DM with only spin-dependent detection possibilities

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The Role of Heavy Fermions in Fundamental Physics

April 11 – 14, 2011, Portorož, Slovenia

- Introduction, direct detection experiments
- Spin-dependent vs. spin-independent [Freytsis and ZL, 1012.5317]
- An unusual DM search in $B \to K^{(*)}\ell^+\ell^-$ [Freytsis, ZL, Thaler, 0911.5355]
- Conclusions

What is dark matter?

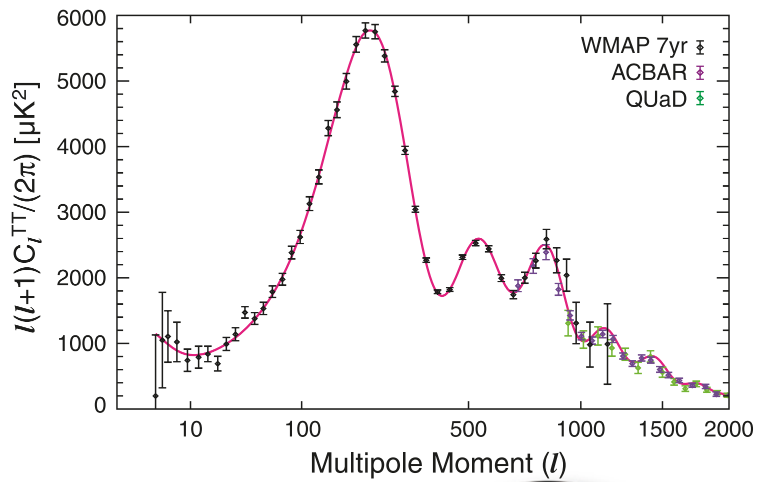
- Homogeneous, isotropic, spatially flat, expanding

  As in flavor physics, the basic paradigm is well-established

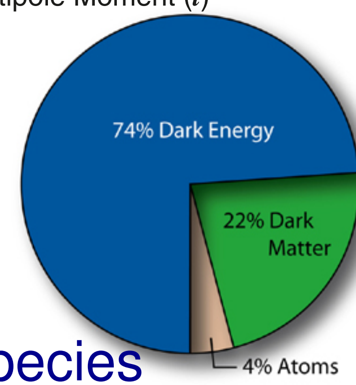
  Looking for corrections:

  – Seek deviations from $w = -1$ / from CKM (FCNCs)?

  – In both cases $10 - 20\ \%$ corrections allowed



- Dark matter: rotation curves, gravitational lensing, cosmology



- We know that DM is not a particle we know:

  Know: non-baryonic, long lived, neutral, abundance

  Don't know: interactions, mass, quantum numbers, one/many species

- Maybe thermal relic of early universe: weakly interacting massive particle (WIMP)

  If so, WIMP mass has to be around the TeV scale — LHC may directly produce it

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Direct DM detection

- All evidence is gravitational — no unambiguous direct detection signals yet

  Steady increase in experimental sensitivity, will continue for some time

- The focus is often on spin-independent (SI) detection experiments, due to coherence effects giving an A^2 enhancement and (much) larger nuclear cross sections

- Uncertainties in nuclear matrix elements is substantial — I'll not talk about them
  Recent LQCD results imply a few times smaller SI cross sections than often used

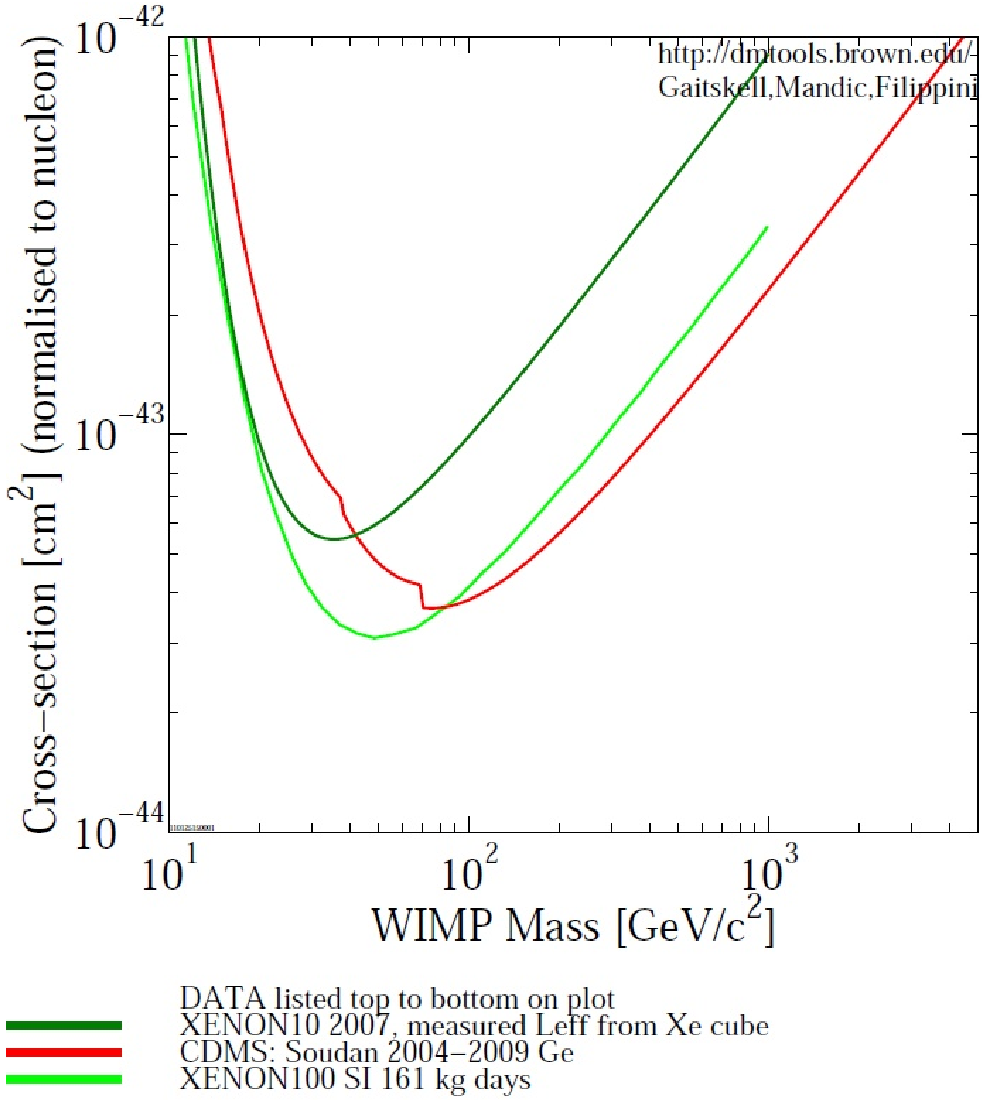
- Experiments capable of detecting SI cross section down to the irreducible atmospheric neutrino background, $10^{-48}\,\mathrm{cm}^2$, seem possible in the foreseeable future

[Note (since I can't remember): $10^{-36}\,\mathrm{cm}^2 = 1\,\mathrm{pb}$]

Current bounds — SI

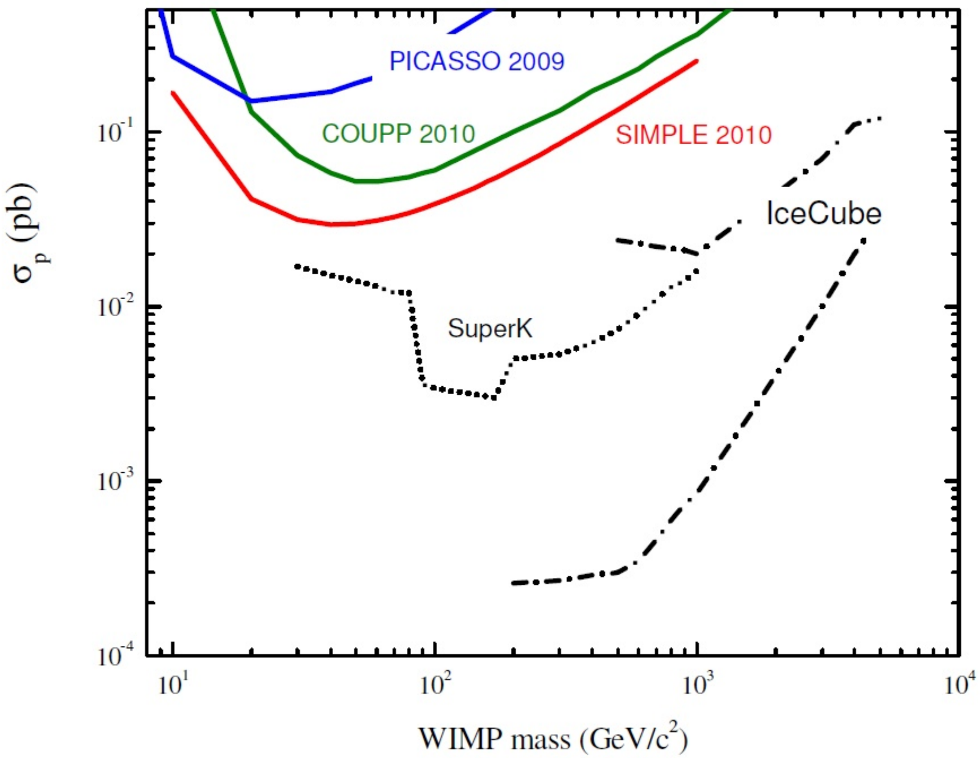
- Cross sections normalized to per-nucleon value for comparison between experiments

  Many other experiements not shown



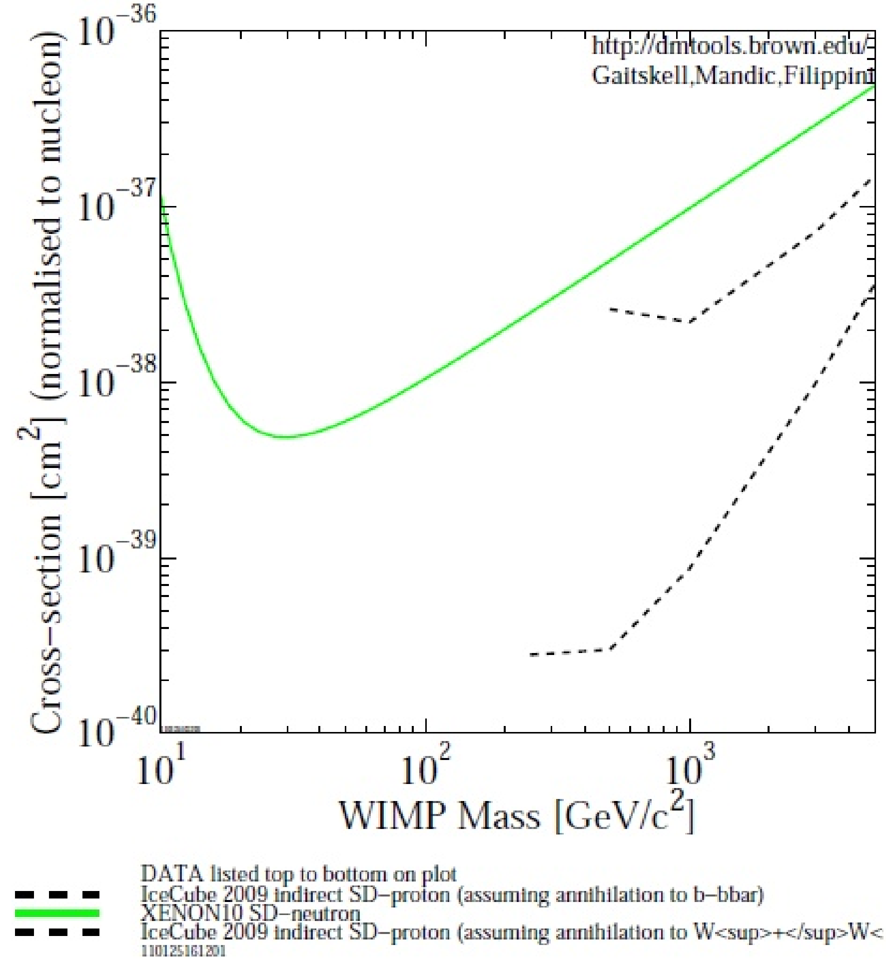
Current bounds — SD

DM – proton cross section



[Girard et al., 1101.1885]

DM – neutron cross section



- SD bounds are $5-6$ orders of magnitude weaker than SI

Future sensitivity

- Near future:

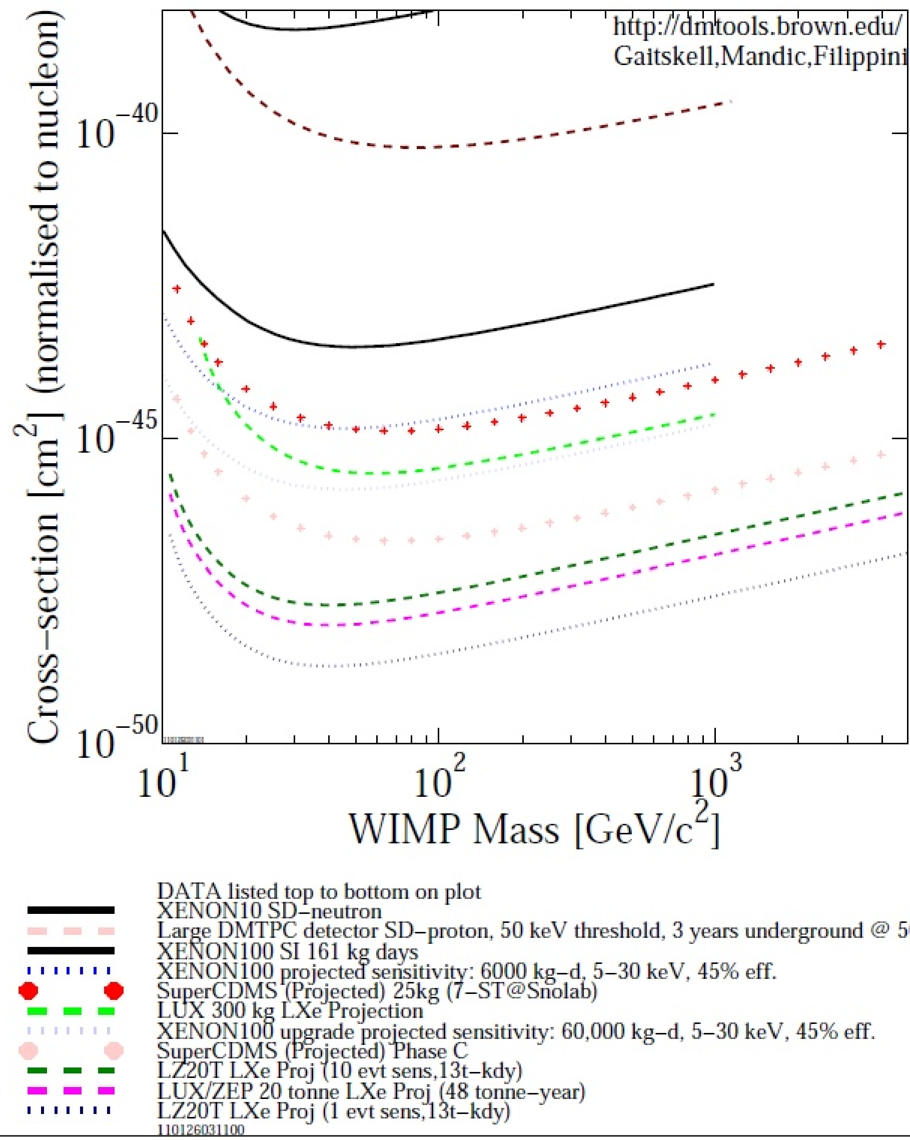
  XENON 100 will get to the 10^{-44} level

  SD experiments (not shown) to $\sim 10^{-40}$

- Next decade (or two):

  SI experiments will maintain (maybe even increase) their greater reach, down to the irreducible neutrino background

  SD sensitivity (COUPP-500) $< 10^{-42}\,\mathrm{cm}^2$



Why bother with spin-dependent?

- Reasons to think about spin-dependent detection appearing on its own:
- The optimist:

  Could the SD dark matter cross section in isolation tell us something interesting?

  Signicant correlation between SI & SD cross sections is claimed in most standard frameworks (MSSM, UED, little Higgs) — observing the contrary would tell us we are on to something unexpected [Bertrone *et al.*, 0705.2502; Belanger *et al.*, 0810.1362; Cohen *et al.*, 1001.3408]
- The pessimist:

  What if no sign of SI dark matter interactions down to the neutrino background?

  Do we give up on direct detection? Could there still be something to detect?

The challenge of uniquely SD detection

- If the tree-level interactions are dominantly (exclusively) SD, they may still be detectable by other means

  Since the sensitivity to SI cross sections is higher by several orders of magnitude (and will stay like that), a signal will only be seen in SD experiments if there are:

  – No detectable kinematically suppressed SI interactions at tree level

  – No detectable loop-induced SI contributions

  Either of these could be just as easy to detect as the "dominant" SD interaction

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- Operators: which ones lead to SD scattering in the non-relativistic limit?

- Mediators: are there models w/ enhanced SD operators, while subleading effects are absent or highly suppressed?

Assumptions: DM recoils off quarks, mediator is heavy enough to act as contact term in NR limit

Operator analysis (1)

- Scalar DM:

Operator		SI / SD	Suppression
$\mathcal{O}_1^s =$	$\phi^2\,\bar{q}q$	SI	—
$\mathcal{O}_2^s =$	$\phi^2\,\bar{q}\gamma^5 q$	SD	q^2
$\mathcal{O}_3^s =$	$\phi^\dagger\partial^\mu\phi\,\bar{q}\gamma_\mu q$	SI	—
$\mathcal{O}_4^s =$	$\phi^\dagger\partial^\mu\phi\,\bar{q}\gamma_\mu\gamma^5 q$	SD	v^2

$\mathcal{O}_3^s$ and $\mathcal{O}_3^s$ are only present for complex scalar DM

Operator analysis (2)

- Fermion DM:

Operator		SI / SD	Suppression
$\mathcal{O}_1^f =$	$\bar{\chi}\chi\,\bar{q}q$	SI	—
$\mathcal{O}_2^f =$	$\bar{\chi}i\gamma^5\chi\,\bar{q}q$	SI	q^2
$\mathcal{O}_3^f =$	$\bar{\chi}\chi\,\bar{q}i\gamma^5 q$	SD	q^2
$\mathcal{O}_4^f =$	$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	SD	q^4
$\mathcal{O}_5^f =$	$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu q$	SI	—
$\mathcal{O}_6^f =$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu q$	SI	v^2
		SD	q^2
$\mathcal{O}_7^f =$	$\bar{\chi}\gamma^\mu\chi\,\bar{q}\gamma_\mu\gamma^5 q$	SD	v^2 or q^2
$\mathcal{O}_8^f =$	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{q}\gamma_\mu\gamma^5 q$	SD	—
$\mathcal{O}_9^f =$	$\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{q}\sigma_{\mu\nu} q$	SD	—
$\mathcal{O}_{10}^f =$	$\bar{\chi}i\sigma^{\mu\nu}\gamma^5\chi\,\bar{q}\sigma_{\mu\nu} q$	SI	q^2

If the DM is Majorana fermion, $\mathcal{O}_5^f,\ \mathcal{O}_7^f,\ \mathcal{O}_9^f,\ \mathcal{O}_{10}^f$ vanish identically (odd under C)

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Operator analysis (3)

- Vector DM:

Operator		SI / SD	Suppression
$\mathcal{O}_1^v =$	$B^\mu B_\mu \,\bar{q}q$	SI	—
$\mathcal{O}_2^v =$	$B^\mu B_\mu \,\bar{q}\gamma^5 q$	SD	q^2
$\mathcal{O}_3^v =$	$B^\dagger_\mu \partial^\nu B^\mu \,\bar{q}\gamma_\nu q$	SI	—
$\mathcal{O}_4^v =$	$B^\dagger_\mu \partial^\nu B^\mu \,\bar{q}\gamma_\nu \gamma^5 q$	SD	v^2
$\mathcal{O}_5^v =$	$B^\mu \partial_\mu B^\nu \,\bar{q}\gamma_\nu q$	SI	$v^2 q^2$
$\mathcal{O}_6^v =$	$B^\mu \partial_\mu B^\nu \,\bar{q}\gamma_\nu \gamma^5 q$	SD	q^2
$\mathcal{O}_7^v =$	$\epsilon_{\mu\nu\rho\sigma} B^\mu \partial^\nu B^\rho \,\bar{q}\gamma^\sigma q$	SI	v^2
		SD	q^2
$\mathcal{O}_8^v =$	$\epsilon_{\mu\nu\rho\sigma} B^\mu \partial^\nu B^\rho \,\bar{q}\gamma^\sigma \gamma^5 q$	SD	—

$\mathcal{O}_3^v$ and $\mathcal{O}_3^v$ are only present for complex vector DM

Viable operators

- Traditionally, disregard kinematically suppressed operators — this leaves for SD:

$$\mathcal{O}_8^f = \bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$$
$$\mathcal{O}_9^f = \bar{\chi}\sigma_{\mu\nu}\chi\,\bar{q}\sigma^{\mu\nu} q$$
$$\mathcal{O}_8^v = \epsilon_{\mu\nu\rho\sigma}\,B^\mu\partial^\nu B^\rho\,\bar{q}\gamma^\sigma\gamma^5 q$$

- A kinematically suppressed operator can be competitive if the mediator scale is low and unsuppressed operators are absent — both of these features are present in the case of spontaneous global symmetry breaking [Chang et al., 0908.3192]

- Need to consider suppressed operators with pseudoscalar currents:

$$\mathcal{O}_2^s = \phi^2\,\bar{q}\gamma^5 q$$
$$\mathcal{O}_4^f = \bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$$
$$\mathcal{O}_2^v = B^\mu B_\mu\,\bar{q}\gamma^5 q$$

Operators from mediators

- Assume: operators from integrating out mediators w/ renormalizable interactions

  Ways to get SD operators and nothing else for heavy mediators [Agrawal *et al.*, 1003.5905]

  Add to their study the possibility of light mediators

- Usually only the leading contribution from each operator is retained

  Kinematic suppressions: $v^2 \sim 10^{-6}$

  $q^2/m_p m_\chi \sim 10^{-6}$ for $q^2 \sim (100\,\mathrm{MeV})^2$

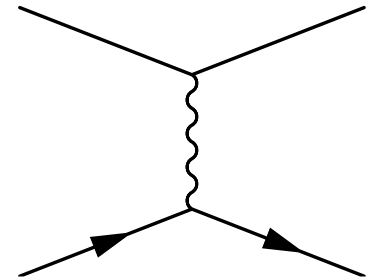
  This is comparable to (SD sensitivity) / (SI sensitivity) — if suppressed SI contributions exist, they should lead to detectable effects at roughly the same time

- Have to check all the possibilities...

  Pseudoscalar a exchange — no additional contributions generated

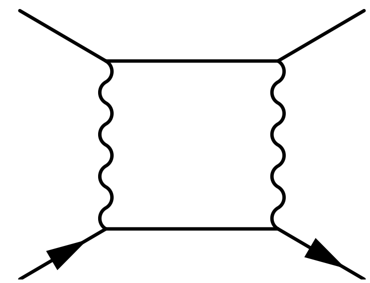
Loop-induced subleading effects

- Consider, e.g., Z exchange at tree level:



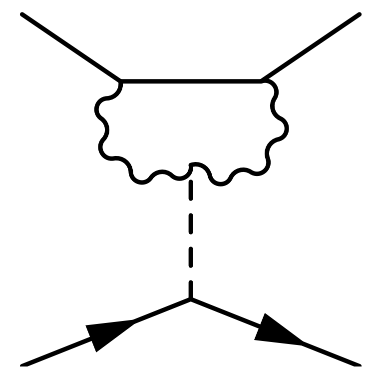
$$\frac{g_2^2}{2\cos^2\theta_W} T_3^q\, Q\, \frac{1}{m_Z^2}\, \bar\chi\gamma^\mu\gamma^5\chi\; \bar q\gamma_\mu\gamma^5 q$$

- Loop effects induce the SI operator:



$$\frac{1}{(4\pi)^2}\frac{g_2^4\, Q^2}{\cos^4\theta_W\, m_Z}\left[\frac{(T_3^q)^2}{2m_Z^2}+\frac{1}{4m_h^2}\right] m_q\,\bar\chi\chi\;\bar q q \qquad (m_q \ll m_Z \ll m_\chi)$$

For $Q\sim\mathcal{O}(1)$, the SI cross section is $6-7$ orders of magnitude smaller than the SD one

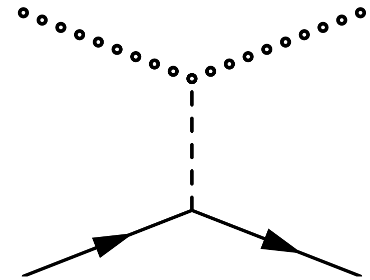


However, if the DM is in an $SU(2)$ n-plet, the cross section $\sim n^2$

Loop effects: pseudoscalar mediator

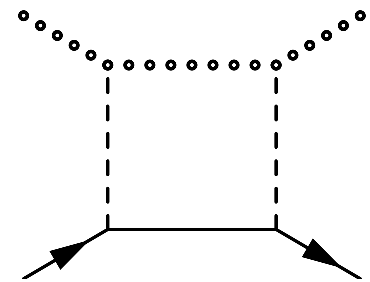
- Tree-level exchange:

$$\frac{1}{m_a^2}\,\xi\, y_q\, m_\phi\, \phi^\dagger \phi\, \bar{q} i \gamma^5 q$$



- Loop effects induce the SI operator:

$$\frac{1}{(4\pi)^2}\,\frac{\xi^2\, y_q^2}{m_\phi^2}\, C_S\, \phi^\dagger \partial^\mu \phi\, \bar{q}\gamma_\mu q$$



Box diagram can be evaluated in terms of Passarino-Veltman integrals — for $m_a/m_\phi = 0.01$, $C_S \sim 80$

[involves $\ln^2(m_a/m_\phi)$ and $\ln(m_a/m_\phi)$ dependence]

- Worked out other cases as well...

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Subleading effects — pseudoscalar mediator

- Unlike Z case, we expect these loops have no detectable contribution — Why?
  - The loop contribution is suppressed by an additional factor of m_a^2/m_χ^2
  - As Goldstone bosons would be expected to couple proportional to quark mass, loop effects should go as (Yukawa)^2

A light pseudoscalar mediator is the only interaction providing a detectable SD cross section that would not be seen in a SI experiment roughly the same time

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- So far, considered exclusively the role of mediators in direct detection
- Can this mechanism be implemented in a viable model?

The "axion portal" provides an example [Nomura, Thaler, 0810.5397]

The axion portal

- A scalar field charged under a new global $U(1)_X$, spontaneously breaks to

$$S = \left(f_a + \frac{s}{\sqrt{2}}\right) \exp\left(\frac{ia}{\sqrt{2} f_a}\right)$$

  New fermion coupled via $\xi S \chi \chi^c + \mathrm{h.c.}$, then generate fermion mass $m_\chi = \xi f_a$

  Let the SM (w/ 2HDM) be charged under $U(1)_X$ so the only coupling to S is via $\mathcal{L} = \lambda S^n H_u H_d + \mathrm{h.c.}$, and $U(1)_X$ is a Peccei-Quinn symmetry

- The new fermions stay in thermal equilibrium though

$$\langle \sigma v \rangle_{\chi\chi^c \to sa} = \frac{m_\chi^2}{64\pi f_a^4}\left(1 - \frac{m_s^2}{4 m_\chi^2}\right) + \mathcal{O}(v^4)$$

- If all scales $\sim \mathrm{TeV}$, $\langle \sigma v \rangle \sim 3 \times 10^{-26}\, \mathrm{cm}^3/s$, so χ has right relic density to be DM

Axion portal and direct detection

- Two mediators present, s and a — Is the SI cross section due to s negligible?

$$\sigma_{\rm SI}^{\chi N} \approx (2\times 10^{-42}\,{\rm cm}^2)\,\xi^2\,\epsilon^2 \left(\frac{100{\rm GeV}}{m_s}\right)^4 \qquad (\epsilon \sim v_{\rm ew} f_a)$$

In original scenario $m_s \sim 10\,{\rm GeV}$ for Sommerfeld enhancement, which was in tension with current bounds — removing this requirement, it is natural to have $m_s \sim f_a$, and SI cross section is below neutrino background

- Is the SD cross section large enough?

$$\sigma_{\rm SD}^{\chi p} \approx (2\times 10^{-37}\,{\rm cm}^2)\,\xi^2 \sin^2\theta\, \frac{q_{\rm ref}^2}{4m_\chi^2} \left(\frac{1{\rm GeV}}{m_a}\right)^4$$

with $\tan\theta = n\sin 2\beta\,[v_{\rm ew}/(2f_a)]$, $q_{\rm ref}^2 = (100\,{\rm MeV})^2$, and $m_a = \mathcal{O}({\rm few}\;100\,{\rm MeV})$, the cross section is ${\rm few}\times 10^{-40}\,{\rm cm}^2$, near current bounds

[SI cross section induced at one-loop is indeed much below the atmospheric neutrino background]

Axion portal and B decays

Dark sectors — the motivation two years ago

- Observations of cosmic ray excesses led to a flurry of DM model building

  Standard WIMPs unable to fit the data (lack of antiprotons, hard lepton spectrum)

- Idea: DM annihilates to SM through light bosons [Pospelov, Ritz, Voloshin; Arkani-Hamed *et al.*]

$$\chi\chi \to \phi^{(*)}\phi^{(*)}, \qquad \phi \to \ell^+\ell^-,\, \pi^+\pi^-,\, \ldots$$

  "Dark bosons" couple to leptons with $\alpha_X = \lambda_X^2/(4\pi)$, lots of different constraints depending on mass and coupling

- Most popular scenario: ϕ^μ couples to $\bar\psi\gamma_\mu\psi$ and mixes with γ ("dark photons")

The axion portal in $B \to K^{(*)}\ell^+\ell^-$?

- The new particle could also be a scalar with axion-like couplings [Nomura, Thaler, 0810.5397]

$$\mathcal{L}_{\rm int} = \frac{\lambda}{f_a}\,(\bar\psi\gamma^\mu\gamma_5\psi)\,\partial_\mu a \quad\to\quad \frac{\lambda\,m_\psi}{f_a}\,(\bar\psi\gamma_5\psi)\,a$$

The most interesting part of parameter space is thought to be:

$$m_K - m_\pi < m_a \lesssim 800\,\text{MeV}, \qquad f_a \sim (1-3)\,\text{TeV}$$

- Coupling to fermions $\propto m_\psi$, so FCNC $b \to sa$ loops are enhanced by m_t

With only $\mathcal{L}_{\rm int}$, divergent loops $\Rightarrow$ need to embed in a renormalizable theory

- A simple explicit model: Peccei-Quinn symmetric NMSSM (2HDM + a singlet)

(SUSY part not directly relevant for us, more general DFSZ-axion)

- At one loop: $\mathcal{M}(b \to sa) \propto \mathcal{M}(b \to sA^0)_{\rm 2HDM}$ (from tW, tH, tHW penguins)

The 2HDM calculation

[Hall and Wise, NPB 187 (1981) 397]

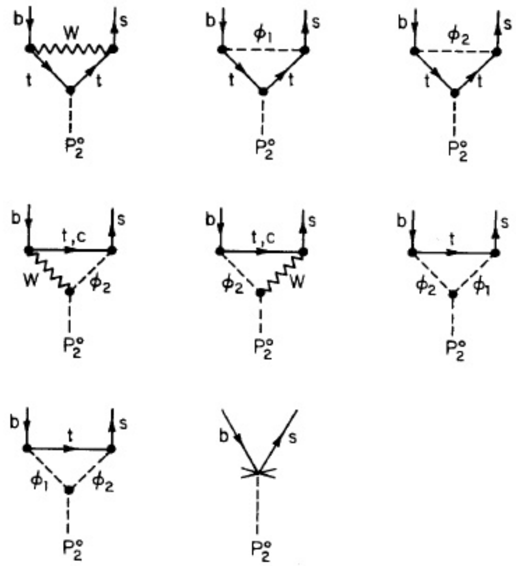
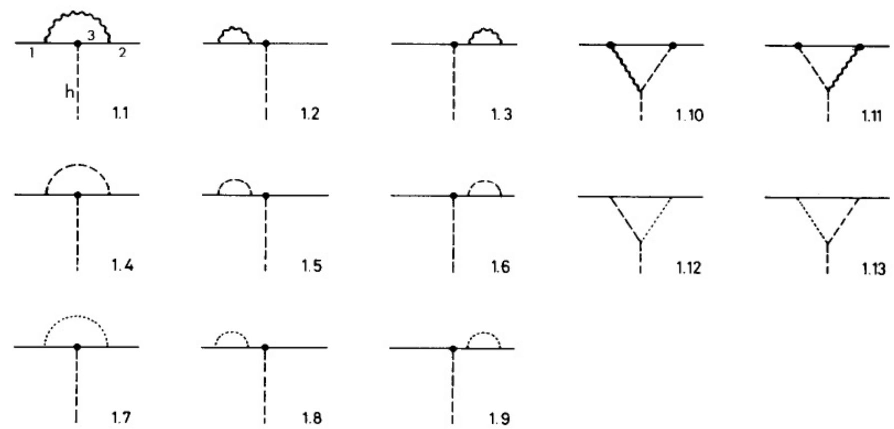


Fig. 2. Feynman diagrams contributing to the b → s P_2^0 amplitude at one-loop.

in both models I and II. The functions $F_i(m, M_{\phi_2}, M_W)$ are

$$\begin{aligned} F_1(m, M_{\phi_2}, M_W) = & \left(\frac{M_W^2 - \frac{1}{2}m^2}{M_W^2 - m^2}\right)\left(\frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right) - 1\right) \\ & + \frac{2M_W^2}{M_W^2 - M_{\phi_2}^2}\left(\frac{M_{\phi_2}^2}{M_{\phi_2}^2 - m^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) - \frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right)\right) \\ & + \tfrac{1}{2}(M_W^2 - M_{\phi_2}^2)\left(\frac{-M_{\phi_2}^2}{(M_W^2 - M_{\phi_2}^2)(M_{\phi_2}^2 - m^2)}\right. \\ & + \frac{M_W^2 M_{\phi_2}^2}{(M_W^2 - m^2)(M_W^2 - M_{\phi_2}^2)^2}\ln\left(\frac{M_W^2}{M_{\phi_2}^2}\right) \\ & + \frac{M_{\phi_2}^2 m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) + \frac{1}{2}\frac{m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)} \\ & + \frac{1}{2}\frac{M_W^4}{(M_W^2 - M_{\phi_2}^2)(M_W^2 - m^2)^2}\ln\left(\frac{M_W^2}{m^2}\right) \\ & - \frac{1}{2}\frac{M_{\phi_2}^4}{(M_W^2 - M_{\phi_2}^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right)\Bigg), \qquad (17) \end{aligned}$$

[Frere, Vermaseren, Gavela, PLB 103 (1981) 129]



$$\begin{aligned} A_1(m) = & \frac{-3M_W^4}{(M_W^2 - m^2)(M_W^2 - M_H^2)}\left(1 + \frac{M_H^2 - m^2}{M_W^2 - m^2}\right) \\ & \times \ln\frac{m^2}{M_W^2} + \frac{M_H^2}{(M_H^2 - m^2)}\left(\frac{6M_W^2}{M_W^2 - M_H^2} + \frac{M_H^2}{M_H^2 - m^2}\right) \\ & \times \ln\frac{m^2}{M_W^2} + 2 + \frac{3M_W^2}{M_W^2 - m^2} + \frac{M_H^2}{M_H^2 - m^2}, \qquad (9) \end{aligned}$$

- Results disagree, neither knew about other
- Many papers cited both, none commented on disagreement... so we computed it all...

The current data

- Considering the combined BaBar / Belle rate measurements and the spectra...

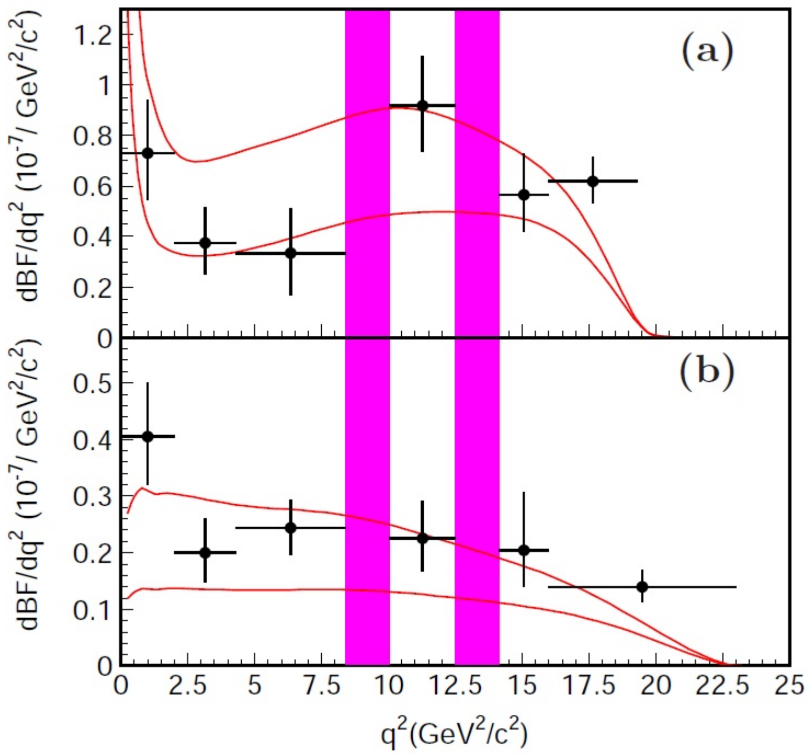
[Wei *et al.*, Belle Collaboration, PRL 103 (2009) 171801]

we used: $\mathcal{B}(B \to Ka)\times\mathcal{B}(a \to \mu^+\mu^-) < 10^{-7}$

[at a high, but who-knows-what CL...]

Can improve independent of form factor uncertainties

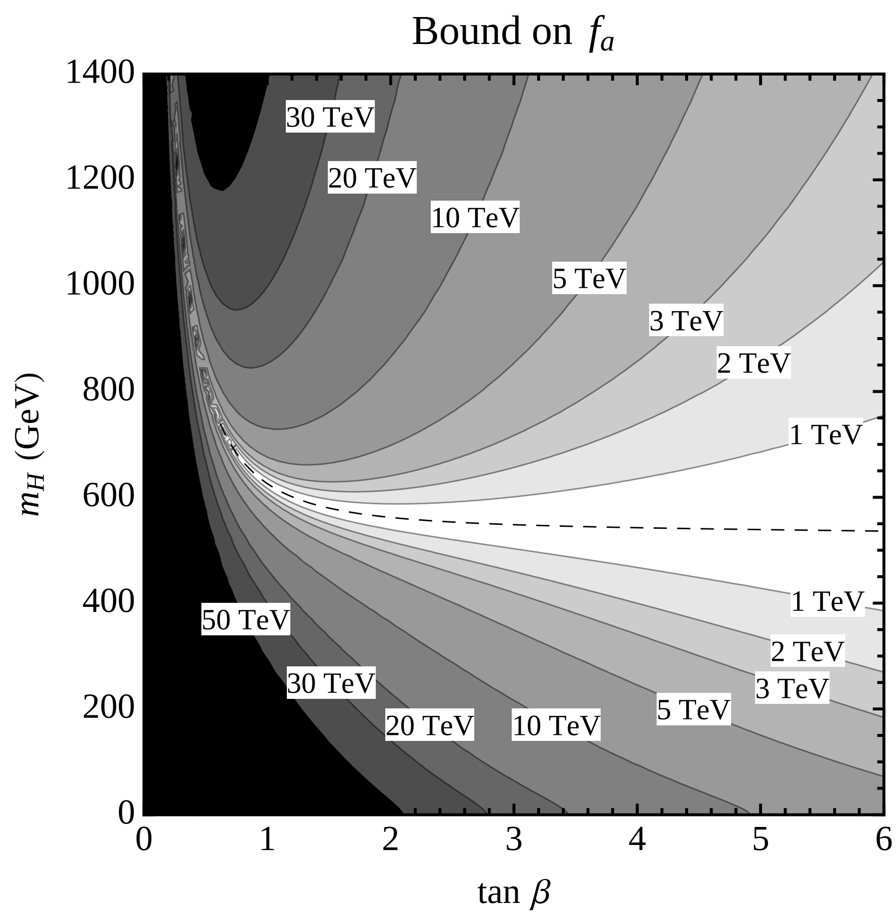
For this physics $K\ell^+\ell^-$ may be better than $K^*\ell^+\ell^-$, since no O_7 (photon penguin) enhancement at small q^2 in K mode



- BaBar and Belle should be able to set a significantly better bound

- LHCb should be able to improve it substantially

The bound from $B \to K\ell^+\ell^-$



[Freytsis, ZL, Thaler, 0911.5355]

- Cancellation in a narrow region near the dashed line (between $\cot\beta$ and $\cot^3\beta$ terms)
- In most of the parameter space this is the best bound (then $\Upsilon(3S) \to \gamma A^0$) [BaBar, 0902.2176]

Conclusions

Summary

- Most DM models with dominantly spin-dependent interactions will not be (much) harder to see in spin-independent experiments through subleading interactions
- Unique exception seems to be cases where the mediators are light pseudoscalars
- A viable dark matter model already exists with such a mechanism
- A significant part of its parameter space is best probed in B and Υ decays
- Do other (not much more complex) models with SD interaction dominance exist?

Backup slides