# Dark Messages from Accelerators

Tim M.P. Tait
University of California, Irvine

UCLADM
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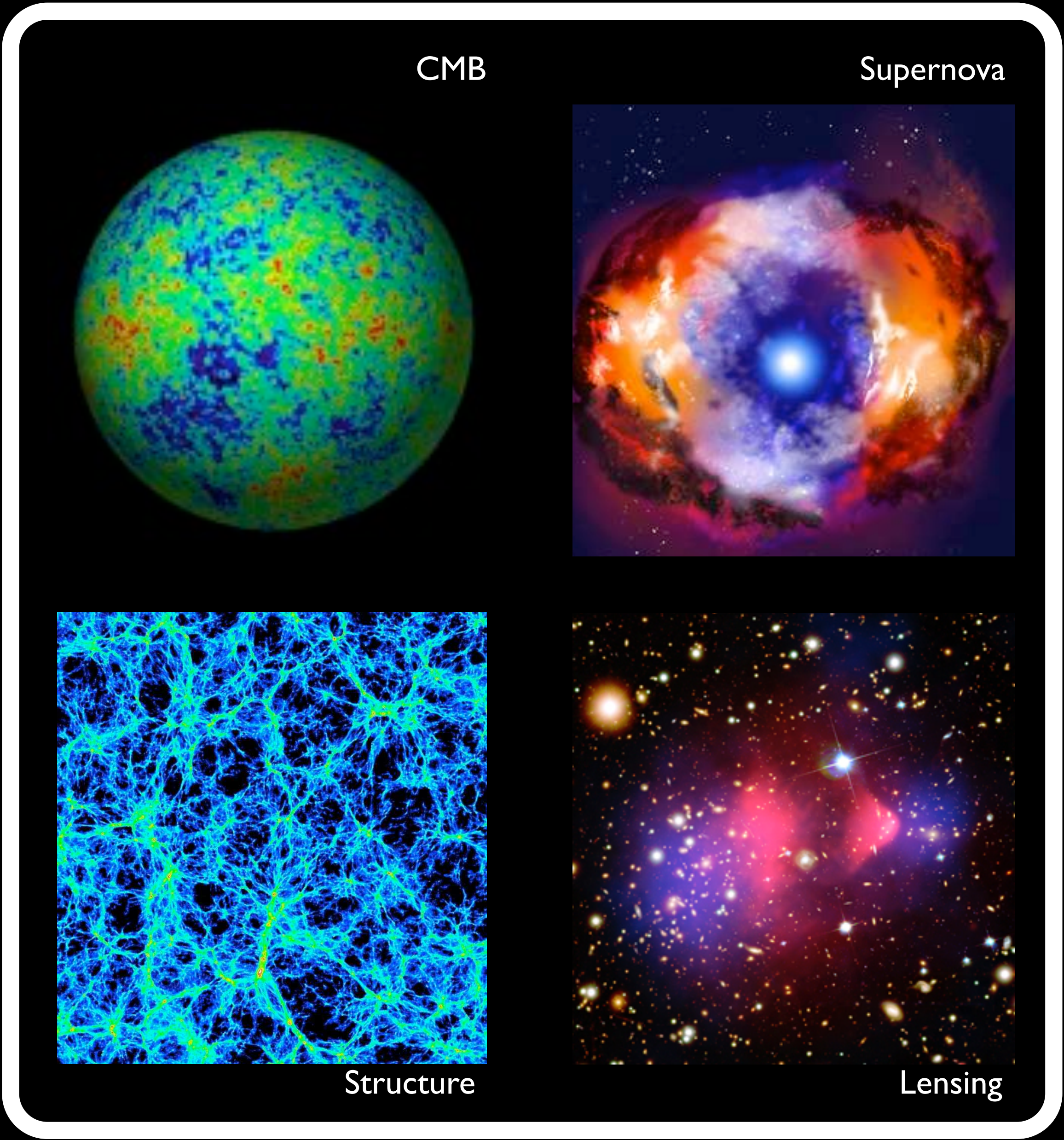
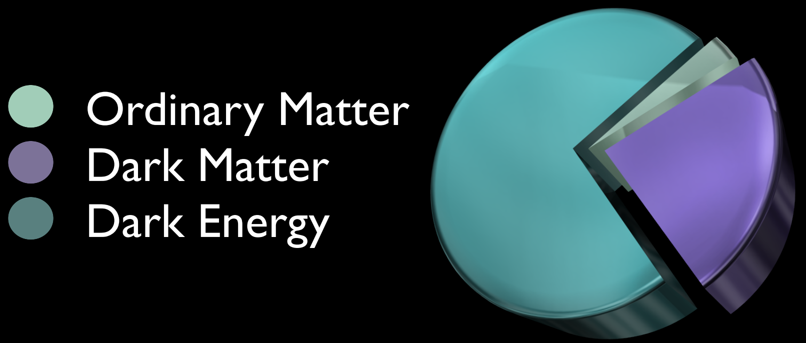
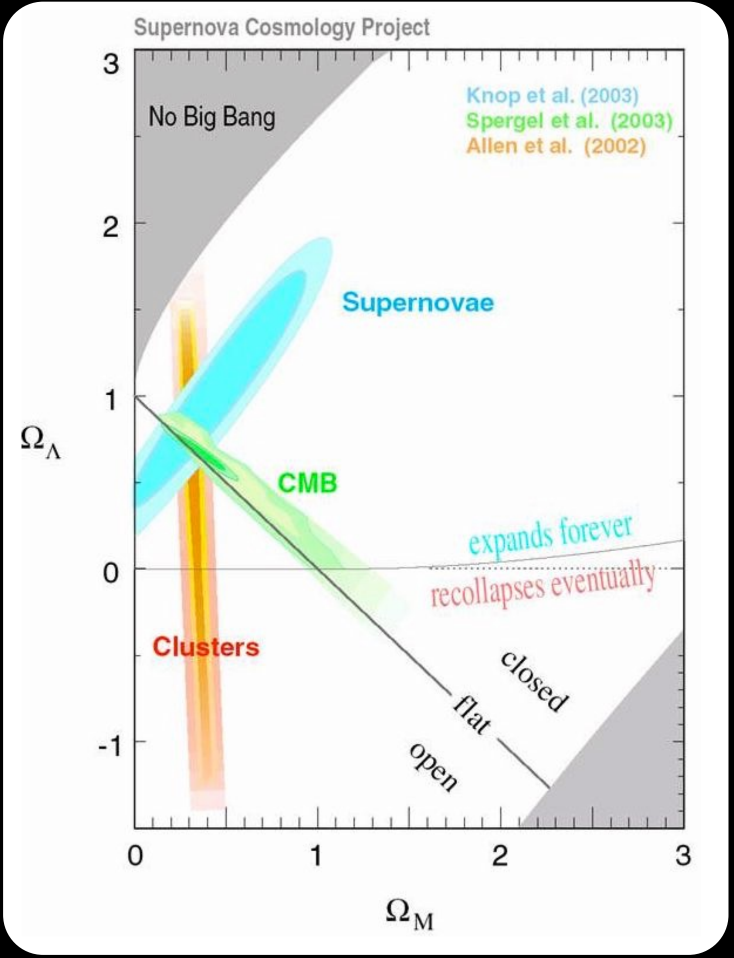
# Dark Matter

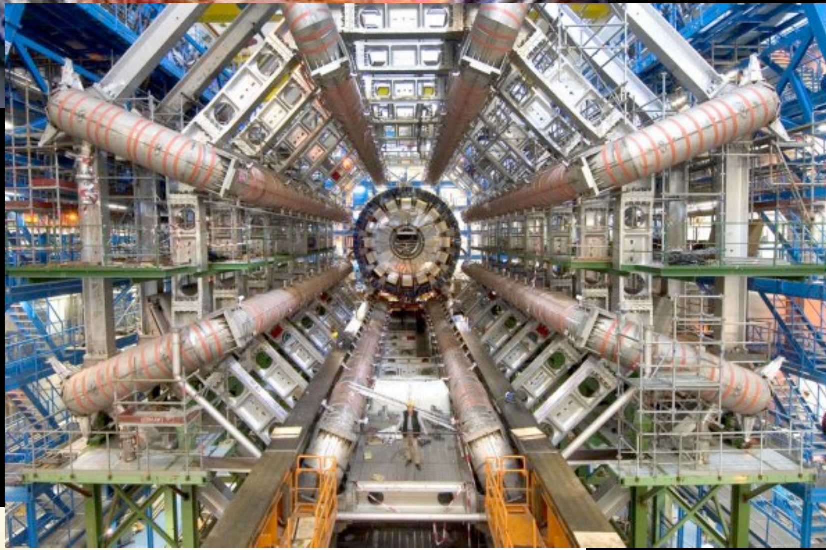

CMB
Supernova
Structure
Lensing

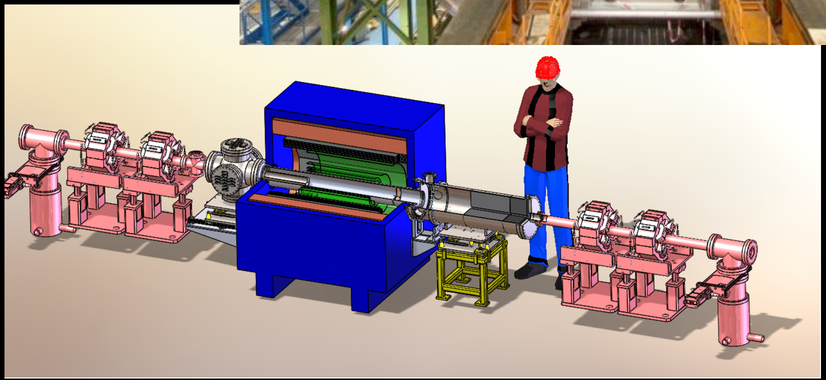

Ordinary Matter
Dark Matter
Dark Energy

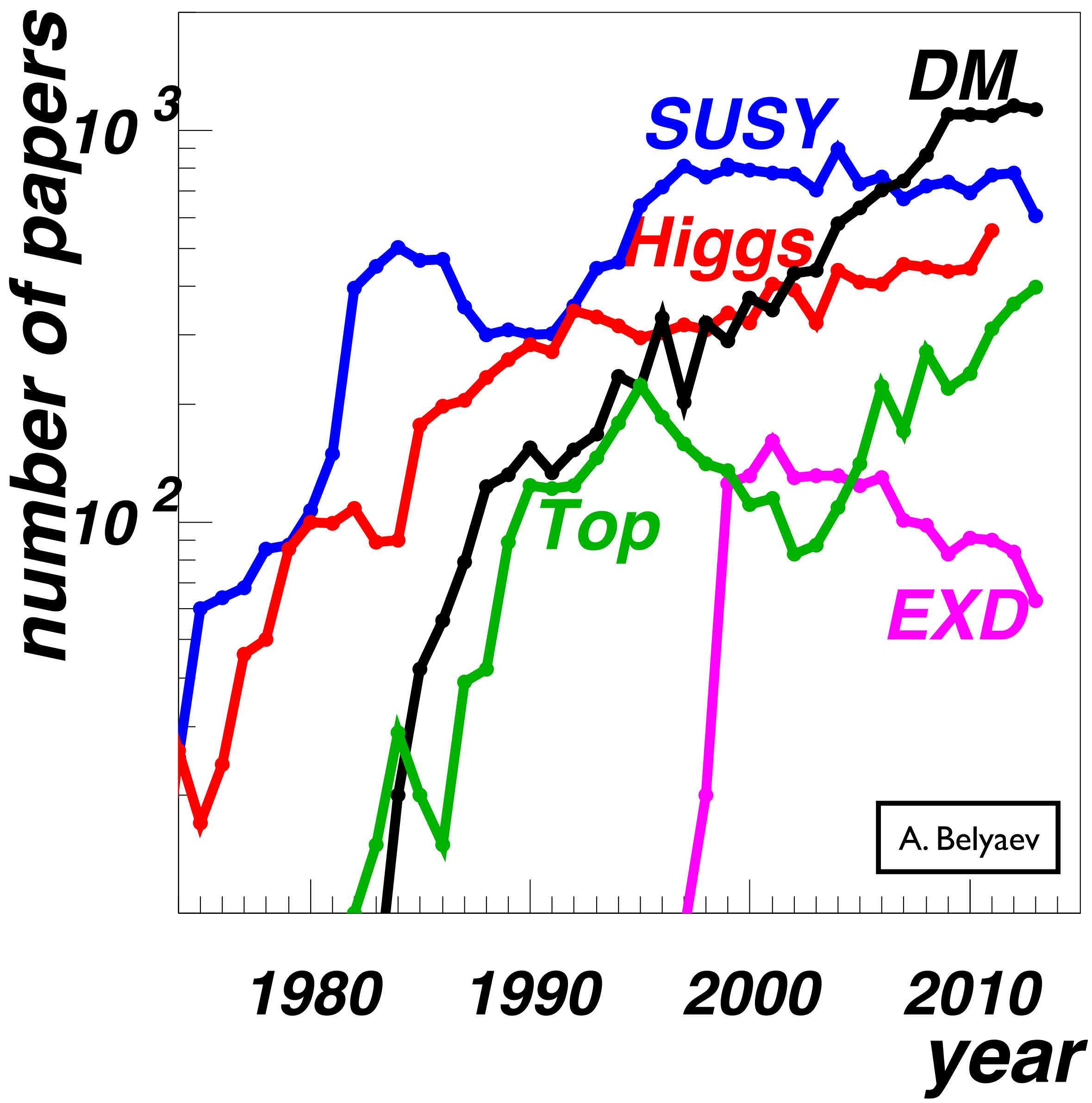

Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
$\Omega_\Lambda$
$\Omega_M$
3
2
1
0
-1
0
1
2
3

# Accelerators

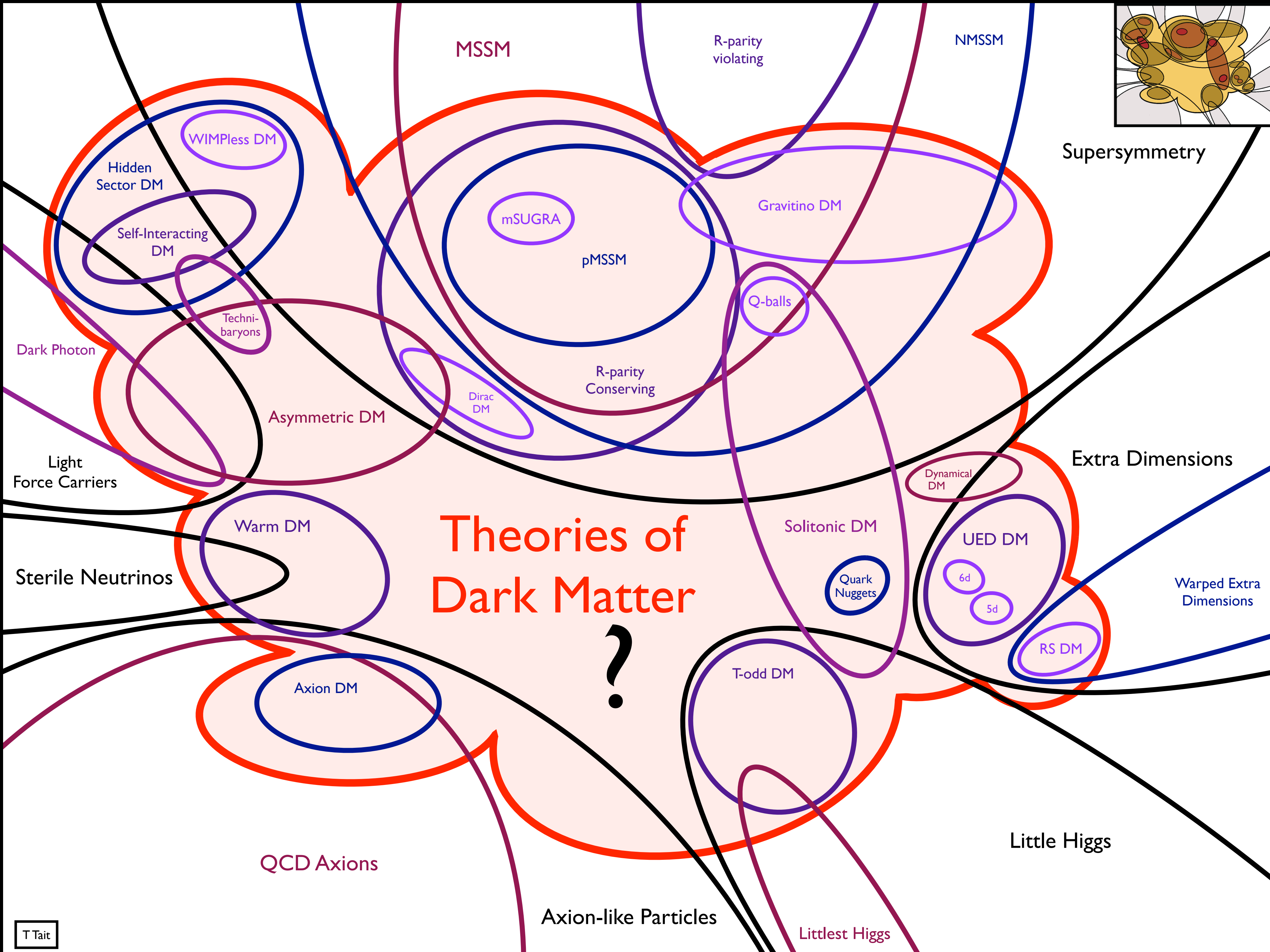
- If  dark particles have sufficient coupling to SM particles we should also be able to produce them at accelerators.
- To make the most of accelerators searches, we need to understand:
  - How their searches map on to our favorite theories of dark matter;
  - What they tell us in general about dark matter's properties;
  - How they fit in with the other kinds of searches for dark matter.
- This is where theory comes in! The question is which theories to use…



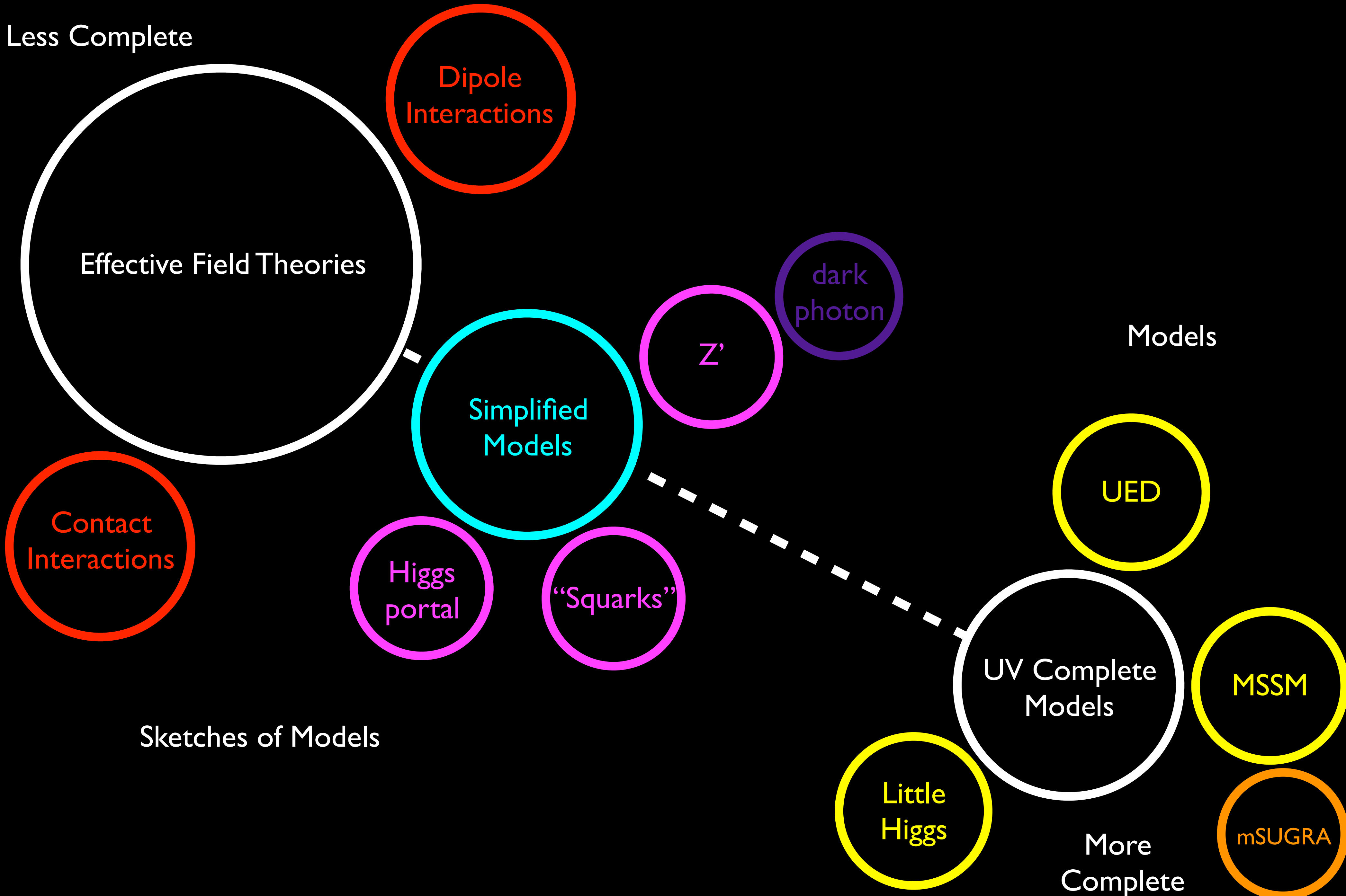




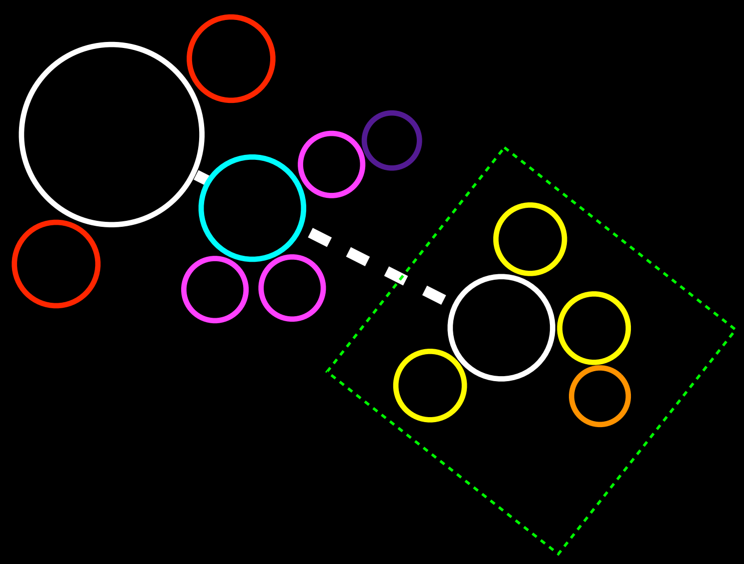
number of papers
$10^3$
$10^2$
DM
SUSY
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year


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
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

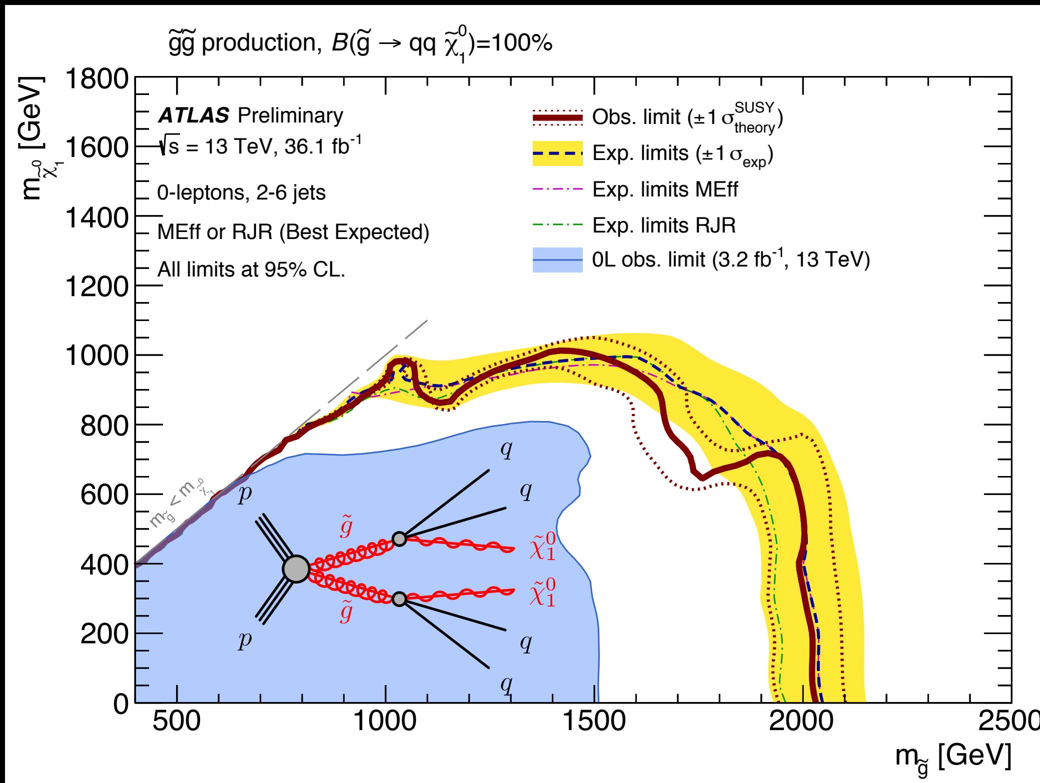
# Spectrum of Theory Space

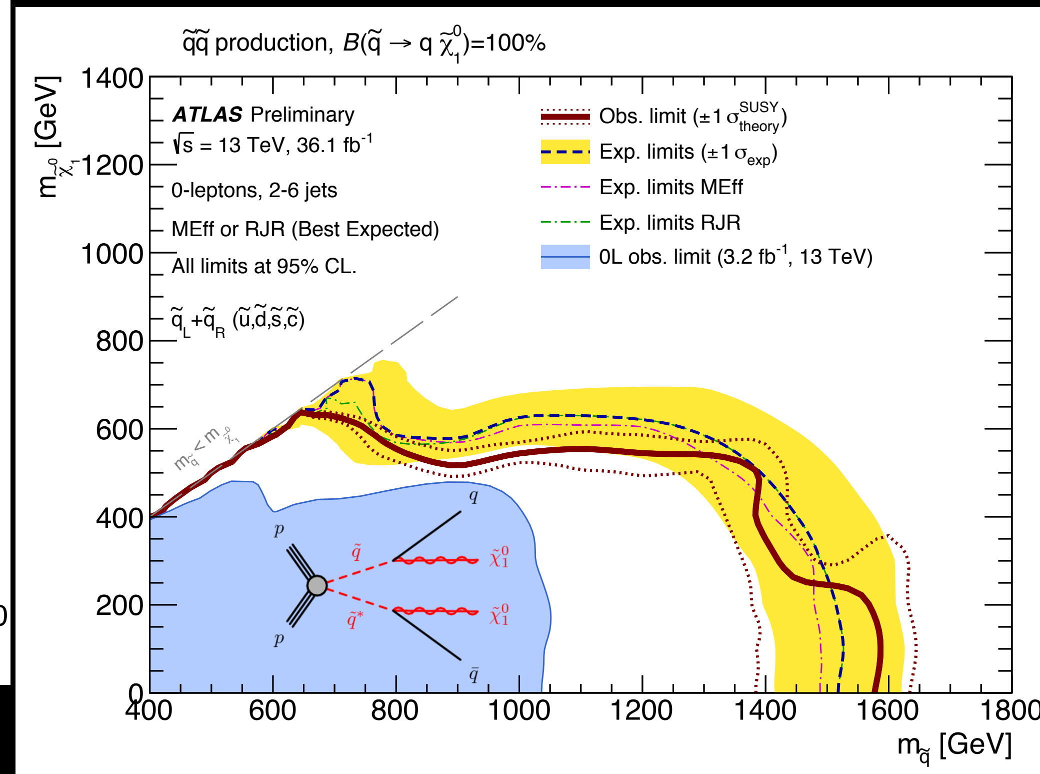


# Complete Theories



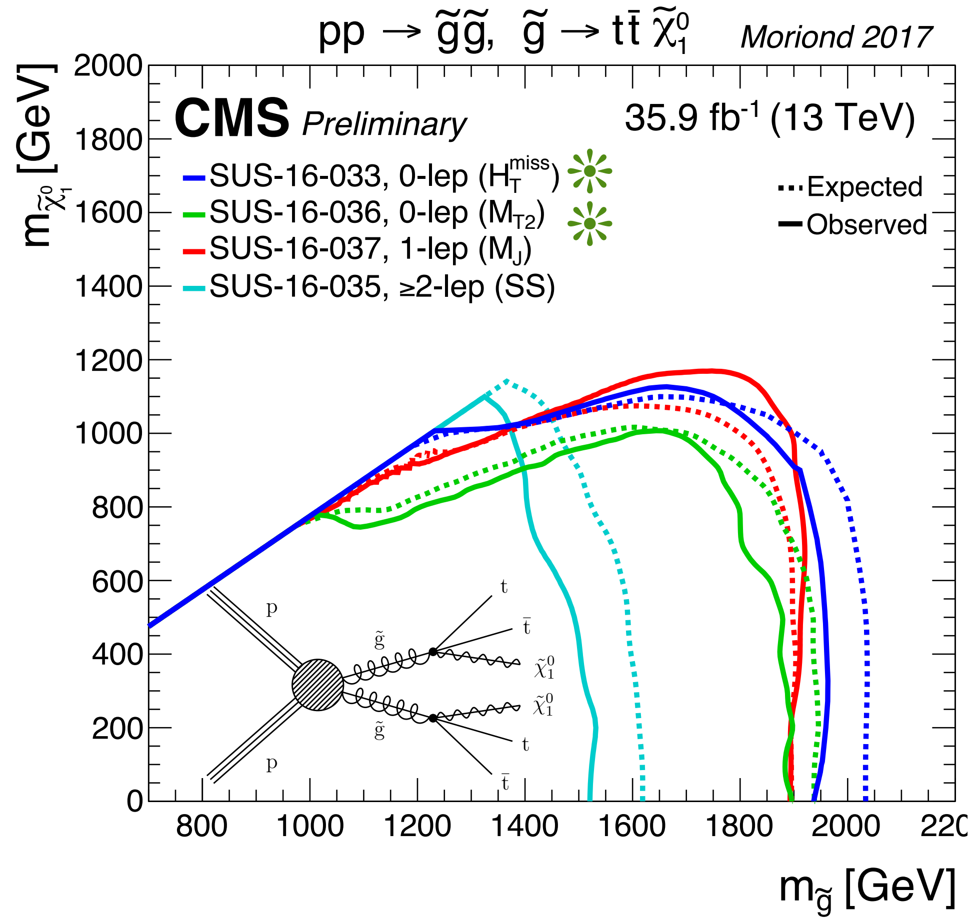
# Squarks and Gluinos

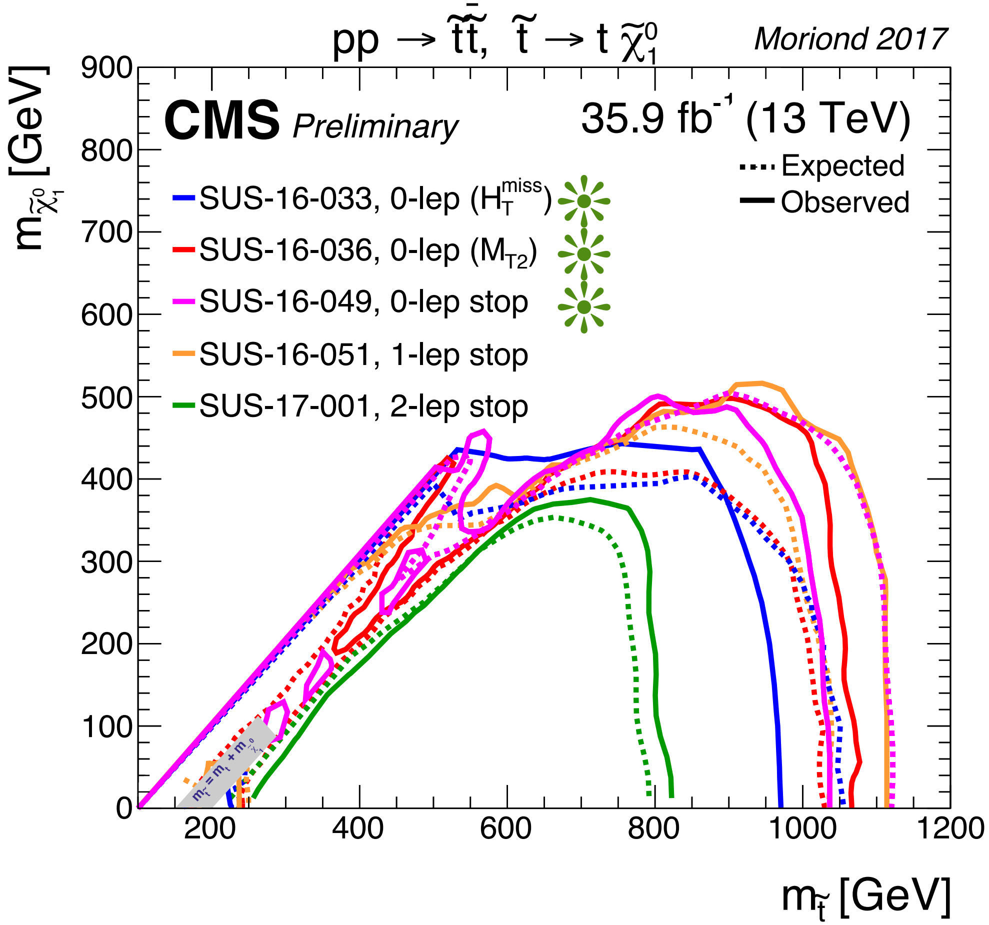



- Searches for missing energy plus various numbers of jets put bounds on squark and/or gluino ("colored sibling") production.
    - Gluinos decay to two jets + WIMP
    - Squarks into one jet + WIMP    [Assuming degenerate "light" squarks]
- These are important constraints on SUSY. The specific message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

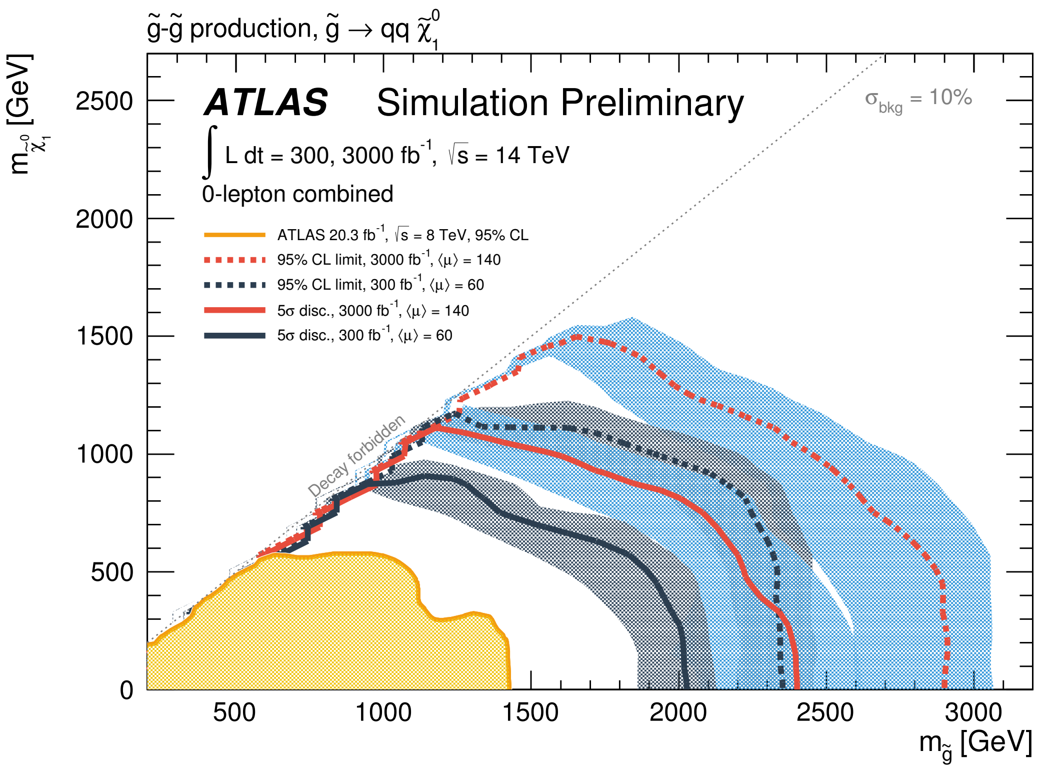
# 3rd Generation Squarks

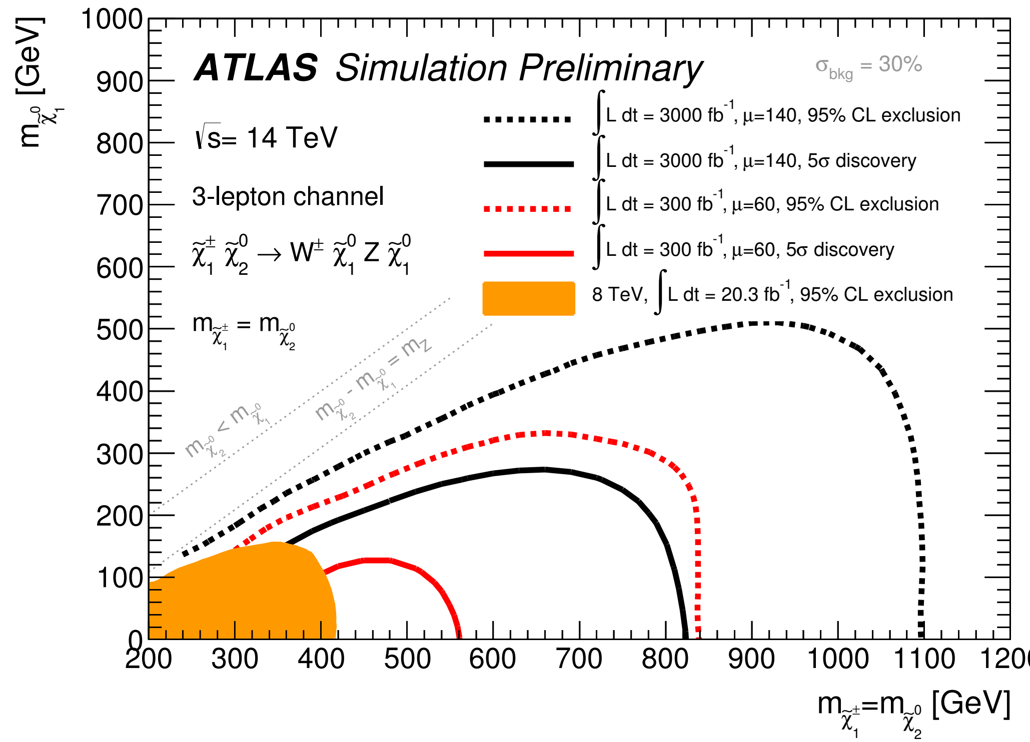



- Searches for the super-partners of top quarkss are starting to reach ~ TeV masses, carving out the natural regions of supersymmetry!

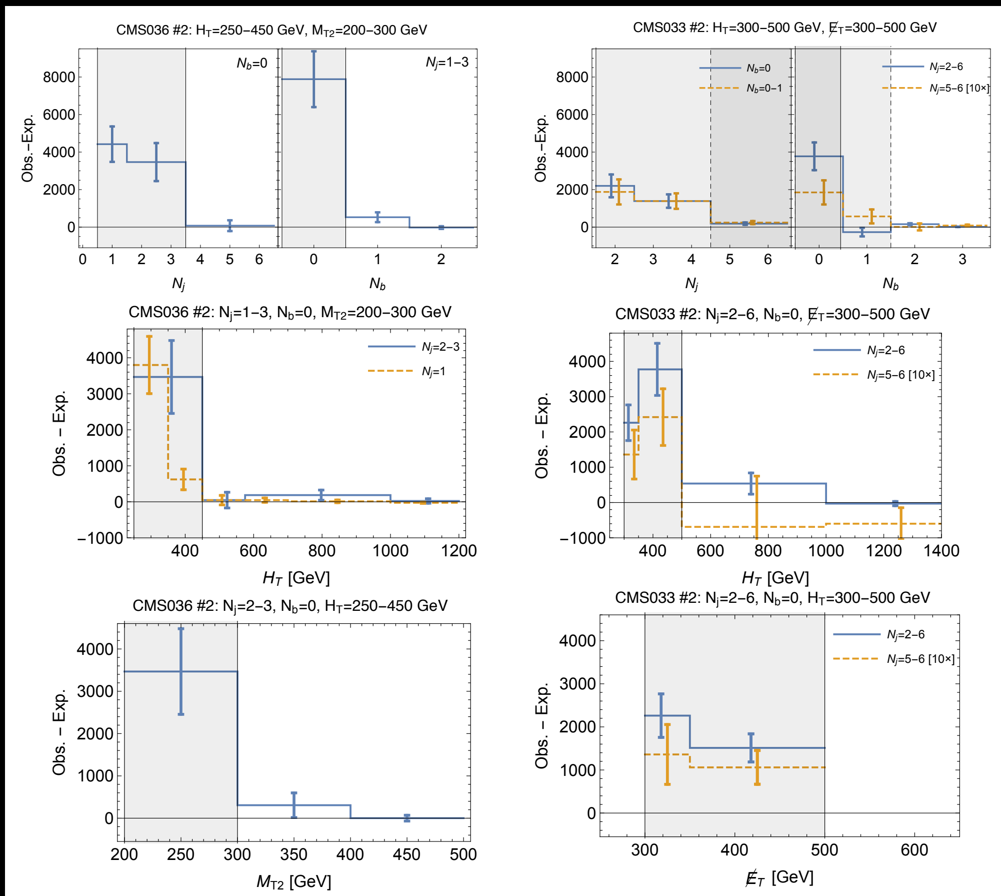
# Future Prospects



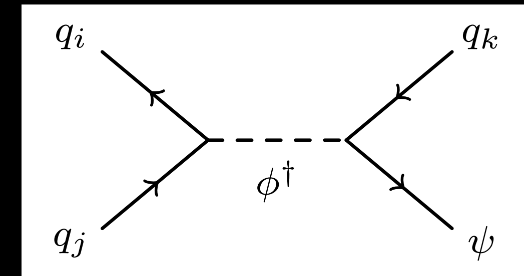



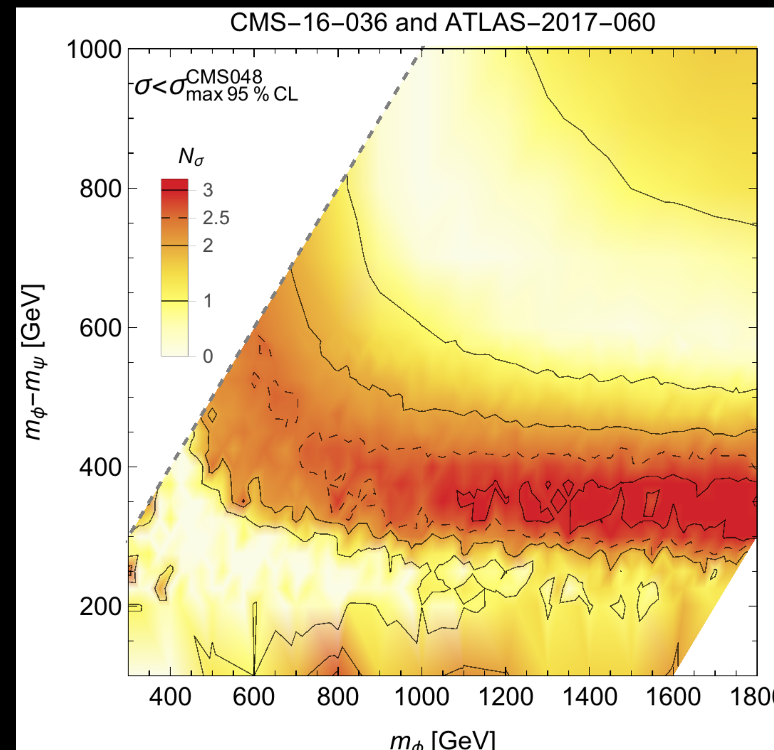

- The eventual reach of the LHC searching for supersymmetric particles is estimated to be around 3 TeV for gluinos and around 1 TeV for electroweakly charged particles.

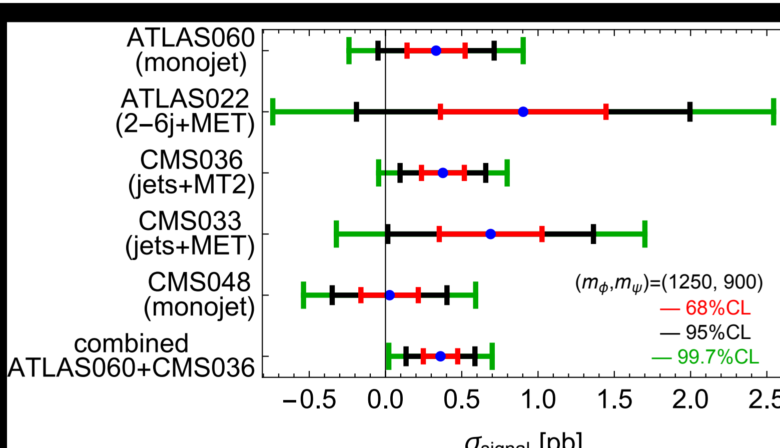
# Excess?




Asadi, Buckley, DiFranzo, Monteux, Shih arXiv:1707.05783 &1712.04939

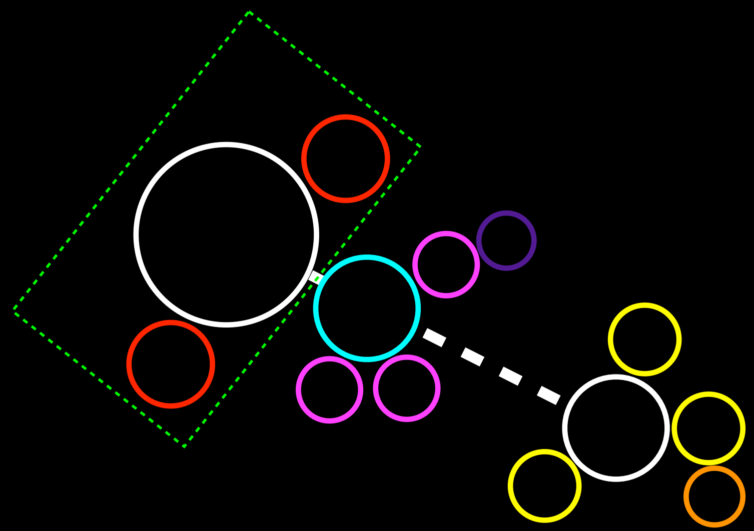


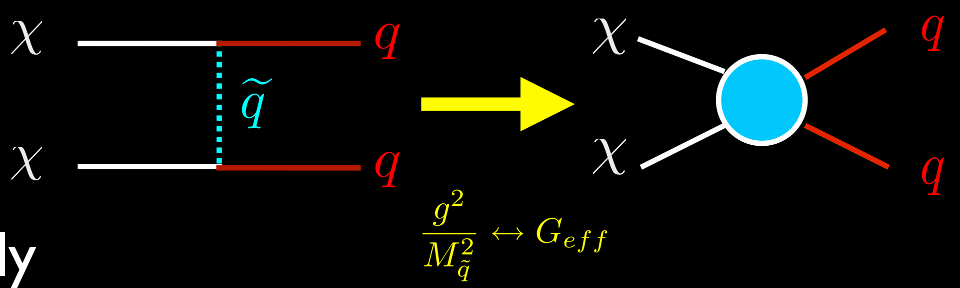




There is a theoretical recast of the jets + MET data that indicates ~2.5σ excesses over backgrounds.

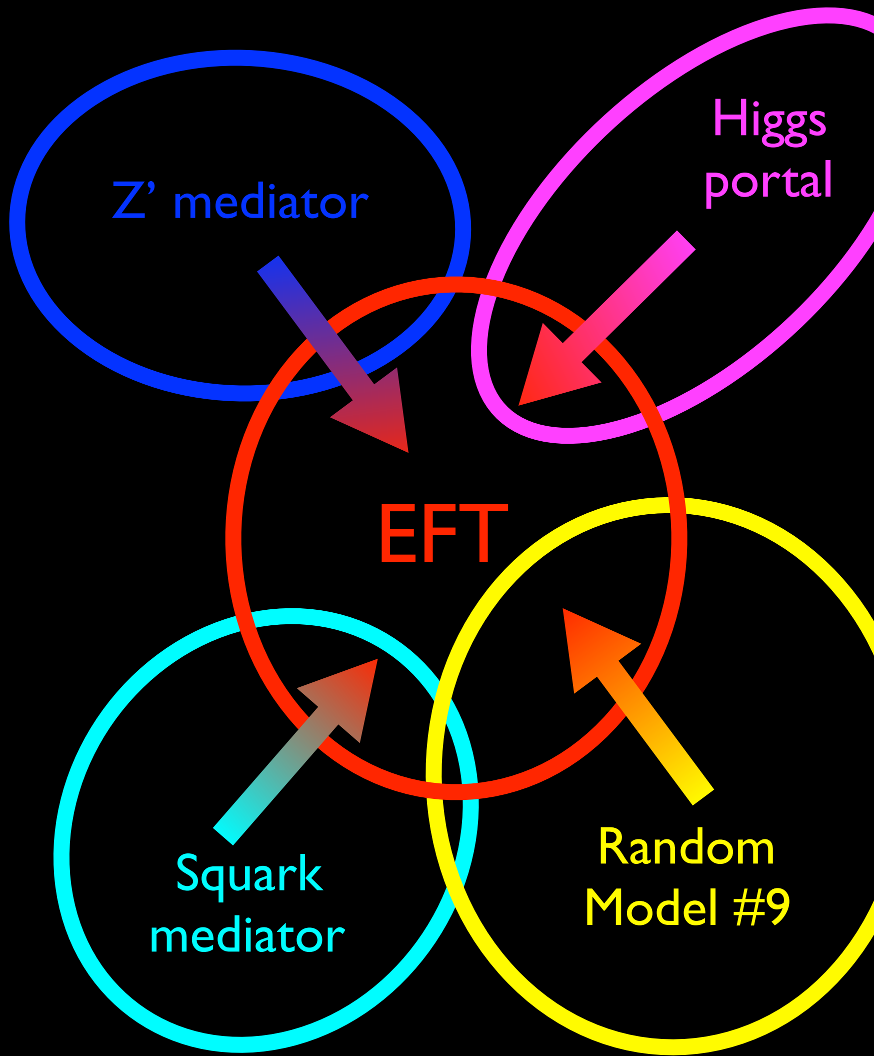
# Contact Interactions (EFT)



# Contact Interactions




- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- 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 the new particles directly.



# Example: Majorana WIMP

- The various types of interactions are accessible to different kinds of experiments. (Technically meaning: the observables are unsuppressed by the small dark matter velocity in our halo, v ~ $10^{-3}$.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

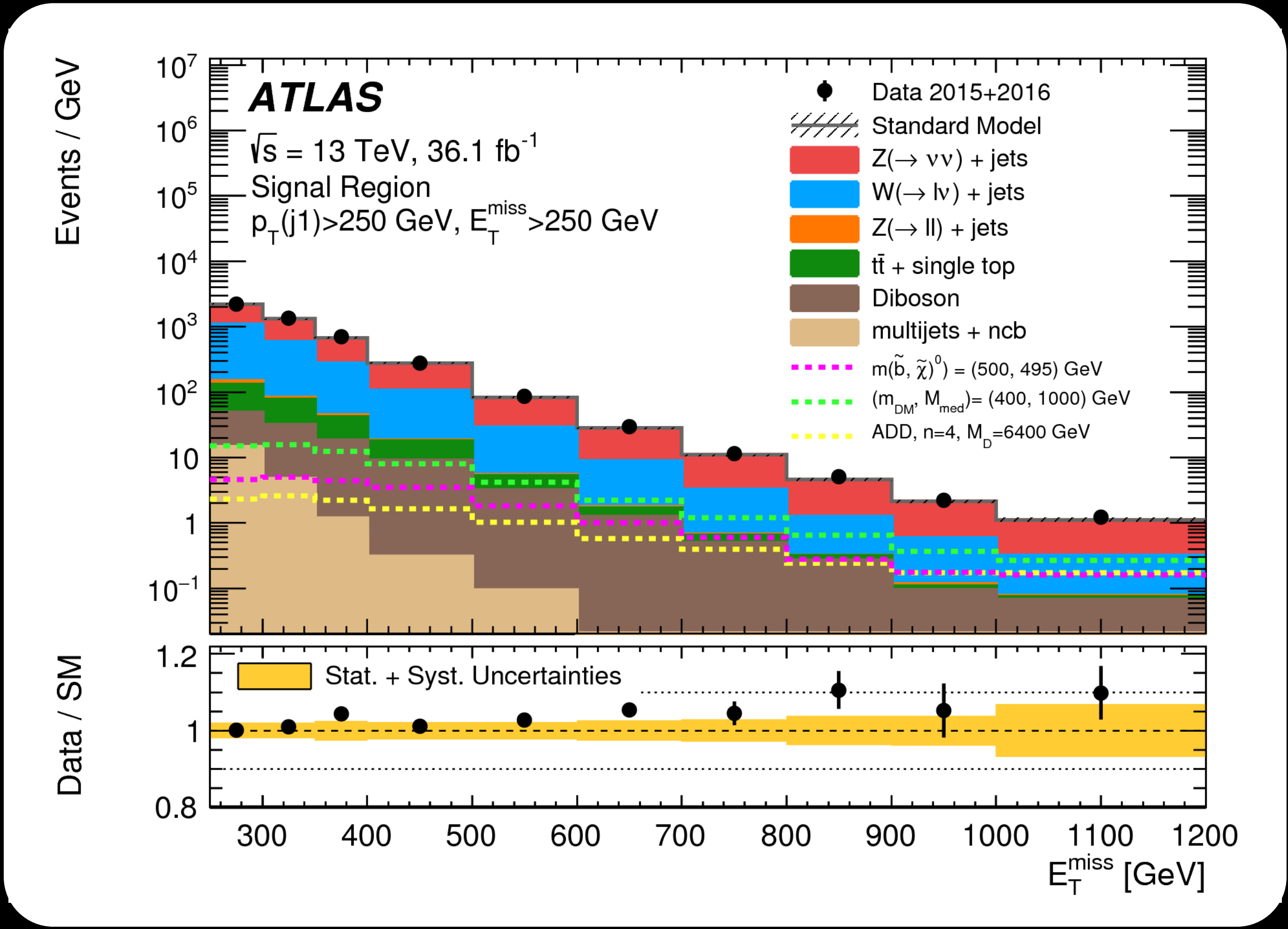
| Name | Type | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | 1 | 1 |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | 1 |
| M3 | $qq$ | $im_q/2M_*^3$ | 1 | $\gamma_5$ |
| M4 | $qq$ | $m_q/2M_*^3$ | $\gamma_5$ | $\gamma_5$ |
| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$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

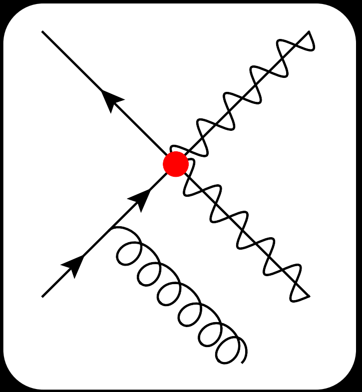
$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

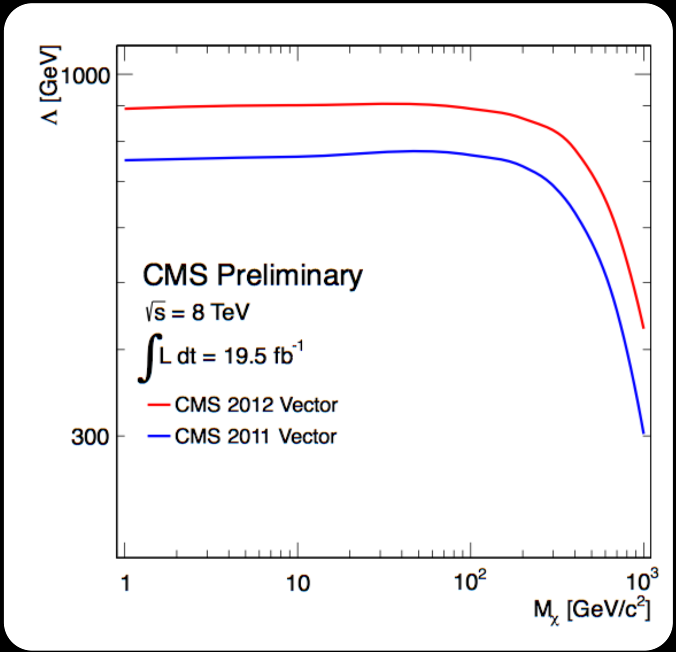
$$\sum_q G_\chi\,[\bar{q}\Gamma^q q]\,[\bar{\chi}\Gamma^\chi\chi]$$

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

# Run II Results



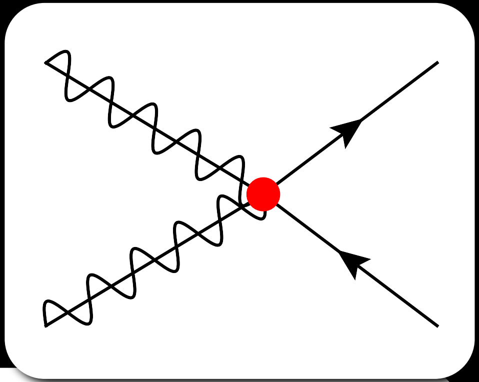



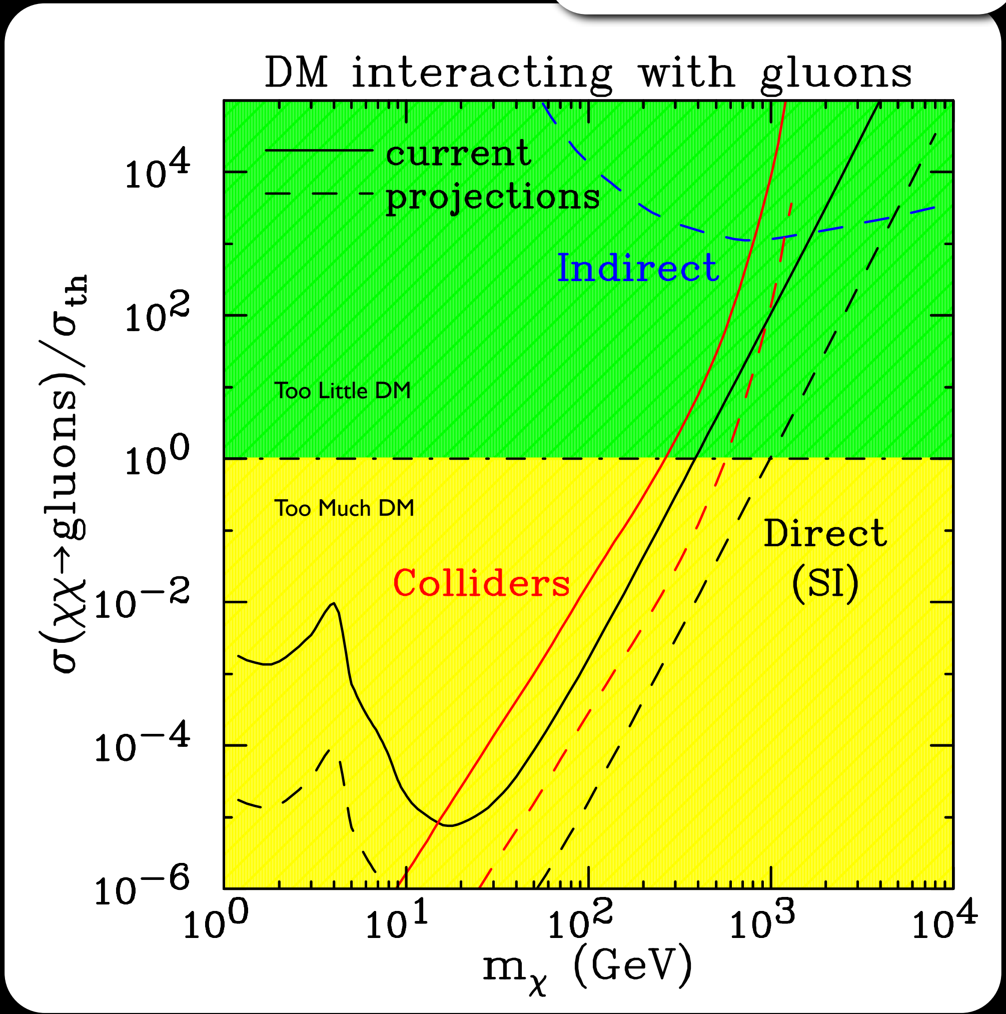



In Run I, both CMS and ATLAS interpreted mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass. (We'll see more recent interpretations shortly).

# Annihilation

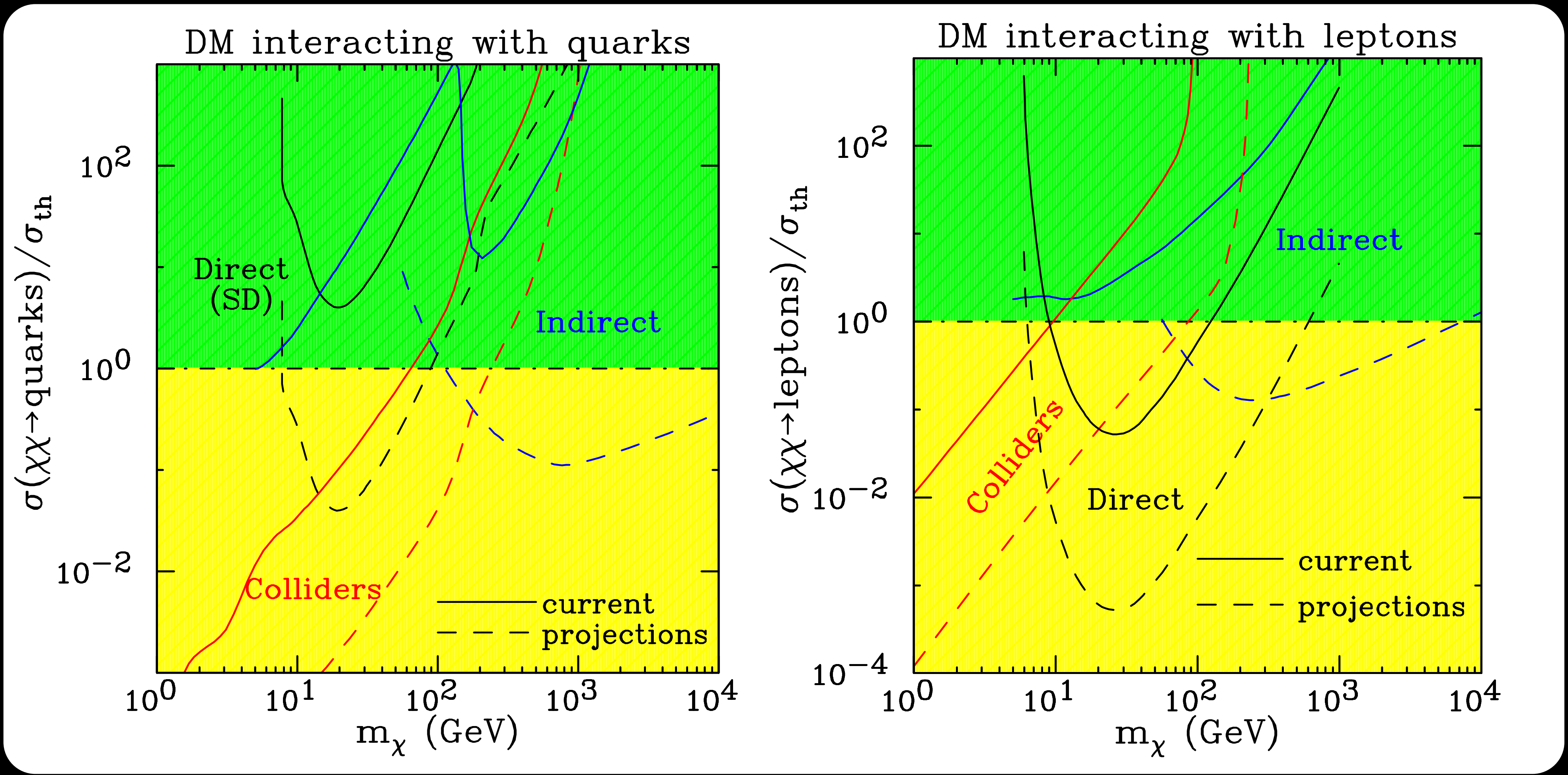
- We can also map interactions into predictions for WIMPs annihilating.
- This allows us to compare with cross sections leading to a thermal relic density through freeze out.
- This example is for dark matter interacting with gluons. The cross section has been normalized to the thermal cross section for a thermal relic at a given mass.
- The LHC does better for lighter WIMPs or p-wave annihilations whereas direct detection is more sensitive for heavy WIMPs.





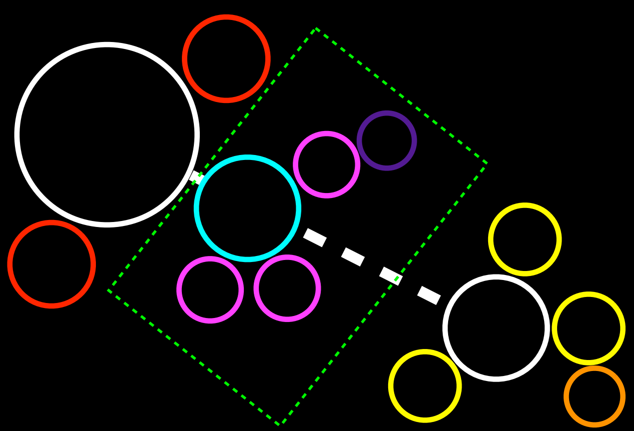

DM Complementarity, arXiv:1305.1605

# Quarks & Leptons

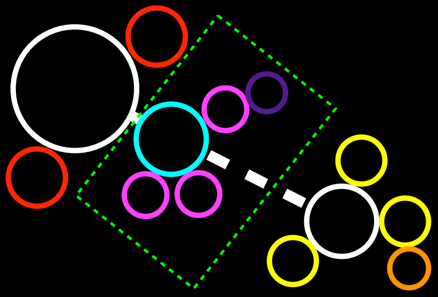



DM Complementarity, arXiv:1305.1605

# Simplified Models



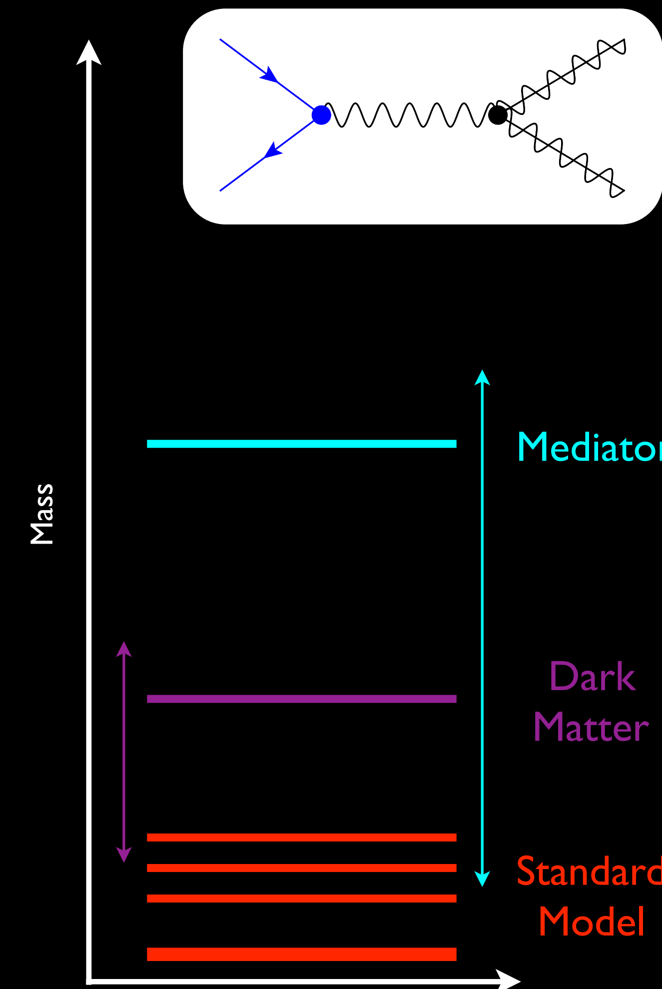
# Simplified Models



- Since the EFT limit cannot describe particles whose masses are accessible to our experiments, it is also fruitful to explore theories which include the mediator particles explicitly.
  - Simplified Models are a middle ground that capture more details of a realistic theory than the EFT, but avoid getting overwhelmed by details in a complete theory such as the MSSM.
- Of course, the number of possible constructions increases as one includes more states.
  - We'll look at a few that are UV complete at the level of LHC phenomenology.
  - In many cases, new and interesting phenomena become accessible!

# Vector Simplified Model

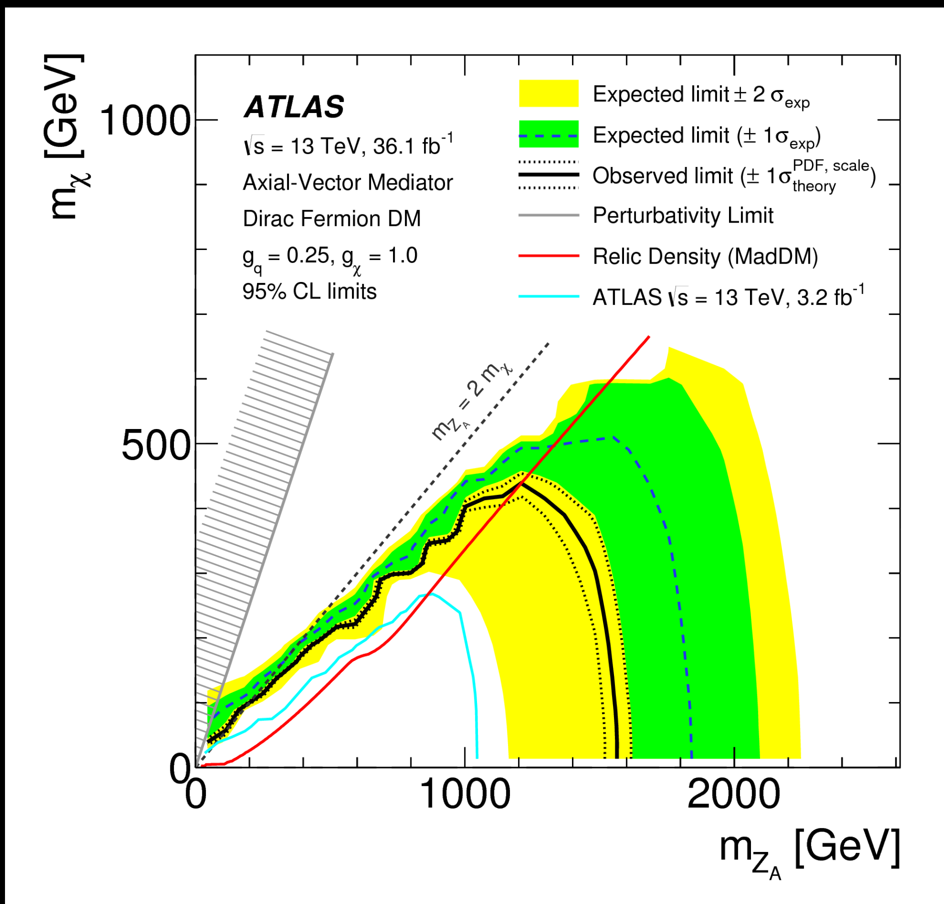
- Vector models have parameters describing the charges of the DM and SM particles.
- Minimal Flavor Violation suggests that uR, dR, qL, eR, lL would all have family-universal but distinct charges, as does the SM Higgs.
    - We would like to be able to write down the SM Yukawa interactions.
- There could be kinetic mixing with $U(1)_Y$.
- There is a dark Higgs sector. It may or may not be relevant for phenomenology.
- Gauge anomalies must cancel, which also may not be very important for accelerator searches.

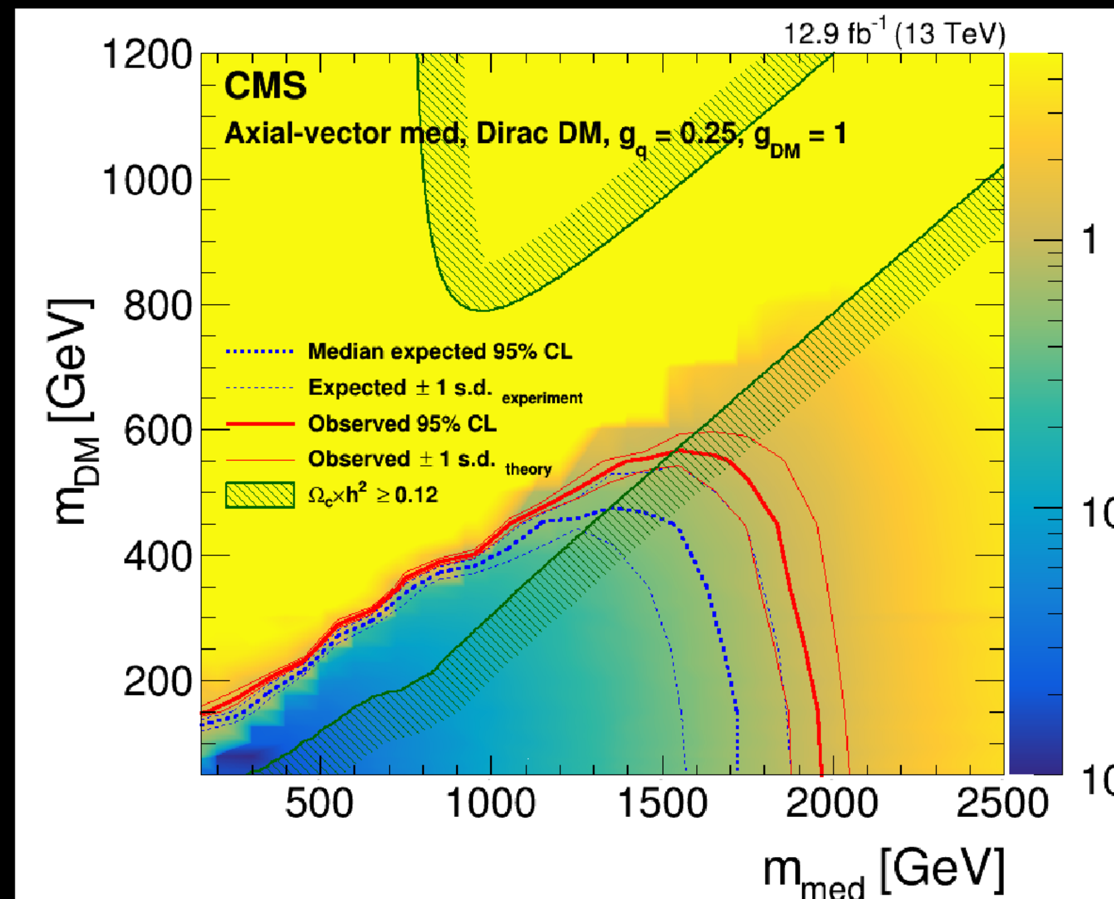



Simplify by assuming
all quark couplings are equal,
and no lepton/Higgs couplings.

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

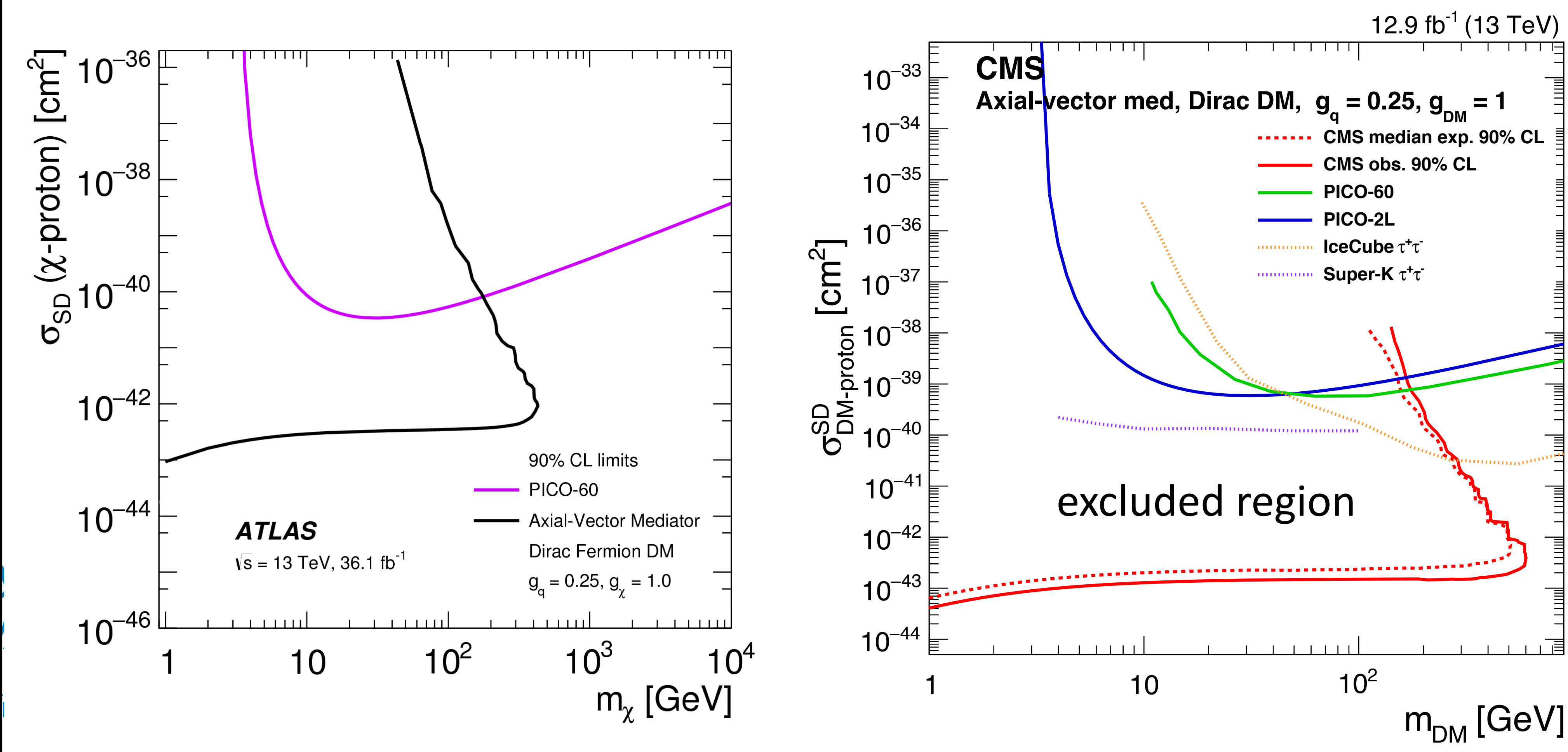
# Axial Vector: Monojet Searches



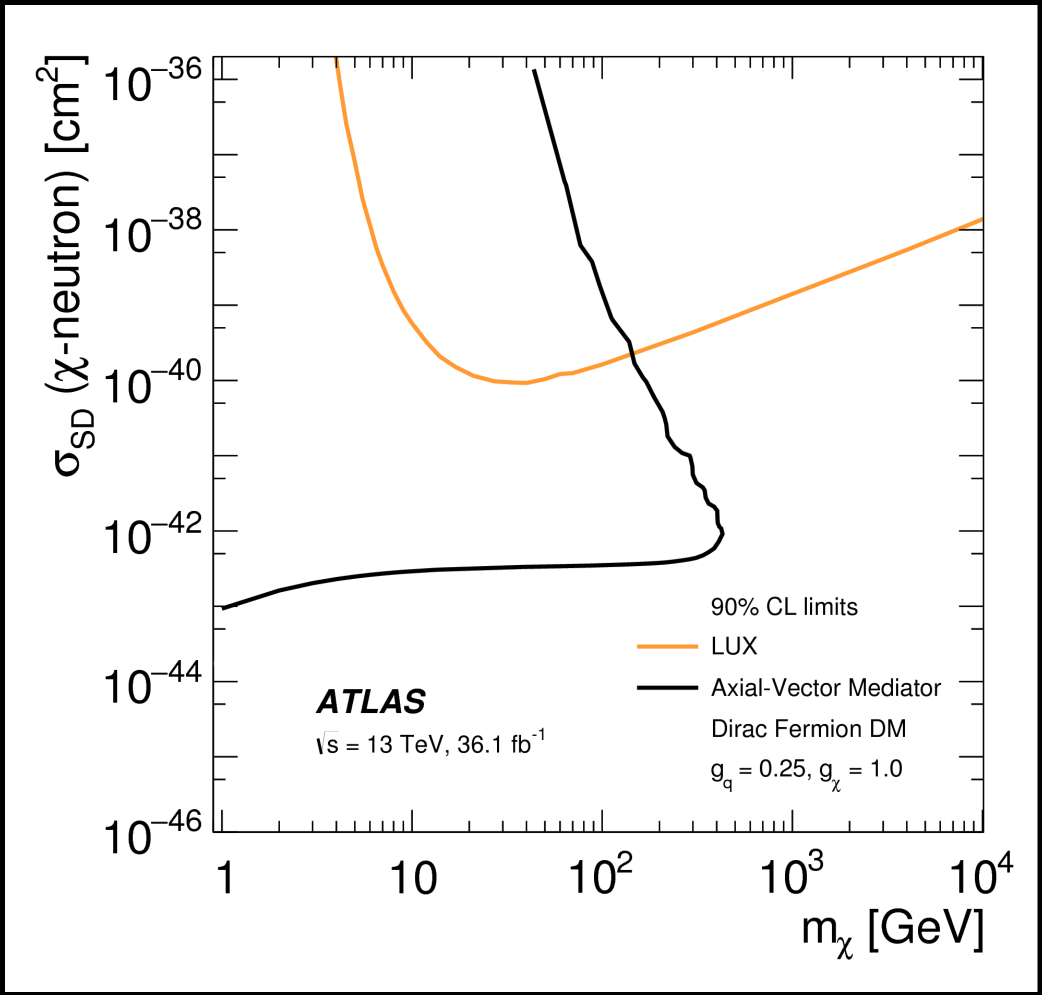



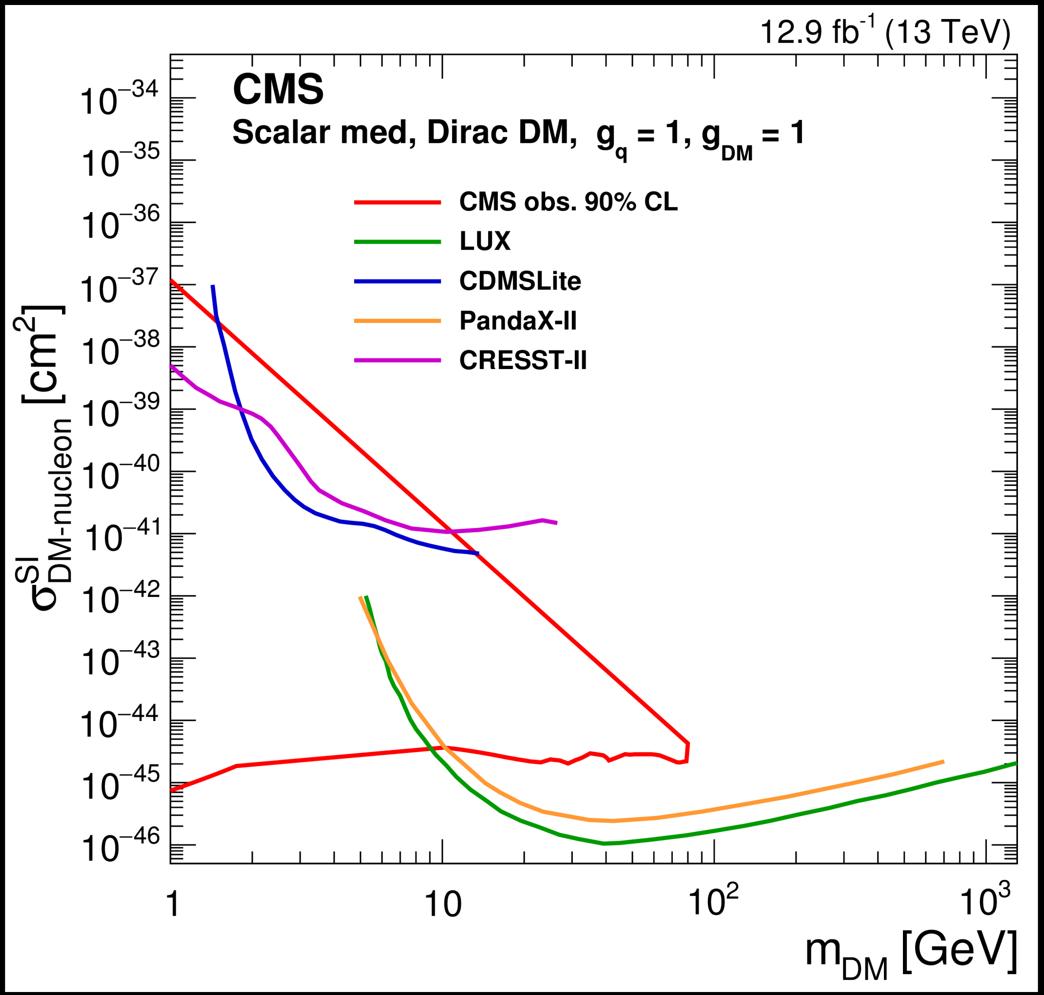
# Axial Vector: Monojet Searches

Axial vector mediator $g_q$=0.25, $g_{DM}$=1.0

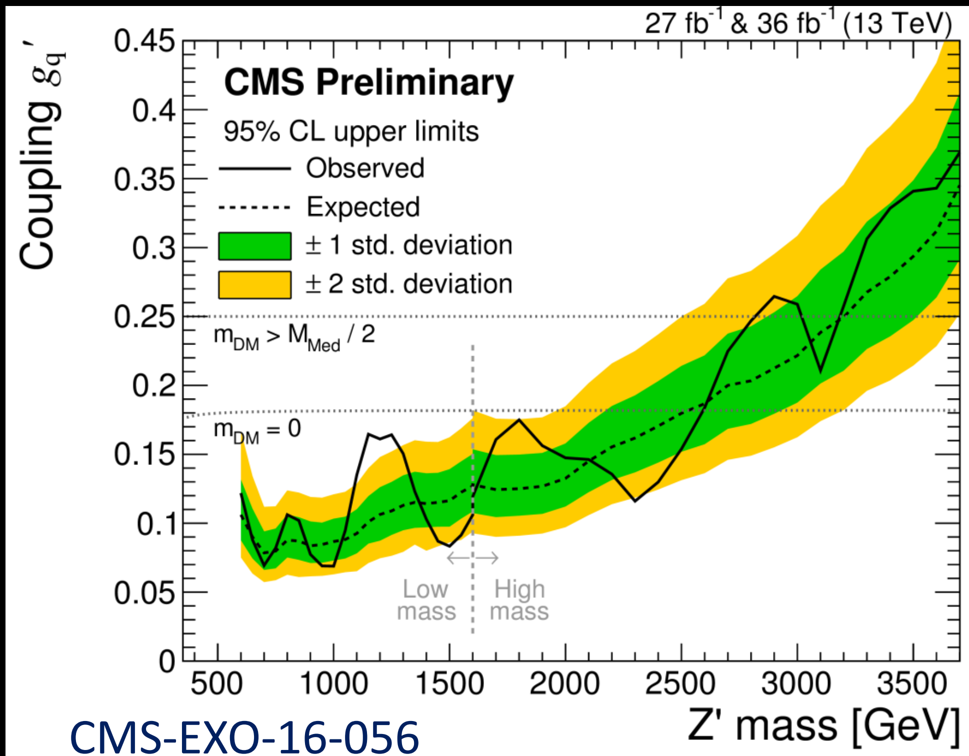


# Monojet Searches: Other Interpretations

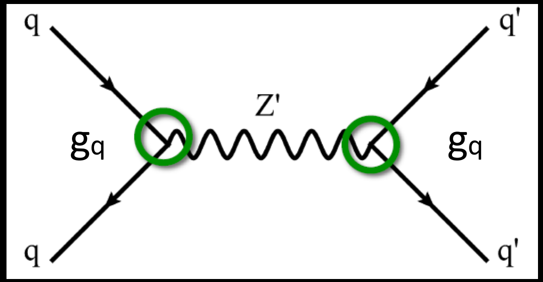


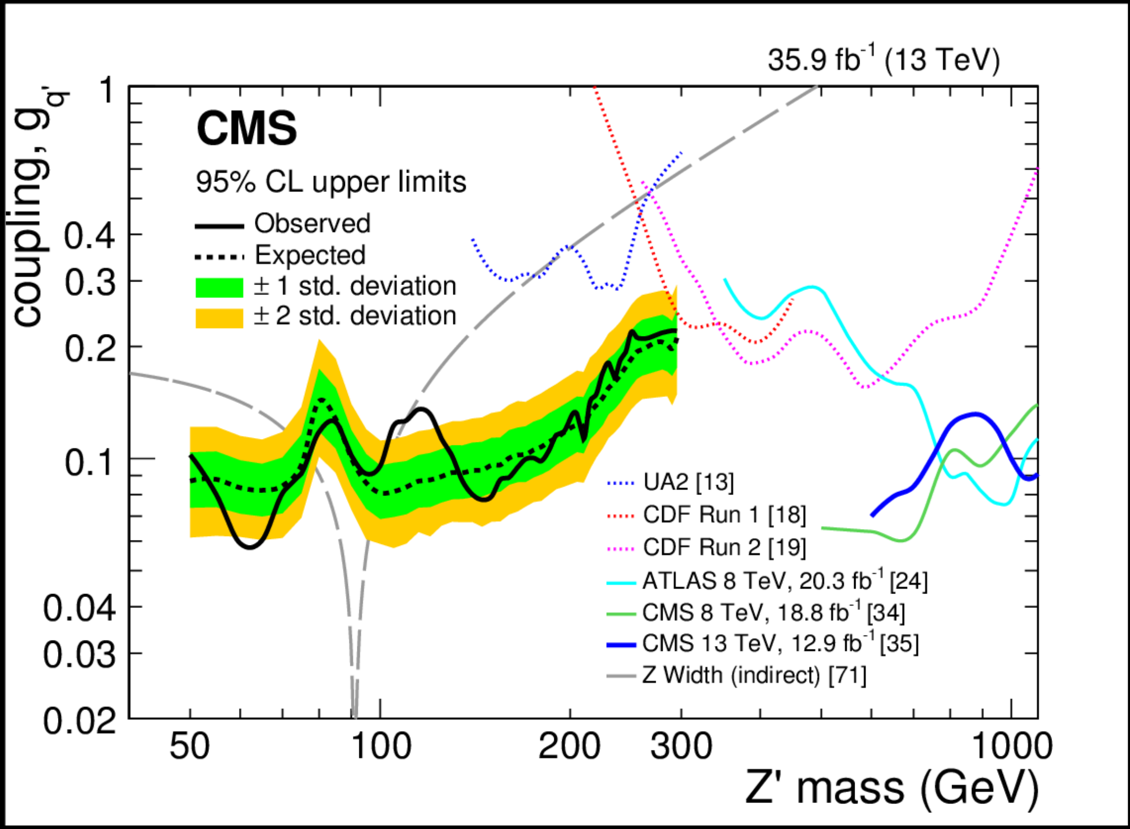



# Dijet Mediator Searches



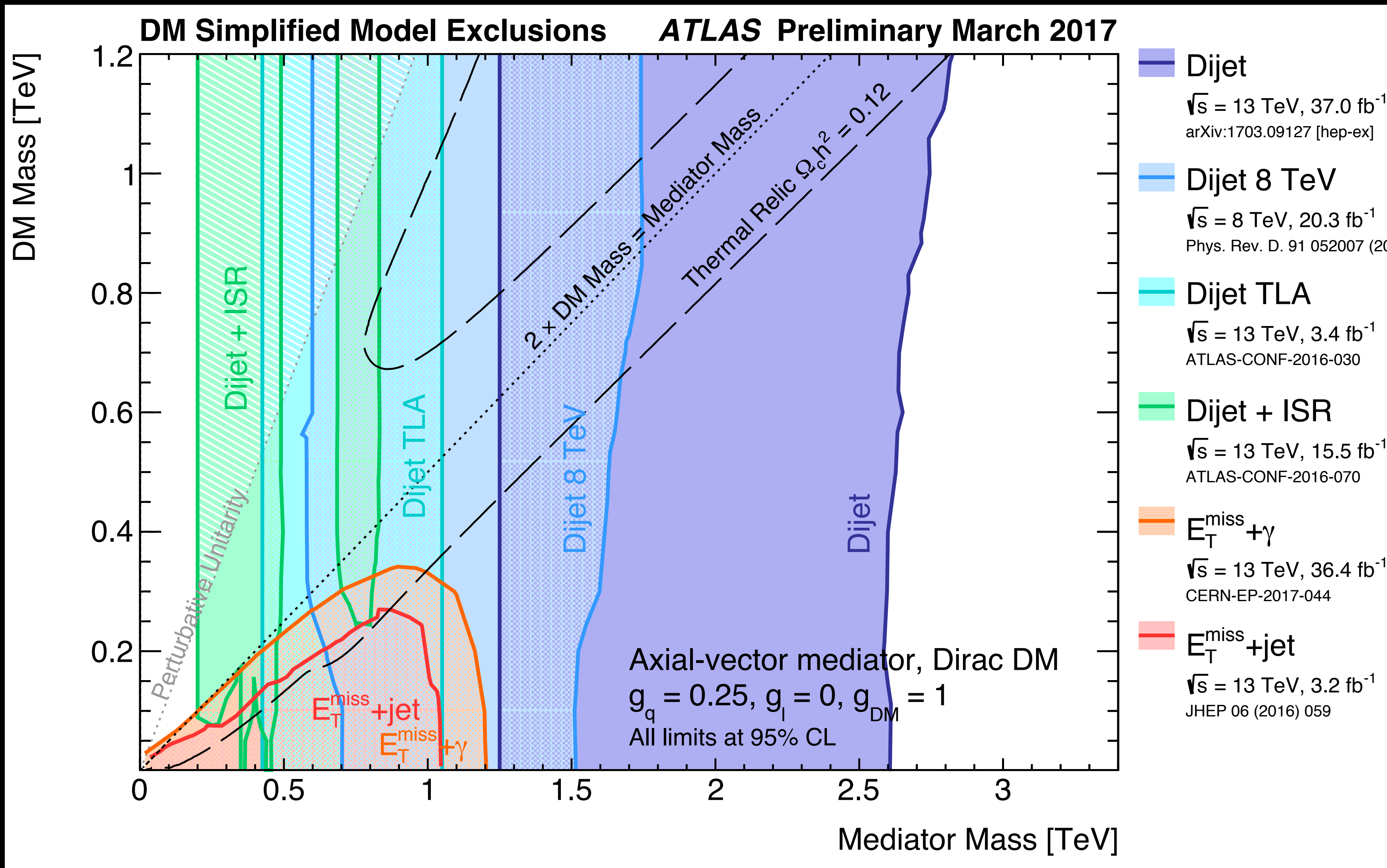

[CMS-EXO-16-056]



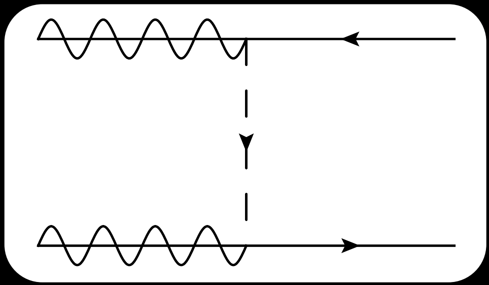

Related searches for dileptons.

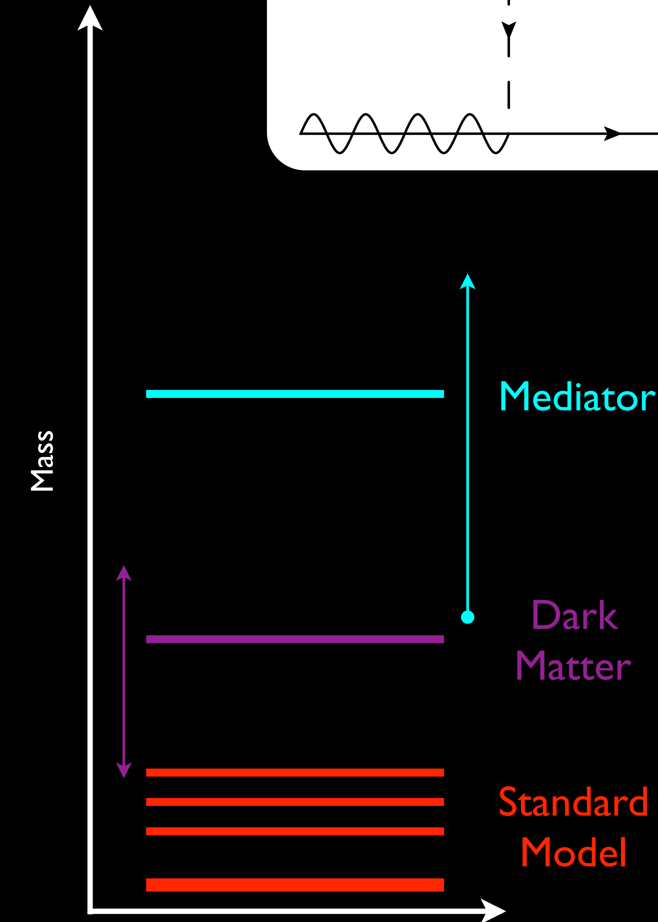
# Dijet Searches



# Colored Scalar

- Another construction has dark matter interacting with quarks via a colored scalar mediator.
- Minimal flavor violation suggests we consider mediators with a flavor index corresponding to {uR,cR,tR}, {dR,sR,bR}, {Q1,Q2,Q3} and/or combinations.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, 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.



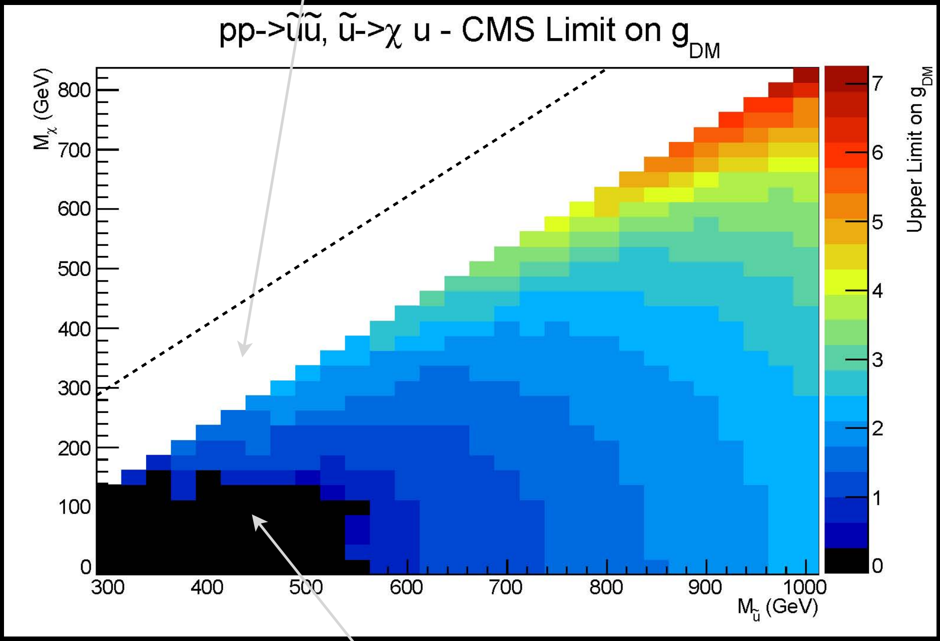



Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679

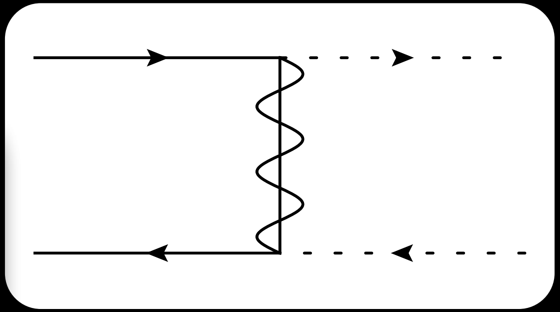
# $\tilde{u}_R$ Model

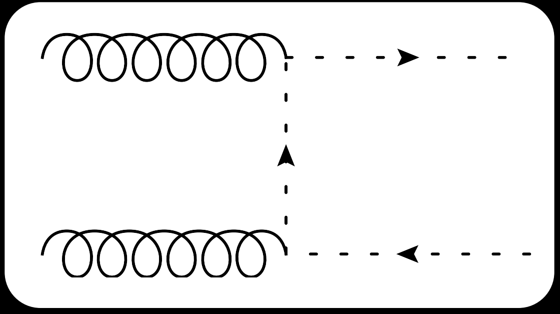
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force or through the interaction with quarks.
- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.

Weak bounds in the mass-degenerate region.

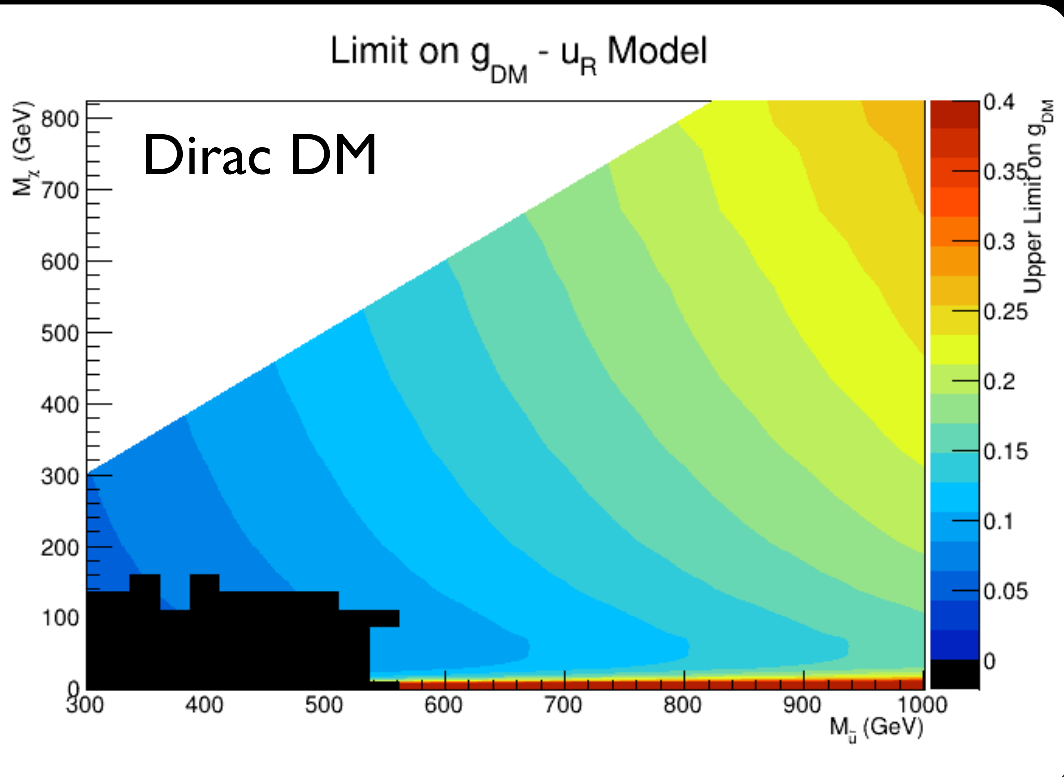



QCD production saturates the CMS limits, resulting in no allowed value of g.

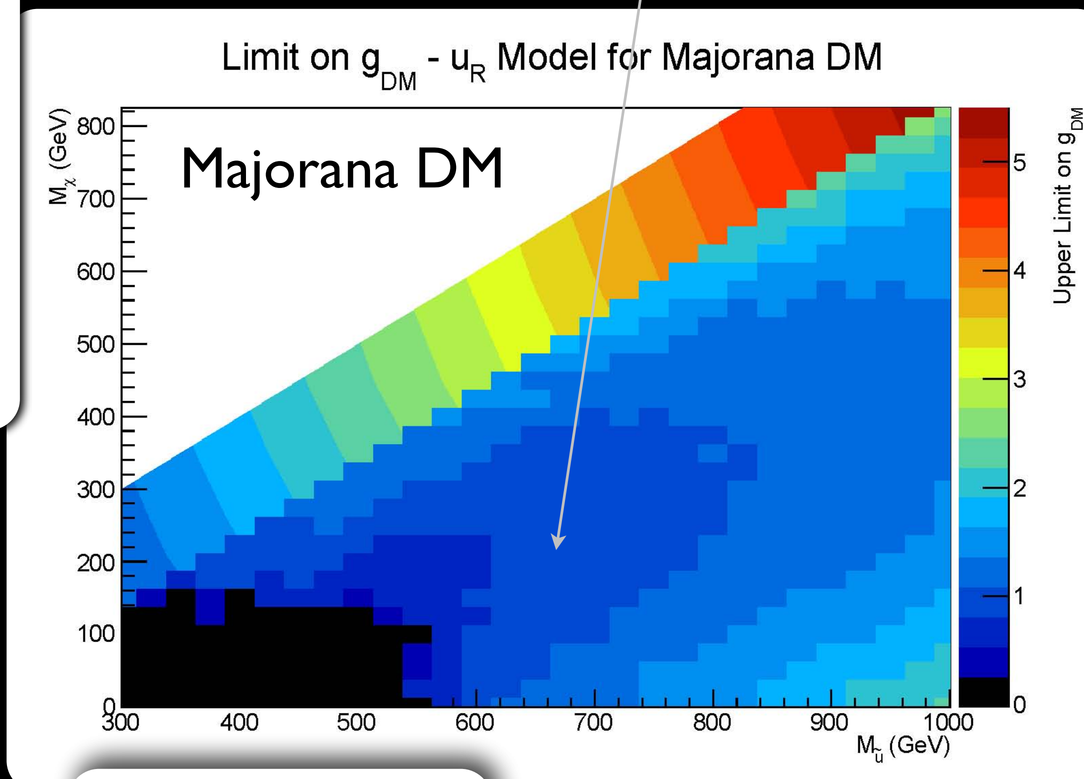


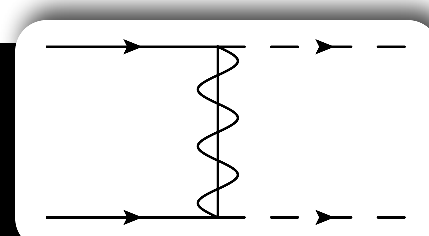


# Majorana versus Dirac




Collider bounds tend to dominate for Majorana DM.



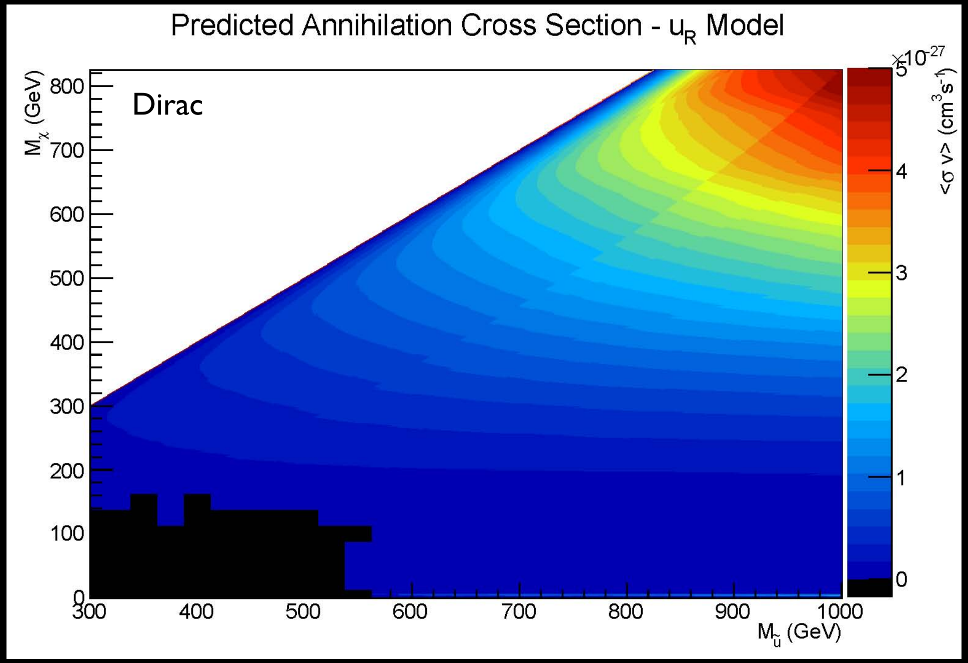
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

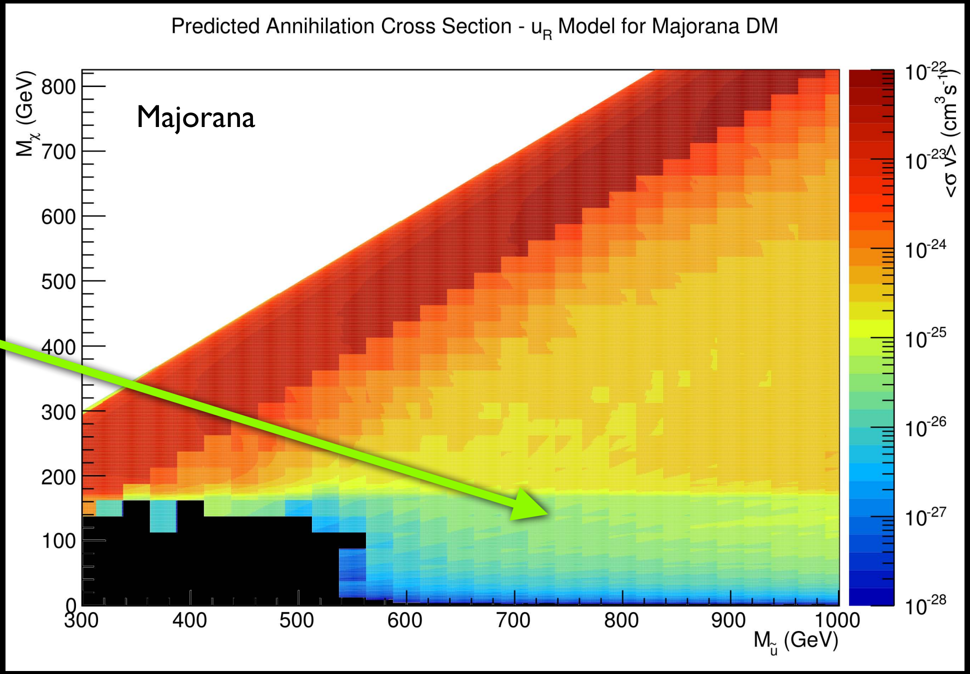
Majorana WIMPs have no tree-level spin-independent scattering in this model.

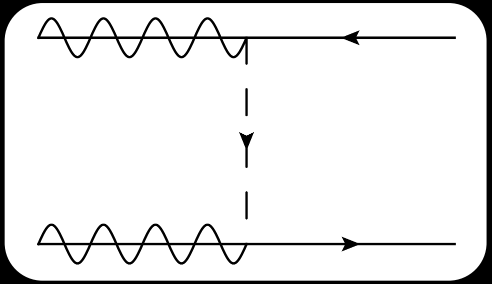
At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.

# $\tilde{u}_R$ Model: Forecasts

- 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 relic which freezes out with the correct relic density ( $\langle\sigma v\rangle \sim 10^{-26}$ cm$^3$/s ).



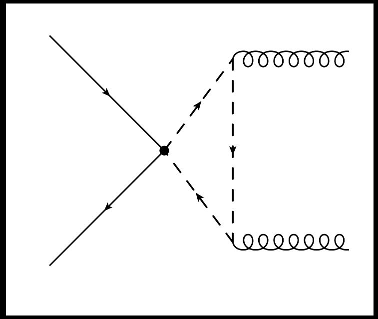
# Dark Matter Coupled to Gluons

Godbole, Mendiratta, TMPT 1506.01408 & JHEP
+Shivaji 1605.04756 & JHEP
Bai, Osborne 1506.07110 & JHEP

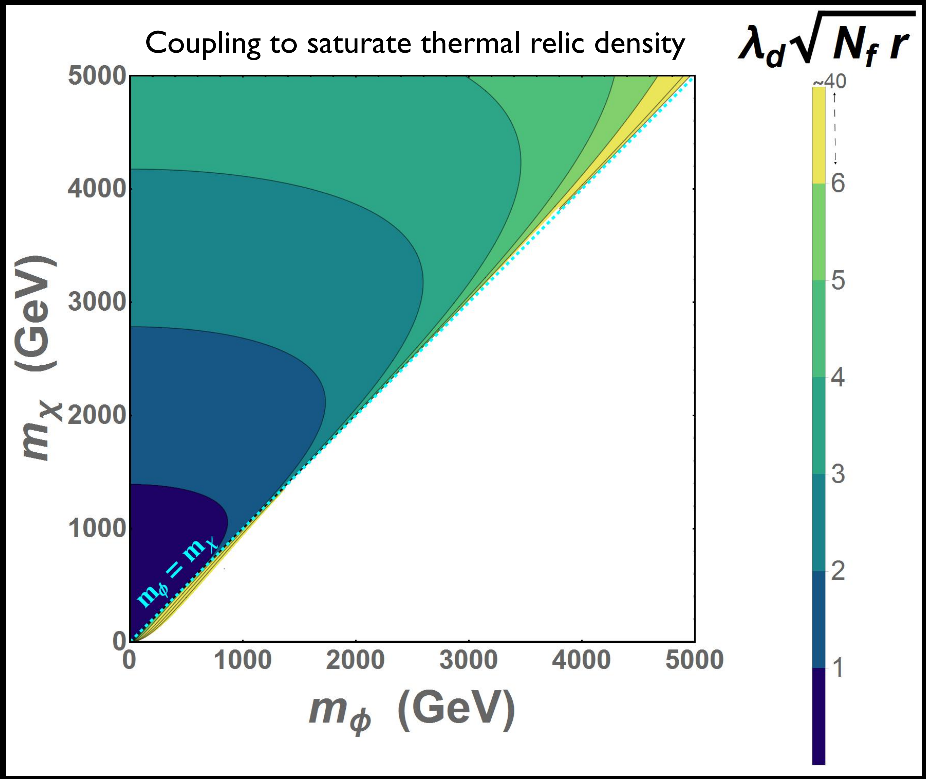
- An interesting variation is possible when both the dark matter and the colored mediator are scalars.
- In that case, a quartic interaction can connect the two.

$$\lambda_d \; |\chi|^2 |\phi|^2$$

- This interaction does not require the scalar to be $Z_2$-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (jn some cases) more like an R-parity violating squark.
- The color and flavor representations (r, Nf) of the mediator are free to choose.
- For perturbative λ, a thermal relic actually favors $m_\varphi < m_\chi$ so annihilation into $\varphi\varphi^*$ is open.

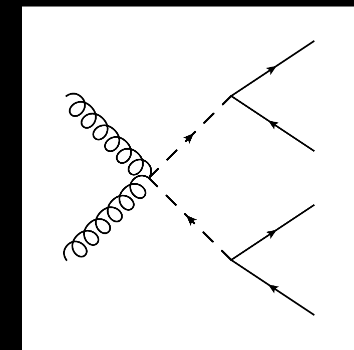


The dominant coupling to the SM is at one loop to gluons!

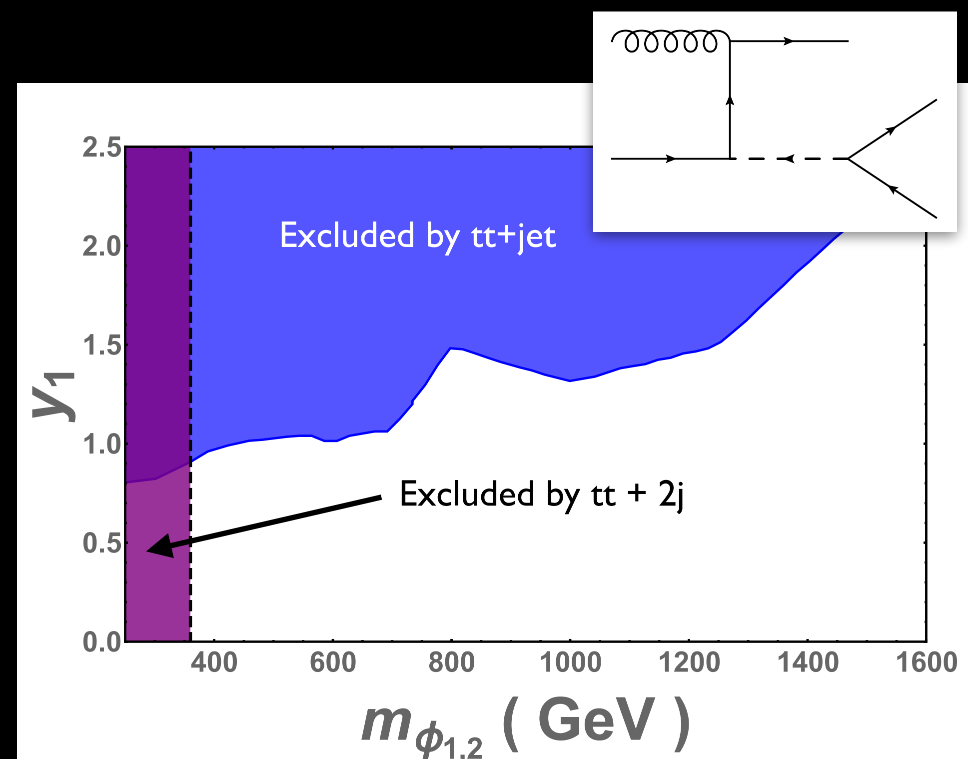


# Mediator Searches

- The physics of the mediators is model-dependent, depending on the color and EW representation.
- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.
- In this case, a MFV theory can be obtained by coupling anti-symmetrically in flavor indices:
$$y\epsilon^{ijk}\phi_i\bar{u}_j u_k^c + h.c.$$
- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints are rather weak.

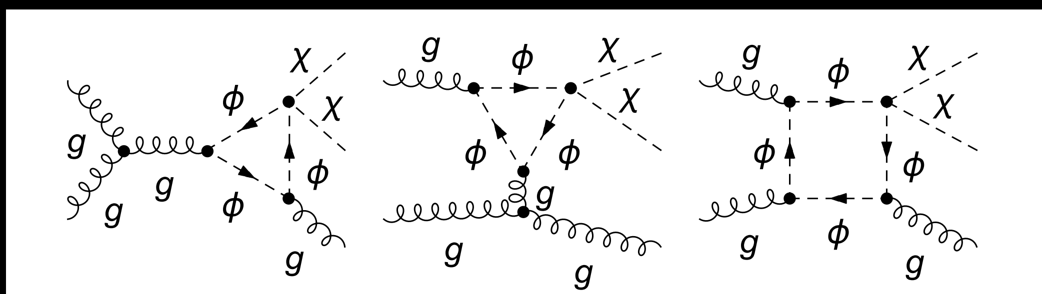


Decays into unflavored jets are bounded by $m_\varphi$ > 350 GeV.

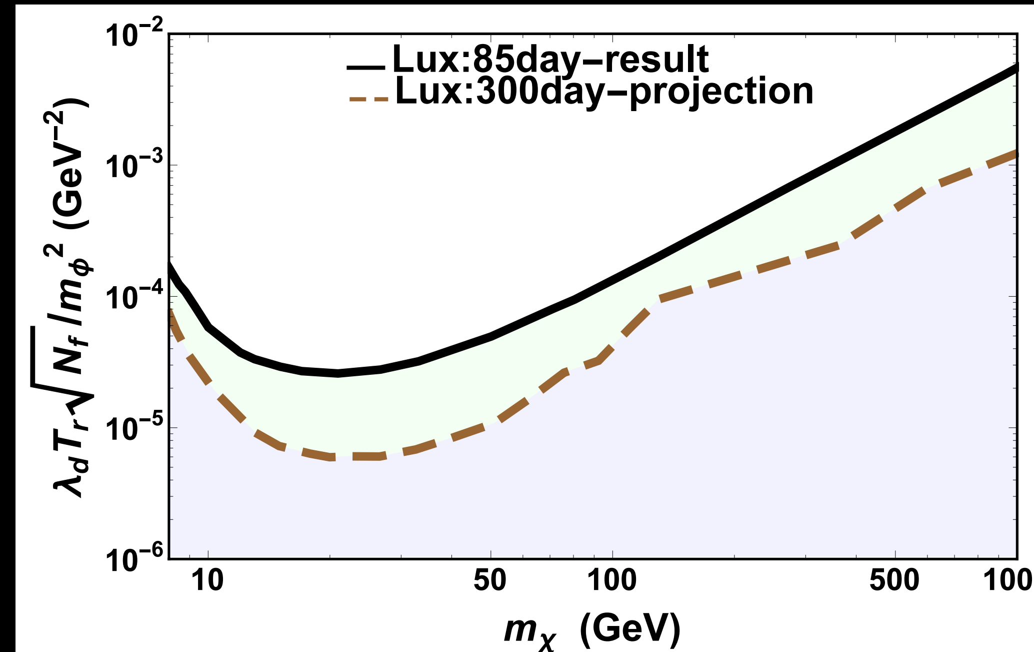


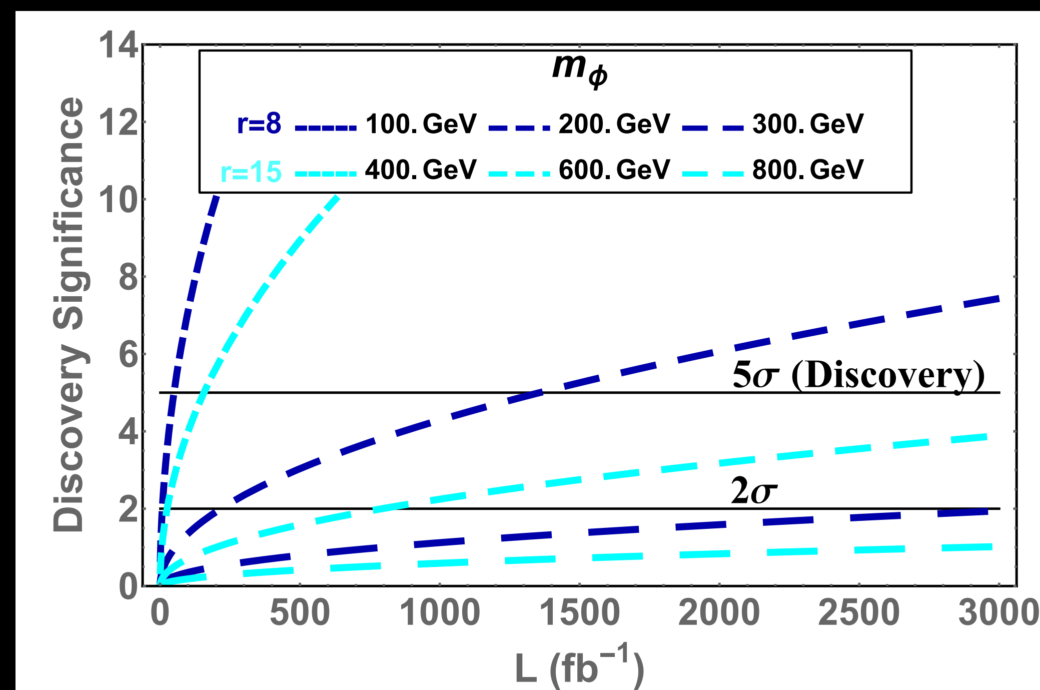
# DM Searches

- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.




- As a result, prospects at the LHC are not particularly hopeful, though for large enough r and λ, it is possible to see something with a very large data set.
- A 100 TeV pp collider would do better…

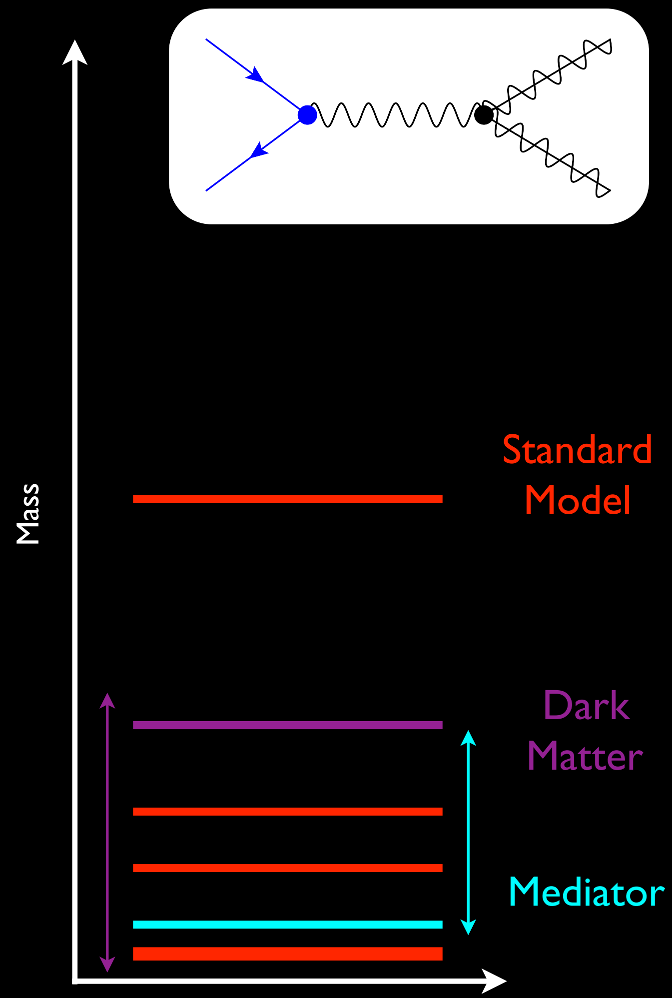


# Ultralight Mediators

# Dark Photons

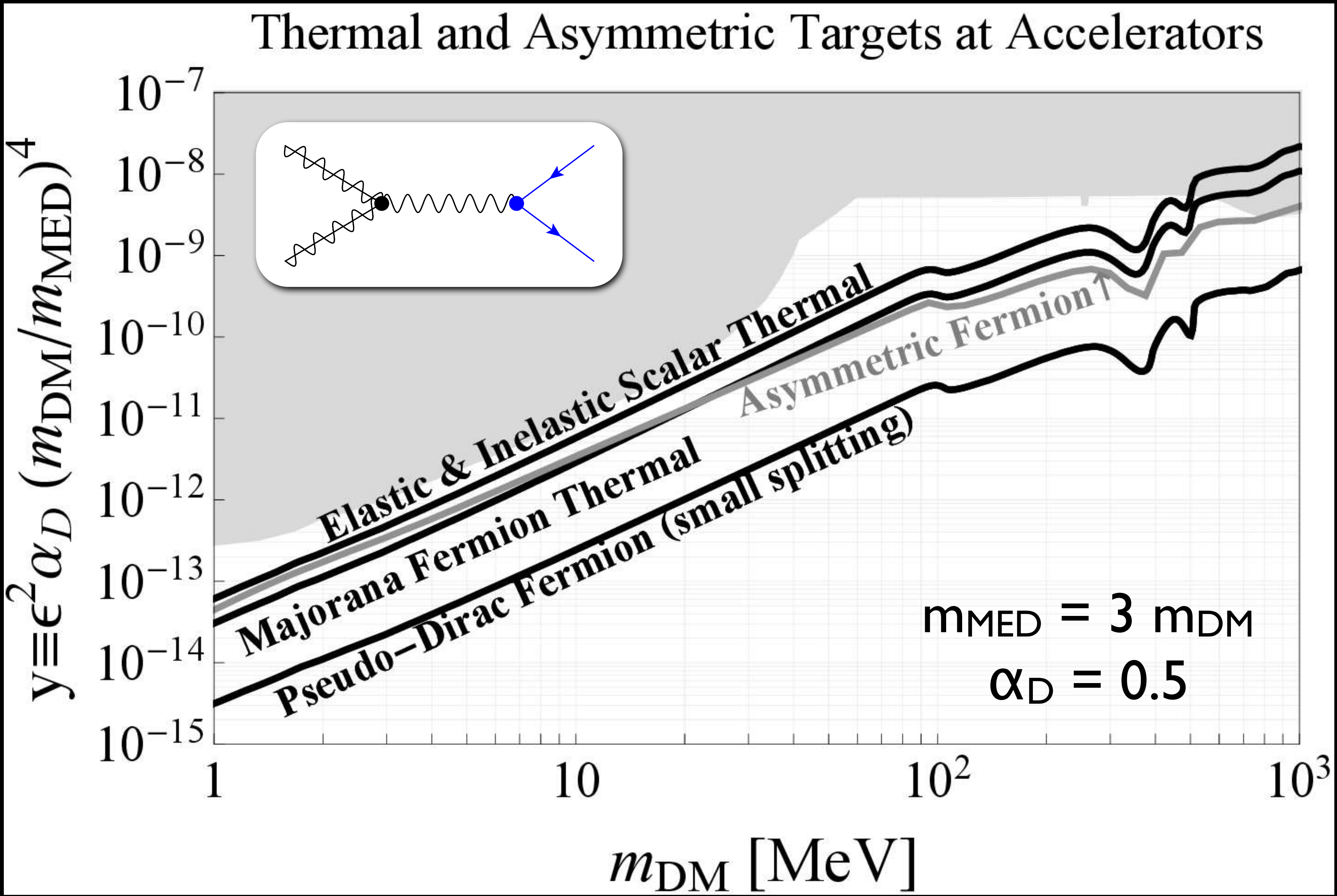
- An interesting part of the parameter space has light mediating particles
- (And maybe light dark matter, as well…)
- In this limit, a natural explanation for the small couplings of the mediator to the standard model is that they come dominantly from kinetic mixing with $U(1)_Y$.
- In this limit, the couplings of the mediator to the SM look like photon couplings scaled down by ε. The mediator in this case is often referred to as a “dark photon”.
- There are other variations with scalars, pseudo-scalars, or vectors with chiral interactions.




**$\gamma_D$ Parameters:**

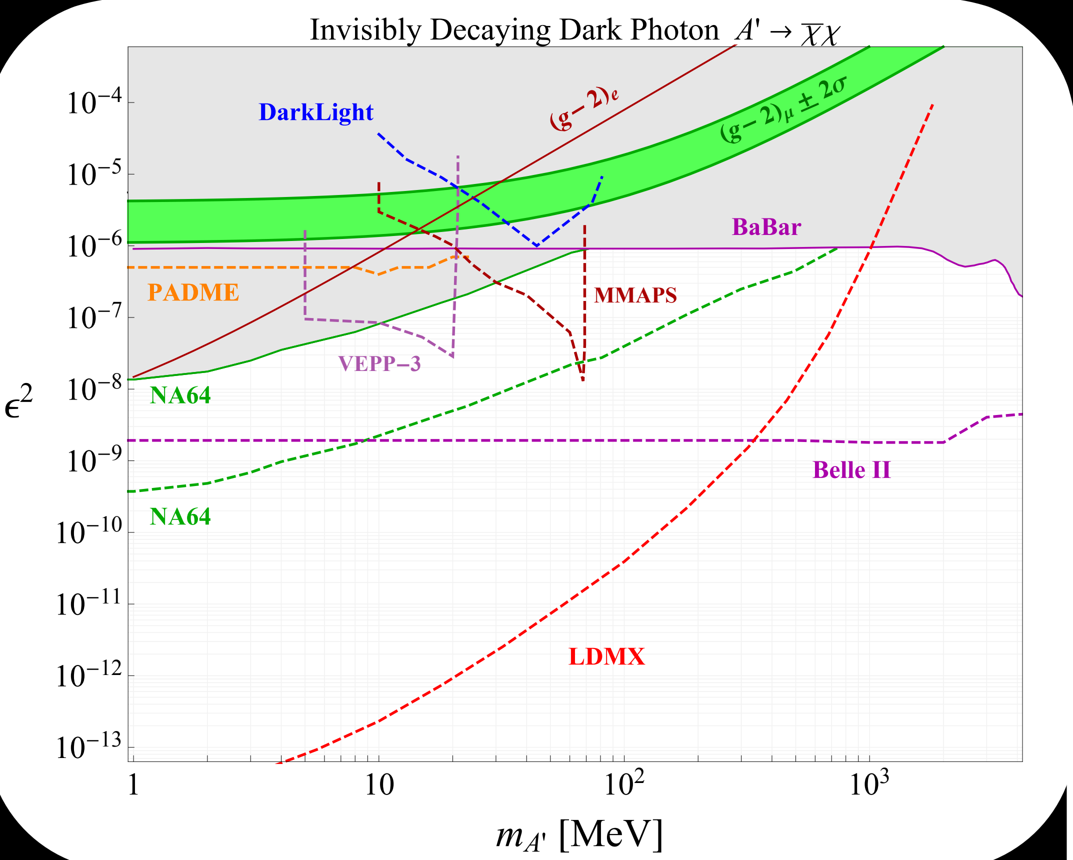
$$\{m_\chi, m_{A'}, \alpha_D, \epsilon\}$$

# MeV Relic Dark Matter

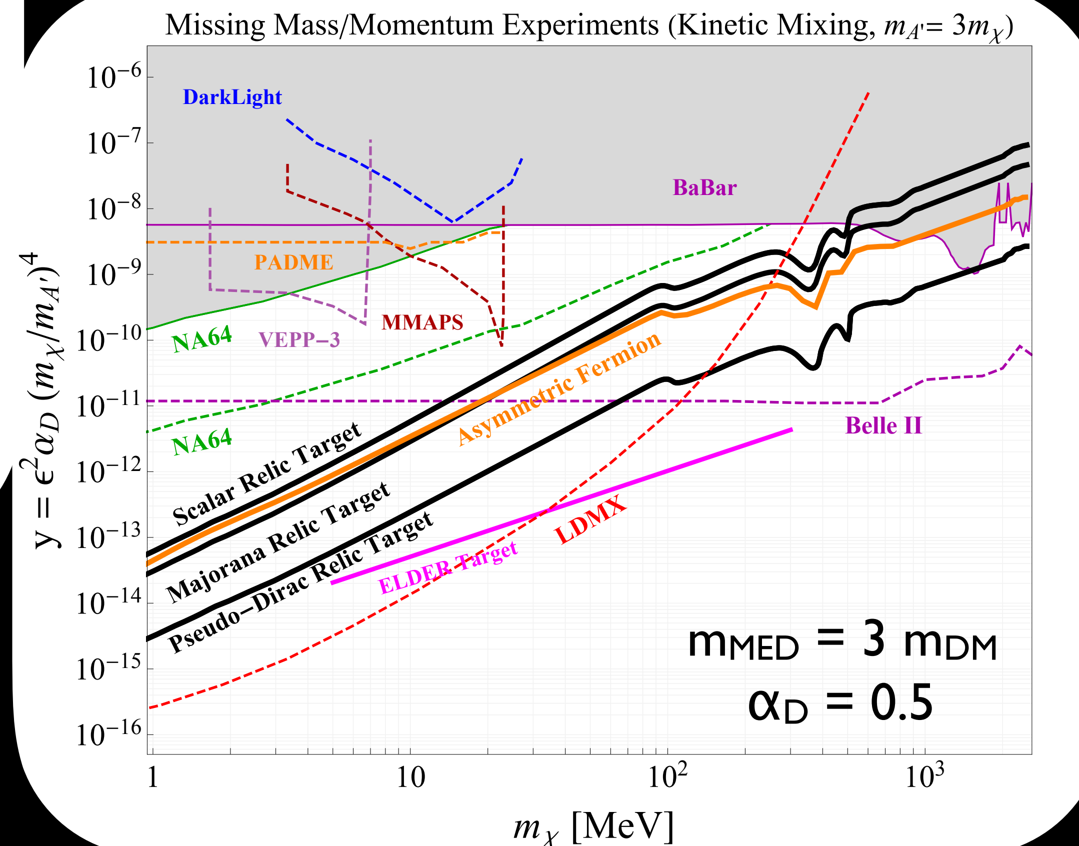



US Cosmic Visions Report
arXiv:1707.04591

# Invisible Searches

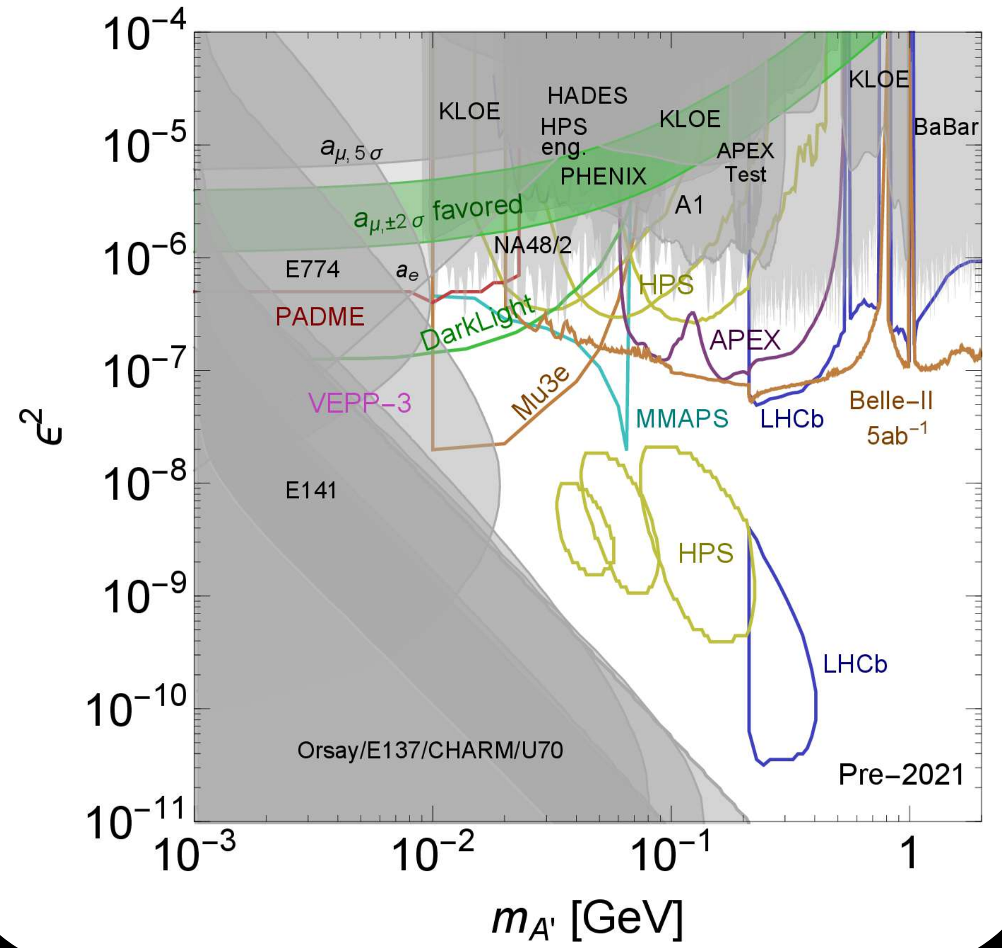



US Cosmic Visions Report
arXiv:1707.04591



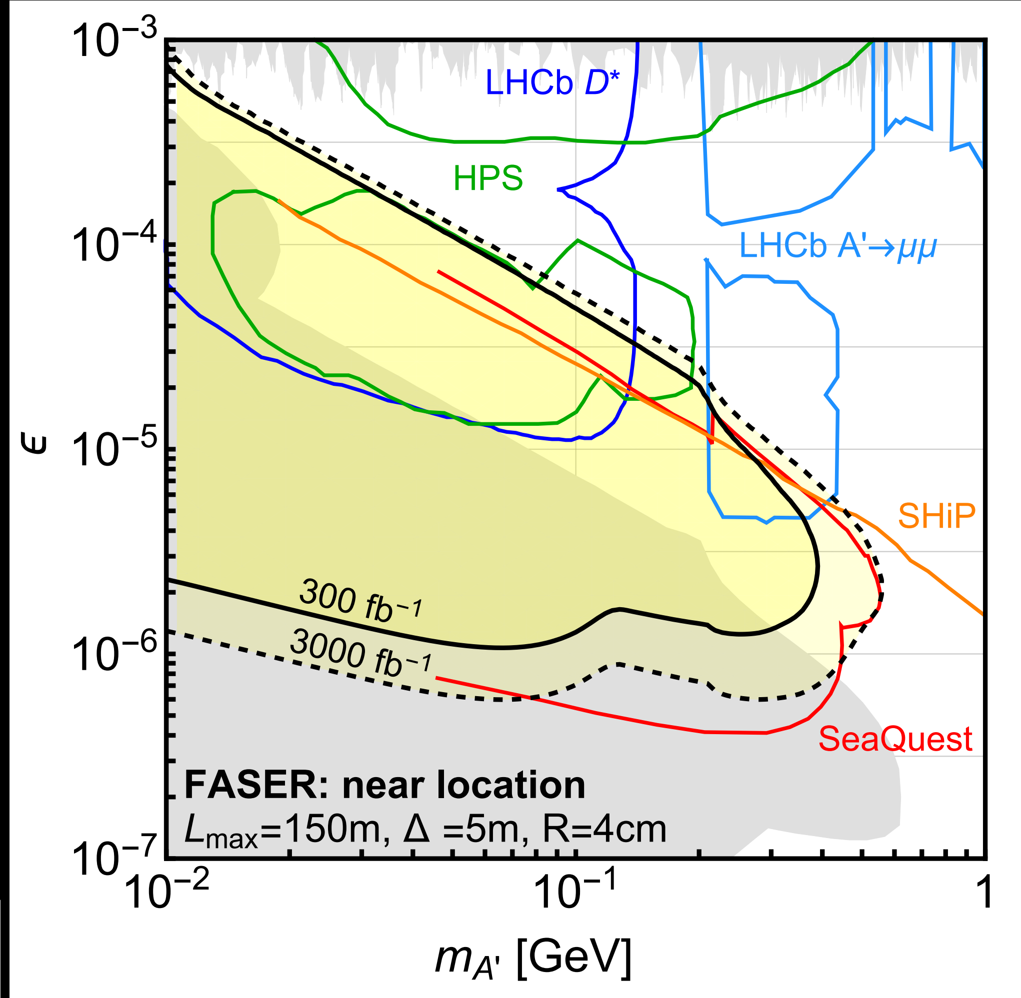

Many projects both underway and proposed can search for mediators decaying (dominantly) invisibly.

# Visible Searches




US Cosmic Visions Report
arXiv:1707.04591

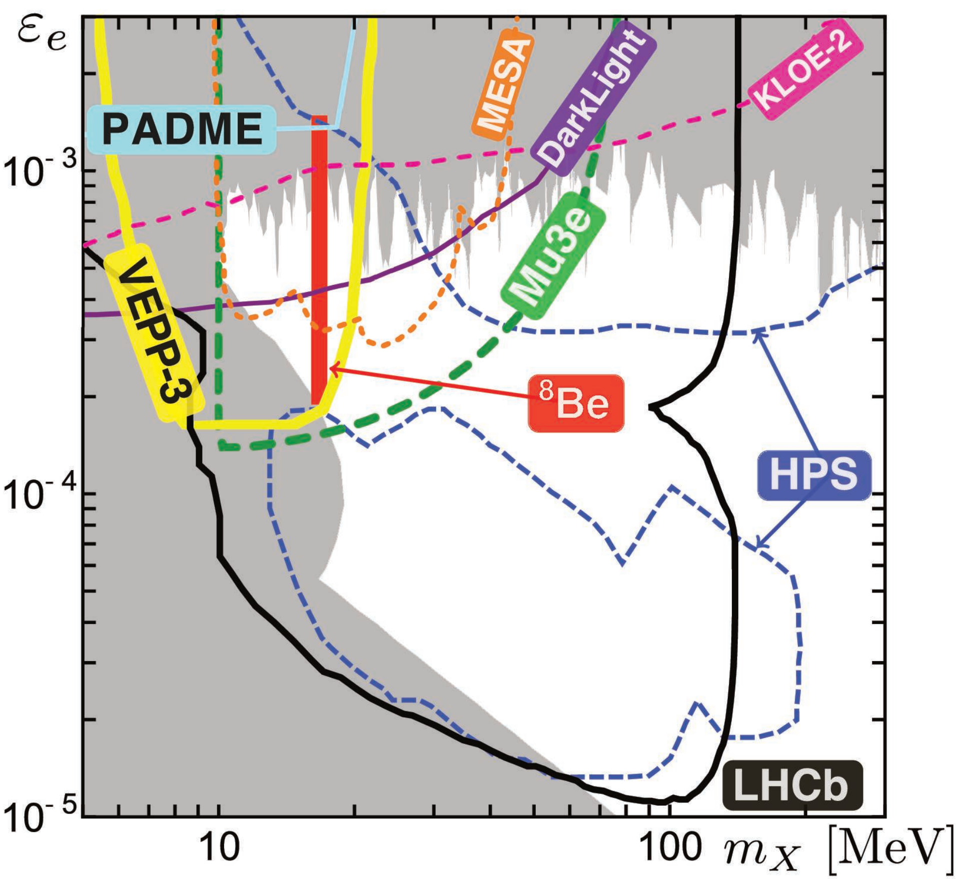
When the dark matter is too heavy, the mediator largely decays visibly into SM states.

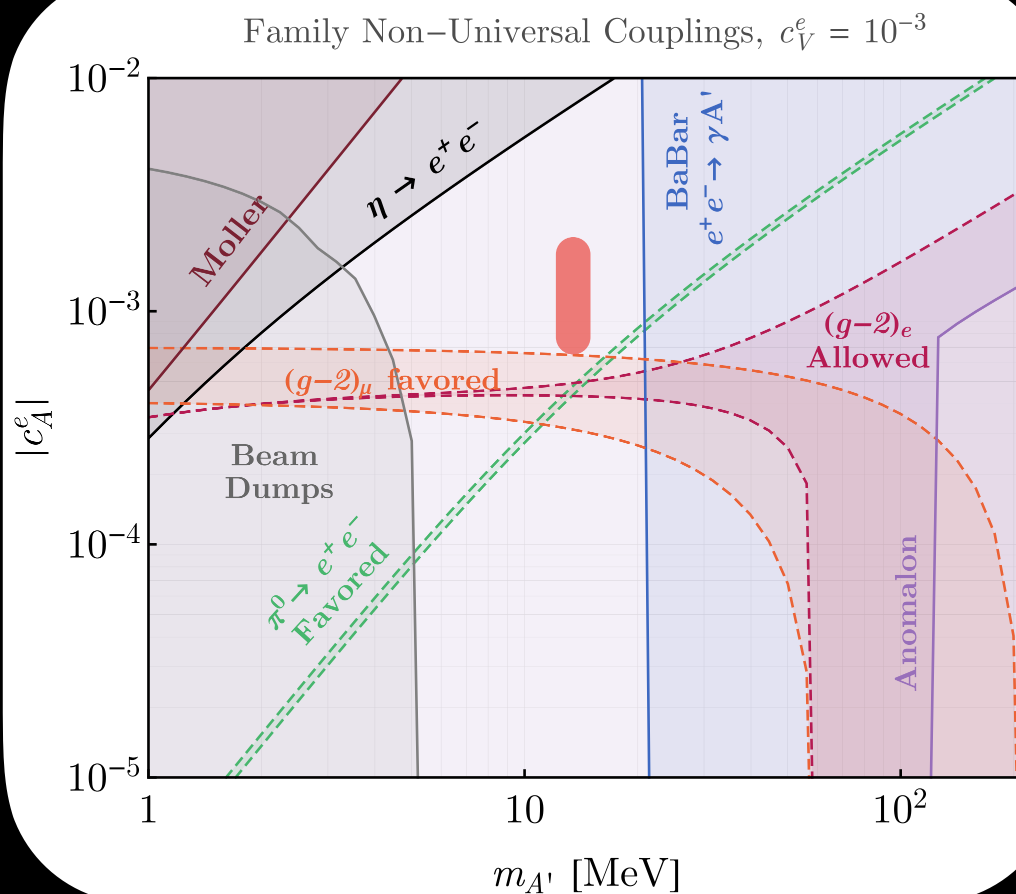



Feng, Galon, Kling, Trojanowski
arXiv:1707.04591

# Beyond Dark Photons

Proto-phobic vector couplings to address the Be-8 anomaly.




Vector particle with chiral interactions

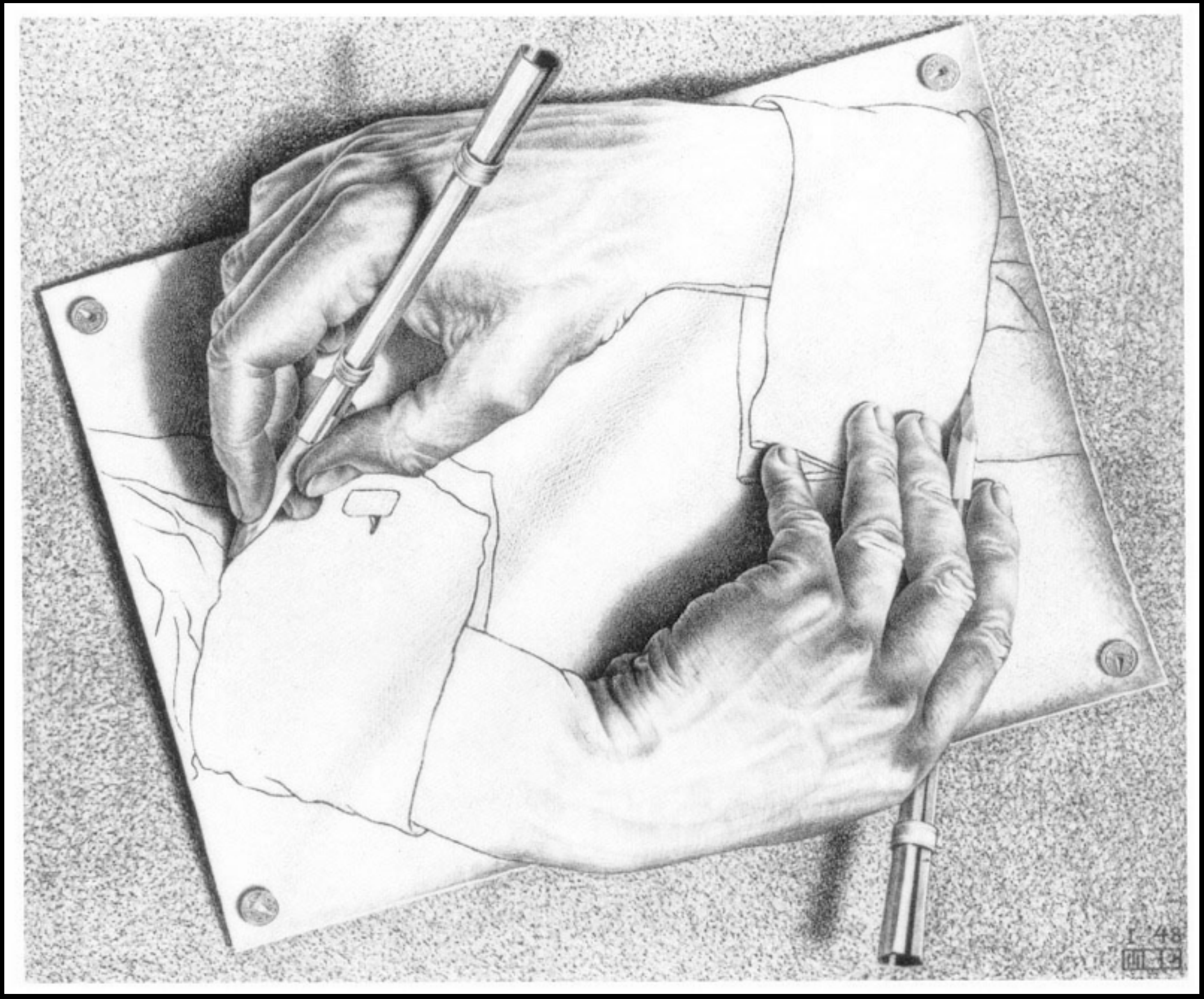
Kahn, Krnjaic, Mishra-Sharma, TMPT
arXiv:1609.09072

Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, TMPT arXiv:1707.04591

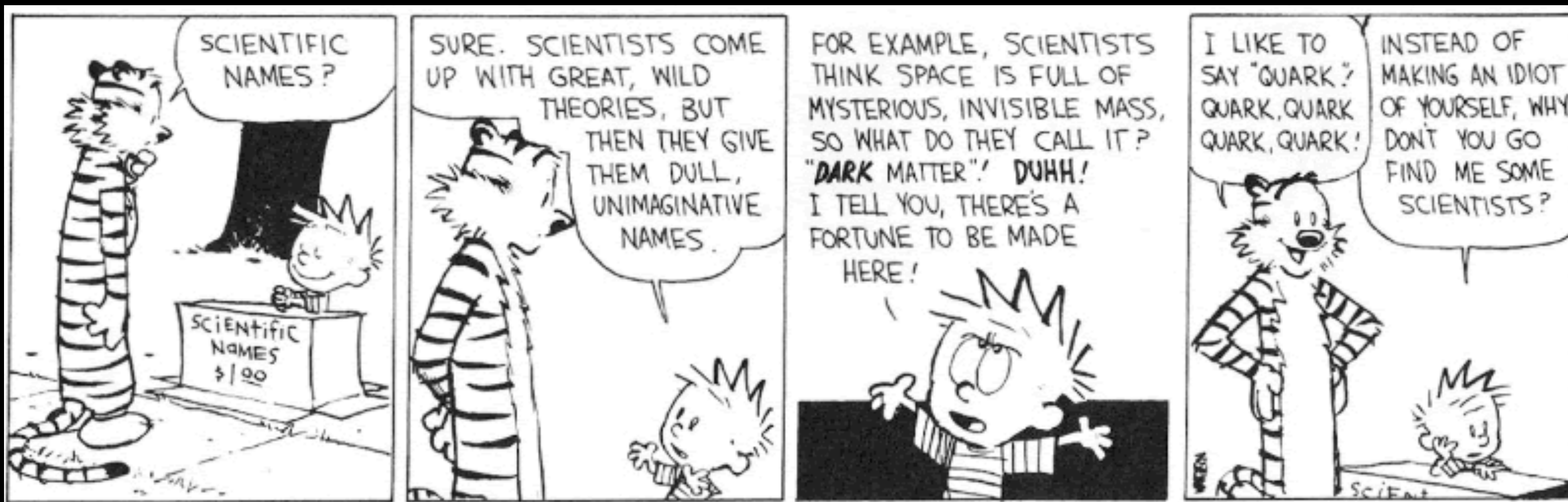
# Outlook

- Accelerators have 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 at the LHC 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.
- Simplified models fill a niche between complete theories like the MSSM and effective field theories which assume the mediators are inaccessible.
- There is a rich program being charted to study lighter dark matter and their attendant light mediators which will probe a wide swath of parameter space for natural relic particles in this regime.
- Theoretical constructions reveal the importance of accelerators for low mass dark matter, low mass mediators, and/or suppressed interactions.
- An observation would start to bring our sketches of theories to life!

# From Sketch to Life



# Sketches of .... ......

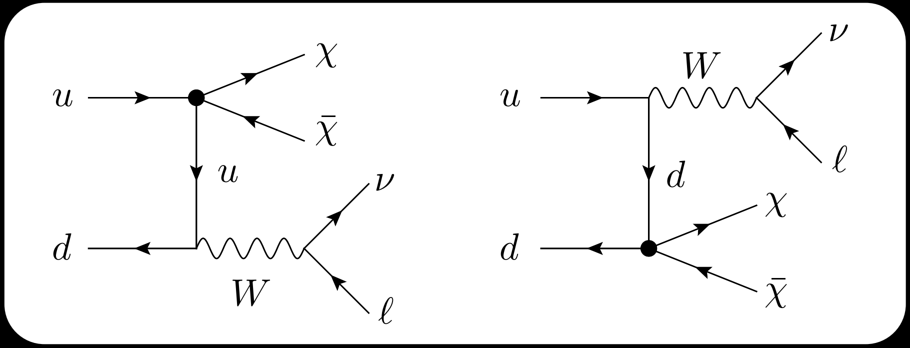


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE 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

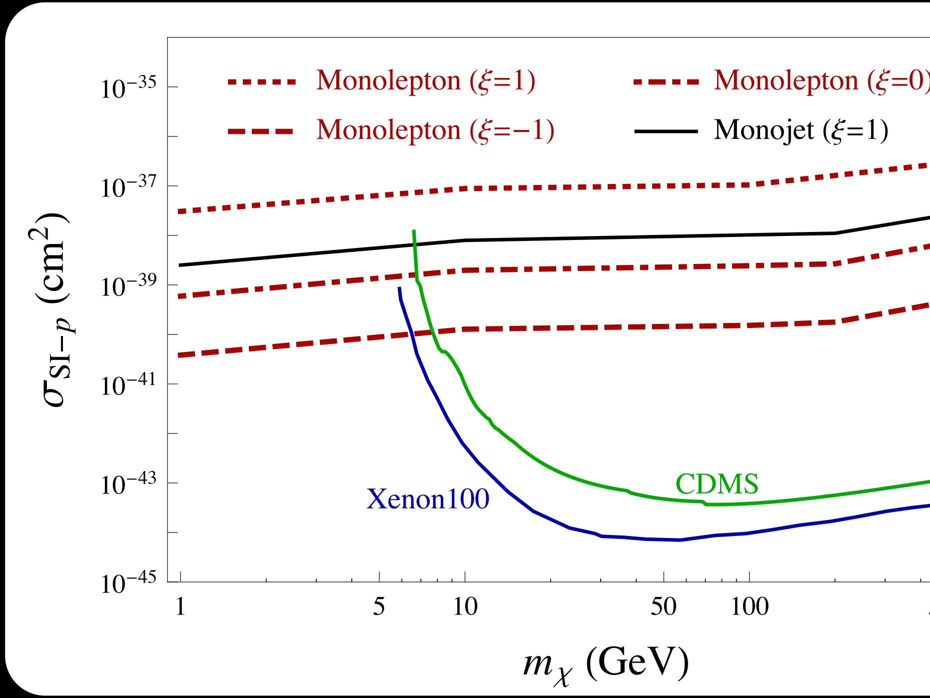
# Mono-Whatever

- 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



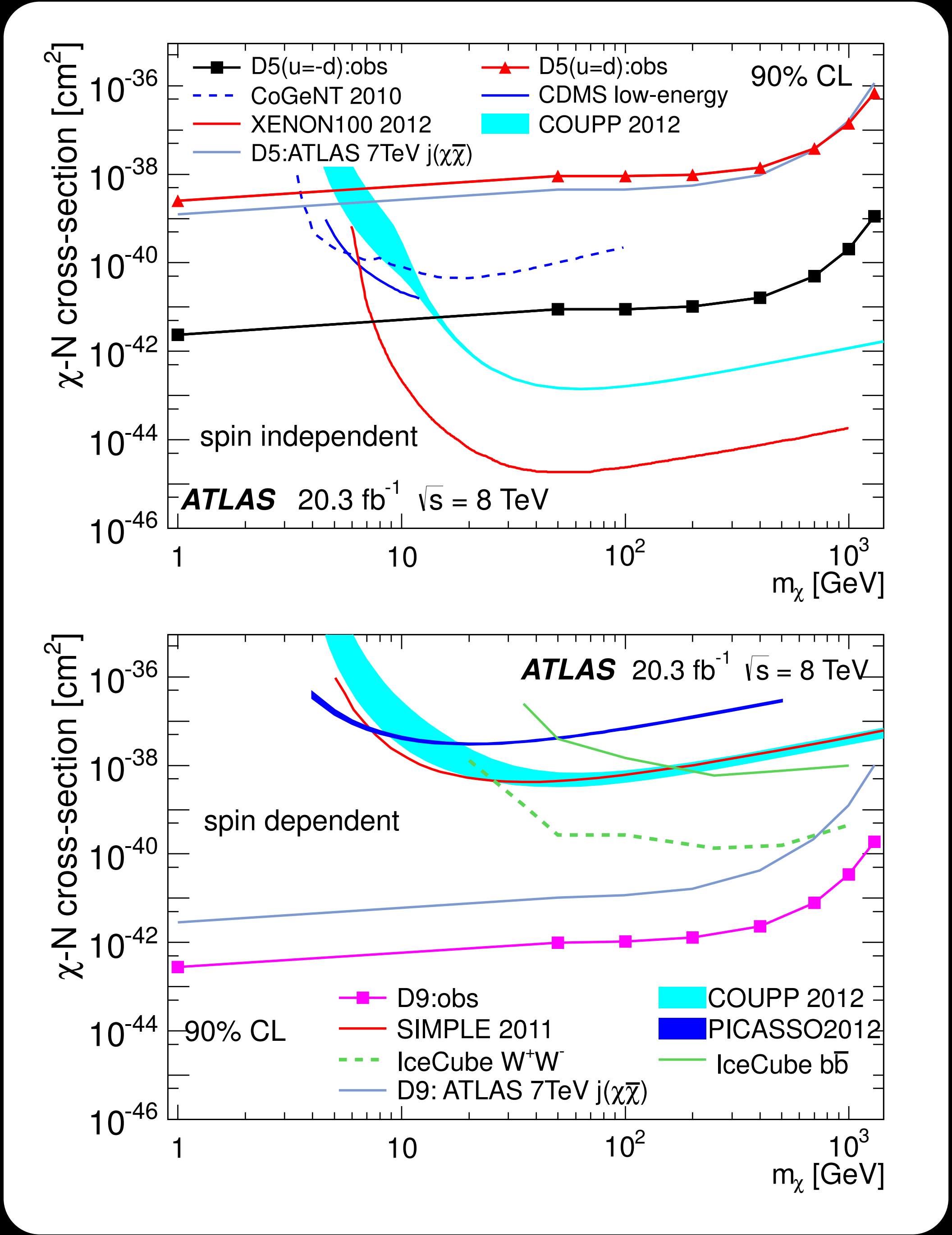

(d coupling) = ξ x (u coupling)

# Jet Substructure!

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

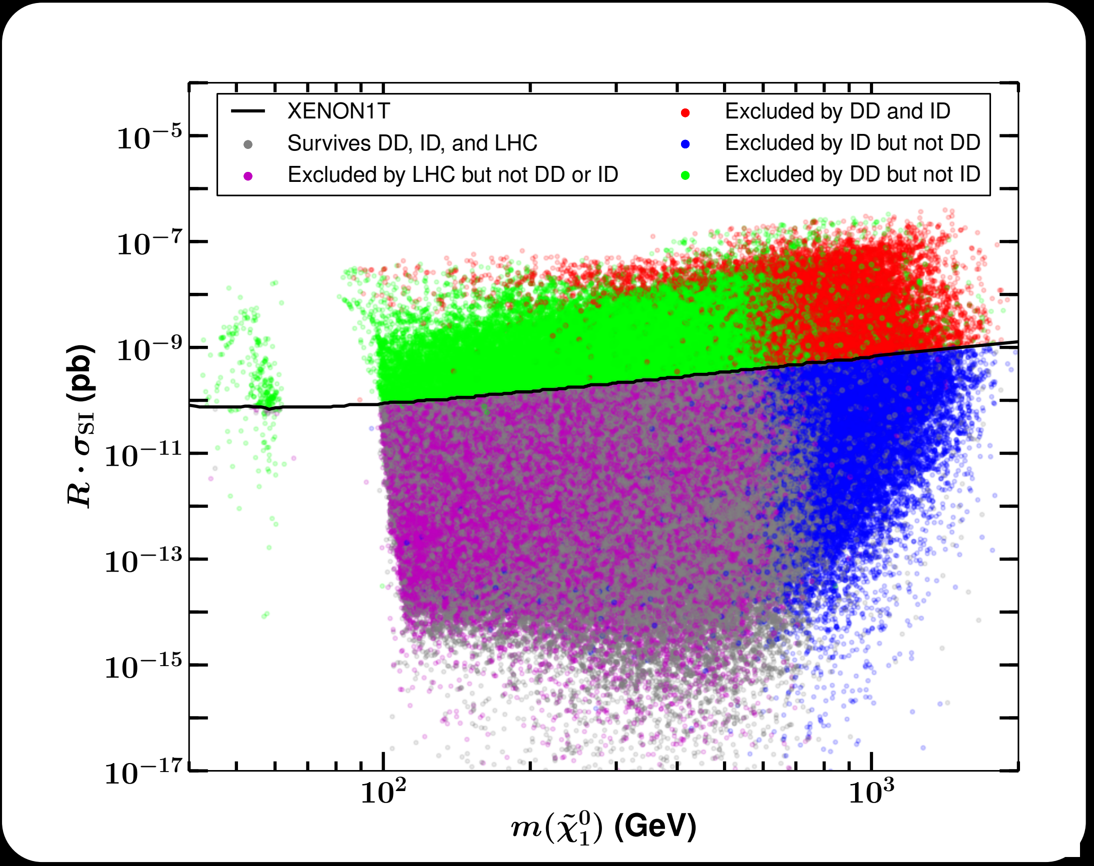
- This helps increase statistics, and ultimately gives a better limit than the lepton channel.

- A recent ATLAS study puts this idea into practice!



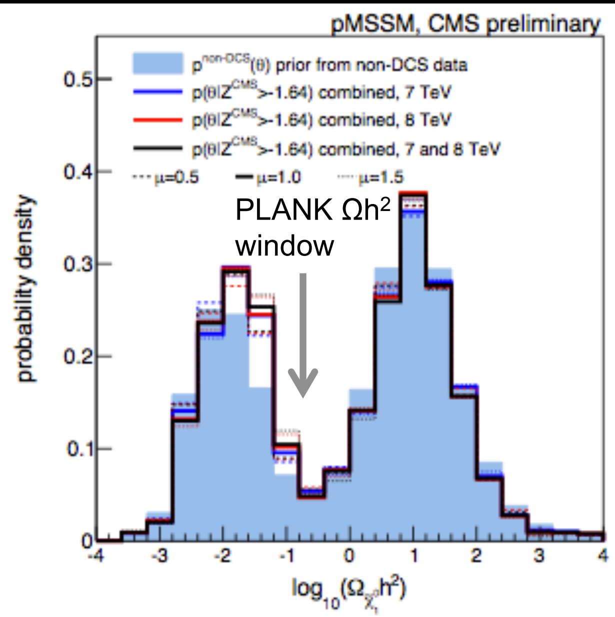
# Supersymmetry: pMSSM

- Interpreting these in the broader scope of SUSY requires a parameterization of the model.
- 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.

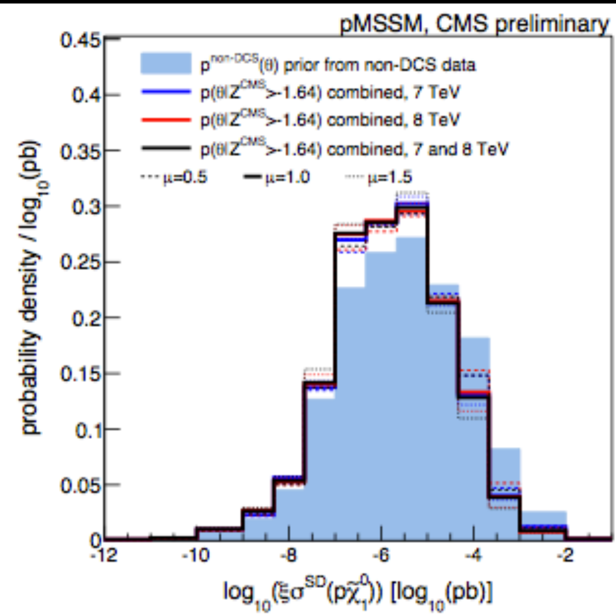



Cahill-Rowley et al, 1305.6921

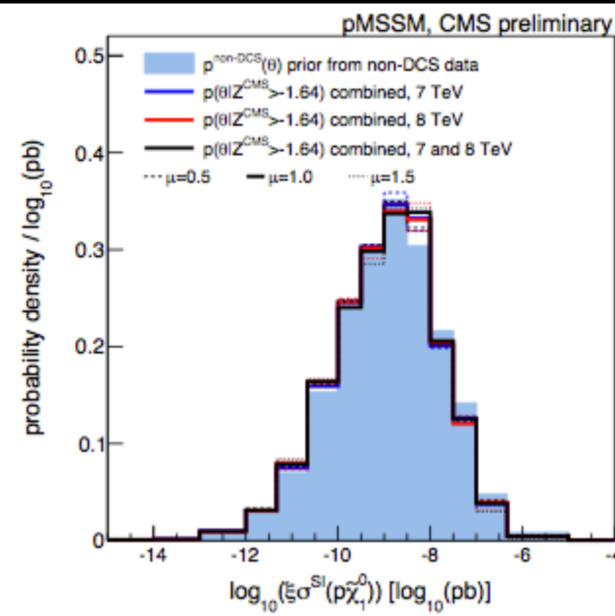
# pMSSM at the LHC




Neutralino relic density




Spin-dependent direct DM detection cross-section

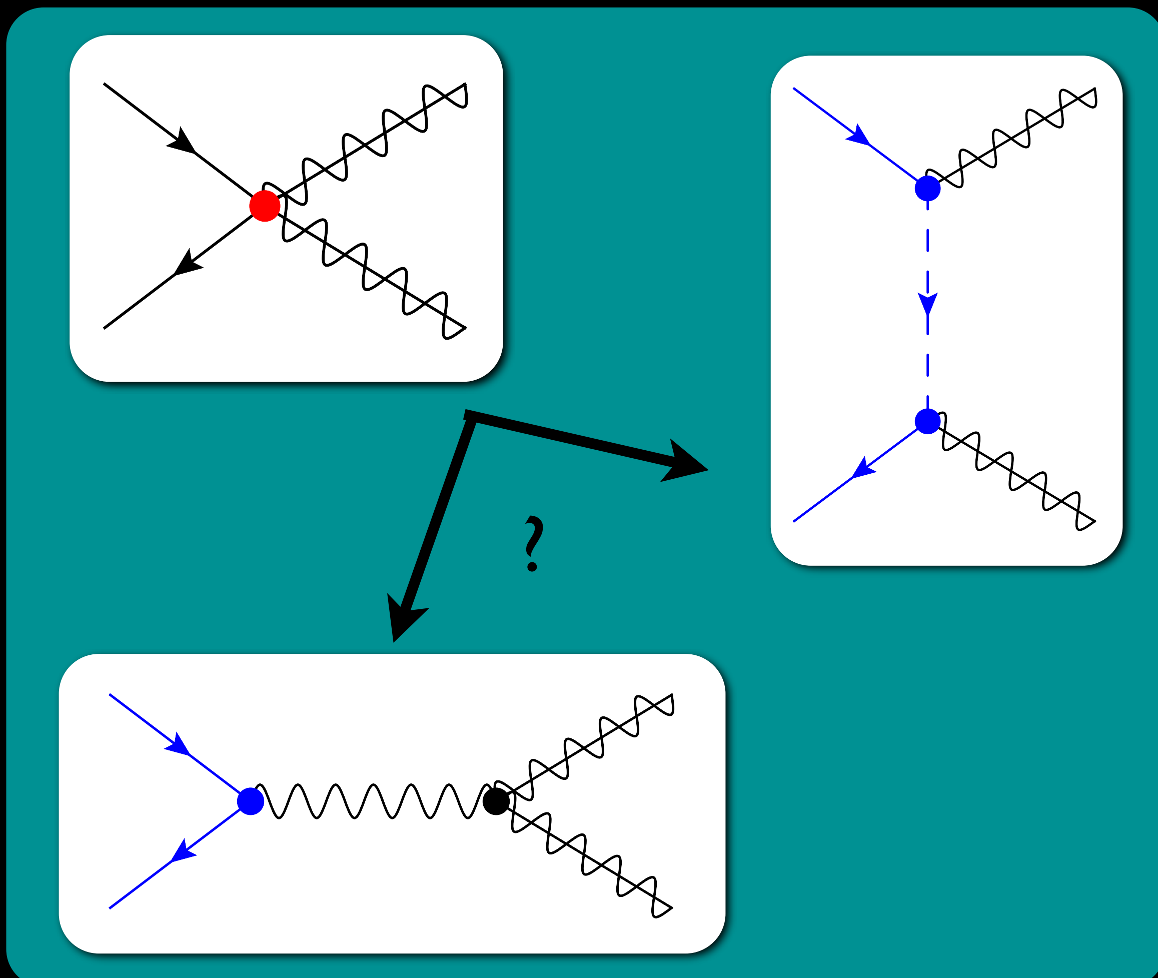



Spin-independent direct DM cross-section

Posterior probabilities give an indication for how dense the coverage is of a given observable for our favorite model.

Note that this depends intimately on the model!

# Simplified Models?

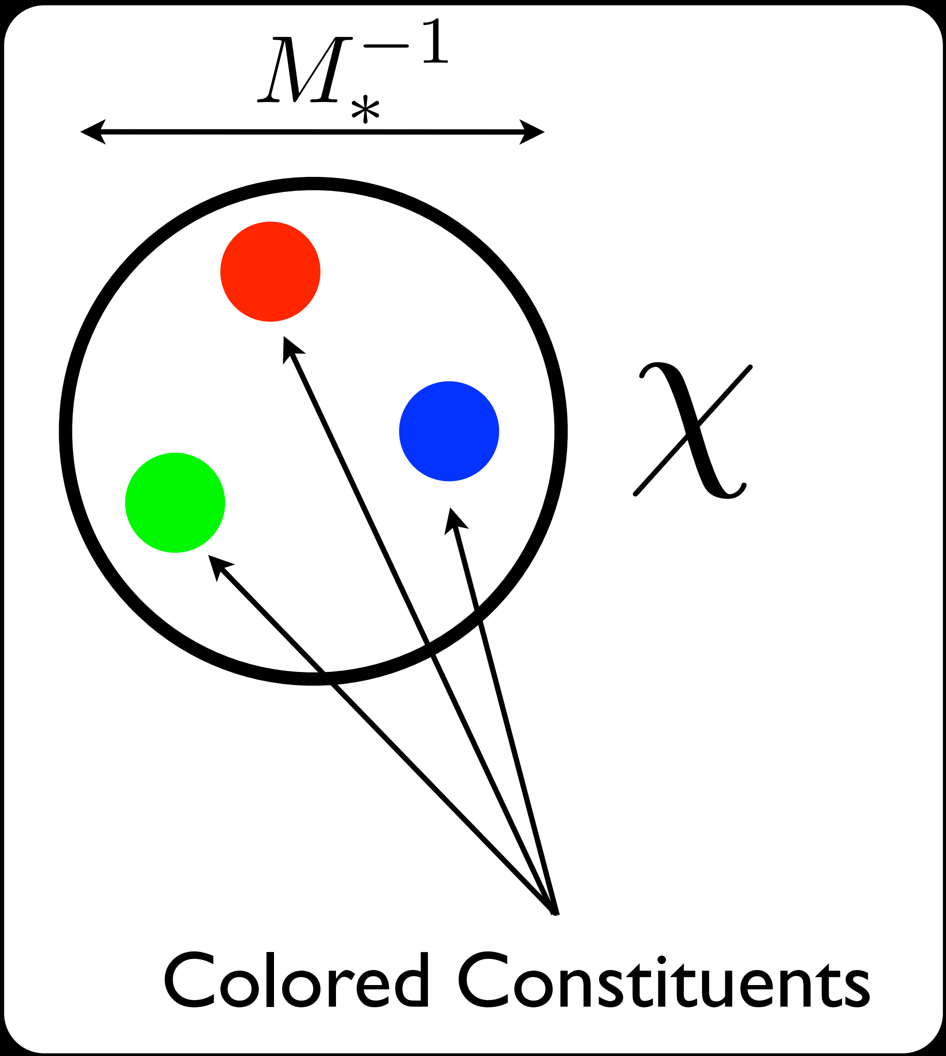



"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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.

One strategy is to try to write down theories with mediators explicitly included.

# A Composite WIMP?




- There are cases where an EFT still says something even when there is no perturbative simplified model that can describe the physics.
- 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.