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Community Summer Study (Snomass 2013)

DARK MATTER IN THE COMING DECADE: COMPLEMENTARY PATHS TO DISCOVERY AND BEYOND

On behalf of the CF4 Working Group (Manoj Kaplinghat, Konstantin Matchev, DH)

The Dark Matter Discovery Age

In a sense, we have already discovered dark matter

- Observations of galaxy dynamics, galaxy clusters, large scale structure, the cosmic microwave background, light element abundances, etc. collectively provide an overwhelming body of evidence in favor of the conclusion that most of the matter in our Universe consists of (relatively) cold and collisionless particles
- Despite considerable effort, no viable alternatives to this conclusion have been proposed

But we have not yet identified the nature of the particle(s) that make up the dark matter

- No particles contained in the standard model are viable dark matter candidates – dark matter is new physics

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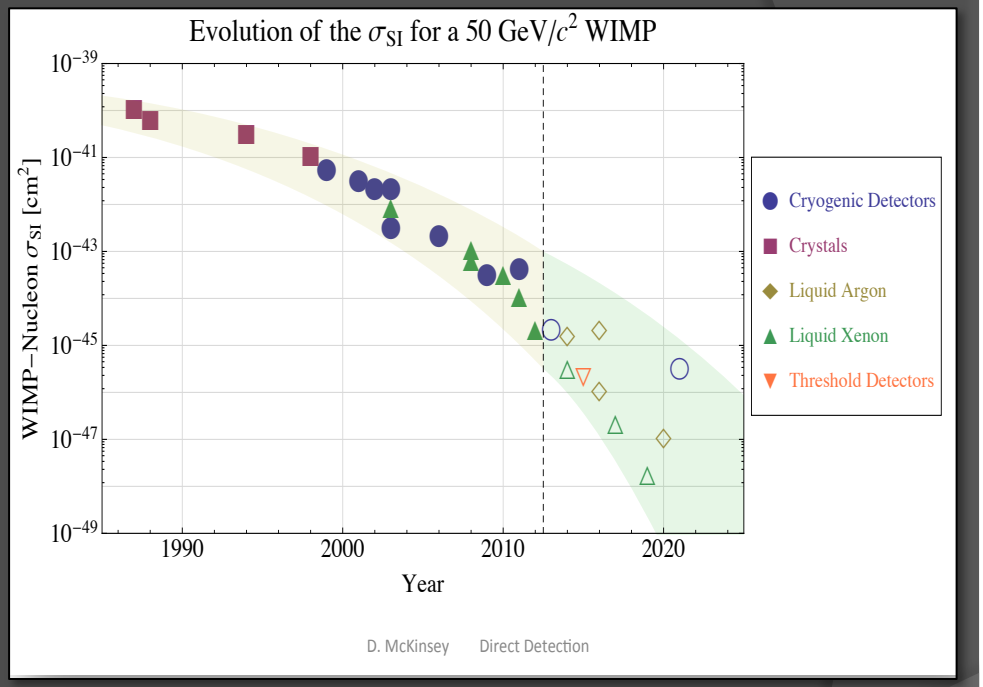
After decades of experimental progress, we are currently in a position in which many or most of the best motivated dark matter candidates are within reach of near future experiments – The successful detection of dark matter particles within the next decade seems likely

Direct Detection

- Over the past dozen years, constraints from direct detection experiments have improved with a Moore's-law like behavior (a factor of 2 every 15 months)



Direct Detection

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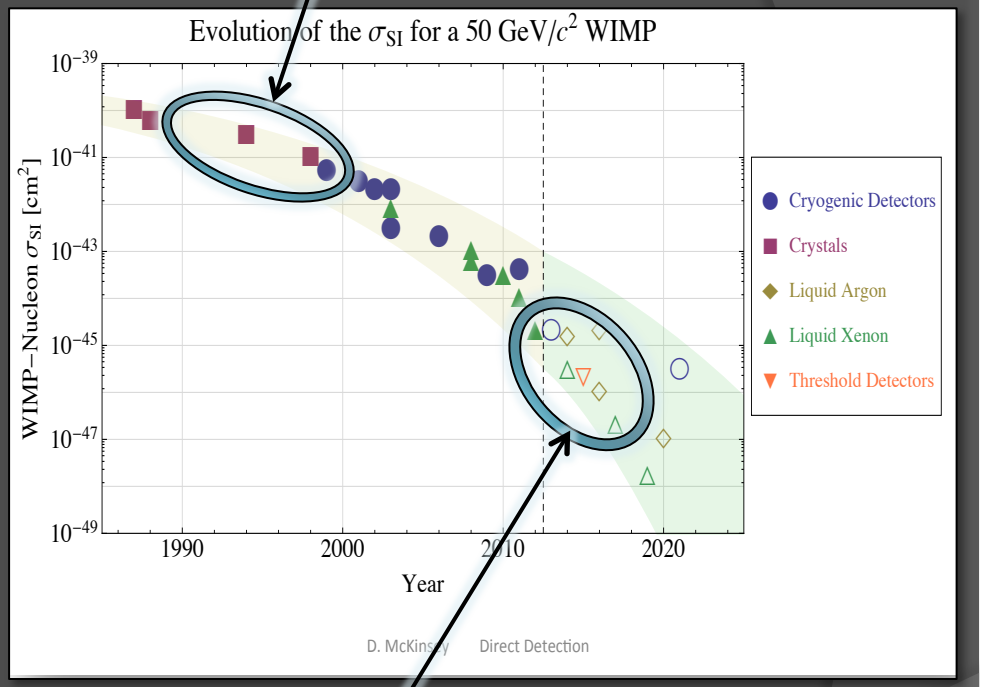
- Some important benchmarks exist along this line:
  - Mid-late 90s: Direct detection experiments excluded the cross sections predicted for a WIMP which scatters and annihilates through Z-exchange
  - Now!: Current experiments are beginning to test WIMPs which interact through Higgs exchange (including many SUSY models)

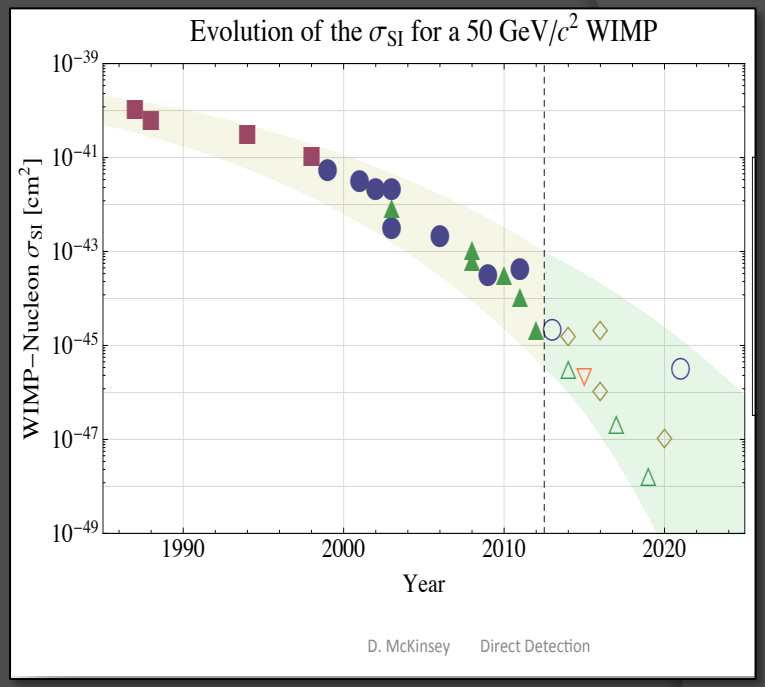
Z-mediated scattering
(sneutrinos, heavy neutrinos)



Higgs-mediated scattering
(A-funnel, focus point neutralinos)

Direct Detection

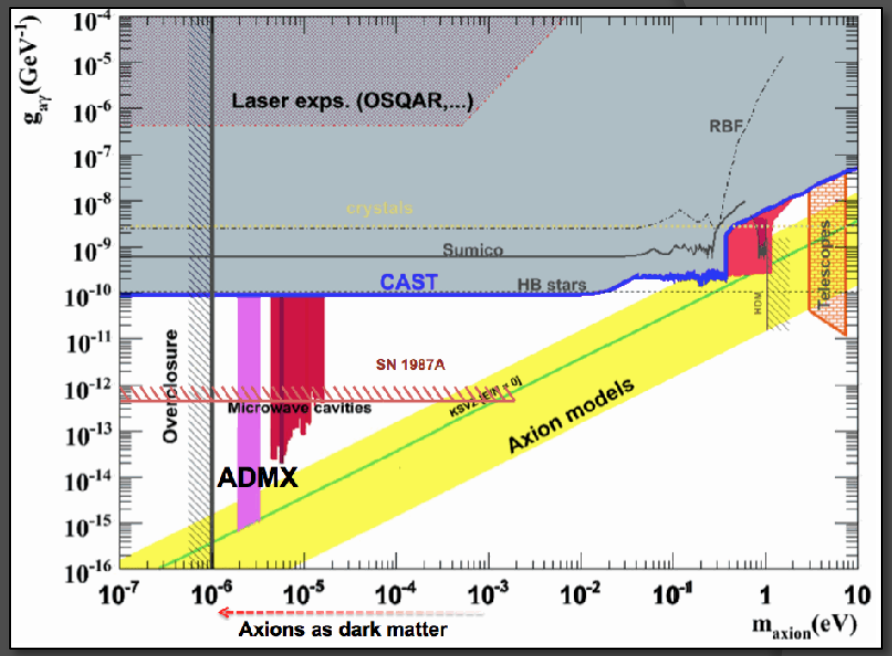
- If this rate of progress continues without the observation of a signal for another ~5 years, the remaining dark matter models will be severely constrained
- In order for WIMPs to evade detection over this time frame, one must consider one or more of the following:
  - WIMPs which couple almost entirely to leptons or gauge bosons, rather than to quarks
  - WIMPs which annihilate in the early universe through a highly-tuned resonance, or through a highly degenerate co-annihilation
  - WIMPs which are light enough to fall below experimental energy thresholds (m_X<10 GeV)
  - Non-standard cosmology (*ie*. low reheating)



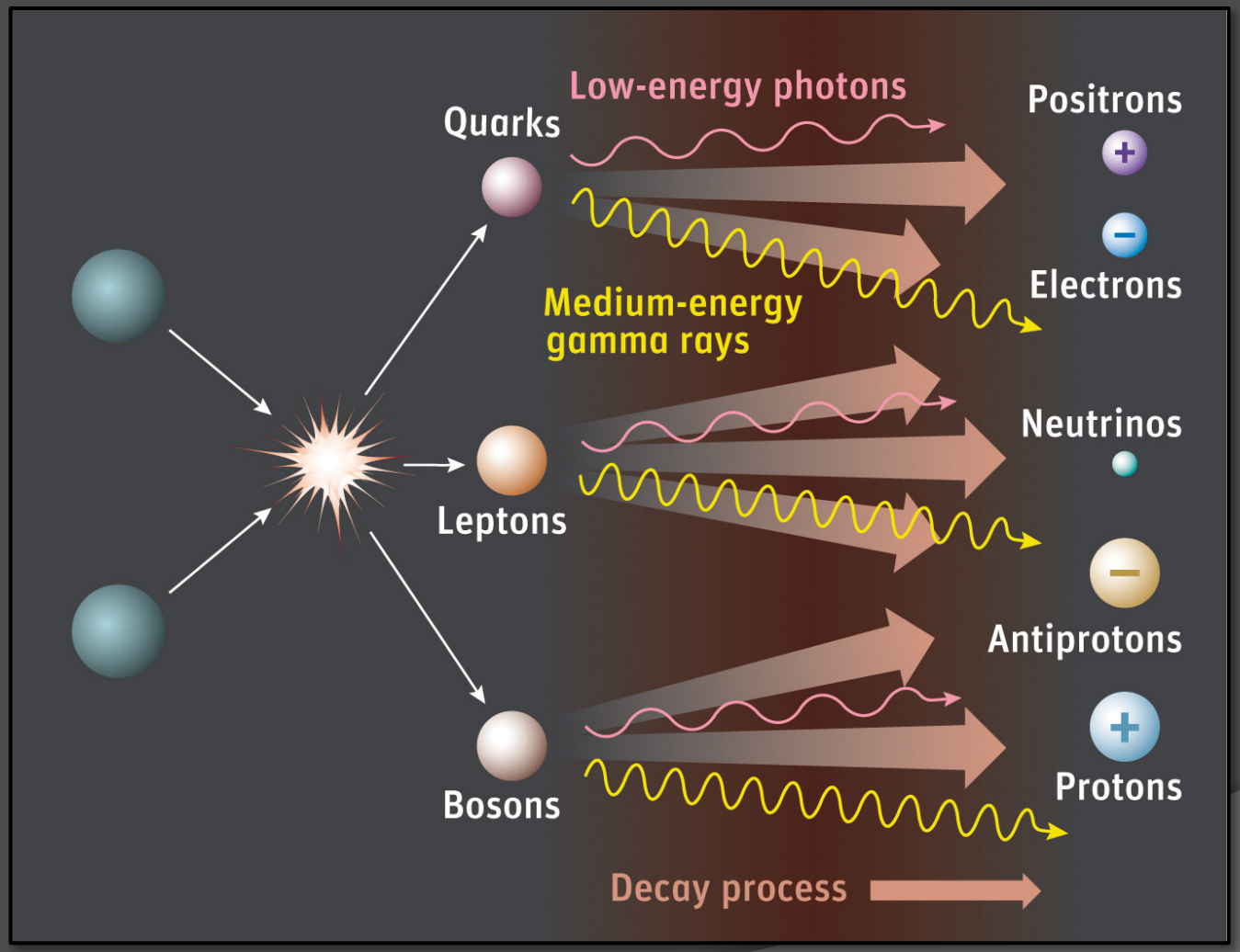
It is starting to become difficult to hide our best motivated dark matter models from direct detection expts. ~5-10 years from now, very few WIMP models will remain out of reach

Direct Detection of Axions

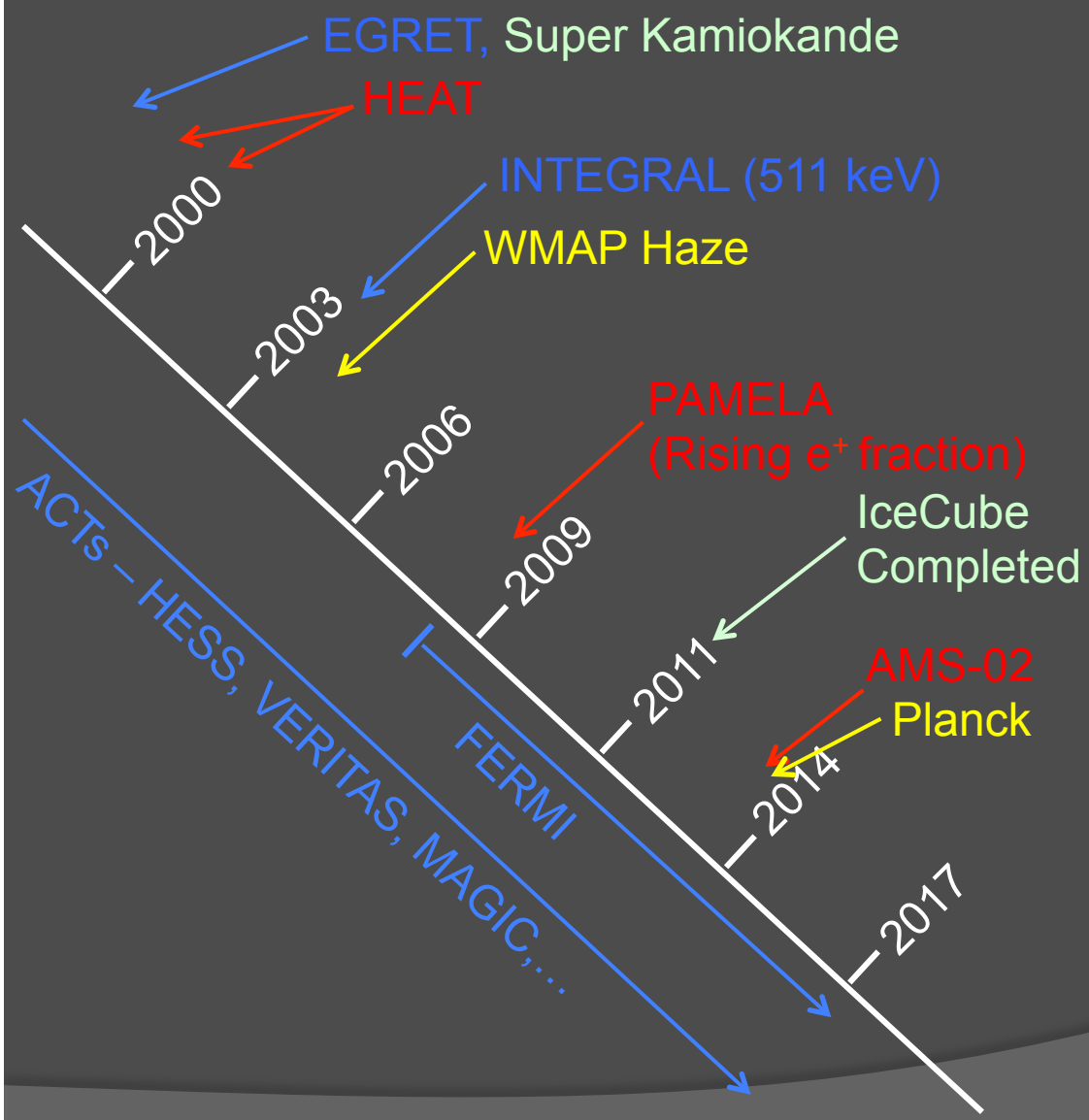
- The QCD axion is a natural consequence of the Pecci-Quinn solution to the strong CP problem, and represents a well motivated and viable candidate for dark matter
- Axion-photon conversion in the presence of strong magnetic field provides a mechanism to directly search for axion dark matter particles
- The mass range predicted for axion dark matter extends over roughly three orders of magnitude, from 10^{-6} to 10^{-3} eV
- ADMX is projected to cover the first of these three decades in its first year of operations, and the second decade over the following two years



Indirect Detection



Some Highlights in Indirect Detection



A **key benchmark for indirect searches:**

-To be produced with the observed dark matter abundance, a thermal relic must have an annihilation (at freeze-out) of $\sigma v \sim 3 \times 10^{-26}$ cm^3/s

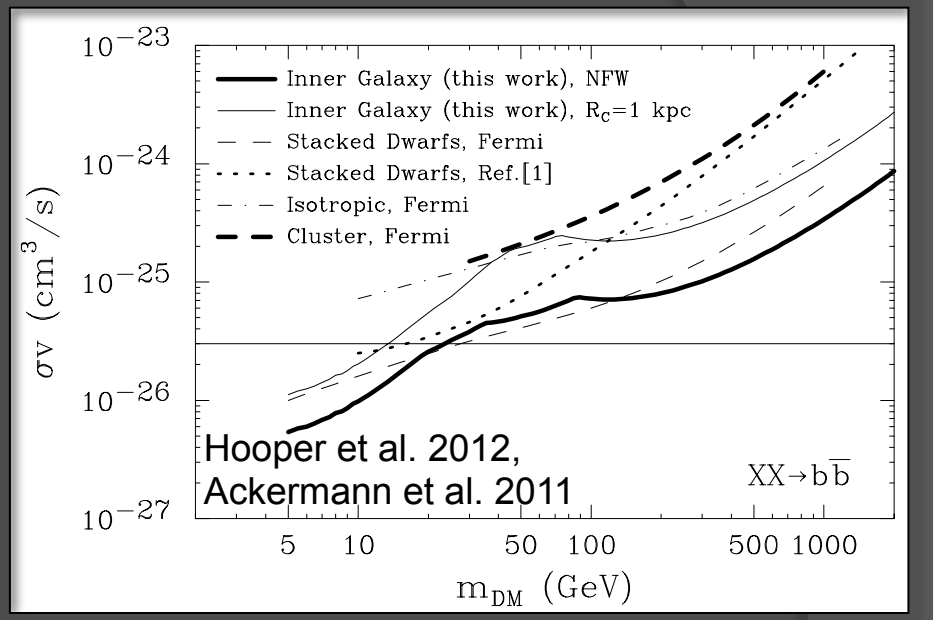
-Although many factors could enable the dark matter to possess a somewhat different cross section today, many models predict current annihilation rates that are within an order of magnitude or so of this estimate

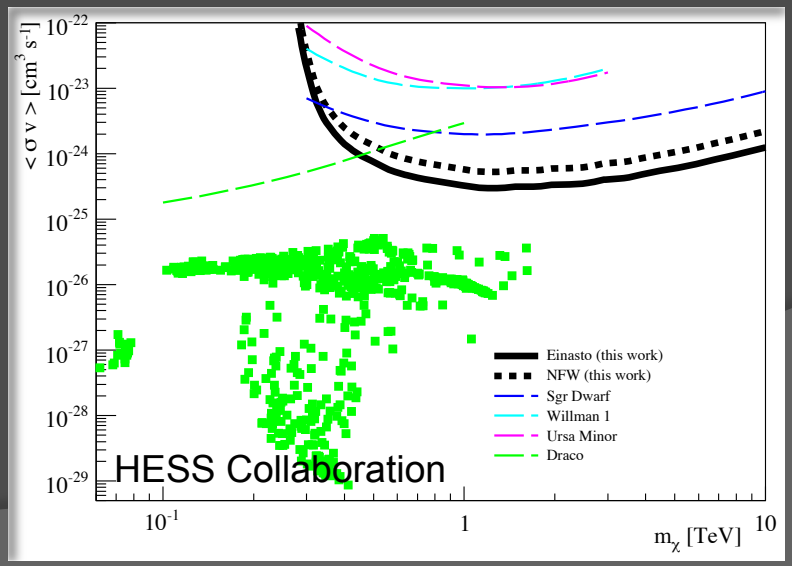
-For the first time, existing experiments are beginning to test WIMPs with an annihilation cross section near this value

Status of Indirect Detection

Gamma-Rays

- The Fermi Gamma-Ray Space Telescope's observations of dwarf spheroidal galaxies and the Galactic Center are sensitive to simple thermal WIMPs lighter than ~30 GeV (weaker but competitive limits have been derived from clusters, the isotropic gamma-ray background, and subhalo searches)
- Ground based telescopes (HESS, VERITAS, MAGIC) are most sensitive to high mass WIMPs





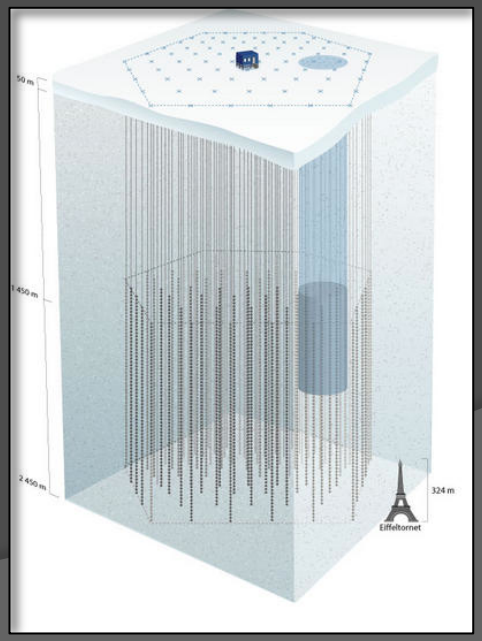
Status of Indirect Detection

Cosmic Rays

- AMS and PAMELA are sensitive to antiprotons and positrons from dark matter annihilations in the halo; in some cases competitive with gamma-ray constraints

Neutrinos

- IceCube is sensitive to dark matter annihilations in the core of the Sun; constraints on spin-dependent scattering are competitive with those from direct detection experiments



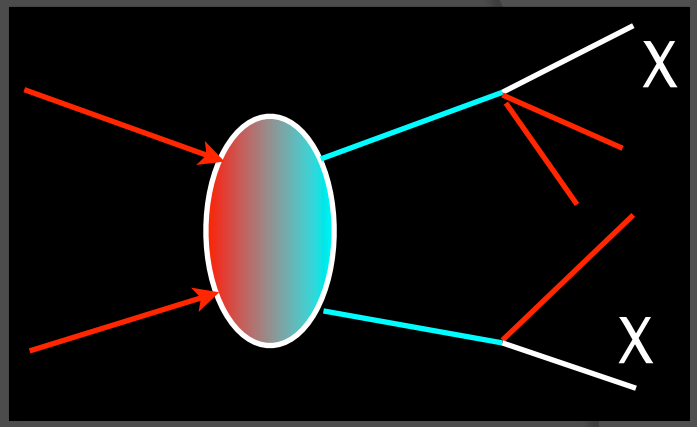
Other Techniques

- Radio and X-ray telescopes, observations of the CMB, and other probes can also constrain the dark matter's annihilation cross section

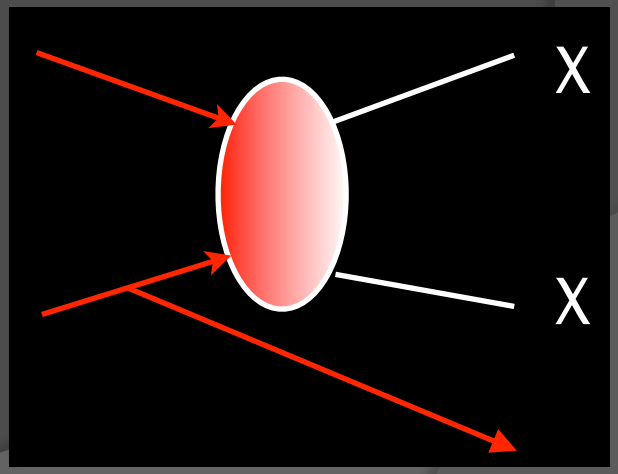
Dark Matter at the LHC

Two basic dark matter strategies:

1) Pair produce strongly interacting particles which decay into dark matter particles, along with standard model particles (ie. squark/gluino production, followed by their decay to the LSP)



2) Produce dark matter pairs directly, along with a single jet or photon



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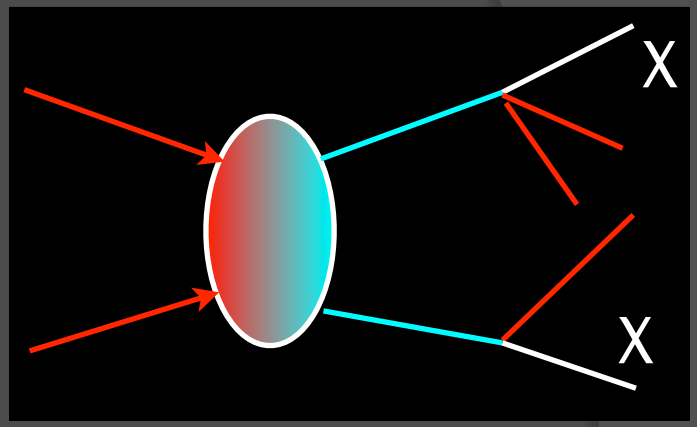
-Potentially high rates

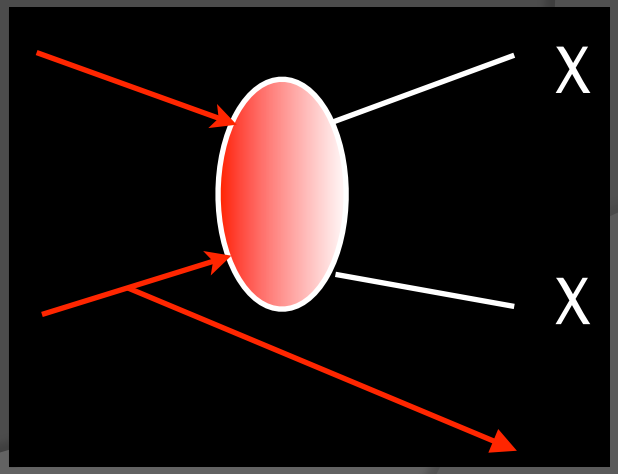
-Prospects depend on masses of the new strongly interacting particles (model dependent)



2) Produce dark matter pairs directly, along with a single jet or photon

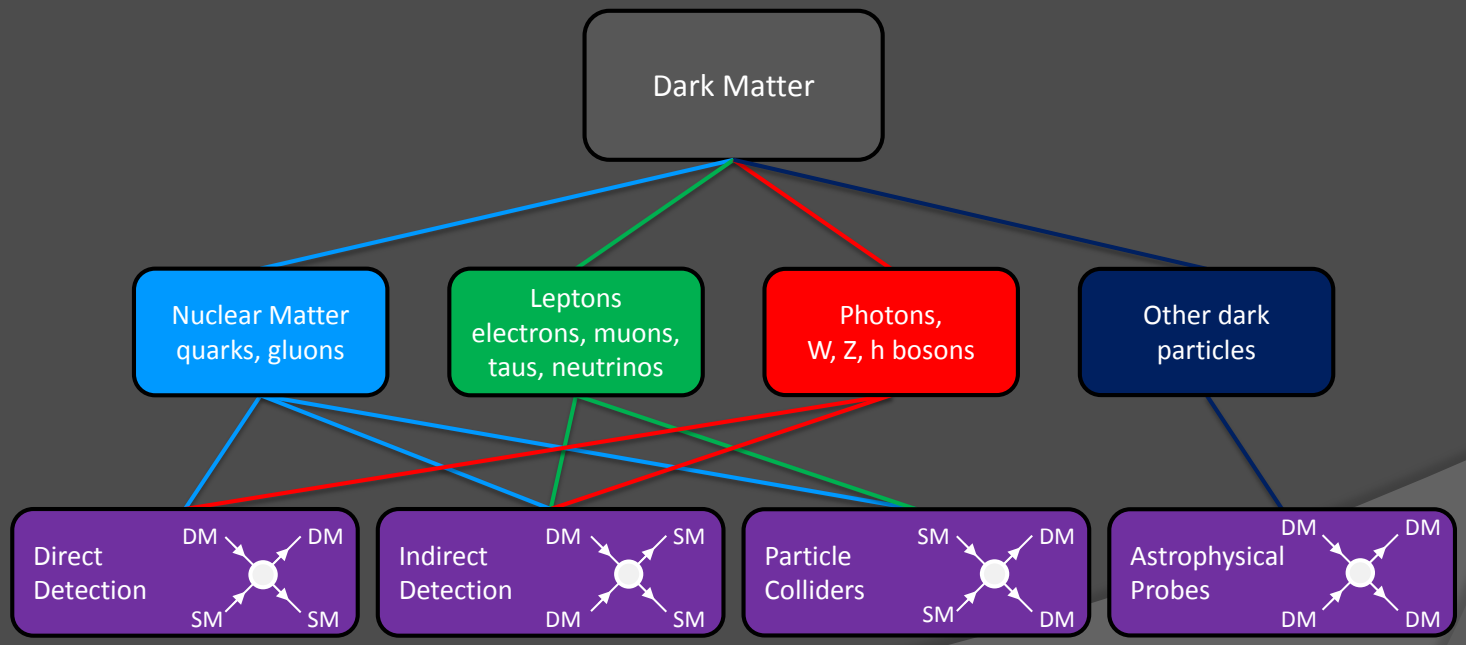
-Lower rates (limited mass reach)

-Less model dependent



Why So Many Techniques?

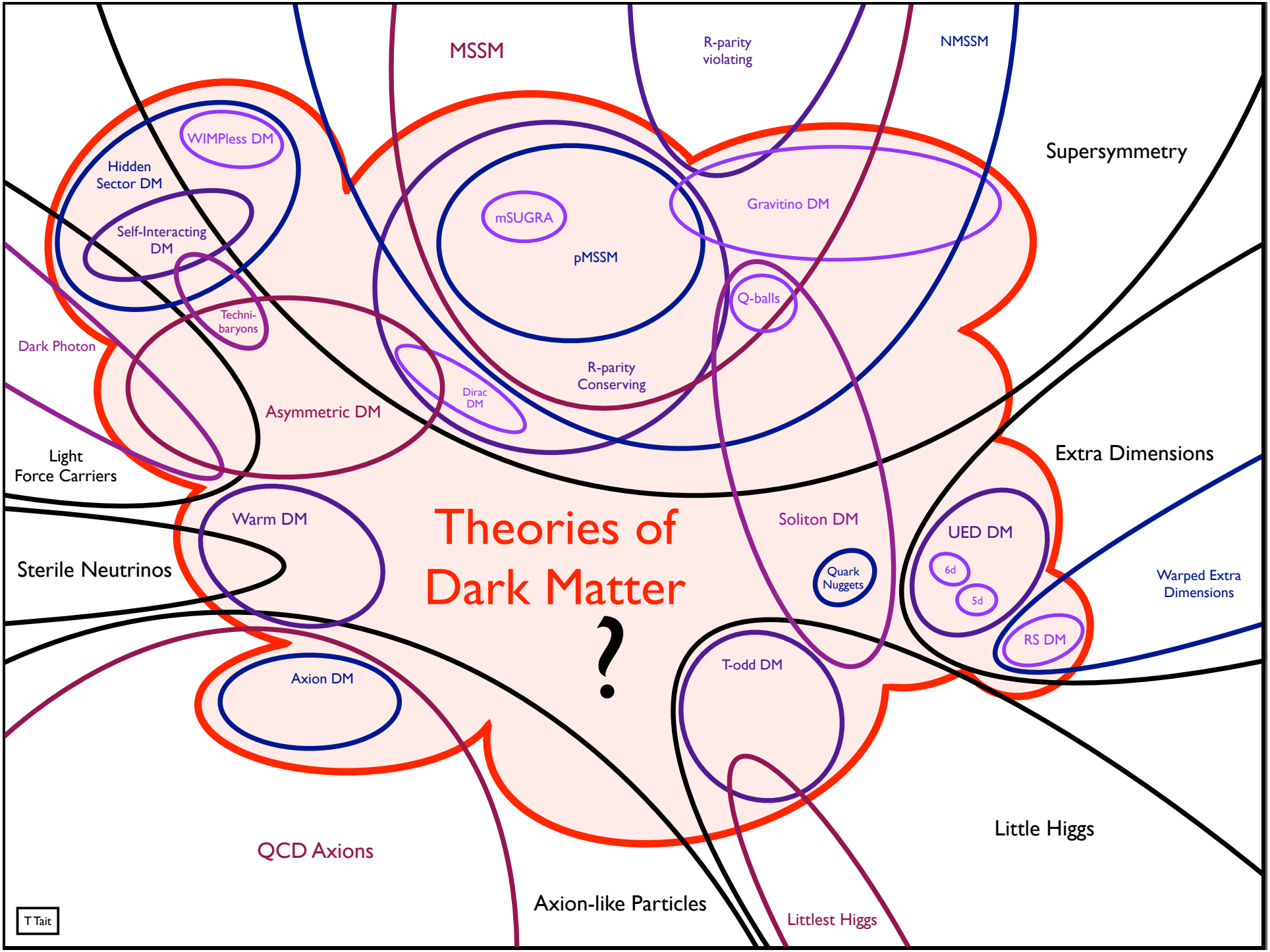
- If we knew what the dark matter consisted of, we could optimize our strategy to observe it
- But we don't. And different experimental approaches are sensitive to dark matter candidates with different characteristics, and provide us with different types of information – complementarity!



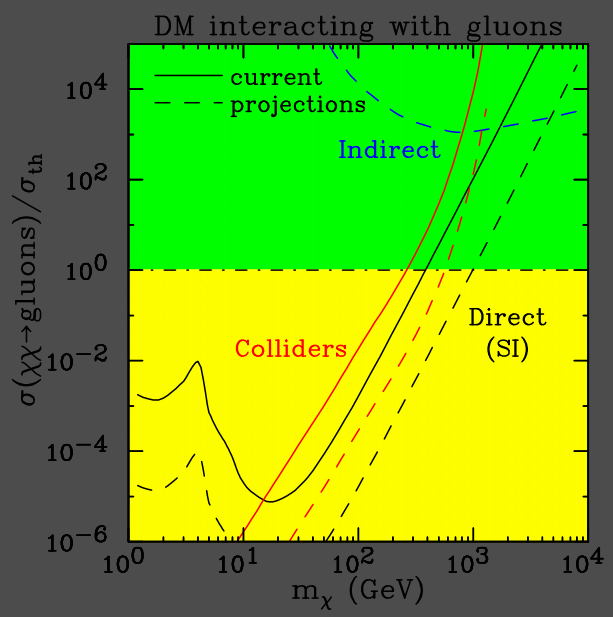
Why So Many Techniques?

No one technique will answer all (or even most) of our questions about the nature of dark matter:

- The LHC cannot tell us whether a weakly interacting particle is stable and cosmologically relevant, or merely long-lived on collider timescales
- Neither direct not indirect detection experiments alone will be able to determine the spin of the dark matter candidate, or identify how these particles interact (although they can narrow down the possibilities)
- These techniques each suffer from different uncertainties and limitations
- By combining information from multiple techniques, a much more detailed description of the dark matter could emerge


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

Complementarity of Direct, Indirect, and Collider Searches for Dark Matter



$$\frac{\alpha_S}{M_g^3}\ \bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu}$$

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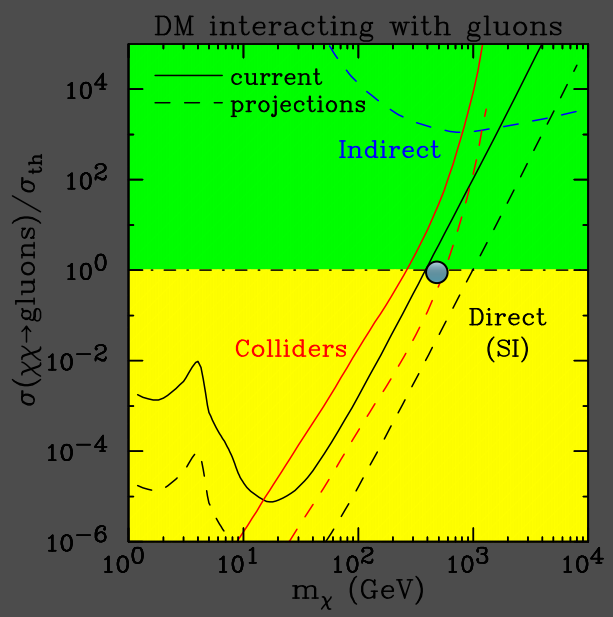

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- In this case, the WIMP will be discovered by both future direct experiments and by the LHC, but not by indirect detection efforts
- These signals strong favor a thermal relic interpretation, without significant annihilations through other couplings

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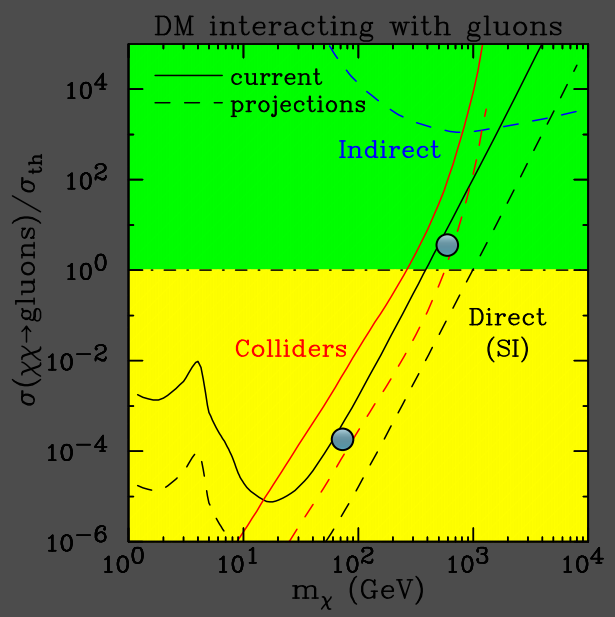

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- In this case, the WIMP will be discovered by both future direct experiments and by the LHC, but not by indirect detection efforts
- These signals strong favor a thermal relic interpretation, without significant annihilations through other couplings
- In other cases, a discovery could be made, but less supporting of the thermal relic interpretation – Other important couplings? Non-thermal origin?

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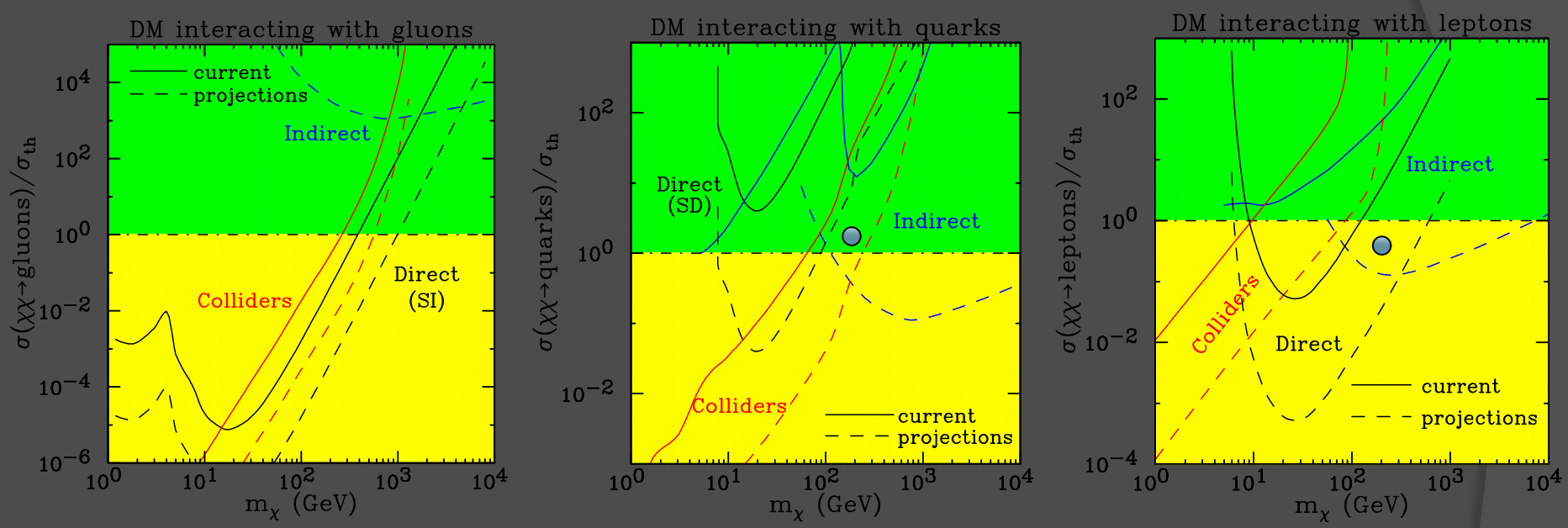

- Alternatively, signals could be seen in a combinations of indirect experiments with either direct experiments or the LHC, again either with or without consistency with a simple thermal origin

$$\frac{1}{M_q^2}\,\bar{\chi}\gamma^\mu\gamma_5\chi\sum_q\bar{q}\gamma_\mu\gamma_5 q+\frac{\alpha_S}{M_g^3}\,\bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu}+\frac{1}{M_\ell^2}\,\bar{\chi}\gamma^\mu\chi\sum_\ell\bar{\ell}\gamma_\mu\ell$$

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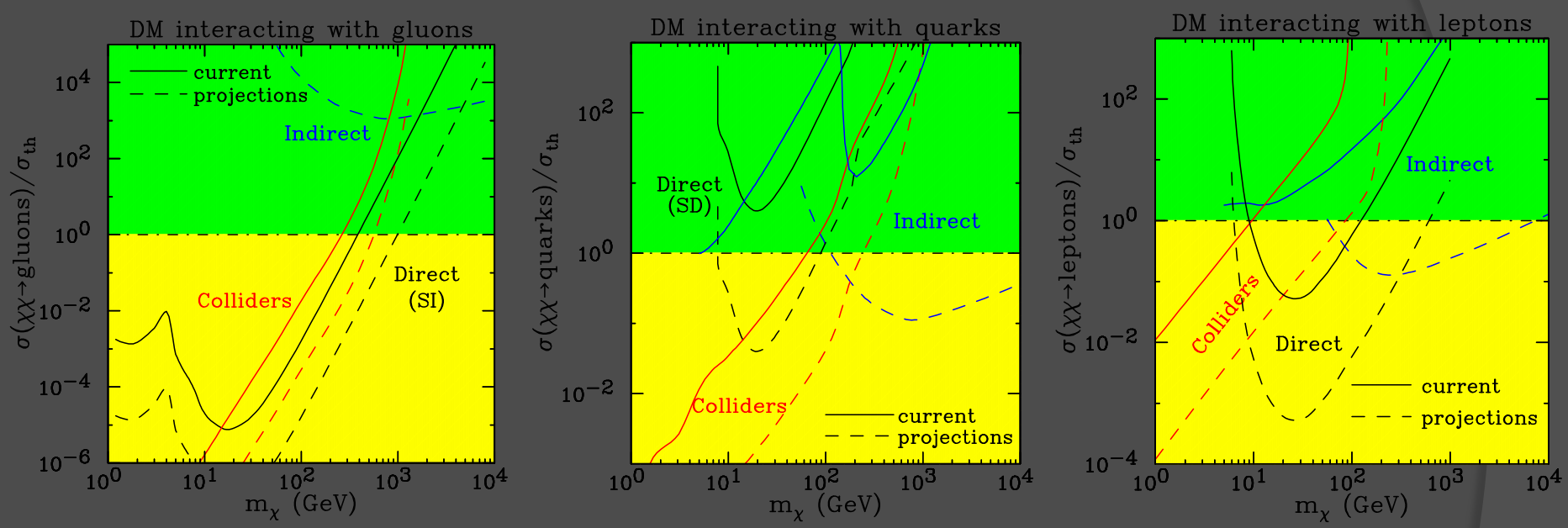

- In all of the cases shown, at least one technique will discover the WIMP if lighter than ~1 TeV (exceptions to this conclusion exist, but they are exceptions)
- The relative discovery prospects for direct, indirect, and LHC searches are very model dependent – any could get there first, and any could see nothing

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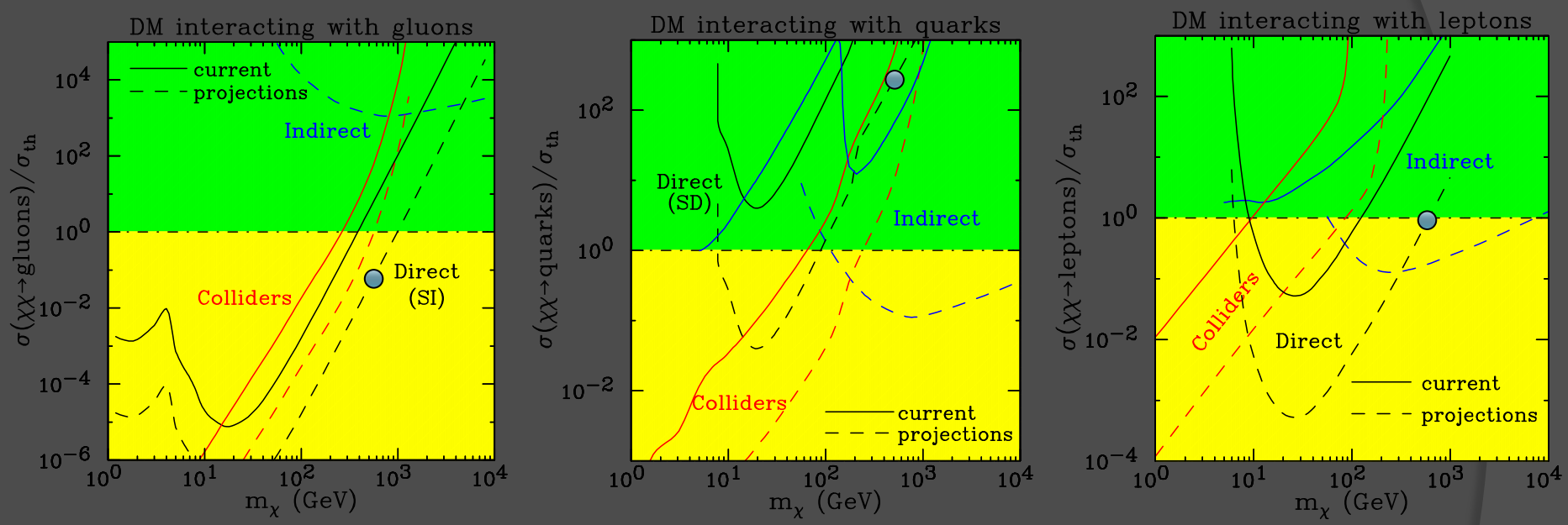

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- The relative discovery prospects for direct, indirect, and LHC searches are very model dependent – any could get there first, and any could see nothing
- We will likely need multiple types of observations to have any chance of identifying the WIMP – for example, the three points shown look the same to direct detection, but have very different indirect and collider signals

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Summary

- Direct and indirect astrophysical searches for dark matter, as well searches at the LHC, are each at or are approaching the sensitivity expected to be required to detect dark matter (in the form of WIMPs) non-gravitationally for the first time
- Similar prospects exist for dark matter in the form of axions
- If ~5-10 years pass without discovery, we will have to radically revise our ideas about the nature of dark matter
- Even if they succeed in detecting dark matter, none of these techniques alone is likely to tell us much about the nature of these particles
- These techniques each offer different information, have different uncertainties, and are sensitive to different types of dark matter candidates
- By taking advantage of the complementarity between these techniques, we can reasonably expect to identify the particle nature of dark matter within the coming decade