Effective Theories of Dark Matter

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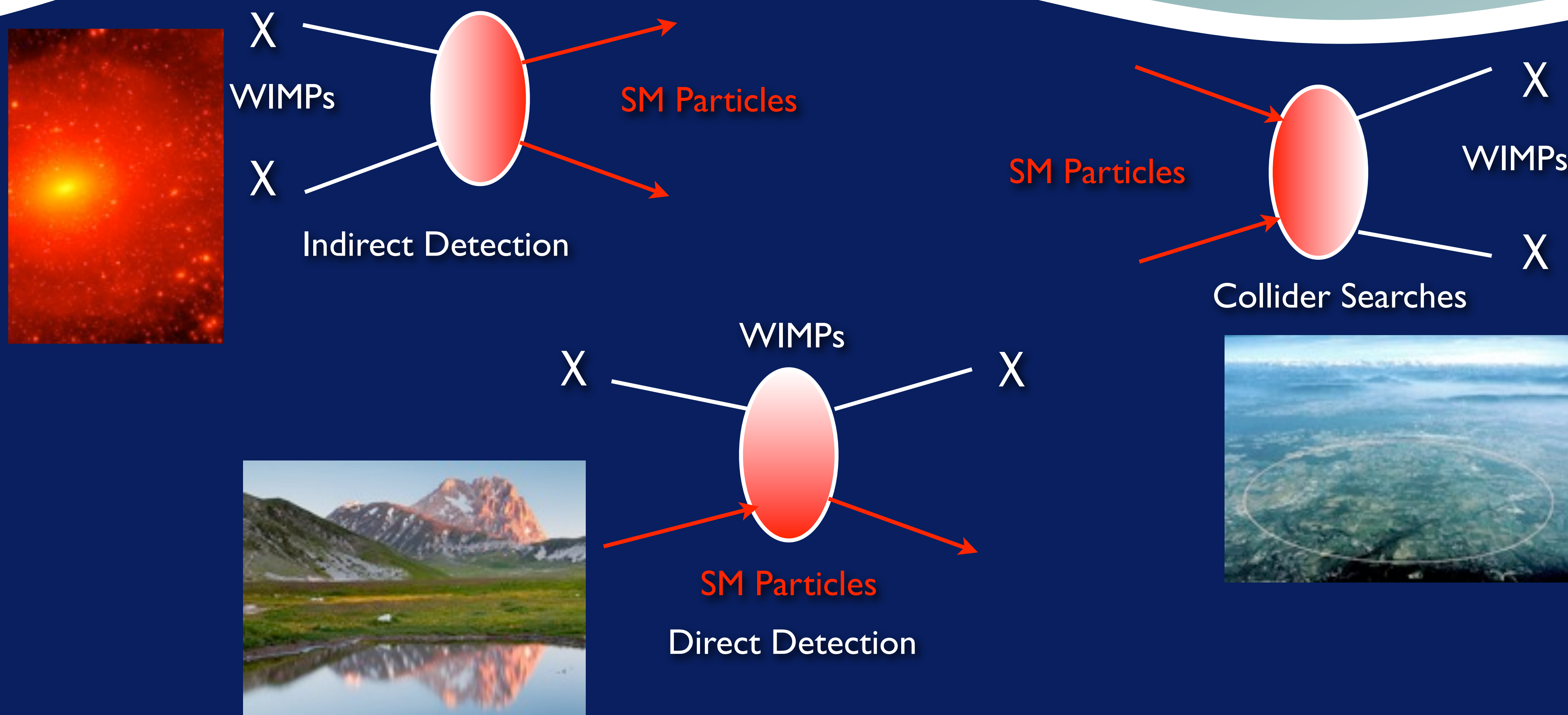
Beltran, Hooper, Kolb, Krusberg, TT, [1002.4137] & JHEP
Goodman, Ibe, Rajaraman, Shepherd, TT, Yu, [1005.1286] & PLB, [1008.1783] & PRD, and [1009.0008] & NPB.

Aspen Winter
February 10, 2011

Outline

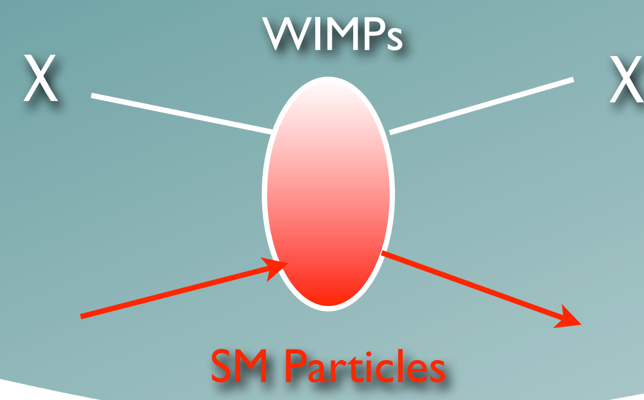
- Motivation: "Generic descriptions" of WIMP-Standard Model Interactions
- Interplay between Experiments
  - Effective Theory Description of Dark Matter Interactions
  - The Impact of Collider Searches on Direct Detection
  - Fermi Line Search
- Outlook

WIMP Searches

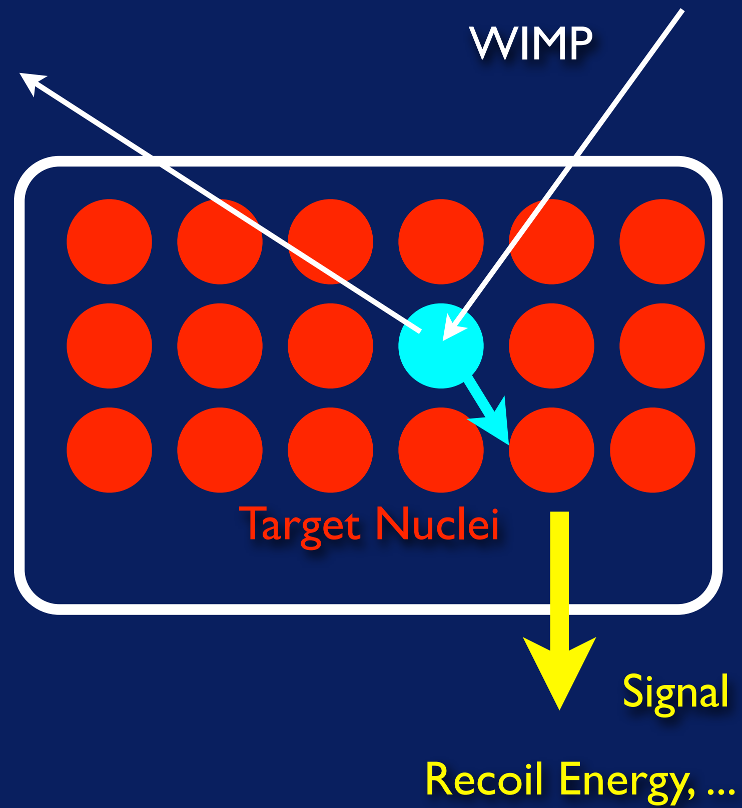


- WIMPs interacting with SM particles allow indirect searches for annihilation products, direct scattering searches, and production at colliders.

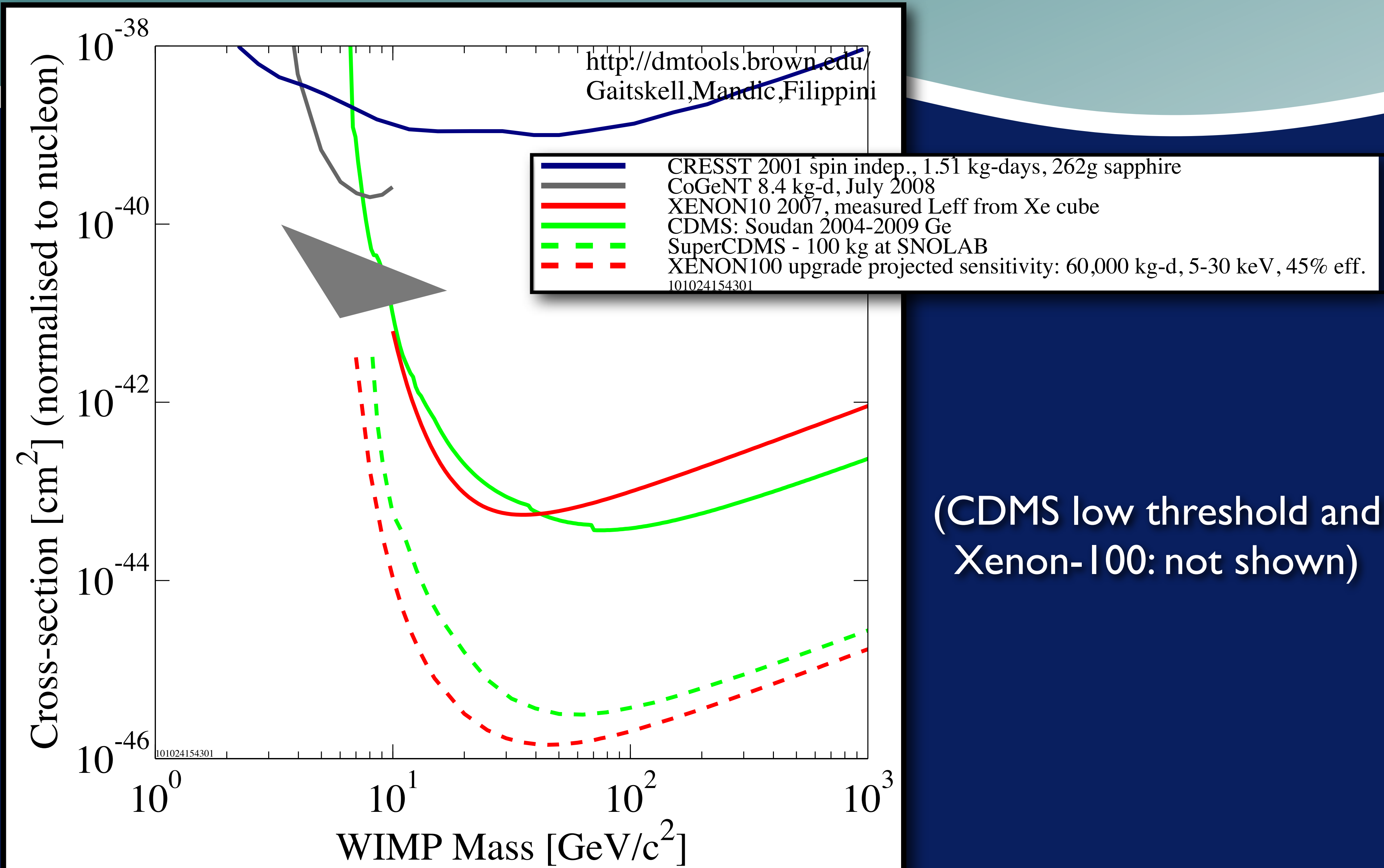
Direct Detection



- 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!



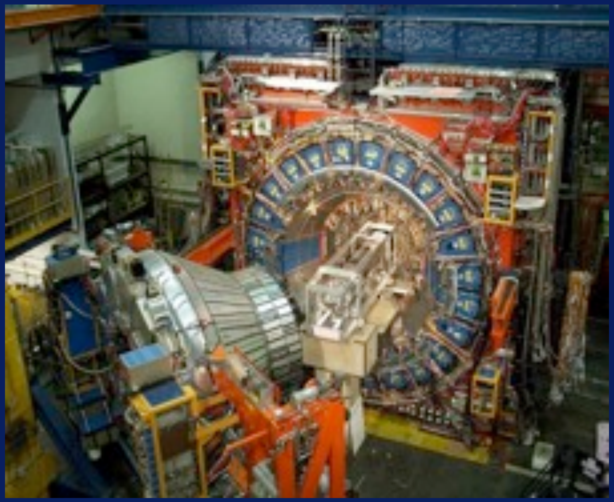
Direct Detection Results



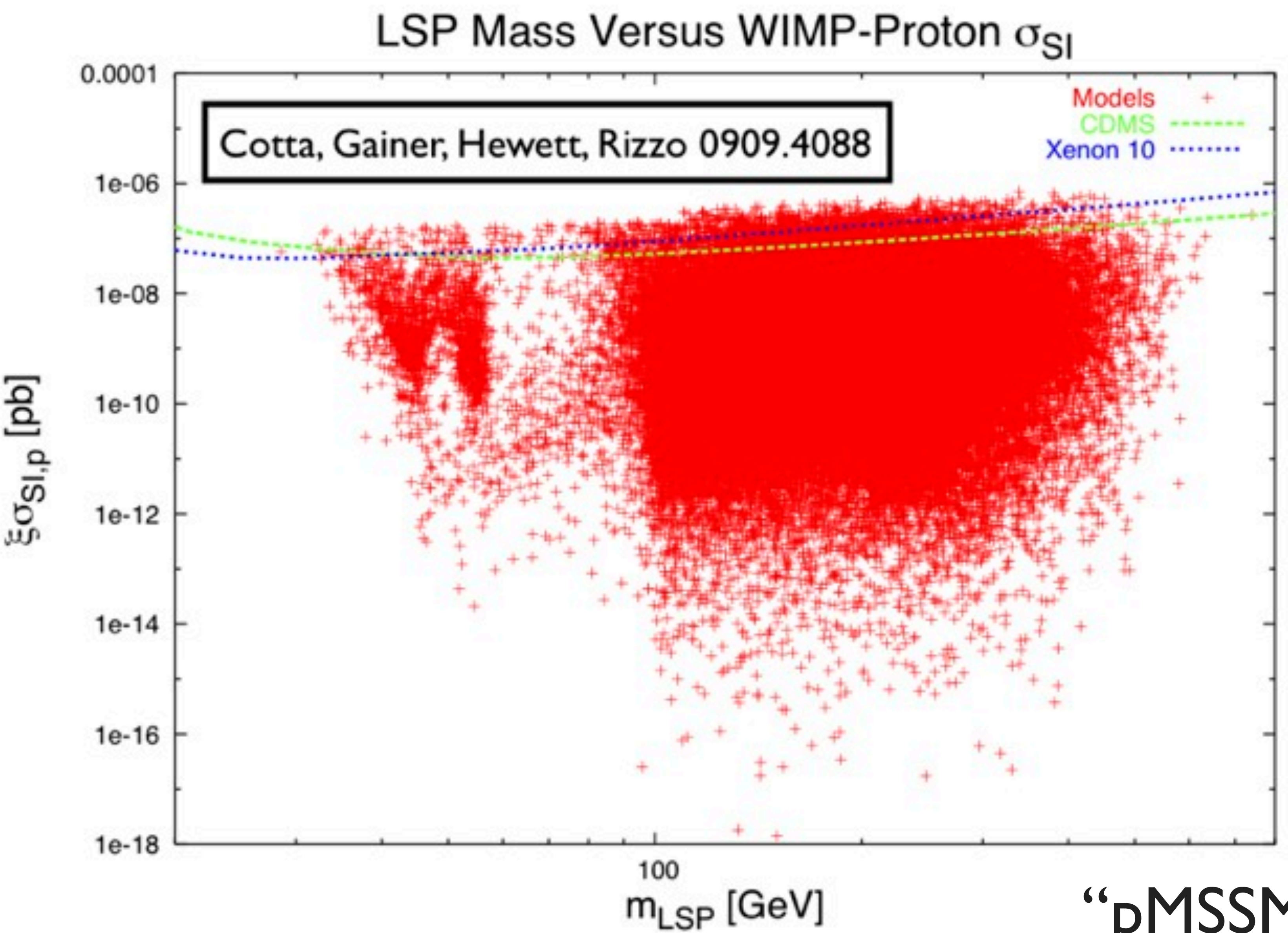
(CDMS low threshold and Xenon-100: not shown)

Other Experiments?

- Direct detection probes WIMP couplings to nucleons (quarks and gluons).
- This raises an important question:
    - **Why are there no bounds from colliders or indirect searches on the direct detection 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 should be able to produce them in high energy collisions of protons.



MSSM

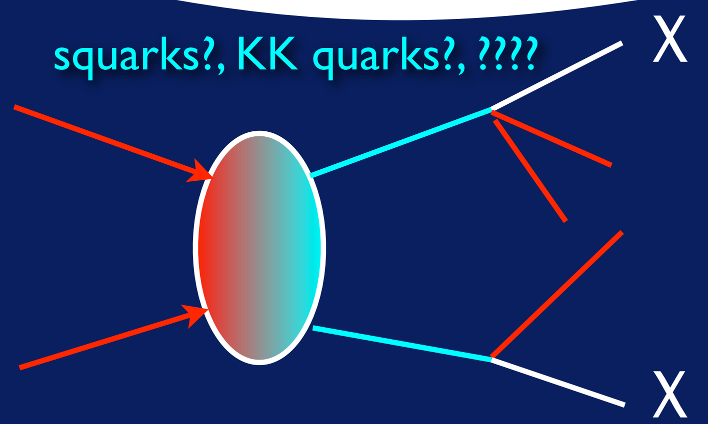


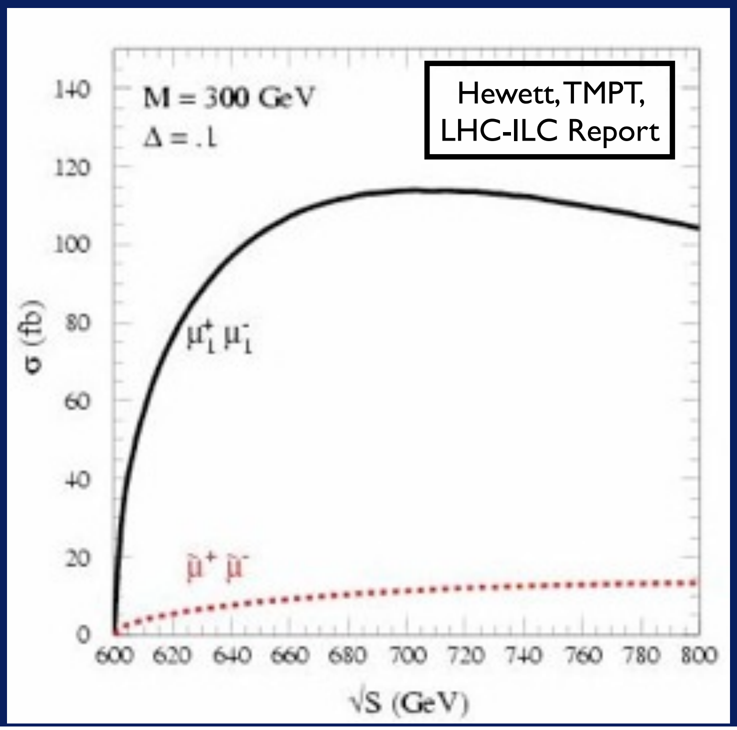
LSP Mass Versus WIMP-Proton σ_{SI}
Cotta, Gainer, Hewett, Rizzo 0909.4088
Models
CDMS
Xenon 10
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
1e-18
$\xi\sigma_{SI,p}$ [pb]
100
m_{LSP} [GeV]

"pMSSM"

Beyond Supersymmetry

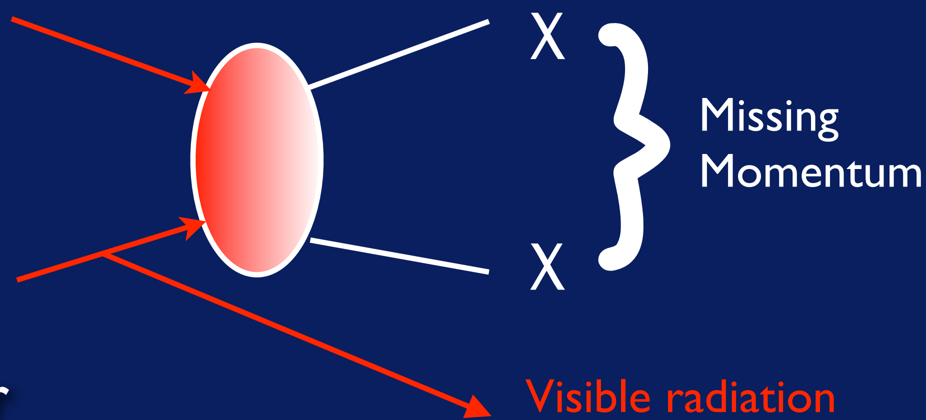
- The main reason why collider searches don't show up on this plot is that one needs to make additional assumptions to put them there.
- The *usual* way to search for WIMPs at colliders is to produce some of the other particles in the dark matter theory, and then watch them decay into WIMPs (as well 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.





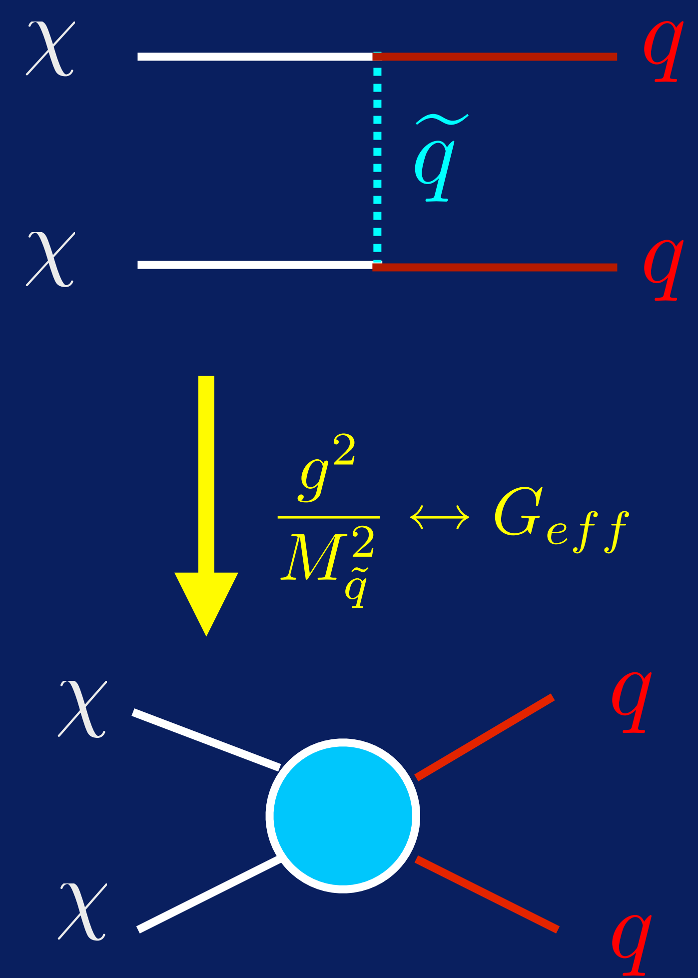
Maverick WIMPs

- 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

- Effective Field theories are a powerful tool to describe physics at a particular energy scale.
- Only the degrees of freedom relevant at the energy scale at hand are included in the description. Heavier particles are "integrated out".
- Theories which look very 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 effective theories describing WIMP interactions.



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 interactions.
    - (For simplicity, we start by choosing 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.

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

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

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

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

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

Example EFT: Majorana WIMP

- As an example, we can write down the 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	-

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

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

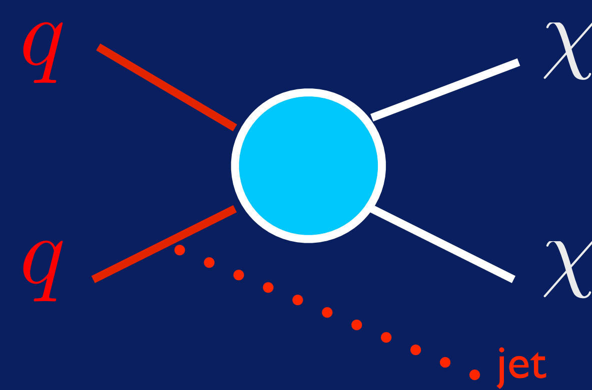
Other operators may be rewritten in this form by using Fierz transformations.

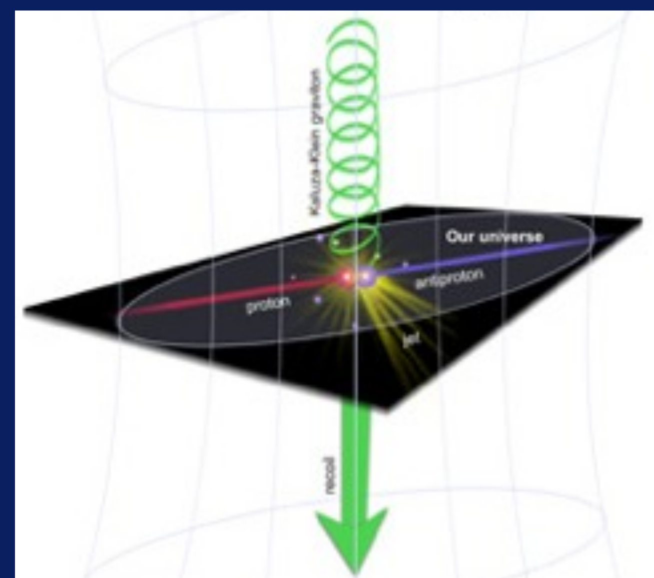
CDF Search

- The **C**ollider **D**etector at **F**ermilab has already performed a search for our signature.
- They were not actually searching for dark matter, but for a kind of theory with large extra dimensions.
- In this theory, gravity becomes strong at the TeV scale and high energy collisions produce gravitons which escape into the extra dimension.

CDF, 0807.3132

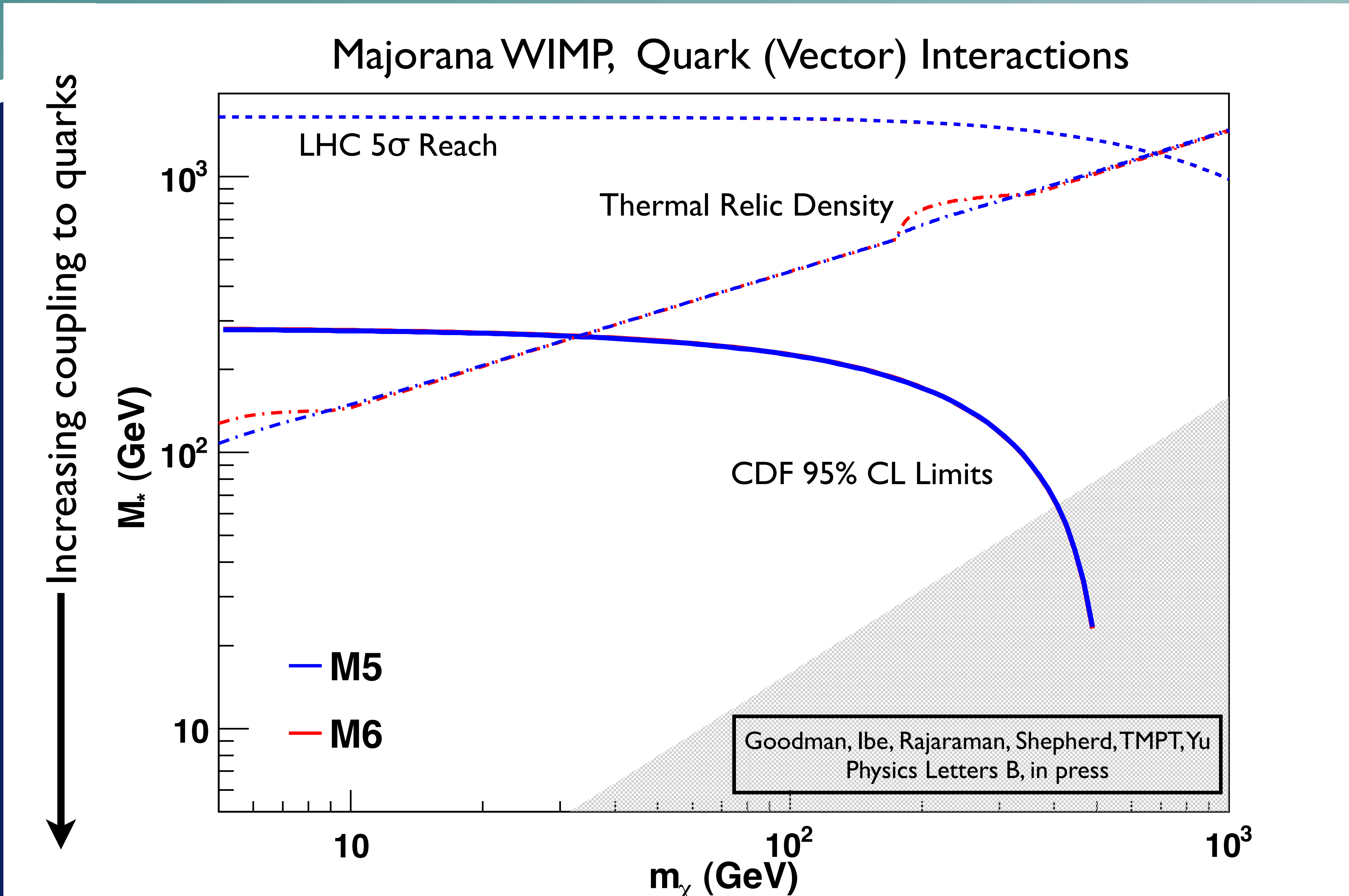
- Having escaped our four dimensional world, the gravitons look like missing energy.
- I'll reinterpret their results to learn something about WIMPs!



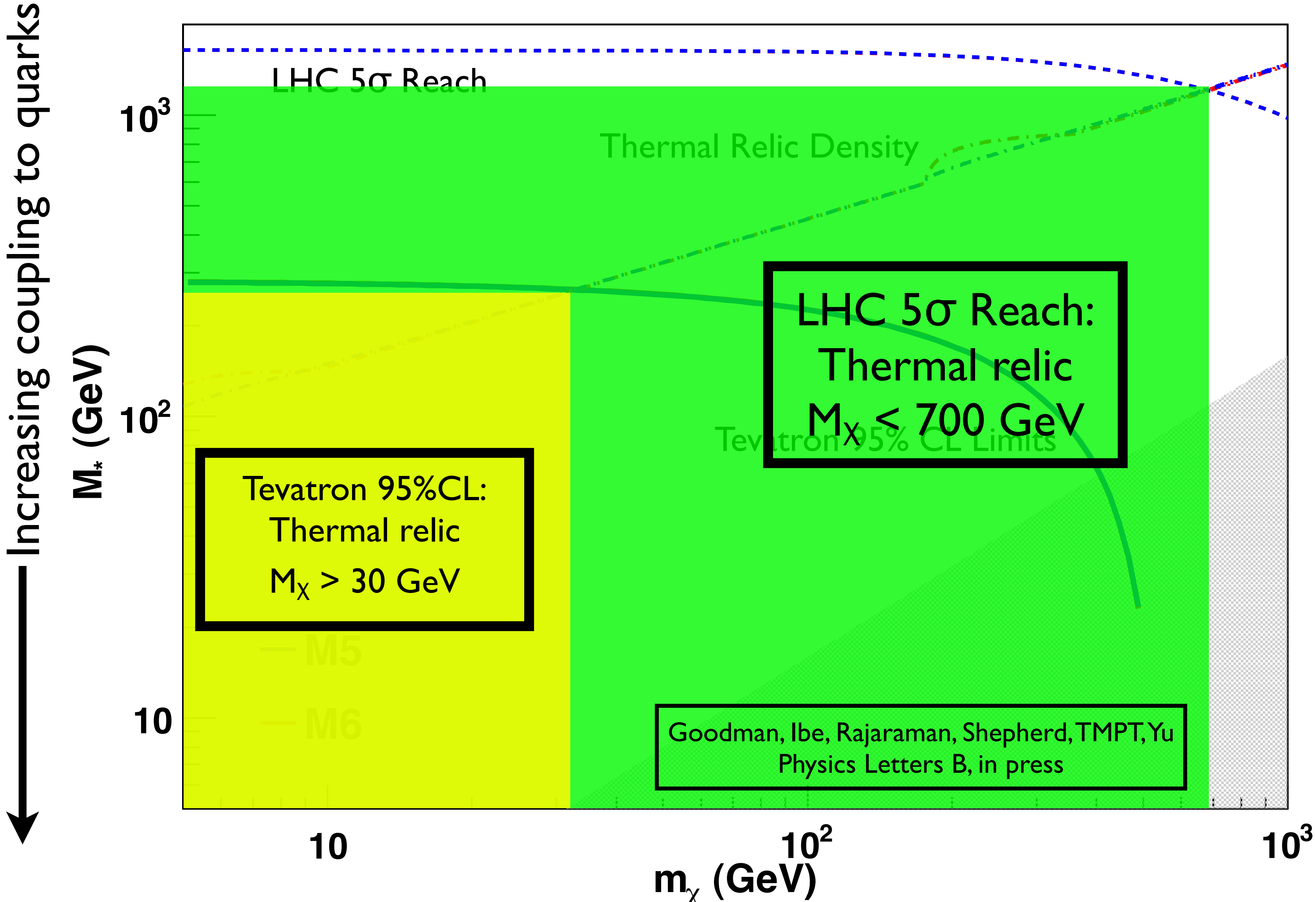


Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

Example of Limits/Sensitivity



Example Limits/Sensitivity



Axial-vector Coupling

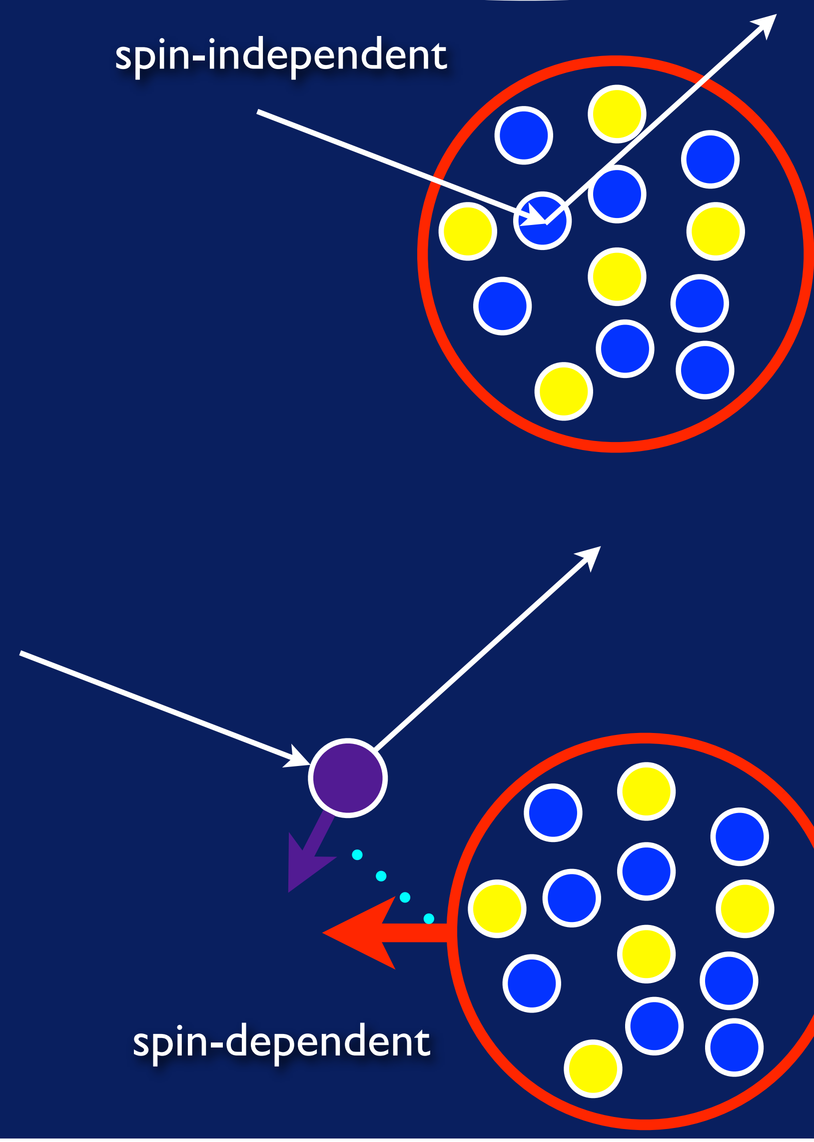
- These operators were particularly amenable to collider searches.
  - They both lead to velocity suppressed WIMP annihilation cross sections.
  - The relic density requires that they have somewhat strong coefficients to over-come the velocity suppression.
- The collider signal produces the WIMPs relativistically, 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	-

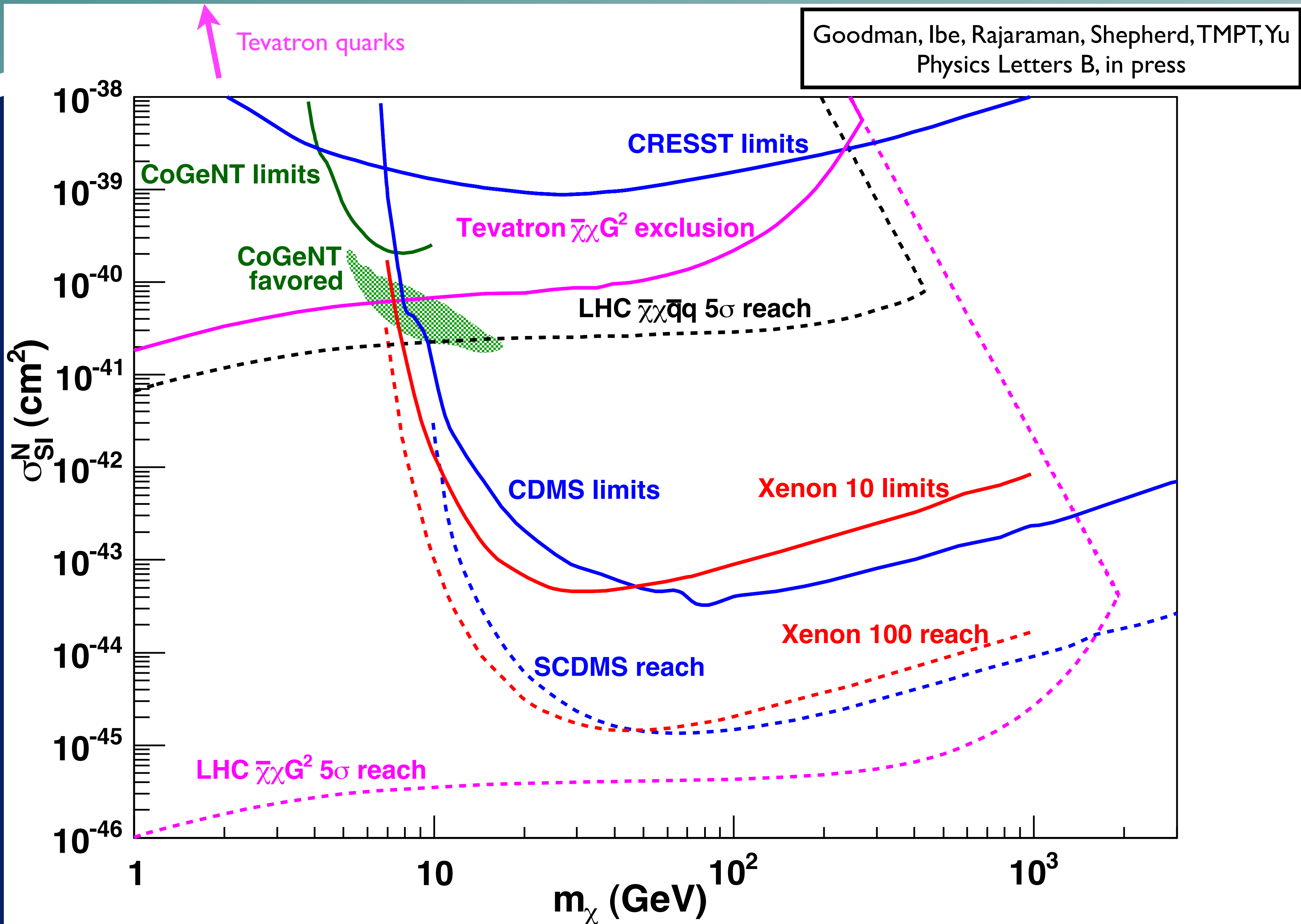
We can make similar plots for any combination of WIMP spin and operator. (And we did.)

Collider to Direct Searches

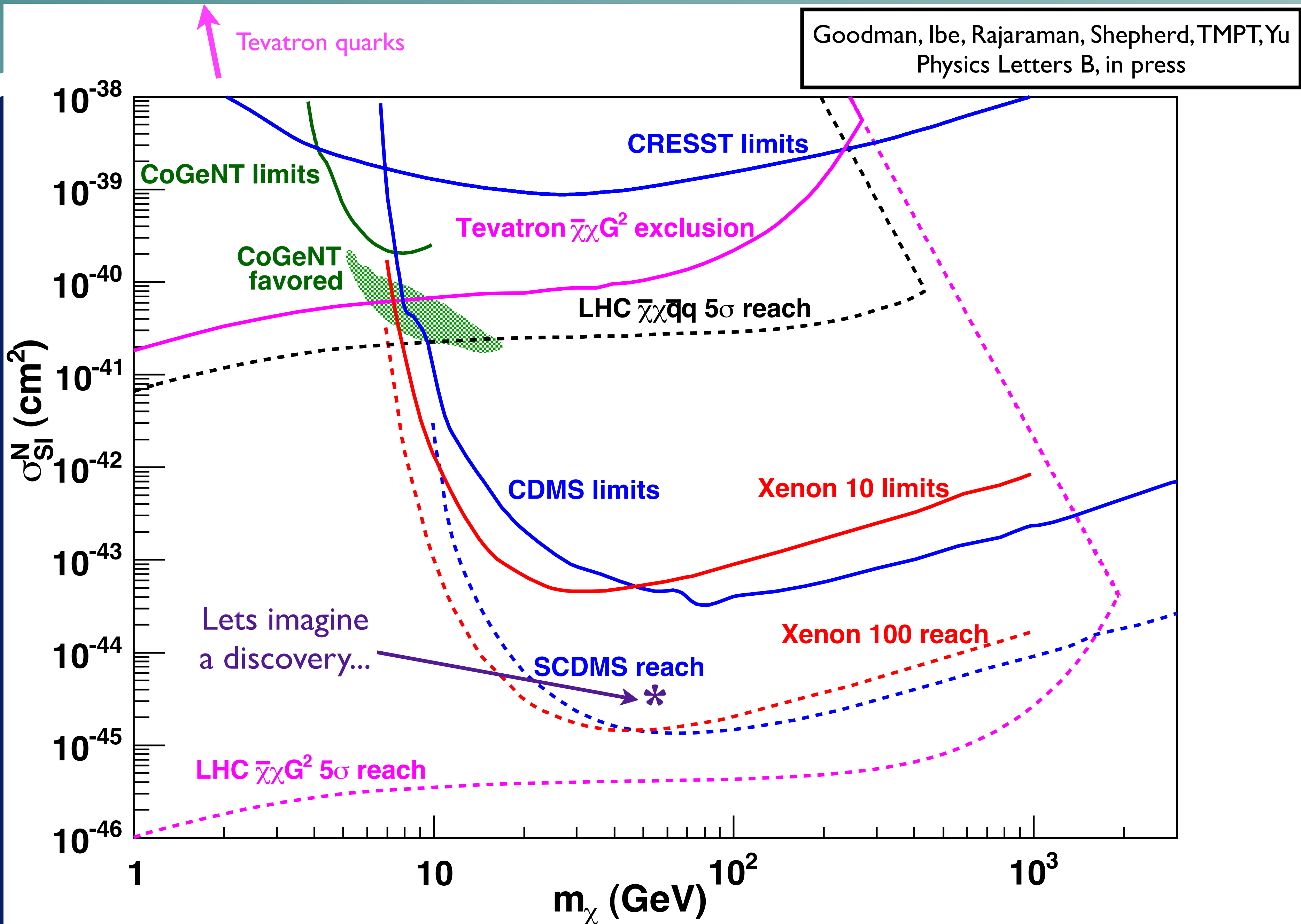
- Since our effective theory describes precisely the interactions of WIMPs with quarks and gluons, we can translate our collider bounds into the direct detection plane.
- There are two distinct classes of direct detection searches to compare with:
  - Spin-independent (SI) scattering looks for direct 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.



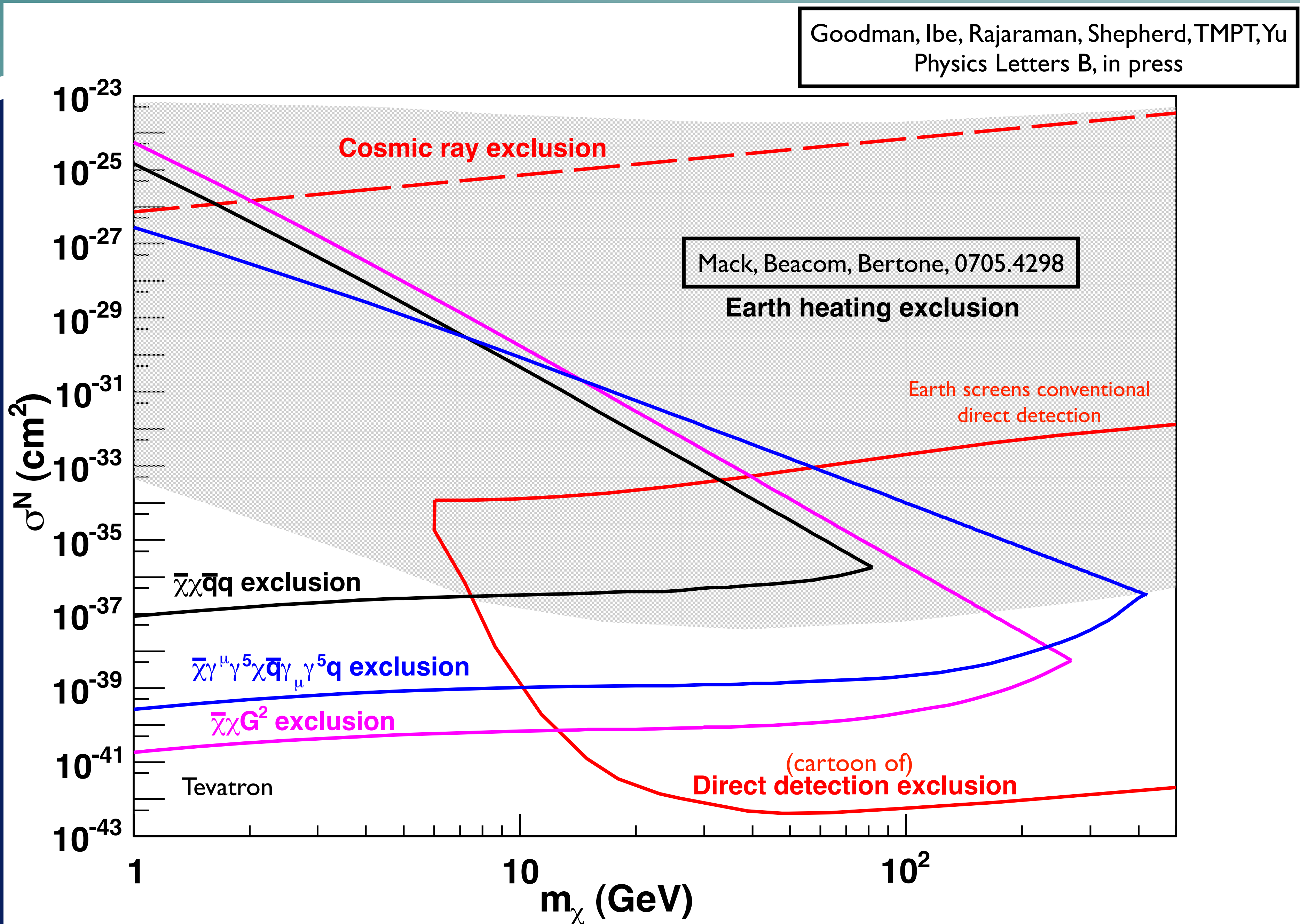
Spin-Independent



Spin-Independent

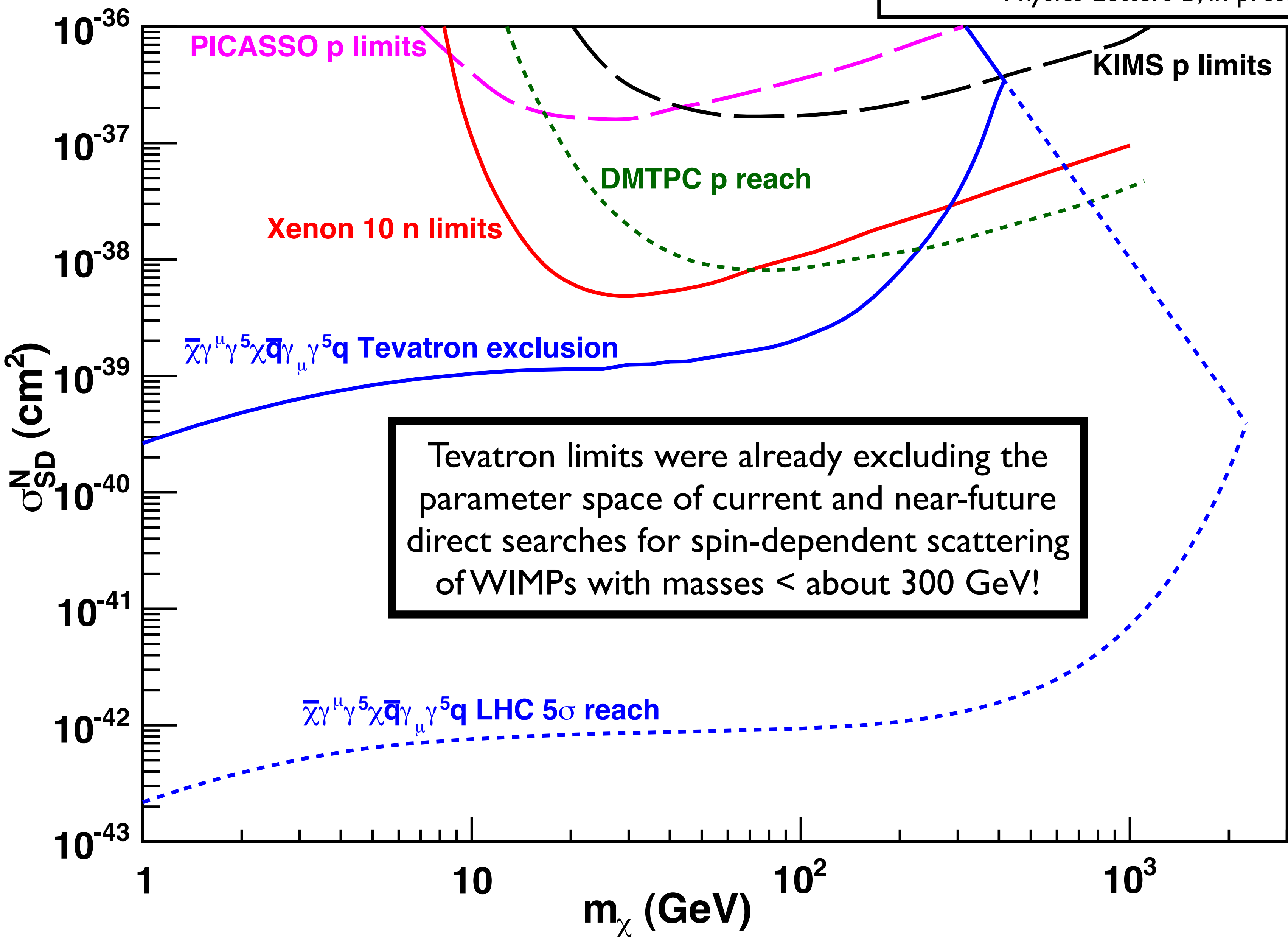


SI: Zoomed Out



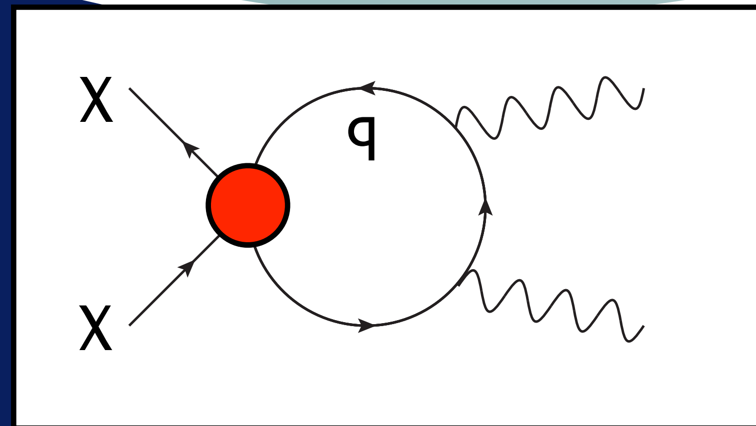
Spin-Dependent

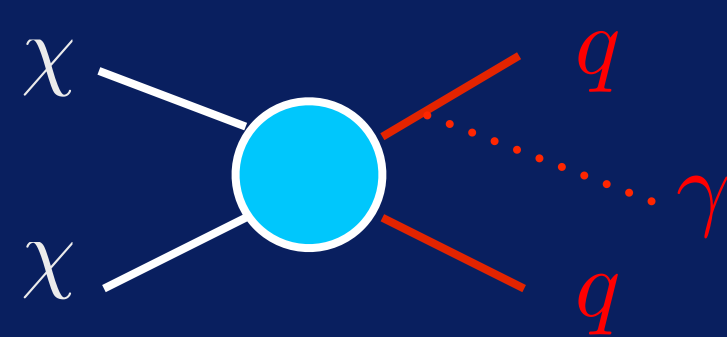
Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu
Physics Letters B, in press



Gamma Ray Lines

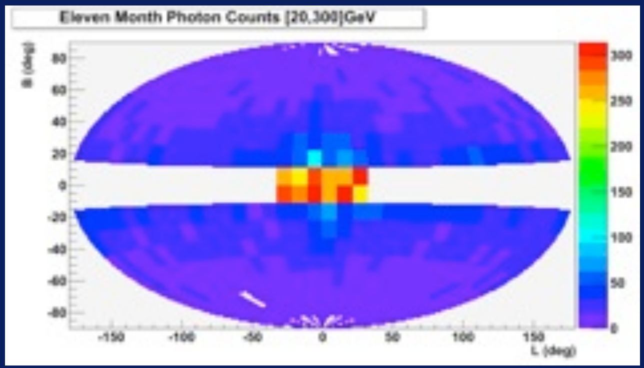
- We can also map our operators at one loop into predictions for WIMPs annihilating into γγ or γZ.
- One could also look for the continuum photons from WIMP annihilations, but the lines are a striking feature which are invaluable in light of astrophysical backgrounds.
  - We decided to use the line analysis as a starting point because it is a very clean analysis.
- Theoretically, it is actually easier to look at continuum gamma rays from tree level processes.

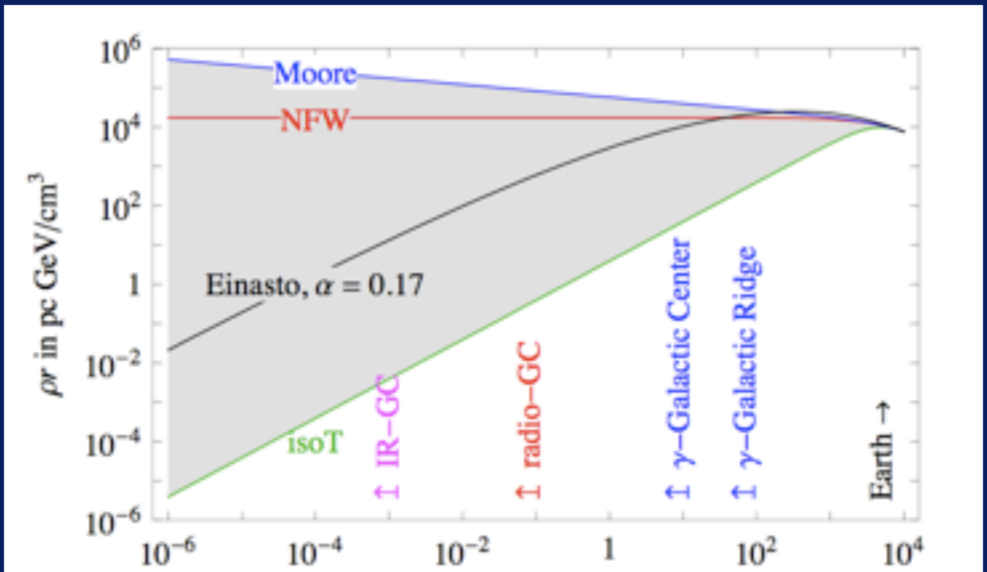




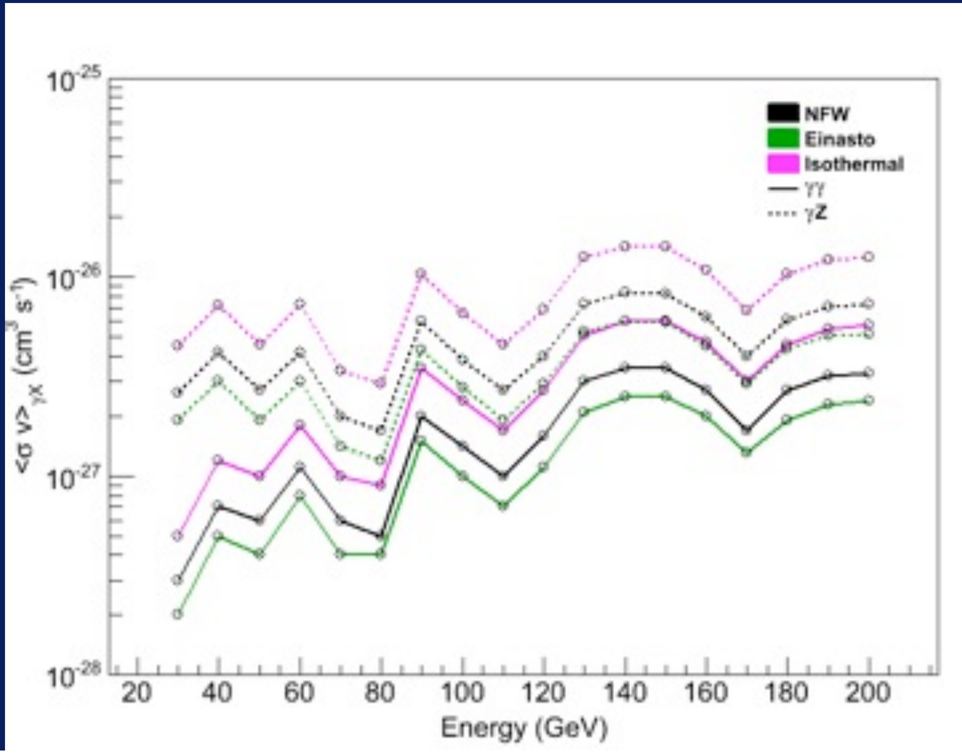
Line Limits from Fermi

- As we already saw earlier this week, Fermi uses a “shape analysis” to derive cross section limits for gamma ray lines for various choices of dark matter profile.
- We’re discussing mapping a wider variety of searches into EFT language.



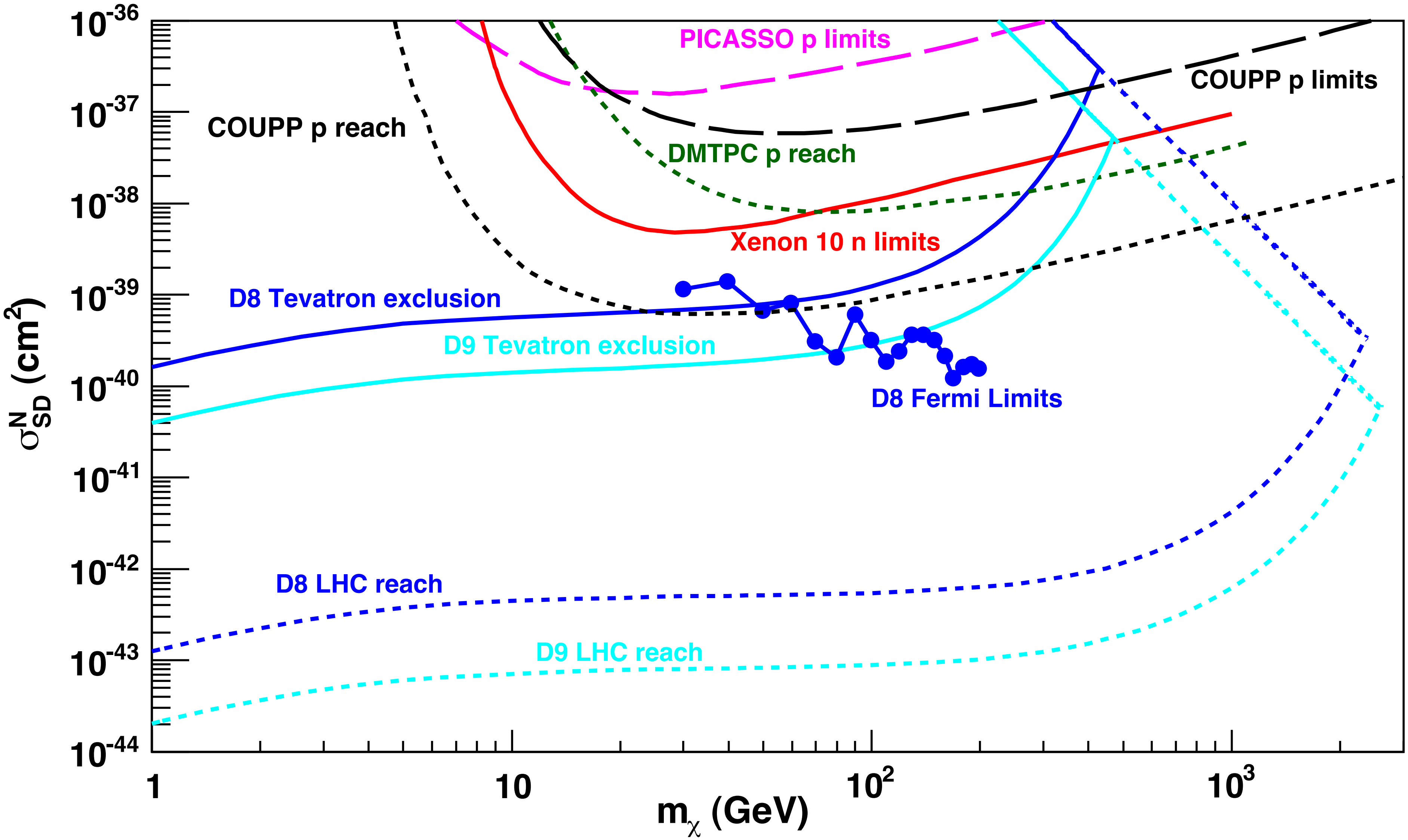


Bertone et al., ’08

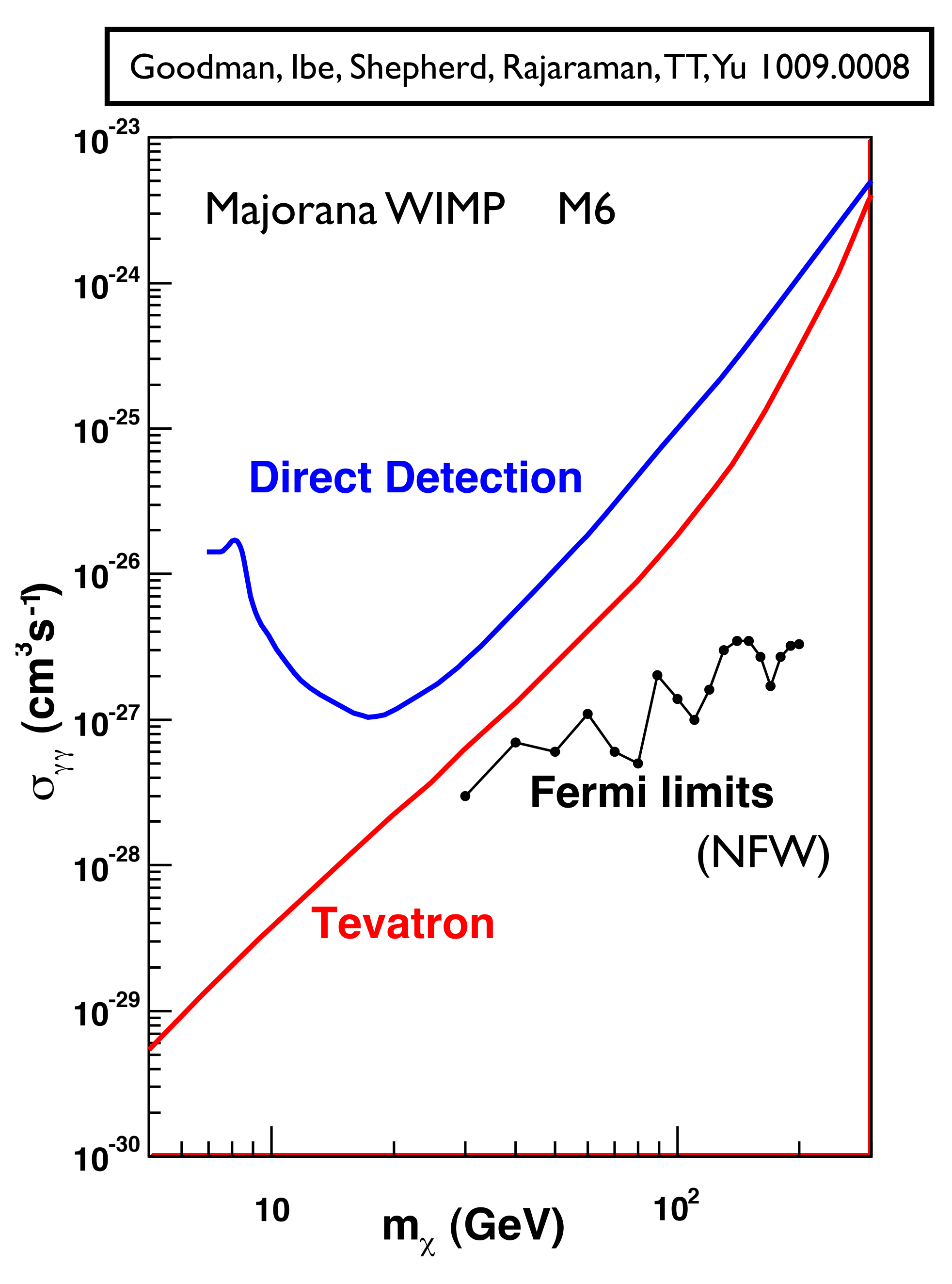


Spin-dependent

Dirac Fermion WIMP



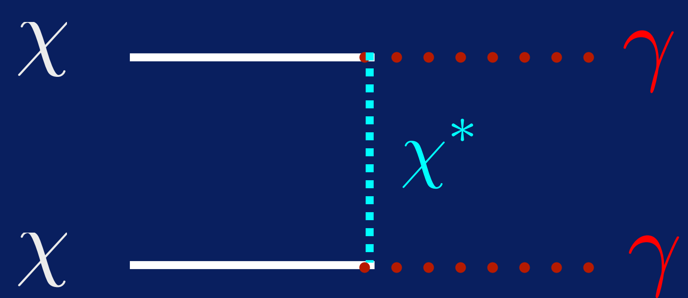
Line Cross Section

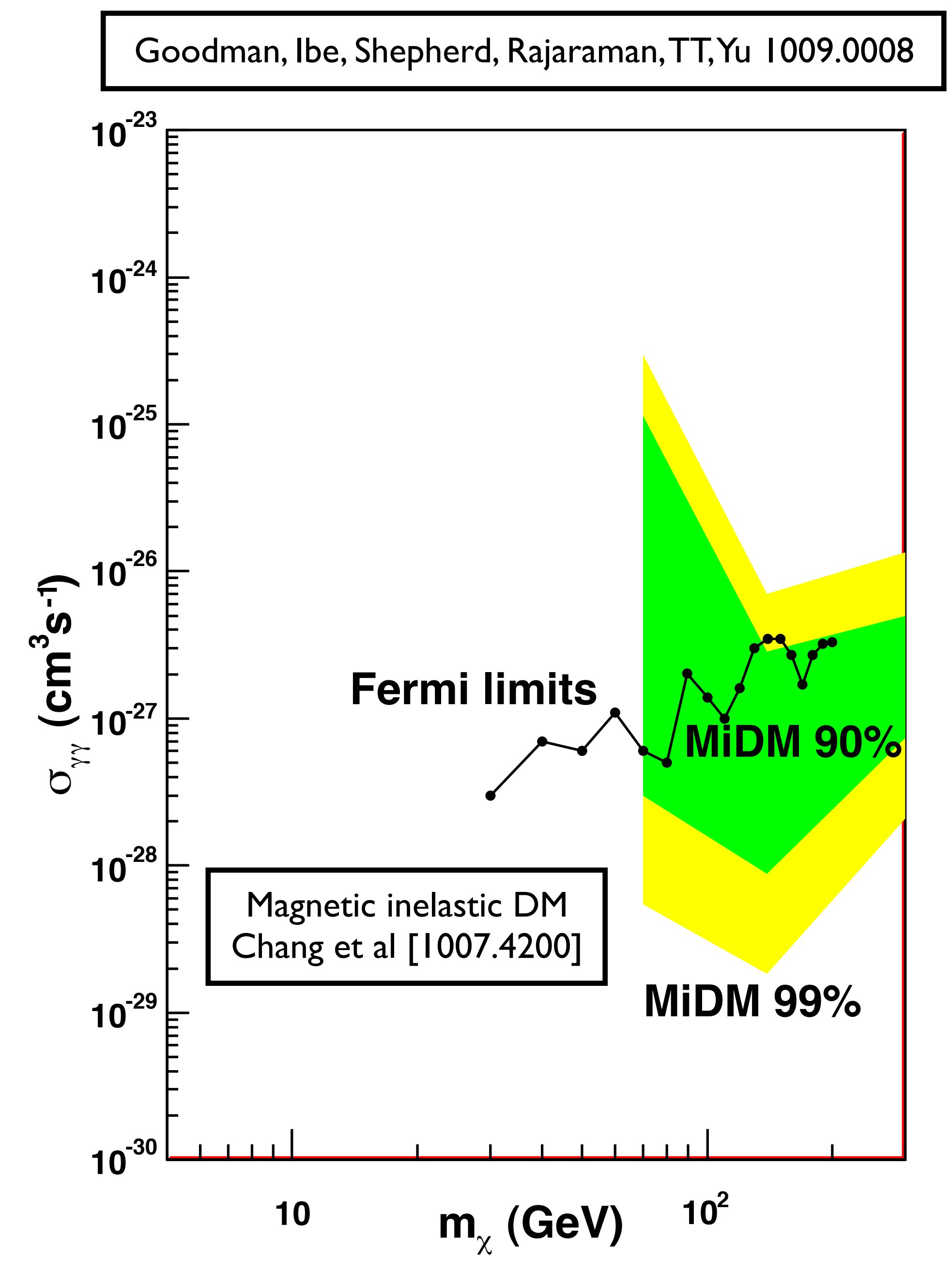


- We can just as easily express the results in terms of, say, the γγ cross section.
- Even for a very conservative iso-thermal profile, Fermi can provide what are currently the best limits on axial vector interactions for the range of WIMP masses to which Fermi is sensitive.
- Tevatron bounds are strongest at masses below Fermi's line limits.
- For larger WIMP masses, direct detection wins.

MiDM

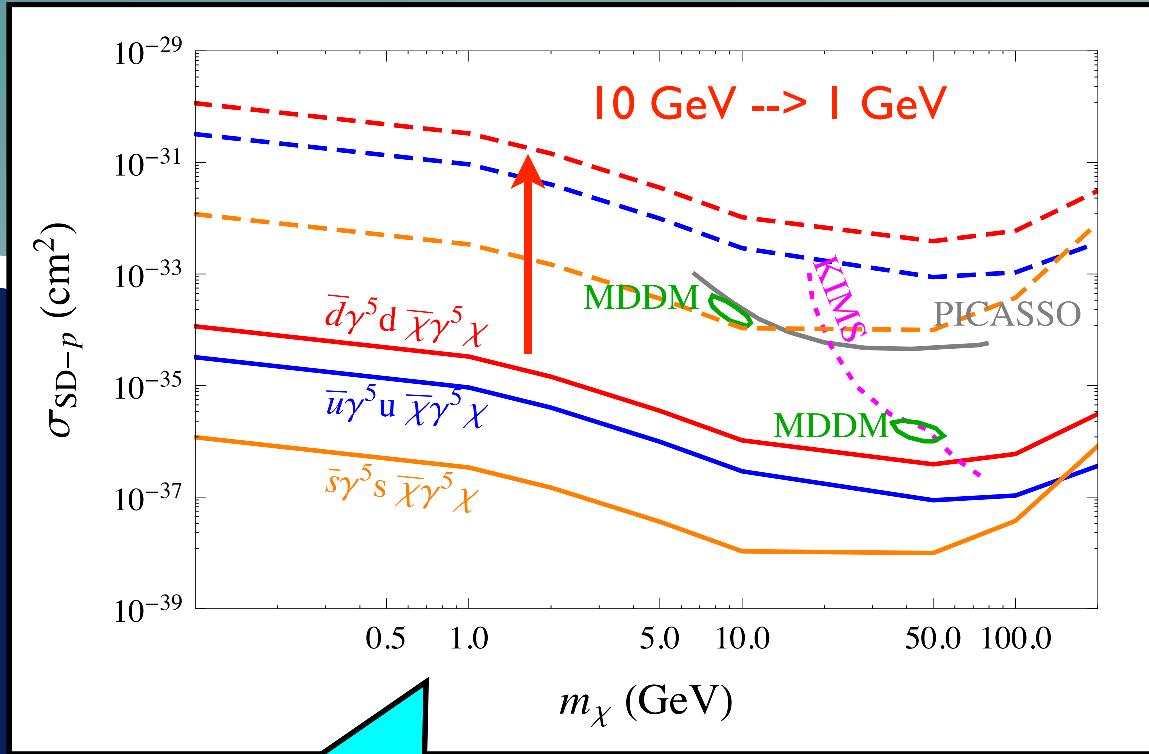
- Fermi can also say something about models designed to explain DAMA's signal consistently with CDMS.
- "Magnetic inelastic dark matter" invokes a WIMP coupling to photons through a magnetic moment, relying on the fact that Iodine nuclei have a large magnetic moment.
- This interaction produces gamma ray lines at "tree level".



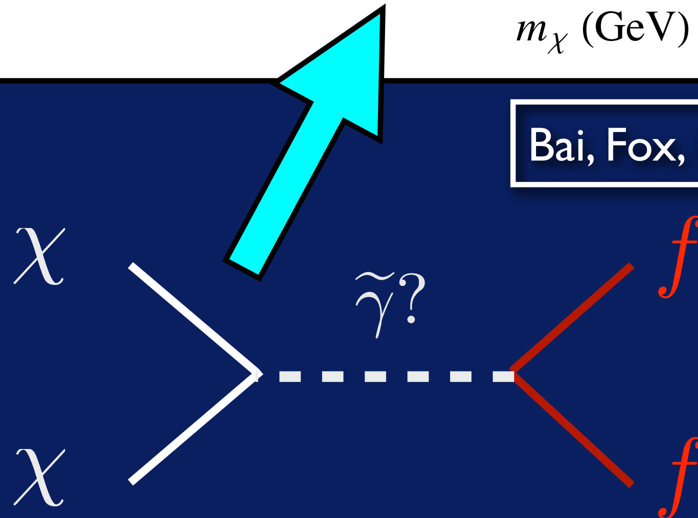


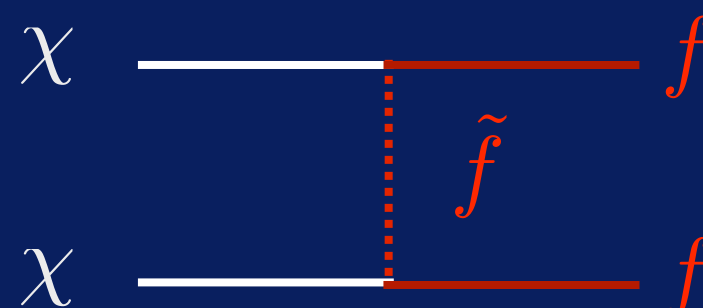
UV Thoughts

- When the effective theory breaks down, 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]





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 accurately describe the physics of processes whose momentum transfer is small compared to the masses of the mediating particles.
- Lots of potential for interplay between collider, direct, and indirect detection.
  - Effective theory pinpoints how they can work together to produce a picture which is far greater than each individual part!

Bonus Material

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

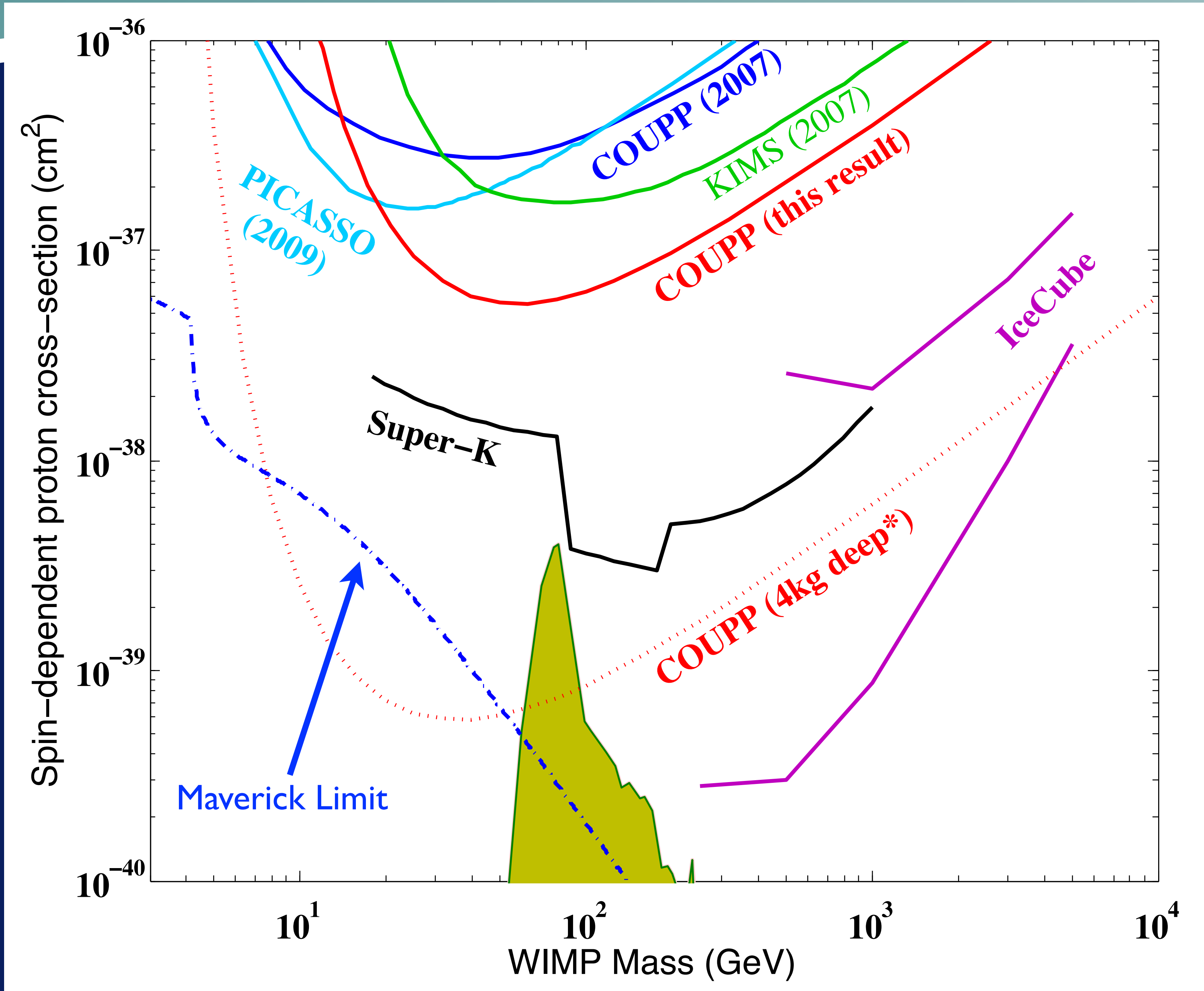
Spin Zero WIMPs

- 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.

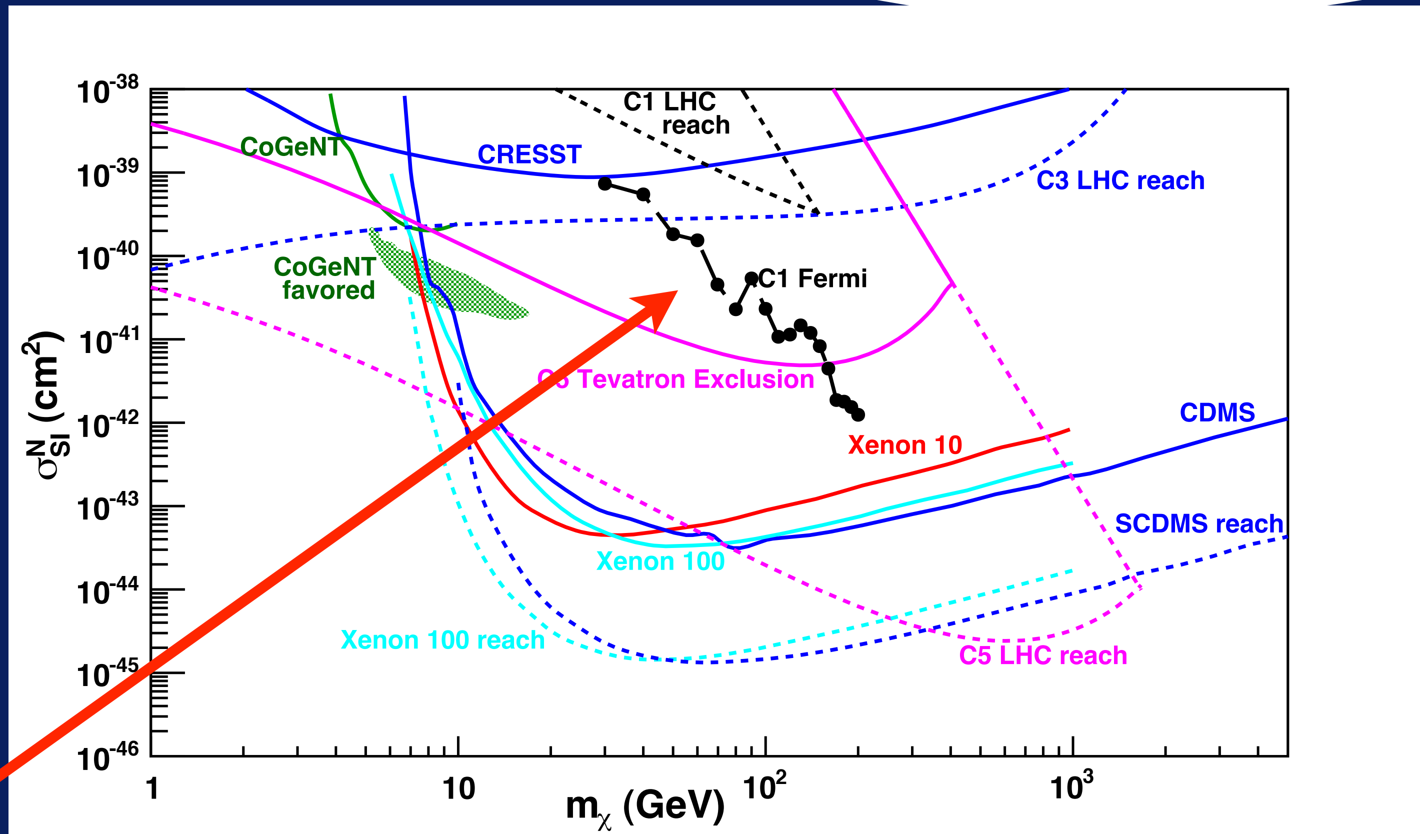
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

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

COUPP Limits



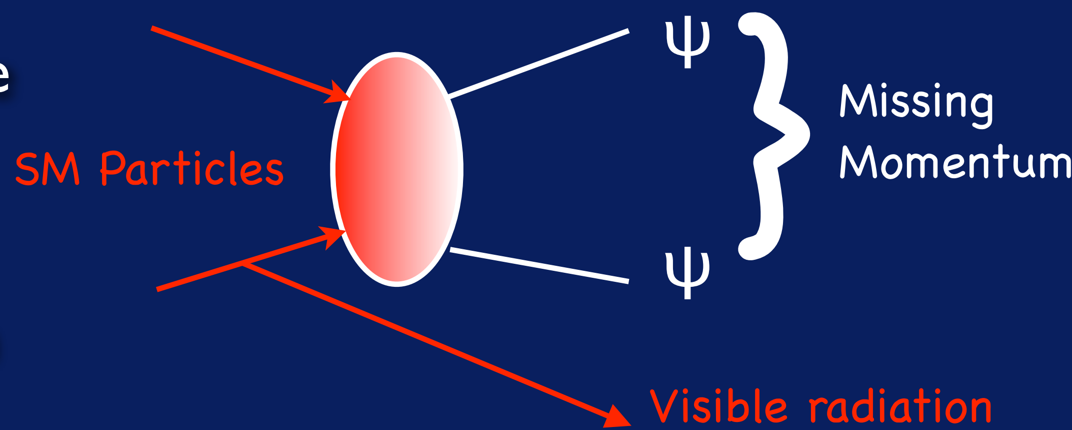
SI : Complex Scalar WIMP



For a scalar WIMP with scalar interactions, Fermi's line search outperforms LHC and is complimentary with existing direct detection searches.

Seeing the Invisible

- The collider signature is one or more hard jets recoiling against the WIMPs -- "nothing" as far as a collider detector is concerned.
- To place bounds, we compare with a CDF monojet search for ADD KK graviton production:
  - 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.

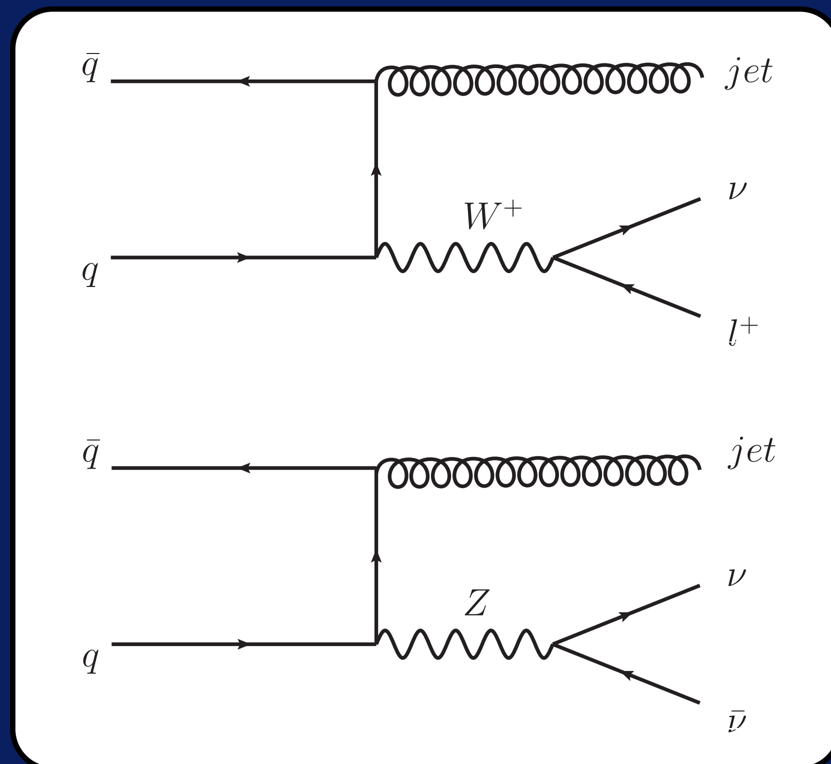


Based on 1 fb^{-1}, CDF constrains new physics (after cuts) $\sigma < 0.6$ pb.

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

Standard Model Backgrounds

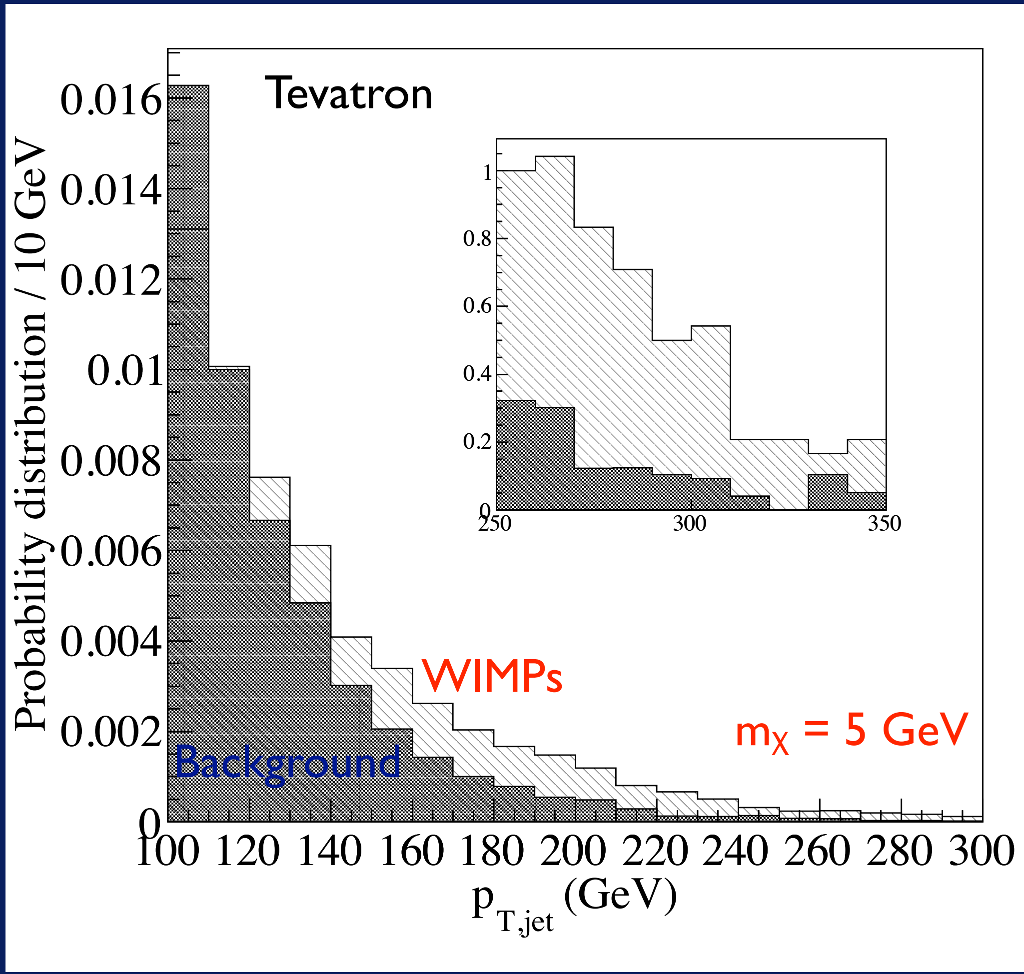
- The Standard Model can also produce "missing energy" events.
- Production of a Z boson along with a jet, followed by the Z decay into neutrinos, produces very similar events leading to an irreducible background.
- Production of a W boson leads to decays into a charged lepton and neutrino. Sometimes the charged lepton falls inside the jet and gets lost. Other times, it may fall outside of the region where the detector is sensitive.
- Finally, when a jet's energy is mis-measured, it can fake an energy imbalance.



Signal and Background

- At the level of quarks and gluons, there is a clear difference between the kinematics of the WIMP events compared with the SM backgrounds.
- The WIMPs are produced by interactions 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.

Shape only

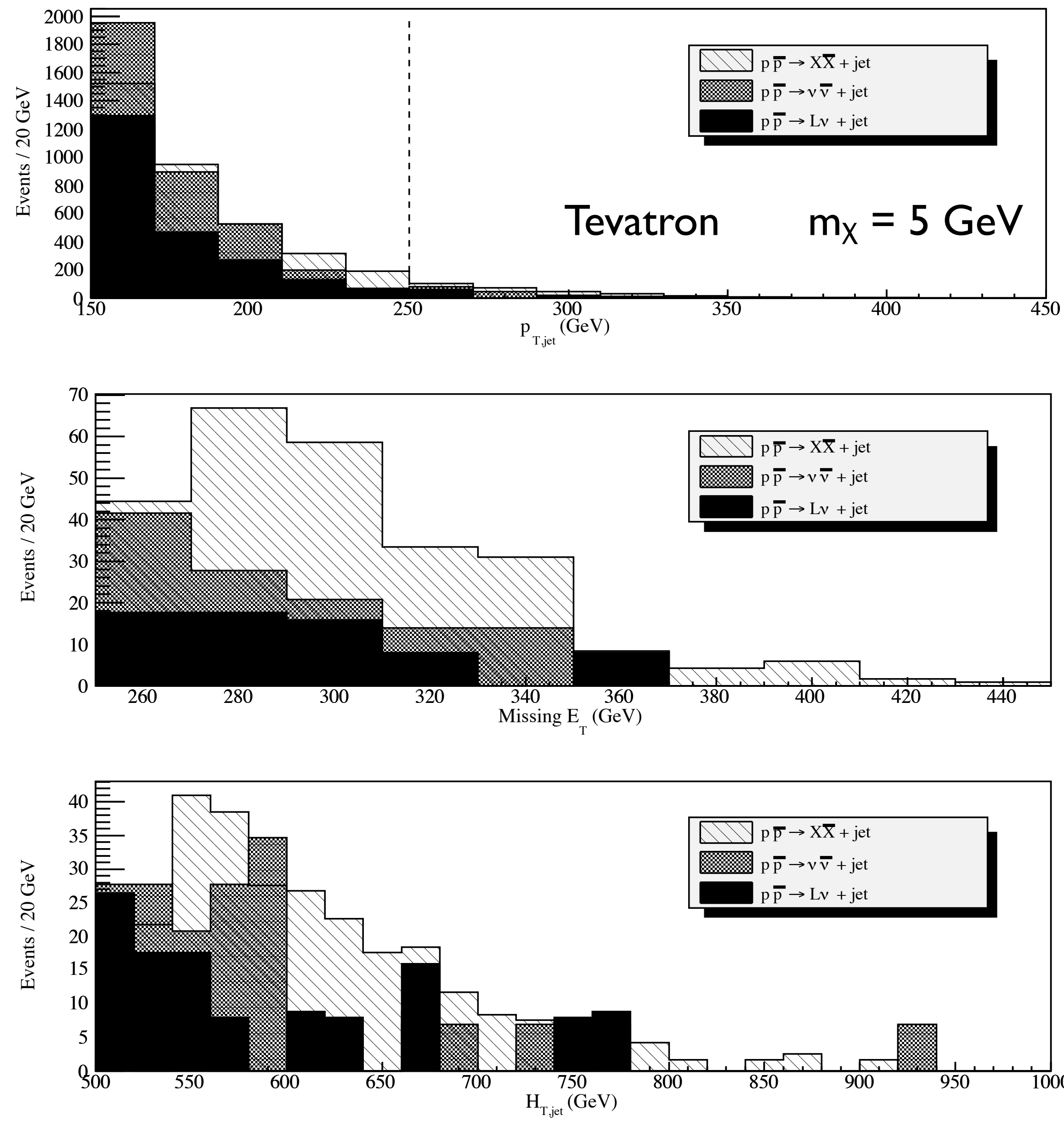


Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

Signal and Background

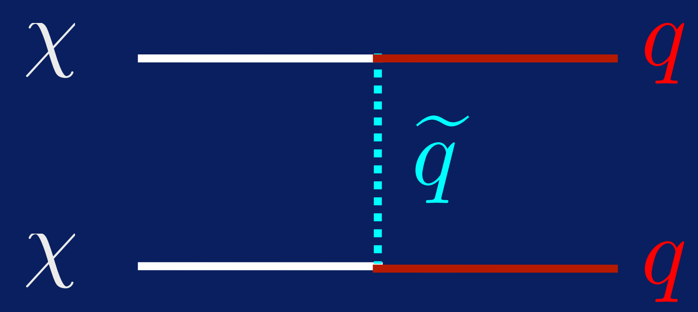
Beltran, Hooper, Kolb, Krusberg, TMPT, JHEP 1009:037 (2010)

- The WIMP signal results in events containing higher average missing energy than the Standard Model background processes.
- Based on our projections, a CDF group is currently performing the more optimized search we suggested.
- Until that is ready, we rely on the existing CDF search for large extra dimensions.



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.



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

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

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

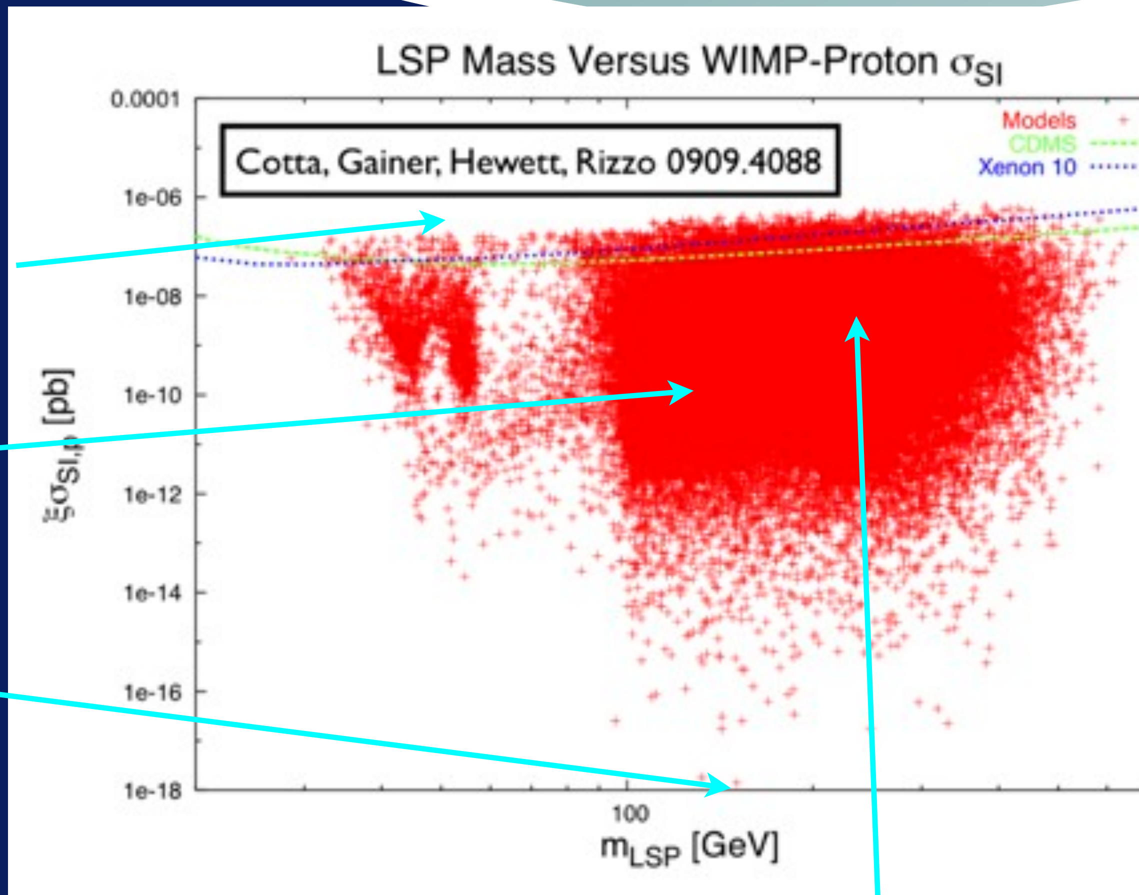
Still many questions...

This plot still still leaves (me) with many questions.

Which search excluded these points?

What happens to this point if I raise the stop mass by 5 GeV?

What happened to this point?



What about "nearby" NMSSM points?

The SLAC model set can actually answer any of these questions (except the last one) with some effort. But it would be nice to have a result which is more robust with respect to model deformations.

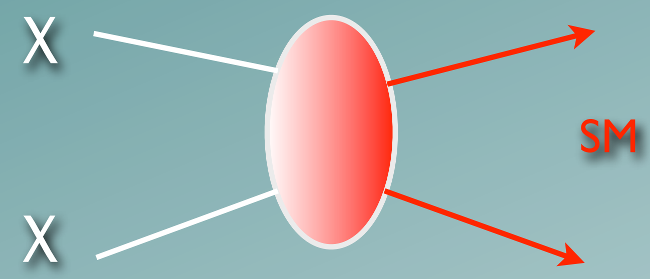
WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe as a thermal relic.
    - The relic density is controlled by the scattering cross section $\sigma(\chi\chi$ -> SM particles).
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.
- I won't get too attached to any specific theory, but instead will use effective quantum field theories to describe WIMPs model-independently.

$59.99 for 20 servings

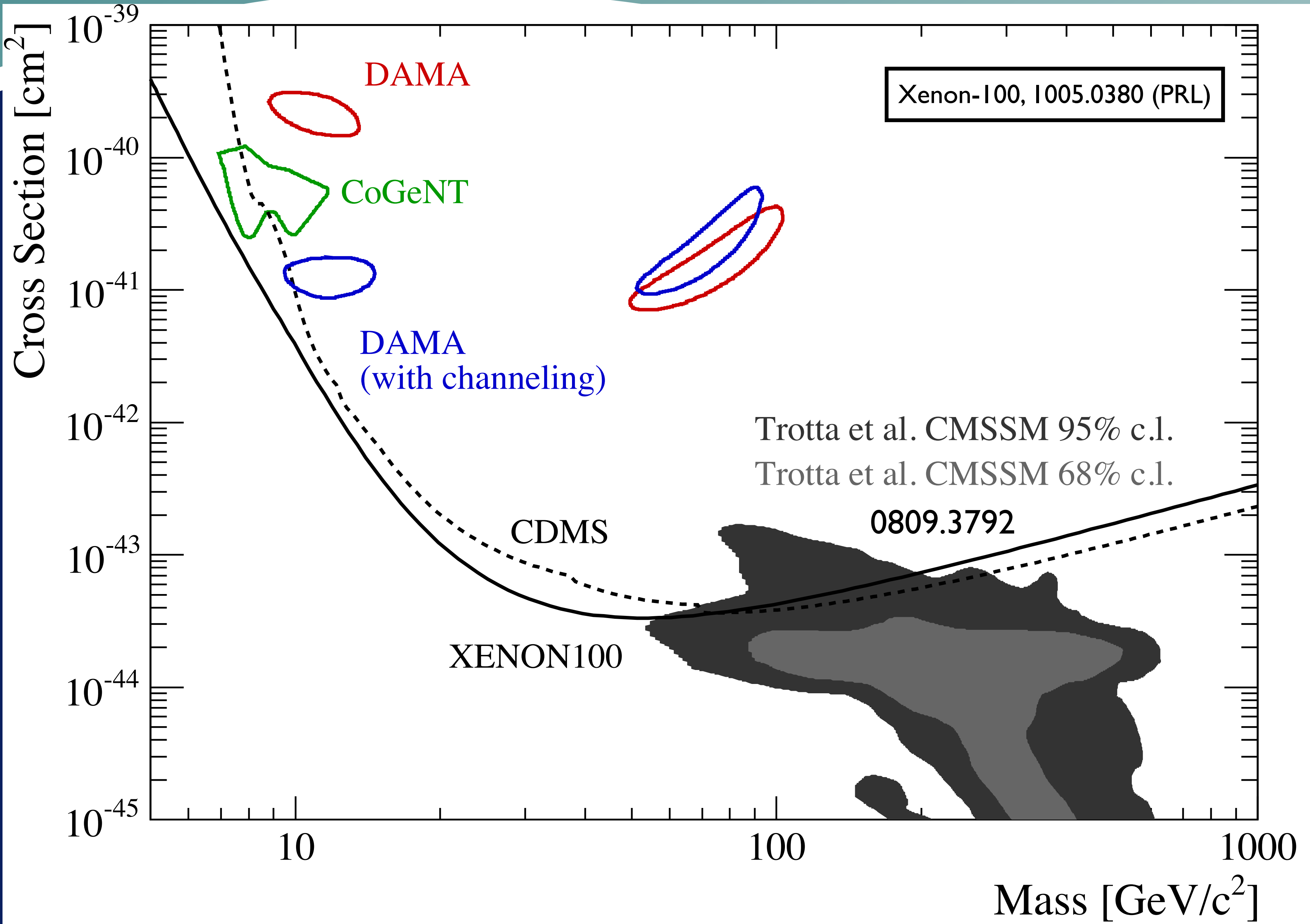
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

WIMP Interactions



- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma(\chi\chi \rightarrow$ SM particles) and check the relic density.
  - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
  - If not, we will look for signs of new physical processes to make up the difference.
- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.

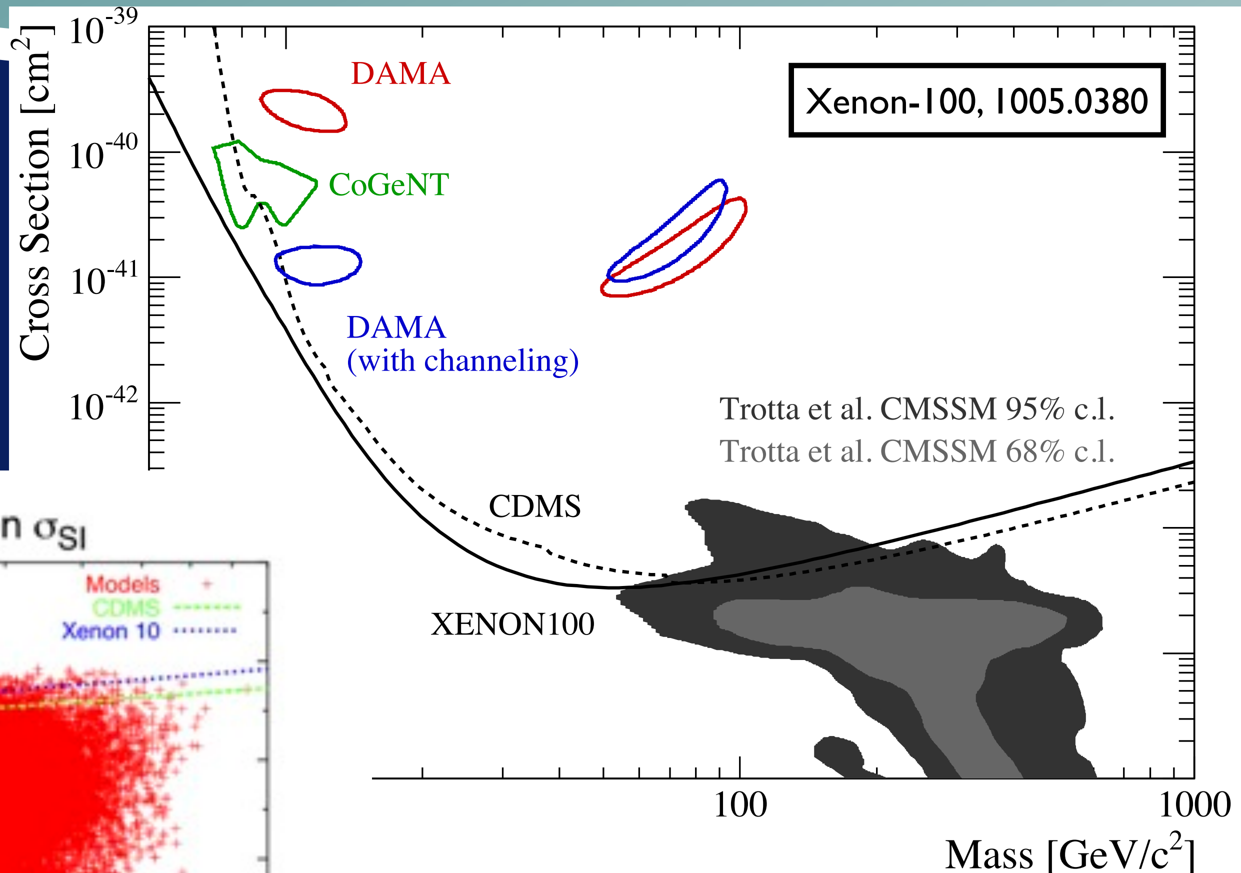
...or maybe...

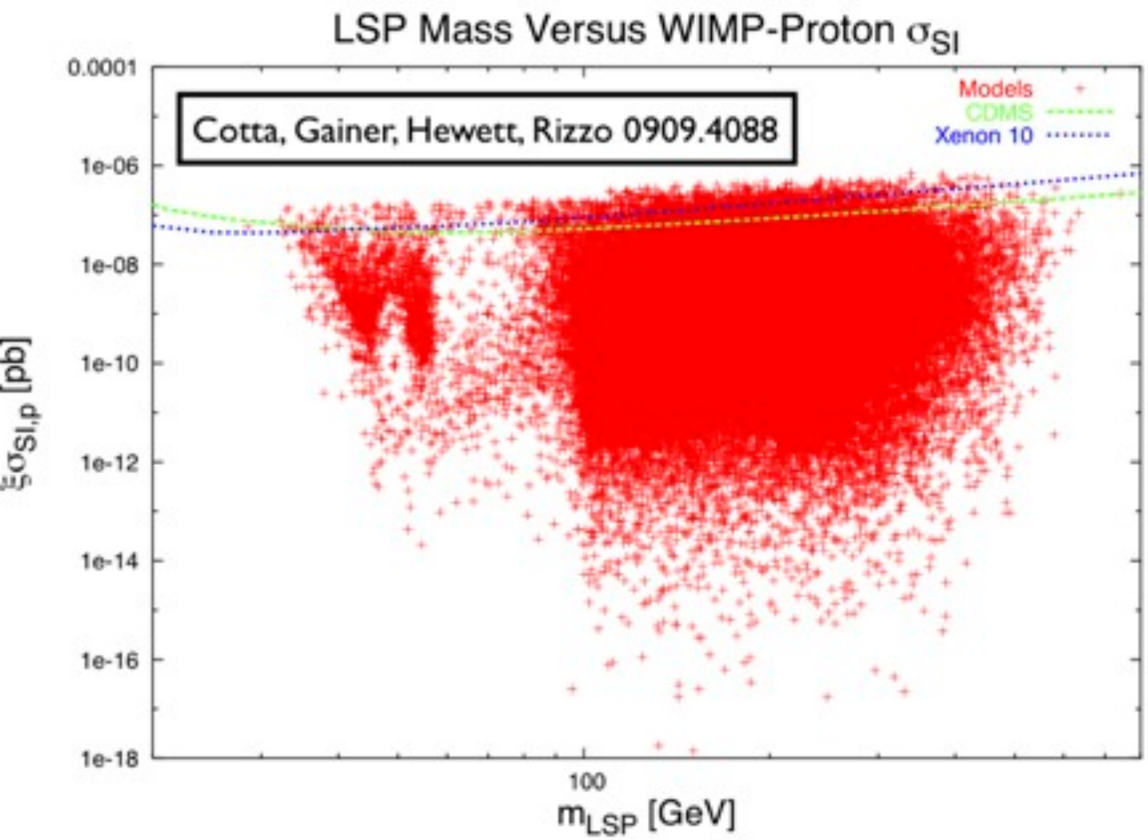


Xenon-100, 1005.0380 (PRL)
DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% c.l.
Trotta et al. CMSSM 68% c.l.
0809.3792
CDMS
XENON100
Cross Section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10
100
1000
Mass [GeV/c^2]

Different conclusions?

Similar Model frameworks: the MSSM



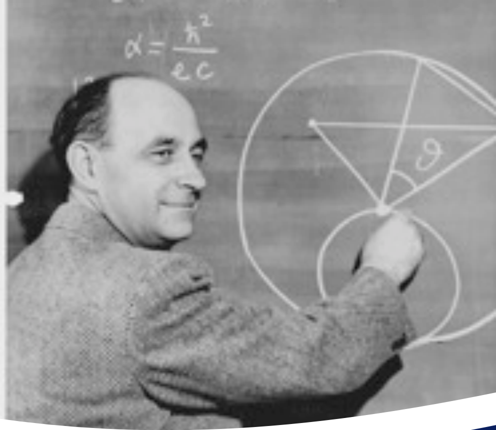


But very different questions.

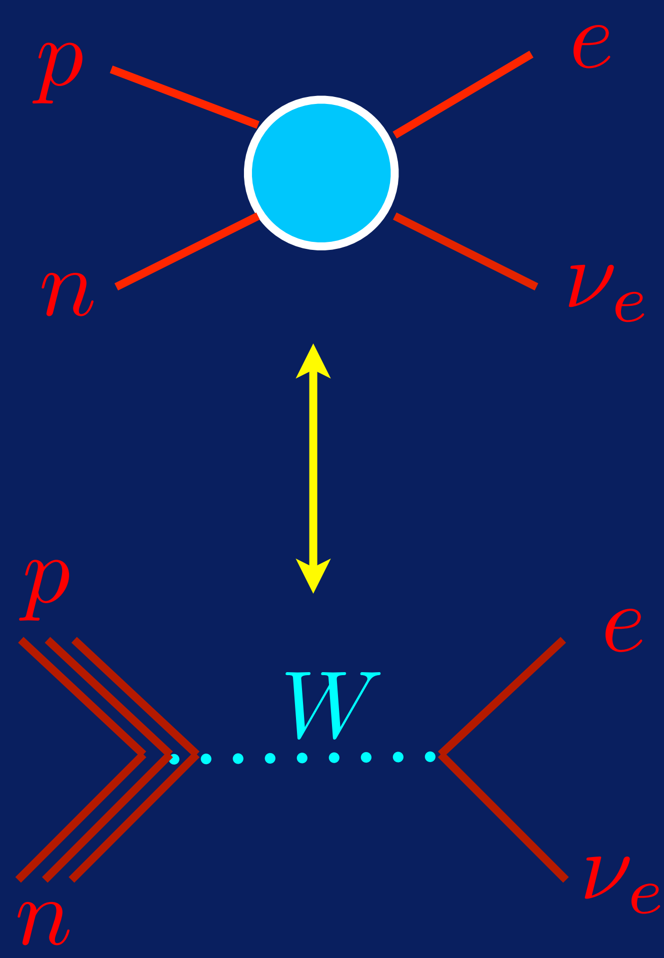
The Bayesians take the cMSSM seriously and construct the most likely parameter space.

The SLAC group just asks for generic points obeying constraints. This is closer to what I was looking for...

Historical Perspective

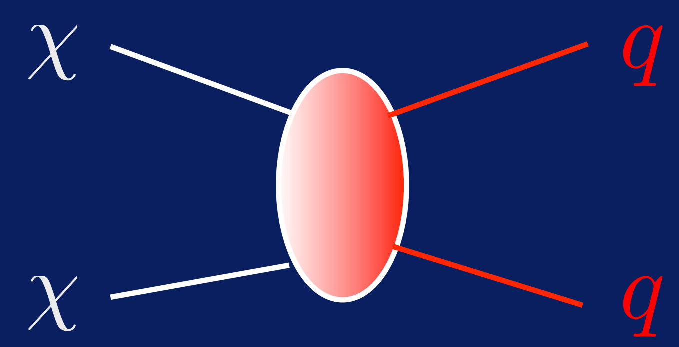


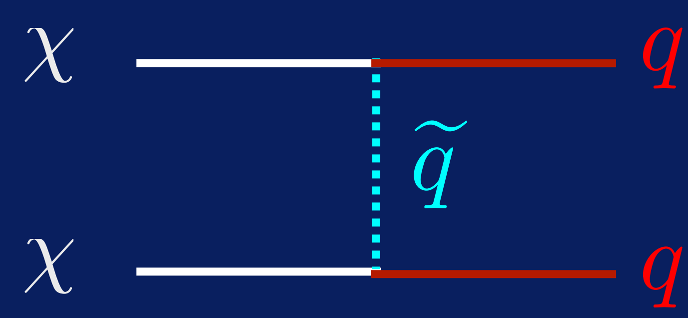
- Effective field theories have a fruitful history:
  - Fermi proposed his theory of beta-decay without knowing about the existence of the W boson (or quarks!).
  - Feynman and Gell-Mann deduced the V - A structure, revealing parity violation.
  - With the advent of the Standard Model, we resolve the interaction into the W boson, resulting in a UV complete description.
- At low energies, the Fermi theory is a perfectly fine description of the physics.
- Quantifying it provides the first hints to construct a more complete high energy theory.



Virtual Particles?

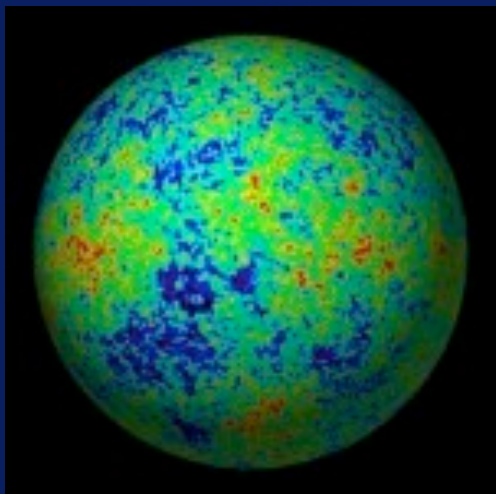
- However, it is a little bit of a cheat to say that this is truly a model independent process, because while we don't produce any of the extra particles directly, they are still involved virtually.
    - The WIMP-WIMP-q-q interaction involves exchange of some particle. In supersymmetry this would be a 'squark'.
- However, though they are still there, the machinery of effective field theory tells us that the physics at low energies is independent of the nature of the mediator particle, so once we specify the WIMP-WIMP-q-q interaction, it captures a limit of *every* theory.



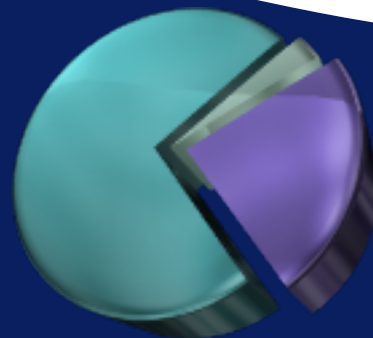


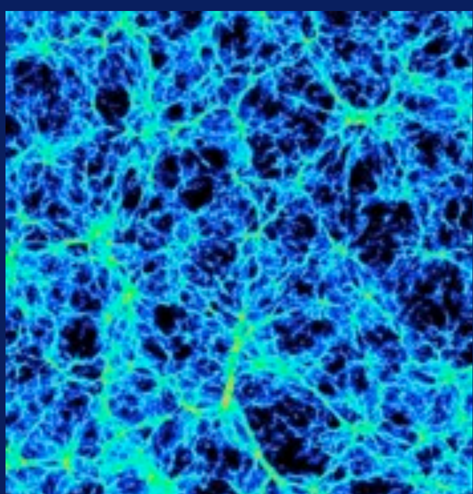
Dark Matter

CMB



Supernova

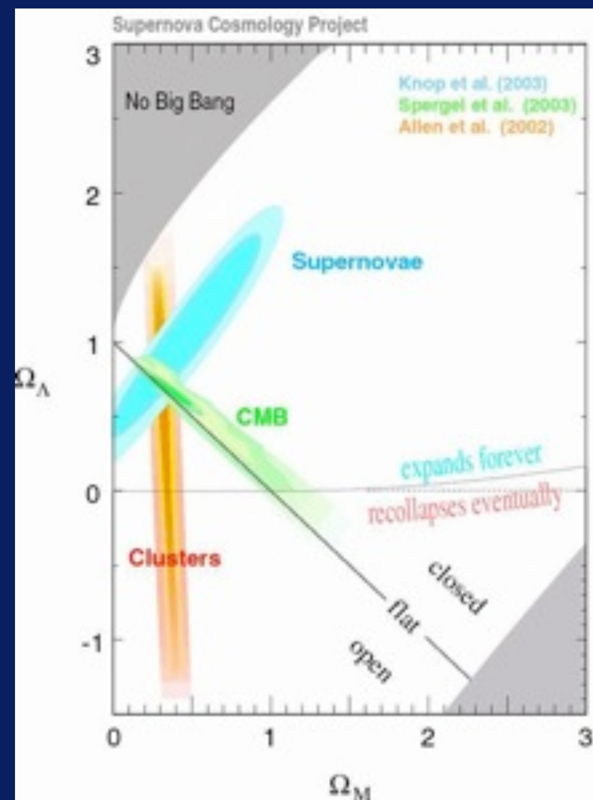




Structure

Lensing

Ordinary Matter
Dark Matter
Dark Energy



So what is this stuff?

"Cold Dark Matter: An Exploded View" by Cornelia Parker

- As a particle physicist I want to know how dark matter fits into a particle description.
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

EFT and WIMP Annihilation

- So the effectiveness of the EFT depends on the momentum transfer of the process.
- When nonrelativistic WIMPs annihilate, the exchanged momentum is the WIMP mass.
- Thus, the requirement is that the mediator particle is heavier than the WIMP.
- In theories like SUSY or UED, that is the case.
  - If another particle were lighter, the "dark matter" would decay into it.
  - More exotic theories may contain extra lighter particles.
  - We can always add them to the EFT...