Complementarity of Searches for Dark Matter

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SSI

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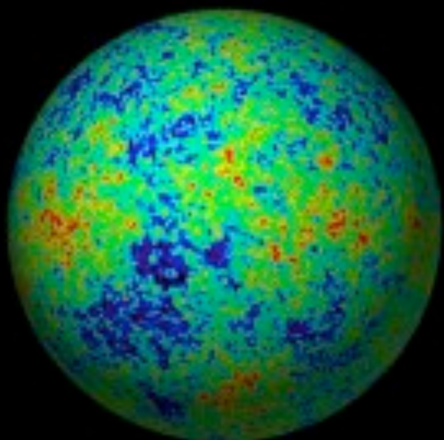
Outline

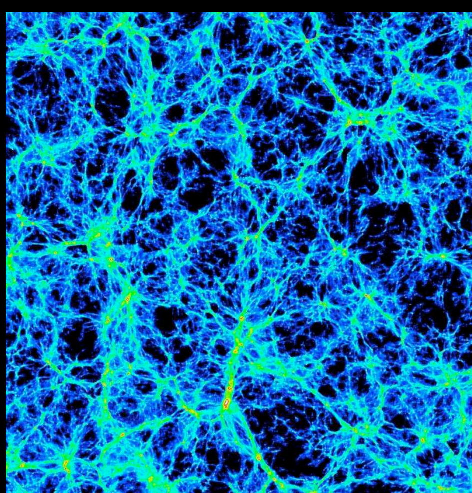
- Motivation: How do Dark Matter Searches fit Together?
  - The Importance of WIMP-Standard Model Interactions
- Theory frameworks for dark matter interactions
  - Contact Interactions
  - Simplified Models
- Outlook

Dark Matter

CMB



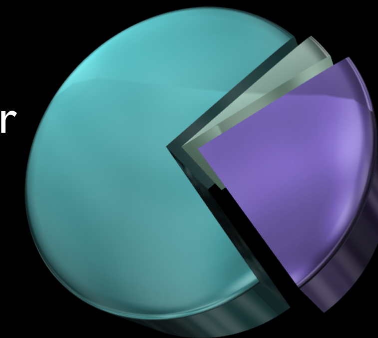
Supernova

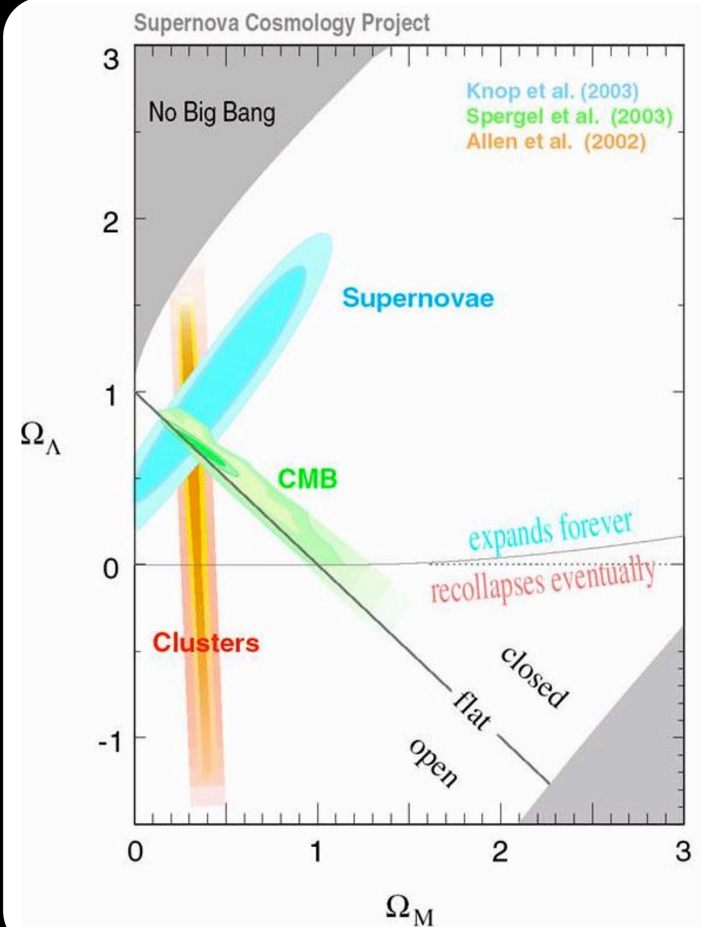


Structure

Lensing

Ordinary Matter
Dark Matter
Dark Energy





So what is Dark Matter?

"Cold Dark Matter: An Exploded View" by Cornelia Parker

- As a particle physicist I want to know how dark matter fits into a particle description.
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

The Dark Matter Questionnaire

- [ ] Mass
- [ ] Spin
- [ ] Stable?
  - [ ] Yes
  - [ ] No

Couplings:

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

Thermal Relic?

- [ ] Yes
- [ ] No

WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.

Kathryn told us about that last week...

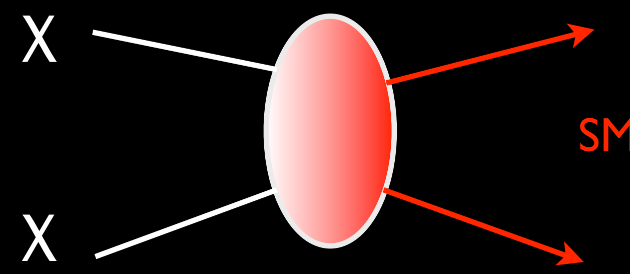
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as supersymmetric extensions with R-parity.
- I will try to avoid any further discussion of specific theories. My attitude is going to be that dark matter is something worth discussing in and of itself rather than a by-product of other theoretical constructions.
  - But we will see that we do need some kind of theoretical framework to put experimental results into context.

$59.99 for 20 servings

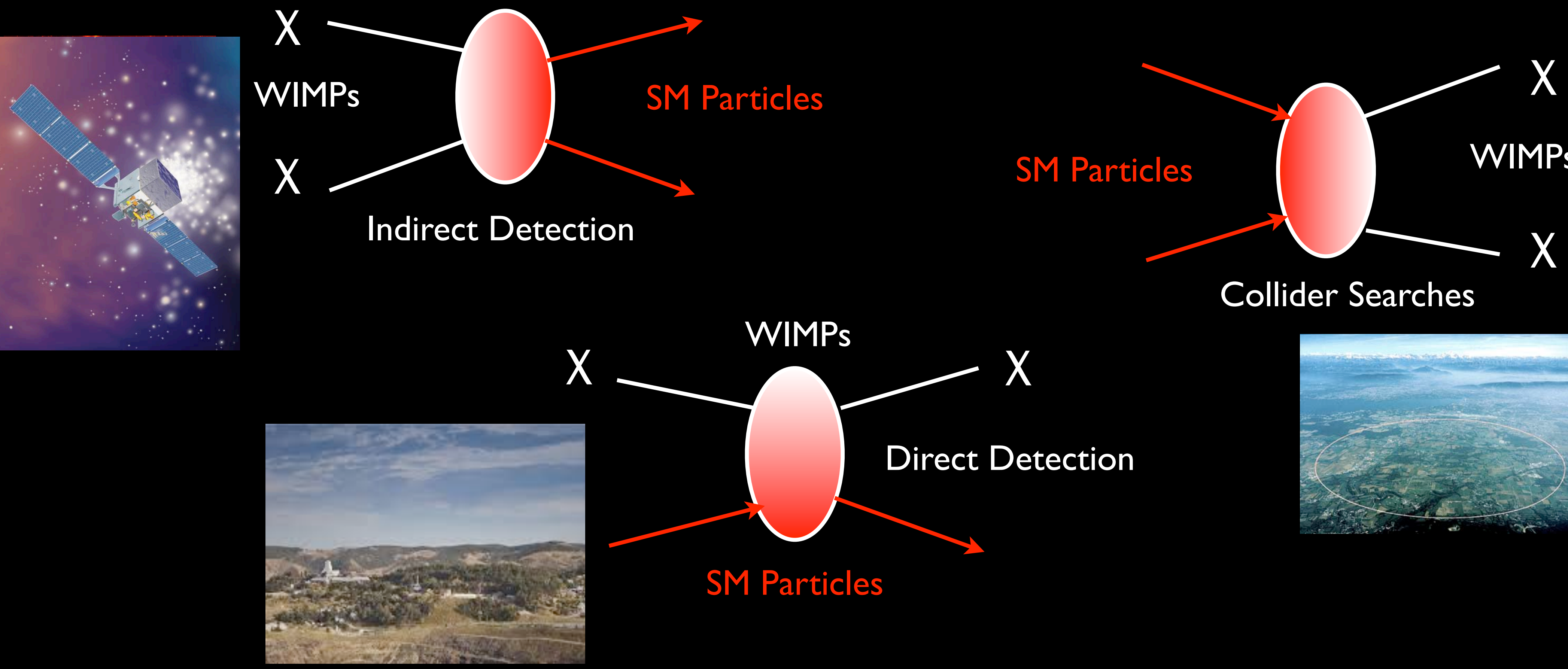
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

WIMP Interactions

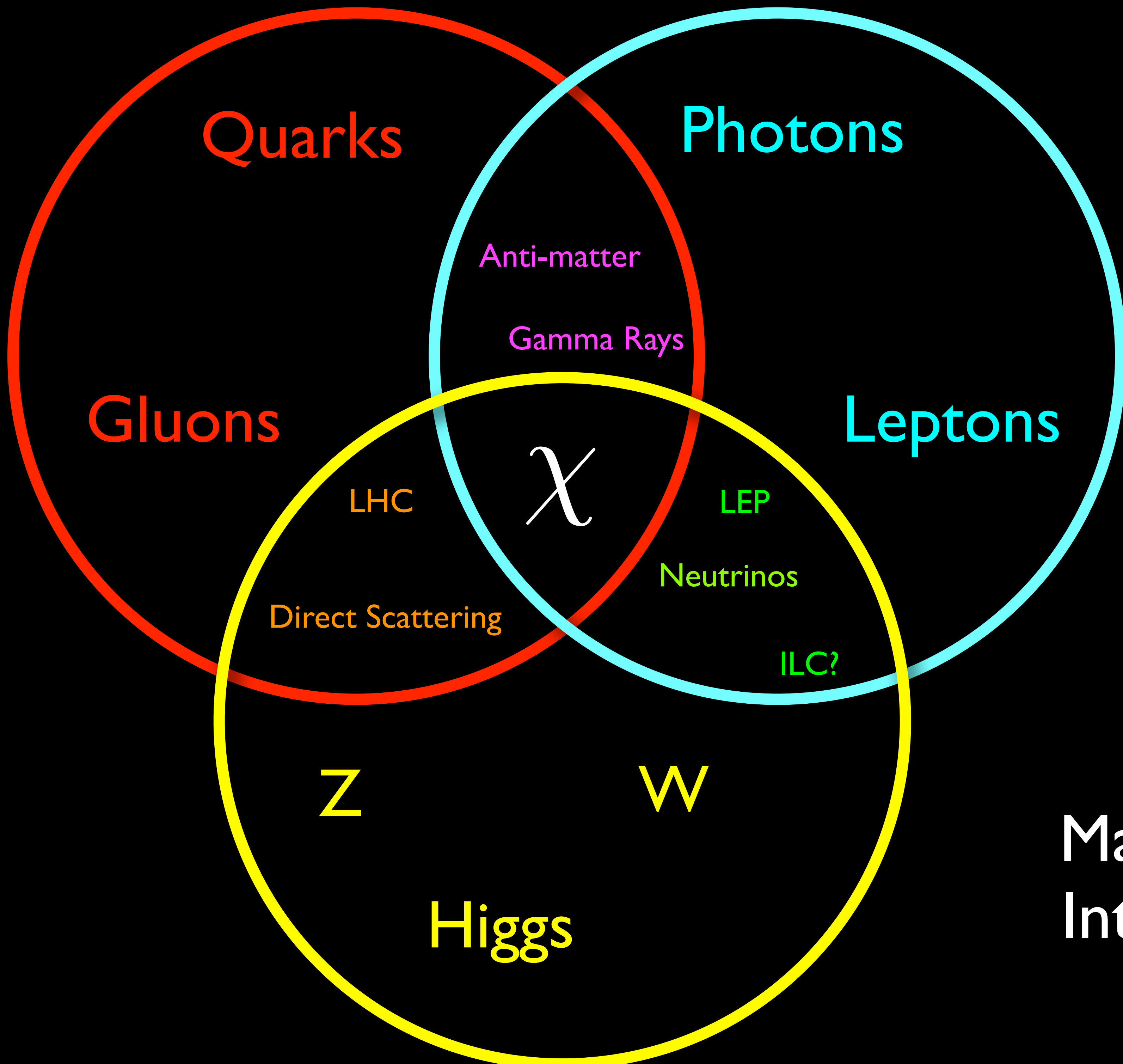
- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute σ(XX -> SM particles) and check the relic density.
  - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
  - If not, we will look for new physical processes to make up the difference.
- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.



Particle Probes of DM



- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

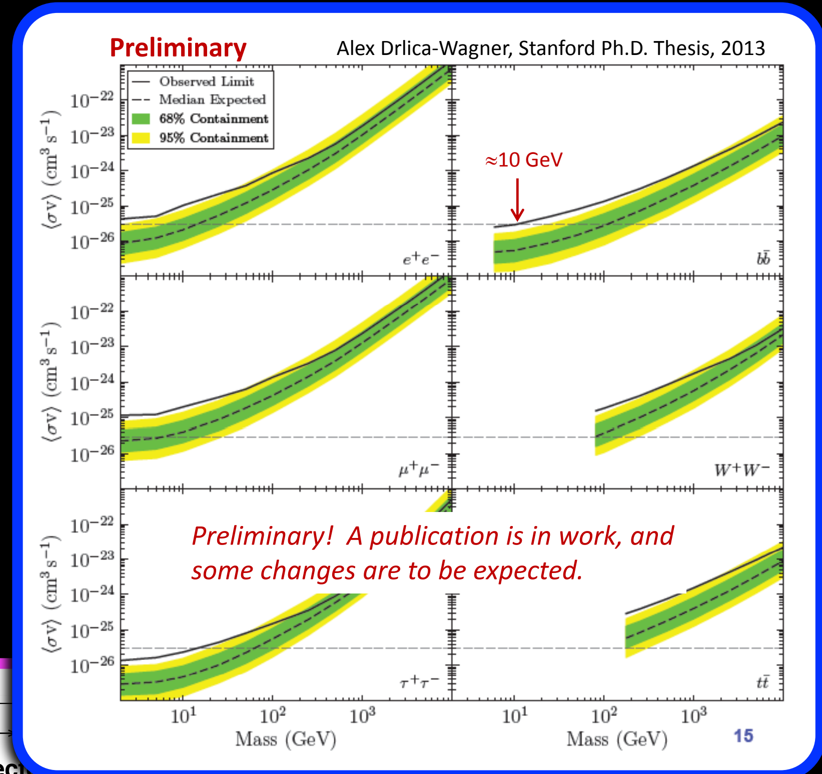


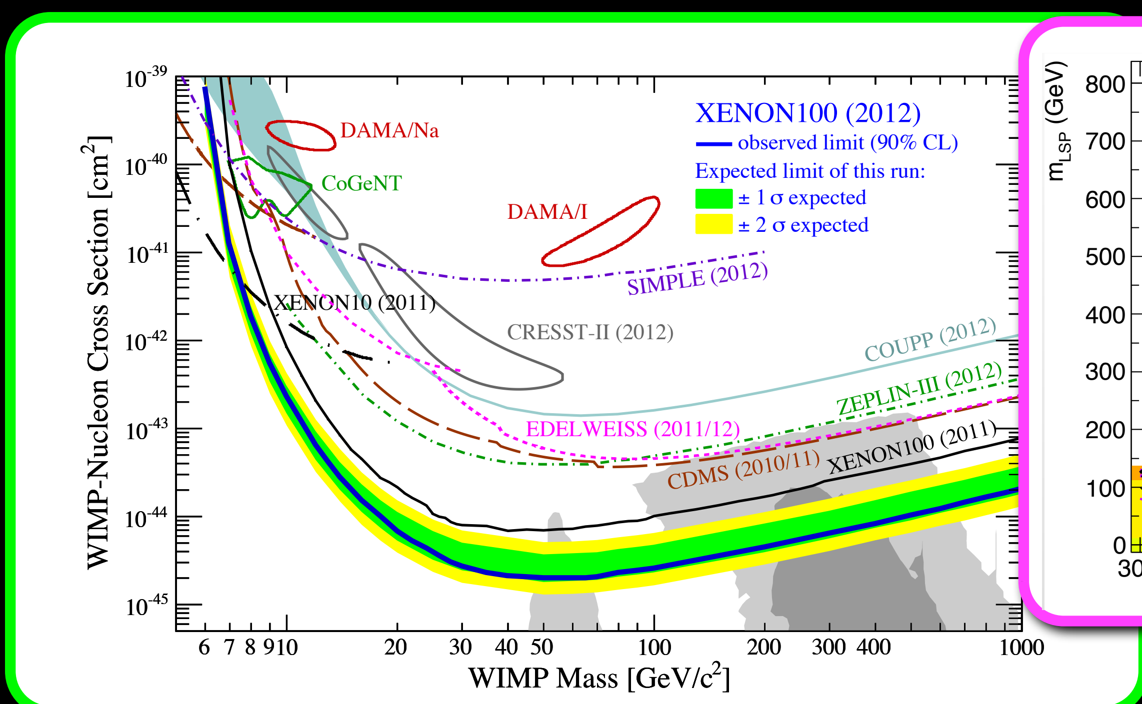
Map of DM Interactions

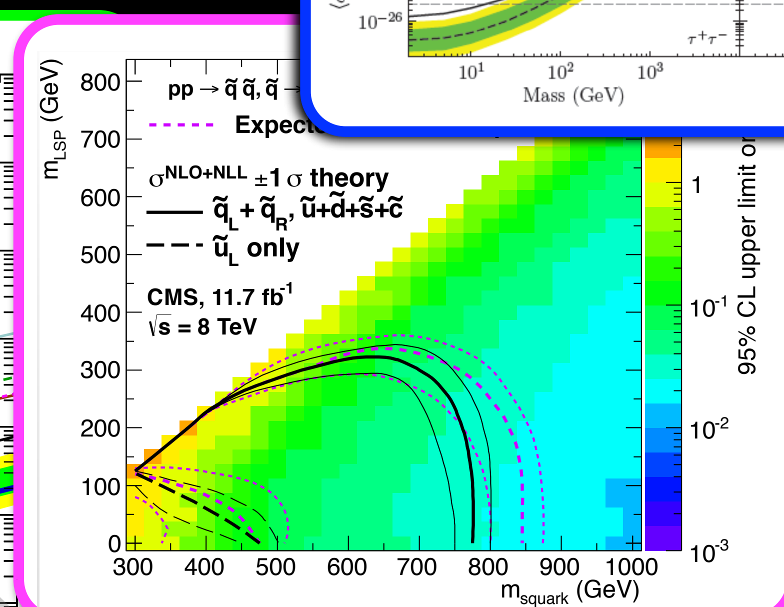
We Need (a) Theory

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

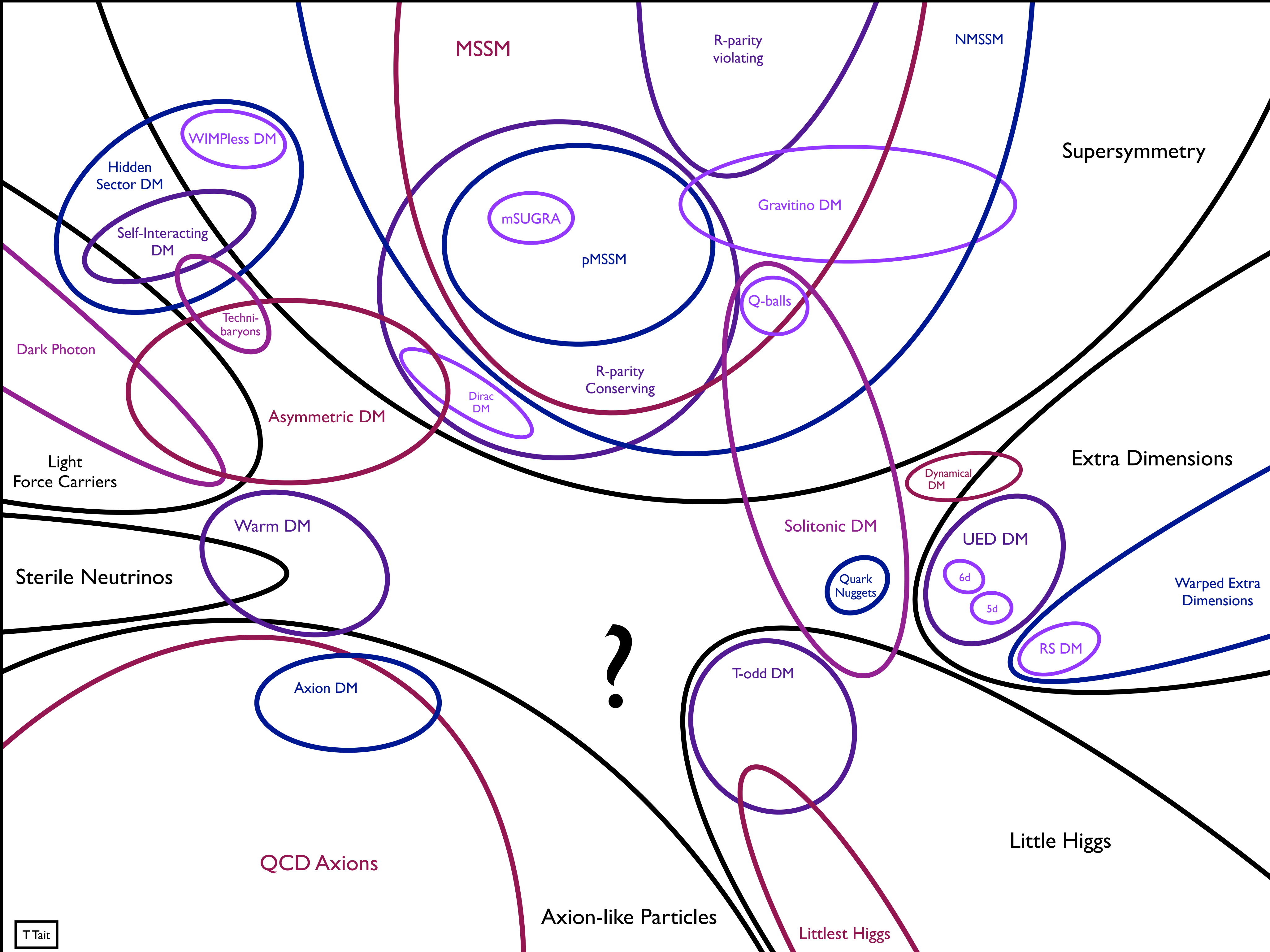
But we *know* they are all attempts to characterize the same thing(s)...

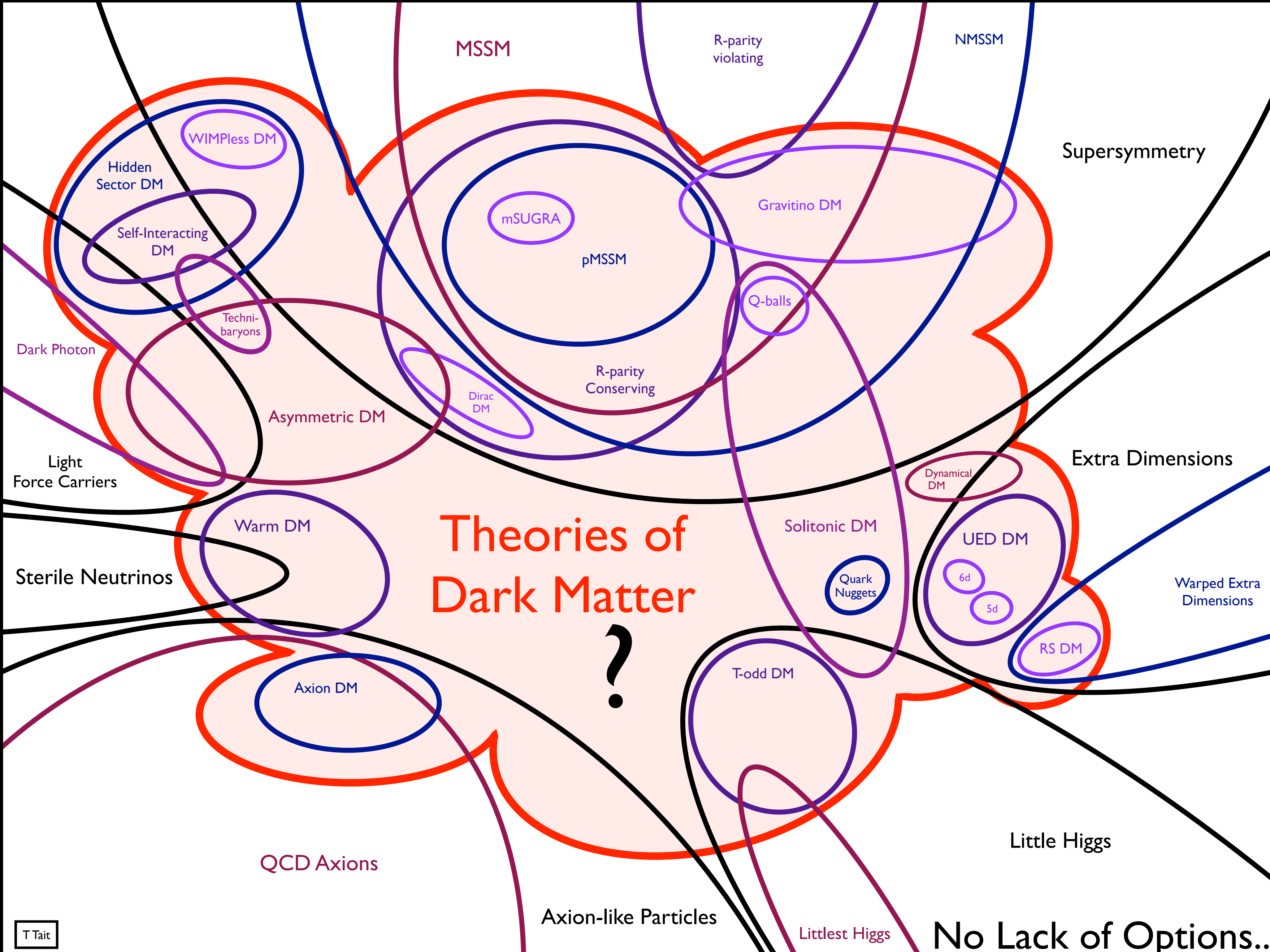






Which theory to use?


MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
Techni-
baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity
Conserving
Dirac
DM
Dark Photon
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
?
Axion DM
T-odd DM
QCD Axions
Little Higgs
Axion-like Particles
Littlest Higgs
T Tait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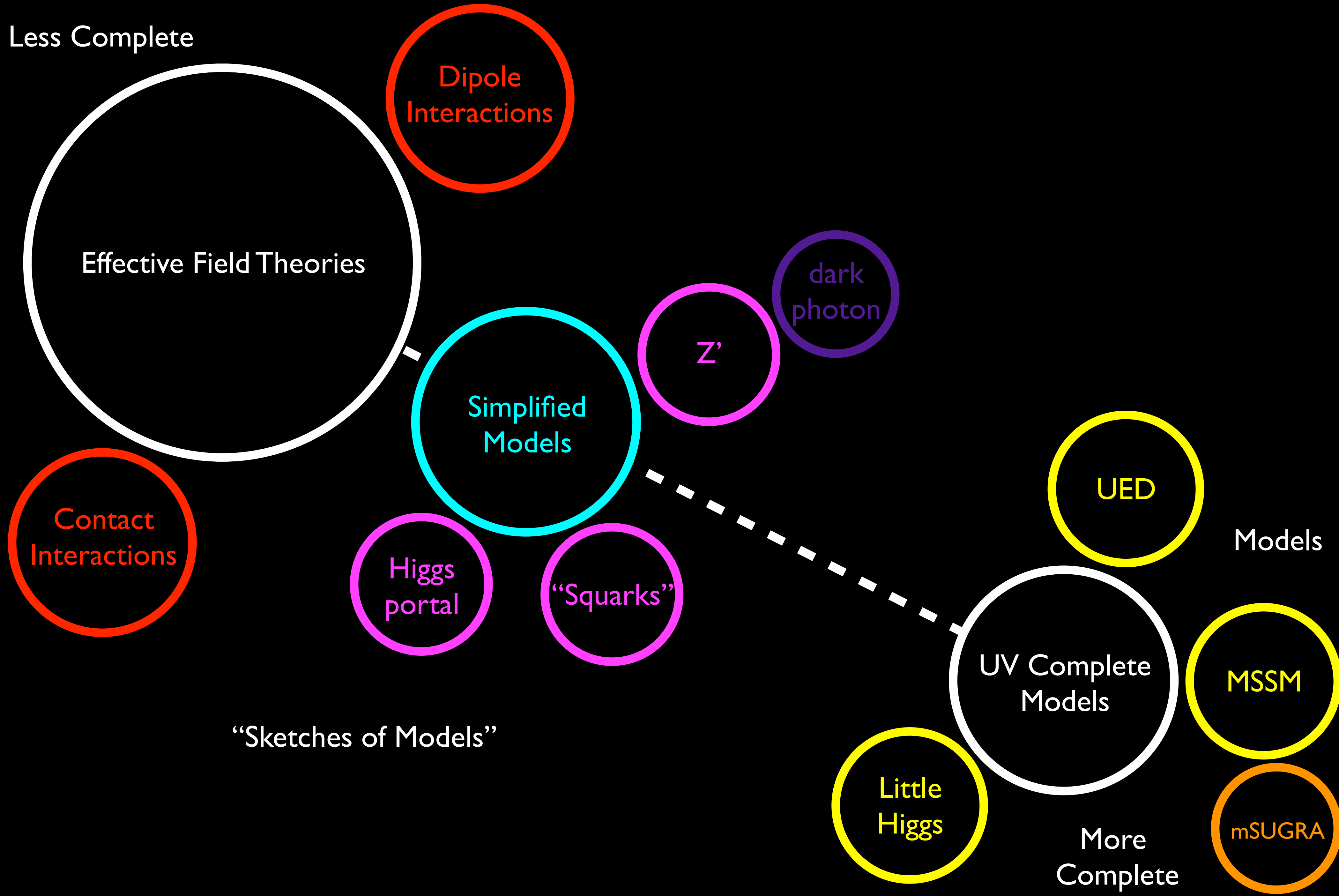
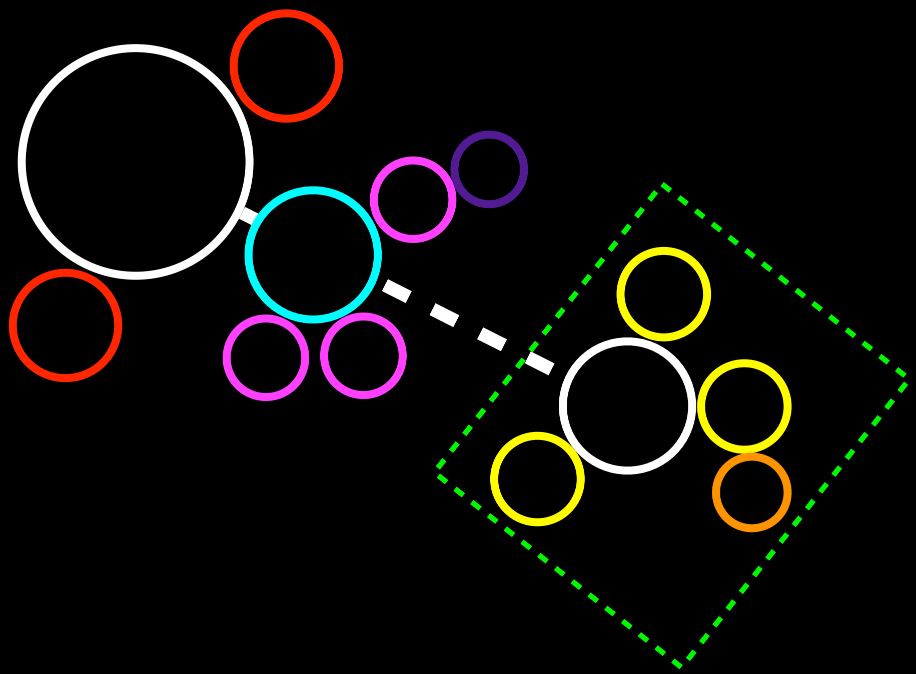
Axion-like Particles
Littlest Higgs
No Lack of Options...
T Tait

Spectrum of Theory Space



“Complete” Theories



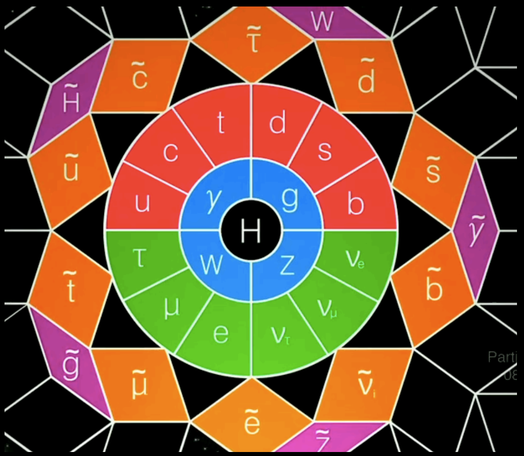
MSSM

- An obvious first place to start would be with complete theories of dark matter, the most obvious example of which is our favorite theory: the MSSM.

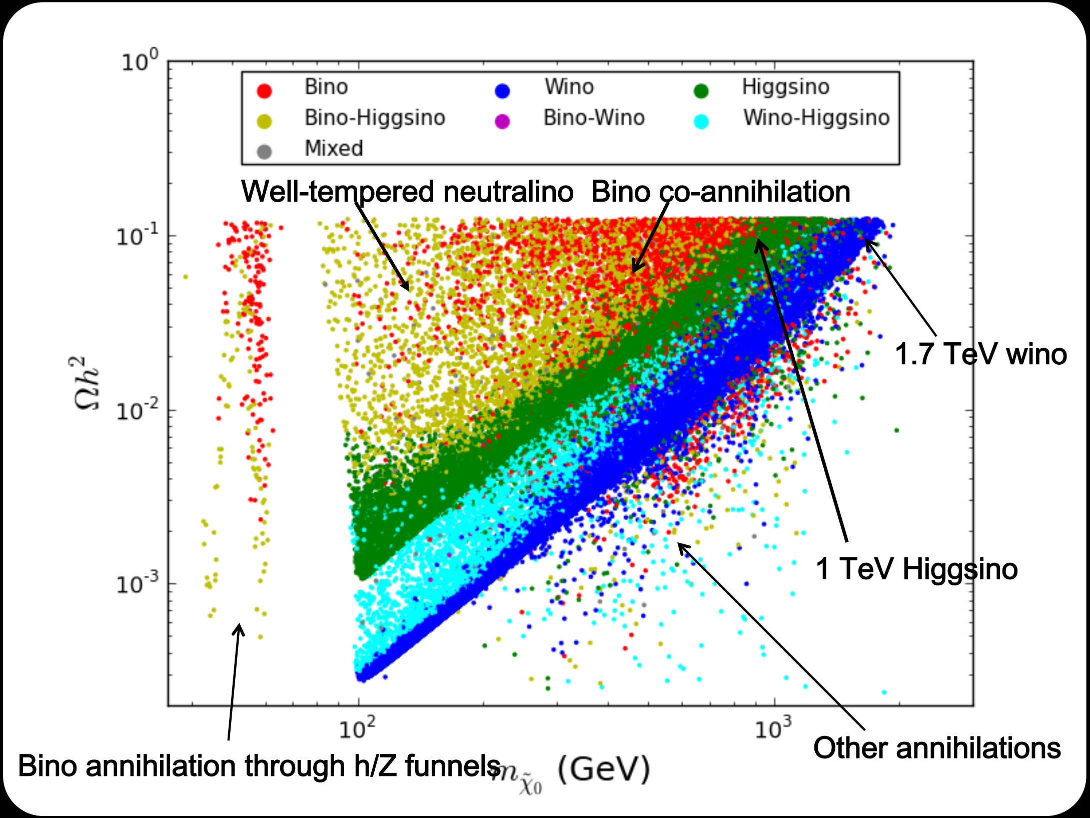
- Reasonable parameterizations have ~20 parameters, leading to rich and varied visions for dark matter.

- This plot shows a scan of the `pMSSM' parameter space by the SLAC group, in the plane of the WIMP mass versus the relic abundance.

- It is evident that the MSSM is a rich theory of dark matter, with several different paths to explain it.



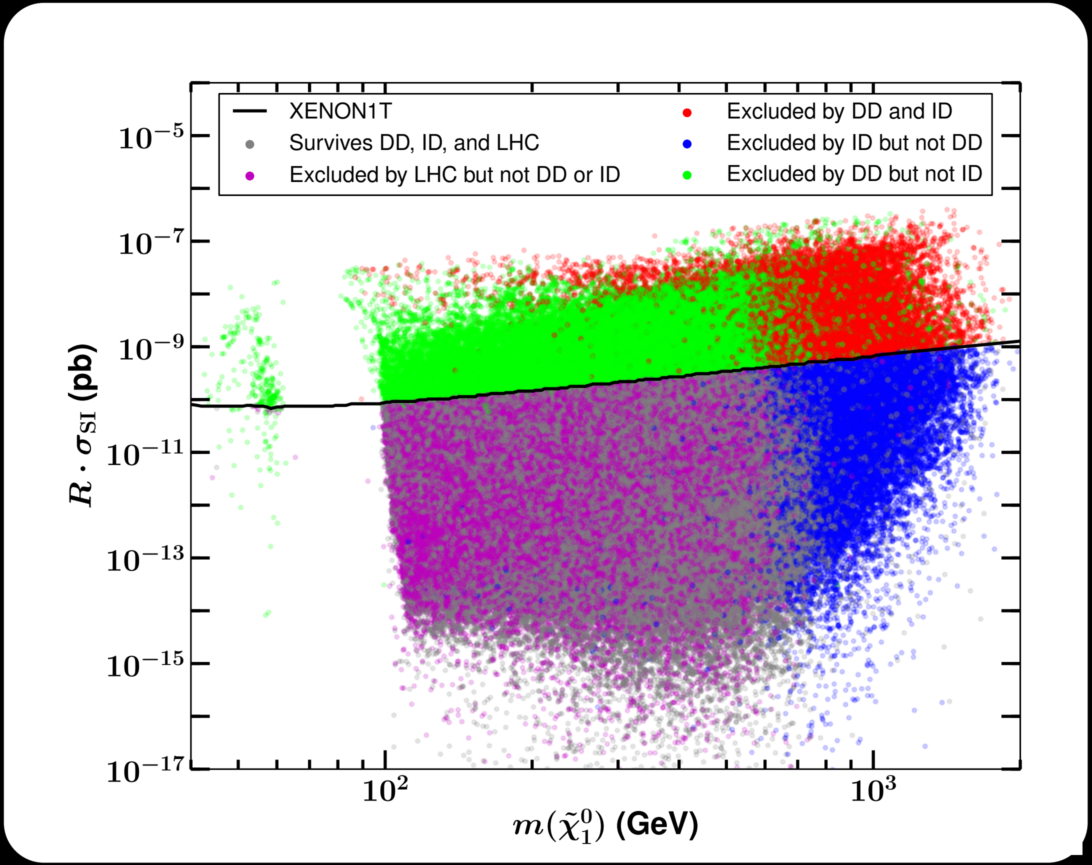
Particle Fever



Cahill-Rowley et al, 1305.6921 & 1405.6716

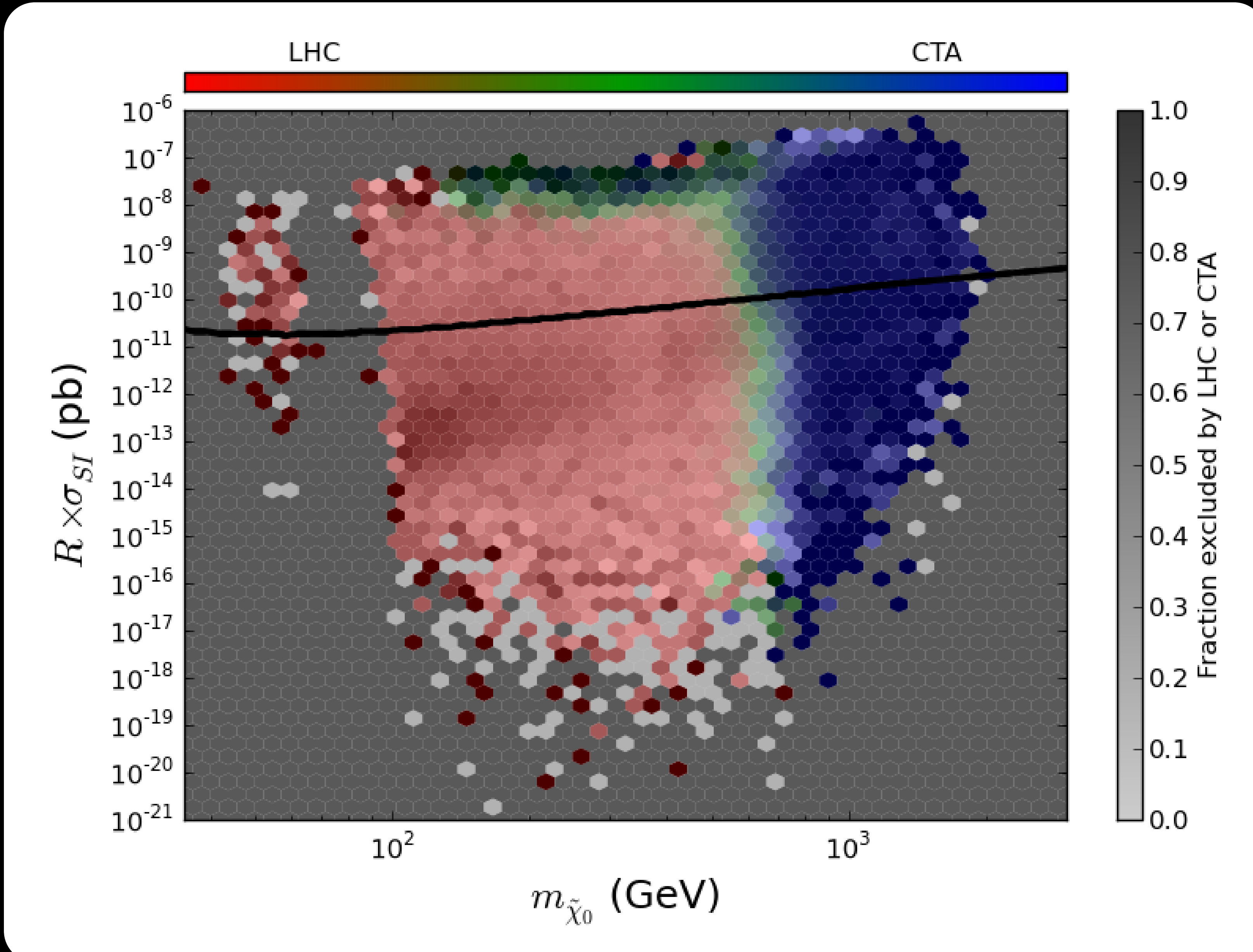
Direct Detection

- Given the large set of model points , they can also be compared with experimental searches. Since 20 dimensional blobs are not very easy to visualize, it is easier to project down onto some parameters of interest.
- This plot shows a projection onto the mass of the dark matter versus the spin-independent cross section.
- Definite trends are visible in addition to the obvious one based on direct detection itself. Heavier dark matter is more easily accessible to indirect searches such as CTA.



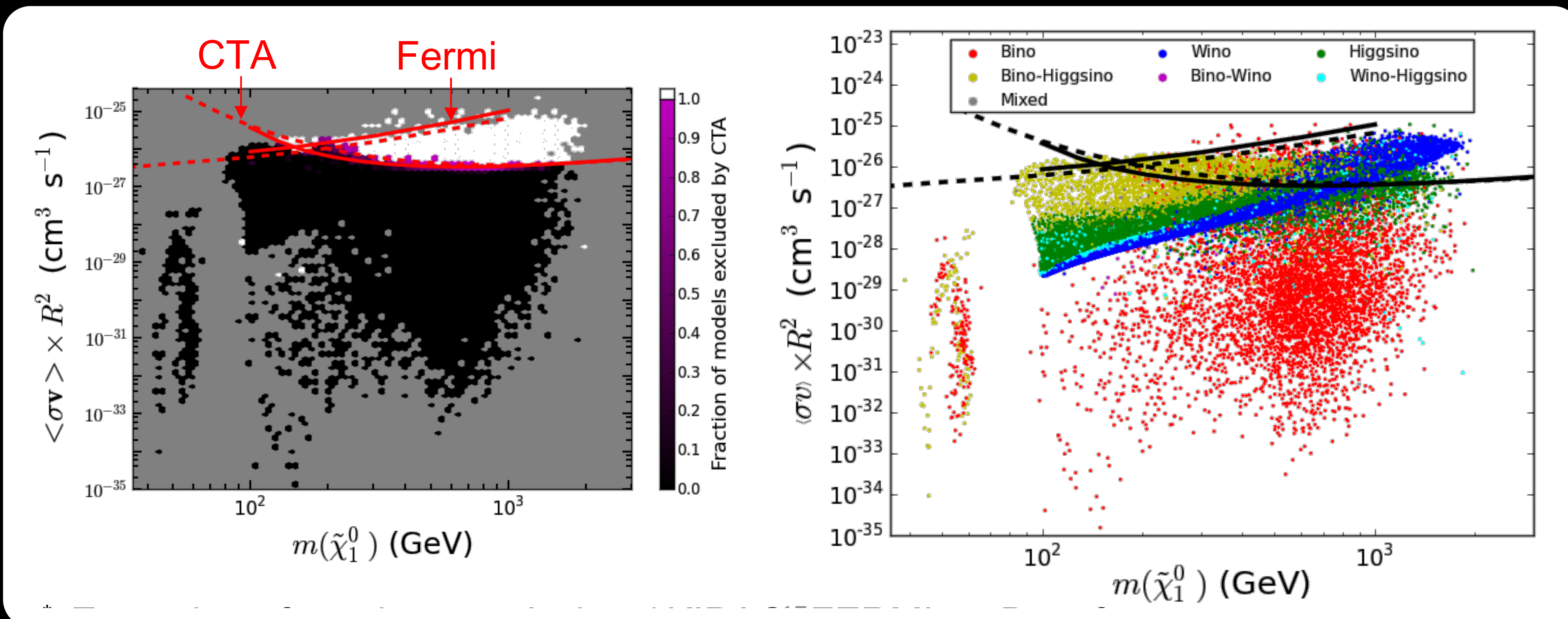
Cahill-Rowley et al, 1305.6921 & 1405.6716

Coverage Distribution



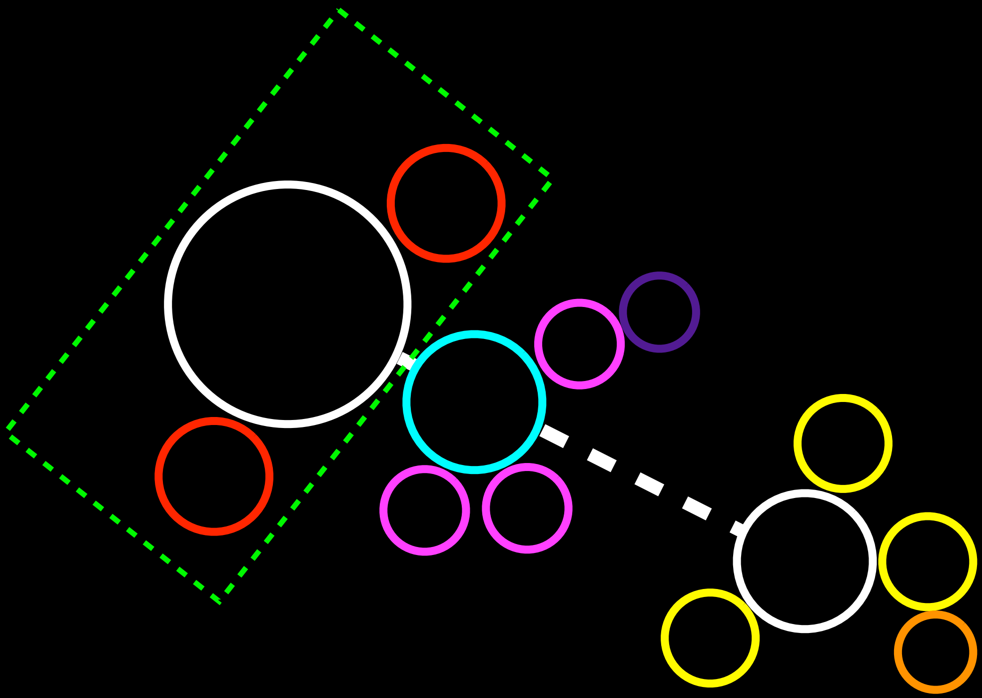
Cahill-Rowley et al, 1305.6921 & 1405.6716

Gamma Rays

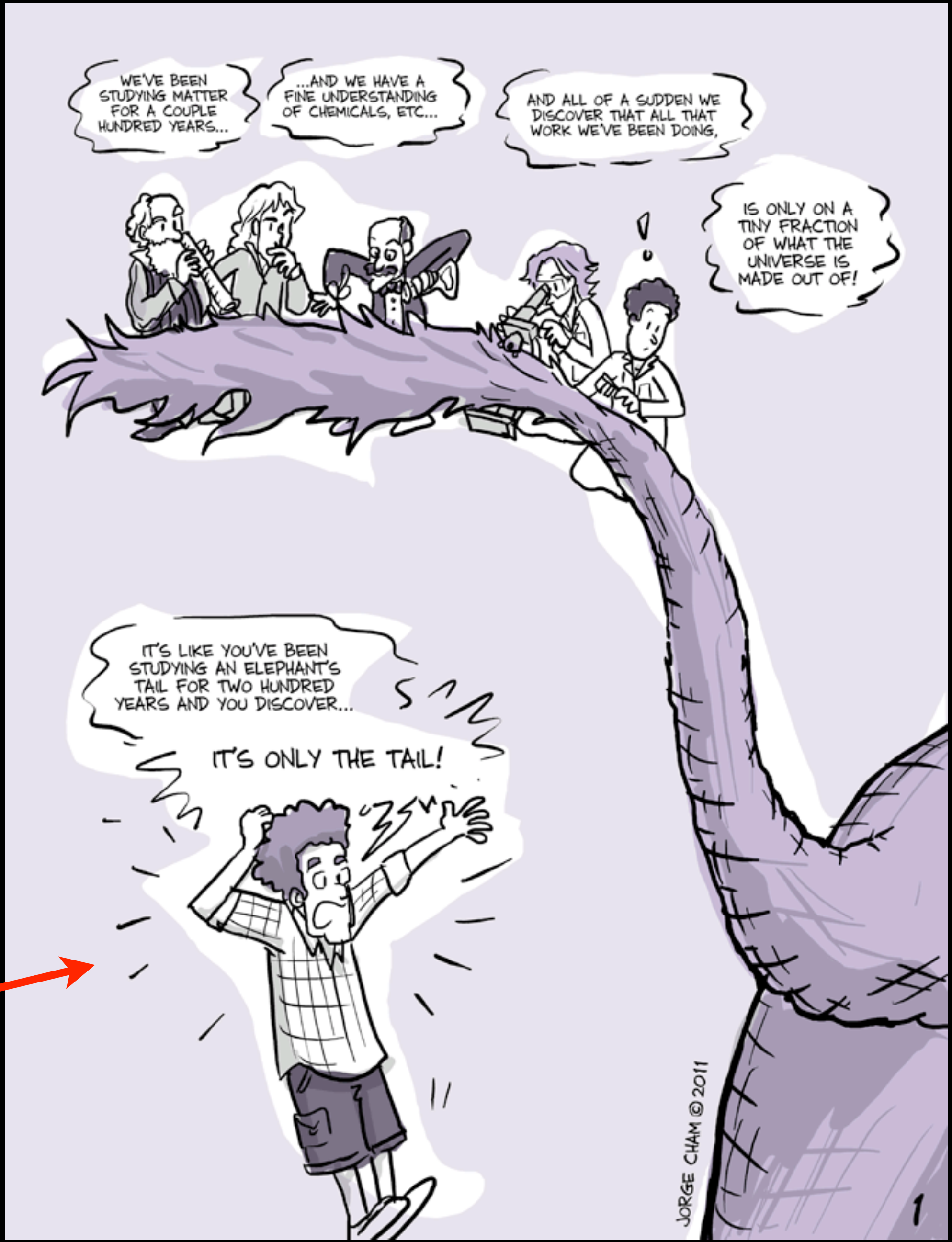


Cahill-Rowley et al, 1305.6921 & 1405.6716

Contact Interactions

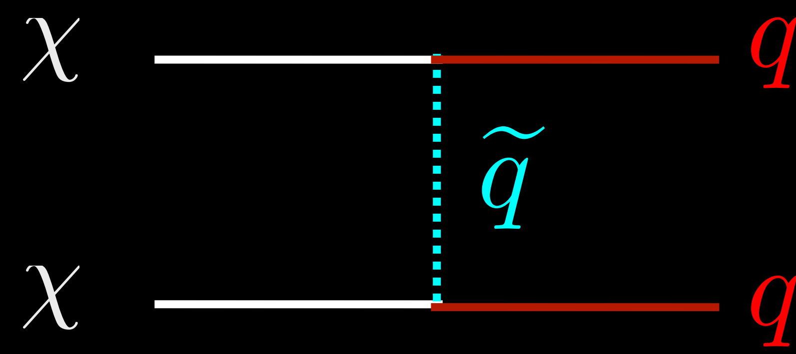


Can One Sketch a Theory?

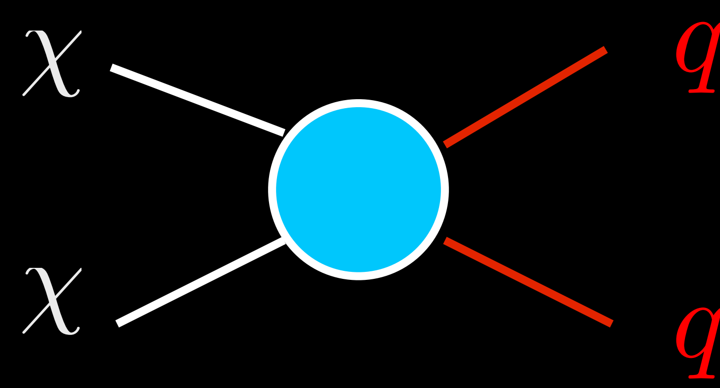


Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible 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 such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will break down at high energies, where one can produce more of the new particles directly.



$$\frac{g^2}{M_{\tilde{q}}^2} \leftrightarrow G_{eff}$$



Example: Majorana WIMP

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- As an example, we can write down the operators of interest for a Majorana WIMP.
- There are 10 leading operators consistent with Lorentz and SU(3) x $U(1)_{EM}$ gauge invariance coupling the WIMP to quarks and gluons.
- Each operator has a (separate) coefficient M_* which parametrizes its strength.
- In principle, a realistic UV theory will turn on some combination of them, with related coefficients.

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	-

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

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

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

Example: Majorana WIMP

- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation
  - Collider Production

Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

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Collider Searches

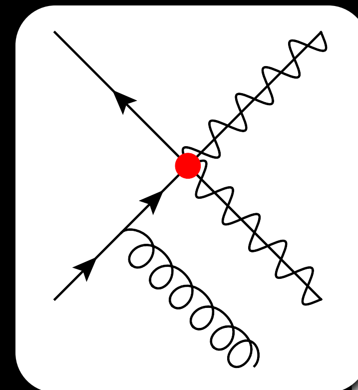
- At colliders, one searches for this type of theory by producing the dark matter directly.

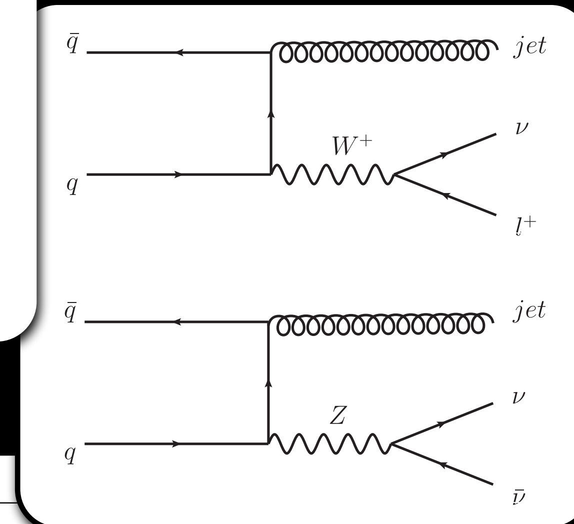
Daniel told us about this last week...

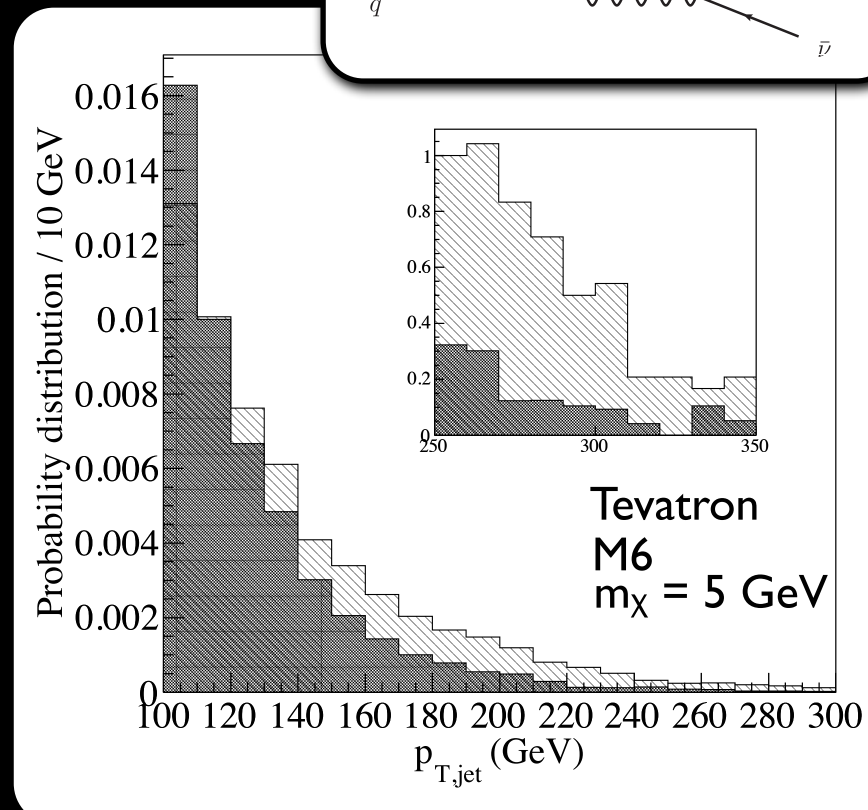
- Since the detector needs something to trigger on, one looks for processes with additional final state particles, and infers the presence of dark matter based on the missing momentum it carries away from the interaction.

- There are the usual SM backgrounds from Z + jets, as well as fake backgrounds from QCD, etc.

- Contact interactions grow with energy, generically leading to a harder MET spectrum than the SM backgrounds.

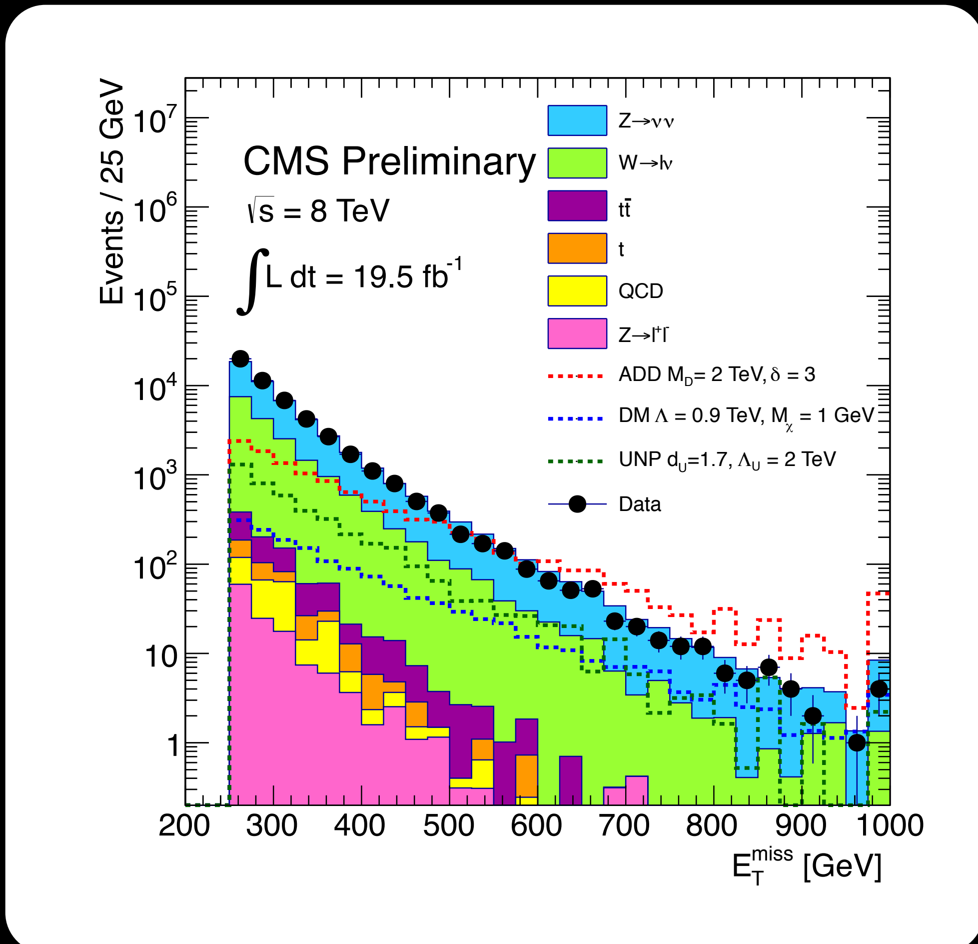


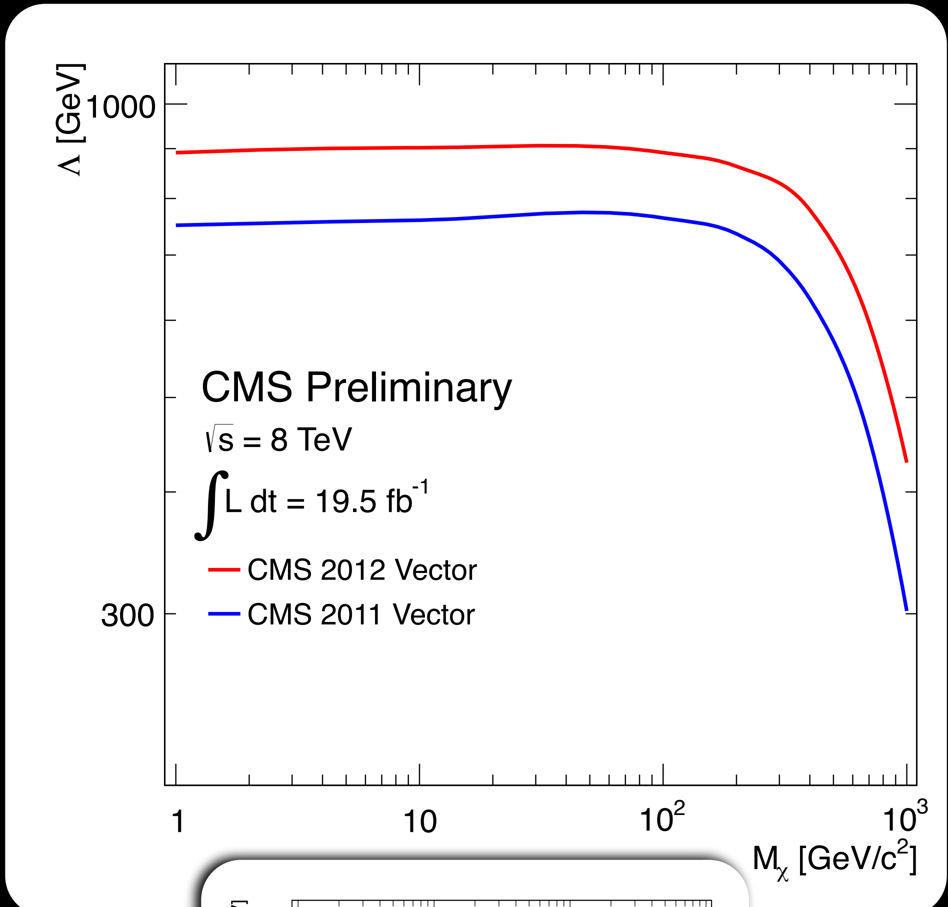


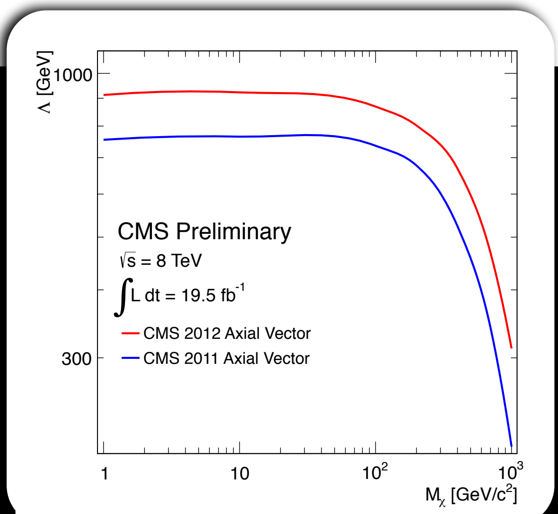


Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP

Collider Results

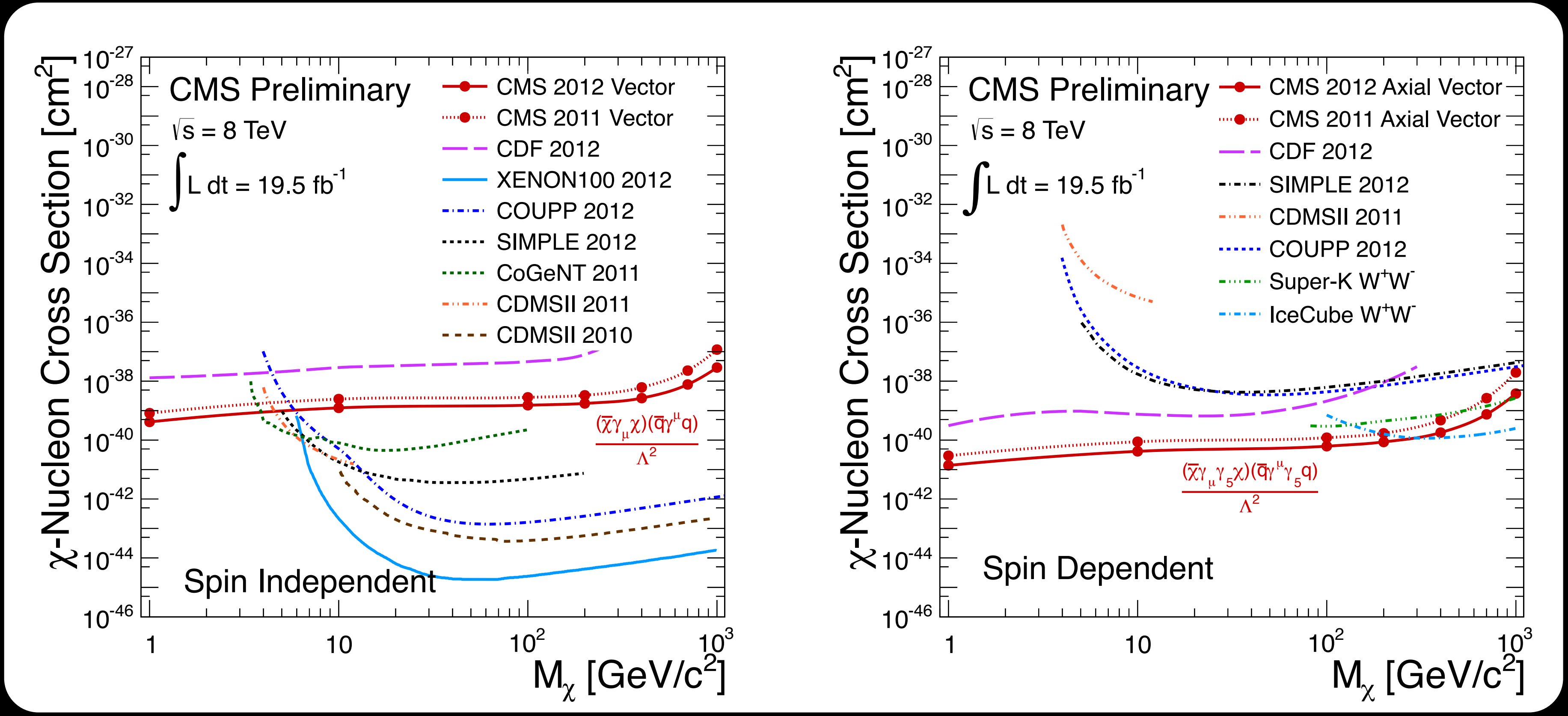






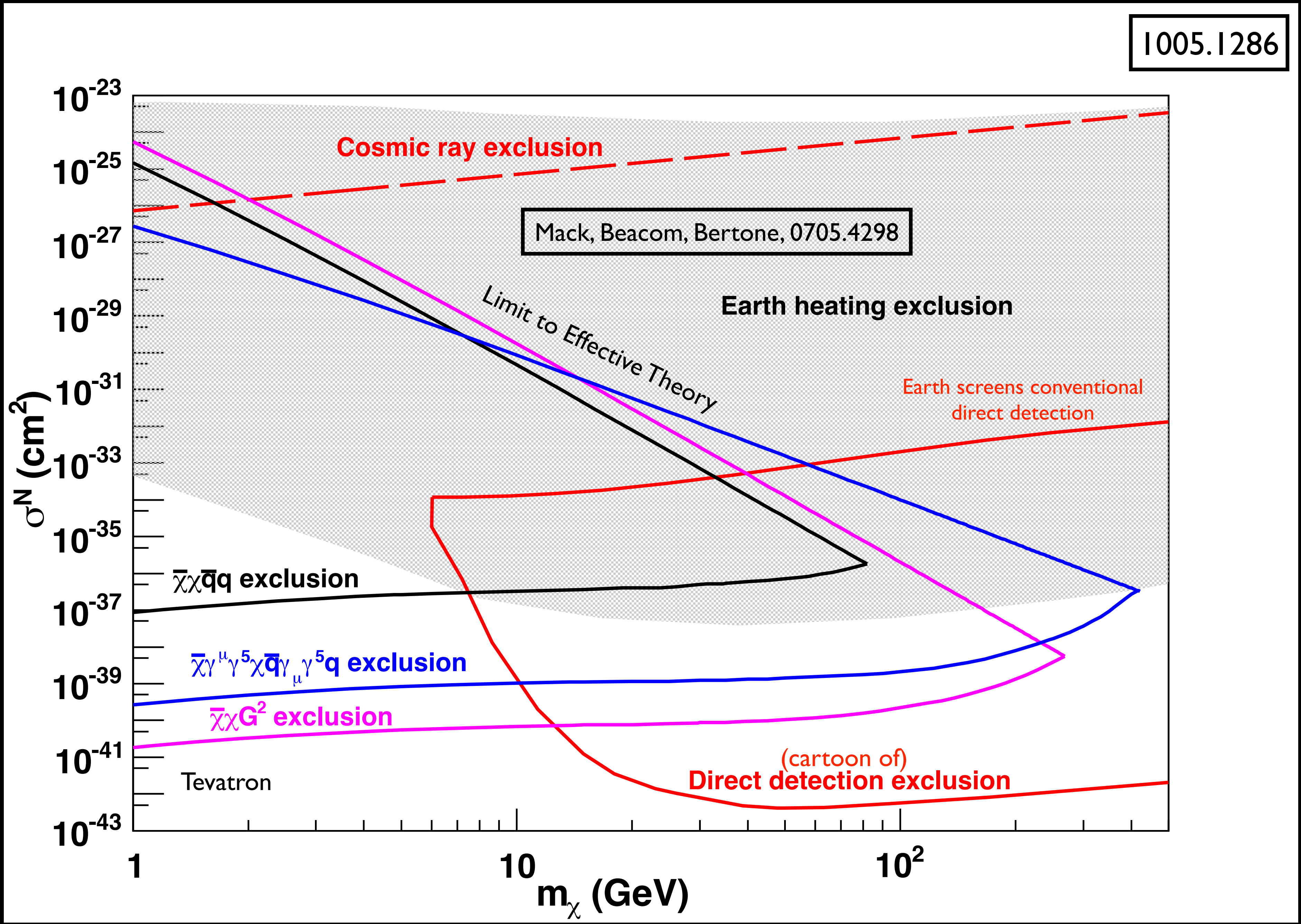
Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

Translation to Elastic Scattering



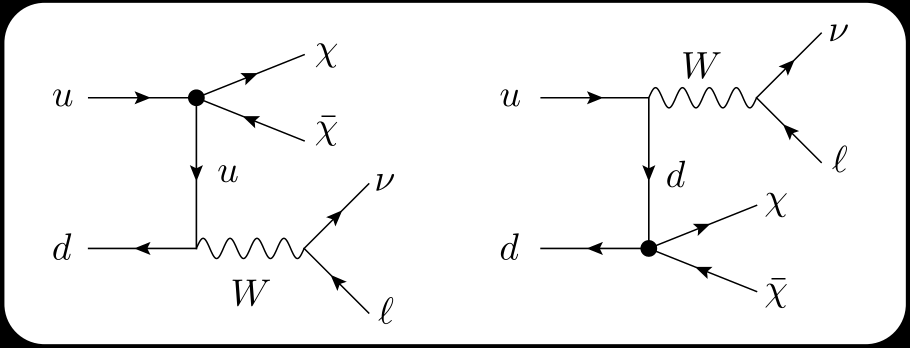
- Colliders can help fill in a challenging region of low dark matter mass and spin-dependent interactions.
- Since they see individual partons, rather than the nucleus coherently, collider results offer a complementary perspective on DM interactions with hadrons.
- The translation assumes a heavy mediating particle (contact interaction).

From WIMPs to SIMPs...



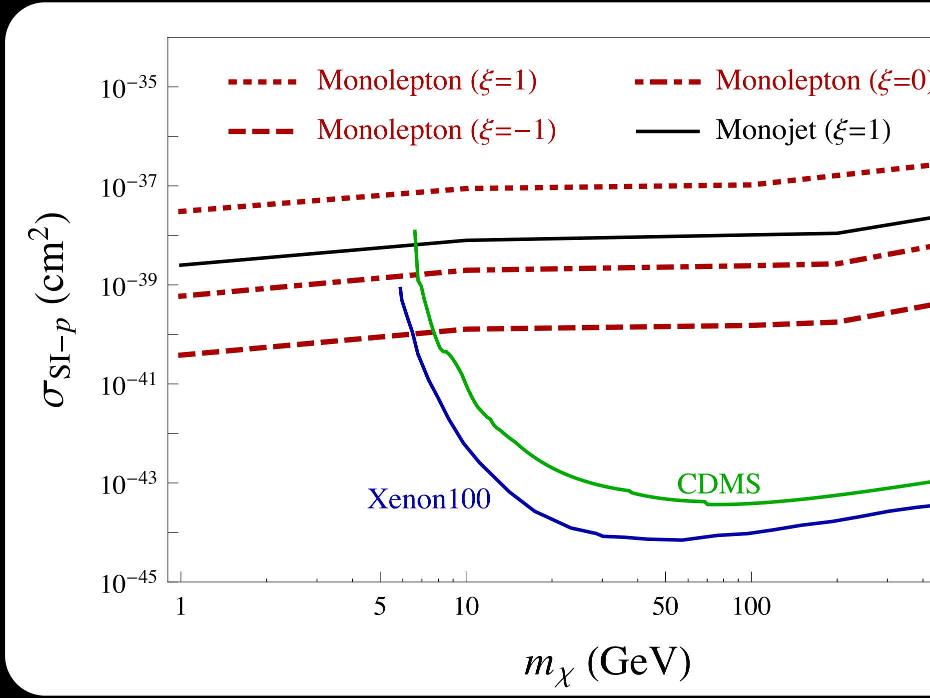
Mono-Whatever

- We've already heard a lot about 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 thus are complementary.
- And even for quarks, if we do see something, they can dissect the couplings to different quark flavors, etc.



CMS W' Search

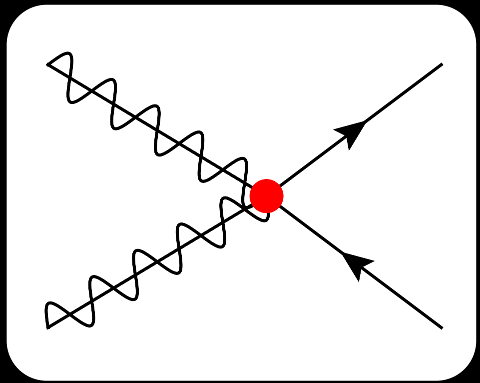
Y. Bai, TMPT, 1207.mono-whenever

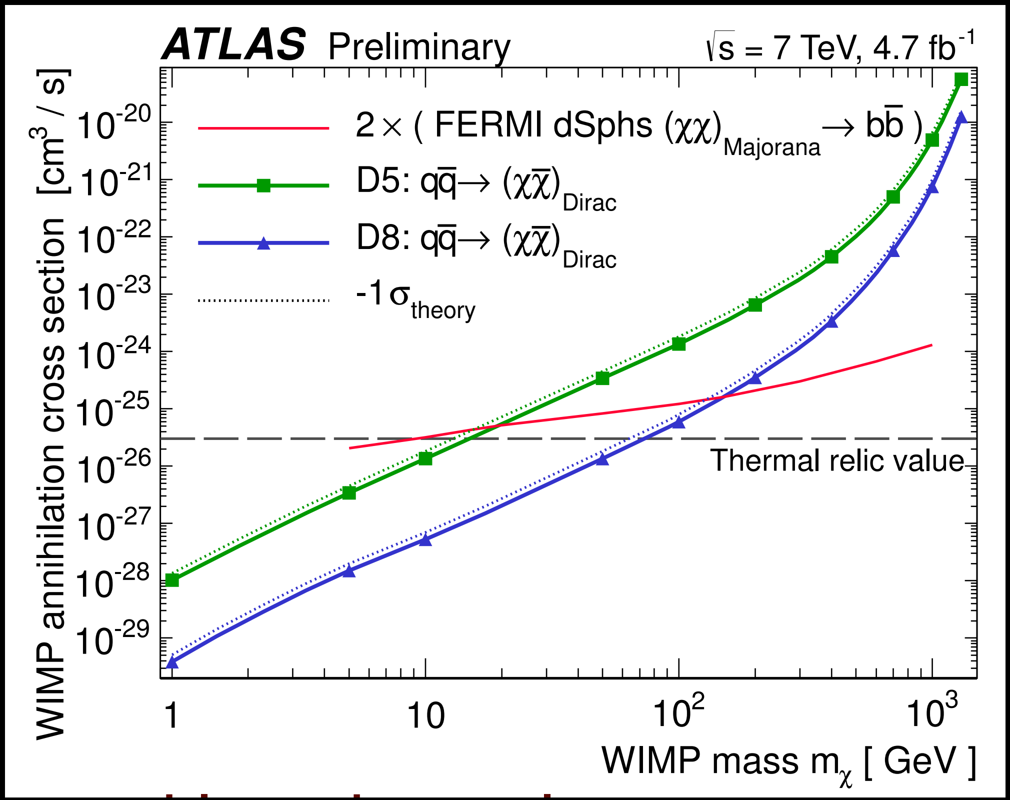


(d coupling) = ξ x (u coupling)

Annihilation into γ-Rays

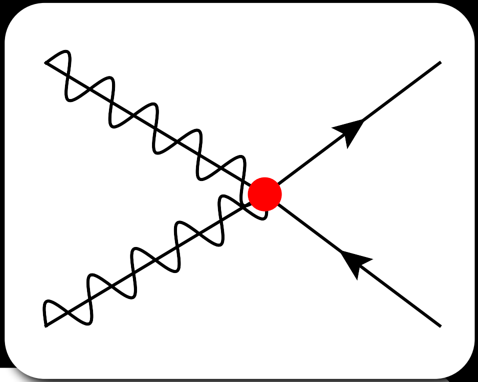
- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks or gluons.
- ATLAS has already presented their results in terms of a corresponding annihilation cross section.
- With assumptions, this maps onto a relic density.
- For operators which lead to p-wave annihilations, the colliders can lead to more stringent bounds than Fermi LAT.

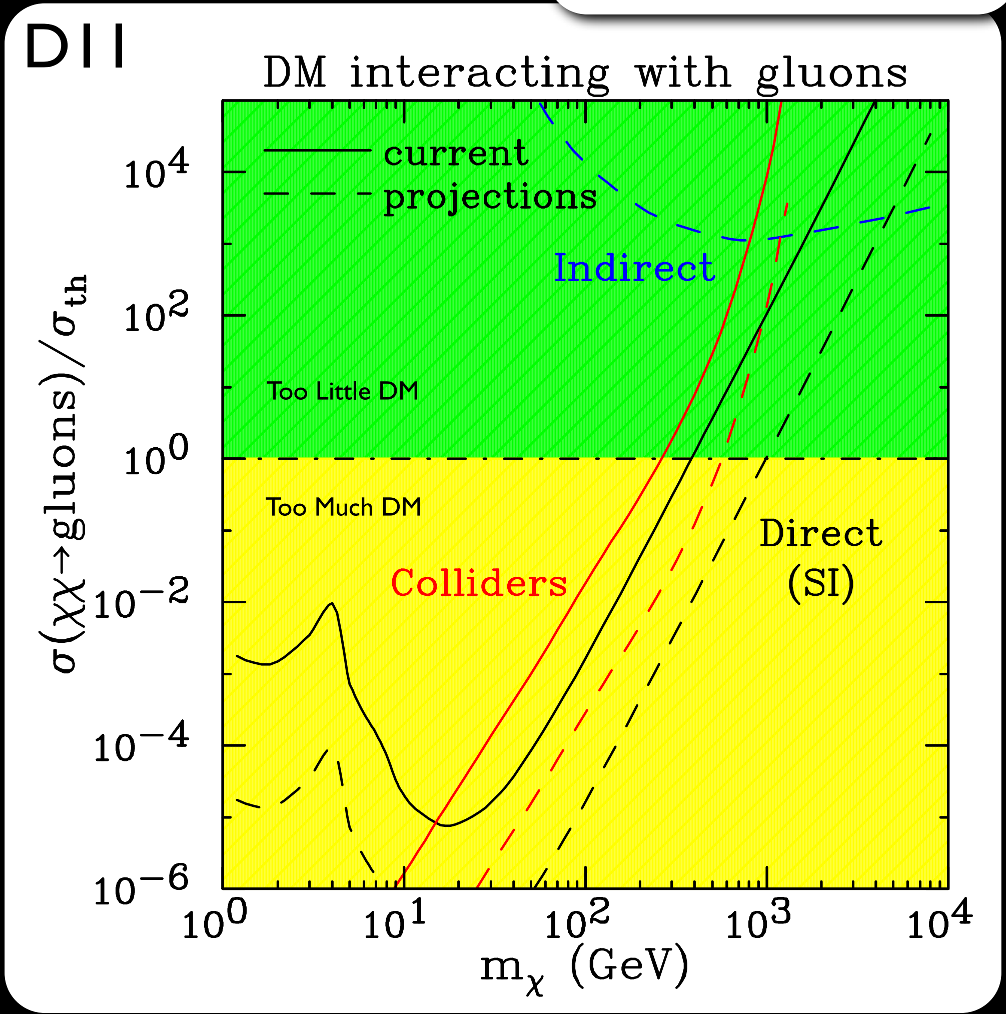




Annihilation

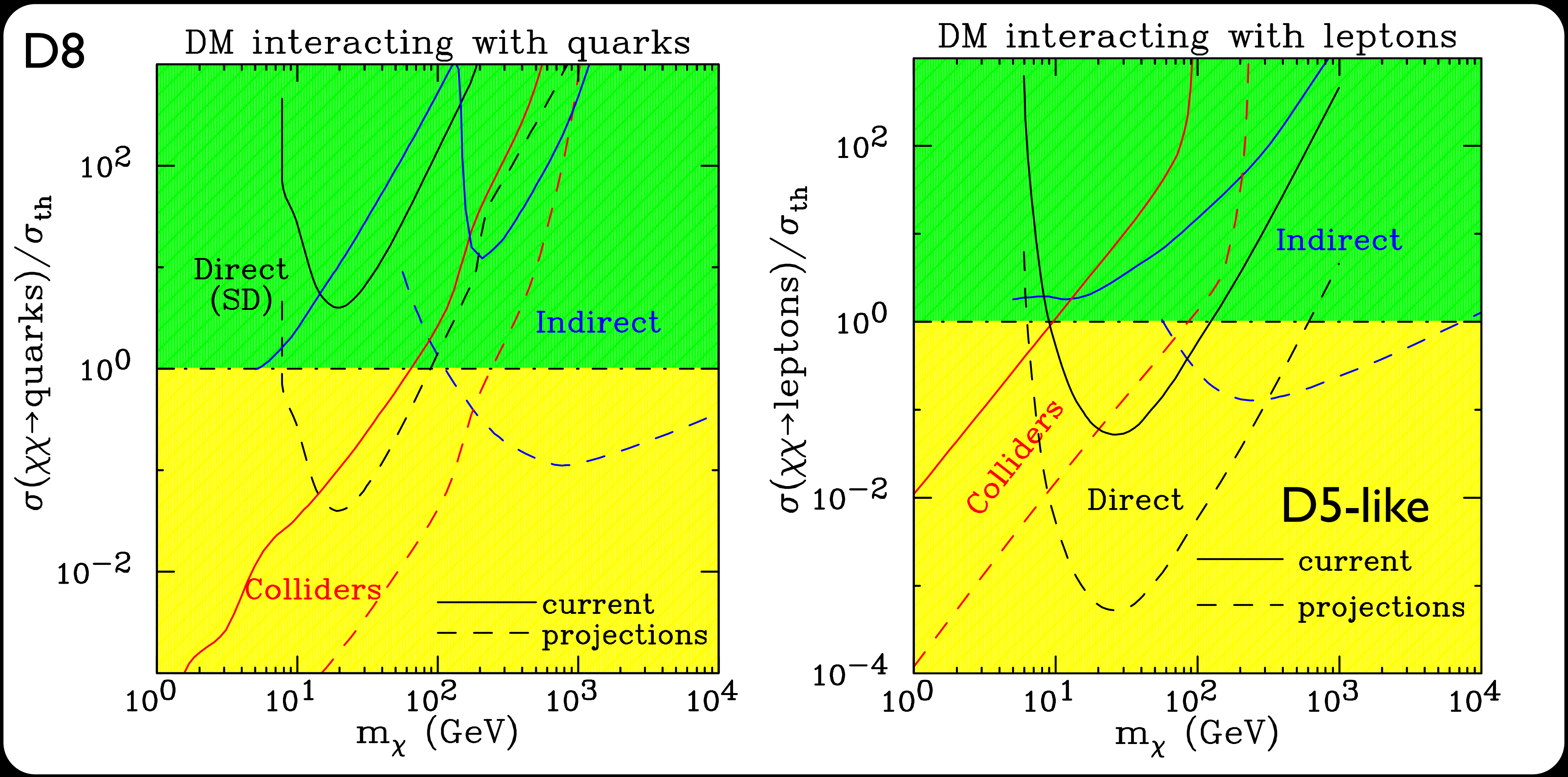
- Let's compare different approaches in the language of annihilations. The annihilation cross section is something we have a preconception about because of the relic density.
- But note that the identification of an annihilation cross section with a relic abundance assumes that the channel is question is the dominant annihilation.
- Colliders continue to do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs.





DM Complementarity, arXiv:1305.1605

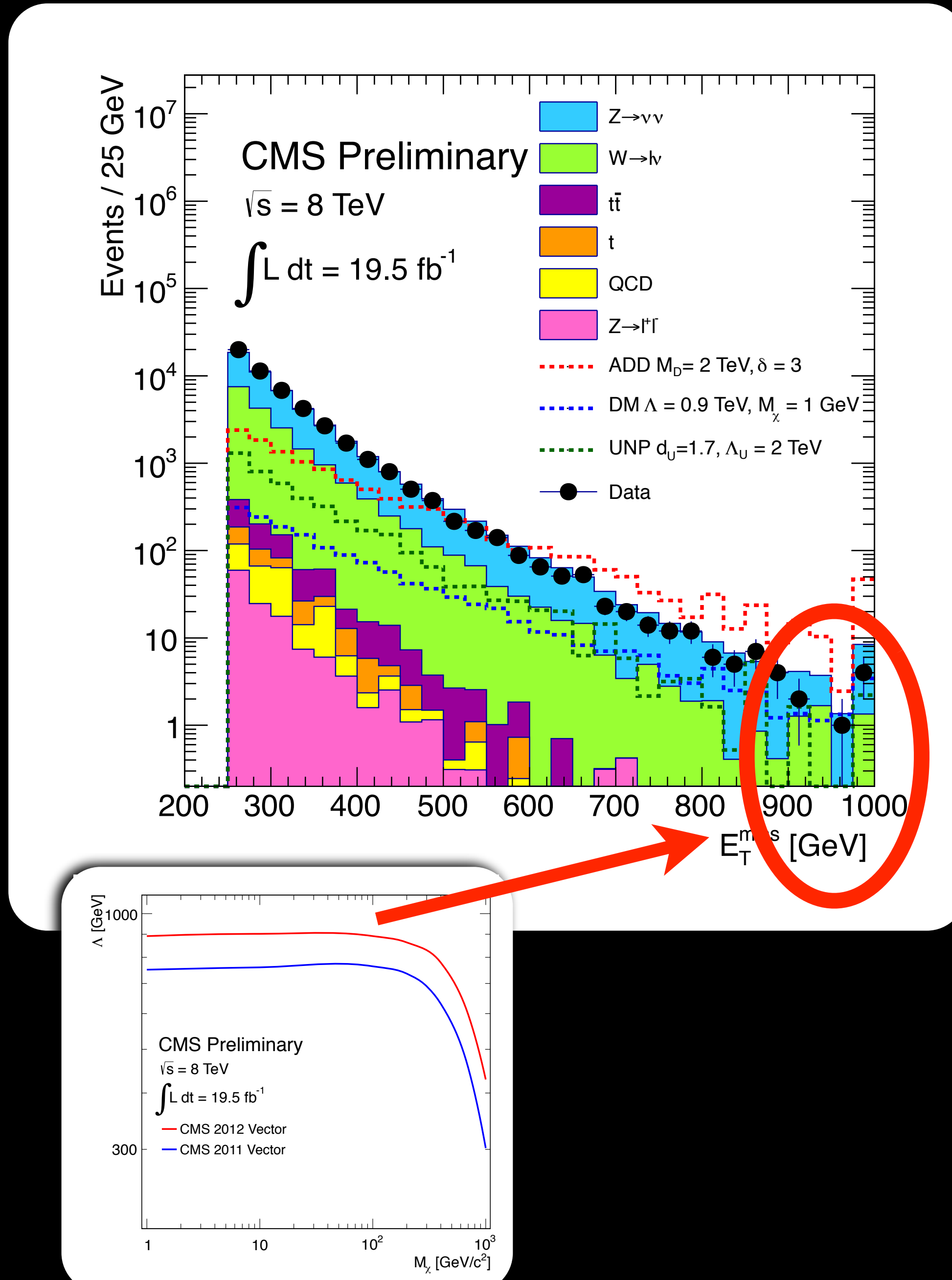
Quarks & Leptons



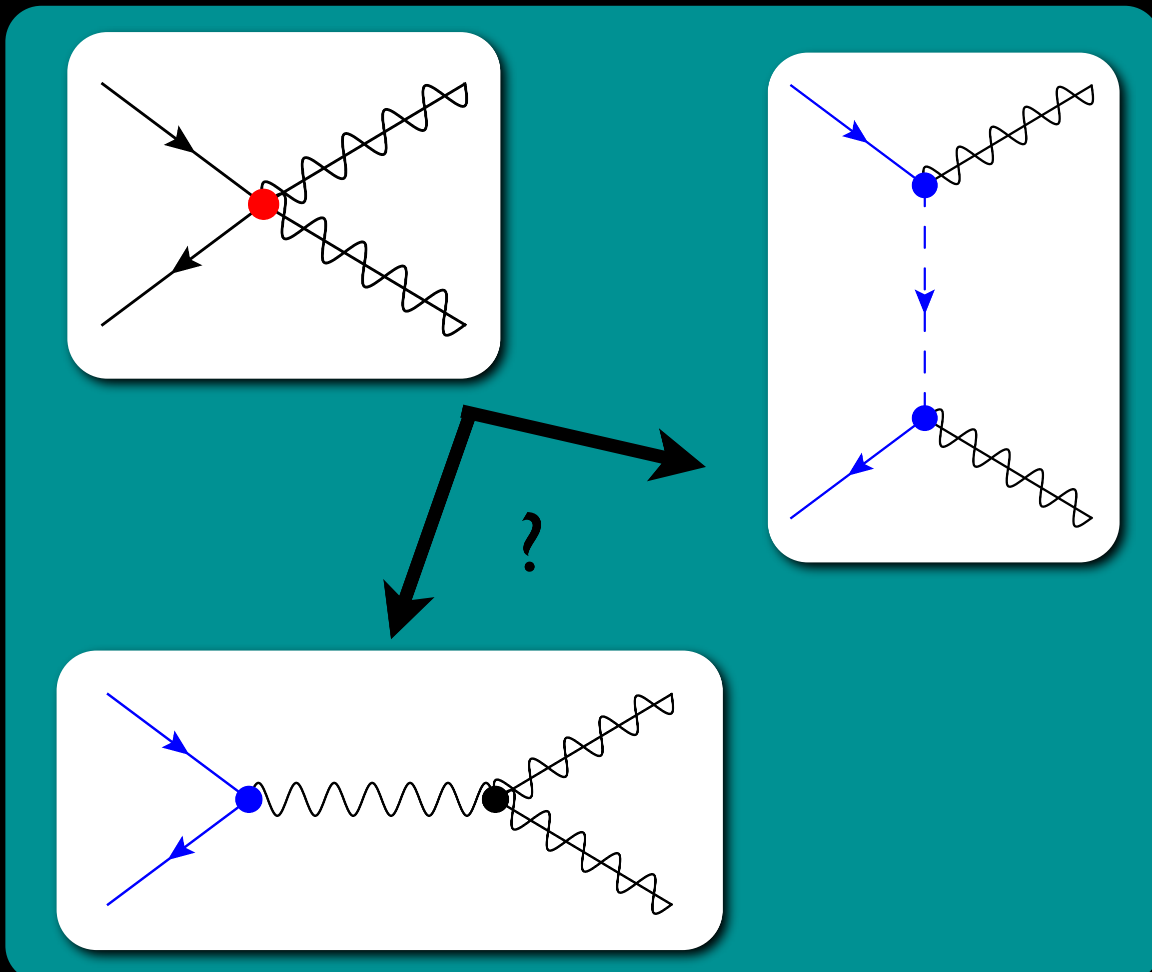
DM Complementarity, arXiv:1305.1605

How Effective a Theory?

- We should worry a little bit about whether what we are doing makes sense.
- The bounds on the scale of the contact interaction are ~ 1 TeV, and we know that LHC collisions are capable of producing higher energies.
- For the highest energy events, we are almost certainly using the wrong theory description.
- It is difficult to be quantitative about precisely where the EFT breaks down, because the energies probed by the LHC depend on the parton distribution functions. [The answer is time (lumi)-dependent in that sense.]



How Effective a Theory?



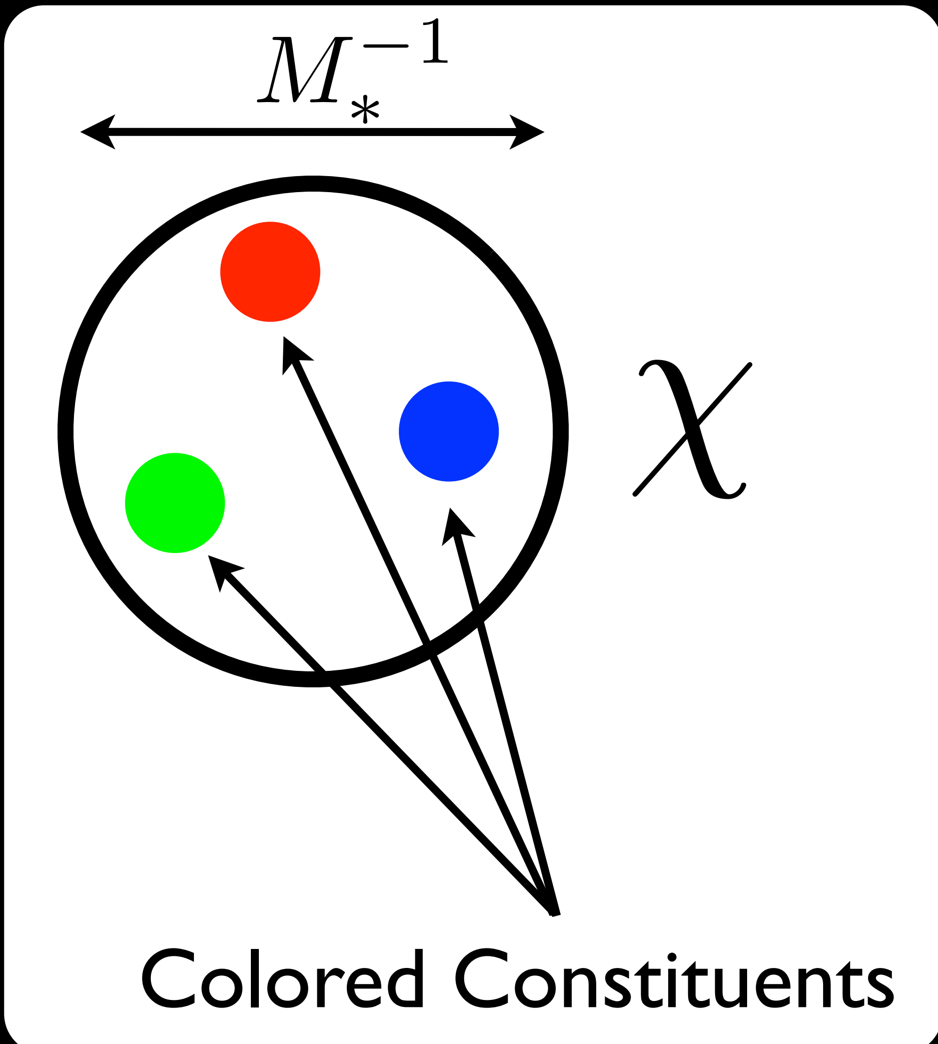
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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 actual UV-completion.

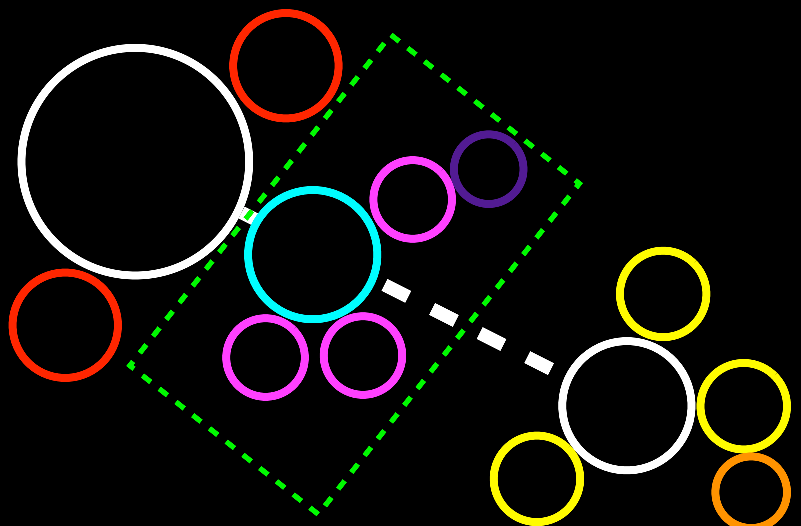
We can understand some general features by imagining how one could resolve the contact interaction into a mediating particle.

A Composite WIMP?

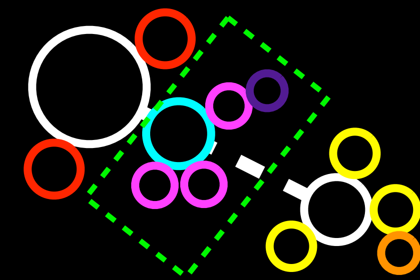


- Even when EFTs are only constraining rather strongly coupled theories, they say something interesting about some (perhaps exotic) visions of dark matter.
- If the dark matter is a (neutral) confined bound state (confined by some dark gauge force, say) of colored constituents, we should expect its coupling 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 dark matter.

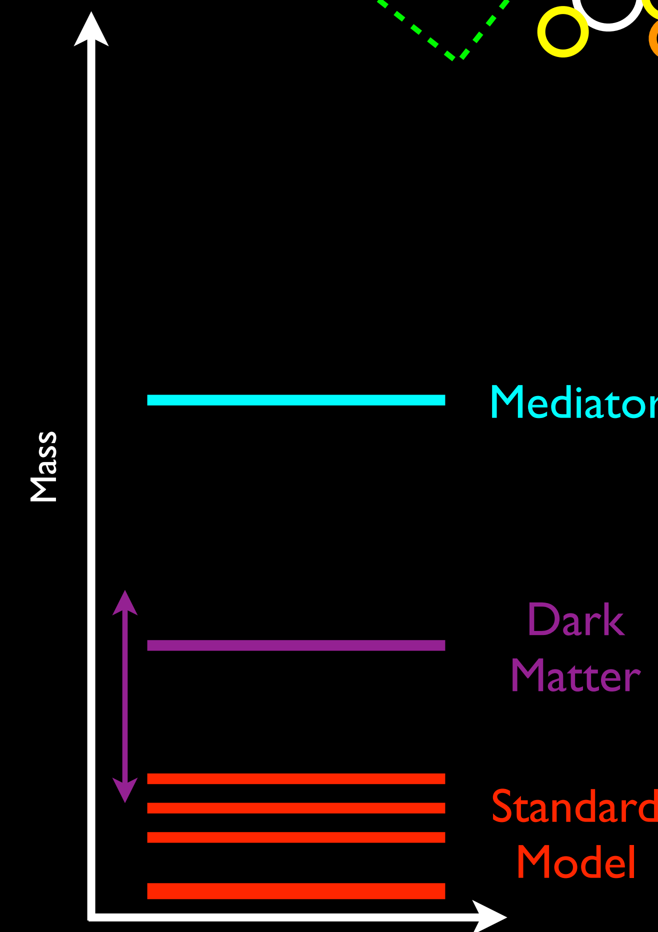
Simplified Models

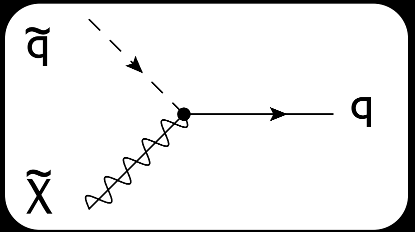


Simplified Model



- Moving away from more complete theories, we can also consider a model containing the dark matter as well as the most important particle(s) mediating its interaction with the SM.
- For example, if we are interesting in dark matter interacting with quarks, we can sketch a theory containing a colored scalar particle which mediates the interaction.
- This looks like part of the MSSM, but has more freedom to choose couplings, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength.

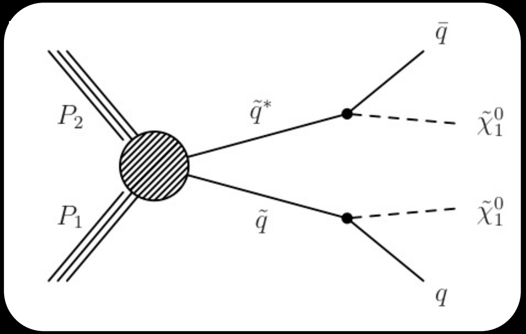




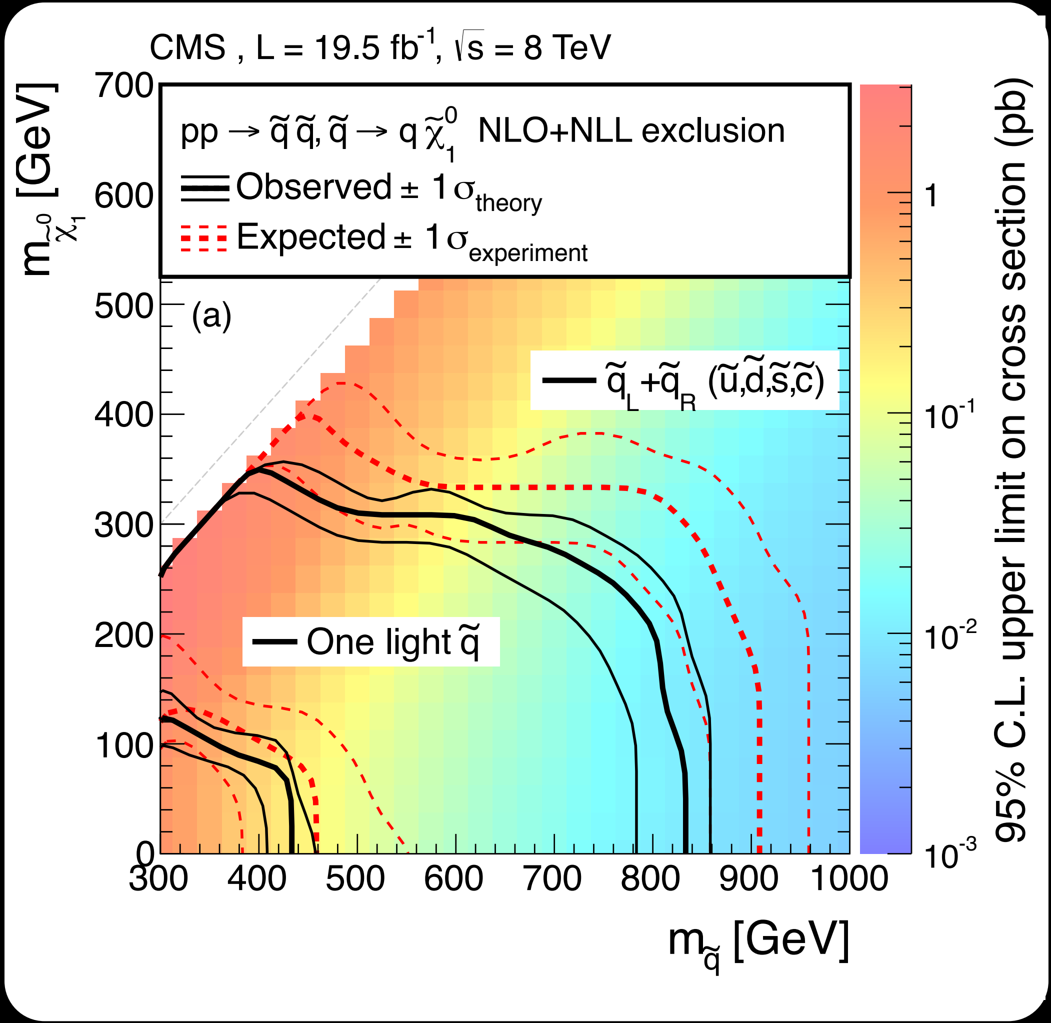
Lots of Recent Activity:

Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
Papucci, Vichi, Zurek 1402.2285
Garny, Ibarra, Rydbeck, Vogl 1403.4634

Simplified Models



- This is a model that is used by the LHC collaborations as a way of presenting more generic searches for a colored particle which decays into a single jet and missing energy.
- If we exchange the LHC production cross section for the mediator coupling to quarks, we can translate the LHC bounds into dark matter properties.



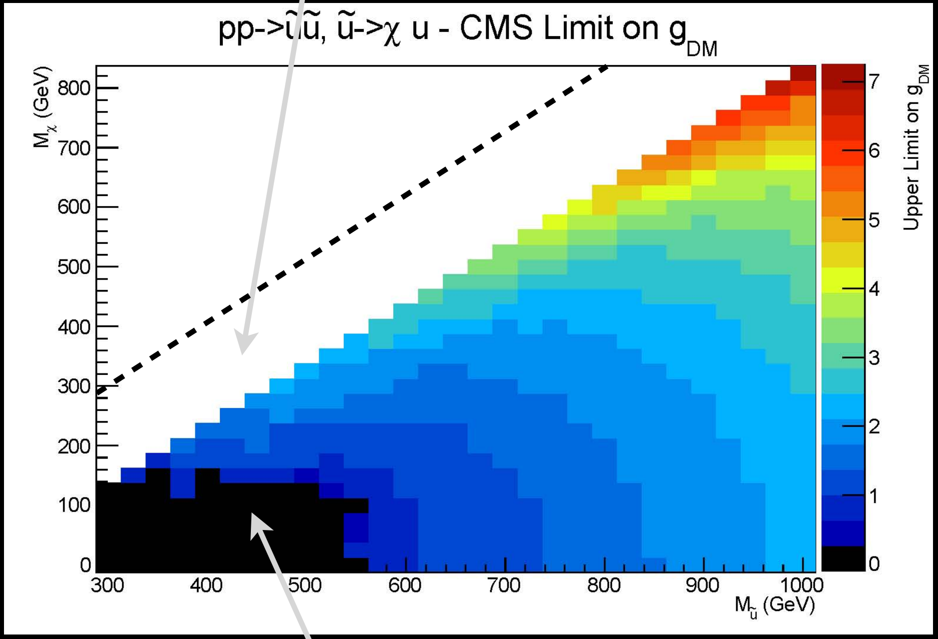
Of course, we can also consider a wider variety of WIMP properties and mediators and get away from MSSM-like theories.

$\tilde{u}_R$ Model

- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- For simplicity, we set the couplings equal for all three generations.
- (But we did not include top-motivated signatures, so this assumption is not very important in what follows, which is based largely on the dijet + MET searches).
- In the parameter plane of the mass of the dark matter and mass of the mediators, we can determine a limit on the coupling strength in the plane of the masses of the dark matter and the mediators.

Mono-jet searches will help fill in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

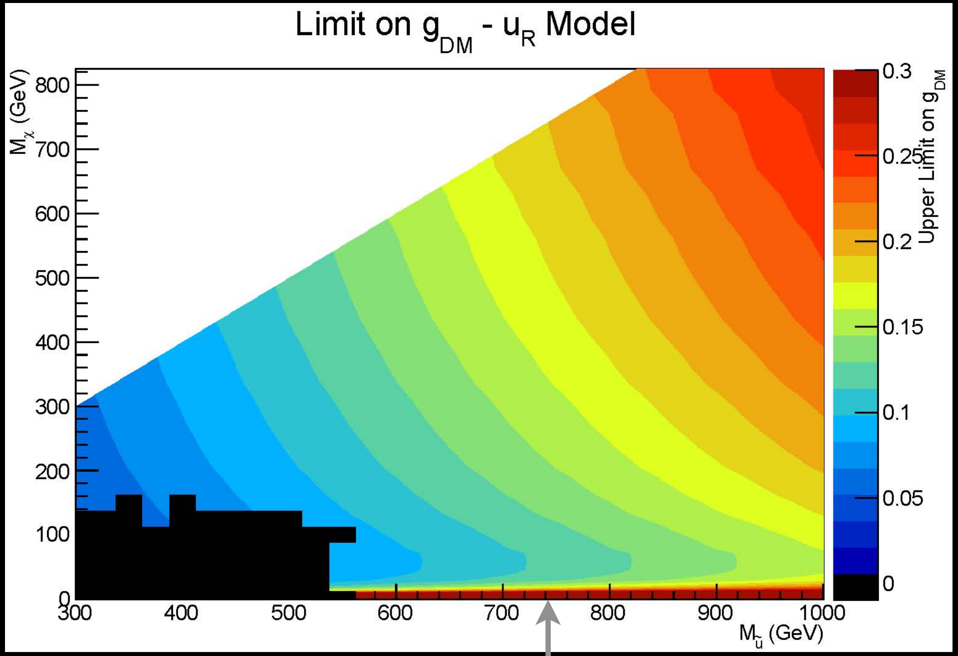


QCD production saturates the CMS limits, resulting in no allowed value of g.

$\tilde{u}_R$ Model

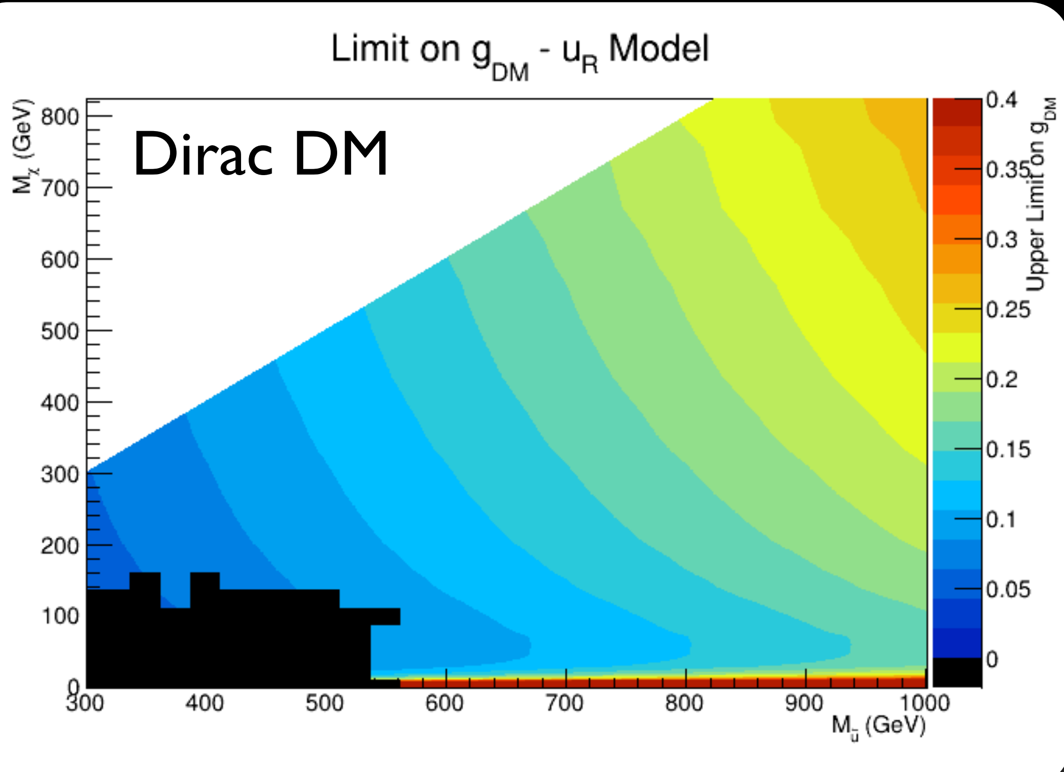
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment. (And soon LUX will say something as well...).
- Elastic scattering does not rule out any parameter space, but it does impose stricter constraints on the coupling in the regions CMS left as allowed.



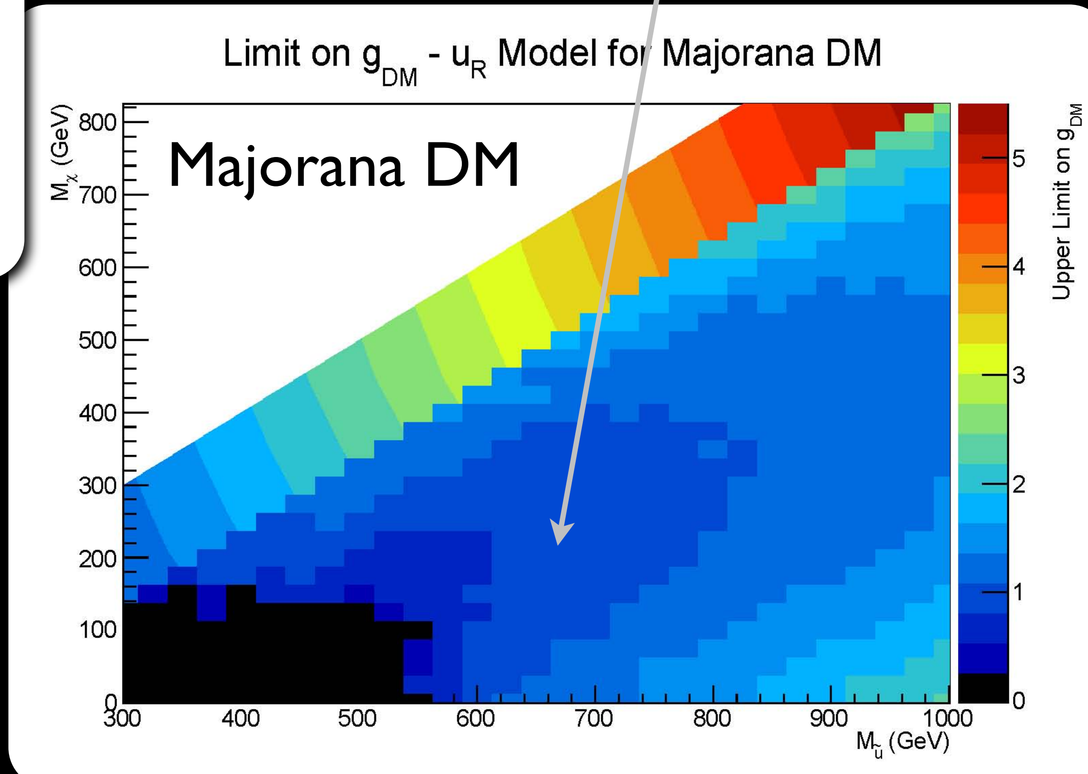
Traditional direct detection searches peter out for masses below about 10 GeV.

$\tilde{u}_R$ Model: Results



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

Collider bounds tend to dominate for Majorana DM.



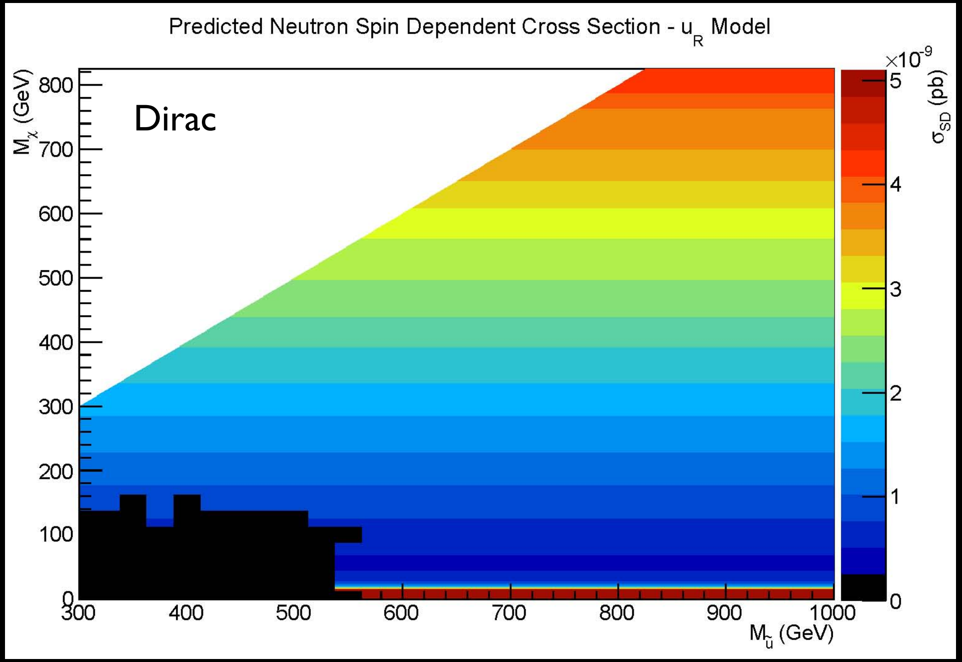
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

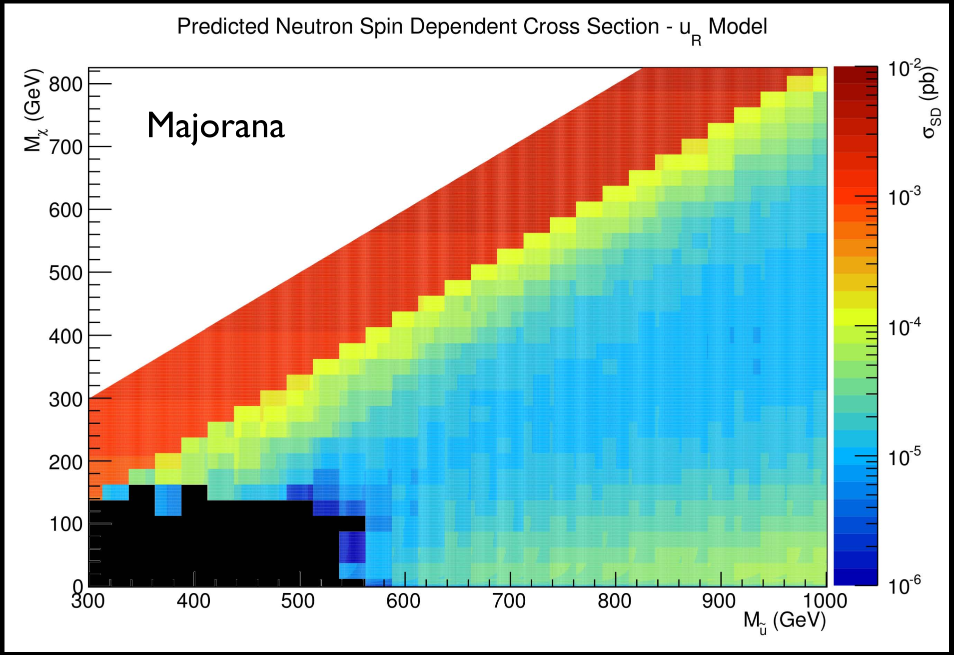
Majorana WIMPs have no tree-level spin-independent scattering in this model.

At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.

ũ$_R$ Model: Forecasts

- Now that we understand the current bounds, we can forecast what this implies for future searches.
- For example, we can plot the largest spin-dependent cross sections that are consistent with CMS and Xenon in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!

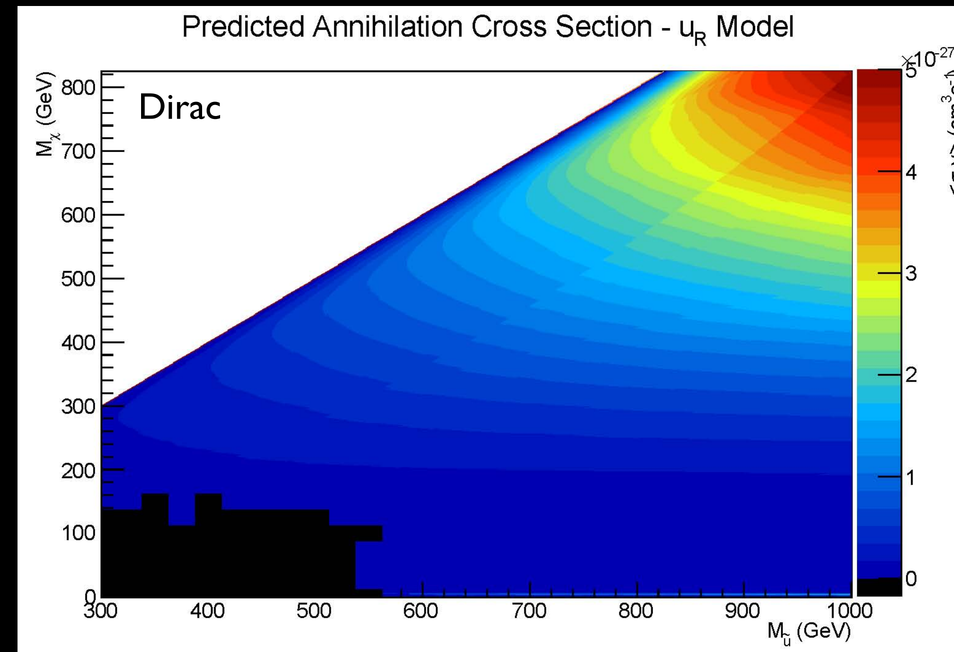


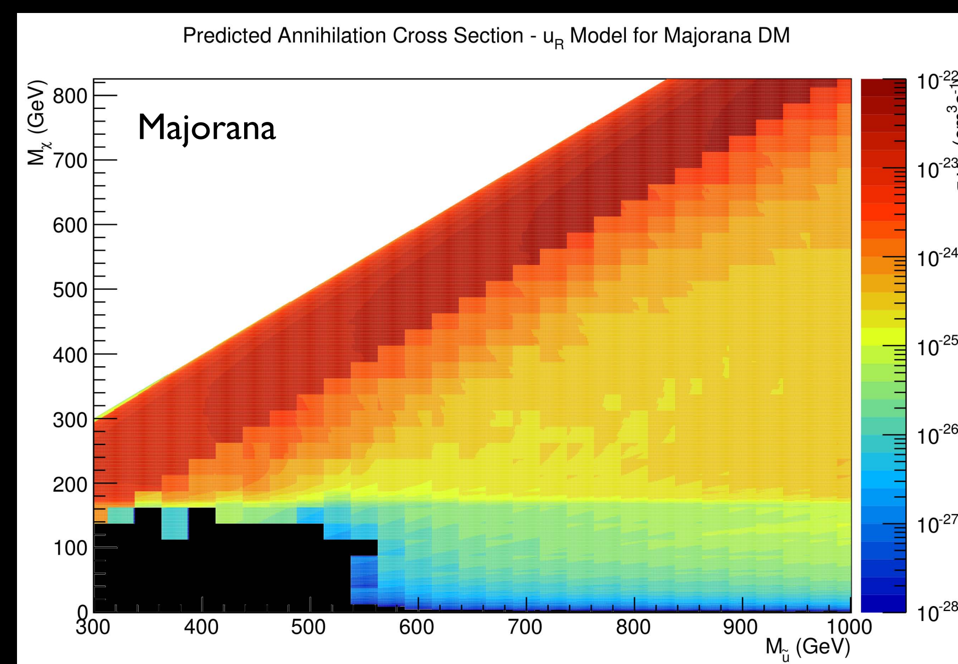


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

$\tilde{u}_R$ Model: Forecasts

- Similarly, we can forecast for the annihilation cross section.
- The Fermi LAT does not put very interesting constraints at the moment, but it is very close to doing so, and limits from dwarf satellite galaxies are likely to be relevant in the near future for Majorana DM.
- We can also ask where in parameter space this simple module would lead to a thermal relic with the correct relic density.

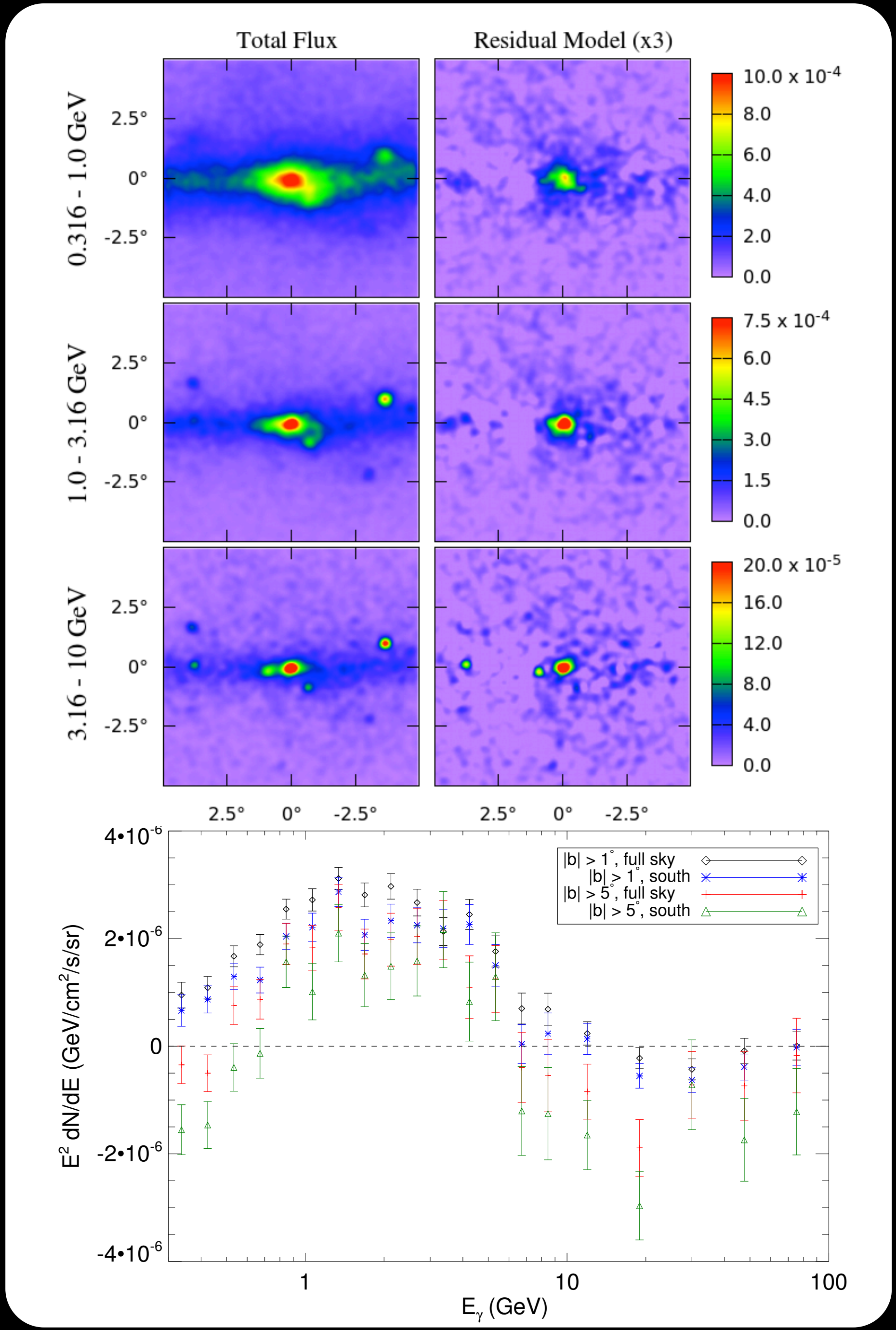




DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

Gamma Ray GeV Excess

- A simplified model allows us to put a (possible) discovery into context and ask what a theory that could explain it should look like.
- As an example: there are hints for what could be a dark matter signal in the Fermi data from the galactic center.
- After subtracting models of the diffuse gamma ray emission, known point sources, etc, an excess remains with a distribution peaking around a few GeV, consistent with the expectations of a 40 GeV dark matter particle annihilating into bottom quarks.

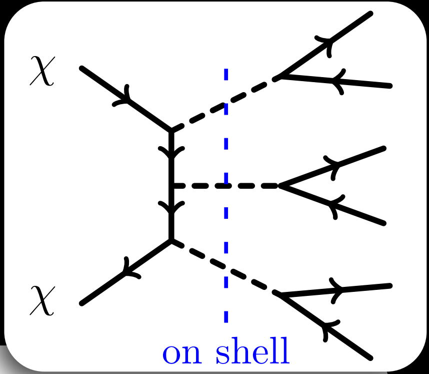


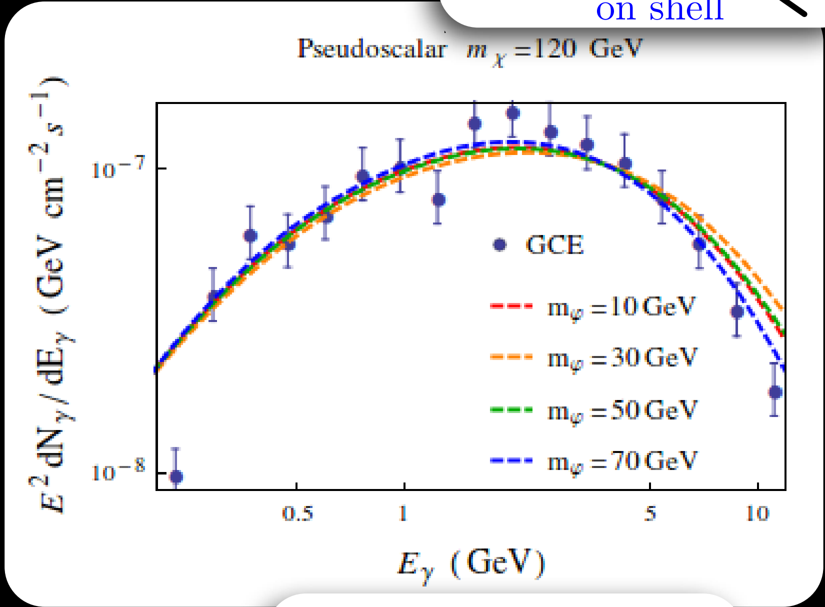
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
see also: Abazajian, Canac, Horiuchi, Kaplinghat 1402.4090

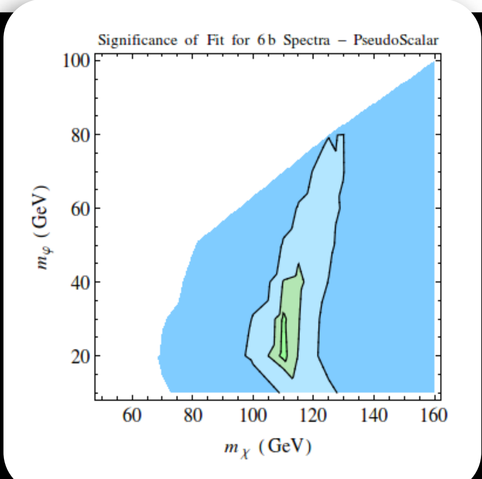
Gamma Ray Excess

- The signal suggests something about the simplified models that could work.
- The signal is large enough that something is going to need to suppress scattering with heavy nuclei.
- For example, the particle communicating between dark matter and the SM could be a pseudoscalar, leading to spin-dependent and velocity suppressed coupling to nuclei.
- Even these tricks won't hide from direct searches forever.
- If the mediating particle is light, the dark matter can decay into on-shell mediators, which further allows weak coupling to the SM particles.

Abdullah, DiFranzo, Rajaraman, TMPT, Tanedo, Wijangco 1404.6528





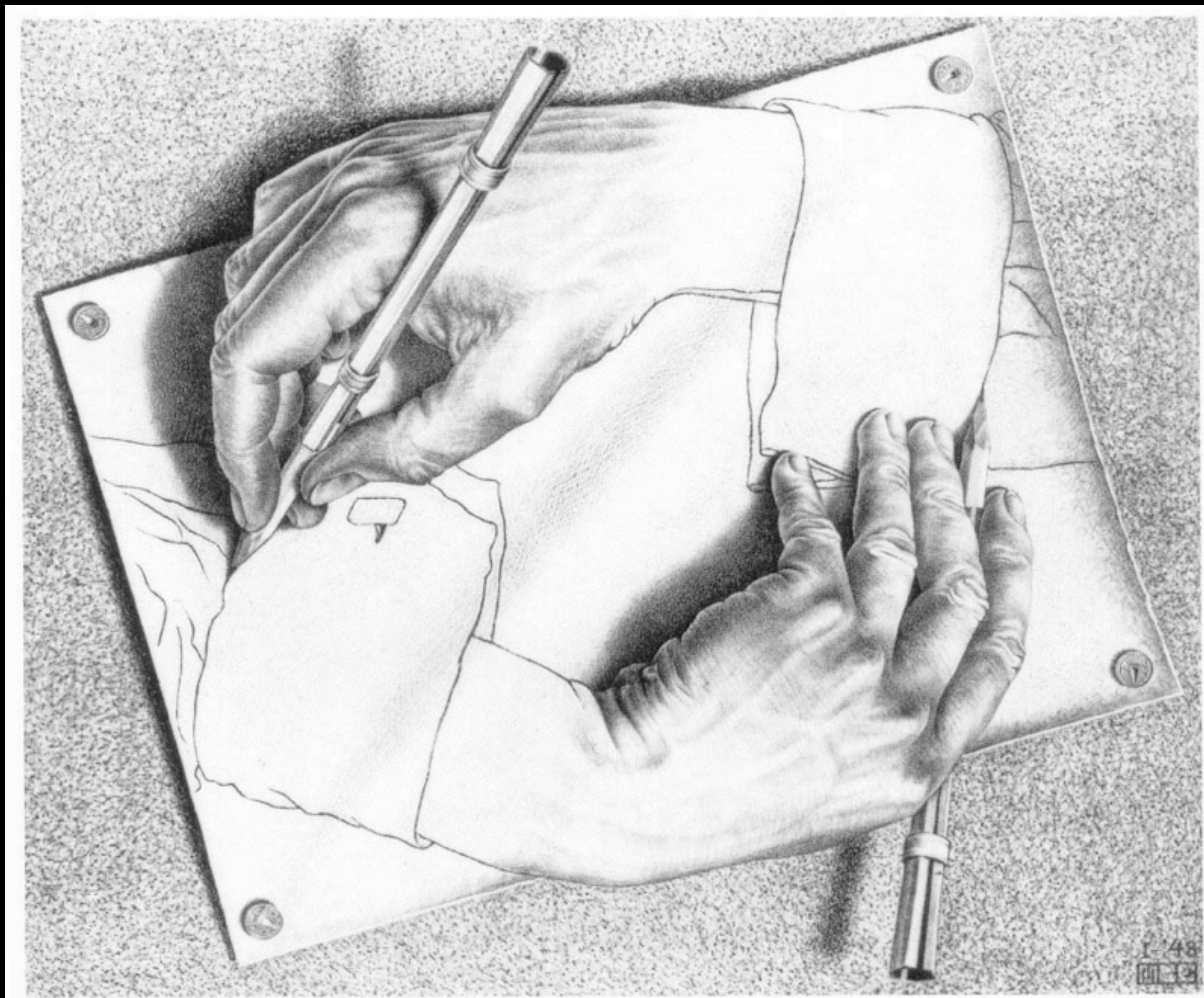


See also: Berlin, Hooper, McDermott 1404.0022
Agrawal, Batell, Hooper, Lin 1404.1373

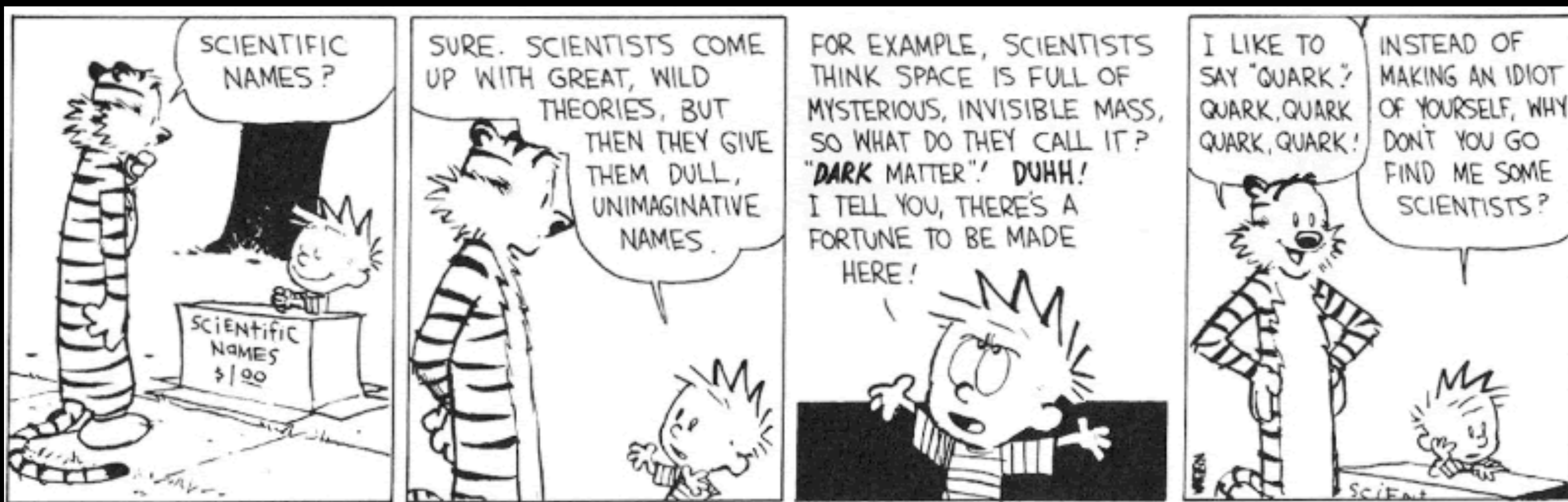
Outlook

- Dark matter is an interesting phenomenon that implies physics beyond the Standard Model. Particle physics offers many opportunities to study it.
- Understanding the relationship between various searches and how they define the viable parameter space requires a theory framework.
    - These can be very concrete complete models such as the MSSM, but it may be fruitful to look at less-defined, more hazy "sketches of theories" as well.
- Put into this context, searches at colliders, for elastic scattering, and for annihilation products all seem to naturally target different parts of dark matter theory-space. They complement one another.
- The full suite of techniques are essential to do justice to the range of possibilities.
- Once we have a discovery, they will ultimately help define and verify it and help lead us to define new experiments to better characterize it.
- Experiments can bring sketches of dark matter to life!

From Sketch to Life



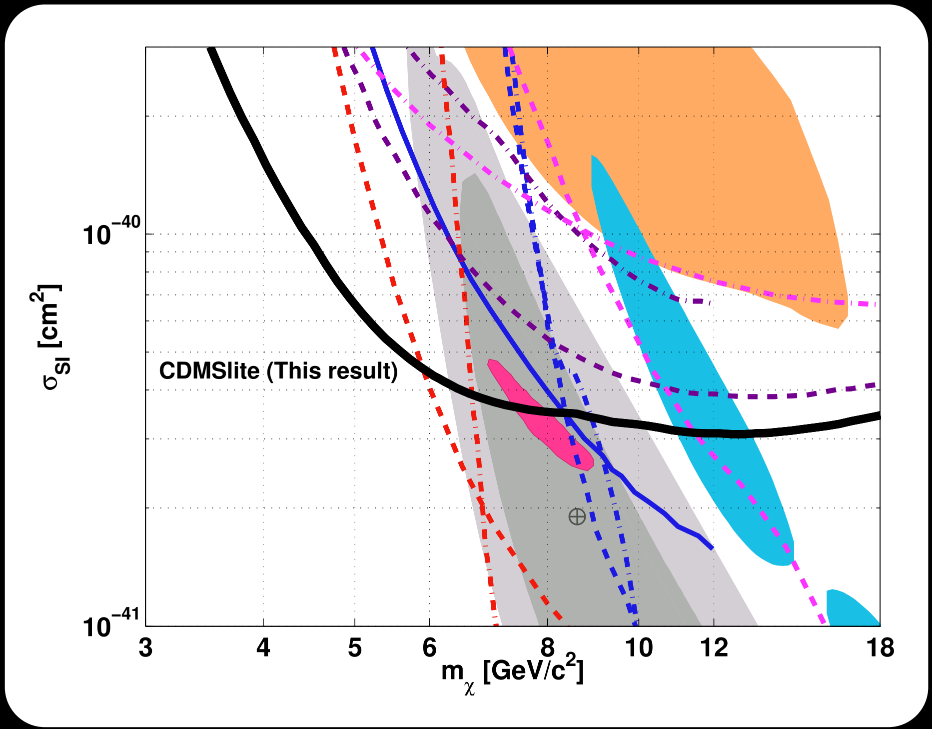
Sketches of ....

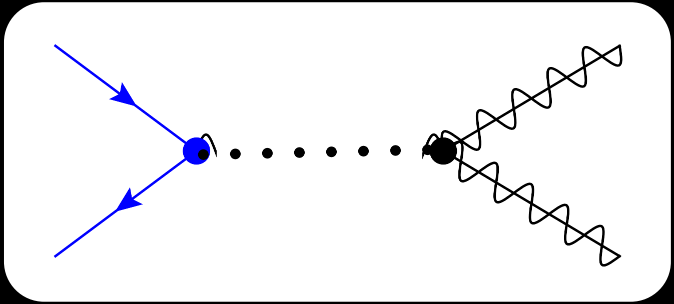


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1 00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
I LIKE TO SAY "QUARK." QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

Bonus Material

s-Channel Mediator

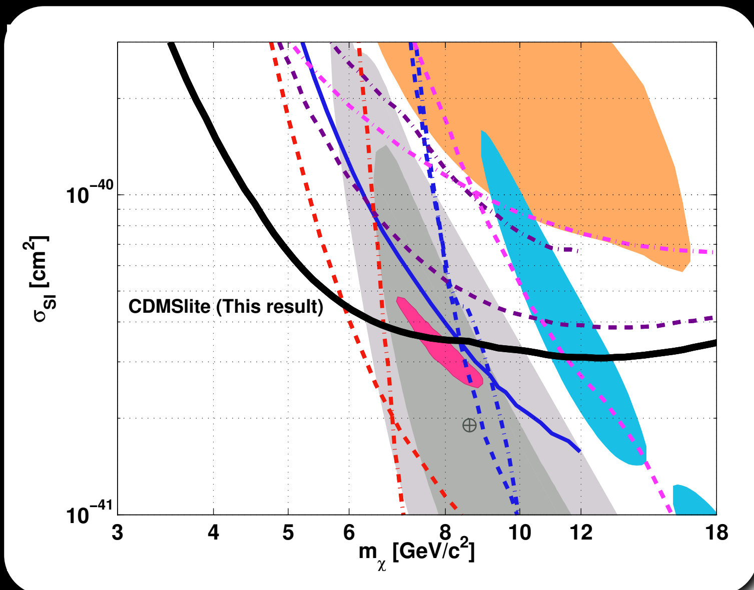


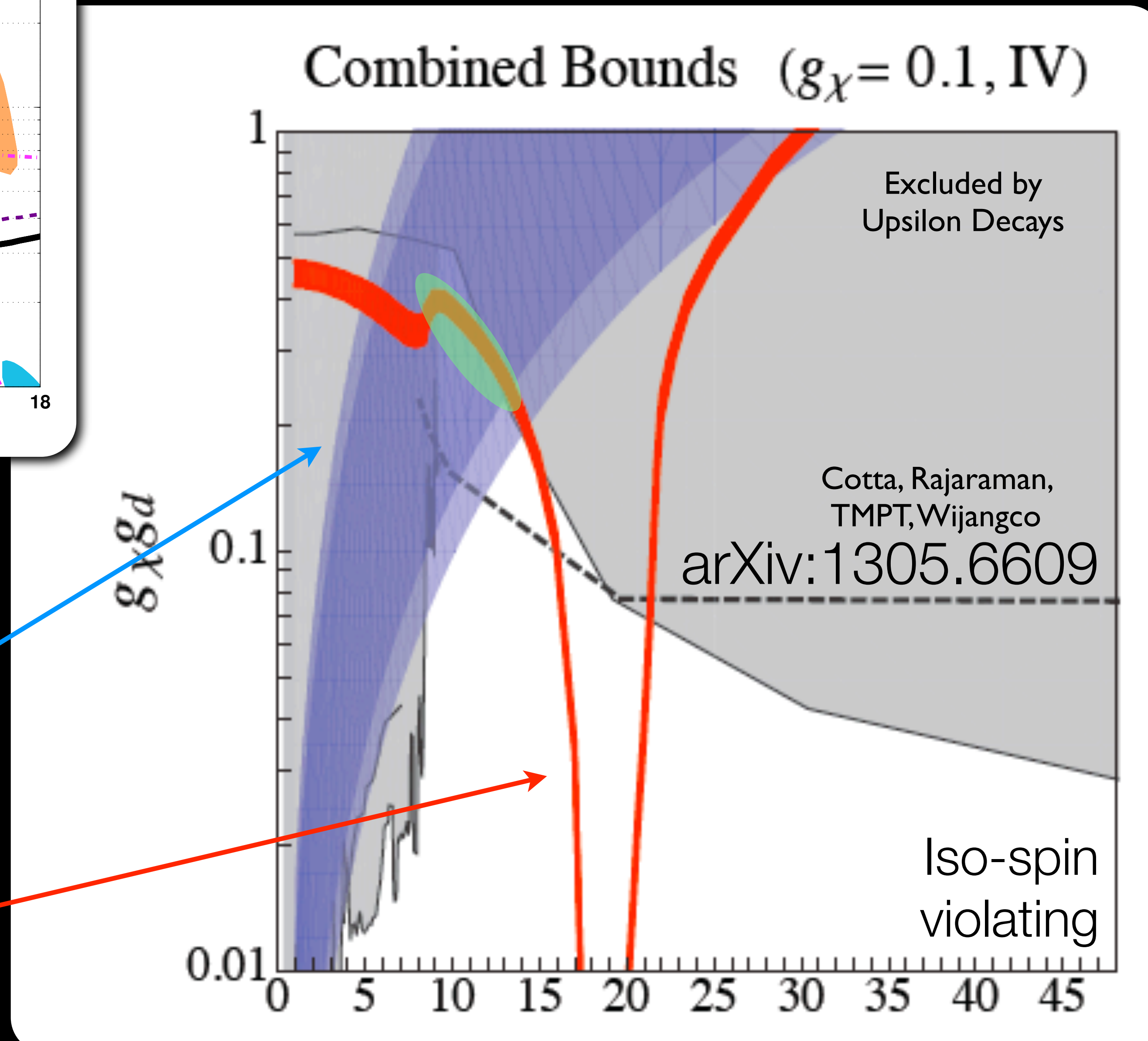


Again, motivated by flavor, constraints we take our coupling to quarks proportional to Yukawa interactions: g_u, g_d

- CDMS-Si shows a tantalizing excess of a handful of events.
- While not significant enough to claim detection of dark matter, it could very well be our first hint, and we should try to understand what that means and where else we could potentially see it.
- The desired cross section looks to be in tension with what we know from collider searches for contact interactions, so we consider a simplified model.
- We need a lighter mediator than is consistent with LHC if it is colored, so we consider an s-channel scalar.

CDMS-Si

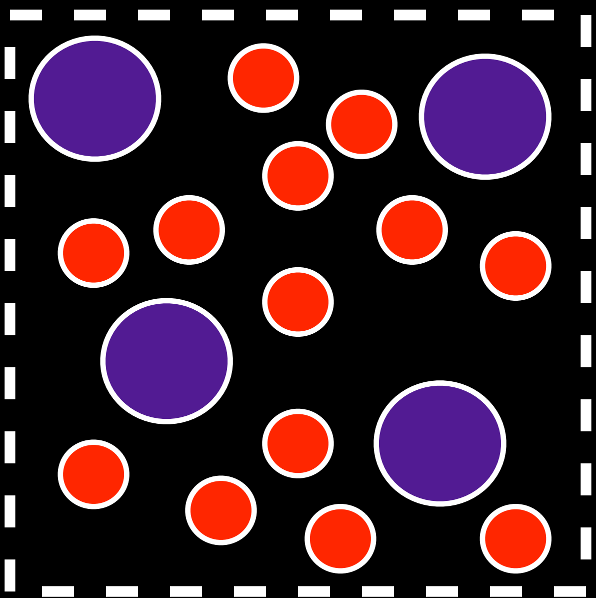




CDMS-SI Preferred

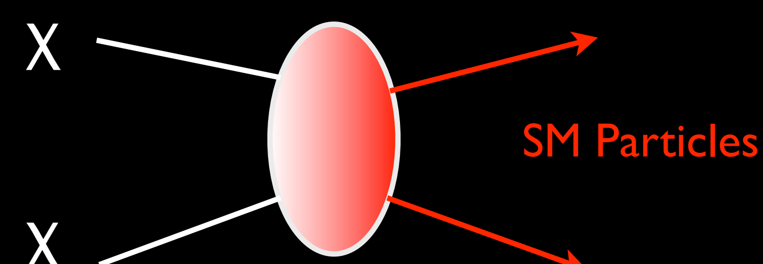
Relic Density

The WIMP Miracle



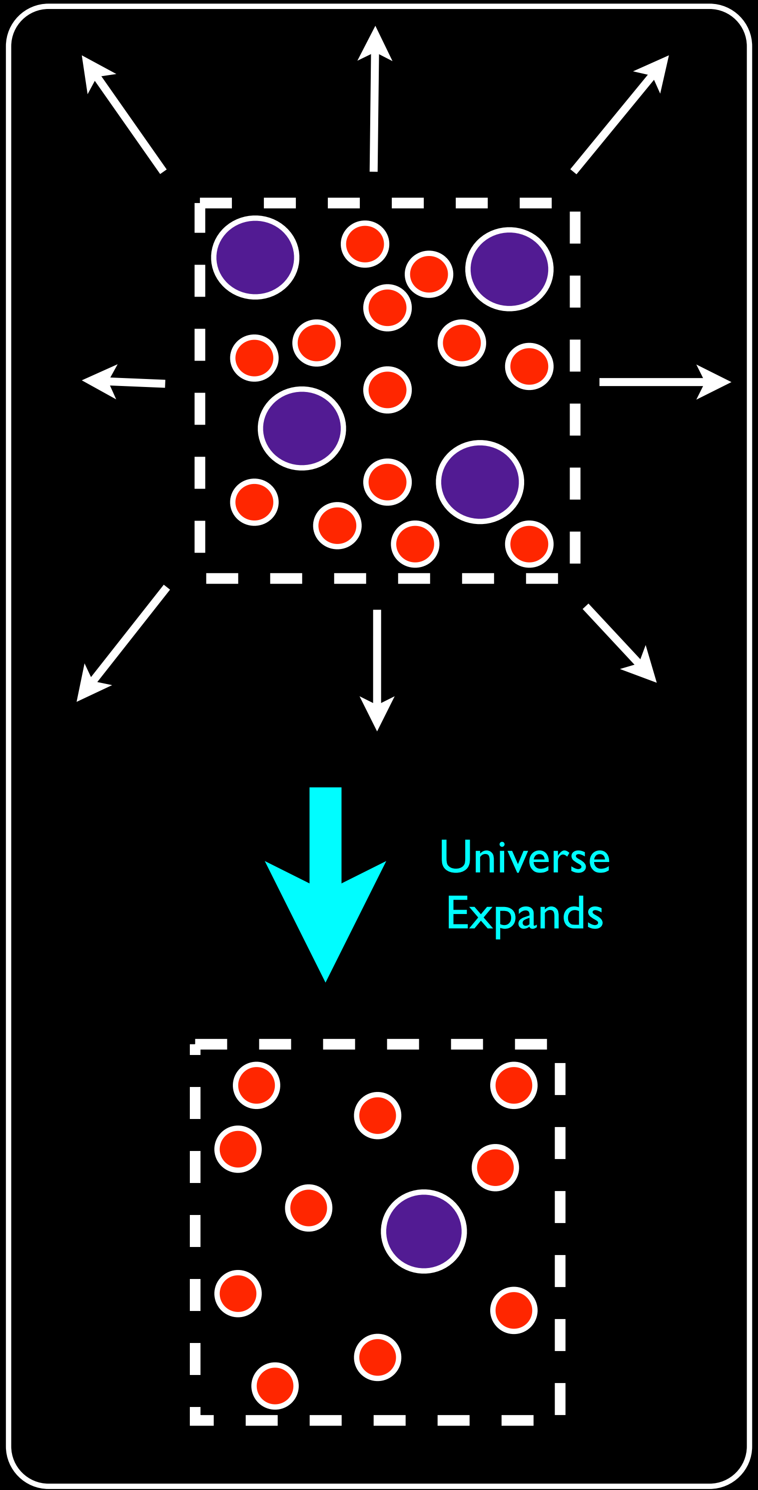
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, XX -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$

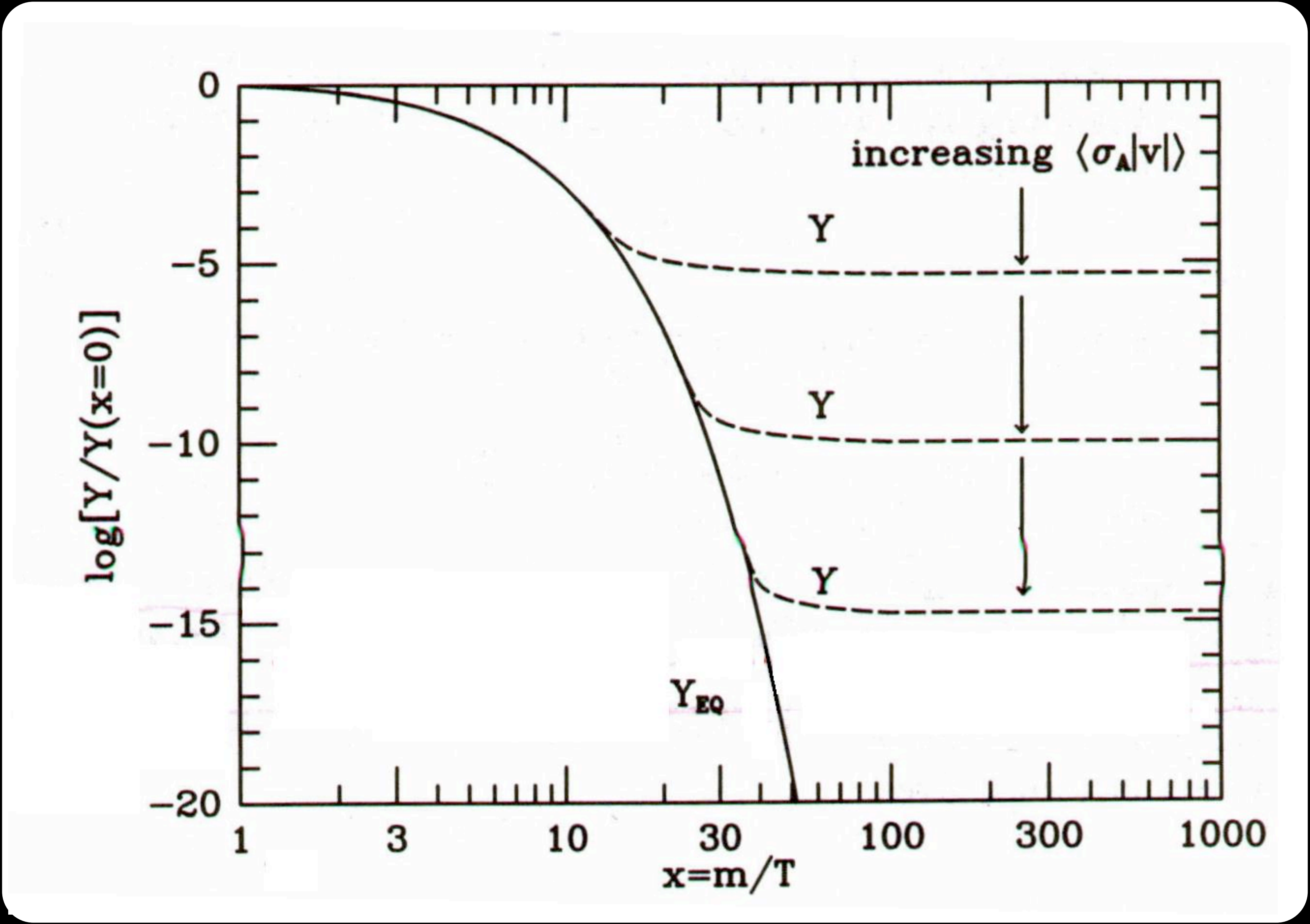


Freeze-Out

- Expansion of the Universe eventually results in a loss of equilibrium.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on σ(χχ -> SM): more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



Relic Density



x=m/T increasing
is
T decreasing
is
time increasing

- The observed quantity of dark matter is suggestive of a cross section for annihilation into the thermal bath (the SM + ...).