# Working Group B: Plans and Ideas

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Snowmass @ SLAC
March 6 2013

# Working Group B:

# ~~Plans and Ideas~~

# Random Thoughts

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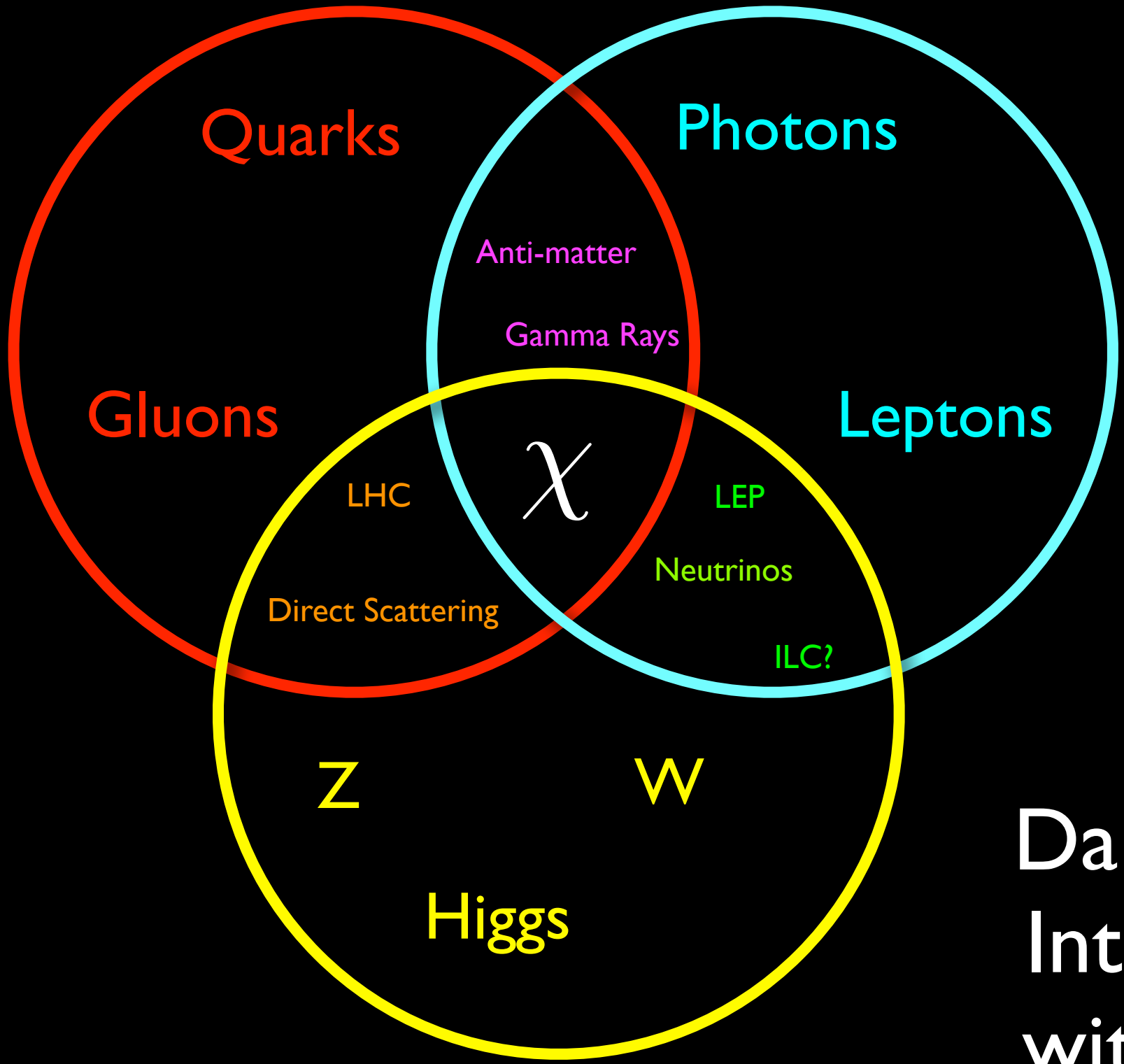
# Working Group B: Charges

- Craft a vision for the suite of future dark matter search experiments needed, which cover the parameter space described by our benchmark models.
- Review the impact of direct searches for dark matter on our knowledge of the generic properties of dark matter.




# Dark Matter Interactions with the SM

# Dirac WIMP

In the limit of heavy particles mediating the interaction between DM and quarks or gluons, there are 14 leading Lorentz structures.

| 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 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
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| 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 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu
PRD 82, 116010 (2010) [1008.1783]

# Dirac WIMP

Spin Independent

| 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 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$ | $i/M_*^2$ |
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| 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 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

# Dirac WIMP

Spin Independent

Spin Dependent

| 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 | $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | $1/M_*^2$ |
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| D12 | $\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
| D13 | $\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
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| D16 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

# Dirac WIMP

Spin Independent

Spin Dependent

Momentum-dependent

| 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 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$ | $1/M_*^2$ |
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| D15 | $\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$ | $M$ |
| D16 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

# Dirac WIMP

Spin Independent

Spin Dependent

Momentum-dependent

E/M Dipole

| 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 | $\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
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| 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 | $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$ | $1/M_*^2$ |
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| 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 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

# Dirac WIMP

Spin Independent

Well Understood

Spin Dependent

Momentum-dependent

Need Work!

E/M Dipole

| 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 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
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# Dirac WIMP

All direct detection experiments are sensitive to finite momentum transfer. They can say something about these interactions, even if they are suppressed at low velocity. What are they telling us about them?

It's not clear which experiments are providing the best limits on these types of interactions.

| 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 | $\bar{\chi}\chi\bar{q}\gamma^5 q$ | $im_q/M_*^3$ |
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| D6 | $\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$ | $1/M_*^2$ |
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| D13 | $\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$ | $i\alpha_s/4M_*^3$ |
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| D15 | $\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$ | $M$ |
| D16 | $\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$ | $D$ |

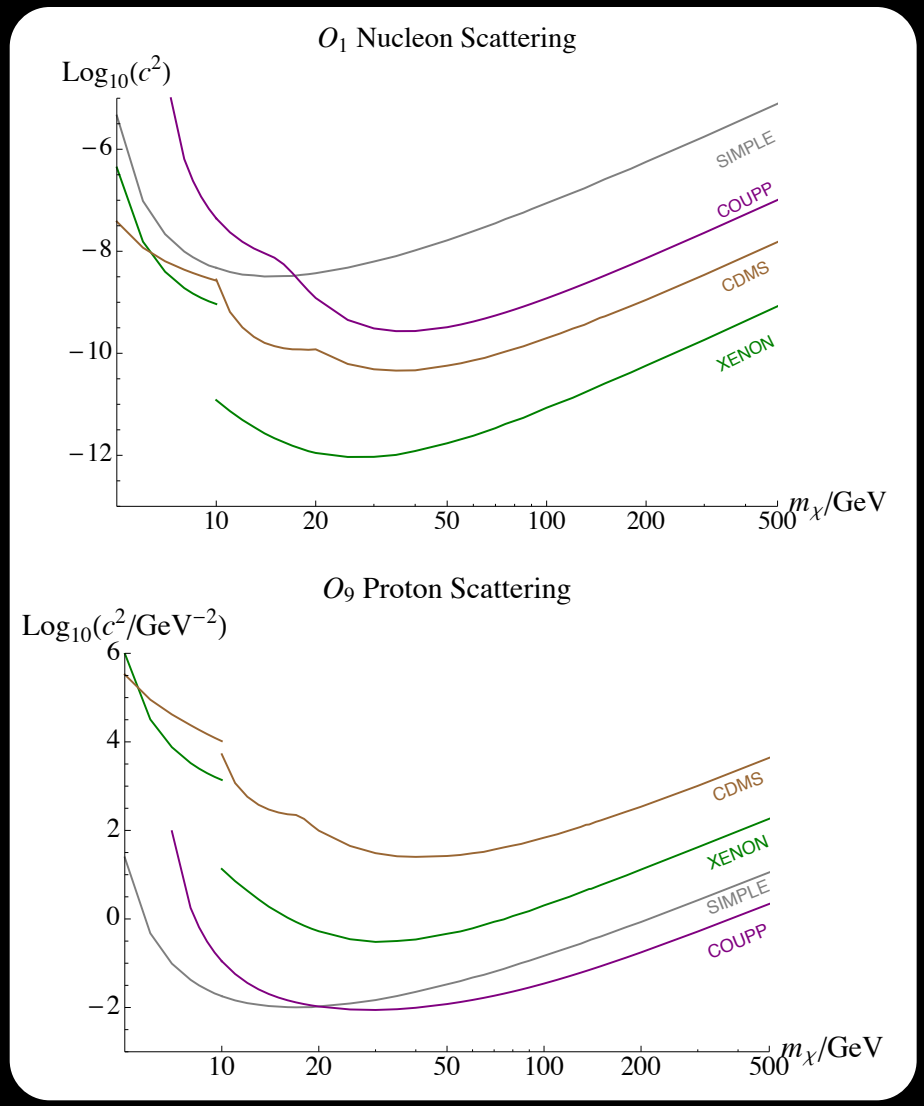
Momentum-dependent

Need Work!

E/M Dipole

# Nuclear Response

- There are five different nuclear responses to low energy scattering with dark matter.
- (The usual SI is one and SD is a linear combination of two others).
- Different target materials are sensitive to different combinations of the various response types.
- A large part of understanding those momentum-suppressed interactions on the previous slides would be captured by understanding how they map onto the response functions and how existing and future experiments map them out.

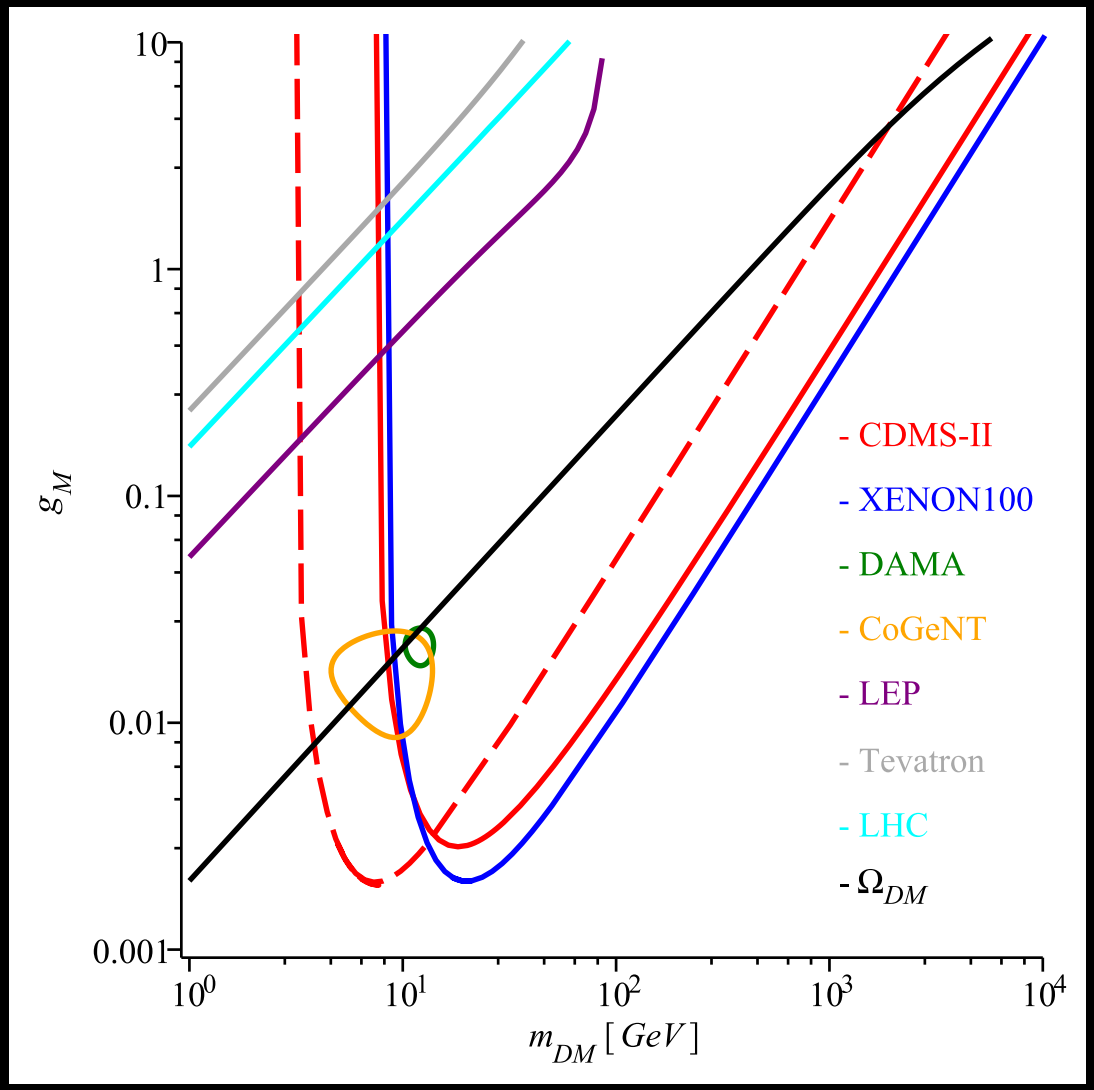



Fitzpatrick, Haxton, Katz, Lubbers, Xu
JCAP 302, 4 (2013 [1203.3542]
& [1211.2818]

# Dipole Interactions

Dipole interactions are very challenging at colliders, but are effectively probed by direct searches.

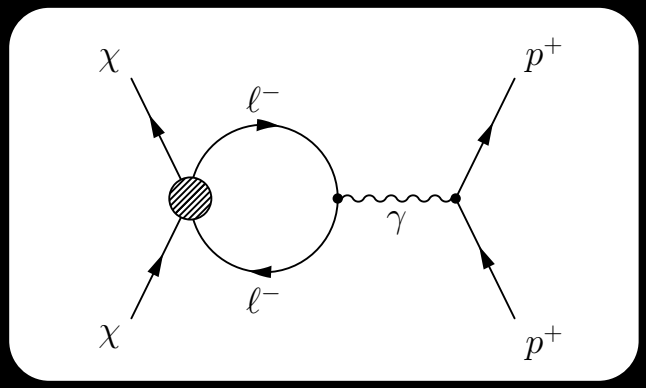
JF Fortin, TMPT
PRD85, 063506 (2012)
[arXiv:1103.3289]

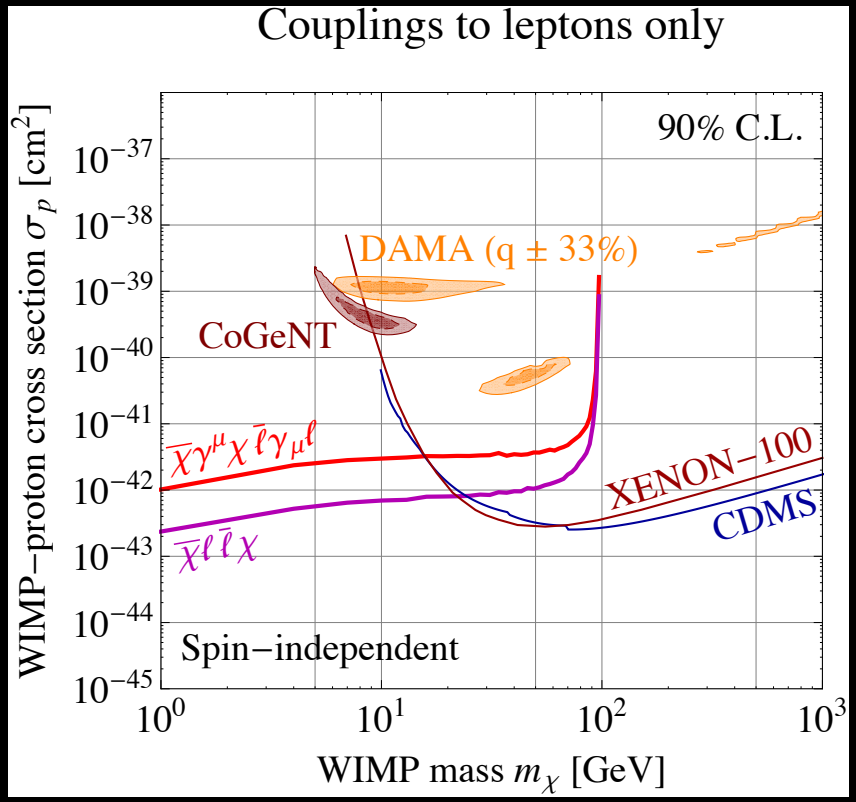



Magnetic Dipole (D15)

# Lepton Interactions?

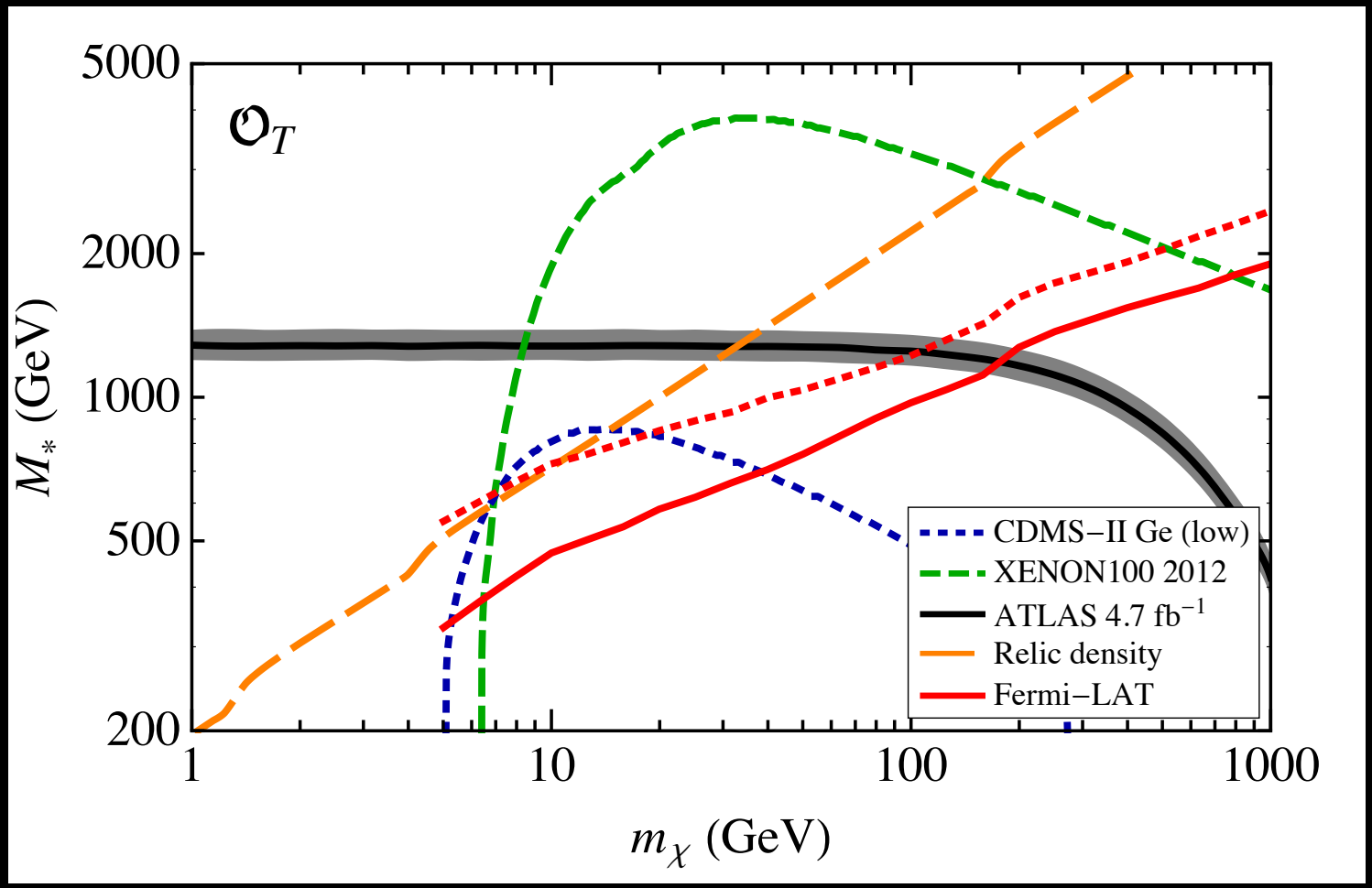
- Lepton interactions are difficult for direct detection, because the electron wave functions are too diffuse at the characteristic momentum scale.
  - But there are interesting things to be said! See Peter Graham's talk from this morning!
- There are also connections between lepton couplings and the E/M dipole interactions.
  - Direct detection can be better than LEP for some masses!

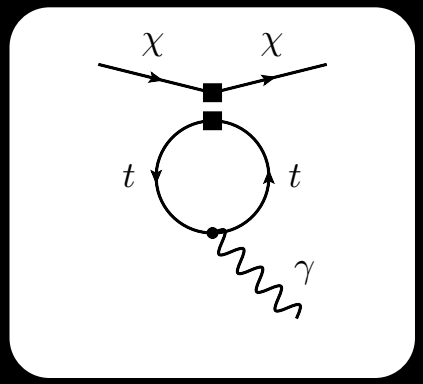



Fox, Harnik, Kopp, Tsai
PRD 84, 014028 (2011)
[1103.0240]

# More Interrelations...




Haisch, Kahlhoefer [1302.4454]

Some of the quark interactions such as D9 feed into SI interaction types and get stronger bounds from DD than one would naively have guessed.

These also improve our predictions for signals (see Richard Hill's talk from this morning).

# There's lots of work to do!

- A very positive step toward answering parts of the charges would be to flesh out these ideas and more.
- Let me emphasize the "more". These are random ideas for directions I am writing down... there are a lot more to discuss!
- Please send an email to me (ttait@uci.edu) with ideas for contributions. I'll try to put like-minded people together and coordinate.
- We'll start having semi-regular meetings to discuss.


PEOPLE COULD LOOK BACK IN 200 YEARS AND SAY...

THIS WAS THE PERIOD THAT REDEFINED OUR UNDERSTANDING OF THE UNIVERSE.

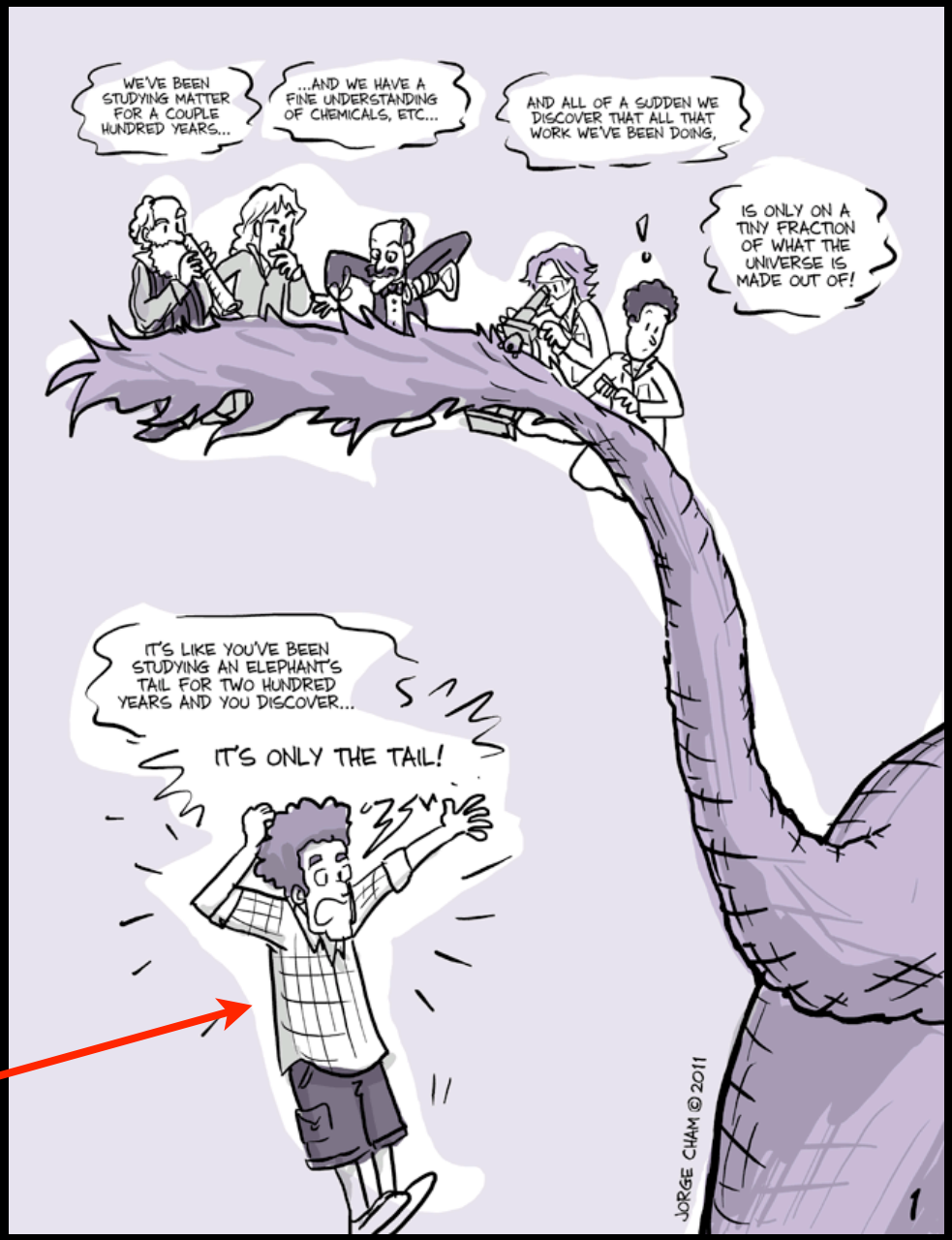
WHAT YOU SHOULD TAKE AWAY FROM ALL OF THIS IS...

WE DON'T KNOW WHAT THE REST OF THE ELEPHANT LOOKS LIKE...

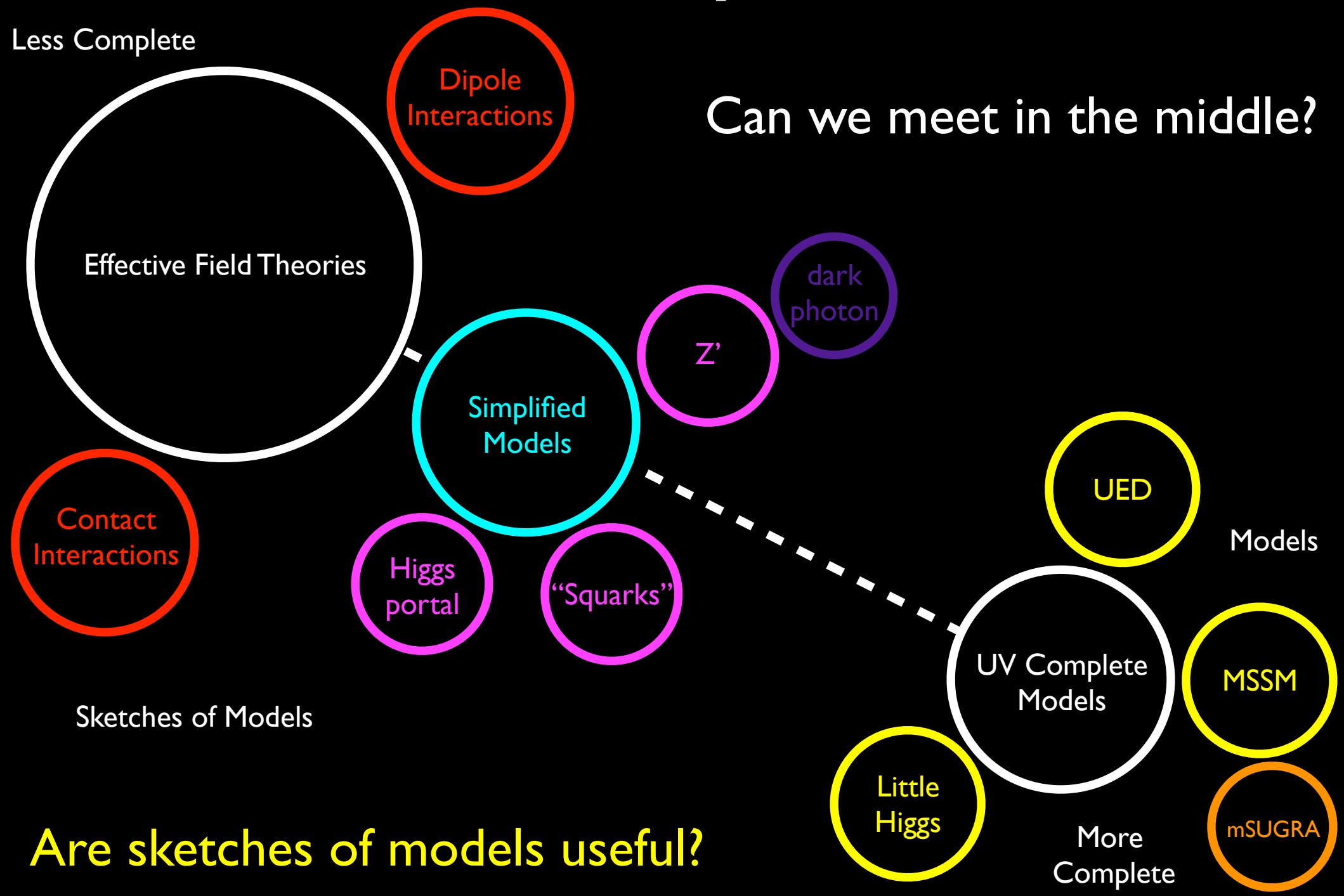
AND YOU SHOULD BE READY FOR SOME SURPRISES.

# Bonus Material

# Sketches Can Be Useful...

# How about Simpler Theories?

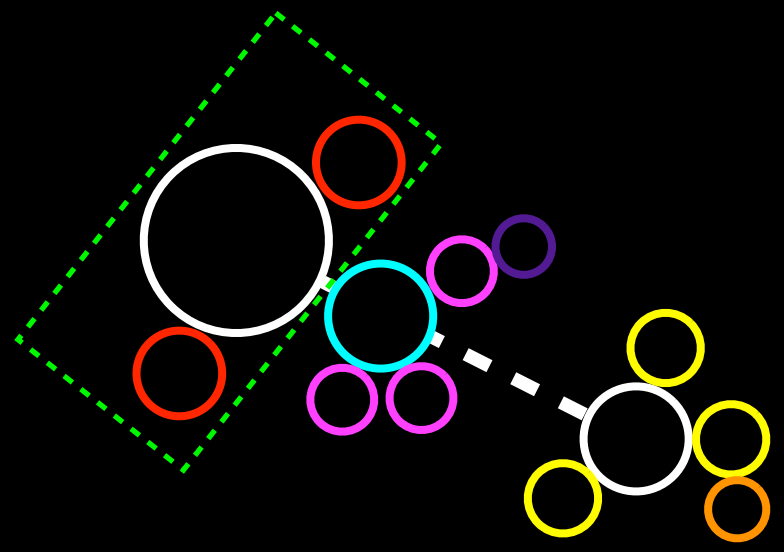


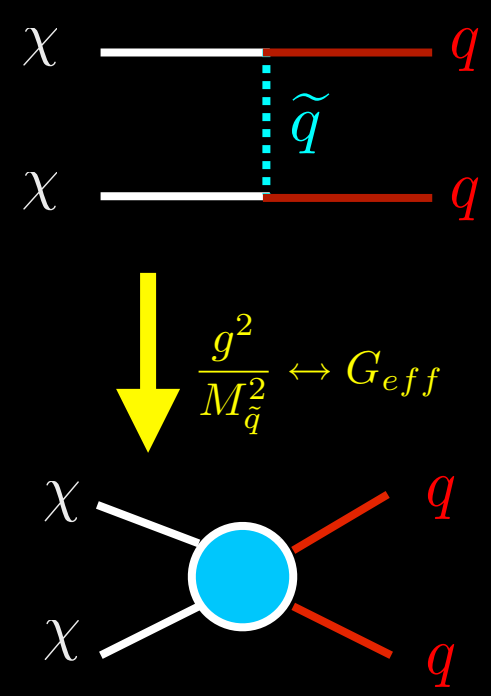

Can we meet in the middle?

Are sketches of models 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 $\alpha_S$, 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 | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | $1$ | $1$ |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | $1$ |
| M3 | $qq$ | $im_q/2M_*^3$ | $1$ | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

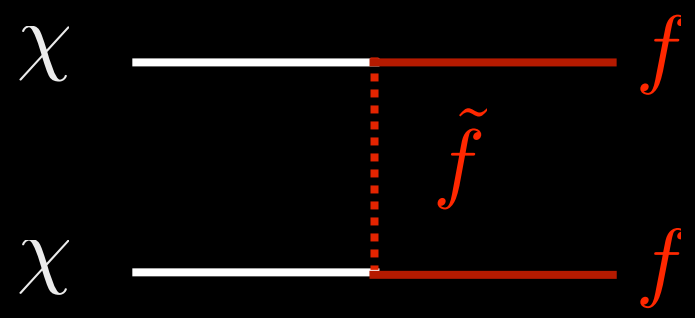
$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

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

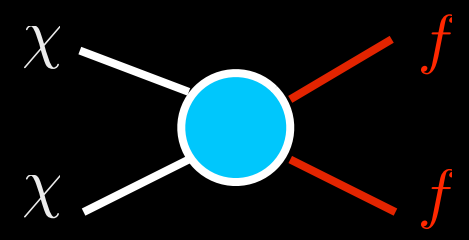
Other operators may be rewritten in this form by using Fierz transformations.

# EFT Cartoon

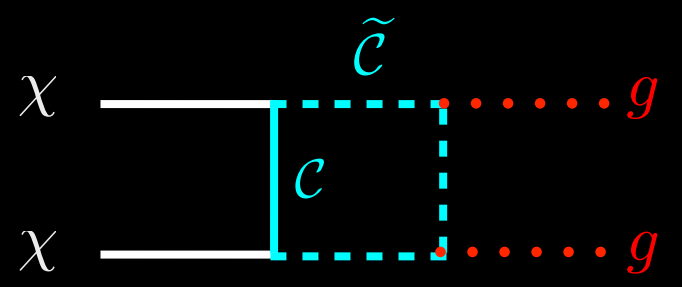
- Here are some cartoons for how a SUSY-like Majorana WIMP can pick up couplings to quarks and/or gluons.
  - Quarks:



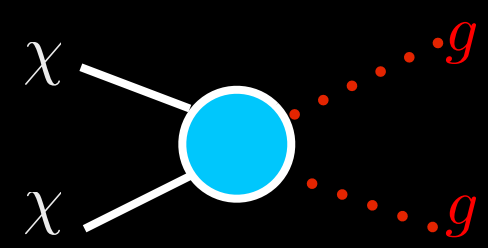

$$\sim \frac{g^2}{M_{\tilde{f}}^2} \leftrightarrow \frac{1}{\Lambda_f^2} =$$




  - Gluons:

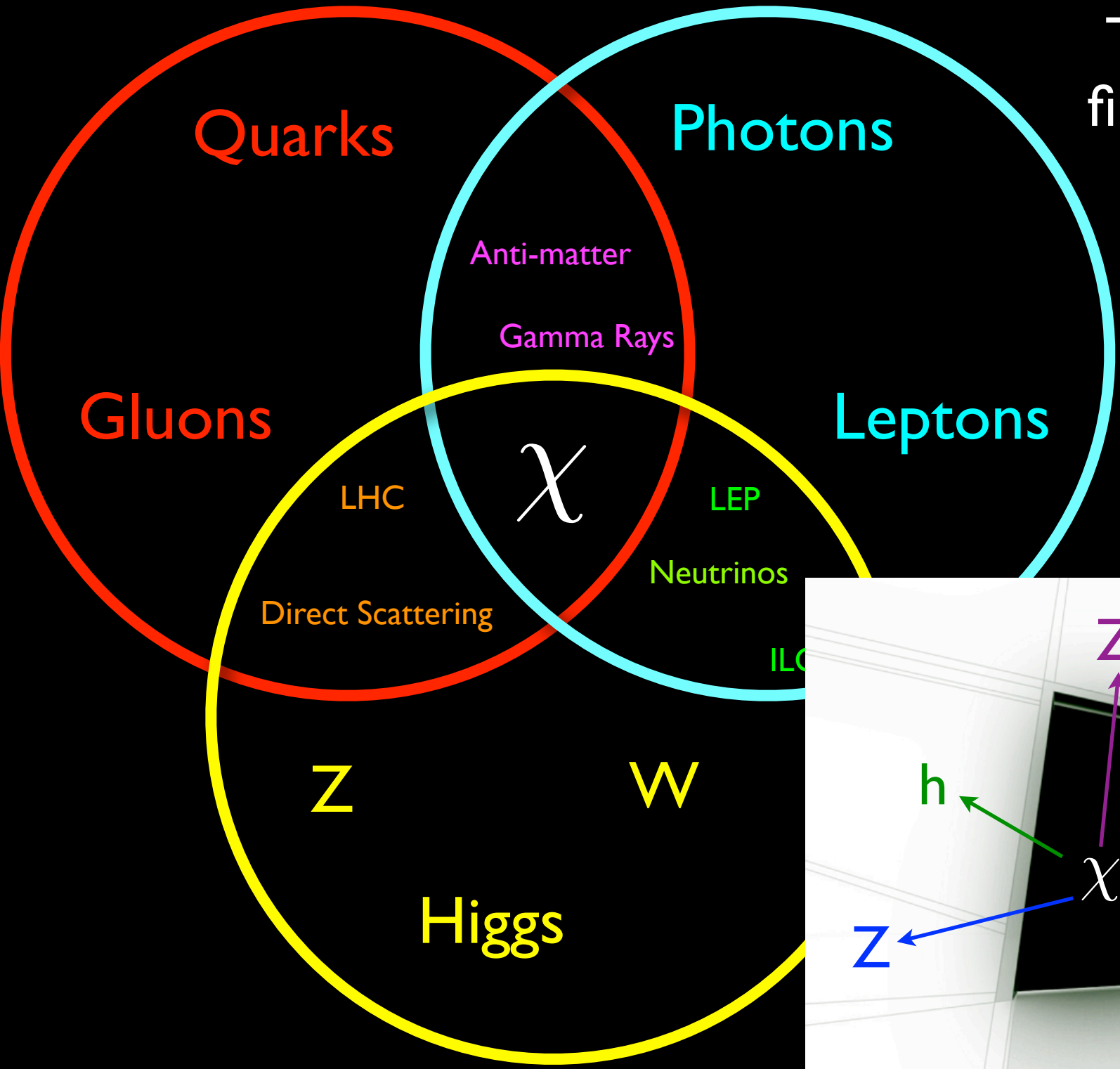


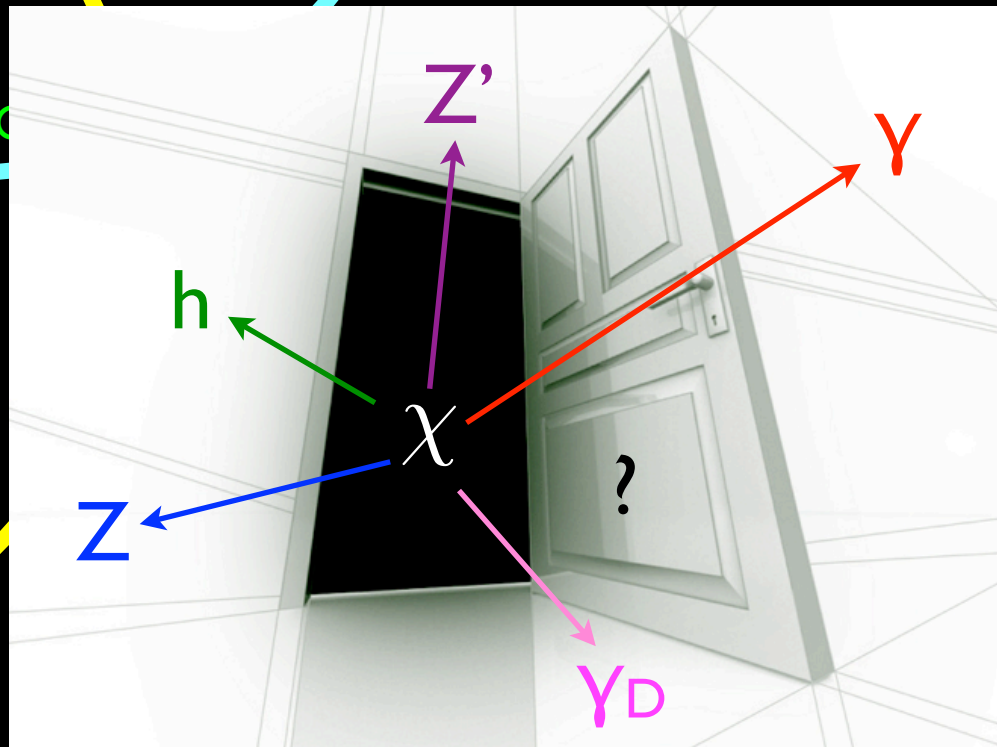

$$\sim \frac{\alpha_S}{4\pi} \frac{g^2}{M_{\mathcal{C}} M_{\tilde{\mathcal{C}}}^2} \leftrightarrow \frac{\alpha_S}{\Lambda_g^3} =$$



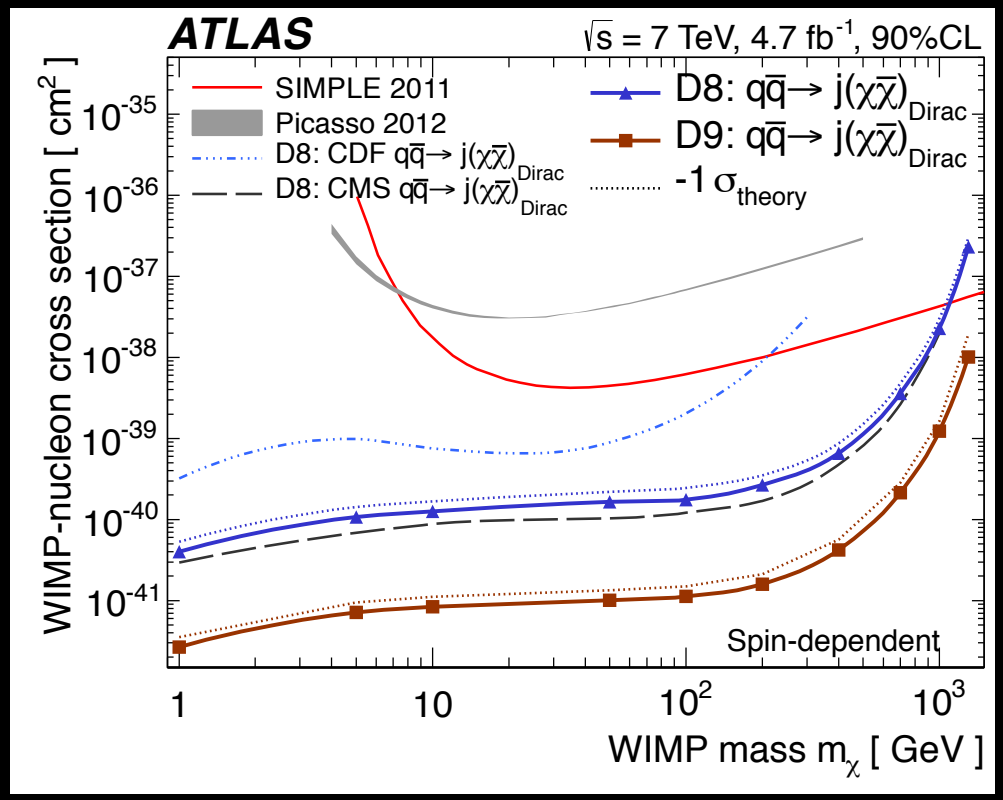

  - Each requires new states with masses heavier than the WIMP.

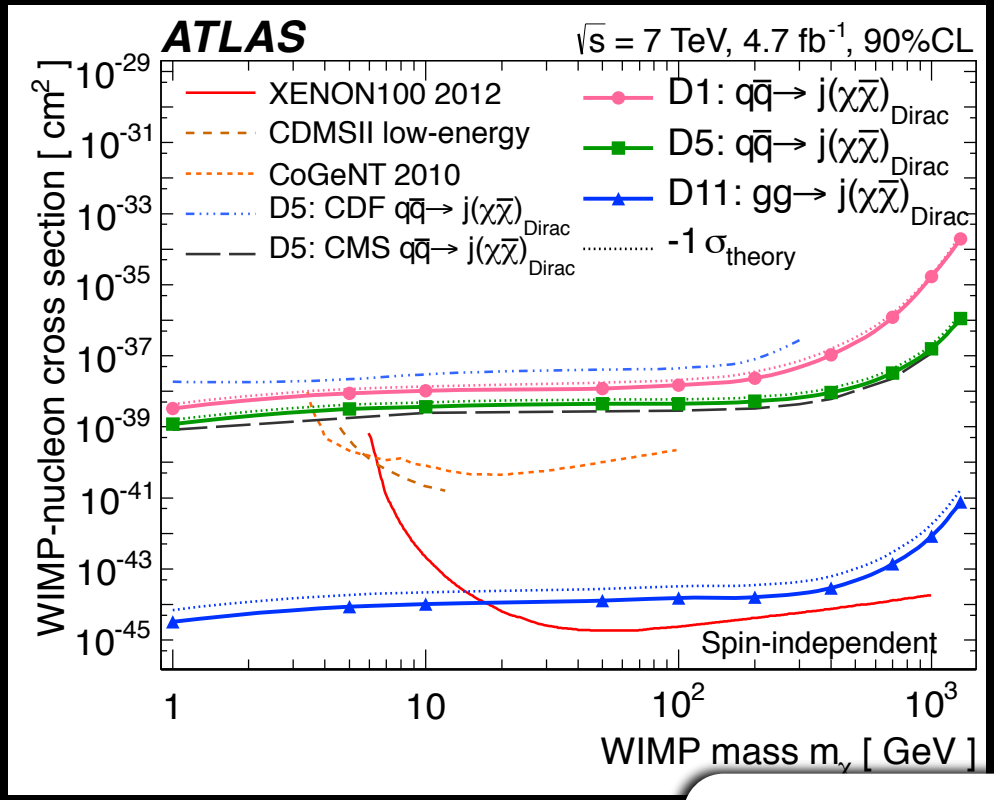
The point is to fill in the puzzle!



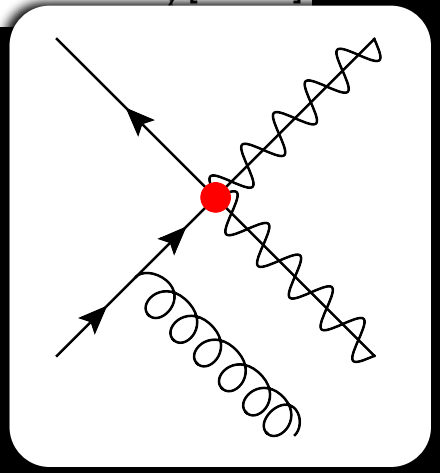



# From Mono-jets into Direct Detection




(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]