Effective Theories of Dark Matter

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(virtually)

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Implications for LHC Results: MET WG

CERN, August 31

References

This talk is based on:

Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137;
Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu
1005.1286, 1008.1783 & 1009.0008;
Fortin, TMPT 1103.3289;
Rajaraman, Shepherd, TMPT, Wijanco 1108.1196.

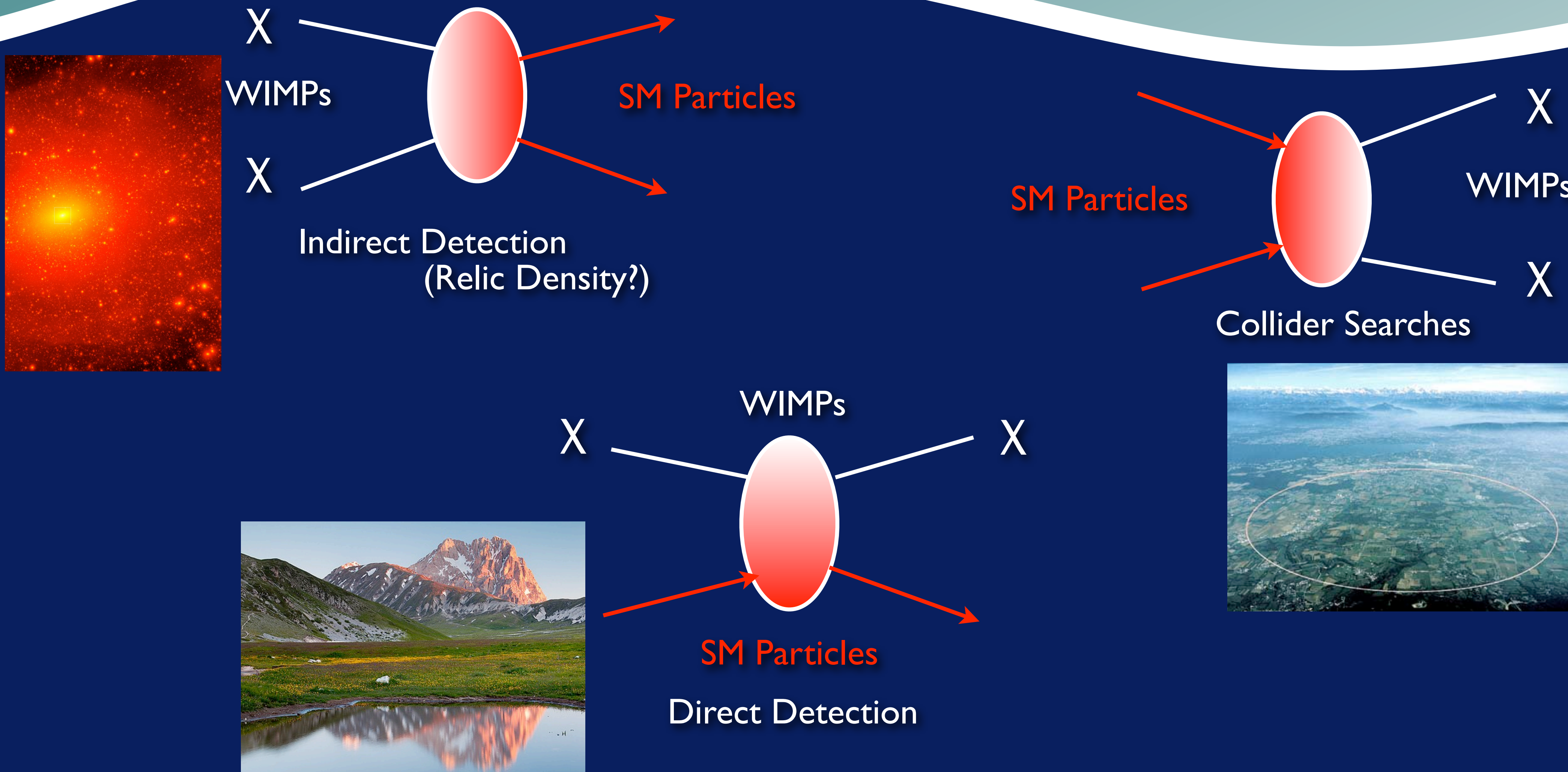
Related work by the FNAL clan:

Bai, Fox, Harnik 1005.3797
Fox, Harnik, Kopp, Tsai 1103.0240

Outline

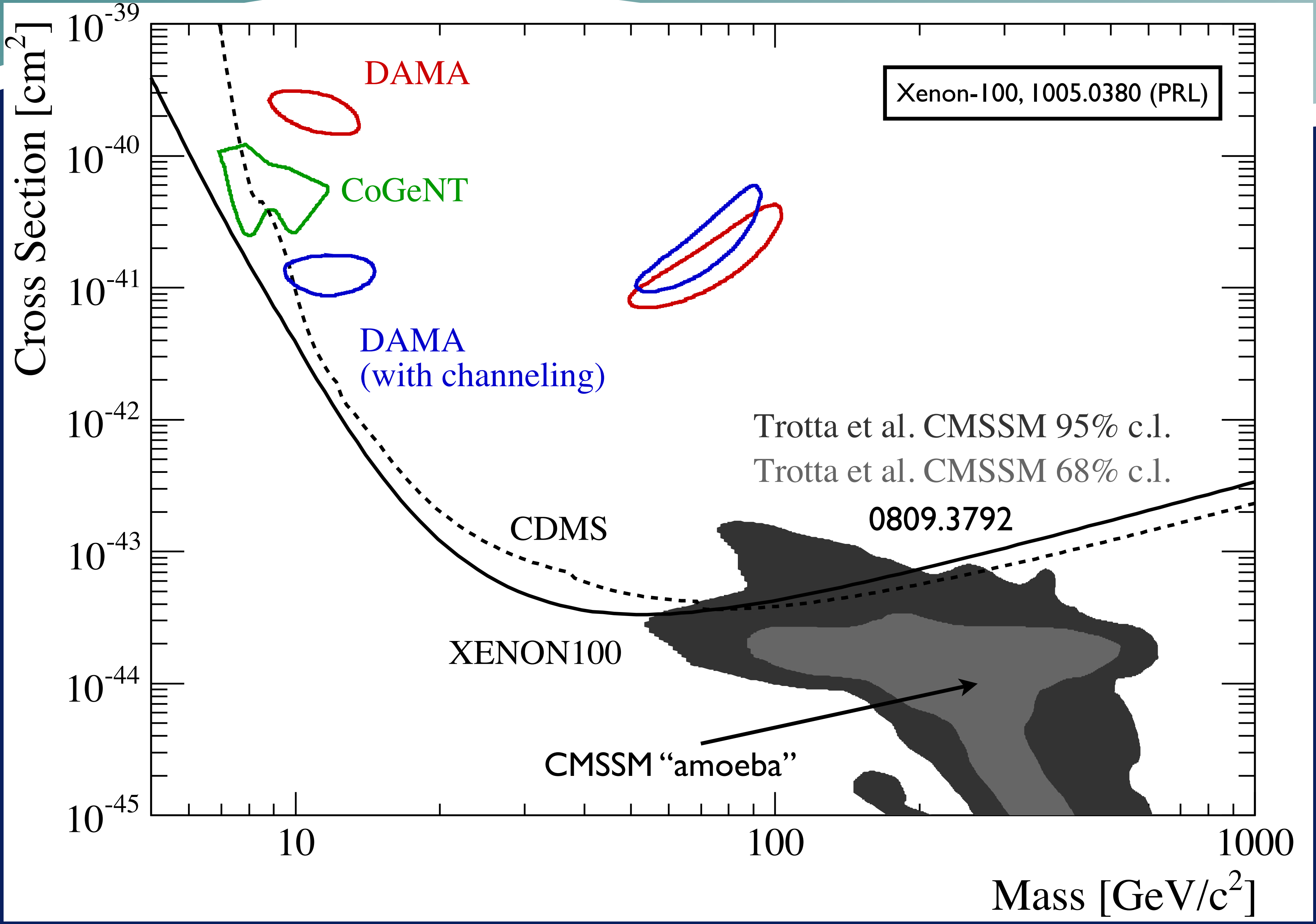
- Motivation: "Generic descriptions" of WIMP-Standard Model Interactions
- Interplay between Experimental Searches
  - Effective Theory Description of Dark Matter Interactions
  - The Impact of Collider Searches on Direct Detection
  - Fermi Line Search
- Outlook

WIMP Searches



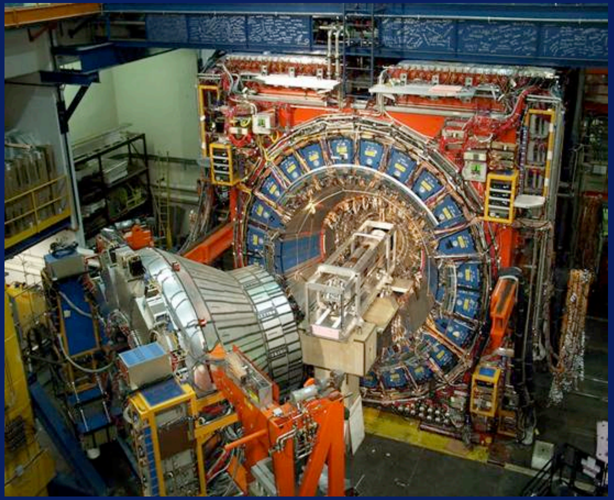
- WIMPs interacting with SM particles allow indirect searches for annihilation products, direct scattering searches, and production at colliders.

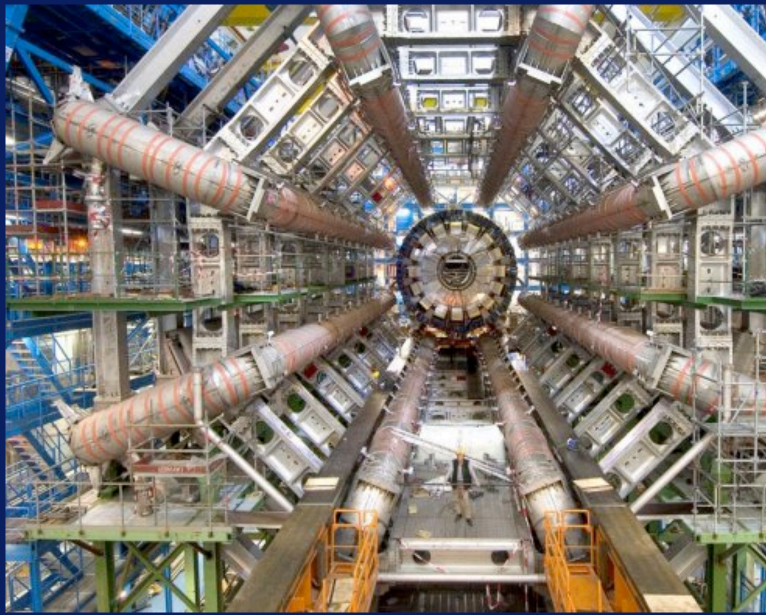
Direct Detection Results



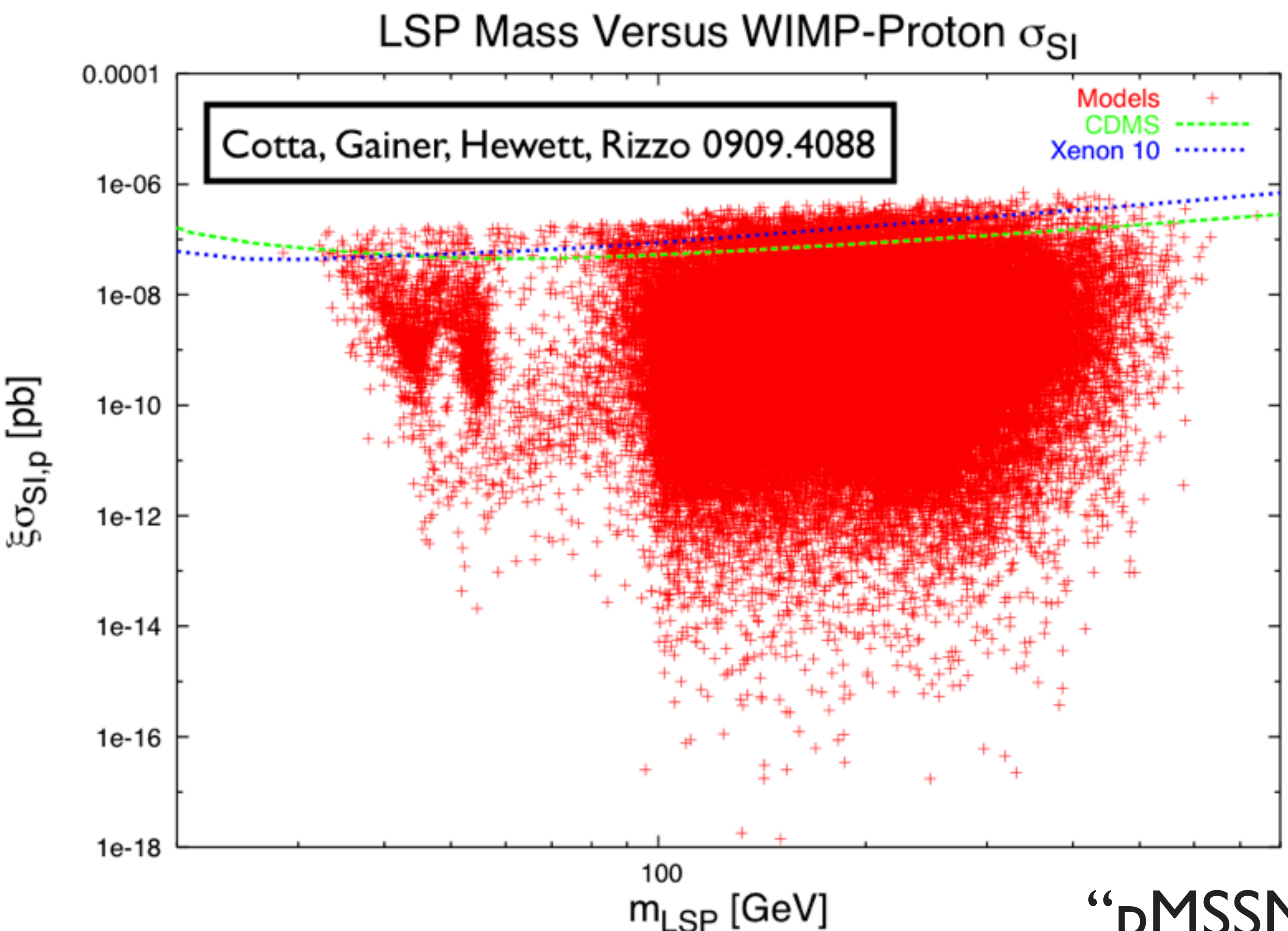
Other Experiments?

- Direct detection probes WIMP couplings to nucleons (quarks and gluons).
- This raises an important question:
  - **Why are there no bounds from colliders on this plot?**
- E.g. High energy accelerators such as the Tevatron and LHC collide (anti-) protons.
- There *must* be some interplay between the two: if WIMPs couple to nucleons, we can produce them in high energy collisions of hadrons.





MSSM

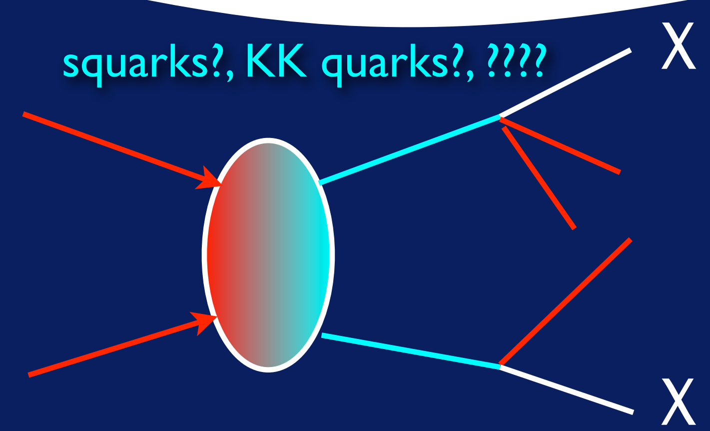


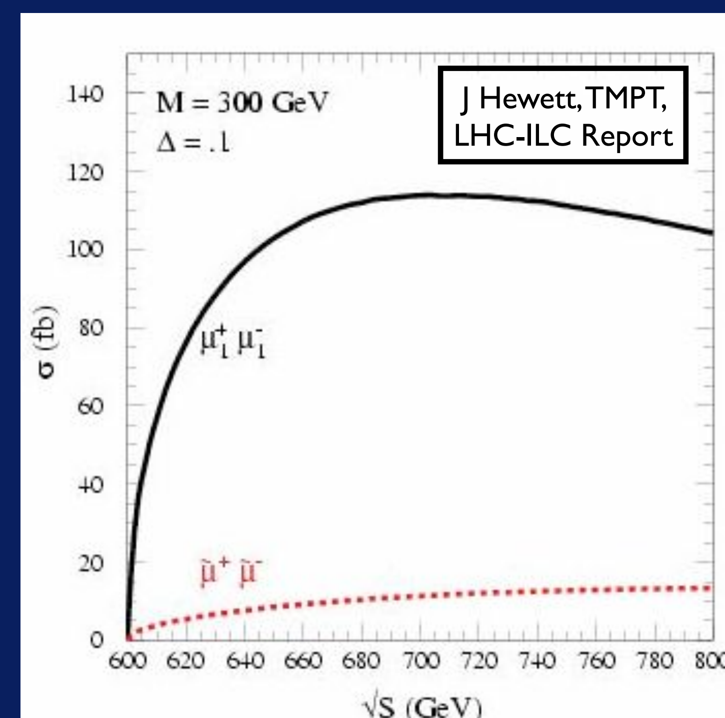
LSP Mass Versus WIMP-Proton σ_{SI}
Cotta, Gainer, Hewett, Rizzo 0909.4088
Models
CDMS
Xenon 10
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
$\xi\sigma_{SI,p}$ [pb]
100
m_{LSP} [GeV]

"pMSSM"

Beyond Supersymmetry

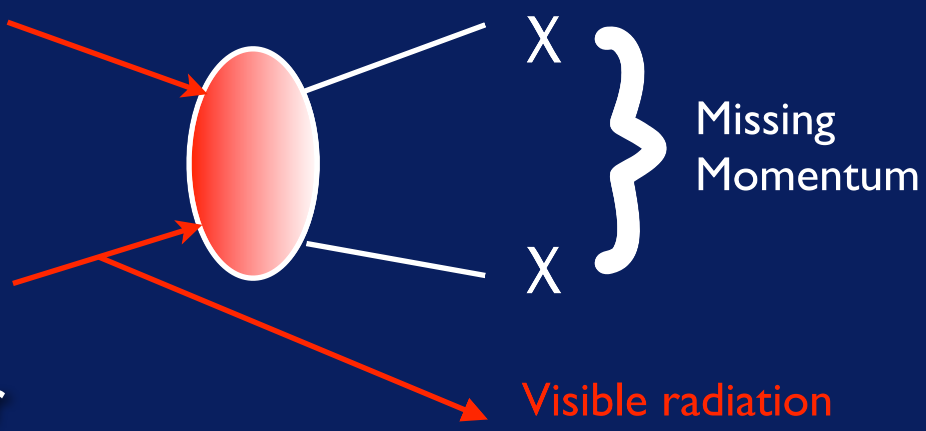
- The main reason why collider searches don't show up on the direct detection plot is that one needs to make additional assumptions to put them there.
- The *usual* way to search for WIMPs at colliders is to produce some of the other particles in the dark matter theory, and then watch them decay into WIMPs (as well as SM particles).
- This process is intrinsically model-dependent.
  - Without knowing the details of these extra particles, we can't even predict what the collider is supposed to be looking for, let alone the expected rate and how it correlates with a direct detection signal.





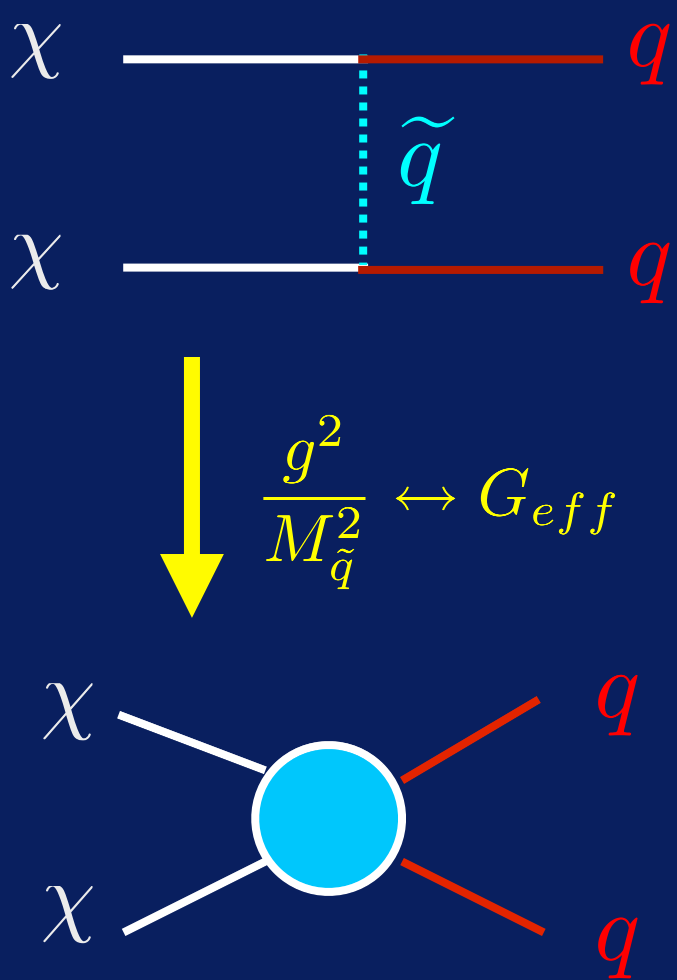
Maverick WIMPs

- Producing the WIMP's siblings is always model-dependent. But we can look at production directly from the WIMP couplings to quarks and gluons.
- This process may result in less spectacular signals than producing other particles in the theory. But it is generic, relying only on the existence of the WIMP itself.
- Since in this process the WIMP appears alone, without any of the other particles of the dark matter theory, I'll refer to it as a "Maverick WIMP".



Effective Field Theory

- I cheated slightly: the WIMP siblings are still part of this process, albeit virtually.
- We bypass this issue by using writing interactions in terms of Effective Field Theories which describe physics in terms of the degrees of freedom relevant at the energy scale of interest. Heavier particles are "integrated out".
- Theories which are different at high energies lead to a small range of low energy phenomena, because their form is dictated by the particles and symmetries present at low energies.
- Capitalizing on these strengths, we construct general EFTs describing WIMP interactions.



Example EFT: Majorana WIMP

- As an example, we can write down operators of interest for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Gluon operators are normalized by α_S, consistent with their having been induced by loops of some heavy colored state.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

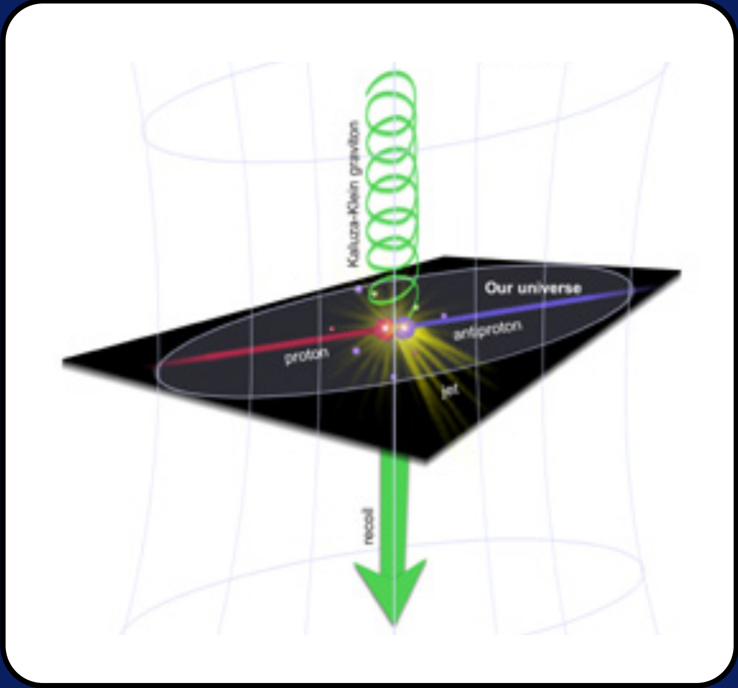
$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

Other operators may be rewritten in this form by using Fierz transformations.

Jets + MET

- CDF has a monojet search aimed at ADD large extra dimensions, where the jet is recoiling against one of a tower of KK gravitons.
- Event Selection:
  - Leading jet PT > 80 GeV.
  - Missing ET > 80 GeV.
  - 2nd jet allowed PT < 30 GeV.
  - Veto more jets PT > 20 GeV.
  - Veto isolated leptons with PT > 10 GeV.
- Based on 1 fb^{-1}, CDF constrains new physics (after cuts) contributions to $\sigma < 0.6$ pb.



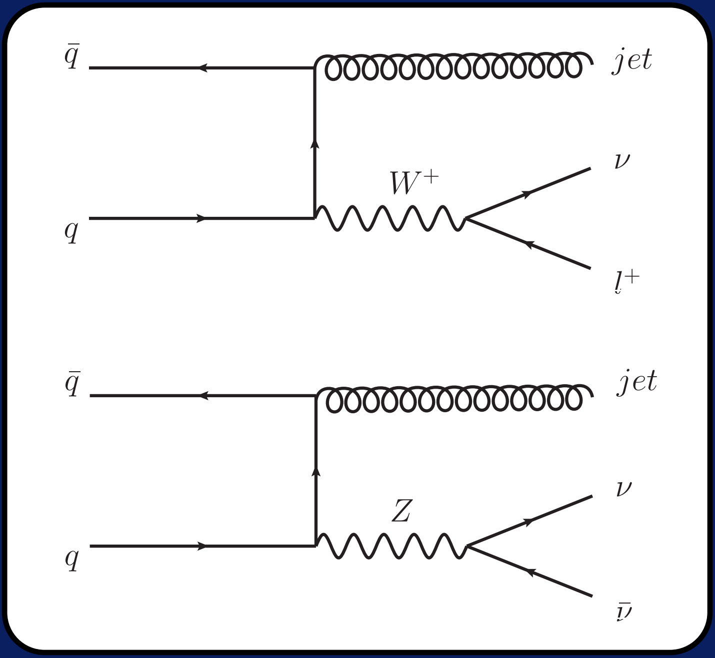
CDF, 0807.3132
http://www-cdf.fnal.gov/physics/exotica/r2a/20070322.mono_jet/public/ykk.html

Backgrounds

- To calibrate our simulations, we reproduce the CDF background using MadEvent with PYTHIA and PGS [CDF detector Model].
  - Including NLO k-factors, we succeeded at the % level.

Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

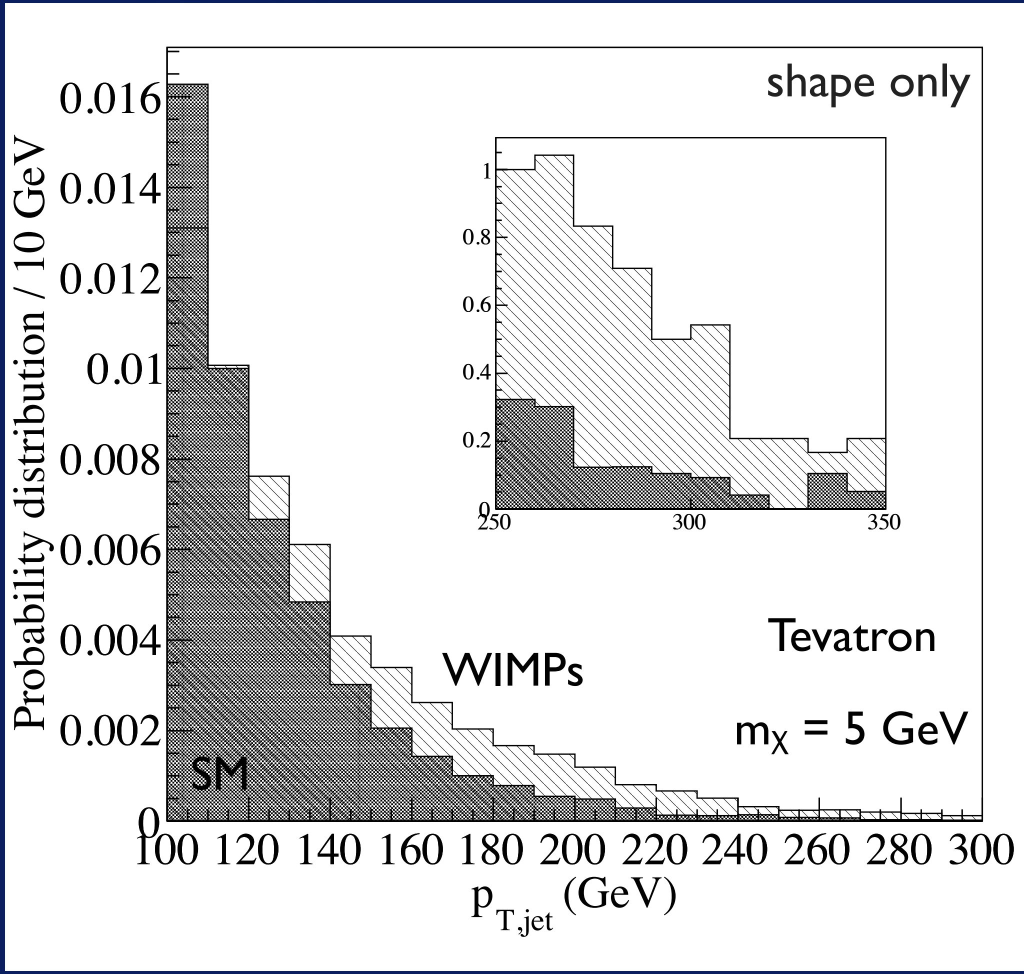
- The dominant physics backgrounds are:
  - Z + jets (with Z-> νν).
  - W + jets (W->eν with the e lost).
  - The "QCD" background from jet mismeasurements creating fake missing energy is subdominant, as determined by CDF itself.
    - (And we don't try to simulate it).



Signal and Background

- At the parton level, there is a clear difference between the kinematics of the WIMP events compared with the SM backgrounds.
- The WIMPs are produced by higher dimensional operators, which grow with energy compared to the softer SM background processes.
- The harder spectrum is reflected in the PT of the associated jet(s), which must balance the WIMPs.

Parton level

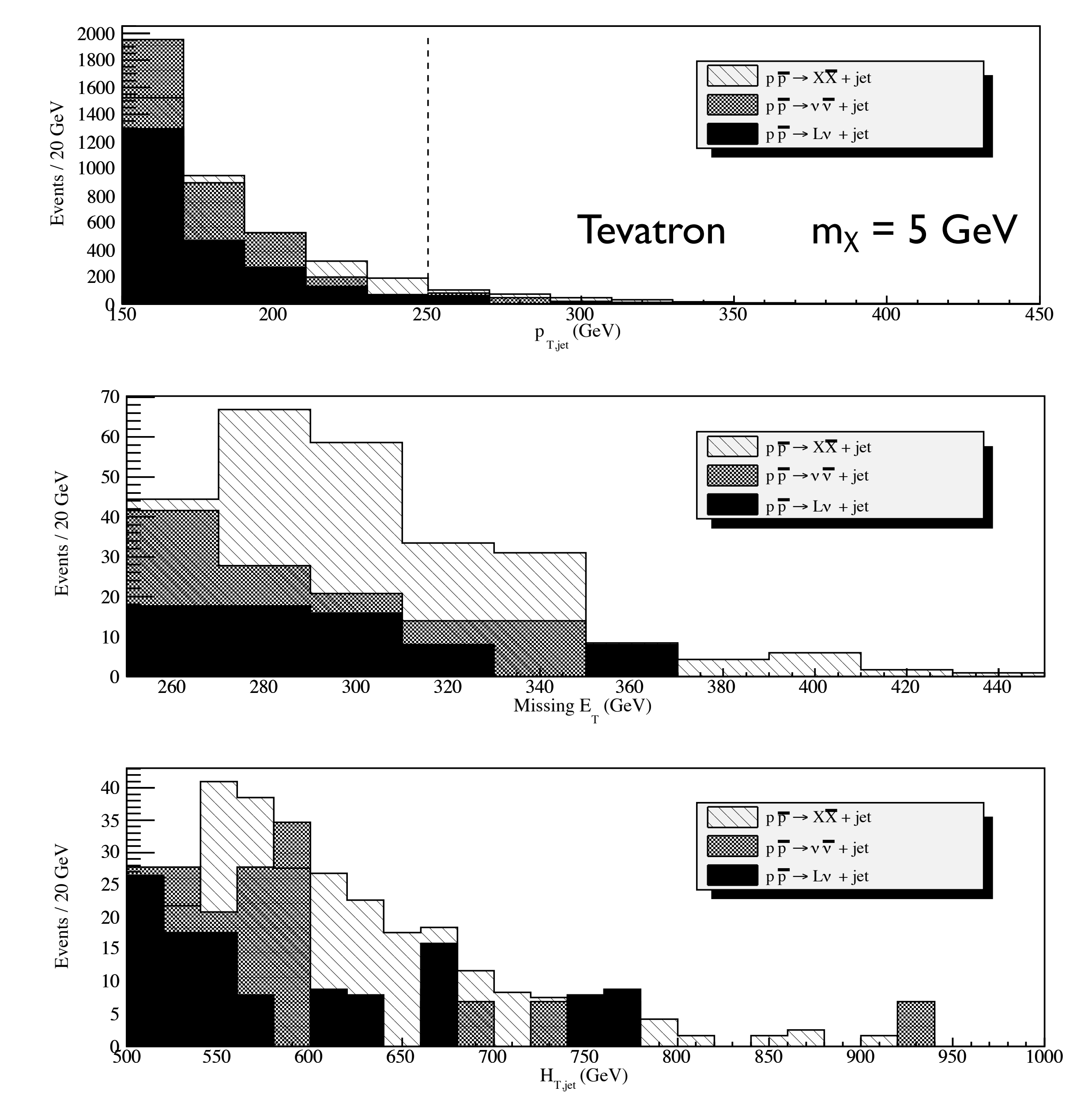


M6: $[\bar{\chi}\gamma^\mu\gamma_5\chi]\,[\bar{q}\gamma_\mu\gamma_5 q]$

Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

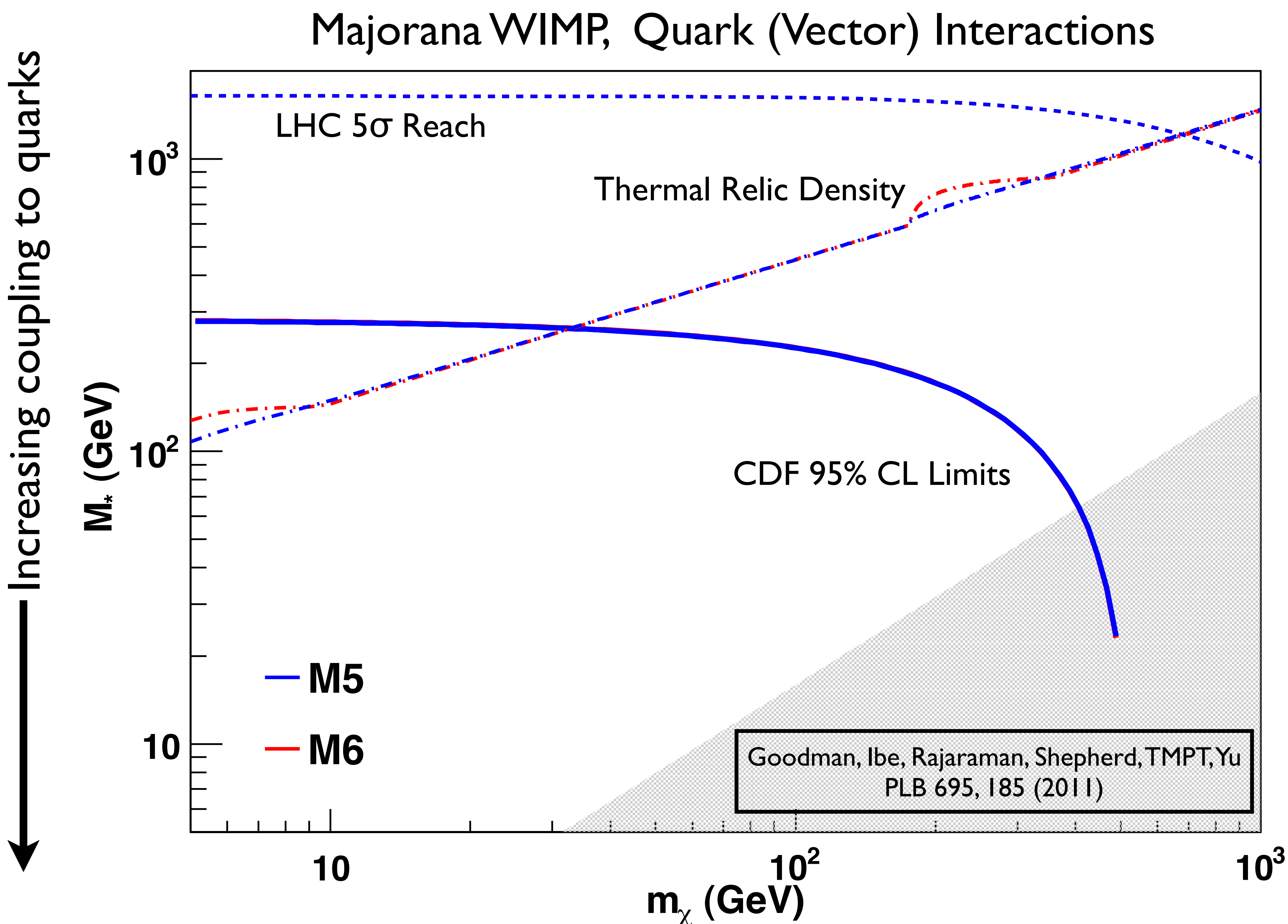
Beyond the Parton Level

- These differences survive parton showering and hadronization and simulated detector response.
- Our detailed study suggests that one can probably optimize a search that does better than the monojet search aimed at ADD, but the existing search is already performing reasonably well.

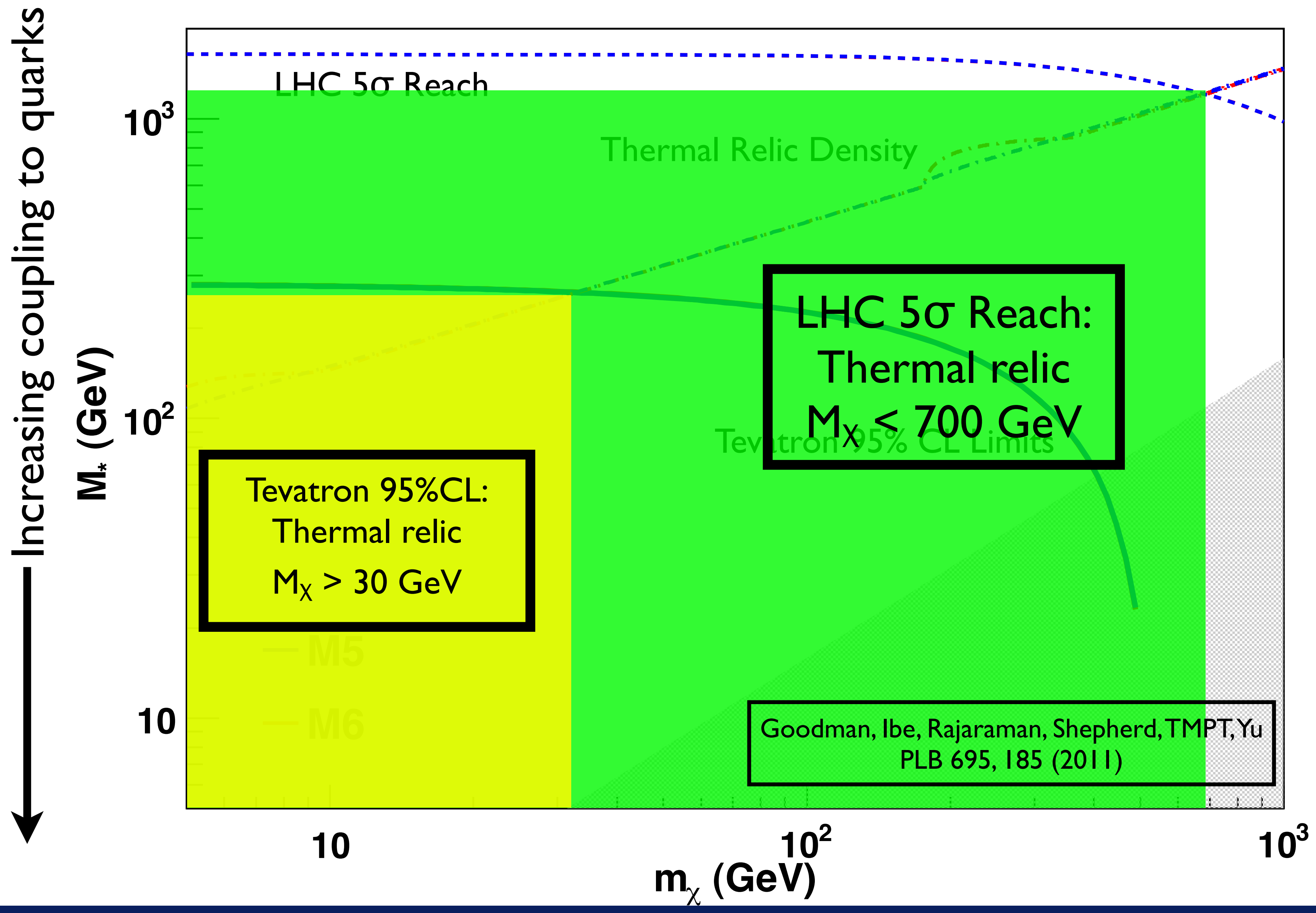


Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

Example of Limits/Sensitivity



Example Limits/Sensitivity



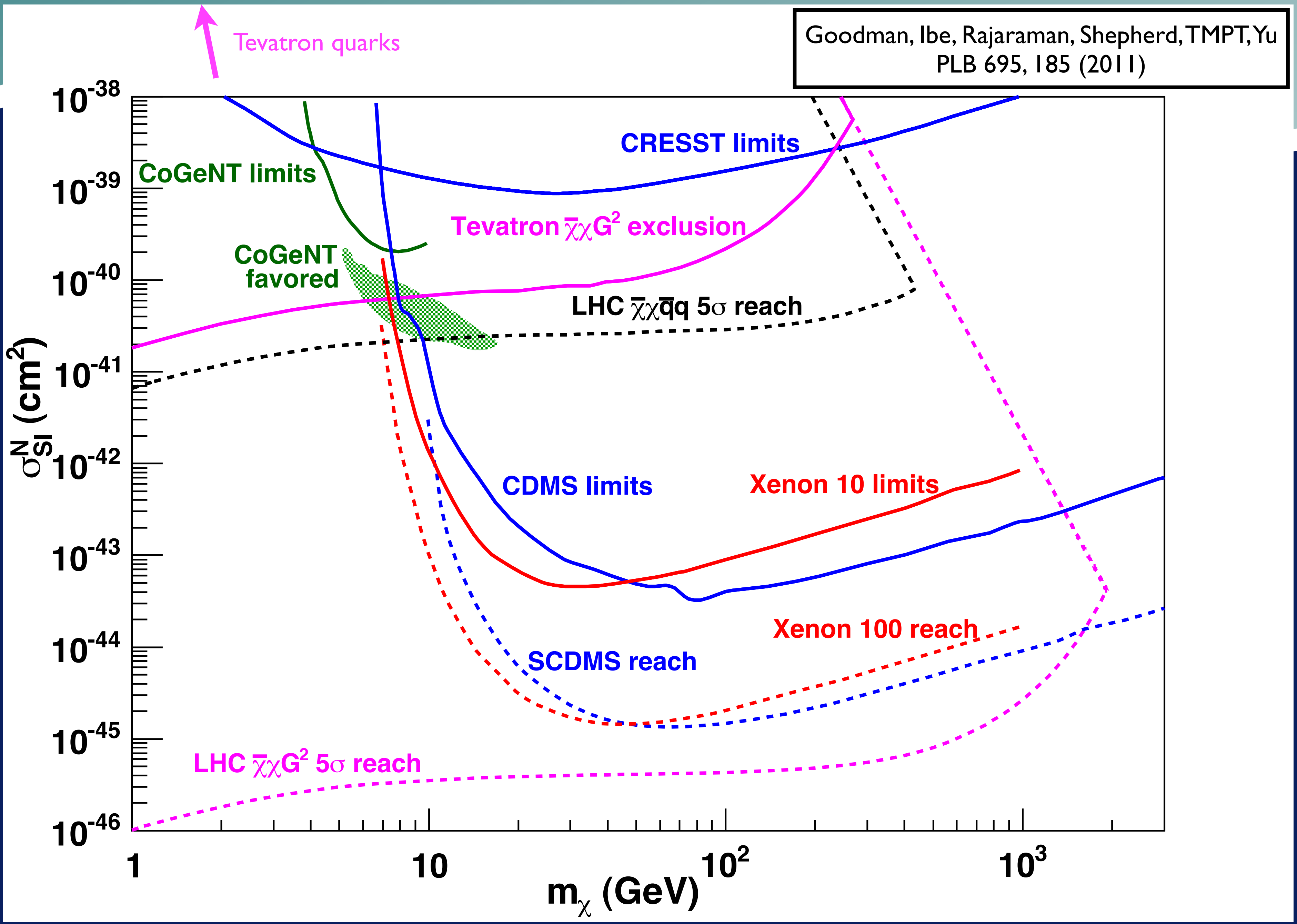
Axial-vector Coupling

- These operators were particularly amenable to collider searches.
  - They both lead to velocity suppressed WIMP annihilation cross sections.
  - The relic density requires that they have somewhat strong coefficients to over-come the velocity suppression.
- The collider signal produces the WIMPs relativistically, with no velocity suppression.
- It's worth reminding ourselves that nothing tells us the annihilation cross section (and thus the relic density) needs to be mediated by this particular interaction.

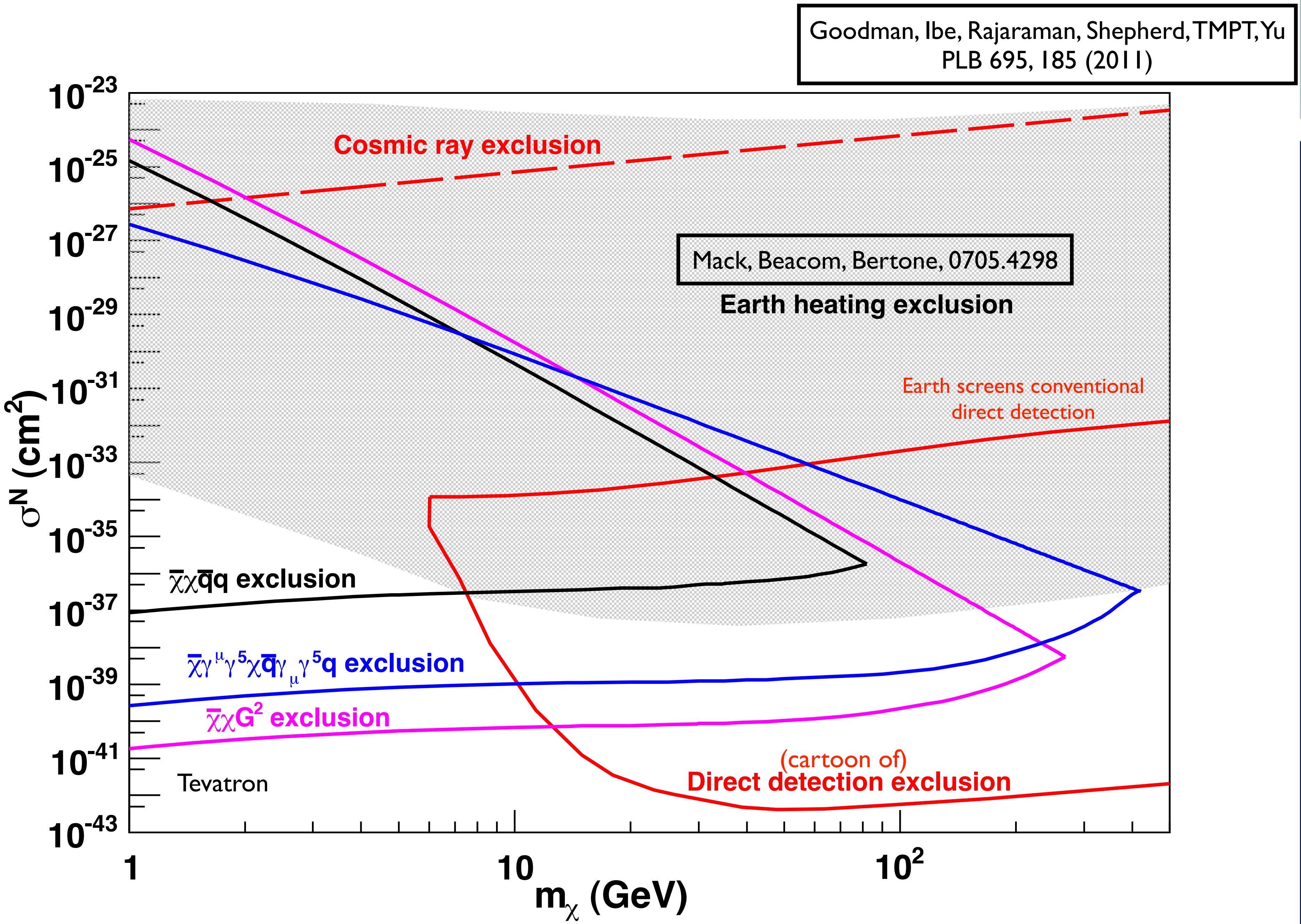
Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

We can make similar plots for any combination of WIMP spin and operator. (And we did in 1008.1783)

Spin-Independent

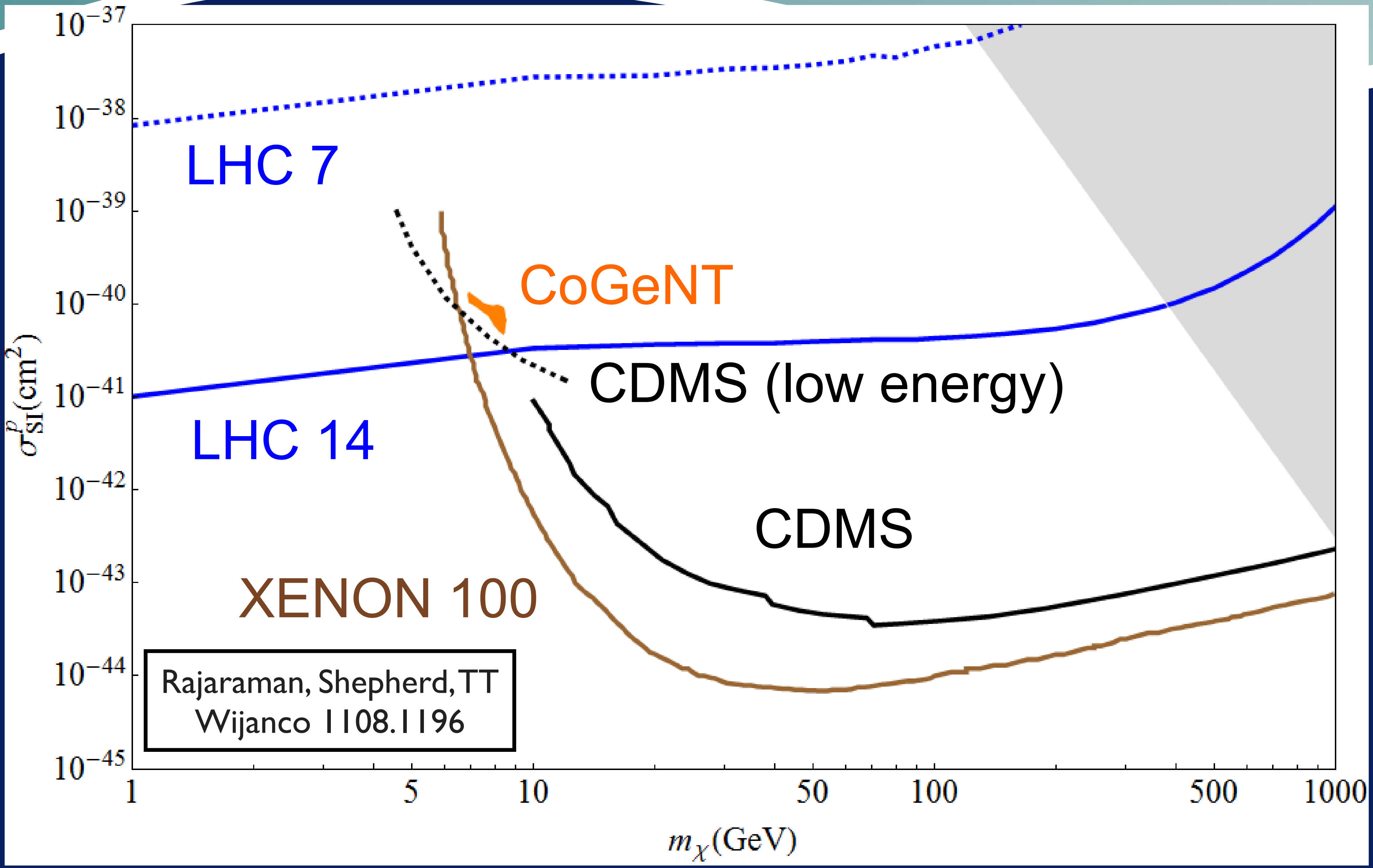


From WIMPs to SIMPs...



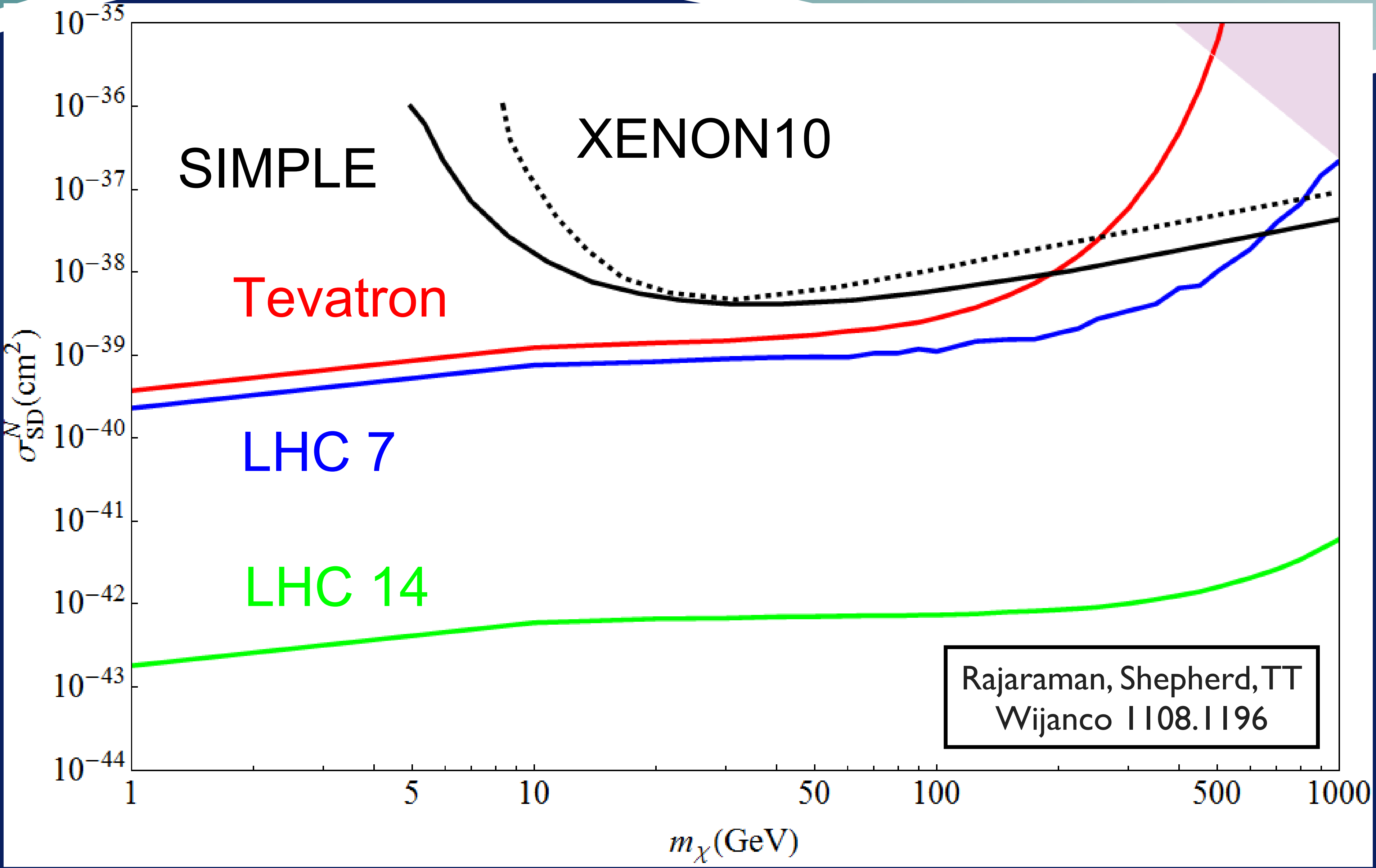
ATLAS Bounds: SI

Equal u- and d- couplings

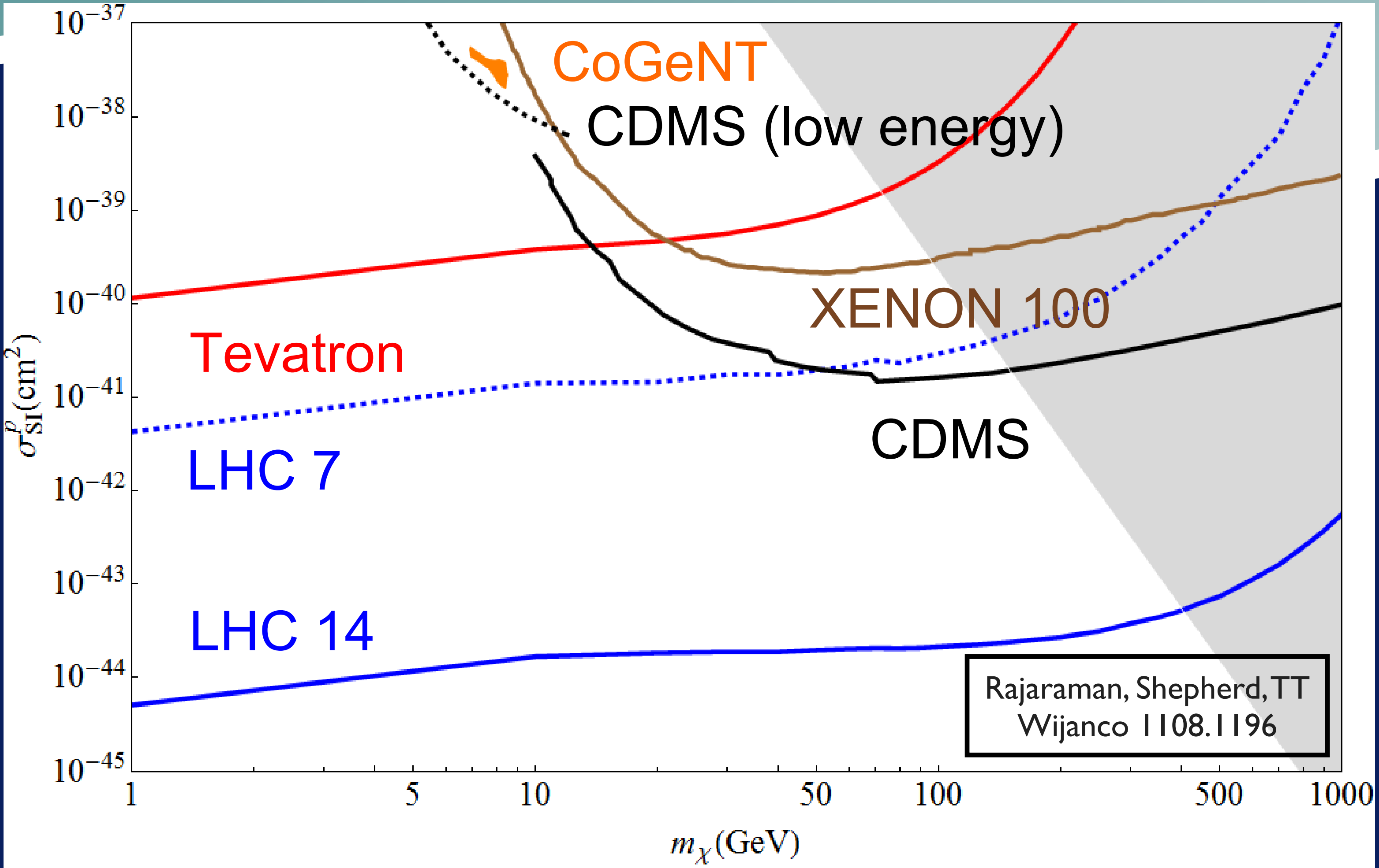


ATLAS Bounds: SD

Equal u- and d- couplings



Iso-spin Violating

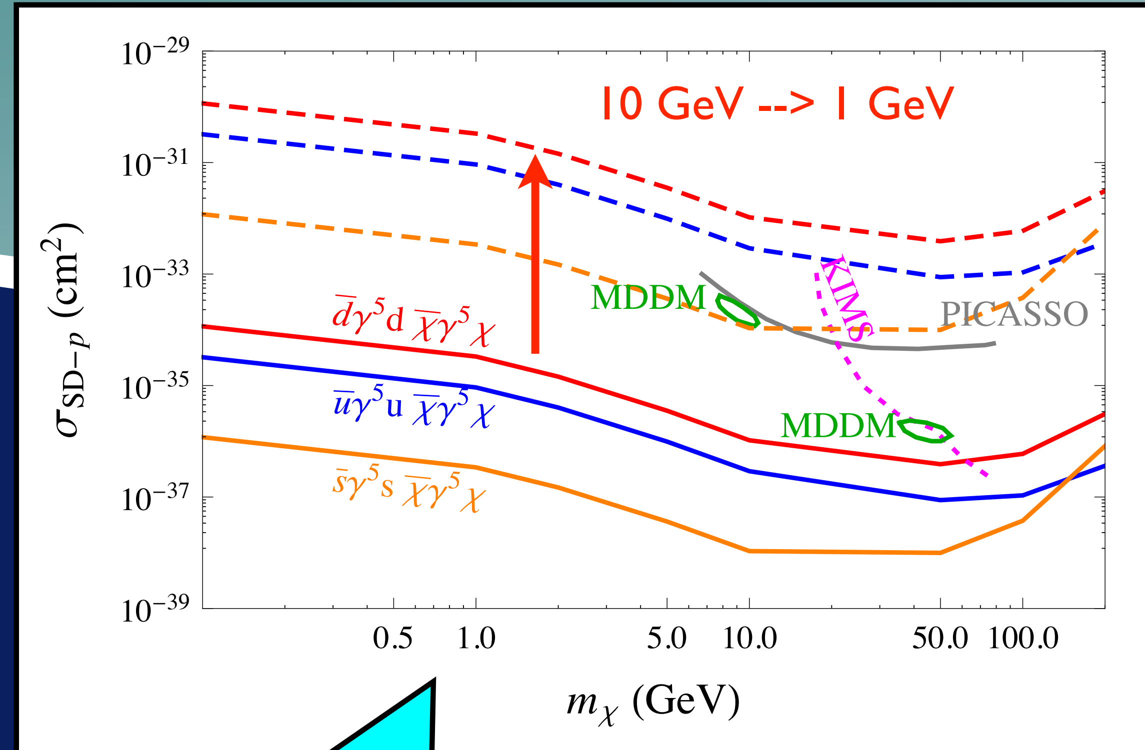


- For up- and down-quark couplings adjusted such that $f_n \sim -0.7\, f_p$, constraints from Xenon are much weaker than the CoGeNT signal.
- Naive MFV implementations are ruled out by colliders, but specific non-MFV constructions survive.

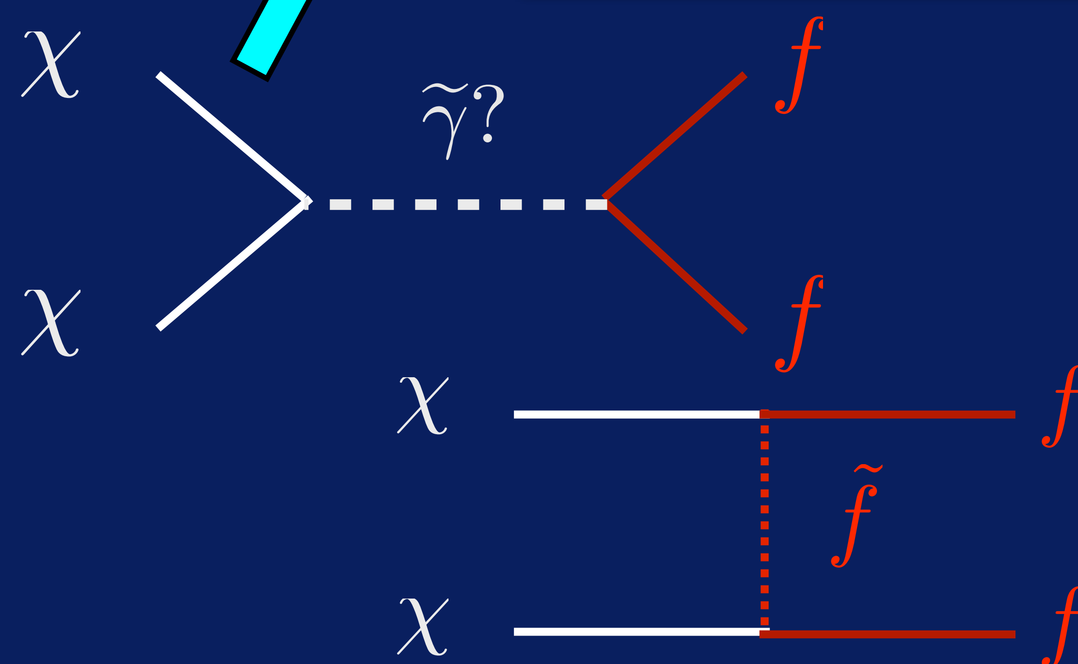
Feng, Kumar, Marfatia, Sanford 1102.4331 (see also: Chang, Pierce, Weiner 1004.0697)

UV Thoughts

- When the mediators are directly accessible to the collider, our conclusions become suspect.
  - This is most worrisome at colliders.
  - How this effects bounds depends a lot on the nature of the UV completion.
  - Light-mediator completions have much weaker bounds.
  - “SUSY-like” completions often have stronger bounds.

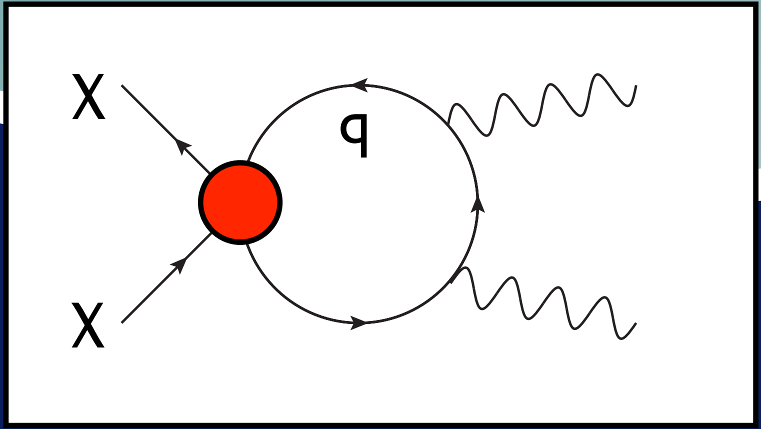


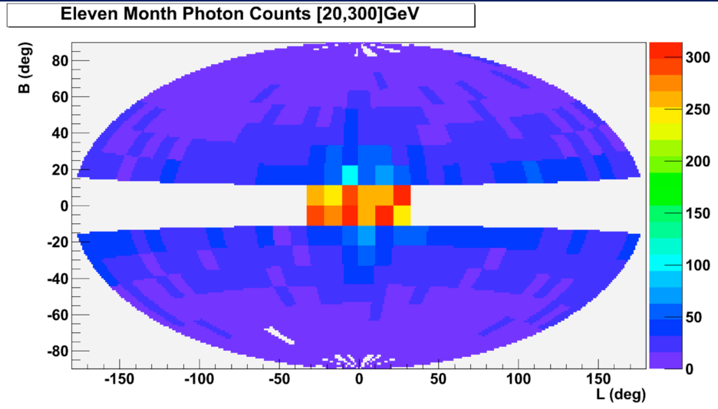
Bai, Fox, Harnik [1005.3797]

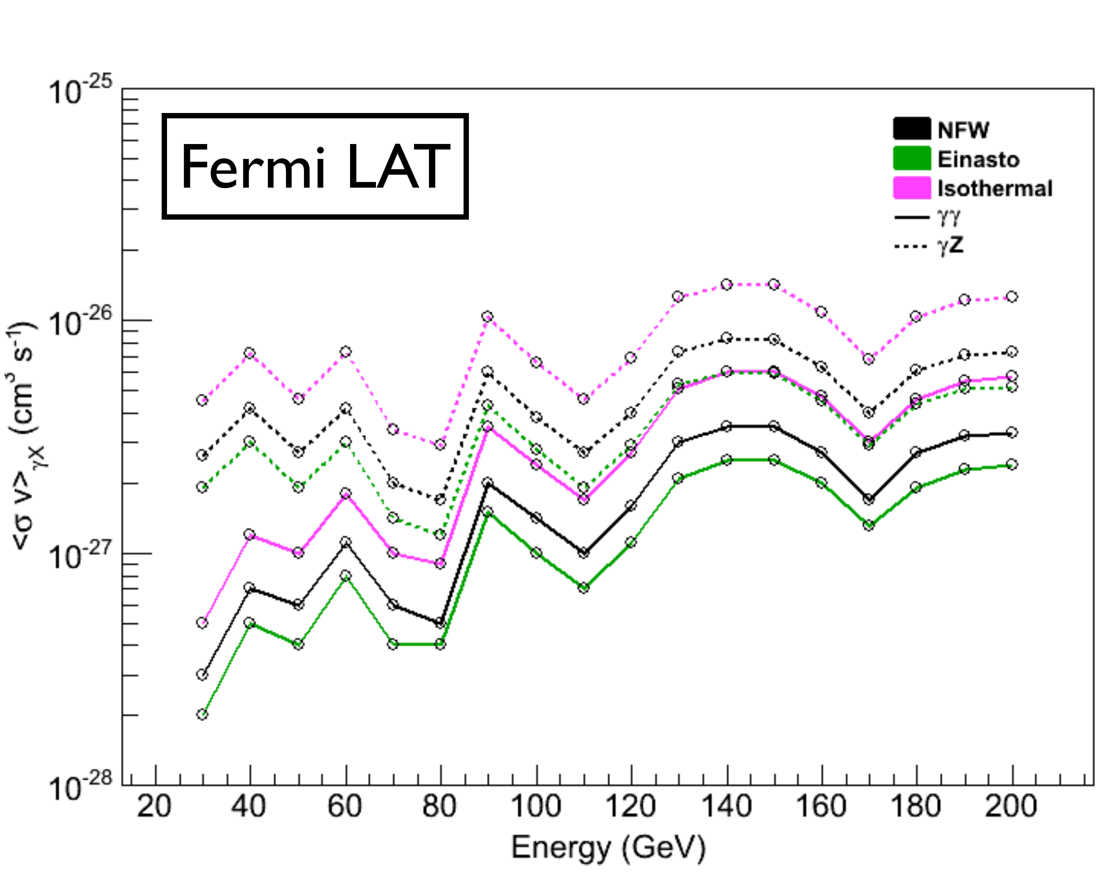


Line Limits from Fermi

- If we close our operators into a loop an attach photons, we have a process where two WIMPs annihilate producing mono-energetic gamma rays.
- Our operators have implications for the Fermi line search!
  - Bounds depend on the galactic distribution of dark matter.

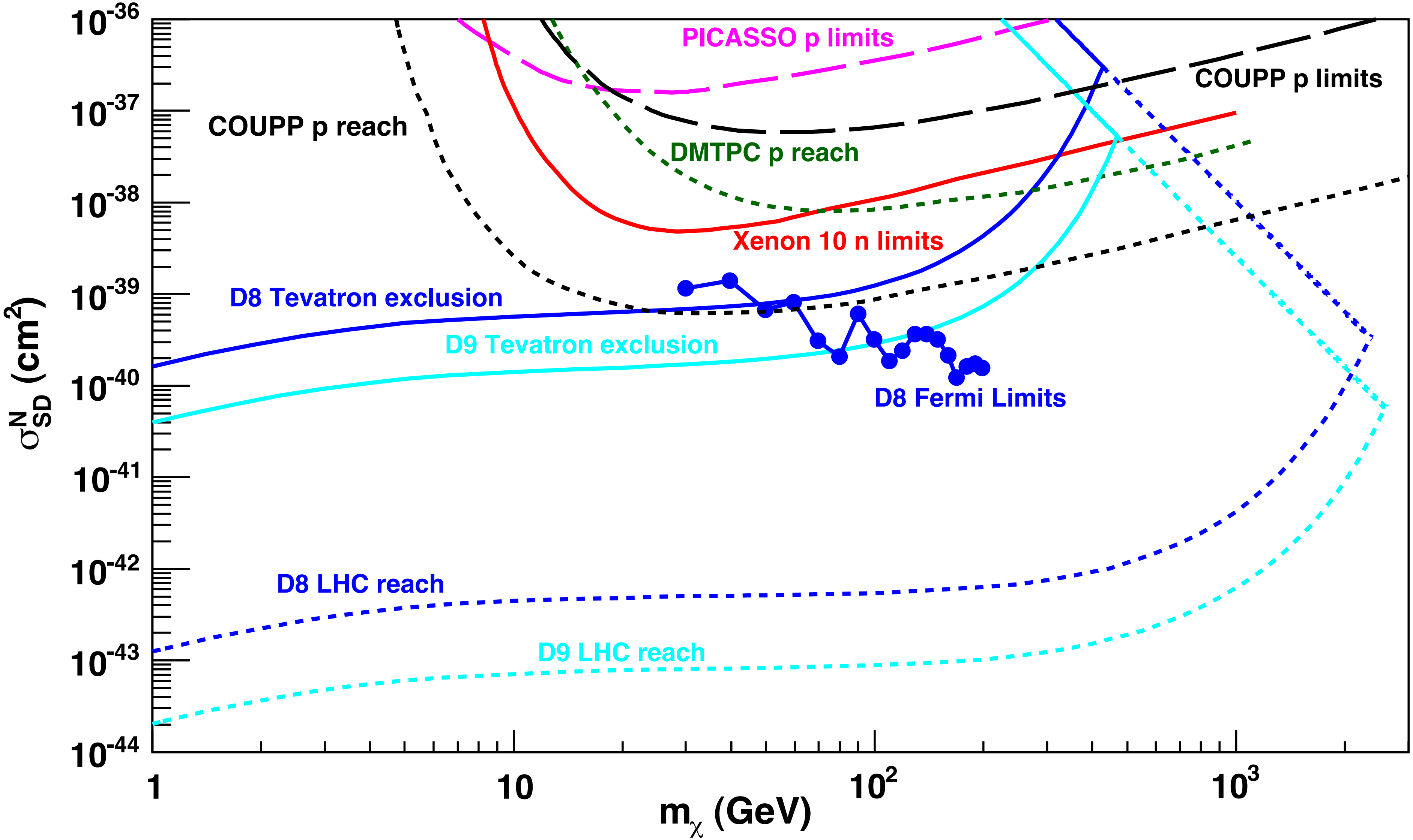




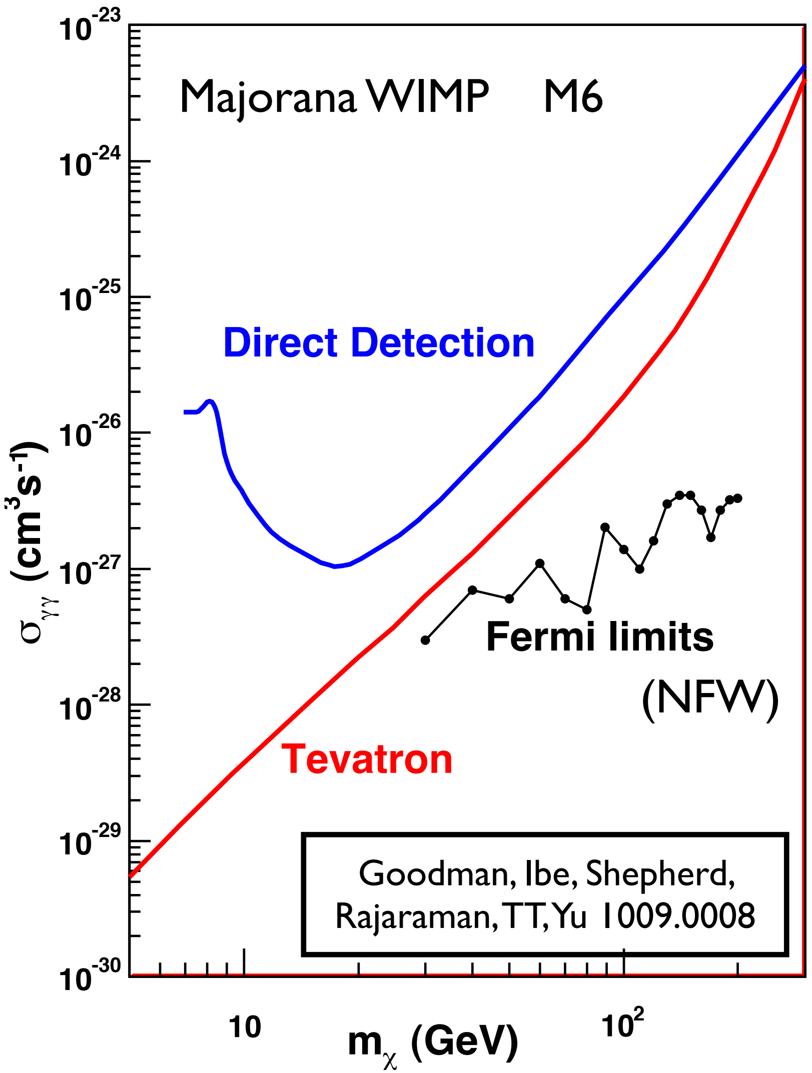


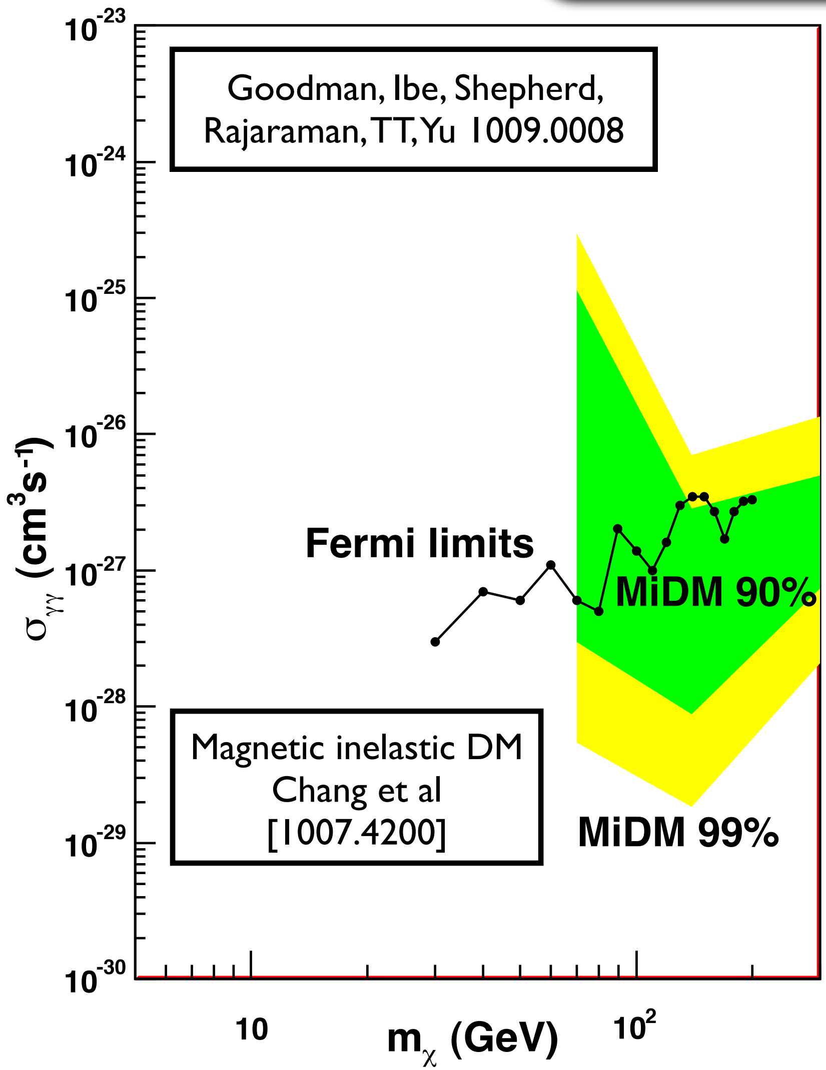
Spin-dependent

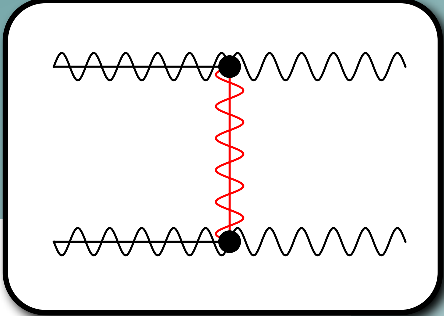
Dirac Fermion WIMP



Line Cross Section







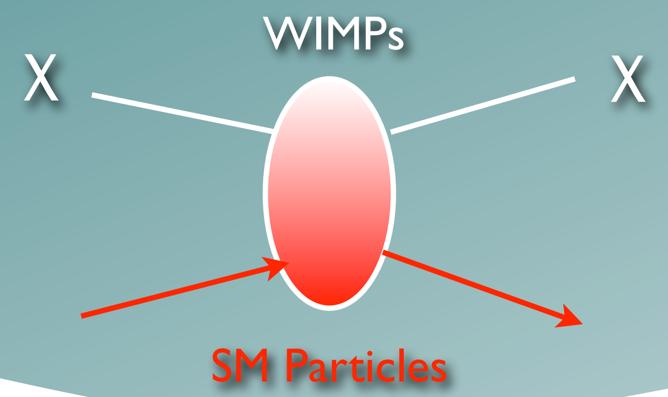
For LEP constraints on dipole-interactions, see: Fortin, TT 1002.3289

Outlook

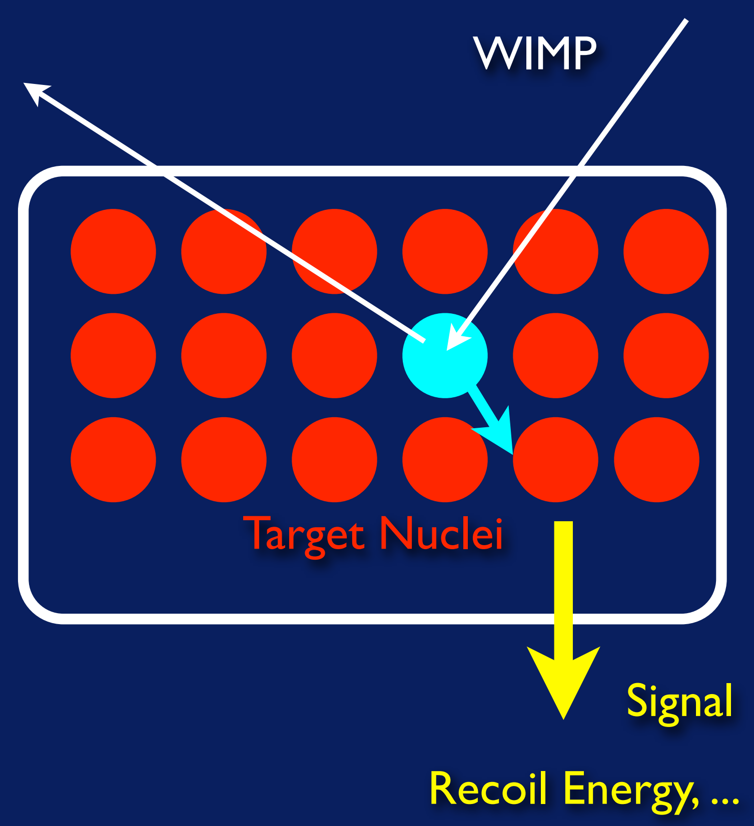
- Effective theories provide a model-independent language to describe the interactions of WIMPs with the Standard Model.
  - They provide a framework with which it makes sense to compare different kinds of experiments together.
  - They can only accurately capture theories whose mediating particles are somewhat heavier than the energies of interest.
- There is lots of potential for interplay between collider, direct, and indirect detection.
  - LHC searches for missing energy have deep implications for dark matter interactions with quarks and gluons.
  - Optimized searches may do somewhat better than reinterpreted ADD searches; but already the ADD searches are very promising!

Bonus Material

Direct Detection

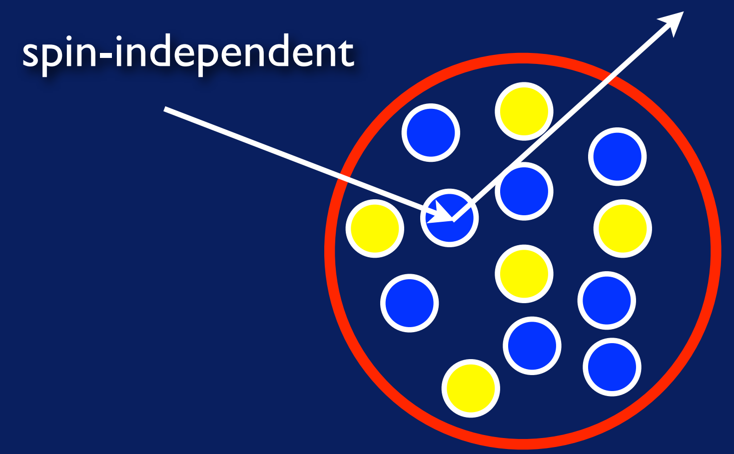


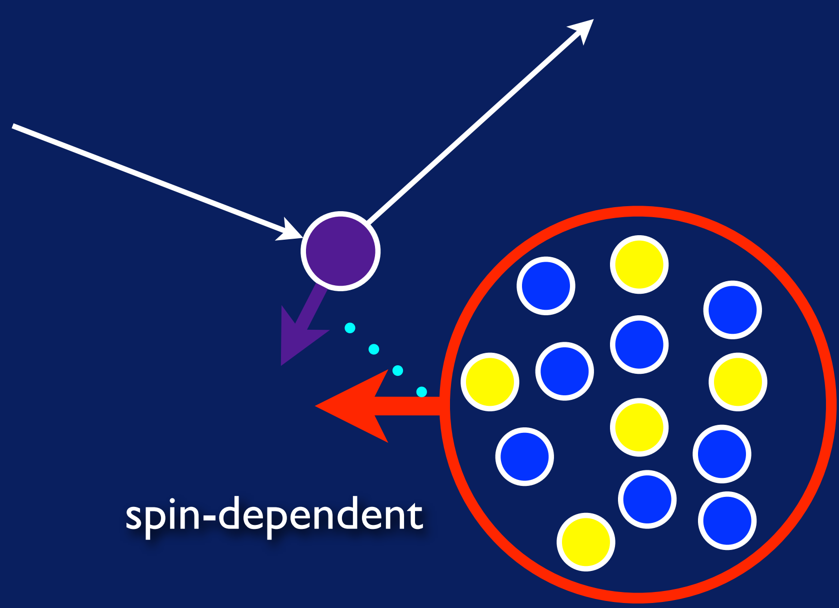
- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when a WIMP brushes against it.
- Direct detection looks for the dark matter in our galaxy's halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- These searches are rapidly advancing, with orders of magnitude improvements in sensitivity expected to take place within the next few years!



Collider to Direct Searches

- Since our effective theory describes precisely the interactions of WIMPs with quarks and gluons, we can translate our collider bounds into the direct detection plane.
- There are two distinct classes of direct detection searches to compare with:
  - Spin-independent (SI) scattering looks for direct scattering of the WIMP from the nucleons in the nucleus.
  - Spin-dependent (SD) scattering looks for interactions coupling the WIMP's spin to the nuclear spin.





An EFT for Dark Matter

- To construct an effective theory description of a WIMP:
  - We start with the Standard Model.
  - We add a dark matter particle, choosing a spin and electroweak representation.
    - (For simplicity, we start by choosing a gauge singlet with no direct electroweak interactions).
  - We add interactions with quarks and gluons, consistent with the exact symmetries of the SM: Lorentz and SU(3) x U(1)$_{EM}$ gauge invariance.
  - To simplify things, we group quark operators together in a way which minimizes constraints from flavor and CP violation.

$$\sum_q m_q \bar{q} q$$

$$\sum_q m_q \bar{q} \gamma_5 q$$

$$\sum_q \bar{q} \gamma^\mu q$$

$$\sum_q \bar{q} \gamma^\mu \gamma_5 q$$

$$\sum_q \bar{q} \sigma^{\mu\nu} q$$

Dirac WIMPs

- We can repeat this exercise for other choices of WIMP spin.
- For a Dirac WIMP, we have a few more Lorentz structures, such as the vector and tensor combinations.
- On top of the operators we had for the Majorana WIMP, magnetic and electric dipole moment operators are possible as well.
- For a Dirac WIMP, we assume (where it matters) that the galactic halo is equal numbers of WIMPs and anti-WIMPs.

"Asymmetric" dark matter would also be interesting!

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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

Spin Zero WIMPs

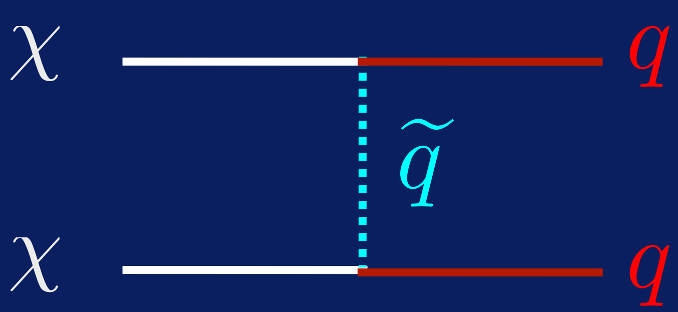
- We can play the same game with scalar WIMPs, both real (R) and complex (C).
- Vector interactions of a real WIMP can be rewritten using the equations of motion in terms of scalar operators.
- As with the Dirac WIMPs, we assume a complex scalar WIMP is not asymmetric -- the dark matter of the Universe is composed of equal amounts WIMPs and anti-WIMPs.

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

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	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

Limits of Effective Theory

- Effective theories describe the leading term in the low energy expansion of the full theory.
  - That's why many different high energy theories lead to the same effective theory description.
- As we approach energy transfers comparable to the mass of the exchanged particle, we need to include higher terms in the series.
- At energies much higher than the mass of the exchanged particle, we can produce it directly.
- At that point, we need the complete ultraviolet theory to describe the physics.



$$\sim \frac{g^2}{p^2 - M^2}$$

$$= -\frac{g^2}{M^2}\left(1 + \frac{p^2}{M^2} + \dots\right)$$

$$\equiv G_{eff}\left(1 + \frac{p^2}{M^2} + \dots\right)$$

LHC

1002.4137

- To estimate the LHC sensitivity we rely on the ATLAS search for jets + missing energy:

  Vacavant, Hinchliffe, J Phys G 27, 1839 (2001)

  - Missing ET > 500 GeV
- Vetoing extra jets is counter-productive at the LHC.
- Since we are interested in the eventual reach of the LHC, we assume 14 TeV and 100 fb^{-1}.
- It would be interesting to see what the LHC can say for 7 TeV and ~ 1 fb^{-1}!