Interpreting direct detection searches

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JHEP 1401 025 (arXiv:1308.6799)
and work in progress

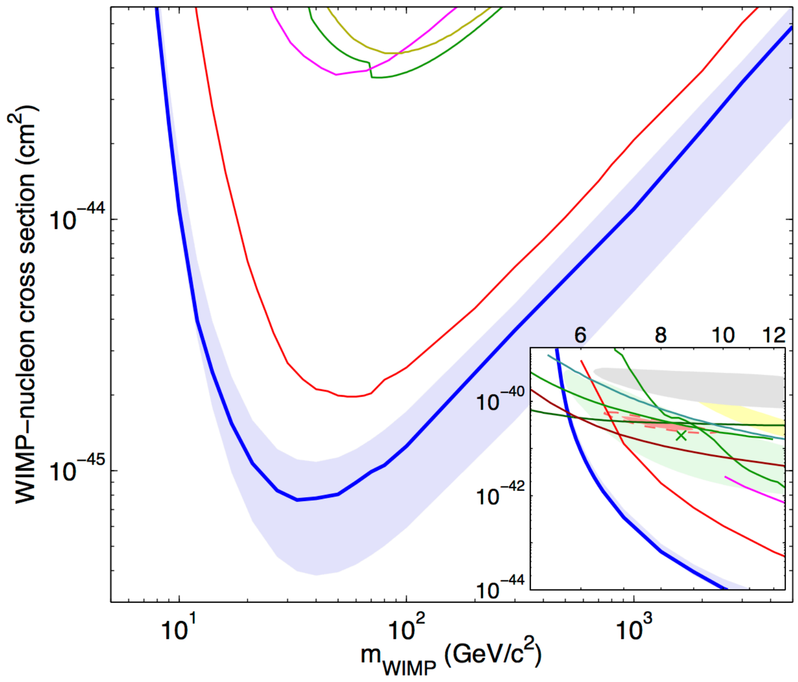
Dark matter brainstorming meeting, Imperial College – 29th May 2014

Outline of this talk

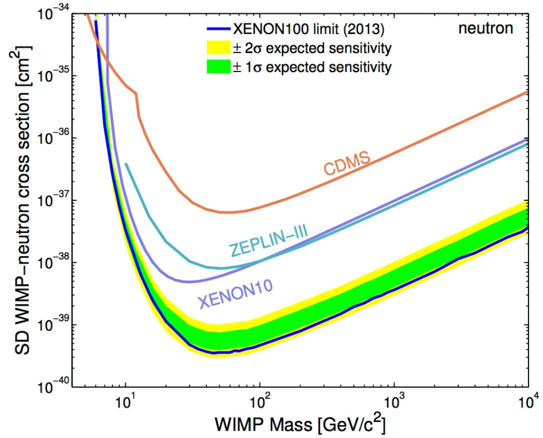
- Standard interpretation of direct detection results
- Application to simple models
- Comparing direct detection and LHC limits

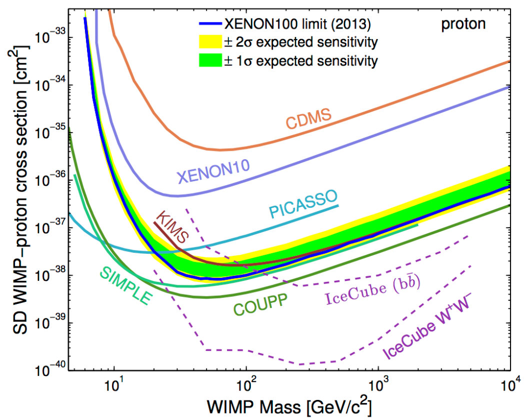
Direct detection results

Spin-independent



Spin-dependent





Why constrain these parameters?

- Interactions that dark matter might have with quarks

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman et al:1008.1783

- Using operators excellent approximation when $M_{\rm med} > 500$ MeV

Why constrain these parameters?

- In the non-relativistic limit ($v_{\rm DM} \sim 10^{-3}$)

$$u = \begin{pmatrix} \sqrt{p.\sigma}\xi \\ \sqrt{p.\bar{\sigma}}\xi \end{pmatrix} \xrightarrow{\text{NR limit}} \sqrt{m}\begin{pmatrix} \xi \\ \xi \end{pmatrix} \qquad v = \begin{pmatrix} \sqrt{p.\sigma}\eta \\ -\sqrt{p.\bar{\sigma}}\eta \end{pmatrix} \xrightarrow{\text{NR limit}} \sqrt{m}\begin{pmatrix} \eta \\ -\eta \end{pmatrix}$$

$$\bar{\chi}\chi\,\bar{q}q \propto \mathbb{I} + \mathcal{O}(v_{\rm DM}^2) \qquad \bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q \propto \vec{s}_{\rm DM}\cdot\vec{s}_{\rm N} + \mathcal{O}(v_{\rm DM}^2)$$

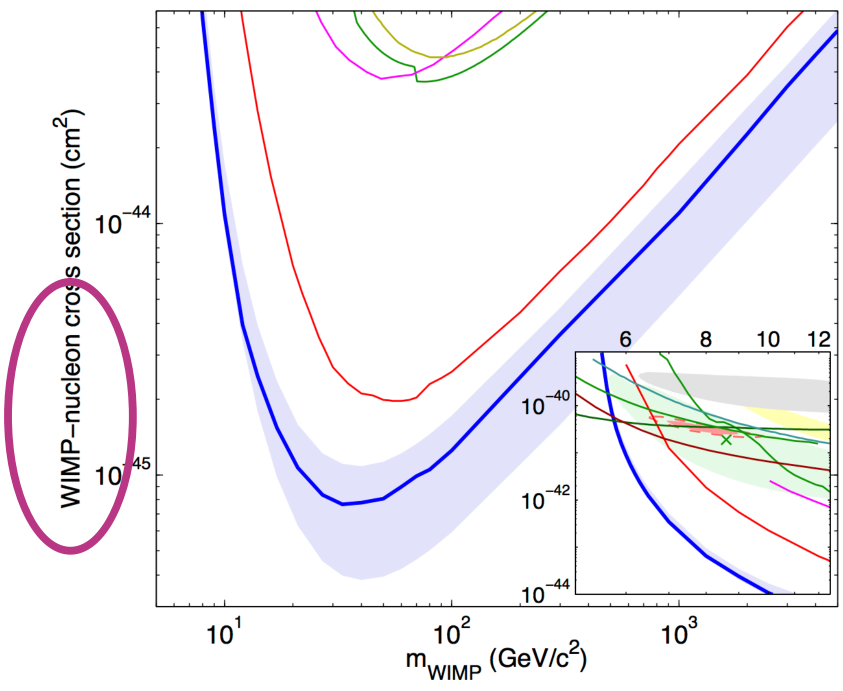
$$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q \propto \mathbb{I} + \mathcal{O}(v_{\rm DM}^2) \qquad \bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q \propto \vec{s}_{\rm DM}\cdot\vec{s}_{\rm N} v_{\rm DM}^2 + \mathcal{O}(v_{\rm DM}^4)$$

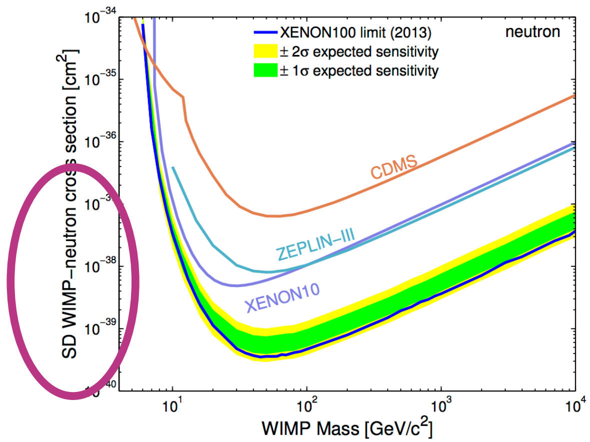
- All interactions fall into two categories:

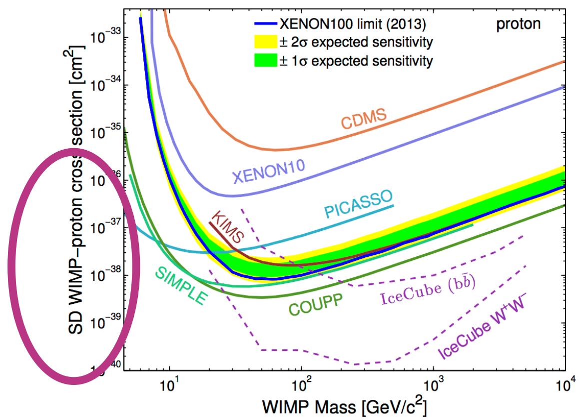
  spin-independent or spin-dependent

Direct detection results

- Constrain the cross-section to scatter with nucleon







Why constrain these parameters?

- Dark matter scatters off the whole nucleus
  ...but different experiments use different target nuclei

- Parameterising in terms of the nucleon cross-section allows an easy comparison of different experiments

- SI limits assume $\sigma_{\mathrm{N}} \propto A^2 \sigma_{\mathrm{n}}$
  - more generally $\sigma_{\mathrm{N}} \propto (f_p Z + f_n (A - Z))^2 \sigma_{\mathrm{n}}$

- SD limits assume the DM couples either to neutron or proton only – good approximation

Mini summary

- All interactions are either spin-independent or spin-dependent
  - Experiments place separate constraints on each

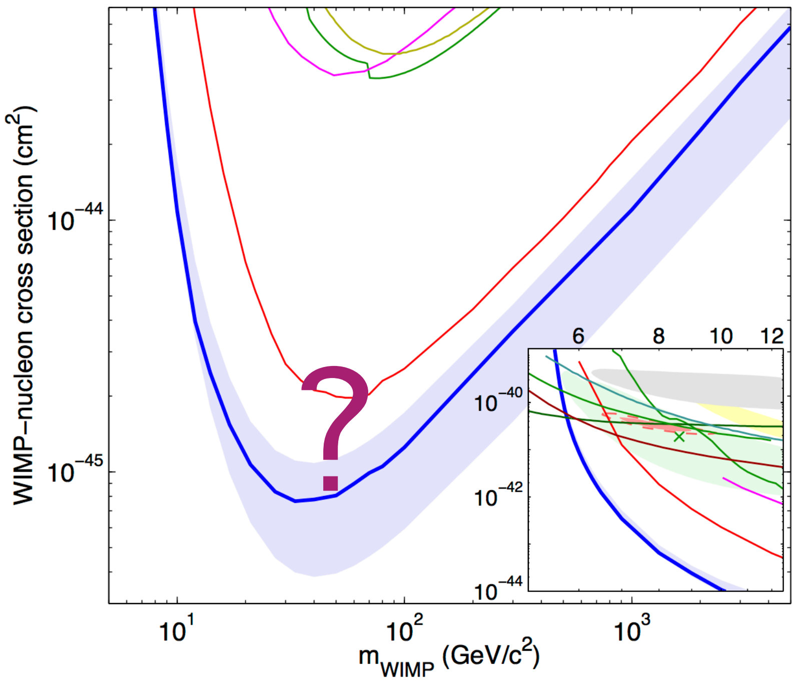
- Limit is on the cross-section to scatter of a nucleon (not the whole nucleus)

- SI limit – assumes equal coupling to protons and neutrons
- SD limit – separate limit for scattering on proton and neutron

Uncertainties?

- How robust are these limits?

- Sources of uncertainty come from
  - Astrophysical parameters
  - Response of the detector
  - Nuclear physics



Astrophysical parameters

- Cross-section is degenerate with the local DM density:

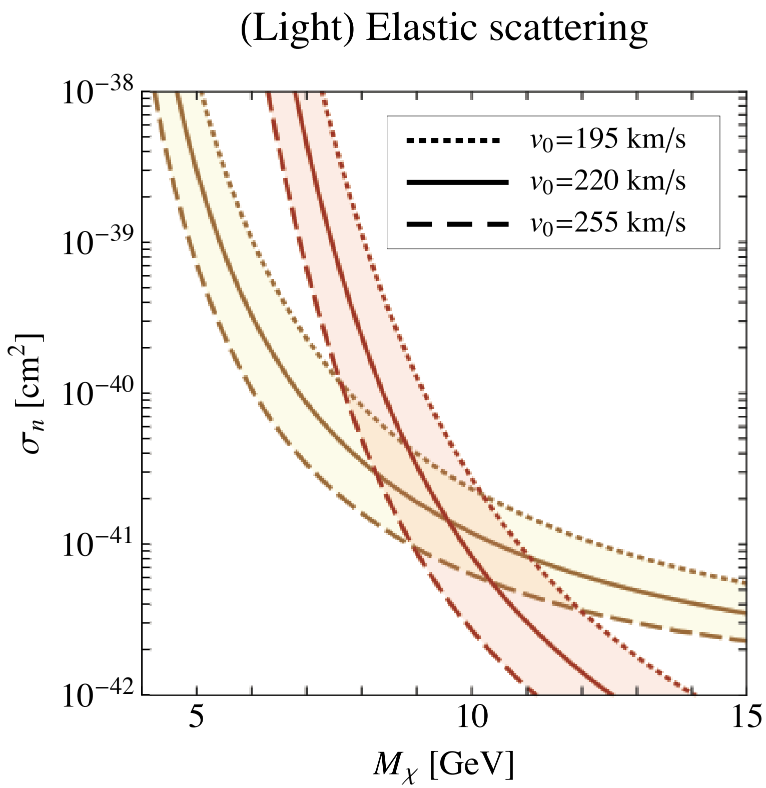
$N_{\rm events} \propto \rho_{\rm DM}\sigma_{\rm n}$ where $\rho_{\rm DM} = 0.3\ {\rm GeV\,cm^{-3}}$

Label	**Reference**	**Description**	**Sampling**	$\rho_{\rm dm}$ $[{\rm M_\odot\,pc^{-3}}]$	$\rho_{\rm dm}$ $[{\rm GeV\,cm^{-3}}]$
a) Local measures ($\rho_{\rm dm}$)					
Kapteyn	Kapteyn (1922)	–	–	0.0076	0.285
Jeans	Jeans (1922)	–	–	0.051	1.935
Oort	Oort (1932)	–	–	0.0006 ± 0.0184	0.0225 ± 0.69
Hill	Hill (1960)	–	–	-0.0054	-0.202
Oort	Oort (1960)	–	–	0.0586 ± 0.015	2.2 ± 0.56
Bahcall	Bahcall (1984a)	–	–	0.033 ± 0.025	1.24 ± 0.94
Bienayme†	Bienayme et al. (1987)	–	–	0.006 ± 0.005	0.22 ± 0.187
KG†	Kuijken & Gilmore (1991)	–	–	0.0072 ± 0.0027	0.27 ± 0.102
Bahcall	Bahcall et al. (1992)	–	–	0.033 ± 0.025	1.24 ± 0.94
Creze	Creze et al. (1998)	–	–	-0.015 ± 0.015	-0.58 ± 0.56
HF†	Holmberg & Flynn (2000b)	–	–	0.011 ± 0.01	0.4 ± 0.375
HF†	Holmberg & Flynn (2004)	–	–	0.0086 ± 0.0027	0.324 ± 0.1
Bienayme	Bienaymé et al. (2006)	–	–	0.0059 ± 0.005	0.51 ± 0.56
Latest measurements					
MB12	Moni Bidin et al. (2012)	CSF	412	0.00062 ± 0.001 $[0 \pm 0.001]$	0.023 ± 0.042 $[0 \pm 0.042]$
BT12	Bovy & Tremaine (2012)	CSF	412	0.008 ± 0.003	0.3 ± 0.11
G12	Garbari et al. (2012)	VC	2×10^3	$0.022^{+0.015}_{-0.013}$	$0.85^{+0.57}_{-0.5}$
G12*	Garbari et al. (2012)	VC + Σ_b	2×10^3	$0.0087^{+0.007}_{-0.002}$	$0.33^{+0.26}_{-0.075}$
S12	Smith et al. (2012)	CSF	10^4	0.005 [no error] [0.015]	0.19 [0.57]
Z13	Zhang et al. (2013)	CSF	10^4	0.0065 ± 0.0023	0.25 ± 0.09
BR13	Bovy & Rix (2013)	CSF + MAP	10^4	0.006 ± 0.0018 $[0.008 \pm 0.0025]$	0.22 ± 0.07 $[0.3 \pm 0.094]$

Read:1404.1938

Astrophysical parameters

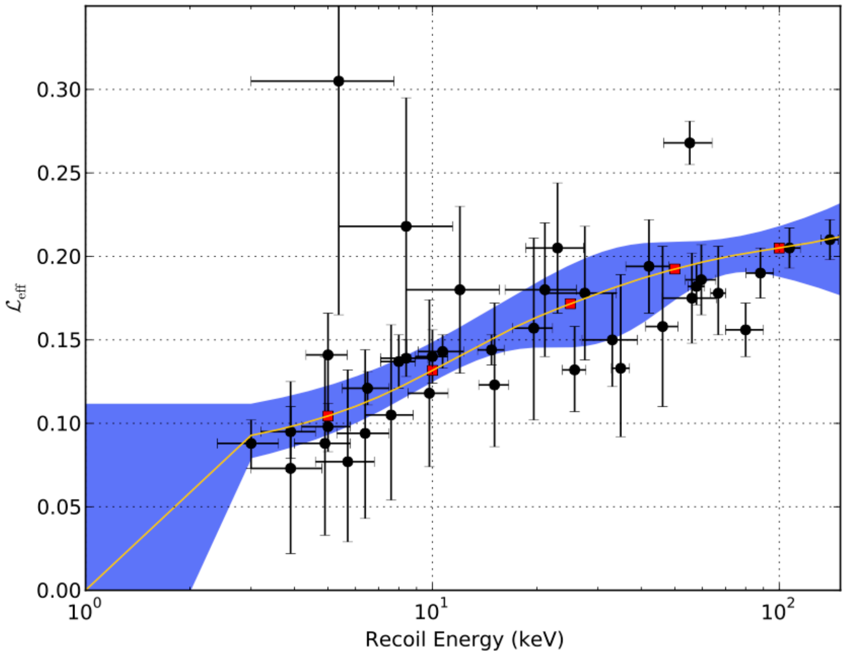
- Velocity parameters of Sun (v0) also has some influence
- Shifts the limit horizontally at low mass

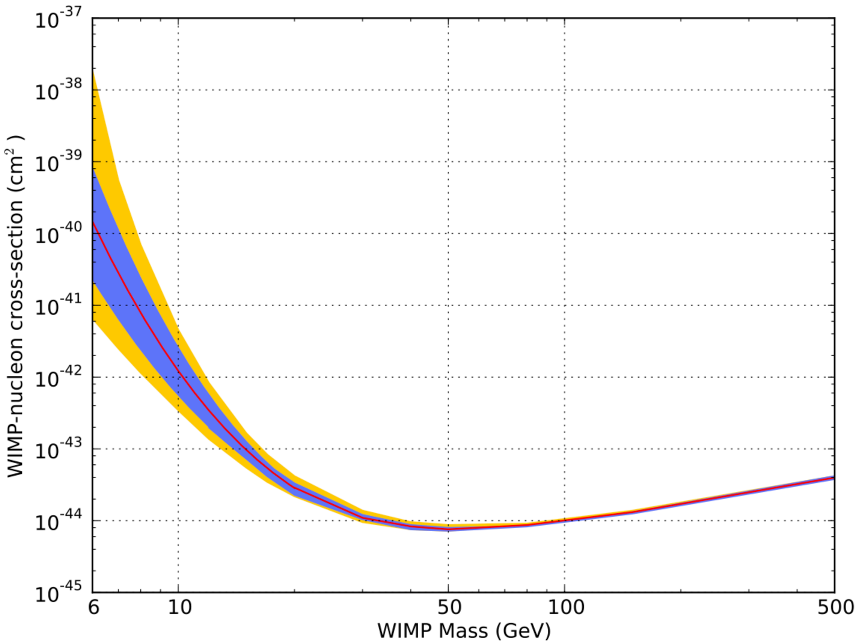


McCabe:1005.0579

Response of the detector

- Detector effects important near threshold
  eg light response of XENON100 (now understood better)

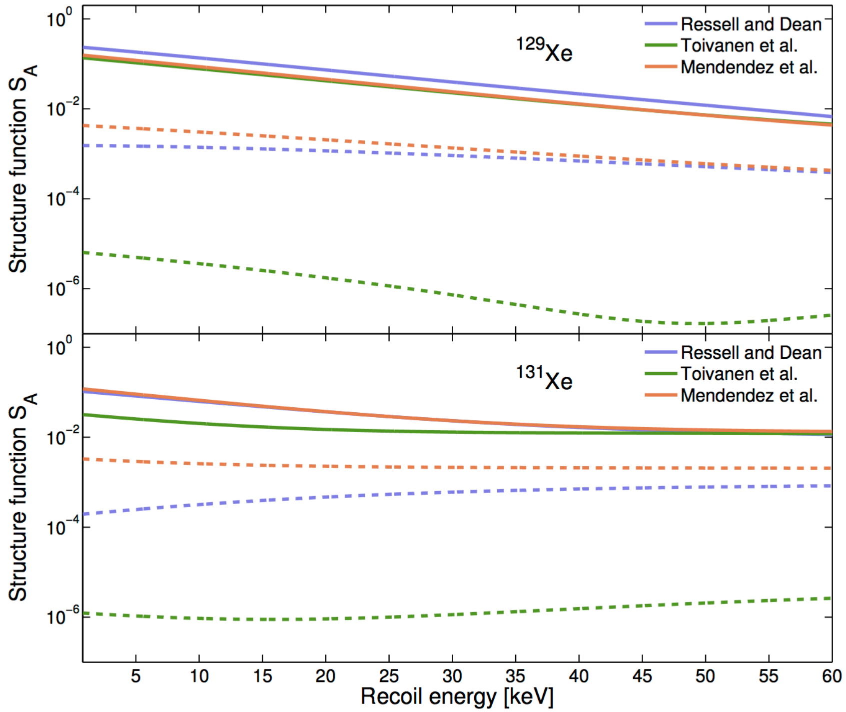


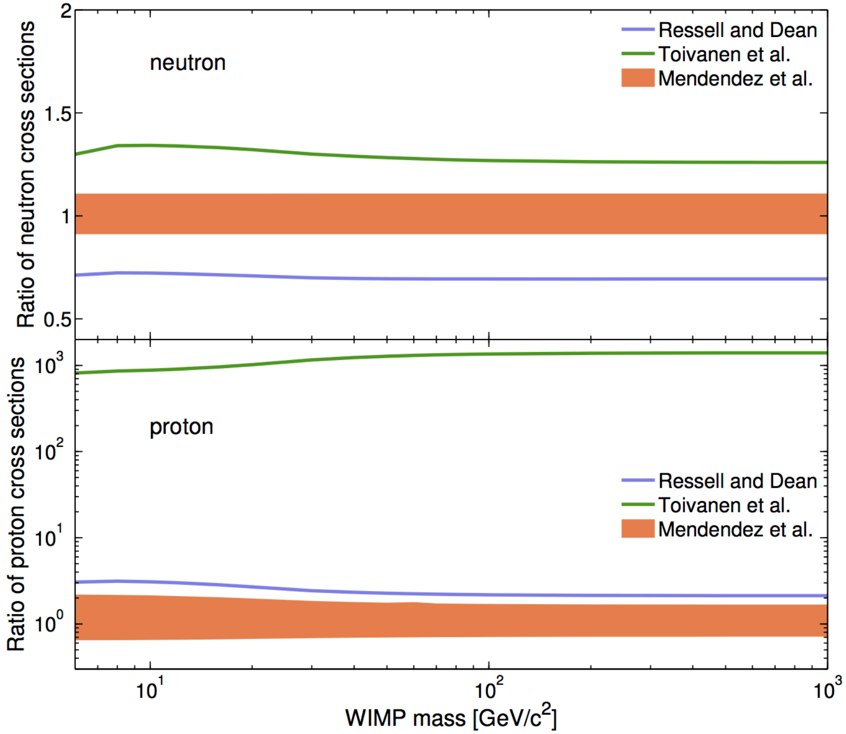


Davis et al:1203.6823

Nuclear physics

- Issue for SD: Spin structure functions not known well



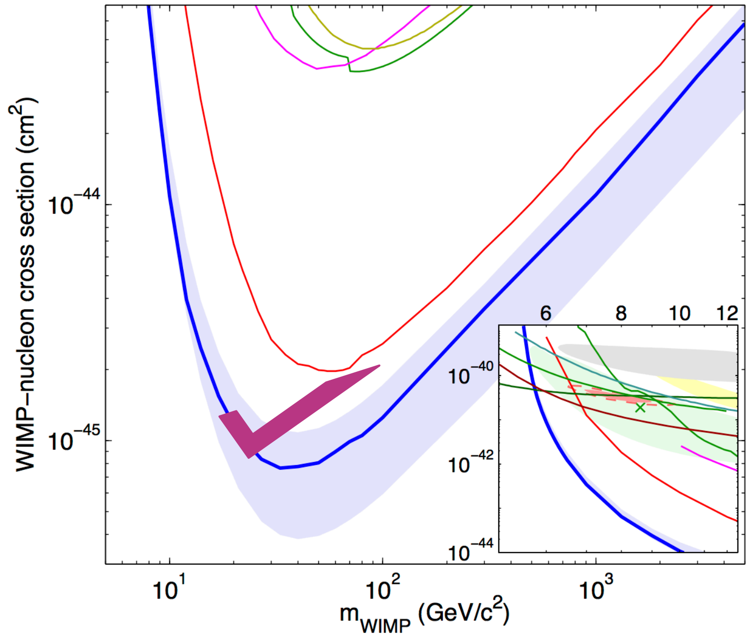


XENON100:1301.6620

Mini summary

- How robust are these limits?

- About a 30-50% uncertainty at 30 GeV and above
- Can be larger at low mass (near threshold)



Application to simple models

- Consider vector mediators

$$\mathcal{L} = \bar{\chi}\gamma^\mu(a + b\gamma^5)\chi Z'_\mu + \bar{q}\gamma^\mu(c + d\gamma^5)q Z'_\mu$$

$$\sum_q \frac{ac}{M_{Z'}^2}\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q \quad \xrightarrow{\text{N.R.}} \quad \text{Spin-independent (SI)}$$

$$\sum_q \frac{bd}{M_{Z'}^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q \quad \xrightarrow{\text{N.R.}} \quad \text{Spin-dependent (SD)}$$

$$\sum_q \frac{bc}{M_{Z'}^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q \quad \xrightarrow{\text{N.R.}} \quad \text{Suppressed by } v_{\text{DM}}^2 \sim 10^{-6}$$

$$\sum_q \frac{ad}{M_{Z'}^2}\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q \quad \xrightarrow{\text{N.R.}} \quad \text{Suppressed by } v_{\text{DM}}^2 \sim 10^{-6}$$

- If vector (SI) interaction is present, it will dominate
  - forbidden for Majorana fermions

Vector interaction (SI)

- The nucleon cross-section is $\sigma_{\rm n} = \frac{f^2 \mu^2}{\pi}$
  - For protons: $f_p = \frac{(g_u + 2 g_d) g_{\rm DM}}{M_{Z'}^2}$
  - For neutrons: $f_n = \frac{(g_u + 2 g_d) g_{\rm DM}}{M_{Z'}^2}$
- Only u, d coupling contributes
- Interactions with proton and neutron generally different

- Simplify problem by assuming all g_q equal

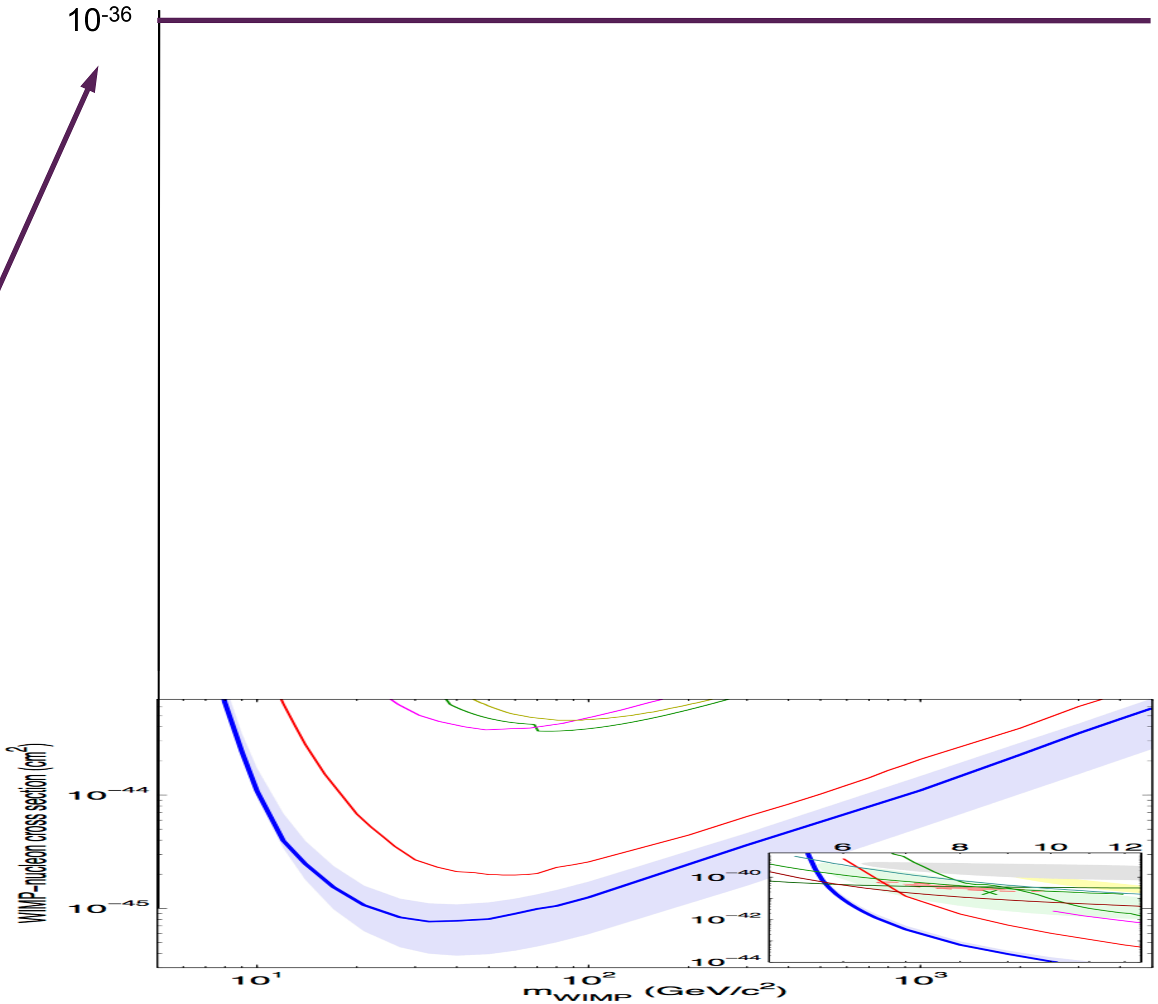
Vector interaction (SI) – some intuition

For

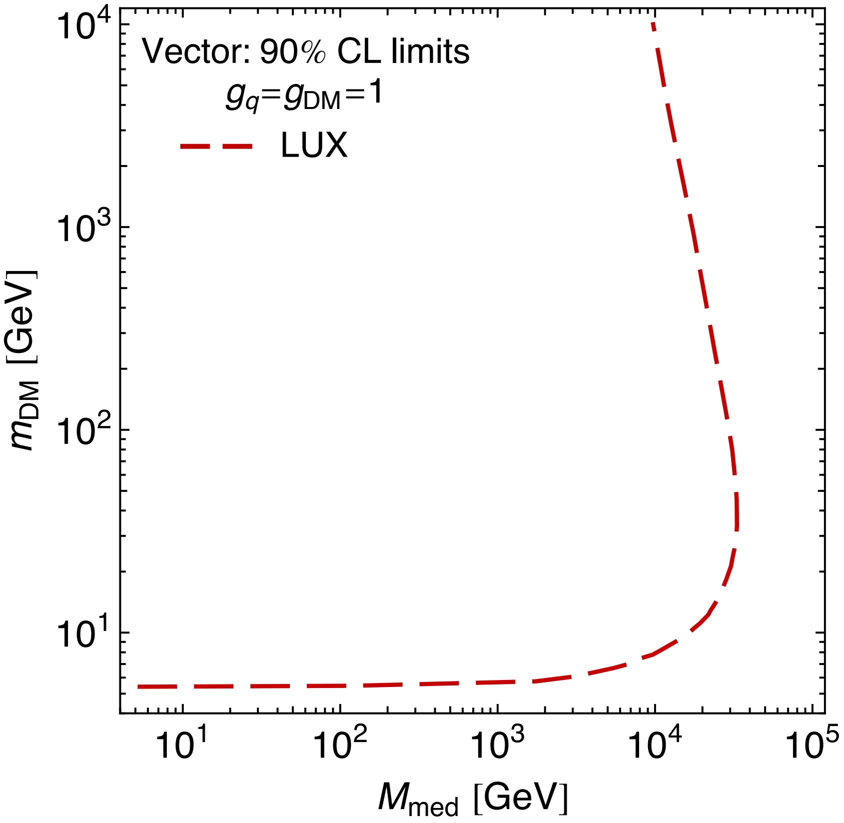
$$g_q \sim g_{\rm DM} \sim 1$$

$$M_{Z'} \sim 100 \text{ GeV}$$

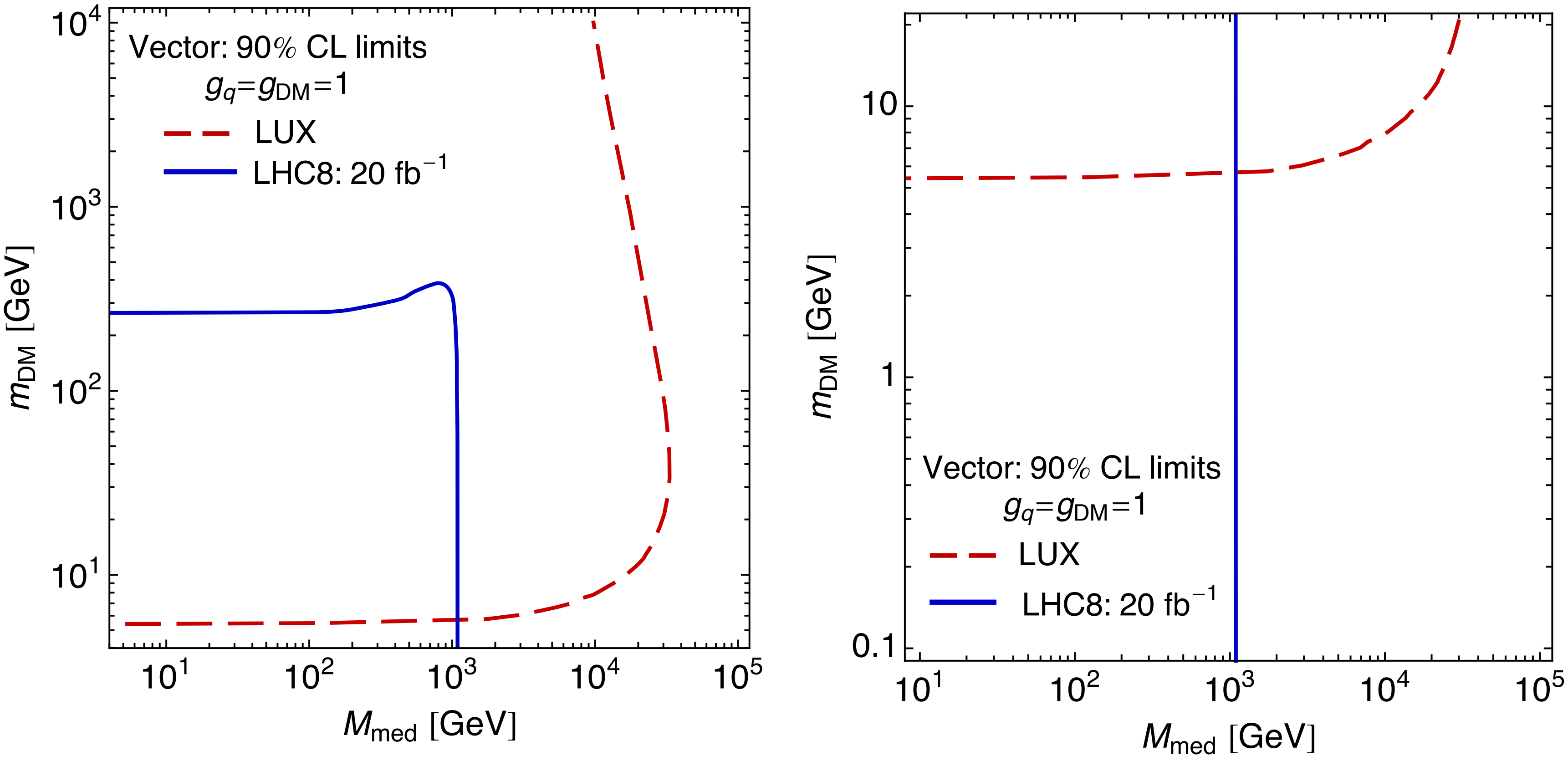
$$\sigma_{\rm n} \approx 10^{-36} \text{ cm}^2$$



Vector interaction (SI)



Vector interaction (SI)



Axial-Vector interaction (SD)

- The nucleon cross-section is $\sigma_{\rm n} = \frac{3f^2\mu^2}{\pi}$
  - For protons: $f_p = \frac{g_{\rm DM}}{M_{Z'}^2} \sum_{q=u,d,s} g_q \Delta_q^p$
  - For neutrons: $f_n = \frac{g_{\rm DM}}{M_{Z'}^2} \sum_{q=u,d,s} g_q \Delta_q^n$

$$\Delta_u^p = \Delta_d^n \approx 0.842$$
$$\Delta_d^p = \Delta_u^n \approx -0.427$$
$$\Delta_s^p \approx \Delta_s^n \approx -0.085$$

- Only u, d, s coupling contributes
- Interactions with proton and neutron generally different

- Simplify problem by assuming all g_q equal

Axial-Vector interaction (SD) – some intuition

For

$$g_q \sim g_{\rm DM} \sim 1$$

$$M_{Z'} \sim 100 \text{ GeV}$$

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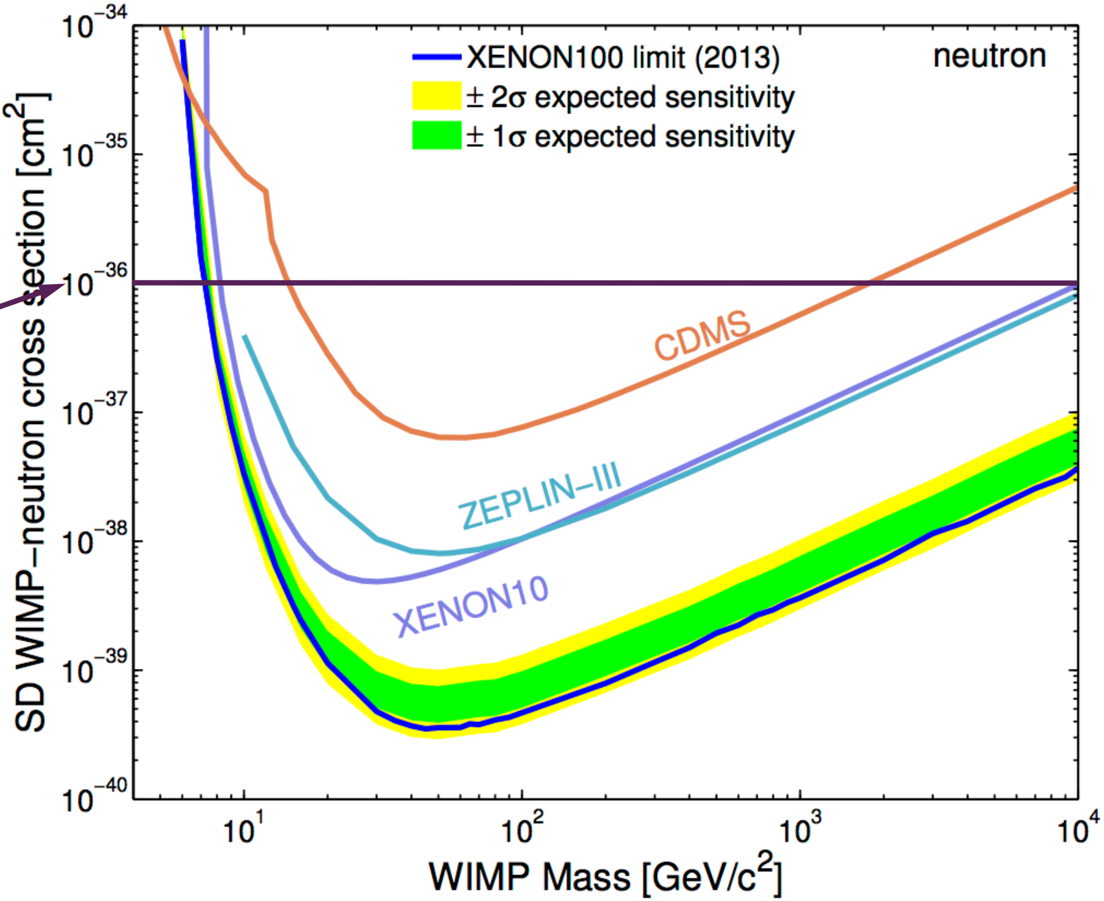
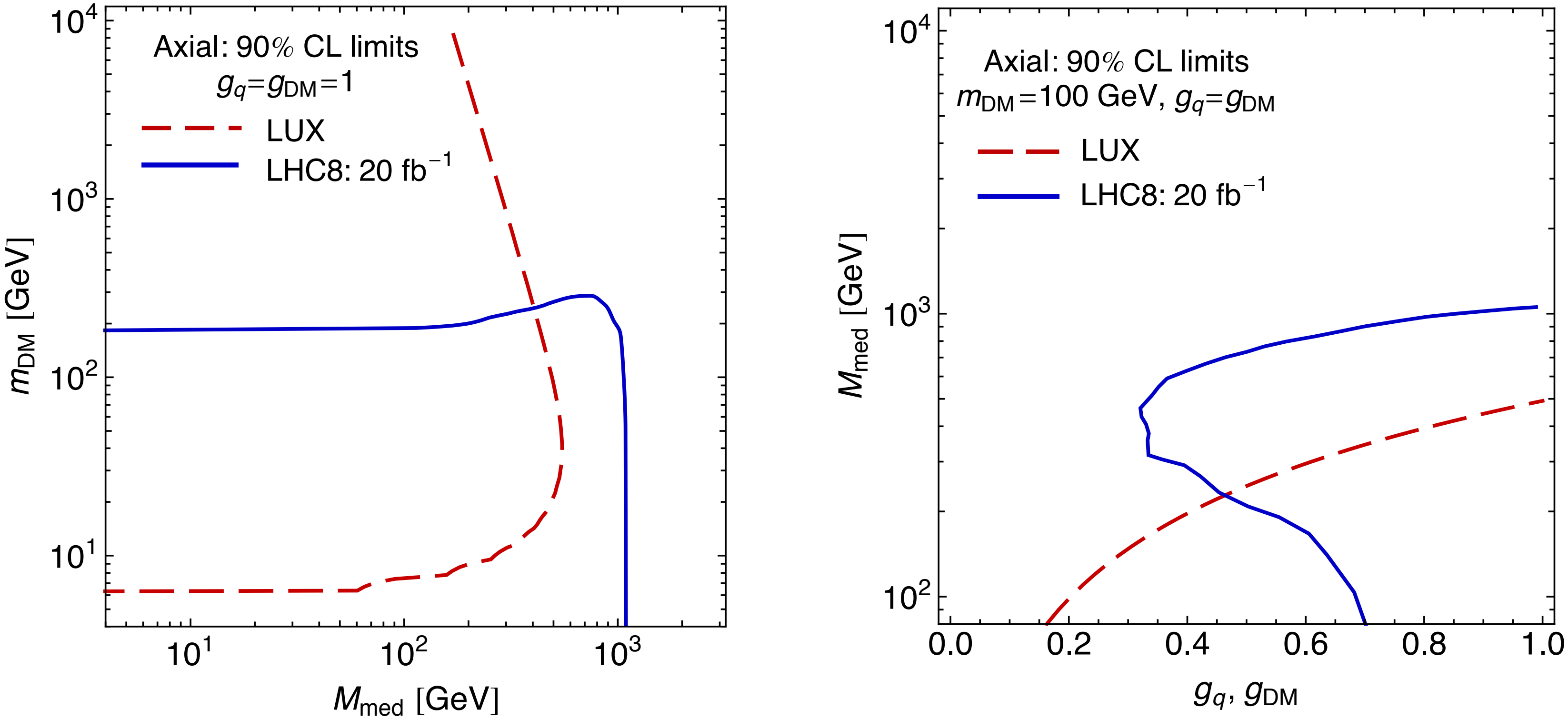


Axial-Vector interaction (SD)

- Searches have comparable sensitivity and are complementary



Axial-Vector interaction (SD)

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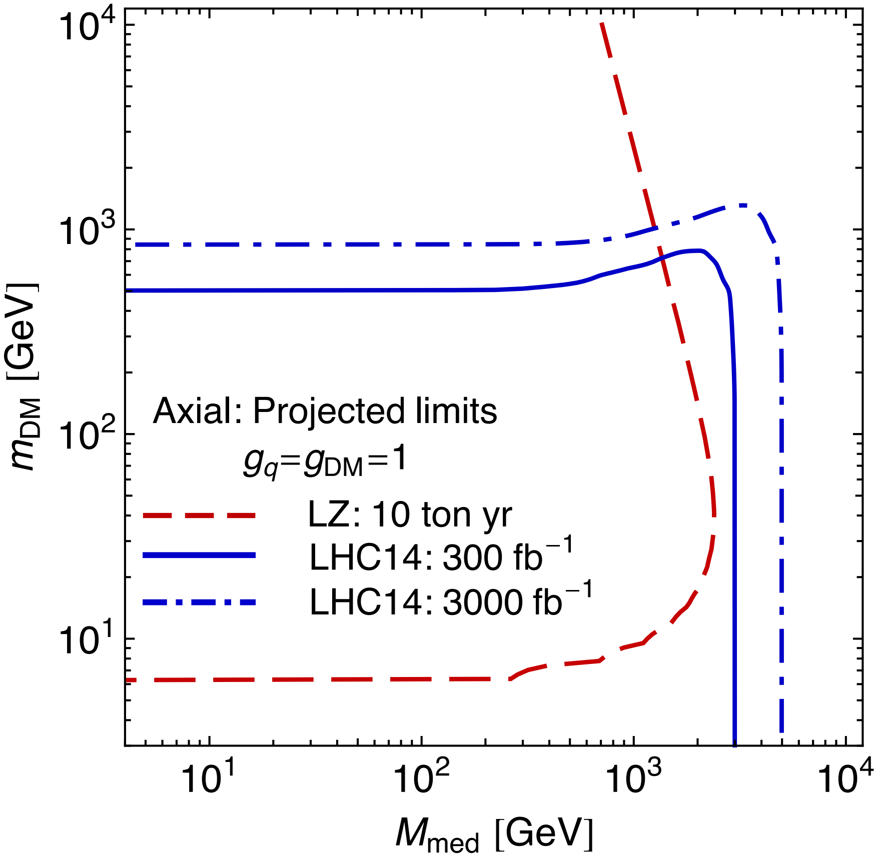
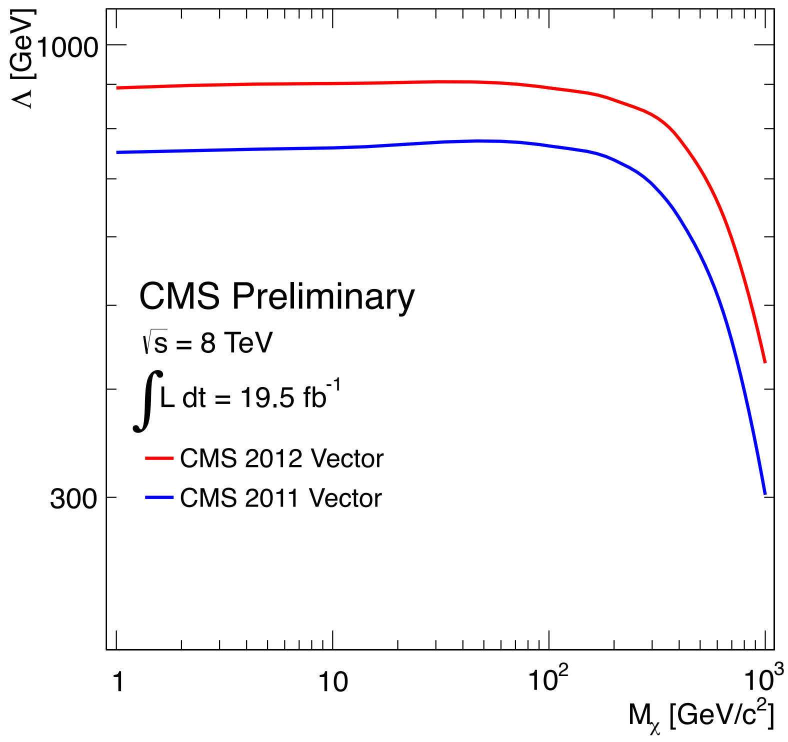
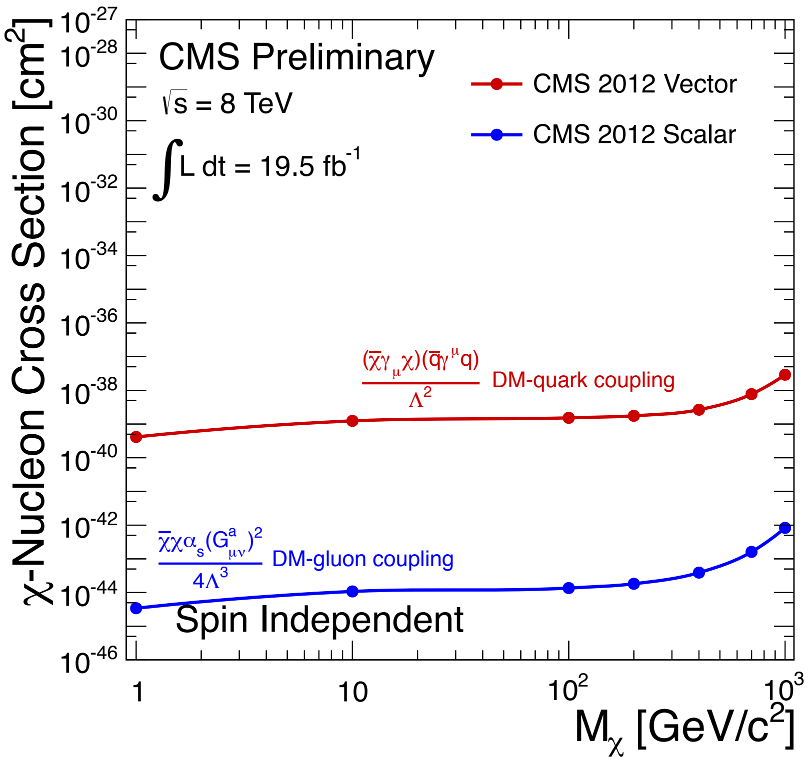


Problems with EFT approach

- Limit on Λ in the EFT approach for

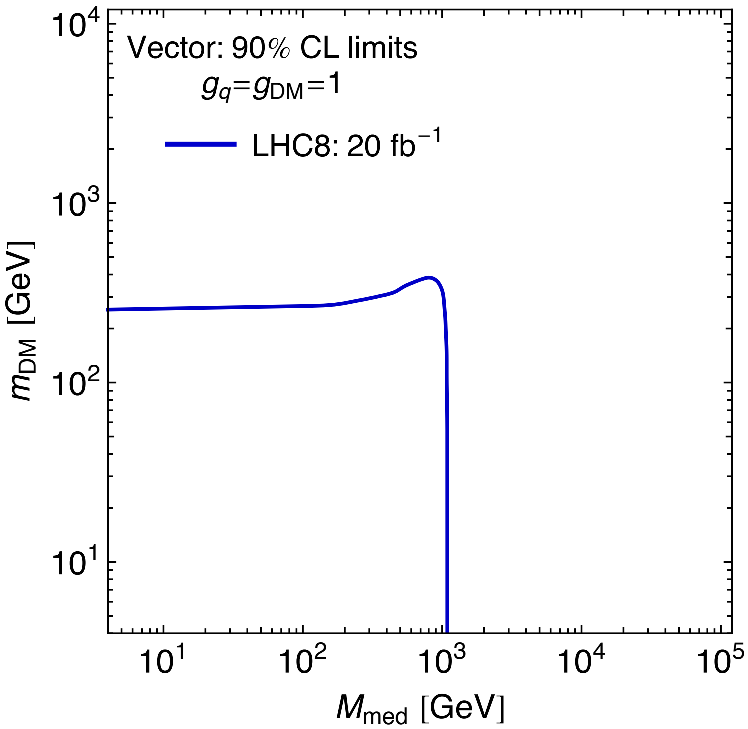


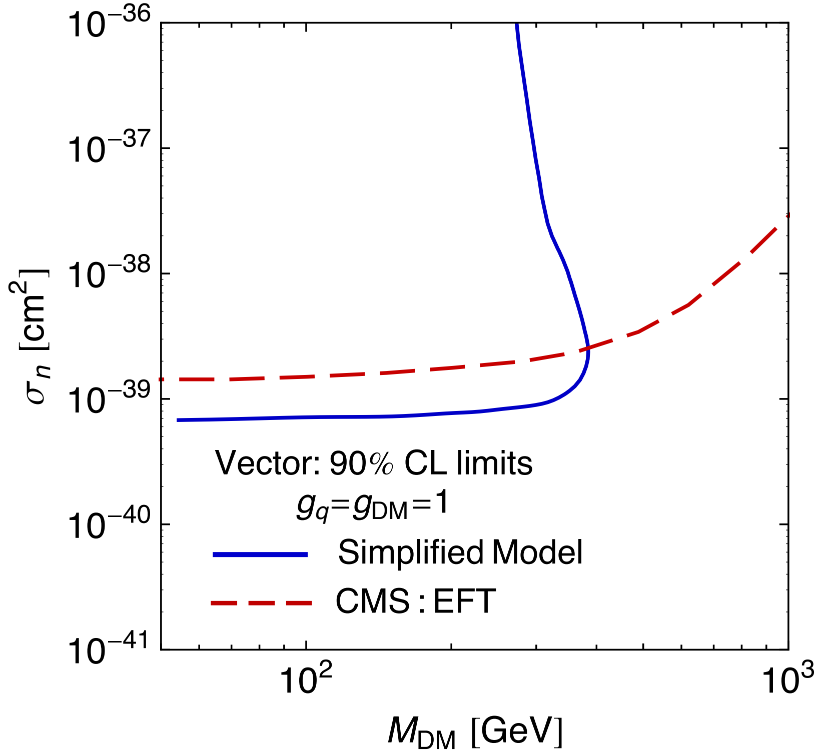


- Are these limits useful?

Problems with EFT approach: Example

- Find limit in simplified model and map back onto direct detection plane:





- EFT limit gives misleading results

Summary

- Important to interpret dark matter searches in the right framework
- Direct detection experiments constrain the 'WIMP-nucleon cross section'
  - Very useful: constrains a large number of theories
  - Straightforward to map limits into other forms
- LHC monojet searches have been interpreted in an EFT framework
  - Limited use: gives wrong constraints when applied to simple models
  - comparison with direct detection limits is misleading