# Dark Matter @ Colliders

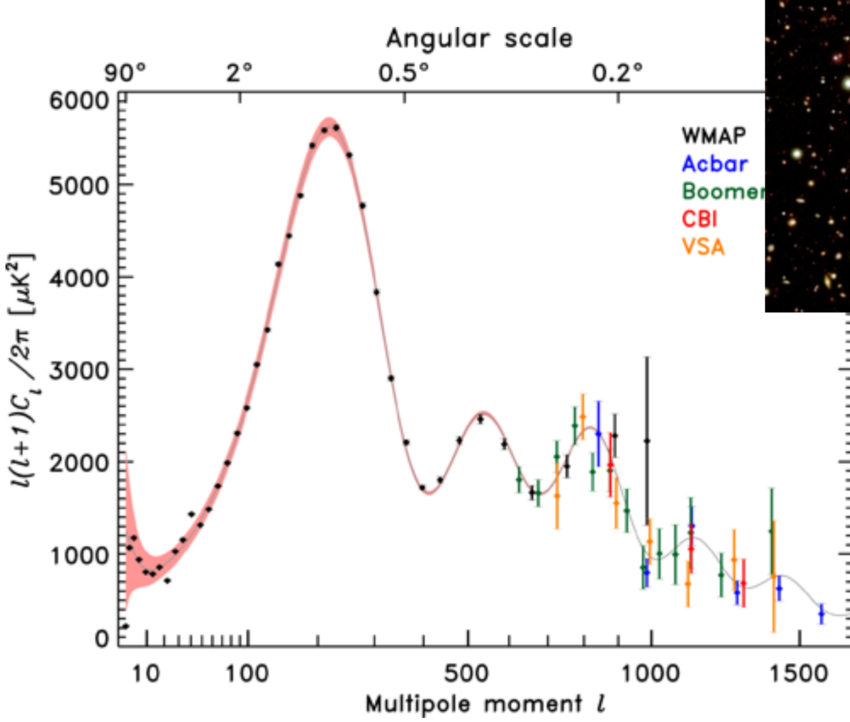
David-fest 2011

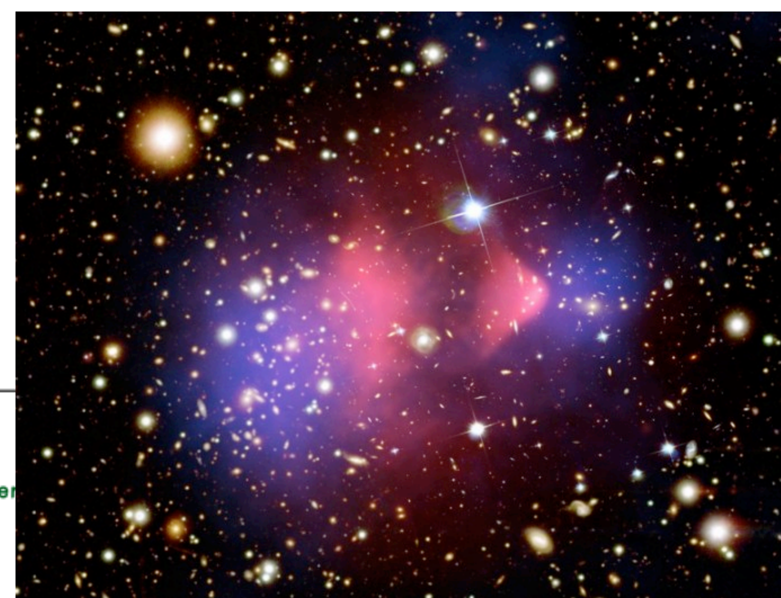
Roni Harnik, Fermilab

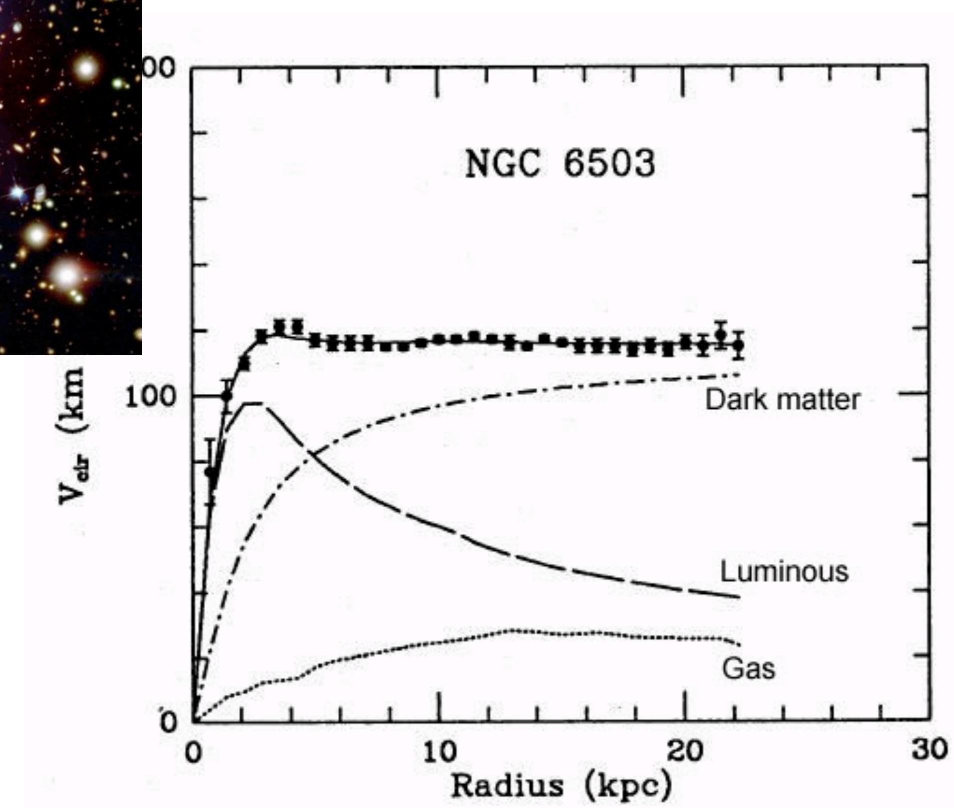
Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - 1109.4389

Very related work by the "Irvine Clan":
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu -1005.1286
Goodman, Ibe, Rajaraman, Shepherd, Tait and Haibo Yu - 1008.1783
Fortin and Tait - 1103.3289
Rajaraman, Shepherd,Tait and Wijangco - 1108.1196
Shepherd and Goodman - 1111.2359

# 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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Answers (and limits) come from
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**Directly complemented by past and present colliders.**

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**LHC** (e.g. Higgs mediated interactions)

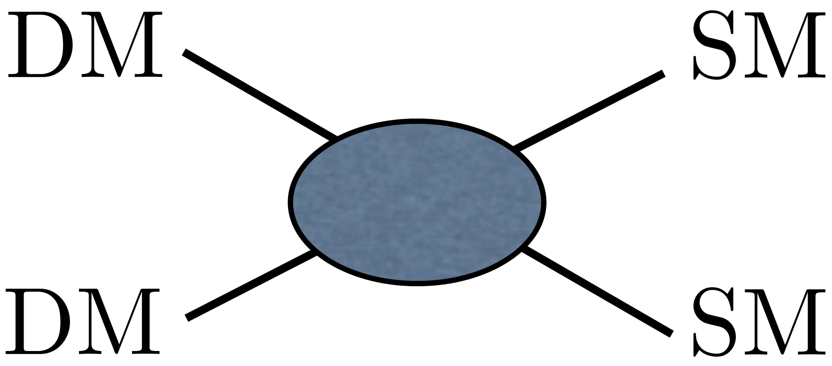
# Outline

* Motivation:
  Colliders as direct detection experiments.
* Tevatron & LHC mono-jets:
  - Rough estimates.
  - Operators
  - Results
* LEP mono-photons.
* Scattering via the Higgs & LHC Higgs searches.
* 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.

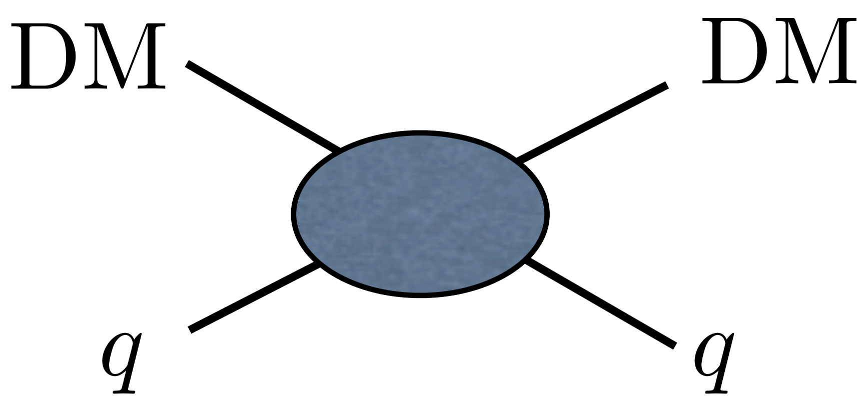
Hint: There *is* an interaction.
Leads to pb-ish cross sections



# Probes of DM Interactions

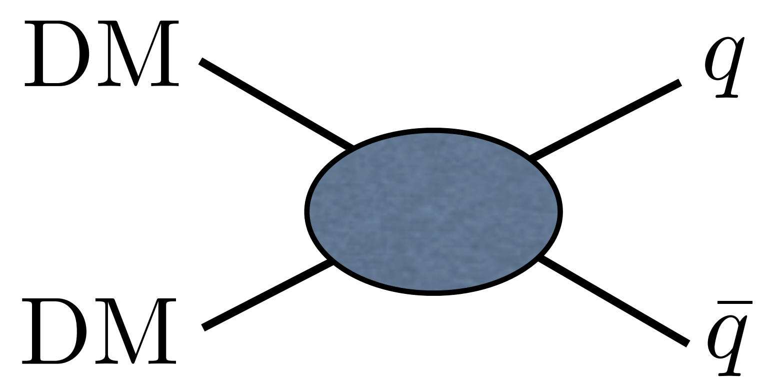
* We hope to probe dark matter in several ways:

*DM-nucleus scattering*




*direct*

*DM annihilation*

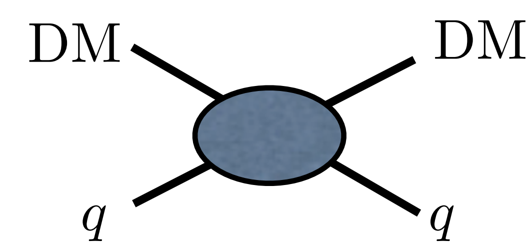



*indirect*

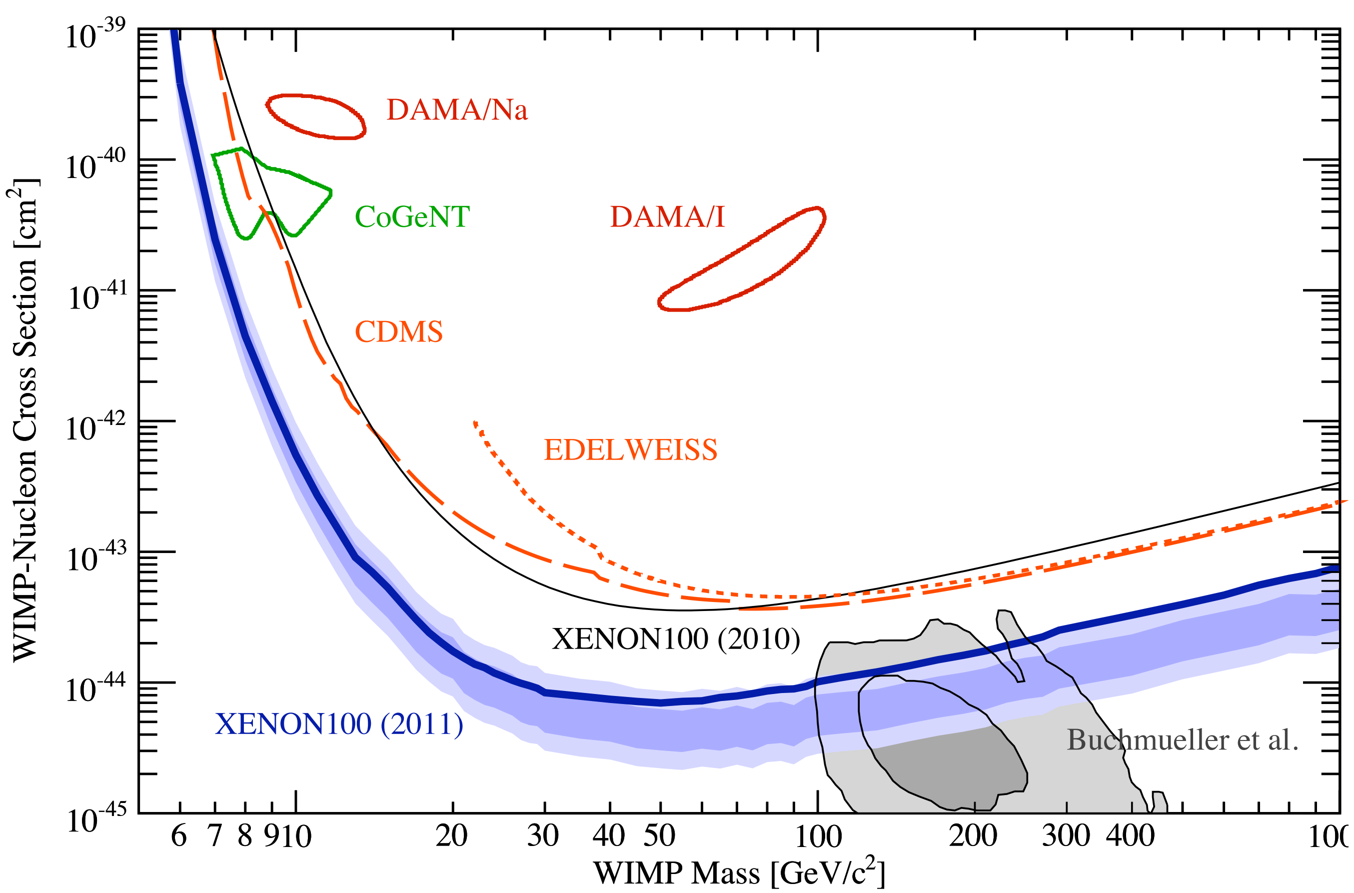
Focus on direct detection in this talk.

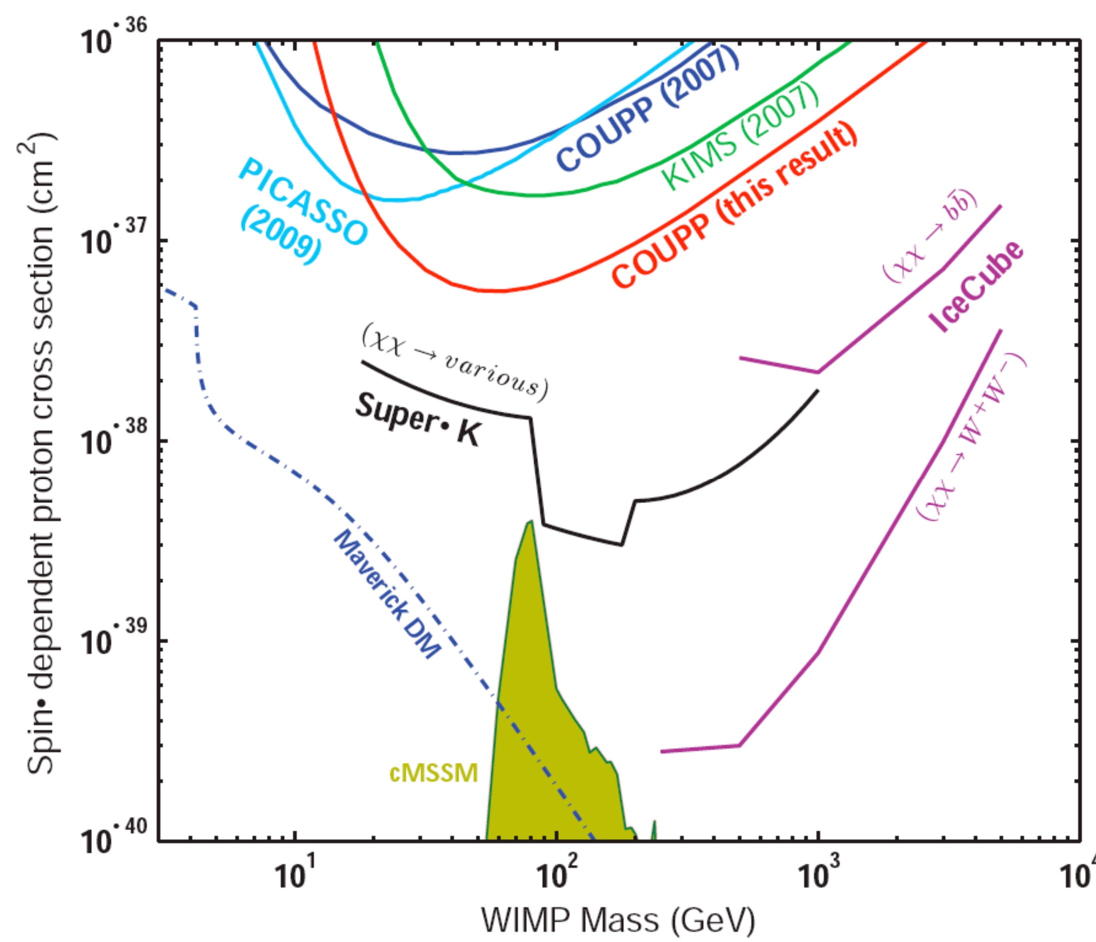
(a similar game can be played for indirect)

# Direct detection

- Direct detection places limits on  .

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



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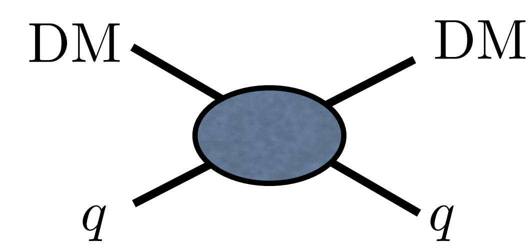
* Direct detection places limits on  .



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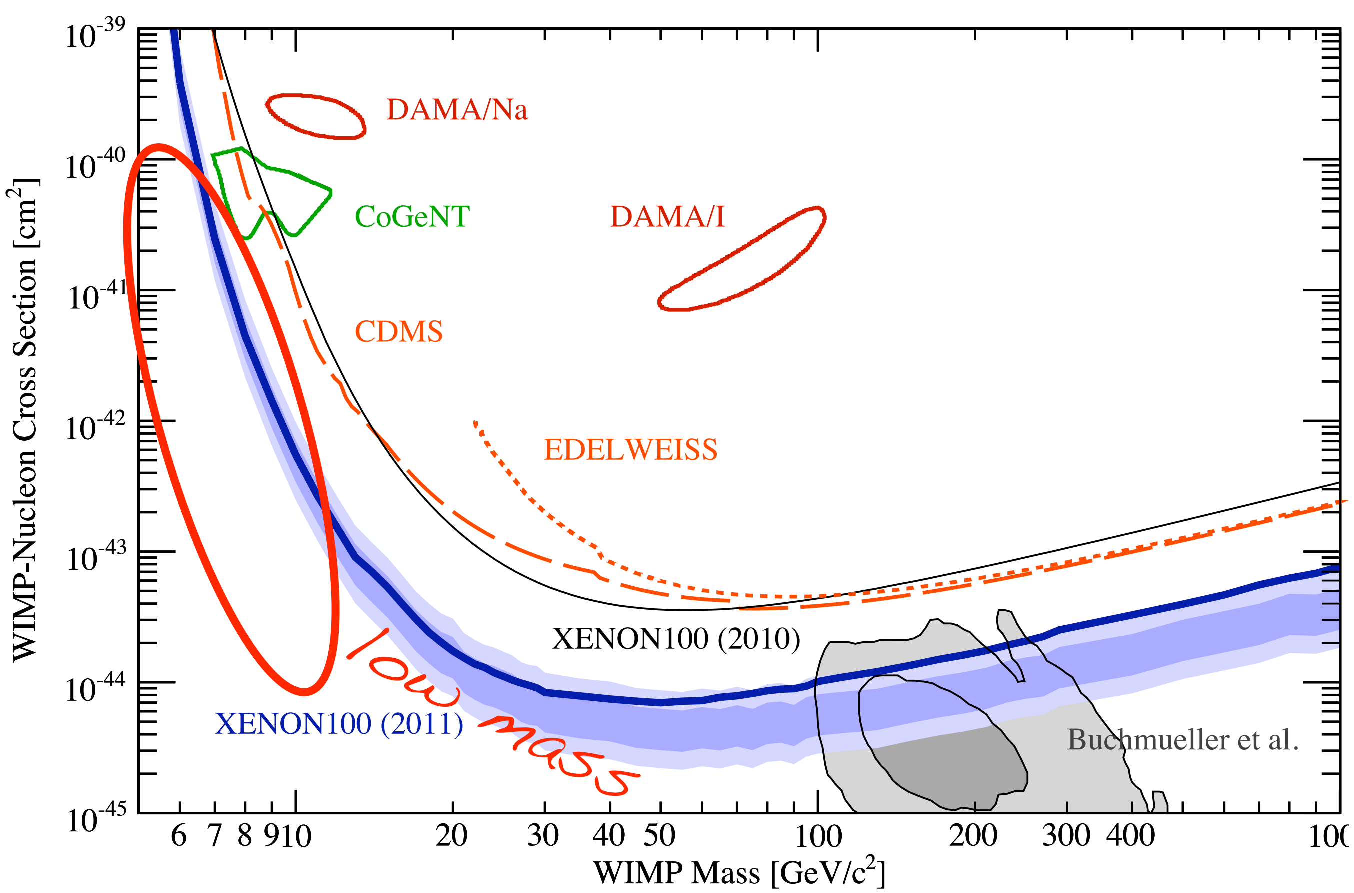



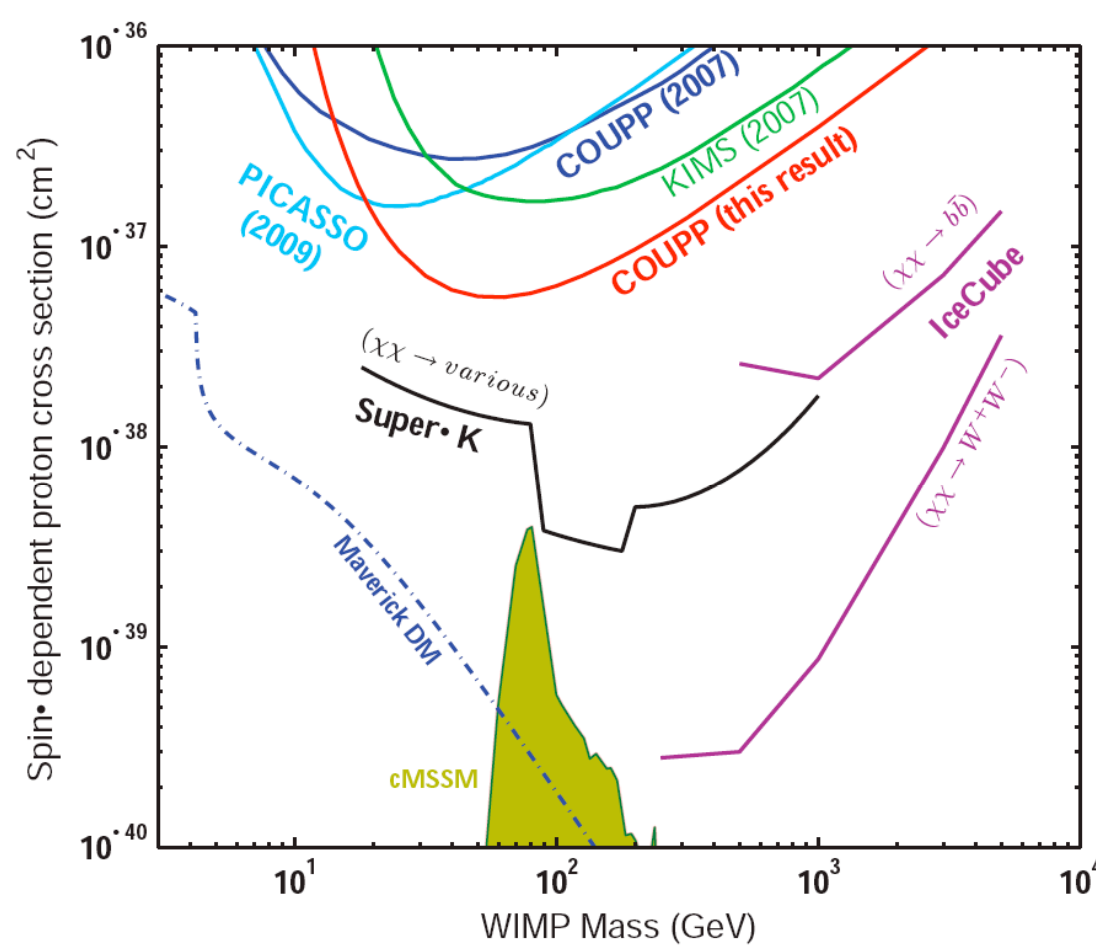

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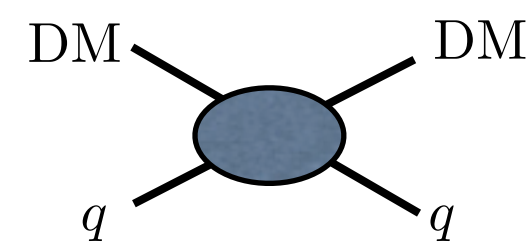
* Direct detection places limits on  .



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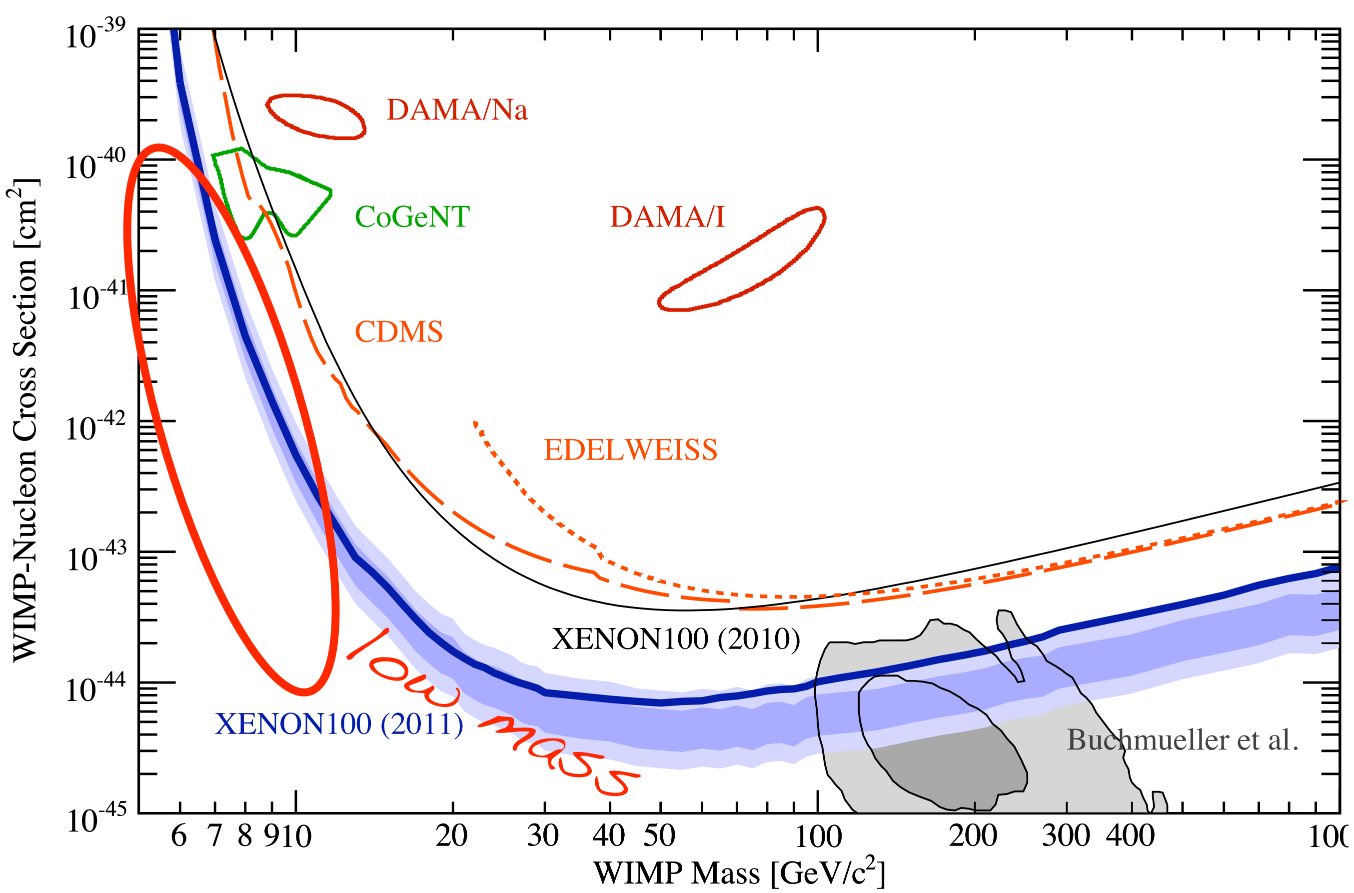



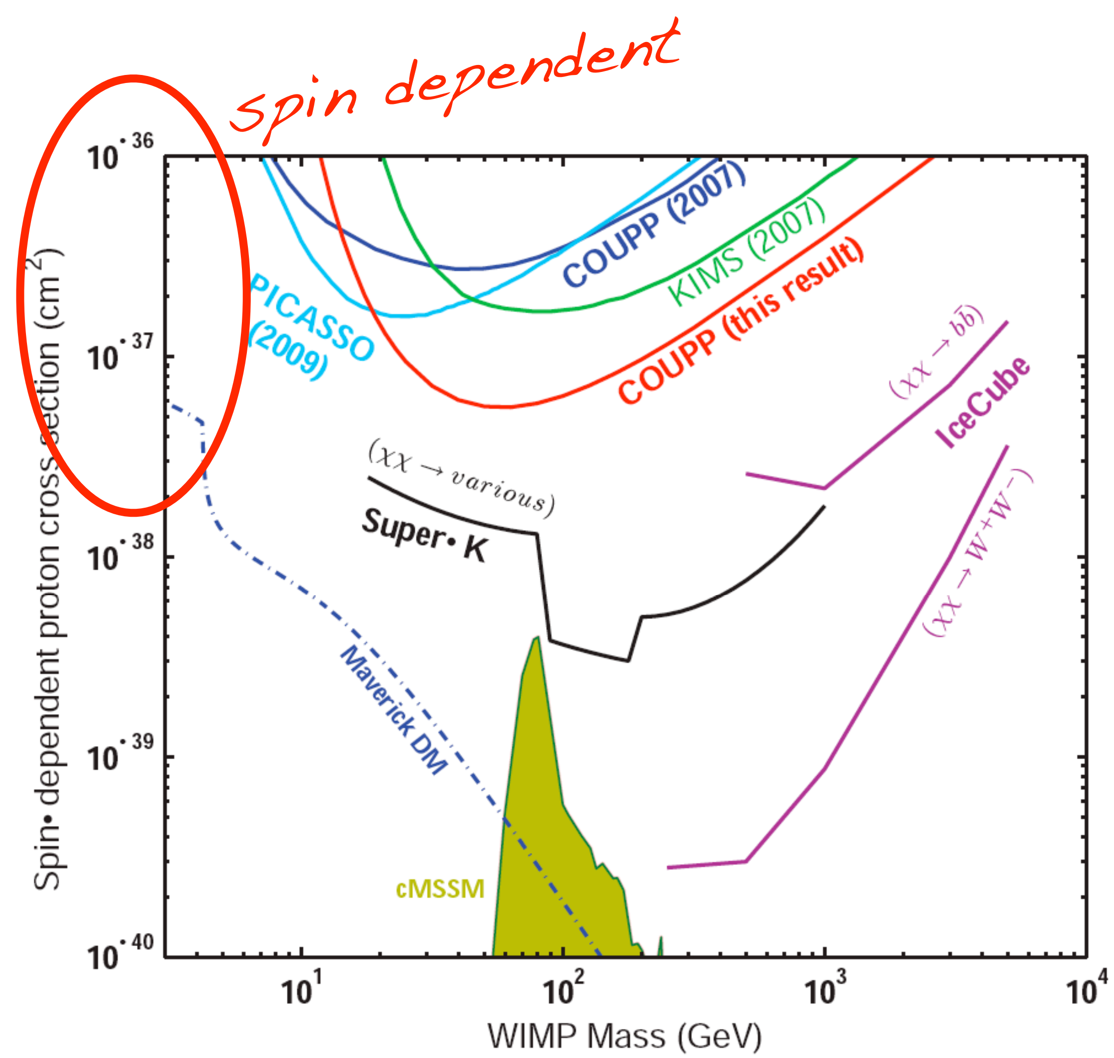

# Collider Connections?

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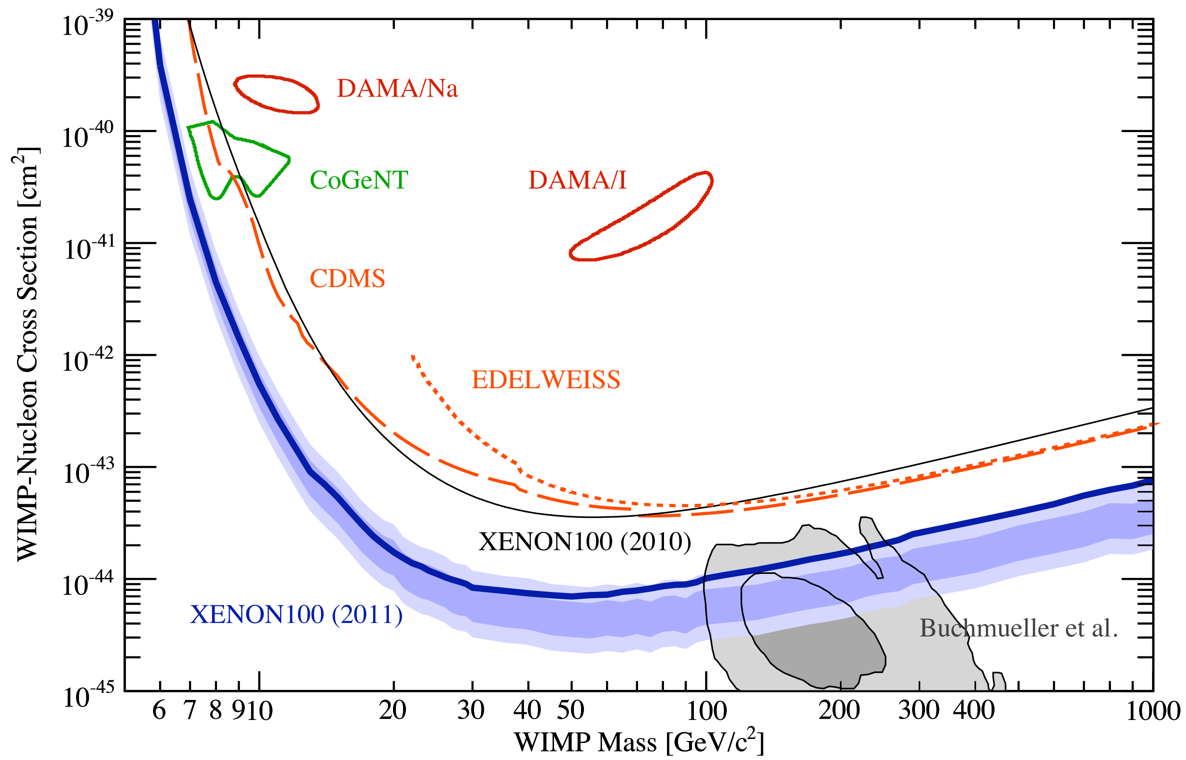

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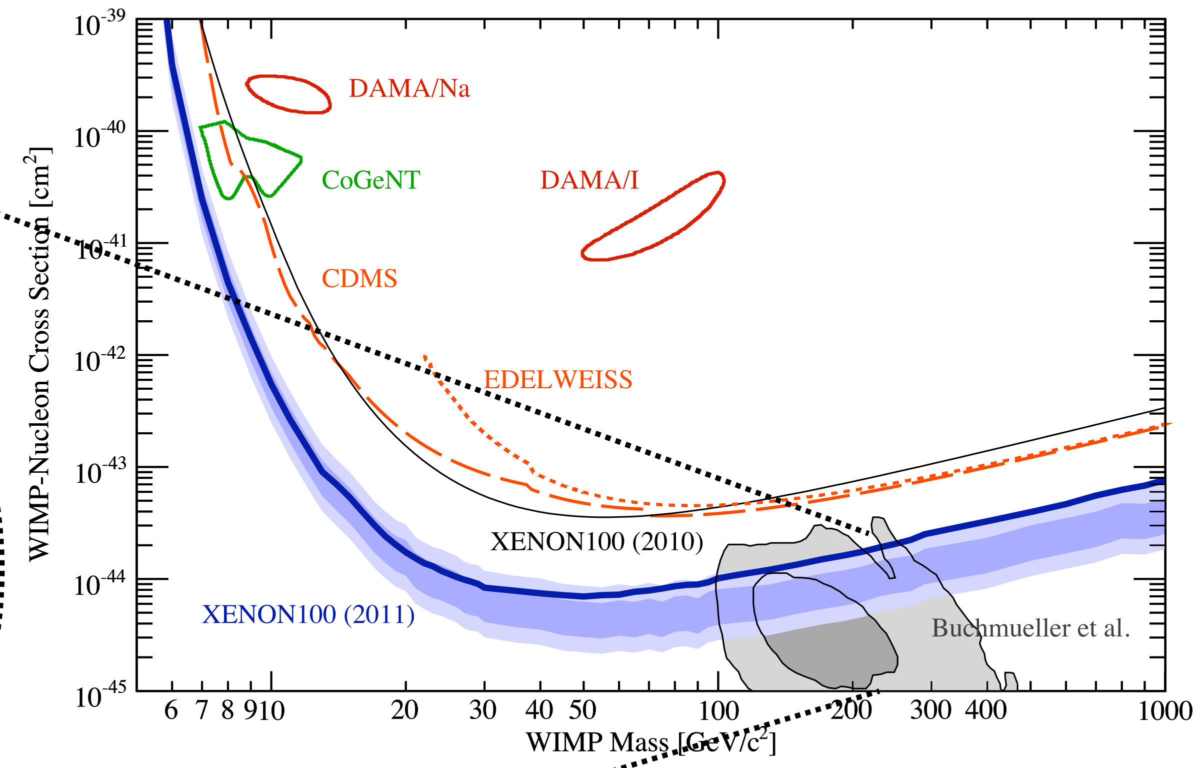

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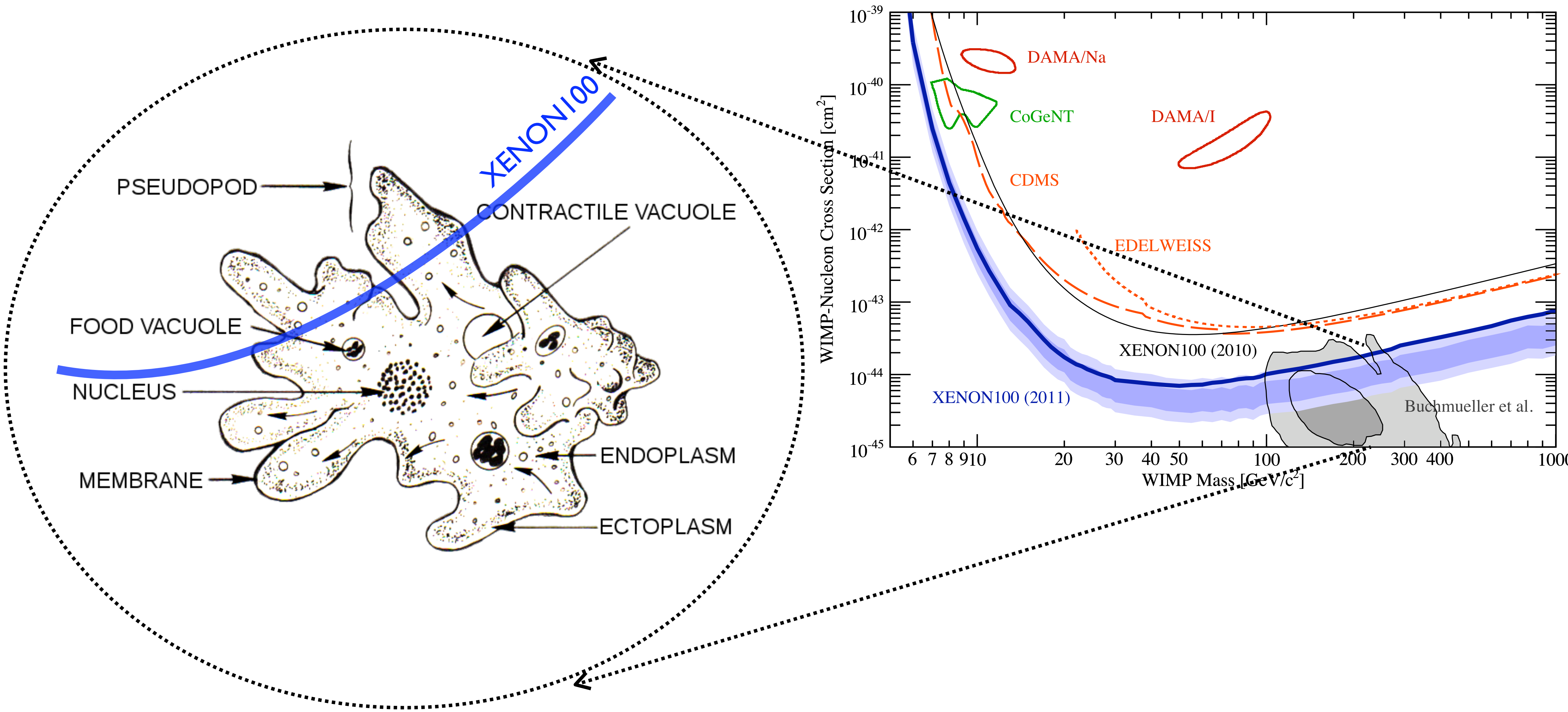

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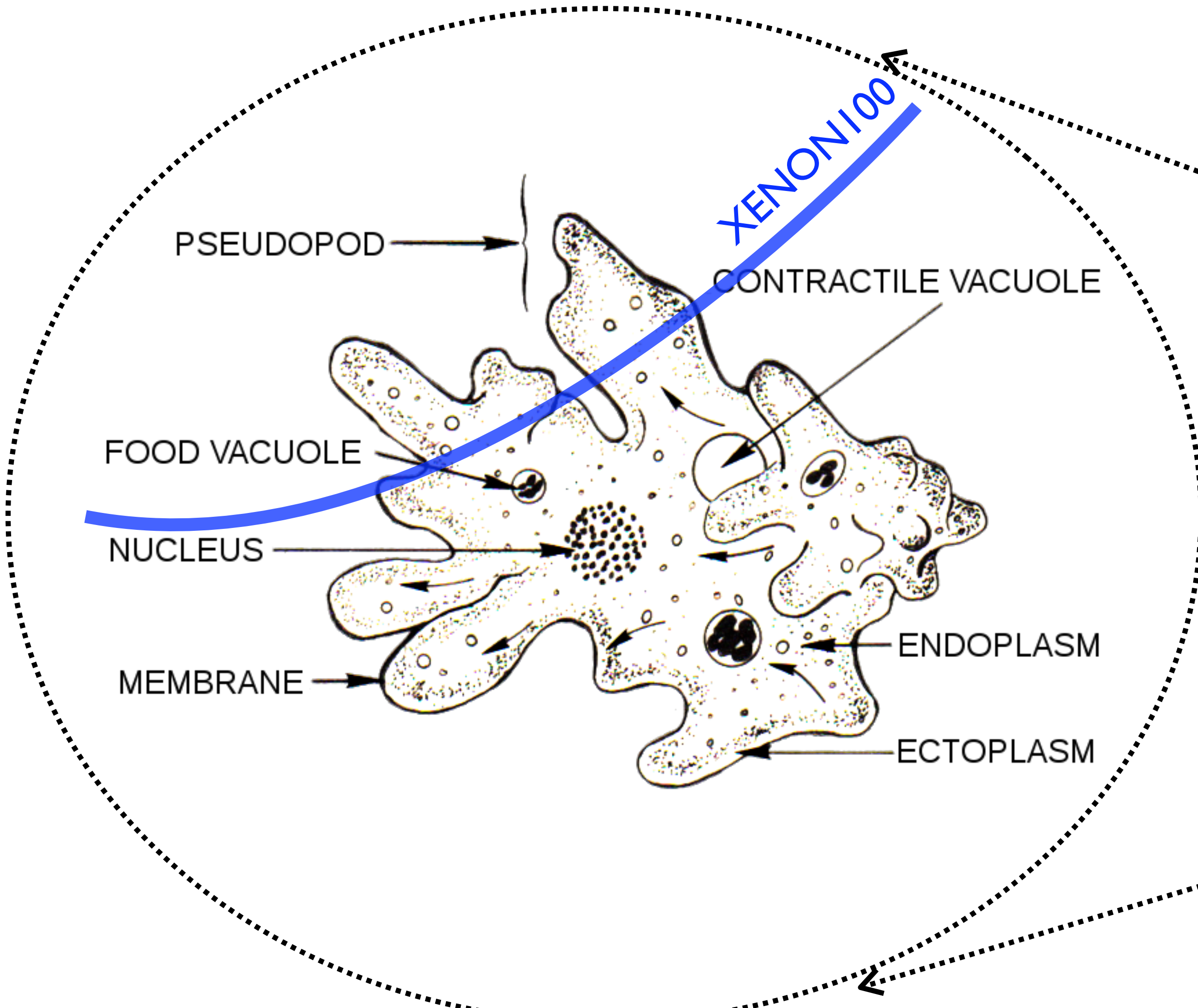


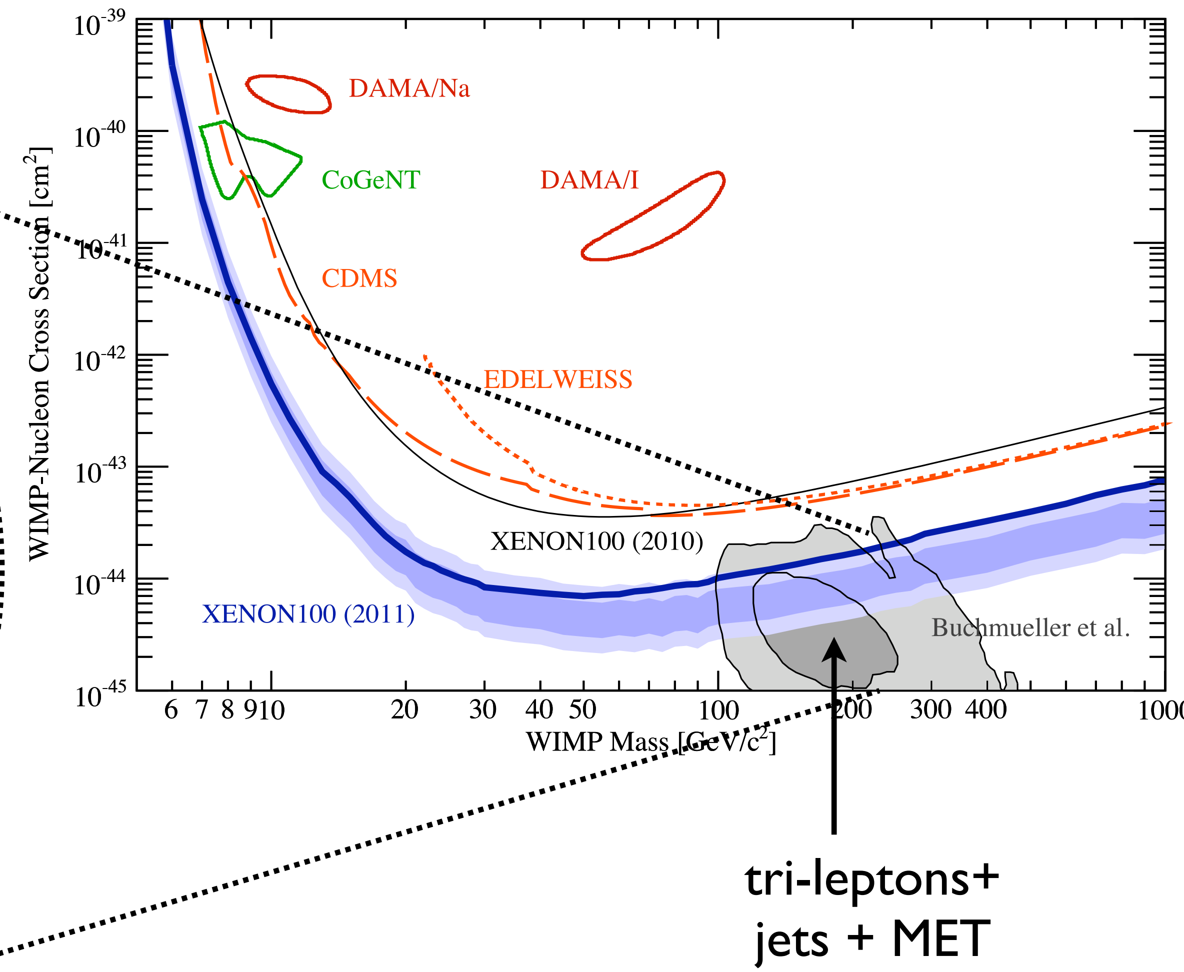

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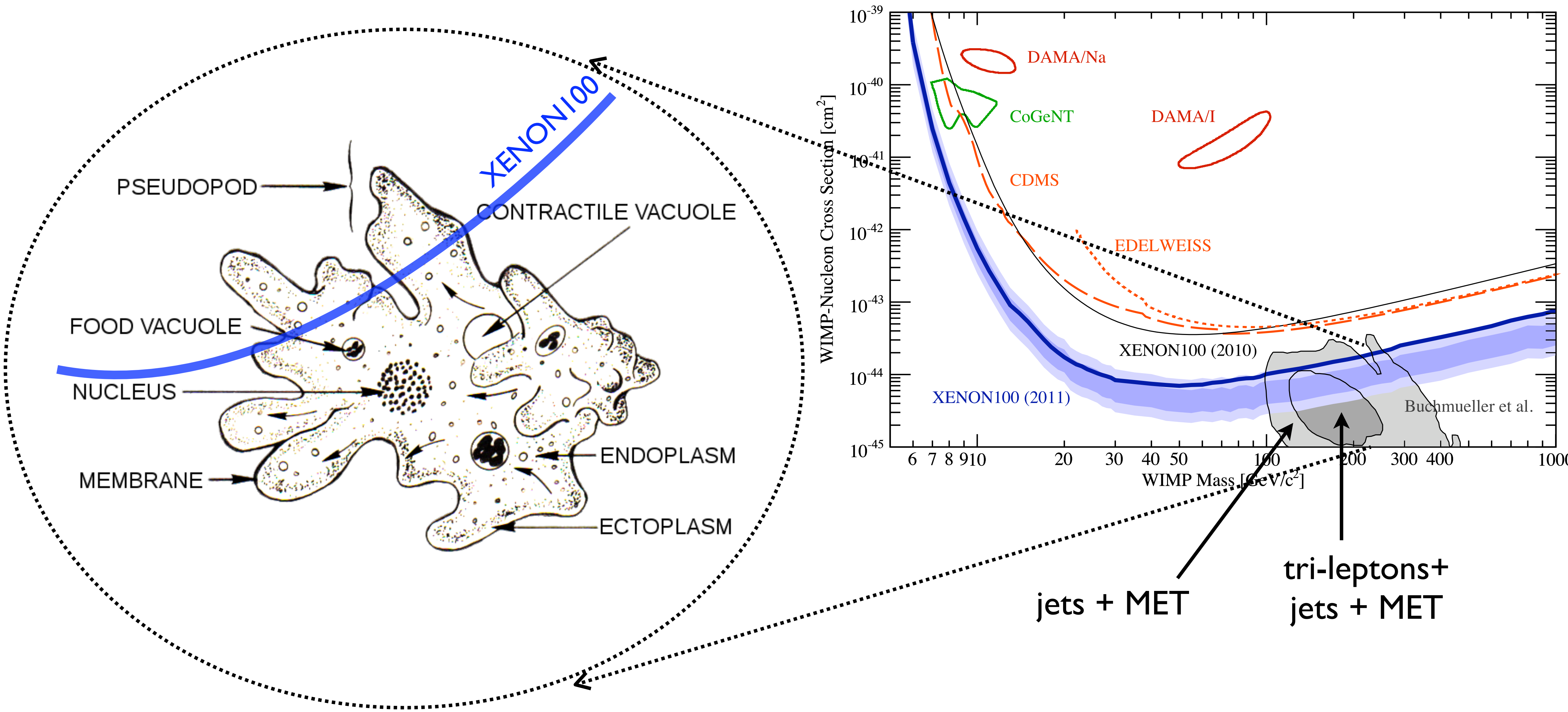

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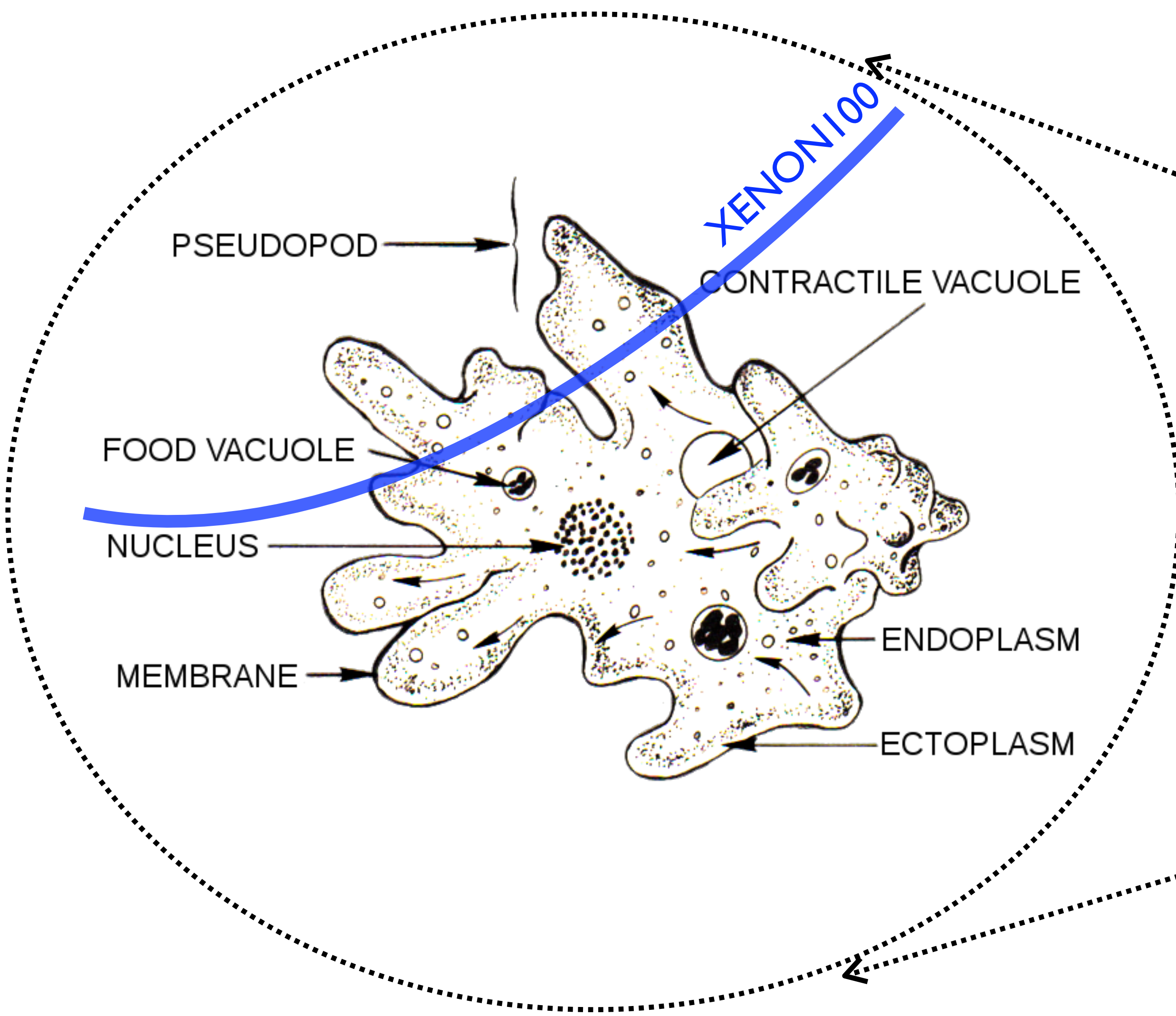


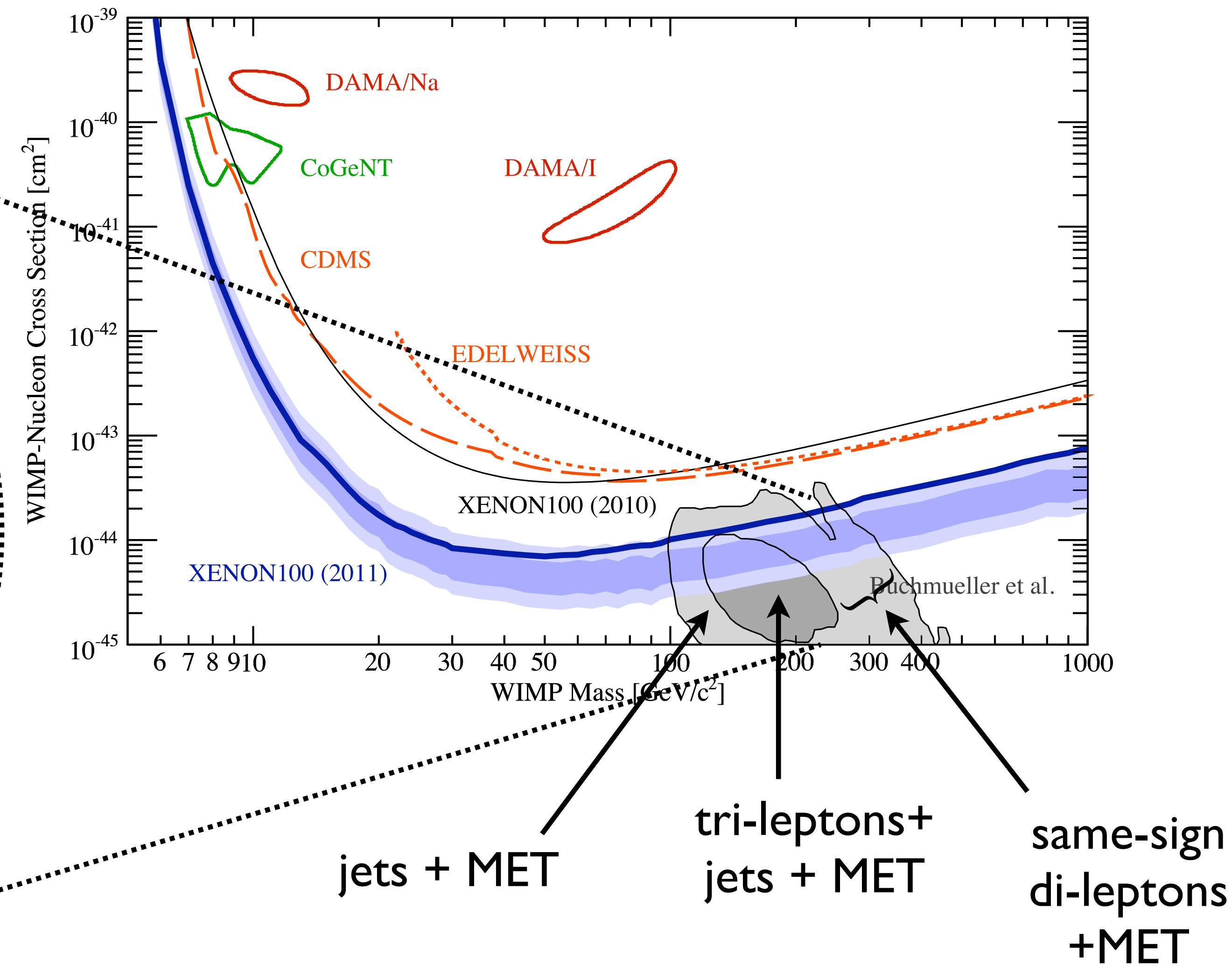

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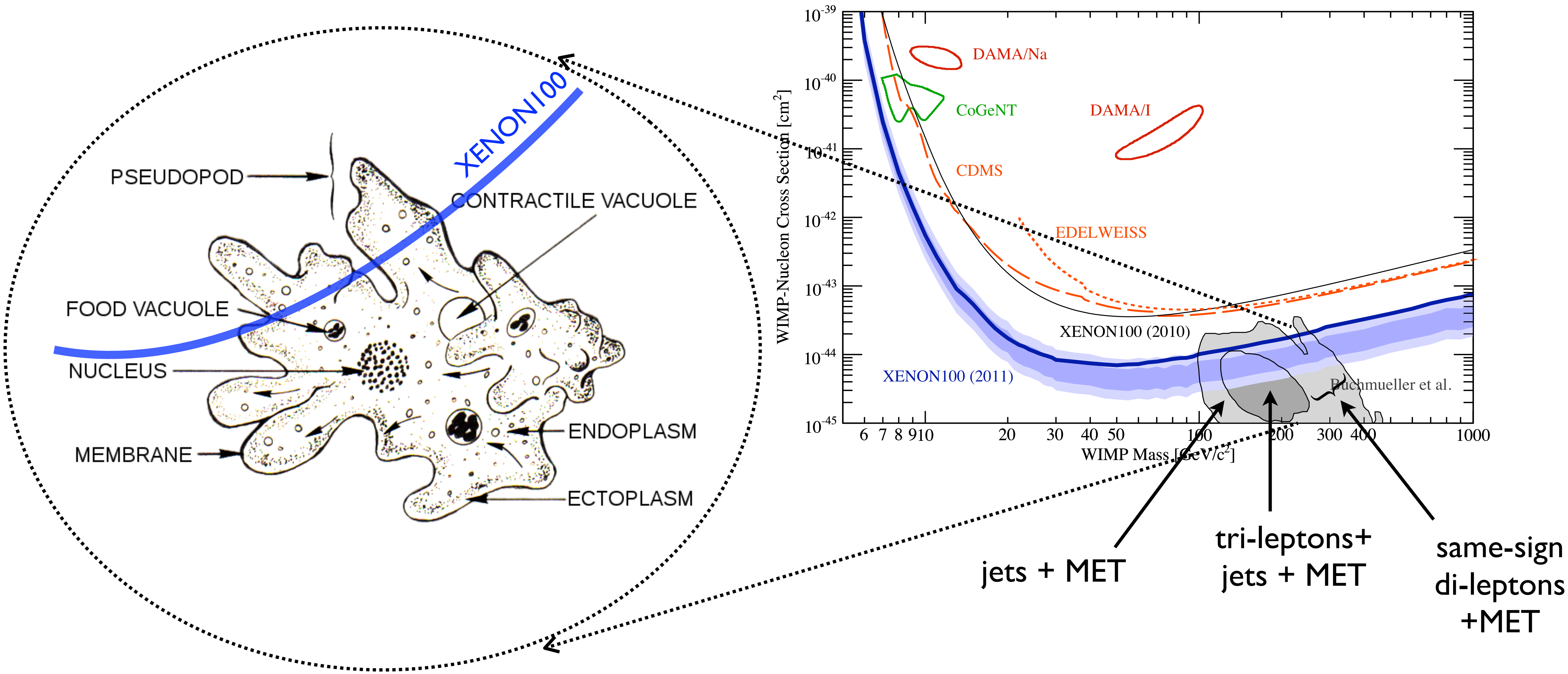
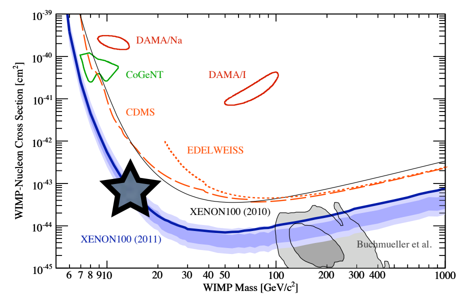
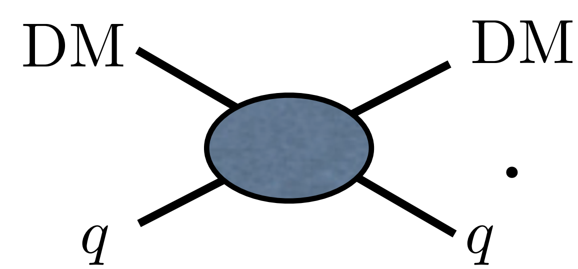



"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [submitted to nature]

# 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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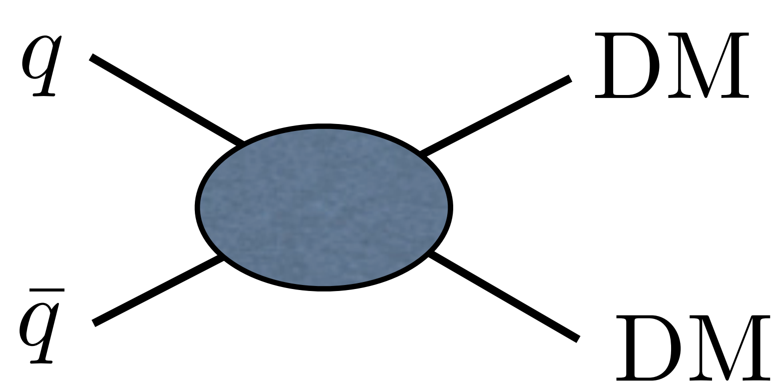
* The same interaction can lead to DM production at a hadron machine.




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

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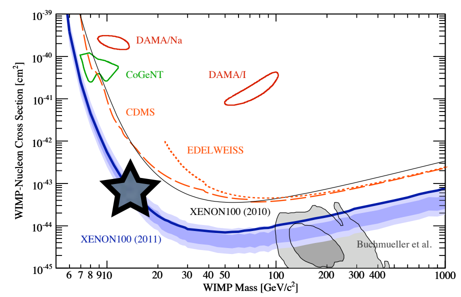
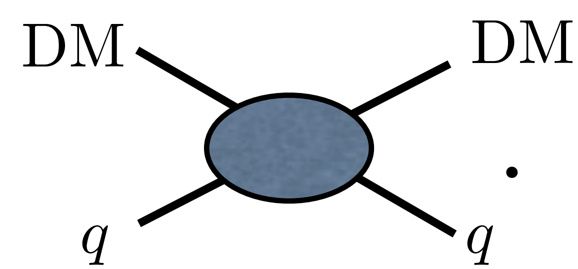
- In order to get a particular DM-nucleon cross section, 

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

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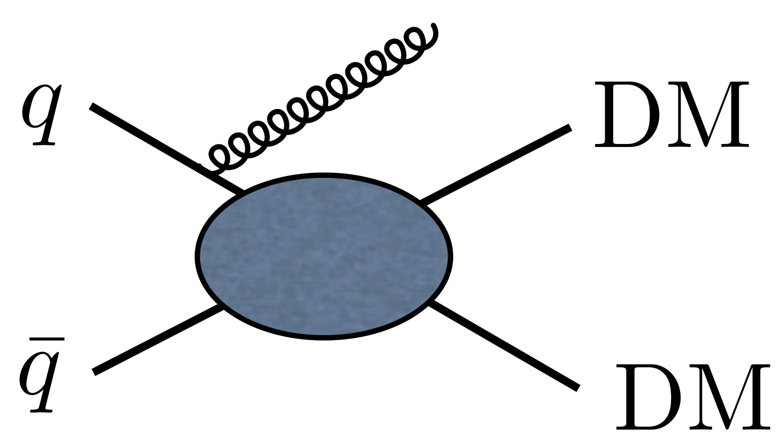
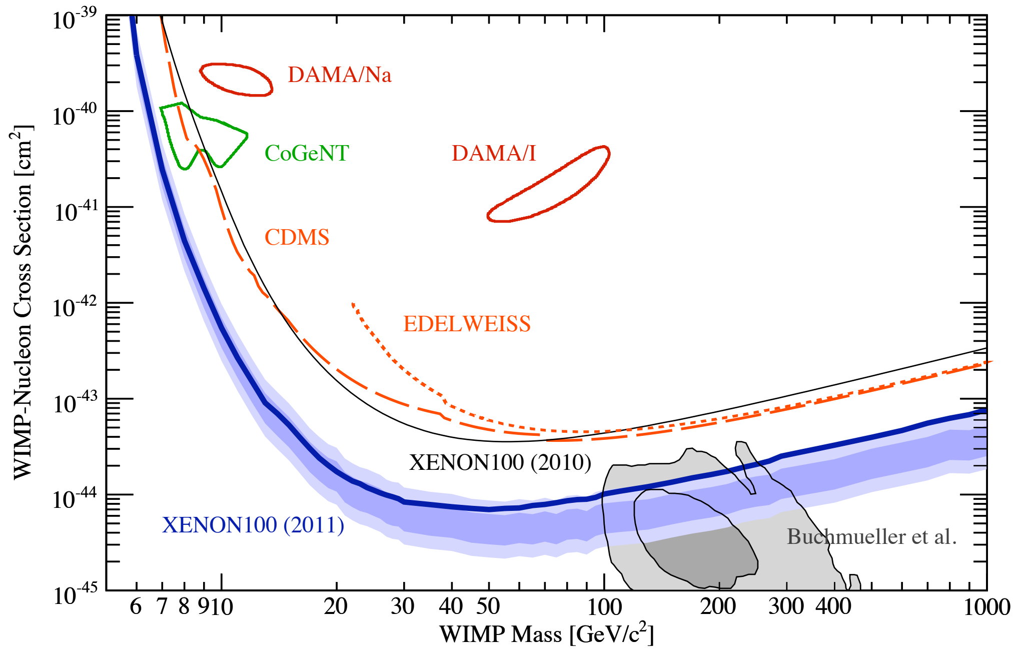
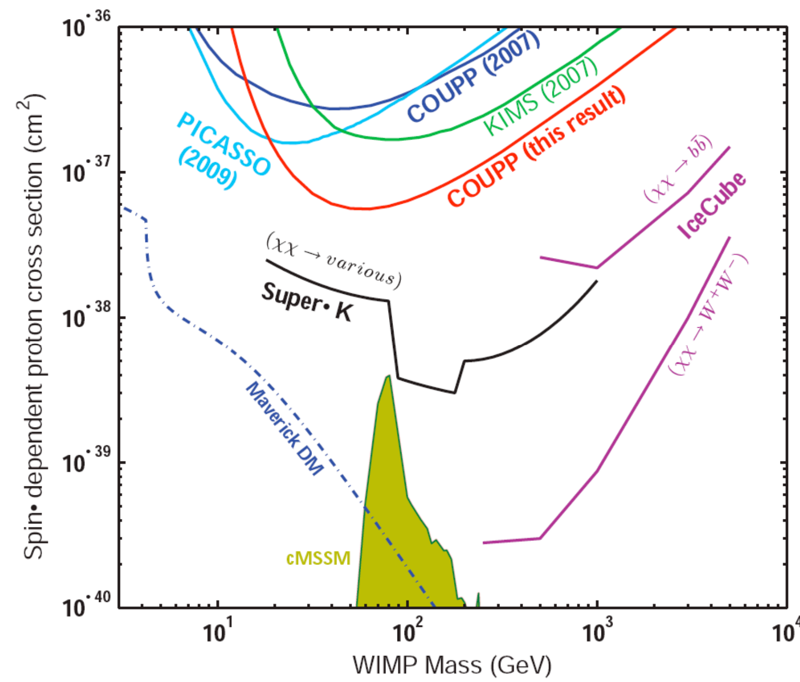



$$p\bar{p} \longrightarrow j + \not{E}_T$$

# A Simple Point

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



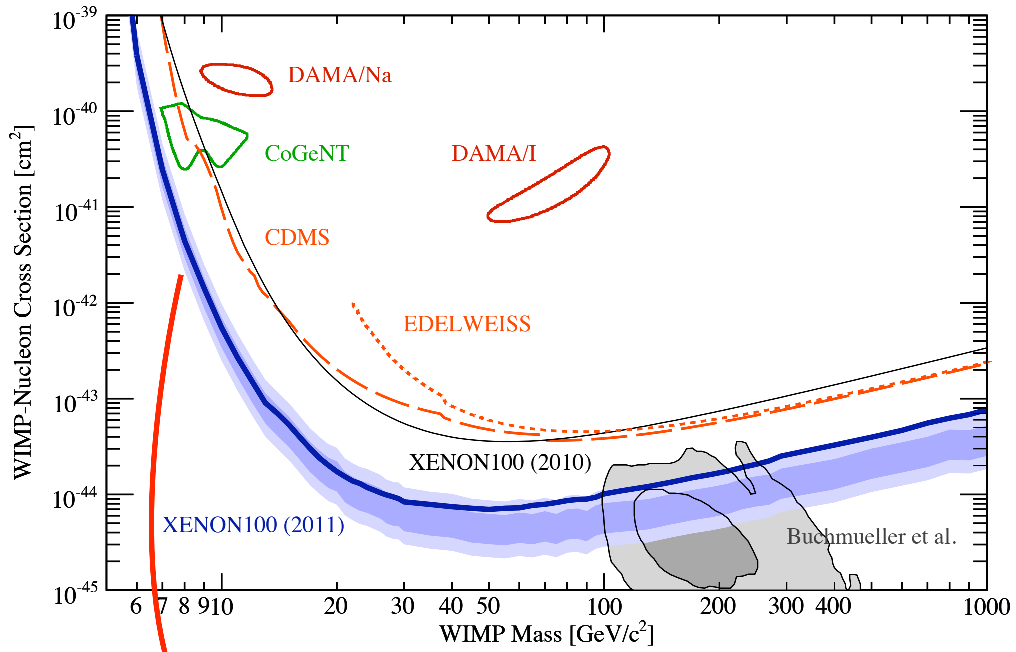



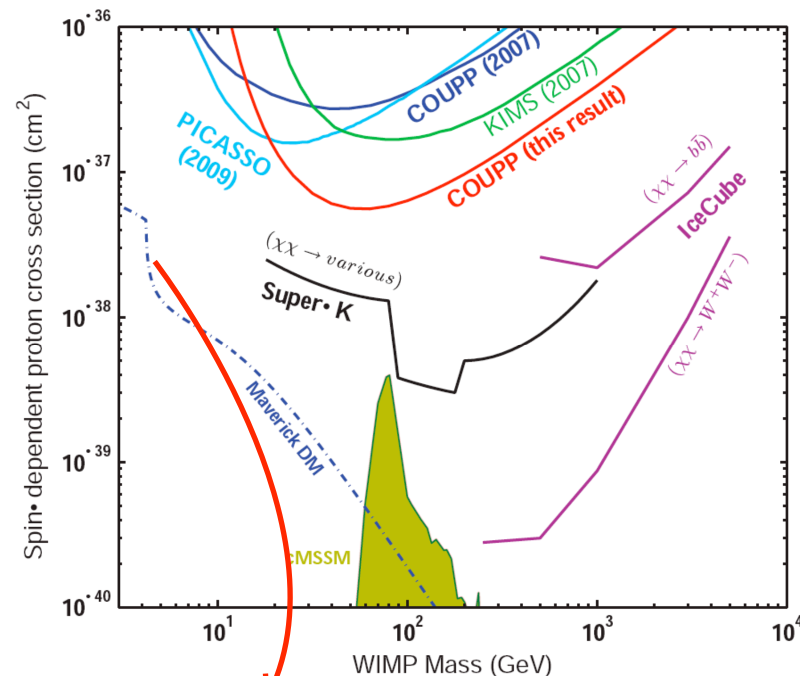

* These are **conservative** limits.
  In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

*But mono-jet are certainly good to set bounds.*

# A Simple Point

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



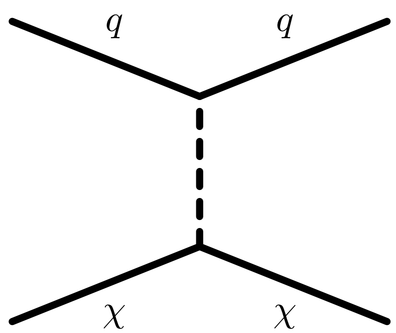




The collider does not have a low energy threshold

The collider does not pay a price for spin dependence

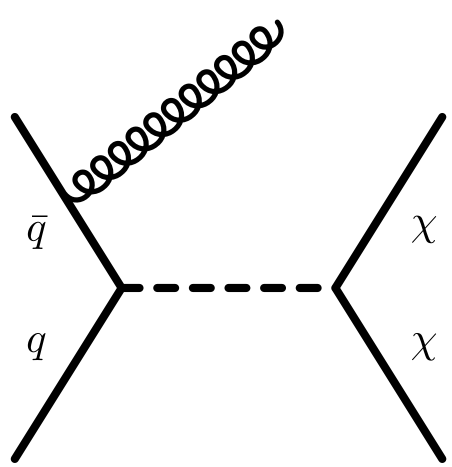
# Cross Sections

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




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

* Mono-jet + $\not{E}_T$ ($q \sim 10 - 100 \text{ GeV}$):




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

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Consider a heavy mediator:

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

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

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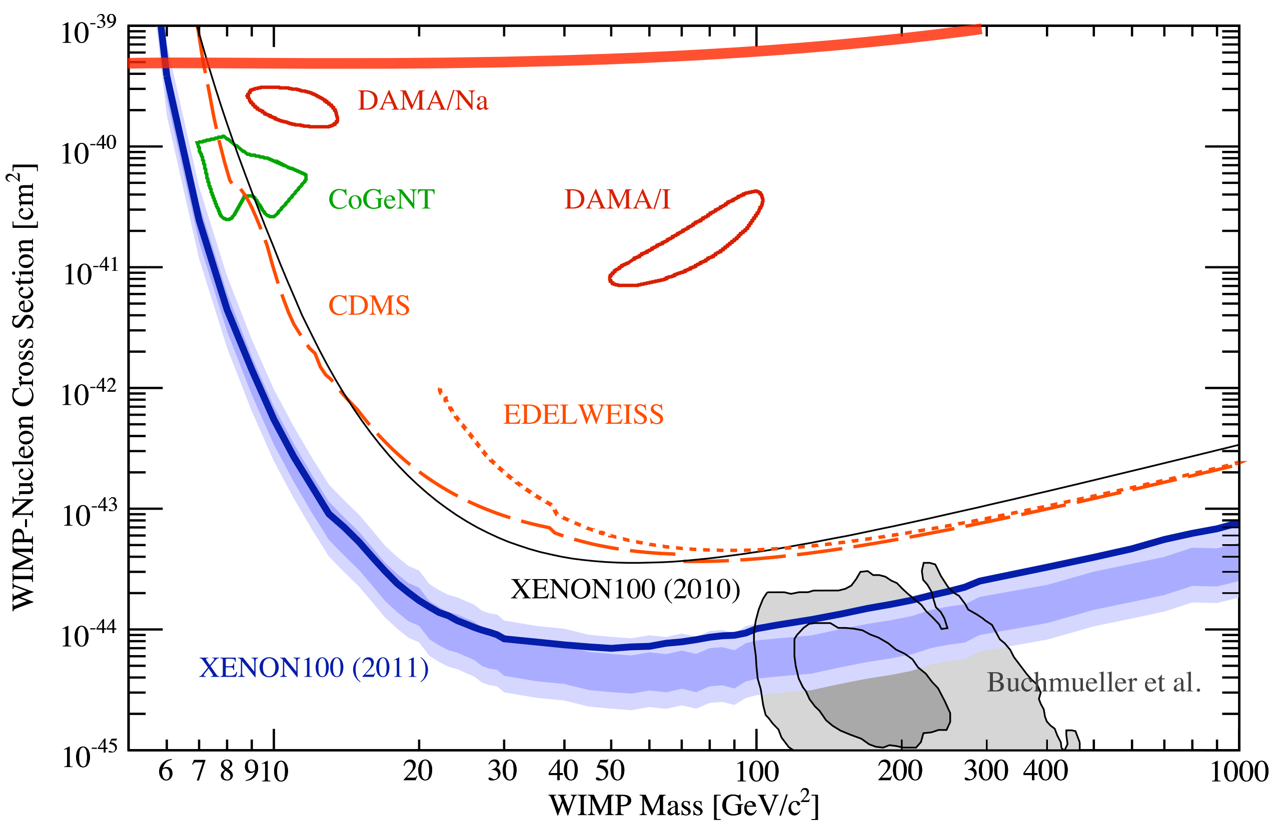
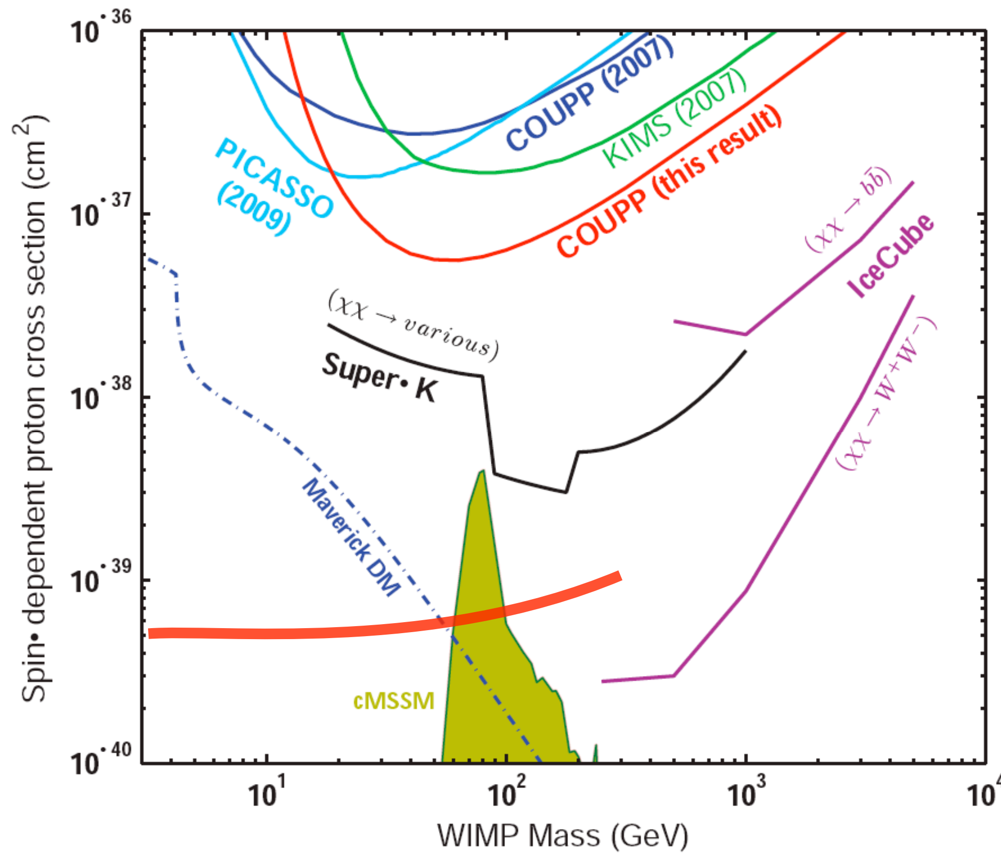
In 1 $fb^{-1}$ CDF saw 8449 mono-jet events, expected $8663 \pm 332$ $\Rightarrow \; \sigma_{1j} \lesssim 500\,\mathrm{fb}$

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

# The Limit

- Estimated limits from a back of the envelope recasting an old CDF study:



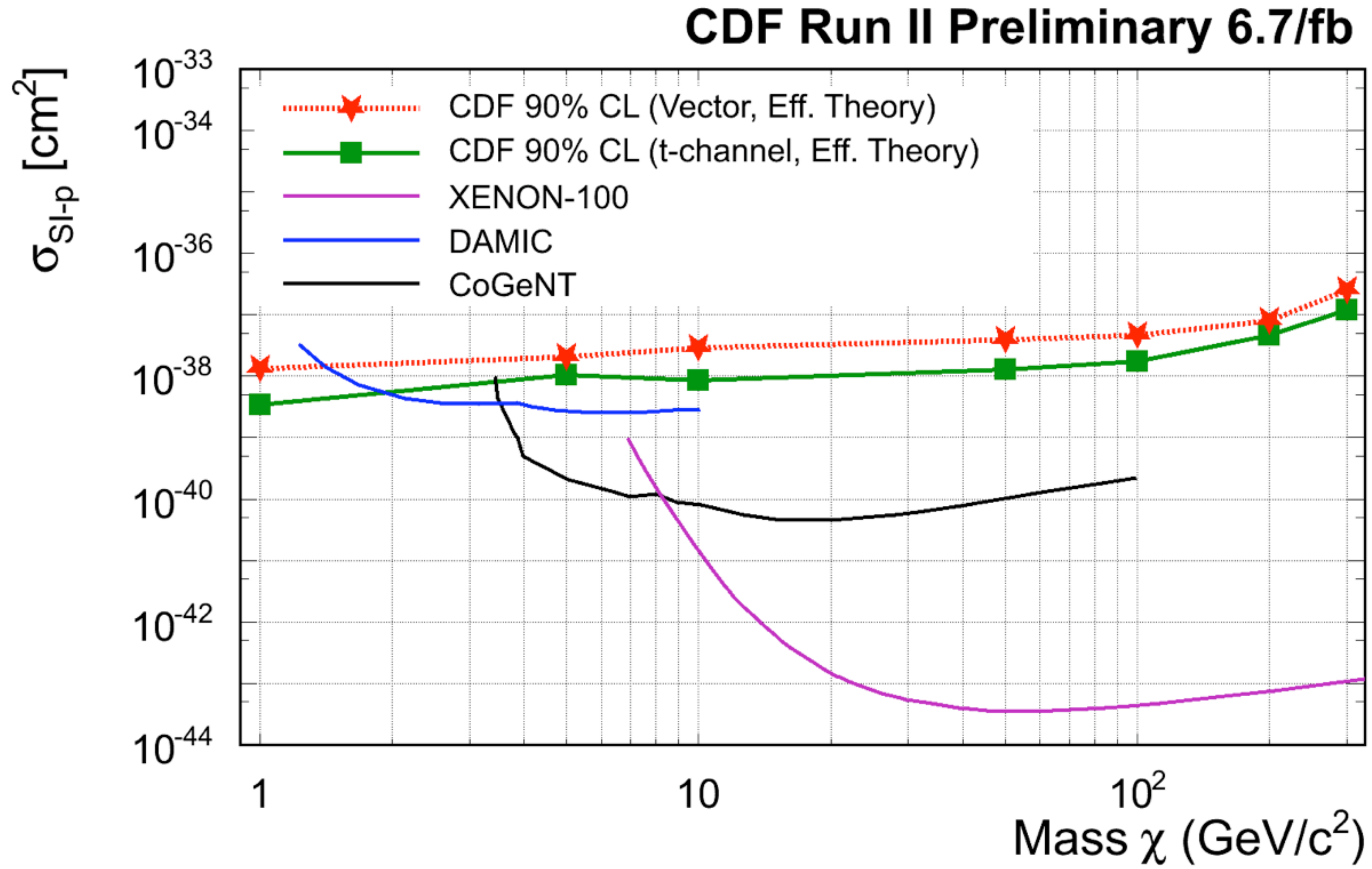



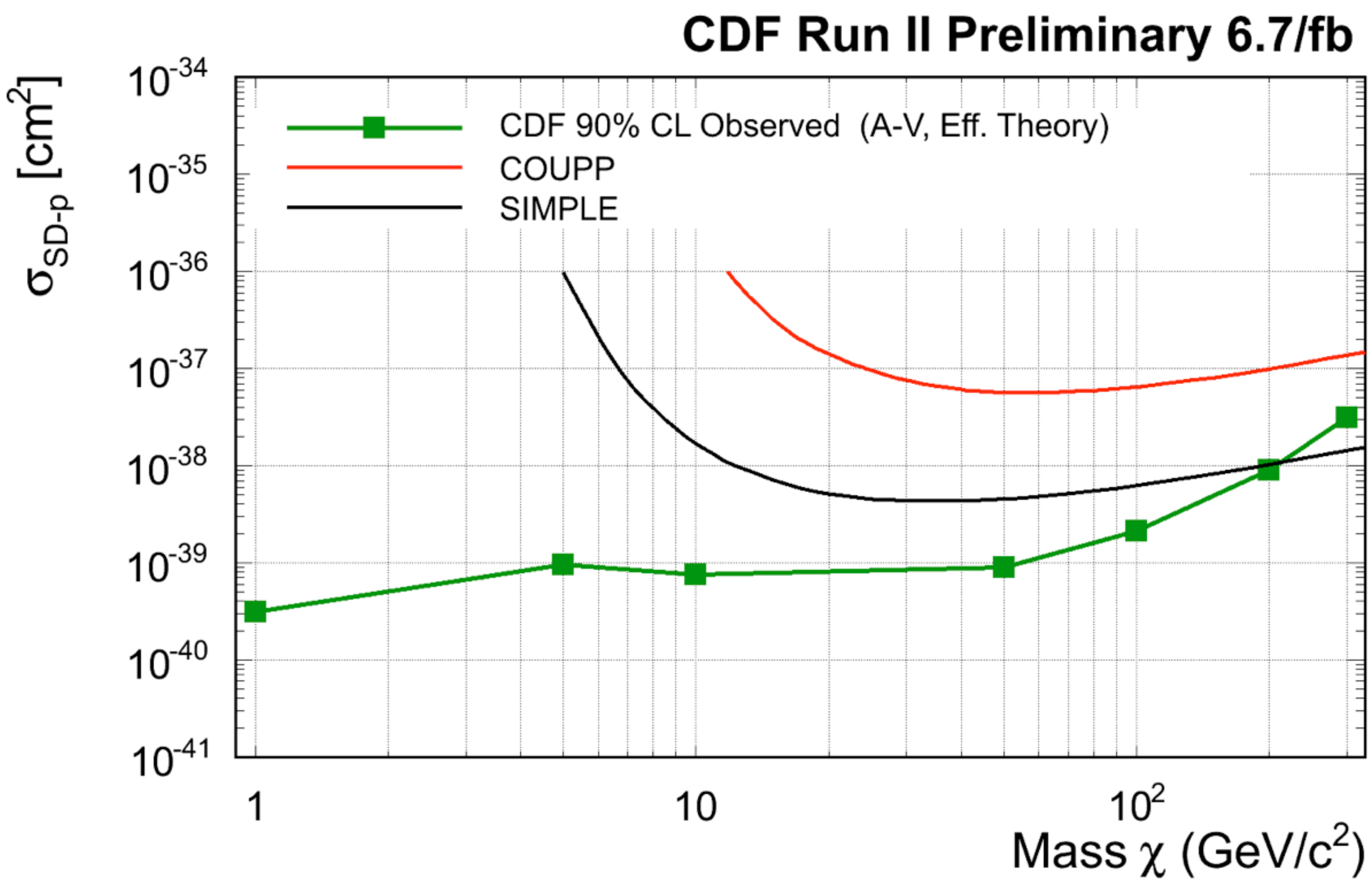

**Sets best limit below ~5GeV.**

**Best limit dependent DM detector.**

# CDF Limits:

- CDF did a dedicated shape analysis of monojet spectra.
-

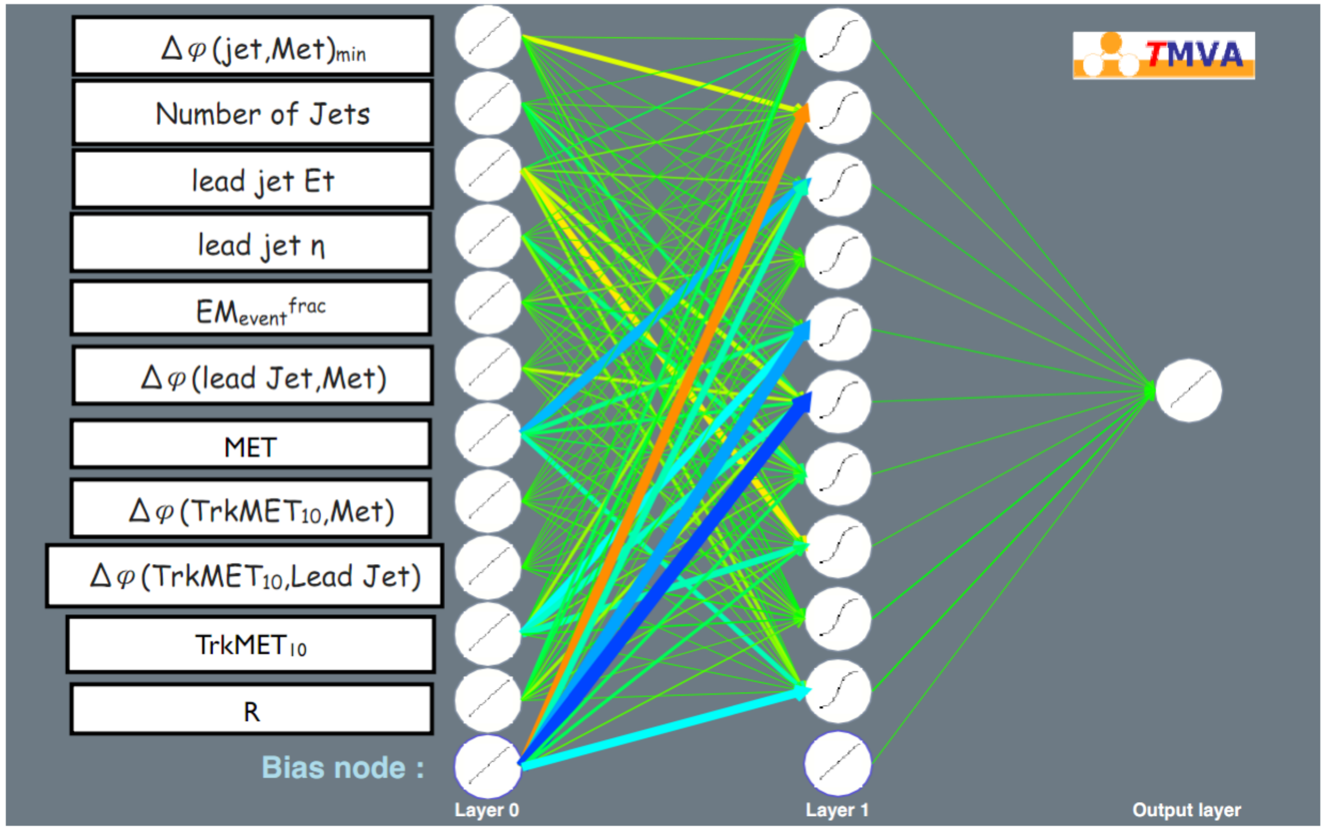


A Search For Dark Matter in the Monojet + Missing Transverse Energy Signature in $6.7\,\mathrm{fb}^{-1}$

S.Z. Shalhout[1], T. Schwarz[2], R. Erbacher[1], J. Conway[1], P. Fox[2], R. Harnik[2], Y. Bai[2]
**UC Davis**[1] **Fermilab**[2]

# A neural net with our name on it ?! :-0



# In the rest of the talk:

How is the translation from Colliders done?

What can LHC say? What did LEP say?

What assumptions are made?

# Operators

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

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}\,,$$

SI, vector exchange

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}\,,$$

SD, axial-vector exchange

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R)\,,$$

SI (or SD), t-channel

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}$$

SI gluon operator

# Which Cuts?

- ATLAS's 1fb analysis employs 3 sets of cuts

`LowPT` Selection requires $\not{E}_T > 120$ GeV, one jet with $p_T(j_1) > 120$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if they contain a second jet with $p_T(j_2) > 30$ GeV and $|\eta(j_2)| < 4.5$.

`HighPT` Selection requires $\not{E}_T > 220$ GeV, one jet with $p_T(j_1) > 250$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not{E}_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

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|---|---|---|---|
| Expected | $15100 \pm 700$ | $1010 \pm 75$ | $193 \pm 25$ |
| Observed | 15740 | 965 | 167 |

Which has most sensitivity?

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| Observed | 15740 | 965 | 167 |

Which has most sensitivity?

# Which Cuts?

* ATLAS's 1fb analysis employs 3 sets of cuts

`LowPT` Selection requires $\not{E}_T > 120$ GeV, one jet with $p_T(j_1) > 120$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if they contain a second jet with $p_T(j_2) > 30$ GeV and $|\eta(j_2)| < 4.5$.

`HighPT` Selection requires $\not{E}_T > 220$ GeV, one jet with $p_T(j_1) > 250$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not{E}_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

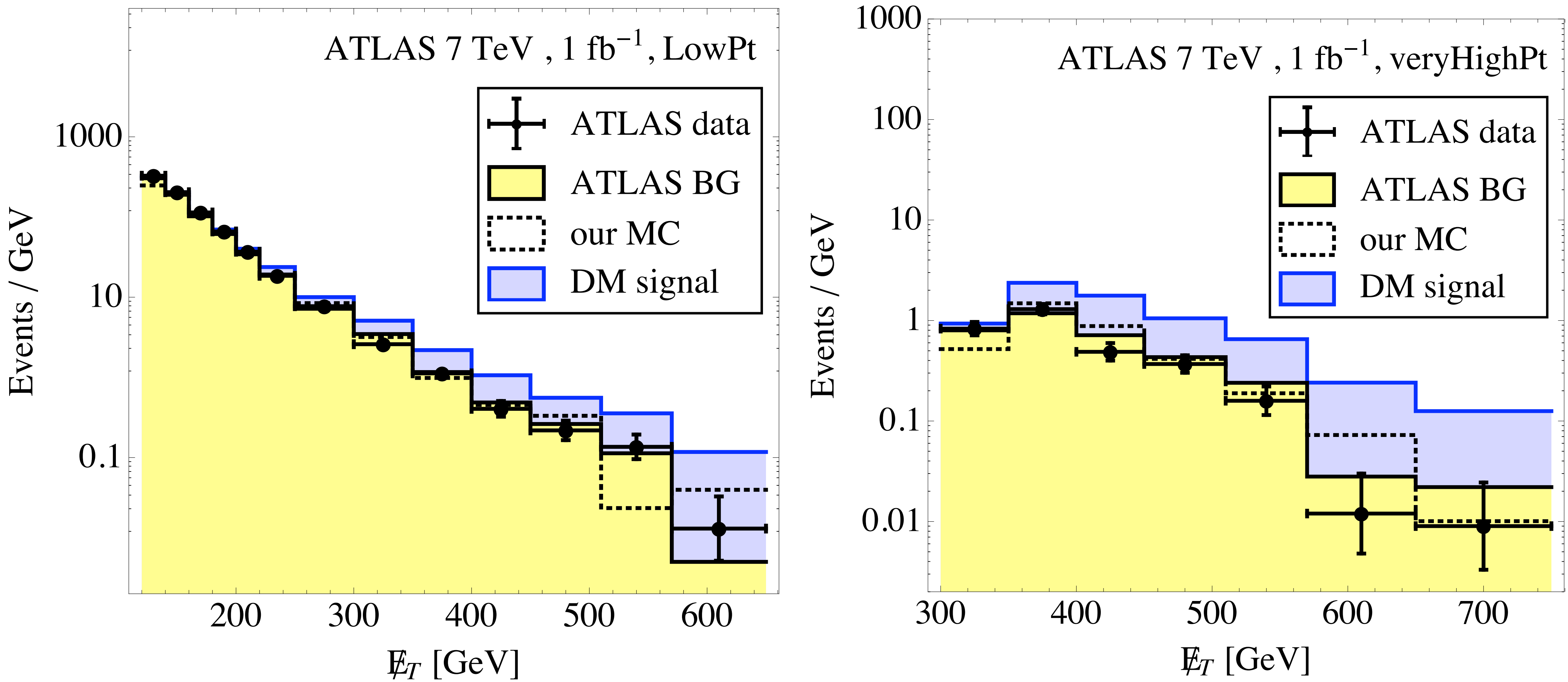
`veryHighPT` Selection requires $\not{E}_T > 300$ GeV, one jet with $p_T(j_1) > 350$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not{E}_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must have $p_T(j_3) < 30$ GeV.

| | ATLAS `LowPT` $1.0\ \text{fb}^{-1}$ | ATLAS `HighPT` $1.0\ \text{fb}^{-1}$ | ATLAS `veryHighPT` $1.0\ \text{fb}^{-1}$ |
|---|---|---|---|
| Expected | $15100 \pm 700$ | $1010 \pm 75$ | $193 \pm 25$ |
| Observed | 15740 | 965 | 167 |

Which has most sensitivity?

# Spectrum

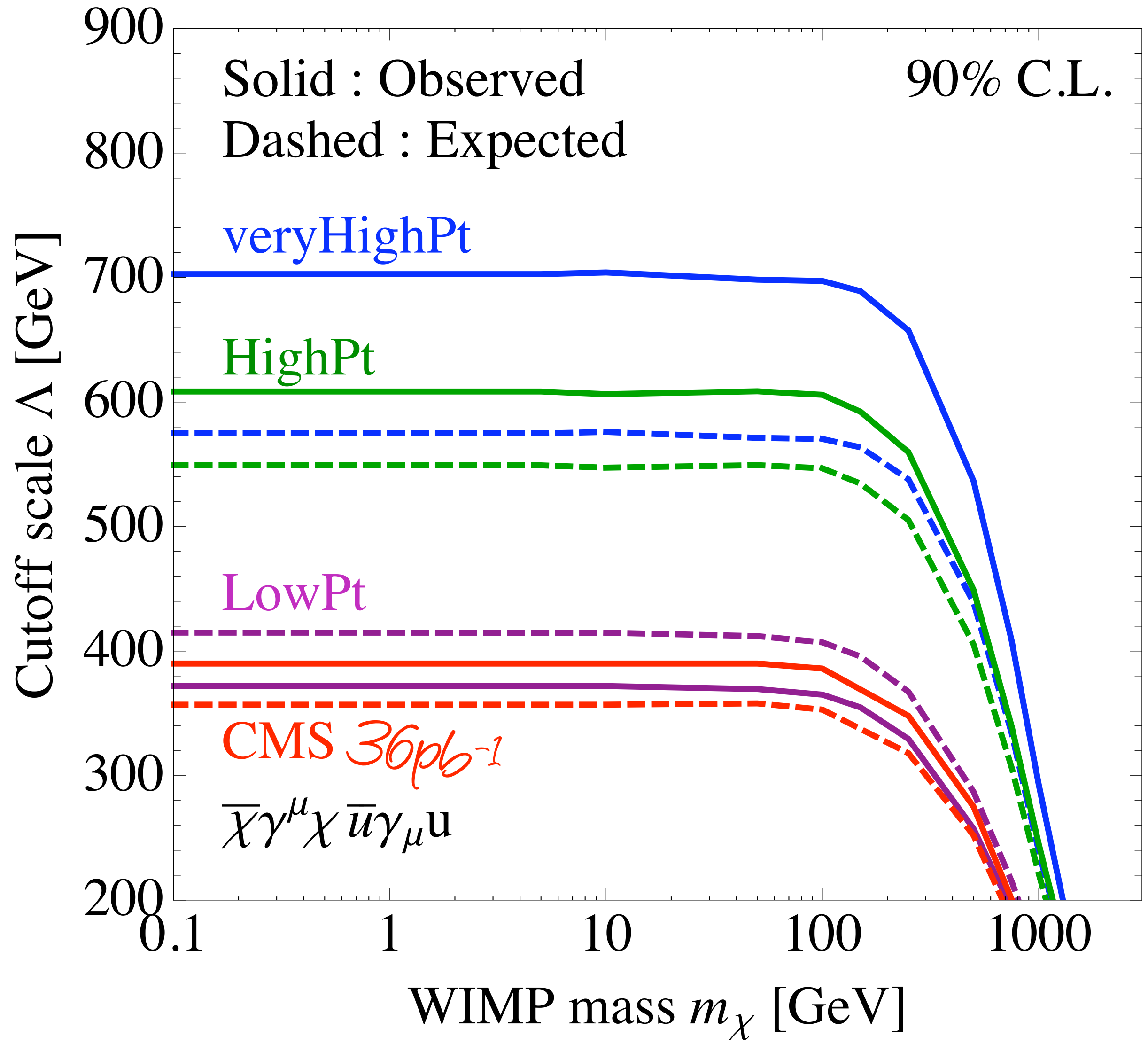
* consider a vector operator with only u-quarks:




Hard cuts are better.

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

- Set 90% CL limits: $\chi^2 \equiv \dfrac{[\Delta_N - N_{\rm DM}(m_\chi,\Lambda)]^2}{N_{\rm DM}(m_\chi,\Lambda) + N_{\rm SM} + \sigma_{\rm SM}^2} = 2.71\,.$




$$\Delta_N = \begin{cases} 0 & \text{expected bound} \\ N_{\rm obs} - N_{\rm SM} & \text{observed bound} \end{cases}$$

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

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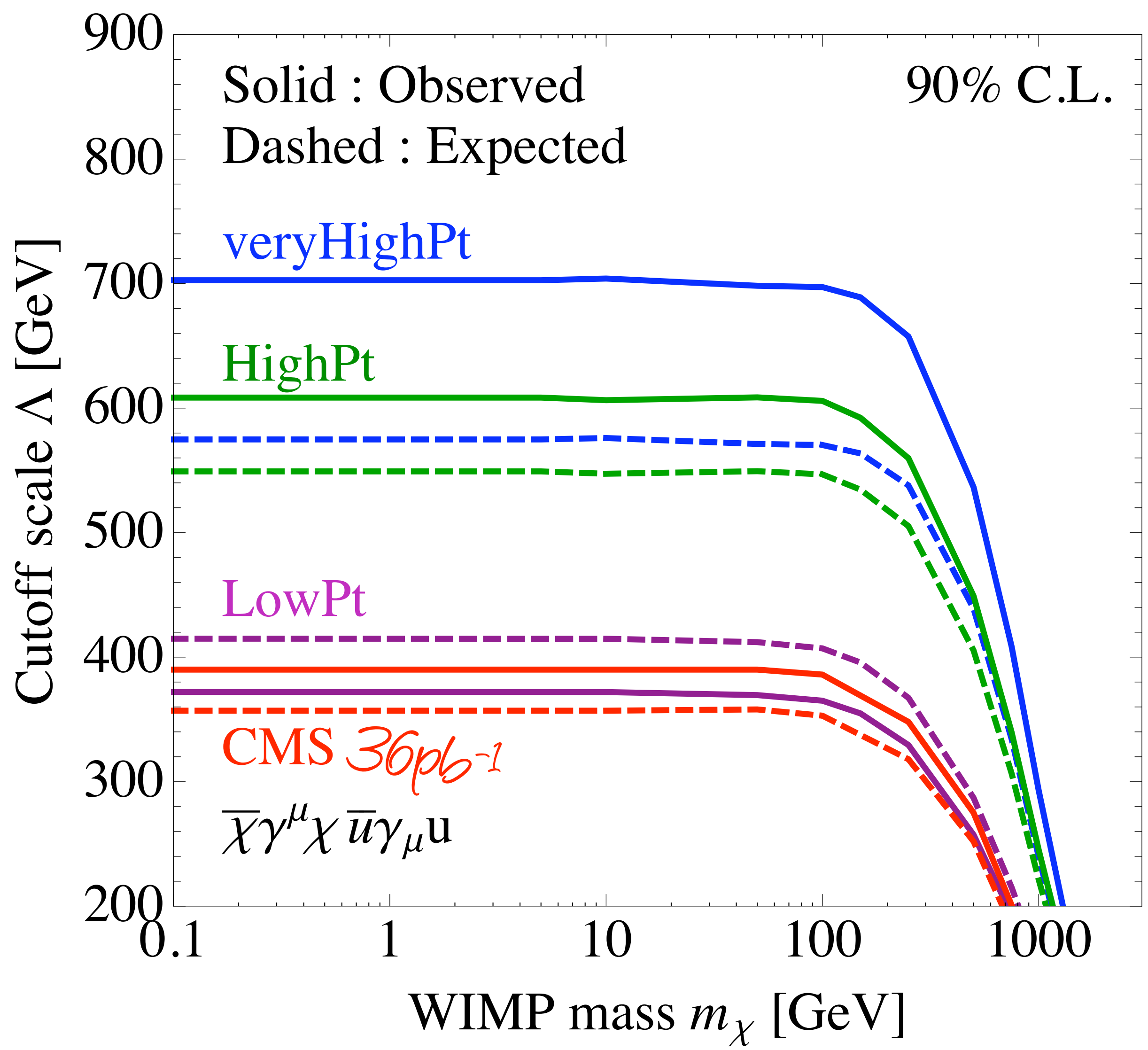



$$\Delta_N = \begin{cases} 0 & \text{expected bound} \\ N_{\rm obs} - N_{\rm SM} & \text{observed bound} \end{cases}$$

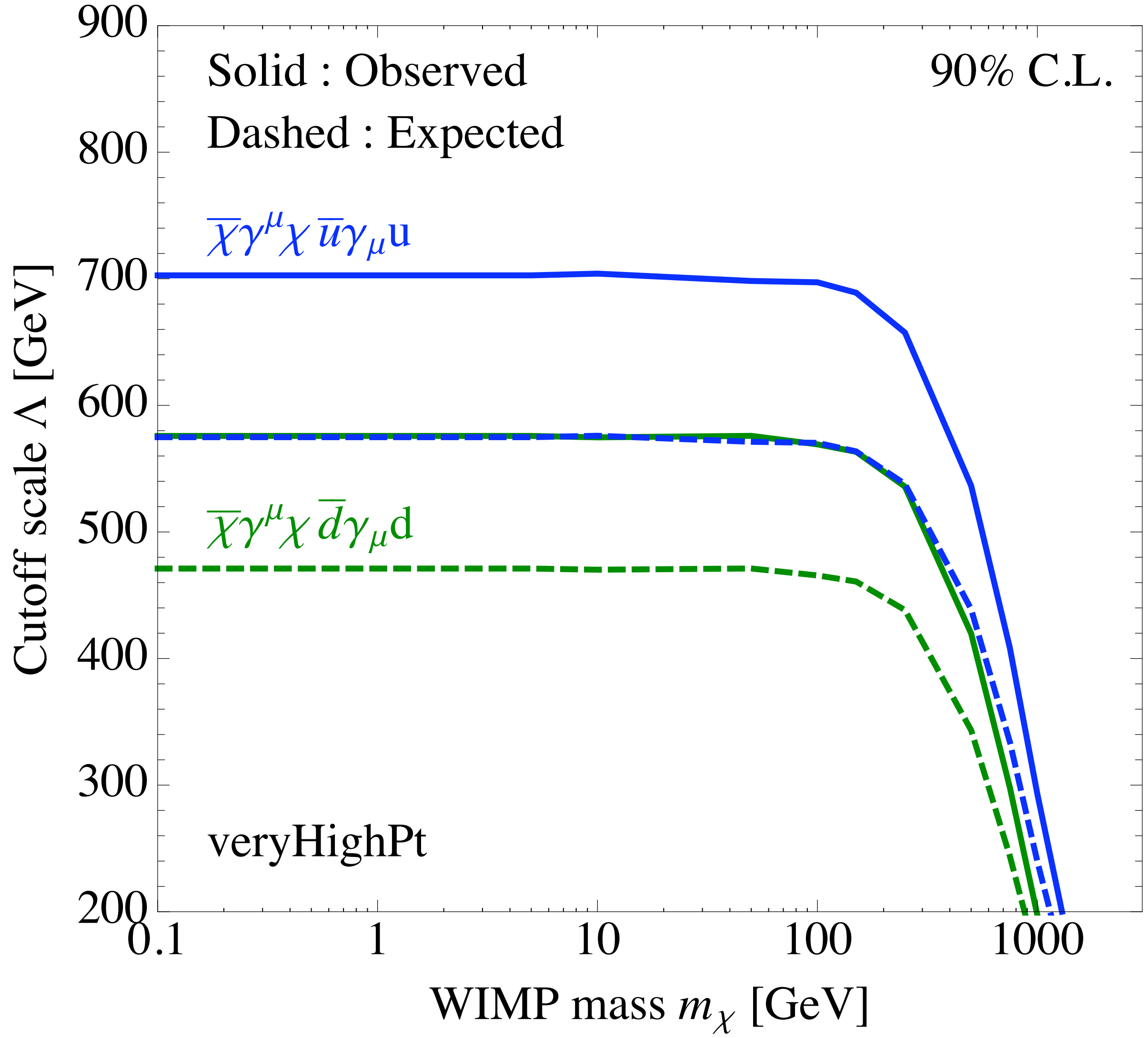
Harder is better.

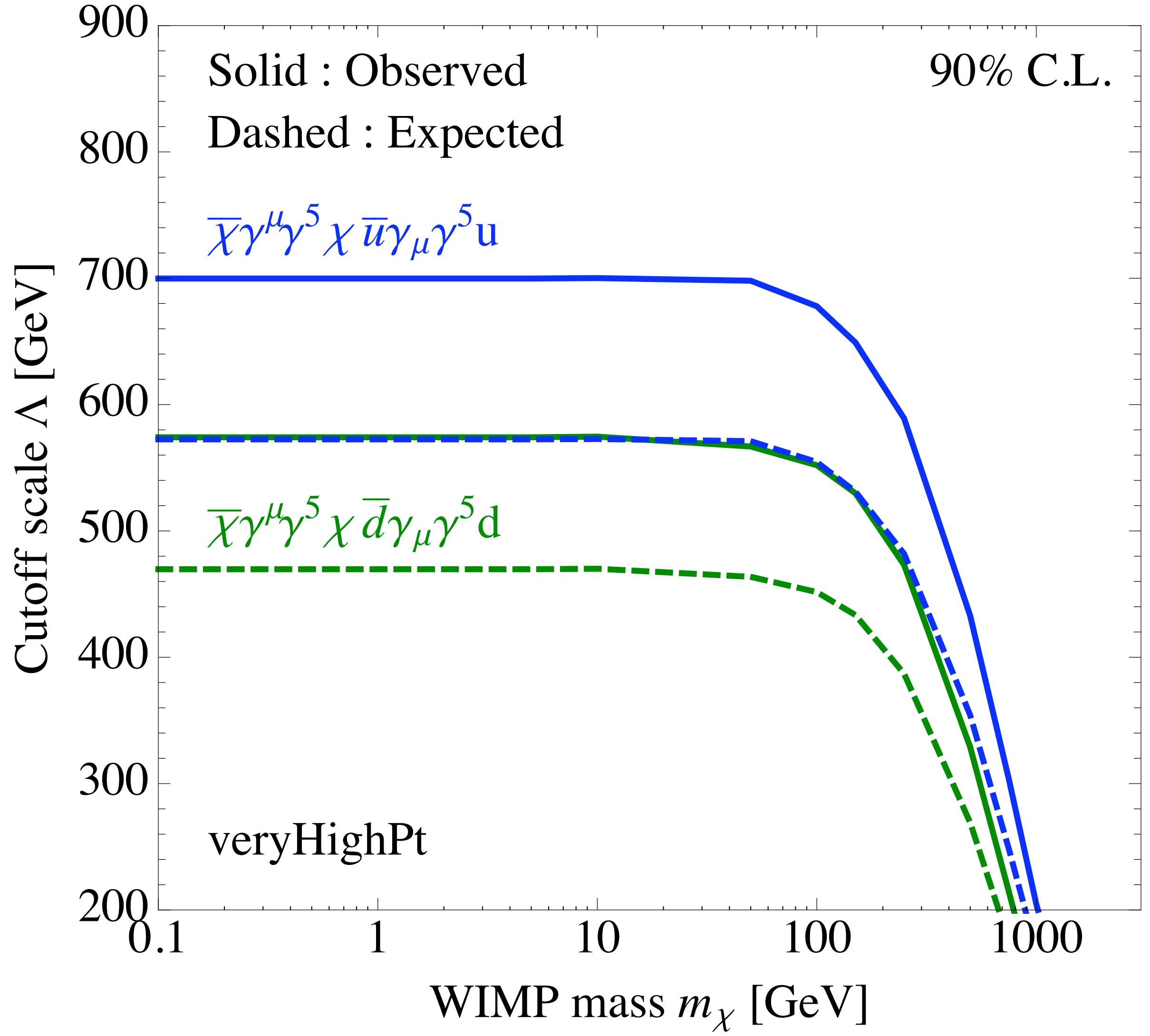
in the future:

populate the tail

and keep cutting harder

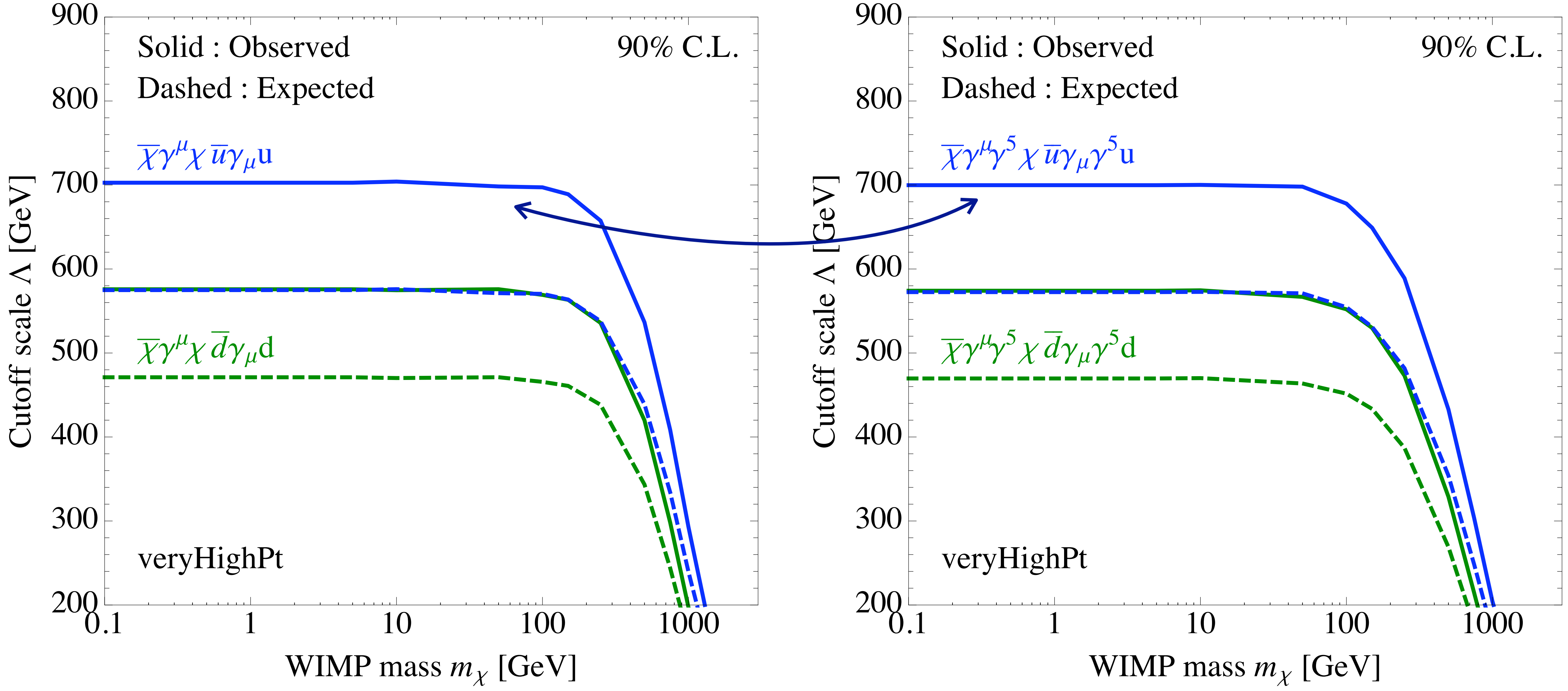
# Other Operators:



# Other Operators:

same limit for
SI and SD



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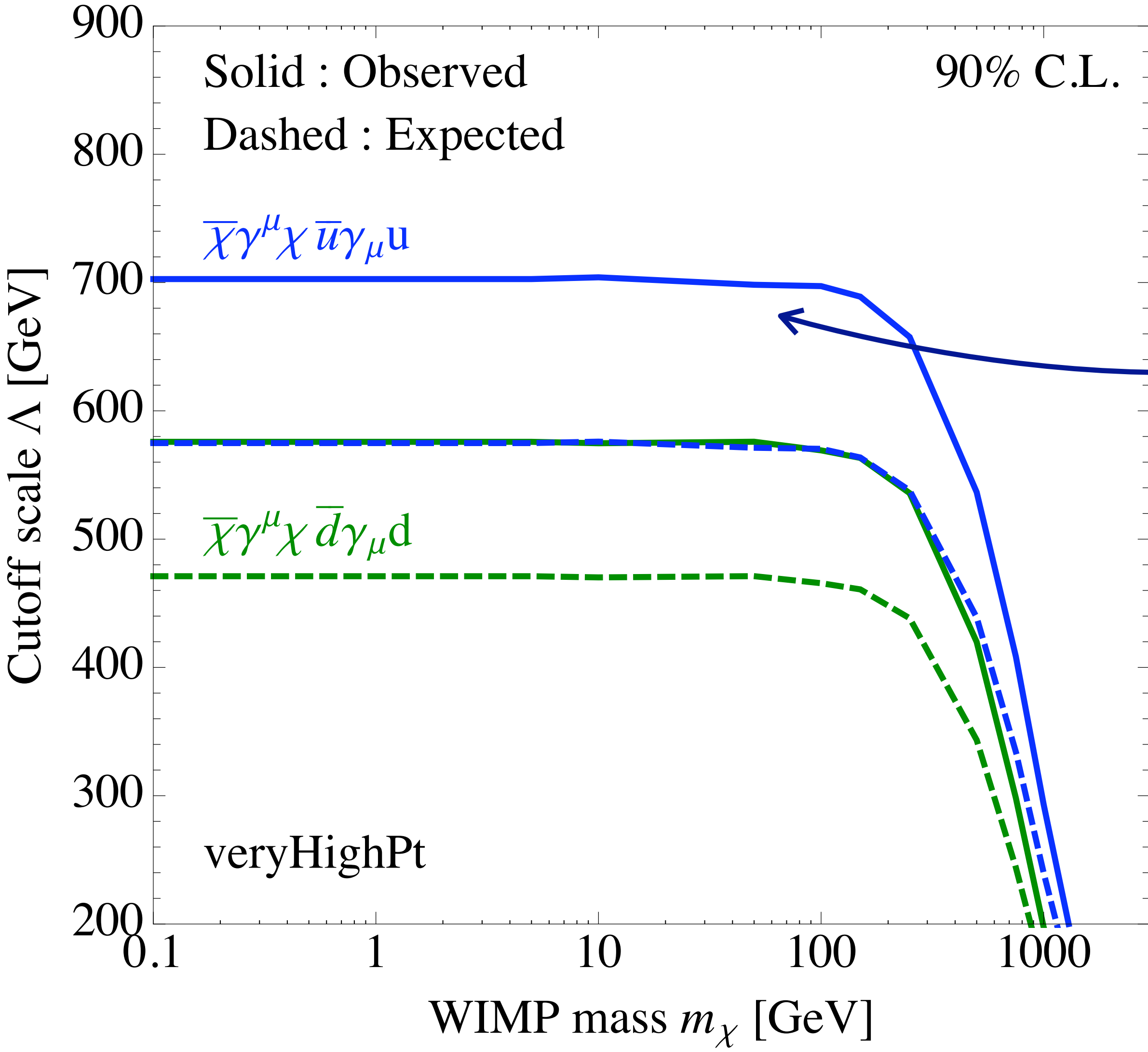
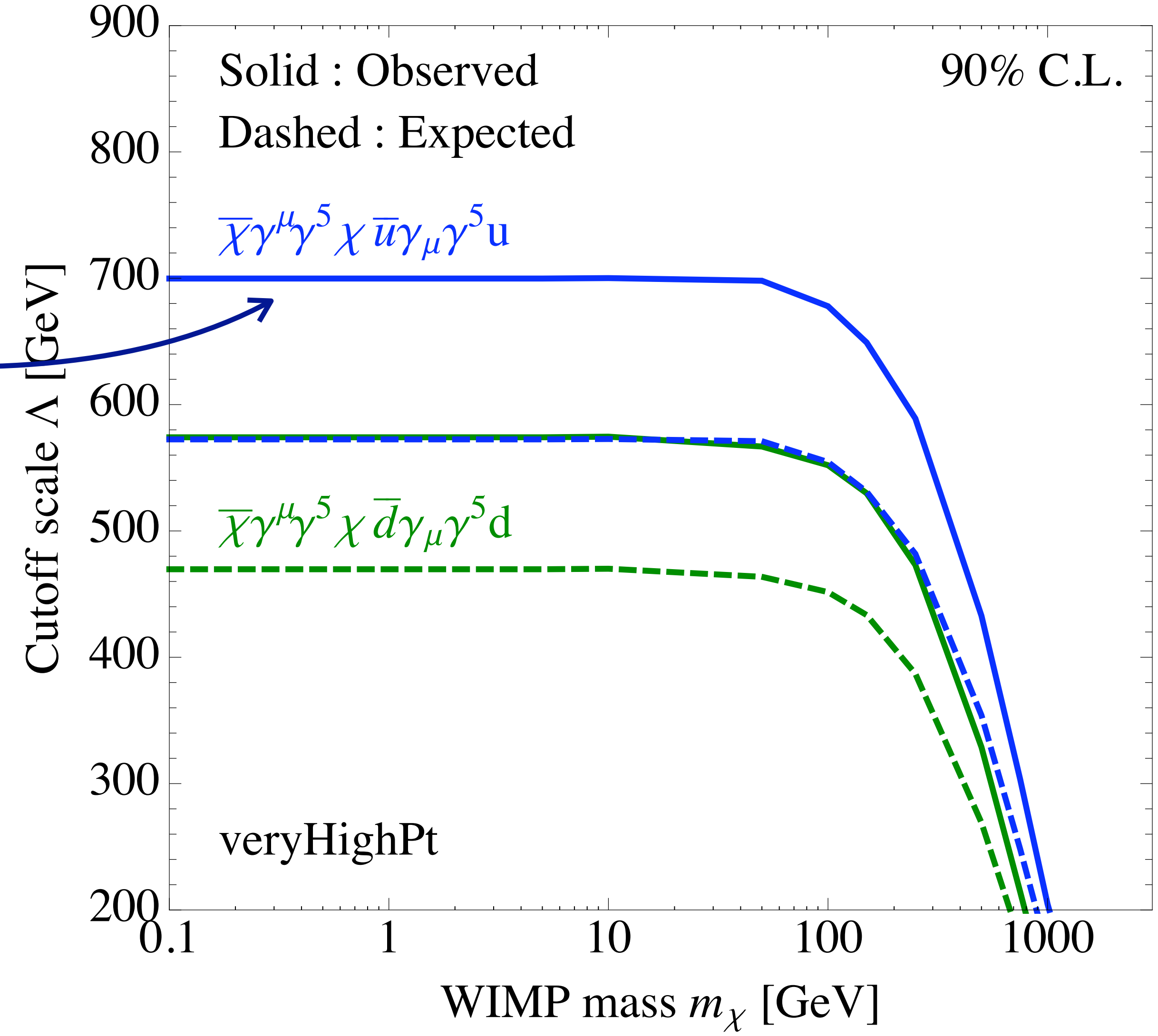
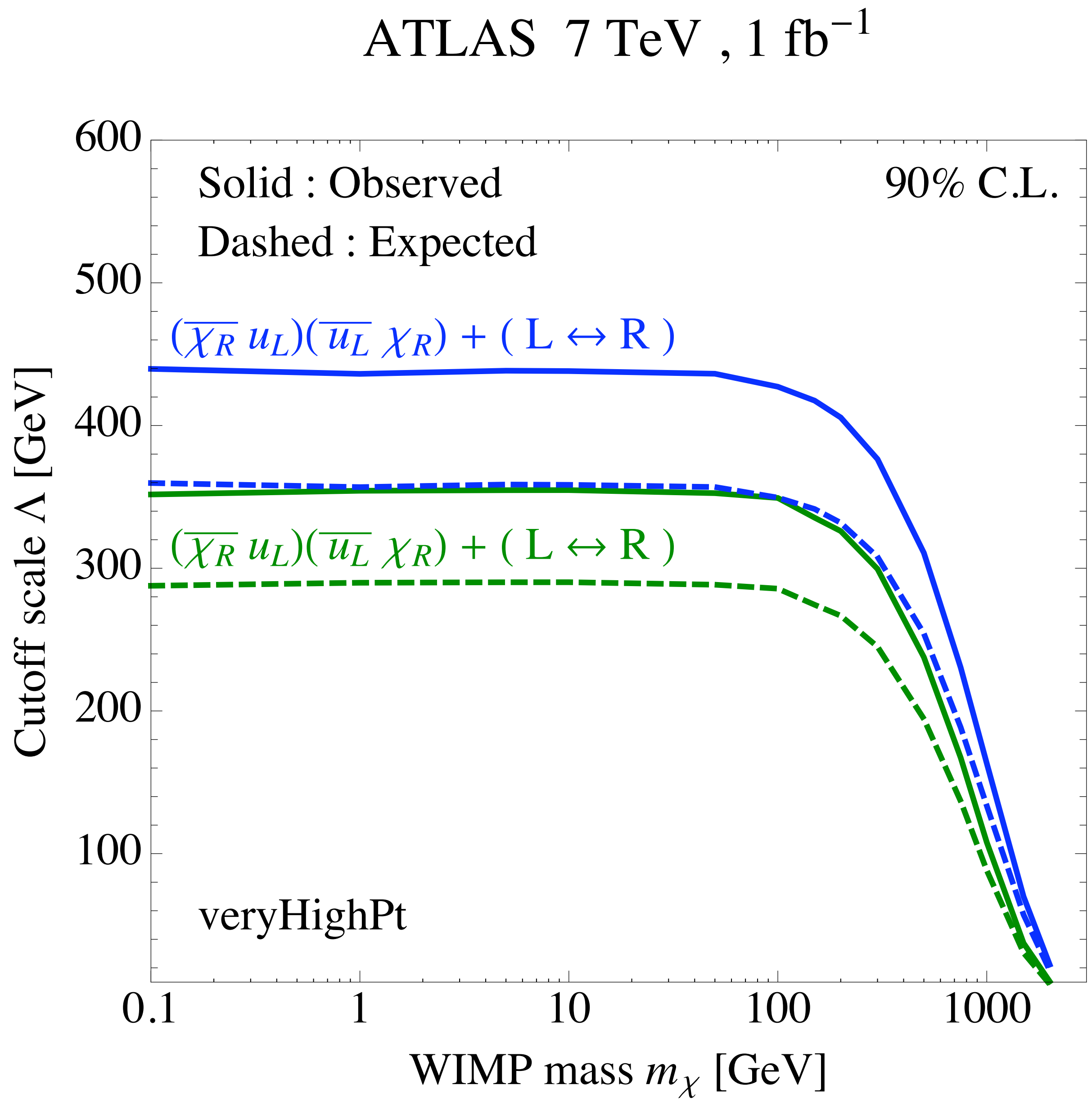
same limit for SI and SD

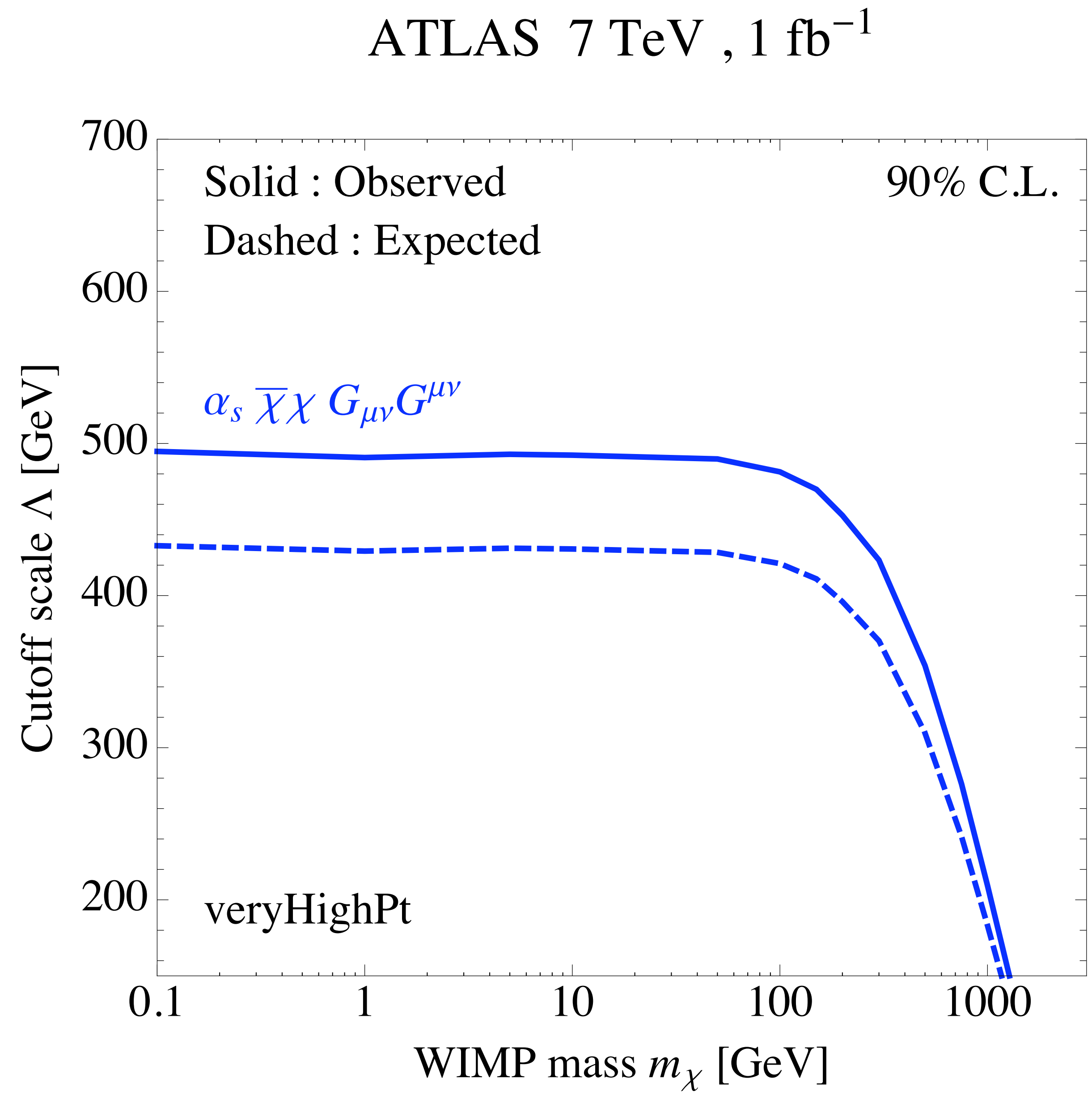



The limit is flat up to ~200 GeV.
Goes all the way to zero.

# Other Operators:




The limit is flat up to ~200 GeV.
Goes all the way to zero.

# 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.
- For DD limits:

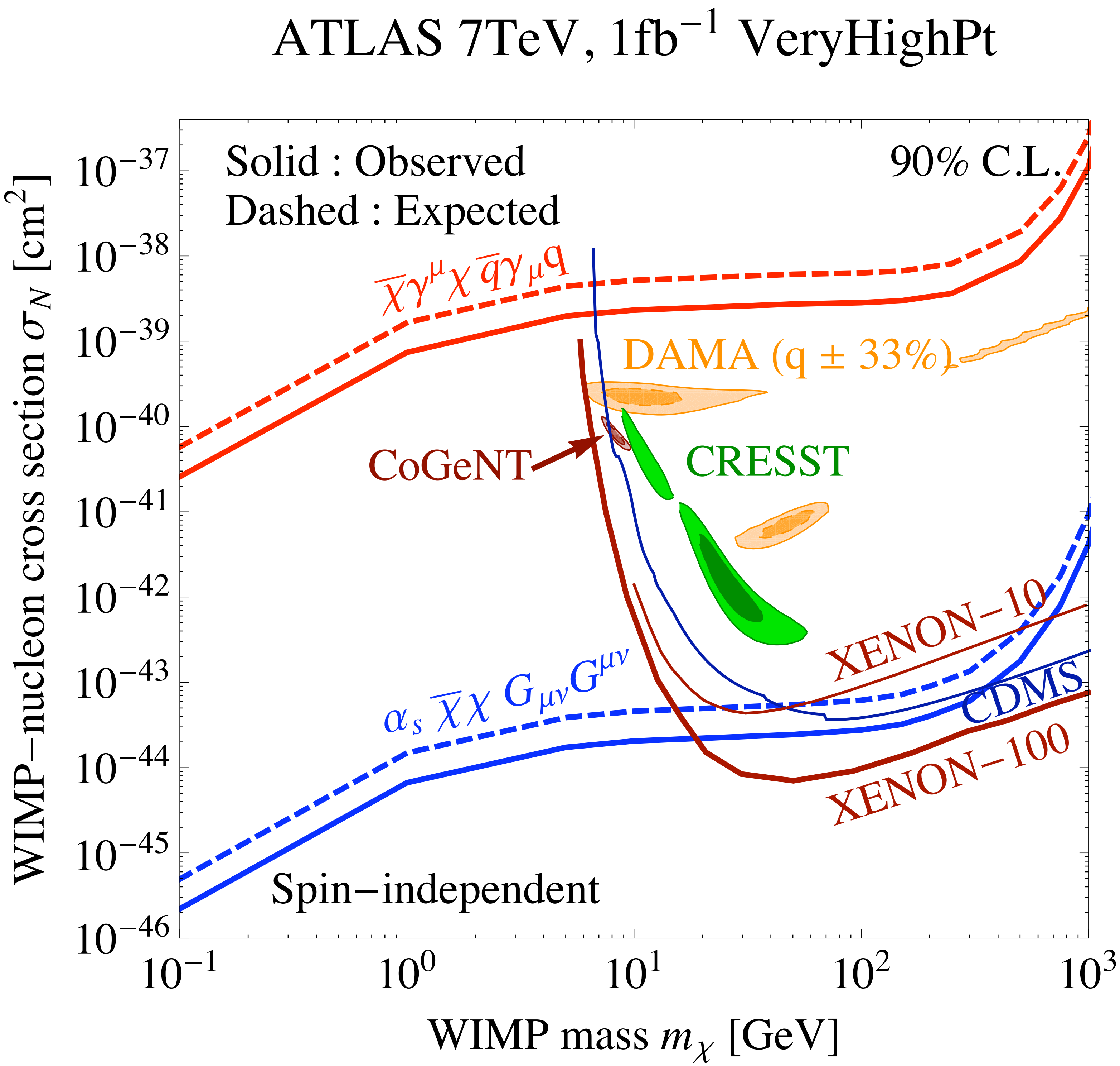
$$\mathcal{O}_2 \;=\; \frac{i\, g_\chi\, g_q}{q^2 - M^2}\,(\bar{q}\gamma_\mu q)\,(\bar{\chi}\gamma^\mu \chi) \quad \Longrightarrow \quad \sigma_2^{Nq} \;=\; \frac{\mu^2}{\pi\Lambda^4}\, f_{Nq}^2\,,$$

with $\begin{array}{c} f_u^p = f_d^n = 2 \\ f_d^p = f_u^n = 1 \end{array}$ . Same can be done for all operators.

# SI Limit

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 \,,$$

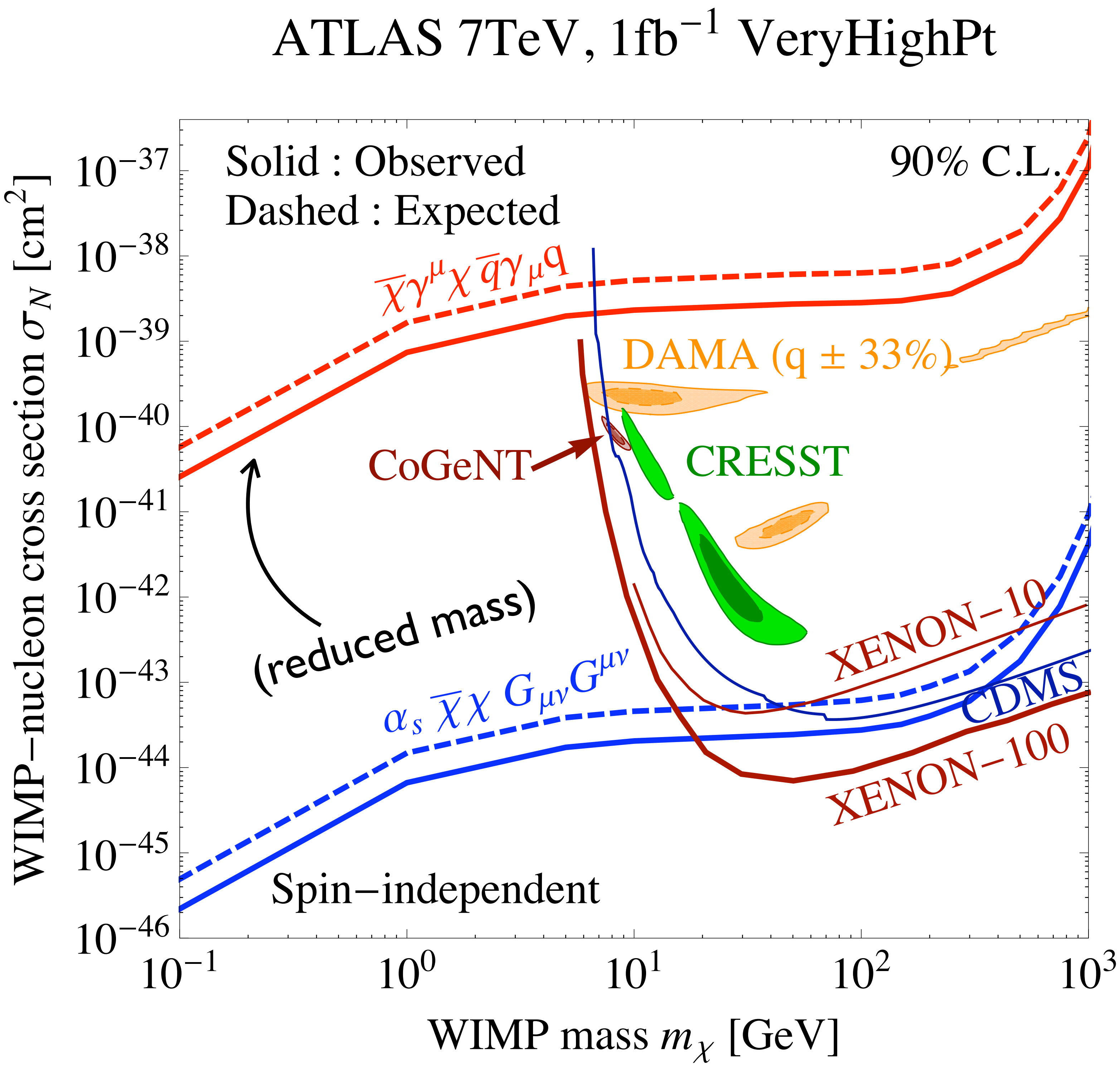
$$\sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2 \,,$$




**Best limit at low mass**

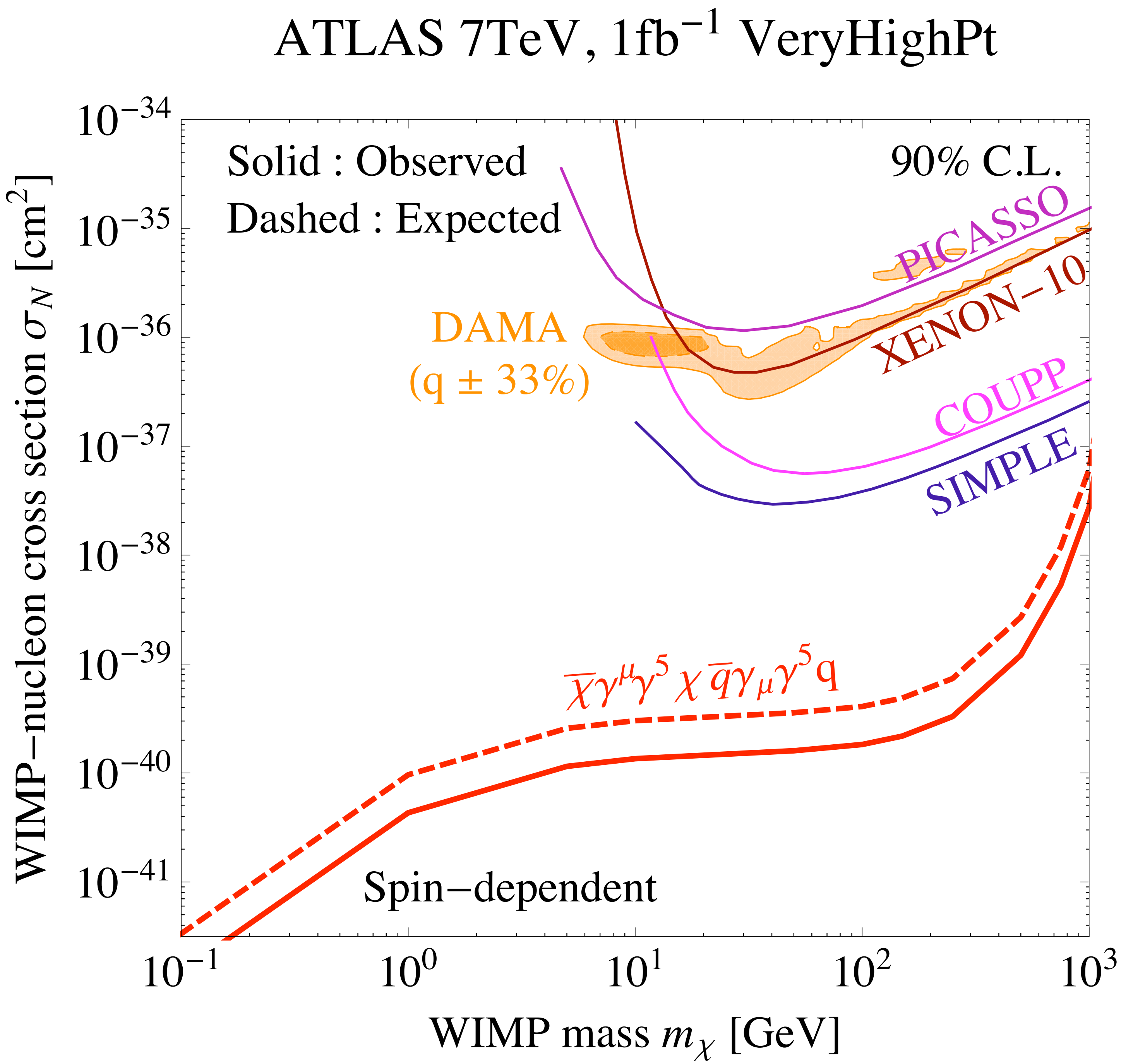
# SI Limit

$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 ,$$
$$\sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2 ,$$




**Best limit at low mass**

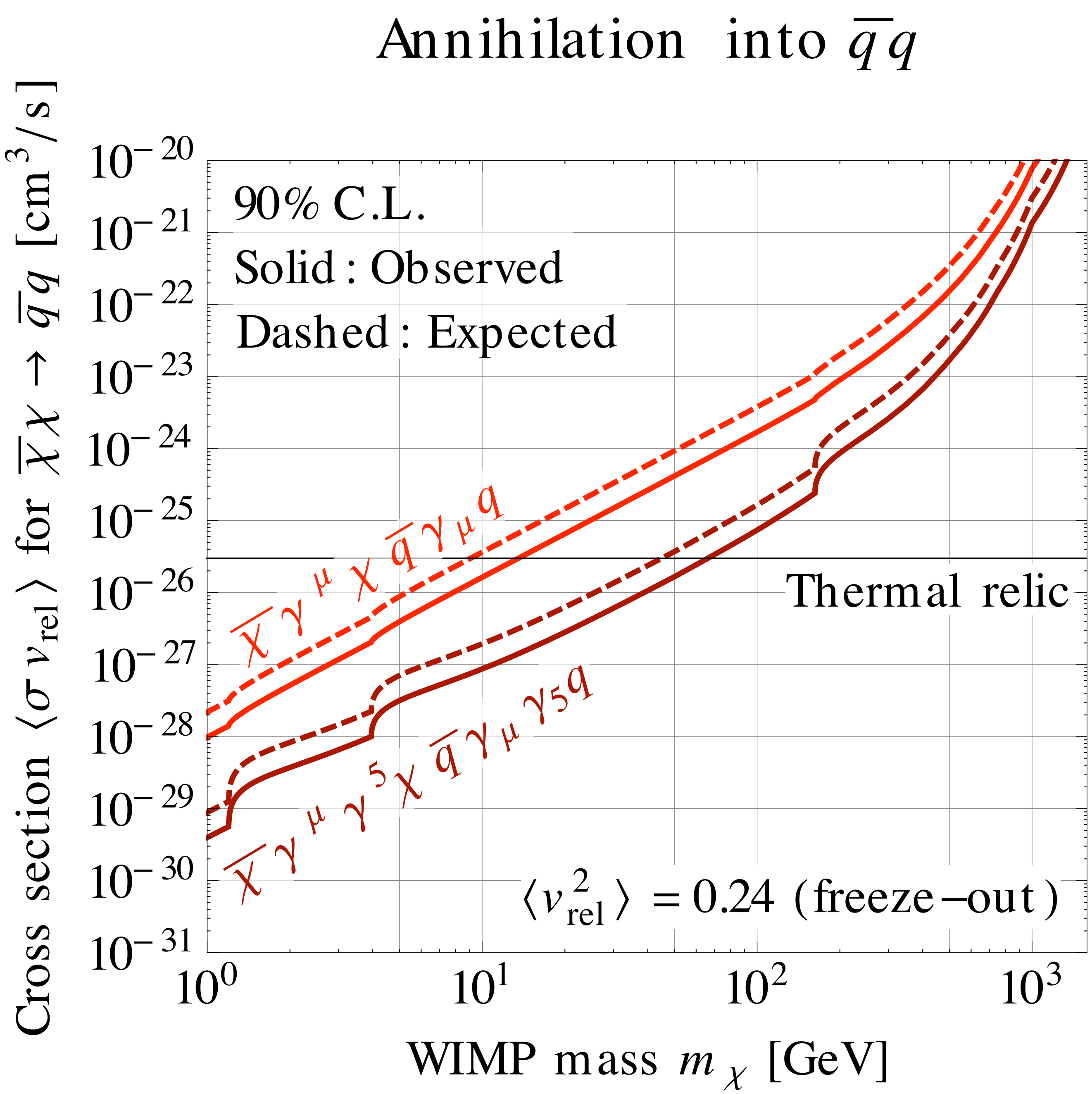
# SD Limit




**Best spin dependent limit.**

# Annihilation

* A minimal light thermal relic is ruled out:



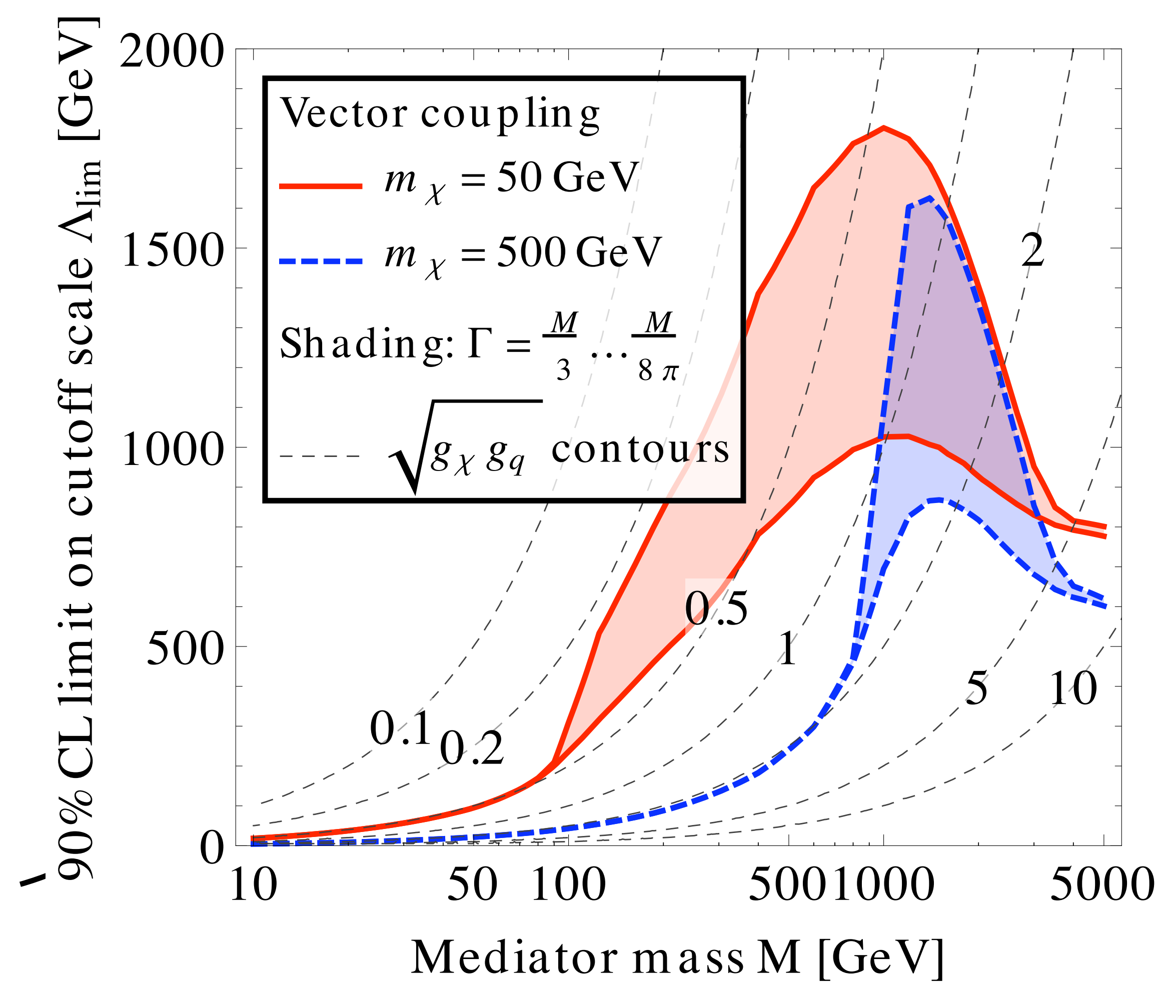
# CDF Analysis

# 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

- For intermediate masses the limits is **enhanced** b/c of on-shell production, (depends on the width).



# 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)

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

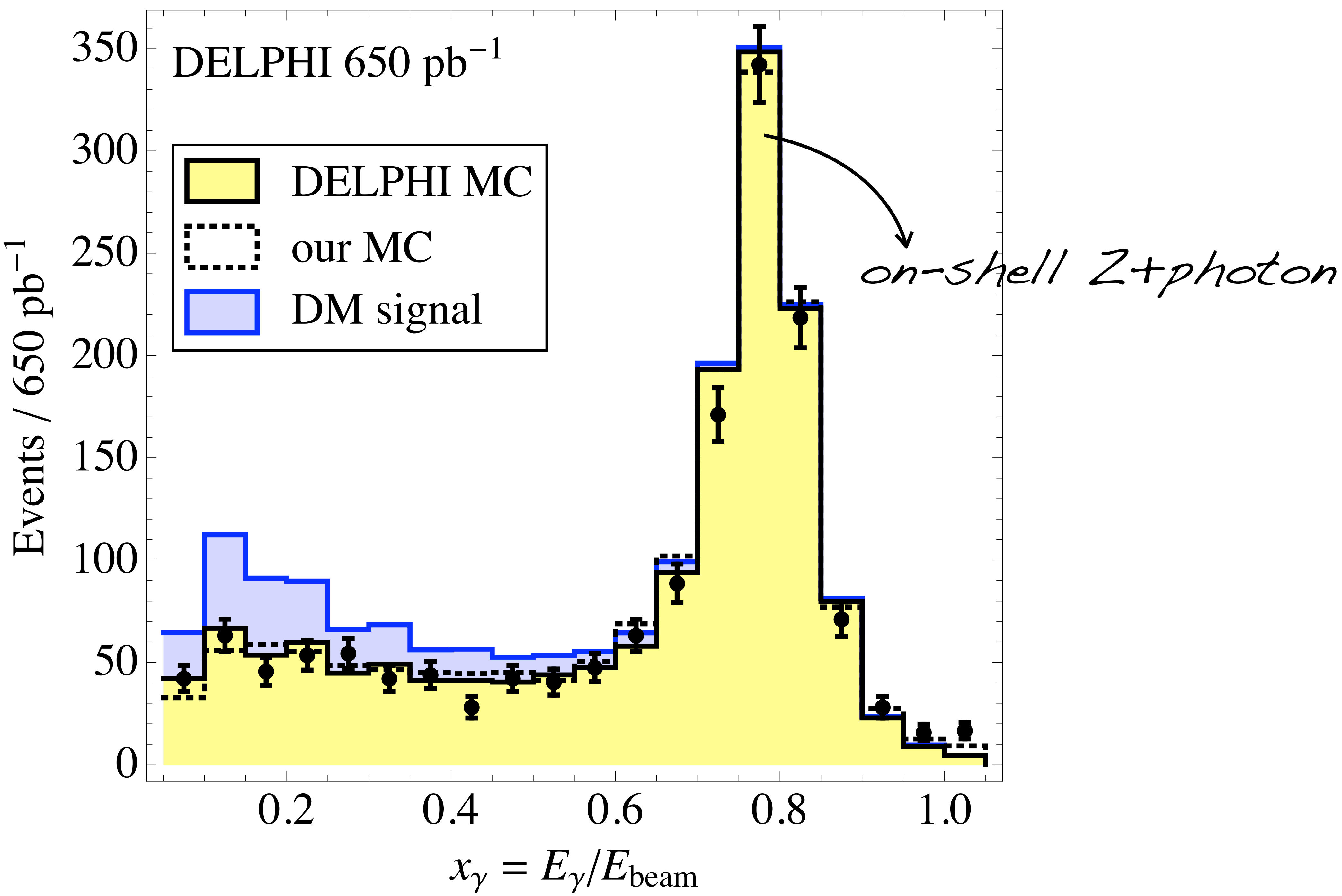
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)}$$

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

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

# Mono-photon

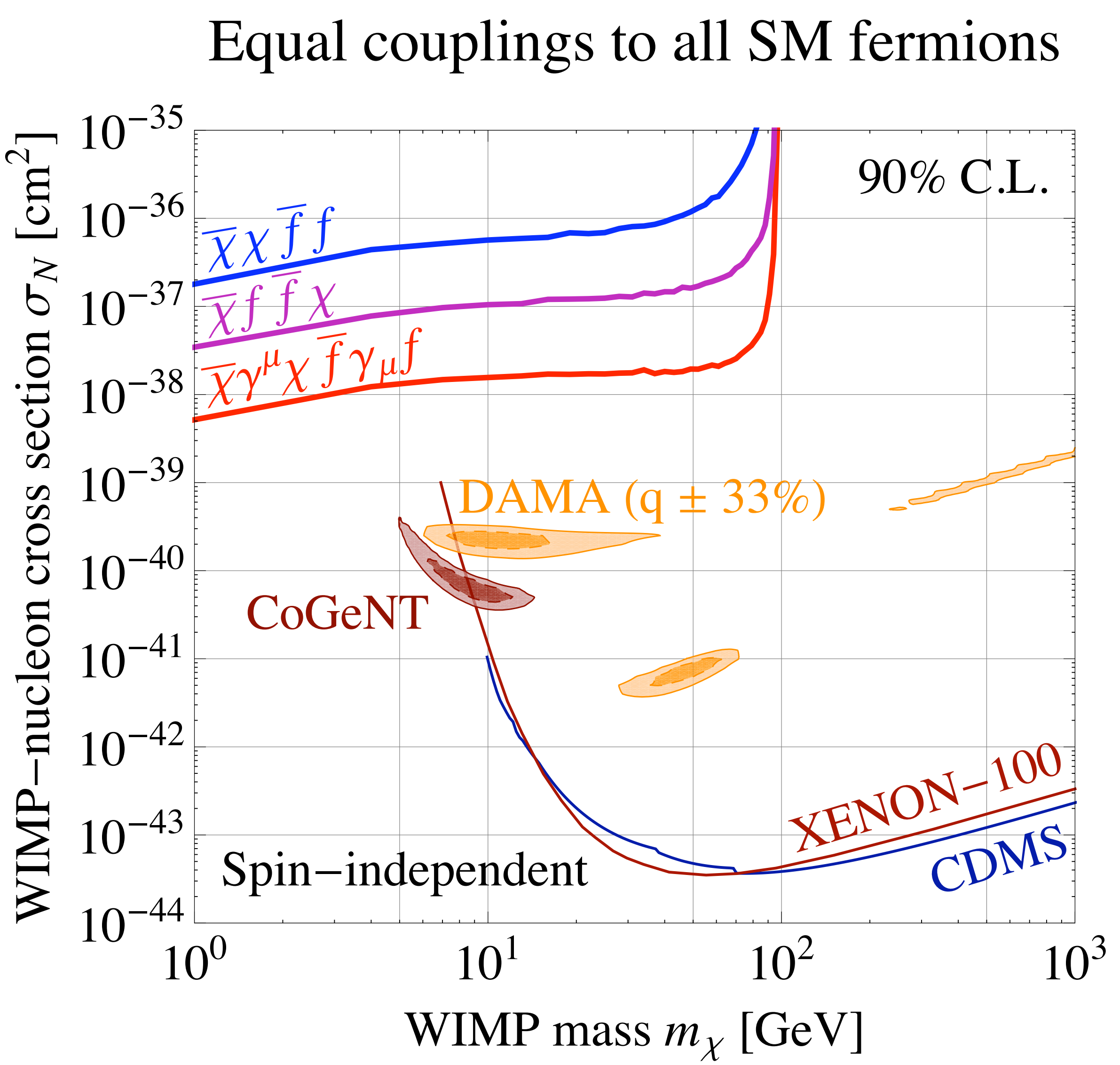
- Use spectrum shape to reject background peak.



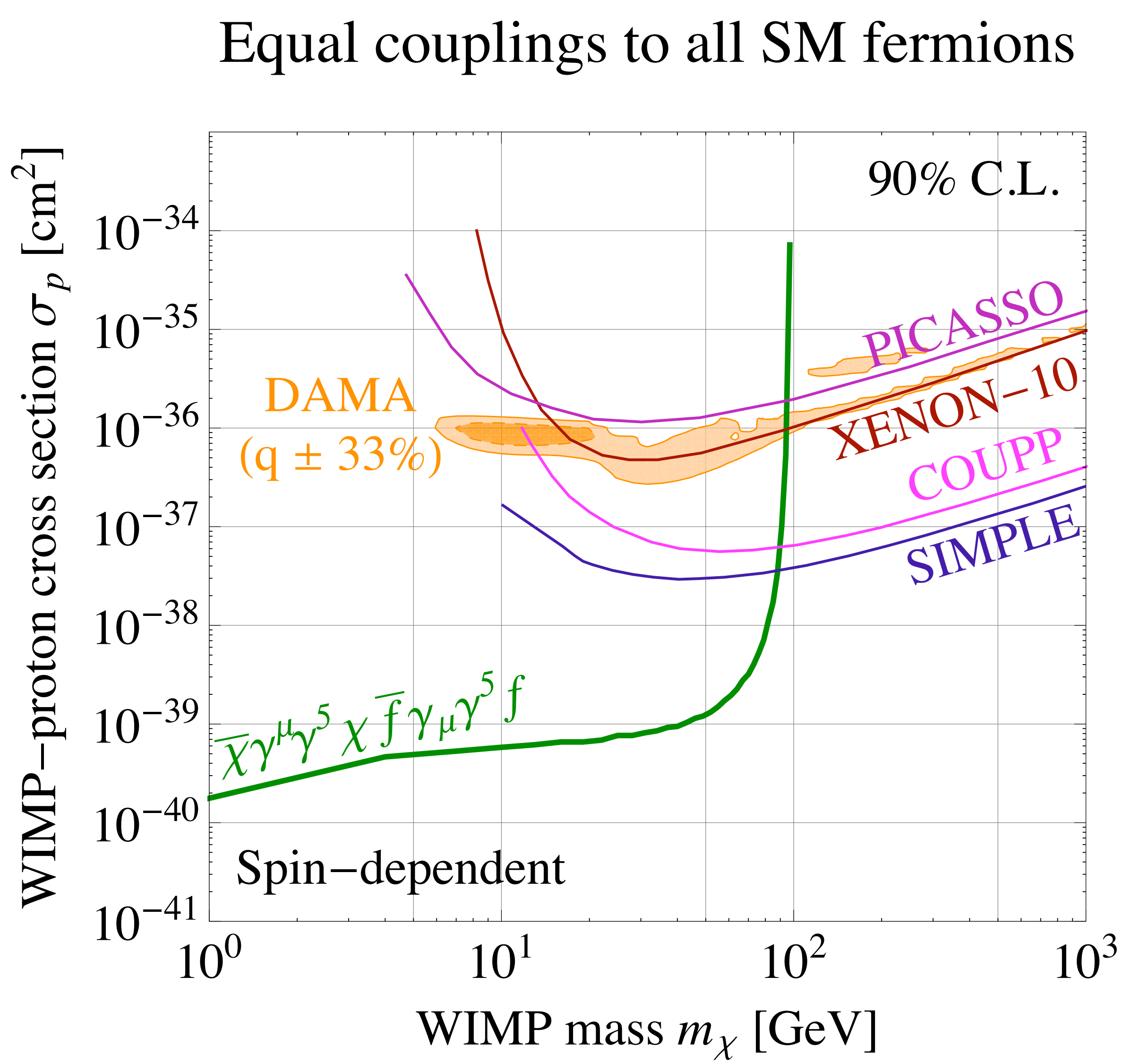
# Model Dependence

* 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

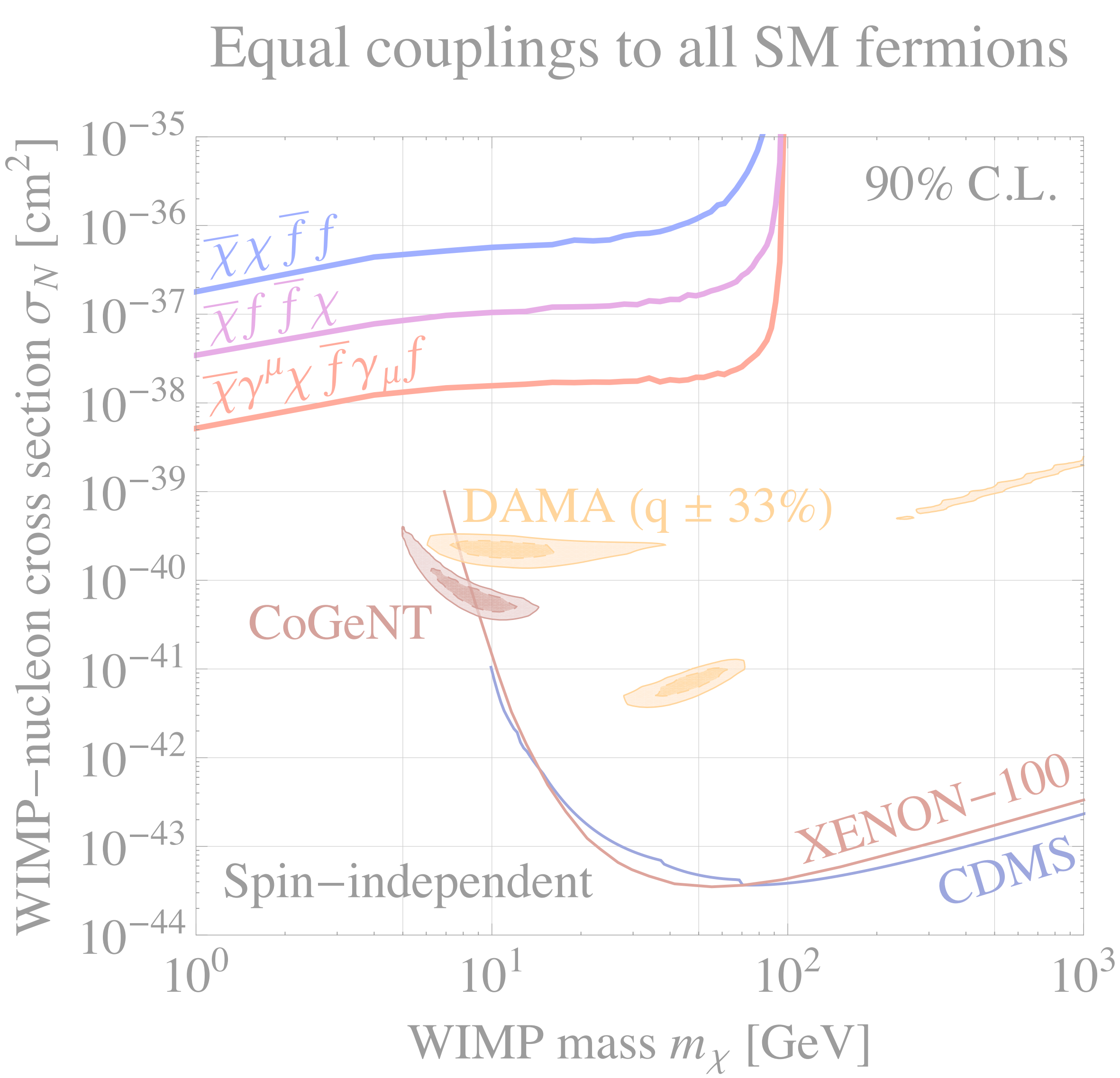


Equal couplings to all SM fermions
90% C.L.
$\bar{\chi}\chi\bar{f}f$
$\bar{\chi}f\bar{f}\chi$
$\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f$
DAMA (q ± 33%)
CoGeNT
XENON−100
CDMS
Spin−independent
WIMP−nucleon cross section $\sigma_N$ [cm$^2$]
WIMP mass $m_\chi$ [GeV]

Equal couplings to all SM fermions
90% C.L.
DAMA
(q ± 33%)
PICASSO
XENON−10
COUPP
SIMPLE
$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma^5 f$
Spin−dependent
WIMP−proton cross section $\sigma_p$ [cm$^2$]
WIMP mass $m_\chi$ [GeV]

# DD Limits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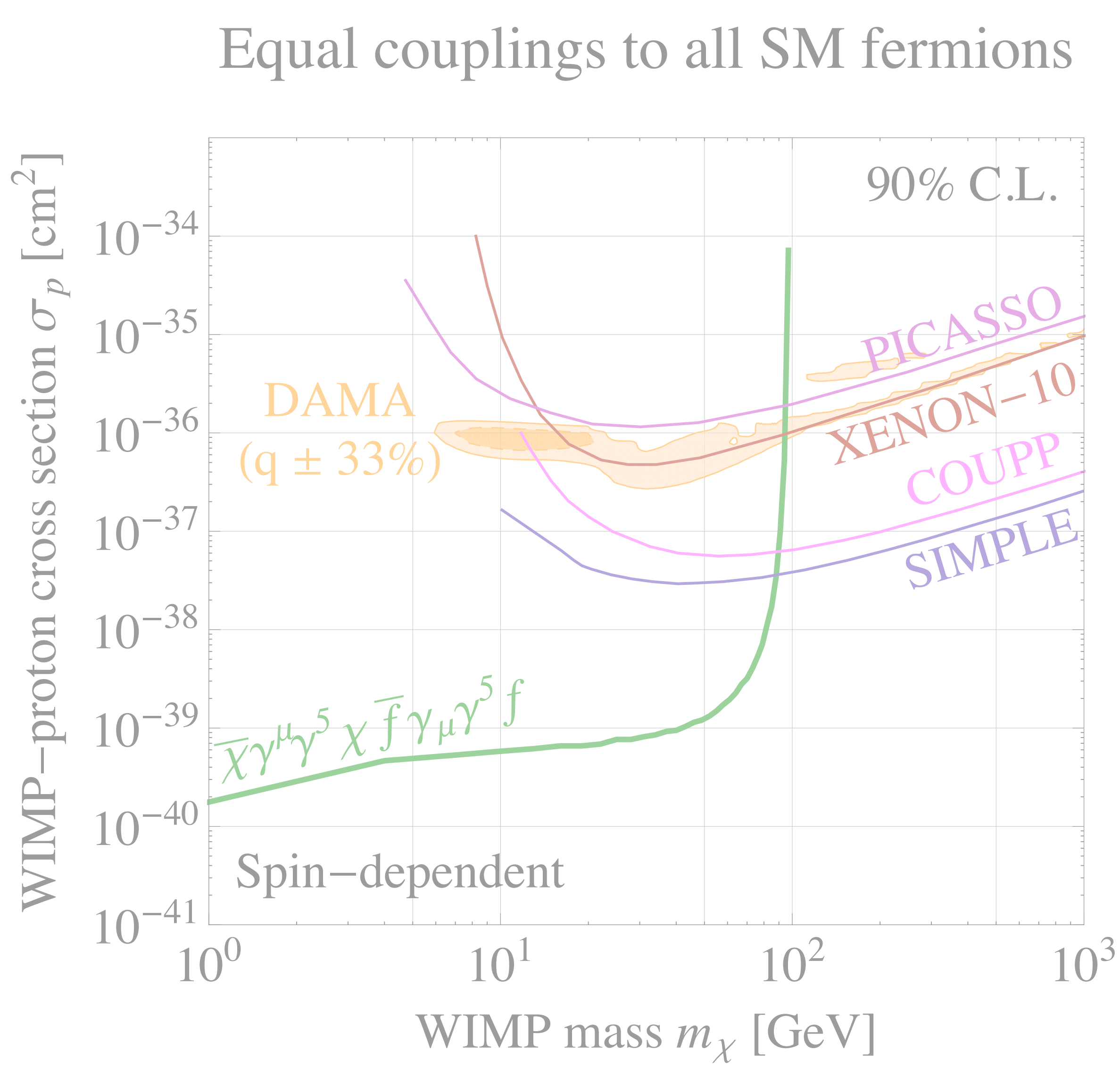
$\overline{\chi}\chi\overline{f}f$
$\overline{\chi}f\overline{f}\chi$
$\overline{\chi}\gamma^\mu\chi\overline{f}\gamma_\mu f$
DAMA (q ± 33%)
CoGeNT
XENON−100
CDMS
Spin−independent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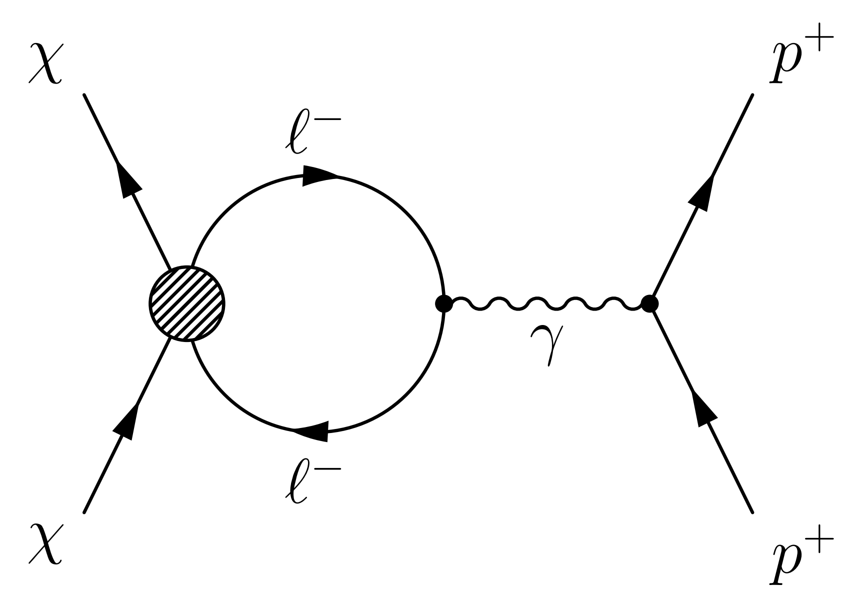
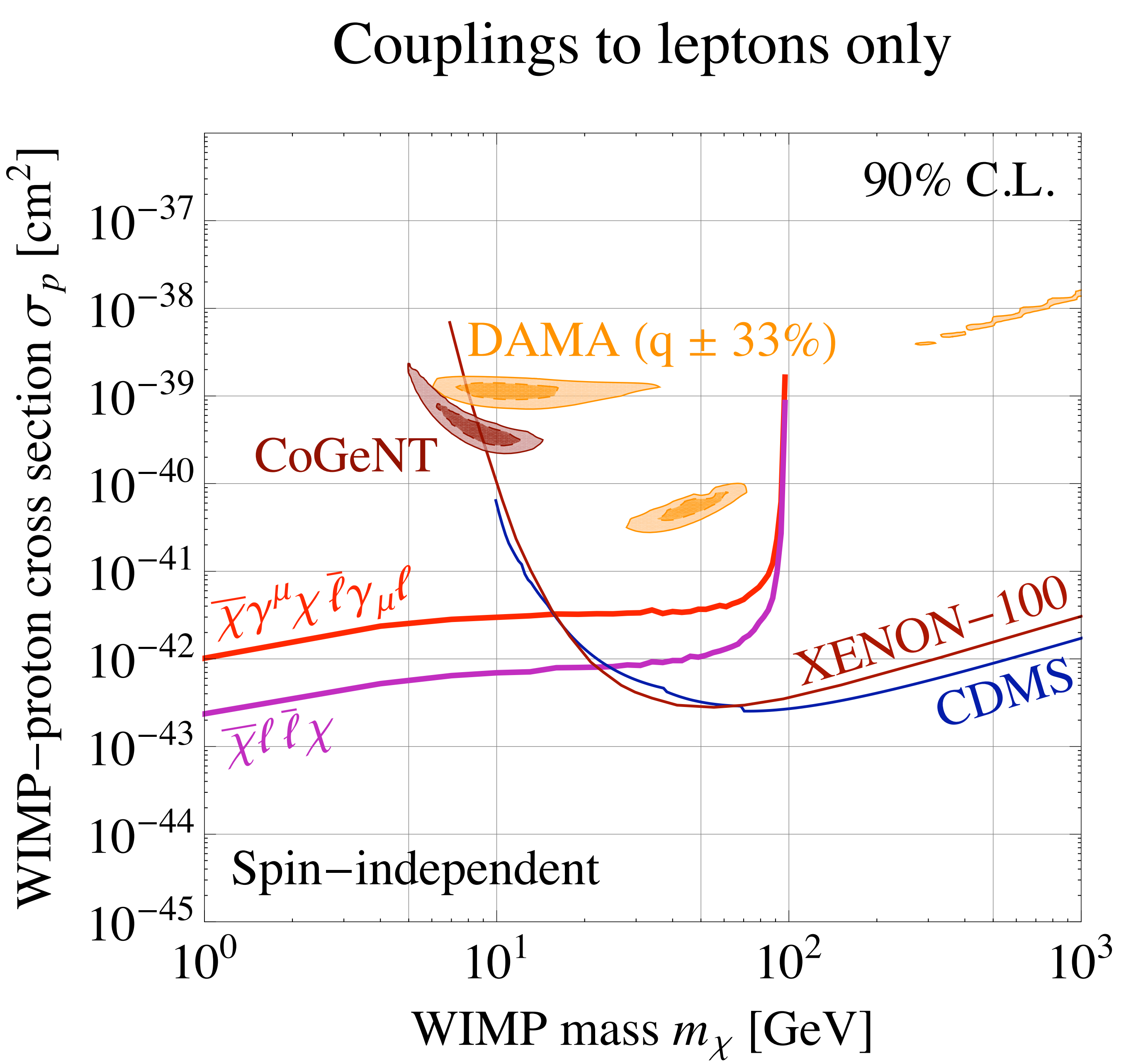
COUPP
SIMPLE
$\overline{\chi}\gamma^\mu\gamma^5\chi\overline{f}\gamma_\mu\gamma^5 f$
Spin−dependent

# Leptophilic DM

- Consider zero couplings to quarks.

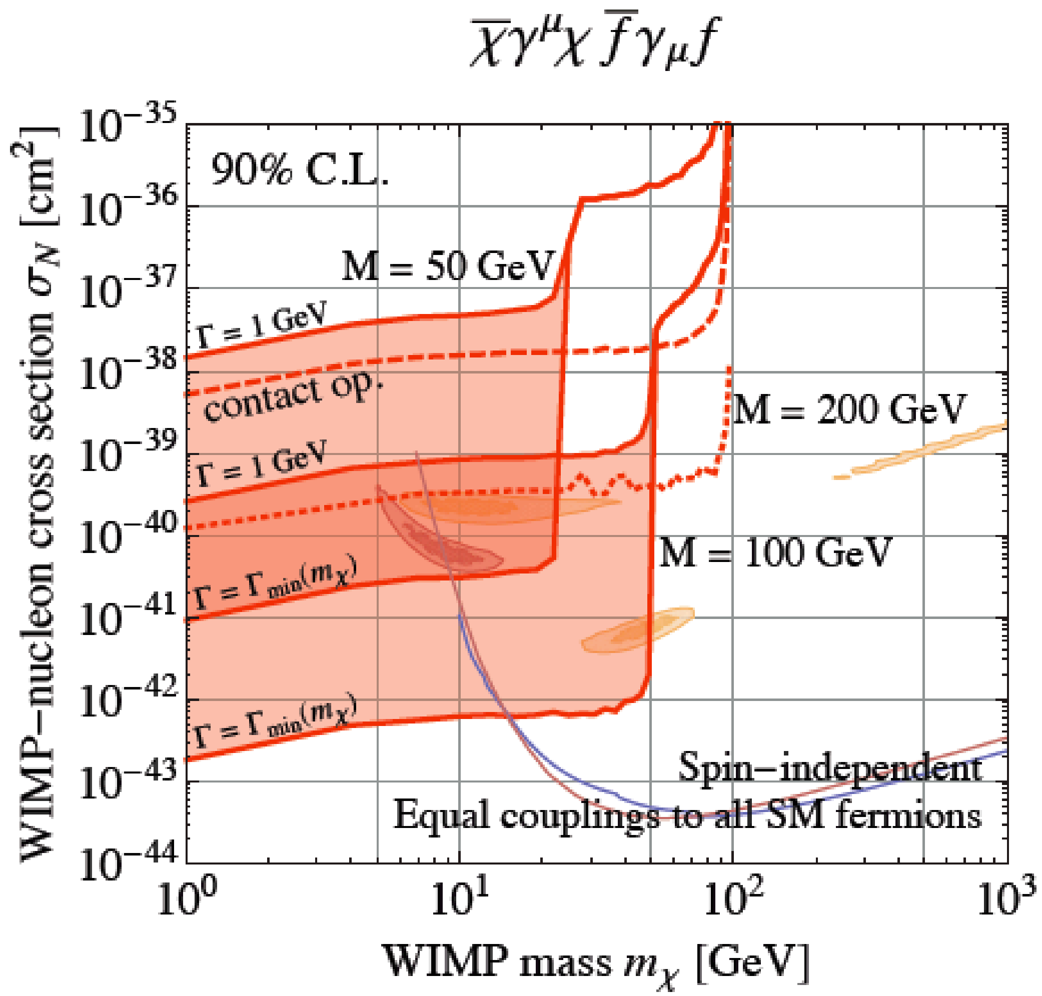



Direct detection pays a big price. Collider limits are strong.

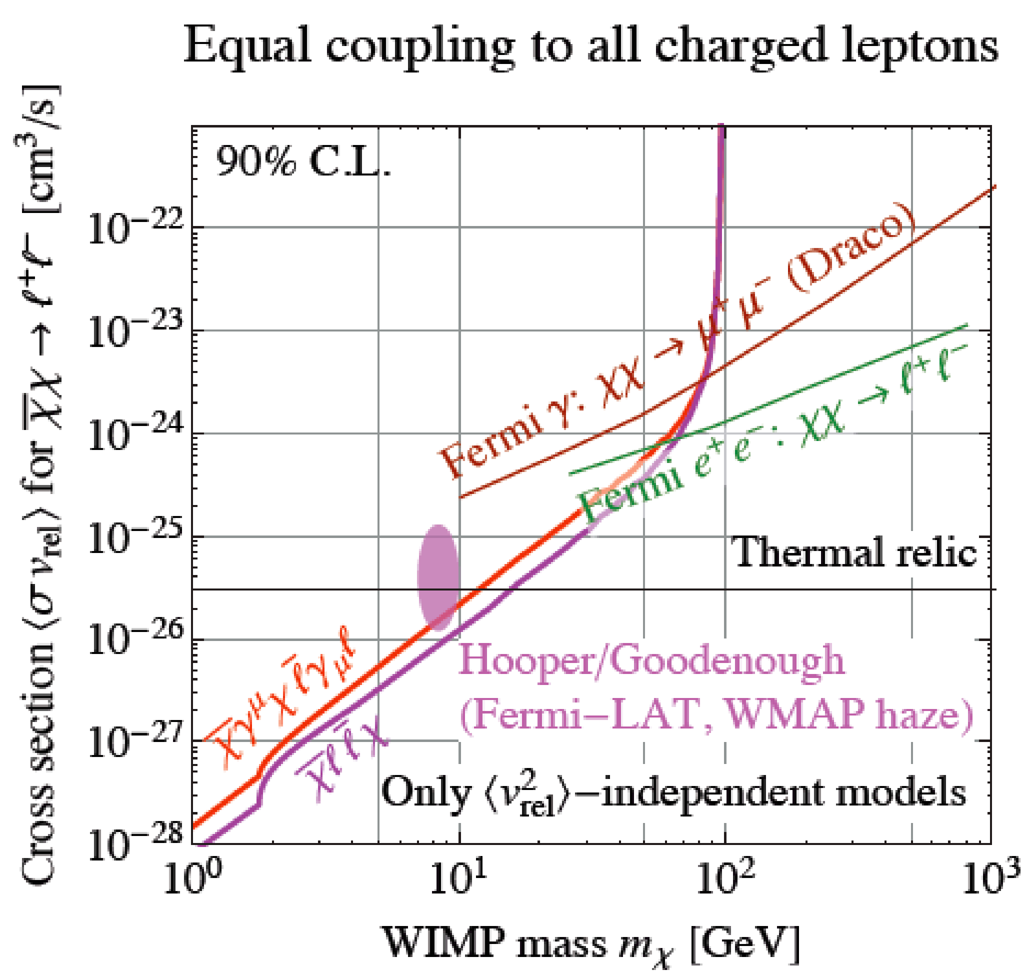


# Many more..

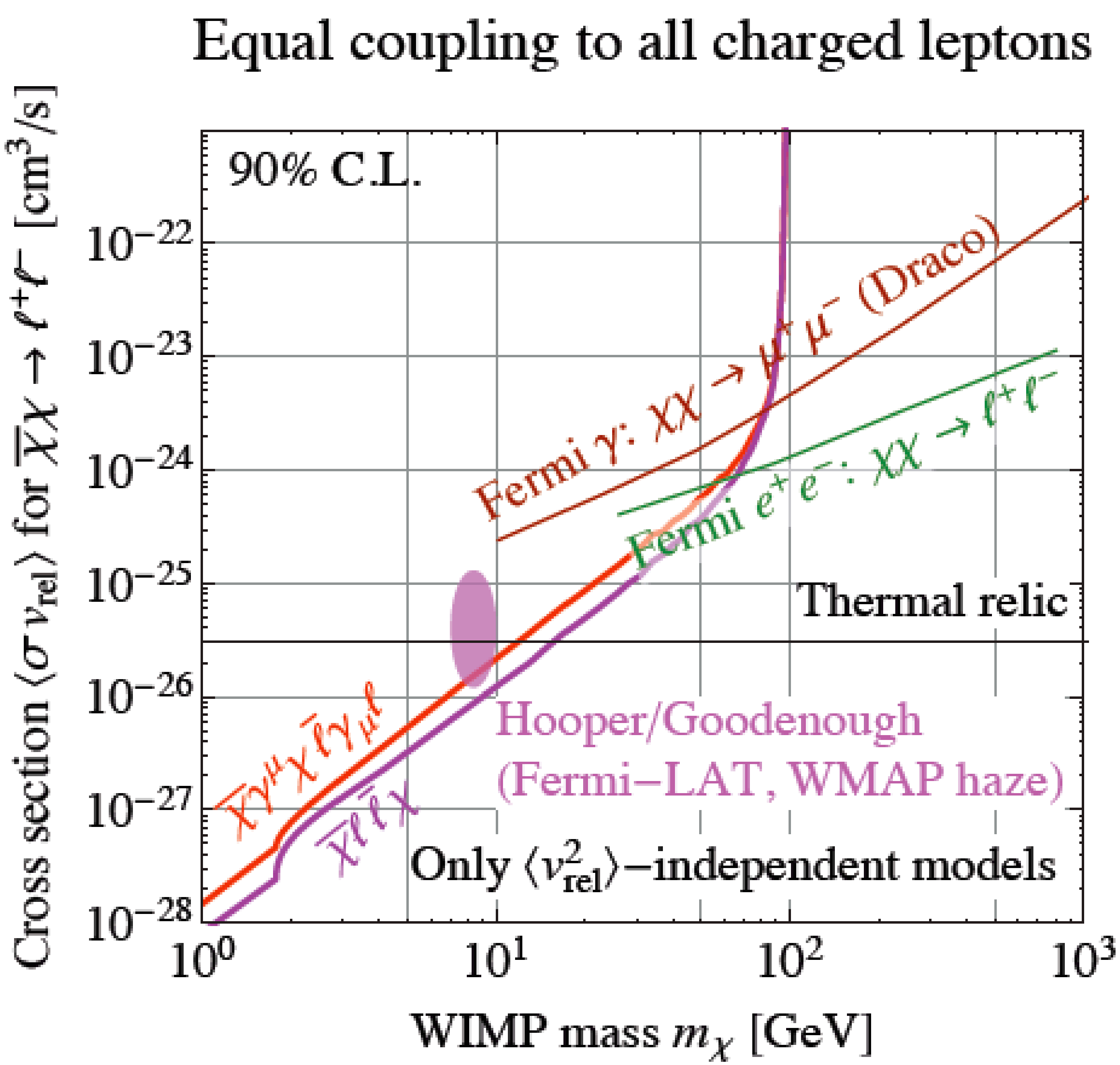
* Light mediators:




* Indirect detection:



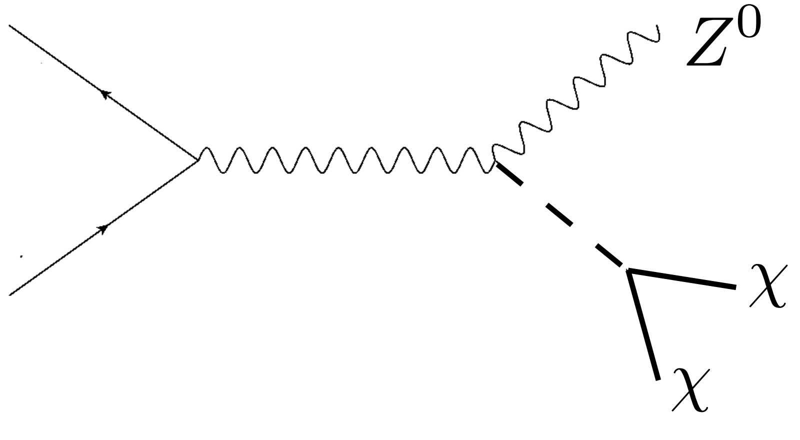
# Indirect Detection




Tension with the "Hooperon". Light thermal relic ruled out.

# Mono-something!

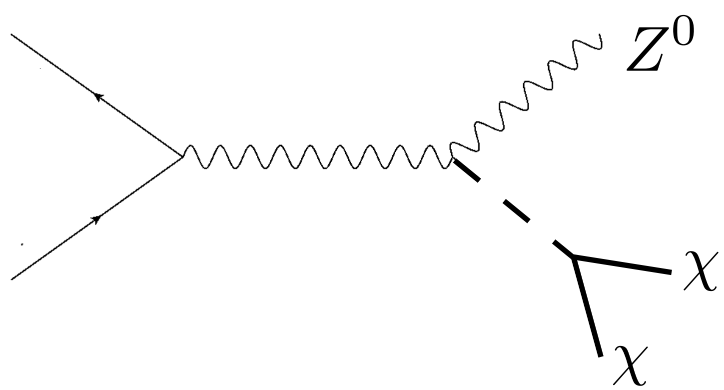
* For specific models, we can probe the identity of the mediator with other mono-somthings.
* **Mono-top** signals can probe DM that is coupling via MFV operators (kamenik and Zupan).
* In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.



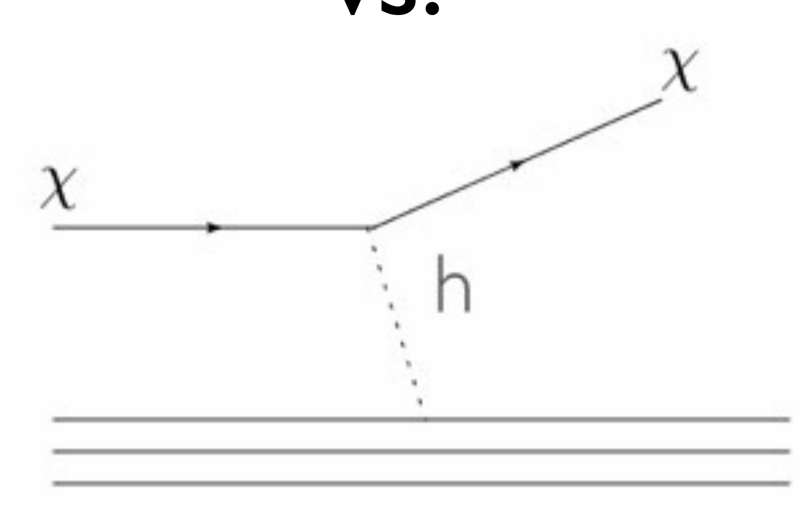

Invisible Higgs searches can be interpreted as "direct detection" experiments!

*A Characteristic Higgs Channel can confirm Higgs mediation!*

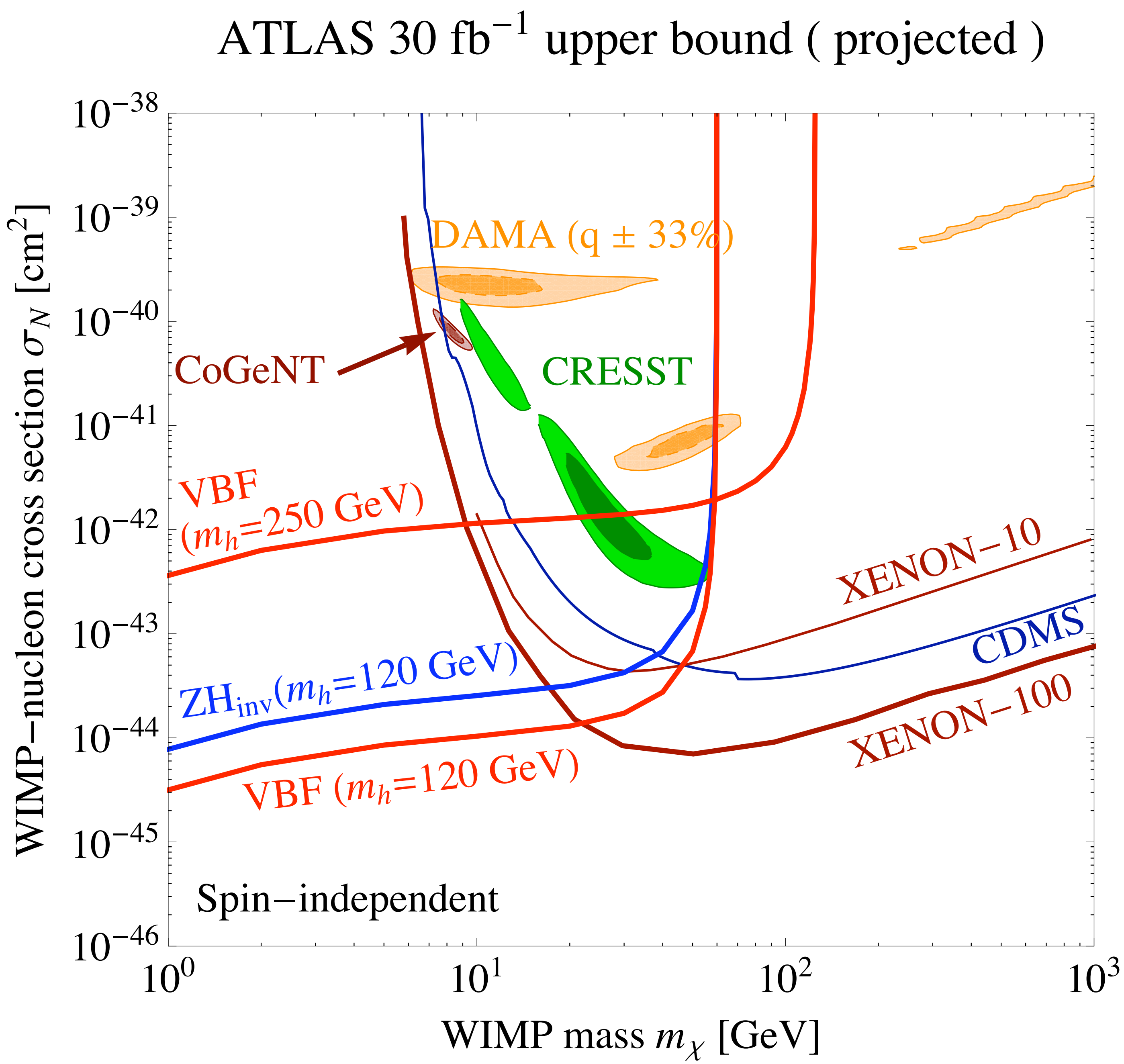
# Higgs Mediator




**vs.**




**Direct detection is parametrically smaller!**




Fox,RH, Kopp and Tsai

# Games: Higgs searches & DM

* *Assume* the Higgs hint is real w/ SM production.
* The fact that is was seen in diphoton with the rate that is has, places limits on competing modes, e.g. Higgs to invisible.
* Places **upper** limit on higgs mediated direct detection.

* *Assume* a Higgs mass that is already excluded for SM.
* *Assume* the reason it was excluded is an invisible branching fraction.
* This places a lower limit on the invisible BR.
  Places a **lower** limit on higgs mediated direct detection.

# To Conclude:

**Colliders are placing competitive and complementary bounds to direct and to indirect detection:**

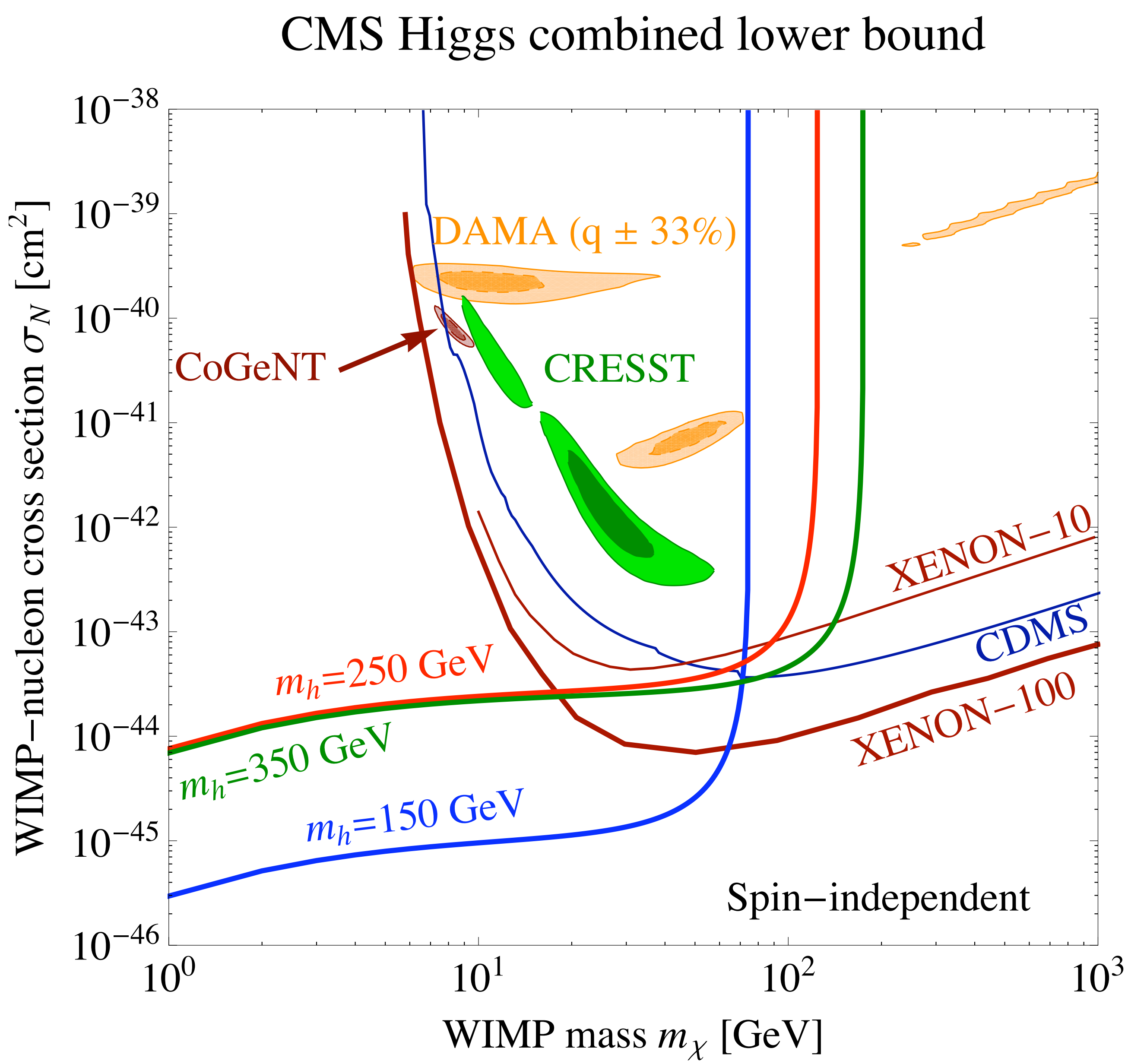
* The ~~**Tevatron**~~ LHC is the world record holder for light dark matter and for spin dependent.
* Dedicated CDF **mono-jet** is out. CMS, and ATLAS studies are underway.
* **LEP** mono-photons provide strong constraints.
* There is a nice interplay b/w visible and invisible Higgs searches and DM searches for **Higgs-coupled DM**.

Happy Birthday Graham!

# Current Higgs limits vs DM

* Assume a Higgs mass that was already excluded for SM.
* *Assume* the reason it was excluded is an invisible branching fraction.
* This places a lower limit on the invisible BR.
* **Places a lower limit on higgs mediated direct detection**.

# Current Higgs limits vs DM

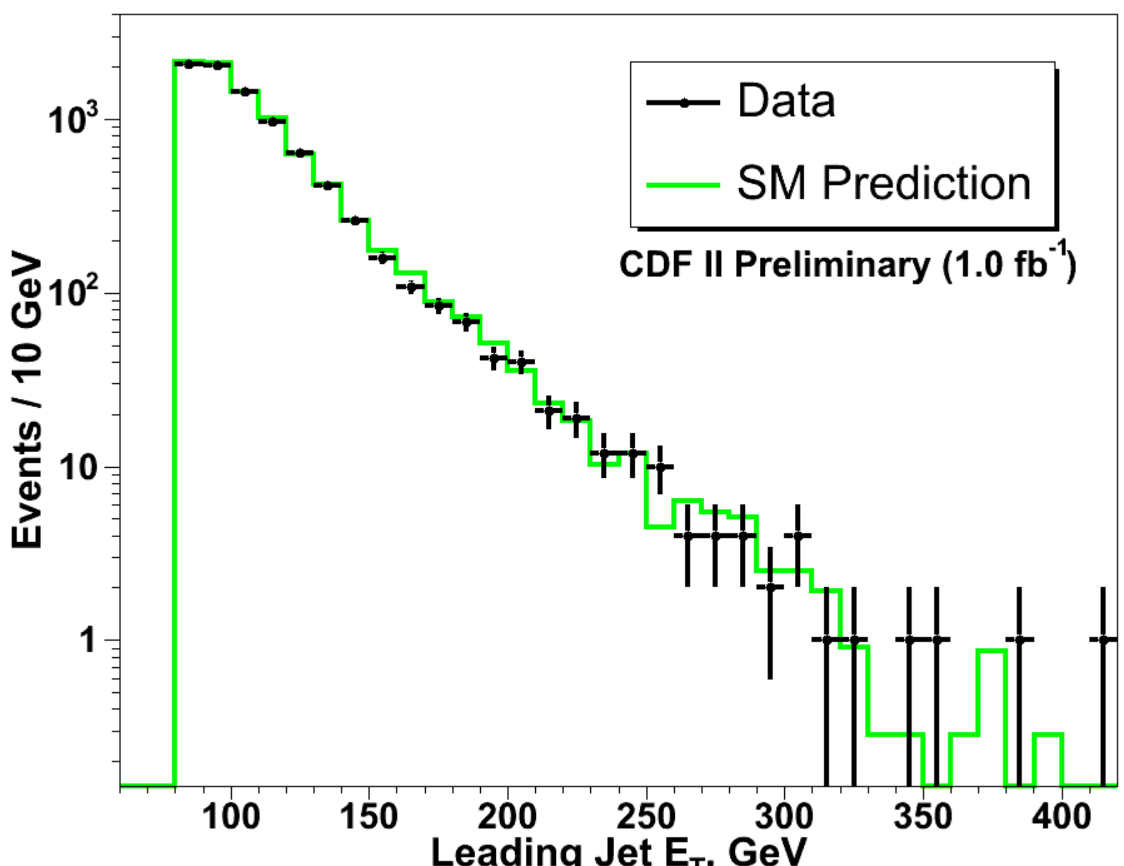



Also, if a light SM Higgs is discovered, an upper limit on DD can be extracted.

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

counting experiment:

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



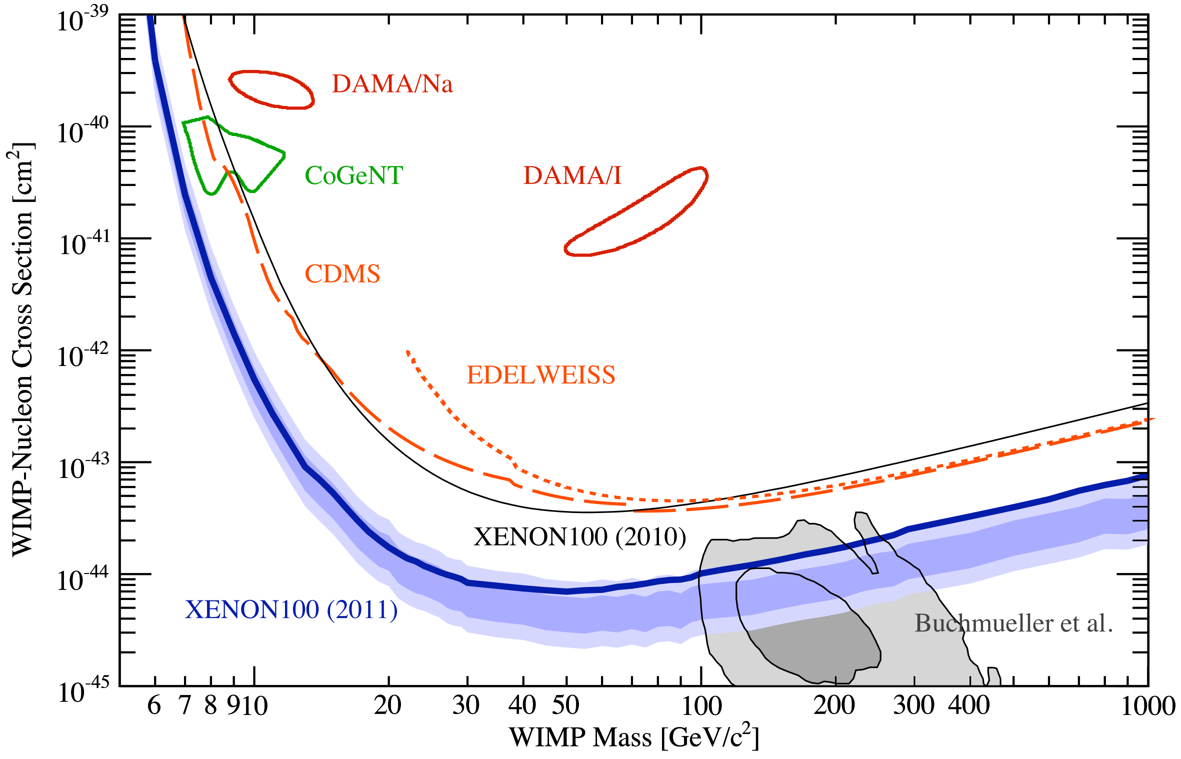

| Background | Number of Events |
|---|---|
| Z -> nu nu | 3203 +/- 137 |
| W -> tau nu | 2010 +/- 69 |
| W -> mu nu | 1570 +/- 54 |
| W -> e nu | 824 +/- 28 |
| Z -> l l | 87 +/- 3 |
| QCD | 708 +/- 146 |
| Gamma plus Jet | 209 +/- 41 |
| Non-Collision | 52 +/- 52 |
| Total Predicted | 8663 +/- 332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

**Observed: 8449 events**

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

# Collider Connections?

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



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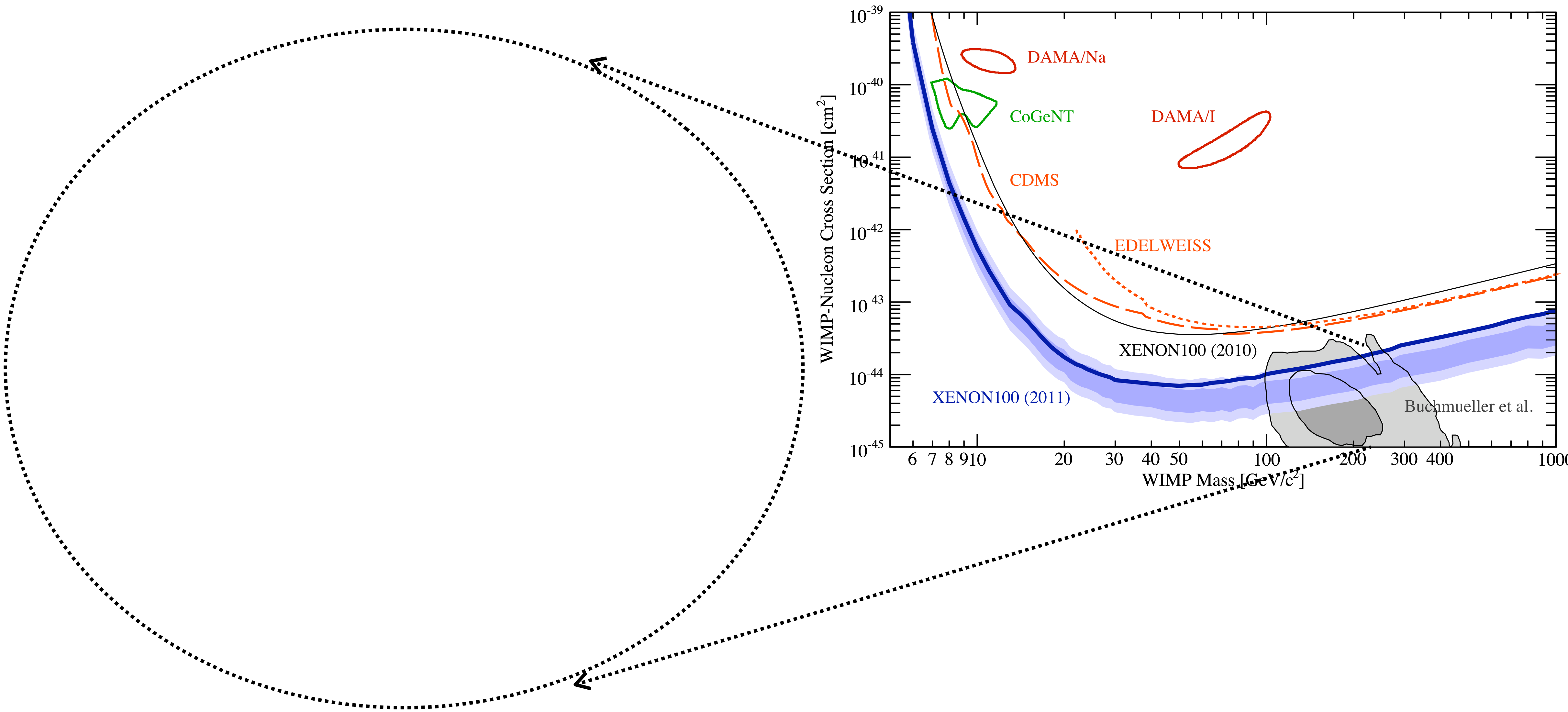

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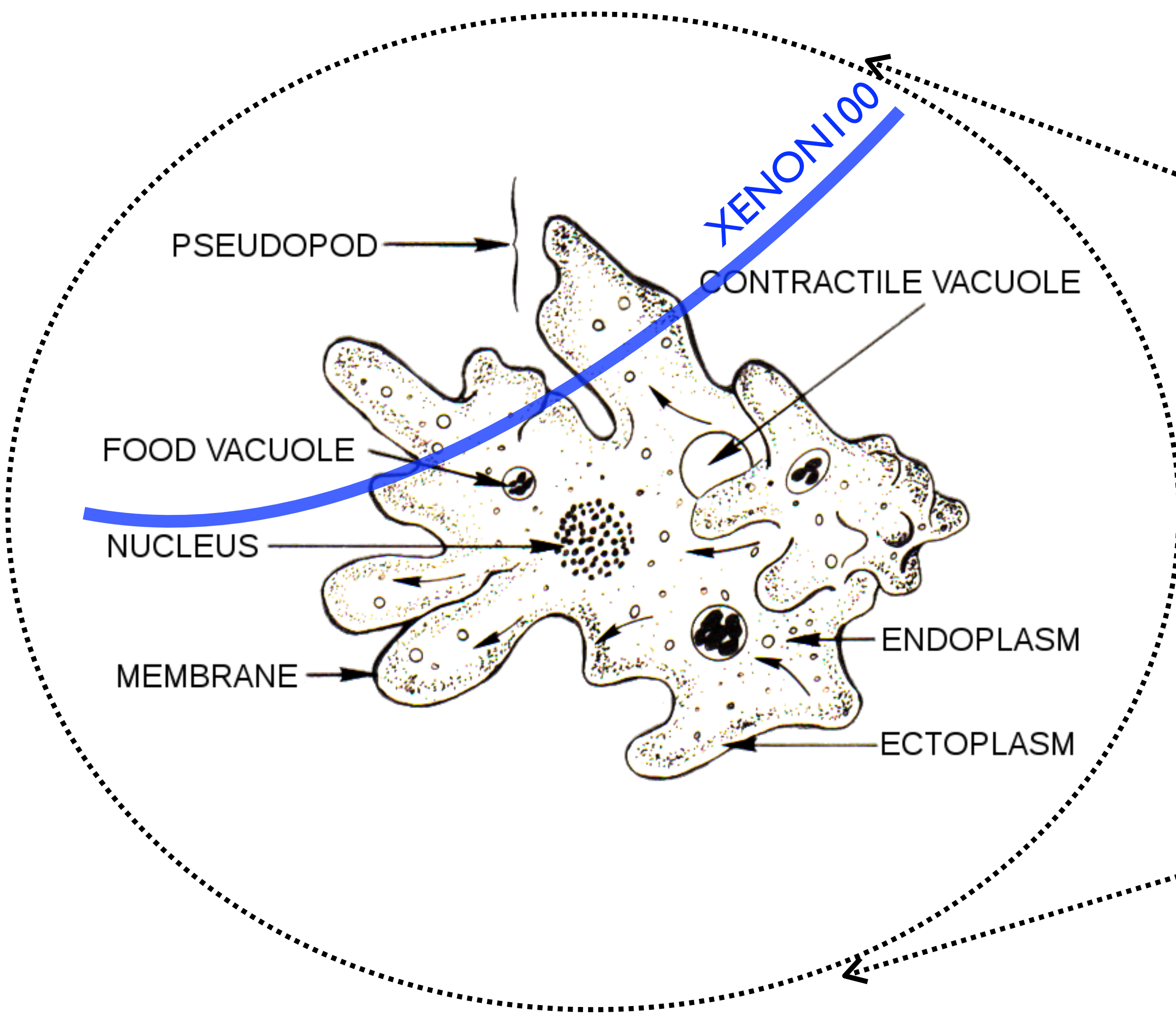


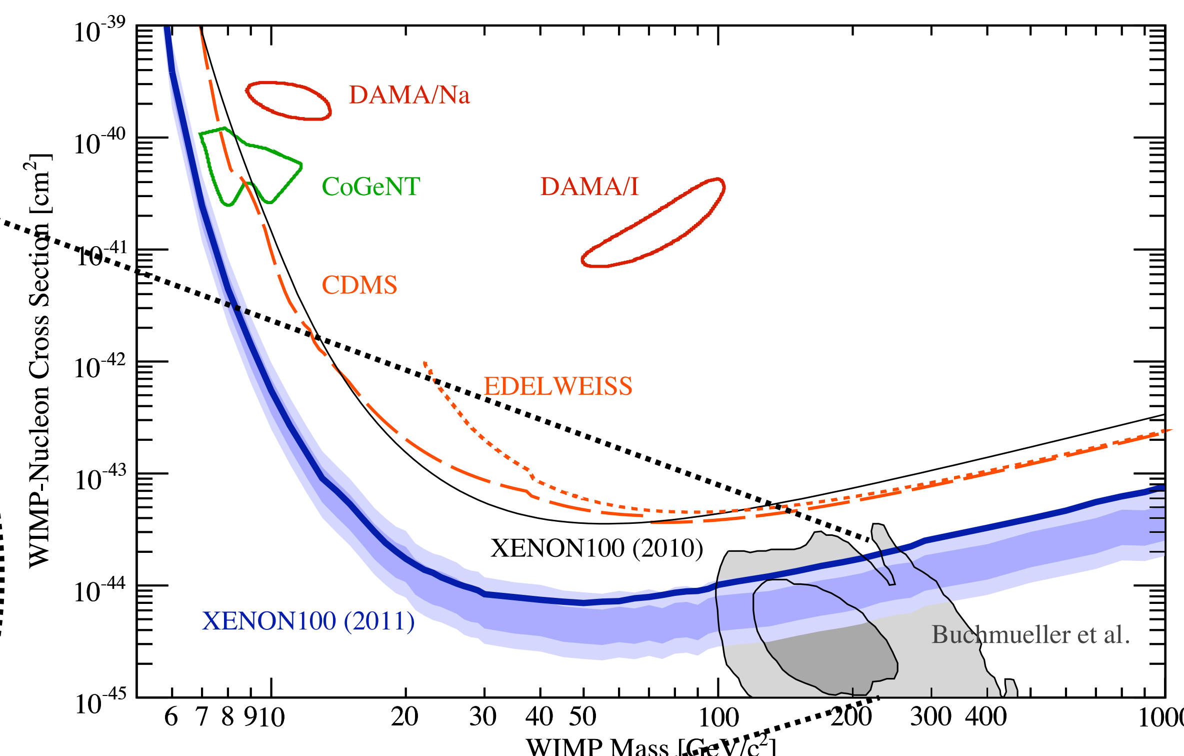

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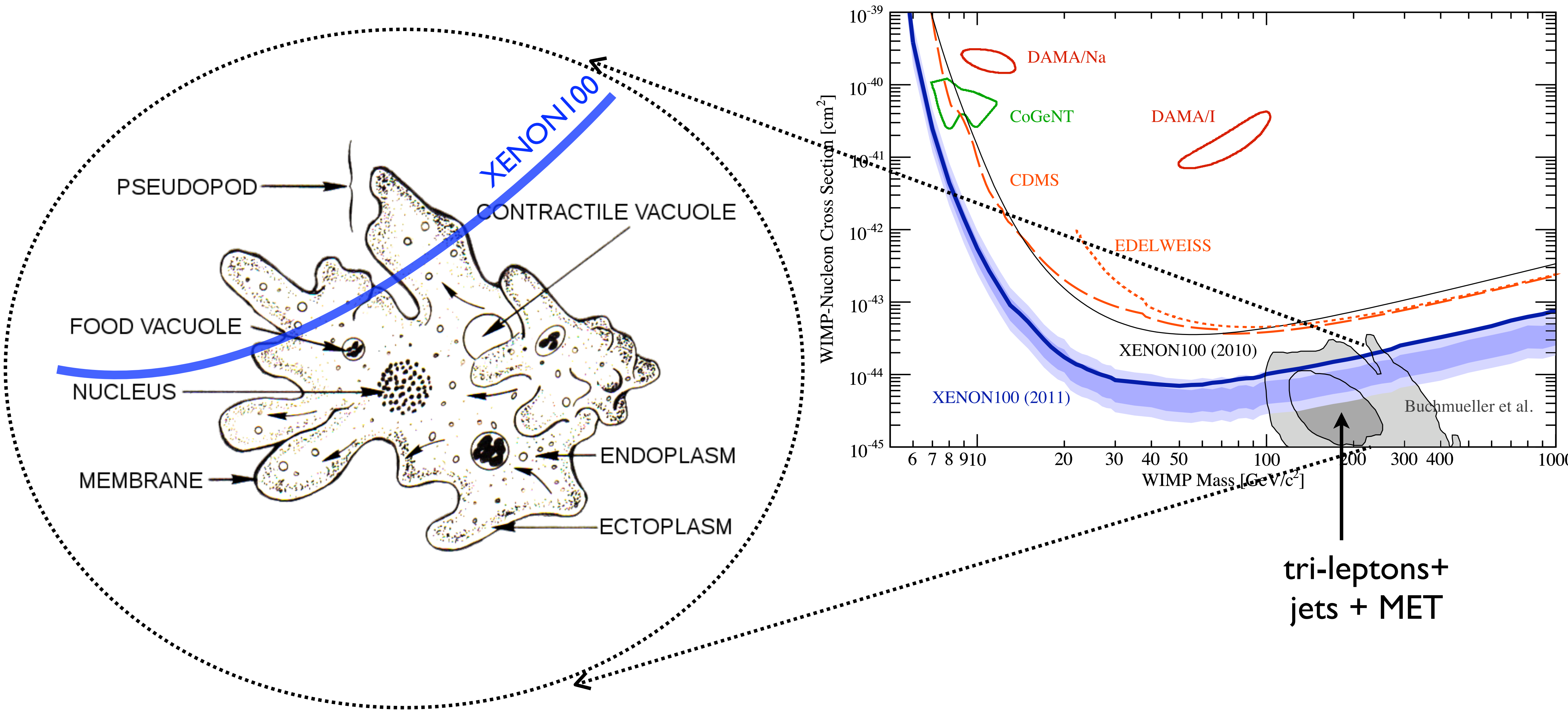

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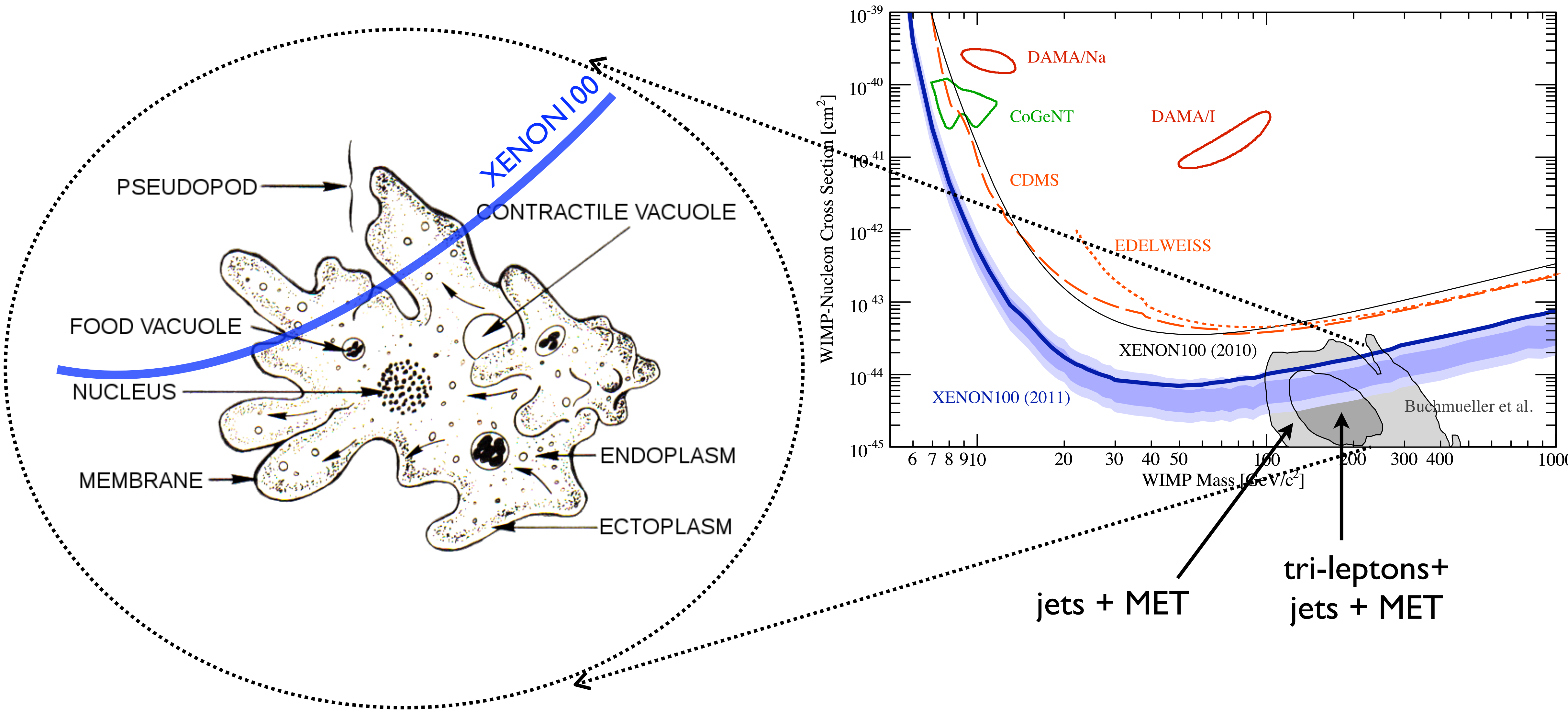

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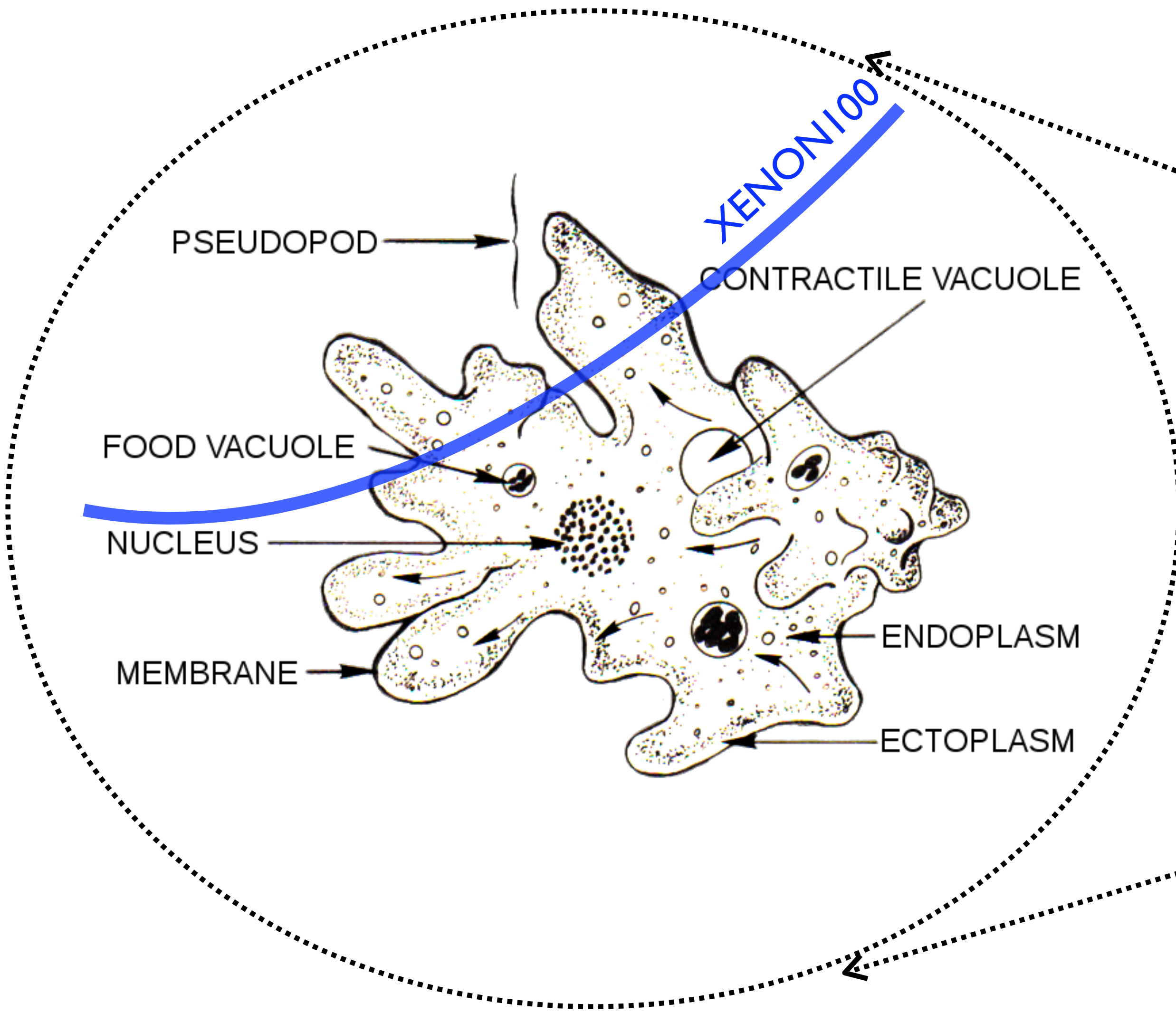


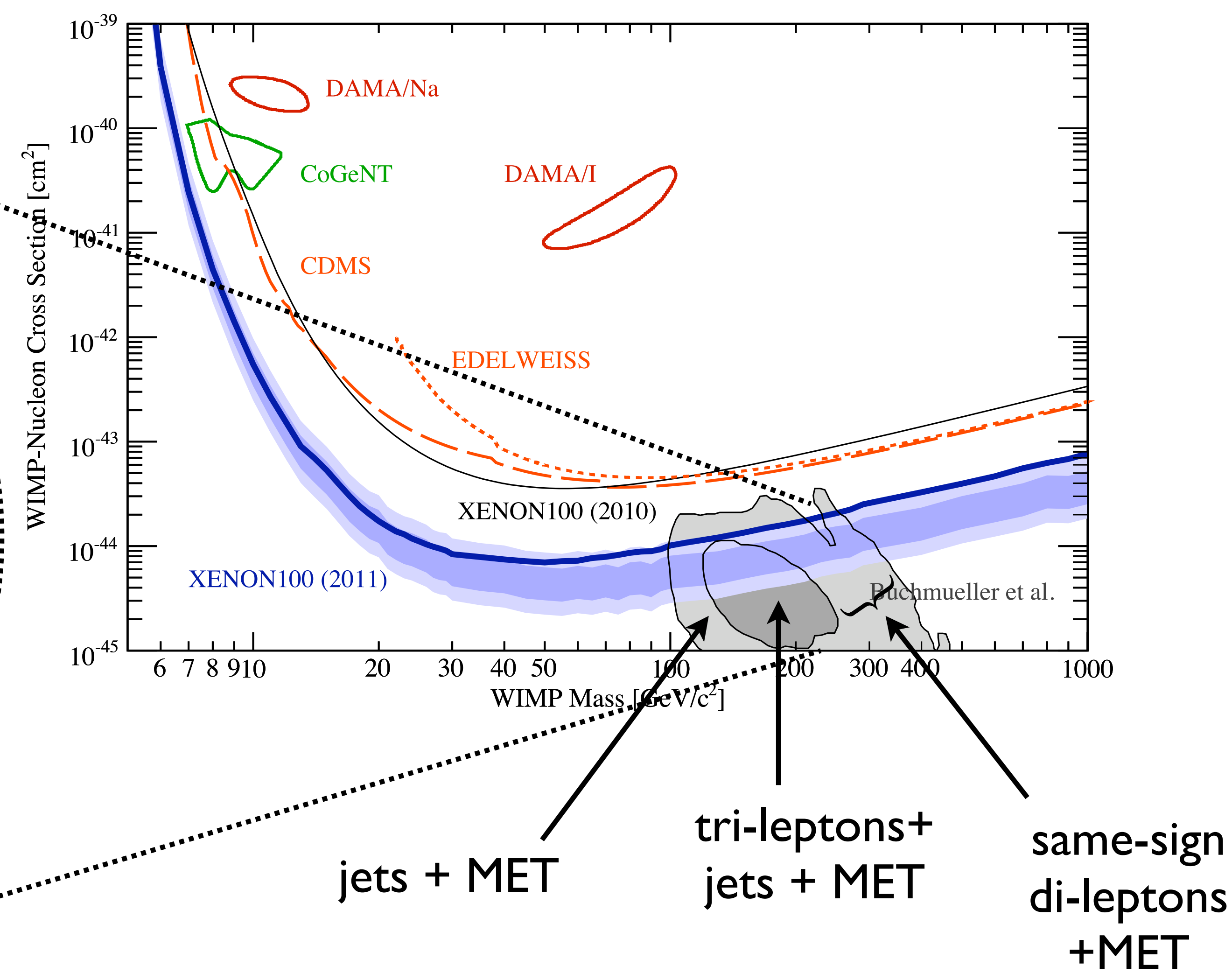

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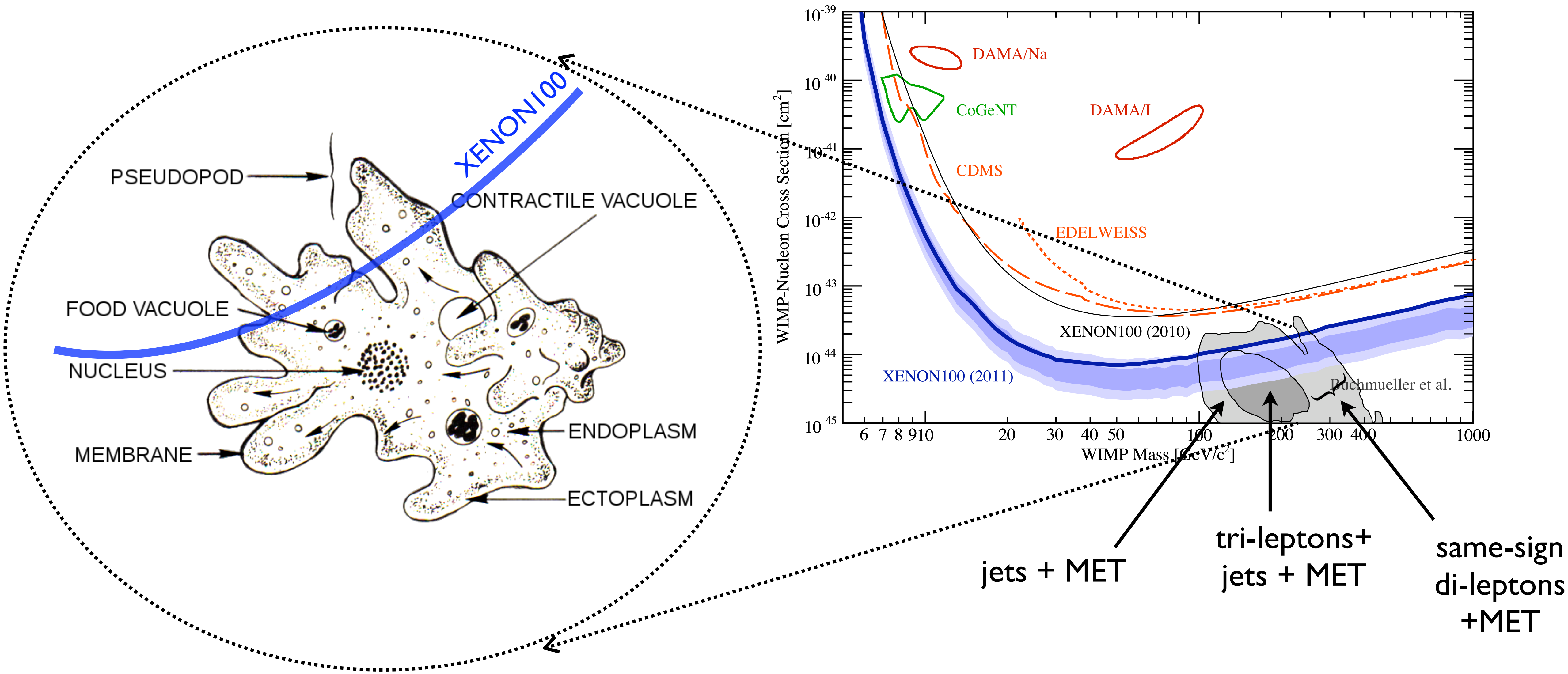


"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [nature **67**, 143 (2011)]

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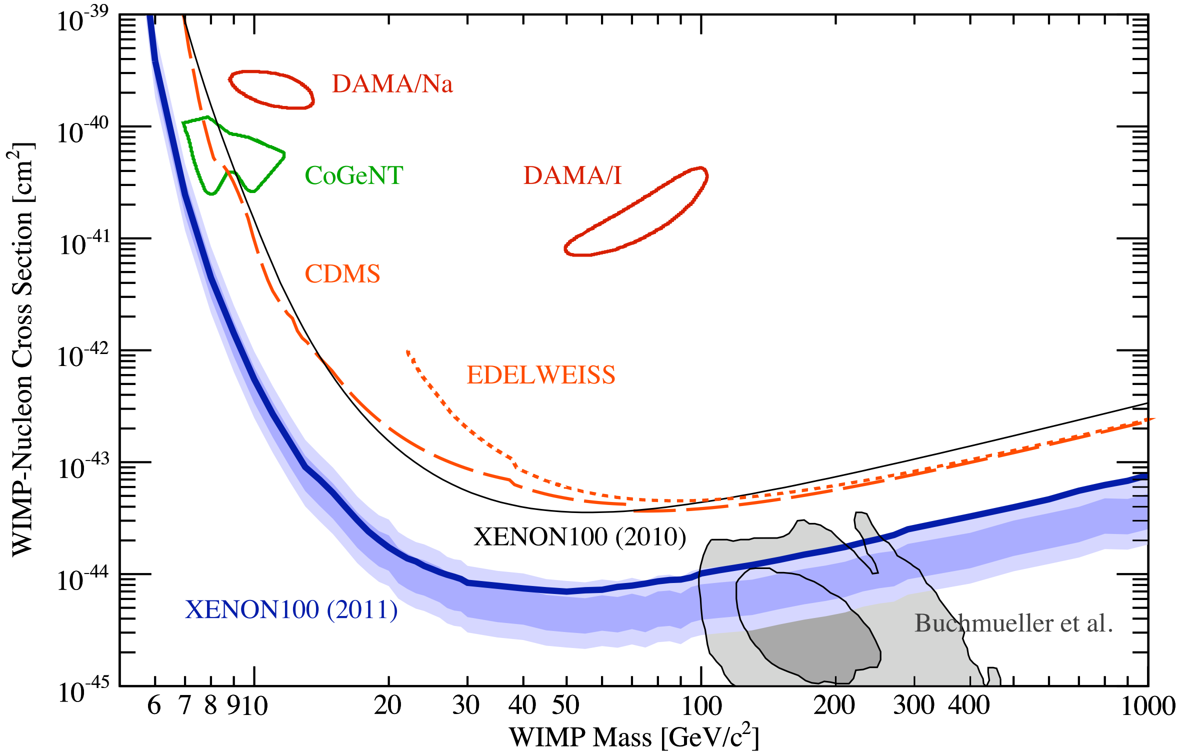

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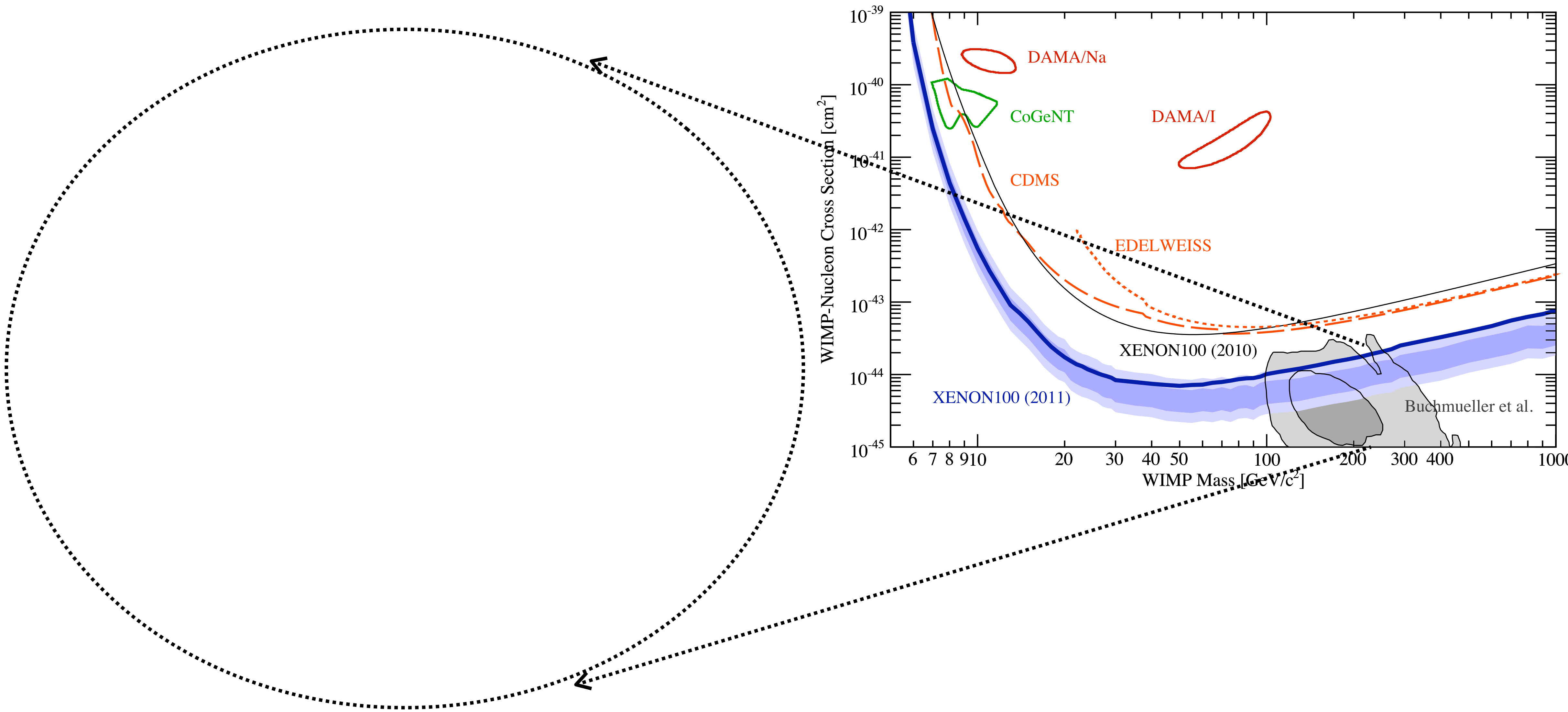

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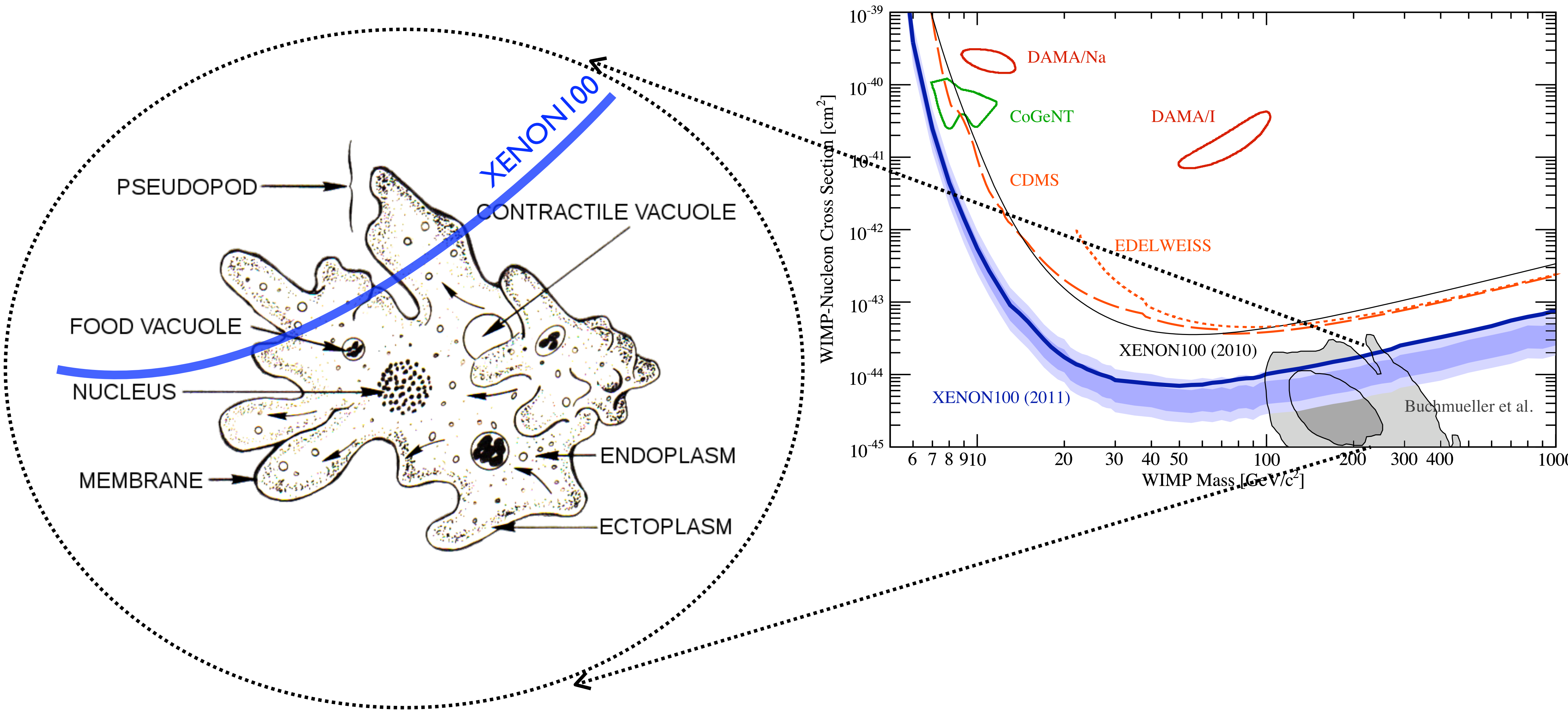
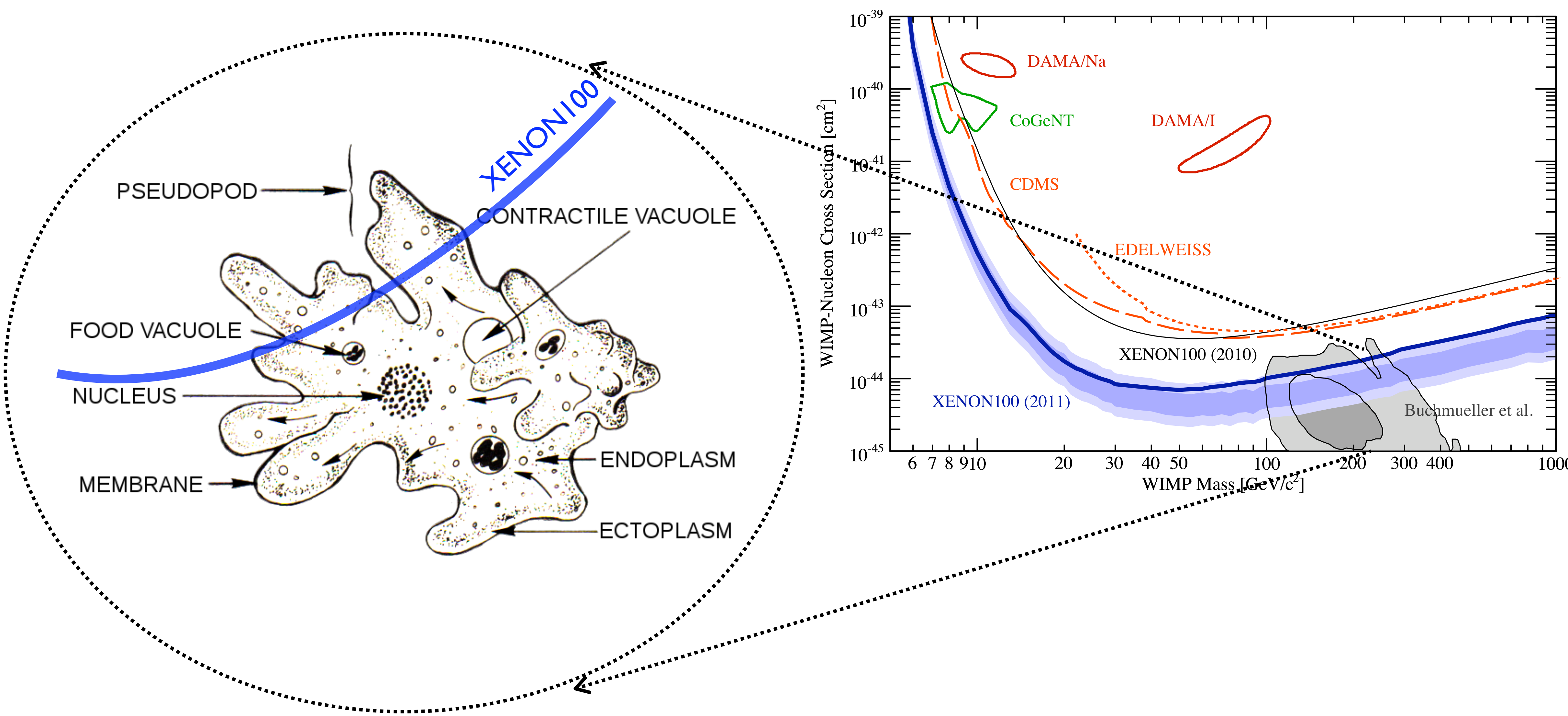


# Collider Connections?

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




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