Constraints on Dark Matter from Colliders

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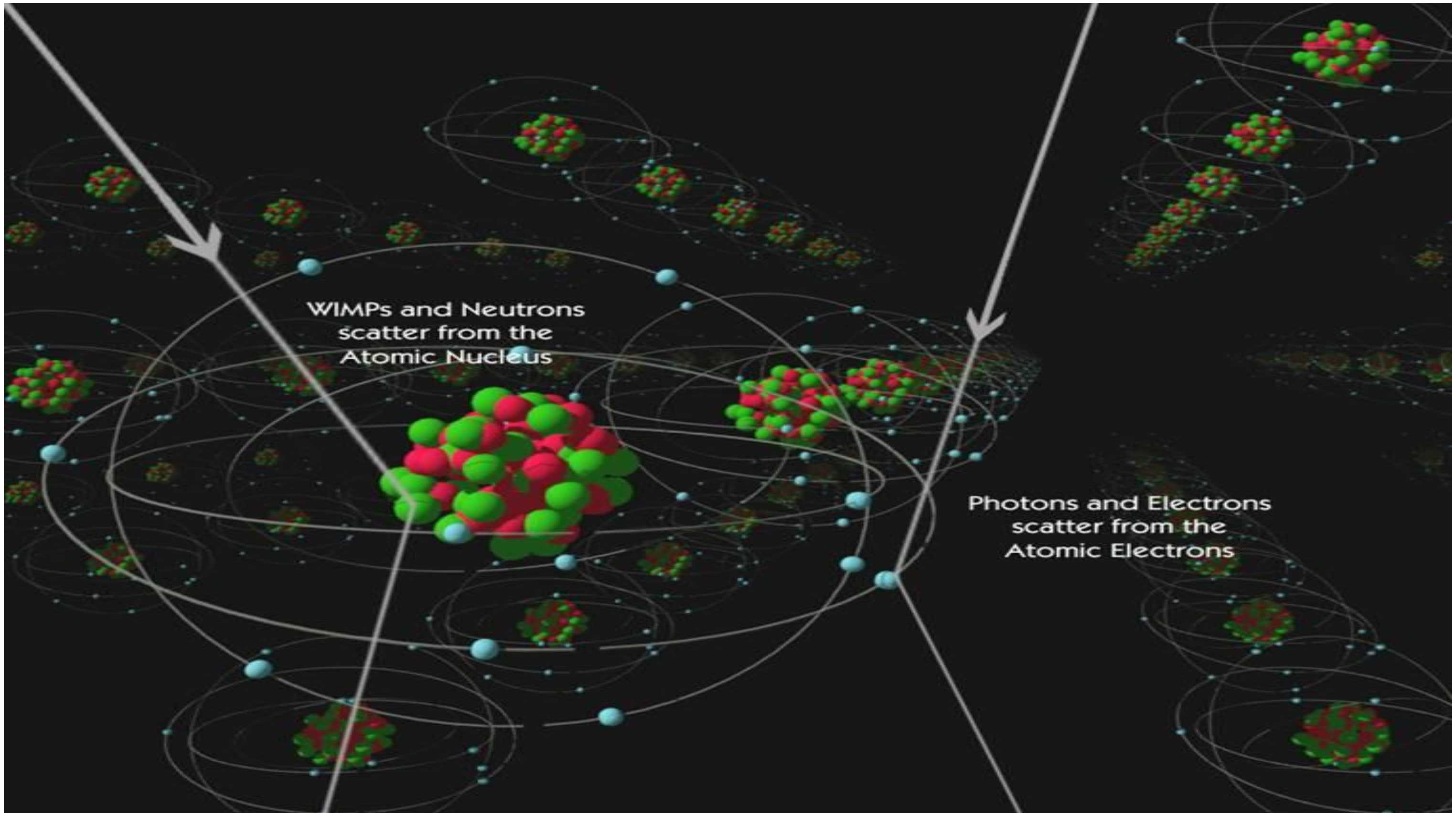
based on arXiv:1005.1286 and ongoing work with J. Goodman, M. Ibe,
W. Shepherd, T. Tait, H. Yu.

Related work: Bai, Fox, Harnik, arXiv:1005.3797

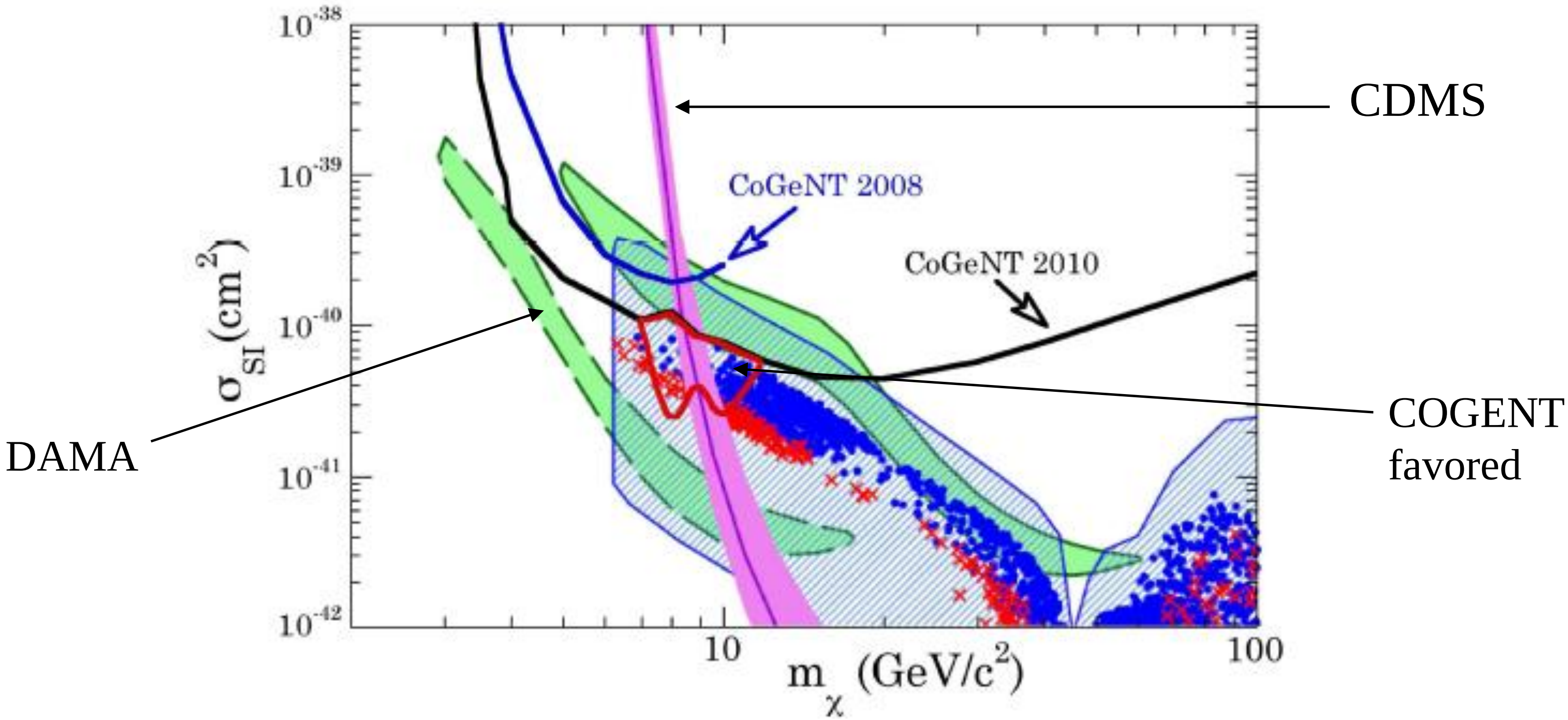
Overview

Many experiments are looking for dark matter through direct detection processes where the dark matter particle scatters off a detector producing signals of energy deposition.



Overview

from 1002.4703 (COGENT)

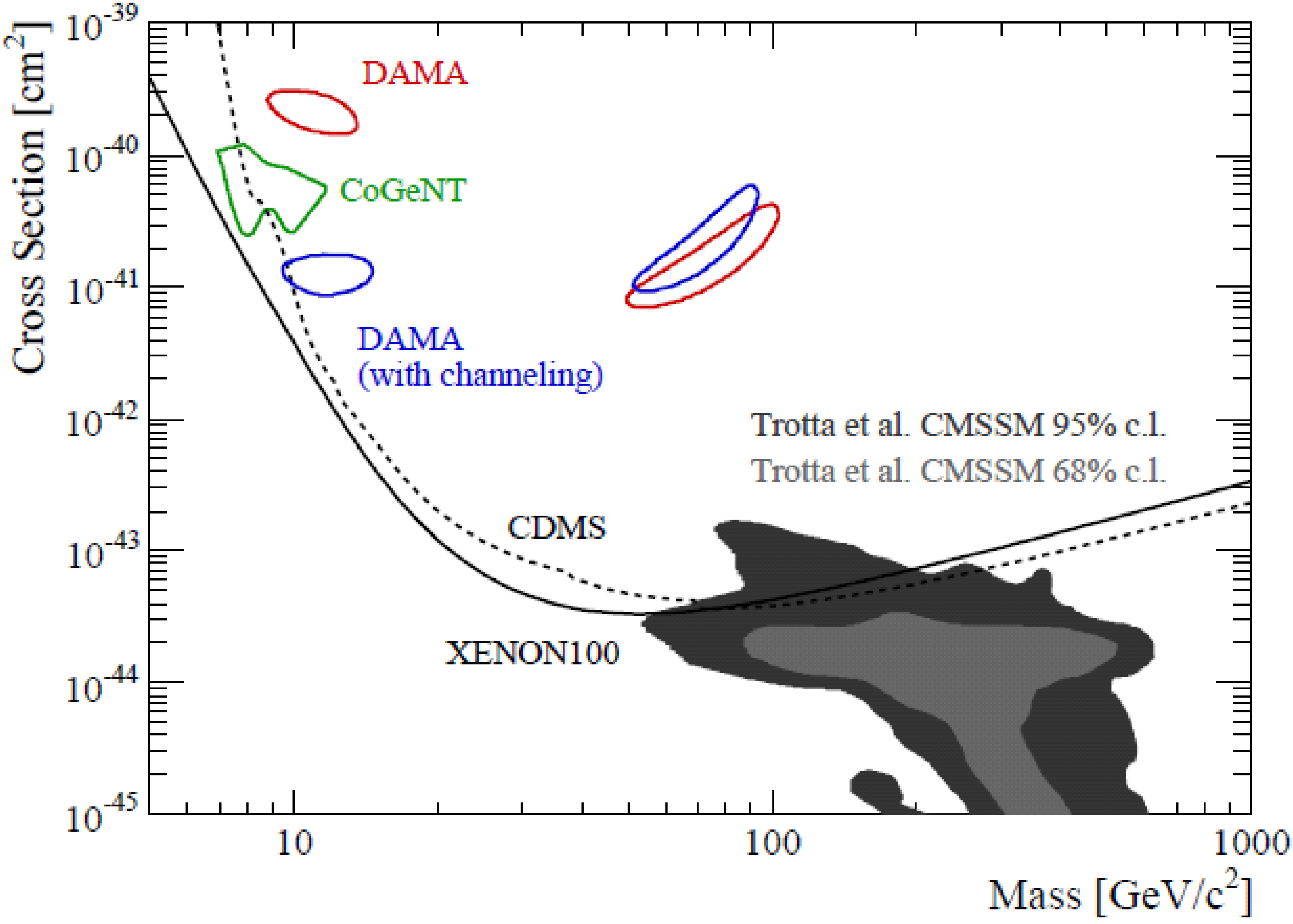


DAMA, COGENT have reported anomalies that can be interpreted as a potential signal of dark matter.

These particles must be very light and much more strongly interacting than expected.

Overview

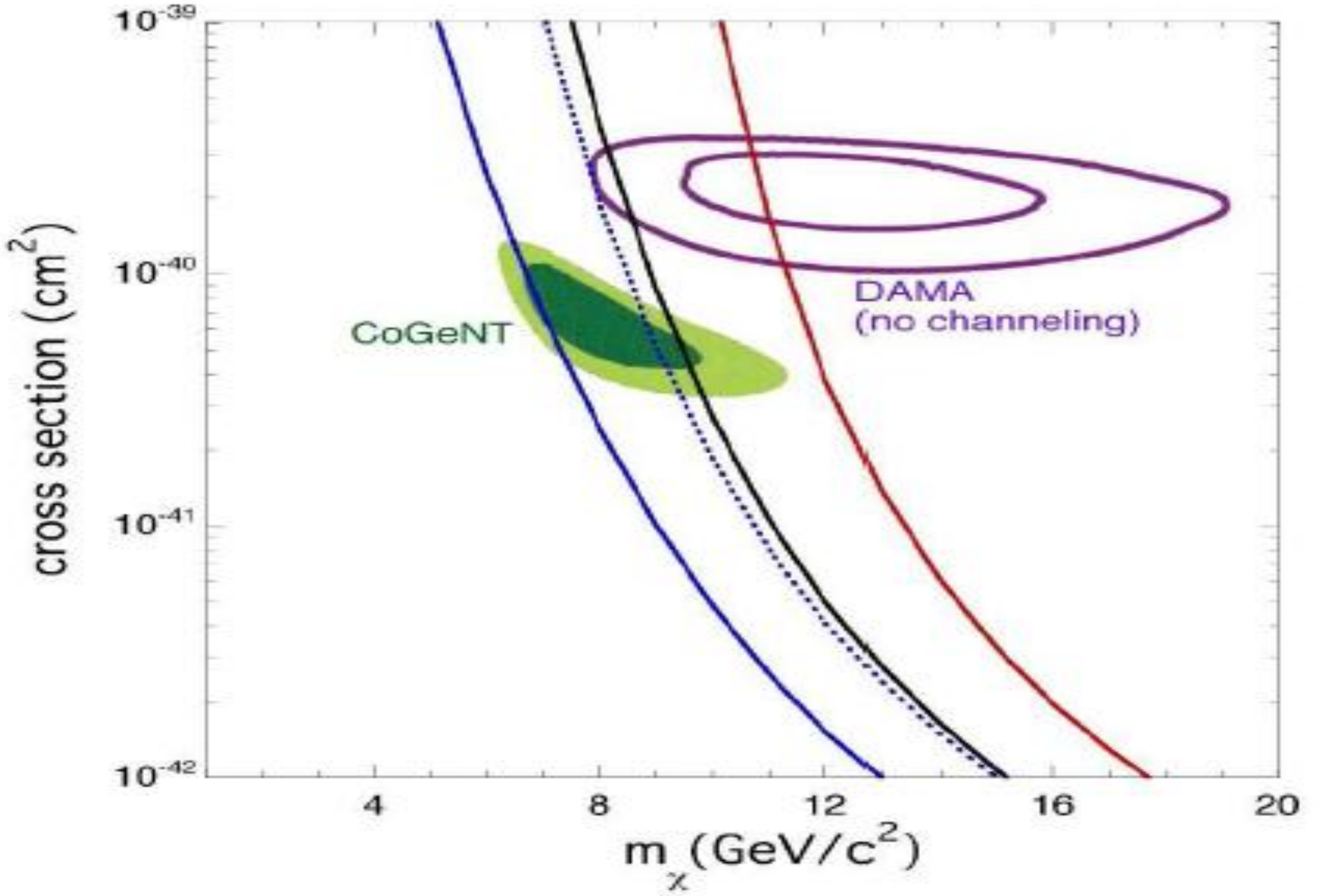
from 1005.0380 (XENON100)



Xenon 100 claims to rule these out….

Overview

from 1005.0838 Collar and Mackenzie



…but these results are controversial.

Overview

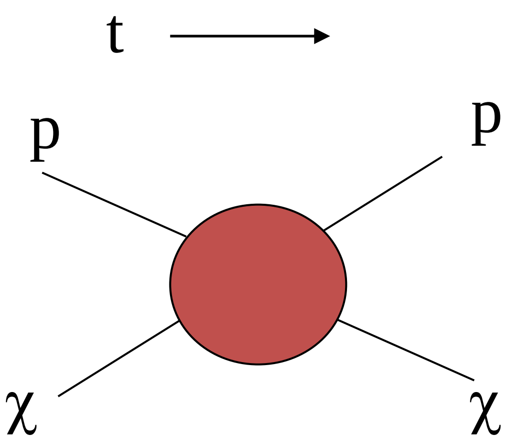
We will not take sides in this controversy, which will be resolved by further experimental studies.

Instead we will ask whether colliders (i.e. Tevatron, LHC) can have anything useful to add to these studies.

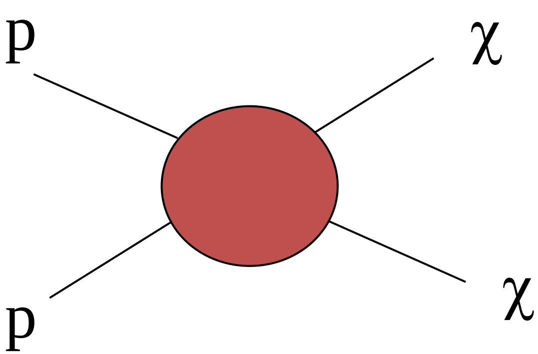
The reason this might be the case is that the region of parameter space where the dark matter is light is very hard to address with direct detection, but is precisely the range where colliders do well.

Even if these experimental anomalies disappear, this provides a complementary search strategy for dark matter.

Overview



Direct detection



Collider production

Also, the underlying processes for direct detection and collider production are related.

A large interaction for direct detection implies a large nucleon-dark matter cross section, which should imply a large rate for collider production.

Model-Independent Dark Matter

To compare collider studies with direct detection, we need a model of the dark matter interactions which is as general as possible.

We will assume that the dark matter particle (χ) is the only new particle in the energy range of interest.

It will then interact with the Standard Model through higher dimensional operators coming from integrating out some other heavy particles.

We will work with this effective theory involving. χ and Standard Model particles.

J.Goodman, M. Ibe, AR, W. Shepherd, T.Tait, H.Yu, arXiv:1005.1286

Model-Independent Dark Matter

We then need to specify the quantum numbers of the dark matter particle, as well as the dominant interaction (we assume only one interaction operator is dominant.)

We take the dark matter to be a singlet under the SM gauge group. The particle can be a scalar (real/complex) or a fermion (Dirac/Majorana).

We will start with the case of a Majorana fermion.

Model-Independent Dark Matter

We will only consider interactions with the quarks and gluons; leptonic couplings contribute neither to direct detection nor to hadronic collider experiments.

Interactions are then of the form

$$\mathcal{L}^{(\mathrm{dim6})}_{\mathrm{int},qq} = G_\chi\,[\bar{\chi}\Gamma^\chi\chi] \times [\bar{q}\Gamma^q q]\ ,$$
$$\mathcal{L}^{(\mathrm{dim7})}_{\mathrm{int},GG} = G_\chi\,[\bar{\chi}\Gamma^\chi\chi] \times (GG\,\mathrm{or}\,G\tilde{G})$$

q runs over the 5 lighter quarks (we are assuming that the top, higgs are also integrated out).

Model-Independent Dark Matter

There are 10 allowed operators (others can be Fierzed away).

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	-

Coefficients chosen with MFV ansatz.

Model-Independent Dark Matter

We should note that the effective theory may not be valid for all values of M_* . There is presumably a new particle which was integrated out to generate this operator; the mass M of this new particle satisfies

$$\frac{1}{M^2_*} = \frac{g^2}{M^2}$$

where g is some coupling. We need $M_\chi < M$ for the validity of our original assumption, and $g^2 < 4\pi$ for perturbativity. We thus have

$$\frac{1}{M^2_*} < \frac{4\pi}{M_\chi^{\ 2}}$$

Outside this range, our effective theory breaks down.

Collider Constraints

We can constrain each of the suppression scales M_* by collider experiments.

The dark matter particles can be produced in the process

$$p\bar{p}\,(pp) \to \chi\chi + \mathrm{jets}\ .$$

These show up as events with missing transverse energy.

Signal events generated by COMPHEP, passed through PYTHIA, PGS.

Dominant background: Z ($\nu\nu$) + jets
Next in importance: W($l\nu$) +jets where the charged lepton is lost.
QCD background with mismeasured jets subdominant.

Collider Constraints

At the Tevatron, we look for a single jet recoiling against nothing - a monojet. This study was performed by CDF with 1.0 fb^{-1} of data and was aimed at looking for large extra dimensions.

0807.3132, http://www-cdf.fnal.gov/physics/exotic/r2a/2070322.monojet/public/ykk.html

This study required

1. Leading jet pT > 80 GeV
2. Missing ET > 80 GeV
3. Second jet allowed if pT < 30 GeV
4. Veto third jet with ET > 20 GeV

Collider Constraints

With these cuts, CDF found 8449 events in 1.0 fb^{-1} of data.

Compare to expected background 8663 $\pm$ 332 events.

Sets an upper bound of $\sigma_{new} < 0.664$ pb for new physics contributions.

Note that we have only performed a simple counting experiment.
There is expected to be a different kinematic distribution
in our model as compared to large extra dimensions.
This suggests that the cuts and bounds can be improved.

Collider Constraints

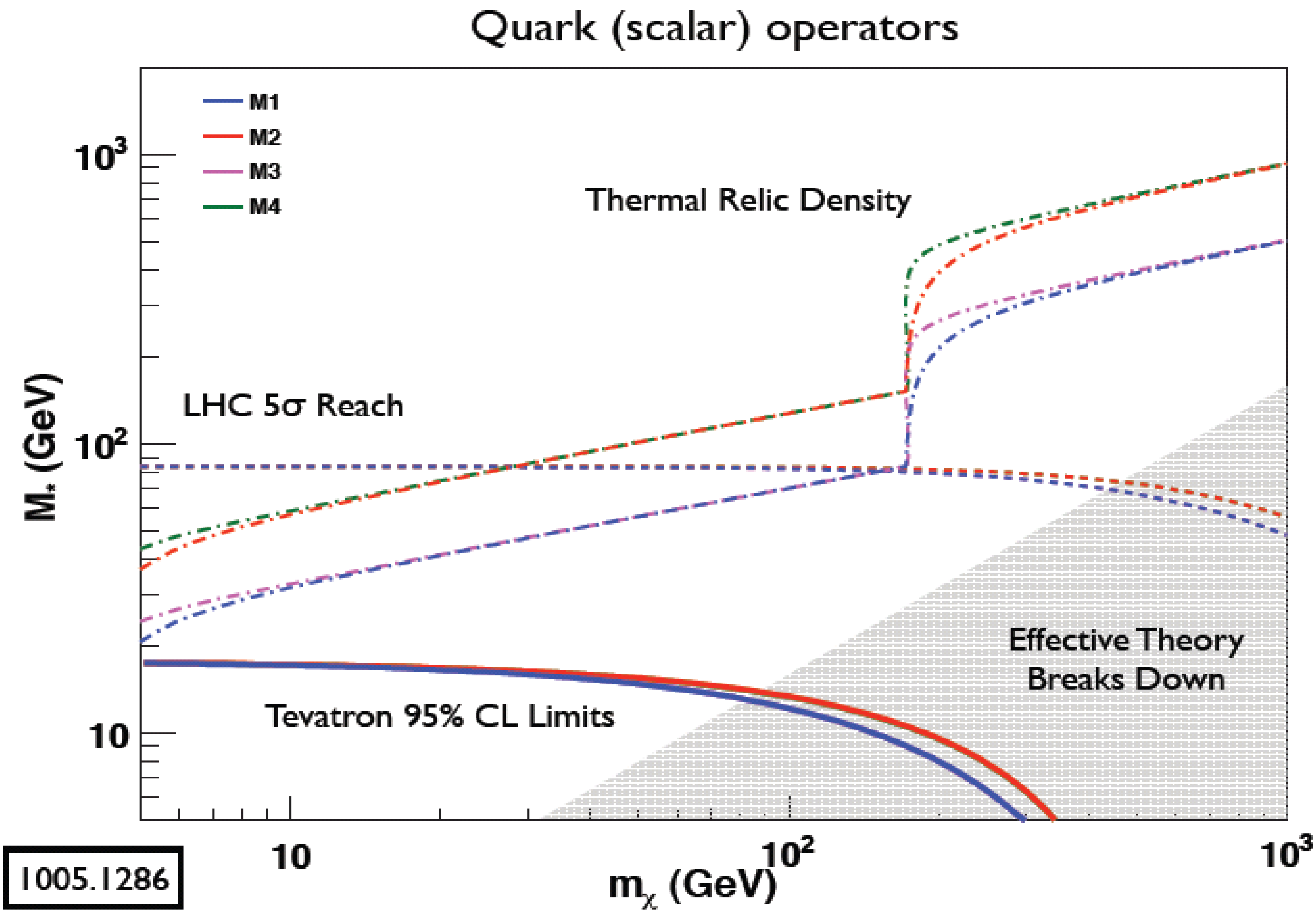
For the LHC, an analysis of events with missing transverse energy was performed by Vacavant and Hinchliffe in 2001, with $\sqrt{s} = 14$ TeV. We follow their analysis.

For the LHC, the cut is only placed on the missing pT (there are too many jets to allow for useful vetoing of extra jets).

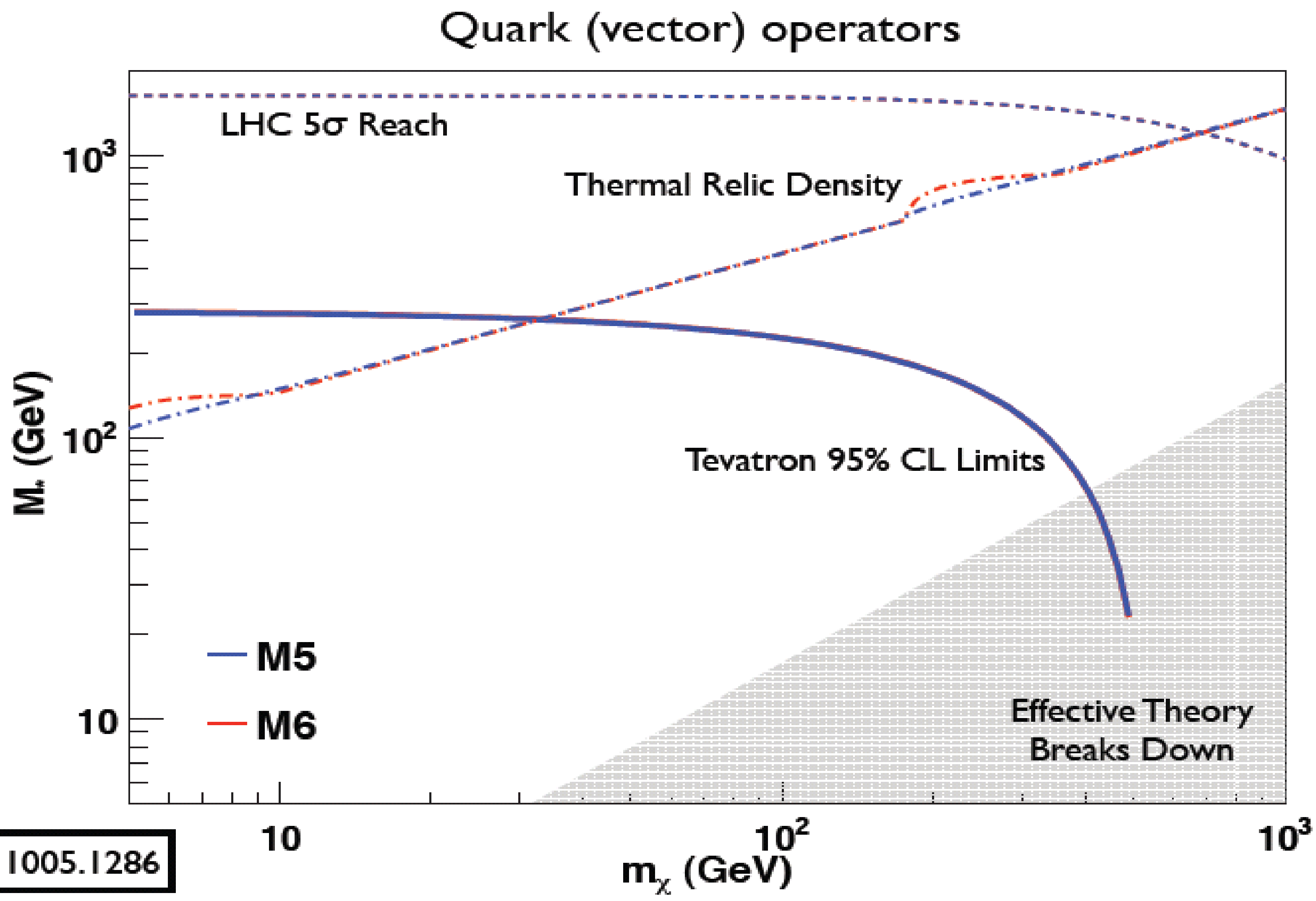
For a pT cut of 500GeV, Vacavant and Hinchliffe found about 20000 background events in 100 fb^{-1} of data. The efficiency to find a signal event was about 90%.

It would be interesting to redo this for 7 TeV energy; not a trivial exercise.

Collider Constraints



Collider Constraints



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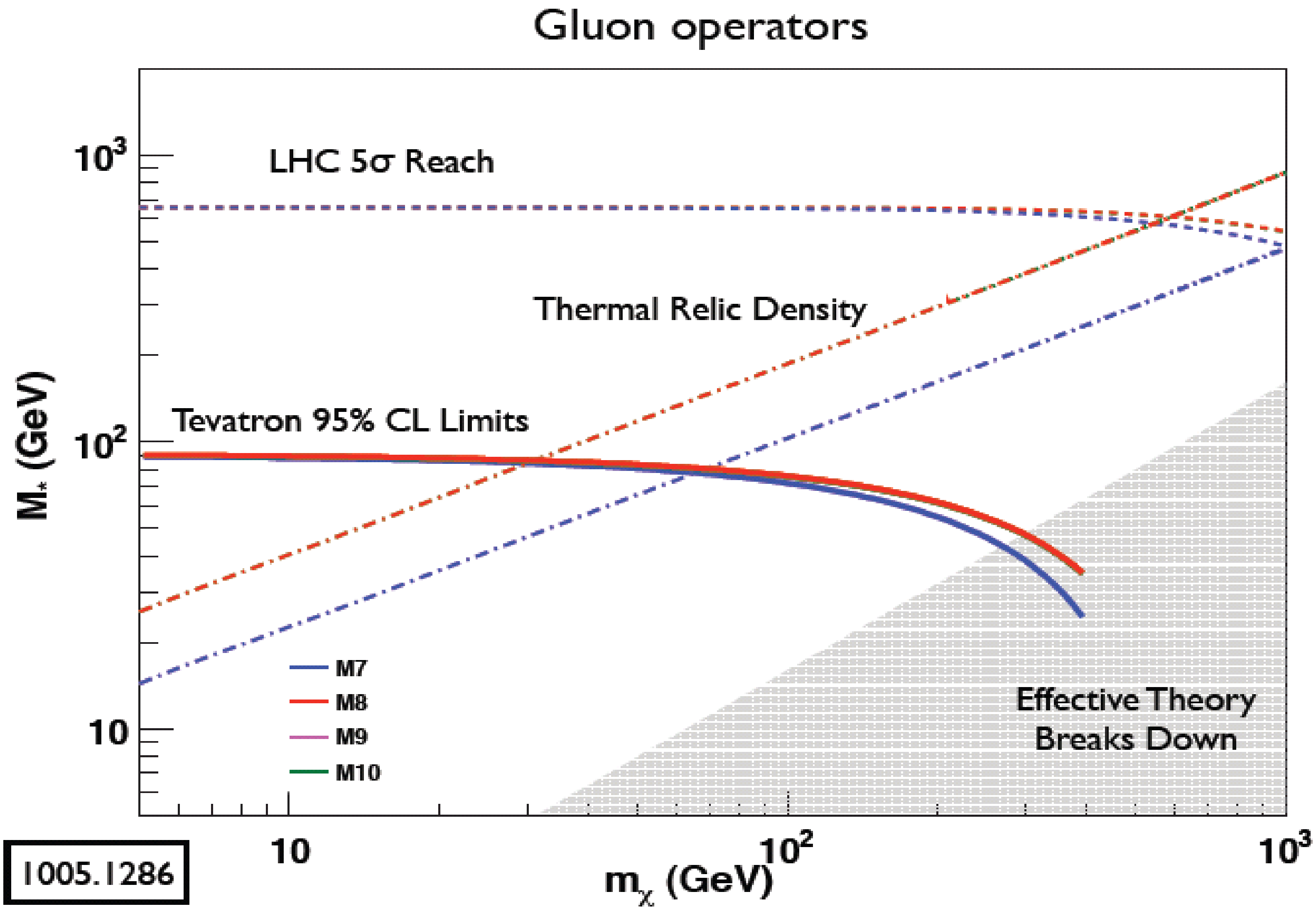
Collider Constraints



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Constraints on Direct Detection

We have found constraints on each of our operators from collider experiments.

We now want to translate these bounds to bounds on spin-independent and spin-dependent cross sections for dark matter scattering.

Only three of these operators contribute to such scattering; the rest are suppressed at low momentum transfer. These are

M1: $(\chi\chi)$ (qq) : contributes to spin independent scattering
M7: $(\chi\chi)$ (G^2) : contributes to spin independent scattering
M6: $(\chi\gamma^5\gamma^\mu\chi)$ $(q\gamma_\mu\gamma_5\, q)$: contributes to spin-dependent scattering

Constraints on Direct Detection

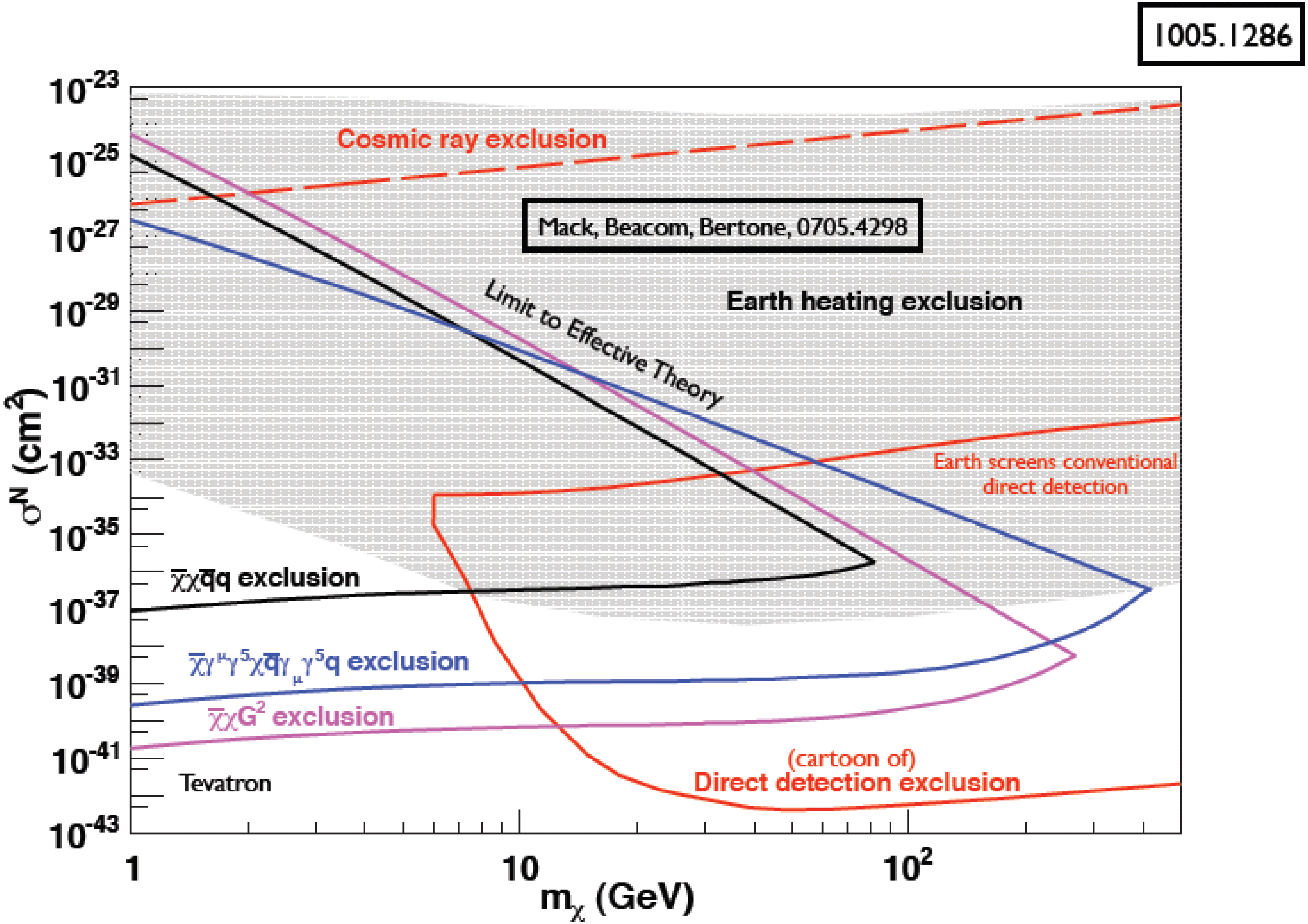
The corresponding cross sections are

$$\sigma^N_{SD;M6} = \frac{16\mu_\chi^2}{\pi}(0.015)\left(\frac{1}{2M_*^2}\right)^2,$$
$$\sigma^N_{SI;M1} = \frac{4\mu_\chi^2}{\pi}(0.082\ \mathrm{GeV}^2)\left(\frac{1}{2M_*^3}\right)^2,$$
$$\sigma^N_{SI;M7} = \frac{4\mu_\chi^2}{\pi}(5.0\ \mathrm{GeV}^2)\left(\frac{1}{8M_*^3}\right)^2,$$

where μ_χ is the reduced mass.

We translate the constraints on M_* to constraints on the cross sections.

Constraints on Direct Detection: SIMPs



Constraints on Direct Detection: SIMPs

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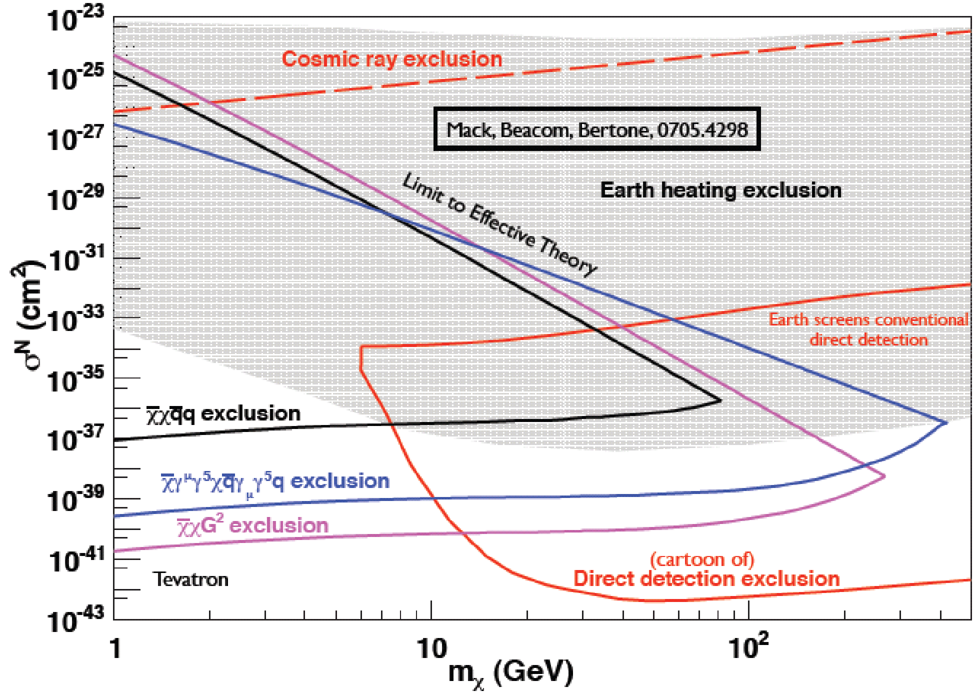

There is a range of dark matter mass and coupling (M_χ < 10GeV, $\sigma \sim 10^{-37}$ cm^2) which can never be probed by direct detection experiments, but which is already constrained by the Tevatron!

Constraints on Direct Detection: Spin-Independent

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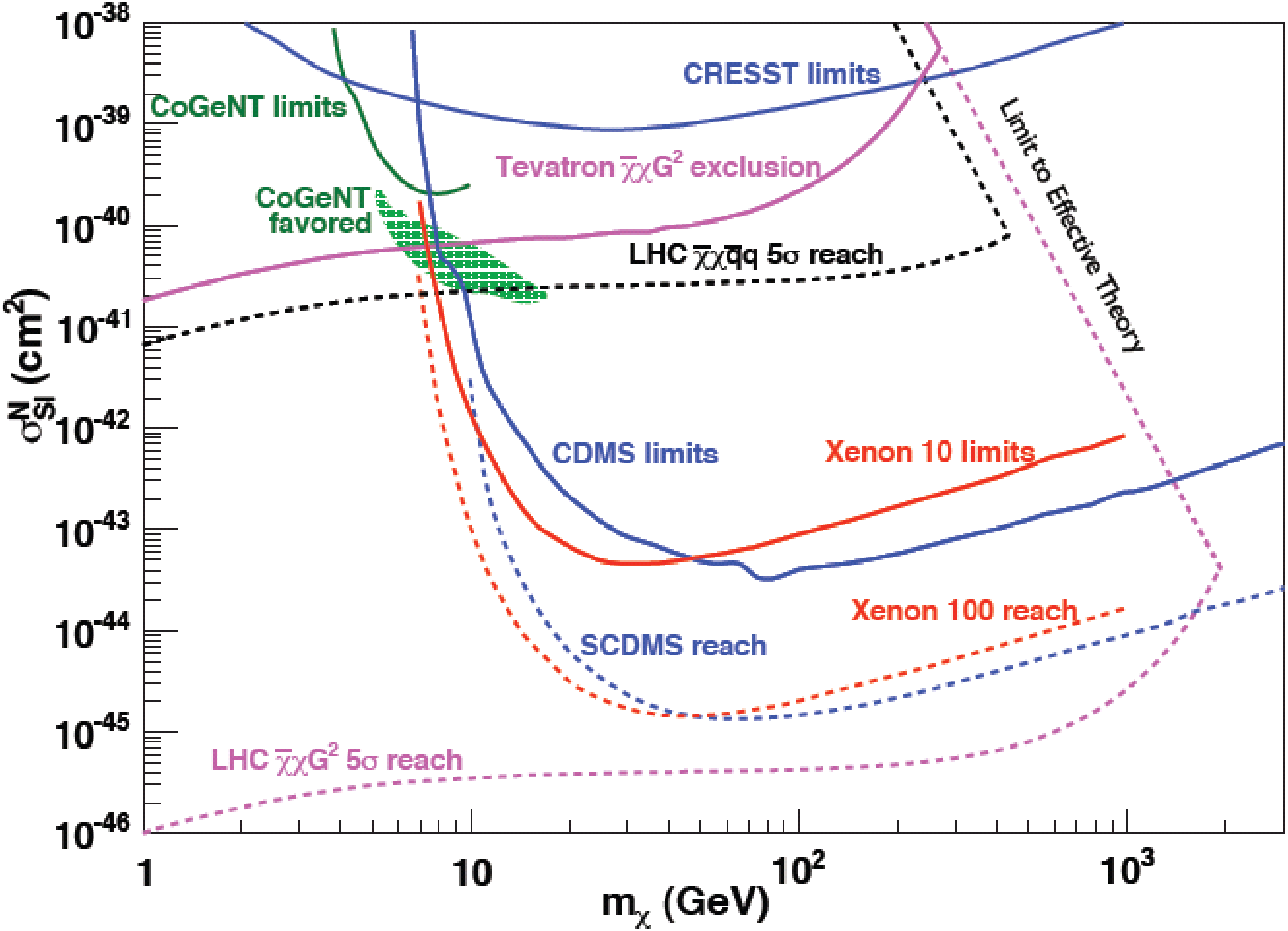

Constraints on Direct Detection: Spin-Independent

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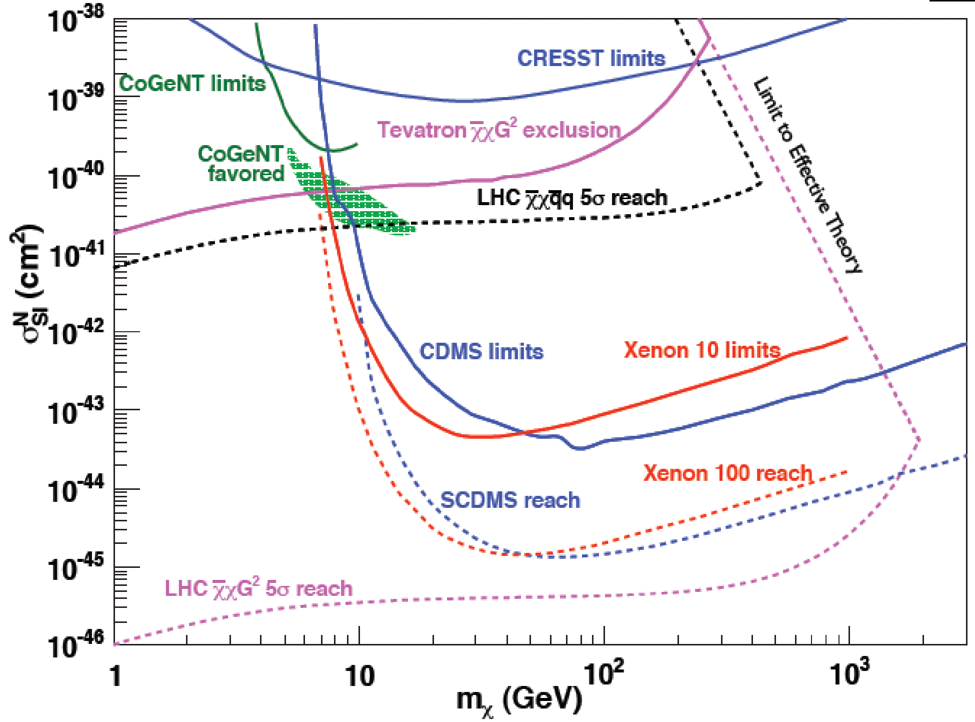

Colliders complementary to direct detection searches.

LHC bounds superior to direct detection searches if the dark matter is light or primarily couples to gluons.

The LHC can independently rule out the COGENT favored region.

Constraints on Direct Detection: Spin-dependent

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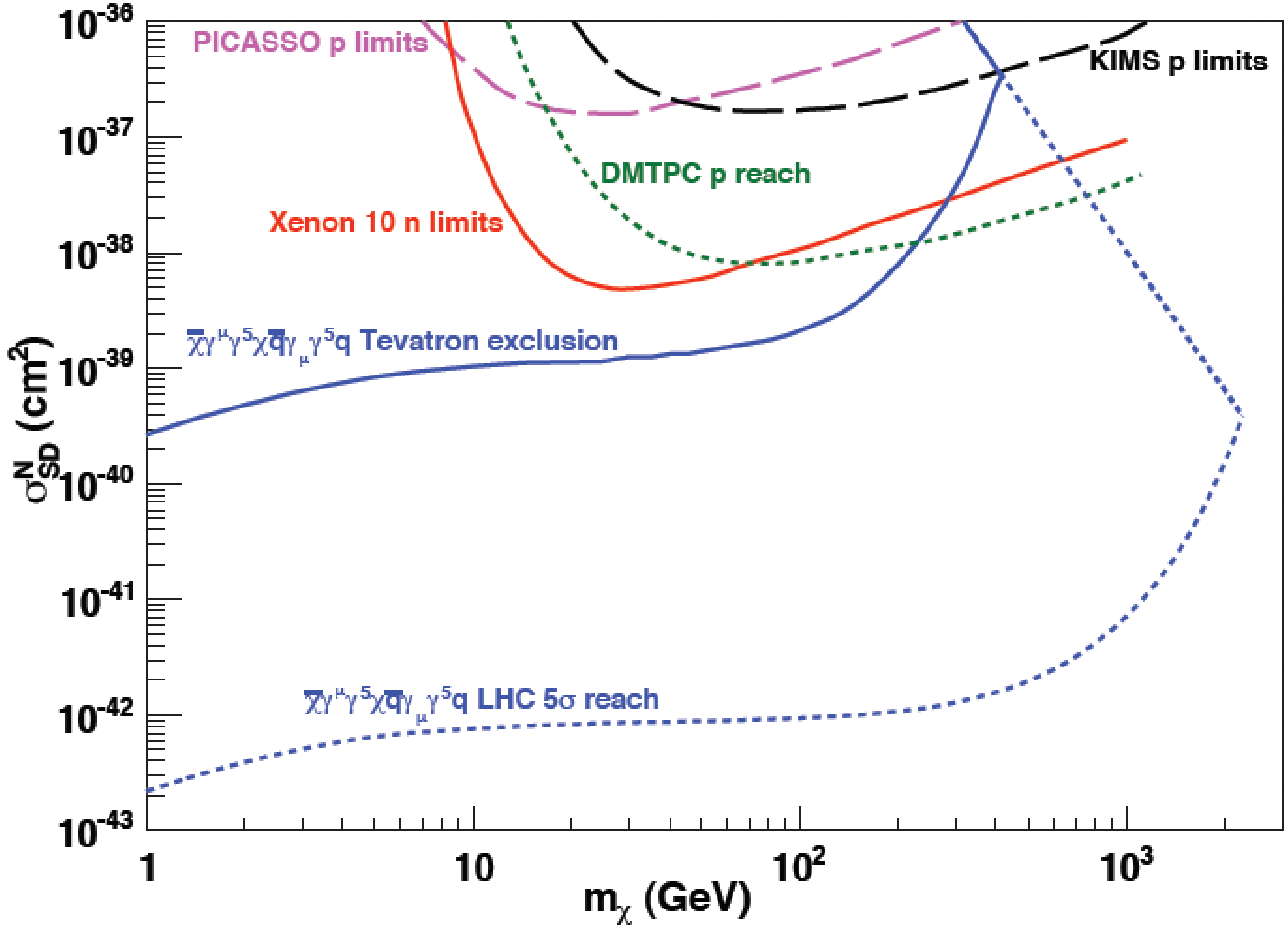
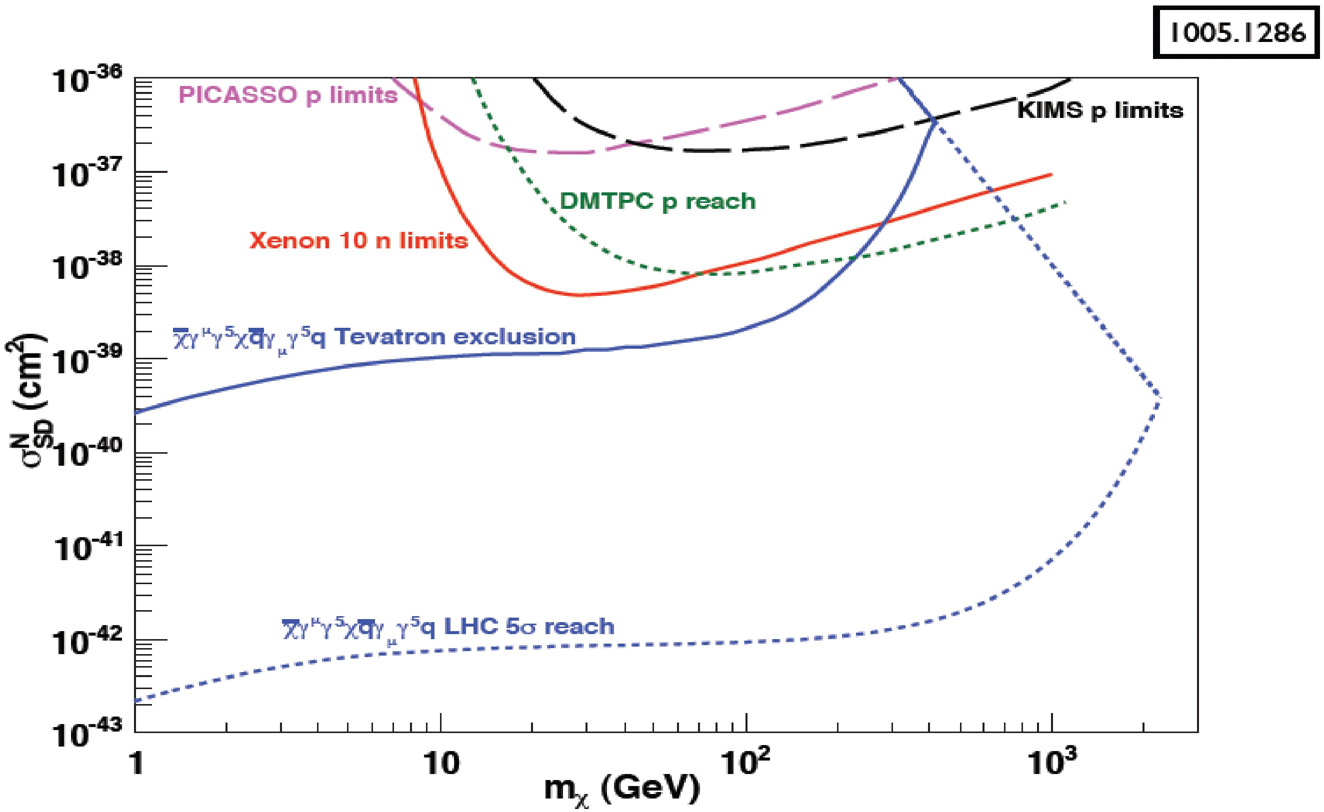


Constraints on Direct Detection: Spin-dependent



Both the Tevatron and LHC are superior to any spin-dependent search over almost all of parameter space (by orders of magnitude!)

Other cases: Scalar, Dirac

We have so far done the Majorana fermion case. It is straightforward to extend our procedure to other cases, where the dark matter is a real or complex scalar, or a Dirac fermion.

This could be done for vector dark matter as well; we found a proliferation of operators that make it hard to do a completely model independent analysis, and we did not consider this case.

As before, we can list all operators and find the bounds on their suppression scale. We then translate these to bounds on direct detection.

J.Goodman, M. Ibe, AR, W. Shepherd, T.Tait, H.Yu, to appear

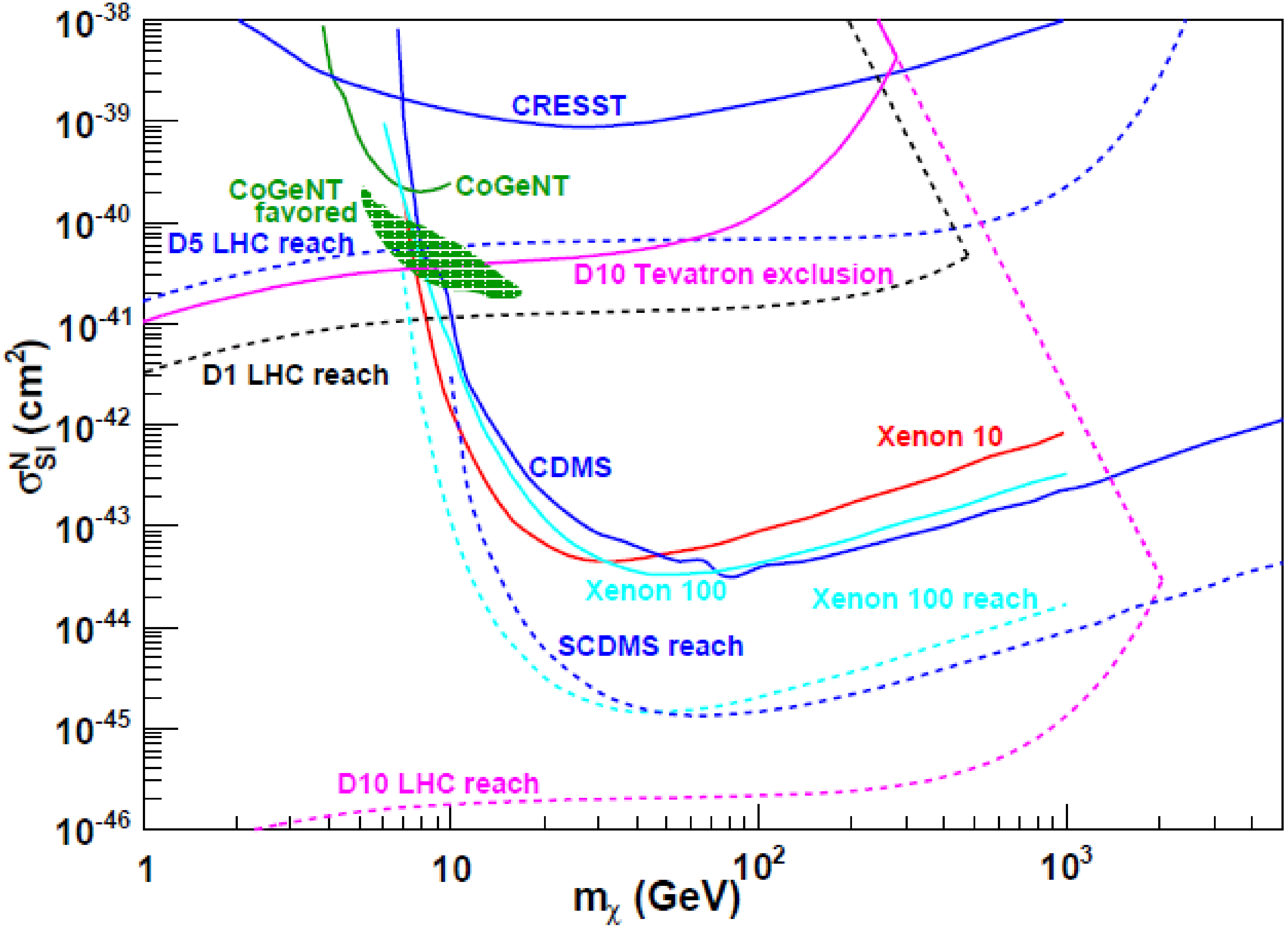
Other cases: Scalar, Dirac

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	$\bar{\chi}\gamma^{\mu\nu}\chi\bar{q}\gamma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D11	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D12	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$

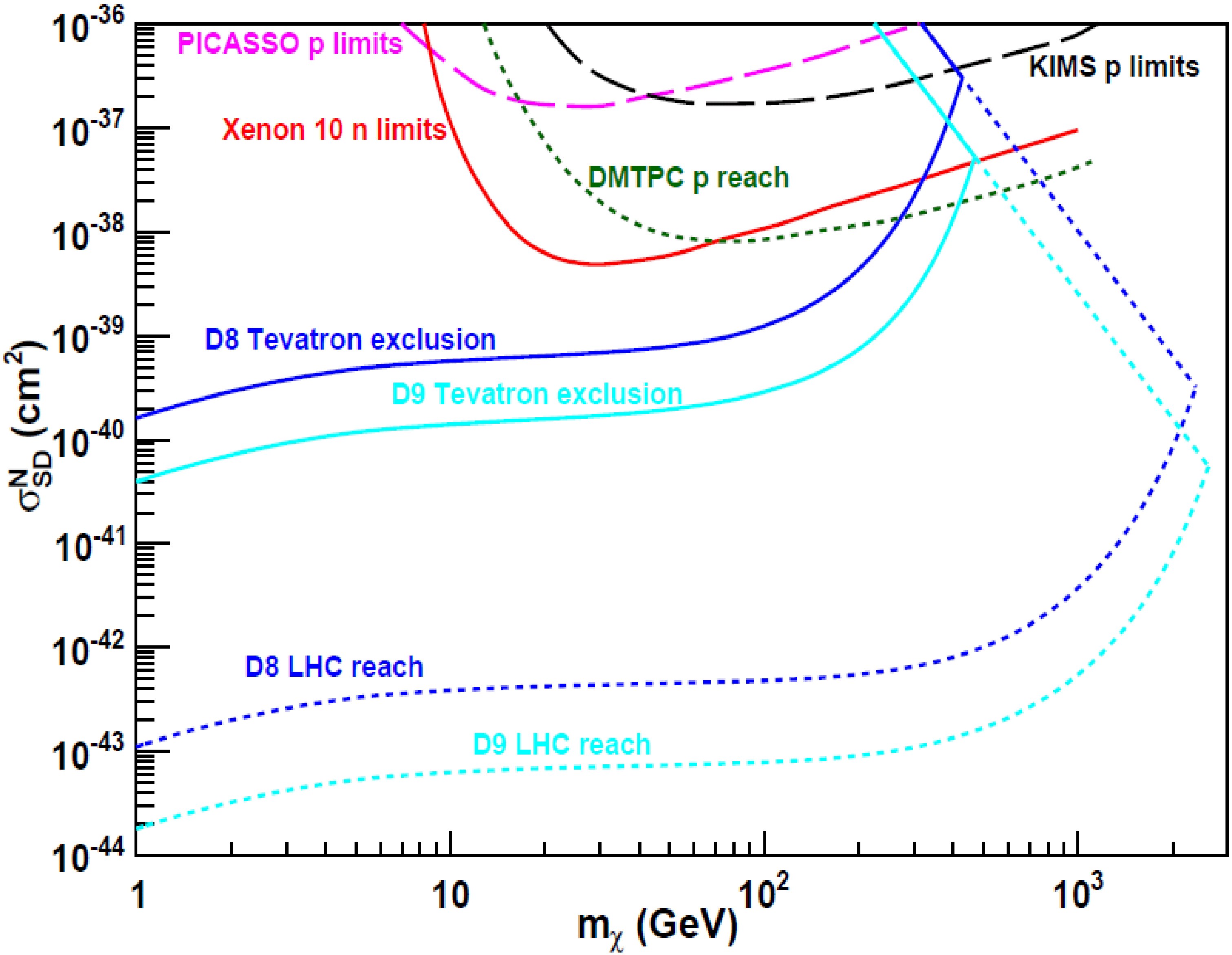
Name	Operator	Coefficient
D13	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

Other cases: Scalar, Dirac



Other cases: Scalar, Dirac



Other cases: Scalar, Dirac

Results qualitatively same for scalars and Dirac fermions.

Colliders still competitive with spin-independent searches, outperform spin-dependent searches.

Light Mediators

Main loophole in our analysis: the dark matter may not be the only light state.

Can have a light mediator e.g. scalar ϕ with couplings $g_1\, \phi\chi\chi$, $g_2\, \phi qq$ and mass $M_\phi < M_\chi$.

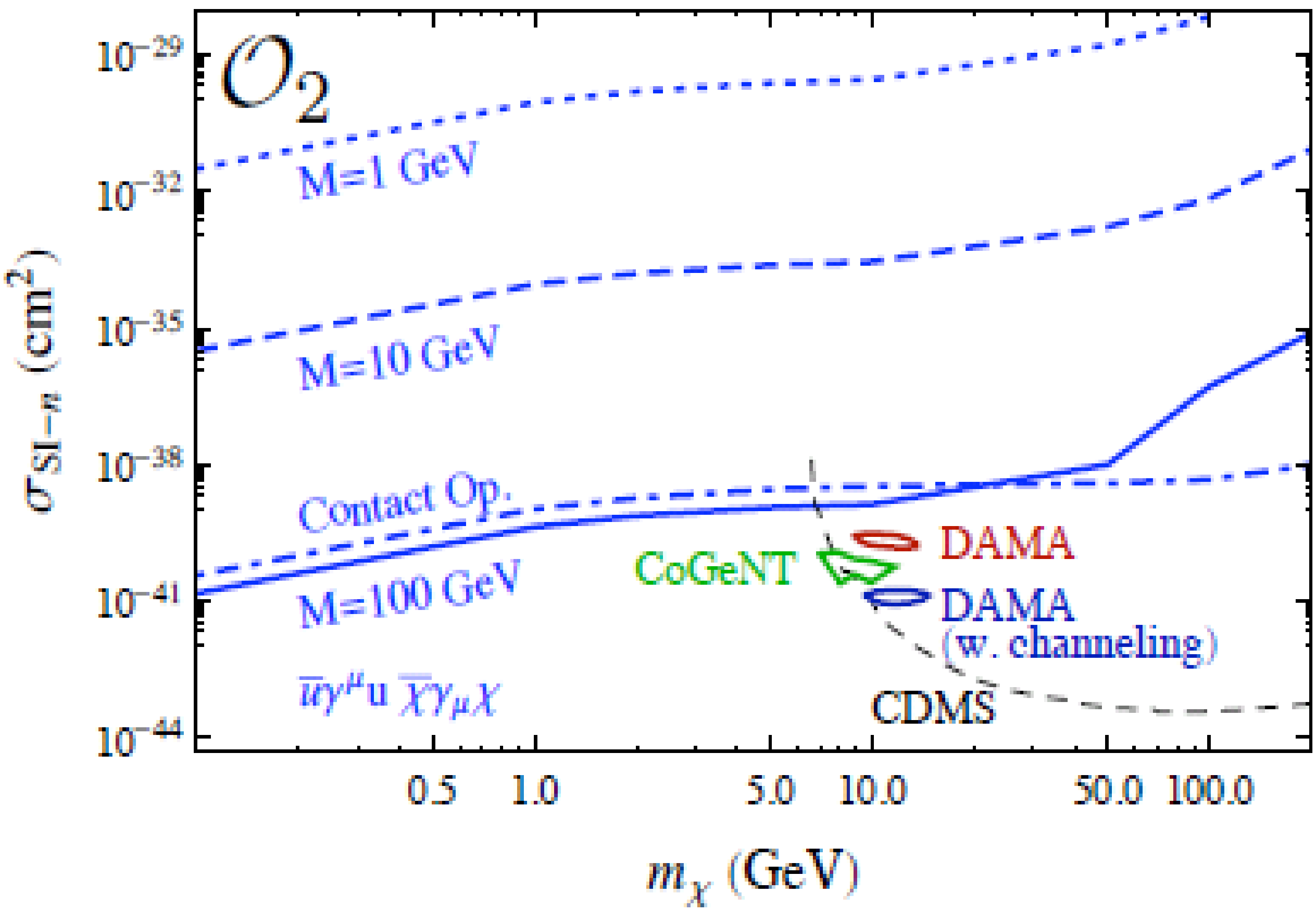
If we take g_1, g_2, $M_\phi \to 0$ keeping the effective coupling

$$\frac{1}{M^2_*} = \frac{g_1 g_2}{M_\phi^{\,2}}$$

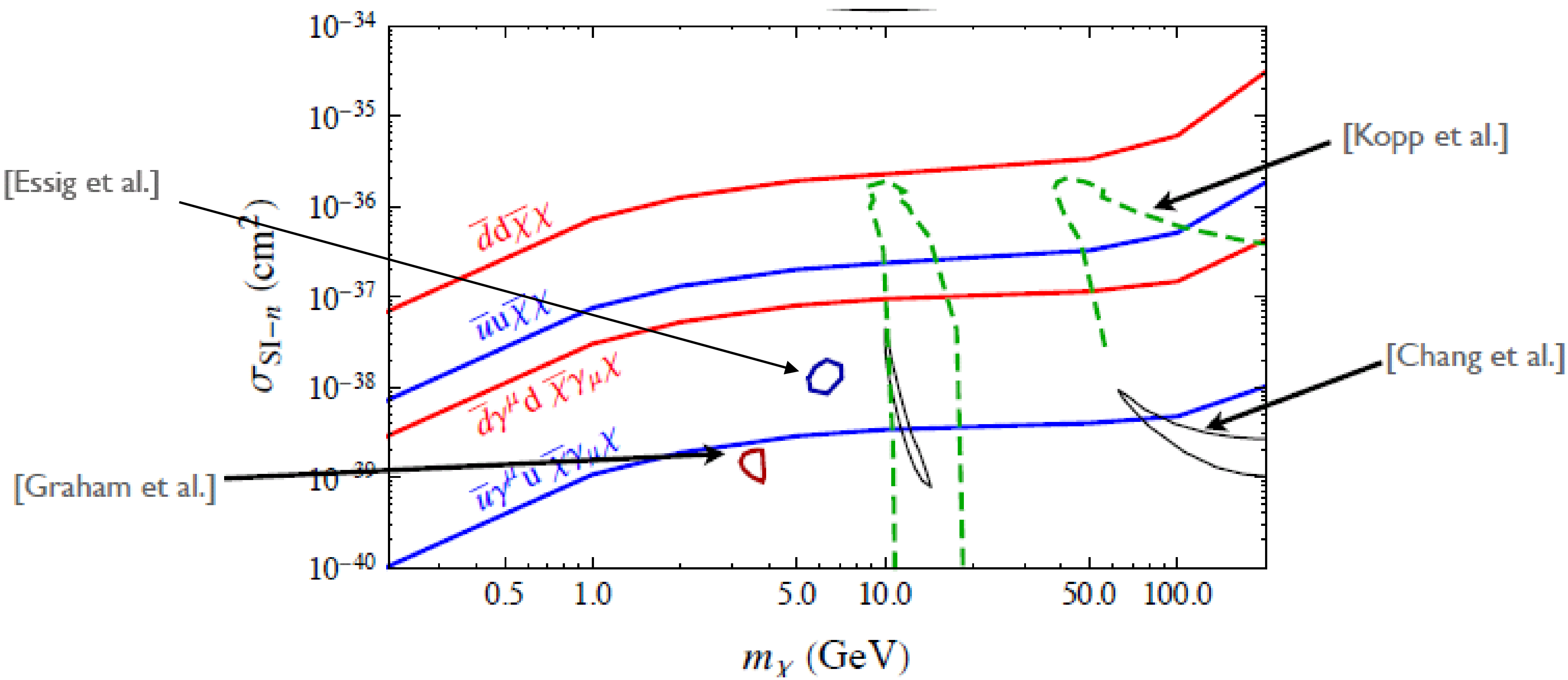
fixed, then collider constraints removed while direct detection rate fixed.

Light Mediators Example

Bai, Fox, Harnik, arXiv:1005.3797



Application to Dark Matter Models: iDM, exoDM



Essig et al model would need light mediator if the coupling is vector-vector.

Bai, Fox, Harnik, arXiv:1005.3797

Conclusions

Colliders provide a complementary approach to searches for dark matter.

If the dark matter is light or primarily couples to gluons, then collider searches can be competitive with or superior to spin-independent direct detection searches.

Colliders outperform spin dependent searches over most of parameter space by orders of magnitude.

If direct searches find a signal while colliders do not, it would indicate a light mediator i.e. we would have found two particles!