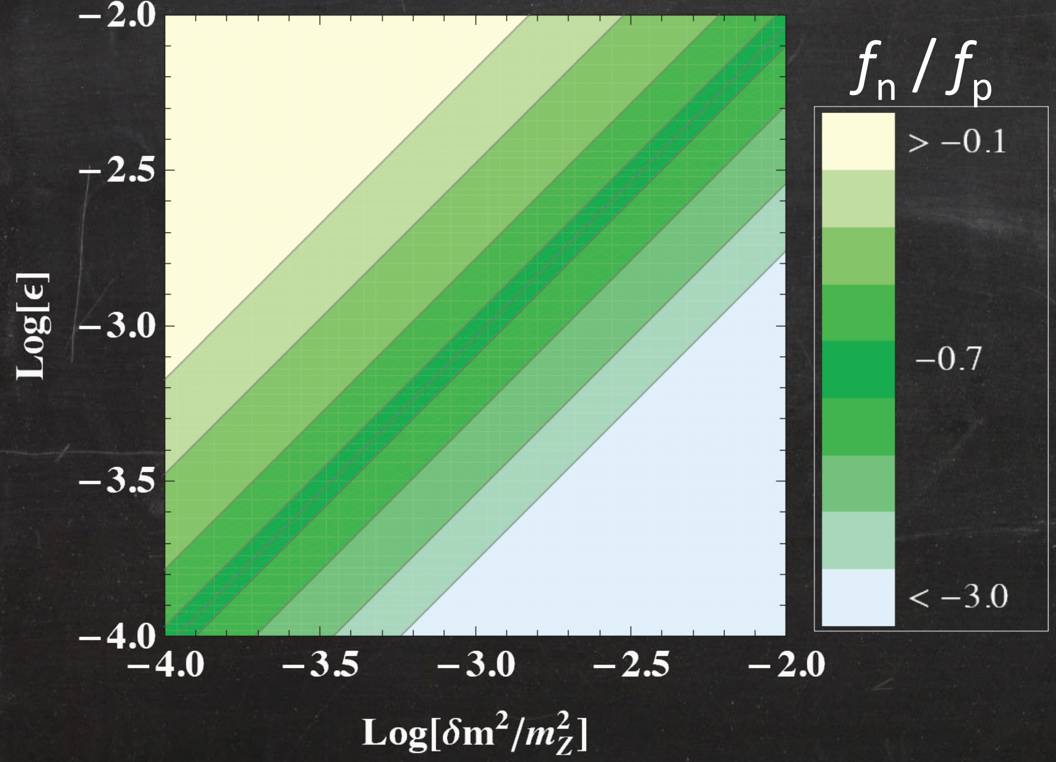
For 300 GeV < $m_{Z'}$ < 1500 GeV, we can use current LHC data to constrain direct detection cross sections



Frandsen, F.K., Preston, Sarkar, Schmidt-Hoberg, arXiv:1204.XXXX

Example: The dark Z′

For $m_{Z'} \sim 5$ GeV, it is possible to choose ε and δm in such a way that $\sigma_p \sim 10^{-38}$ cm^2 and $f_n / f_p = -0.7$



We can thus remove the tension between DAMA and XENON

Frandsen, F.K., Sarkar, Schmidt-Hoberg, JHEP 1109 (2011), 128

Conclusions

- Vector mediators are interesting because they can give a wide range of values for f_n/f_p and large direct detection cross section.
- Heavy mediators ($M_R \geq 100$ GeV) can be tested and constrained by current LHC data.
- Lighter mediators are also appealing, but more difficult to constrain.
- Attractive model: Dark *Z'* with mixing.