Complementarity of Dark Searches

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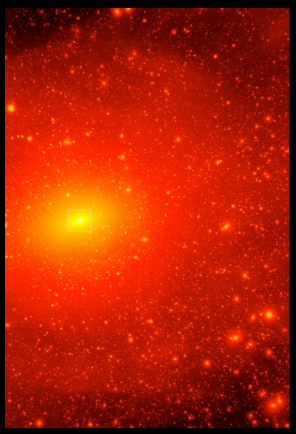
Outline

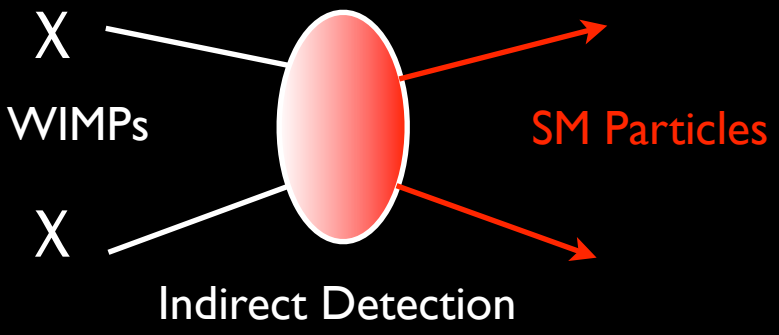
- Aspects of complementarity
- Assembling the Picture of WIMP Searches
- Beyond the simplest Effective Field Theories
- Outlook

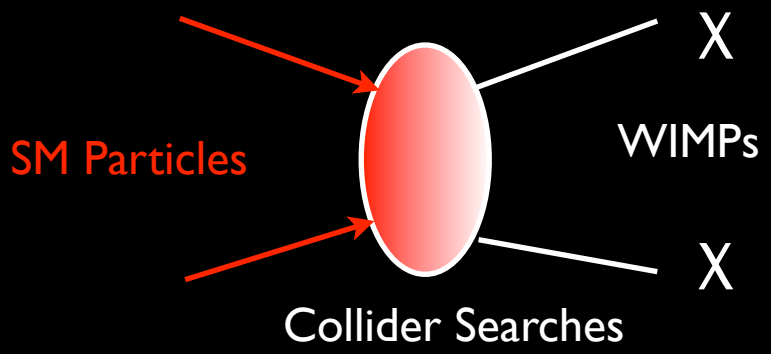
Question #1:

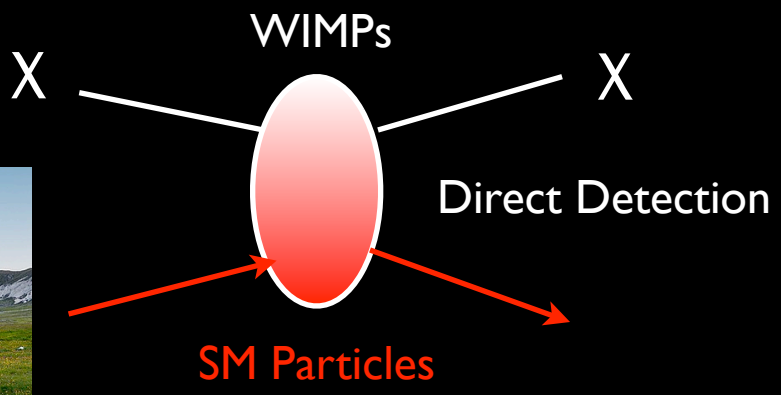
Does it even make sense to ask how searches for DM complement each other?

Yes!





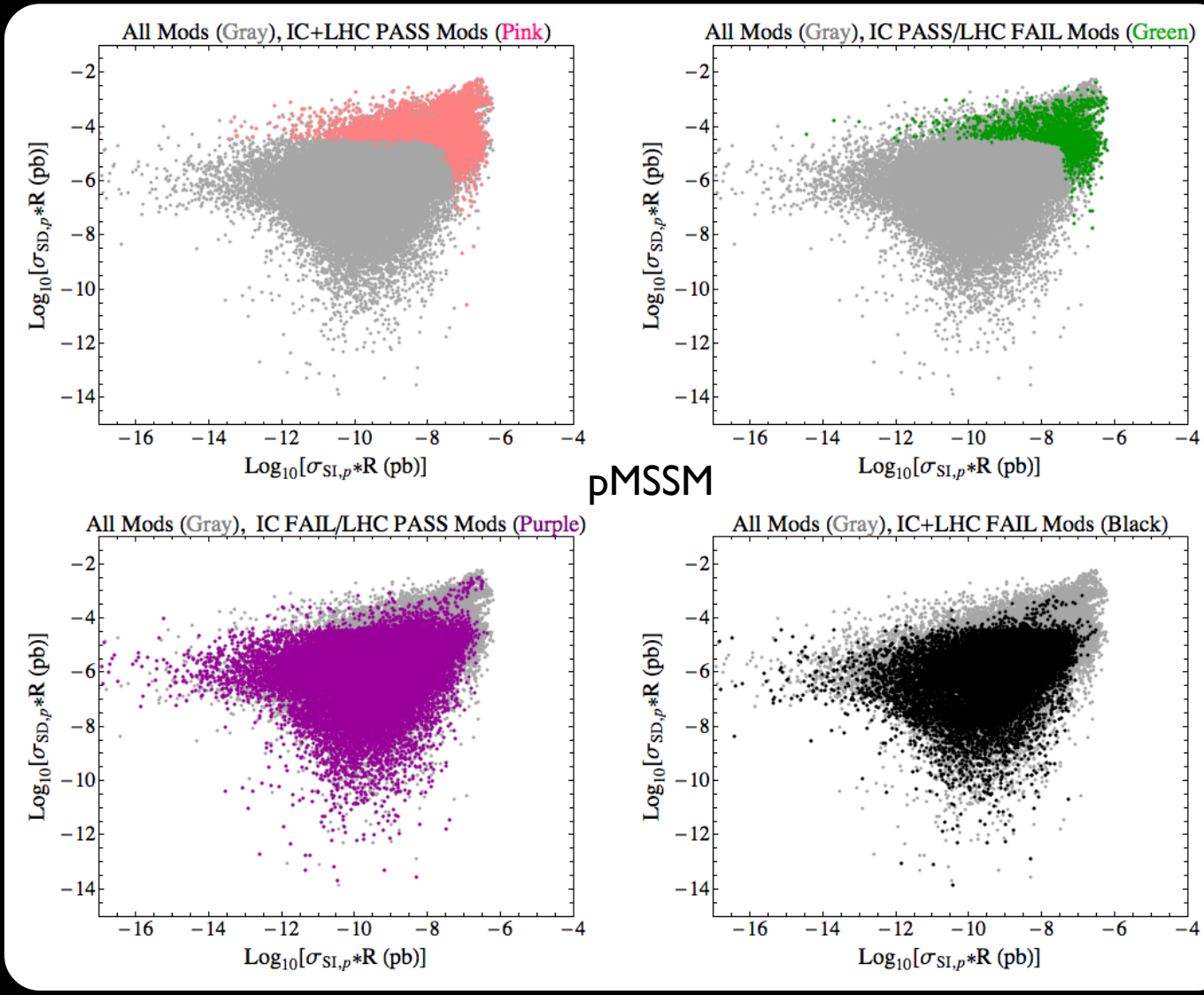




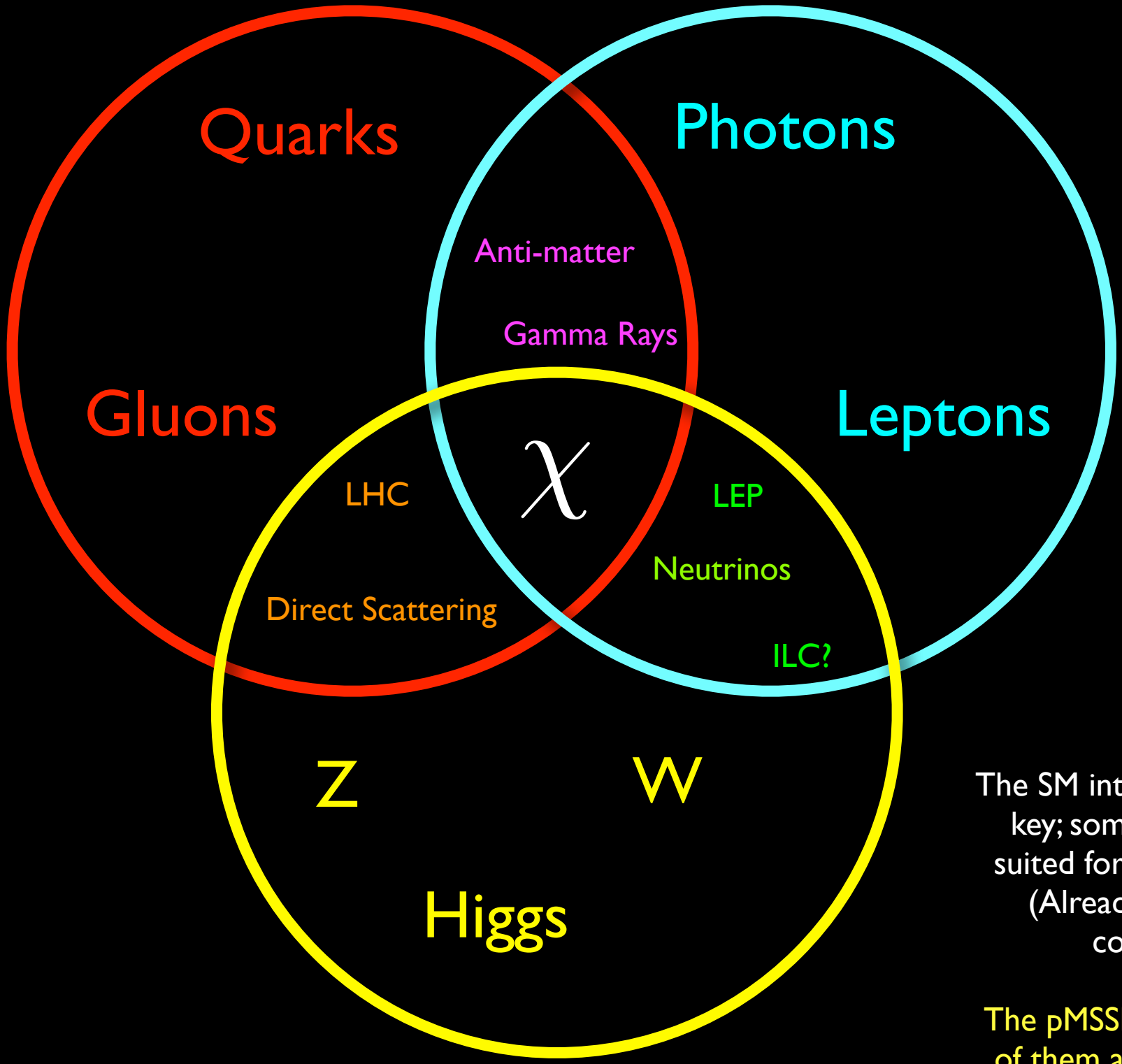
- The common thread that ties up direct, indirect, and collider searches for dark matter is how WIMPs interact with the Standard Model.

No?

- Studies of the MSSM (like the pMSSM study here) show that often DM properties are not very strongly correlated with LHC signals.
- In this case, both Ice Cube and LHC searches detect some model points, but LHC accessible models do not show strong correlations with DD cross sections.
- Instead, the total density of points decreases roughly uniformly...



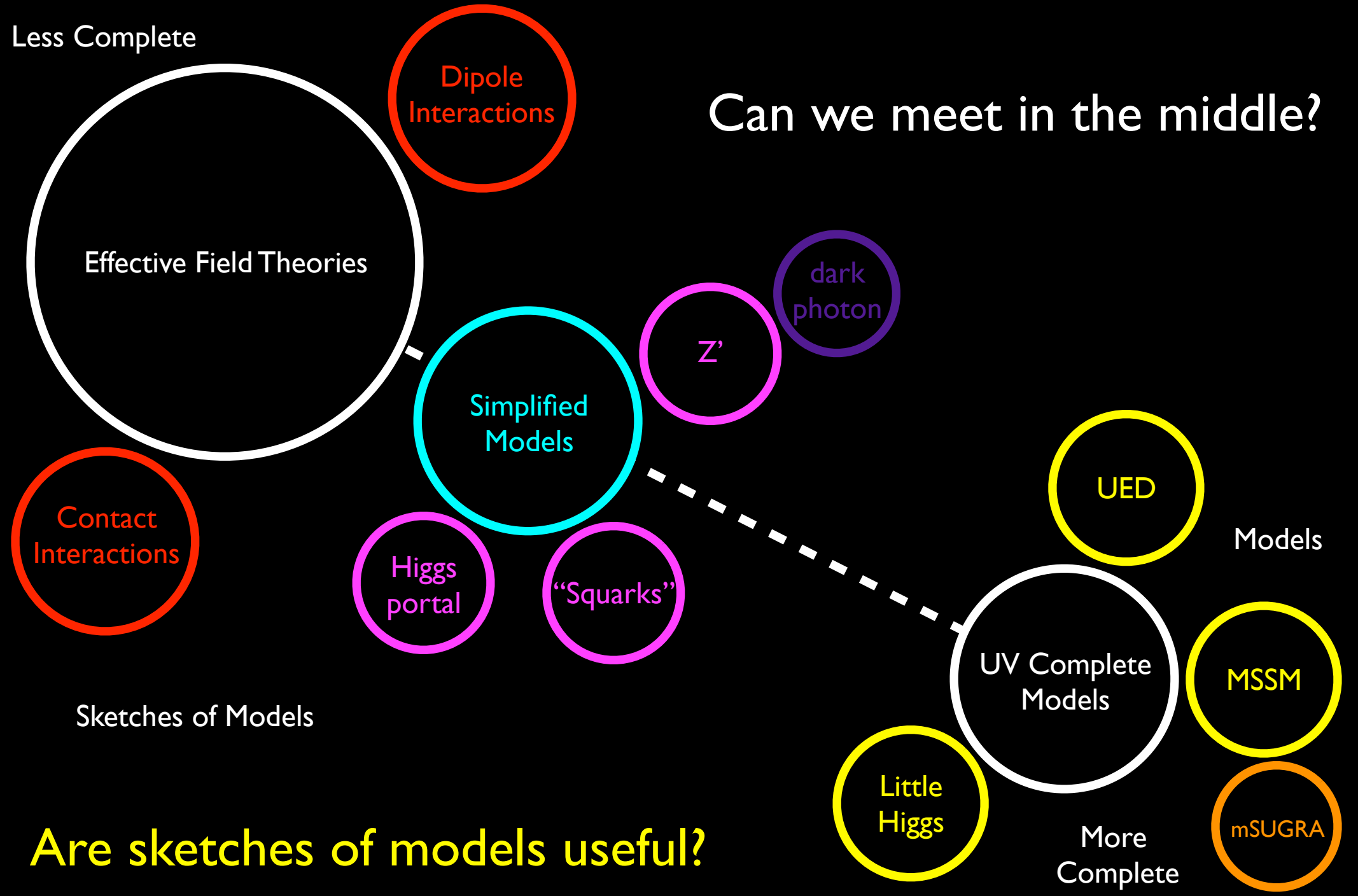
Neutrinos from Ice Cube
Cotta, Howe, Hewett, Rizzo arXiv:1105.1199



The SM interactions are always the key; some searches are better suited for some SM messengers. (Already itself a message of complementarity)

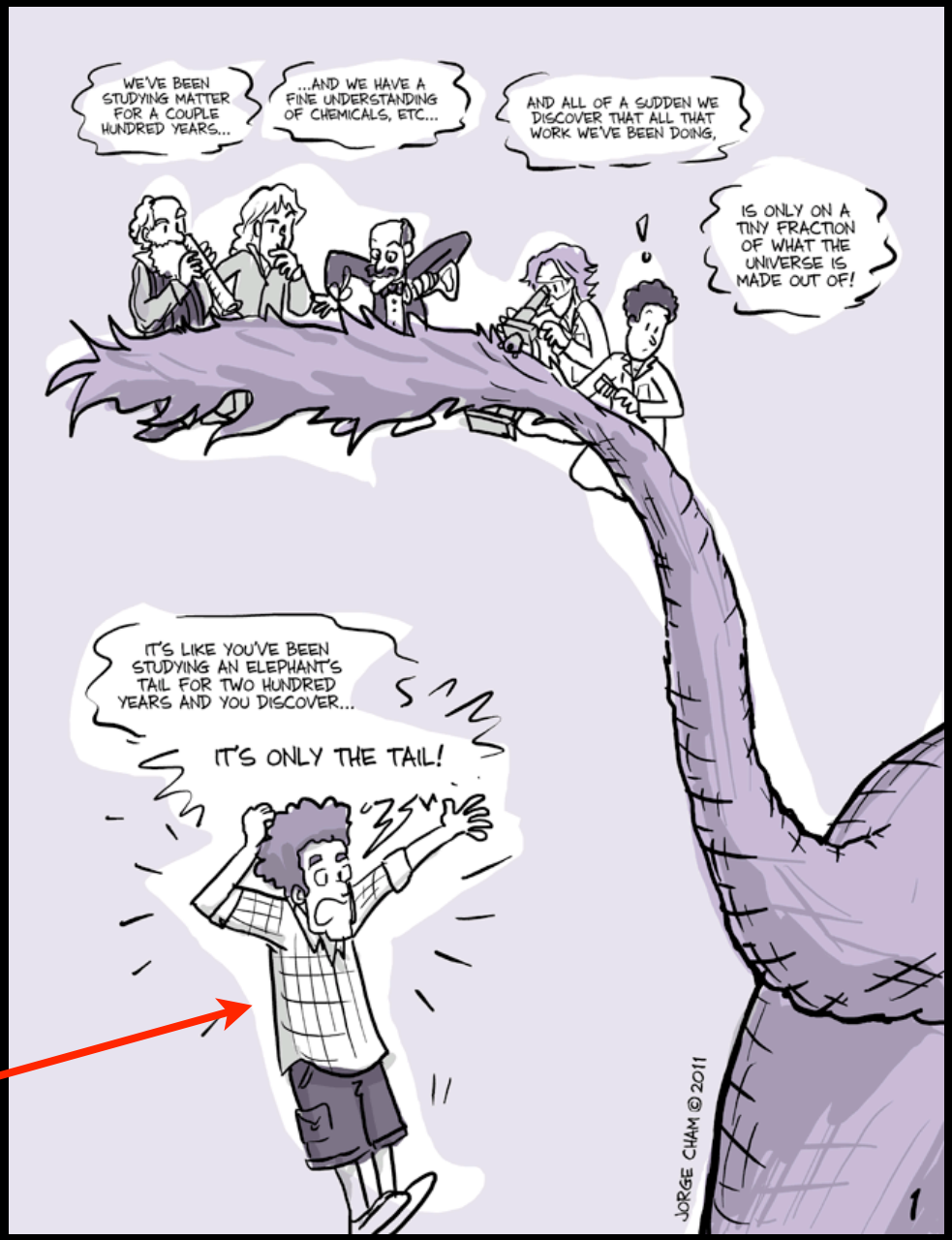
The pMSSM is a case where many of them are important at once...

How about Simpler Theories?



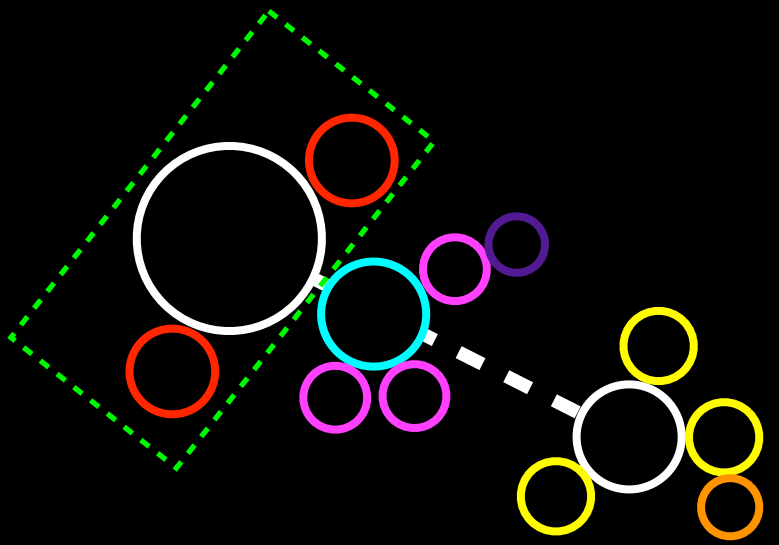
Are sketches of models useful?

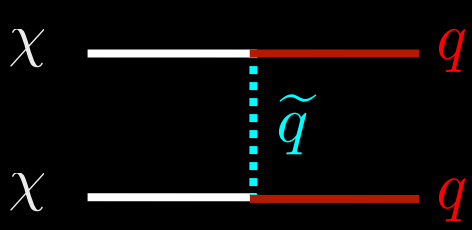
Sketches Can Be Useful...

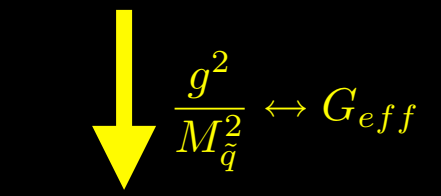


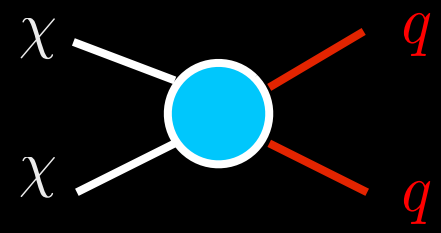
Contact Interactions

- Most of the work so far on the "less complete" end of the spectrum has been in the language of contact interactions describing ultra-heavy mediators.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is that it can't answer every question.
  - E.g. Quark interactions are disconnected from lepton interactions.
- Outside of its domain of validity (at high enough energy), it just breaks down.









Majorana WIMP

- As an example, we can write down the operators of interest for a Majorana WIMP interacting with quarks and/or gluons.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Gluon operators are normalized by α_S, consistent with their having been induced by loops of some heavy colored state.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.

Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

$$G_\chi \left[\bar{\chi}\Gamma^\chi\chi\right] G^2$$

$$\sum_q G_\chi \left[\bar{q}\Gamma^q q\right] \left[\bar{\chi}\Gamma^\chi\chi\right]$$

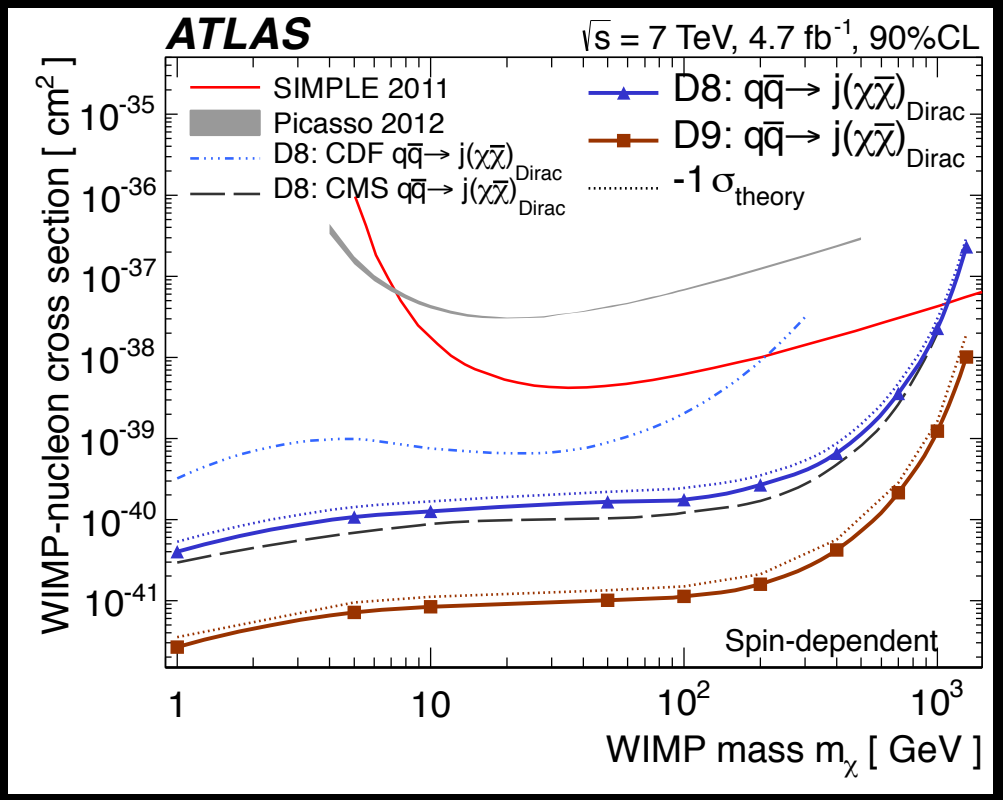
Other operators may be rewritten in this form by using Fierz transformations.

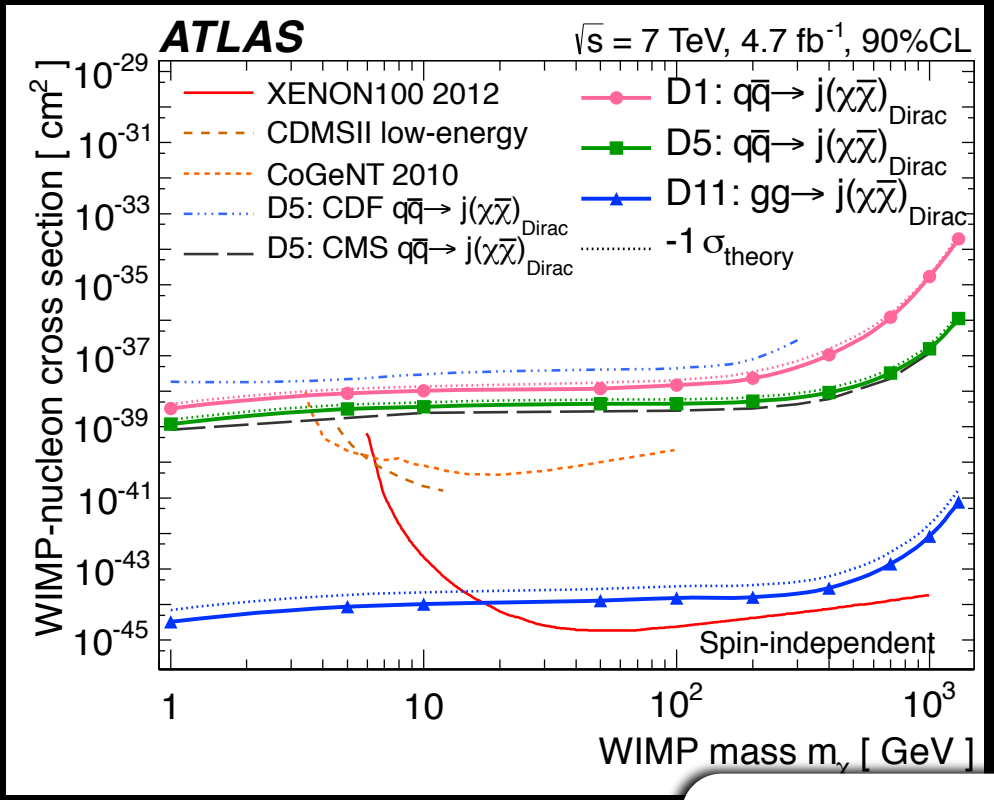
Dirac WIMP

- We can repeat this exercise for other choices of WIMP spin.
- For a Dirac WIMP, we have a few more Lorentz structures, such as the vector and tensor combinations.
- On top of the operators we had for the Majorana WIMP, magnetic and electric dipole moment operators are possible as well.

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

From Mono-jets into Direct Detection

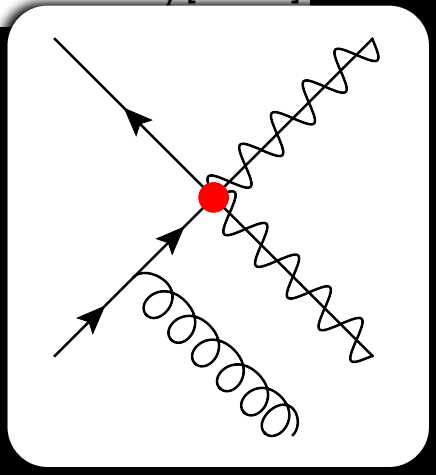




(See also: CMS for D5 and D8 from mono-jets/photons)

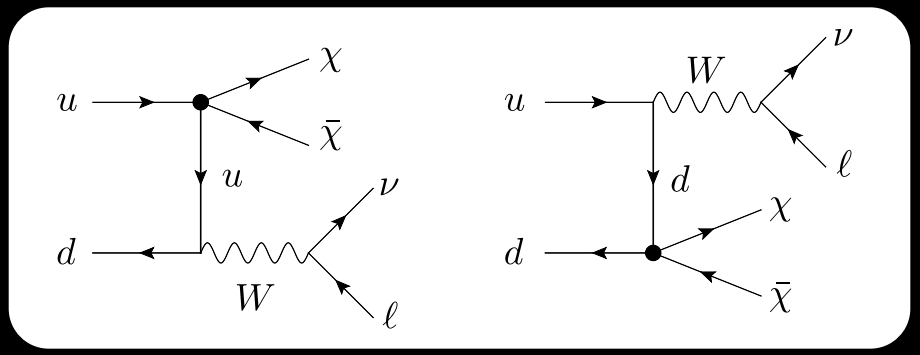
Original Theory mappings:

Beltran, Hooper, Kolb, Krusberg, TMPT JHEP [1002.4137]
Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu PLB [1005.1286] and PRD [1008.1783]
Rajaraman, Shepherd, TMPT, Wijangco PRD [1108.1196]
Bai, Fox, Harnik JHEP [1005.3797]
Fox, Harnik, Kopp, Tsai PRD [1109.4398]



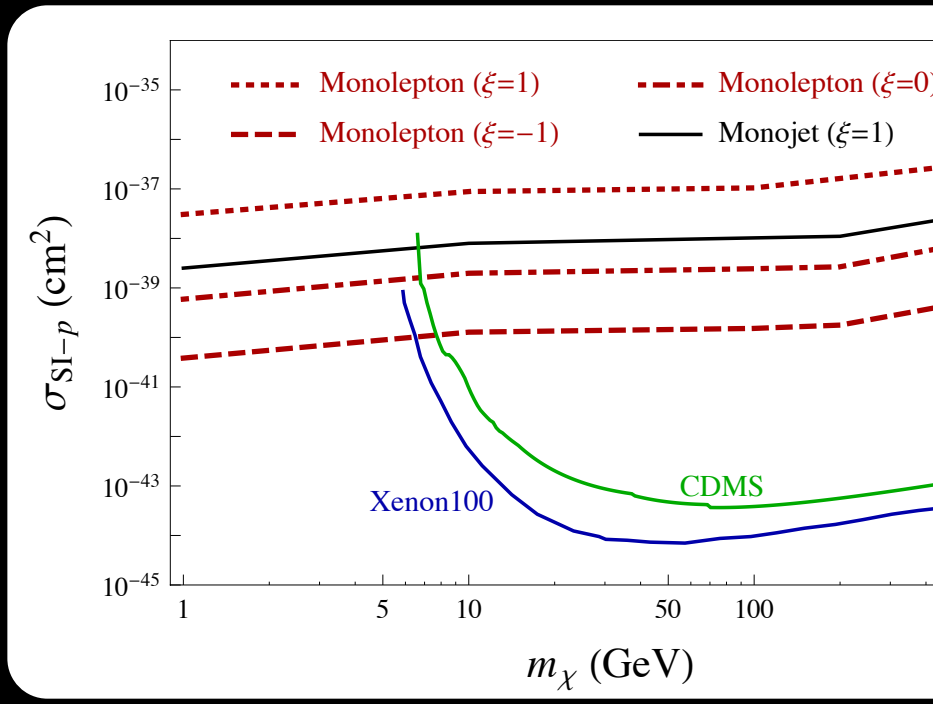
Mono-Whatever

- We can go beyond mono-jets and mono-photons.
- One can imagine similar searches involving other SM particles, such as mono-Ws (leptons), mono-Zs (dileptons), or even mono-Higgs.
- If we're just interested in the interactions of WIMPs with quarks and gluons, these processes are not going to add much.
- But they are also sensitive to interactions directly involving the bosons.
- And even for quarks, if we do see something, they can dissect the couplings to different quark flavors, etc.



CMS W' Search

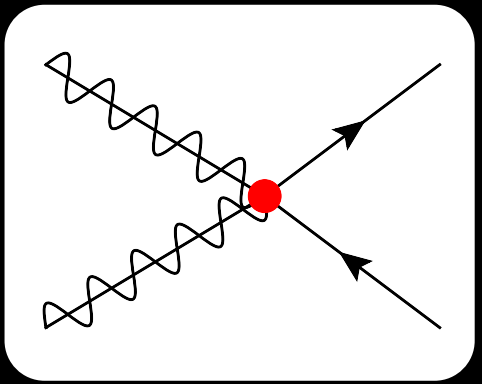
Y. Bai, TMPT, 1207.mono-whenever

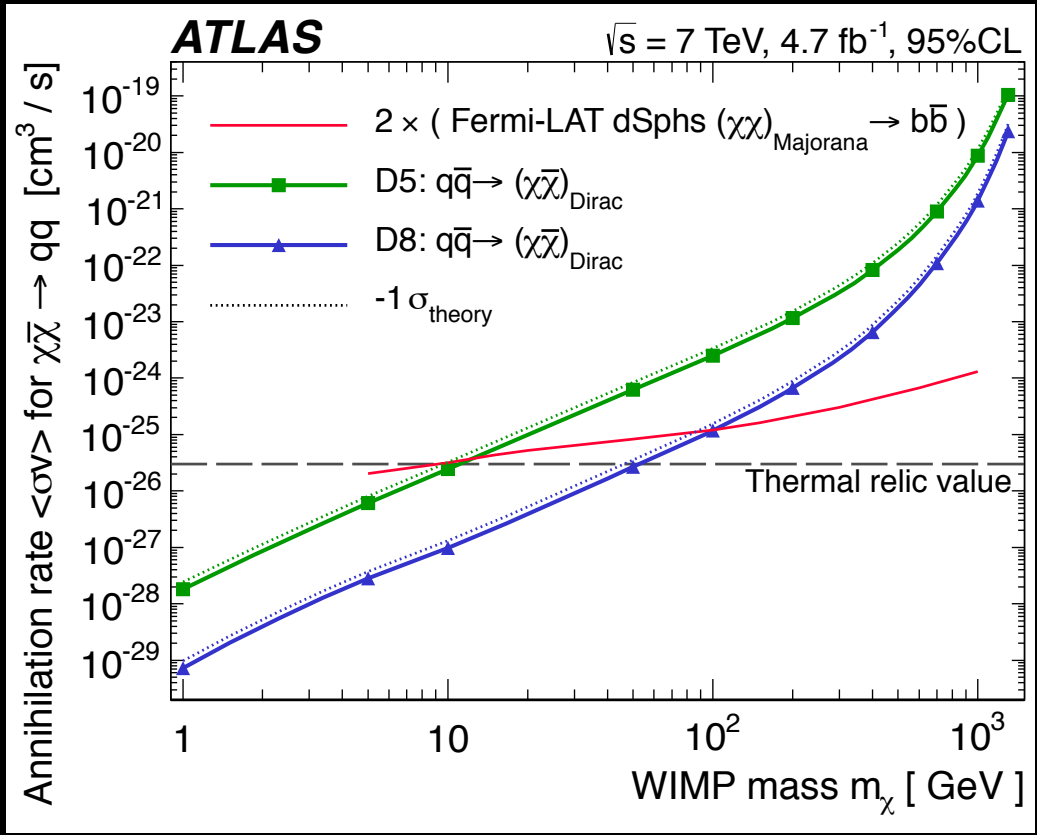


(d coupling) = ξ x (u coupling)

Annihilation into γ-Rays

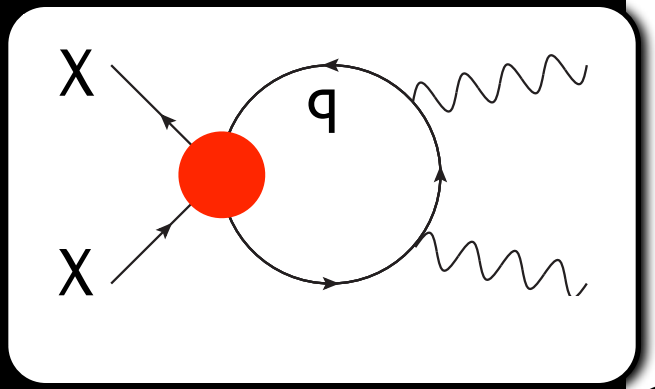
- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- ATLAS has already presented their results in terms of a corresponding annihilation cross section.
- With assumptions, this maps onto a thermal relic density.
- Colliders do better for lighter WIMPs or p-wave annihilations.
- Indirect detection is more sensitive to heavy WIMPs.





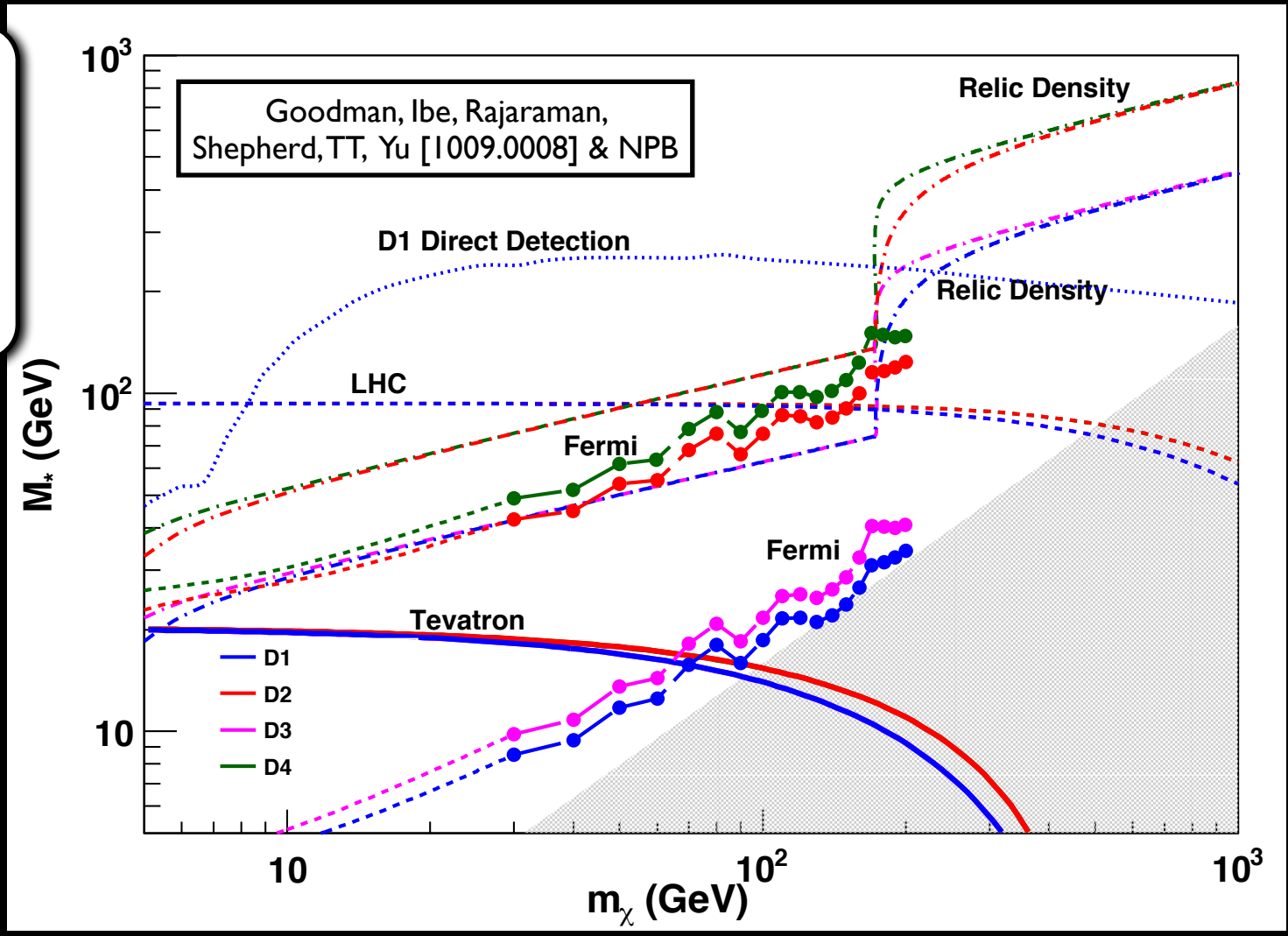
All Together

- One can also close the quark line into a loop prediction for gamma ray lines: a striking feature which may stand out from astrophysical backgrounds.



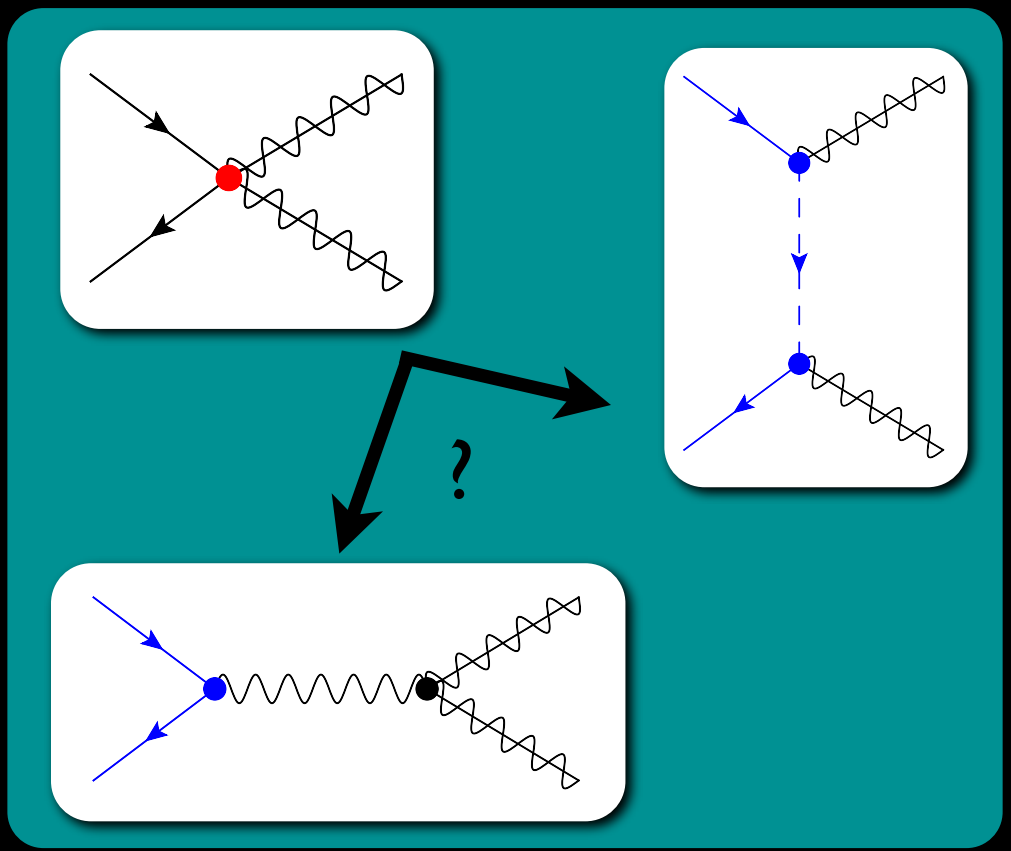
Scalar and pseudo-scalar interactions with quarks.

(Sorry: All of these limits are already out of date today, except for LHC which are 14 TeV, 100 fb^{-1} projections)

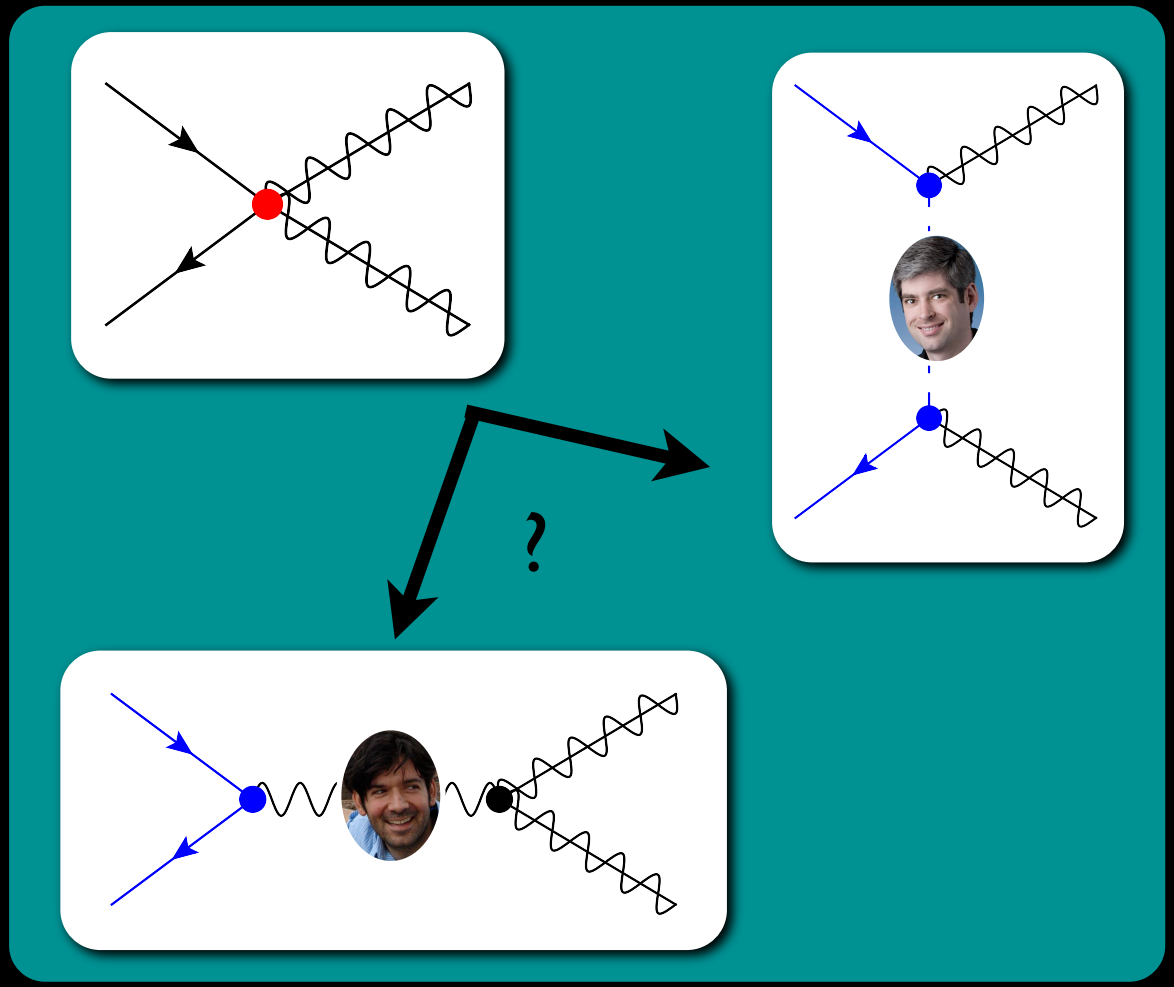


How Effective a Theory?

- How well does the contact interaction treatment work as an approximation to the complete theory?
- It depends on the momentum transfer of the process.
- Direct Detection: $Q^2 \sim (50\ \mathrm{MeV})^2$.
  - EFT should work well unless you have ultralight mediators.
- Annihilation: $Q^2 \sim M^2$.
  - Fine in many theories, problematic for light Z' type models, quirky WIMPs or co-annihilators.
- Colliders: $Q^2 \sim p_T^2$
  - Mono-jet bounds are generically too conservative for colored mediators.
  - Too stringent for light neutral mediators.



How Effective a Theory?



"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

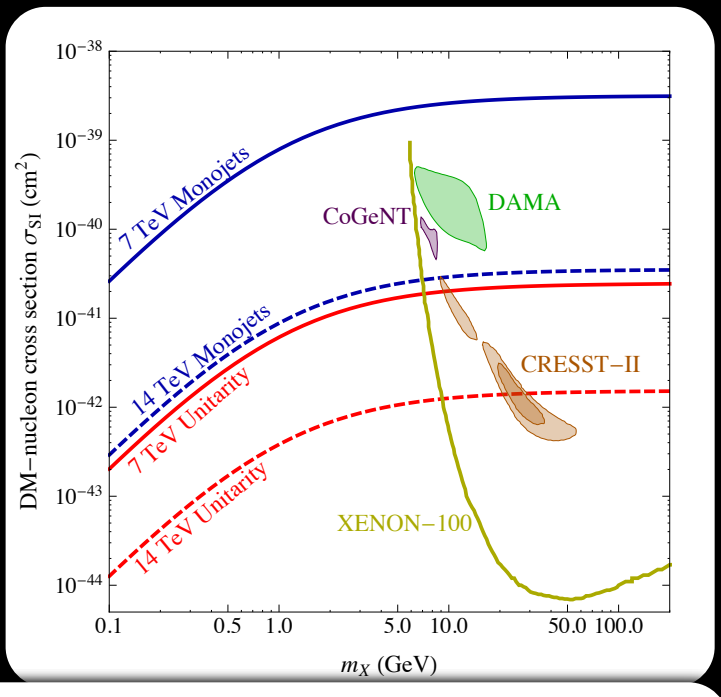
"s-channel" mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

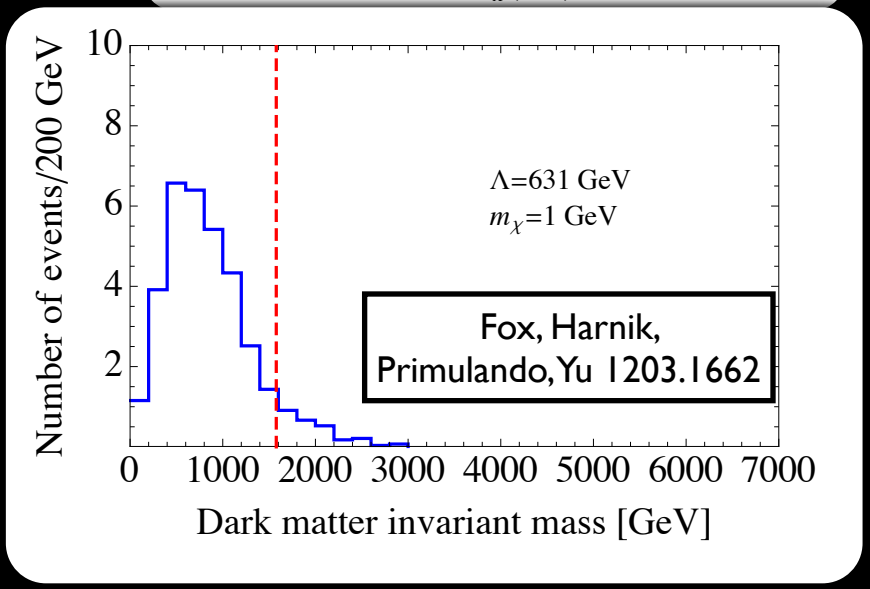
More details for vector mediators in: Frandsen, Kahlhoefer, Preston, Sarkar, Schmidt-Hoberg 1204.3839

"Bounds" from Unitarity

- Even if we don't want to worry about a UV theory and whether the EFT is a good approximation to it or not, we can still sometimes tell the EFT description is sick.
- There are regimes where the effective theory admits no perturbative UV completion.
- Non-renormalizable theories are intrinsically sick at high energies, leading to a break-down of perturbative unitarity. If this happens at energies we are interested in, our description at those energies is highly suspect.
  - Where this occurs at the LHC is not trivial to define.

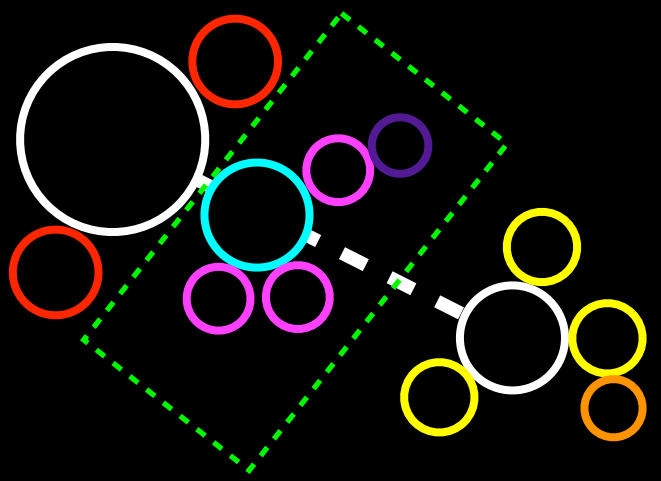
Shoemaker, Vecchi 1112.5457

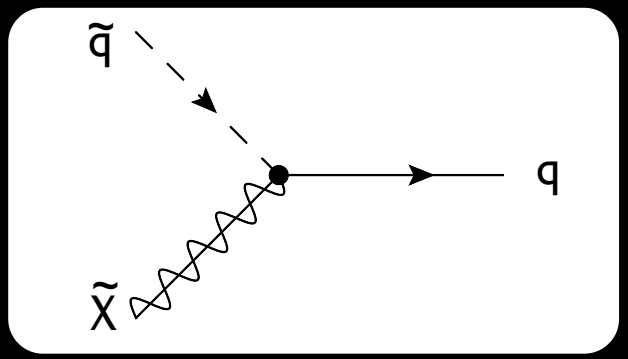




From Contact Interactions to Simplified Models

- Since LHC energies can call into question the contact interaction approximation, we can expand our level of detail toward simplified models.
- For example, a singlet fermion WIMP interacting with quarks can be resolved into a model with the WIMP and a color triplet scalar.
- SU(2)xU(1) charges of the scalar are dictated by EW gauge invariance (subsets of squarks of the MSSM): ``$\widetilde{u}_R$'', ``$\widetilde{d}_R$'', ``$\widetilde{Q}_L$''.
- Minimal Flavor Violation suggests we consider triplets in family space with equal masses and couplings.

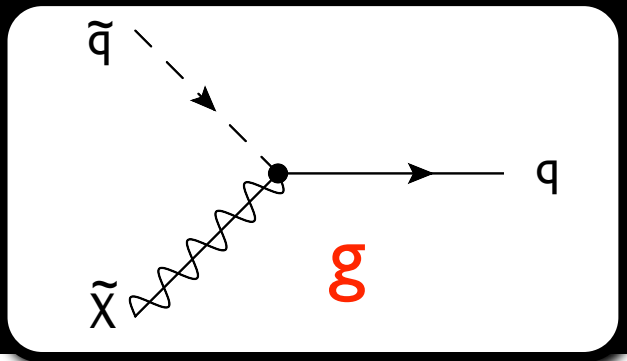


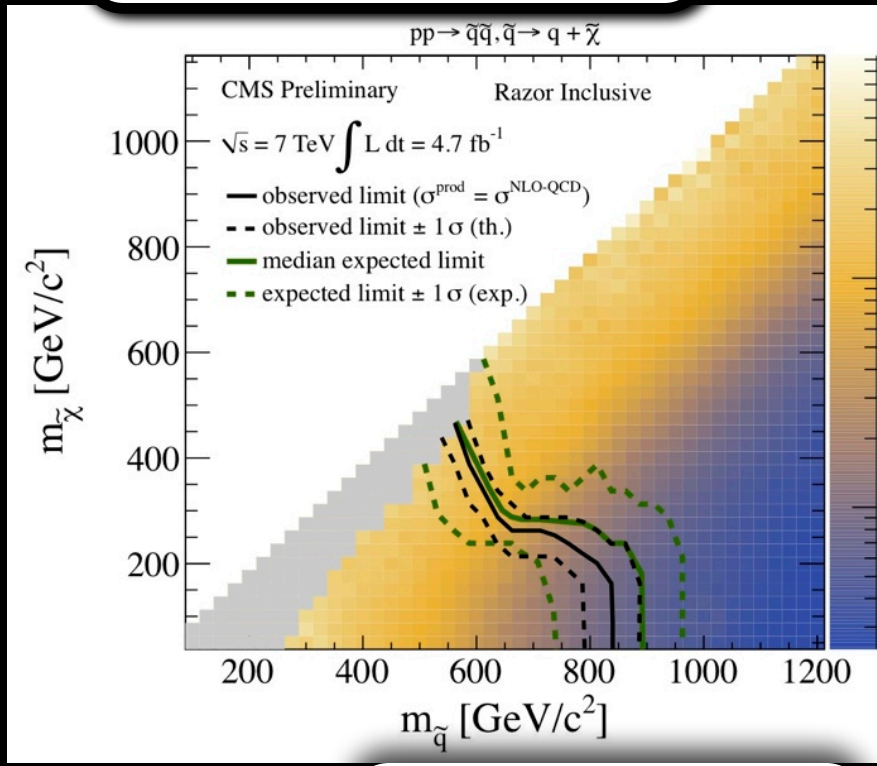


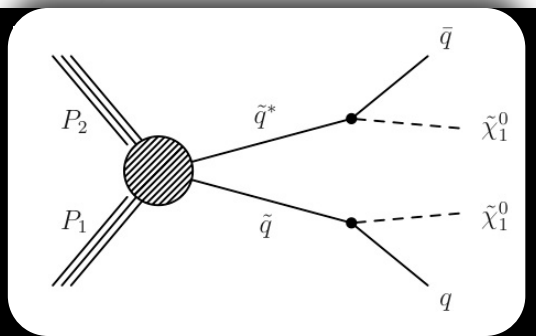
Of course, we can also consider a wider variety of WIMP properties and get away from MSSM-like theories.

Simple-fied Model

- This is a simplified model we already use to interpret MSSM searches at the LHC.
- The current version has 3 parameters: m_{χ}, mq, and the LHC production cross section.
- To make this useful to connect to (in)direct searches we should trade these for: m_{χ}, $m_{\tilde{q}}$, and g.
- Collider P\production can be computed in terms of these quantities. There are interesting differences between, e.g. Majorana and Dirac WIMPs.
- We can map them into the direct/indirect parameter spaces.
- We can also find the bounds from direct/ indirect searches and map them back!





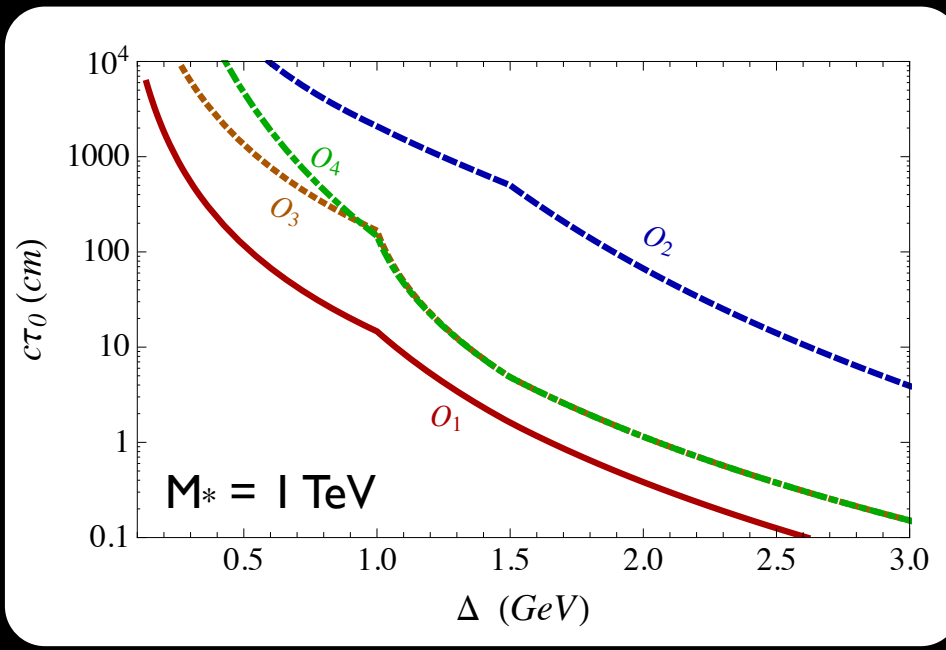


Dark Siblings

- We can also expand the dark sector to include theories like, say, iDM.
  - We can explore a wider parameter space, collider signals, etc...
- For example, spin-dependent interactions can lead to the excited WIMP dominantly decaying into a single π^0 and a WIMP.
- LHC can produce $\chi\chi^*$
- Depending on the mass splitting Δ and the size of the interaction, the excited WIMP may decay inside or outside of an LHC detector.
- Monojet signals can be dressed up with displaced π^0's or mini-jets!

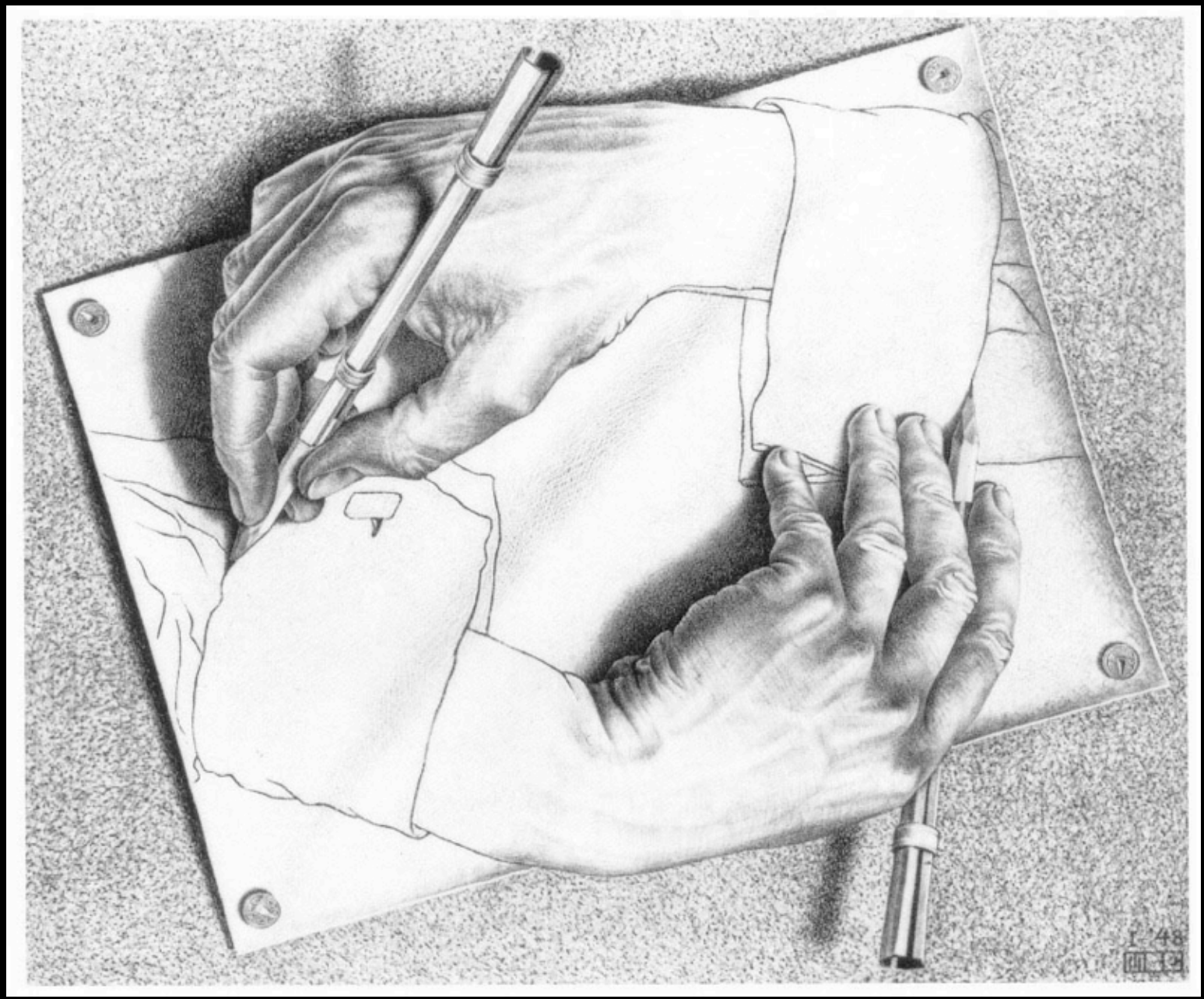
$$\frac{1}{M_*^2}\left[\bar{\chi}_*\gamma^\mu\gamma_5\chi\right]\left[\bar{u}\gamma^\mu\gamma_5 u\right]$$

$$\rightarrow \frac{f_\pi}{M_*^2}\left[\bar{\chi}_*\gamma^\mu\gamma_5\chi\right]\partial_\mu\pi^0$$

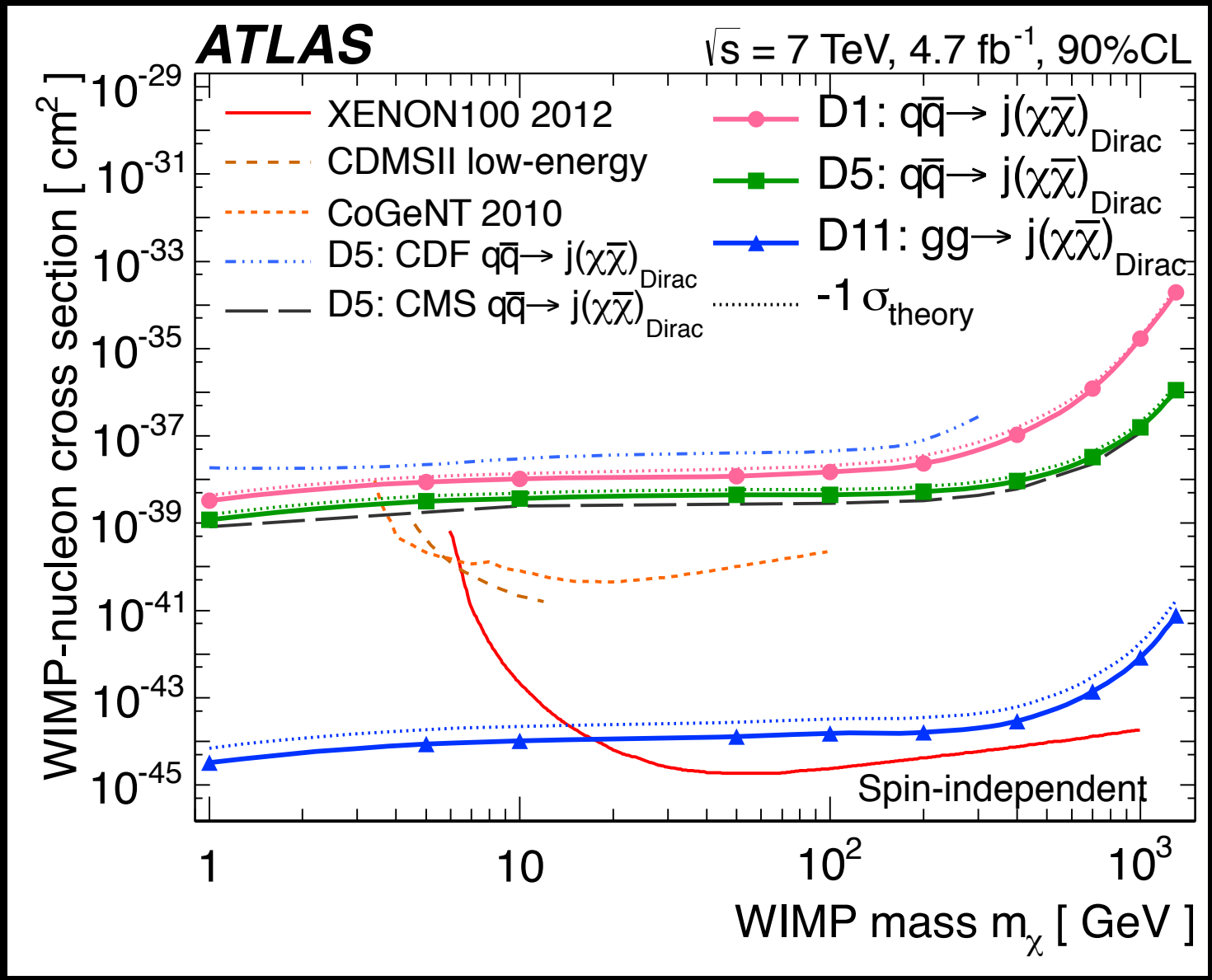


Y. Bai, TMPT PLB & 1109.4144

From Sketch to Life

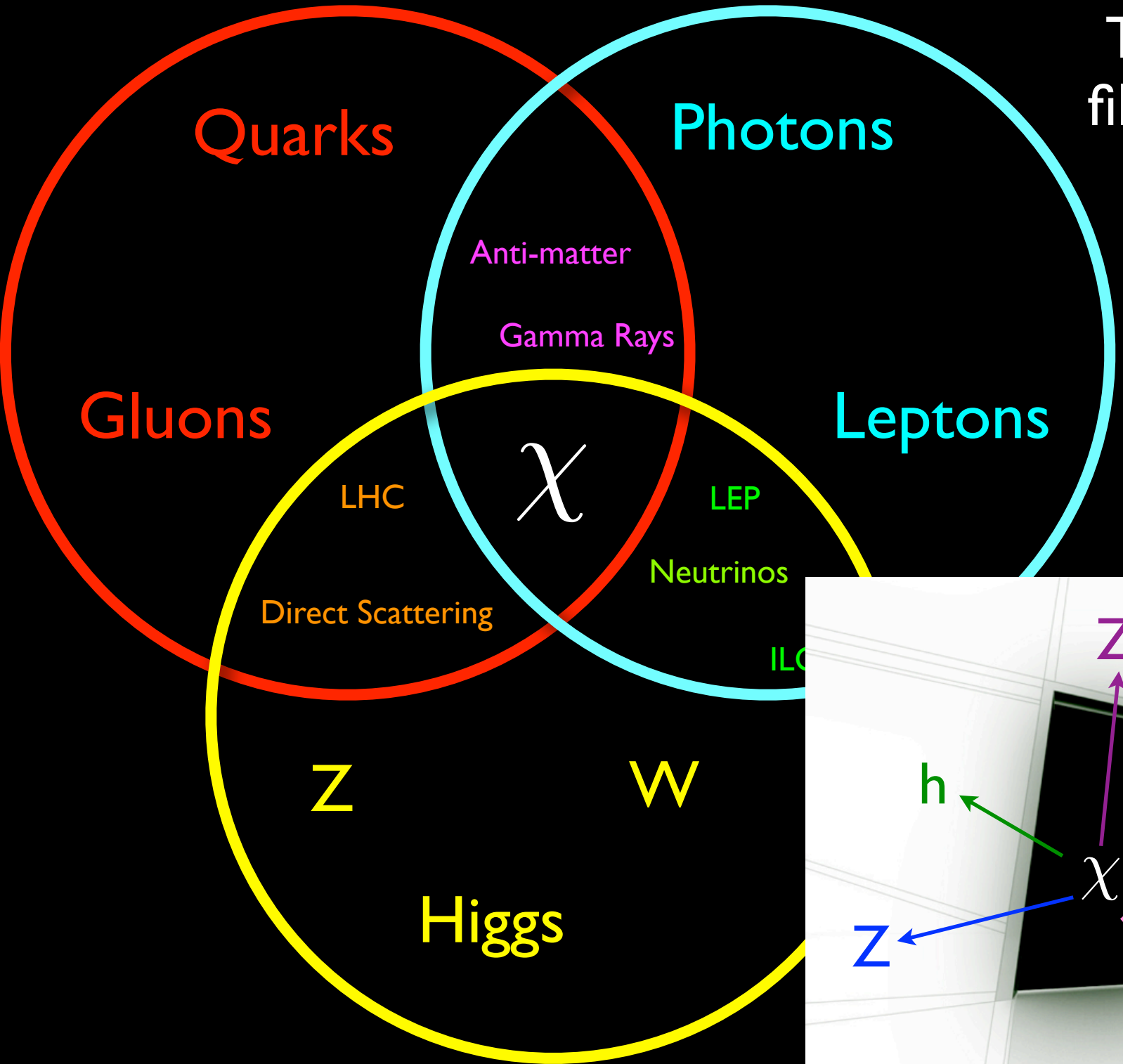


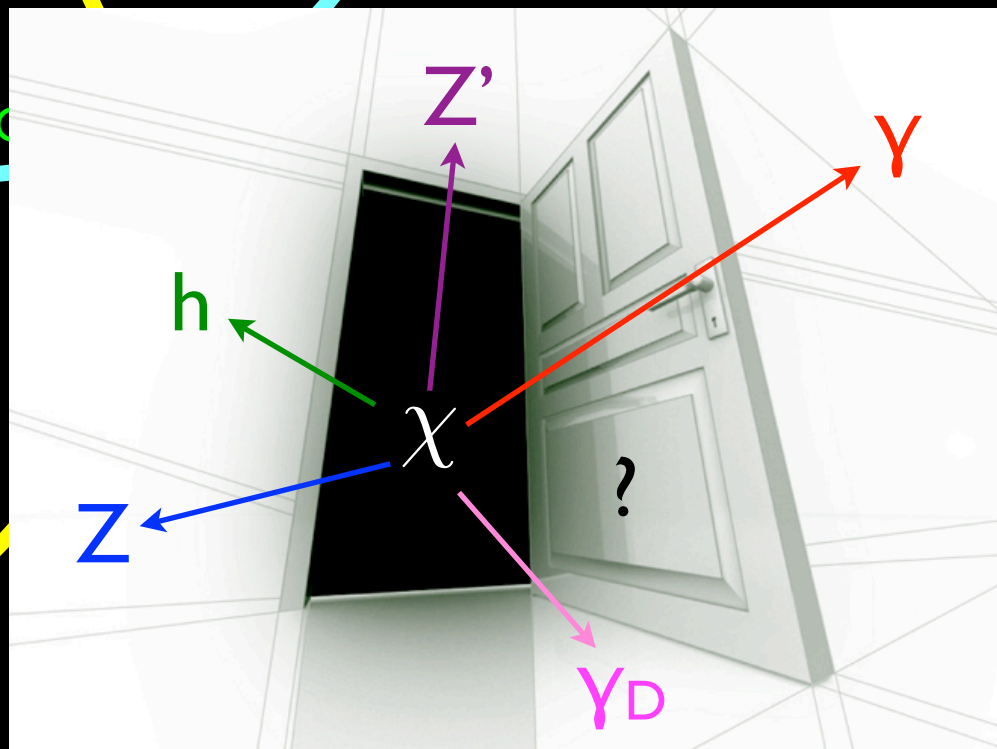
This Plot is Not the Point



(But it is interesting, and a good way to compare how to different categories of searches are doing with respect to a certain class of interaction types.)

The point is to fill in the puzzle!

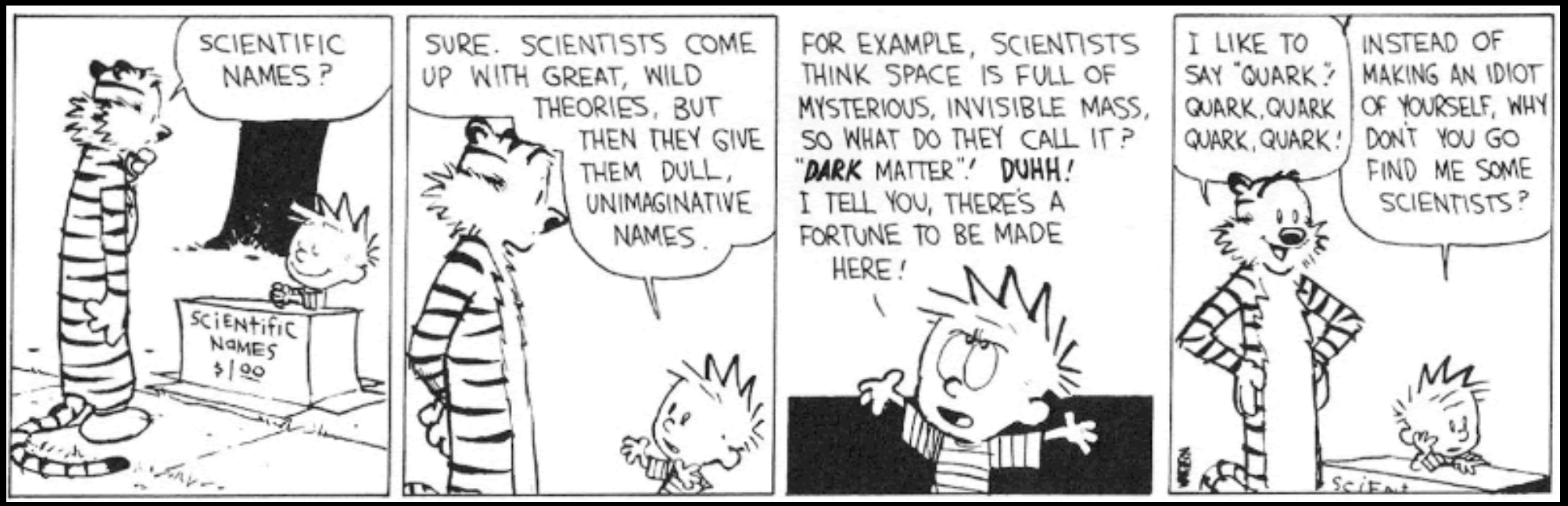




Outlook

- The three pillars of dark searches have a lot of interplay and probe complementary parts of theory space.
  - We can already see signs of that fact in wide angle views of very specific, UV-complete models, such as the MSSM.
- Before we have a full-fledged theory of dark matter, we may find it useful to start with a sketch.
- A sketch can be minimal and simple like the theory of contact interactions, or it may contain more states in the dark sector with richer phenomenology.
- Whatever the search or the signal of interest, we can construct our sketches and explore where they lead us.
- Ultimately, the goal is to flesh out the sketches into a full theory of dark matter.
- So who brought the crayons...?

Sketches of ....

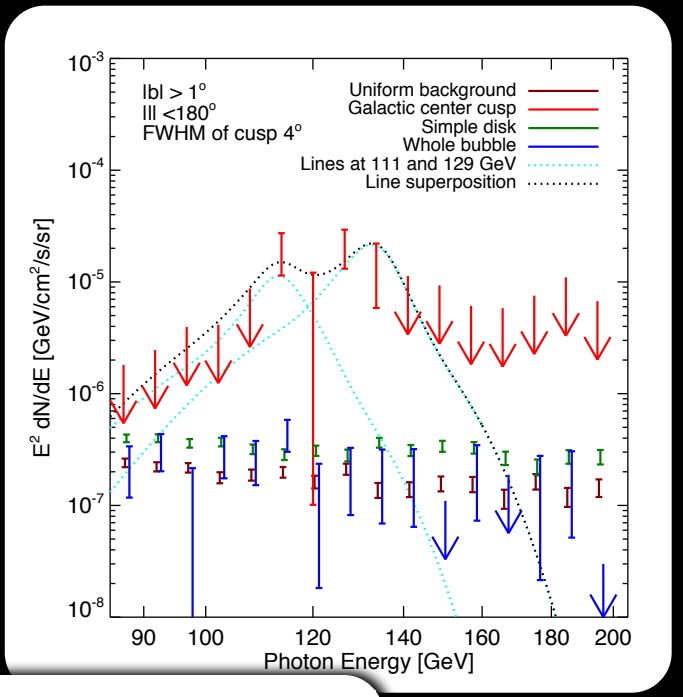


...submit your dark papers here!
(Open Access Journal, NO AUTHOR FEES)

Bonus Material

EFTs for Lines

Finkbeiner, Su 1206.1616

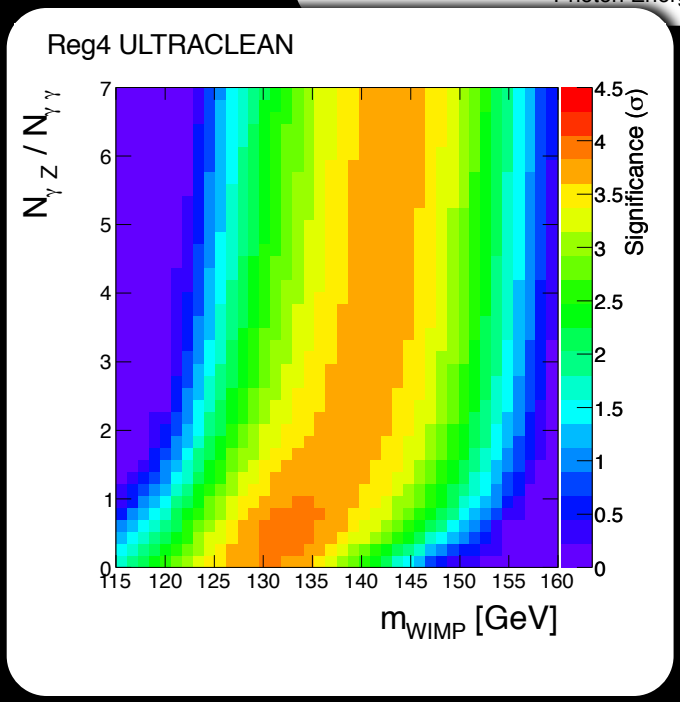


- We can play the same games with effective interactions leading *directly* to gamma ray lines.
- The operators consistent with gauge and Lorentz invariance reveal an interesting feature -- every likely operator leads to at least two lines, γγ+γZ or γZ+γh.

Rajaraman, TMPT, Whiteson 1205.4723

- This is not shocking, but it does suggest a new feature to look for in line searches: two lines at correlated energies!

$$\chi\chi \to \gamma Y \quad : E_\gamma = m_\chi \left(1 - \frac{M_Y^2}{4m_\chi^2}\right)$$



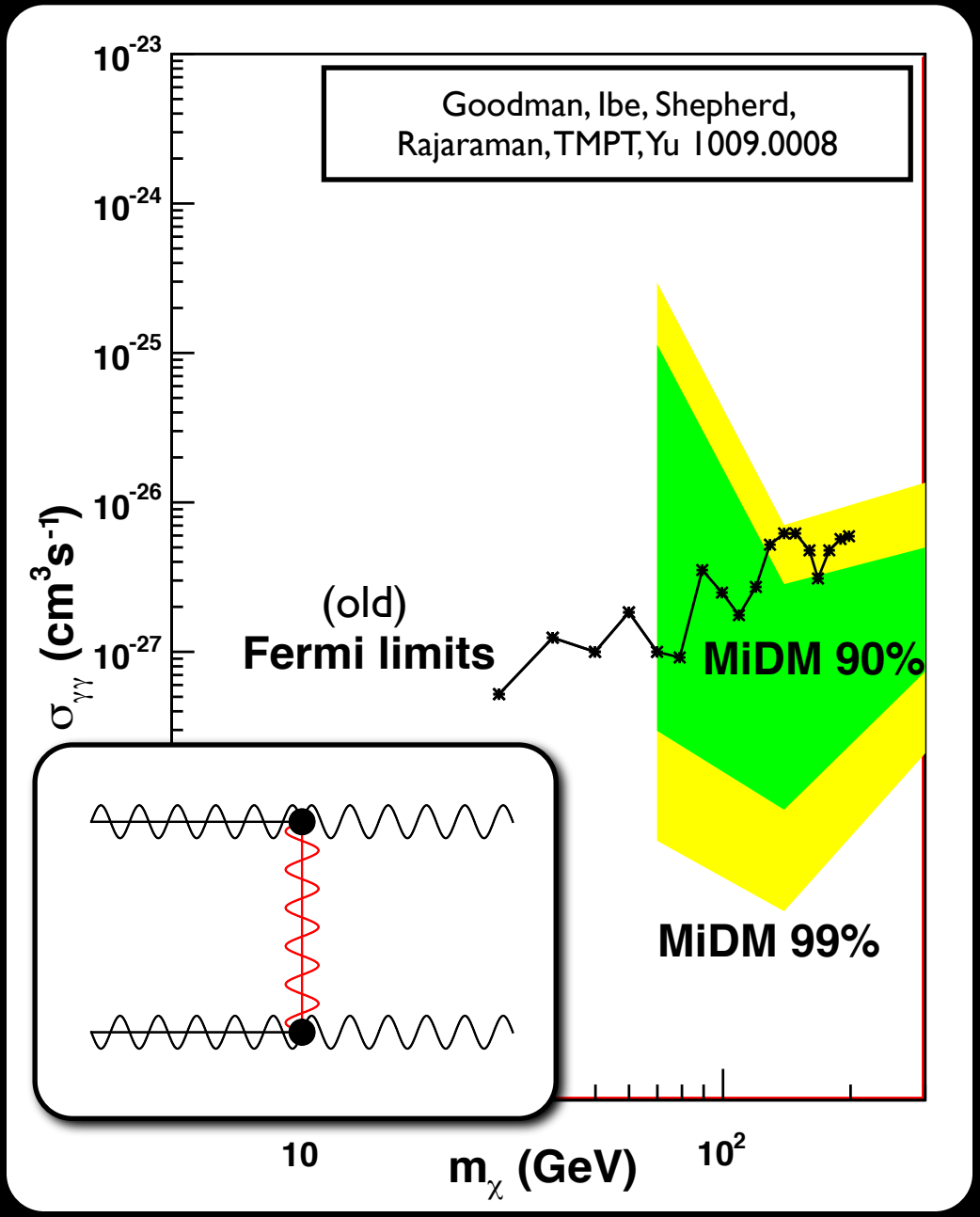
MiDM

- We can consider an inelastically scattering WIMP whose main interaction is through the photon portal.
- These models were proposed to reconcile DAMA with null results from other experiments.

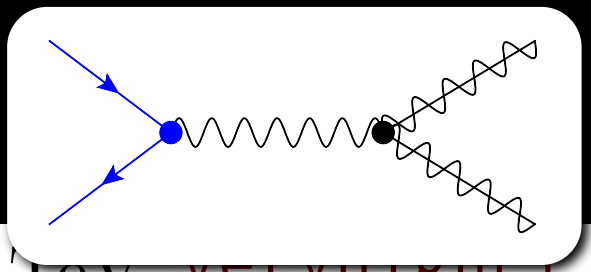
S. Chang, N. Weiner, I. Yavin
PRD & 1107.4200

- Amazingly enough, they also seem to work for similar parameters to explain the ~130 GeV feature in the Fermi gamma rays.

N. Weiner, I. Yavin 1206.2910



Filling in Some Details

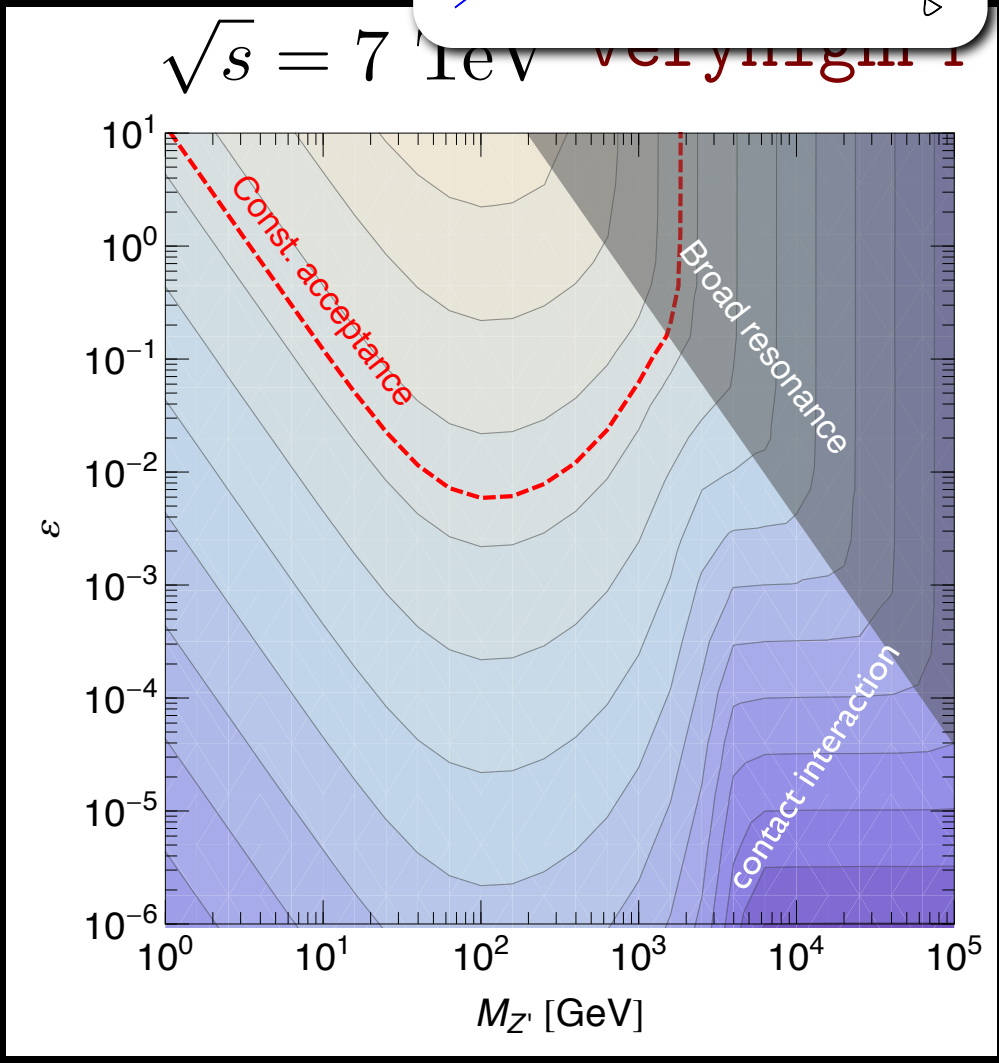


- We can consider a wider range of simplified models with the mediating particles included explicitly.
- There is already some work in this direction on the case of a Z'-mediator completion.

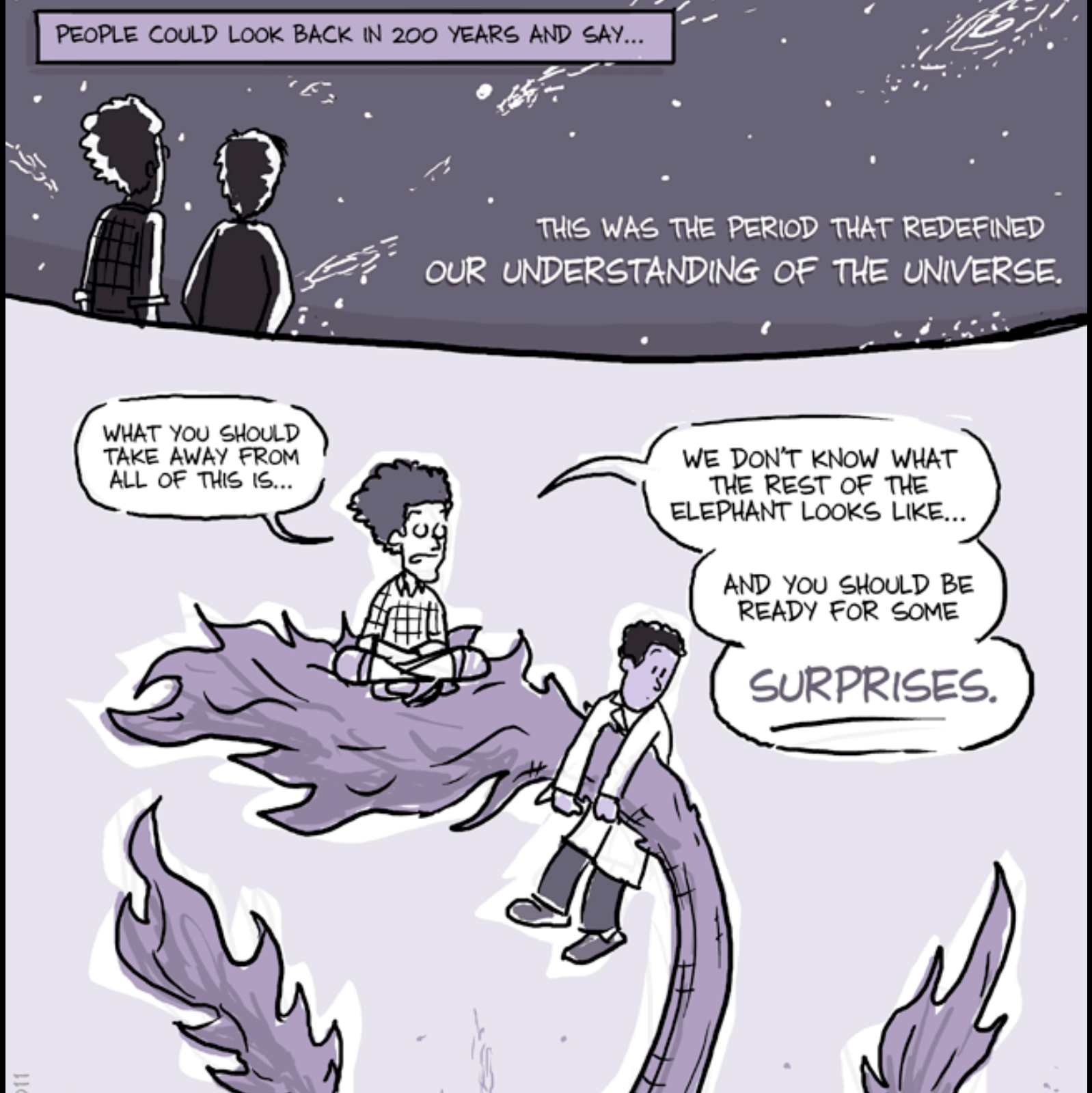
Frandsen, Kahlhoefer, Preston, Sarkar, Schmidt-Hoberg 1204.3839

- For a given collider energy, we can see the different regimes of Z' mass and coupling.

$$\epsilon = g^2 / M_{Z'}^2$$

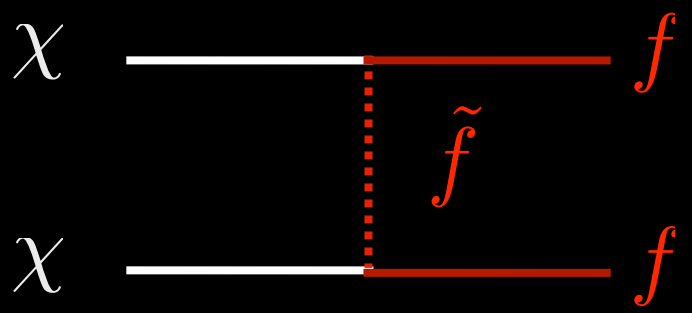


Ian Shoemaker, talk at UC Davis 4/13/2012

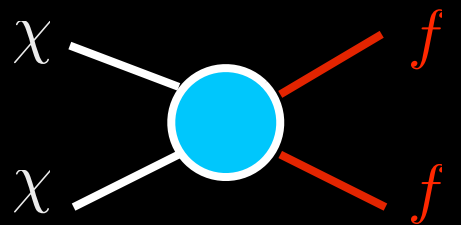

PEOPLE COULD LOOK BACK IN 200 YEARS AND SAY...
THIS WAS THE PERIOD THAT REDEFINED OUR UNDERSTANDING OF THE UNIVERSE.
WHAT YOU SHOULD TAKE AWAY FROM ALL OF THIS IS...
WE DON'T KNOW WHAT THE REST OF THE ELEPHANT LOOKS LIKE...
AND YOU SHOULD BE READY FOR SOME
SURPRISES.

EFT Cartoon

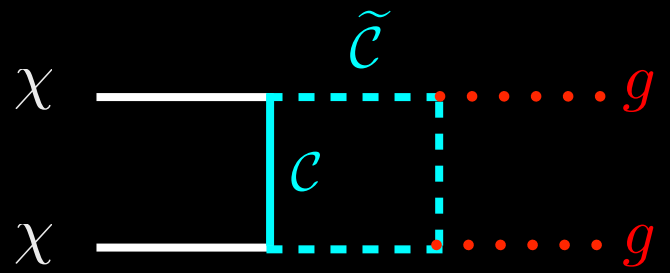
- Here are some cartoons for how a SUSY-like Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



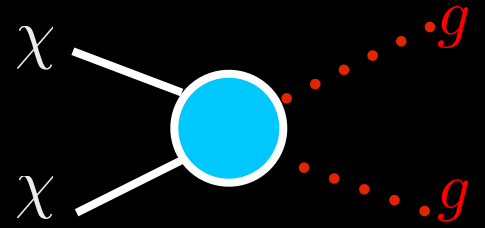
$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$



  - Gluons:

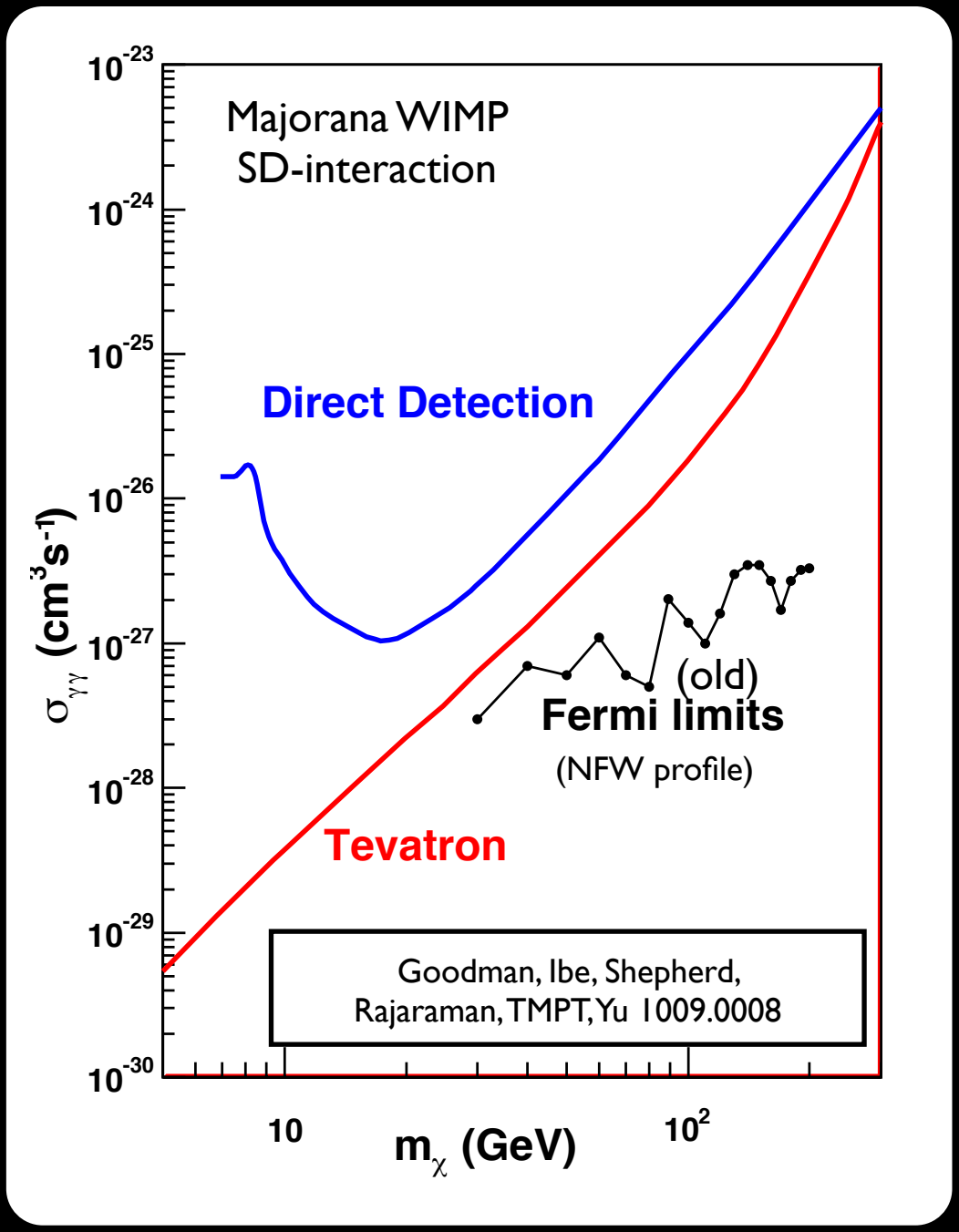


$$\sim \frac{\alpha_S}{4\pi} \frac{g^2}{M_c M_{\tilde{c}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



  - Each requires new states with masses heavier than the WIMP.

Bounds from Lines



Neal Weiner
5 hours ago near Denver, CO ·

Aspen bound! (Weather permitting)

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You, Daniel Whiteson, Kevork Abazajian, Mark Jackson and 4 others like this.

Tim Tait Weather didn't permit me... good luck!
4 hours ago · Edited · Like

Thomas G Rizzo What happened Tim? I was almost trapped there by low pressure..
3 hours ago · Like

Neal Weiner Tim – are you coming tomorrow?
about an hour ago via mobile · Like

Tim Tait Yeah, all the flights after 8 AM from LAX or SFO were cancelled, but I'm rebooked through DEN tomorrow. If all goes well, I'll land around noon. Fingers crossed!
about an hour ago via mobile · Like

Jennifer Siegal-Gaskins Yeah, I was also forbidden by the (Aspen) weather... trying again tomorrow AM, direct. Good luck Tim!
57 minutes ago · Like

Neal Weiner Tim if you don't show, I'm totally going to give your talk "Complimenting searches for dark matter": Jeter – nice suit! Rafael – great plots! Pierluigi – loved your rendition of the aria from "La Traviata"! Simona – loved the paper on the bubbles that the fermi collaboration recently published... Err.
33 minutes ago via mobile · Unlike · 2

Write a comment...