Dark Messages from the LHC

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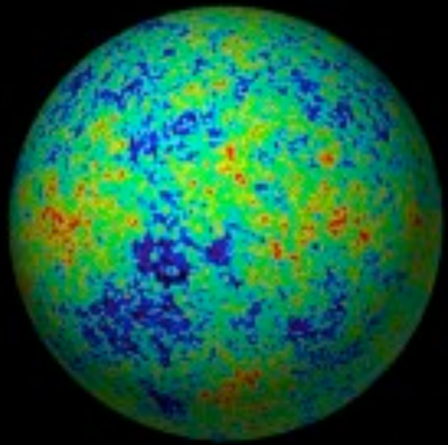
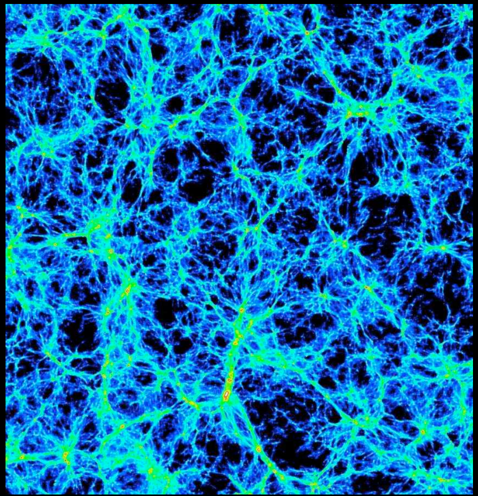
UCLA Dark Matter
February 17, 2016

Dark Matter

CMB



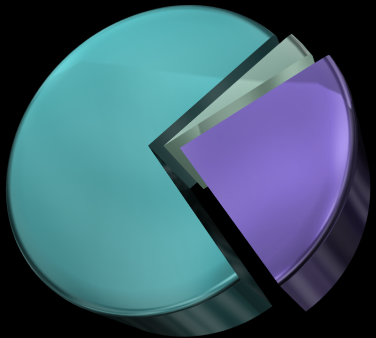
Supernova

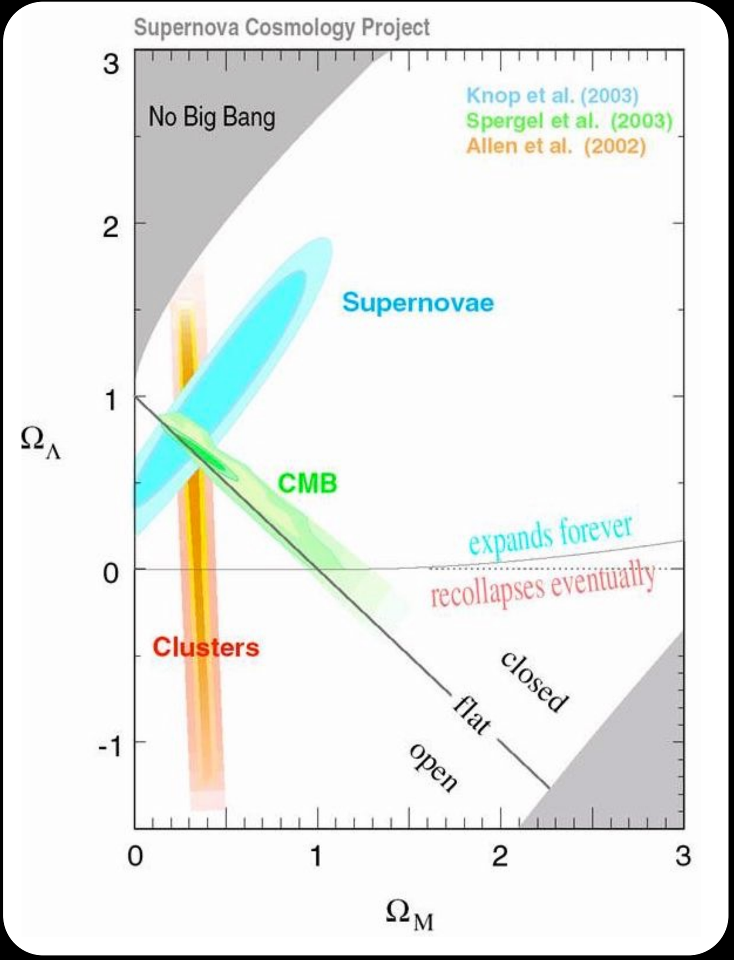


Structure

Lensing

Ordinary Matter
Dark Matter
Dark Energy



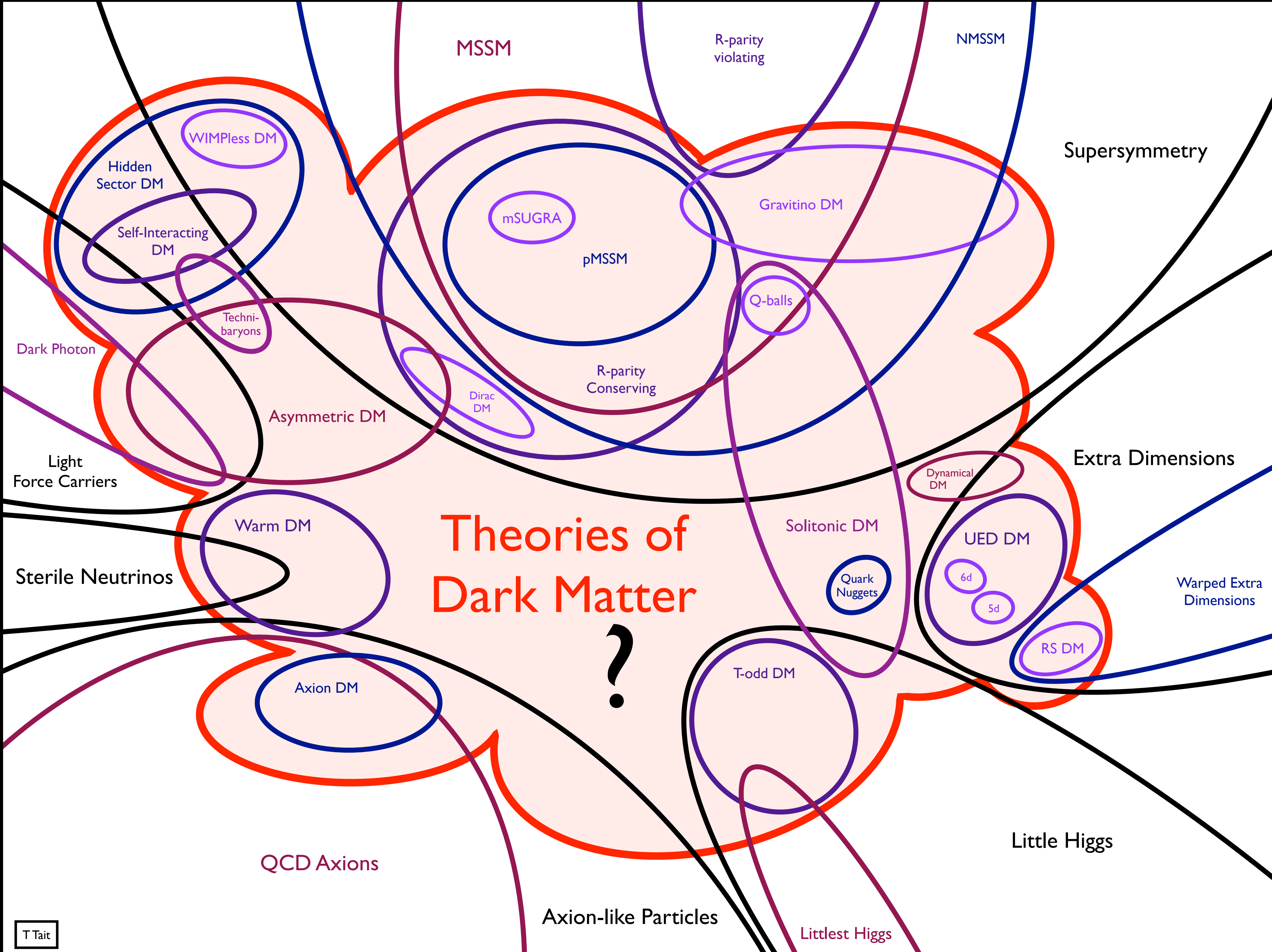


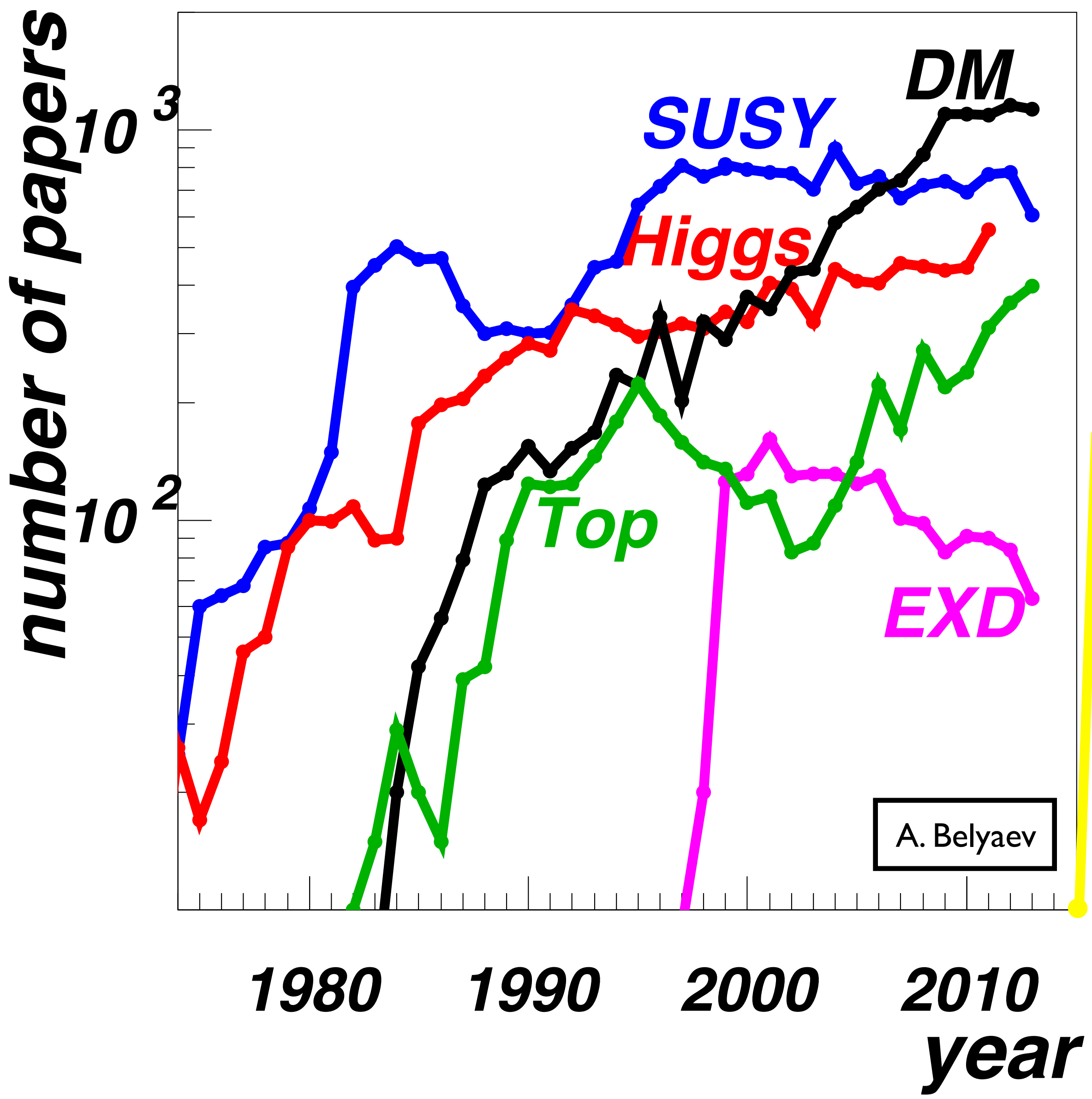
Evidence for dark matter is overwhelming…

Missing Energy Signals

- Missing energy signals are a big part of the new physics menu at colliders, largely because of the potential connection to dark matter.
- The relic density suggests that it should have reasonably large couplings to at least some of the Standard Model, in order to explain its abundance in the Universe.
- Colliders have the disadvantage that they aren't looking for the ambient dark matter around us.
    - They could easily discover a form of missing momentum that has nothing to do with DM.
    - Limits are more robust.
- Translating these searches into information about DM requires some kind of model.

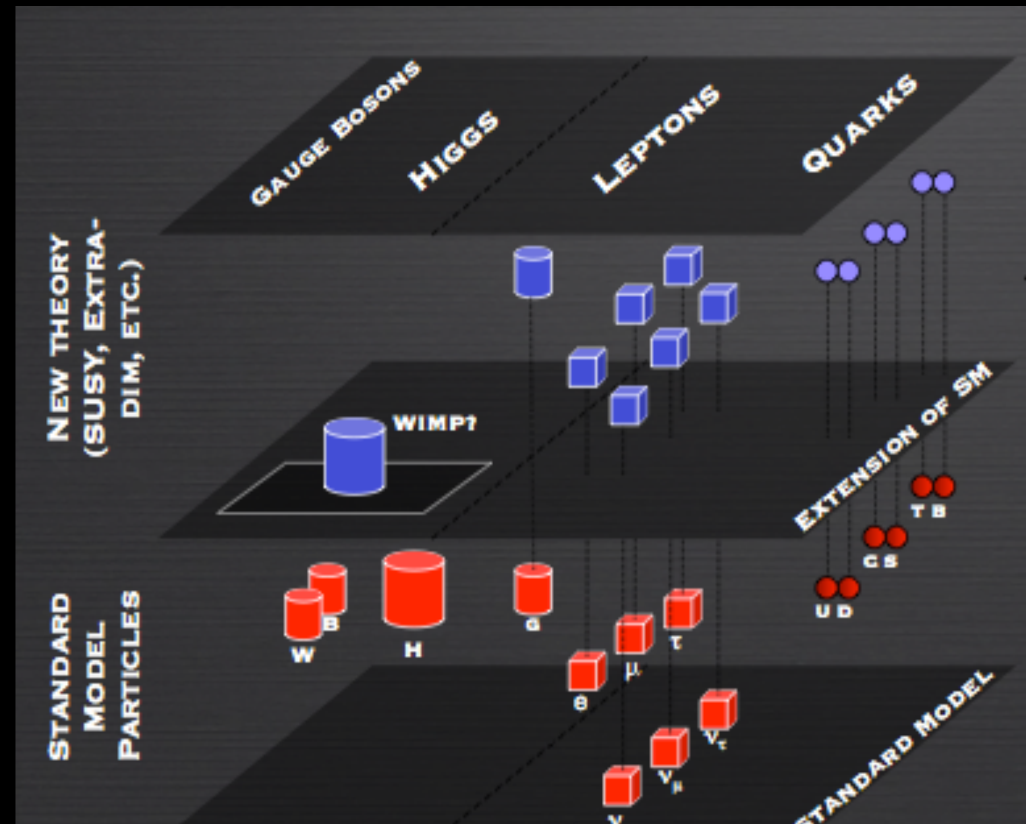
"Cold Dark Matter: An Exploded View" by Cornelia Parker


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

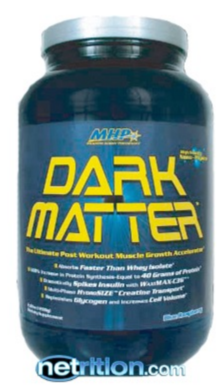

number of papers
10^3
10^2
SUSY
DM
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year

A Cartoon WIMP Theory

- A typical WIMP theory has a whole "layer" of new particles.
    - E.g. SUSY, UED, Little Higgs, ...
- The WIMP is the lightest of these new states, and must be neutral and ~stable to be viable dark matter.
- Most of the heavier "WIMP siblings" usually are colored and/or charged, and thus interact much more strongly with the Standard Model particles than the WIMP does.
- The details of the model determine how LHC signals translate into other properties of dark matter, such as annihilation and nuclear scattering.



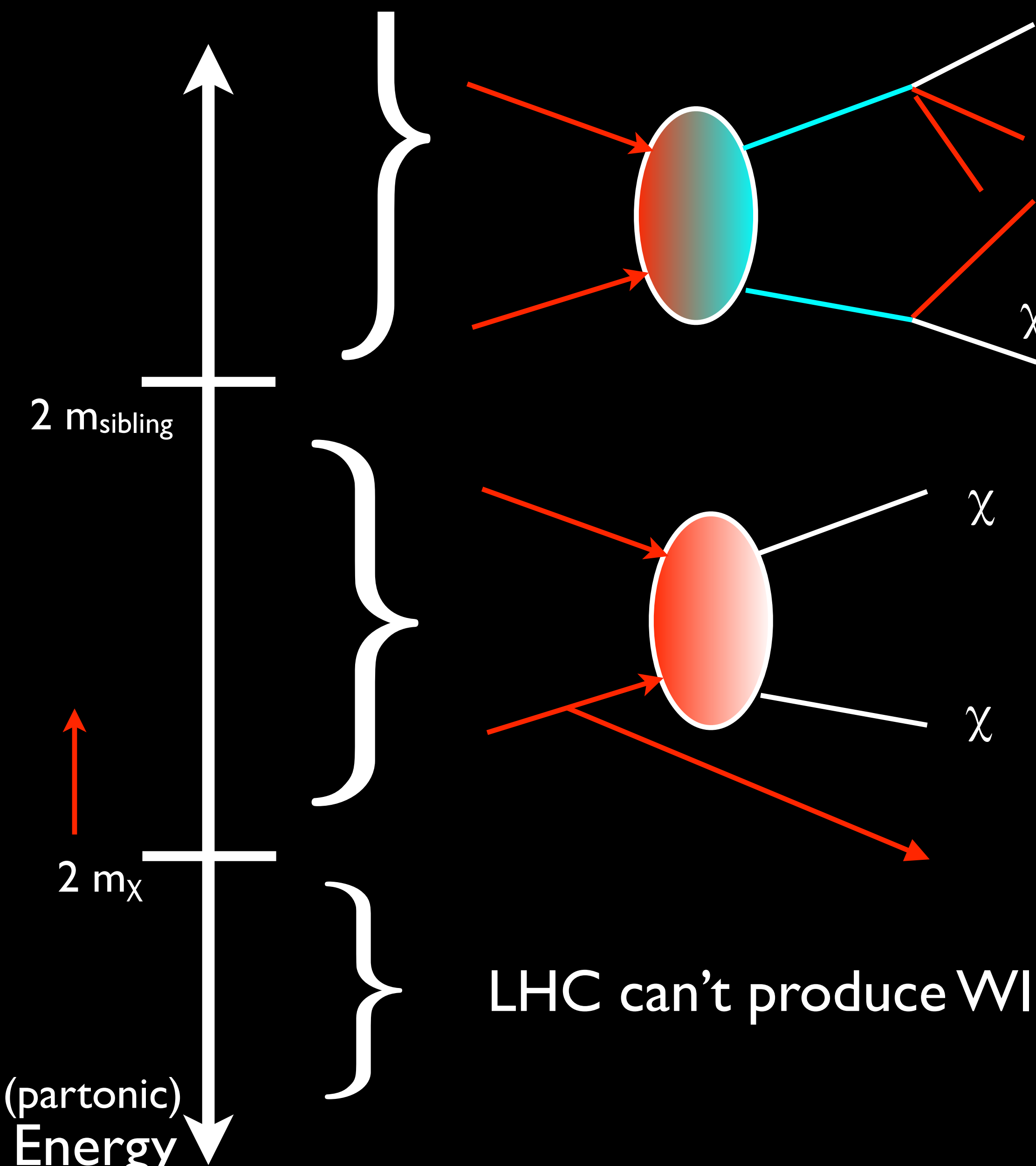
G. Bertone



$60.00 for 20 servings

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

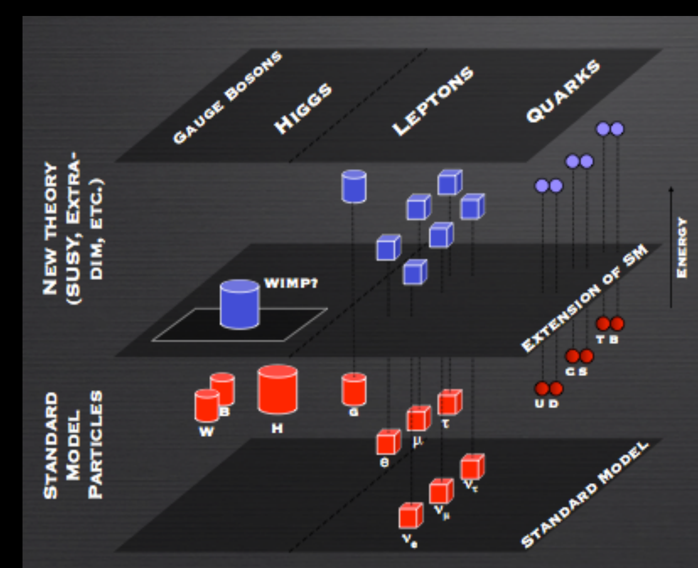
LHC WIMP Production



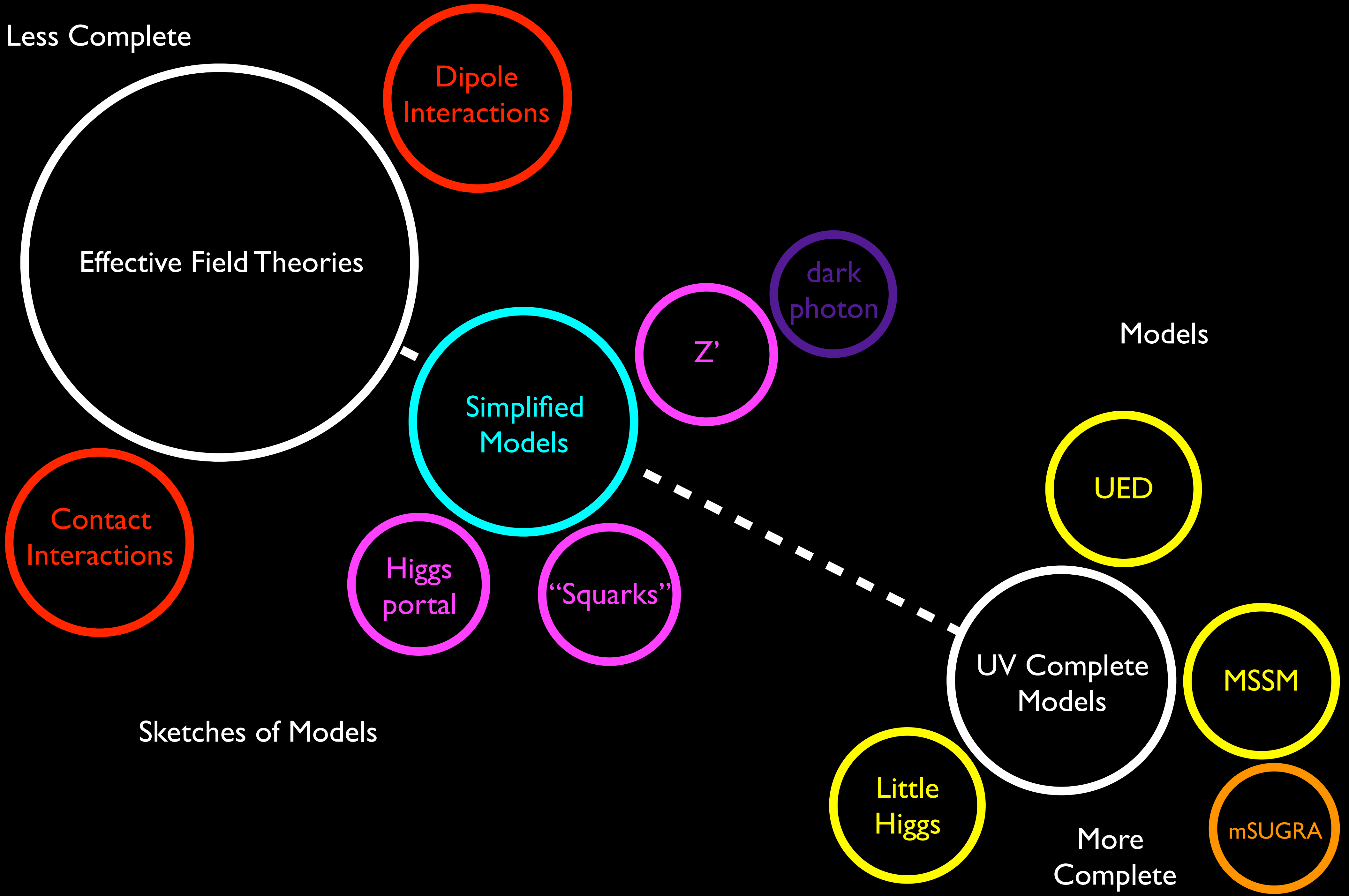
LHC can produce WIMP siblings, which decay into WIMPs and other SM particles.

LHC can directly produce WIMP pairs.

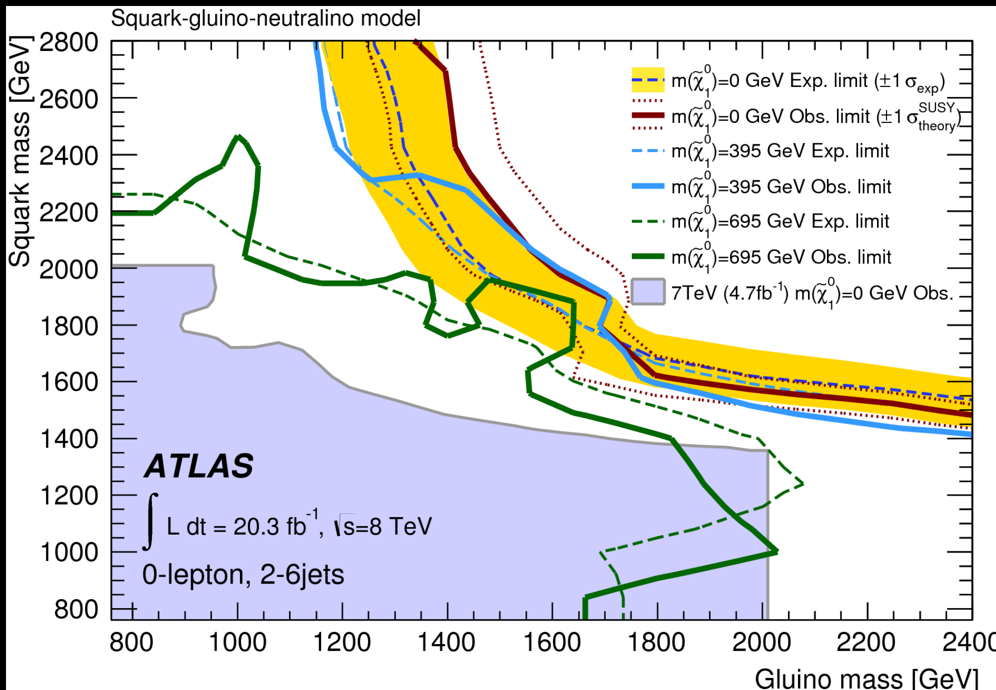
LHC can't produce WIMPs.

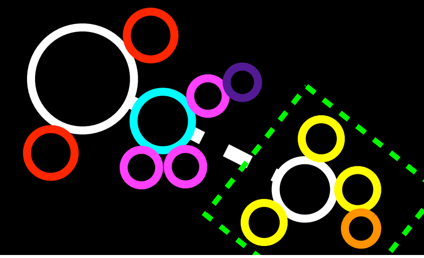


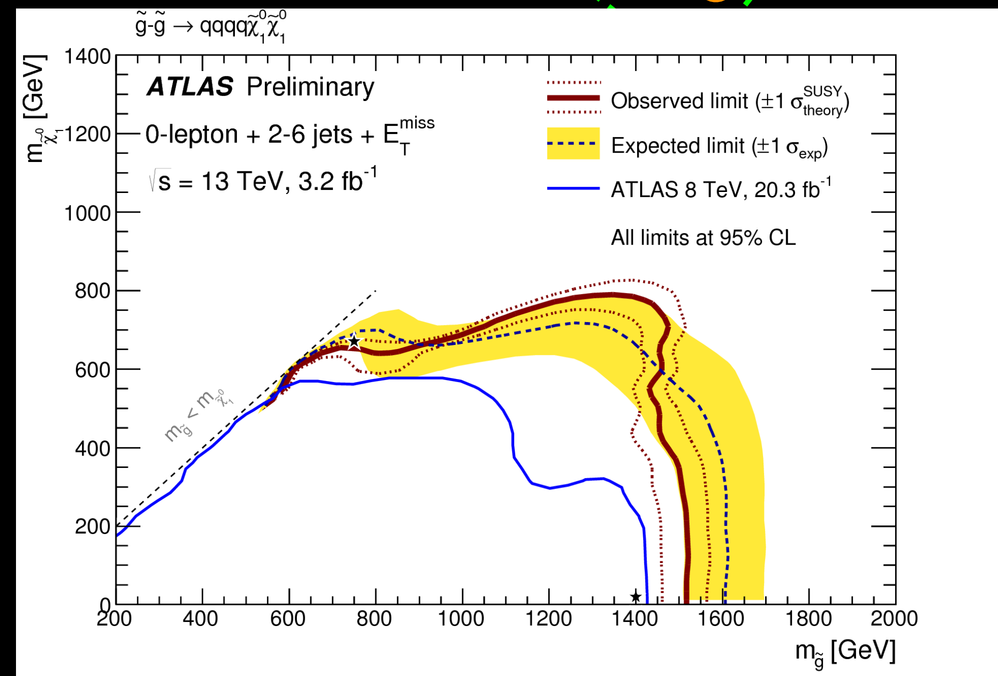
Spectrum of Theory Space



Squarks and Gluinos

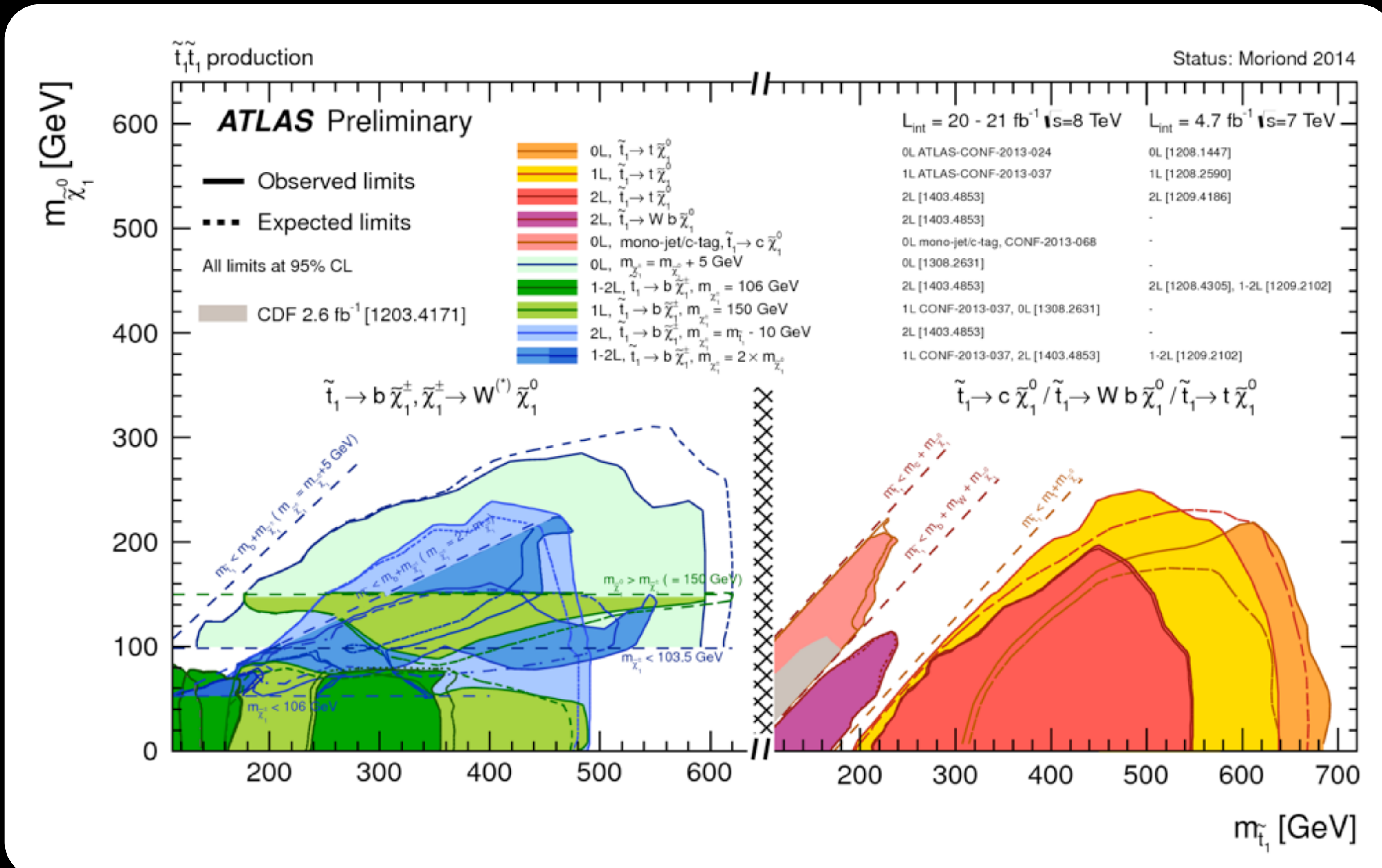






- Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino (“colored sibling”) production.
  - Gluinos decay to two jets + WIMP
  - Squarks into one jet + WIMP   [Assuming degenerate “light” squarks]
- These are important constraints on SUSY. The specific message for dark matter depends very much on the model parameters.

3rd Generation Squarks

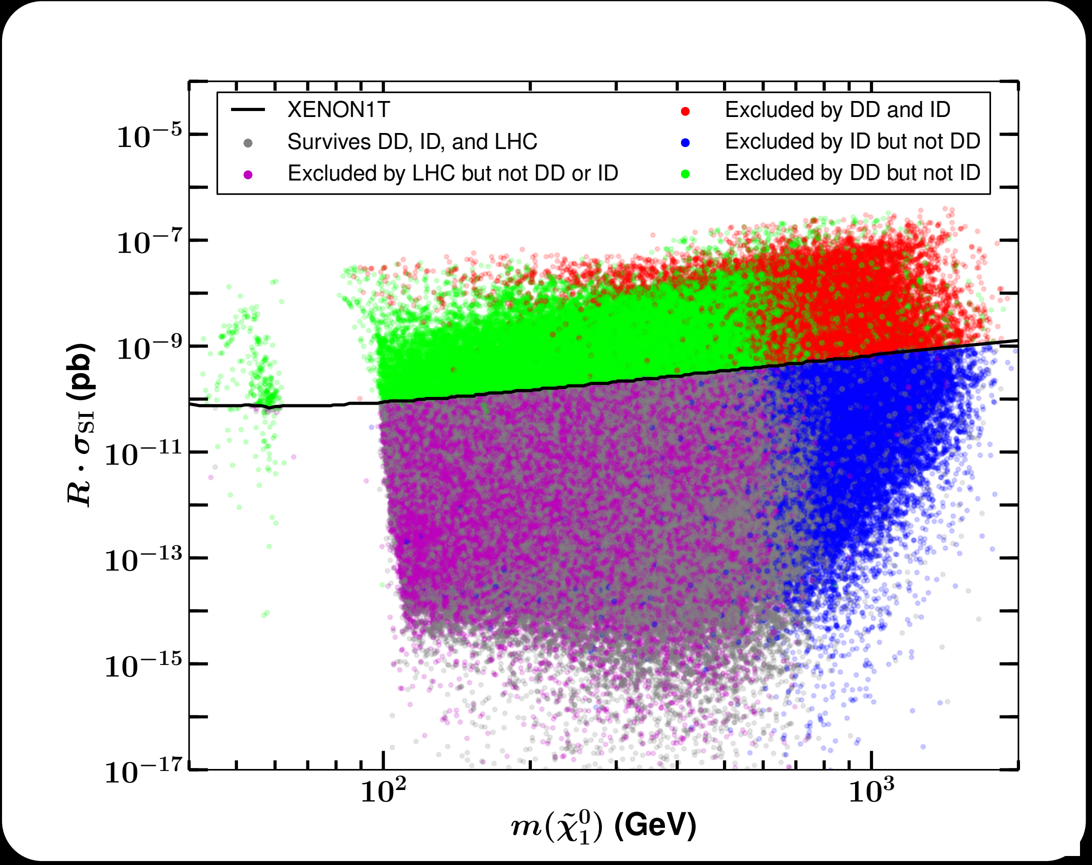


- Naturalness would suggest SUSY would like light(ish) stops. This should be balanced by the fact that in the MSSM, the Higgs mass is calculable, suggesting the stops aren't *too* light.
- Searches for stops are starting to reach 600-700 GeV, and carving out the natural regions of supersymmetry!

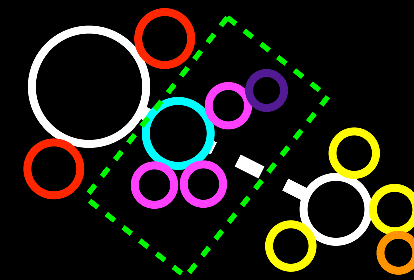
Supersymmetry: pMSSM

- Interpreting these in the broader scope of SUSY requires a parameterization.
- Simple illustrative models have a handful of parameters, more general models have ~20, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can't be discovered.
- LHC helps in regions where direct detection is weaker due to cancellations and the dark matter mass is not too heavy.

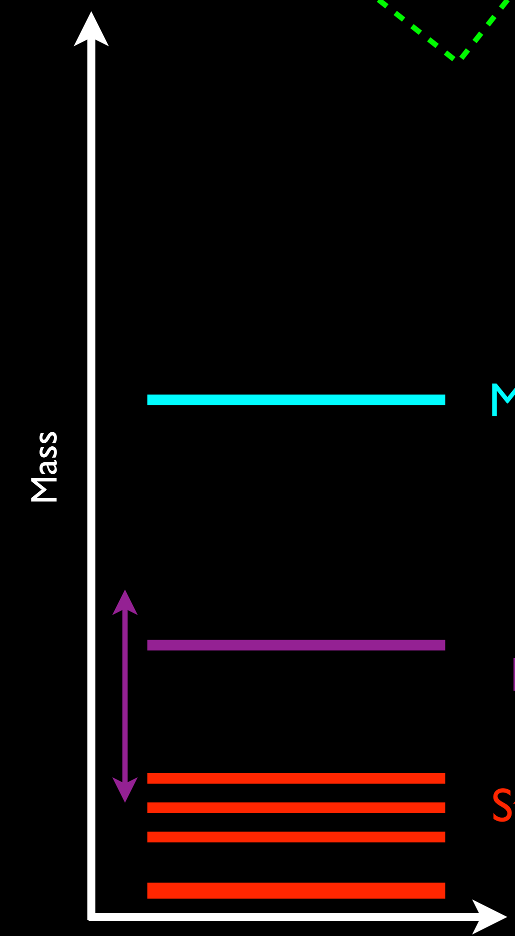
Cahill-Rowley et al, 1305.6921

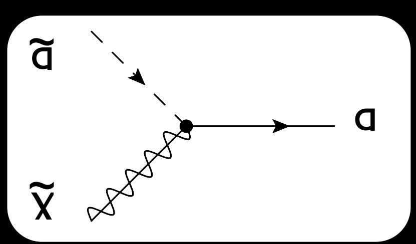


Simplified Model



- 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.

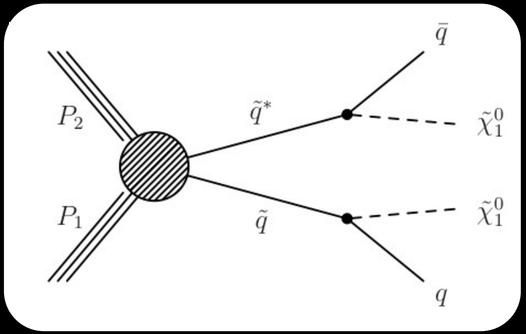




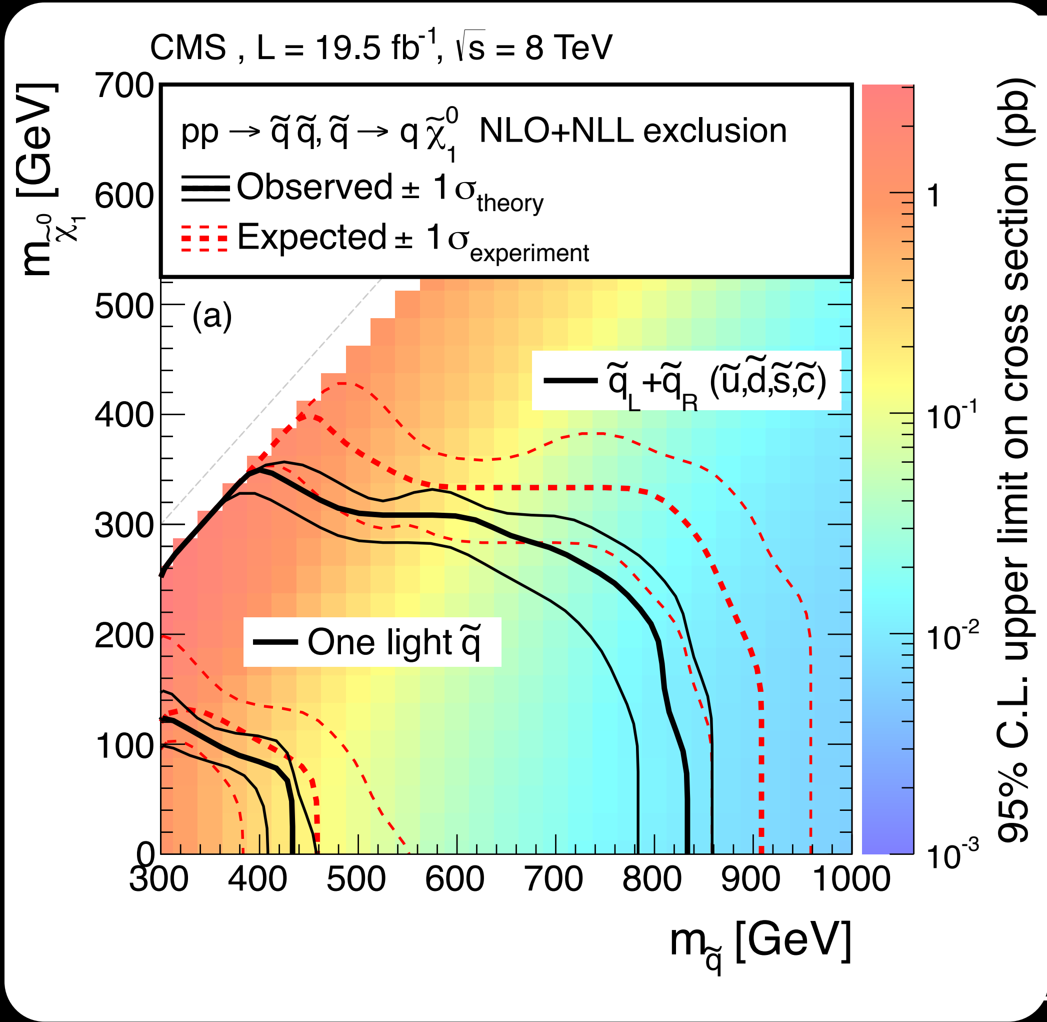
Lots of Recent Activity:

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 Model



- 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.



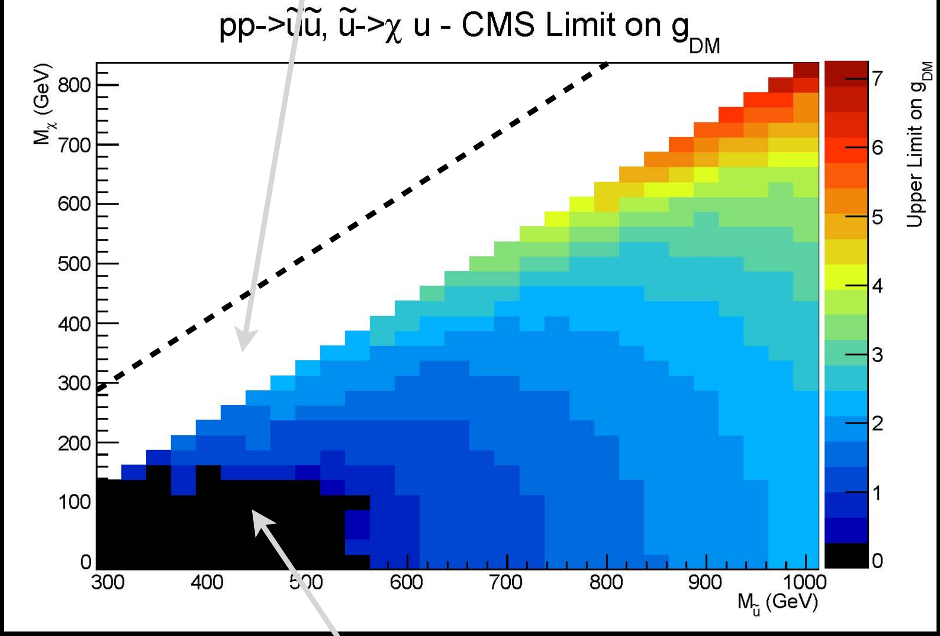
Of course, we can also consider a wider variety of WIMP properties and mediators and get away from MSSM-like theories.

$\tilde{u}_R$ Model

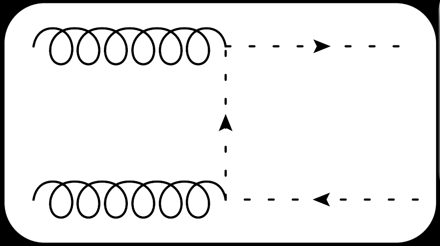
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- Motivated by MFV we set the couplings and mediator masses equal for all three generations.
  - Third generation could actually look much different. (But this would not change the results here much).
- 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.

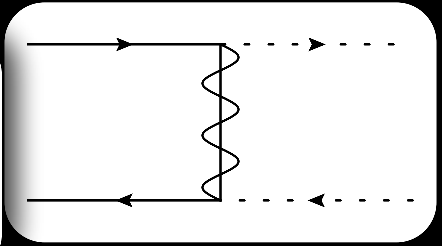
Mono-jet searches will help fill in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679 & JHEP



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

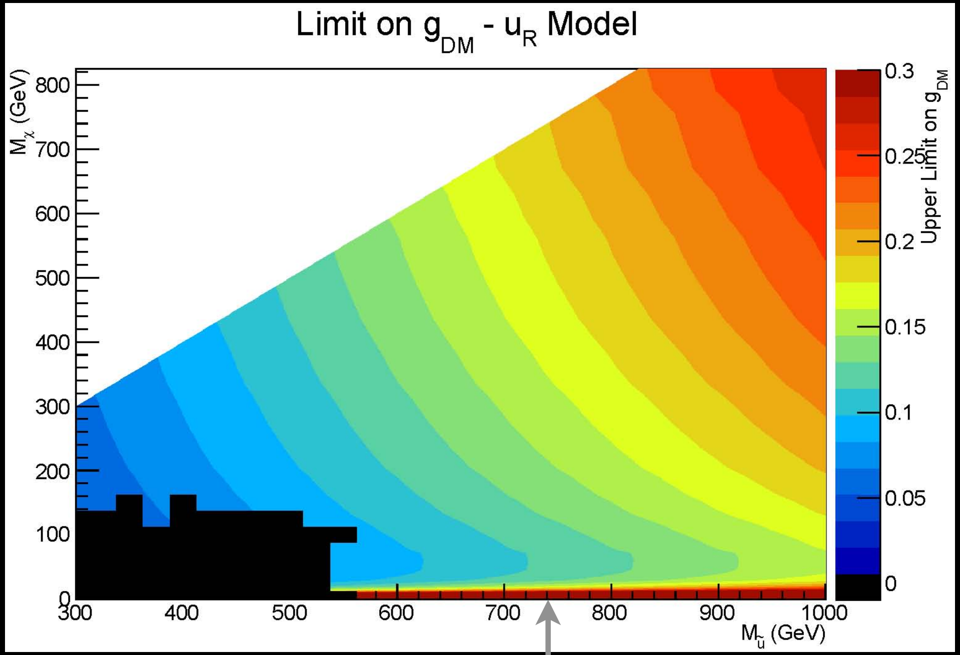




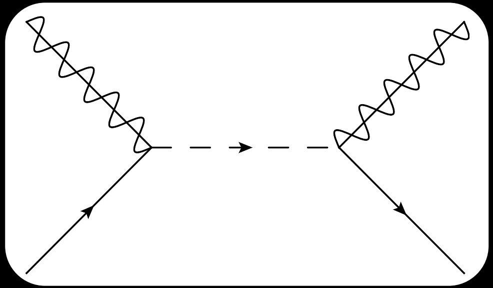
$\tilde{u}_R$ Model

- A Dirac WIMP also has spin-independent scattering with nucleons. For most of the parameter space, there are bounds from the Xenon-100 experiment.
  - Not included here are the recent LUX results, which improve these bounds by a factor of ~2 at a DM mass of ~100 GeV.
- Elastic scattering does not rule out any point of the mass plane, but it does impose stricter constraints on the coupling in the regions CMS left as allowed.

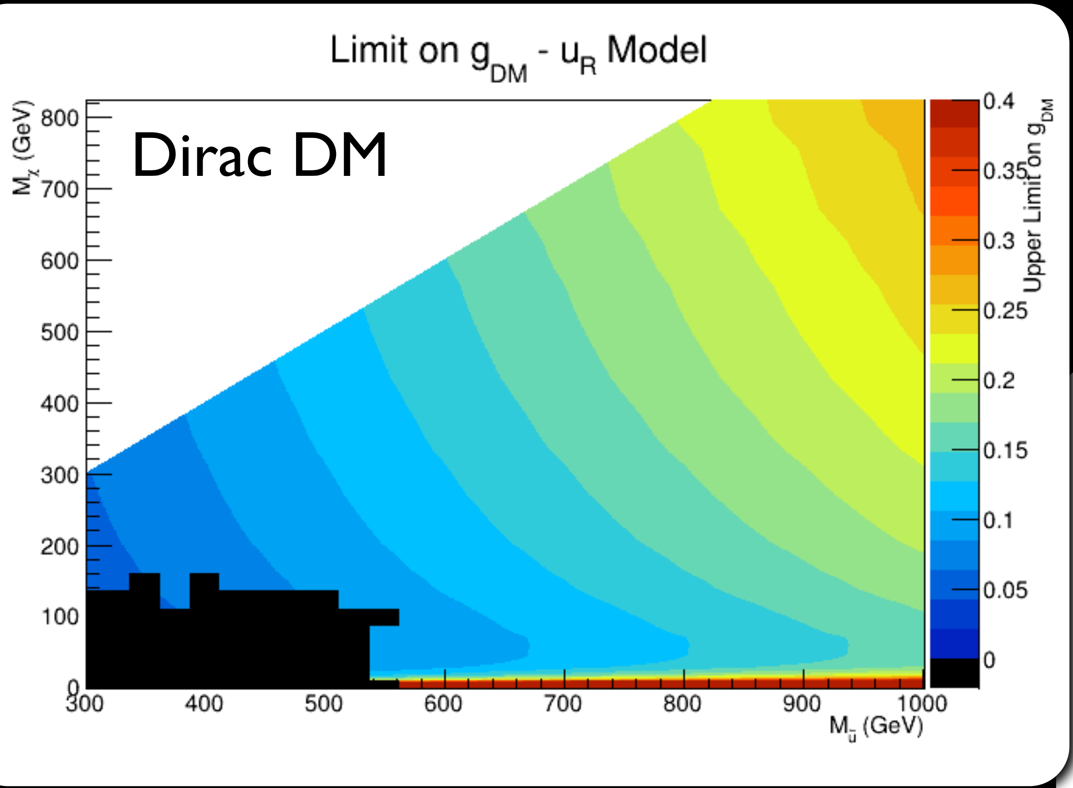
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679 & JHEP



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

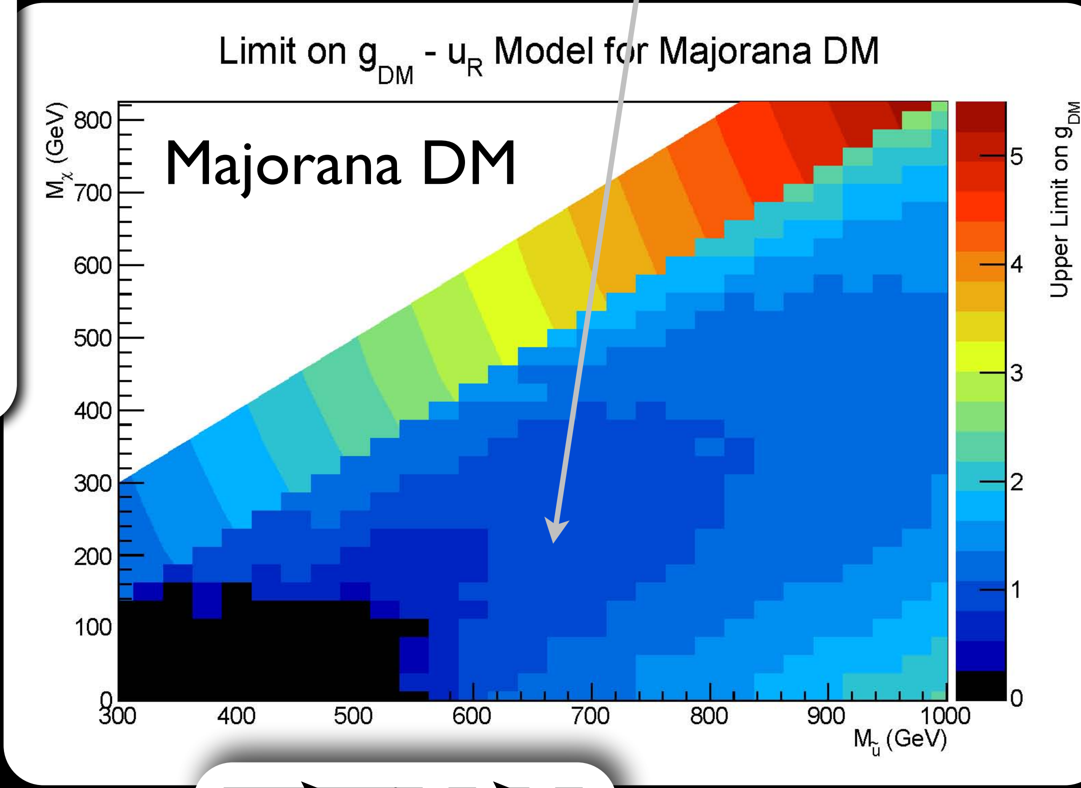


Majorana versus Dirac



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679 & JHEP

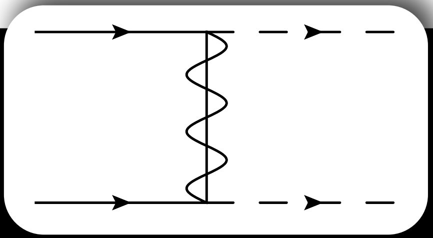
Collider bounds tend to dominate for Majorana DM.



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

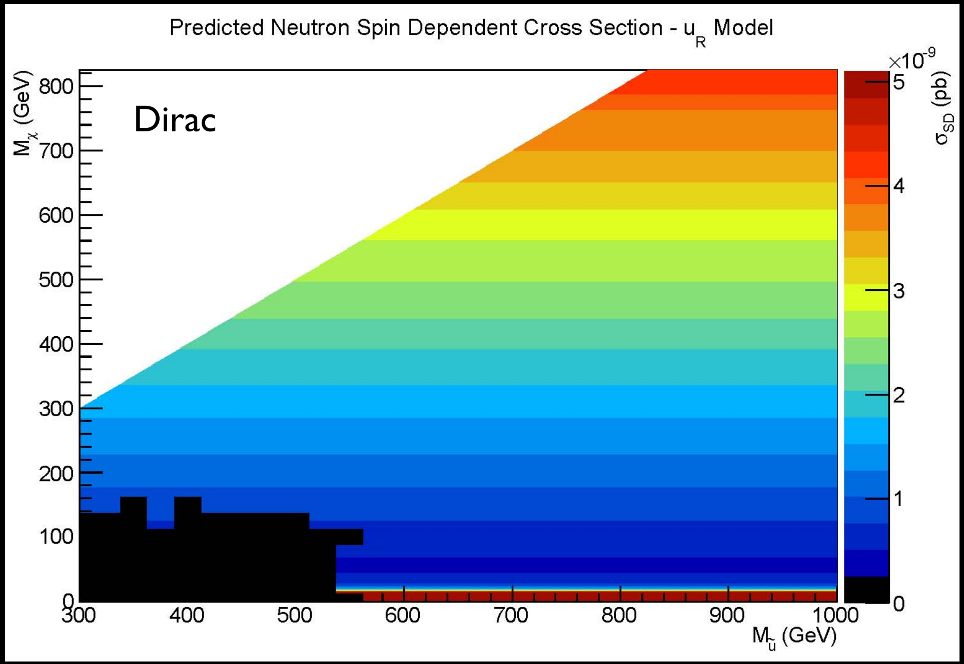
Majorana WIMPs have no tree-level spin-independent scattering in this model.

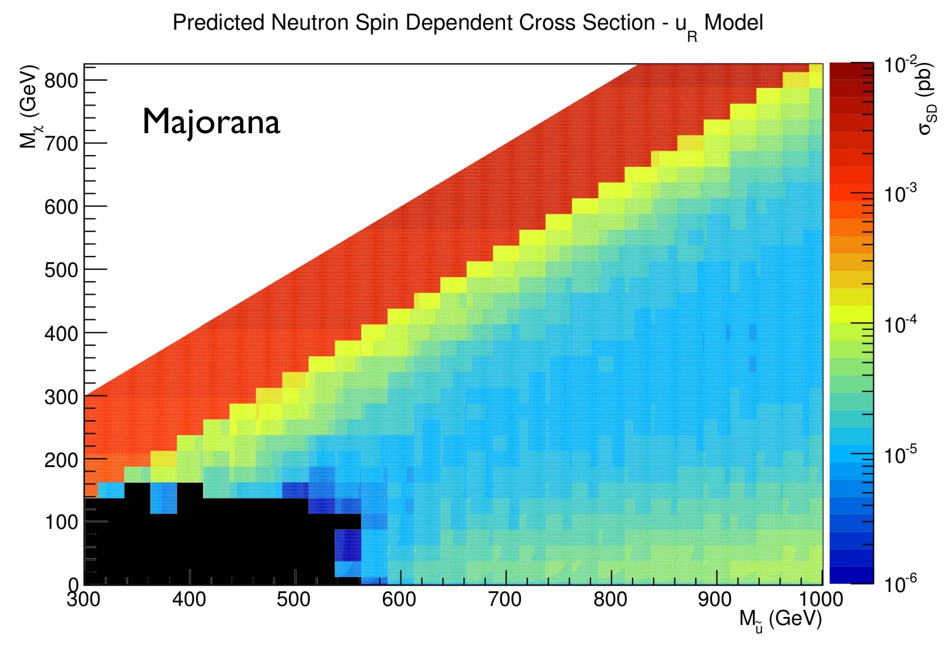
At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.



$\tilde{u}_R$ 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 CMS and Xenon in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!

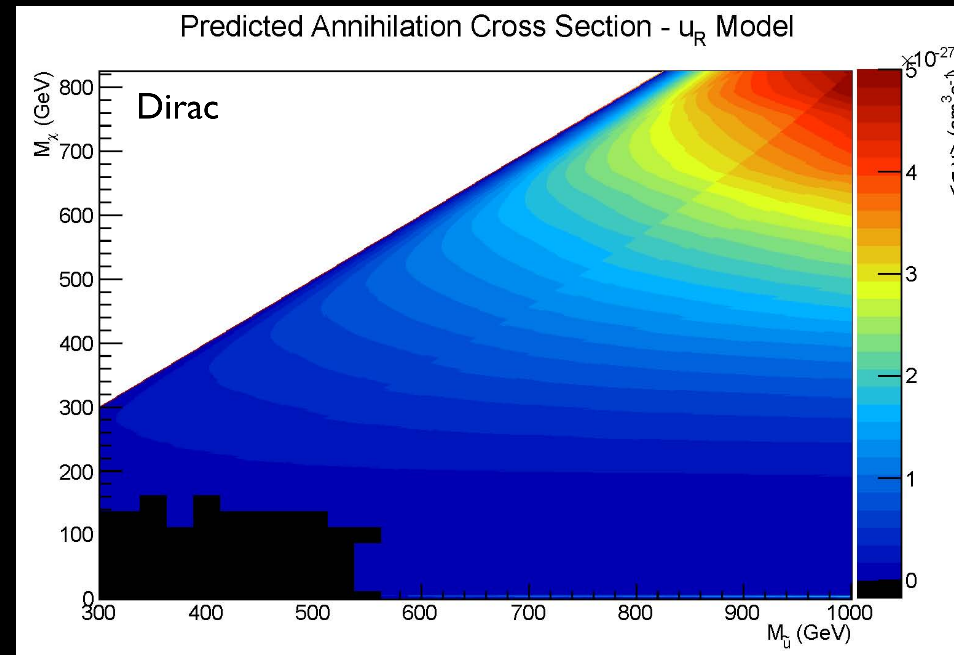


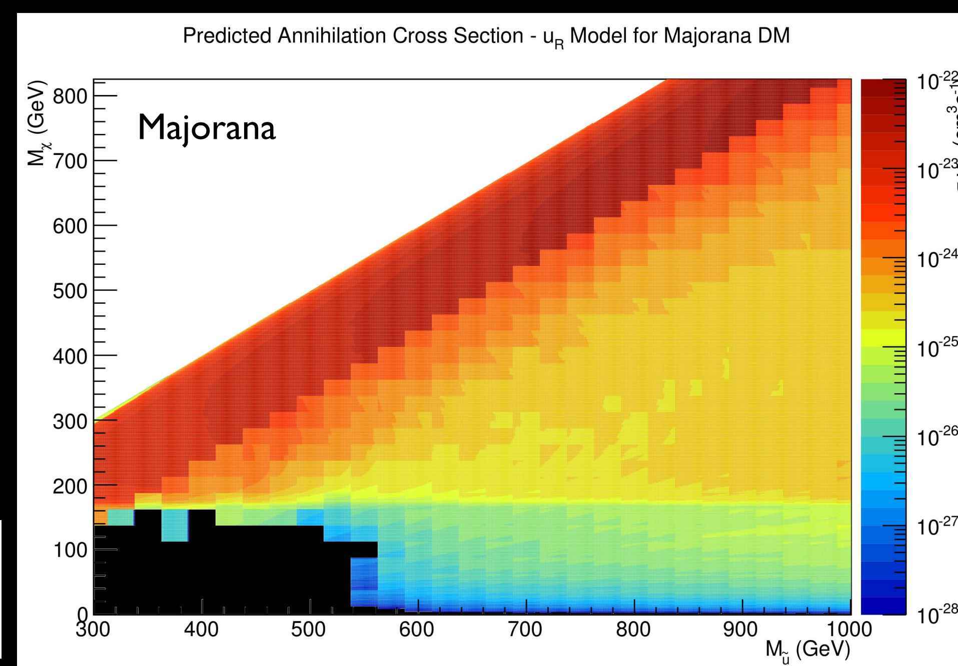


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679 & JHEP

$\tilde{u}_R$ 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 ($\sigma v \sim 10^{-26}$ cm^3/s).

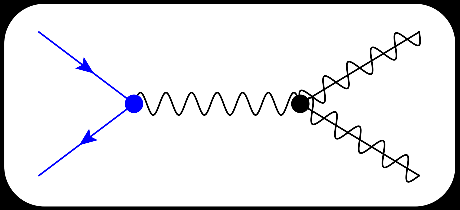


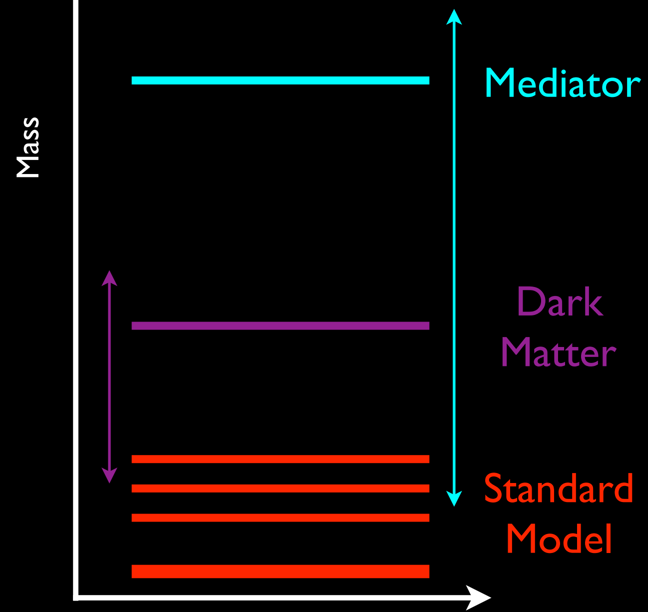


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679 & JHEP

S-Channel : Vector

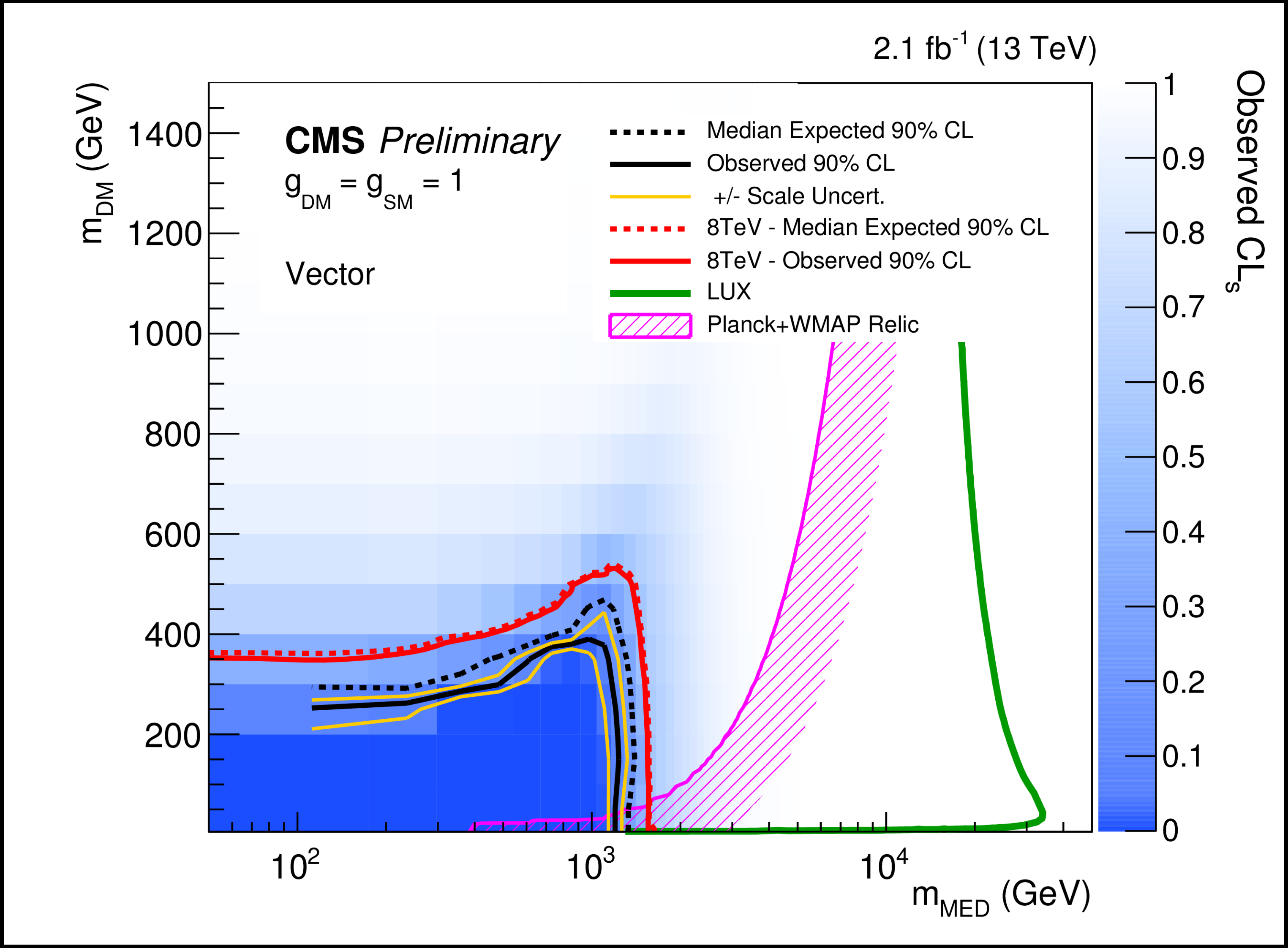
- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
  - We would like to be able to write down the SM Yukawa interactions.
  - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.
- 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: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

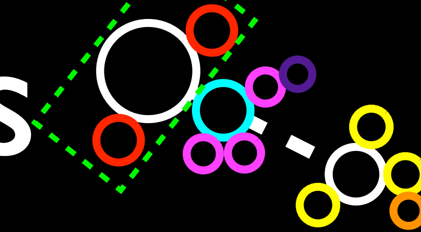
S-Channel : Vector



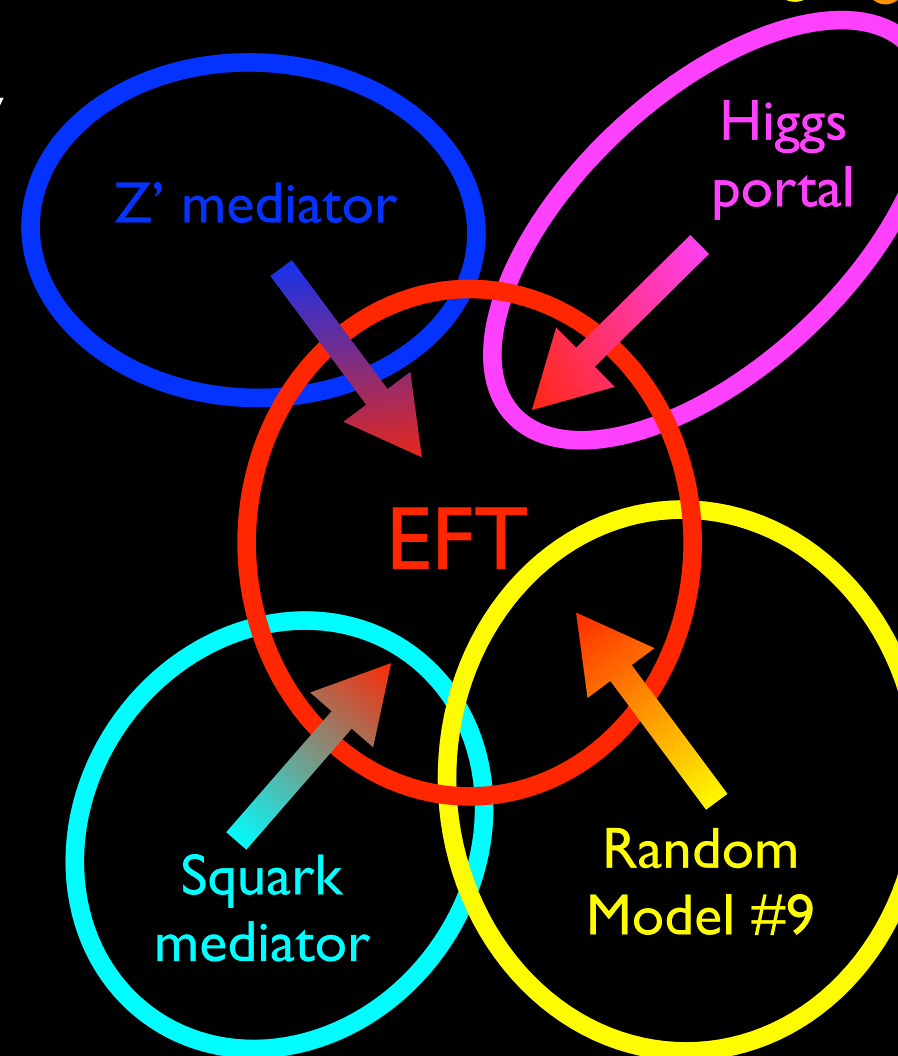
All couplings set equal.

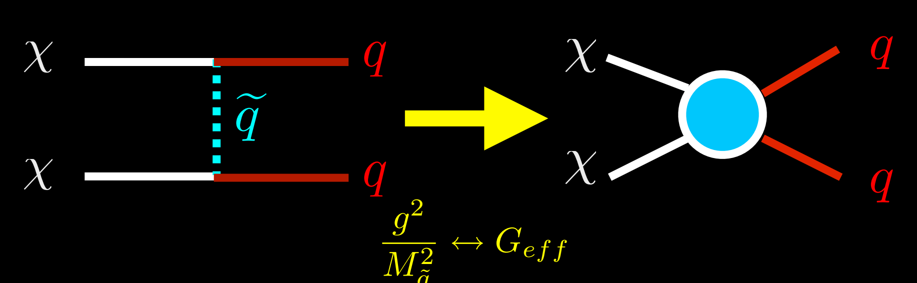
Current understanding is dominated by σ_{SI} for most masses.

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.



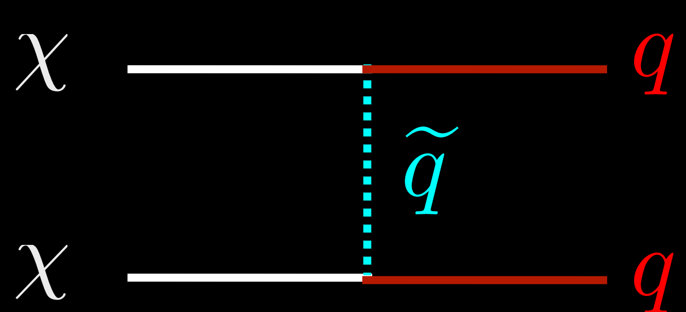


Example: Majorana WIMP

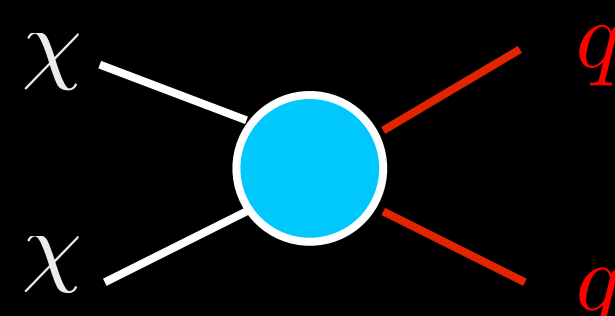
Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB

- As an example, we can write down 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.

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	-



$$\frac{g^2}{M_{\tilde{q}}^2} \leftrightarrow \frac{1}{M_*^2}$$



Example: Majorana WIMP

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 in the galactic halo
  - Collider Production

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	-

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

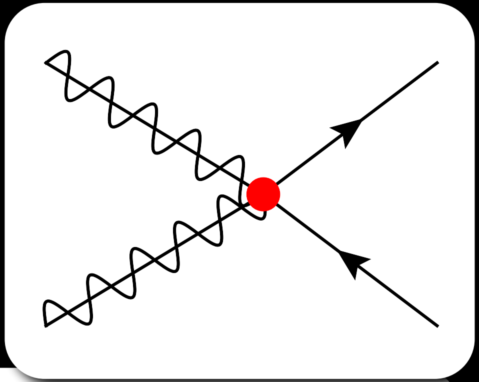
$$\sum_q G_\chi\,[\bar q\Gamma^q q]\,[\bar\chi\Gamma^\chi\chi]$$

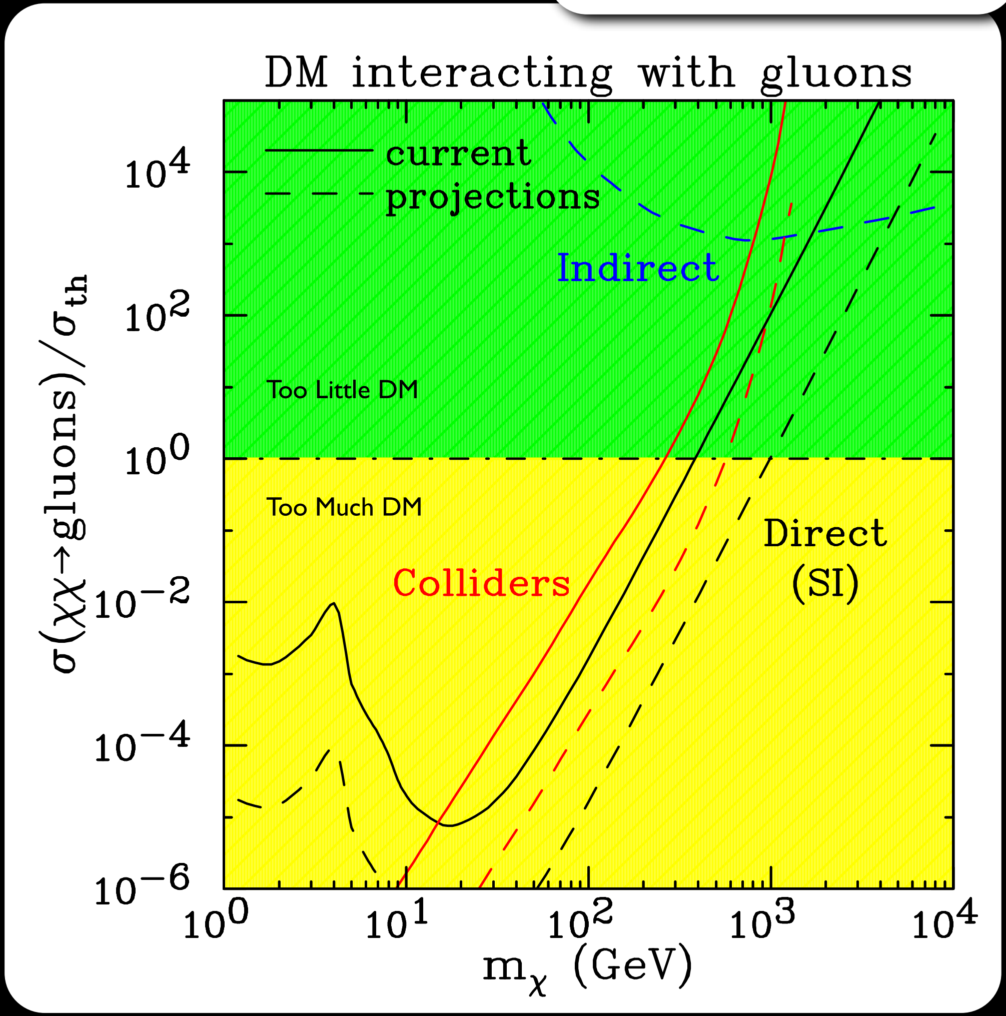
Other operators may be rewritten in this form by using Fierz transformations.

Note the important assumption of a heavy mediator!

Annihilation

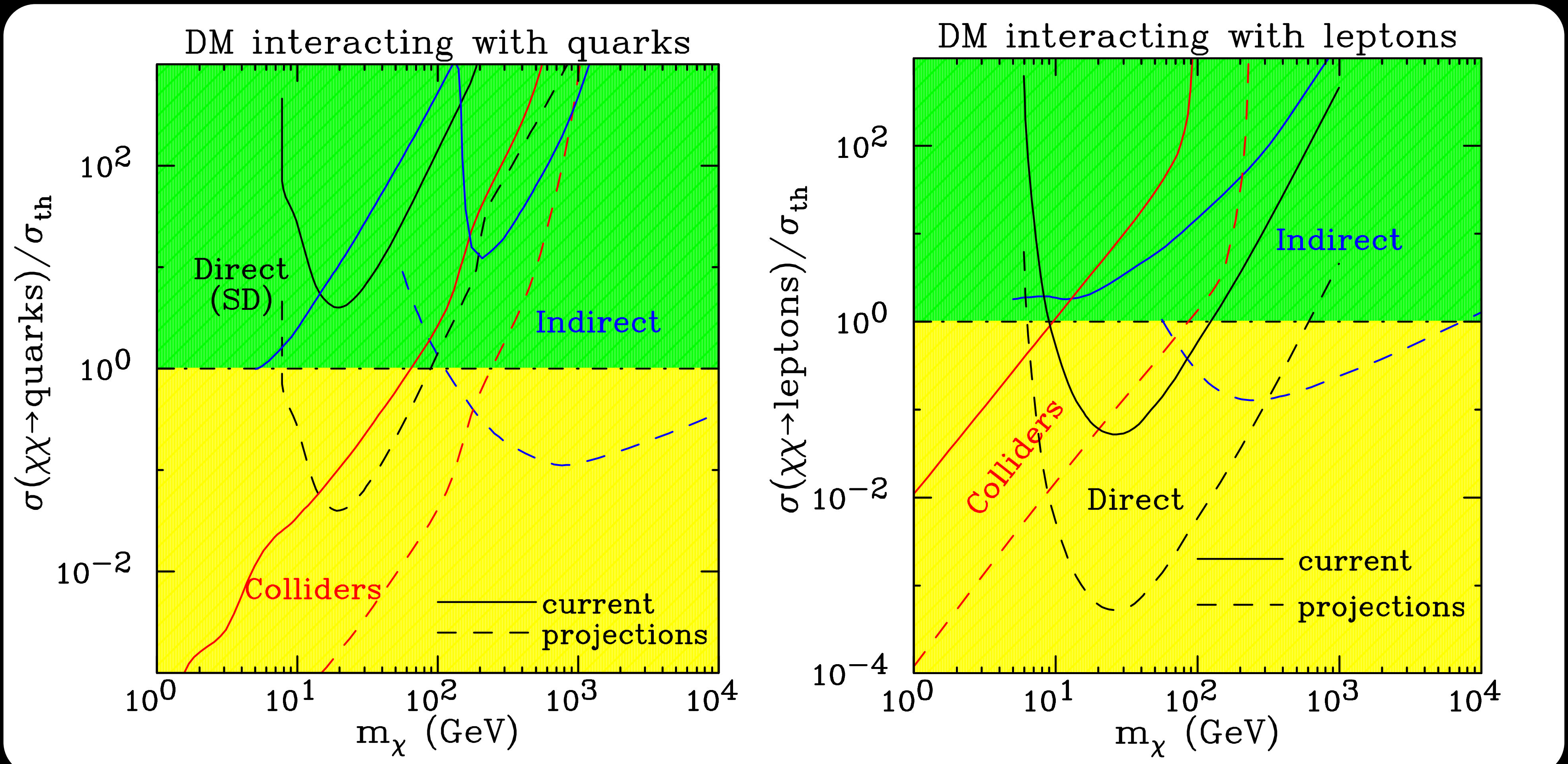
- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- We see similar trends as were present before: Colliders do better for lighter WIMPs or p-wave annihilations whereas indirect detection is more sensitive to heavy WIMPs.





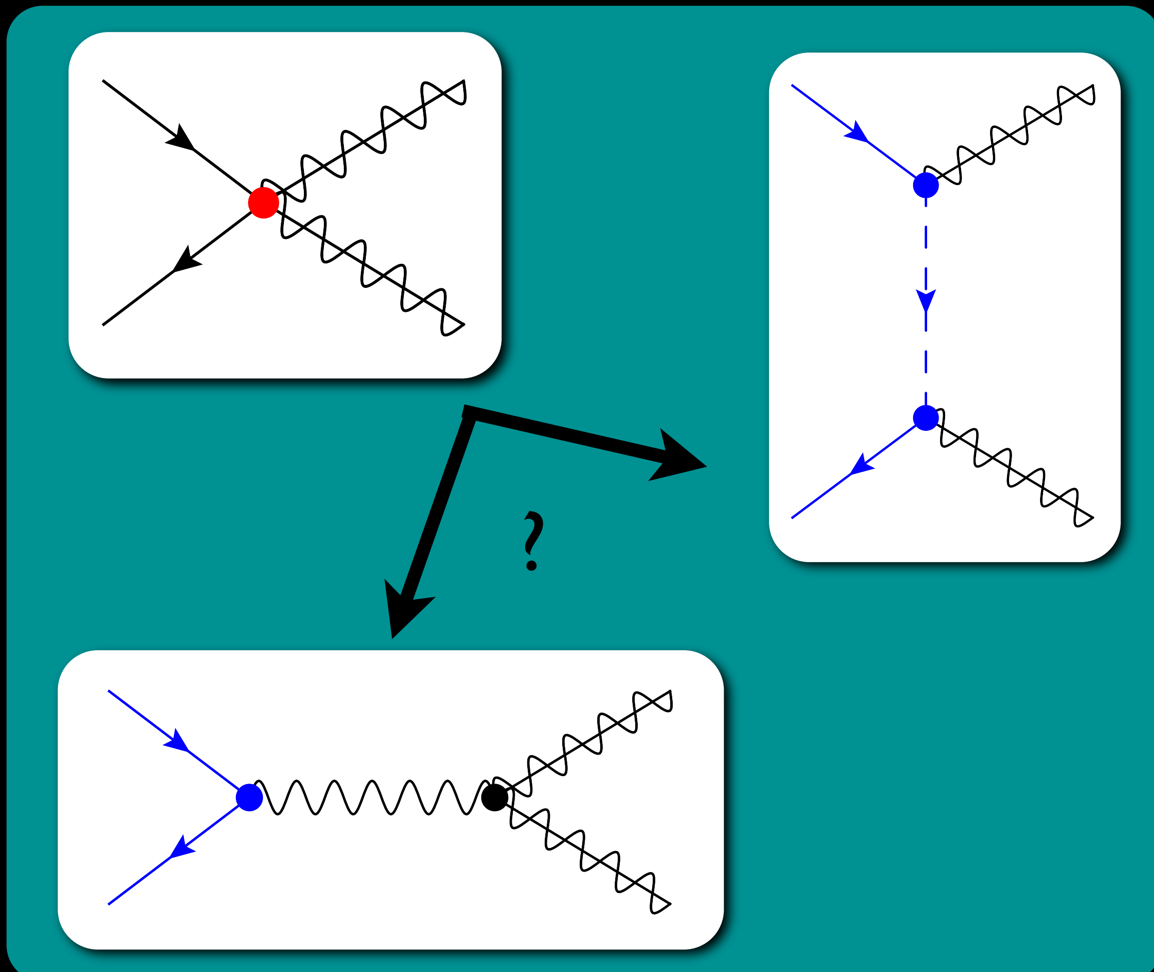
DM Complementarity, arXiv:1305.1605

Quarks & Leptons



DM Complementarity, arXiv:1305.1605

How Effective a Theory?

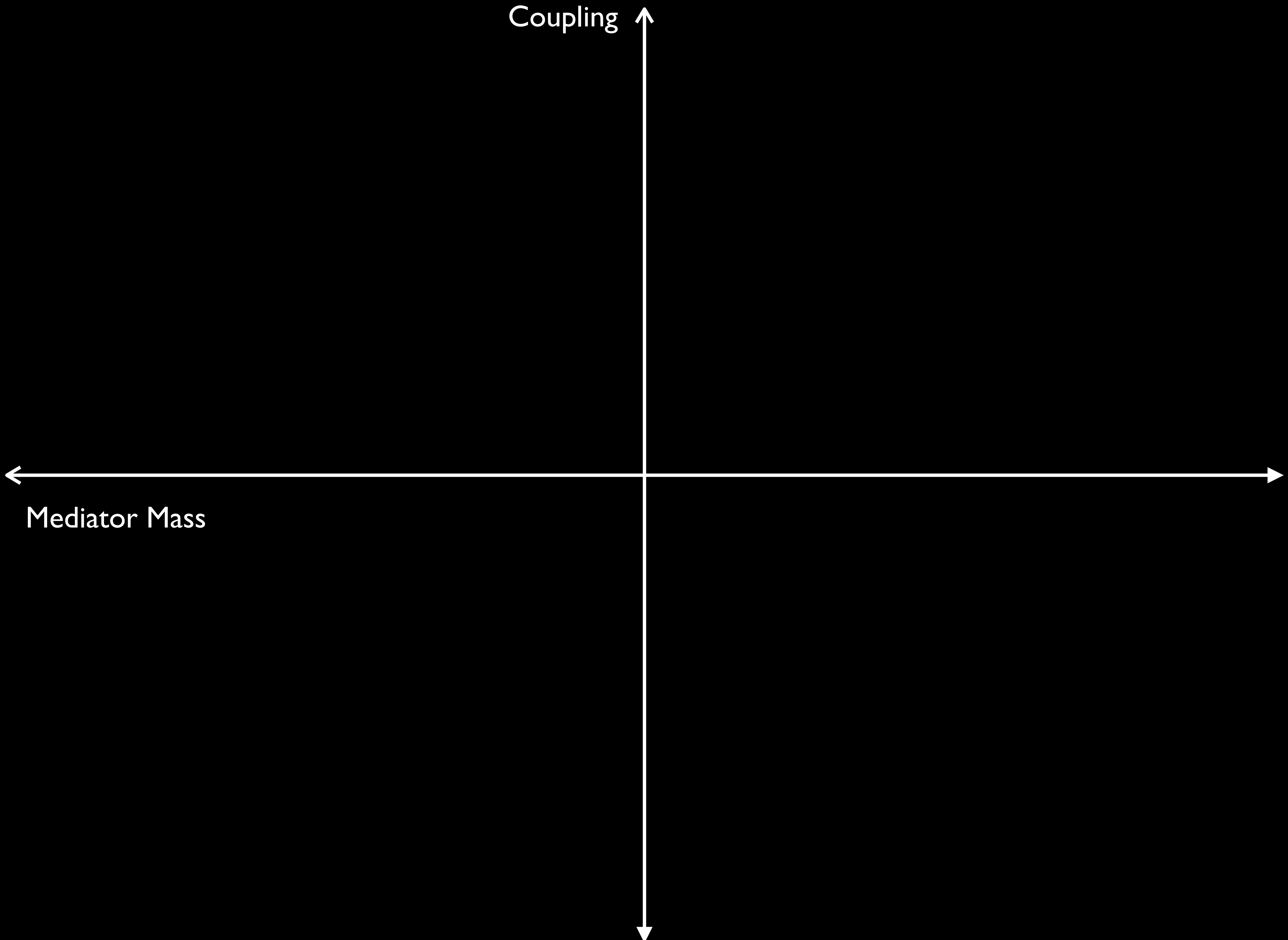


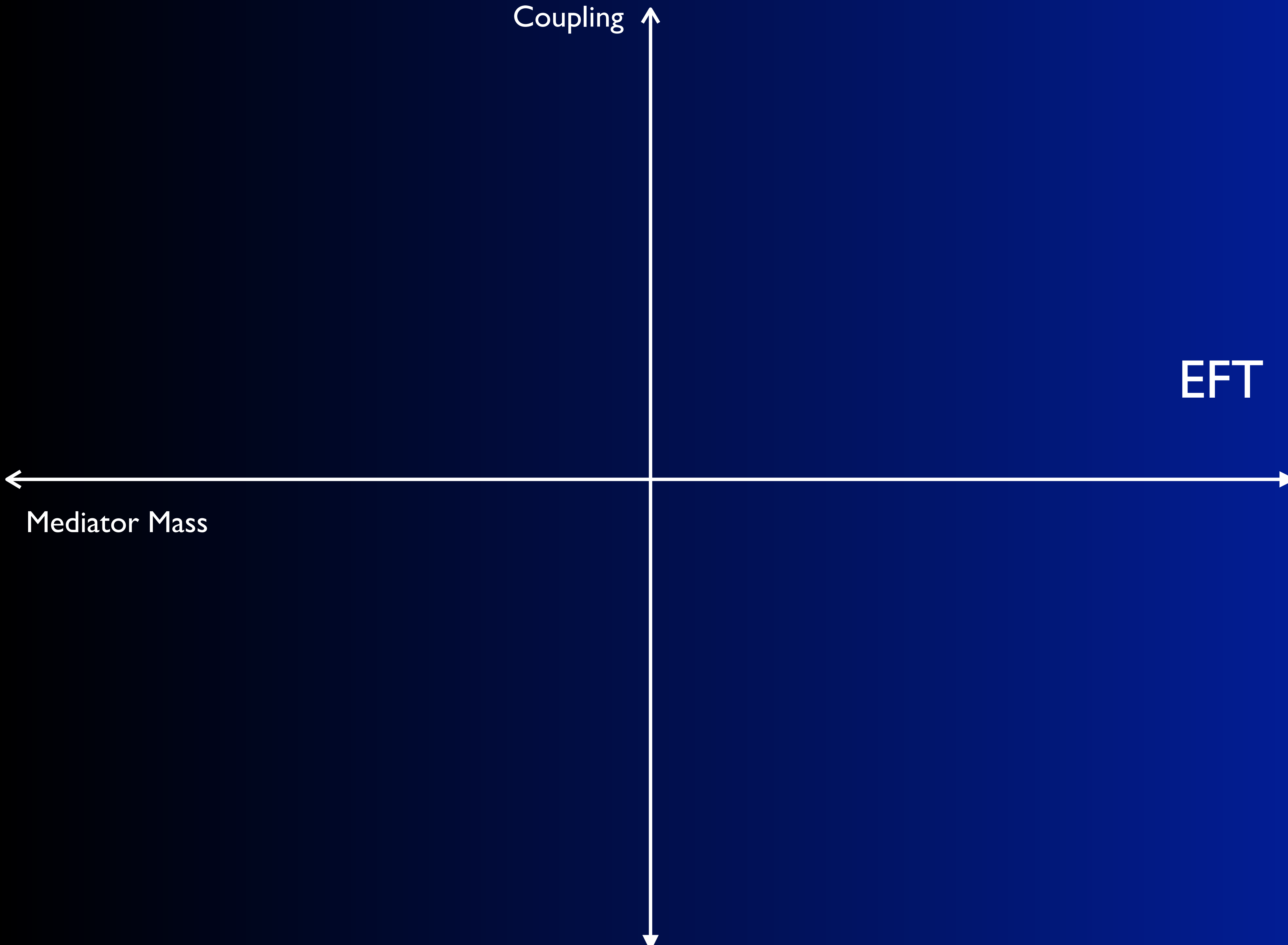
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

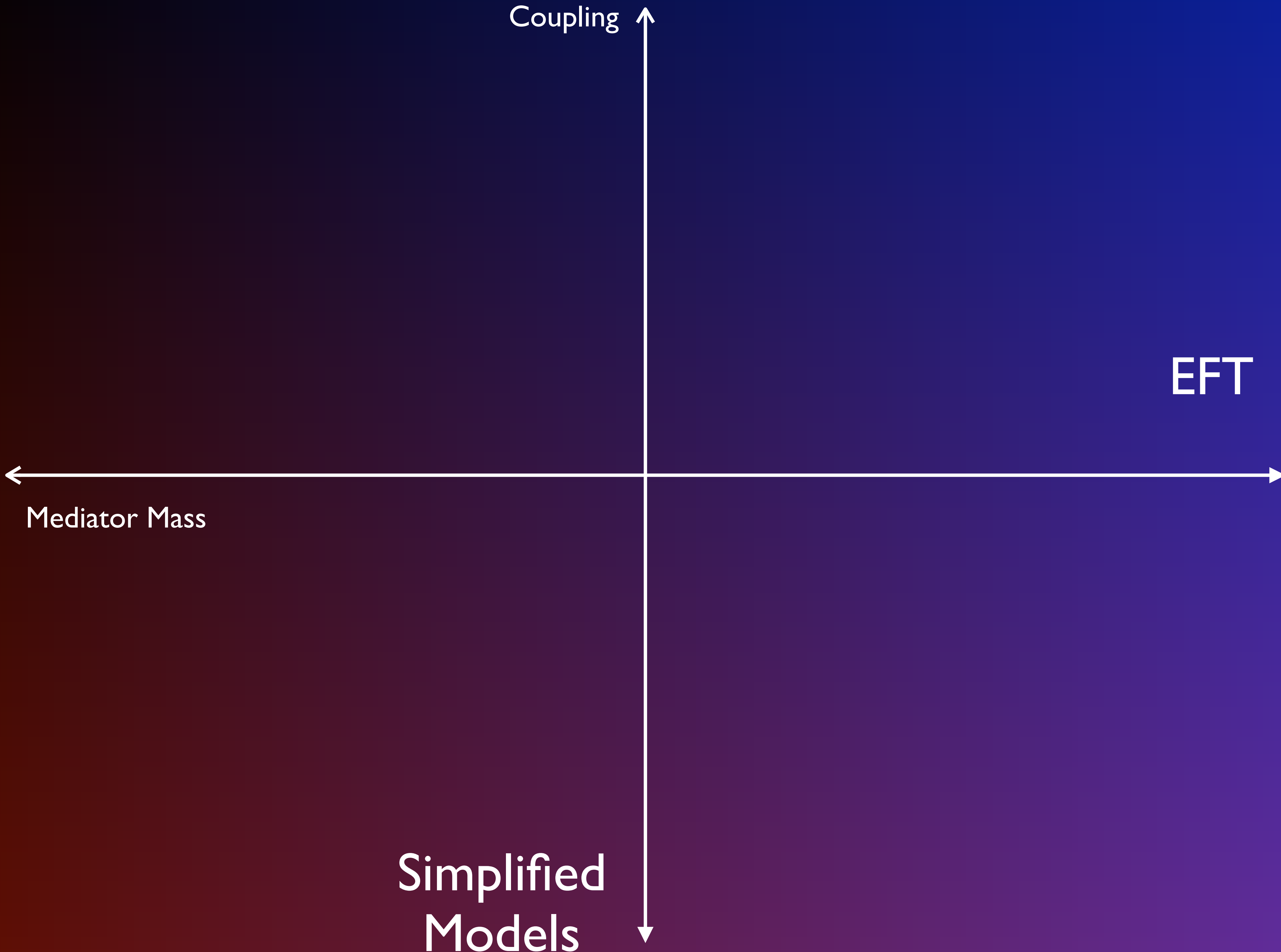
"s-channel" mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

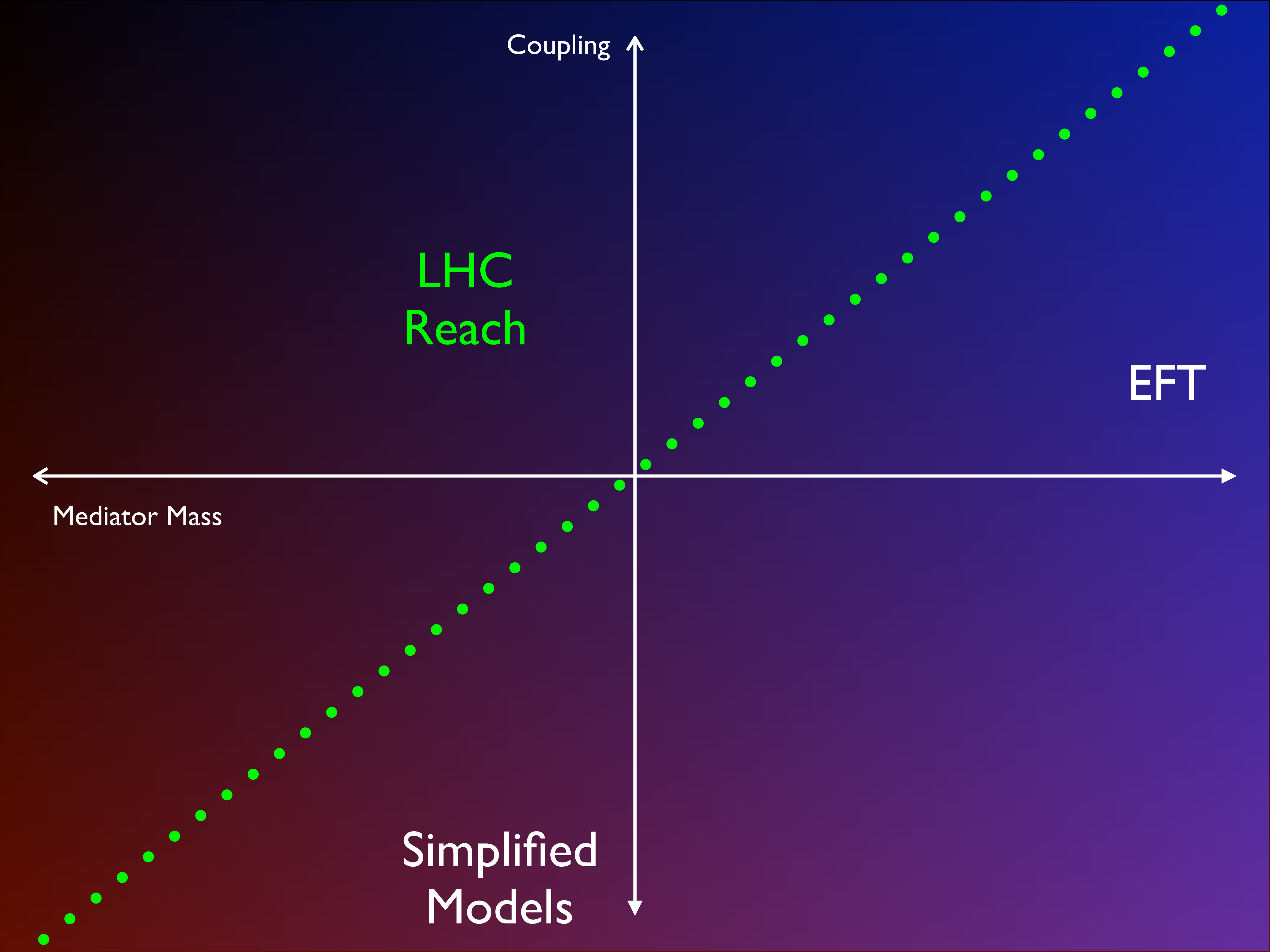
Where things can go wrong, and by how much, depends on the actual UV-completion.

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

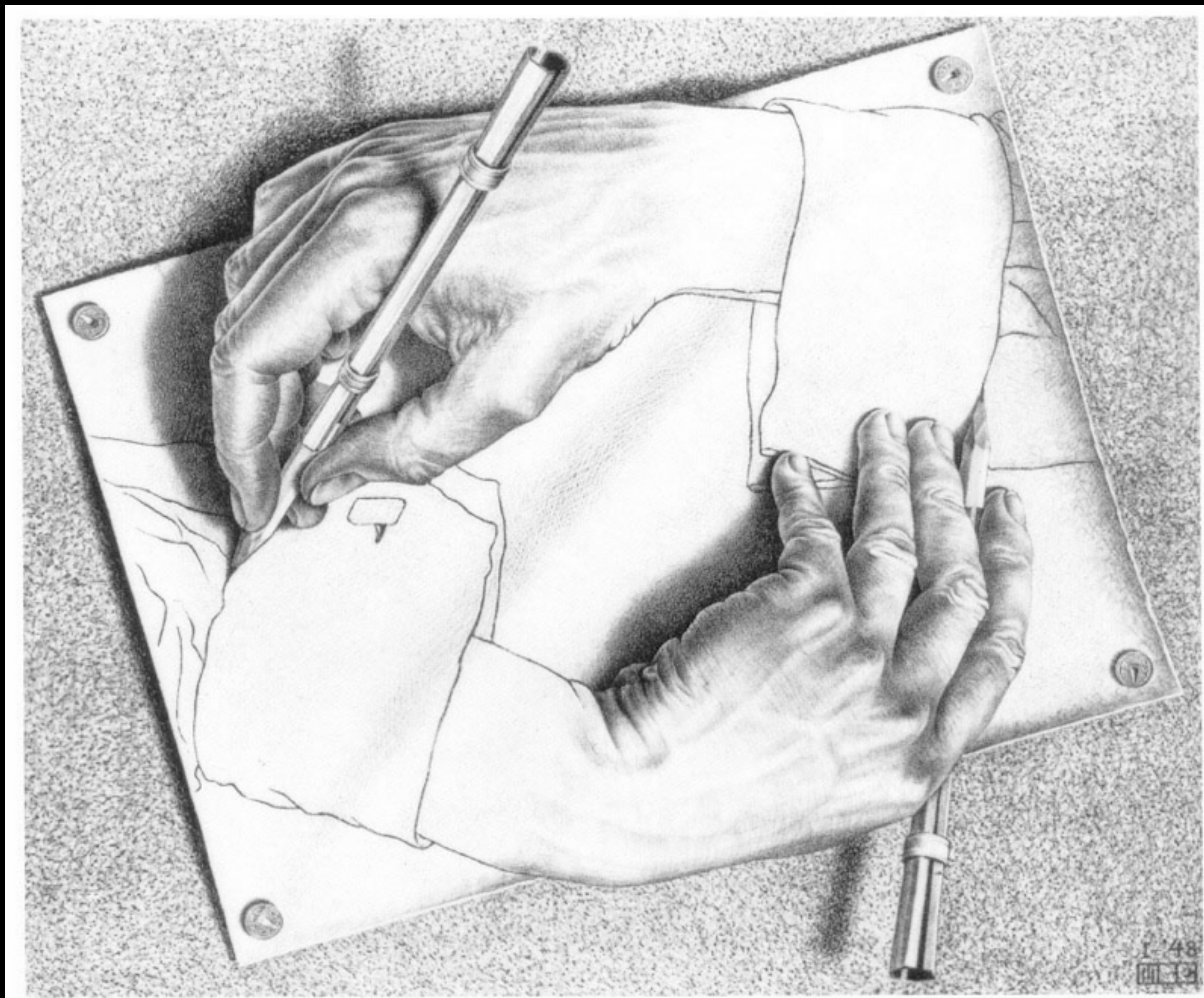

Coupling
Mediator Mass


Coupling
EFT
Mediator Mass


Coupling
EFT
Mediator Mass
Simplified Models


Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

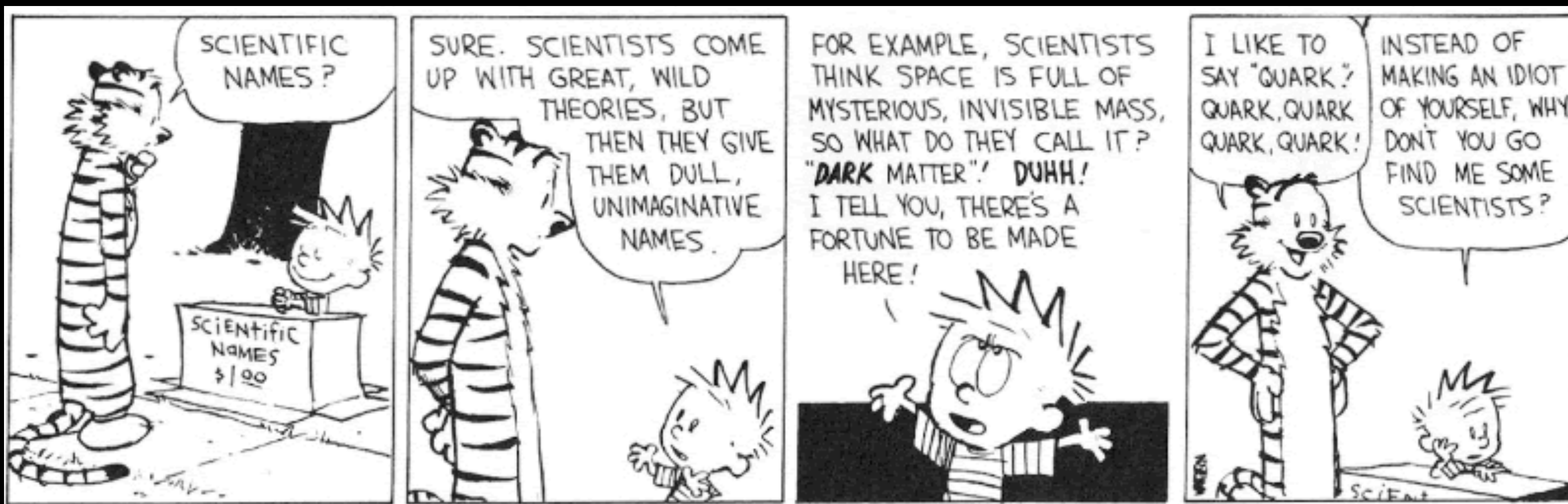
From Sketch to Life



Outlook

- LHC has a lot to tell us about dark matter!
- Already big statements are being made about missing energy, dark matter, and supersymmetric theories with R-parity conservation.
- The next years will get into very interesting territory, with sensitivity to scalar stops and gluinos which should cover the most well-motivated regions of SUSY parameter space.
  - (And to say nothing about the Higgs mass and the MSSM...)
- More direct maverick production of dark matter is less effective than traditional SUSY searches if we can produce coloured mediator particles directly. If they are too heavy, maverick production will be how we fall back to quantify limits on dark matter interactions, and make contact between accelerator data and (in)direct searches.
- Simplified models fill a niche between complete theories like the MSSM and effective field theories which assume the mediators are inaccessible.

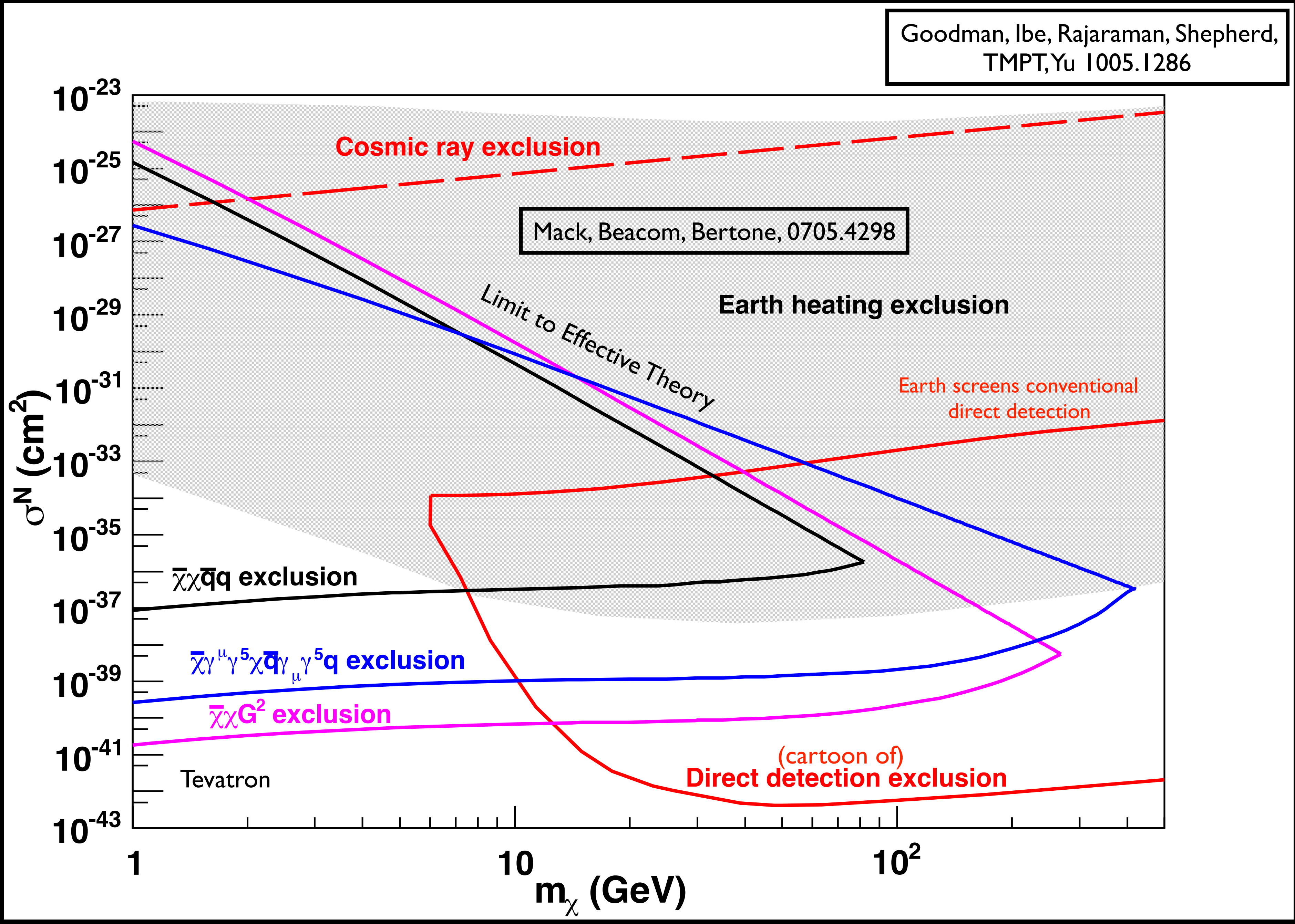
Sketches of ....



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?

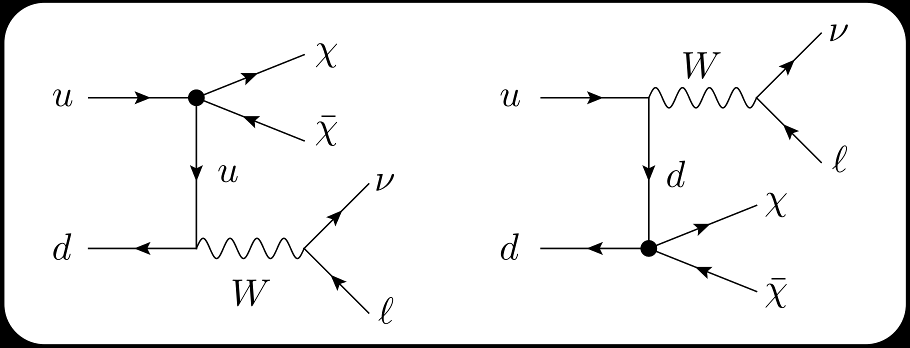
Bonus Material

From WIMPs to SIMPs...



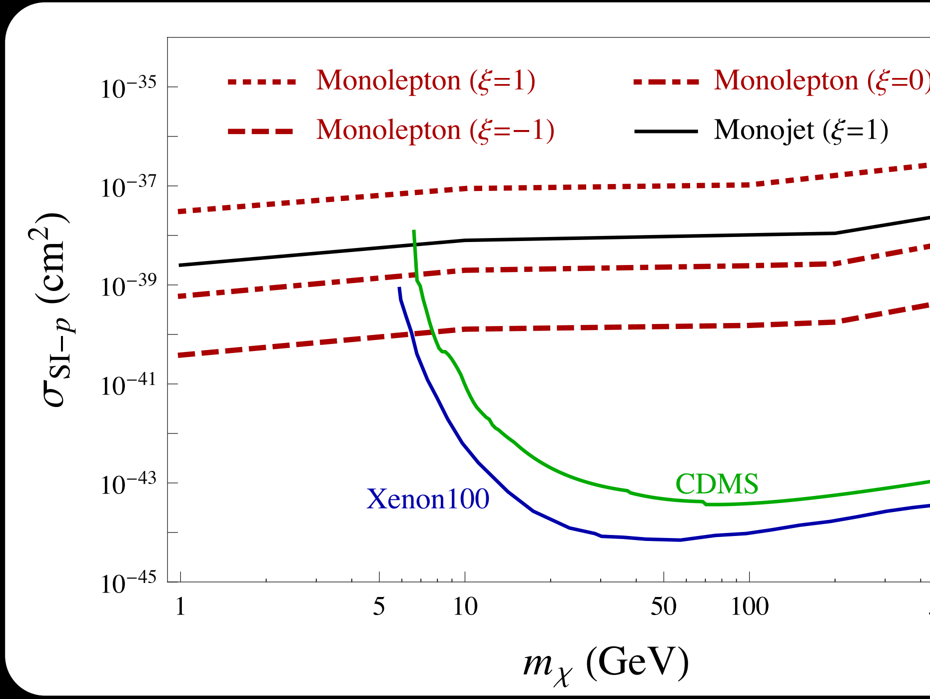
Mono-Whatever

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



CMS W' Search

Y. Bai, TMPT, 1208.4361 & PLB



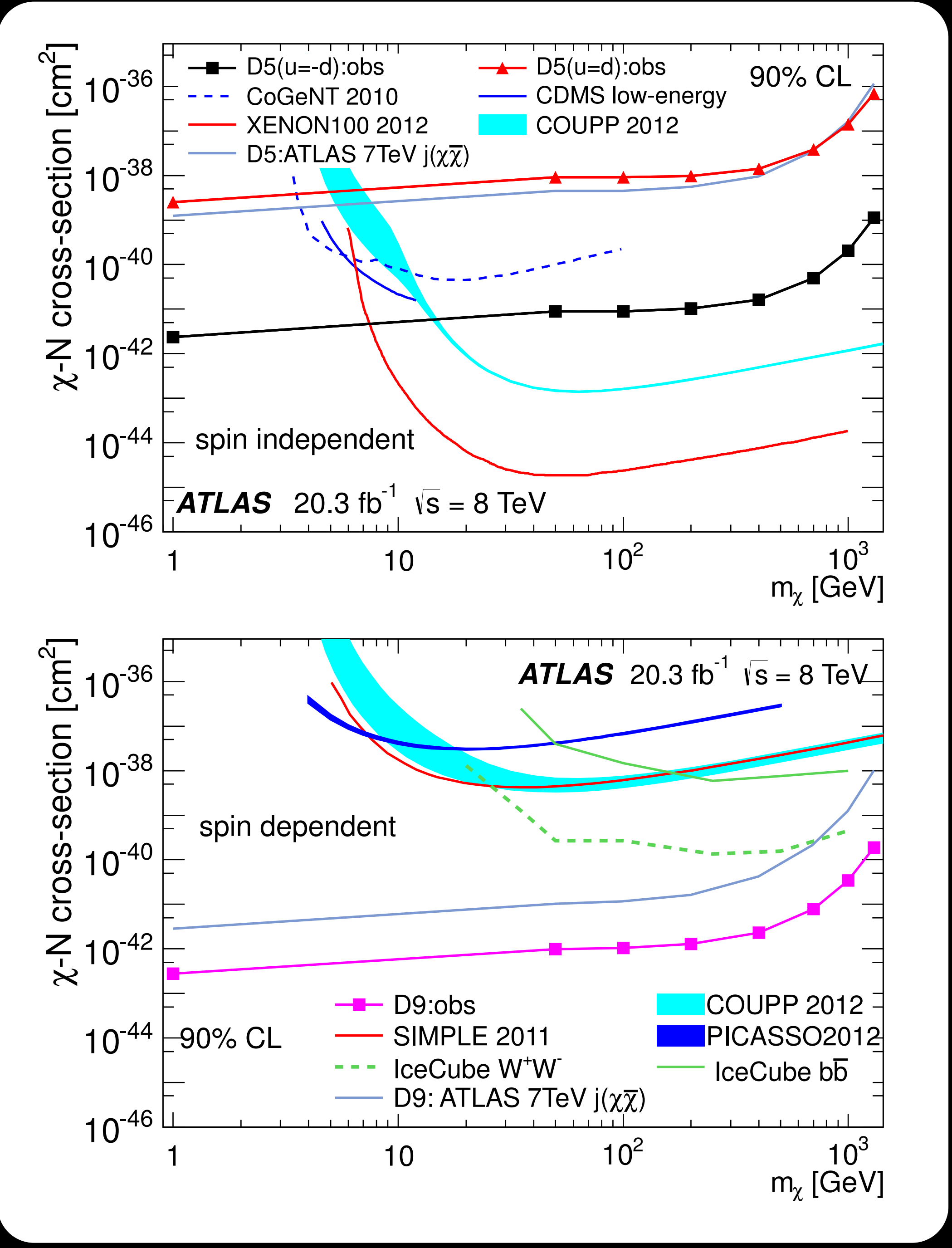
(d coupling) = ξ x (u coupling)

Jet Substructure!

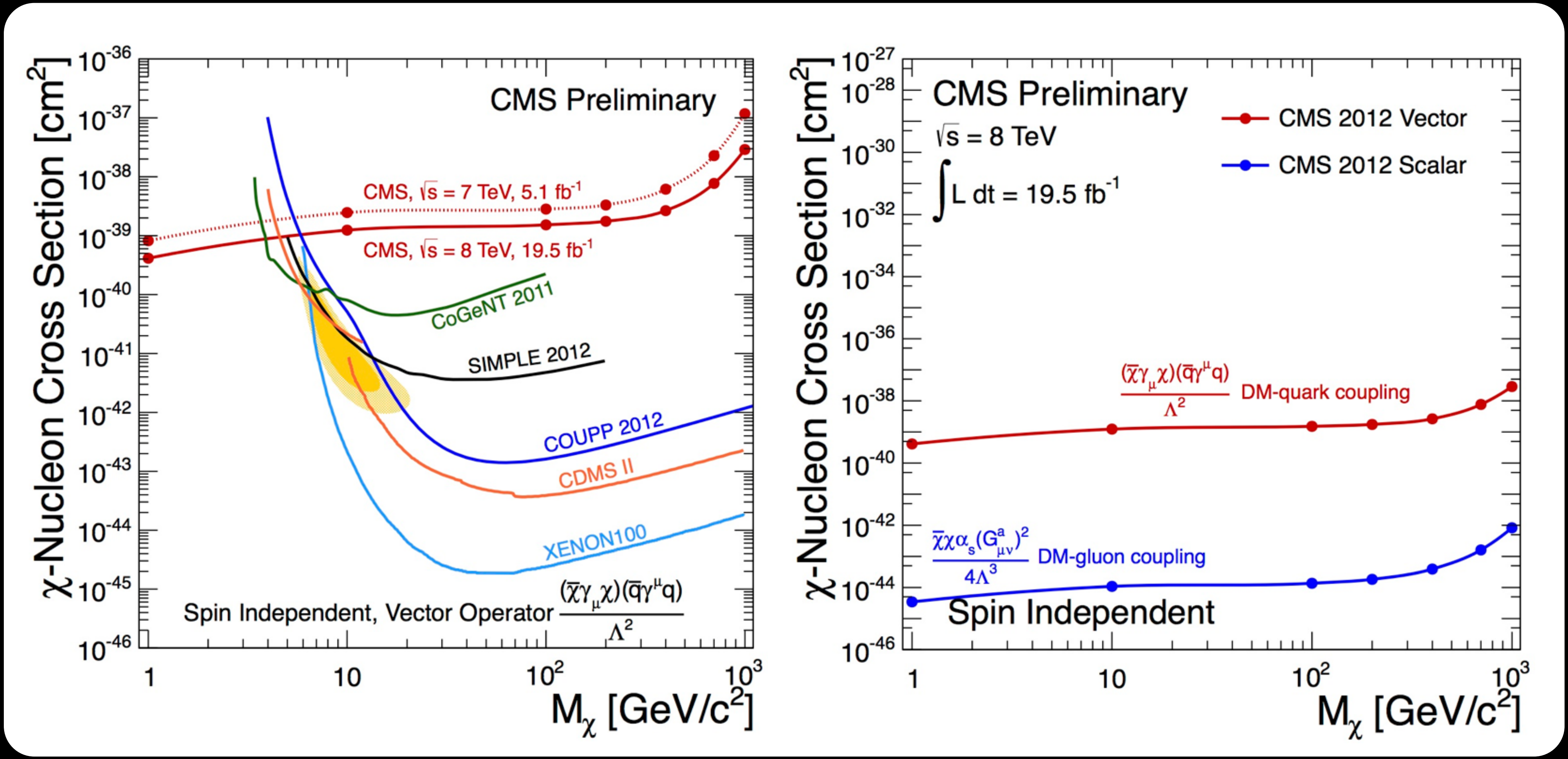
- Since the events of interest have boosted Ws, one can use substructure techniques to try to capture hadronically decaying Ws.

- This helps increase statistics, and ultimately gives a better limit than the lepton channel.

- A recent ATLAS study puts this idea into practice!



From Colliders to Direct Detection



Note the important assumption of a heavy mediator!