Dark Matter Phenomenology

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IDM
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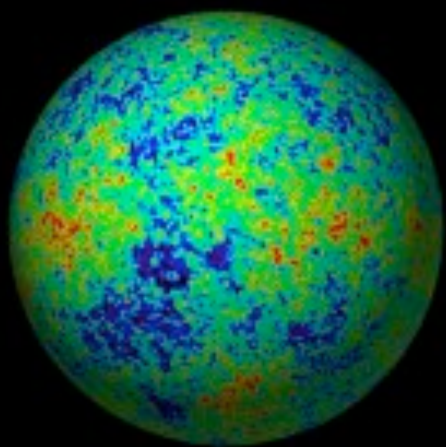
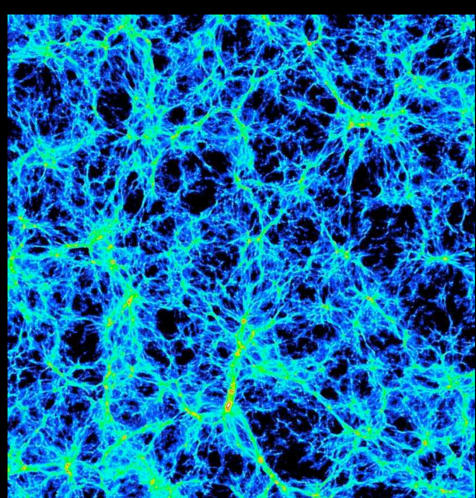
Dark Matter

CMB



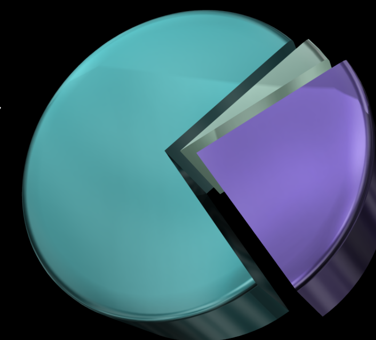
Supernova

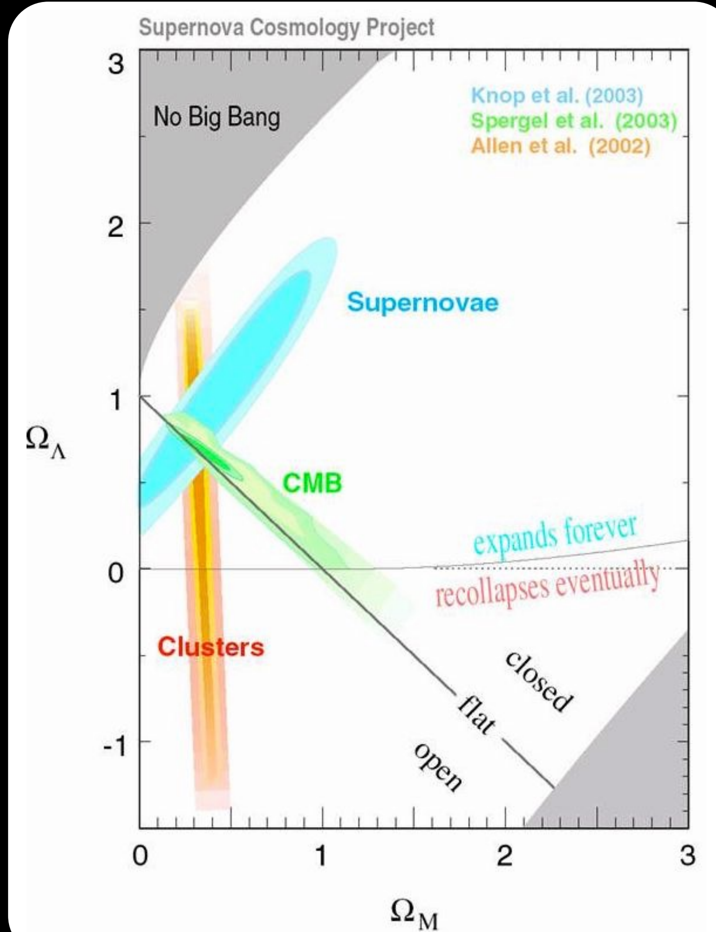


Structure

Lensing

- Ordinary Matter
- Dark Matter
- Dark Energy





So what is this stuff?

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

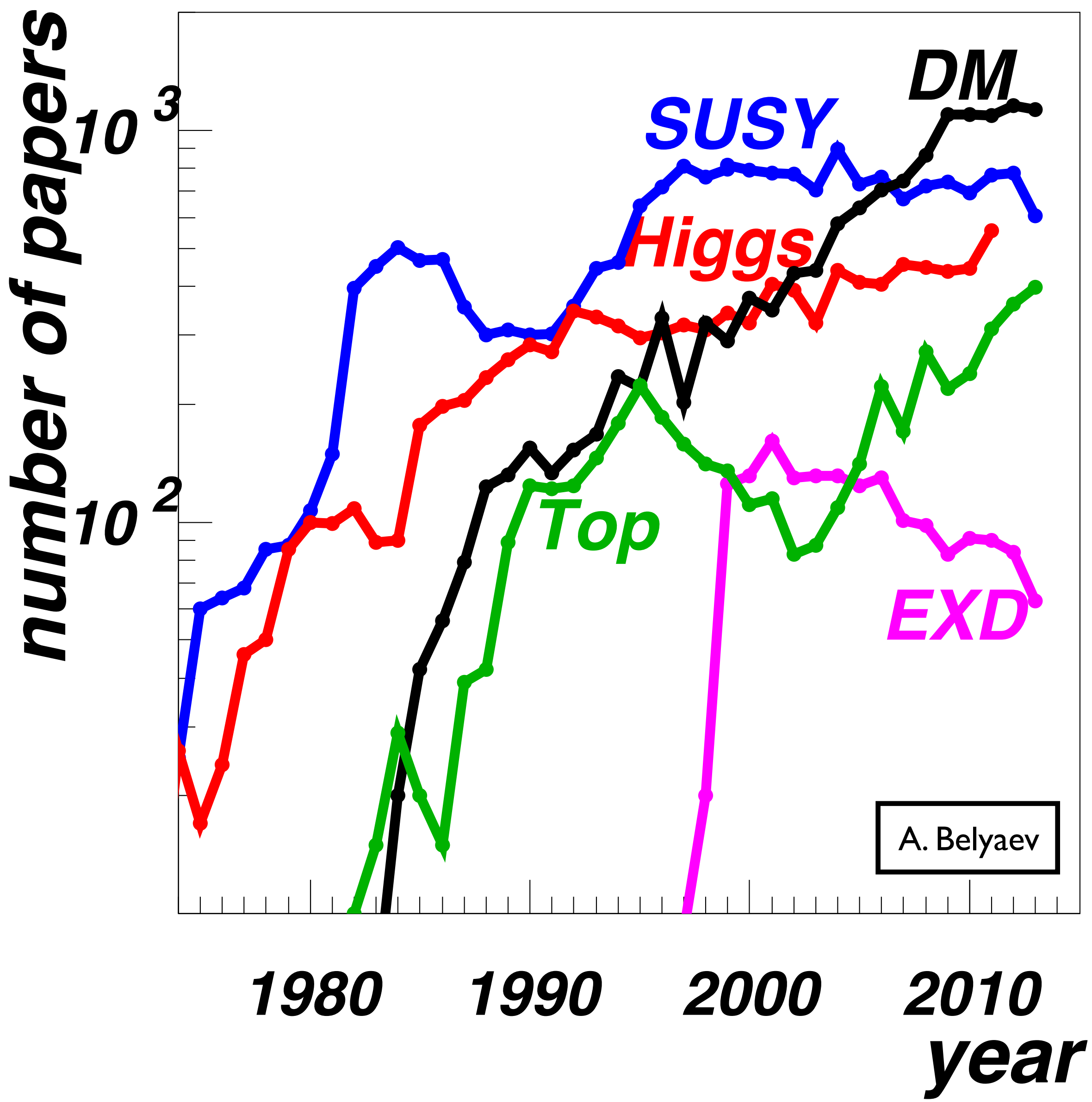
- As a particle physicist, my job is to explore how dark matter fits into the bigger picture of particles.
- What do we know about dark matter?
  - Dark (neutral)
  - Massive
  - Still around today
  - Stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.

The Dark Matter Questionnaire

- Mass: ______
- Spin : ______
- Exactly Stable?
  - Yes
  - No

Couplings:

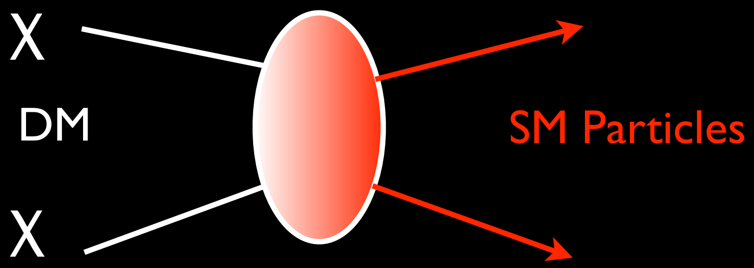
- ✔ Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons?
- Leptons?
- Self-Interacting?
- Cosmological Production

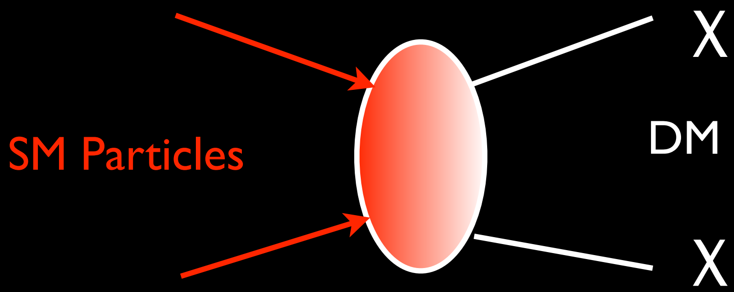


number of papers
10^3
10^2
DM
SUSY
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year

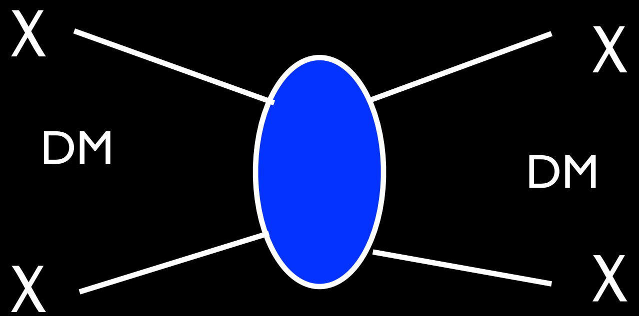
DM Phenomena

Indirect Detection

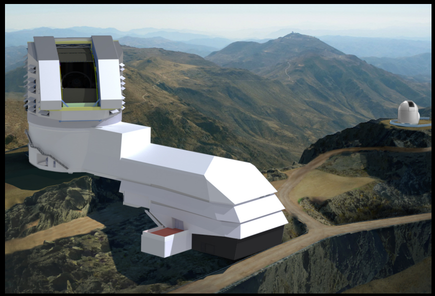




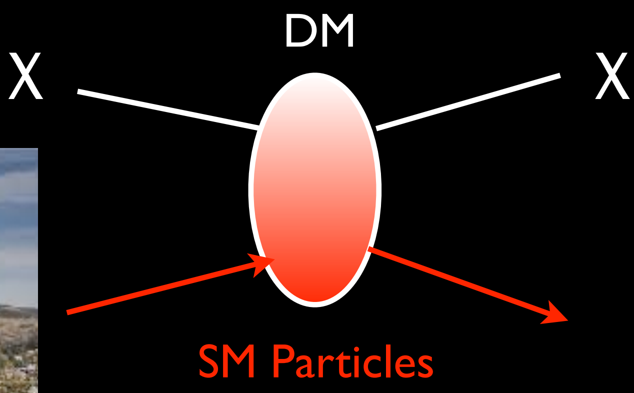
Collider Searches



Self-Interactions

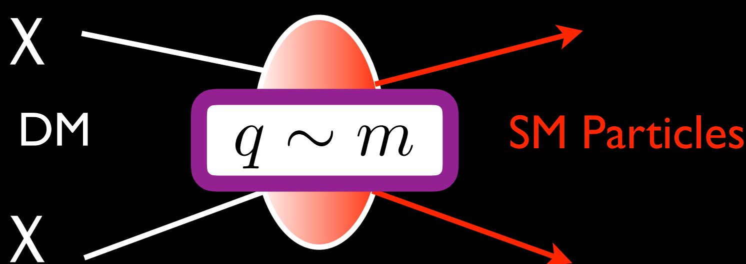


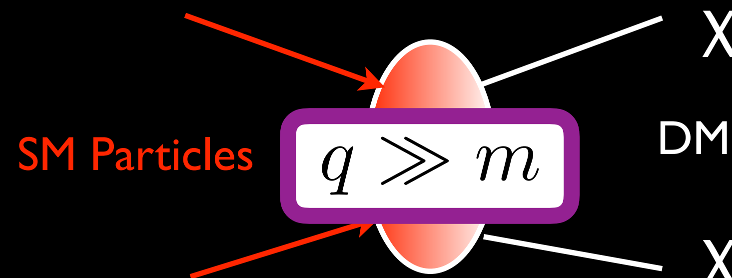
Direct Detection



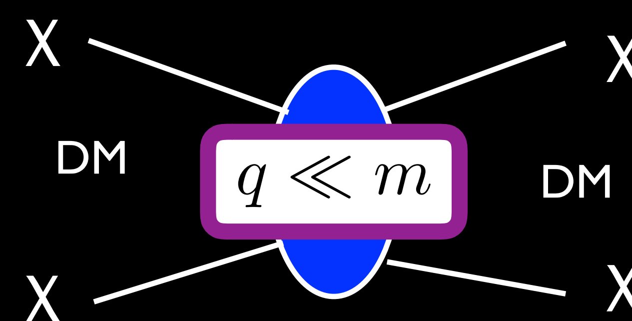
DM Phenomena

Indirect Detection

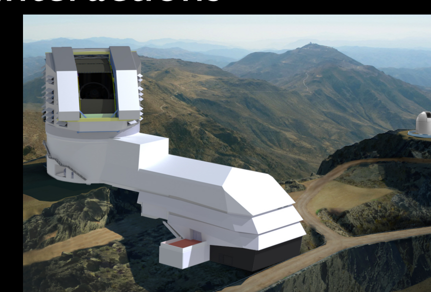




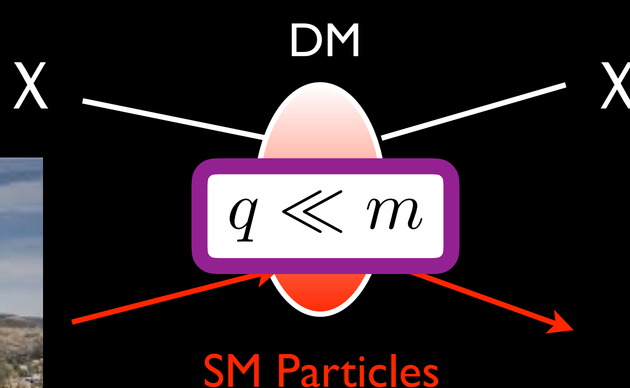
Collider Searches



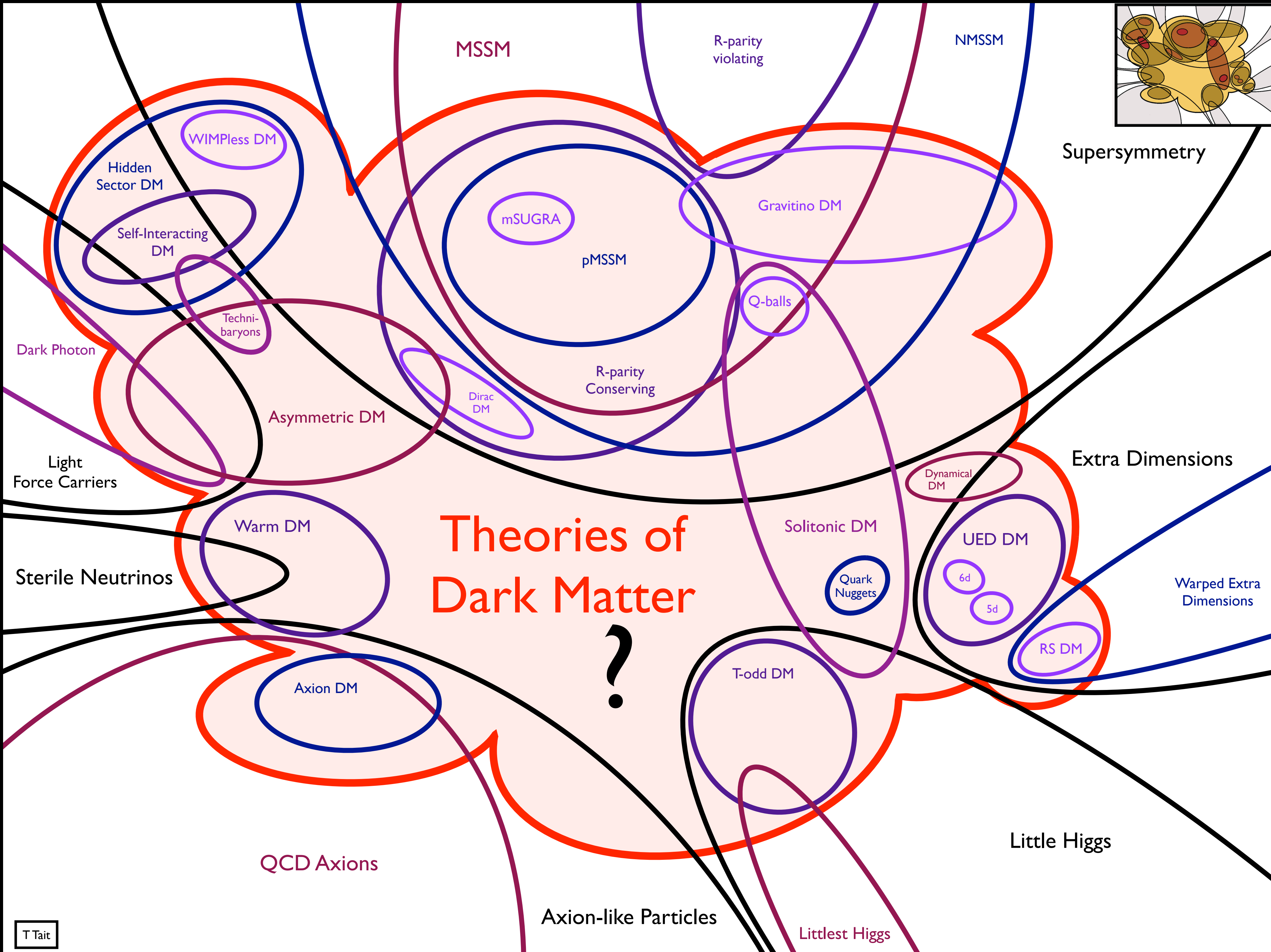
Self-Interactions



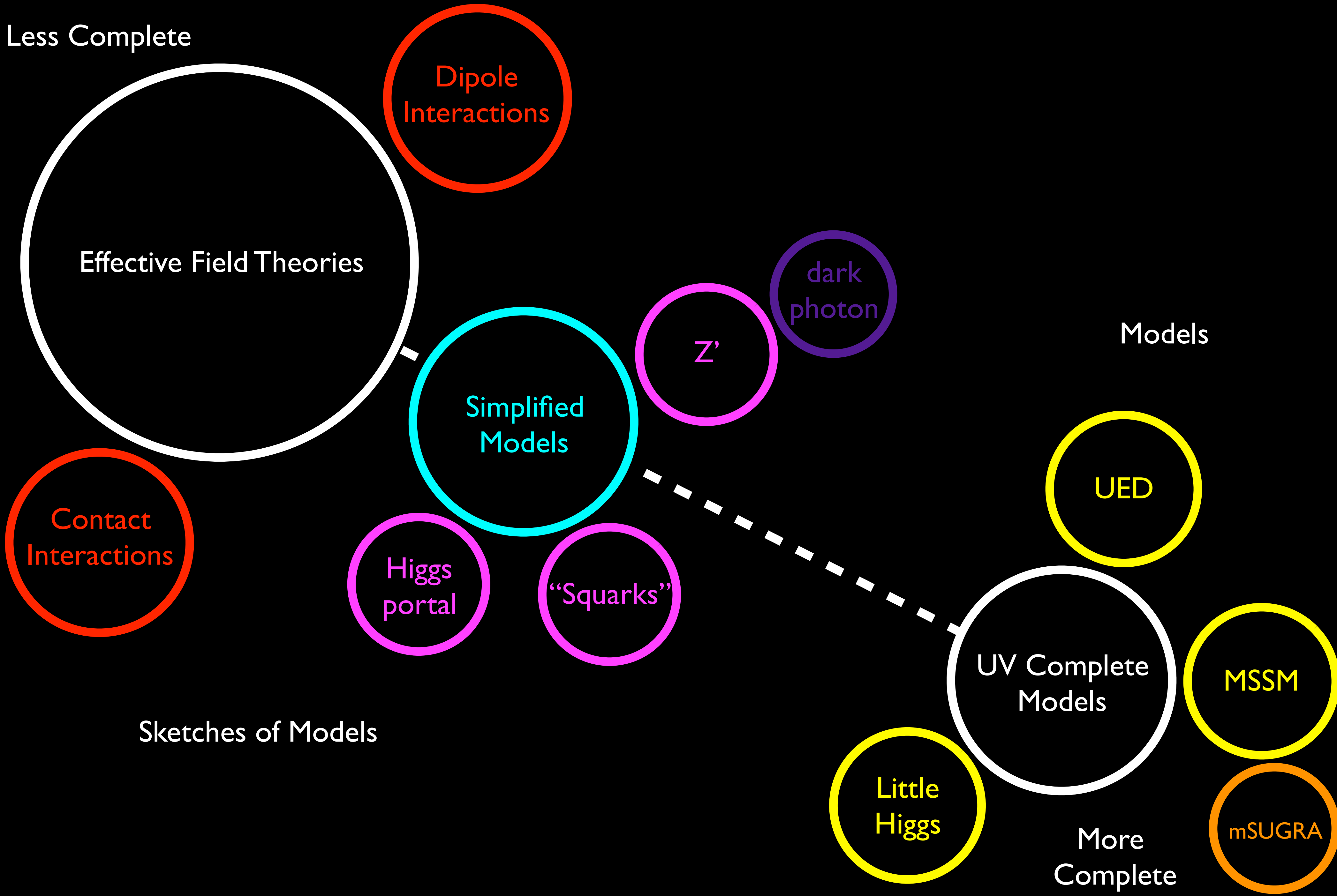
Direct Detection



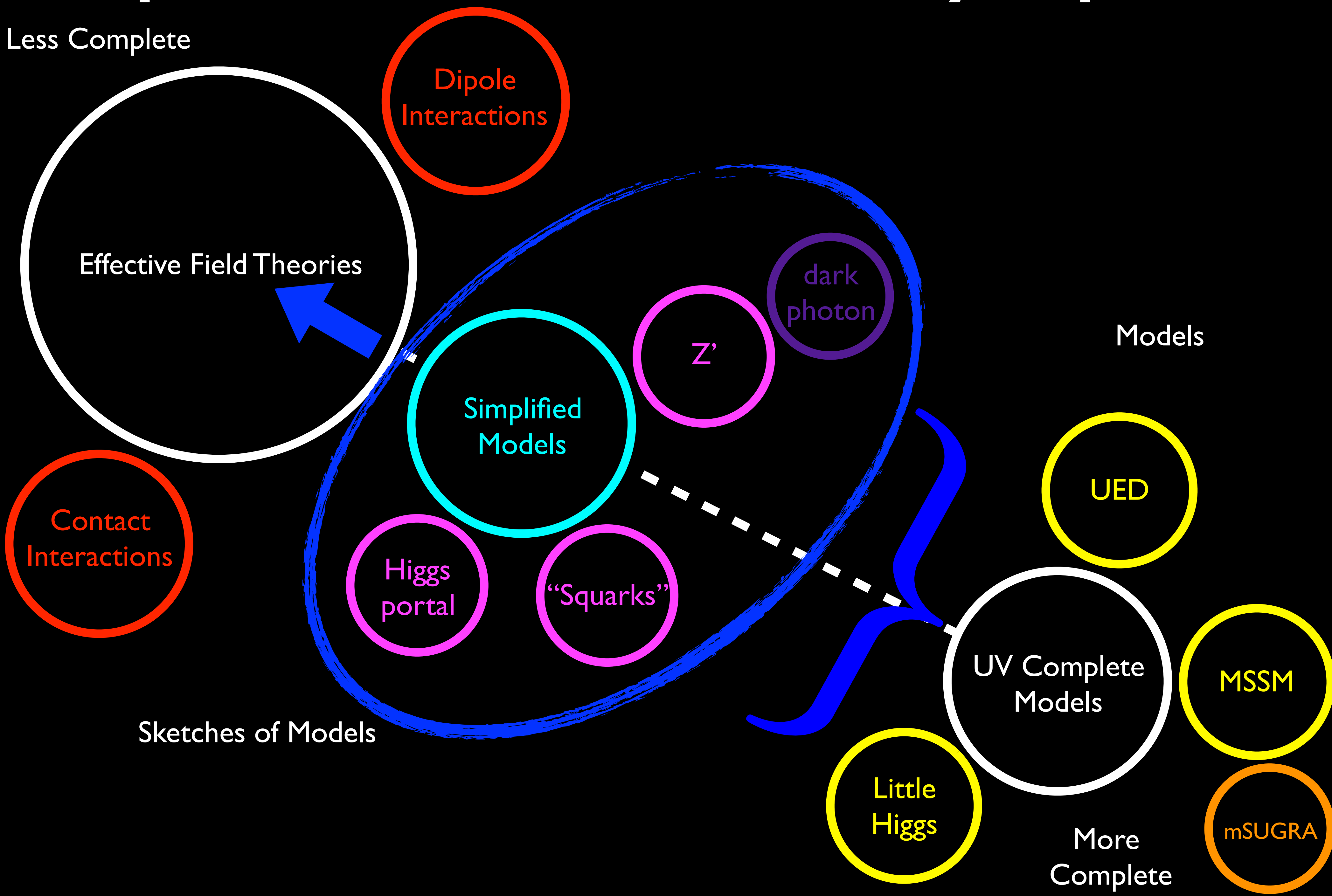
Which one matters
depends on the theory….


Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
Light Force Carriers
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Extra Dimensions
Dynamical DM
Solitonic DM
Warm DM
Sterile Neutrinos
UED DM
6d
5d
Quark Nuggets
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

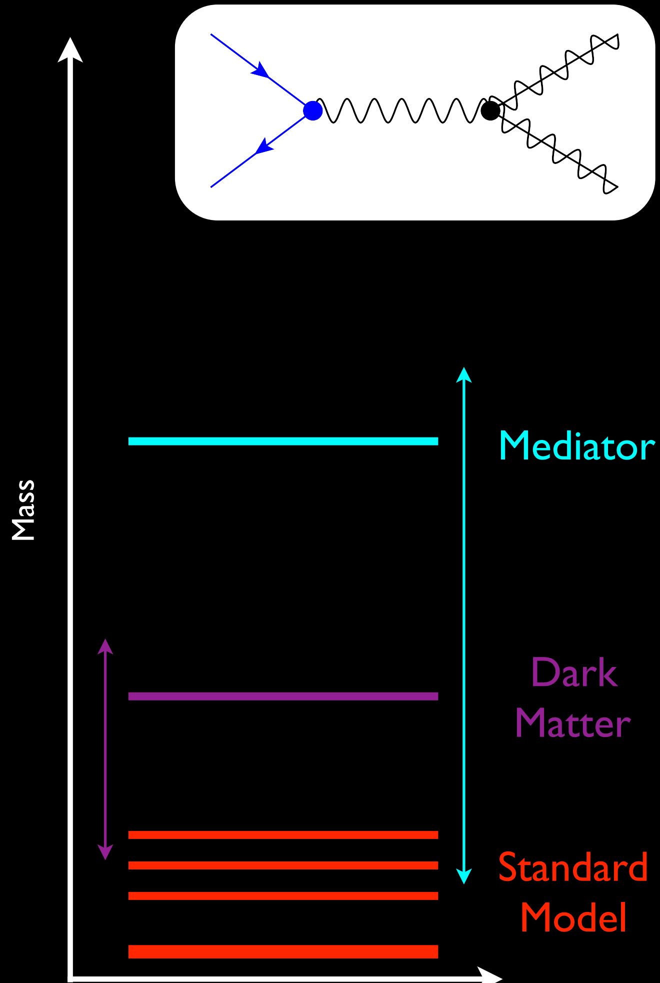


Spectrum of Theory Space



Vector Simplified Model

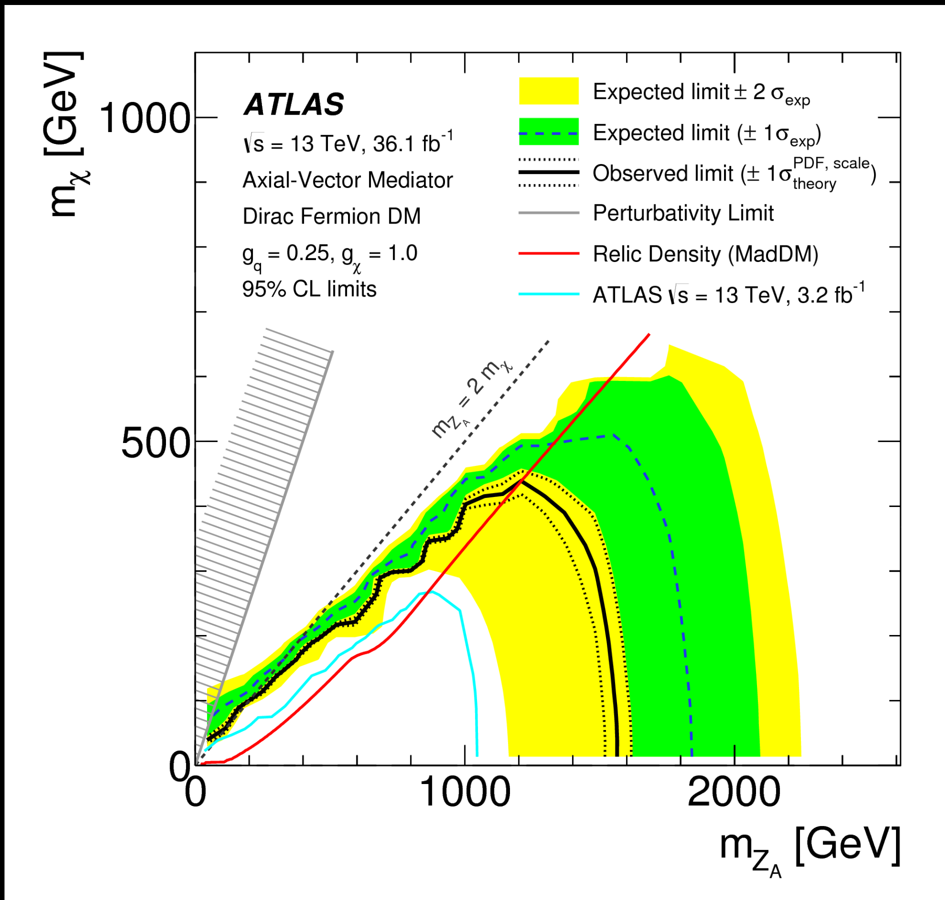
- One simple picture introduces a vector particle as a dark force carrier which couples to both (parts of) the SM and the dark matter.
- Chiral structure (left- versus right-handed) charges for each SM fermion can be very important.
- There could be kinetic mixing with $U(1)_Y$.
- There are theoretical considerations (such as a dark Higgs sector, more particles to cancel gauge anomalies, etc), which are important but may or may not be very important for some searches.

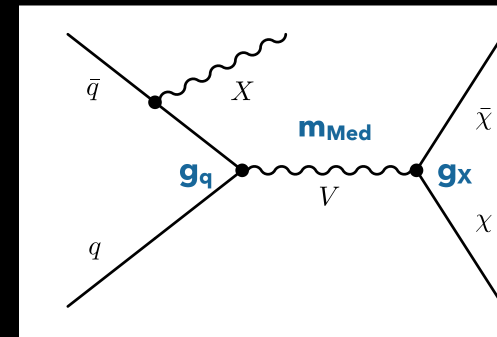


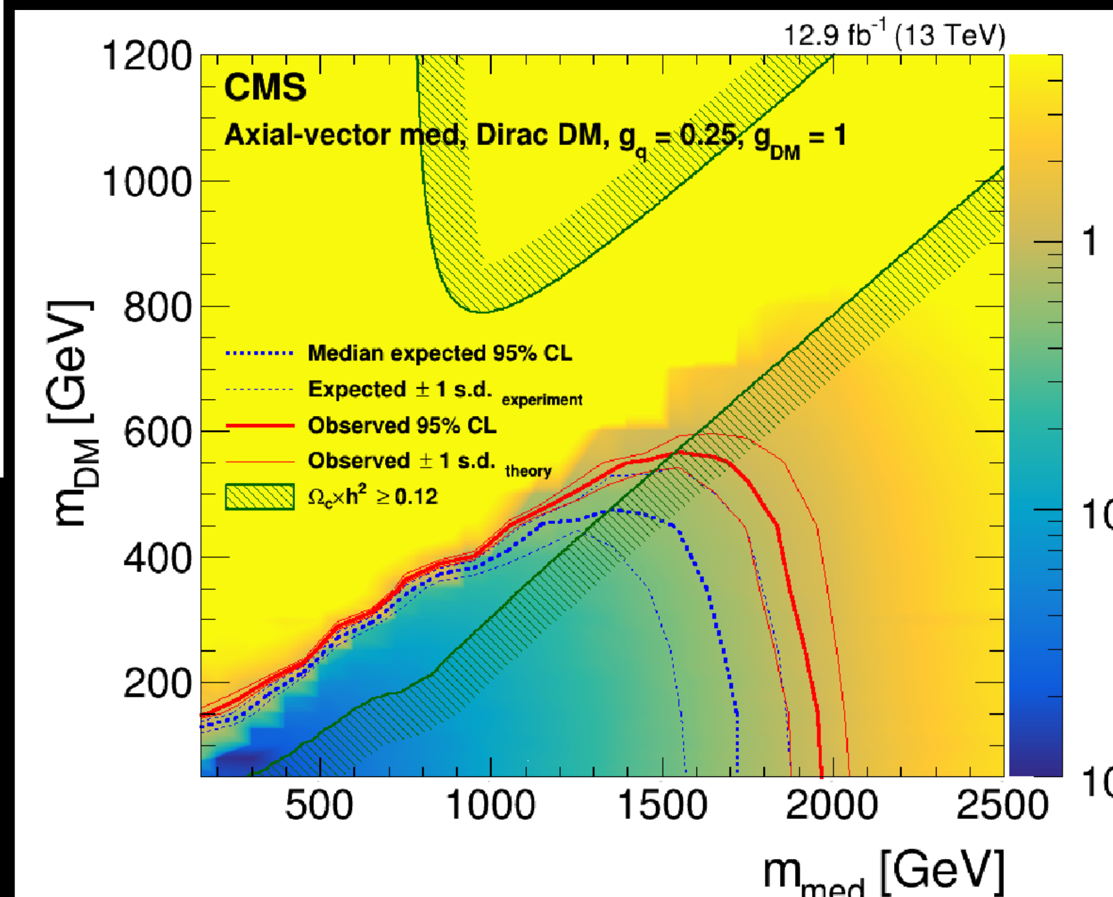
NB: Simplified by assuming
Some couplings are equal,
or zero.

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

Axial Vector

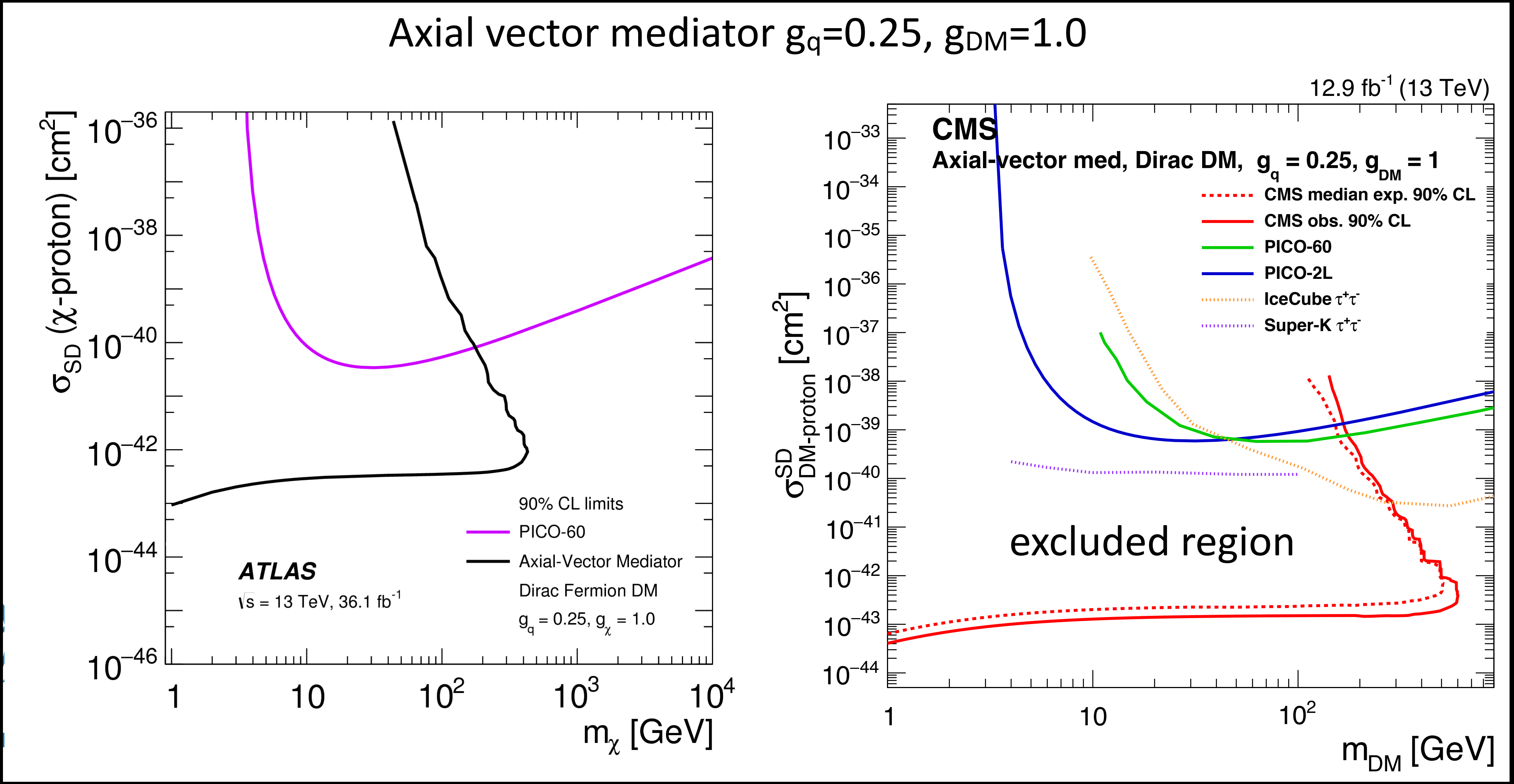




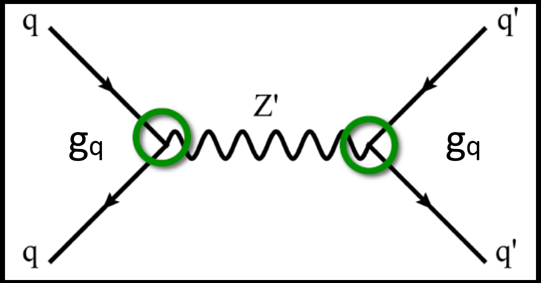


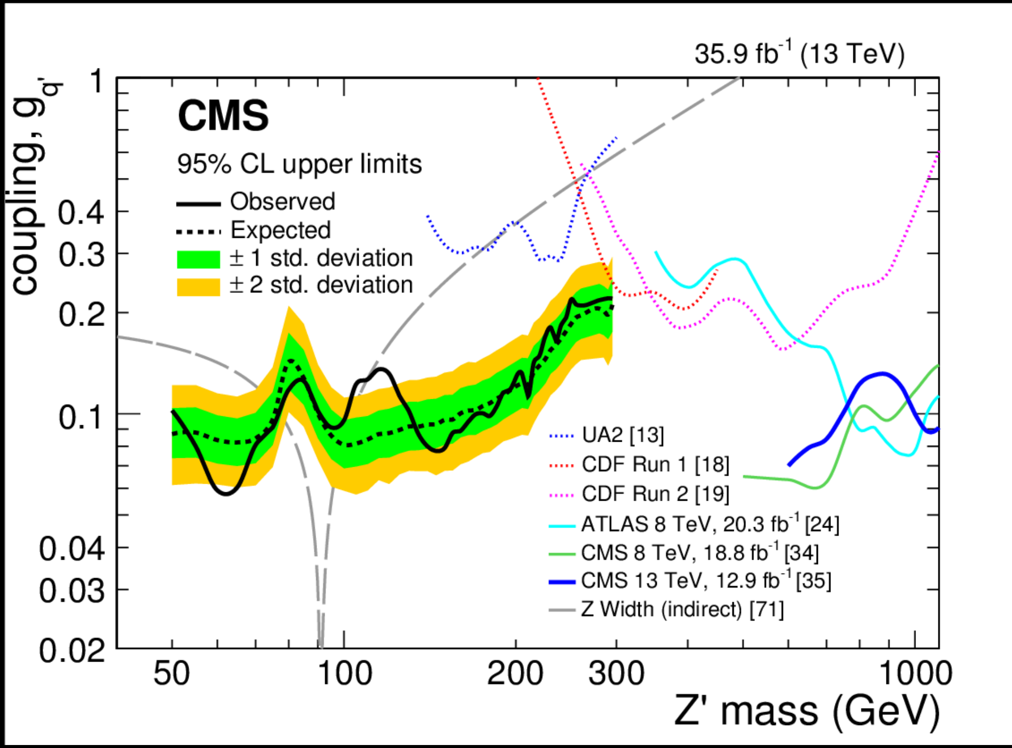
Mono-jet Searches

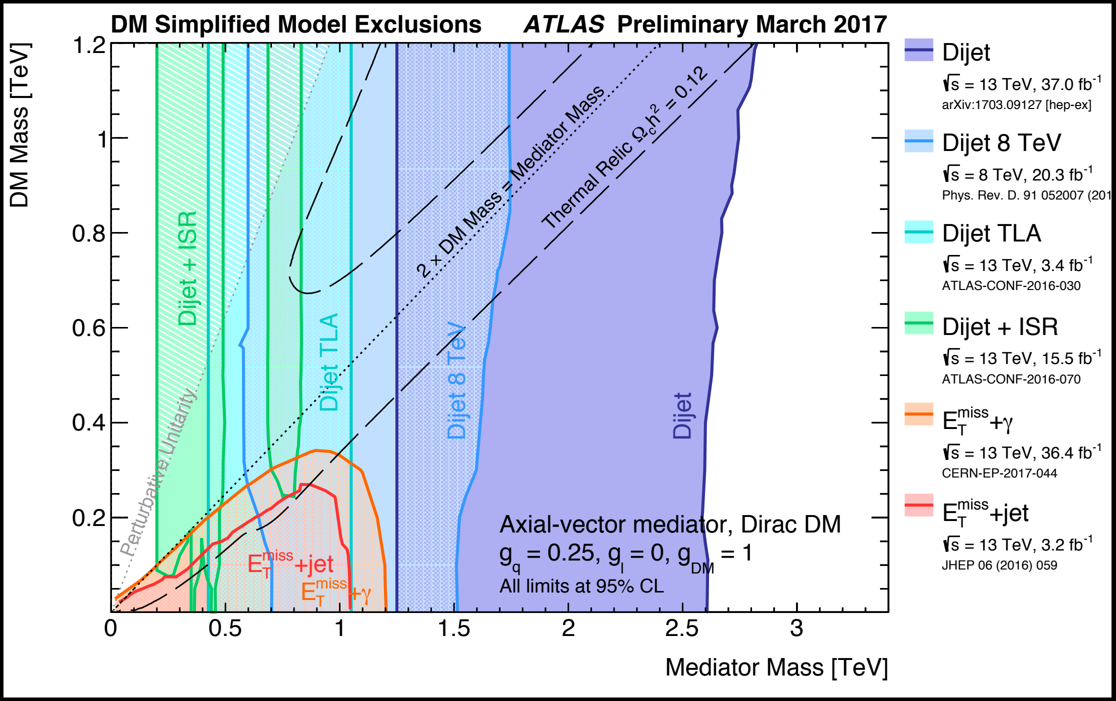
Axial Vector



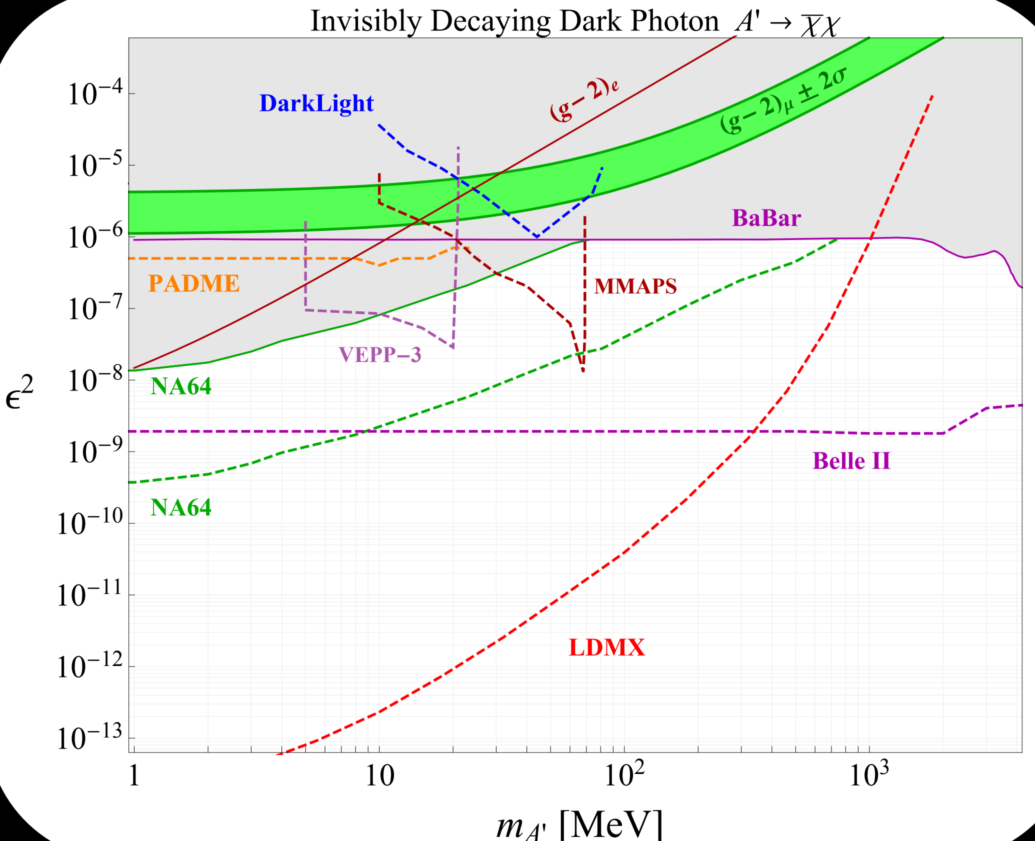
Mediator Searches





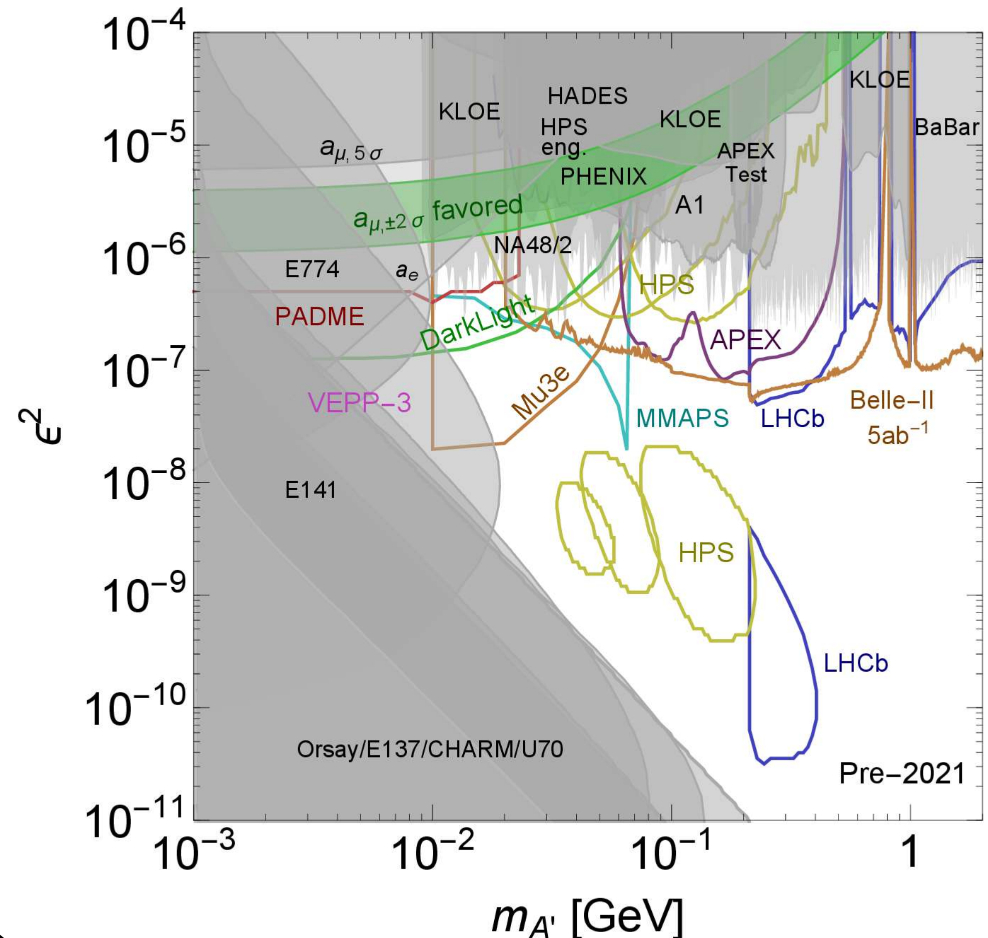


Light Mediators



~100% BR into invisible channels.

~100% BR into visible channels.

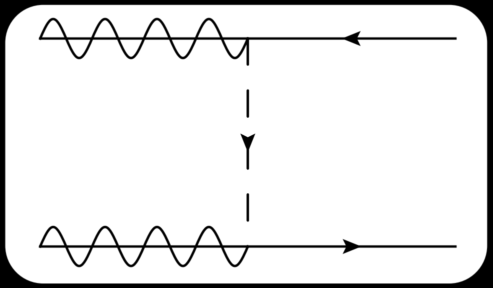


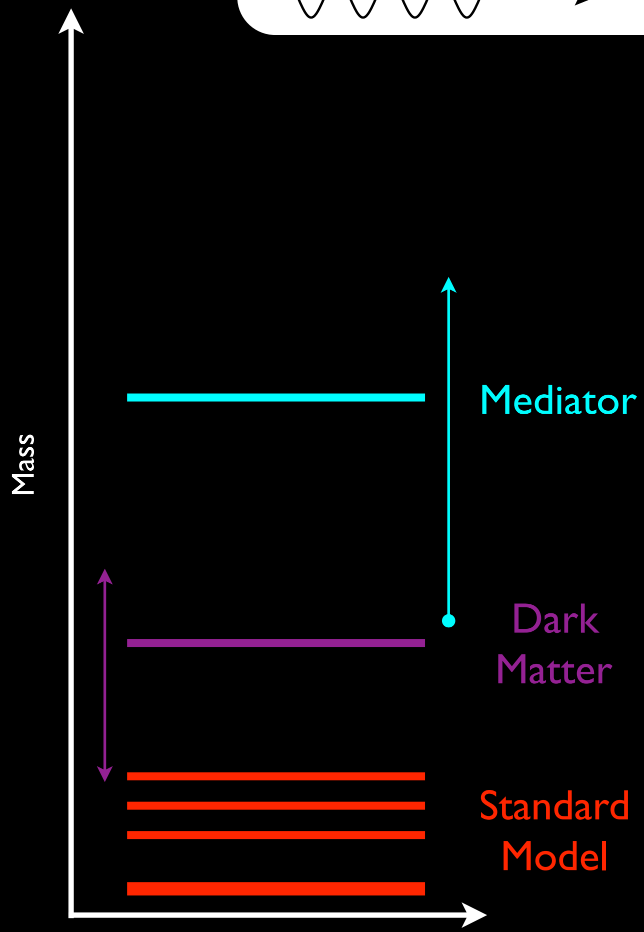
US Cosmic Visions Report
arXiv:1707.04591

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

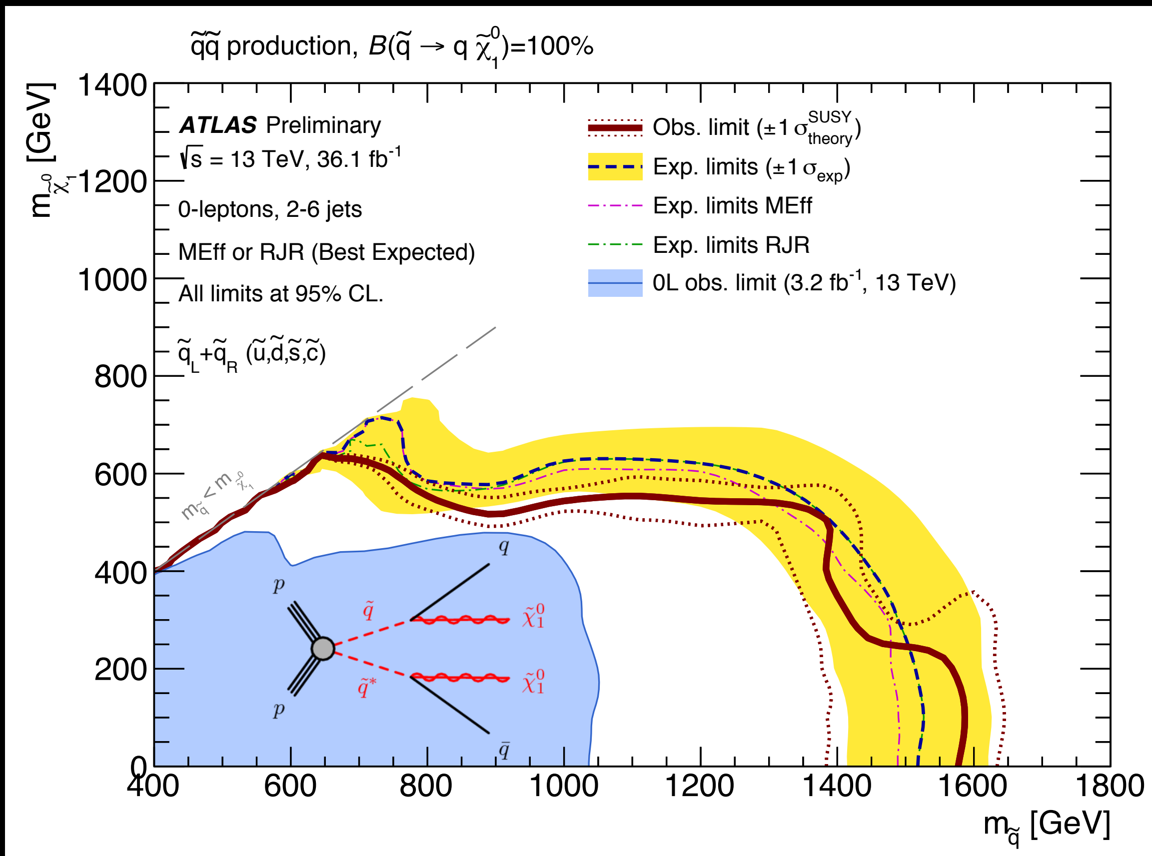
Colored Scalar

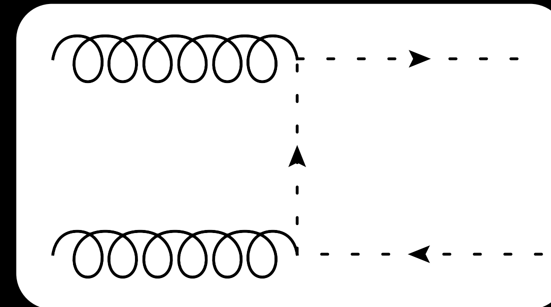
- Another common structure has dark matter interacting with quarks via a colored scalar mediator.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, masses, etc.
- If we assume that the quark couplings are family-universal, there are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.



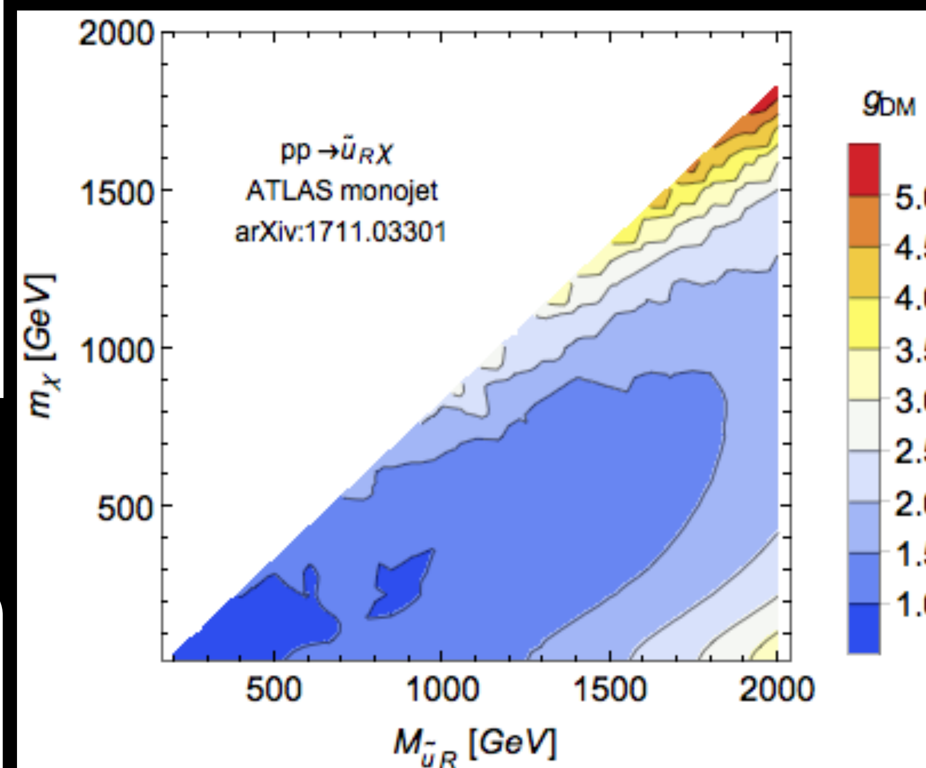


“Squarks”

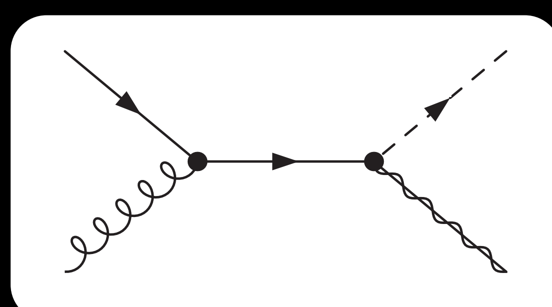




Pair Production

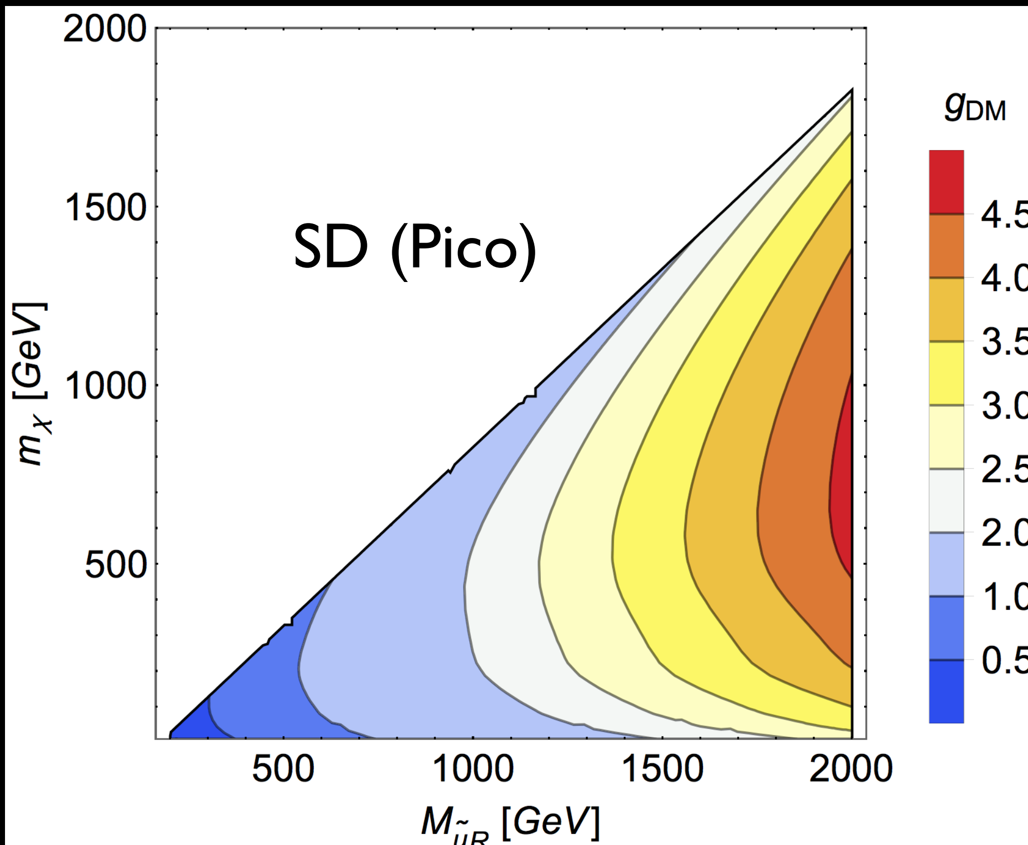


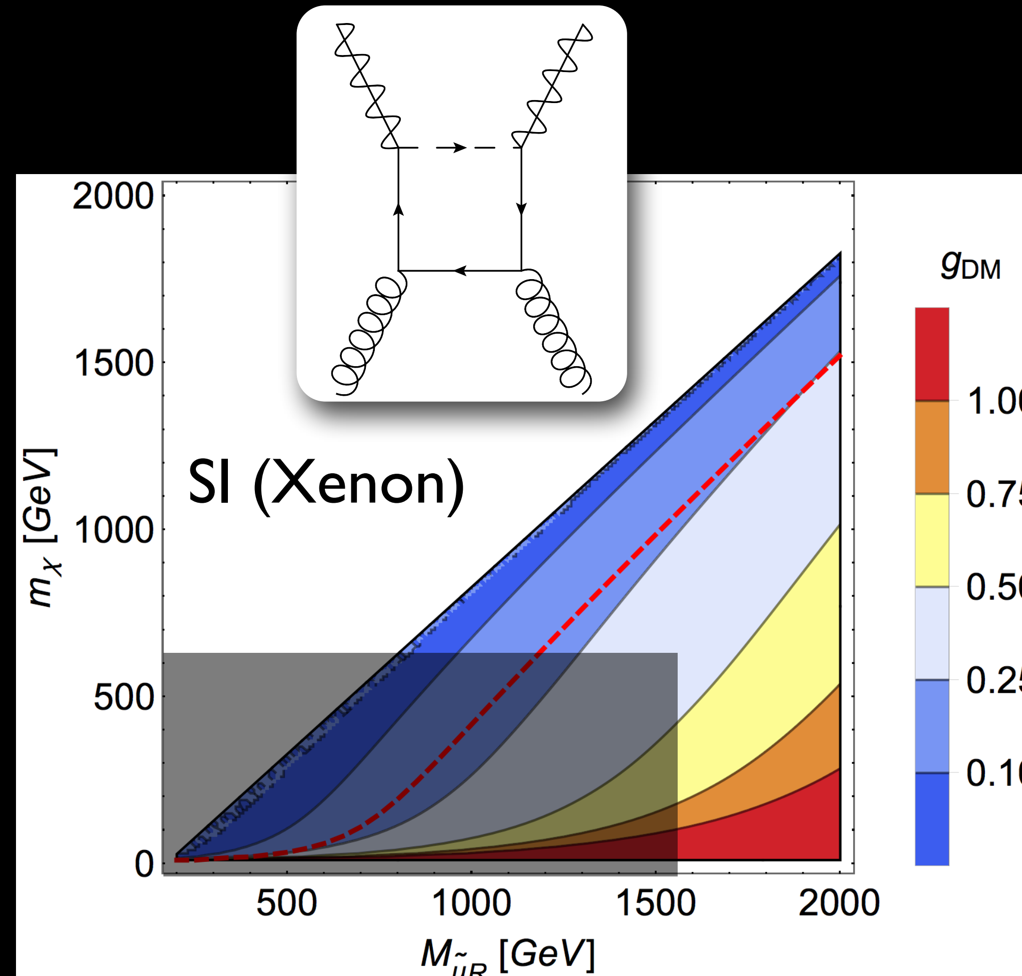
“Monojet”



Mohan, Sengupta, TMPT, Yan, Yuan in progress

Direct Detection





Mohan, Sengupta, TMPT, Yan, Yuan in progress

- At tree level, the fact that Majorana particles have vanishing vector current implies that the scattering with nuclei is spin-dependent..
- But at one loop, the scattering is spin-independent, and these are the dominant constraint- the smaller rate is compensated by the stronger experimental bounds.

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.

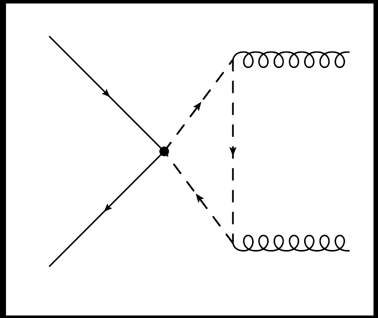
- In that case, a quartic interaction can connect the two.

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

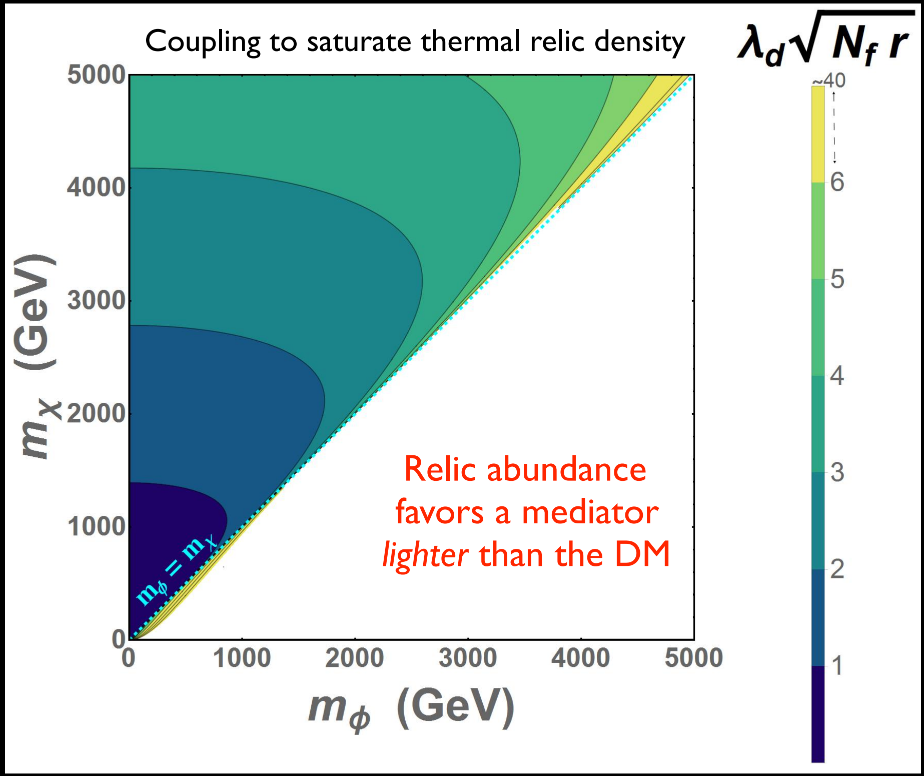
- This interaction does not require the scalar to be Z_2-stabilized, and (given an appropriate choice of EW charges) it can decay into a number of quarks, looking (jn some cases) more like an R-parity violating squark.

- 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.

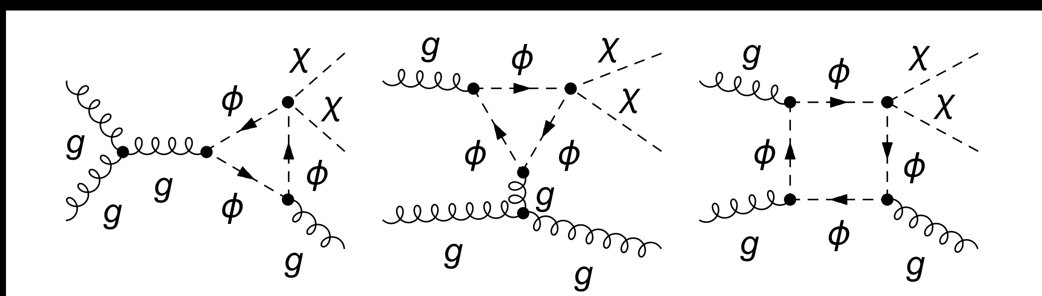


The dominant coupling to the SM is at one loop to gluons!

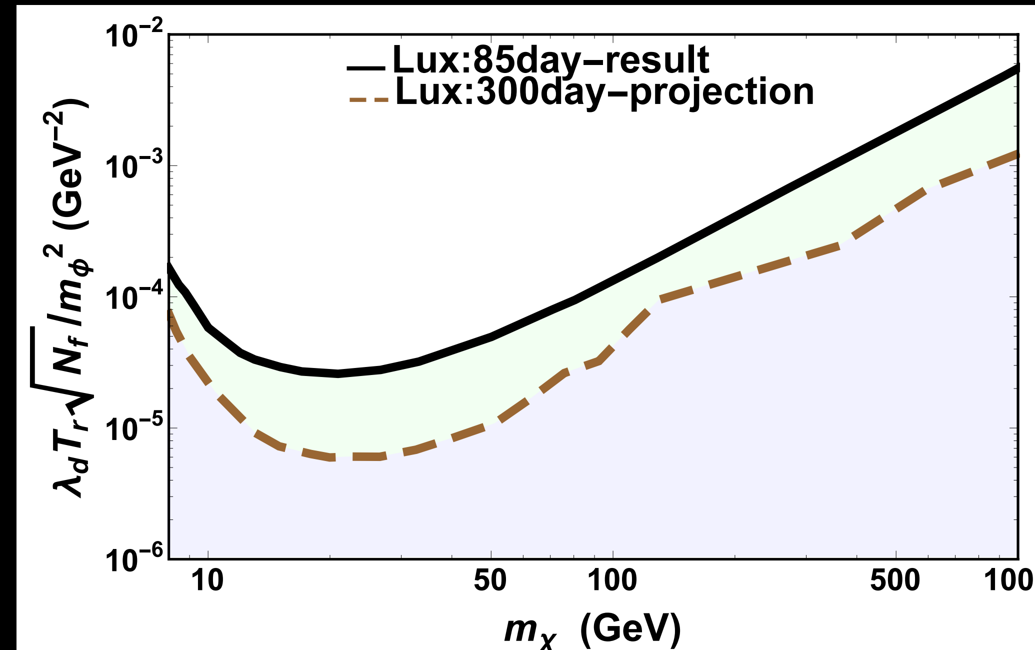


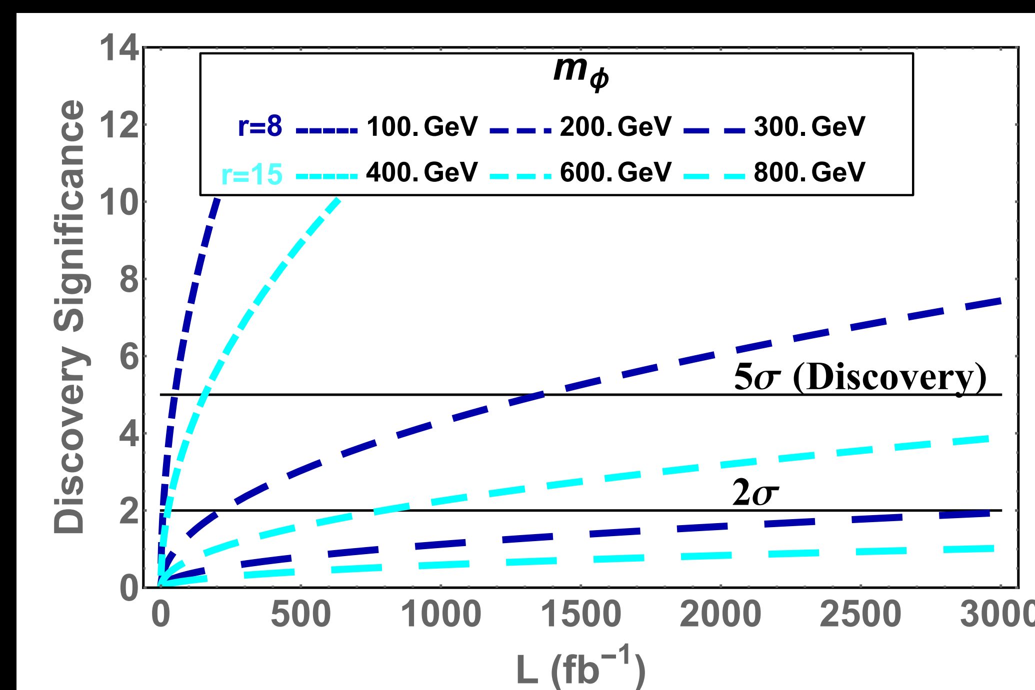
DM Searches

- 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…



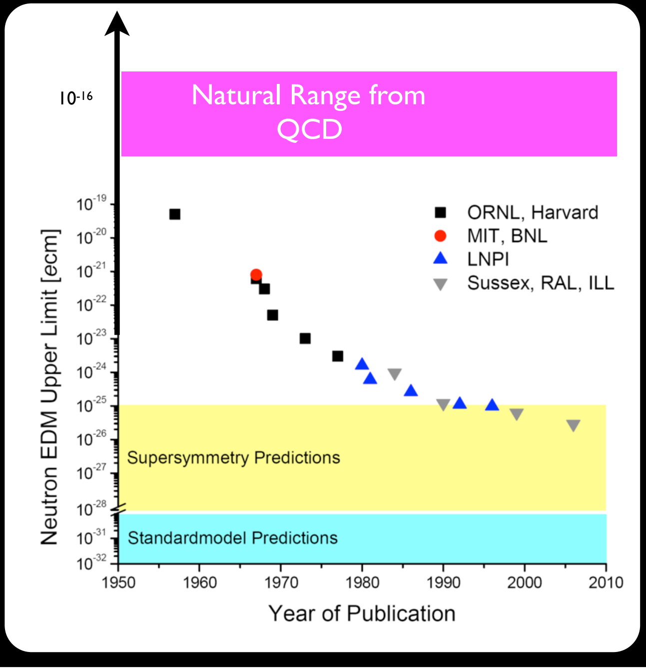


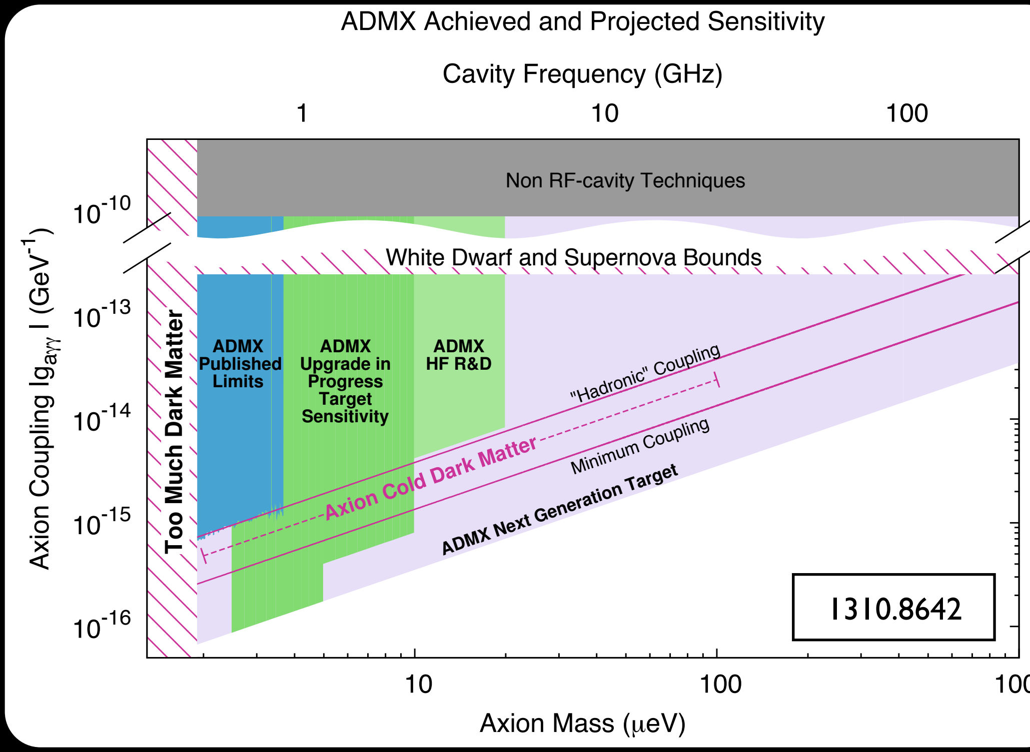
Axion Dark Matter

- The axion is motivated by the strong CP-problem, where the QCD θ term is cancelled by introducing a scalar field -- the QCD axion.
- The axion's mass and couplings are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

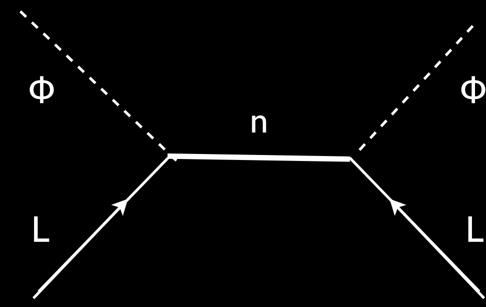
$$m_a \sim f_\pi / f_a \times m_\pi$$

- The axion is unstable, but its tiny mass and weak couplings allow a lifetime is much greater than the age of the Universe.
- QCD Axions have electromagnetic couplings that allow an external magnetic field to convert an axion into a photon (and vice-versa). This is one cool way to search for them!



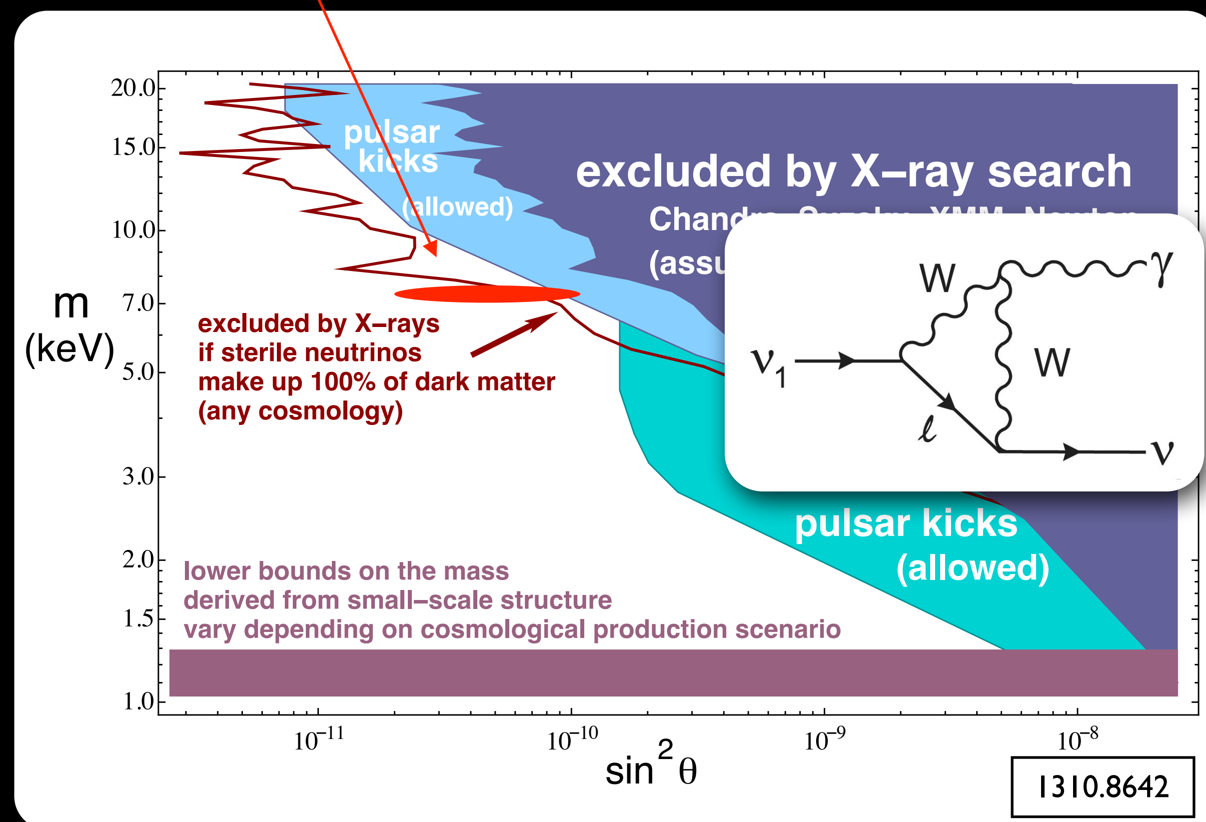


Sterile Neutrino DM



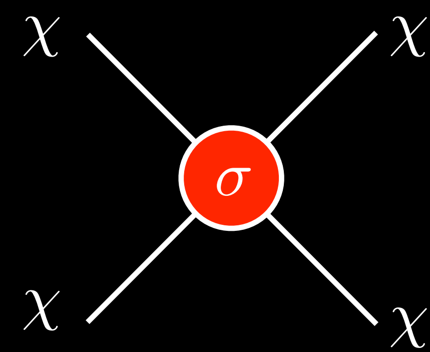
- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.
- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.
- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision electroweak data), they can be stable on the scale of the age of the Universe and play the role of dark matter.

Possible X-ray Signal
[Bulbul et al 2014]



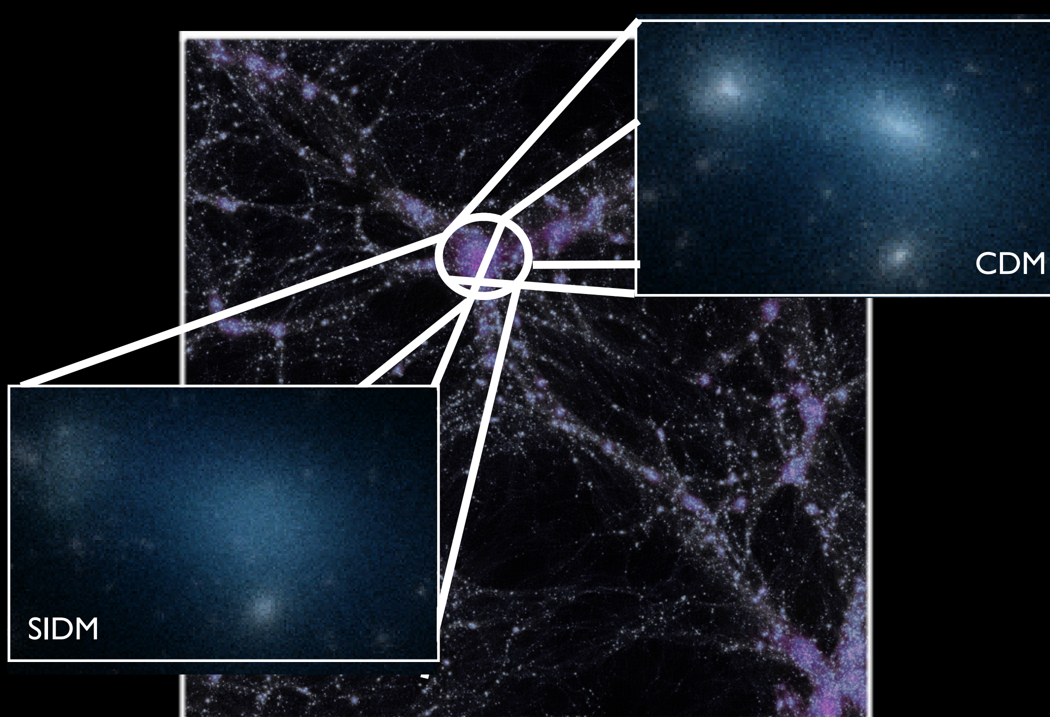
Self-Interacting DM?

- Dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- There is some (controversial) evidence that this may help simulation better describe observation.
- It could also be that the tension arises from the fact that the simulations don't properly model the impact of baryonic matter.
- Astronomy provides a unique perspective on properties that particle searches cannot probe.



σ / m < 0.7 cm^2 / g

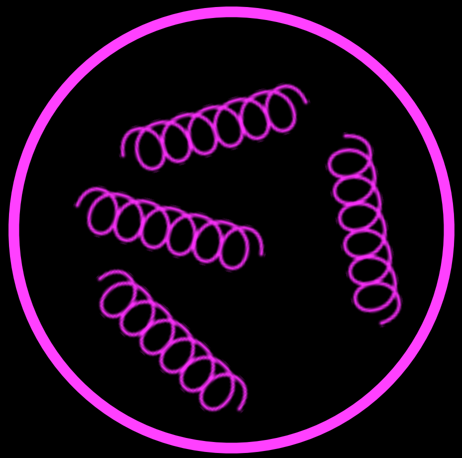
(at a relative speed of ~3000 km/s)

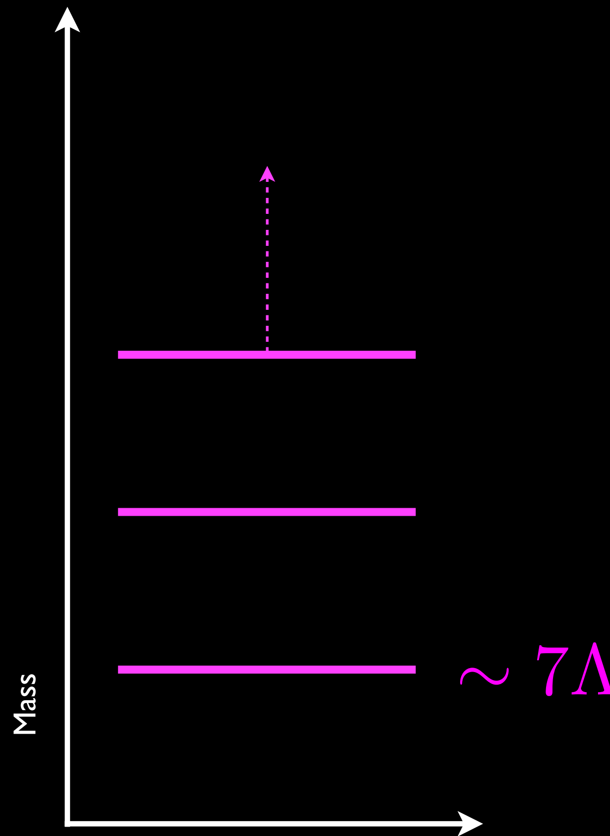


Composite Dark Matter

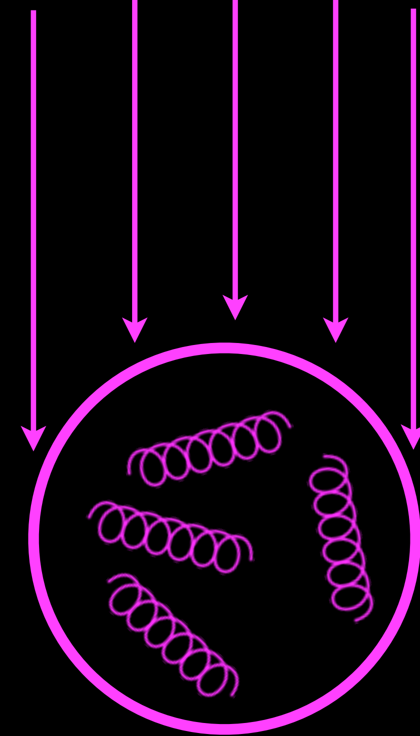
- To have a visible effect on astronomy, the self-scattering cross section must be rather large.
- A new confined gauge force generically produces massive composite particles which could play the role of dark matter.
- If any matter charged under the hidden gauge group and the SM is extremely heavy, there is no relevant interaction between the dark sector and the SM.
- At high energies, the theory is described by weakly coupled dark gluons.
- At low energies, the dark gluons confine into massive dark glueballs.
- The theory is defined by the number of colors N and confinement scale Λ, which characterizes the mass of the lowest glueball state, and the splitting between the various glueballs.

Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014



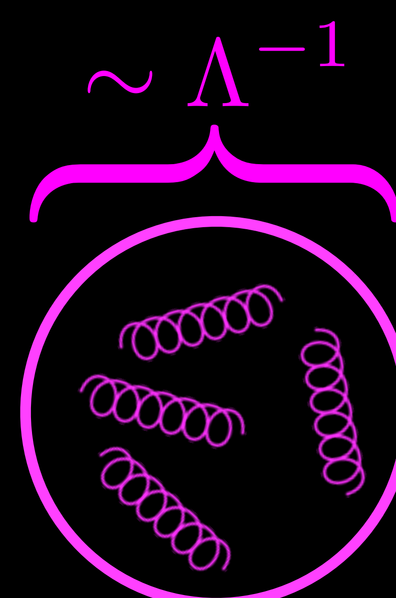


Glueball Interactions



- In this theory, nothing can be computed very reliably in perturbation theory.
  - Lattice gauge theory may be able to help.
- Nonetheless, the self-interactions of the glueballs will be roughly given by the geometric cross section for strongly coupled objects of size ~ 1 / Λ.

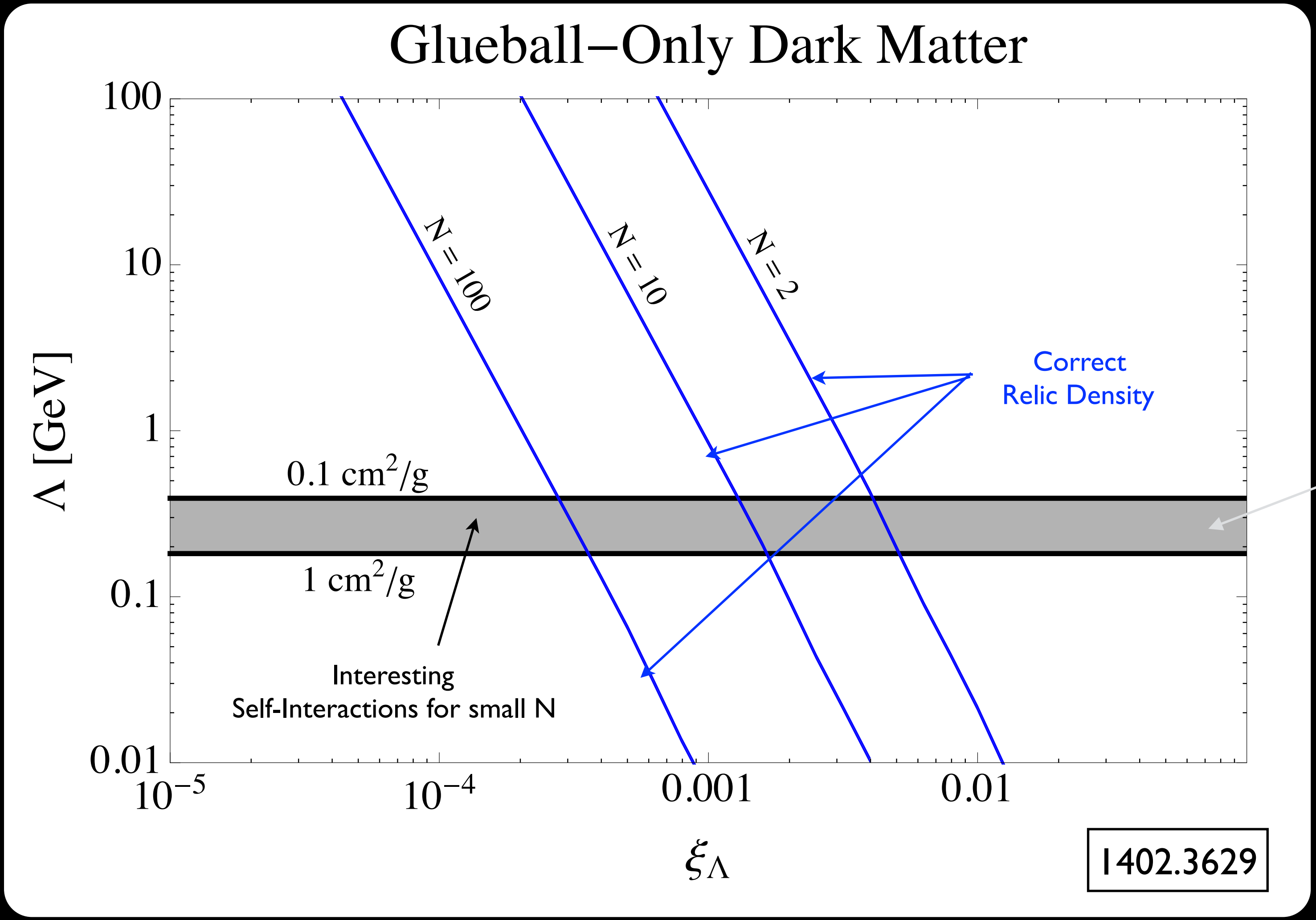
$$\sigma\,(\mathrm{gb\ gb} \rightarrow \mathrm{gb\ gb}) \sim \frac{4\pi}{\Lambda^2 N^2}$$



- Since the single parameter Λ controls both the mass and the cross section (for small N), arranging for an interesting value of σ/m essentially fixes Λ ~ 500 MeV.

Amusingly close to Λ_{QCD}…

Glueball Parameter Space



~ right SIDM σ
for small N

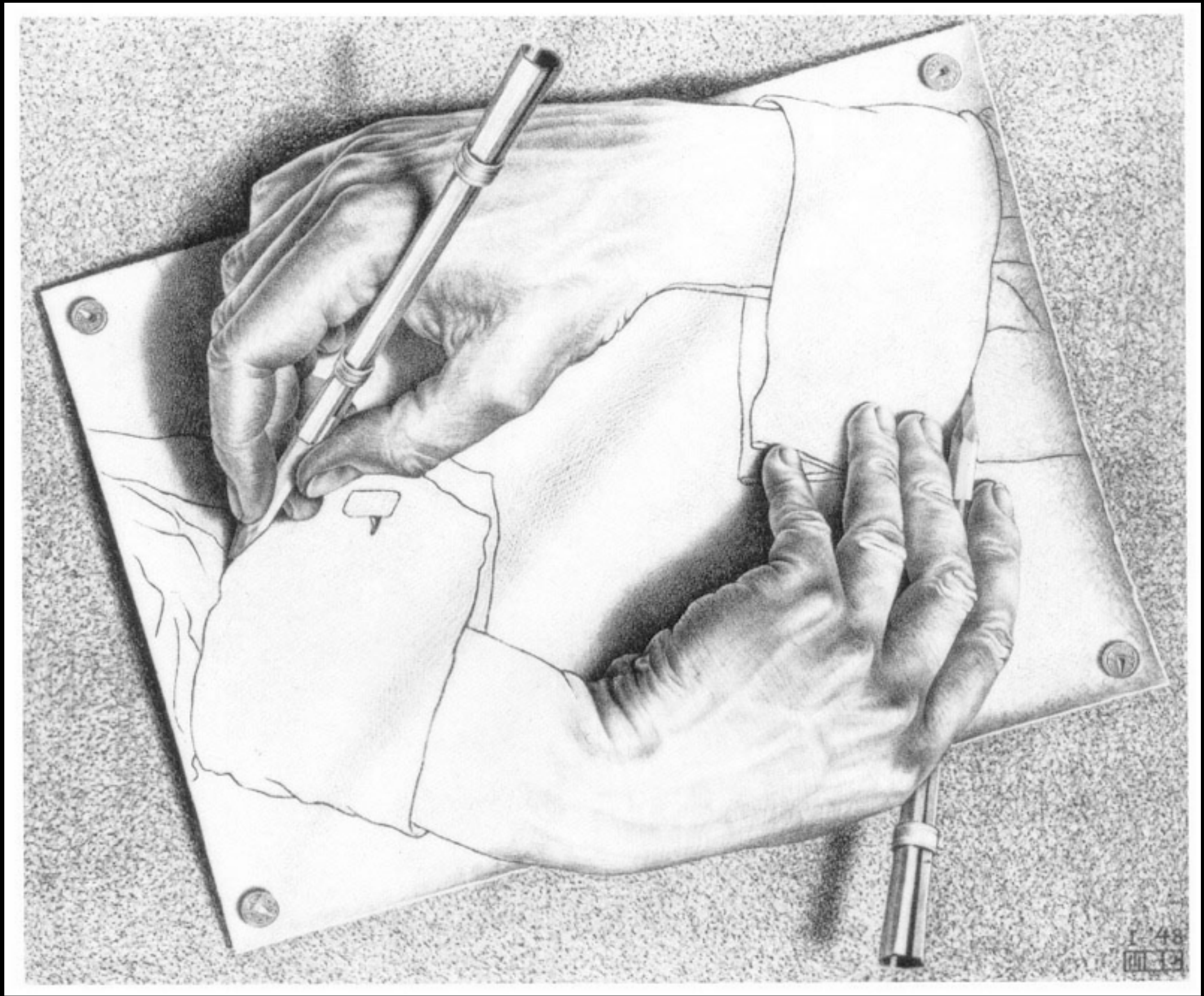
Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014

- The relic density of the glueballs depends on the temperature of the hidden sector relative to the SM ($\xi = T_h / T_{SM}$). An interesting parameter space has ~ observable self-interactions and the correct relic density.

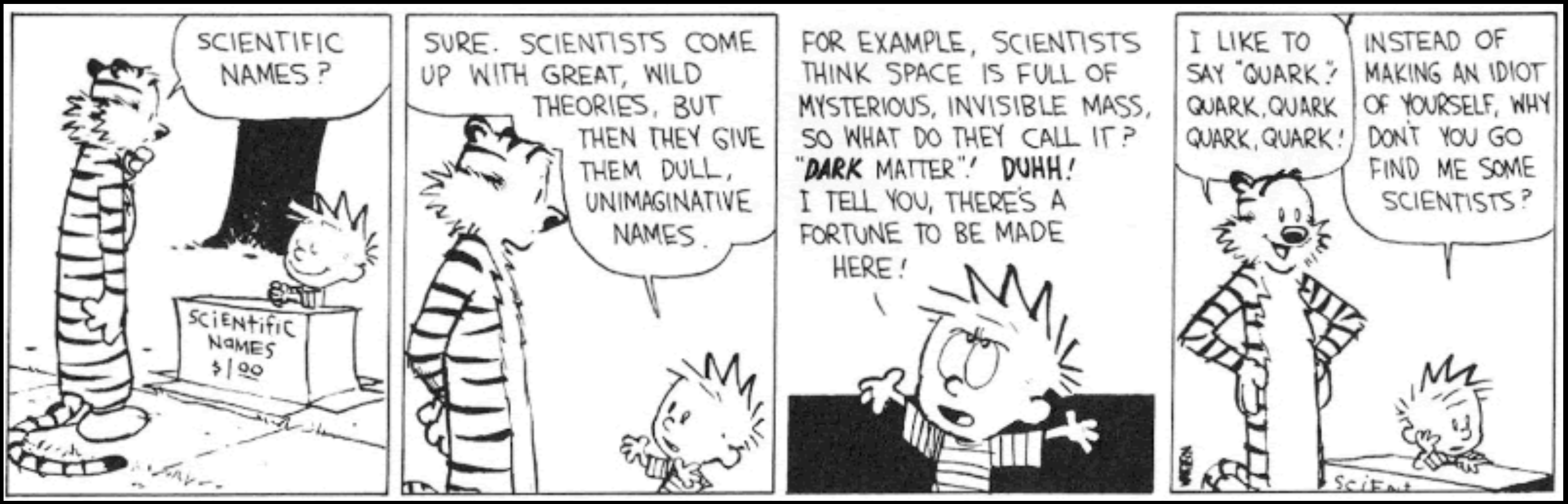
Outlook

- The identity of the dark matter is one of the pressing questions which faces particle physics and astronomy.
- As yet, our relatively poor understanding of its nature implies that a wide variety of phenomena may provide the key observation that helps us unravel the mystery.
- It's very important to have a full complement of experimental searches, and to continue to push the boundaries of theory to maximize the potential for discovery.
- Once there is a discovery, experimental data will bring our theoretical sketches of theories to life!

From Sketch to Life



Sketches of ....

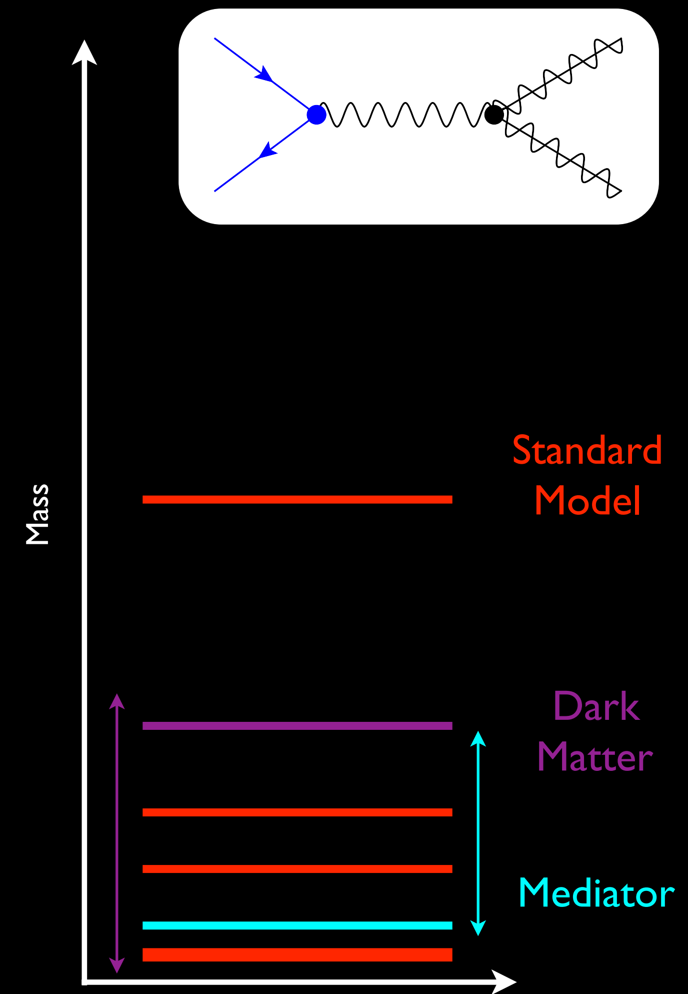


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1.00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE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

Dark Photons

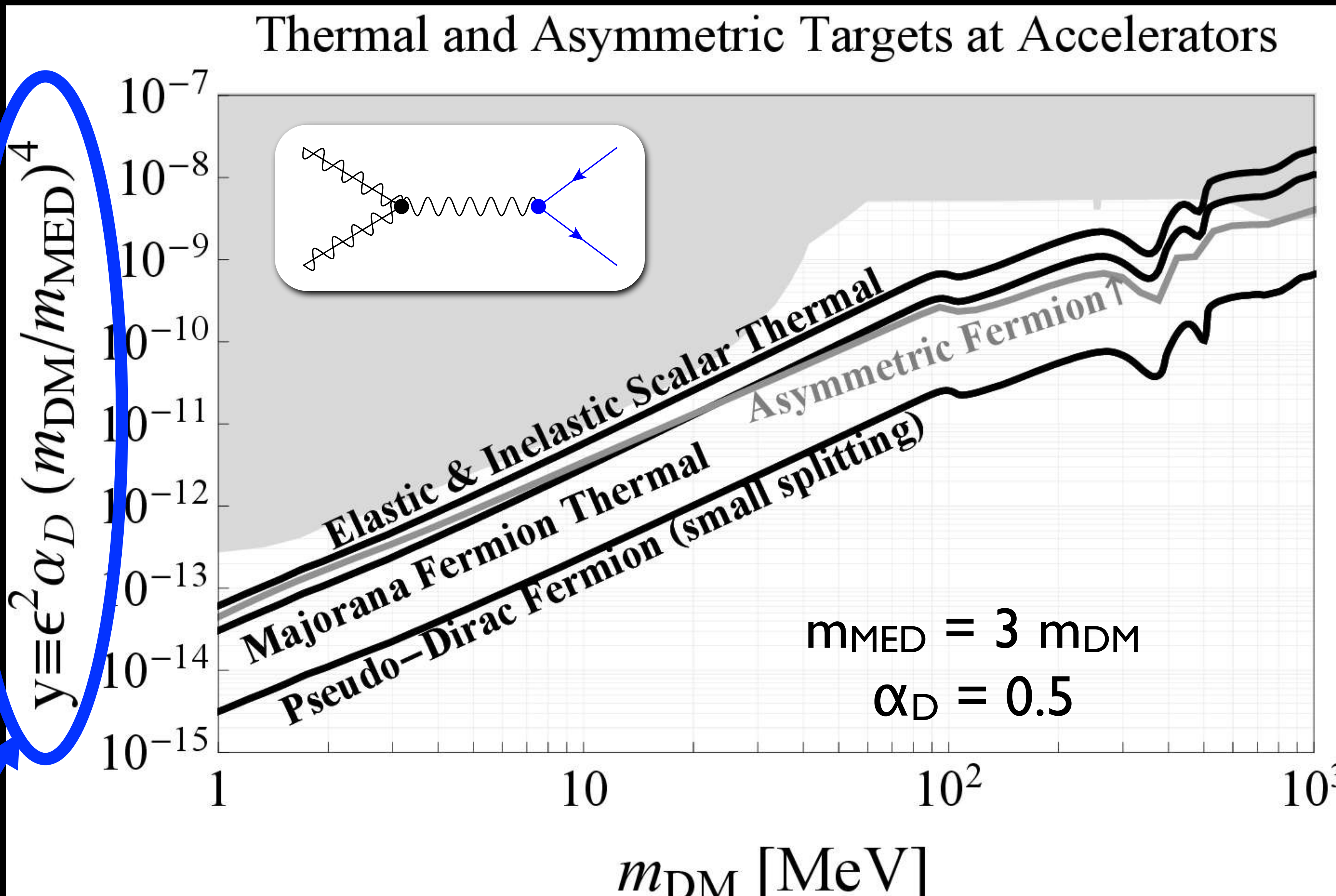
- An interesting part of the parameter space has light mediating particles
- (And maybe light dark matter, as well…)
- In this limit, a natural explanation for the small couplings of the mediator to the standard model is that they come dominantly from kinetic mixing with $U(1)_Y$.
- In this limit, the 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.



γ_D **Parameters:**

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

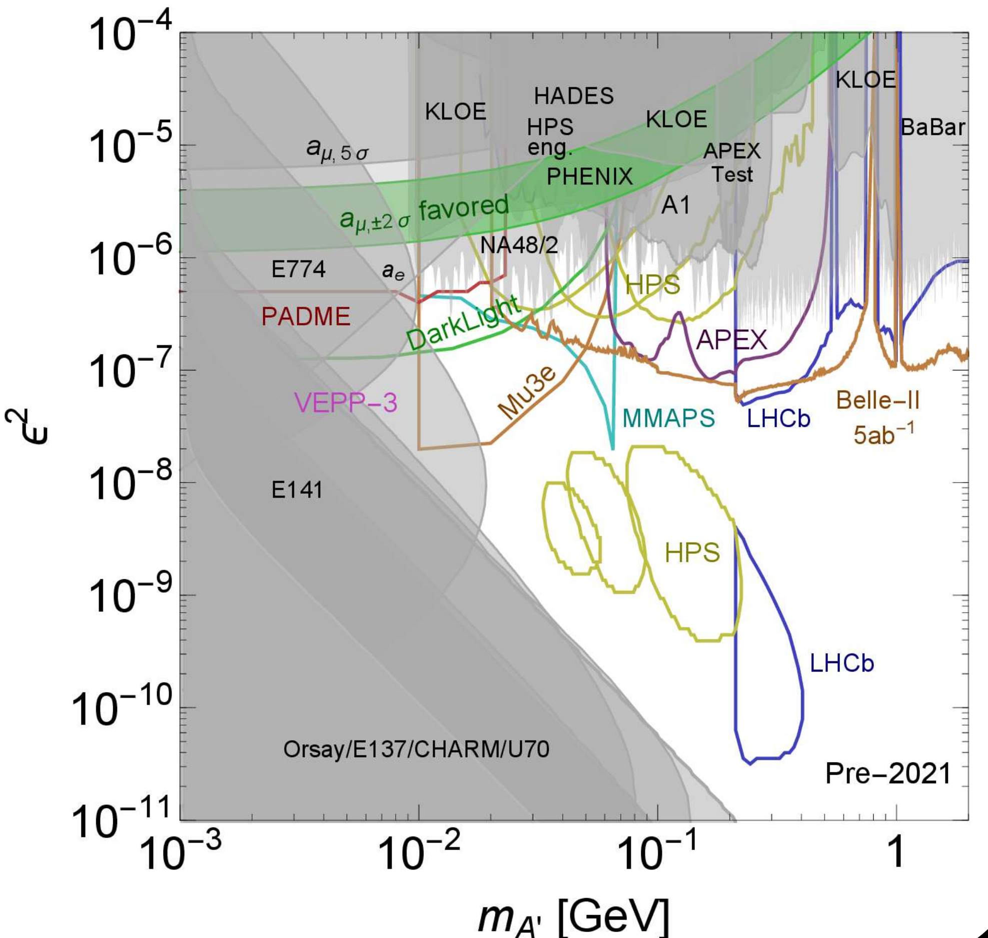
MeV Relic Dark Matter



The y parameter is the combination that controls the relic density in this regime.

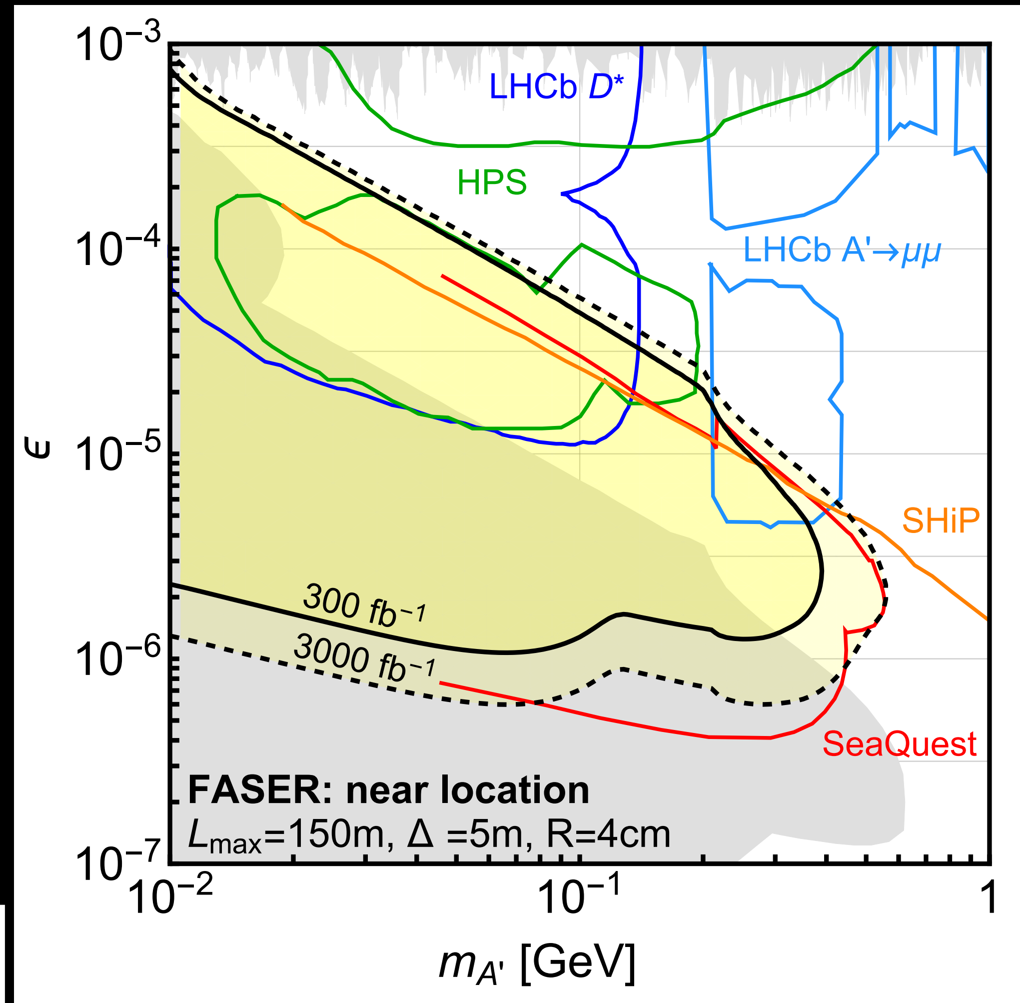
US Cosmic Visions Report
arXiv:1707.04591

Visible Searches



US Cosmic Visions Report
arXiv:1707.04591

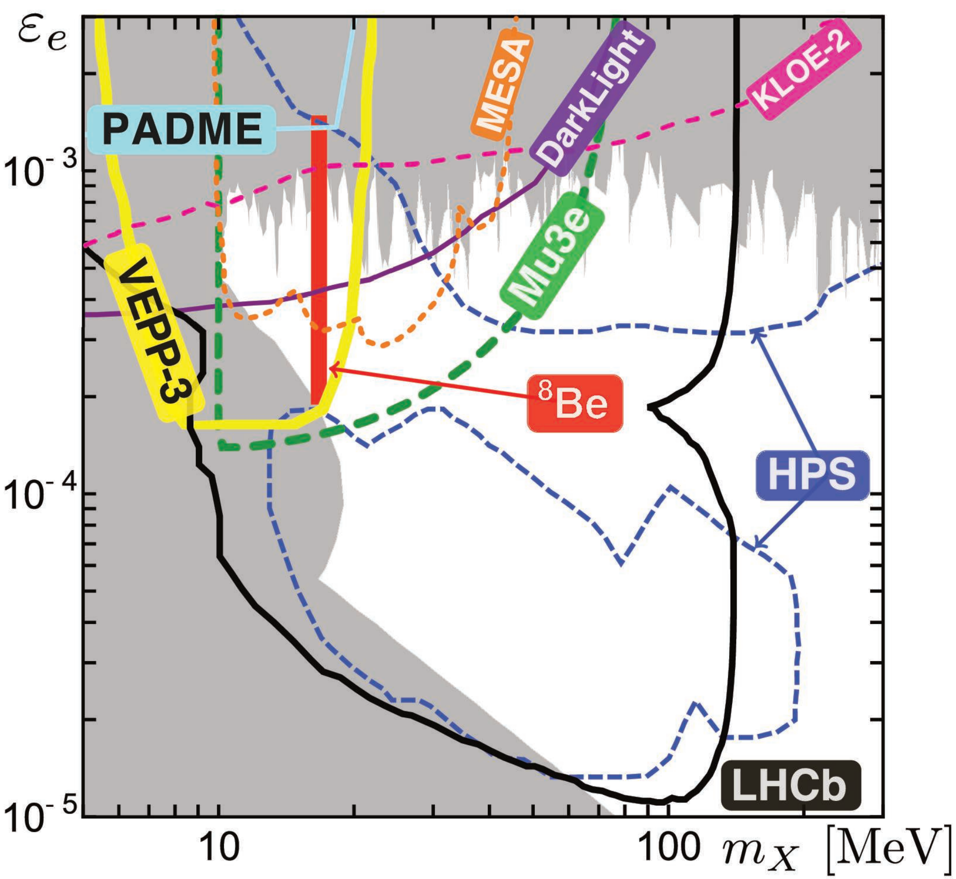
When the dark matter is too heavy, the mediator largely decays visibly into SM states.



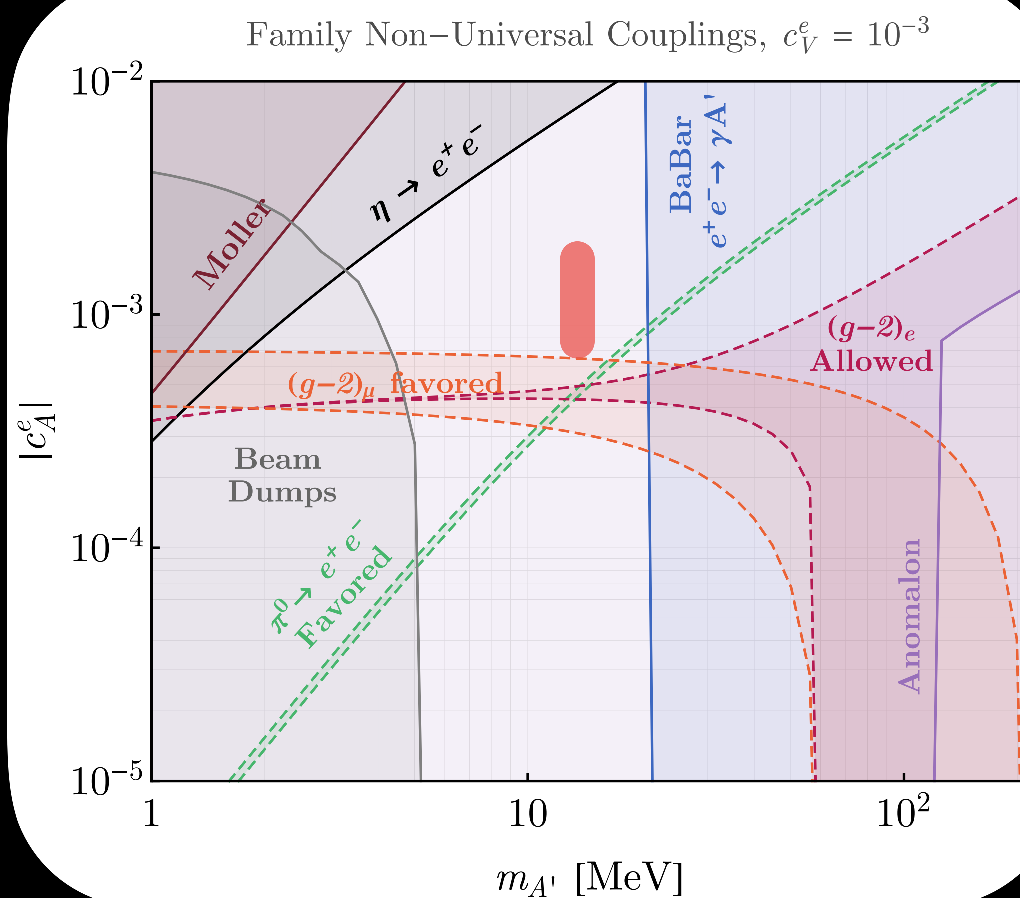
Feng, Galon, Kling, Trojanowski
arXiv:1707.04591

Beyond Dark Photons

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



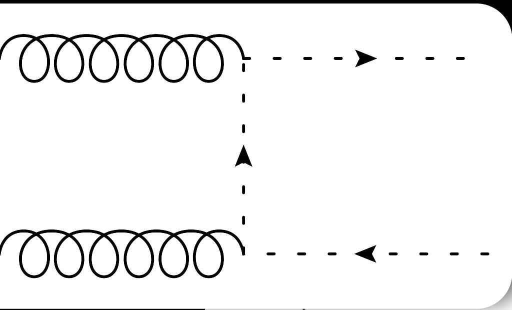
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, TMPT arXiv:1707.04591

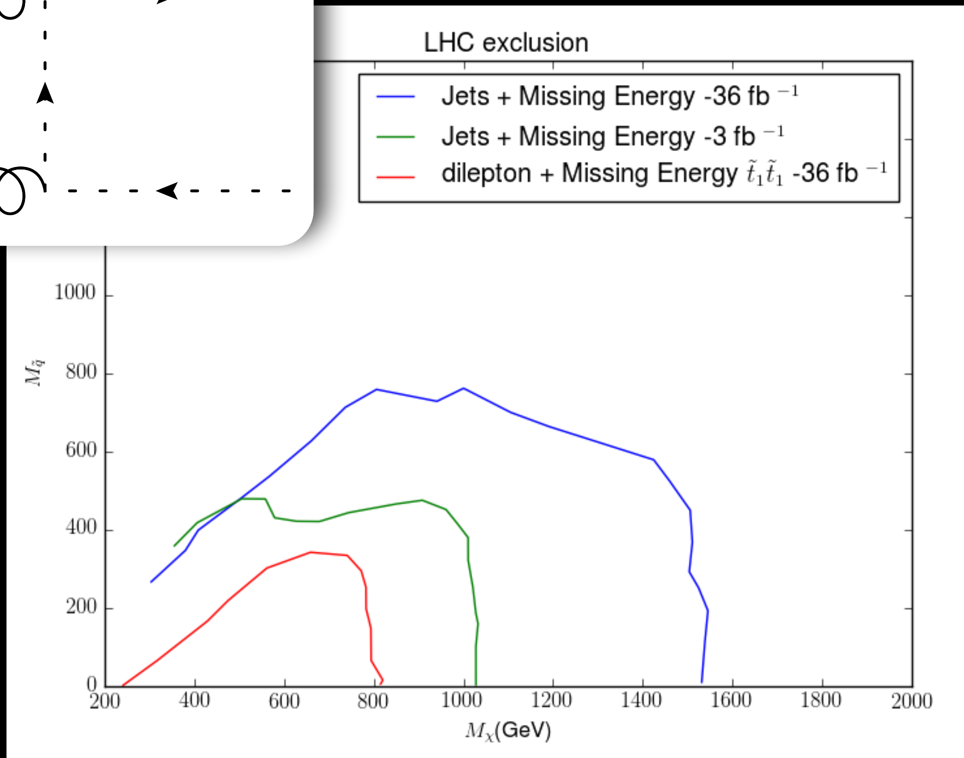


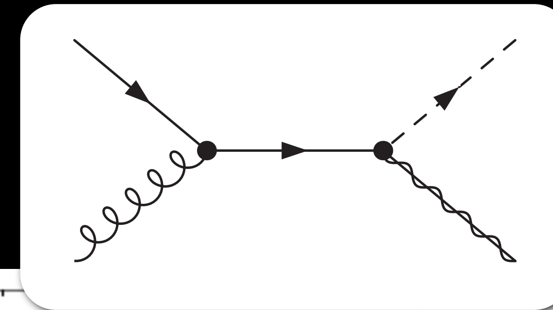
Vector particle with chiral interactions

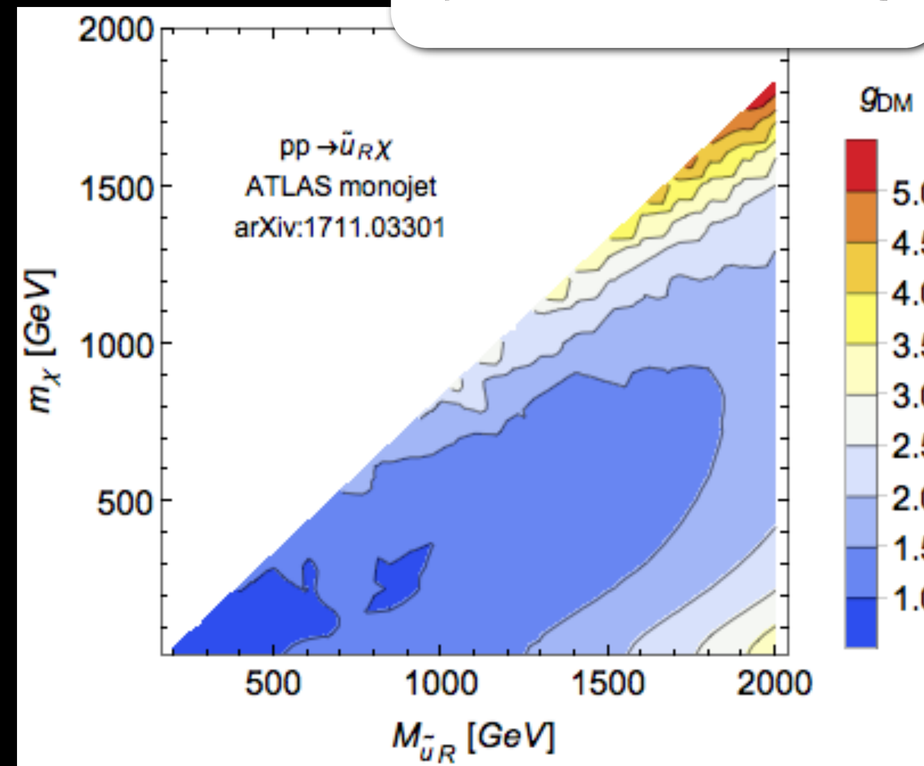
Kahn, Krnjaic, Mishra-Sharma, TMPT arXiv:1609.09072

$\tilde{u}_R$ Model









Mohan, Sengupta, TMPT, Yan, Yuan in progress

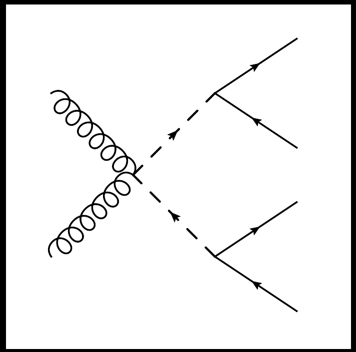
- For example, we can look at a model where a Majorana DM particle couples to right-handed up-type quarks.
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force or through the interaction with quarks.
- Once produced, the mediator will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

Mediator Searches

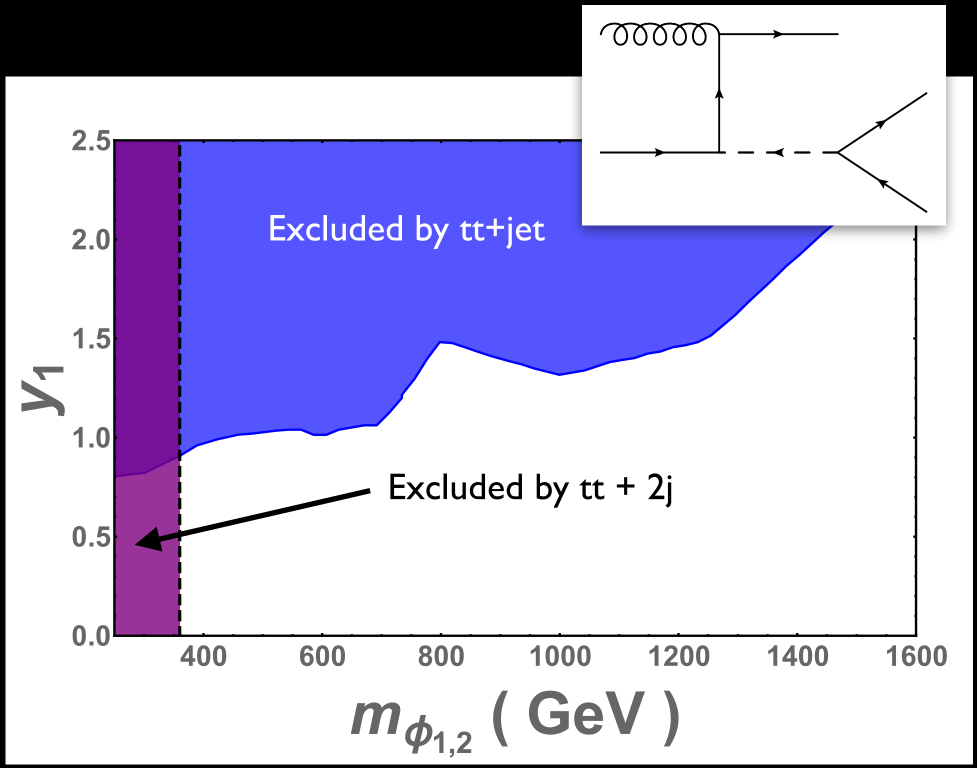
- The physics of the mediators is model-dependent, depending on the color and EW representation.
- As a starting point, we considered mediators of charge 4/3 coupling to 2 uR quarks.
- In this case, a MFV theory can be obtained by coupling anti-symmetrically in flavor indices:

$$y\epsilon^{ijk}\phi_i\bar{u}_j u^c_k + h.c.$$

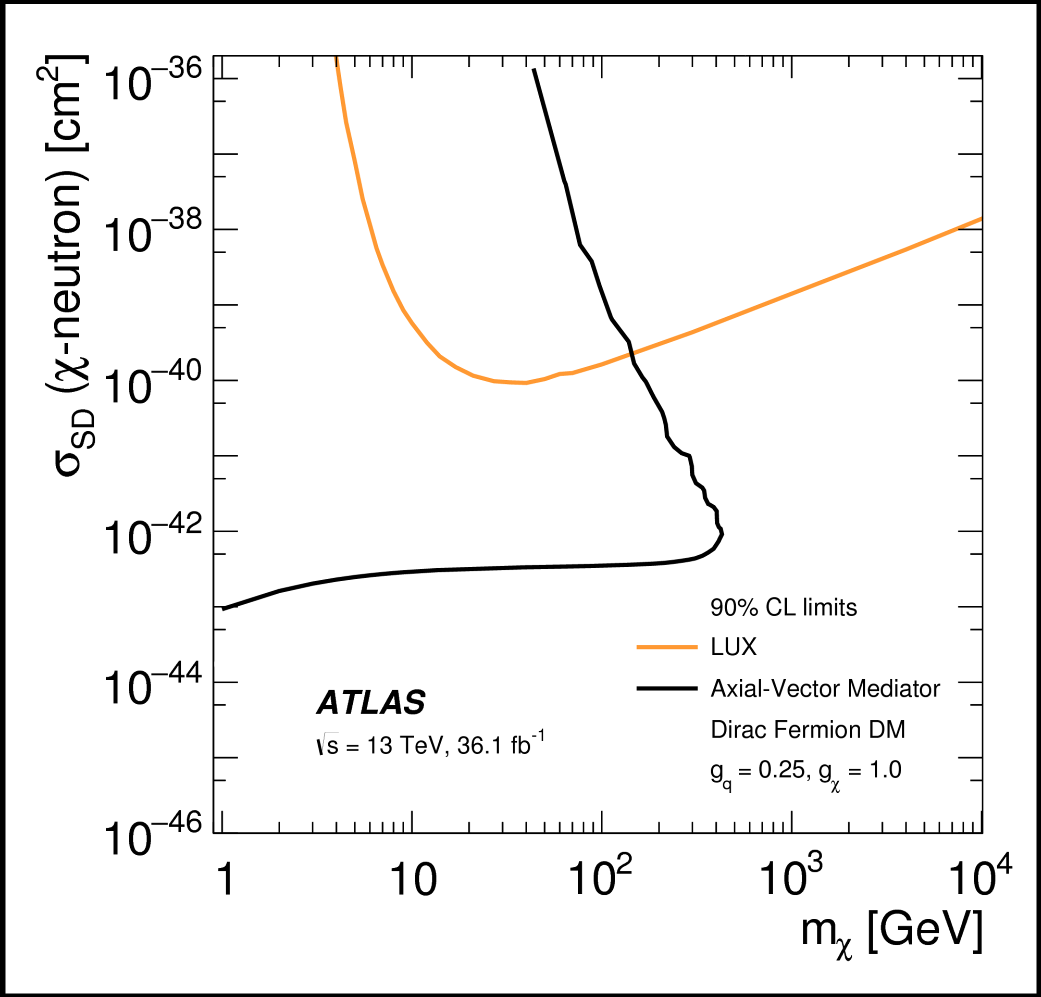
- There are interesting searches for pairs of dijet resonances and also potential impacts on top quark physics.
- All of these constraints are rather weak.

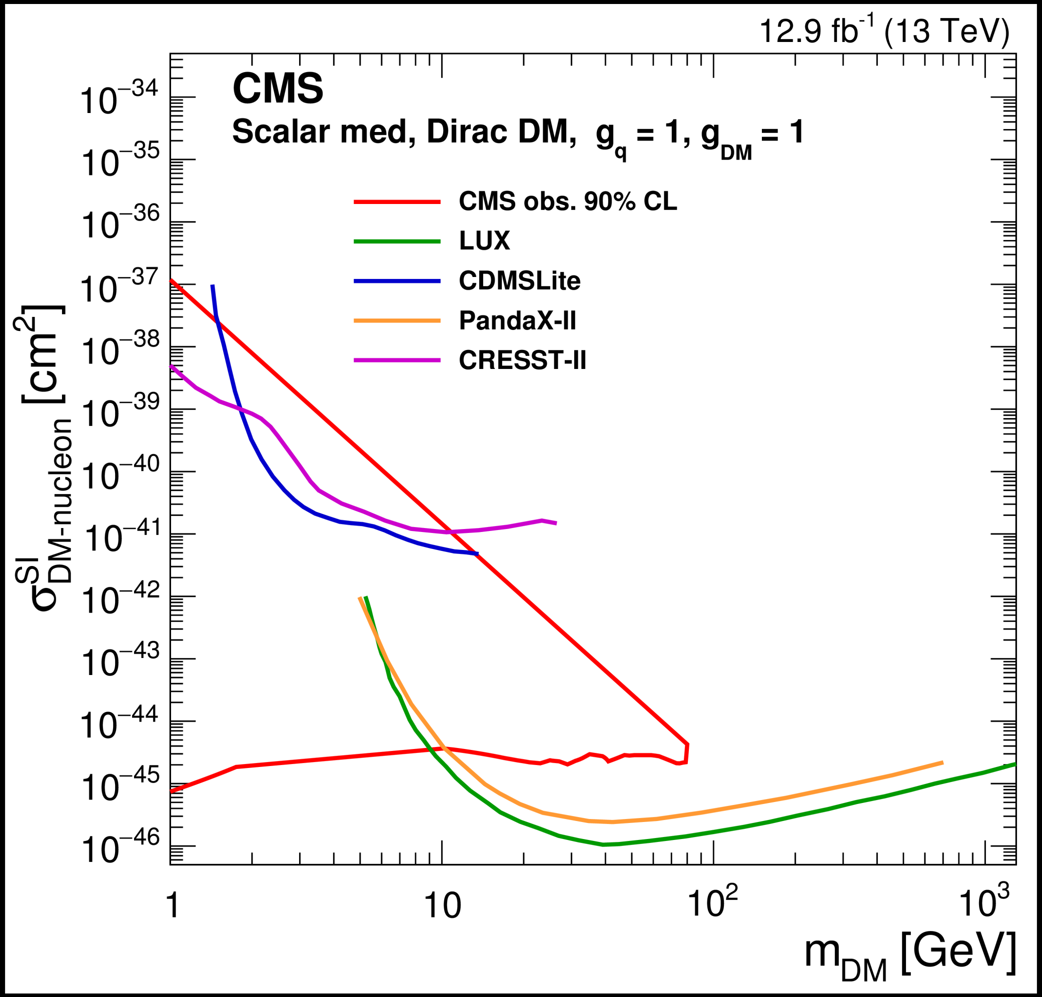


Decays into unflavored jets are bounded by m_φ > 350 GeV.



Monojet Searches: Other Interpretations

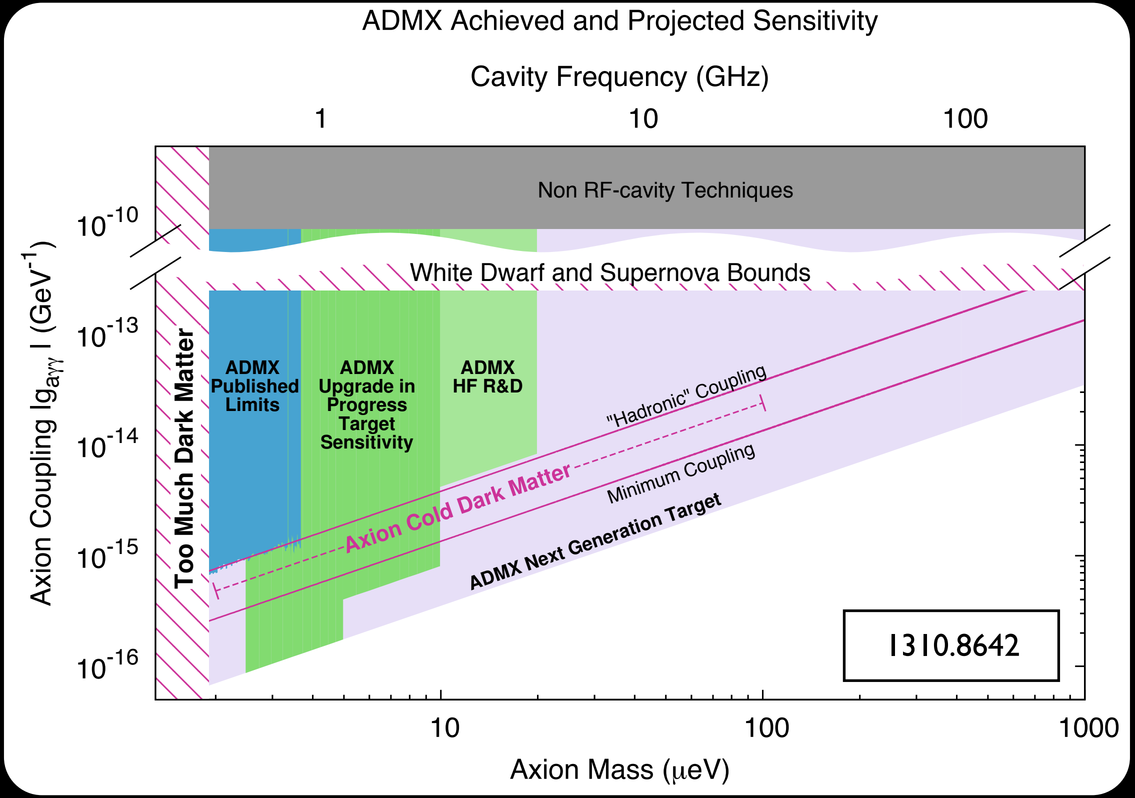




Axion Conversion

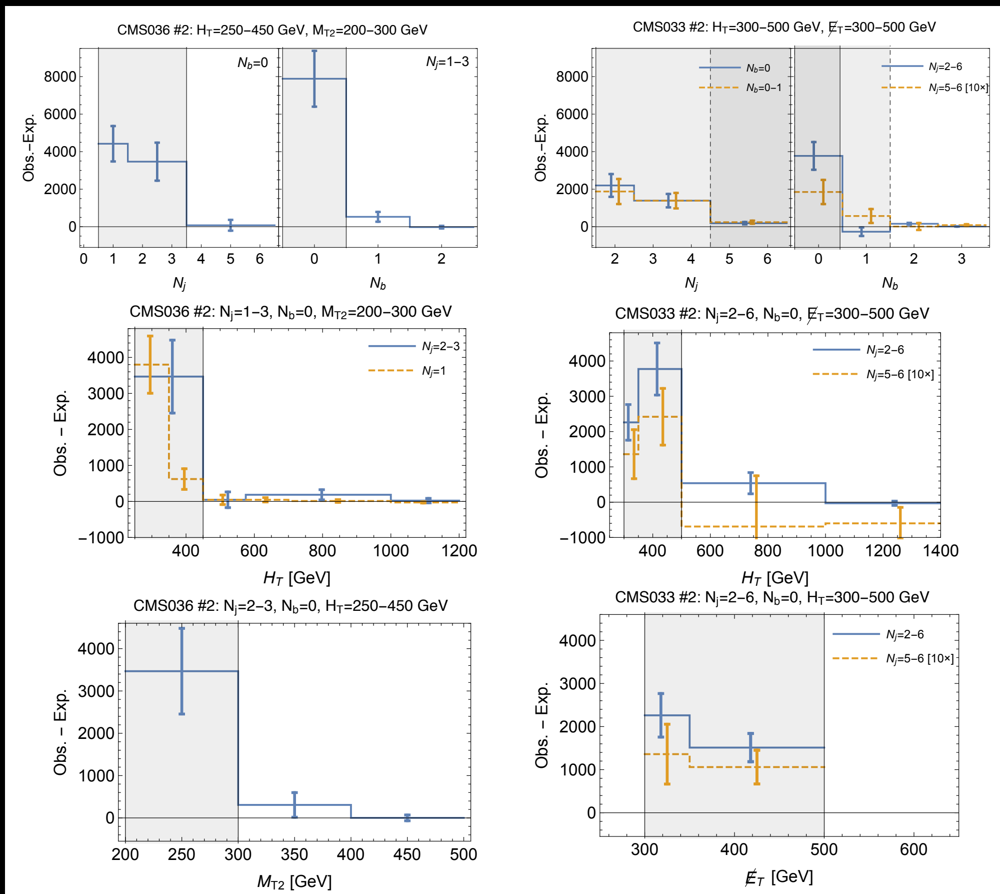
$$\frac{1}{f_a}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu} \;\longrightarrow\; \frac{1}{f_a}\, a\, \vec{E}\cdot\vec{B}$$

- The axion has a model-dependent coupling to electromagnetic fields that is somewhat smaller than 1 / f_a.
- There is a rich and varied program of axion searches based on this coupling.
- One particular search looks for ambient axions converting into EM signals in the presence of a strong background magnetic field.
- Other very interesting new ideas are to look for time variation in the neutron EDM or the induced current in an LC circuit.

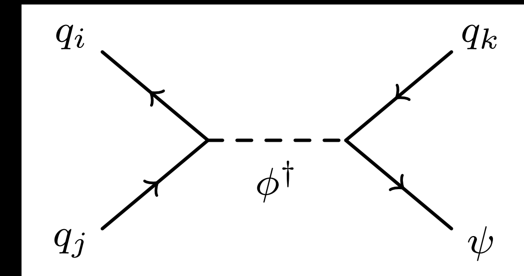


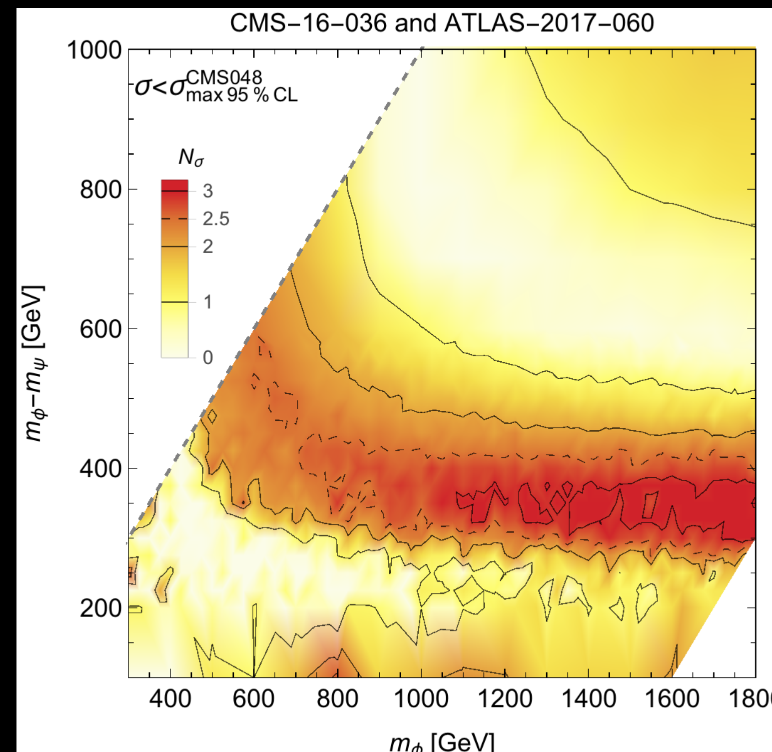
1306.6088 & 1310.8545

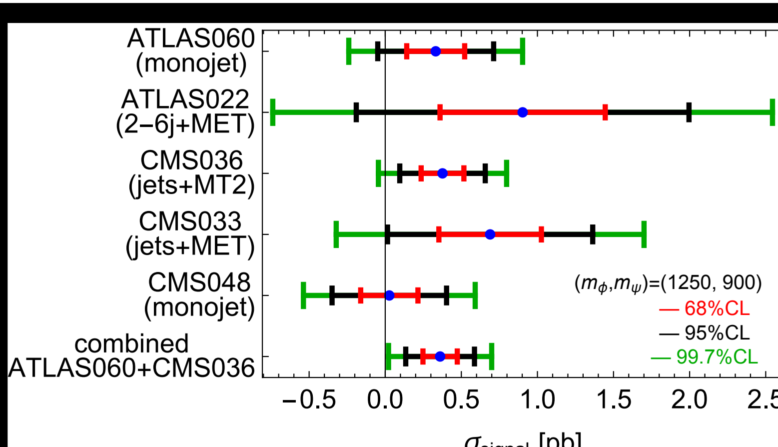
Excess?



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

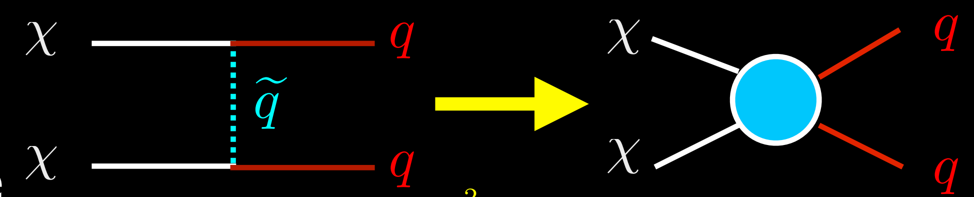






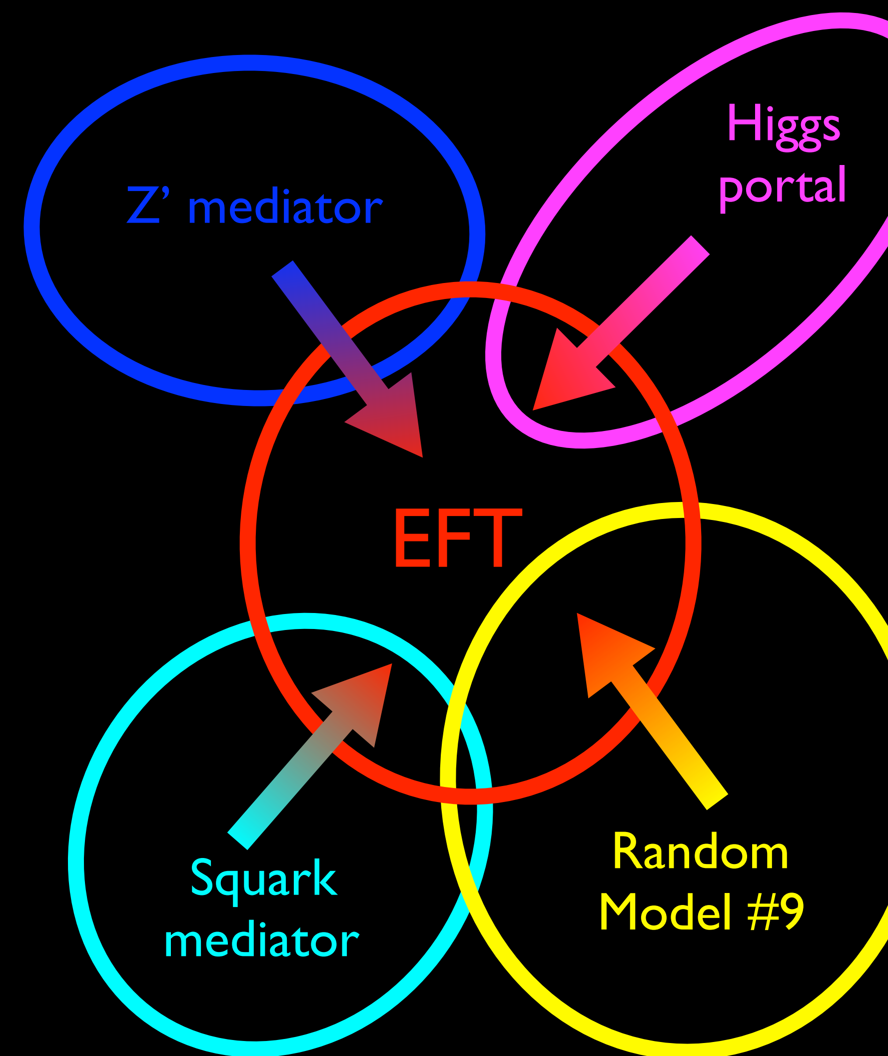
There is a theoretical recast of the jets + MET data that indicates ~2.5σ excesses over backgrounds.

Contact Interactions



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

- 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_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.