# Searches for Particle Dark Matter


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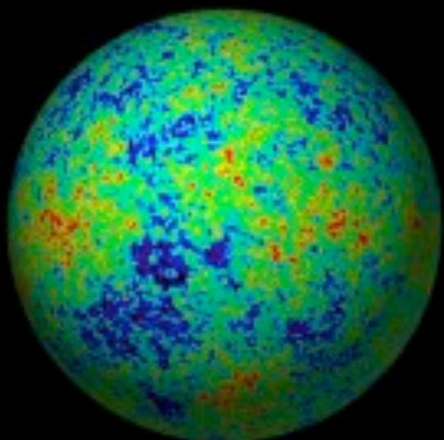
# Outline

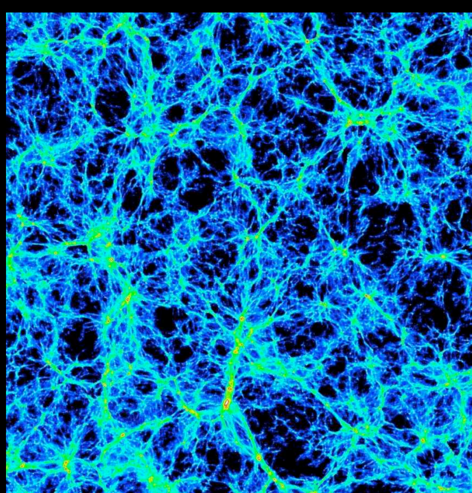
- Motivation: Particle Dark Matter
  - The Allure of WIMPs
  - The Importance of WIMP-Standard Model Interactions
- Theory frameworks for dark matter interactions
  - Contact Interactions
  - Simplified Models
- Outlook

# Dark Matter

CMB



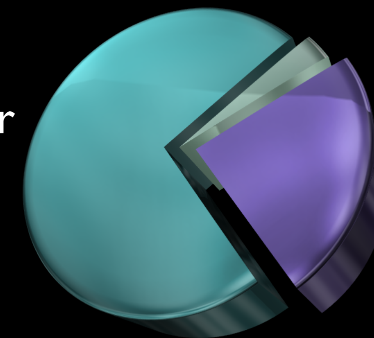
Supernova

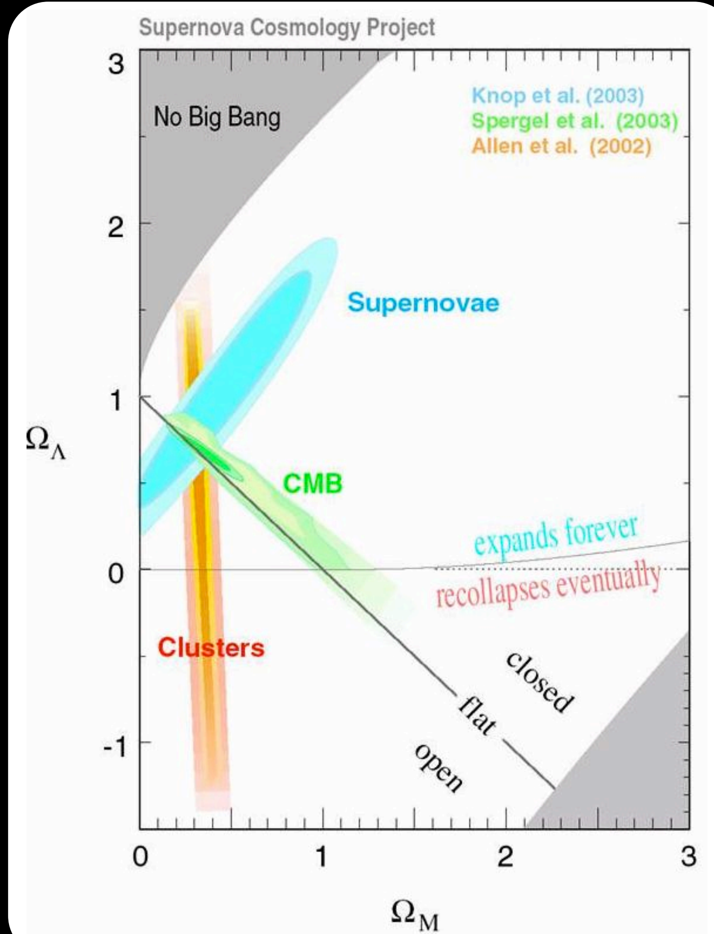


Structure

Lensing

- Ordinary Matter
- Dark Matter
- Dark Energy





# So what is Dark Matter?

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

- 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).
- Nothing in the Standard Model of particle physics fits the description.

# The Dark Matter Questionnaire

- [ ] Mass: ________
- [ ] Spin: ________
- [ ] Stable?
  - [ ] Yes
  - [ ] No

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?

Thermal Relic?

- [ ] Yes
- [ ] No

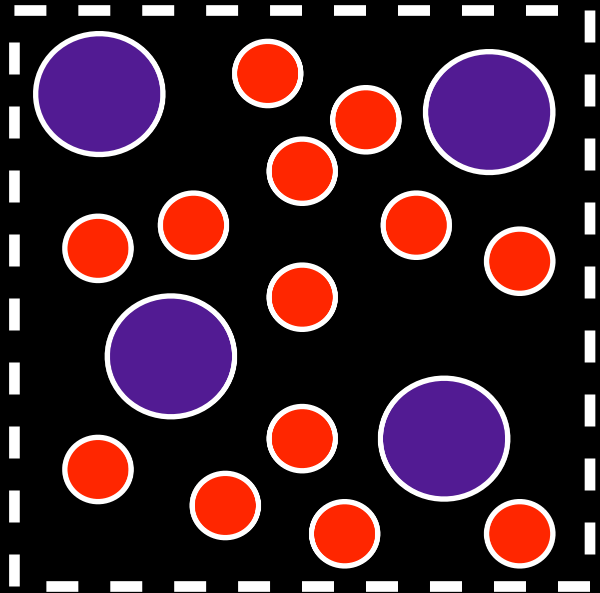
# WIMPs

- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
  - WIMPs automatically occur in many models of physics beyond the Standard Model, such as supersymmetric extensions with R-parity.
- I will try to avoid any further discussion of specific theories. My attitude is going to be that dark matter is something worth discussing in and of itself rather than a by-product of other theoretical constructions.
  - But we will see that we do need some kind of theoretical framework to put experimental results into context.


$59.99 for 20 servings

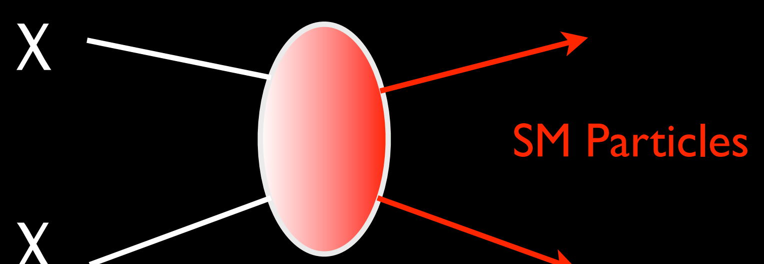
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

# The WIMP Miracle



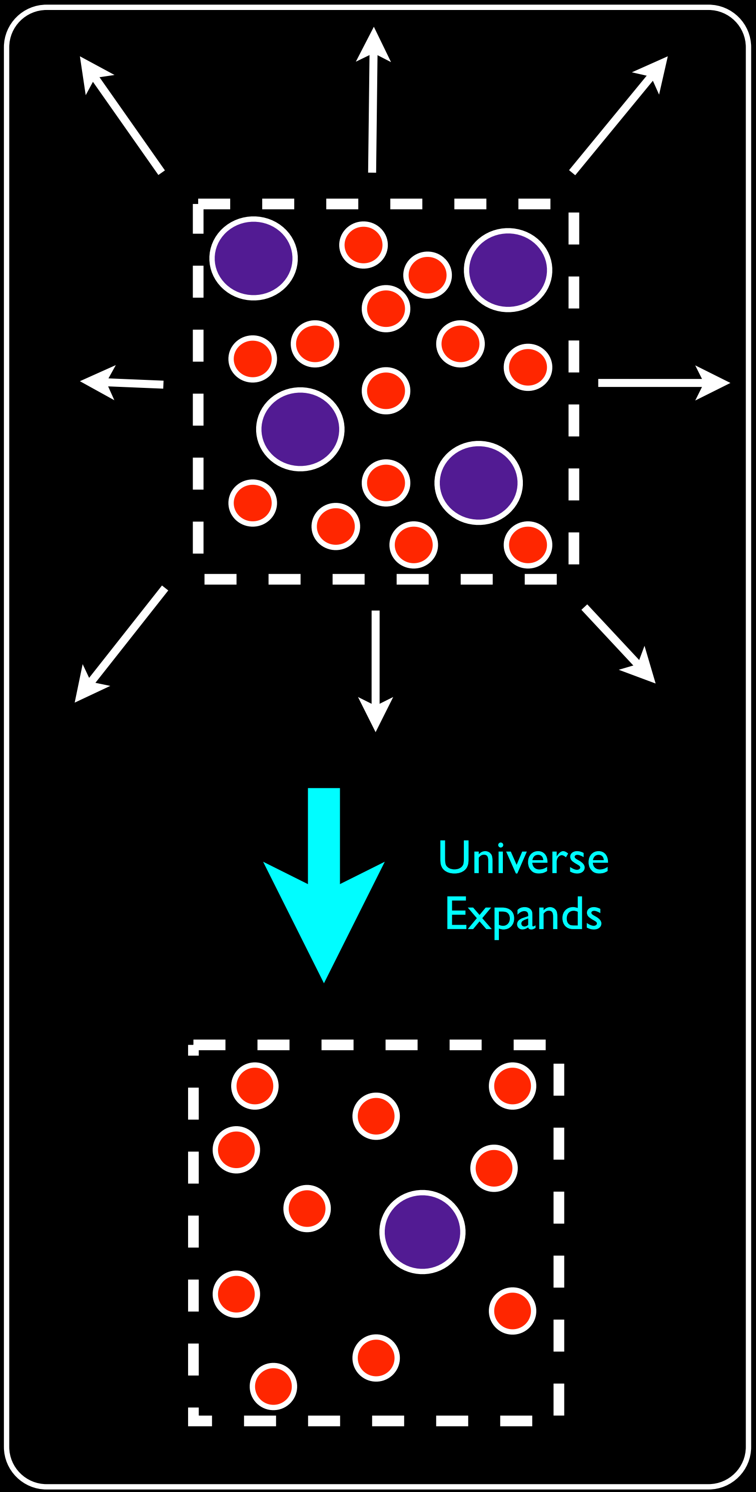
- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, XX -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:

$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$

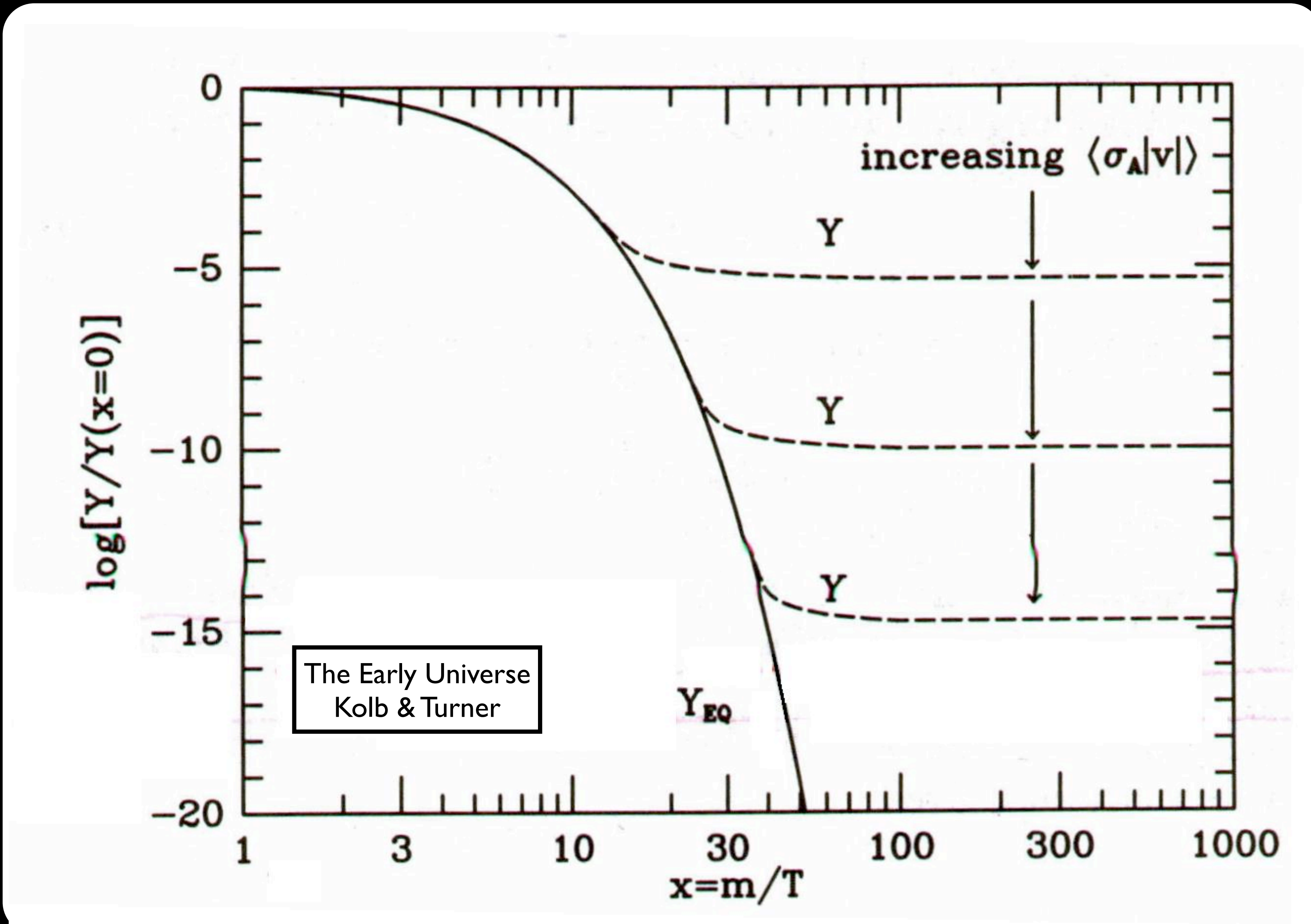


# Freeze-Out

- Expansion of the Universe eventually results in a loss of equilibrium.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on σ(χχ -> SM): more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



# Relic Density

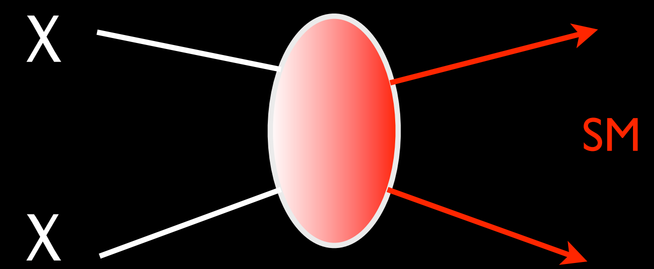


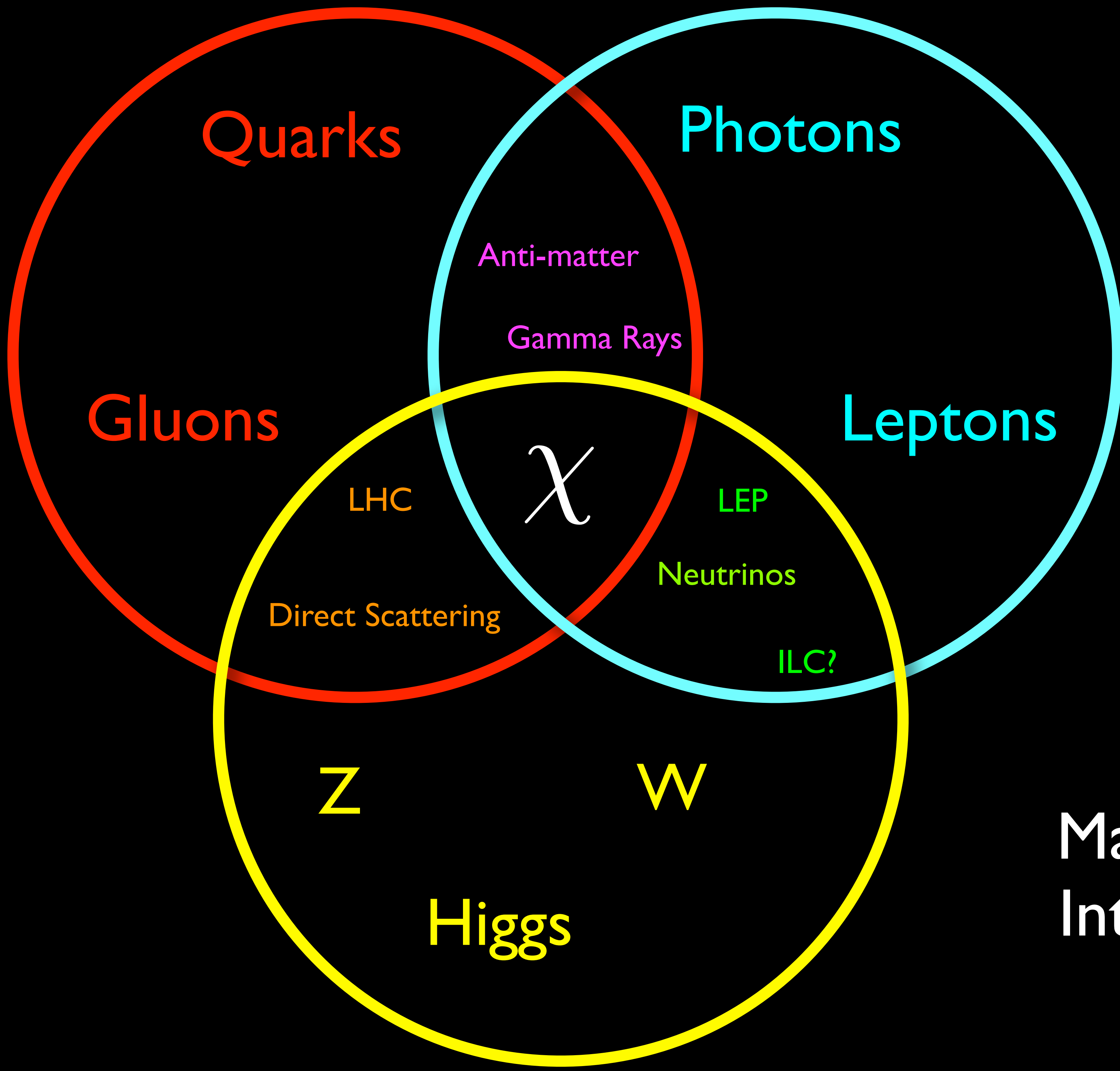

x=m/T increasing
is
T decreasing
is
time increasing

- The observed quantity of dark matter is suggestive of a cross section for annihilation into the thermal bath (the SM + ....).

# WIMP Interactions

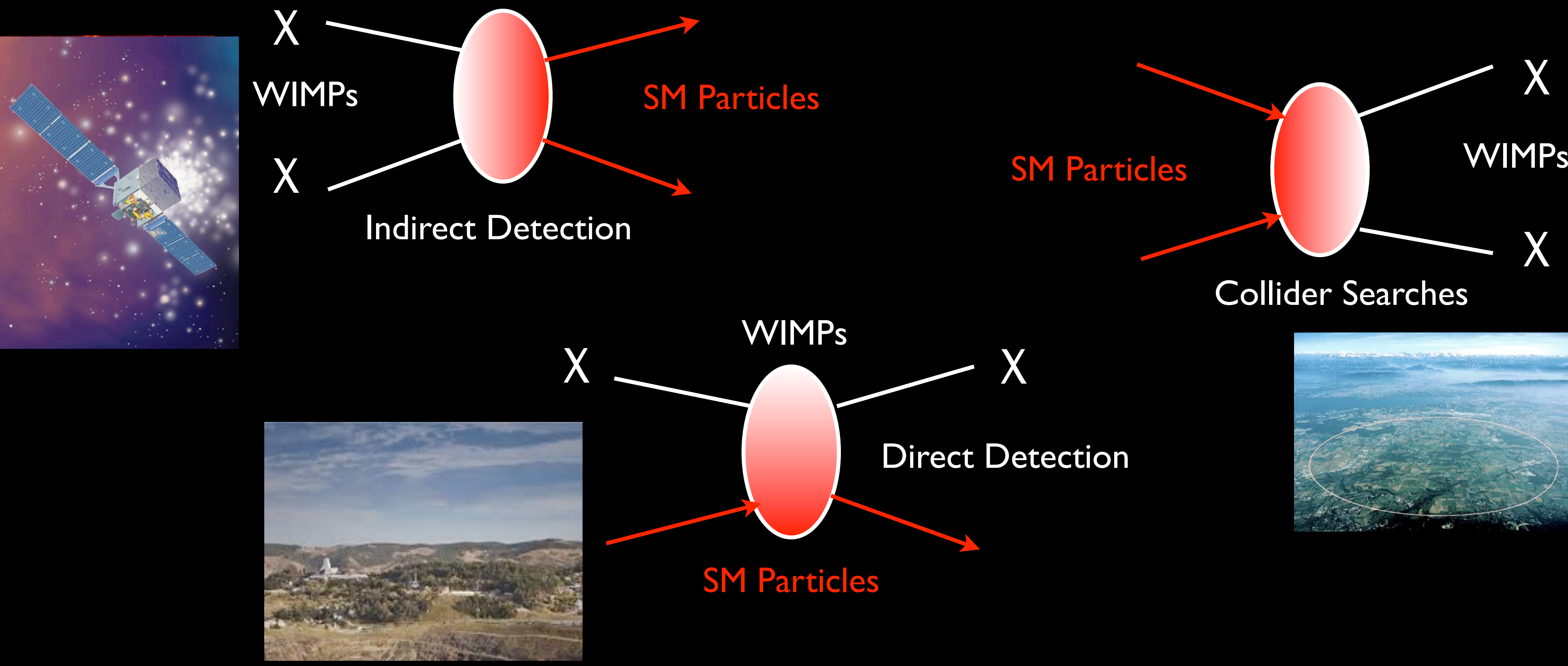
- Ideally, we would like to measure WIMP interactions with the Standard Model, allowing us to compute $\sigma$(XX -> SM particles) and check the relic density.
    - If our predictions "check out" we have indirect evidence that our extrapolation backward to higher temperatures is working.
    - If not, we will look for new physical processes to make up the difference.
- The first step is to actually rediscover dark matter by seeing it interact through some force other than gravitational.
- That tells us which SM particles it likes to talk to and in some cases something about its spin, mass, etc.



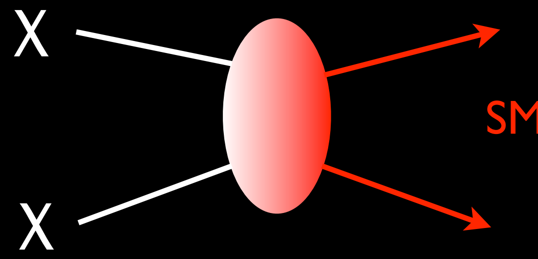

Map of DM Interactions

# Particle Probes of DM



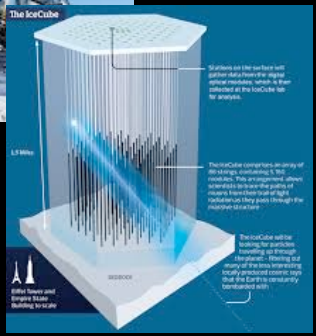

- The common feature of particle searches for WIMPs is that all of them are determined by how WIMPs interact with the Standard Model.

# Indirect Detection




- There is a process which could allow us to see (at least part of) the process $\chi\chi$-> SM directly.
- WIMPs in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.
- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.
- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them could be noticeable.



# Indirect Detection

- For high energy photons and neutrinos, annihilation in our galaxy is described by a cross section which depends on the WIMP model, and the density of WIMPs squared, at the place where they are annihilating.

Distance along line of sight

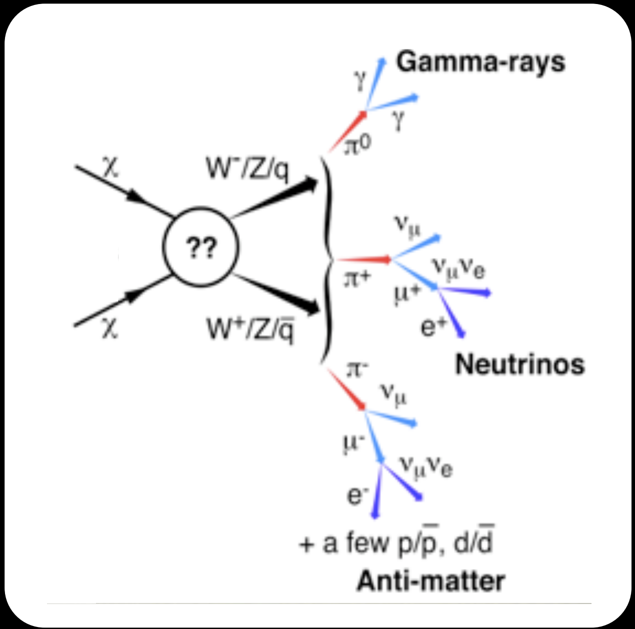
Microphysics

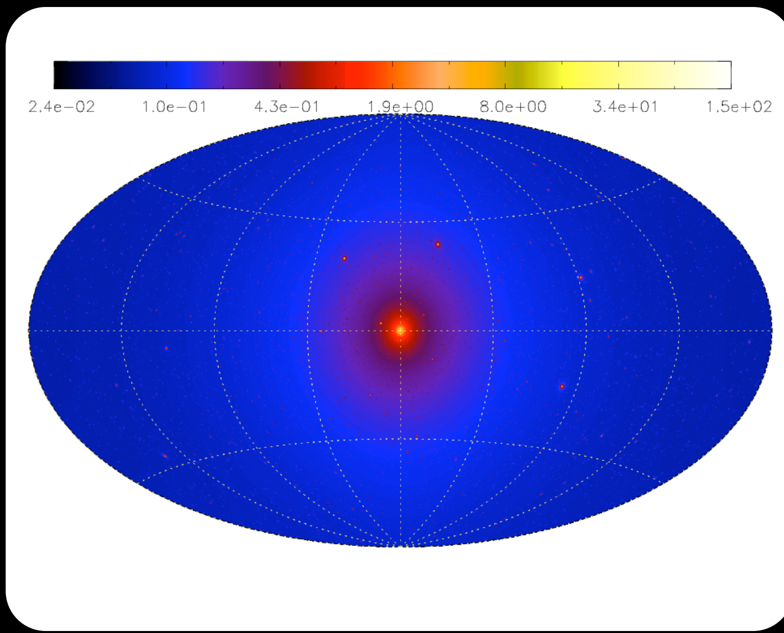
DM density

$$\frac{dN}{E} = \frac{d\langle\sigma v\rangle}{dE} \int dl \, \rho^2_{DM}(l)$$

- Models of galaxy formation predict the integral, but with a considerable uncertainty.

- For charged particles, a slight complication is that they typically scatter on their way through the galaxy. Propagation through the ISM needs to be accounted for.

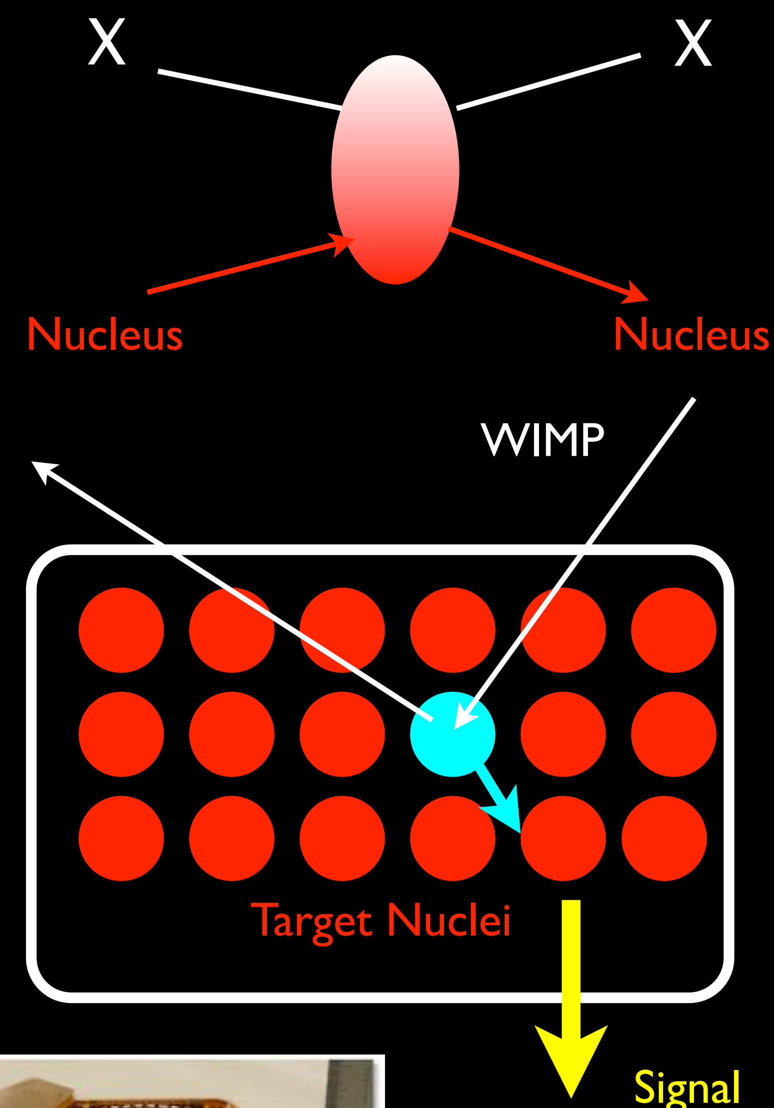


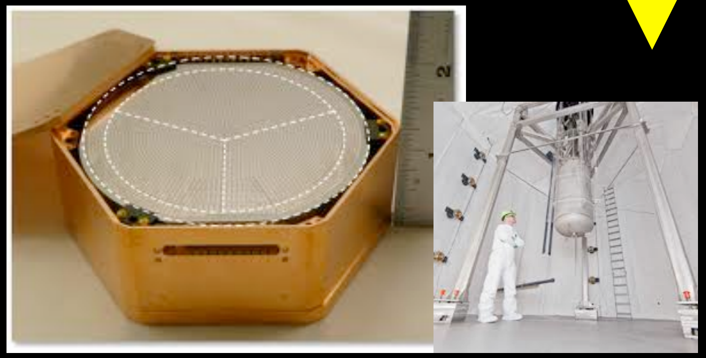




Pieri et al arXiv:0908.0195

# Direct Detection

- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus when a WIMP brushes against it.
- Direct detection looks for the dark matter in our galaxy's halo, and a positive signal would be a direct observation.
- Heavy shielding and secondary characteristics of the interaction, such as scintillation light or timing help filter out backgrounds.
- These searches are rapidly advancing, with orders of magnitude improvements in sensitivity every few years!



# Direct Detection

- The rate of a direct detection experiment depends on one power of the WIMP density (close to the Earth).

Nuclear Physics

DM density

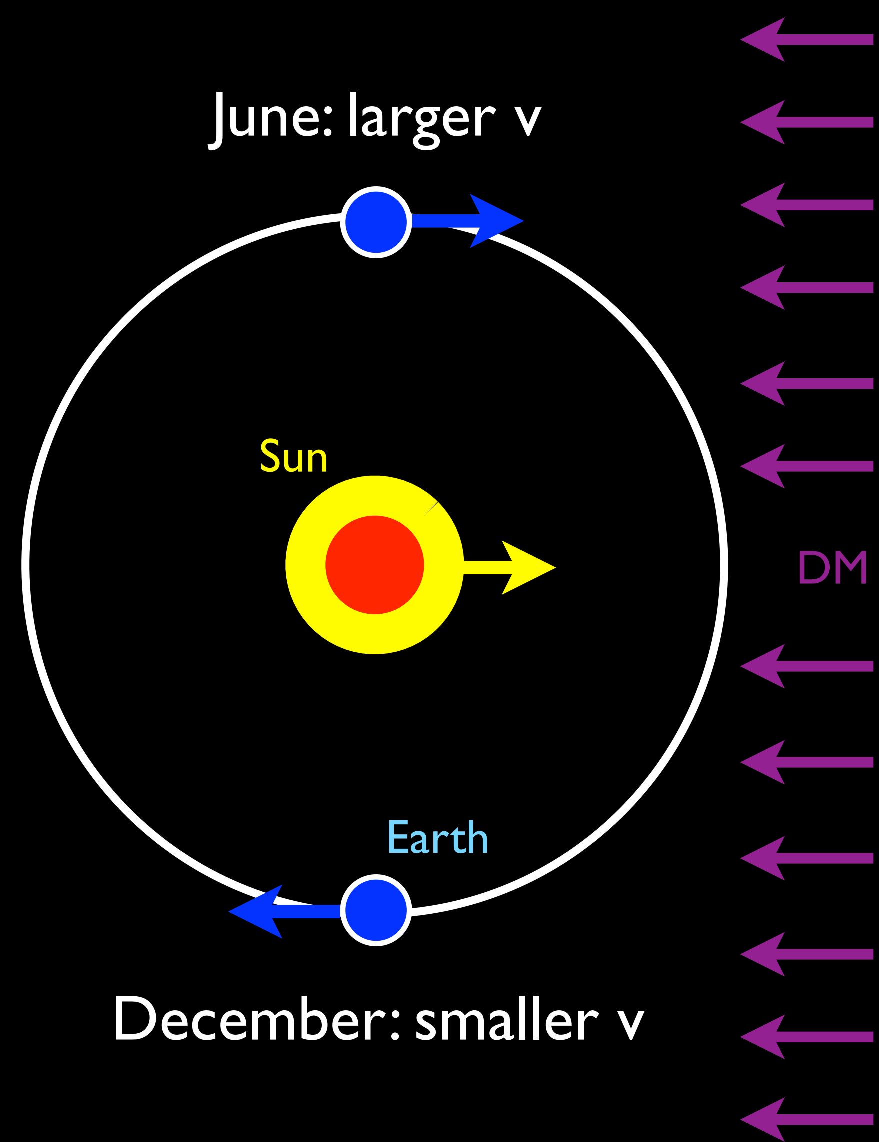
$$\frac{dN}{dE} = \sigma_0 \, \frac{\rho}{m} \int dv f(v) \, F(E)$$

WIMP velocity distribution

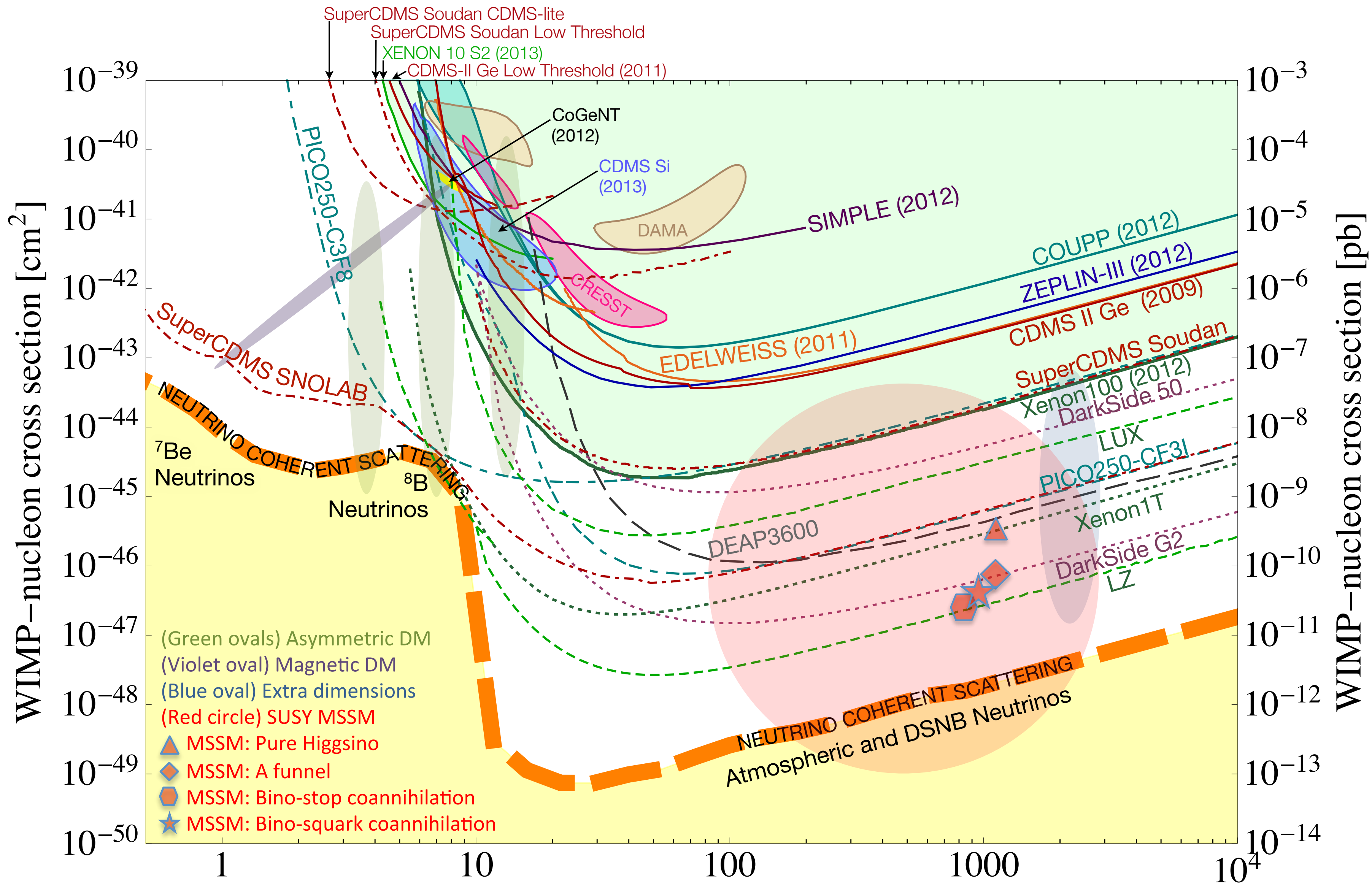
- The energy spectrum of the recoiling nucleus depends on the WIMP mass, its coupling to quarks, and nuclear physics.

- The cross section is dominated by the effective WIMP interactions with quarks and gluons.

- An interesting handle on the signal is an expected annual modulation.



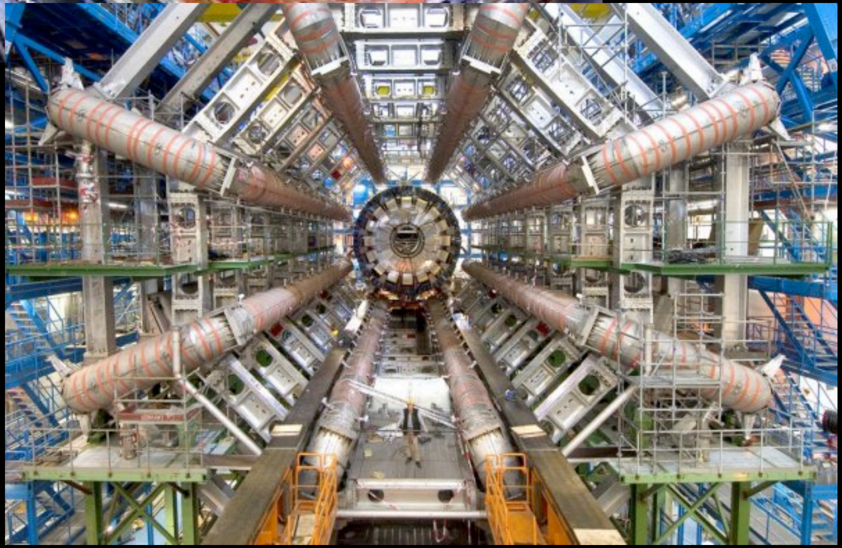
# A Bright Future




Cushman et al,
Snowmass CF1 Report

# Collider Production

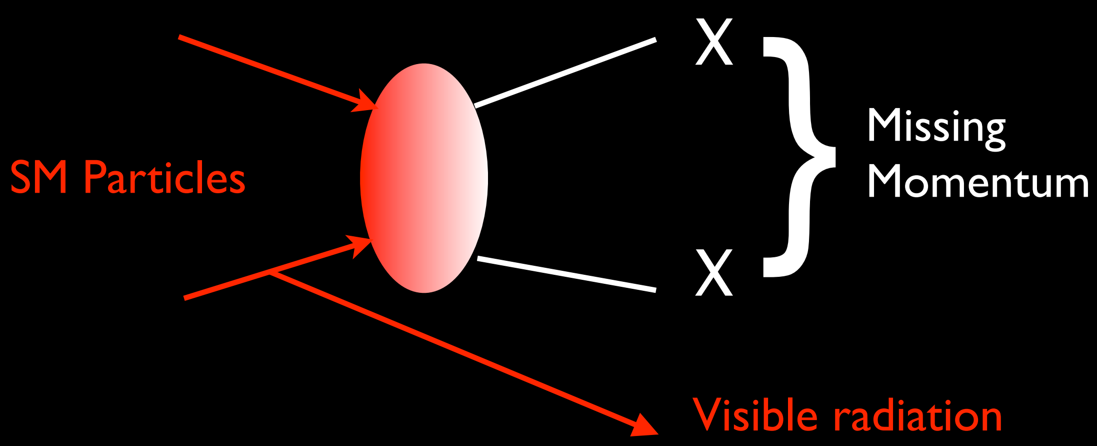
- If WIMPs couple to quarks or gluons, we should also be able to produce them at high energy colliders.
- By studying the production of WIMPs in collisions of SM particles, we are seeing the inverse of the process which kept the WIMPs in equilibrium in the early Universe.
- Provided they have enough energy to produce them, colliders may allow us to study other elements of the "dark sector", which are no longer present in the Universe today.

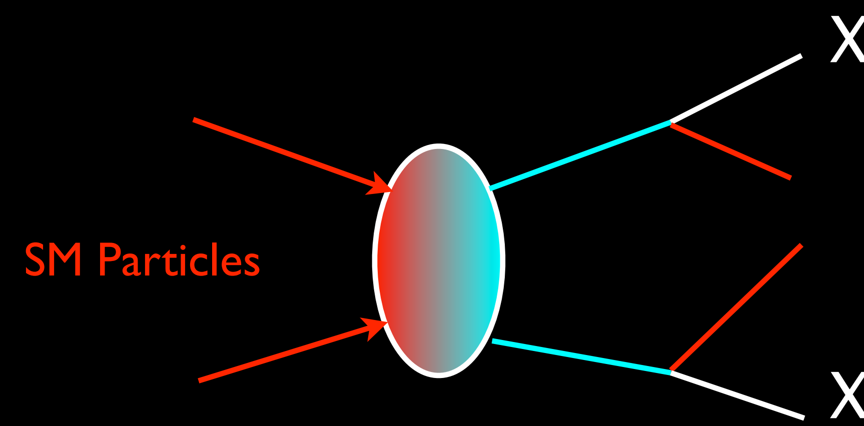


Very sophisticated detectors with many, many (many!) subsystems: But no WIMP detectors.

# Seeing the Invisible?

- WIMPs interact so weakly that they are expected to pass through the detector components without any significant interaction, making them effective invisible (much like neutrinos).
- There are two ways we can try to "see" them nonetheless:



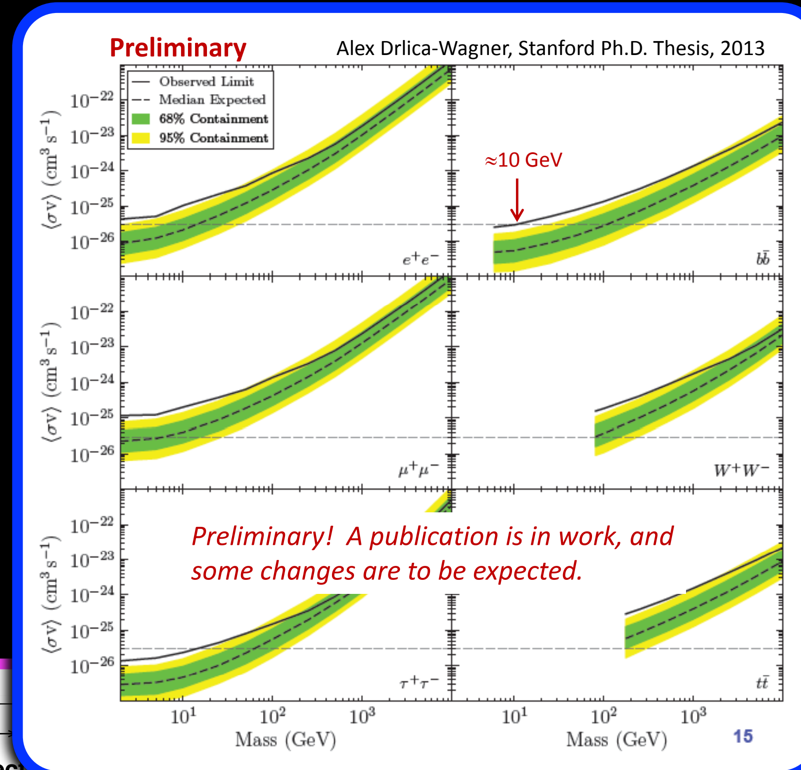

Radiation from the SM side of the reaction.

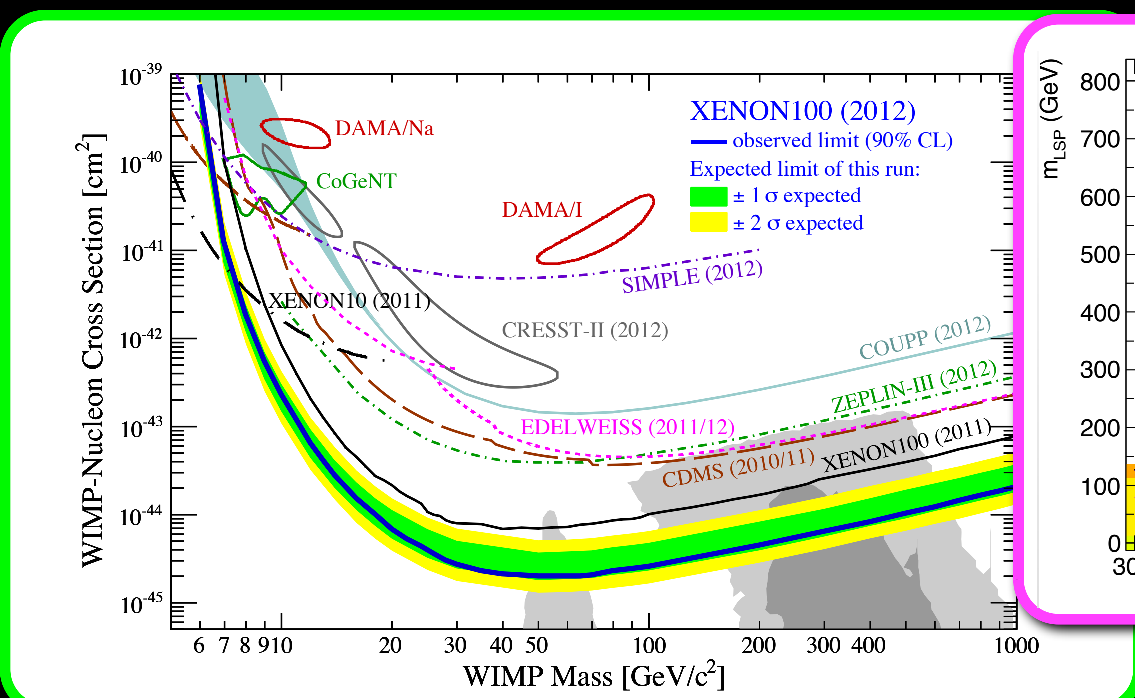
Production of "partners" which decay into WIMPS + SM particles.

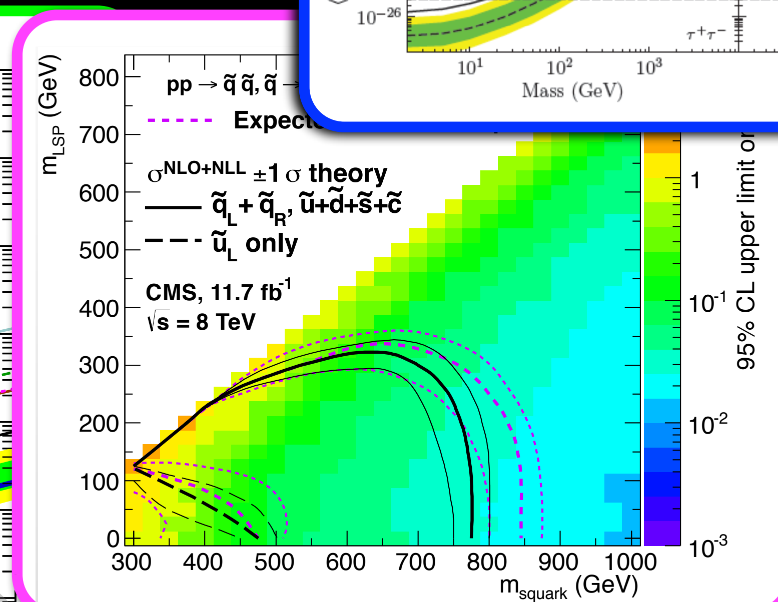
# We Need (a) Theory

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

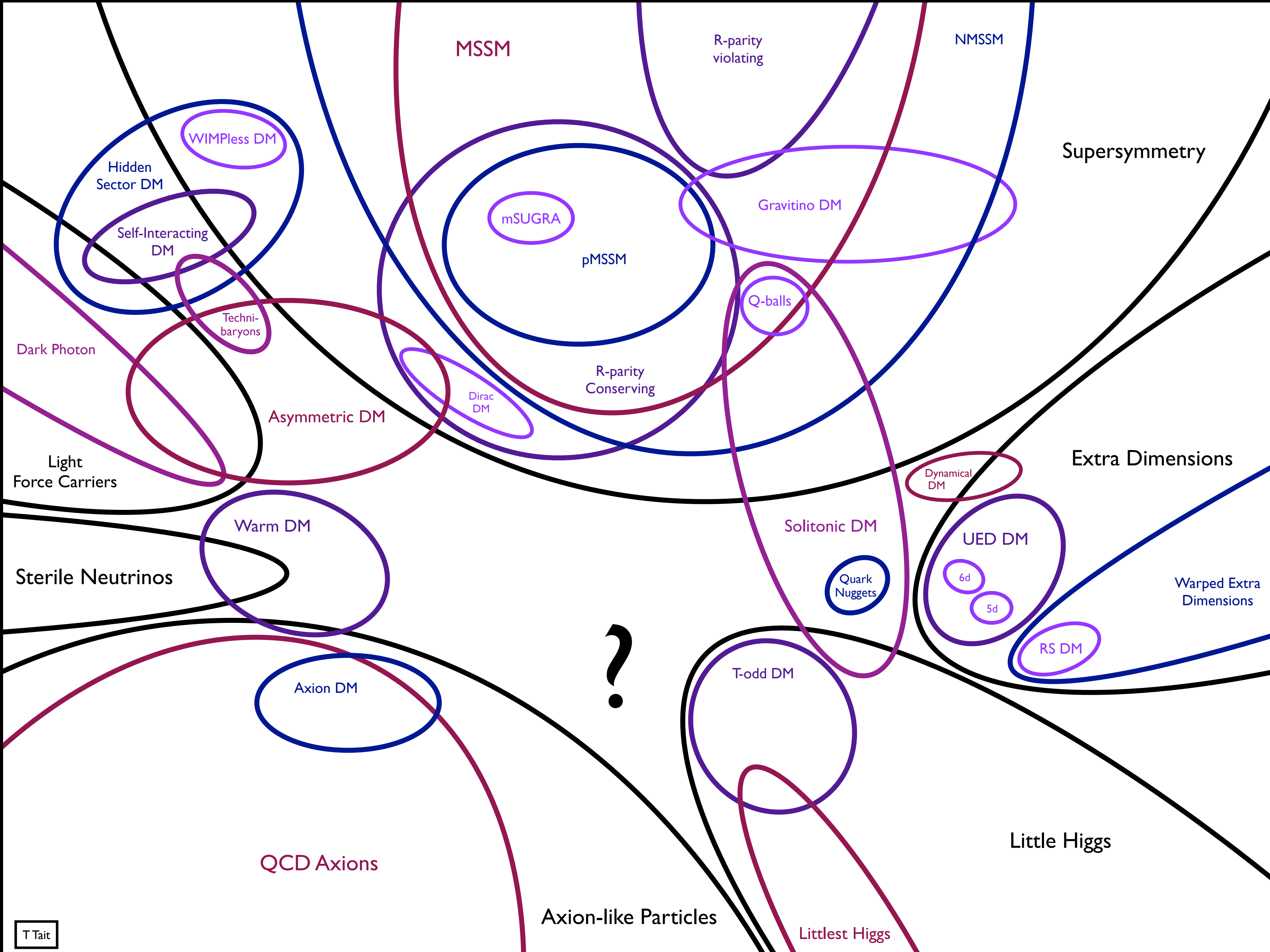
But we *know* they are all attempts to characterize the same thing(s)...



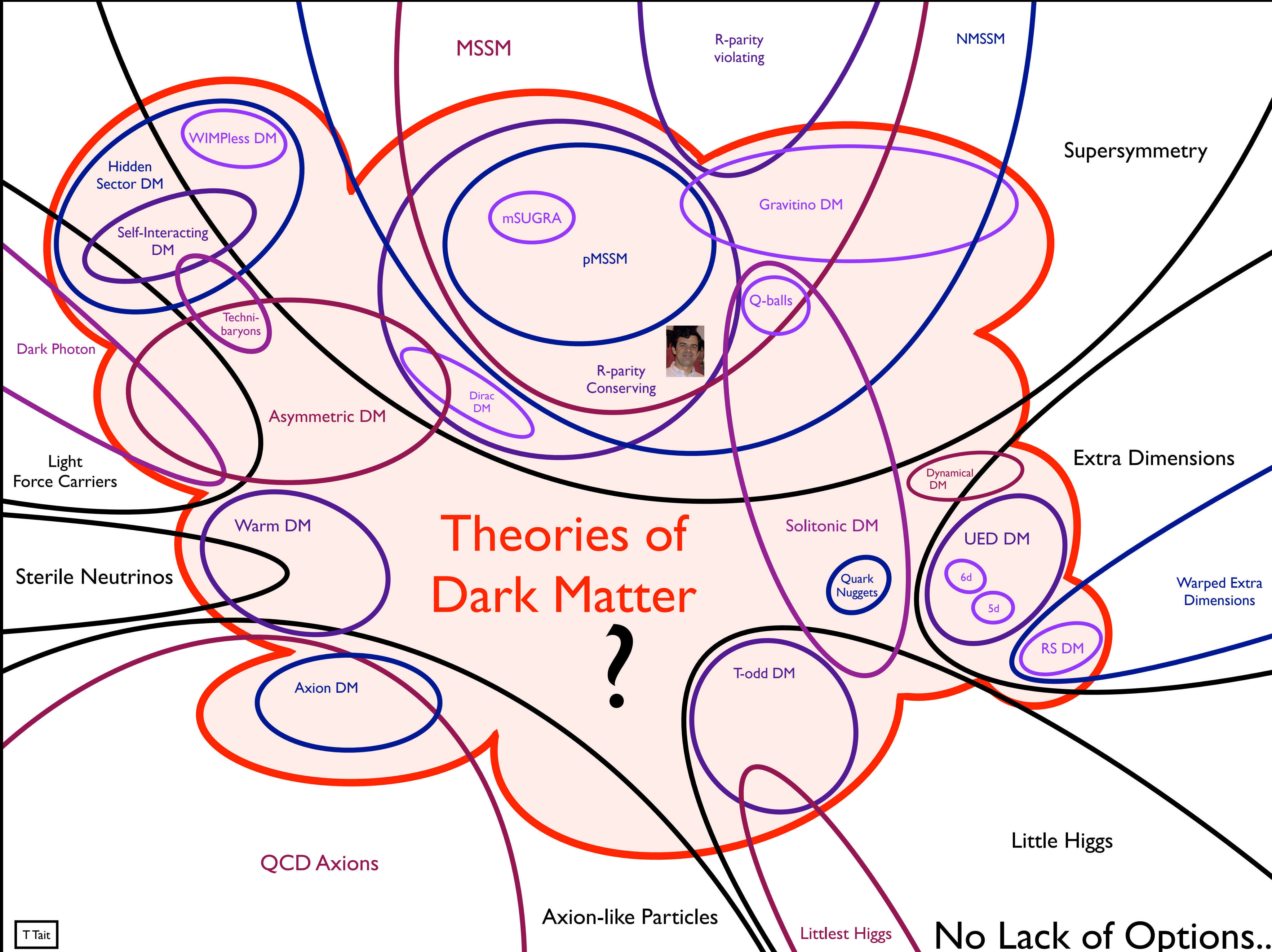




Which theory to use?



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Solitonic DM
Warm DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait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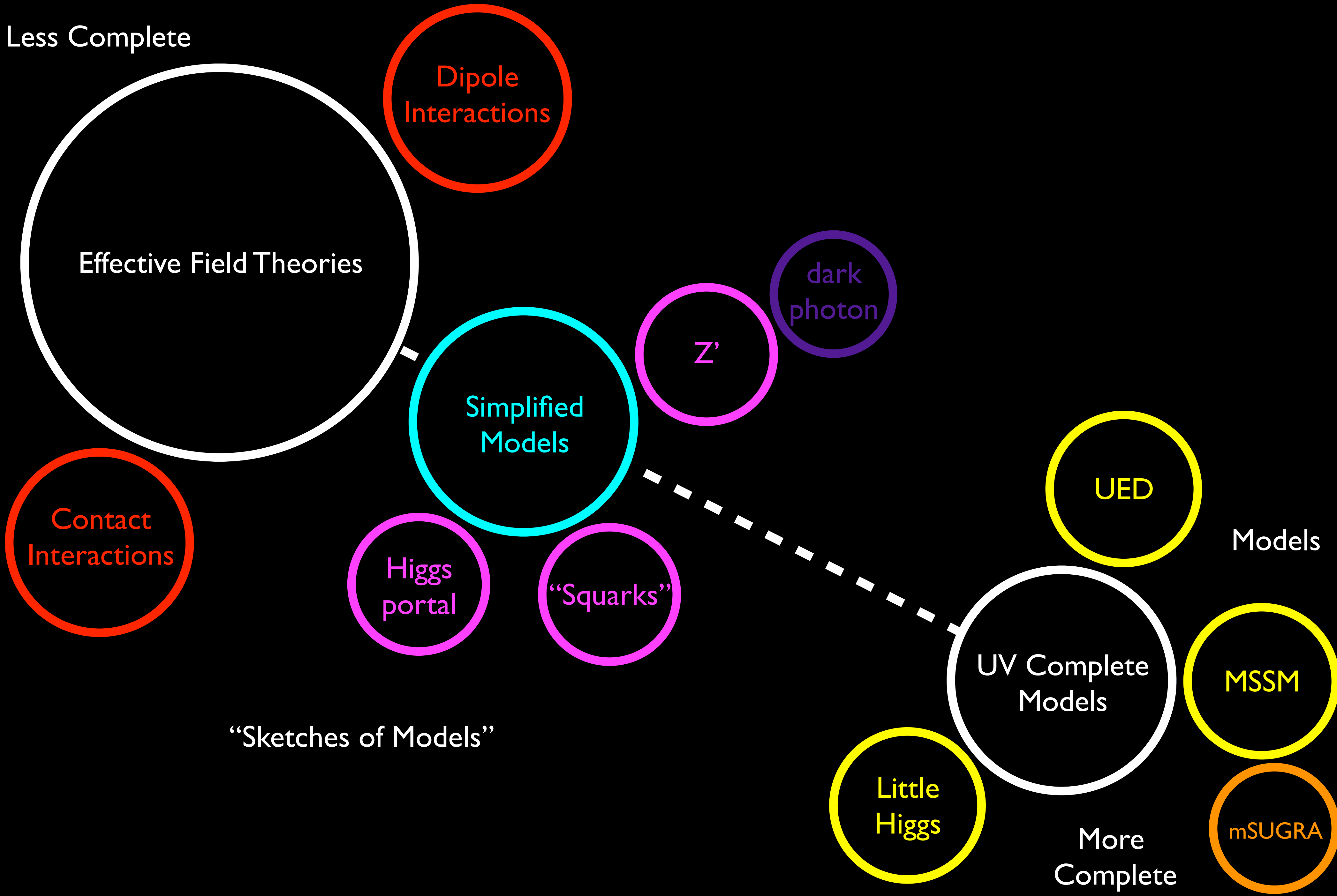
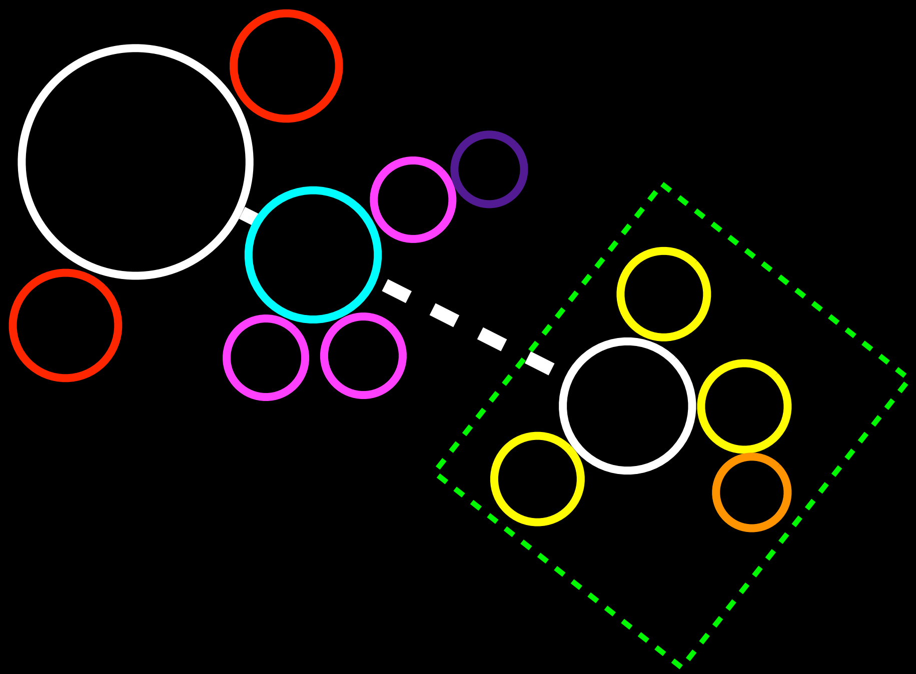
Littlest Higgs
No Lack of Options...
T Tait

# Spectrum of Theory Space

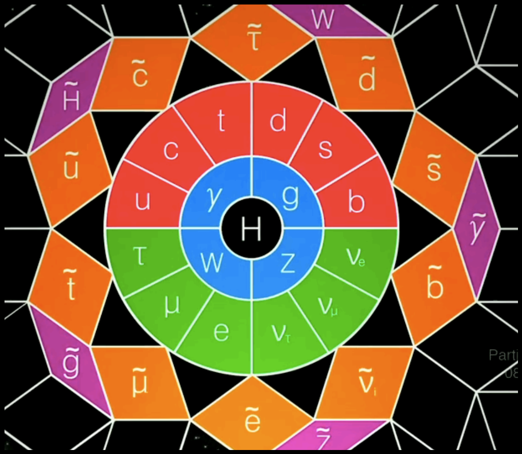


# “Complete” Theories

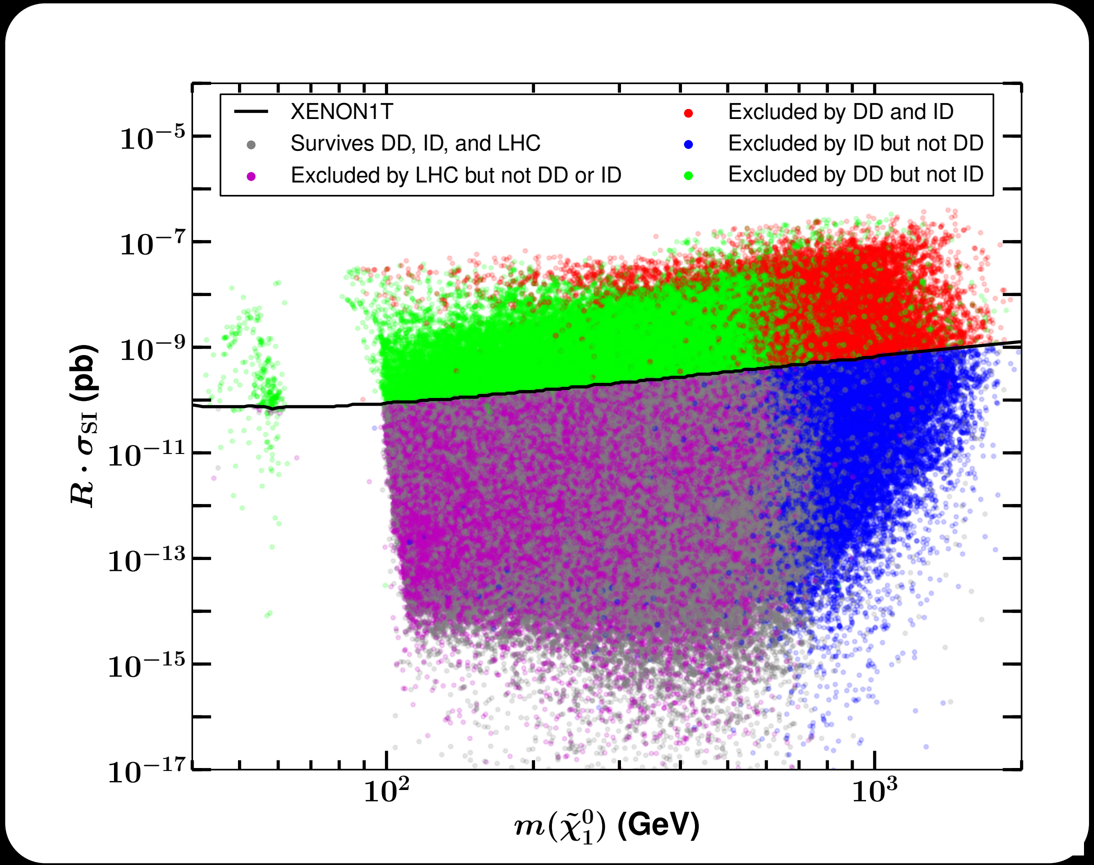


# MSSM

- An obvious first place to start would be with complete theories of dark matter, the most obvious example of which is our favorite theory: the MSSM.
- Reasonable parameterizations have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space by the SLAC group, in the plane of the WIMP mass versus the SI cross section.
- The scan is still somewhat sparse in terms of the huge parameter space. But it does show nice trends of viable MSSM models.

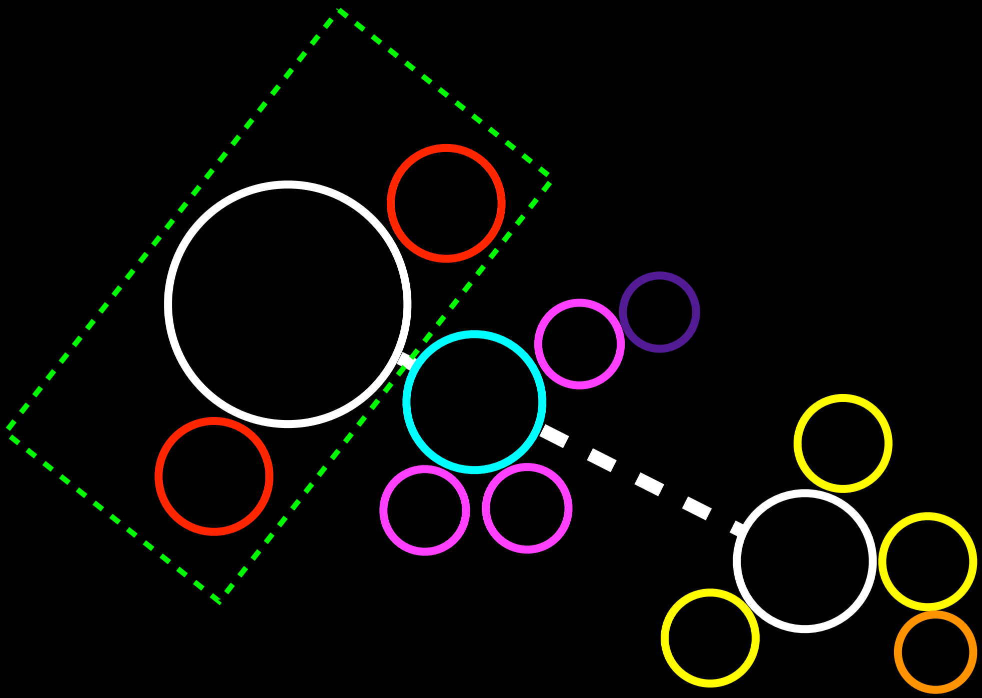



Particle Fever



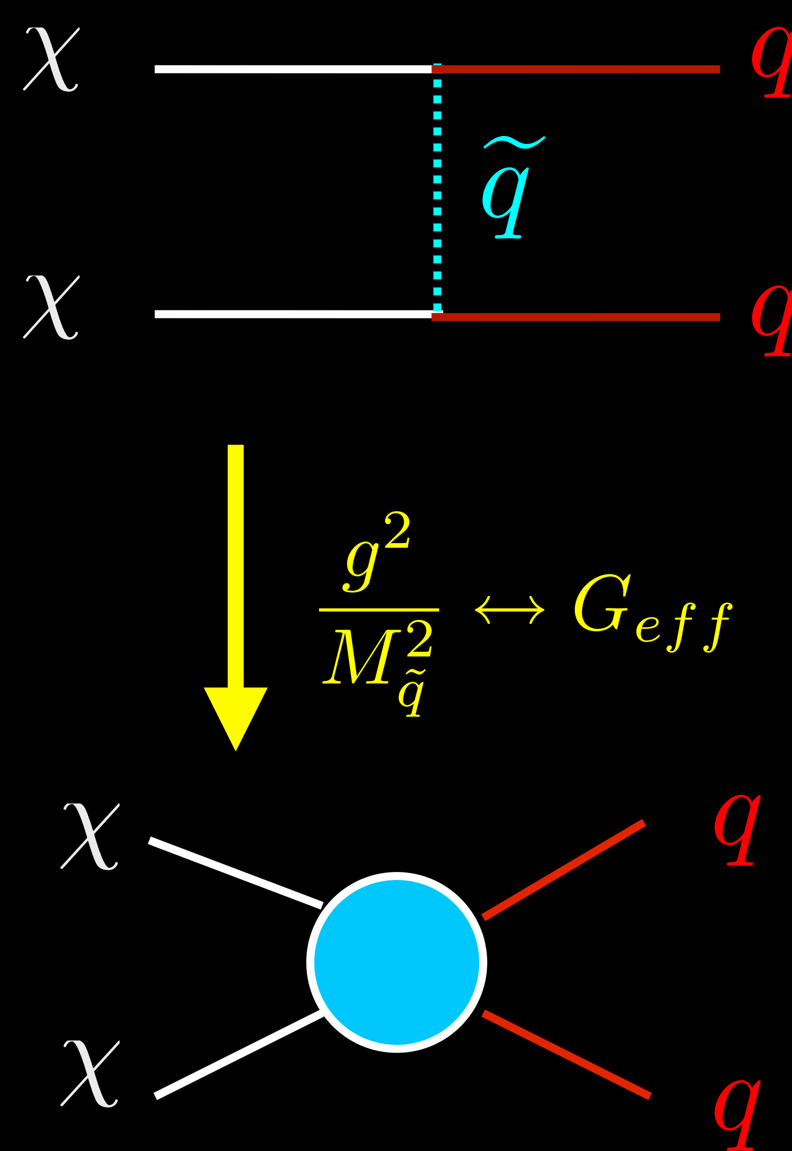

Cahill-Rowley et al, 1305.6921

# Contact Interactions



# Contact Interactions

- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to the energies involved.
- The drawback to a less complete theory is such a simplified description will undoubtably miss out on correlations between quantities which are obvious in a complete theory.
- And it will break down at high energies, where one can produce more of the new particles directly.



# Example: Majorana WIMP

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

- As an example, we can write down 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 | $G_\chi$ | $\Gamma^\chi$ | $\Gamma^q$ |
|---|---|---|---|---|
| M1 | $qq$ | $m_q/2M_*^3$ | $1$ | $1$ |
| M2 | $qq$ | $im_q/2M_*^3$ | $\gamma_5$ | $1$ |
| M3 | $qq$ | $im_q/2M_*^3$ | $1$ | $\gamma_5$ |
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| M5 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma^\mu$ |
| M6 | $qq$ | $1/2M_*^2$ | $\gamma_5\gamma_\mu$ | $\gamma_5\gamma^\mu$ |
| M7 | $GG$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M8 | $GG$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |
| M9 | $G\tilde{G}$ | $\alpha_s/8M_*^3$ | $1$ | - |
| M10 | $G\tilde{G}$ | $i\alpha_s/8M_*^3$ | $\gamma_5$ | - |

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

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

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

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

- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation
  - Collider Production

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

# Example: Majorana WIMP

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

- The various types of interactions are accessible to different kinds of experiments.
  - Spin-independent elastic scattering
  - Spin-dependent elastic scattering
  - Annihilation in the galactic halo
  - Collider Production

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

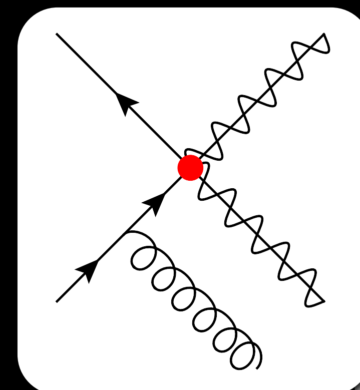
$$G_\chi\,[\bar\chi\Gamma^\chi\chi]\,G^2$$

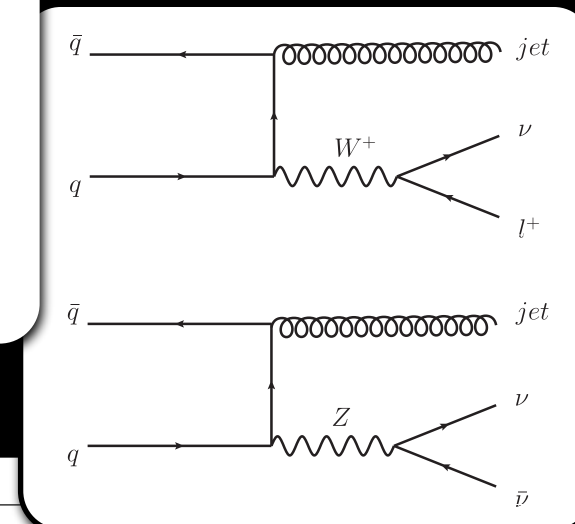
$$\sum_q G_\chi\,[\bar q\Gamma^q q]\,[\bar\chi\Gamma^\chi\chi]$$

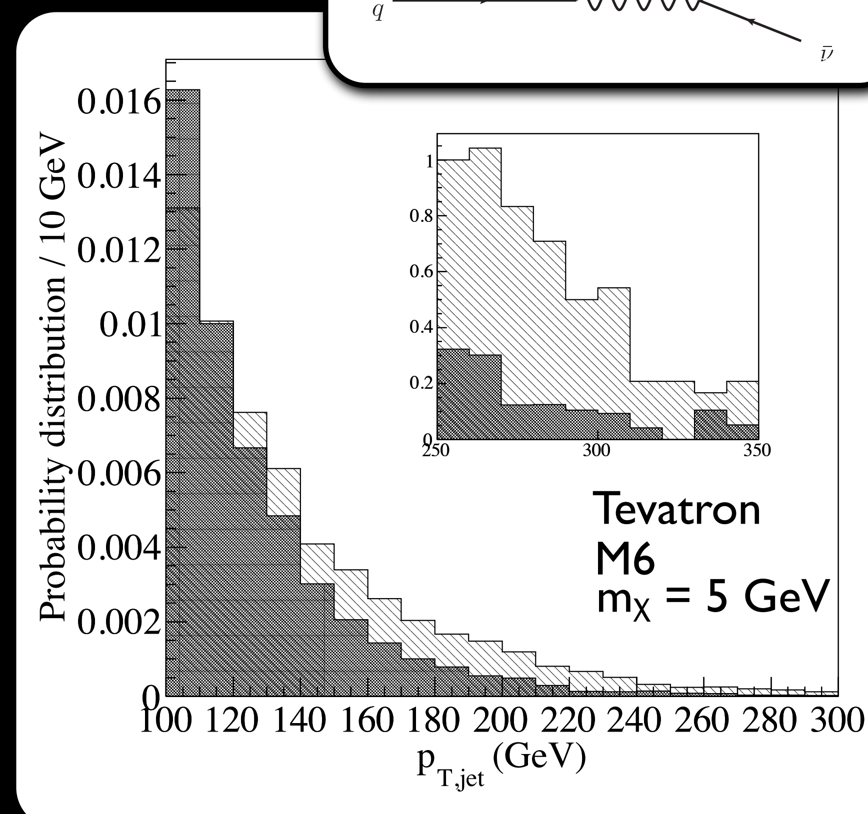
Other operators may be rewritten in this form by using Fierz transformations.

# 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.

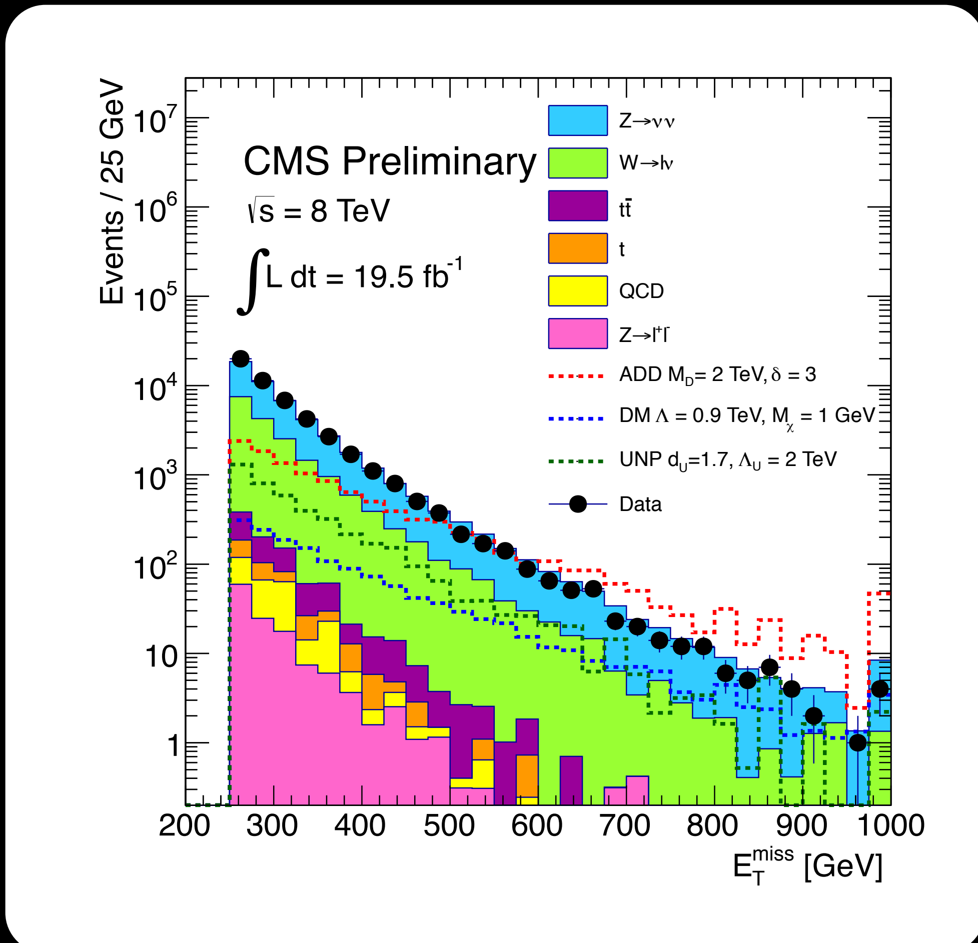


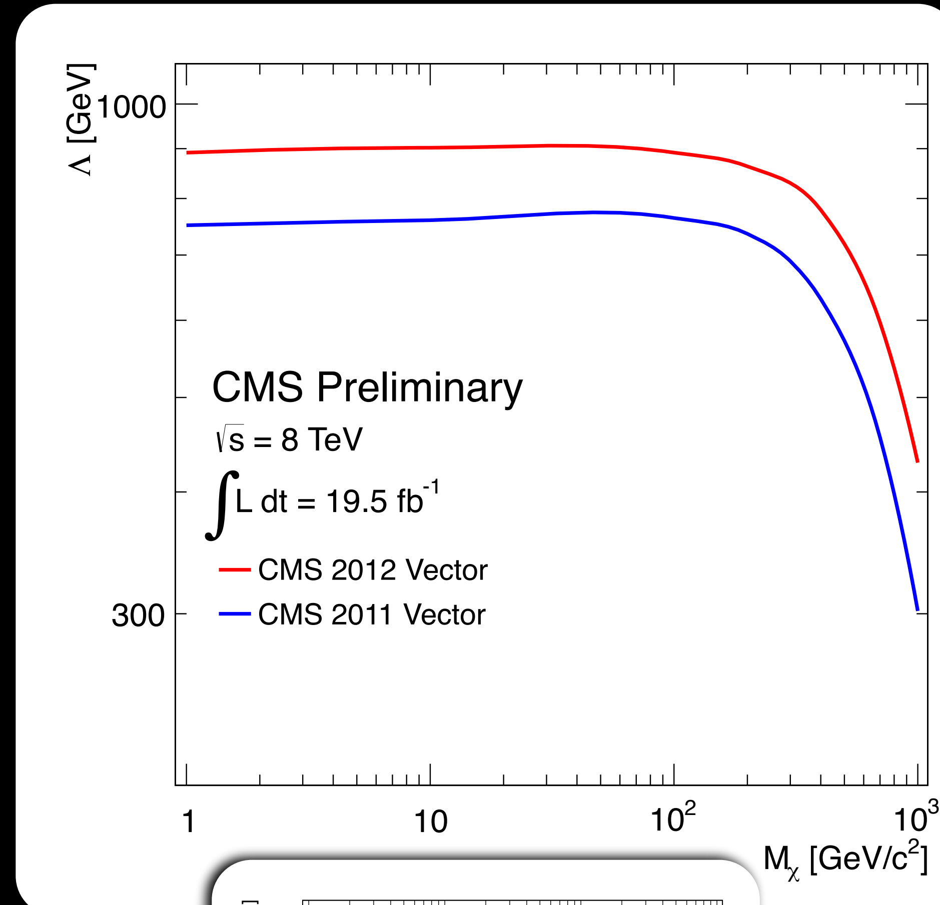


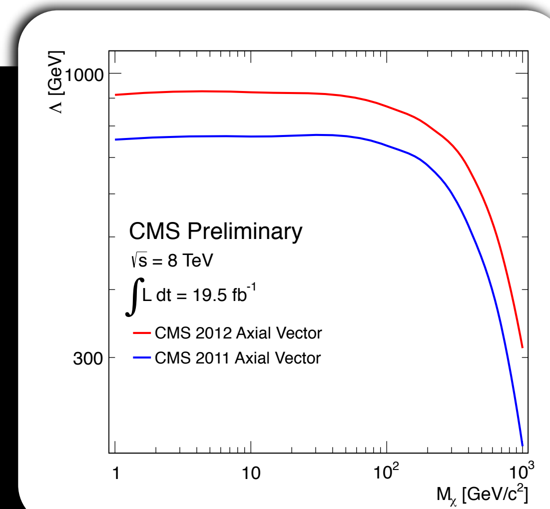




Beltran, Hooper, Kolb, Krusberg, TMPT 1002.4137 & JHEP

# Collider Results

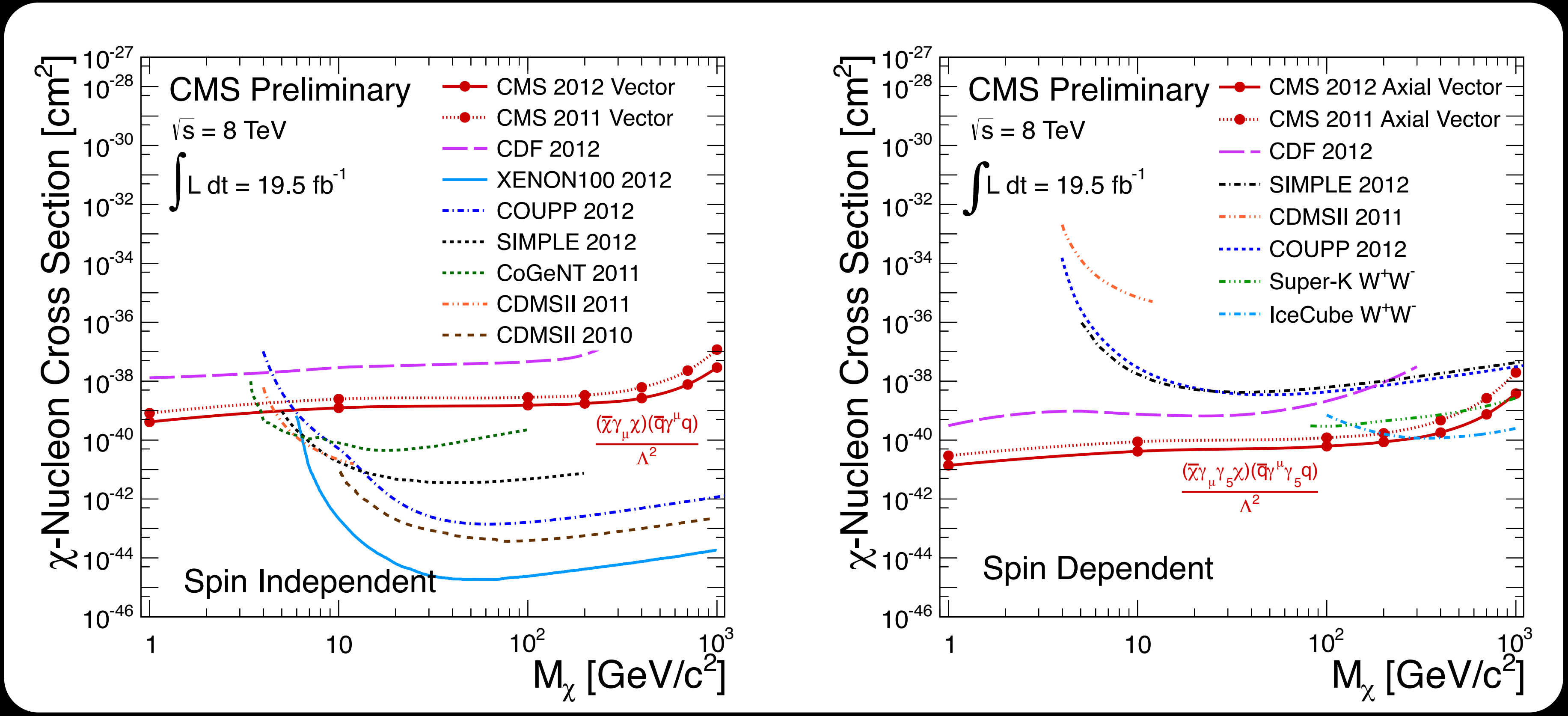


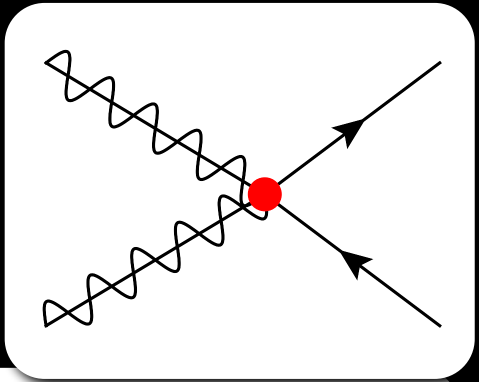

Both CMS and ATLAS have made very nice progress interpreting mono-jet (etc) searches in terms of the interaction strengths of a number of the most interesting interactions as a function of DM mass.

# Translation to Elastic Scattering

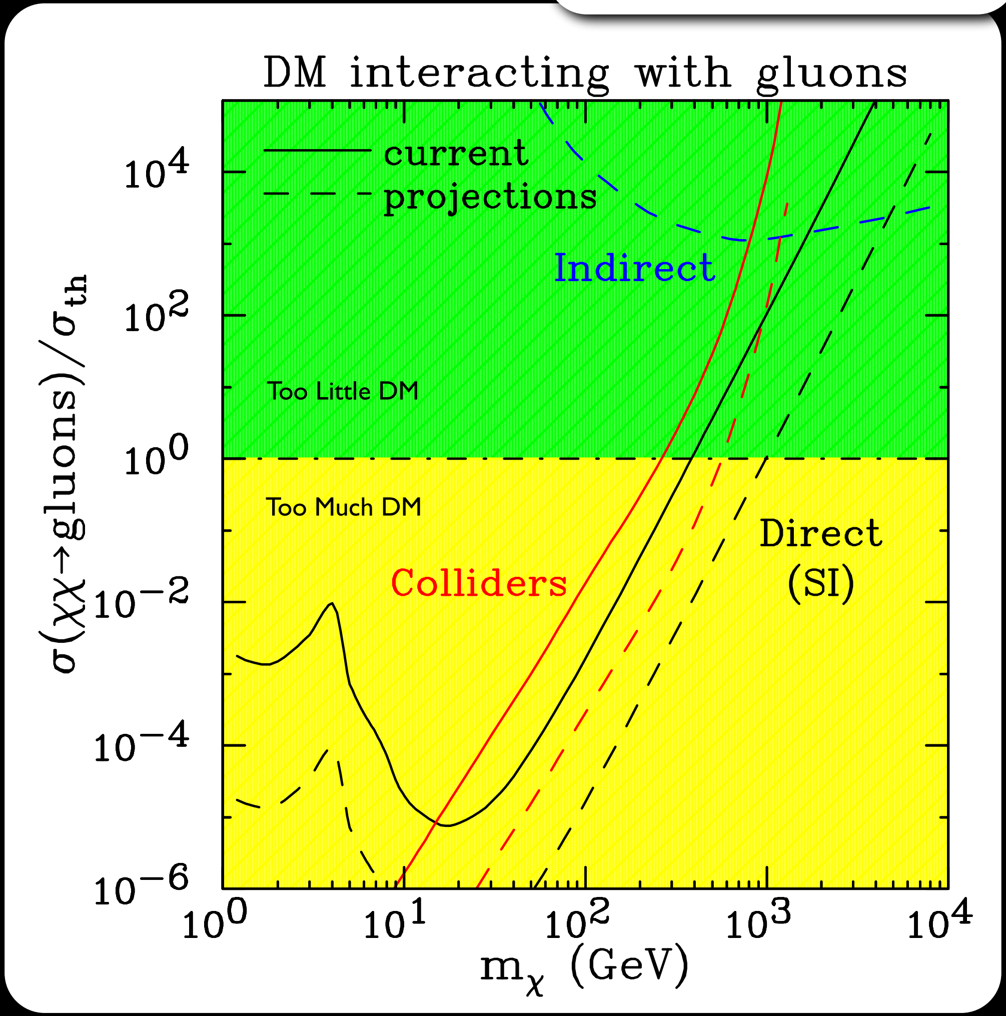



- Colliders can help fill in a challenging region of low dark matter mass and spin-dependent interactions.
- Since they see individual partons, rather than the nucleus coherently, collider results offer a complementary perspective on DM interactions with hadrons.
- The translation assumes a heavy mediating particle (contact interaction).

# Annihilation

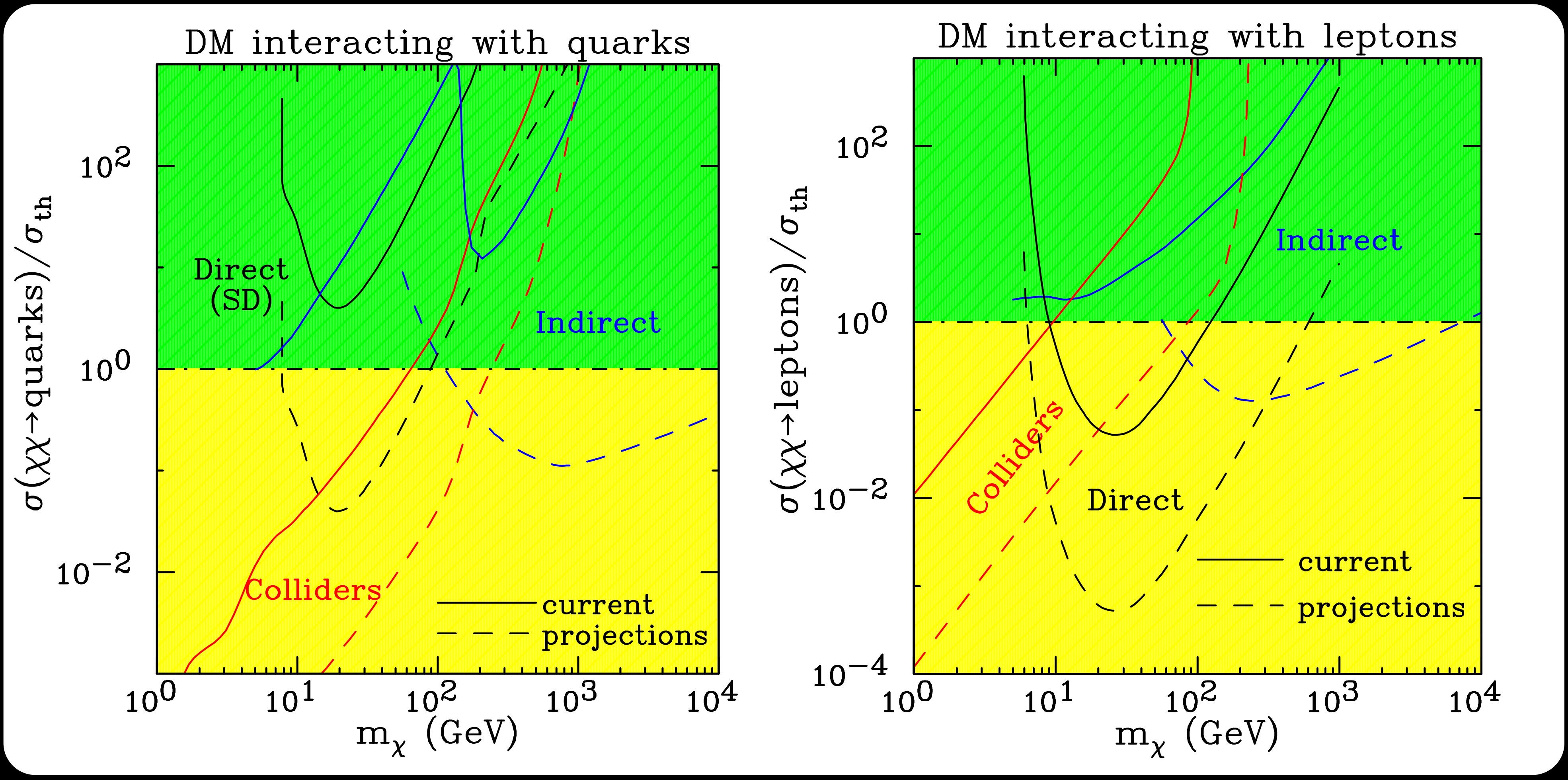


- We can also map interactions into predictions for WIMPs annihilating.
- For example, into continuum photons from a given tree level final state involving quarks/gluons.
- This allows us to consider bounds from indirect detection, and with assumptions, maps onto a thermal relic density.
- Colliders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

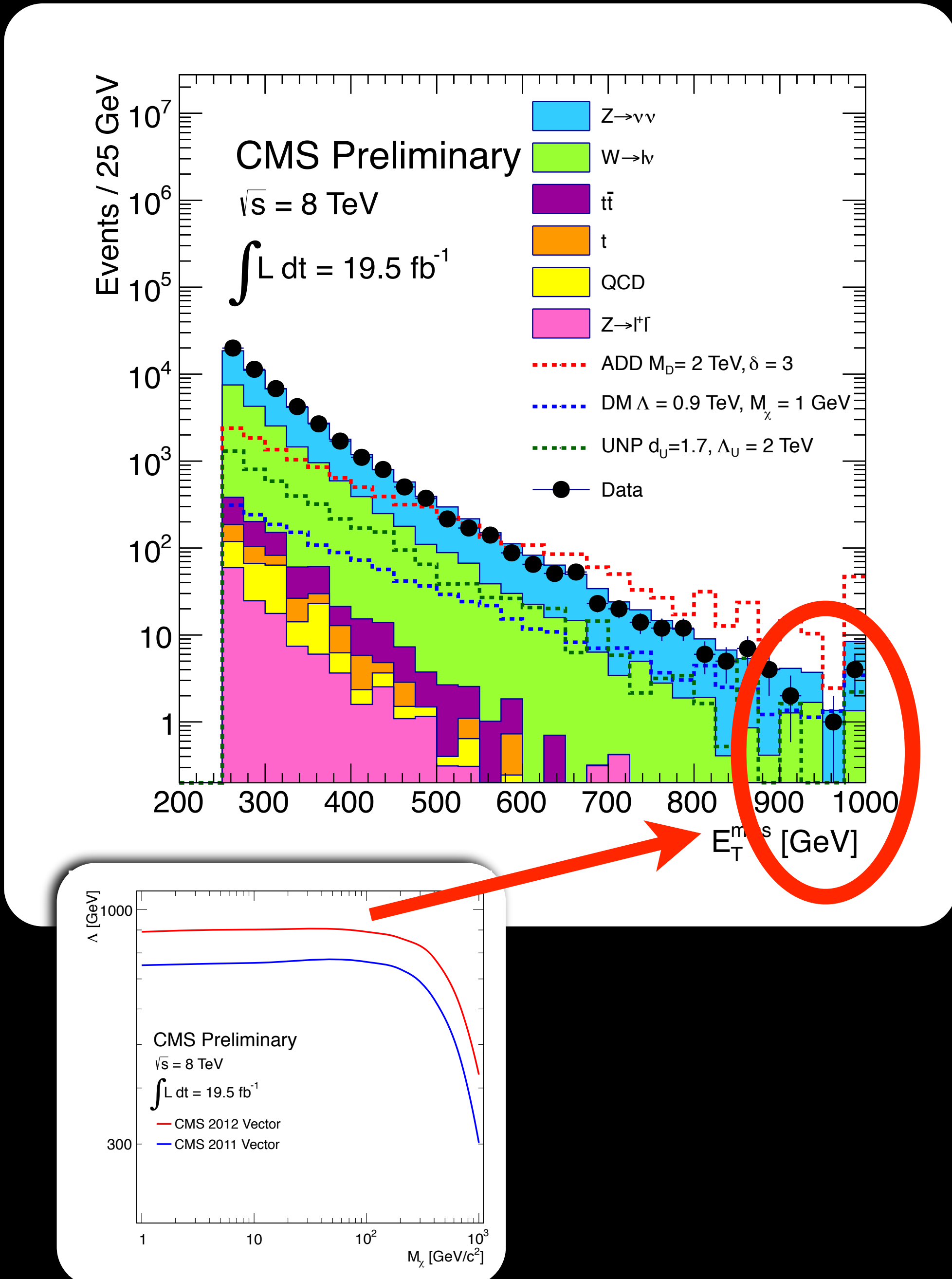
# Quarks & Leptons



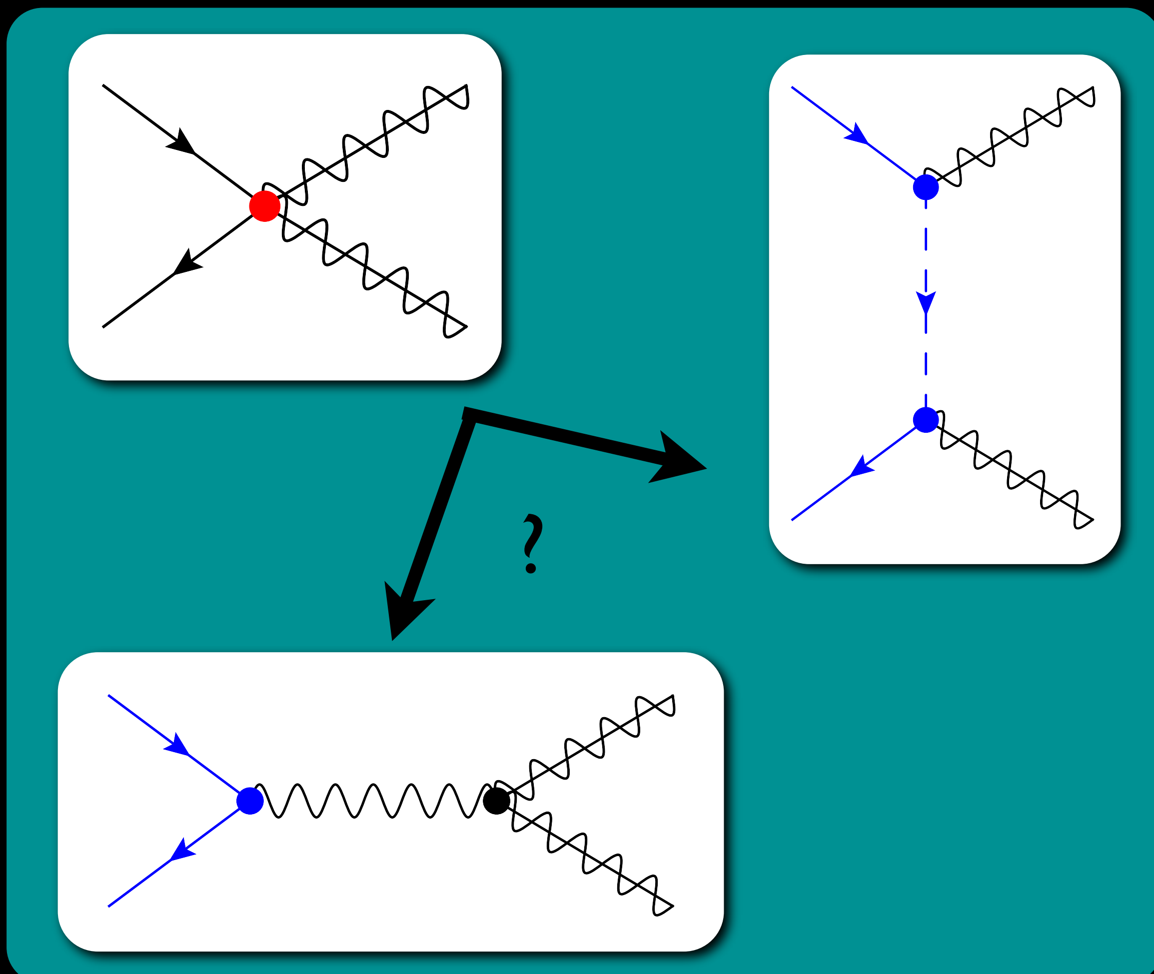

DM Complementarity, arXiv:1305.1605

# 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 are almost certainly 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.]



# How Effective a Theory?



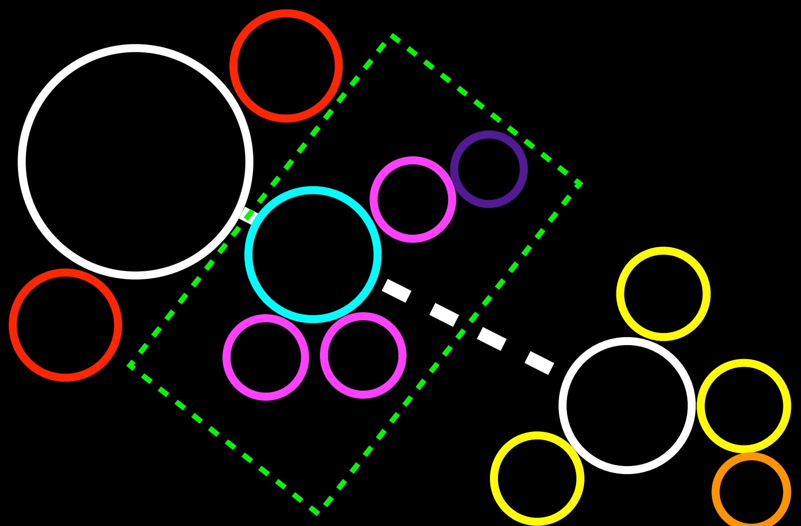

"t-channel" mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

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

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

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

# Simplified Models

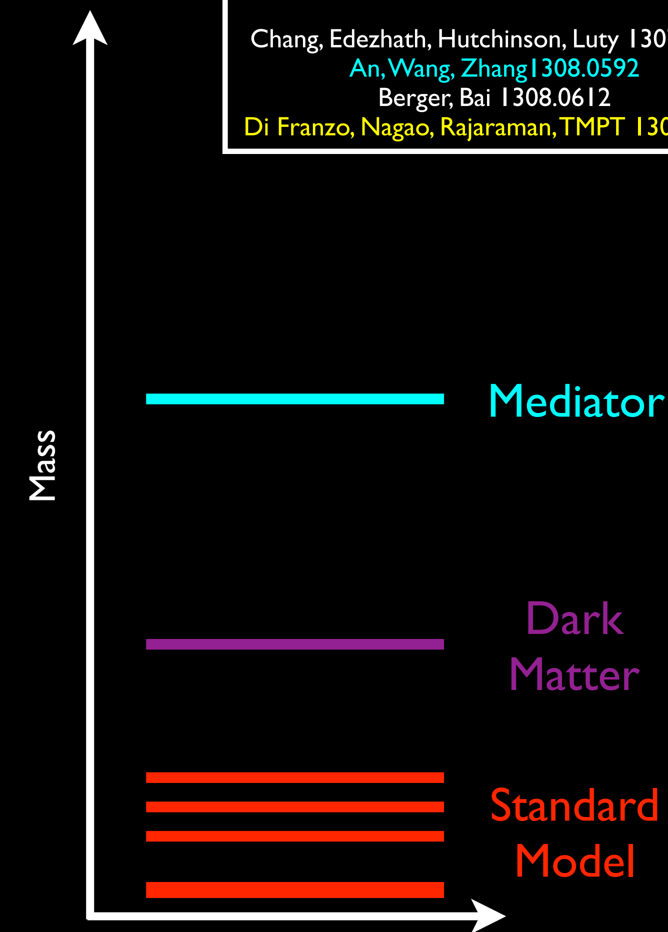


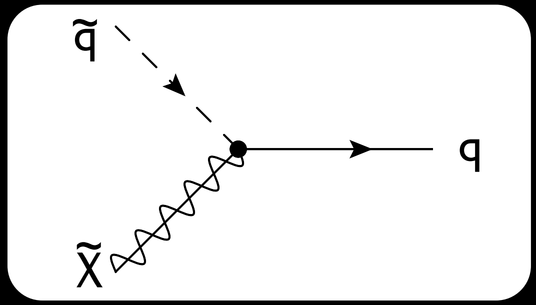
# Simplified Model

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

- 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.



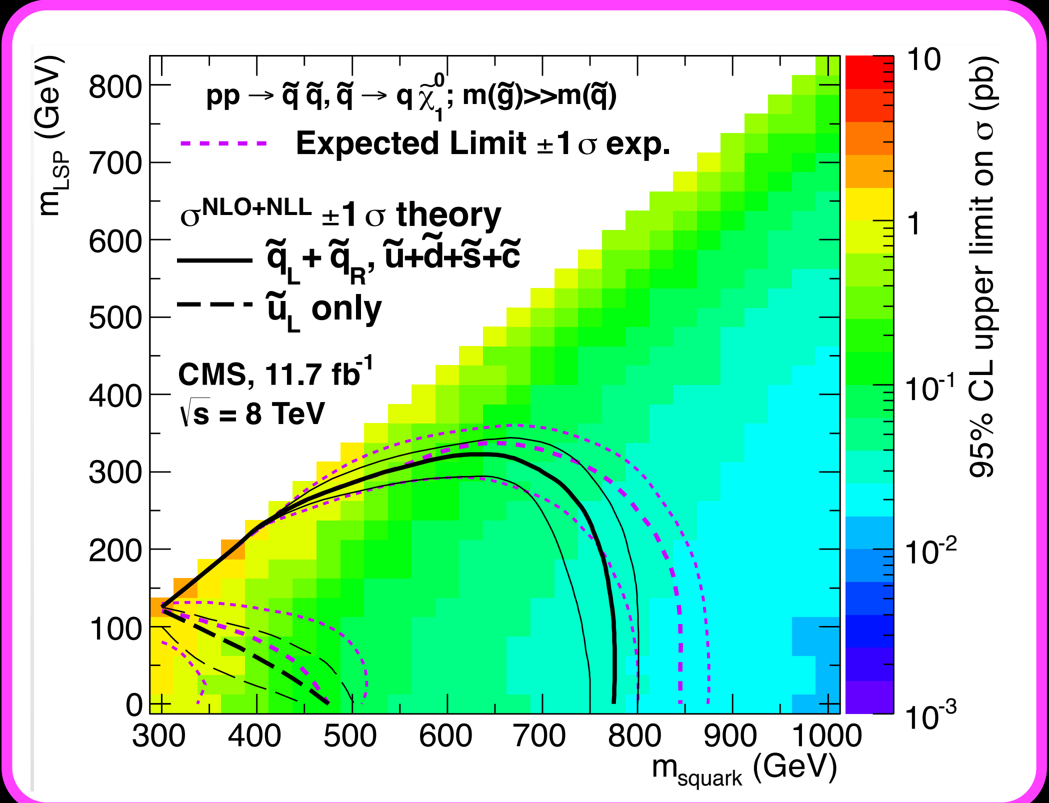



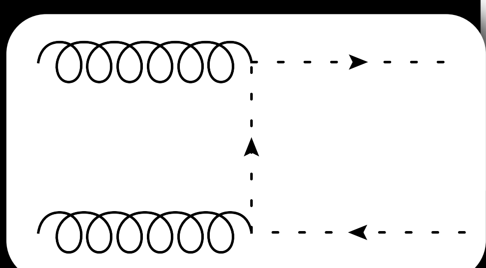
# $\tilde{u}_R$ Model

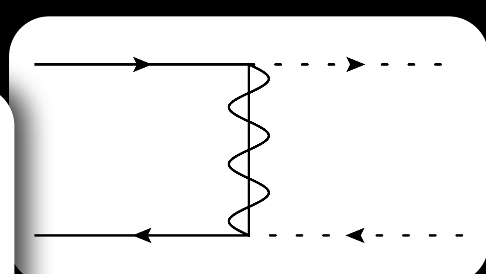
- For example, we can look at a model where a Dirac DM particle couples to right-handed up-type quarks.

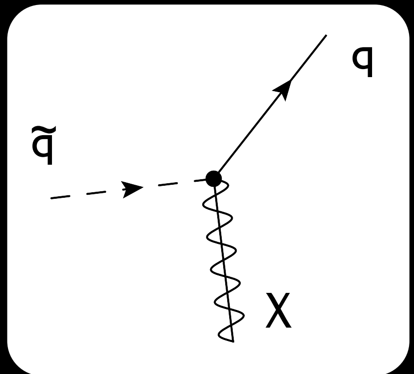
- At colliders, the fact that the mediator is colored implies we can produce it at the LHC using the strong nuclear force (QCD; mostly from initial gluons) or through the interaction with quarks.

- Once produced, the mediator will decay into an ordinary quark and a dark matter particle.





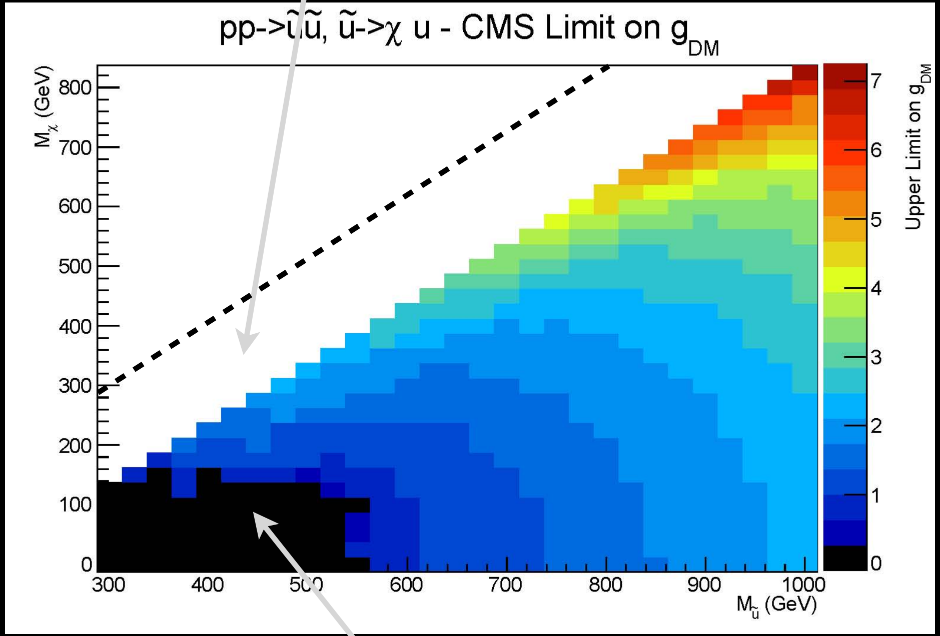


# $\tilde{u}_R$ Model

- 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



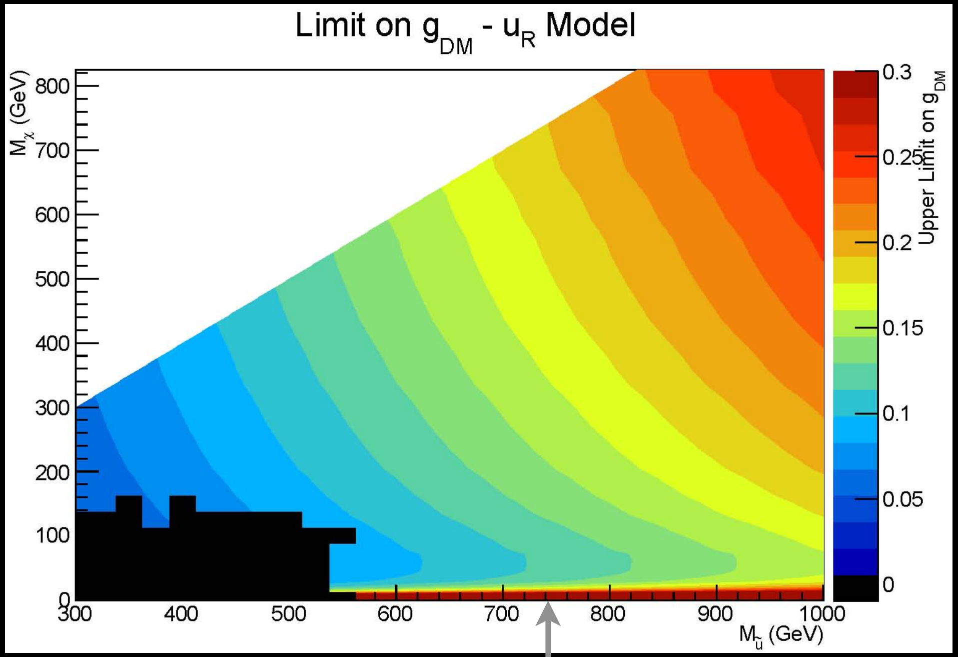

QCD production saturates the CMS limits, resulting in no allowed value of g.

All mediator masses and couplings assumed equal.

# $\tilde{u}_R$ Model

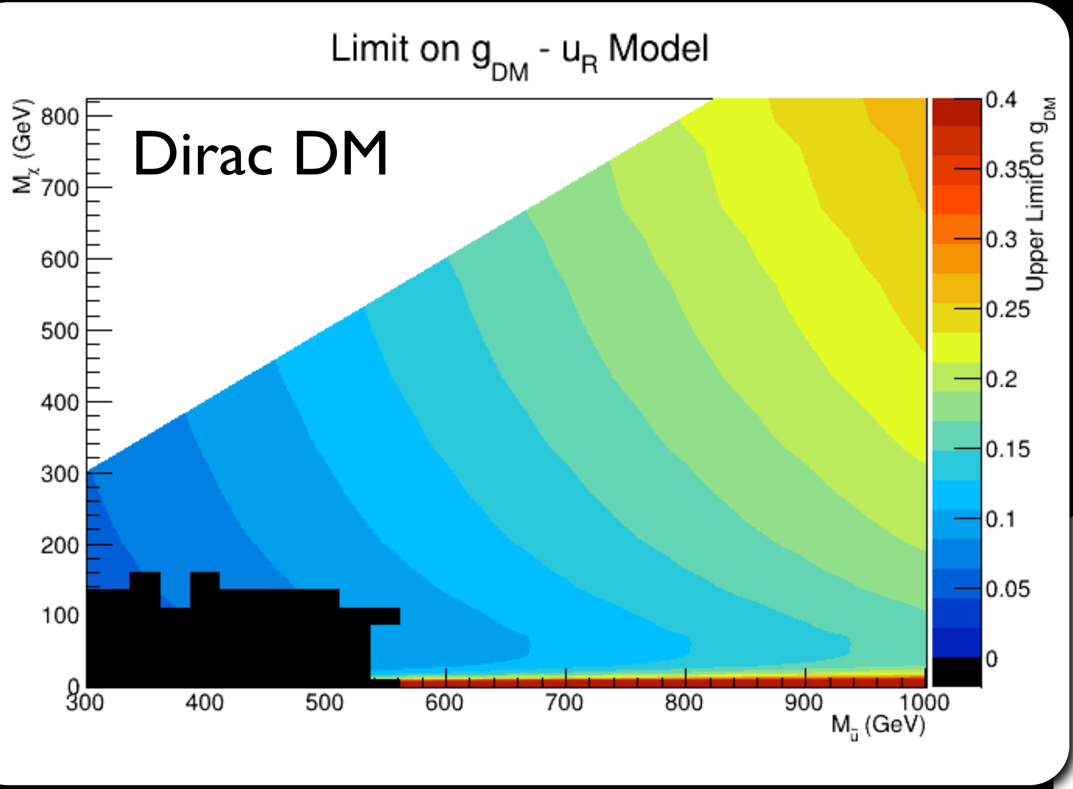
DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

- 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 stricter constraints on the coupling in the regions the LHC left as allowed.



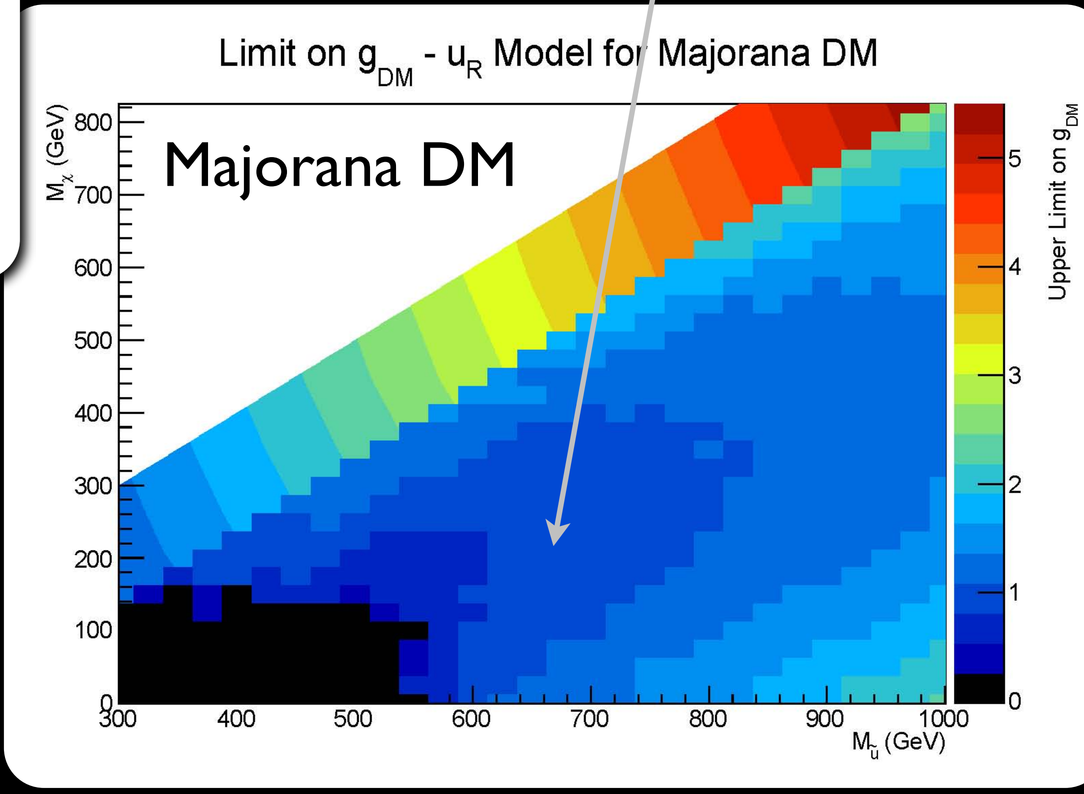

Traditional direct detection searches peter out for masses below about 10 GeV.

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




DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

Collider bounds tend to dominate for Majorana DM.



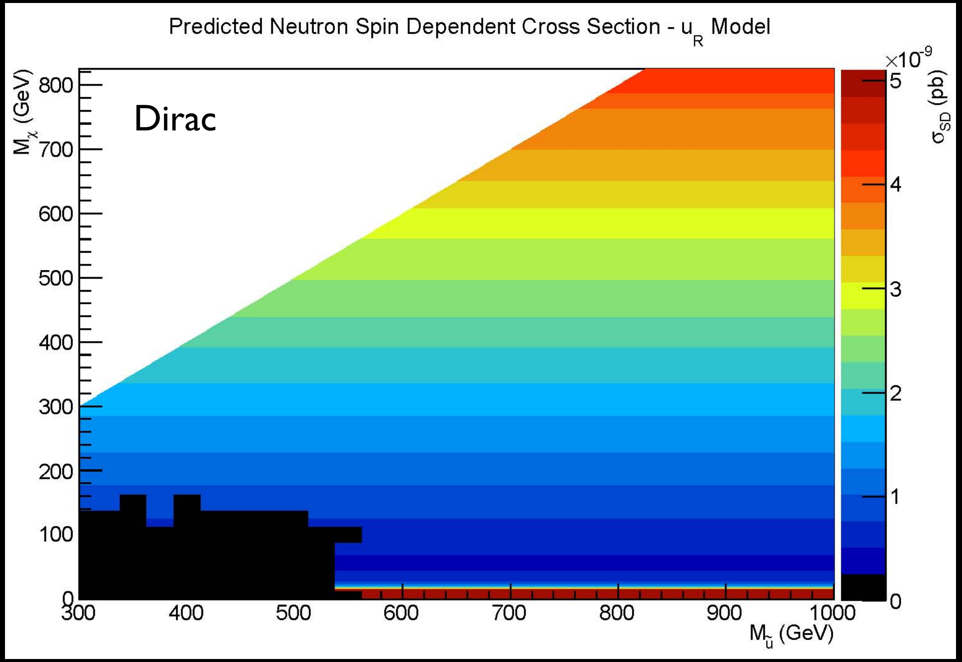

There are interesting differences that arise even from very simple changes, like considering a Majorana compared to a Dirac DM particle.

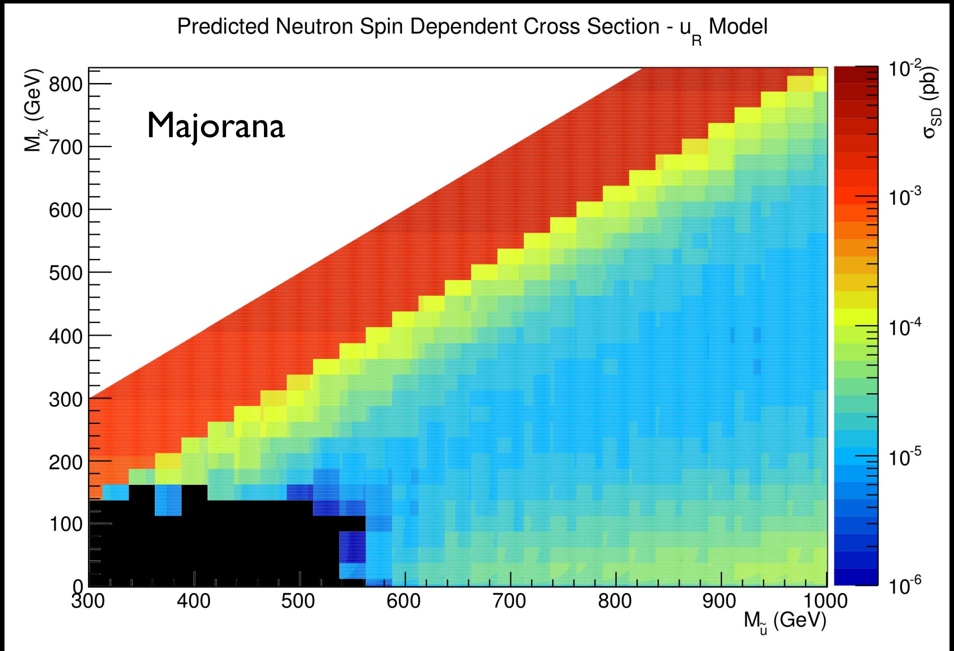
Majorana WIMPs have no tree-level spin-independent scattering in this model.

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

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

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

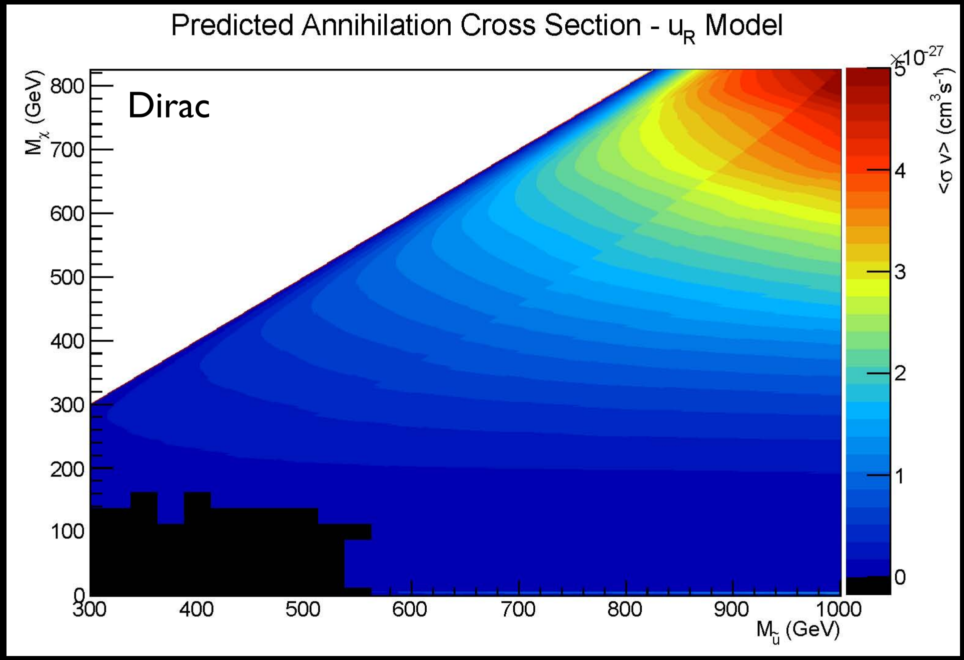


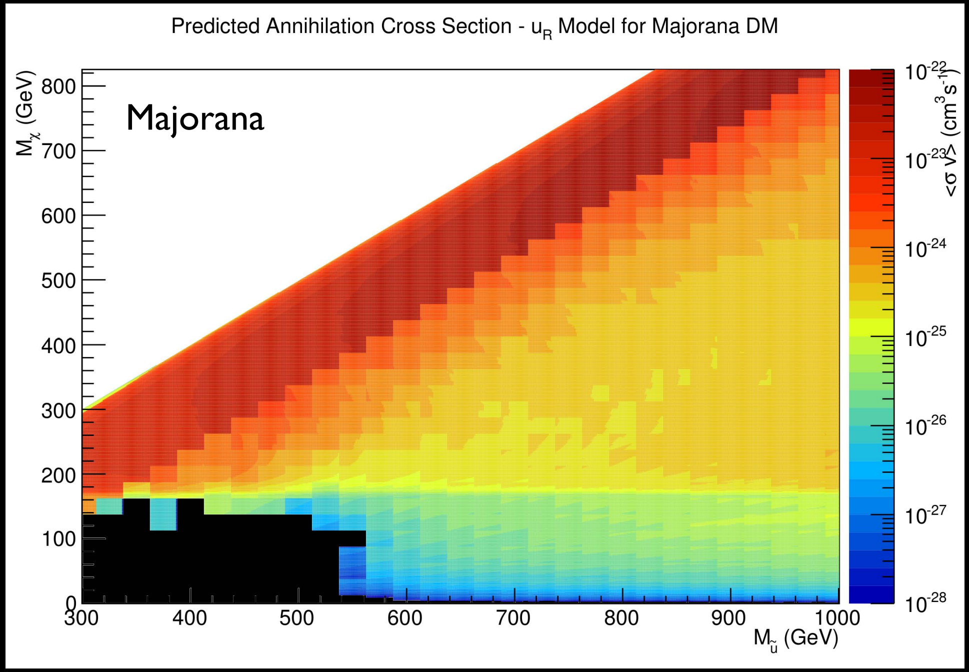




DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

# $\tilde{u}_R$ 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.

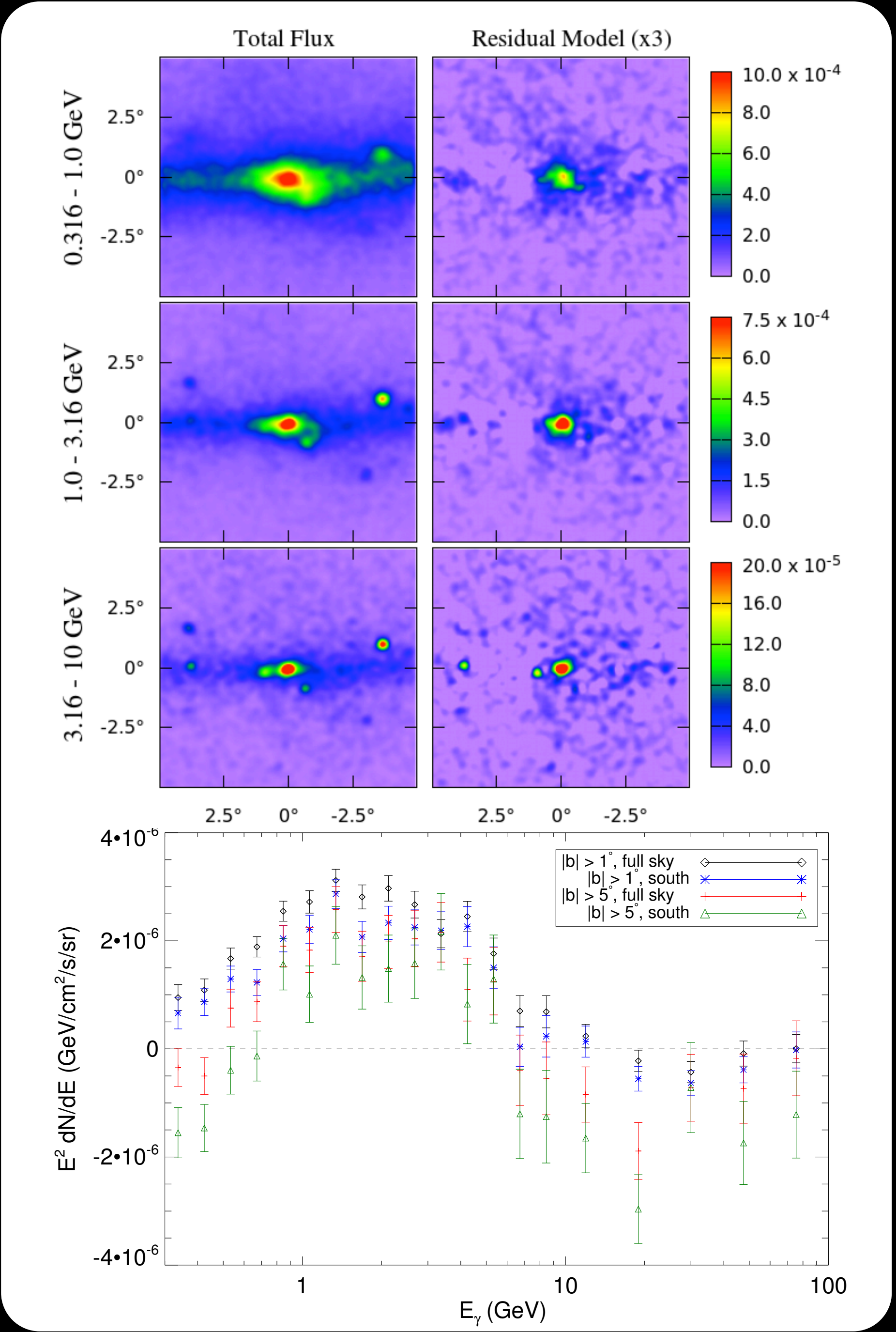



DiFranzo, Nagao, Rajaraman, TMPT
arXiv:1308.2679

# Gamma Ray GeV Excess

- A simplified model allows us to put a (possible) discovery into context and ask what a theory that could explain it should look like.
- As an example: there are hints for what could be a dark matter signal in the Fermi data from the galactic center.
- After subtracting models of the diffuse gamma ray emission, known point sources, etc, an excess remains with a distribution peaking around a few GeV, consistent with the expectations of a 40 GeV dark matter particle annihilating into bottom quarks.

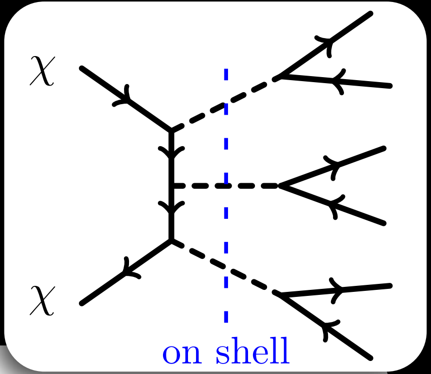


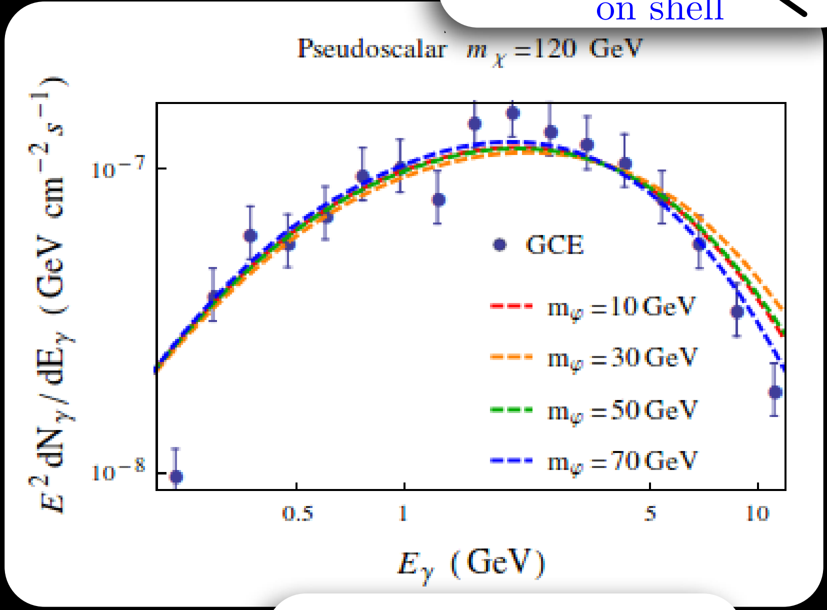

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703
see also: Abazajian, Canac, Horiuchi, Kaplinghat 1402.4090

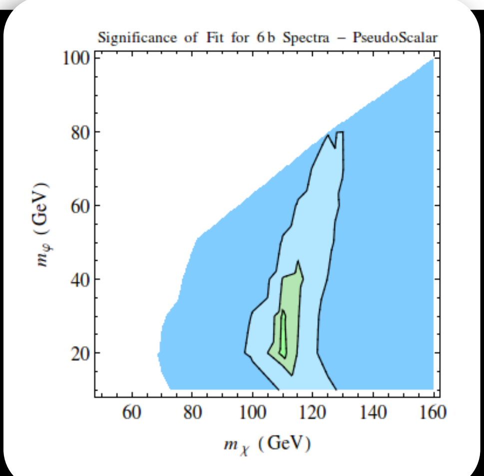
# Gamma Ray Excess

- The signal suggests something about the simplified models that could work.
- The signal is large enough that something is going to need to suppress scattering with heavy nuclei.
- For example, the particle communicating between dark matter and the SM could be a pseudoscalar, leading to spin-dependent and velocity suppressed coupling to nuclei.
- Even these tricks won't hide from direct searches forever.
- If the mediating particle is light, the dark matter can decay into on-shell mediators, which further allows weak coupling to the SM particles.

Abdullah, DiFranzo, Rajaraman, TMPT, Tanedo, Wijangco 1404.6528



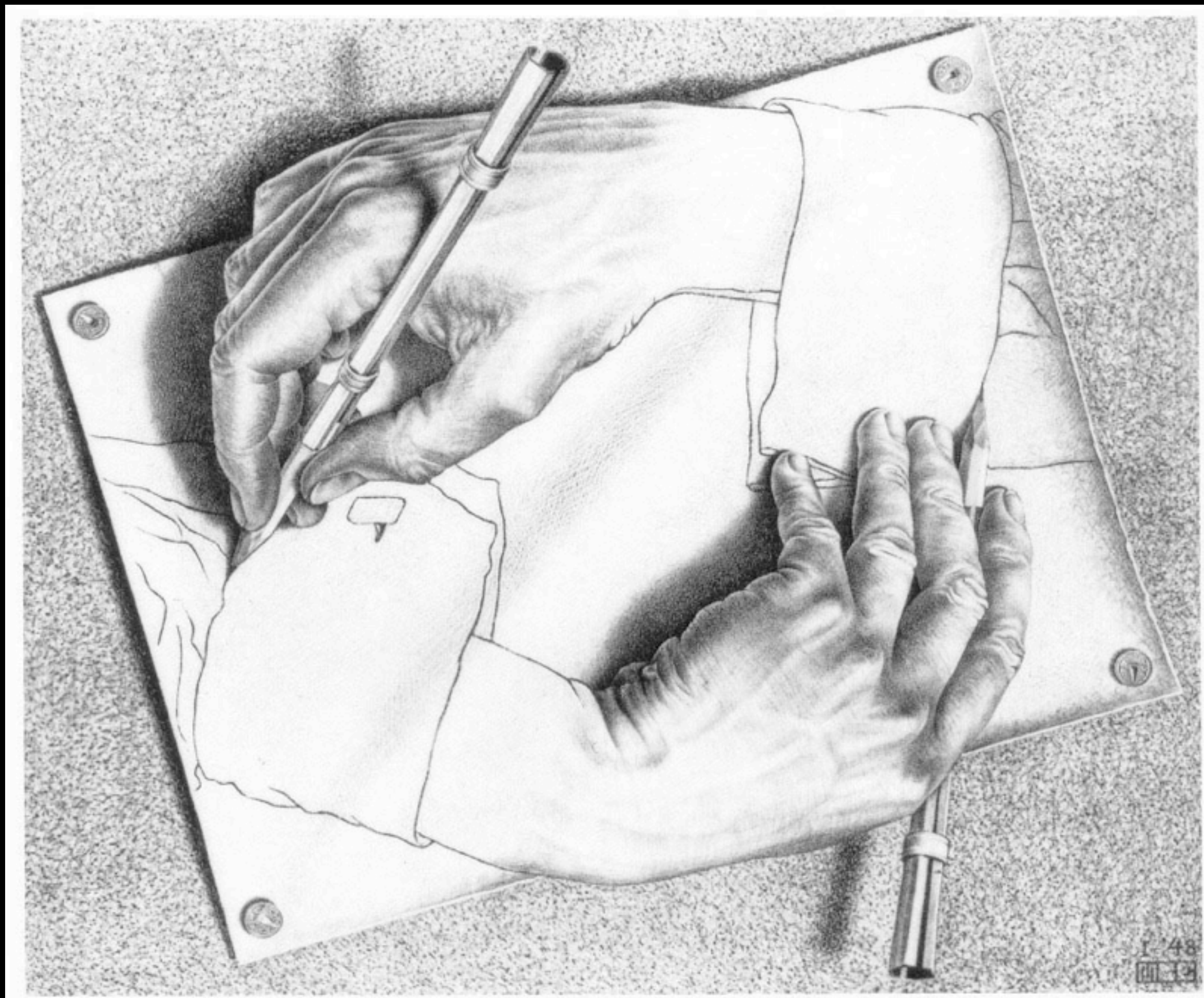




See also: Berlin, Hooper, McDermott 1404.0022
Agrawal, Batell, Hooper, Lin 1404.1373

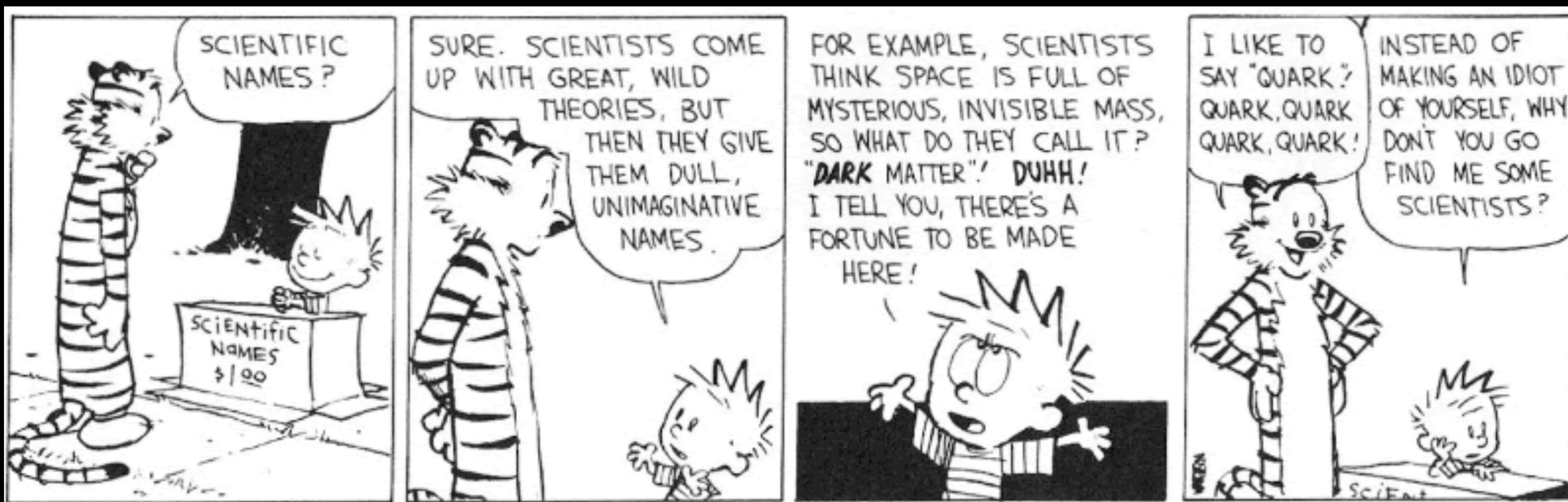
# Outlook

- Dark matter is an interesting phenomenon that implies physics beyond the Standard Model. Particle physics offers many opportunities to study it.
- Understanding the relationship between various searches and how they define the viable parameter space requires a theory framework.
    - These can be very concrete complete models such as the MSSM, but it may be fruitful to look at less-defined, more hazy "sketches of theories" as well.
- Put into this context, searches at colliders, for elastic scattering, and for annihilation products all seem to naturally target different parts of dark matter theory-space. They complement one another.
- The full suite of techniques are essential to do justice to the range of possibilities.
- Once we have a discovery, they will ultimately help define and verify it and help lead us to define new experiments to better characterize it.
- Experiments can bring sketches of dark matter to life!

# From Sketch to Life

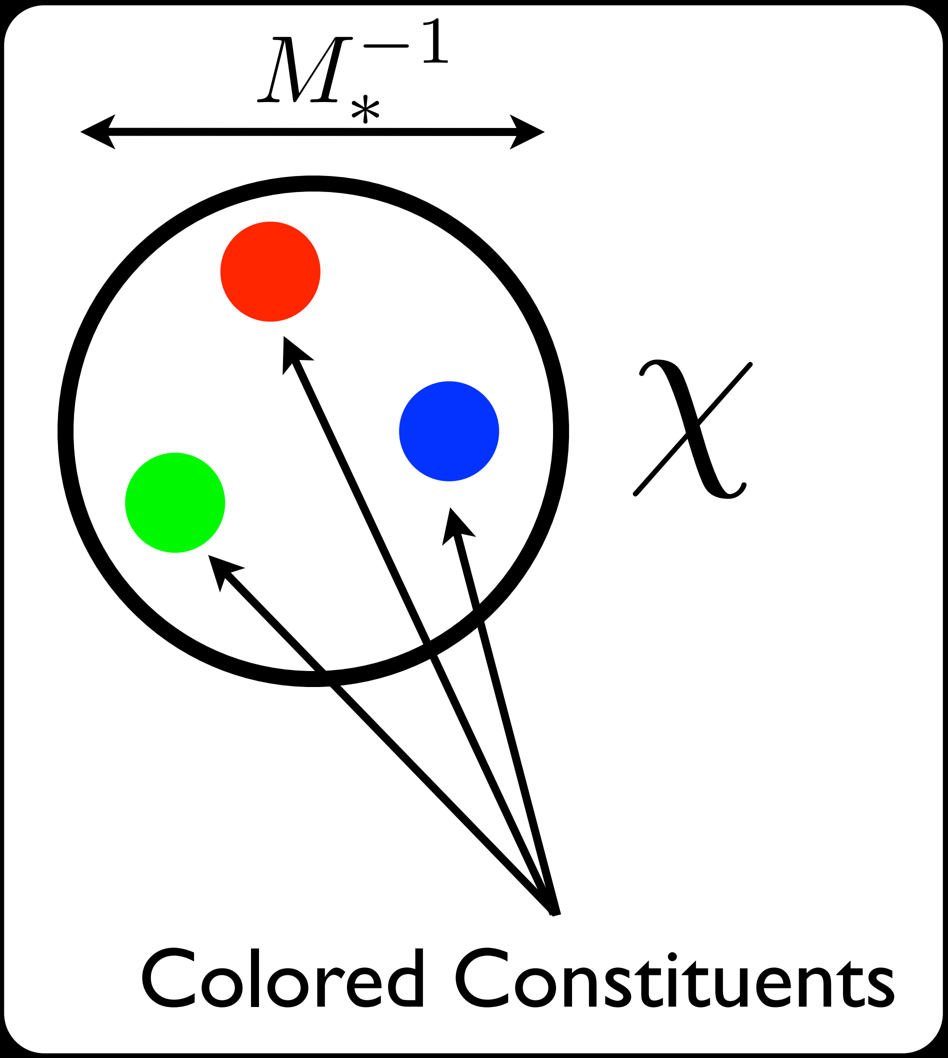


# Sketches of .... ......


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?
WATERSON

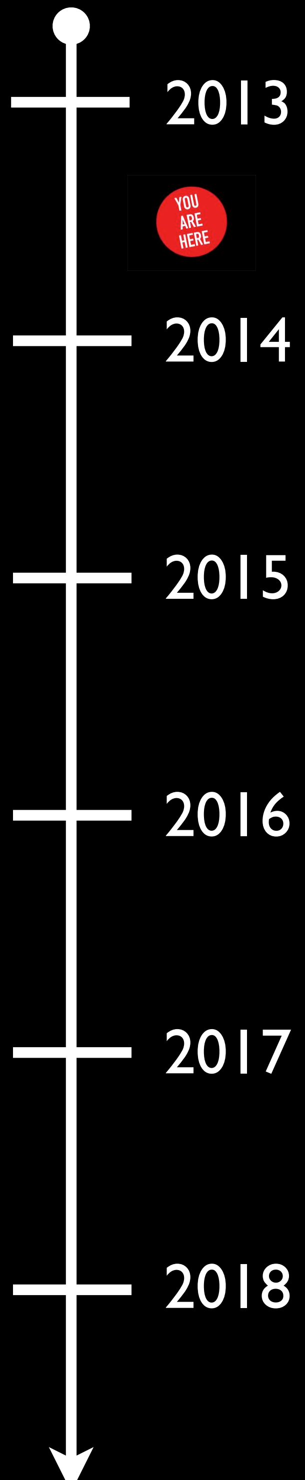
# Bonus Material

# A Composite WIMP?




- Even when EFTs are only constraining rather strongly coupled theories, they say something interesting about some (perhaps exotic) visions of dark matter.
- 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 new confinement scale -- the "radius" of the dark matter.

# A Possible Timeline





- [ ] Mass
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

# A Possible Timeline

- 2013


- 2014
- 2015
- 2016
- 2017
- 2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

- [?] Mass: < 200 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons?
- [ ] Leptons?
- [ ] Thermal Relic?

# A Possible Timeline

2013


2014

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

2015

2016

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- [ ] Leptons?
- [ ] Thermal Relic?

2017

2018

# A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Two LHC experiments see a significant excess of leptons plus missing energy.

Xenon sees a similar signal.

- [x] Mass: 150 +/- 15 GeV
- [ ] Spin
- [ ] Stable?

Couplings:

- [x] Gravity
- ? Weak Interaction?
- [ ] Higgs?
- [x] Quarks / Gluons
- ? Leptons?
- [ ] Thermal Relic?

# A Possible Timeline


2013

YOU ARE HERE

2014

2015

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Xenon sees
gnal.

Two LHC experiments see a significant excess of leptons plus missing energy.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

No jets + MET

Neutrinos are seen coming from the Sun by IceCube.

- ☑ Mass: 150 +/- 15 GeV
- ☑ Spin: > 0
- ☐ Stable?

Couplings:

- ☑ Gravity
- ☒ Weak Interaction?
- ☐ Higgs?
- ☑ Quarks / Gluons
- ☑ Leptons
- ☐ Thermal Relic?

# A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Xenon sees a similar signal.

A positive signal of axion conversion is observed at an upgraded ADMX.

Two LHC experiments see a si
lept

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

| | |
|---|---|
| ✓ Mass: 150 +/- 15 GeV | ✓ Mass: 20 μeV |
| ✓ Spin: > 0 | ✓ Spin: 0 |
| ☐ Stable? | ✗ Stable? |
| Couplings: | Couplings: |
| ✓ Gravity | ✓ Gravity |
| ✗ Weak Interaction? | ✓ Photon Interaction |
| ☐ Higgs? | ☐ Higgs? |
| ✓ Quarks / Gluons | ☐ Quarks / Gluons? |
| ✓ Leptons | ☐ Leptons? |
| ☐ Thermal Relic? | ✗ Thermal Relic? |

# A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

????

| | |
|---|---|
| ✓ Mass: 150 +/- 0.1 GeV | ✓ Mass: 20 μeV |
| ✓ Spin: > 0 | ✓ Spin: 0 |
| ☐ Stable? | ✗ Stable? |
| Couplings: | Couplings: |
| ✓ Gravity | ✓ Gravity |
| ✗ Weak Interaction? | ✓ Photon Interaction |
| ☐ Higgs? | ☐ Higgs? |
| ✓ Quarks / Gluons | ☐ Quarks / Gluons? |
| ✓ Leptons | ☐ Leptons? |
| ✓ Thermal Relic | ✗ Thermal Relic? |

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.

# A Possible Timeline

2013

YOU ARE HERE

2014

2015

2016

2017

2018

????

LUX sees
elastic scat
consistent
mass <

Xeno
a simil

- ☑ Mass: 150 +/- 0.1 GeV
- ☑ Spin: > 0
- ☐ Stable?

Couplings:

- ☑ Gravity
- ☒ Weak Interaction?
- ☐ Higgs?
- ☑ Quarks / Gluons
- ☑ Leptons
- ☑ Thermal Relic

- ☑ Mass: 20 μeV
- ☑ Spin: 0
- ☒ Stable?

Couplings:

- ☑ Gravity
- ☑ Weak Interaction
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?
- ☒ Thermal Relic?

A multi-pronged search strategy identifies a mixture of dark matter which is 50% classic WIMP and 50% axion.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.