Title: Dark matter models with uniquely spin-dependent detection

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Abstract: It is often assumed that the first evidence for direct dark matter detection will come from experiments probing spin-independent interactions, because of higher sensitivities due to coherence effects. We explore the possibility of models that would be invisible in such experiments, but detectable via spin-dependent interactions. The existence of much larger (or only) spin-dependent tree-level interactions is not sufficient, due to potential spin-independent subdominant or loop-induced interactions. We find that most models with detectable spin-dependent interactions would also generate detectable spin-independent interactions. Models in which a light pseudoscalar acts as the mediator seem to uniquely evade this conclusion. We present a viable dark matter model generating such an interaction.

DM with only spin-dependent detection possibilities

Zoltan Ligeti

Perimeter Institute, May 6, 2011

- 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

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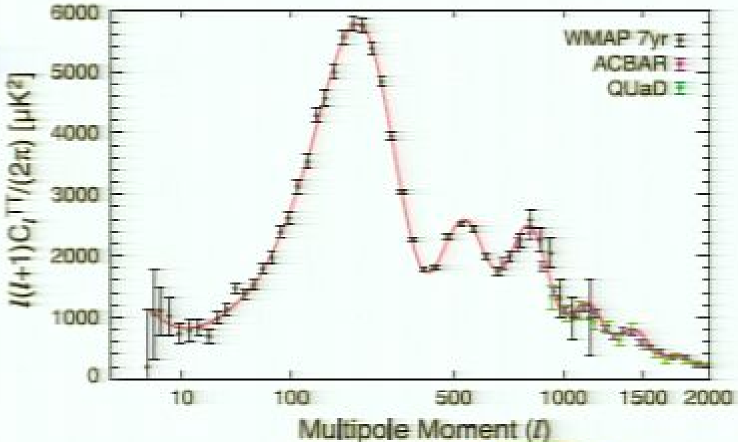
What is dark matter?



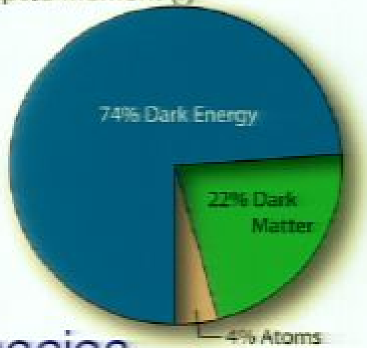
- Homogeneous, isotropic, spatially flat, expanding

  Basic paradigm is well-established, looking for corrections:

  – Seek deviations from $w = -1$

  – Order $10-20\,\%$ 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

Direct DM detection

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

  Steady increase in experimental sensitivity, and will continue for a while

- 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 section than often used [e.g., DarkSUSY]

- 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): $10^{-36}\,\mathrm{cm}^2 = 1\,\mathrm{pb}$]

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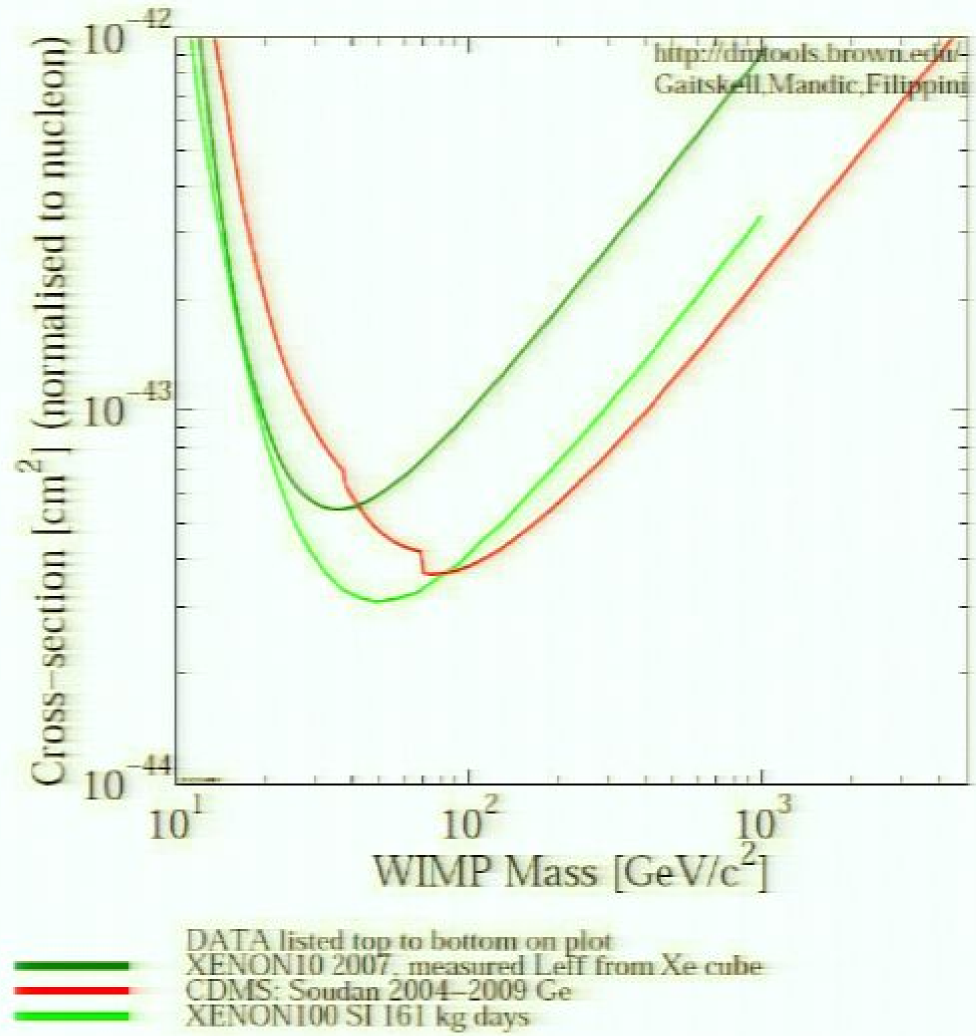
Current bounds — SI

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

  Many other experiements not shown



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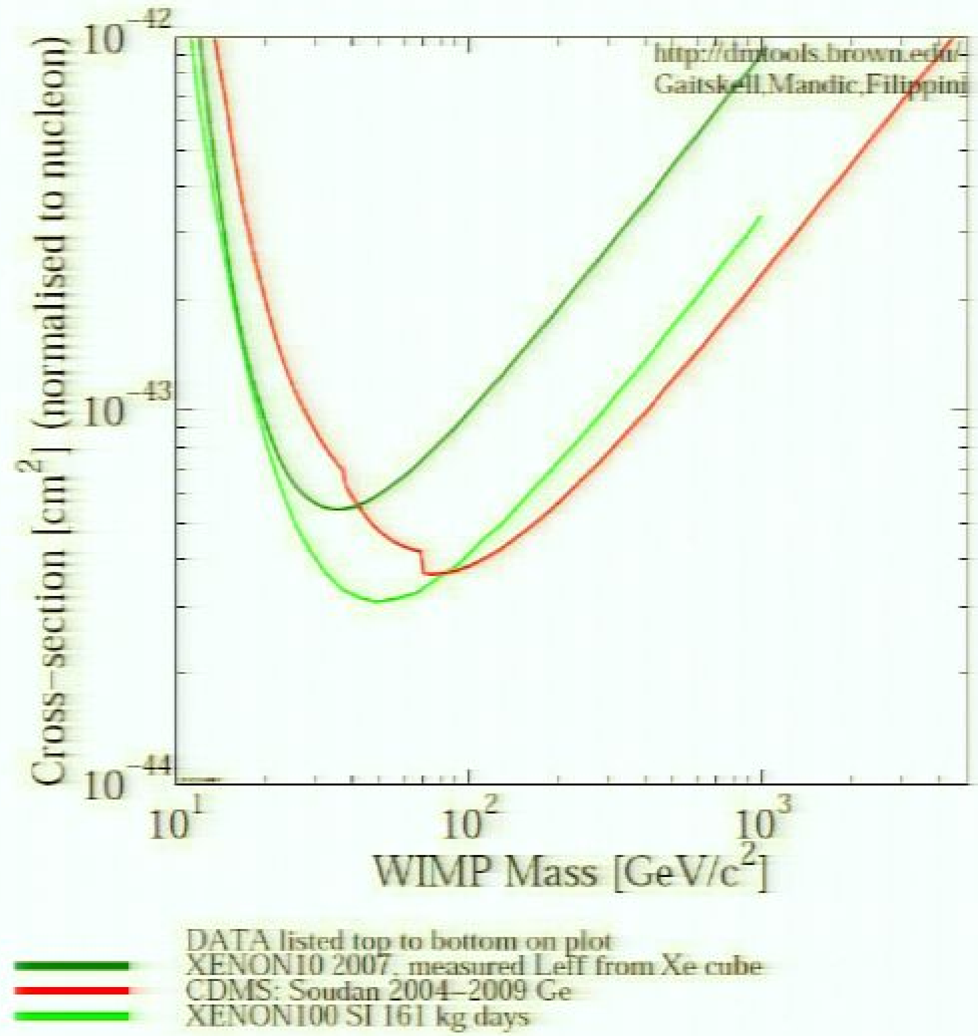
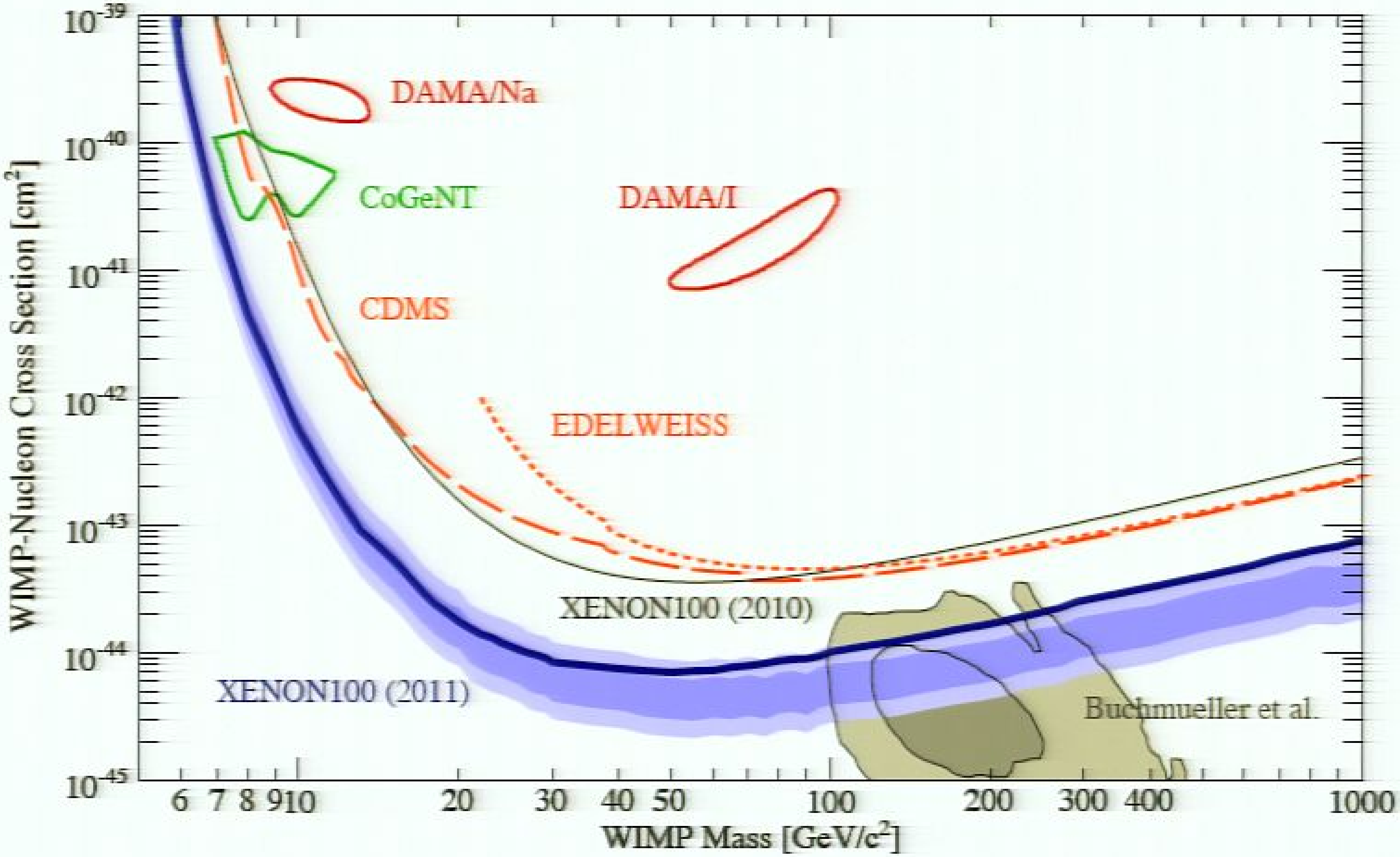
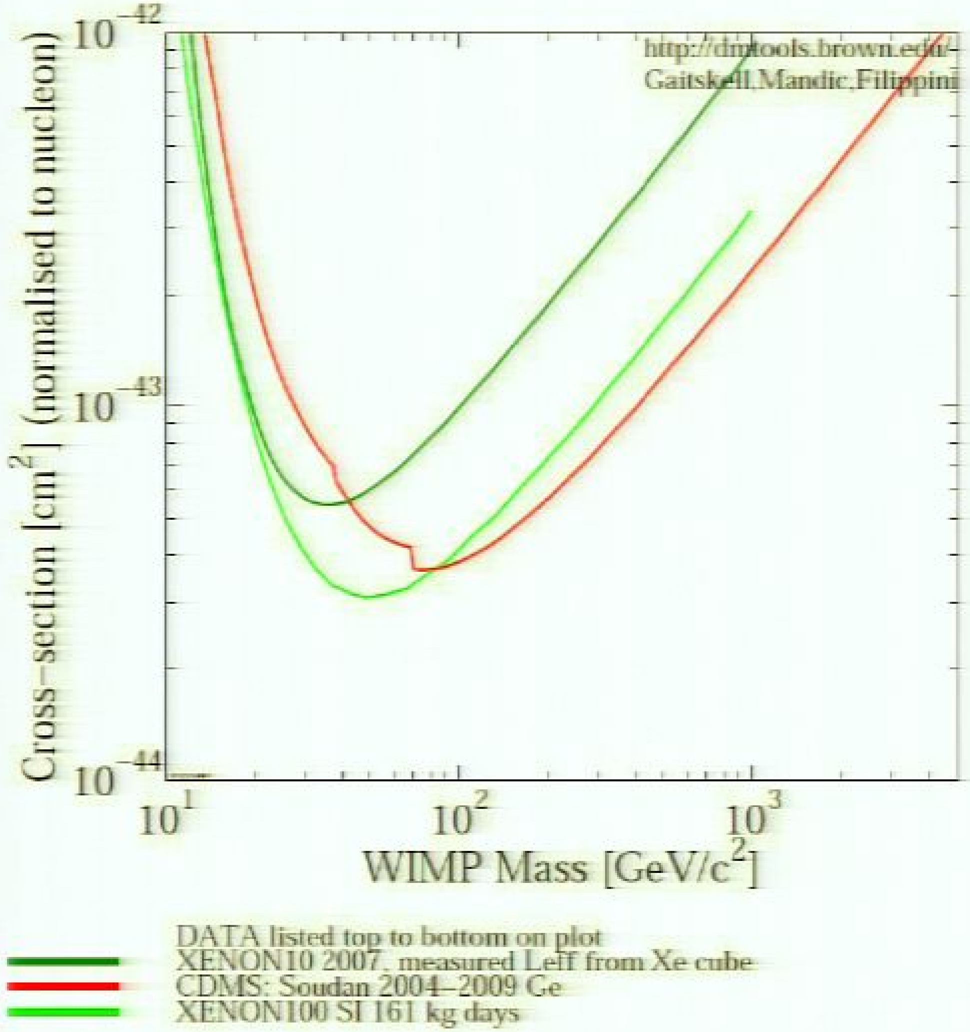


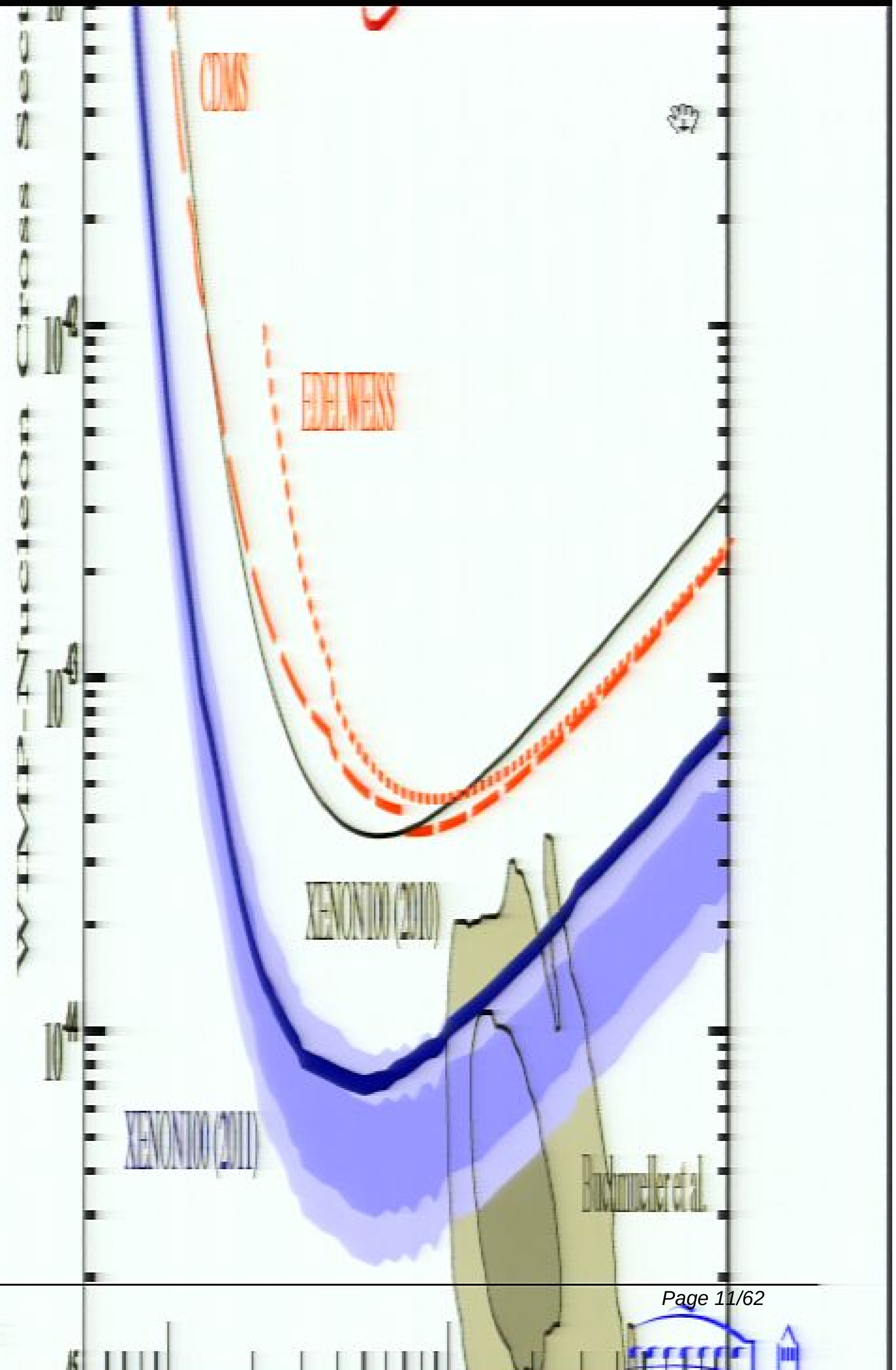
XENON 100, just last month



[arXiv:1104.2549]

The comparison

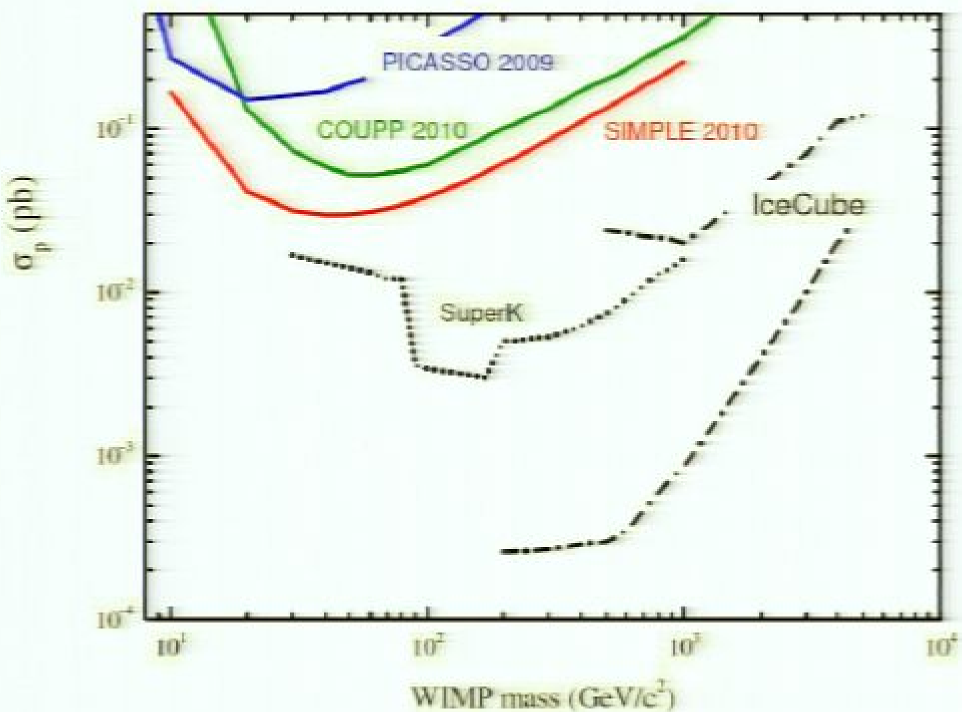




ZL – p. 5

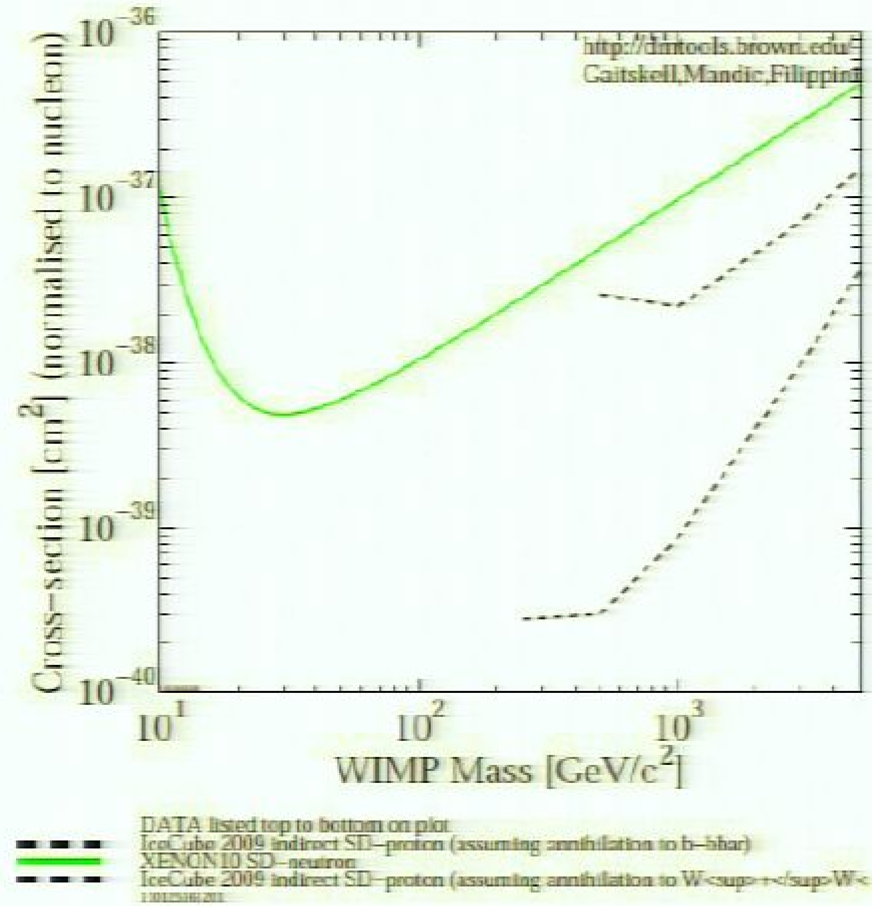
Current bounds — SD

DM − proton cross section



[Girard et al., 1101.1885]

DM − neutron cross section



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

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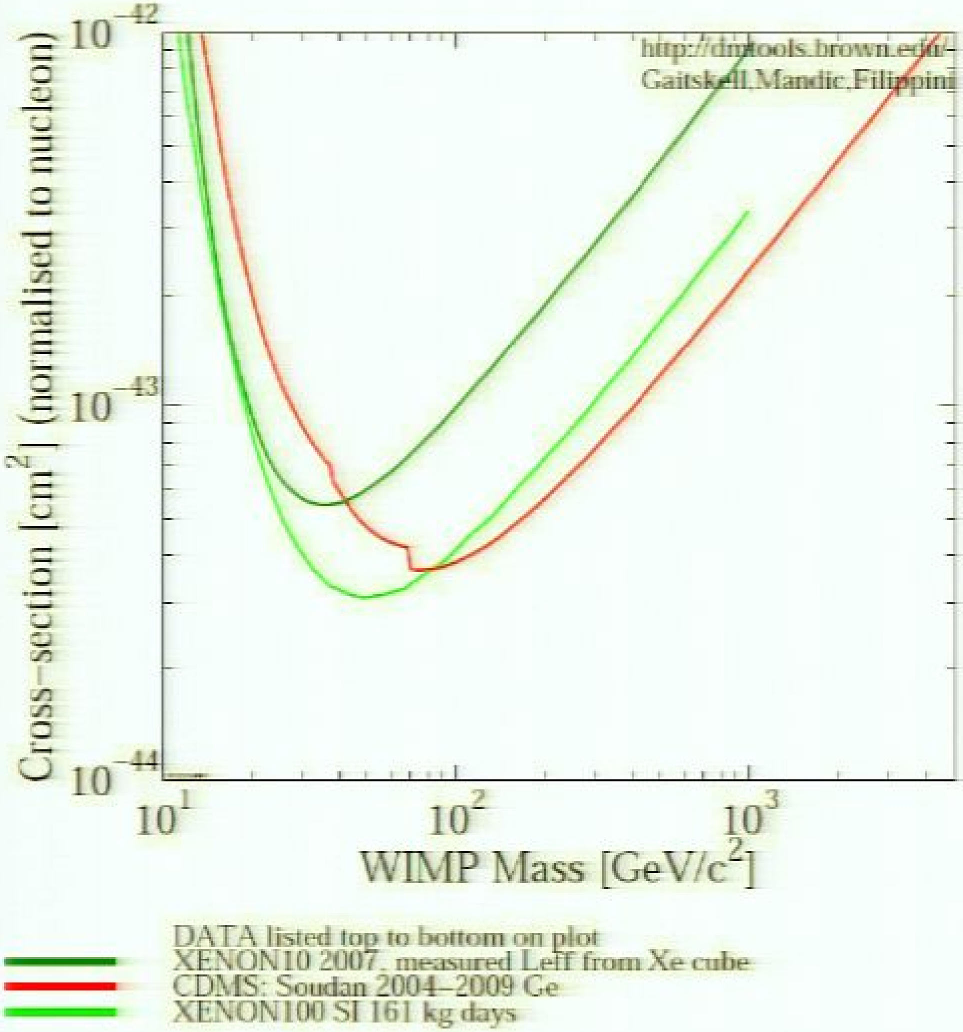

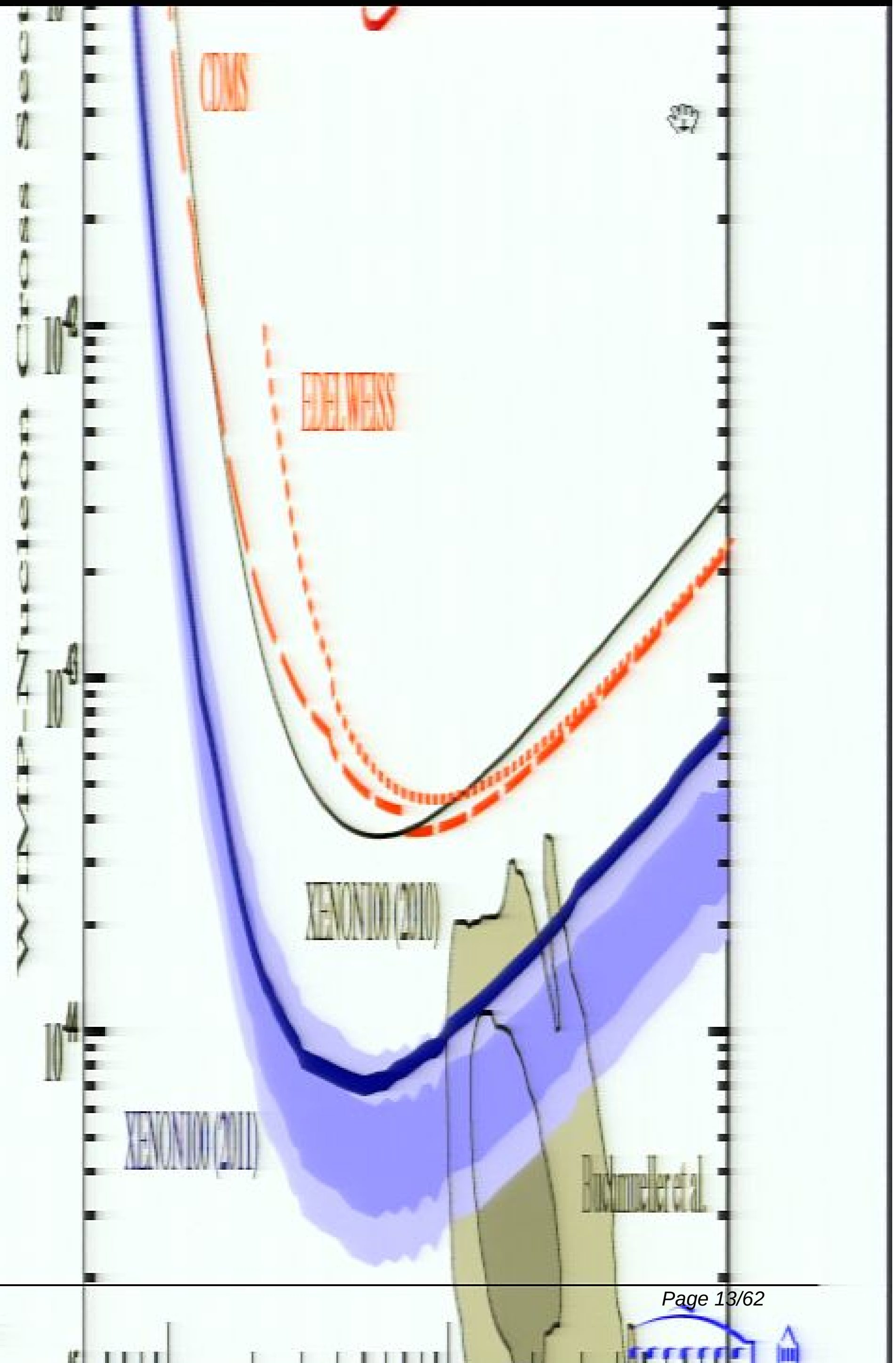

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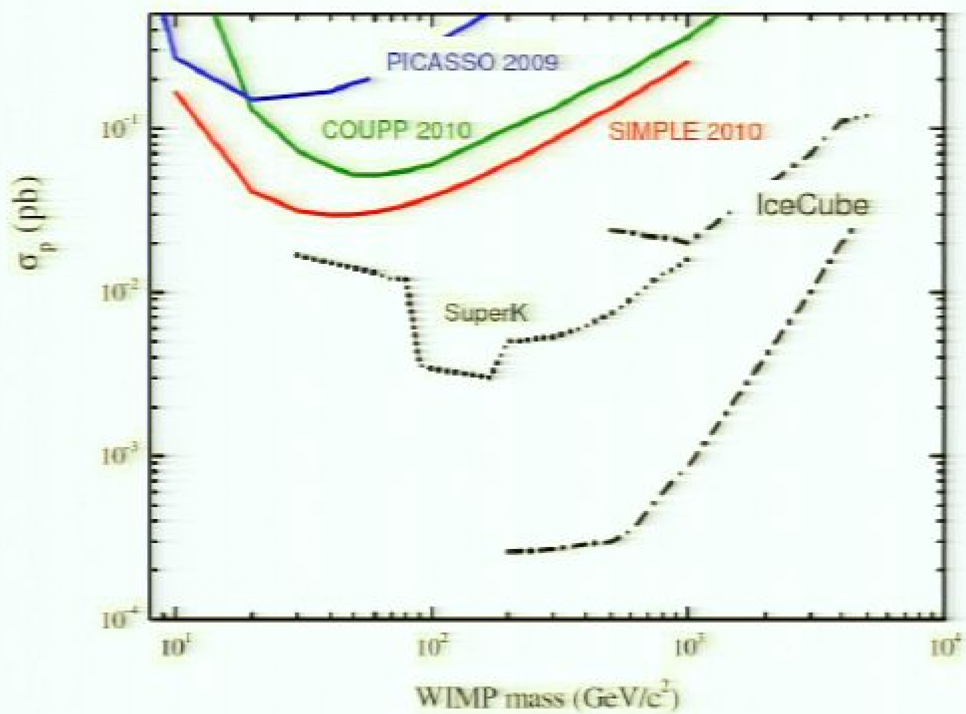

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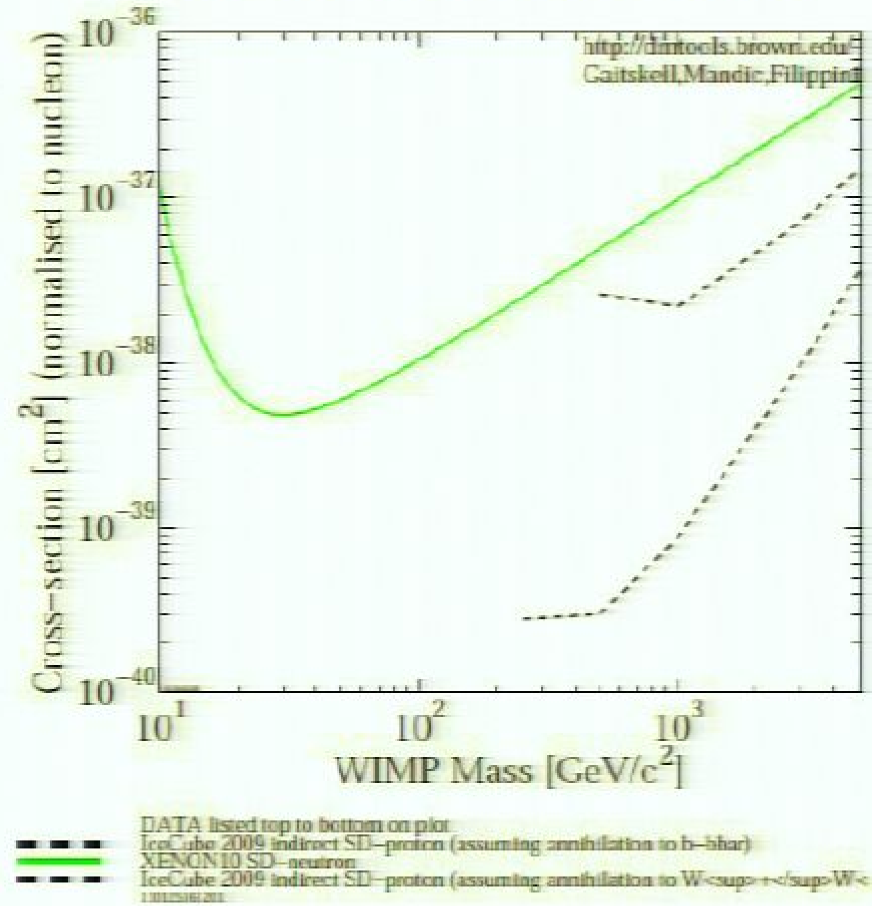
DM − neutron cross section



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Future sensitivity

- Near future:

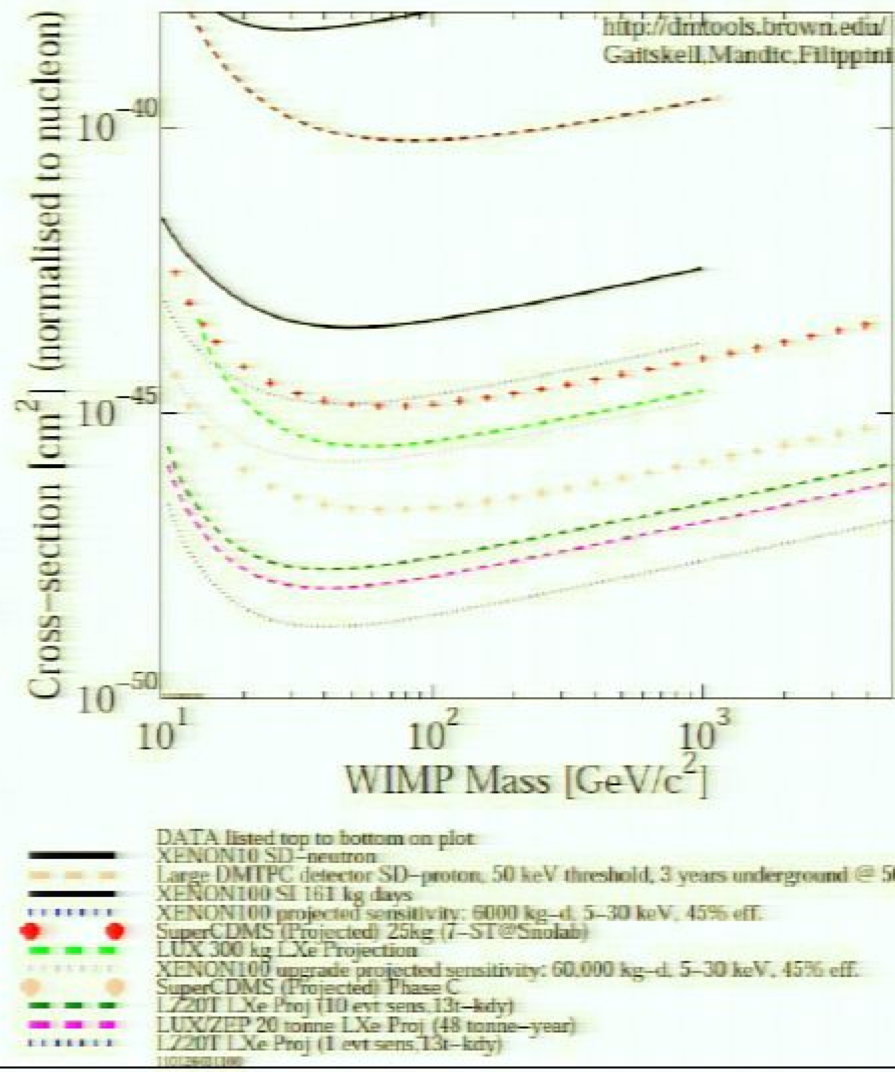
XENON 100 will improve a factor of few

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 tell us something interesting?

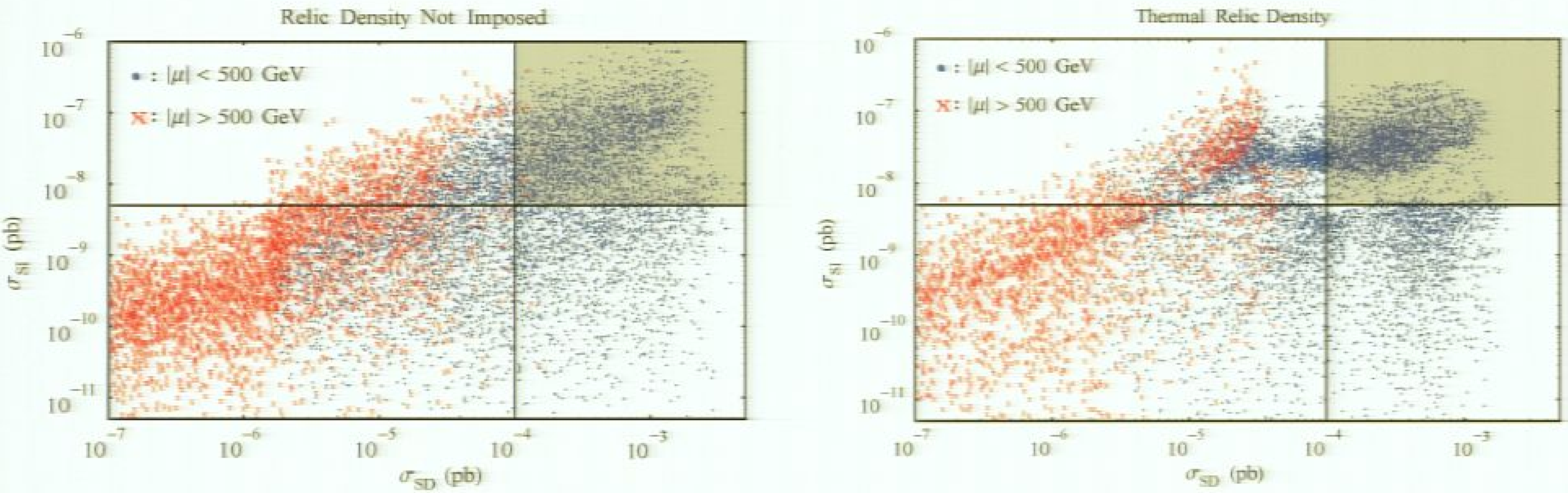
  Signicant correlation between SI & SD cross sections is claimed in most standard frameworks (MSSM, UED, little Higgs) — observing the contrary would tell us we are on to something unexpected [Bertrone *et al.*, 0705.2502; Belanger *et al.*, 0810.1362; Cohen *et al.*, 1001.3408]
- The pessimist:

  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?
- Can spin-dependent win?

E.g.: SUSY parameter space

- Knowing m_Z and m_h in the MSSM implies correlation between SI and SD signals



[Cohen, Phalen, Pierce, 1001.3408]

- In most of the parameter space $\sigma_{\rm SI} > 10^{-5}\,\sigma_{\rm SD}$

- Can select parameter values where huge cancellations occur (highly non-generic)

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

---

- 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

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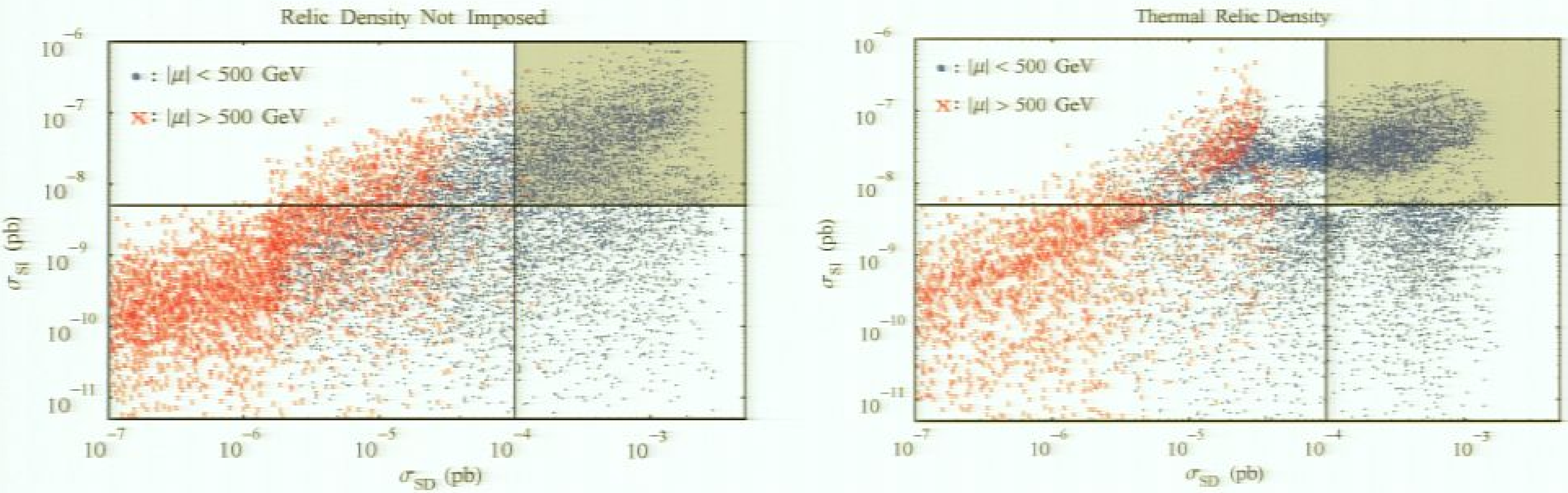

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Operator analysis (1)

- 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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Viable operators

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

$$\mathcal{O}_8^f = \bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$$
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- A kinematically suppressed operator can be competitive if the mediator scale is low and unsuppressed operators are absent [Chang et al., 0908.3192]

  Both features are present in the case of spontaneous global symmetry breaking

- Need to consider suppressed operators with pseudoscalar currents:

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Operators from mediators

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

  What interactions yield the SD operators and nothing else?

  This was studied for heavy mediators [Agrawal *et al.*, 1003.5905]

  Include the possibility of light mediators

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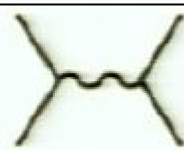
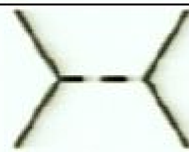
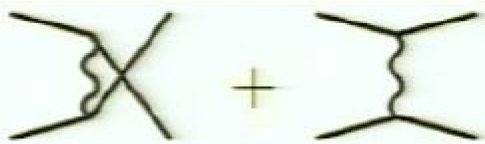
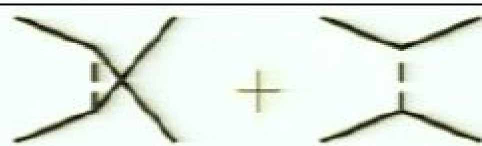
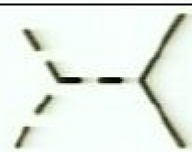
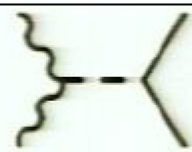
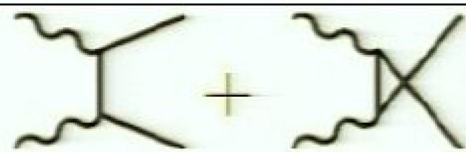
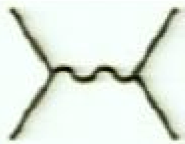
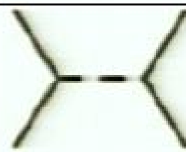
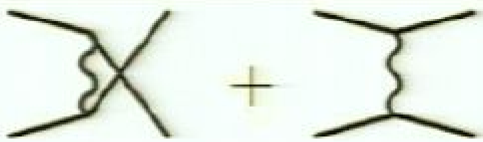
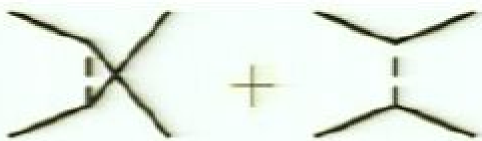
Fermion DM with SD scattering

Mediator	Process	Comments
Z, Z'		Majorana
a		
X		Majorana + chiral coupling
Φ		Majorana + chiral coupling

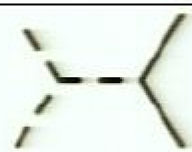
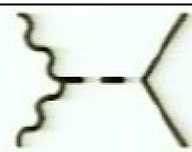
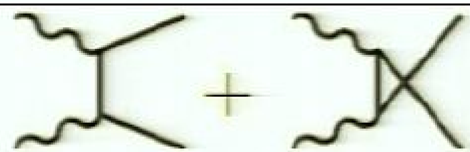
Boson DM with SD scattering

Mediator	Process	Comments
a		
a		
Q		Real + chiral coupling

Fermion DM with SD scattering

Mediator	Process	Comments
Z, Z'		Majorana
a		
X		Majorana + chiral coupling
Φ		Majorana + chiral coupling

Boson DM with SD scattering

Mediator	Process	Comments
a		
a		
Q		Real + chiral coupling

Kinematically suppressed contributions

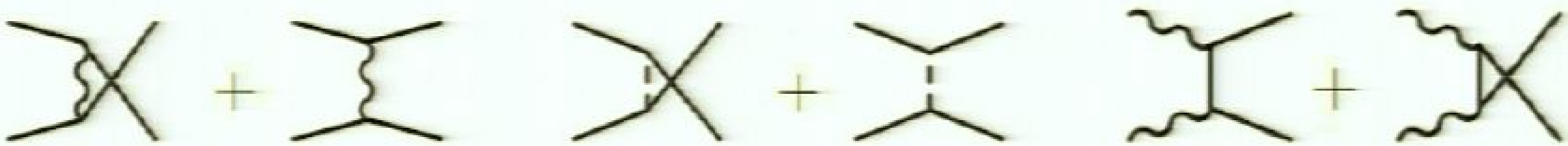
- Usually only the leading contribution from each operator is retained

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

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

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

- Typically get v^2 suppressed SI operators:

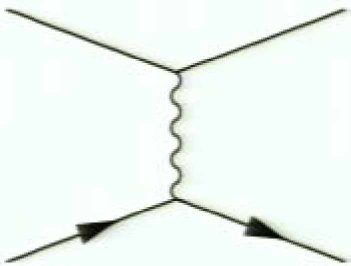


$Z^{(\prime)}$ exchange Φ exchange Q exchange

- Pseudoscalar a exchange — no additional contributions generated

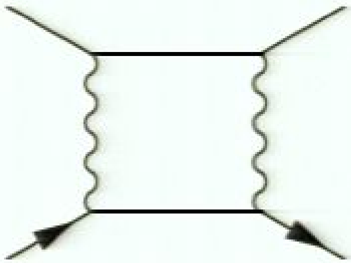
Loop-induced subleading effects

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



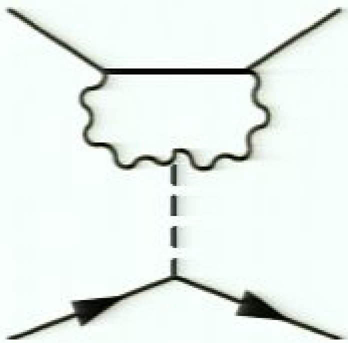
$$\frac{g_2^2}{2\cos^2\theta_W} T_3^q\, Q\, \frac{1}{m_Z^2}\, \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q$$

- Loop effects induce the SI operator:



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

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 $\sim n^2$

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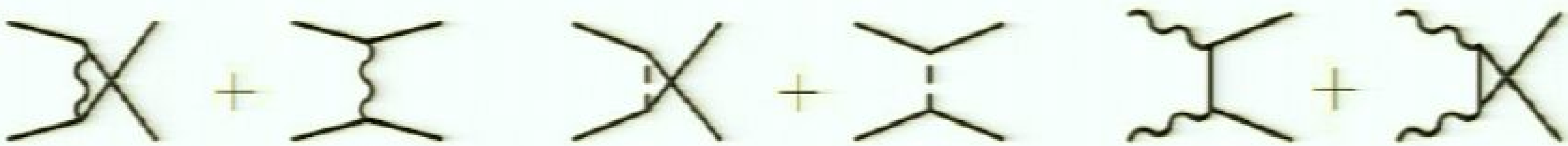

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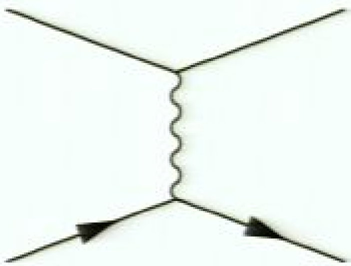

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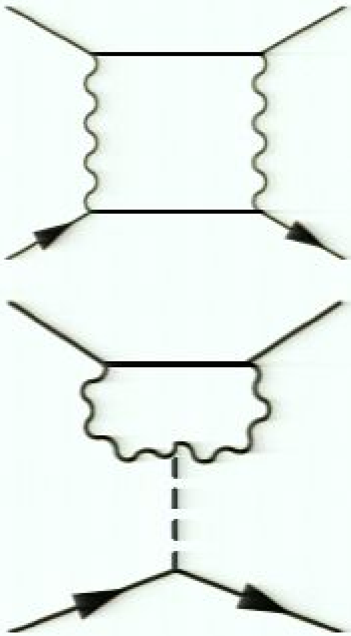

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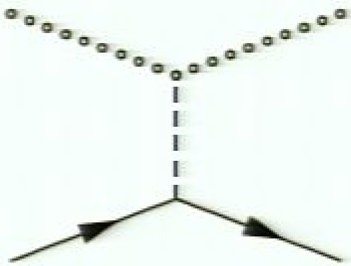
However, if the DM is in an $SU(2)$ n-plet, the cross section $\sim n^2$

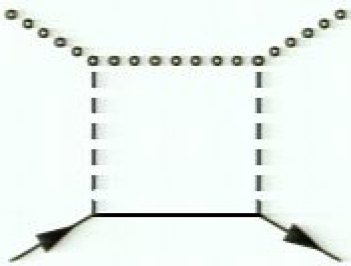
Loop effects: pseudoscalar mediator

- 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...

Subleading effects — pseudoscalar mediator

- Unlike Z case, we expect these loops have no detectable contribution:
  - 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

---

- 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 $\xi S \chi \chi^c + \text{h.c.}$, 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 $\mathcal{L} = \lambda S^n H_u H_d + \text{h.c.}$, and $U(1)_X$ is a Peccei-Quinn symmetry

- The new fermions stay in thermal equilibrium though

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

- If all scales $\sim \text{TeV}$, $\langle \sigma v \rangle \sim 3 \times 10^{-26}\, \text{cm}^3/s$, 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 $m_s \sim f_a$; then the SI cross section is below the 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]

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Axion portal and B decays

Axion portal and direct detection

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[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:

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

- 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]

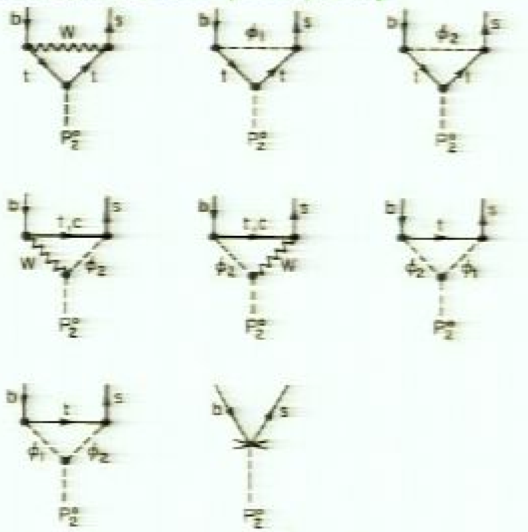

Fig. 2. Feynman diagrams contributing to the $b \to s P_2^0$ amplitude at one-loop.

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

$$F_1(m, M_{\phi_2}, M_W) = \left(\frac{M_W^2 - \frac{1}{2}m^2}{M_W^2 - m^2}\right)\left(\frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right) - 1\right)$$
$$+ \frac{2M_W^2}{M_W^2 - M_{\phi_2}^2}\left(\frac{M_{\phi_2}^2}{M_{\phi_2}^2 - m^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) - \frac{M_W^2}{M_W^2 - m^2}\ln\left(\frac{M_W^2}{m^2}\right)\right)$$
$$+ \tfrac{1}{2}(M_W^2 - M_{\phi_2}^2)\left(\frac{-M_{\phi_2}^2}{(M_W^2 - M_{\phi_2}^2)(M_{\phi_2}^2 - m^2)}\right.$$
$$+ \frac{M_W^2 M_{\phi_2}^2}{(M_W^2 - m^2)(M_W^2 - M_{\phi_2}^2)^2}\ln\left(\frac{M_W^2}{M_{\phi_2}^2}\right)$$
$$+ \frac{M_{\phi_2}^2 m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) + \frac{1}{2}\frac{m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)}$$
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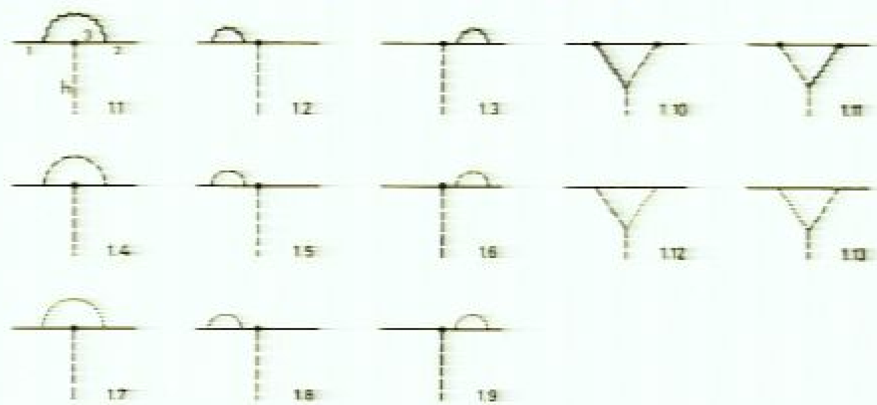
[Frere, Vermaseren, Gavela, PLB 103 (1981) 129]



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

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

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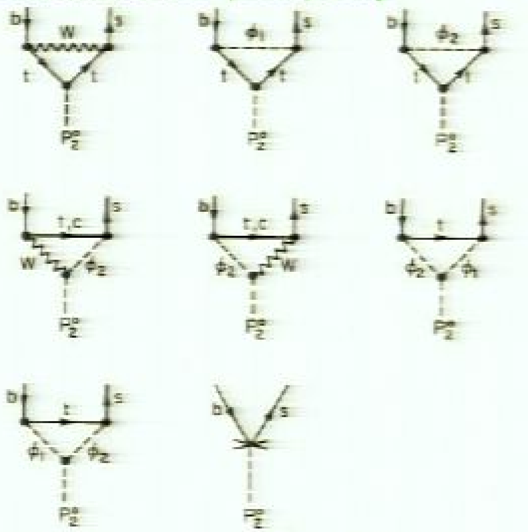

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$$+ \frac{M_{\phi_2}^2 m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)^2}\ln\left(\frac{M_{\phi_2}^2}{m^2}\right) + \frac{1}{2}\frac{m^2}{(M_W^2 - m^2)(M_{\phi_2}^2 - m^2)}$$
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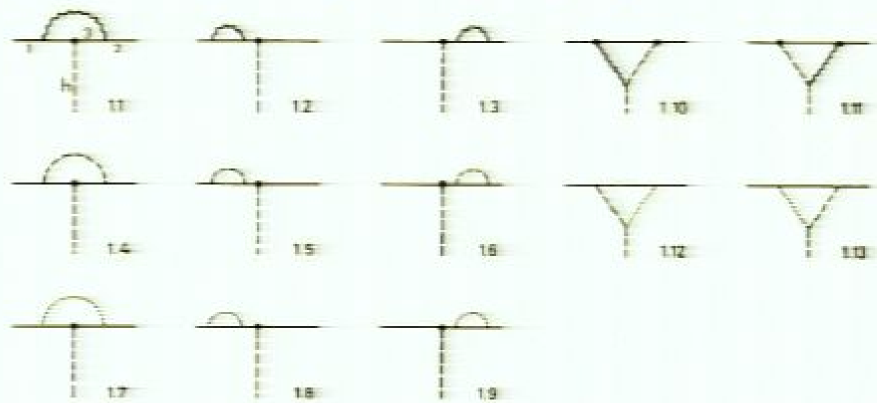

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$$\times \ln\frac{m^2}{M_W^2} + \frac{M_H^2}{(M_H^2 - m^2)}\left(\frac{6M_W^2}{M_W^2 - M_H^2} + \frac{M_H^2}{M_H^2 - m^2}\right)$$
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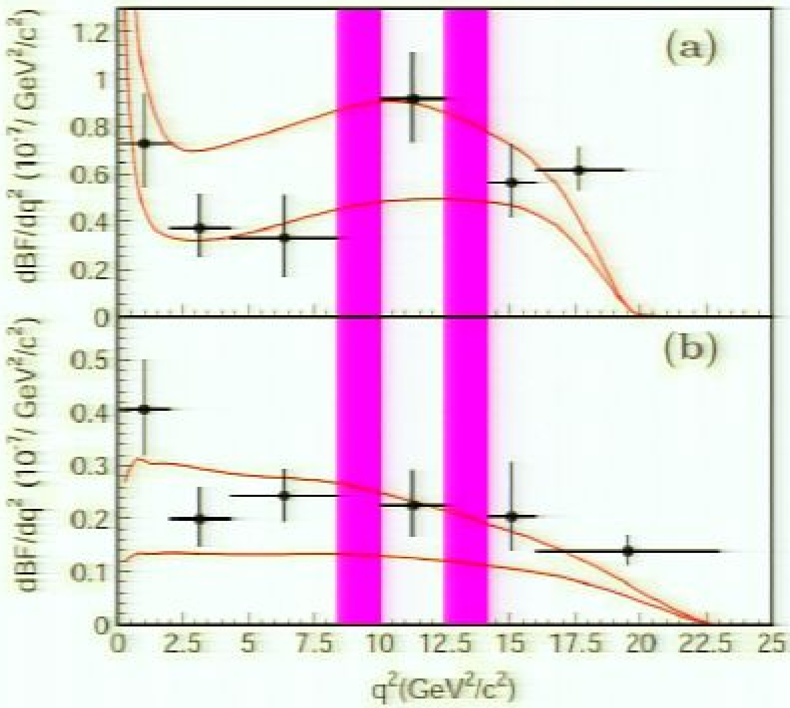
[Wei *et al.*, Belle Collaboration, PRL 103 (2009) 171801]



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

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The 2HDM calculation

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

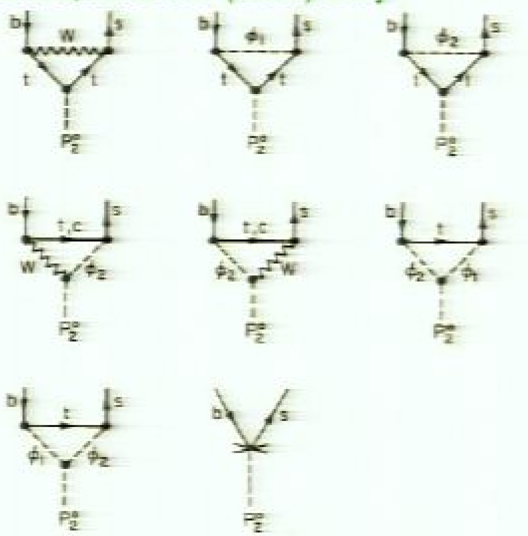
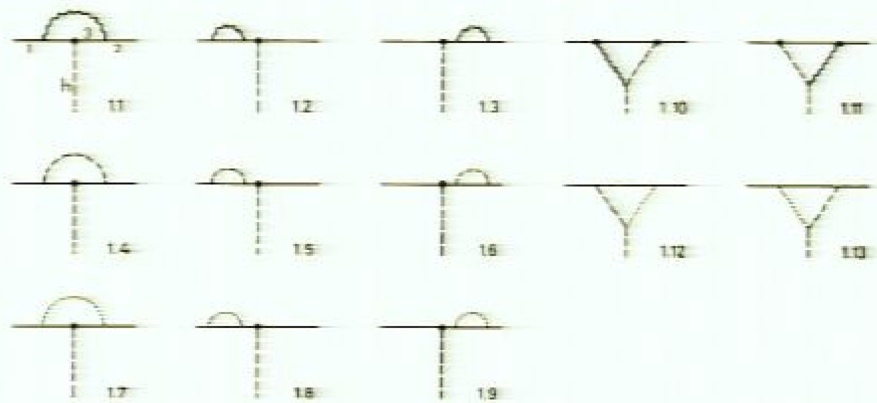


Fig. 2. Feynman diagrams contributing to the $b \to s\, P_2^0$ amplitude at one-loop.

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

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

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



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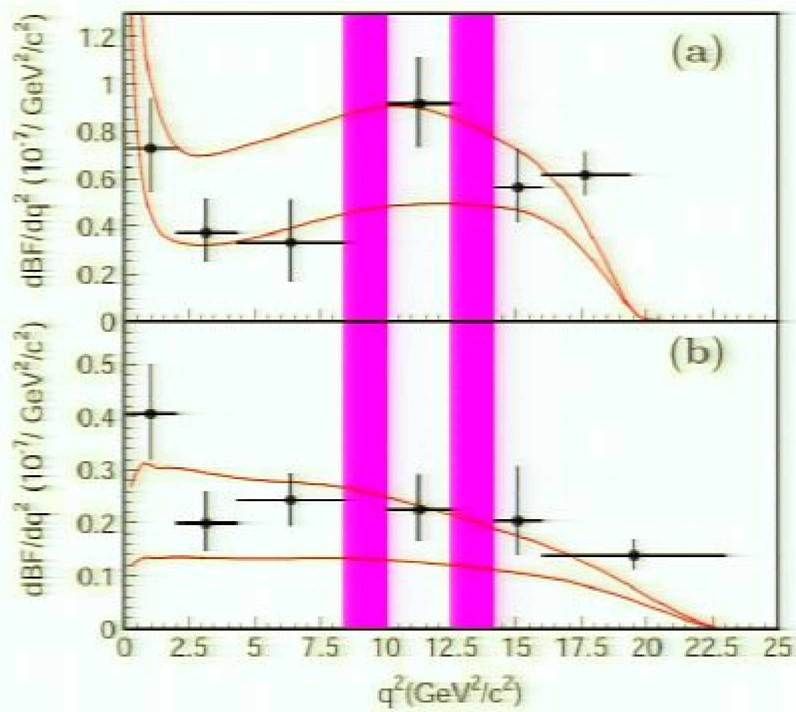

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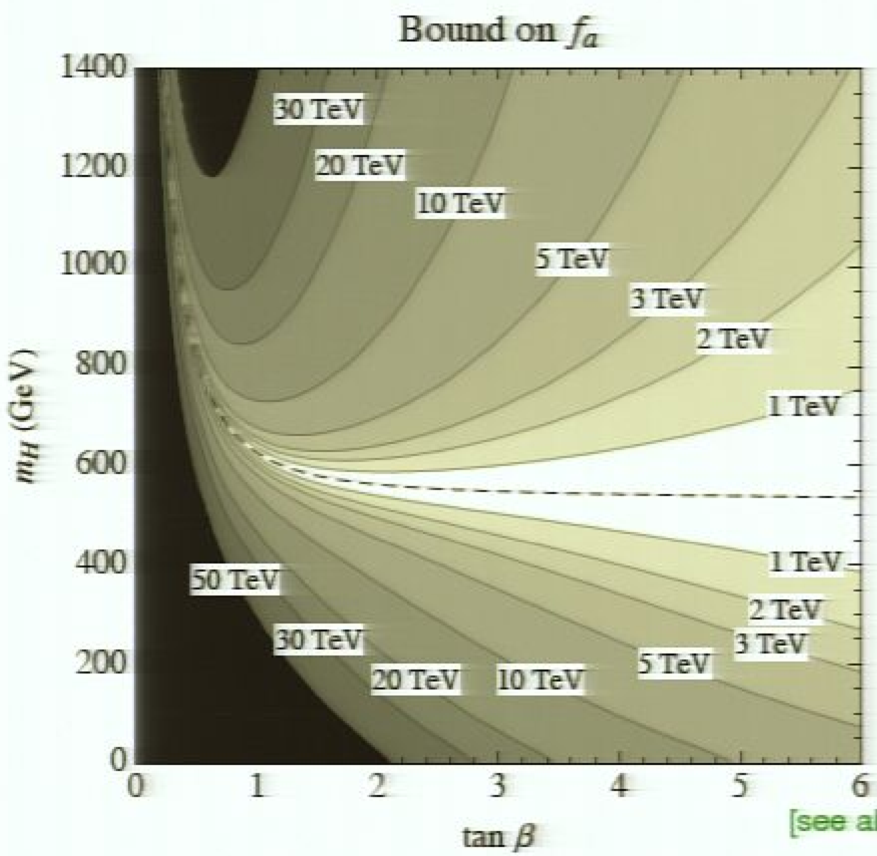
The bound from $B \to K\ell^+\ell^-$



[Freytsis, ZL, Thaler, 0911.5355]

[see also: Batell, Pospelov, Ritz, 0911.4938]

- 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?

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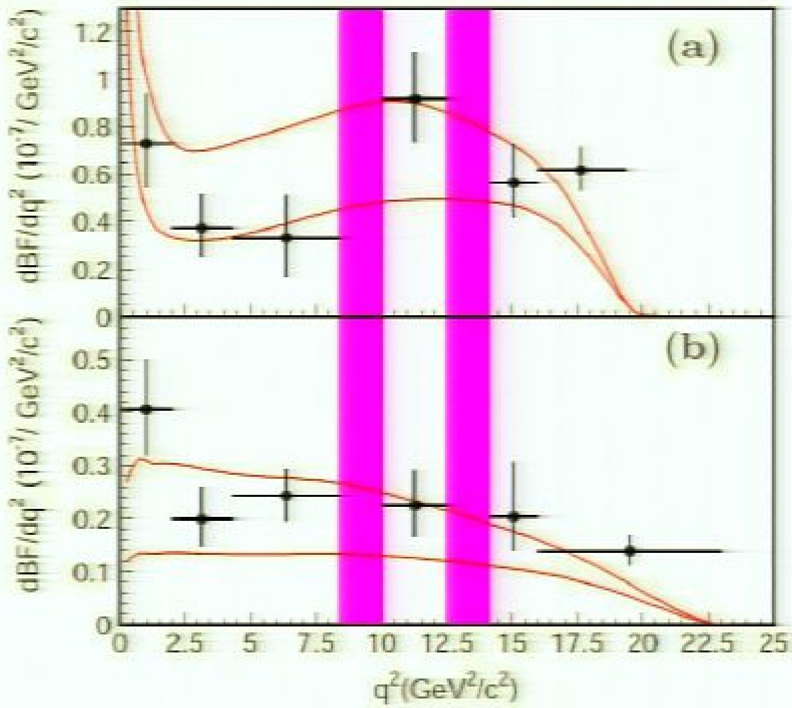

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