# Collider Statements about Interactions of Dark Matter


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Physics Opportunities at 7 TeV
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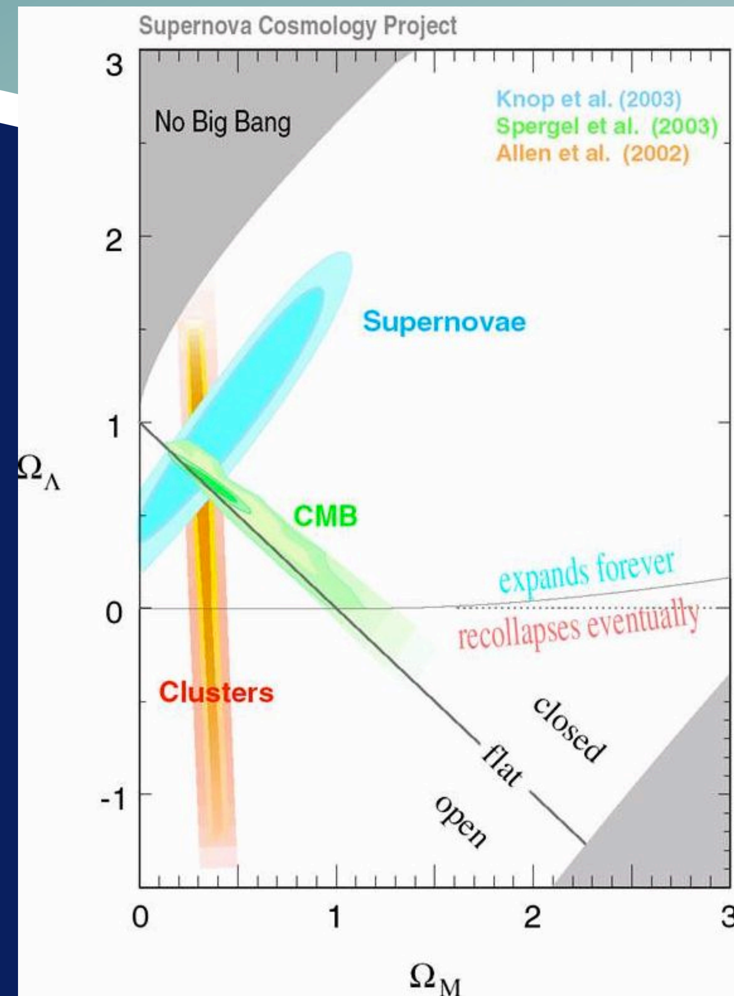
# Outline

- Introduction and Motivation
- Windows on WIMP Properties
  - Direct Detection
  - Collider Searches
  - Gamma Ray Line Searches
- Outlook

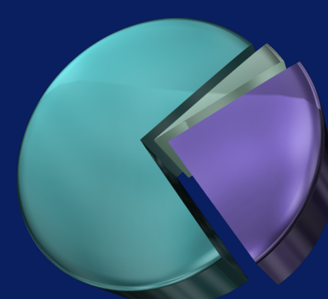
# Suggestion from the Cosmos?

- Mihoko labeled this session "suggestion from the Cosmos".
- One very important "suggestion" from the cosmos is that it is filled with dark matter.
- For particle physics, the question is what this stuff is and how it fits into a fundamental theory.




¥4719 for 20 servings

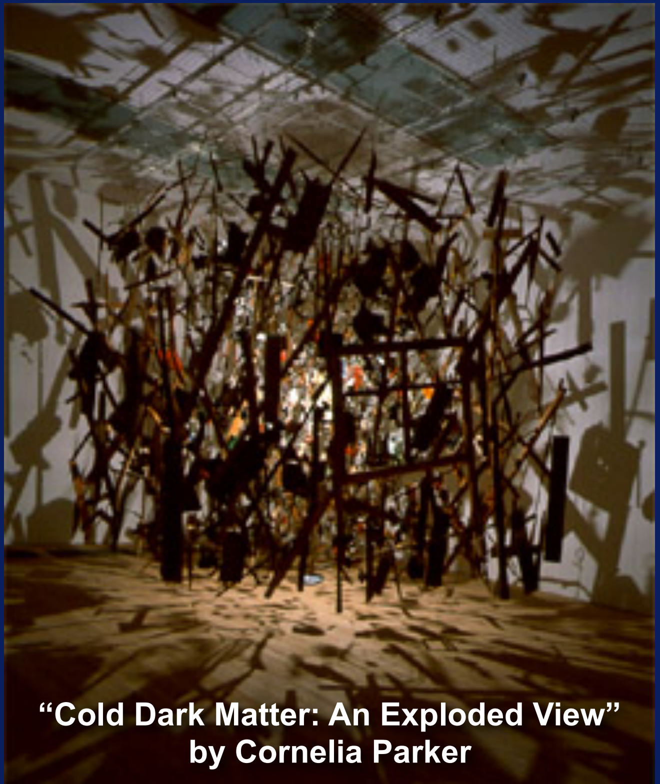
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

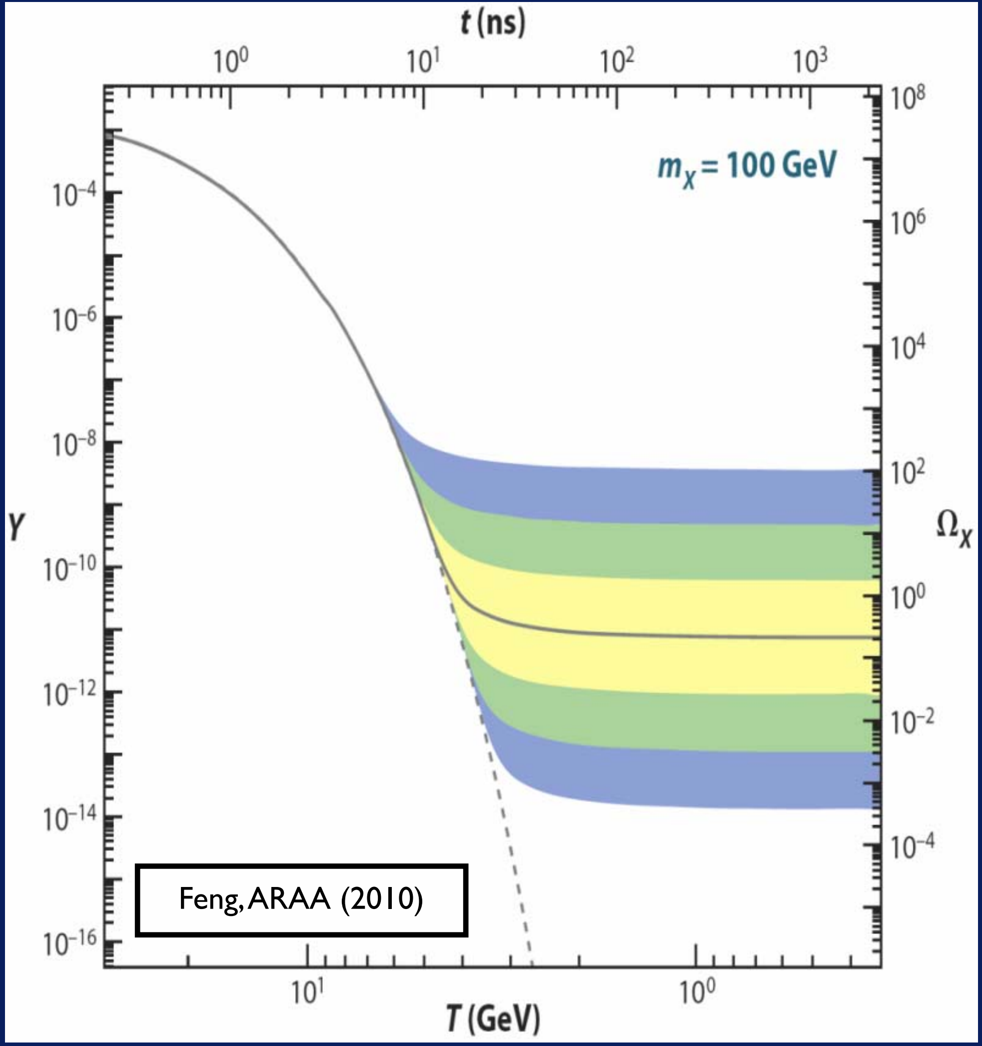
- Ordinary Matter
- Dark Matter
- Dark Energy

# Dark Wonderland?

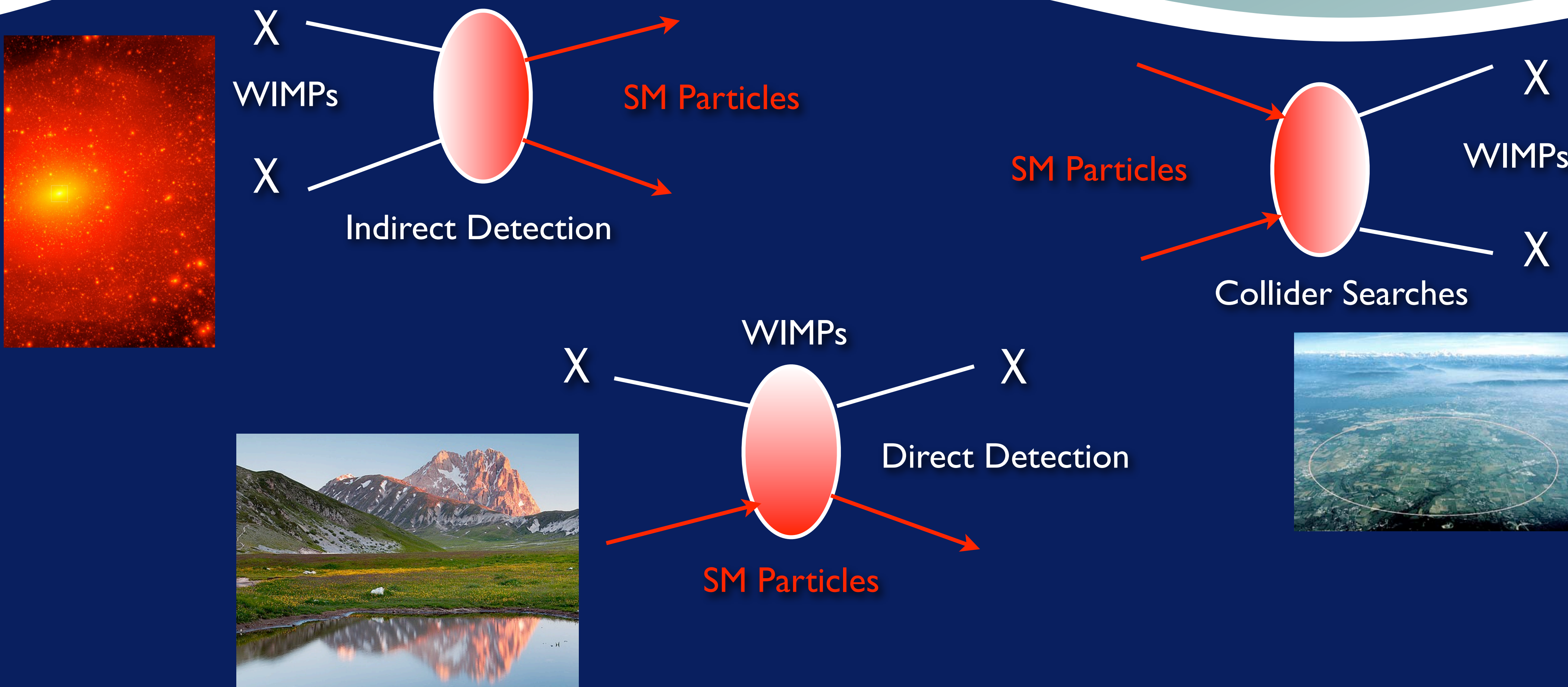

- The relic density suggests that dark matter may have ``large'' couplings to the SM, opening the door to detecting dark matter through non-gravitational interactions.



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

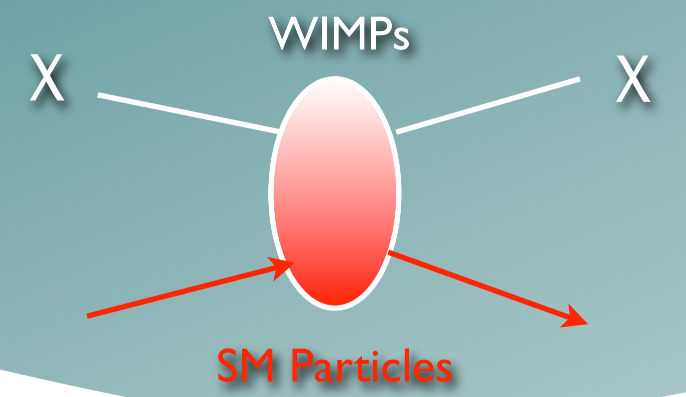


# DM Search Strategies

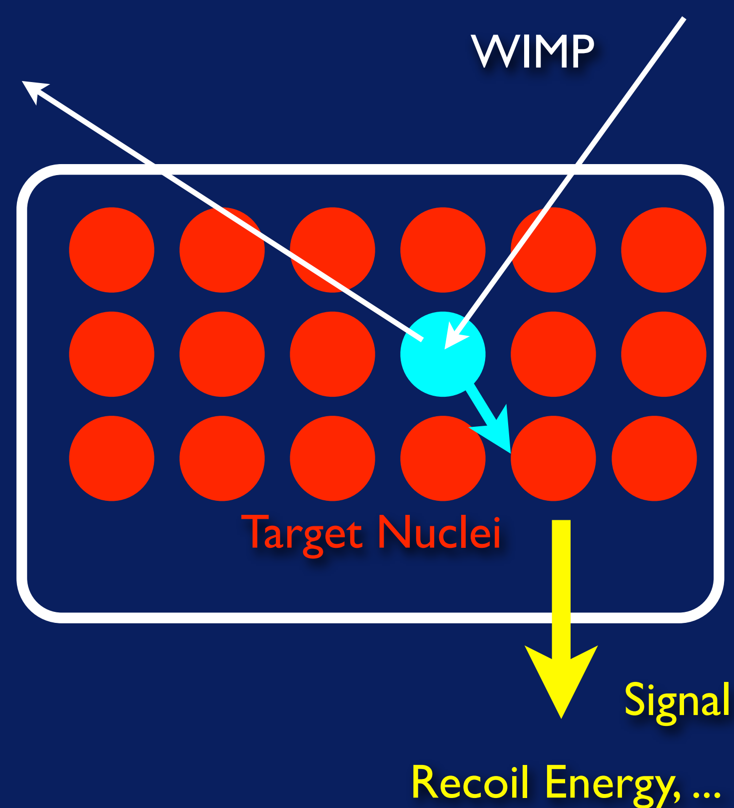



- The common thread that ties up direct, indirect, and collider searches for dark matter is how WIMPs interact with the Standard Model.

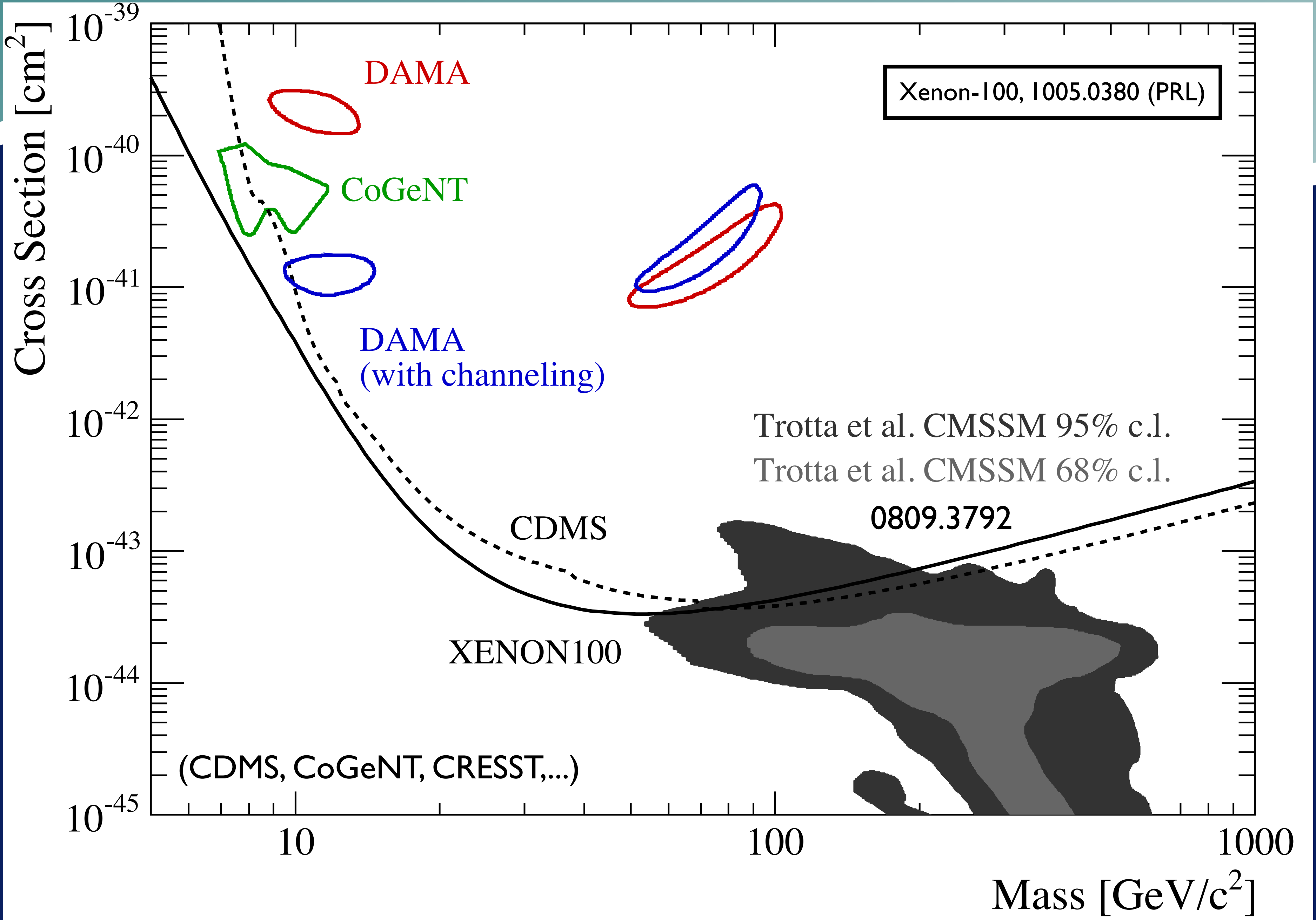
# Direct Detection




- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when a WIMP brushes against it.
- Heavy shielding screens out Standard Model backgrounds.
- The particle originating the recoil can be distinguished with the help of secondary characteristics of the interaction, such as scintillation light or timing.
- The rate has strong dependence on the local density of dark matter and (depending on the model) its velocity distribution.
- One advantage is that direct detection looks for the dark matter in our galaxy's halo.



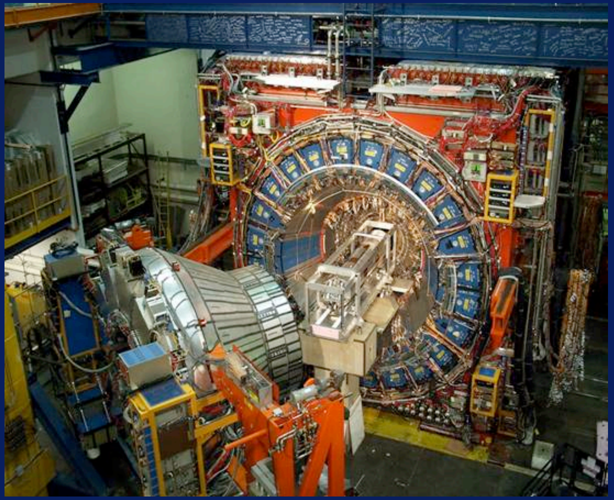
# The Situation

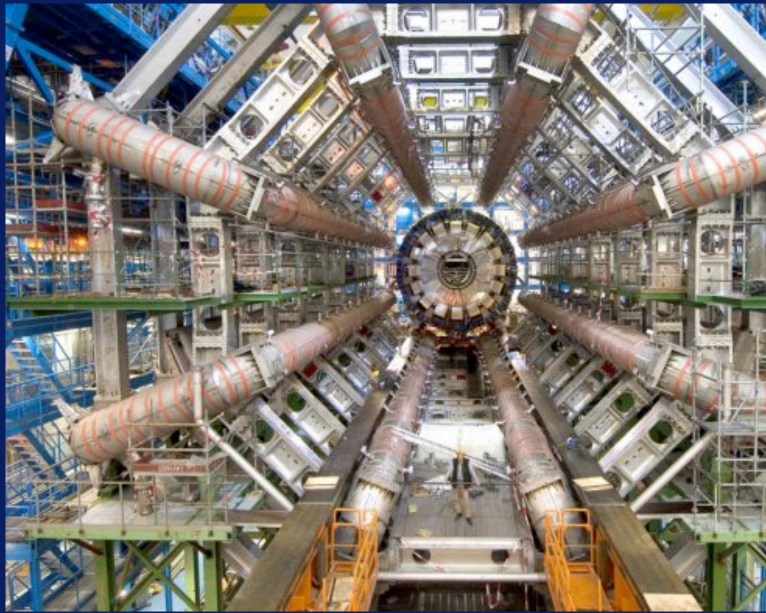



Spin-independent; assumes equal couplings to protons and neutrons.

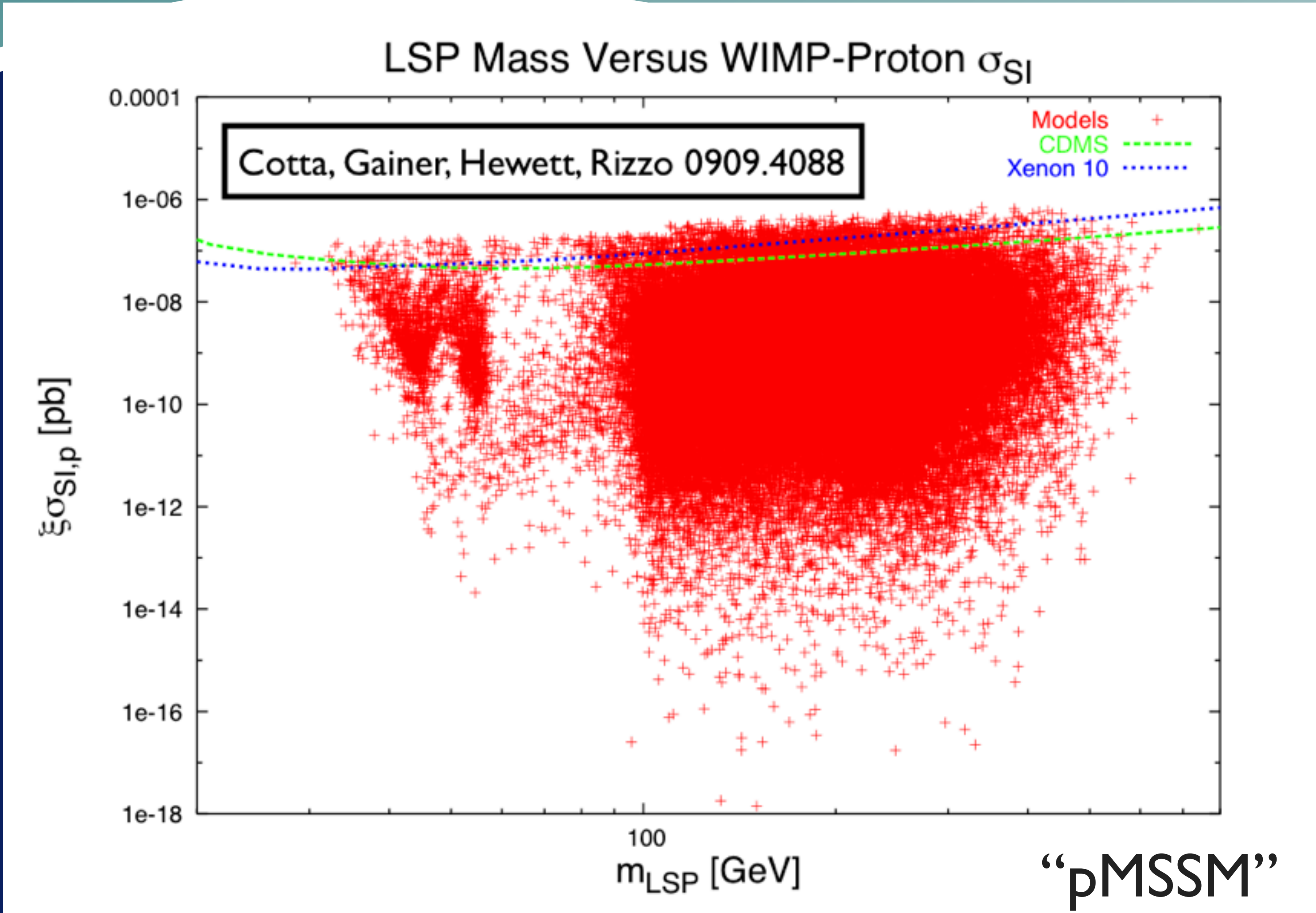
# Other Experiments?

- Direct detection probes WIMP couplings to nucleons (quarks and gluons).
- This raises an important question:
  - **What do colliders say about this plot?**
- 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.



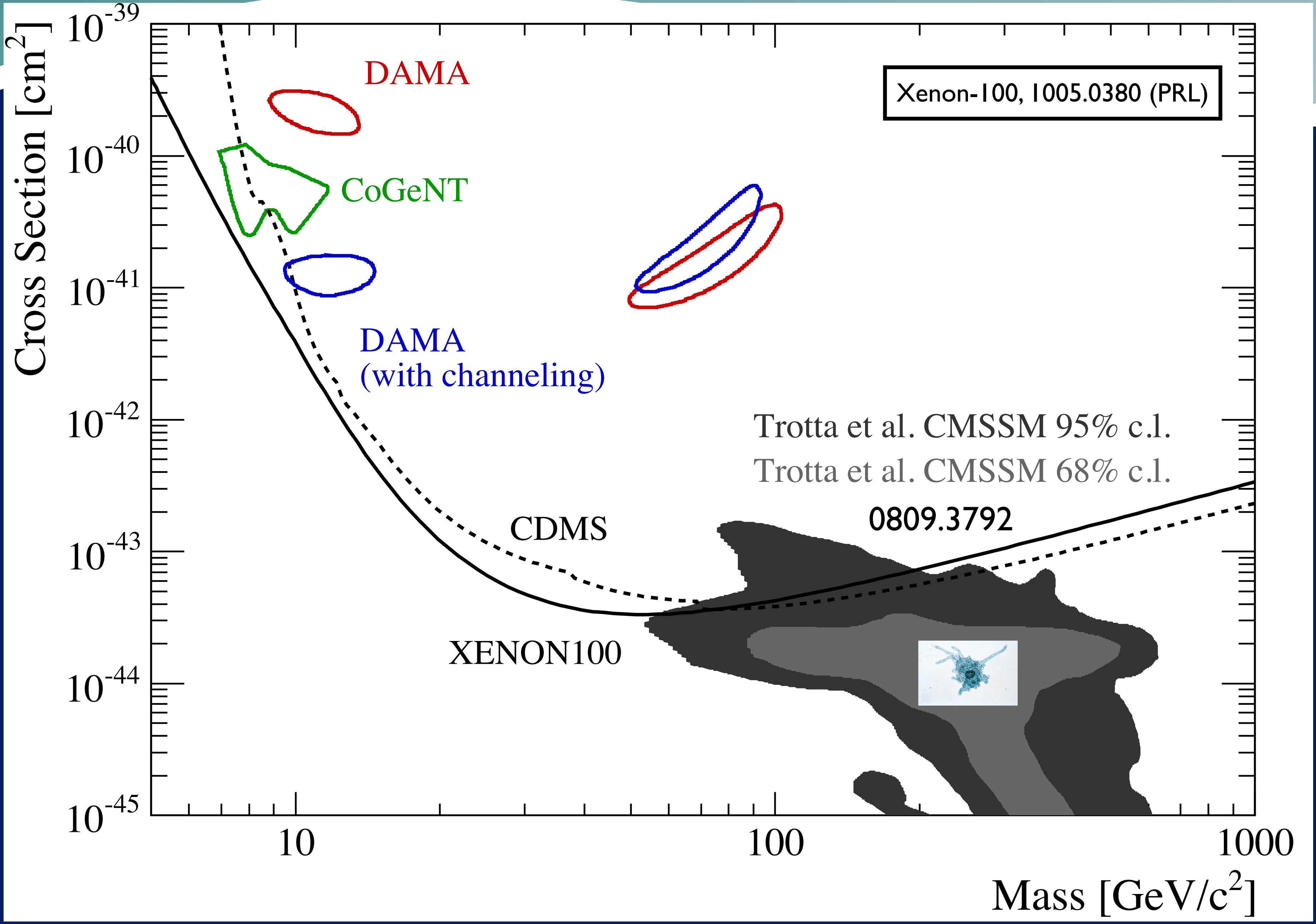


# Clearly Something.




"pMSSM"

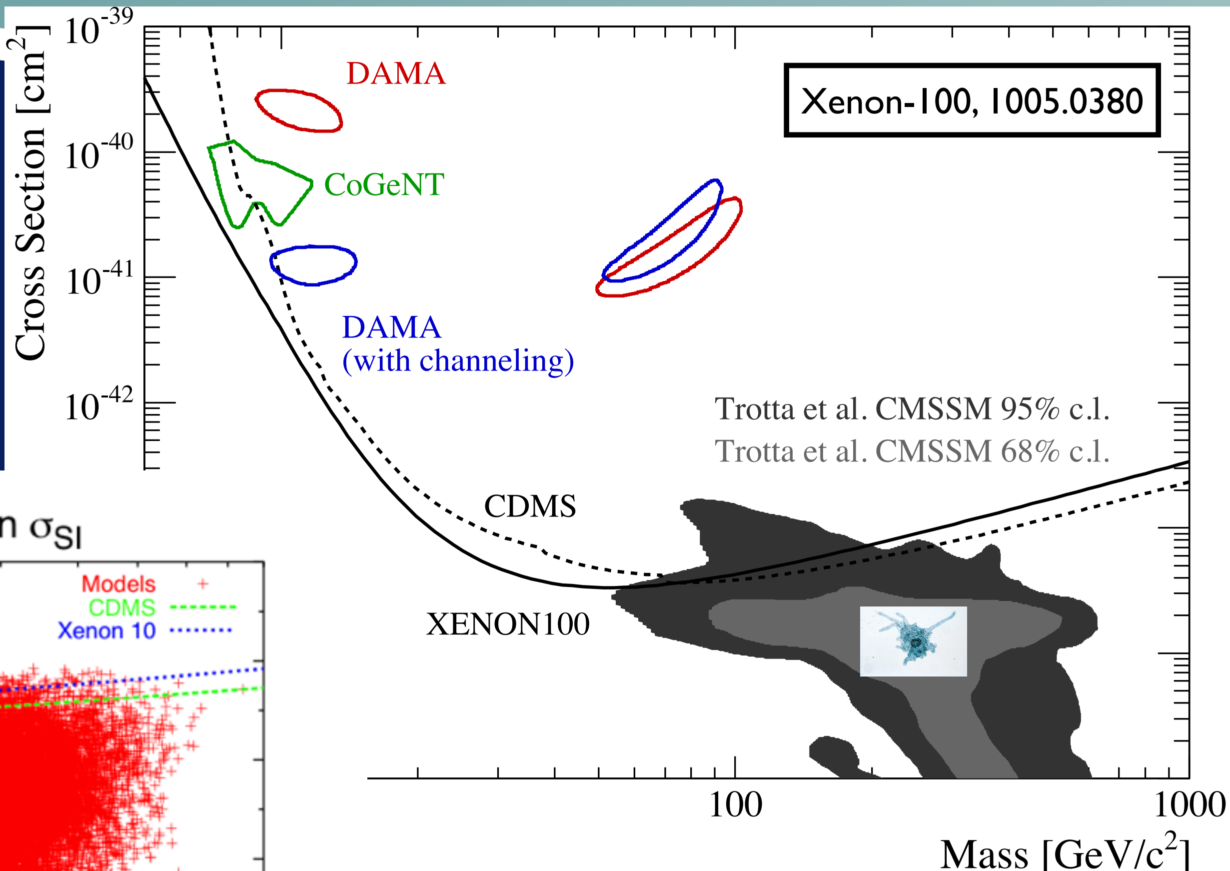
# Or maybe...

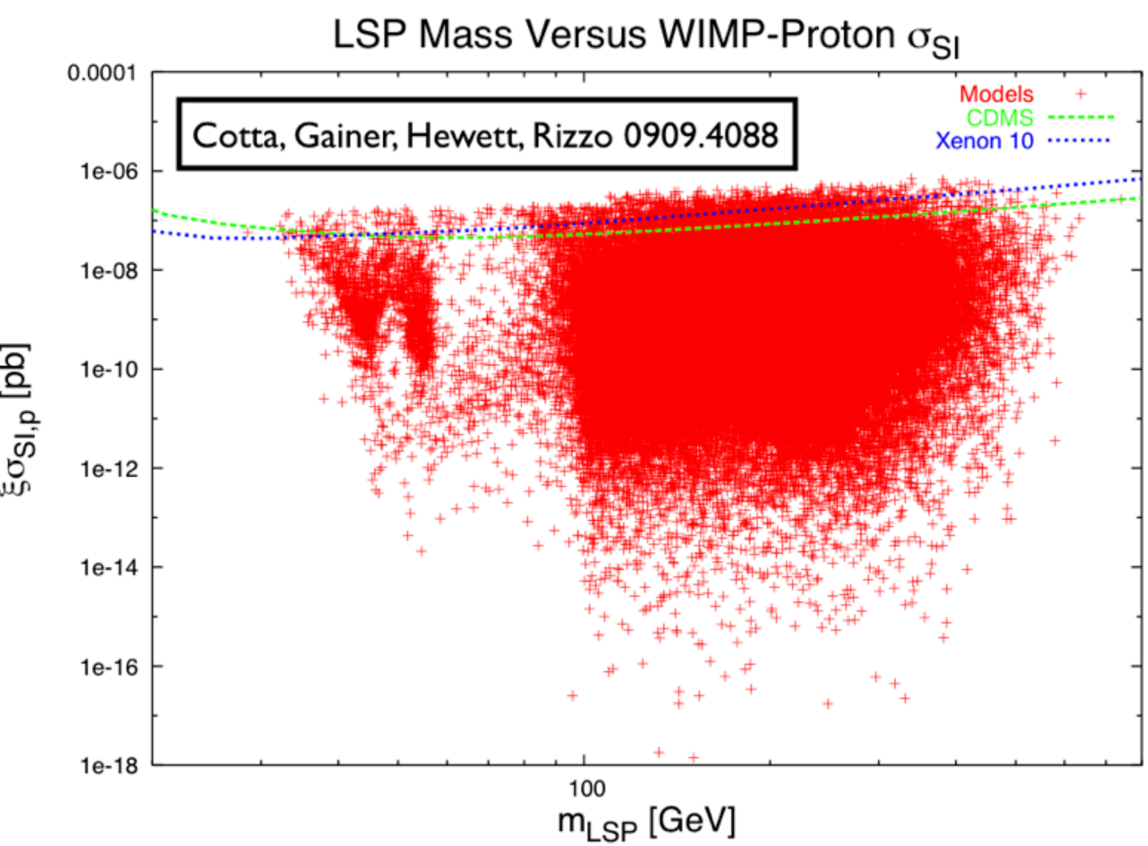


Xenon-100, 1005.0380 (PRL)
DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% c.l.
Trotta et al. CMSSM 68% c.l.
0809.3792
CDMS
XENON100
Cross Section [cm$^2$]
Mass [GeV/c$^2$]
$10^{-39}$
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
10
100
1000

# Different conclusions?

Similar Model frameworks: the MSSM



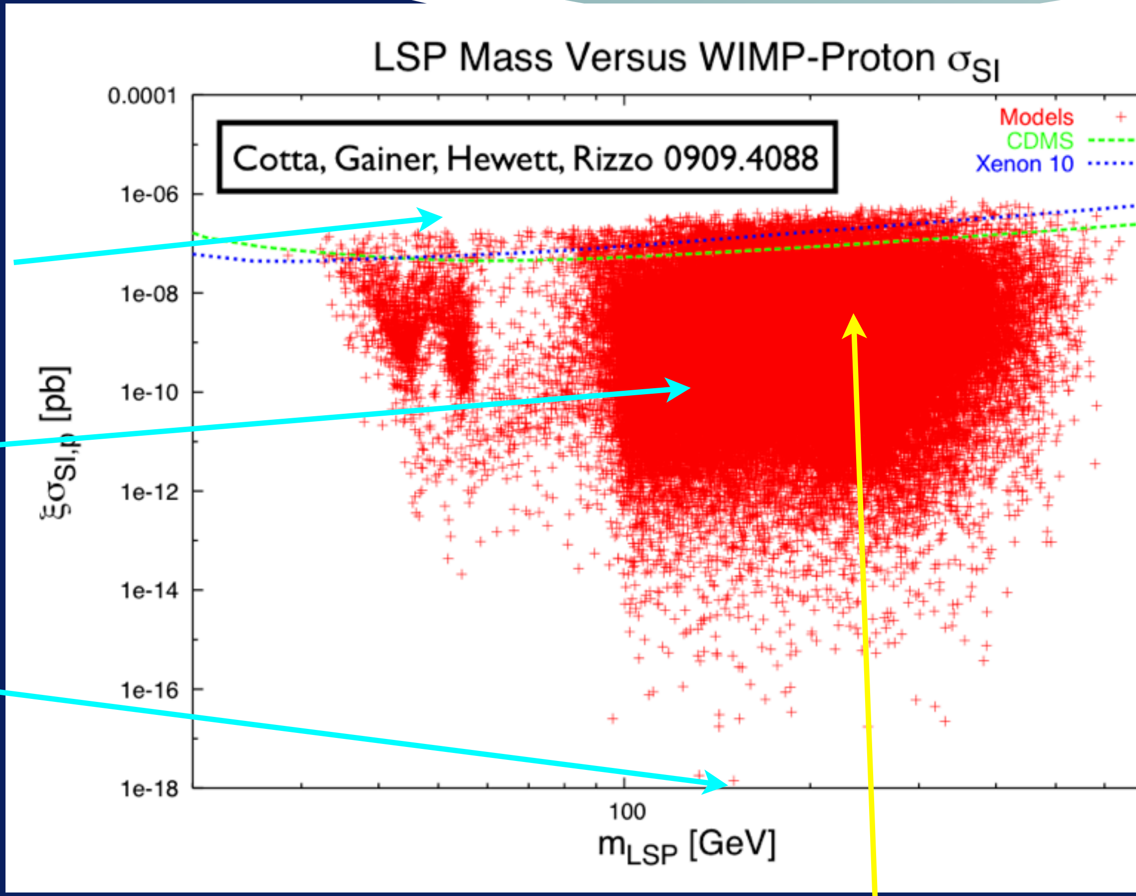

But very different questions.

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...

# 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?

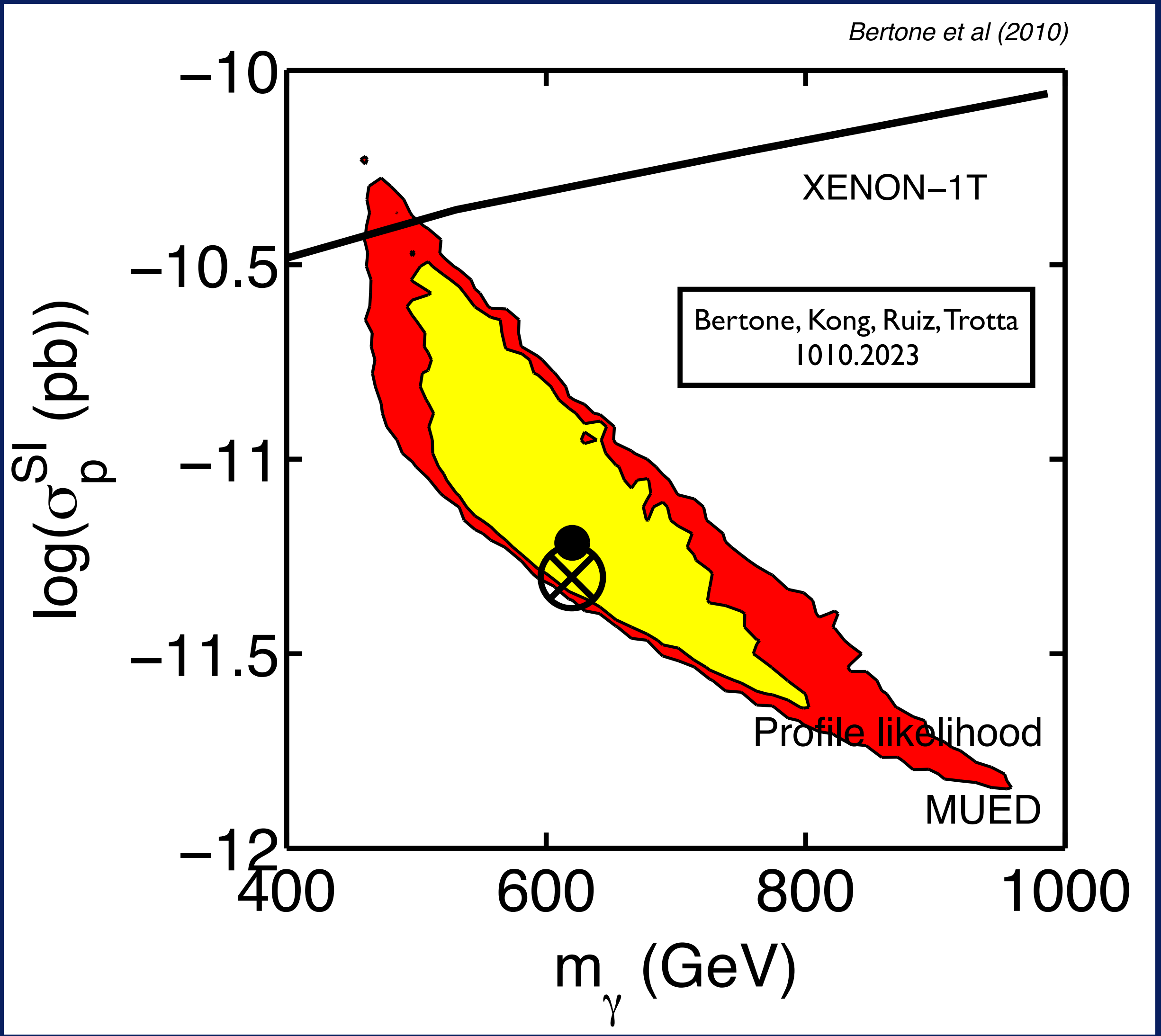
How representative are these points compared to other models?

What about "nearby" NMSSM points?

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

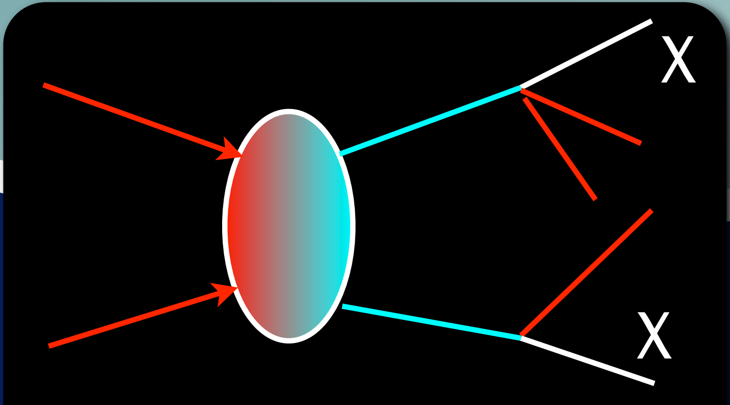
# Another Model?

- That was the MSSM. What about UED?
- A Bayesian study in 1010.2023 concludes that it looks hopeless even for Xenon-1ton.
- What drives this conclusion turns out to be precision electroweak corrections forcing a large ~300 GeV SM Higgs mass
- The conclusion is very dependent on the choice of "minimal" UED...

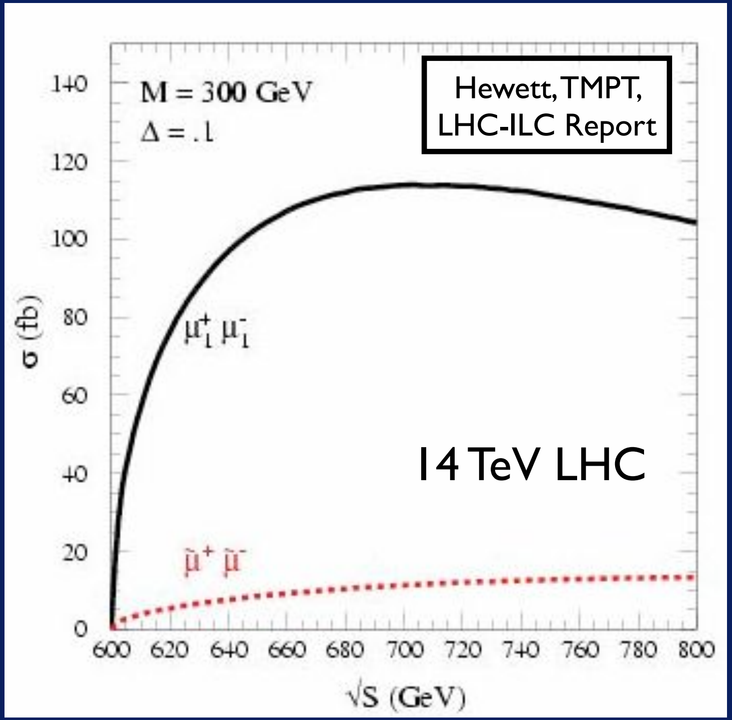


# Model-Dependent

- 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 the signature, let alone the expected rate and how it correlates with direct detection.

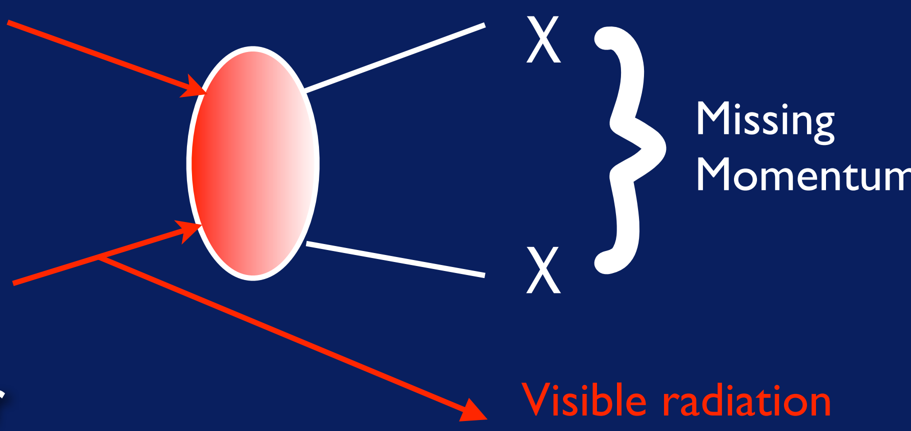



"KK Sgluquarkino Pair Production Followed by Decay into WIMPs"

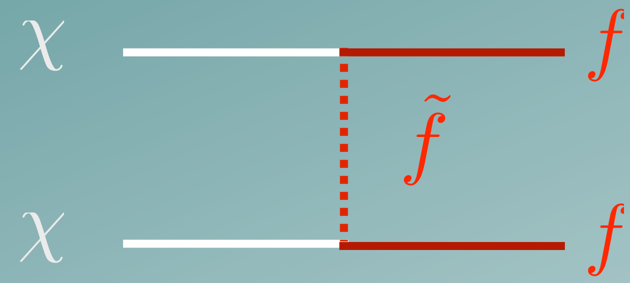


# Maverick WIMP Production

- 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 generally results 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 Theories




- Of course this is something of a cheat; the WIMP siblings are still in these graphs, but they appear virtually.
- Still, depending on how they appear, I can to some approximation ignore them in detail and instead work at the level of an effective quantum field theory (EFT) description of dark matter - SM interactions.
- As effective theories, they have a range of energies which we can hope they describe the physics correctly. Whether they turn out to be useful will depend on what kind of WIMP nature has provided for us.
- They provide a language we can use to discuss how WIMPs interact with various Standard Model fields. Using this language, we can compute predictions for various observables, and see how they all come together to tell us something about how WIMPs interact with the SM.

# Small Flavor Violation

- In defining interactions, I will make a choice motivated by the need to control new sources of flavor and CP-violation.
  - Scalar combinations of fermions are proportional to the fermion masses.
  - Vector combinations have universal couplings.
  - These choices could be motivated by minimal flavor violation.
  - (But, at least as mostly implemented here, they represent much stronger assumptions than MFV strictly implies).

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

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

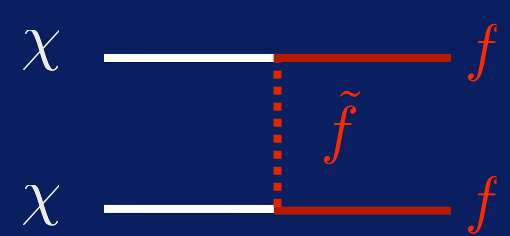
$$\sum_q \bar{q} \gamma^\mu q$$

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

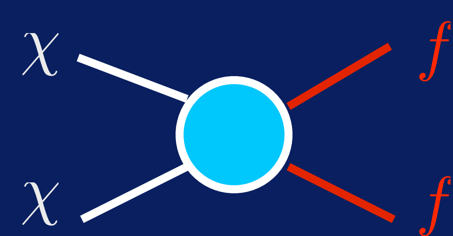
$$\sum_q \bar{q} \sigma^{\mu\nu} q$$

# EFT Cartoon

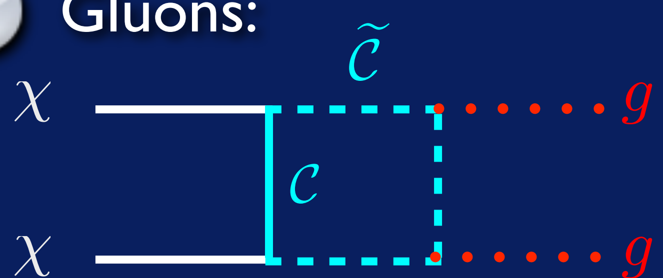
- Here are some cartoons for how a SUSY-like Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



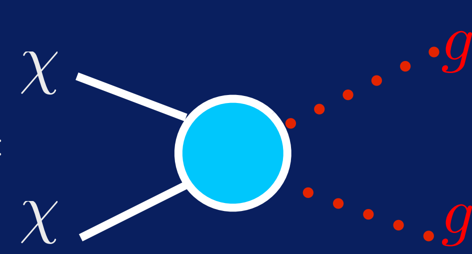

$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$




  - Gluons:




$$\sim \frac{\alpha_S}{4\pi} \frac{g^2}{M_{\mathcal{C}} M_{\tilde{\mathcal{C}}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$




  - Each requires new states with masses heavier than the WIMP.

# 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 $\alpha_S$, 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 | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | $1$ | $1$ |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | $1$ |
| M3 | $qq$ | $im_q/2M_*^3$ | $1$ | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

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

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

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

# 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

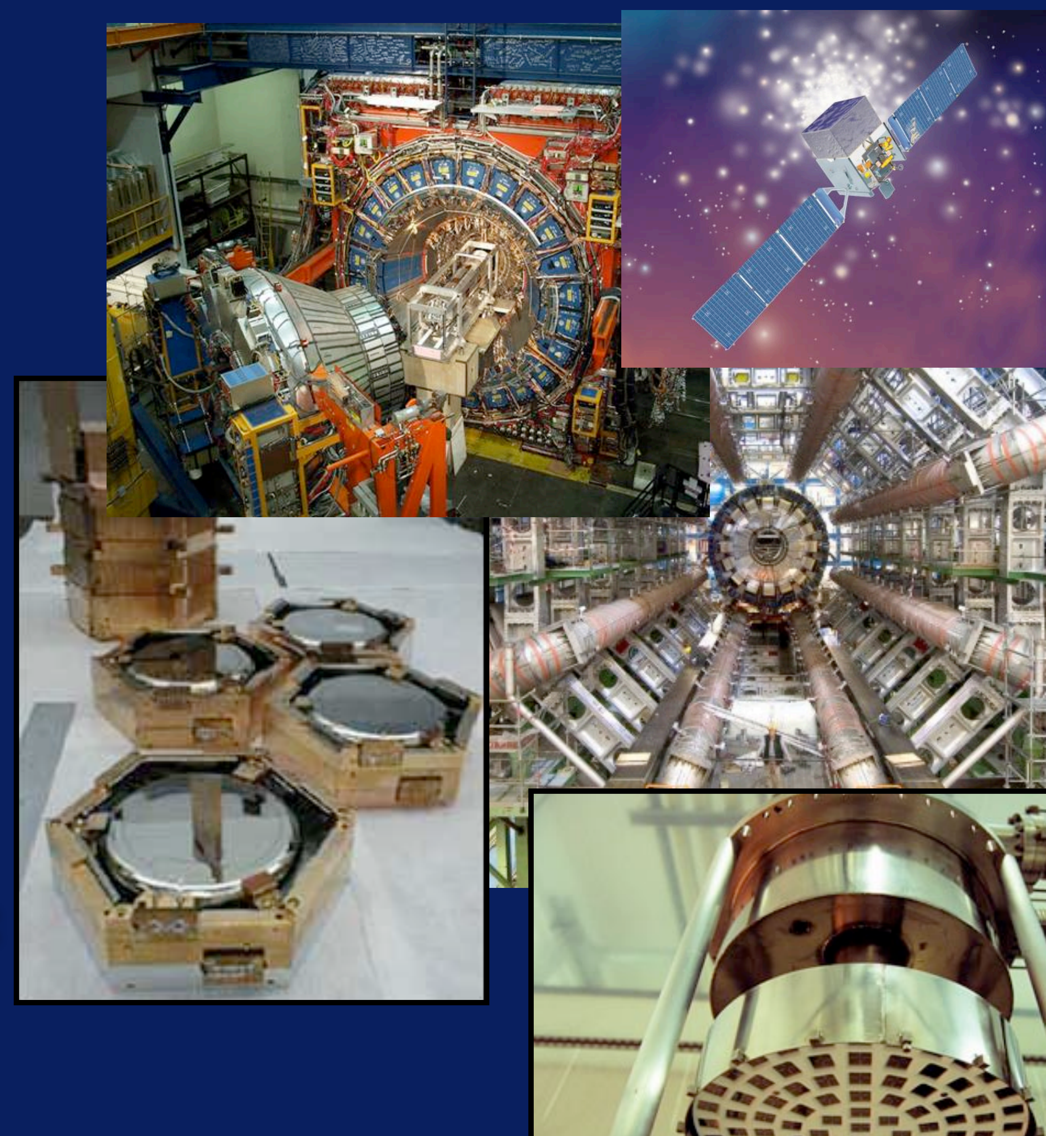
- We can play the same game with scalar WIMPs, both real (R) and complex (C).
- Vector interactions of a real WIMP can be rewritten using the equations of motion in terms of scalar operators.
- As with the Dirac WIMPs, we assume a complex scalar WIMP is not asymmetric -- the dark matter of the Universe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

| | | |
|---|---|---|
| R1 | $\chi^2 \bar{q} q$ | $m_q / 2M_*^2$ |
| R2 | $\chi^2 \bar{q} \gamma^5 q$ | $i m_q / 2M_*^2$ |
| 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 | $\chi^\dagger \chi \bar{q} \gamma^5 q$ | $i m_q / M_*^2$ |
| 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 | $\chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$ | $i\alpha_s / 4M_*^2$ |

# Confronting Experiments

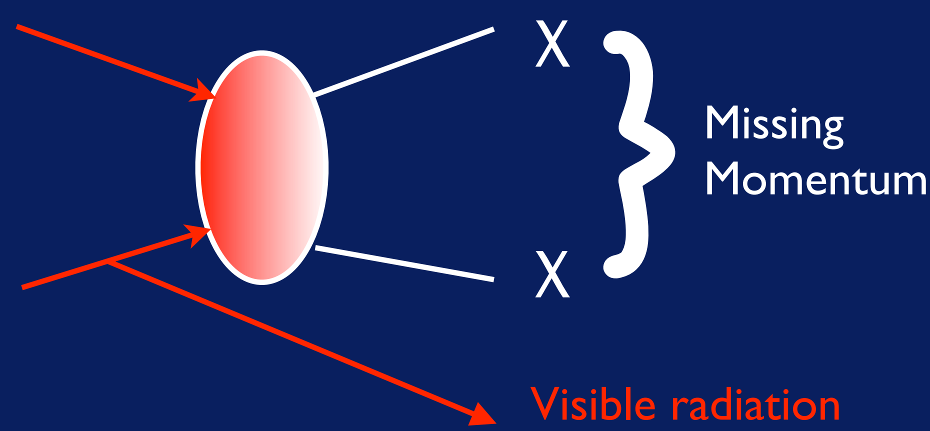
- Collider searches
  - CDF
  - LHC
- Direct Detection
  - Spin-independent
  - Spin-dependent
- Gamma rays
  - Fermi / GLAST line search
- For comparison, I'll look at the relic density, but this is not a bound the same way null search results are.



# Collider Searches

# Jets + Missing Energy

- We look at a more generic signature, where the WIMPs are pair-produced from incoming partons and recoil against a jet.
- 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.

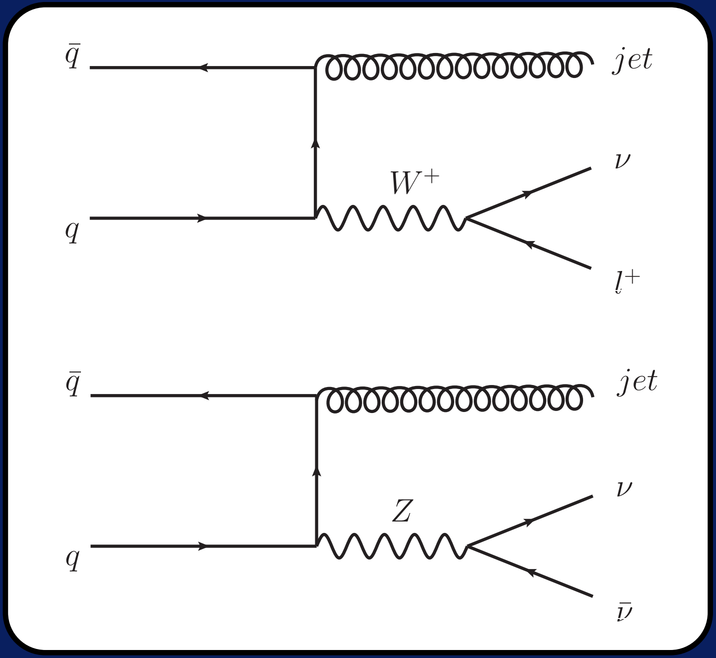



Based on 1 $fb^{-1}$, CDF constrains new physics (after cuts) $\sigma < 0.6$ pb.

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

# Backgrounds

- To calibrate our simulations, we reproduced the CDF background using MadEvent with PYTHIA and PGS.
- 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 didn't try to simulate it).

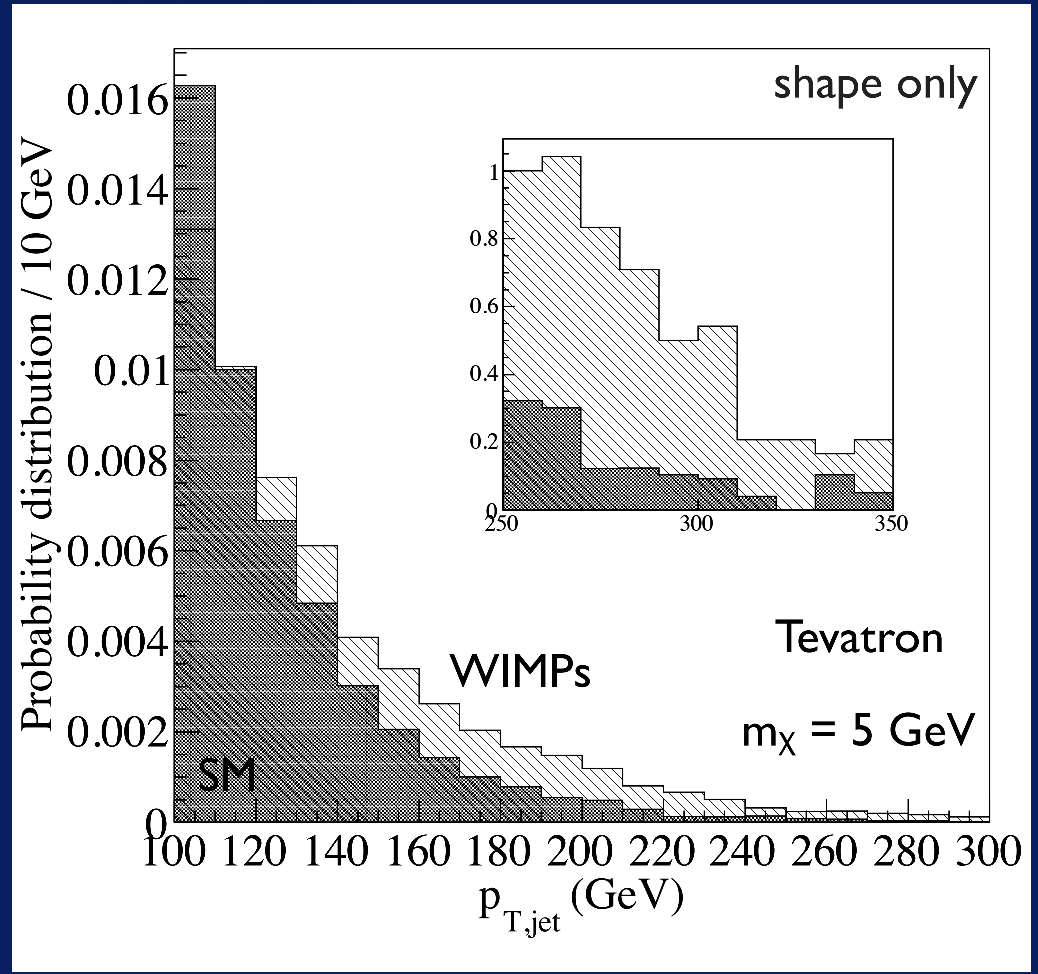


# Signal and Background

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

- At the parton level, there is a 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

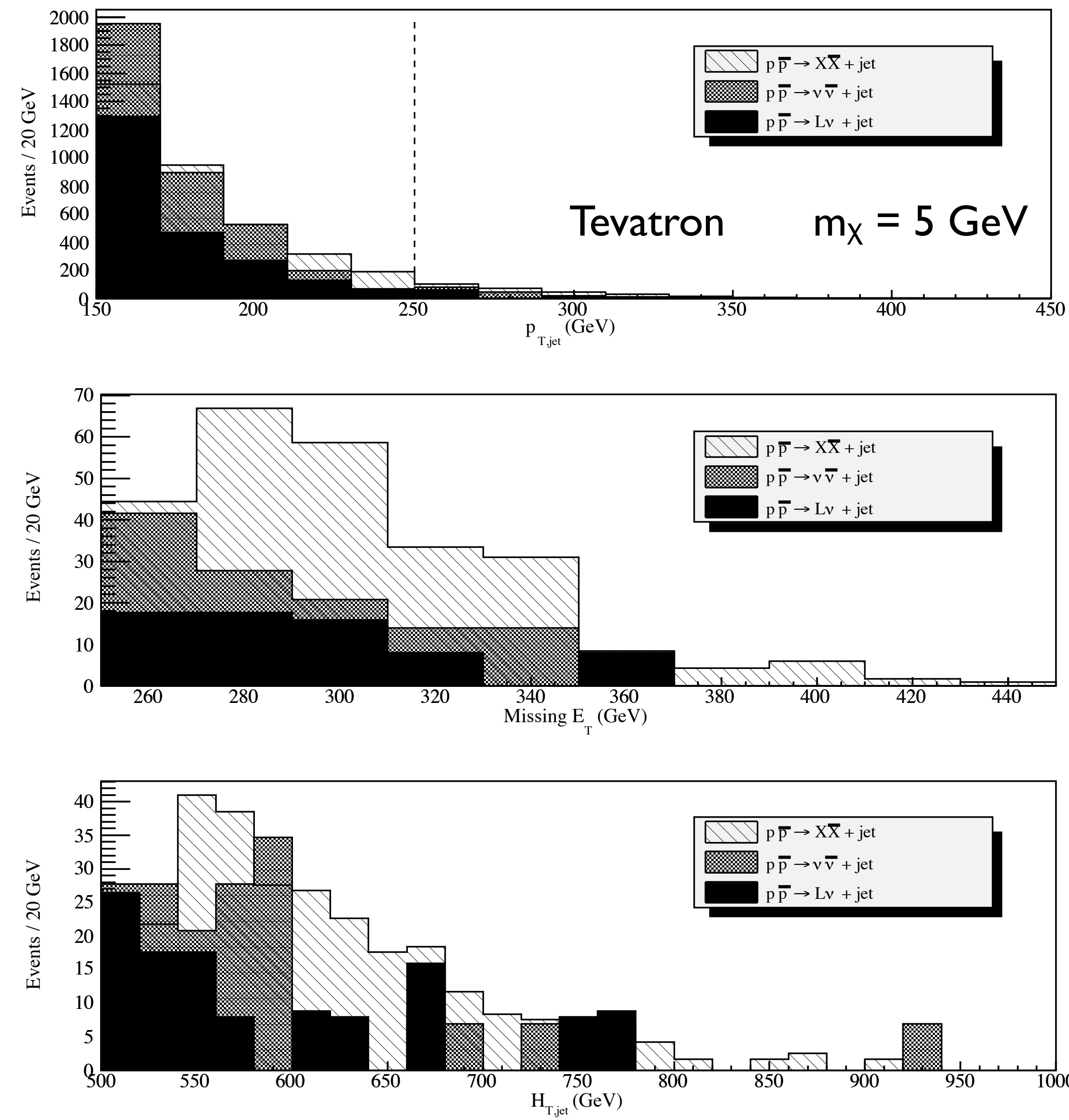



M6: $[\bar{\chi}\gamma^\mu\gamma_5\chi]\,[\bar{q}\gamma_\mu\gamma_5 q]$

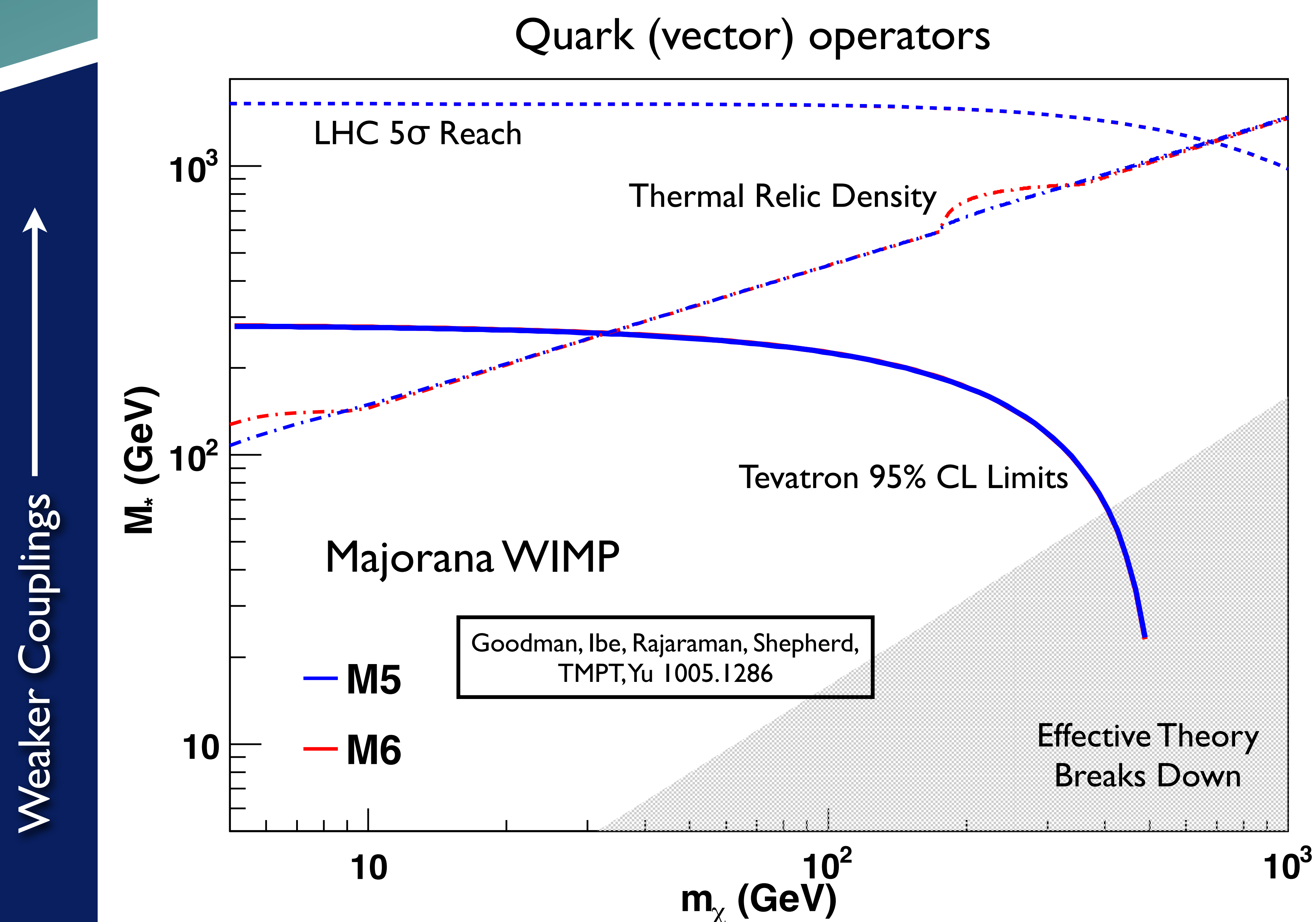
# Beyond the Parton Level

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

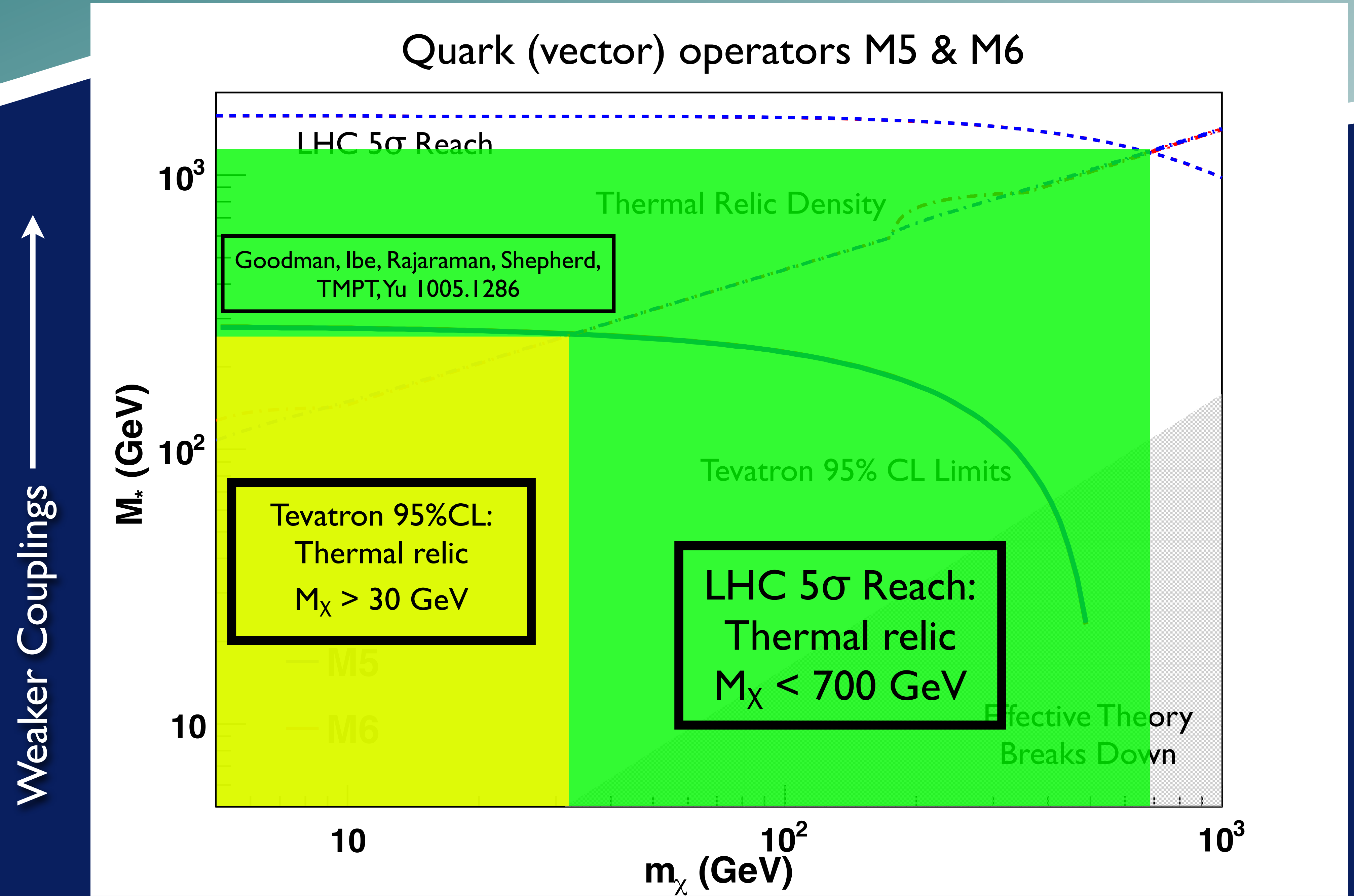
- These differences survive parton showering and hadronization (simulated by PYTHIA) and detector response (simulated by PGS in its default CDF detector model).
- Our detailed study suggests that one can probably optimize a search and do better than the CDF monojet search aimed at Large Extra Dimensions.



# Example Limits/Sensitivity



# Example Limits/Sensitivity



# Axial-vector Coupling

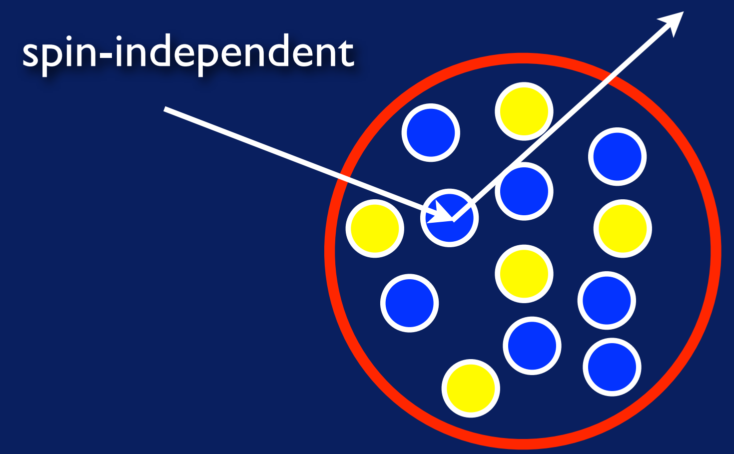
- These operators were particularly amenable to collider searches.
  - They both lead to velocity suppressed WIMP annihilation cross sections.
  - The relic density requires that they have somewhat strong coefficients to over-come the velocity suppression.
- The collider signal produces the WIMPs relativistically,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

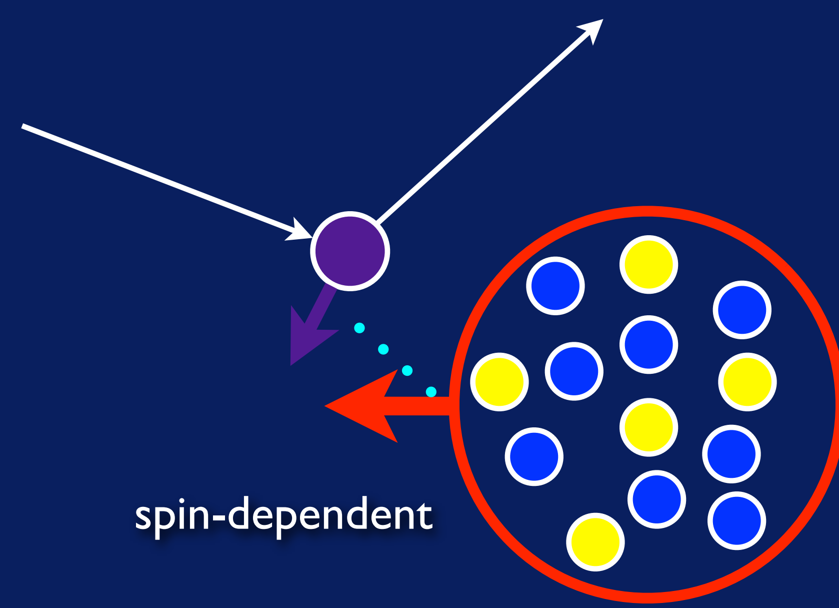
| Name | Type | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | 1 | 1 |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | 1 |
| M3 | $qq$ | $im_q/2M_*^3$ | 1 | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | 1 | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | 1 | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

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.



# Direct Detection

- Our operators can also be translated into direct detection experiments.
- Only a subset of operators contribute to non-velocity-suppressed WIMP scattering with a heavy nucleus.
  - Three types of operators potentially contribute to spin-independent scattering.
  - Two operators potentially contribute to spin-dependent scattering.
- We follow the usual procedure and quote WIMP-nucleon cross sections.
- Many operators have very weak direct detection bounds -- they are v-suppressed.

Spin-independent:

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

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

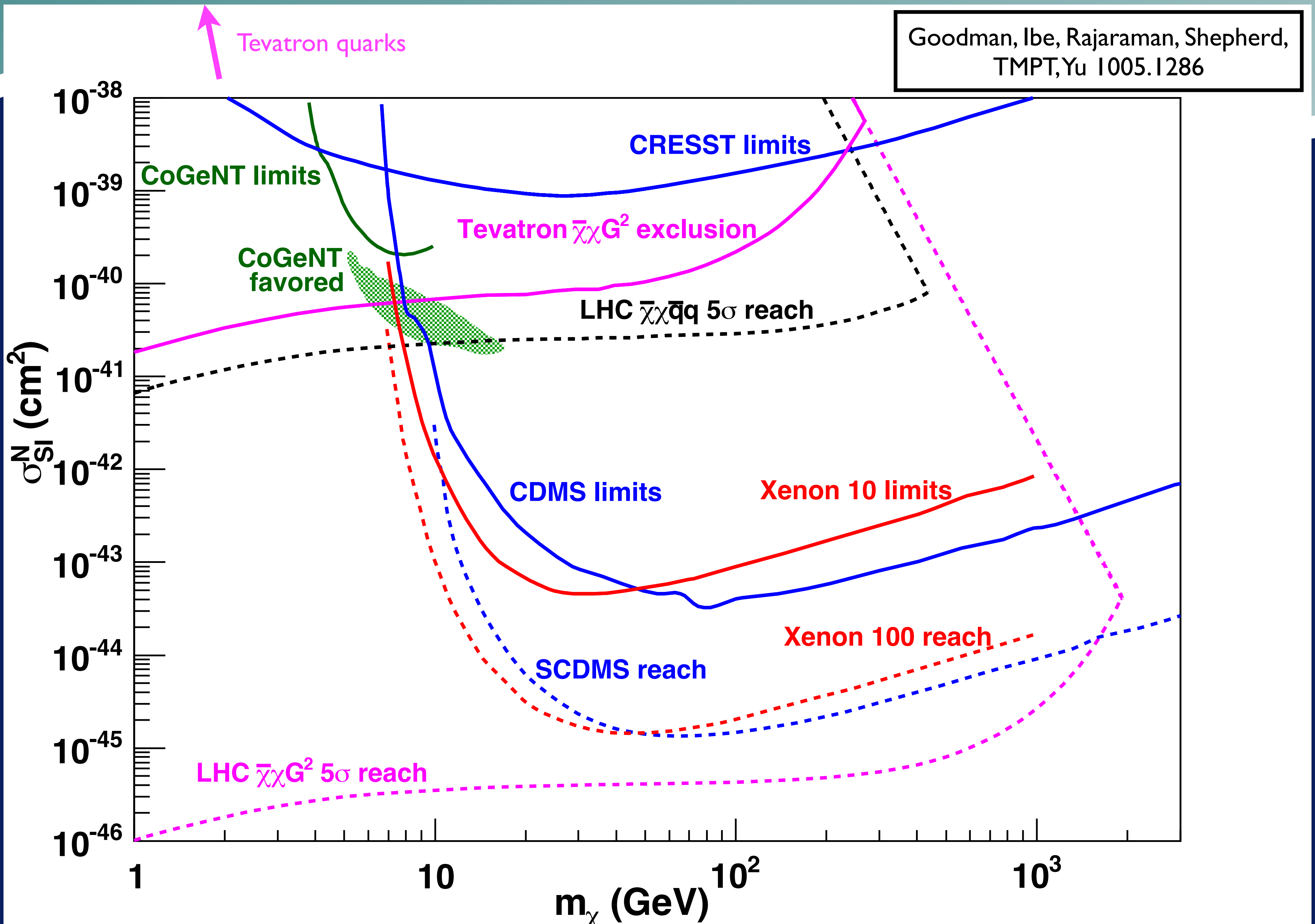
$$\alpha_S G^a_{\mu\nu} G^{a\ \mu\nu}$$

Spin-dependent:

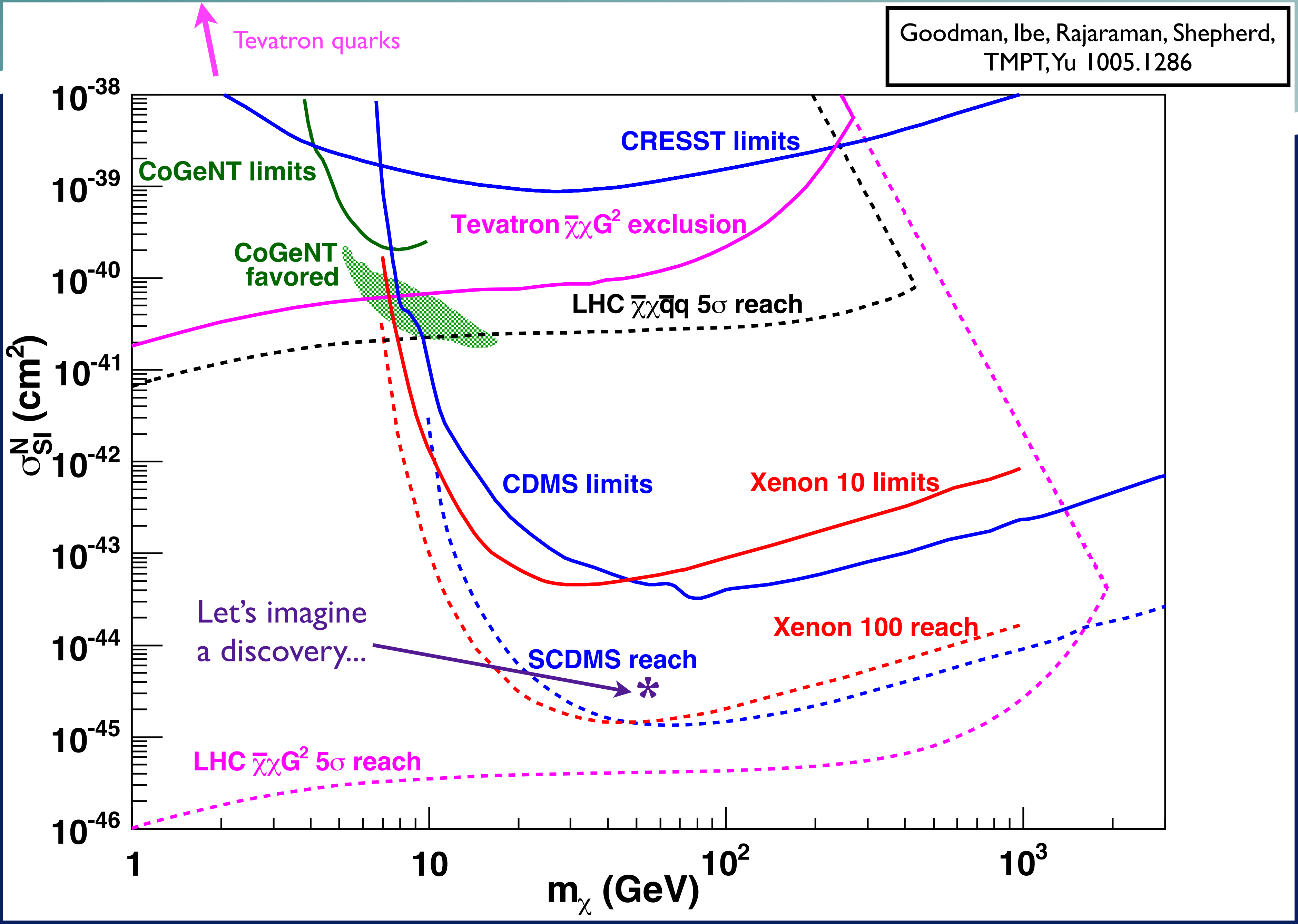
$$\sum_q \bar{q} \sigma^{\mu\nu} q$$

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

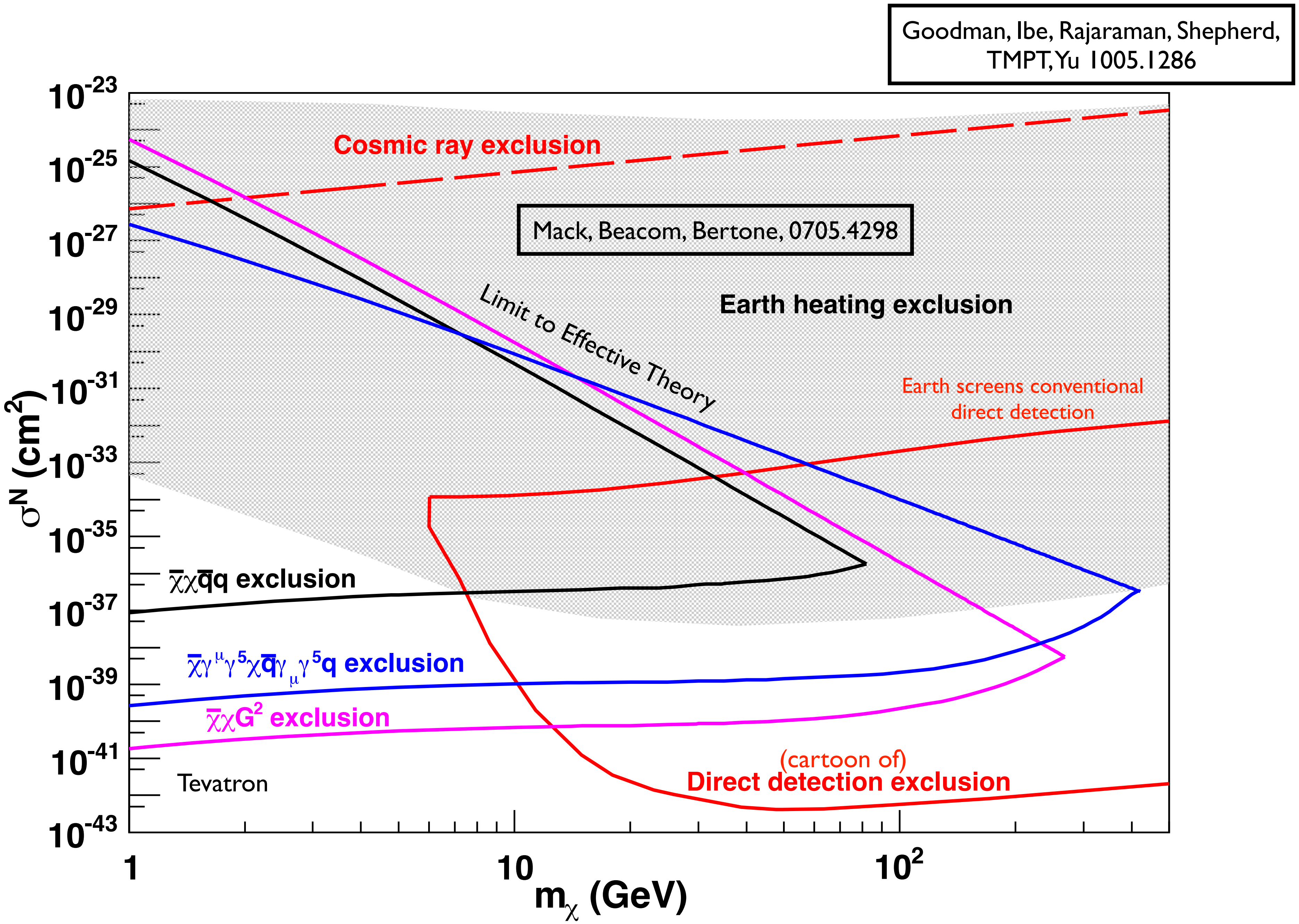
# Spin-Independent



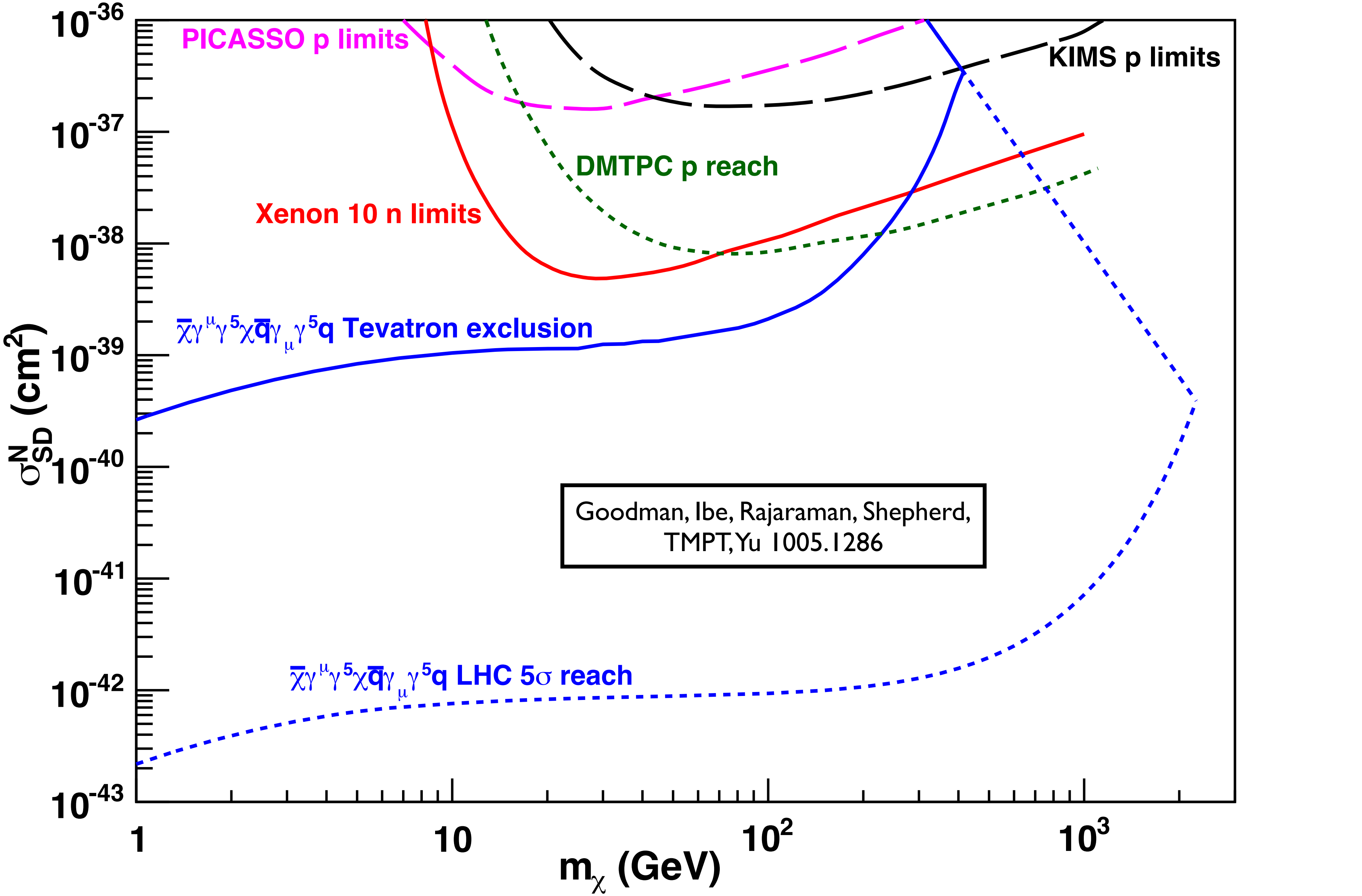
# Spin-Independent



# From WIMPs to SIMPs...

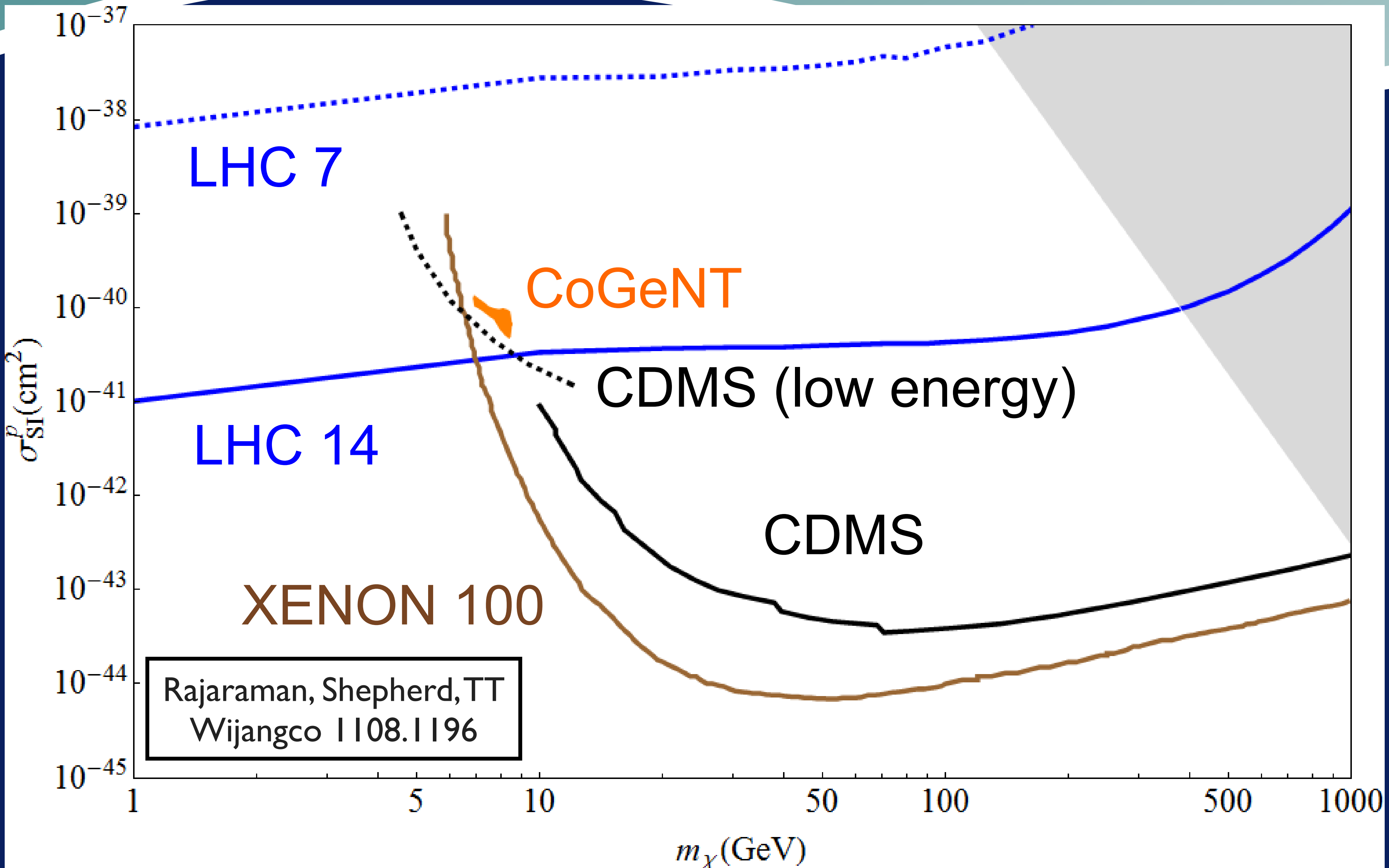


# Spin-Dependent



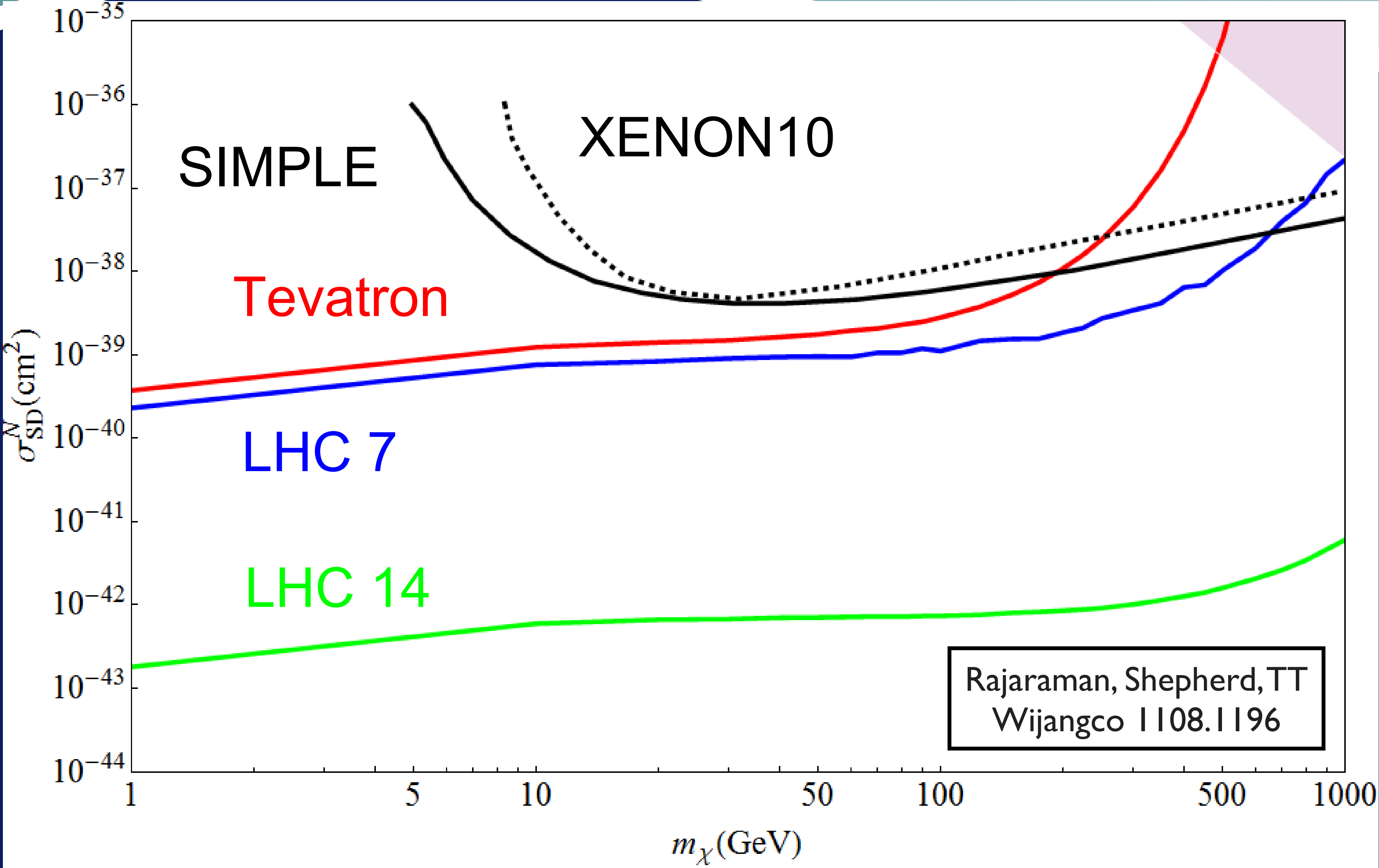
# ATLAS Bounds: SI

Equal u- and d- couplings

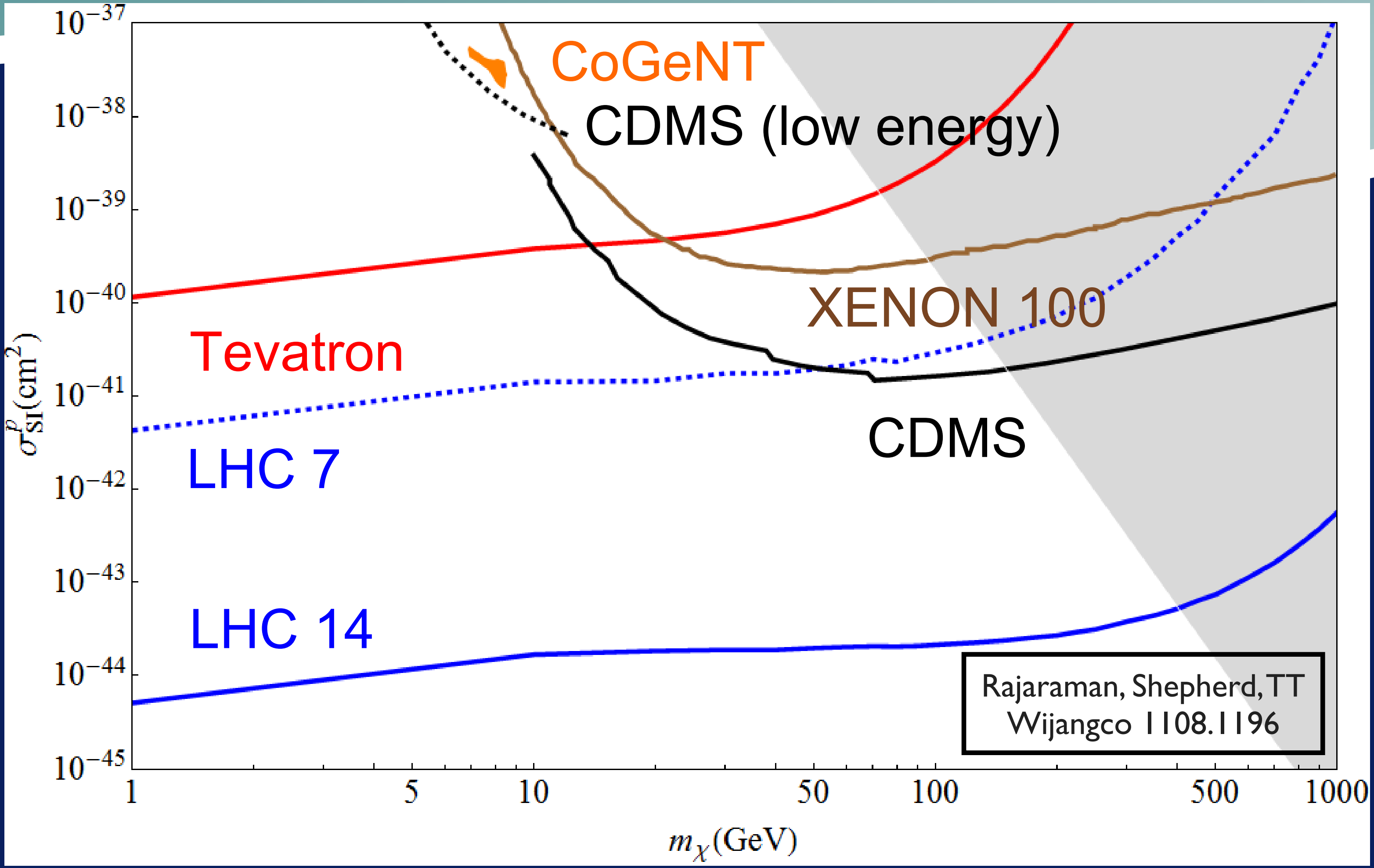


# ATLAS Bounds: SD

Equal u- and d- couplings



# Iso-spin Violating

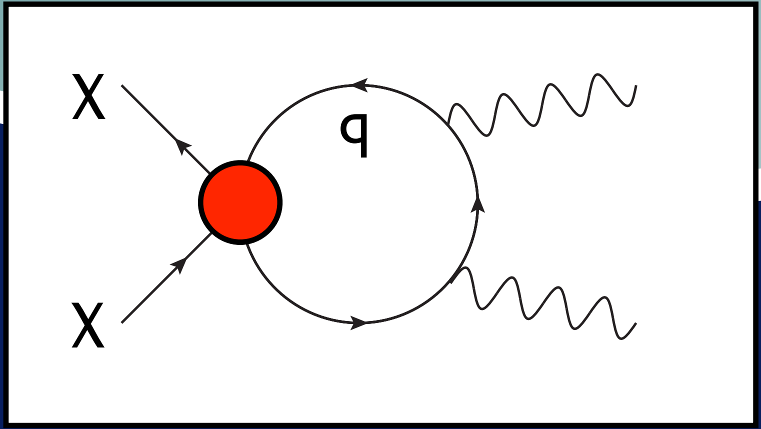


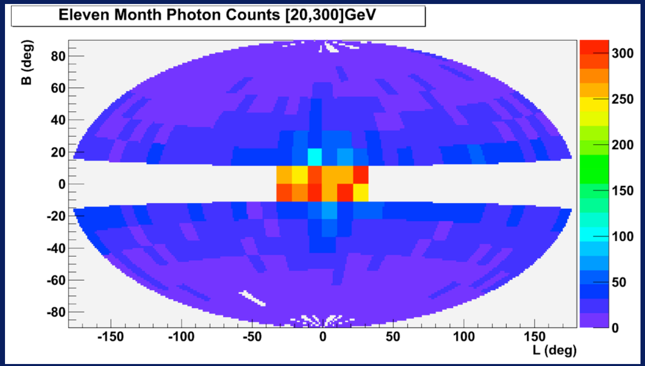

- For up- and down-quark couplings adjusted such that fn ~ -0.7 fp, constraints from Xenon are much weaker than the CoGeNT signal.
- Naive MFV implementations are ruled out by colliders, but specific non-MFV constructions survive.

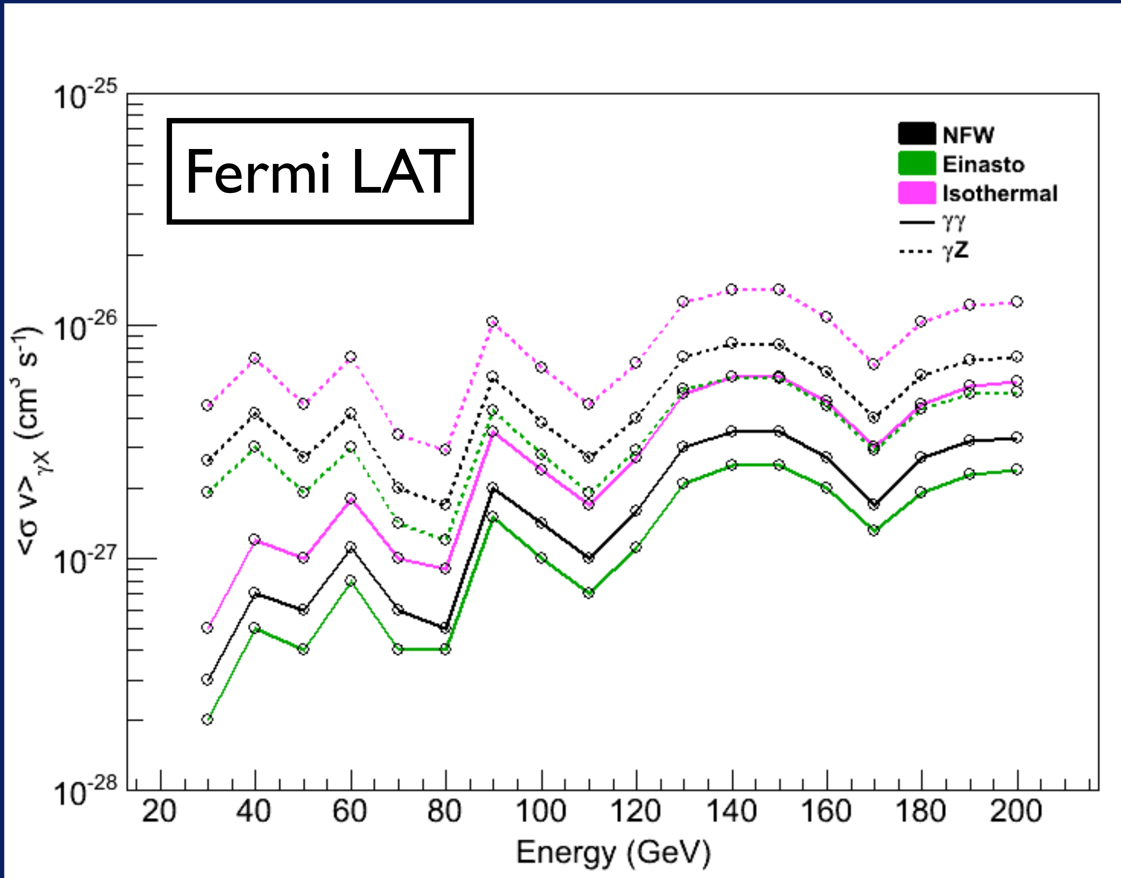
Feng, Kumar, Marfatia, Sanford 1102.4331 (see also: Chang, Pierce, Weiner 1004.0697)

# Line Limits from Fermi

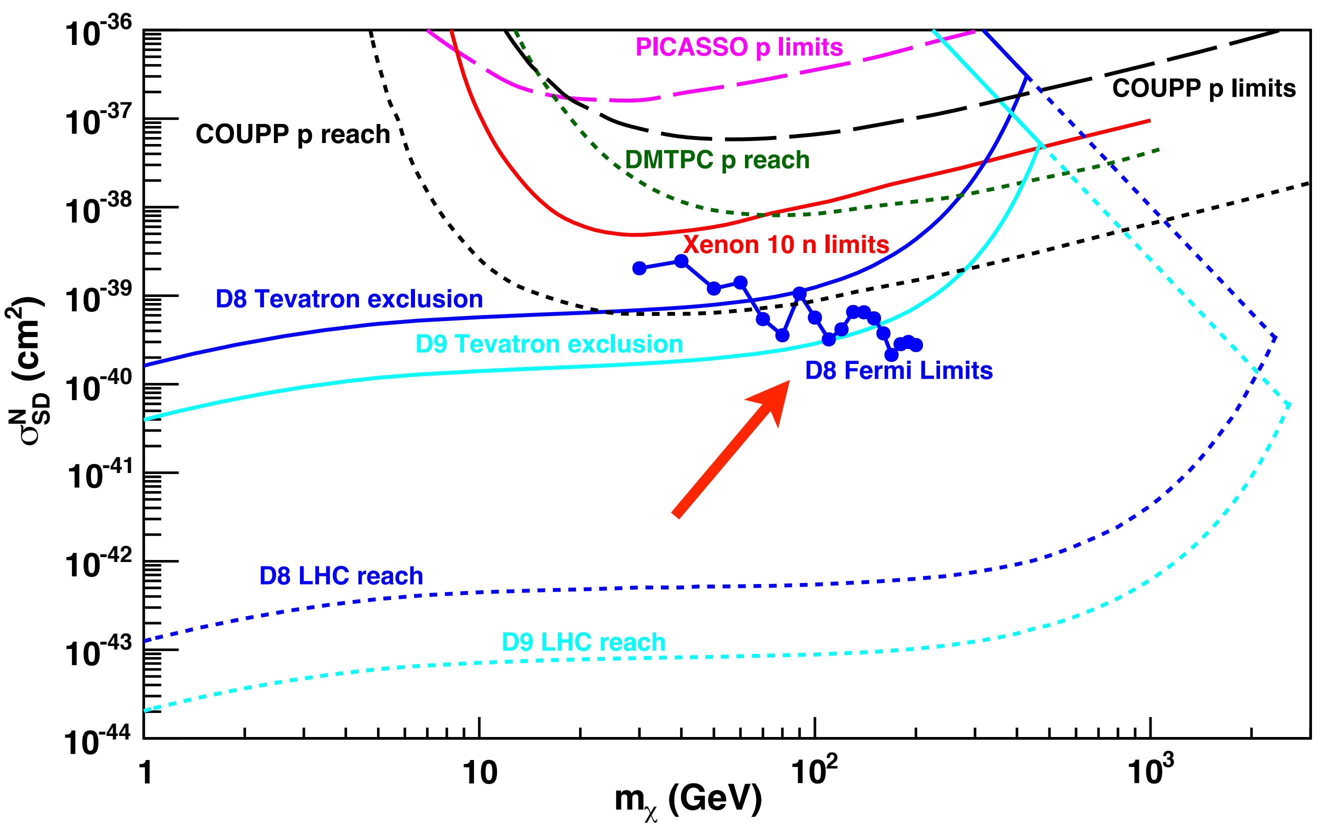
- If we close our operators into a loop an attach photons, we have a process where two WIMPs annihilate producing mono-energetic gamma rays.
- We can learn about our operators from the Fermi (null) line search.
    - Bounds depend on the galactic distribution of dark matter.



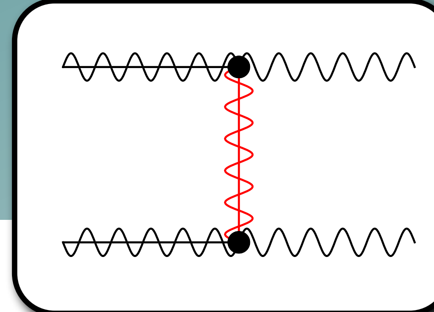



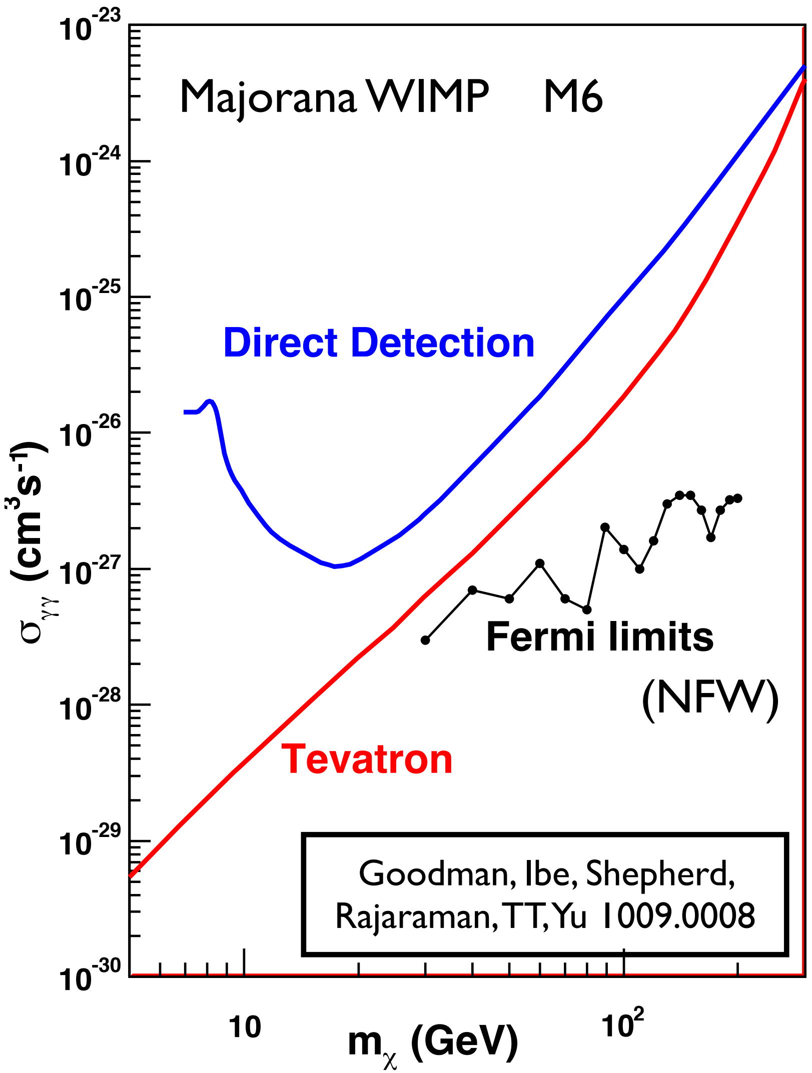
# Spin-dependent

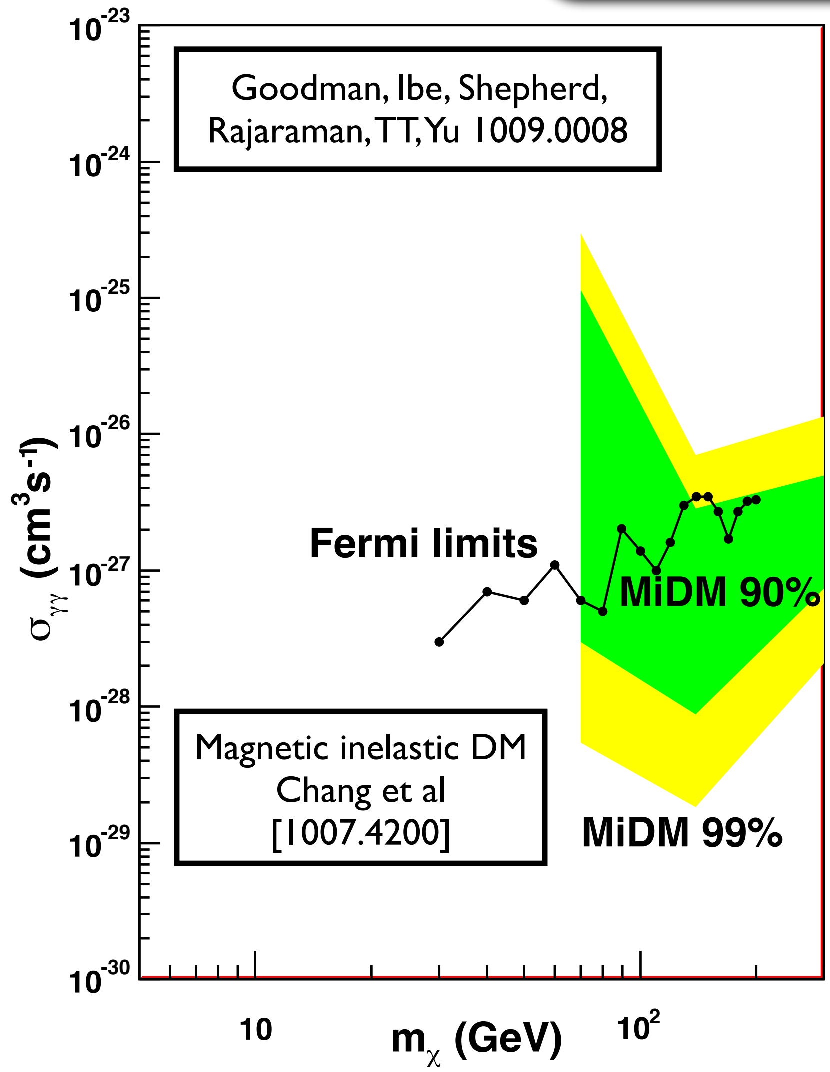



- Colliders already do an excellent job for spin-dependent scattering WIMPs.
  - Tevatron limits are better than existing or near future direct limits, except at large masses.
- The line search is competitive with the Tevatron for medium masses.

# Line Cross Section



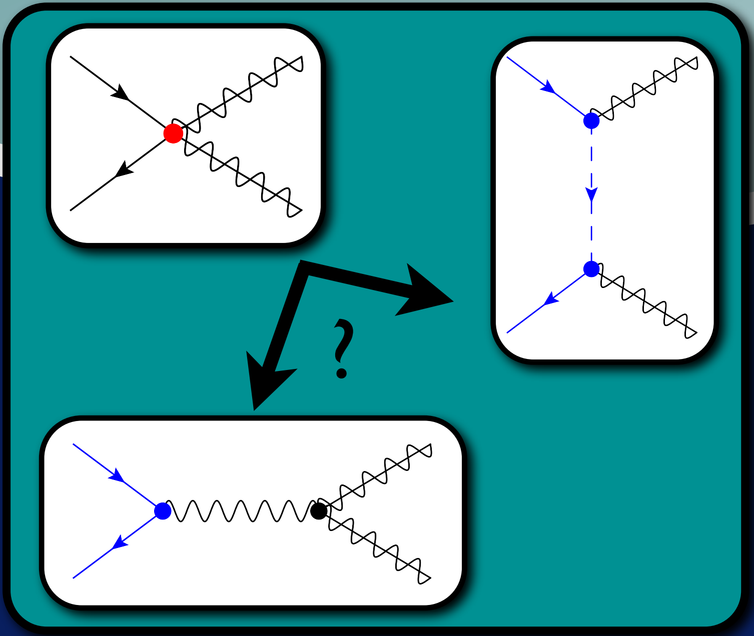


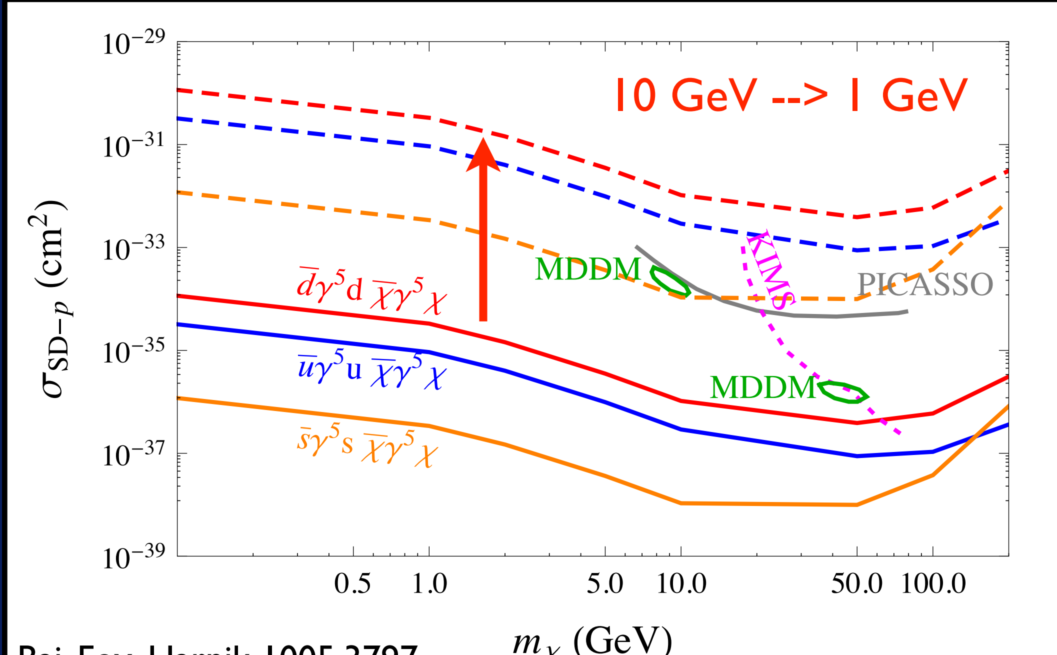




For LEP constraints, see: Fox, Harnik, Kopp, Tsai 1103.0240; Fortin, TMPT 1002.3289

# How Effective a Theory?

- How good is the EFT approximation?
- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \text{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in SUSY-like theories, problematic for quirky WIMPs or maybe co-annihilators.
- Colliders: $Q^2 \sim p_T^2$
  - Bounds are generically too conservative for colored mediators.
  - Too stringent for light neutral mediators.




Bai, Fox, Harnik 1005.3797

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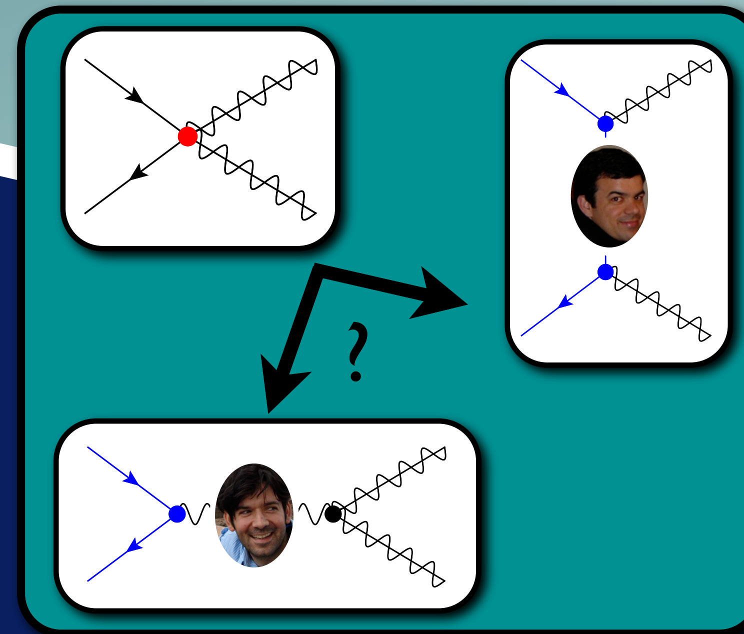
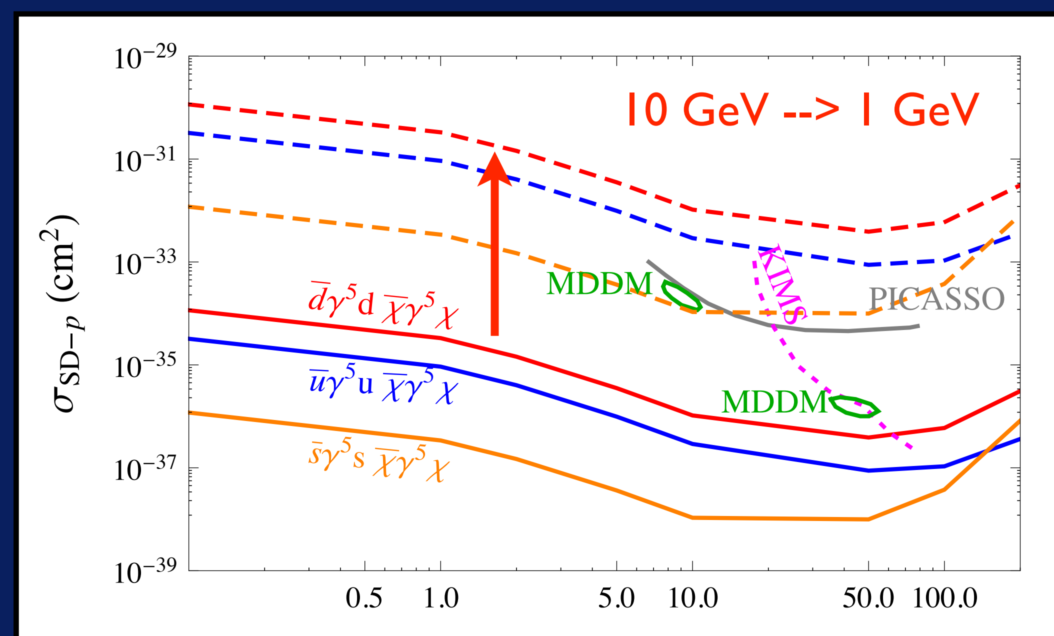


Bai, Fox, Harnik 1005.3797

# Outlook

- Effective field theories can be used to study WIMP interactions, and provide a common language for direct, indirect, and collider searches.
- Colliders can provide interesting bounds on WIMPs. In this specific case, we have looked at theories where bounds don't originate from production of some exotic colored particle which decays into WIMPs.
    - Where this assumption does not hold, bounds could get stronger or weaker, depending on how one UV-completes the operator description.
- Already, Tevatron puts interesting constraints on spin-dependent interactions which are stronger than direct searches.
- LHC has a large degree of complementarity with spin-independent searches.
- Line searches contribute something unique, particularly for scalar WIMPs.

# Outlook

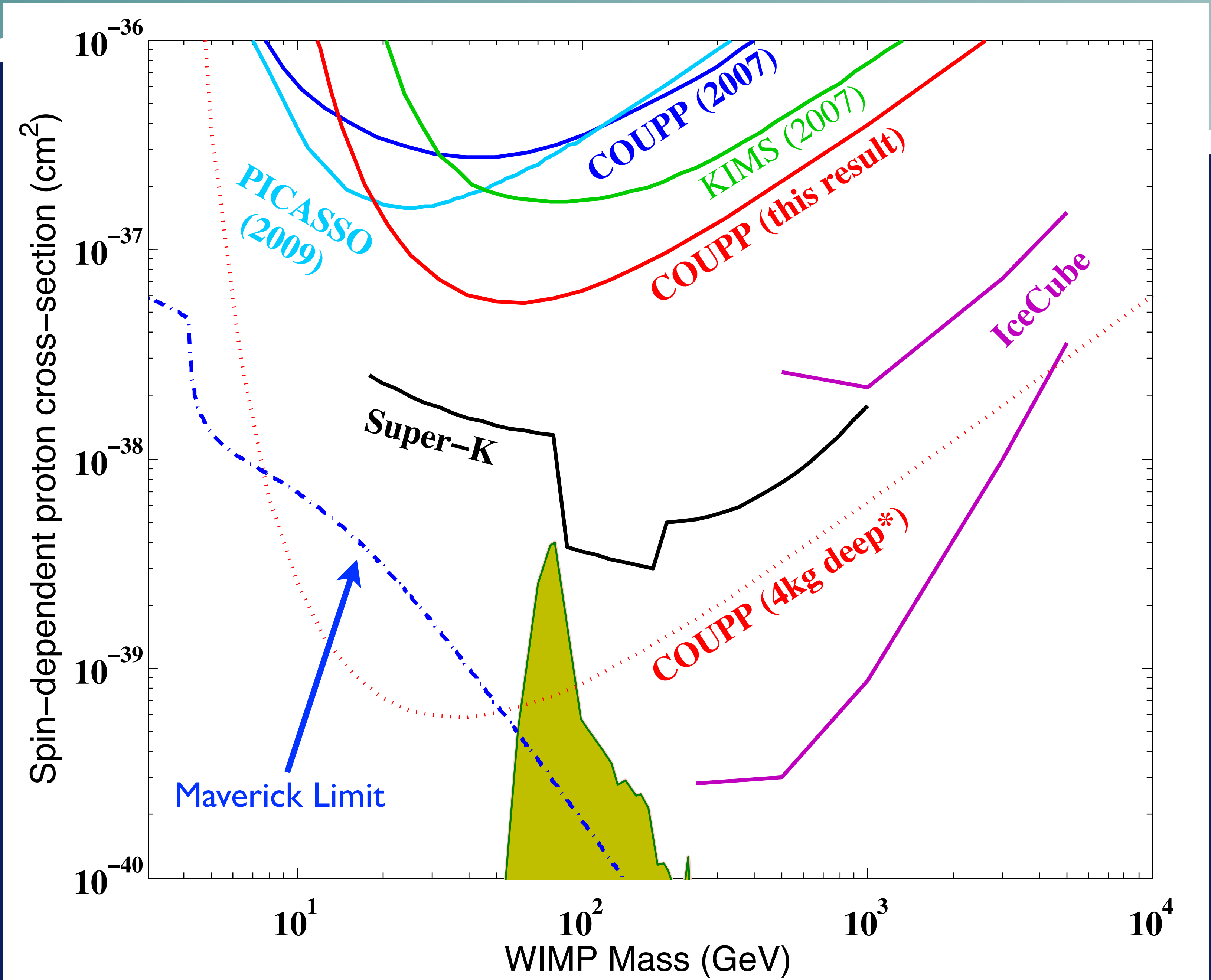
- One could extend these kinds of analyses to cover other cases:
  - Electroweakly charged WIMPs
  - Higgs interactions
  - Couplings to Leptons
  - Different kinds of light mediators/more complicated hidden sectors.
- Once we start to see signals, comparing them can favor some EFT operators over others.
  - This is the first step to understanding the UV theory!
- Together, direct, indirect, and collider searches offer a more complete picture of dark matter interactions with the Standard Model.

# Bonus Material

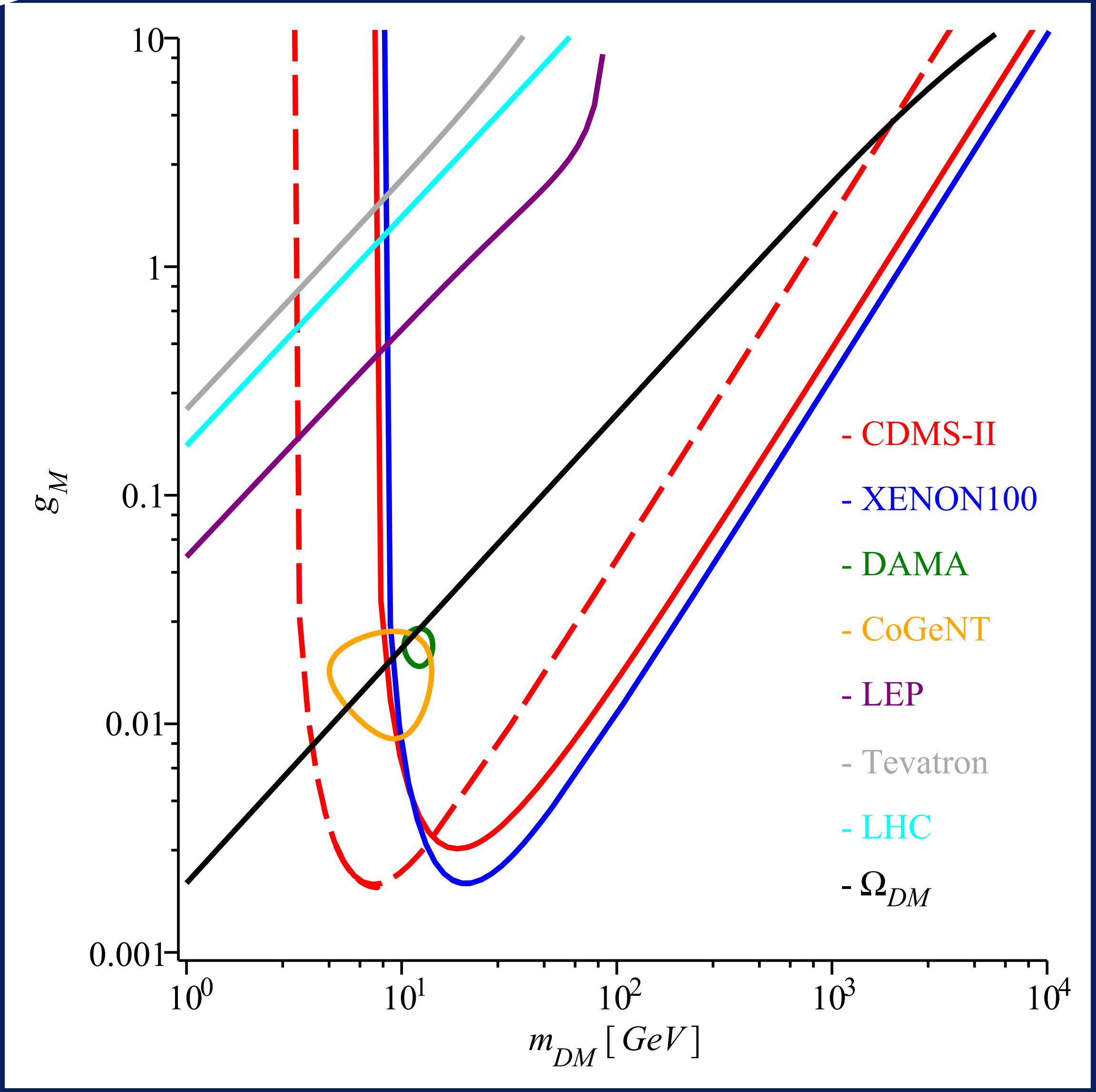
# ATLAS Monojets

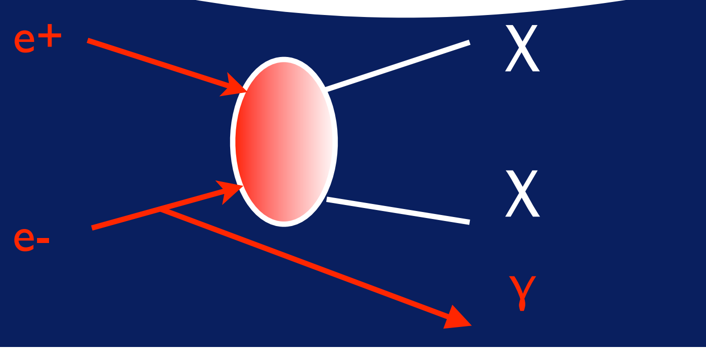
- “Very High PT”:
  - MET > 350 GeV.
  - Leading jet > 300 GeV.
  - 2nd jet < 60 GeV.
  - 3rd jet < 30 GeV.
- 95% CL on signal cross section: 0.035 pb.

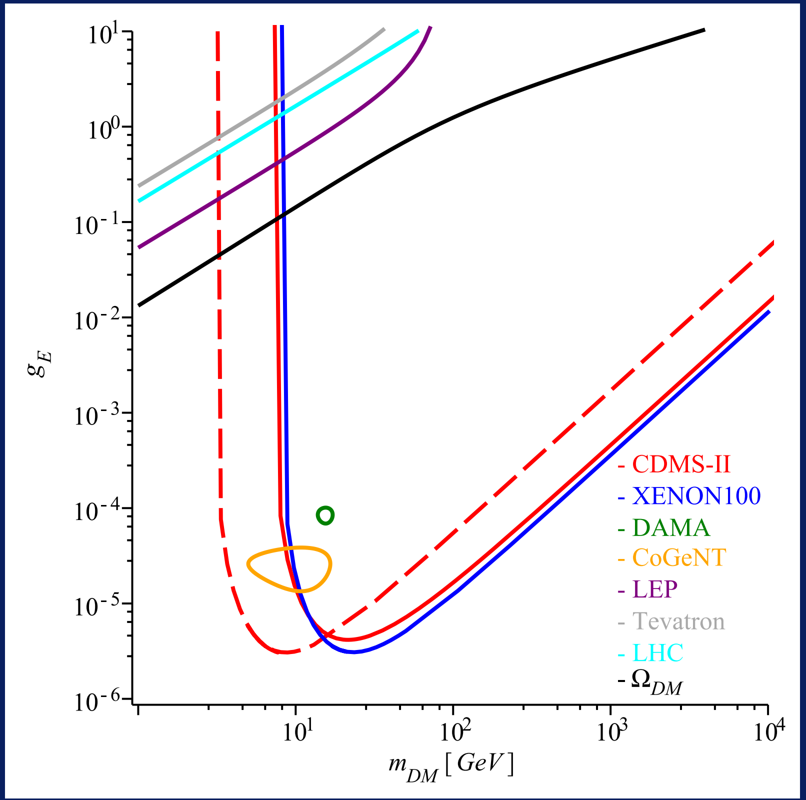
# COUPP Limits



# Dipole Interactions

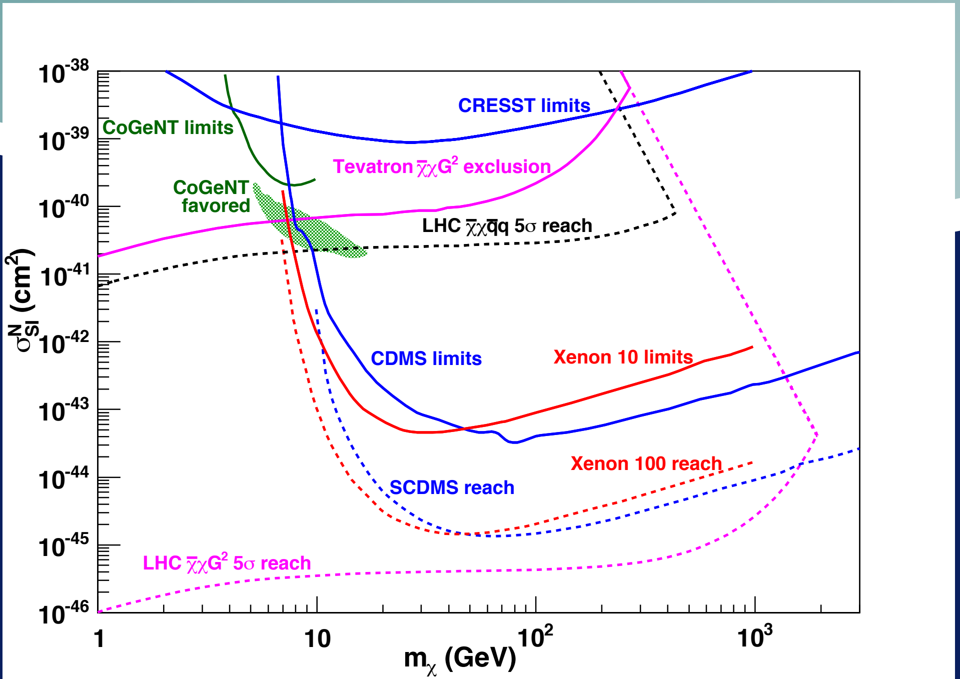


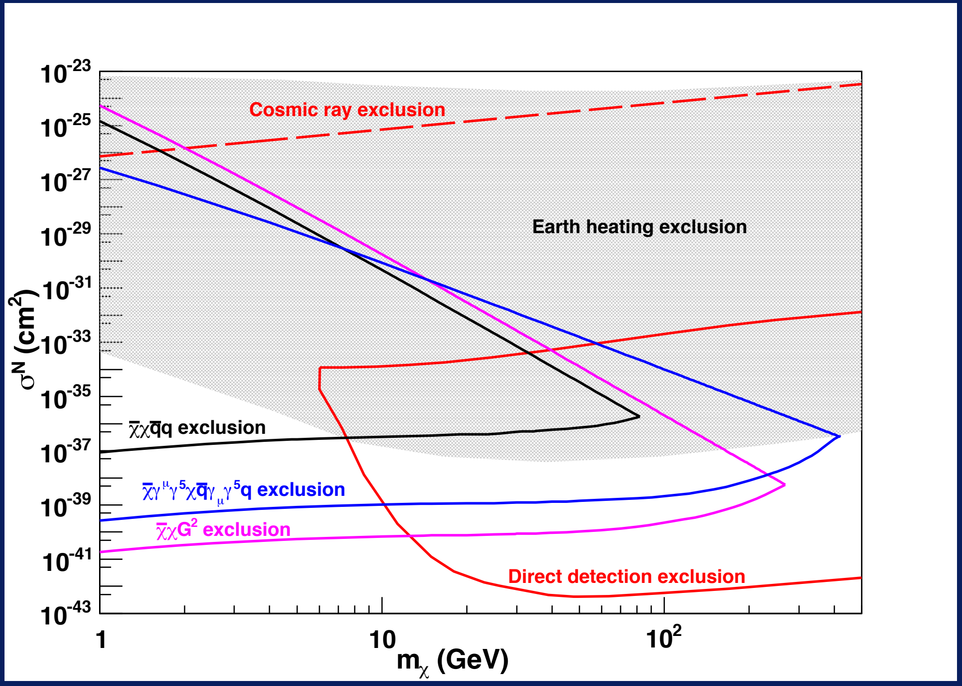



# Collider/Direct Synergy

- For spin-independent scattering, colliders and direct searches show a lot of complementarity.
  - Colliders win at low WIMP masses and for gluon interactions.
  - Direct detection can reach much lower cross sections for quark-scattering at ~100 GeV masses.
  - Tevatron already says something about the DAMA/CoGeNT low mass region; LHC will say a lot.
  - A DD signal without an LHC discovery would tell us the DD signal is not a gluon coupling.



# Limits of Effective Theory

- Our effective theory description breaks down if there are multiple states beyond the WIMP accessible at a given energy.
  - Extra states can be added to the effective theory description.
  - Direct detection is pretty insensitive to such states, because the energy transfer is so limited.
    - But remember inelastic scattering!
  - At colliders, it is much less clear we won't be accessing multiple states. If so, operators may be UV-completed, and this may affect the collider bounds.
    - If the "excited" WIMP state in inelastic scattering looks like missing energy (on detector scales), our bounds will continue to hold!
- For $\Lambda < M_X / (4\pi)$, there can be no perturbative UV completion: we won't try to say anything at all in this regime.

# Effective Theory

- For given choices of the WIMP spin, EW representation, etc, we can construct an effective theory describing interactions with the SM:
  - For example, a complex scalar WIMP that is an EW singlet:

$$\lambda|\chi|^2|H|^2 + \sum_f \left\{ \frac{y_f}{\Lambda_f^2}|\chi|^2 H \bar{f}_L f_R + \frac{1}{\Lambda_{f_R}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left[\bar{f}_R \gamma^\mu f_R\right] + \frac{1}{\Lambda_{f_L}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left[\bar{f}_L \gamma^\mu f_L\right] \right\}$$

$$+\frac{1}{\Lambda_{H4}^2}|\chi|^2|H|^4 + \frac{1}{\Lambda_{DH}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left(H^\dagger D^\mu H\right) + \frac{1}{\Lambda_W^2}|\chi|^2 W_{\mu\nu}W^{\mu\nu} + \frac{1}{\Lambda_B^2}|\chi|^2 B_{\mu\nu}B^{\mu\nu} + H.c.$$

Shepherd, TT, Zaharijas
arXiv:0901.2125 (PRD)

  - This example has a conserved $U(1)_\chi$.
  - Each parameter Λ (and λ) is a (different) coupling, and in principle is something to measure in order to understand the particle physics of WIMPs.
  - The theory is a power series in 1 / Λ's, descriptive for energies < Λ.

# "Model Independent"

- There is a different effective theory for different choices of spin, complexity, EW representation, etc, for the WIMP.
  - Many important properties (such as spin-suppression) are evident even in the effective theory.

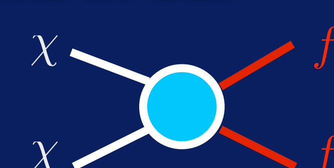
χ real:

$$\sum_f \left\{ \frac{y_f}{\Lambda_f^2} \chi^2 H \bar{f}_L f_R + \frac{1}{\Lambda_{f_R}^2} \left( \chi \overleftrightarrow{\partial}_\mu \chi \right) \left[ \bar{f}_R \gamma^\mu f_R \right] + \frac{1}{\Lambda_{f_L}^2} \left( \chi \overleftrightarrow{\partial}_\mu \chi \right) \left[ \bar{f}_L \gamma^\mu f_L \right] \right\}$$

$$\to \frac{y_f}{\Lambda_f^2} \chi^2 H \bar{f}_L f_R$$

- In principle, for any fundamental theory of WIMPs, I can map the parameters of the theory onto the effective interactions in our Lagrangian.


$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



# Operators

- For both colliders and direct detection, the most relevant operators are the ones which connect WIMPs to quarks or gluons.
- I'll focus on the case in which the (Majorana) WIMP is the only accessible new physics to a given experiment -- a "Maverick" particle.
- This limits the leading operators of interest to the set of 10 which preserve Lorentz and gauge invariance. (Others can be Fierz'd into this form).
- We assume minimal flavor violation; leading terms in vector operators are universal and scalar operators are proportional to quark masses.

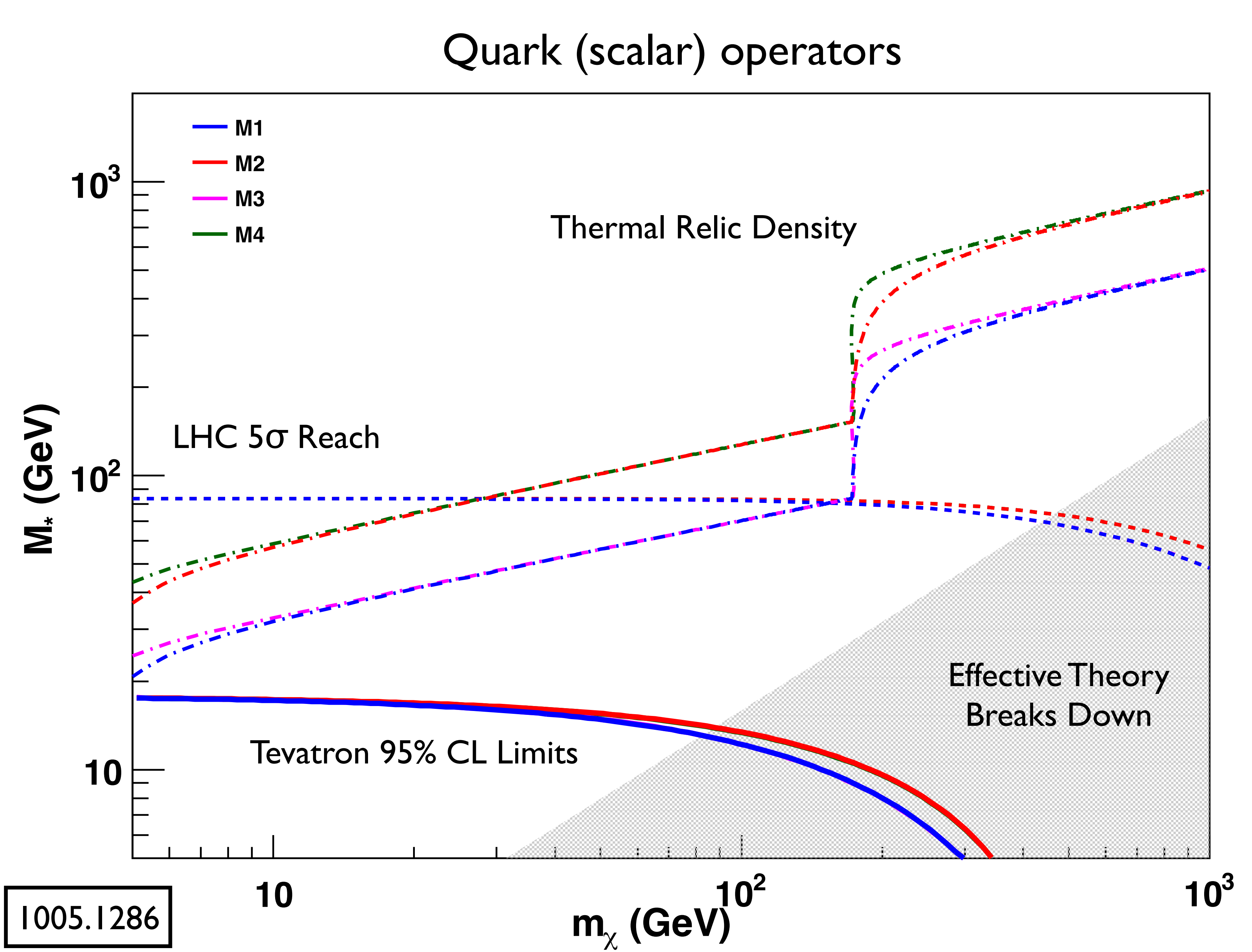
| Name | Type | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | 1 | 1 |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | 1 |
| M3 | $qq$ | $im_q/2M_*^3$ | 1 | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | 1 | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | 1 | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

(M* is what we previously called Λ.)

$$\sum_q \left[\bar{q}\Gamma^q q\right]\left[\bar{\chi}\Gamma^\chi\chi\right]$$

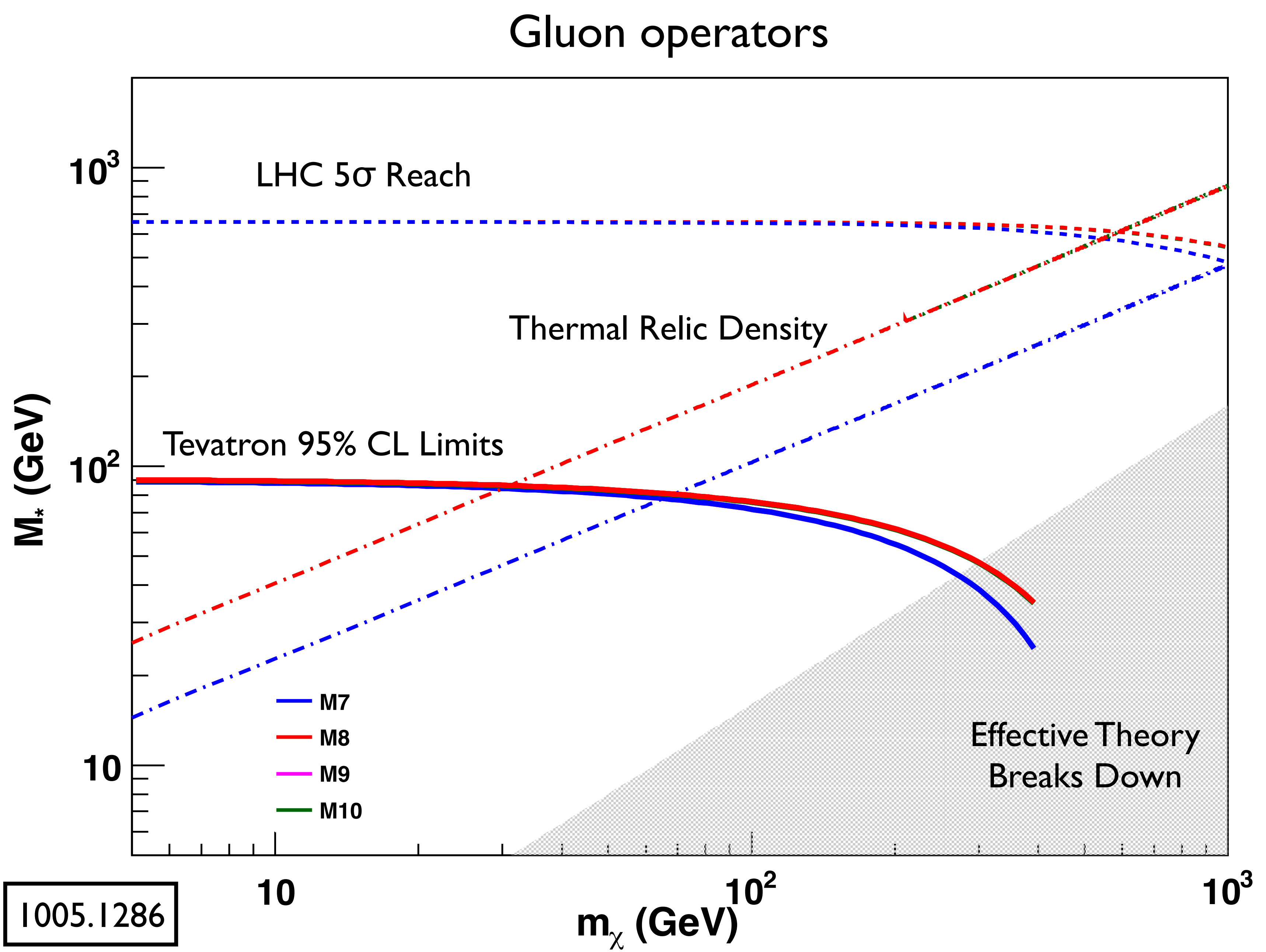
$$\left[\bar{\chi}\Gamma^\chi\chi\right] G_{\mu\nu}G^{\mu\nu}$$

# Limits/Sensitivity




1005.1286

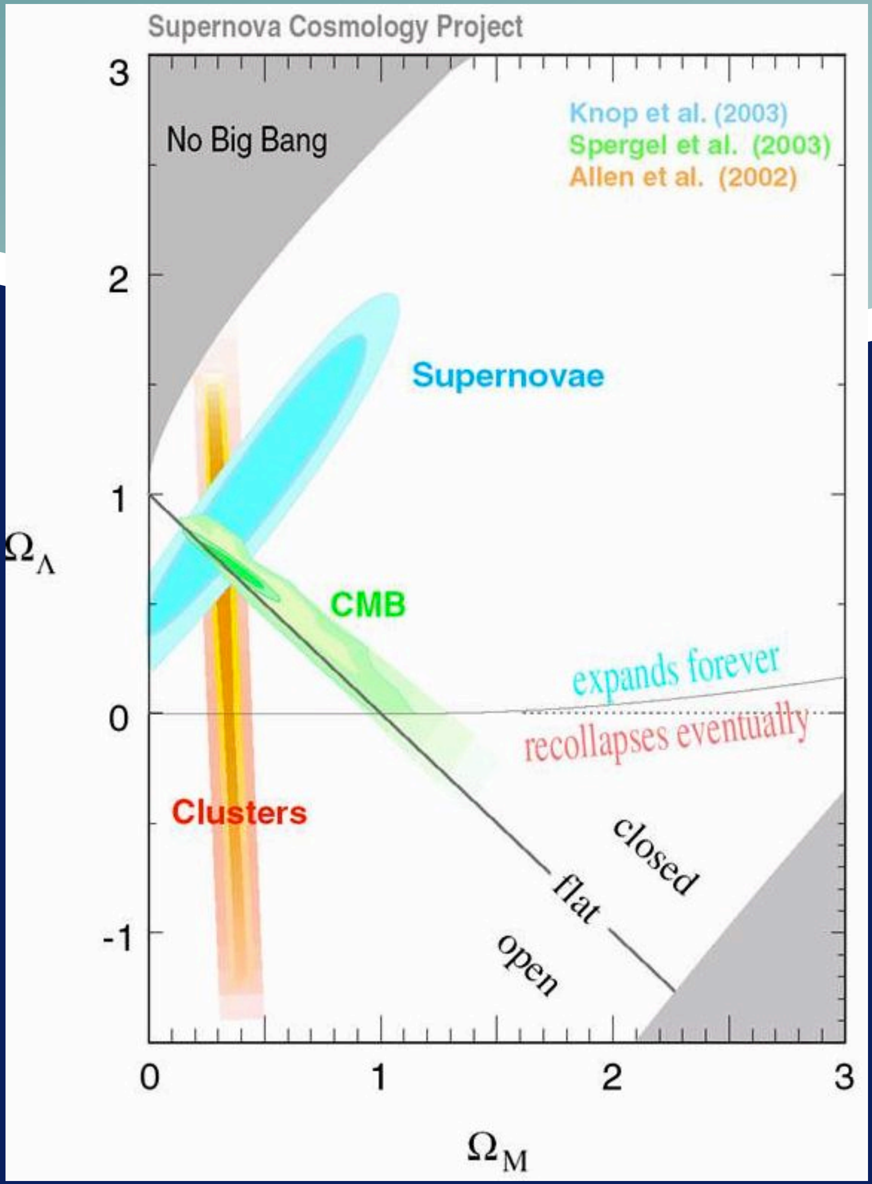
# Limits / Sensitivity




1005.1286

# Dark Matter

- The nature of dark matter is one of the defining questions for particle and astroparticle physics.
- Dark matter is one of the only iron-clad signs we have that there is physics beyond the Standard Model.
- Cosmological observations paint a convincing picture and tell us how much dark matter is needed to explain observations.
- For a particle physicist, that still leaves us asking what dark matter is and how it fits into a microscopic description of nature.




# 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.
  - 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 try to describe WIMPs model-independently.


$59.99 for 20 servings

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

# Categorizing WIMPs

- Dark matter is physics beyond the SM:
  - Neutral, massive, and (at least approximately) stable.
- That still leaves a lot unknown:
  - Spin
  - Electroweak charge
  - Real/Majorana or Complex/Dirac or ????
- The usual approach is to explore dark matter that occurs as a by-product of solutions to other problems.
  - That is probably going to be the case.
  - We  still need to be ready for a host of possibilities and variations.

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

Dark matter is an experimental "problem", and deserves its own theoretical description!

# WIMP Interactions

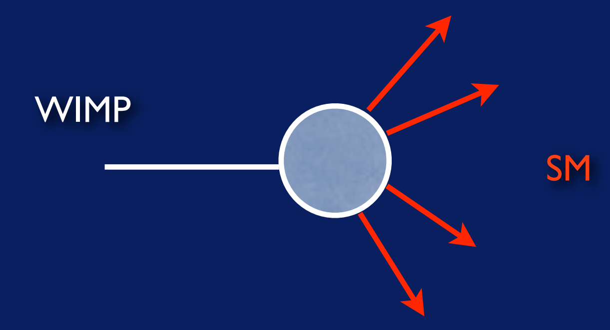
- In term of searching for dark matter, WIMPs are also particularly exciting, because they have "large" interactions with the Standard Model.
  - Large here means roughly electroweak strength or only a little smaller-- much larger than gravity.
  - The interesting implication is that we have many handles to search for such particles.
  - A non-gravitational observation would teach us a lot about the nature of dark matter!

# #1: The WIMP has spin $\leq$ 1/2

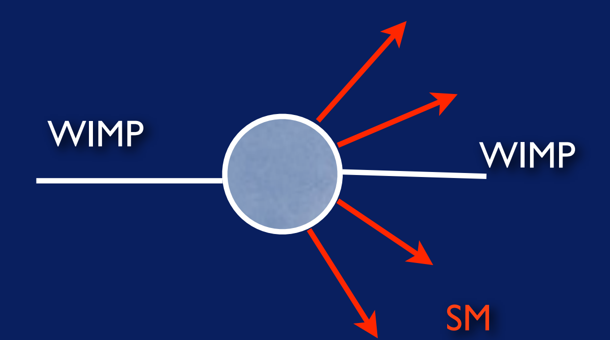
- I'll only consider WIMPs which are spin zero or spin 1/2.
  - That covers both fermion and boson WIMPs (complex and real scalars, and Majorana and Dirac fermions).
  - Vector WIMPs need a (spontaneously broken) gauge symmetry to have a consistent UV description, which at some level requires extra baggage such as a "dark Higgs sector" etc.
    - Nonetheless, we lose out on the most common WIMP of 5d Universal Extra Dimensions models: the LKP.
  - Higher spin WIMPs? Perhaps as a composite state (in analogy with the $\Delta$ baryons)?
- All of these other cases are worth exploring!

# #2: The WIMP is Stable

- I will assume that the WIMP is absolutely stable. Measurements require a lifetime of the order of the age of the Universe, but not absolute stability.
- When engineering interactions, this implies that there is always an even number of WIMPs interacting with Standard Model fields.
  - The most interesting involve a pair of WIMPs and some number of SM fields.
- For a real WIMP, this boils down to a new $Z_2$ "WIMP Parity" being exact. For a complex WIMP, it could either be the parity or a whole U(1) "WIMP charge" symmetry.




The WIMP decays.




WIMP-Number is conserved.

# #3: The WIMP is a Maverick

- A very important choice is the degrees of freedom included in the EFT.
- Any states relevant for the process at hand needs to be included.
- I will assume that the relevant degrees of freedom consist of the Standard Model + the WIMP (and nothing else...).
  - I'll assume the SM Higgs is also heavy, just as a starting point.
- These assumptions are easy to relax.
- They work in limits of SUSY and UED, but prevent consideration of exotic light states like the dark photon.

I'll focus on the couplings to quarks and gluons, motivated by the connection to direct detection experiments.
Adding leptons is no problem...
e.g. Fox, Harnik, Kopp, Tsai 1103.0240

# #4: The WIMP is a SM Singlet

- I will further assume the WIMP is an SU(2) x U(1) singlet. So it has no charged SU(2) siblings with nearby masses.
  - Like the Bino in SUSY or $B^{(1)}$ in UED.
  - This was already motivated by the choice that it be the only BSM degree of freedom in the theory anyway.
- As a consequence, the WIMP doesn't have electroweak strength couplings mediated by the W and Z bosons.
  - The WIMP could still have couplings to W's and Z's induced by heavier states we have integrated out of the EFT description.
- I'm also not going to consider a WIMP which couples to the SM through a light 'Higgs portal' -- though a heavy Higgs could induce some of our operators.

Eg: Kanemura, Matsumoto, Nabeshima, Okada 1005.5651

# Effective Theories

- Once one has an effective theory which captures the physics one wants to explore, one is ready to compare with experimental data and make predictions.
  - I should emphasize again that I chose my effective theories as a simple starting point -- but one can repeat the exercise for with whatever assumptions one likes.
- An effective theory accurately describe physics below its cut off scale.
  - For direct and indirect experiments, only in theories with somewhat surprisingly light exotic states will there be relevant modifications.
  - For colliders, the situation is less clear and depends on the theory.
  - The cut-off will be something like the masses of the particles which mediate the interactions with SM states,

# Comparison with CDF Study

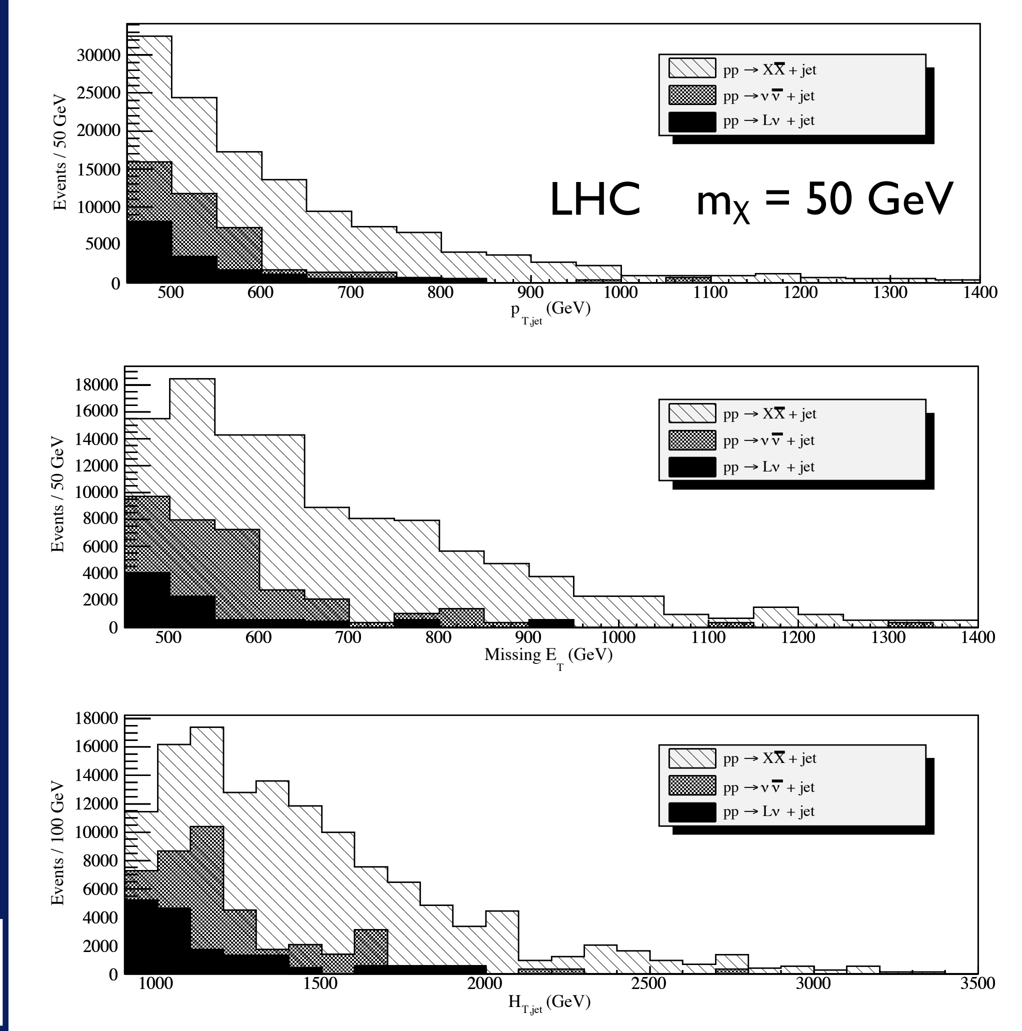
- In 1002.4137 we were able to reproduce the backgrounds CDF found based on its own Monte Carlo simulations (improved with data):
  - The dominant background is Z + jets with the Z decaying into neutrinos.
    - Efficiencies from Monte Carlo, matched to Z + jet data with Z decaying into charged leptons (correcting for the branching ratios).
  - Next in importance is W + jets (where the charged lepton from the W decay gets lost).
    - Veto isolated ($\Delta R > 0.4$) leptons with PT > 10 GeV.
    - k-factor for W + jets with jet PT > 80 GeV.
  - Theory uncertainties in background rates ~ few %; NLO rates available and LO rates are driven by quark PDFs.

# LHC

- 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 $fb^{-1}$!




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