Assembling a Theory of Dark Matter

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Snowmass
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What is Dark Matter?

“Cold Dark Matter: An Exploded View” by Cornelia Parker

The Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

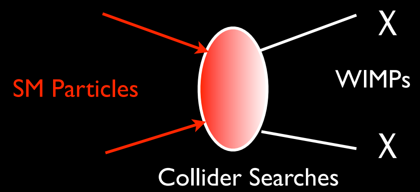
Couplings:

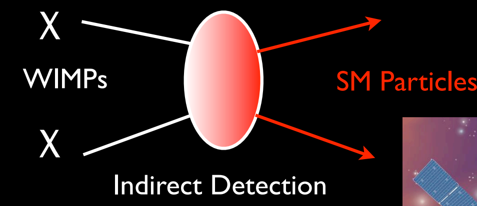
- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

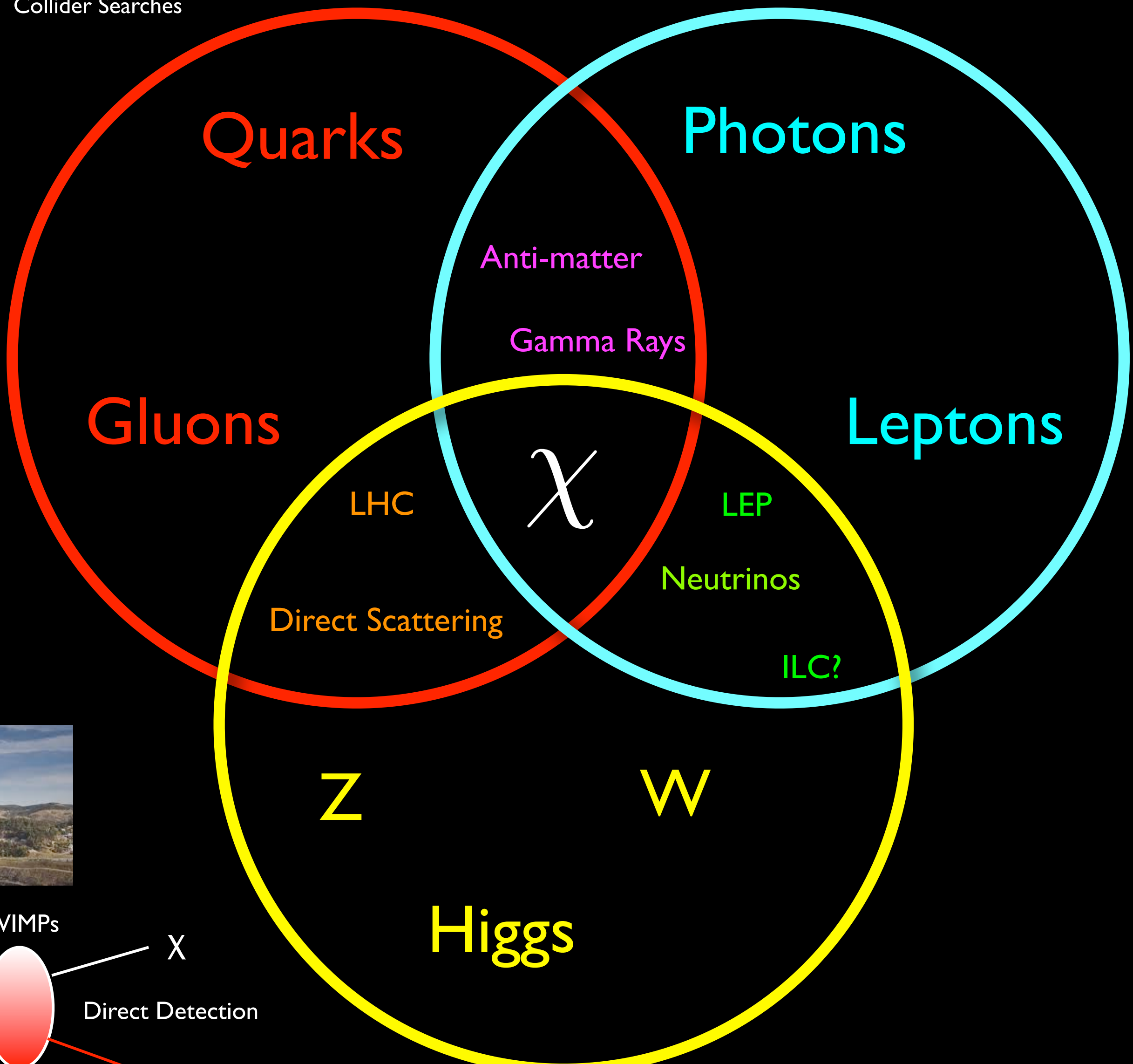
Thermal Relic?

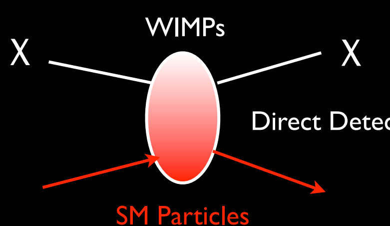
- ☐ Yes ☐ No

Map of DM-SM Interactions





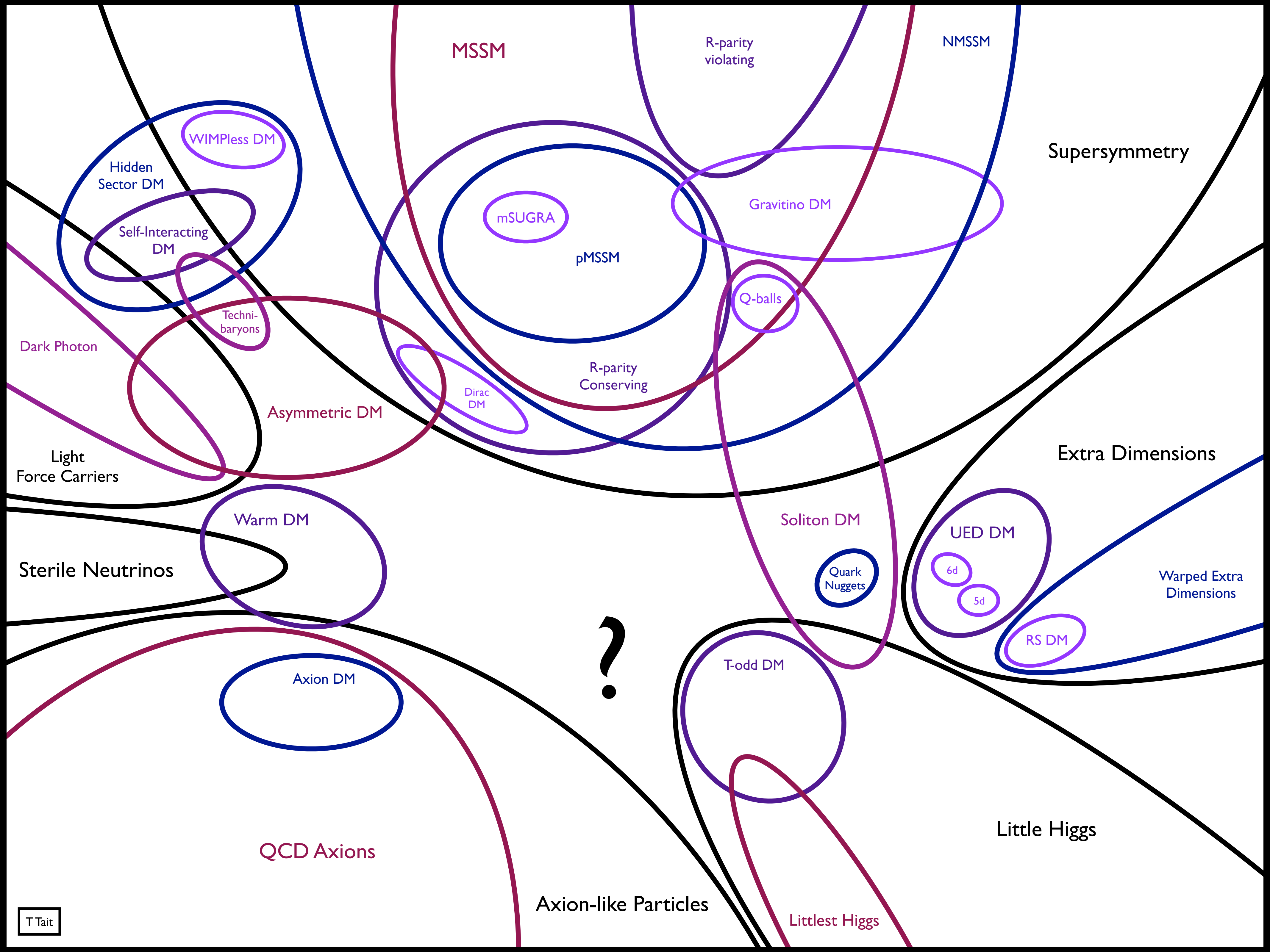




Ultimately, we need to fill out the questionnaire experimentally. But as we try to relate the results of experiments to one another and unravel the deeper theoretical underpinning, we need at least some kind of theoretical framework in which to cast our progress.

What could the theory be?

No lack of possibilities...


MSSM
R-parity violating
NMSSM
Supersymmetry
Hidden Sector DM
WIMPless DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dark Photon
Asymmetric DM
Dirac DM
Light Force Carriers
Extra Dimensions
Warm DM
Soliton DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
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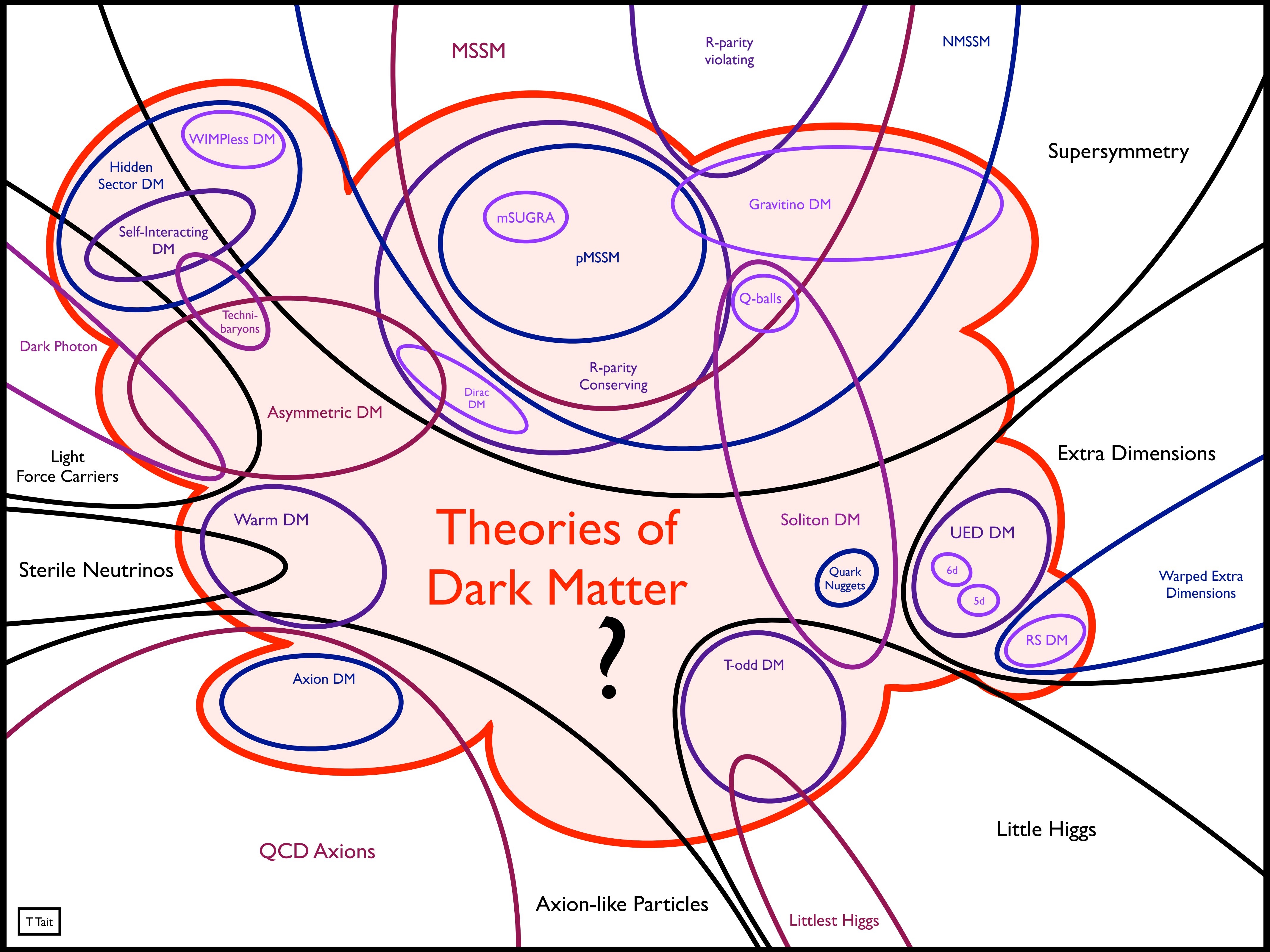

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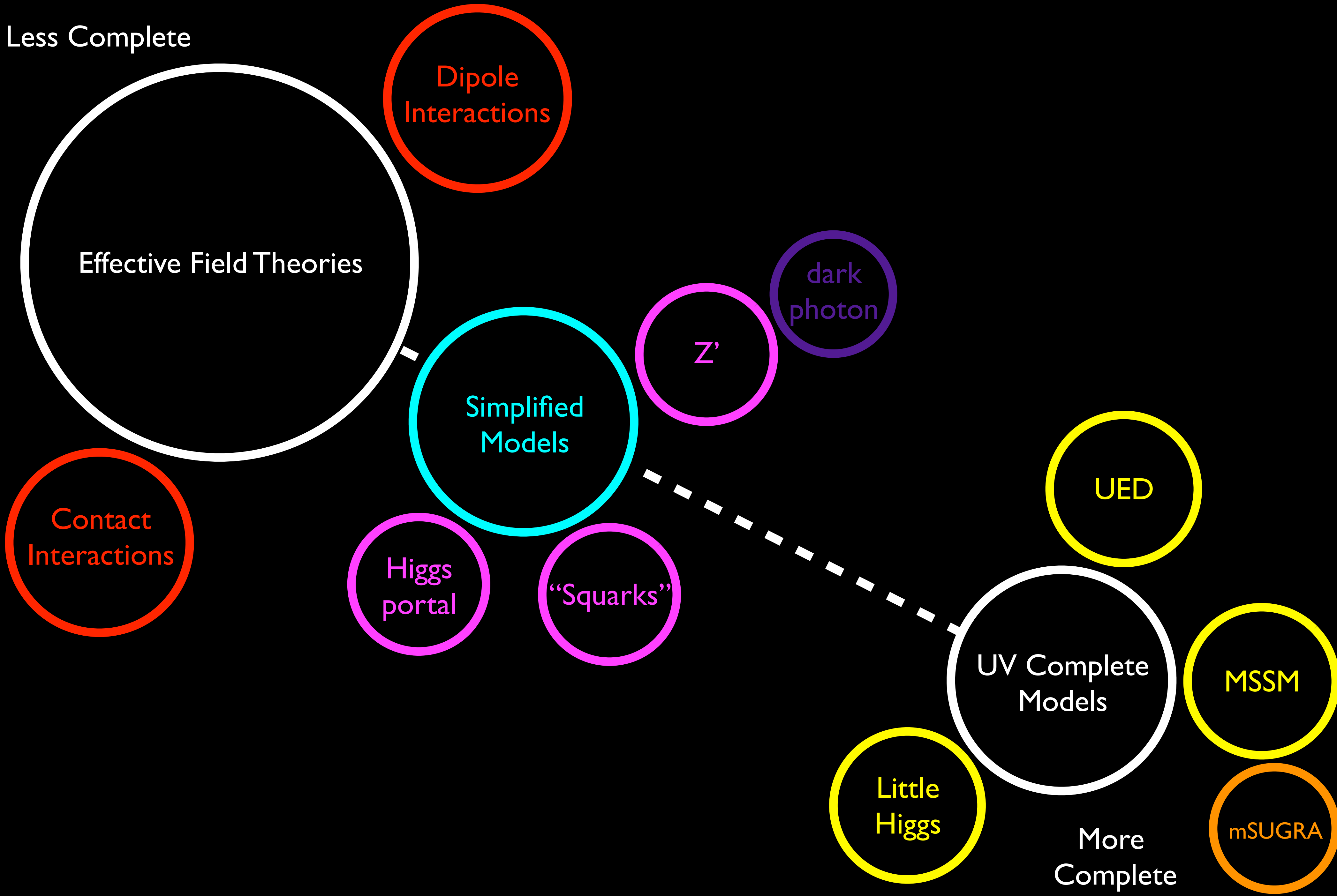
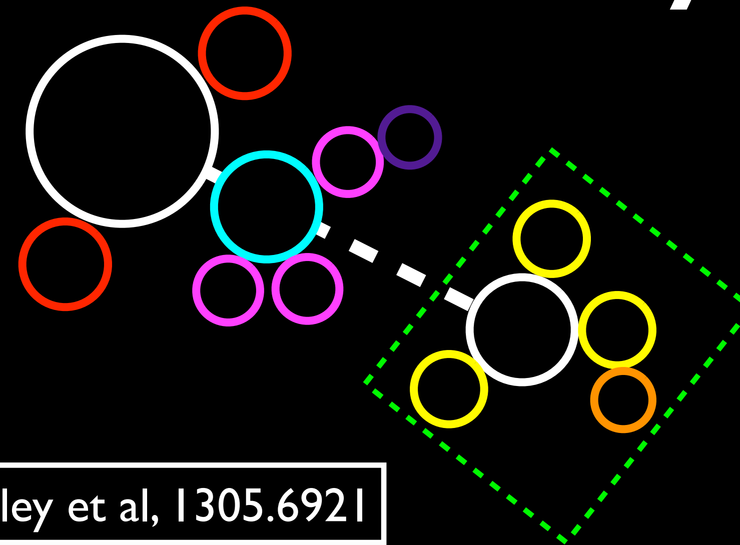
Spectrum of Theory Space

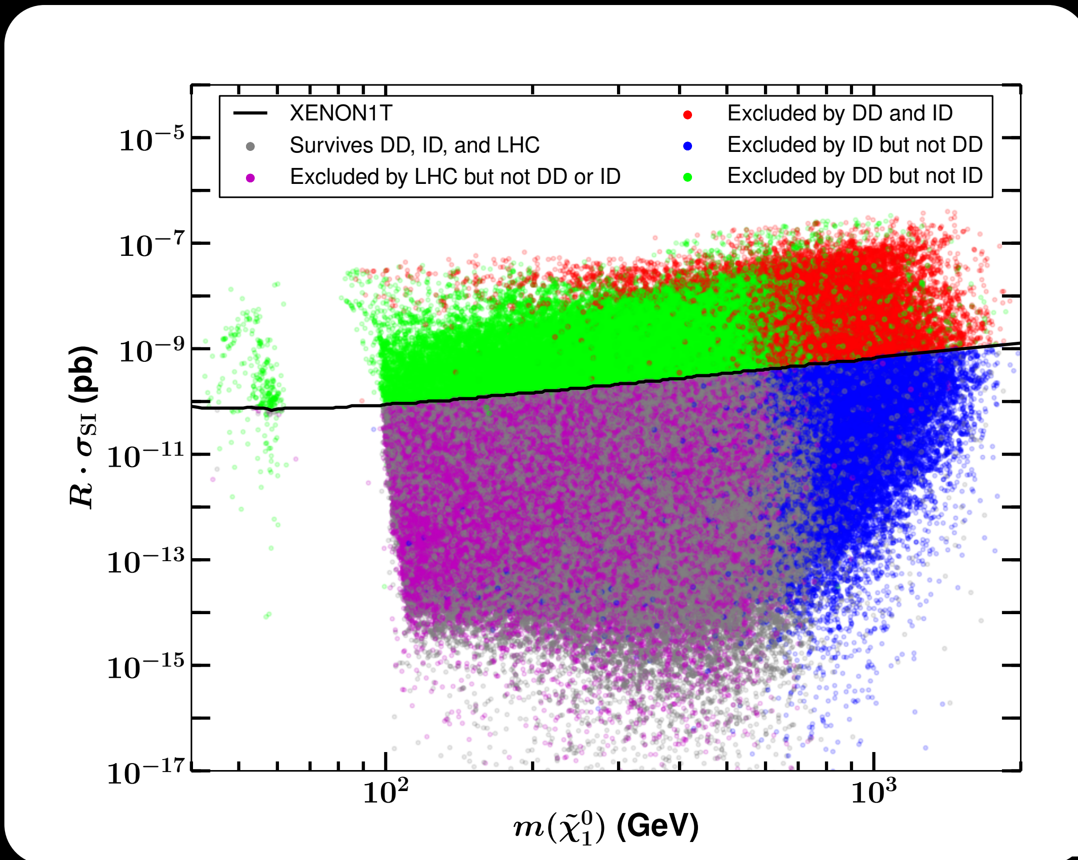


The Most Complete Theory

- On the “complete” end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM’ parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1ton only, CTA only, both Xenon and CTA, or can’t be discovered.
- It is clear that just based on which experiments see a signal, and which don’t, that there could be (potentially soon) suggestions of favored parameter space(s) from data.



Cahill-Rowley et al, 1305.6921



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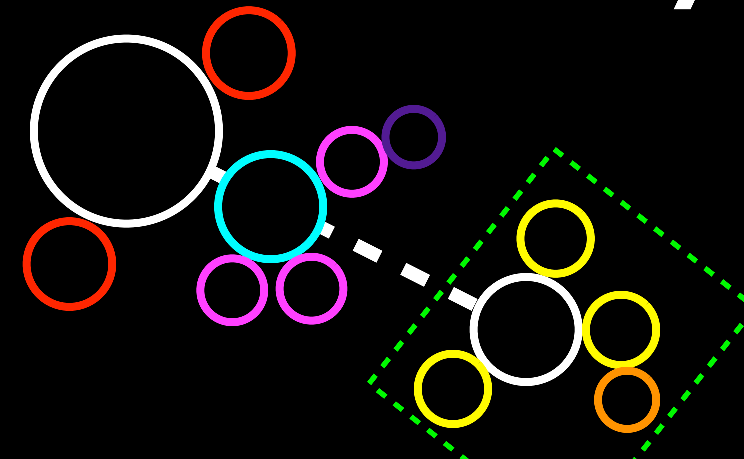
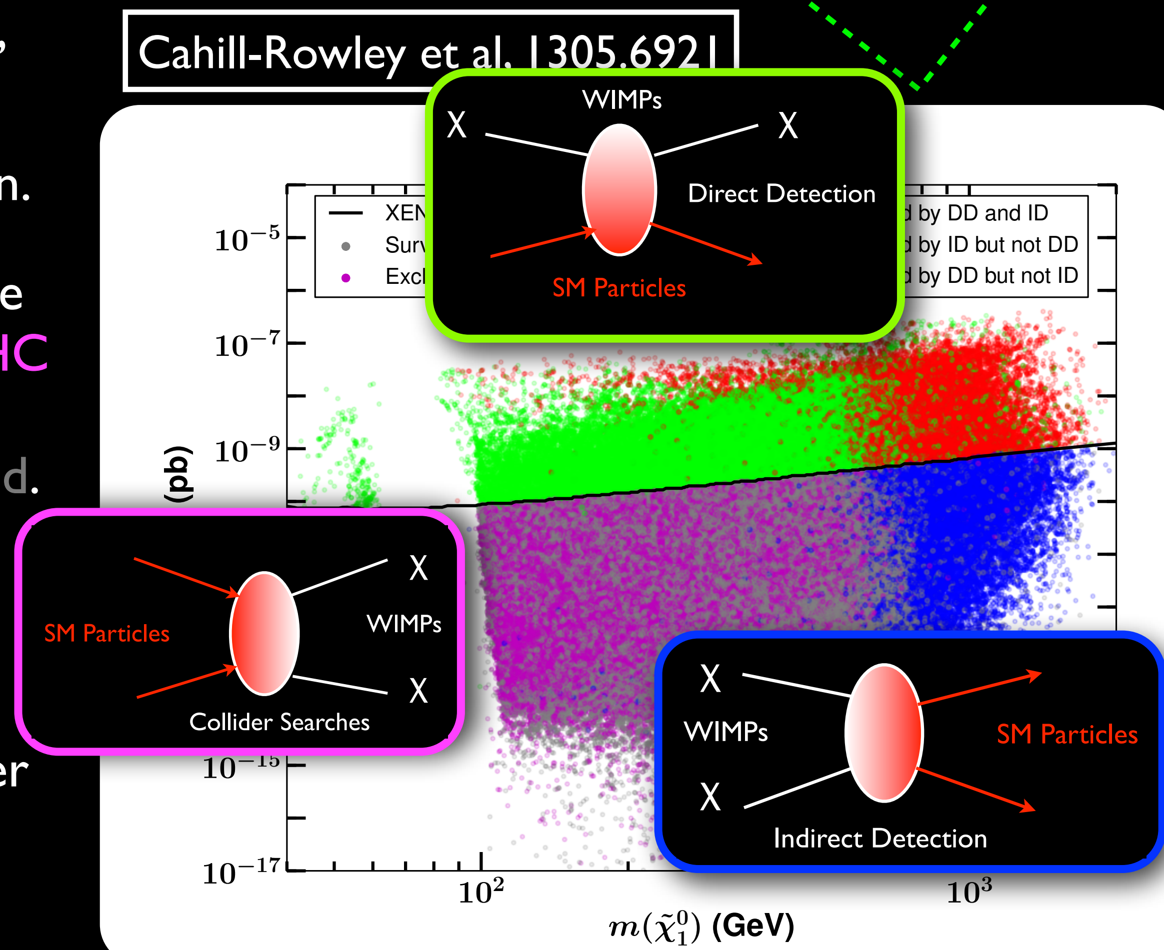
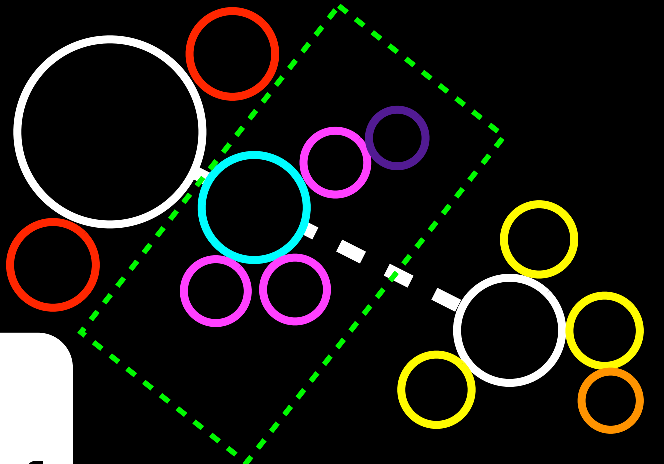
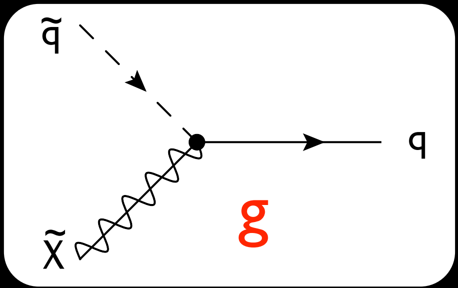


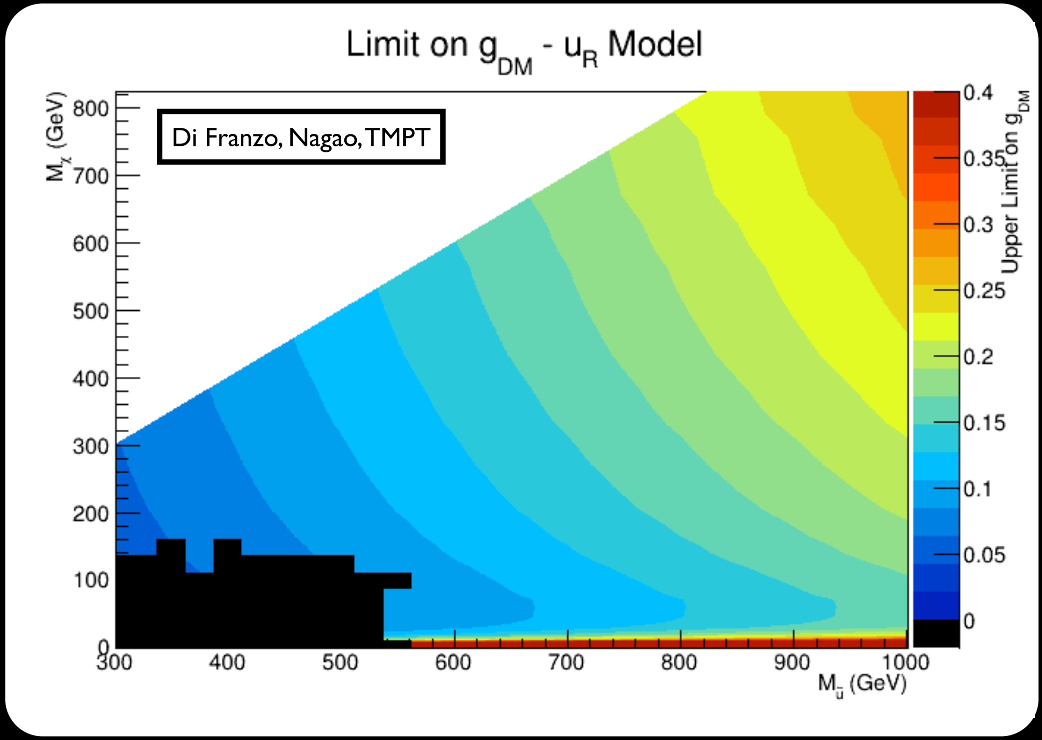


Simplified Models

- Moving away from complete theories, we come to simplified models.
- These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.
- As a simple example, we can look at a theory where the dark matter is a Dirac fermion which interacts with a quark and a (colored) scalar mediating particle.
- There are three parameters: the DM mass, the mediator mass, and the coupling g.
- These are like the particles of the MSSM, but with subtle differences in their properties and more freedom in their interactions.
- Just like the MSSM was one example of a complete theory, this is only one example of a "partially complete" one.







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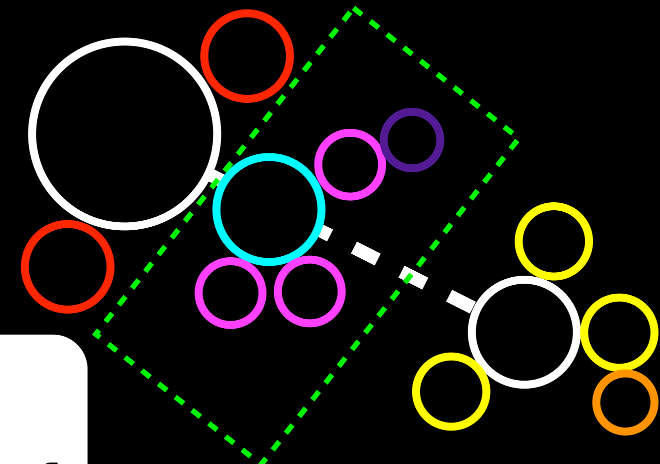
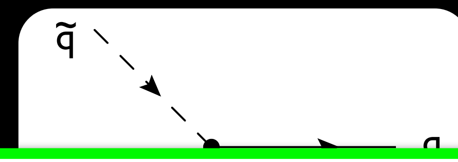
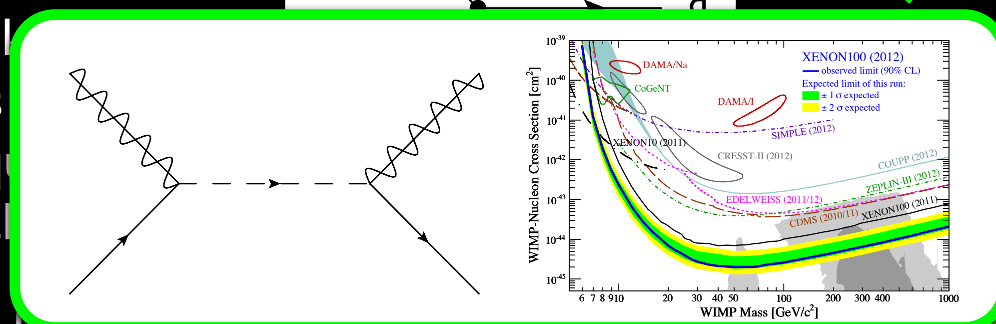
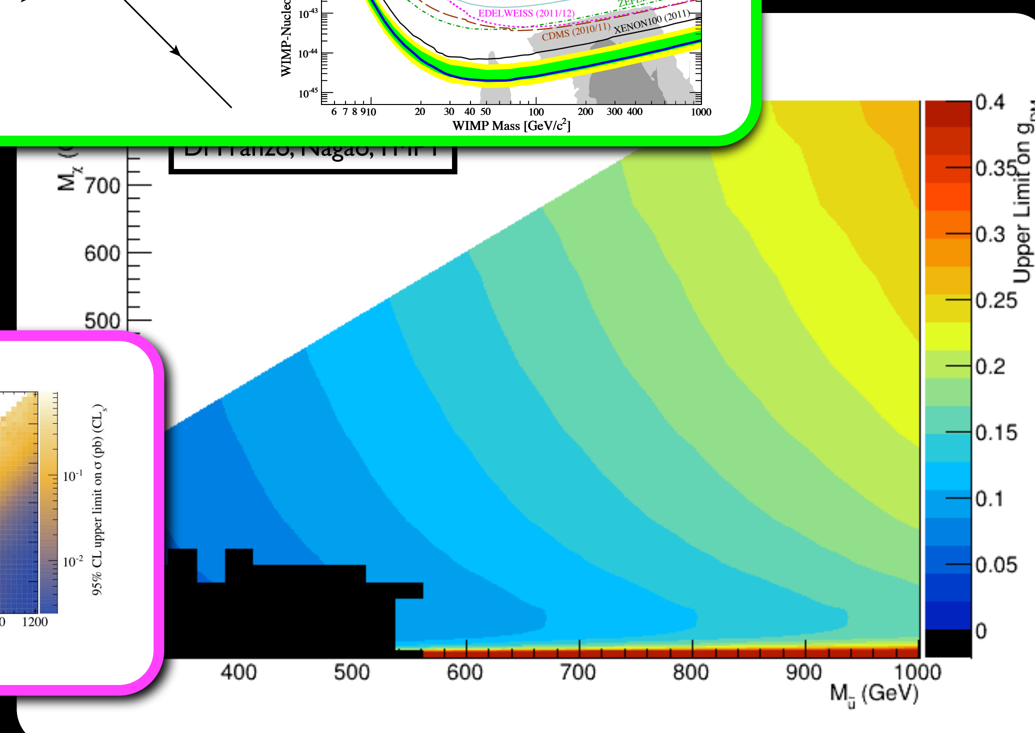
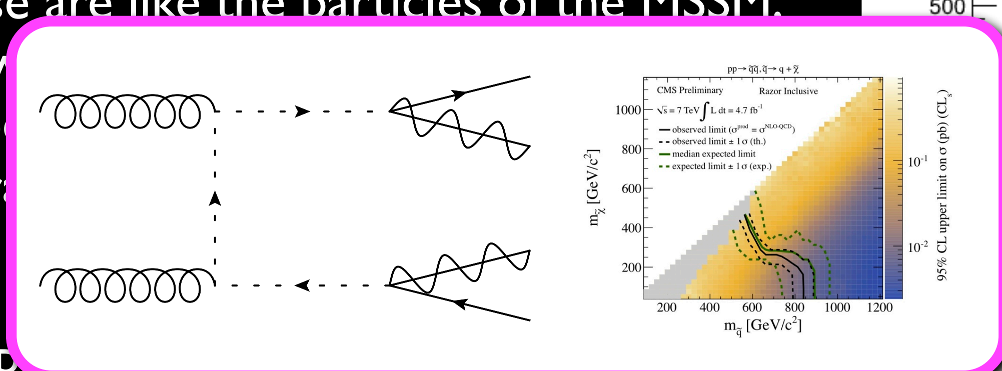


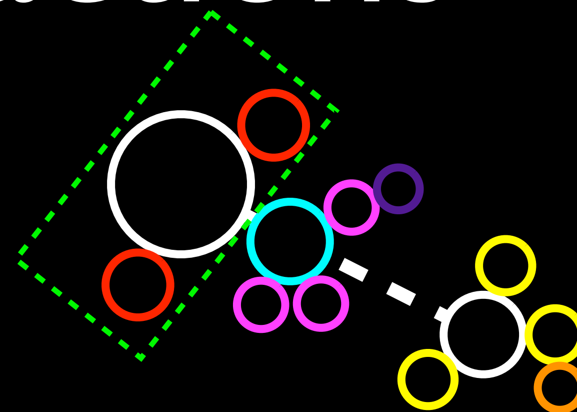




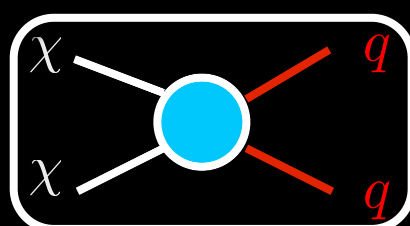




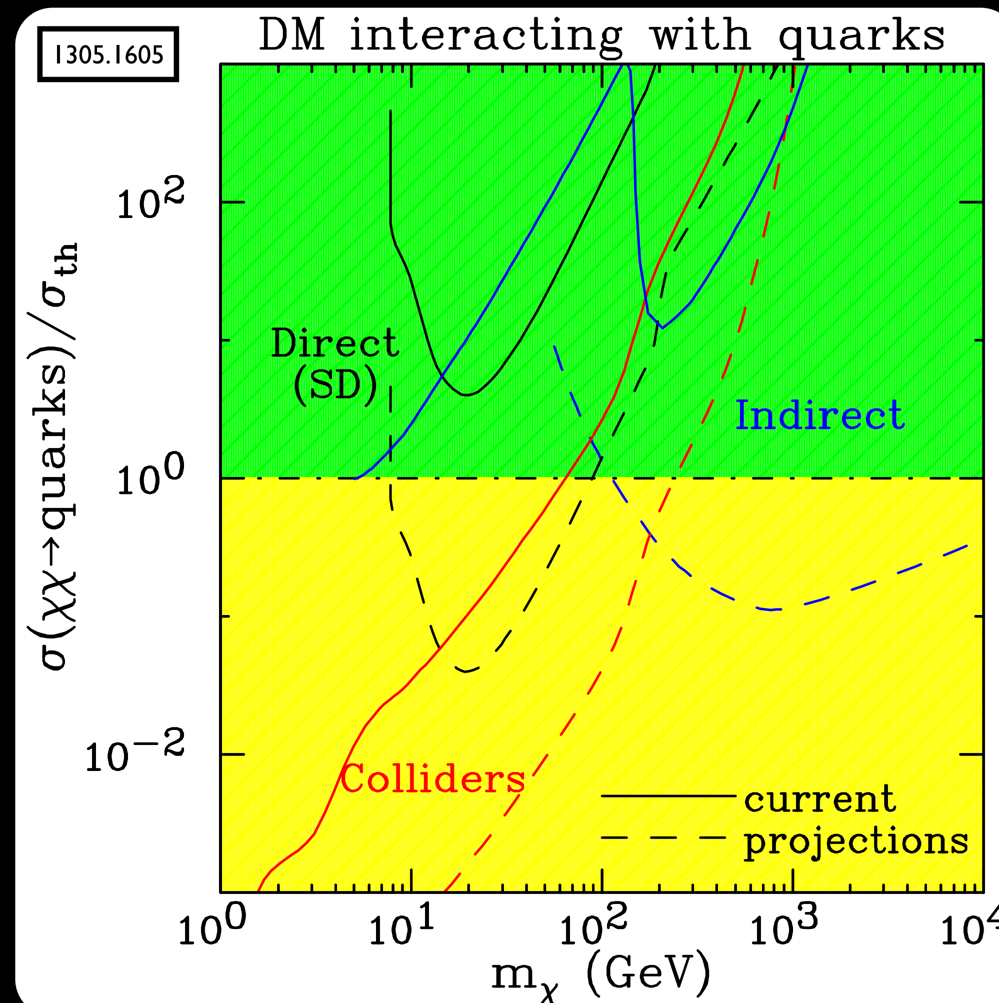
Contact Interactions



- In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.
- The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.



- These are the simplest and least complete description of dark matter we can imagine.
- For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.



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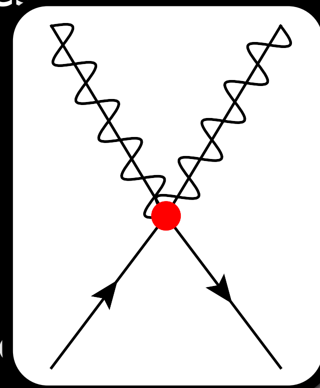

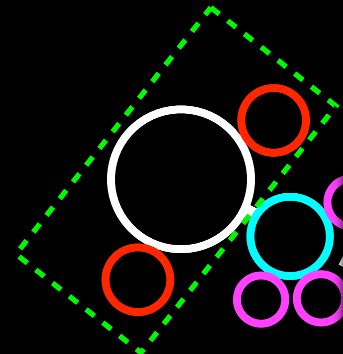

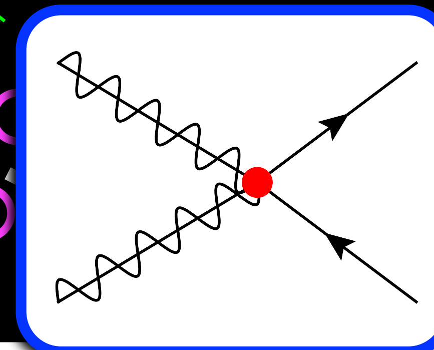

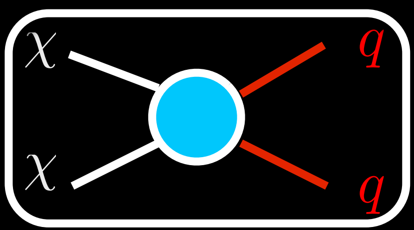

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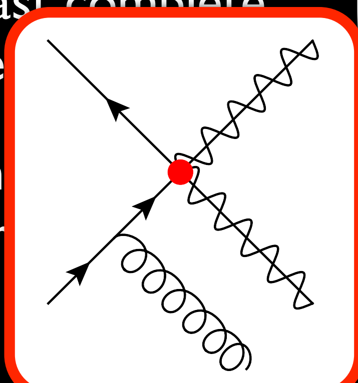
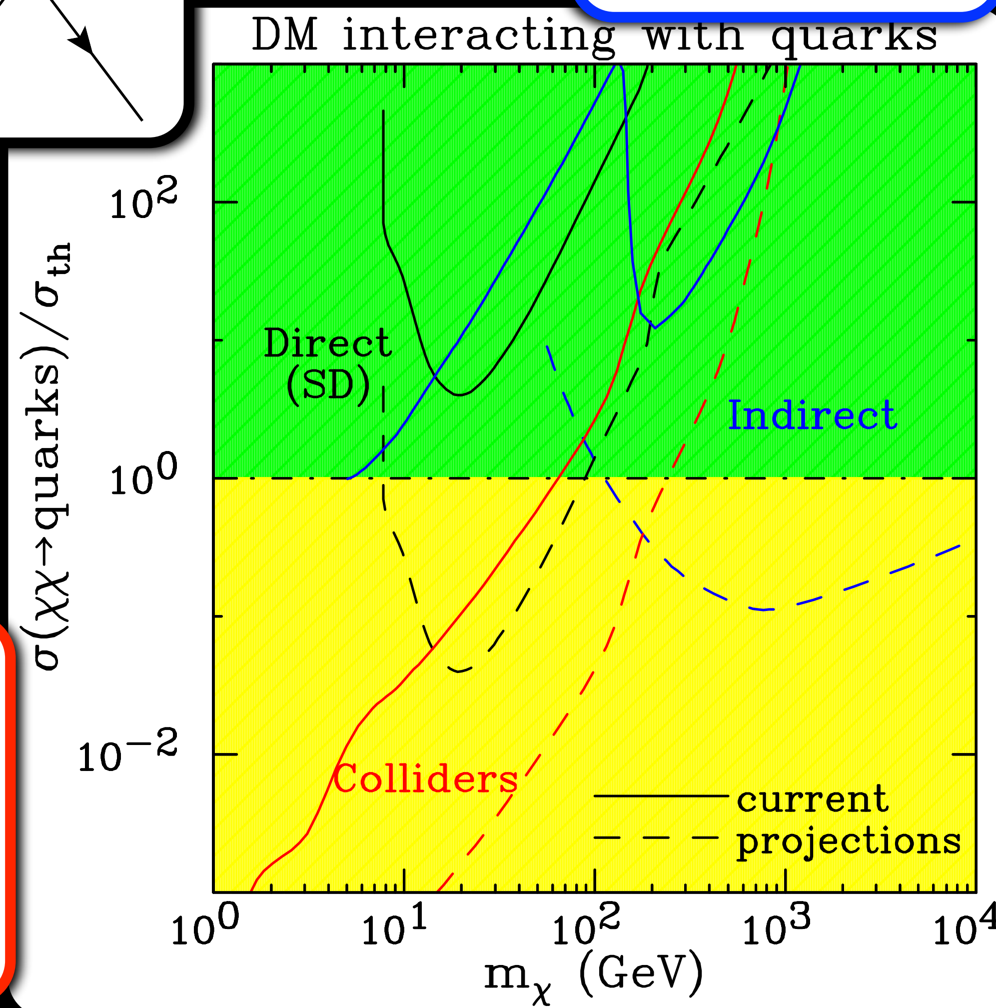
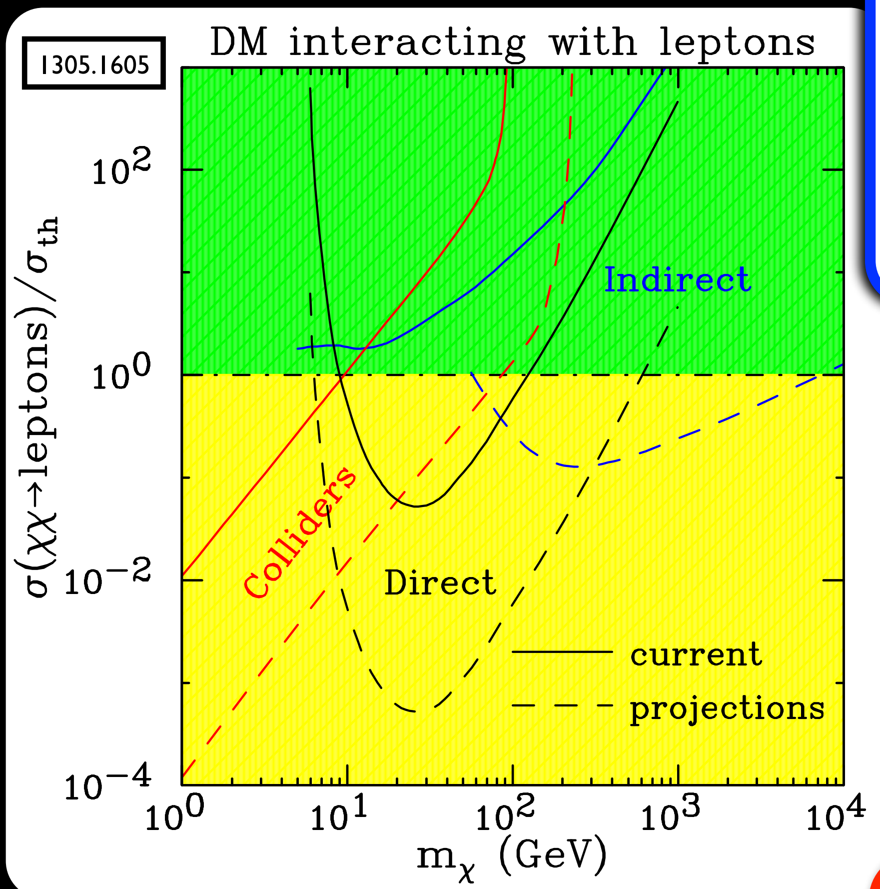
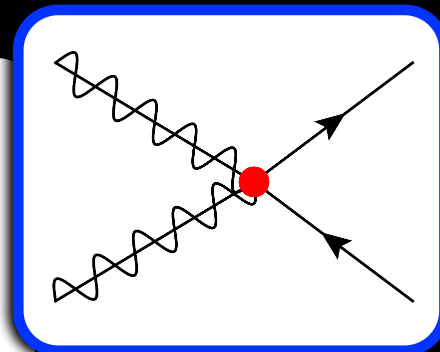
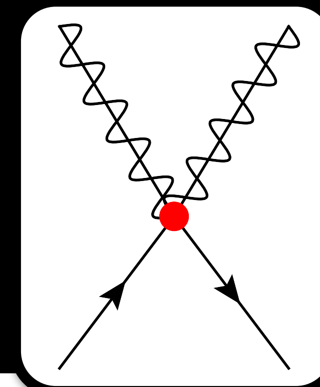


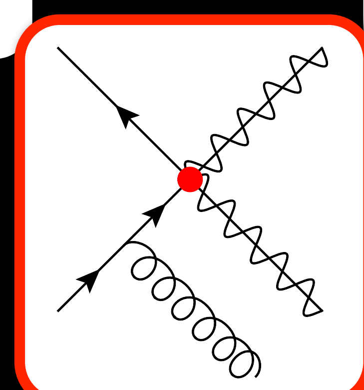


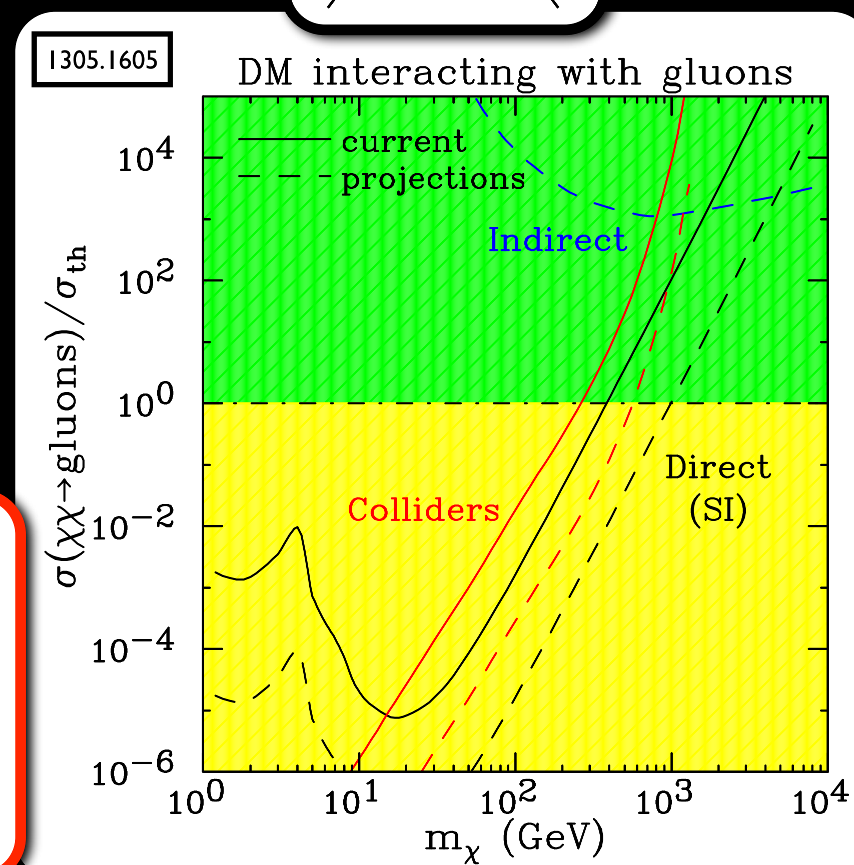
Lepton/Gluon Interactions











A Possible Timeline

2013

2014

2015

2016

2017

2018

- ☐ Mass
- ☐ Spin
- ☐ Stable?

Couplings:

- ☑ 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

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.

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

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
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A Possible Timeline

2013

YOU ARE HERE

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

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

Xenon sees a similar signal.

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

Couplings:

- ☑ Gravity
- ? Weak Interaction?
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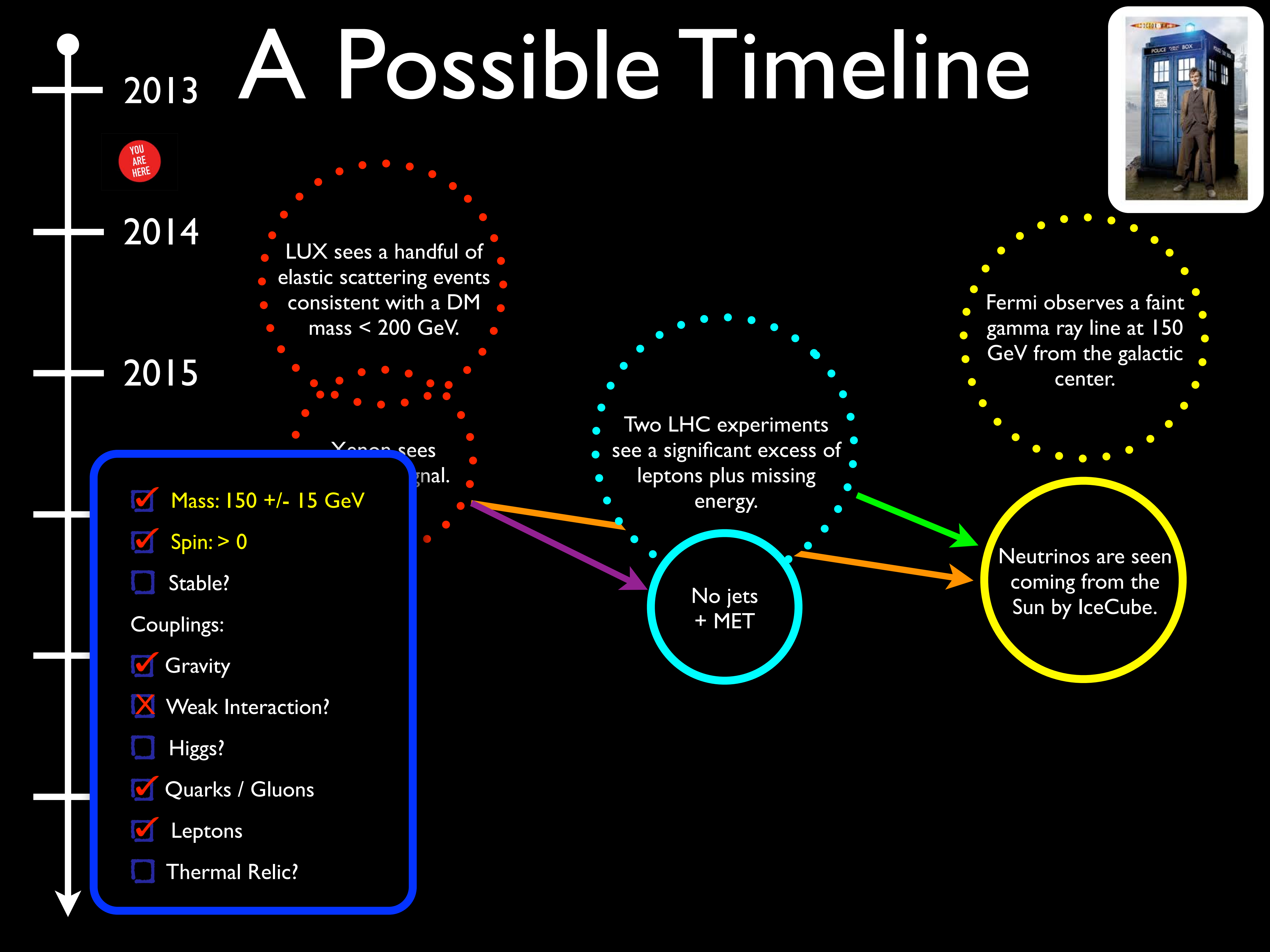

A Possible Timeline
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YOU ARE HERE
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Xenon sees
Two LHC experiments see a significant excess of leptons plus missing energy.
Fermi observes a faint gamma ray line at 150 GeV from the galactic center.
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

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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?

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

A Possible Timeline

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????

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elastic scat
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mass <

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- ☑ 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.

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Neutrinos are seen coming from the Sun by IceCube.

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Outlook

- Putting together a detailed particle description of dark matter will necessarily involve many experimental measurements.
- Important details such as the mass and spin will hopefully come along as part of that program.
- The three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.
  - They are highly complementary to one another in terms of discovery potential.
  - Together they can probe a large fraction of the space of interesting WIMP models in the near future.
  - Input from all of them is likely to be necessary to reconstruct enough of the couplings to be able to firmly understand the dark matter relic density.

“ Ωh^2 or bust! ”