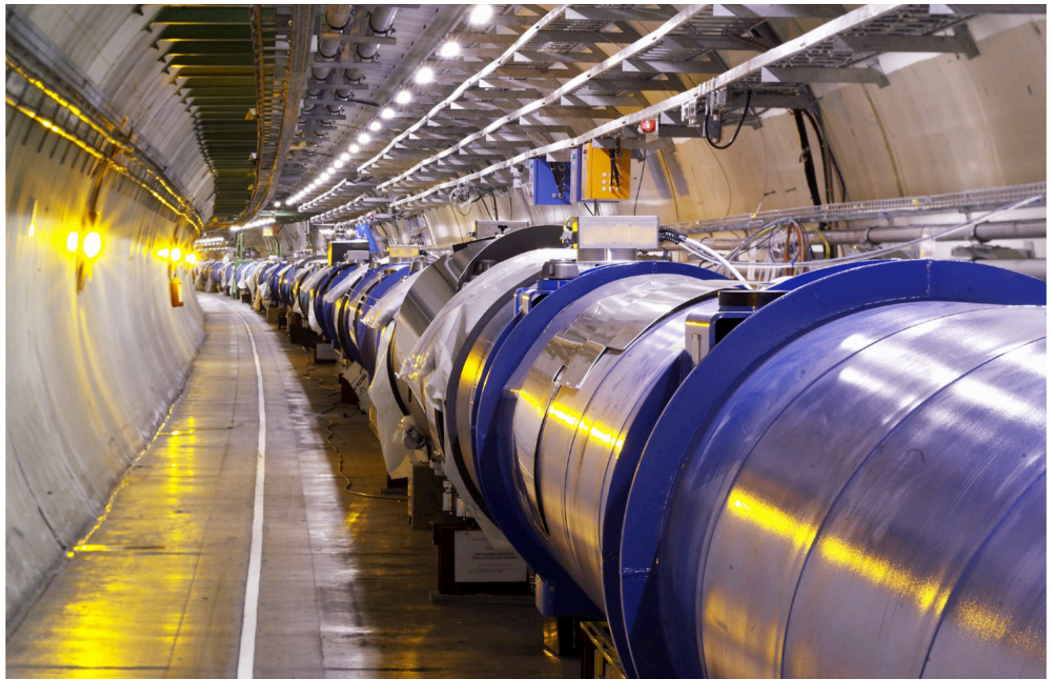
Connections of Colliders to Astrophysics

and Cosmology



Roni Harnik, Fermilab

Stuff I owe you

(for discussion?)

Big Bang Nucleosynthesis

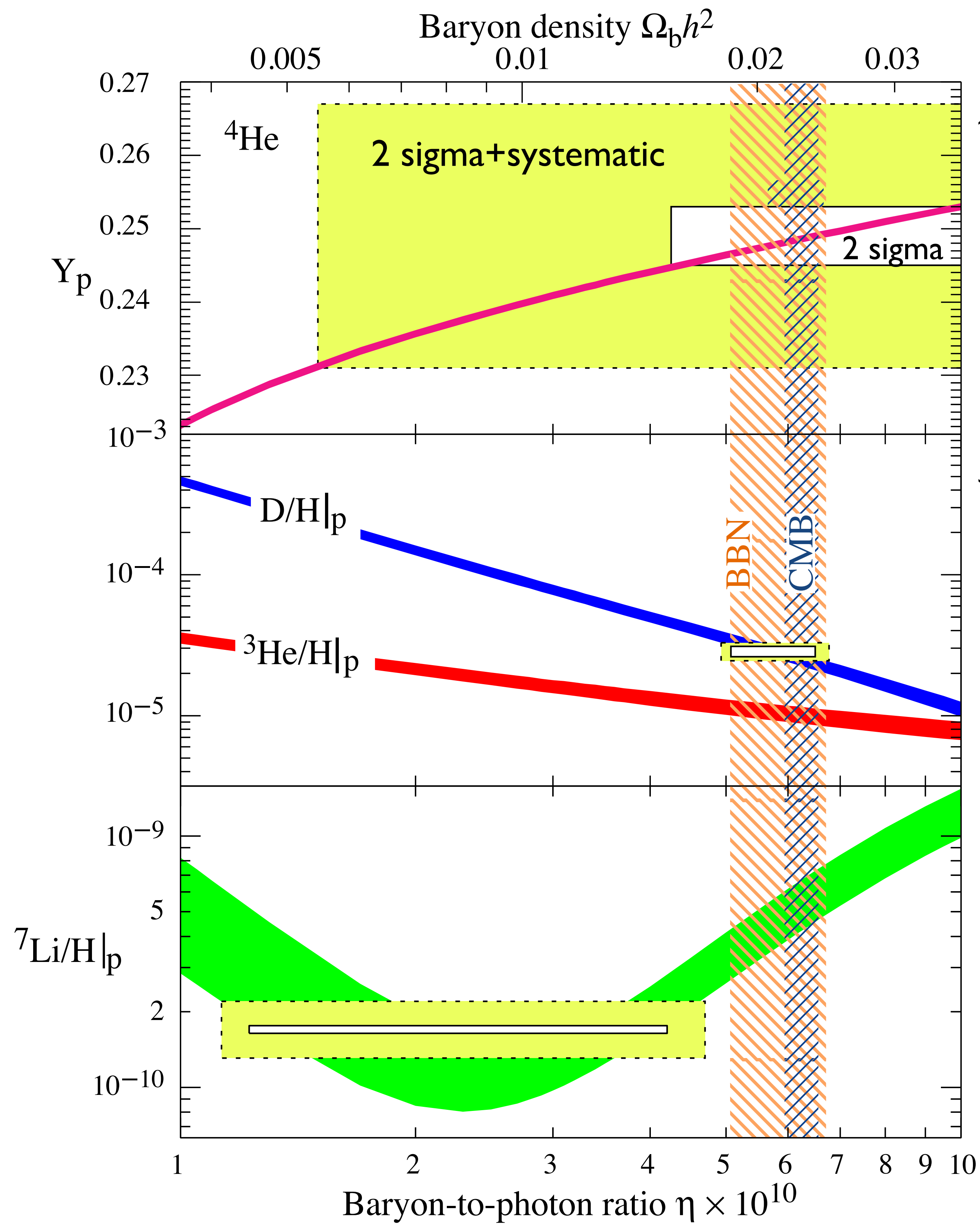
Baryons amount to
4% of the Universe.

From other sources:
Total matter is 22%.

↓

DM is non-baryonic.

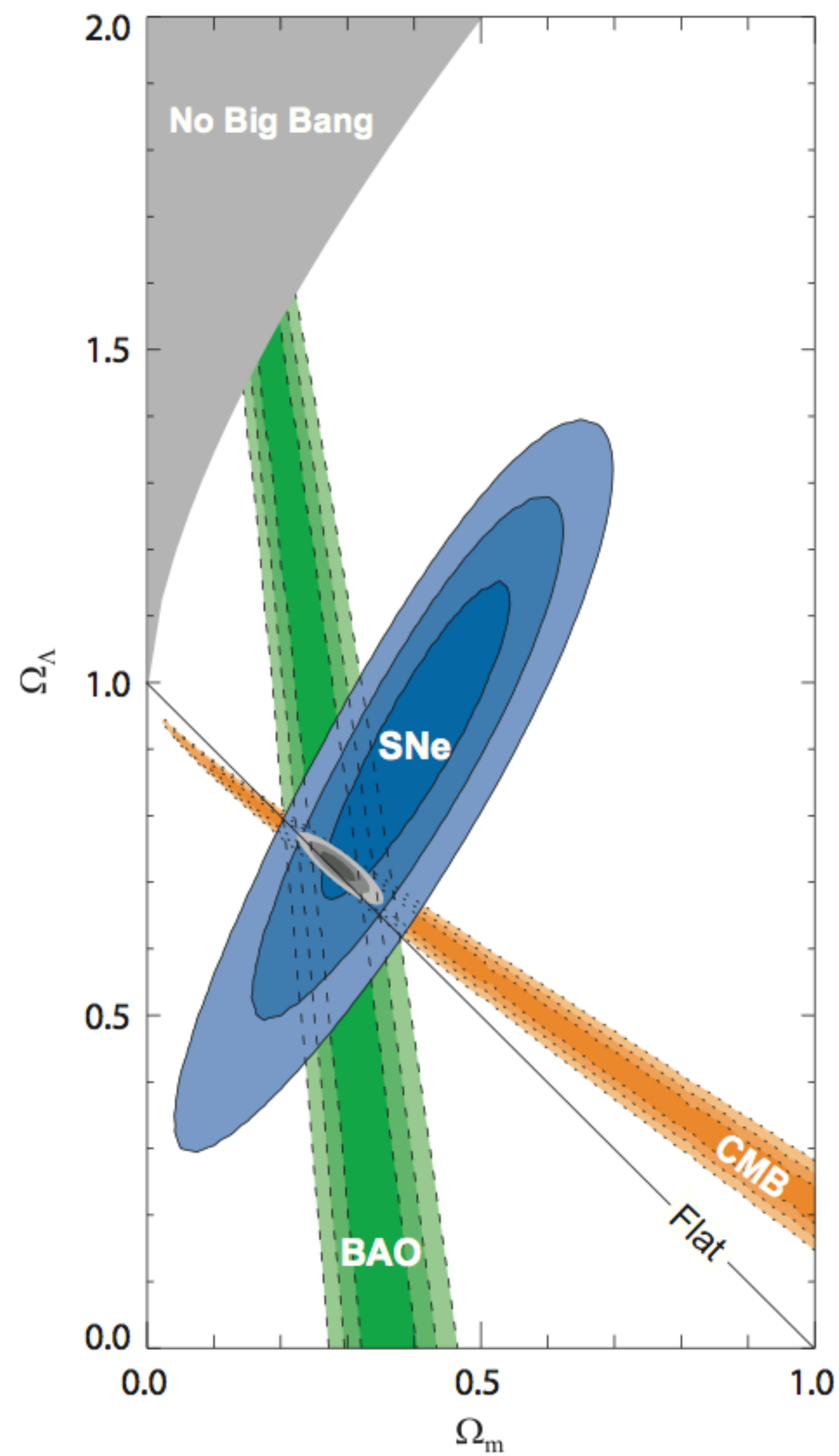
(there went my theory of "sneaker dark matter")



(PDG review on BBN)

The nice plot

- BAO= baryon acoustic oscilations. Power spectrum of large scale structure.
- SNe = supernovae type 1A
- CMB=CMB.
- Notice theat each technique alone has a “degenerate direction.
- The combination rocks.



Did anyone find DM in their Beer?

DM Properties

* ***cold***:
  Simulations of the formation of large scale structure seems to favors cold (a.k.a non-relativistic) DM.

* ***long lived***:
  DM is still around today. It should not decay faster than the age of the Universe. If it decays to SM particles the limits are *much* stronger:

Decay Channel	τ Lower Limit	Experiment
$q\bar{q}$	10^{27} s	PAMELA antiprotons
e^+e^- or $\mu^+\mu^-$	2×10^{25} s $\left(\frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)$	PAMELA positrons
$\tau^+\tau^-$	10^{25} s $\left(1 + \frac{\mathrm{TeV}}{m_{\mathrm{DM}}}\right)$	EGRET + PAMELA
WW	3×10^{26} s	PAMELA antiprotons
$\gamma\gamma$	2×10^{25} s	PAMELA antiprotons
$\nu\bar{\nu}$	10^{25} s $\left(\frac{m_{\mathrm{DM}}}{\mathrm{TeV}}\right)$	AMANDA, Super-K

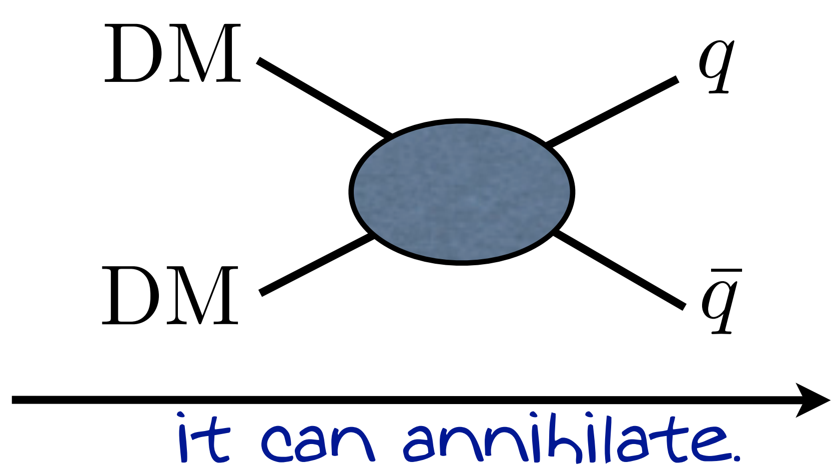
DM Properties

* ***does not interact much***:
  Obviously. Its dark.
  But due to halo shapes we know-
  - it does not interact strongly with itself, otherwise halos would be too spherical (e.g. Fox and Buckley 2009).
  - it does not interact with massless particles, otherwise those could be radiated, and the halo would collapse to a disk.

Does it have any non-gravitational interactions?

Relic abundance: WIMPS

* What sets the amount of DM?
* Lets assume that DM has a weak interaction with matter:



* What happens if we add such a particle to the primordial hot soup?

Relic abundance: WIMPS

Disney Version:

* Initially DM is in thermal equilibrium.

$$\chi\chi \leftrightarrow \bar{f}f$$

* As the T drops below the mass it is "energetically favorable" for DM pair to convert to SM particles.

  → DM abundance begins to drop.

* At some point, DM particles will not find friend to annihilate with. The abundance is set. ***Freeze-out*.**

Relic abundance: WIMPS

* When is it that two WIMPs can't find each other?

annihilation rate ~ Expansion rate of the Universe

or

(Particle Physics) $$n_{\rm DM}\langle\sigma v\rangle \sim \frac{\dot{a}}{a} \sim \frac{T^2}{M_{\rm pl}}$$ (Cosmology)

(But in practice we solve a Boltzman equation)

This gives an intriguing result...

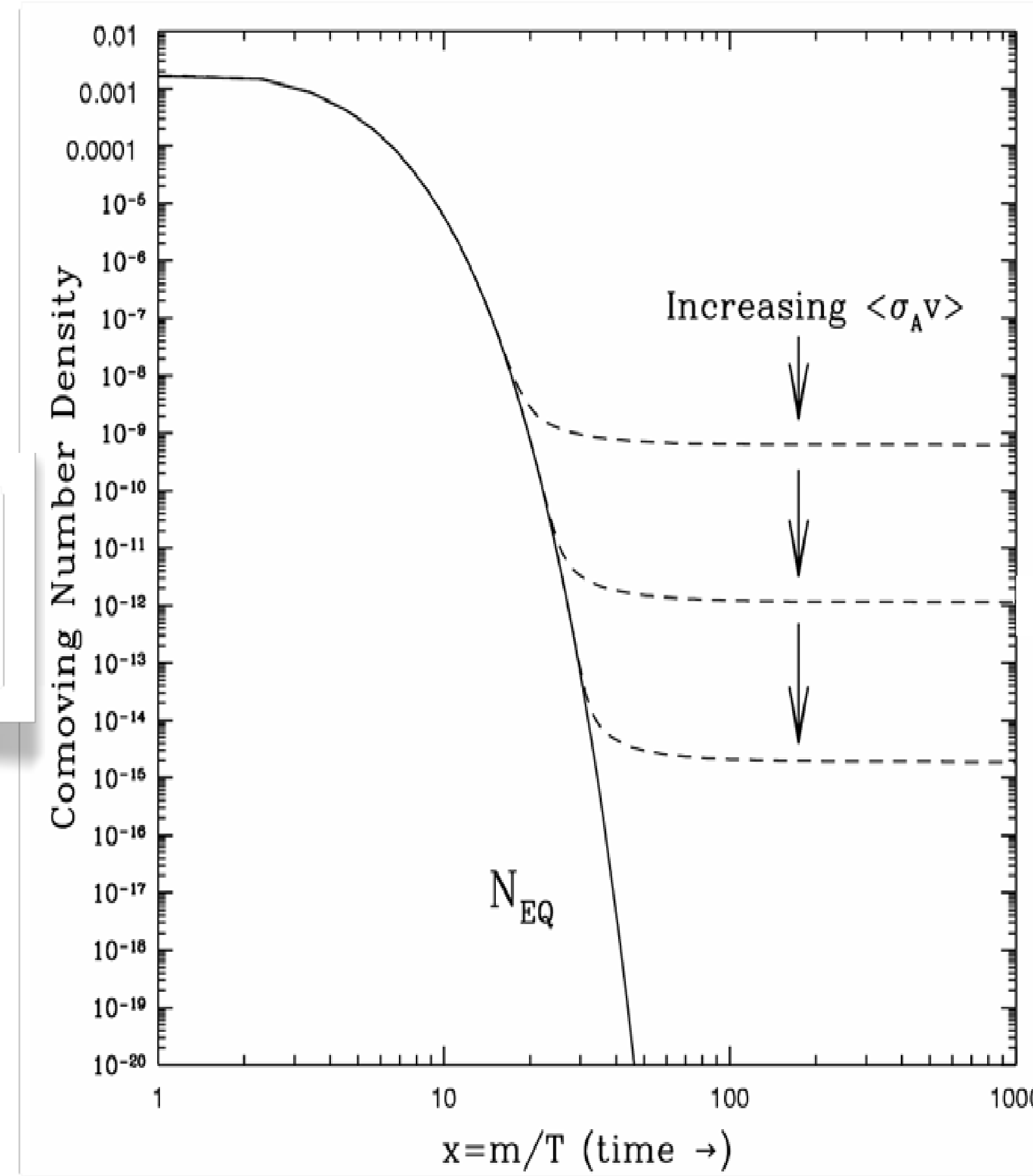
Relic abundance: WIMPS

- Abundance is *independent* of initial conditions. :-)
- Set by annihilation cross-section:

$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right)\left(\frac{g_*}{80}\right)^{-1}\left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

or

$$\langle \sigma v\rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

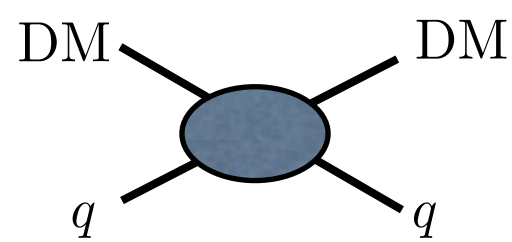


EW cross-sections! what a coincidence!

WIMPs :-)

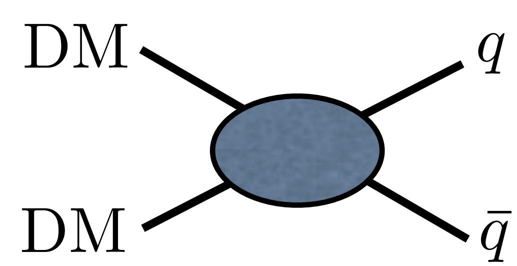
* ***Experiment***:
  A new particle with weak scale mass and cross section around 1 pb. sounds good! Could lead to:

  - Scattering off a nucleus.



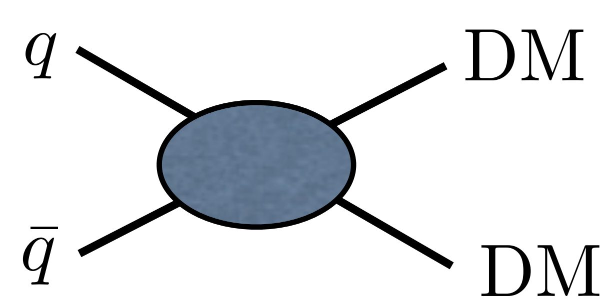
direct detection

  - Annihilation in our galaxy.



indirect detection

  - Production at a collider.



Production.
(though we'd better find another diagram)

Just keep turning the diagram on its side.... (more later)

WIMPs :-)

* ***Theory***:
  Dark matter needs to annihilate with ***weak-scale*** cross-sections.

New physics at the weak or TeV scale .

We have plenty of those lying around!

For examples, see Lian Tao's Talk:
SUSY, Extra dimensions, compsiteness...

* ***Experiment (again)***:
  Many of these theories have new colored particles.
  Produced strongly. Decay to DM.

High rates for NP signals with MET !!!

At this point I was going to tell
you about DM in SUSY.
I won't.

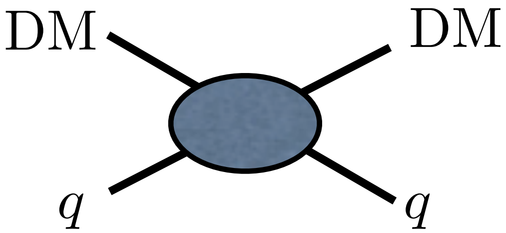
you can check out the "deleted scenes"
section of these slides.

Searches for DM

Direct & Indirect

How can we devise collider searches that complement these experiments directly?

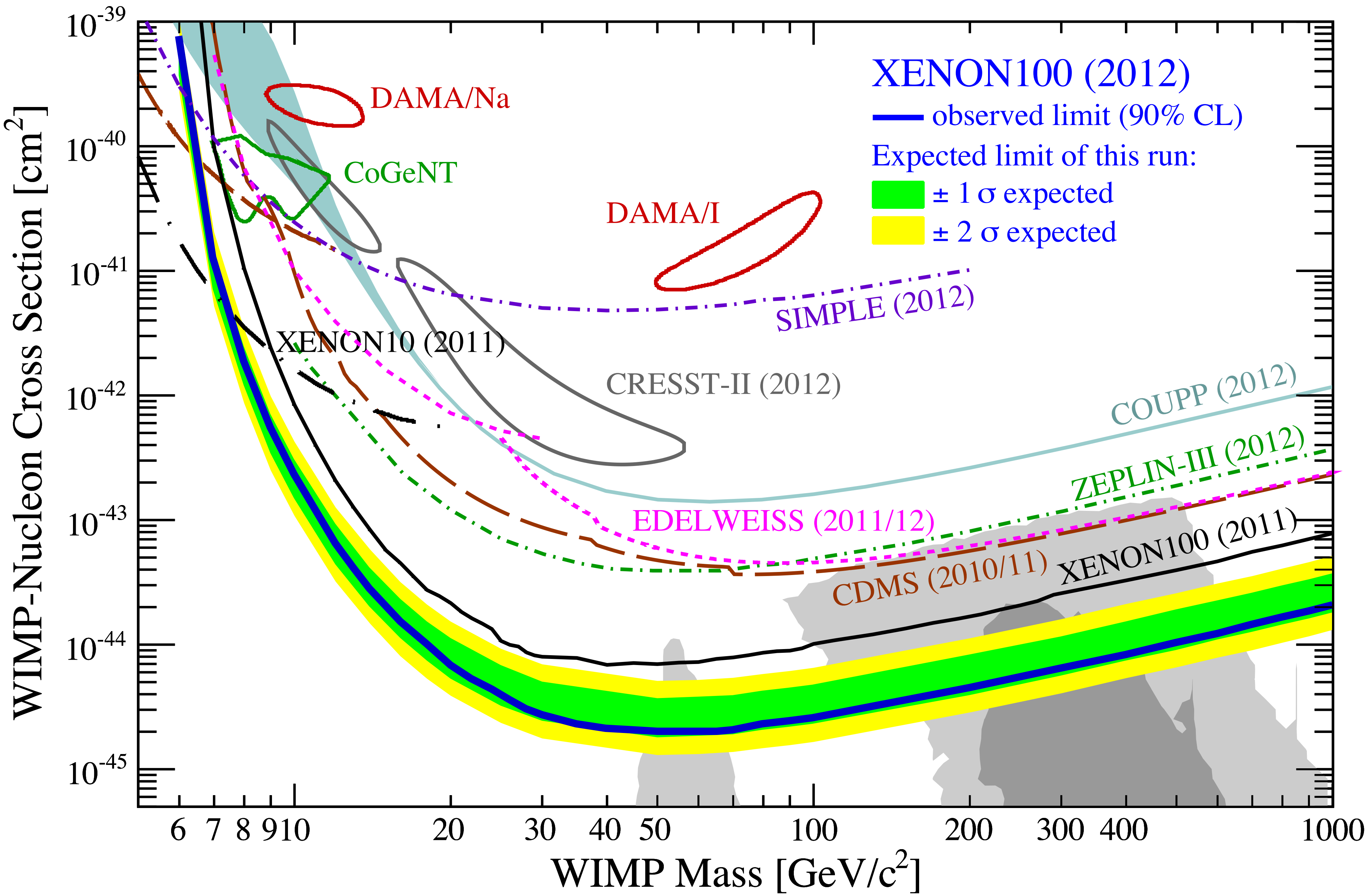
Direct detection

* Direct detection places limits on  .

* Heroic effort with remarkable results:
  - Devise an ultra sensitive detector w/ low threshold.
  - Build this detector from ultra clean materials.
  - Find a deep (and dirty!) mine.
  - Set up your detector don there (keeping it clean).
  - Wait till a WIMP kicks your detector
* DM velocity ~ 10^{-3}.
  Kinetic energy ~few-100 keV.
  Energy threshold need to be this low!

Direct Detection

* Parameter Space - spin independent:



Direct Detection

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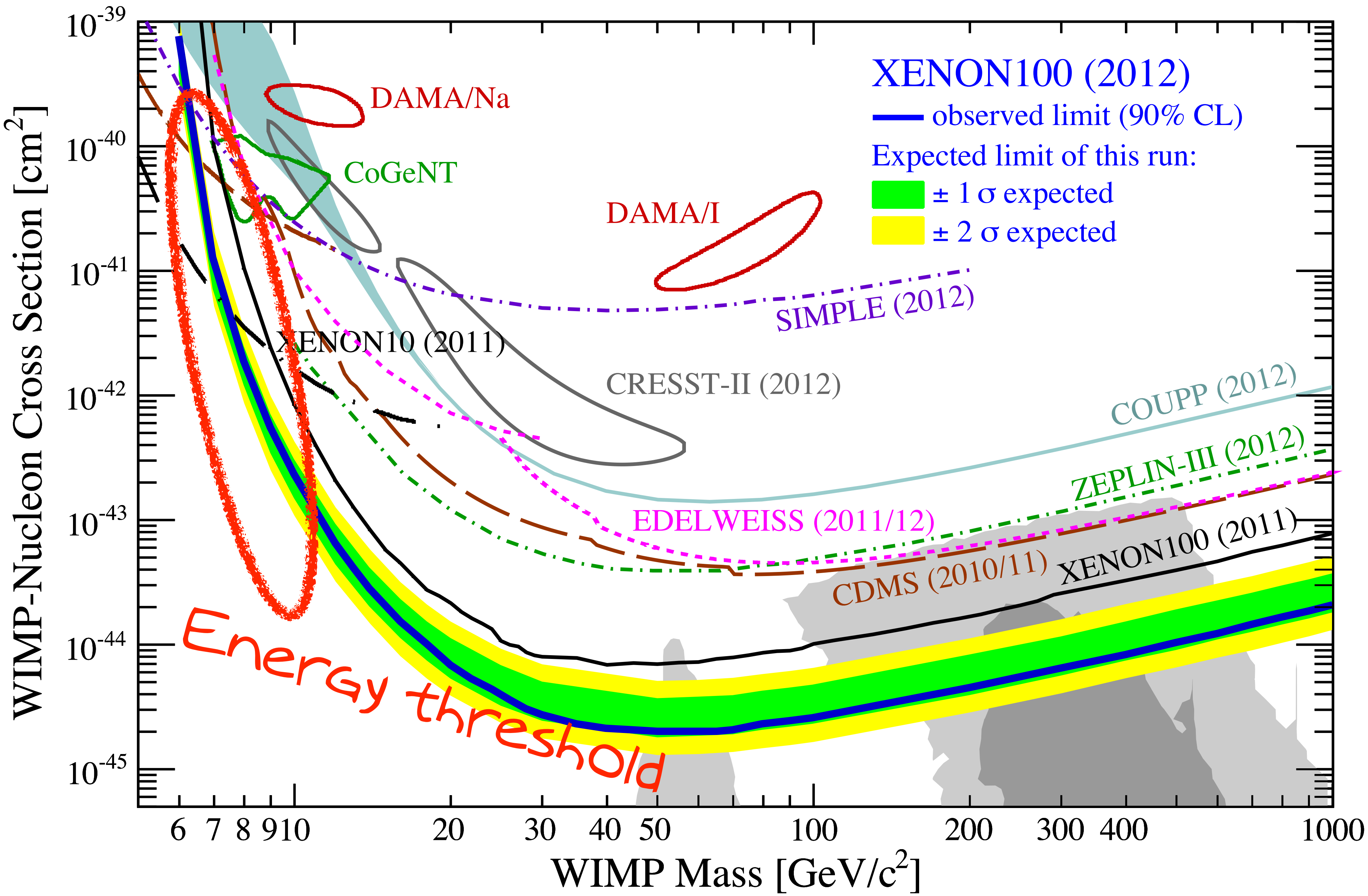

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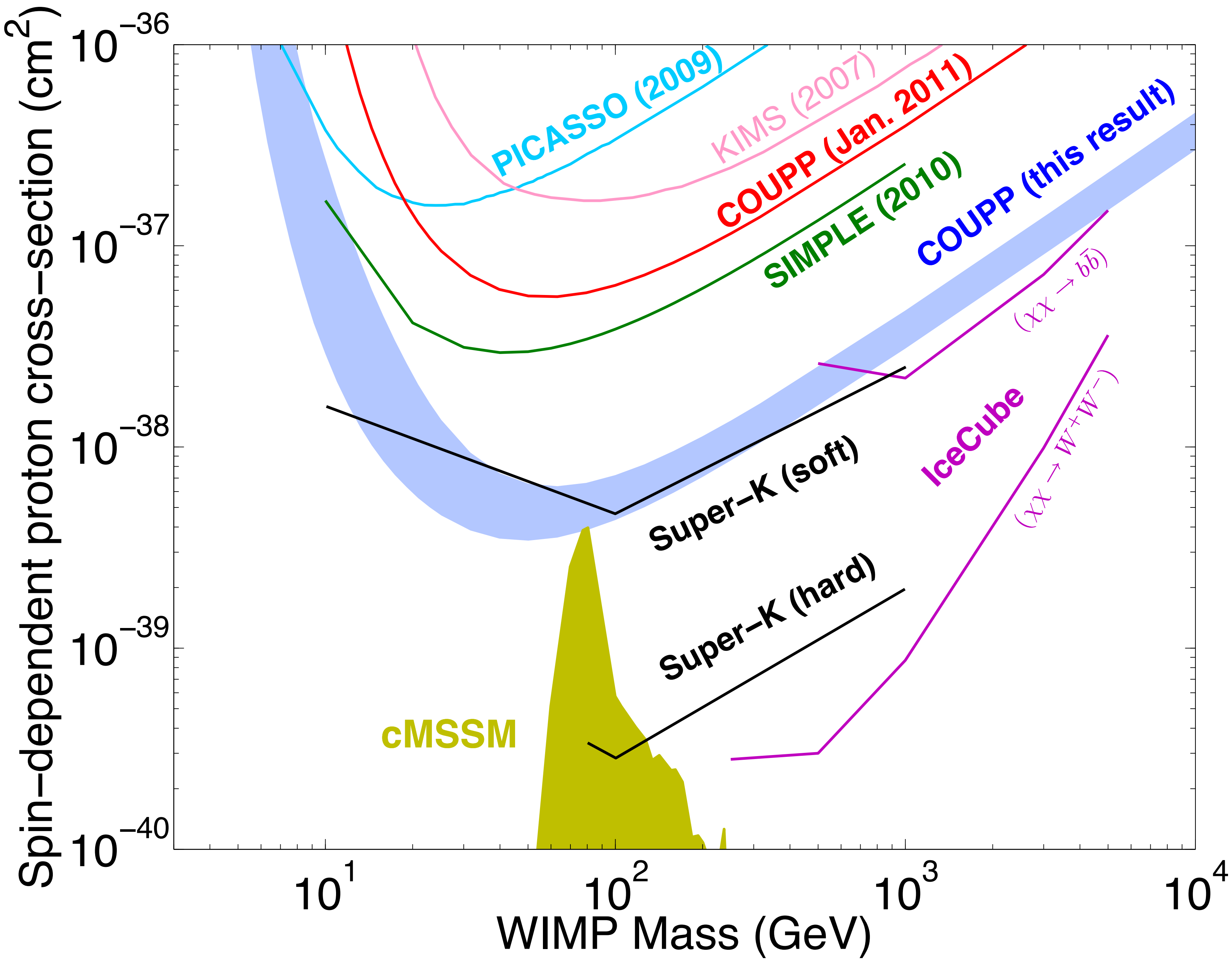

Direct Detection

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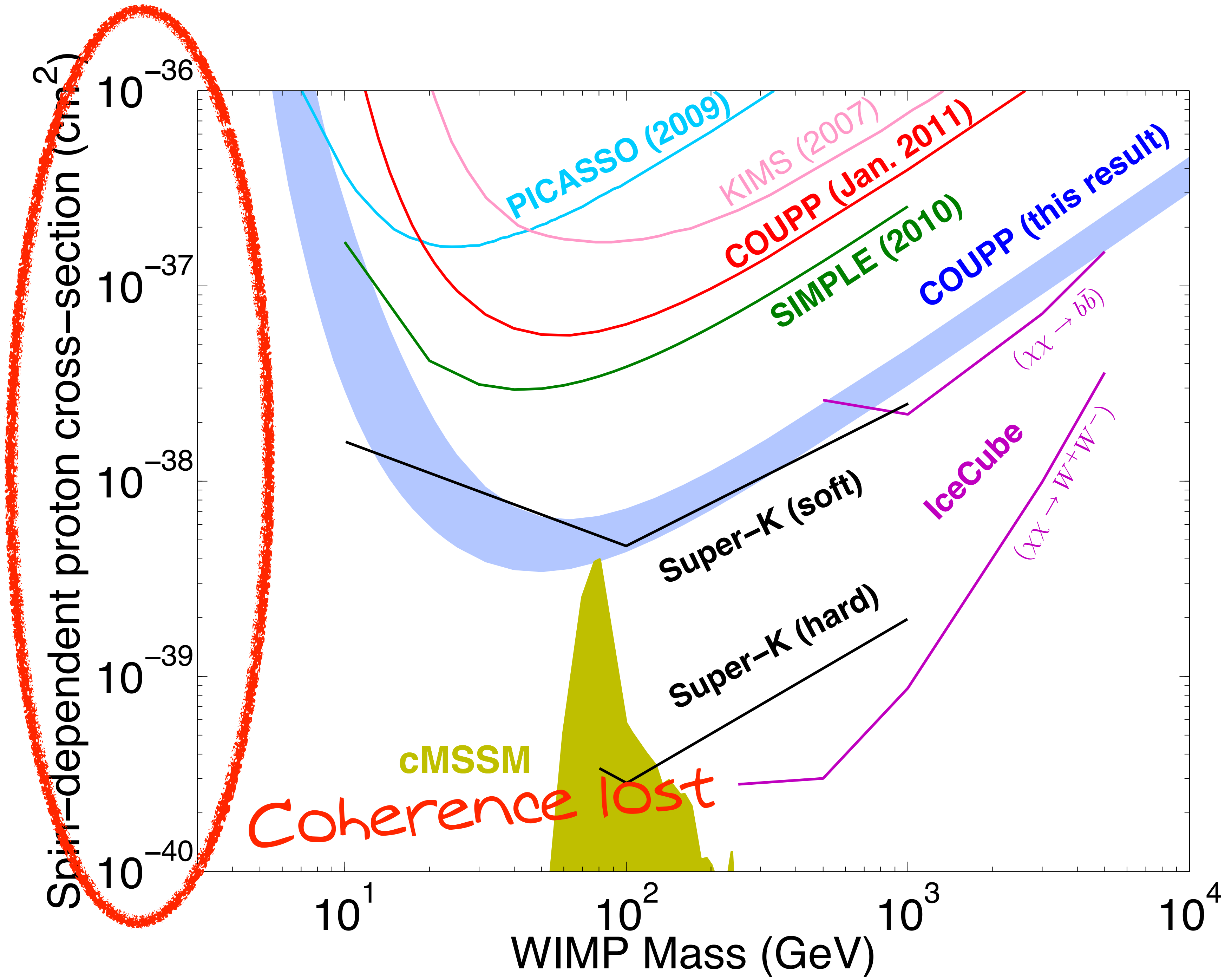
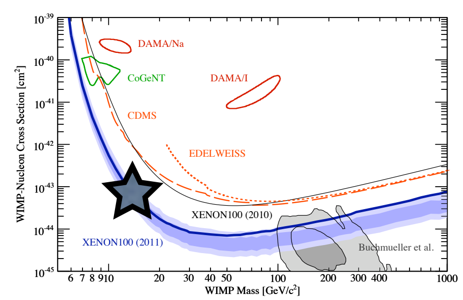
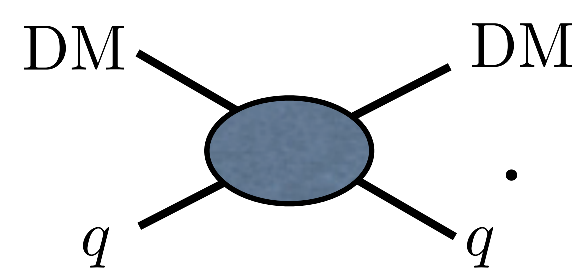


Direct detection

* Heroic effort with remarkable results.
* DD has some "weaknesses":
  - Low mass.
  - Spin-dependent cross sections.
  - Astrophysical uncertainties.
  - Threshold uncertainties.
* As you will see colliders are complementary.

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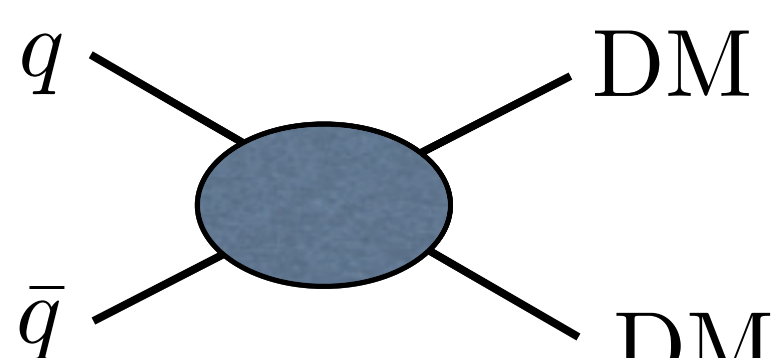
* The same interaction can lead to DM production at a hadron machine.



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

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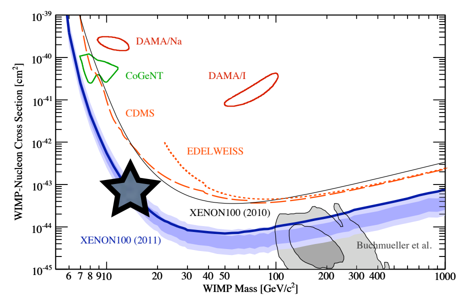
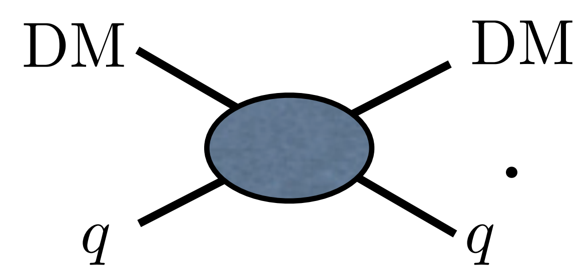
- In order to get a particular DM-nucleon cross section, 

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

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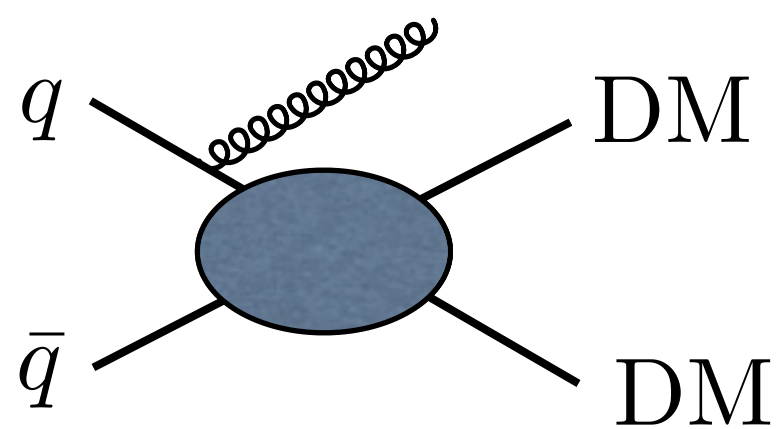

$$p\bar{p} \longrightarrow j + \not{E}_T$$

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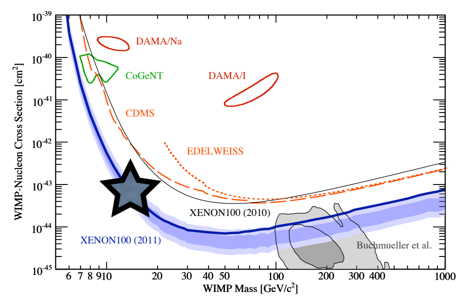
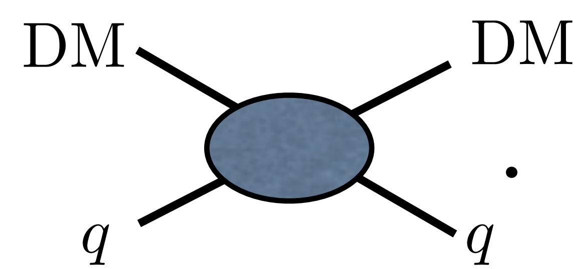
- In order to get a particular DM-nucleon cross section, 

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

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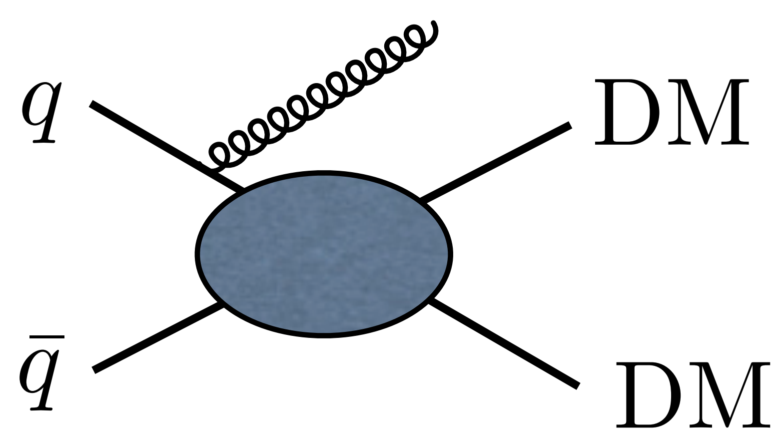
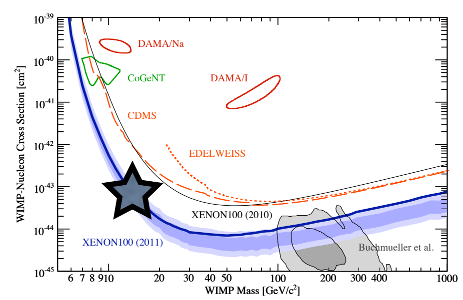
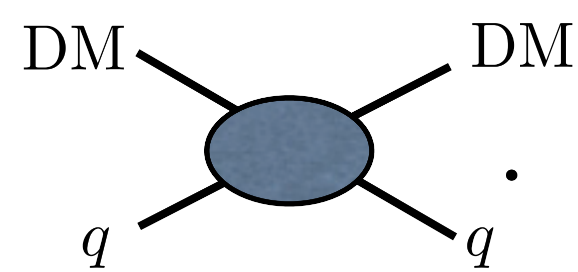


$$p\bar{p} \longrightarrow \begin{matrix} j \\ \gamma \end{matrix} + \not{E}_T$$

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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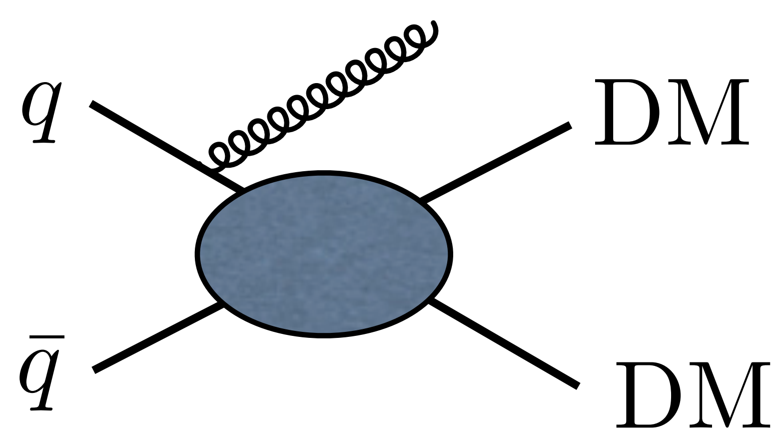

$$p\bar{p} \longrightarrow j + \not{E}_T$$
$$\gamma$$
$$Z$$

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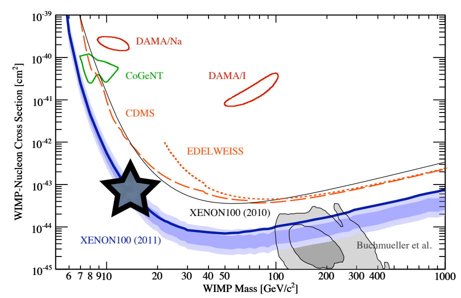
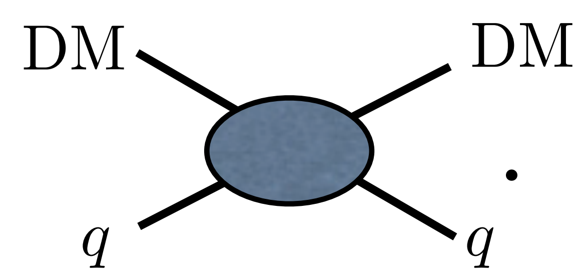
- In order to get a particular DM-nucleon cross section, 

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

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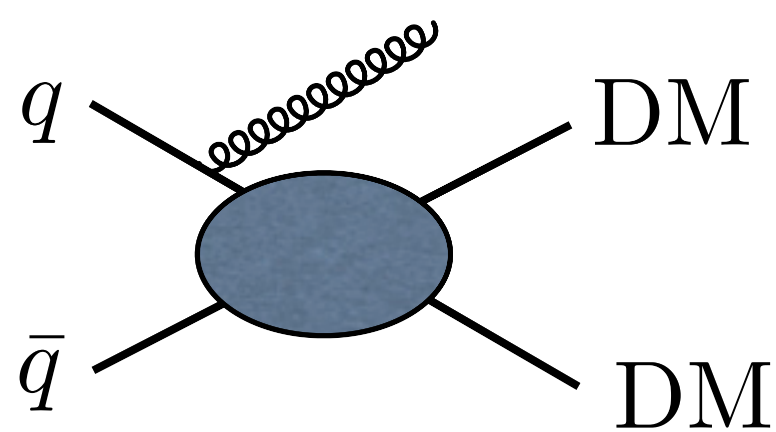

$$p\bar{p} \longrightarrow j + \not{E}_T$$

$$Z \quad \gamma \quad W$$

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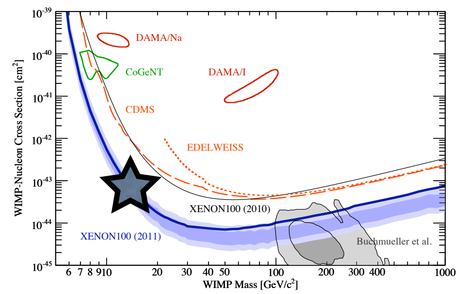
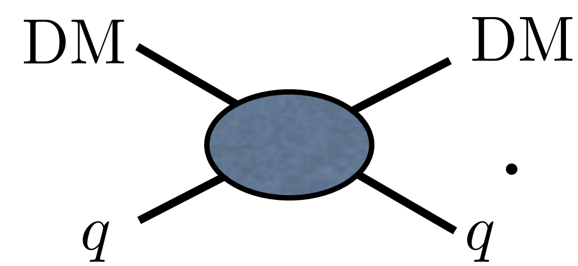
* In order to get a particular DM-nucleon cross section, 

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

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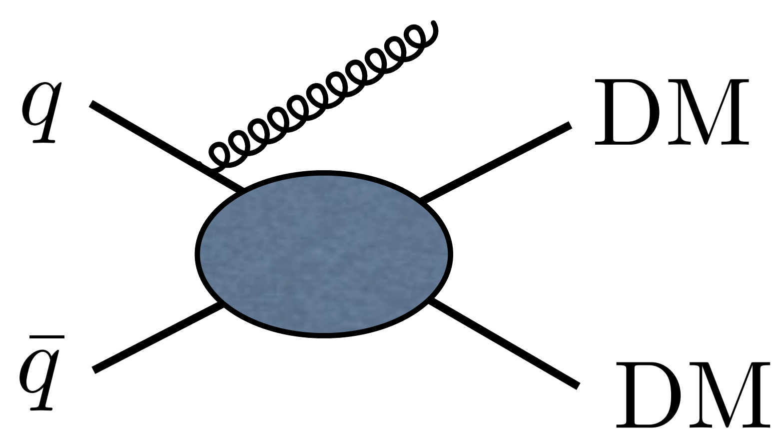
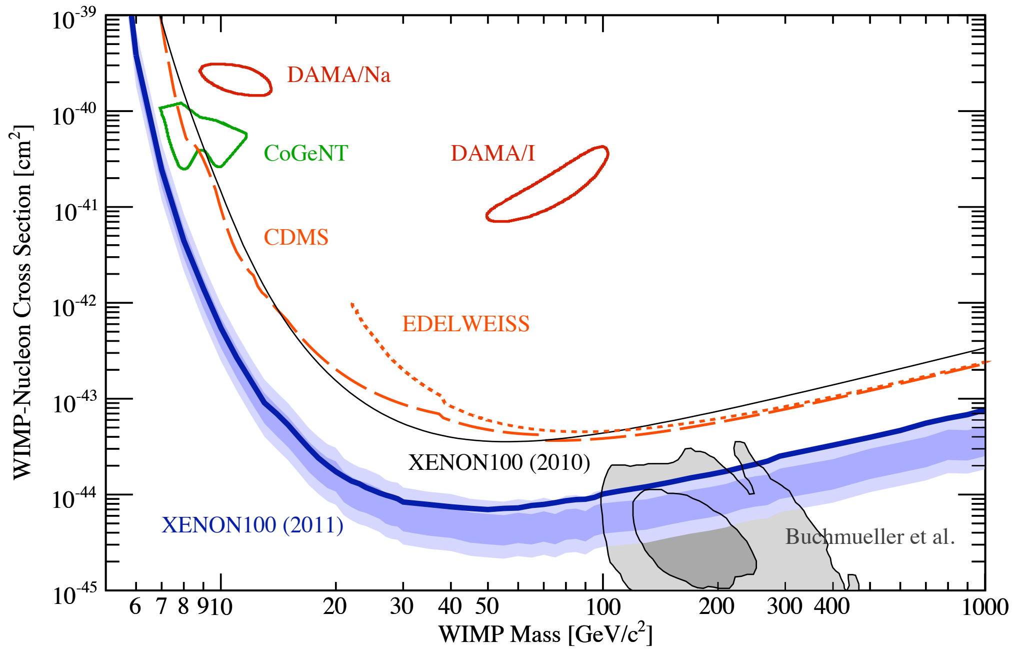


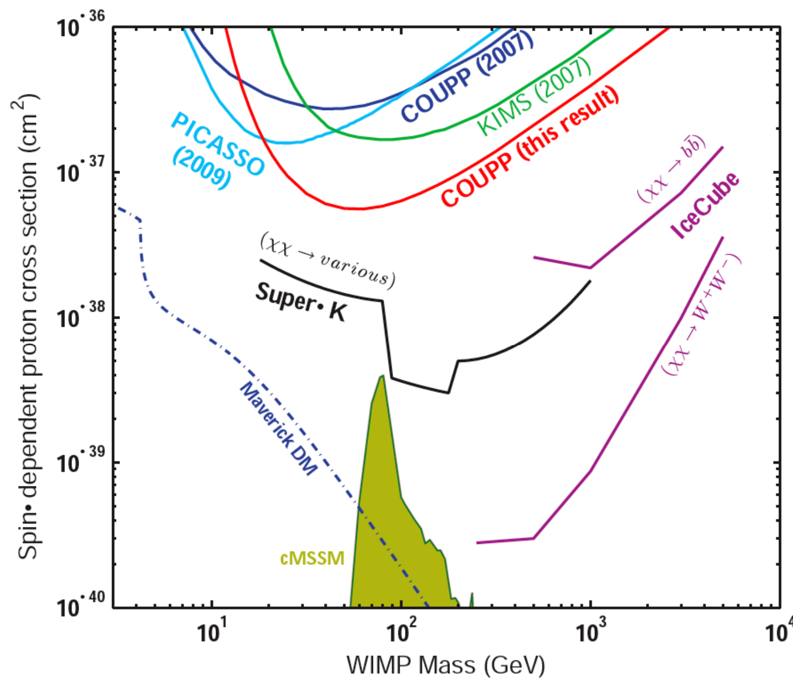
$$p\bar{p} \longrightarrow j + \not{E}_T$$

γ Z W jets

A Simple Point

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



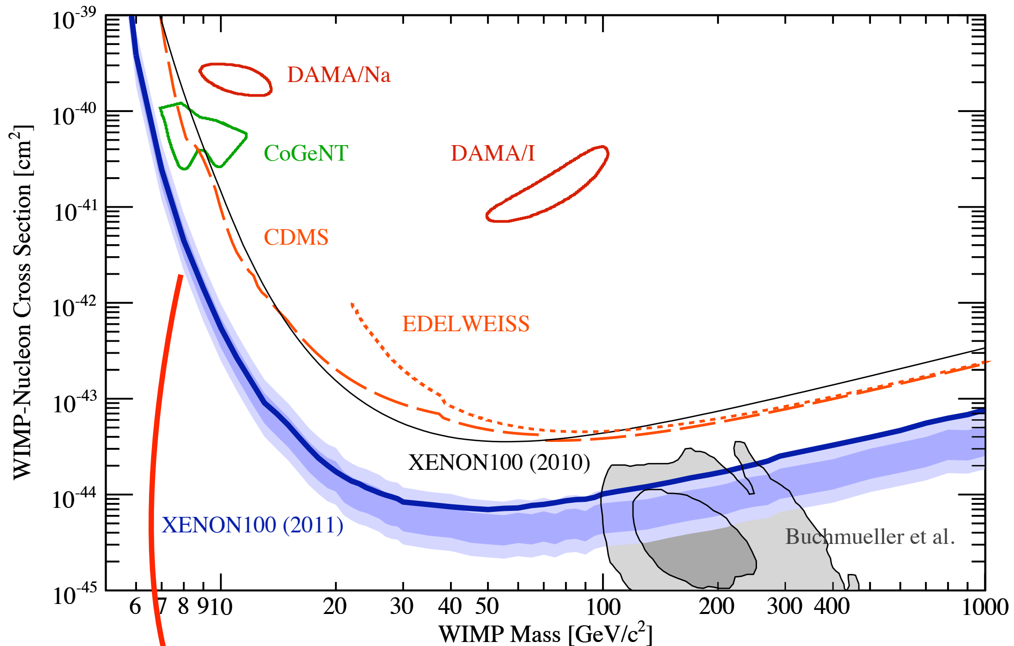


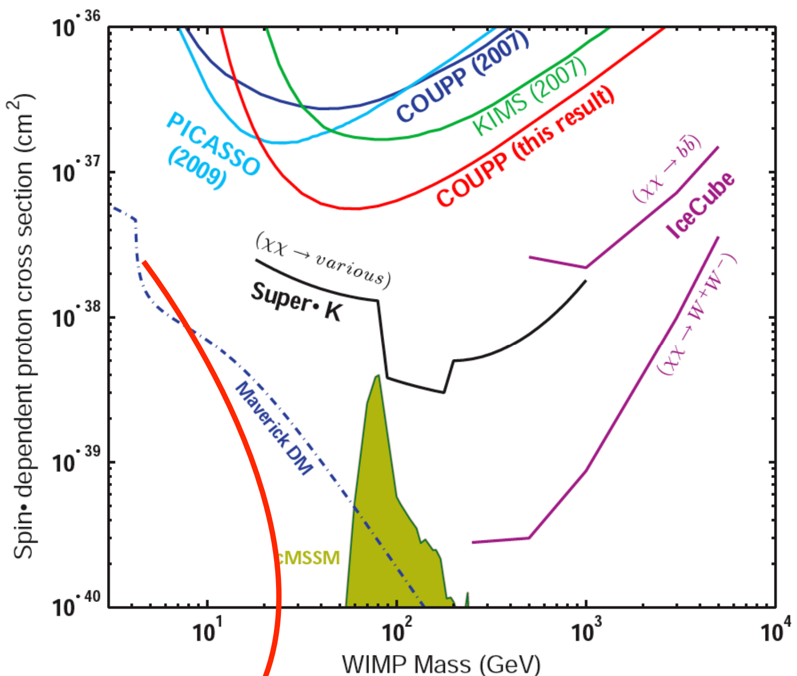
- These are **conservative** limits.
  In a specific model there may be other ways to produce DM, e.g. through cascades from heavy colored states.

But mono-X 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

Recent theoretical activity:

Goodman, Jessica et al. Phys.Lett. B695 (2011) 185-188
Goodman, Jessica et al. Phys.Rev. D82 (2010) 116010
Goodman, Jessica et al. arXiv:1111.2359
Rajaraman, Arvind et al. Phys.Rev. D84 (2011) 095013
Fortin, Jean-Francois et al. Phys.Rev. D85 (2012) 063506
Bai, Yang et al. JHEP 1012 (2010) 048
PJF, Harnik, et al. Phys.Rev. D85 (2012) 056011
PJF, Harnik et al. Phys.Rev. D84 (2011) 014028
PJF, Harnik et al arXiv:1203.1662
Shoemaker, Vecchi arXiv:1112.5457
An, Jia and Wang: arXiv:1202.2894

⋮

(Paddy, thanks for making this list...)

What goes into these limits?

Direct Detection - EFT

* Direct detection experiments probe ~100 MeV. The interaction is always "contact". Effective field theory (EFT) valid:

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

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"

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

SI gluon operator

Two possibilities:

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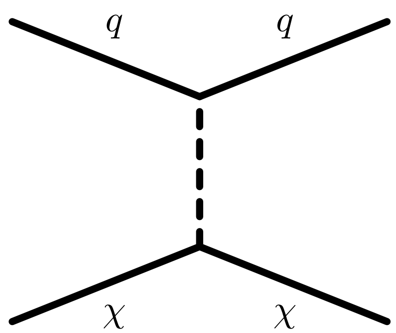
Two possibilities:

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

EFT - valid or not?

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

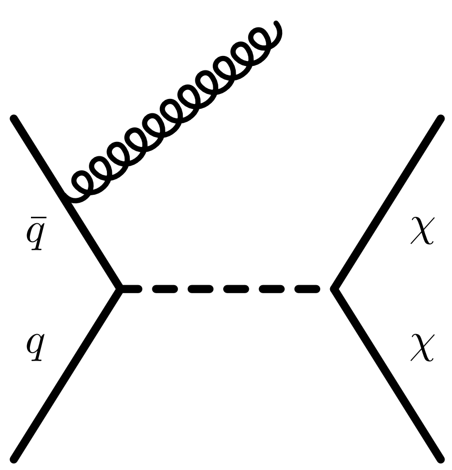


$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

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

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

* At a collider consider two extreme limits:

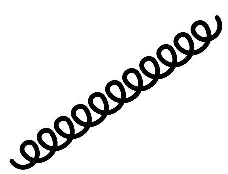


$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \ll \sqrt{s_*} \quad \text{suppressed.} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M > \sqrt{s_*} \quad \text{"same" as DD.} \end{cases}$$

There's an interesting middle region...

A Search

- The search is pretty straightforward. CMS's monojet (ATLAS is similar):
  - 1 or 2 jets ("mono-di-jet"?)
  - MET > 350 GeV.
  - dphi(j1,j2)<2.5.



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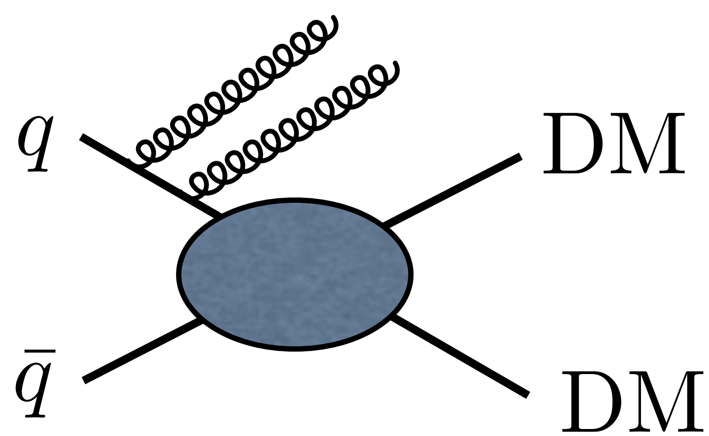

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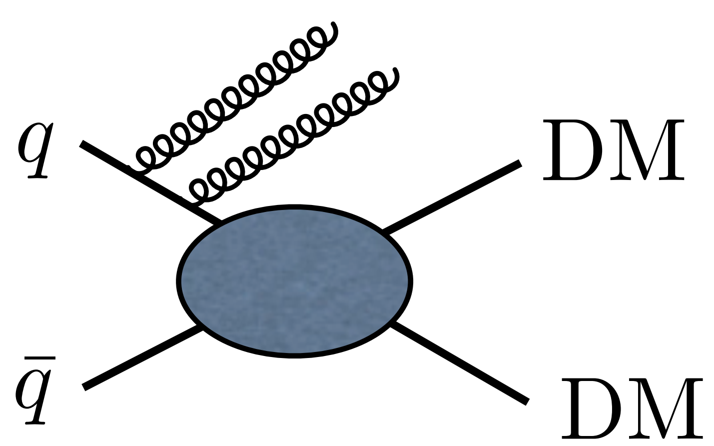
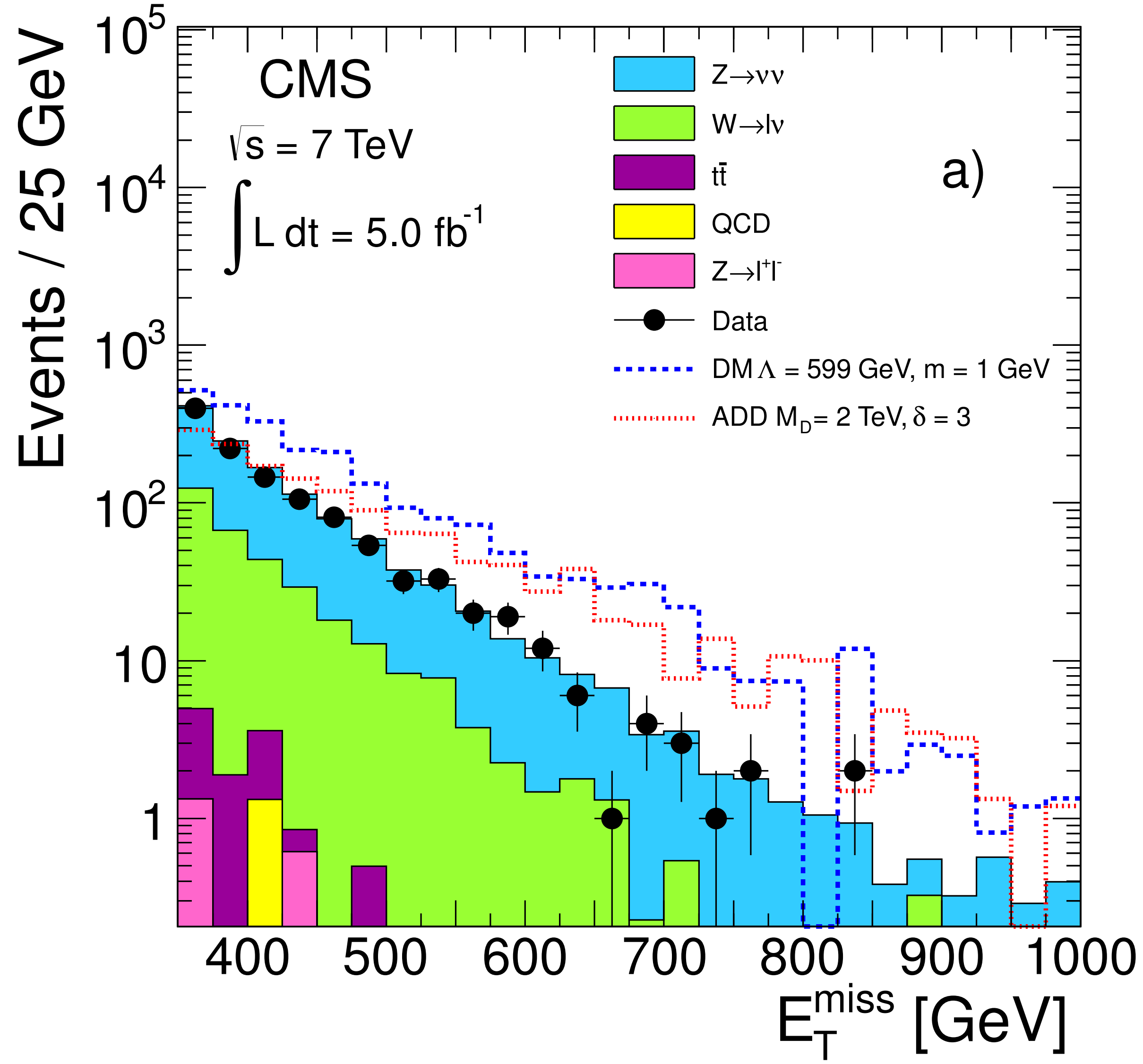
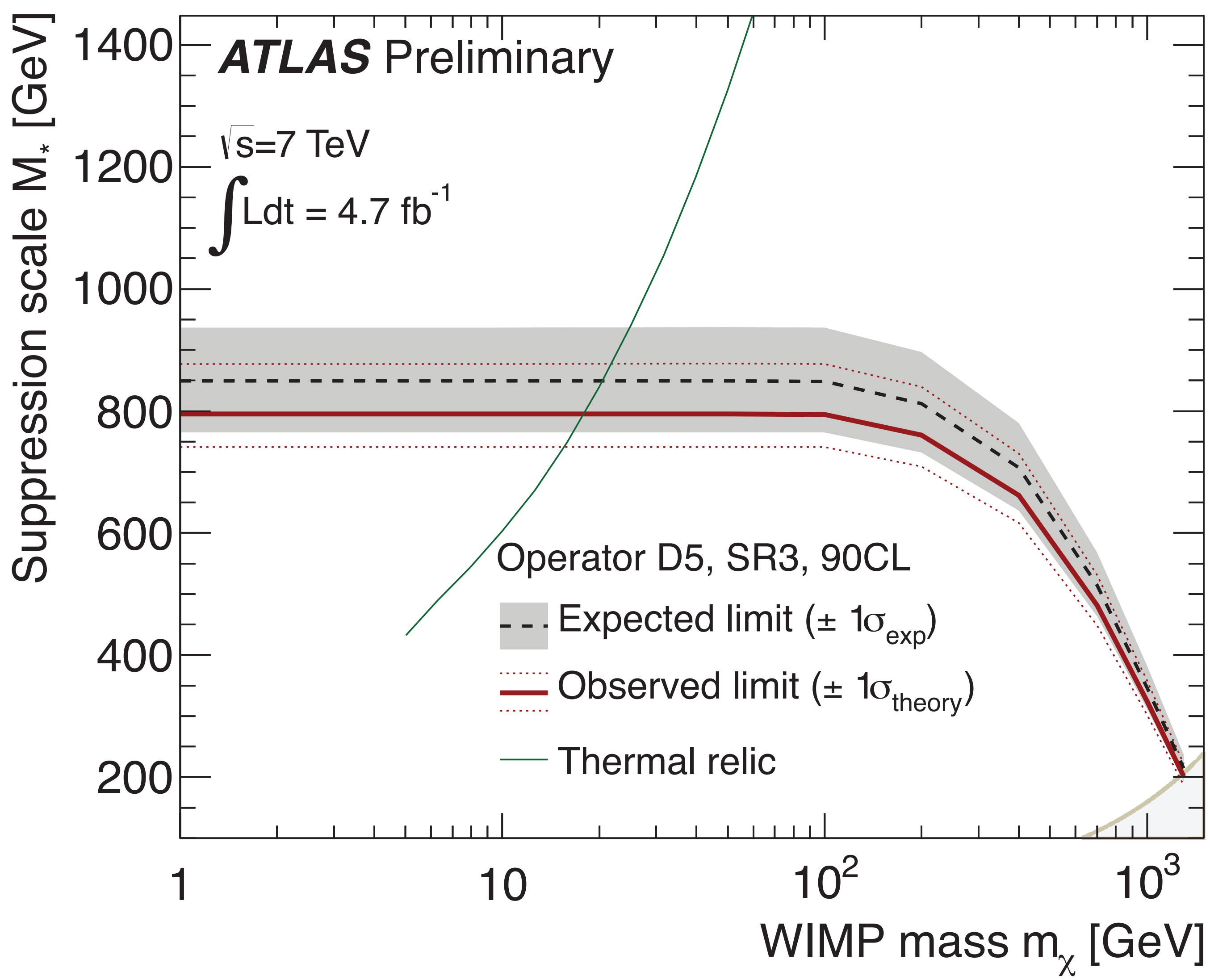




Limit

Vector coupling



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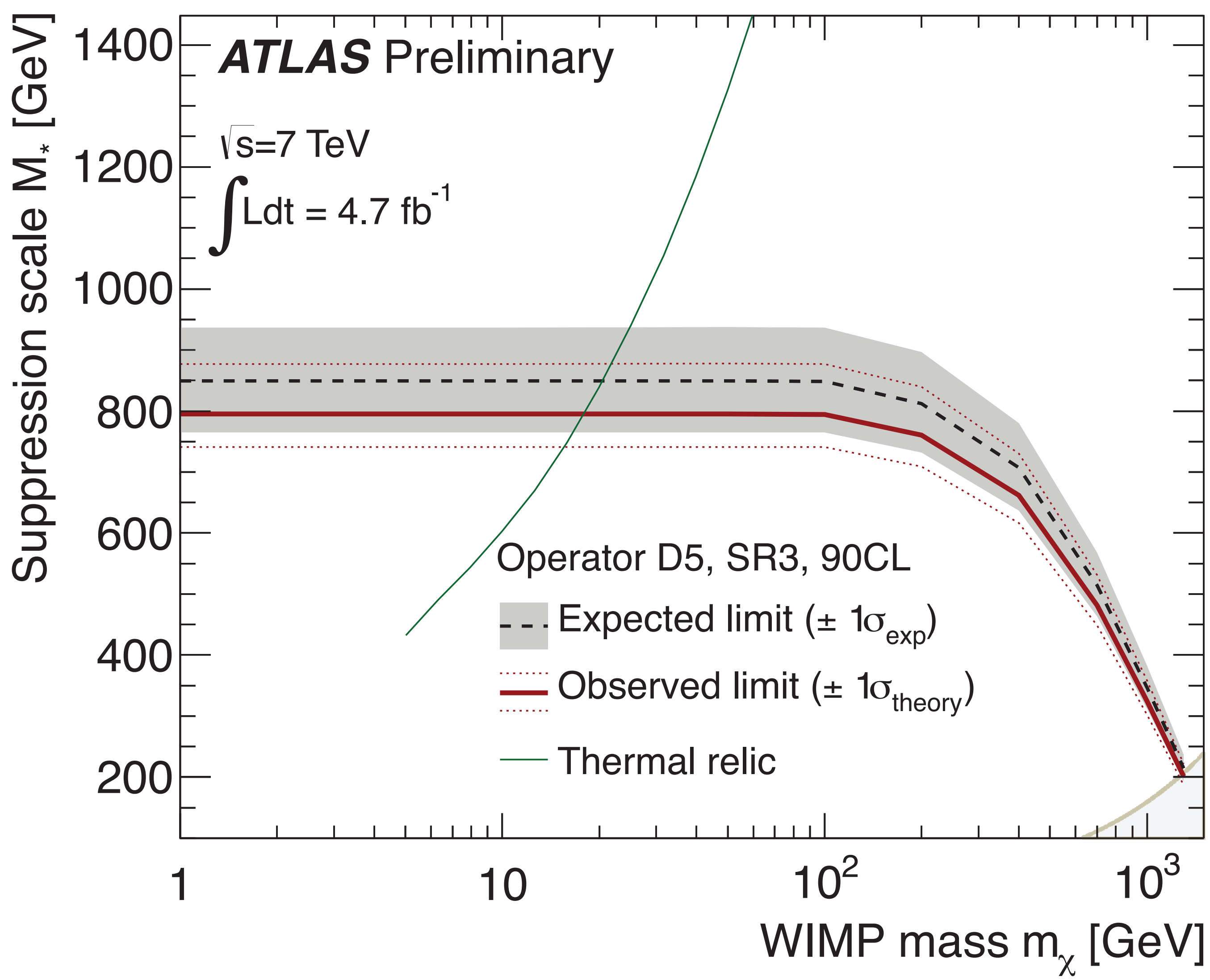
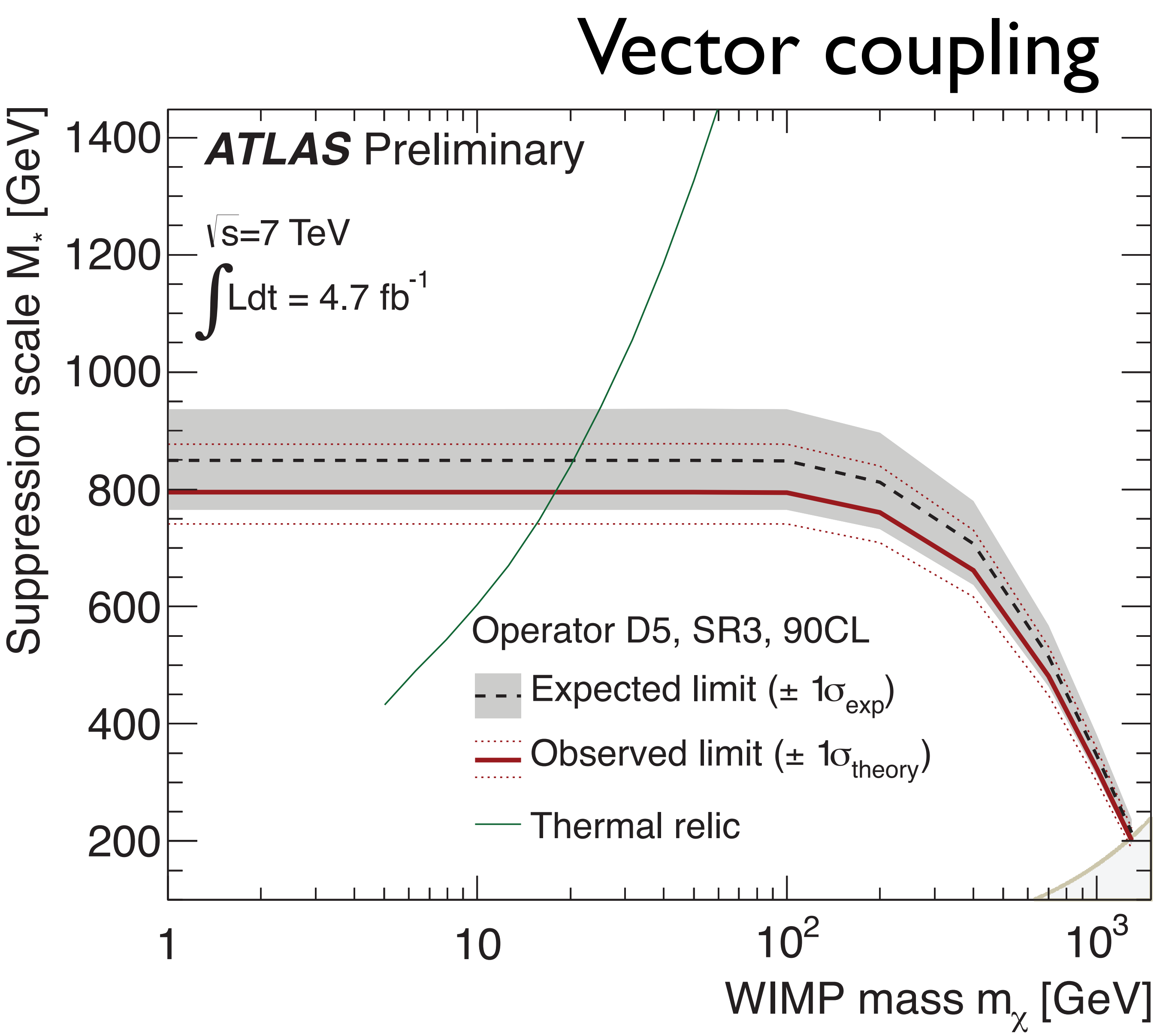
Vector coupling



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

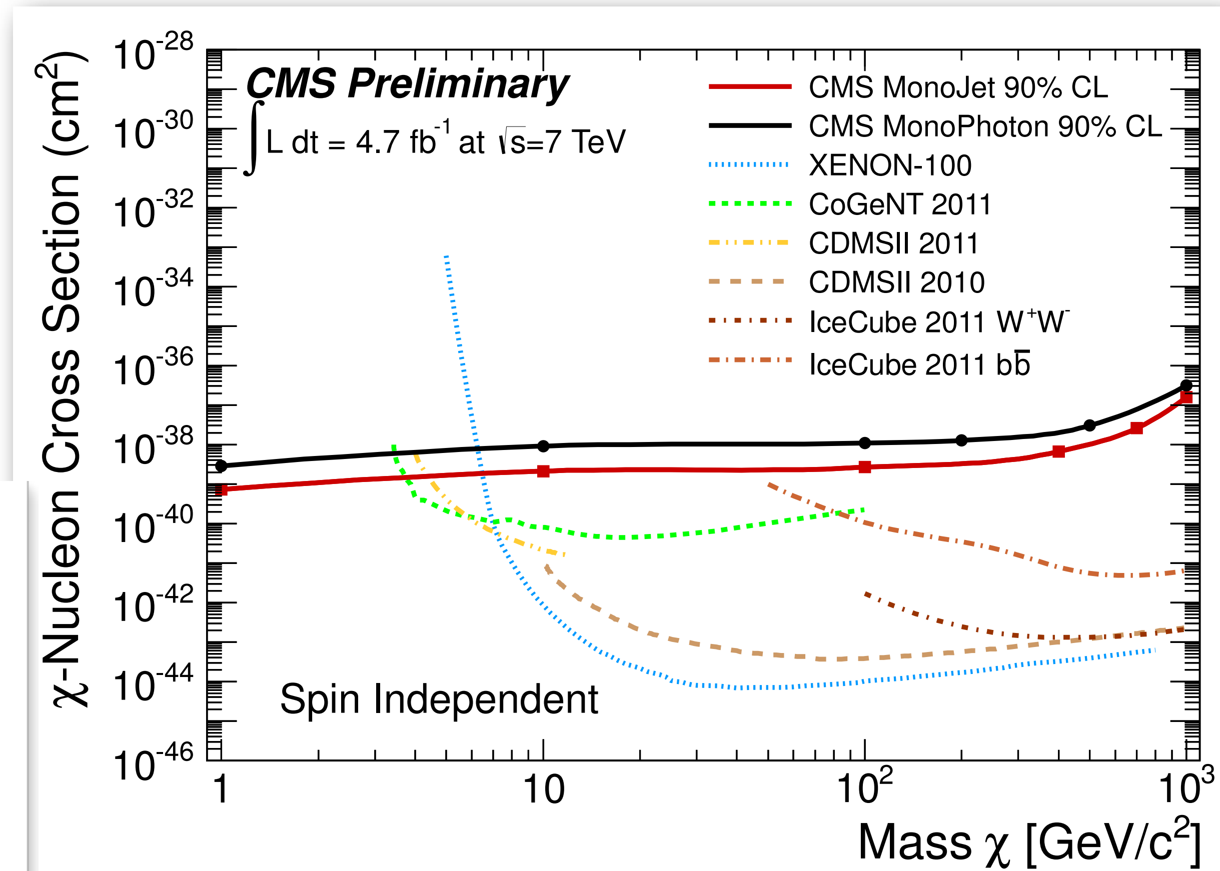
Limit

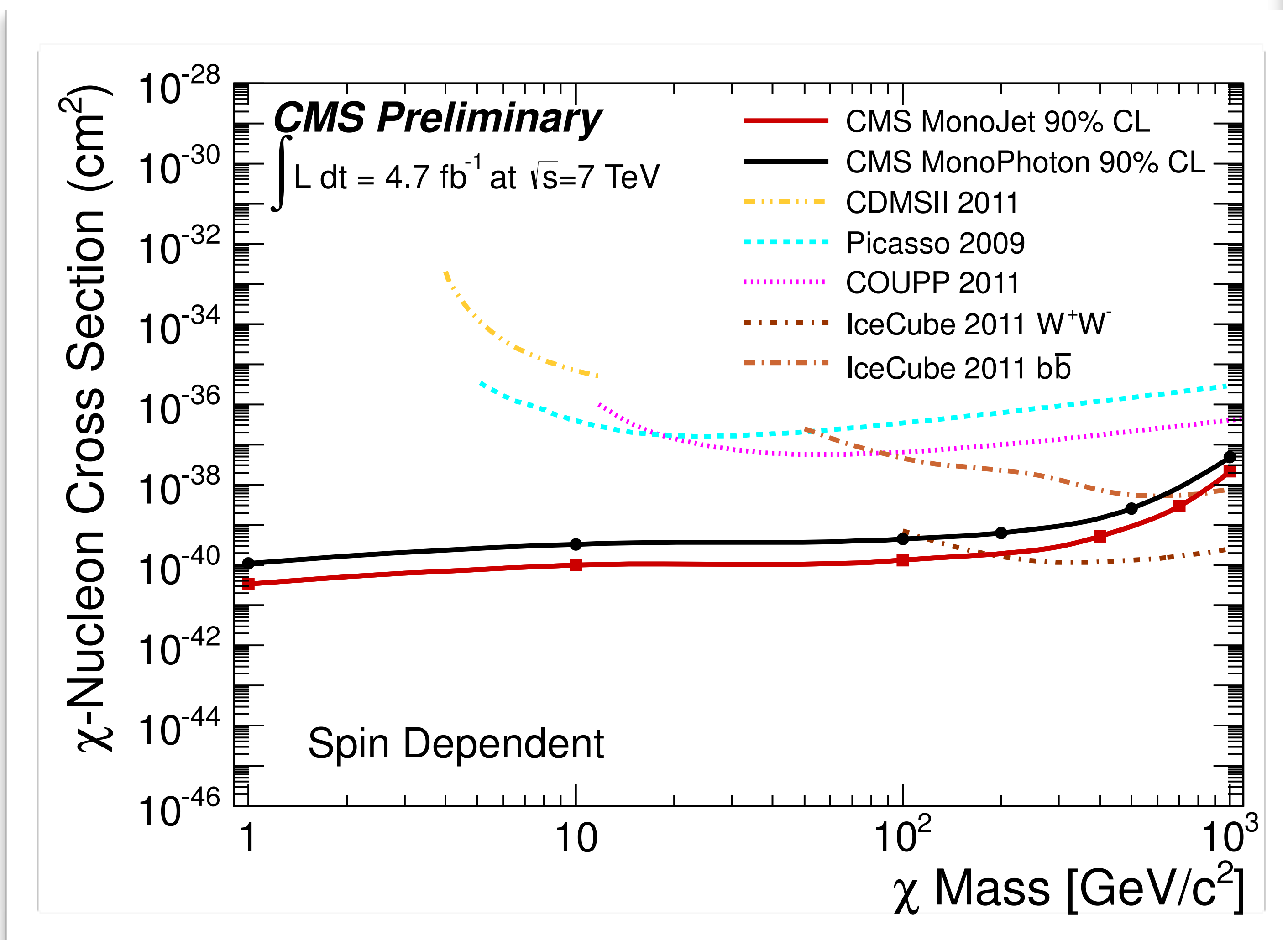


The limit is flat up to ~200 GeV. Goes all the way to zero.

SD & SI limits look very similar.

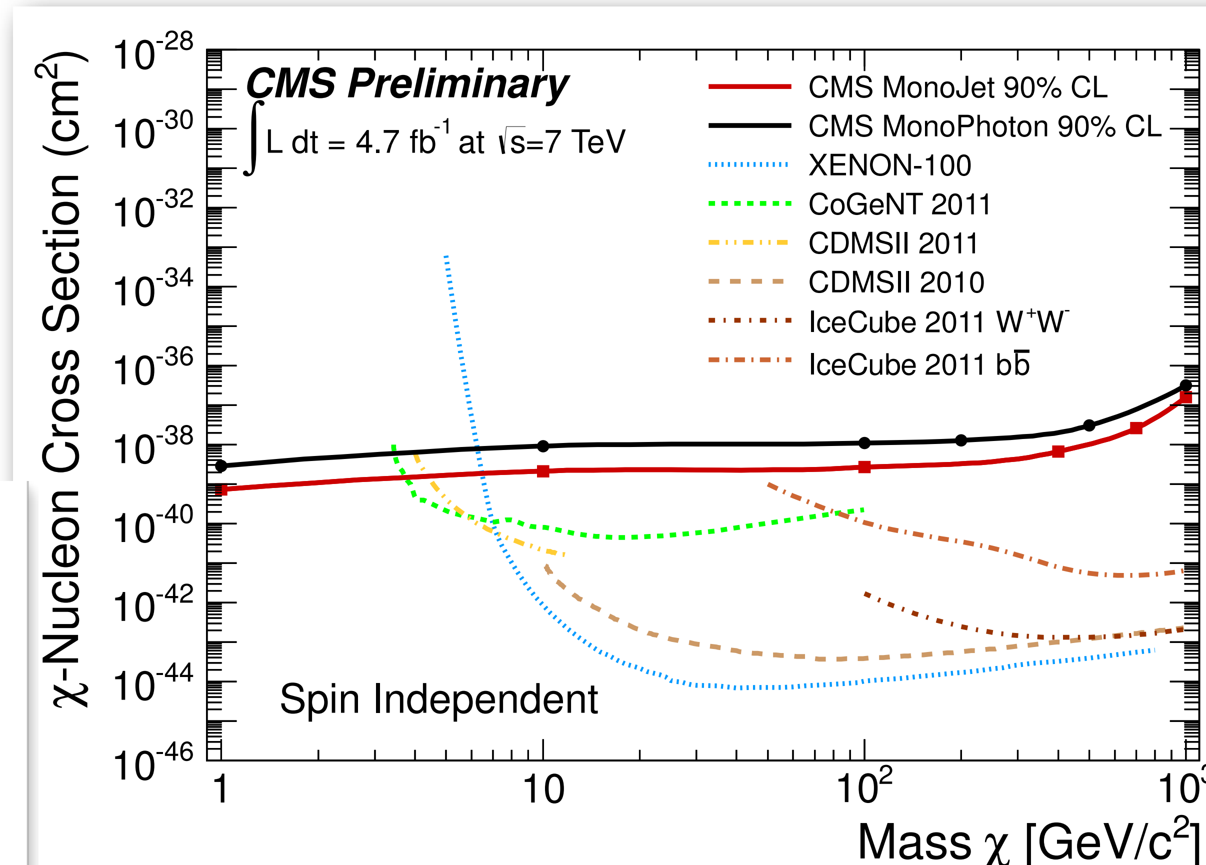
CMS Limits

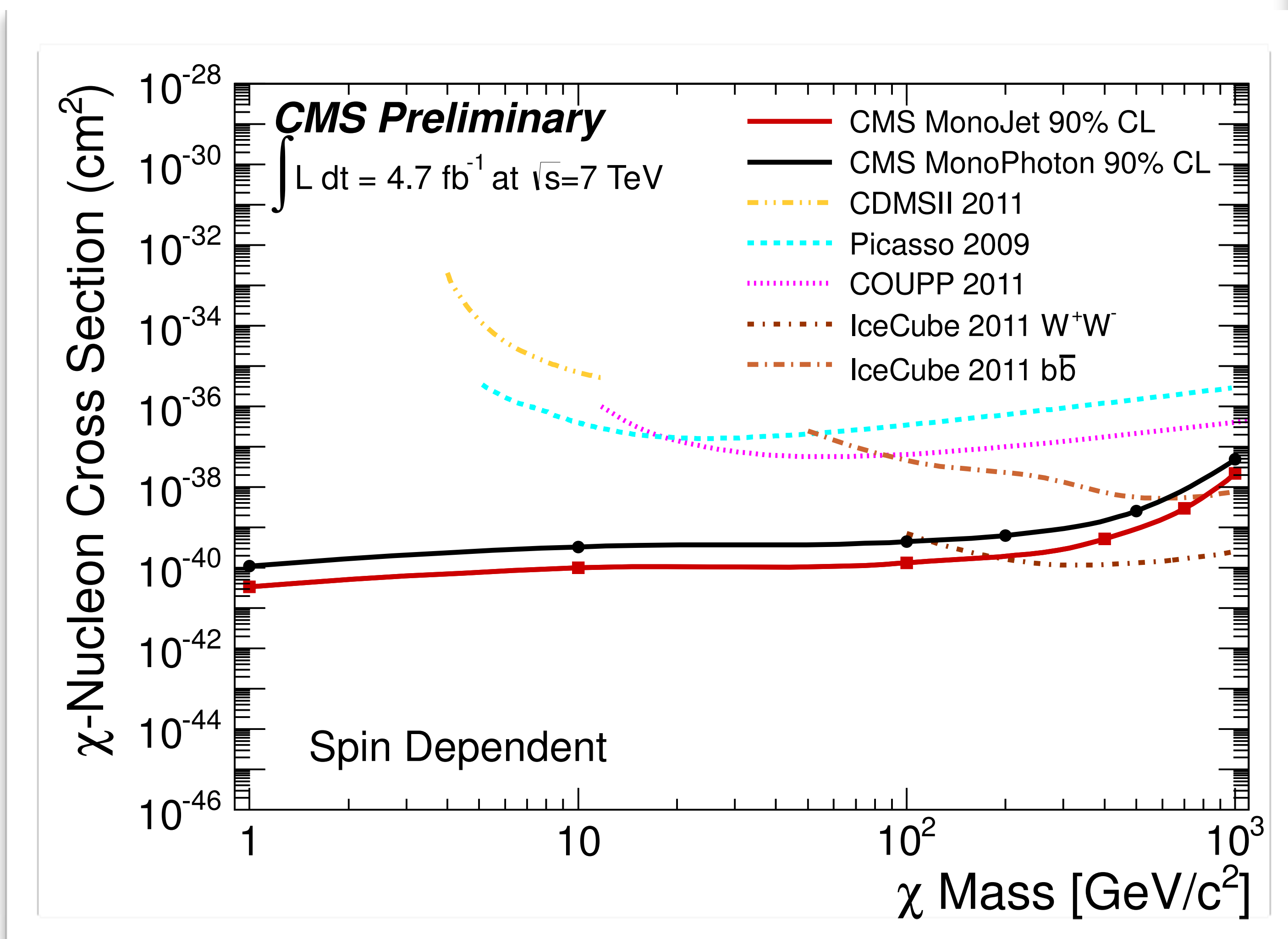

CMS Preliminary
∫L dt = 4.7 fb⁻¹ at √s=7 TeV
CMS MonoJet 90% CL
CMS MonoPhoton 90% CL
XENON-100
CoGeNT 2011
CDMSII 2011
CDMSII 2010
IceCube 2011 W⁺W⁻
IceCube 2011 bb̄
Spin Independent
χ-Nucleon Cross Section (cm²)
Mass χ [GeV/c²]


CMS Preliminary
∫L dt = 4.7 fb⁻¹ at √s=7 TeV
CMS MonoJet 90% CL
CMS MonoPhoton 90% CL
CDMSII 2011
Picasso 2009
COUPP 2011
IceCube 2011 W⁺W⁻
IceCube 2011 bb̄
Spin Dependent
χ-Nucleon Cross Section (cm²)
χ Mass [GeV/c²]

CMS Limits

Best limit for light DM:





CMS Limits

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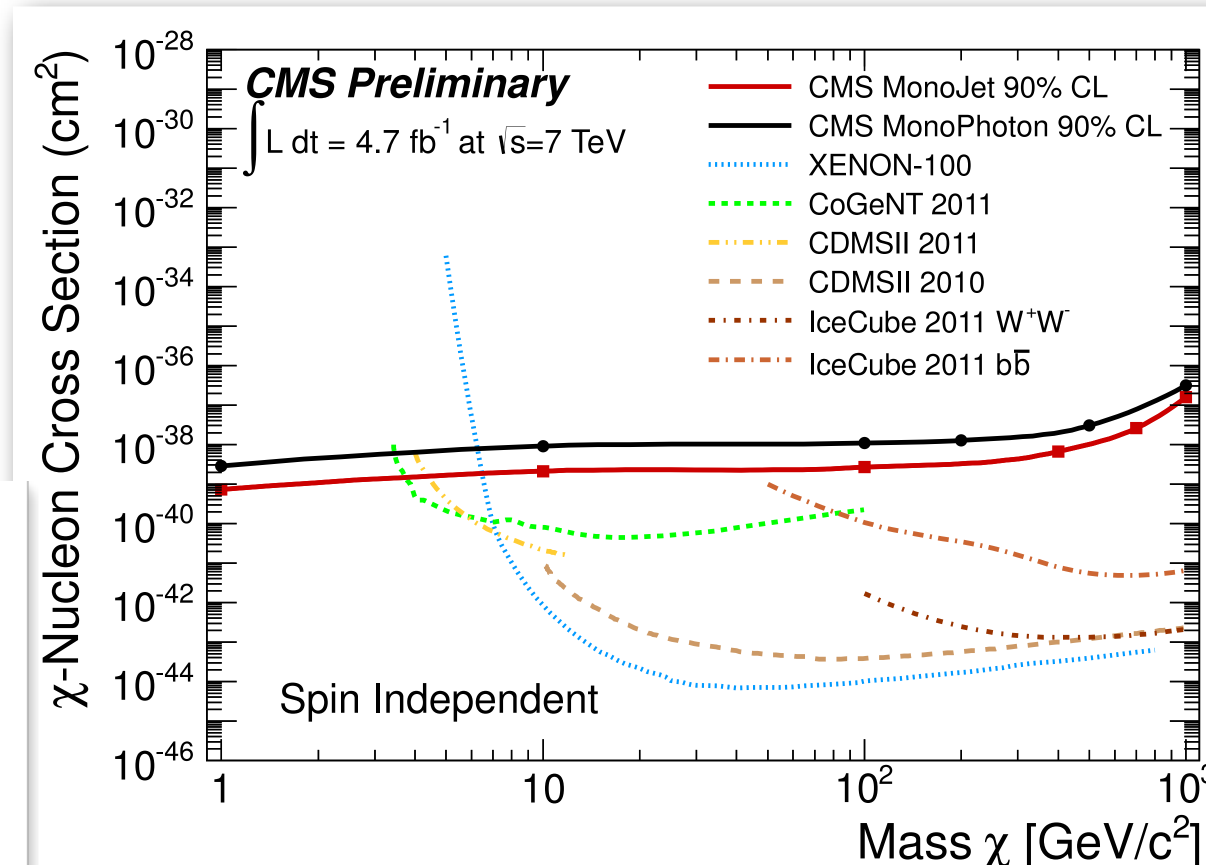
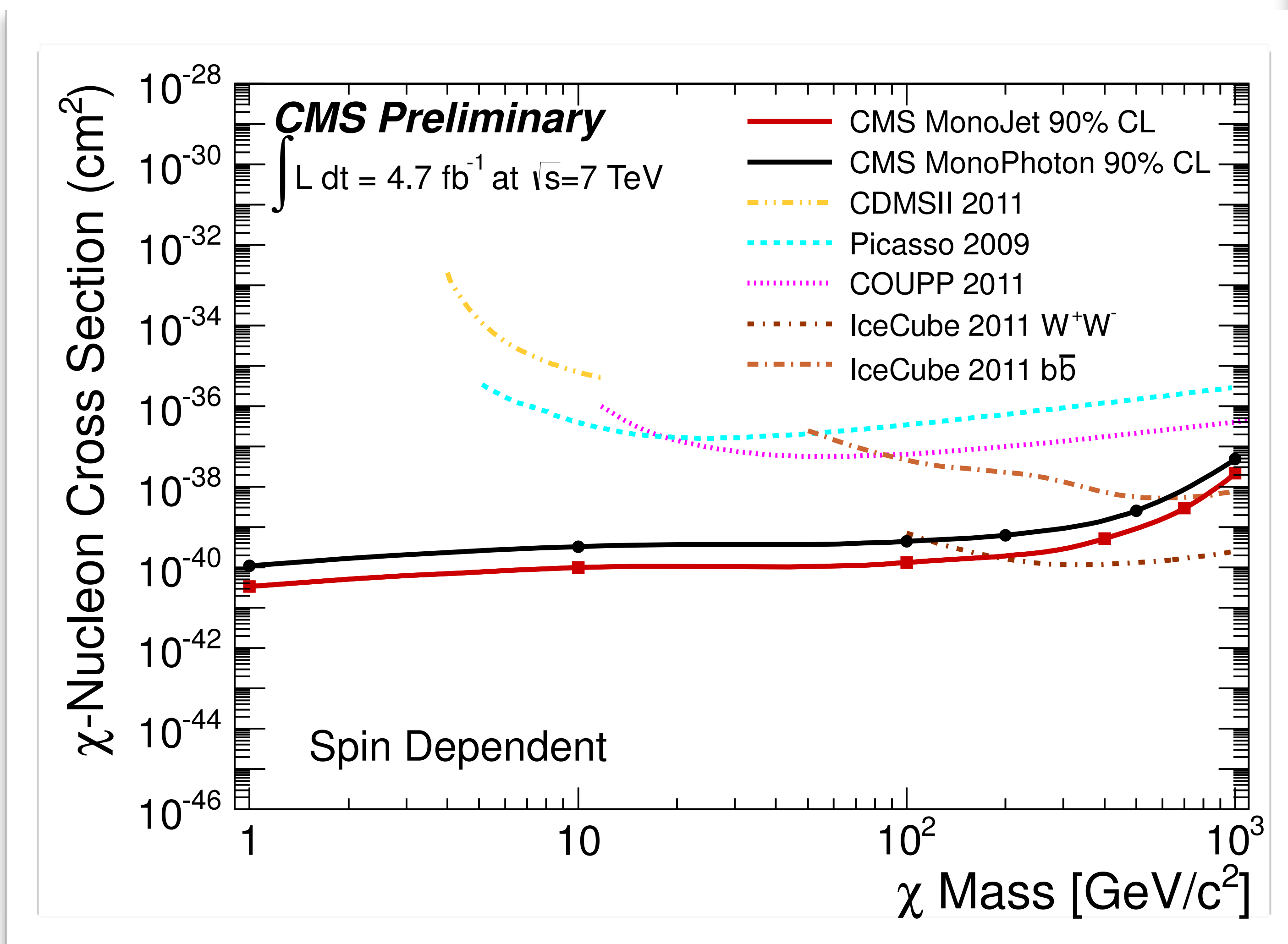
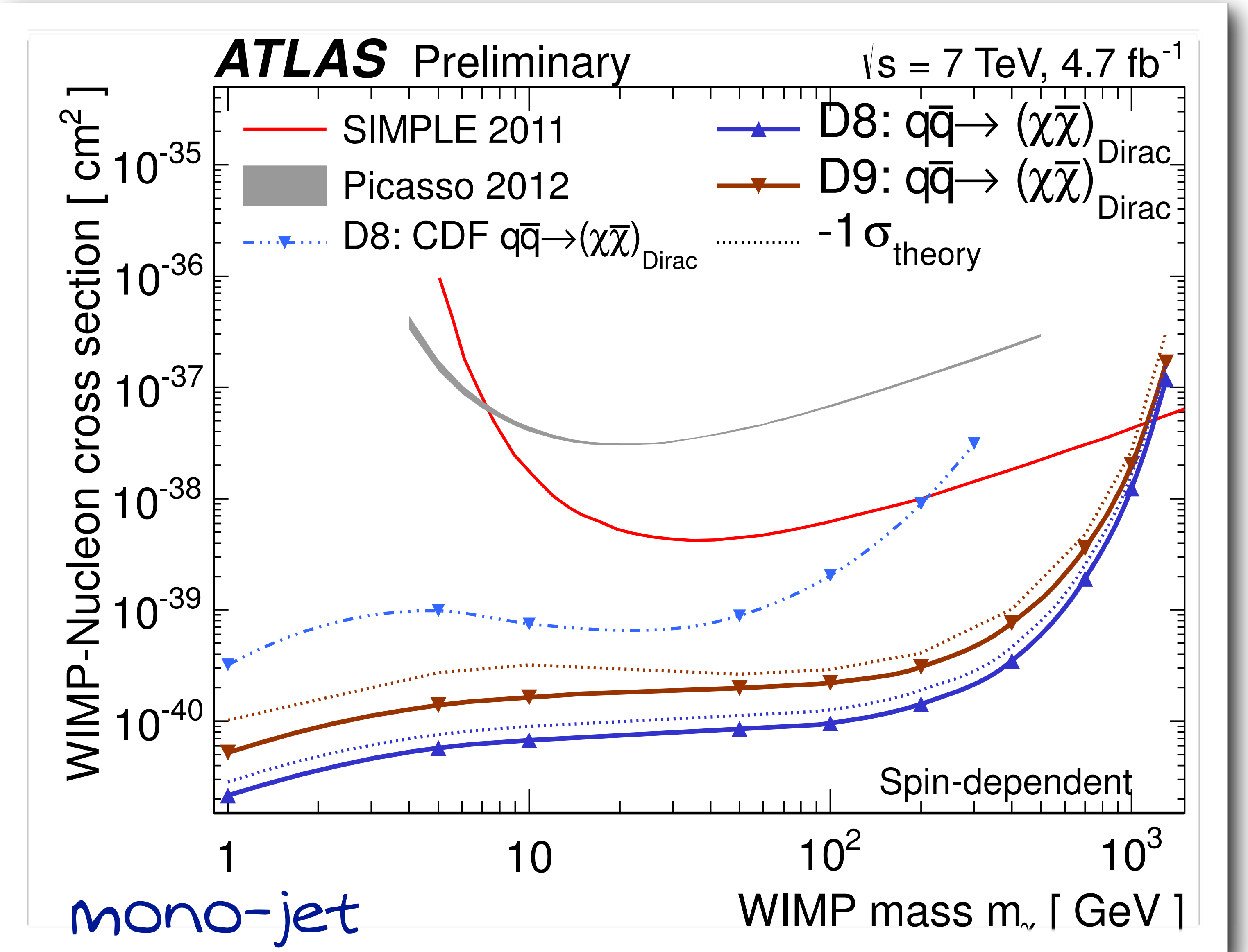




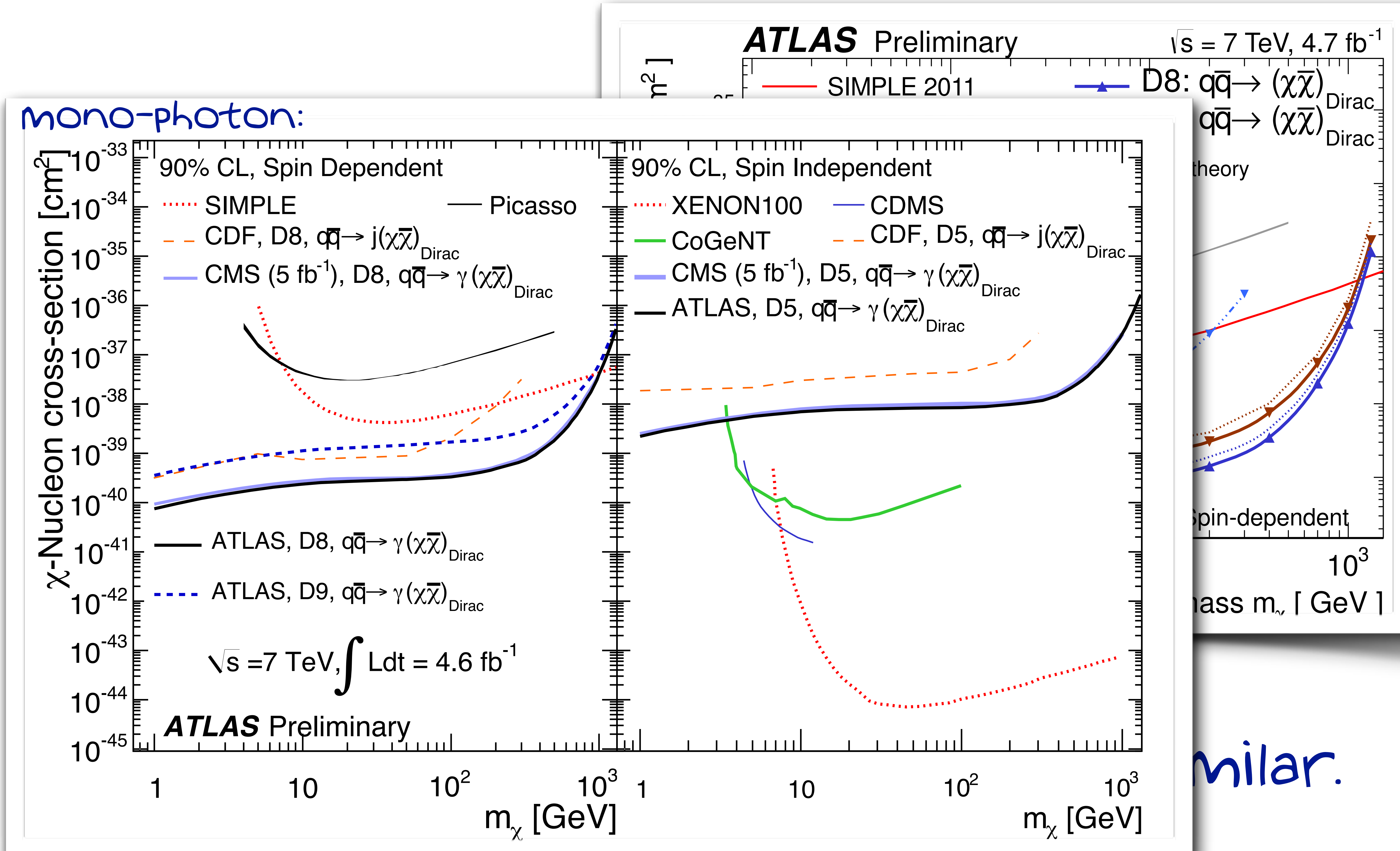
-> Best limit for SD.

ATLAS Limits



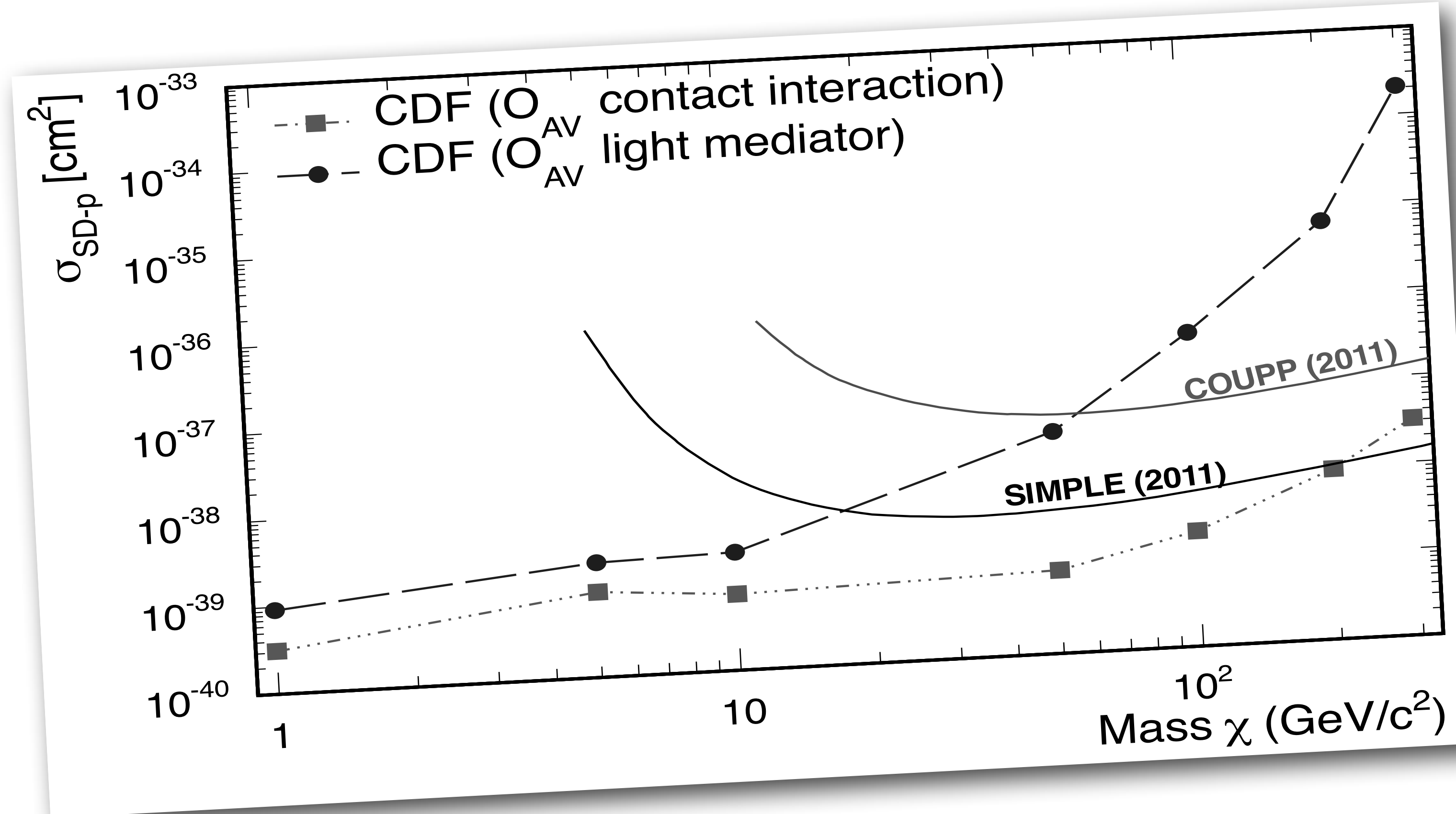
Similar.

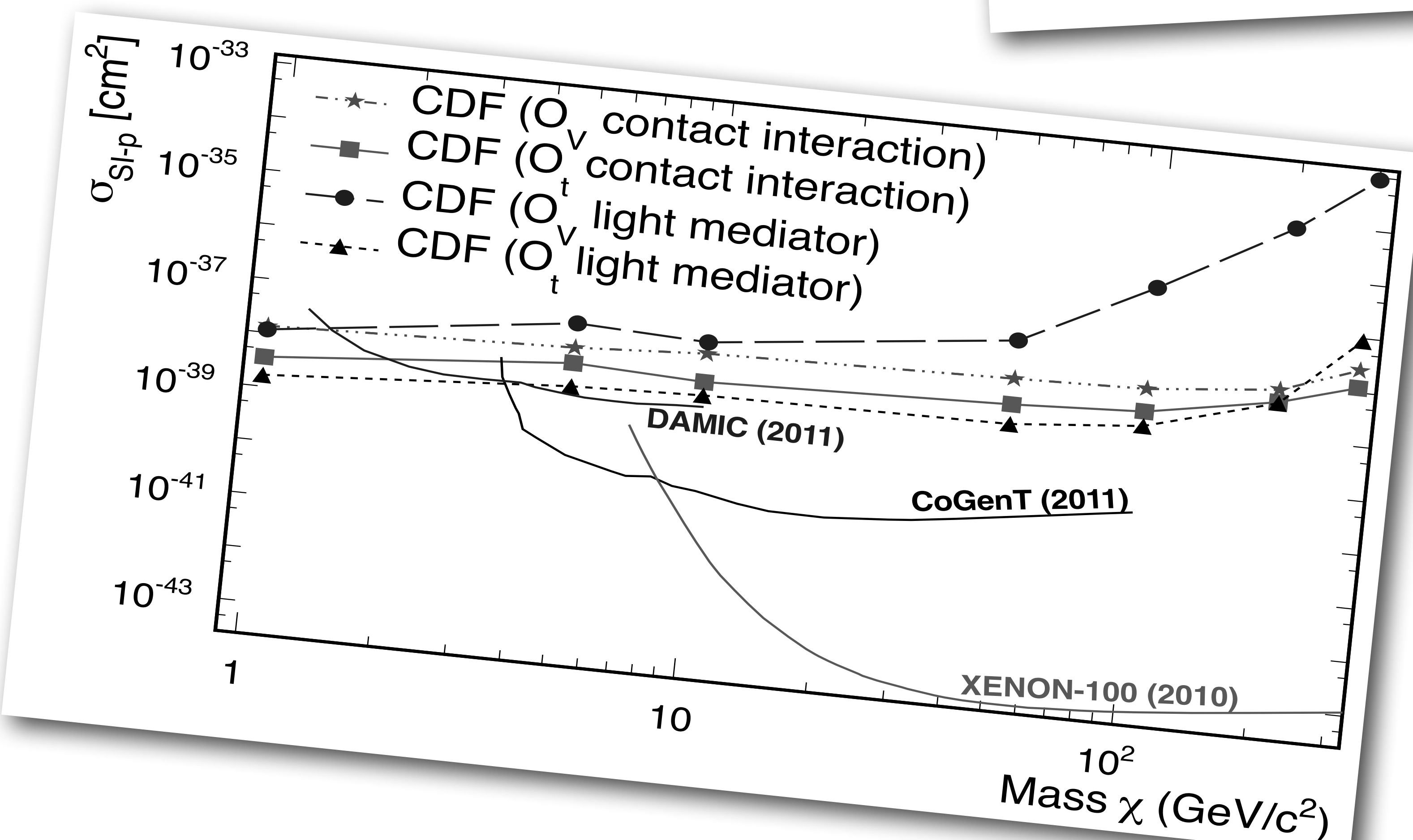
ATLAS Limits



CDF Limits:

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

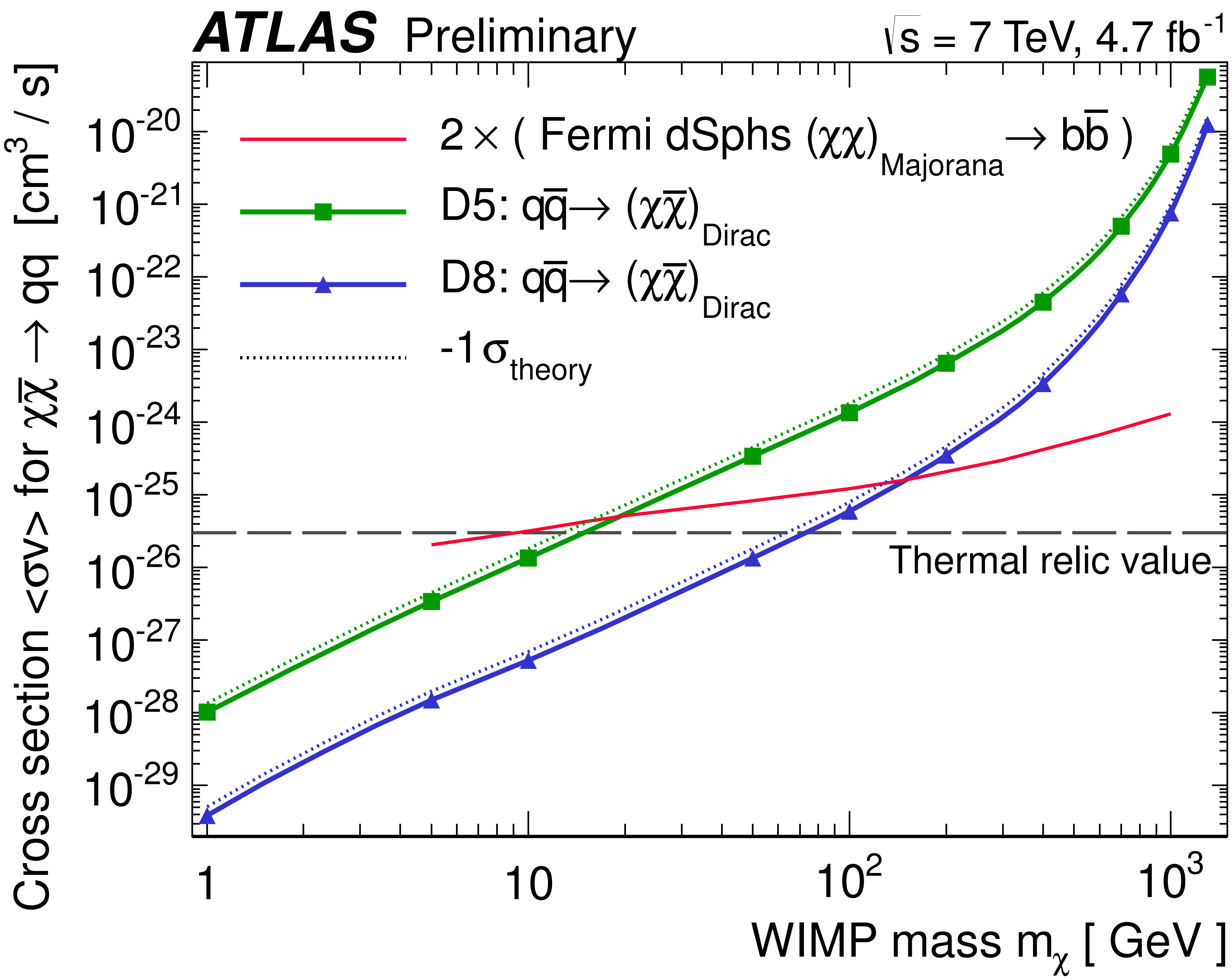




1203.0742

Indirect Detection

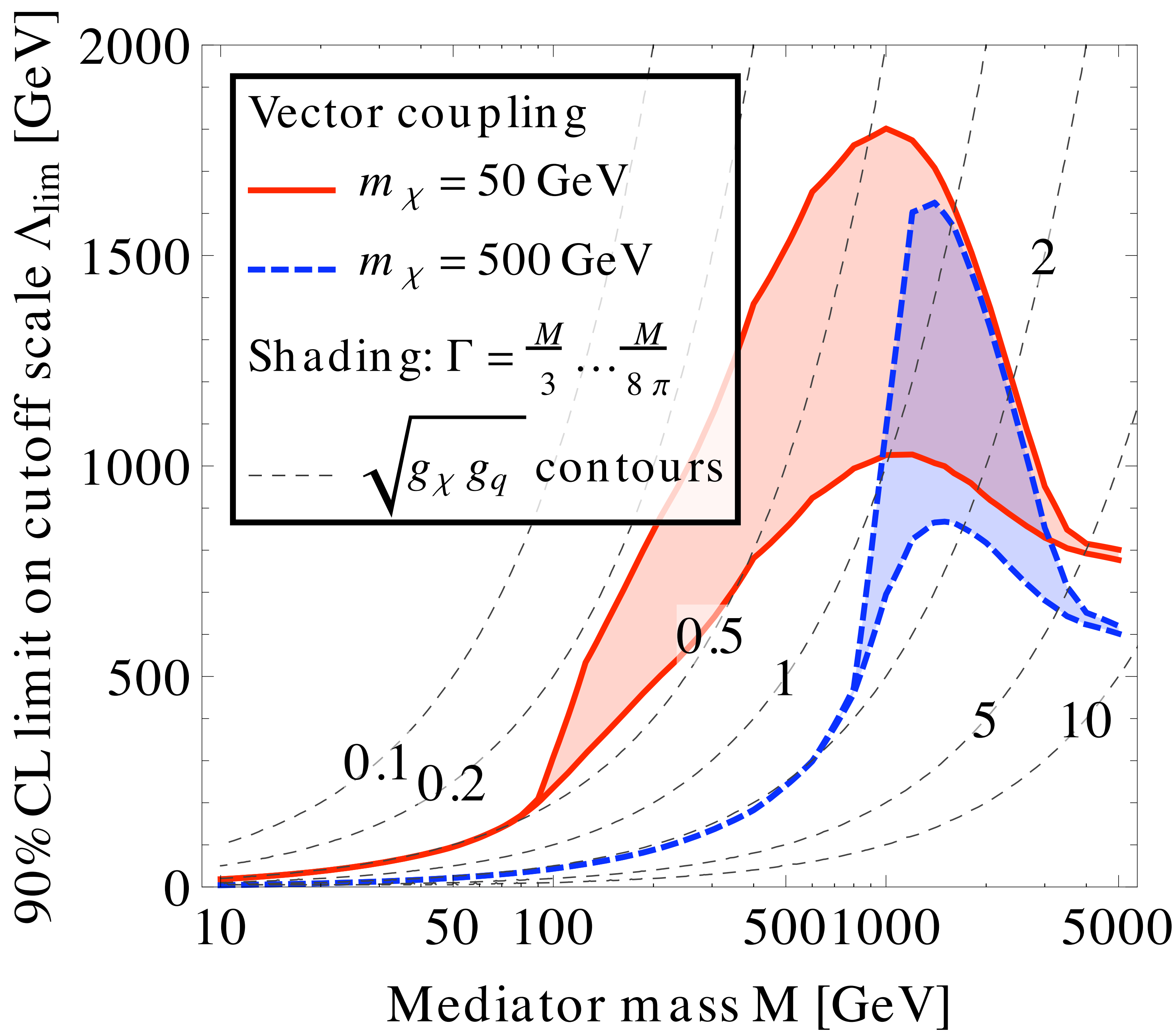
* Thermal relic cross sections are being probed!



What happens when the mediator is light?

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

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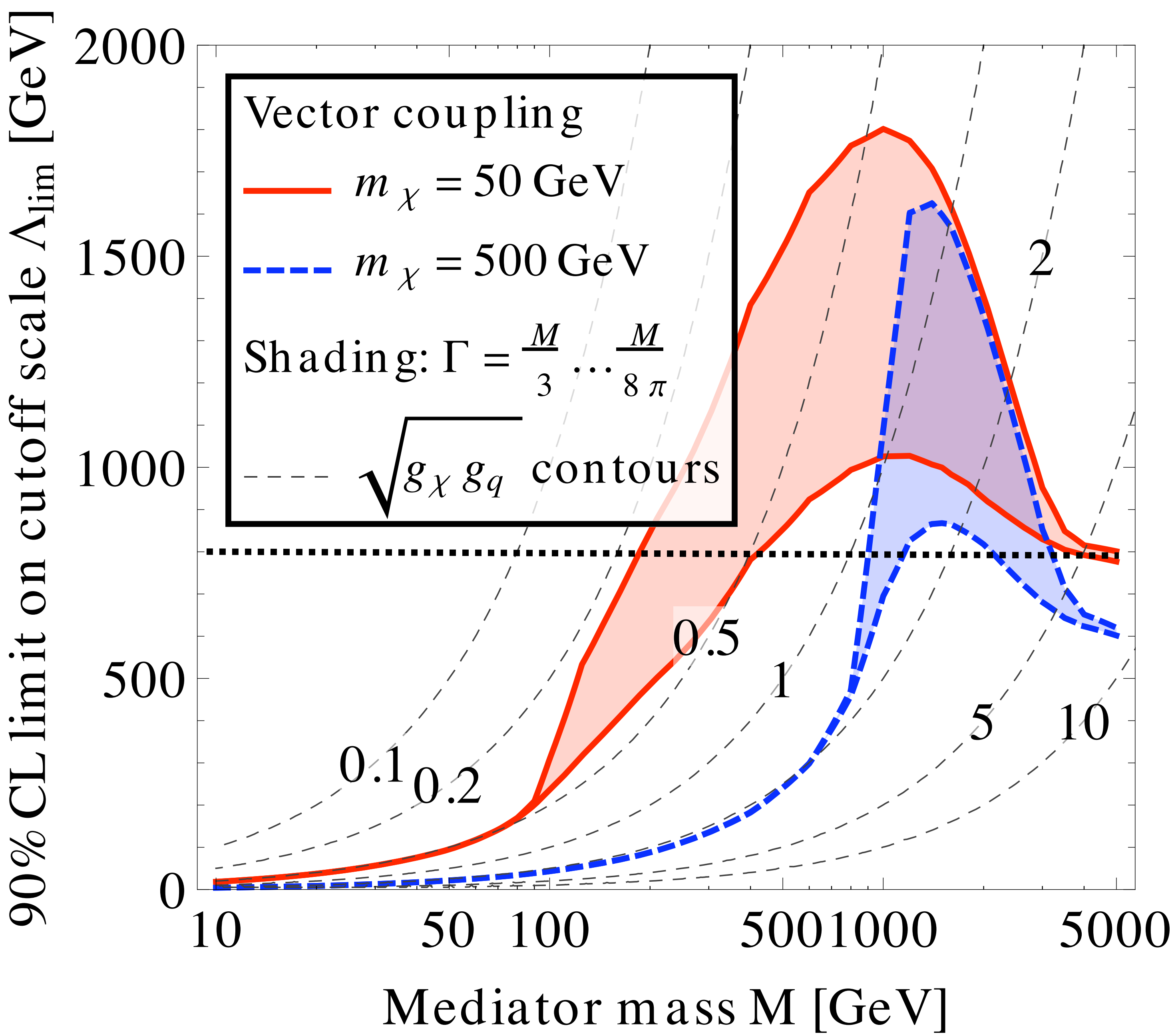

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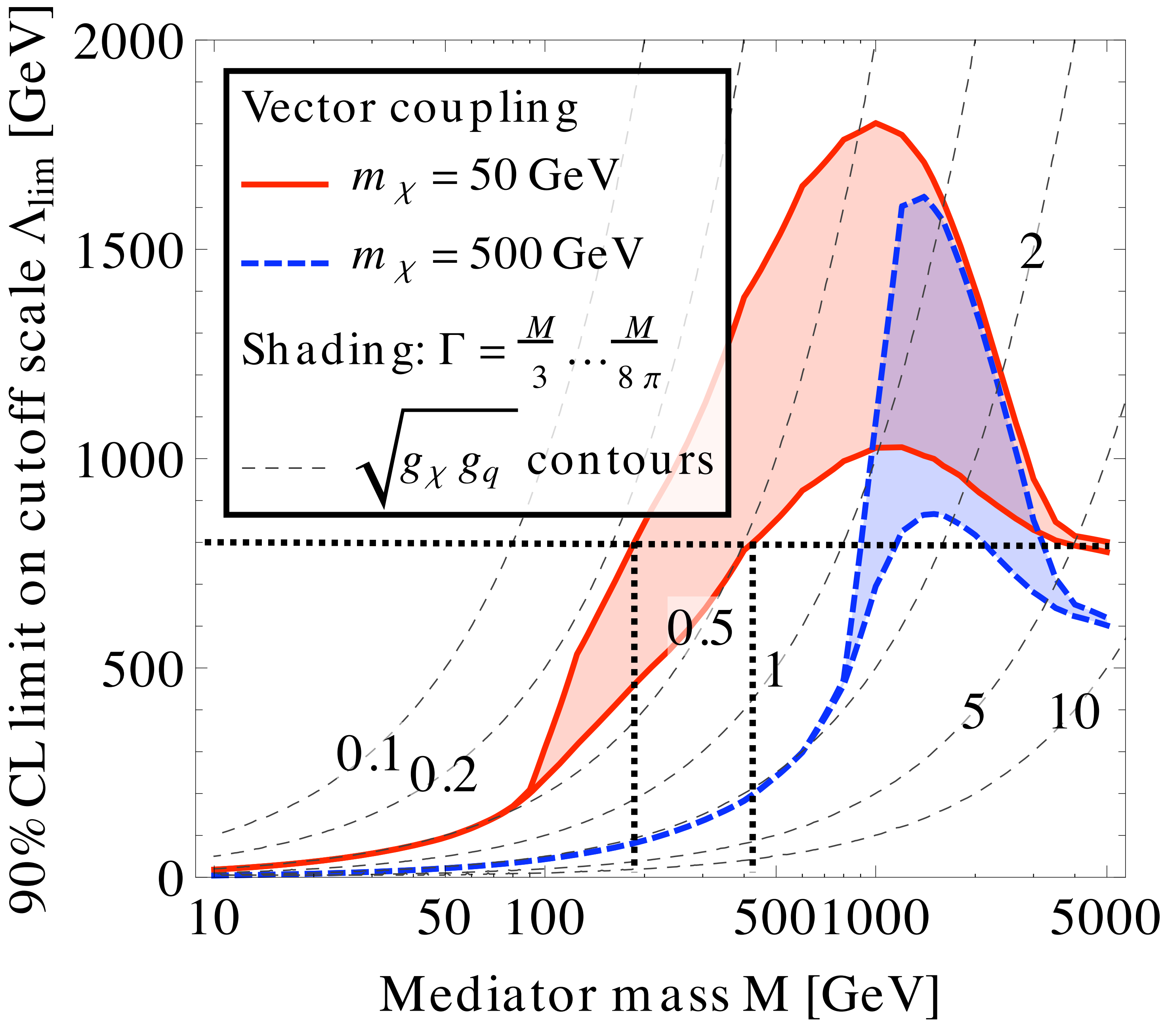
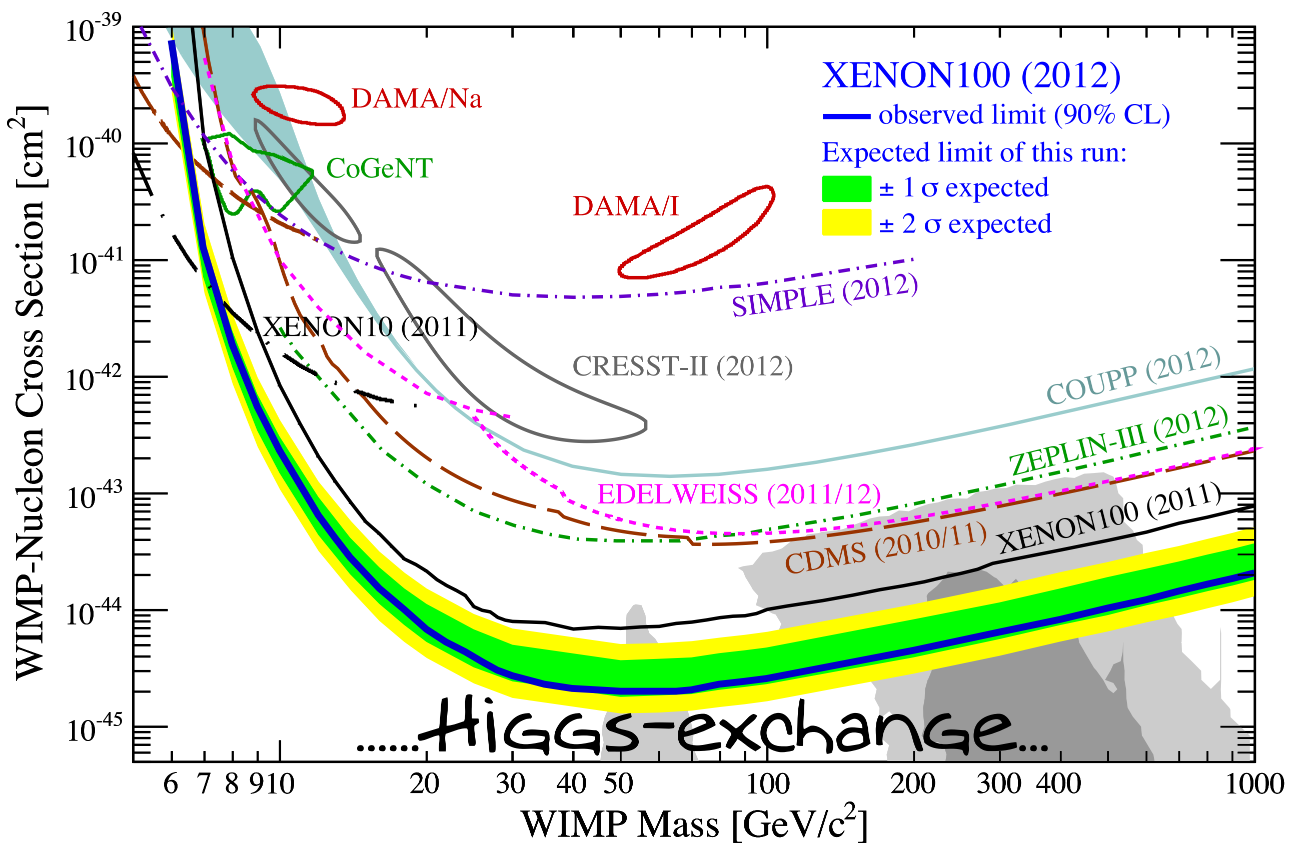


EFT limits are **conservative** so long as the mediator is above a few hundred GeV (and the mediator decays to DM).

Does Higgs have anything to do with DM?

Higgs Exchange

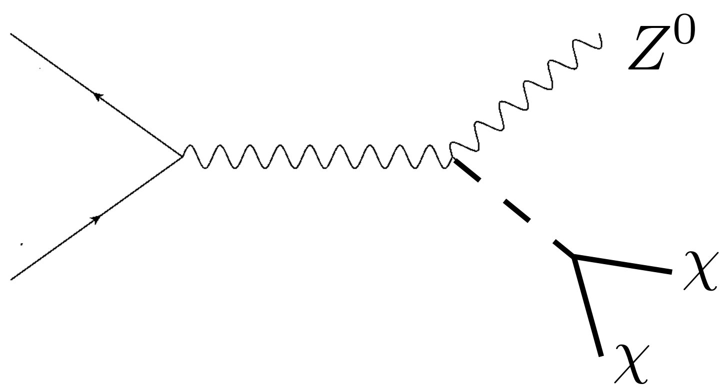
- Current DD limits are probing Higgs exchange.



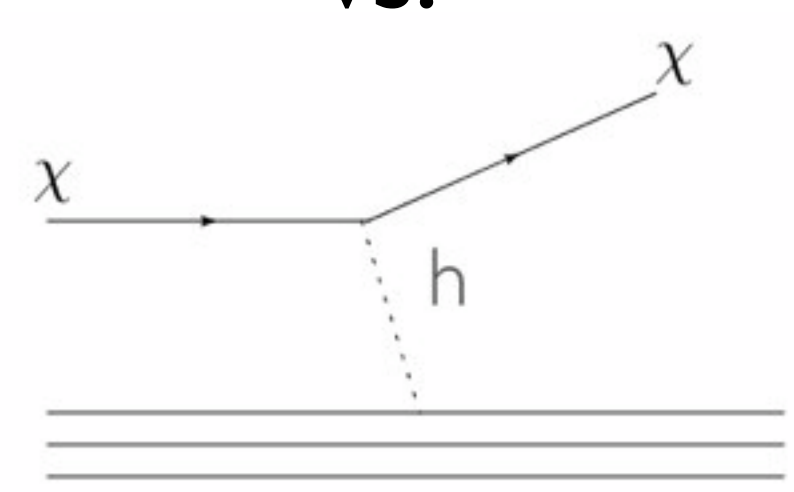
- If DM is light, Higgs could decay to a DM pair.

Invisible Higgs searches can be redrawn as direct detection limits.

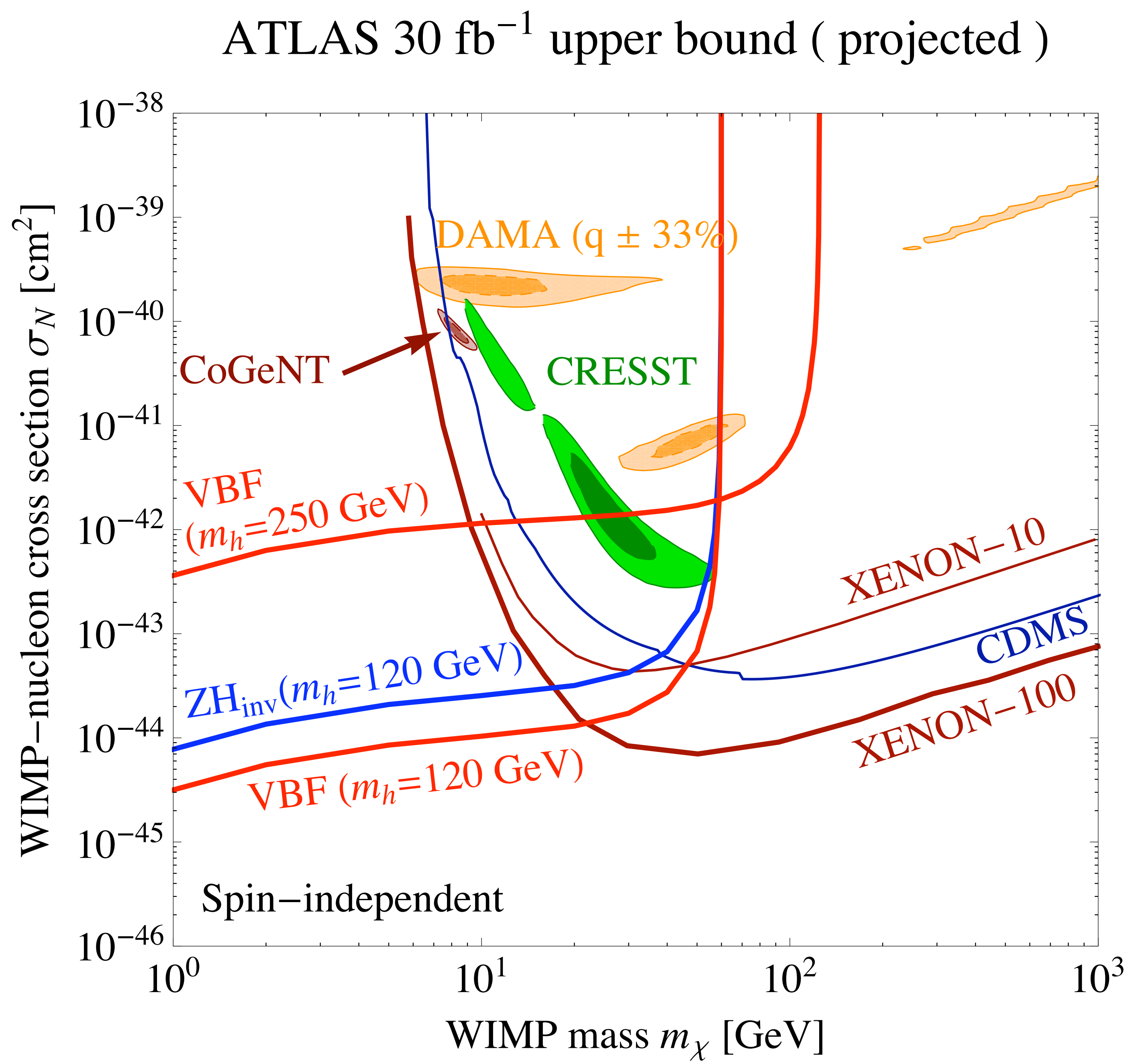
Higgs Mediator



vs.



Direct detection is parametrically smaller!



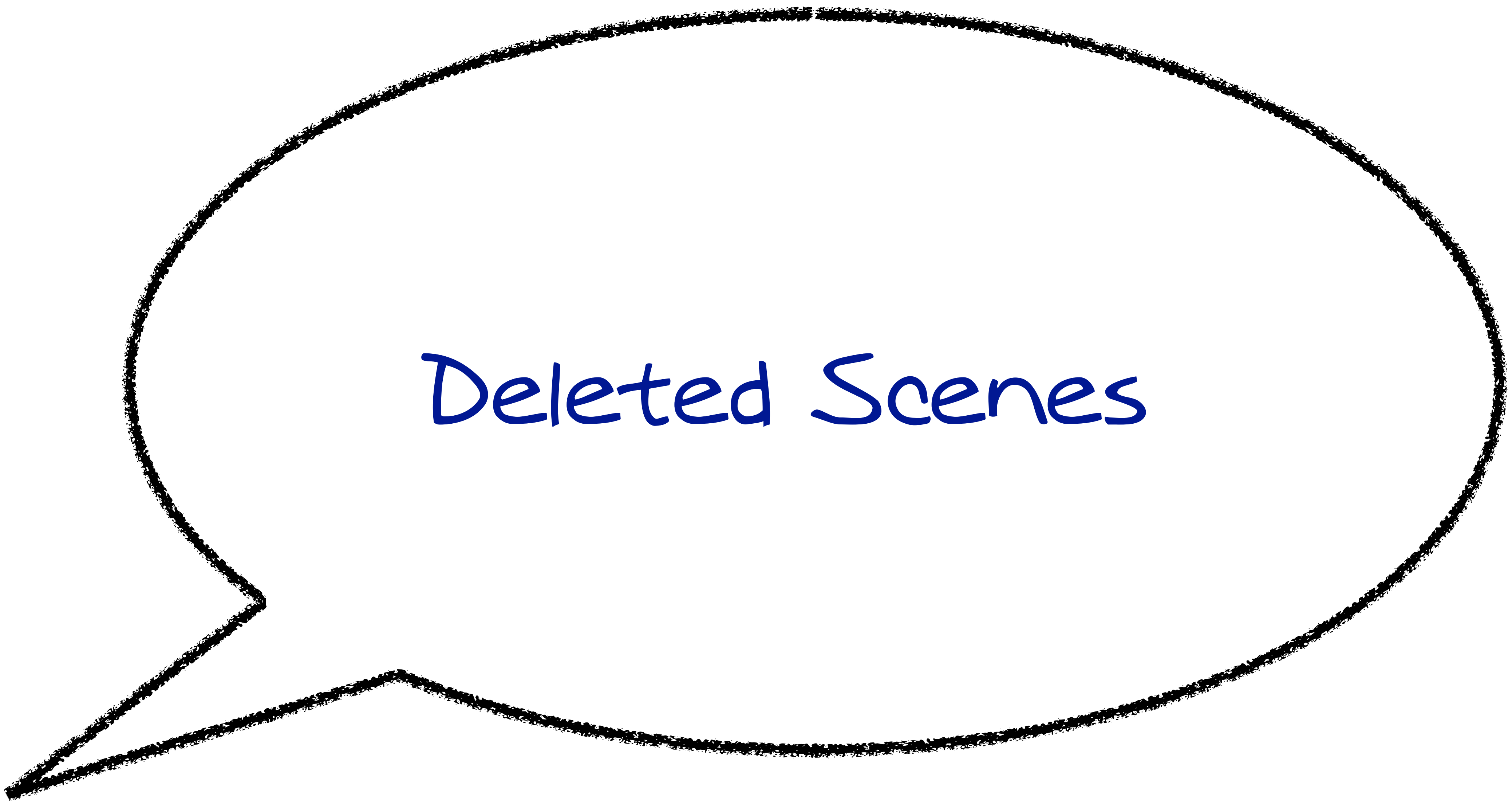
Fox, RH, Kopp and Tsai

Summary

- DM is real and exciting!
- You can probe in in new and complementary ways at the LHC.

Go find it!

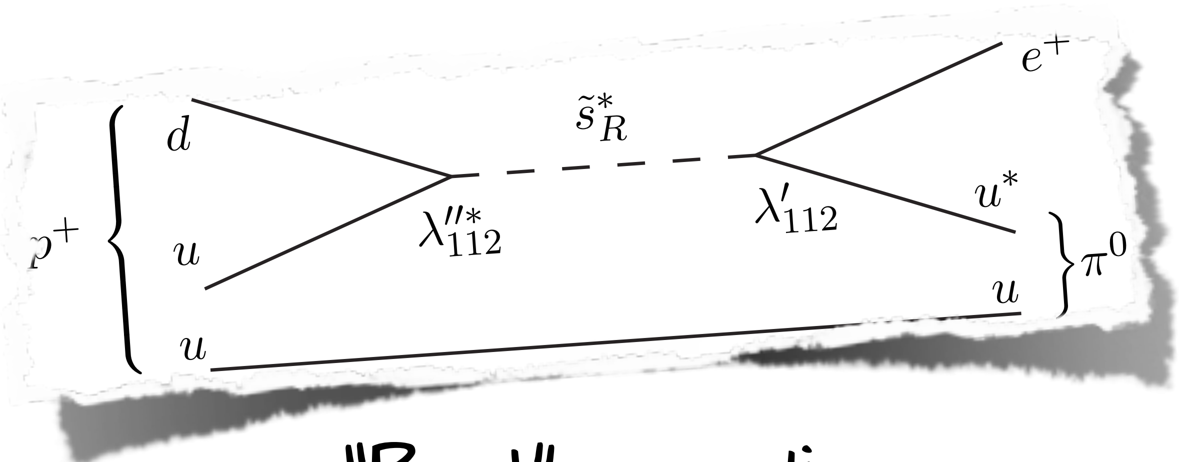
cheers.


Deleted Scenes

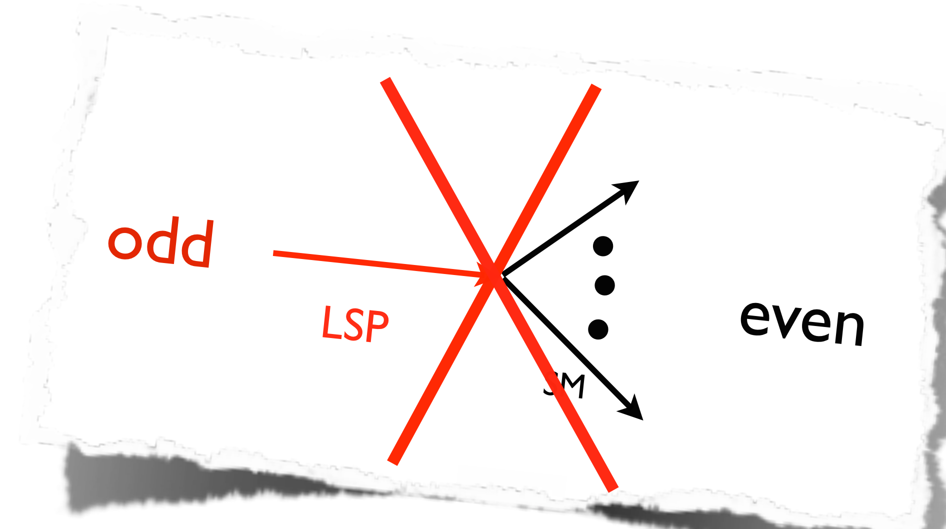
WIMPs in BSM e.g. SUSY

- In many theories a new parity was needed to, say, prevent proton decay (in SUSY):

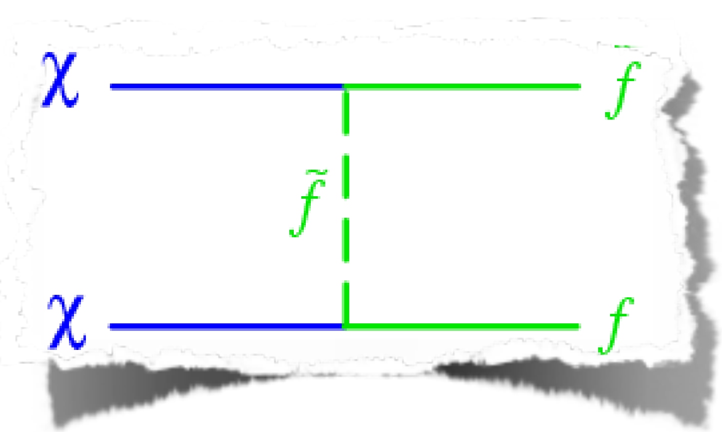
(ripped from Lian Tao's talk)



"Bad" coupling forbidden.



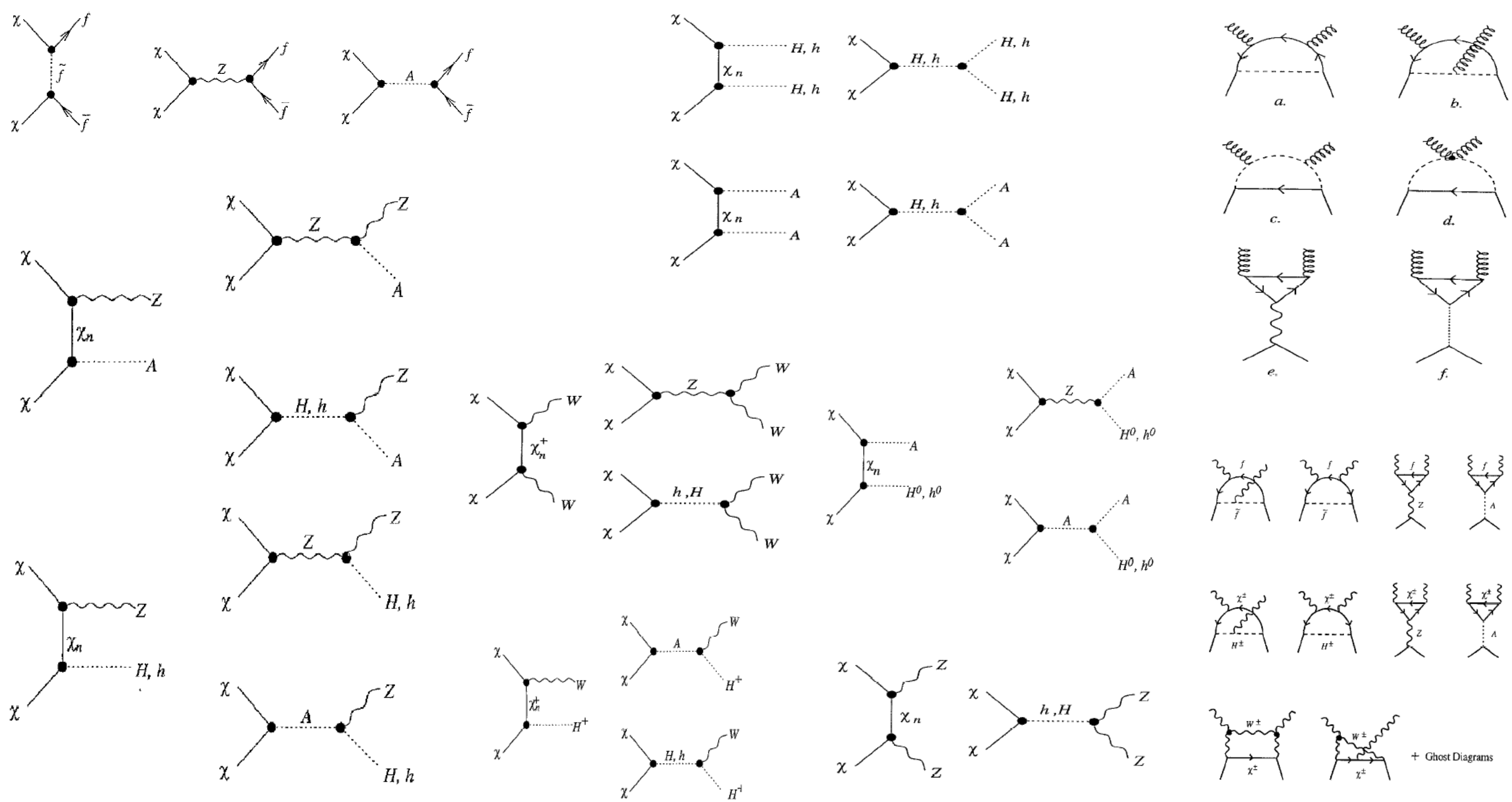
Lightest odd particle is stable (for "free"? No).



But it can annihilate via sparticle exchange. sparticle mass is set to solve other problems!

SUSY WIMPs

* In fact, neutralinos can annihilate in many many ways:



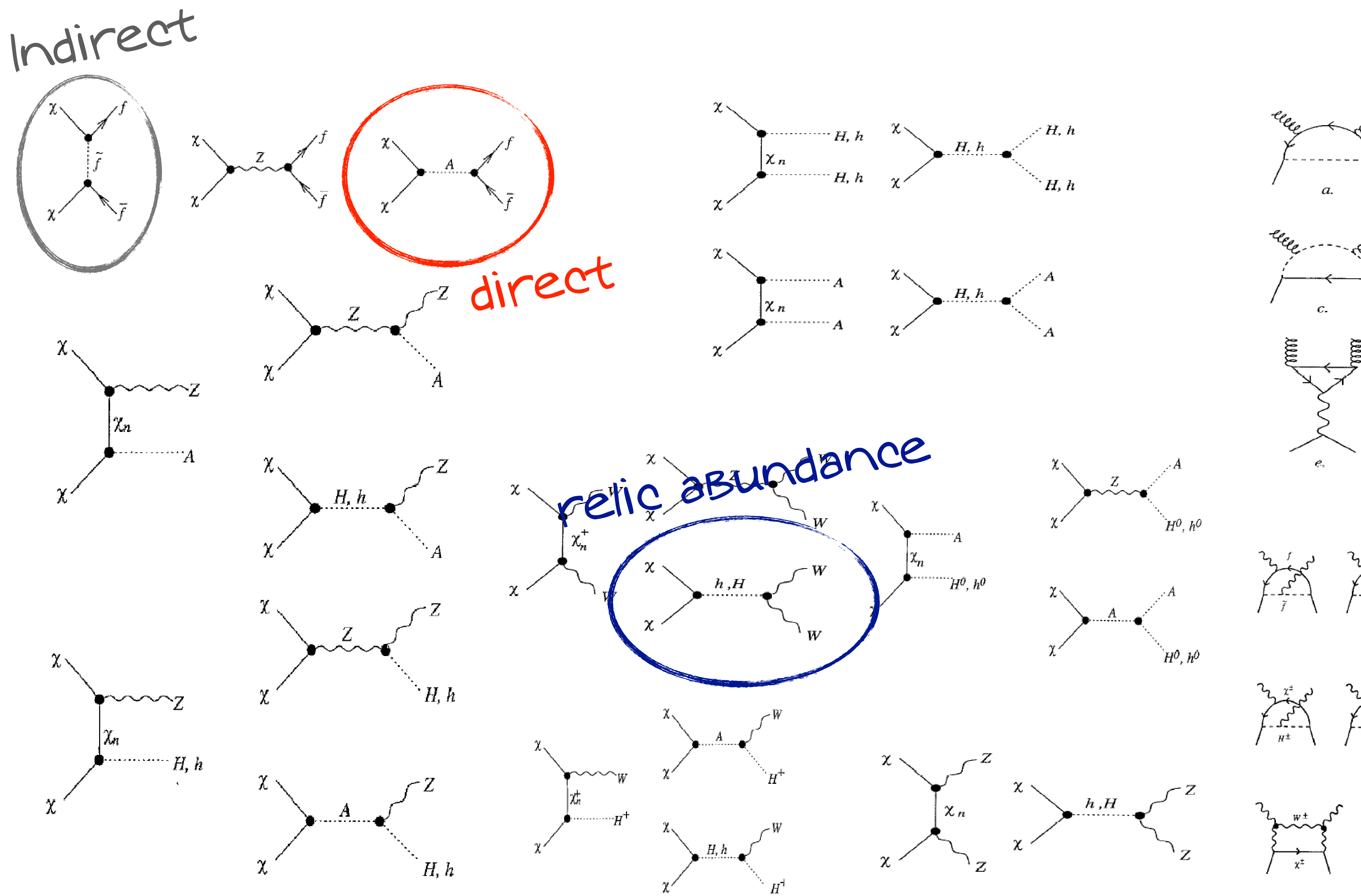
Jungman, Kamionkowski, Griest (1995)

SUSY WIMPs

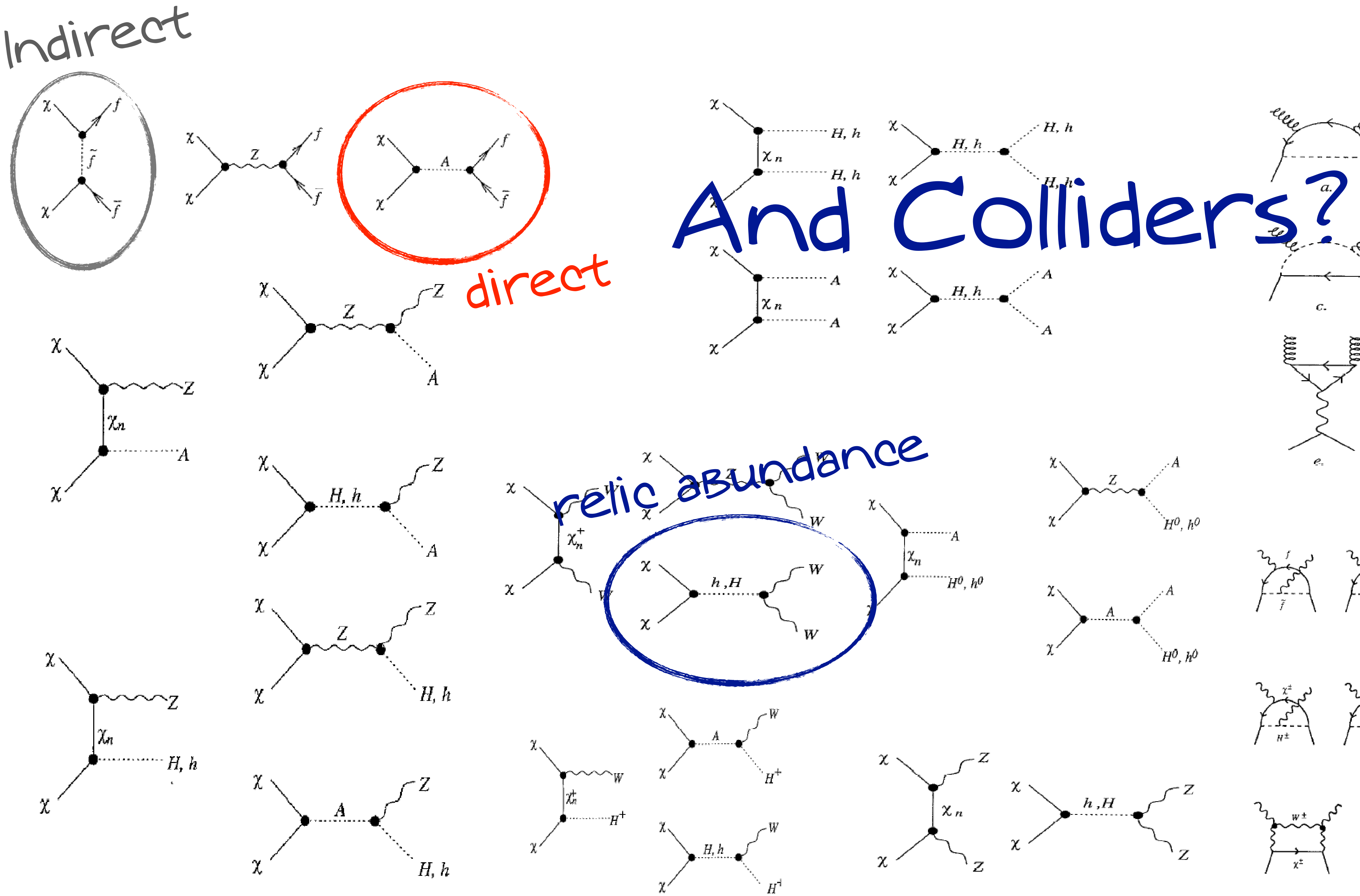
* A variety of possibilities: interesting phenomenology, but also...
* Connections between experiments are highly model dependent.

No longer turning a single diagram on its side...

For example:



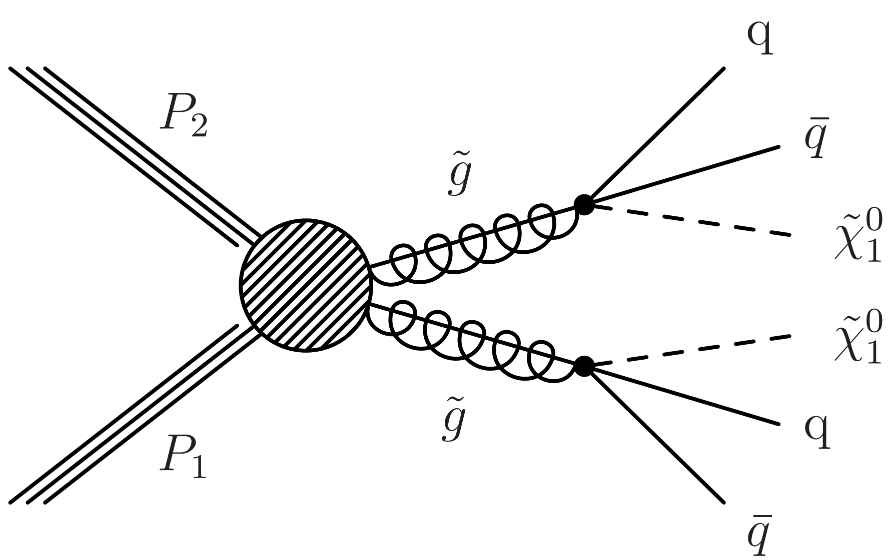
Jungman, Kamionkowski, Griest (1995)

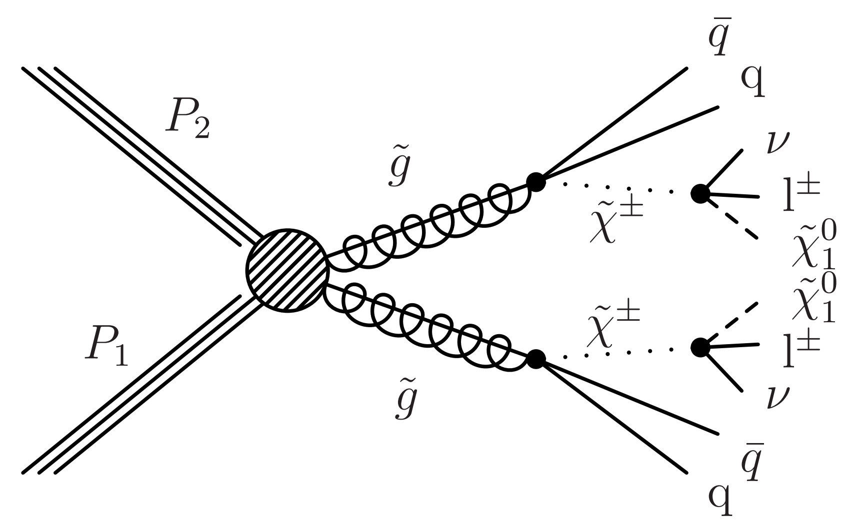


Jungman, Kamionkowski, Griest (1995)

SUSY & Colliders

- SUSY particles are produced via colored squarks or gluinos.



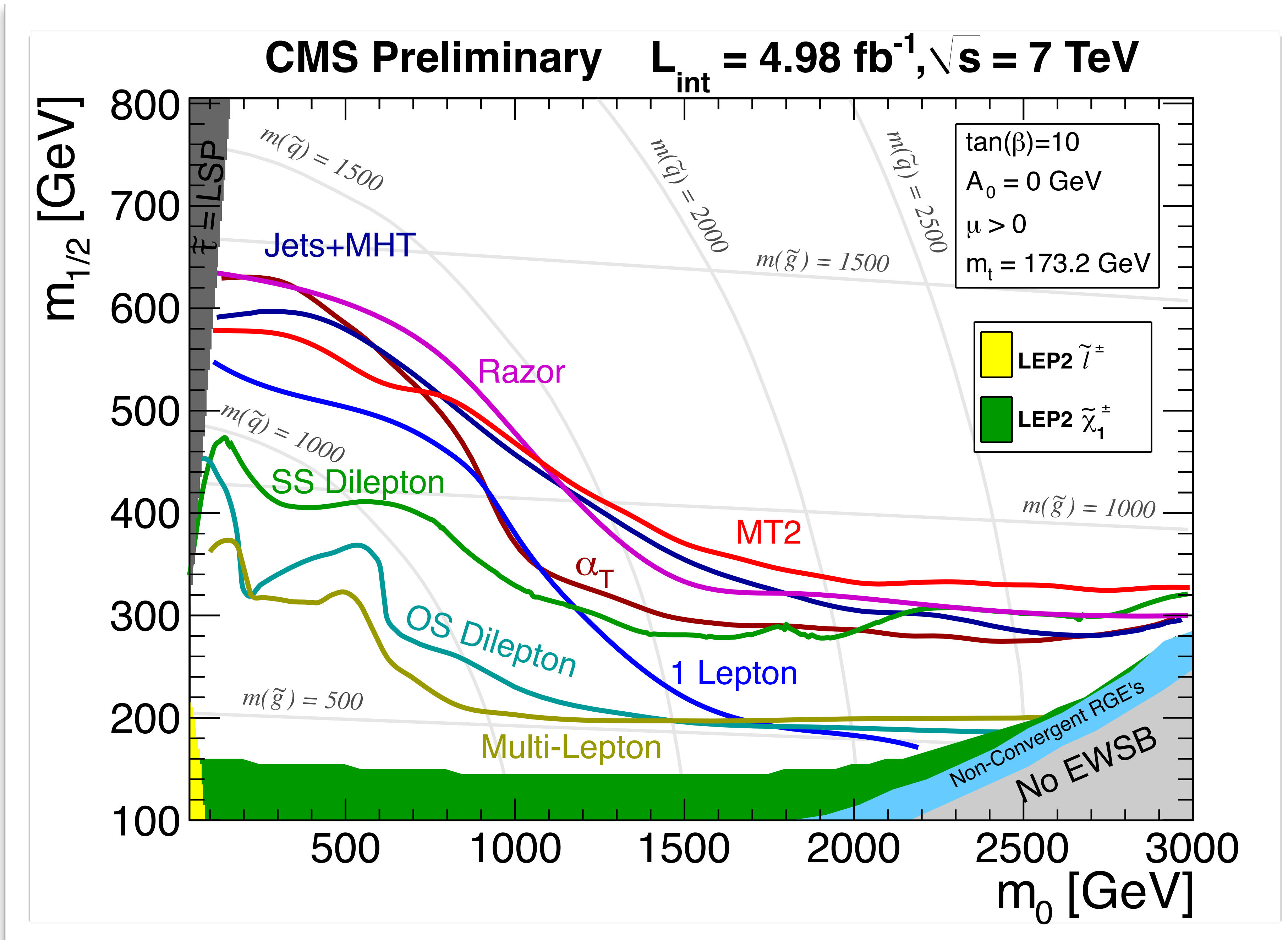


- This is great for discovering New Physics, but hard to make the connections to dark matter.
  (nature can certainly be this way).

Indeed, I wish we had this problem....

SUSY Limits

- Limits on SUSY also are model dependent:



Which means there are ways to evade them! :-)

SUSY Limits

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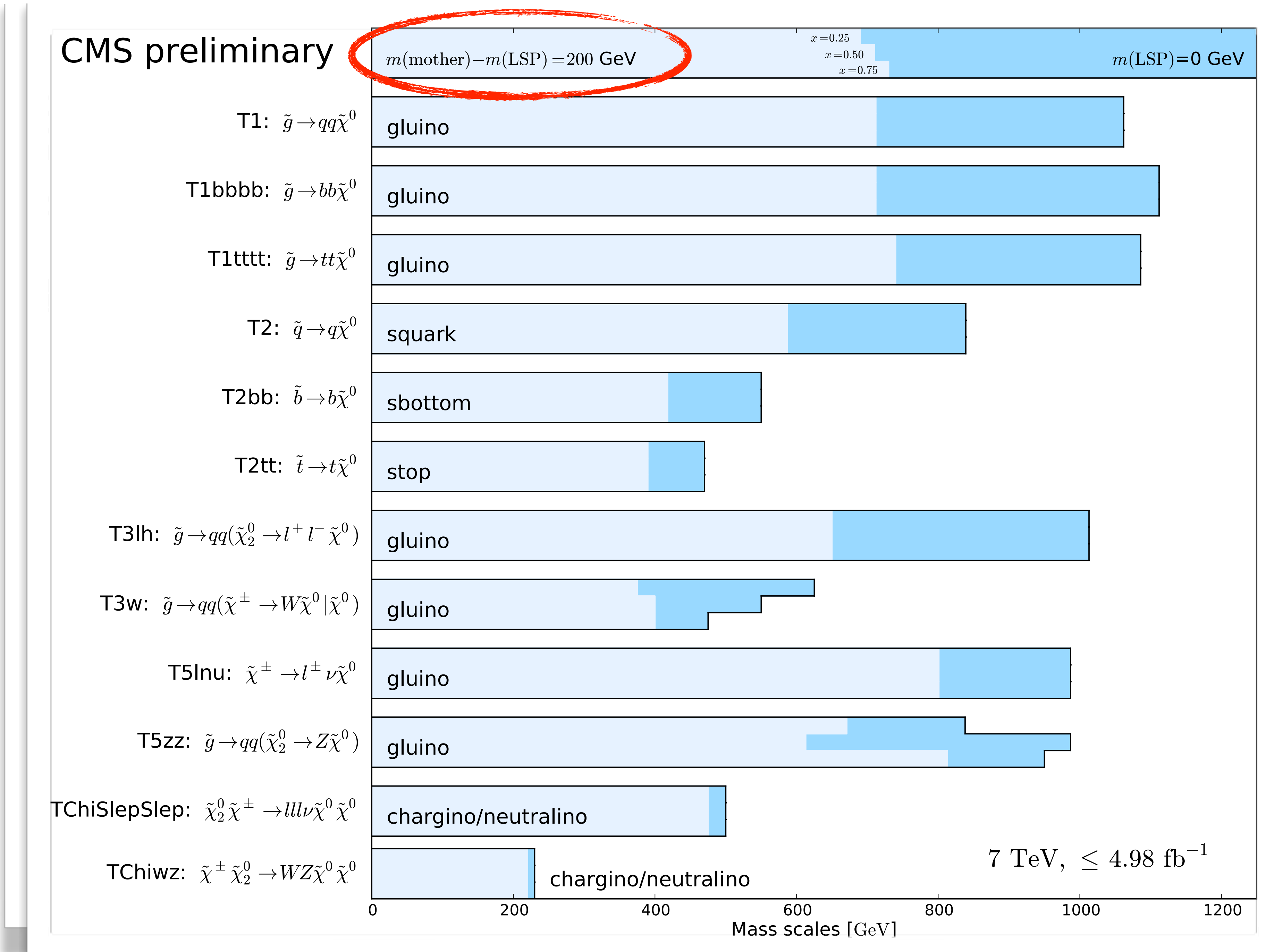
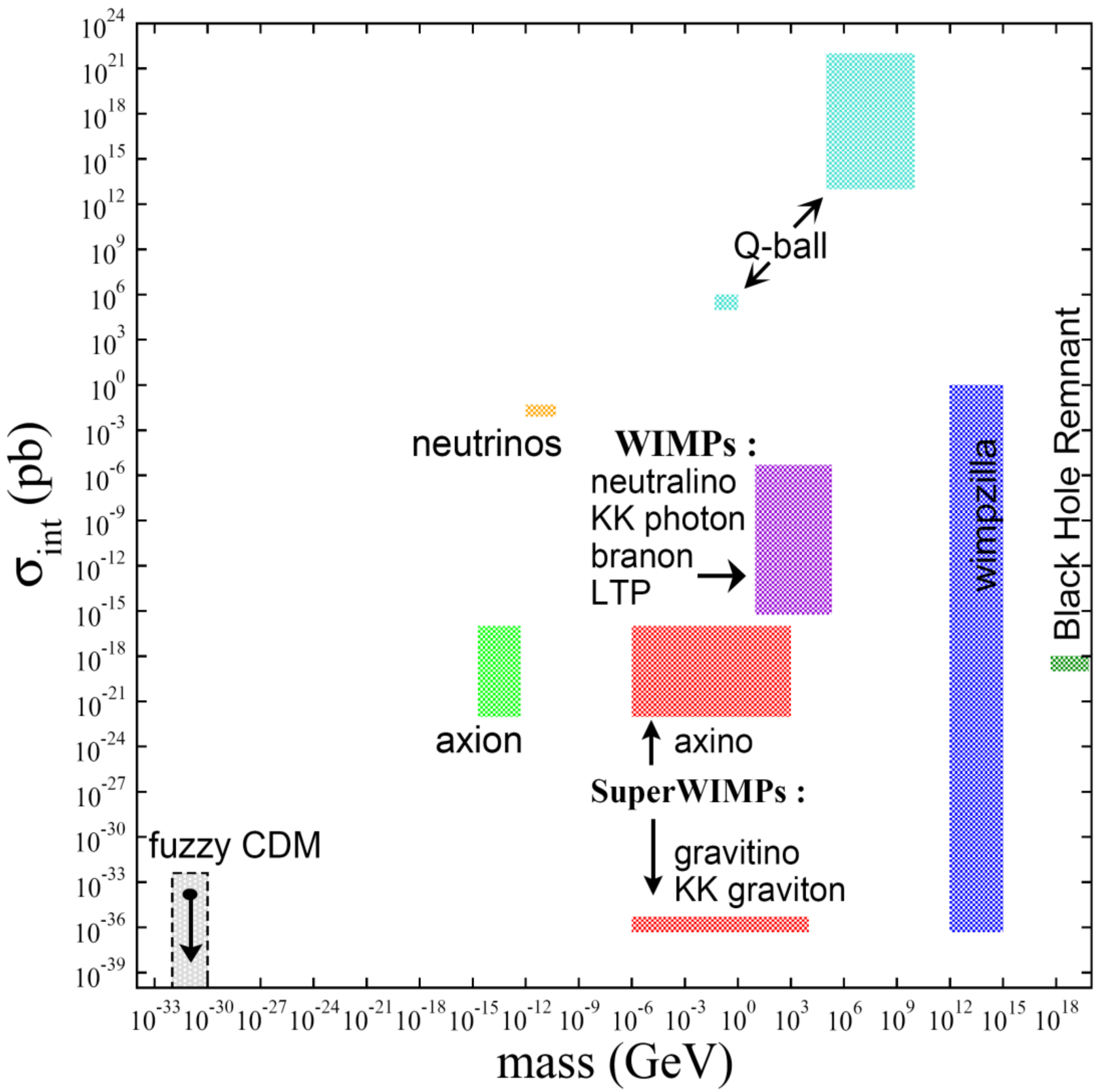


Which means there are ways to evade them! :-)

Other DM Candidates

- ***Other Wimps-***
  - KK-photons (extra dimensions), LTP (little Higgs), Inert doublet,
- ***Axions- (not a WIMP!)***
  - Originally proposed to for the strong CP problem.
  - it is a *very* weakly coupled and very light particle.
  - Searches are far fewer (opportunity!), and non-collider.
- ***Asymmetric DM- (also not a WIMP)***
  - Exploit the fact that $\rho_{\rm DM} \sim {\rm few} \times \rho_{\rm matter}$.
  - Invoked an asymmetry b/w DM and anti-DM (like us).
  - Signals are model dependent, but possible everywhere.

Many More...



σ_{int} (pb)
mass (GeV)
Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM

Direct, indirect, collider

Direct detection

Current Anomalies

Indirect

Colliders