Dark Matter: eV Scale and Above

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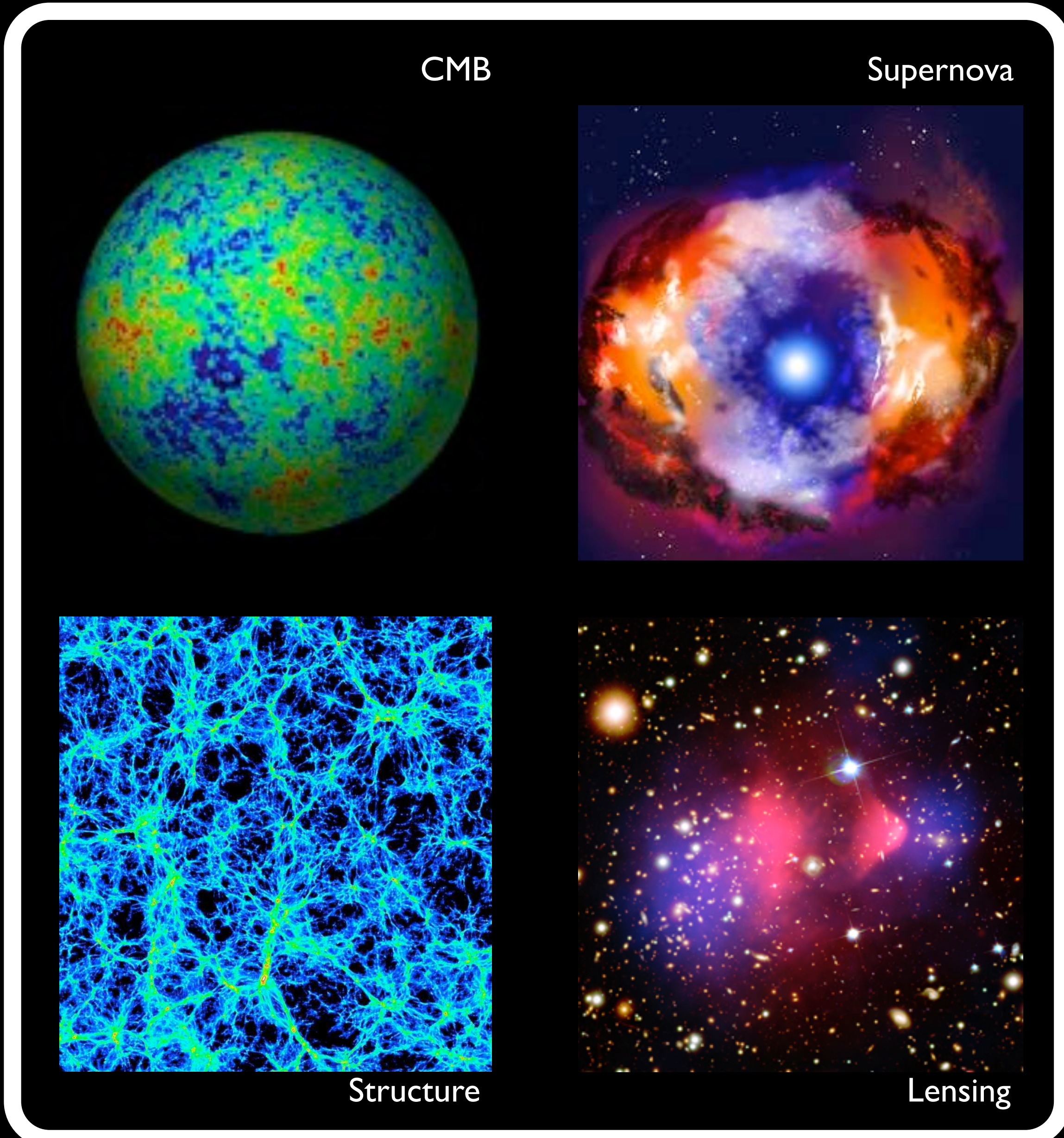
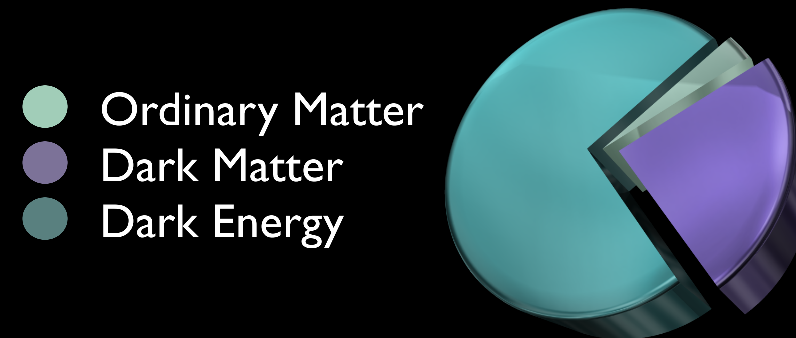
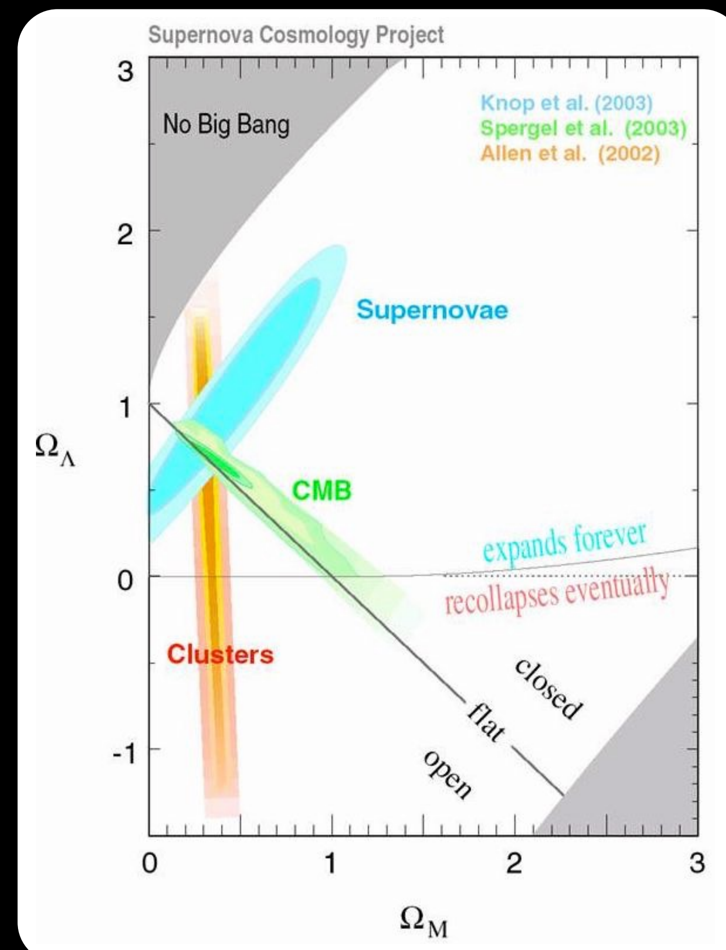
University of California, Irvine

CPAD
October 8, 2016

Dark Matter







Evidence for dark matter is overwhelming…

So what is Dark Matter?


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

- As particle physicists, we want 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.

The Dark Matter Questionnaire

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

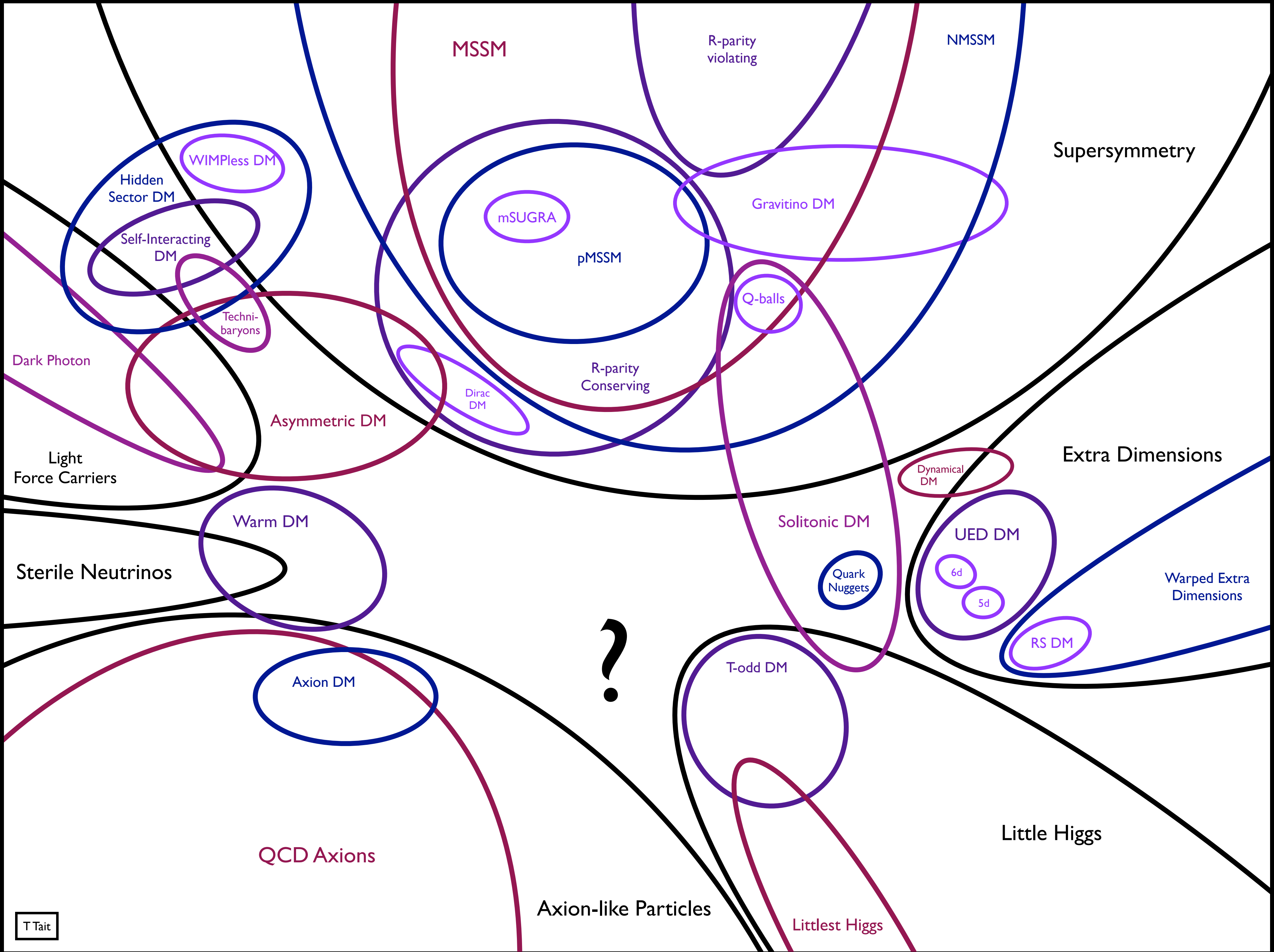
Couplings:

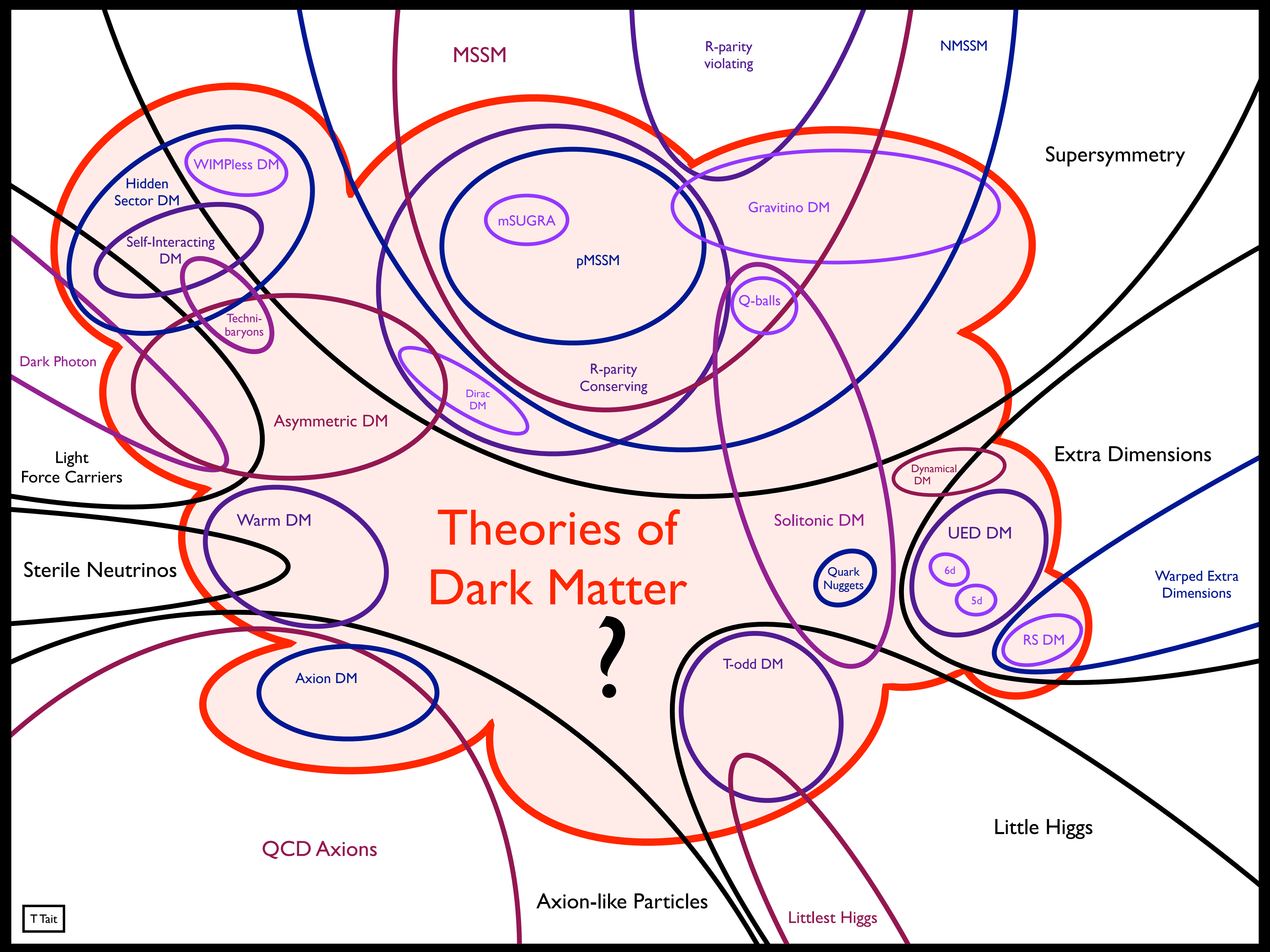
- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?

Thermal Relic?

- [ ] Yes
- [ ] No

Candidates


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
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
T-odd DM
Axion DM
QCD Axions
Little Higgs
Axion-like Particles
Littlest Higgs
T Tait



Theories of Dark Matter
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R-parity violating
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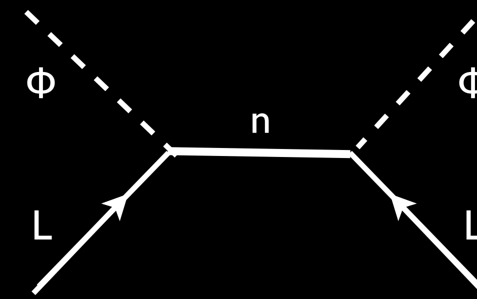
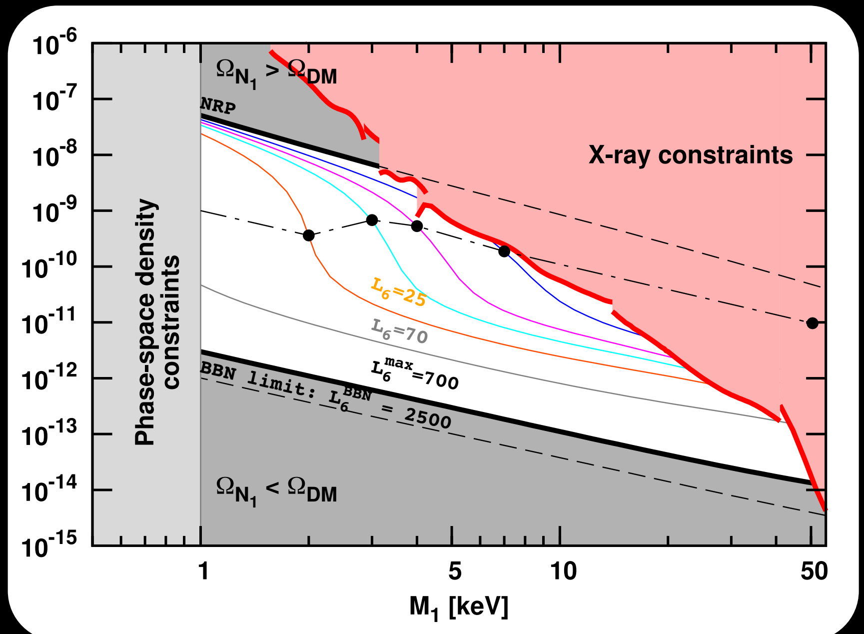
Sterile Neutrino DM

- 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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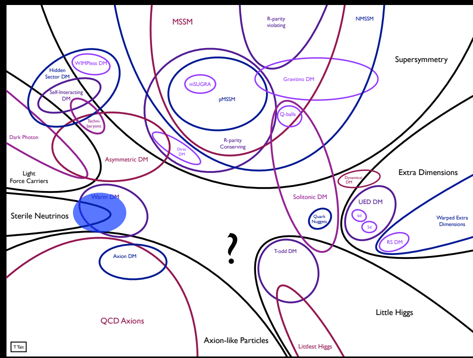
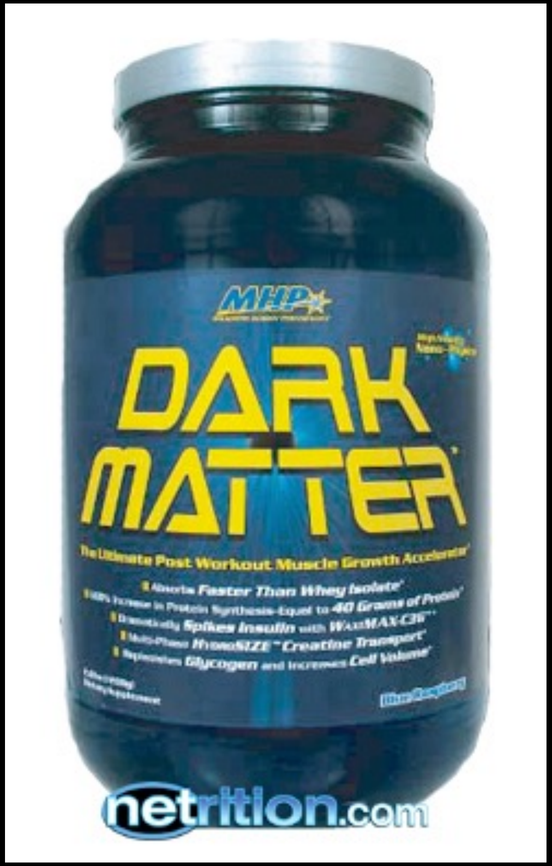
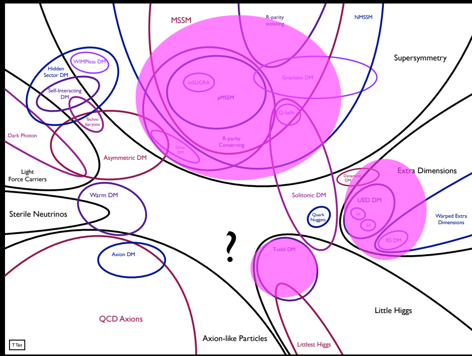


WIMPs

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

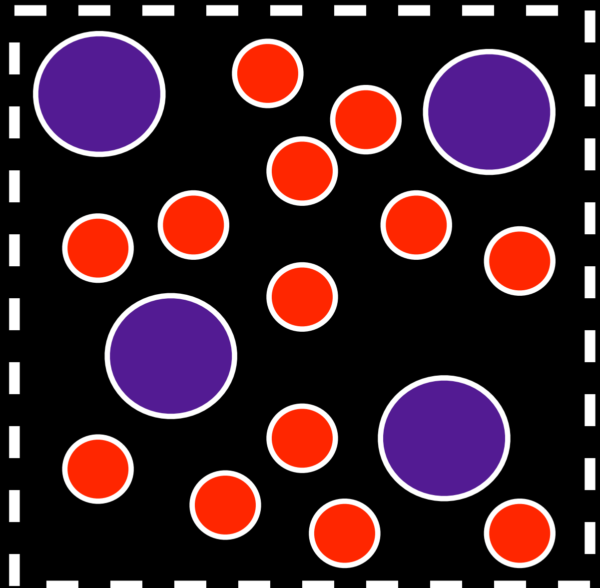


55 Euro for 20 servings
Available in Blue Raspberry, Fruit Punch, and Grape flavors....



The WIMP Miracle

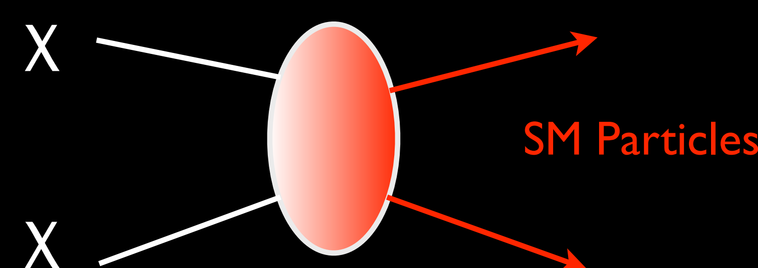
- One of the primary motivations for WIMPs is the “WIMP miracle”, an attractive picture explaining the density of dark matter in the Universe today.



- 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, χχ -> SM.

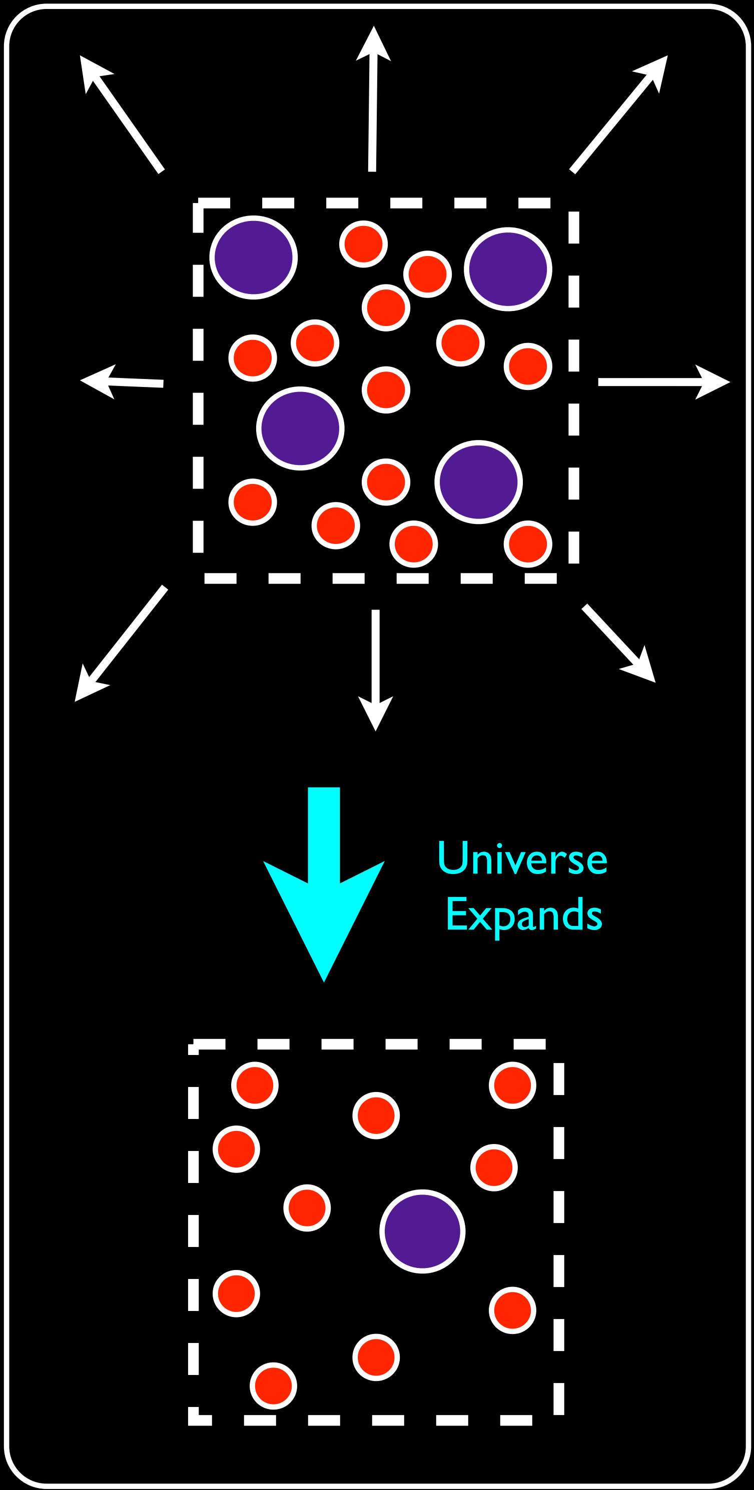
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:



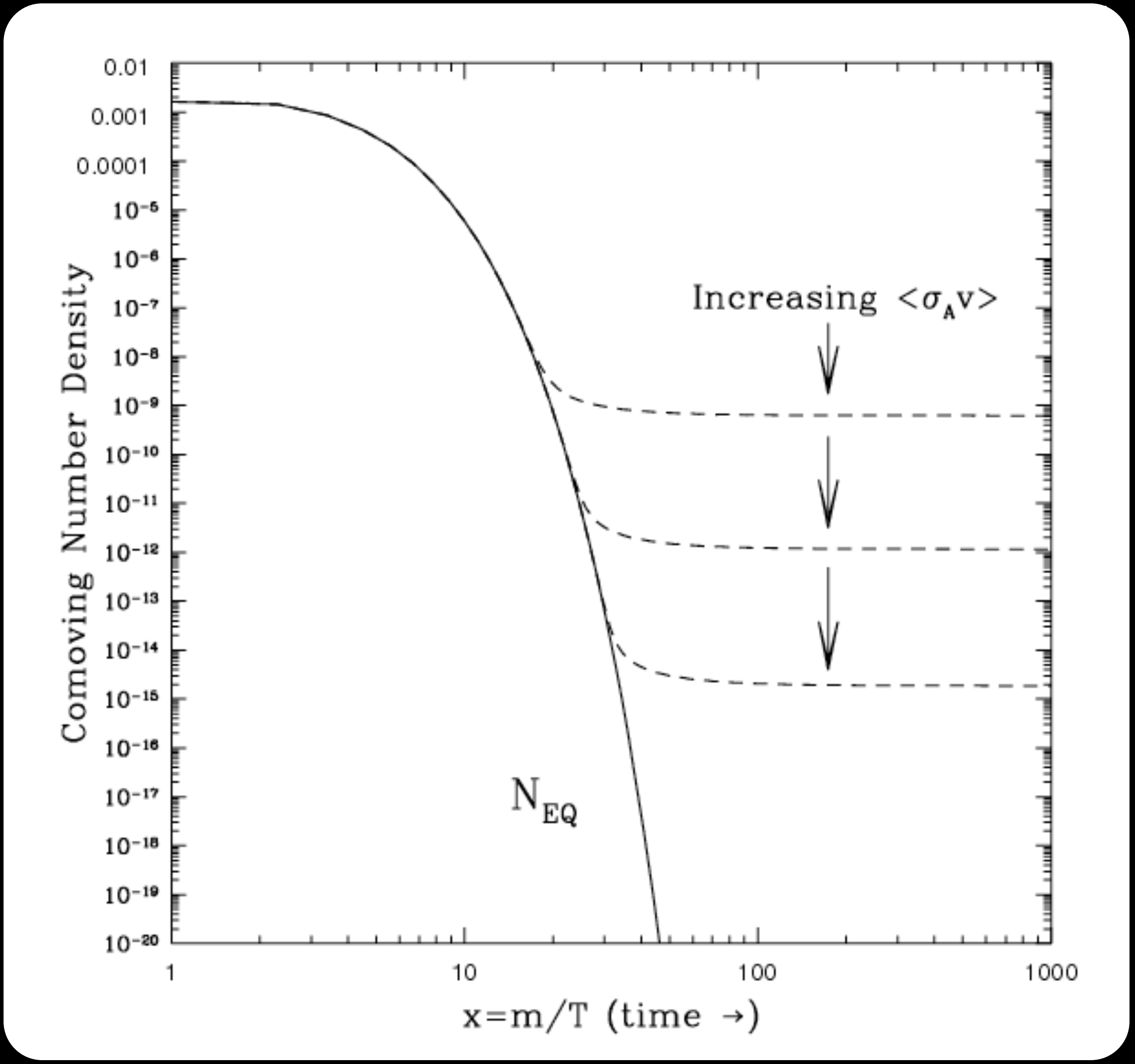
$$n_{eq} = g \left(\frac{mT}{2\pi} \right)^{3/2} \mathrm{Exp}\left[-m/T \right]$$

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 $\sigma(\chi\chi \to$ 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

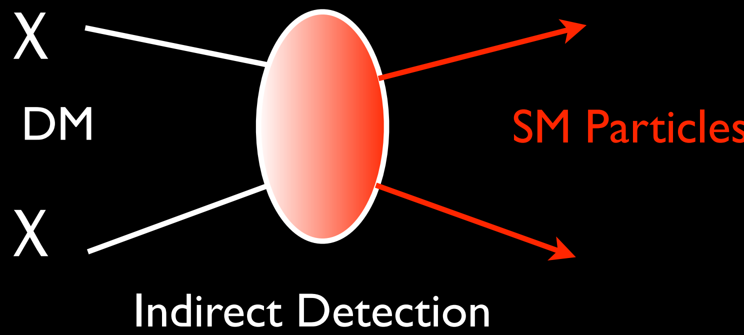


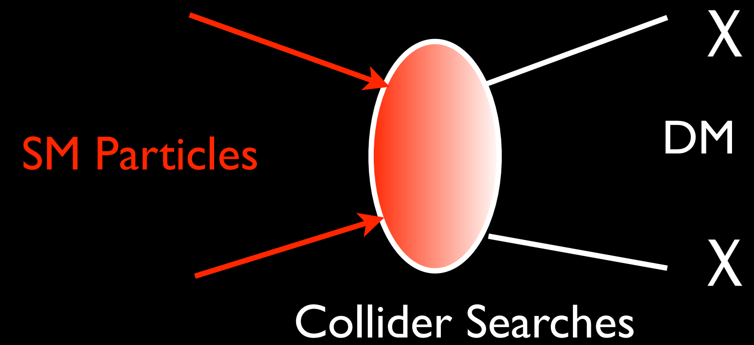
x=m/T increasing
is
T decreasing
is
time increasing

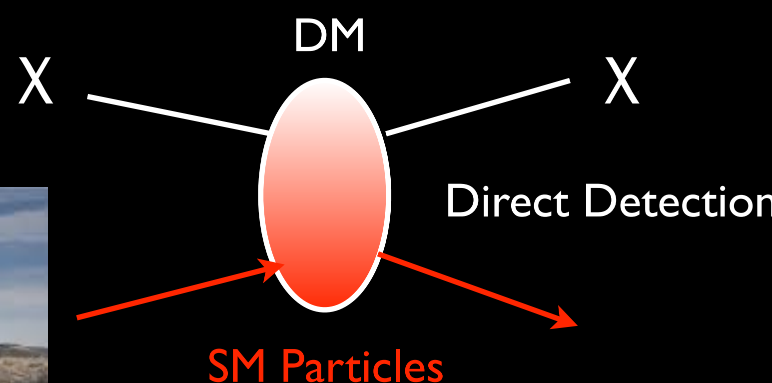
- The observed quantity of dark matter is suggestive of a cross section for annihilation into SM particles: $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm^3/s, roughly independently of the mass of the dark matter.

Probes

Particle Probes of DM



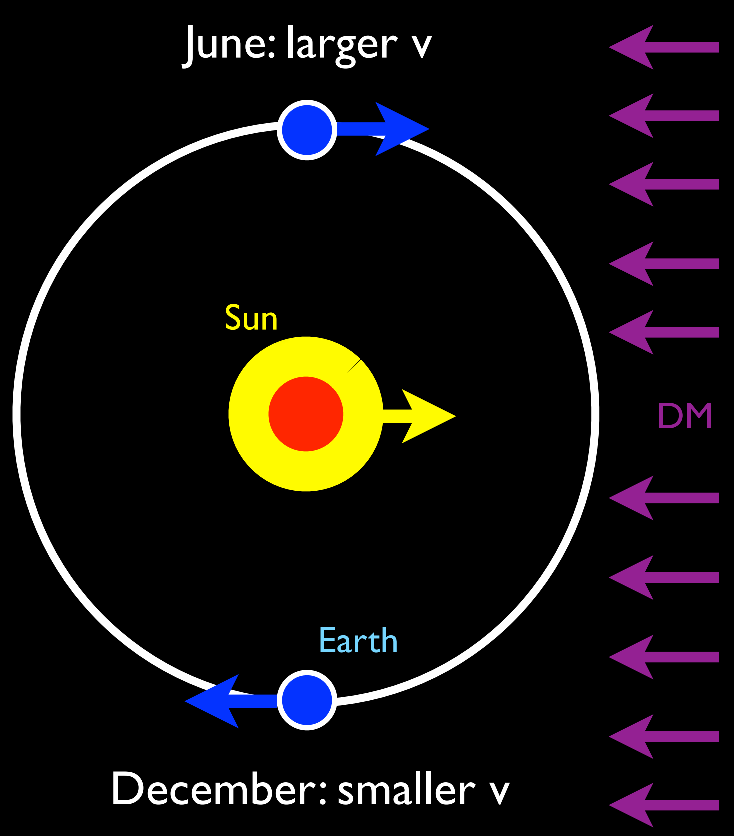


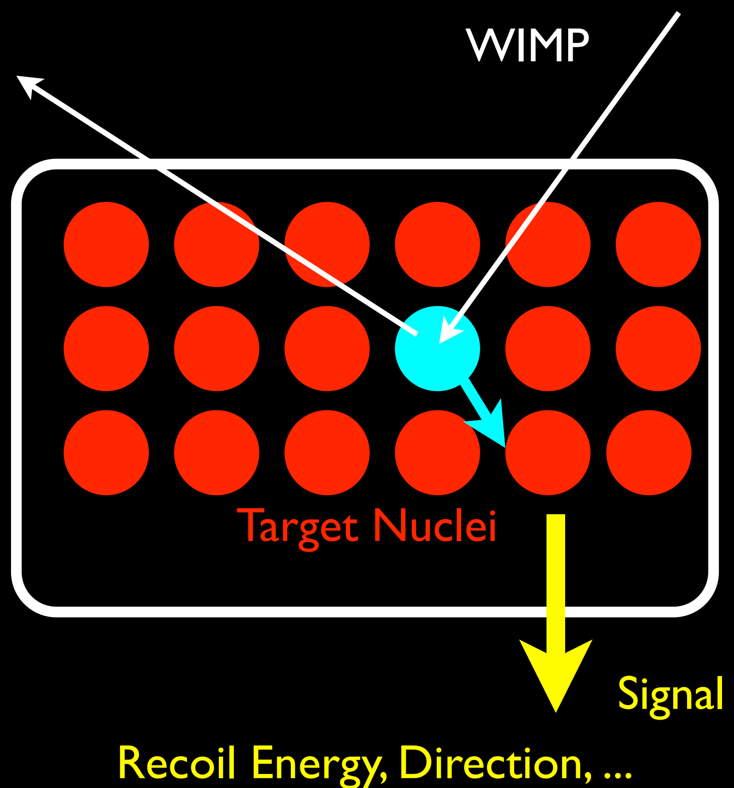


- The common feature of particle searches for dark matter is that all of them are determined by how it interacts with the Standard Model.

Direct Detection

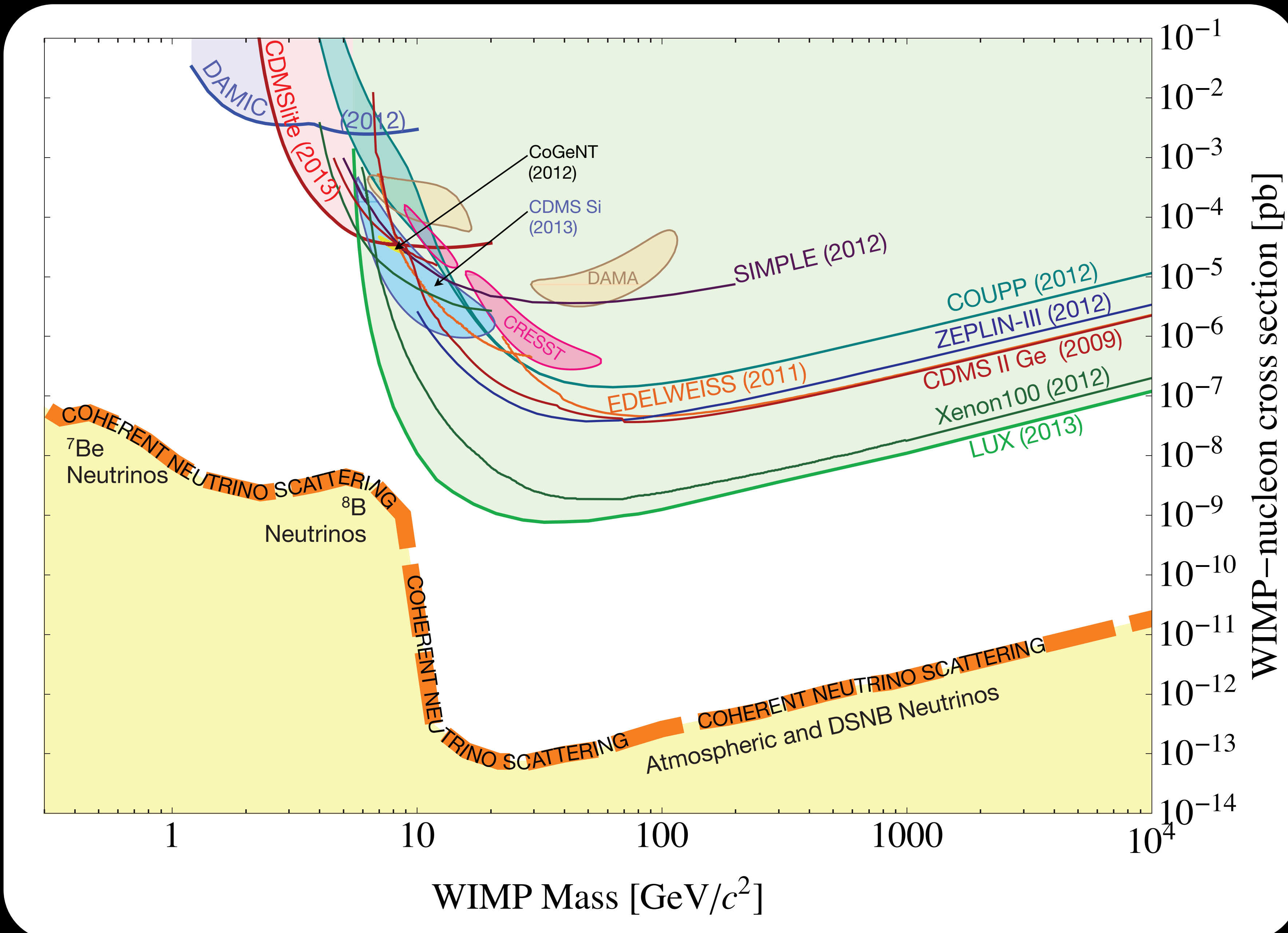
- Direct detection searches for ambient dark matter scattering off of terrestrial targets.
- Amazing progress has shown that backgrounds can be rejected to a very high degree.
- Handles include the recoil energy spectrum, distribution of recoil direction, and modulation of the signal with time.





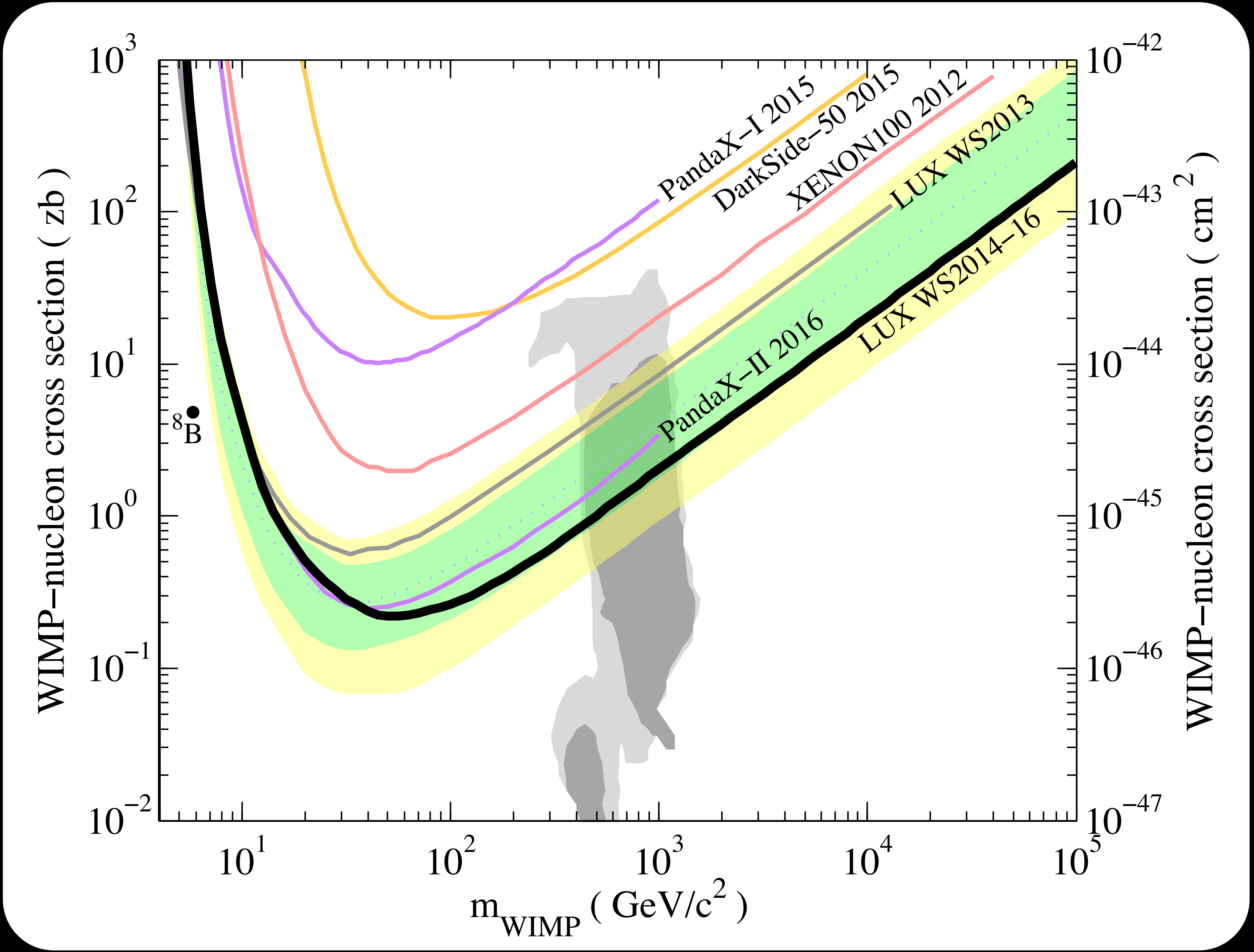
- One challenge for the future is improving sensitivity to low mass dark matter (which carries less momentum and results in smaller signals).
- Eventually experiments will reach sensitivity to background neutrinos, which are independently interesting but will complicate WIMP searches.

Direct Detection



Billard, Figueroa-Feliciano, Strigari 1307.5458

Direct Detection



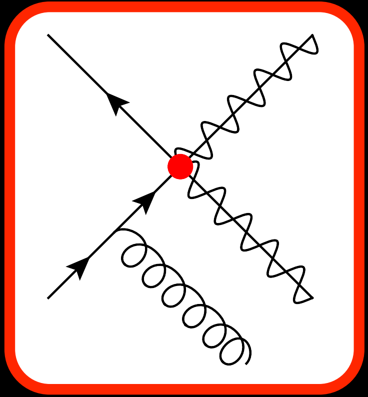
LUX 1608.07648

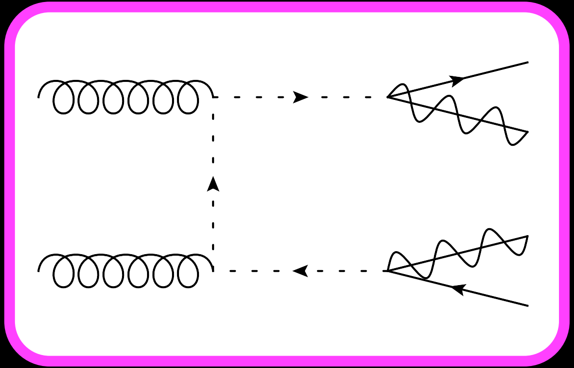
More from Scott Hertel shortly…

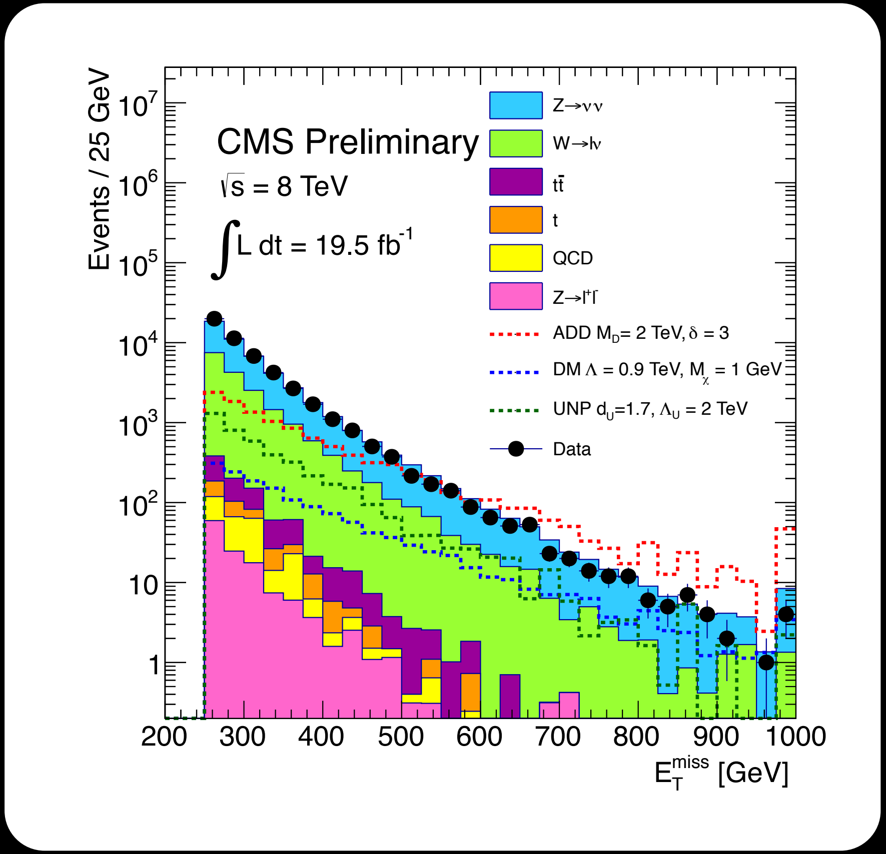
Colliders

More from Antonio Boveia…

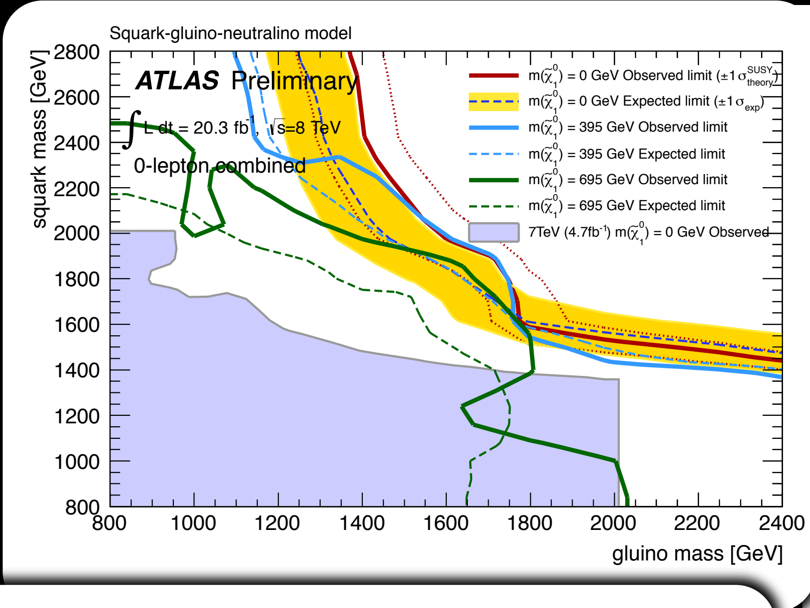
- High energy colliders offer the opportunity to produce dark matter in the laboratory.
- Since dark matter typically does not interact with a collider detector in transit, it reveals its presence as an imbalance in momentum conservation.
- Colliders have strengths in their exquisite control over the 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.

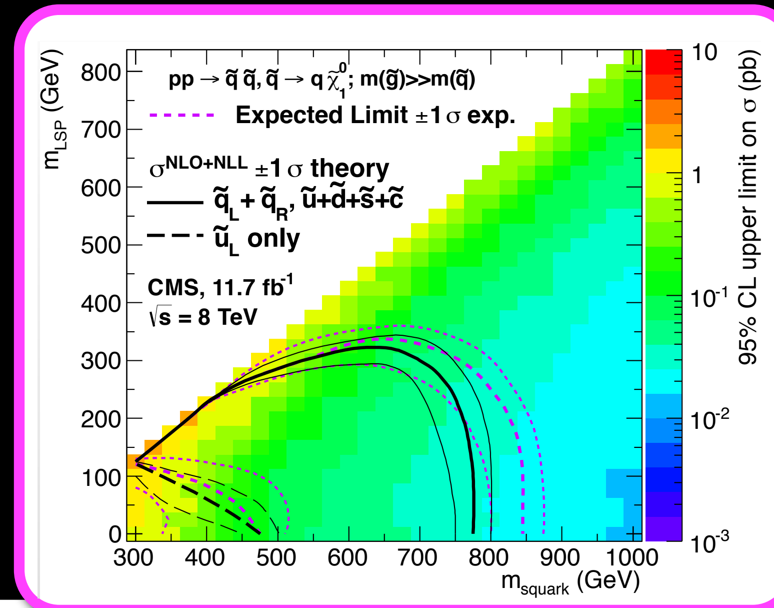


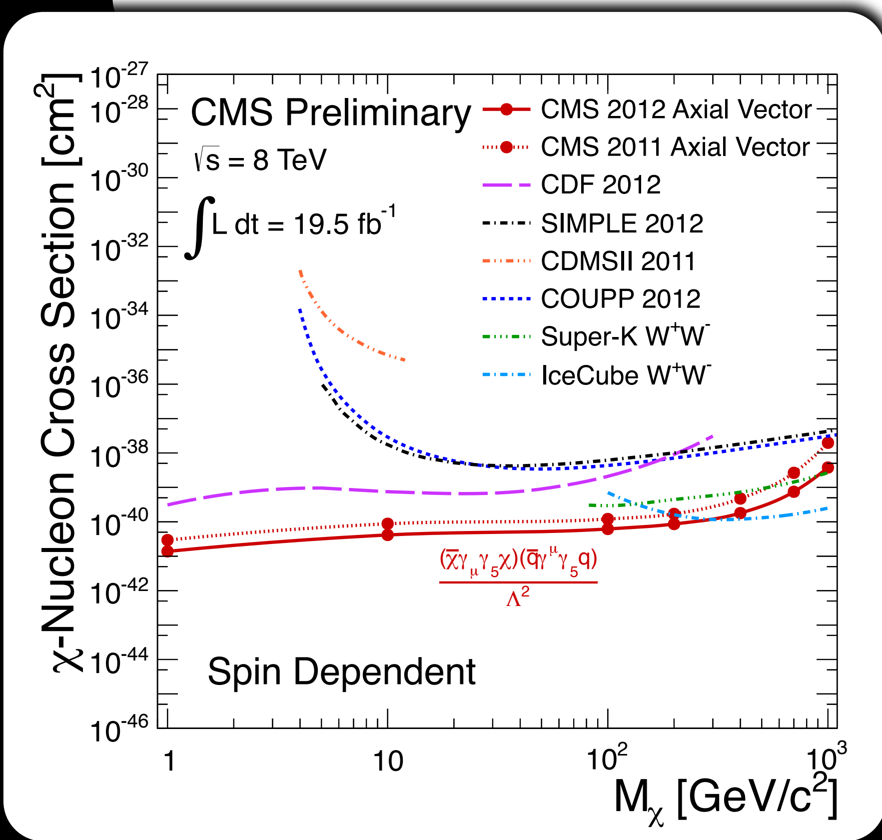


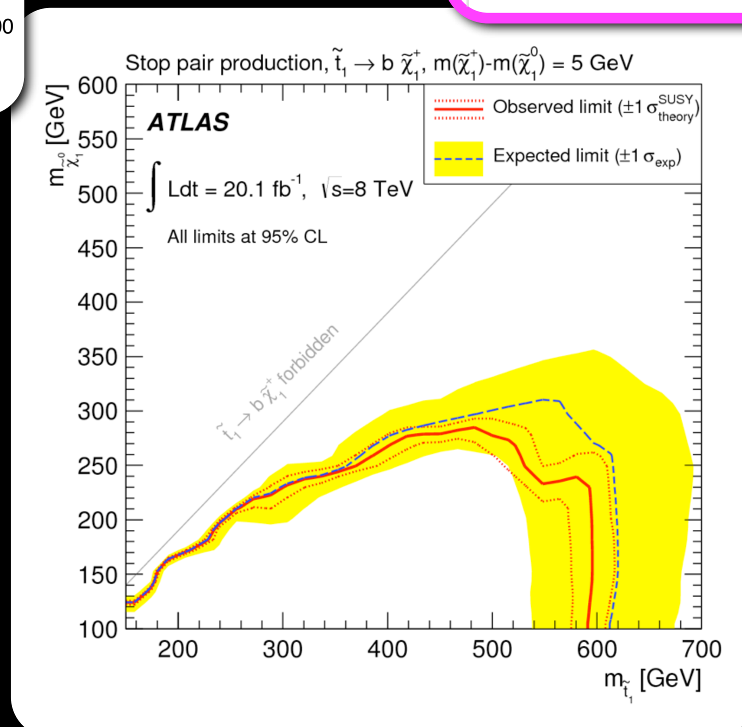


Colliders







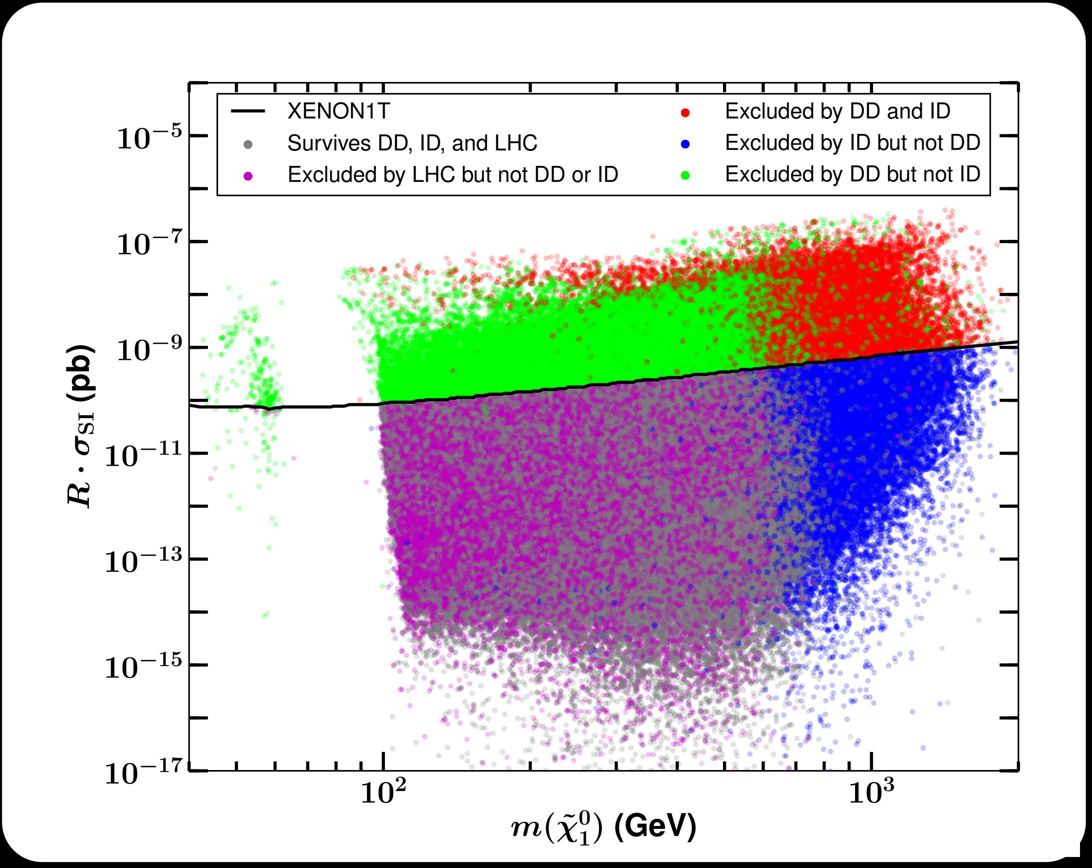


Many different collider searches are sensitive to various types of WIMP dark mater.

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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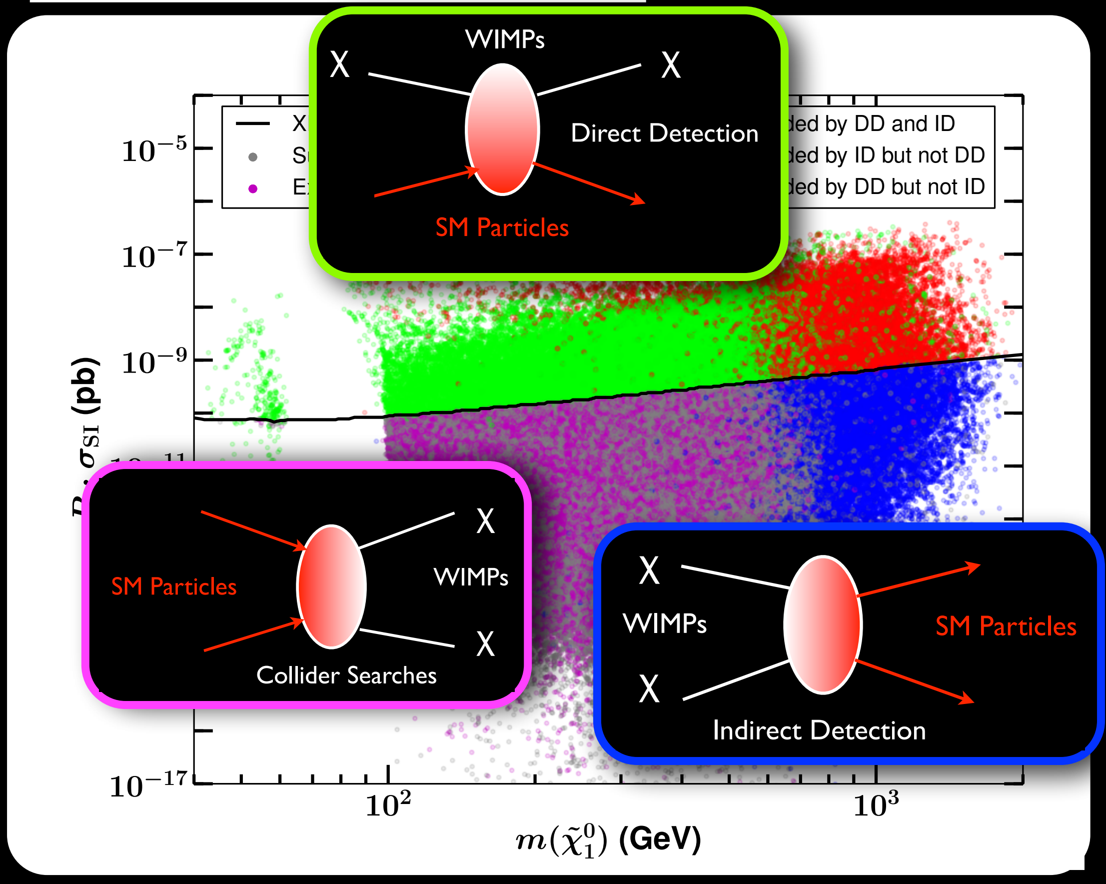
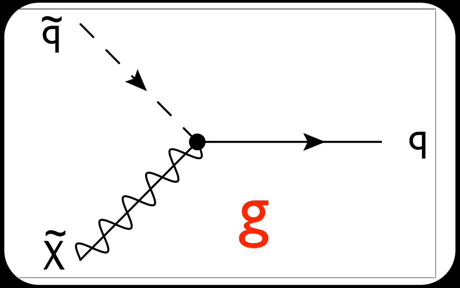
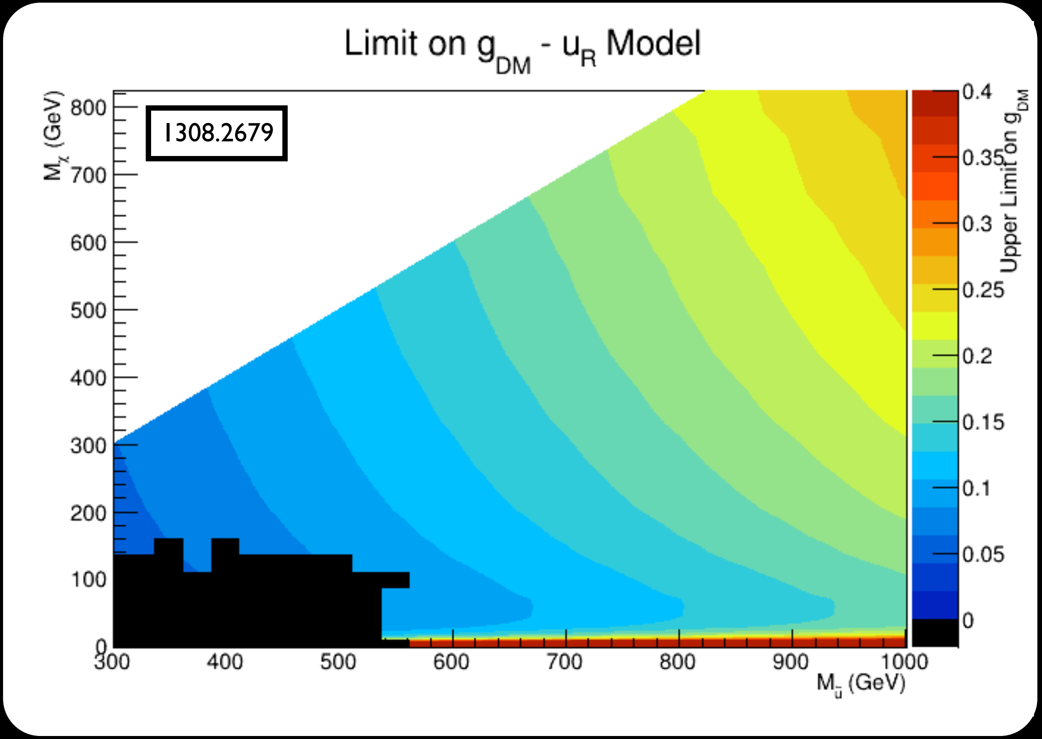


Simplified Models

- 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.



"T-Channel Model"



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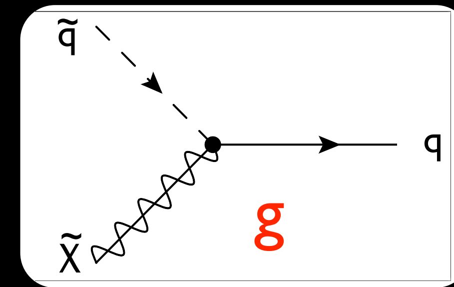
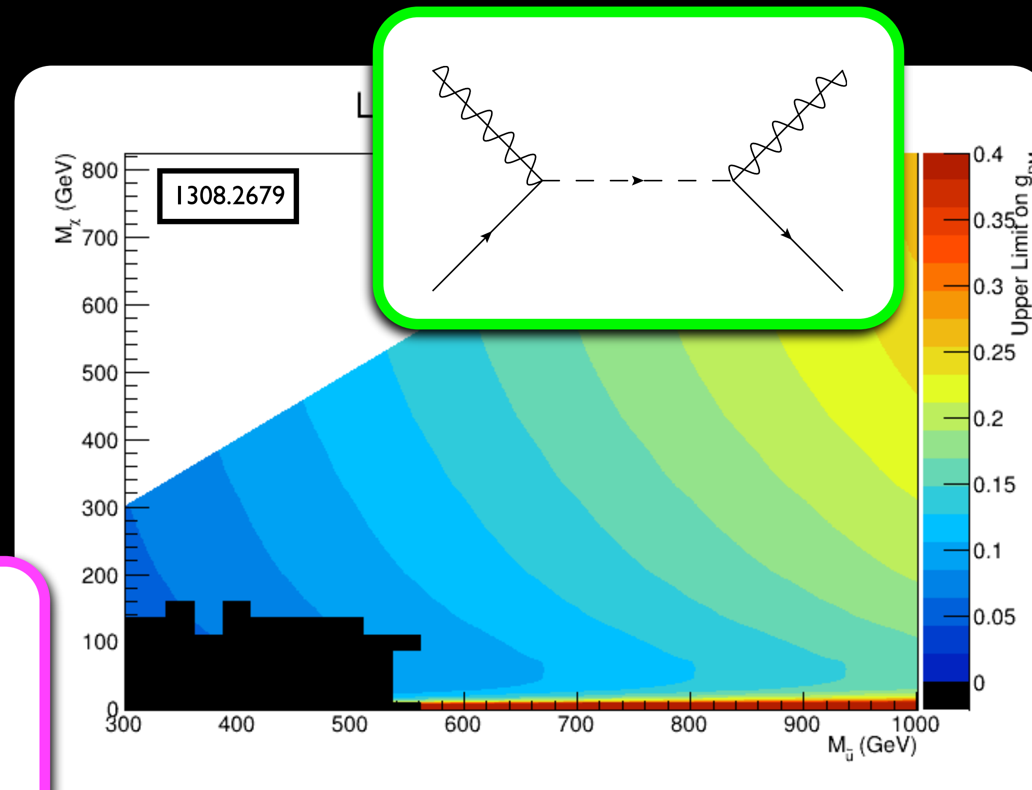
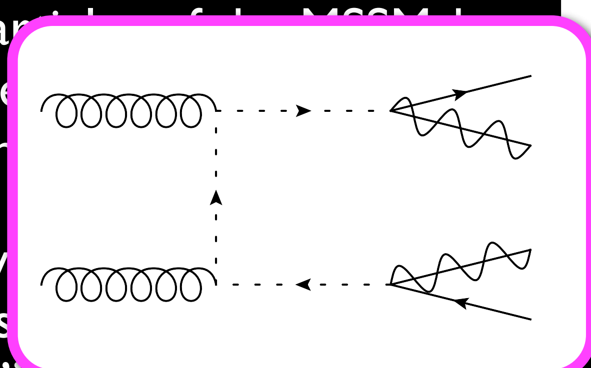
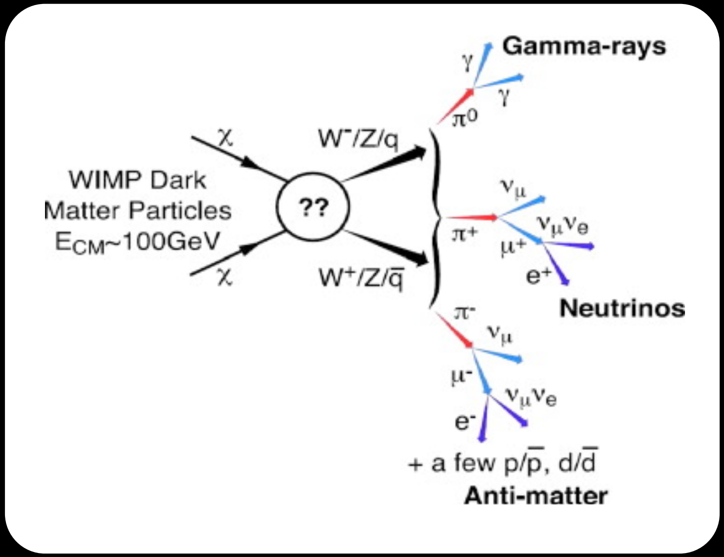






Indirect Detection

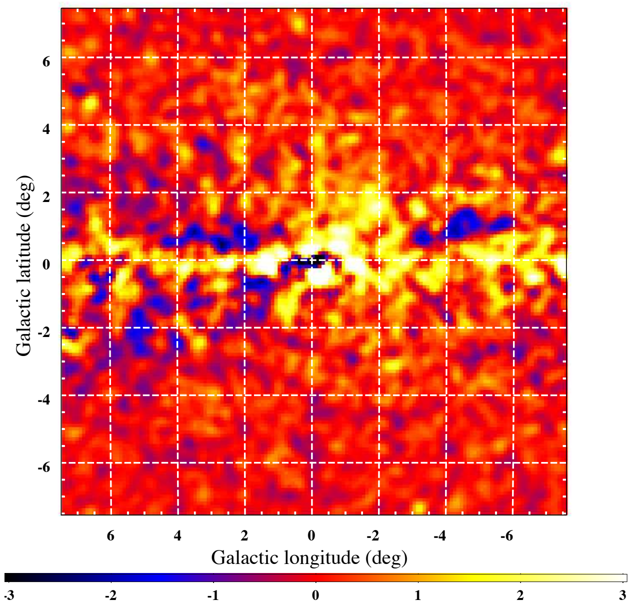
- Indirect detection looks for distinctive products of WIMP annihilation.
- High energy gamma rays, neutrinos, and anti-matter are all interesting messengers that could reveal the presence of dark matter annihilations.
  - Gamma rays: point back to their source and have relatively little propagation 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.

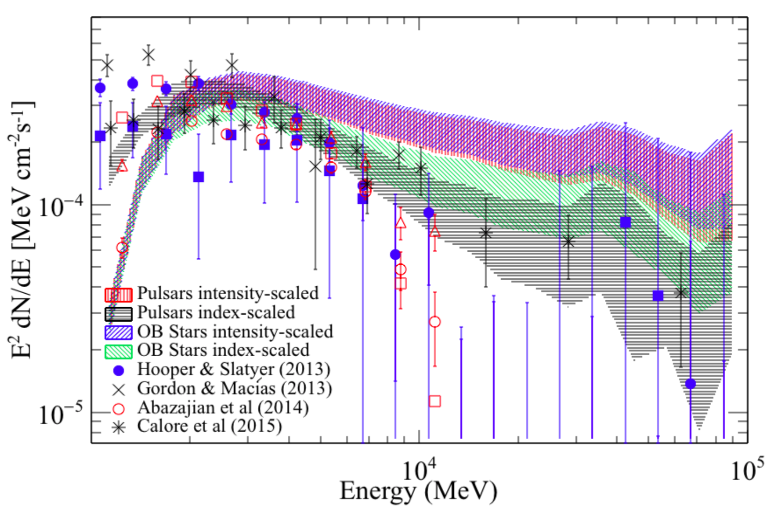


More from Simona Murgia…

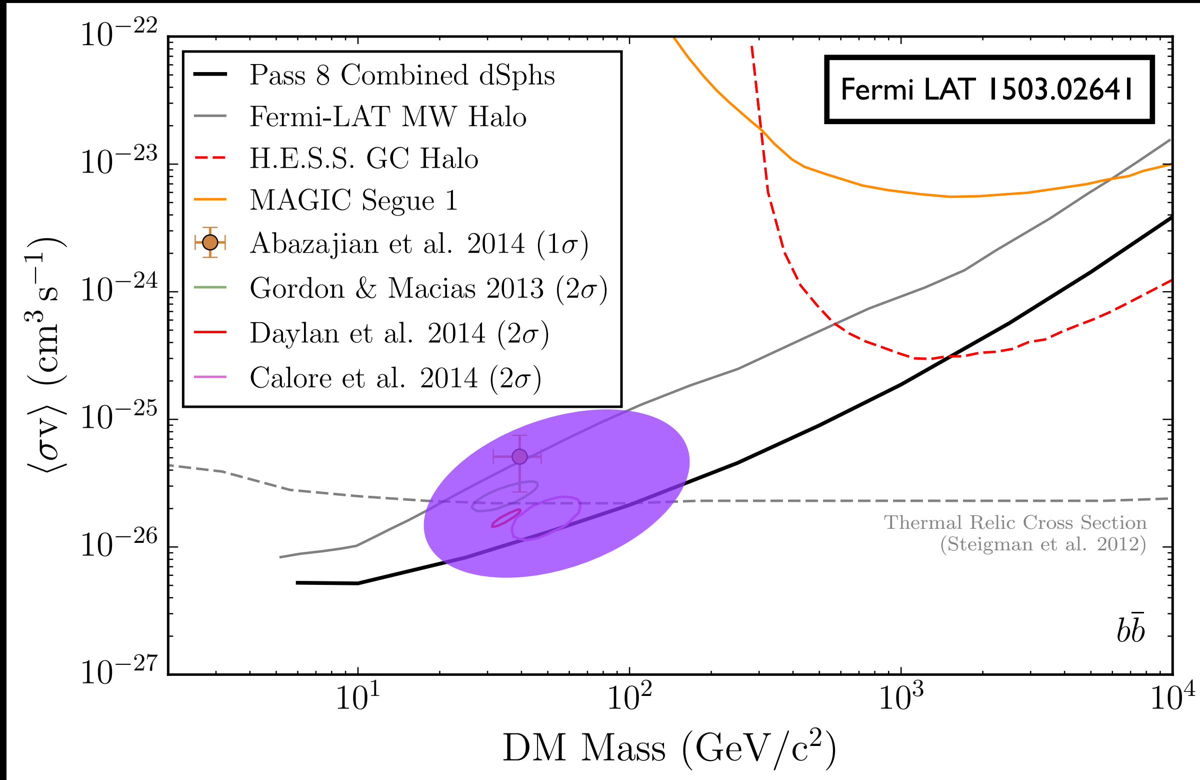
Gamma Rays

The Galactic Center "GeV Excess"





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

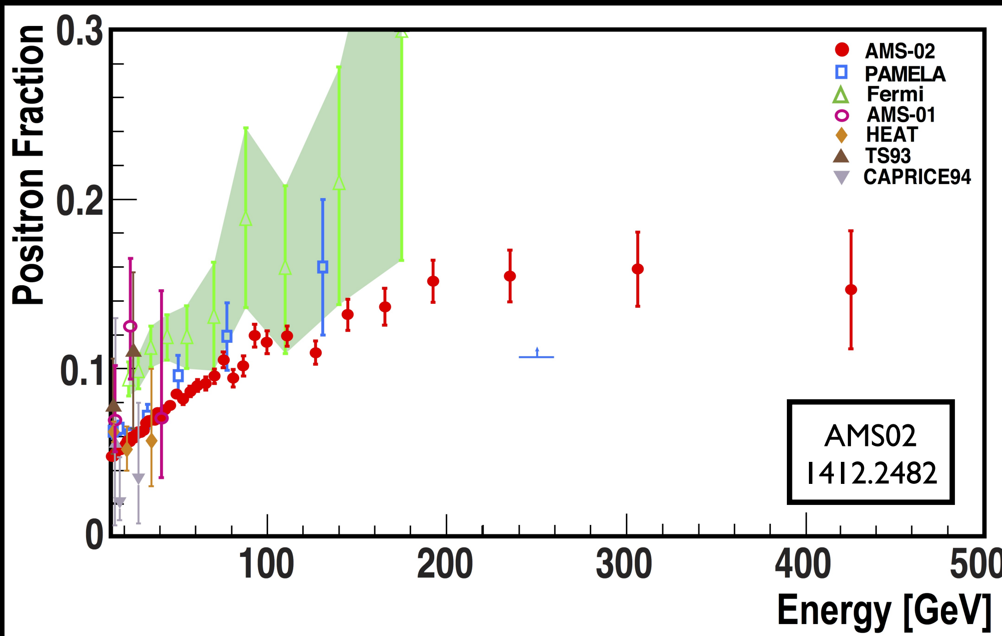


Excludes a thermal relic entirely annihilating into bb with a mass less than about 100 GeV.

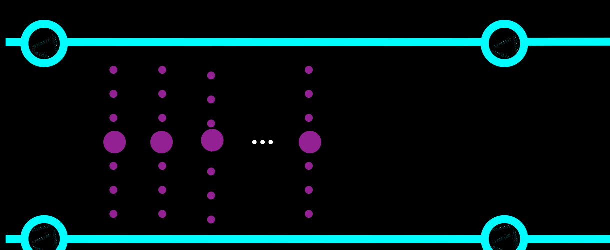
Fermi LAT 1511.02938

Indirect Detection

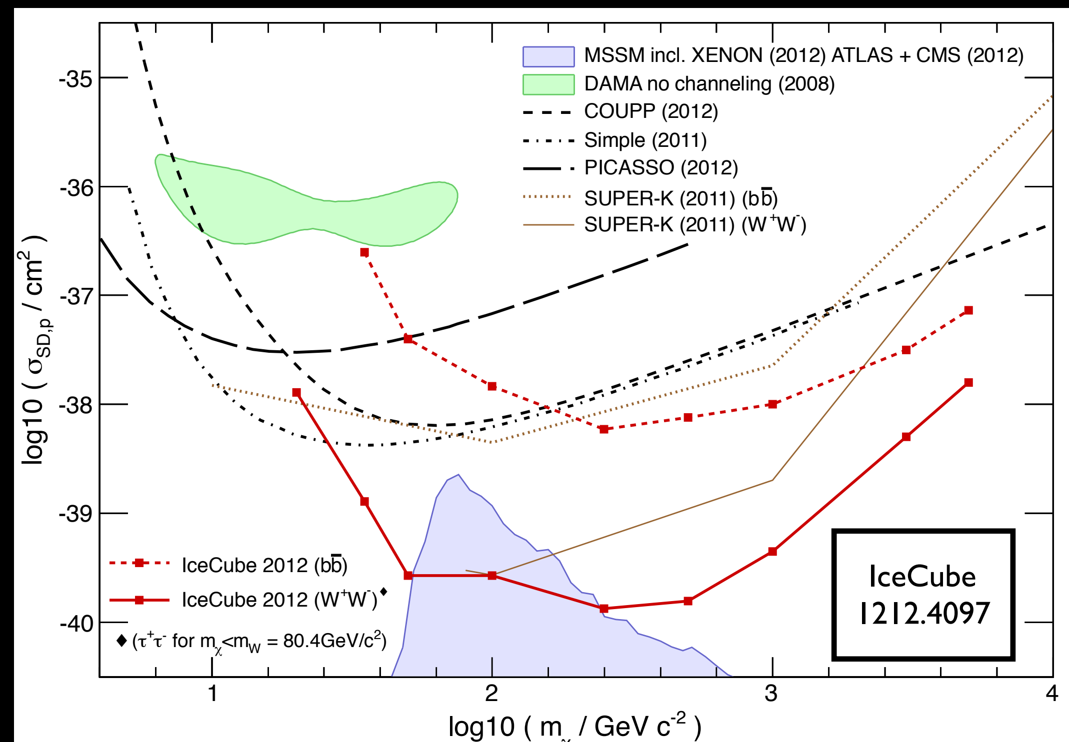
Positron Fraction at High Energies



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



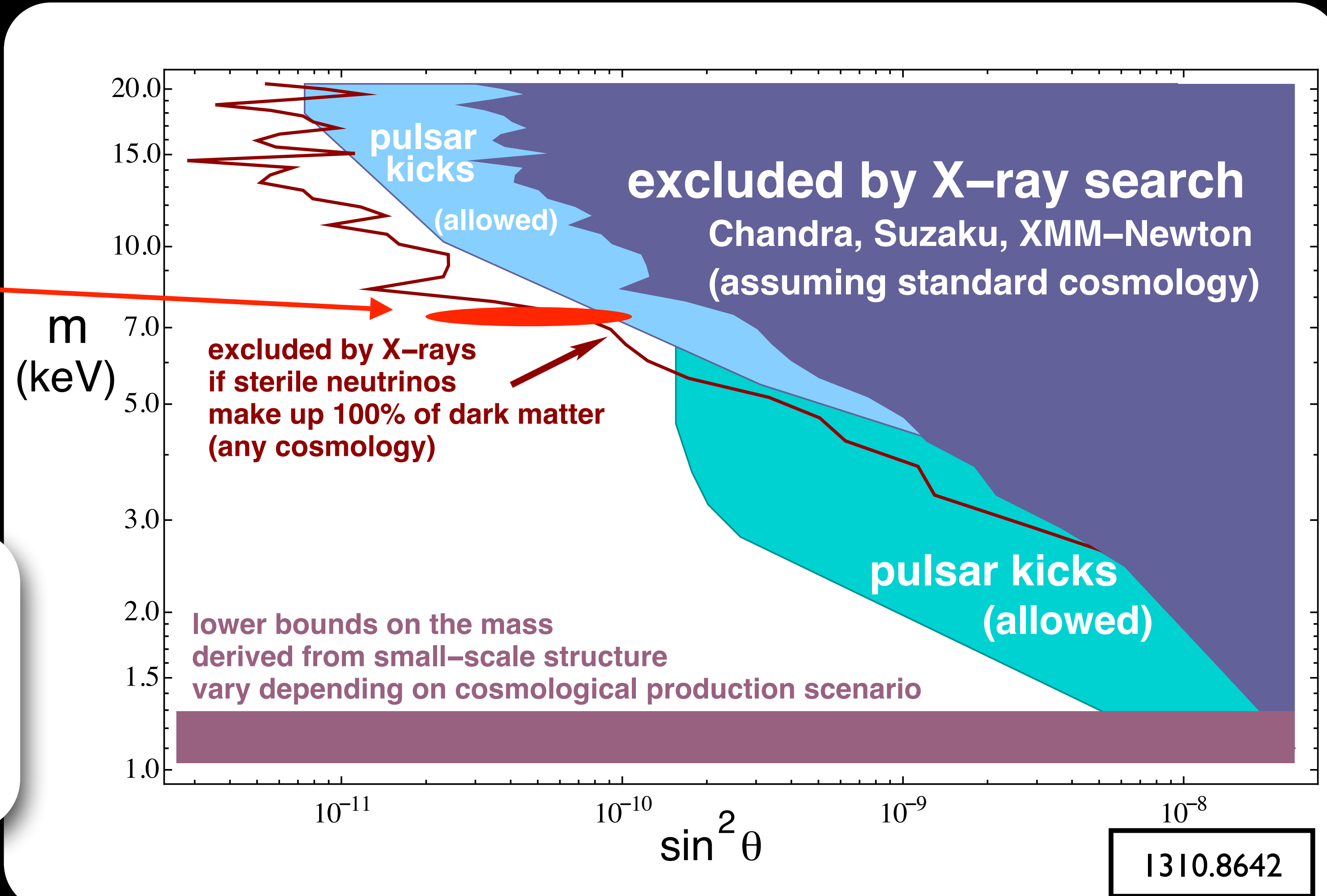
Sensitive to scattering rate with protons because accumulation in the Sun is the limiting factor.

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)



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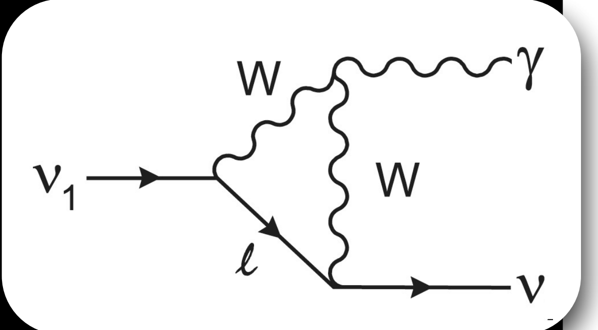
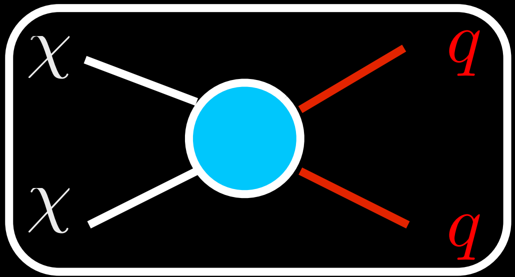
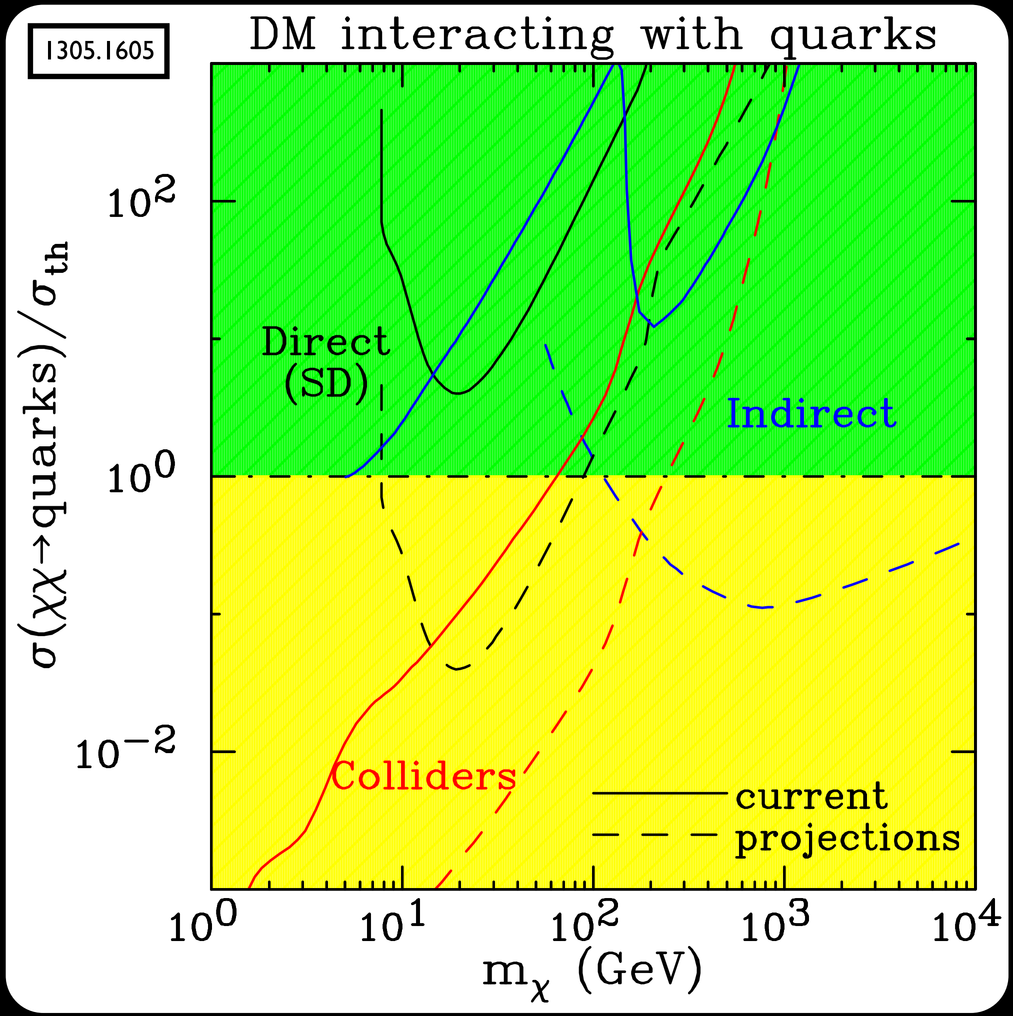


Complementarity



- These strategies for detecting WIMPs 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 better at larger masses, and for interactions which are non-vanishing in the non-relativistic limit.



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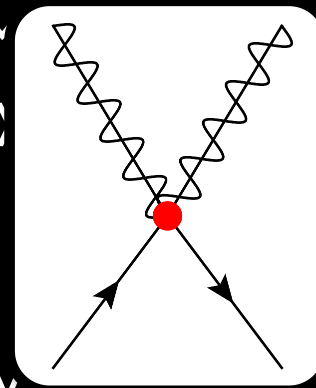

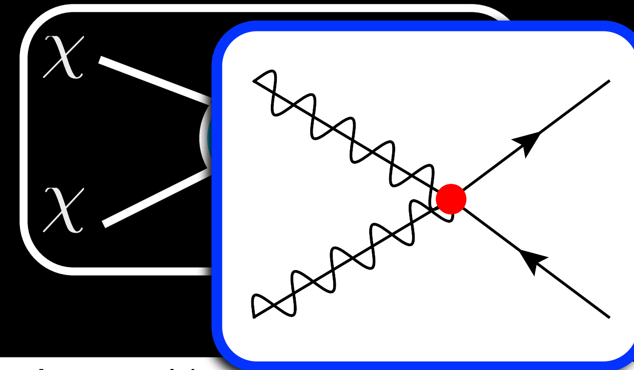

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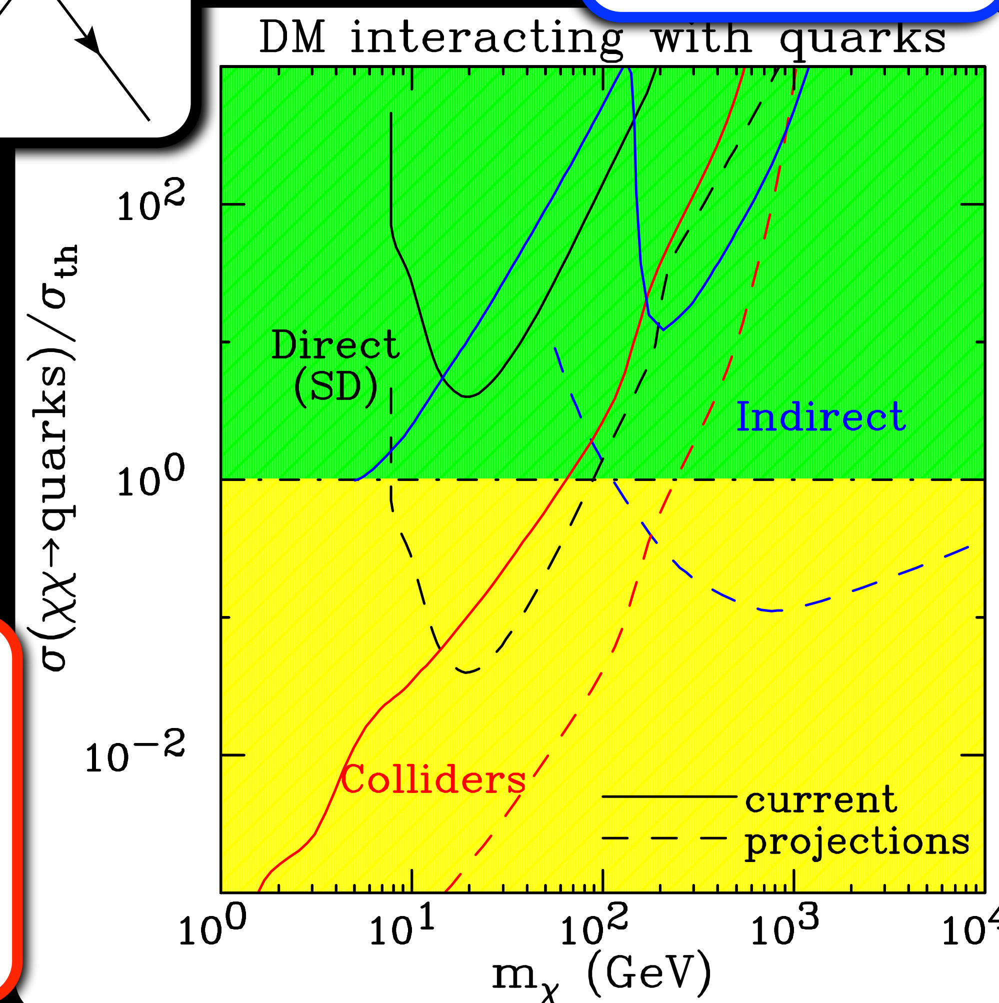
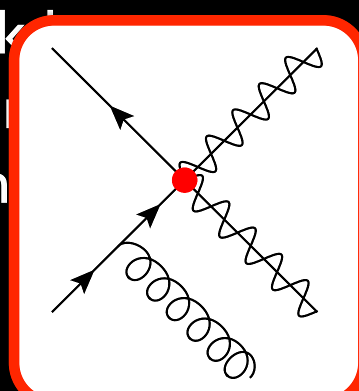
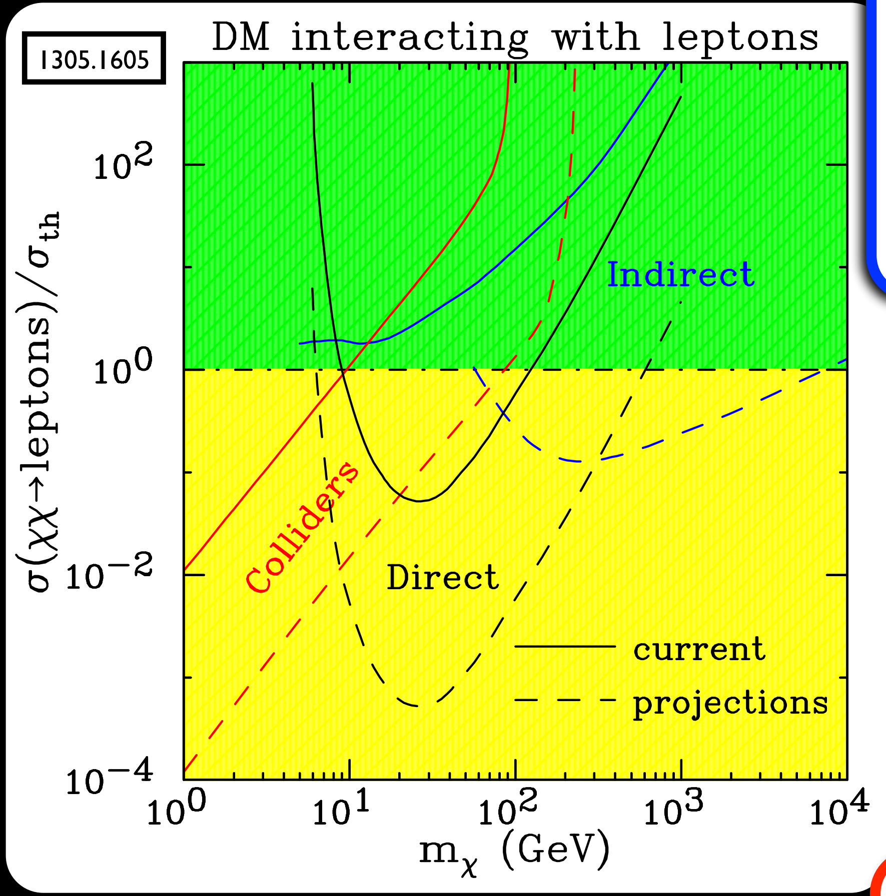
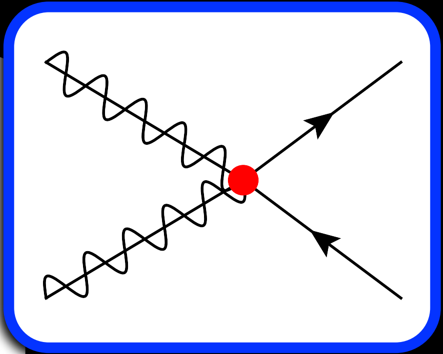


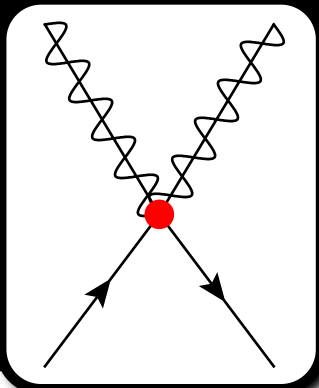
- Trends emerge: colliders are powerful at very low masses, whereas direct and indirect searches work l larger masses, and for inte which are non-vanishing in relativistic limit.

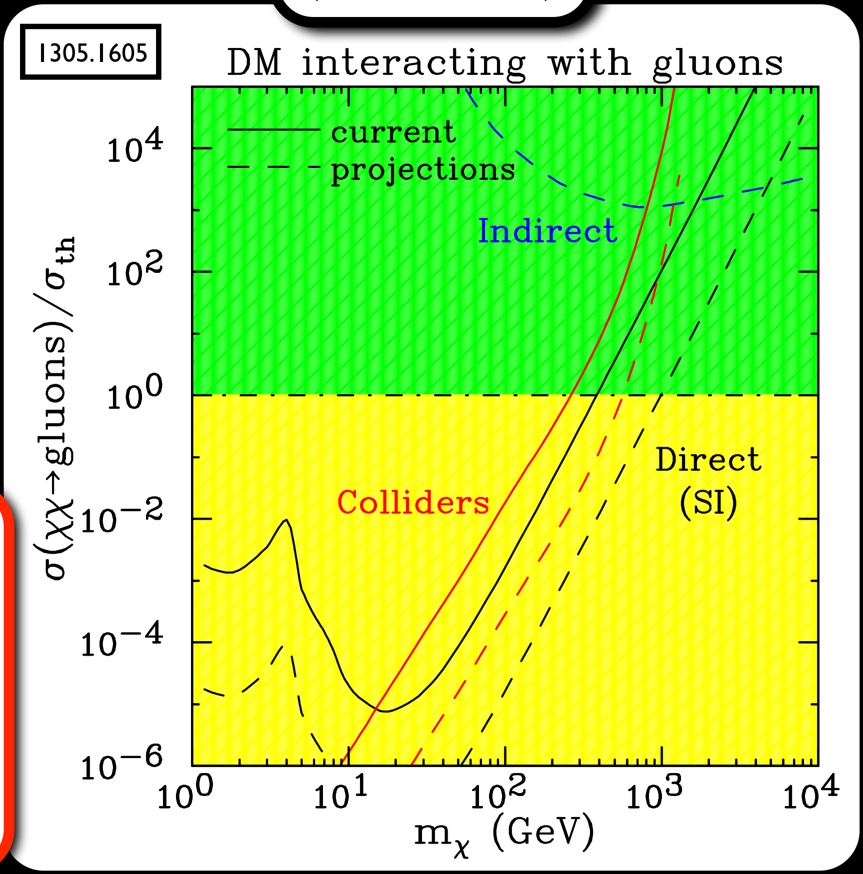


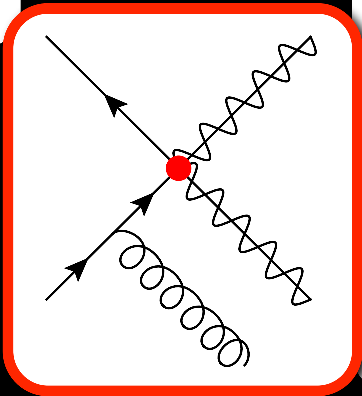
Lepton/Gluon Interactions





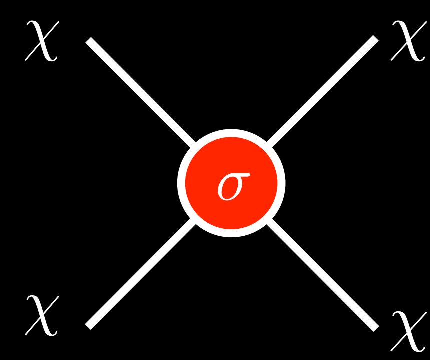






Astronomical Probes?

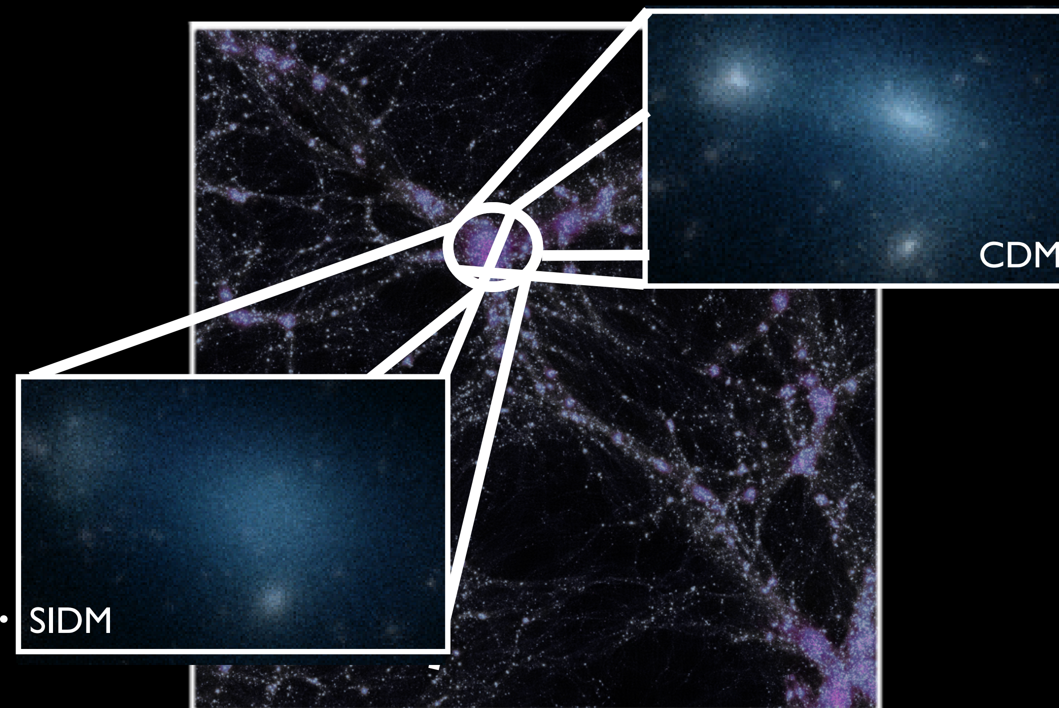
- The distribution of dark matter could reveal particle properties of dark matter.
- For example, dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- There is some (controversial) evidence 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

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

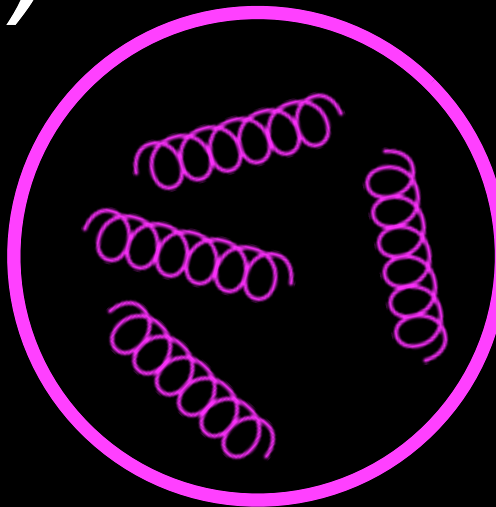
(at a relative speed of ~3000 km/s)



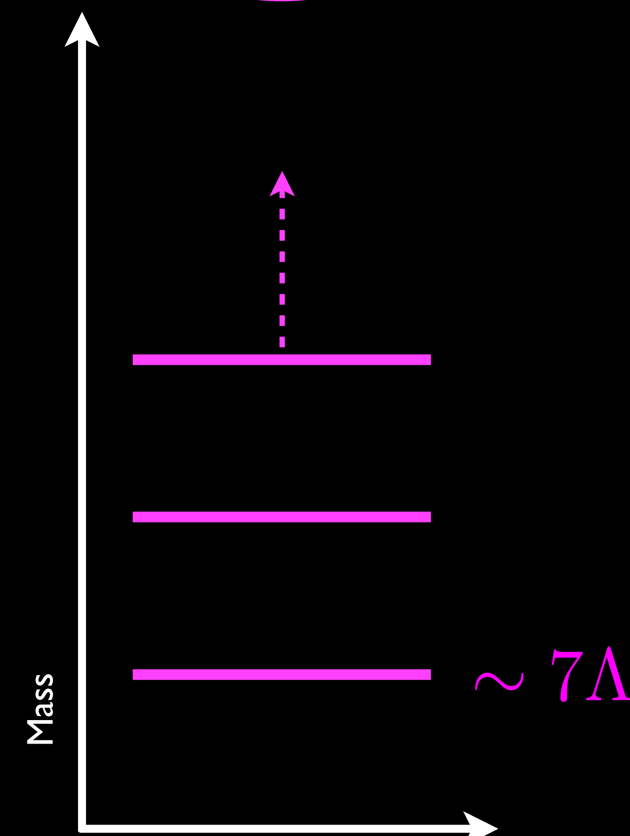
A Dark SU(N)

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

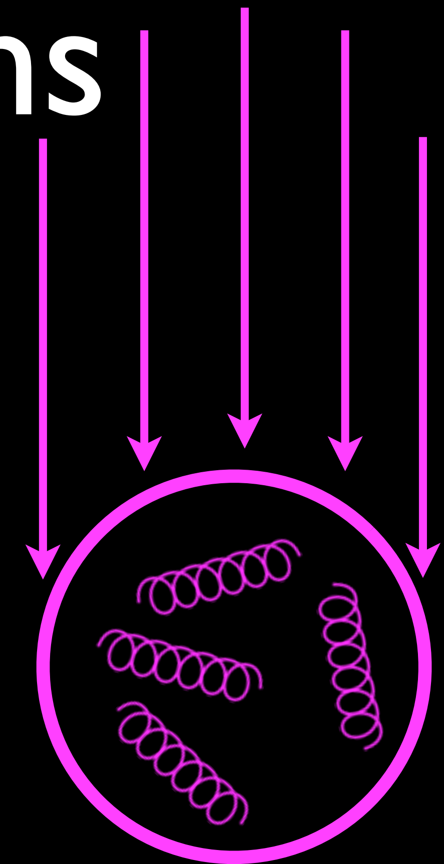
Boddy, Feng, Kaplinghat, Shadmi, TMPT 2014



- 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.

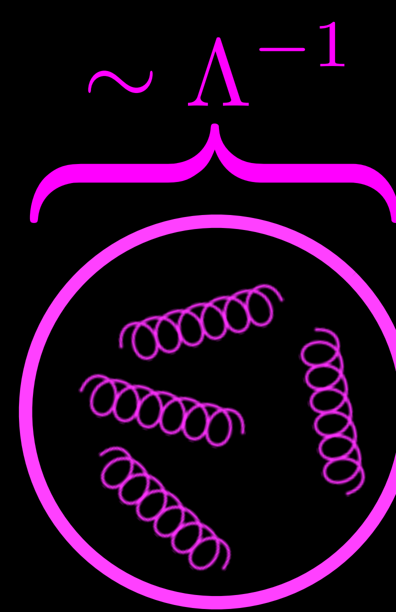


Glueball Interactions



- 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.

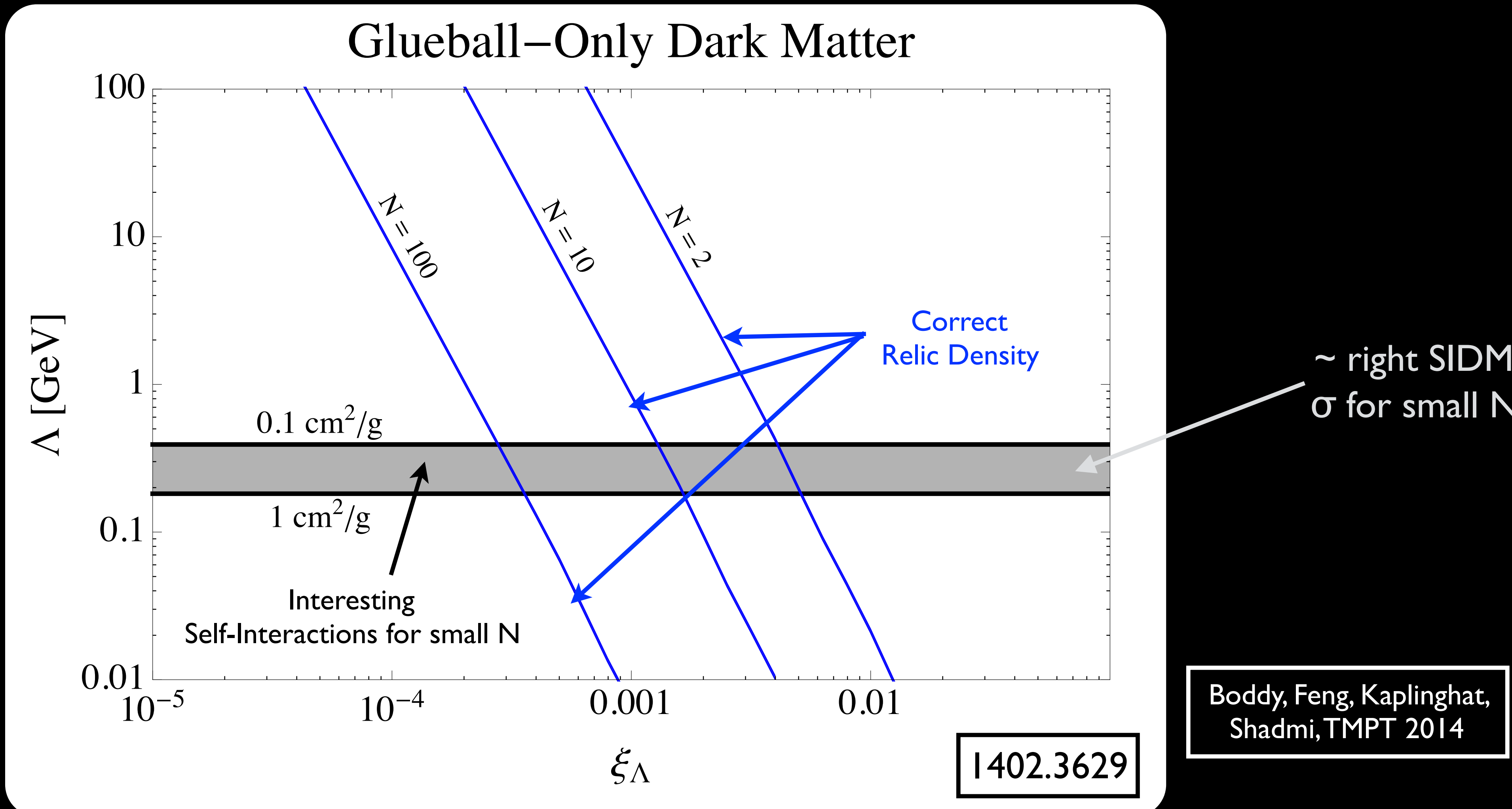
$$\sigma\,(\mathrm{gb}\ \mathrm{gb} \to \mathrm{gb}\ \mathrm{gb}) \sim \frac{4\pi}{\Lambda^2 N^2}$$



- 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



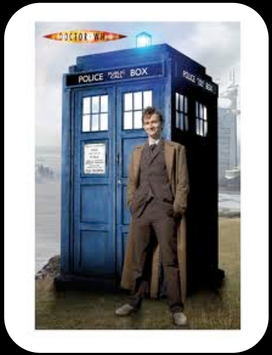
- The relic density of the glueballs depends on the temperature of the hidden sector relative to the SM ($\xi = T_h / T_{SM}$). An interesting parameter space has ~ observable self-interactions and the correct relic density.

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

A Possible Timeline



2015

2016

2017

2018

2019

2020

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

Couplings:

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

A Possible Timeline

2015

2016

Xenon-1ton sees a handful of elastic scattering events consistent with a DM mass < 400 GeV.

2017

2018

2019

2020

- ? Mass: < 400 GeV
- ☐ Spin
- ☐ Stable?

Couplings:

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

A Possible Timeline

2015

2016

YOU ARE HERE

2017

2018

2019

2020

Xenon-1ton sees a handful of elastic scattering events consistent with a DM mass < 400 GeV.

H.E.S.S. observes a faint gamma ray line at 350 GeV from the galactic center.

- [x] Mass: 350 +/- 50 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

Xenon-1ton sees a handful of elastic scattering events consistent with a DM m V.

Super-CDMS sees a similar signal.

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

H.E.S.S. observes a faint gamma ray line at 350 GeV from the galactic center.

- ☑ Mass: 350 +/- 50 GeV
- ☐ Spin
- ☐ Stable?

Couplings:

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

A Possible Timeline

2015

2016

YOU ARE HERE

2017

Xenon-1ton sees a handful of elastic scattering events consistent with a DM mass < 400 GeV.

Super CDMS sees
gnal.

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

Veritas observes a faint gamma ray line at 350 GeV from the galactic center.

No jets + MET

Neutrinos are seen coming from the Sun by IceCube.

- ☑ Mass: 350 +/- 50 GeV
- ☑ Spin: > 0
- ☐ Stable?

Couplings:

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

A Possible Timeline

2015

2016

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2018

2019

2020

Xenon-1ton sees a handful of elastic scattering events consistent with a DM mass < 400 GeV.

Super-CDMS sees a similar signal.

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

Veritas observes a faint gamma ray line at 350 GeV from the galactic center.

☑ Mass: 350 +/- 50 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: 350 +/- 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?

Veritas observes a faint gamma ray line at 350 GeV from the galactic center.

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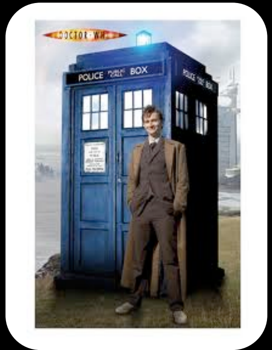
Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.

A Possible Timeline



2015

2016

YOU ARE HERE

2017

2018

2019

2020

????

- ☑ Mass: 350 +/- 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 composed of classic WIMPs and axions.

Xenon-1 handful scatteri consistent mass <

Super-C a simila

Veritas observes a faint gamma ray line at 350 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.

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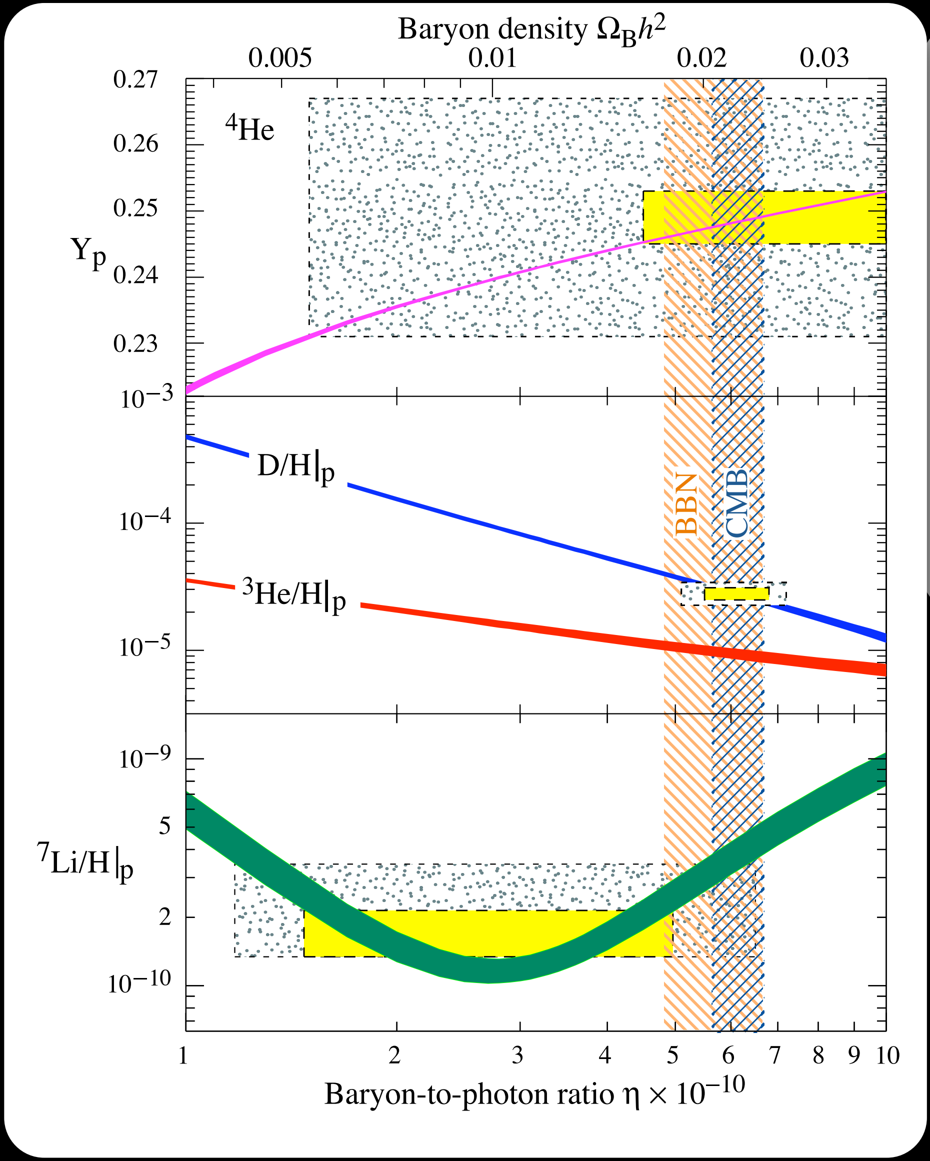
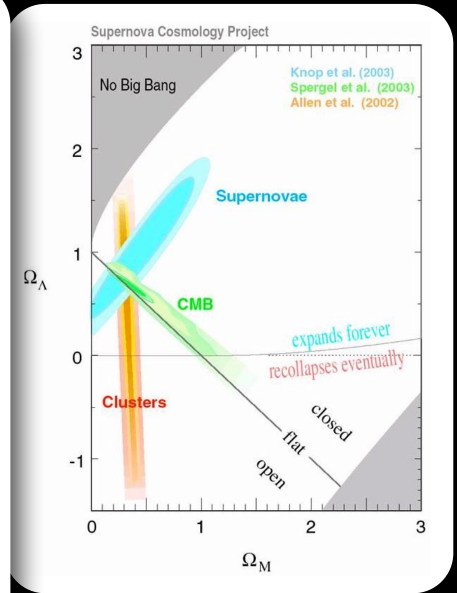
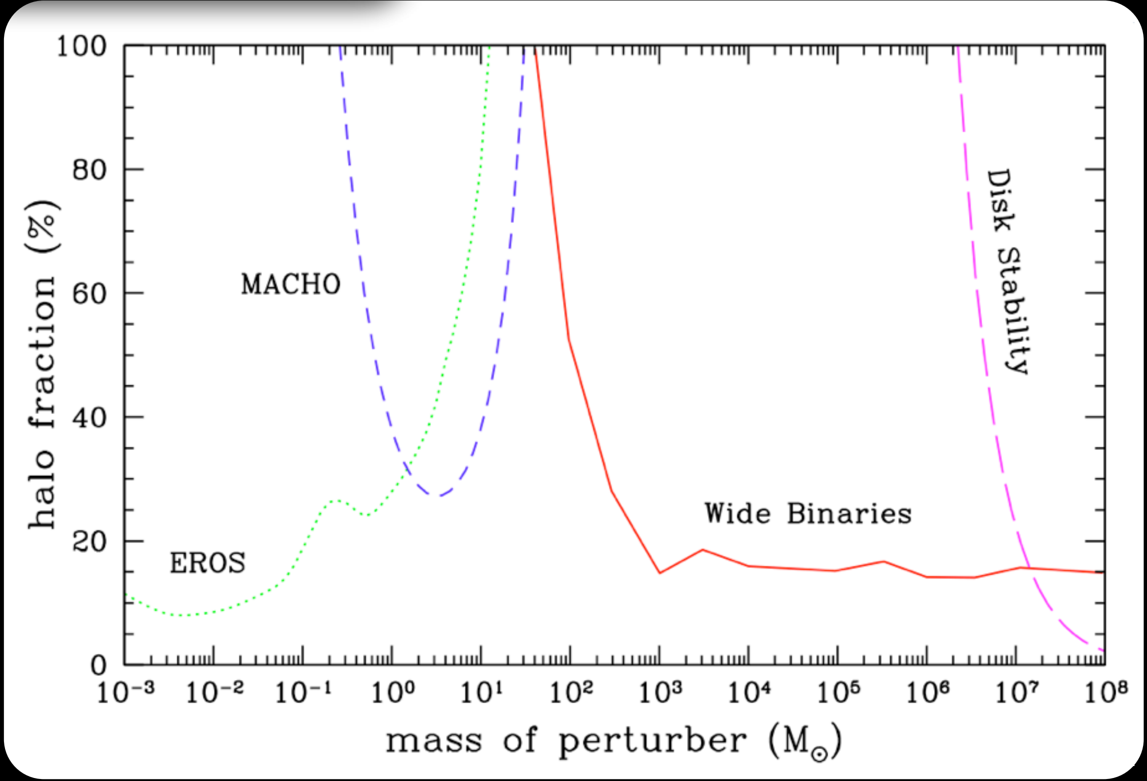
No Ordinary Matter…





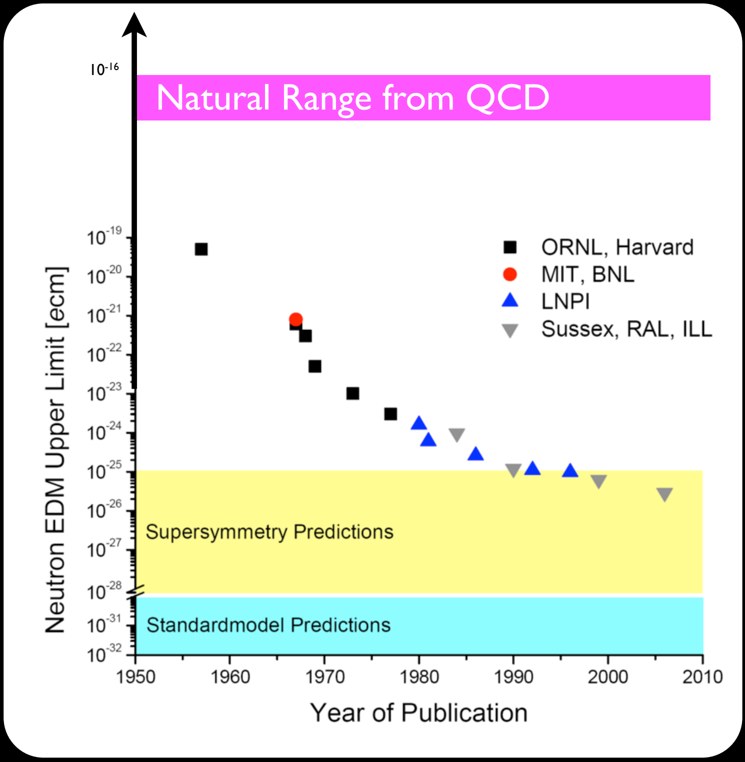
Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.

Primordial black holes remain a possible candidate, but would need some kind of mechanism to explain their production and mass distribution.



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.

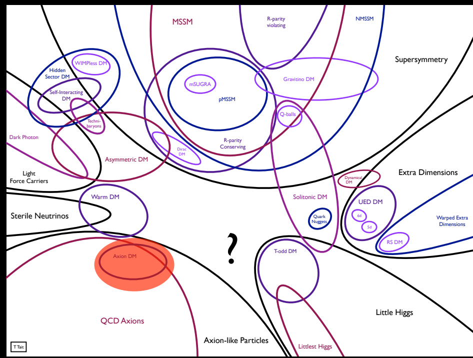


- The axion's mass and coupling are determined by virtue of its being a pseudo-Goldstone boson and are characterized by the energy scale $f_a > 10^9$ GeV.

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

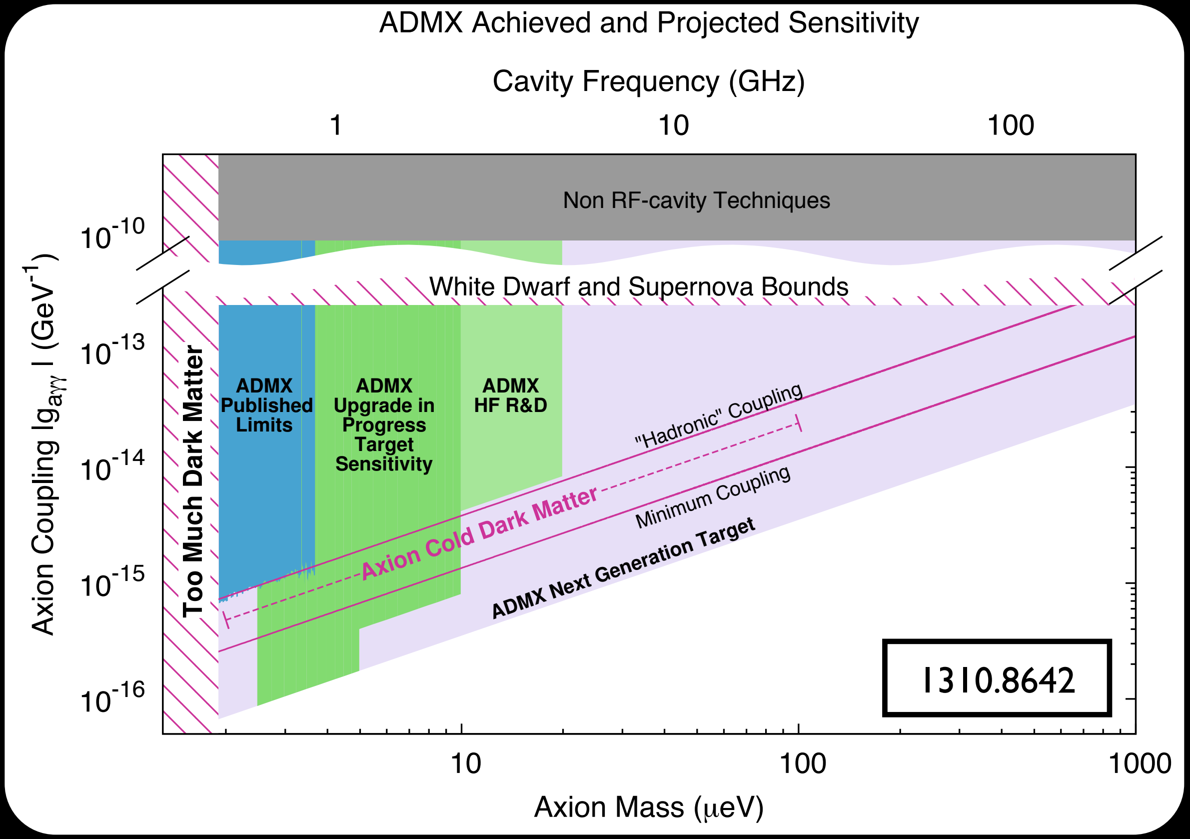
- The axion is unstable, but its tiny mass and weak couplings conspire to predict that for much of the viable parameter space its lifetime is much greater than the age of the Universe itself.

- 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.



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.



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