Constraints on Light Majorana WIMPs from Colliders

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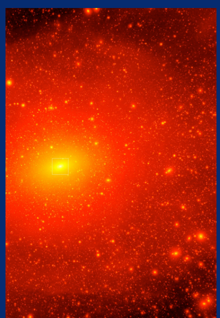
Shepherd, TT, Zaharijas, 0901.2125;
Beltran, Hooper, Kolb, Krusberg, TT, 1002.4137;
Goodman, Ibe, Rajaraman, Shepherd, TT, Yu, 1005.1286

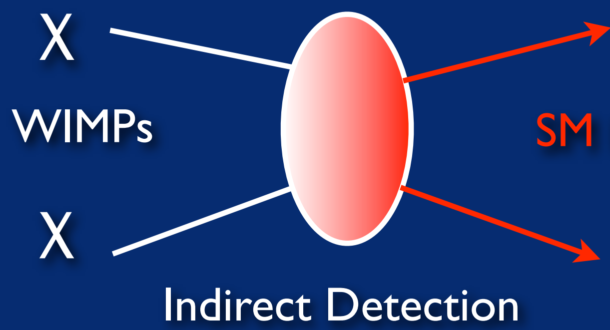
GGI Dark Matter
May 17, 2010

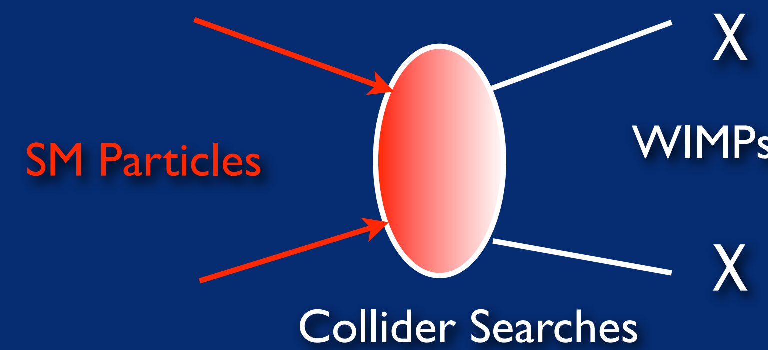
Outline

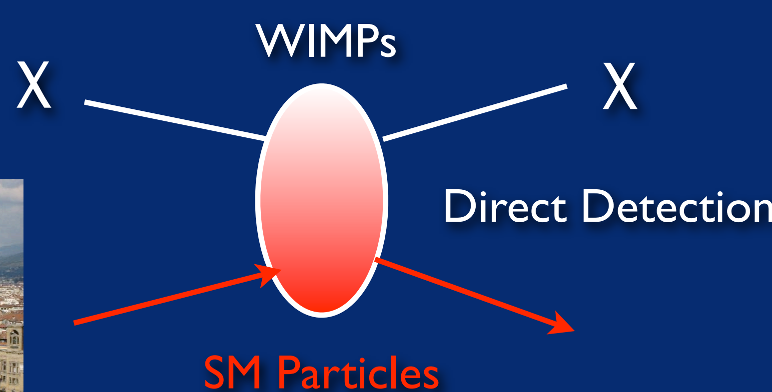
- Effective theories as a language to describe dark matter interactions.
- Bounds from Collider Searches.
- Comparison with Direct Detection.
- Outlook.

WIMP-SM Interactions





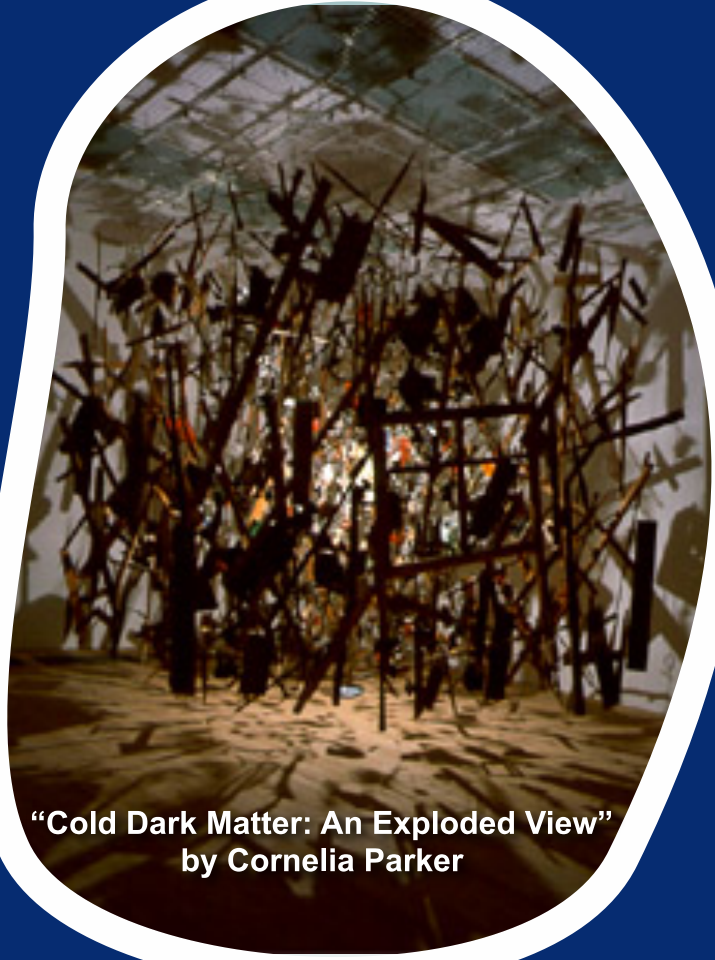




- The common thread that ties up direct, indirect, and collider searches for dark matter is how WIMPs interact with the Standard Model.
- Fitting these interactions into the context of the Standard Model involves formulating a quantum field theory of WIMPs.

Categorizing WIMPs

- WIMPs are 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
- The usual approach is to explore WIMPs that occur 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!

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"

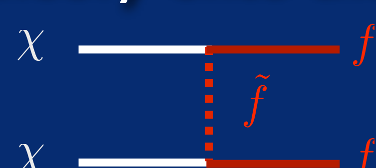
- There is a different effective theory for different choices of spin, complexity, EW representation, etc, for the WIMP.
    - Many important properties (such as spin-suppression) are evident even in the effective theory.

χ real:

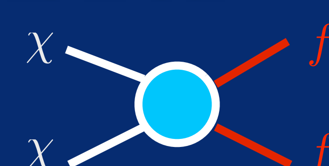
$$\sum_f \left\{ \frac{y_f}{\Lambda_f^2} \chi^2 H \bar{f}_L f_R + \frac{1}{\Lambda_{f_R}^2} \left(\chi \overleftrightarrow{\partial}_\mu \chi \right) \left[\bar{f}_R \gamma^\mu f_R \right] + \frac{1}{\Lambda_{f_L}^2} \left(\chi \overleftrightarrow{\partial}_\mu \chi \right) \left[\bar{f}_L \gamma^\mu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

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

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



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



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.

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_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	-

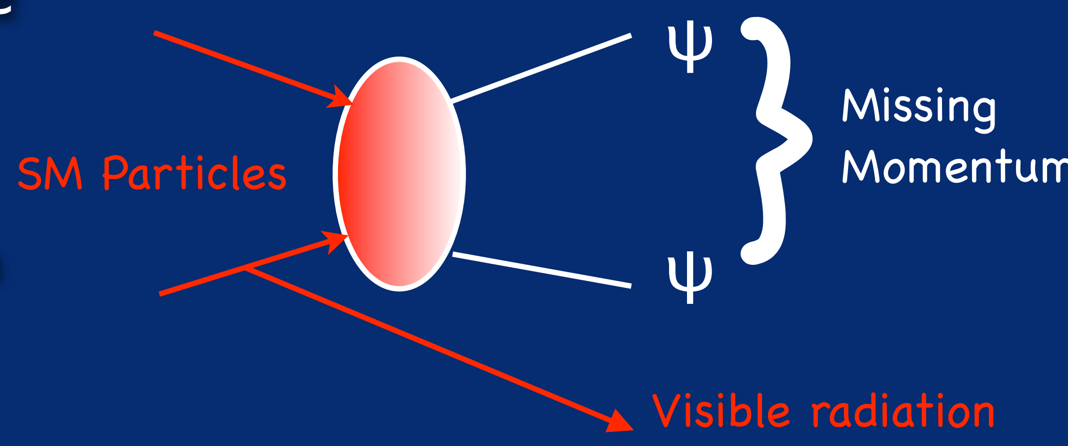
(M* is what we previously called Λ.)

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

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

Jets + Missing Energy

- 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.

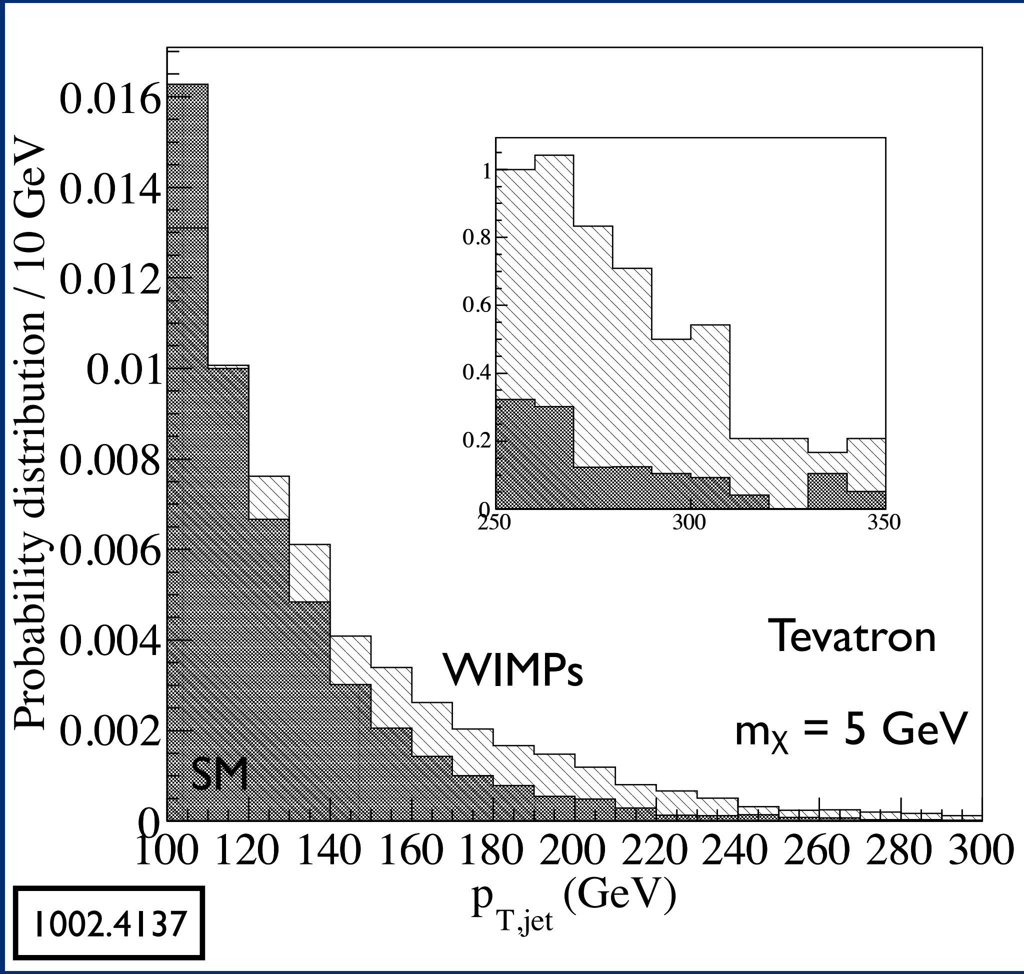
CDF, 0807.3132
http://www-cdf.fnal.gov/physics/exotica/r2a/20070322.mono_jet/public/ykk.html

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 with Z decaying into leptons data (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.
  - The "QCD" background from mismeasured jets was negligible.
  - Theory uncertainties in background rates ~ %; (N)NLO rates available and LO rates are driven by quark PDFs.

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.

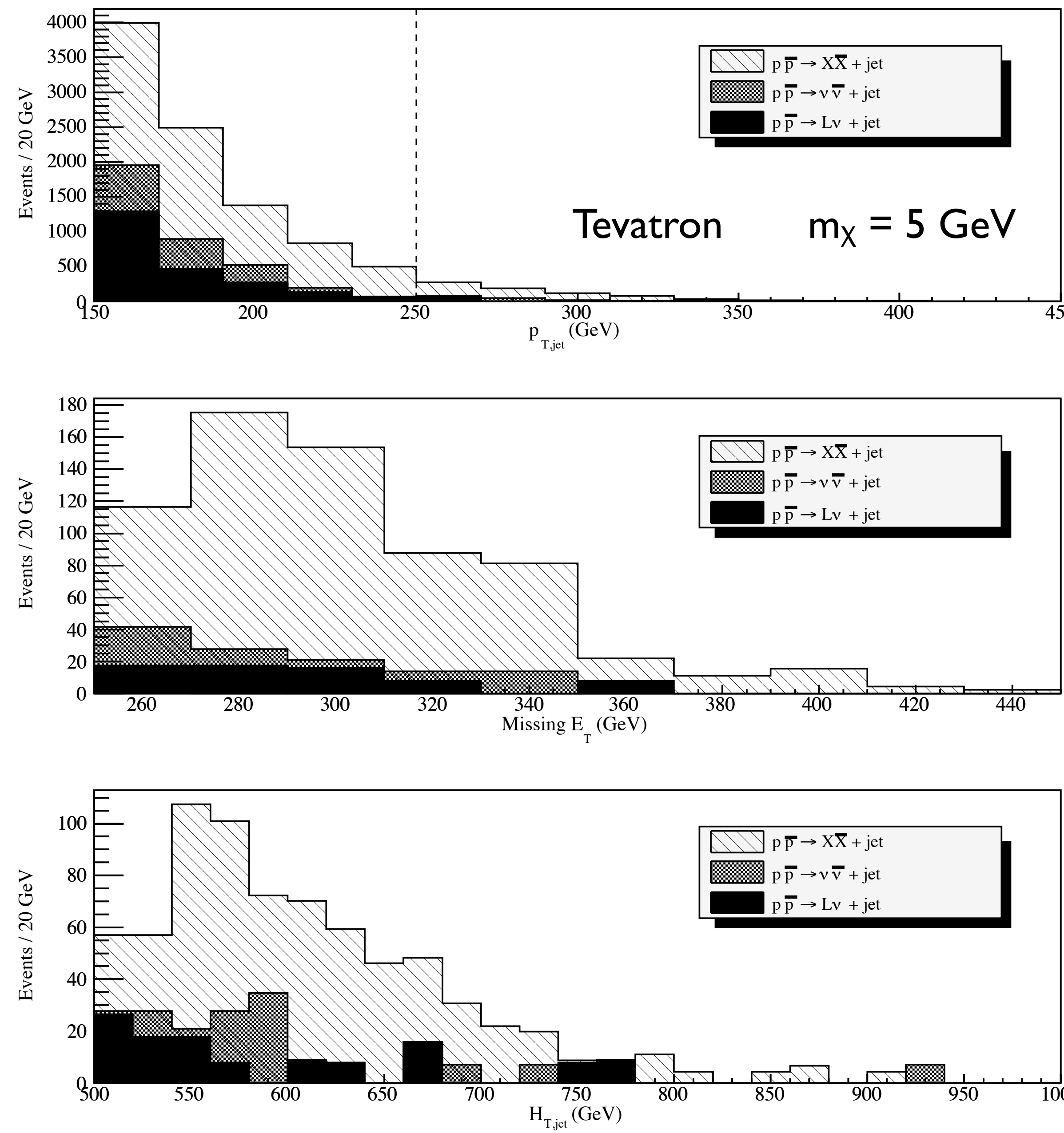


M6: $[\bar{\chi}\gamma^{\mu}\gamma_5\chi]\,[\bar{q}\gamma_{\mu}\gamma_5 q]$

Beyond the Parton Level

1002.4137

- These differences survive parton showering and hadronization (simulated by PYTHIA) and detector response (simulated by PGS in its default Tevatron 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.



LHC

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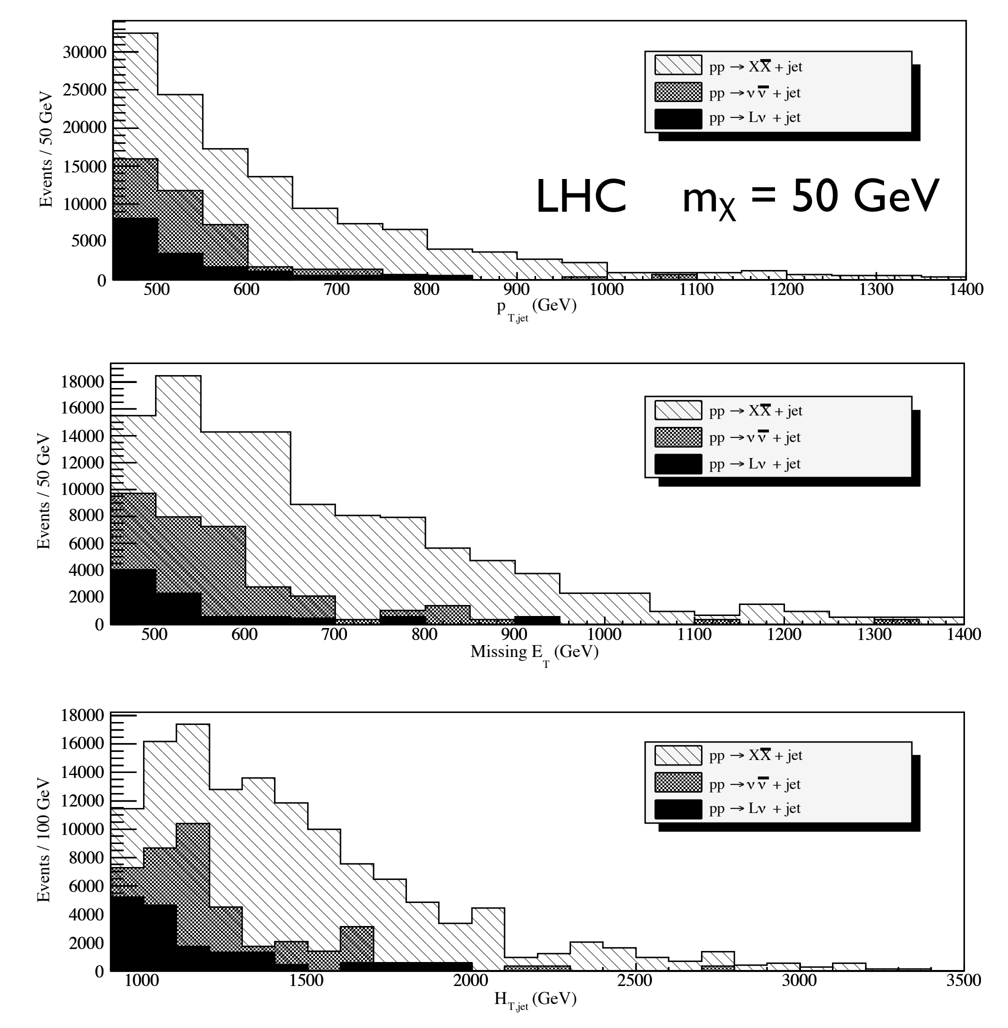
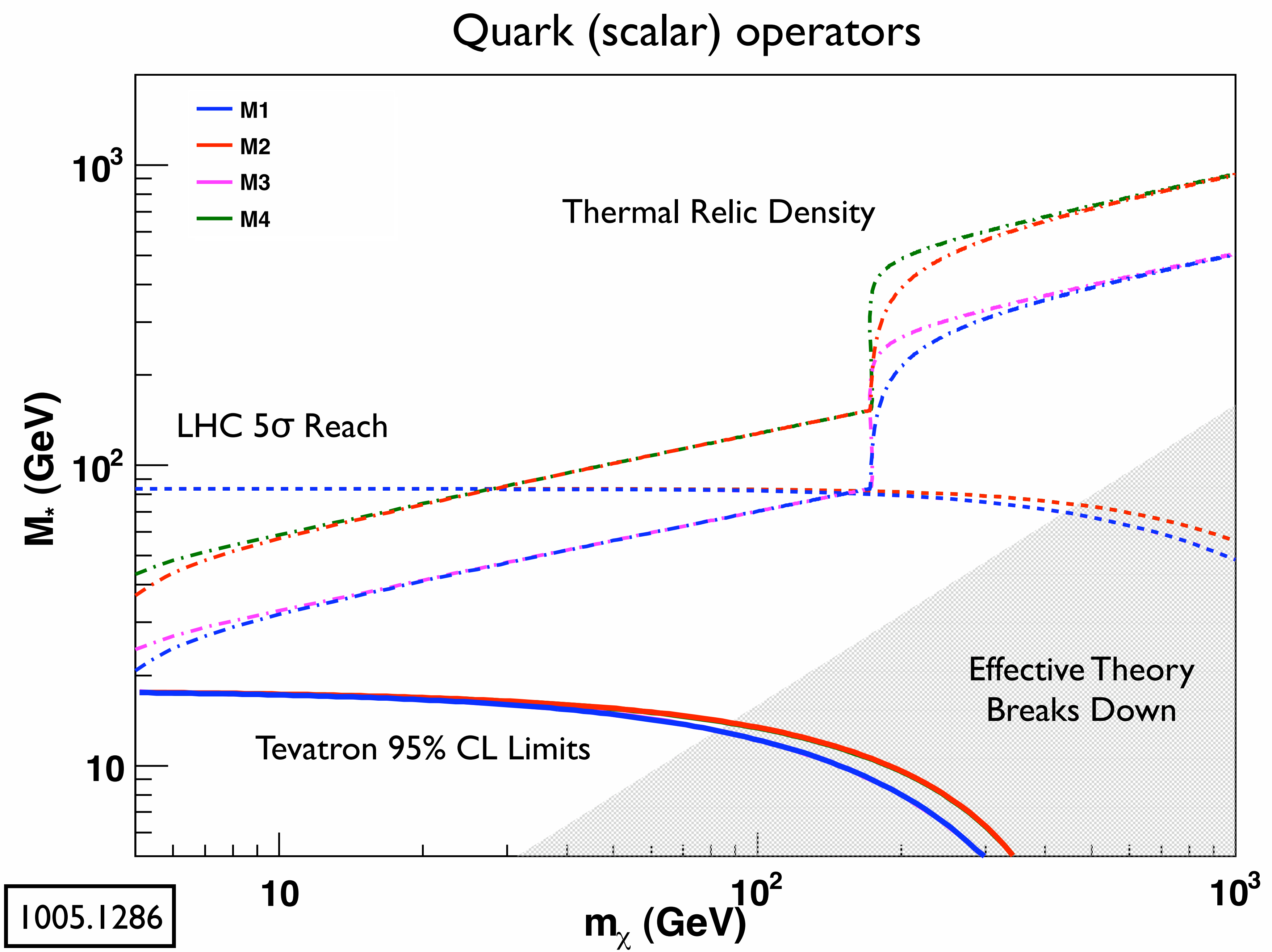
- To estimate the LHC sensitivity we rely on the ATLAS search for jets + missing energy:
  - Missing ET > 500 GeV

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

- 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} -- it is probably non-trivial!



Limits/Sensitivity



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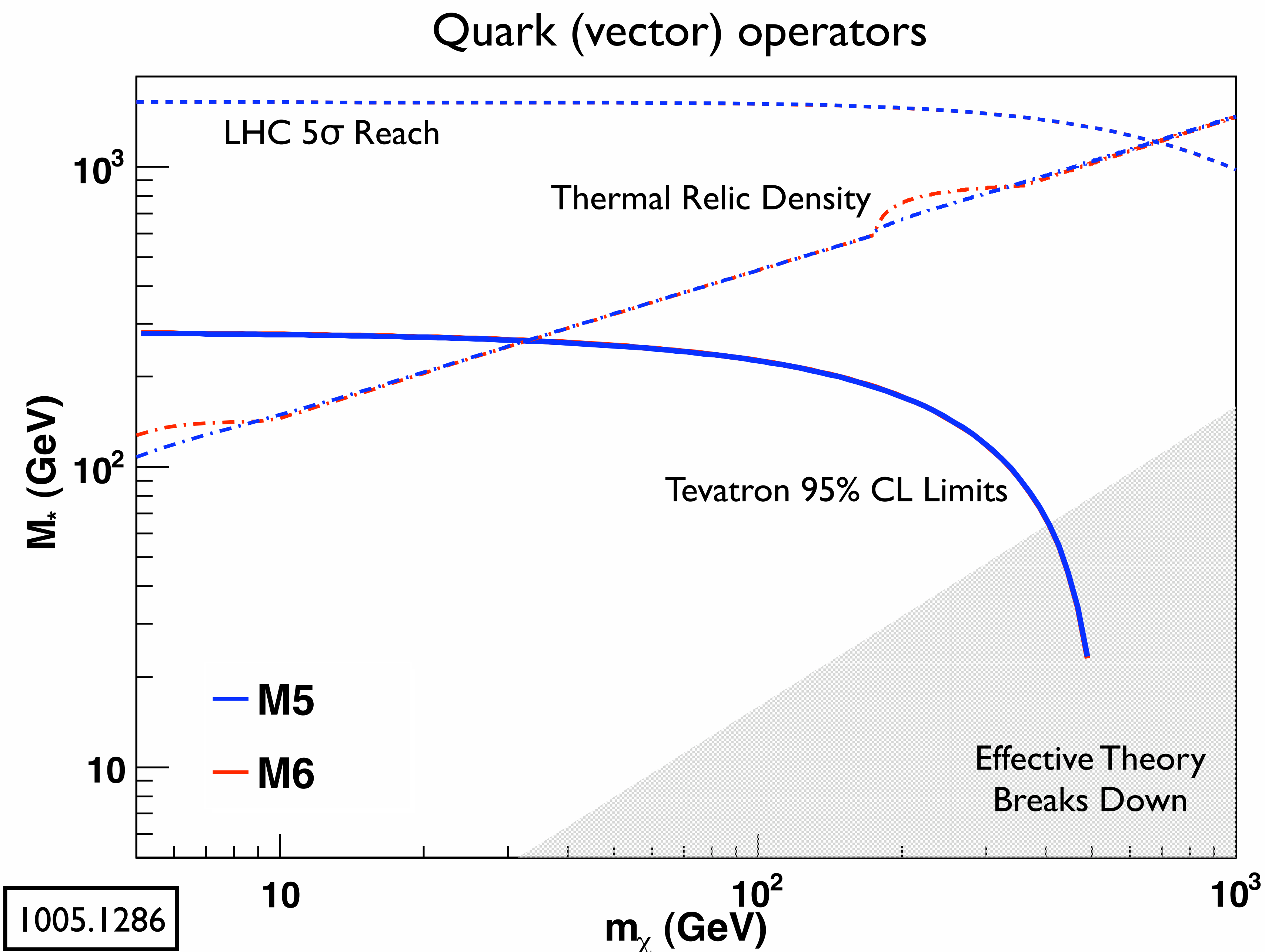
Limits/Sensitivity



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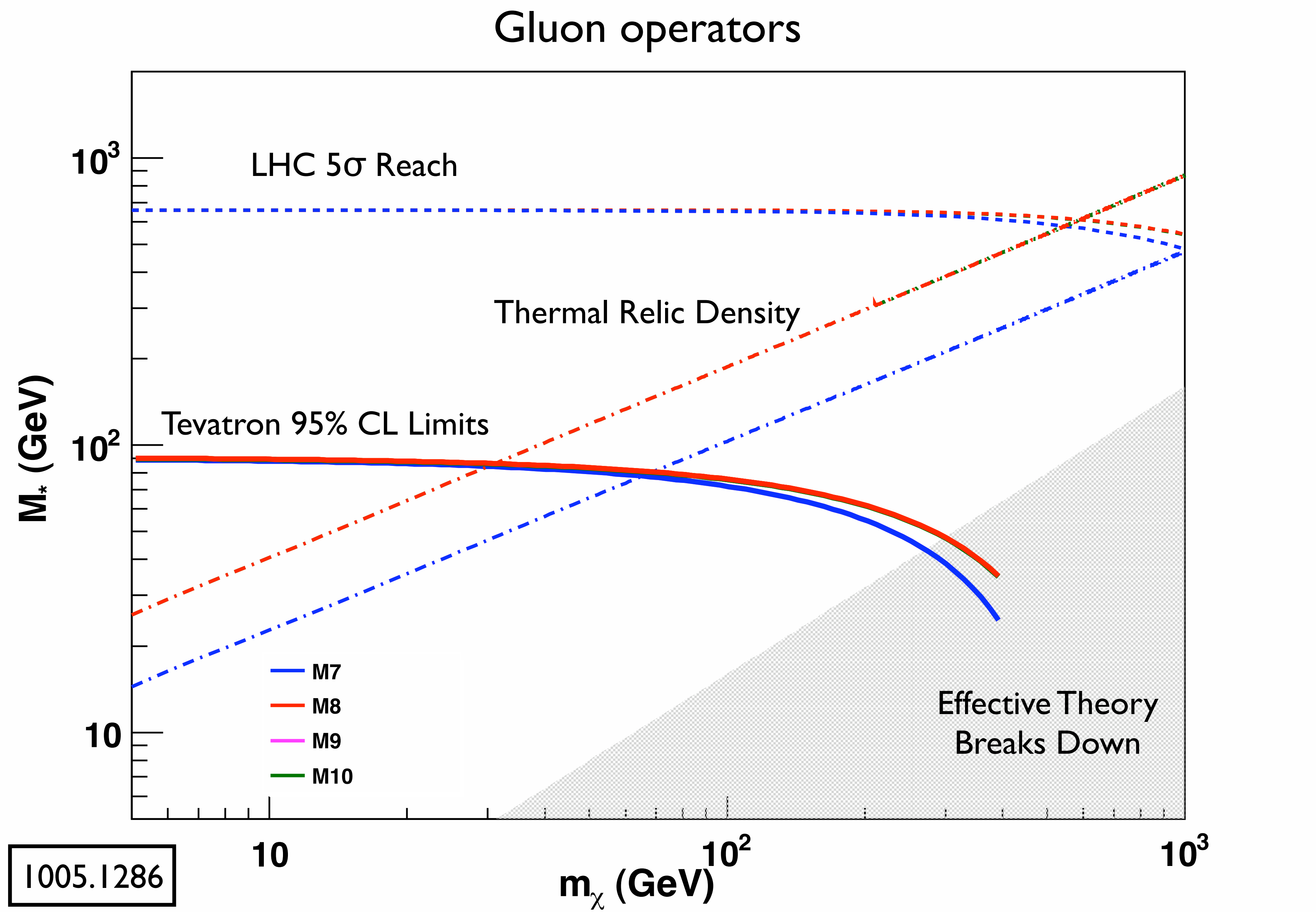
Limits / Sensitivity



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Direct Detection

- Our operators can also be translated into direct detection experiments.
- Only three operators contribute to non-relativistic Majorana WIMP scattering with a heavy nucleus.
  - Two operators potentially contribute to spin-independent scattering.
  - One operator potentially contributes to spin-dependent scattering.
- We follow the usual procedure and quote WIMP-nucleon cross sections. In terms of M* we have:

$$\sigma^N_{SI;M1} = \frac{4\mu_\chi^2}{\pi}\left(0.082\ \mathrm{GeV}^2\right)\left(\frac{1}{2M_*^3}\right)^2 \qquad \sigma^N_{SD;M6} = \frac{16\mu_\chi^2}{\pi}\left(0.015\right)\left(\frac{1}{2M_*^2}\right)^2$$

$$\sigma^N_{SI;M7} = \frac{4\mu_\chi^2}{\pi}\left(5.0\ \mathrm{GeV}^2\right)\left(\frac{1}{8M_*^3}\right)^2$$

Spin-independent

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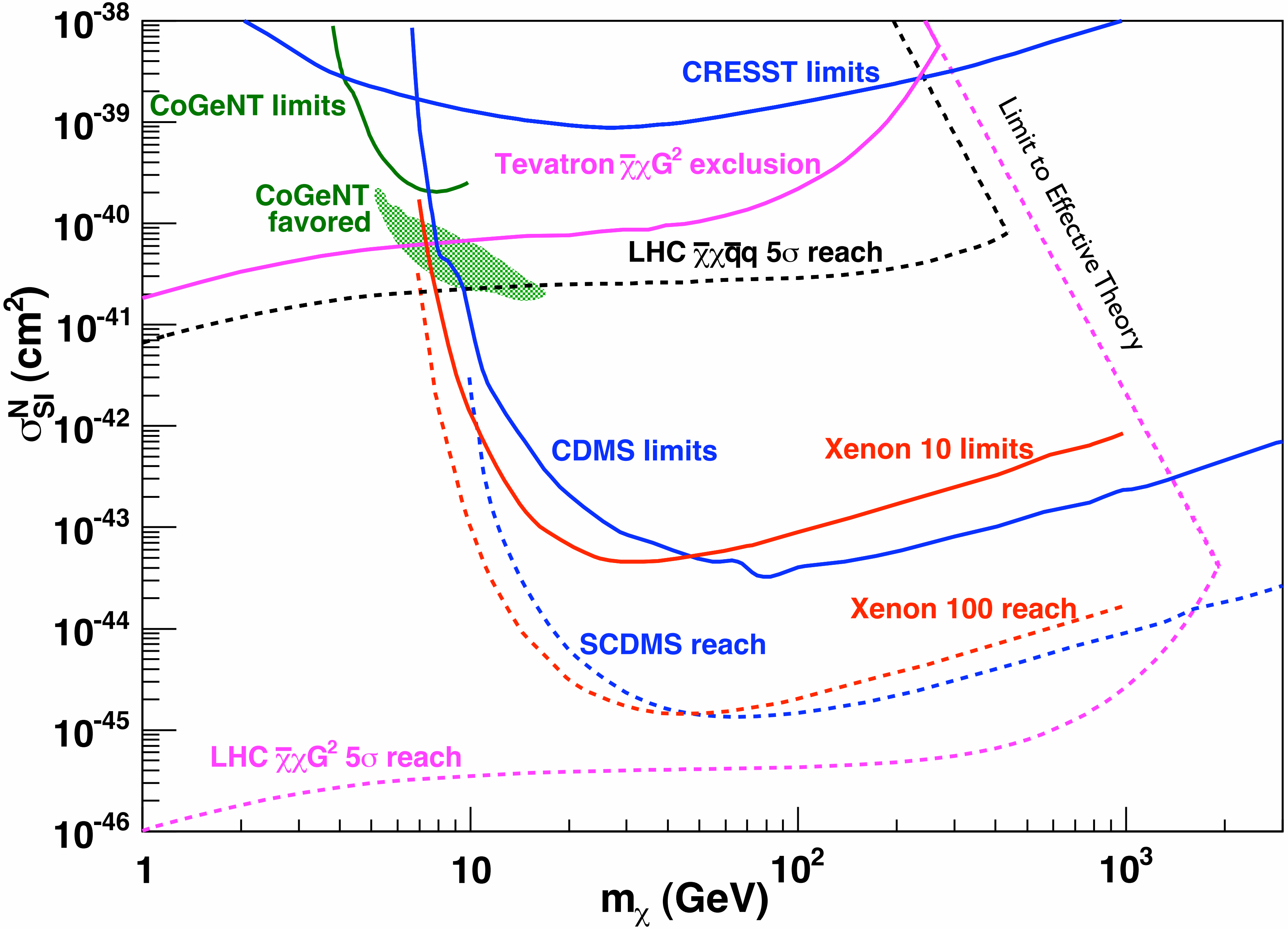
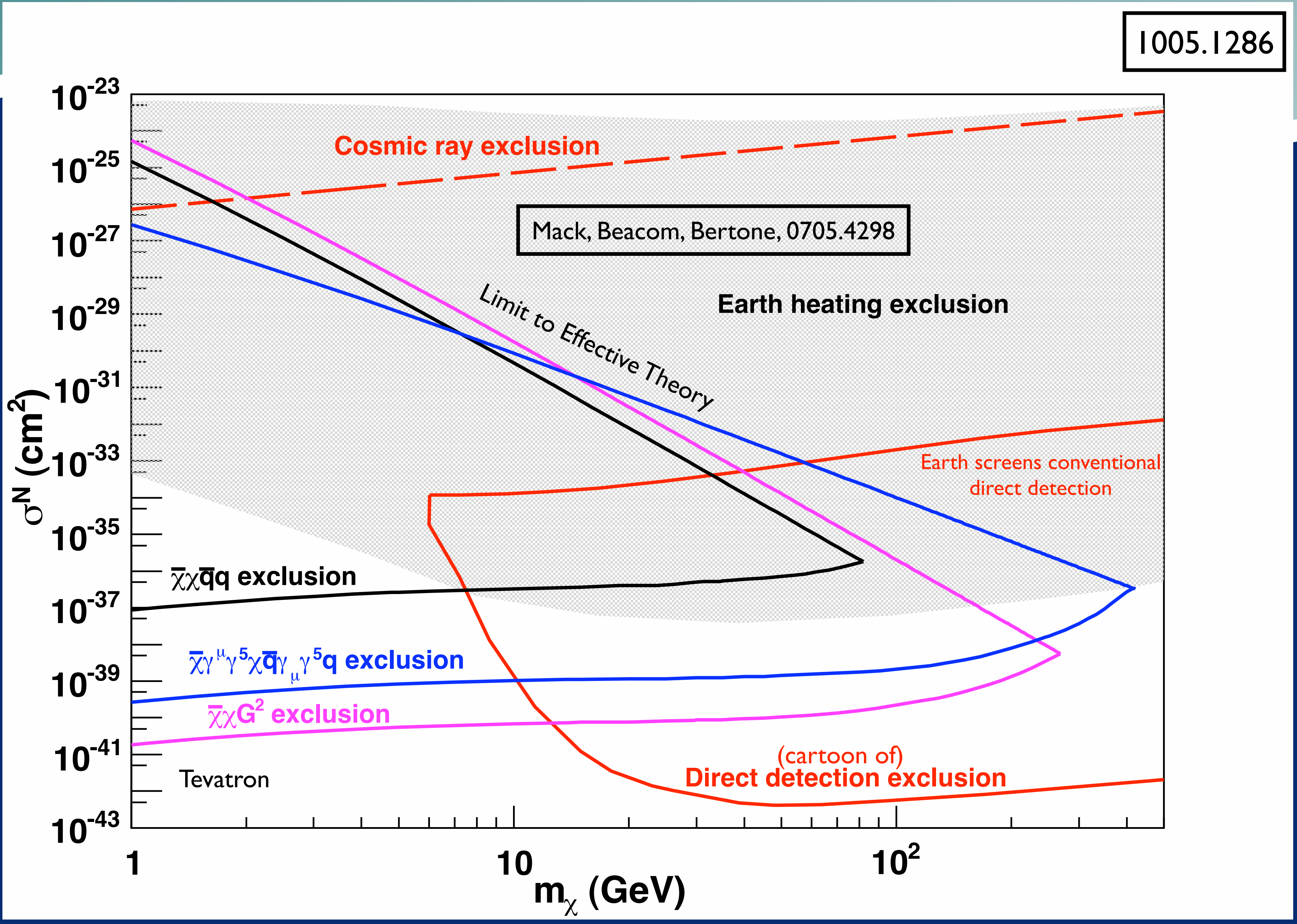
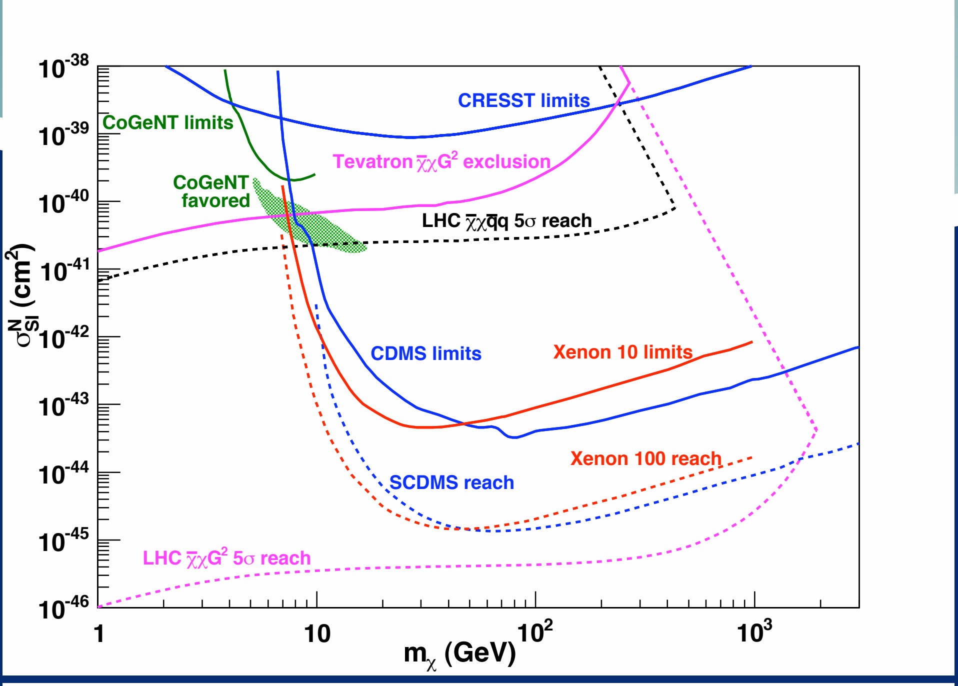


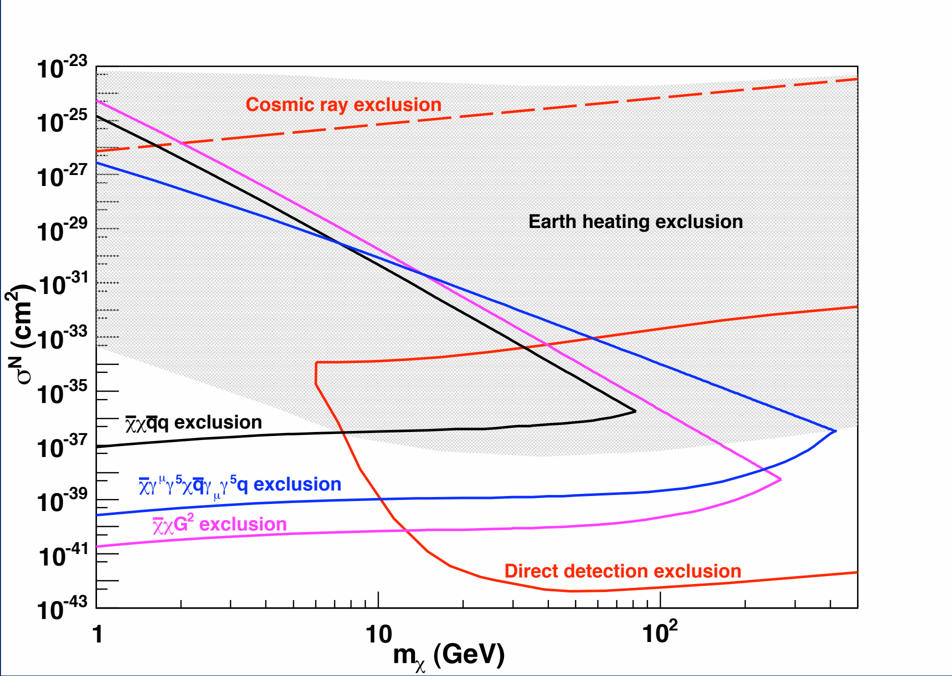
From WIMPs to SIMPs...



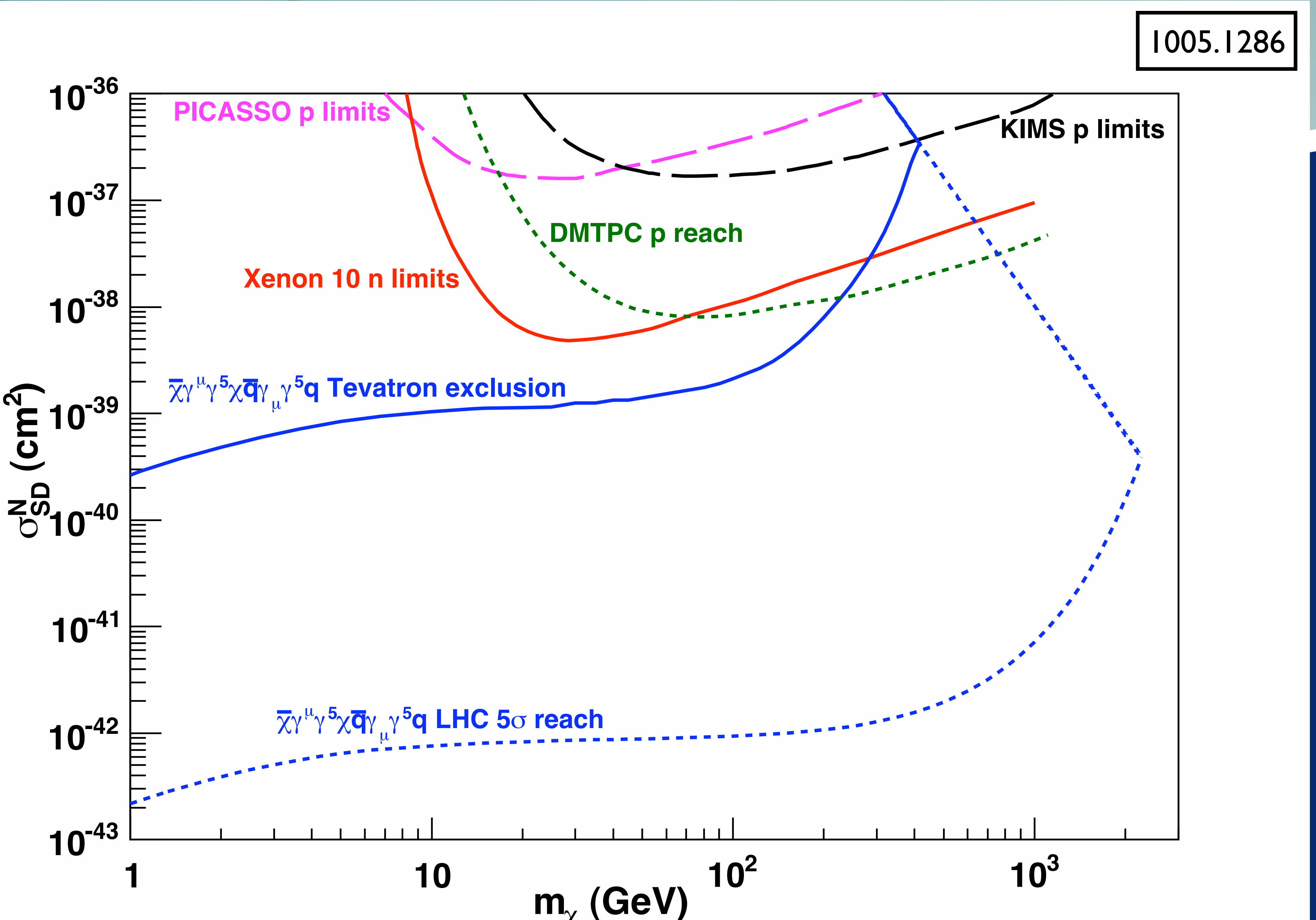
Collider/Direct Synergy

- 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.
  - Also note: Xenon100 low mass analysis. (which I guess Elena will show us tomorrow).



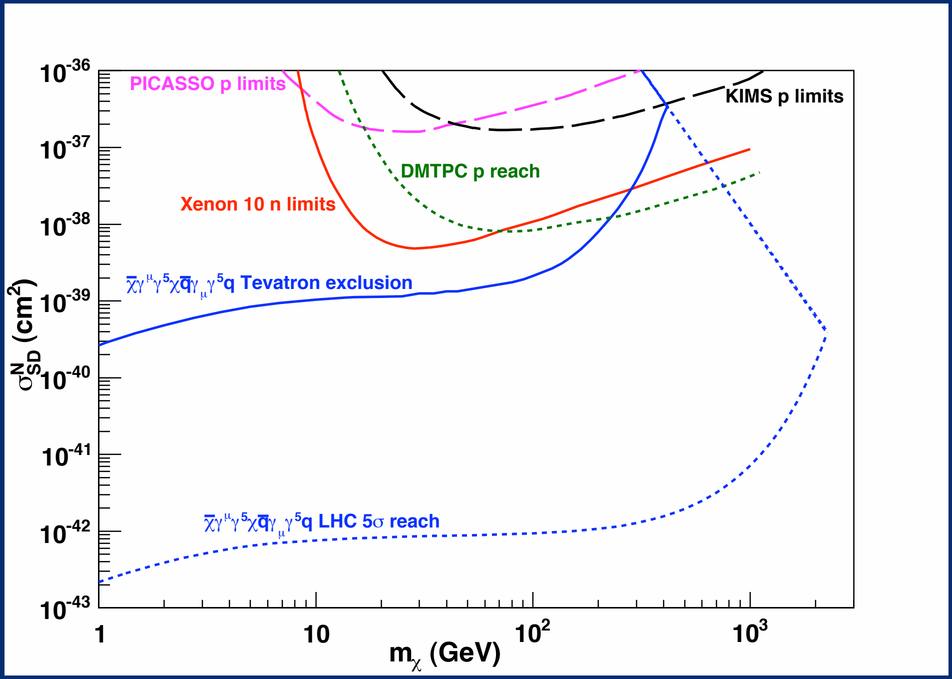


Spin-dependent



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.
- Generally, colliders easily handle even higher dimensional operators with more momentum dependence, because colliders are not energy limited except for large masses.
- Such as have been invoked to explain DAMA versus other experiments -- "momentum-dependent dark matter"



Chang, Pierce, Weiner,
0908.3192

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.
- Together, direct, indirect, and collider searches offer a more complete picture of dark matter interactions with the Standard Model!

Bonus Material