Dark Matter @ Colliders

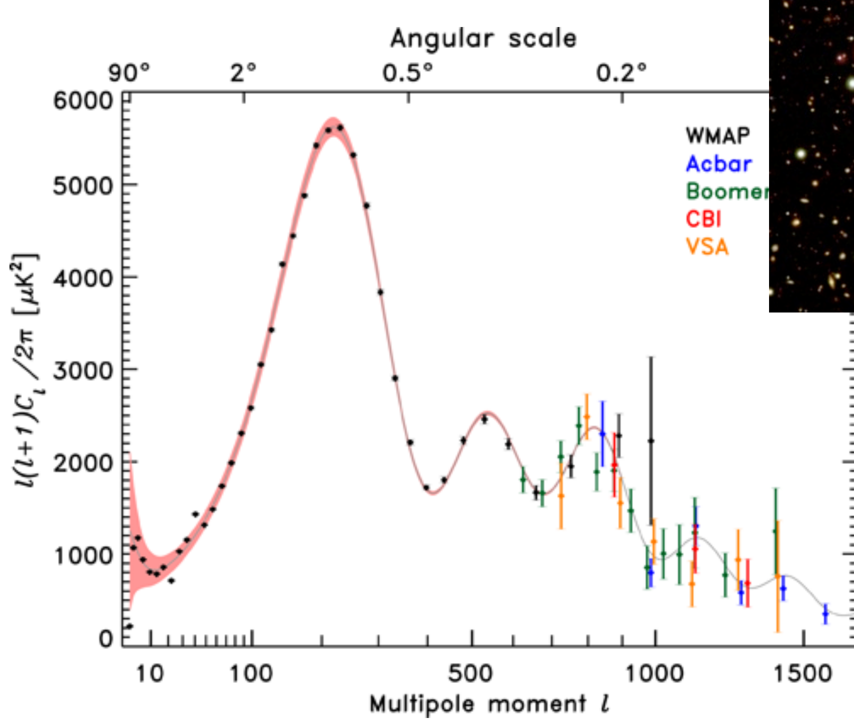
Roni Harnik, Fermilab

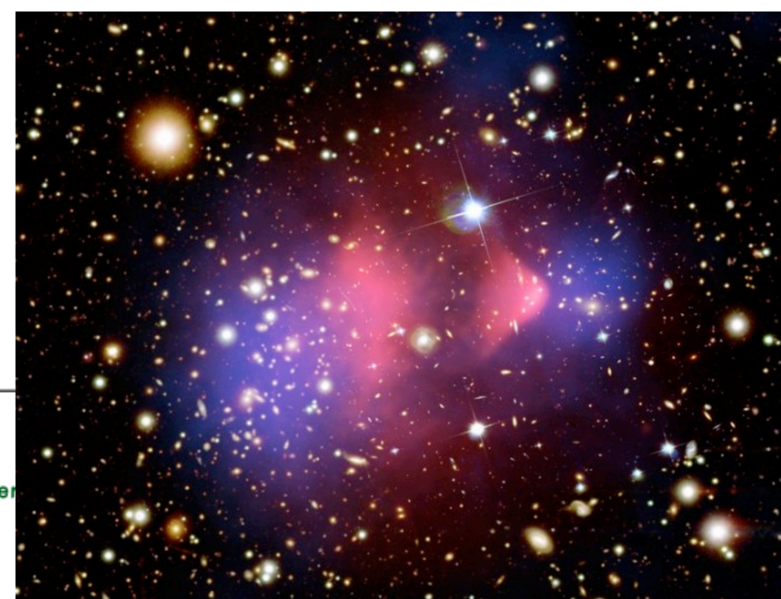
Bai, Fox, RH - 1005.3797
Fox, RH, Kopp, Tsai -1103.0240
Fox, RH, Kopp, Tsai - 1109.4389
Fox, RH, Primulando, Yu - 1203.1662

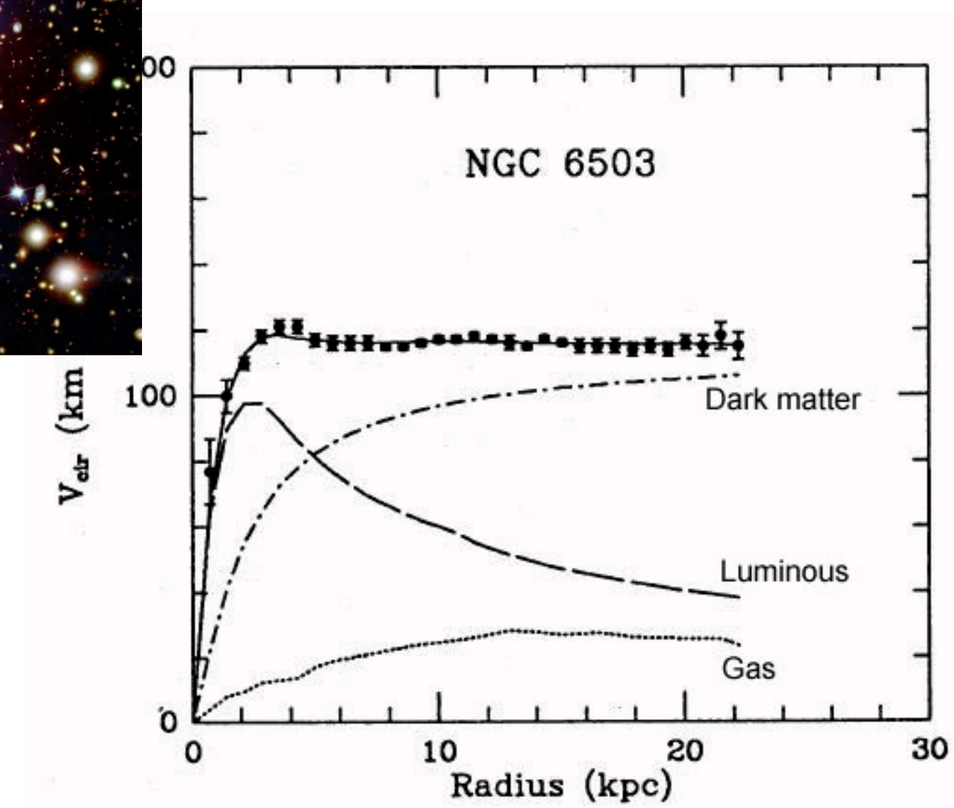
Fermilab fellows!! next year's deadline is coming up.

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.

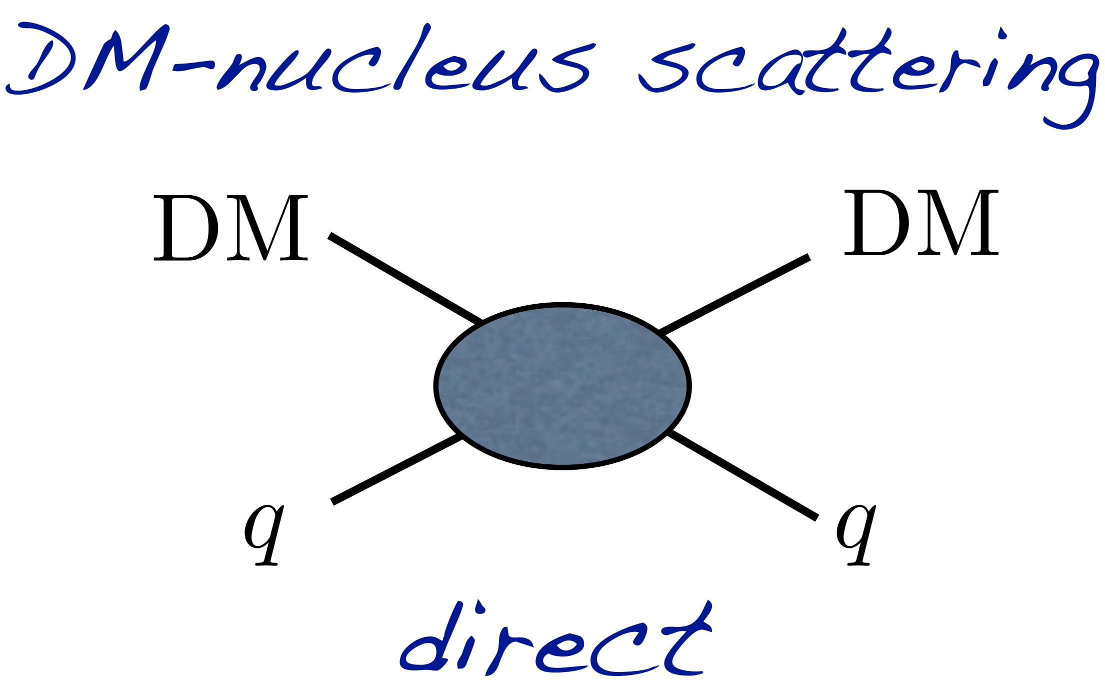


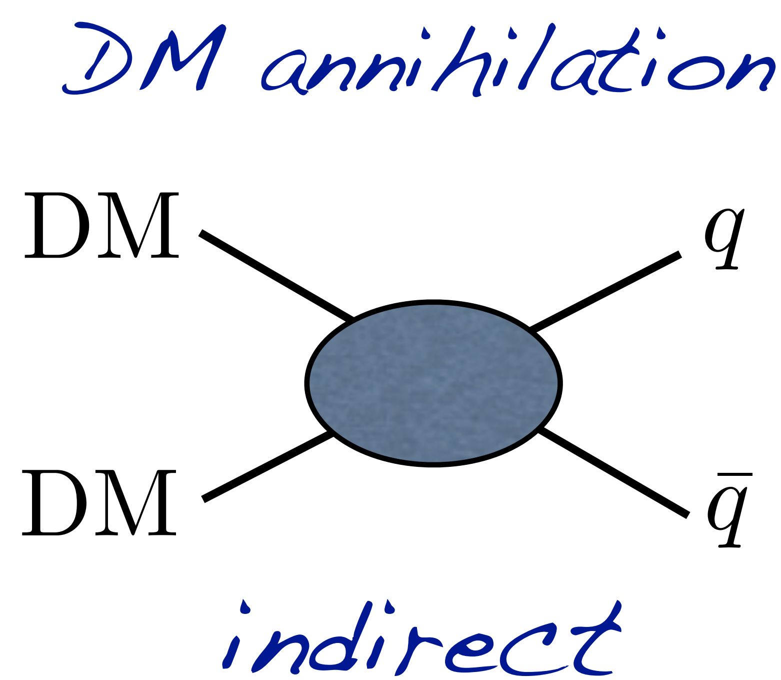




Probes of DM Interactions

- "WIMP coincidence" hints that DM has is an interaction w/ matter. picobarn-ish cross sections!?
- We hope to probe dark matter in several ways:

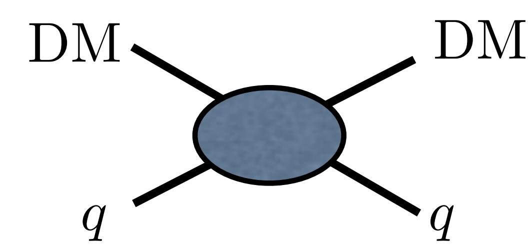




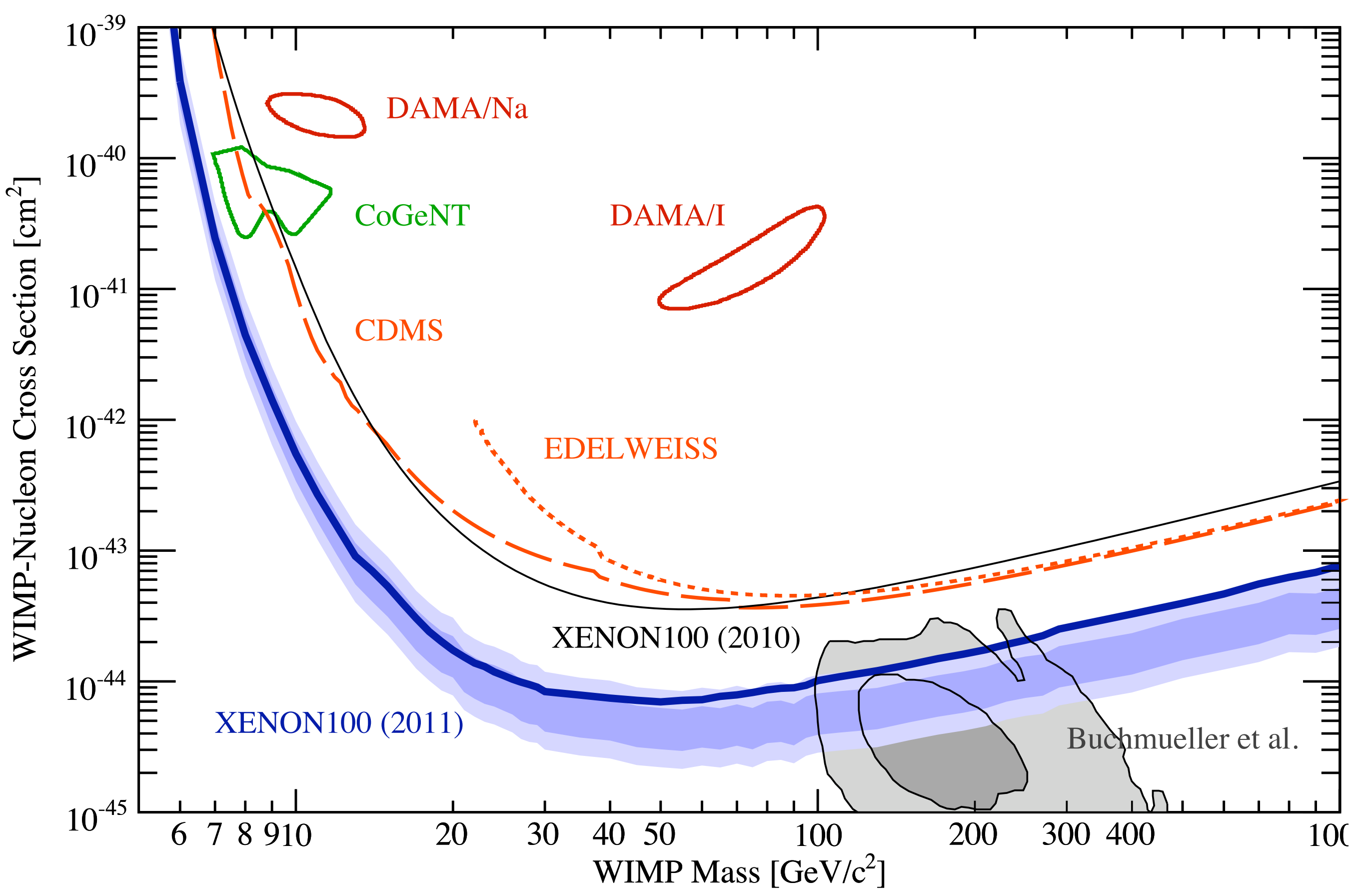
Focus on direct detection in this talk.

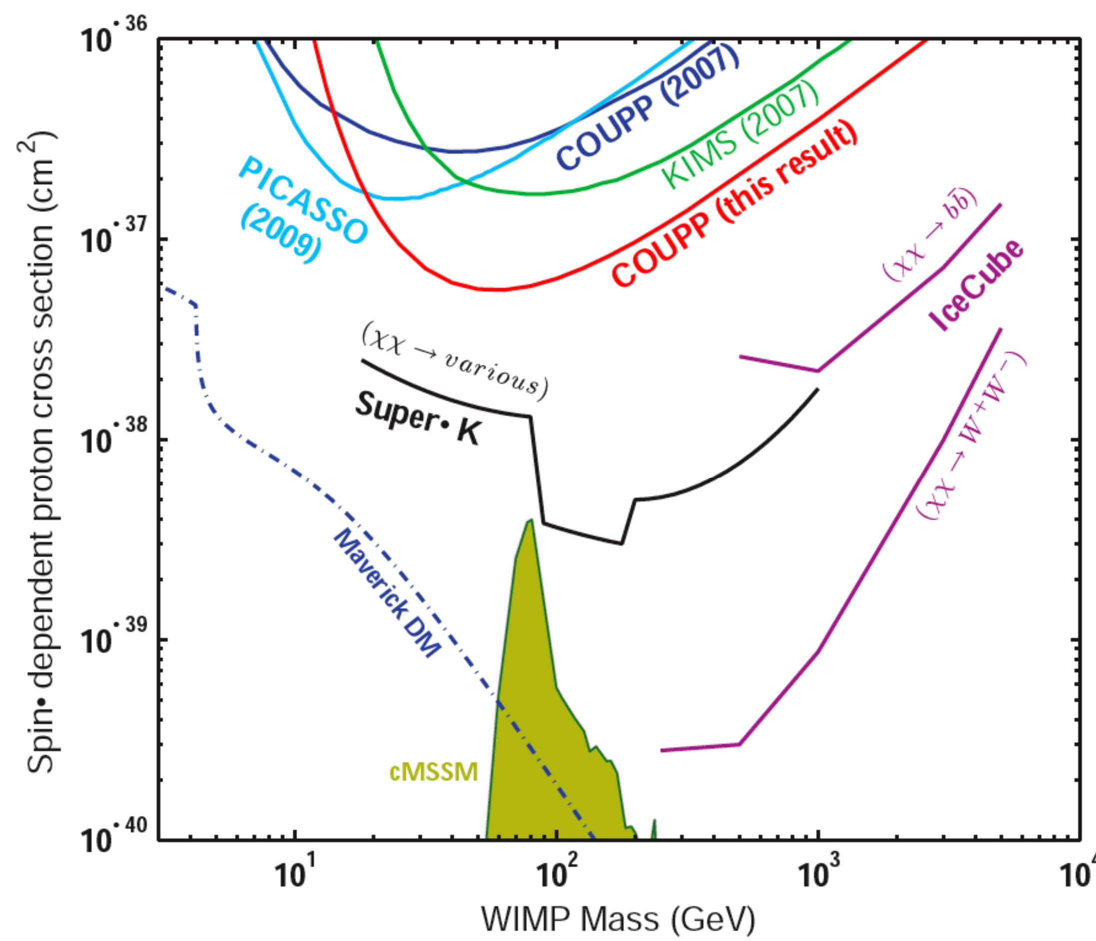
(a similar game can be played for indirect)

Direct detection

* Direct detection places limits on  .

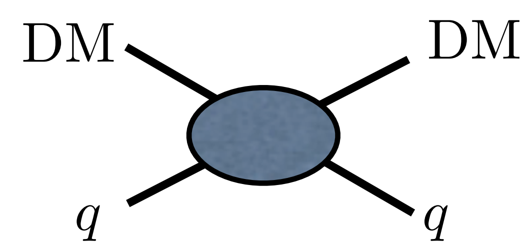
* Heroic effort with remarkable results.
* DD has some weaknesses.





What do colliders tell us about this parameter space?

Direct detection

- Direct detection places limits on  .

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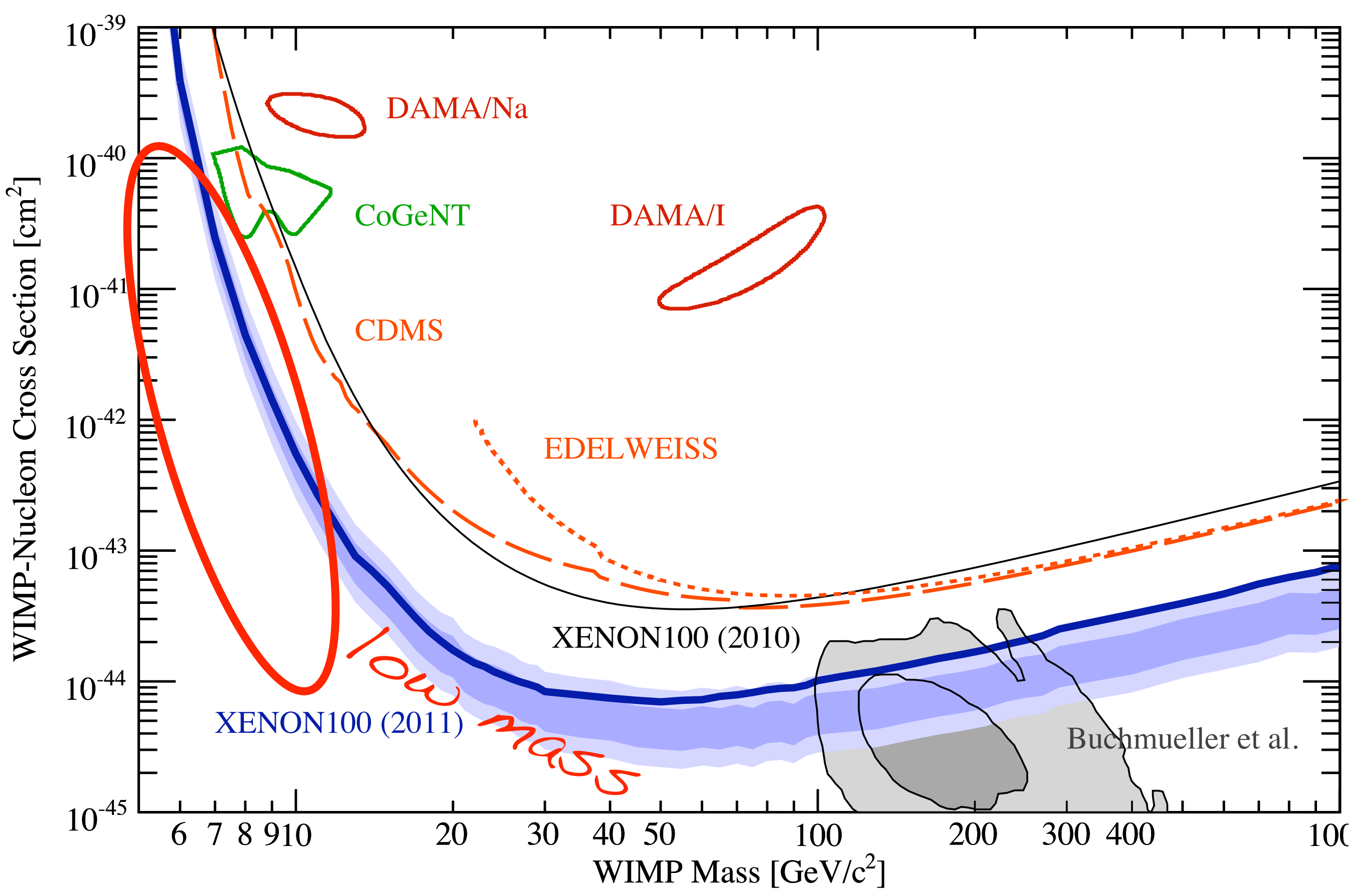

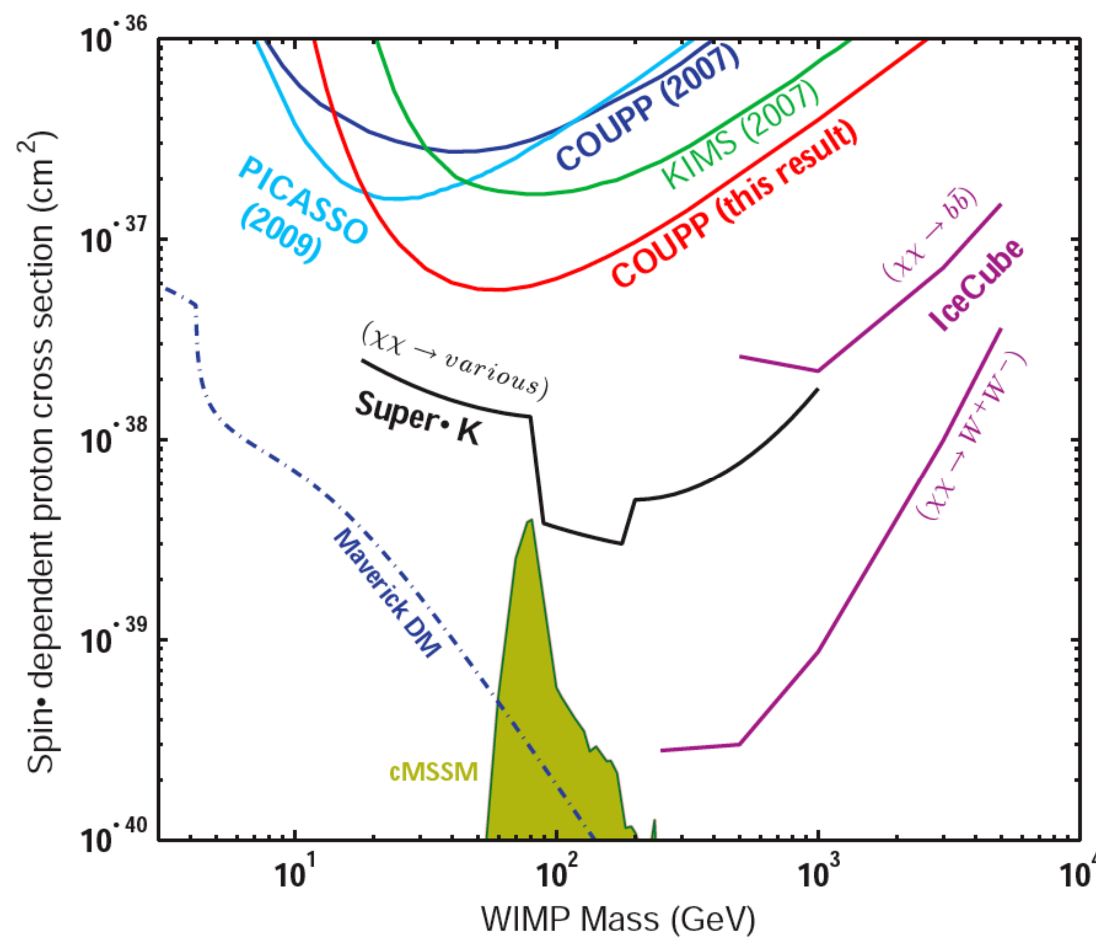

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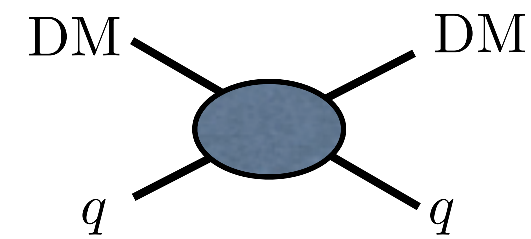
- Direct detection places limits on  .

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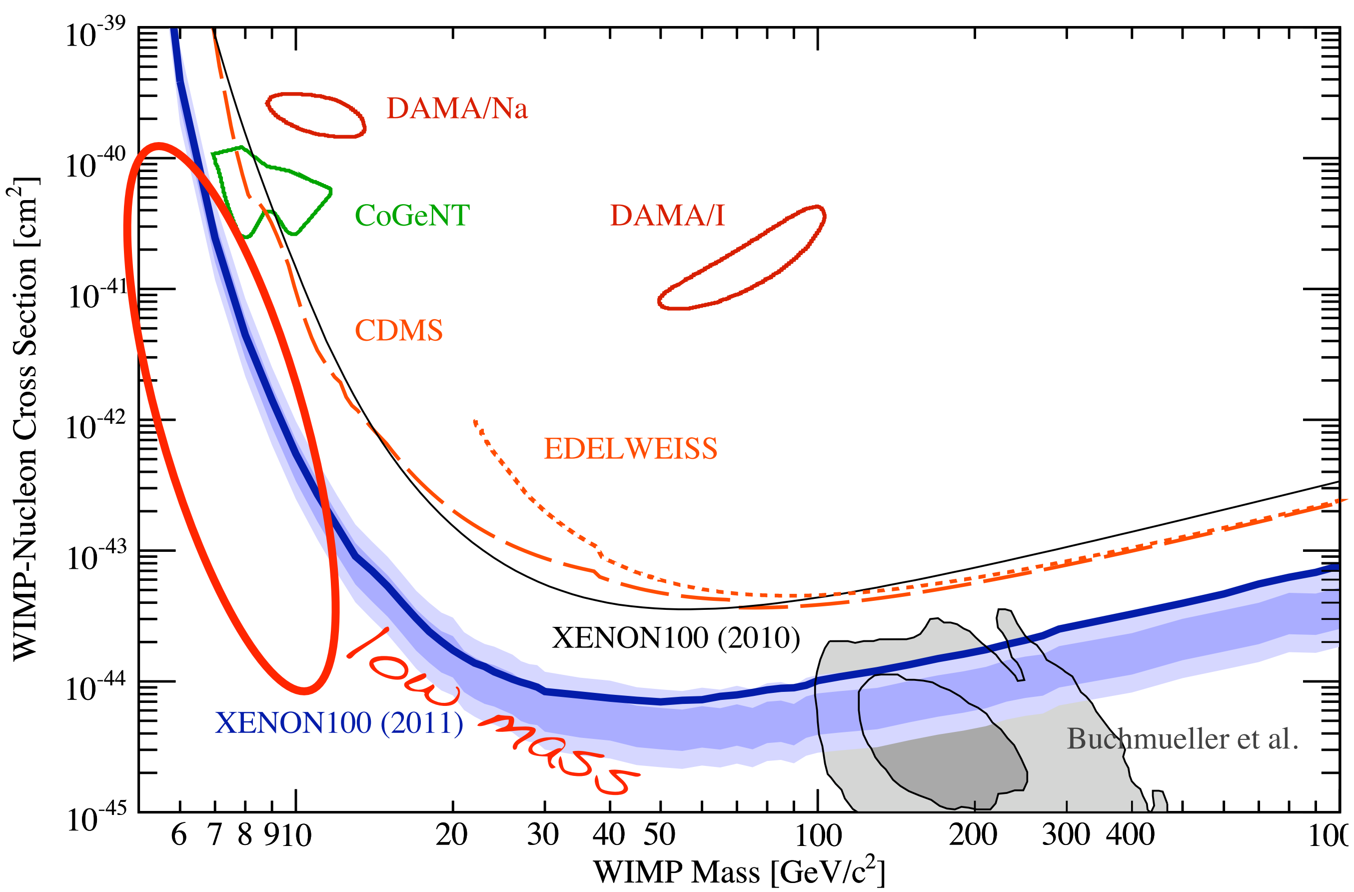

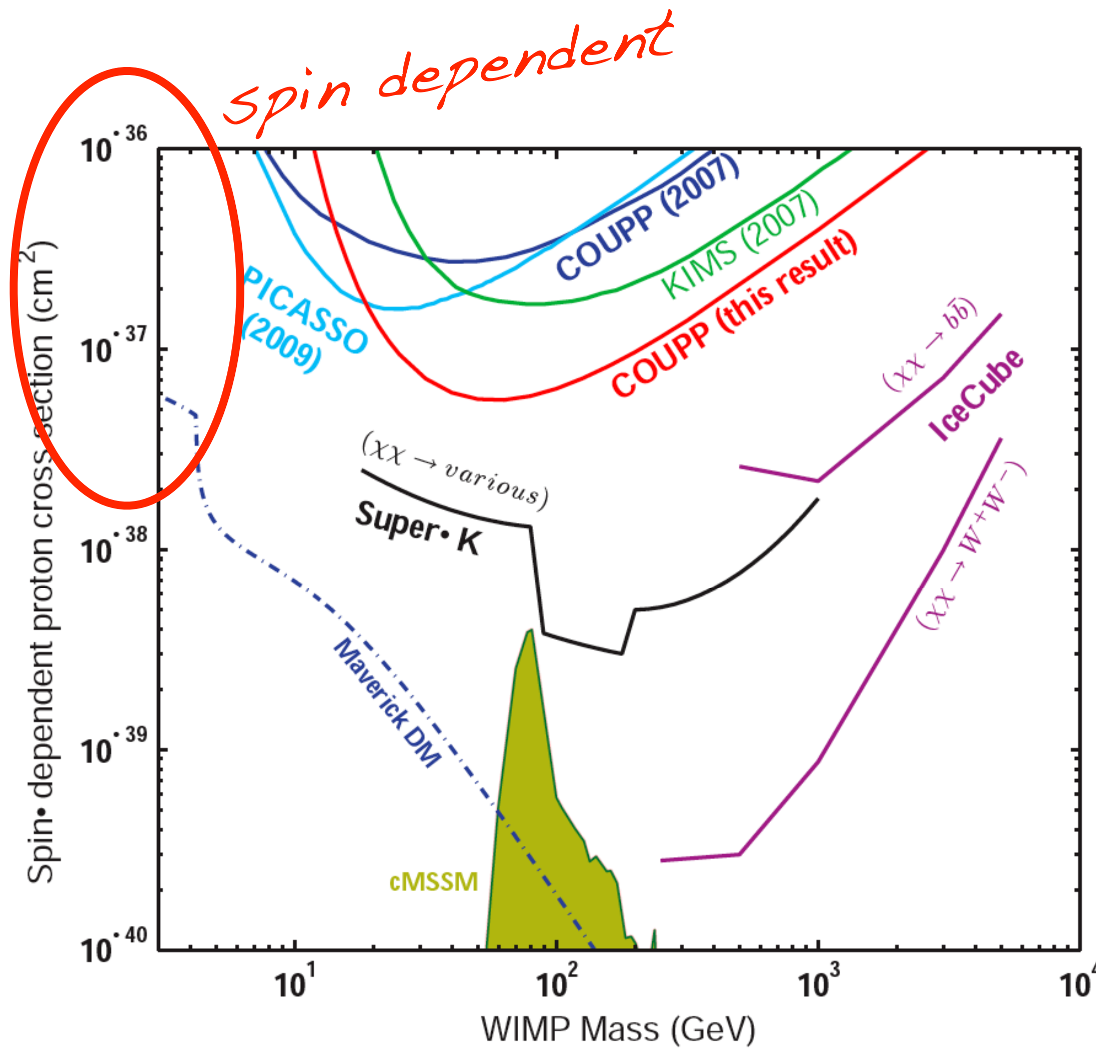

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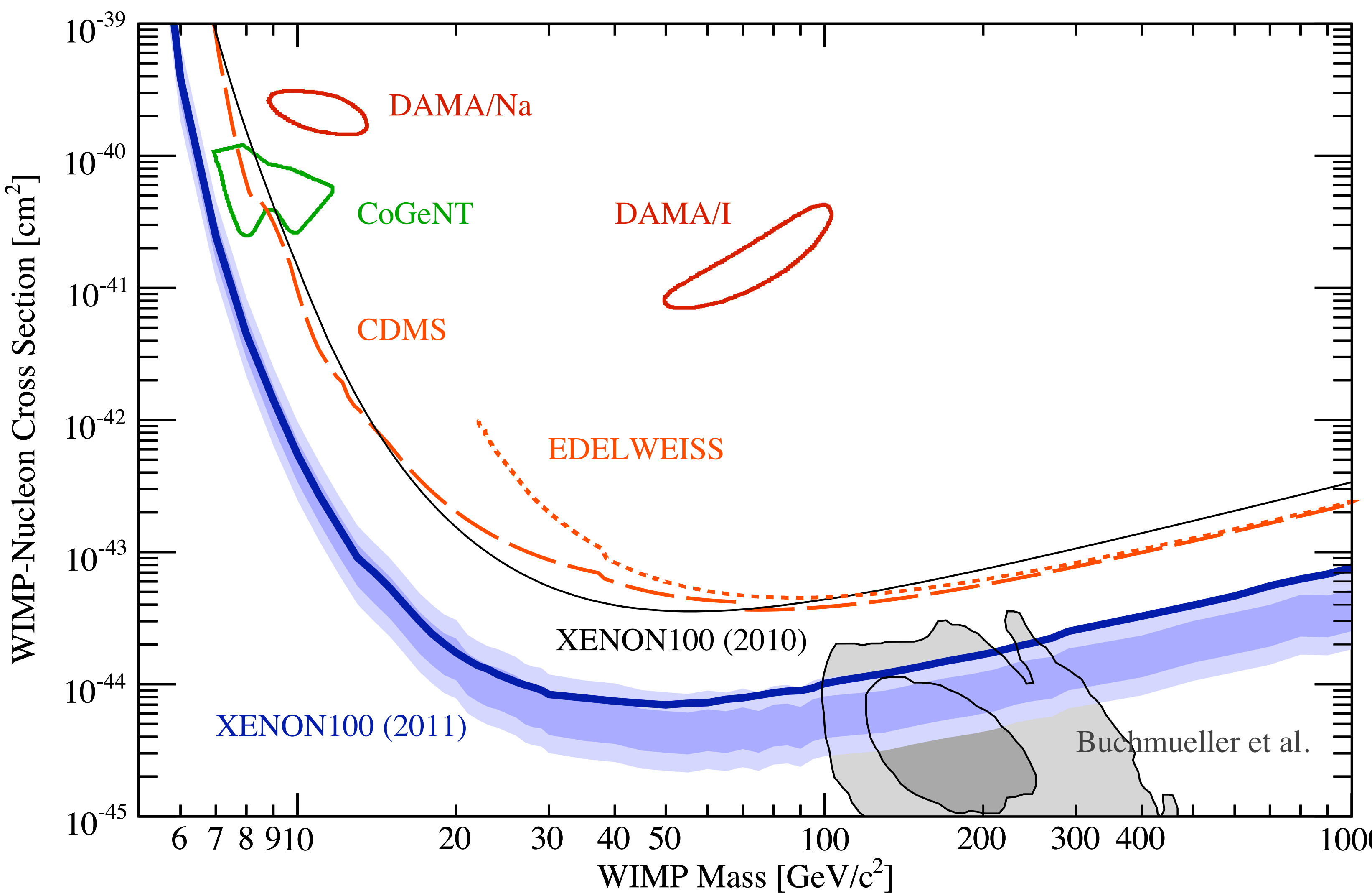
Collider Connections?

* DM experiments and colliders are often said to be related via SUSY, with theory priors.
  But can't we pick other priors?



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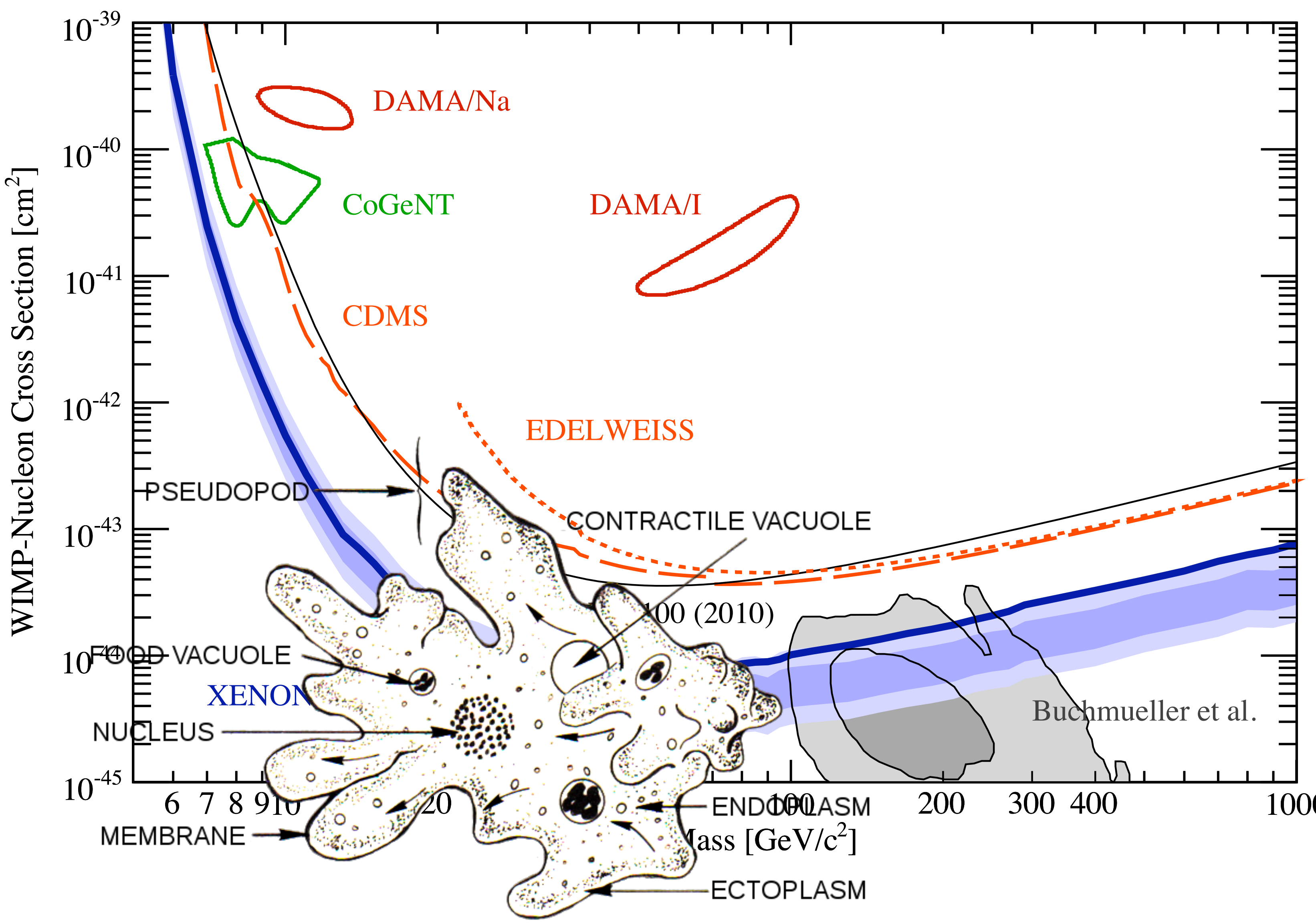

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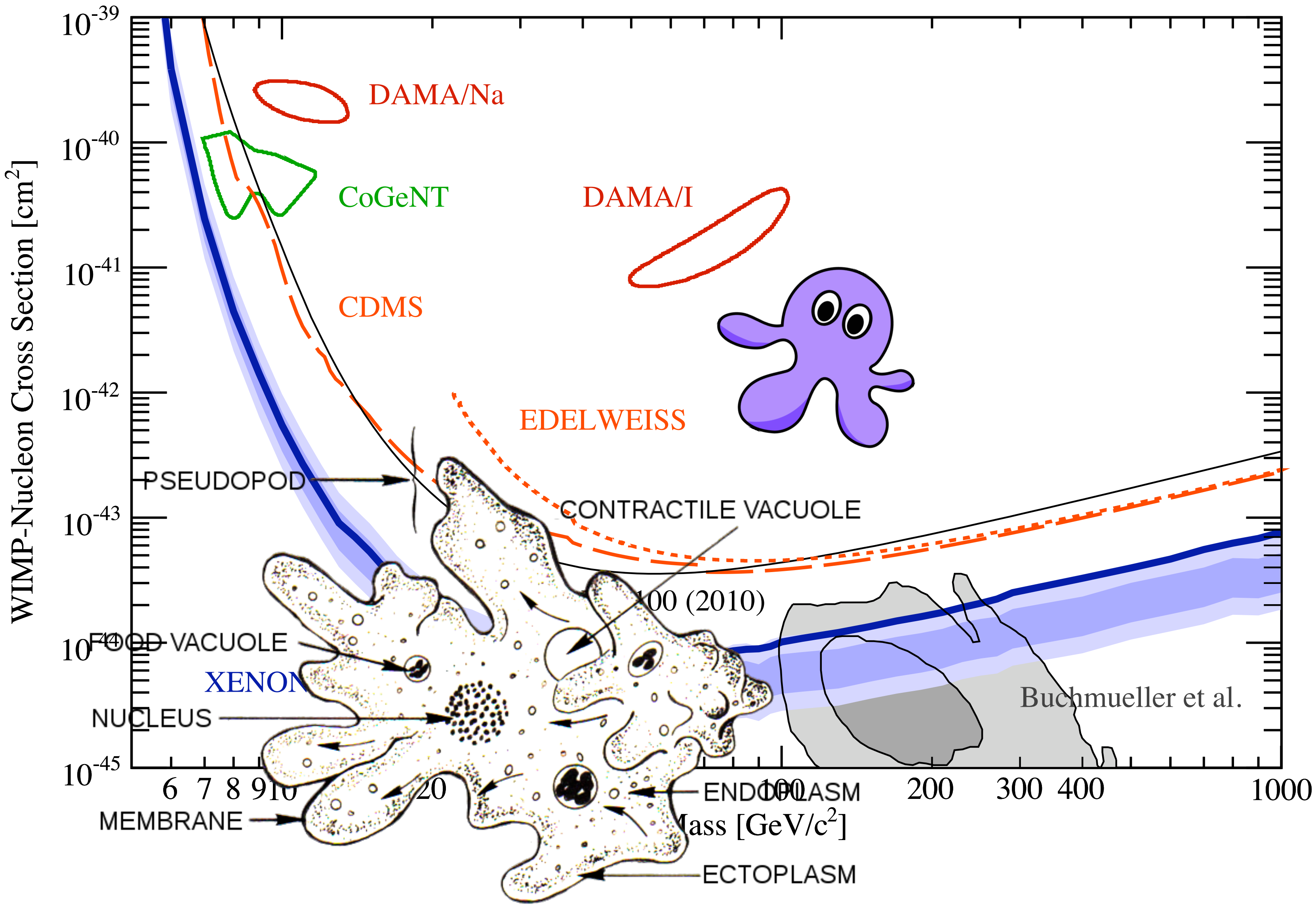

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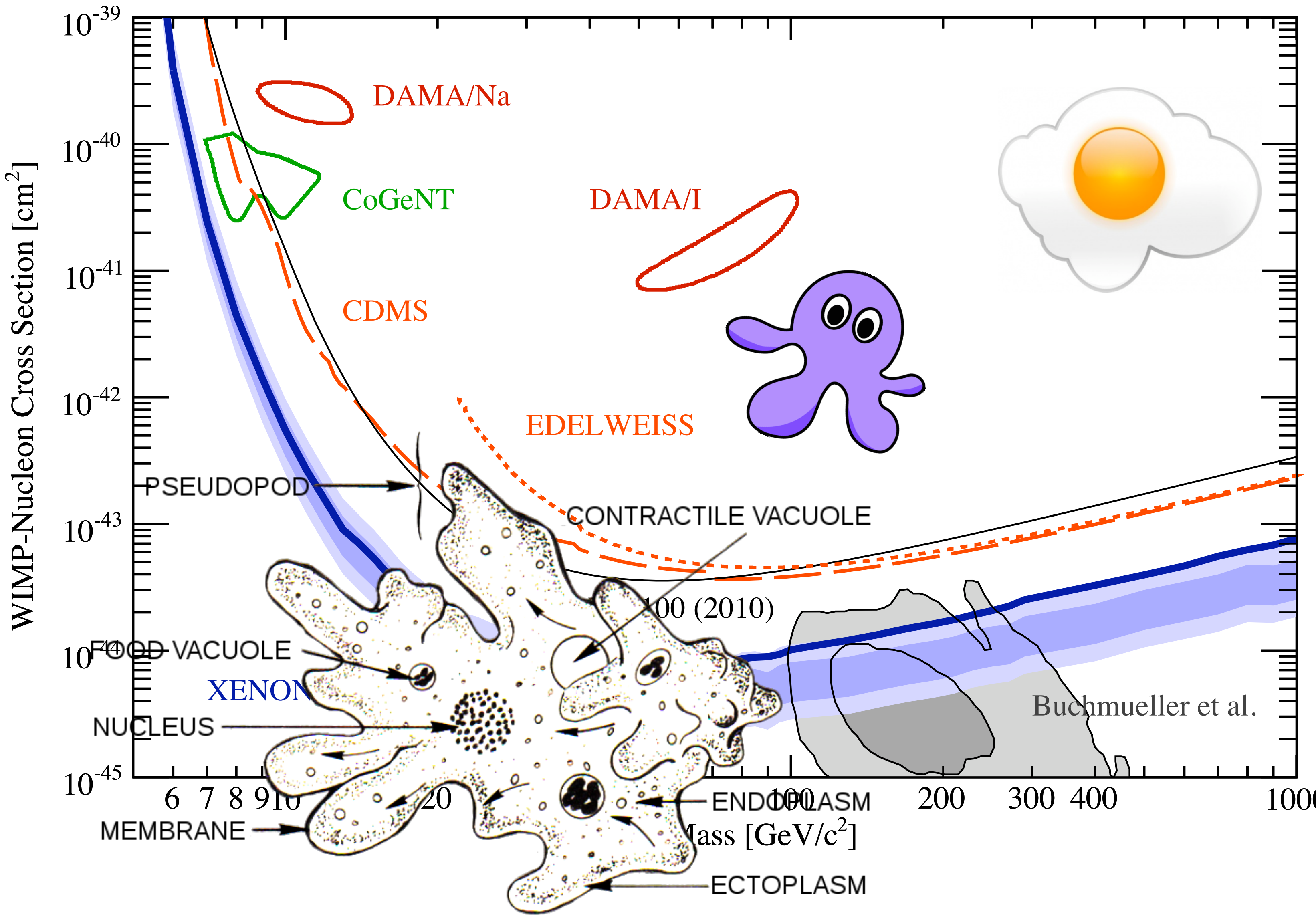

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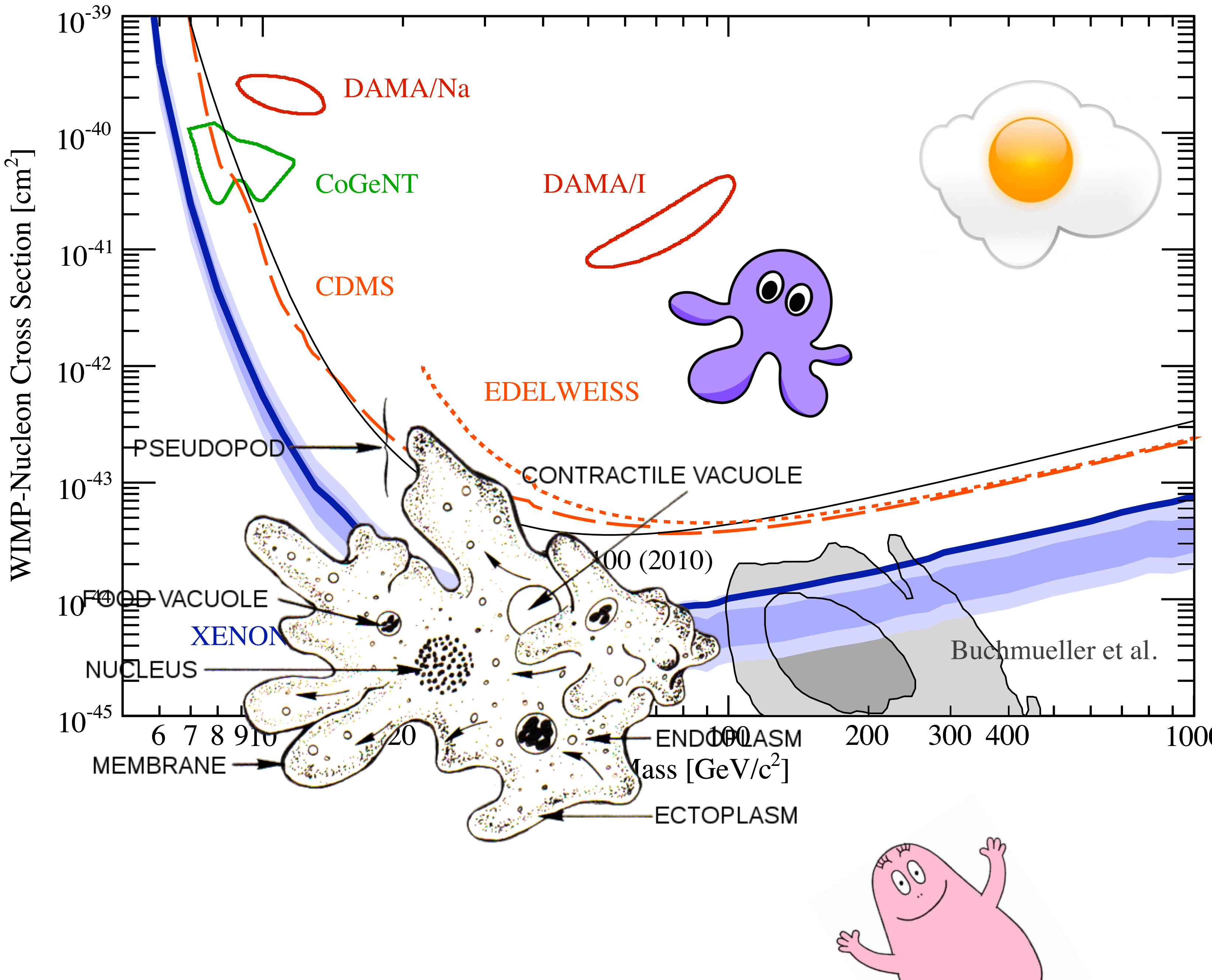

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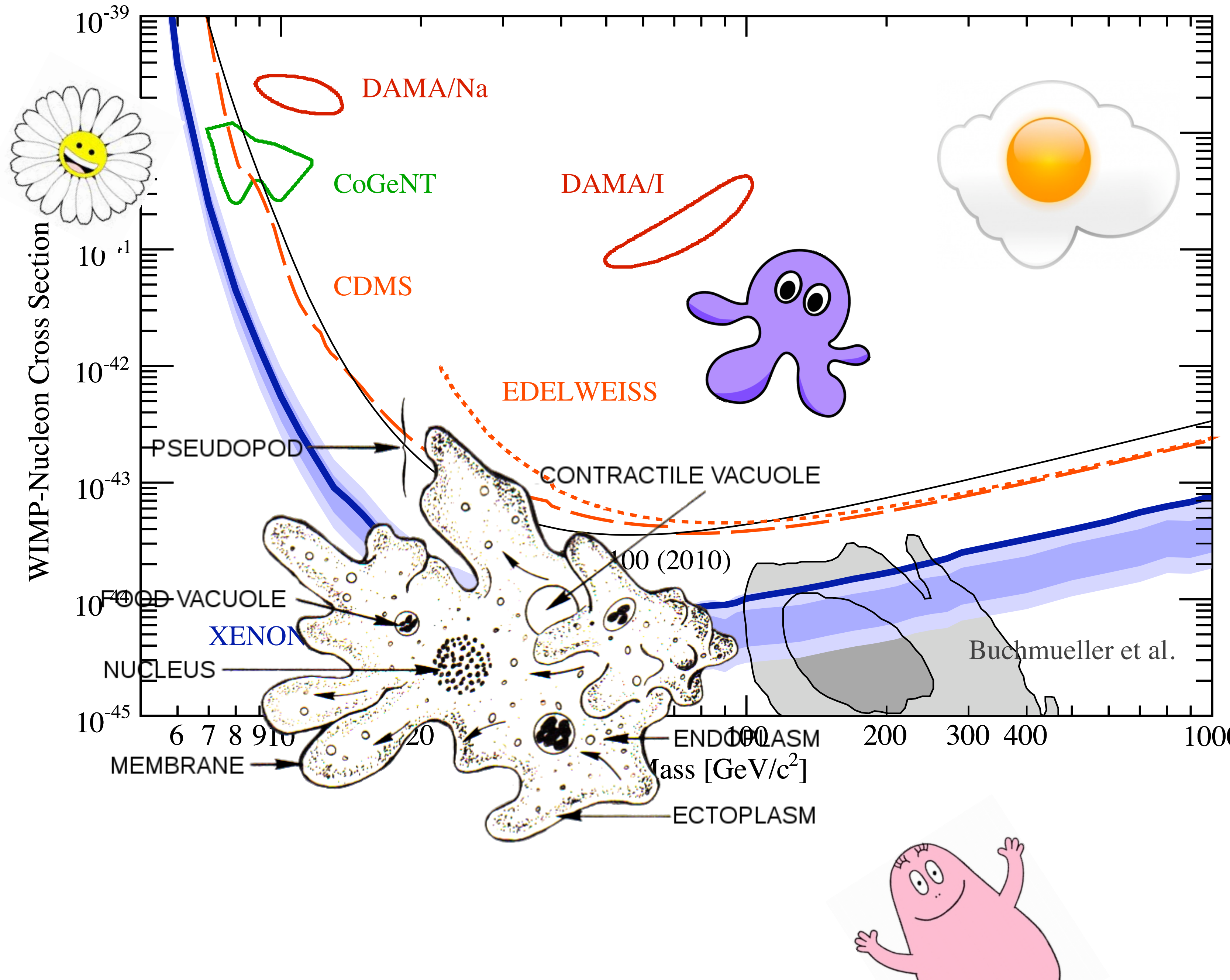
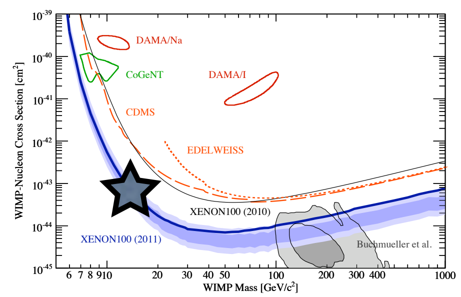
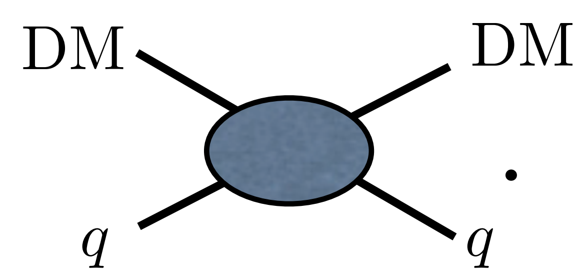
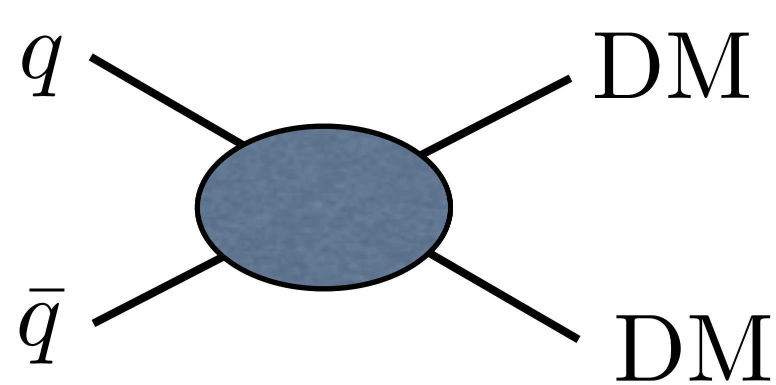


A Simple Point

- In order to get a particular DM-nucleon cross section,  , we assume the existence of a DM-hadron interaction,  .

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



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

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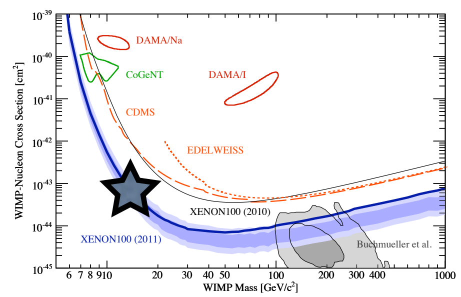
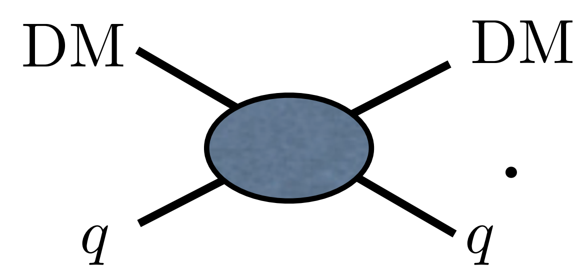
- In order to get a particular DM-nucleon cross section, 

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

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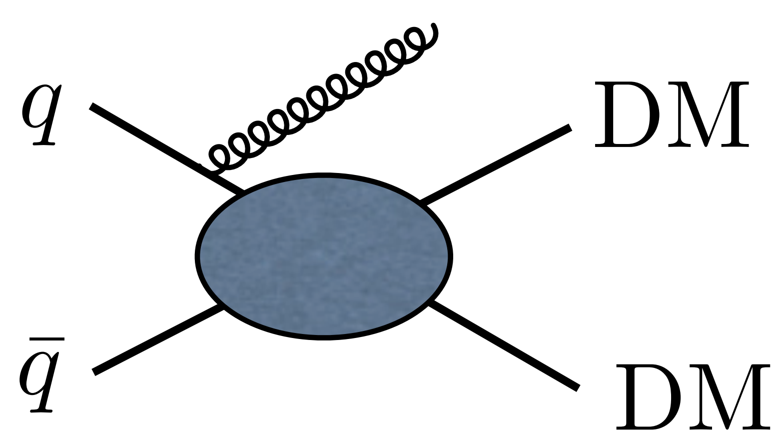
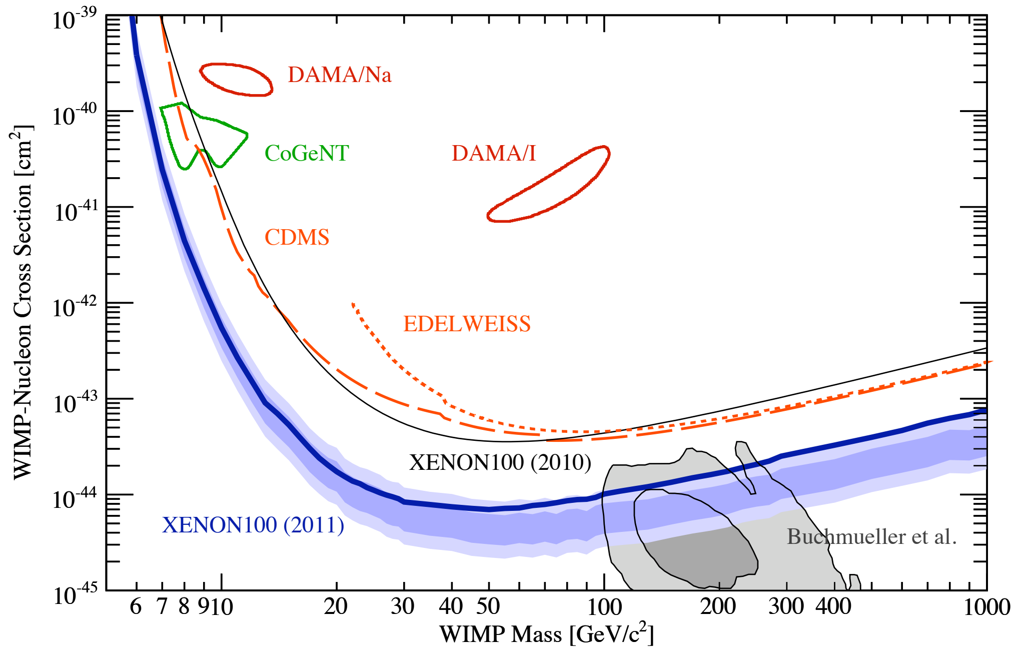
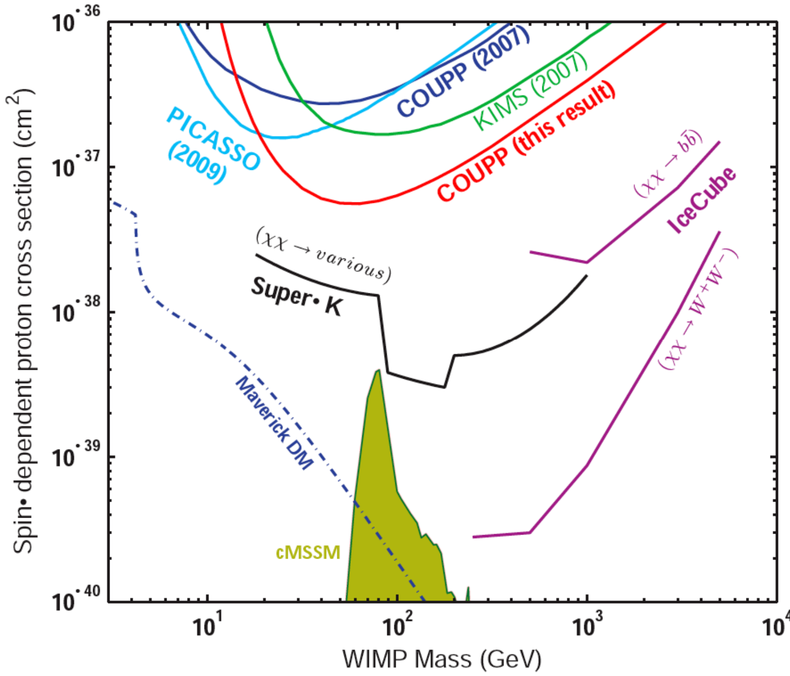


$$p\bar{p} \longrightarrow j + \not{E}_T$$

A Simple Point

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



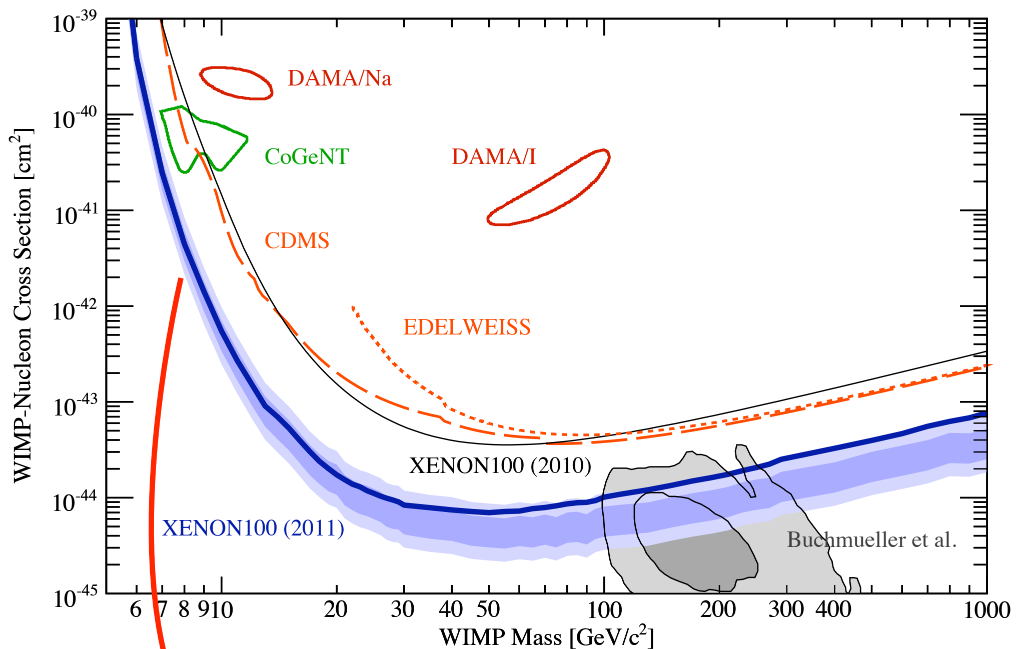


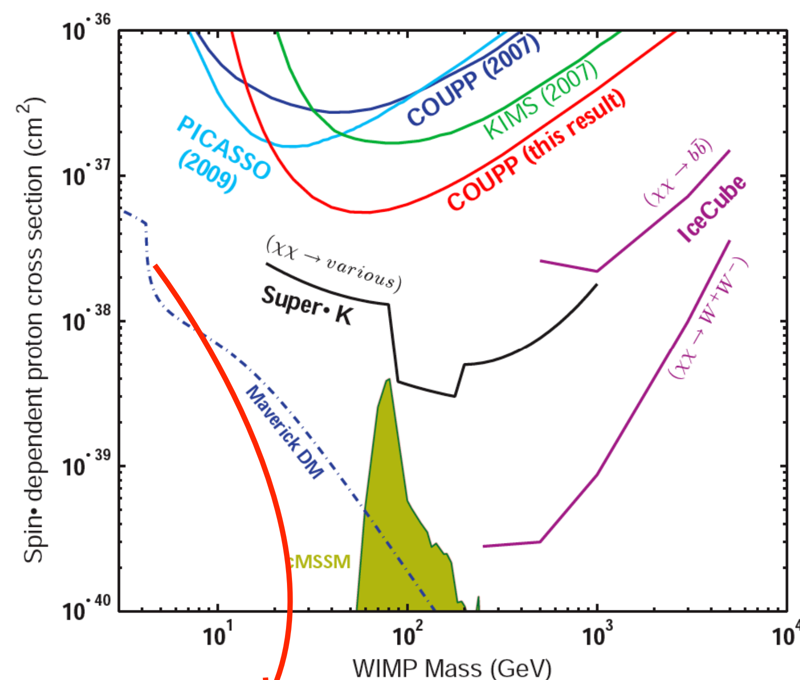
* These are **conservative** limits.
  In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

But mono-jet are certainly good to set bounds.

A Simple Point

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



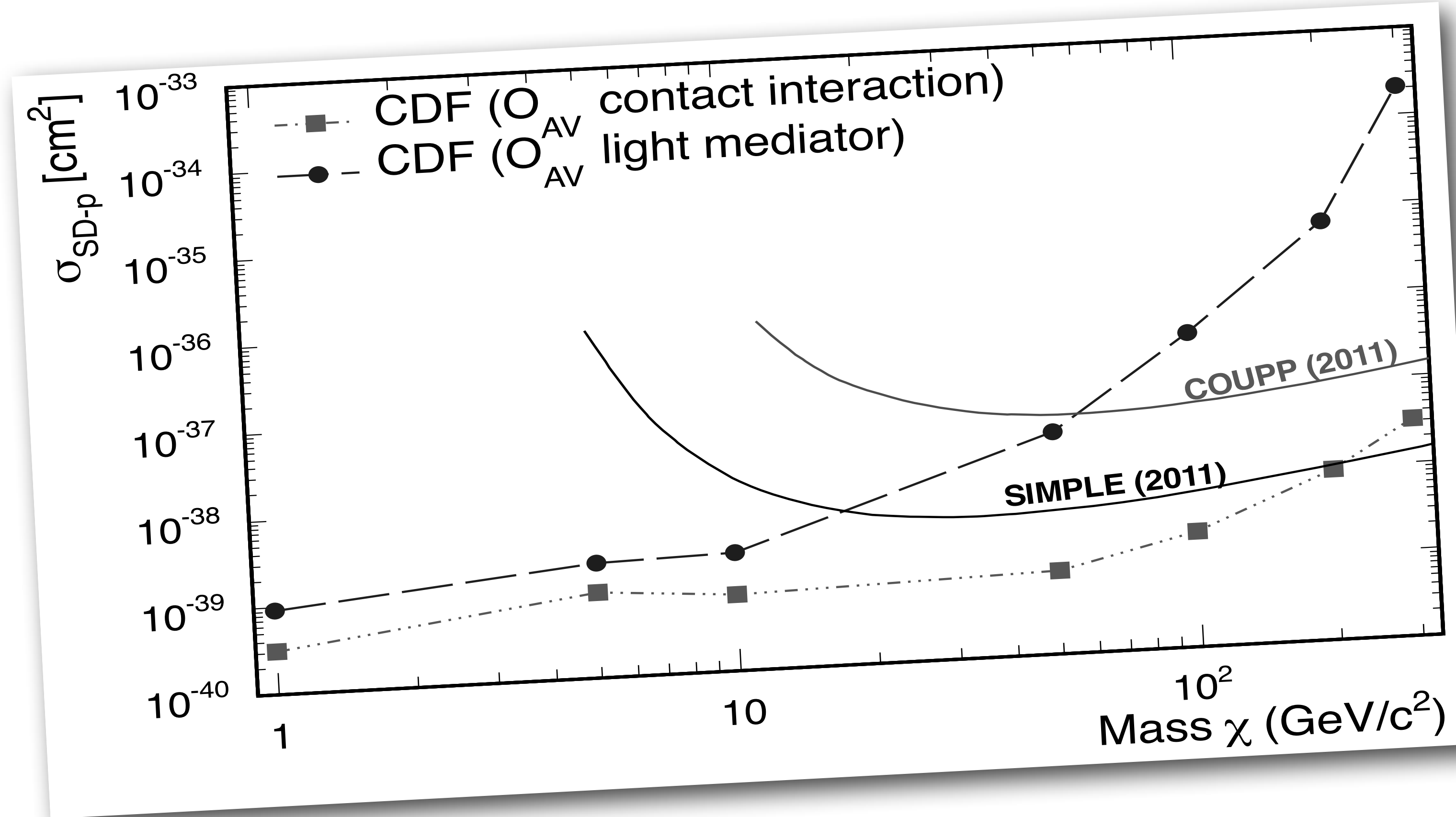


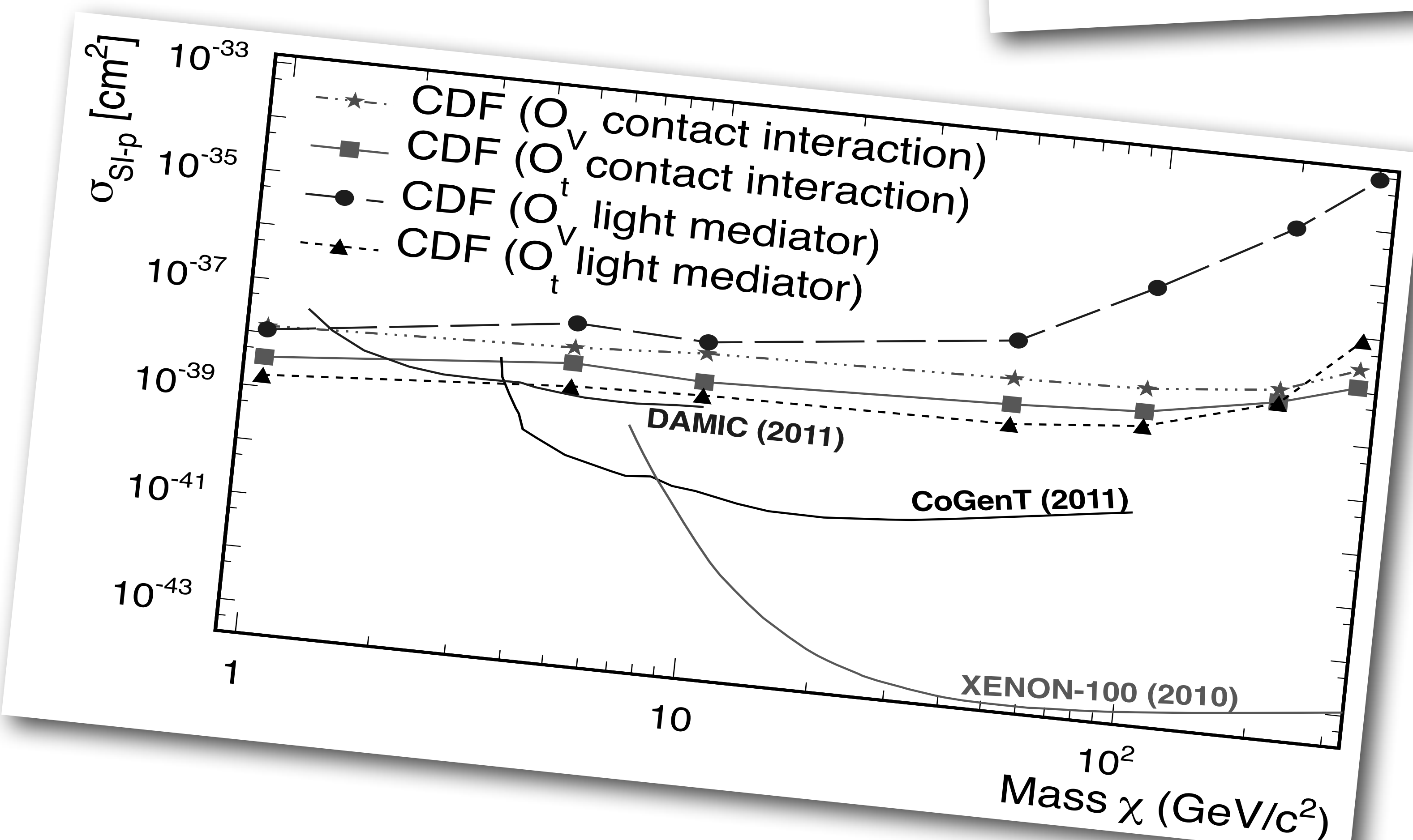
The collider does not have a low energy threshold

The collider does not pay a price for spin dependence

CDF Limits:

- CDF (+ 3 theorists) did a dedicated shape analysis of monojet spectra (with 6.7 fb^{-1}).

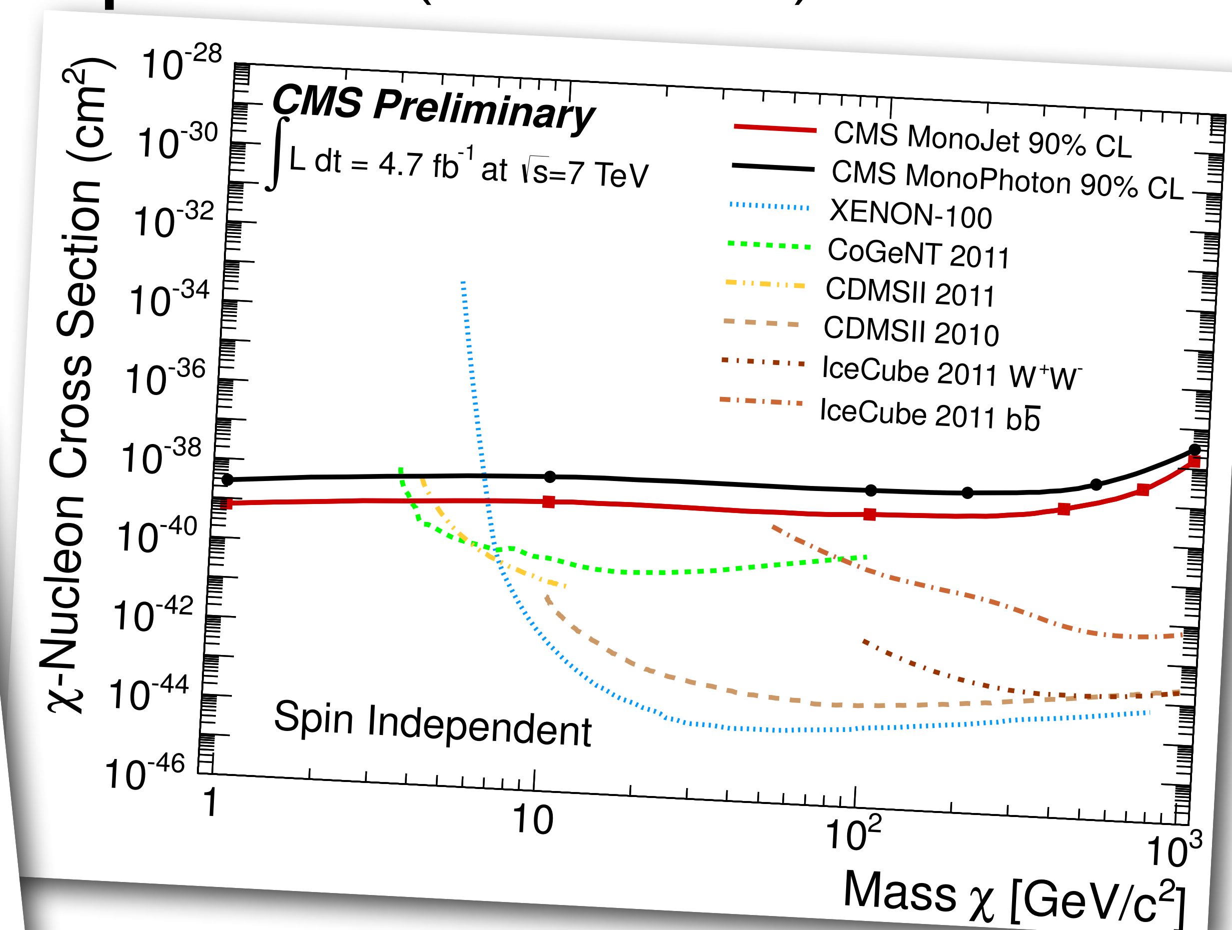


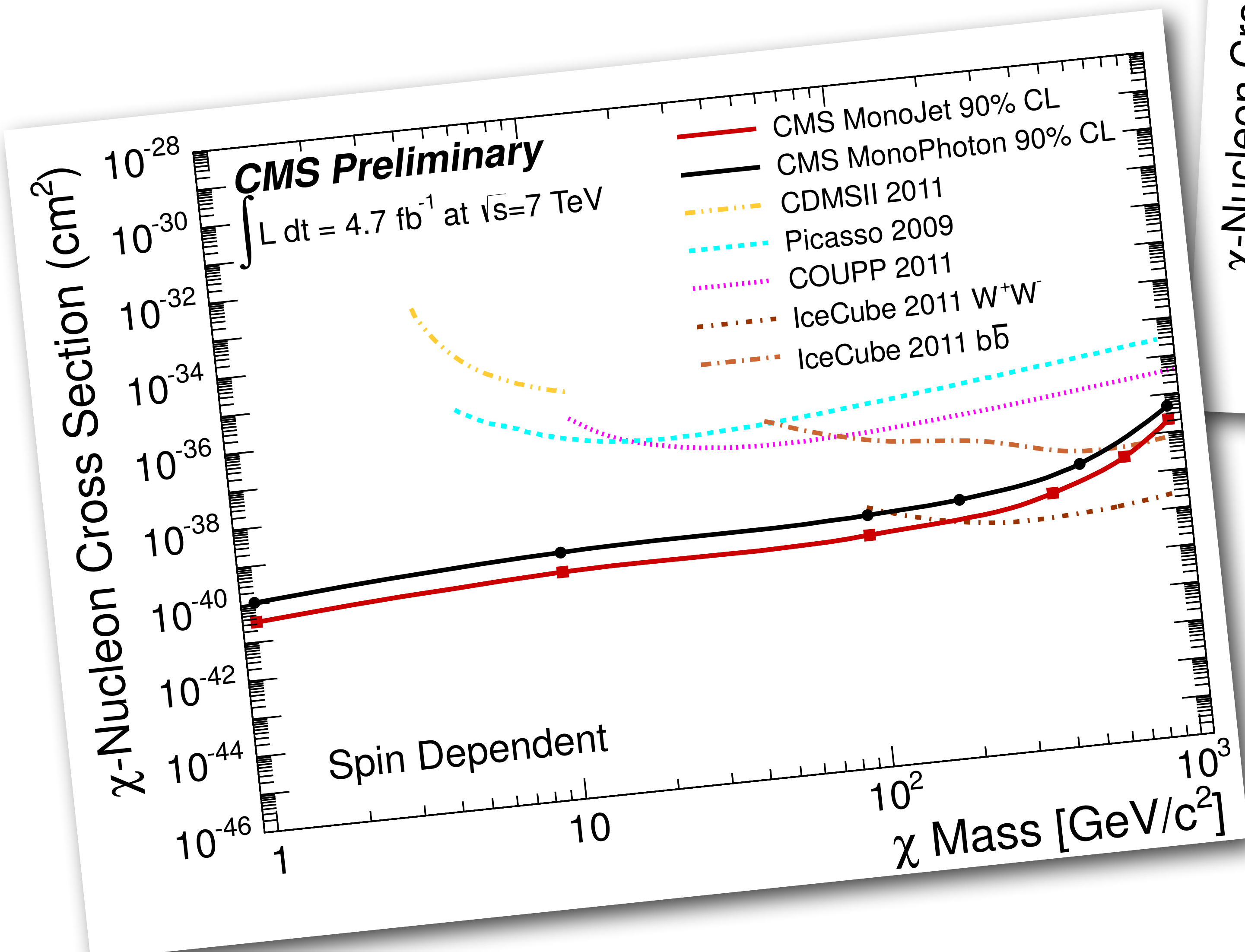


1203.0742

CMS Limits

- Both mono-jet and mono-photon (with 4.7 fb^{-1}).





ATLAS on the way.

Questions

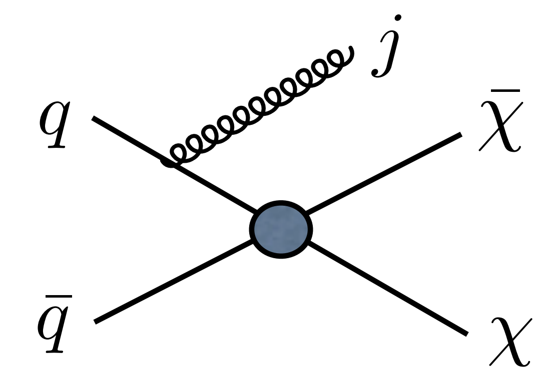
- How are these bounds produced?
- How can we improve these bounds?
- Which LHC searches are relevant?
- Which are optimal?

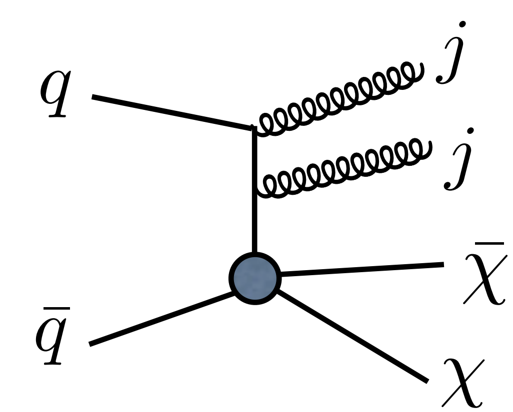
Relevant for other searches:
The LHC is entering a high luminosity phase,
where new physics that is produced only with
EW strengths is about to be probed.

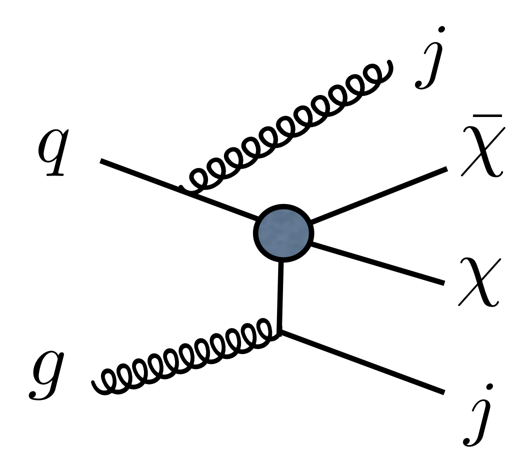
- What theoretical assumptions go into the bounds?
- How can collider bounds be evaded?

Outline

- Setup - operators and mediators
- Mono-Jets & Mono-photons.
- Multi-jets plus MET.
  - Handles on S vs B.
  - Razor analysis.
- Note on validity of EFT.
- DM Higgs interplay?







Direct Detection - EFT

* The EFT that described DM interaction in direct detection experiments:

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

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 "squark exchange"

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

SI gluon operator

Two possibilities:

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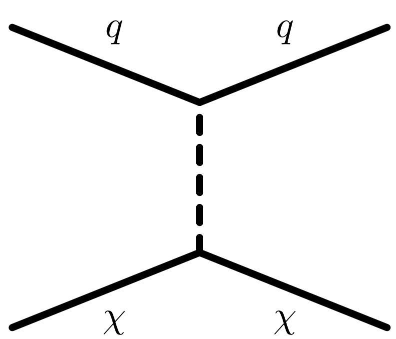
Two possibilities:

1) EFT is valid at LHC.
2) It's not.

EFT vs Light Mediator

* The EFT is valid for direct detection($q \sim 100$ MeV):

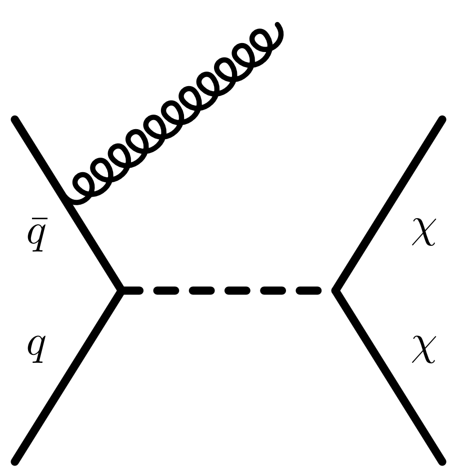


$$\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

$$\mu = \frac{m_\chi m_N}{m_N + m_\chi}$$

$$\Lambda \equiv \frac{M}{\sqrt{g_q g_\chi}}$$

* At a collider the EFT is either valid or not. In the two extreme limits:



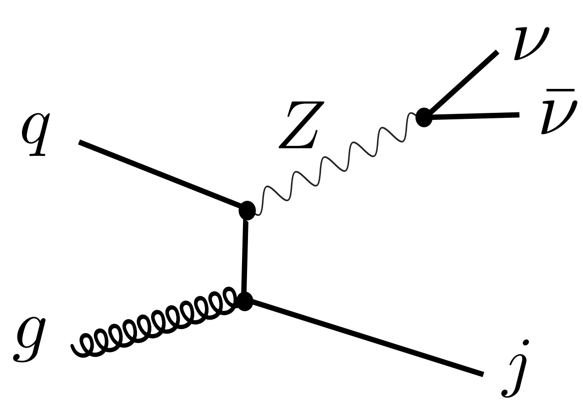
$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \ll \sqrt{s_*} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M > \sqrt{s_*} \end{cases}$$

Mono-Jet

Mono-Jet

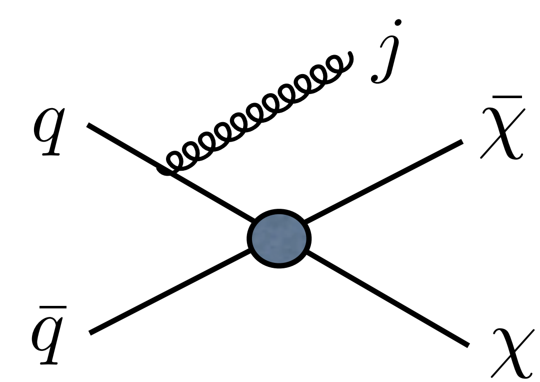
- *Assume* the EFT is valid at the LHC.
- Consider contact operator involving u or d.
- The signal spectrum is harder than backgrounds.

<u>dominant background</u>:
Z plus jet (qg initial state).



Z is typically emitted forward, with low p_T.

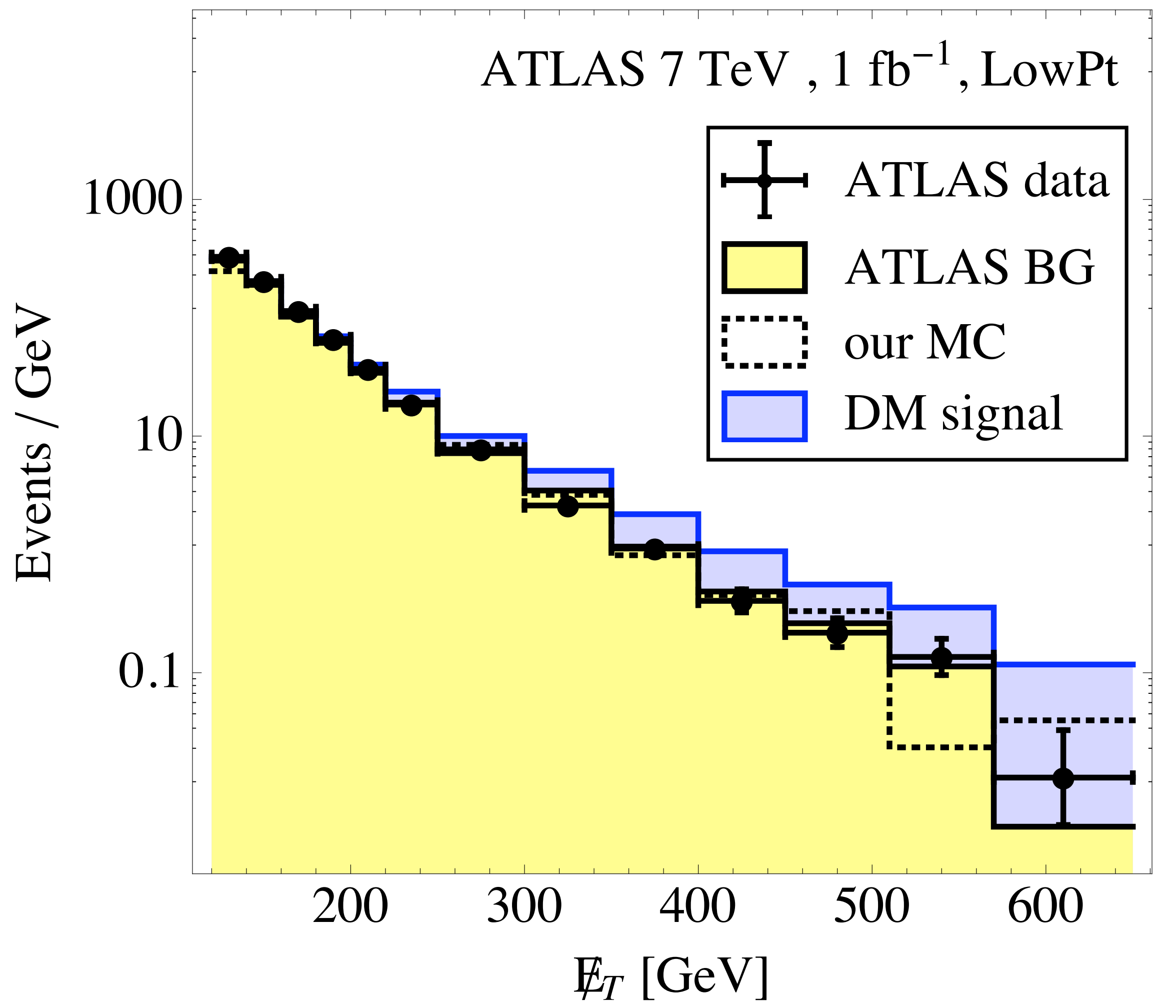
<u>dominant signal</u>:
$q\bar{q}$ initial state.



DM system emitted isotropically.

Mono-Jet

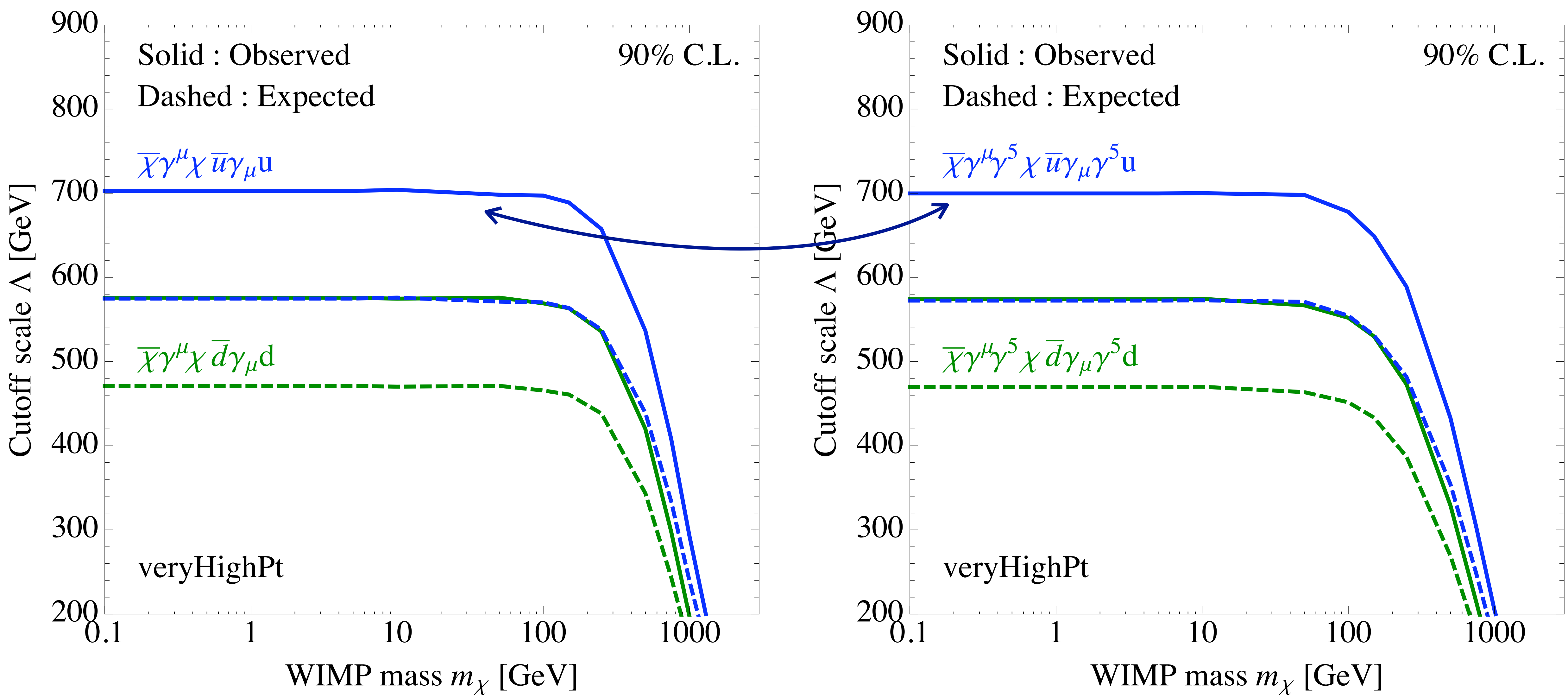
* For example, The ATLAS mono-jet search:



* Harder cuts are more sensitive.
  (unless DM couples to sea quarks).

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

same limit for SI and SD



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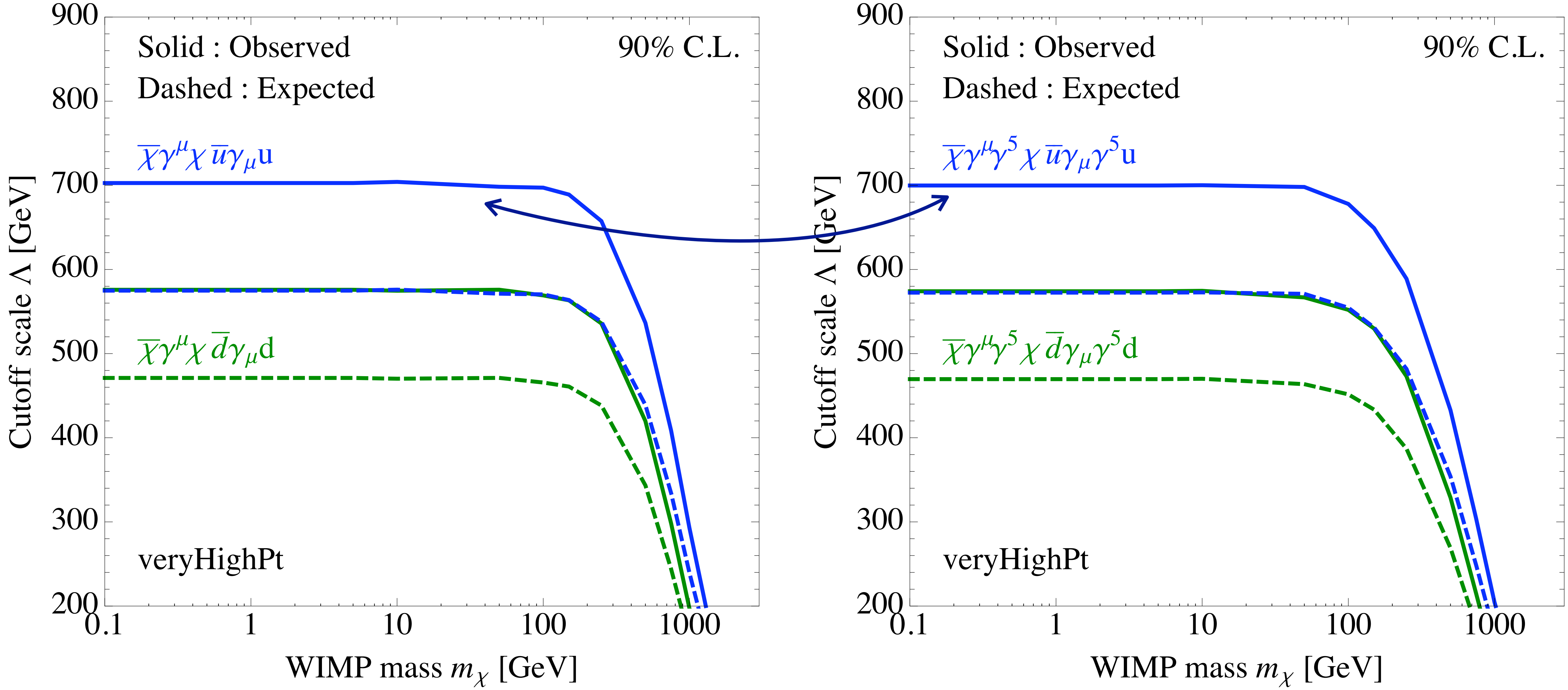
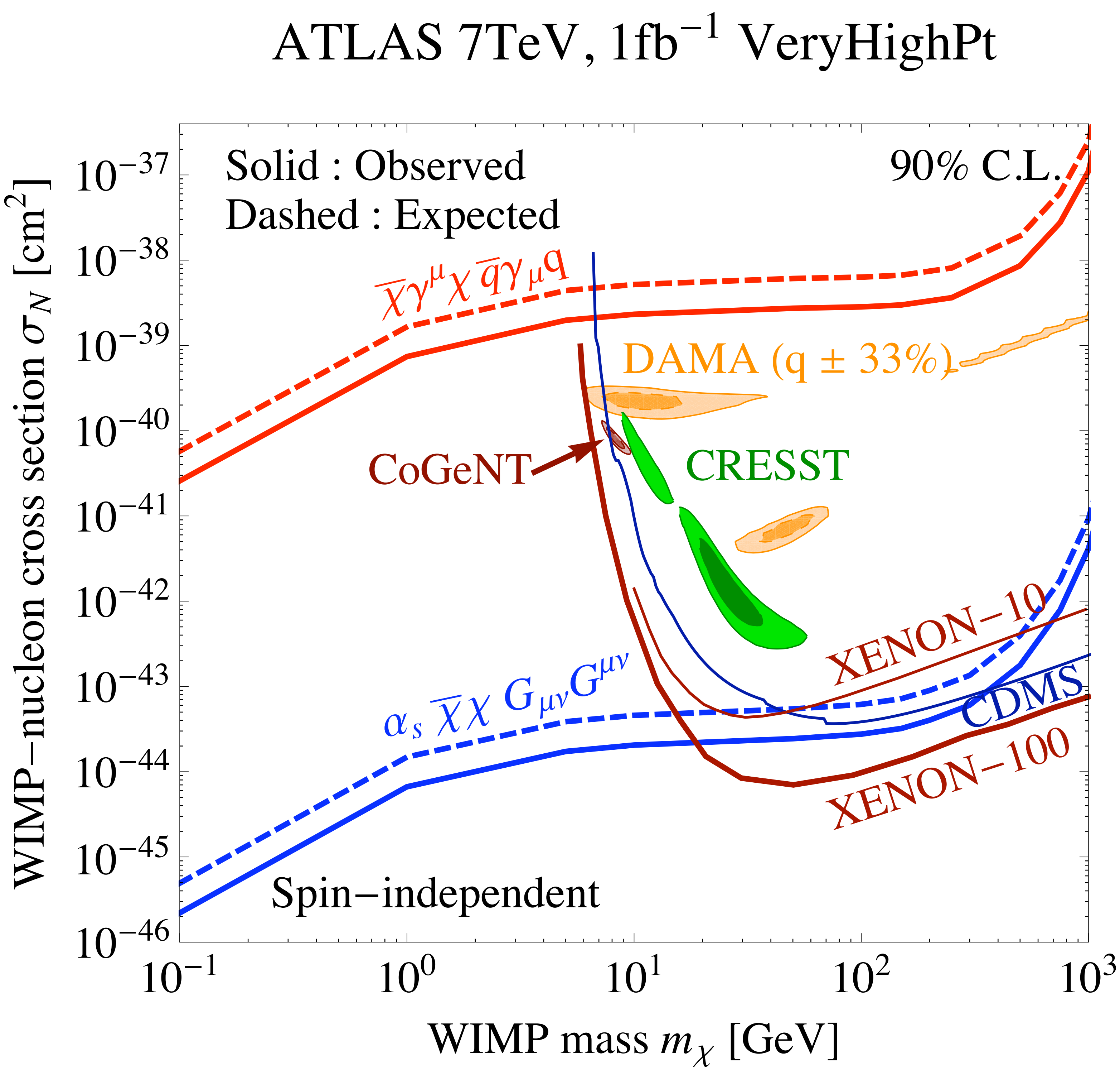


The limit is flat up to ~200 GeV.
Goes all the way to zero.

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

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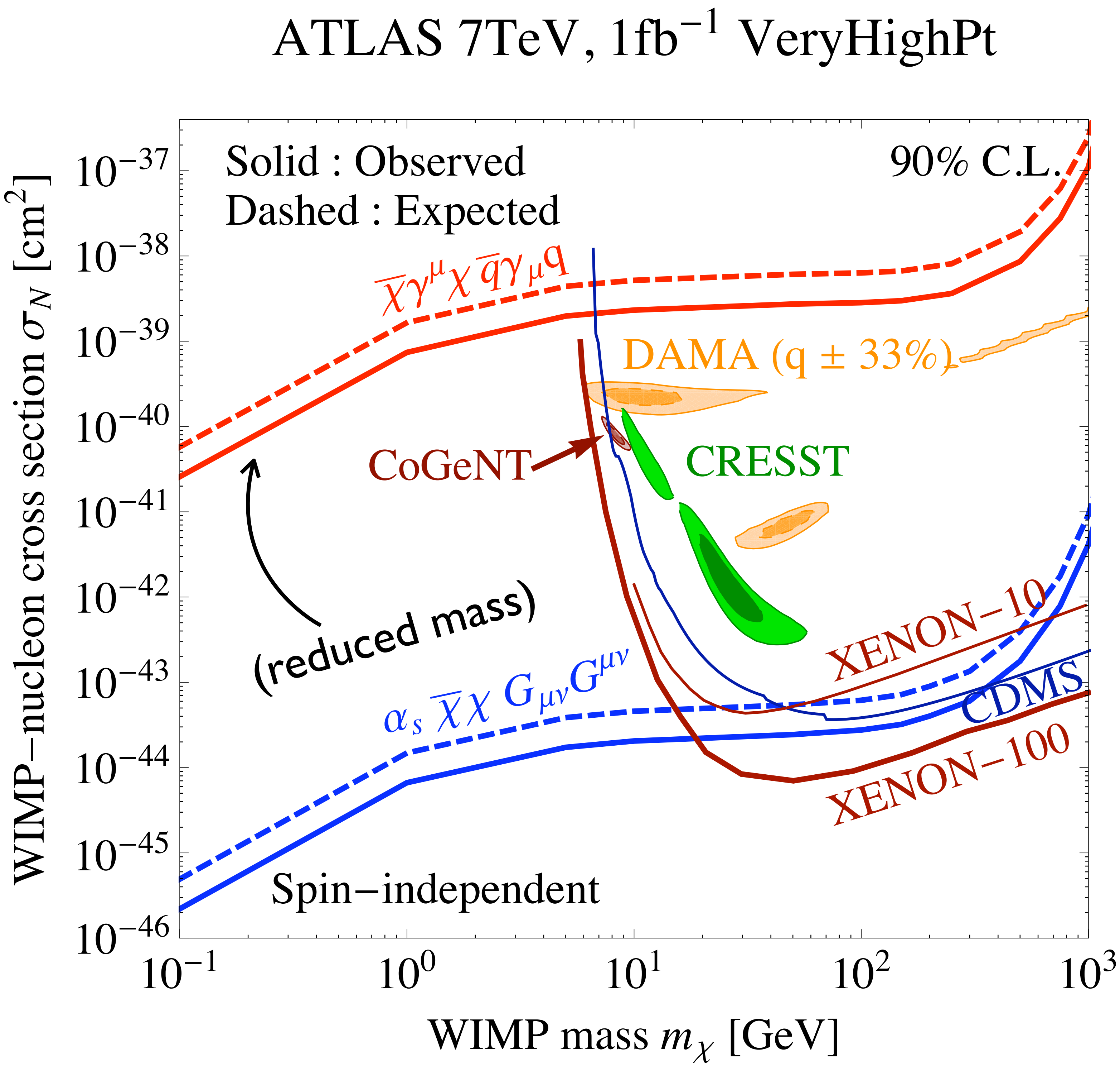
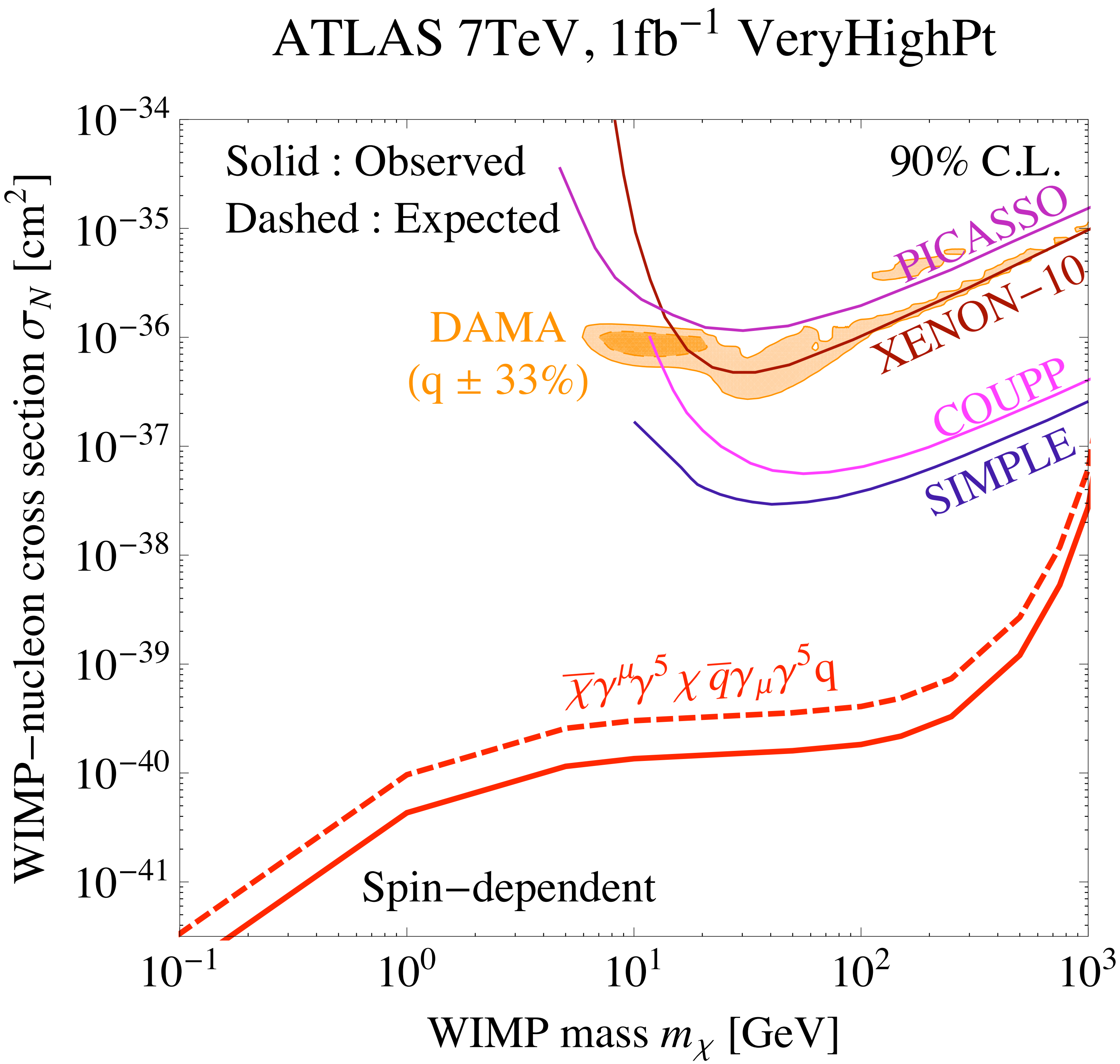


Best limit at low mass

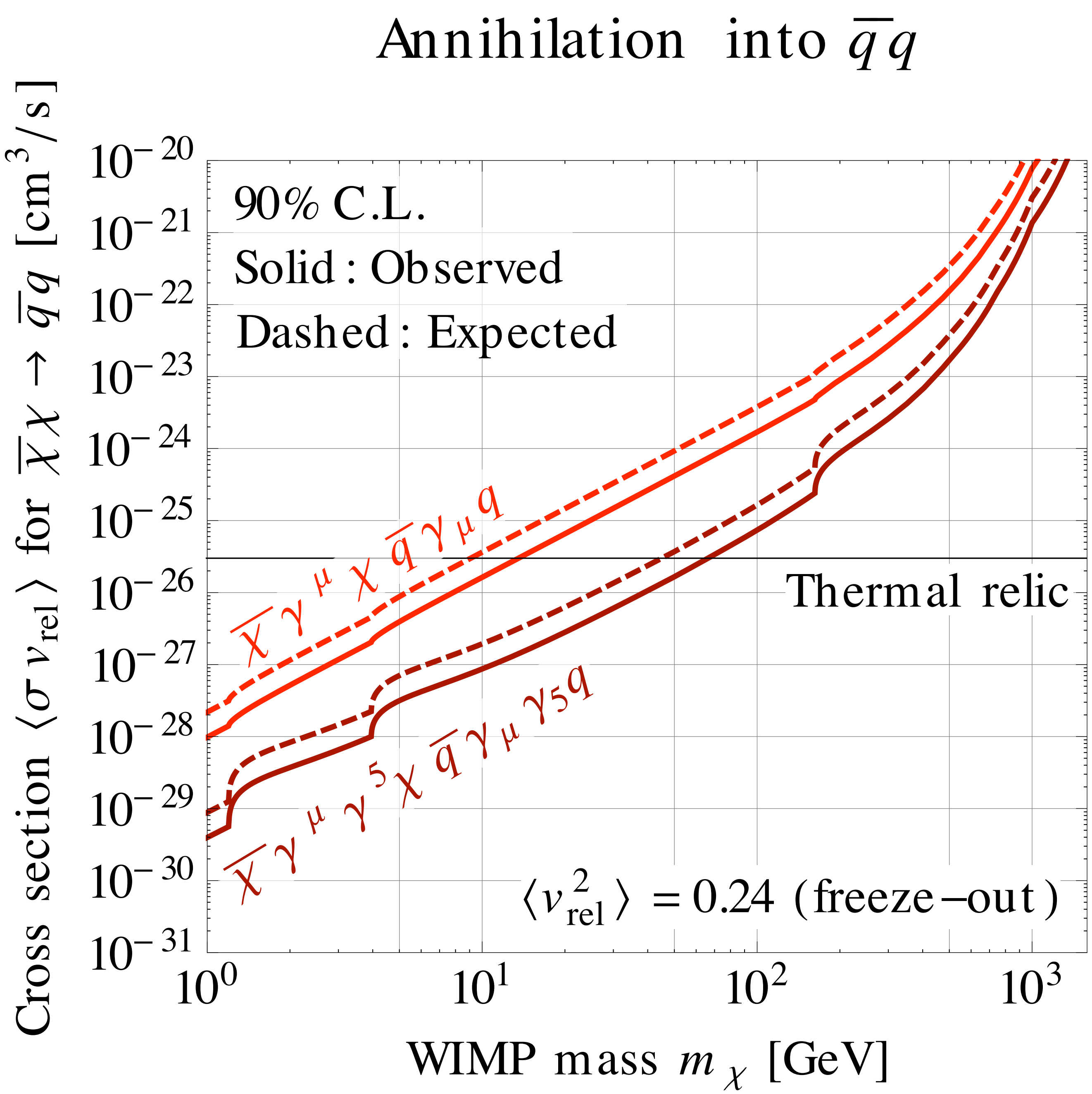
SD Limit



Best spin dependent limit.

Annihilation

* A minimal light thermal relic is ruled out:



Can we evade bounds?

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$ and lower M.

  The couplings must be decreased to compensate.

* Then for very small M we get to the regime where

$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

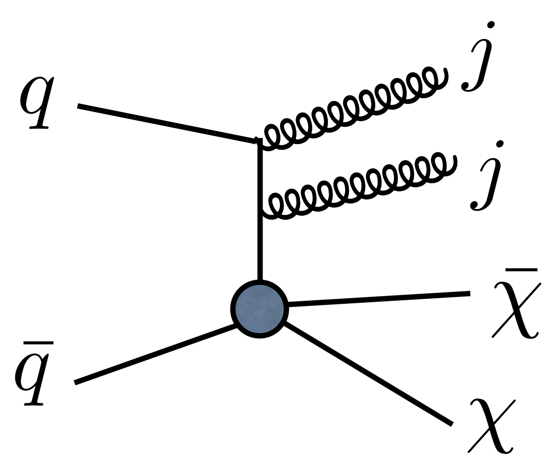
* The cross section drops as M^4.

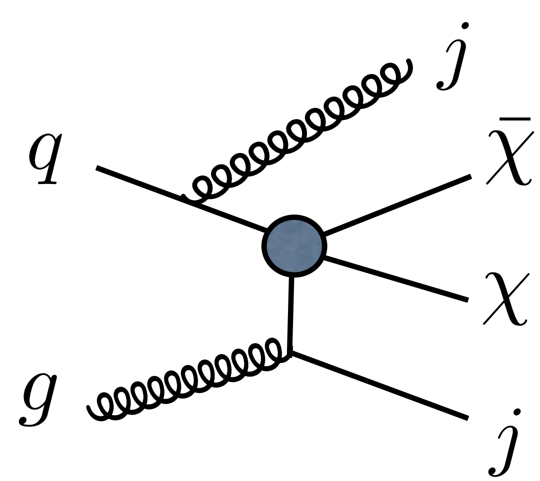
* **Theories with light mediators always evade the collider bound.**

(**But**....more on the intermediate regime later)

Jets plus MET

(with Fox, Primulando and Yu, 1203.1662)



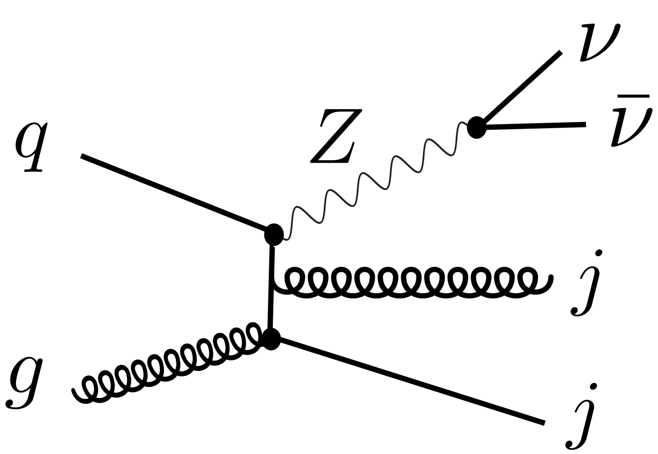


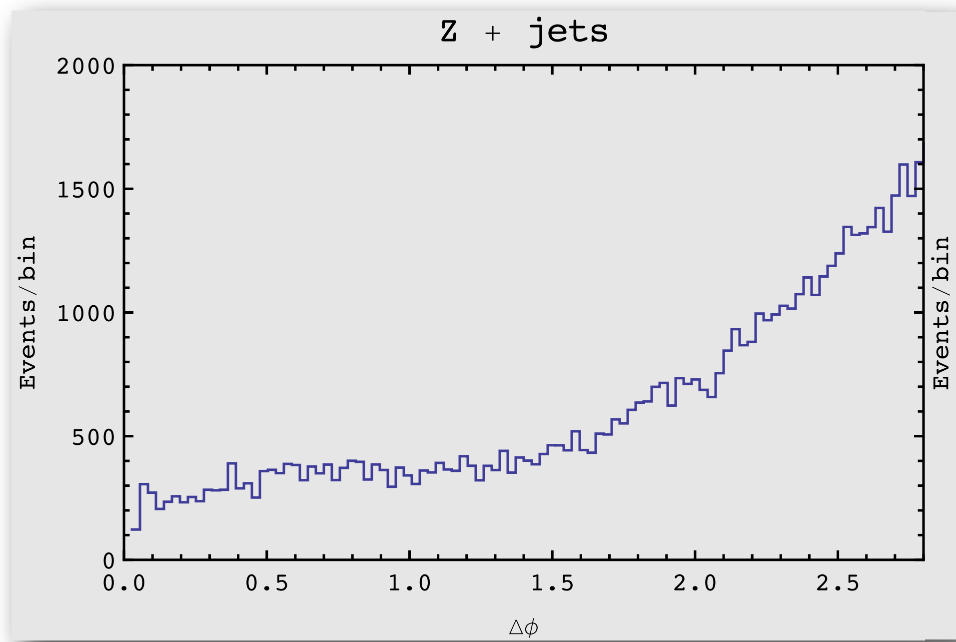
More Jets

* Applying a veto on the second jet reduces signal efficiency, and increases theory uncertainty.
* Indeed, most recent CMS (and upcoming ATLAS) mono-jet searches allow for a **hard second jet**, so-long as its not back to back with first jet.
* Inclusive jets plus MET searches for SUSY exist. Can we use them as searches for dark matter?

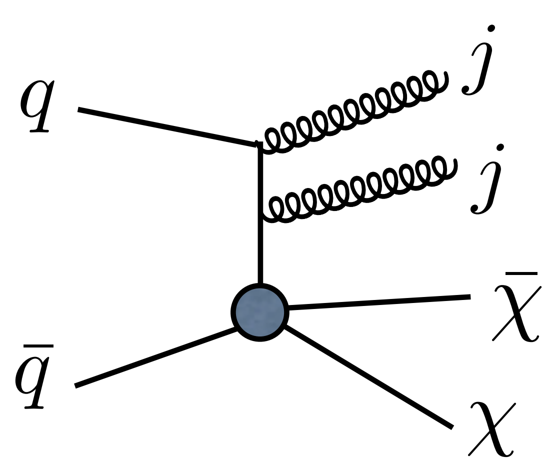
More Jets

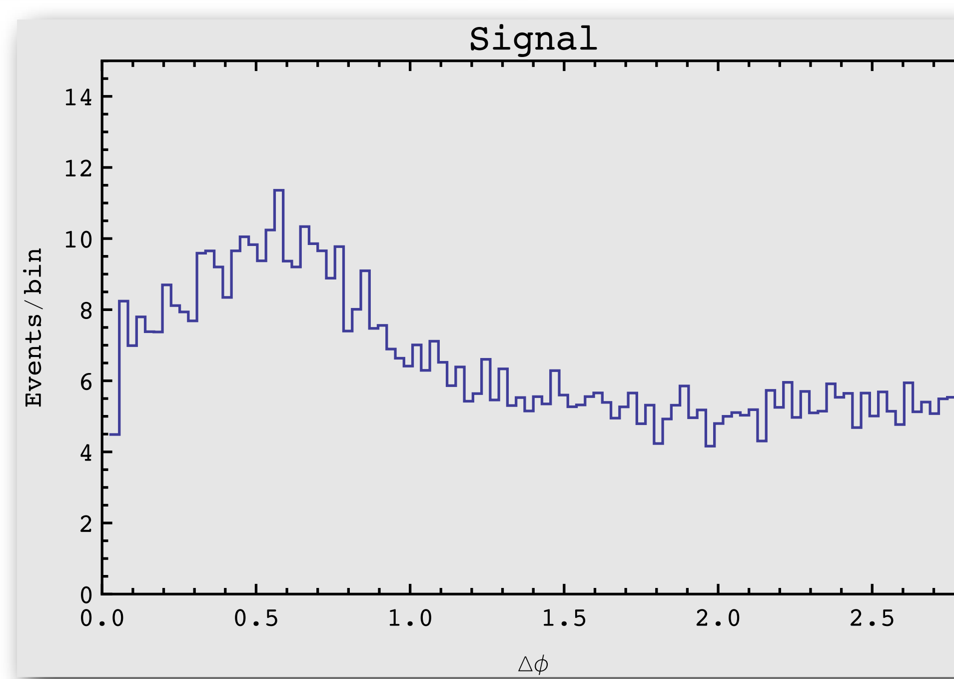
* Signal and Background have different dominant initial states, different angular distributions:





Azimuthal angle b/w jets





Razor

- We would like an analysis that is also sensitive to the angular distribution of jets and to MET.
- CMS's Razor analysis limits SUSY by inspecting a 2D distribution of two kinematic variables.
- The Razor variables follow simple exponential distributions - a data driven analysis.

Razor

- Consider events

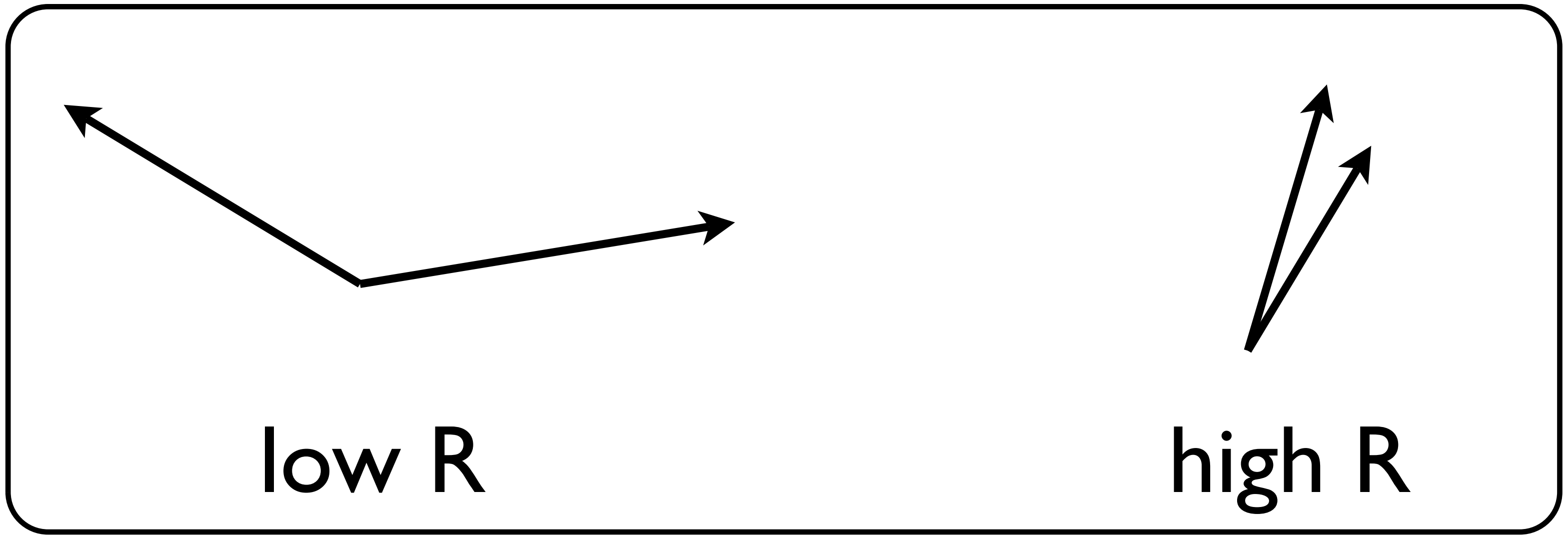
$$M_R = \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

$$M_R^T = \sqrt{\frac{\not{E}_T(p_T^{j_1} + p_T^{j_2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j_1} + \vec{p}_T^{j_2})}{2}}$$

$$R = \frac{M_R^T}{M_R}$$

Estimators for characteristic scale in the event

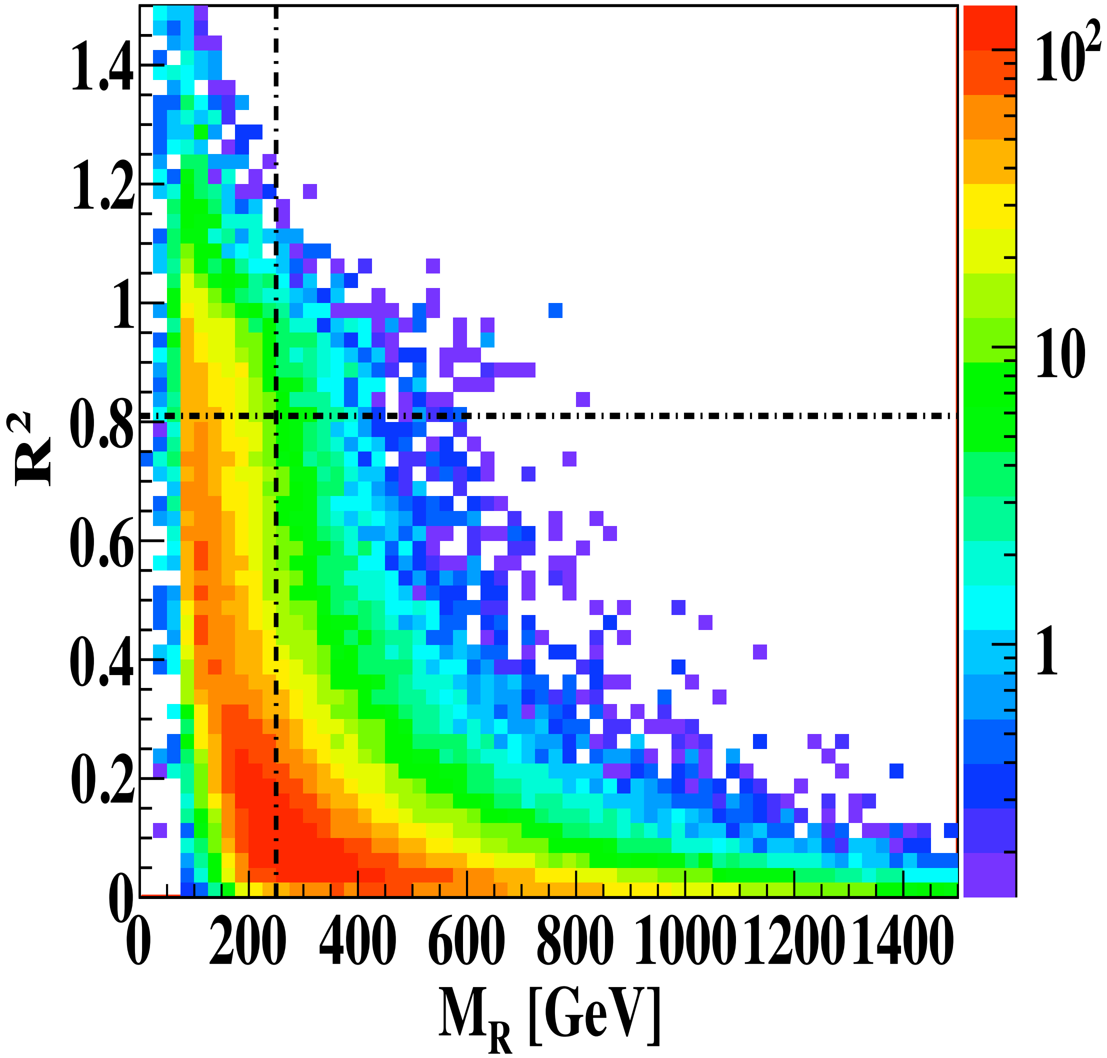
roughly: R=ratio of MET to visible.



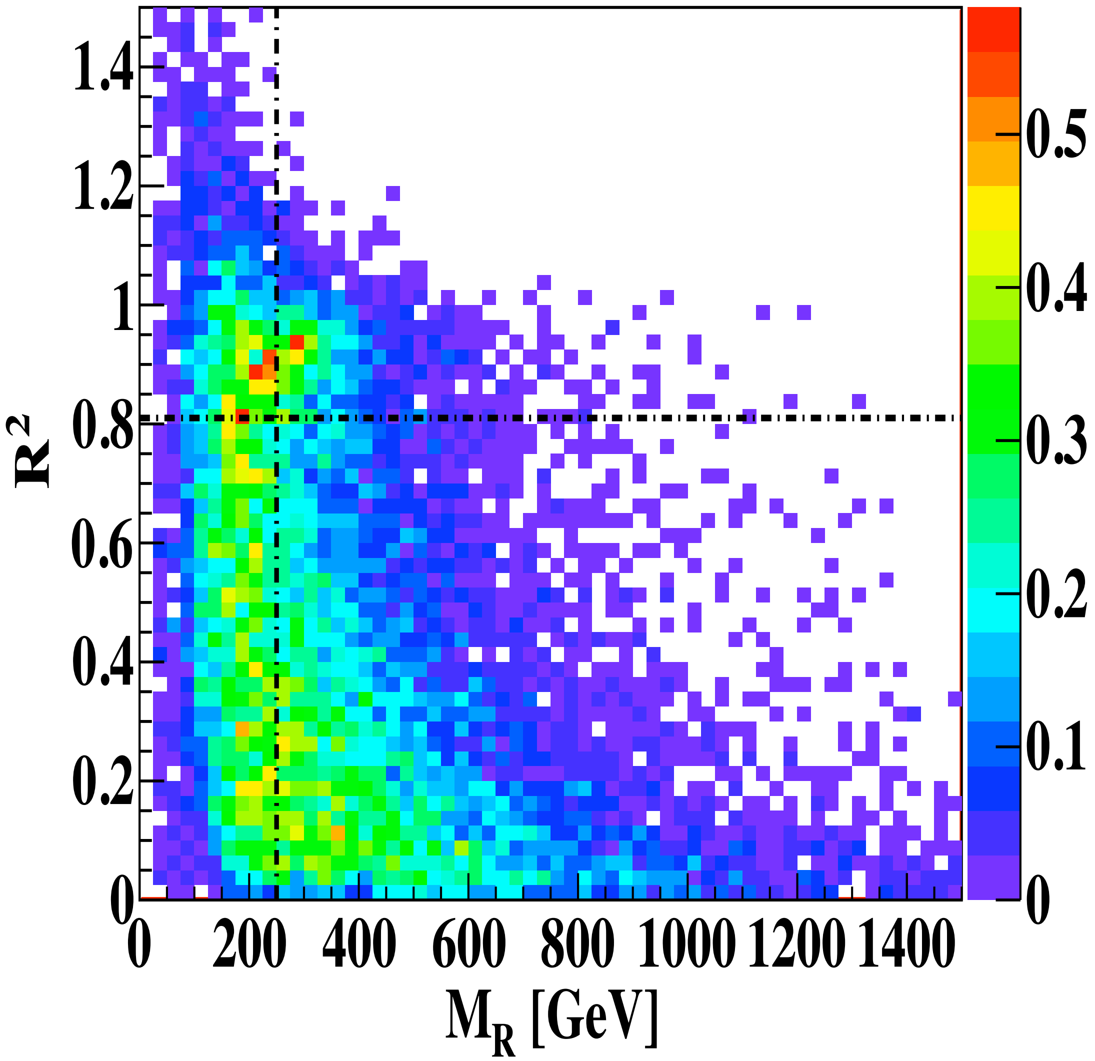
Razor

- Background and Signal shapes in M_R vs R:

Z+jets



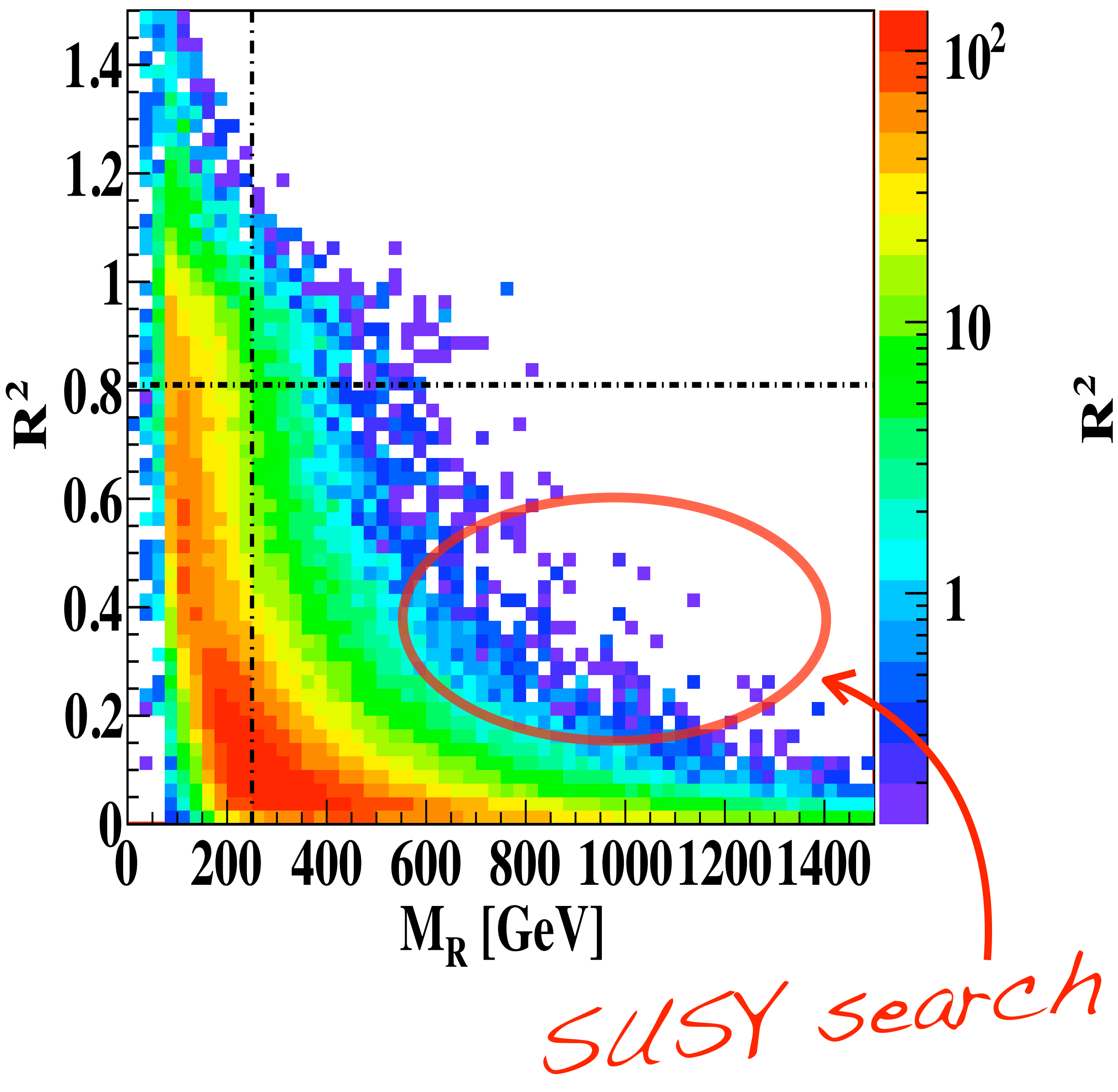
Signal. 100 GeV DM.



Razor

* Background and Signal shapes in M_R vs R:

Z+jets



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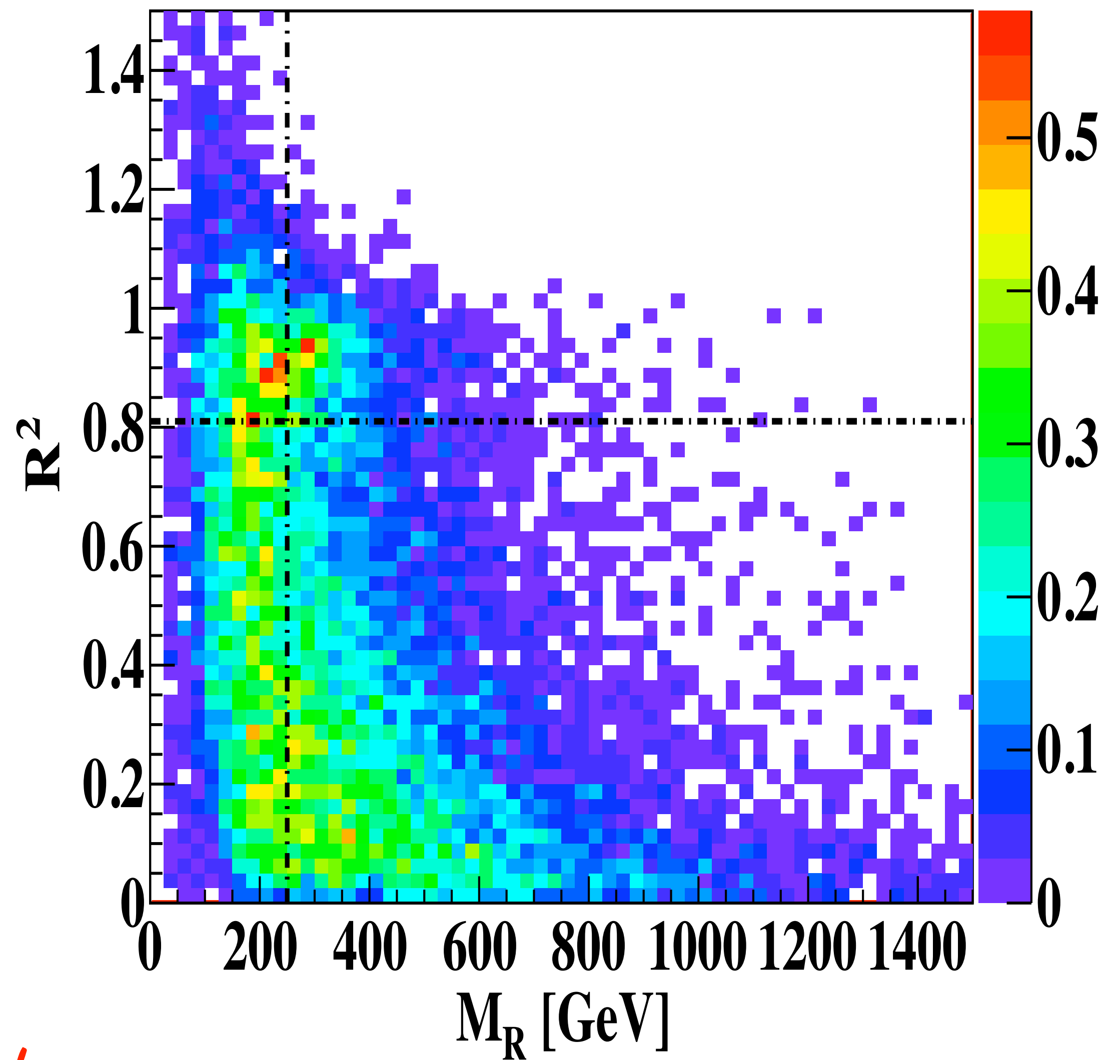
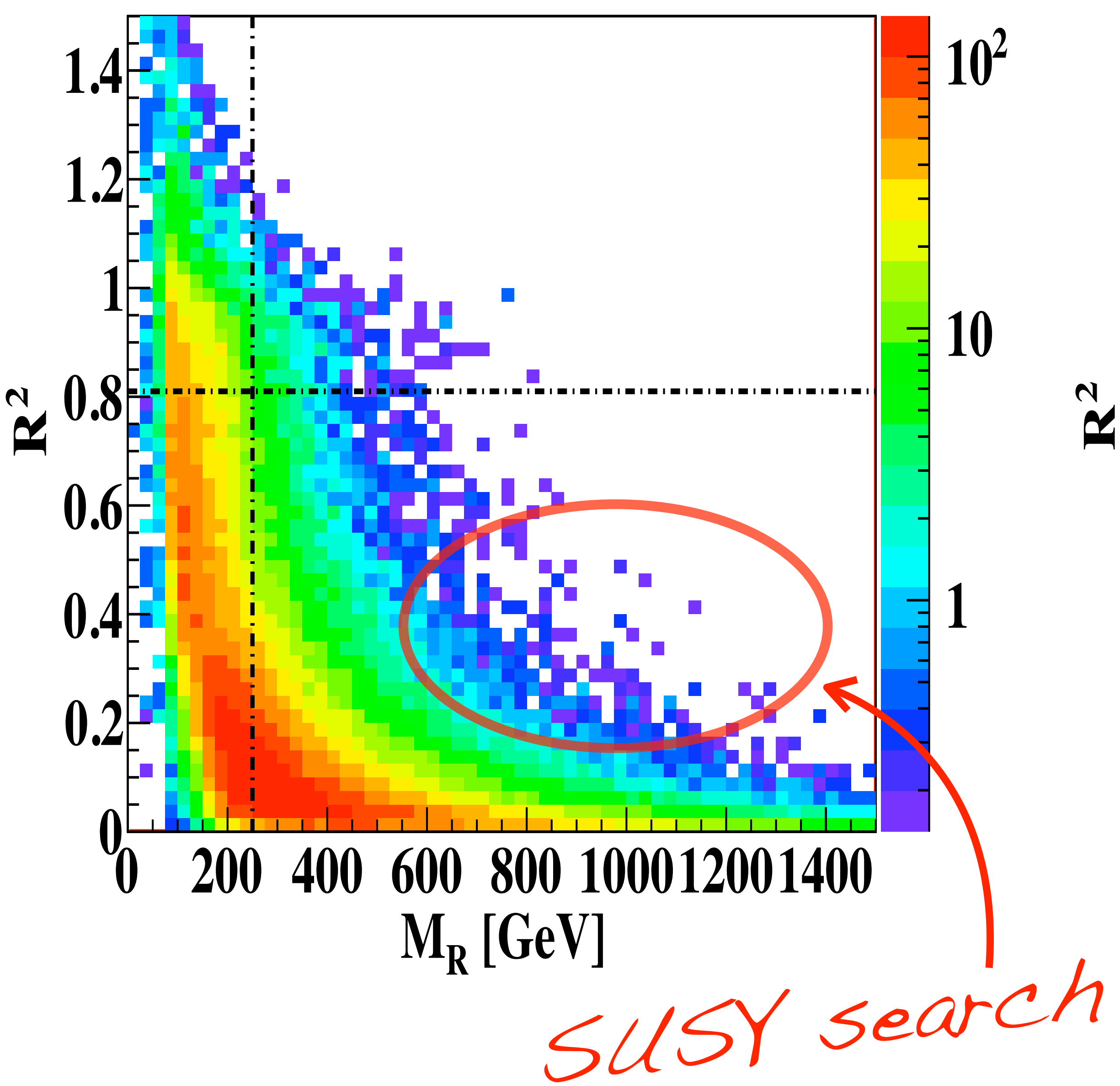


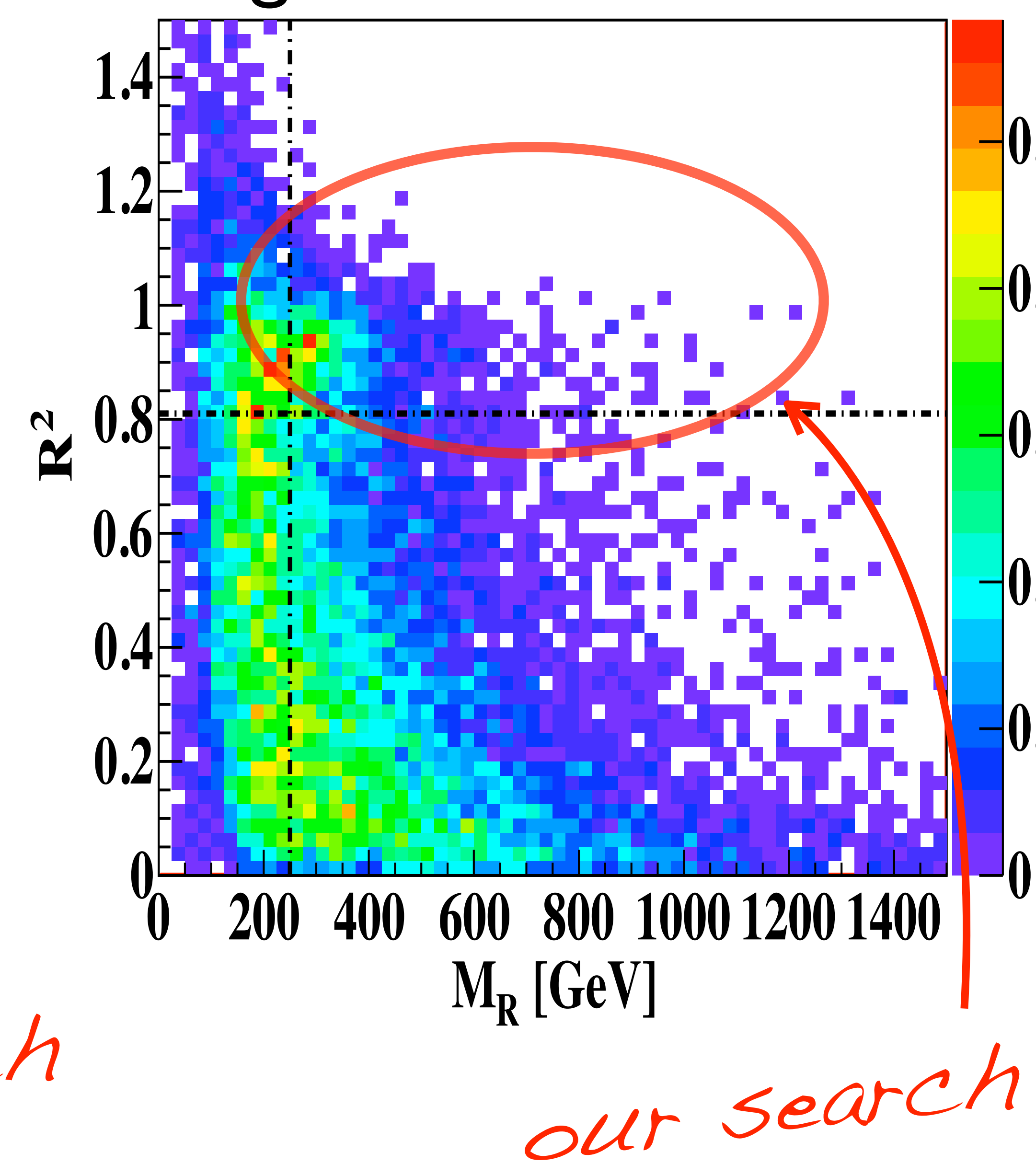
Razor

* Background and Signal shapes in M_R vs R:

Z+jets

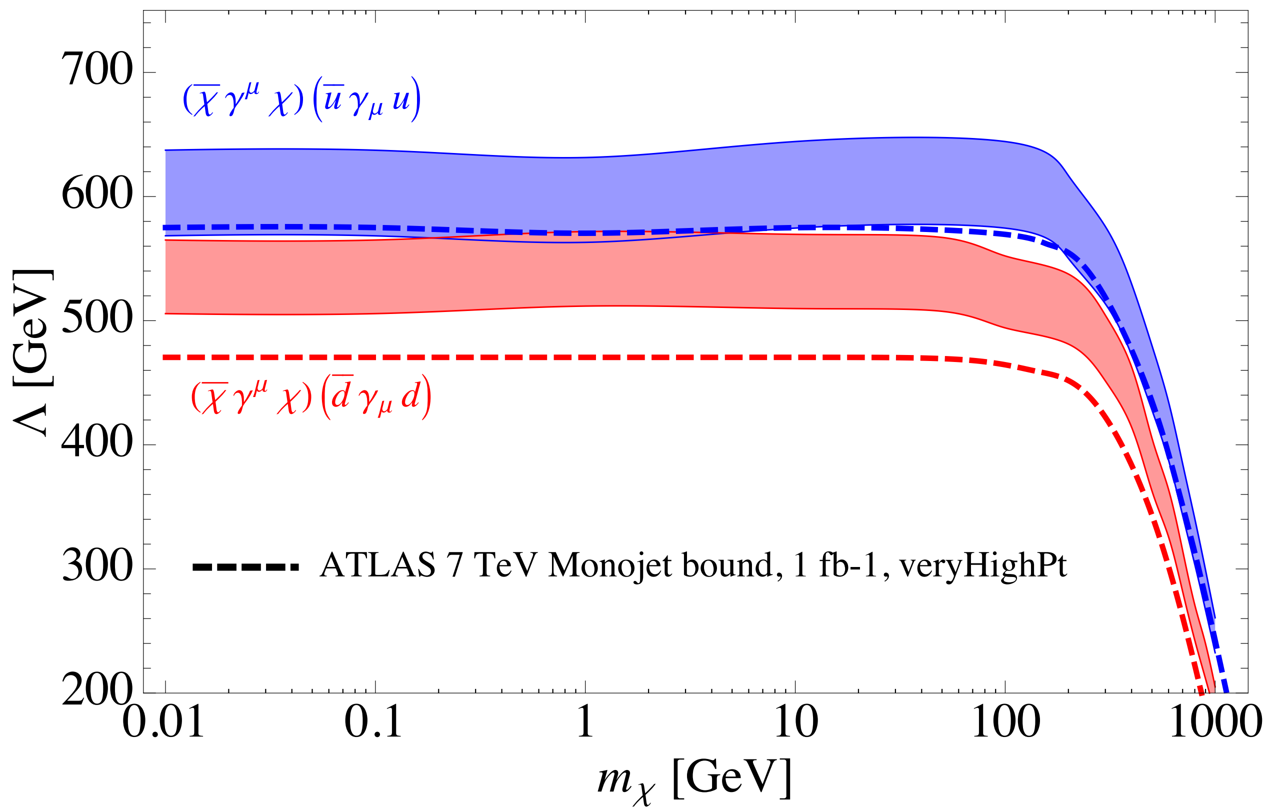


Signal. 100 GeV DM.

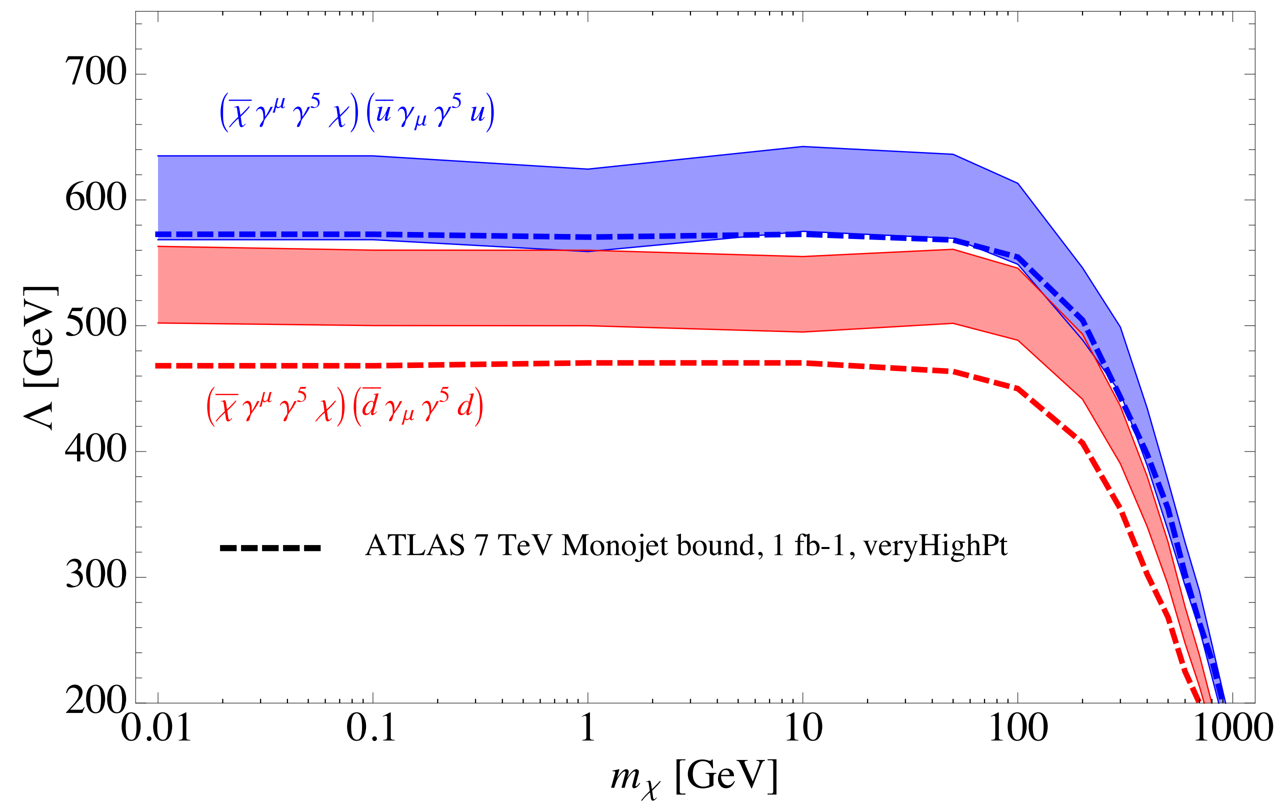


Razor Limits

- With 800 fb^{-1}:



(a) Vector couplings.

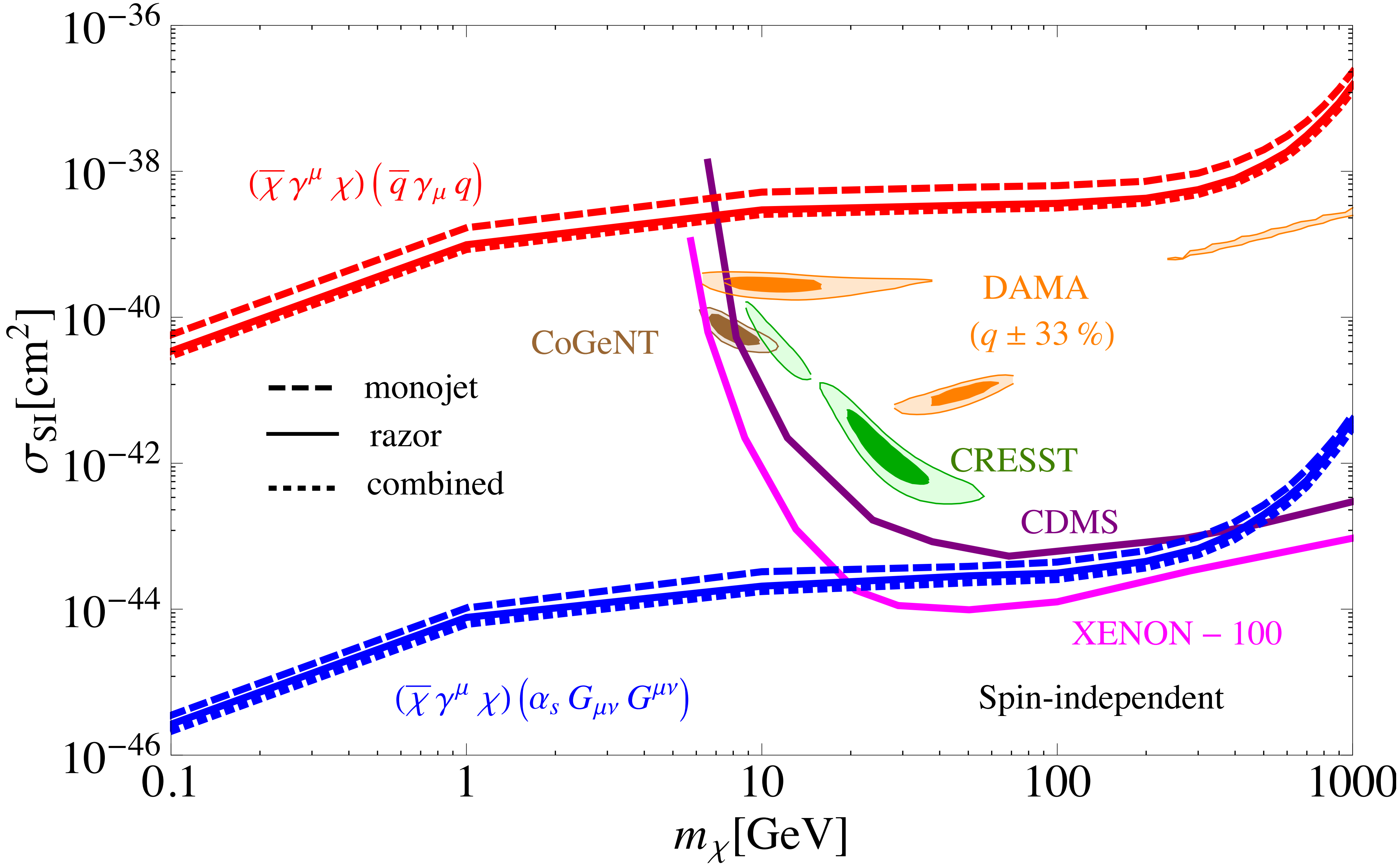


(b) Axial couplings

* The band represents two assumption about uncertainties: (1) statistics only, and (2) systematic=statistic. truth is probably closer to (1).

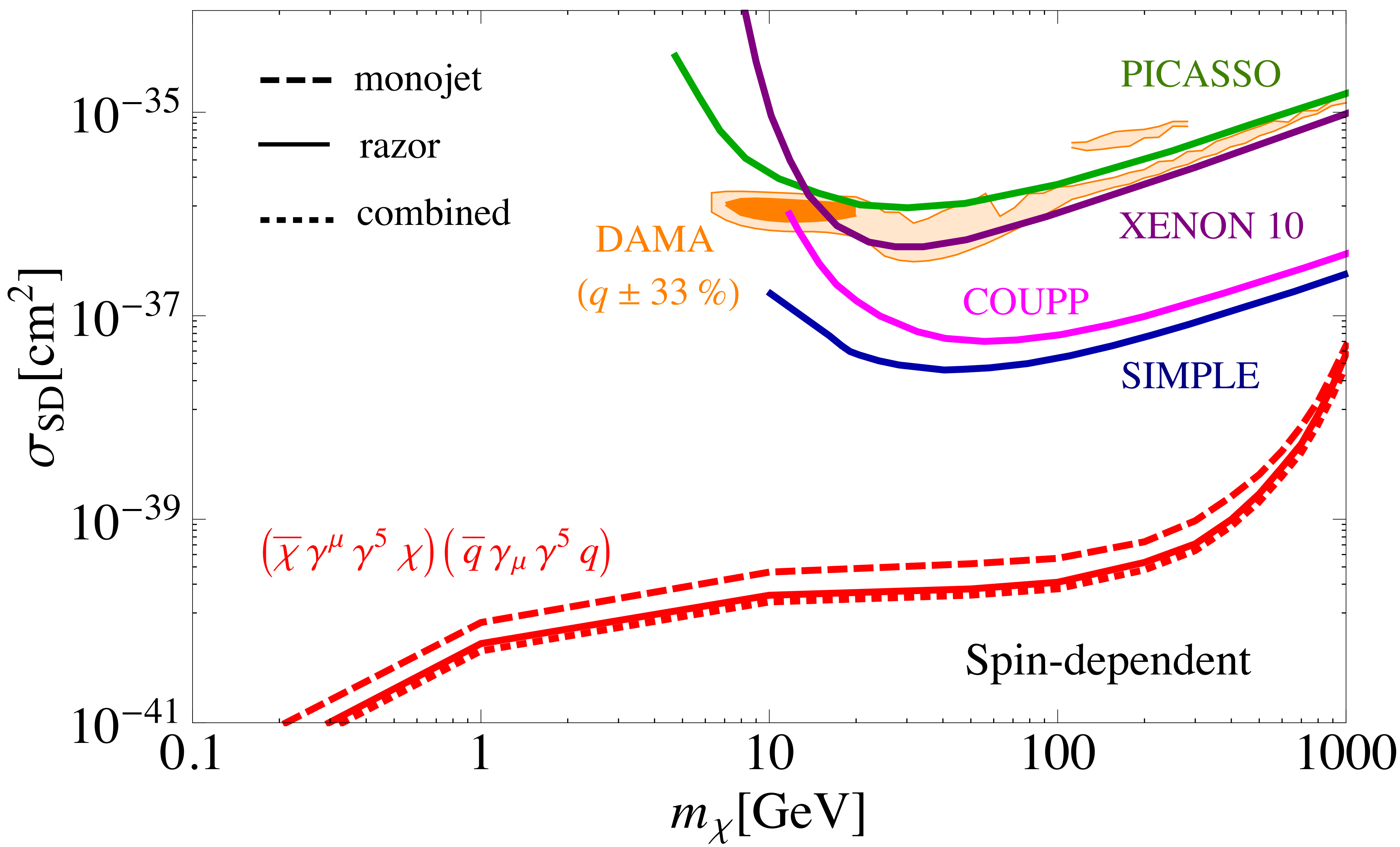
Razor Limits

* Spin-Independent (with 800 fb^{-1}):



Razor Limits

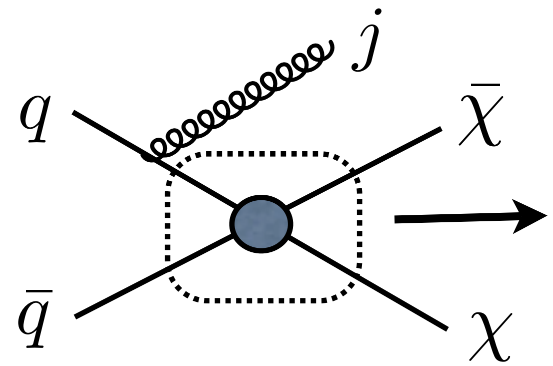
- Spin-Dependent:



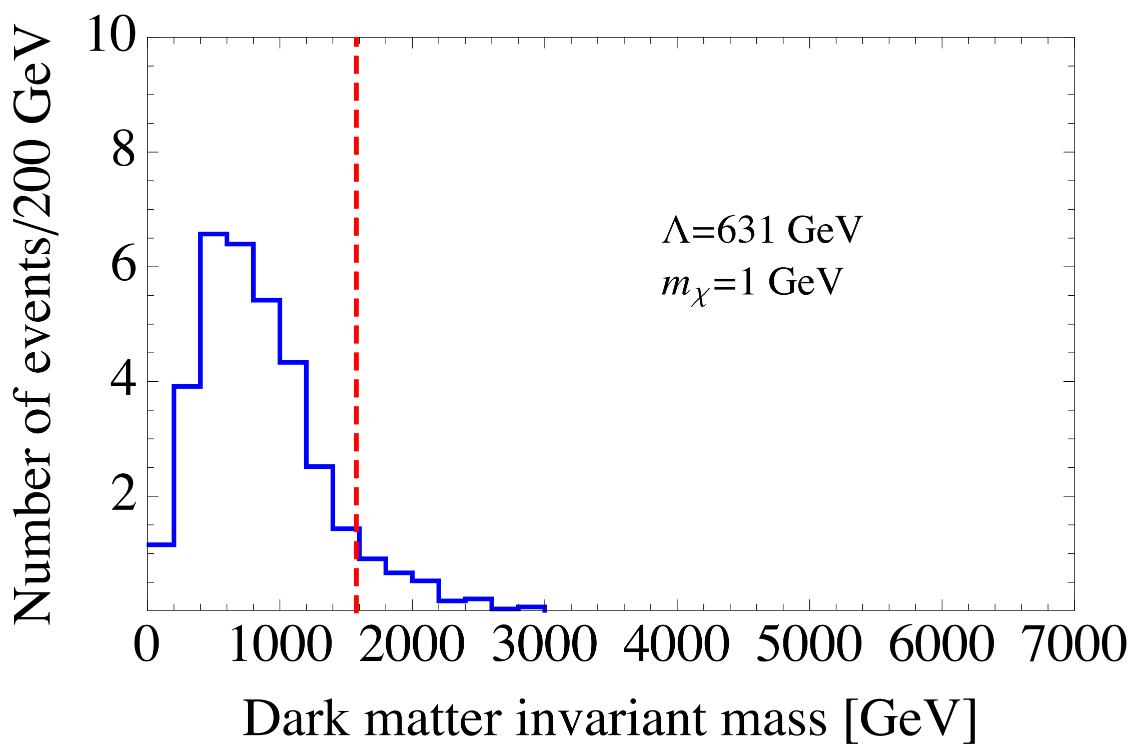
Violating EFT

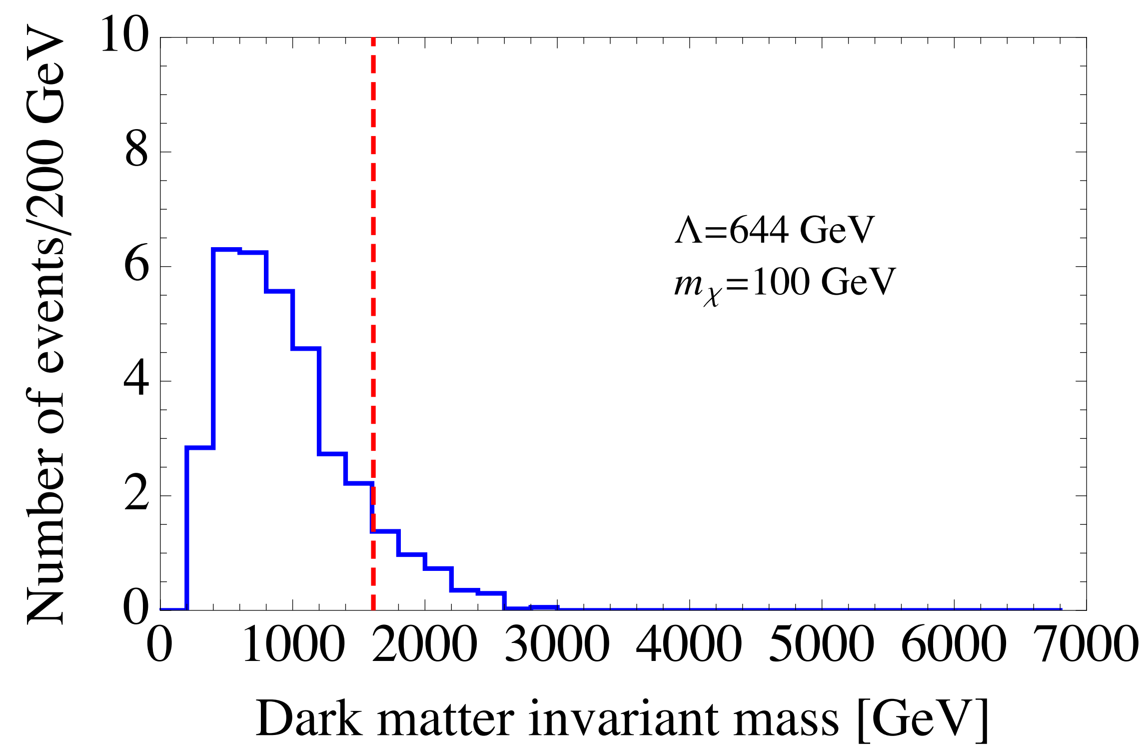
Unitarity

* Vechi and Shoemaker point to a unitarity limit:



$$\Lambda \gtrsim 0.4\sqrt{\beta(\hat{s})\hat{s}} \longrightarrow m_{\chi\chi} < \frac{\Lambda}{0.4}$$

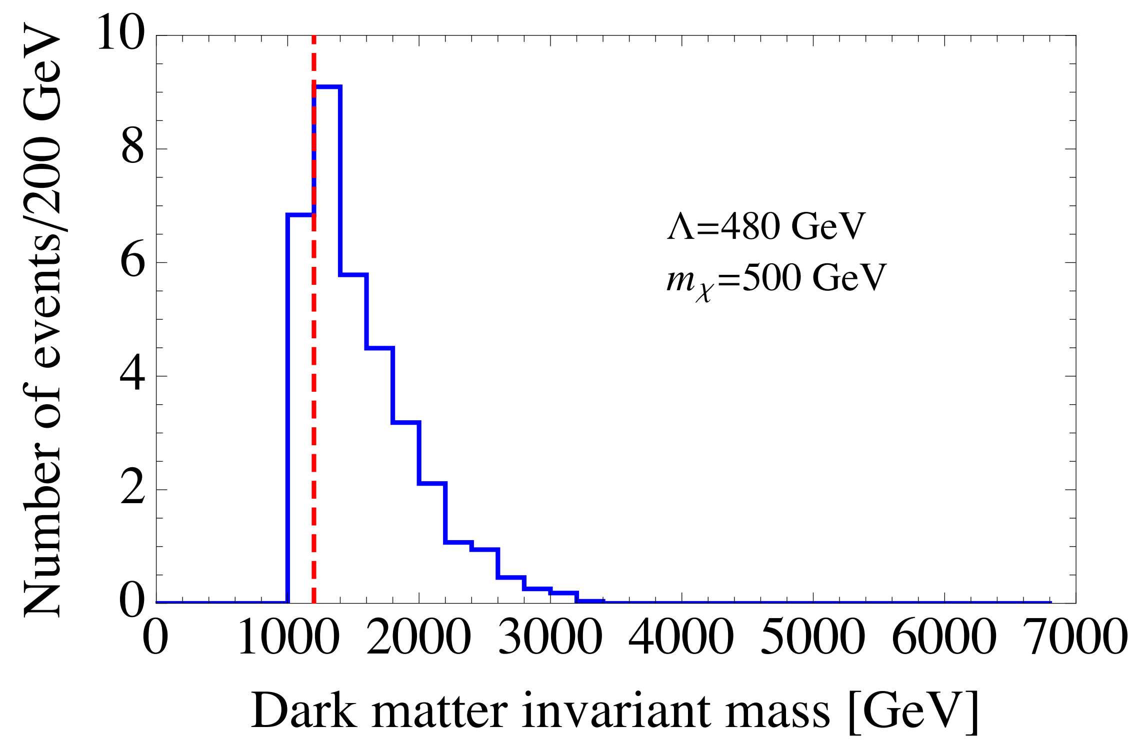




The EFT may be accurate to ~10% for light DM.

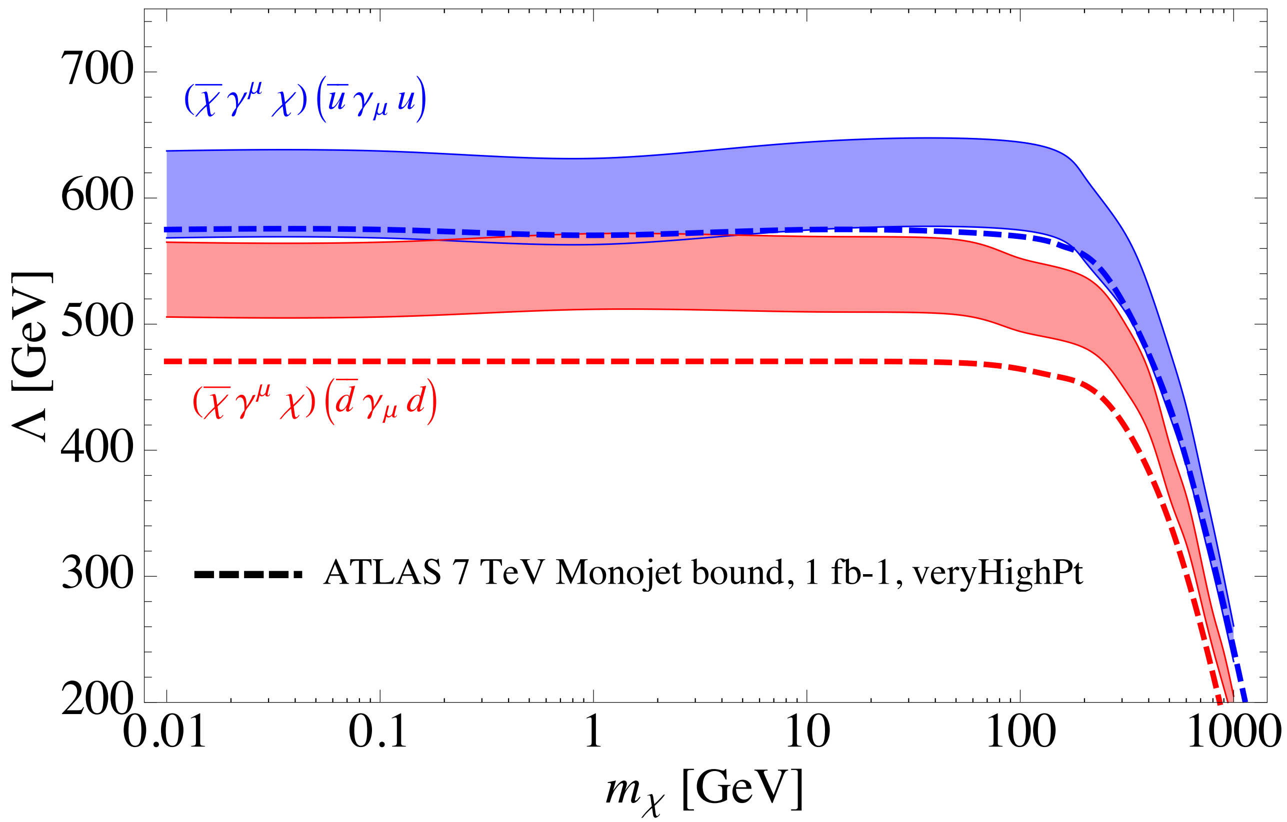
Unitarity

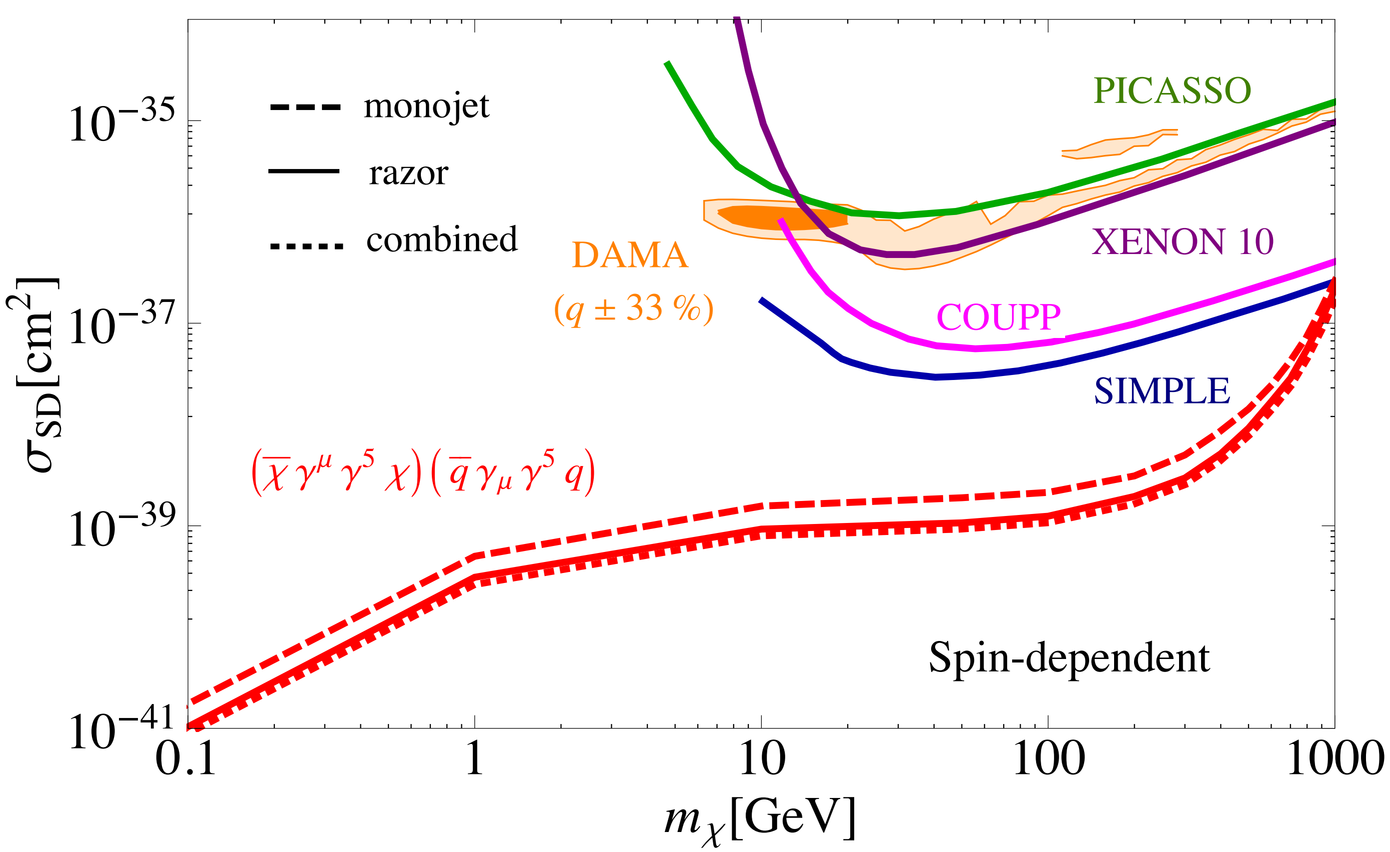
* For heavy dark matter the EFT is not valid:



Unitarity

- Strictly speaking, the EFT analysis is not valid at small Λ.





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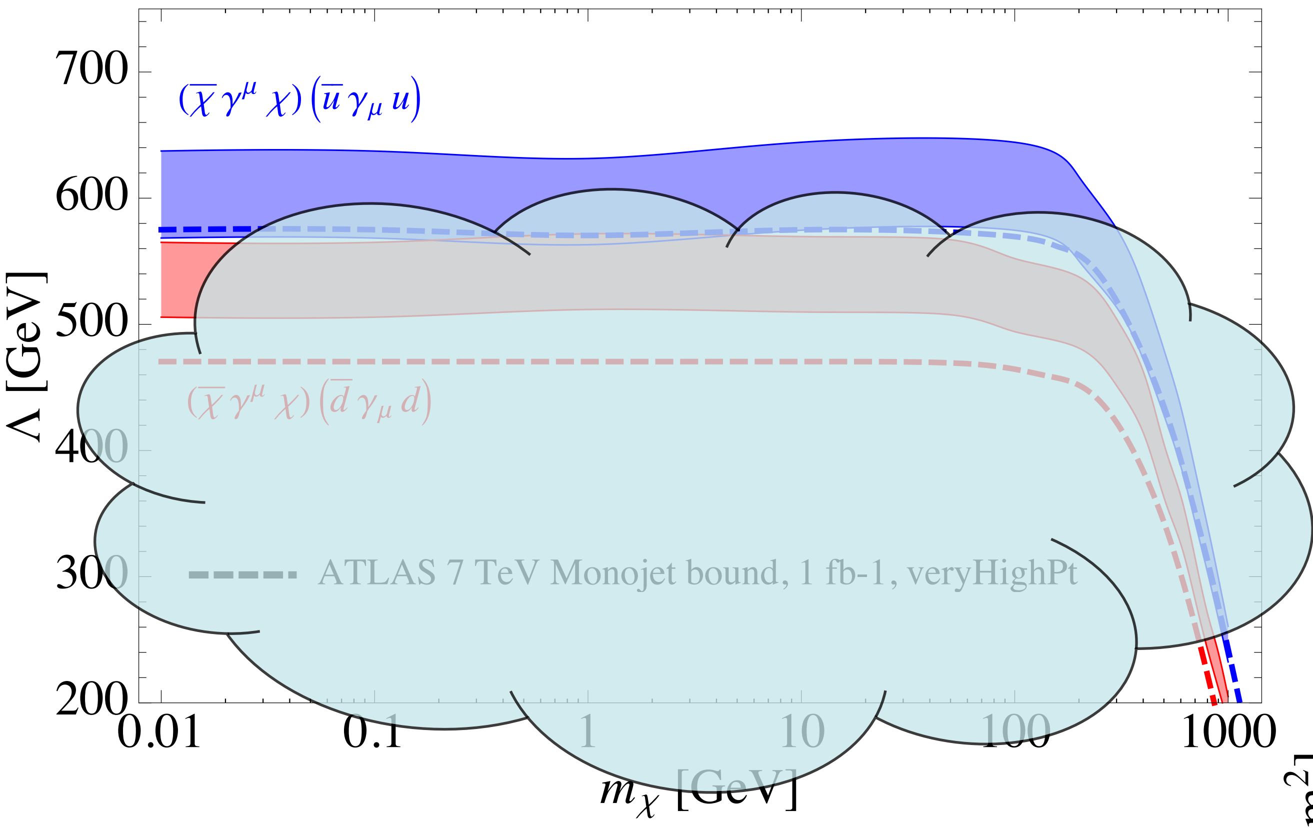

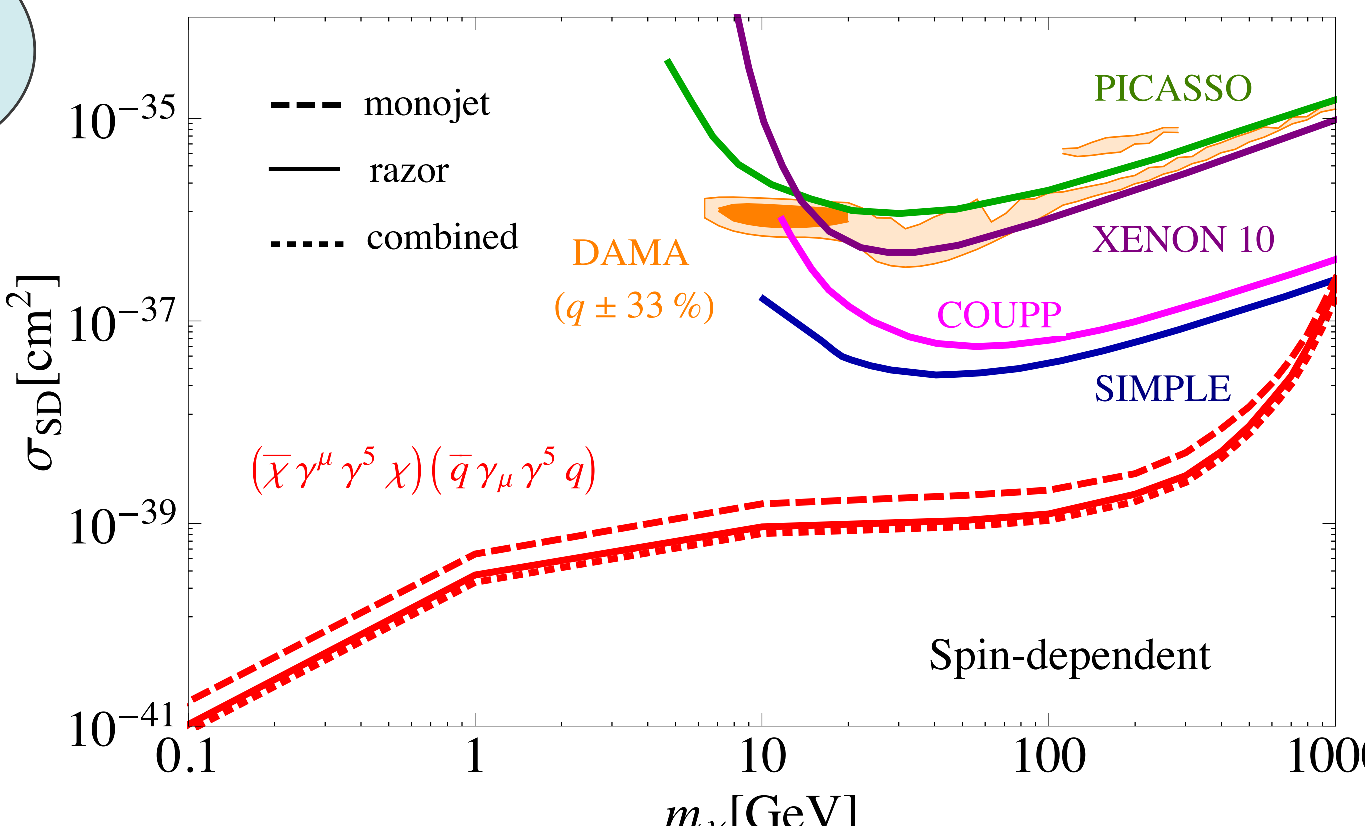

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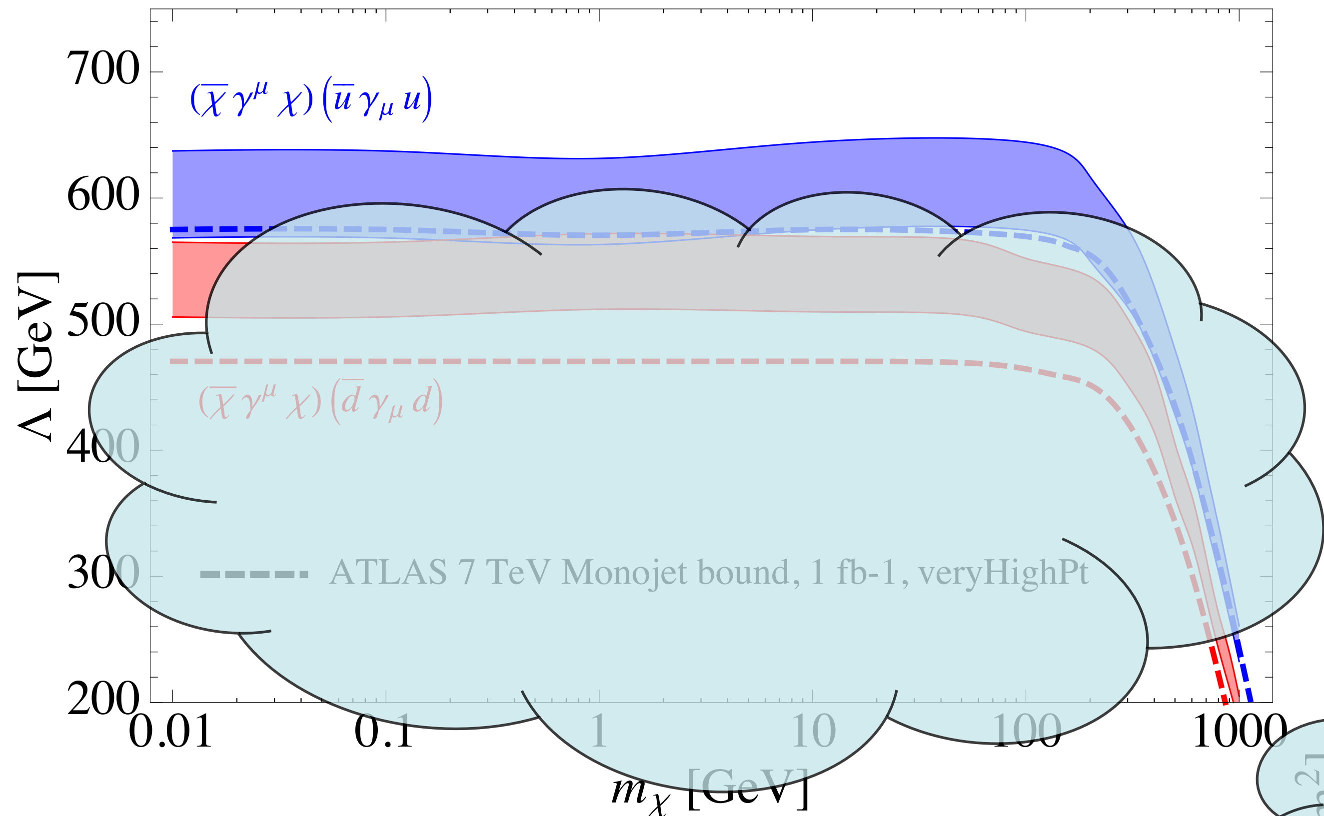

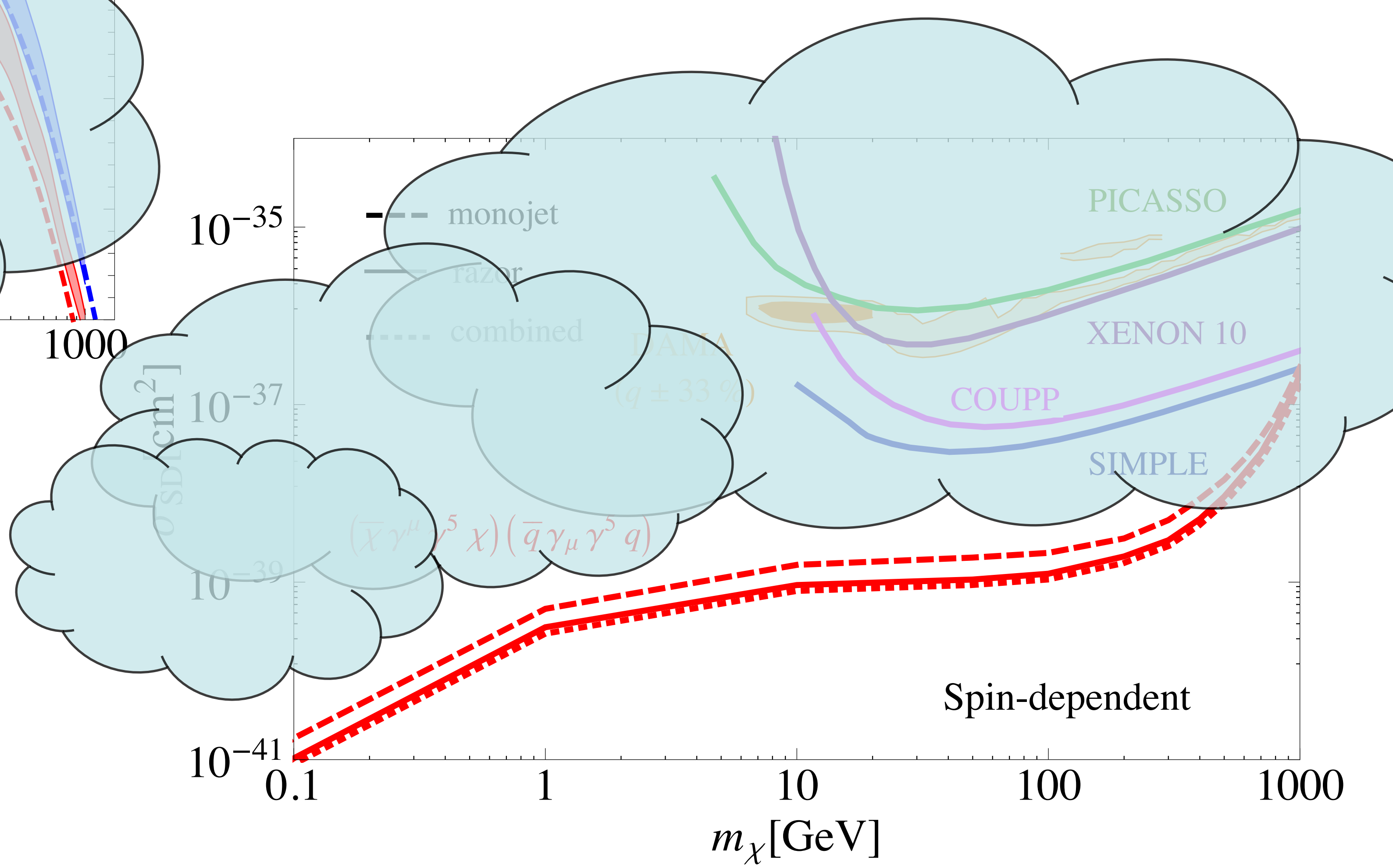

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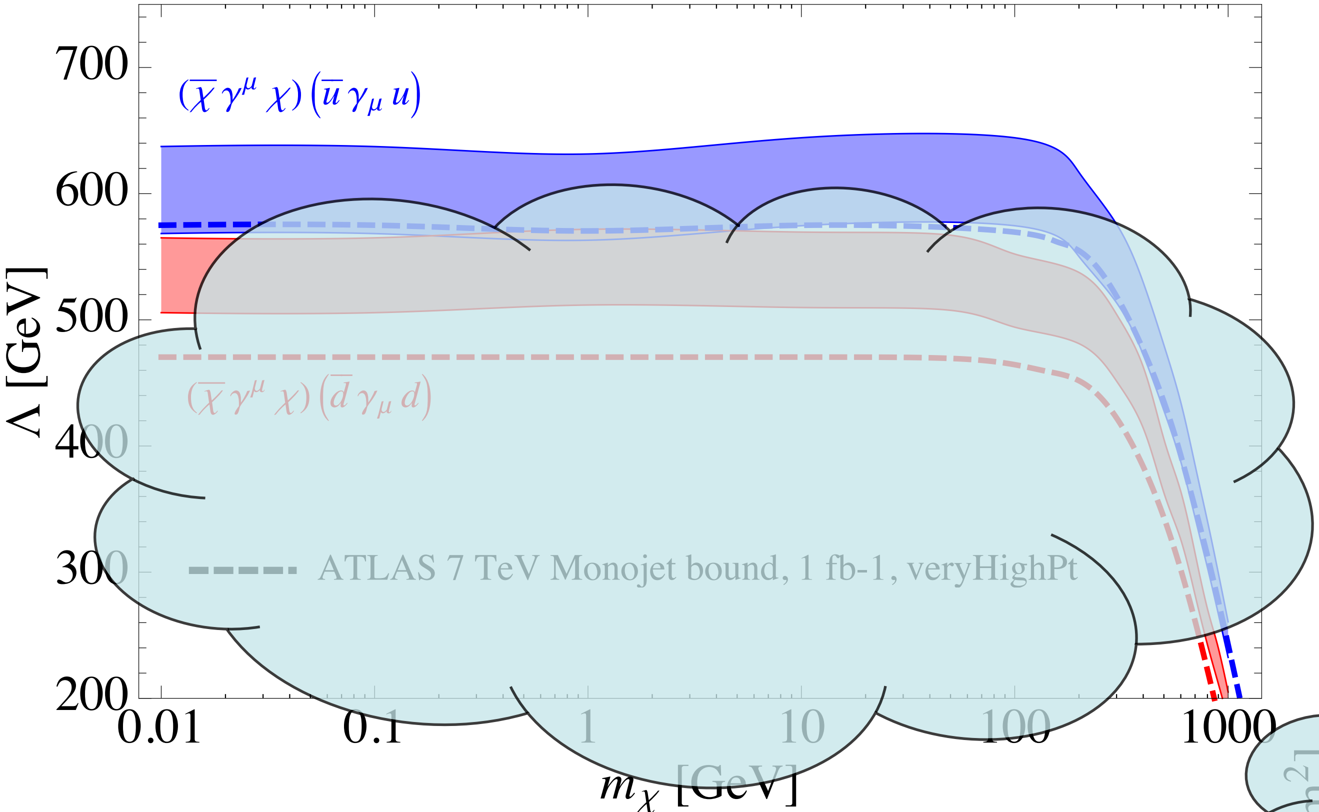
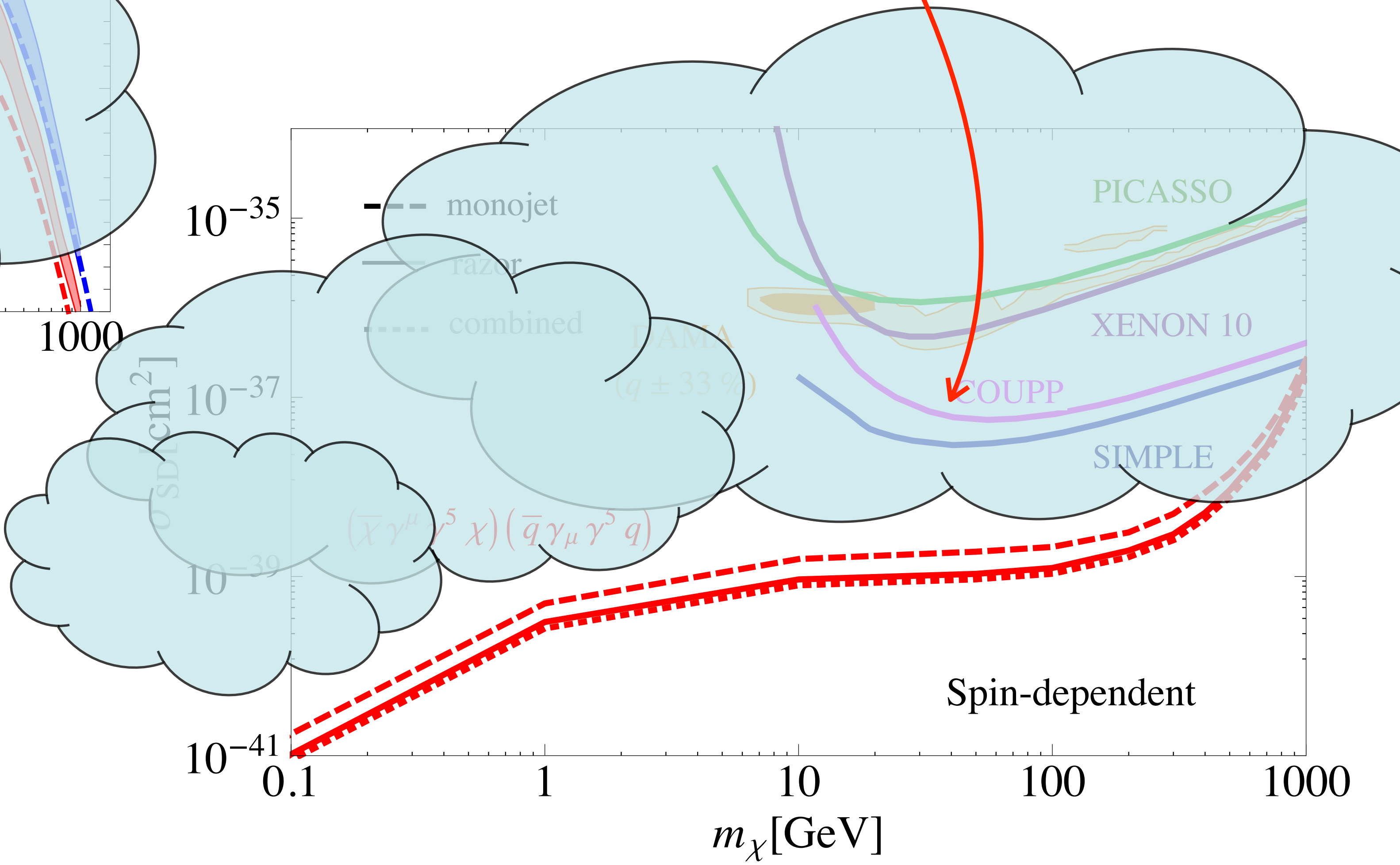


Does this mean a theory that lives here is alive?



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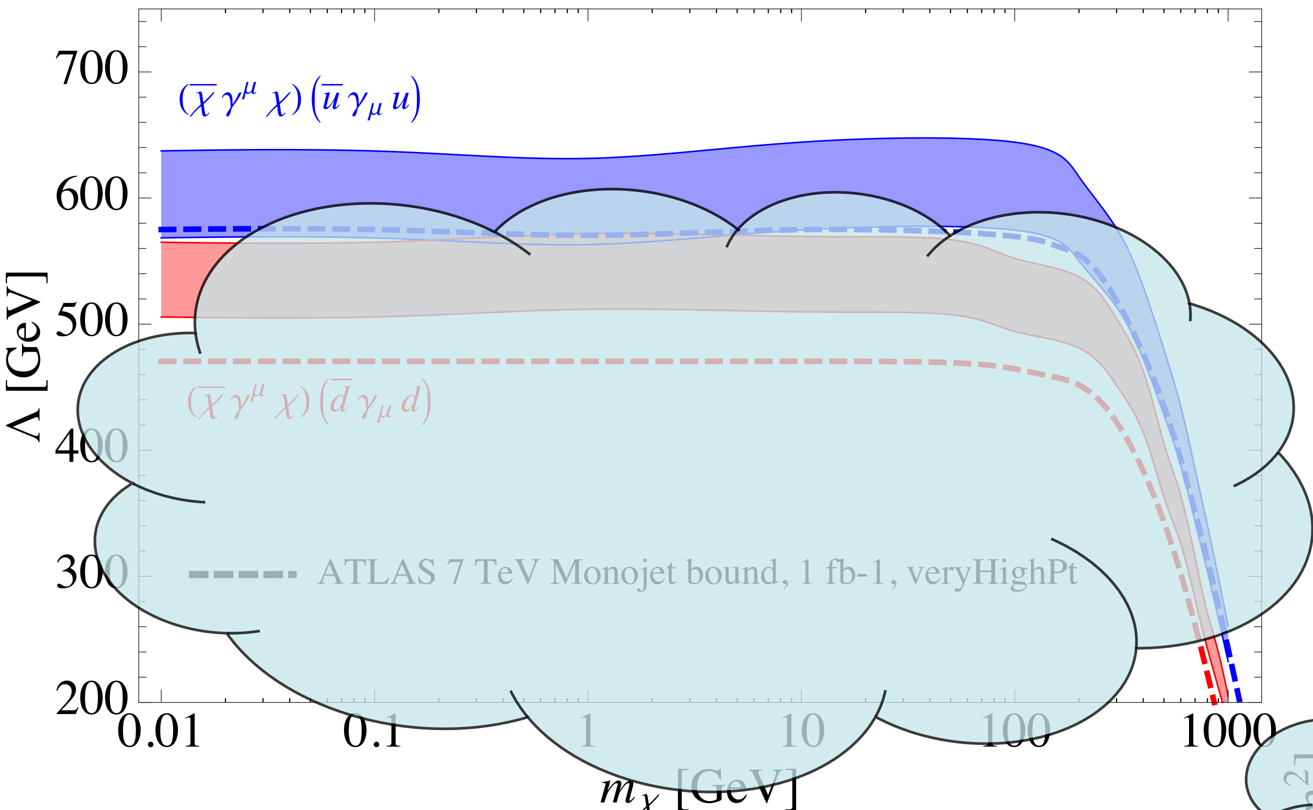

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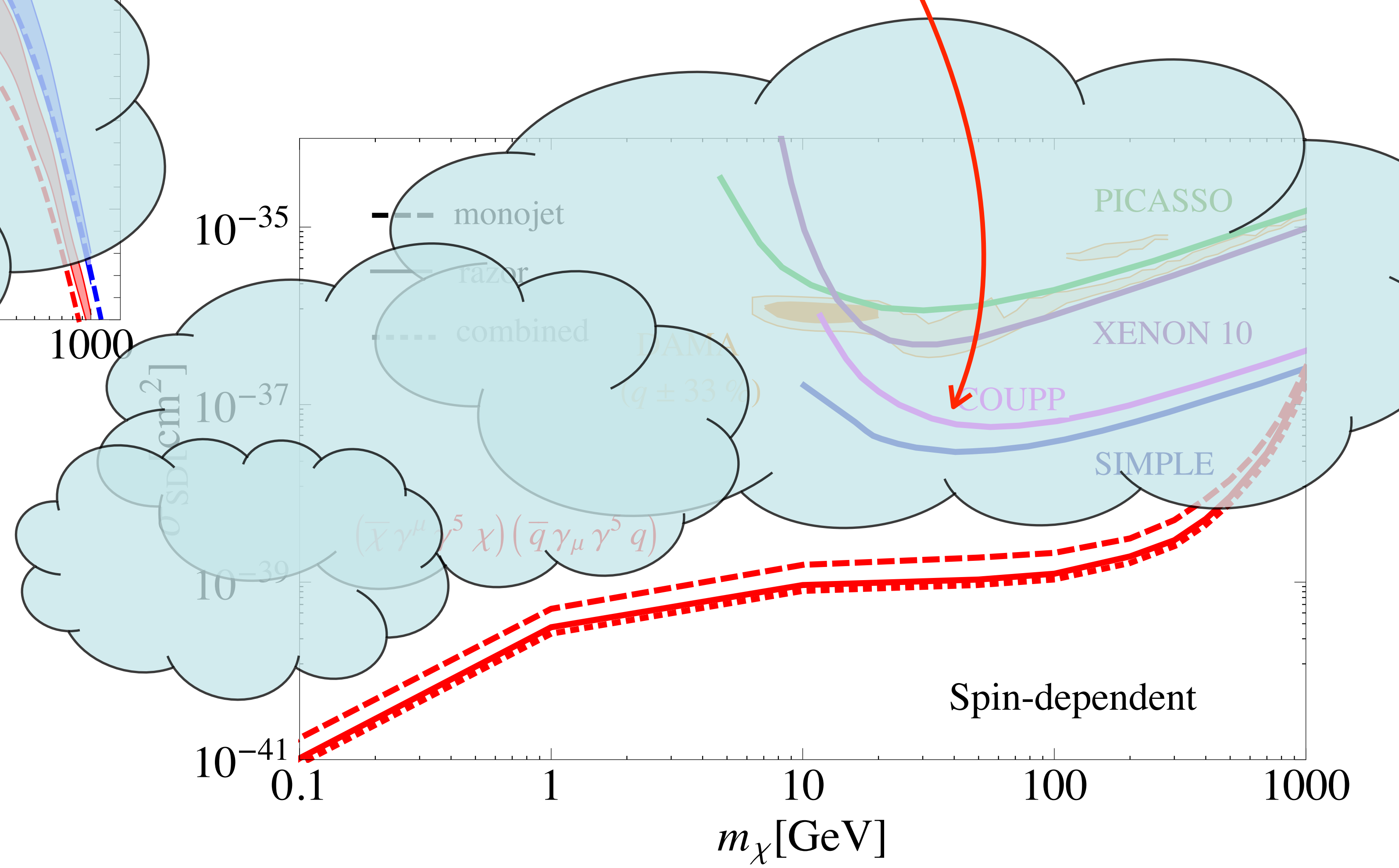
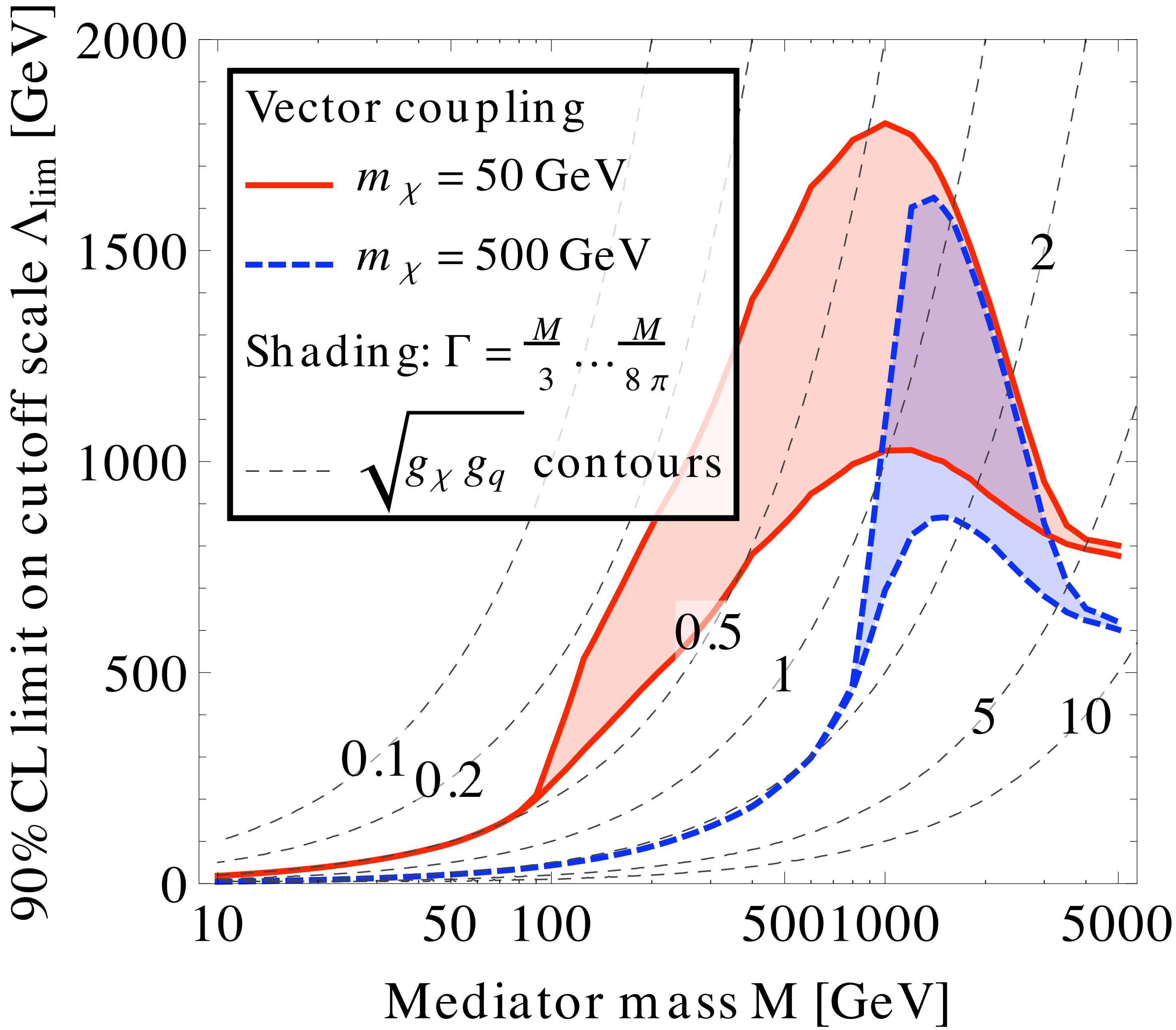


No.

In fact it may be even more dead.

Light Madiator

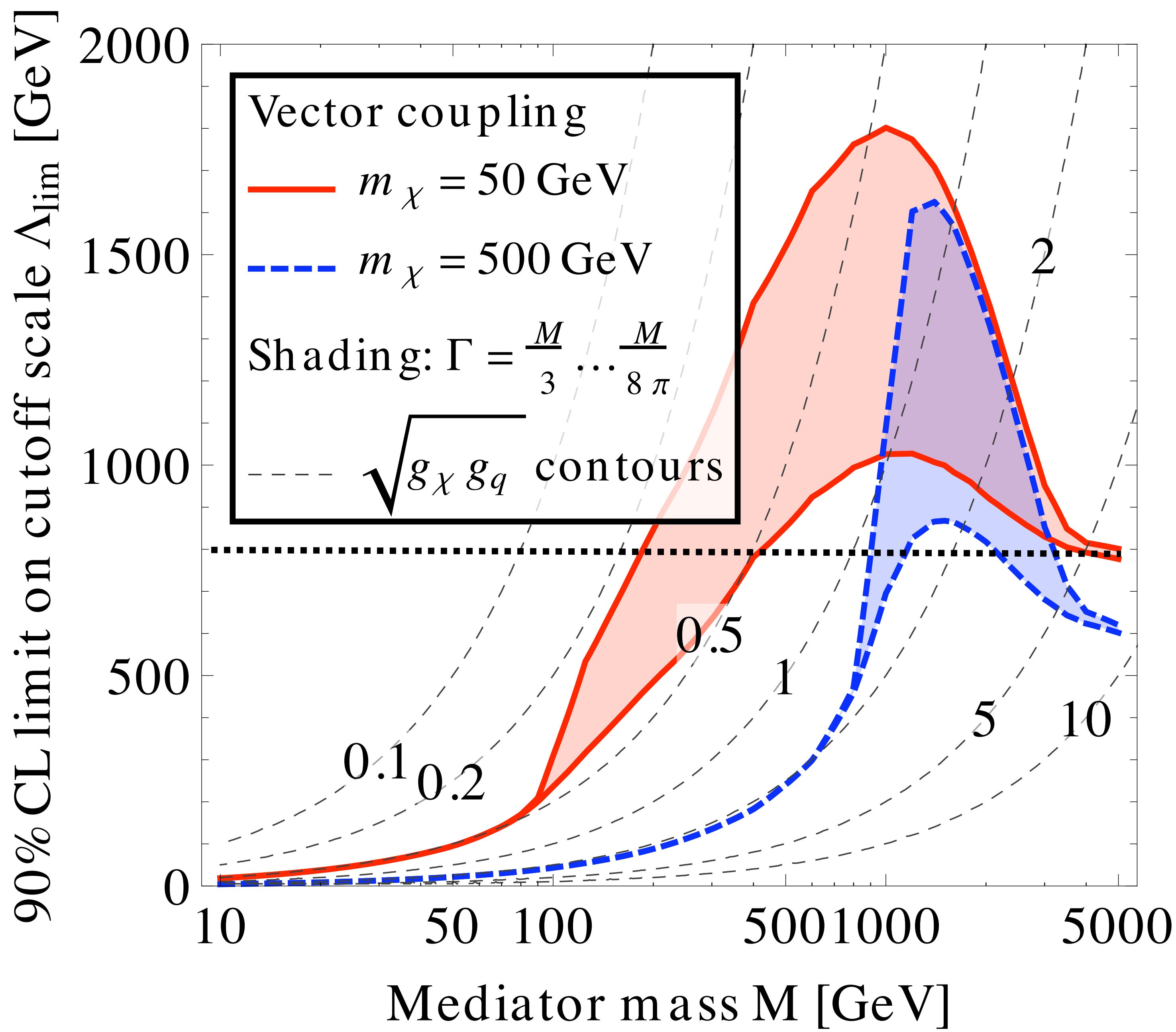
- The limit become better before it gets worse:



EFT limits are **conservative** so long as the mediator is above a few hundred GeV (and the mediator decays to DM).

Light Madiator

- The limit become better before it gets worse:



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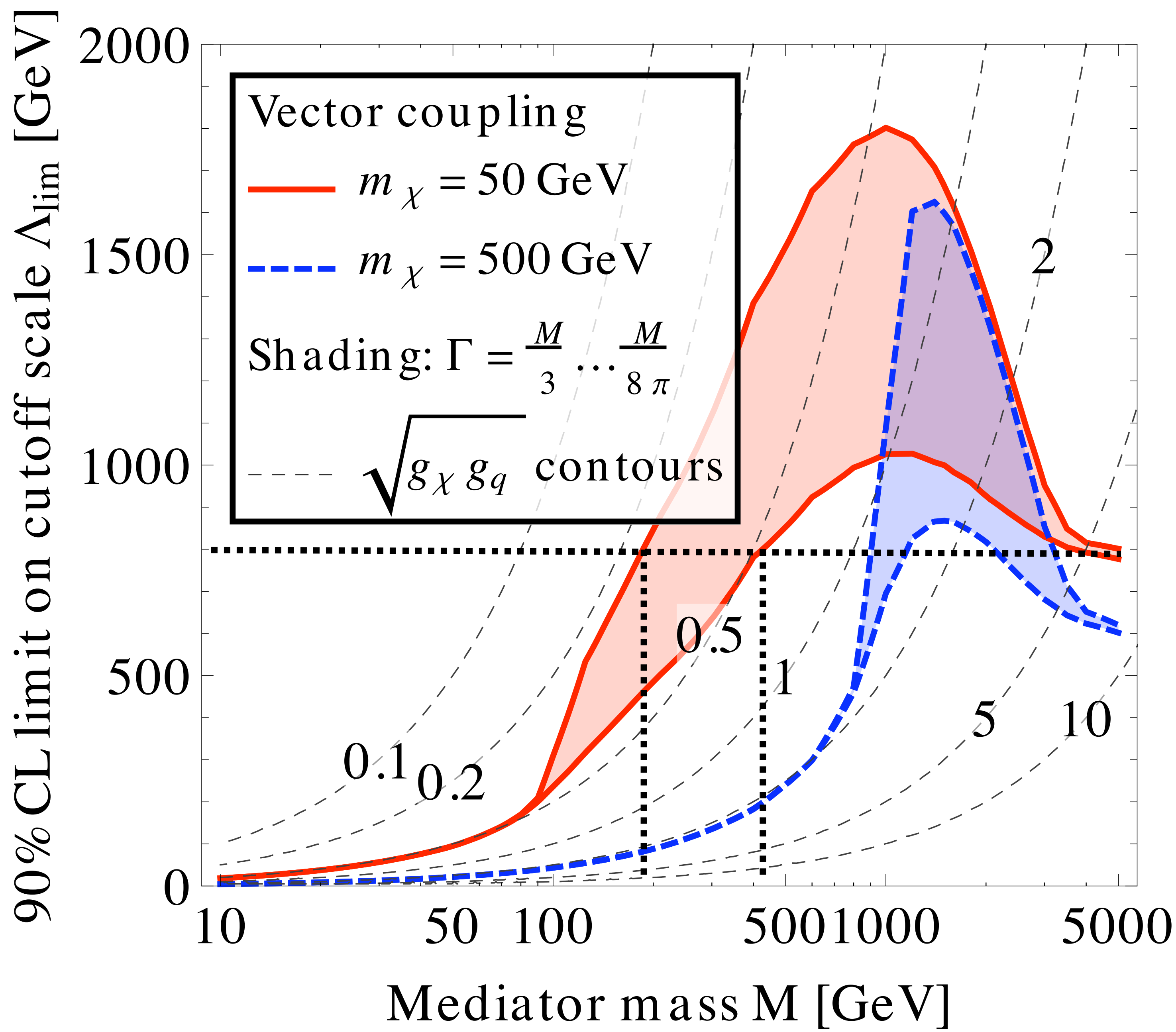
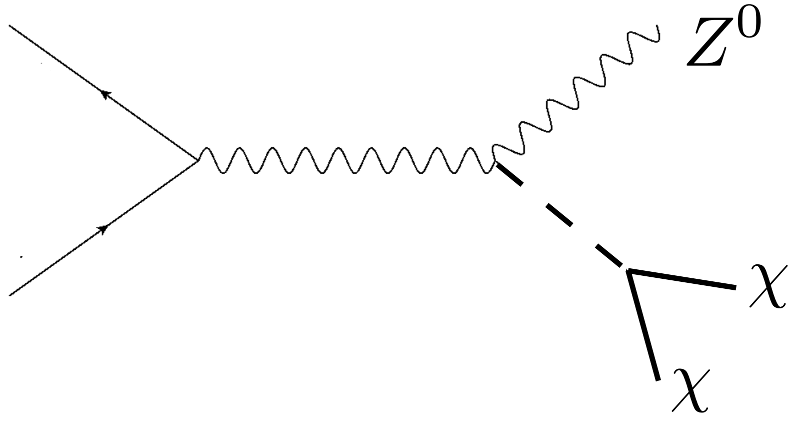


EFT limits are **conservative** so long as the mediator is above a few hundred GeV (and the mediator decays to DM).

Higgs Portal DM

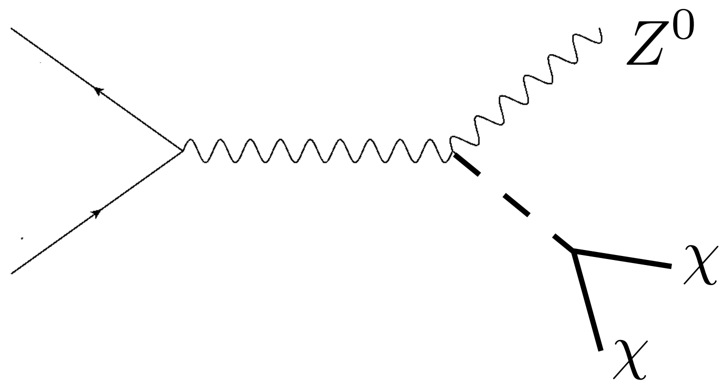
- For specific models, we can probe the identity of the mediator with other mono-somthings.
- In many models DM couples via the **Higgs**. **Mono-Z** (and **VBF**) may be sensitive to this.



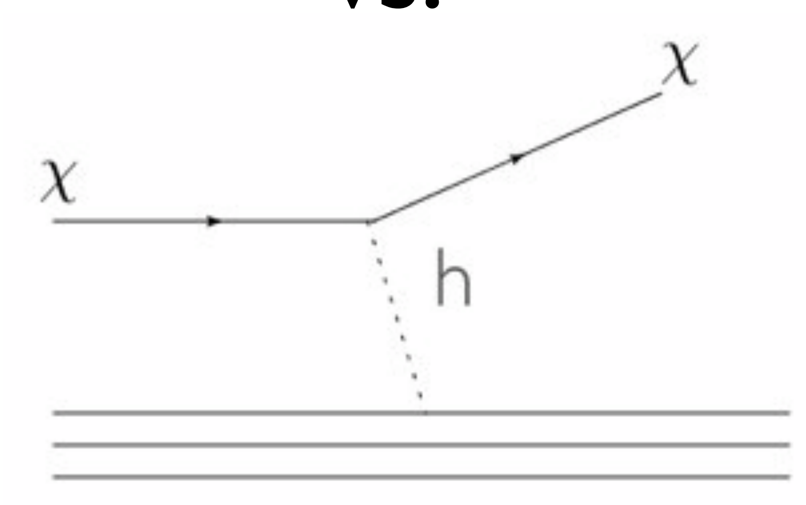
Invisible Higgs searches can be interpreted as "direct detection" experiments!

A Characteristic Higgs Channel can confirm Higgs mediation!

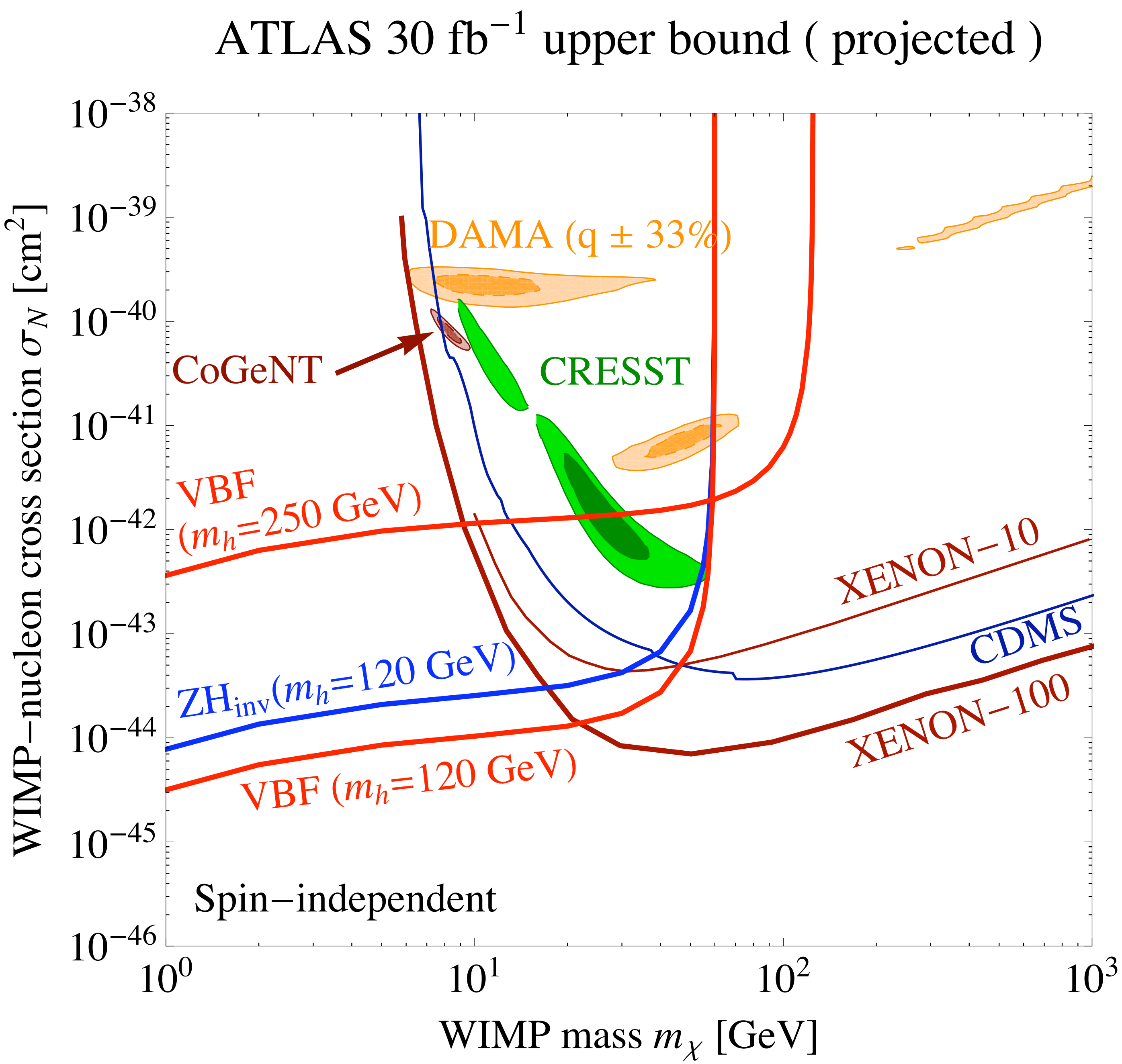
Higgs Mediator



vs.



Direct detection is parametrically smaller!



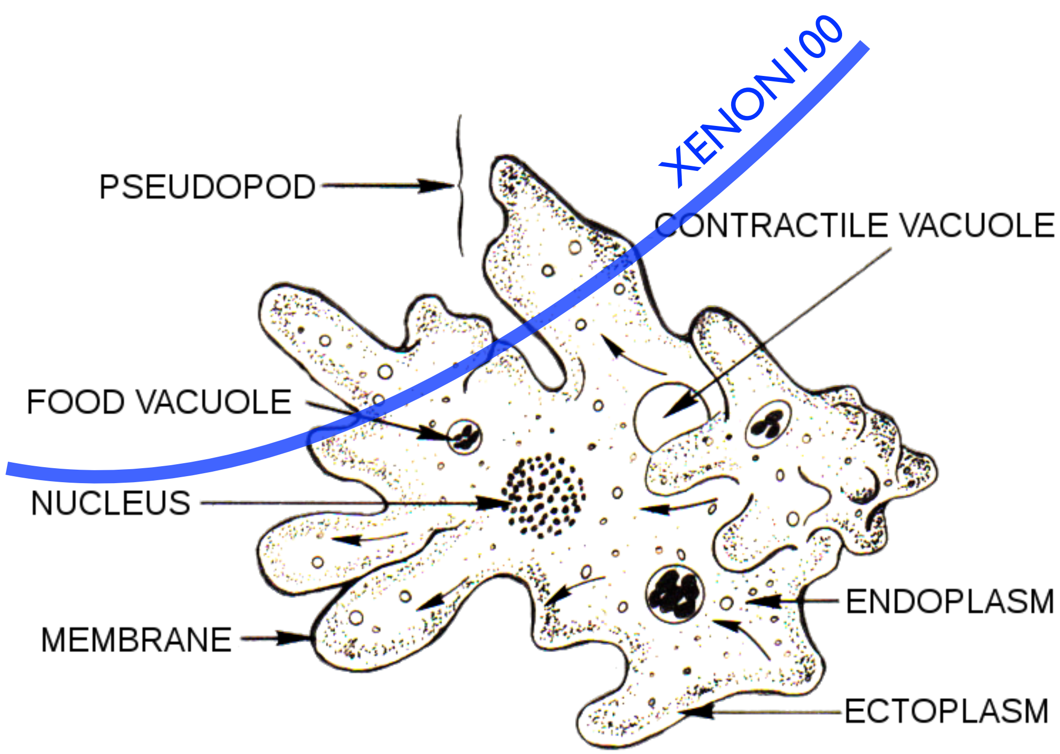
Fox, RH, Kopp and Tsai

To Conclude:

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

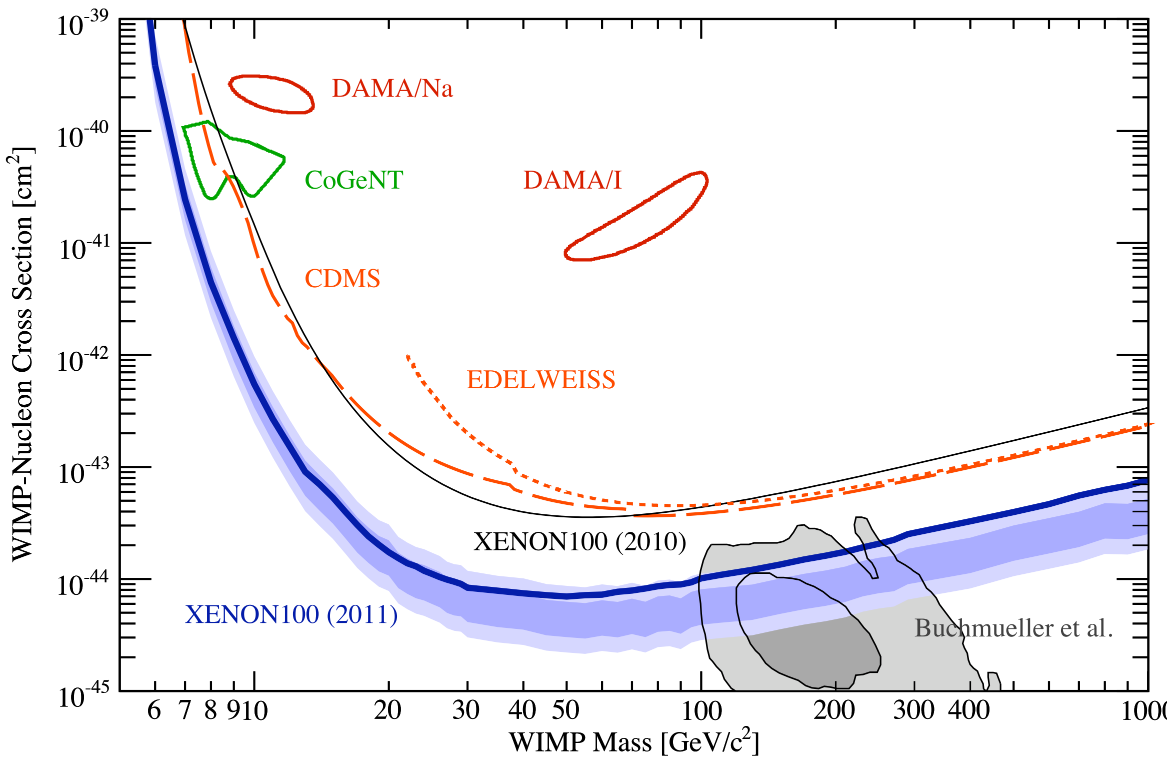
- The ~~**Tevatron**~~ LHC is the world record holder for light dark matter and for spin dependent.
- Dedicated CDF, CMS, and ATLAS **mono-jet** studies are out (or underway). CMS **mono-photon** too.
- Inclusive Jets plus MET studies may have additional discriminating power (Razor).
- **Higgs** and **DM** play nicely together.

Deleted Scenes



Collider Connections?

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



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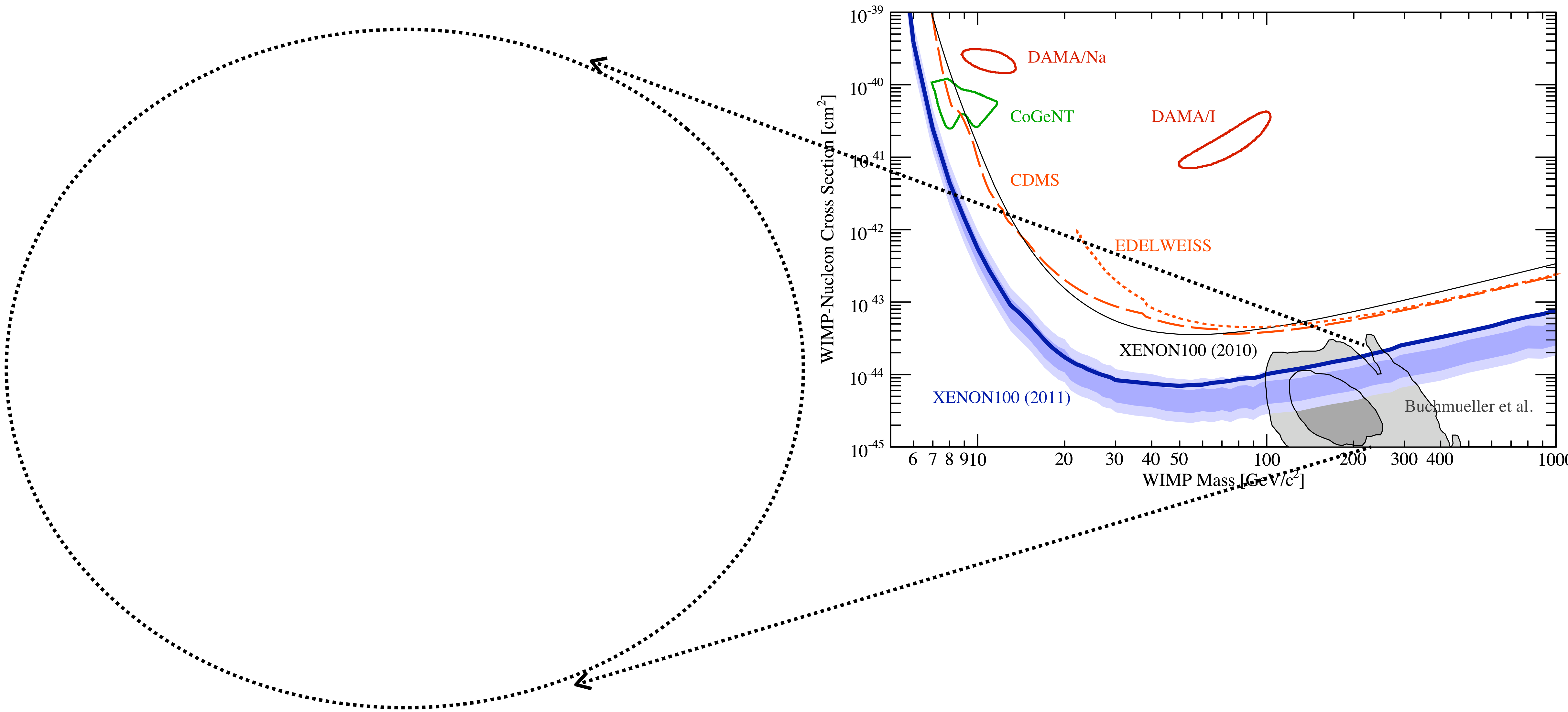

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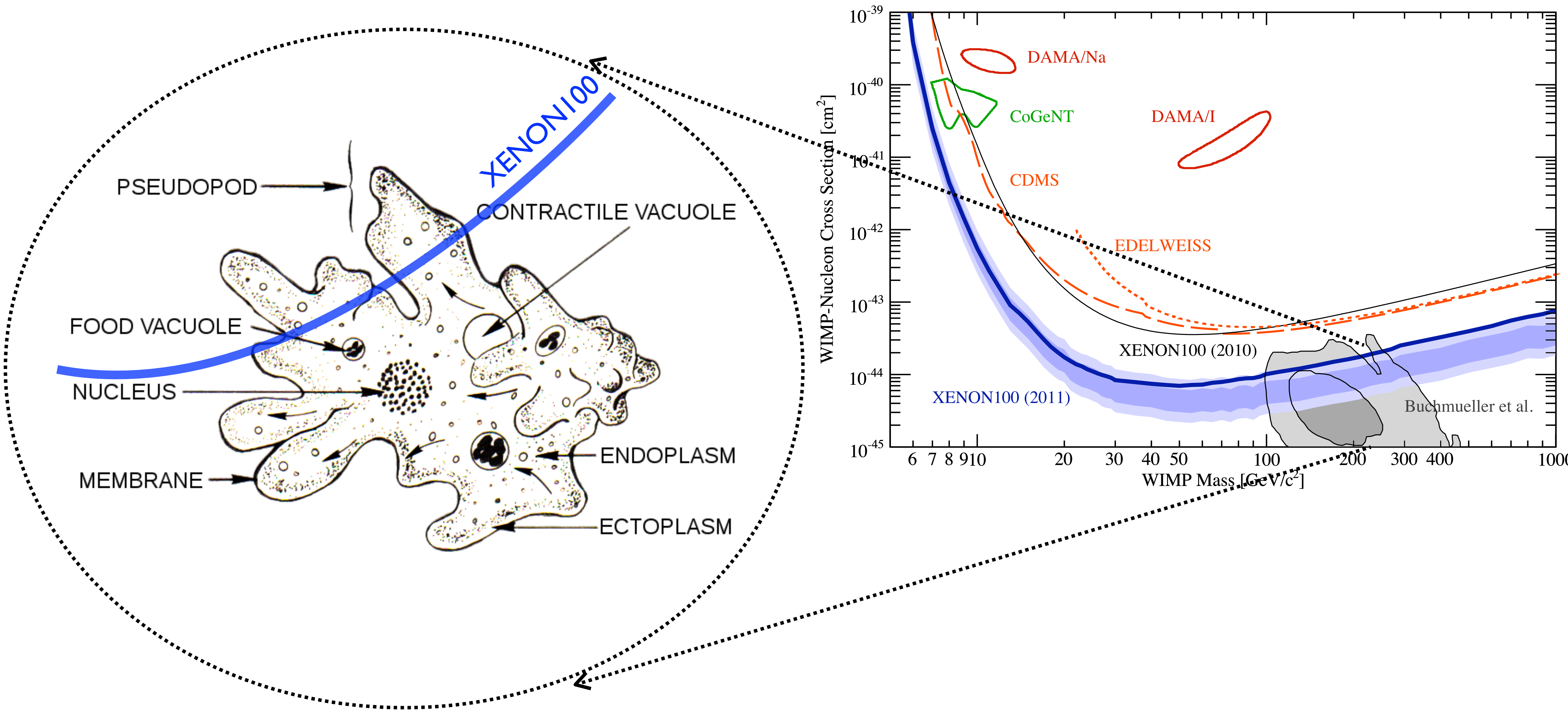

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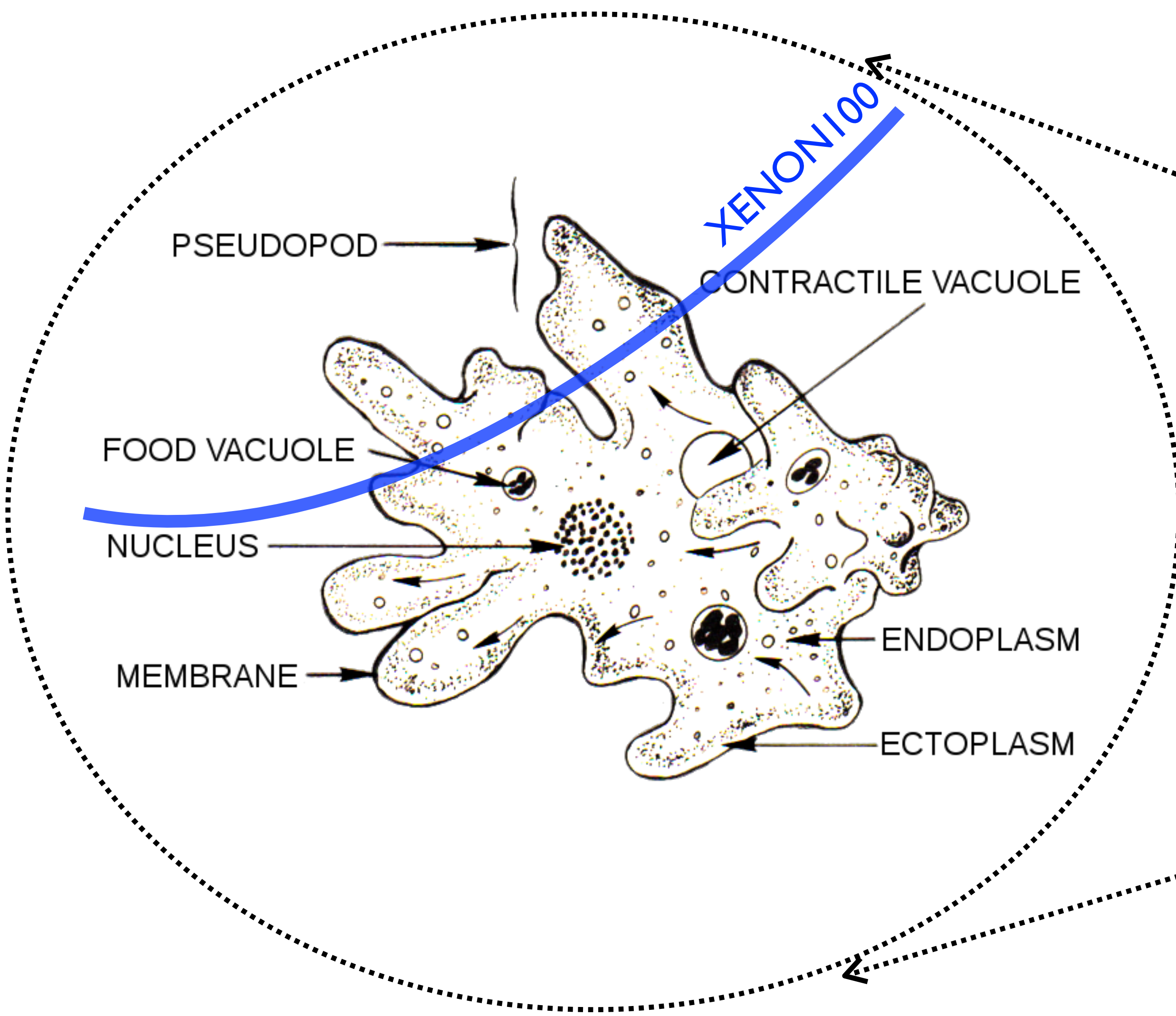

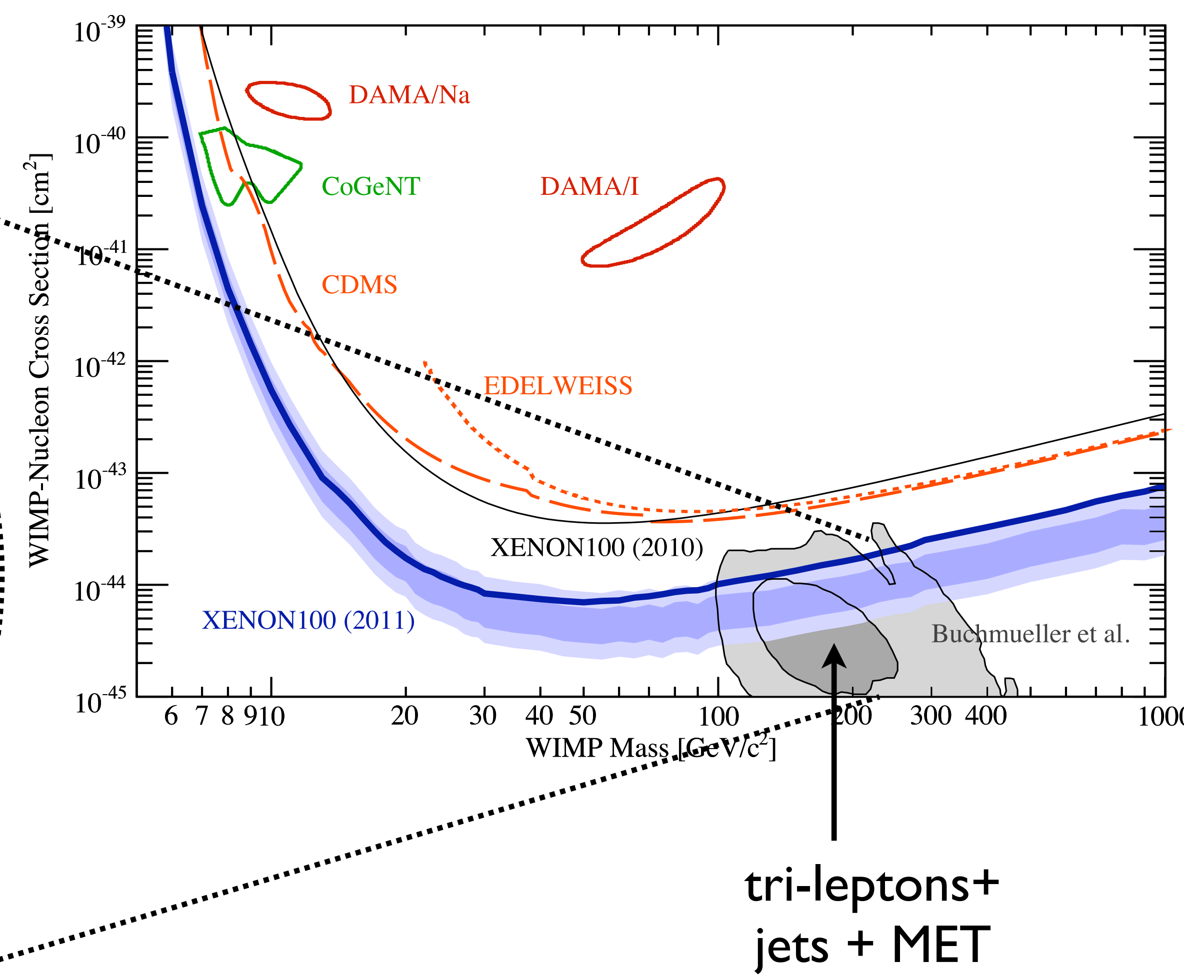

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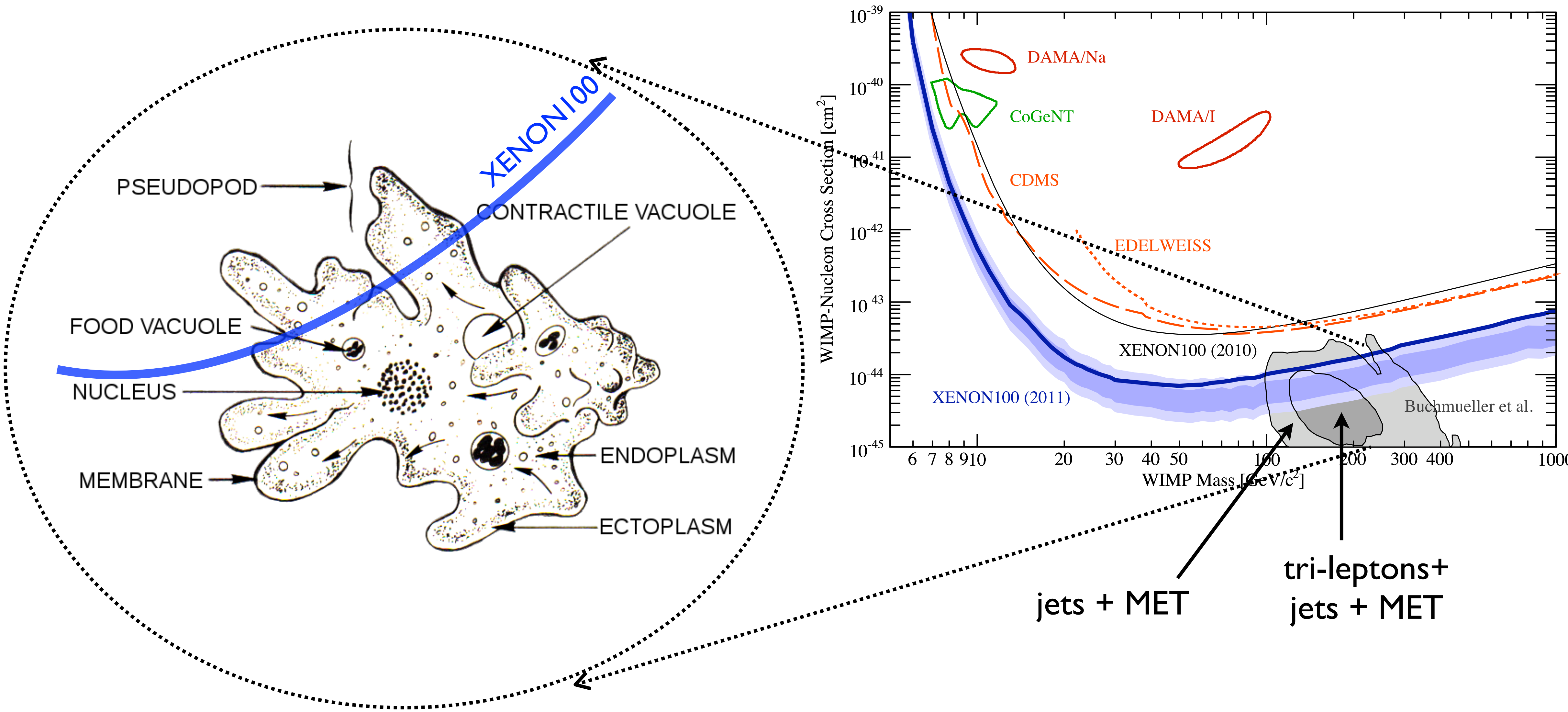

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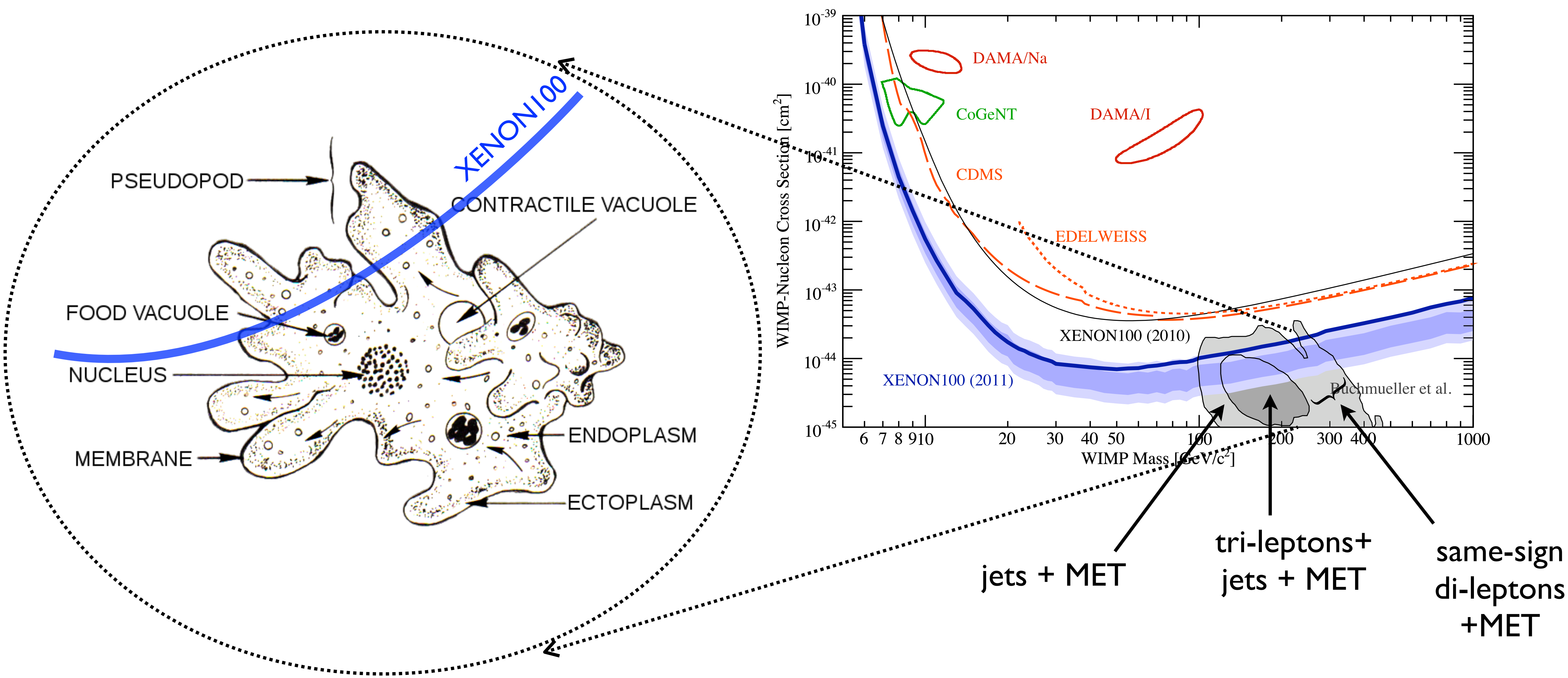

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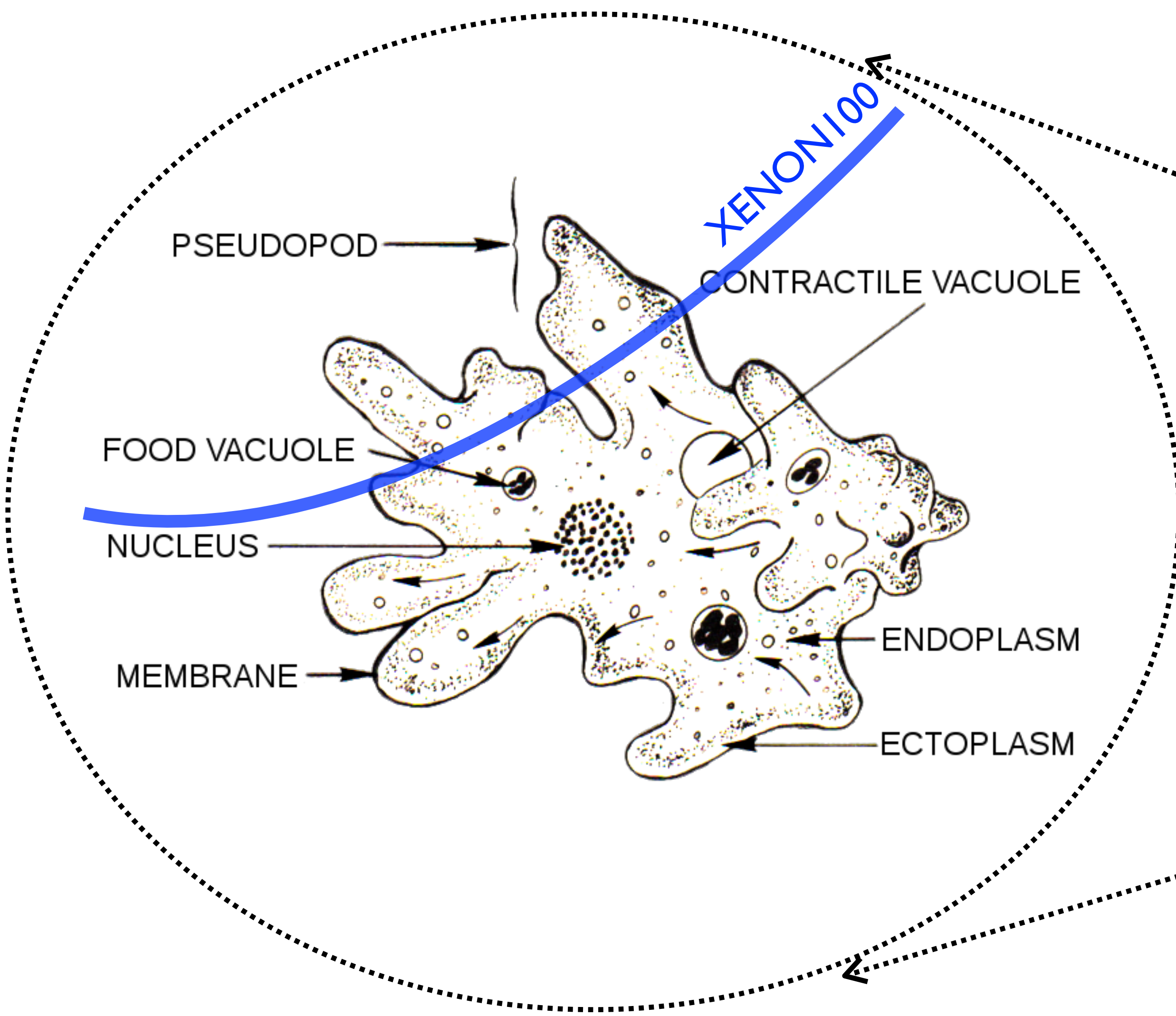
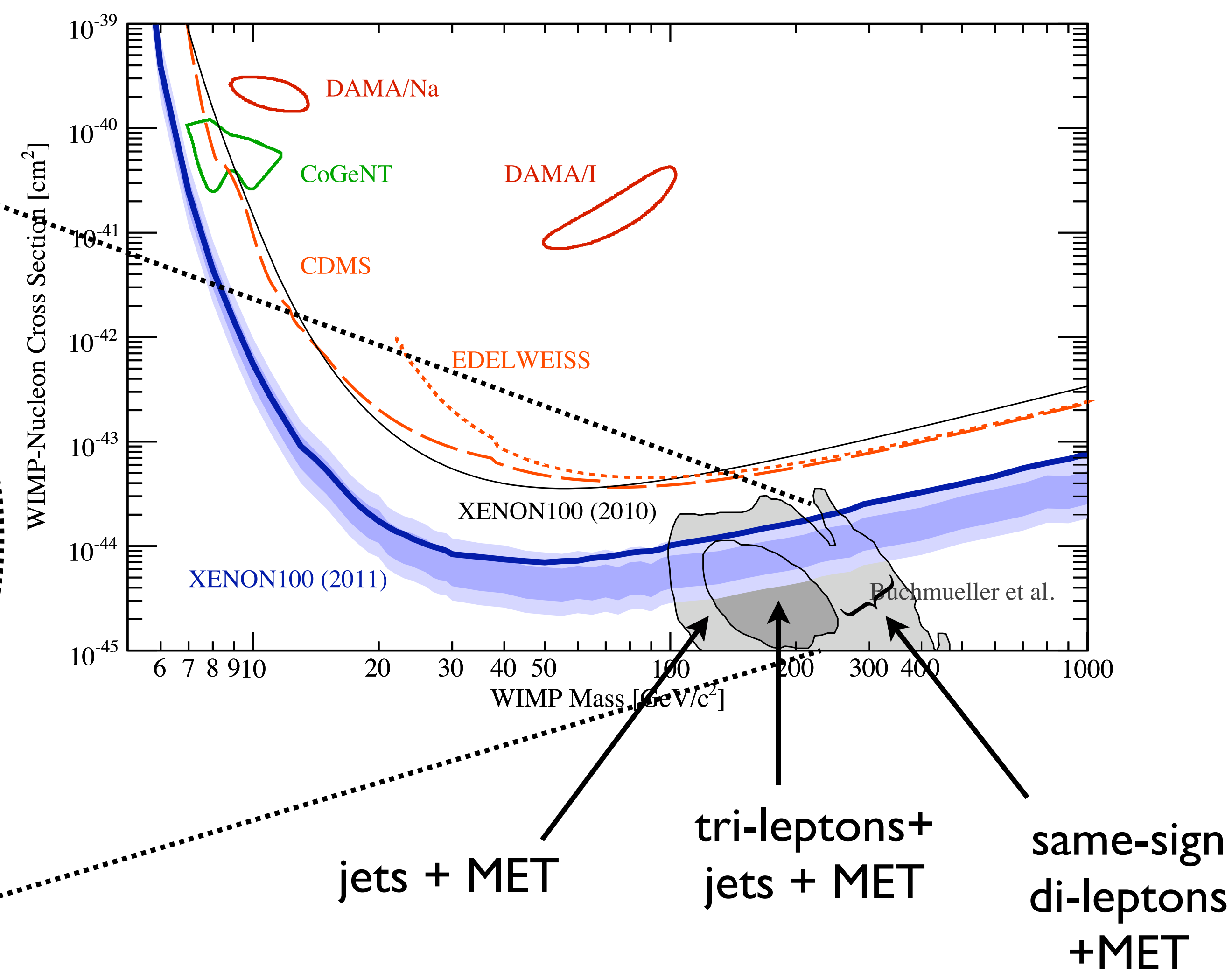




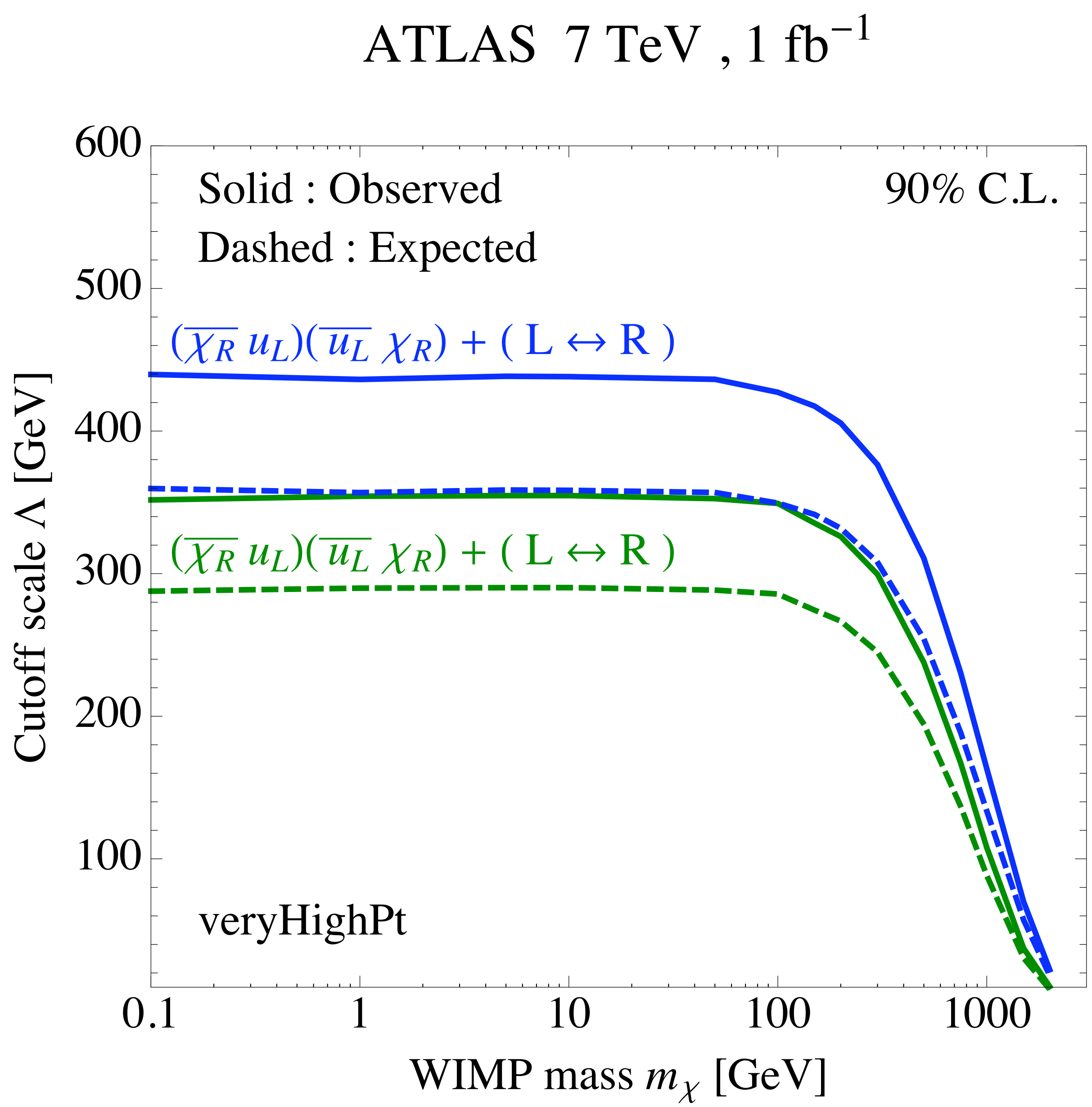
"XENON100 is starting to probe the MSSM's pseudopod, LHC killed the Membrane, but the ectoplasm is still safe." [submitted to nature]

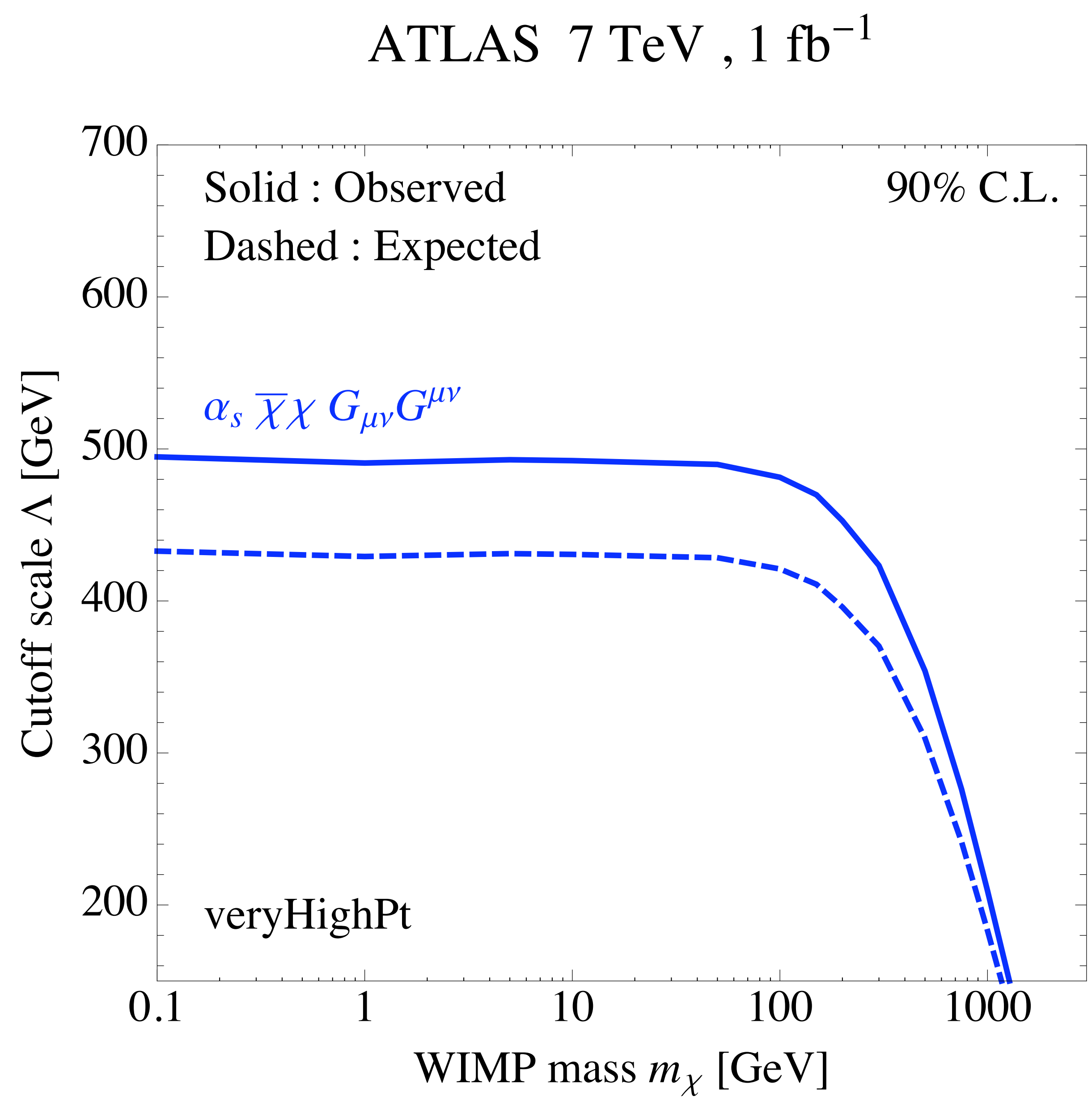
Games: Higgs searches & DM

* *Assume* the Higgs hint is real w/ SM production.
* The fact that is was seen in di-photon 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.

Other Operators:

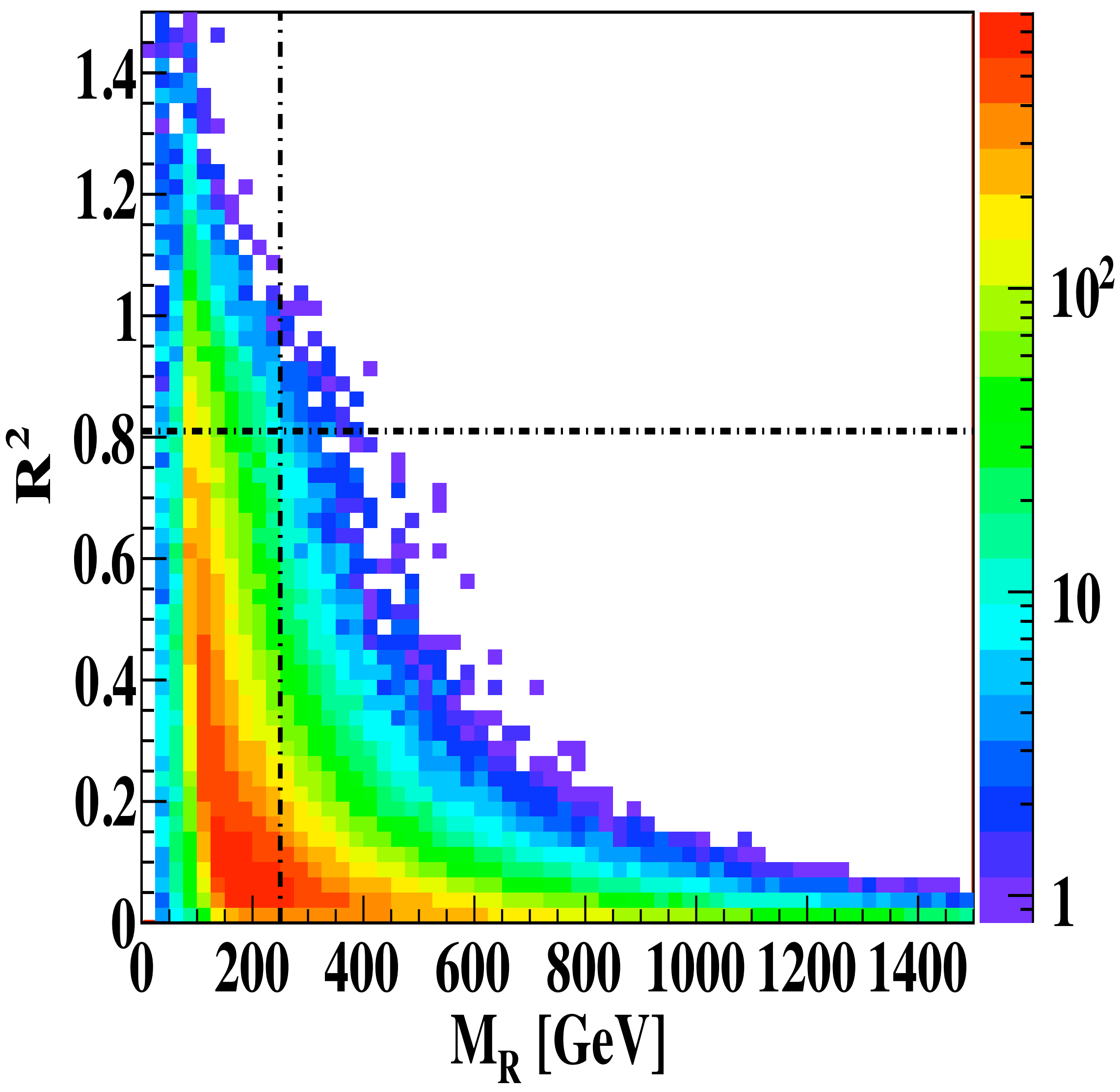




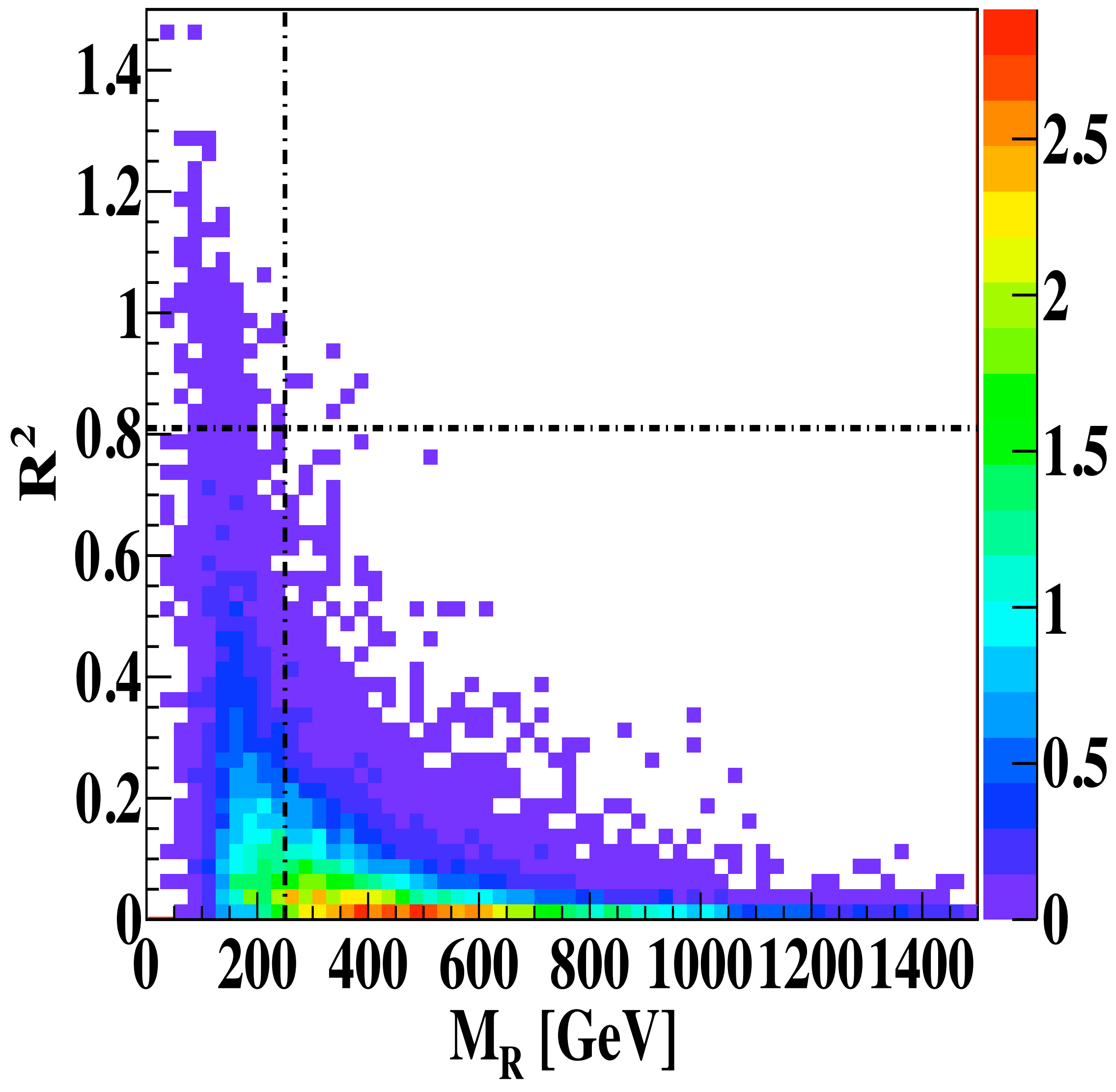
The limit is flat up to ~200 GeV.
Goes all the way to zero.

Razor Shapes

* Other Backgrounds:

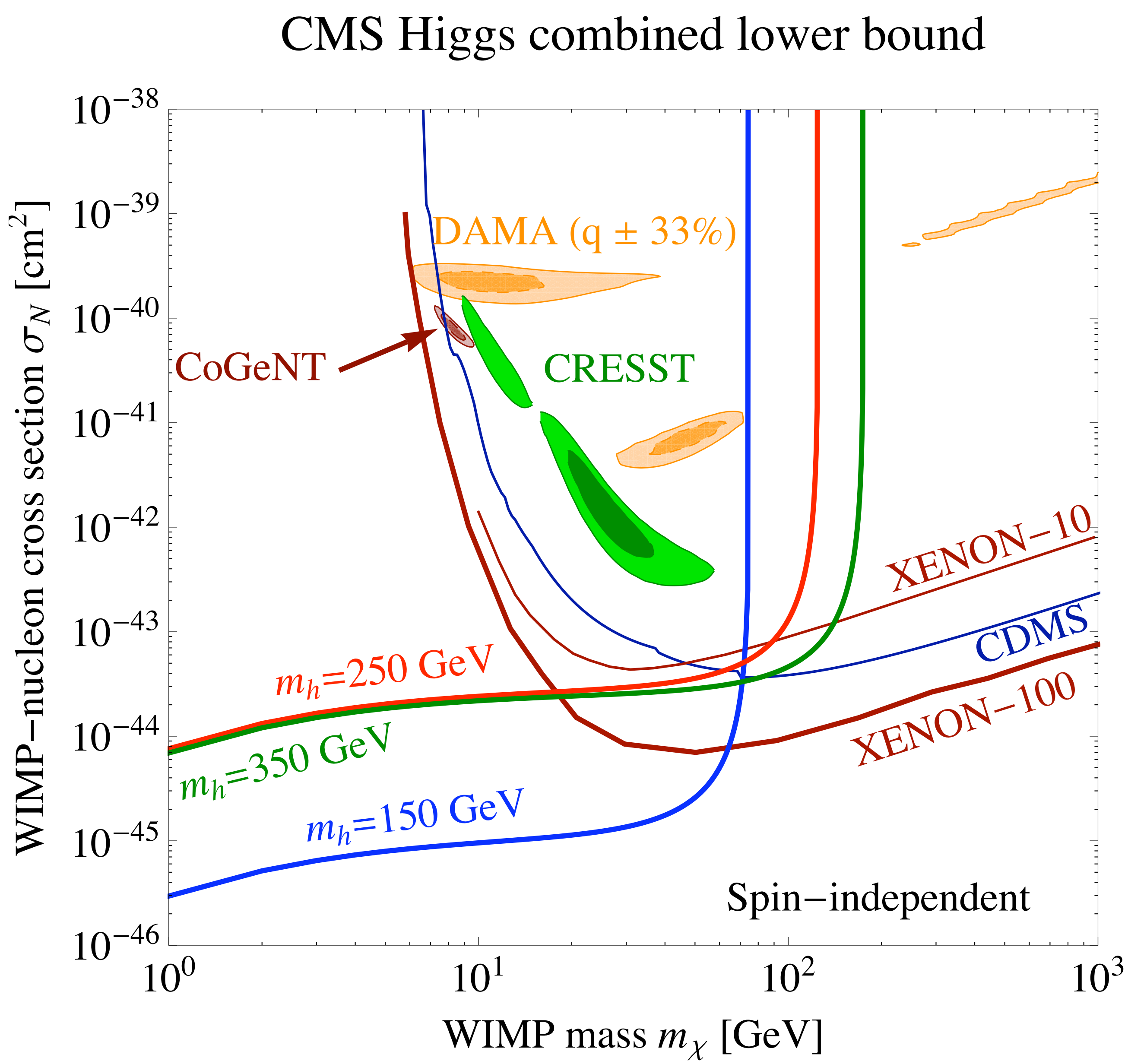


(b) W+jets.



(c) $t\bar{t}$.

Current Higgs limits vs DM

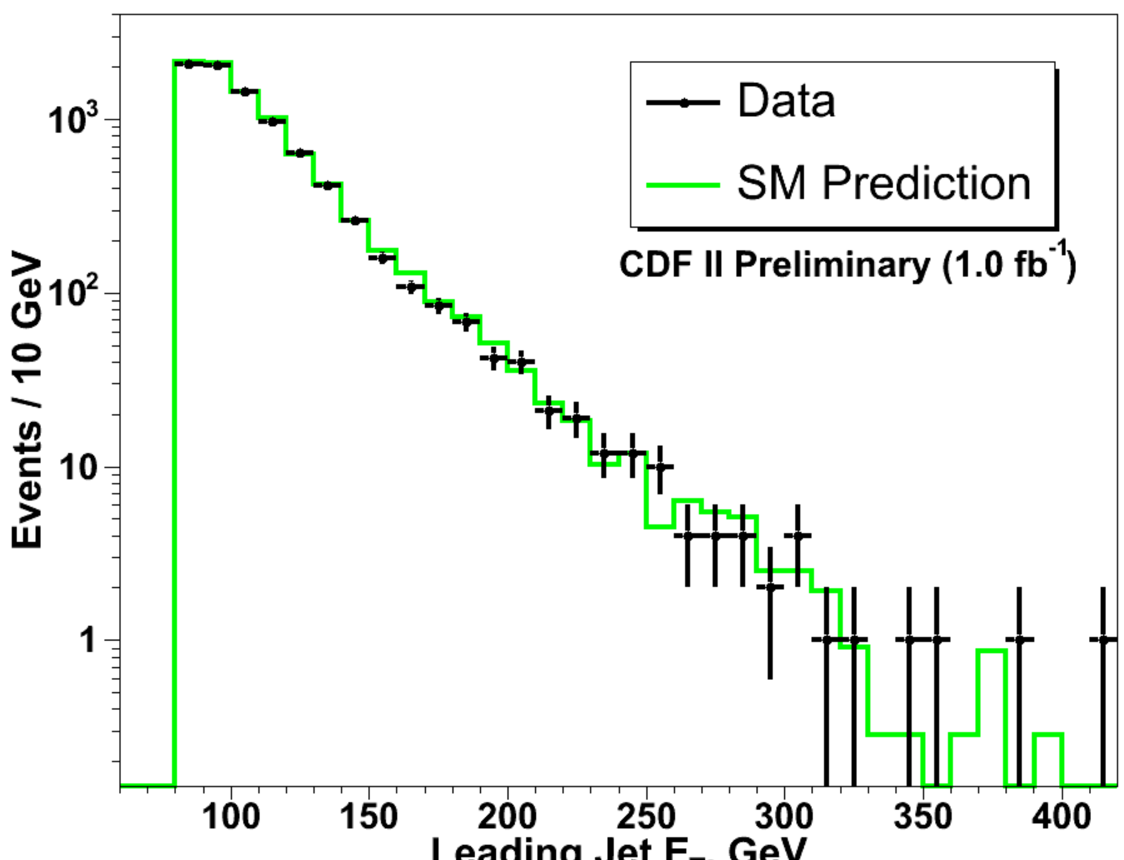


Also, if a light SM Higgs is discovered, an upper limit on DD can be extracted.

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]

ATLAS Analysis

- 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 $|\eta(j_2)| < 4.5$.

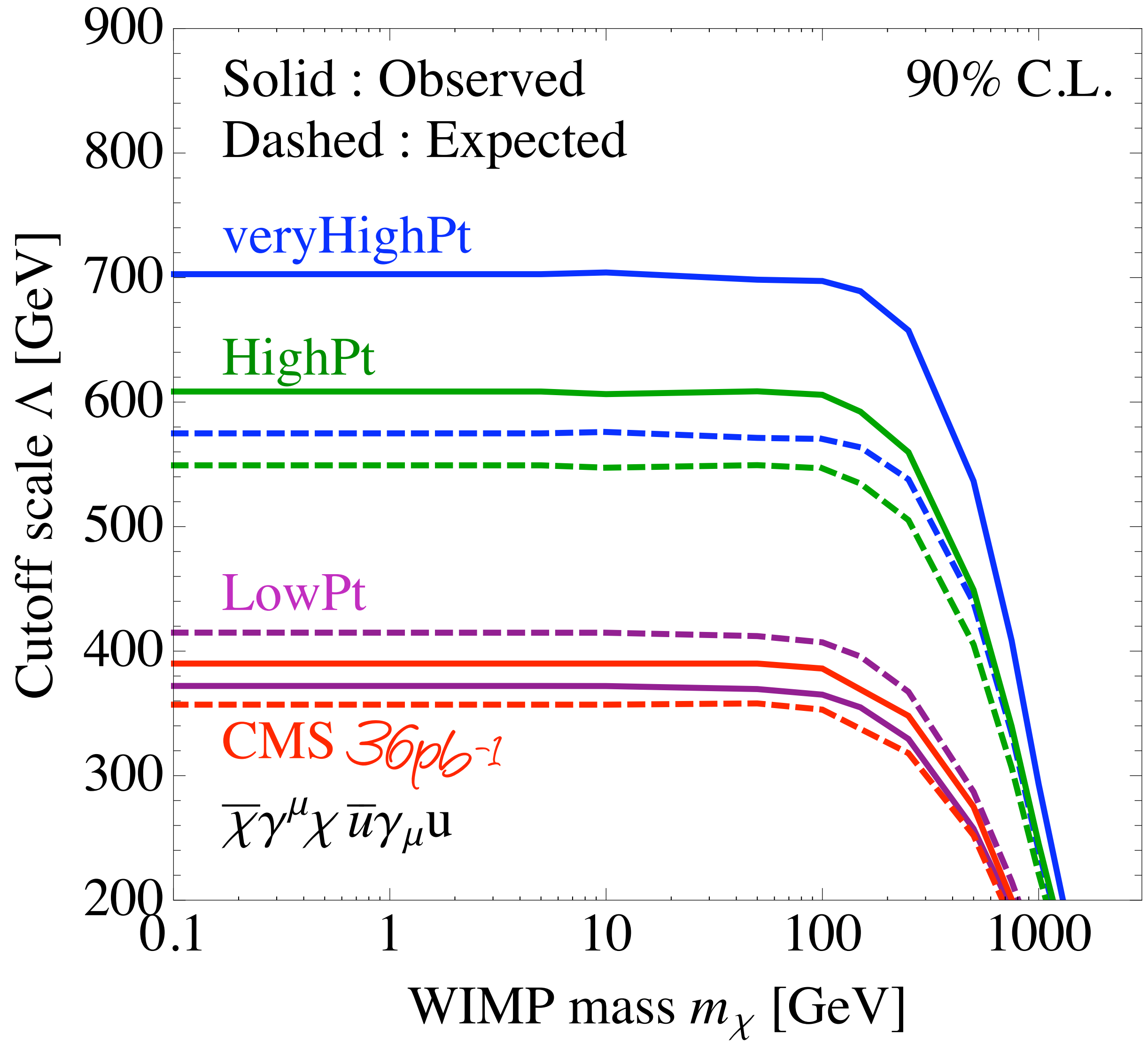
`HighPT` Selection requires $\not\!\!E_T > 220$ GeV, one jet with $p_T(j_1) > 250$ GeV, $|\eta(j_1)| < 2$, and events are vetoed if there is a second jet with $|\eta(j_2)| < 4.5$ and with either $p_T(j_2) > 60$ GeV or $\Delta\phi(j_2, \not\!\!E_T) < 0.5$. Any further jets with $|\eta(j_2)| < 4.5$ must 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 fb^{-1}	ATLAS `HighPT` 1.0 fb^{-1}	ATLAS `veryHighPT` 1.0 fb^{-1}
Expected	15100 ± 700	1010 ± 75	193 ± 25
Observed	15740	965	167

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

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



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

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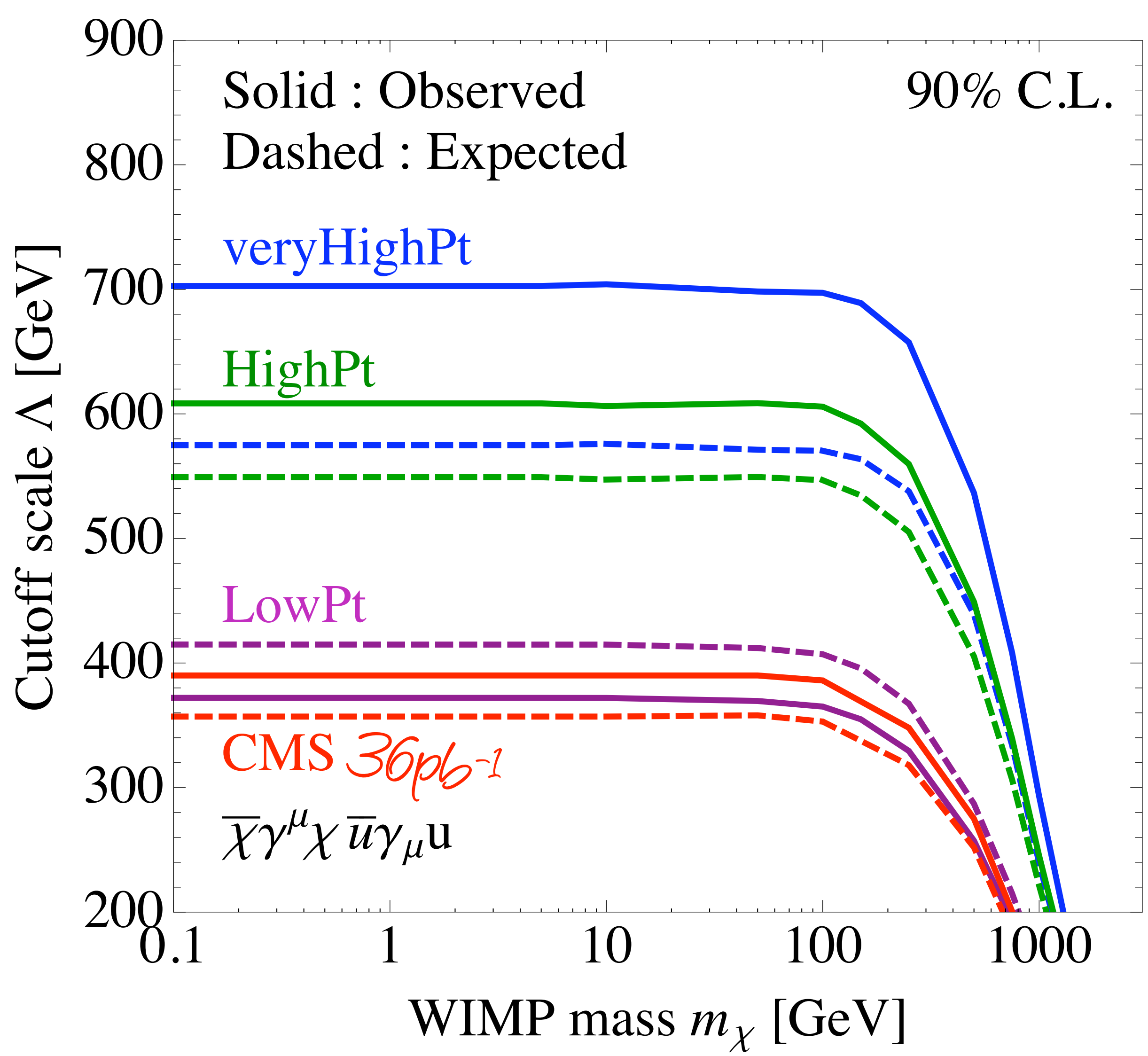


$$\Delta_N = \begin{cases} 0 & \text{expected bound} \\ N_{\rm obs} - N_{\rm SM} & \text{observed bound} \end{cases}$$

Harder is better.

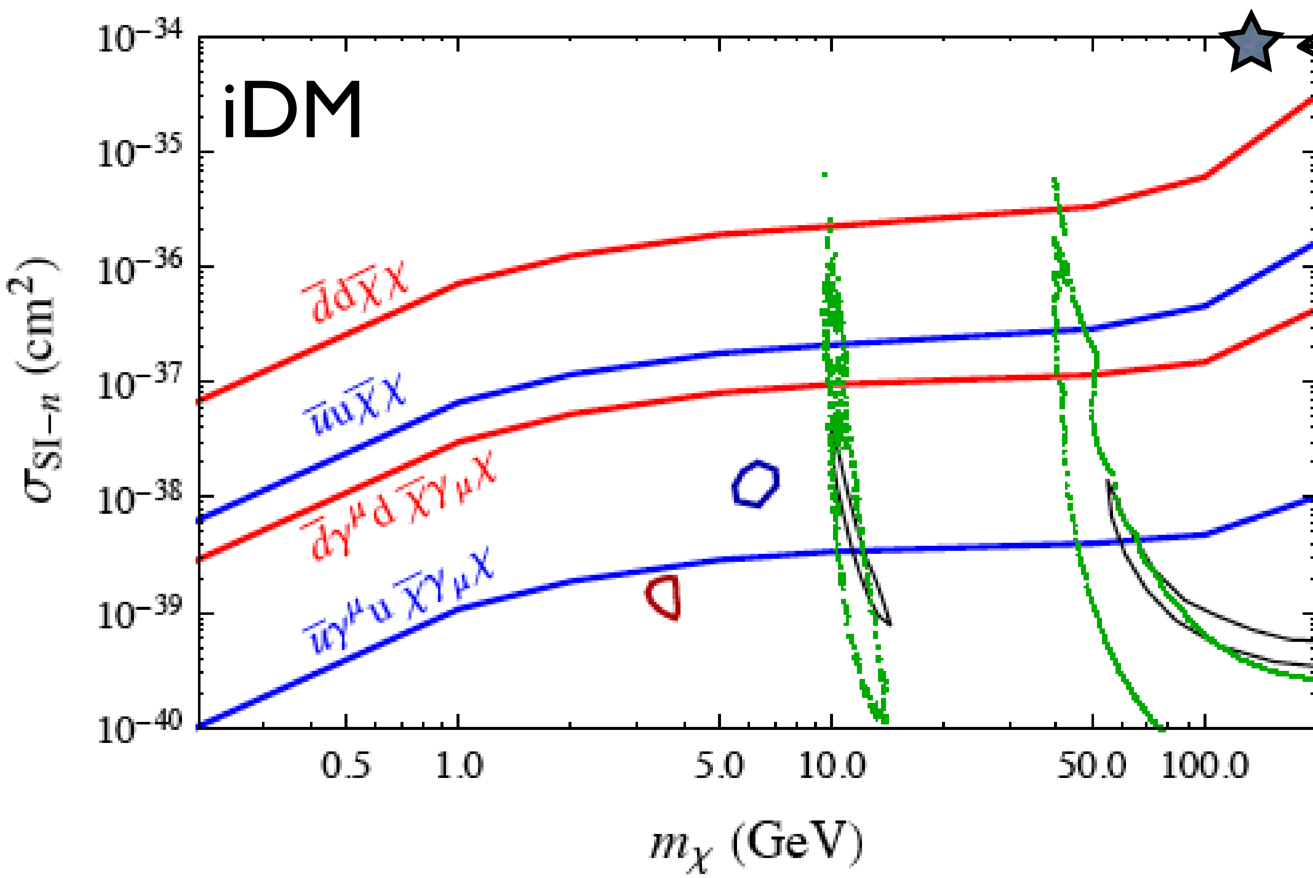
in the future:

populate the tail

and keep cutting harder

iDM, MDDM, ...

- There are other scenarios in which DD is suppressed, but colliders don't care:



impure thoughts... can survive with light mediator.

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)

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

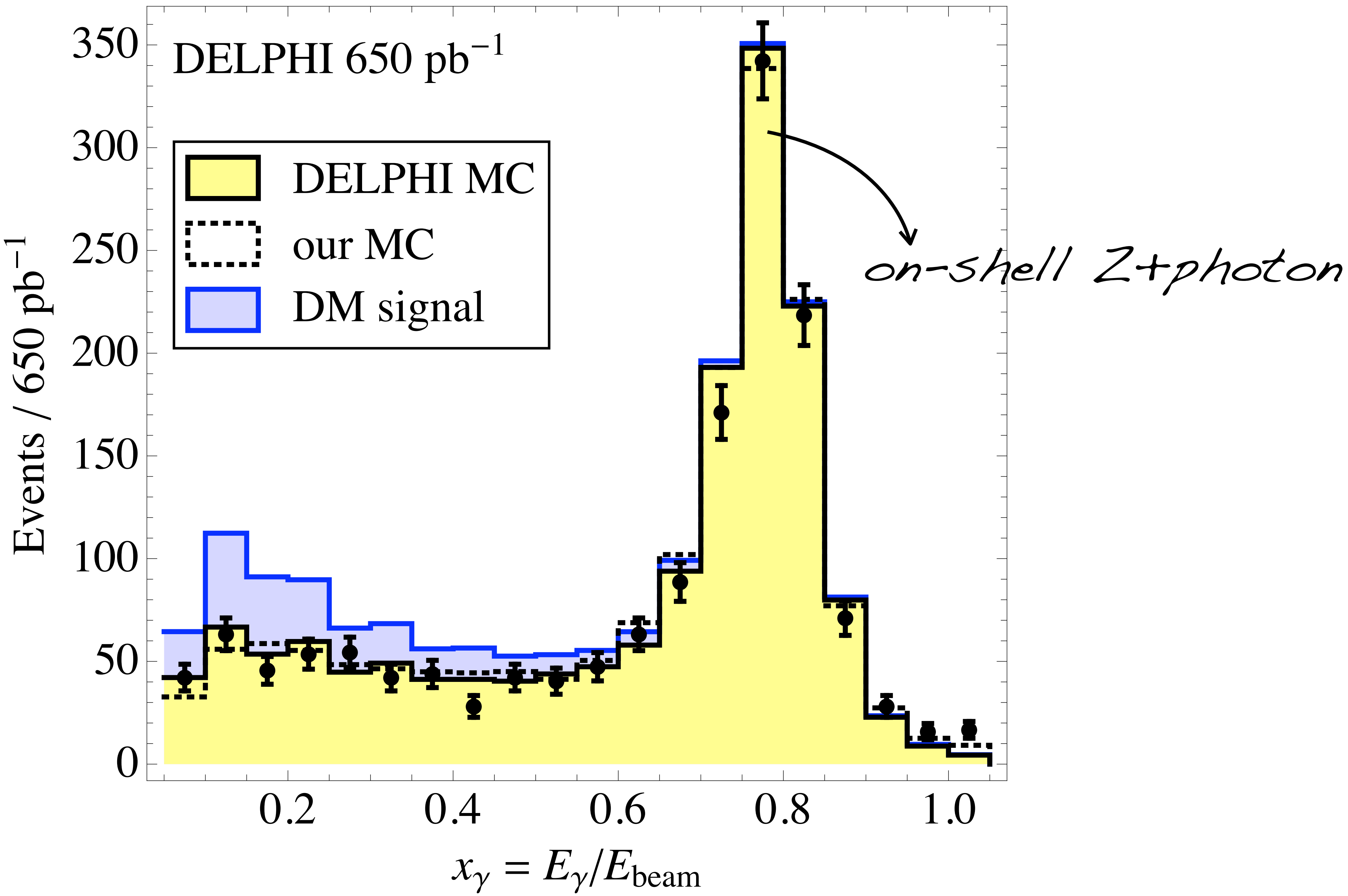
$$\mathcal{O}_S = \frac{(\bar{\chi}\chi)(\bar{\ell}\ell)}{\Lambda^2}\,, \qquad \text{(scalar, } s\text{-channel)}$$

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

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

Mono-photon

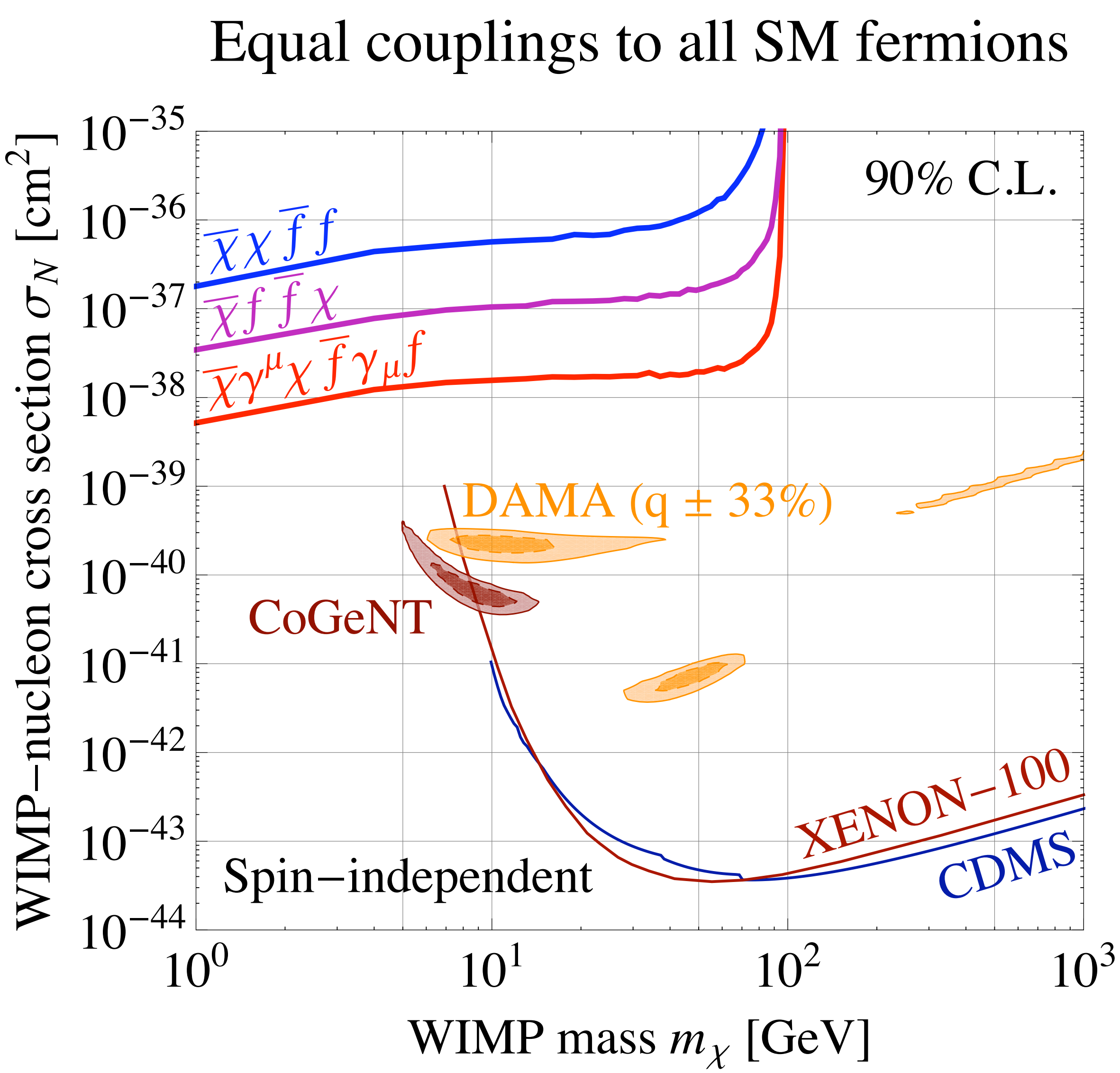
* Use spectrum shape to reject background peak.

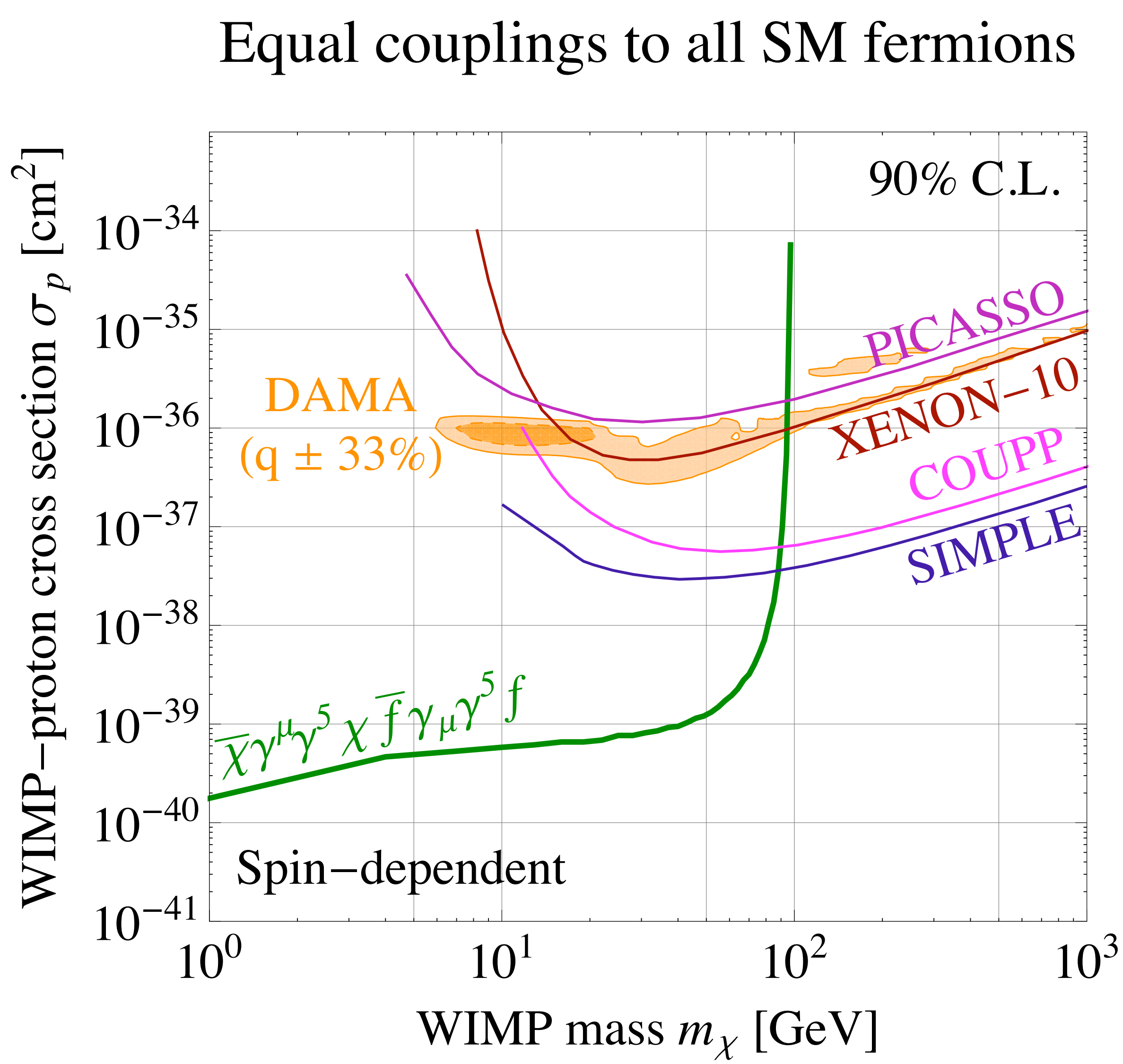


Model Dependence

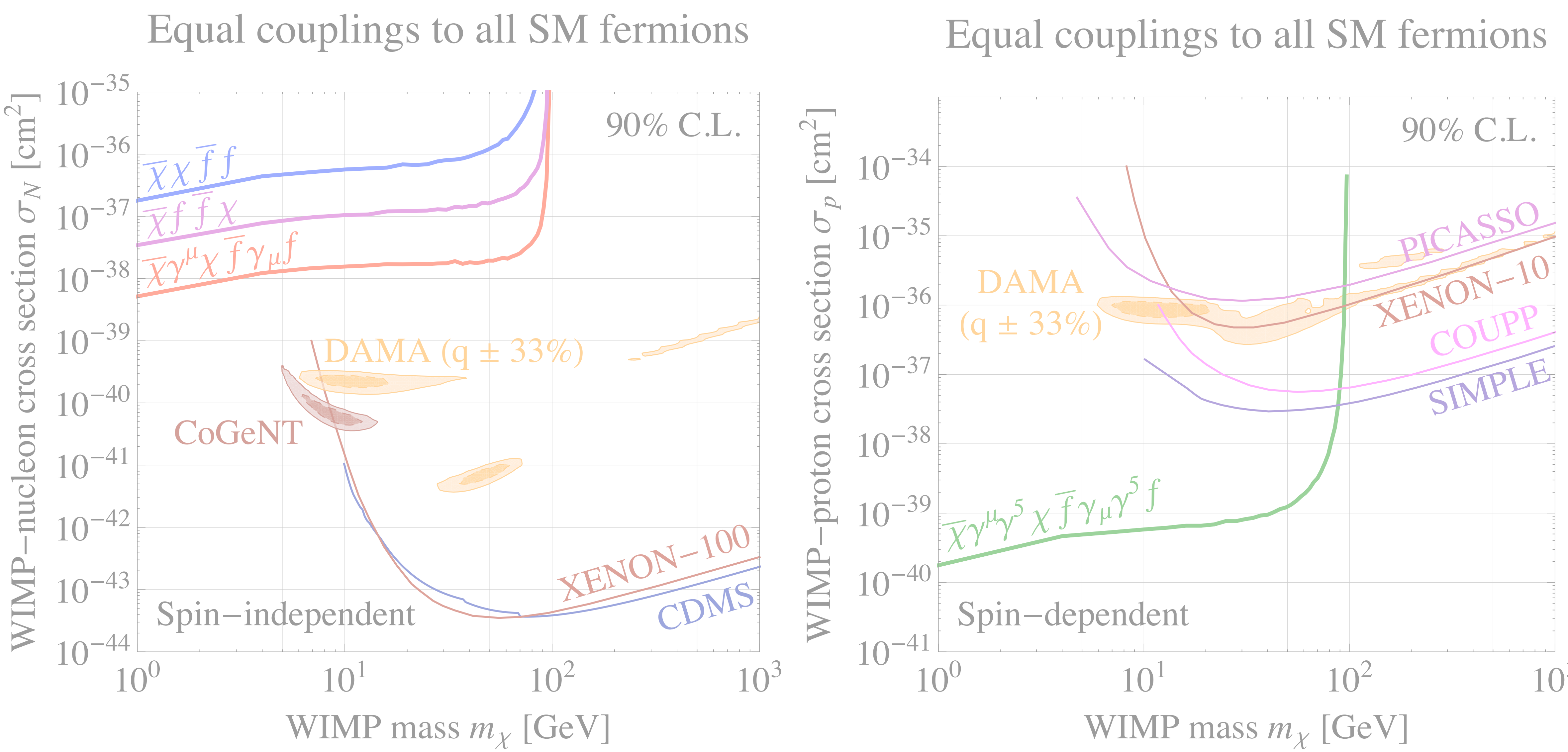
* We limit lepton couplings.
* But how does DM couple to quarks?
* Consider 2 extreme cases:
    * Couplings to **quarks are same as leptons**.
    * Couplings to quarks are **zero**.
* *Any* other case can be derived from these two.

DD Limits


Equal couplings to all SM fermions
90% C.L.
WIMP−nucleon cross section σ_N [cm^2]
WIMP mass m_χ [GeV]
χ̄χ f̄f
χ̄f f̄χ
χ̄γ^μχ f̄γ_μf
DAMA (q ± 33%)
CoGeNT
XENON−100
CDMS
Spin−independent


Equal couplings to all SM fermions
90% C.L.
WIMP−proton cross section σ_p [cm^2]
WIMP mass m_χ [GeV]
DAMA
(q ± 33%)
PICASSO
XENON−10
COUPP
SIMPLE
χ̄γ^μγ^5χ f̄γ_μγ^5f
Spin−dependent

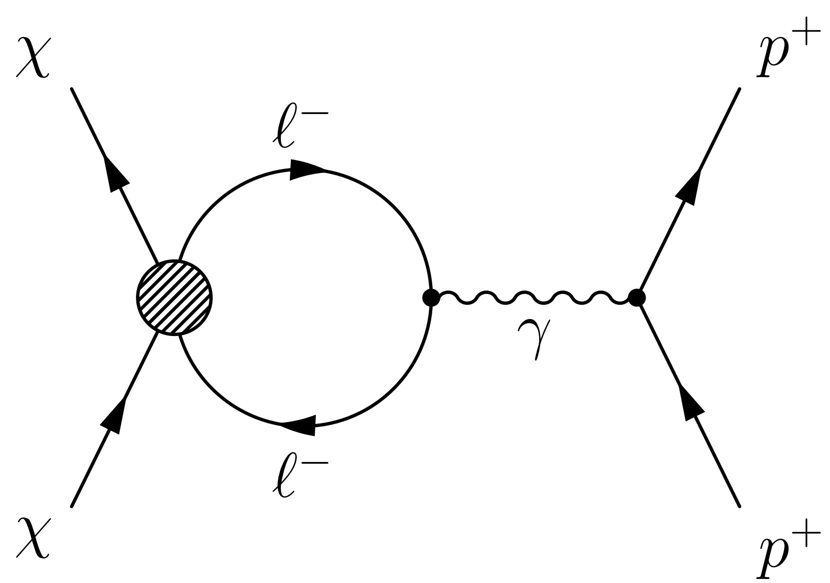
DD Limits



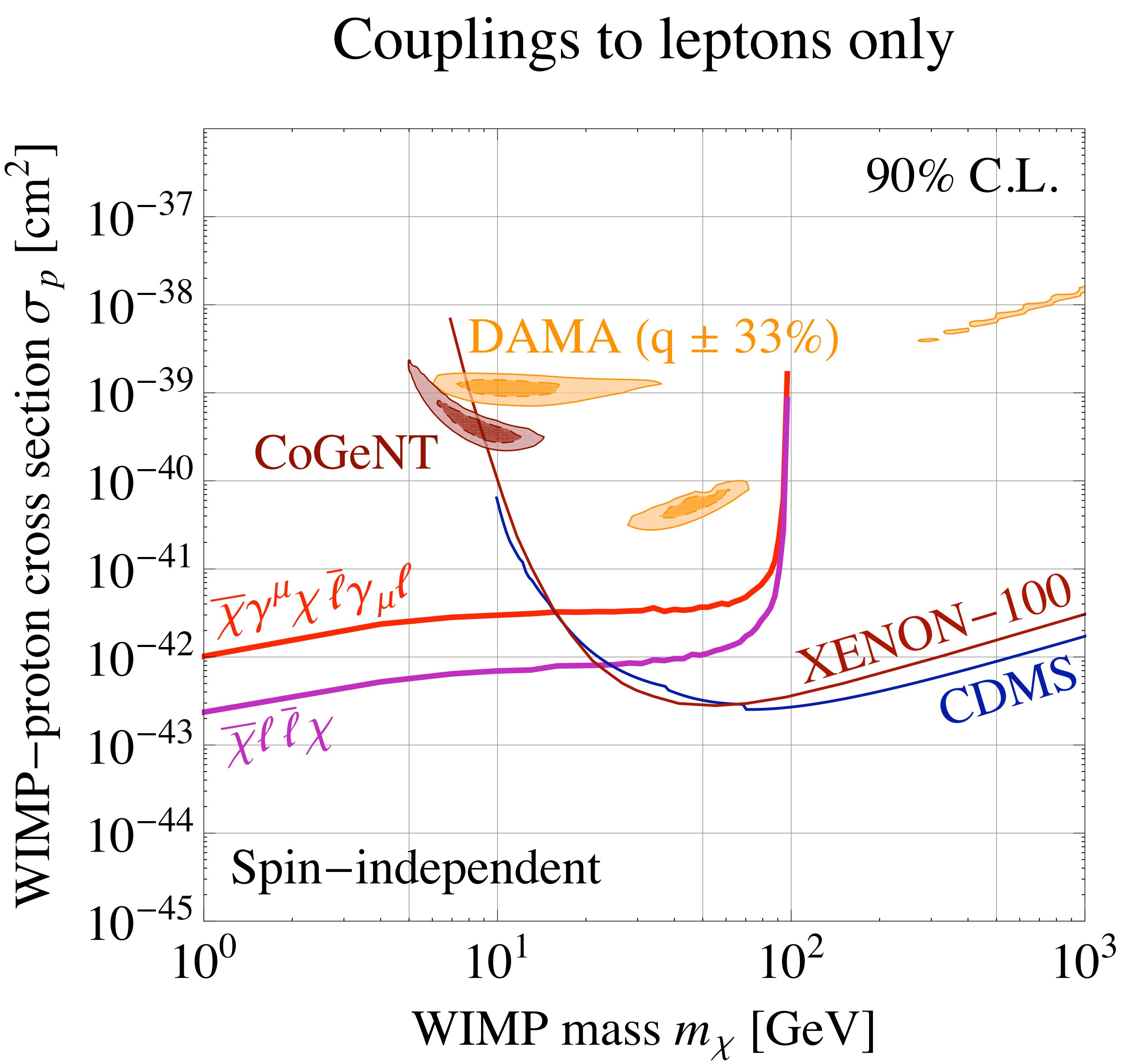
Equal couplings to all SM fermions
90% C.L.
$\overline{\chi}\chi\overline{f}f$
$\overline{\chi}f\overline{f}\chi$
$\overline{\chi}\gamma^{\mu}\chi\overline{f}\gamma_{\mu}f$
DAMA (q ± 33%)
CoGeNT
XENON−100
CDMS
Spin−independent
WIMP−nucleon cross section σ_N [cm^2]
WIMP mass m_χ [GeV]
Equal couplings to all SM fermions
90% C.L.
PICASSO
XENON−10
COUPP
SIMPLE
DAMA (q ± 33%)
$\overline{\chi}\gamma^{\mu}\gamma^5\chi\overline{f}\gamma_{\mu}\gamma^5 f$
Spin−dependent
WIMP−proton cross section σ_p [cm^2]
WIMP mass m_χ [GeV]

Leptophilic DM

- Consider zero couplings to quarks.

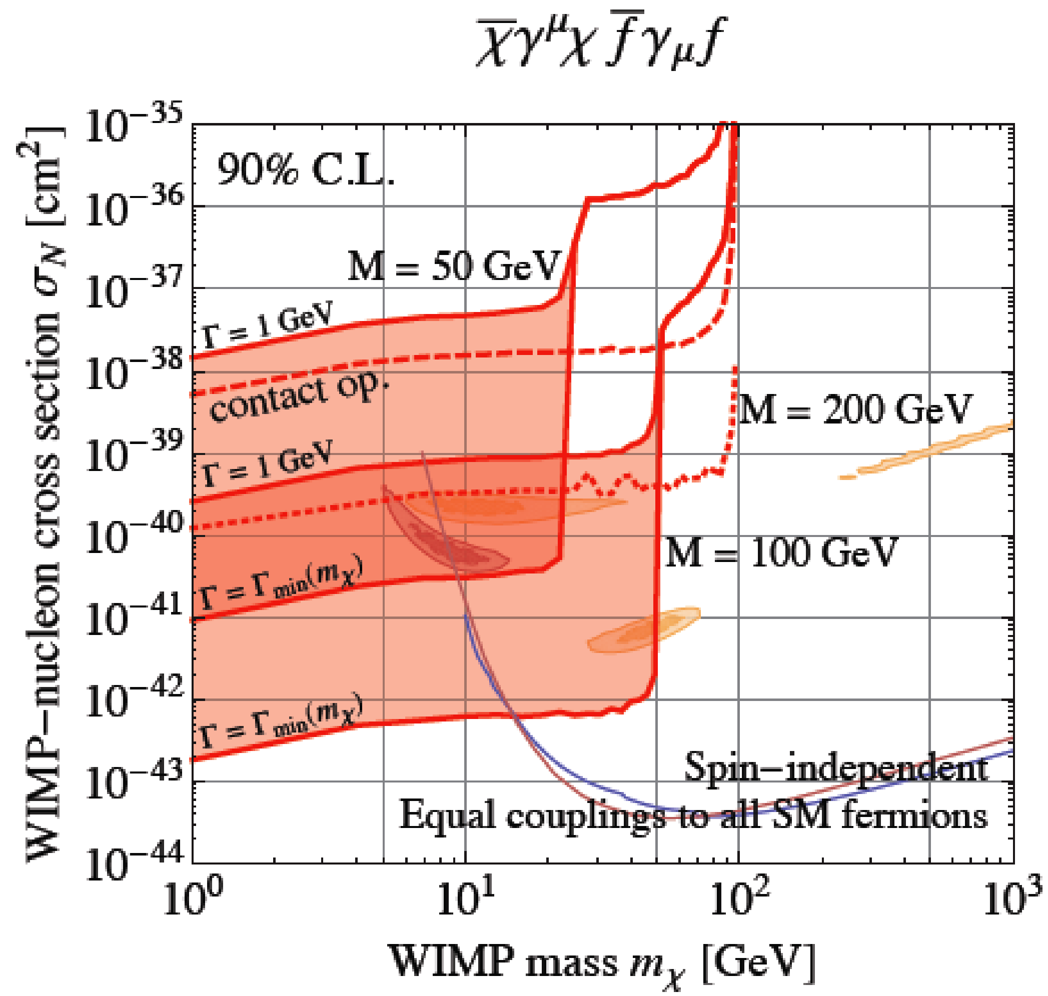


Direct detection pays a big price. Collider limits are strong.

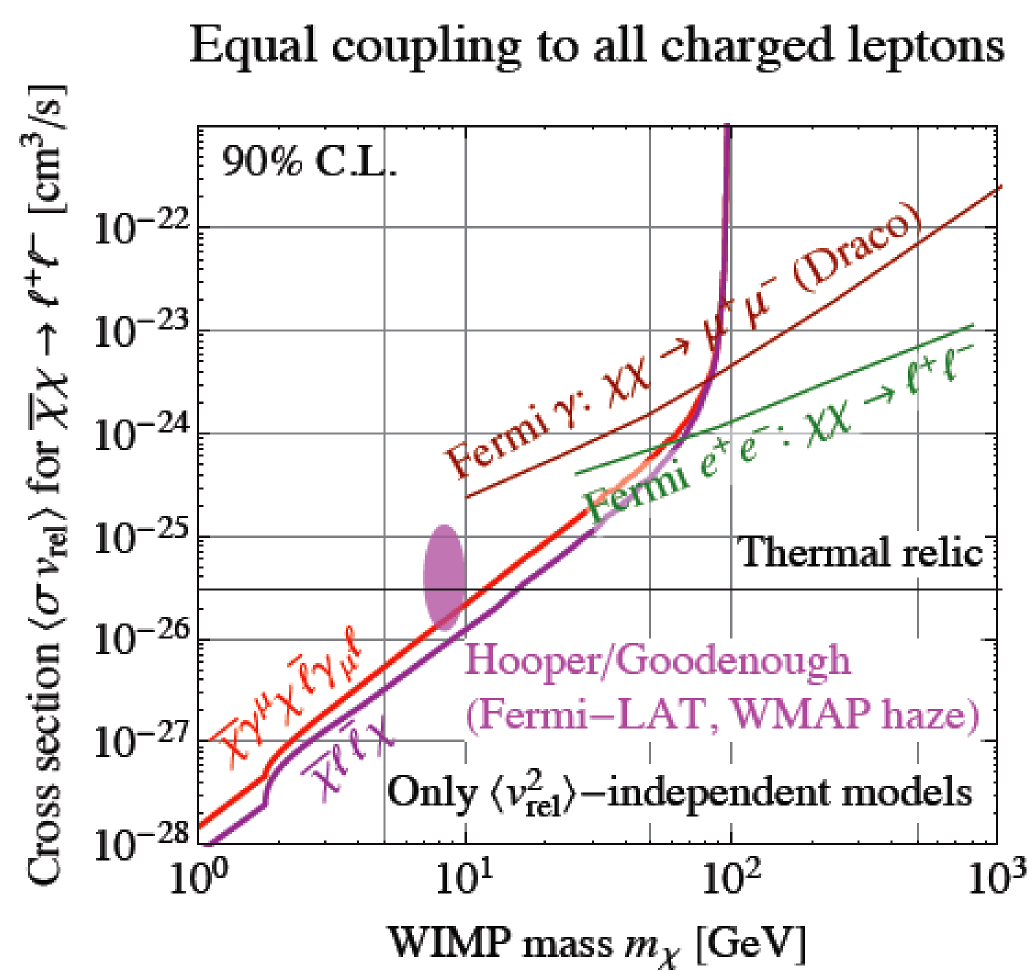


Many more..

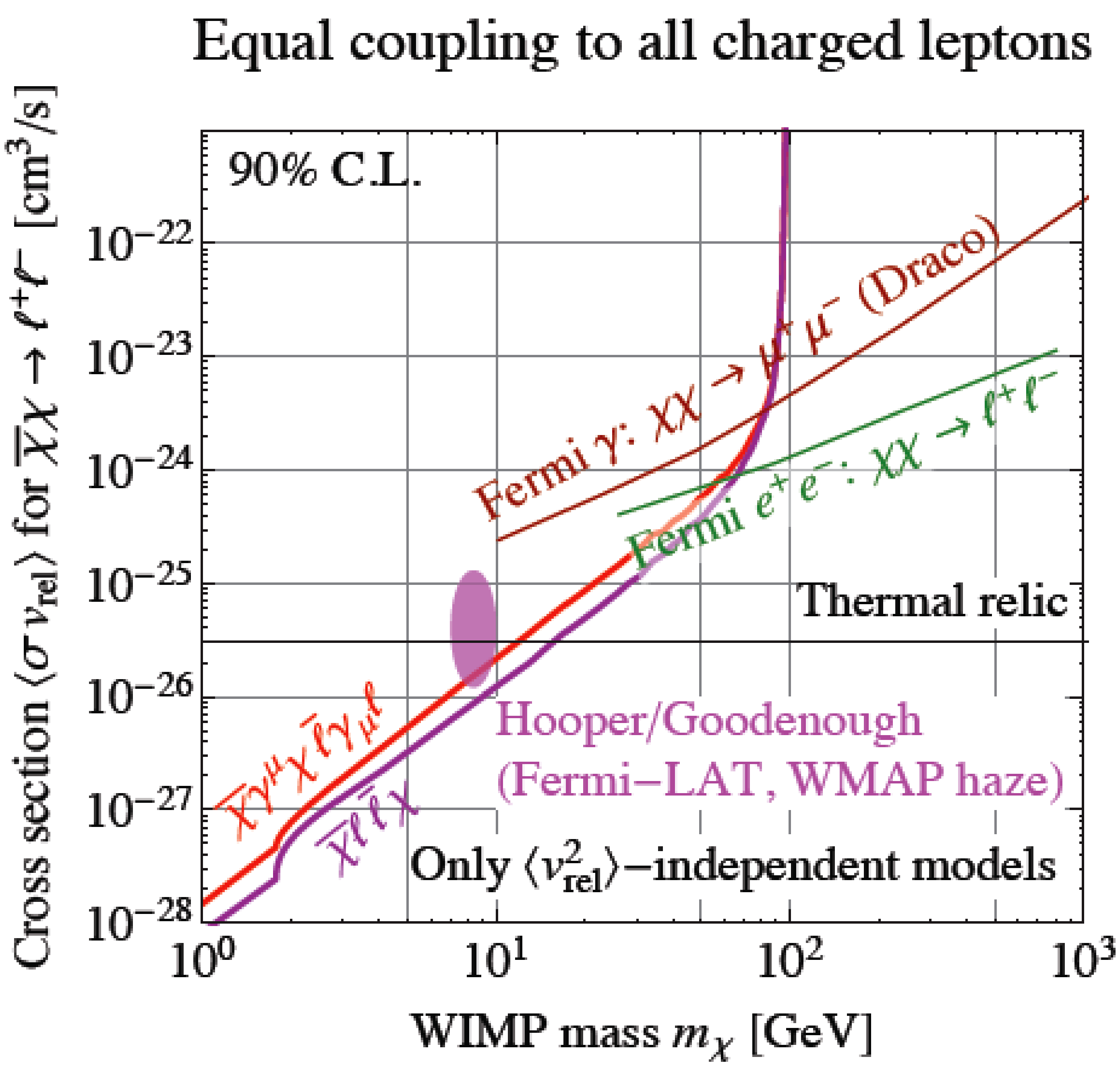
* Light mediators:



* Indirect detection:



Indirect Detection



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

Light Mediators

* Lets fix $\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$ and lower M.

  The couplings must be decreased to compensate.

* Then for very small M we get to the regime where

$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

* The cross section drops as M^4.
* **But what happens in the intermediate regime?**

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

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