Bounds on Dark Matter from Colliders

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University of California, Irvine

UW/INT DM Workshop
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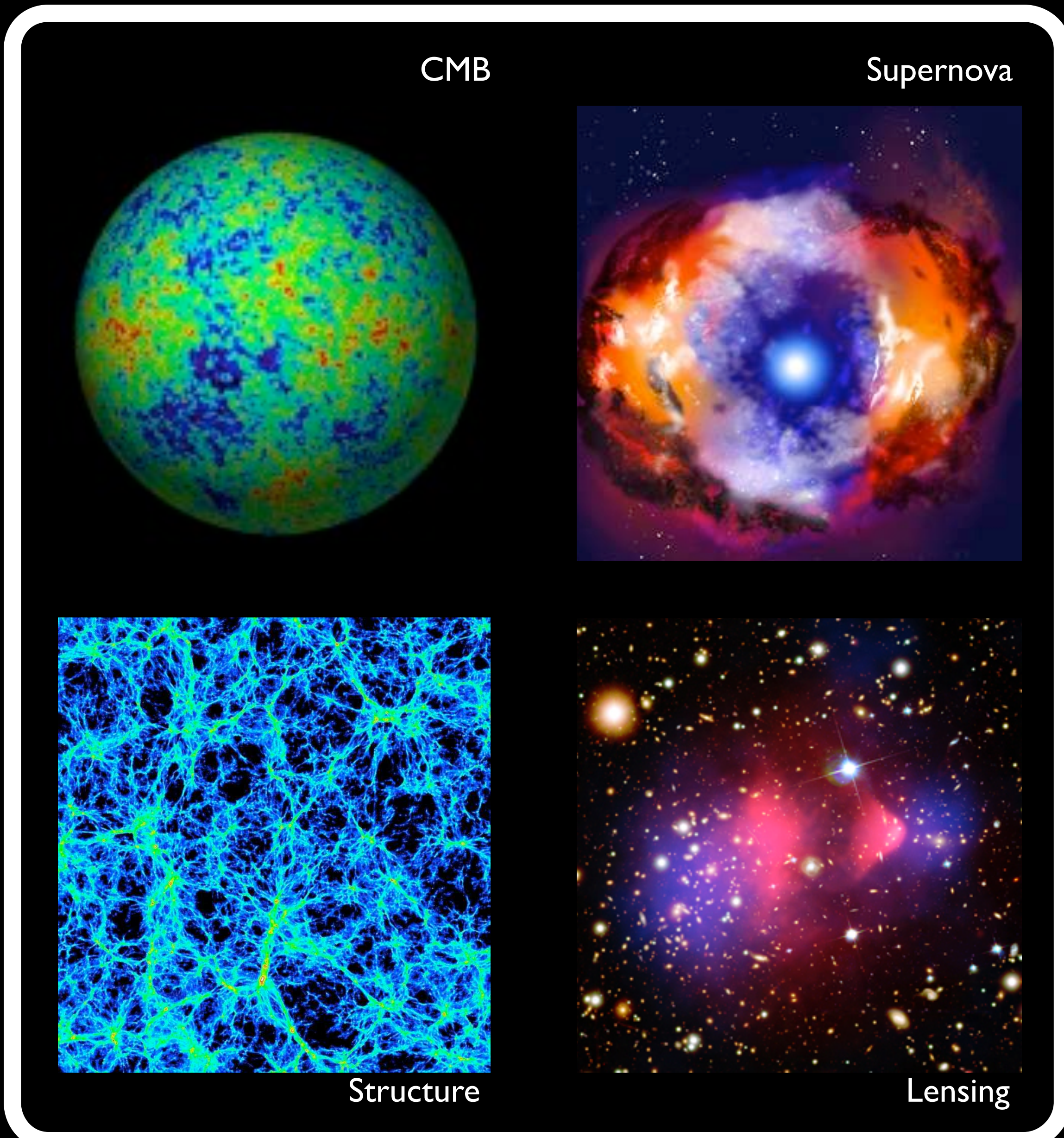
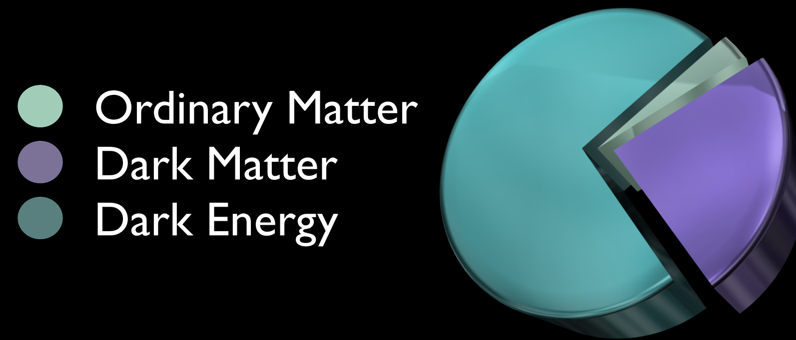
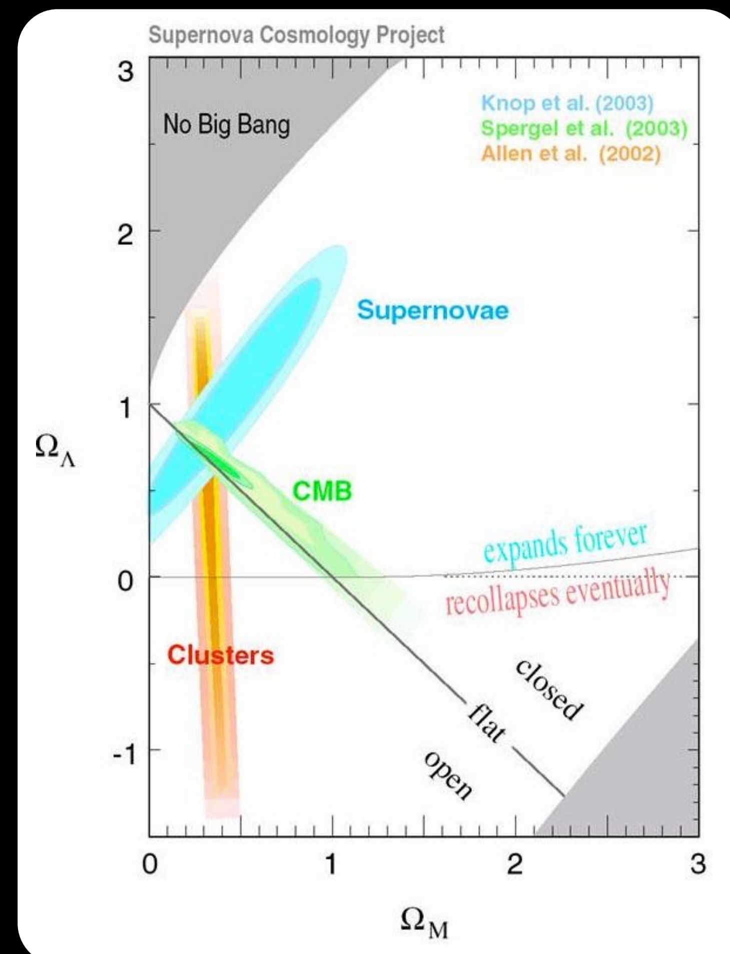
Dark Matter


CMB
Supernova
Structure
Lensing


Ordinary Matter
Dark Matter
Dark Energy


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
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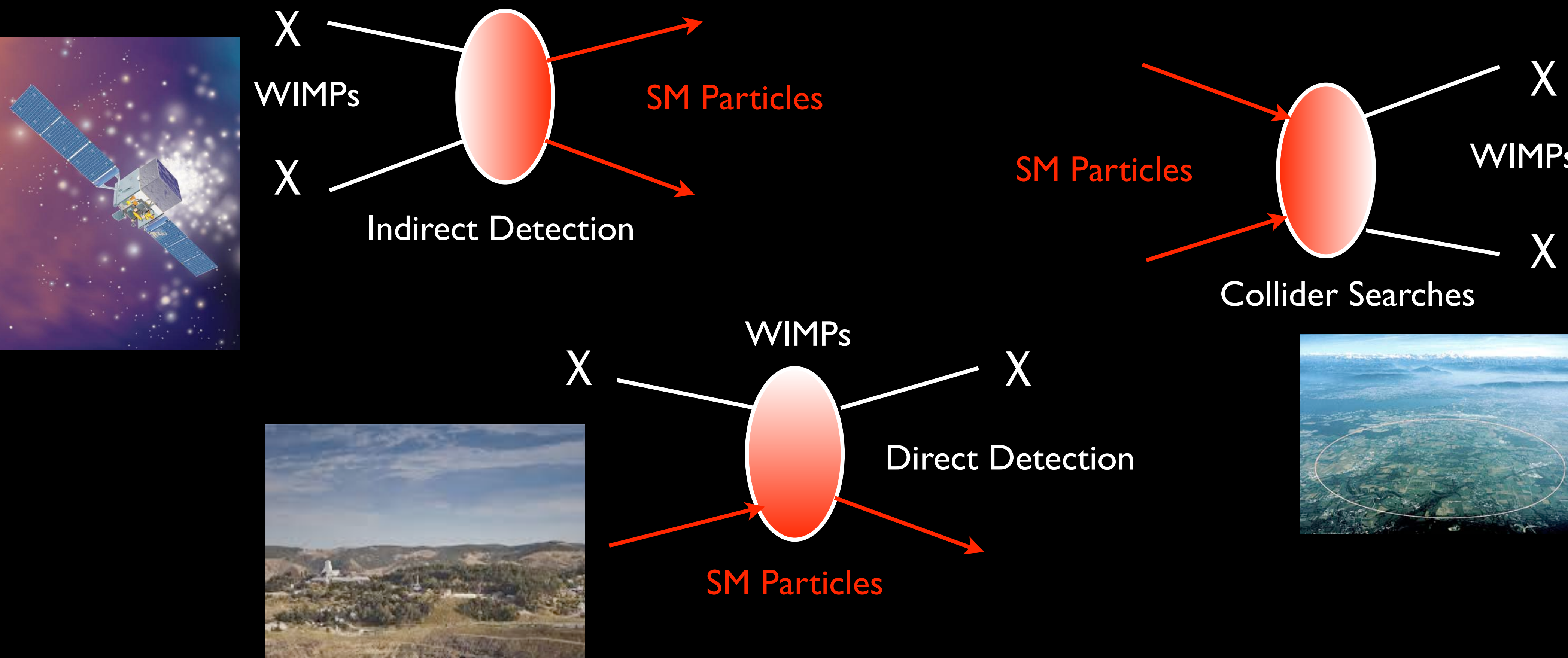
3

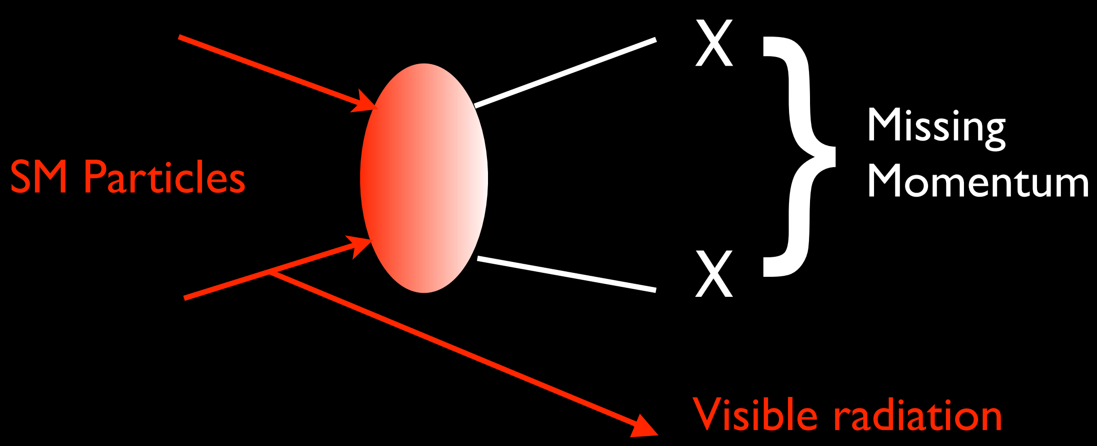
Particle Probes of DM

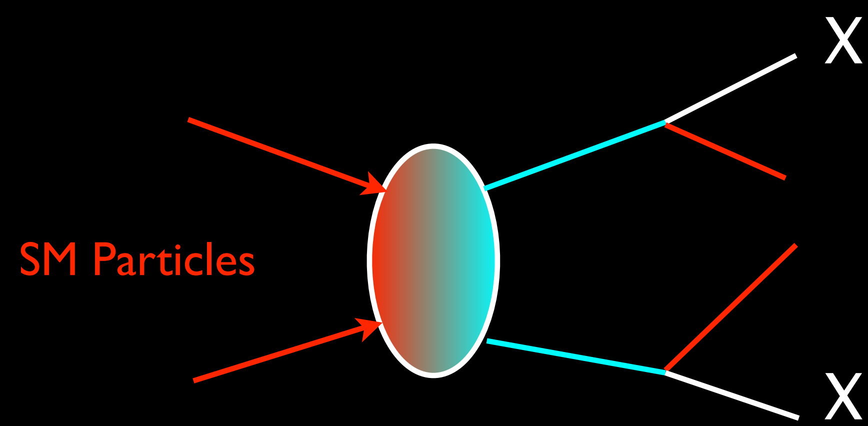


- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

Seeing the Invisible?

- WIMPs interact so weakly that they are expected to pass through the detector components without any significant interaction, making them effective invisible (much like neutrinos).
- There are two ways we can try to “see” them nonetheless:





“KK Sgluquarkino Pair Production”

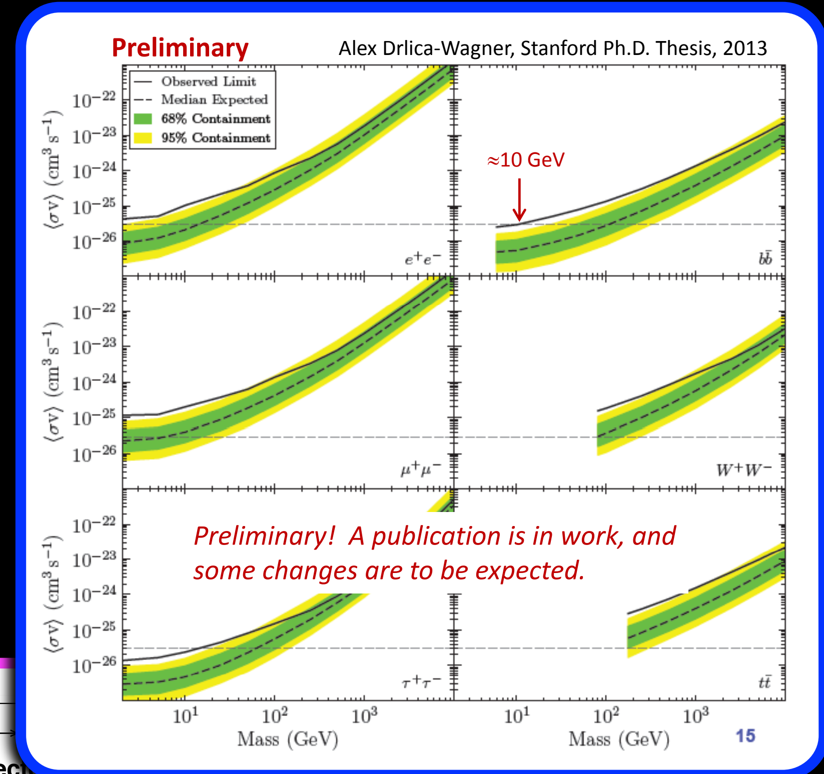
Radiation from the SM side of the reaction.

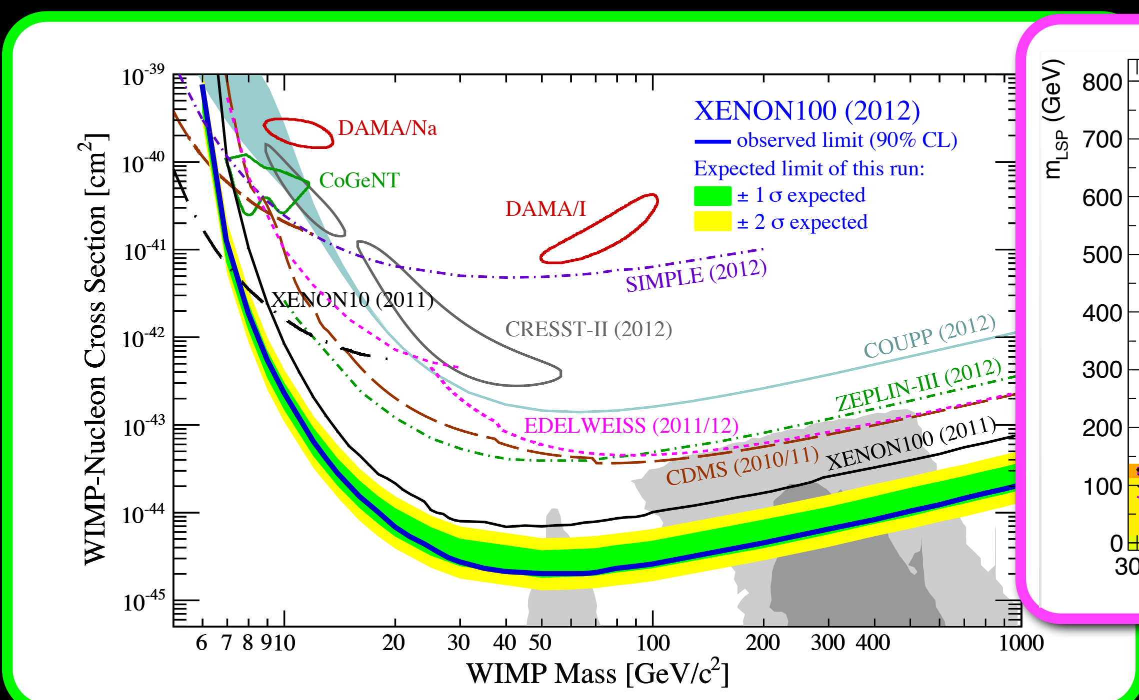
Production of “partners” which decay into WIMPS + SM particles.

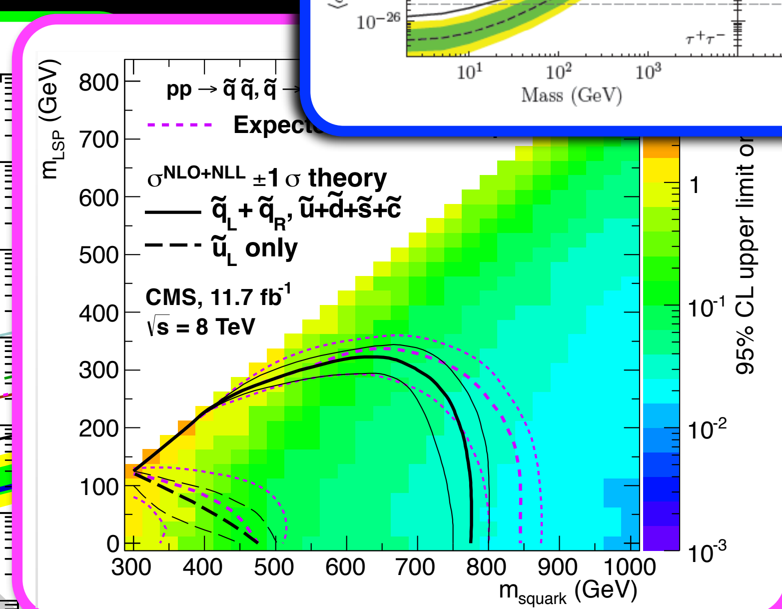
We Need (a) Theory

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

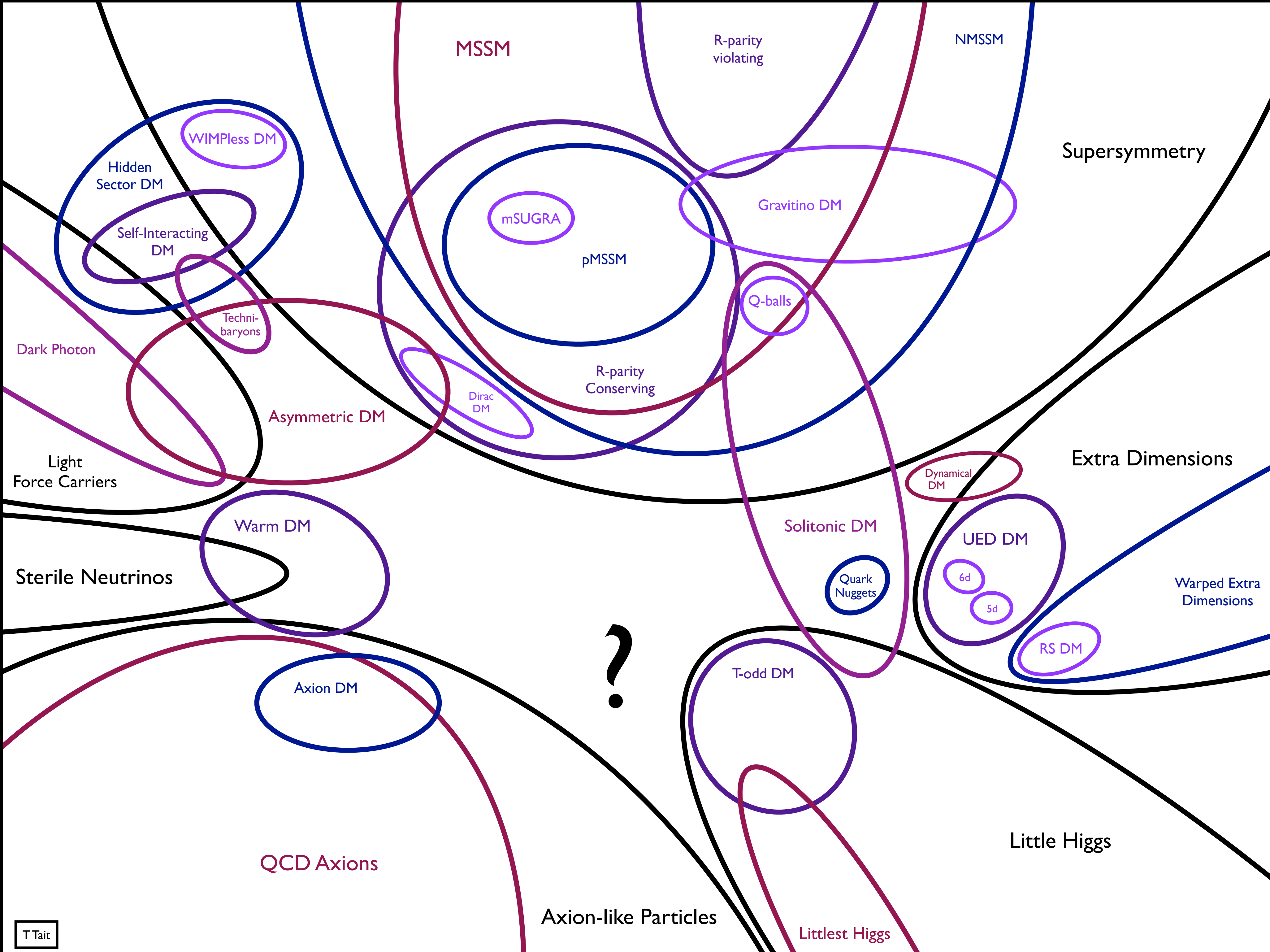
But we *know* they are all attempts to characterize the same thing(s)...

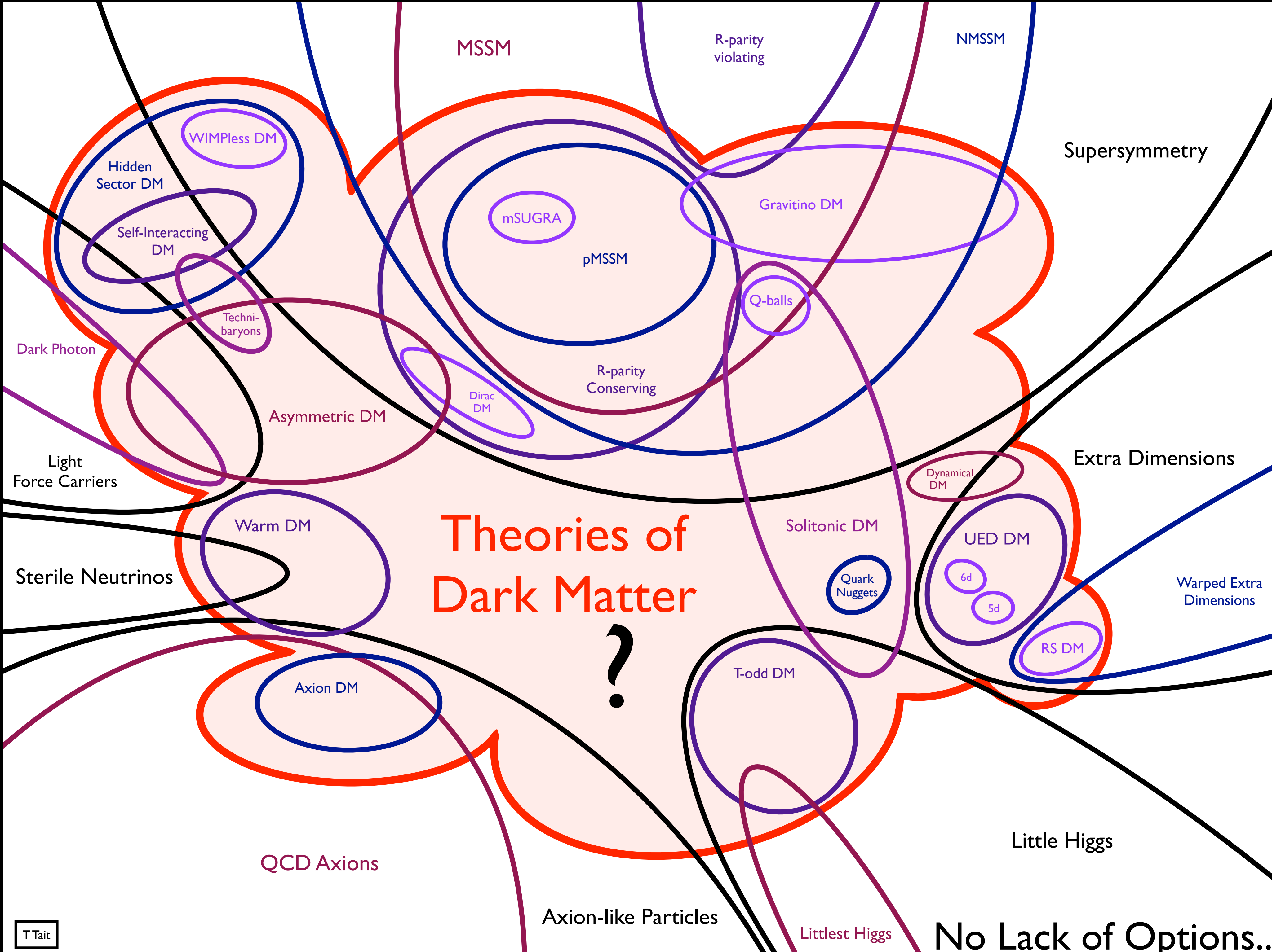






Which theory to use?


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
Dynamical
DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
6d
5d
Warped Extra
Dimensions
Sterile Neutrinos
Quark
Nuggets
RS DM
Axion DM
?
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait



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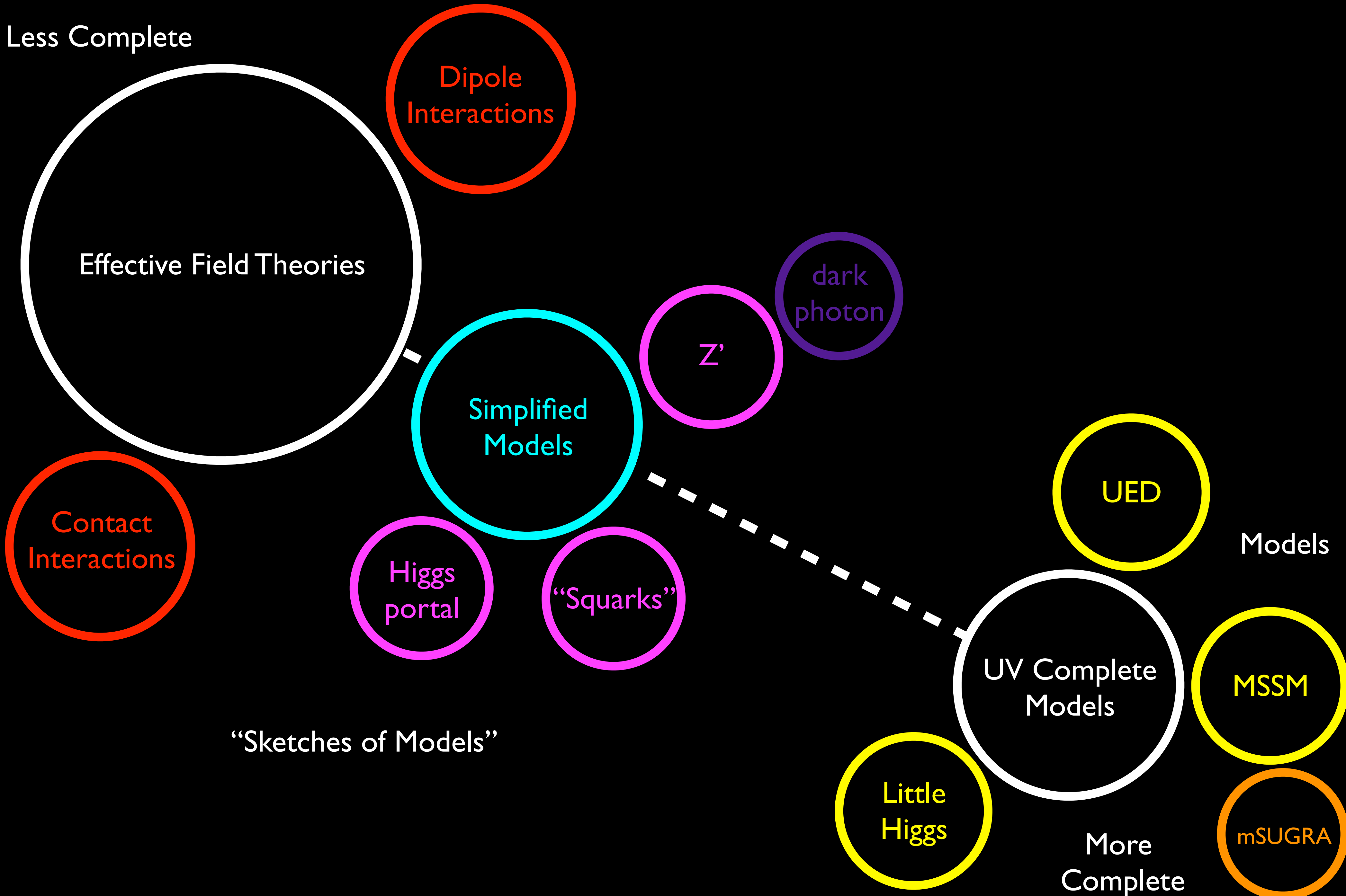
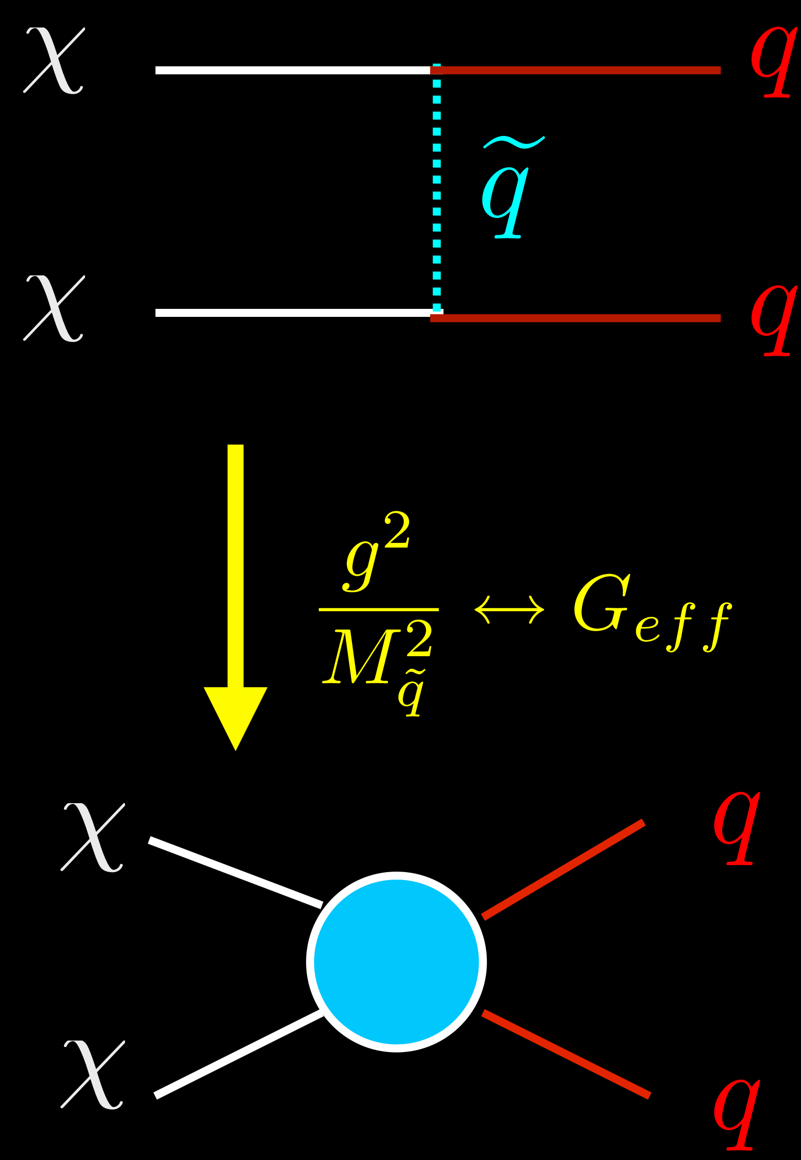
No Lack of Options...
T Tait

Spectrum of Theory Space



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.



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
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M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
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M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
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$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

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

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

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

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

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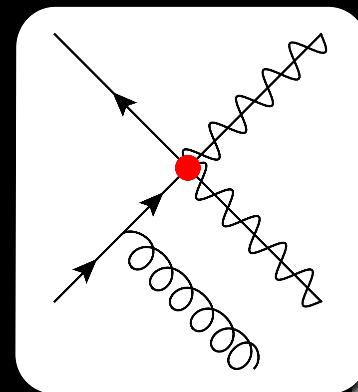
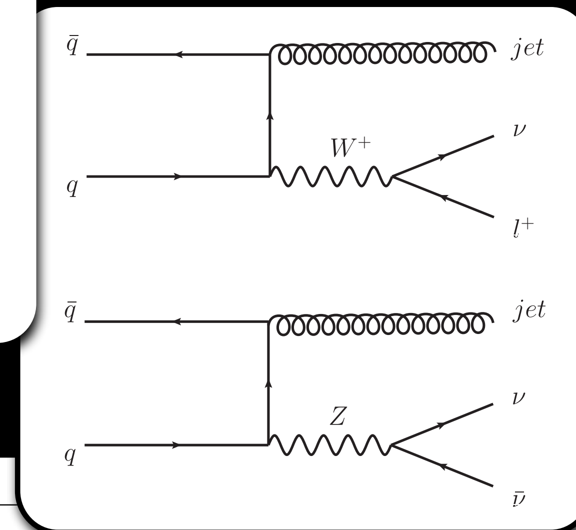
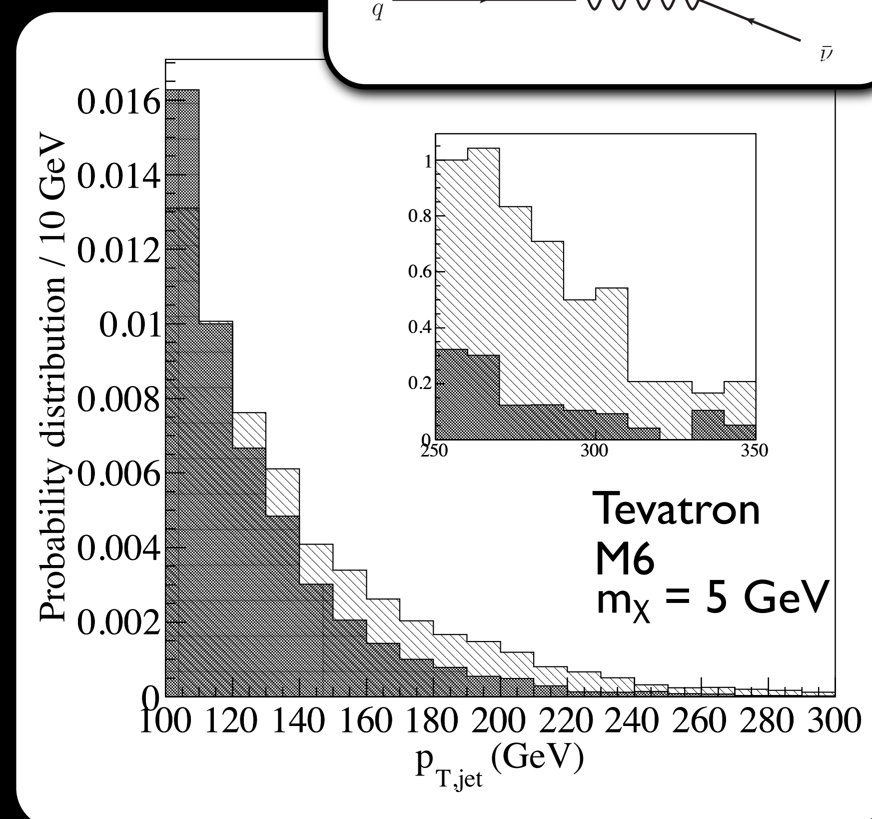
Collider Searches

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

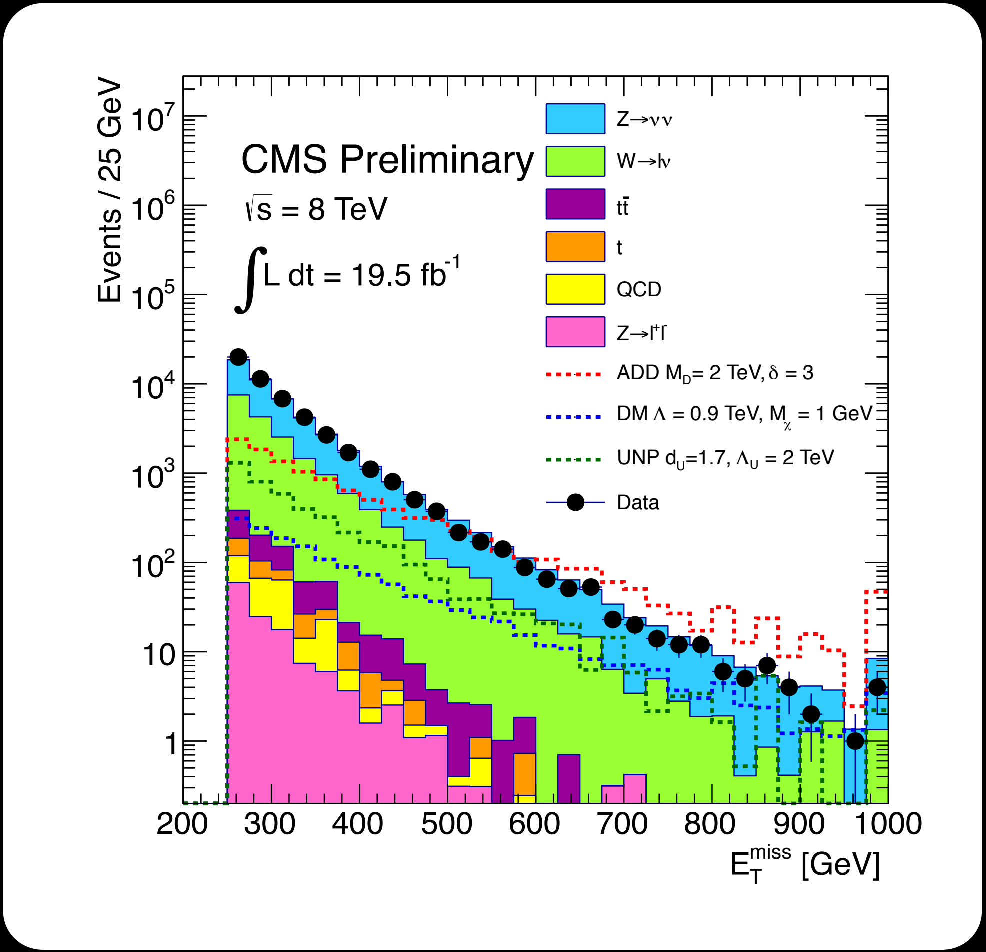


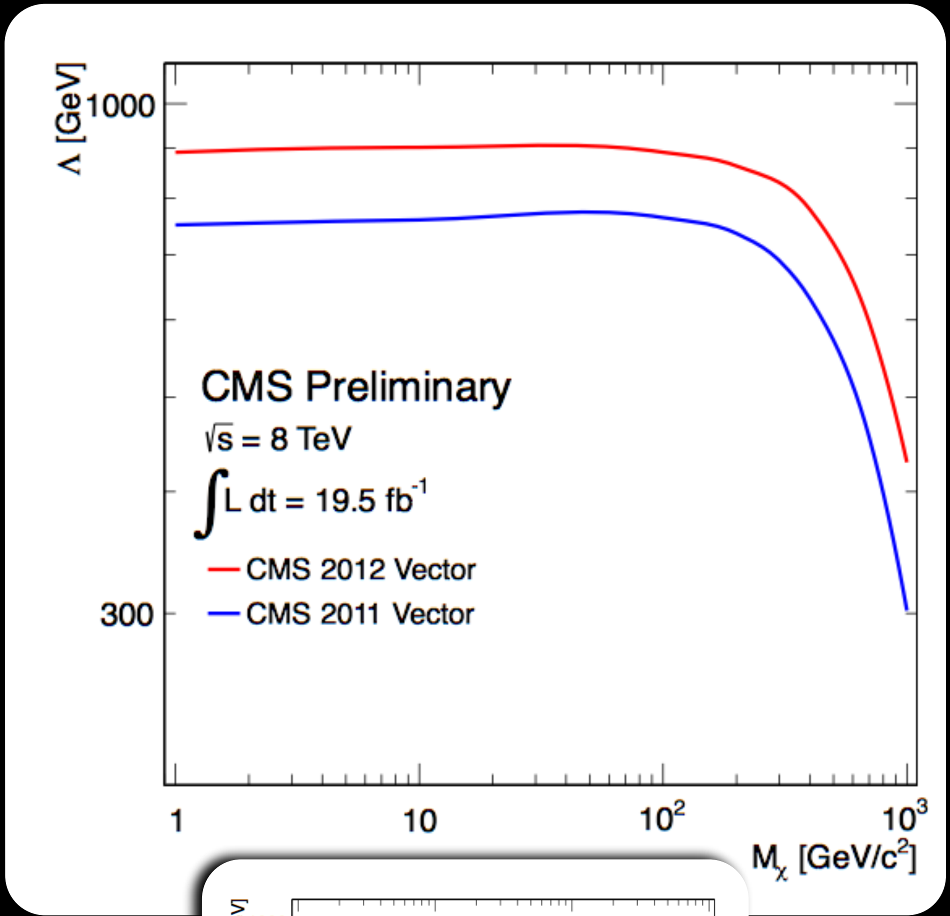


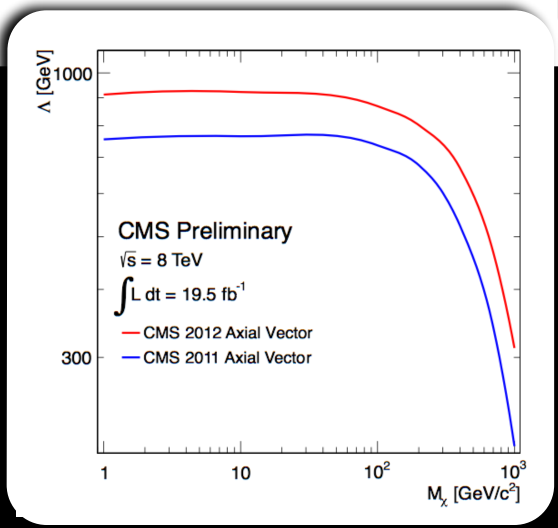


Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP

Collider Results

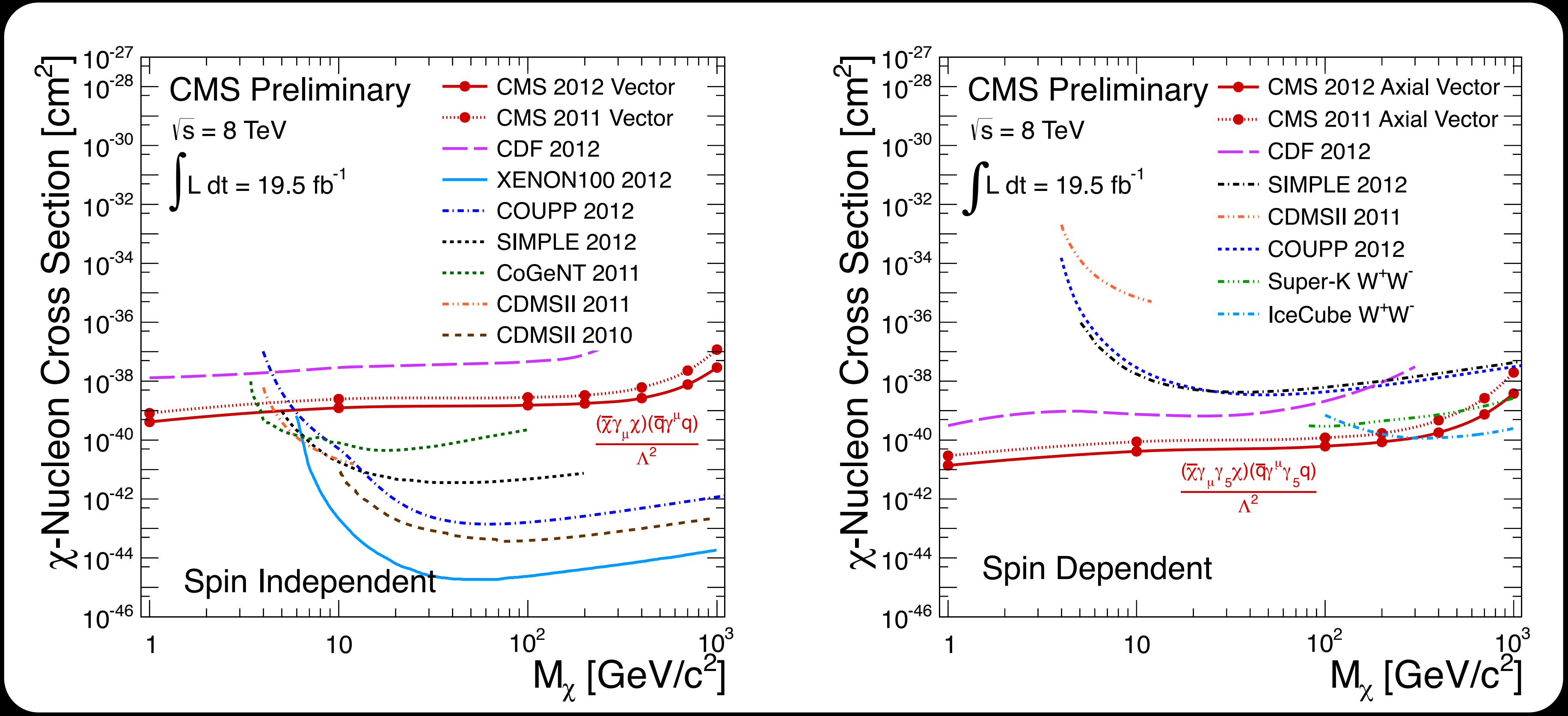






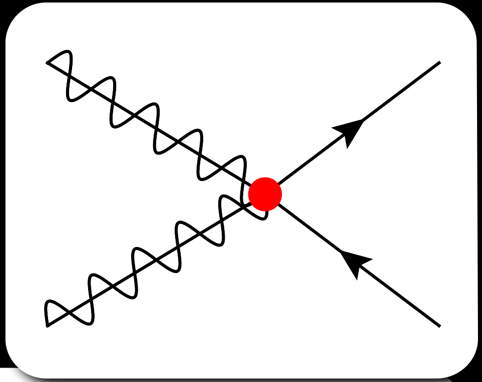
Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

Translation to Elastic Scattering

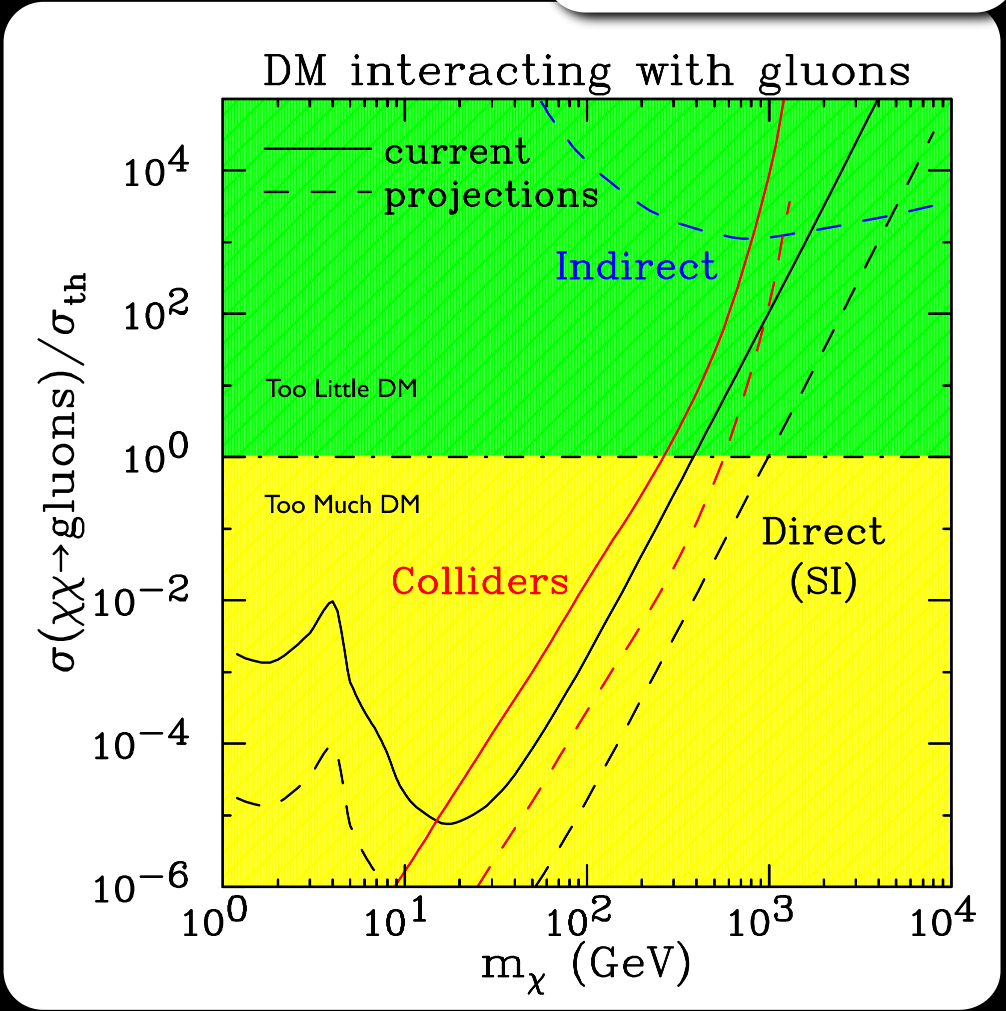


- Colliders can help fill in a challenging region of low dark matter mass and spin-dependent interactions.
- Since they see individual partons, rather than the nucleus coherently, collider results offer a complementary perspective on DM interactions with hadrons.
- The translation assumes a heavy mediating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

Annihilation

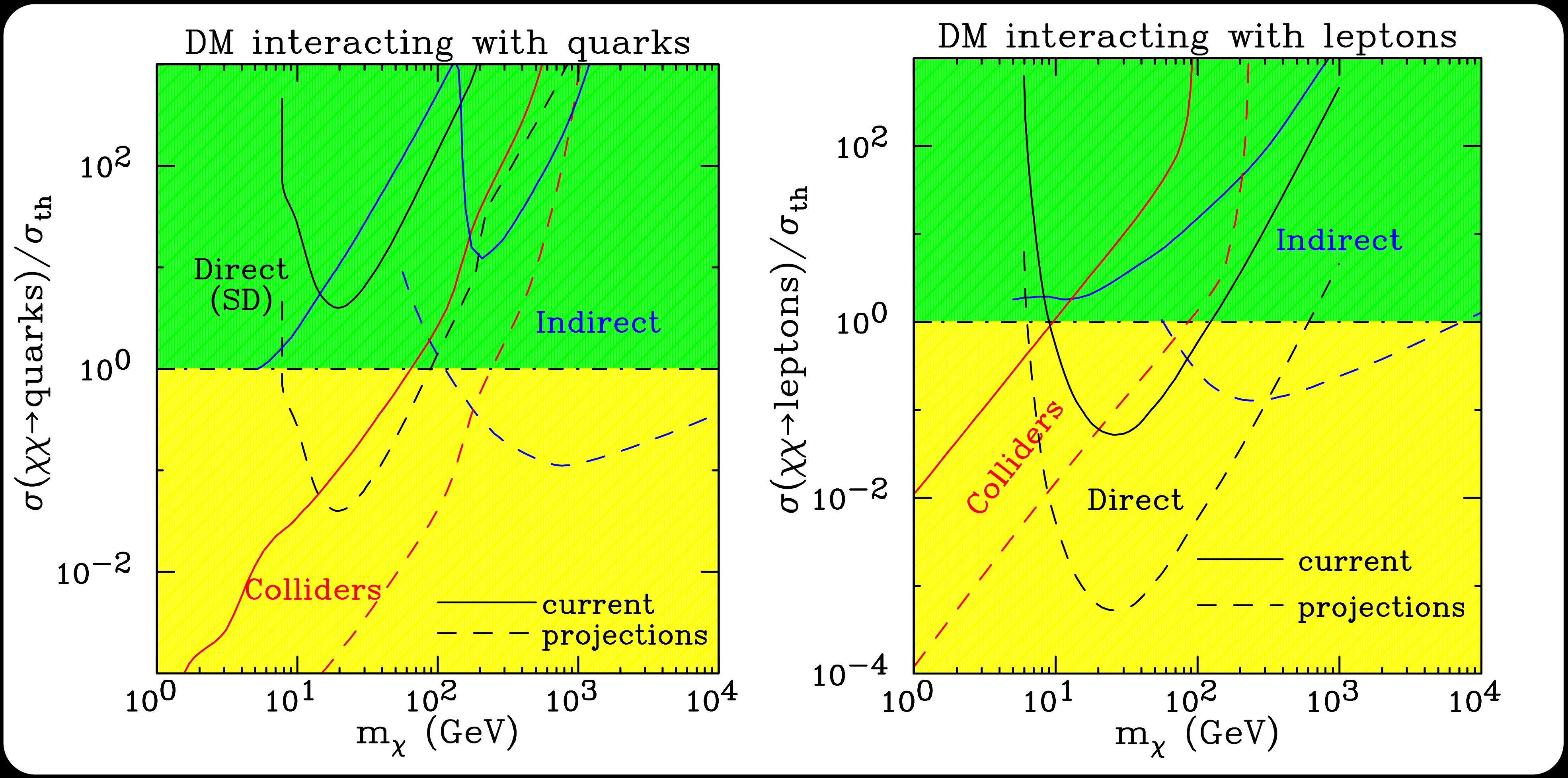


- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders 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

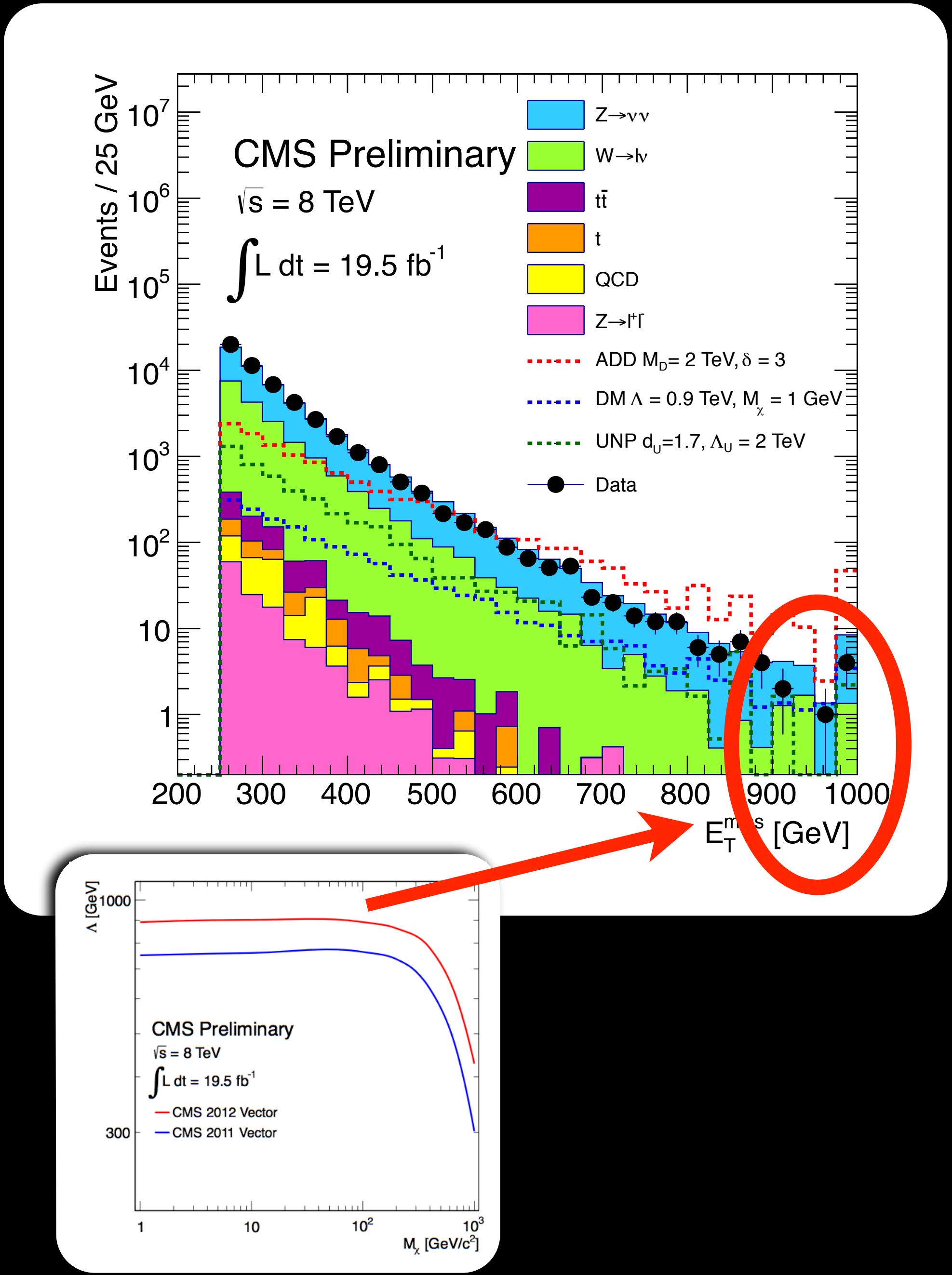
Quarks & Leptons



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-dependent in that sense.]



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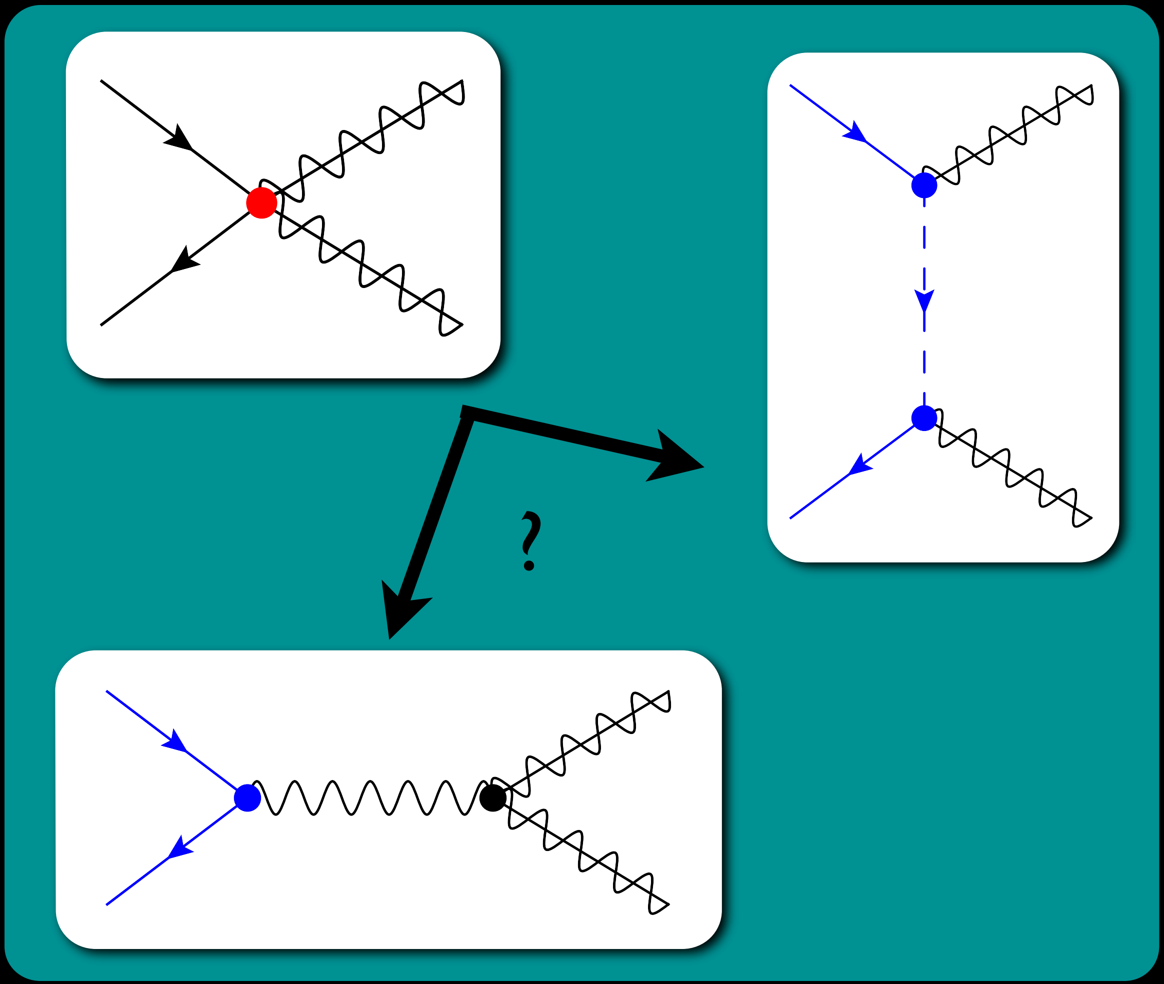


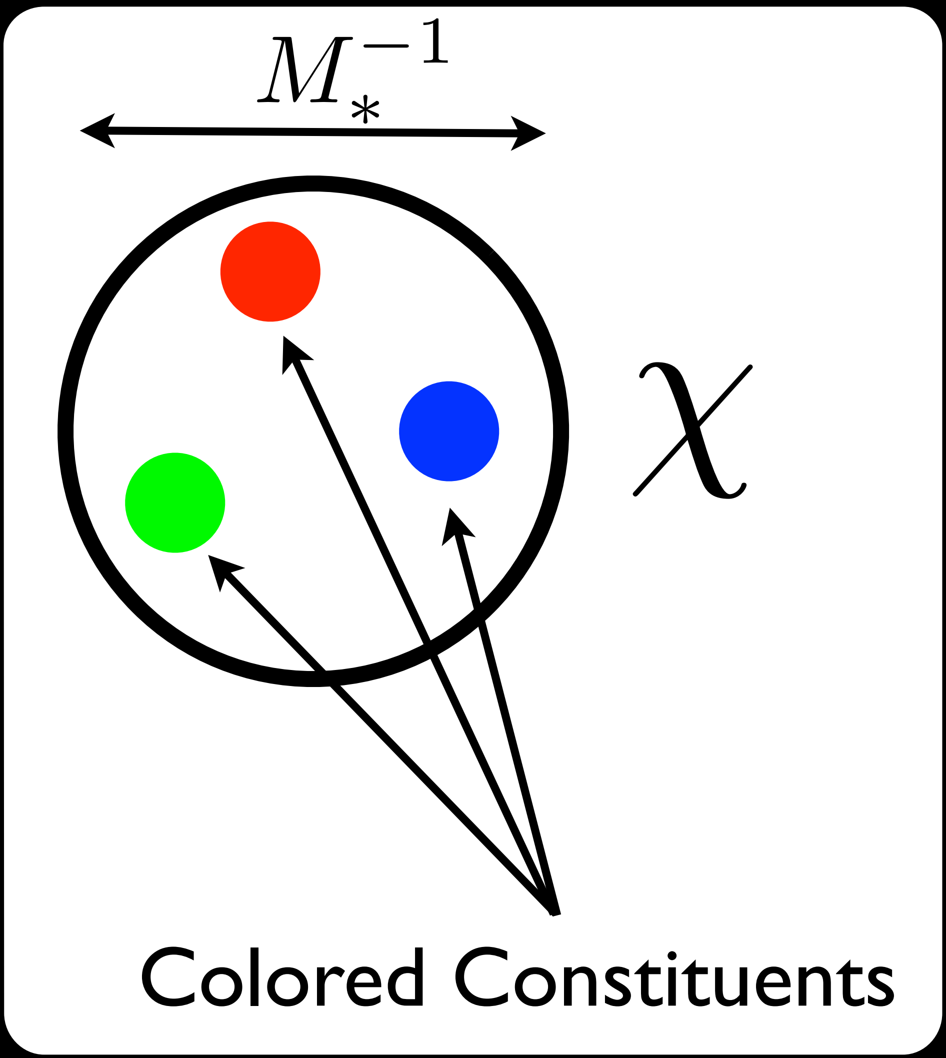
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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.

One way to understand this issue would be to try to explore the space of reasonable UV completions and see how things look.

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 dark confinement scale -- the "radius" of the dark matter.

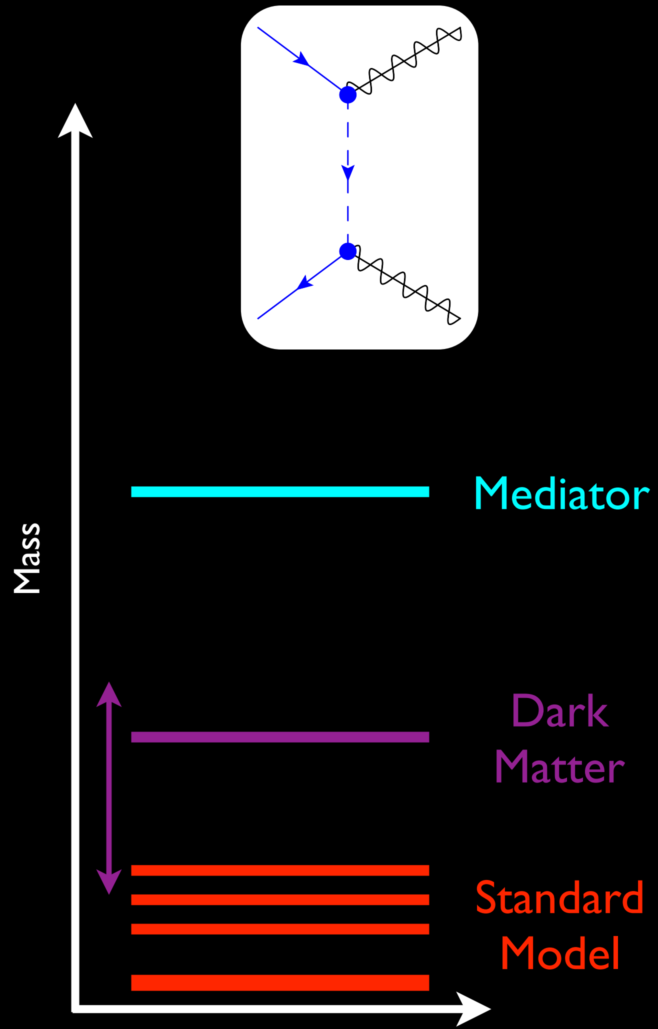
Simplified Model

- Moving toward a more complete theory, we can also consider a model containing the dark matter as well as the most important particle mediating its interaction with the Standard Model.

- 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 theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing 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 with quarks.

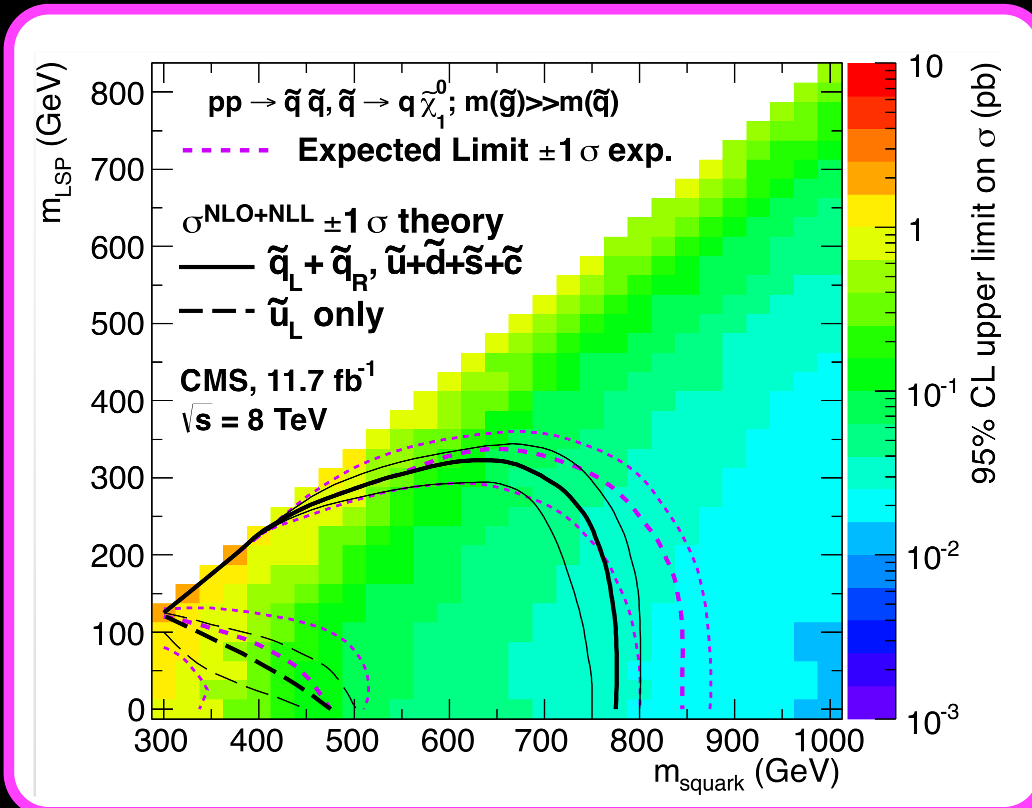


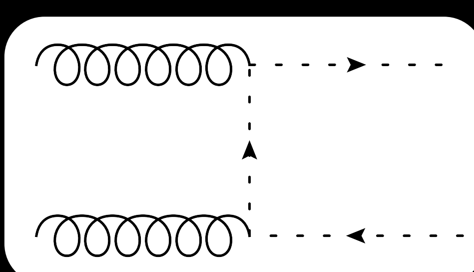
Lots of Recent Activity:

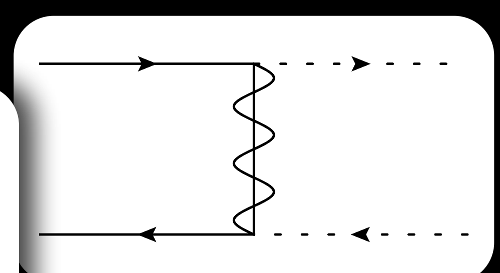
Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
Papucci, Vichi, Zurek 1402.2285
+ follow ups.

$\tilde{u}_R$ Model

- To start with, consider a theory where a Dirac DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force (QCD; mostly from initial gluons) or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.
- This is effectively a simplified model the collaborations already consider in searching for squark-like particles.





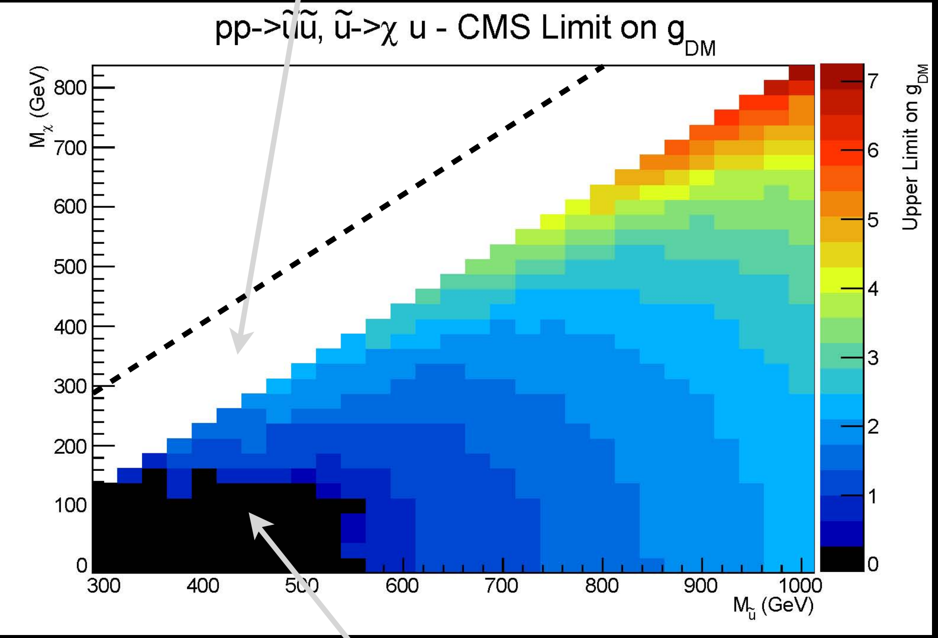


$\tilde{u}_R$ Model

- In order to avoid strong flavor constraints, we implement minimal flavor violation by promoting the colored mediator to a flavor triplet.
- MFV would suggest that the first two generations have almost equal couplings, but is more agnostic about the coupling of the top quark to its mediator.
- Similarly, the masses of the first two generation mediators should be close to degenerate, and there is more freedom for the top-mediator.
- 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.

Weak bounds in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



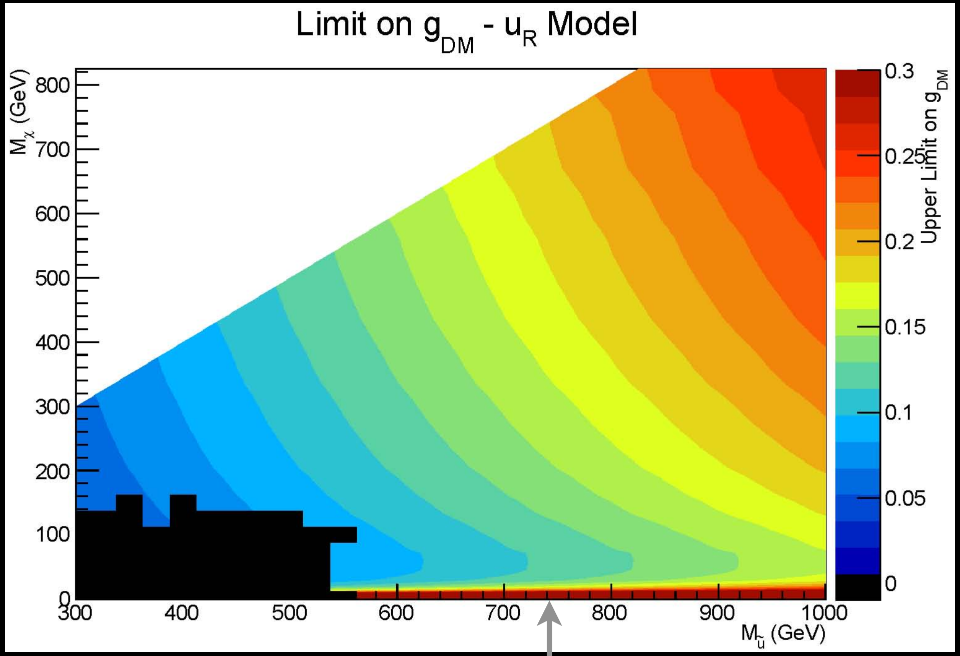
QCD production saturates the CMS limits, resulting in no allowed value of g.

All mediator masses and couplings assumed equal.

$\tilde{u}_R$ Model

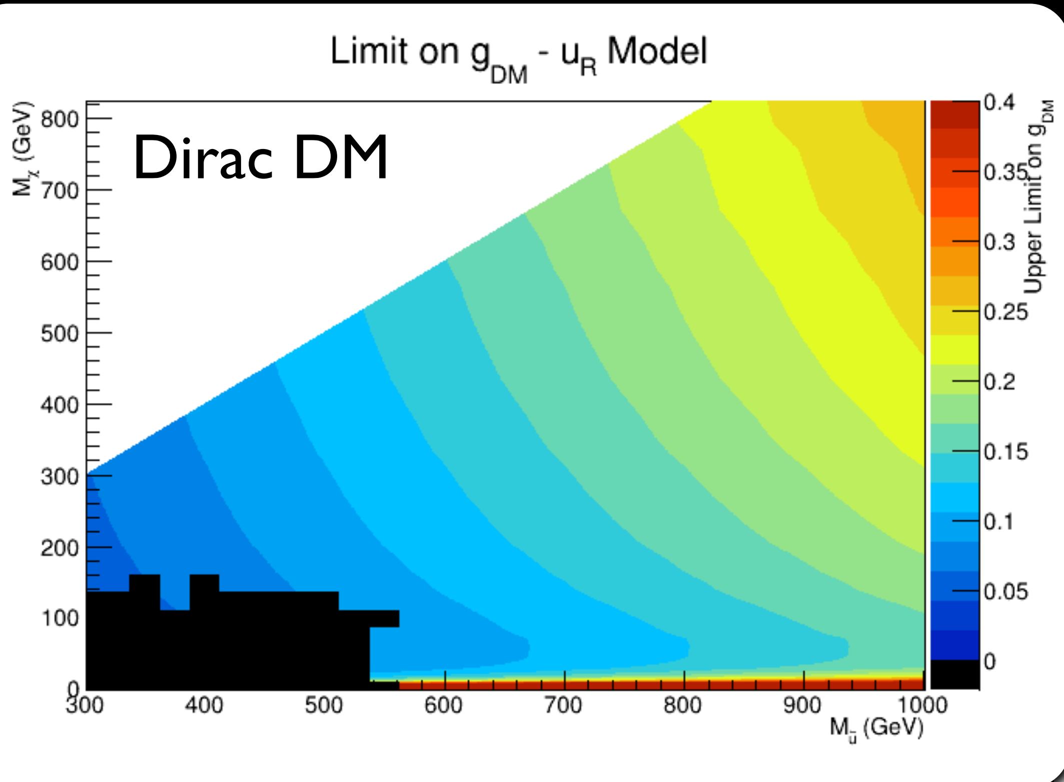
- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment. (And LUX has recently improved these bounds by roughly a factor of two for dark matter masses around 100 GeV).
- Elastic scattering does not rule out any parameter space, but it does impose much stricter constraints on the coupling in the regions the LHC left as allowed.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



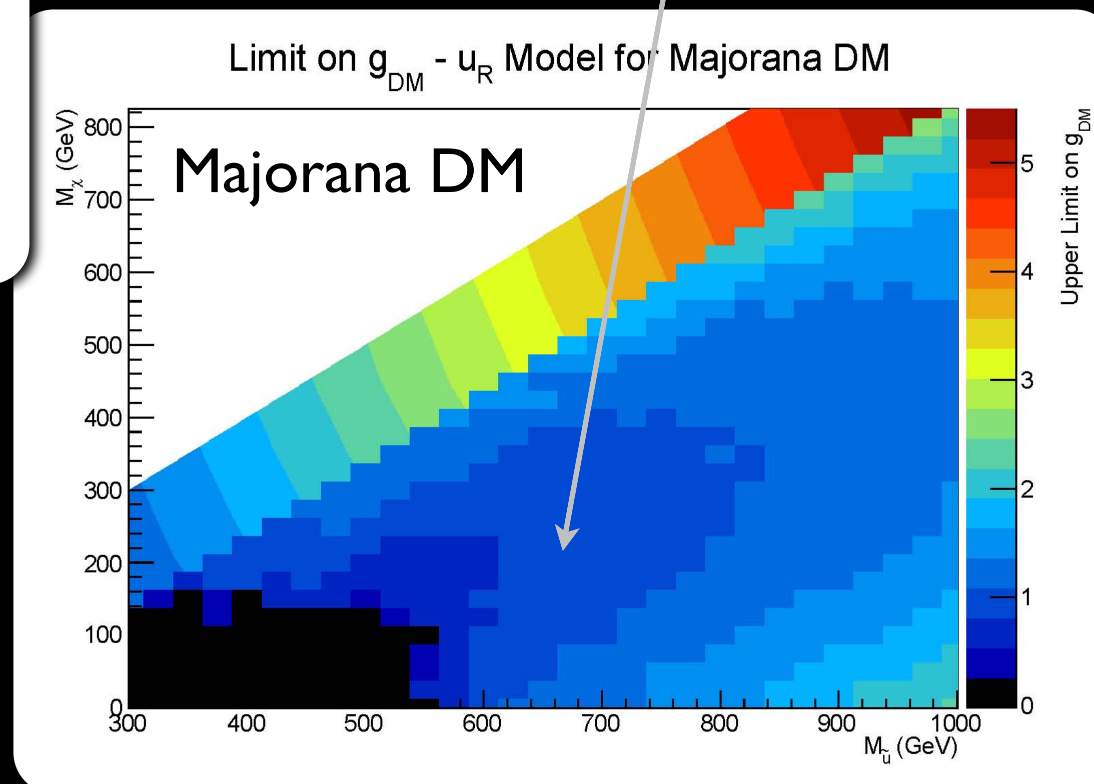
Traditional direct detection searches peter out for masses below about 10 GeV.

$\tilde{u}_R$ Model: Results



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

Collider bounds tend to dominate for Majorana DM at tree level.



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.

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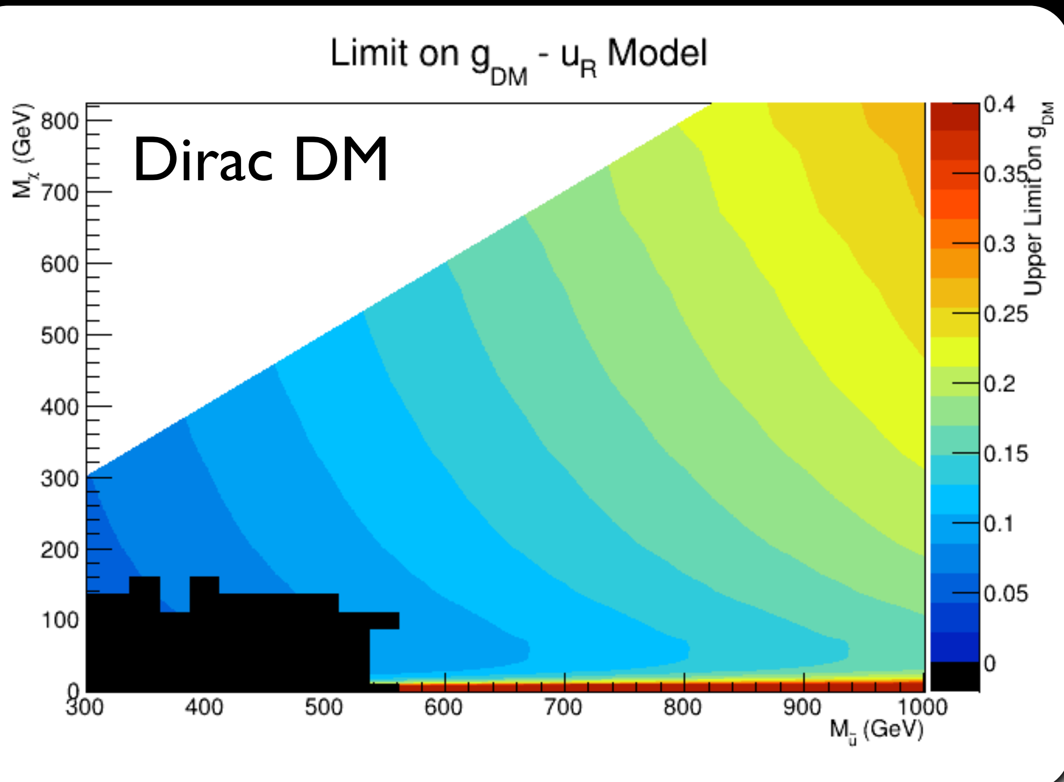

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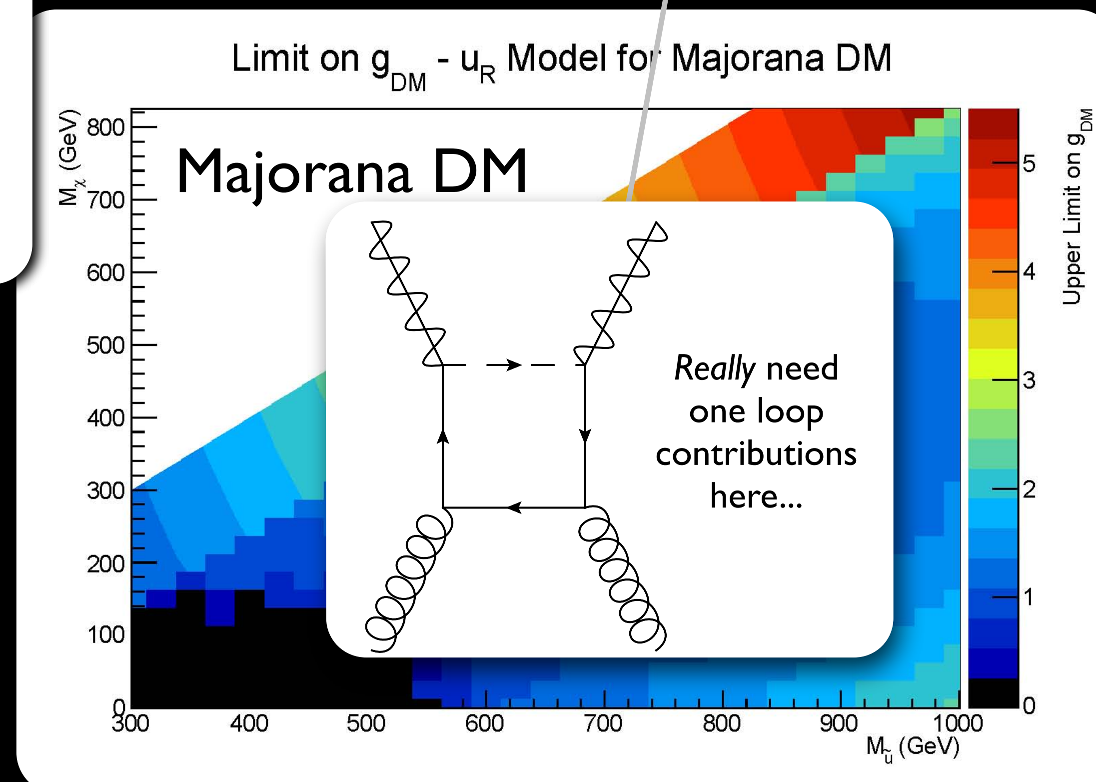

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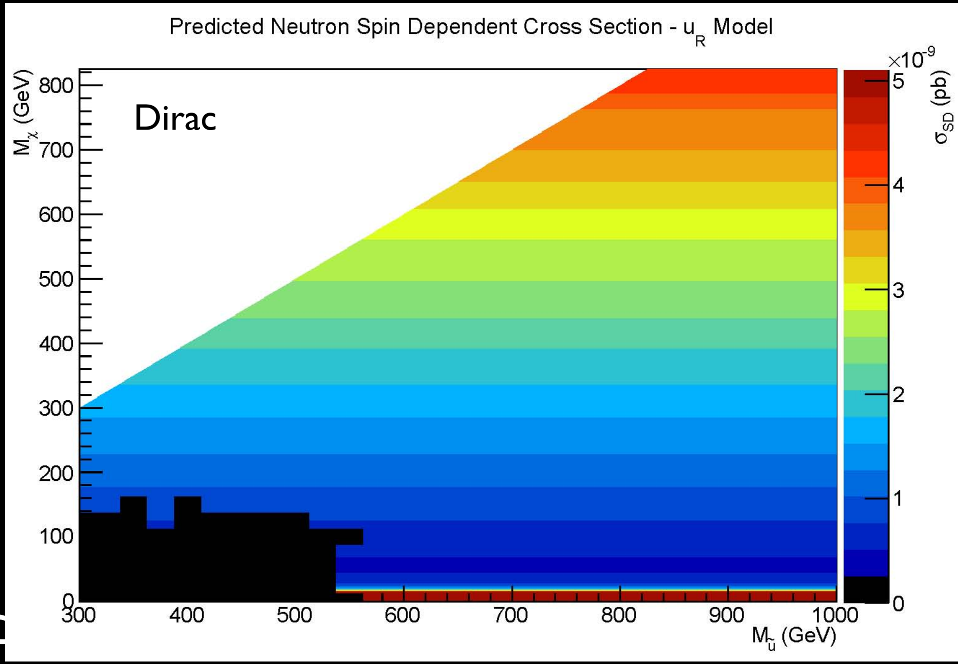
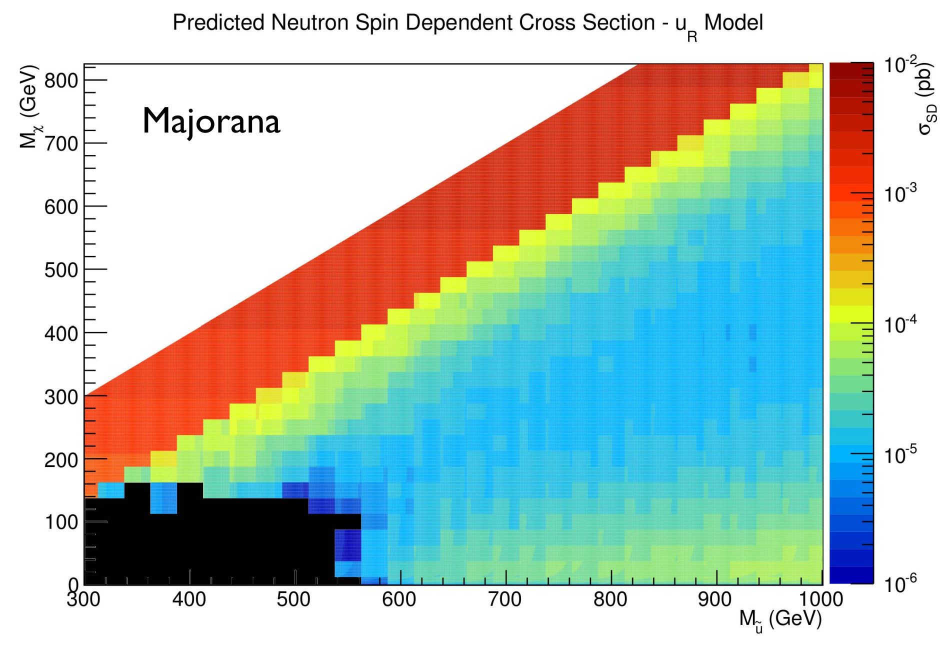
$\tilde{u}_R$ Model: Forecasts

- 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 the LHC constraints and Xenon-100 in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!

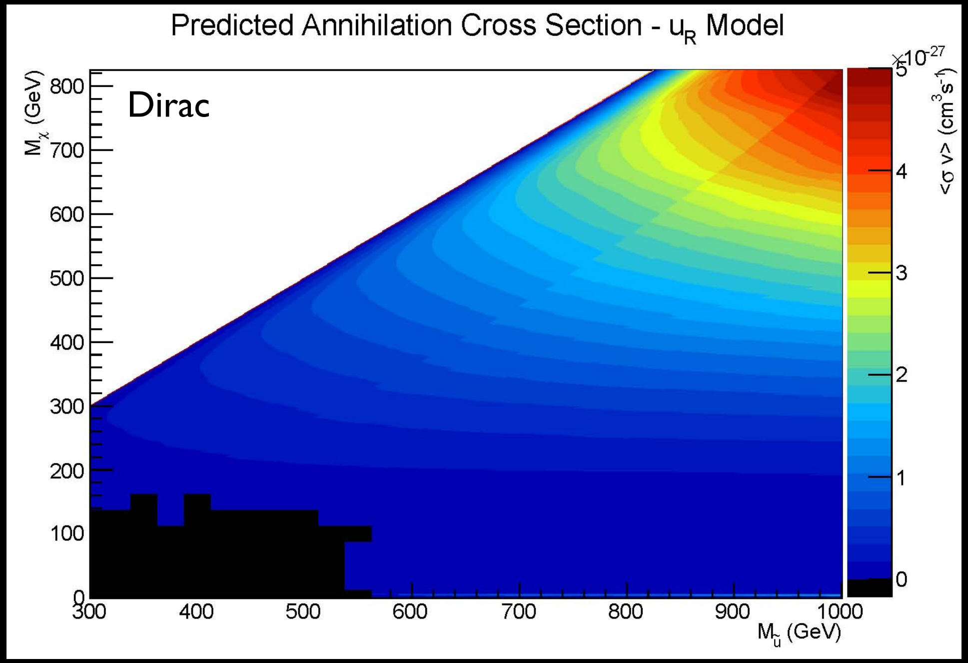


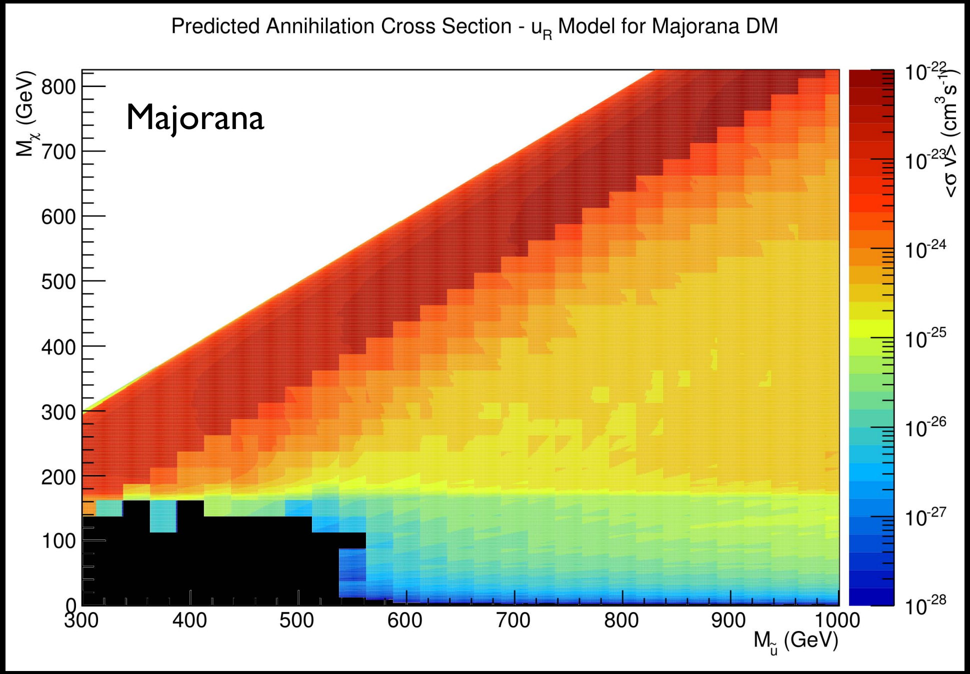


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

$\tilde{u}_R$ 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. 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.

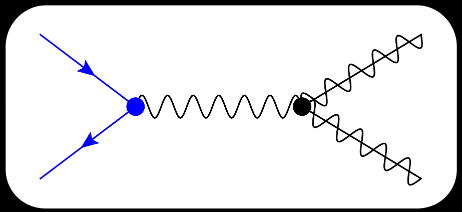


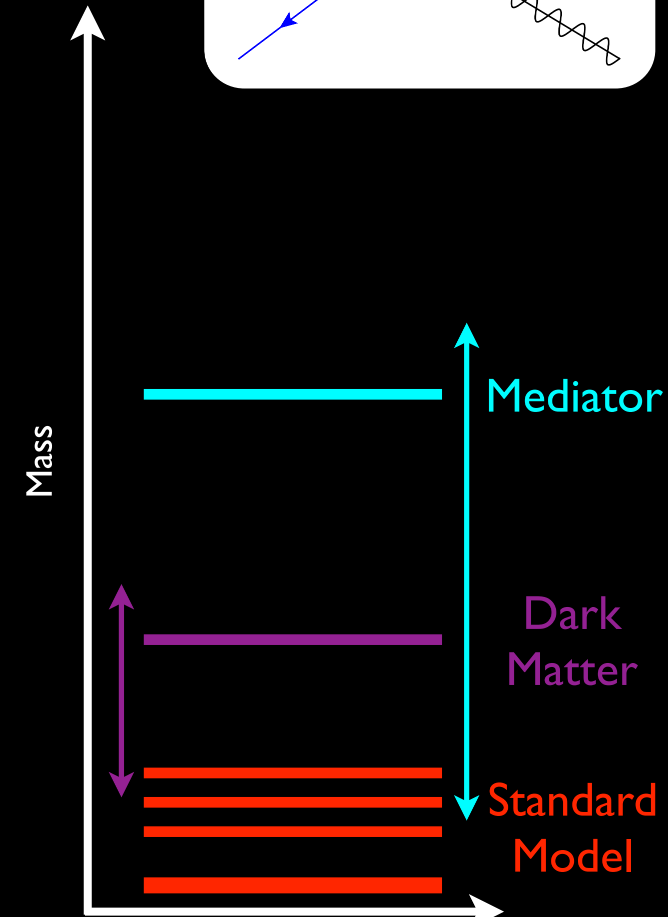


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

S-Channel : Vector

- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
  - We would like to be able to write down the SM Yukawa interactions.
  - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.
- There is a dark Higgs sector. It may not be very important for LHC phenomenology.
- Gauge anomalies must cancel, which also may not be very important for LHC phenomenology.



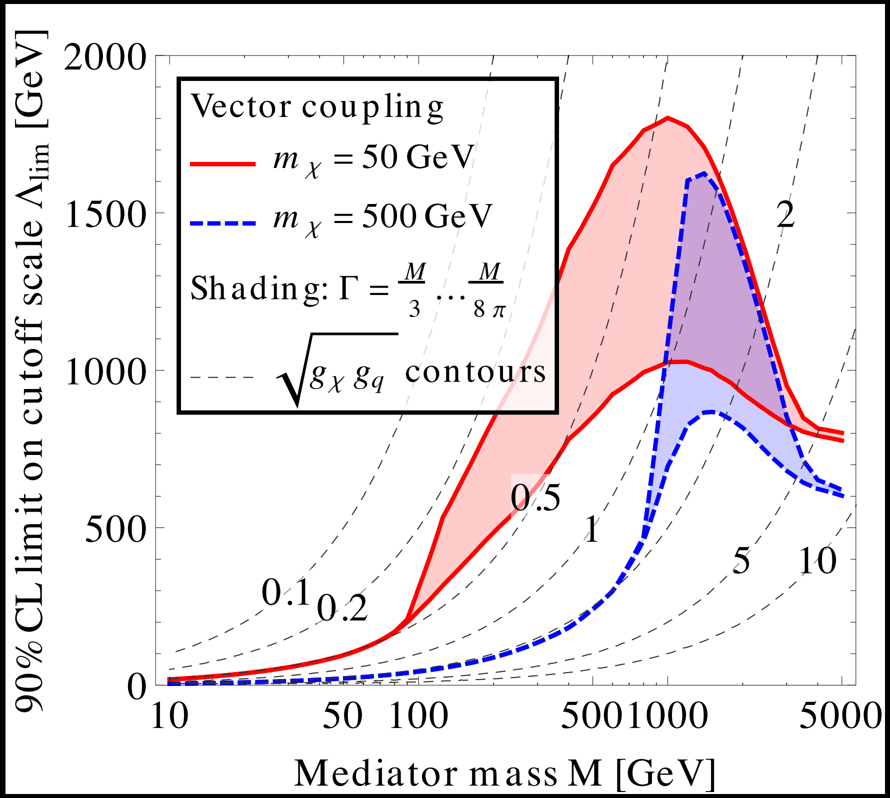


Parameters: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

How Effective a Theory?

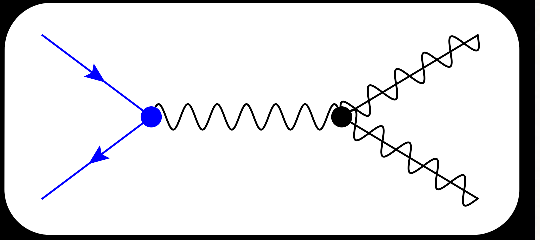
- There is a large literature asking how simplified models match up with the EFT, starting with some of the original EFT papers themselves.

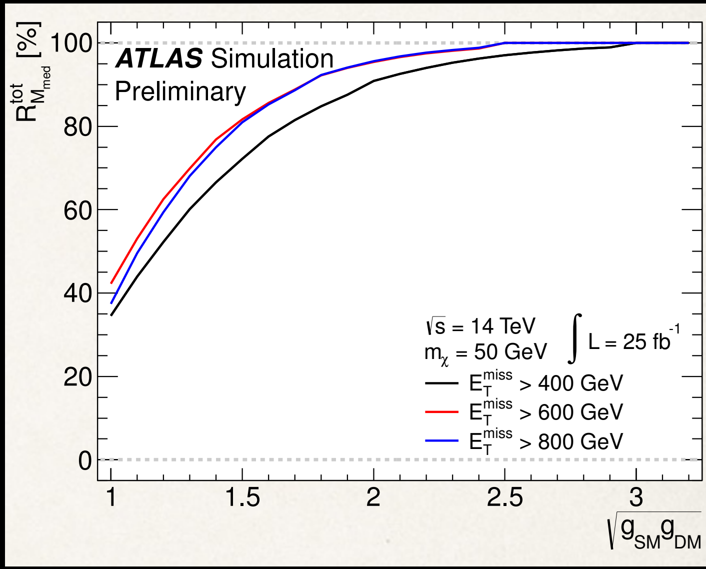
Fox, Harnik, Kopp, Tsai
1109.4398 & PRD



- Pushing the mass of the mediator higher for fixed EFT coupling corresponds to assuming the mediator is more strongly coupled.

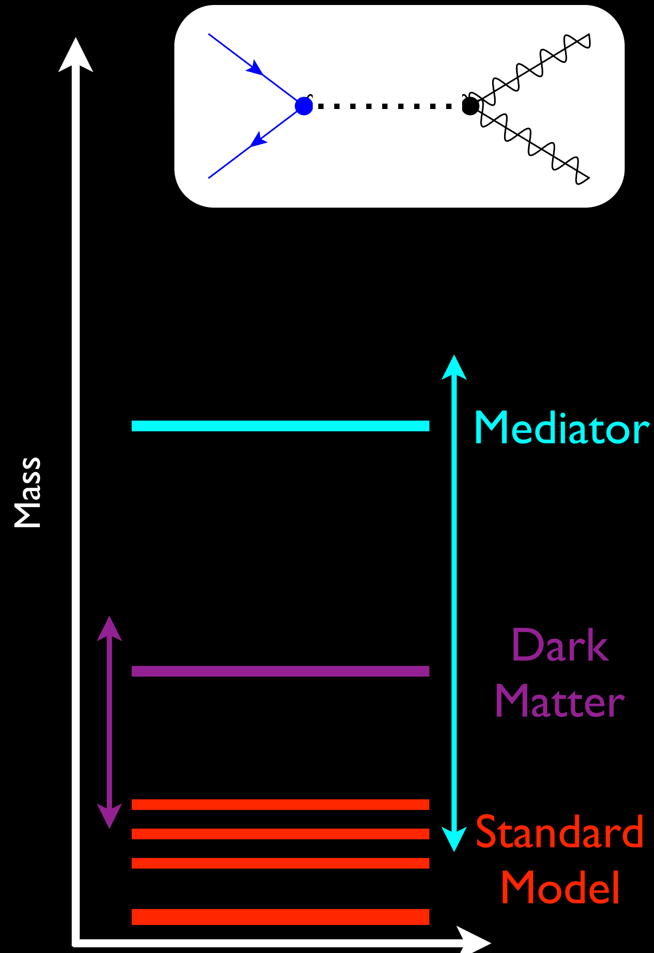
- Depending on how they are implemented, there are additional constraints from processes like dijet resonance searches, or Z'-like searches for dilepton resonances.





S-Channel : Scalar

- A singlet scalar could be real or complex.
- Scalar couplings are chirality flipping. The scalar mediator consistent with MFV couples proportionally to Yukawa couplings.
- In the SM, the only relevant parameters are the masses, and the degree of mixing with the SM Higgs through electroweak breaking.
- If the SM is extended to a two (or more) Higgs doublet model, the coupling to up-quarks, down-quarks, and/or leptons become de-correlated.
- Much like the Higgs itself, there can be important coupling to gluons induced at loop level.

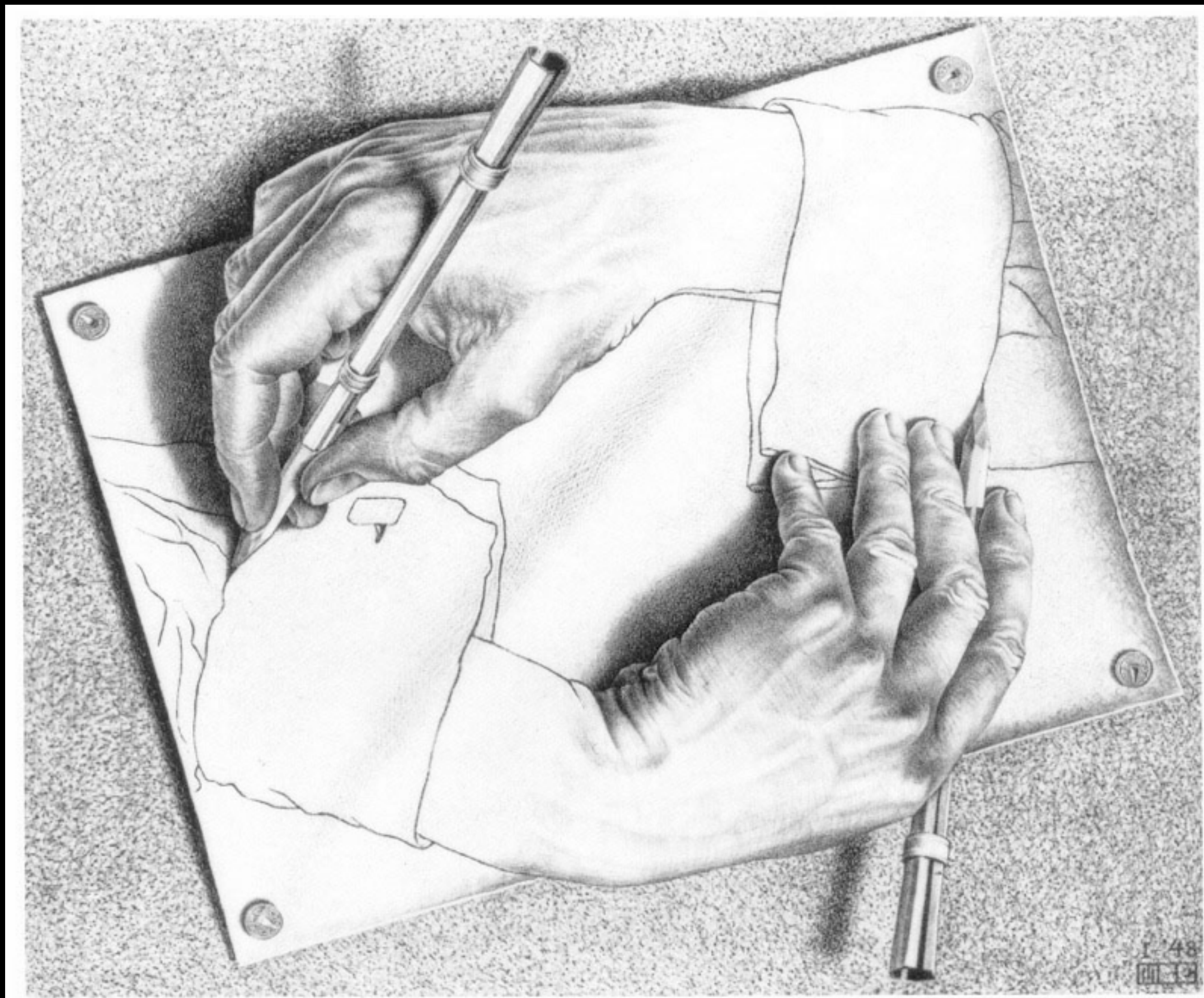


Buckley, Feld, Goncalves 1410.6497
Harris, Khoze, Spannowsky, Williams 1411.0535
+ others

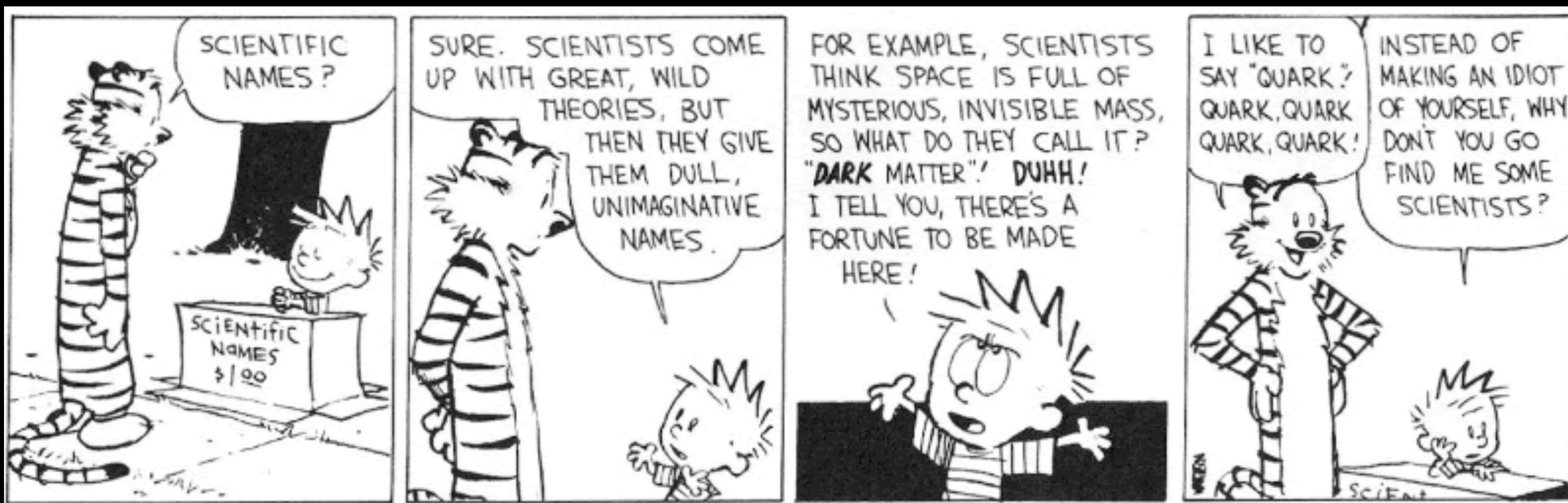
Outlook

- Colliders have important things to say about dark matter. But to understand what they are saying requires a theoretical structure.
- These could be complicated and complete like the MSSM, or simpler sketches of theories like simplified models or their EFT limits.
- I've discussed several levels and versions of sketches of theories.
- Much like the discussion of the nuclear/nucleon level EFTs of yesterday, there is need for a nuanced interpretation. None of these theories are fool-proof.
- The EFT is a conservative bound on many types of theories, but it is not supposed to be a good description for light mediators (and it can over-estimate bounds on such cases).
- Ultimately, experiment needs to bring the sketches to life.

From Sketch to Life



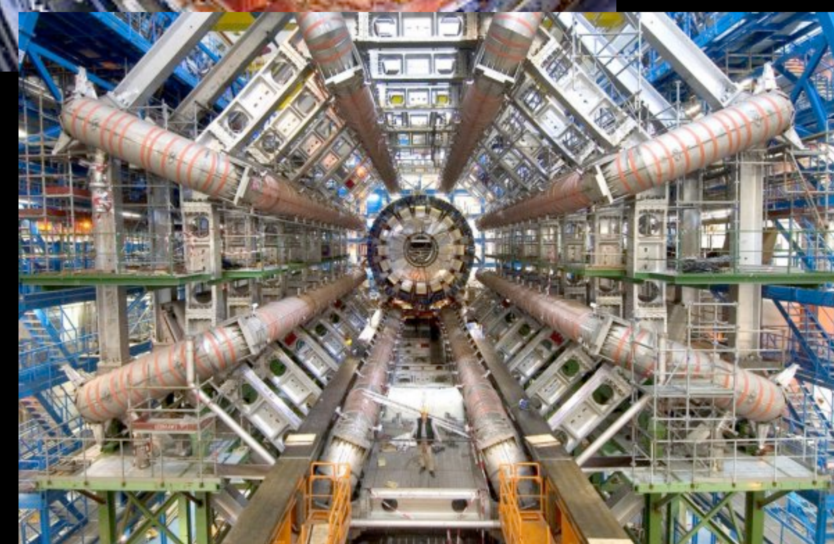
Sketches of ....


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

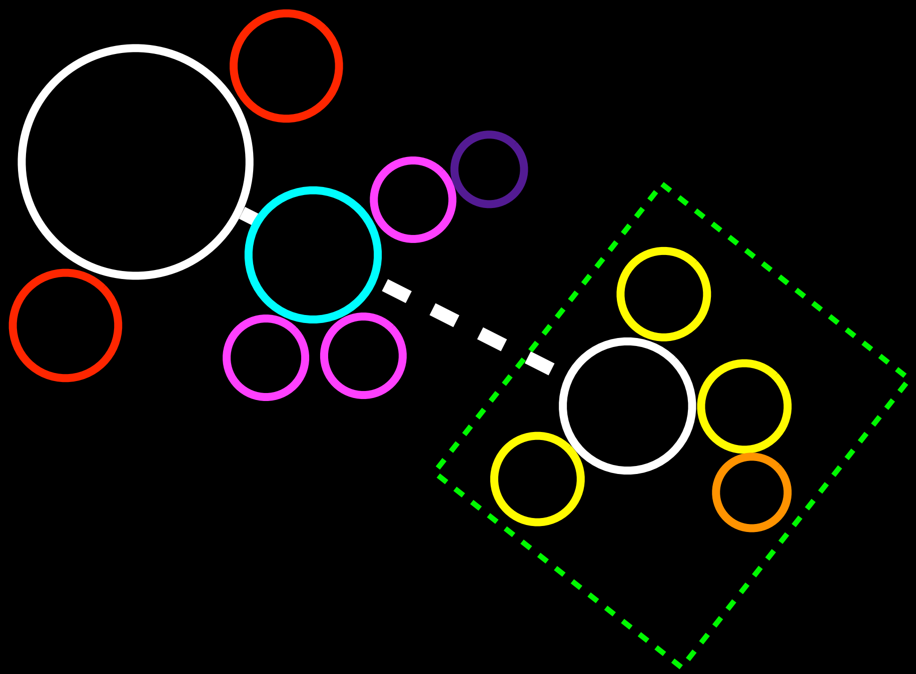
Collider Production

- If WIMPs couple to quarks or gluons, we should also be able to produce them at high energy colliders.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Provided they have enough energy to produce them, colliders may allow us to study other elements of the "dark sector", which are no longer present in the Universe today.

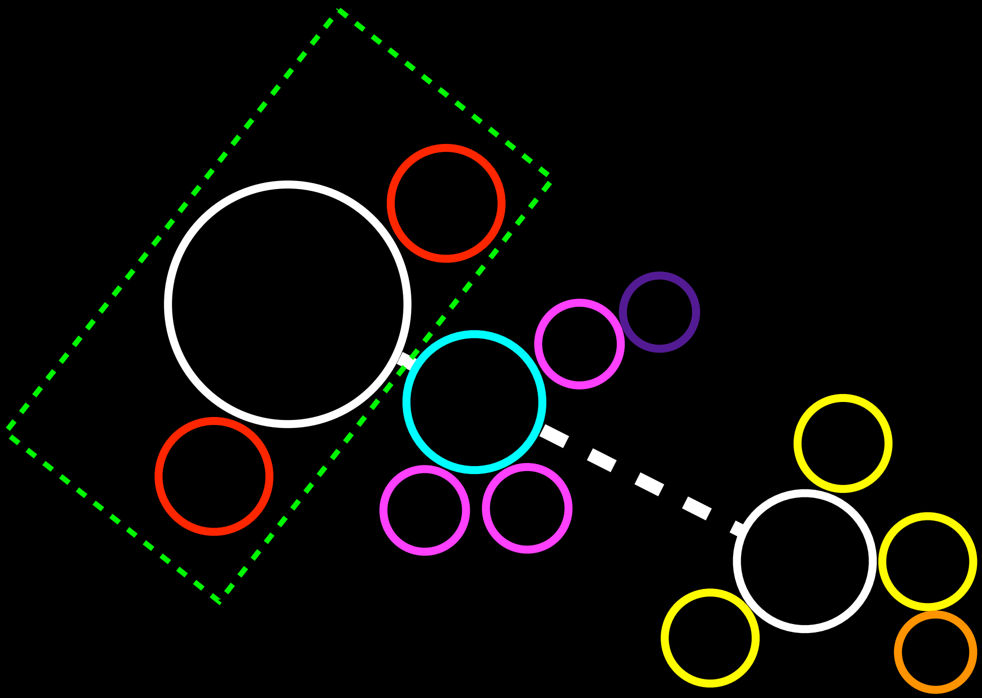


Very sophisticated detectors with many, many (many!) subsystems: But no WIMP detectors.

“Complete” Theories



Contact Interactions



Simplified Models