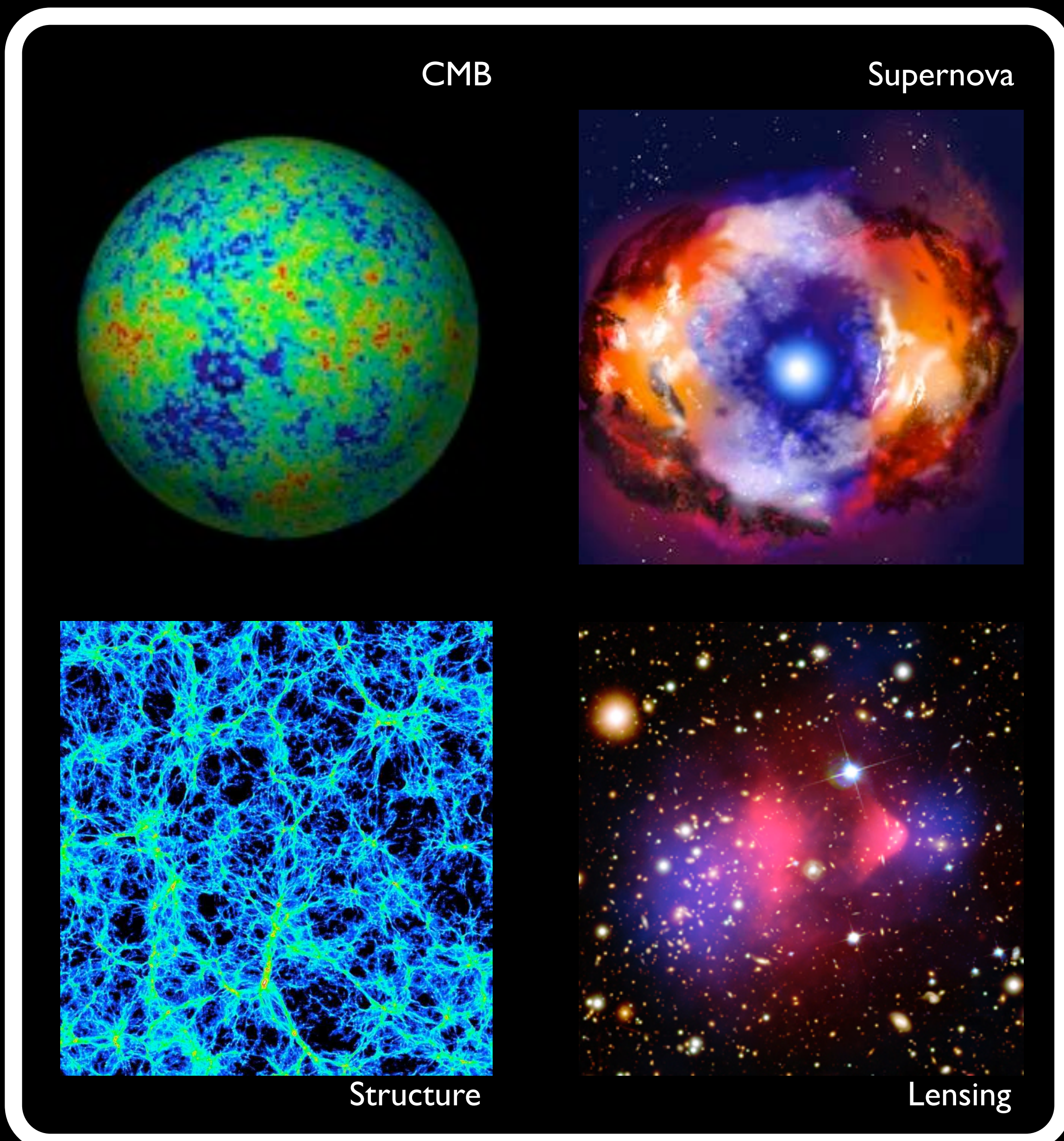
EFTs for Dark Matter

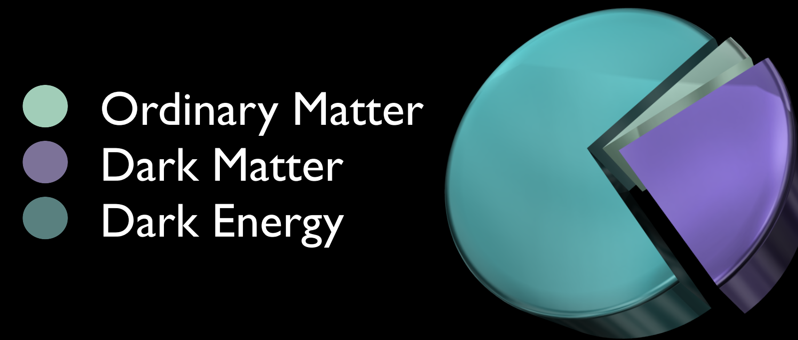
Tim M.P. Tait
University of California, Irvine

HEFT 2015 Chicago
November 4, 2015

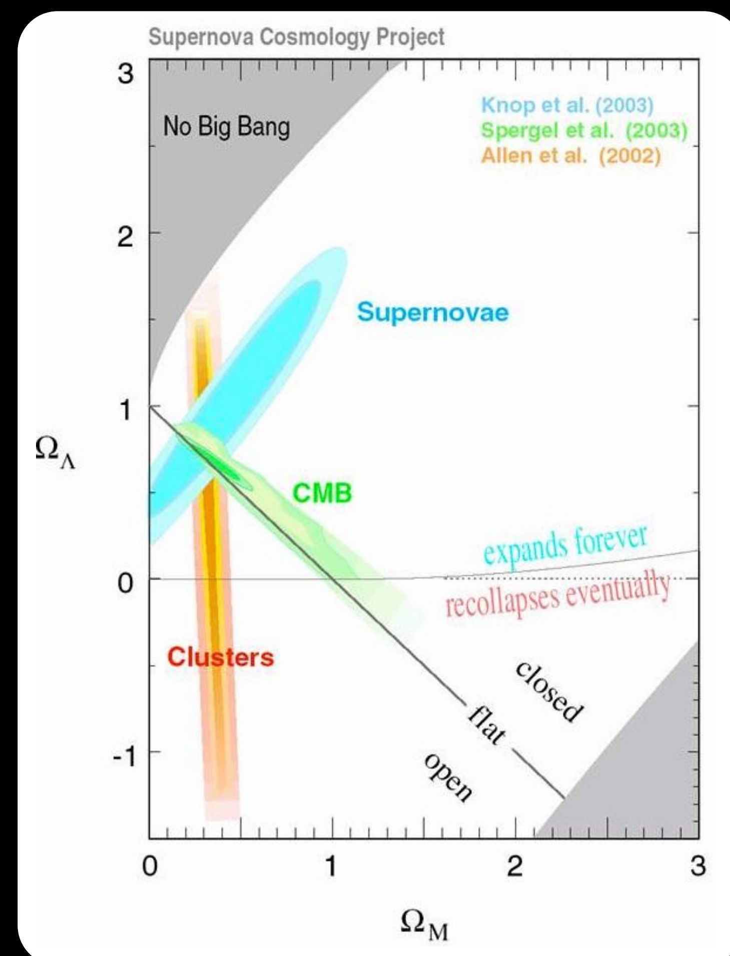
Dark Matter



CMB
Supernova
Structure
Lensing

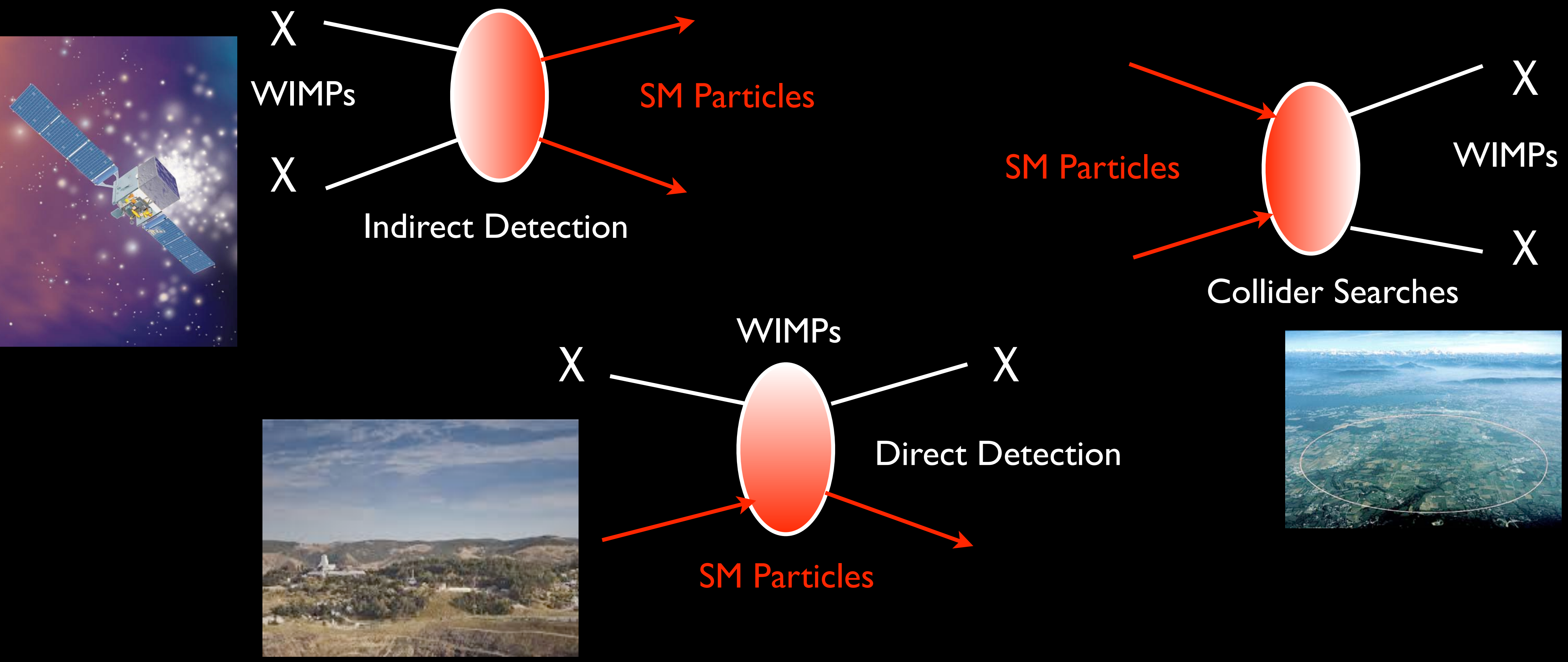


Ordinary Matter
Dark Matter
Dark Energy



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

Particle Probes of DM

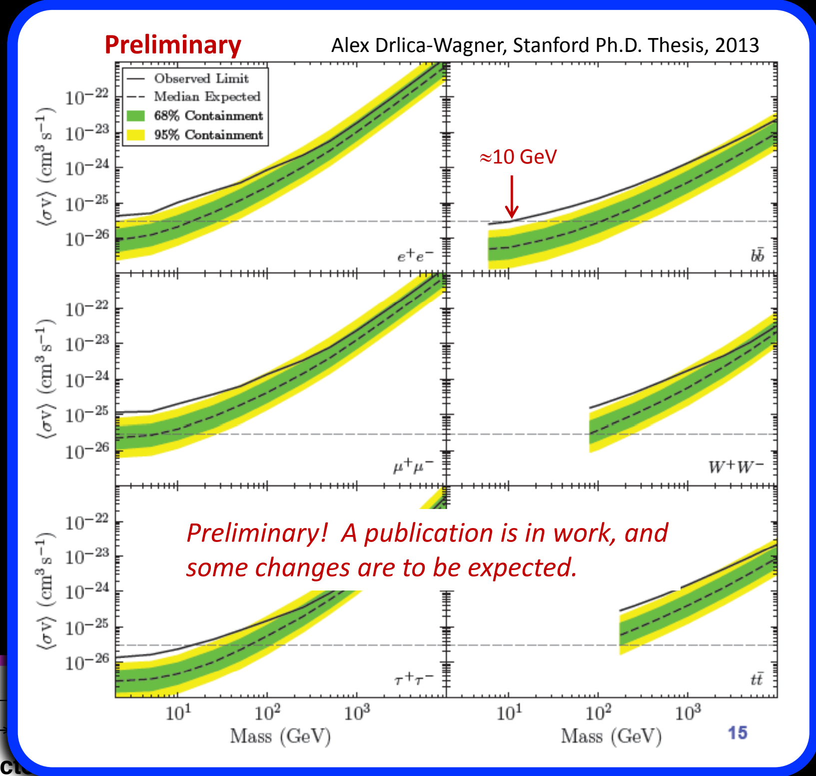


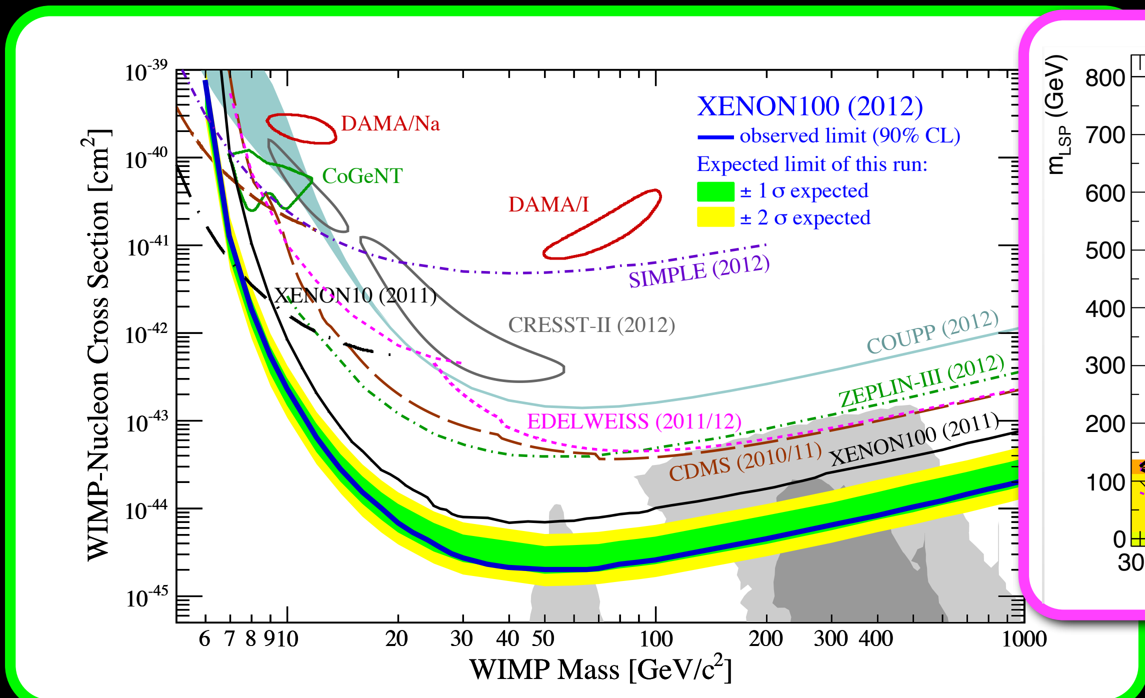
- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

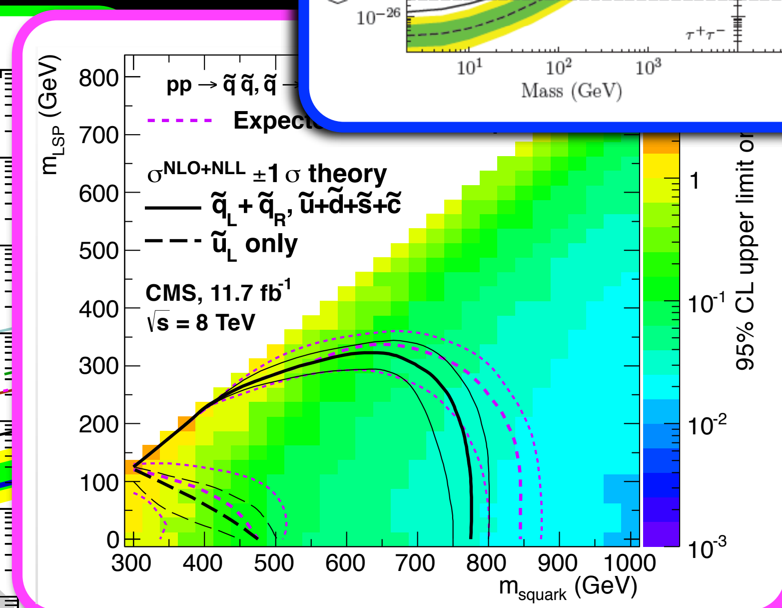
We Need (a) Theory

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

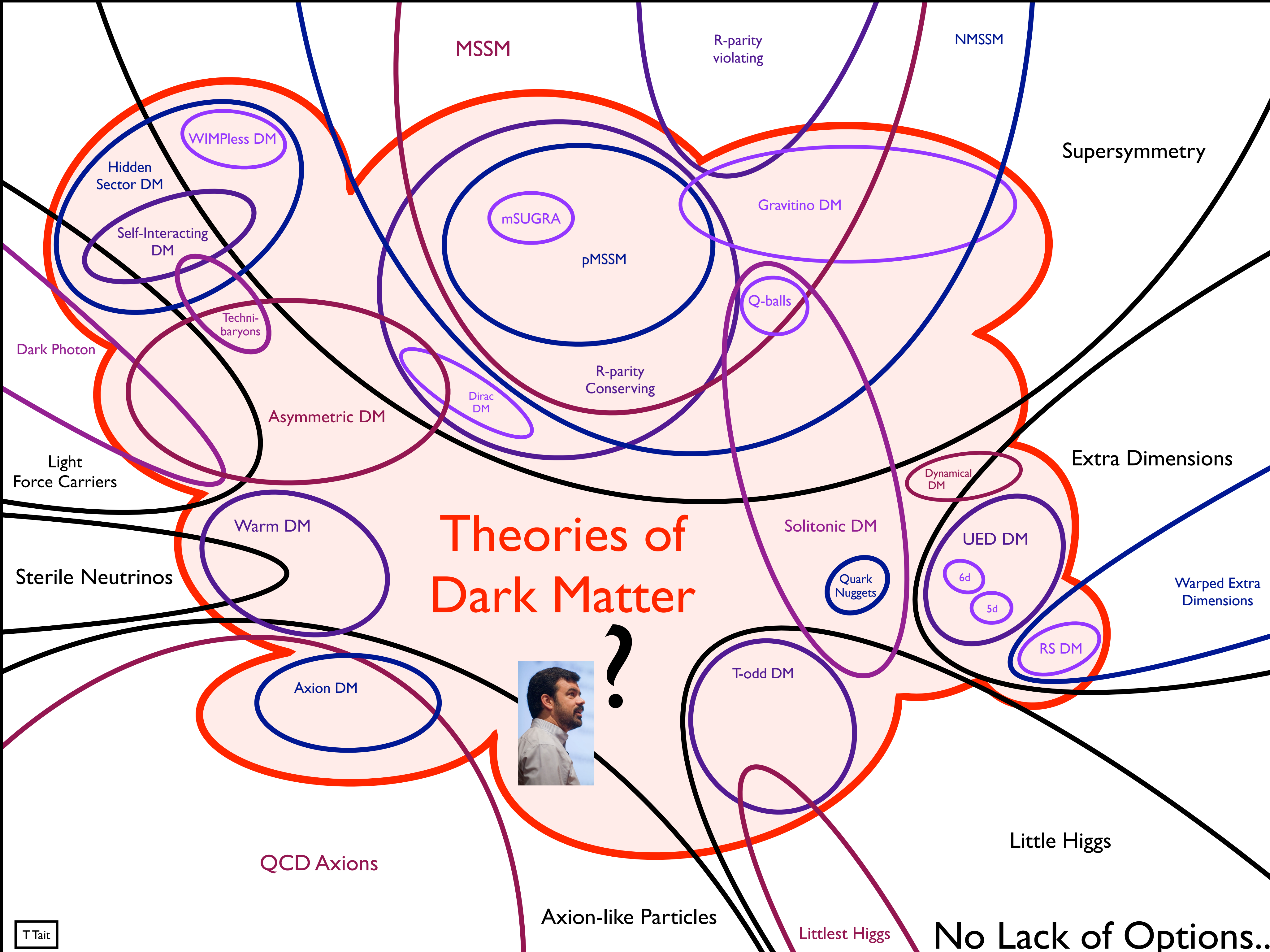
But we *know* they are all attempts to characterize the same thing(s)...



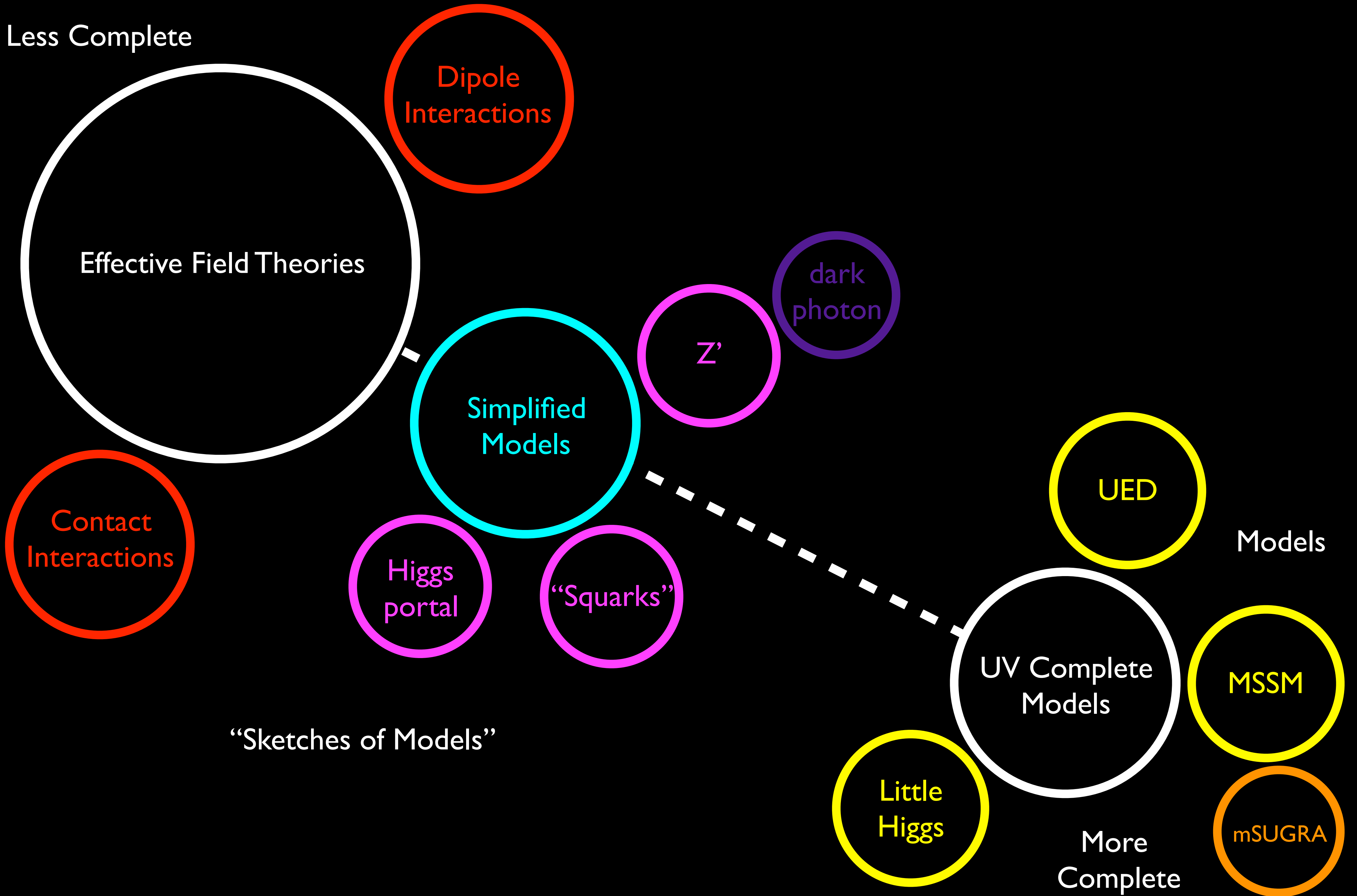




Which theory to use?

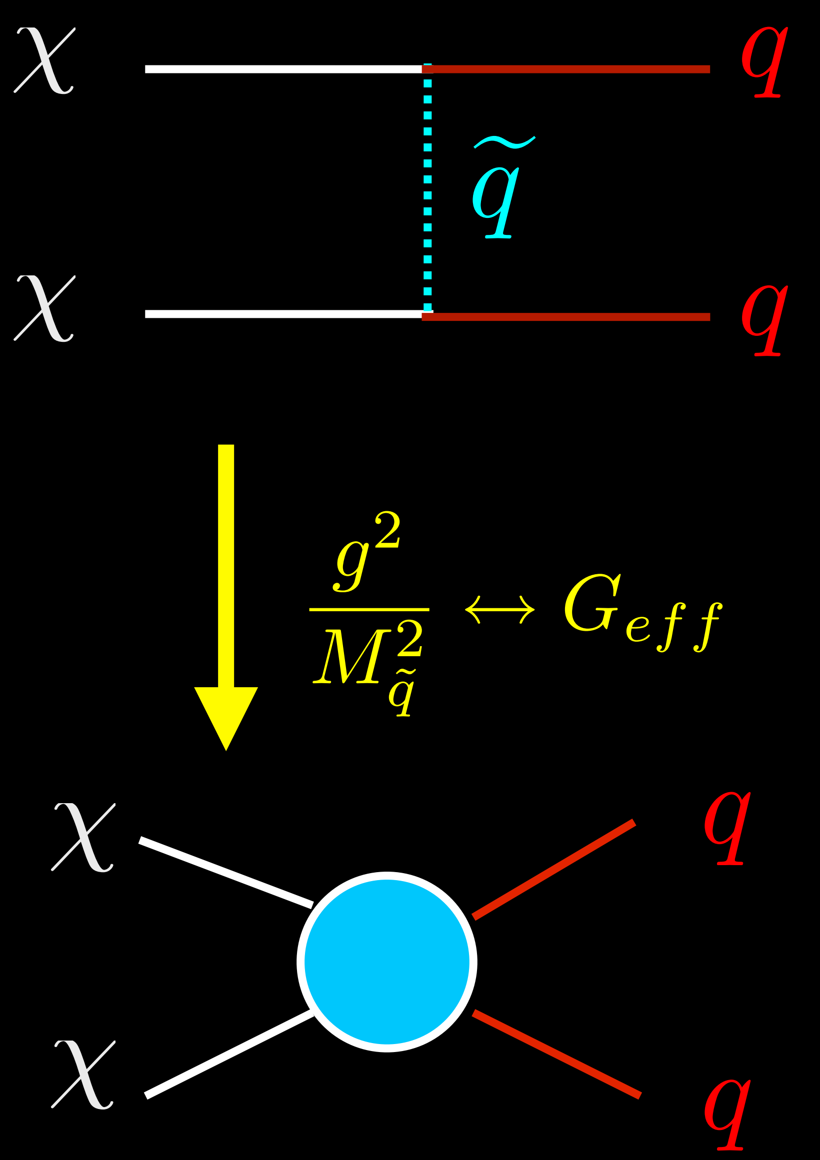

MSSM
R-parity
violating
NMSSM
Supersymmetry
WIMPless DM
Hidden
Sector DM
Self-Interacting
DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-
baryons
Dark Photon
R-parity
Conserving
Dirac
DM
Asymmetric DM
Light
Force Carriers
Dynamical
DM
Extra Dimensions
Warm DM
Theories of
Dark Matter
?
Solitonic DM
UED DM
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
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M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
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M7	GG	$\alpha_s/8M_*^3$	1	-
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$$G_\chi\,[\bar{\chi}\Gamma^\chi\chi]\,G^2$$

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

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

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- 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
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  - Annihilation in the galactic halo
  - Collider Production

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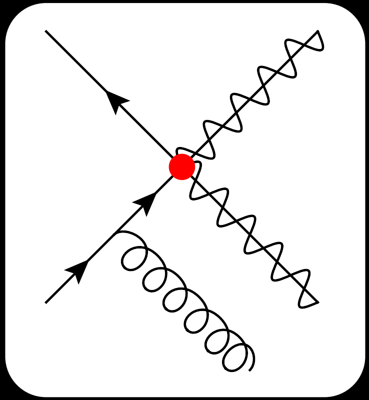
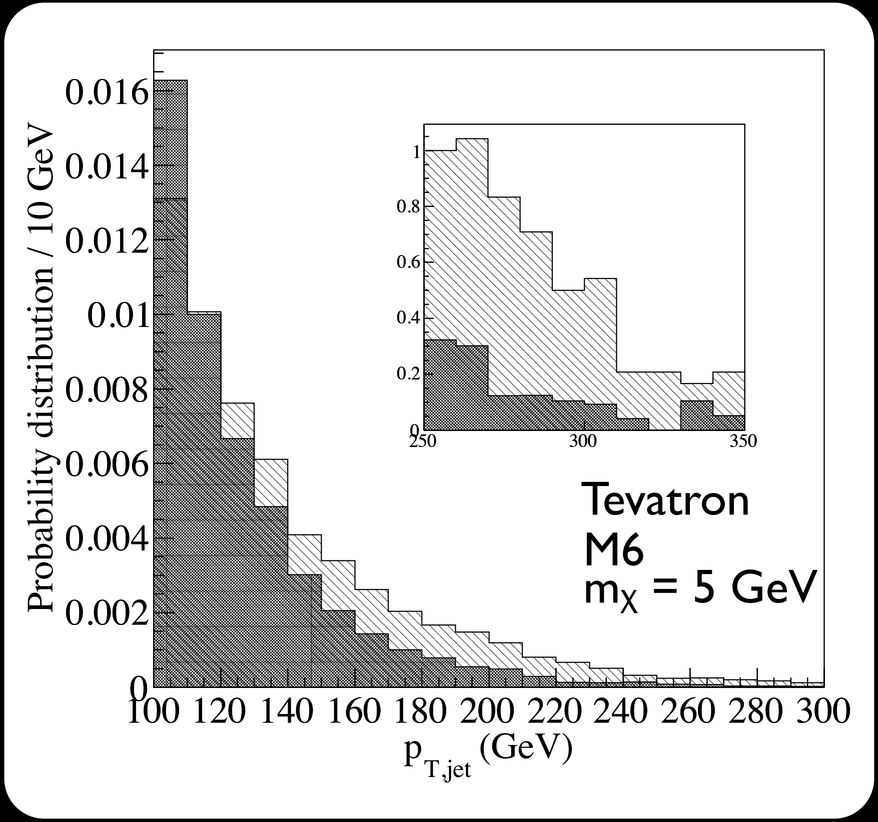
Collider Searches

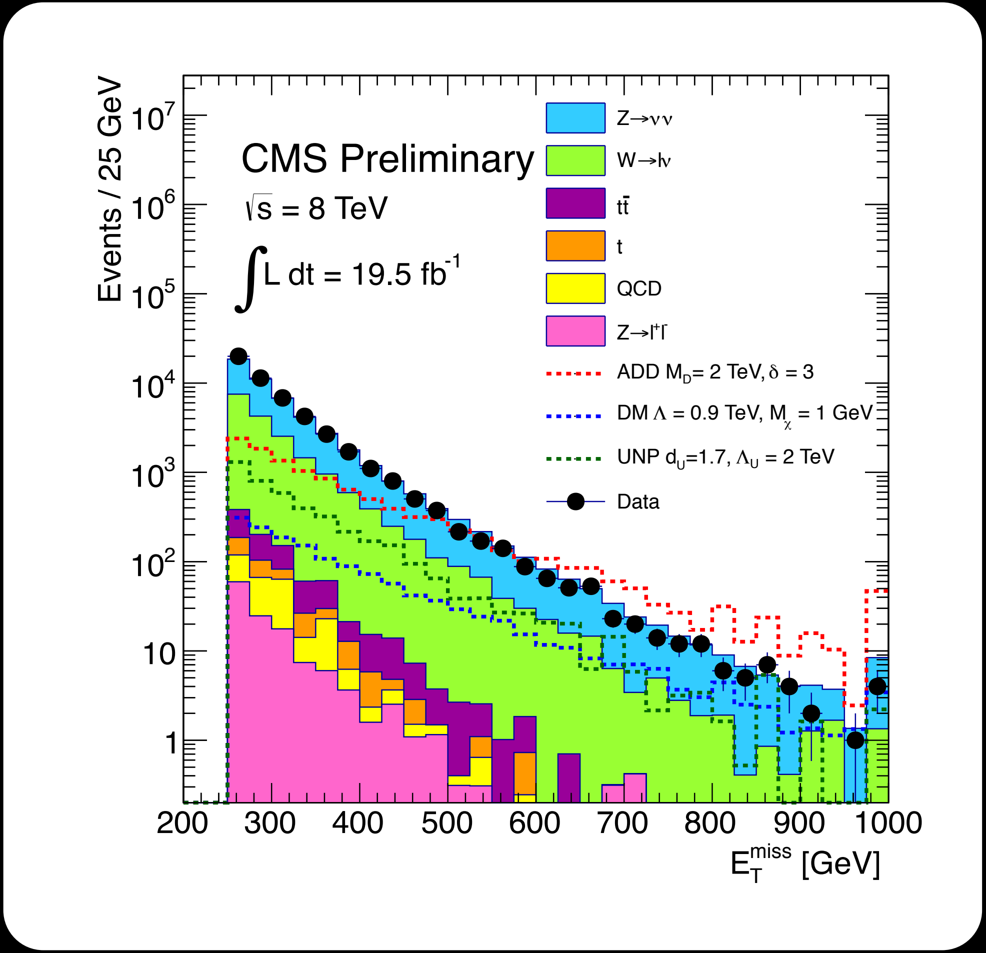
- At colliders, one searches for this type of theory by producing the dark matter directly.
- Since the detector needs something to trigger on, one looks for processes with additional final state particles, and infers the presence of dark matter based on the missing momentum it carries away from the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

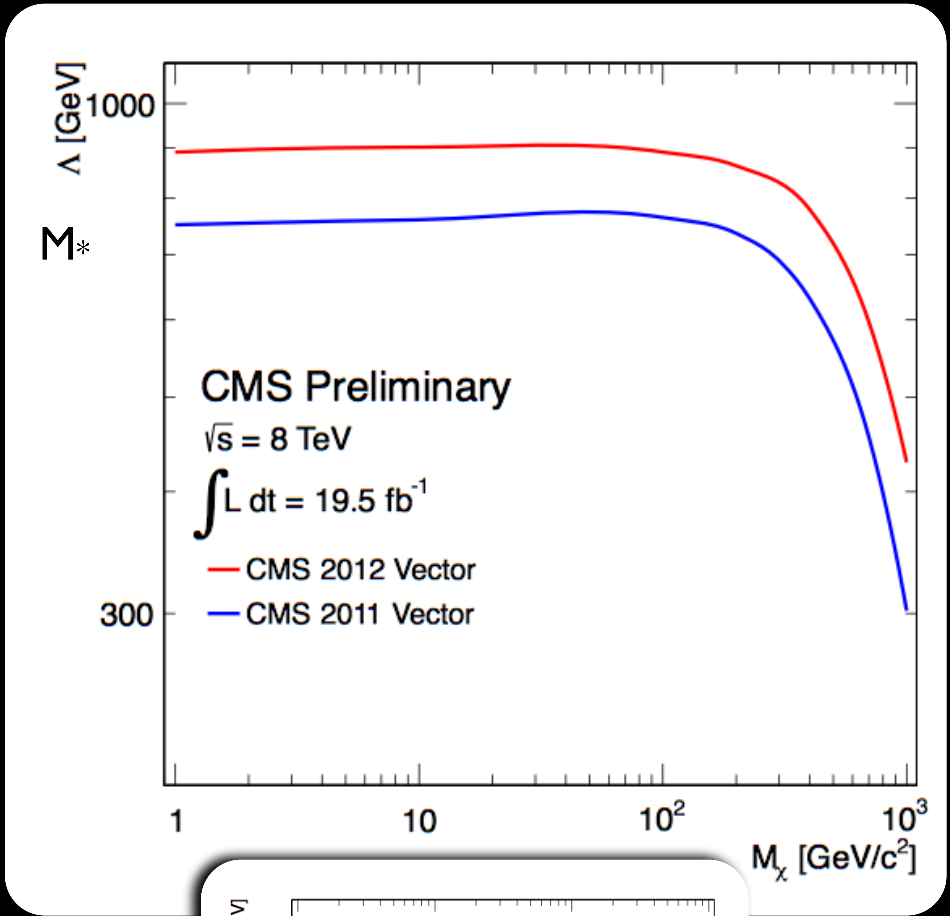


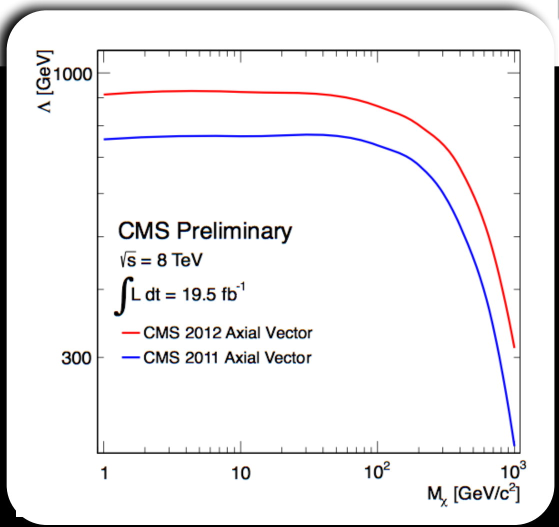
Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP



Collider Results

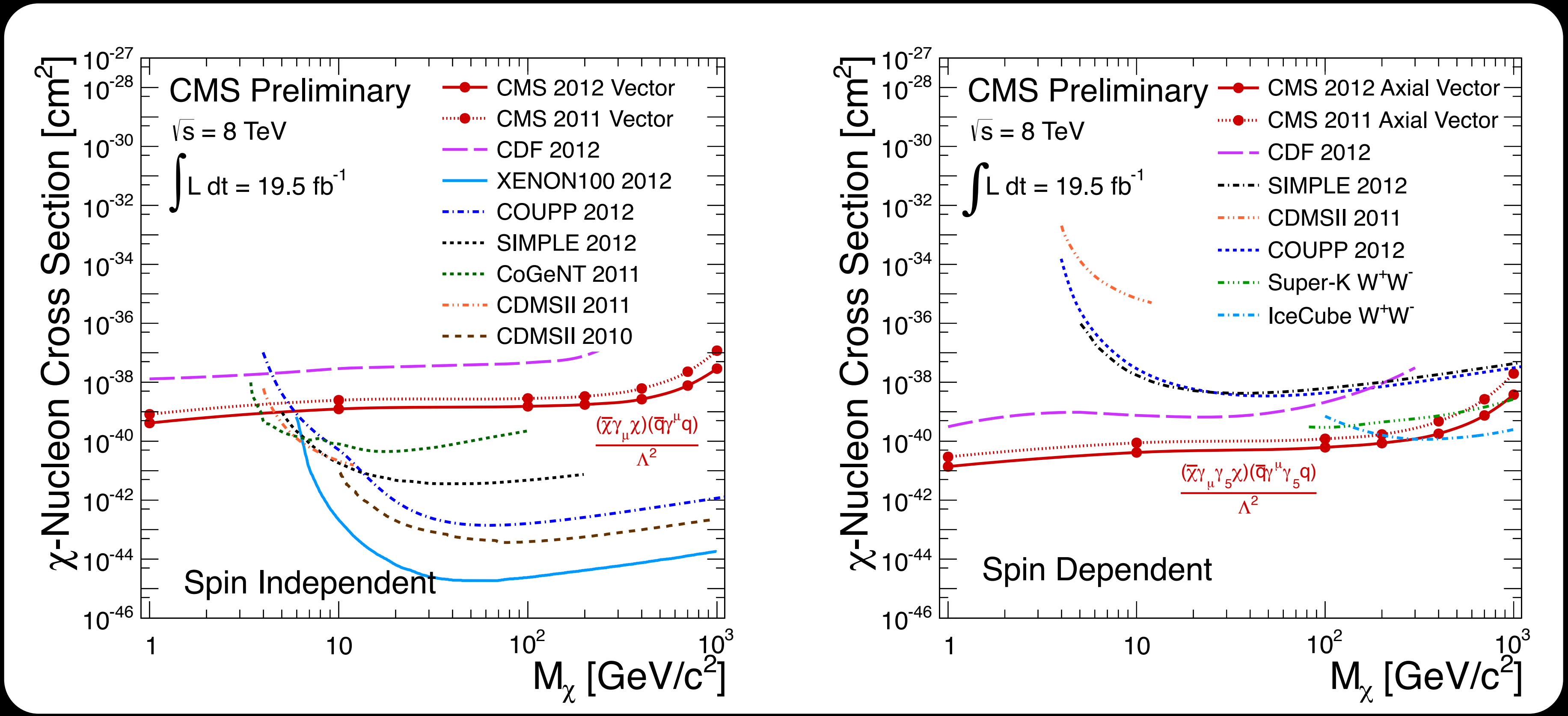






Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

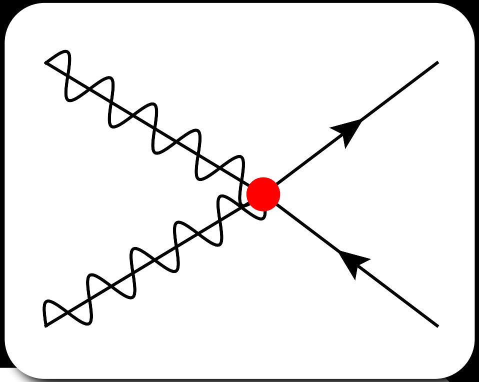
Translation to Elastic Scattering



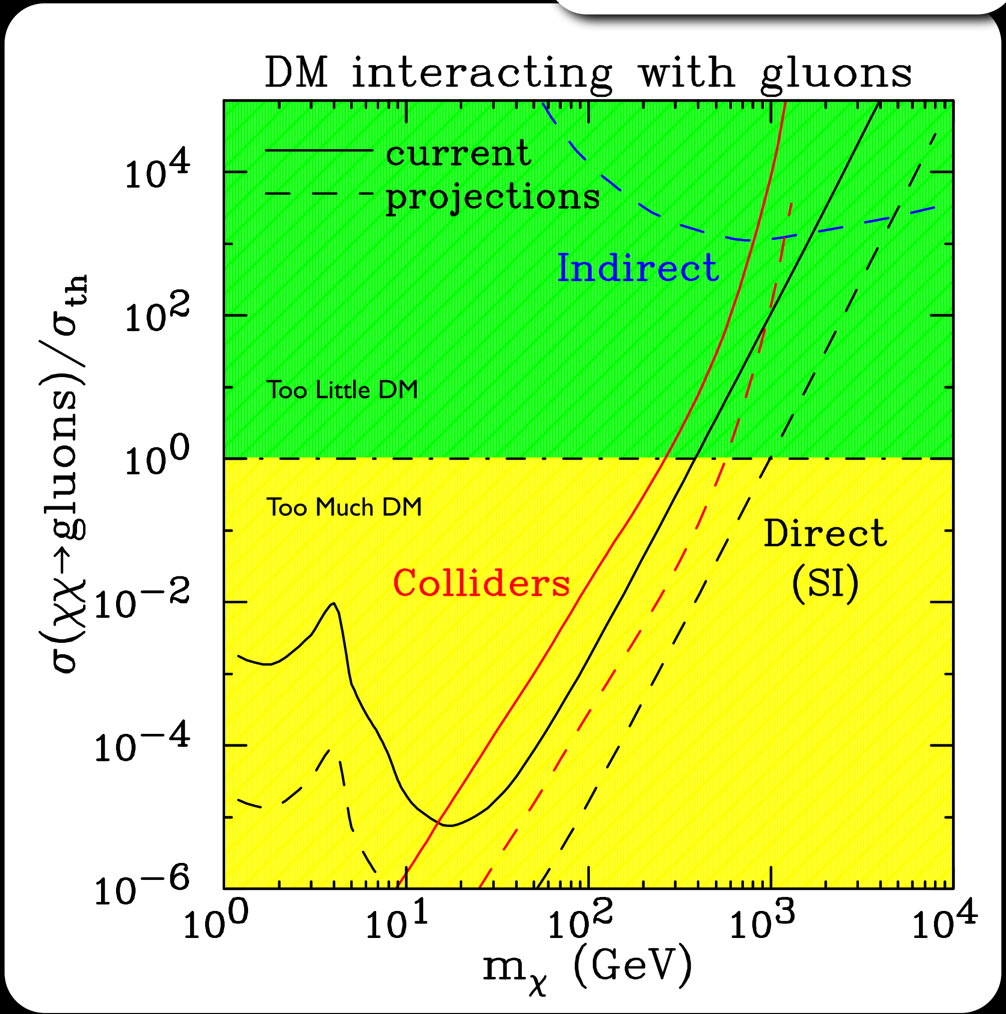
See: Goodman, Ibe, Rajaraman, Shepherd, TMPT, Yu 1005.1286 & PLB; Bai, Fox, Harnik 1005.3797 & JHEP; and lots of other papers…

- 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

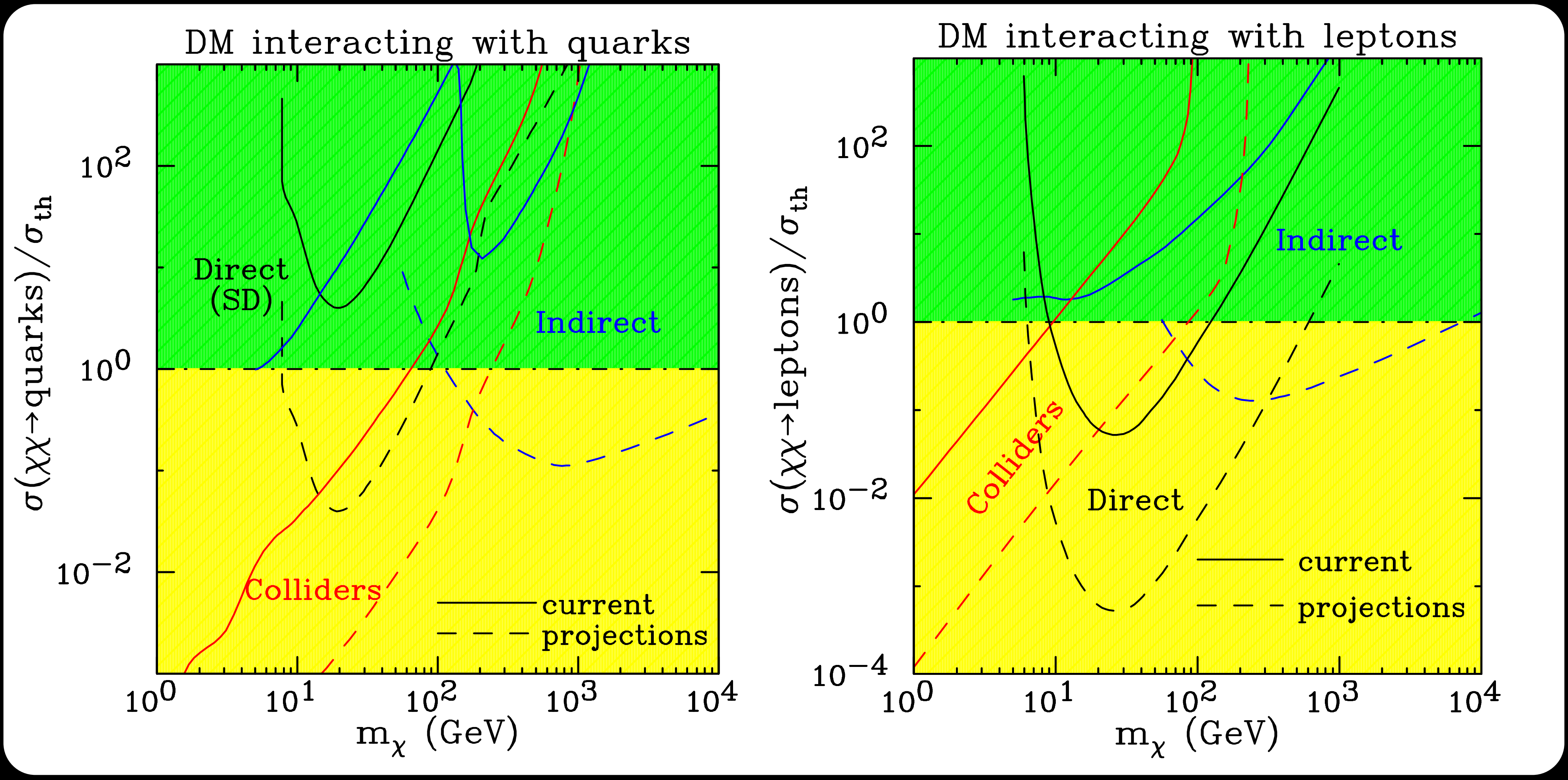


- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders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

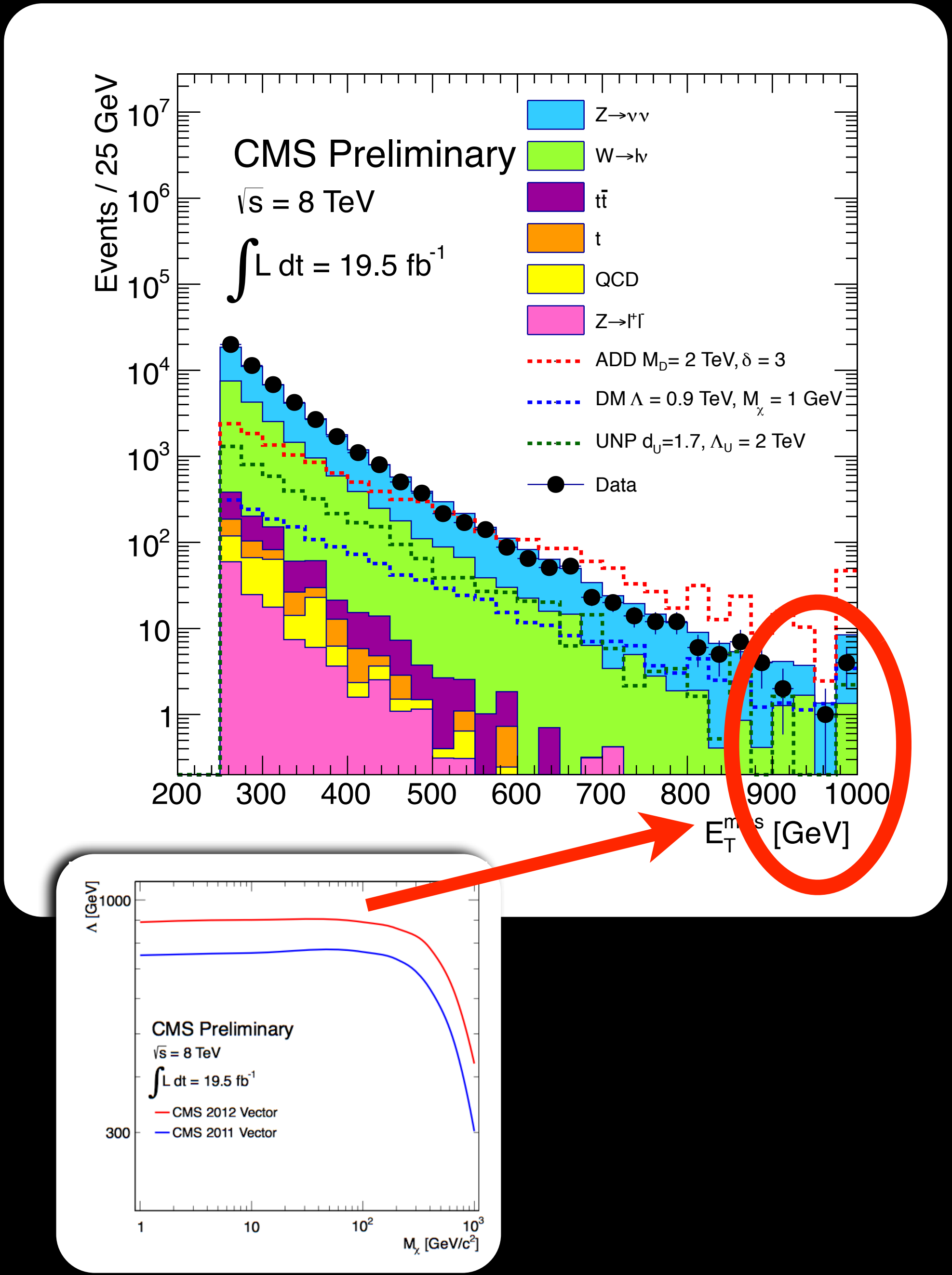
Quarks & Leptons



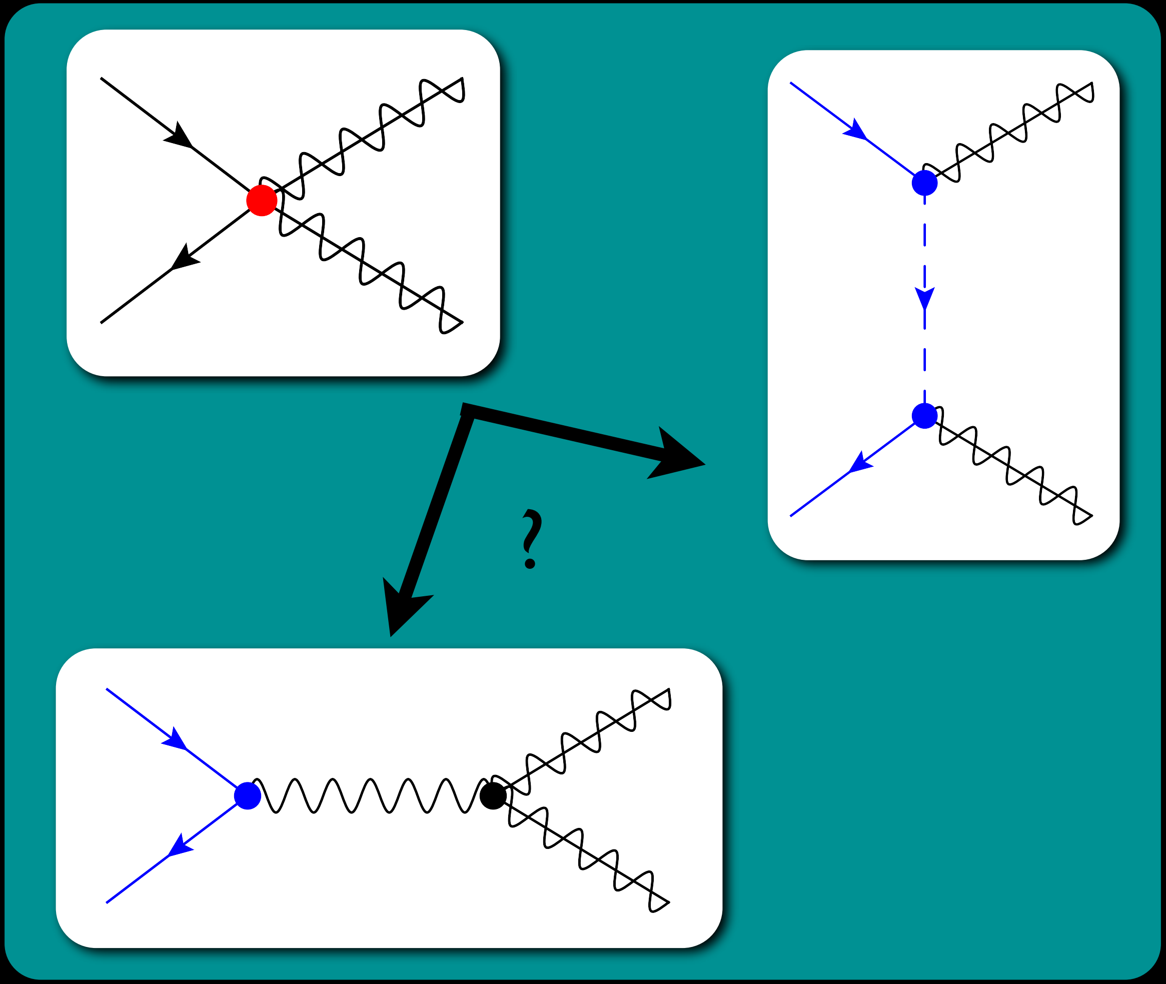
DM Complementarity, arXiv:1305.1605

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.]



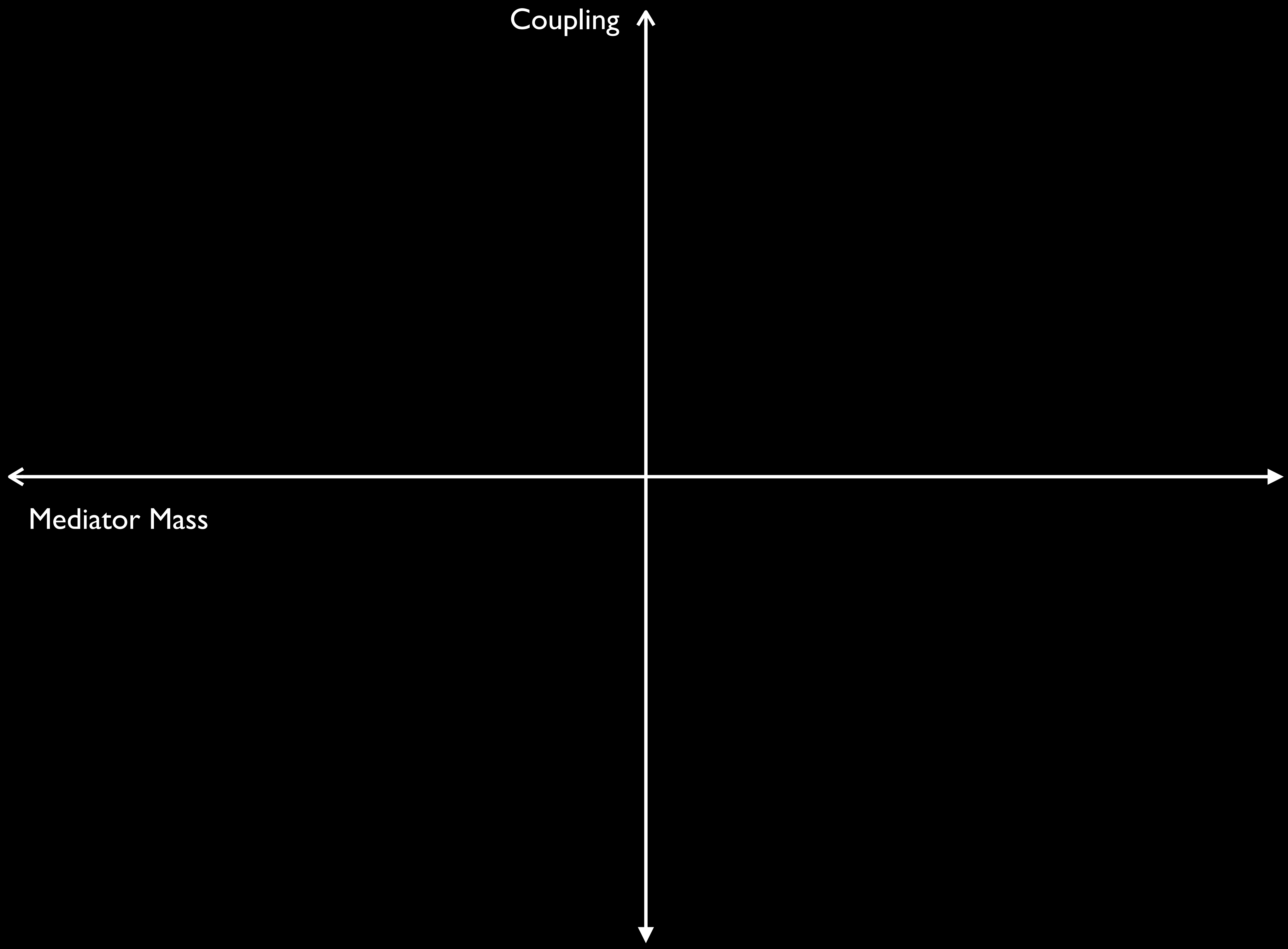
Simplified Models?

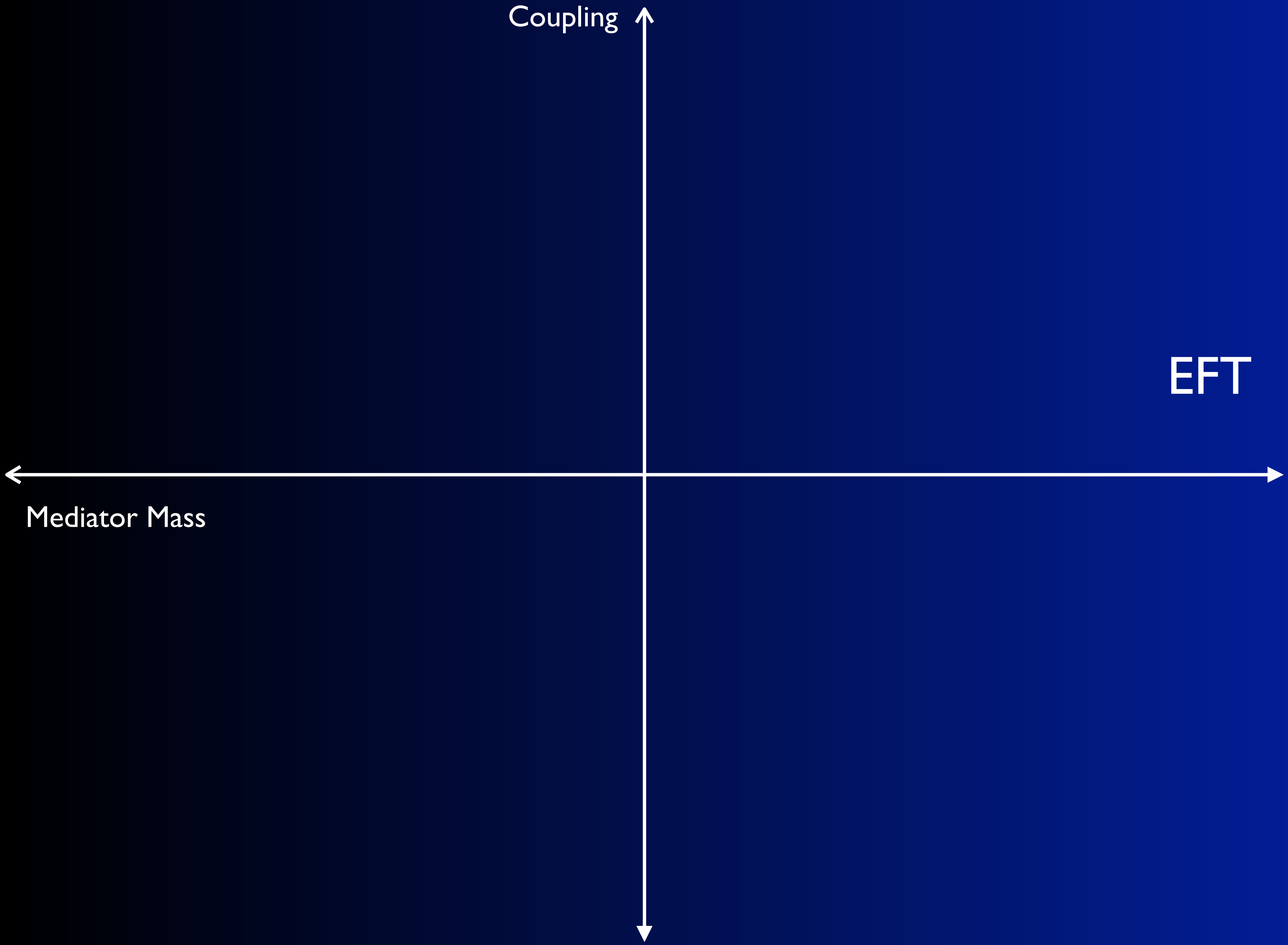


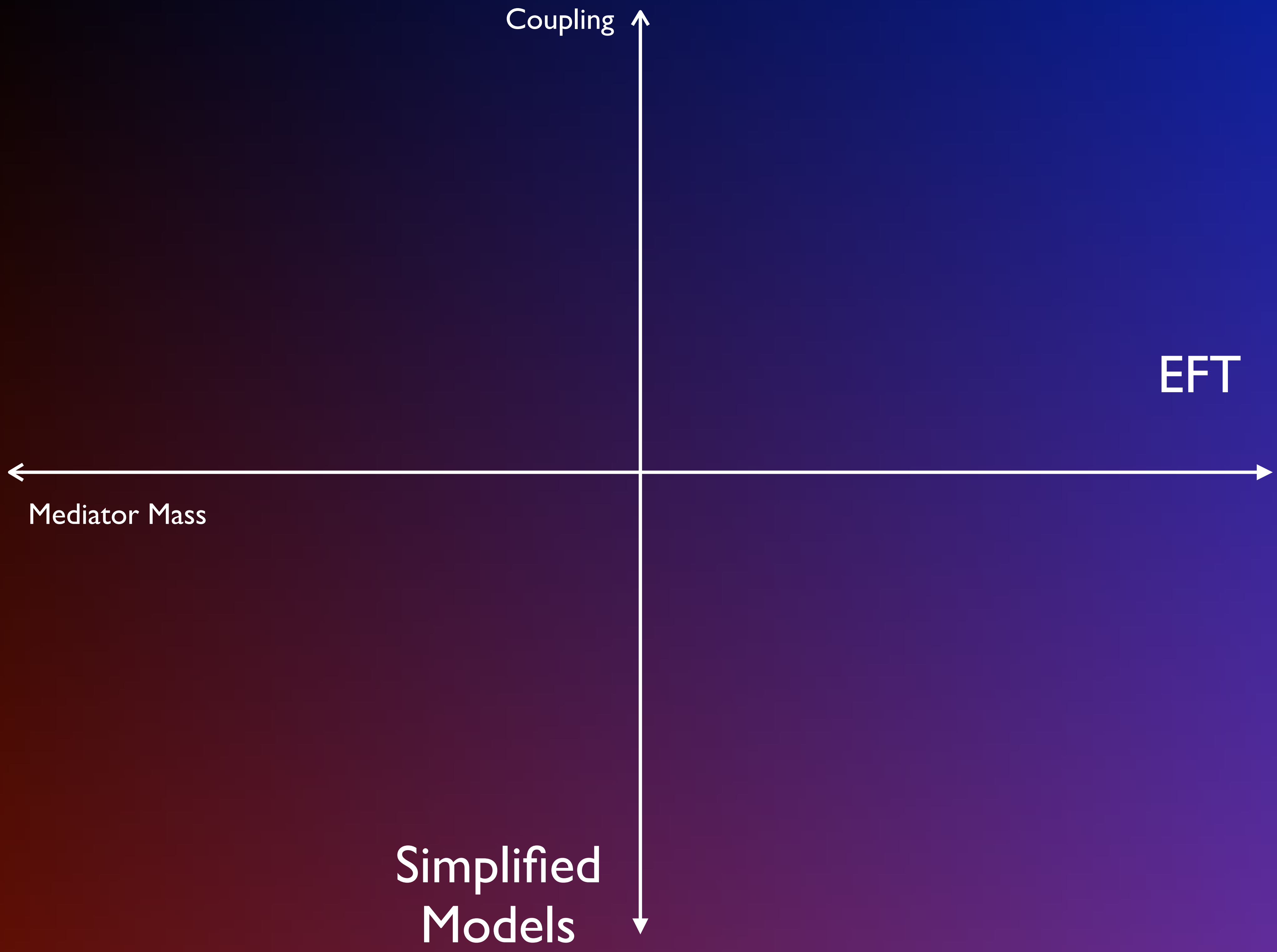
"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

"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
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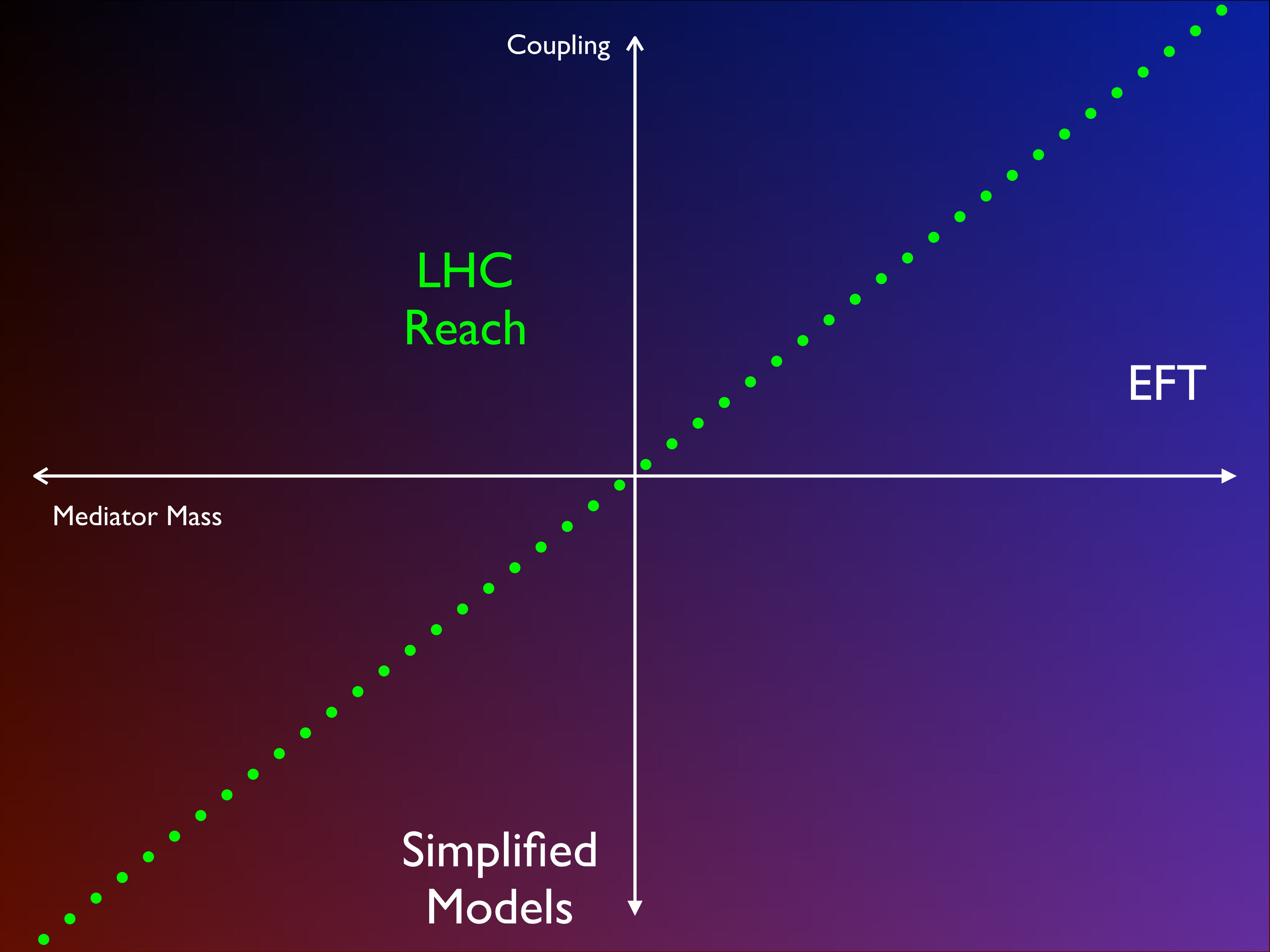
Simplified
Models



Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

Much Ado…

At this point, one typically hears a lot of fuzzy, qualitative, and often just plain absurd statements, such as:

1. “The effective field theory doesn’t work at the LHC”

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Much Ado…

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3. "The parameter space of the EFT is already ruled out."

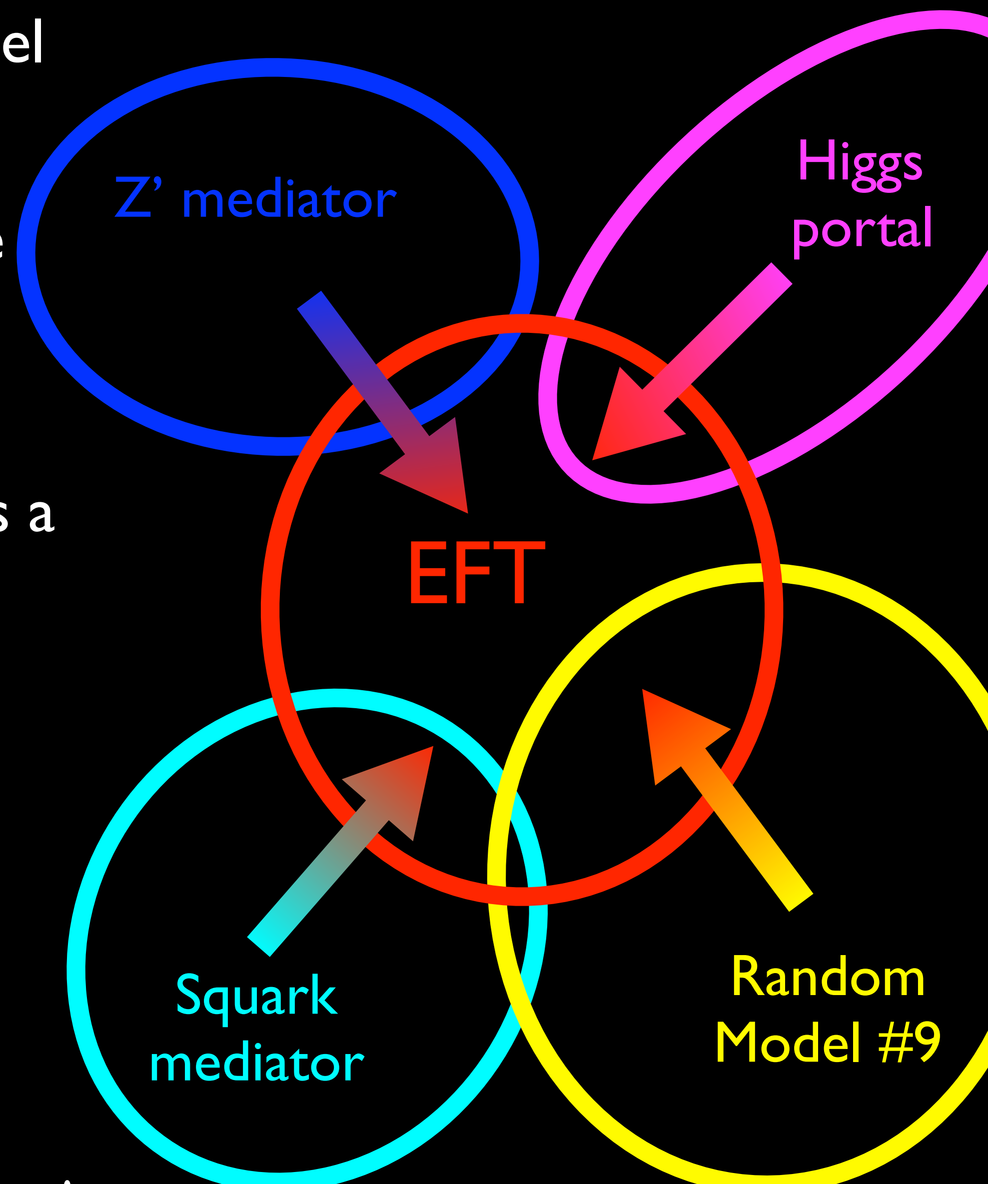
Much Ado…

At this point, one typically hears a lot of fuzzy, qualitative, and often just plain absurd statements, such as:

1. “The effective field theory doesn’t work at the LHC”
2. “The higher energies of Run II will cause the EFT to break down.”
3. “The parameter space of the EFT is already ruled out.”
4. “The early work on EFTs has brain-washed people.”

1. "EFT Doesn't Work at LHC"

- A lot of the discussion is driven by conflation of a particular simplified model with the EFT itself.
  - This is inspired to some extent by the fact that the EFT is the universal large mass limit of any simplified model.
  - One should remember that the EFT is a superset of a limit of all simplified models: any one of them does not typically characterize all of them.
  - It is logistically impossible to rule out application of the EFT *in general* based on one *specific* model.
  - Instead, this reminds us that the EFT cannot itself describe all the possibilities!



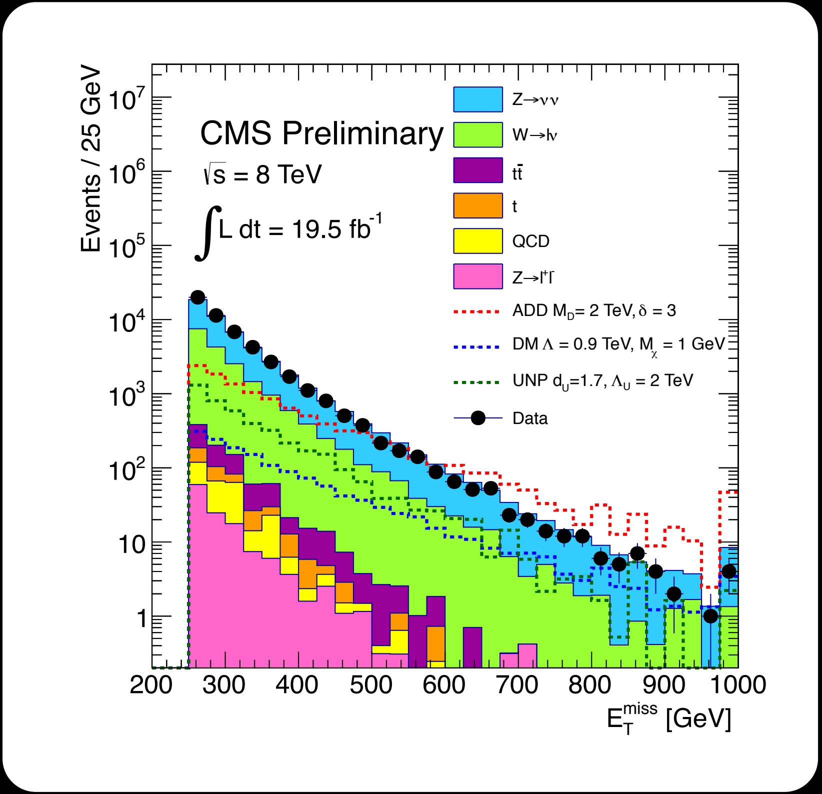
1. "EFT Doesn't Work at LHC"

- So what can we learn from the EFT itself?
- The EFT is an expansion in energy: E / M_*.
  - If E is too large, loop contributions to the observables will contribute as much as the tree level, and the theory ceases to be predictive.
  - Where that happens for fixed M_* is somewhere around:

$$E \gtrsim 4\pi \ M_*$$

(We can argue about whether this should be 4π or 2π or some other number. One is as indefensible as another.)

  - For the Run I limits of $M_* \sim 1$ TeV, this forbids us from using events with energies larger than about 10 TeV.

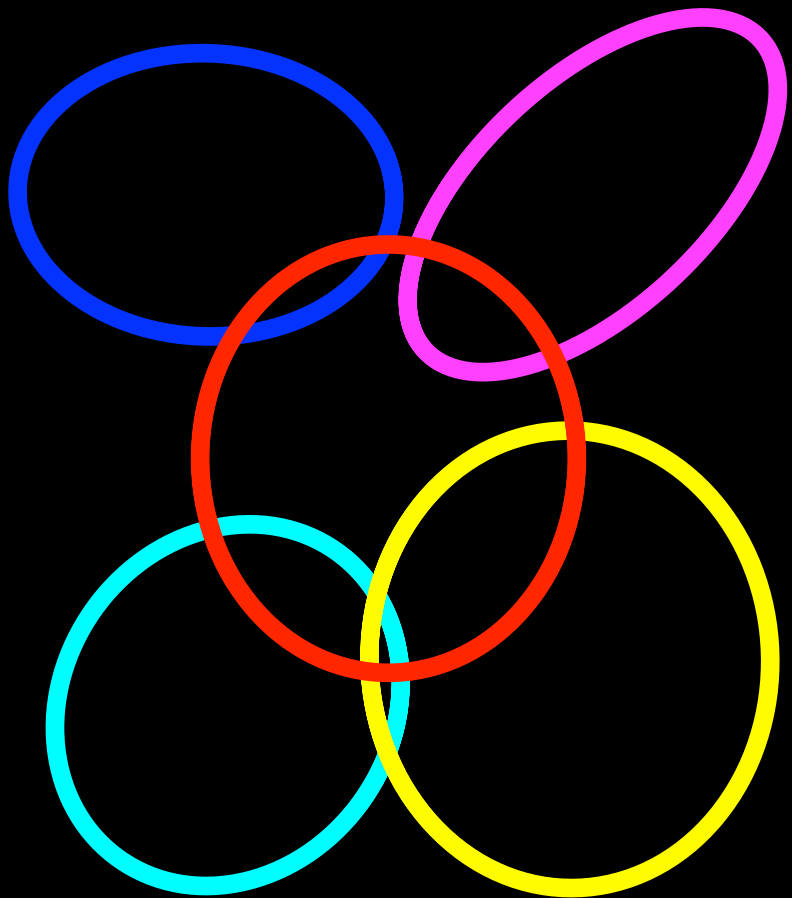


Not a big problem at Run I…

(even in the limit 4π -> ~1!)

2. "EFT Doesn't Work at Run 2"

- Uhh… Again:
  - One single simplified model cannot rule out the applicability of the EFT in general.
  - The EFT itself breaks down for energies much higher than the interaction scale M_*.
- Run II projections are for bounds on M_* which are around 2-3 TeV. (Obviously this involves things like the fake MET rate, so mileage may vary).
- If you believe the mediator must have a mass less than a few TeV and/or very small couplings, the EFT won't describe it.
- If you think it could be heavier, it might.

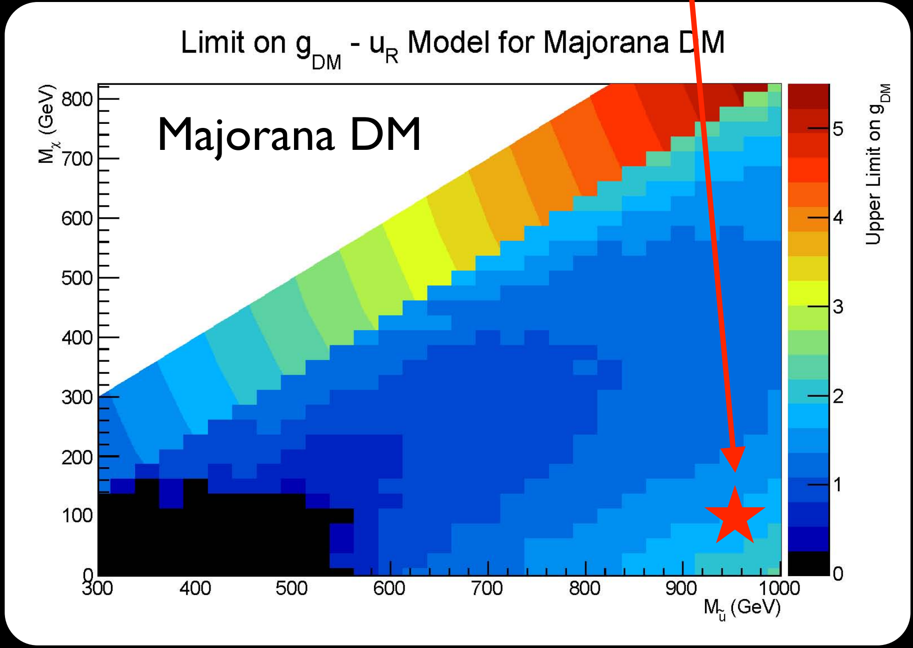


3. "The EFT Describes Models Which are Already Ruled Out"

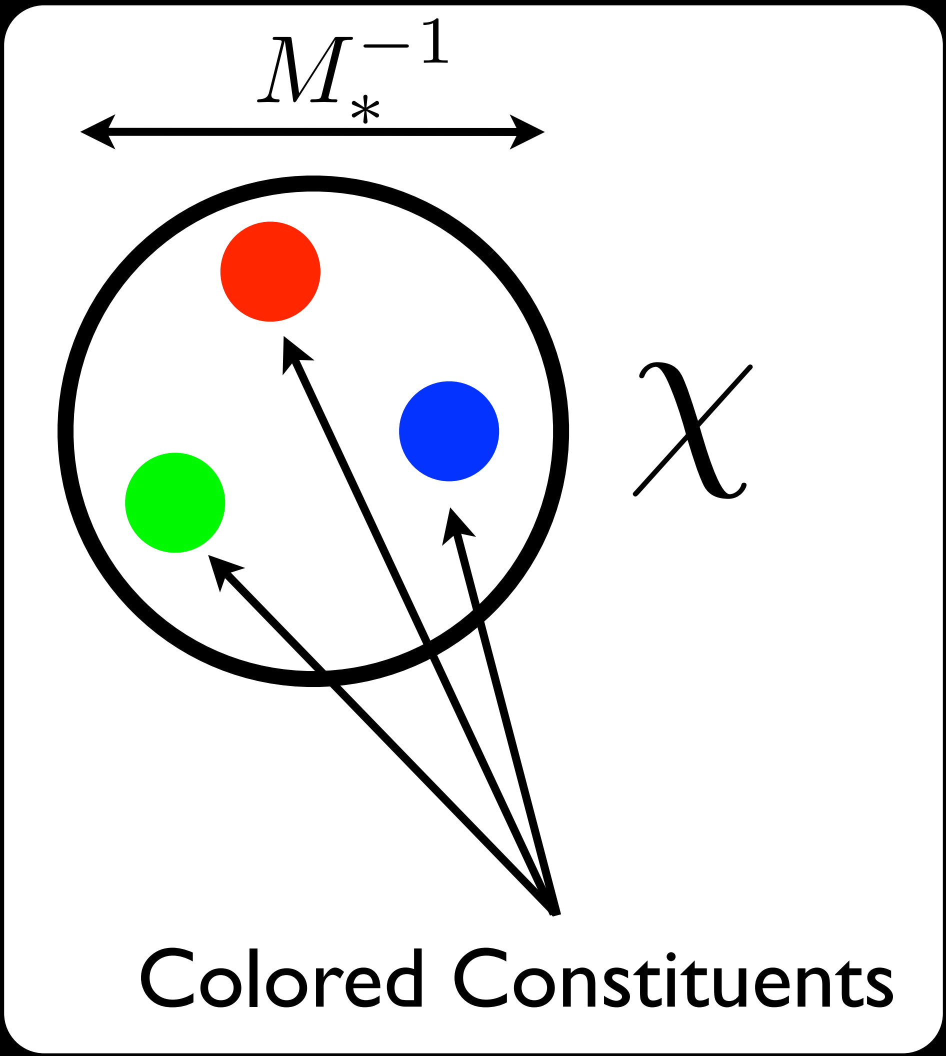
- It's true that for any given simplified model, one may find that the LHC limits apply for large couplings and widths.
  - Watch for hidden assumptions like setting couplings equal which needn't be.
- Sometimes other searches give better limits.
  - For example, a Z' mediator with large coupling to light quarks can be bounded by dijet resonance searches.
- In general, one can find regions of parameter space where the EFT is a good description of weakly-ish coupled models with heavy-ish mediators.

Direct searches for the mediator are actually somewhat weaker than mono-jet bounds here.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



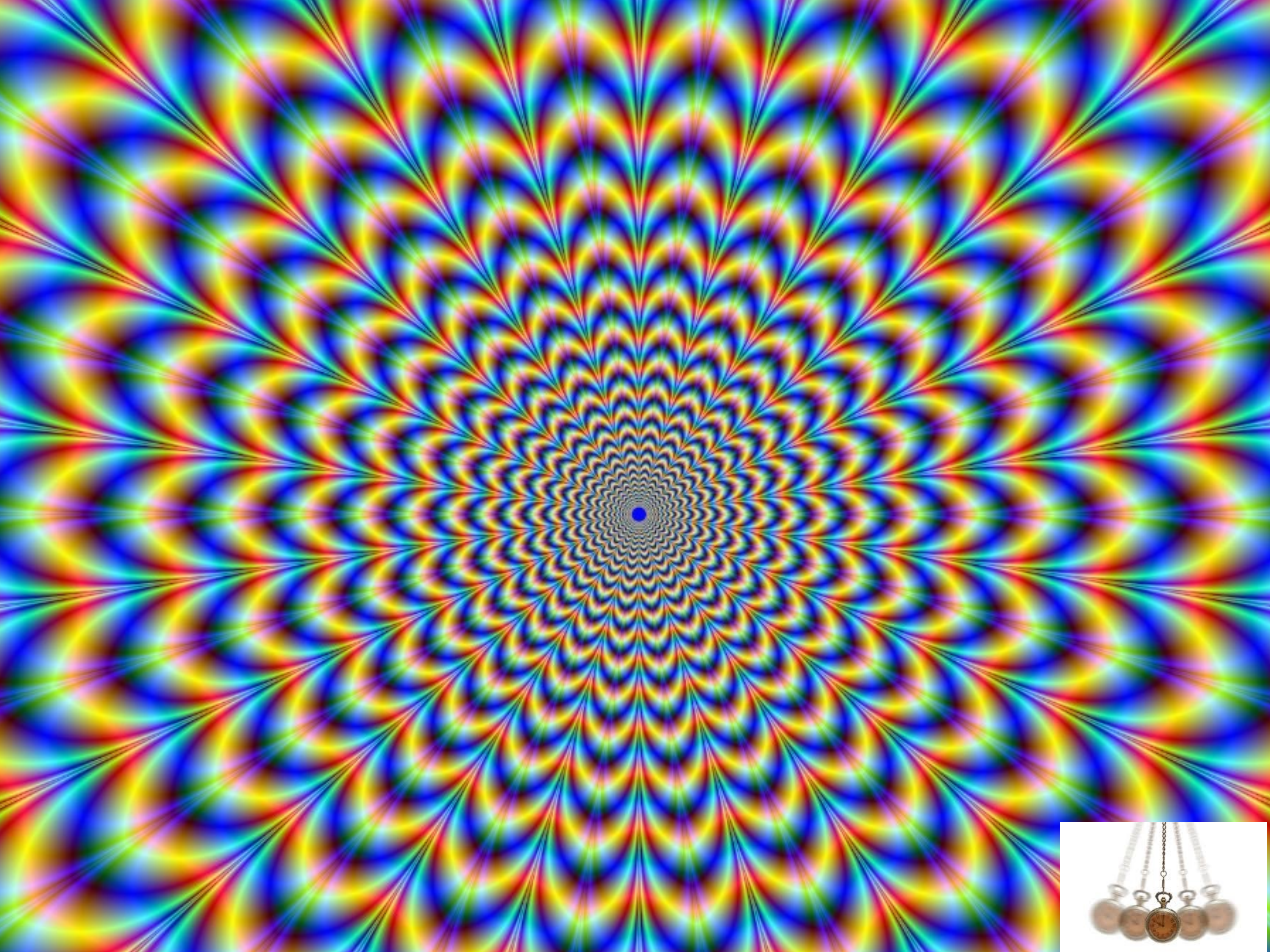
A Composite WIMP?



- 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.

4. “The EFT has brain-washed people.”

- I actually don’t have any evidence that this is not true.
- Let’s settle it once and for all experimentally:

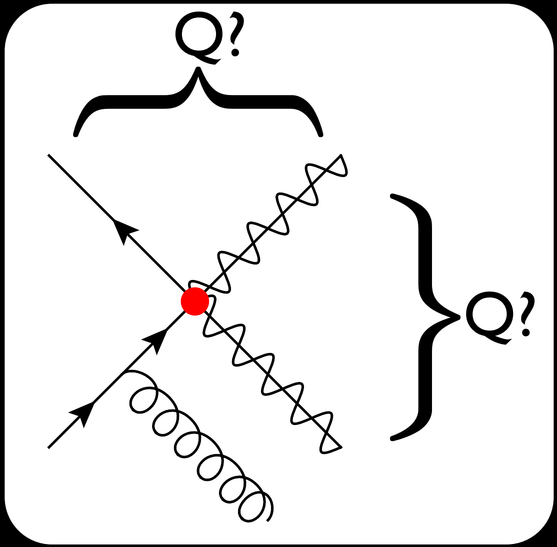


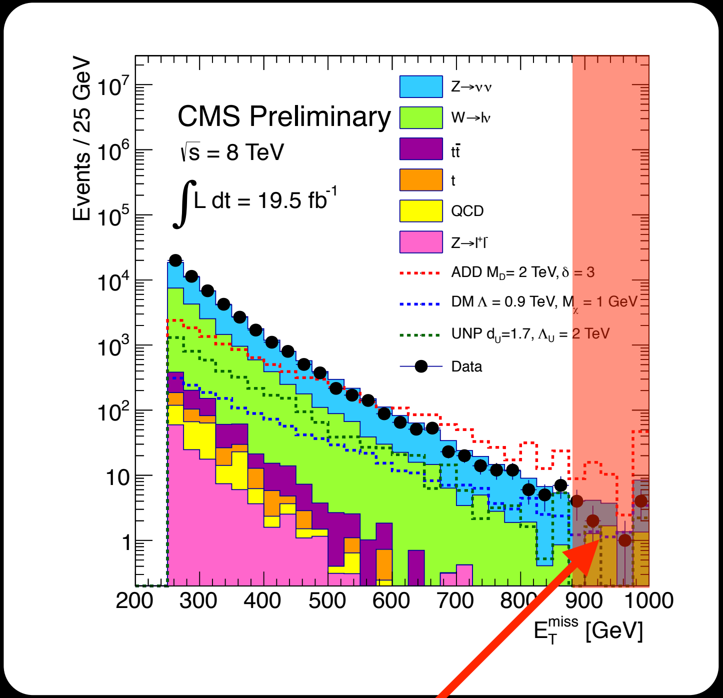
4. “The EFT has brain-washed people.”

- I actually don’t have any evidence that this is not true.
- Let’s settle it once and for all experimentally:
  - None of you are currently clucking like a chicken, so I think it is safe to declare this particular experiment a failure.

Truncation

- A good idea which I think Andrea will shortly describe in some detail 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_*.

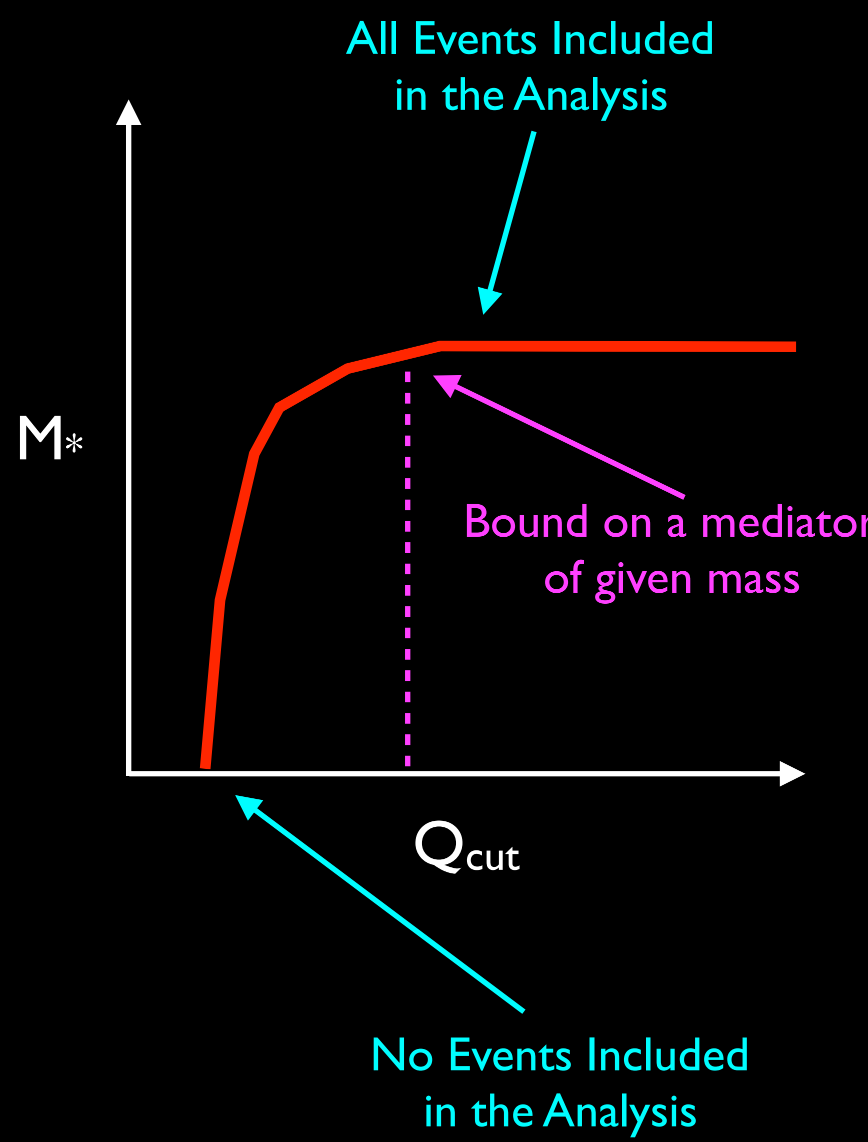




Exclude these Events for Q_{cut} = 900 GeV.

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.



Outlook

- EFTs have been used to describe dark matter interactions. They 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.
  - 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.
- Higgs physics successfully uses EFTs to describe both its coupling to gluons and to parameterize physics beyond the Standard Model.
- A lot of this currently is (rightly) focused on Higgs decays, for which the expansion parameter is m_h / M_*.
- But as data increases, it will be tempting to turn to high energy processes, as often these have a larger lever arm to constrain new physics.

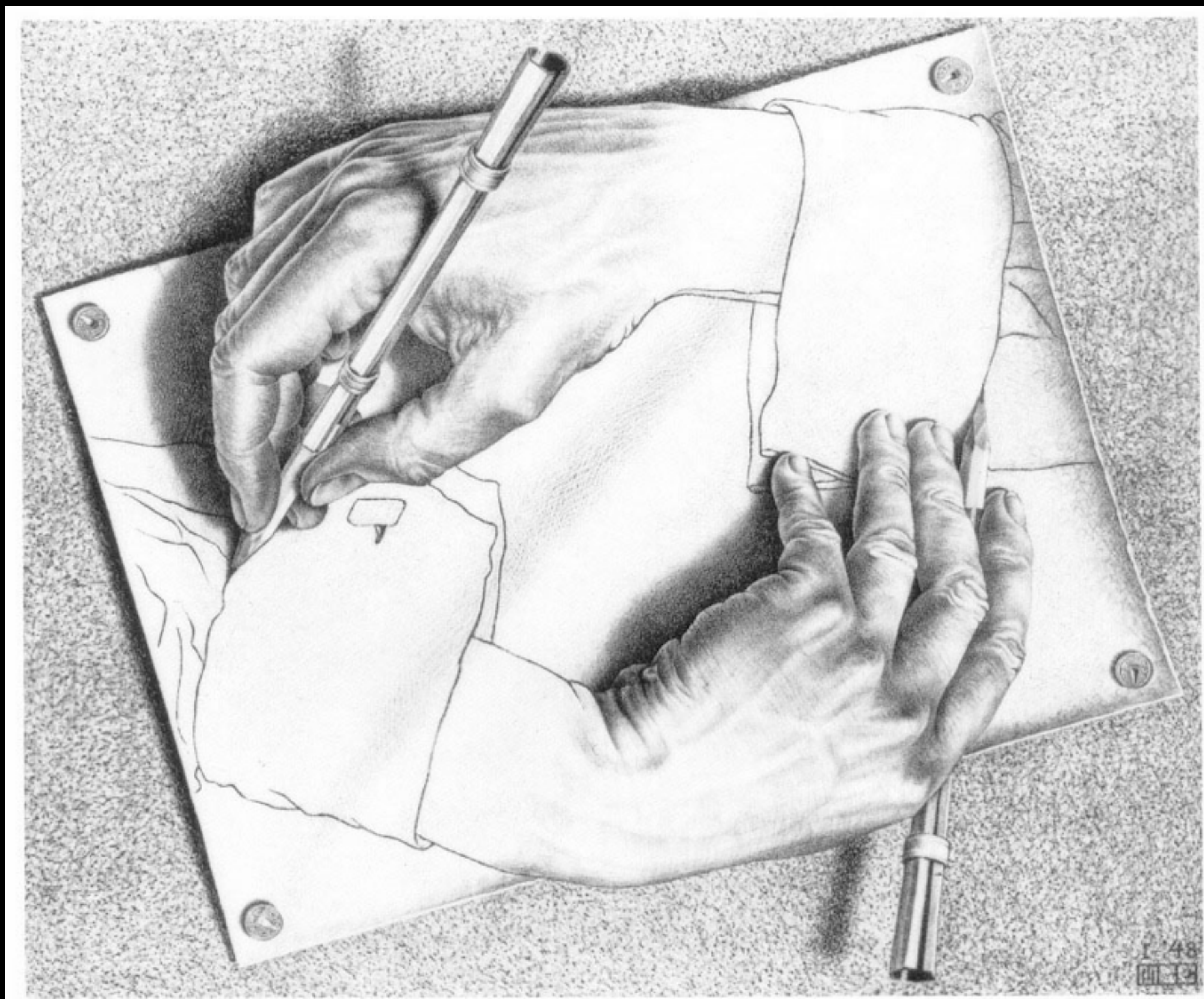
Outlook

- All of the complaints/criticisms (valid and not) of the DM results are likely to come up for Higgs analysis at that point.
- In that regime, some of the experience from dark matter will hopefully be useful:
  - When new particles are light, simplified models can help describe regions that are pathological from the EFT standpoint.

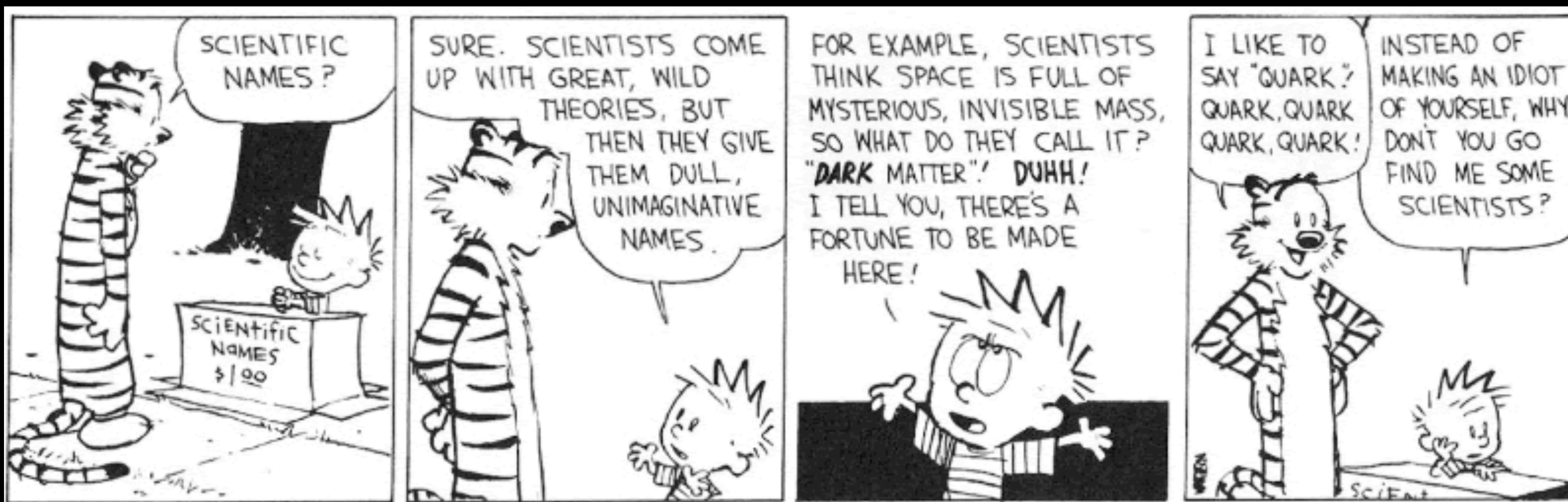
    e.g. Brehmer, Freitas, Lopez-Val, Plehn 1510.03443

  - EFT results can be presented in such a way that the user can make the most of them, via truncation or some other sliding analysis cut.
  - From my experience, it would be useful to "get ahead of the curve" and cultivate a useful way to think of the EFT results before you are forced to rant and rave the way I am today.
- EFTs are powerful tools and Higgs physics is a beautiful place to make use of them!

From Sketch to Life



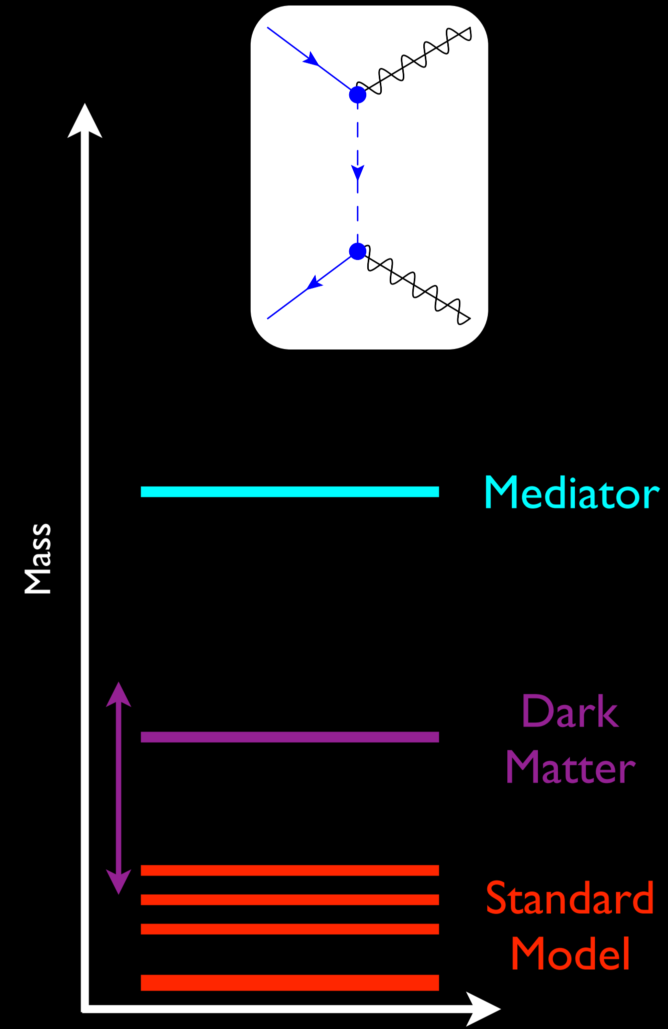
Sketches of ....


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

Simplified Model

- Moving toward a more complete theory, we can also consider a model containing the dark matter as well as the most important particle mediating its interaction with the Standard Model.
- For example, if we are interesting in dark matter interacting with quarks, we can sketch a theory containing a colored scalar particle which mediates the interaction.
- This theory looks kind of like a little part of a SUSY model, but has more freedom in terms of choosing couplings, etc.
- There are basically three parameters to this model: the mass of the dark matter, the mass of the mediator, and the coupling strength with quarks.

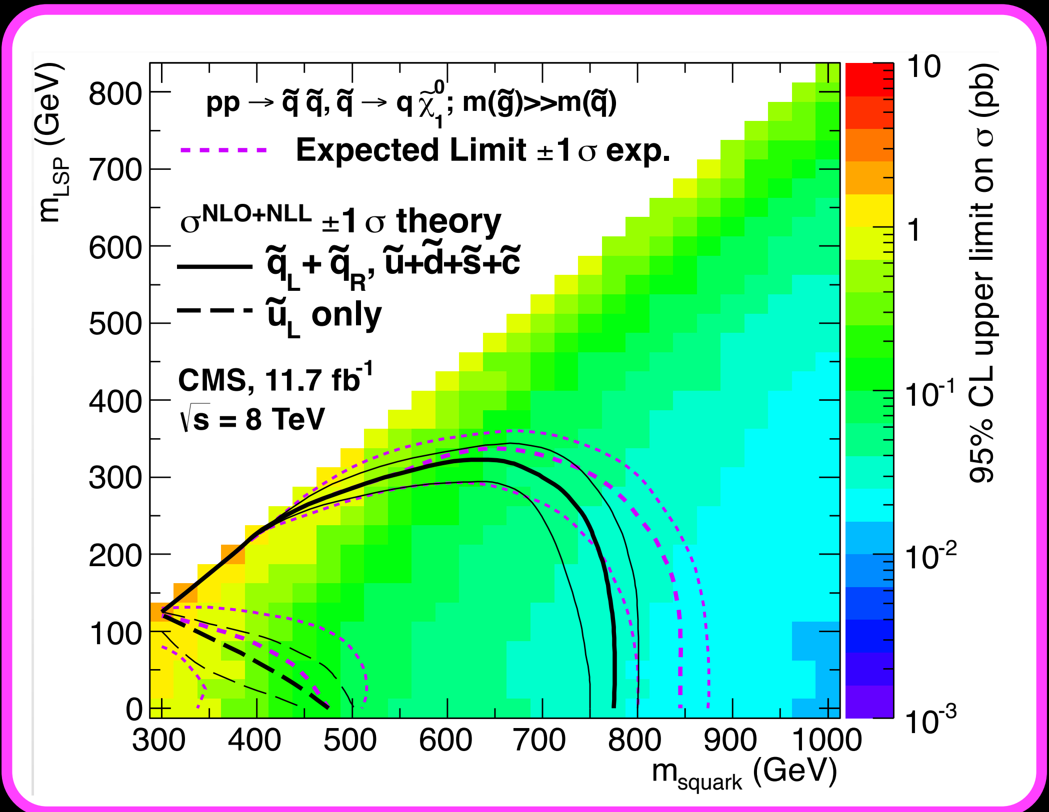


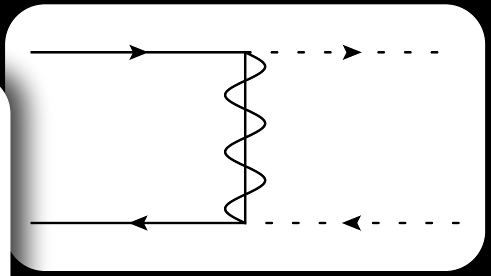
Lots of Recent Activity:

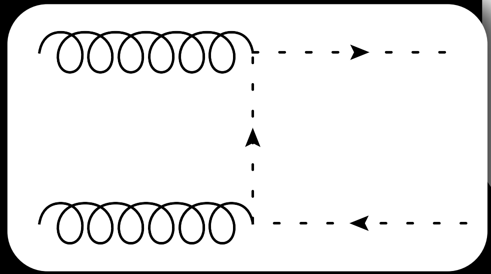
Chang, Edezhath, Hutchinson, Luty 1307.8120
An, Wang, Zhang 1308.0592
Berger, Bai 1308.0612
Di Franzo, Nagao, Rajaraman, TMPT 1308.2679
Papucci, Vichi, Zurek 1402.2285
+ follow ups.

$\tilde{u}_R$ Model

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





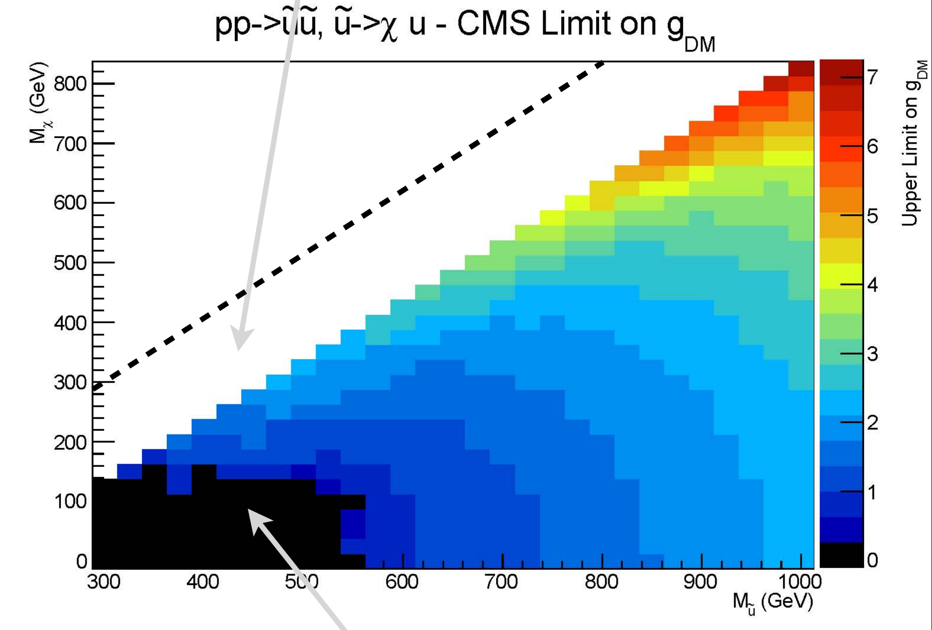


$\tilde{u}_R$ Model

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

Weak bounds in the mass-degenerate region.

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



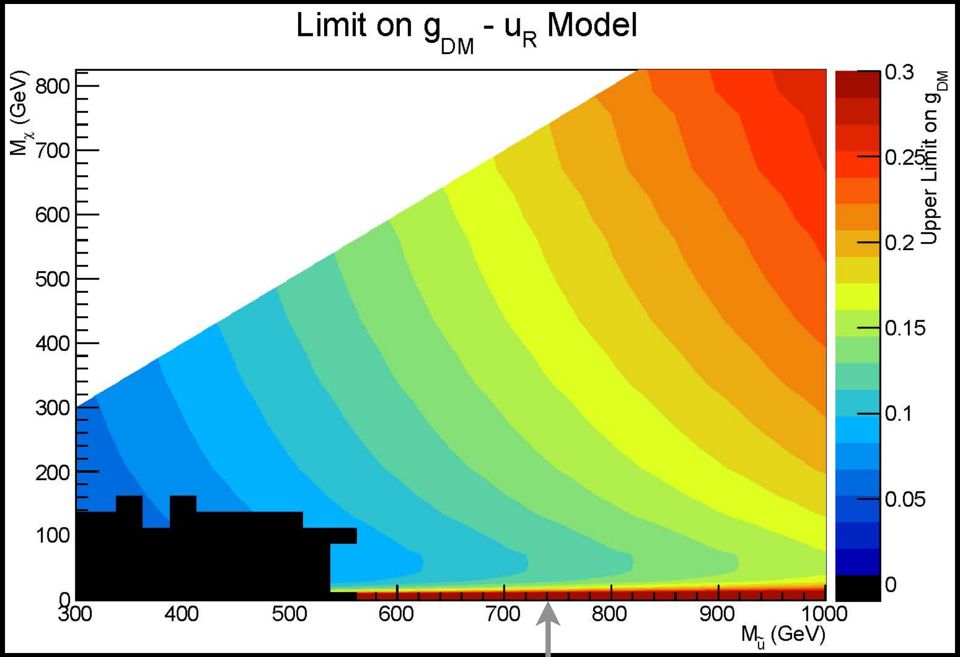
QCD production saturates the CMS limits, resulting in no allowed value of g.

All mediator masses and couplings assumed equal.

$\tilde{u}_R$ Model

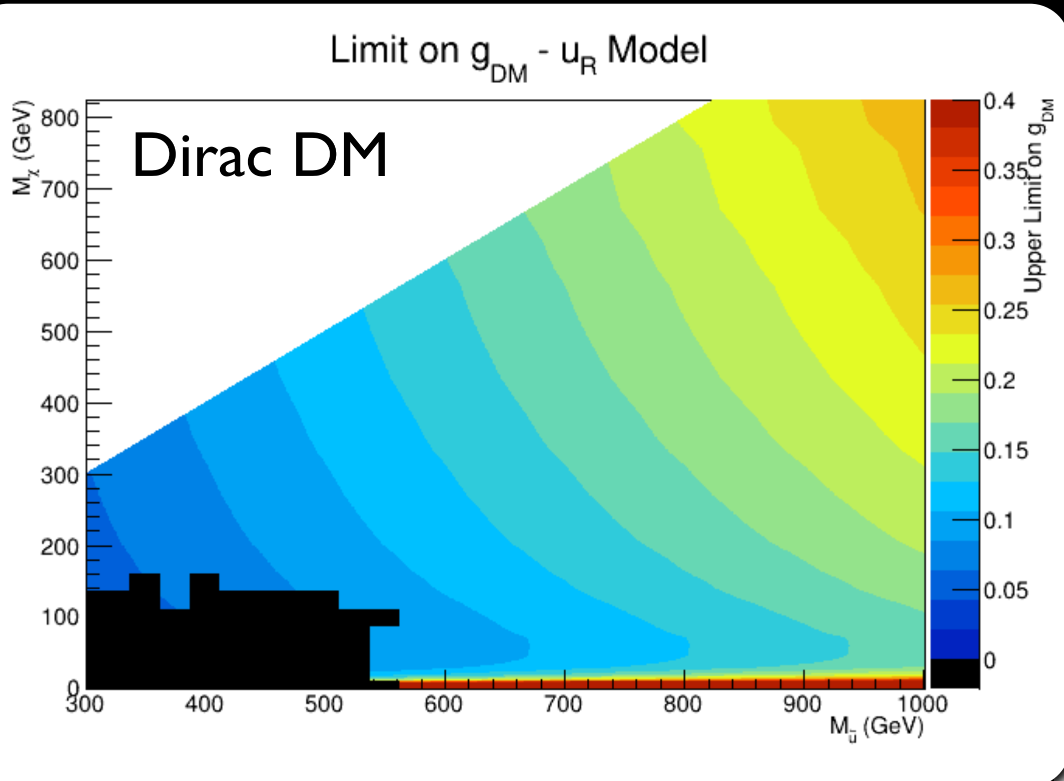
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

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



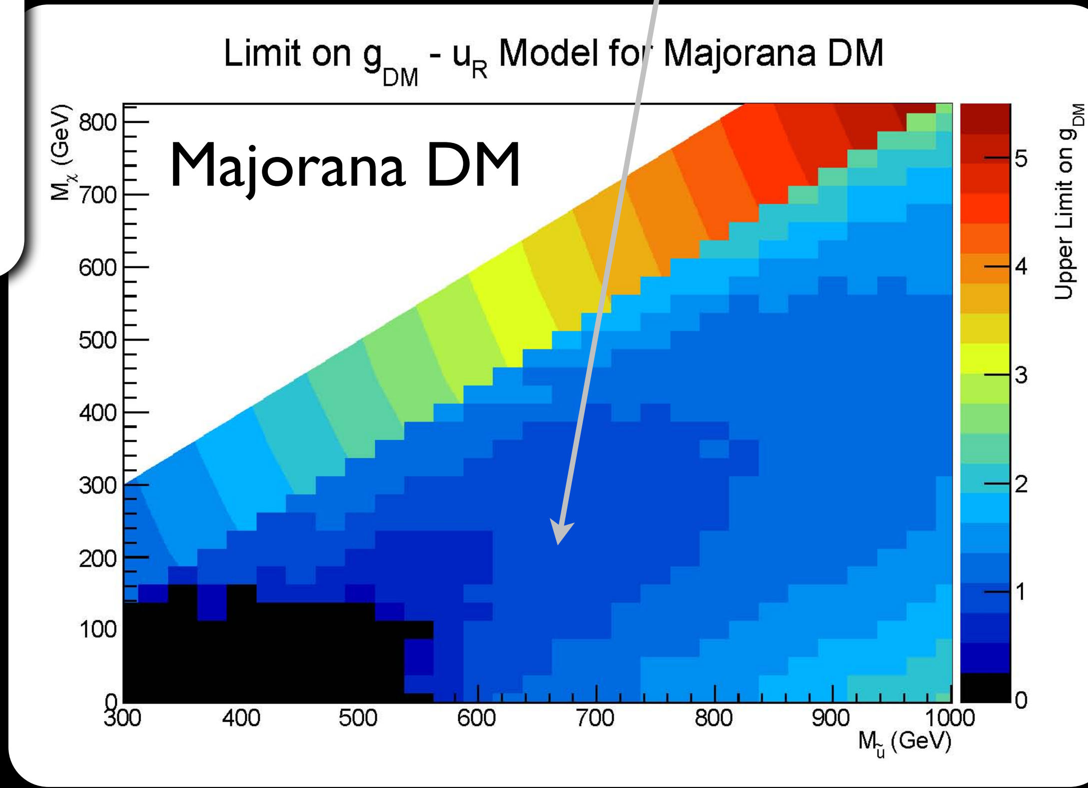
Traditional direct detection searches peter out for masses below about 10 GeV.

$\tilde{u}_R$ Model: Results



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

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



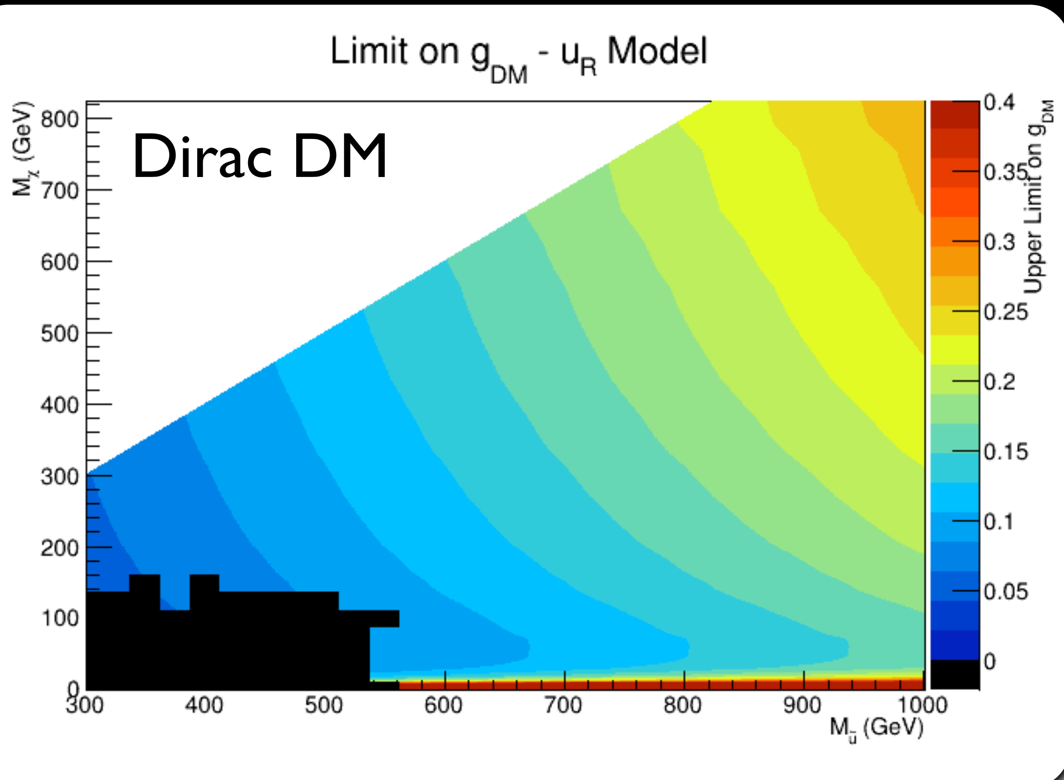
There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

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

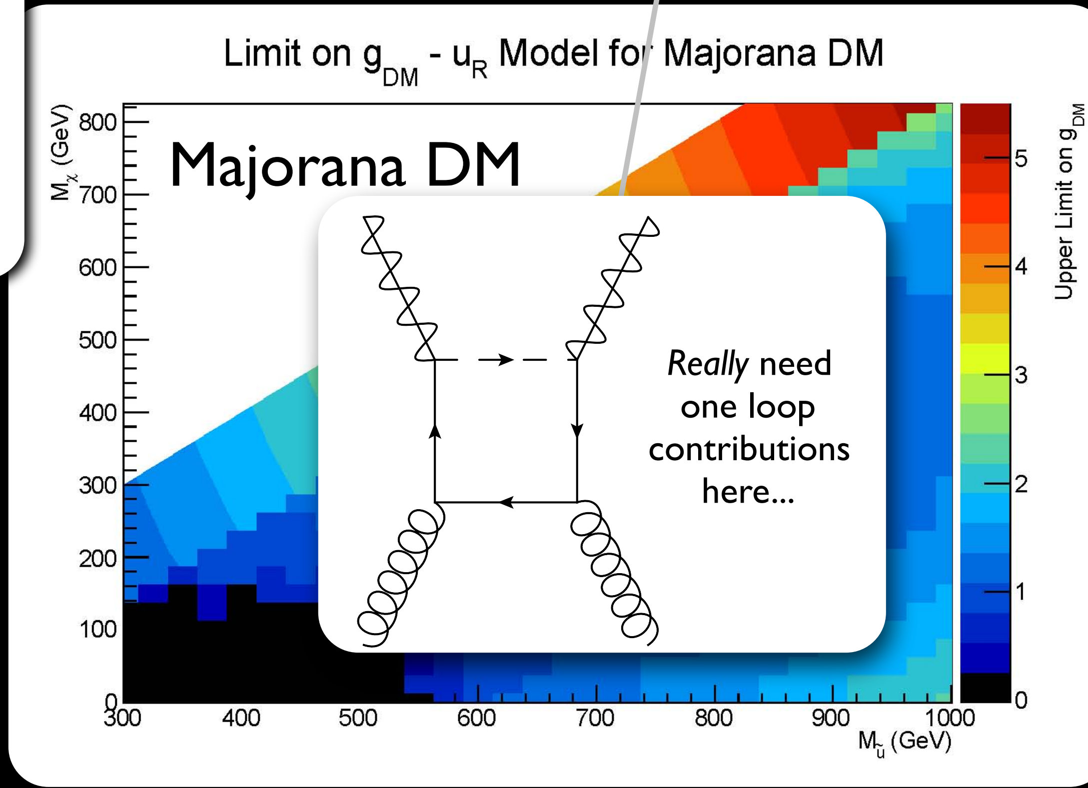
At colliders, t-channel exchange of a Majorana WIMP can produce two mediators, leading to a PDF-friendly qq initial state.

$\tilde{u}_R$ Model: Results

DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679



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



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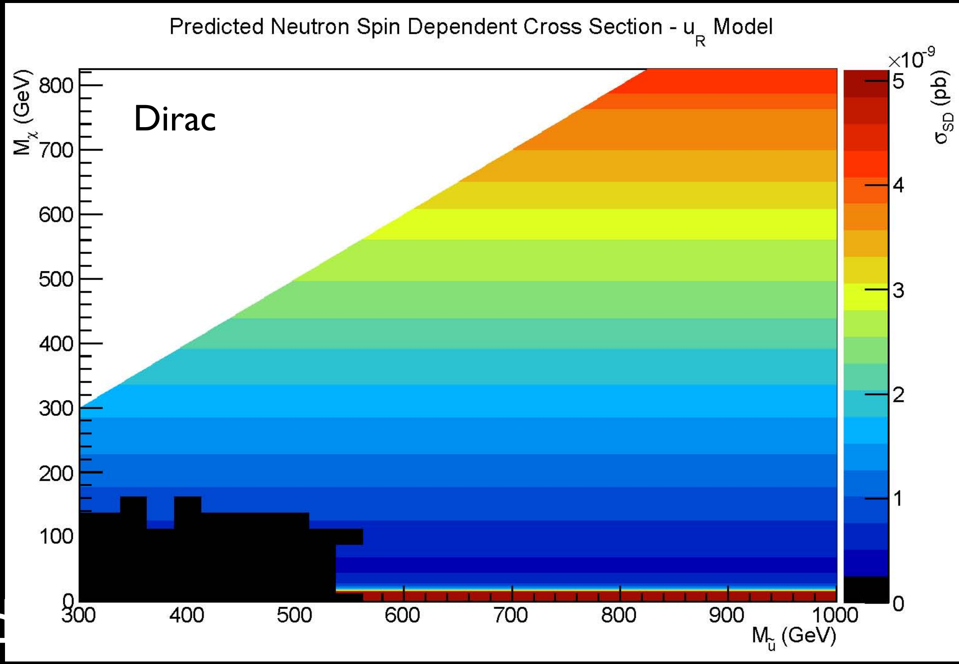
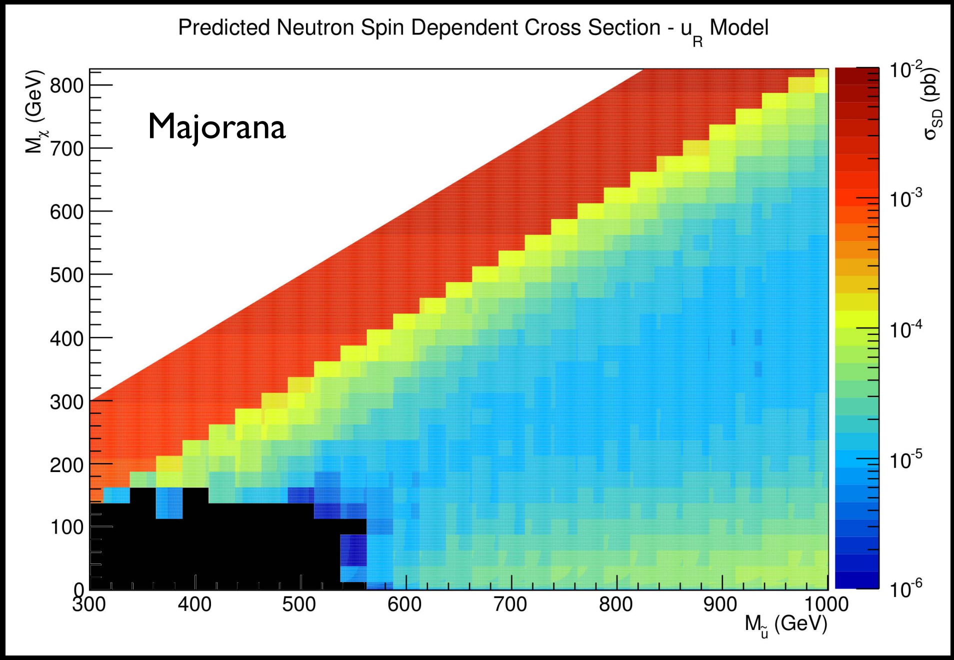
$\tilde{u}_R$ Model: Forecasts

- Now that we understand the current bounds, we can forecast what this implies for future searches.
- For example, we can plot the largest spin-dependent cross sections that are consistent with the LHC constraints and Xenon-100 in this simplified model.
- Again, Dirac versus Majorana dark matter look very different from one another!

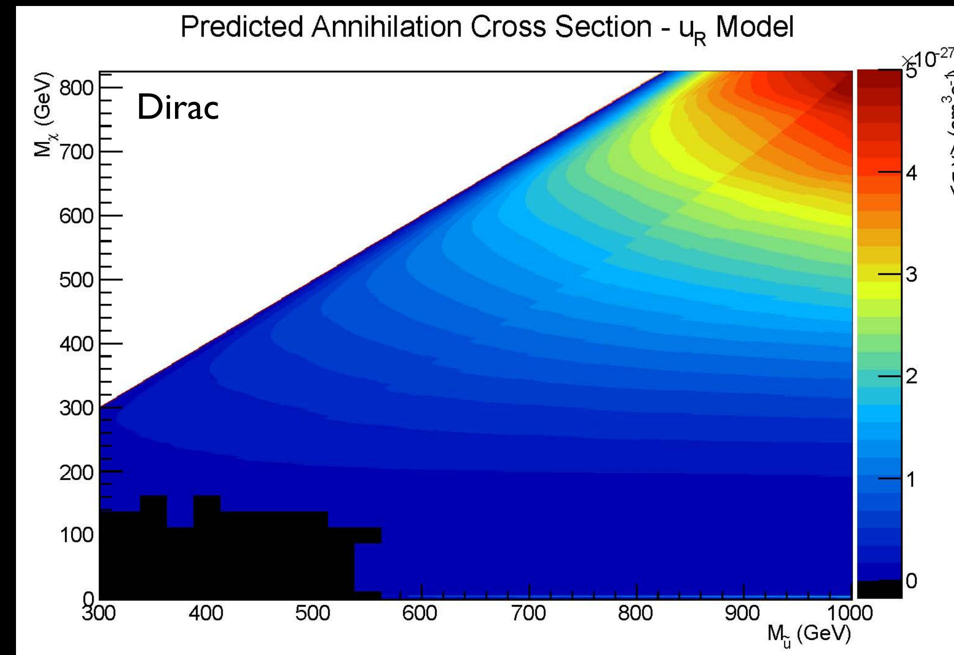


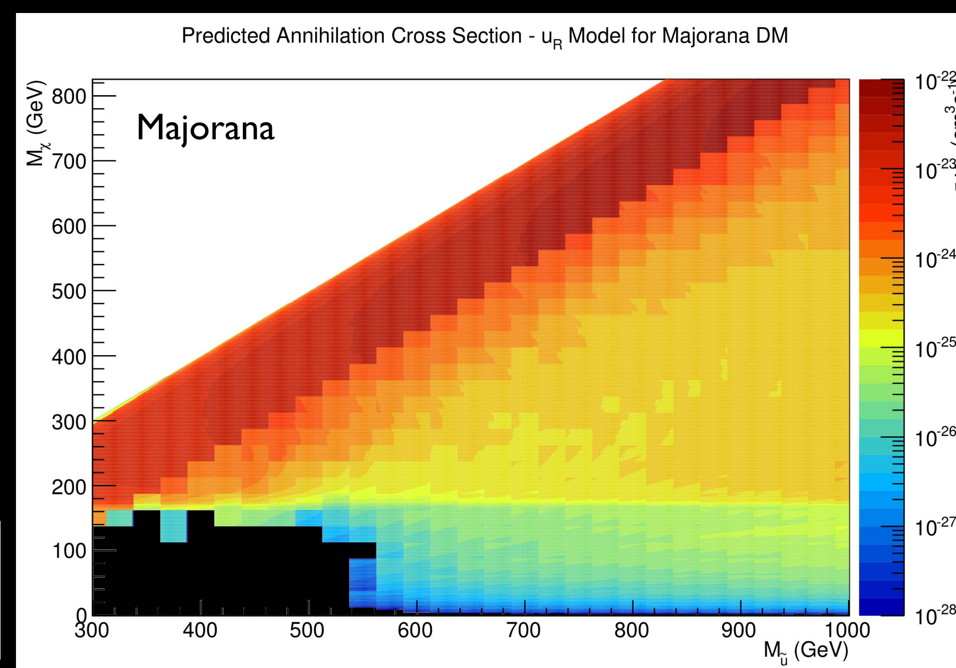


DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

$\tilde{u}_R$ Model: Forecasts

- Similarly, we can forecast for the annihilation cross section.
- The Fermi LAT does not put very interesting constraints at the moment, but it is very close to doing so. Limits from dwarf satellite galaxies are likely to be relevant in the near future for Majorana DM.
- We can also ask where in parameter space this simple module would lead to a thermal relic with the correct relic density.

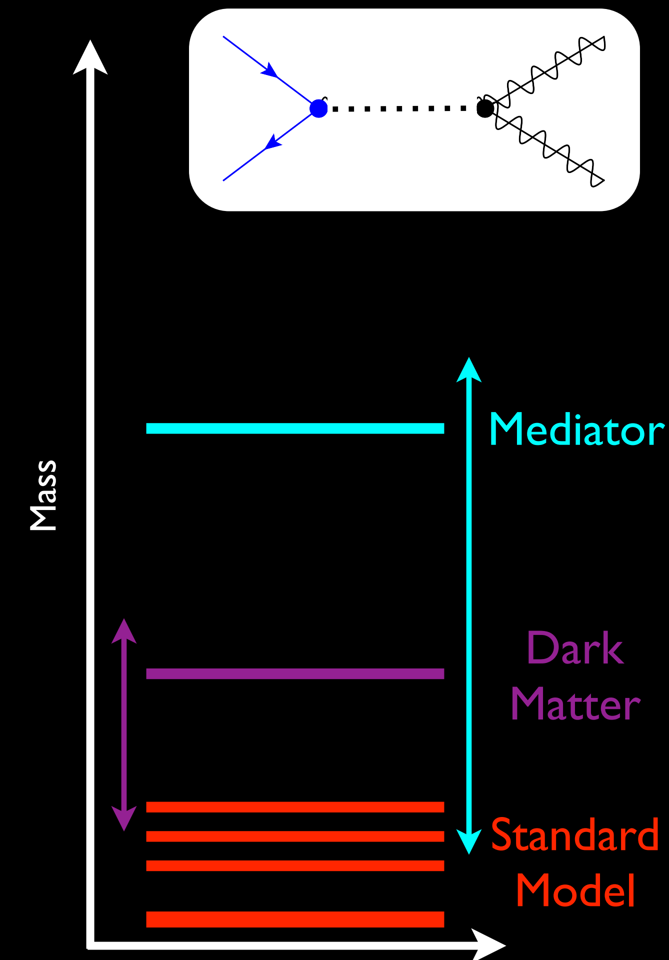




DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

S-Channel : Scalar

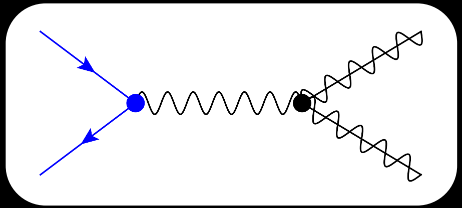
- A singlet scalar could be real or complex.
- Scalar couplings are chirality flipping. The scalar mediator consistent with MFV couples proportionally to Yukawa couplings.
- In the SM, the only relevant parameters are the masses, and the degree of mixing with the SM Higgs through electroweak breaking.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

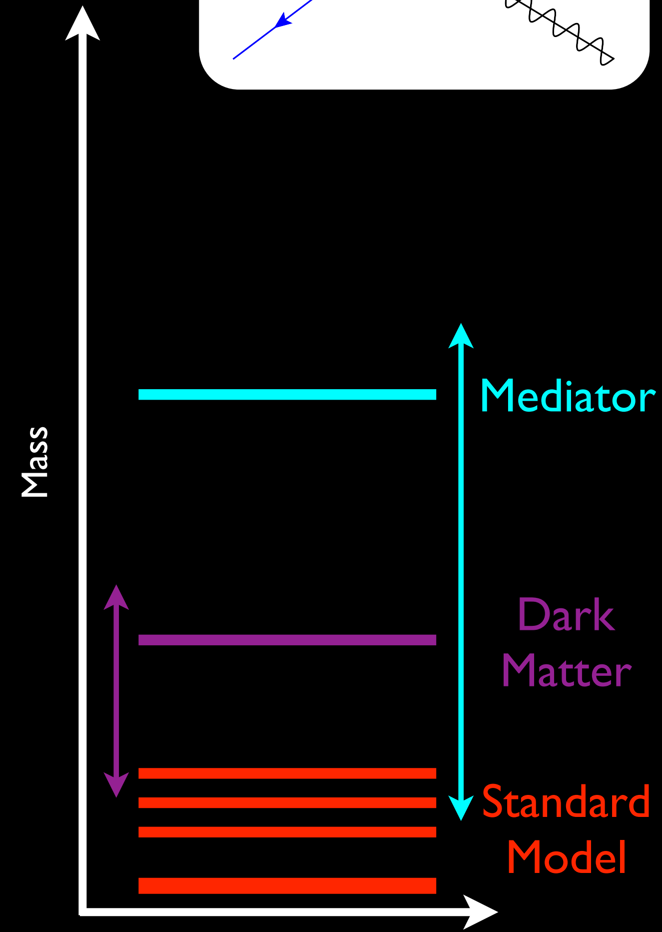


Buckley, Feld, Goncalves 1410.6497
Harris, Khoze, Spannowsky, Williams 1411.0535
+ others

S-Channel : Vector

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



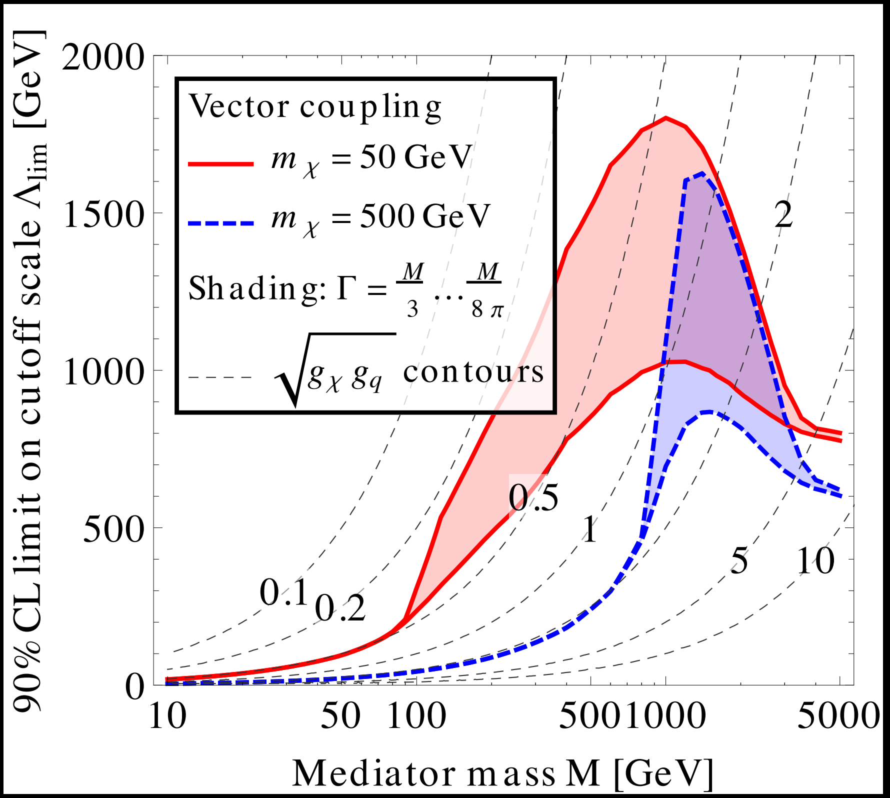


Parameters: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

How Effective a Theory?

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

Fox, Harnik, Kopp, Tsai
1109.4398 & PRD



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

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