EFTs for Dark Matter

Tim M.P. Tait
University of California, Irvine

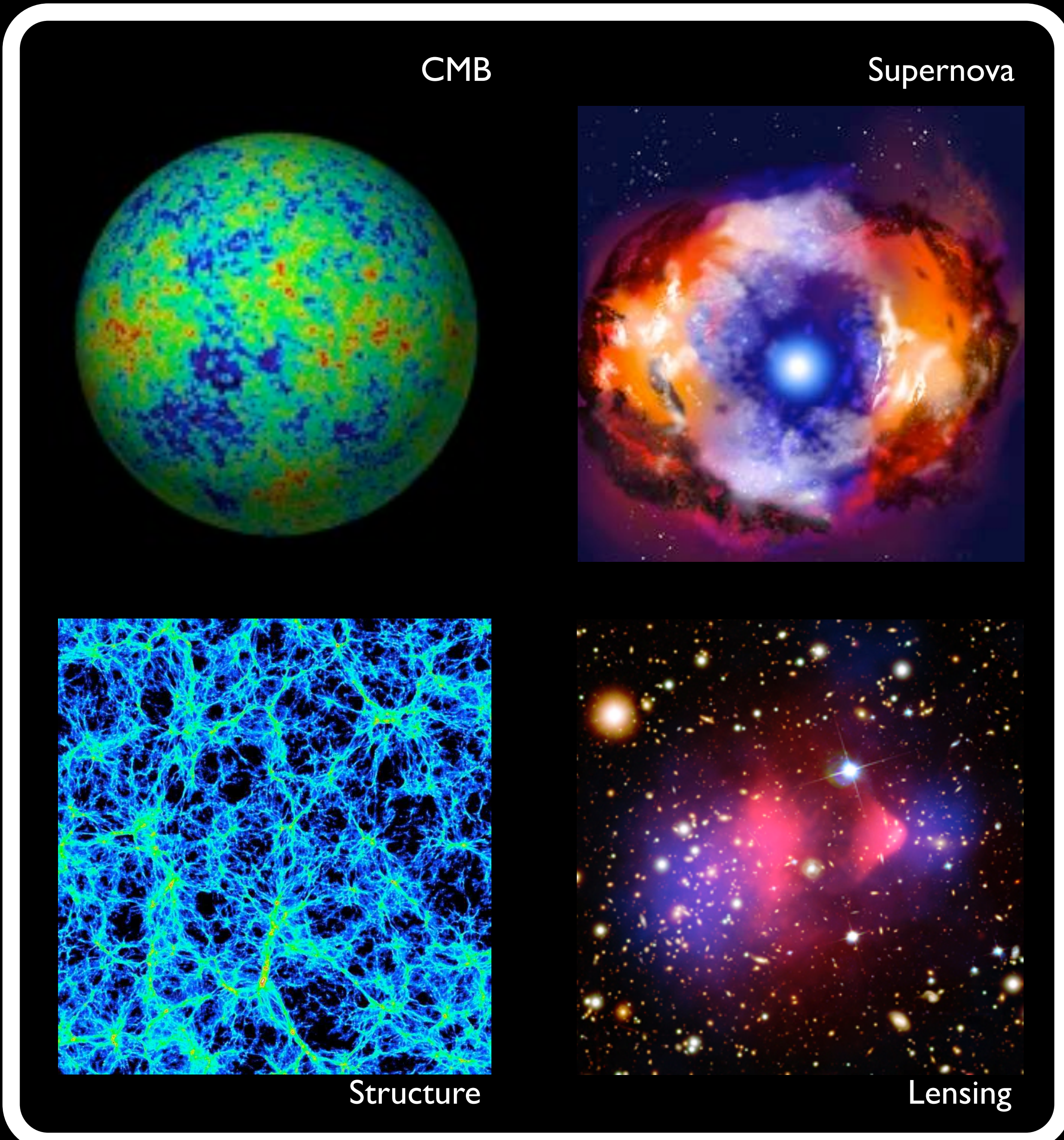
IMEPNP
February 9, 2022

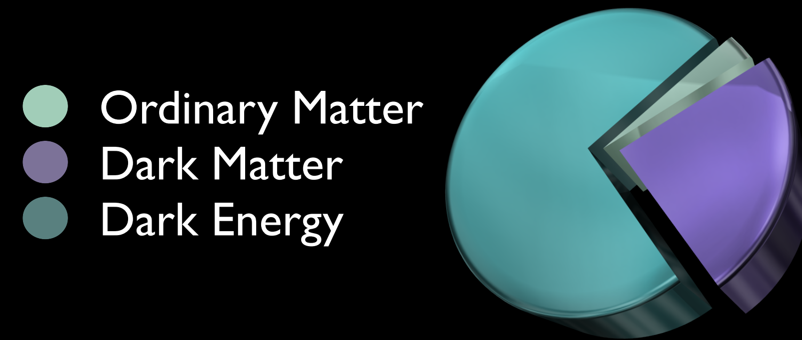
EFTs in DM

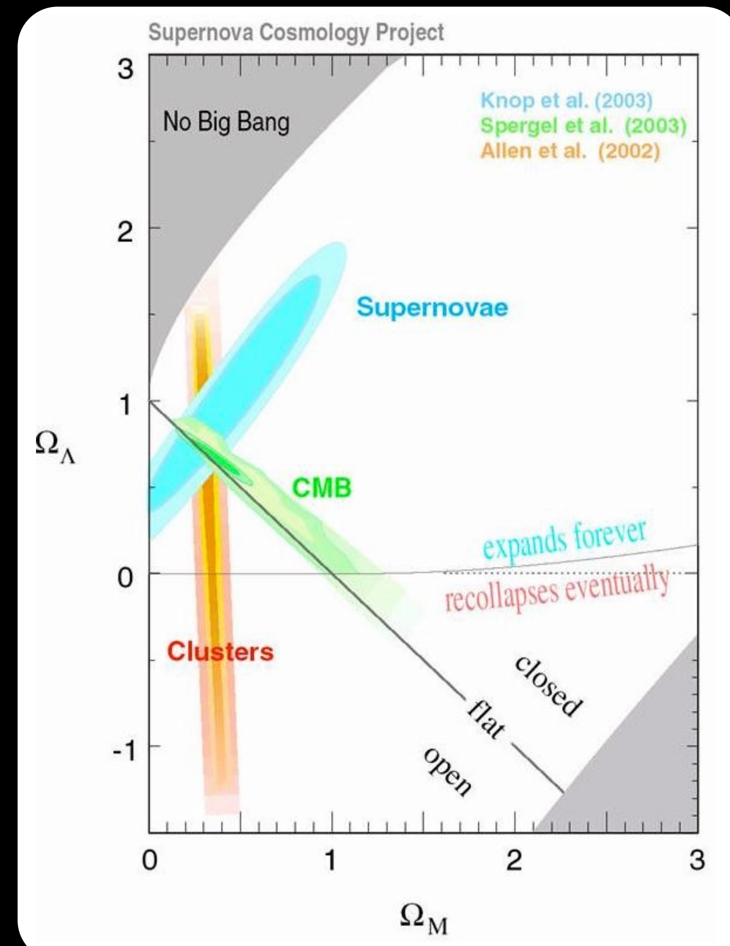
- We see EFTs used in dark matter research in much the same way they are used in other fields. All applications rely on the fact that EFTs are the universal low energy limits of many UV theories:
  - EFTs can parameterize our ignorance, giving us a framework we can use to describe a generic UV theory in a certain limit.
  - EFTs often easier to work with than full UV theories, allowing us to simplify calculations.
  - EFTs can sometimes be used to describe theories which are difficult to deal with because they involve strong coupling or other pathologies.

Generic Features of DM EFTs

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
1
0
-1
0
1
2
3

What is Dark Matter?

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

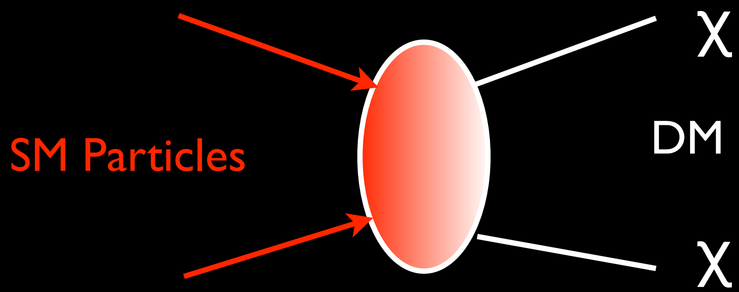
- It's remarkable that measurements on very different scales all indicate a self-consistent picture of a Universe containing dark matter.
- As a particle physicist I want to know how dark matter fits into a particle description.
- What do we know about it?
  - Dark (neutral)
  - Massive
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).

EFT Features

- These features guide the typical construction of an EFT description of dark matter.
- For the DM to be approximately stable, any decay process must be suppressed. Typically any interaction term must contain two dark matter particles (or at least, two particles charged under a symmetry that stabilizes it).
  - Very weak couplings could also work (e.g. dark photons, sterile neutrinos, axions…)
- The Lorentz representation (spin, complexity, etc) and SU(2) representation (with a neutral component) are not determined, and must be chosen.
  - If SU(2)-charged, there will necessarily be renormalizable interactions with the SM.
- A few cases (e.g. Higgs portal) allow for renormalizable interactions, but in many cases the leading interactions will be non-renormalizable.

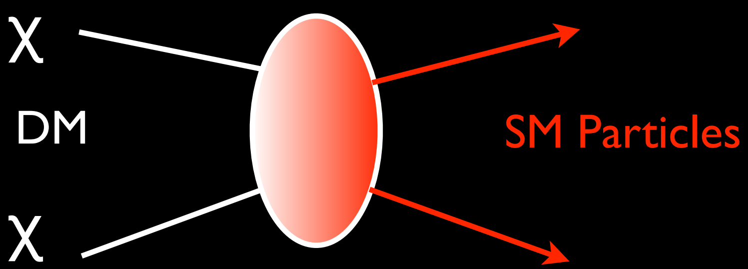
Parameterizing Ignorance
(& Simplifying Calculations!)

Particle Probes of DM



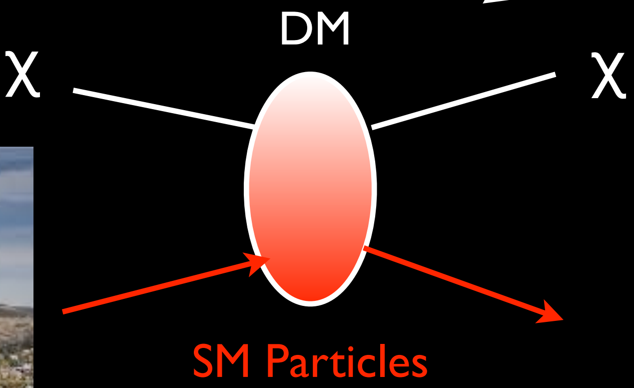
Indirect Detection

Collider Searches



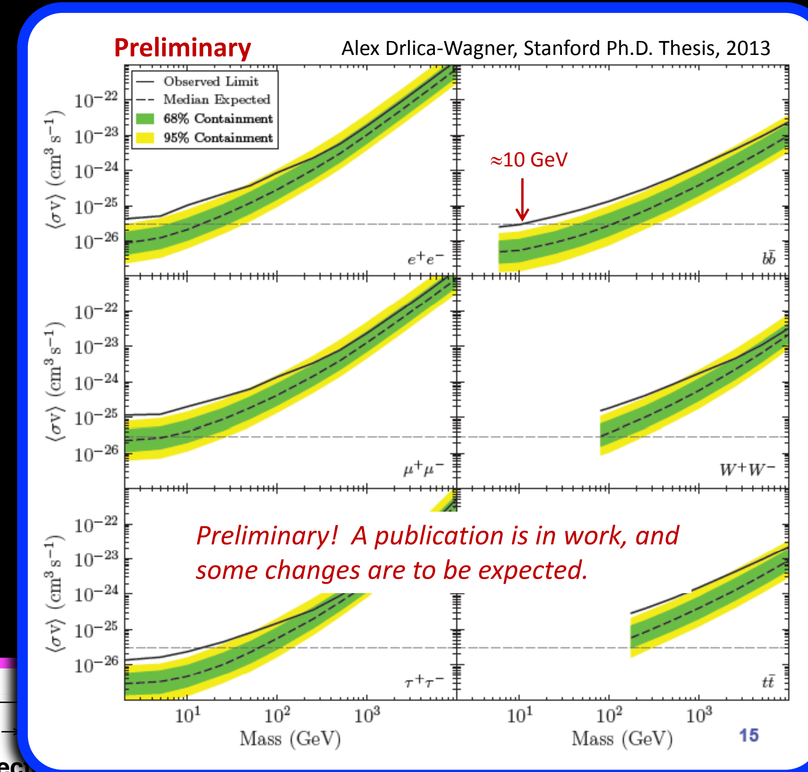
These searches are all attempts to understand how DM couples to ordinary matter

Direct Detection

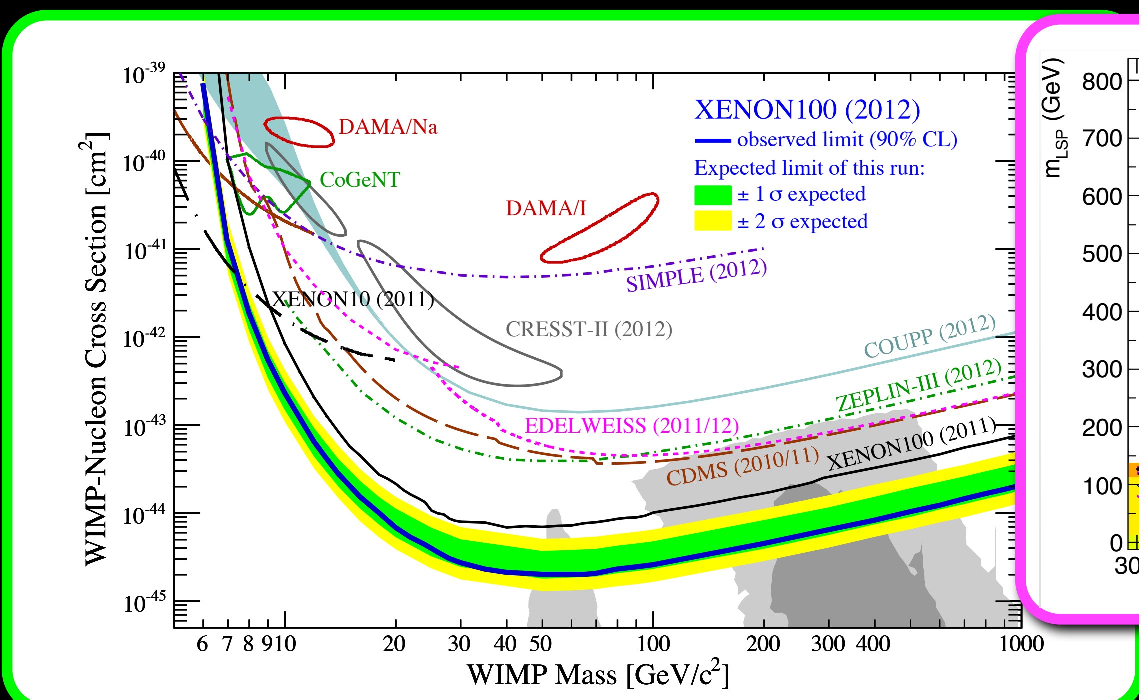


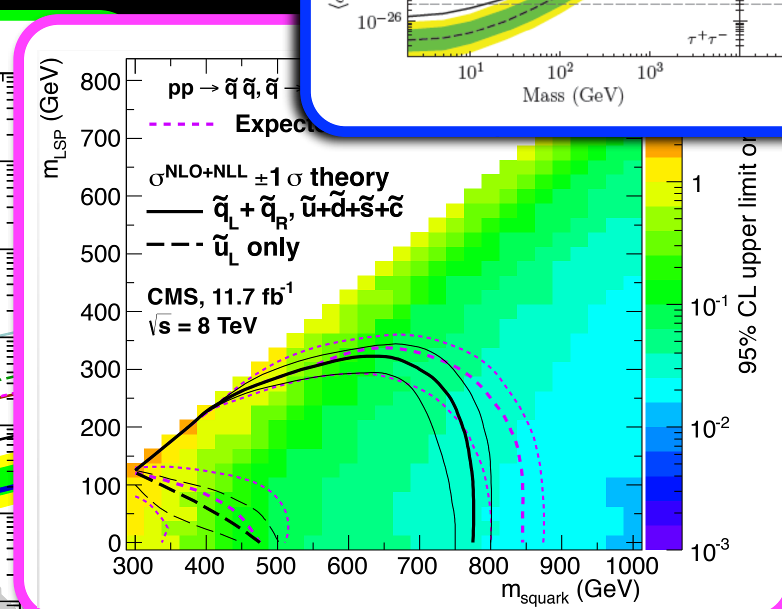
We Need (a) Theory

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

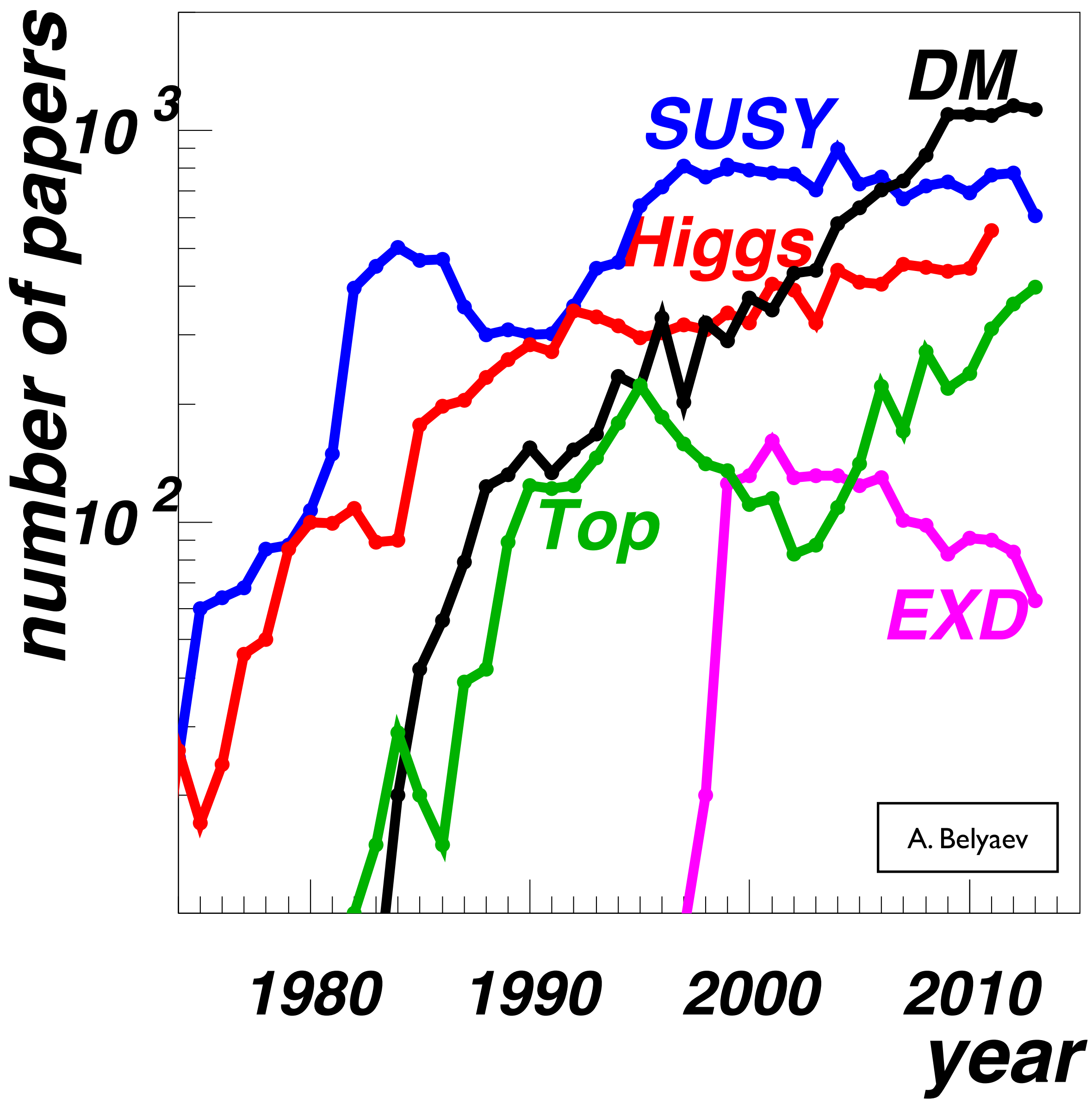


But we *know* they are all attempts to characterize the same thing(s)...

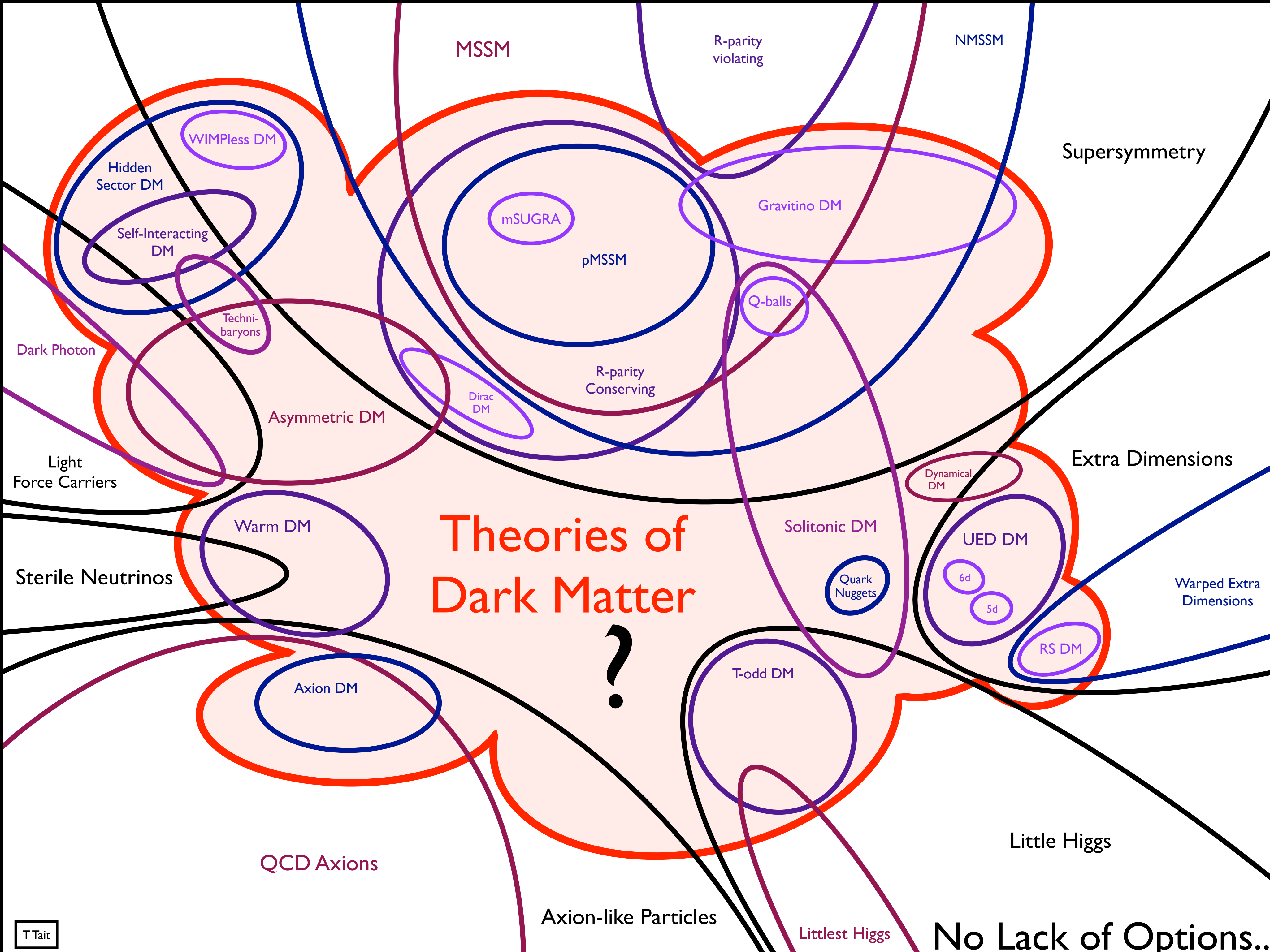




Which theory to use?

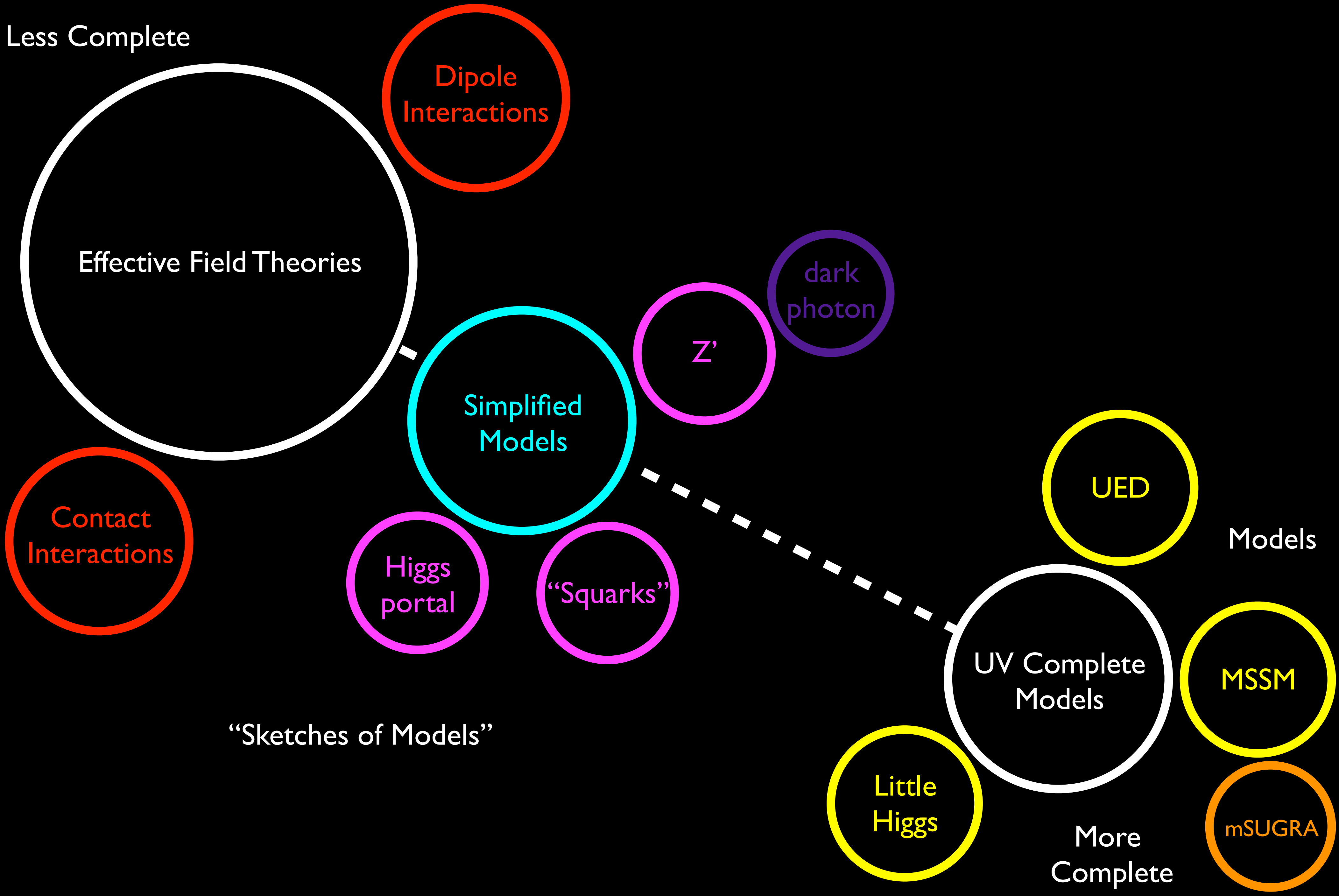


number of papers
10 3
10 2
SUSY
DM
Higgs
Top
EXD
A. Belyaev
1980
1990
2000
2010
year



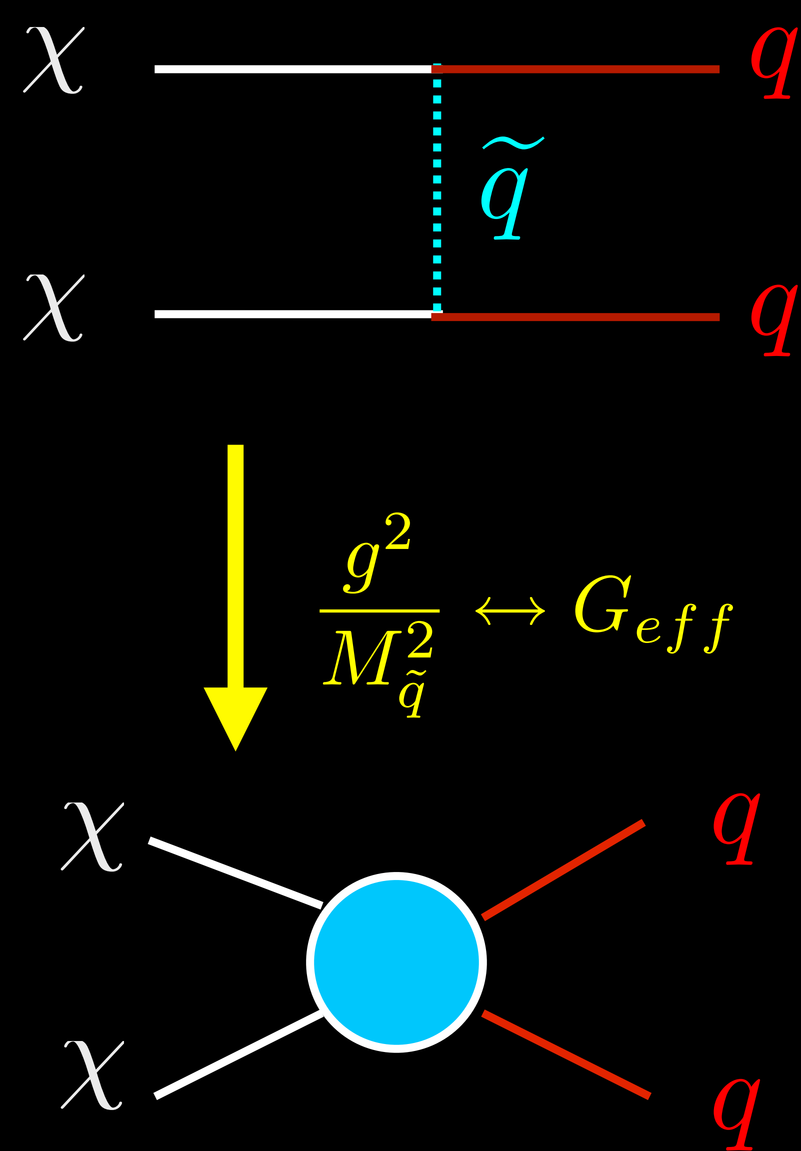
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
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
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 fail to describe 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
M4	qq	$m_q/2M_*^3$	γ_5	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	-
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.

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- 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

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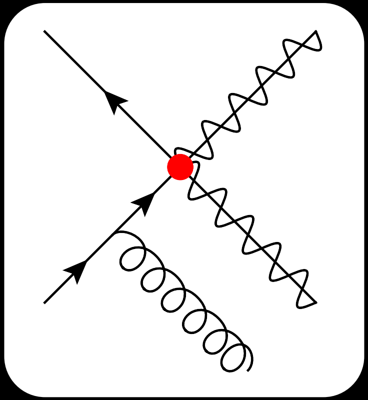
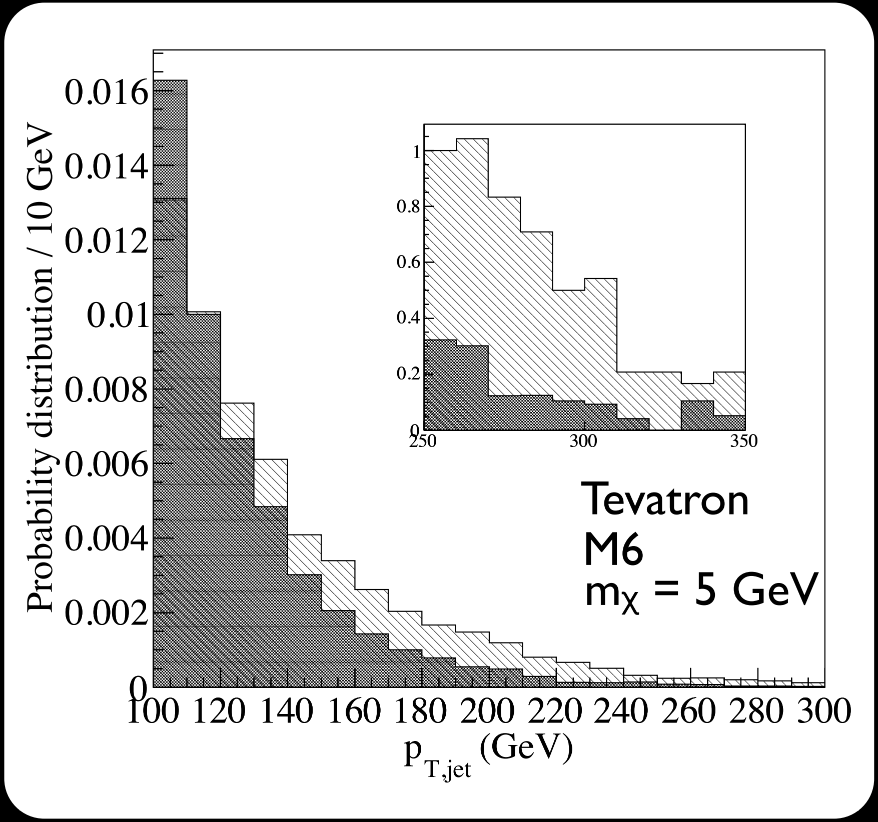
Collider Searches

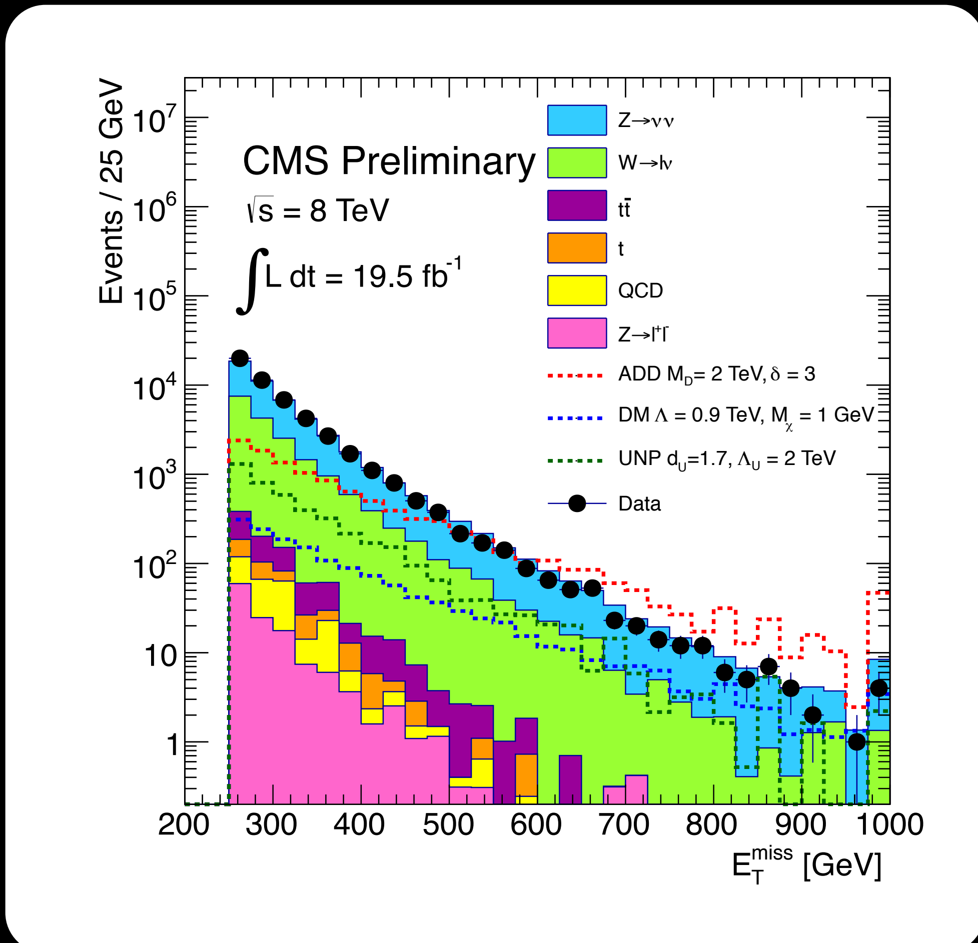
- At colliders, one searches for this type of theory by producing the dark matter directly.
- Since the detector needs something to trigger on, one looks for processes with additional final state particles, and infers the presence of dark matter based on the missing momentum it carries away from the 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.

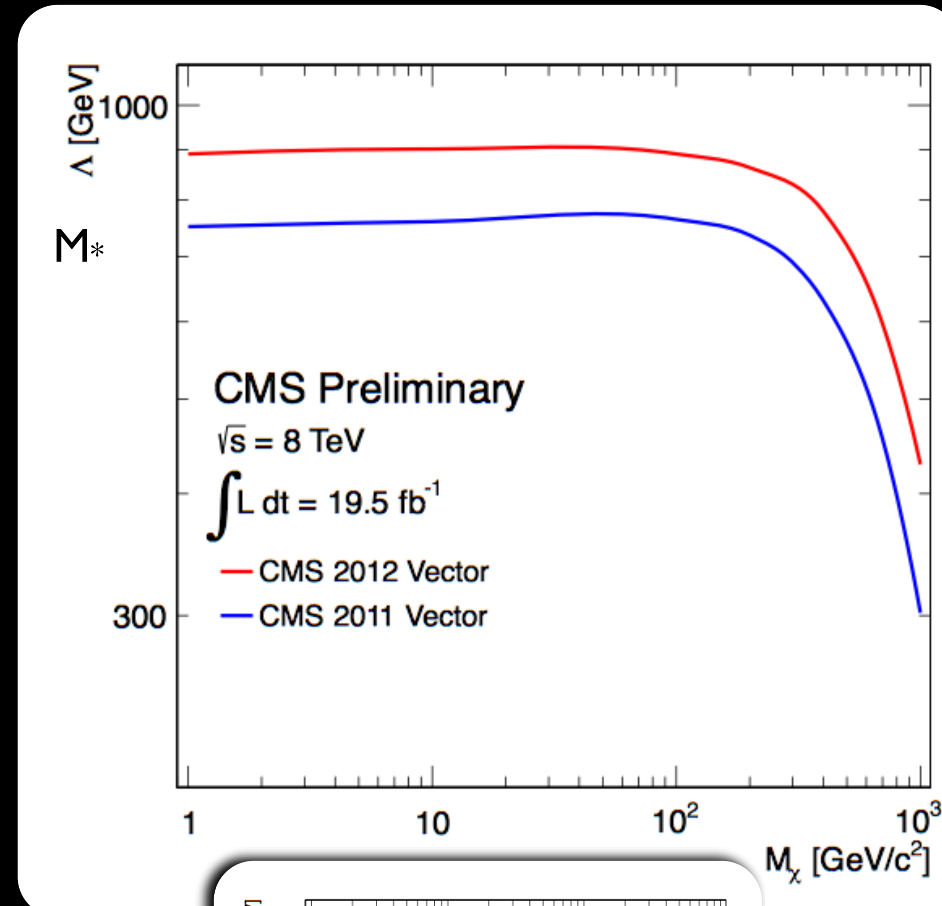


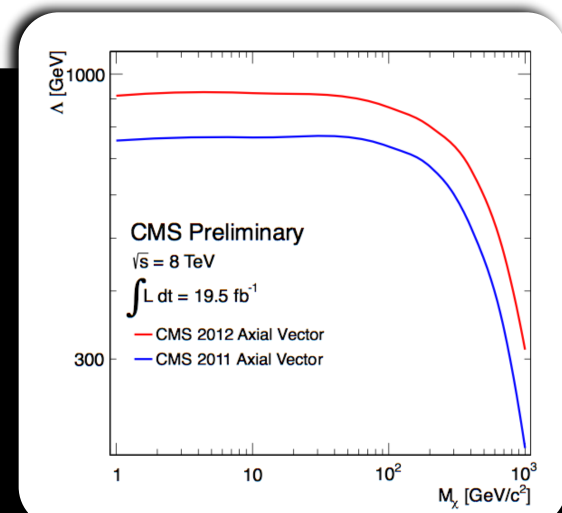
Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP



Collider Results

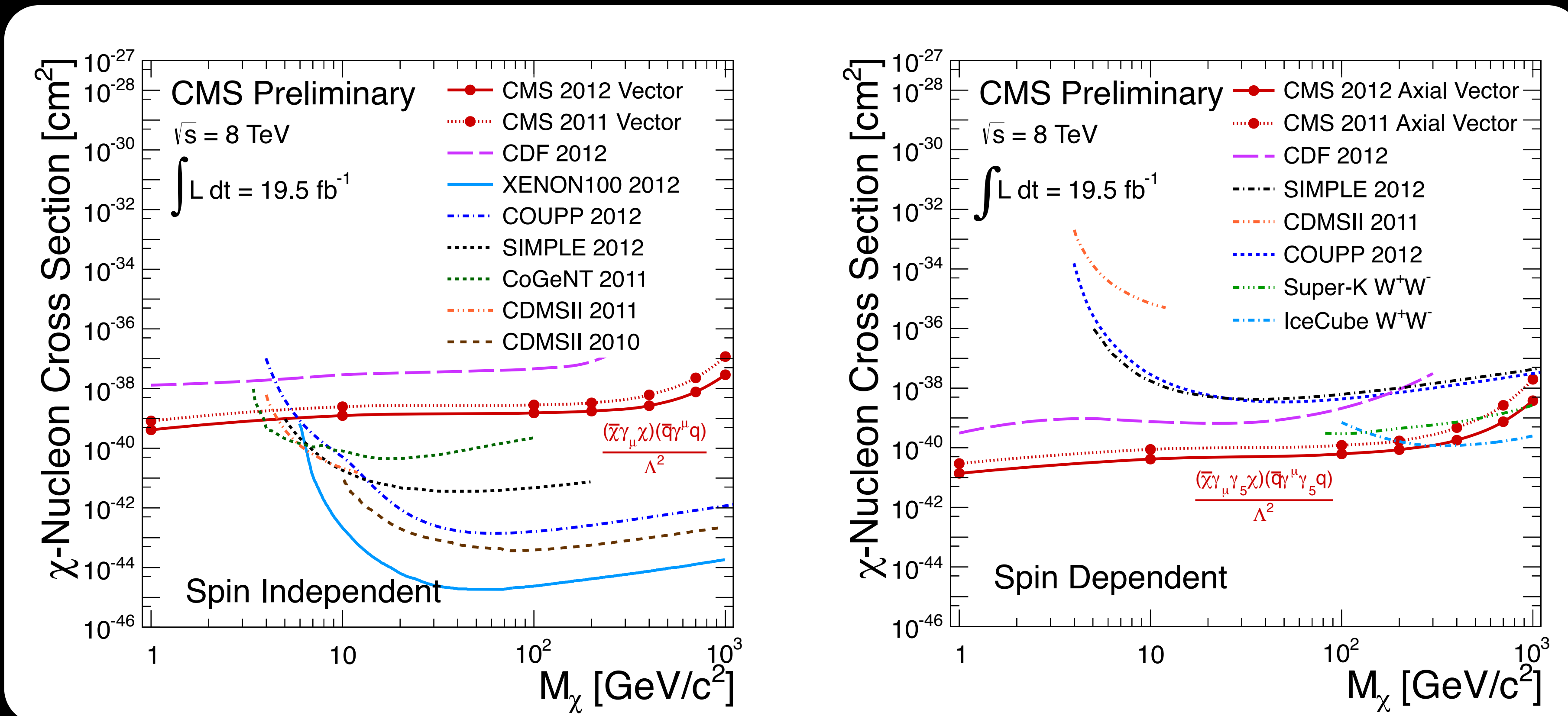






Both CMS and ATLAS have results interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

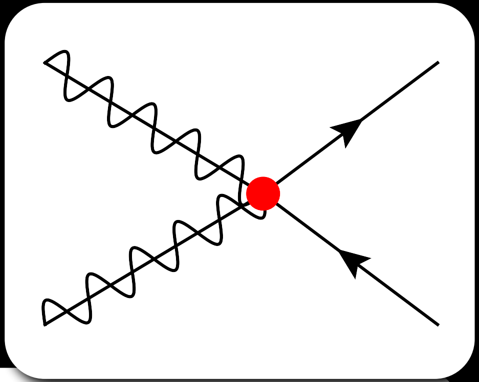
Translation to Elastic Scattering



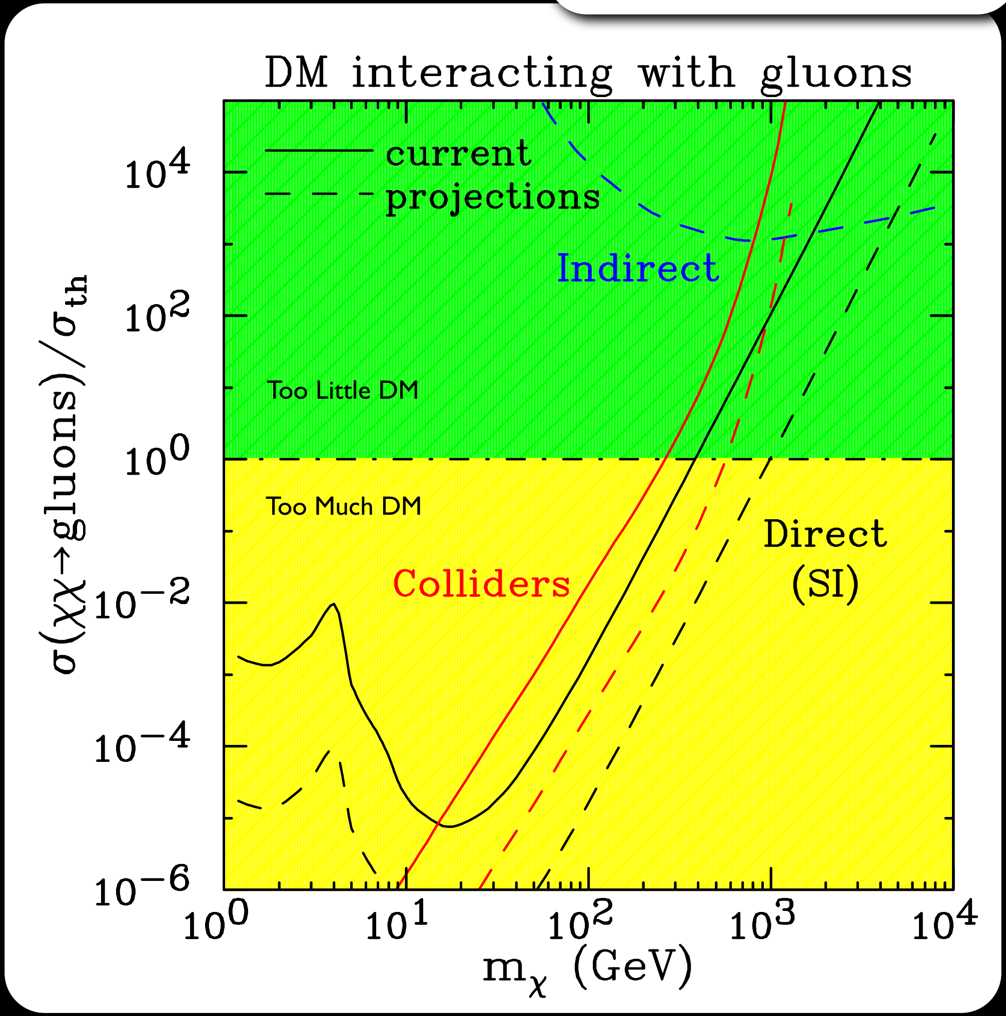
See: Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB; Bai, Fox, Harnik 1005.3797 & JHEP; and lots of other papers…

- 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

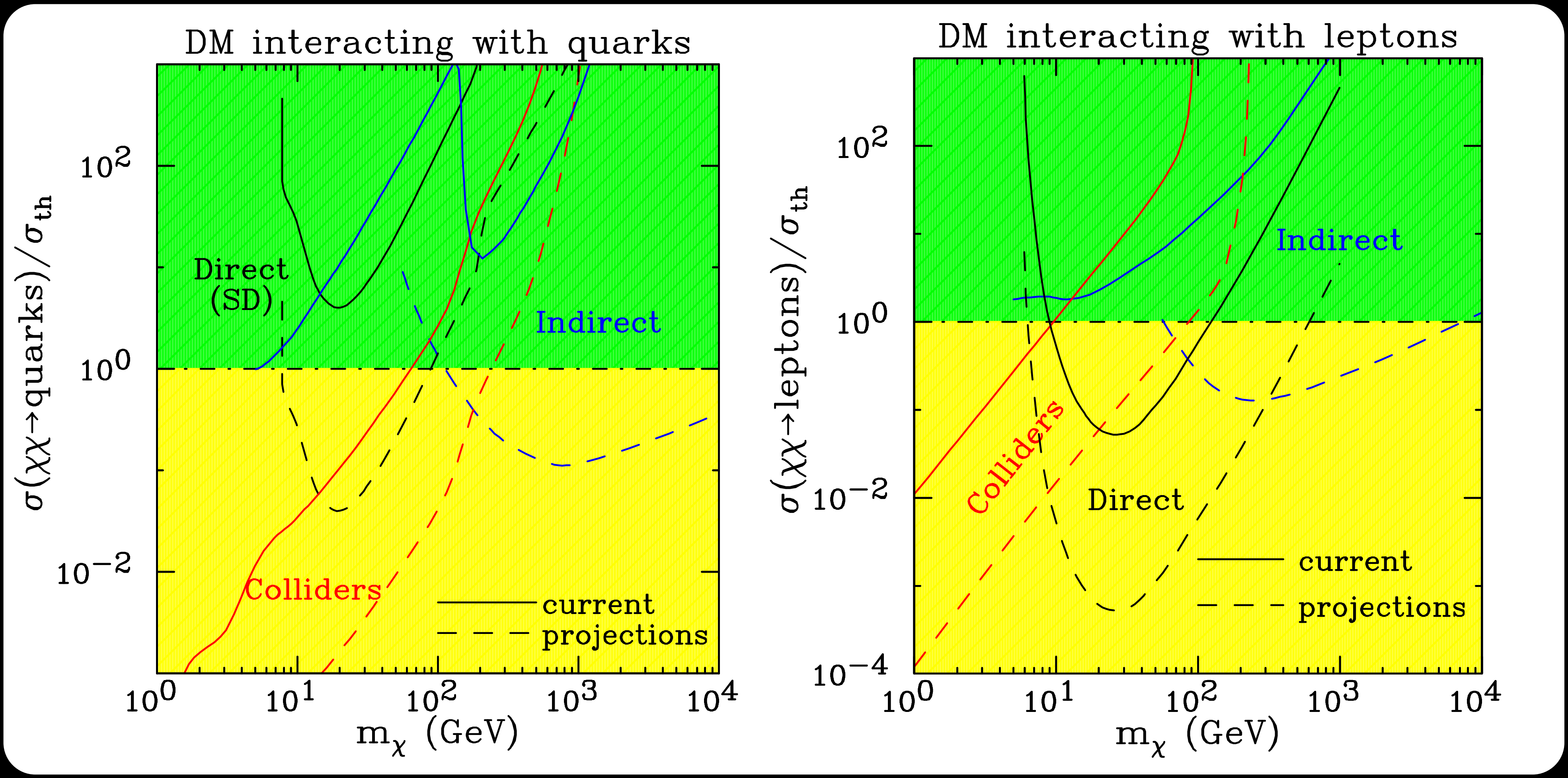


- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders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

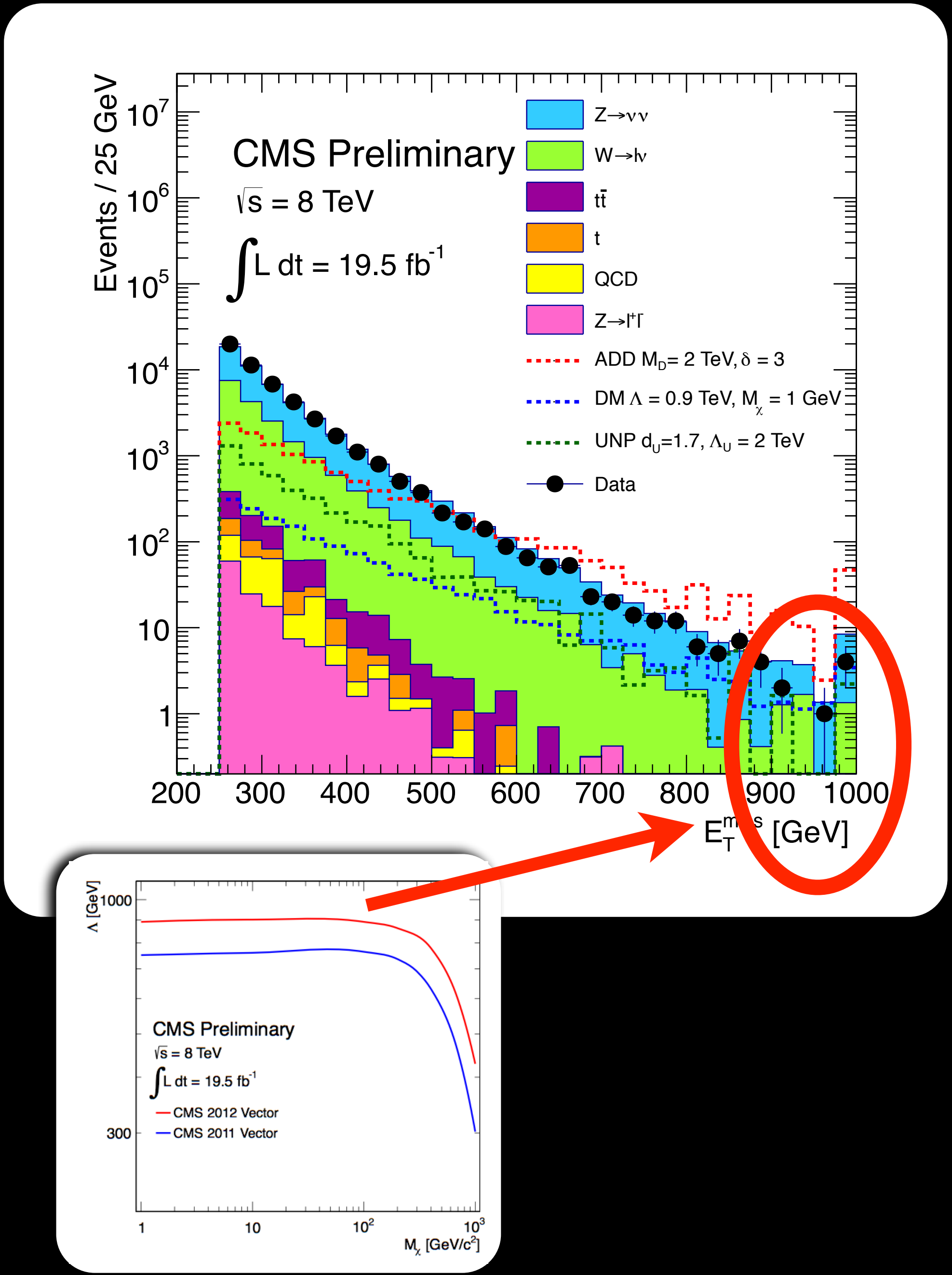
Quarks & Leptons



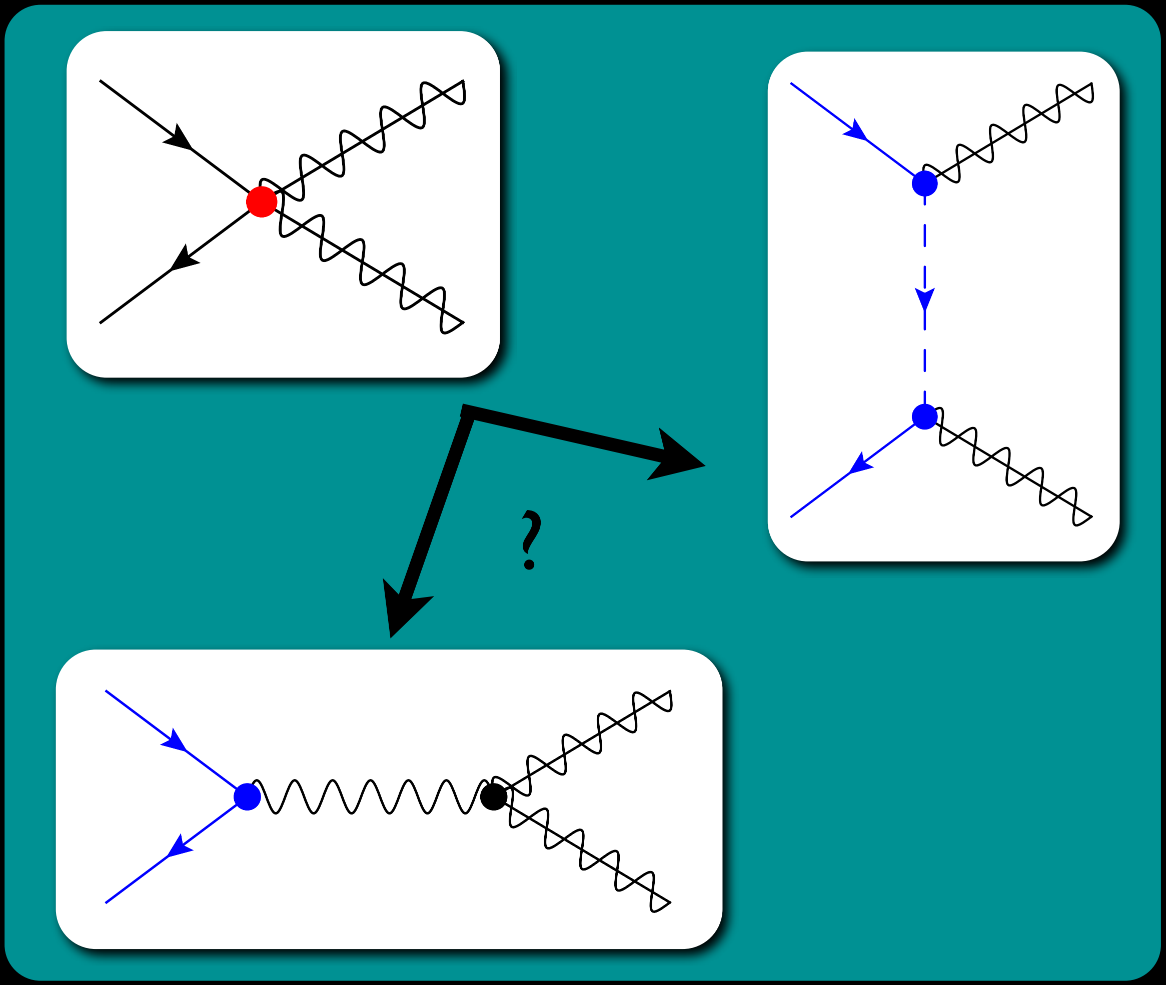
DM Complementarity, arXiv:1305.1605

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 might be 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.]



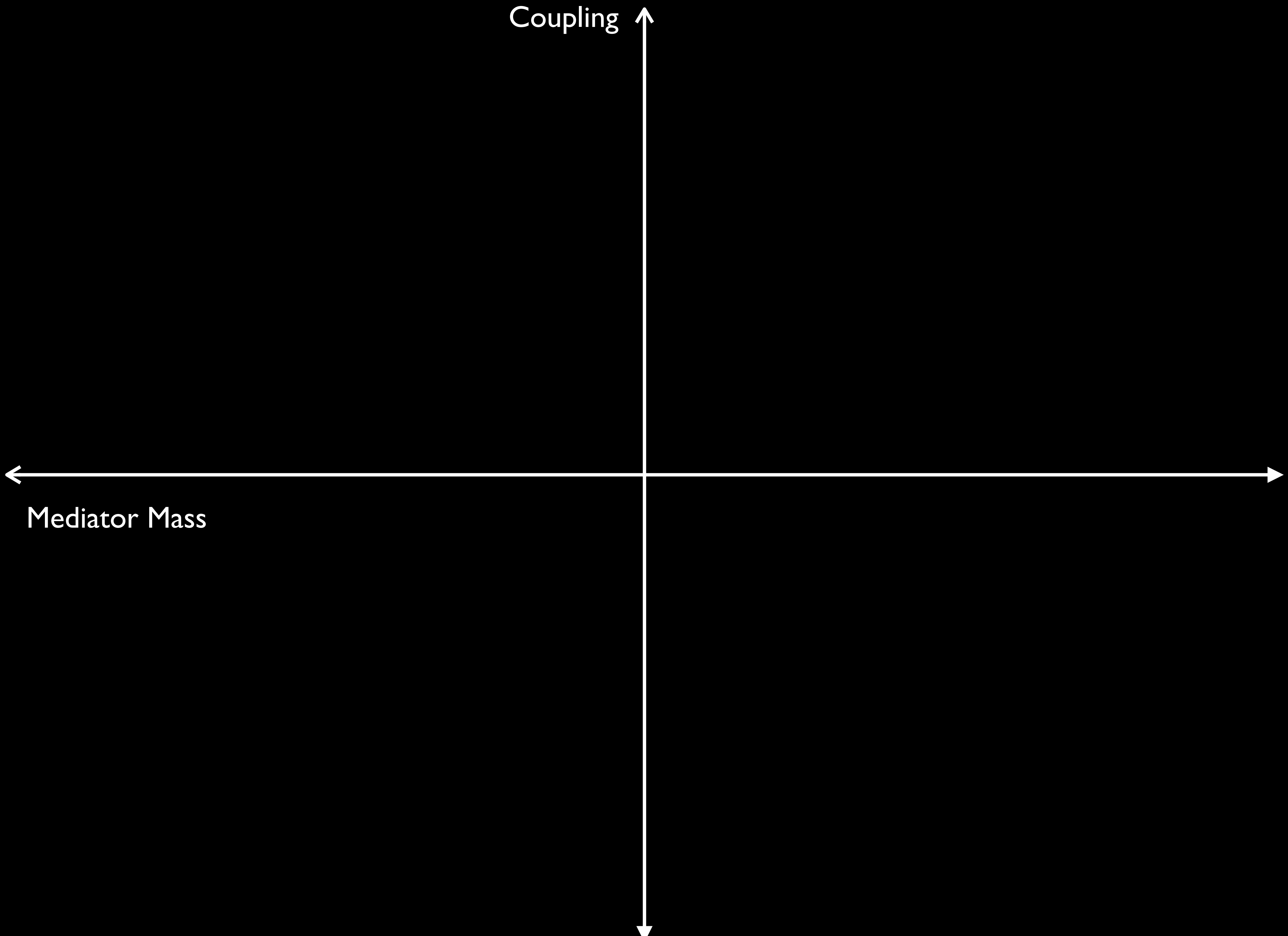
Simplified Models?

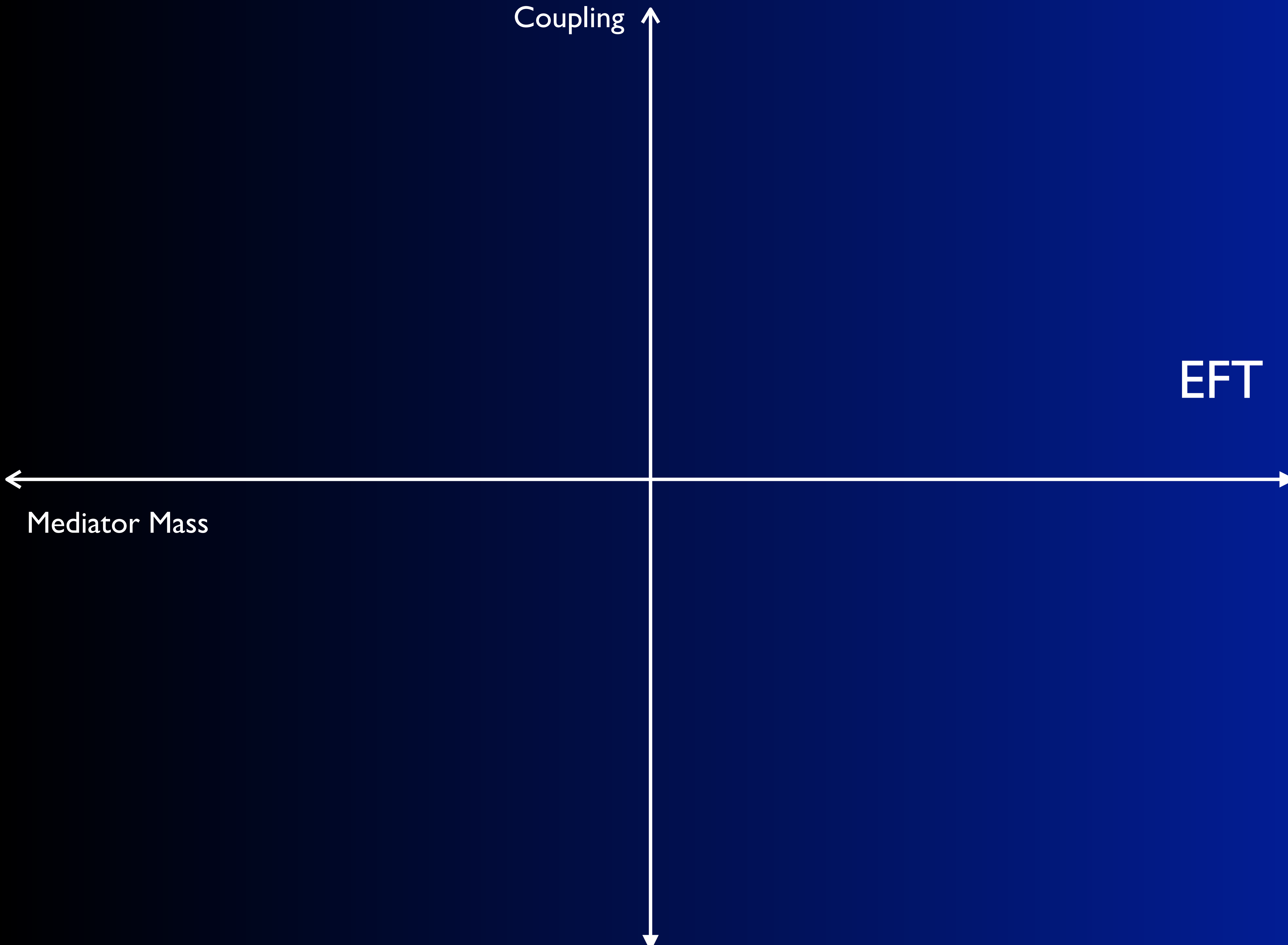


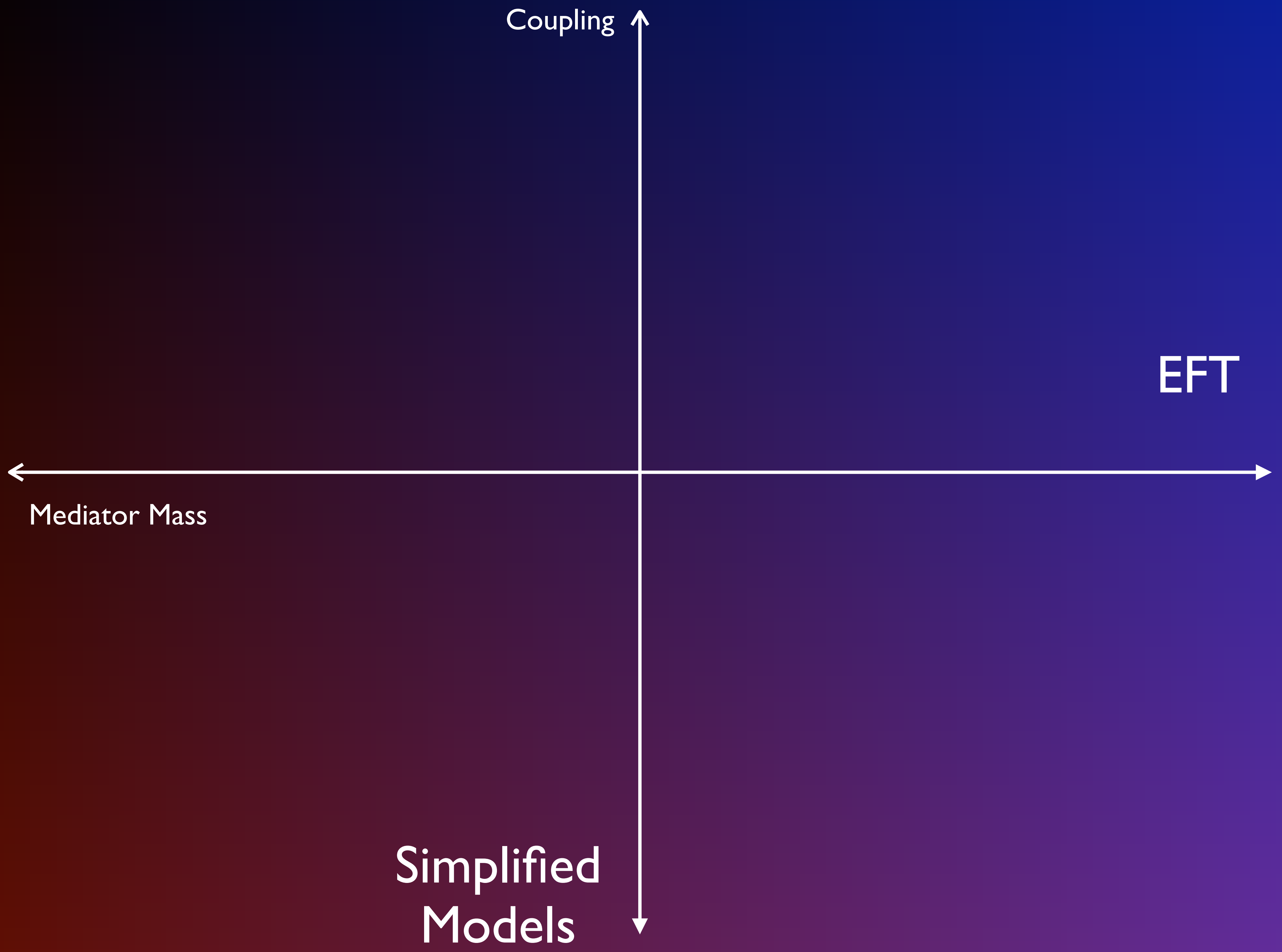
“t-channel” mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

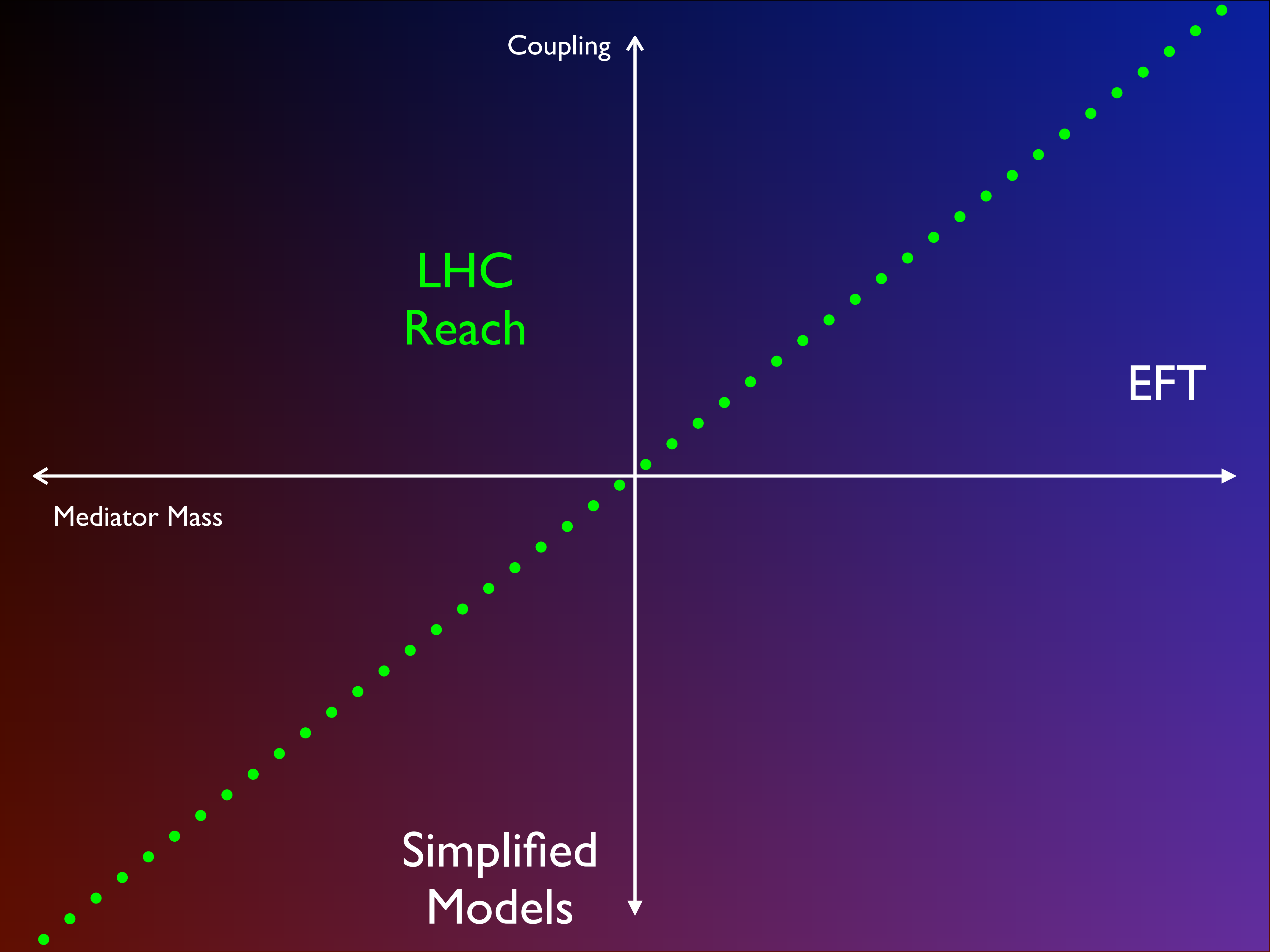
“s-channel” mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

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

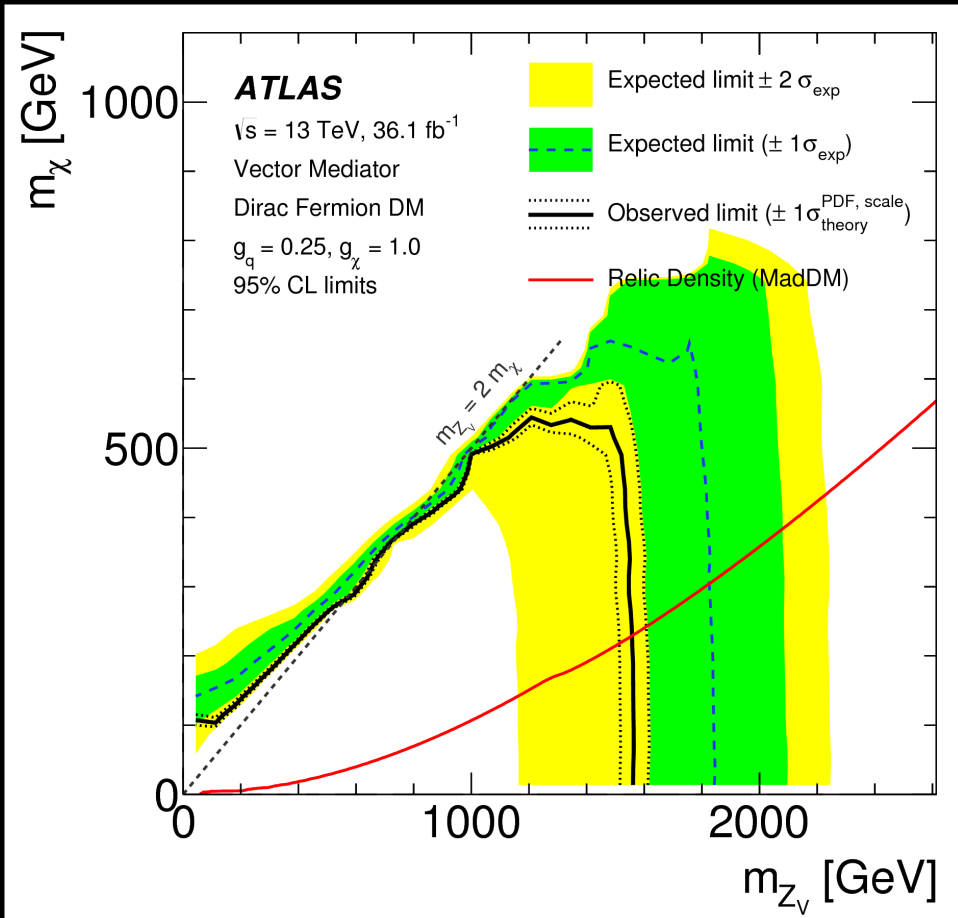

Coupling
Mediator Mass

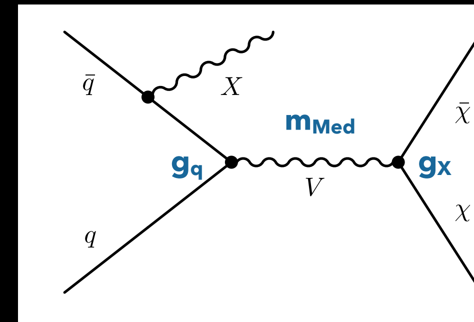

Coupling
EFT
Mediator Mass

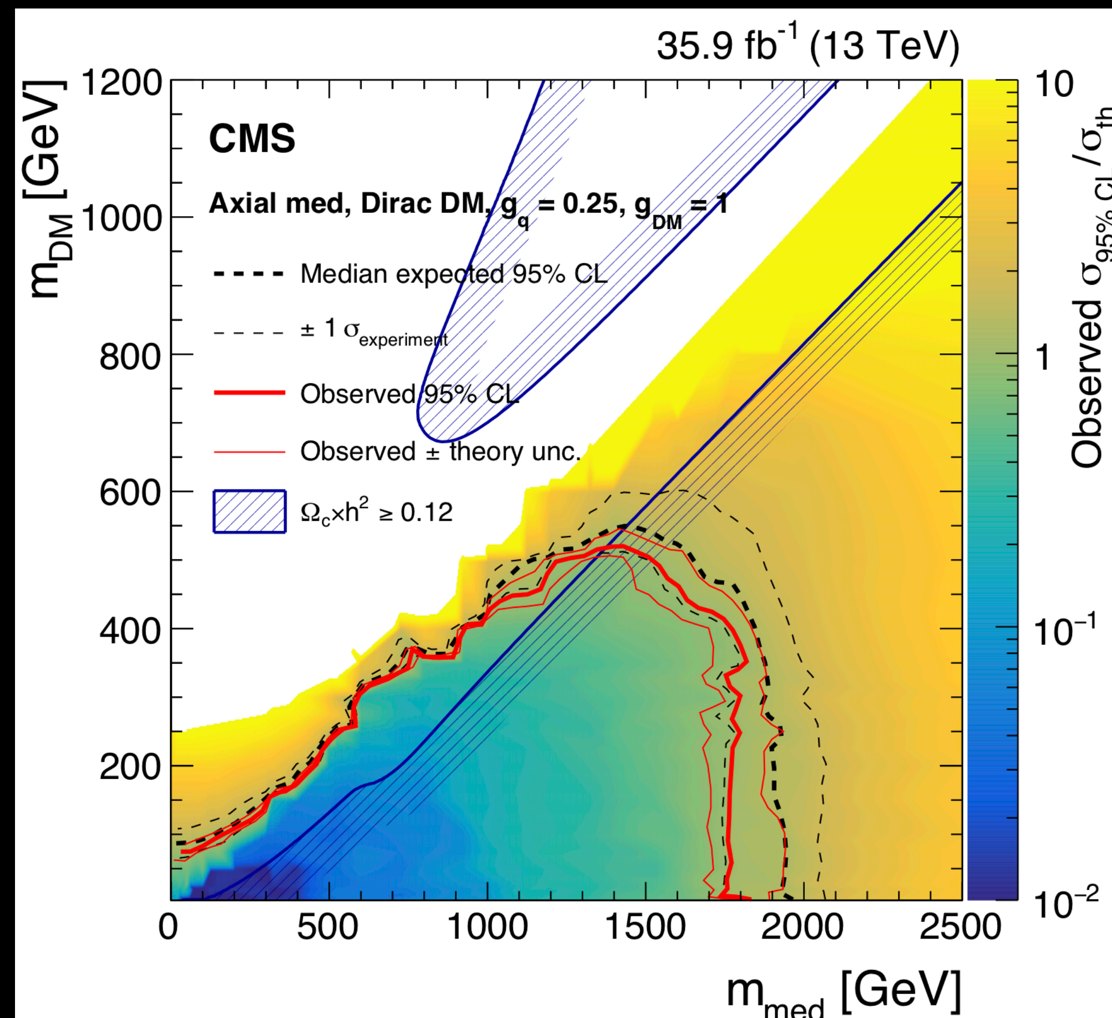

Coupling
EFT
Mediator Mass
Simplified
Models


Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

Mono-jet Searches

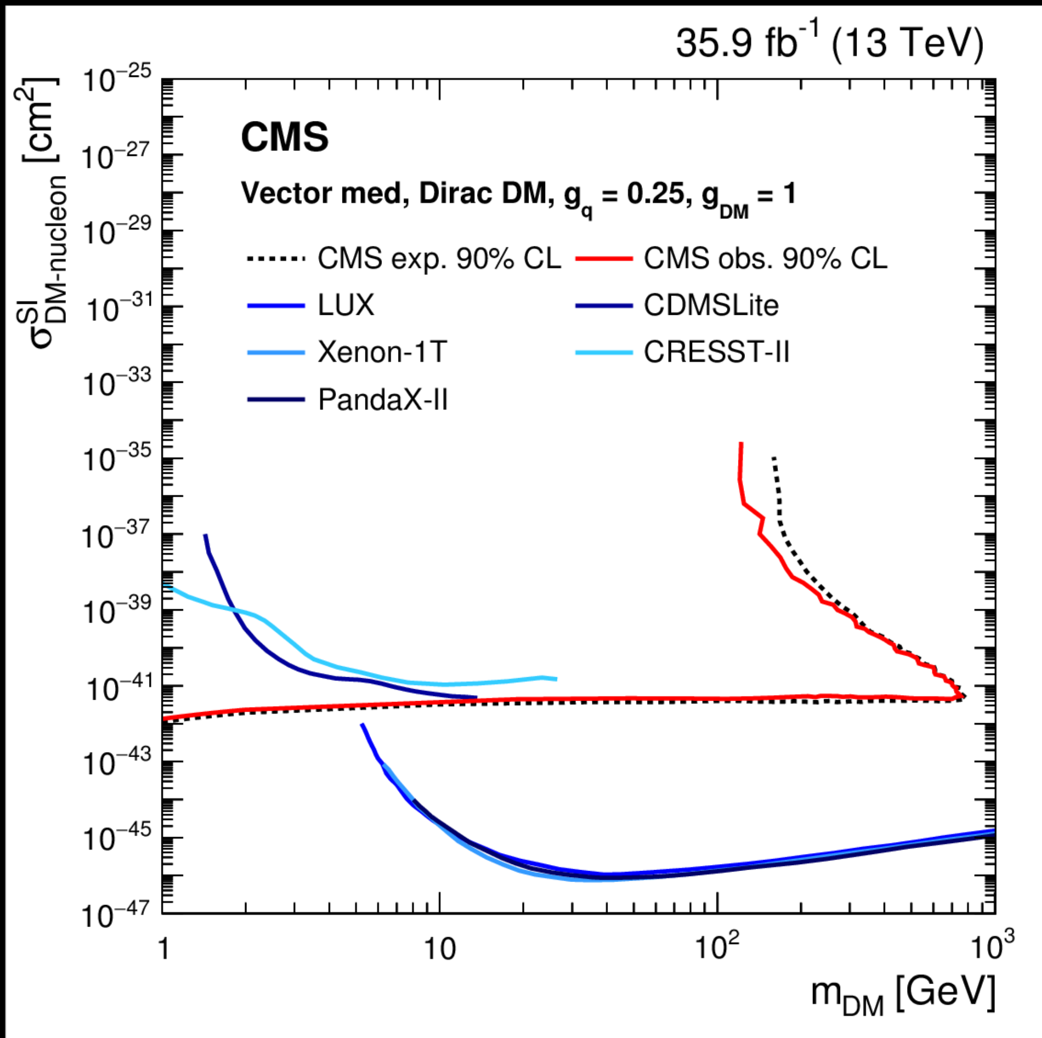




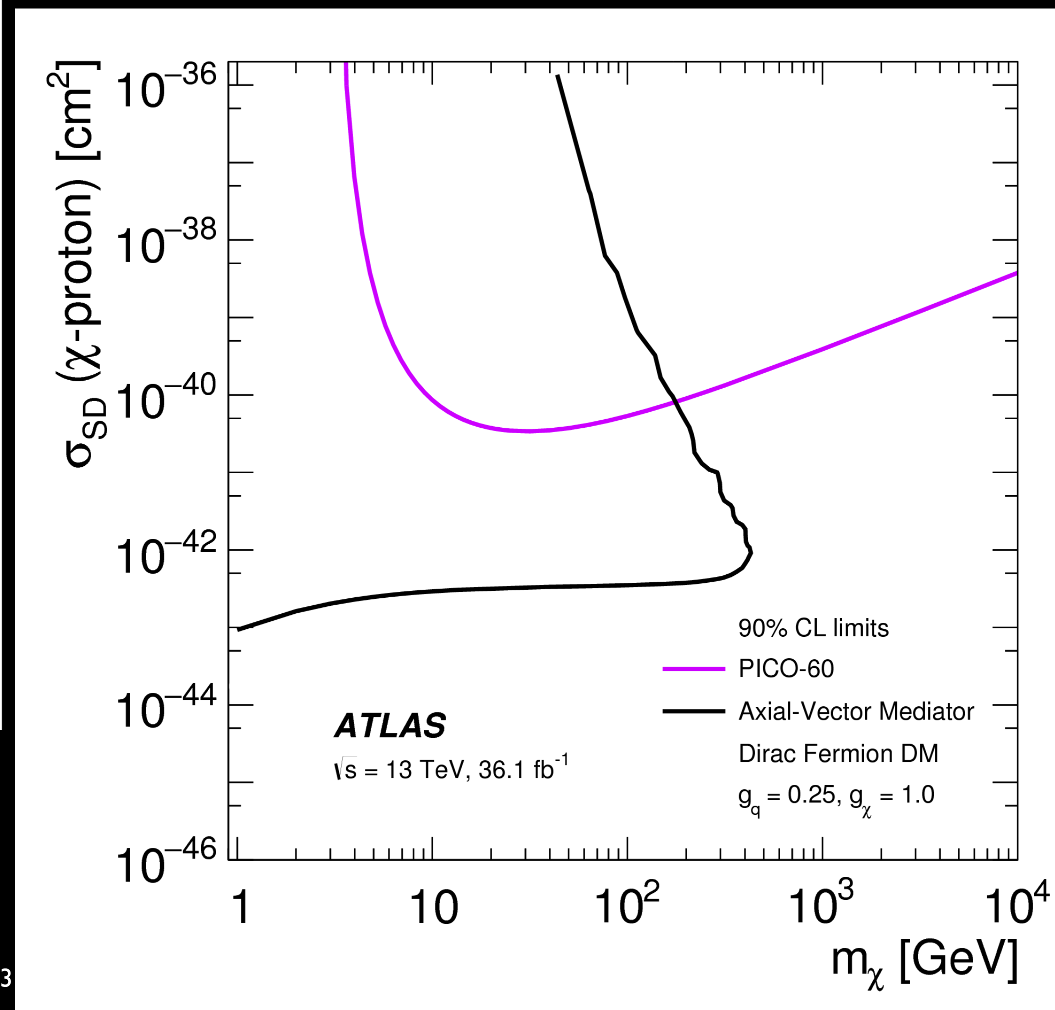


Searches for dark matter (missing momentum) plus a jet of hadrons places limits on the masses and couplings.

Axial Vector



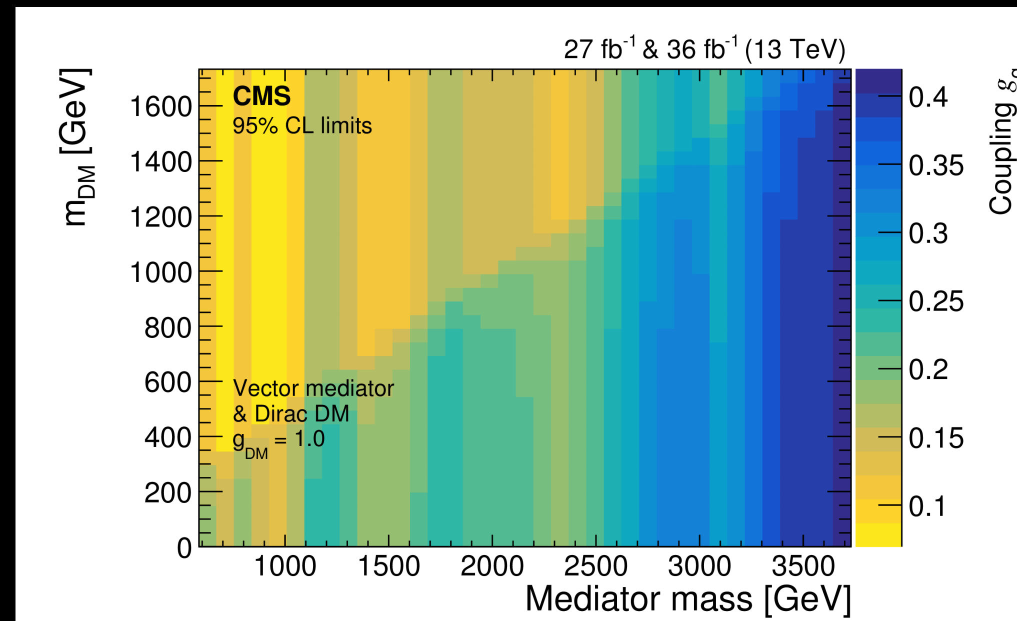
Mapped into the plane of Direct Detection

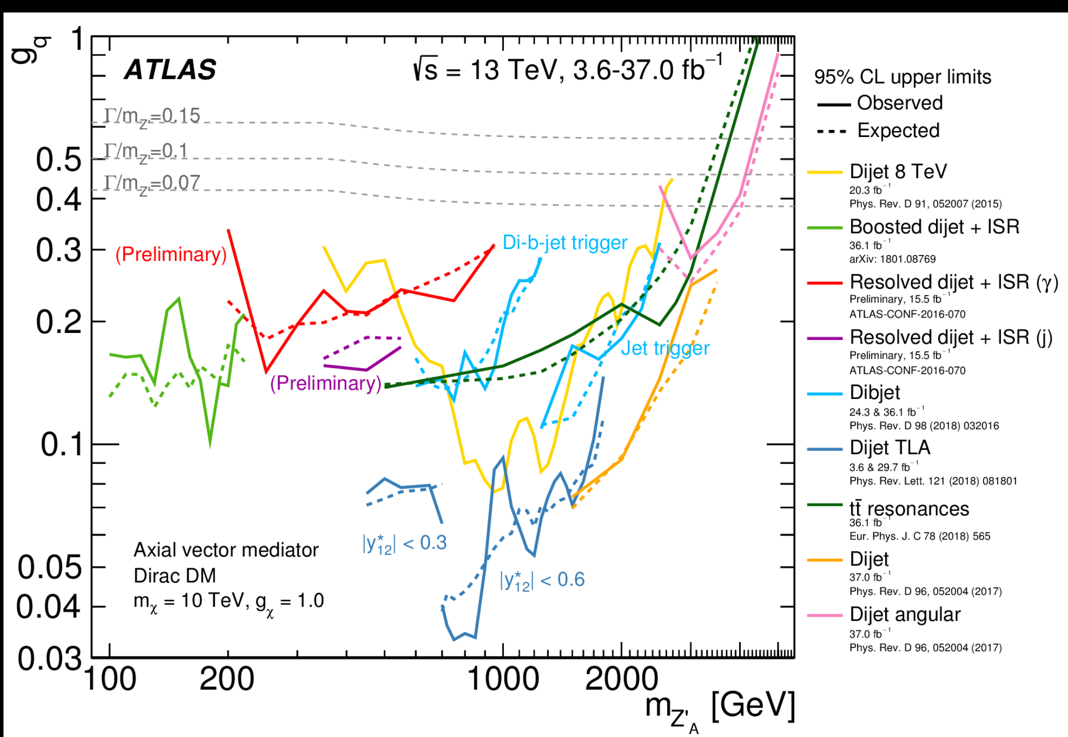


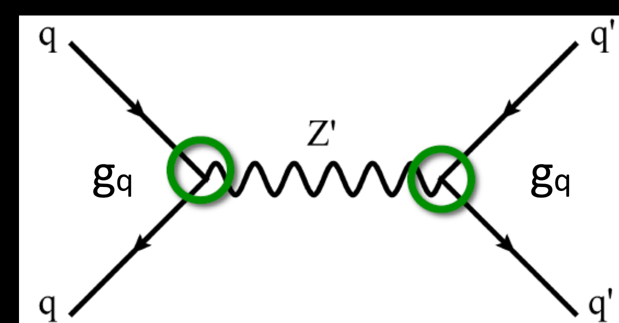
In the context of this simplified model, collider limits can be translated into the parameter space of the direct searches.

Mediator Searches

There are also searches purely for the mediator particles, by looking for cases in which it is produced and then decays back into ordinary particles such as electrons or jets of hadrons.

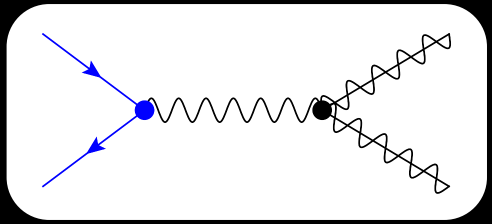


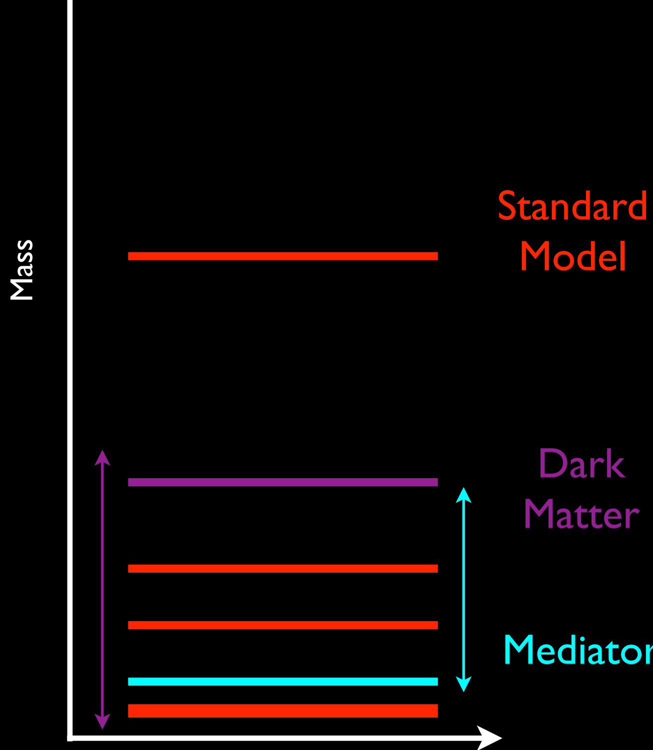




Dark Photons

- An interesting part of the parameter space has light mediating particles
- This opens up a window where the relic density turns out correctly for light (~MeV) dark matter.
- 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".
- This regime motivates different kinds of searches, including for long-lived and/or low mass ultra weakly interacting particles.

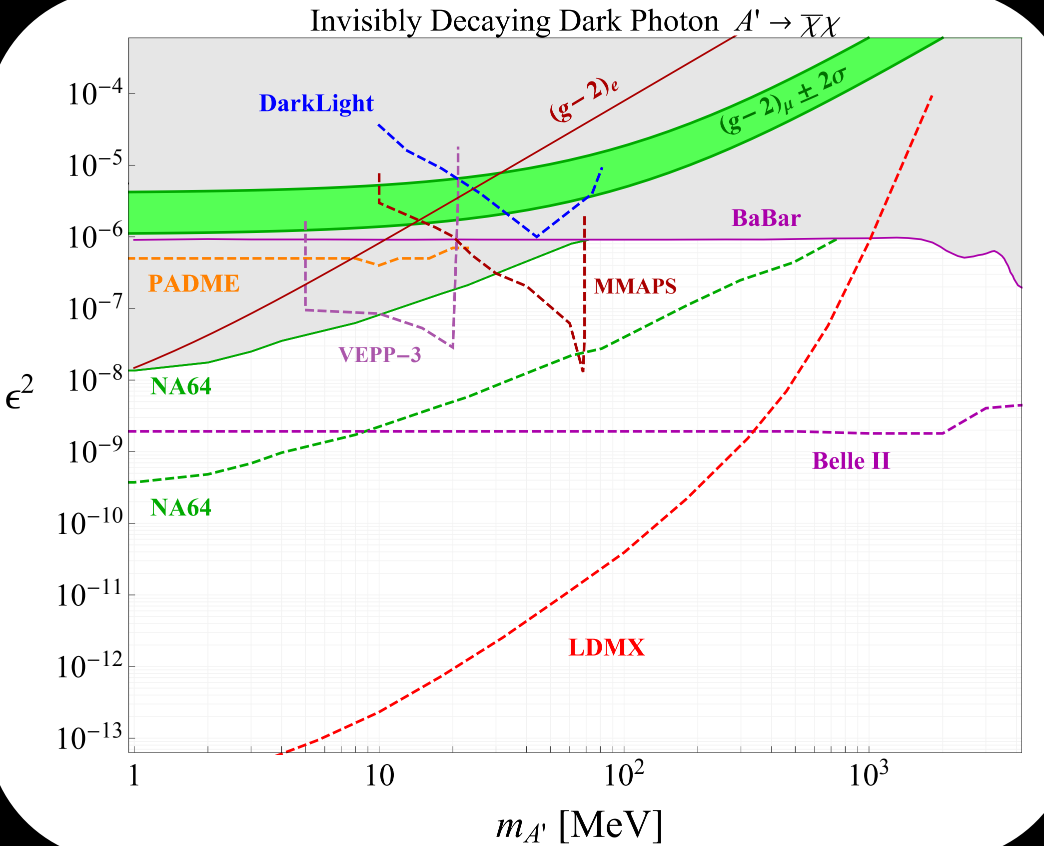




γ_D Parameters:

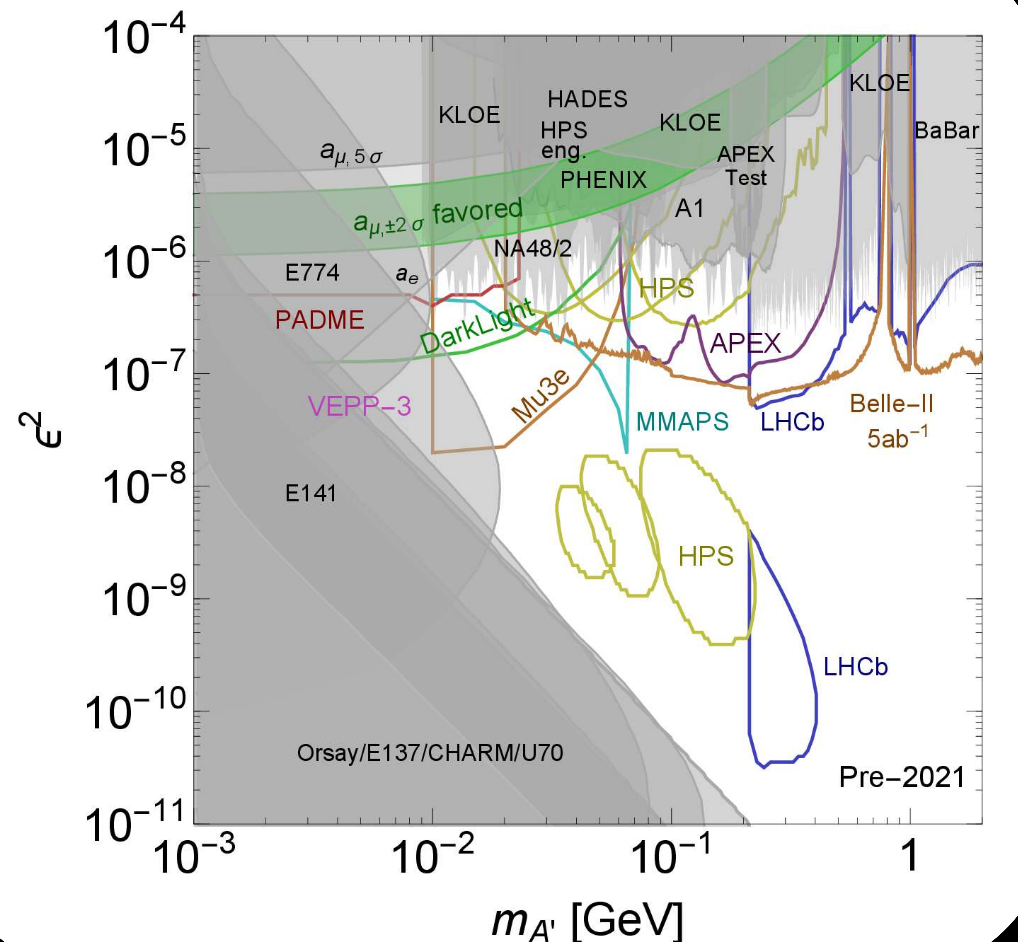
$$\{m_\chi, m_{A'}, \alpha_D, \epsilon\}$$

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.

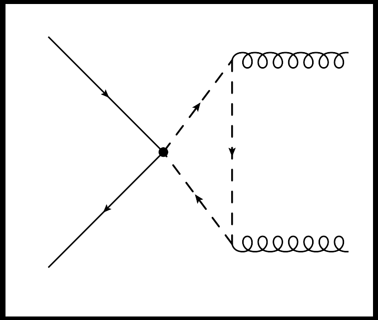
Dark Matter Coupled to Gluons

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

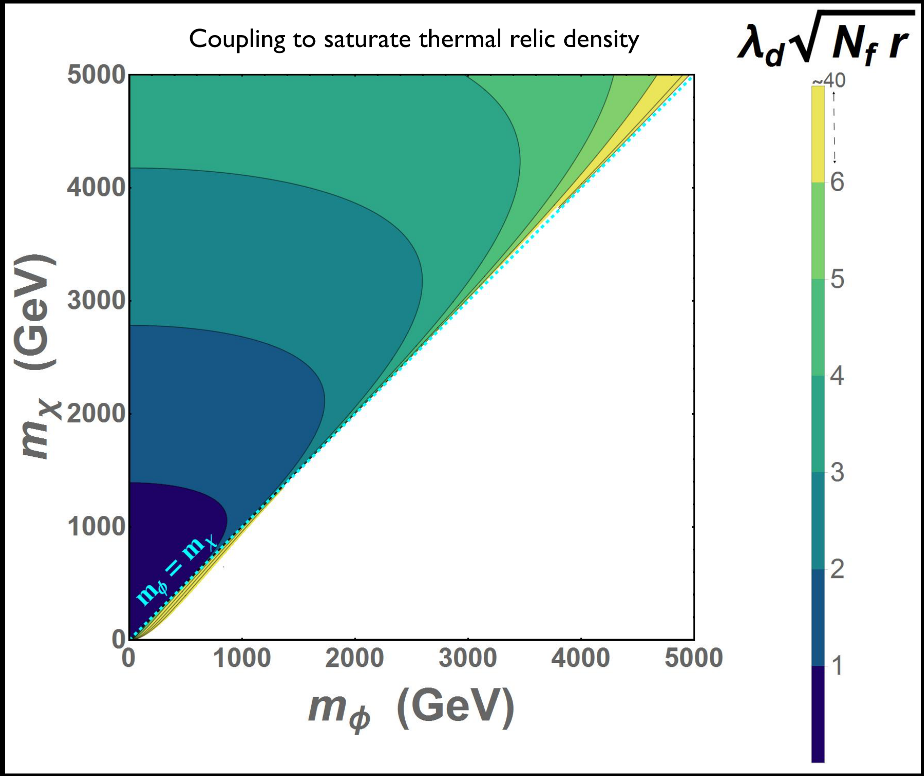
- An interesting variation is possible when both the dark matter and the colored mediator are scalars.
- In that case, a quartic interaction can connect the two.

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

- 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 $m_\phi < m_\chi$ so annihilation into $\phi\phi^*$ is open.

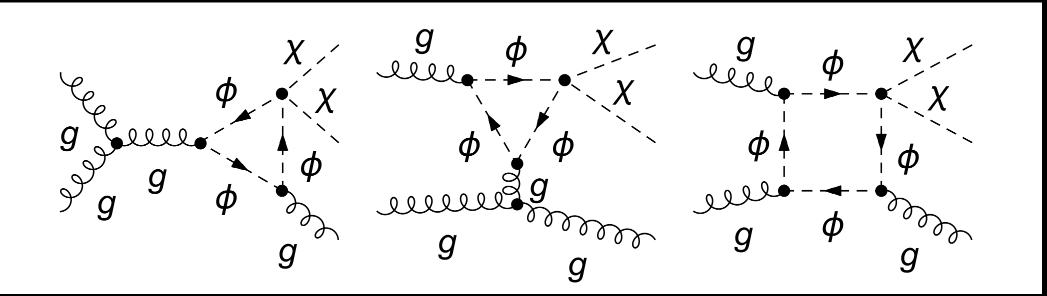


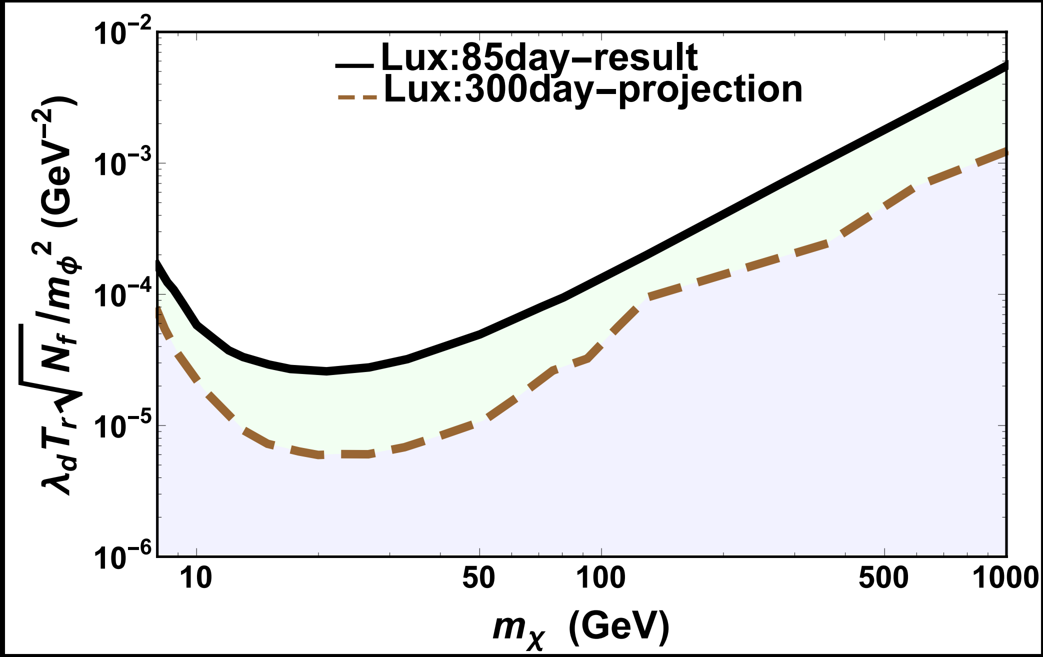
The dominant coupling to the SM is often at one loop to gluons!



DM Searches

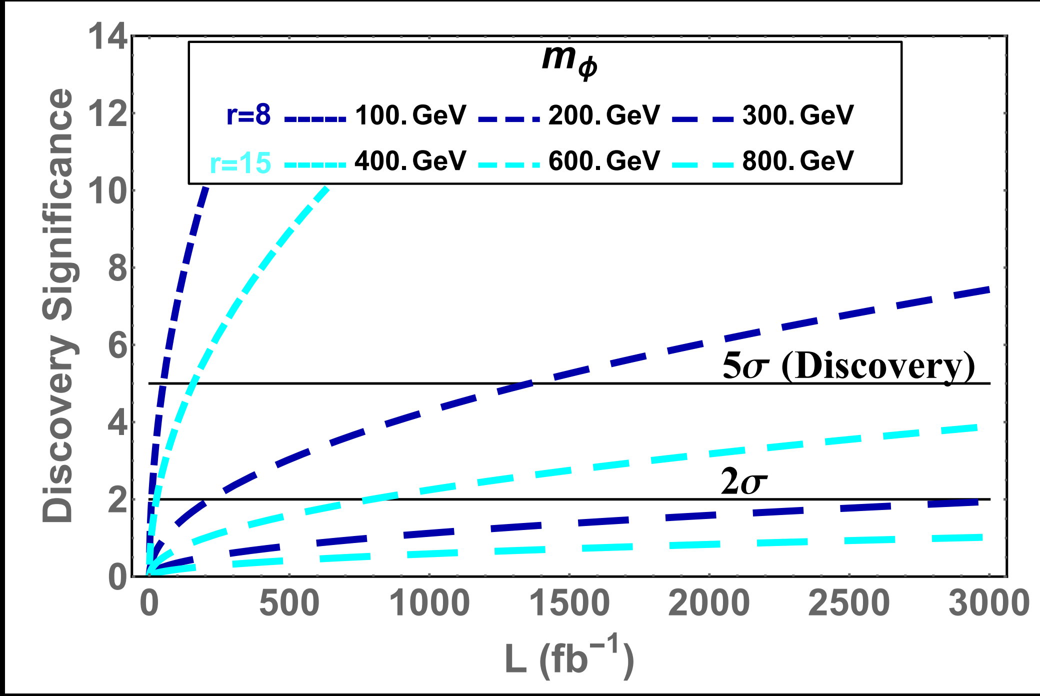
- Direct detection generally provides a strong bound unless the dark matter mass is particularly small.
- At a hadron collider, the mono-jet signature occurs at one loop.





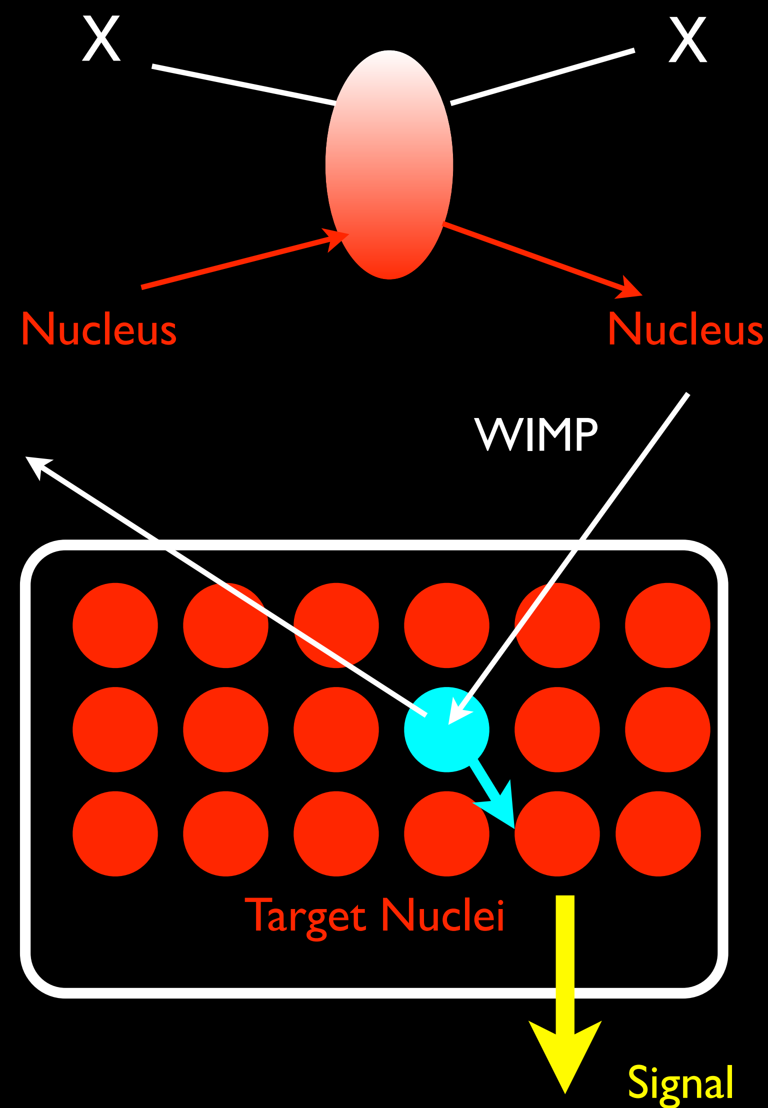
- Much simplification happens when the mediator is heavy, and this turns into an EFT vertex!

C5	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	$\alpha_s/4M_*^2$



Strong Couplings

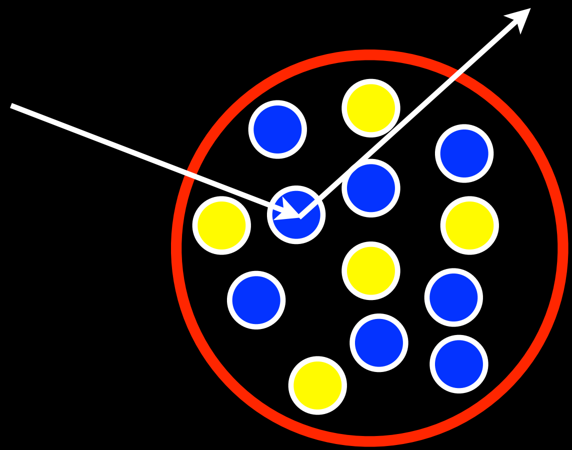
Direct Detection



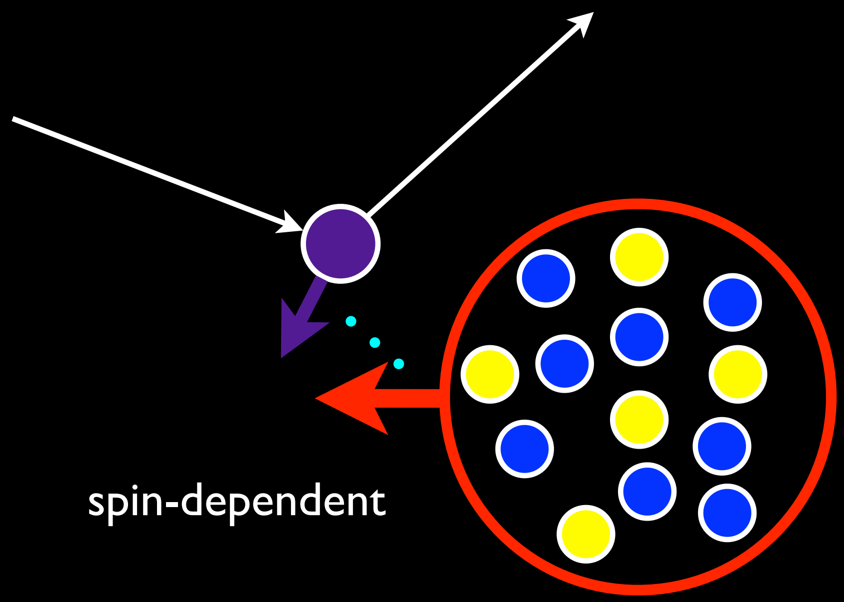
- The basic strategy of direct detection for WIMPs is to look for the low energy recoil of a heavy nucleus when dark matter brushes against it.
- The fact that the targets are heavy nuclei means that aspects of both QCD (and its low energy manifestation as nuclear physics) are relevant!
- Typically we use an EFT to capture the leading nuclear effects, which allows us to map back to interactions of WIMPs with nuclei.
- But is this too cavalier…?

NR Scattering

- Two distinct classes of direct detection searches receive the main attention:
  - Spin-independent (SI) scattering looks for direct scattering of the WIMP from the nucleons in the nucleus.
  - Spin-dependent (SD) scattering looks for interactions coupling the WIMP's spin to the nuclear spin.
- Because of the low momentum transfer, the dark matter typically probes the entire nucleus.
  - The SI scattering receives a coherent enhancement for large nuclei.
  - The strongest limits are currently on SI cross sections for Xenon targets.



spin-independent



spin-dependent

Nuclear EFT

- The SI and SD cross sections are the unique scatterings that are non-zero when the dark matter velocity goes to zero.
- But there are more structures we can write down, in a "NR EFT" that treats the nuclei as the relevant degrees of freedom.
- Maybe the leading terms are too crude a simplification…?

Nonrelativistic EFT

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp),$$

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \qquad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp), \qquad \mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}),$$

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \qquad \mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$

5. P-odd, S_χ-independent:

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q},$$

6. P-odd, S_χ-dependent

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}.$$

Fitzpatrick et al, 1203.3542

R versus NR

Relativistic EFT

More Realistic

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$

Goodman et al, 1008.1783

v -> 0

Nonrelativistic EFT

1. P-even, S_χ-independent

$$\mathcal{O}_1 = \mathbf{1}, \qquad \mathcal{O}_2 = (v^\perp)^2, \qquad \mathcal{O}_3 = i\vec S_N \cdot (\vec q \times \vec v^\perp),$$

2. P-even, S_χ-dependent

$$\mathcal{O}_4 = \vec S_\chi \cdot \vec S_N, \qquad \mathcal{O}_5 = i\vec S_\chi \cdot (\vec q \times \vec v^\perp), \qquad \mathcal{O}_6 = (\vec S_\chi \cdot \vec q)(\vec S_N \cdot \vec q),$$

3. P-odd, S_χ-independent

$$\mathcal{O}_7 = \vec S_N \cdot \vec v^\perp,$$

4. P-odd, S_χ-dependent

$$\mathcal{O}_8 = \vec S_\chi \cdot \vec v^\perp, \qquad \mathcal{O}_9 = i\vec S_\chi \cdot (\vec S_N \times \vec q)$$

5. P-odd, S_χ-independent:

$$\mathcal{O}_{10} = i\vec S_N \cdot \vec q,$$

6. P-odd, S_χ-dependent

$$\mathcal{O}_{11} = i\vec S_\chi \cdot \vec q.$$

More general

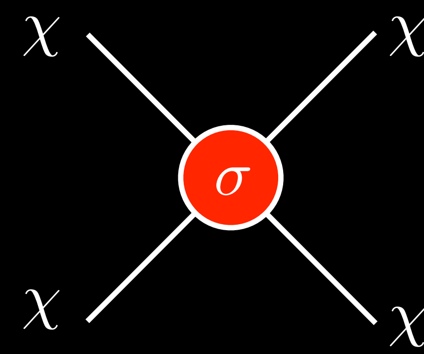
Fitzpatrick et al, 1203.3542

This description knows that physics respects special relativity.

This description is the natural language for the scattering problem.

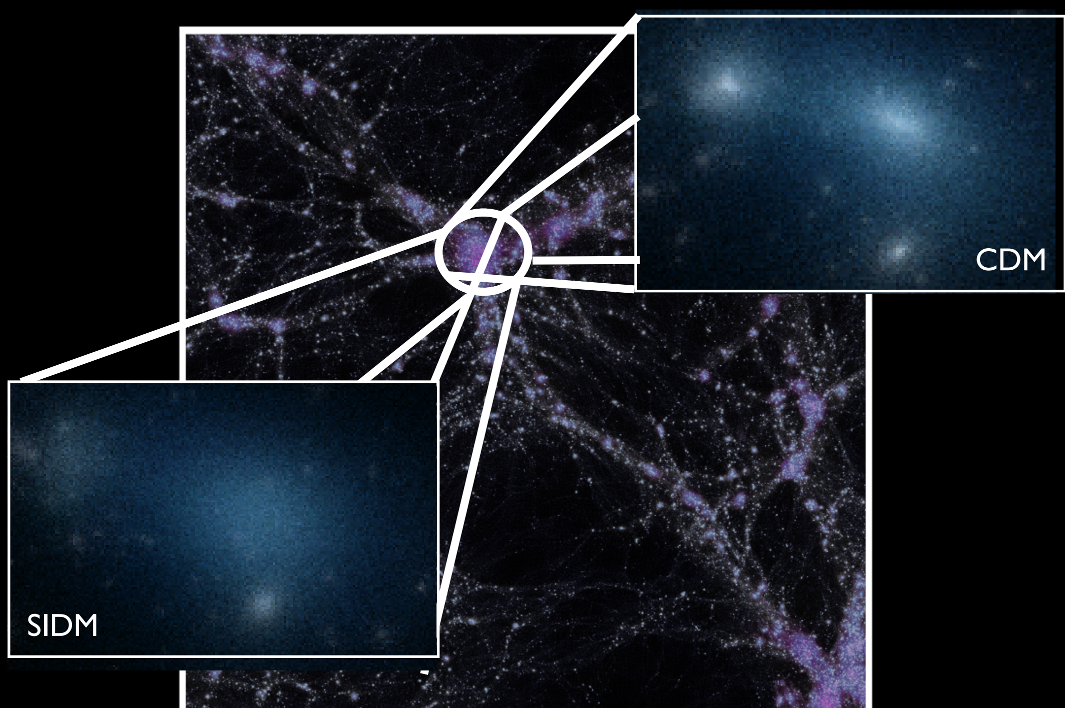
E.g. Astronomical Probes

- 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.



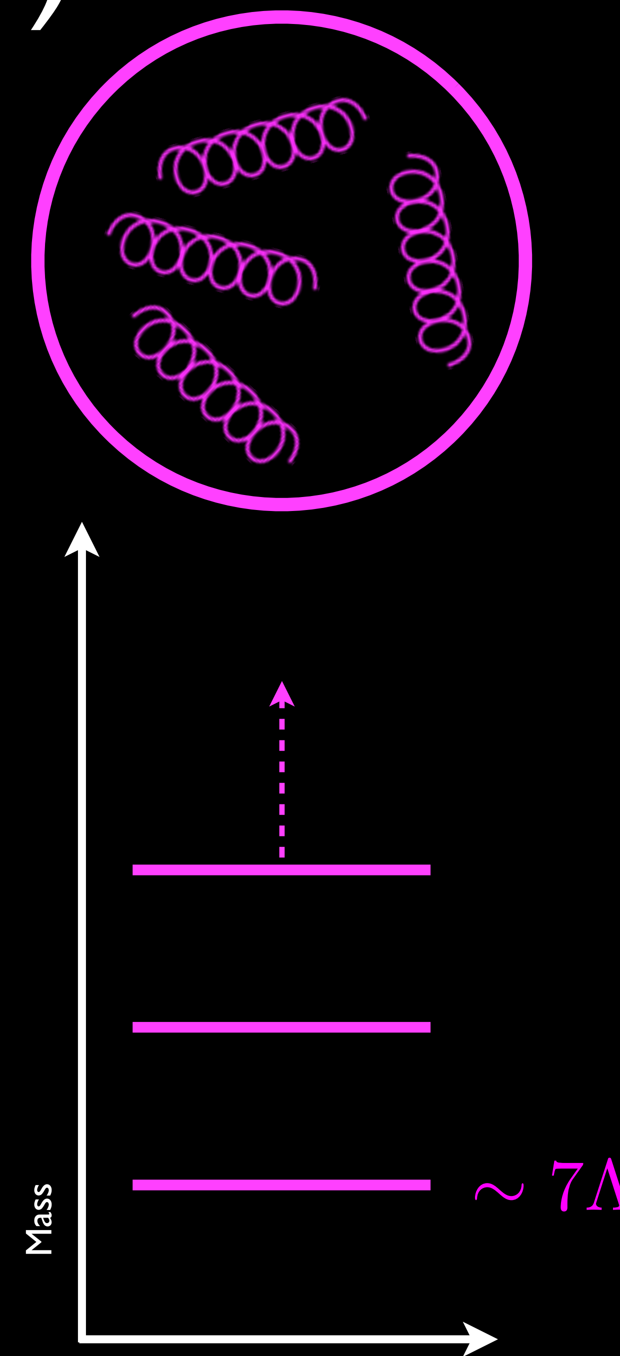
$\sigma / m < 0.7\ cm^2 / g$

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



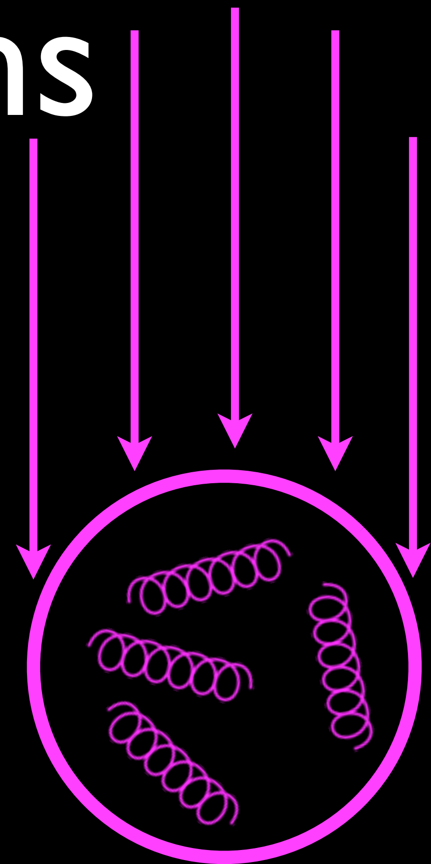
A Dark SU(N)

- The simplest module we can consider is a pure gauge theory consisting of a hidden sector SU(N).
- To begin with, we imagine that any matter charged under the hidden gauge group and the SM is extremely heavy, and thus irrelevant for the low energy physics.
  - This is a variation on models where the dark matter is e.g. a dark pion-like object.
- 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.
- From here on, dark/hidden should be understood whenever I use terms like “gluons” or “glueballs”.



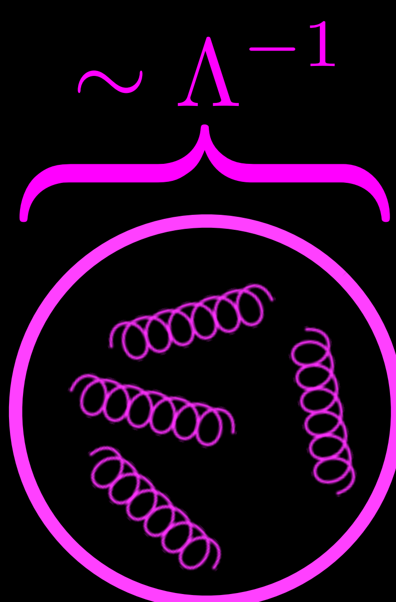
Glueball Interactions

- In this theory, nothing can be computed very reliably in perturbation theory. But we can construct an EFT that captures the salient features!
    - Lattice may help calibrate the EFT coefficients.



- Since this construction has one energy scale in it, at low energies the EFT must be an expansion in 1 / Λ.

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



- 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}…

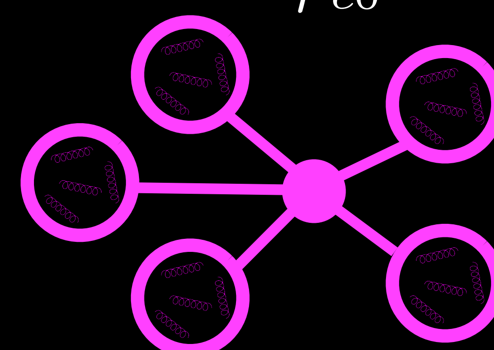
Glueball Relic Density

- We can estimate the relic density of the glueballs by tracking the relic density of the gluons to the temperature at which the theory confines.
- At this temperature, something around Λ, the energy in the dark gluons will get converted into glueballs.
- We can estimate the relic density of glueballs by matching across the phase transition.
- If there are no relevant connectors between the visible and hidden sectors, the temperature in the hidden sector T^h and the visible temperature T could generically be different.
- We parameterize this possibility with the ratio of temperatures $\xi = T^h / T$.
- There are interesting corrections to the usual thermal distribution: cannibalization!

$$Y \equiv \frac{n_{\rm gb}}{s}$$
$$= \frac{g_{\rm eff}[\zeta(3)/\pi^2]T_h^3}{g_{*S}[2\pi^2/45]T^3}$$
$$= \frac{g_{\rm eff}45\zeta(3)}{g_{*S}2\pi^4} \times \xi_f^3$$

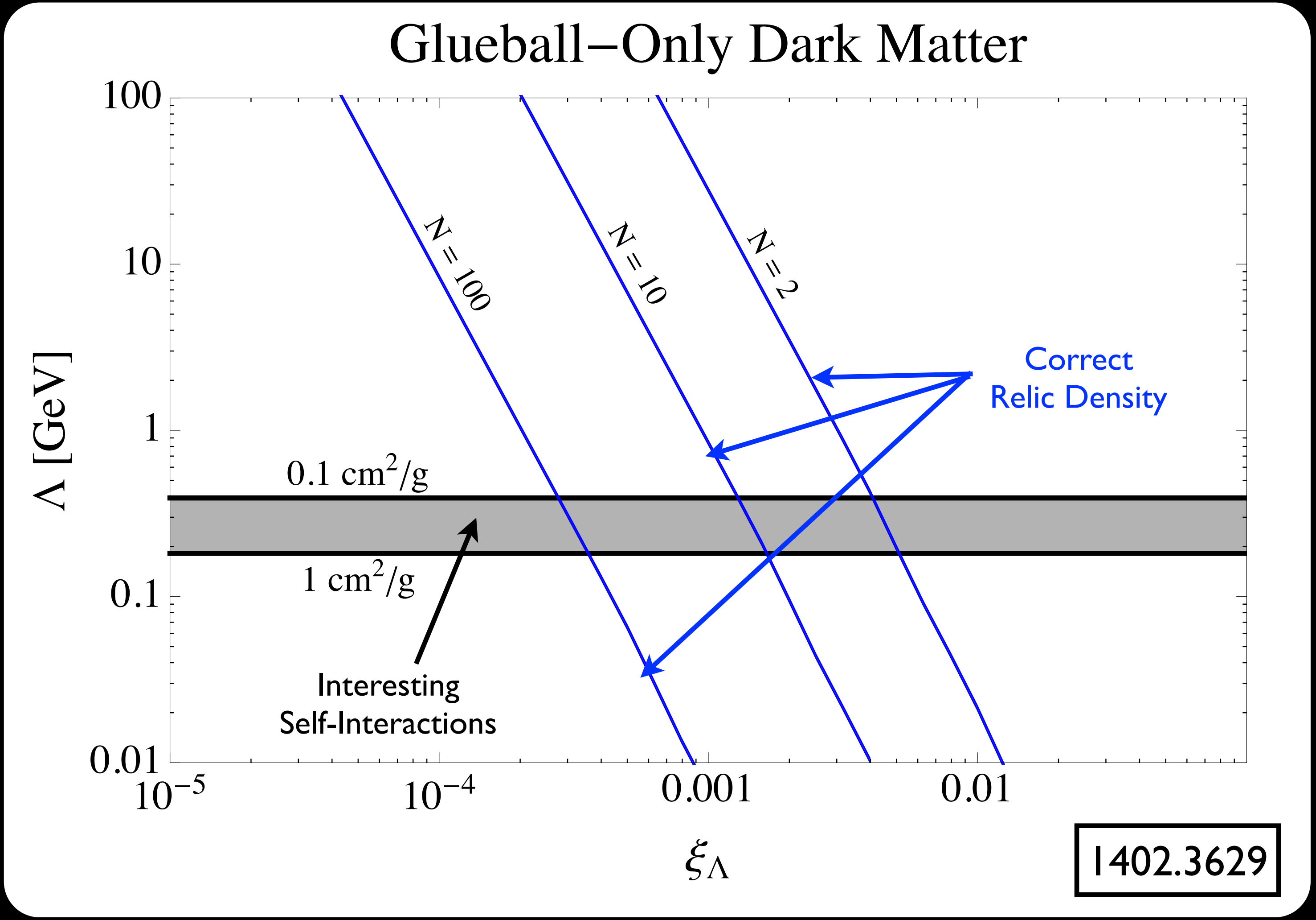
For SU(N), $g_{\rm eff} = 2 \times (N^2-1)$

$$\Omega_{\rm gb} \sim \frac{Y s_0 \Lambda}{\rho_{c0}}$$



Carlson, Machacek, Hall 1991
Hochberg, Kuflik, Volansky, Wacker 2014

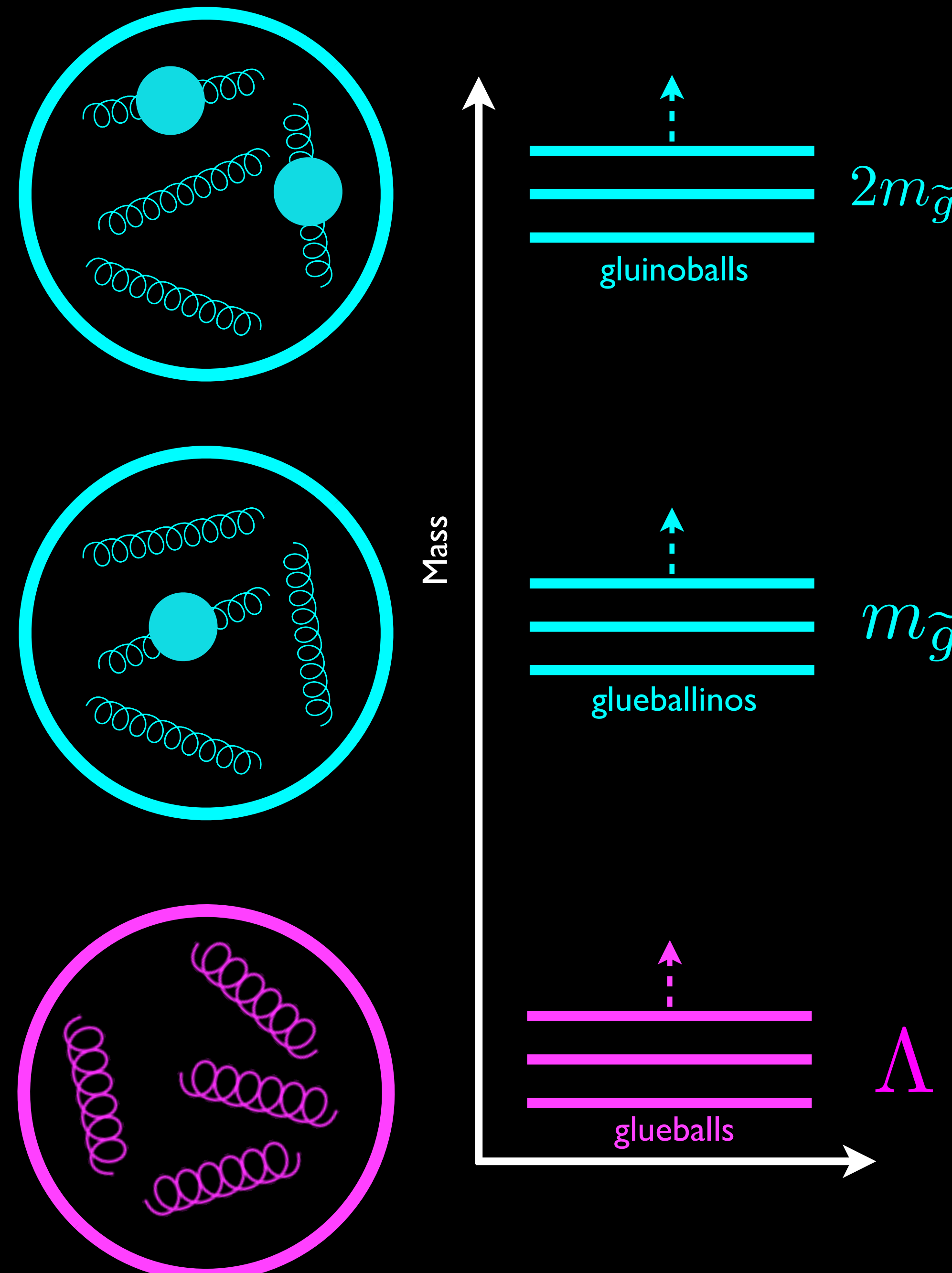
Glueball Parameter Space



- For a given N, there are two parameters, the confinement scale and the ratio of hidden to visible temperatures at the time of confinement, ξ_Λ. Provided one allows for a somewhat colder hidden sector, one can achieve interesting self-interaction rates at the observed relic density!

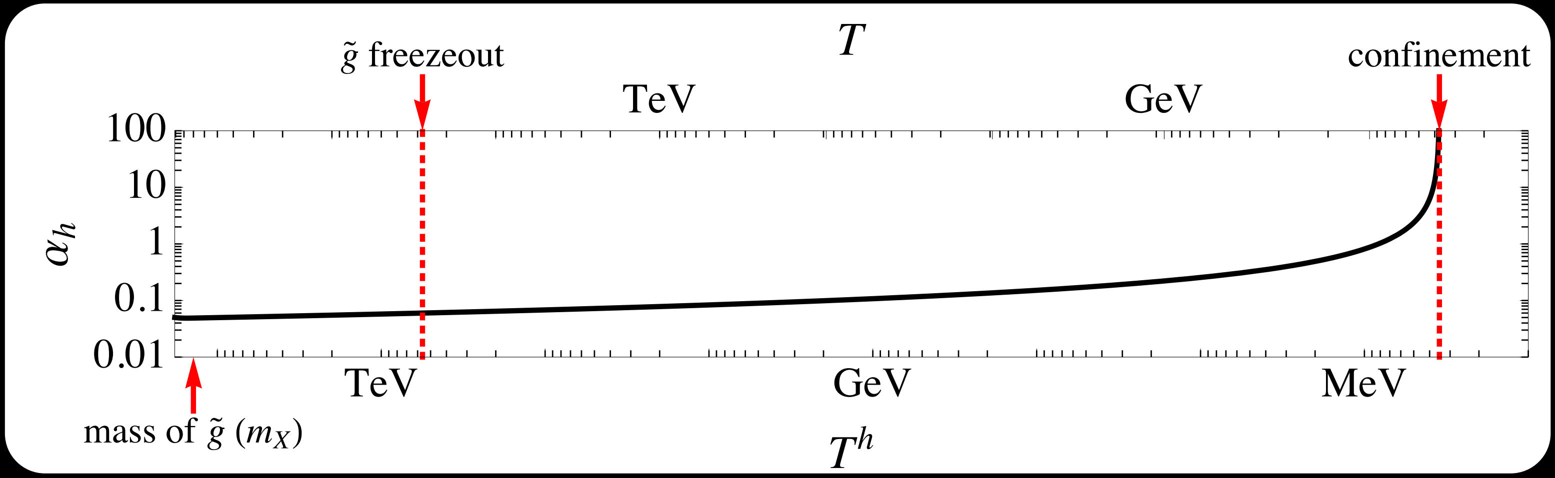
SU(N) + Adjoint

- A very simple extension is to add an adjoint (Majorana) fermion to the dark sector.
- If one likes, this could be considered a supersymmetrized version of the pure gauge model, with the adjoint playing the role of the gluino.
- The spectrum consists of glueballs as before, and (for m >> Λ) a family of fermionic glueballinos at mass ~ m.
- These glueballinos are strongly interacting with the glueballs and are sort of analogues of heavy-light mesons in this theory.

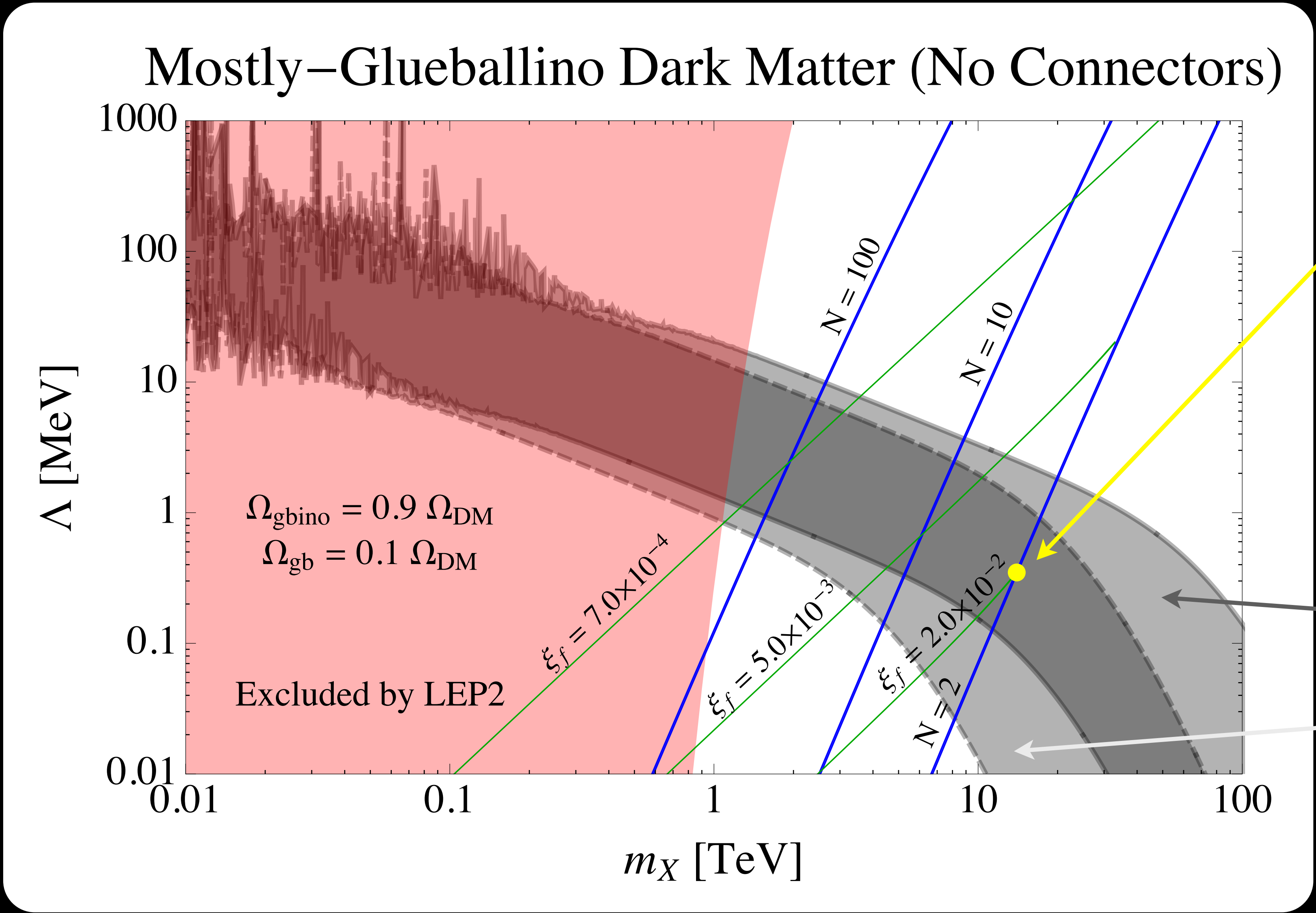


Mixed Dark Matter

- Since the theory will still contain glueballs, this is generically a theory of multi-component dark matter.
- Which component will dominate depends on their relative masses (m and Λ) and the temperature in the hidden sector, ξ.
- The precise behavior under structure formation for this kind of multi-component system probably requires simulations to understand properly. We'll look at some representative limiting cases.
- All of this is enabled by constructing an EFT for the glueballs and glueballinos and how they interact with one another.



Glueballino Dominated



Sample Model:

N=2
m = 14 TeV
Λ = 0.35 MeV
ξ = 0.02

Dwarfs
(glueballinos only)
Clusters

Pink shaded: LEP-2 wino bound

Blue curves: N fixed (ξ varies)
Green curves: ξ fixed (N varies)

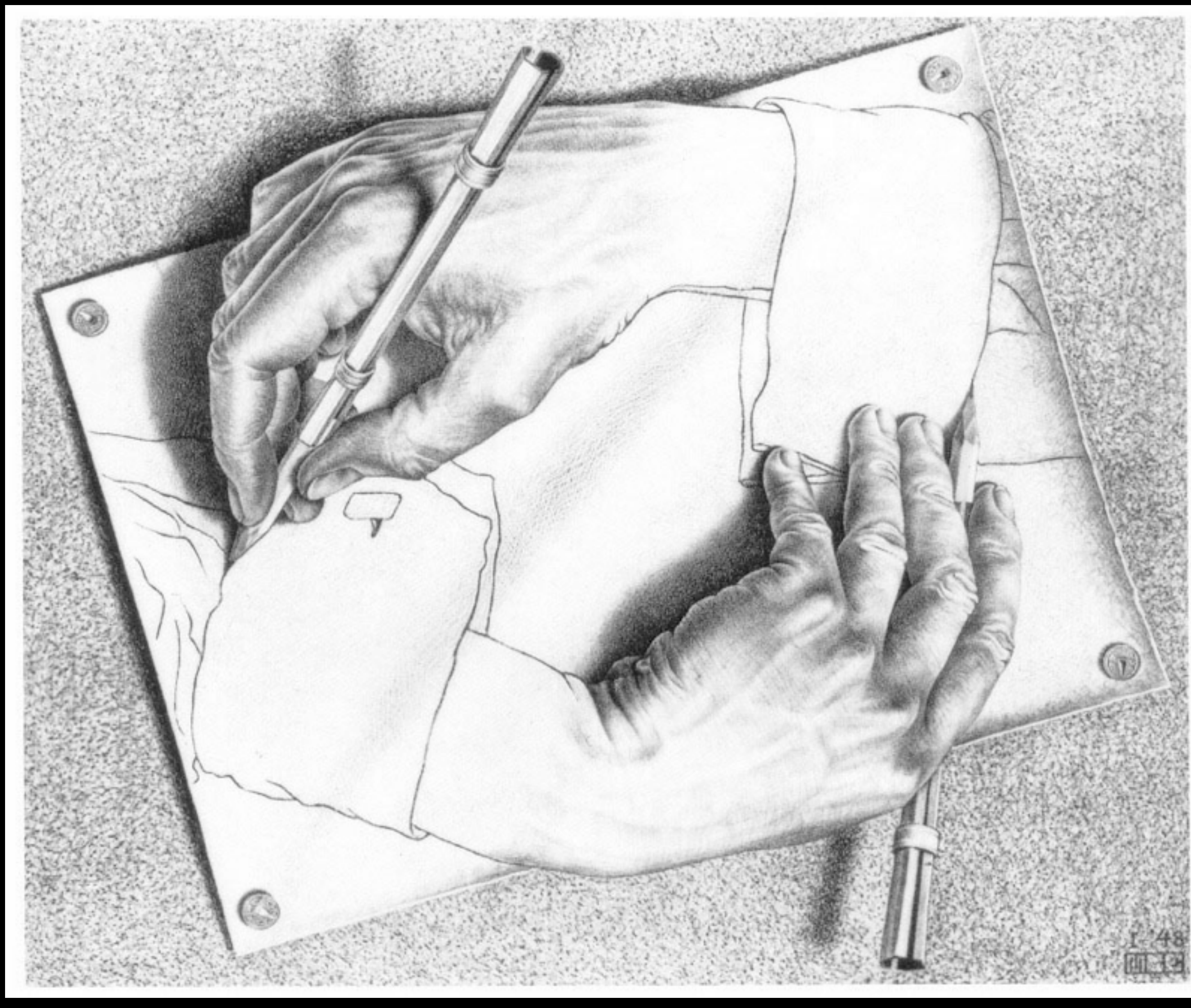
Outlook

- EFTs have been used to describe dark matter interactions.
  - They can parametrize ignorance, simplify calculations, and describe the low energy behavior of strongly coupled systems.
- EFTs sometimes provide a convenient framework and have offered some insights into how different kinds of searches fit together.
- There is a fair amount of confusion related to the fact that they break down at large energies.
  - Any time we descend into an IR theory, we lose details from the UV that could be relevant. At the same time, we become more general and more focused on what matters in the IR.
  - If we're interested in a particular simplified model, we should study that model and forget about the EFT.
  - The EFT remains useful for the rest, including ones we didn't think of.

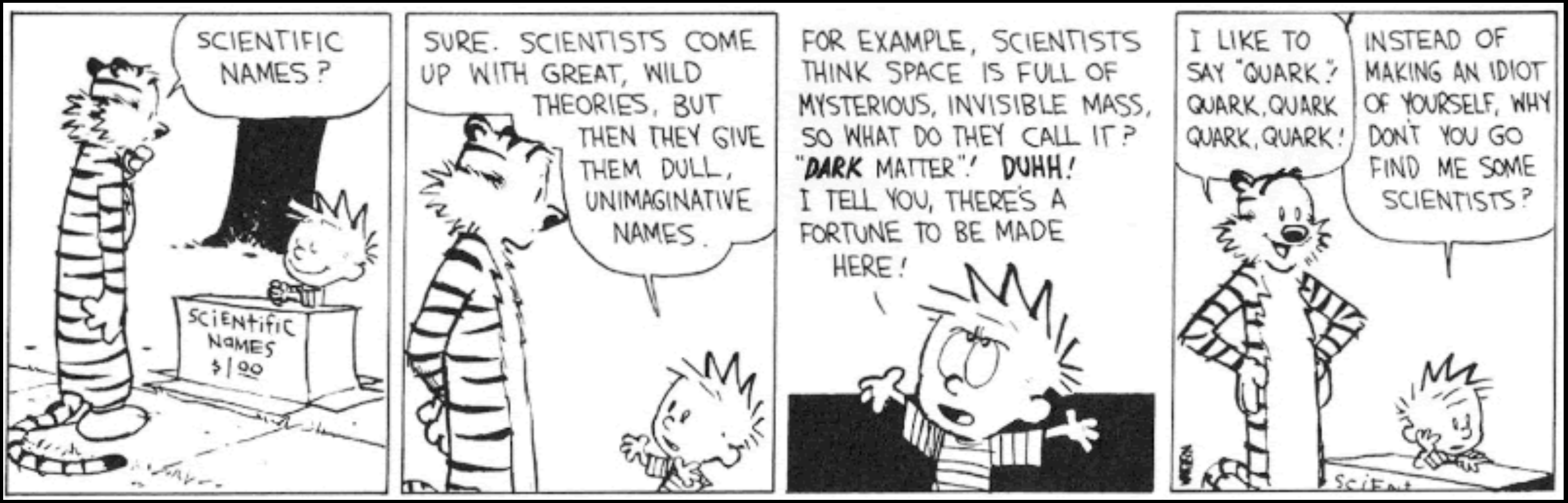
Outlook

- EFTs are powerful tools. They provide a sketch of the space of possibilities for dark matter
  - We should use them to take advantage of their best features, and remain aware of where they break down or may confuse us!
- Ultimately, what matters is experiment, which will focus us on the relevant degrees of freedom and tell us how to construct a theory that describes observations.
- Experiments bring EFTs and sketches of DM to life!

From Sketch to Life

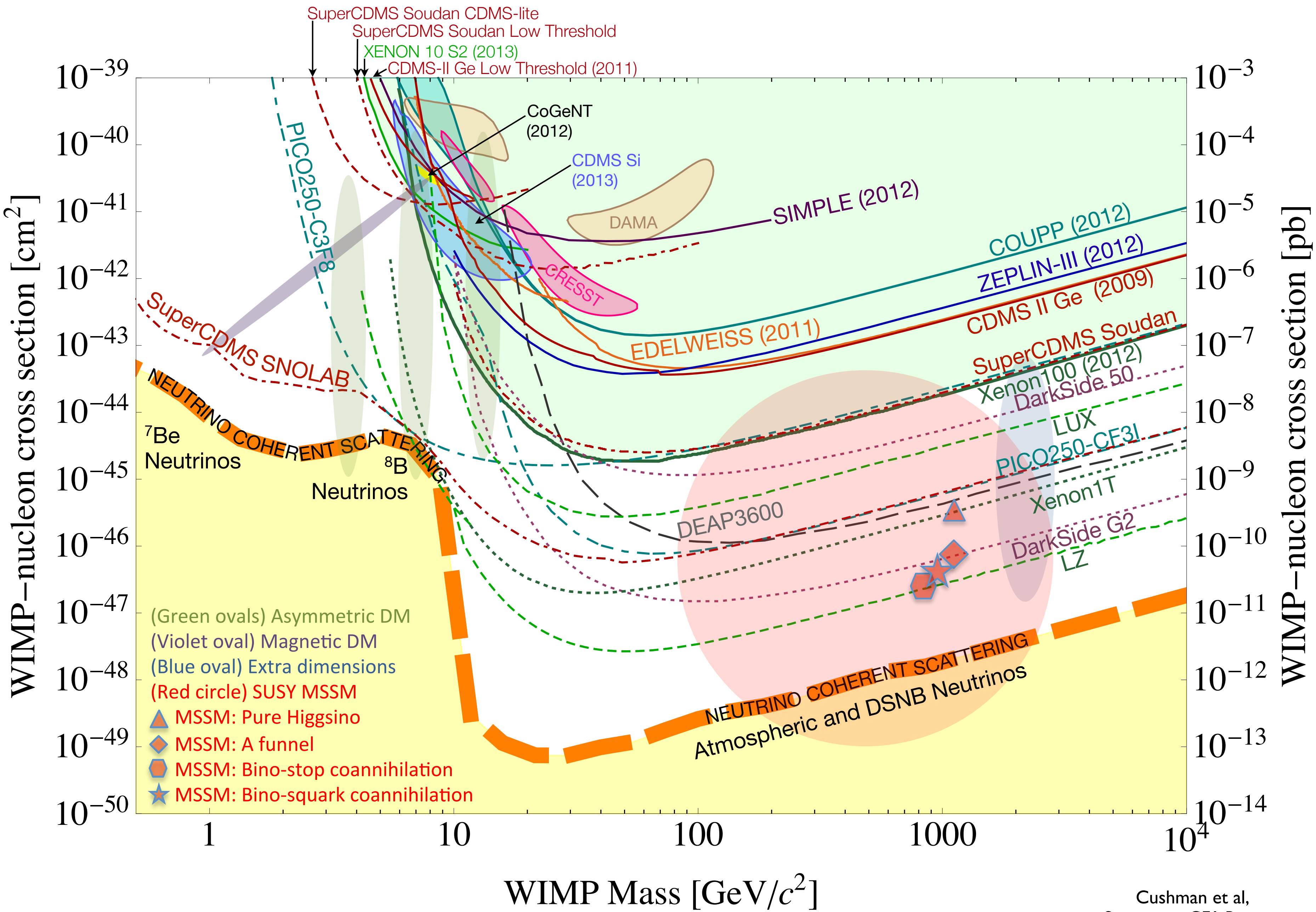


Sketches of ....


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

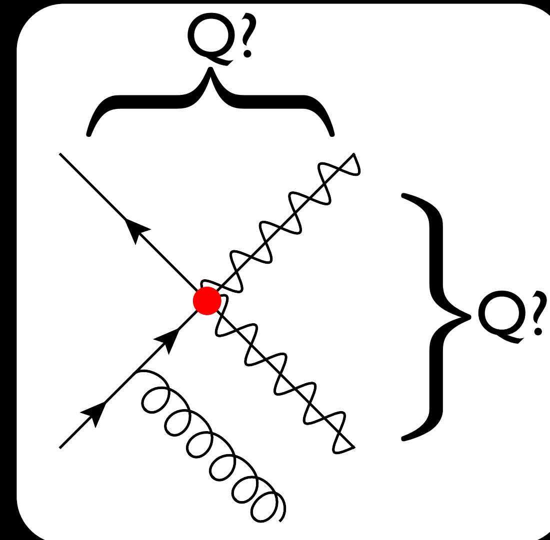
Lots of Activity

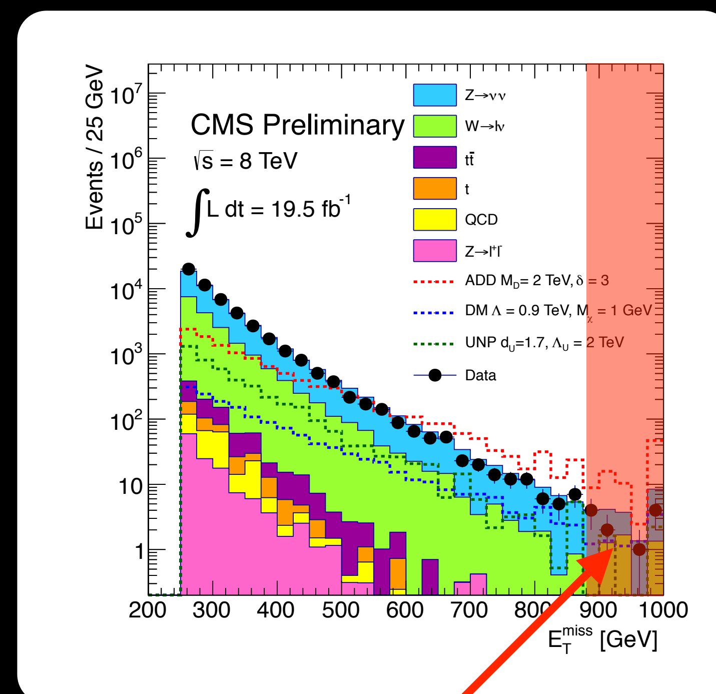


Cushman et al, Snowmass CF1 Report

Truncation

- A good idea is to present EFT bounds using "truncation".
- The idea is to exclude the events with the largest momentum transfer from the bound, since they are the most likely to be badly modeled by the EFT.
- If one imagines a simple t-channel or s-channel model, two different quantities ("Q") characterize the momentum through the implicit propagator.
    - The EFT can't tell you which one to use.
    - (Neither really can be measured anyway).
- Events with Q larger than some cut value Q_{cut} are excluded from the analysis bounding M_*.

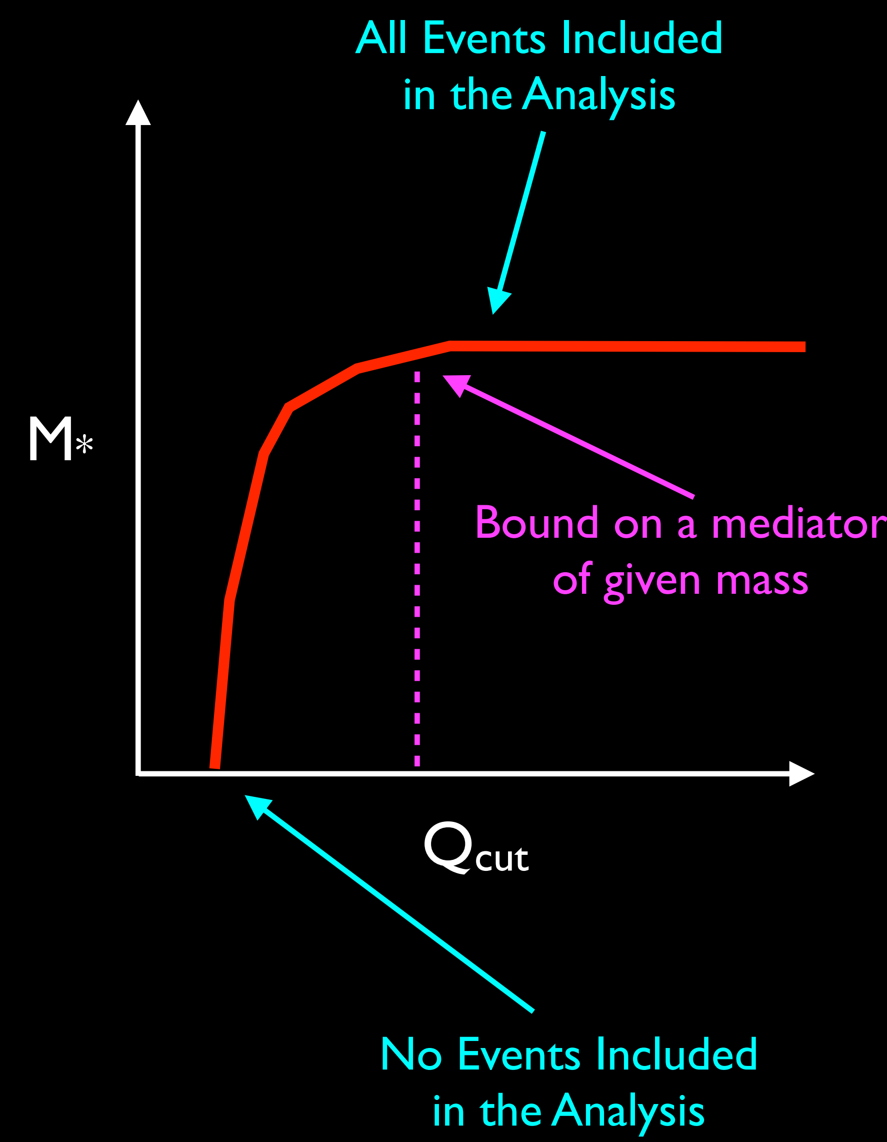




Exclude these Events for Q_{cut} = 900 GeV.

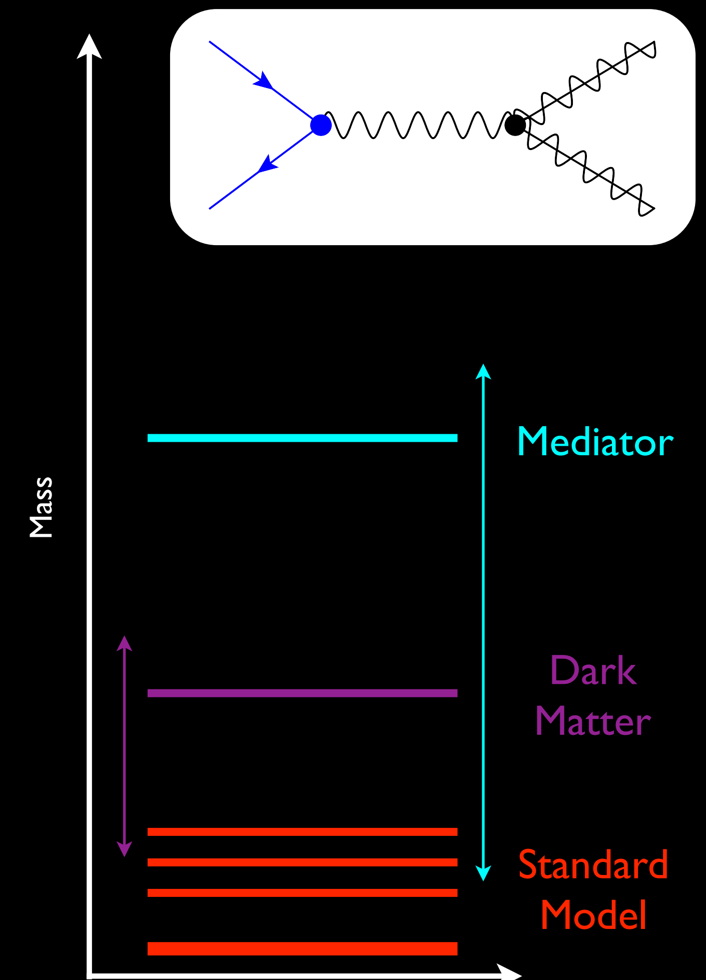
Truncation

- Probably the most useful way to present results would be to show the resulting bound on M_* as a function of Q_{cut}.
- That way, the end user can decide (based on the masses of the particles in her theory) what value of Q_{cut} is appropriate, and find the conservative limit on her model.
- (And of course dedicated searches for mediators will be important, too).
- This the final recommendation made by the "ATLAS/CMS Dark Matter Forum", 1507.00966 for presenting the results in terms of EFT parameterizations.



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.



DM@LHC WG: Boveia et al

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