Dark Matter: Theoretical Overview

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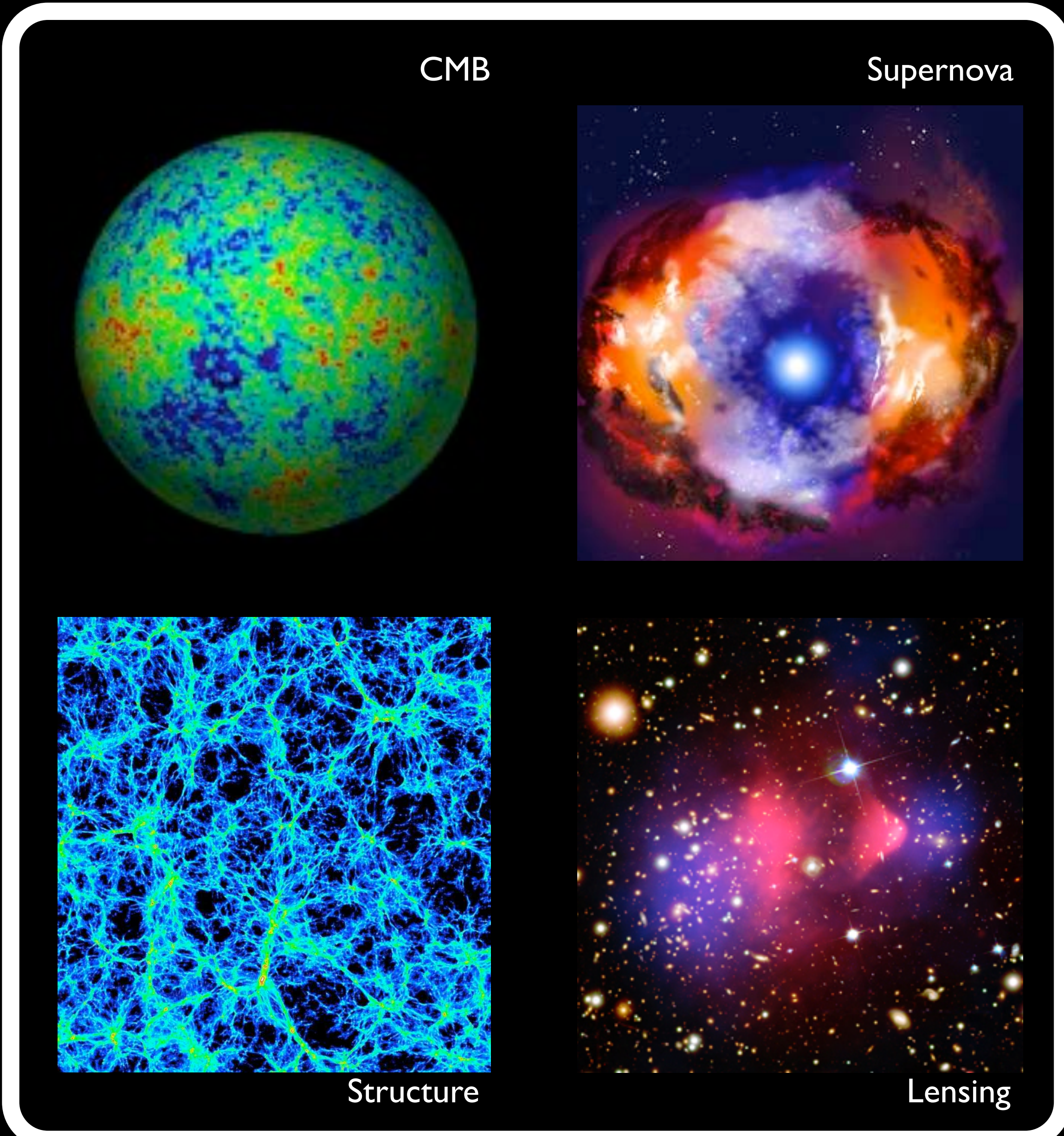
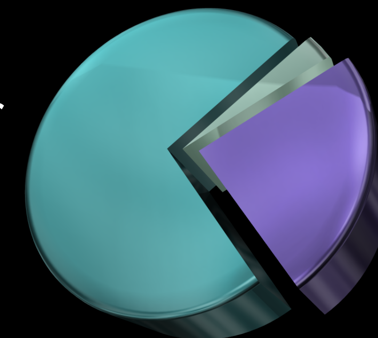
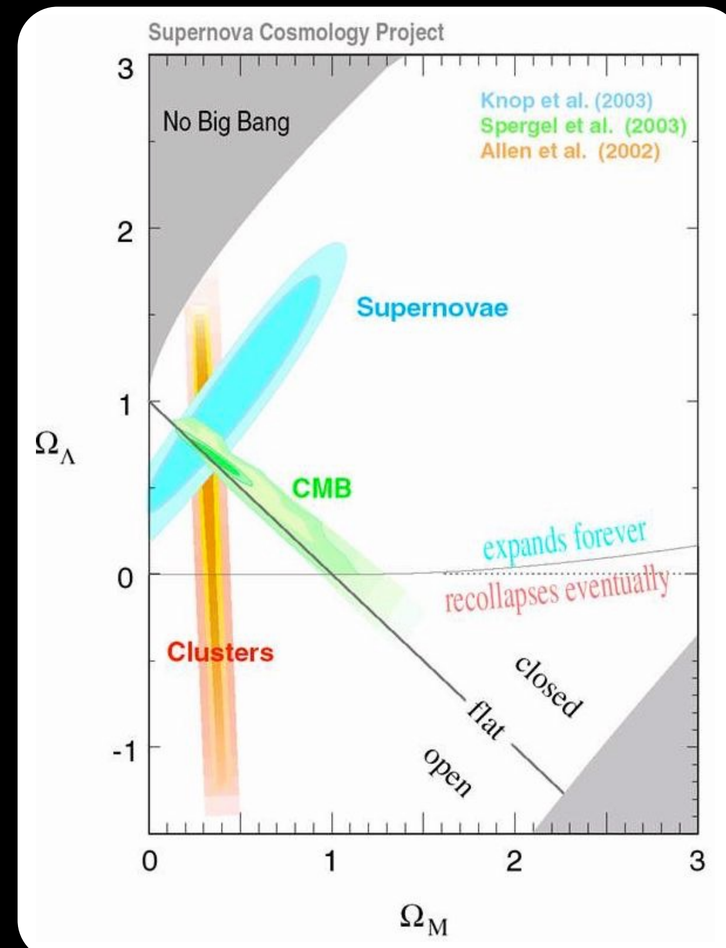
Dark Matter



- Ordinary Matter
- Dark Matter
- Dark Energy



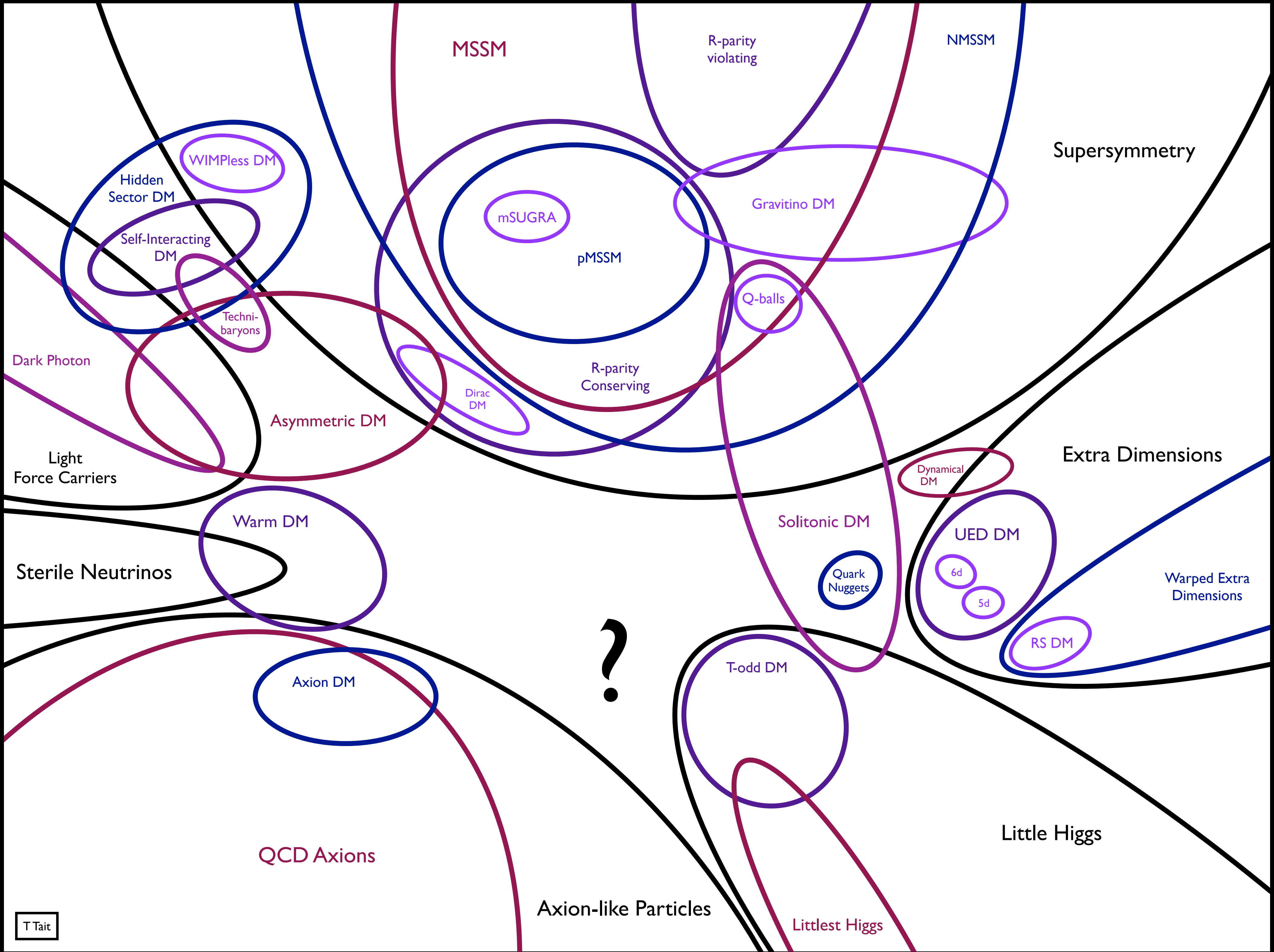


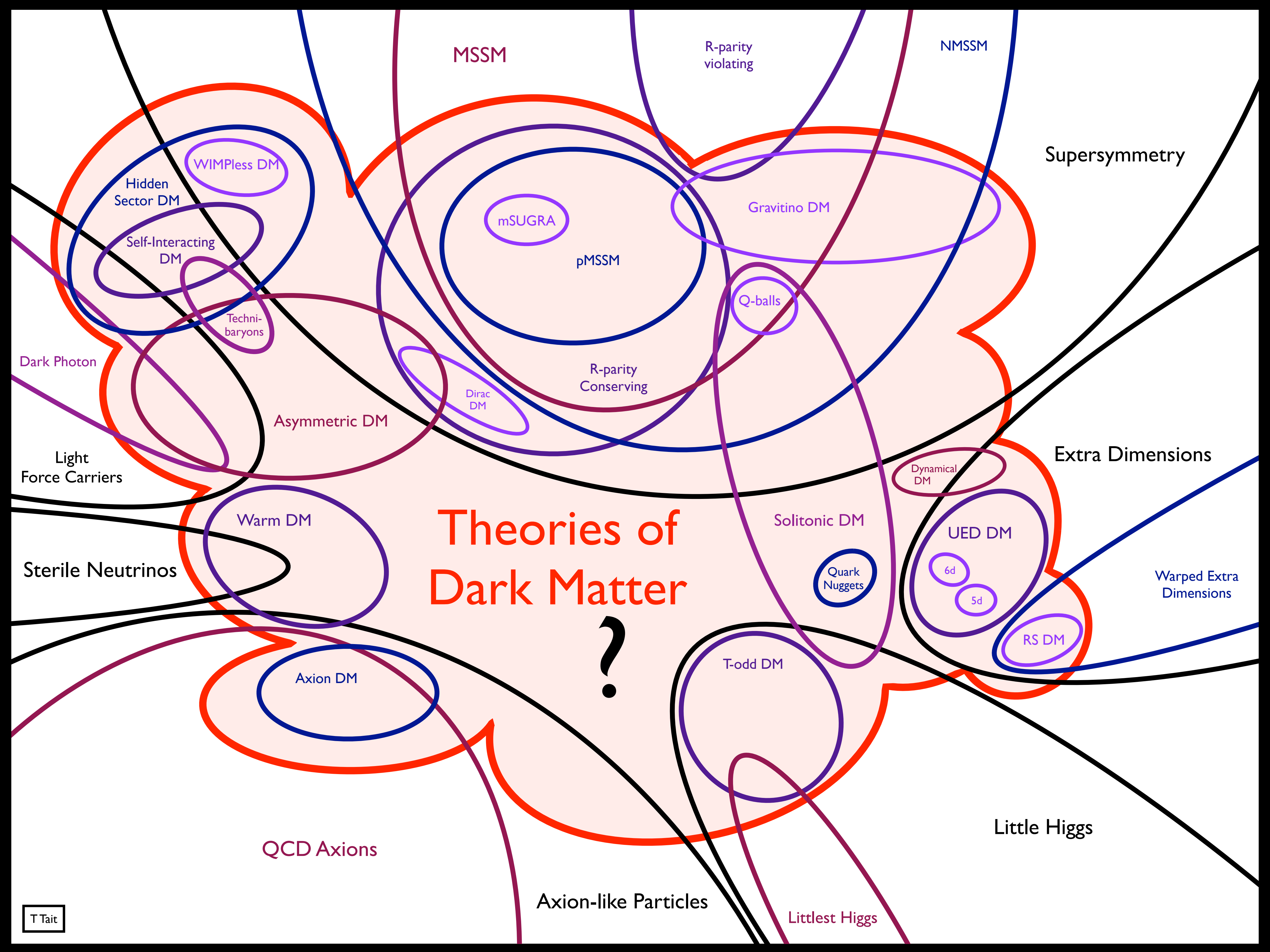
Evidence for dark matter is overwhelming…

So what is Dark Matter?


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

- As particle physicist, I need to know how dark matter fits into a particle description of Nature.
- What do we know about it?
  - Dark (neutral)
  - Massive (cold/non-relativistic)
  - 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.


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
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
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
T Tait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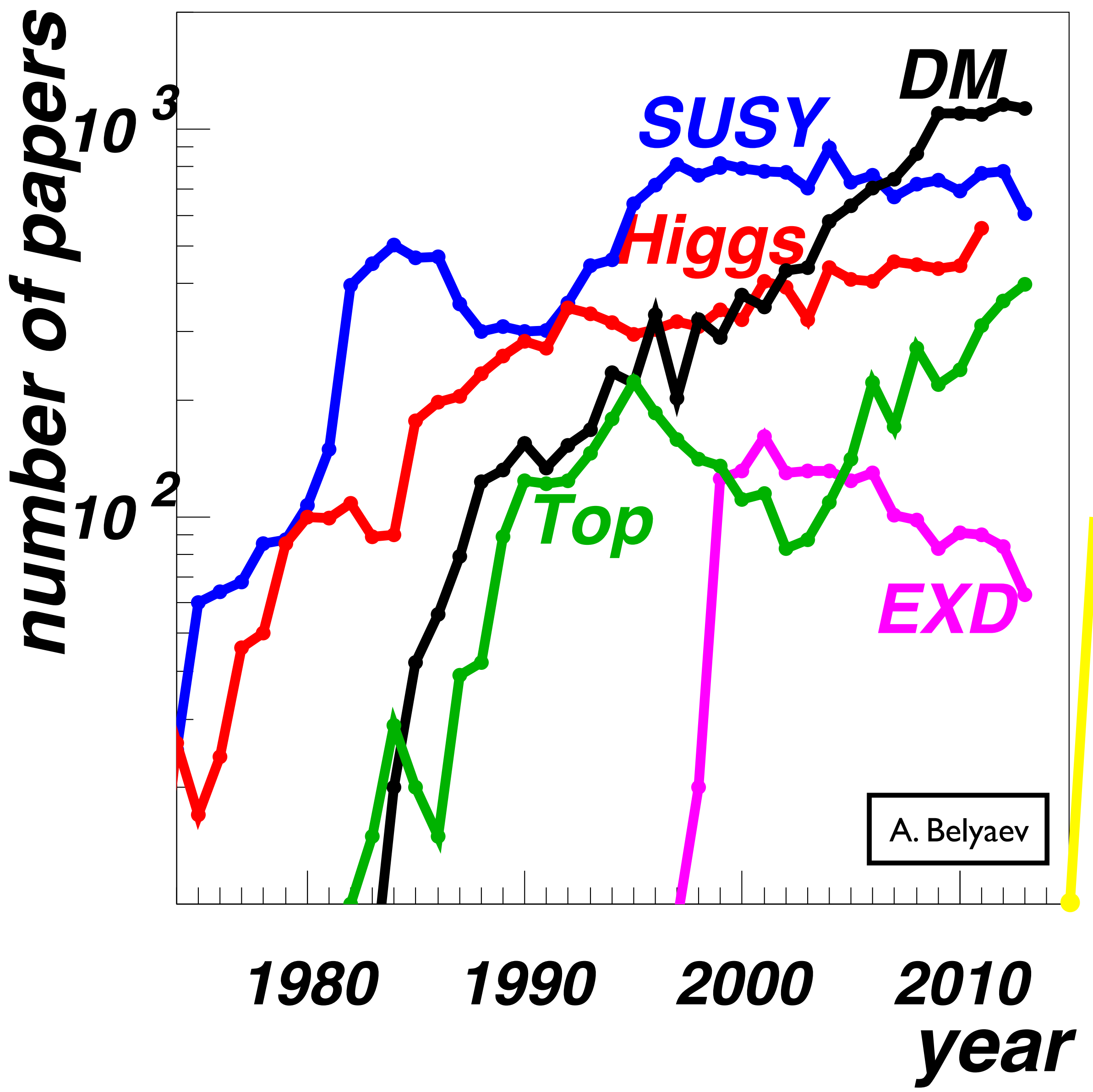
number of papers
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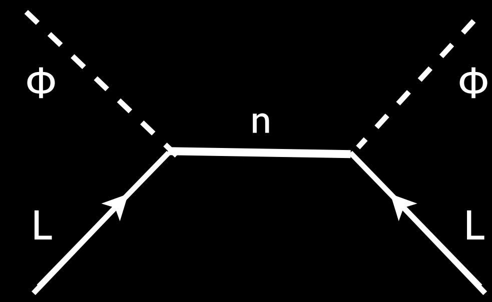
Sterile Neutrino DM

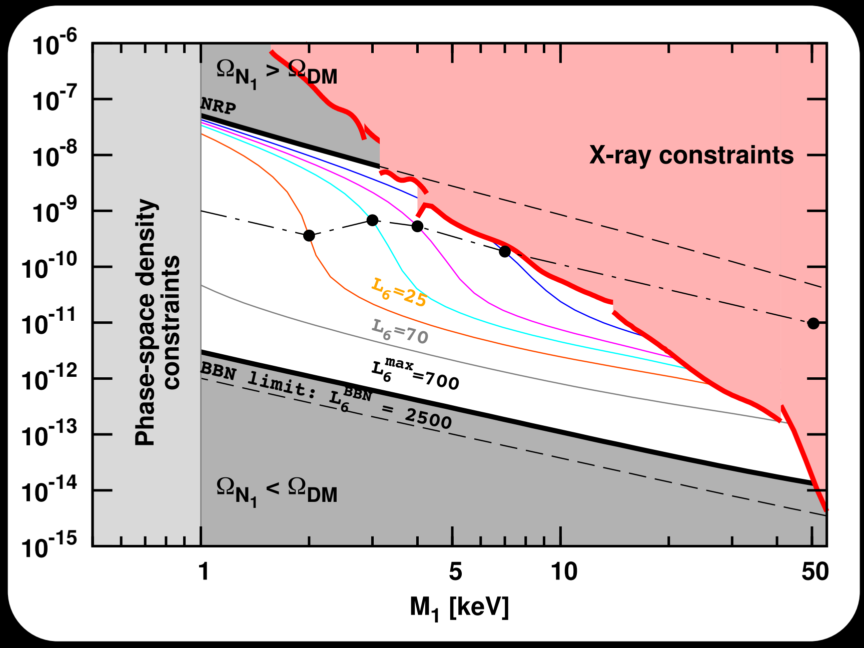


- Dark matter may be connected to one of the other incontrovertible signals of physics beyond the SM: neutrino masses.

- The simplest way to generate neutrino masses in the SM is to add some number of gauge singlet fermions to play the role of the right-handed neutrinos.

- If the additional states are light and not strongly mixed with the active neutrinos (as required by precision electroweak data), they can be stable on the scale of the age of the Universe and play the role of dark matter.

- Arriving at the right amount of dark matter typically requires delicately choosing the mass and mixing angle, or invoking some other new physics.



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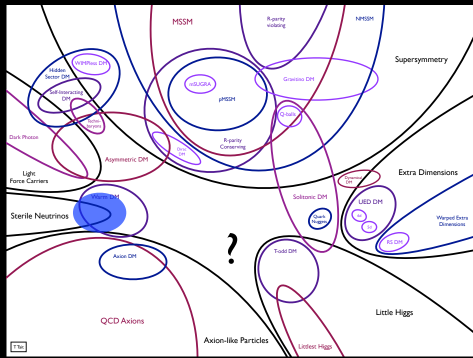
See also talks by Ina Sarcevic and Silvia Pascoli



Axion Dark Matter

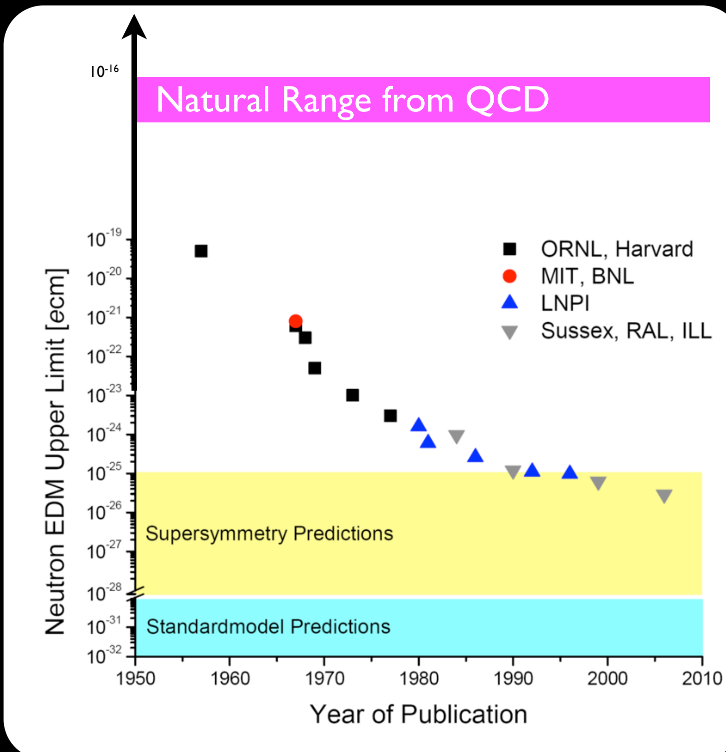
- The axion is motivated by the strong CP-problem, where the QCD θ term is cancelled by introducing a scalar field -- the QCD axion.

- The axion's mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

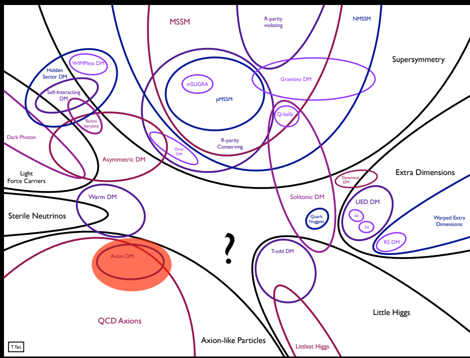
$$m_a \sim f_\pi / f_a \times m_\pi$$

- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

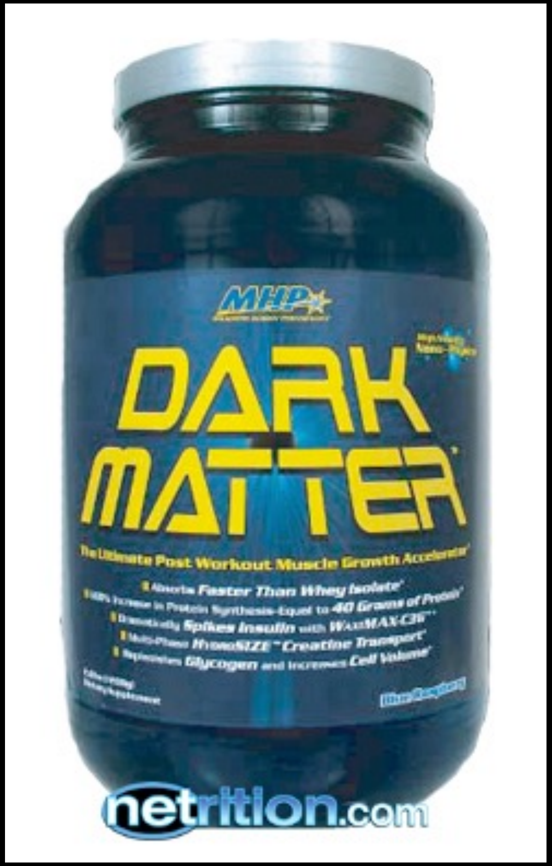
- More generally, string theories often contain axion-like particles which are long-lived and can play the role of dark matter but have less tight correlations between their masses and couplings.



See also talk by Dmitry Budker



WIMPs



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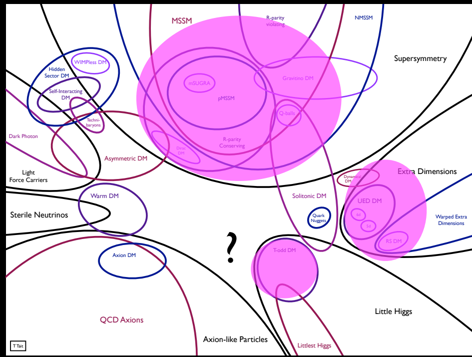
Available in Blue Raspberry, Fruit Punch, and Grape flavors....

- 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:
    - Supersymmetric extensions with R-parity;
    - Extra-dimensional theories with KK-parity;
    - Natural theories of electroweak symmetry breaking with T-parity.

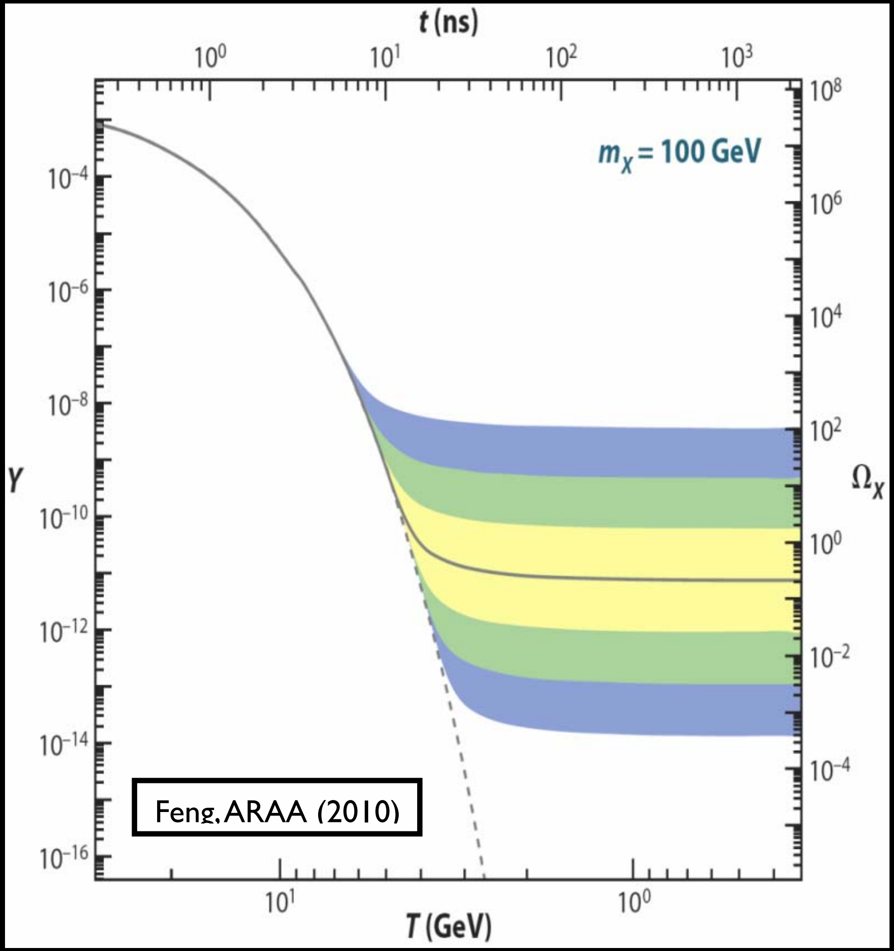


The WIMP Miracle

- If dark matter is a thermal relic, annihilation into the SM control its abundance in the Universe.
  - The observed relic abundance is suggestive of a cross section:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

  - Without a detailed model, it isn't clear how to translate it into an LHC or direct detection rate.
  - The dark matter could also be produced non-thermally, or the history of the Universe could be non-standard.



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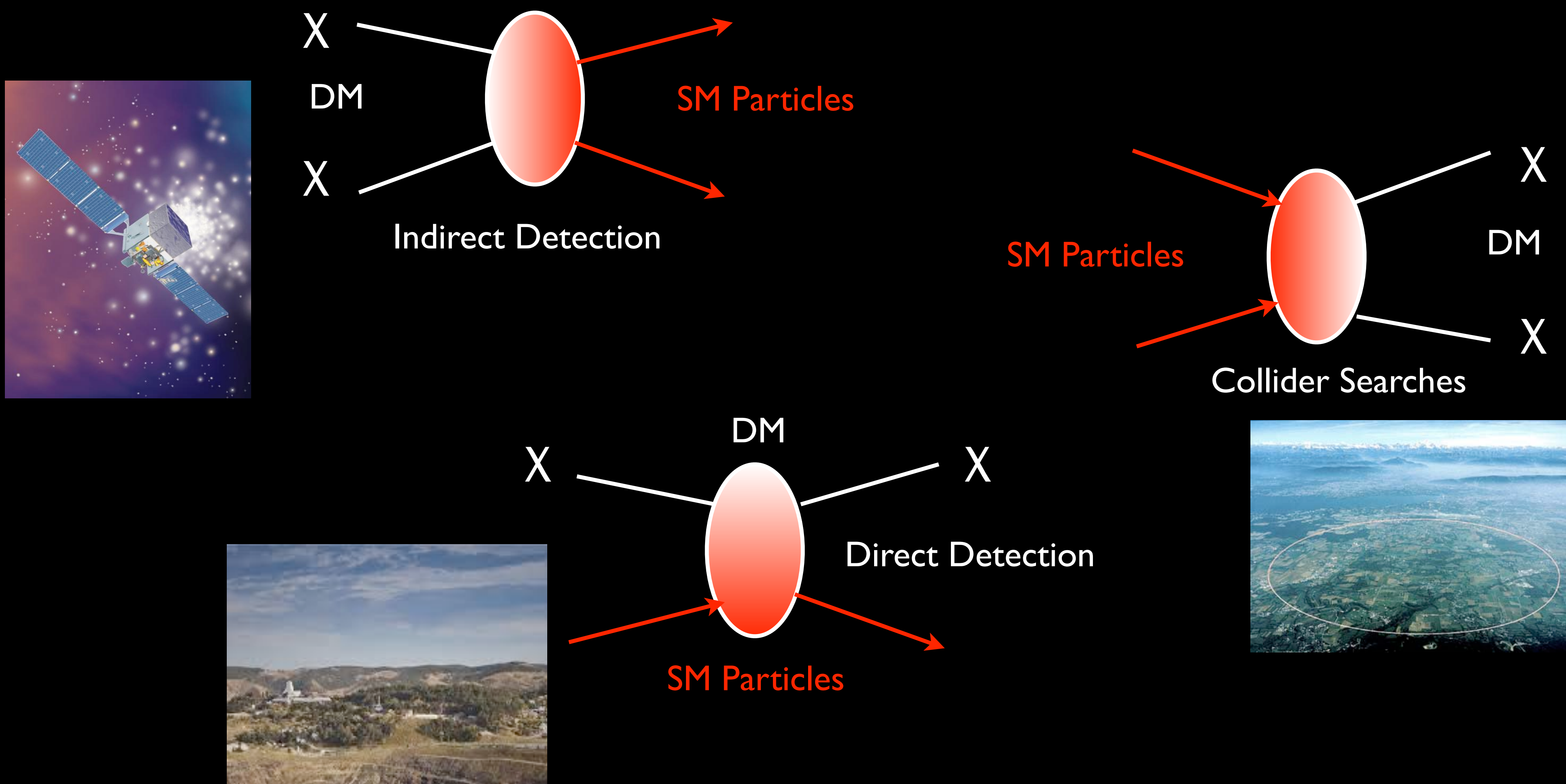
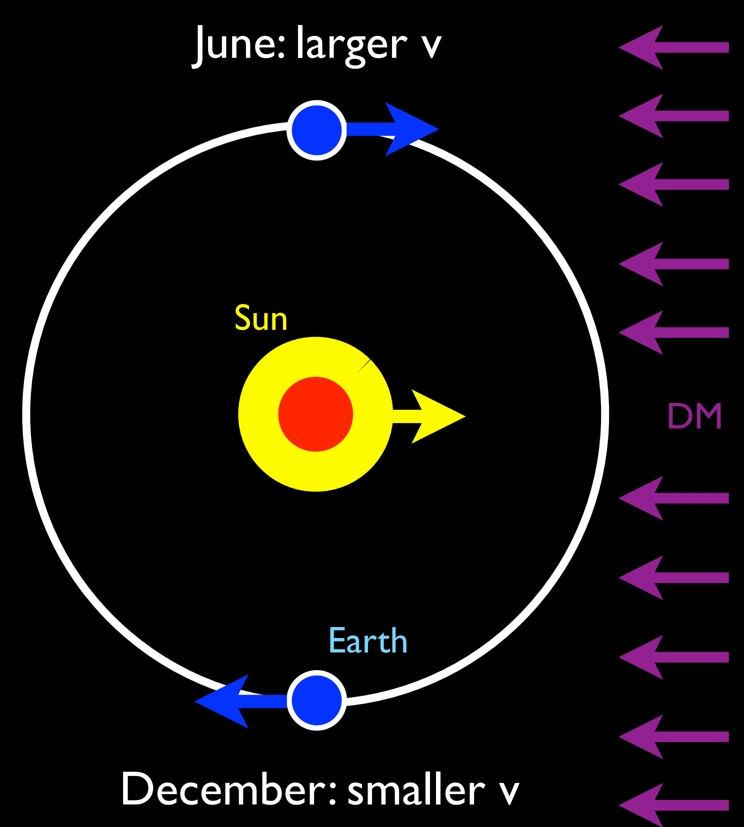
Particle Probes of DM

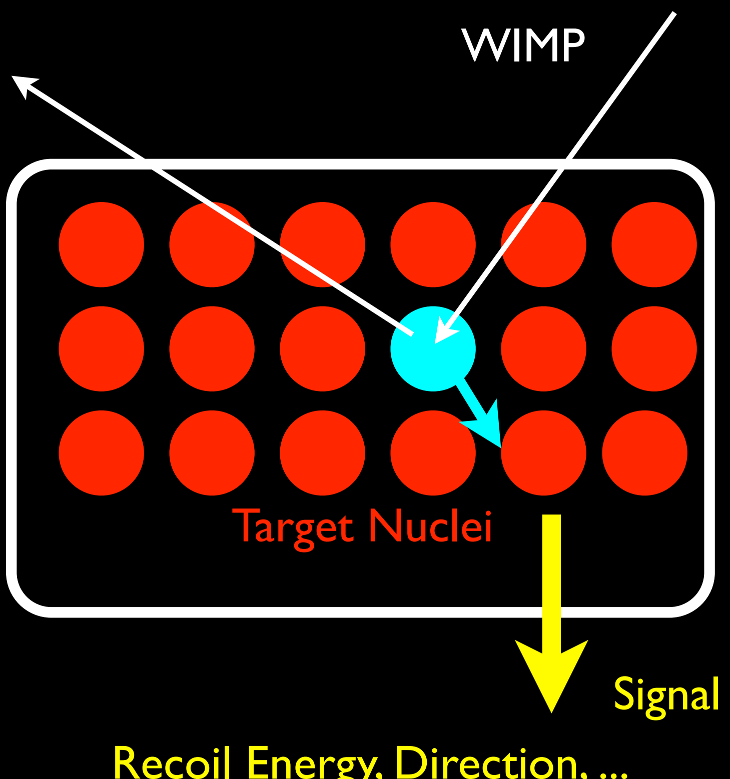


- The common feature of particle searches for dark matter is that all of them are determined by how it interacts with the Standard Model.

Direct Detection

- Direct detection searches for ambient dark matter scattering off of terrestrial targets.
- Amazing progress has shown that backgrounds can be rejected to a very high degree.
- Handles include the recoil energy spectrum, distribution of recoil direction, and modulation of the signal with time.

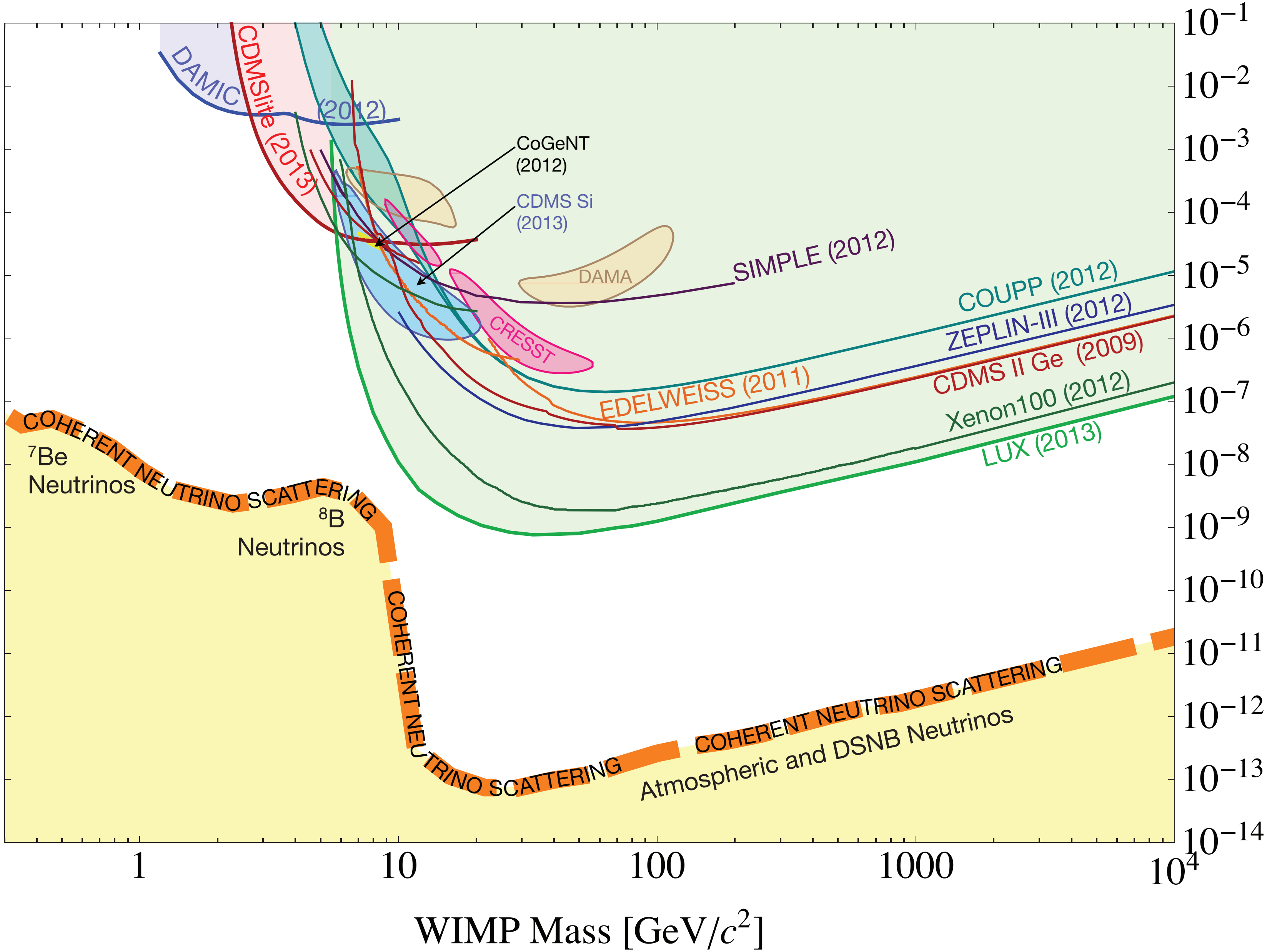




See also talks by Rafael Lang and Richard Hill

- One challenge for the future is improving sensitivity to low mass dark matter (which carries less momentum and results in smaller signals).
- Eventually experiments will reach sensitivity to background neutrinos, which are independently interesting but will complicate WIMP searches.

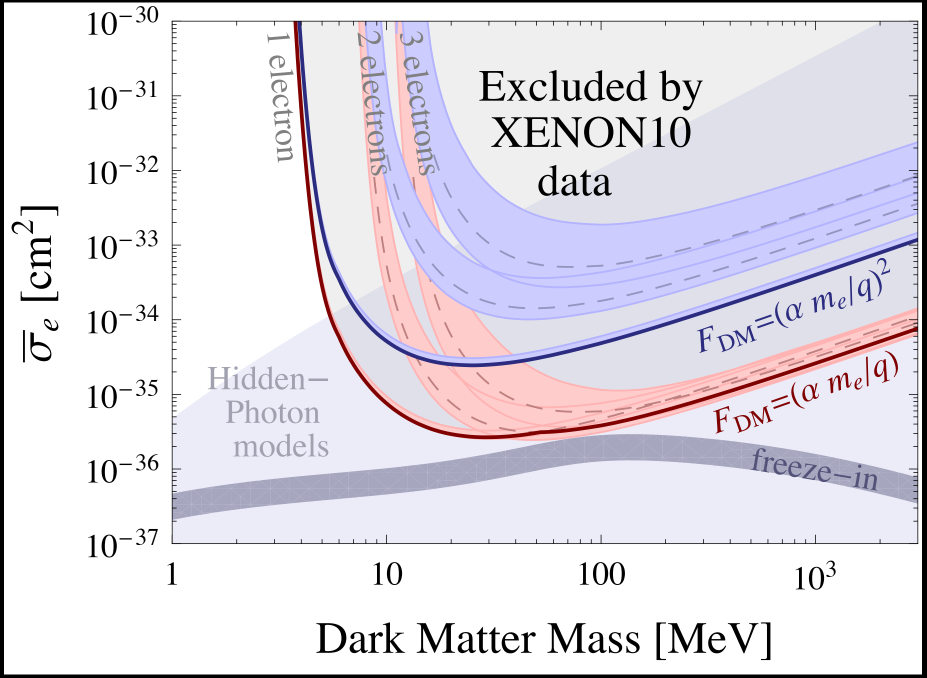
Direct Detection



Billard, Figueroa-Feliciano, Strigari 1307.5458

Beyond WIMPs

- Nuclear recoils become challenged for DM masses below a few GeV.
- There are interesting ideas to search for much lower mass dark matter based on the possibility that it scatters with electrons.
  - One can push existing technology to assay its sensitivity.
  - One can devise new systems based on exciting semi-conductors or Cooper pairs in a super-conductor.



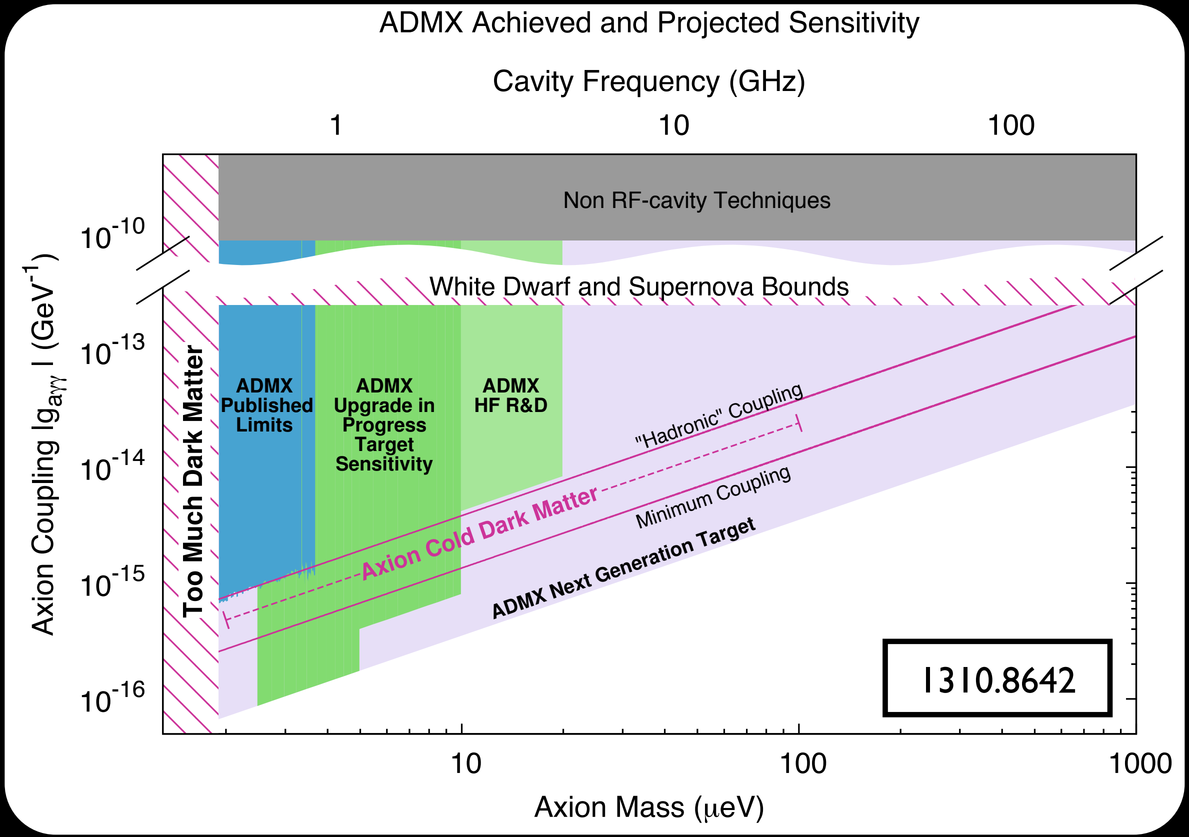
Essig, Manalaysay, Mardon, Sorenson, Volansky 1206.2644

Hochberg, Pyle, Zhao, Zurek 1504.07237 & 1512.0433
Essig, Fernandez-Serra, Madron, Soto, Volansky, Yu 1509.01598

Axion Conversion

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

1306.6088 & 1310.8545

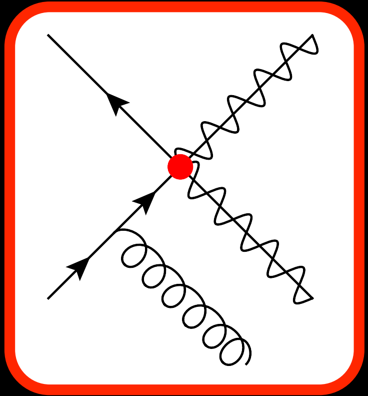


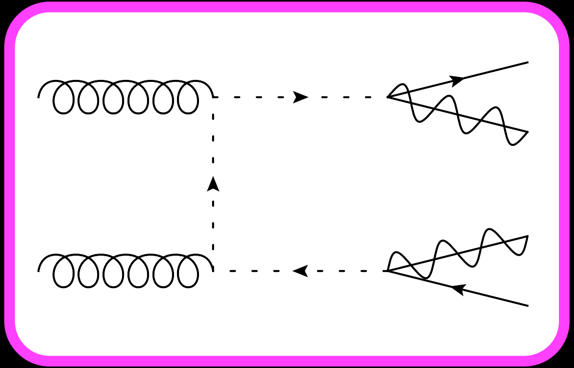
See also talk by Dmitry Budker

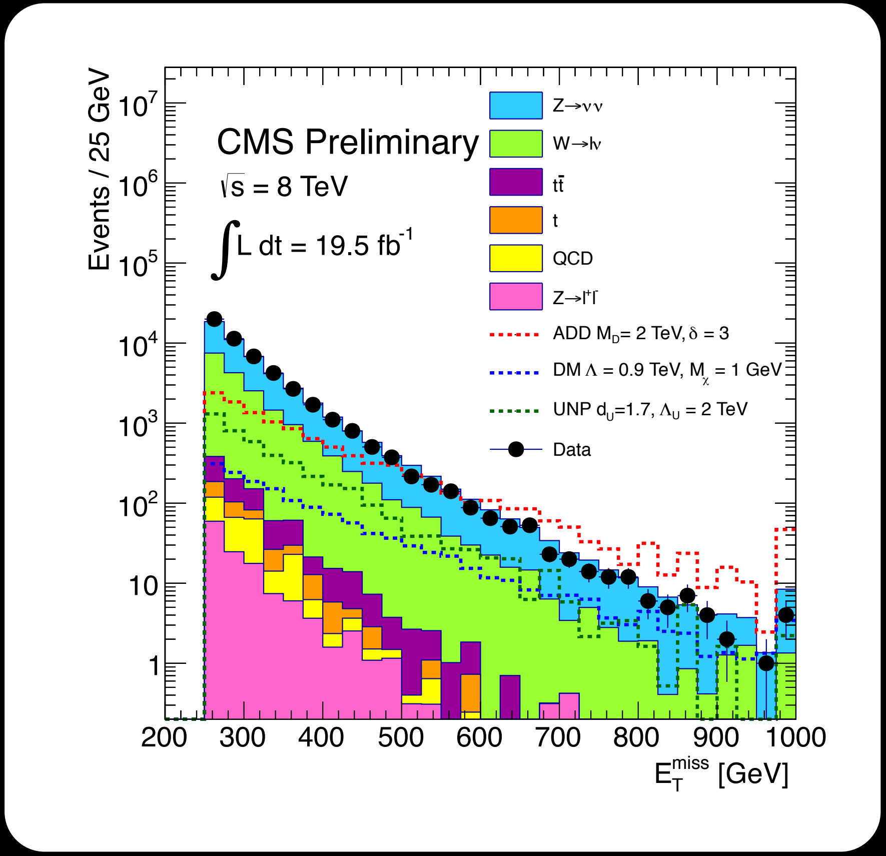
Colliders

- High energy colliders offer the opportunity to produce dark matter in the laboratory.
- Since dark matter typically does not interact with a collider detector in transit, it reveals its presence as an imbalance in momentum conservation.
- Colliders have strengths in their exquisite control over the initial state, and well understood backgrounds.
- An important challenge is the fact that any observation of missing momentum will not be uniquely connected to dark matter: particles with lifetimes of ~1 s and ~14 Gyr are essentially the same signature.

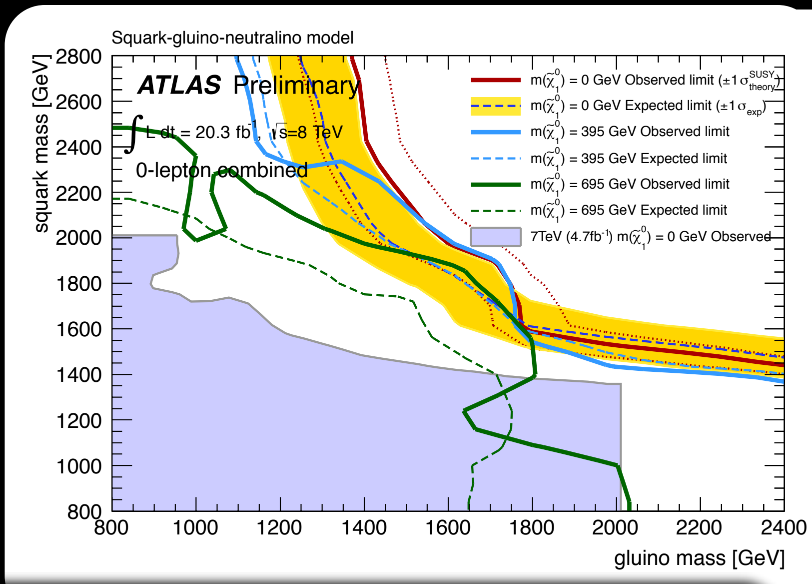
See also talks by Haichen Wang and Keti Kaadze

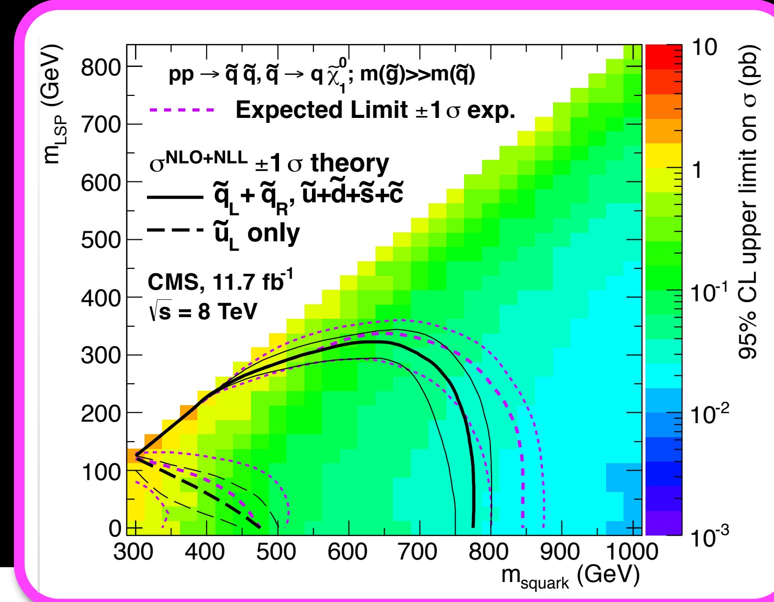


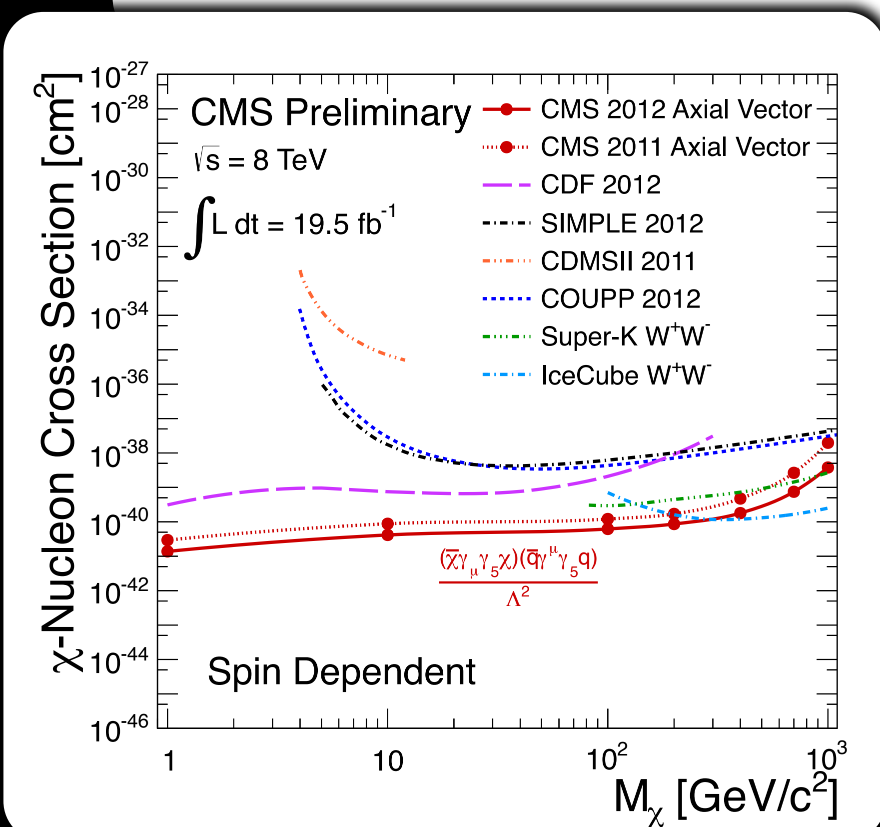


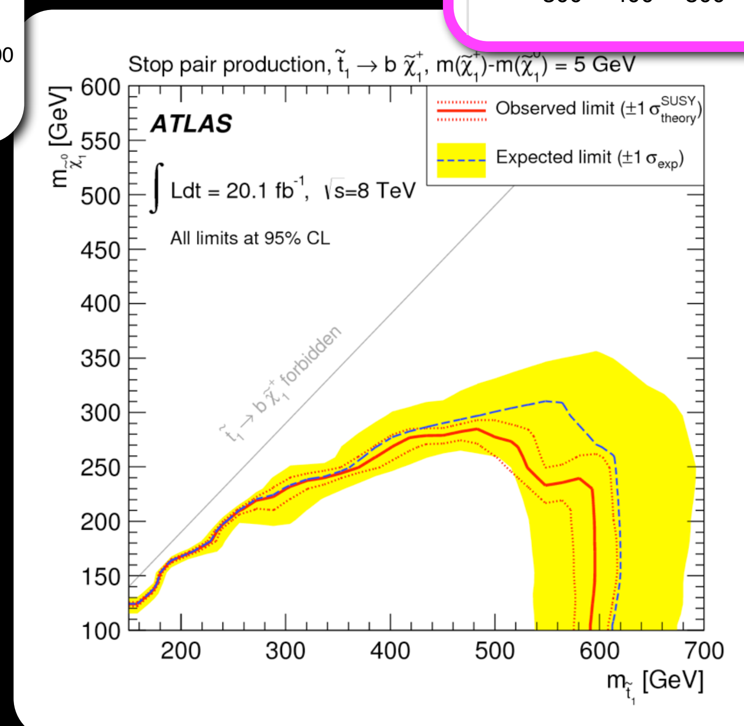


Colliders







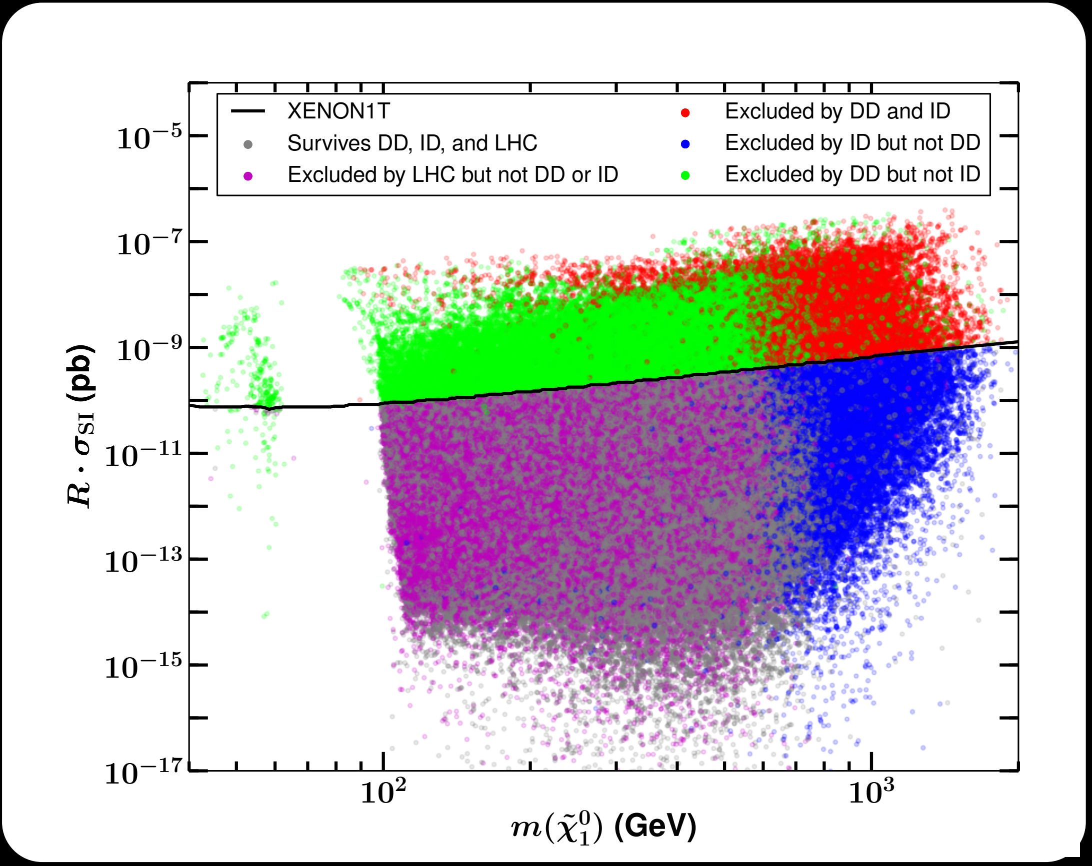


Many different collider searches are sensitive to various types of WIMP dark mater.

Supersymmetry: pMSSM

- The MSSM is still our best-studied and best-motivated vision for physics beyond the Standard Model.
- 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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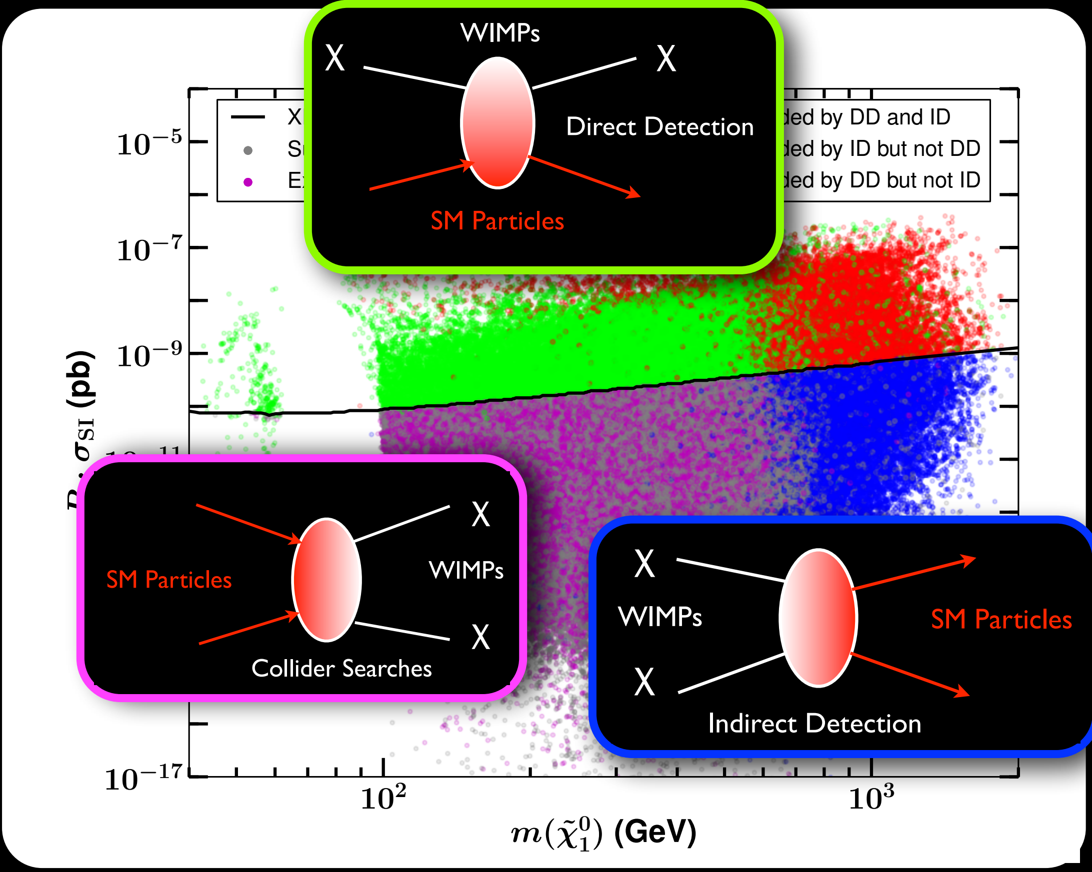
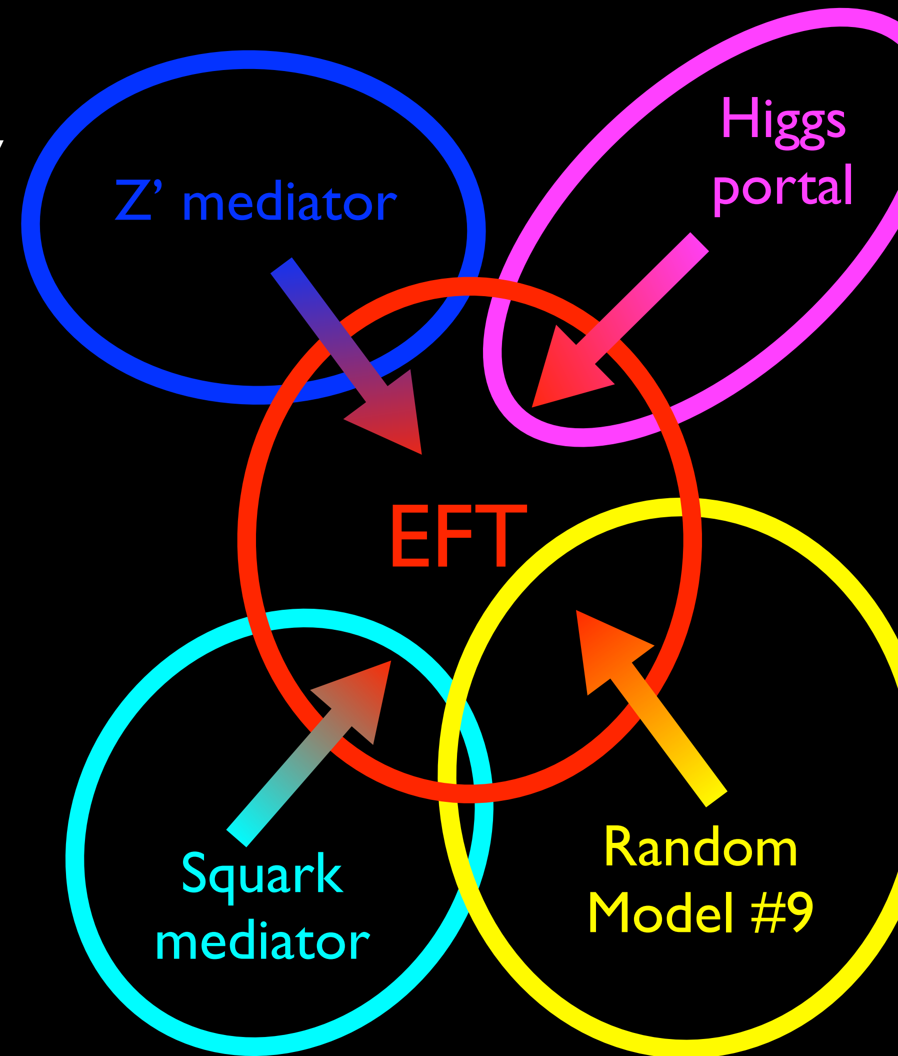
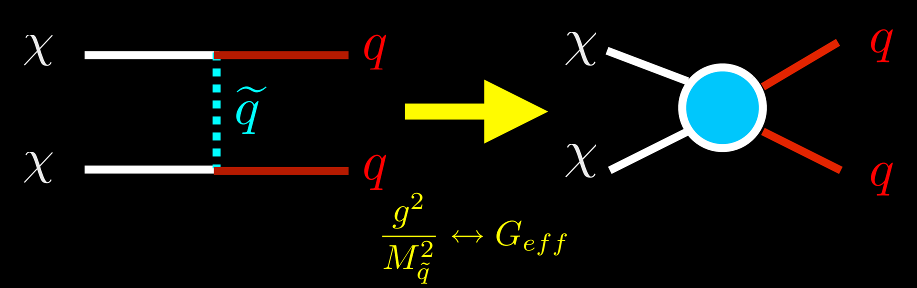


Contact Interactions

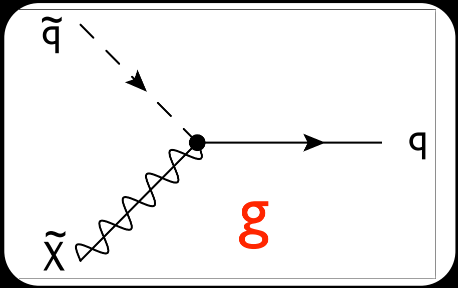
- On the "simple" end of the spectrum are theories where the dark matter is the only state accessible to our experiments.
- This is a natural place to start, since effective field theory tells us that many theories will show common low energy behavior when the mediating particles are heavy compared to 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.

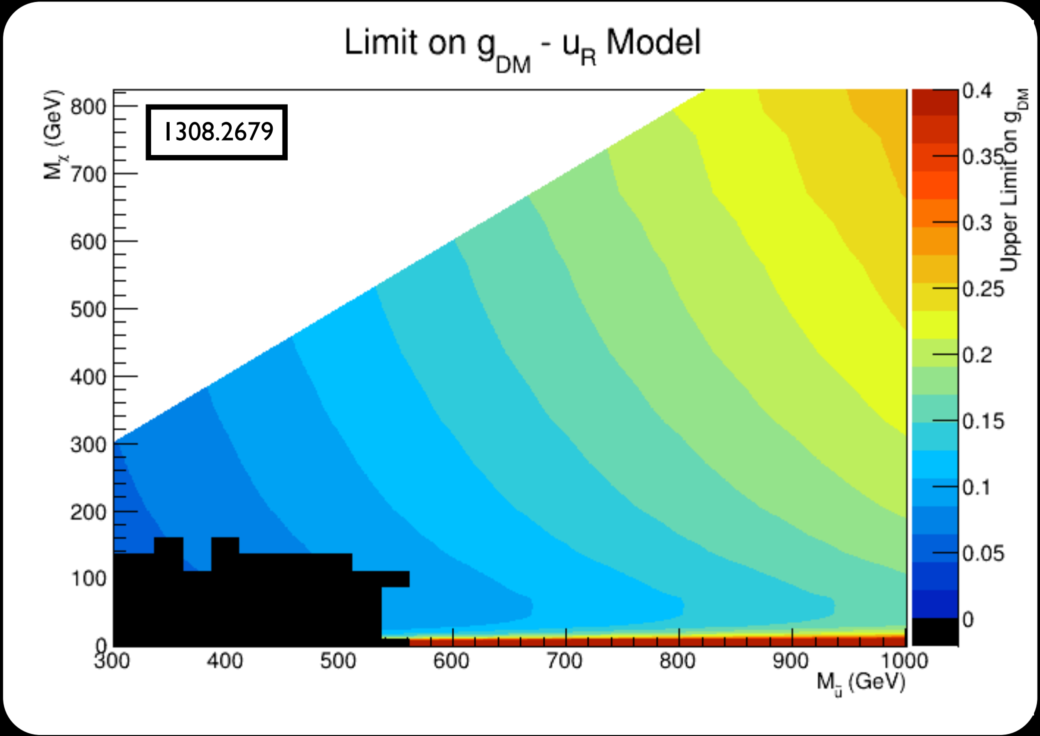




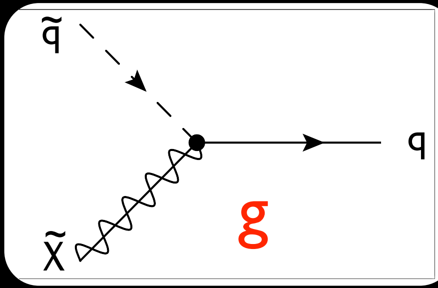
Simplified Models

- We can also analyze dark matter searches in the context of 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 just one example of a complete theory, this is only one example of a "partially complete" one.





Simplified Models



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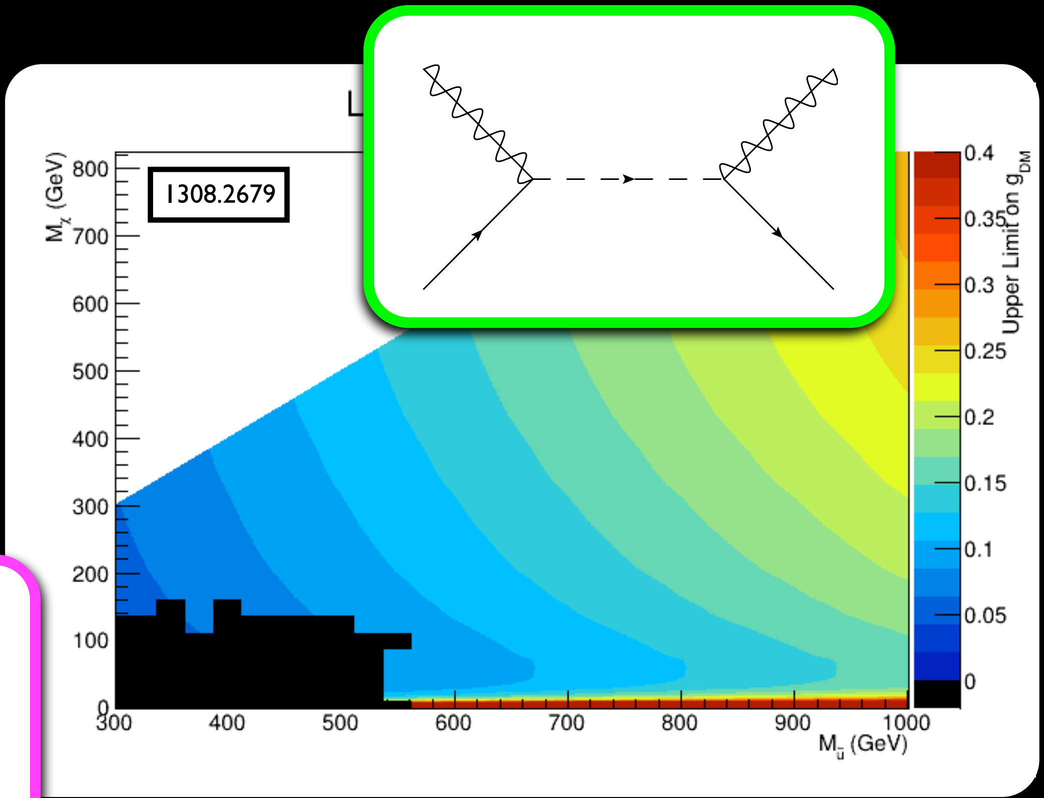
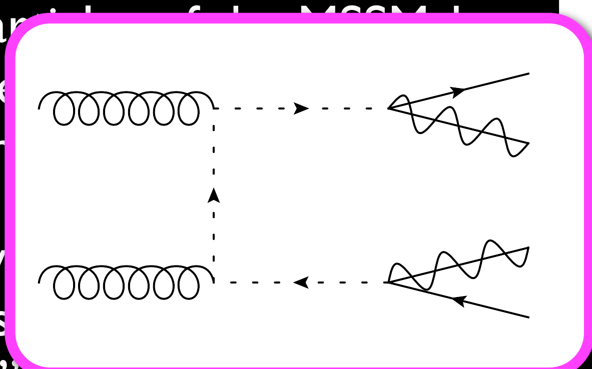
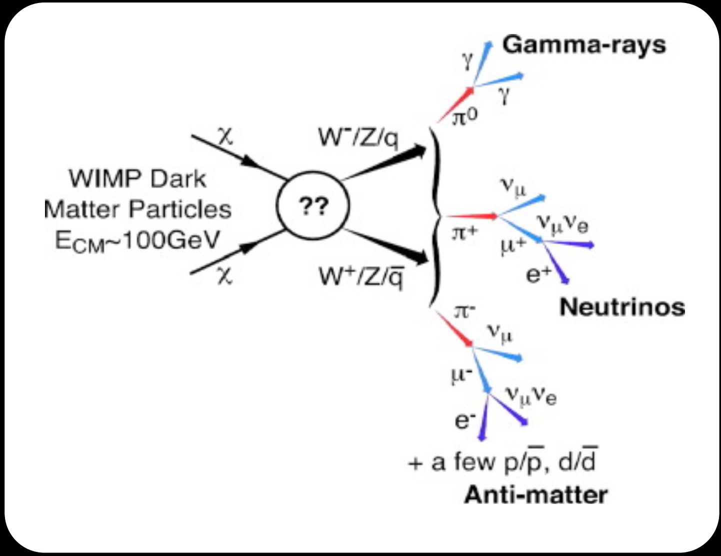




Indirect Detection

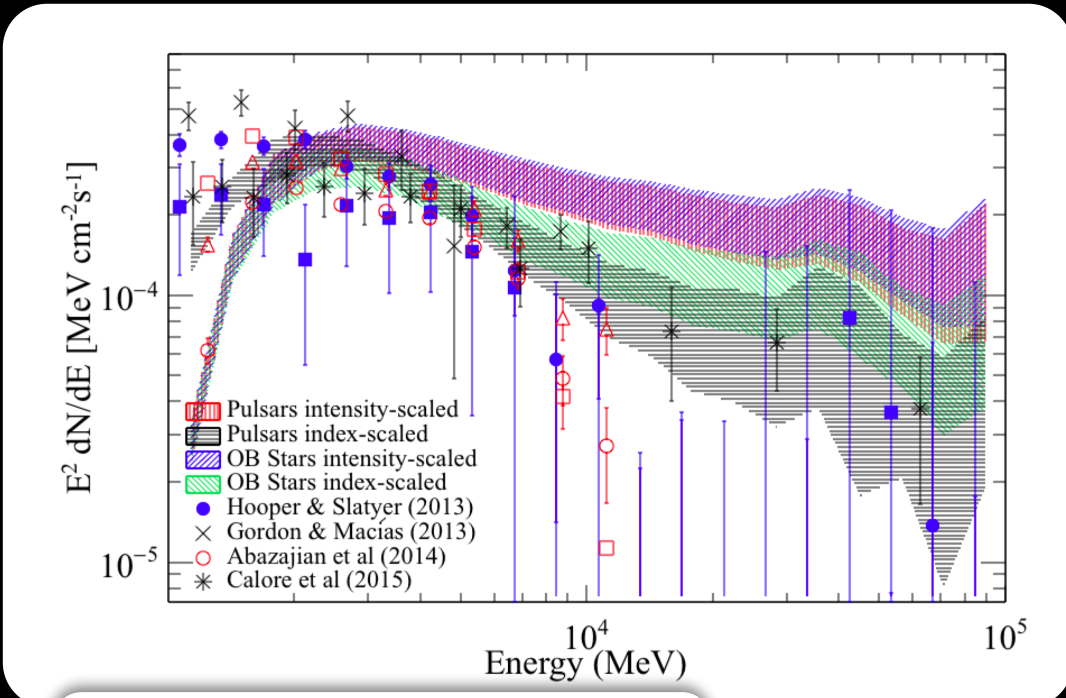
- Indirect detection looks for distinctive products of WIMP annihilation.
- High energy gamma rays, neutrinos, and anti-matter are all interesting messengers that could reveal the presence of dark matter annihilations.
  - Gamma rays: point back to their source and have relatively little propagation uncertainty in the galaxy.
  - Neutrinos: arrive essentially unchanged from galactic sources.
  - Anti-matter: very distinctive signal, but lose direction and energy en route.
- Challenges include large and often poorly understood backgrounds and uncertainties in the dark matter distribution.

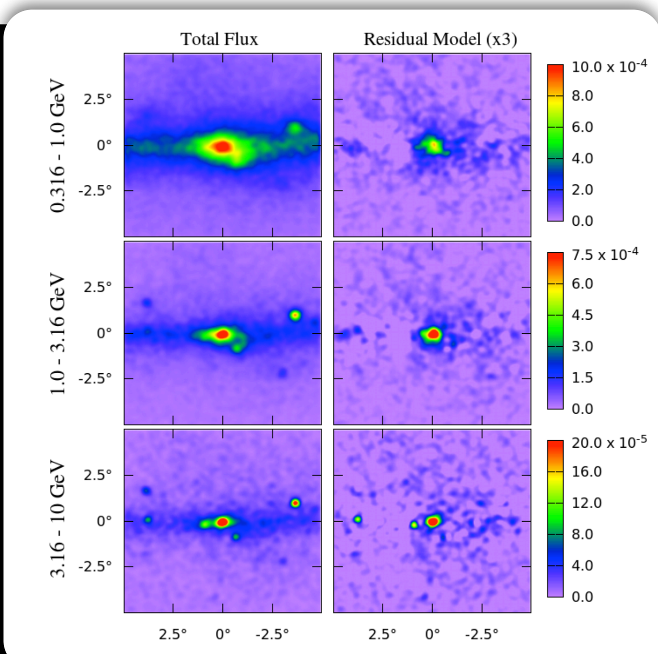


See also talks by Simona Murgia, Savvas Koushiappas, Brian Humensky, and Jordan Goodman

Gamma Rays

The Galactic Center "GeV Excess"





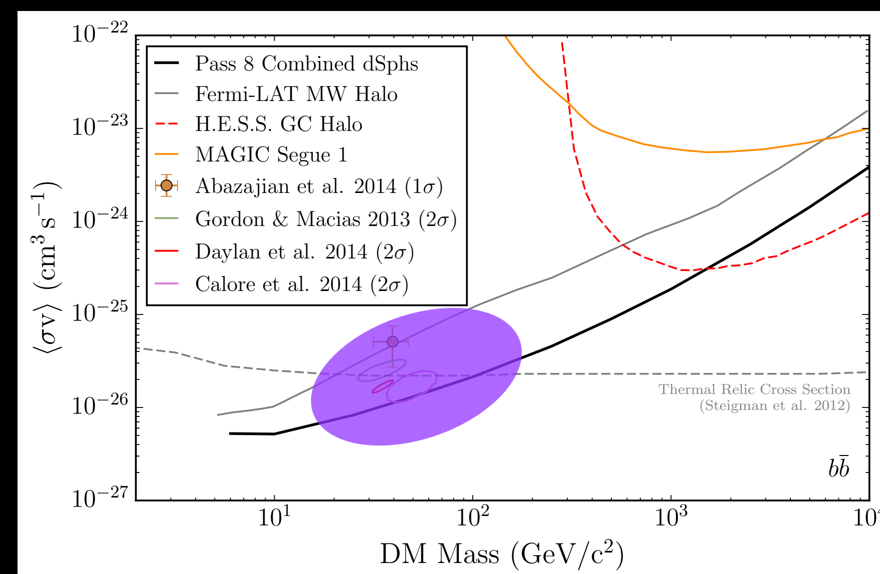
Fermi LAT 1511.02938

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer 1402.6703

See also talk by Simona Murgia,

Search for Gamma-rays from Dark Matter annihilating in Dwarf Spheroidal Galaxies

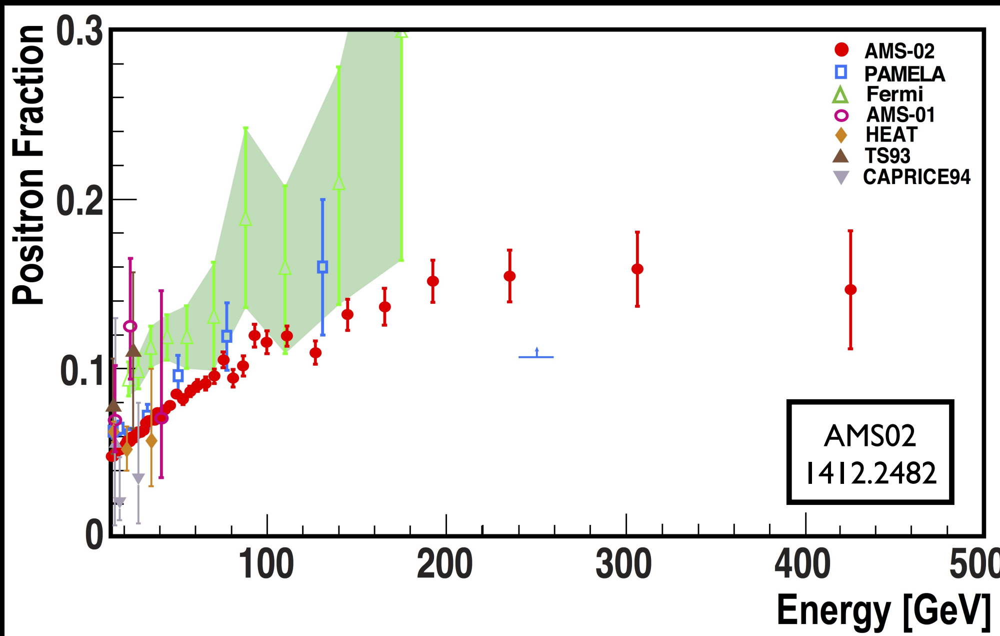
Fermi LAT 1503.02641



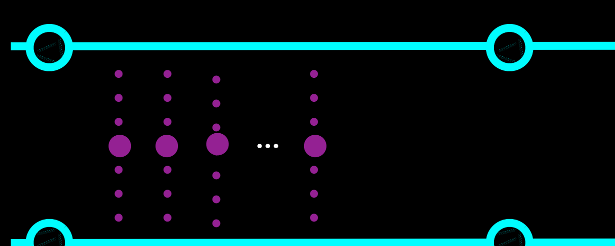
Excludes a thermal relic entirely annihilating 100% into bb with a mass less than about 100 GeV.

Indirect Detection

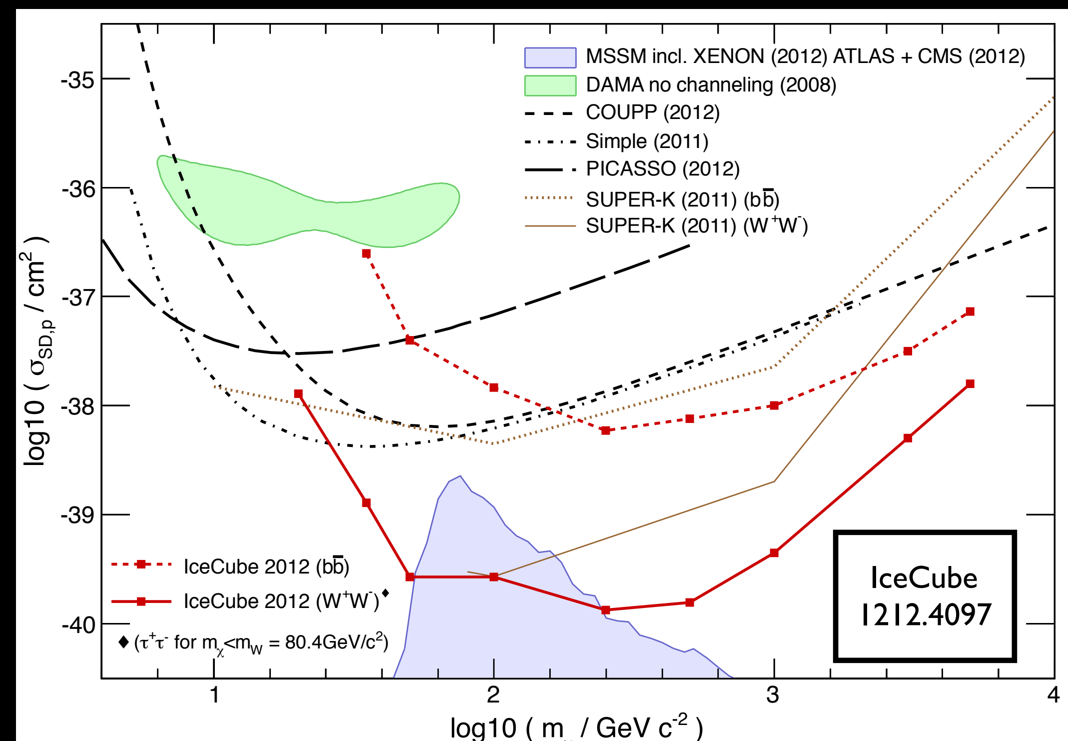
Positron Fraction at High Energies



Very interesting and still not very well understood. It is somewhat shockingly large as a signal of dark matter, motivating physics which boosts the rate, such as e.g. a Sommerfeld-like enhancement.



Search for Neutrinos from Dark Matter annihilating in the Sun



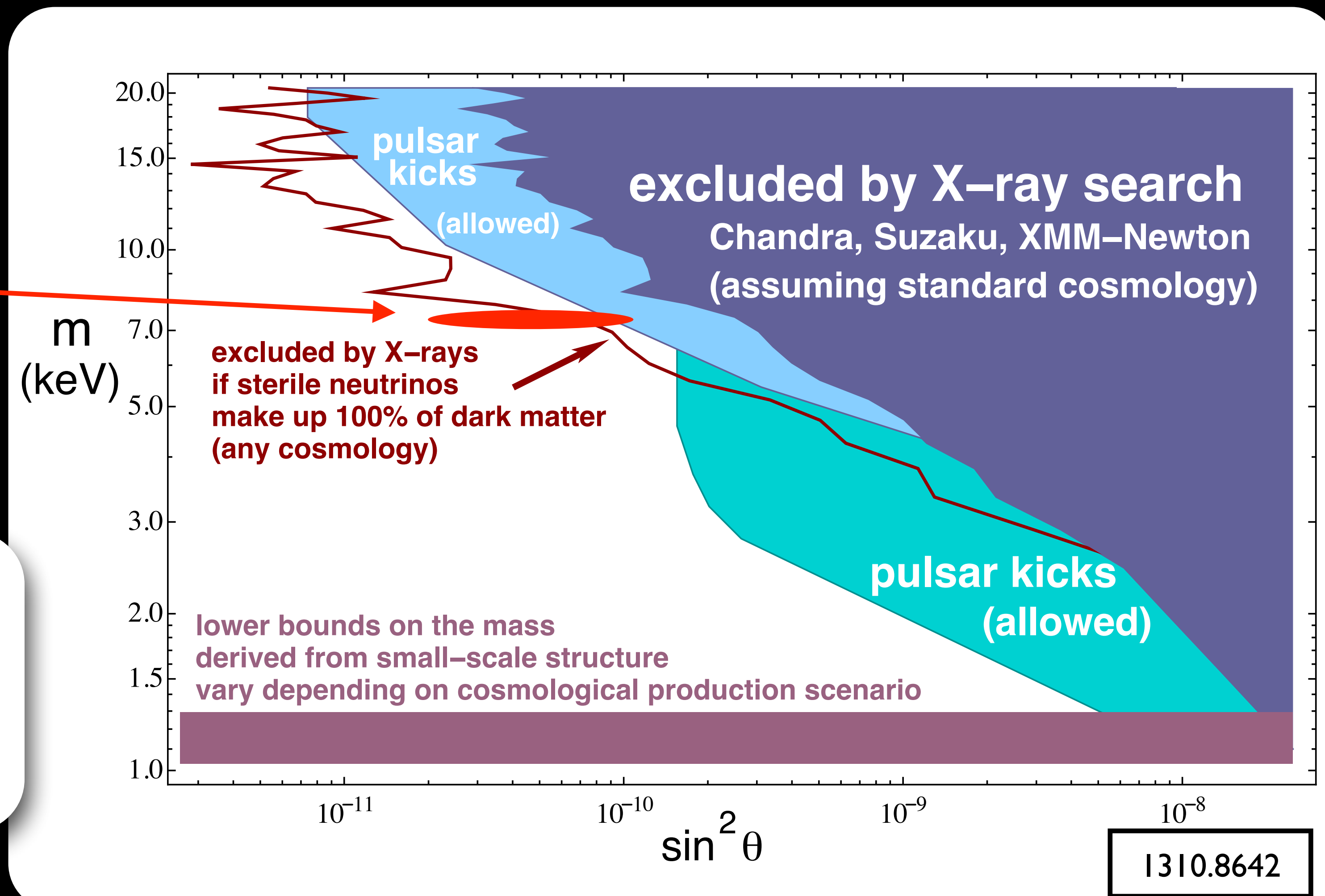
Sensitive to scattering rate with protons because accumulation in the Sun is the limiting factor.

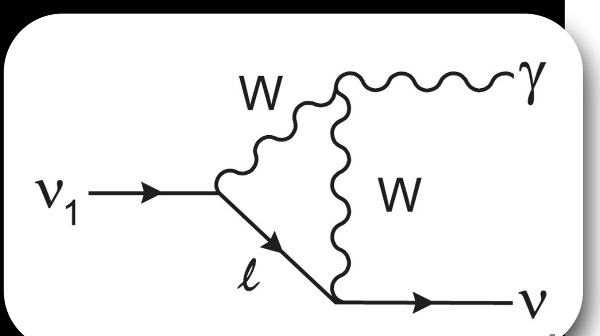
Sterile Neutrino Decay

- Though rare, sterile neutrinos can decay into ordinary neutrinos and a photon, resulting in (mono-energetic) keV energy photons.
- Constraints from the lack of observation of such a signal put limits in the plane of the mass versus the mixing angle.

Possible X-ray Signal
[Bulbul et al 2014]

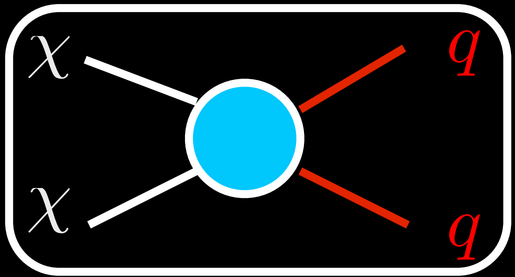
Extracted from
[Abazajian 2014]

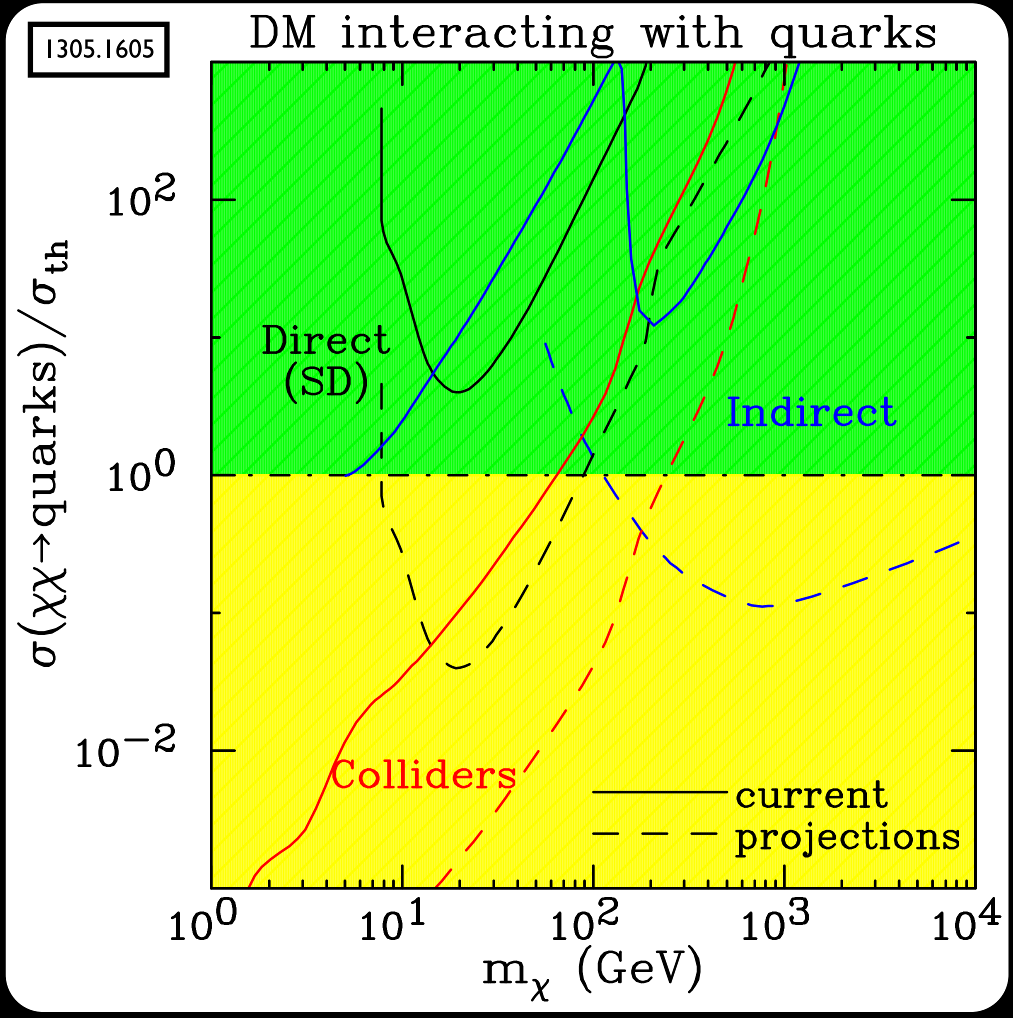




Complementarity

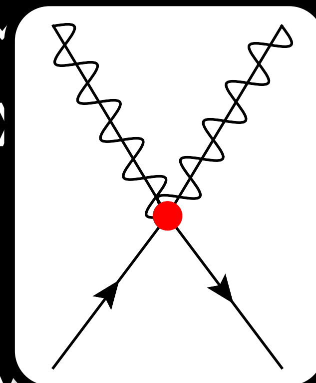
- These strategies for detecting WIMPs work together in a complementary way.
- As an example when the particles mediating the interactions are heavy, we compare the results of different types of searches to see how they cover the parameter space.
- Here we use the language of indirect detection: <σv> vs. the DM mass.
- Trends emerge: colliders are powerful at very low masses, whereas direct and indirect searches work better at larger masses, and for interactions which are non-vanishing in the non-relativistic limit.

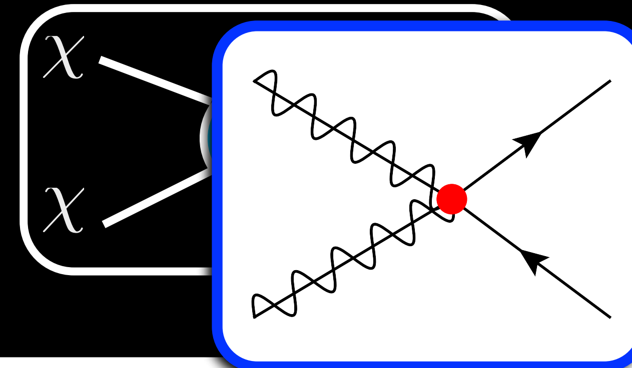


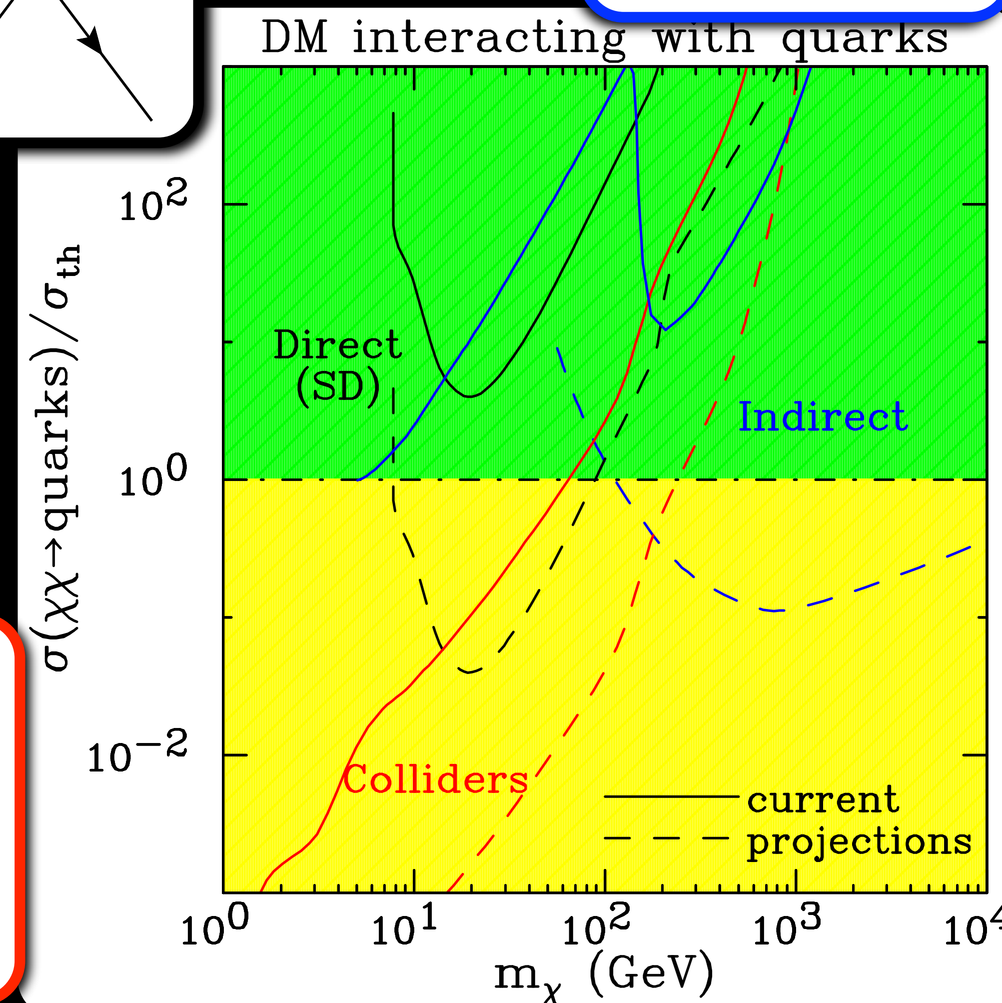


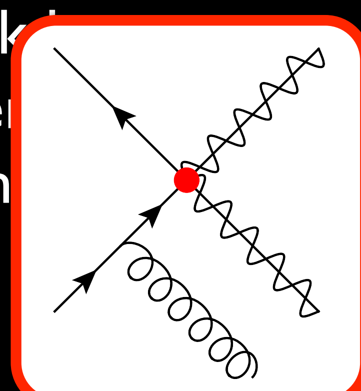
Complementarity

- These strategies for detecting WIM work together in a complementary way.
- For example, when the particles mediating the interactions are heavy, we can compare the results of different types of searches to see how they cover the parameter space.
- Trends emerge: colliders are powerful at very low masses, whereas direct and indirect searches work larger masses, and for inter which are non-vanishing in relativistic limit.

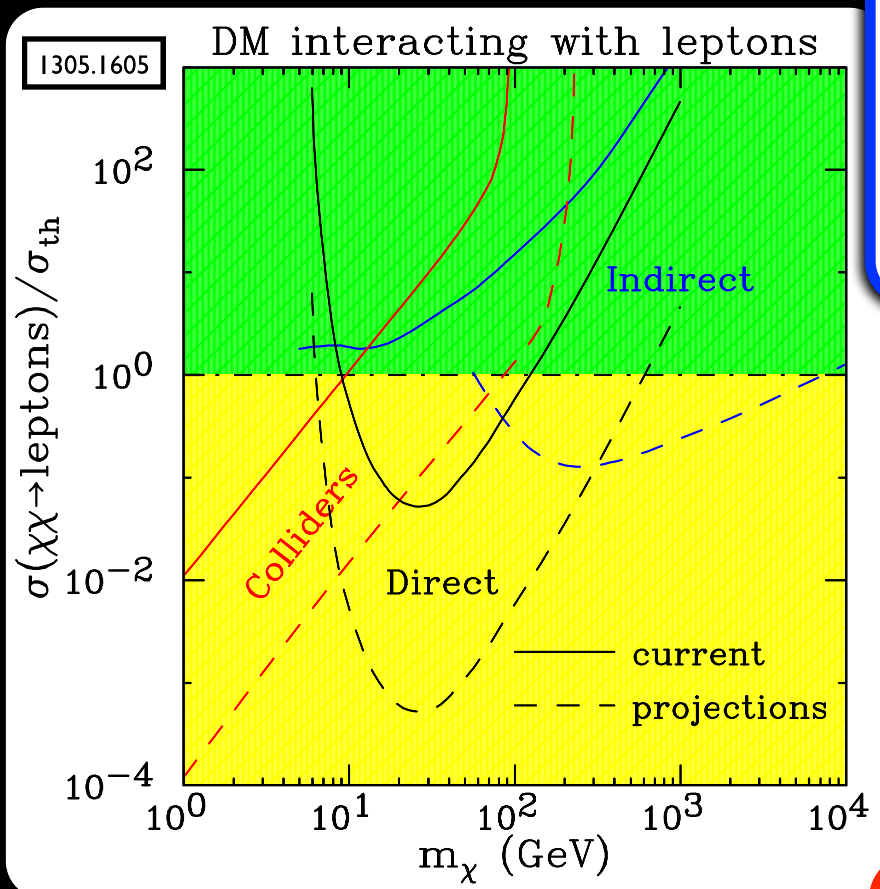


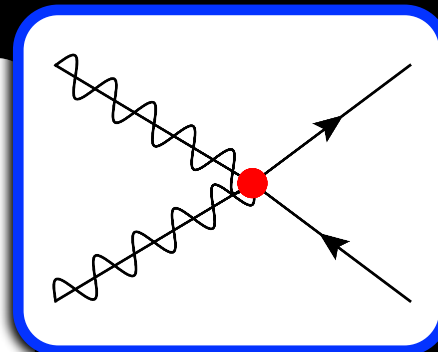


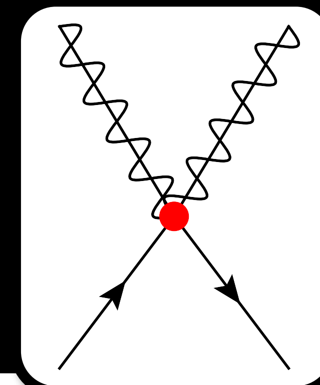


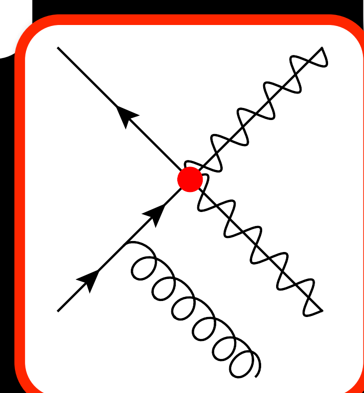


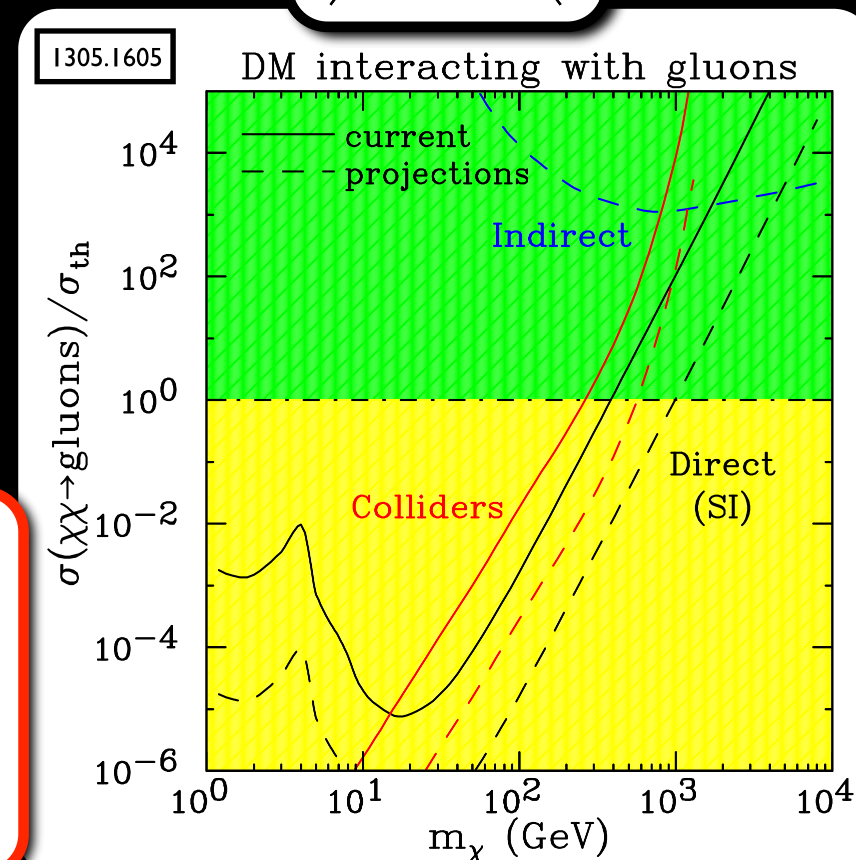
Lepton/Gluon Interactions





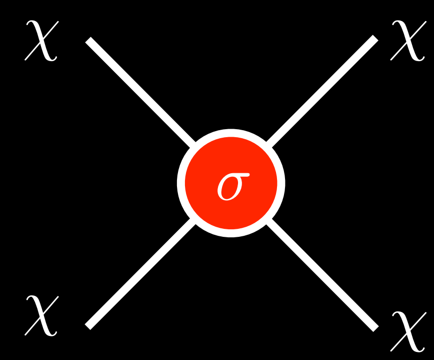






Astronomical Probes?

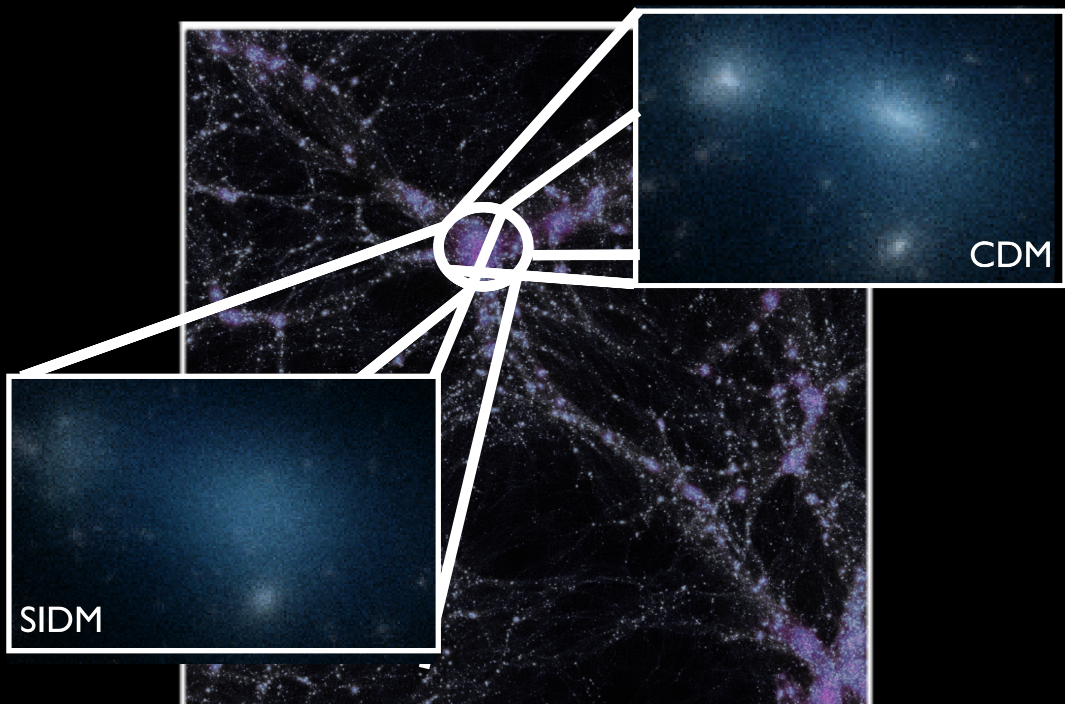
- The distribution of dark matter could reveal particle properties of dark matter.
- For example, dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- There is some (controversial) evidence that this may help simulation better describe observation.
- Nonetheless, astronomy provides a unique perspective on properties that particle searches cannot probe.



Markevitch et al; Clowe et al

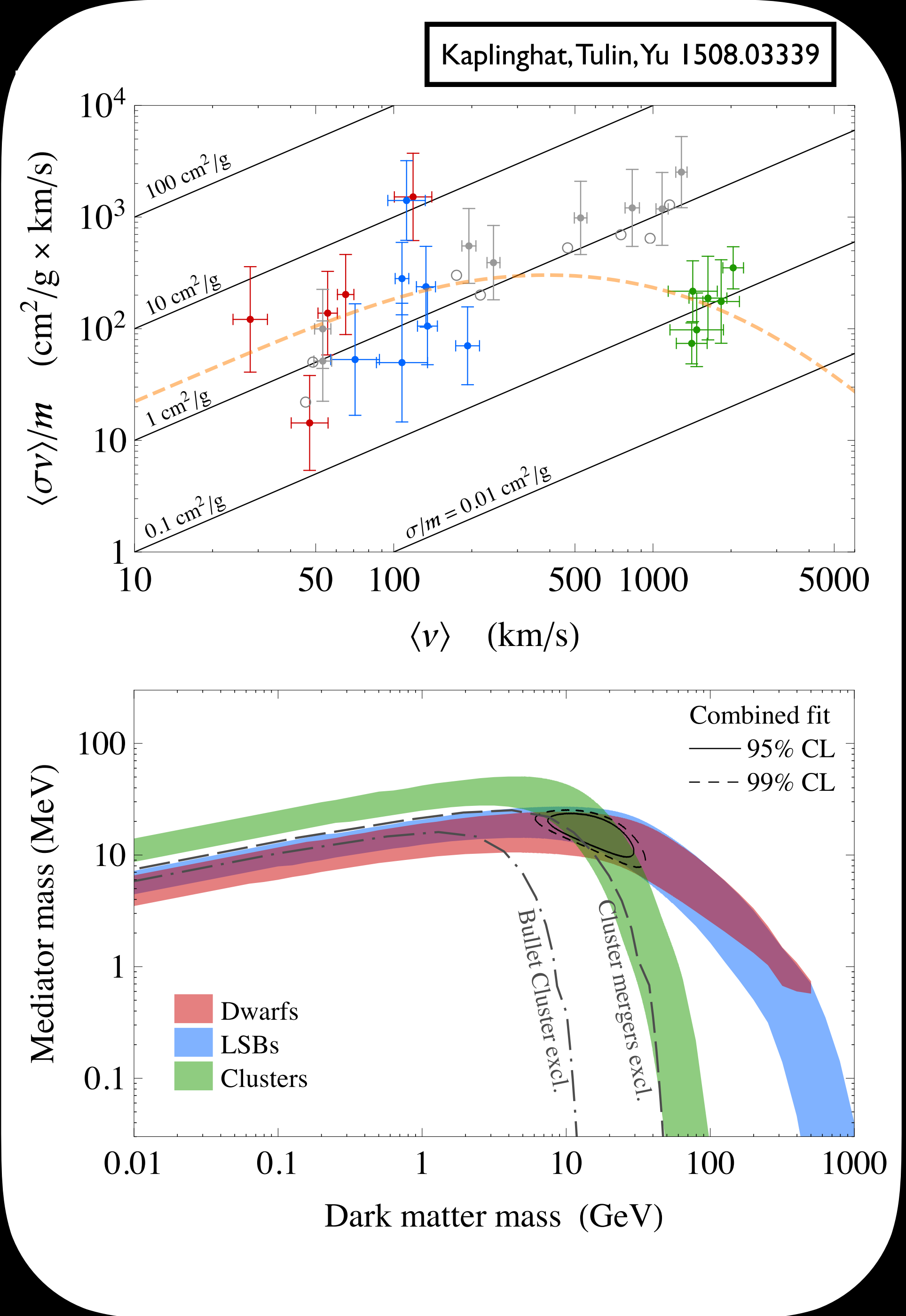
$$\sigma / m < 0.7 \text{ cm}^2 / \text{g}$$

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



SIDM Parameter Space

- In a typical microscopic description, the cross section depends on the relative velocity of the collision.
- Dwarf galaxies, LSBs and clusters are characterized by different <v>'s, allowing us to construct the velocity dependence.
- Clusters (with the largest <v> prefer a smaller cross section than dwarf galaxies and LSBs.
- For simple models, the region favored by all three has ~weak scale dark matter masses and mediator masses ~10 MeV.

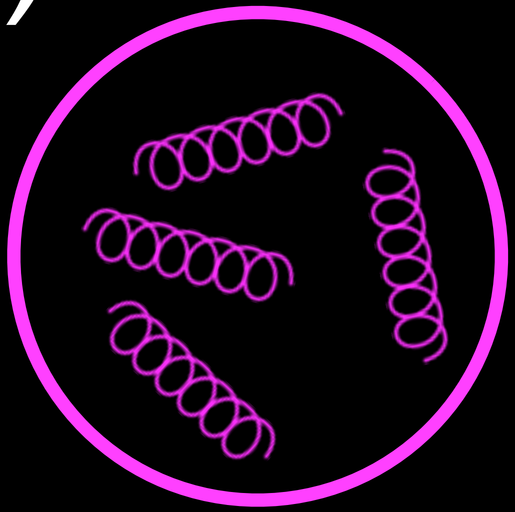


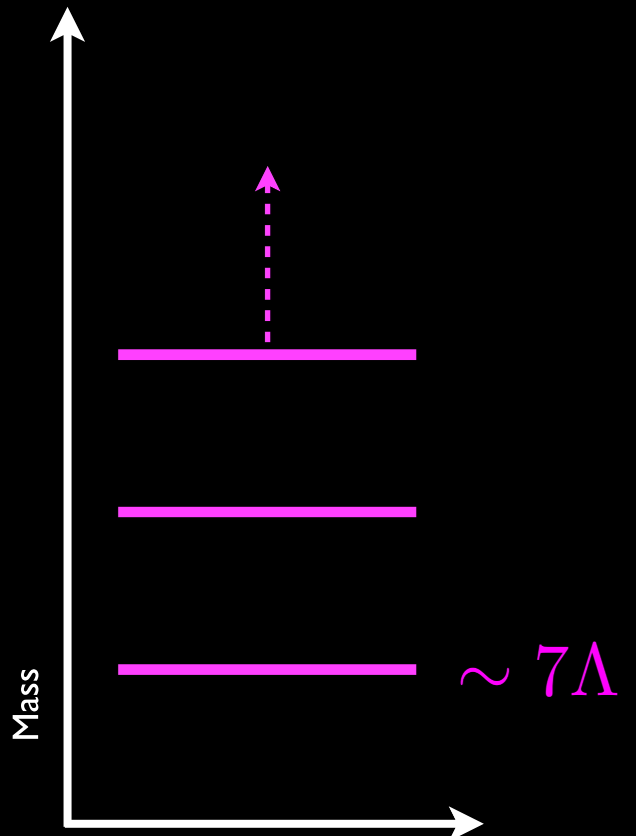
A Dark SU(N)

- We can engineer large self interaction by considering a dark sector which is pure gauge theory hidden sector SU(N).

Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014

- If any matter charged under the hidden gauge group and the SM is extremely heavy, there is no relevant interaction between the dark sector and the SM.
- At high energies, the theory is described by weakly coupled dark gluons.
- At low energies, the dark gluons confine into massive dark glueballs.
- The theory is defined by the number of colors N and confinement scale Λ, which characterizes the mass of the lowest glueball state, and the splitting between the various glueballs.





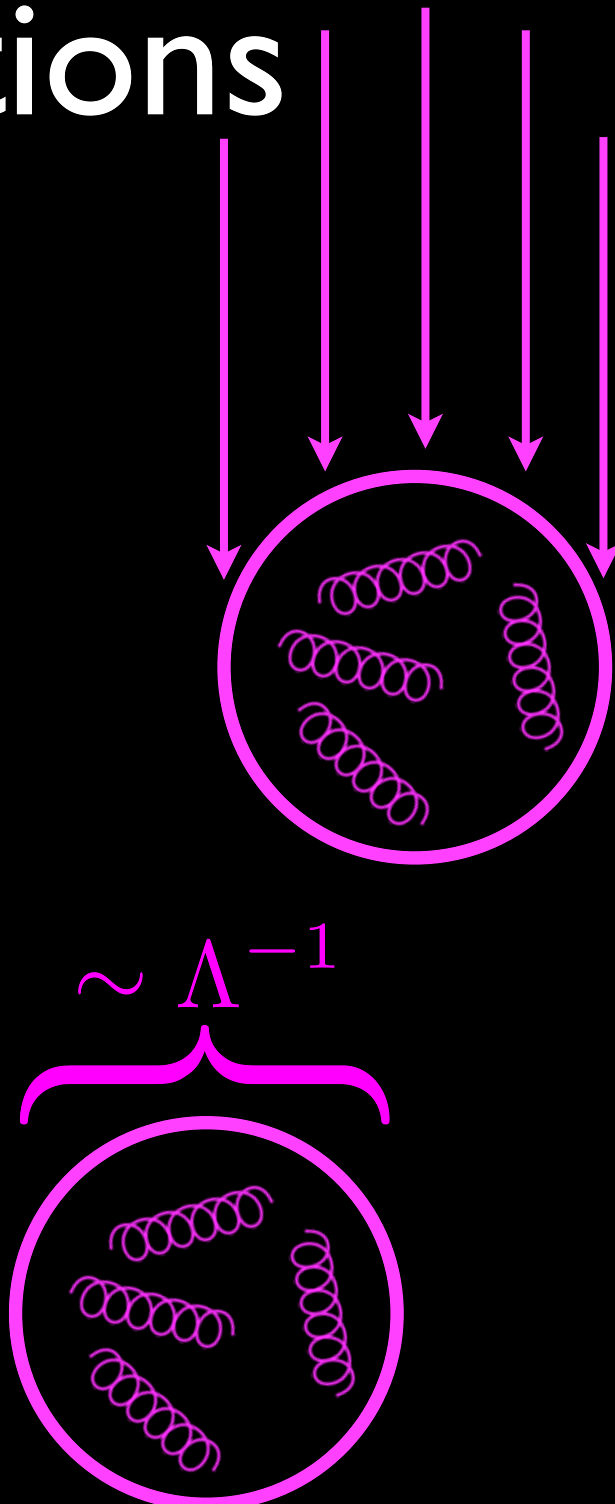
Glueball Interactions

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

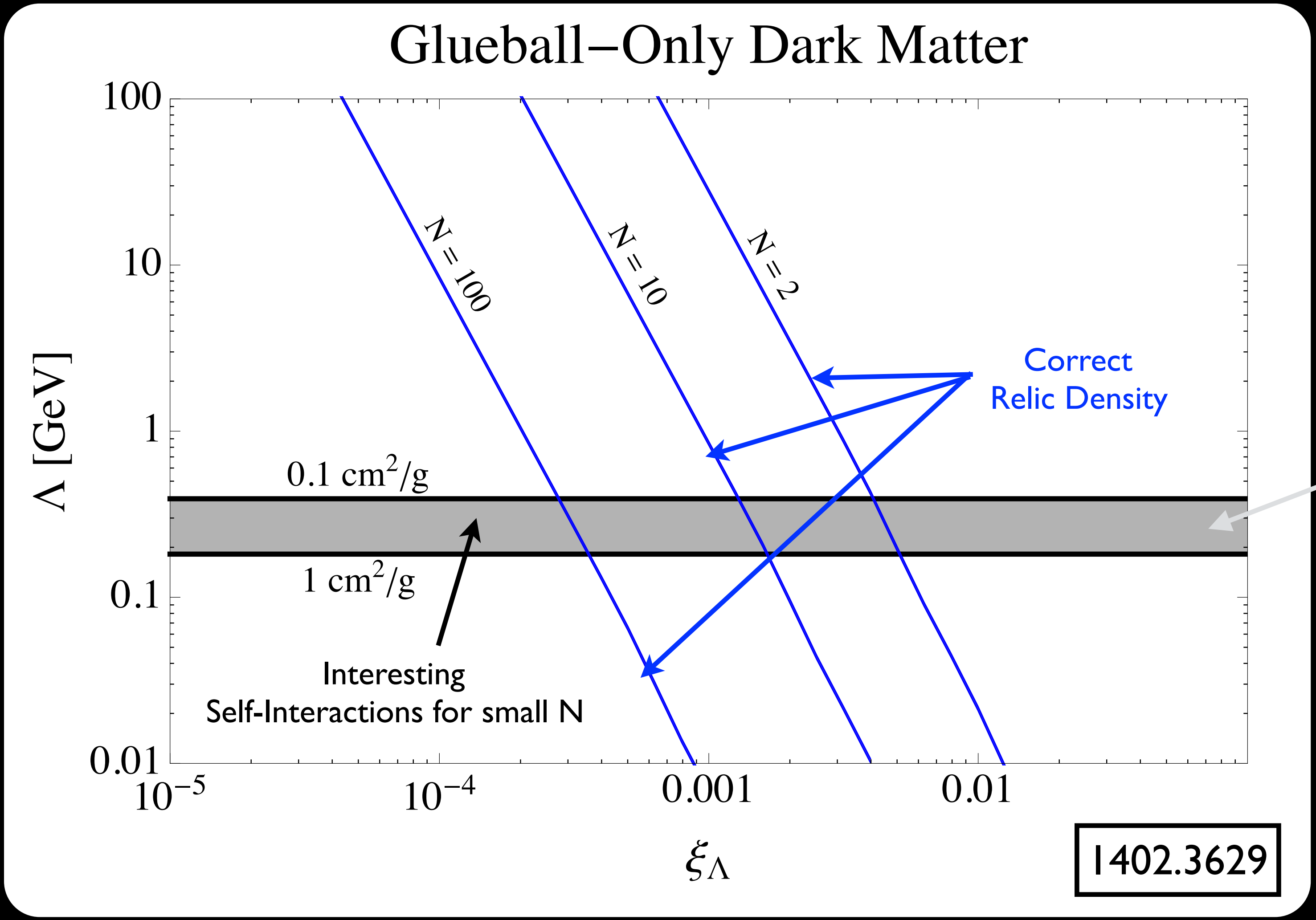
$$\sigma\left(\mathrm{gb\ gb} \rightarrow \mathrm{gb\ gb}\right) \sim \frac{4\pi}{\Lambda^2 N^2}$$

- 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 Parameter Space



~ right SIDM
σ for small N

Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014

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

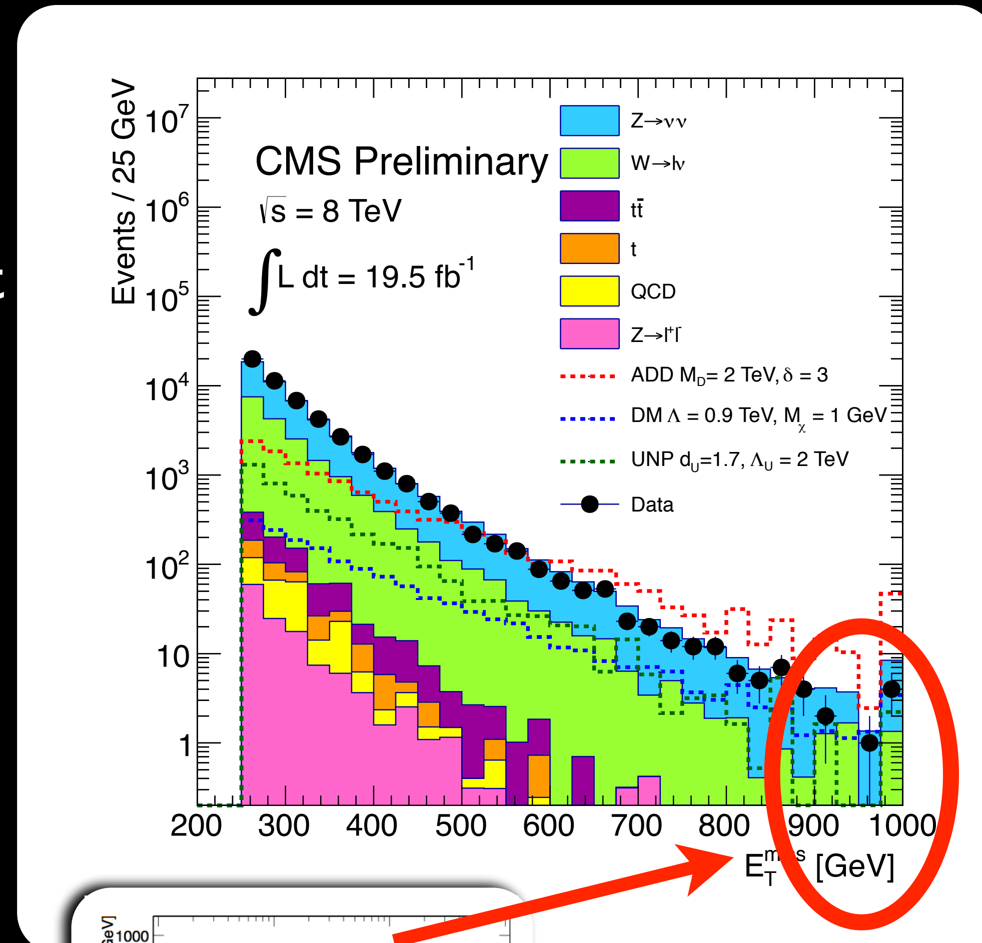
Outlook

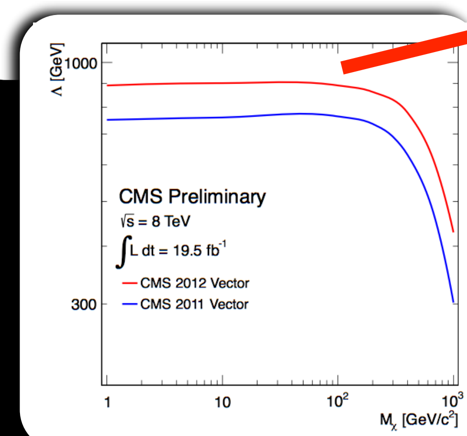
- Putting together a detailed description of the particle properties of dark matter is vital to better understand fundamental physics.
- There is a rich landscape of theoretical ideas; what is needed are experimental results to select among them and refine the parameter space.
- There is a vibrant program that covers a huge space of possibility from ultra-weakly interacting particles such as axions and sterile neutrinos to WIMPs and beyond.
- For WIMPs, the three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.
- Astronomical probes can access properties such as the rate of self-interaction which are otherwise difficult to extract, and difficult cases where the interactions between dark matter and the SM are very tiny.
- All together, there is vast potential for discovery in the near future!

Bonus Material

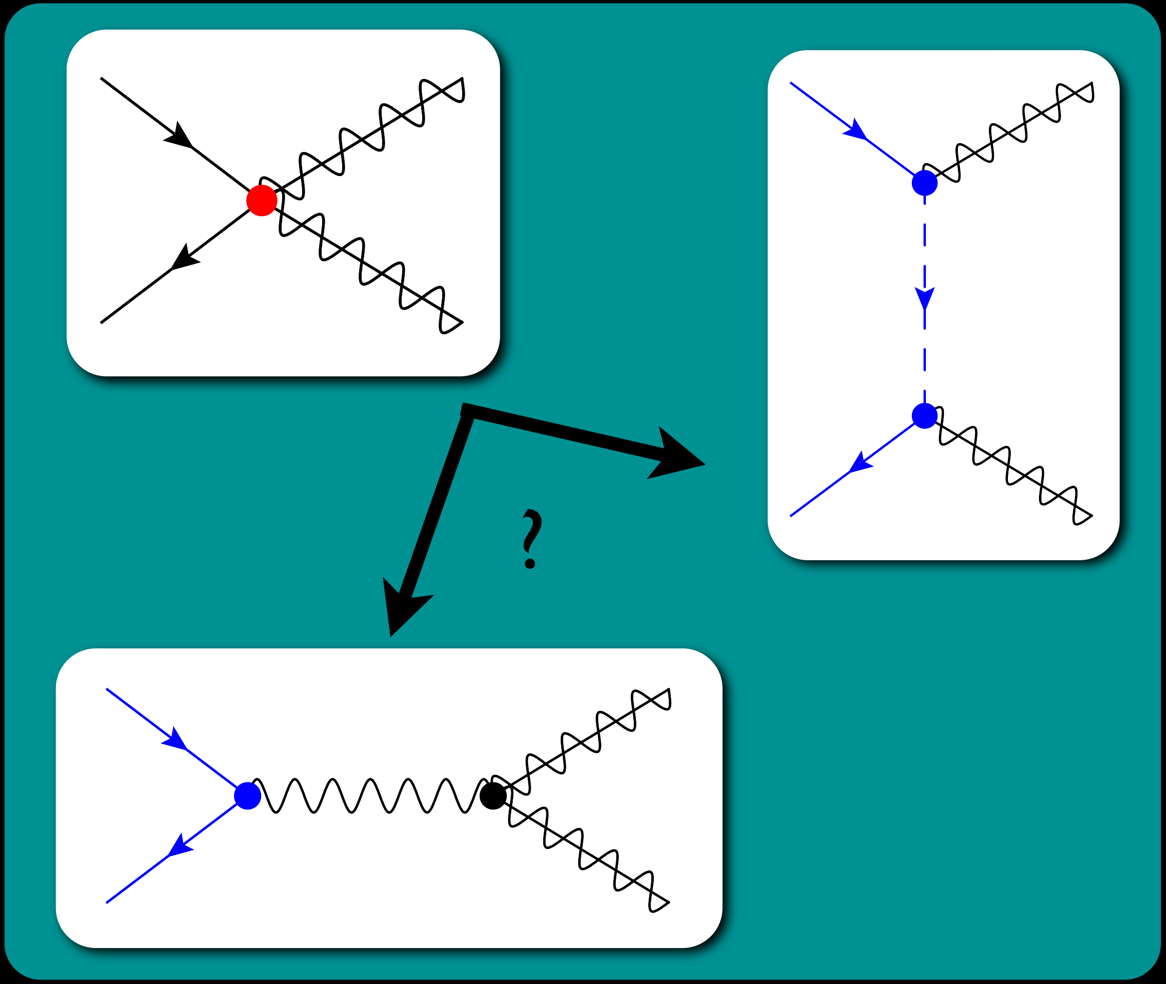
How Effective a Theory?

- 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.]





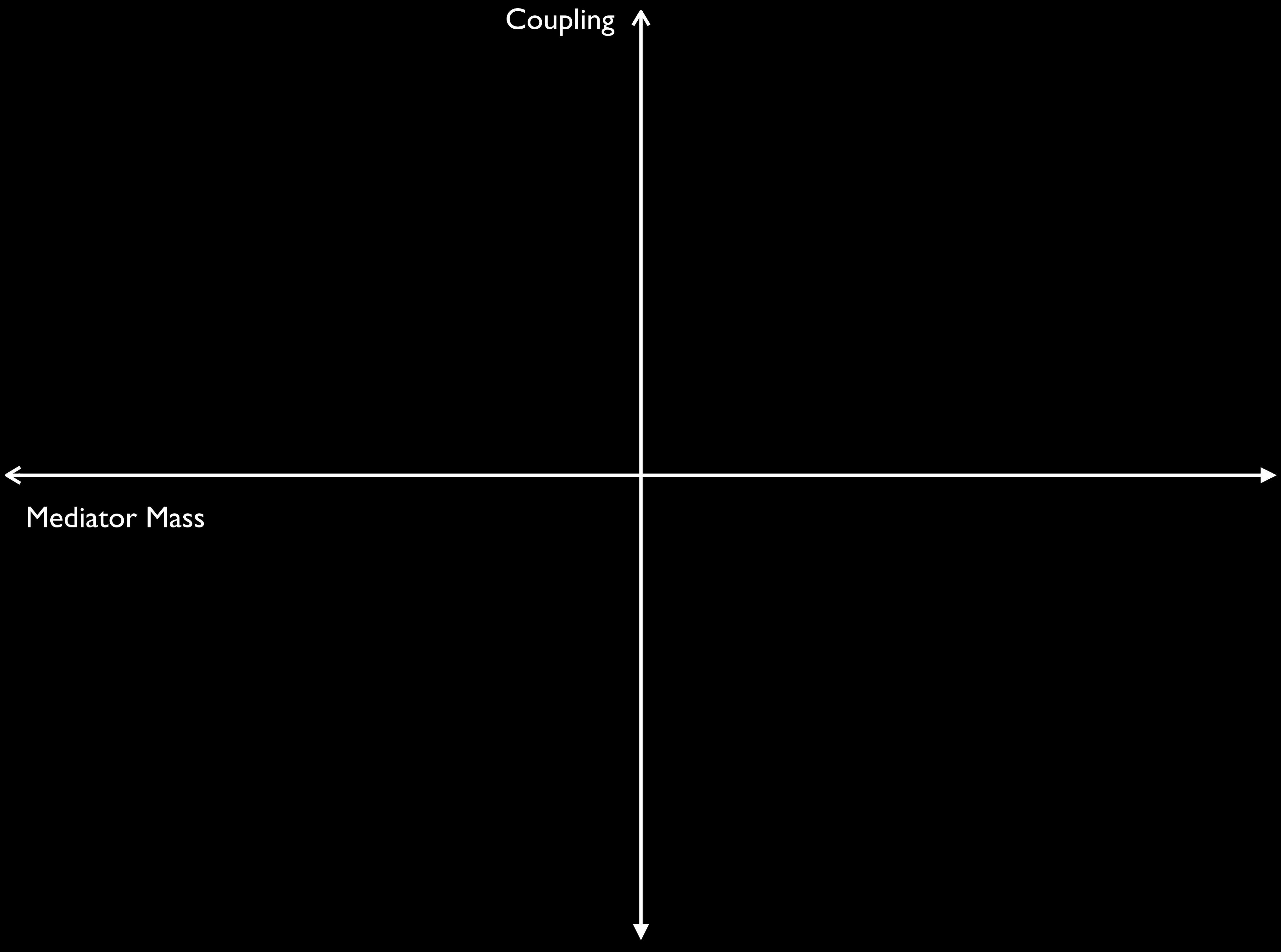
Simplified Models?

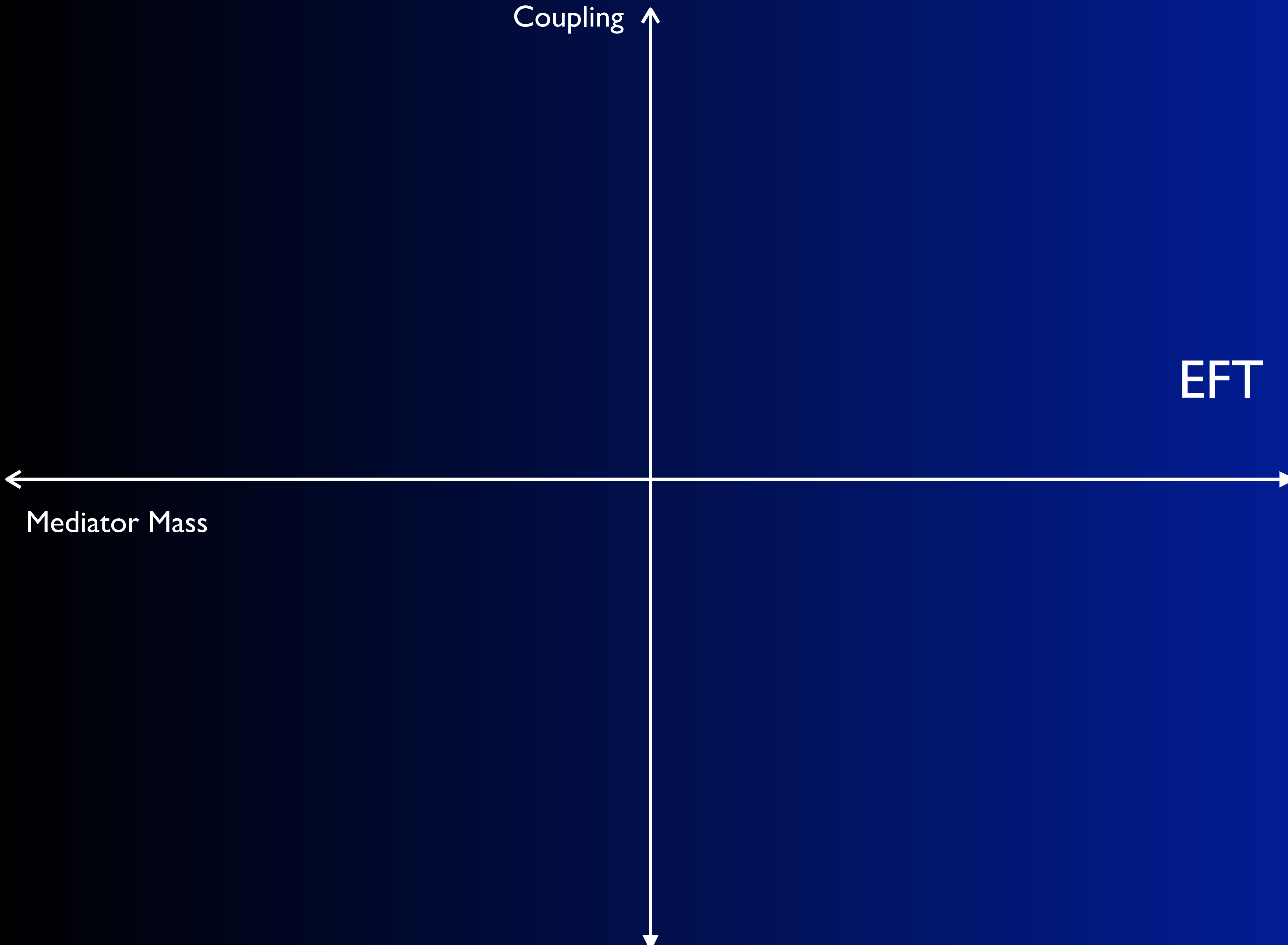


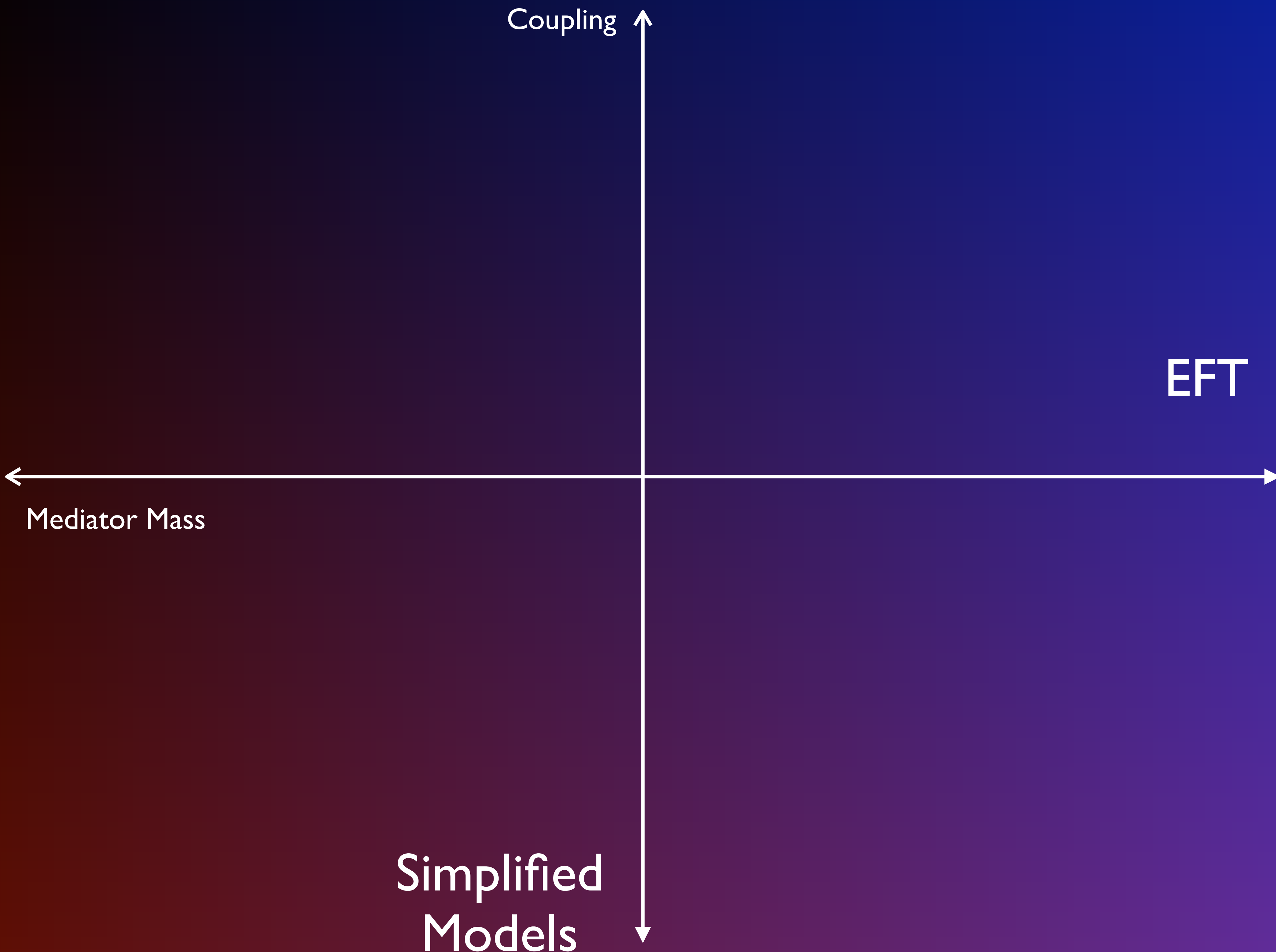
“t-channel” mediators are protected by the WIMP stabilization symmetry. They must couple at least one WIMP as well as some number of SM particles. Their masses are greater than the WIMP mass (or else the WIMP would just decay into them).

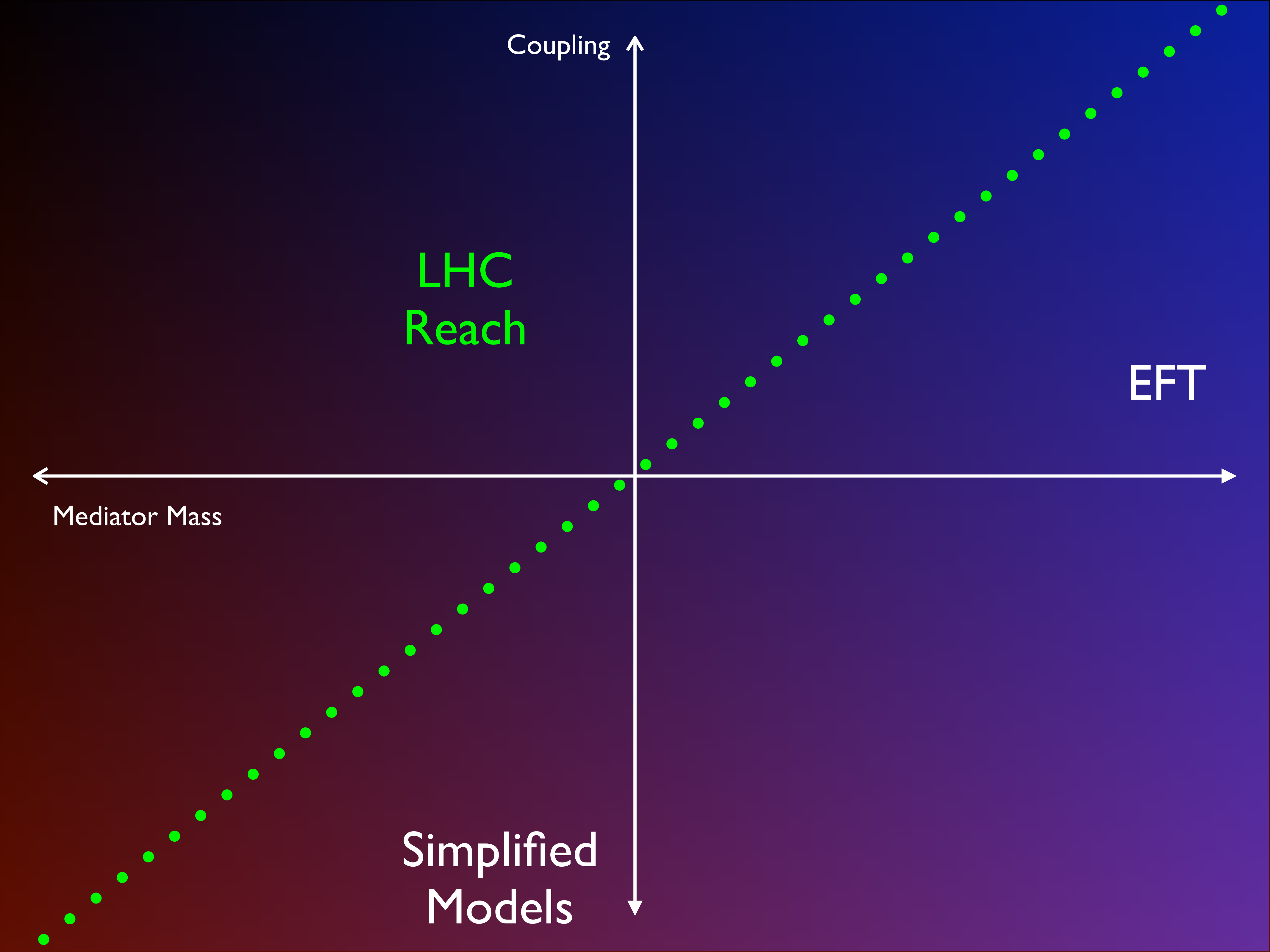
“s-channel” mediators are not protected by the WIMP stabilization symmetry. They can couple to SM particles directly, and their masses can be larger or smaller than the WIMP mass itself.

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


Coupling
Mediator Mass

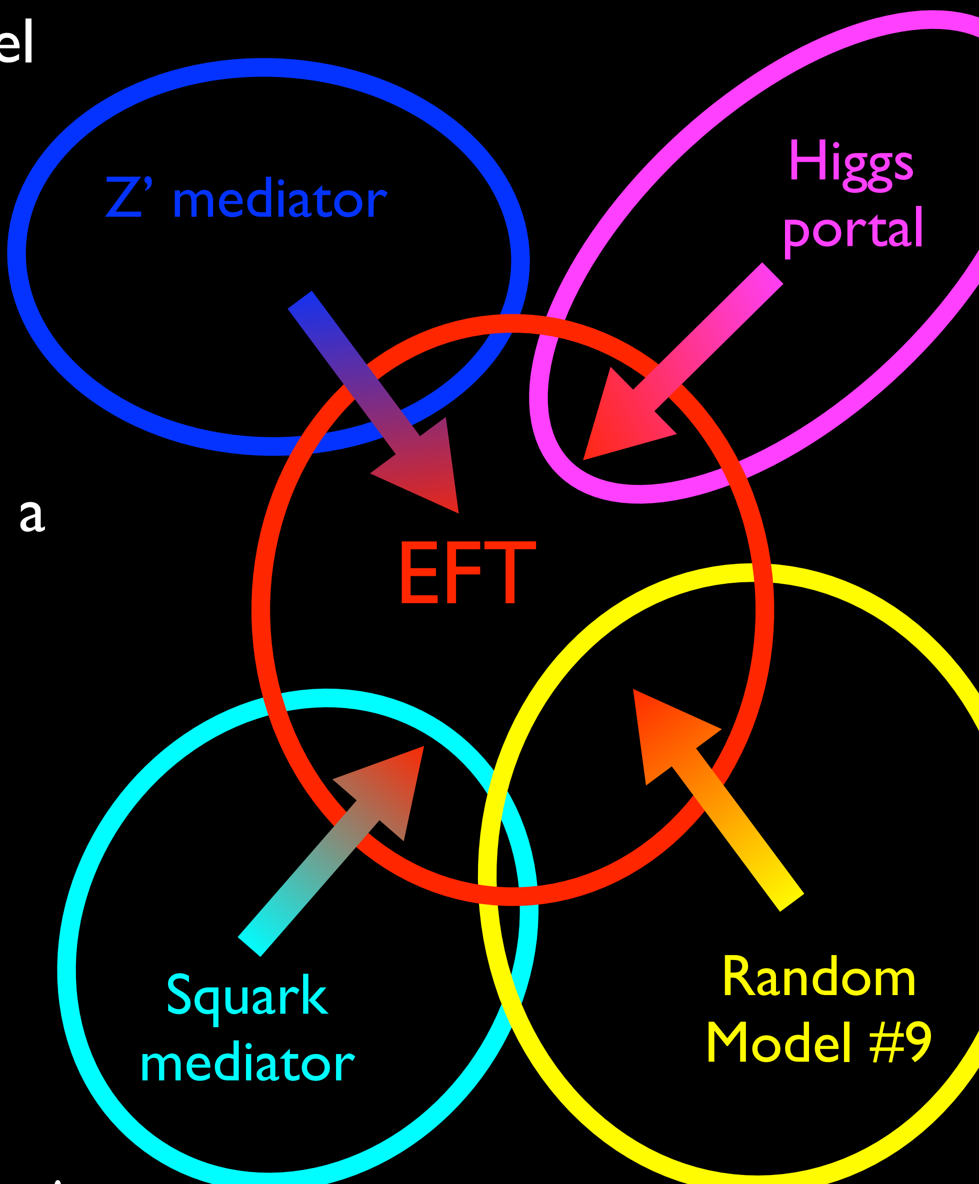

Coupling
EFT
Mediator Mass


Coupling
EFT
Mediator Mass
Simplified
Models


Coupling
LHC
Reach
EFT
Mediator Mass
Simplified
Models

"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!



The Dark Matter Questionnaire

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

Couplings:

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

Thermal Relic?

- ☐ Yes ☐ No

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

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

Couplings:

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

A Possible Timeline

2015

2016

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

2017

2018

2019

2020

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

Couplings:

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

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

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?
- [x] Quarks / Gluons
- [ ] Leptons?
- [ ] Thermal Relic?

A Possible Timeline

2015

2016

YOU ARE HERE

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2019

2020

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.

Super-CDMS 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

2015

2016

YOU ARE HERE

2017

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

Super CDMS sees
gnal.

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

No jets
+ MET

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

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

2015

2016

YOU ARE HERE

2017

2018

2019

2020

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

Super-CDMS 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

2015
2016
YOU ARE HERE
2017
2018
2019
2020
????

☑ 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

2015

2016

YOU ARE HERE

2017

2018

2019

2020

????

LUX sees elastic scat... consistent... mass <...

Super-C... a simil...

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

A multi-pronged search strategy identifies a mixture of dark matter composed of classic WIMPs and axions.

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.