Perspectives on Dark Matter Interactions

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DM@LHC, U Chicago
September 21 2013

Thanks to the Organizers!

No Complaints!

What is Dark Matter?

“Cold Dark Matter: An Exploded View” by Cornelia Parker

The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

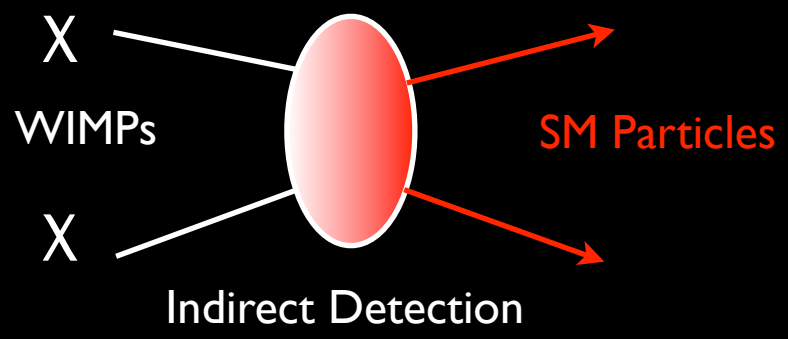
Couplings:

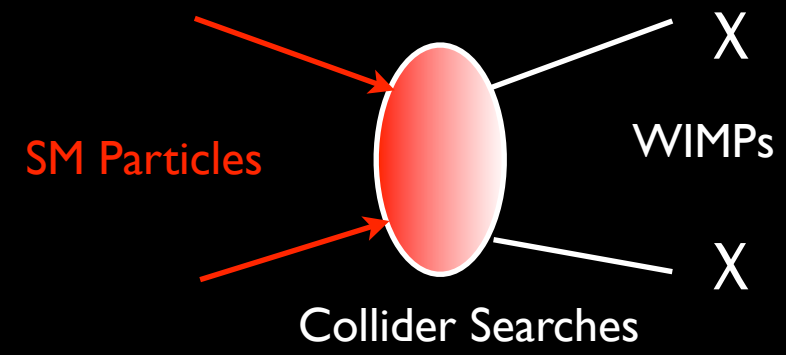
- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

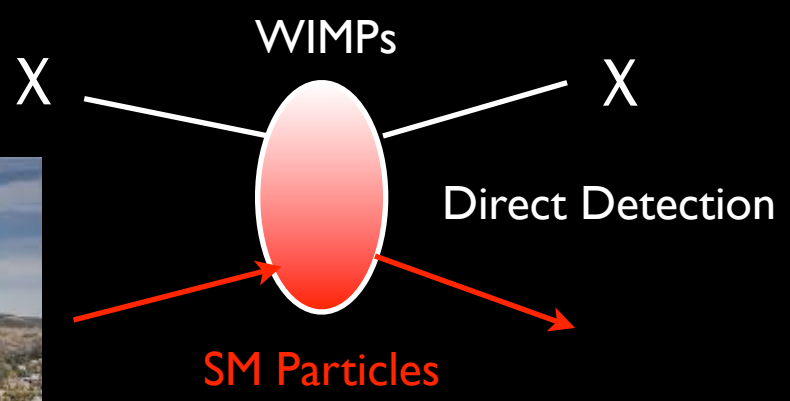
Thermal Relic?

- ☐ Yes ☐ No

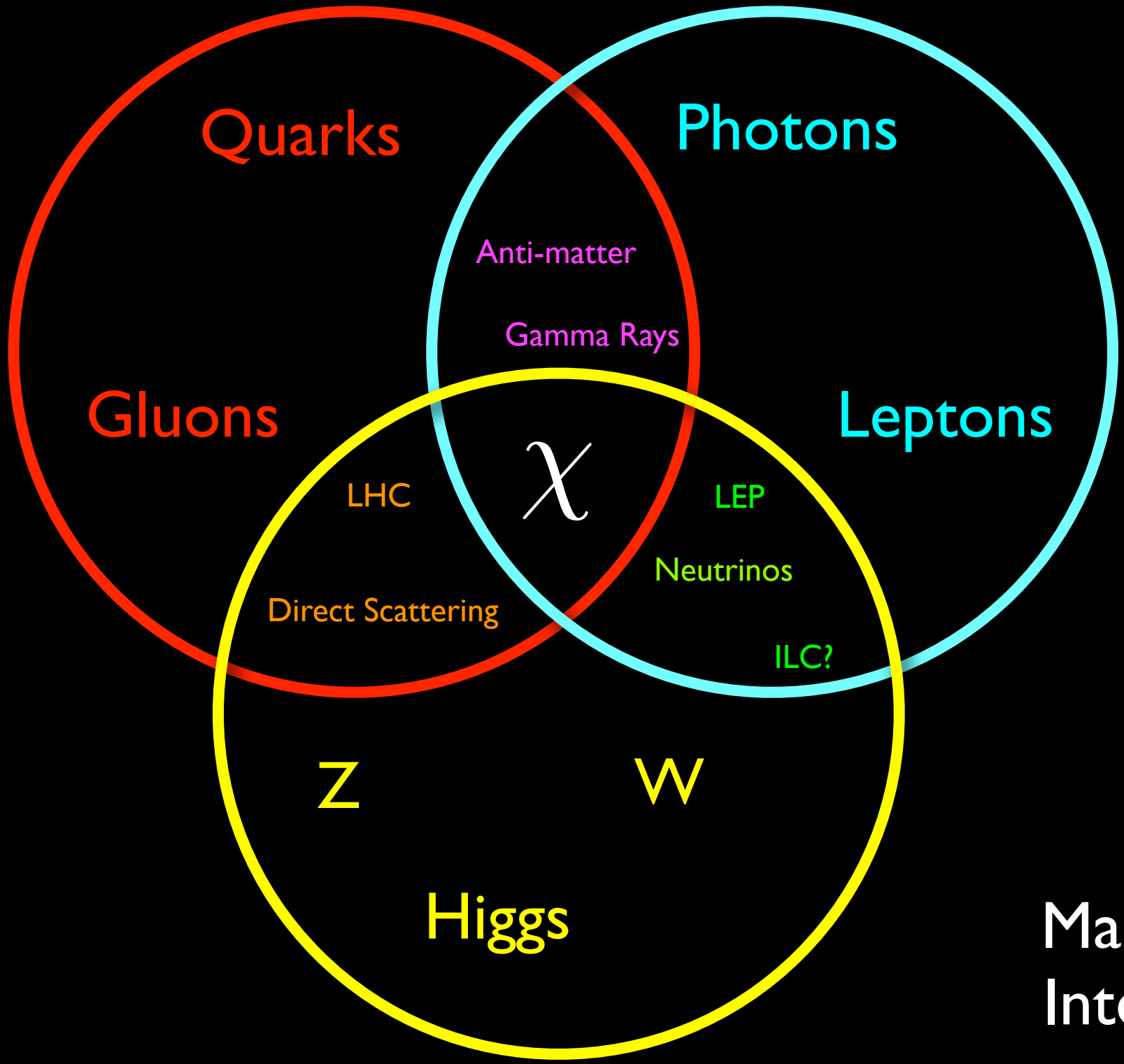
Particle Probes of DM







- All of these processes are determined by how WIMPs interact with the Standard Model. They necessarily contain overlap and complementarity!

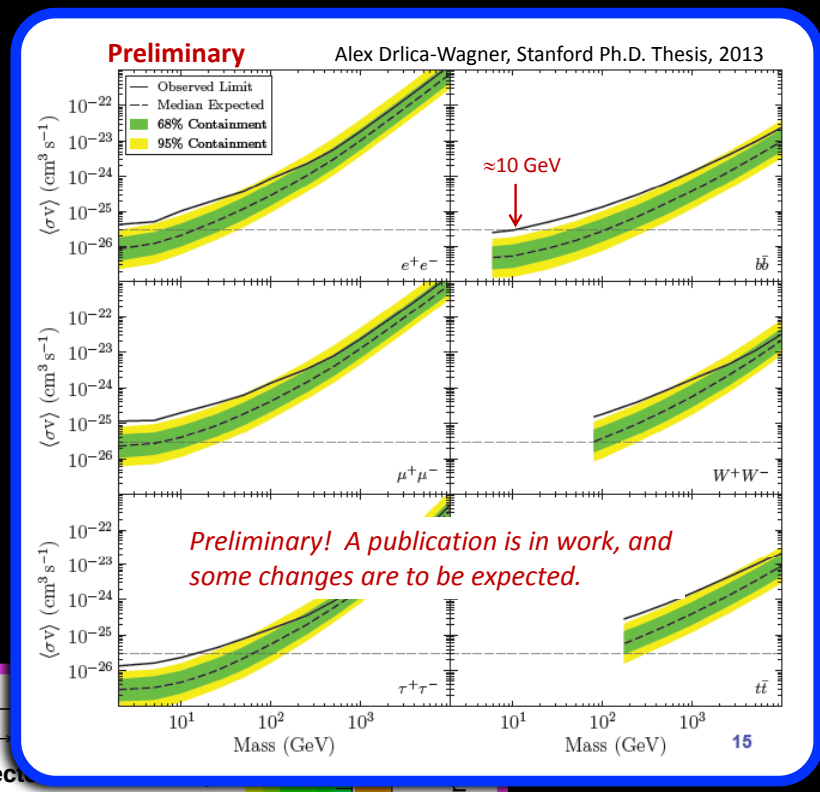


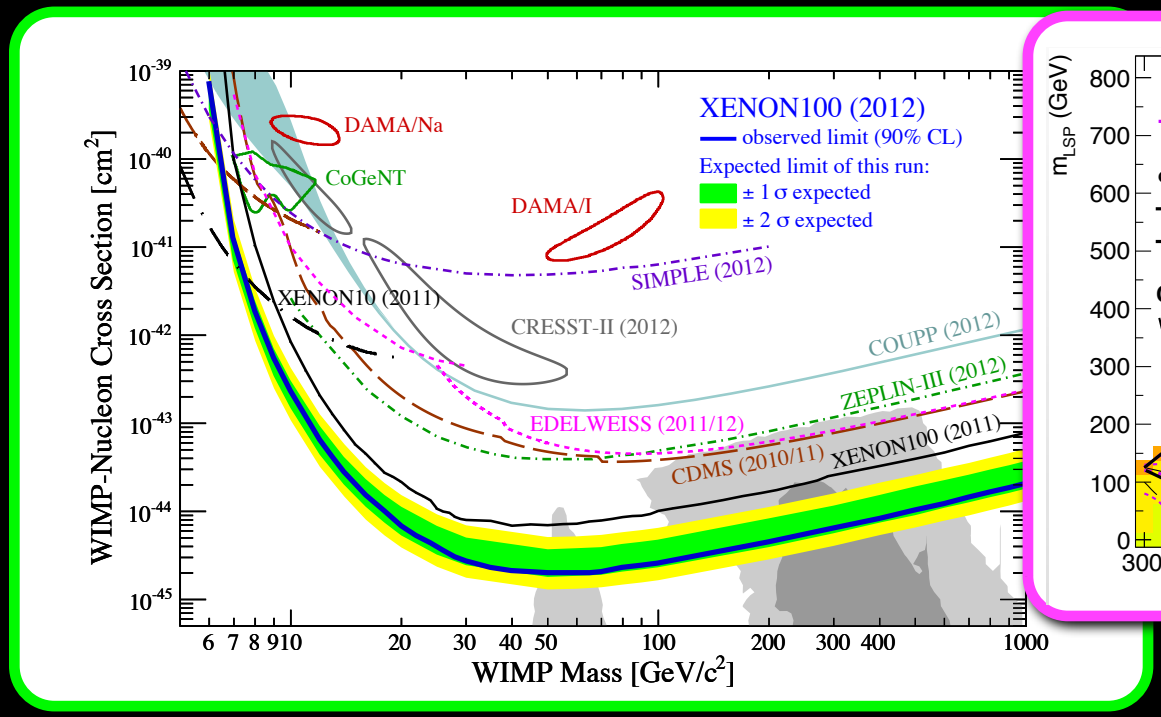
Map of DM Interactions

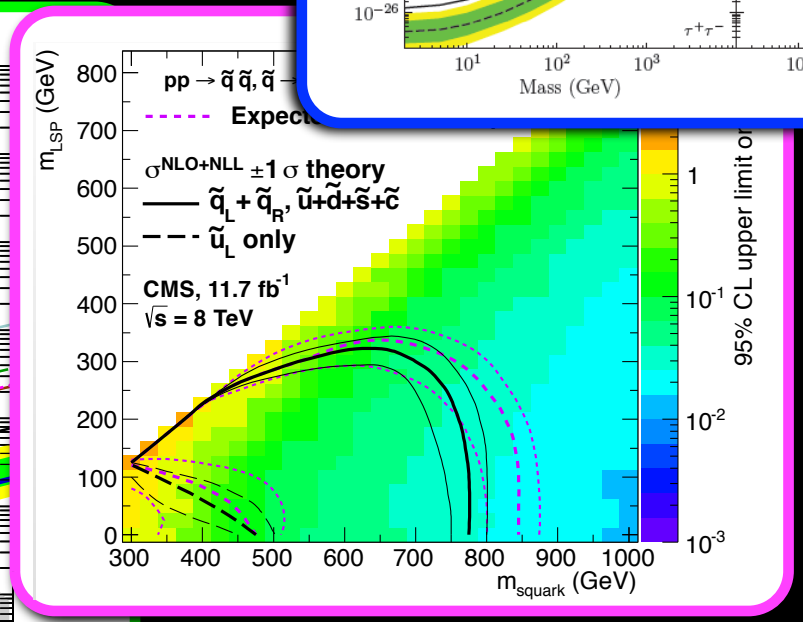
We Need (a) Theory

Individually, dark matter searches of all kinds put limits on different cross sections. Without some kind of theoretical structure, we can't compare them.

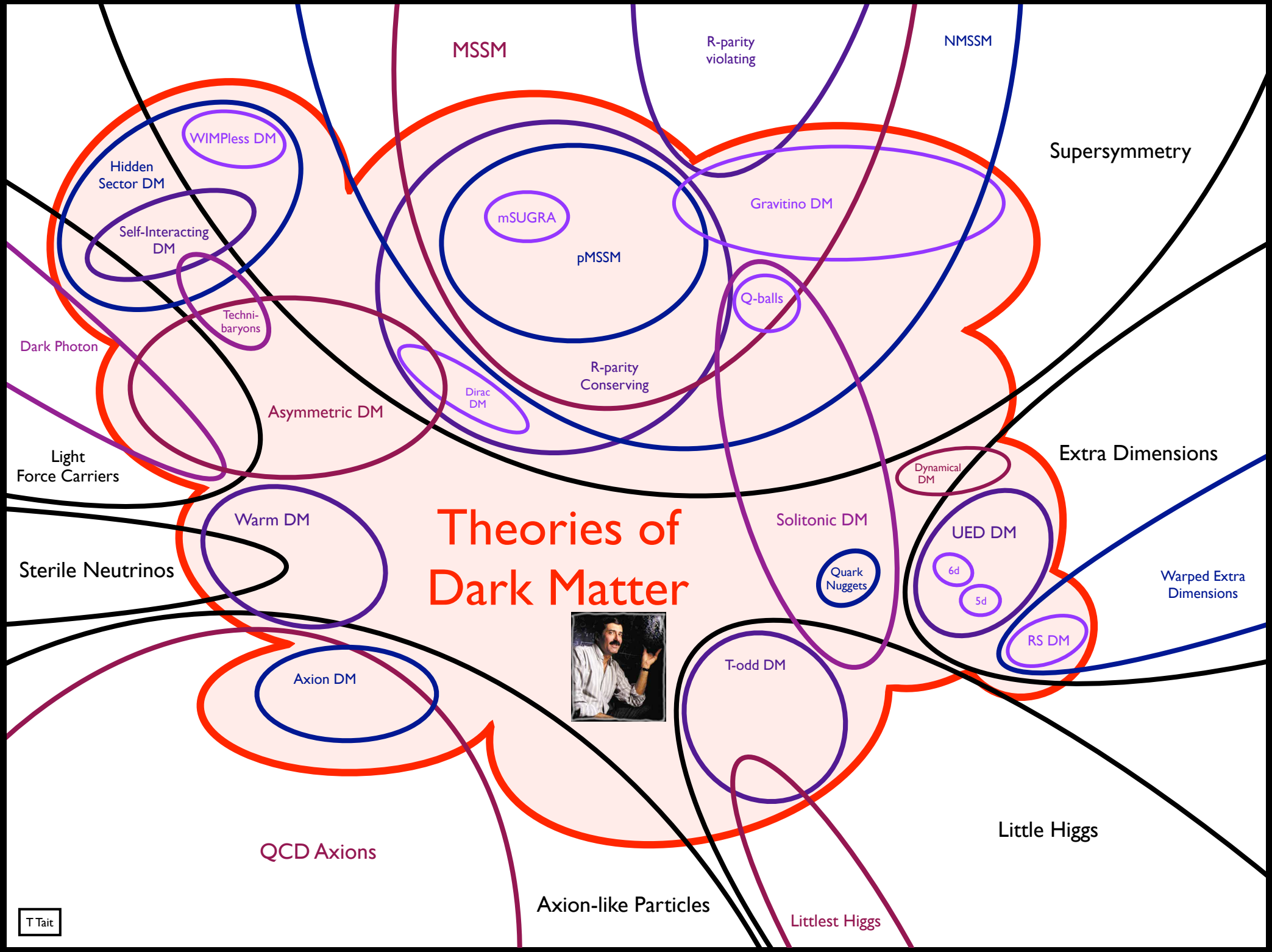
But we *know* they are all attempts to characterize the same thing(s)...



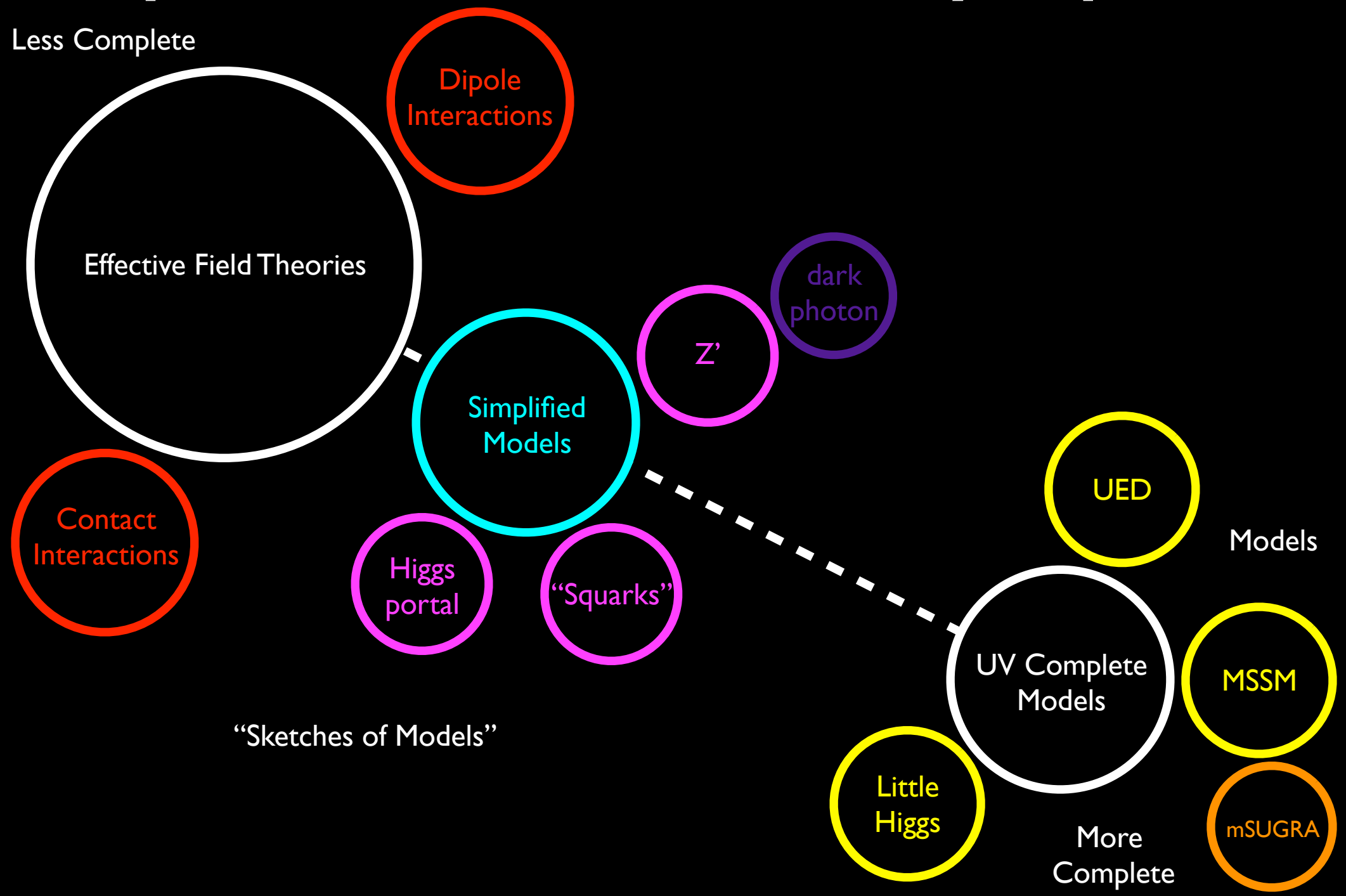




Which theory to use?

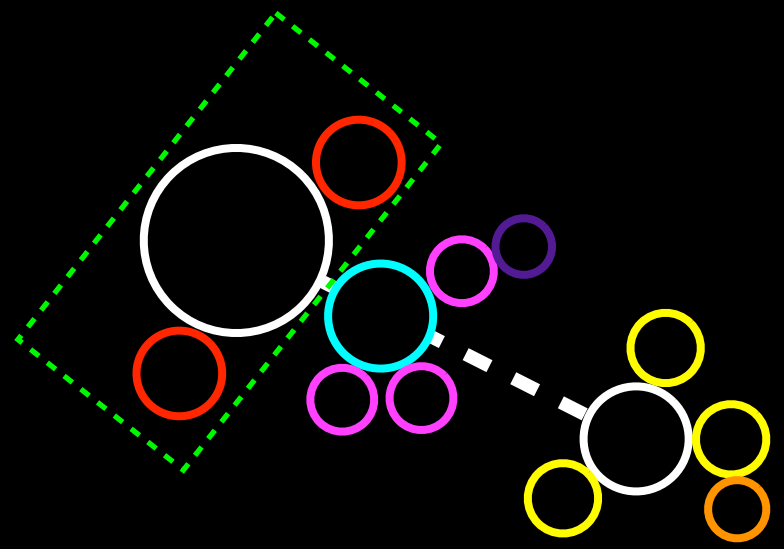

Theories of Dark Matter
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

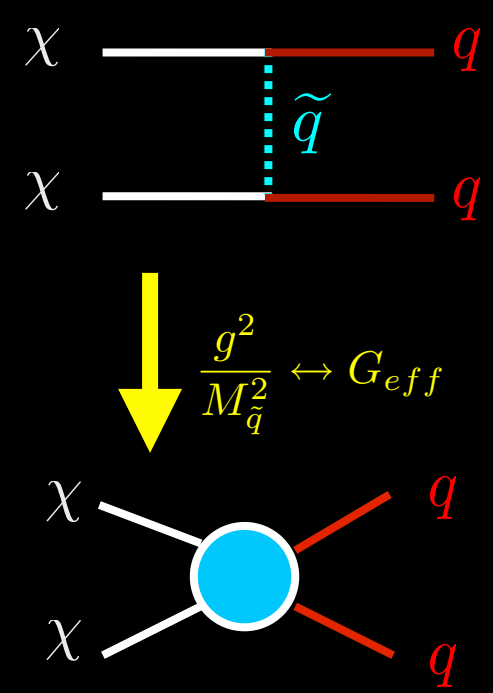
Spectrum of Theory Space



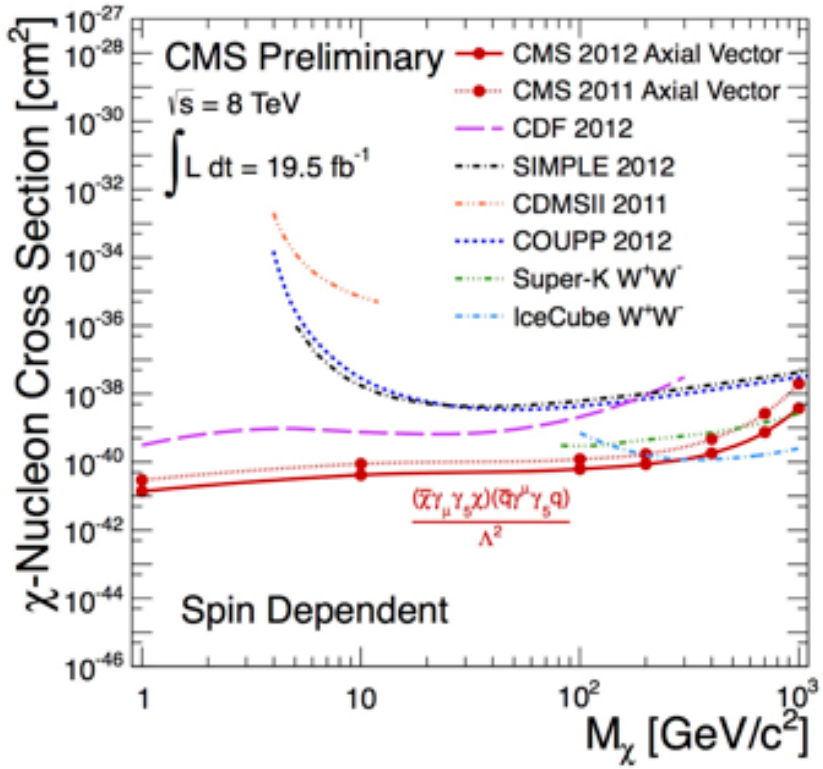
Contact Interactions

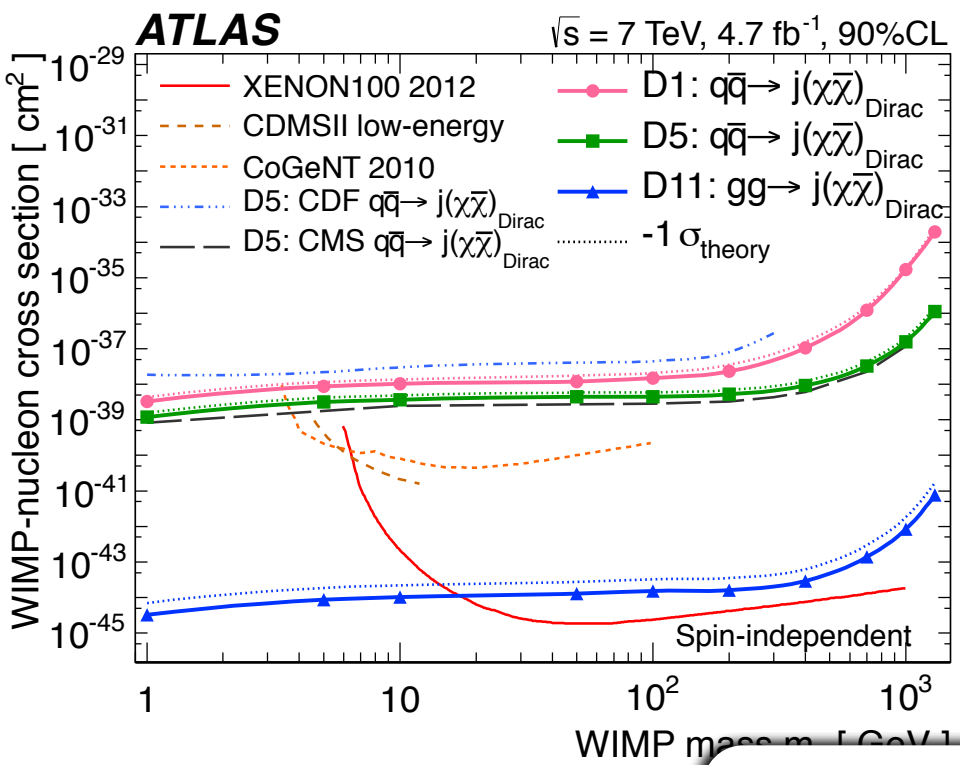
- On the "simple" end of the spectrum, we have theories where the dark matter may be the only accessible state to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared 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.

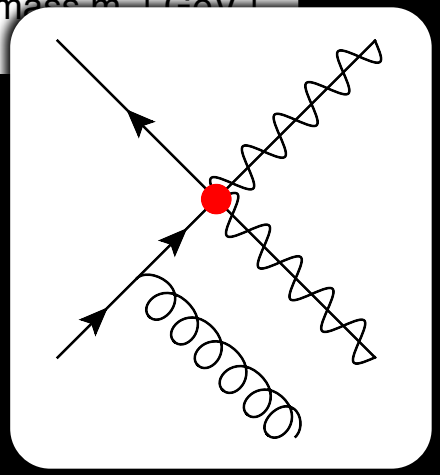




From Mono-jets into Direct Detection





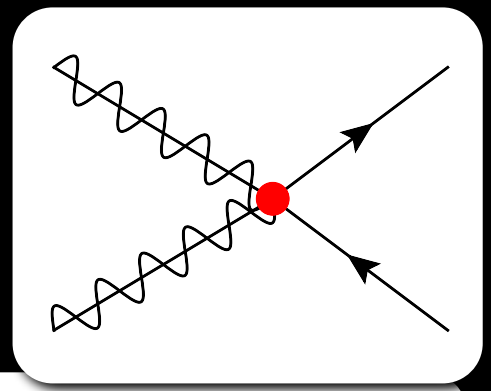


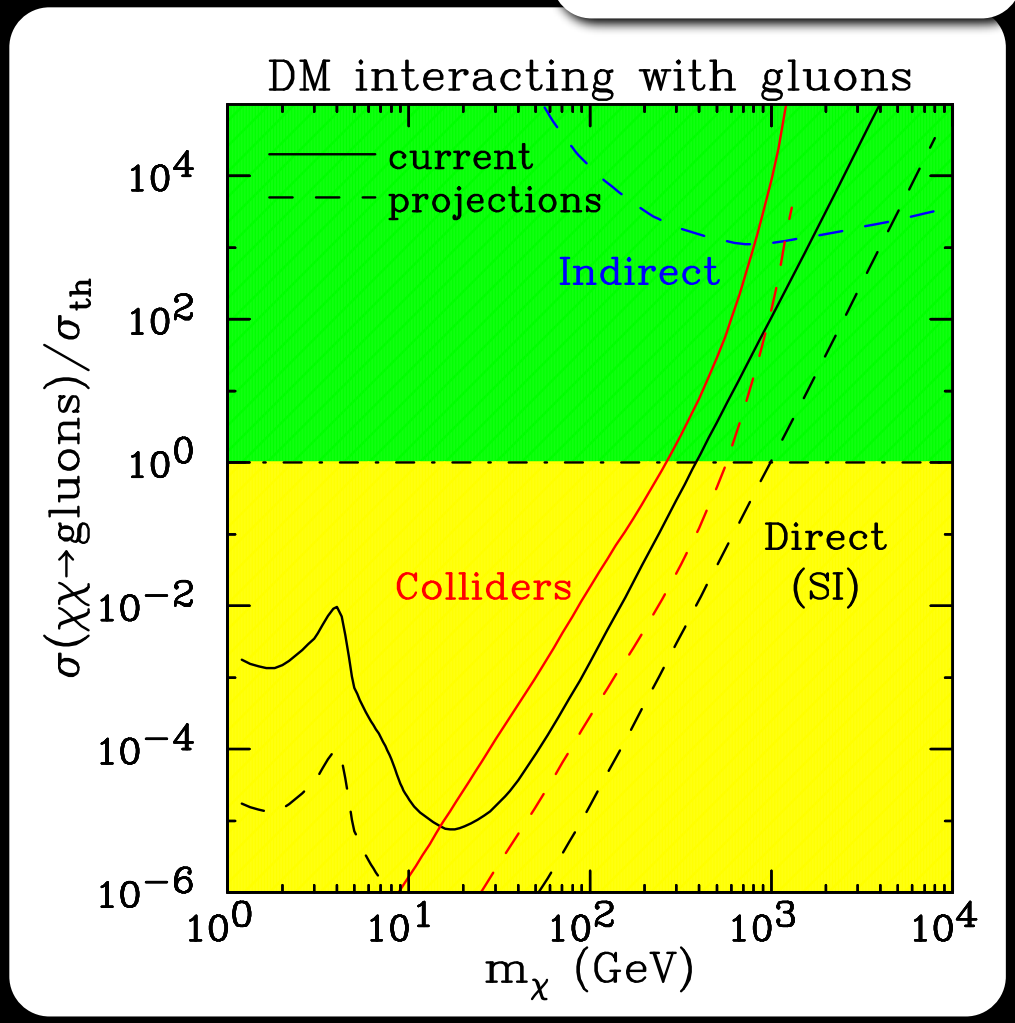
- As advertised, we can map the collider results into other spaces, such as the direct detection parameter space.
- This obviously relies on the theory-framework.

Annihilation

- 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.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- We see similar trends as were present in the pMSSM: Colliders do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs.

DI1

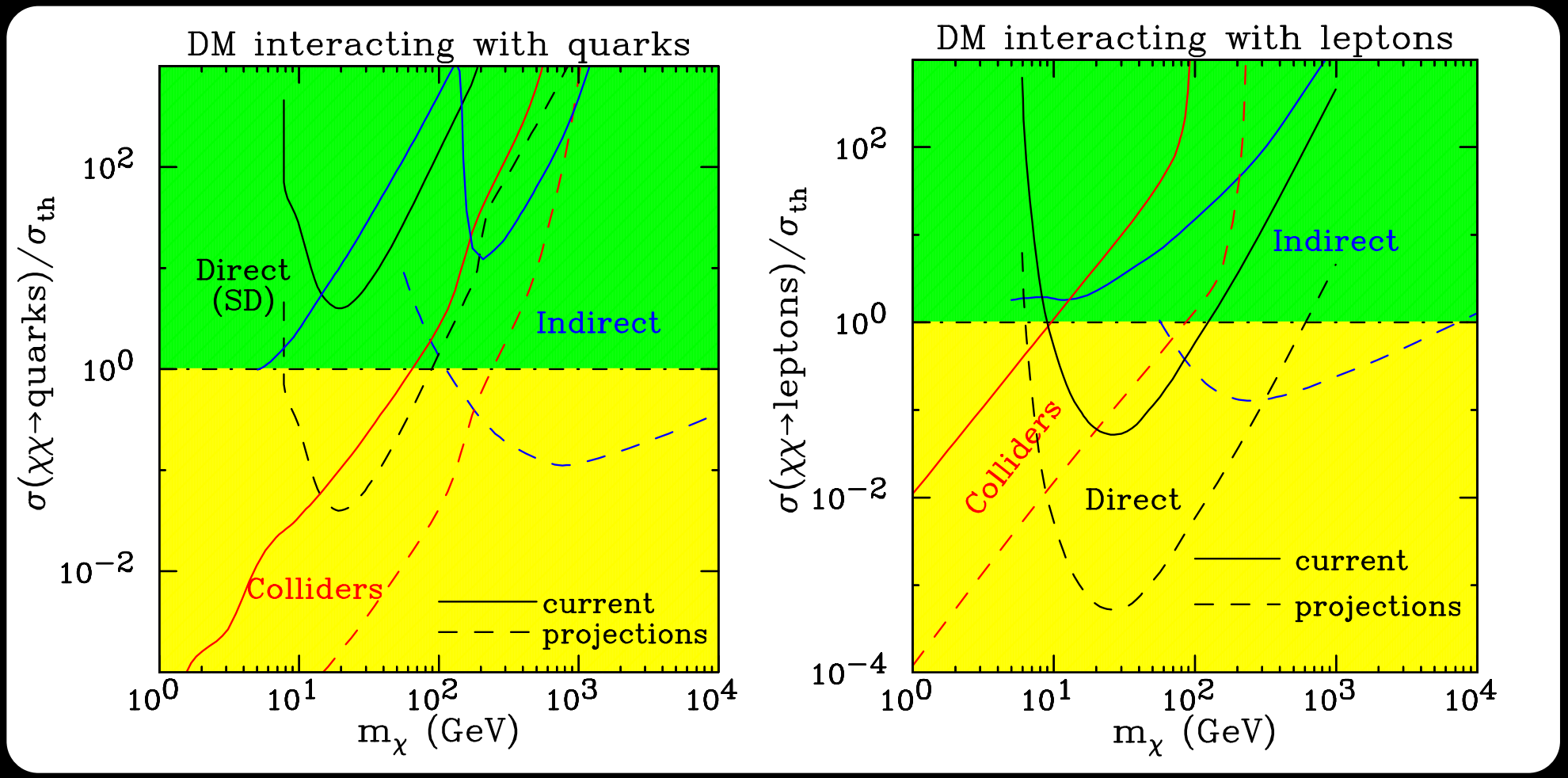




DM Complimentarity, arXiv:1305.1605

Quarks & Leptons

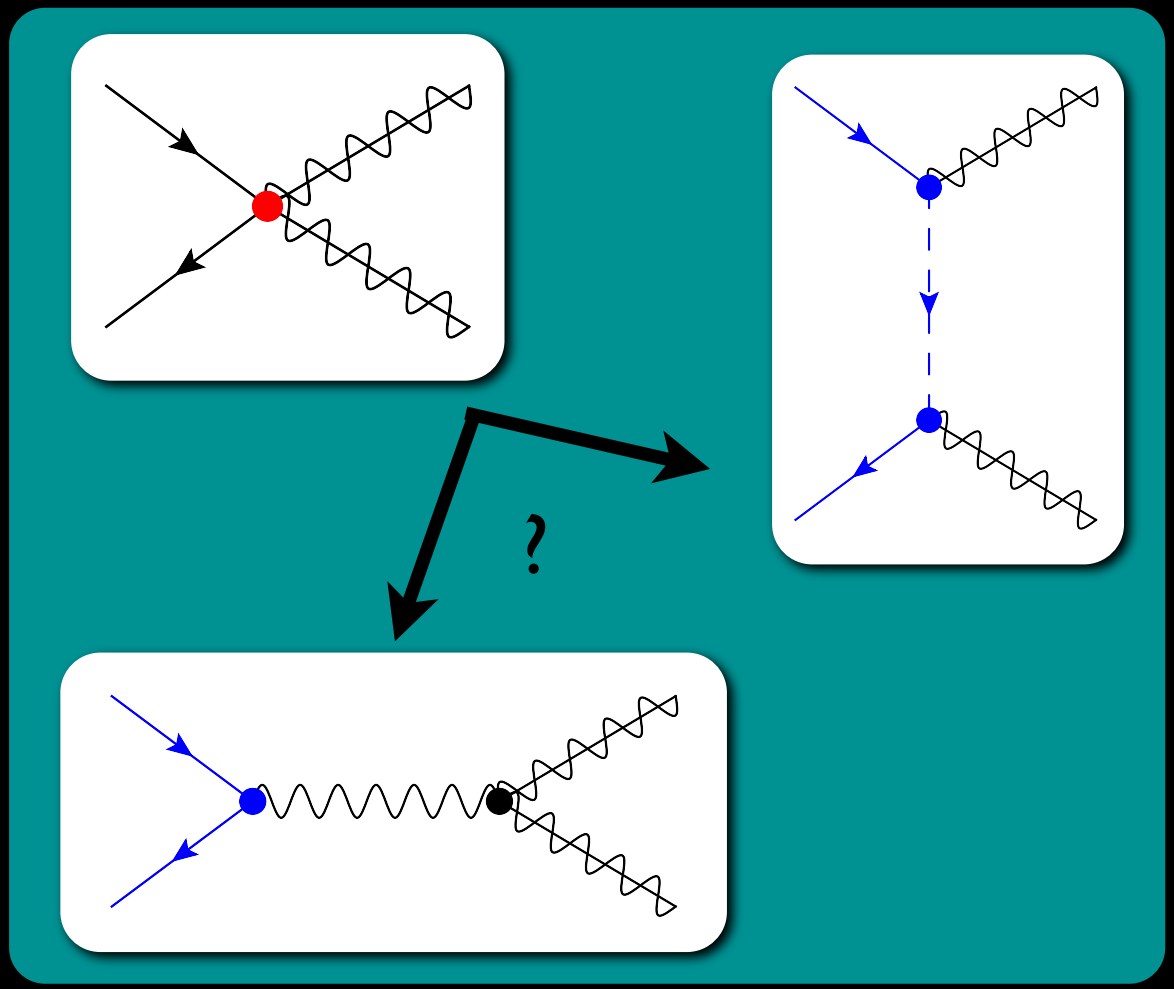
D5-like



D8

DM Complimentarity, arXiv:1305.1605

How Effective a Theory?



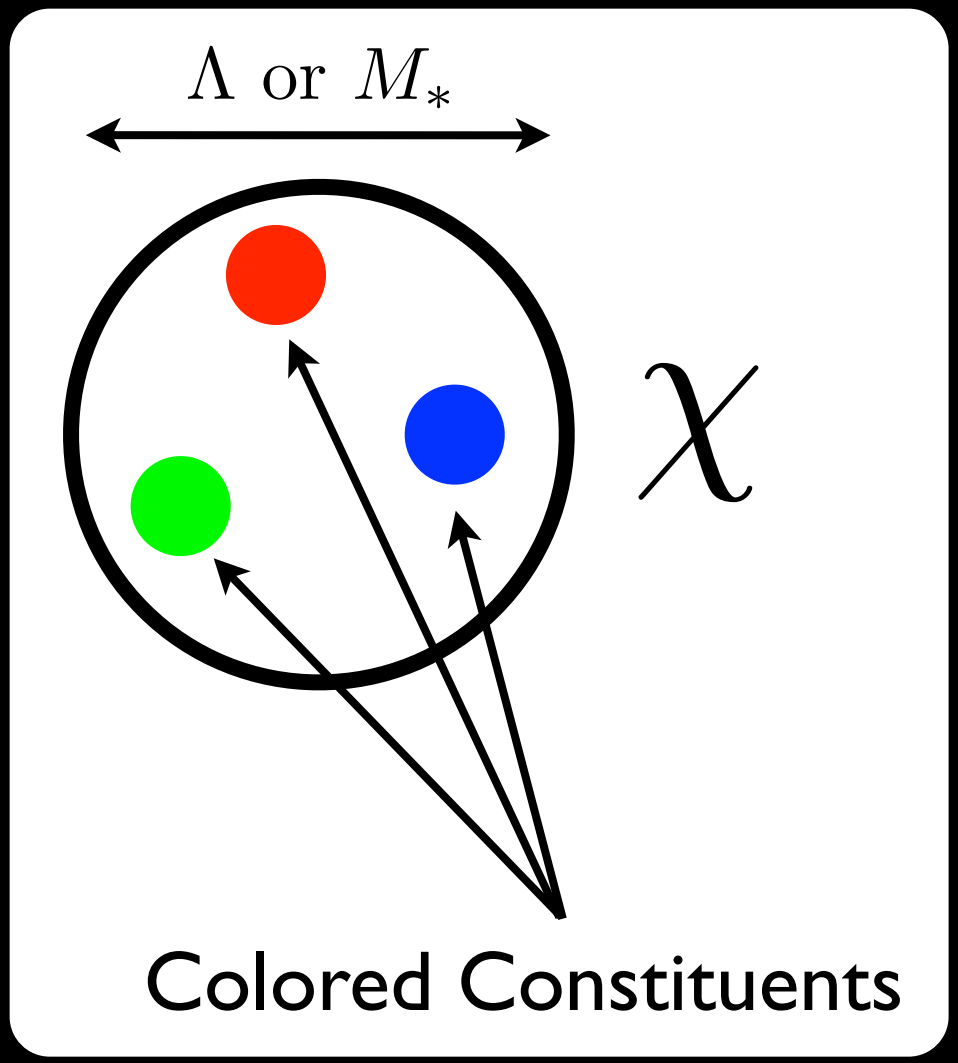
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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.

Where things can go wrong, and by how much, depends on the UV-completion.

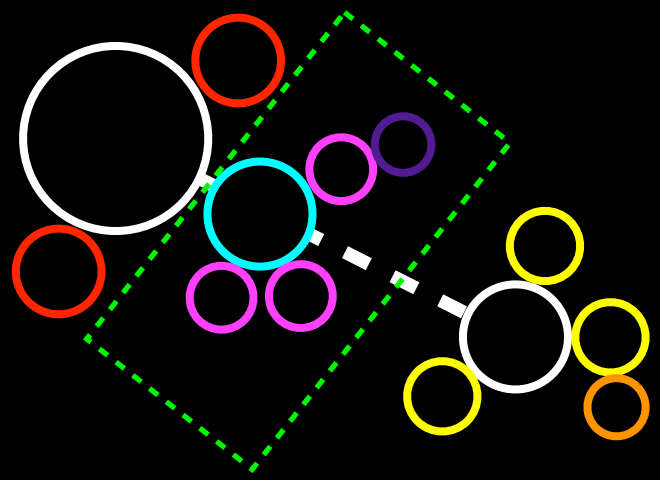
We're just now starting to really understand this quantitatively. One of the major developments that this workshop puts into perspective is this program!

A Composite WIMP?

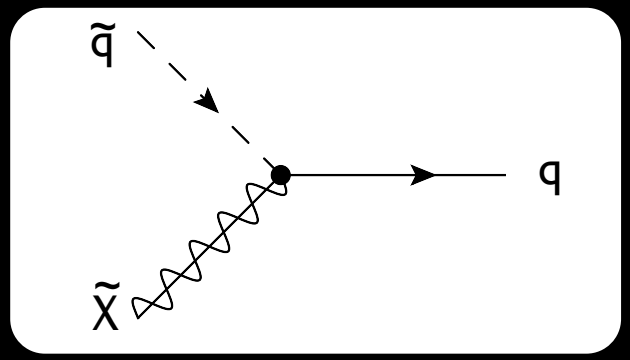


- Even when EFTs are only constraining rather strongly coupled theories, they say something interesting about (perhaps exotic) DM theories.
- If the dark matter is a (neutral) confined bound state (confined by some dark gauge force, say) of colored mediators, we should expect its coupling to quarks and gluons to be represented by higher dimensional operators whose strength is characterized by the new confinement scale.
- Bounds on EFTs constrain the new confinement scale -- the "radius" of the DM.

From Contact Interactions to Simplified Models



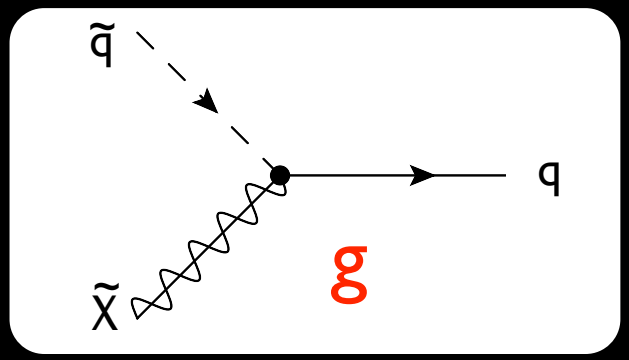
- LHC energies can call into question the contact interaction approximation, we can expand our level of detail toward simplified models.
- For example, a singlet fermion WIMP interacting with quarks can be resolved into a model with the WIMP and a color triplet scalar.
- We heard a lot about these kinds of theories yesterday from Spencer, Yang, and Hao.

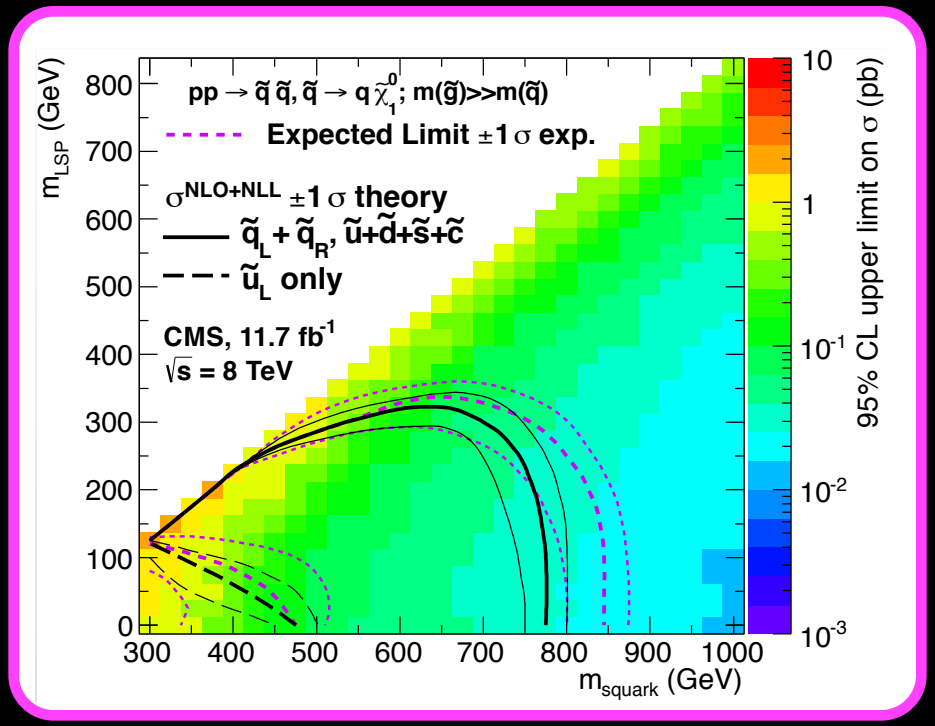


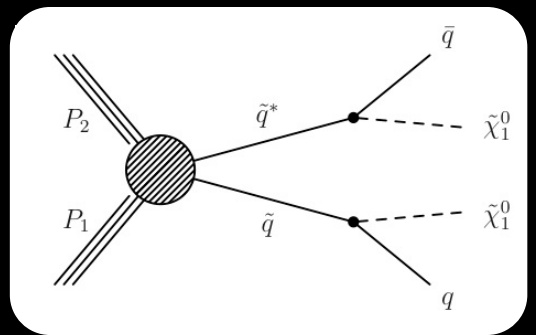
Of course, we can also consider a wider variety of WIMP properties and mediators and get away from MSSM-like theories.

Simple-fied Model

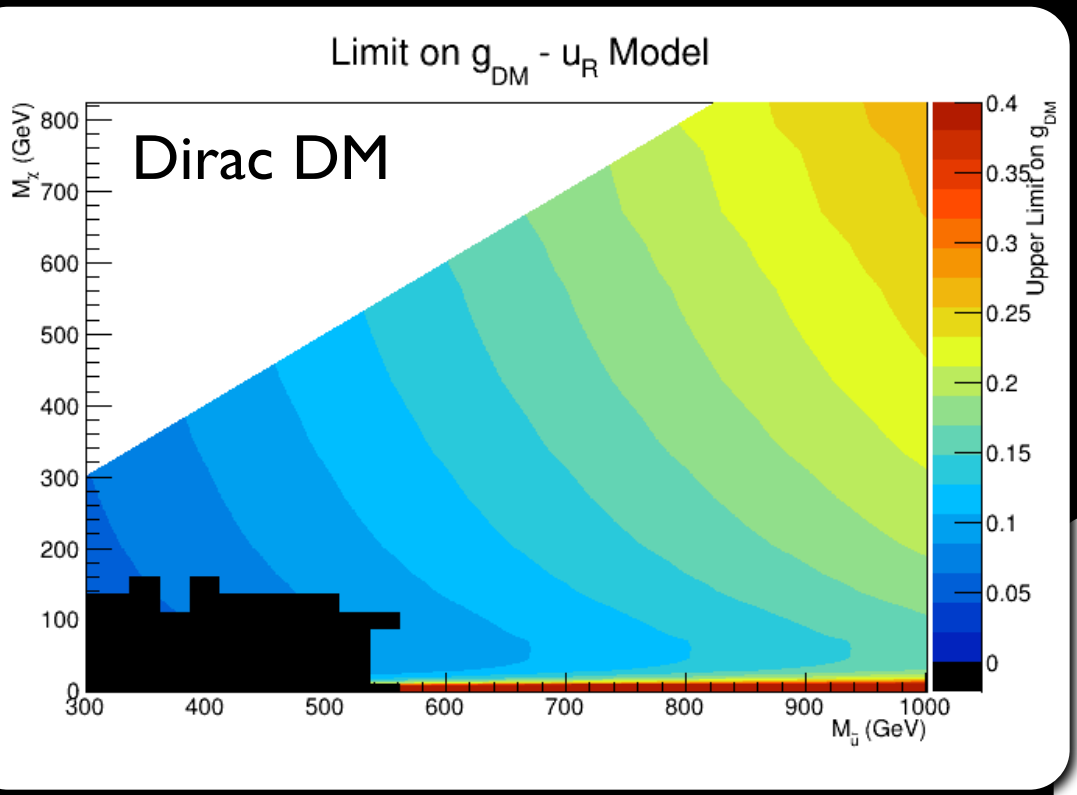
- This is a simplified model we already use to interpret searches at the LHC.
- The current version has 3 parameters: $m_{\tilde{\chi}}$, m_q, and the LHC production σ.
- To make this useful to connect to (in)direct searches we should trade these for: $m_{\tilde{\chi}}$, m_q, and g.
- Collider production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





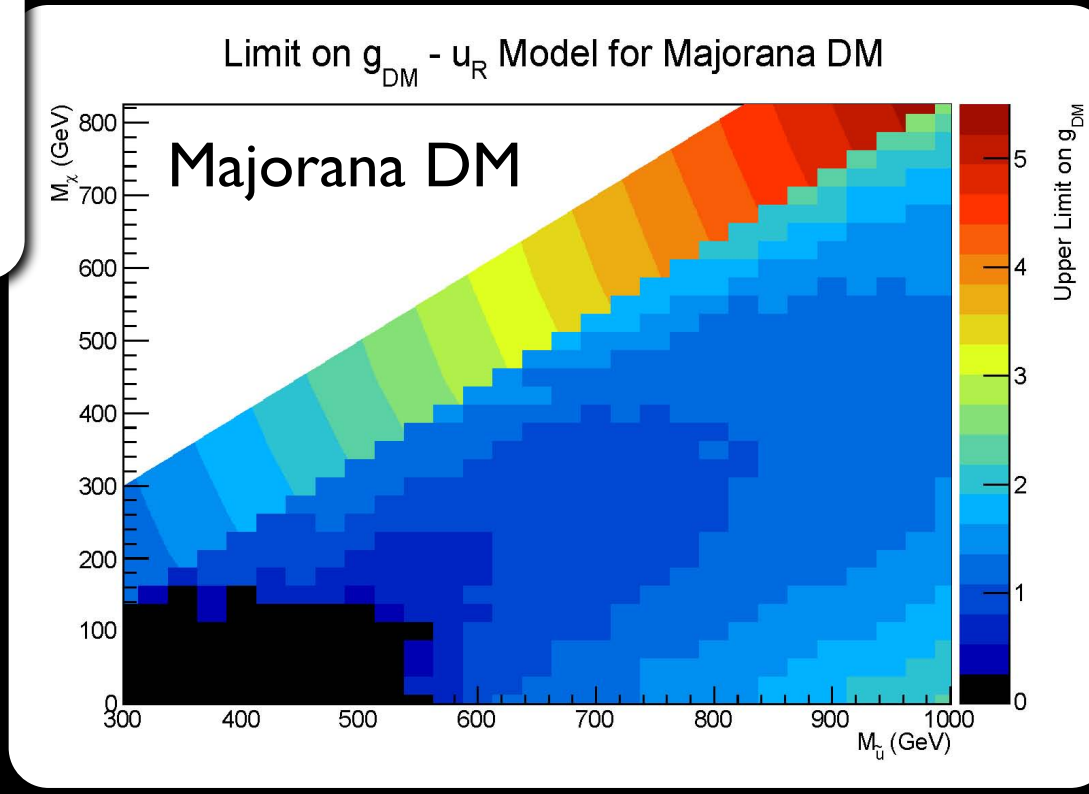


$\tilde{u}_R$ Model: Results



DiFranzo, Nagao, Rajaraman, Tait
arXiv:1308.2679

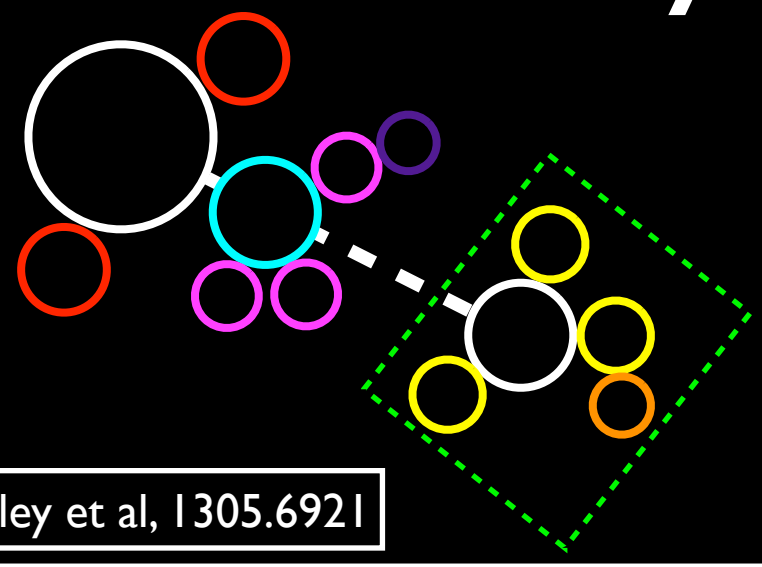
(And see the talks by Spencer, Yang, and Hao yesterday for other ways to present the parameter space.)



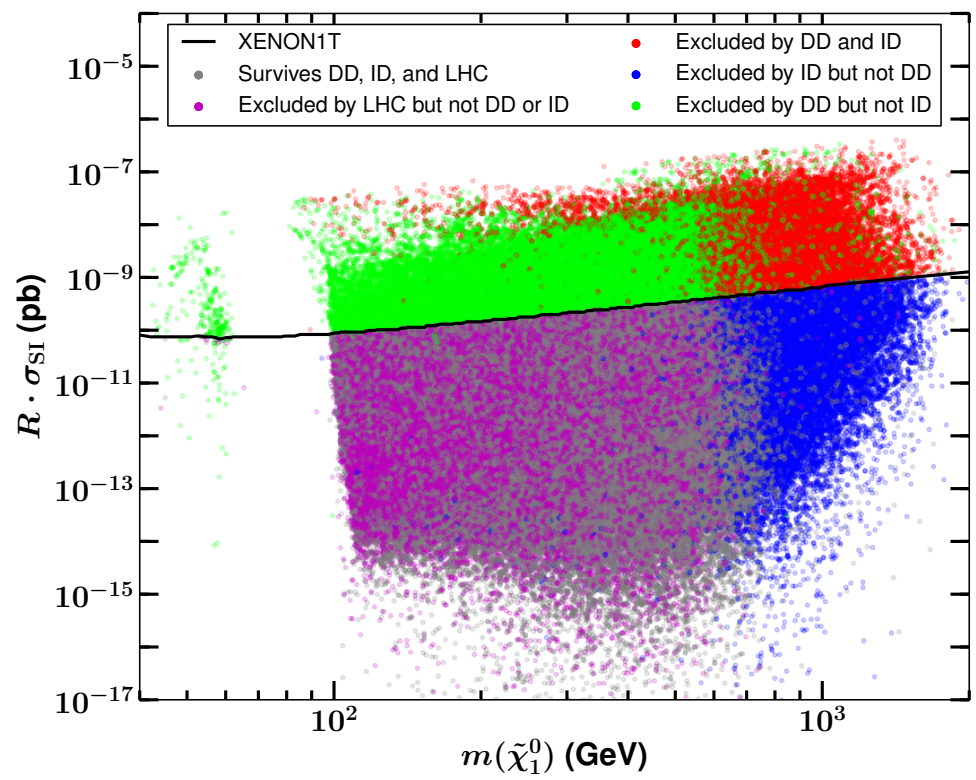
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

The Most Complete Theory

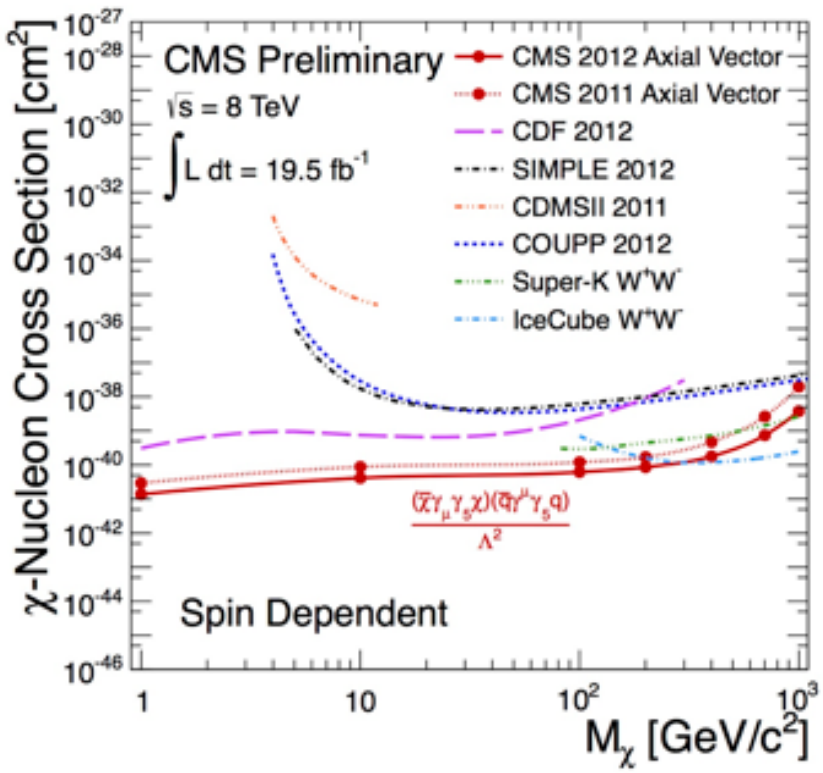
- On the "complete" end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space by the SLAC group, in the plane of the WIMP mass versus the SI cross section.
- Ahmed told us about the pMSSM scans earlier this morning, and how indirect, direct, and collider searches complement each other.

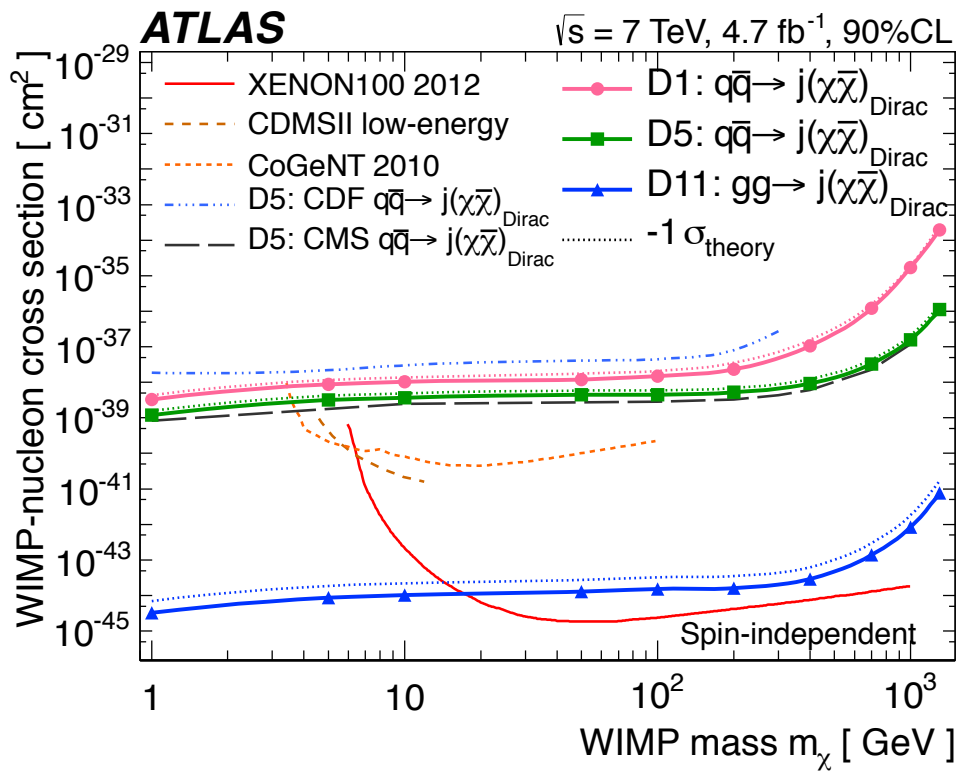


Cahill-Rowley et al, 1305.6921



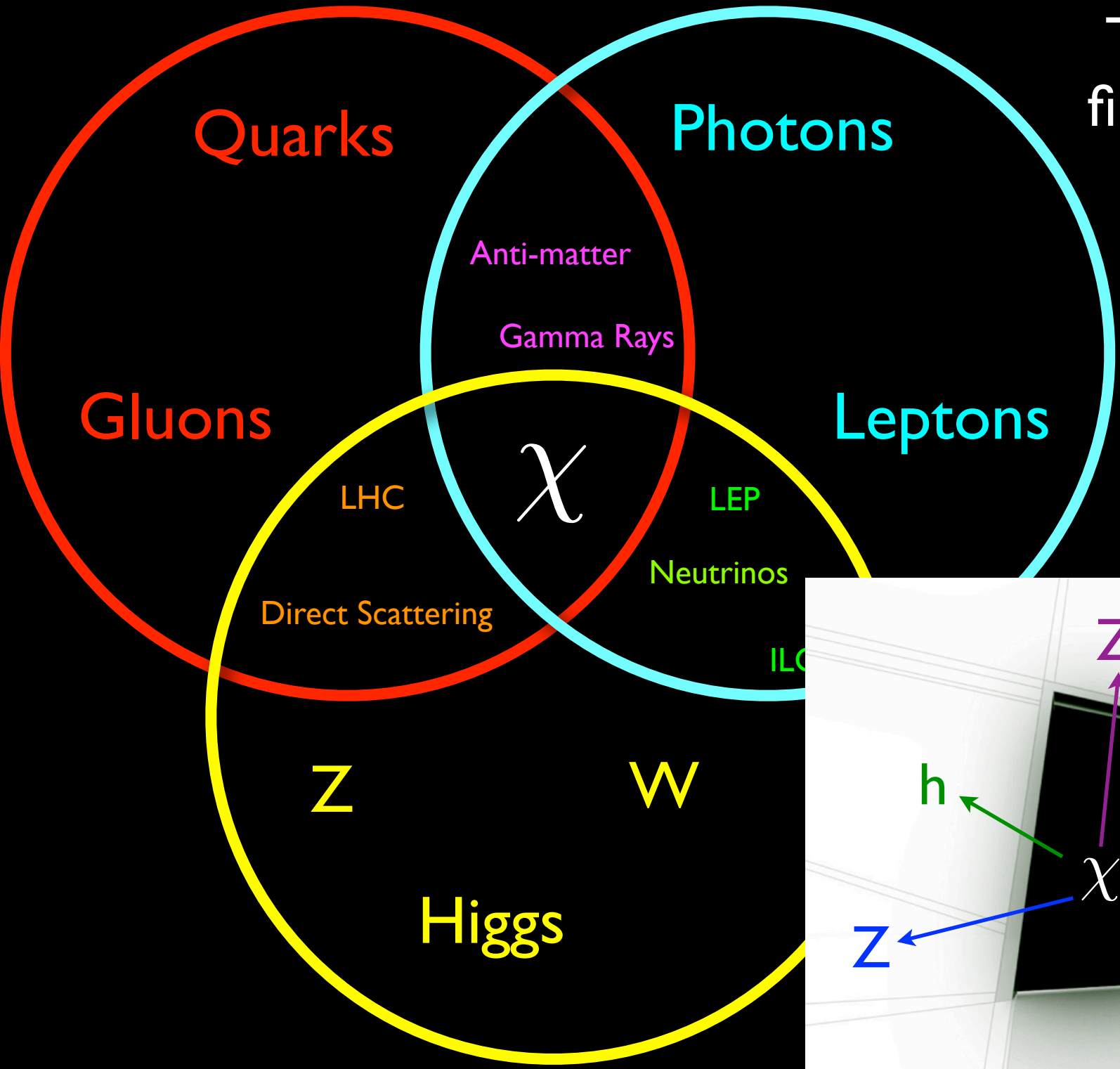
These Plots are Not the Point

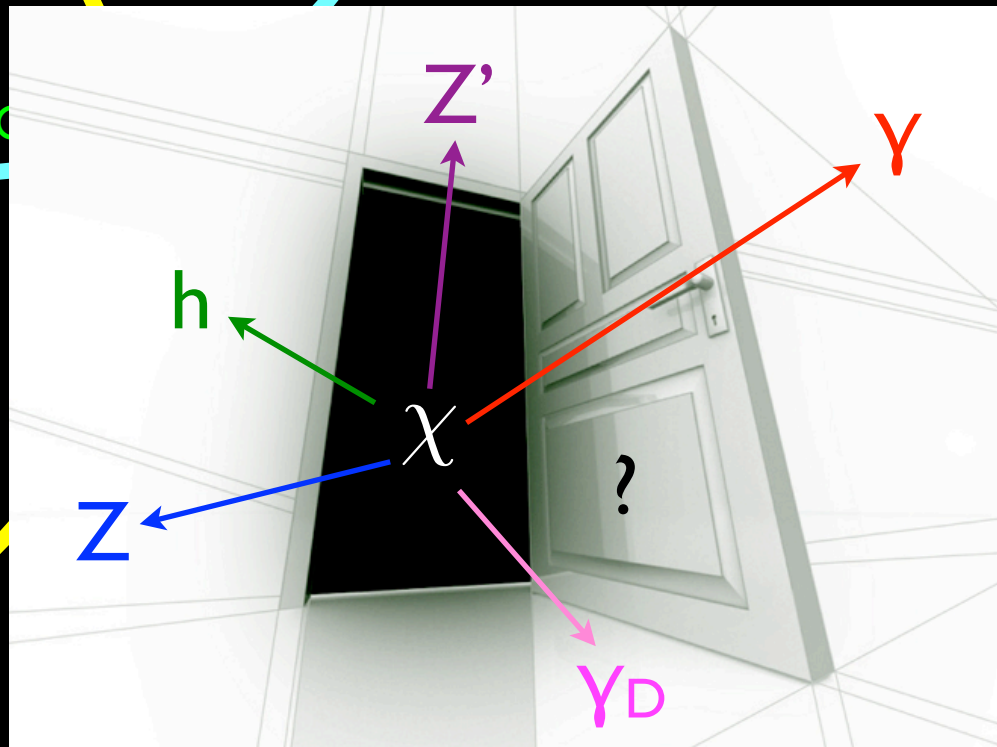




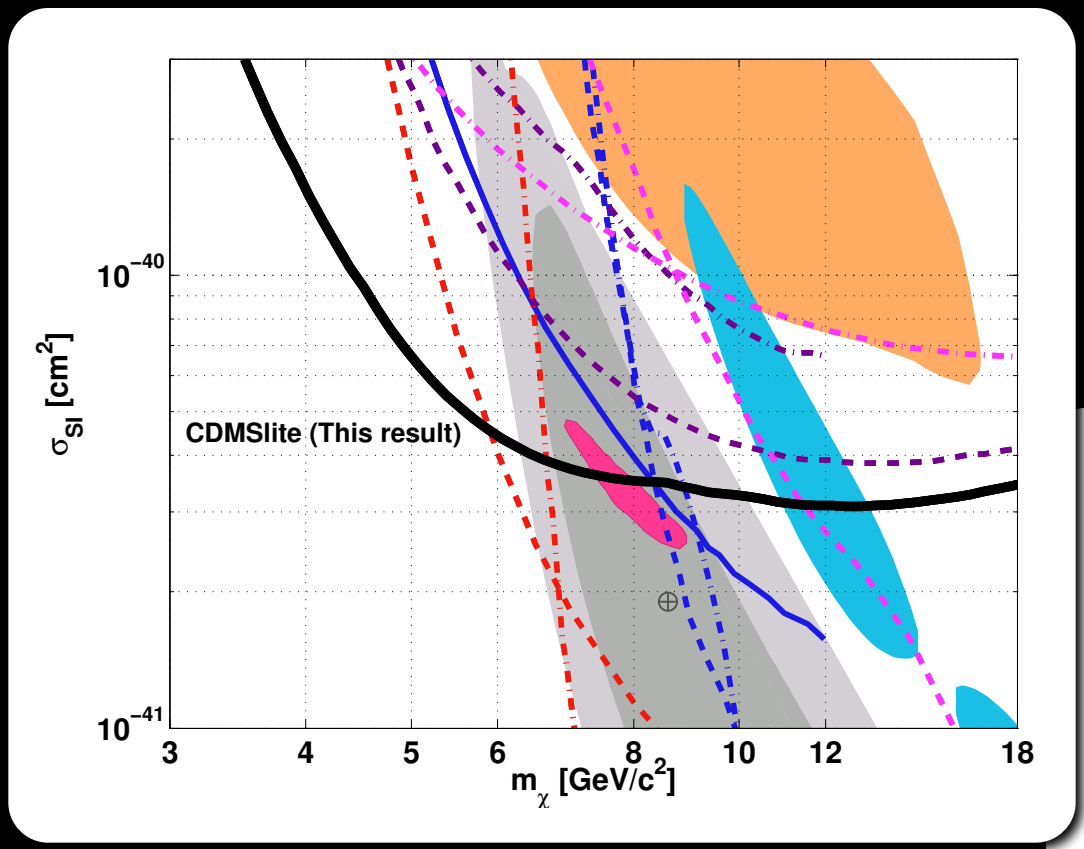
(But they are a lot of fun!)

The point is to fill in the puzzle!

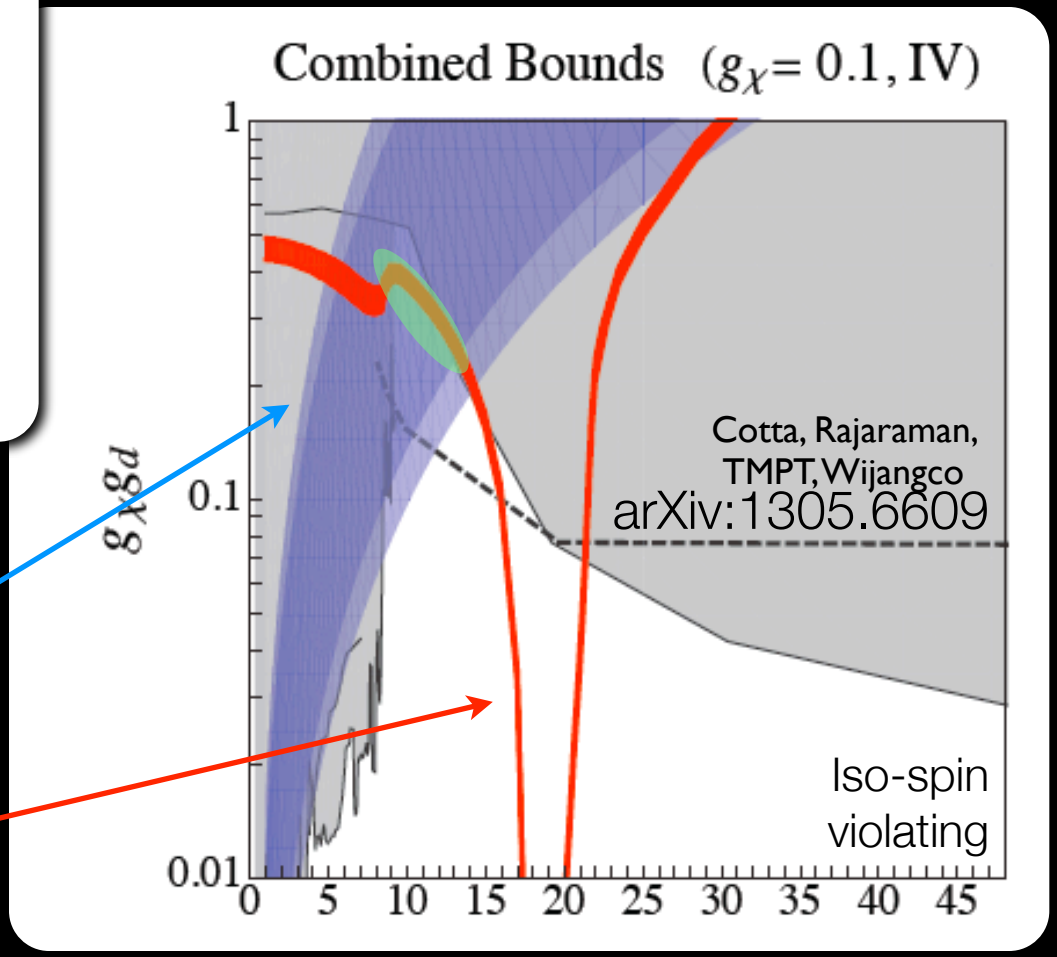




Discovery Mindset



A theory framework is going to be essential if we are ever going to believe a claim of DM discovery.



Simplified Model with Scalar Mediator

CDMS-SI Preferred

Relic Density

Some similarities with what I think "Marcela" will show us today...

Outlook

- The move from theoretical descriptions of dark matter that attempts to characterize its properties from "dark matter as a side effect" is healthy (perhaps essential) development.
- Theories can be understood in context based on where they lie along an axis defining how complete they are:
  - Fully complete models can answer any question satisfactorily, but we worry that they may be so well-formed as to be getting some of the details wrong.
  - Simplified models will probably miss important correlations between observables, but try to capture some set of signals accurately to LHC energies (and beyond).
  - Effective theories are the (universal) heavy limit of simplified models, but we must always worry whether they capture the physics at the energy scales of interest.
- All of these are interesting frameworks, and could very well lead to discoveries!

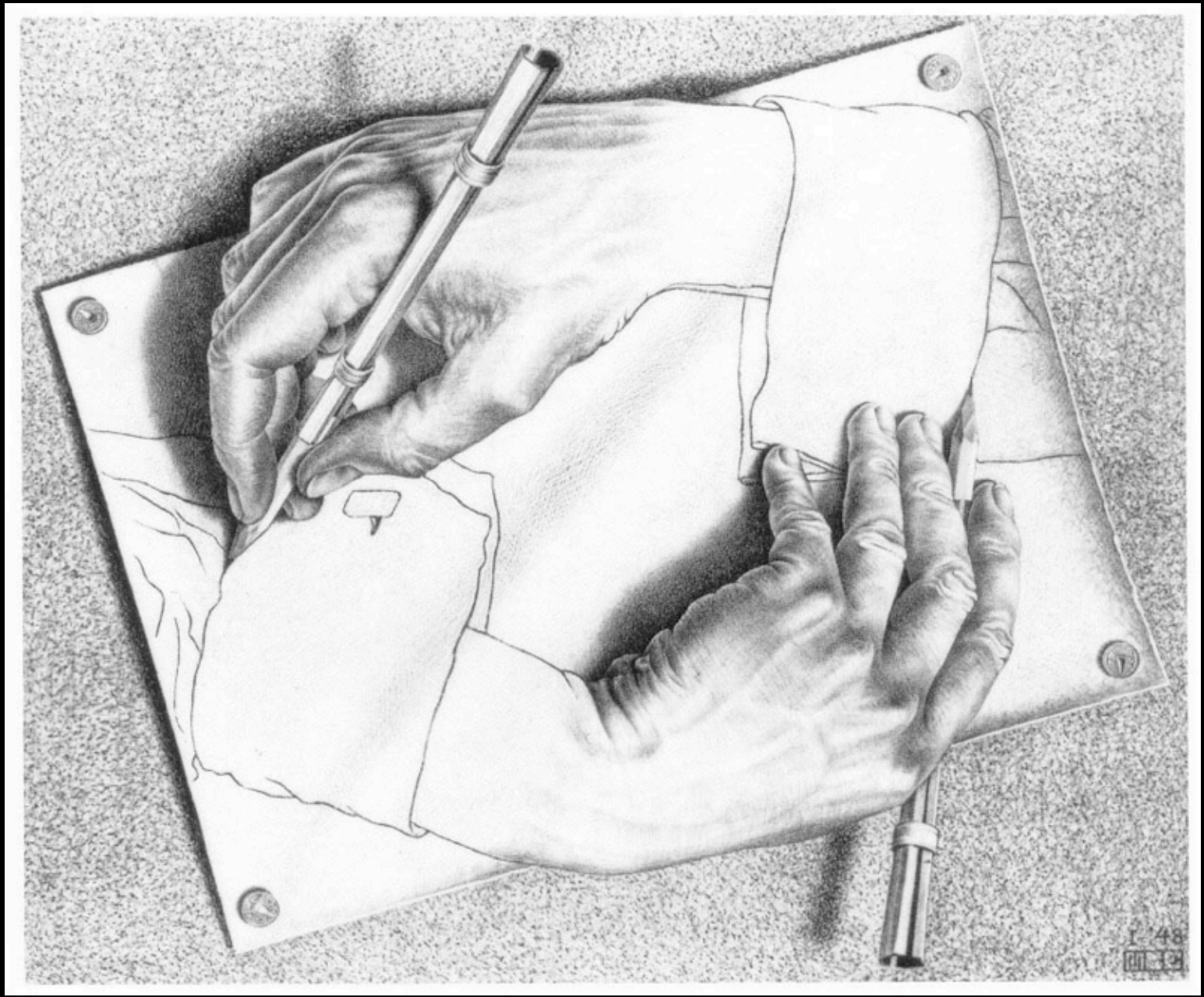
Outlook

- There are still interesting directions to explore!
- In terms of formulating model-frameworks:
  - EFTs with quarks and gluons for singlet DM are well-established. Leptons are fairly easily extrapolated and work to describe weak (& Higgs) bosons is well-underway (motivated in part by the Fermi line 'signal').
  - We have simplified models to describe simple colored mediators. Together with the Z'-like and scalar mediators, we have a handful of simplified models with a (reasonably) small set of parameters to play with.
  - We heard that leptons are underway as well.
  - There are still directions worth exploring connecting to Higgs or weak bosons.
  - Fully realized models should march forward, limited by our imaginations.

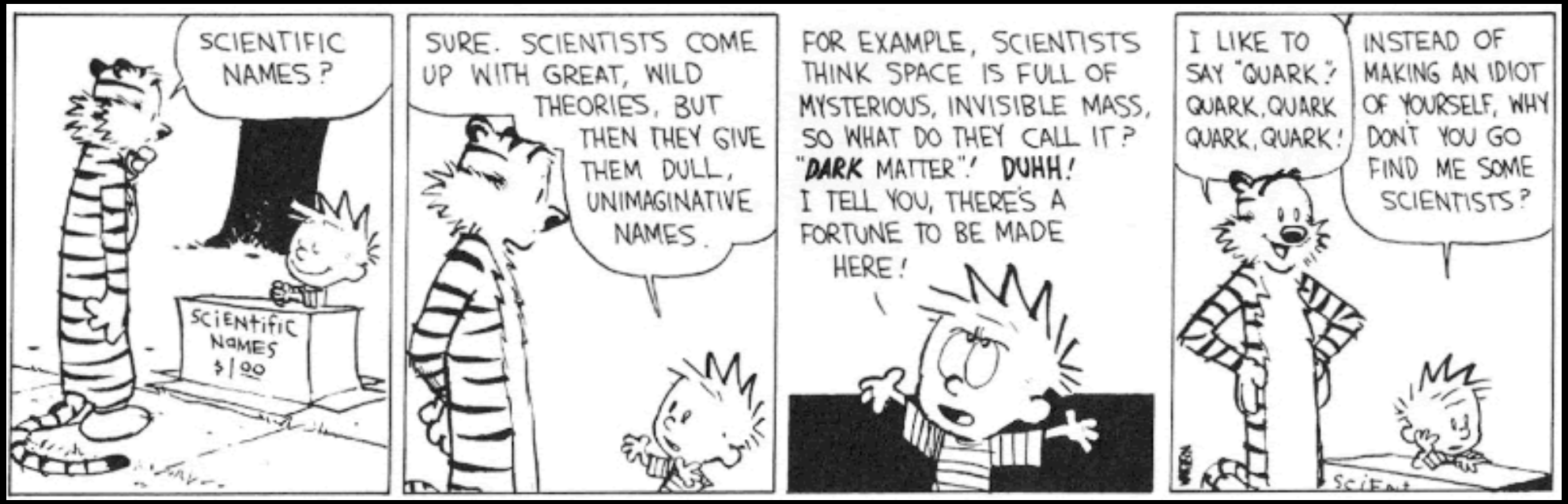
Outlook

- We have made a lot of progress in terms of understanding the existing model frameworks:
  - pMSSM scans characterize the MSSM parameter space to a degree that (finally!) makes many of us comfortable.
    - Can we realize a pNMSSM? Do we want something else as well?
  - We have seen at this workshop:
    - Explorations of the range of validity of the EFTs
    - Higher order corrections: mixing operators and improving the accuracy of predictions.
    - Exploration of new signals such as (s)razor and heavy flavor
    - We still have directions to explore: e.g. flavor constraints
  - We would like to understand the simplified models at the same level!
- Most importantly, we have beautiful experimental work that extends the reach and depth of our understanding of the properties of dark matter!

From Sketch to Life



Sketches of ....



Thank you!

Bonus Material

A Possible Timeline

2013

2014

2015

2016

2017

2018

- [ ] Mass
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

2016

2017

2018

- [?] Mass: < 200 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

2016

2017

2018

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Two LHC experiments see a significant excess of leptons plus missing energy.

Xenon sees a similar signal.

2016

2017

2018

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [?] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [?] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

2015

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Xenon sees
gnal.

Two LHC experiments see a significant excess of leptons plus missing energy.

No jets + MET

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Neutrinos are seen coming from the Sun by IceCube.

- [x] Mass: 150 +/- 15 GeV
- [x] Spin: > 0
- [ ] Stable?

Couplings:

- [x] Gravity
- [x] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [x] Leptons
- [ ] Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

2015

Xenon sees a similar signal.

2016

Two LHC experiments see a si
lept

2017

A positive signal of axion conversion is observed at an upgraded ADMX.

2018

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

☑ Mass: 150 +/- 15 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Photon Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☐ Thermal Relic?	☒ Thermal Relic?

A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

????

✓ Mass: 150 +/- 0.1 GeV	✓ Mass: 20 μeV
✓ Spin: > 0	✓ Spin: 0
☐ Stable?	✗ Stable?
Couplings:	Couplings:
✓ Gravity	✓ Gravity
✗ Weak Interaction?	✓ Photon Interaction
☐ Higgs?	☐ Higgs?
✓ Quarks / Gluons	☐ Quarks / Gluons?
✓ Leptons	☐ Leptons?
✓ Thermal Relic	✗ Thermal Relic?

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.

A Possible Timeline

2013

2014

2015

2016

2017

2018

????

LUX sees
elastic scat
consistent
mass <

Xenc
a simil

A positive signal of axion conversion is observed at an upgraded ADMX.

☑ Mass: 150 +/- 0.1 GeV	☑ Mass: 20 μeV
☑ Spin: > 0	☑ Spin: 0
☐ Stable?	☒ Stable?
Couplings:	Couplings:
☑ Gravity	☑ Gravity
☒ Weak Interaction?	☑ Weak Interaction
☐ Higgs?	☐ Higgs?
☑ Quarks / Gluons	☐ Quarks / Gluons?
☑ Leptons	☐ Leptons?
☑ Thermal Relic	☒ Thermal Relic?

A multi-pronged search strategy identifies a mixture of dark matter which is 50% classic WIMP and 50% axion.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Neutrinos are seen coming from the Sun by IceCube.

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.