Hunting for Dark Matter @ Colliders

CERN Workshop:
Dark Matter in Hell and in the Heavens

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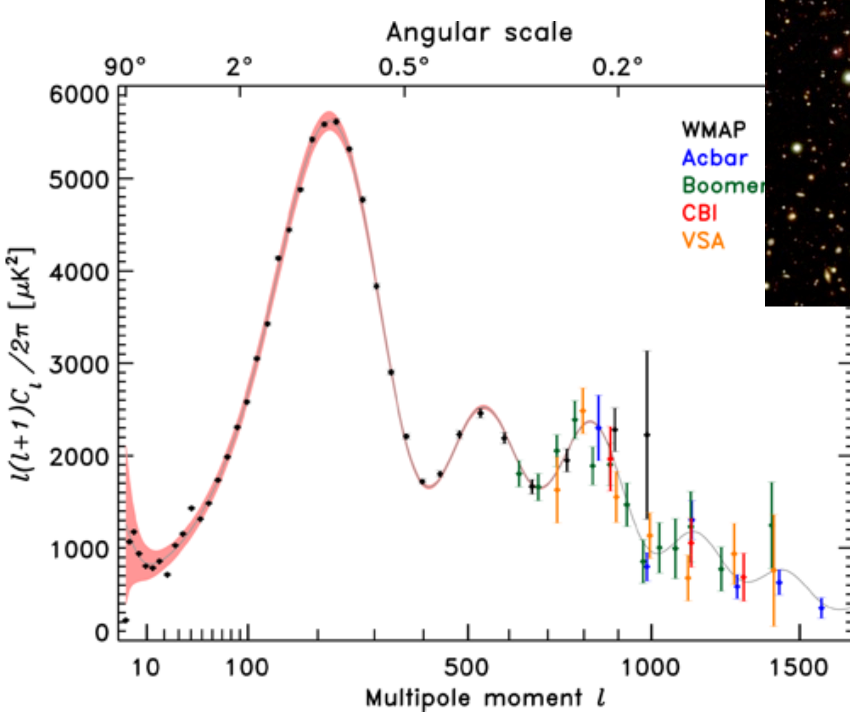
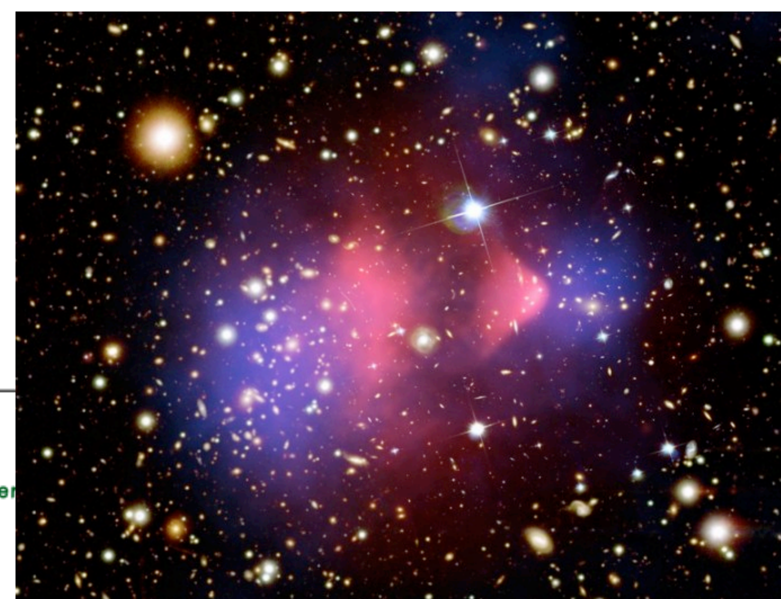
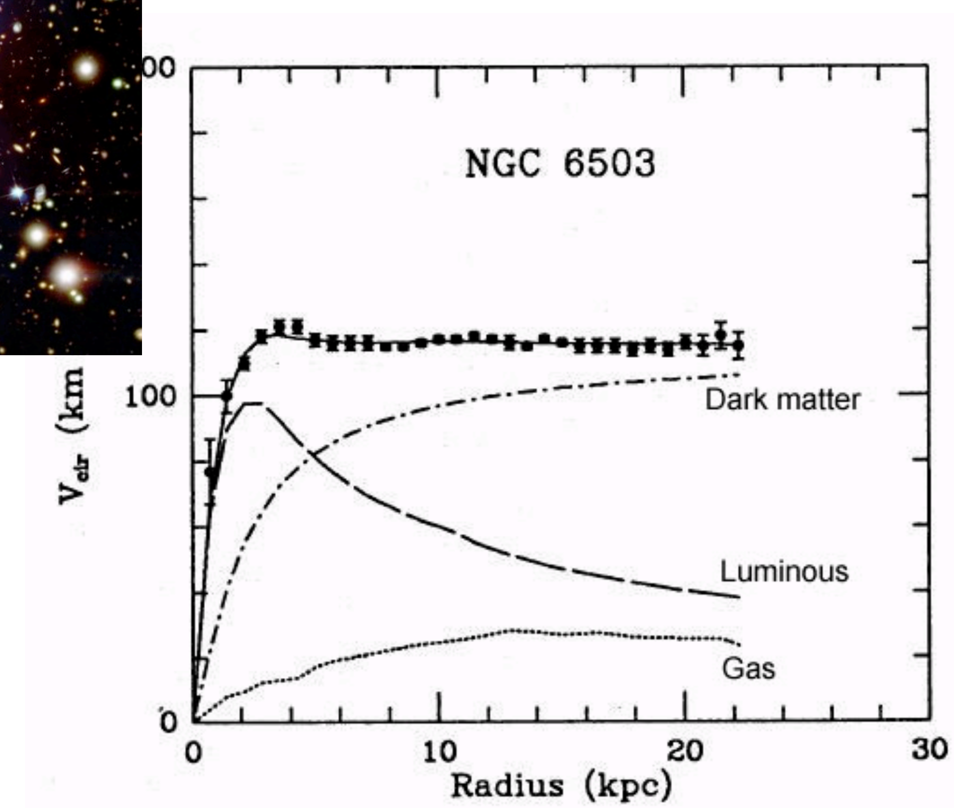
Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - in progress

Dark Matter needs no introduction.







But it has a lot to answer for:

* What sets its abundance?
* Does it interact with matter *apart* from gravity?
* How strong/weak are these interactions?

* Does it fit into a larger framework?
* What is the particle mediating this interaction?

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Directly complemented by past and present colliders.

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LHC (e.g. Higgs mediated interactions)

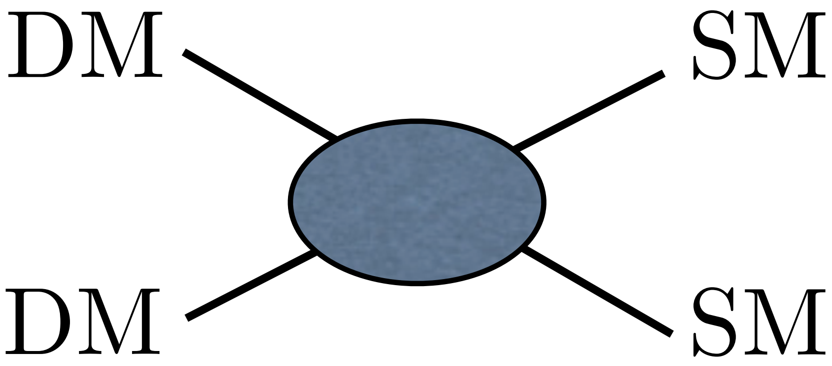
Outline

* Motivation:
  Colliders as direct detection experiments.
* Tevatron mono-jets:
  - Operators and rough estimates.
  - Results
  - Breaking news: New LHC limits.
  - Future improvementes
* LEP mono-photons.
* Prospects for LHC: scattering via the Higgs.
* Coffee.

The WIMP Hint

* Does DM have interactions with matter?
* If we throw a weakly interacting particle with weak scale mass into the primordial hot soup,  , the DM abundance comes out roughly right.

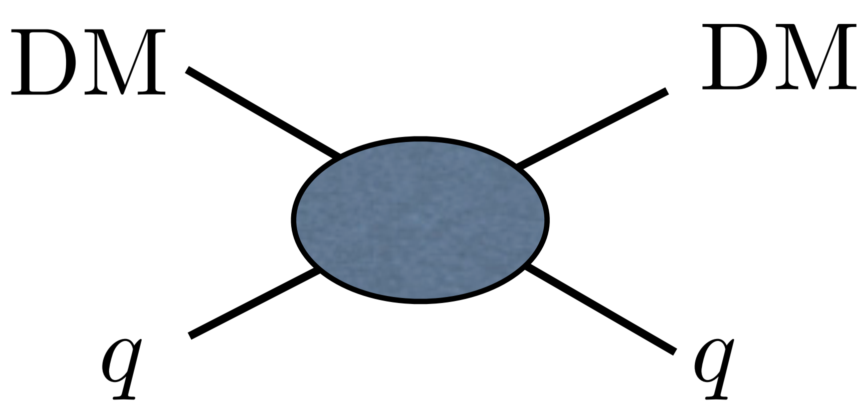
Hint: There is an interaction.
Leads to pb-ish cross sections



Probes of DM Interactions

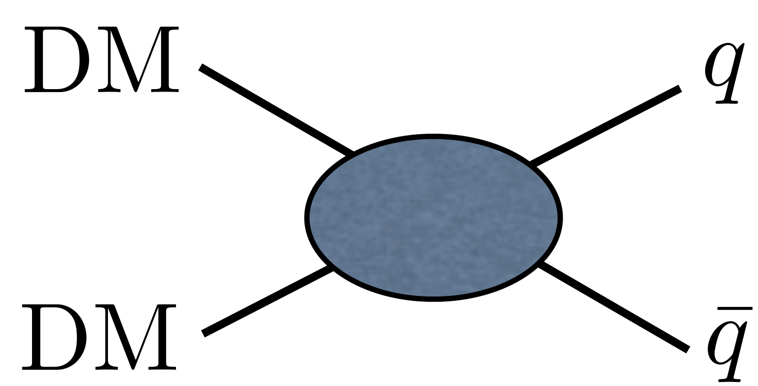
* We hope to probe dark matter in several ways:

DM-nucleus scattering



direct

DM annihilation

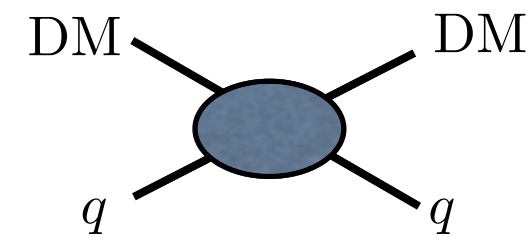


indirect

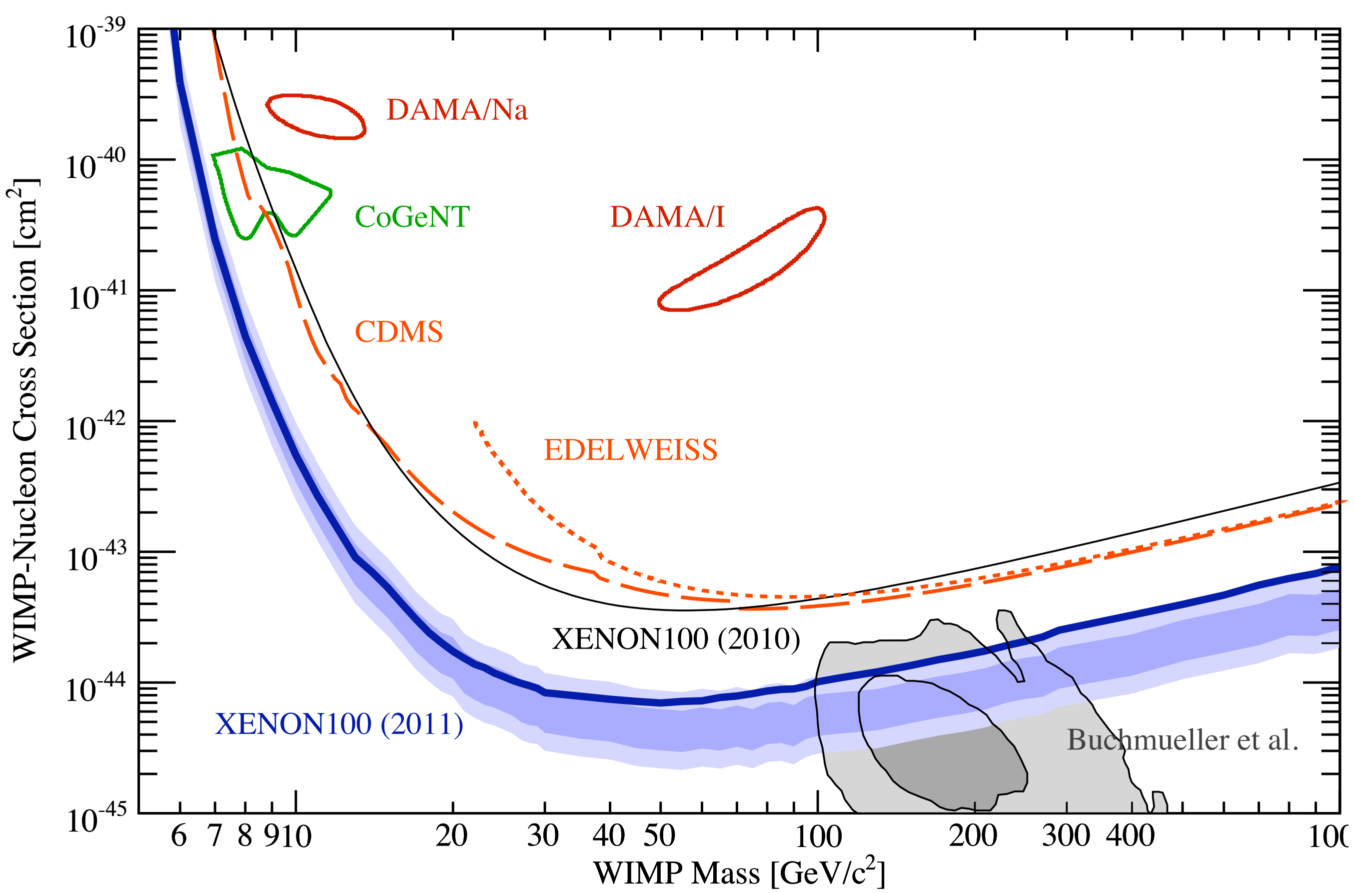
Focus on direct detection in this talk.

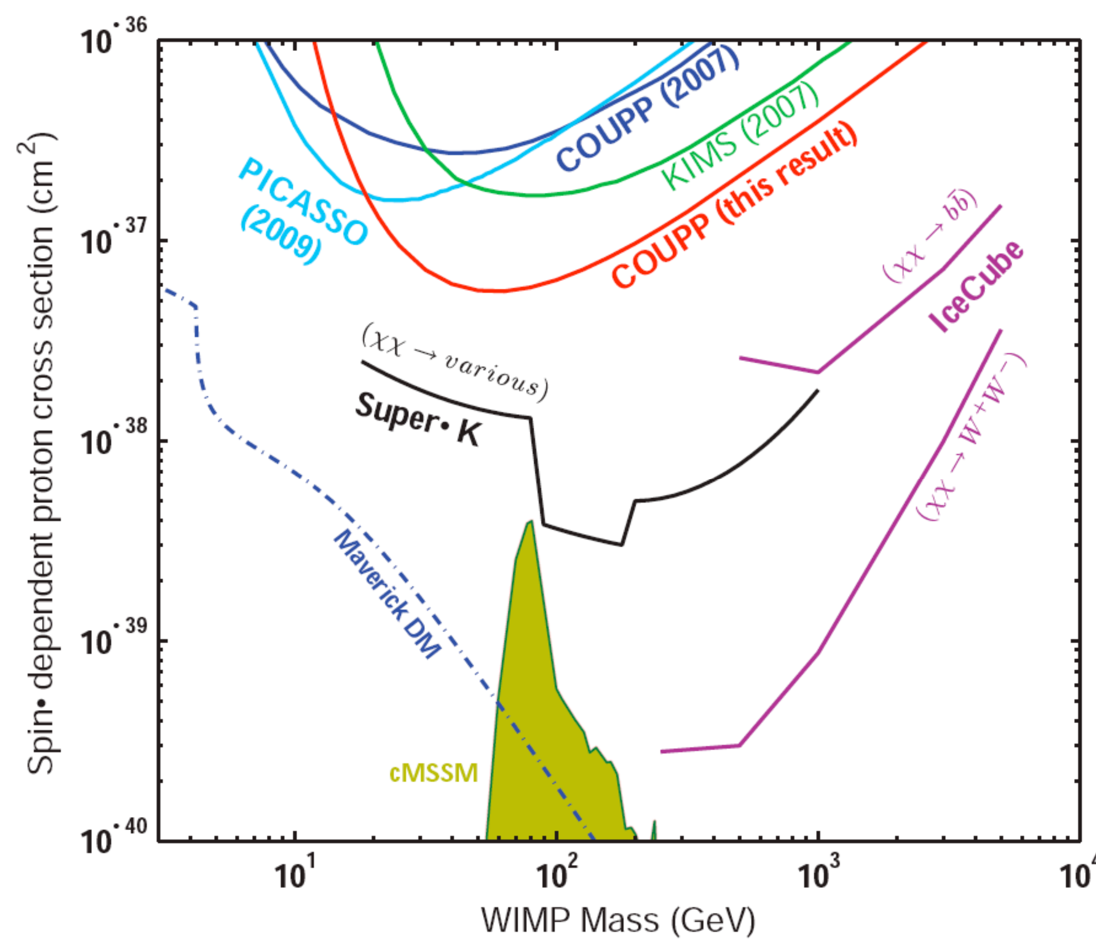
(a similar game can be played for indirect)

Direct detection

* Direct detection places limits on  .

* Heroic effort with remarkable results.
* DD has some weaknesses.





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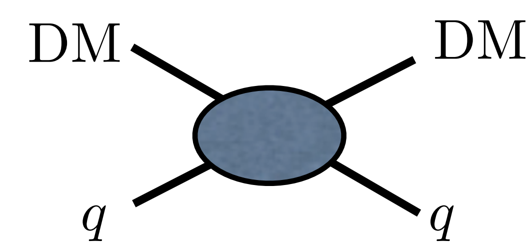
* Direct detection places limits on  .

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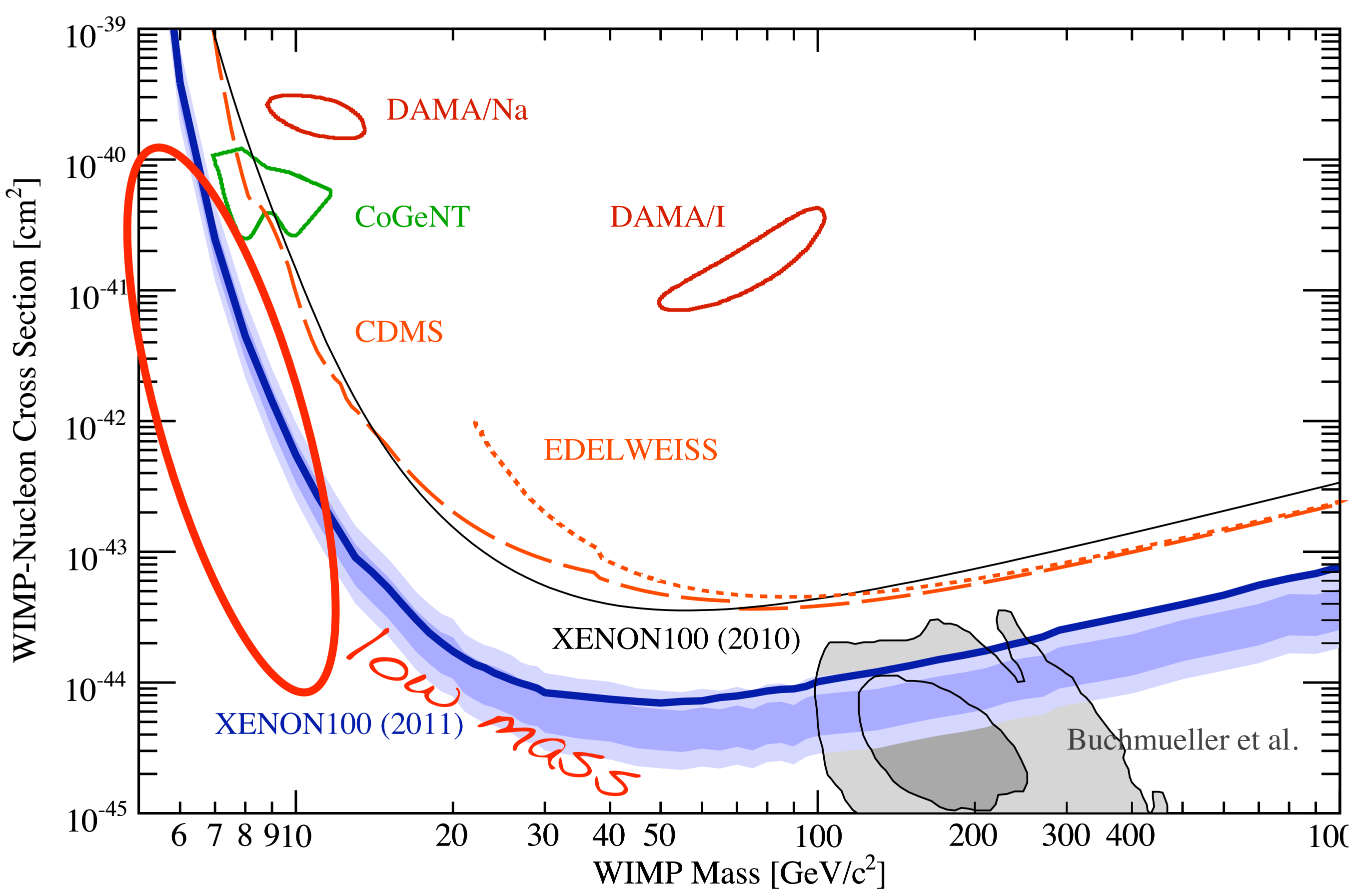

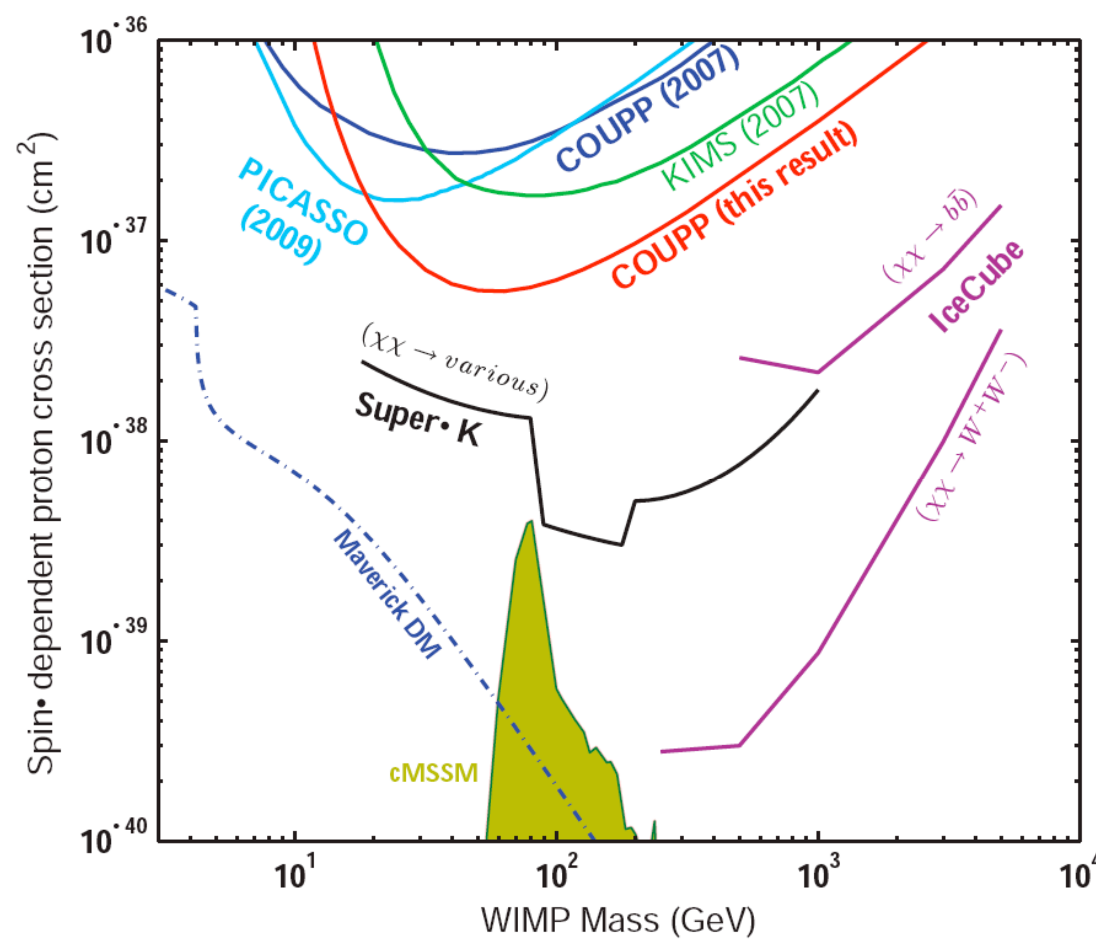

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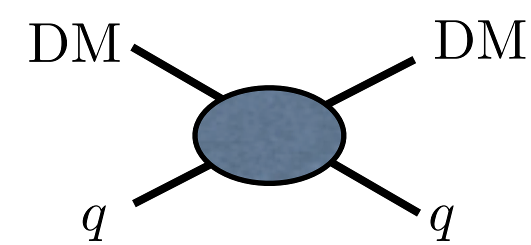
* Direct detection places limits on  .

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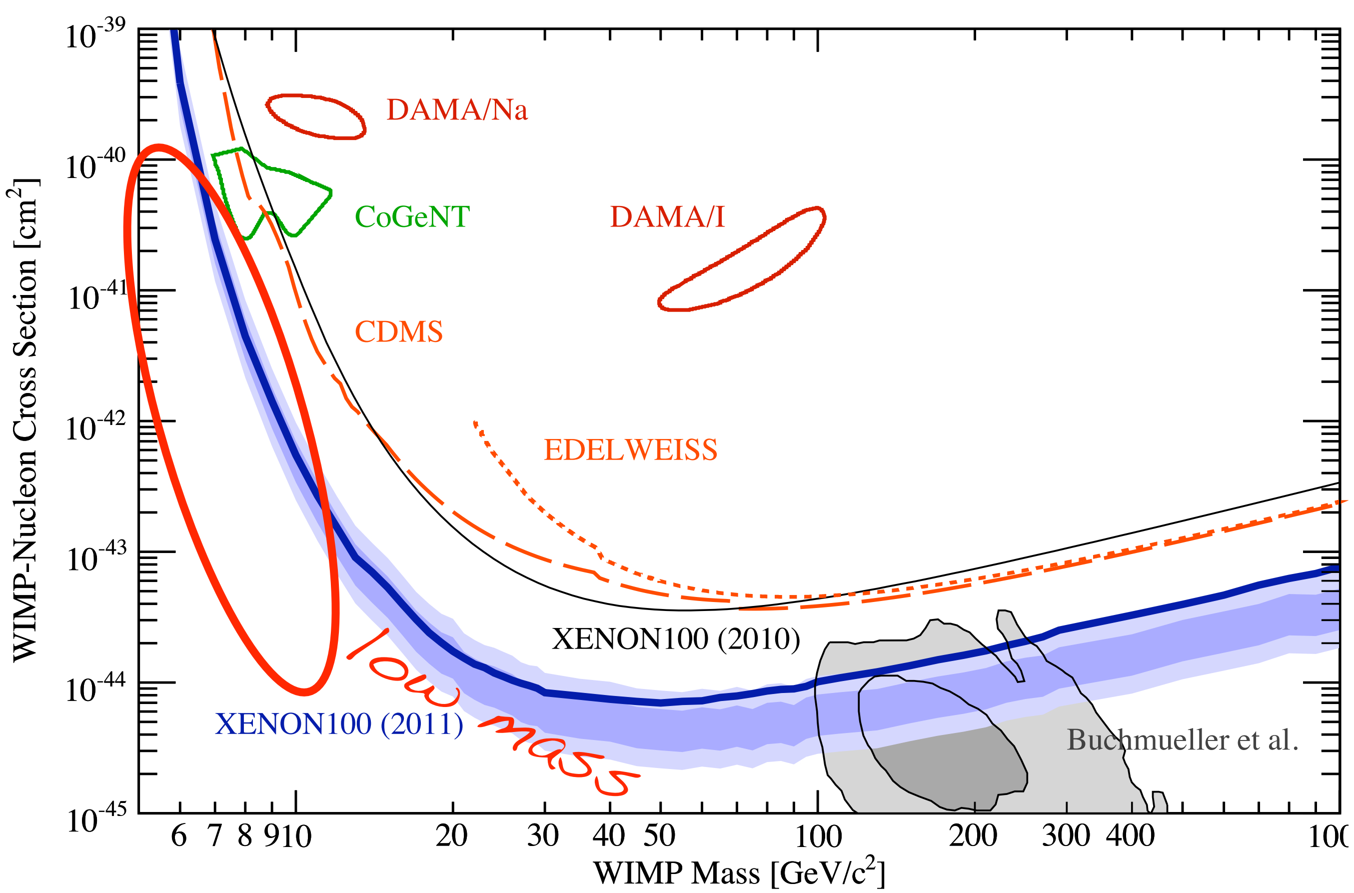
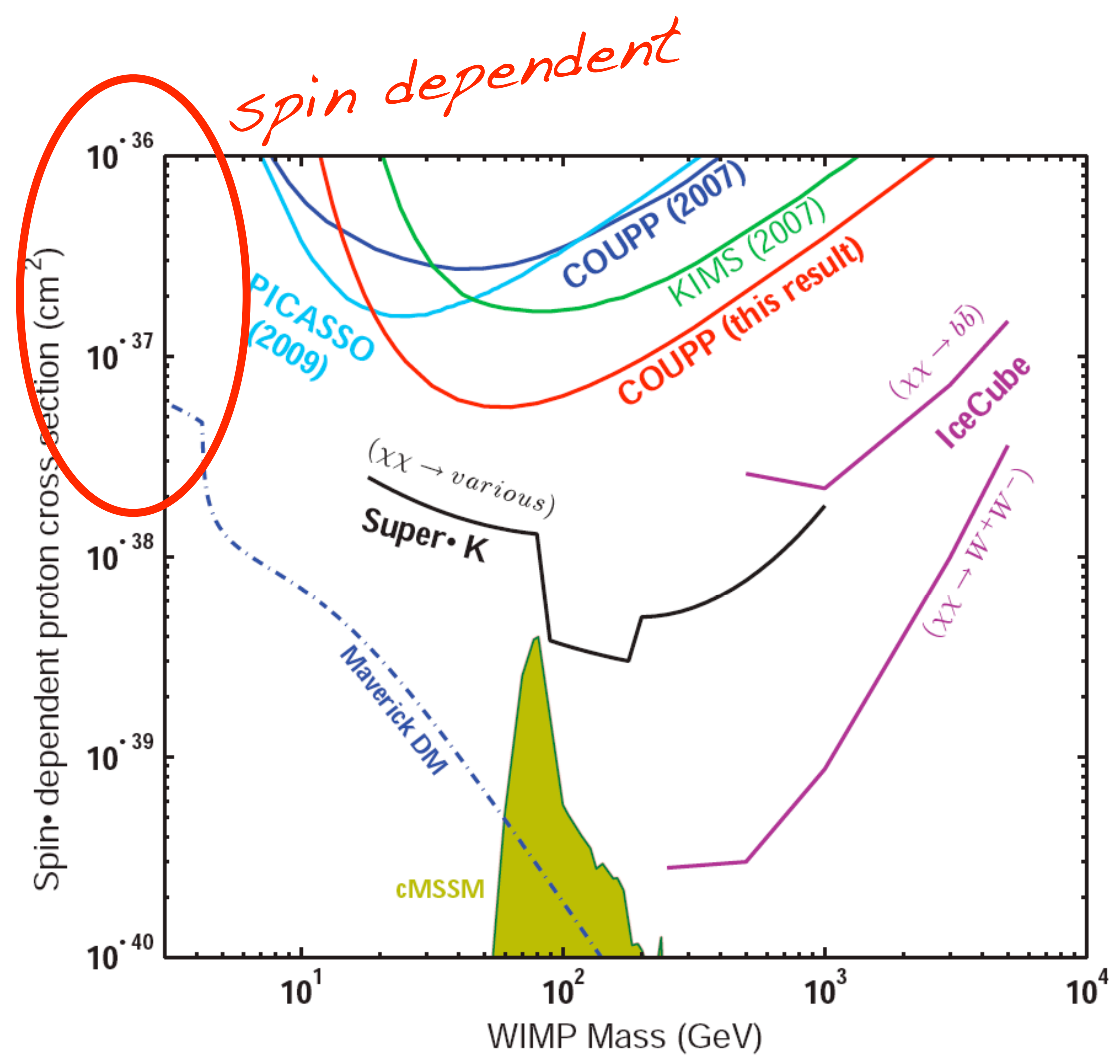
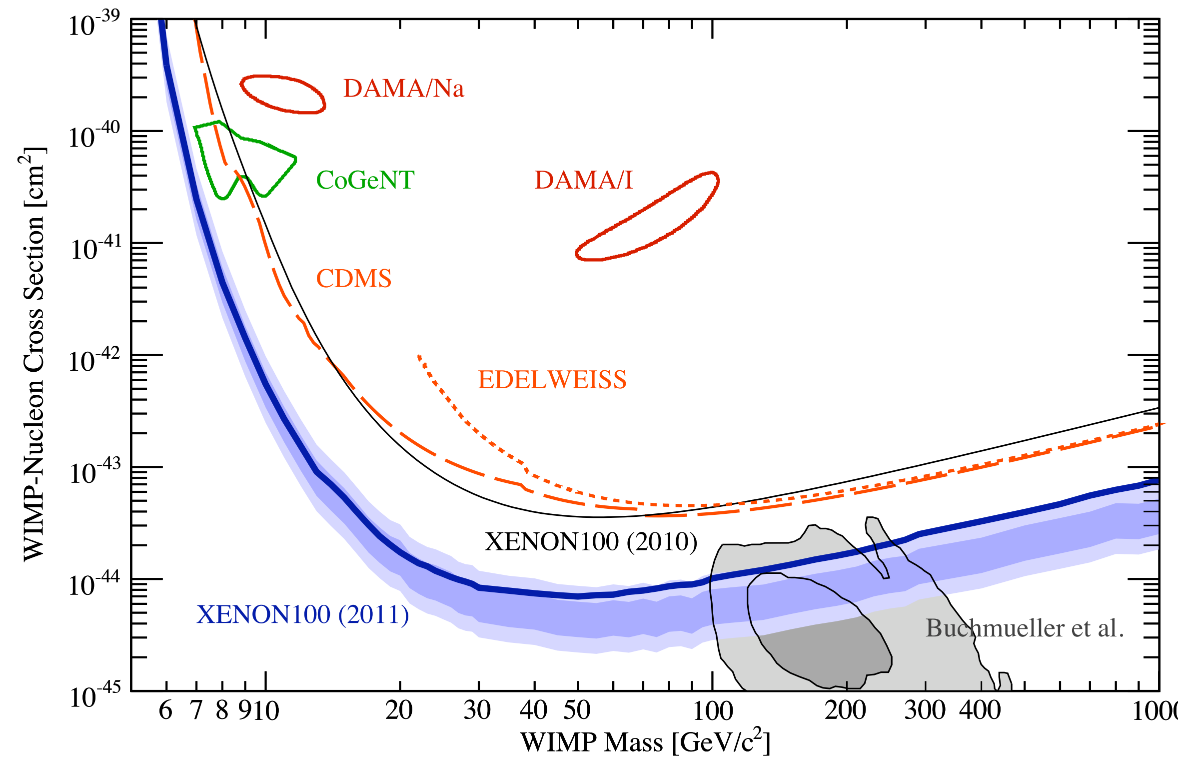




Collider Connections?

* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).



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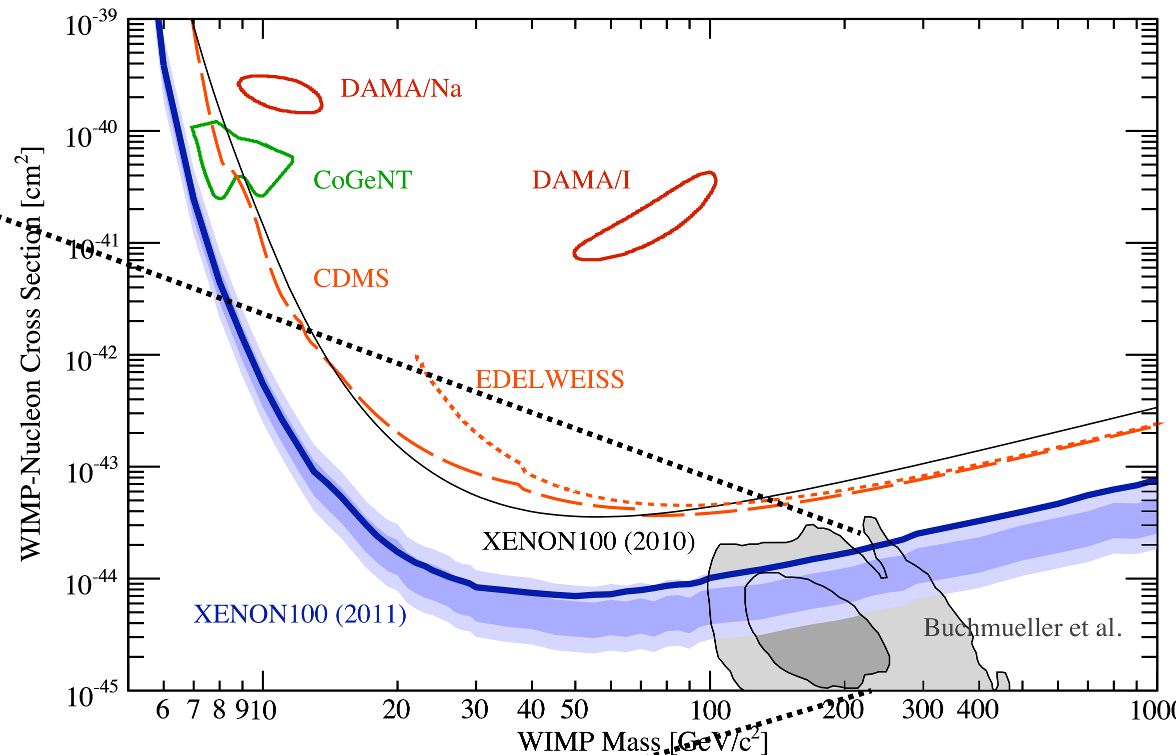

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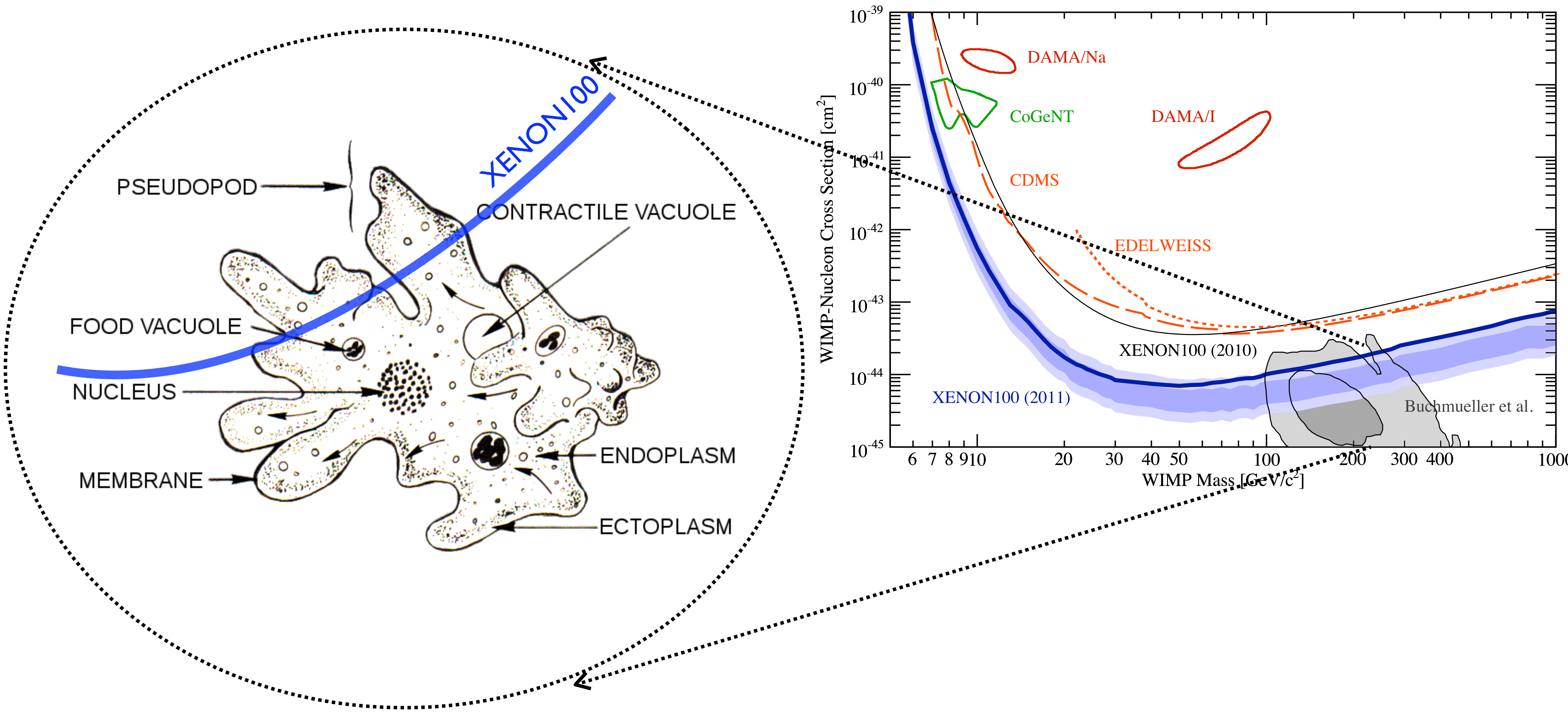

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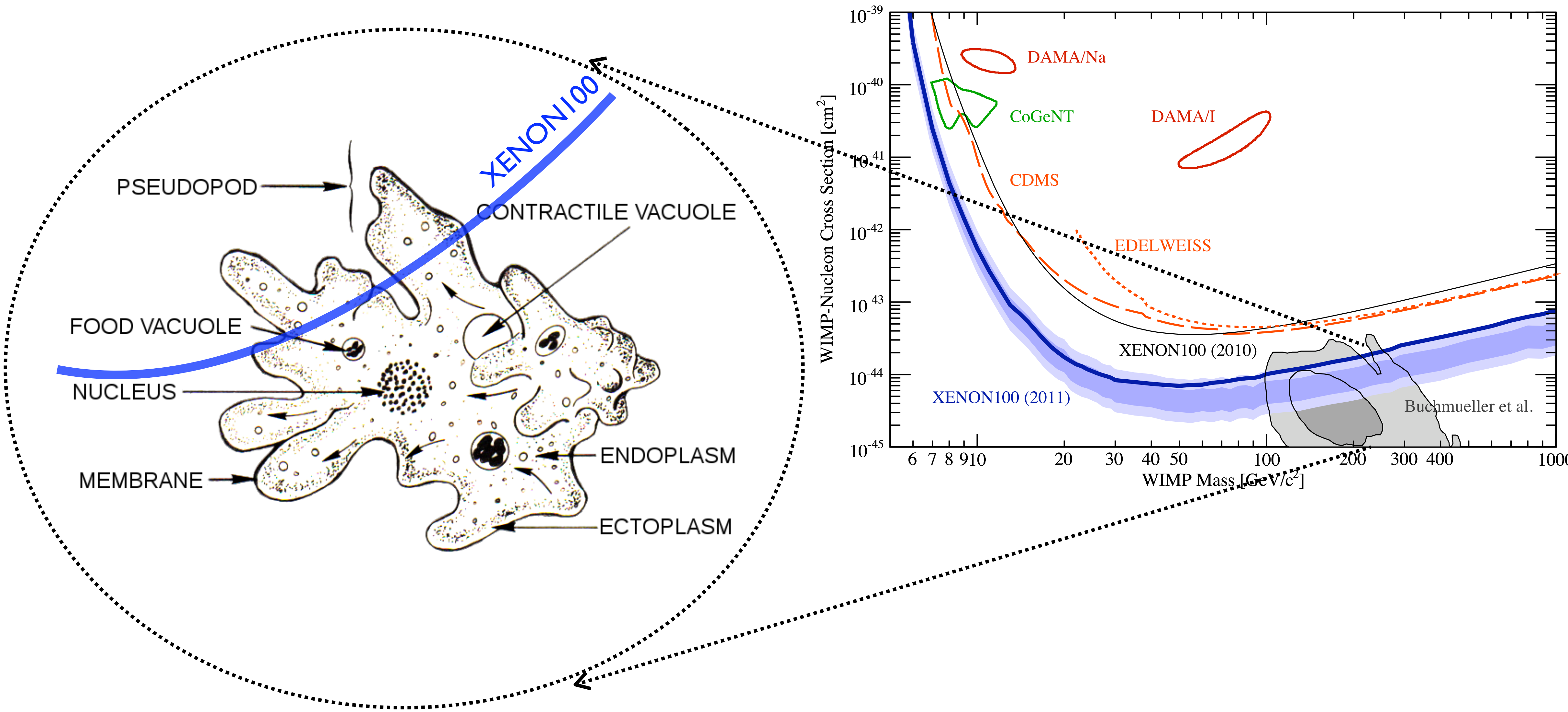
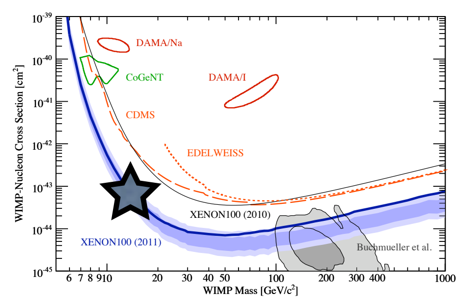
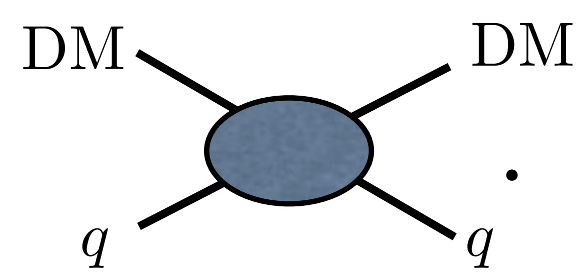


“XENON100 is starting to probe the MSSM’s pseudopod, LHC killed the Membrane, but the ectoplasm is still safe.” [nature **67**, 143 (2011)]

A Simple Point

* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

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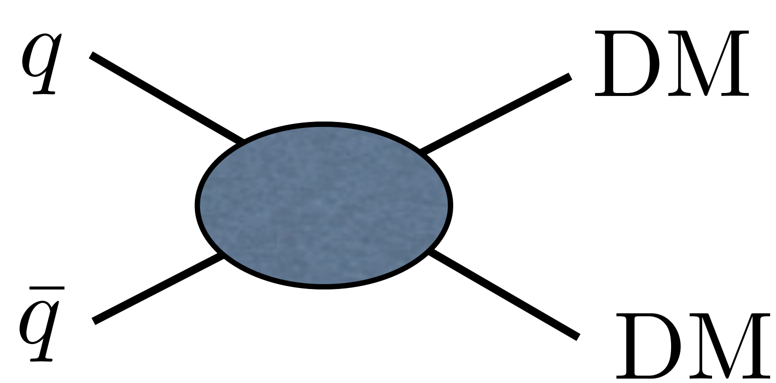

$$p\bar{p} \rightarrow \text{ nothing}$$

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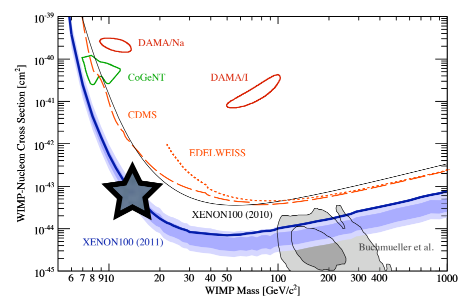
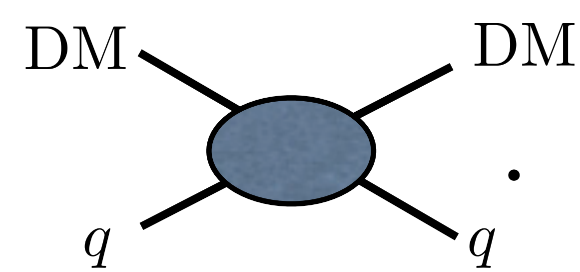
* In order to get a particular DM-nucleon cross section, 

, we assume the existence of a DM-hadron interaction, 

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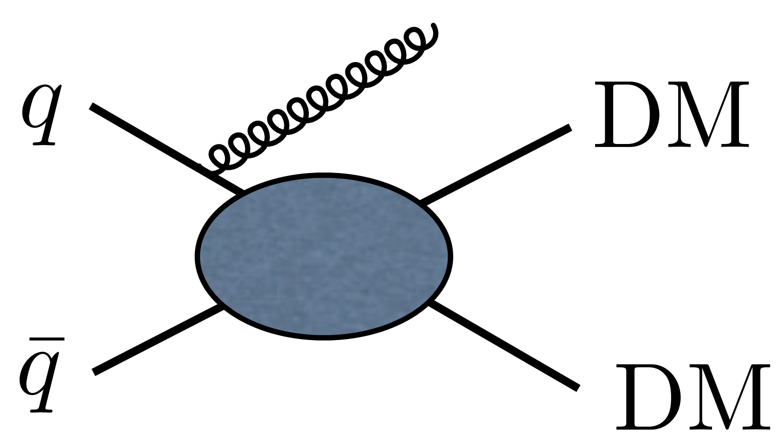
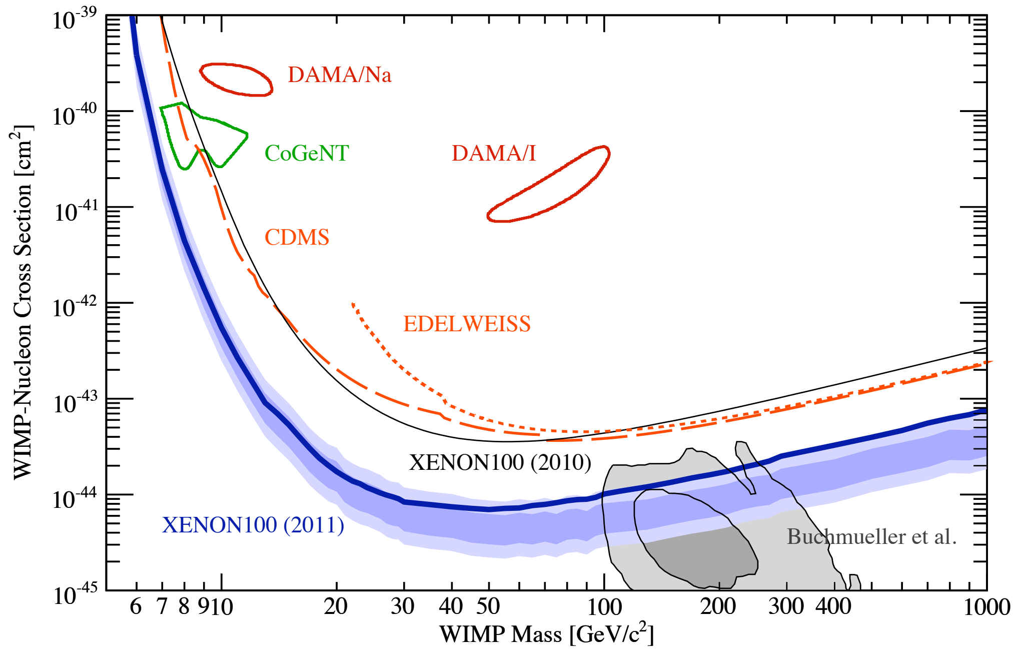
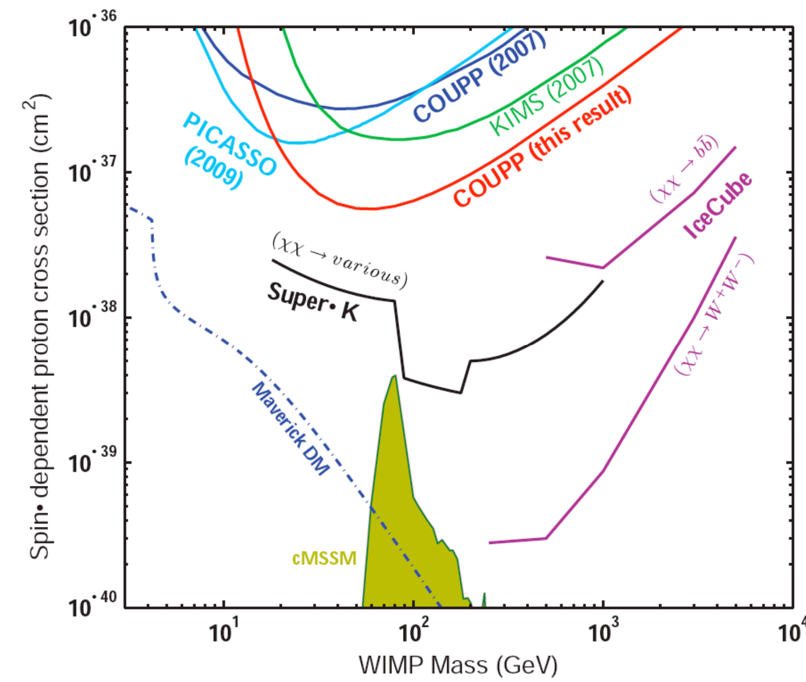


$$p\bar{p} \longrightarrow j + \not{E}_T$$

A Simple Point

* **Mono-jet searches can place limits on the plane.**





* These are **conservative** limits.
In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

But mono-jet are certainly good to set bounds.

A Simple Point

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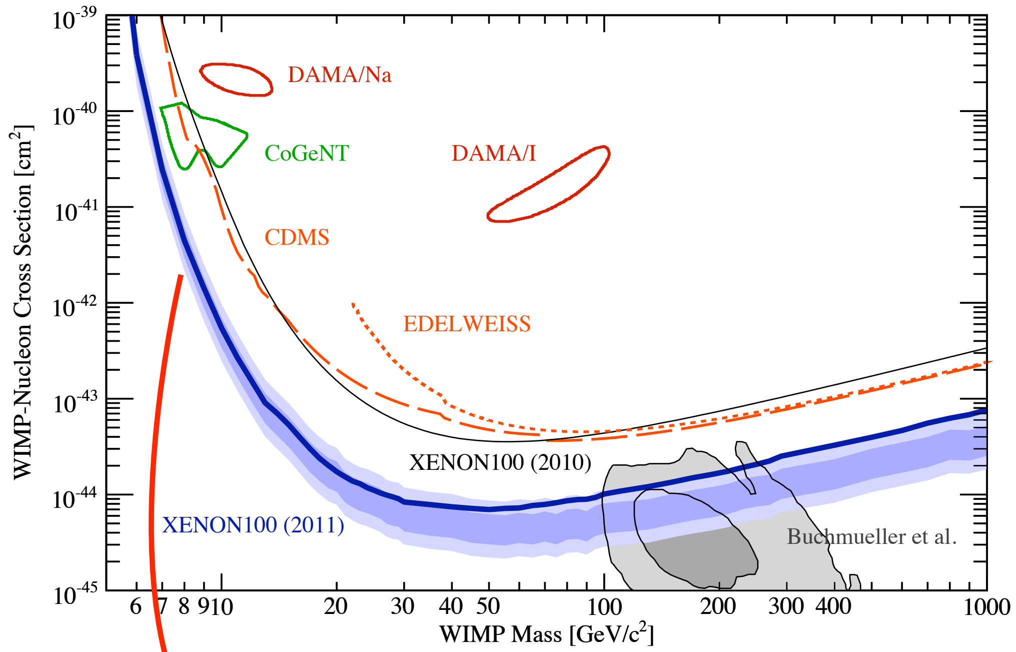
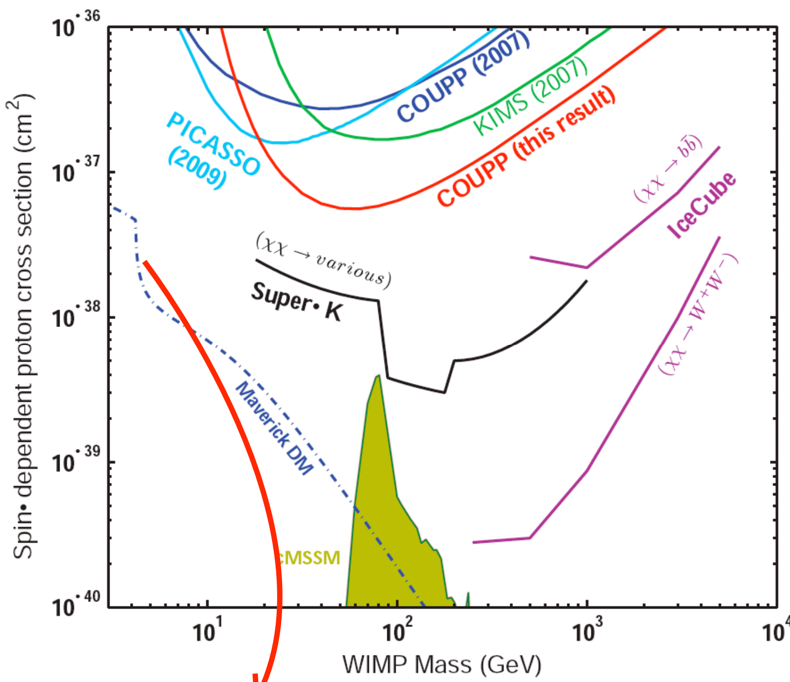


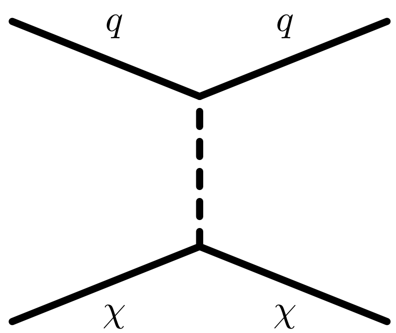


The collider does not have a low energy threshold

The collider does not pay a price for spin dependence

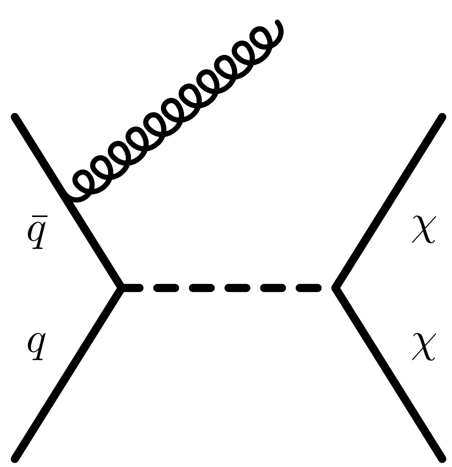
Cross Sections

* The direct detection cross section ($q \sim 100$ MeV):



$$\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4} \qquad\qquad \mu = \frac{m_\chi m_N}{m_N + m_\chi}$$

* Mono-jet + $\not\!\!E_T$ ($q \sim 10 - 100$ GeV):



$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \lesssim 100 \text{ GeV} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M \gtrsim 100 \text{ GeV} \end{cases}$$

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Consider a heavy mediator:

assume $p_T < M$ (just a contact operator)

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$$(p_T \sim 100\,{\rm GeV}) \qquad (\mu \sim 1\,{\rm GeV})$$

$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000)$$

Front of an Envelope:

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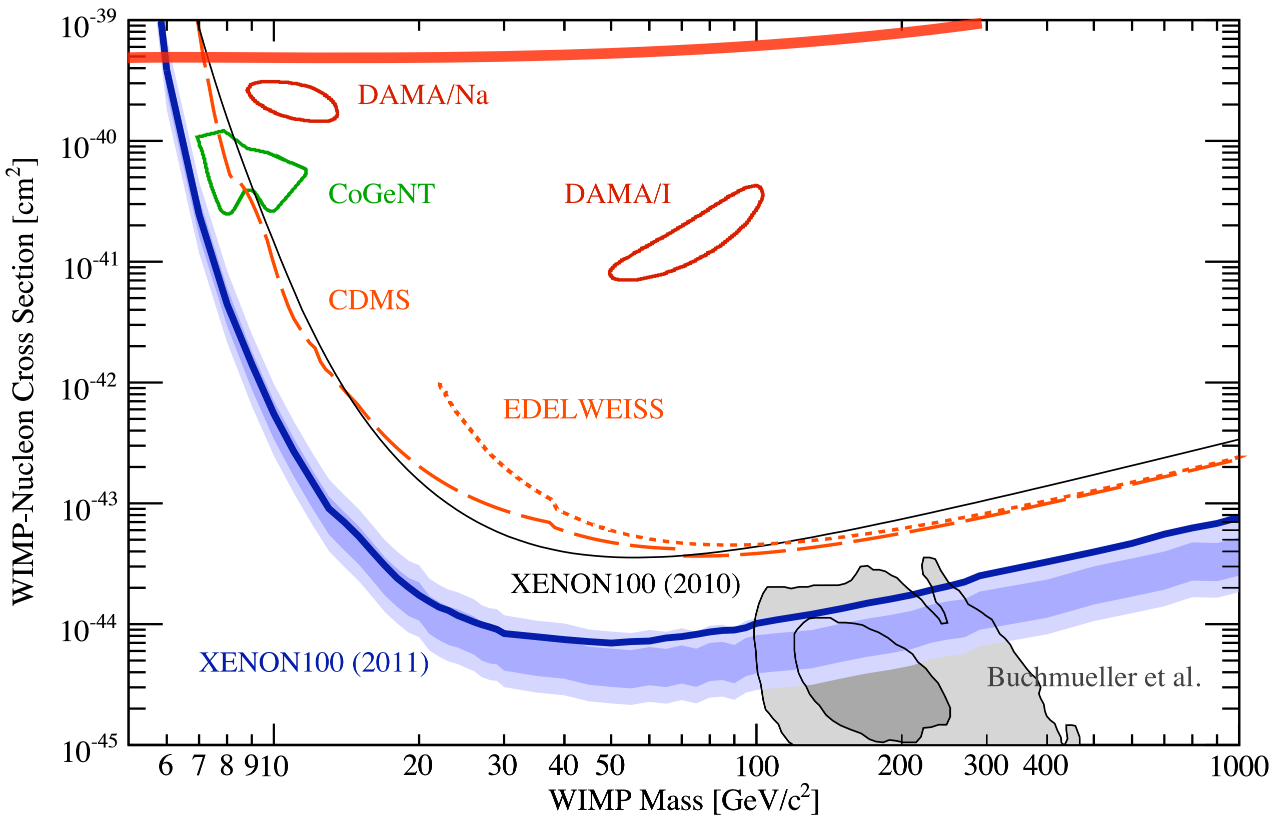
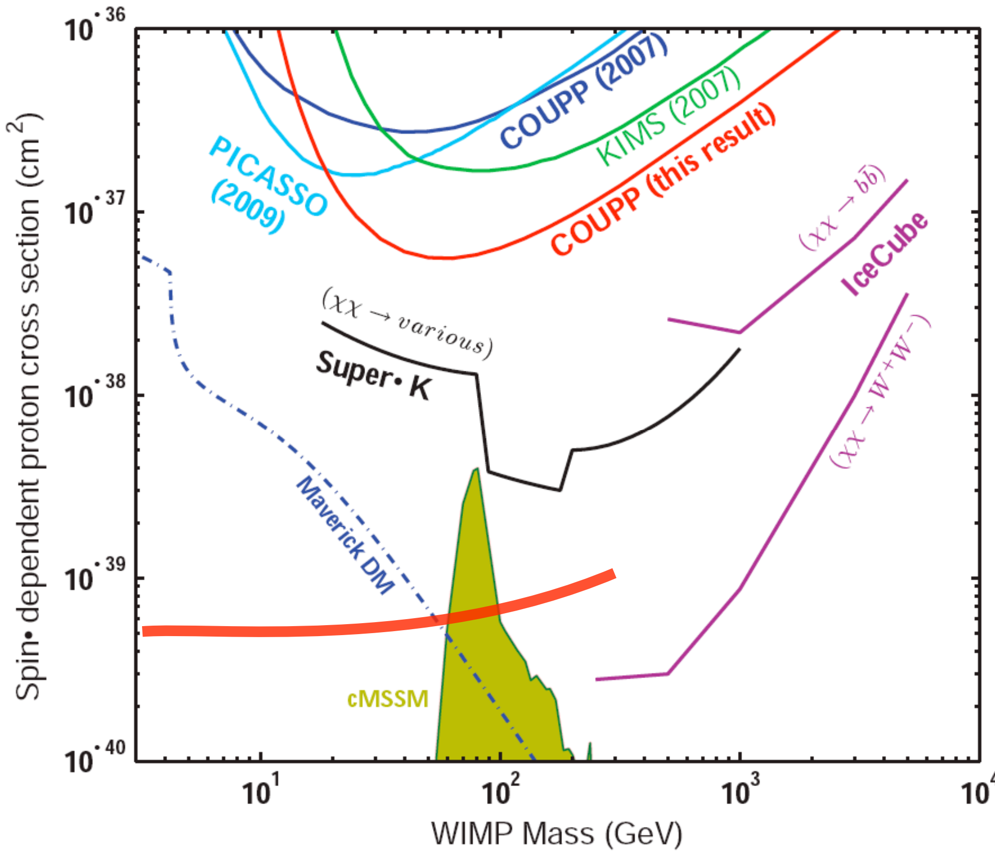
In 1 fb^{-1} CDF saw 8449 mono-jet events, expected 8663 ± 332 $\Rightarrow\ \sigma_{1j} \lesssim 500\,\text{fb}$

$$\sigma_{DD} \lesssim 0.5\,\text{fb} = 5 \times 10^{-40}\text{cm}^2$$

The Limit

- Our Estimated limits:





Tevatron sets best limit below ~5GeV.

Tevatron is the best spin dependent DM detector.

Setting Actual Limits

Operators

* Describe DM interactions as higher DM operators (possibly mediated by light mediators)

$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} q) (\bar{\chi}\chi) \; ,$$

SI, scalar exchange

$$\mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q) (\bar{\chi}\gamma^\mu \chi) \; ,$$

SI, vector exchange

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu\gamma_5 q) (\bar{\chi}\gamma^\mu\gamma_5 \chi) \; ,$$

SD, axial-vector exchange

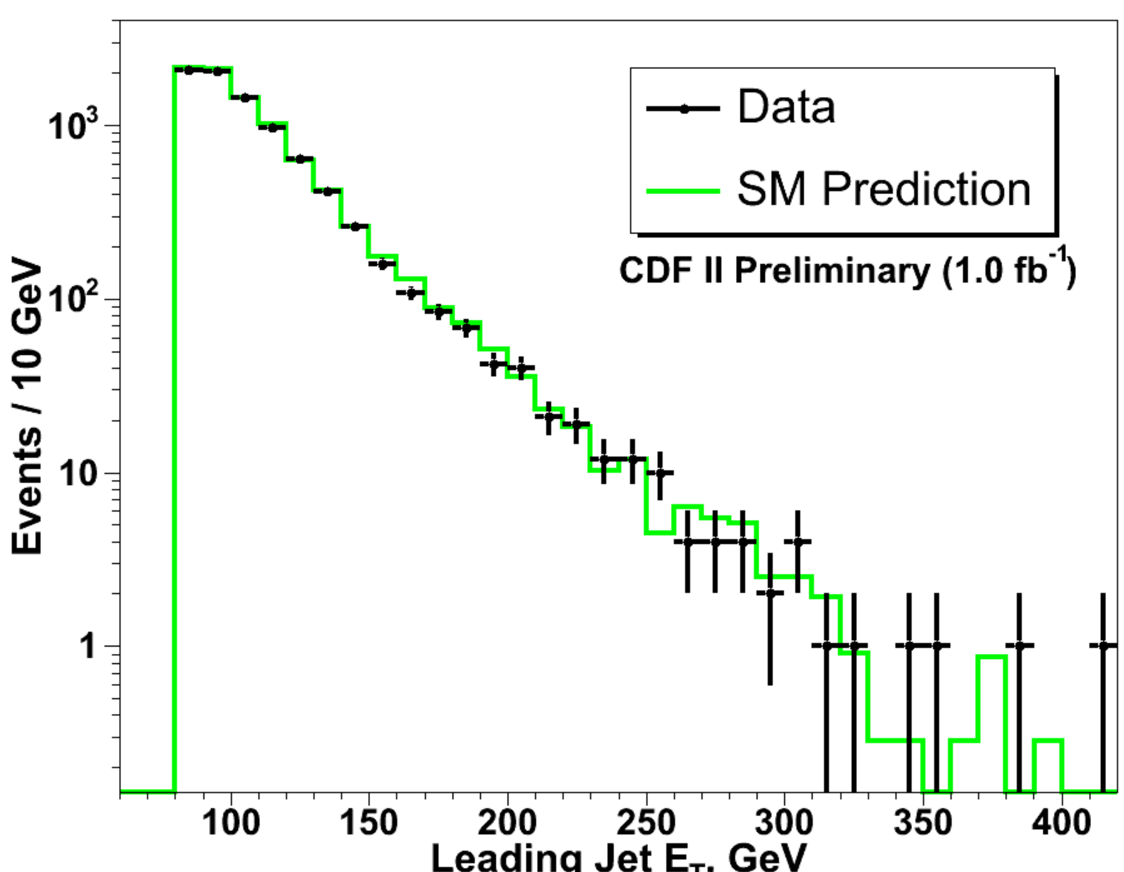
$$\mathcal{O}_4 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_5 q) (\bar{\chi}\gamma_5 \chi) \; ,$$

SD and mom. dep., psuedo-scalar exchange

CDF: jet + MET (1fb^{-1})

counting experiment:

$$\not{E}_T > 80\,\mathrm{GeV}$$
$$p_T(j1) > 80\,\mathrm{GeV}$$
$$p_T(j2) < 30\,\mathrm{GeV}$$
$$p_T(j3) < 20\,\mathrm{GeV}$$



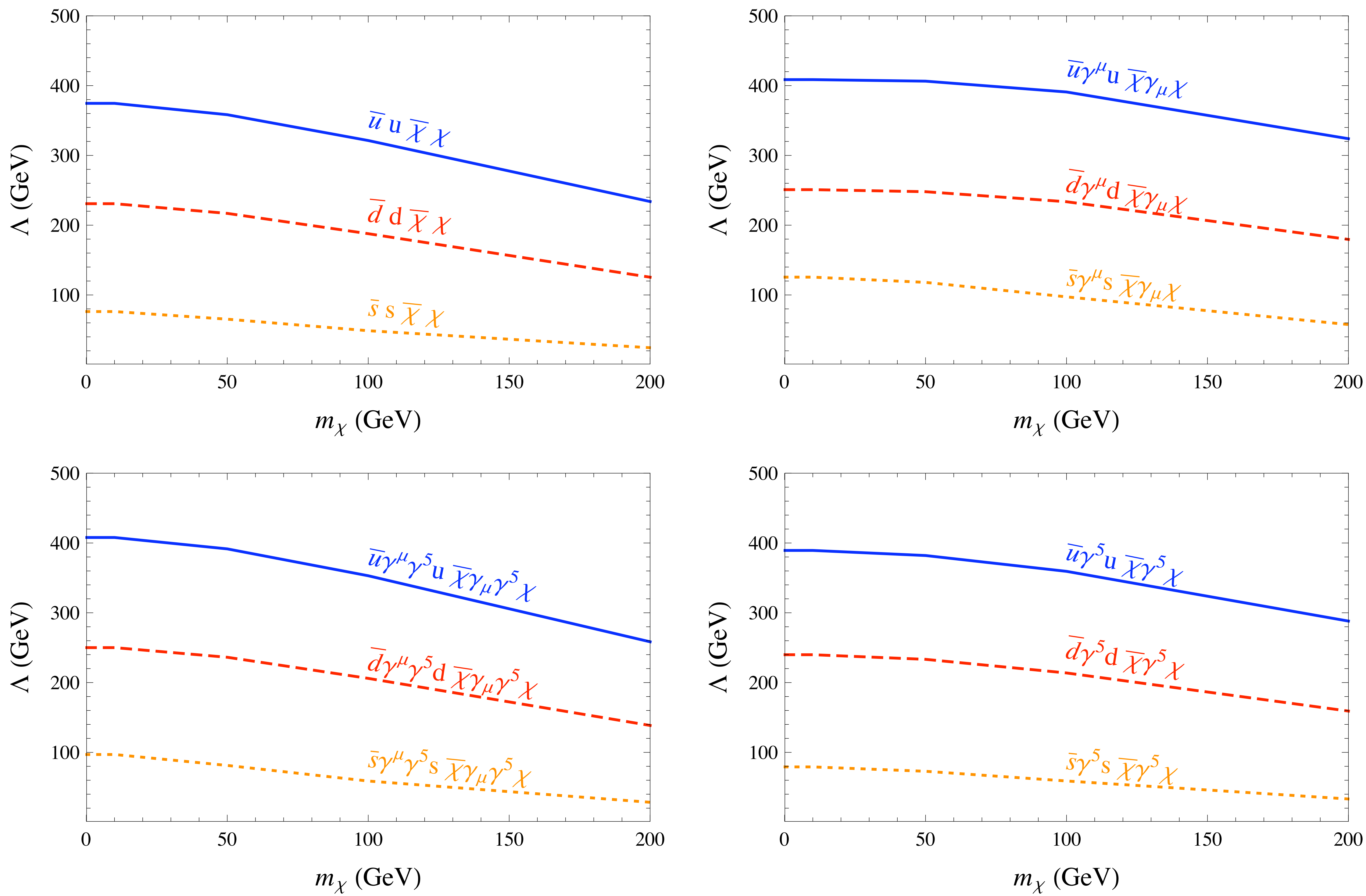
Background	Number of Events
Z -> nu nu	3203 +/- 137
W -> tau nu	2010 +/- 69
W -> mu nu	1570 +/- 54
W -> e nu	824 +/- 28
Z -> ll	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

Observed: 8449 events

[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html]

Limits on $\Lambda \equiv \dfrac{M}{\sqrt{g_\chi g_1}}$:

- Simulate events with CalcHEP. Limits on cutoff:



Limits on $\Lambda \equiv \frac{M}{\sqrt{g_\chi g_1}}$:

* The limits are fairly flat in mass (upto ~200 GeV).
* The limits are fairly independent of the operator structure. Strong SD constraints.
* These limits apply to iDM - Tevatron doesn't care about 100 keV splittings.

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$$\begin{aligned} \mathcal{O}_1 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}q)(\bar{\chi}\chi)\ , \\ \mathcal{O}_2 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu \chi) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \sigma_1^{Nq} &= \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2\, , \\ \sigma_2^{Nq} &= \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2\, , \end{aligned}$$

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$$\begin{aligned} B_u^p &= B_d^n &= 8.22 \pm 2.26\,, \\ B_d^p &= B_u^n &= 6.62 \pm 1.92\,, \\ B_s^p &= B_s^n &= 3.36 \pm 1.45 \end{aligned}$$

$$f_u^p = f_d^n = 2$$
$$f_d^p = f_u^n = 1$$

$$\begin{aligned} \mathcal{O}_1 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2}\,(\bar{q}q)\,(\bar{\chi}\chi)\,, \\ \mathcal{O}_2 &= \frac{i\, g_\chi\, g_q}{q^2 - M^2}\,(\bar{q}\gamma_\mu q)\,(\bar{\chi}\gamma^\mu\chi) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \sigma_1^{Nq} &= \frac{\mu^2}{\pi\Lambda^4}\, B_{Nq}^2\,, \\ \sigma_2^{Nq} &= \frac{\mu^2}{\pi\Lambda^4}\, f_{Nq}^2\,, \end{aligned}$$

SI Limit

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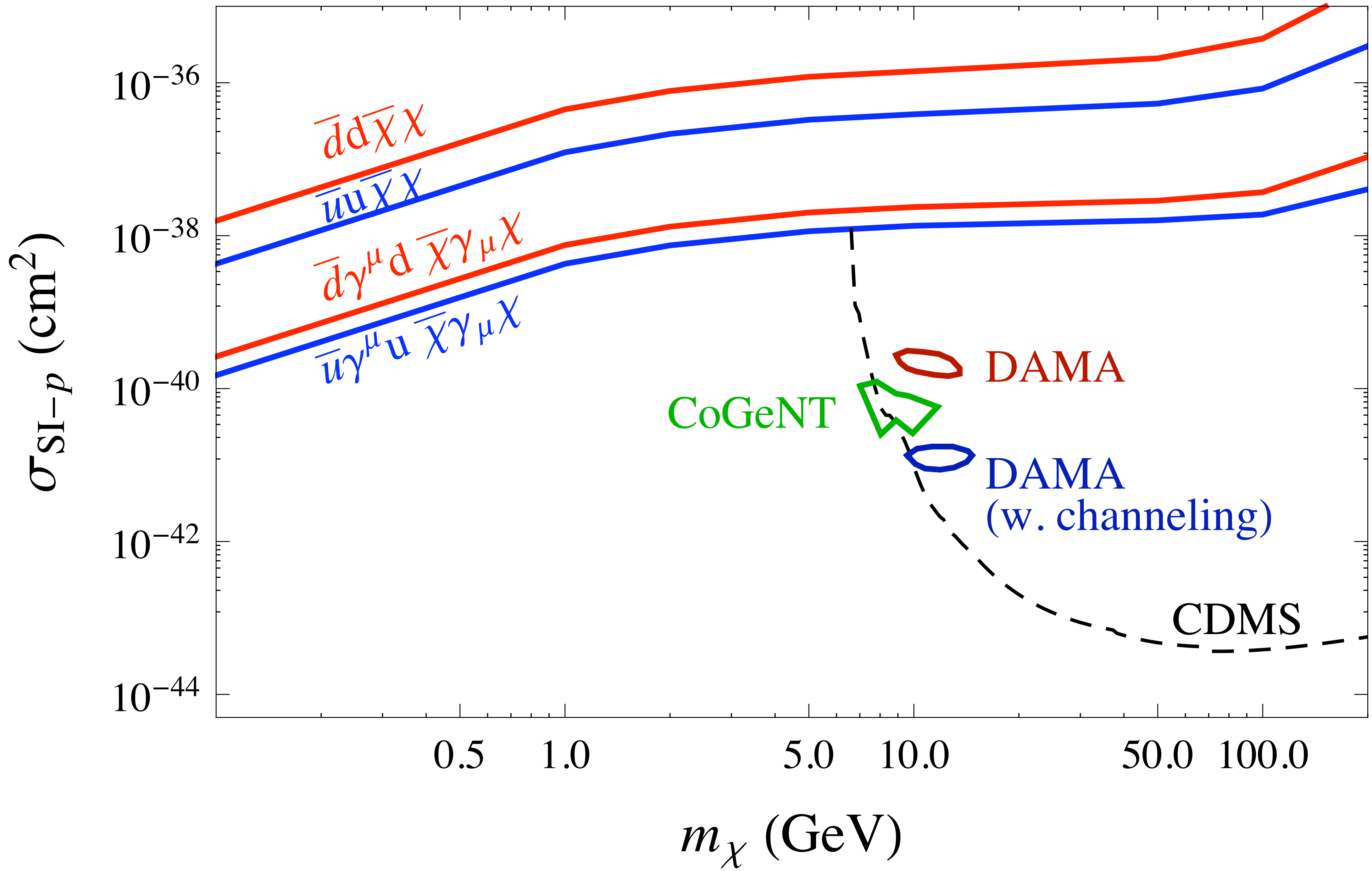

Best limit at low mass

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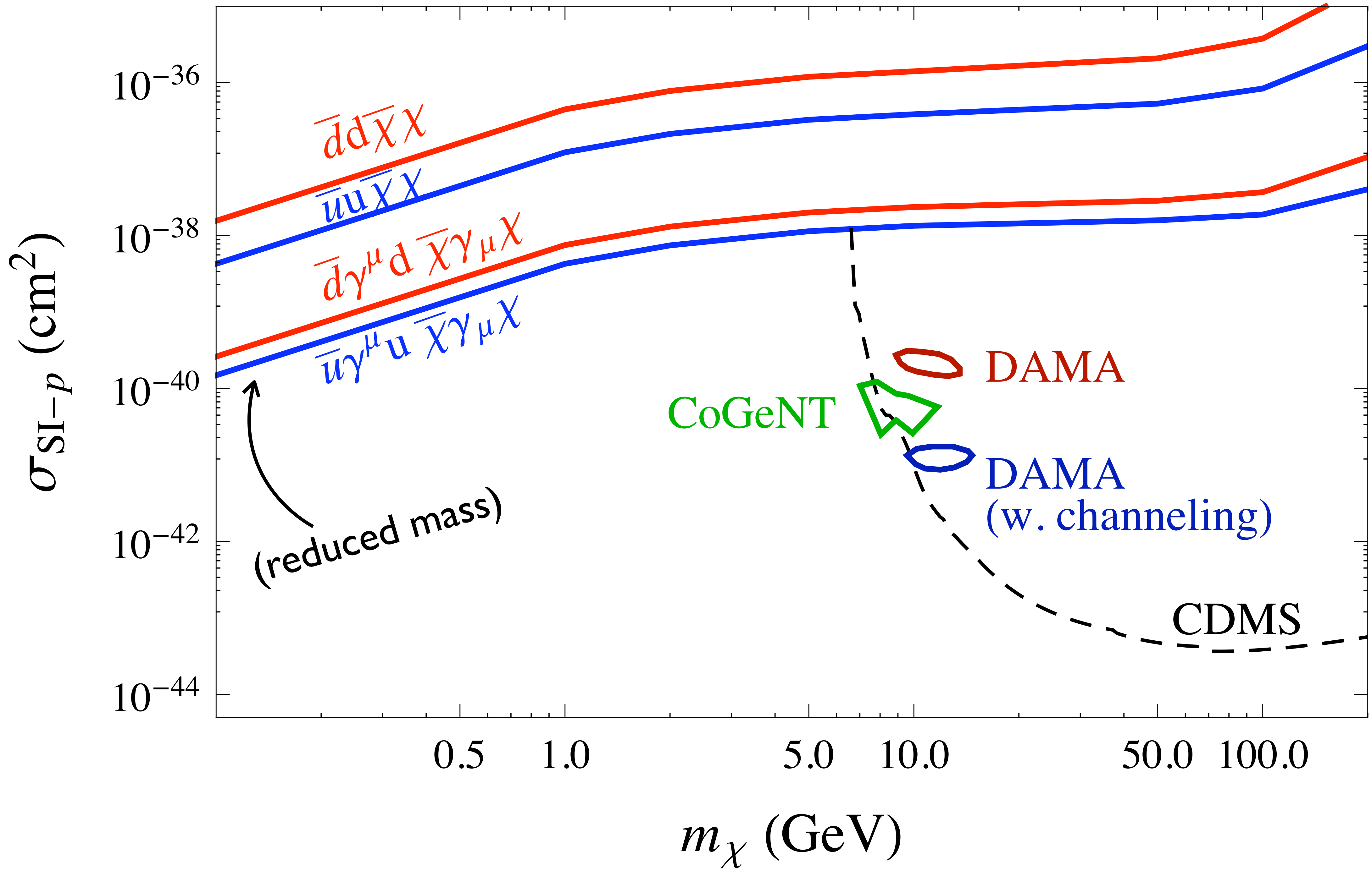

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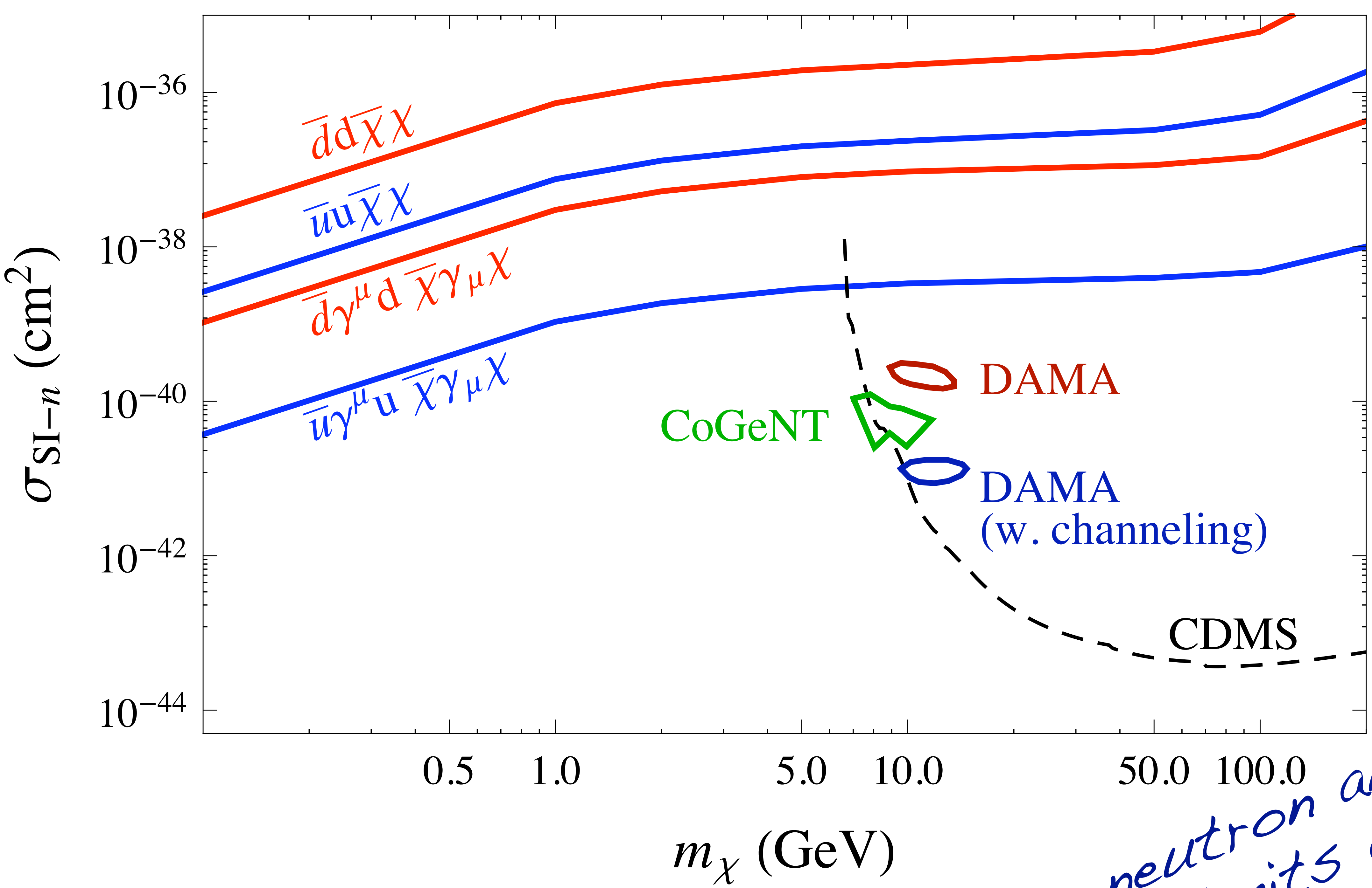


neutron and proton limits are a bit different:

Best limit at low mass

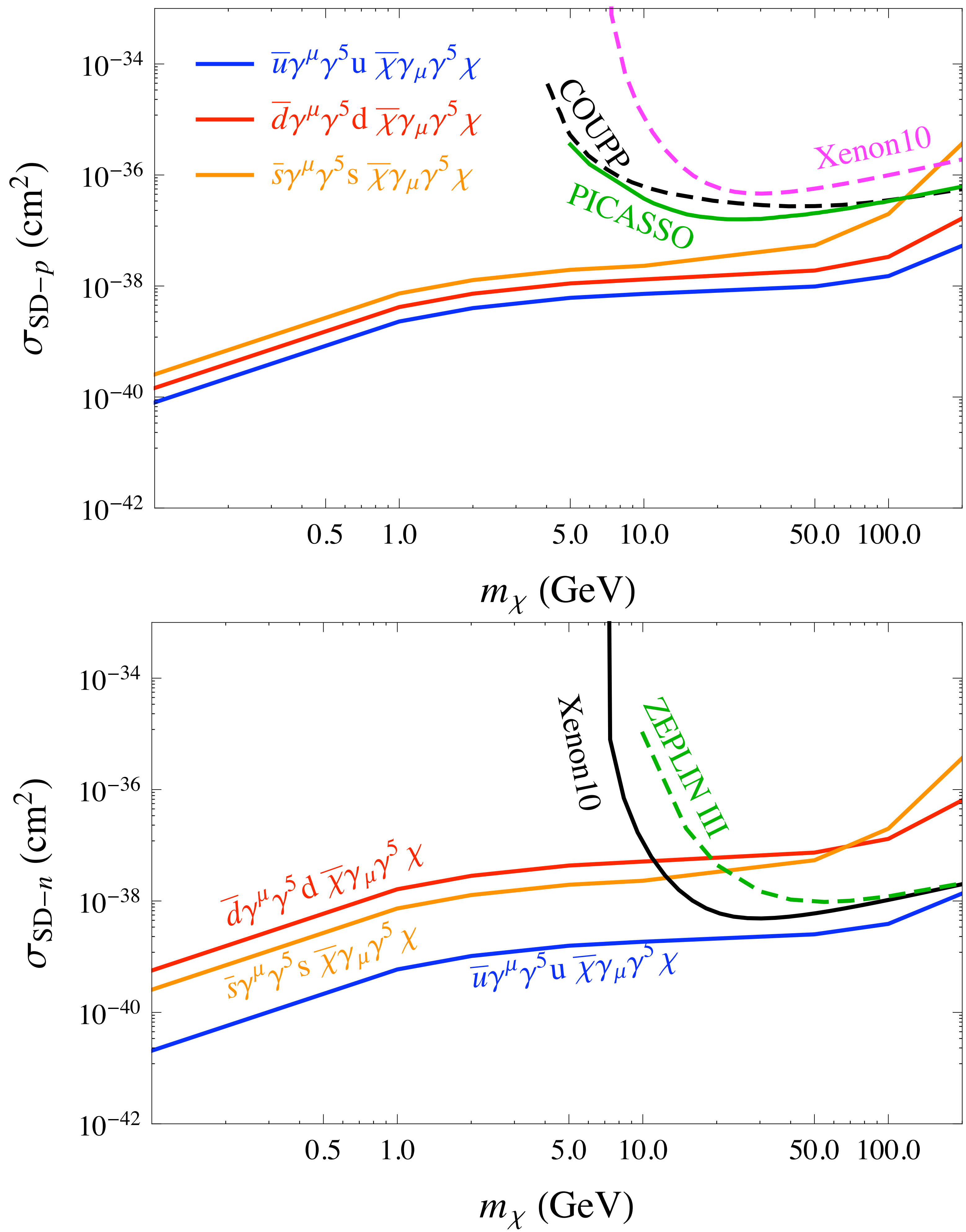
SD Limits:

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

$$\sigma_3^{Nq} = \frac{3\,\mu^2}{\pi\,\Lambda^4}\,(\Delta_q^N)^2$$

$$\Delta_u^p = \Delta_d^n = 0.842 \pm 0.012\,,$$
$$\Delta_d^p = \Delta_u^n = -0.427 \pm 0.013\,,$$
$$\Delta_s^p = \Delta_s^n = -0.085 \pm 0.018\,.$$

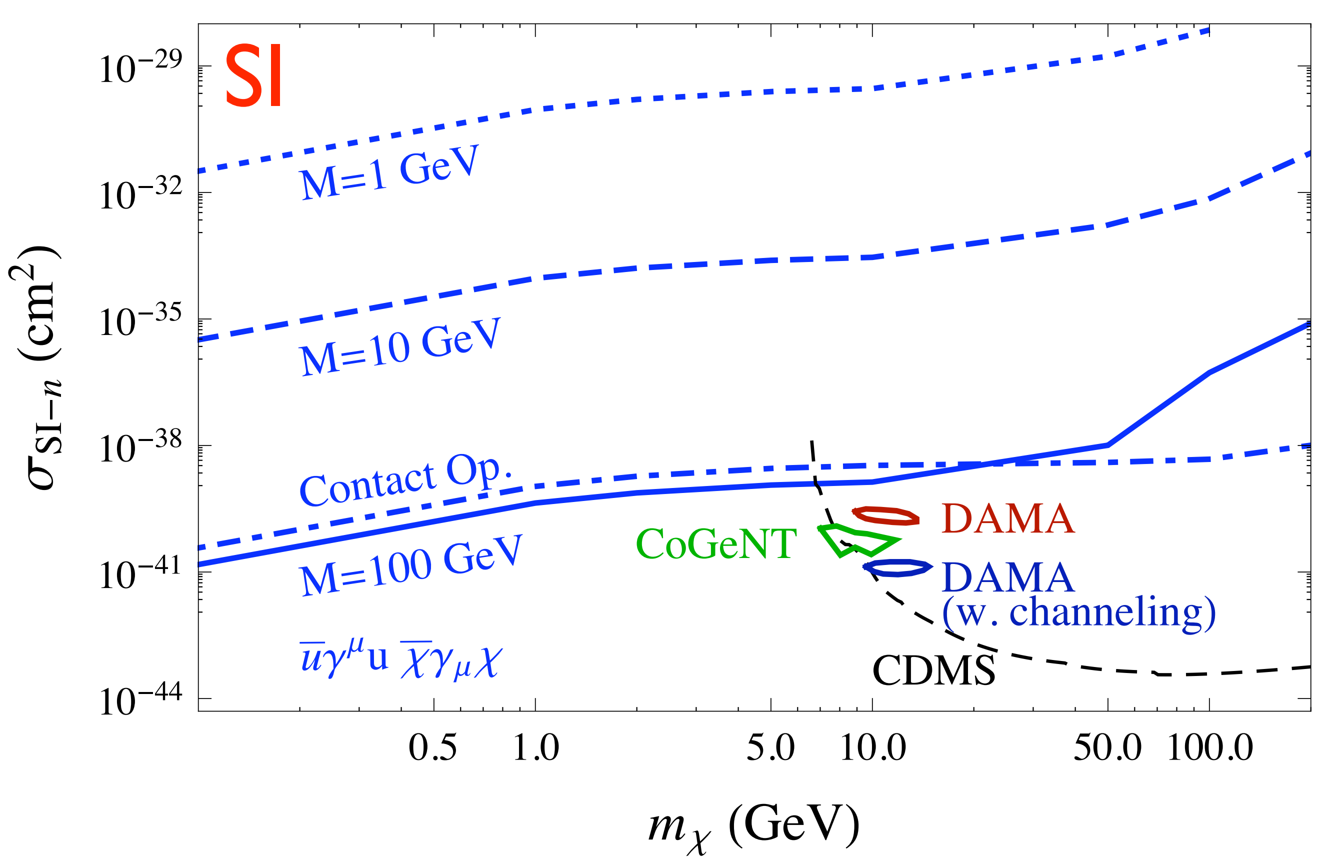
Best SD Limits over a wide mass range.

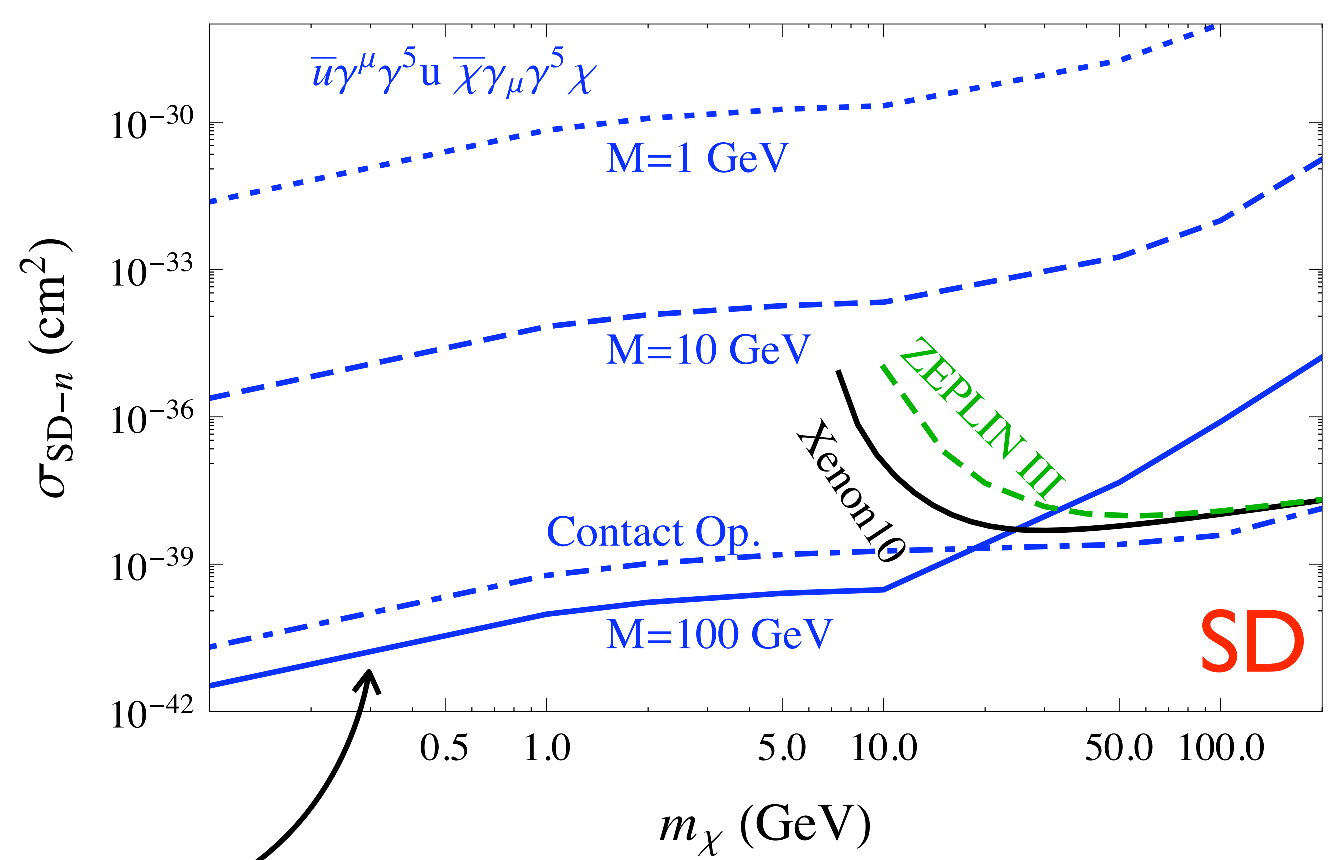


Light Mediators

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2 \, g_q^2 \, \frac{\mu^2}{M^4}$ and lower M.
* Then $\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$ drops as M^4.

Collider losses quickly





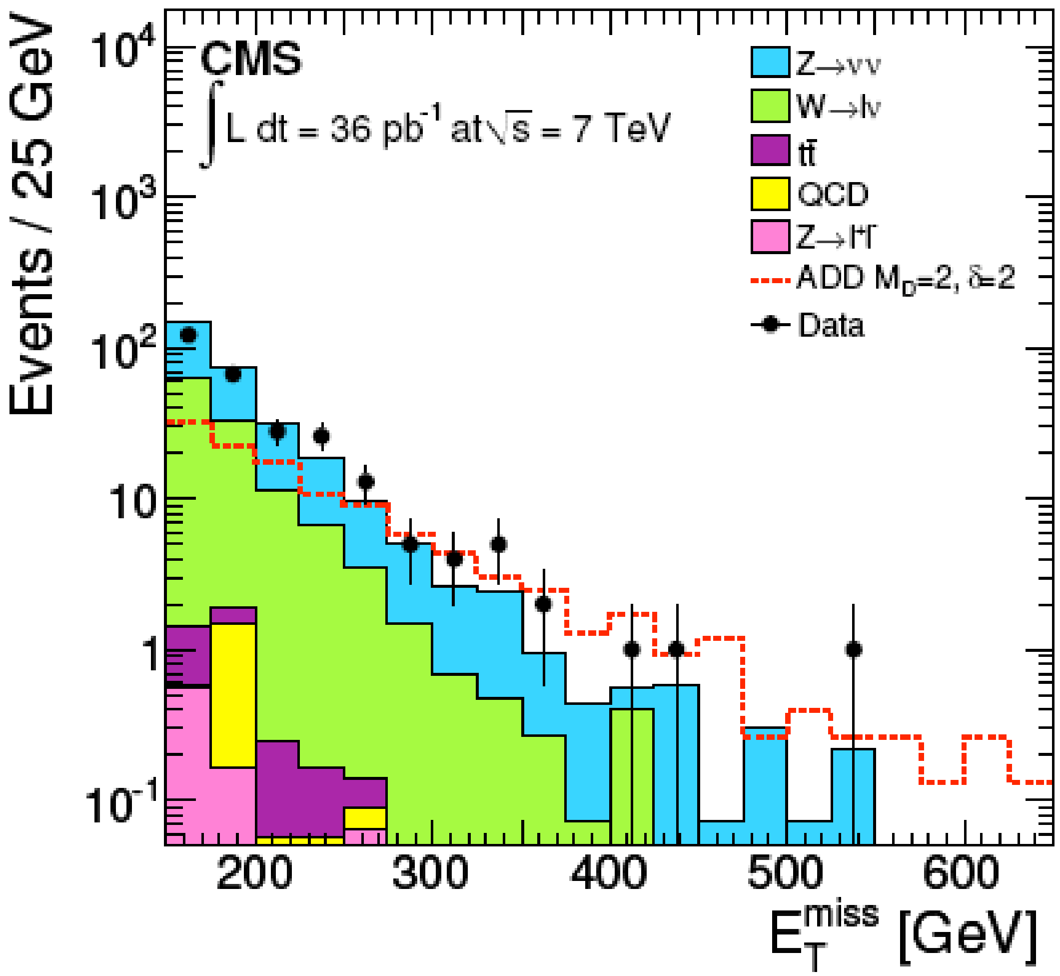
on-shell mediator

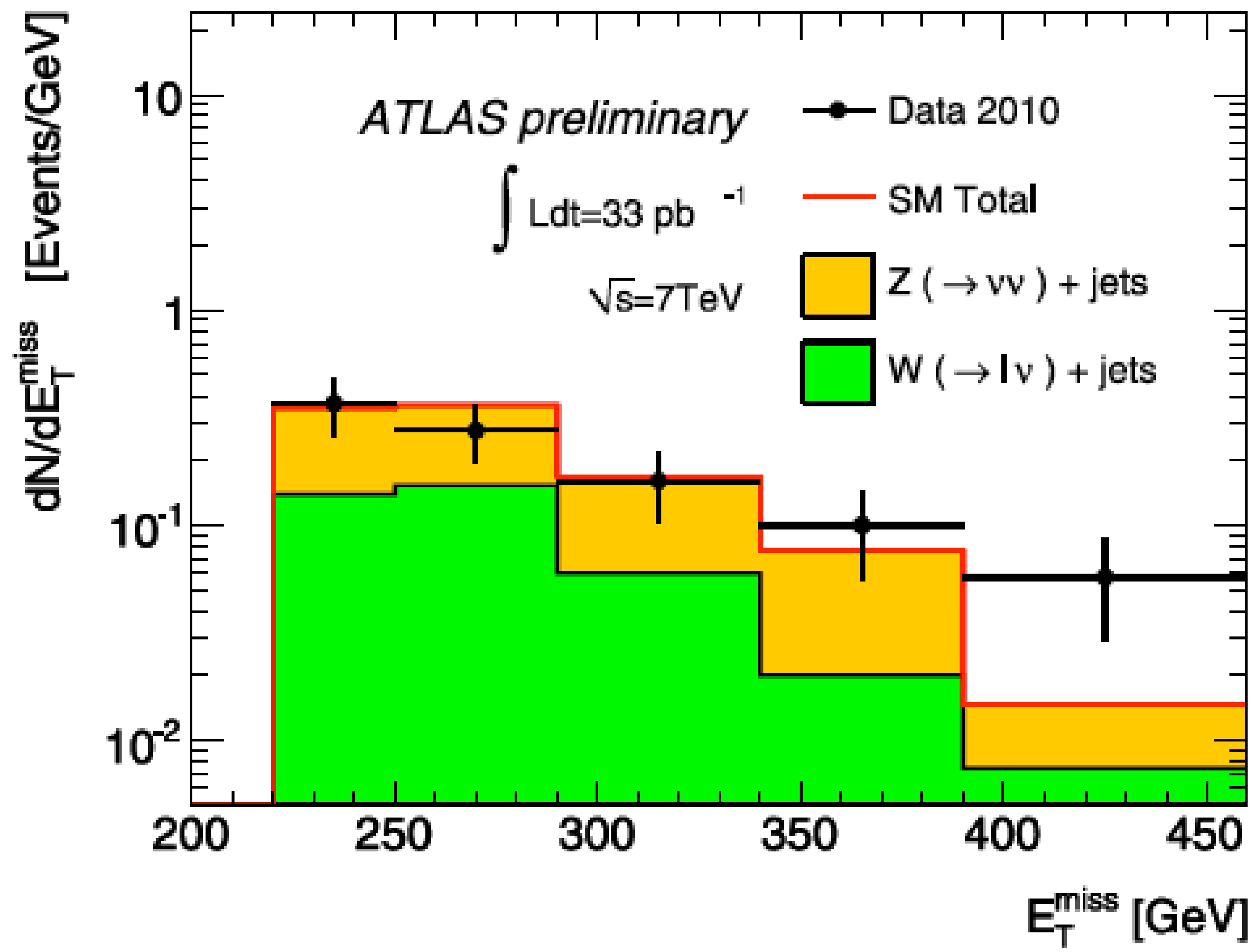
Thats great!
The Tevatron rocks!

Hold on...
is there another working collider somewhere nearby?

LHC Mono-jets

* Both CMS and ATLAS have mono-jet searches out:





Can 36 pb⁻¹ beat 1 fb⁻¹??? Naaah.

LHC limit

* well.....for heavy mediators LHC gains immediately:

$$\sigma_{\rm DM} \propto \frac{\hat{s}}{M^4}$$

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LHC limit

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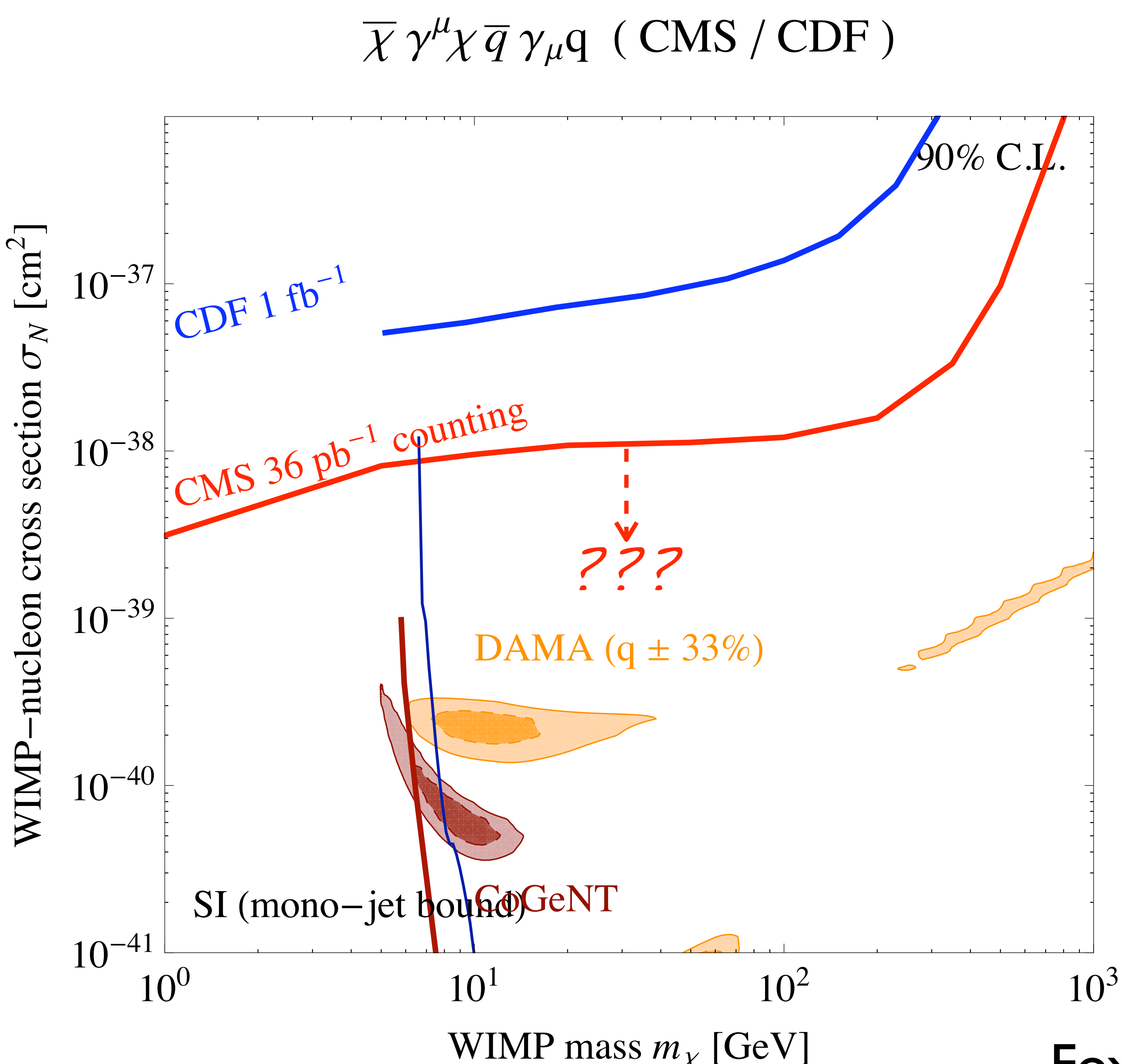


$$\sigma_{\rm DM} \propto \frac{\hat{s}}{M^4}$$

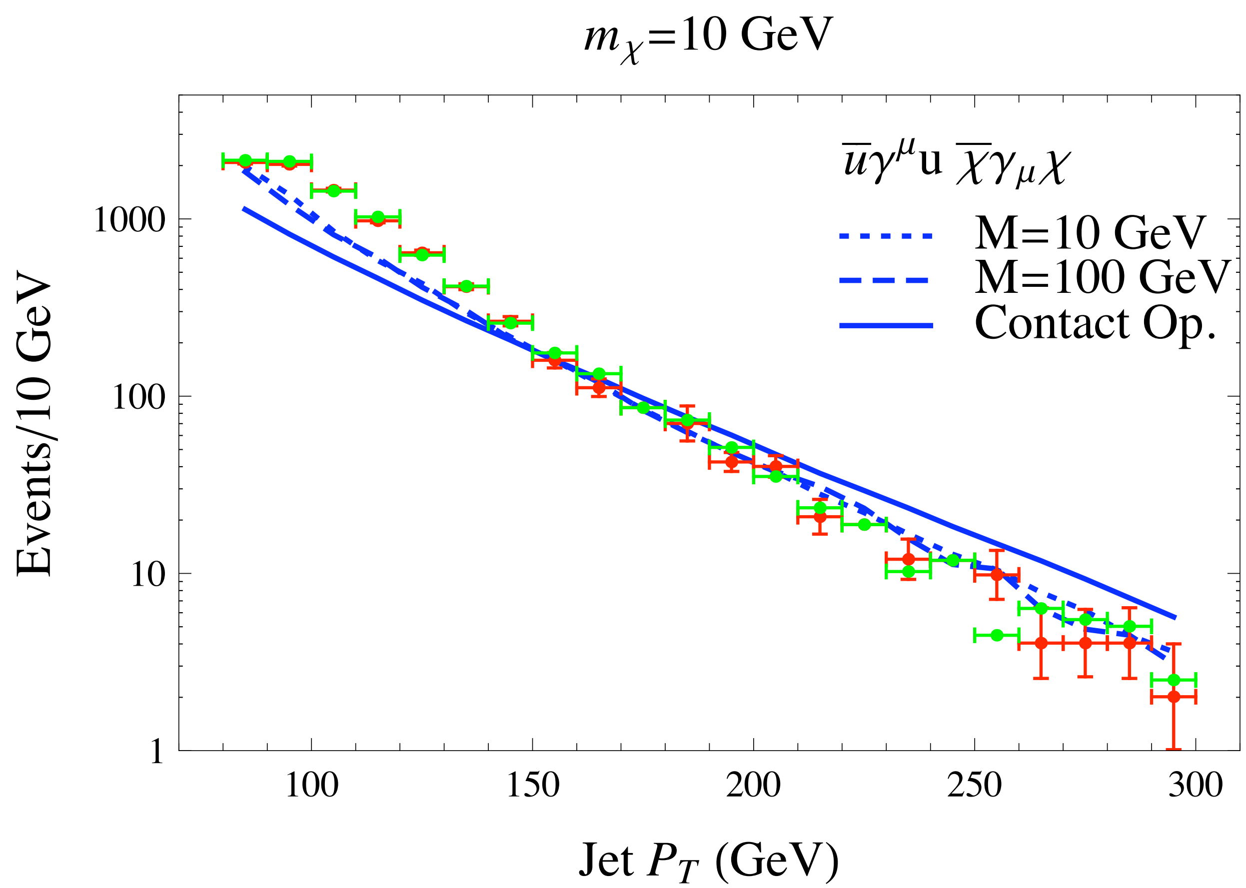
$$\sigma_{\rm BG} \propto \frac{1}{\hat{s}}$$

Mono jet searches may get updated **tomorrow**!

Fox, RH, Kopp, Tsai (**Preliminary**)

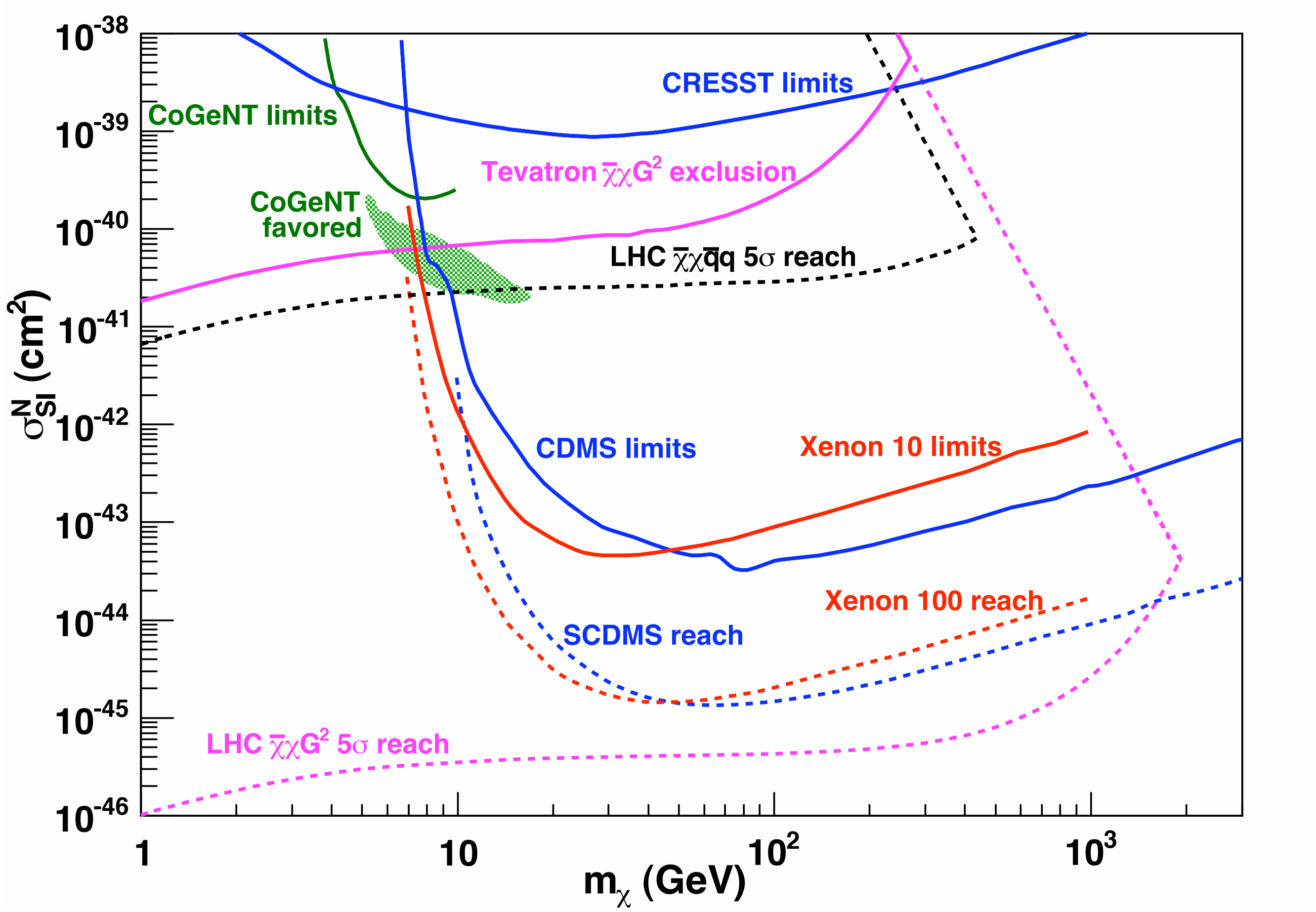
Future

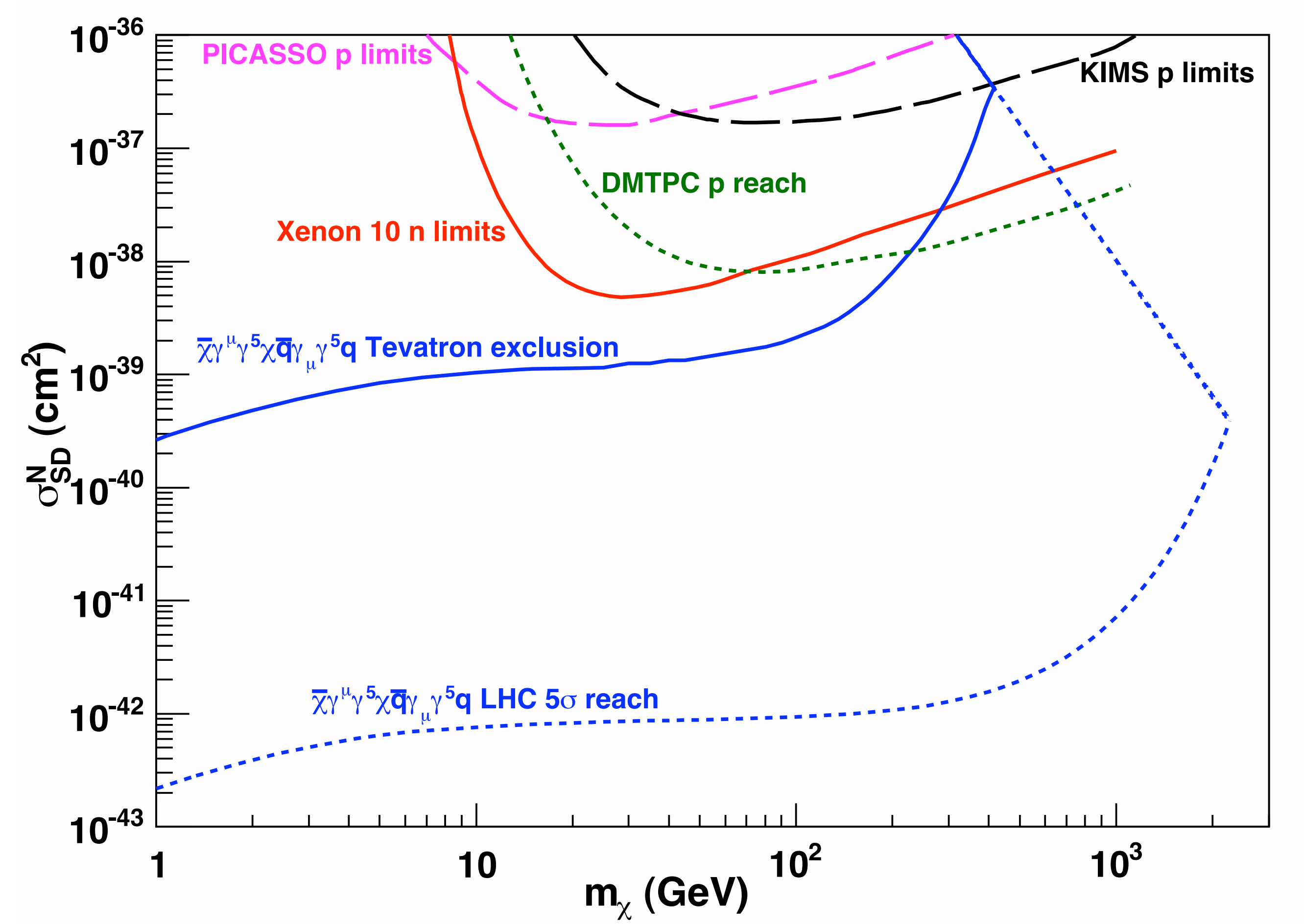
* Shape:



* A dedicated analysis may be more powerful.
* CDF is working on a dedicated analysis!
* So are CMS and ATLAS!
* Mono-photon is also be interesting, complementary.

LHC - Deep Future





$$\sqrt{s} = 14 \text{ TeV}$$

$$\mathcal{L} = 100 \text{ fb}^{-1}$$

$$\not{E}_T > 500 \text{ GeV}$$

Note:
Counting experiment.
Systematics *not* considered.
No longer a monojet search.

Tait & co.

LEP mono-photon

w/ Fox, Kopp and Tsai
arXiv:1103.0240

LEP

* Directly constrain DM coupling to electrons.
* **But**, in many models quark and lepton coupling are related (consider 2 benchmarks).
* LEP is a clean environment. Ability to measure missing mass.
* Places non-trivial limits also on indirect searches in lepton channels (e.g. the Hooperon).

Operators

* Same story w/ leptons (assume universality)

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{\ell}\gamma^\mu\ell)}{\Lambda^2}\,, \qquad \text{(vector, } s\text{-channel)}$$

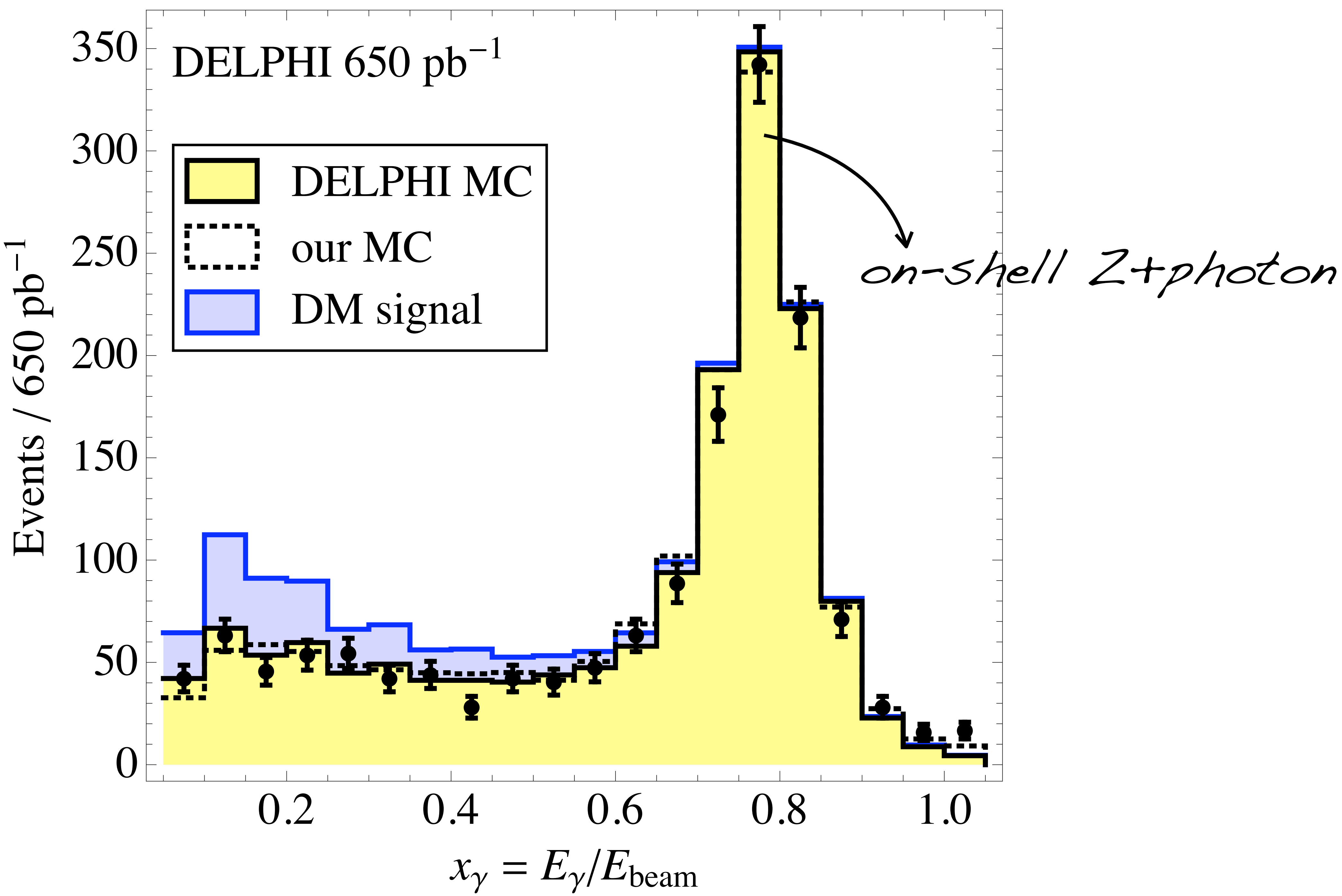
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)}$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{\ell}\gamma^\mu\gamma_5\ell)}{\Lambda^2}\,, \qquad \text{(axial vector, } s\text{-channel)}$$

$$\mathcal{O}_t = \frac{(\bar{\chi}\ell)(\bar{\ell}\chi)}{\Lambda^2}\,, \qquad \text{(scalar, } t\text{-channel)}$$

Mono-photon

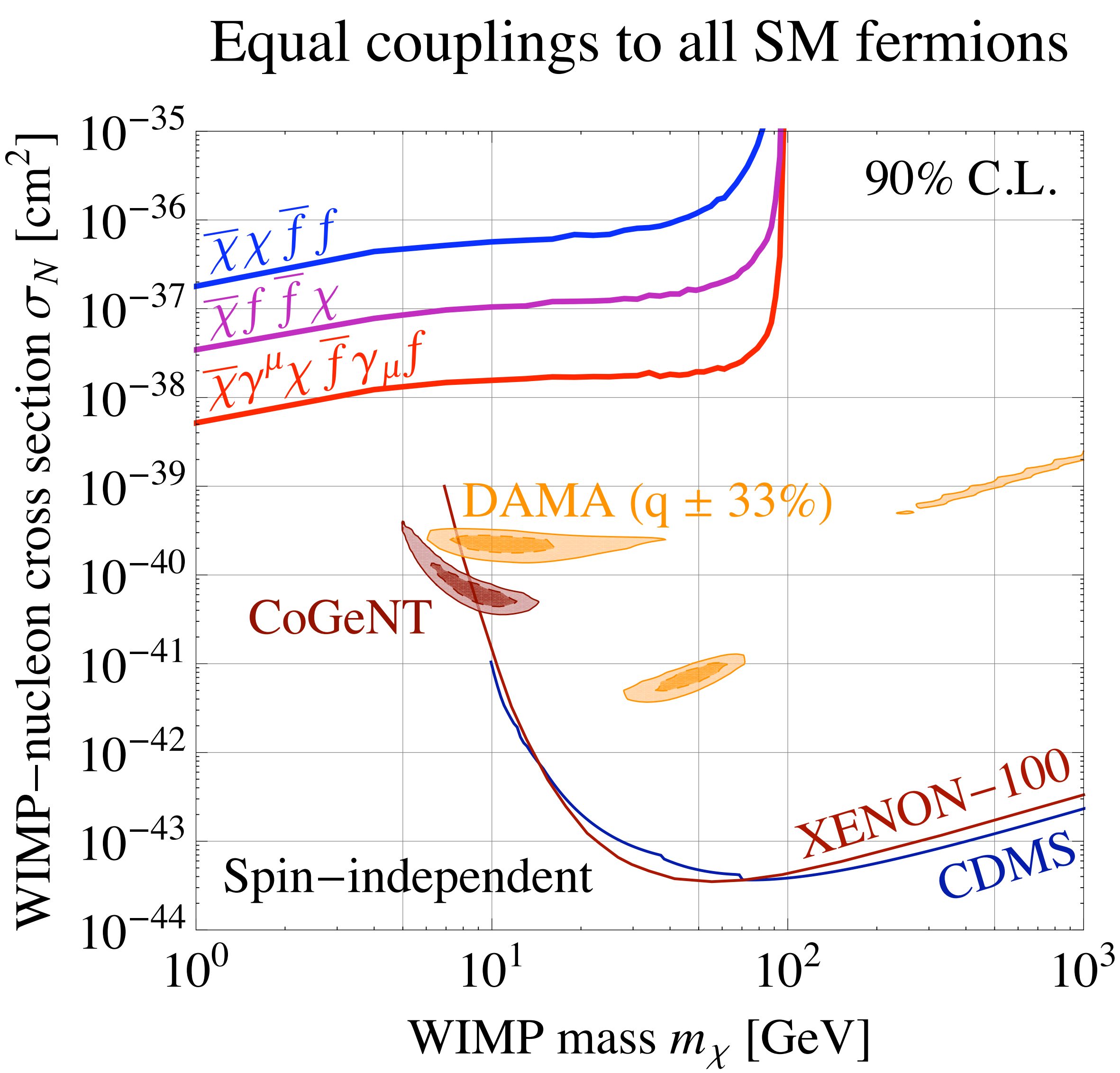
- Use spectrum shape to reject background peak.



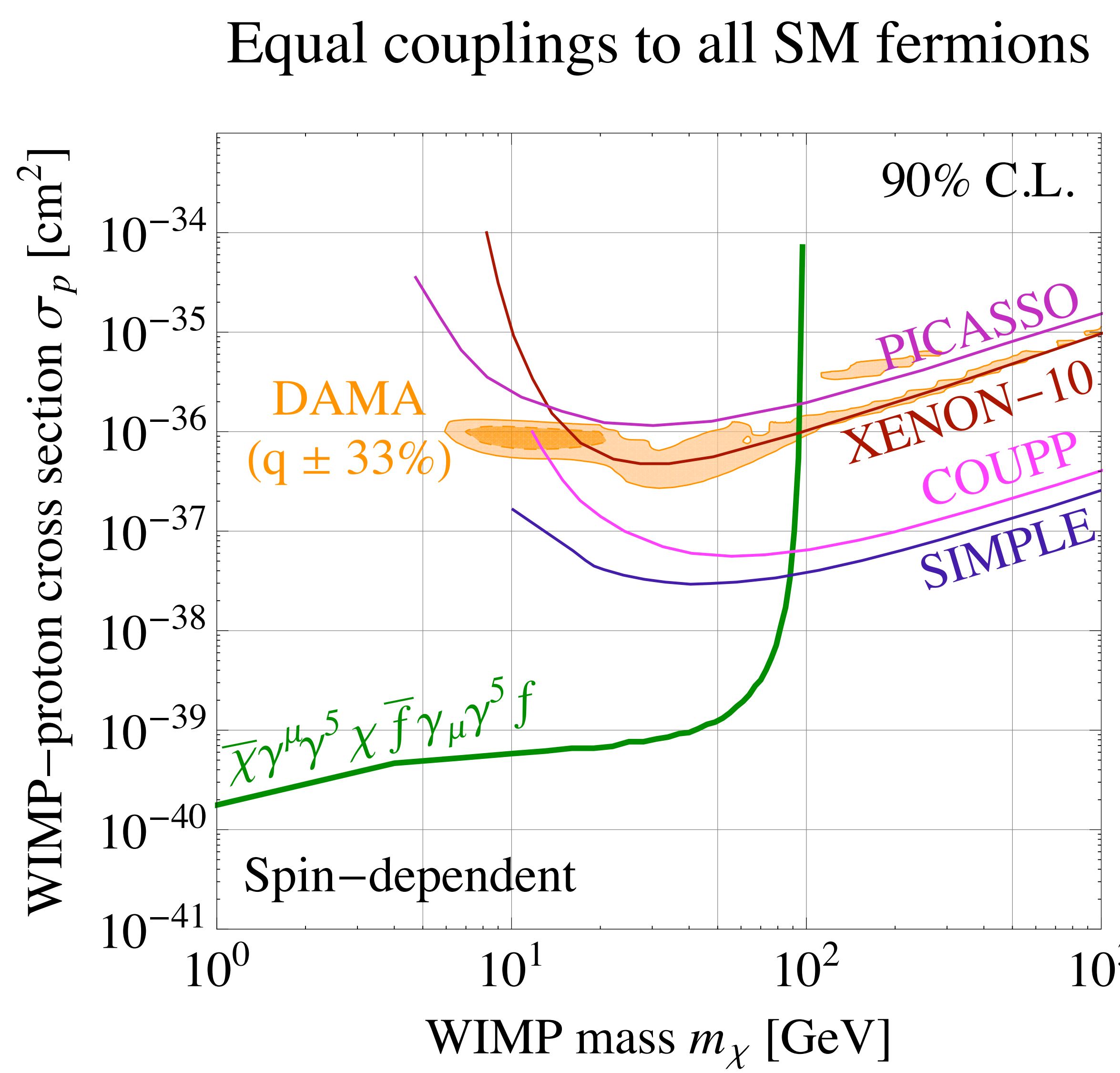
Model Dependence

* We limit lepton couplings.
* But how does DM couple to quarks?
* Consider 2 extreme cases:
  - Couplings to **quarks are same as leptons**.
  - Couplings to quarks are **zero**.
* *Any* other case can be derived from these two.

DD Limits



Equal couplings to all SM fermions
90% C.L.
DAMA (q ± 33%)
CoGeNT
XENON−100
CDMS
Spin−independent
WIMP−nucleon cross section σ_N [cm^2]
WIMP mass m_χ [GeV]
$\bar{\chi}\chi\bar{f}f$
$\bar{\chi}f\bar{f}\chi$
$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$



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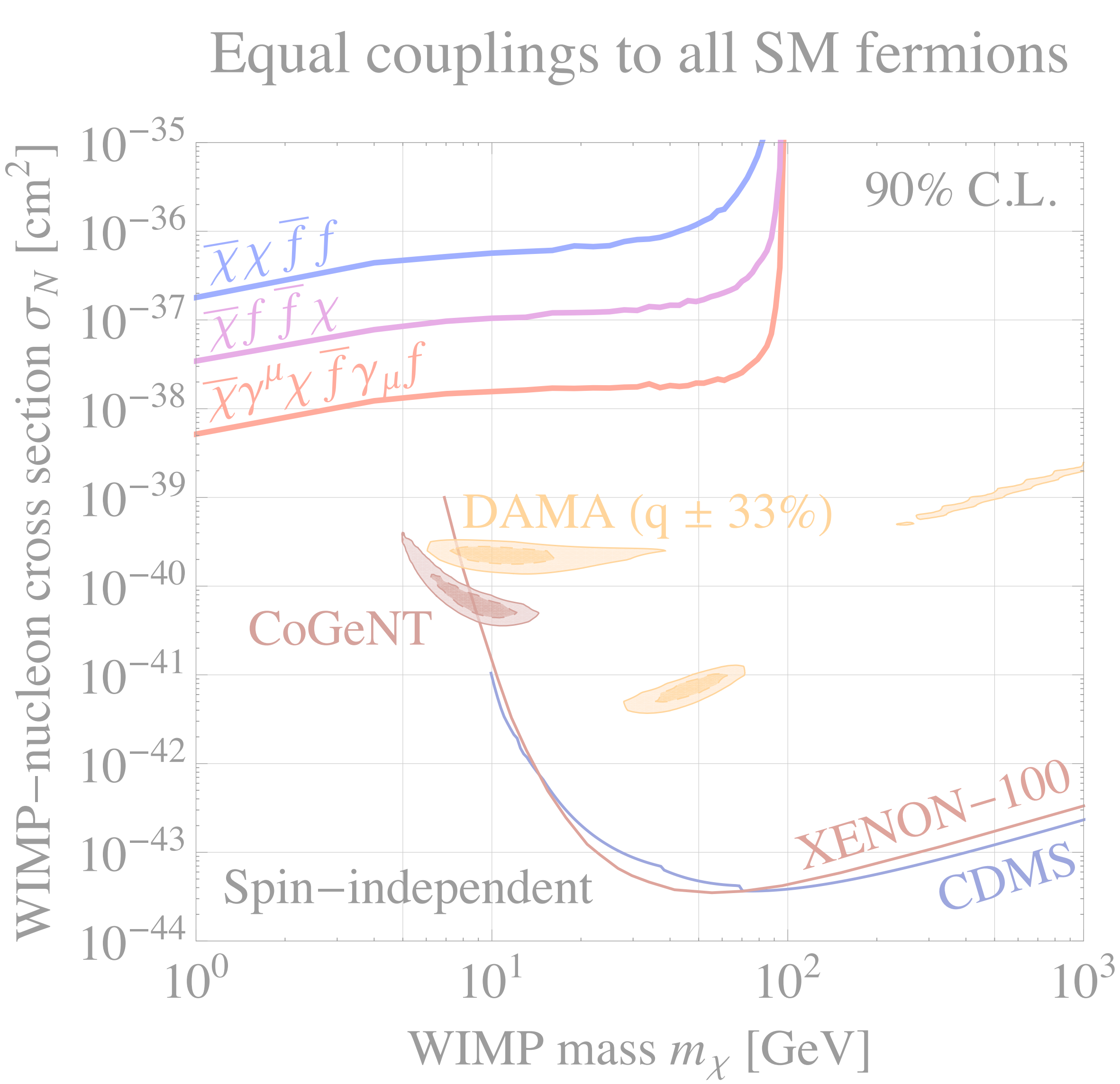
DD Limits



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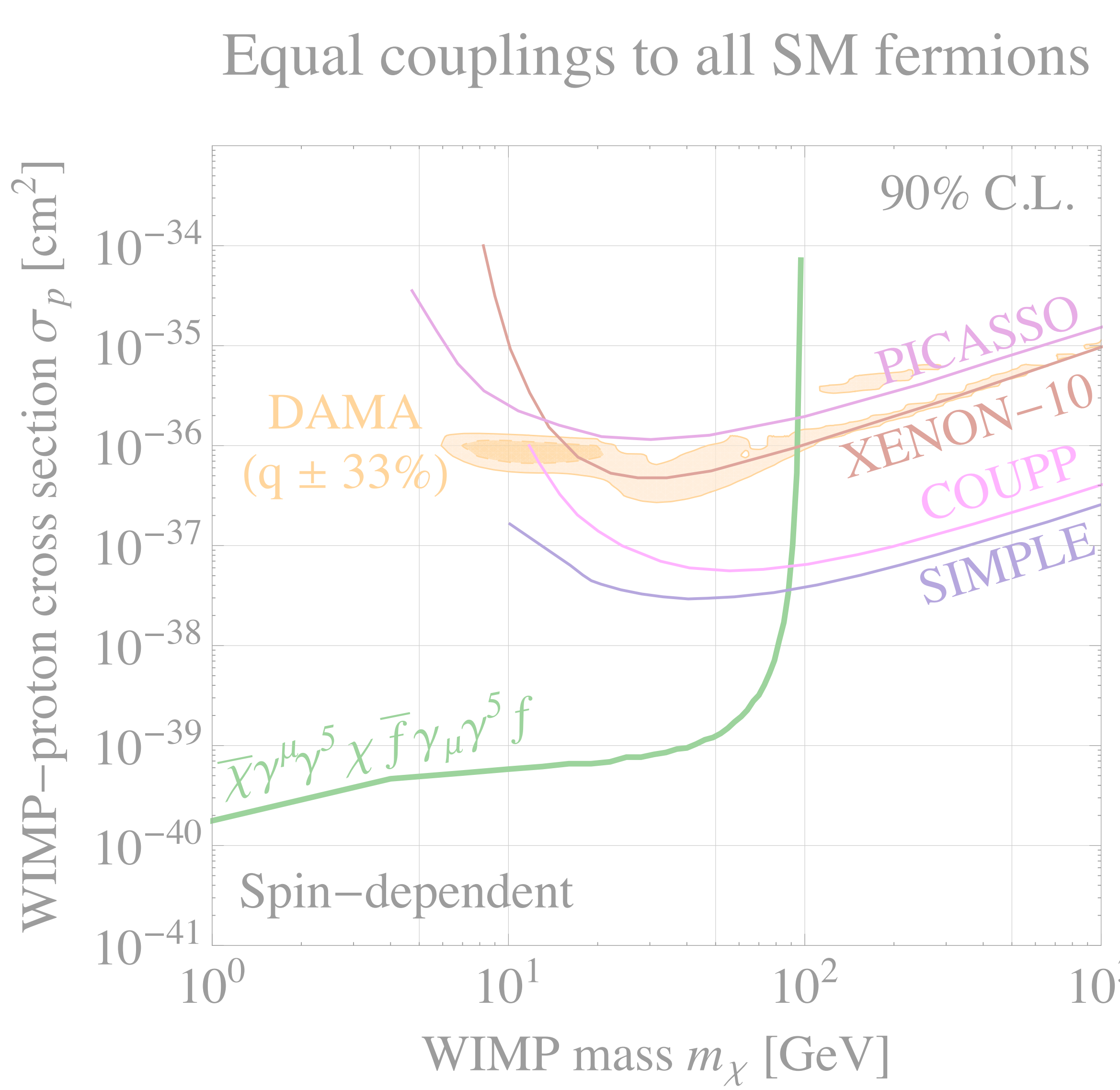

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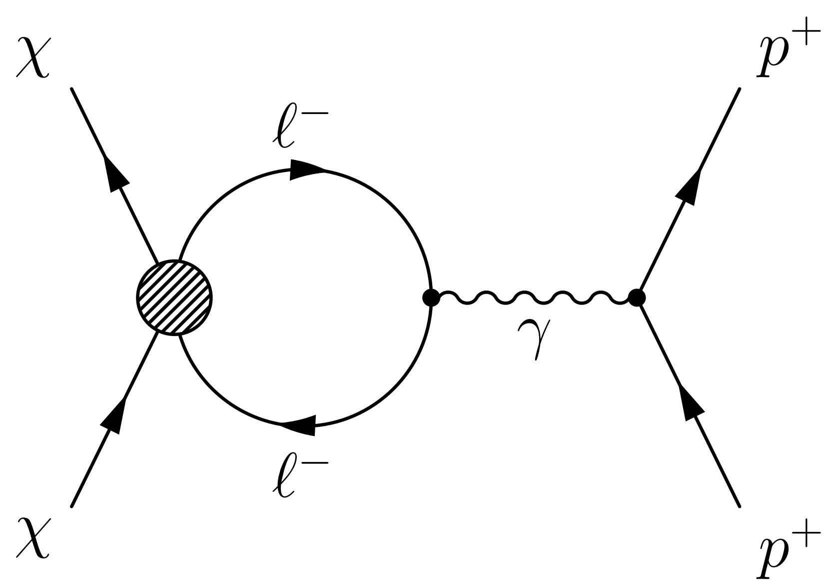
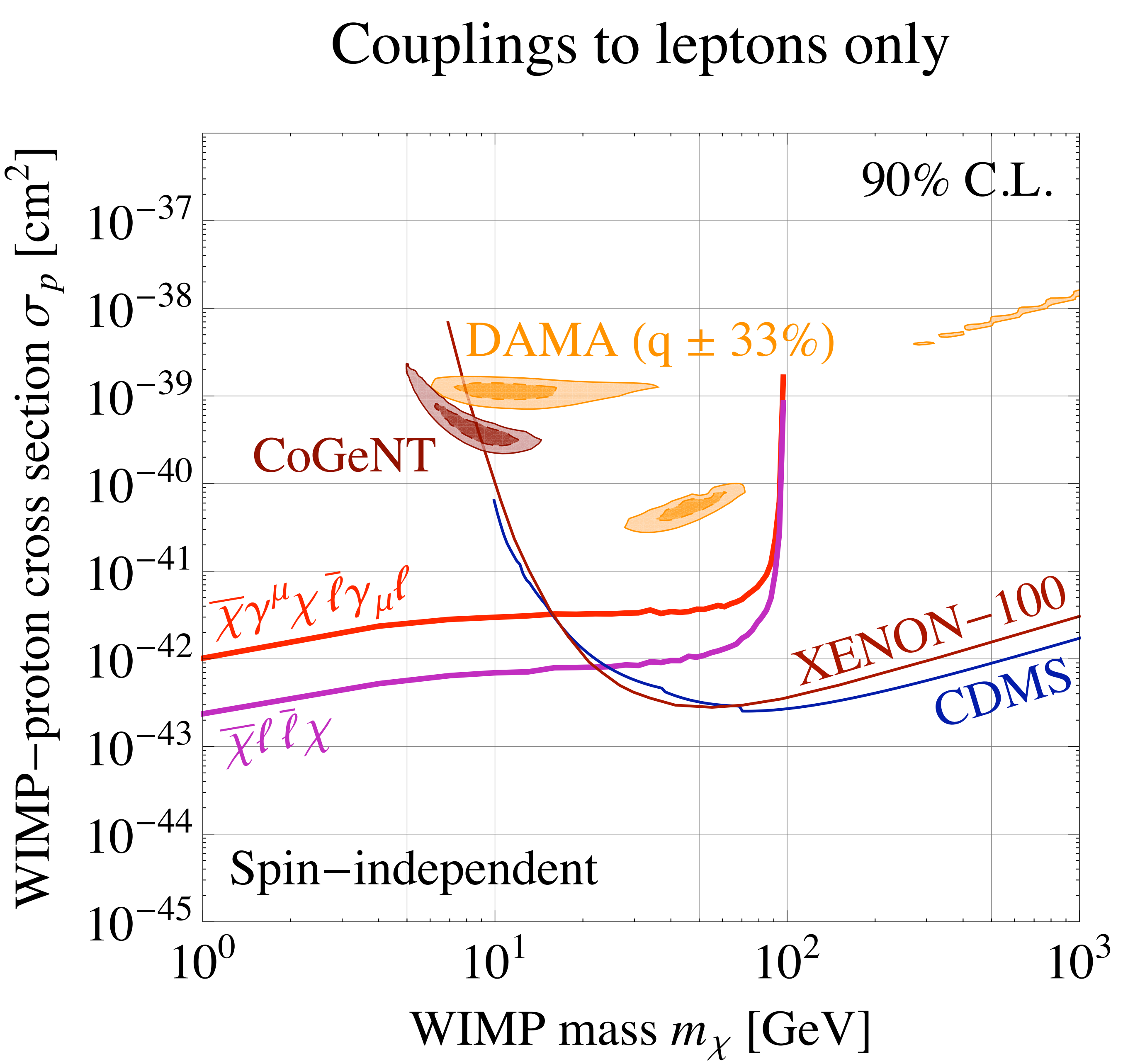
Leptophilic DM

* Consider zero couplings to quarks.

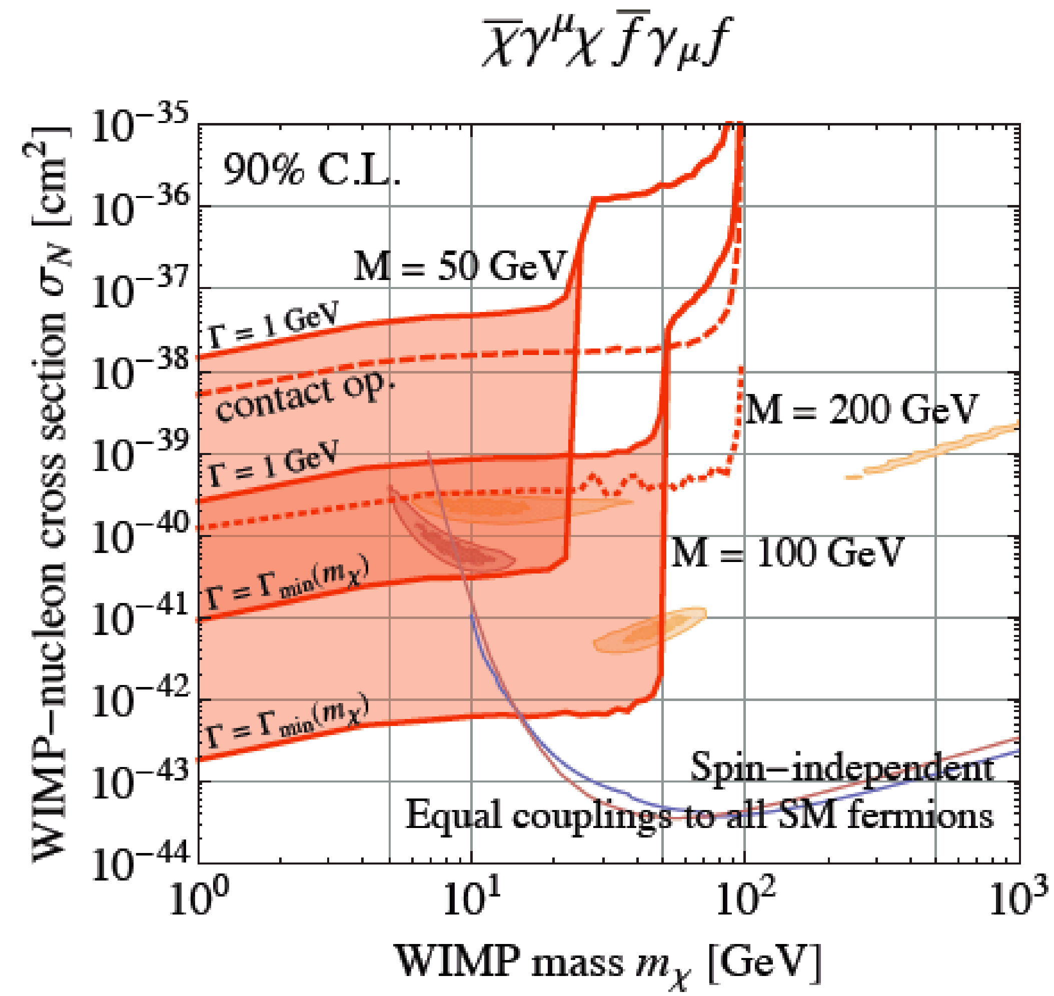


Direct detection pays a big price.
Collider limits are strong.

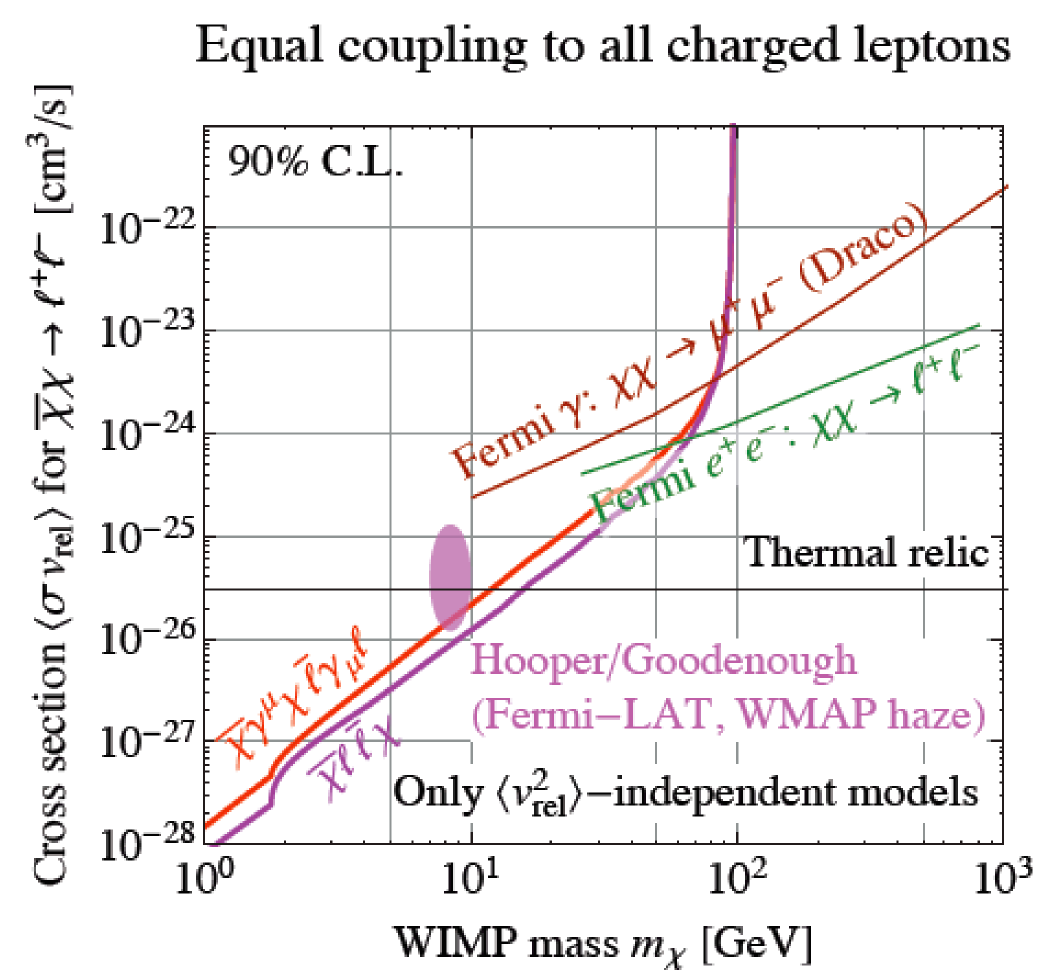


Many more..

* Light mediators:

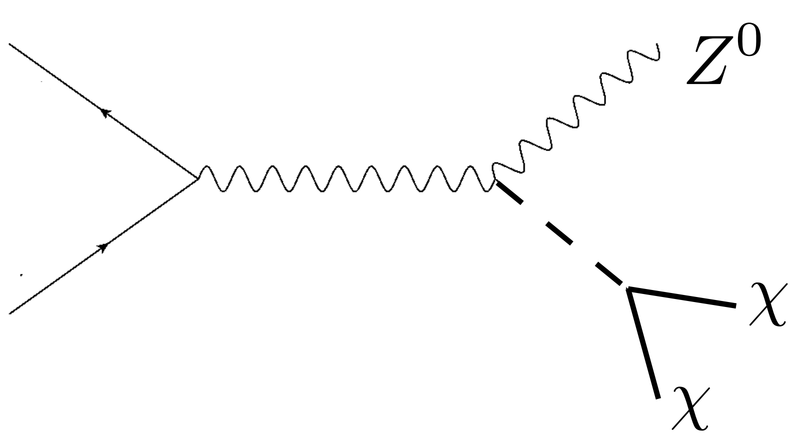


* Indirect detection:



Mono-something!

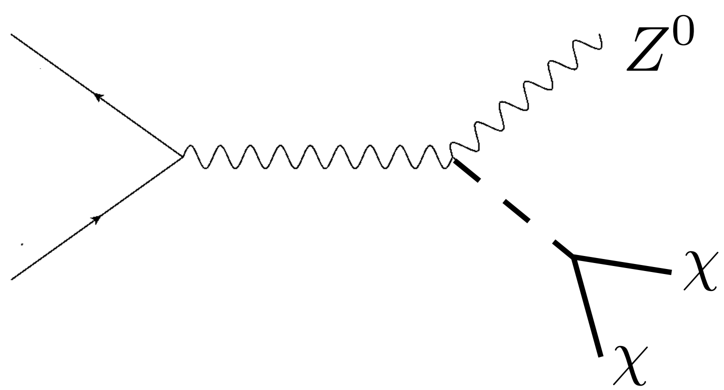
* For specific models, we can probe the identity of the mediator with other mono-somthings.
* **Mono-top** signals can probe DM that is coupling via MFV operators (kamenik and Zupan).
* In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.



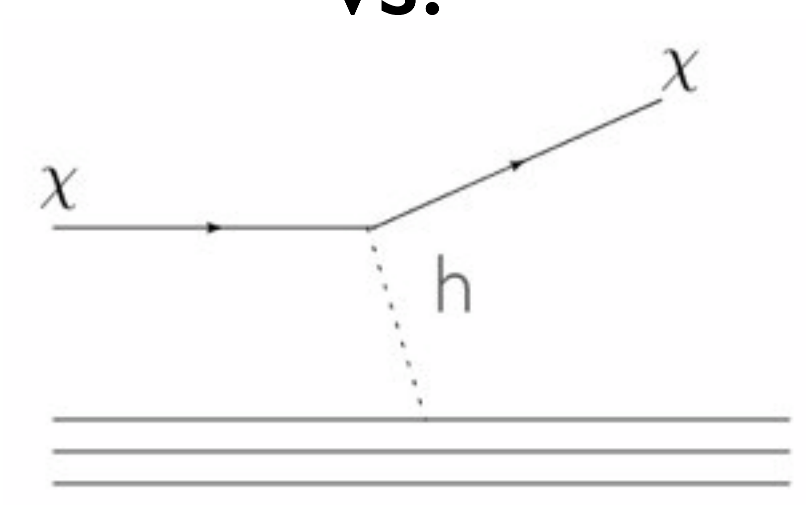
Invisible Higgs searches can be interpreted as "direct detection" experiments!

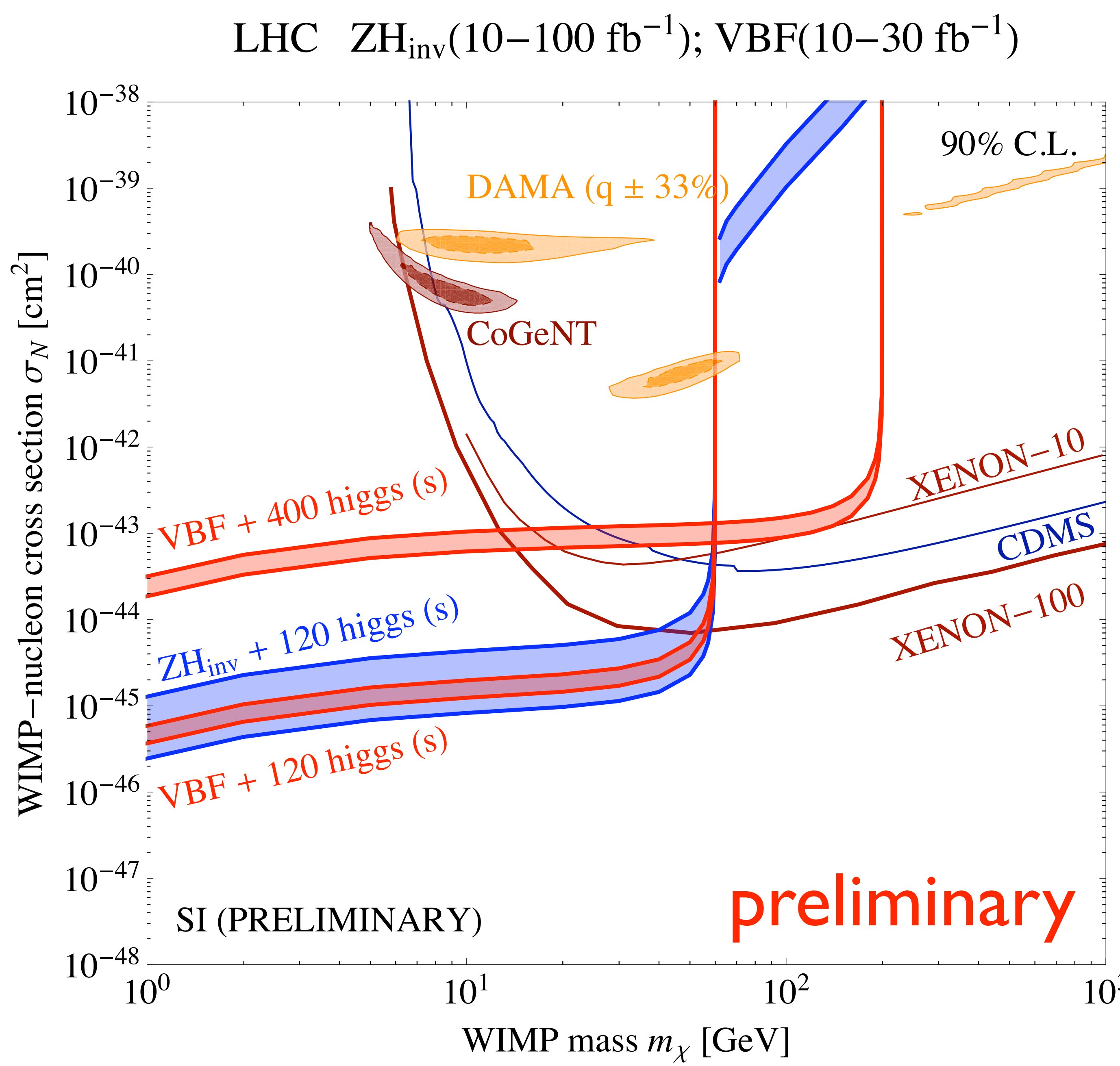
A Characteristic Higgs Channel can confirm Higgs mediation!

Higgs Mediator



vs.





Direct detection is parametrically smaller!

In progress, with Fox Kopp and Tsai

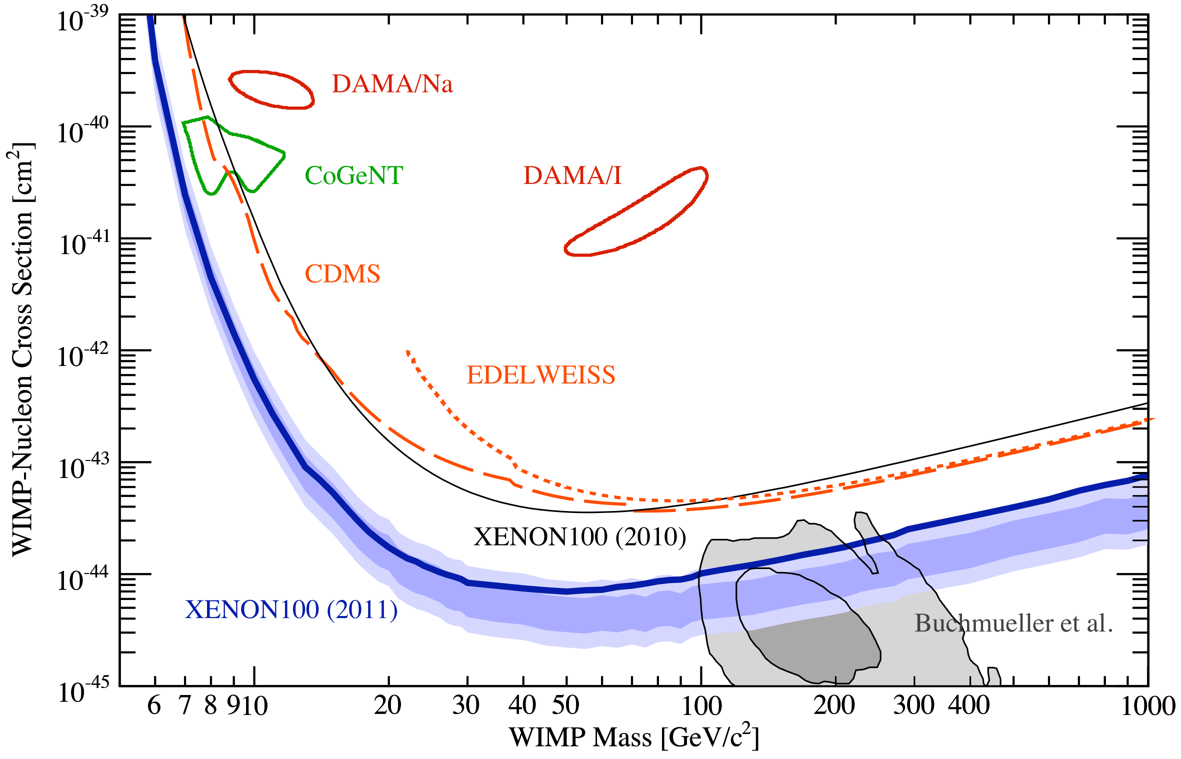
To Conclude:

Colliders are placing competitive and complementary bounds to direct detection:

- The ~~**Tevatron**~~ LHC is the world record holder for light dark matter and for spin dependent.
- Dedicated CDF, CMS, ATLAS **mono-jet** studies are underway.
- **LEP** mono-photons provide strong constraints.
- The **LHC** can also be competitive in the case of **scattering through the Higgs**. May identify the the Higgs as the mediator.

Collider Connections?

* DM experiments and colliders are often said to be related *in a specific framework* (SUSY).



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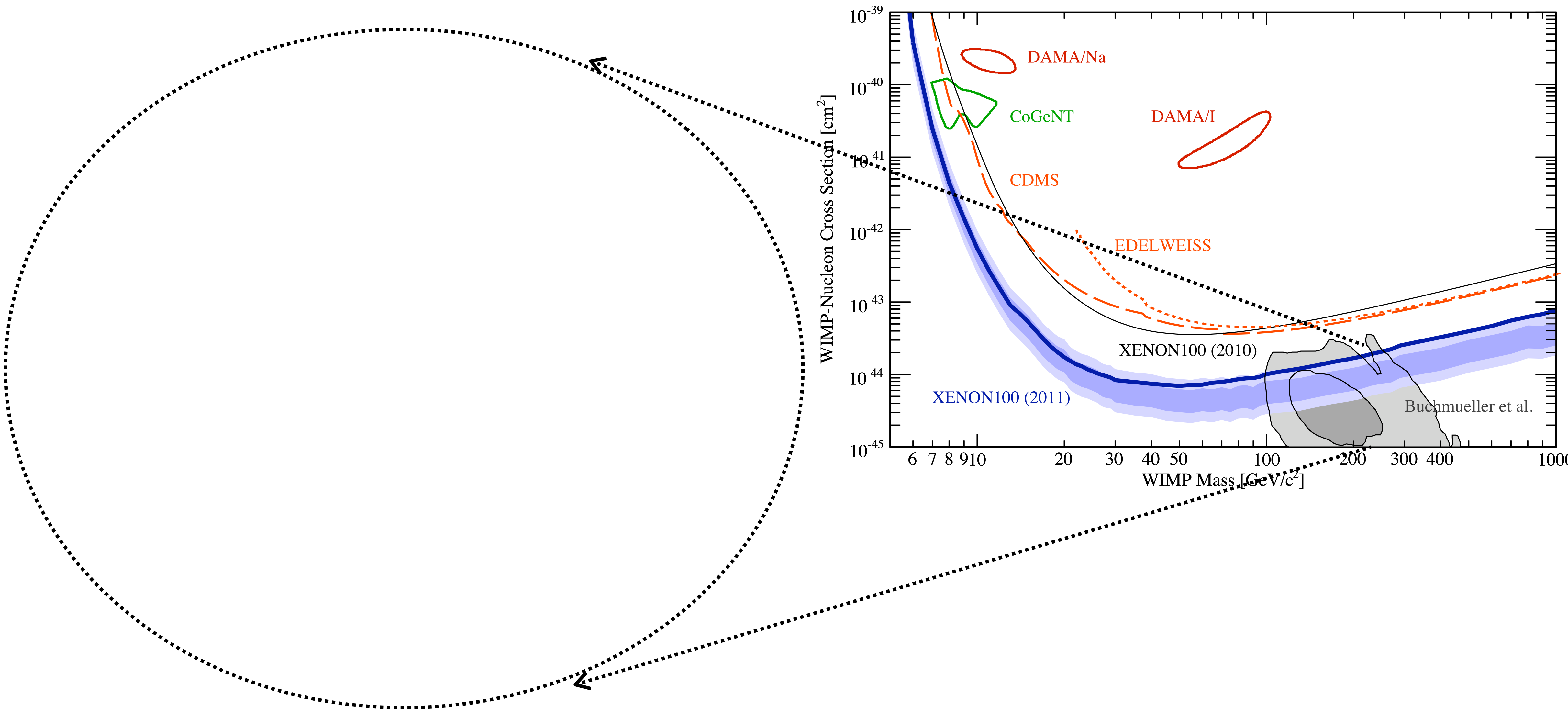

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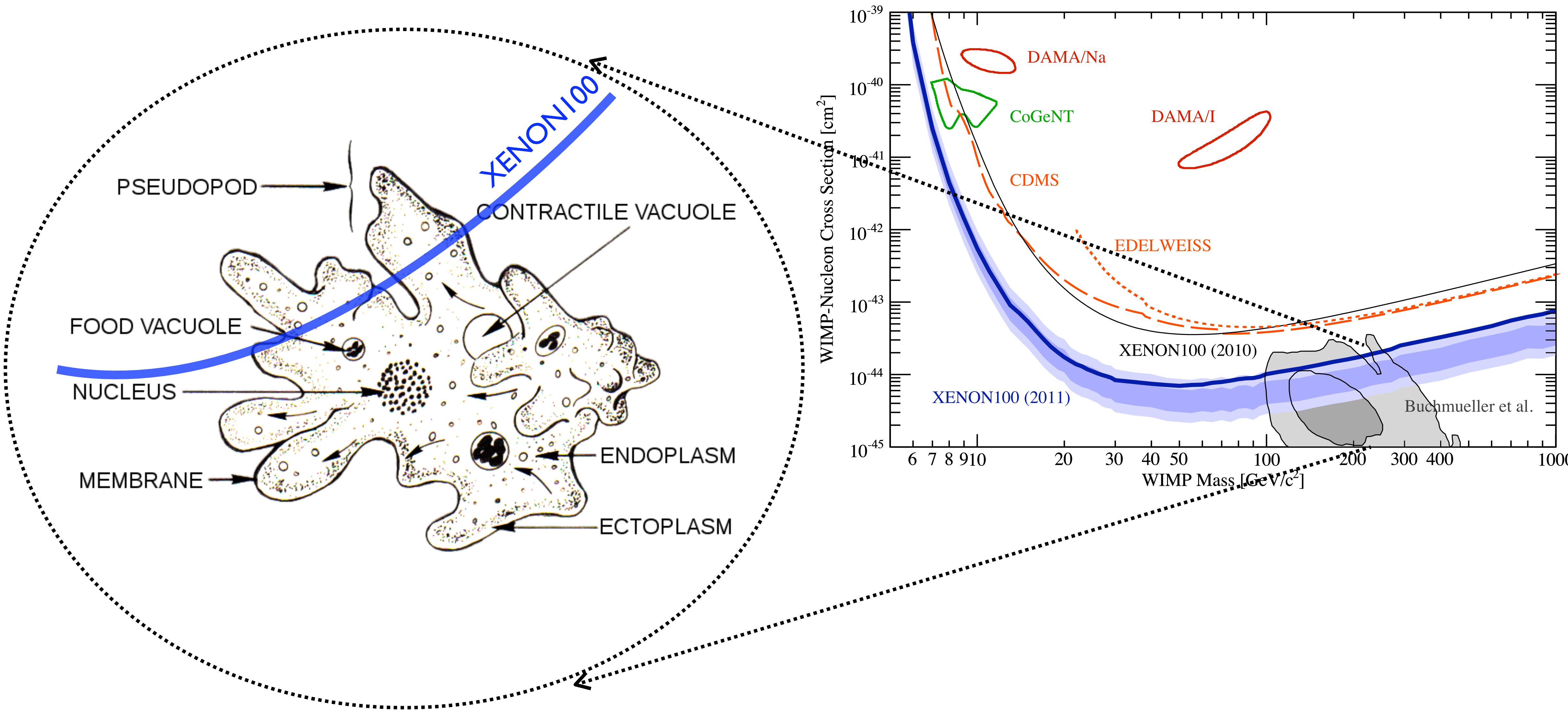

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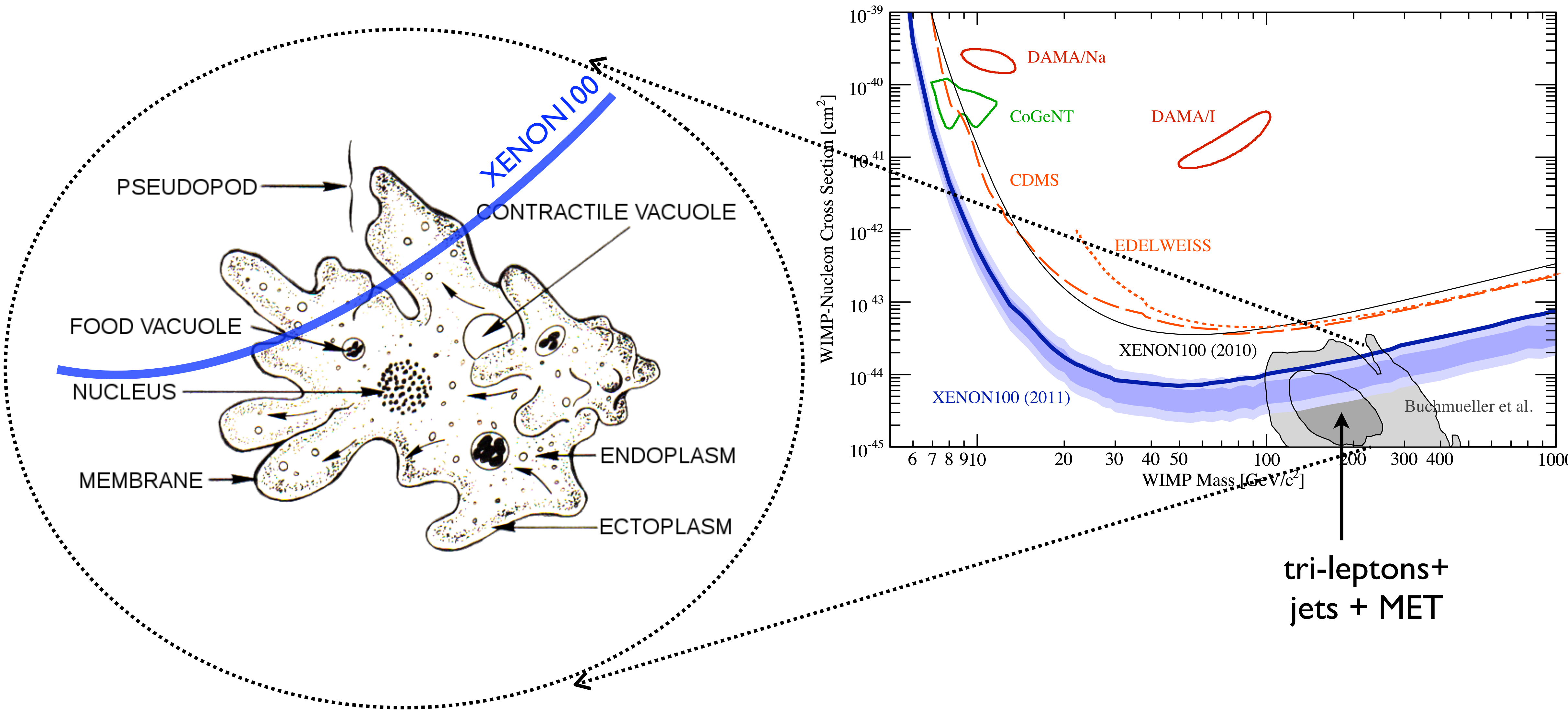

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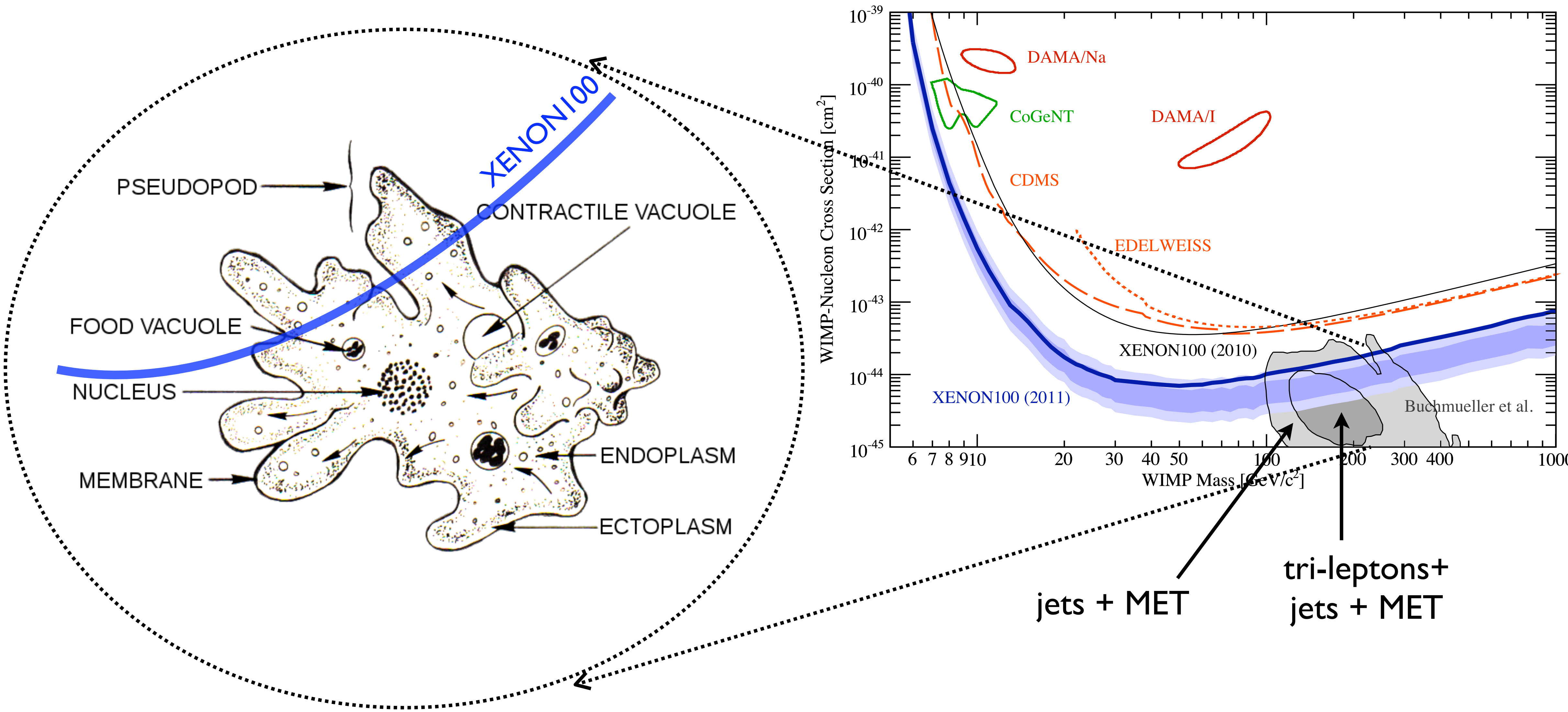

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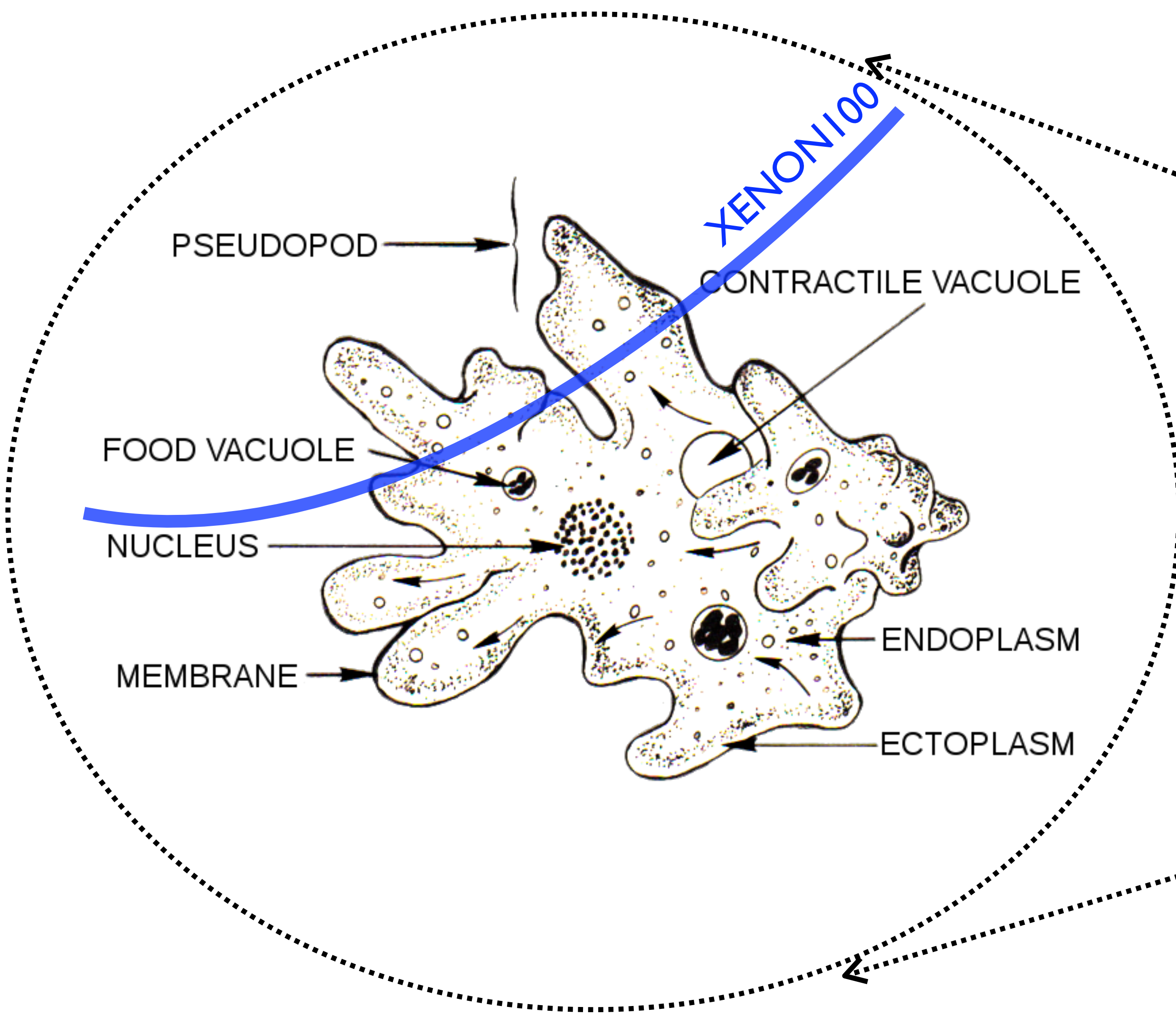

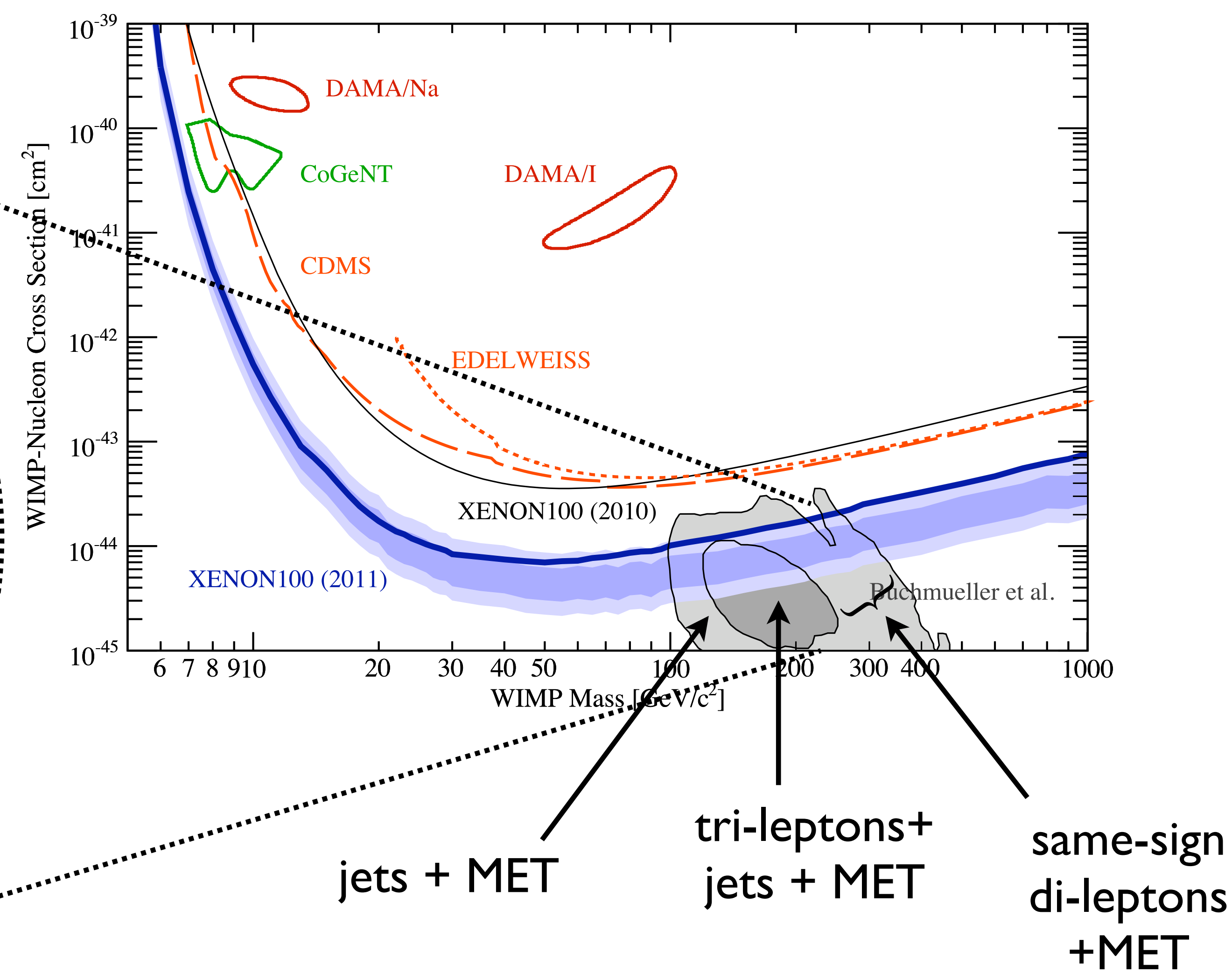

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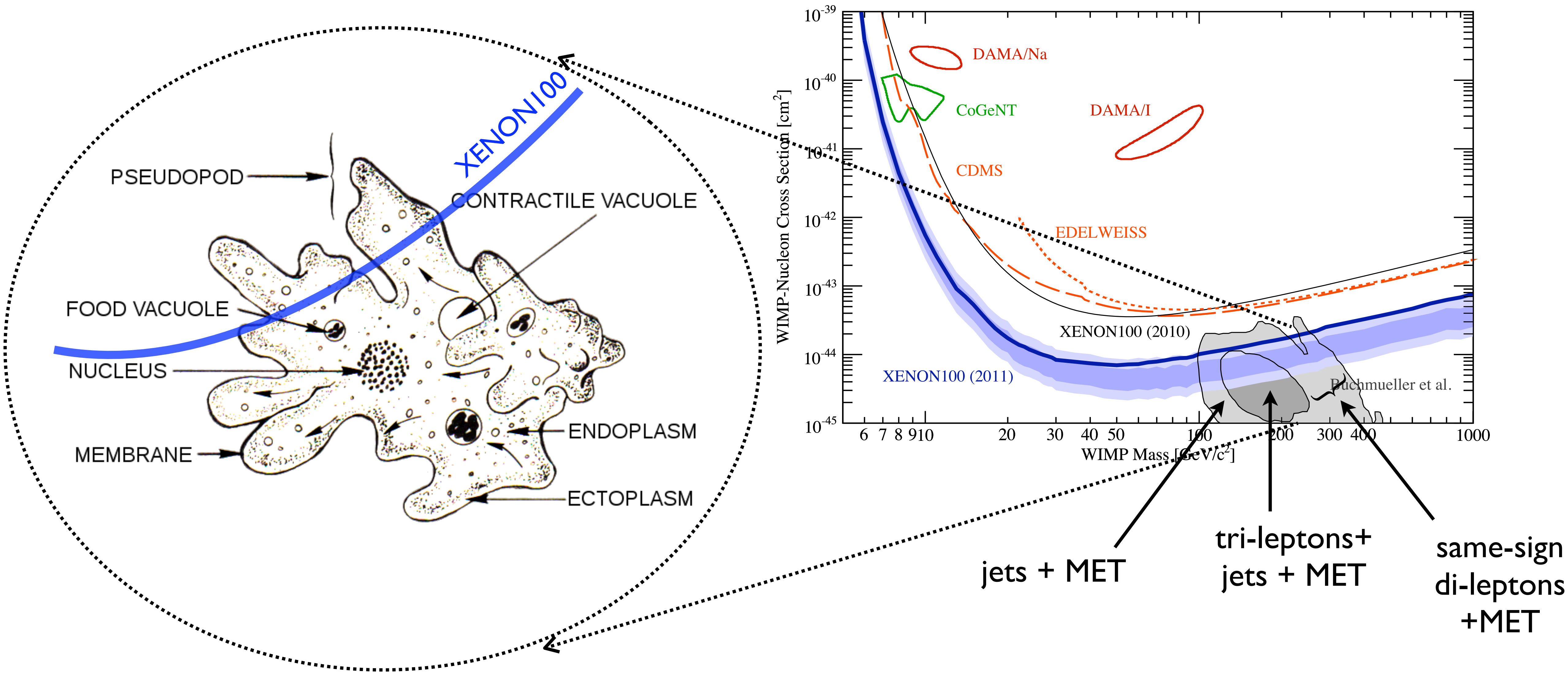

"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [nature **67**, 143 (2011)]