Beyond the Standard Model

Tim M.P. Tait

University of California, Irvine

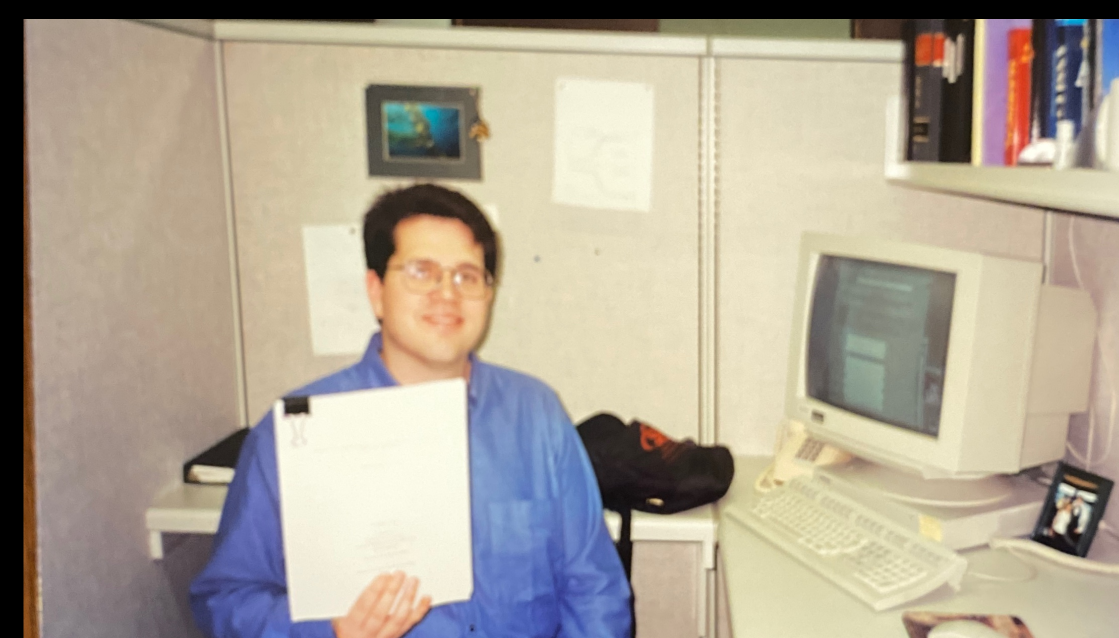
DIS 2023

March 27, 2023


Conferences
5 '99


5'99


5 '99



Outline

- Introduction: Physics beyond the Standard Model

- Neutrino Masses
- Cosmic Acceleration
- The Baryon Asymmetry of the Universe
- Dark Matter
- Exploring the Unknown

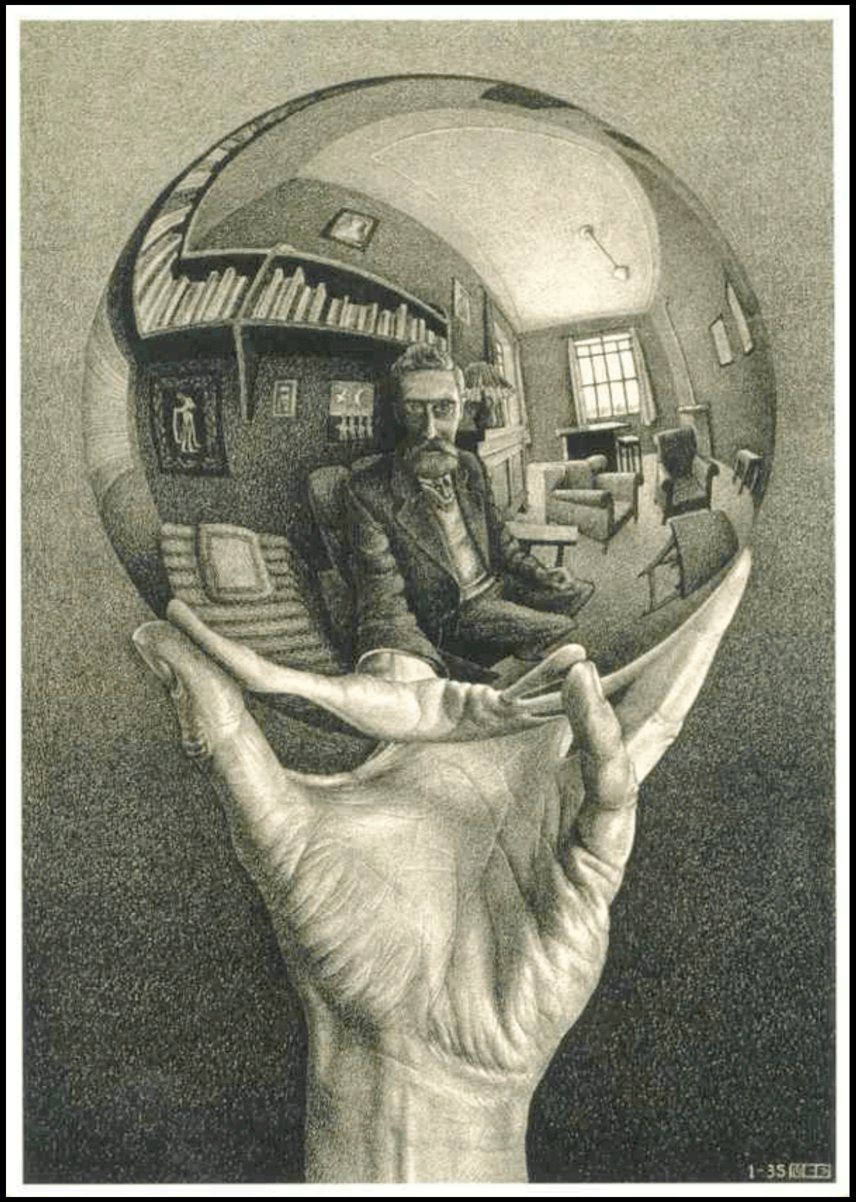
- Outlook

Beyond the SM?

Traditional techniques for predicting physics beyond the Standard Model include: reading tea leaves, meditating, casting rune stones, drawing tarot cards, gazing into crystal balls, and (even) talking to particle theorists!

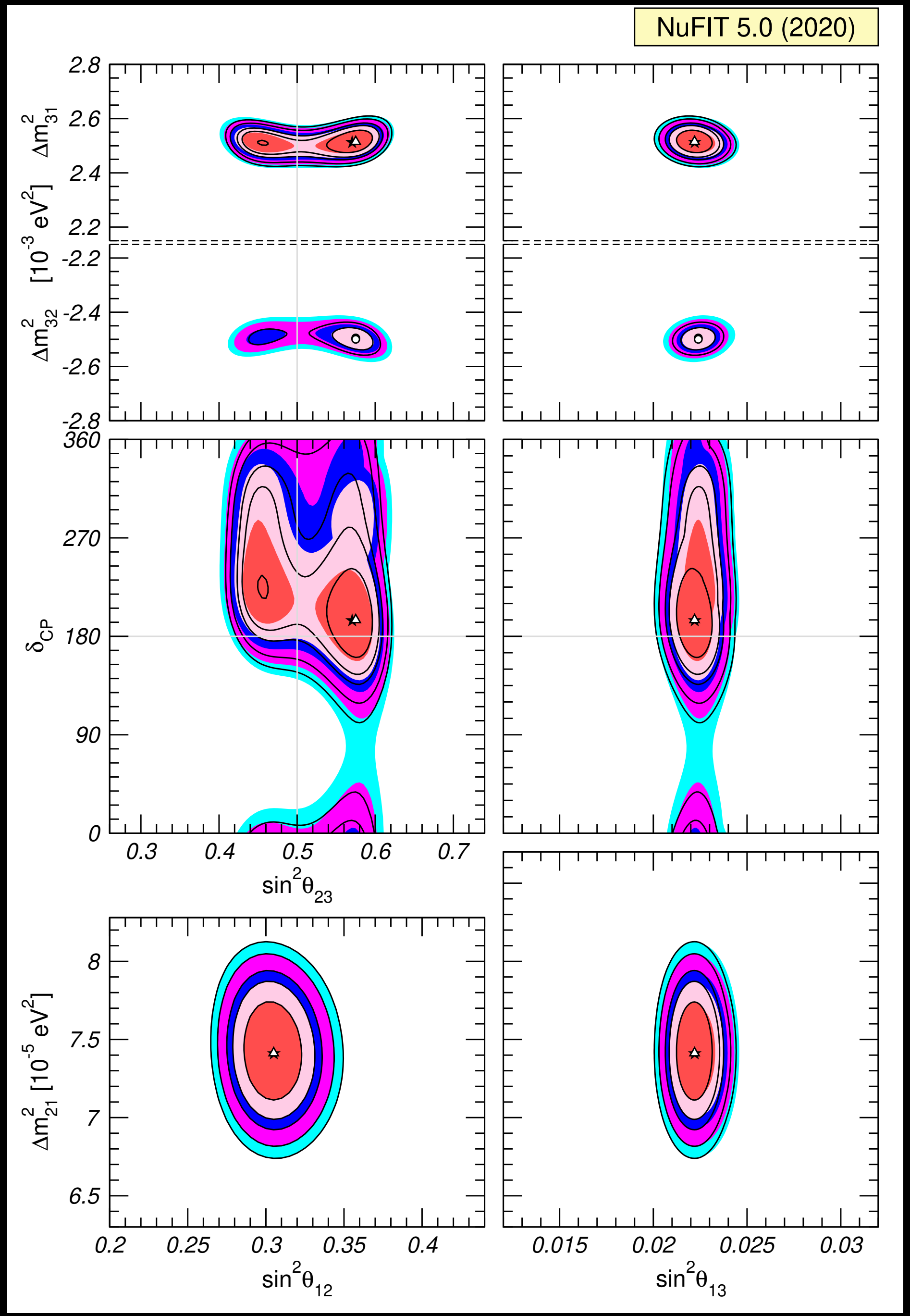
Foretelling the Future?

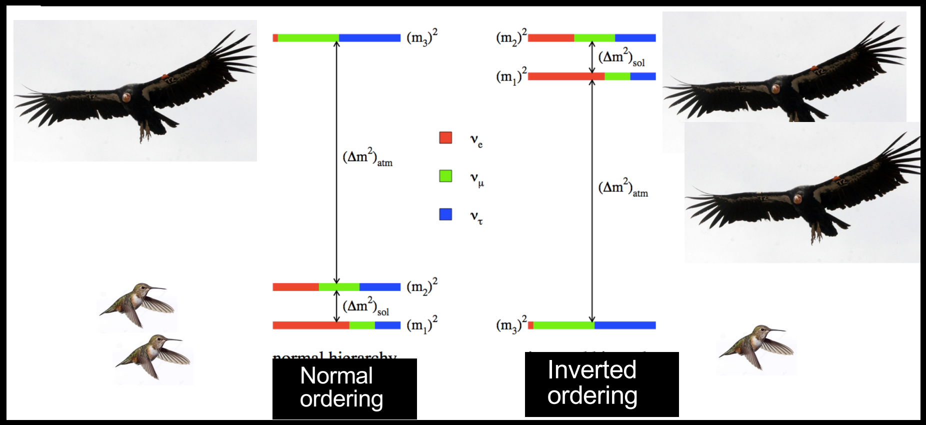
- Physics beyond the Standard Model is a huge topic, far beyond what it is possible to cover here.
- I'm choosing to unpack it in terms of places where we have experimental evidence that the Standard Model is incomplete. This is far from the only way to engage with the topic.
- My favorite crystal ball is the one by Escher to the right. It reminds me that sometimes predicting the future is more about who we are ourselves, than what is likely to happen.
- Personally I would be surprised if any of our favorite models turned out to be precisely true in their current form.
- But I think it is likely that some contain **elements** of the truth.
- Exploration of BSM physics serves several important goals:
  - It tries to describe phenomena the SM can't explain.
  - It suggests new directions and new experiments to extend our reach in understanding fundamental physics.
  - It clarifies the interface between what is known and what is not.



Neutrino Masses

- The observation of neutrino oscillations is clear evidence of BSM physics. All evidence points to these oscillations as arising from non-zero neutrino masses.
- The SM predicts that neutrino masses are zero.
- Current measurements allow for two 'hierarchies' of masses, with measurements of the 12 and 23 mixings.
- There are measurements of the mass differences, all three of the real oscillation angles, and mild hints that the CP-violating phase is large.
- The over-all mass scale, and the ordering of the neutrinos remains unknown.
- The main question for BSM physics is how to extend the SM to include them, and why they display the flavor patterns that we observe.





Kate Scholberg, P5 Town Hall

The νSM?

- From a low energy perspective, there are two possibilities:
  - The first is to introduce right-handed partners for the neutrinos (n), and write down Yukawa interactions just like we did for the rest of the SM fermions:

$$(i\sigma_2\Phi^*)Y^{\nu}_{ij}\bar{L}_i n_j + H.c.$$

    - Replacing the Higgs by its VEV results in Dirac neutrino masses : $m_\nu \sim Y v$.
  - A second option is to invoke a non-renormalizable interactions. For example, at dimension-5:

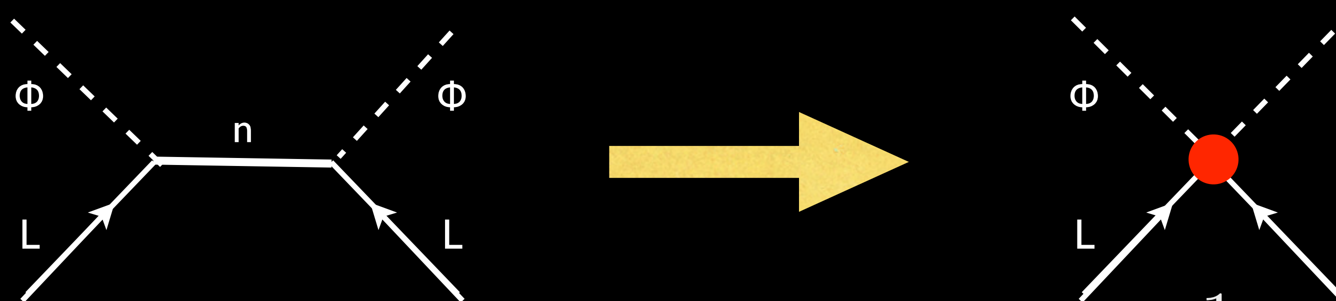
$$\frac{1}{\Lambda_{ij}}\left(\bar{L}_i\Phi\right)\left(L^c_j\Phi\right) + H.c.$$

  - These operators are the unique dimension 5 additions to the SM (e.g. in the SMEFT), often referred to as the `Weinberg operator', and lead to Majorana neutrino masses. Replacing the Higgses by their VEVs, we get the `see-saw' formula: $m_\nu \sim v^2 / \Lambda$.
  - The fact that there are two broad categories of solution is part of the reason why we haven't absorbed neutrino masses into some kind of redefined SM to include them.

UV Completions

- There are multiple ways to UV-complete the Weinberg operator:
  - We can generate it by integrating out a gauge singlet fermion (RH neutrino):

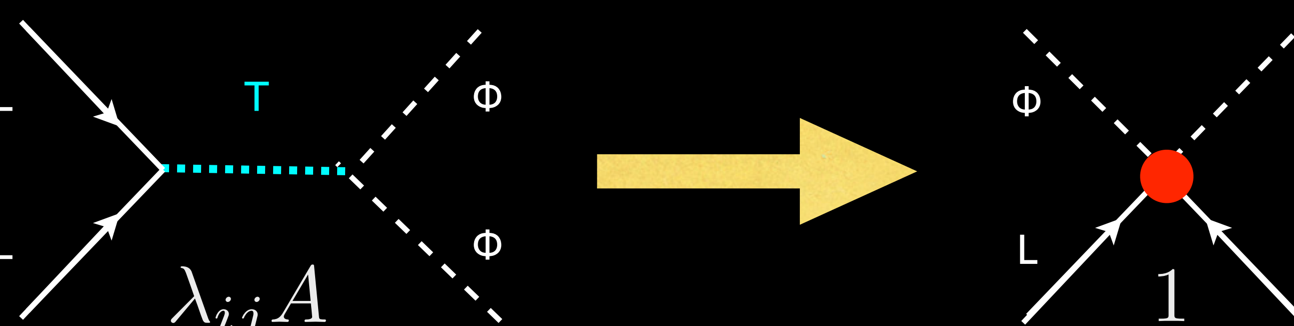
$$(i\sigma_2\Phi^*)Y^\nu_{ij}\bar{L}_i n_j + M\bar{n}n^c + H.c.$$



$$\sum_k Y^\nu_{ik}\frac{1}{M_k}Y^\nu_{kj} \qquad \frac{1}{\Lambda_{ij}}$$

  - We can generate it by integrating out an SU(2)-triplet Higgs-like field:

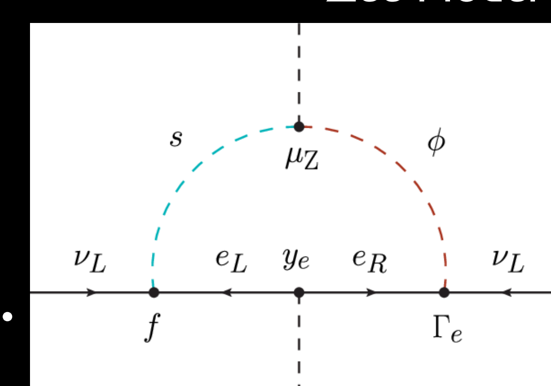
$$AT\Phi^2 + \lambda_{ij}\bar{L}_i L^c_j T + H.c.$$



$$\frac{\lambda_{ij}A}{M_T^2} \qquad \frac{1}{\Lambda_{ij}}$$

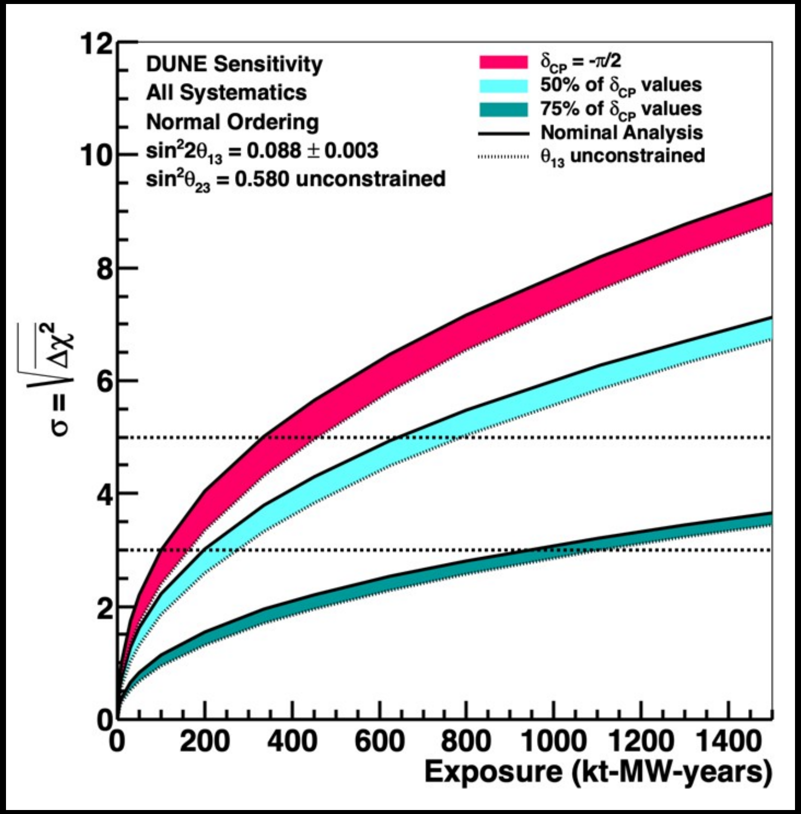
  - There are others ways, such as for example via loop diagrams.

“Zee Model”

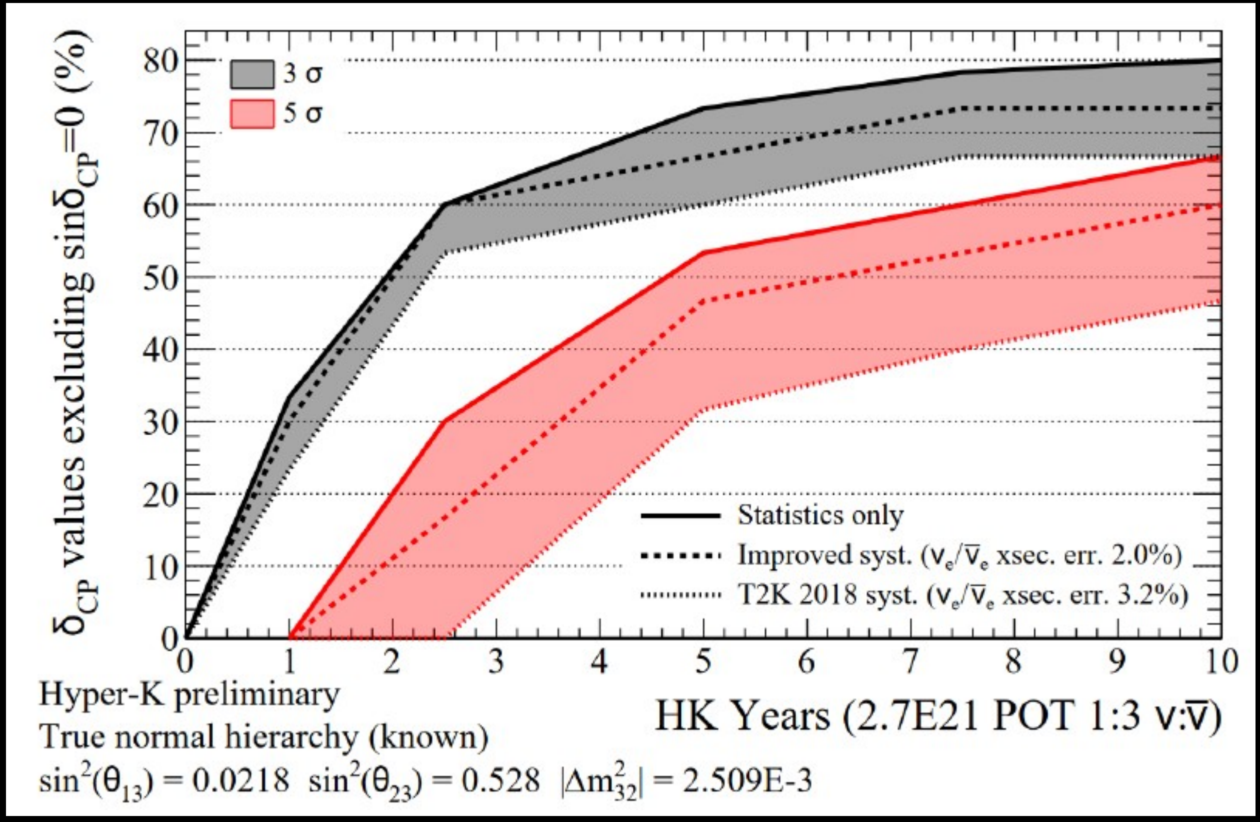


Future Long Baseline

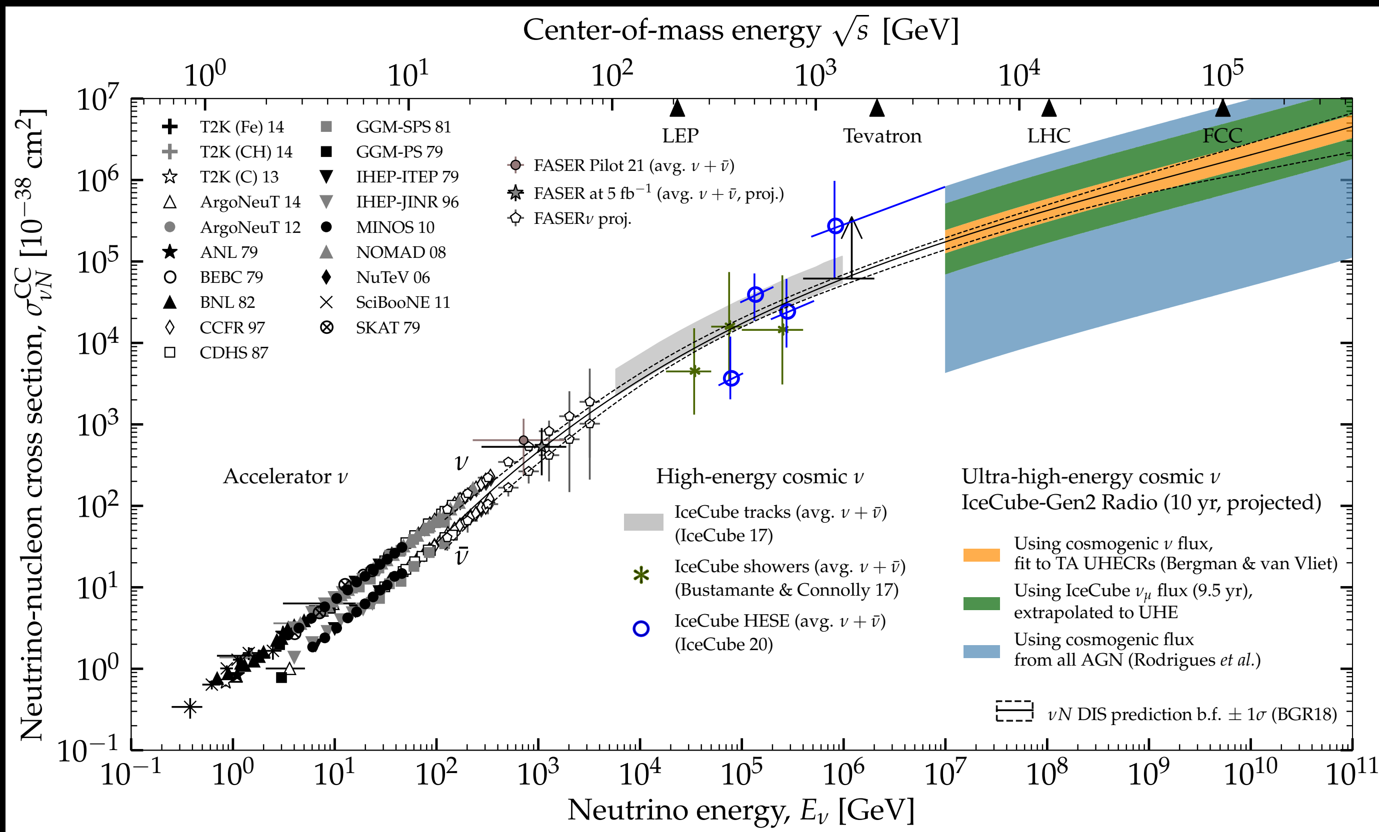
- As we all know, there are vigorous upcoming program to pin down the remaining unknowns in the oscillation parameters, centered in the US and Japan.
- These experiments will eventually measure every parameter, but will not significantly over-constrain the PMNS matrix.
- It's unlikely that oscillation data will be able to determine the UV physics.
- Colliders could potentially produce right-handed neutrinos or triplet Higgses, but these particles could be heavy enough to be far beyond their reach.
- Sterile neutrinos could be dark matter, in a narrow window of mass around ~ keV.

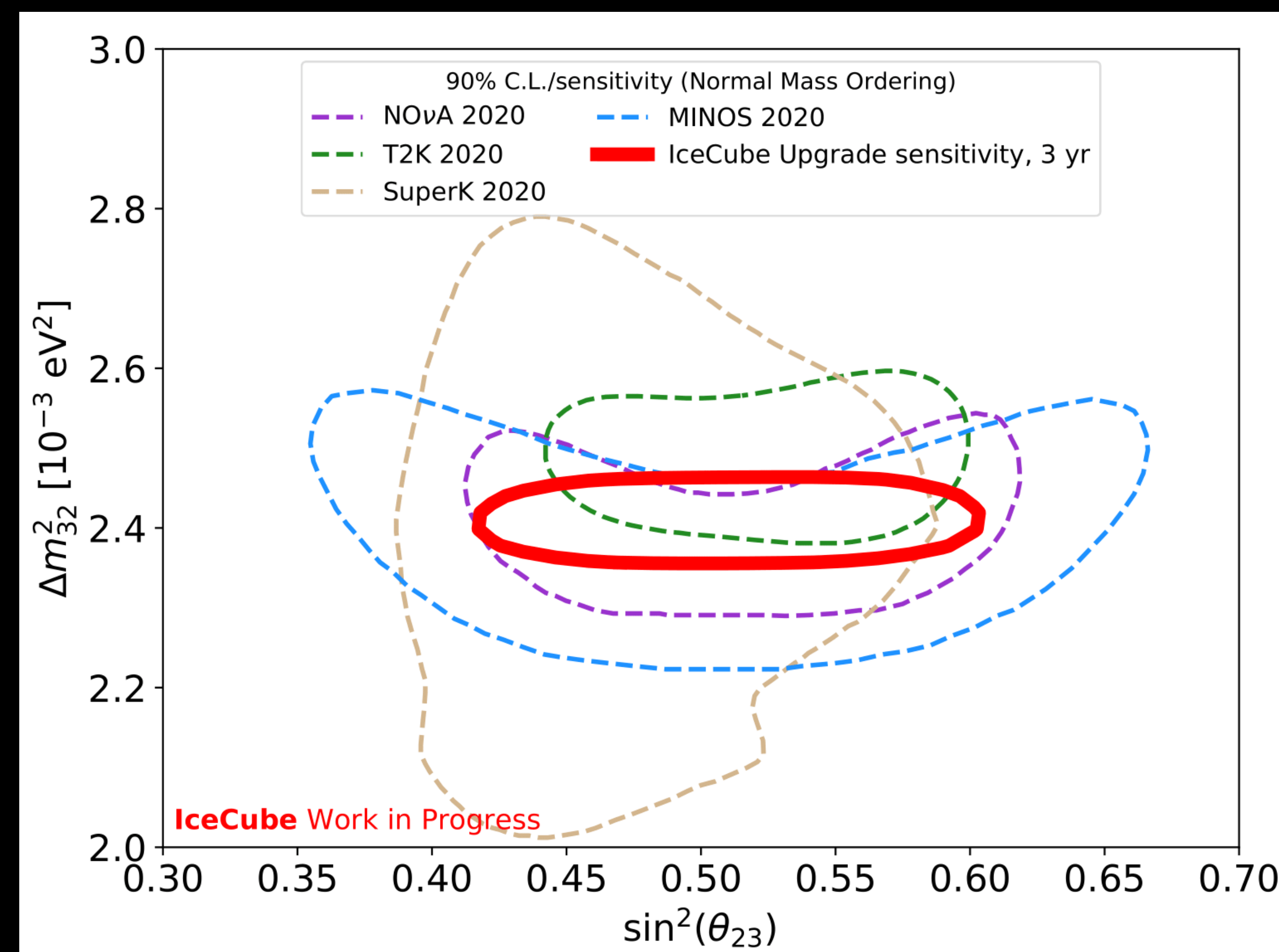


Chris Marshall, P5 Town Hall



High Energy Neutrinos

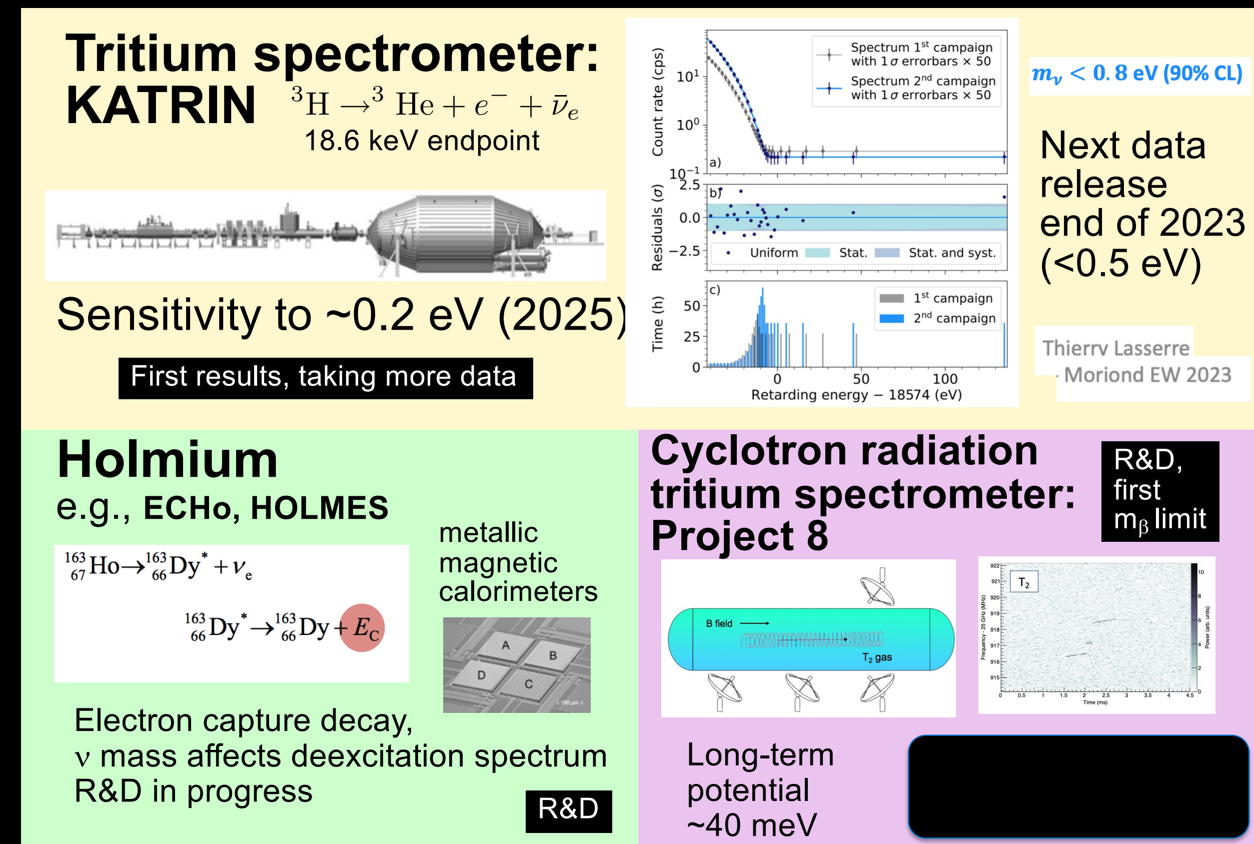




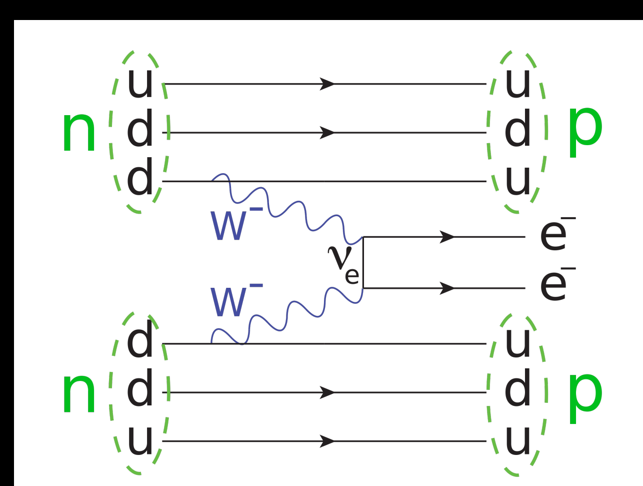
- High energy neutrinos offer an interesting opportunity to test whether oscillations work the same at high energies as they do at the ~GeV energies where neutrino beams operate.

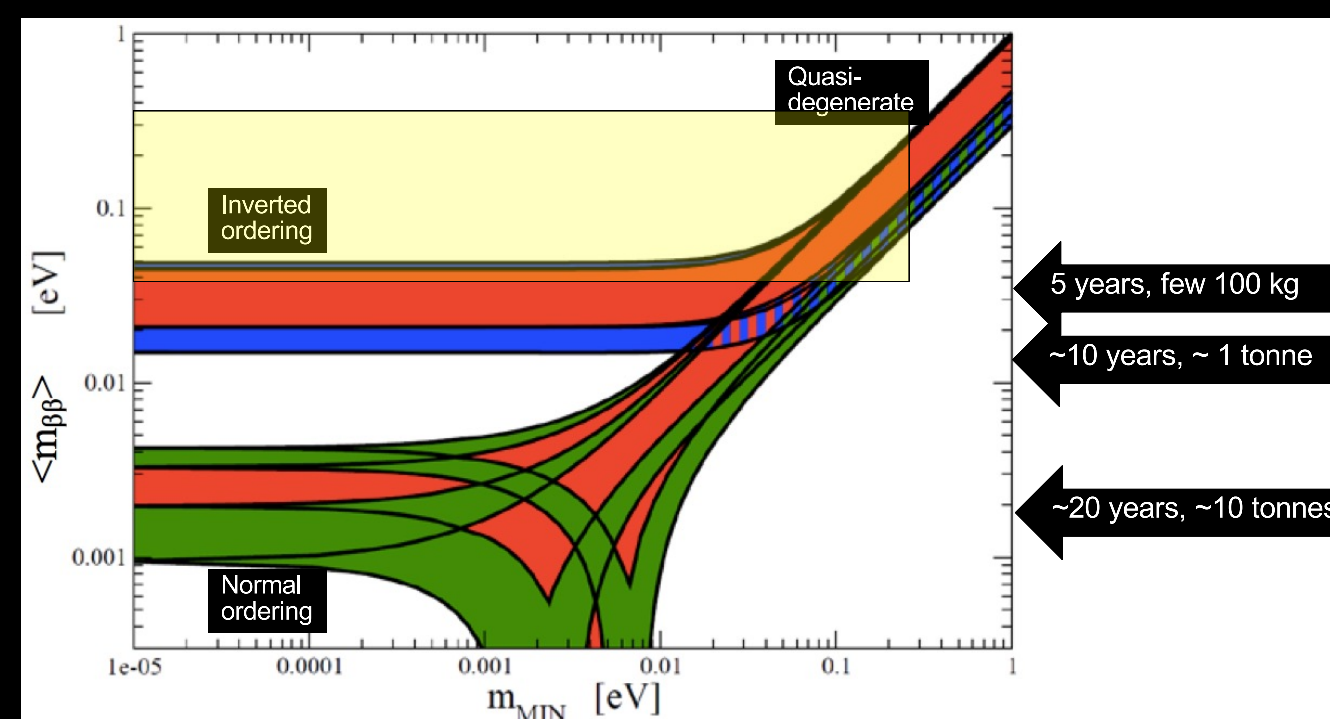
Neutrino Masses

- Kinematic experiments attempt to infer the absolute scale of the neutrino mass by measuring the endpoint in beta decays.
- Cosmological bounds based on the number of light degrees of freedom in the Universe reach similar sensitivity.
- Neutrinoless double-beta decay experiments look for a signature that exists if neutrinos are Majorana, but would be forbidden from taking place if they are Dirac.



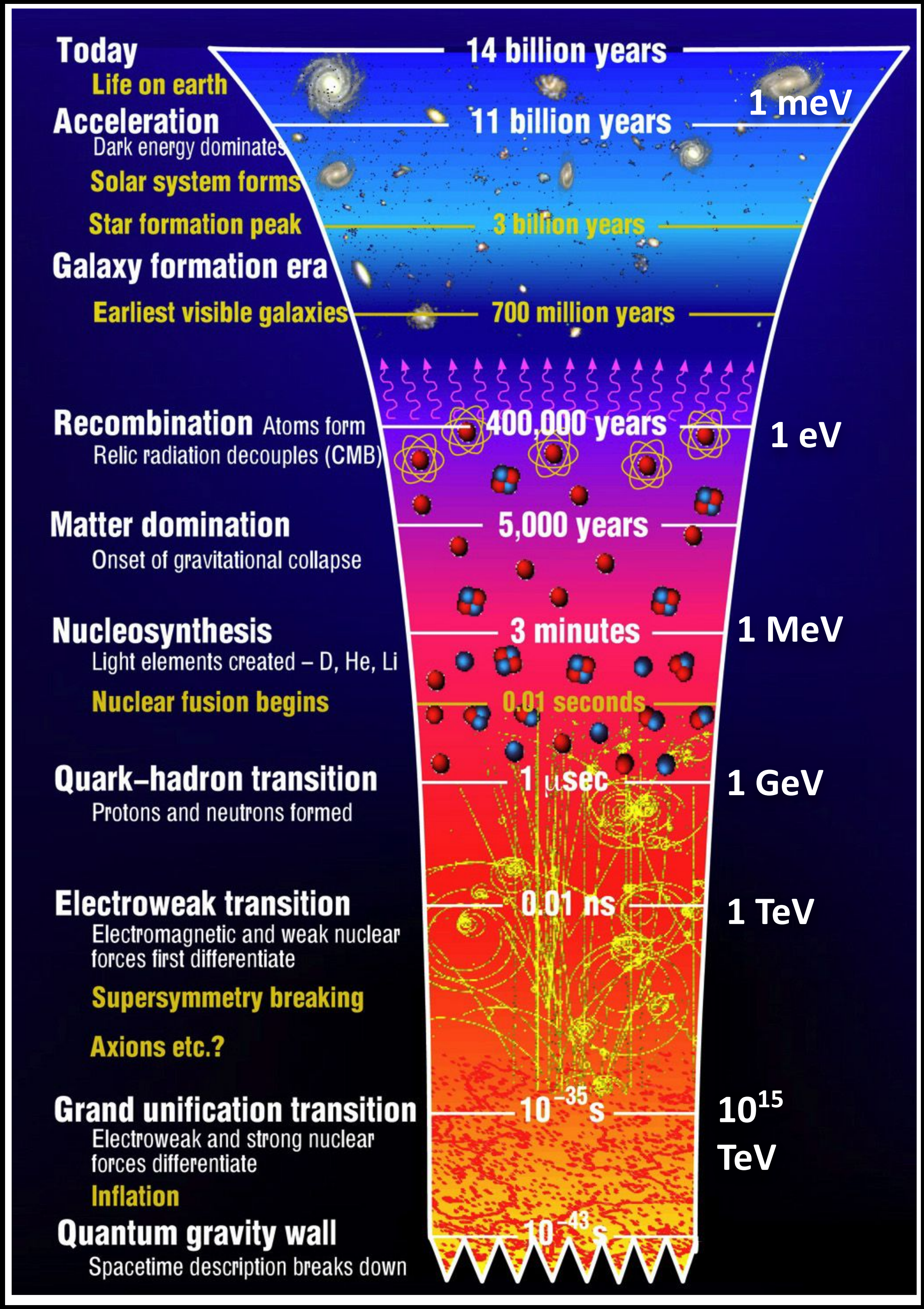
Kate Scholberg, P5 Town Hall



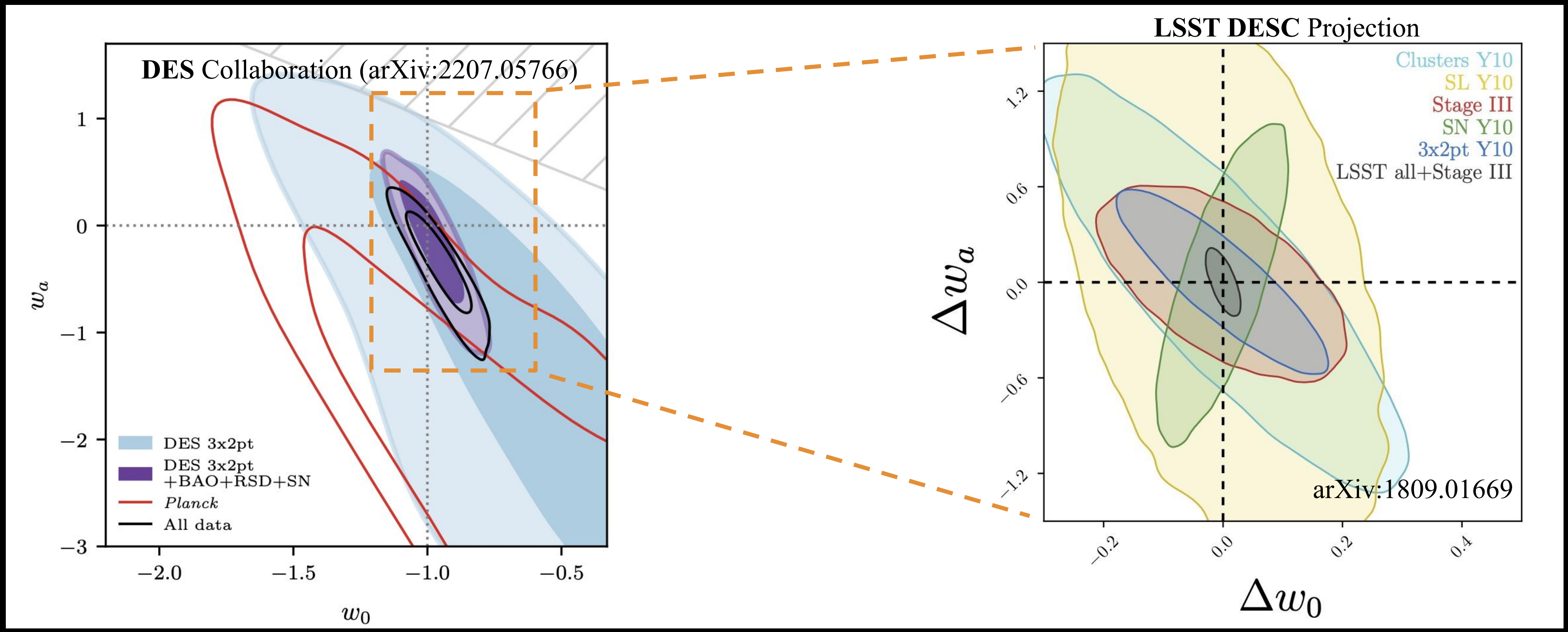


Cosmic Acceleration

- Cosmic observations indicate that the expansion of the Universe is currently accelerating.
- This could be an indication that there is a non-zero cosmological constant, or it could be a dynamical process that changes with time.
- Other puzzling features of the Universe point to an early period of cosmic inflation, to explain why it is so flat and so homogeneous.
- That earlier period of cosmic acceleration had to end to give birth to the Universe we live in, so it was certainly a dynamical process.



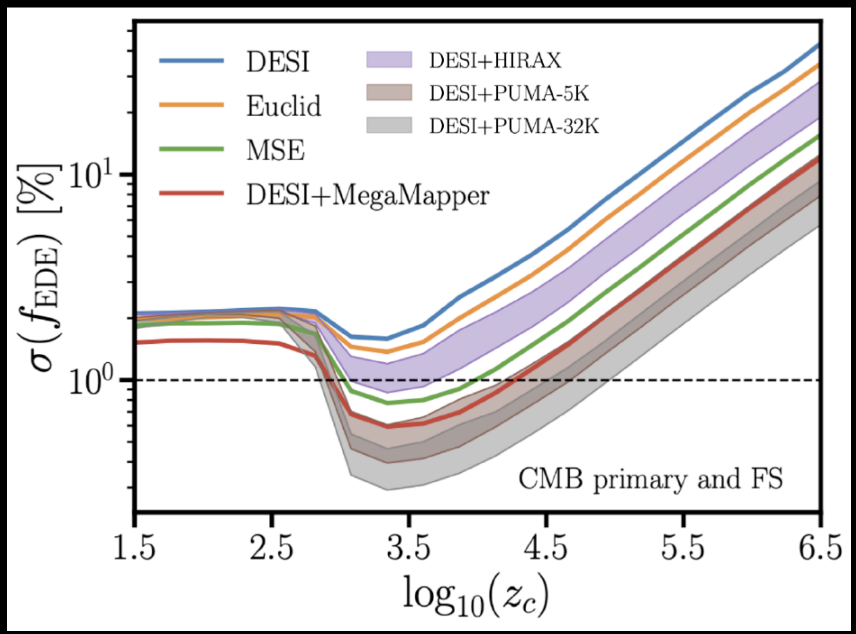
Dark Energy

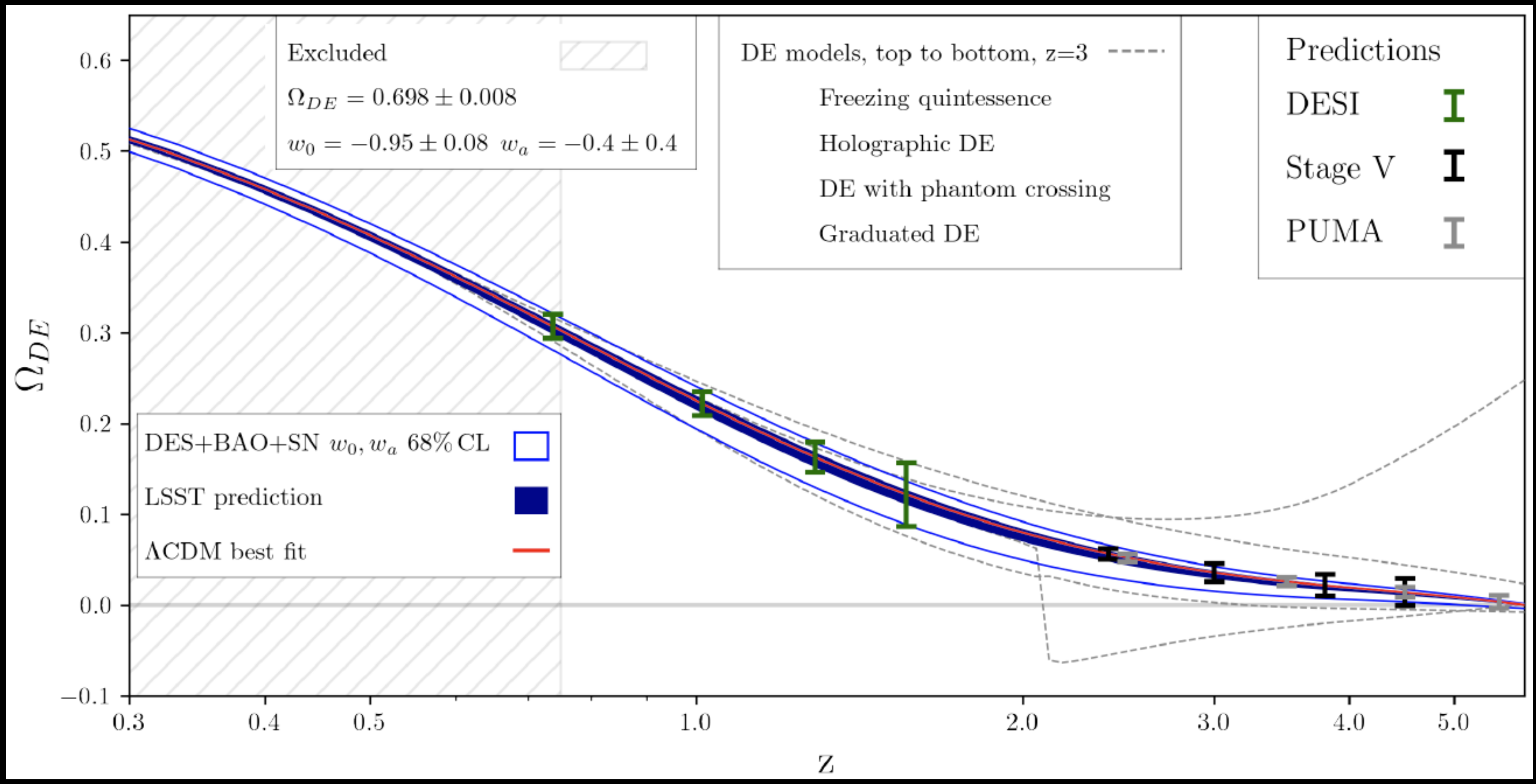


- Modern cosmic surveys will pin down the equation of state parameters for dark energy to the ~ % level.

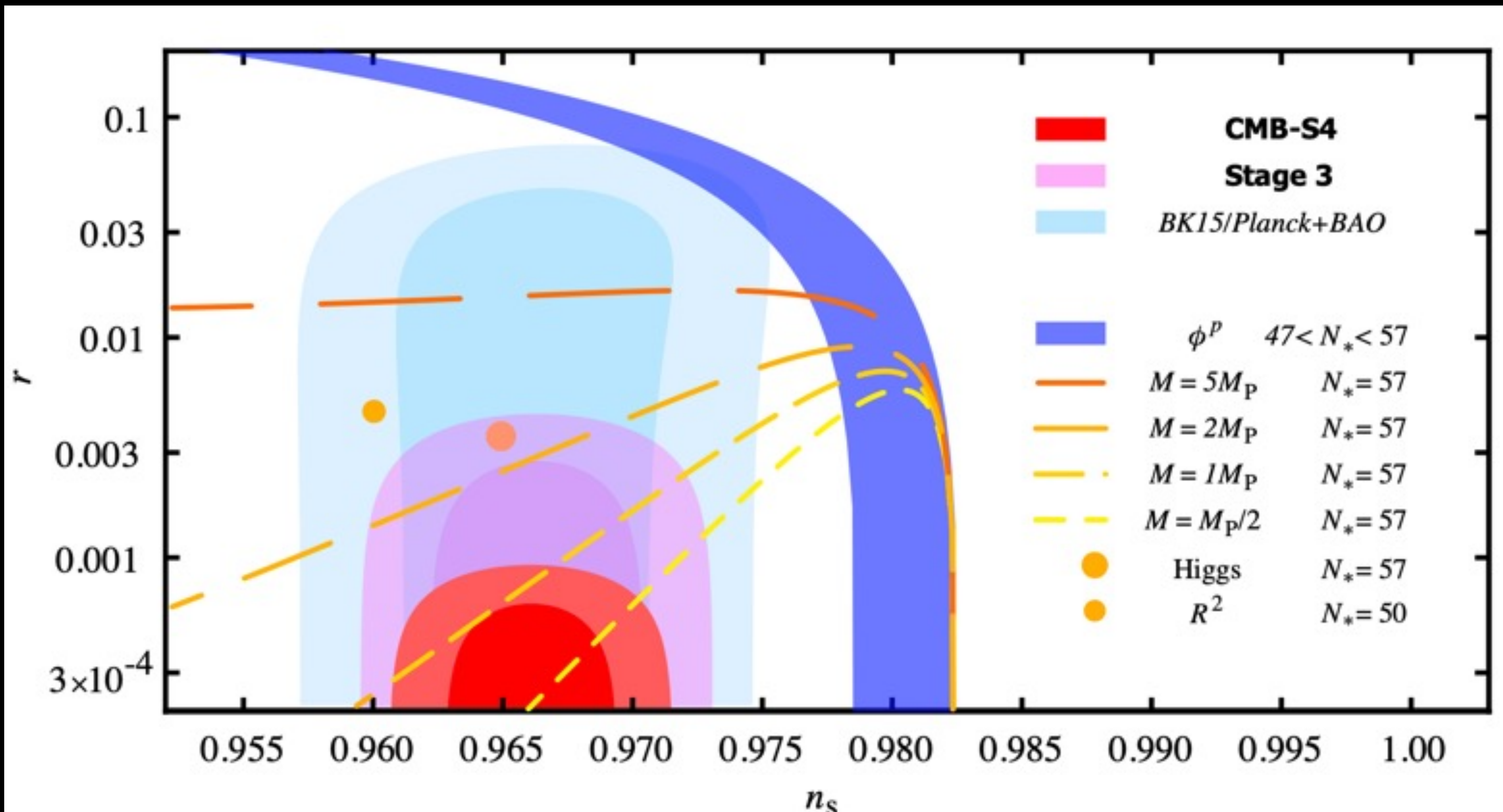
- Future surveys will be able to track the influence of dark energy back to early times, providing direct determination of its cosmic evolution.

Snowmass CF Report





Cosmic Inflation



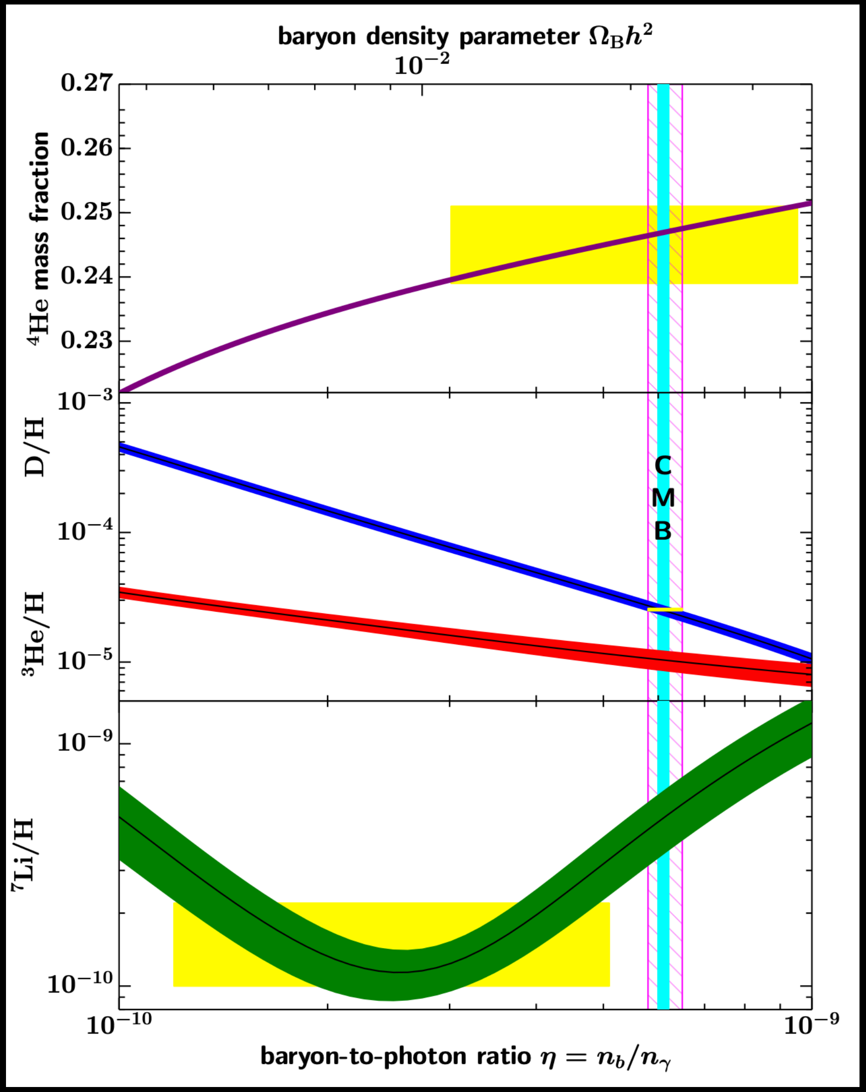
Snowmass CF Report

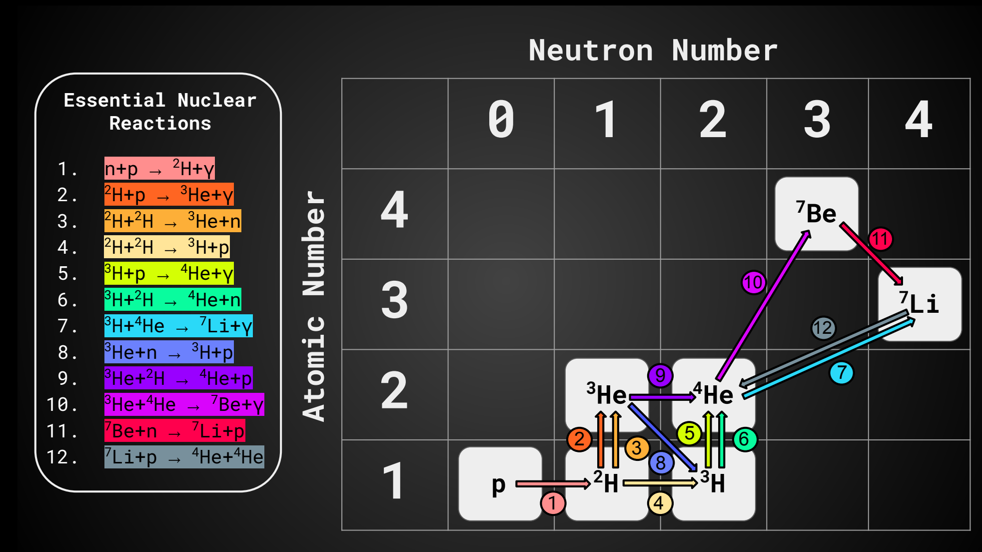
- Cosmic inflation leaves its imprints on the CMB and matter spectrum. Future measurements can distinguish models of inflation and reconstruct the energy scale at which inflation took place.

Baryon Asymmetry

- Our Universe is made of matter and not anti-matter! That is surprising because the laws of physics largely treat the two equivalently, and cosmic inflation should have wiped out any accidental primordial asymmetry between the two.
- BBN and CMB measurements infer the same value for the baryon asymmetry.
- Sakharov identified three conditions under which a baryon-symmetric Universe can evolve into an anti-symmetric one.

1. B violation
2. C & CP violation
3. Period out of equilibrium

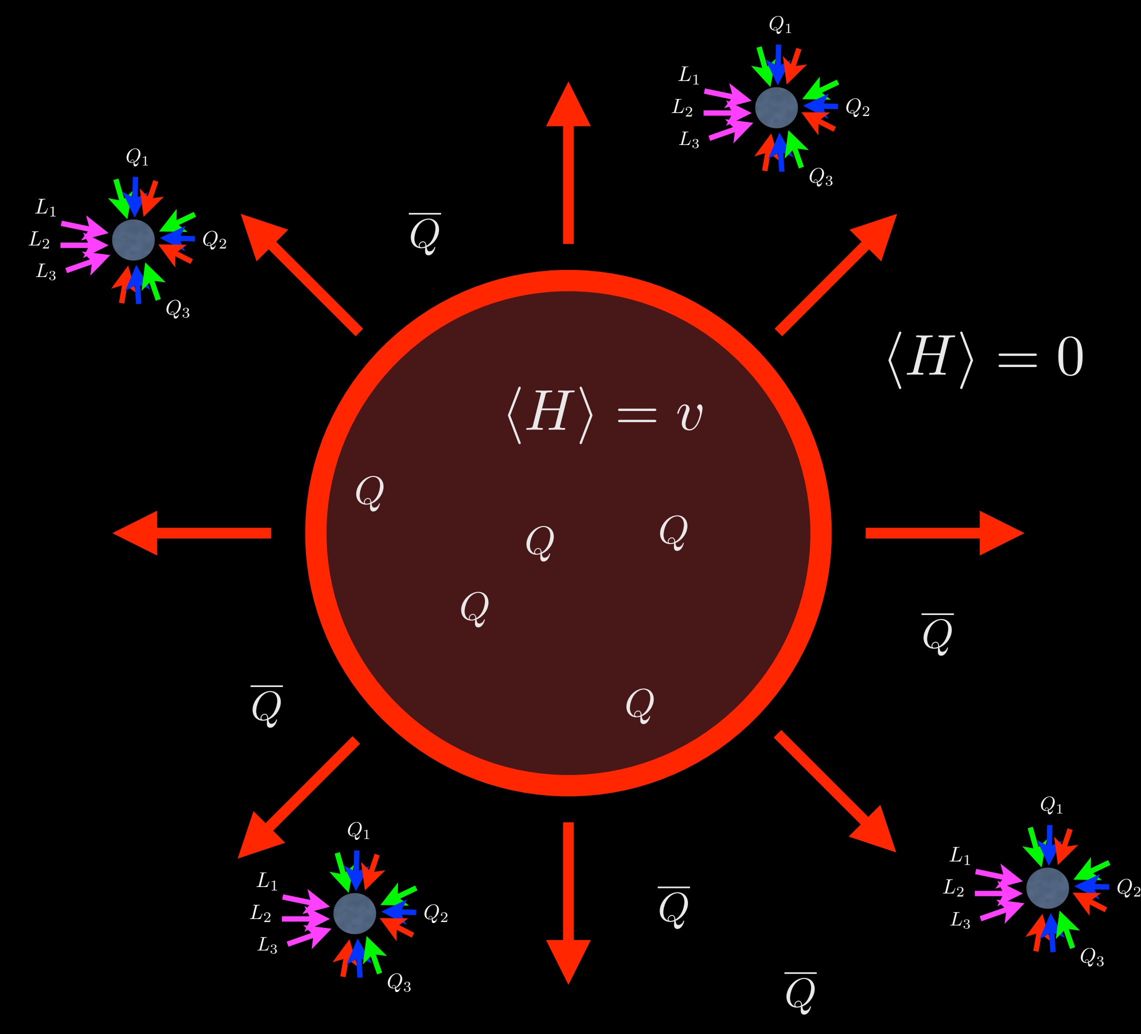




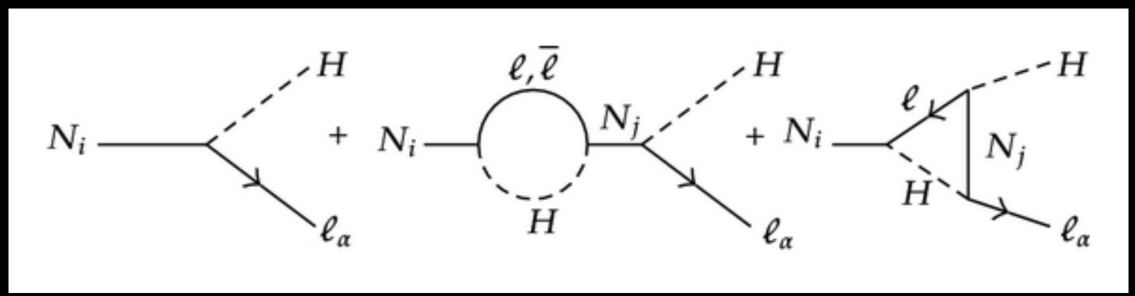
"Prymordial" (Python Code:) Burns, TMPT, Valli 2304.xxxxx

Generating the BAU

- There are a plethora of theories that succeed at generating a baryon asymmetry, using a variety of mechanisms.
- Two of the most popular are:
    - Electroweak baryogenesis, in which BSM physics modifies the electroweak phase transition to first order and provides sufficient CP violation.
    - Leptogenesis, in which the out-of-equilibrium decay of heavy sterile neutrinos generates an asymmetry in leptons, which the SU(2) instantons process into a baryon asymmetry.
- Both use the natural B+L violation present non-perturbatively in the SM at high temperatures.



Schematic of the EW Phase Transition



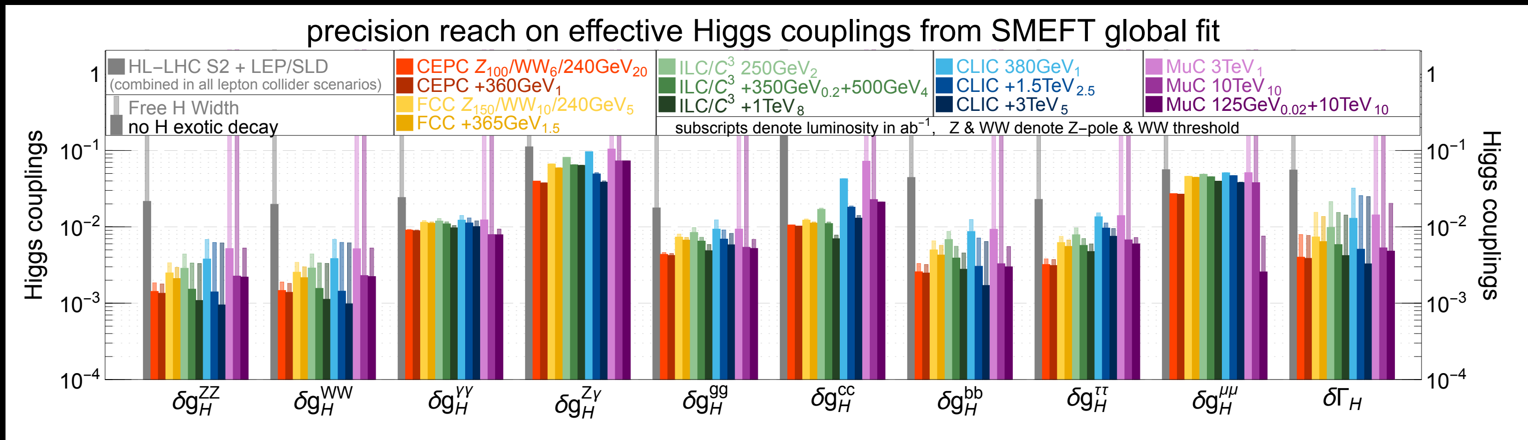
CP-violation in Leptogenesis

Testing Baryogenesis

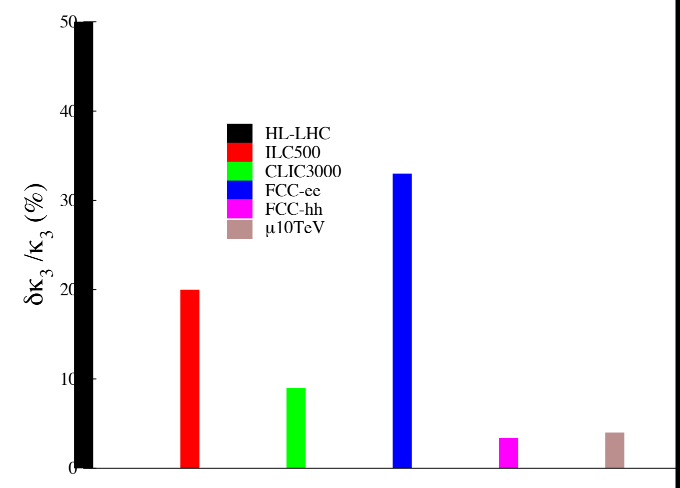
- Baryogenesis models could live down at the electroweak scale, or up at the seesaw scale. No one type of experimental probe can uniquely probe them.

- For example, Precision measurements of the Higgs self-couplings through di-Higgs production and interactions with other SM particles can reveal details of the Higgs potential, and suggest it had a first order phase transition.

- A stochastic background of gravitational waves can reveal the presence of a phase transition in the early Universe.

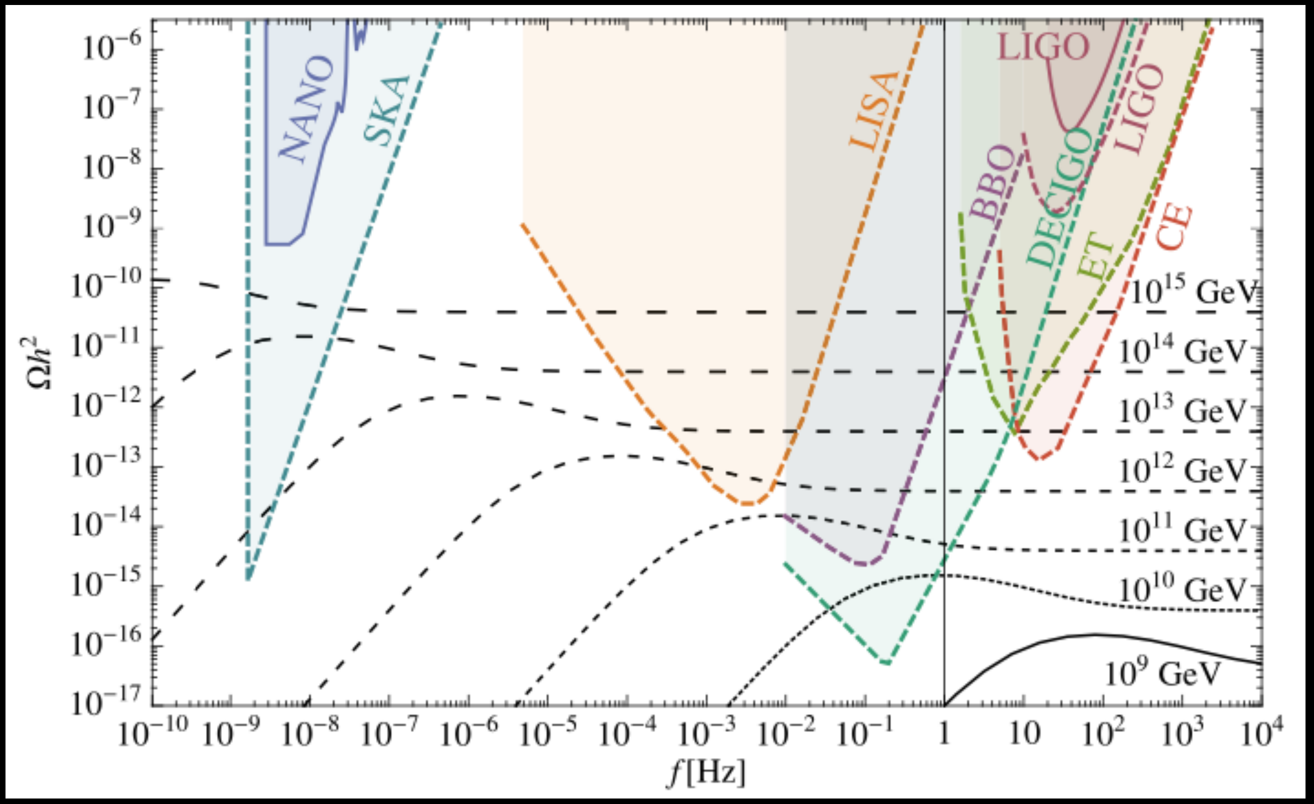


Snowmass EF01+02 Report



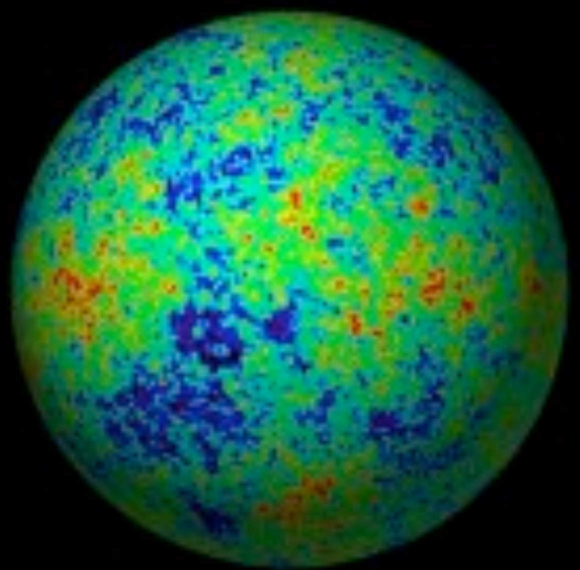
I am 4.5σ sure that Laura already talked about these measurements.

Dror et al 1908.03227

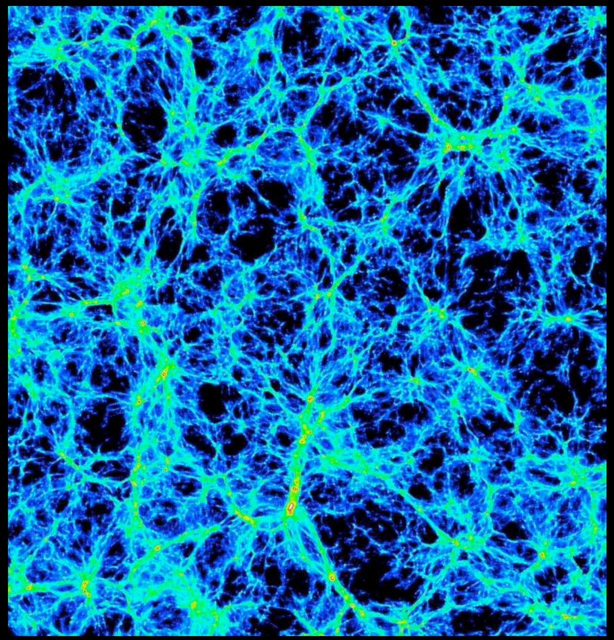


Dark Matter

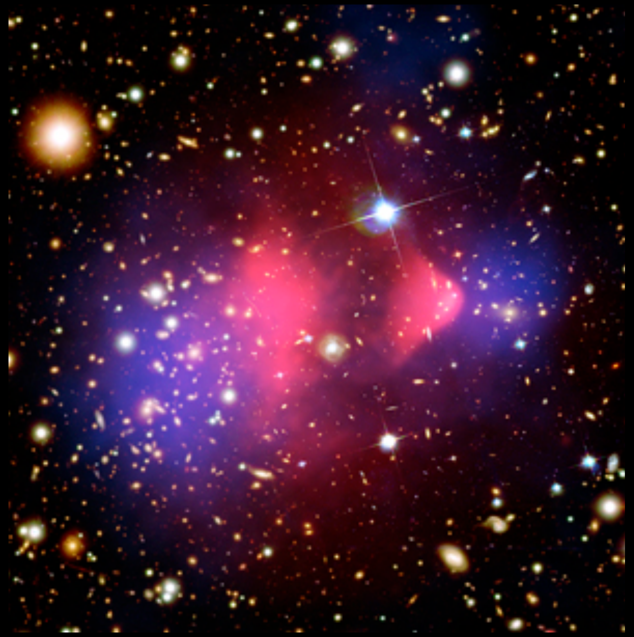
CMB



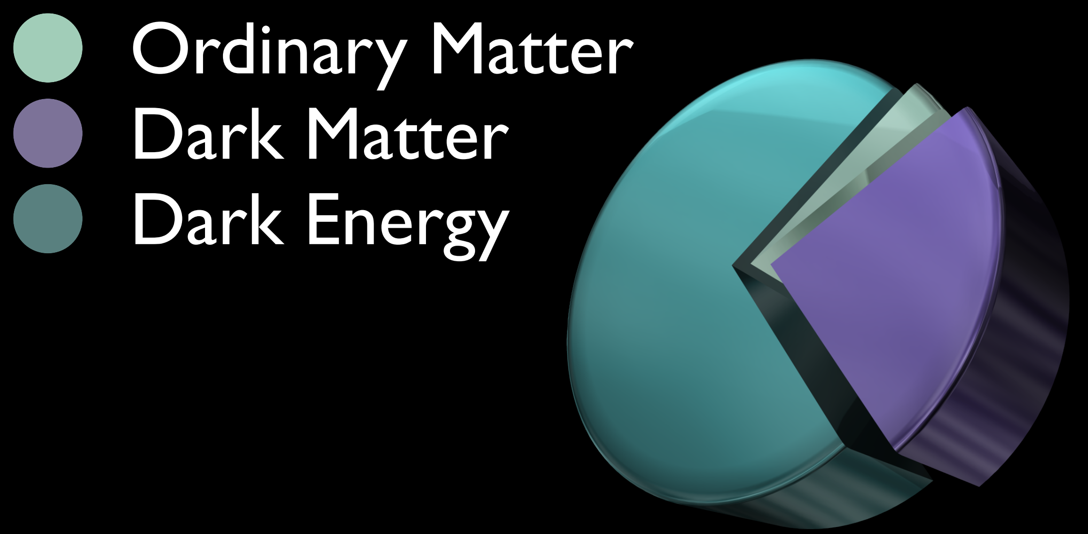
Supernova

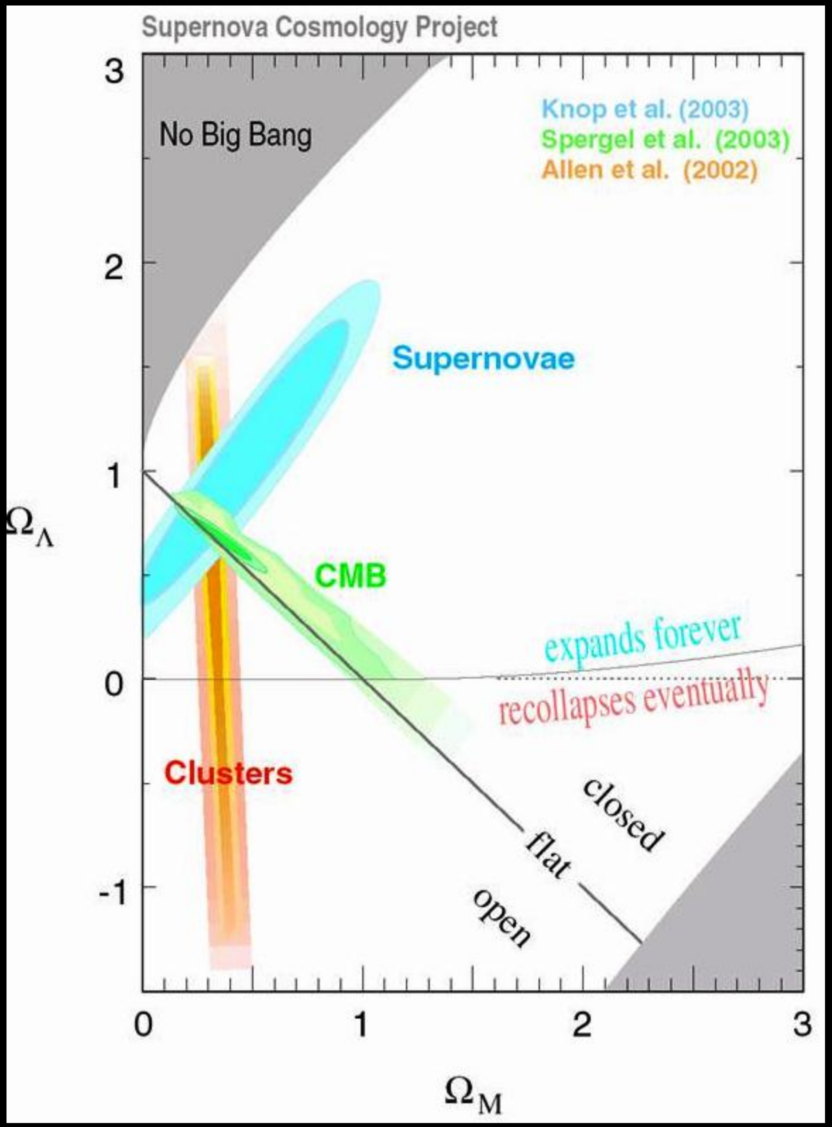


Structure

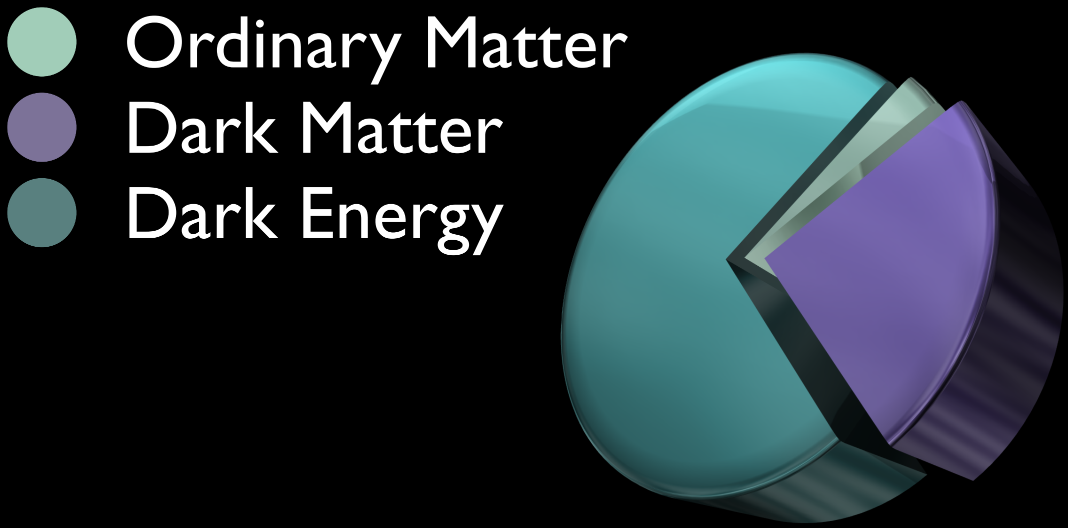


Lensing

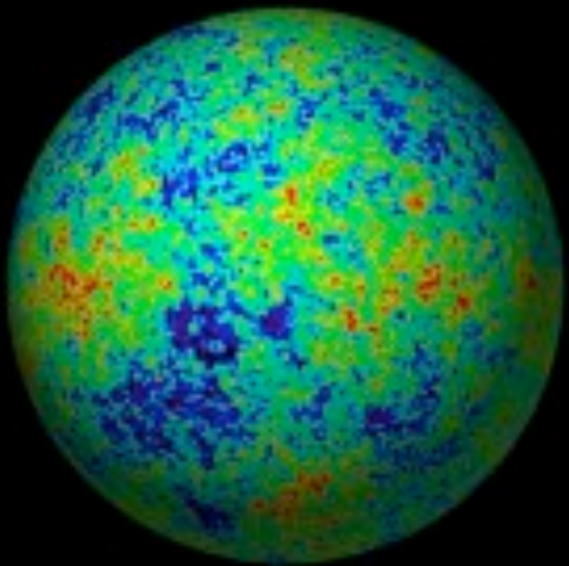




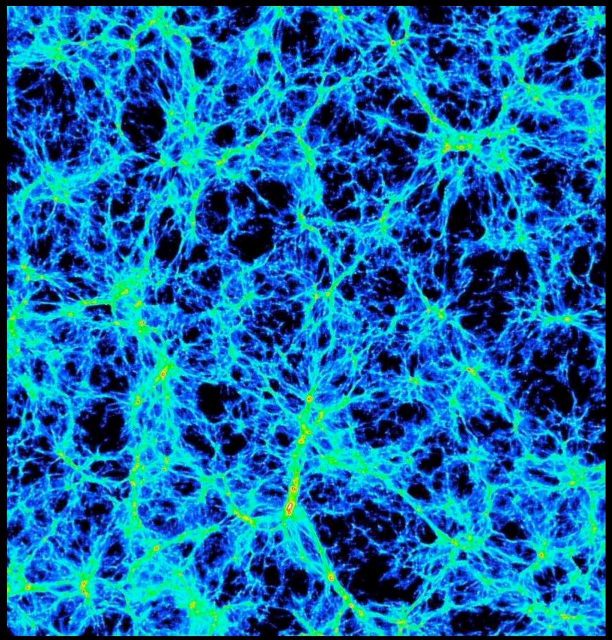
Dark Matter



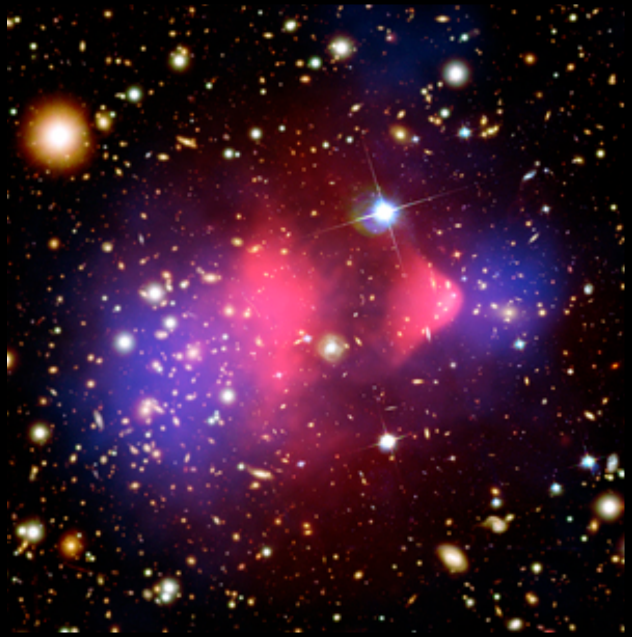
CMB



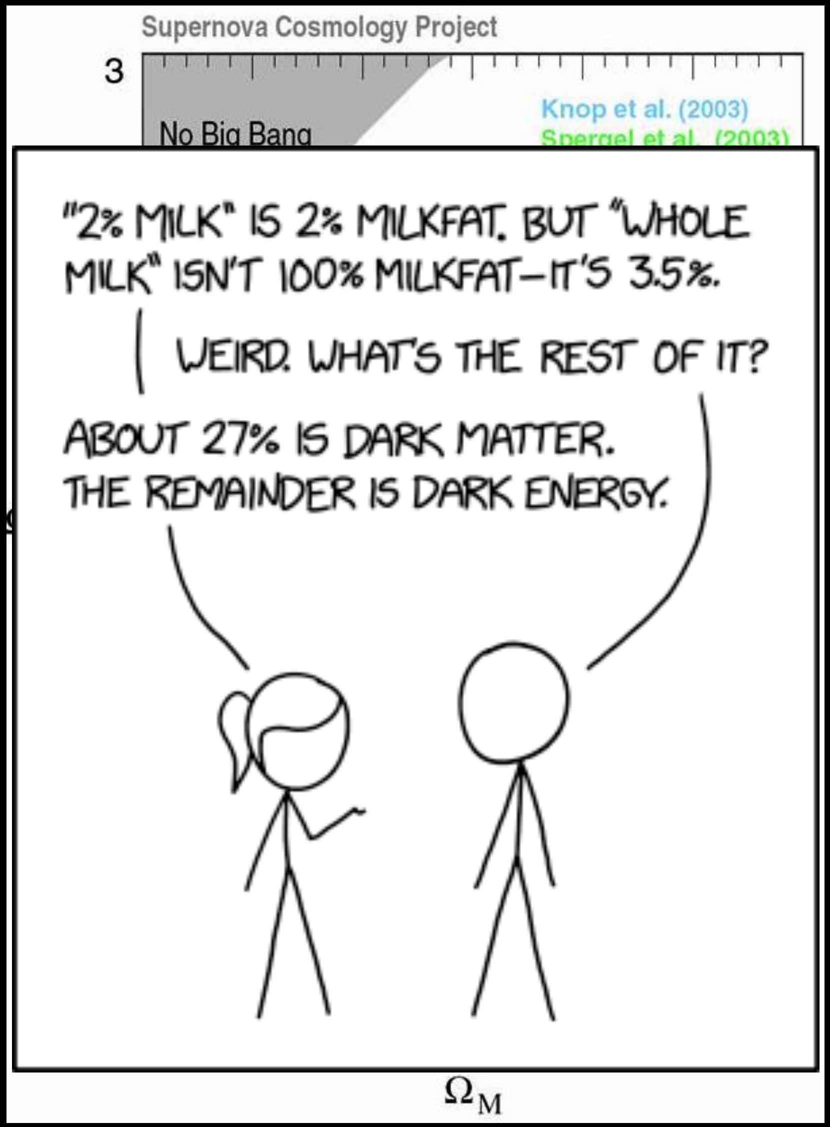
Supernova



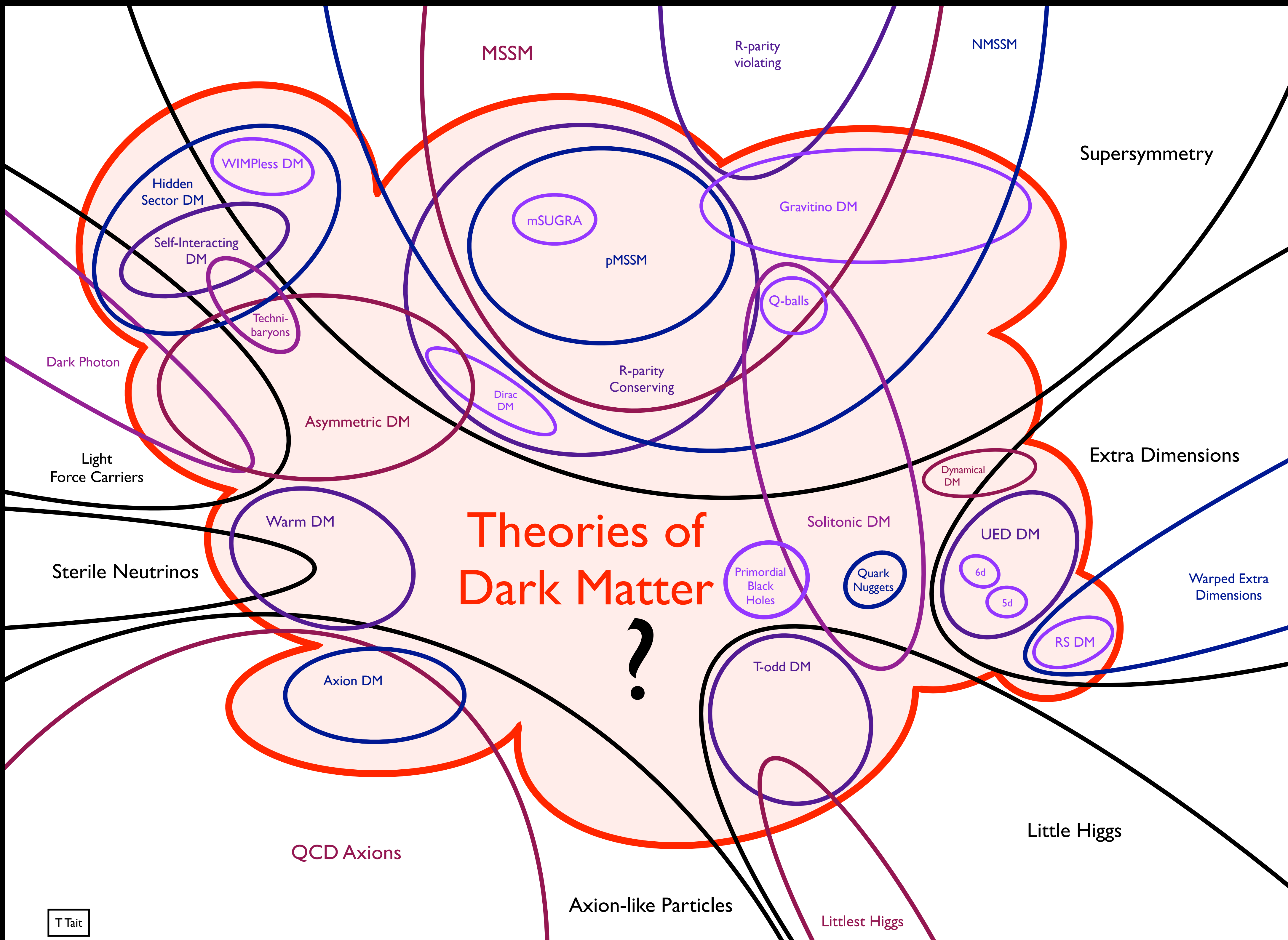
Structure



Lensing

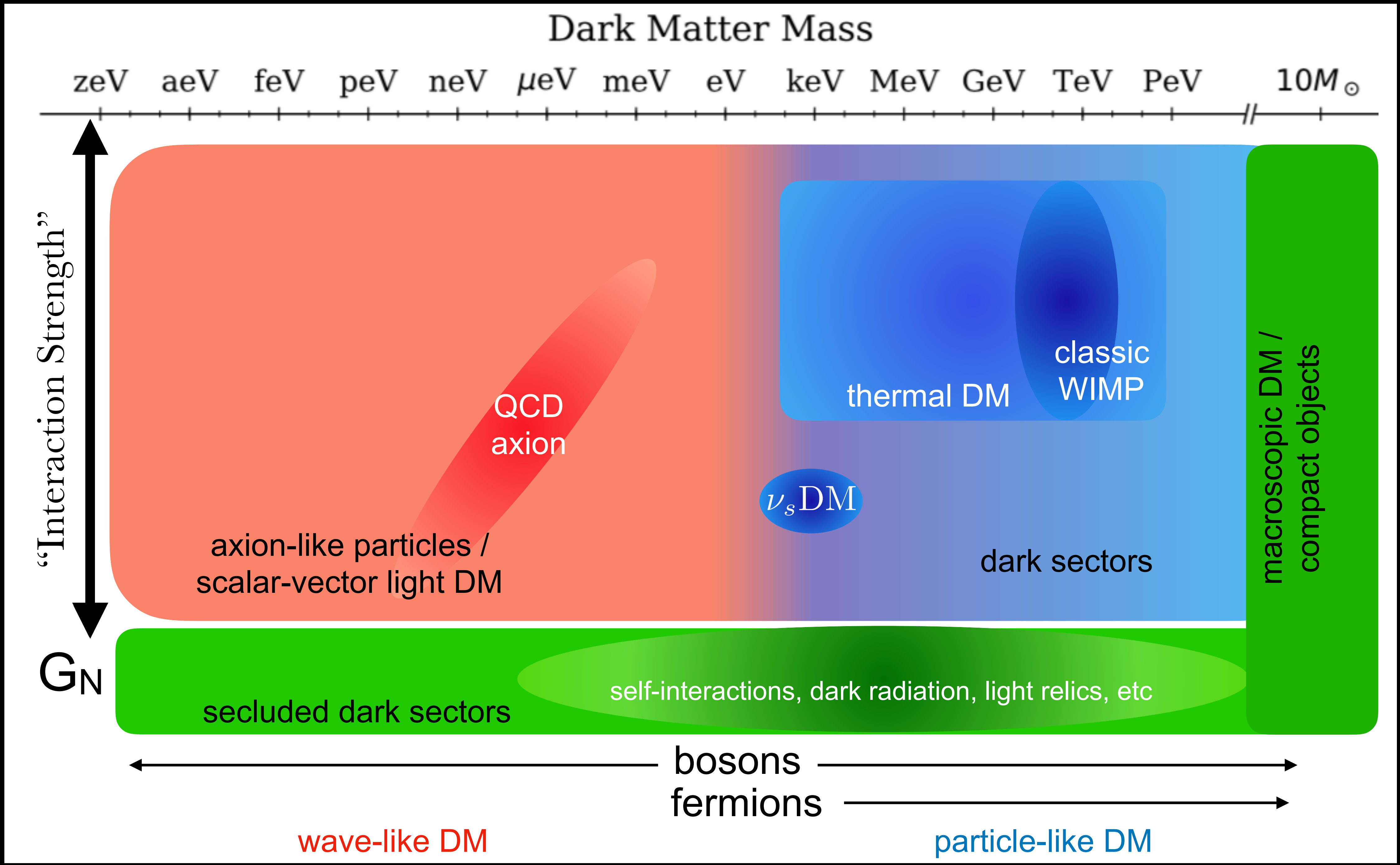


Dark Matter



There are many, many, many theories of what dark matter could be.

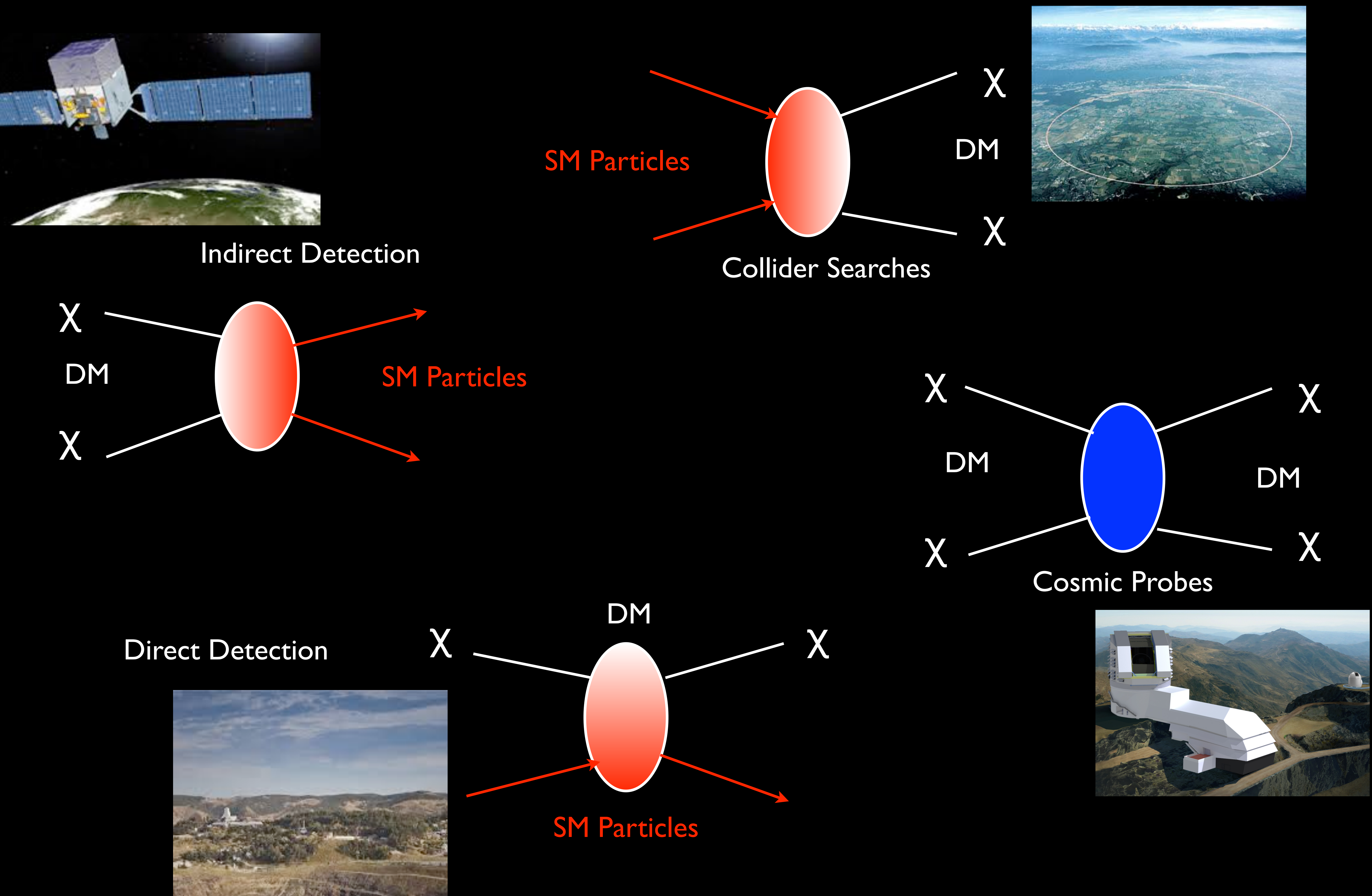
A Vast Landscape



Snowmass CF Report

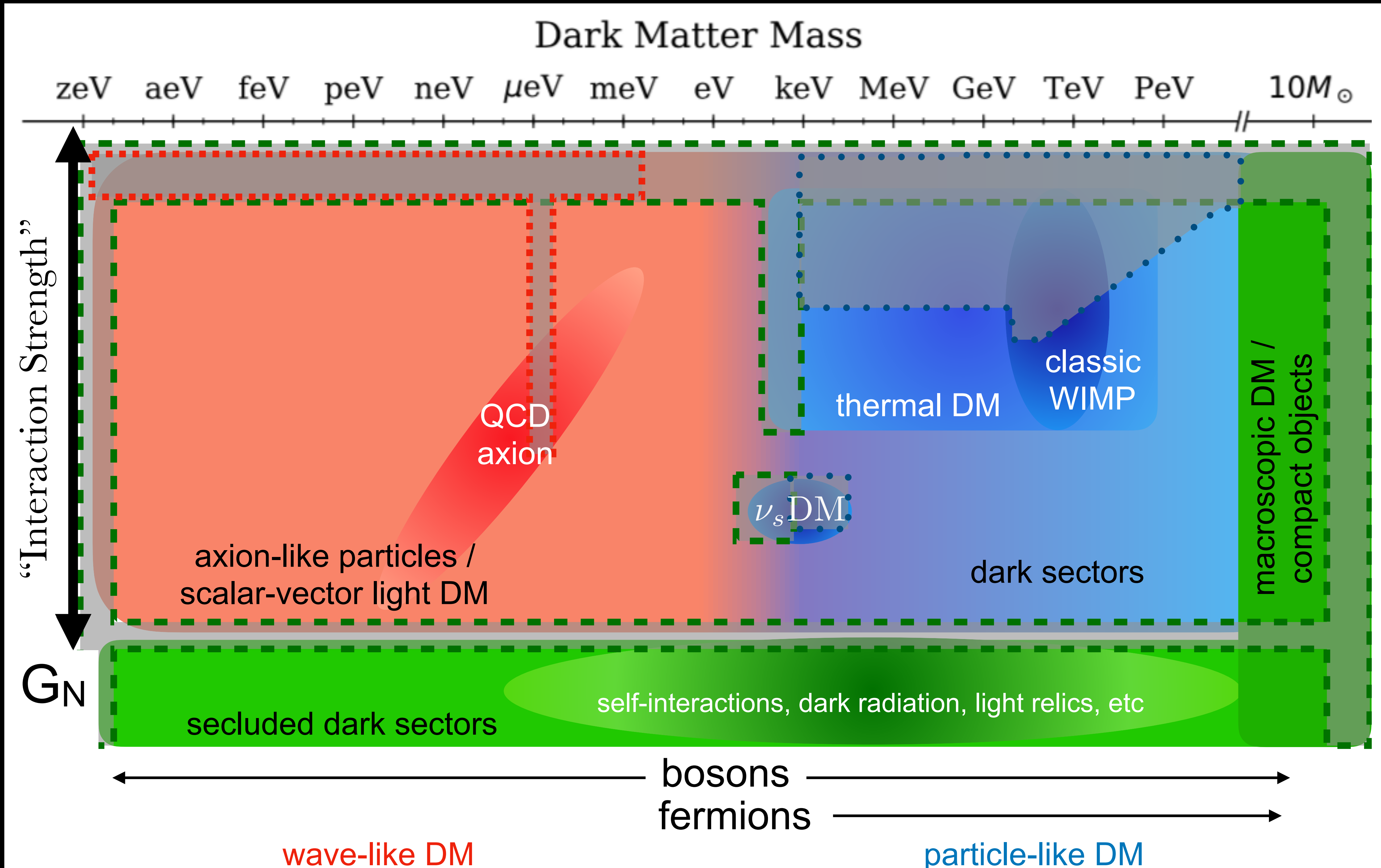
Snowmass 2021 developed this cartoon which encapsulates a broad brush parameter space of DM mass versus coupling to the Standard Model.

Probes of DM



SM Particles
X
DM
X
Collider Searches
Indirect Detection
X
DM
X
SM Particles
X
DM
X
X
DM
X
Cosmic Probes
Direct Detection
DM
X
X
SM Particles

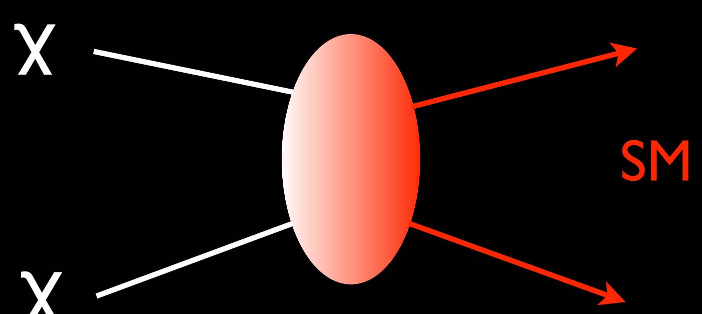
The Current Progress



Snowmass CF Report

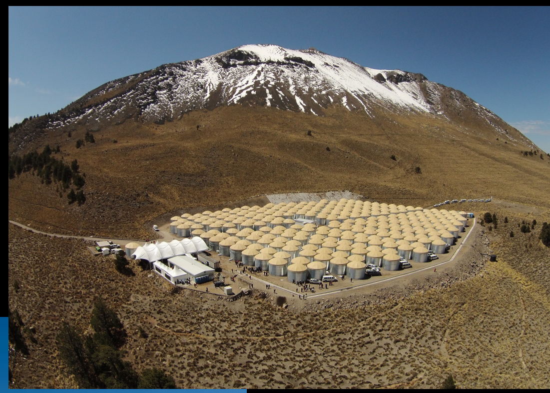
The searches we've done so far have made in-roads to some regions of parameter space, but there is still a wide landscape left to check…

Indirect Detection



- Indirect detection tries to see dark matter annihilating.
- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.

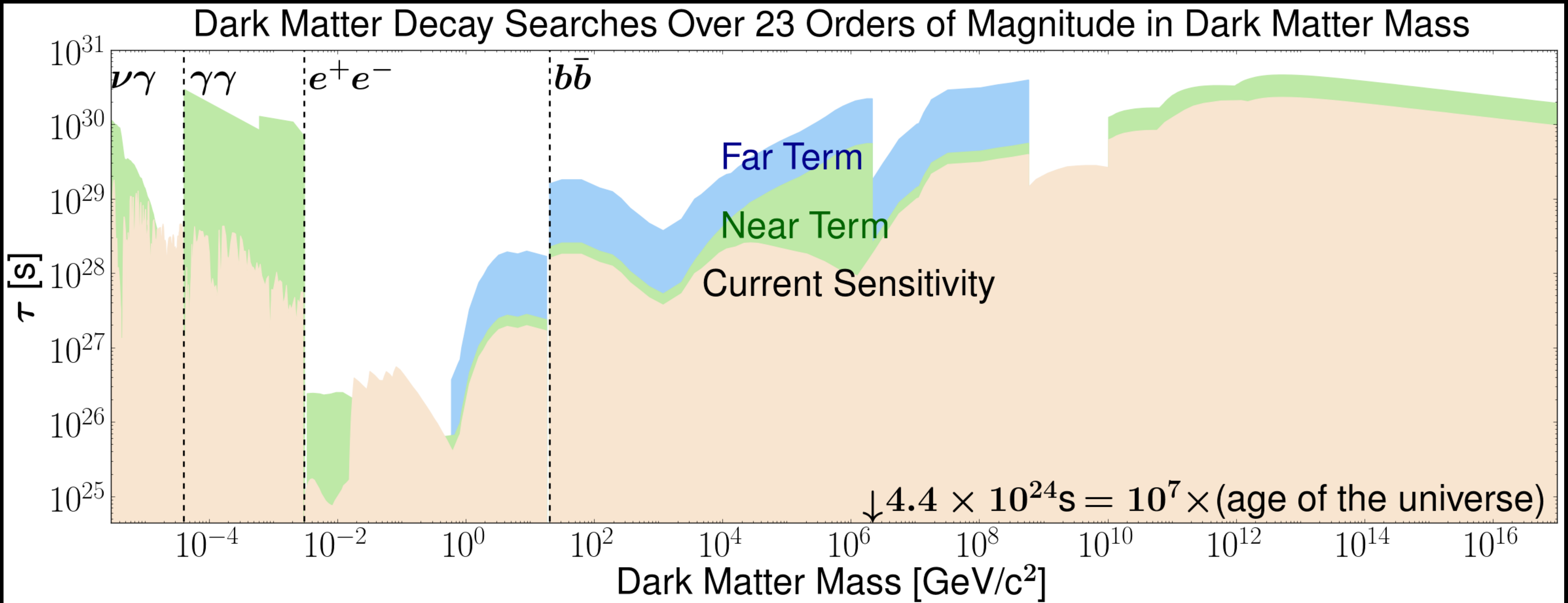
- In particular, photons and neutrinos interact sufficiently weakly with the interstellar medium, and might be detected on the Earth with directional information.



- Charged particles will generally be deflected on their way to us, but high energy anti-matter particles are rare enough that an excess of them could be noticeable.

Indirect Detection

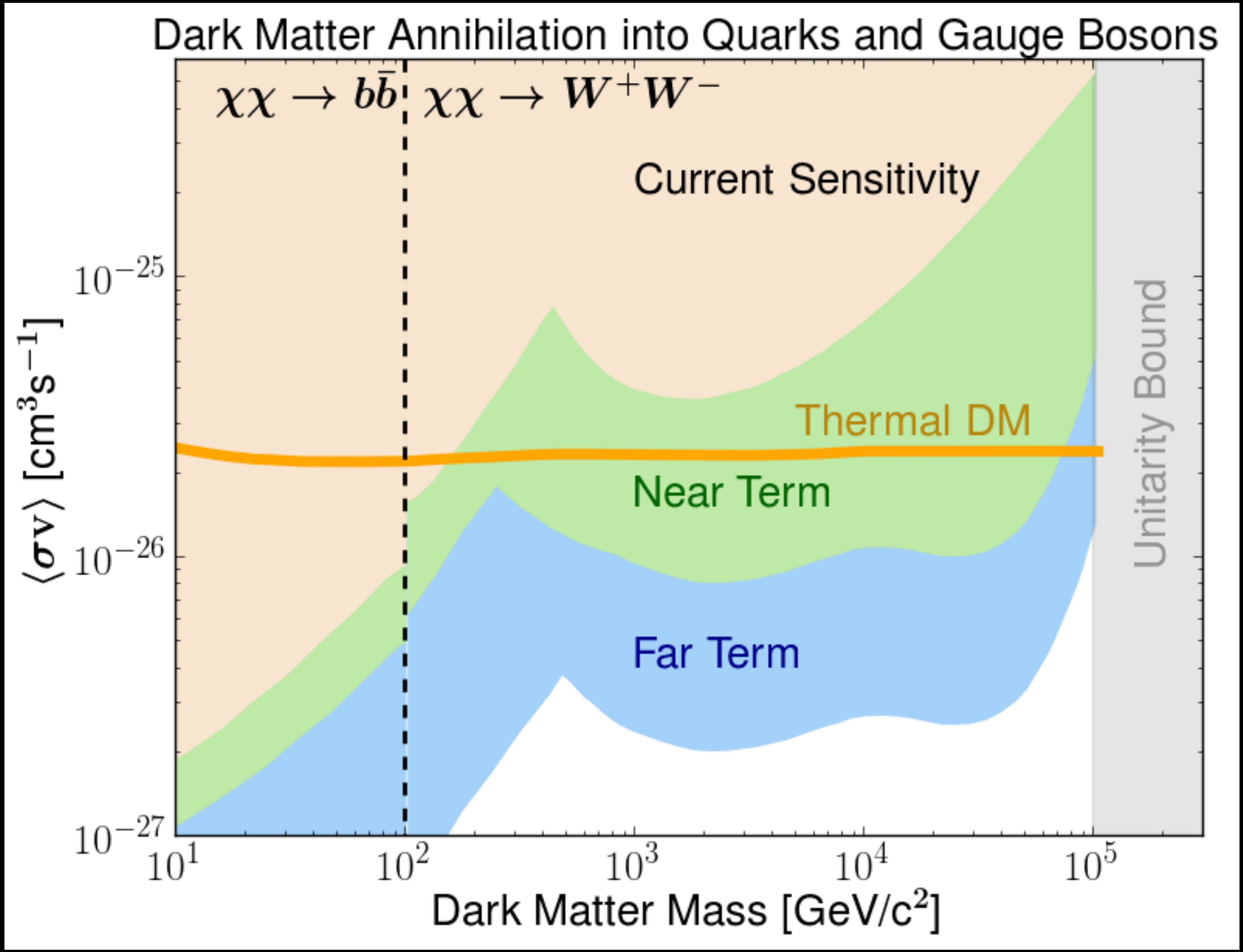
Snowmass CF1 Report



Indirect searches can access unique properties of the dark matter, such as its lifetime, which are essentially impossible to test with other experimental probes.

Astroparticle probes searching for a variety of annihilation products bound the DM lifetime to be more than many times the age of the Universe.

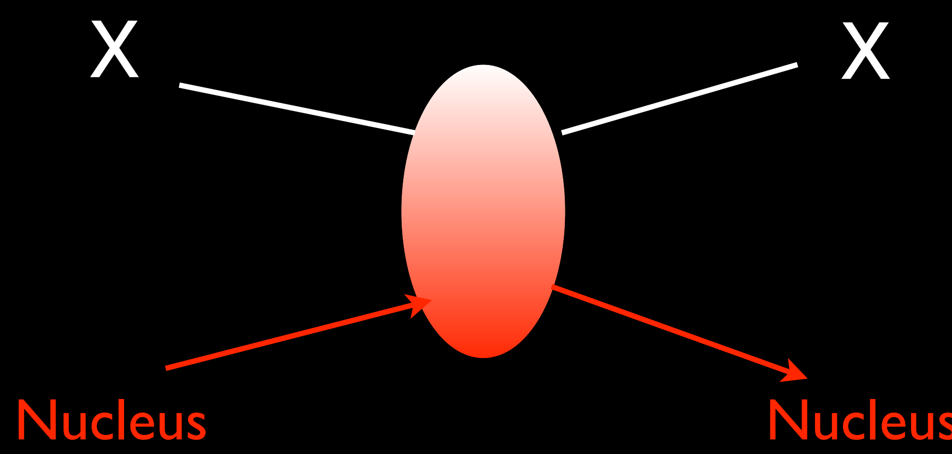
Indirect Detection



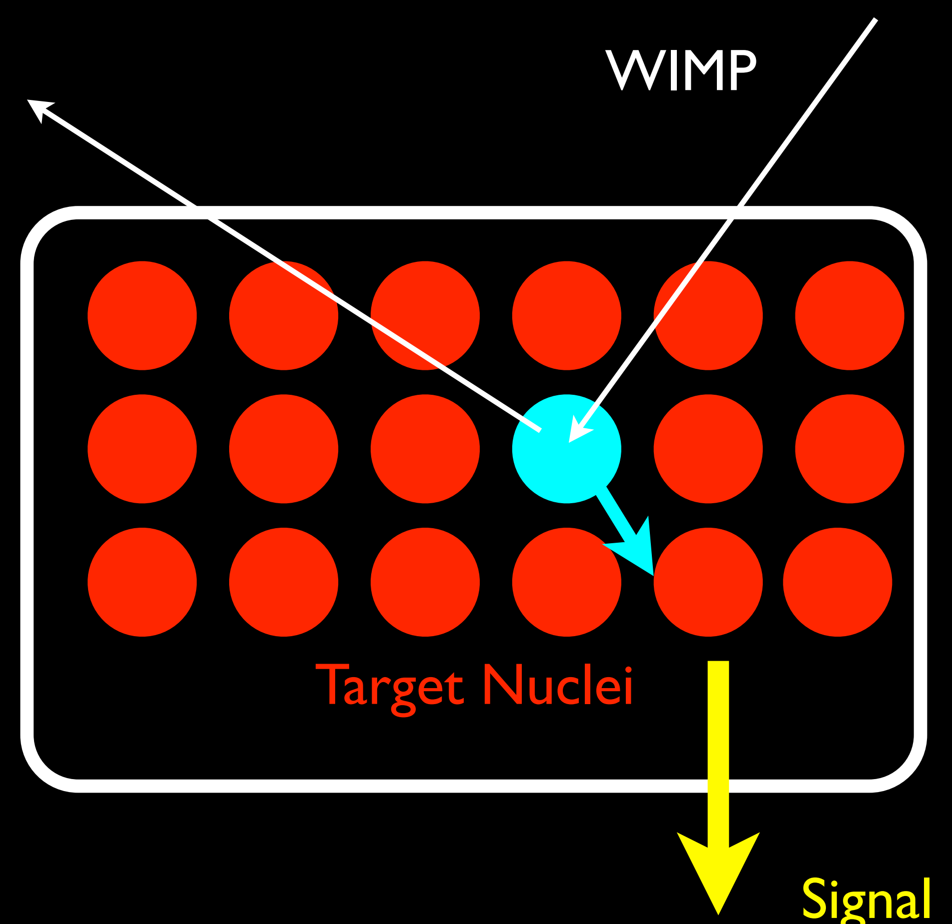
Indirect searches are sensitive to thermal relic dark matter with masses well beyond the reach of particle accelerators.

Snowmass CF1 Report

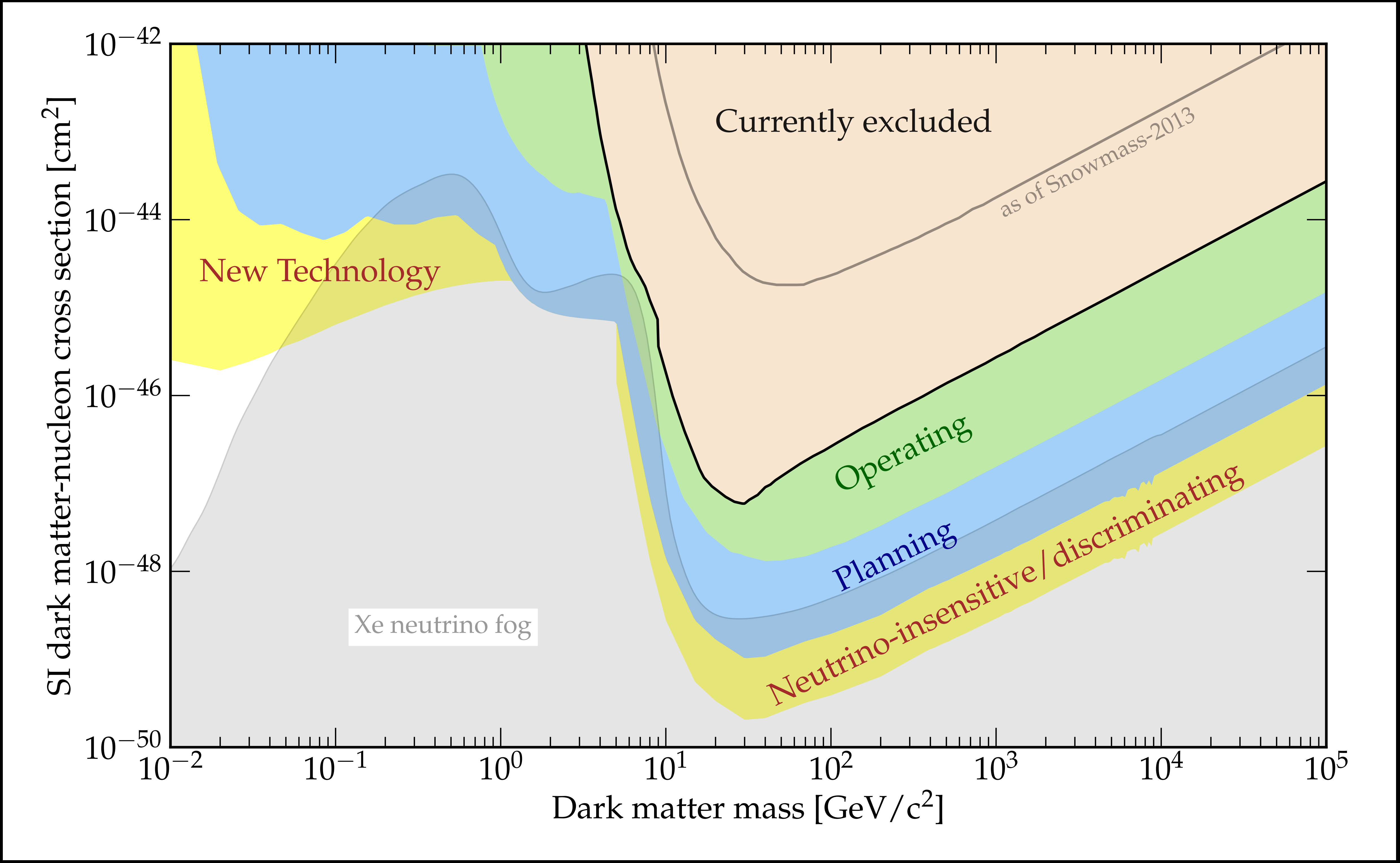
Direct Detection



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

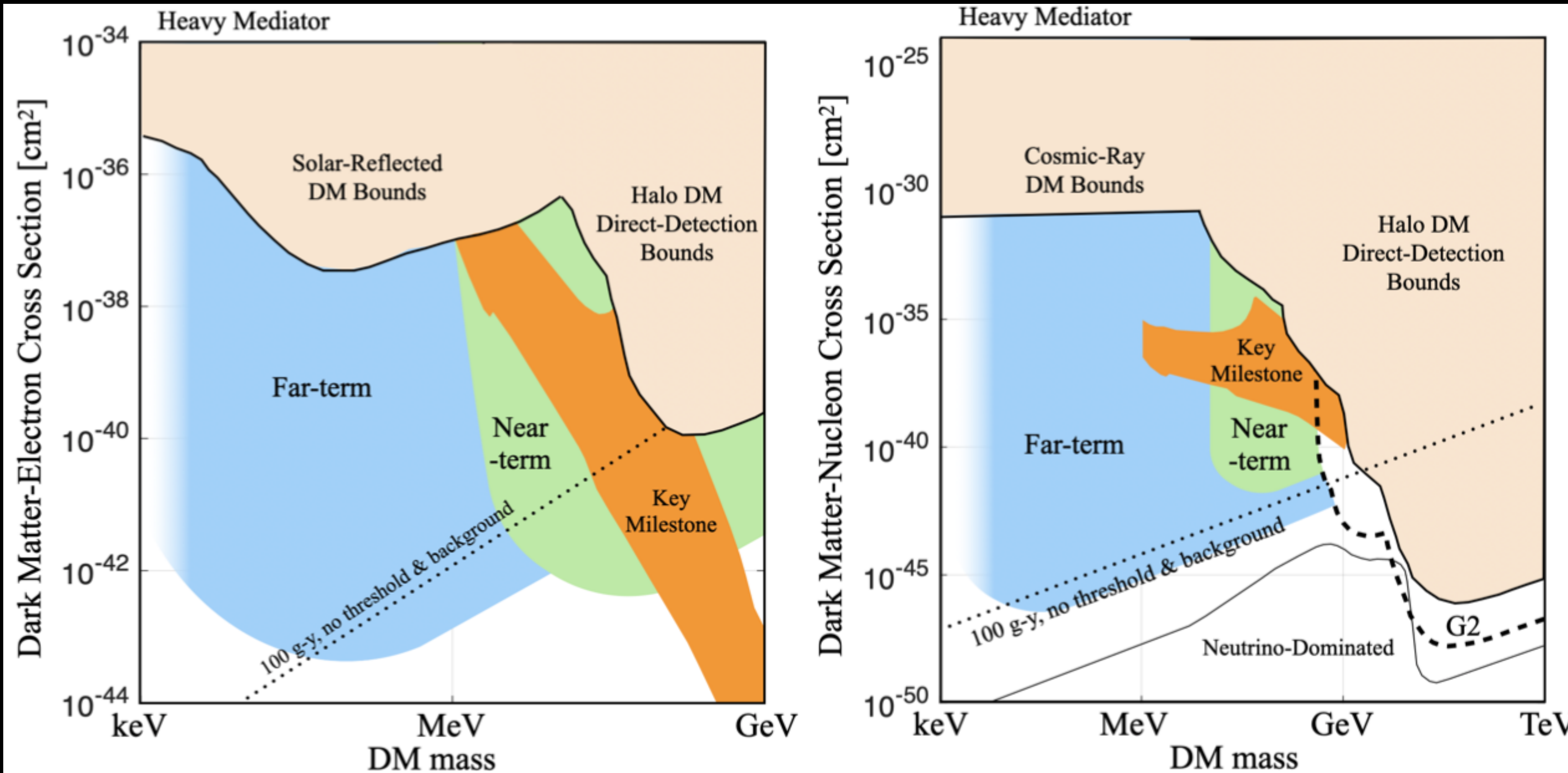


Racing to the Neutrino Fog



Snowmass CF1 Report

Exploring Lower Masses

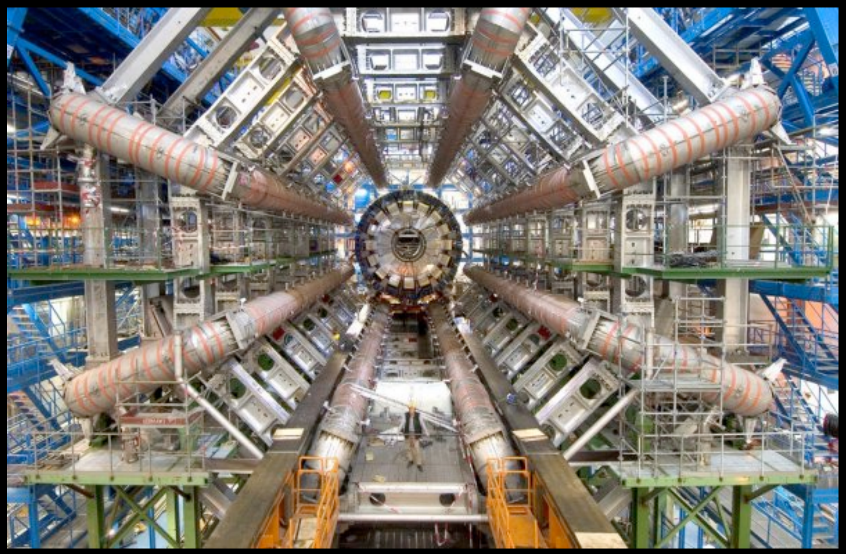


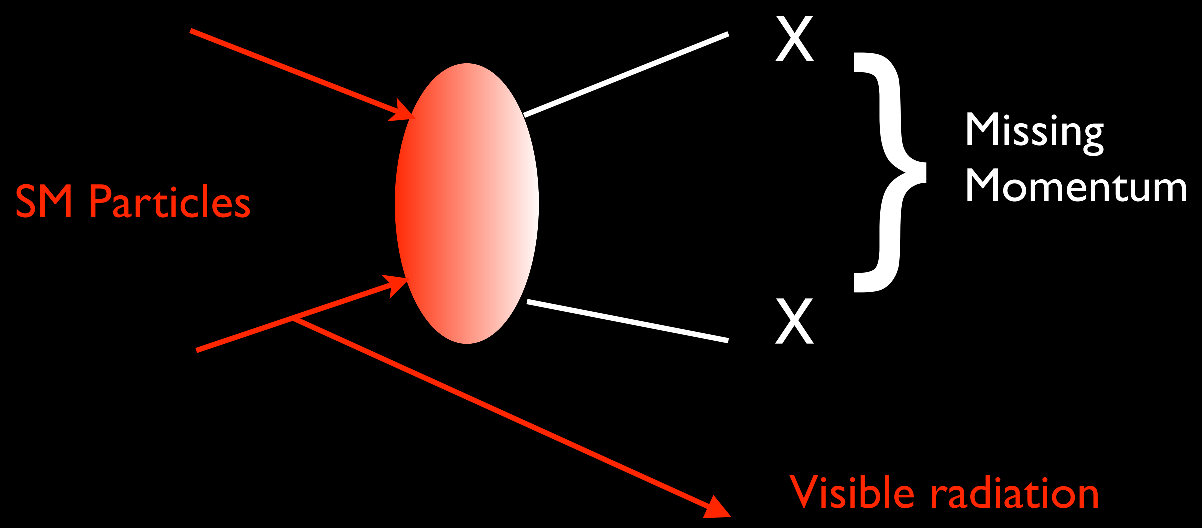
Going to lower DM masses is a challenge, because the ambient dark matter carries very little energy/momentum. Scattering with electrons or collective excitations in the detector offer opportunities to explore the ~MeV mass regime.

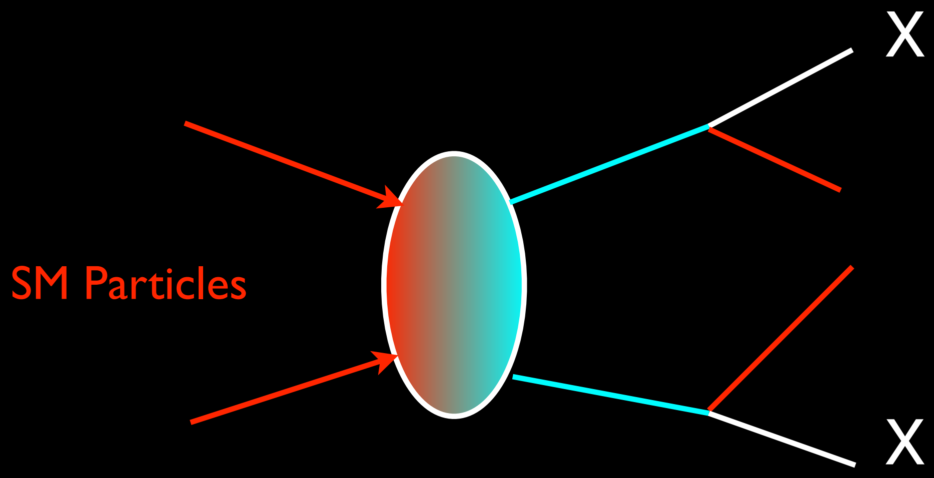
Snowmass CF1 Report

Collider Production

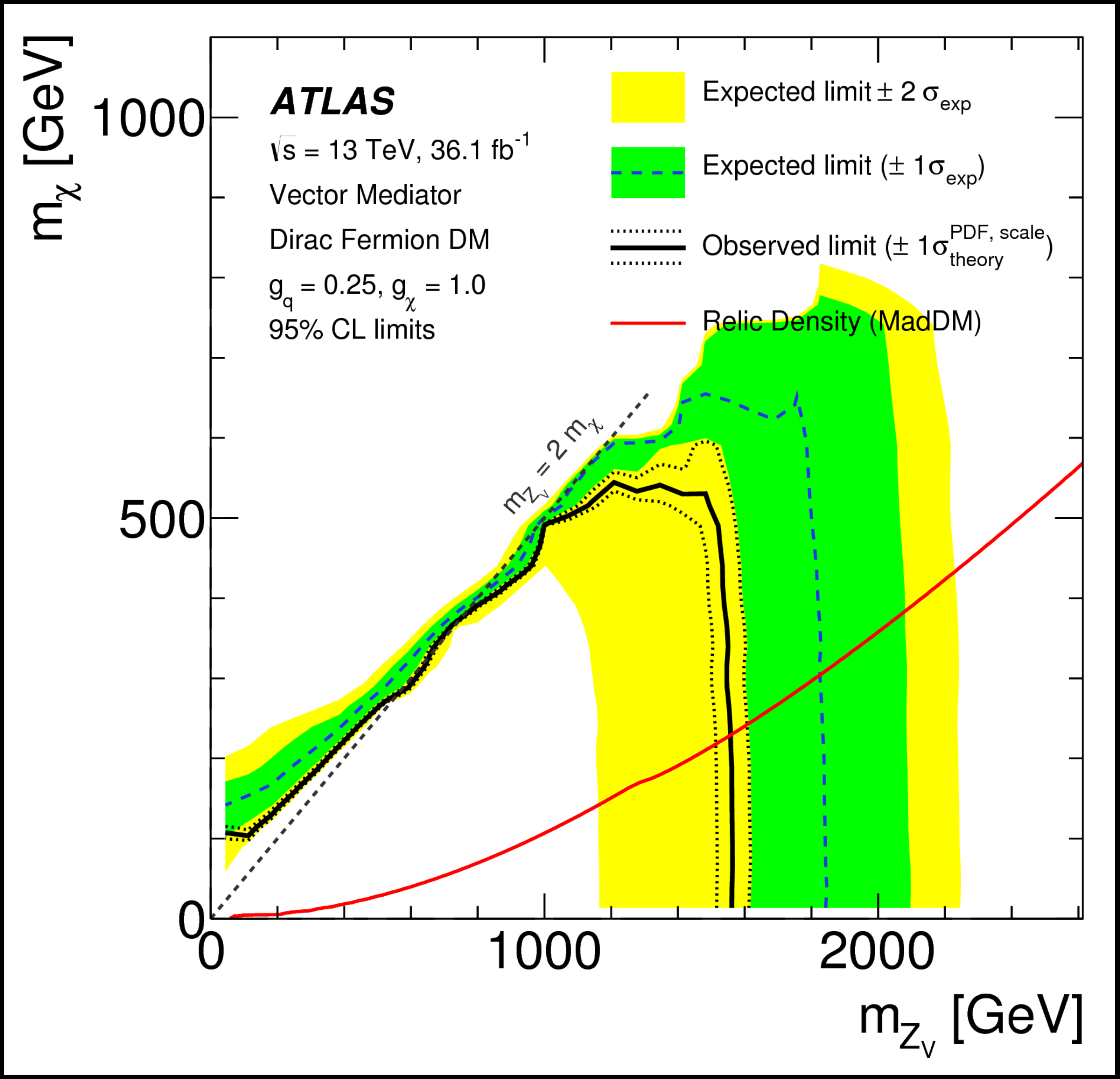
- If dark matter couples to quarks or gluons, we should also be able to produce it at high energy colliders.
- Since the DM is expected to interact very weakly, it is likely to pass through the detector and manifests as an imbalance in momentum.
- Provided they have enough energy to produce them, colliders may allow us to study DM and maybe even other elements of the “dark sector”, which are no longer present in the Universe today.

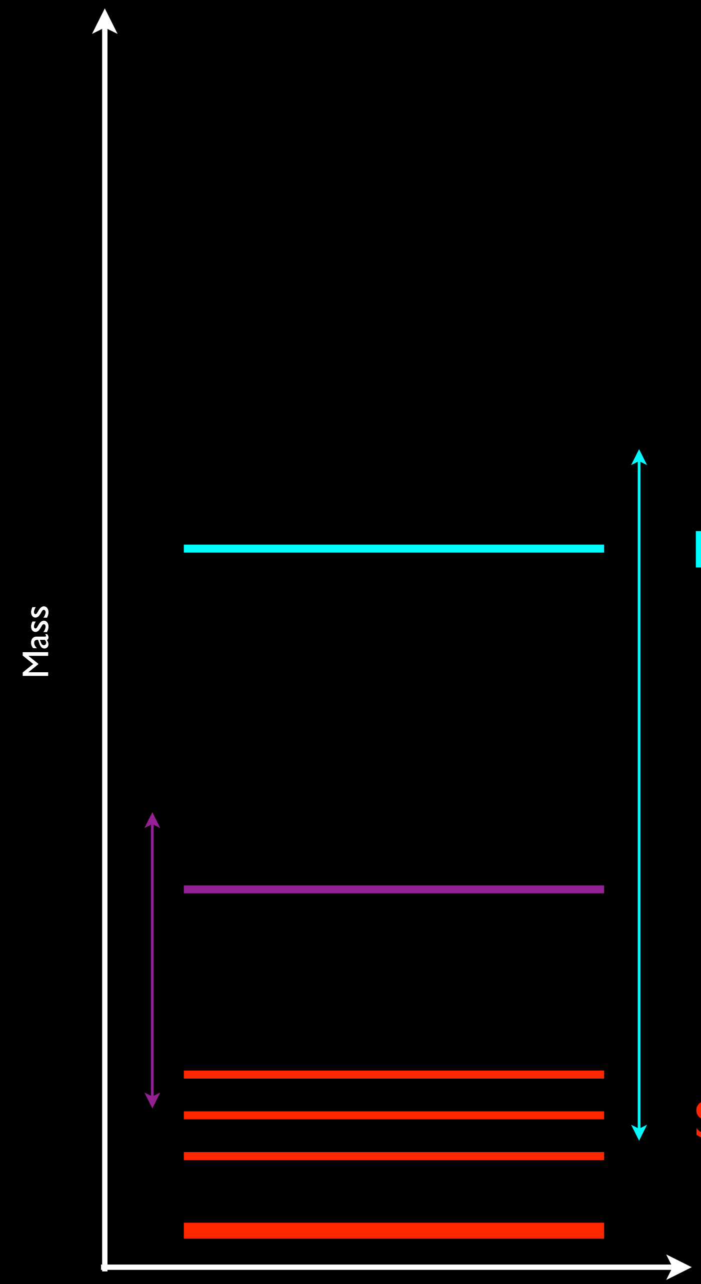




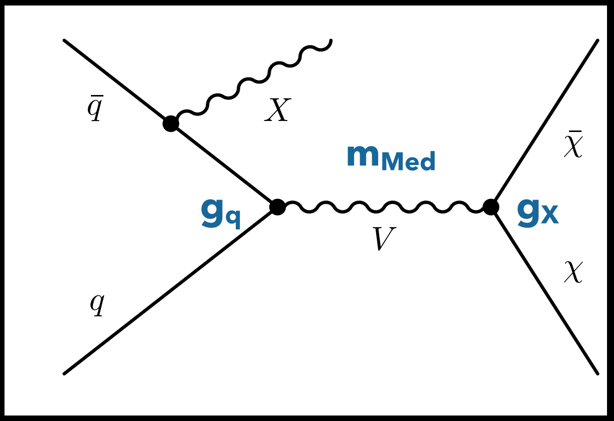


Mono-jet Searches



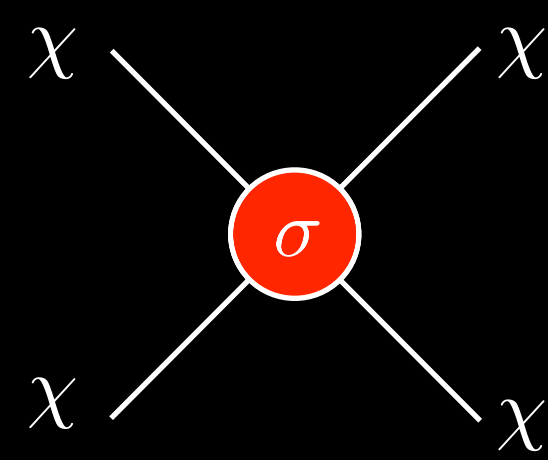


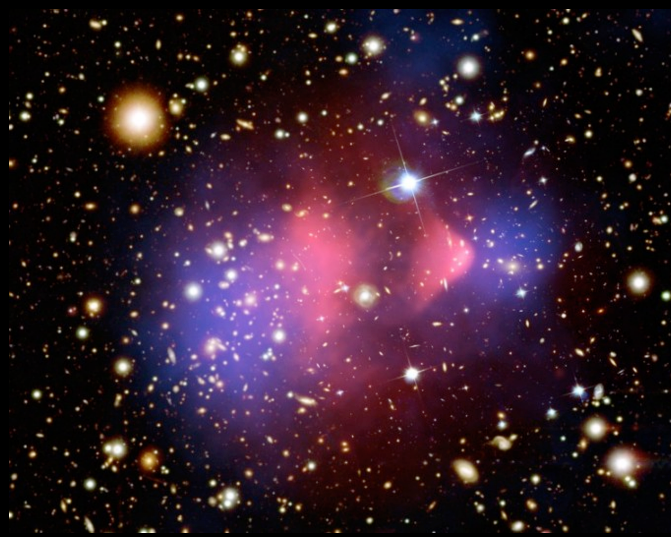
Searches for dark matter (missing momentum) plus a jet of hadrons places limits on the masses and couplings of the dark matter to mediator particles and quarks.



Cosmic Probes of DM

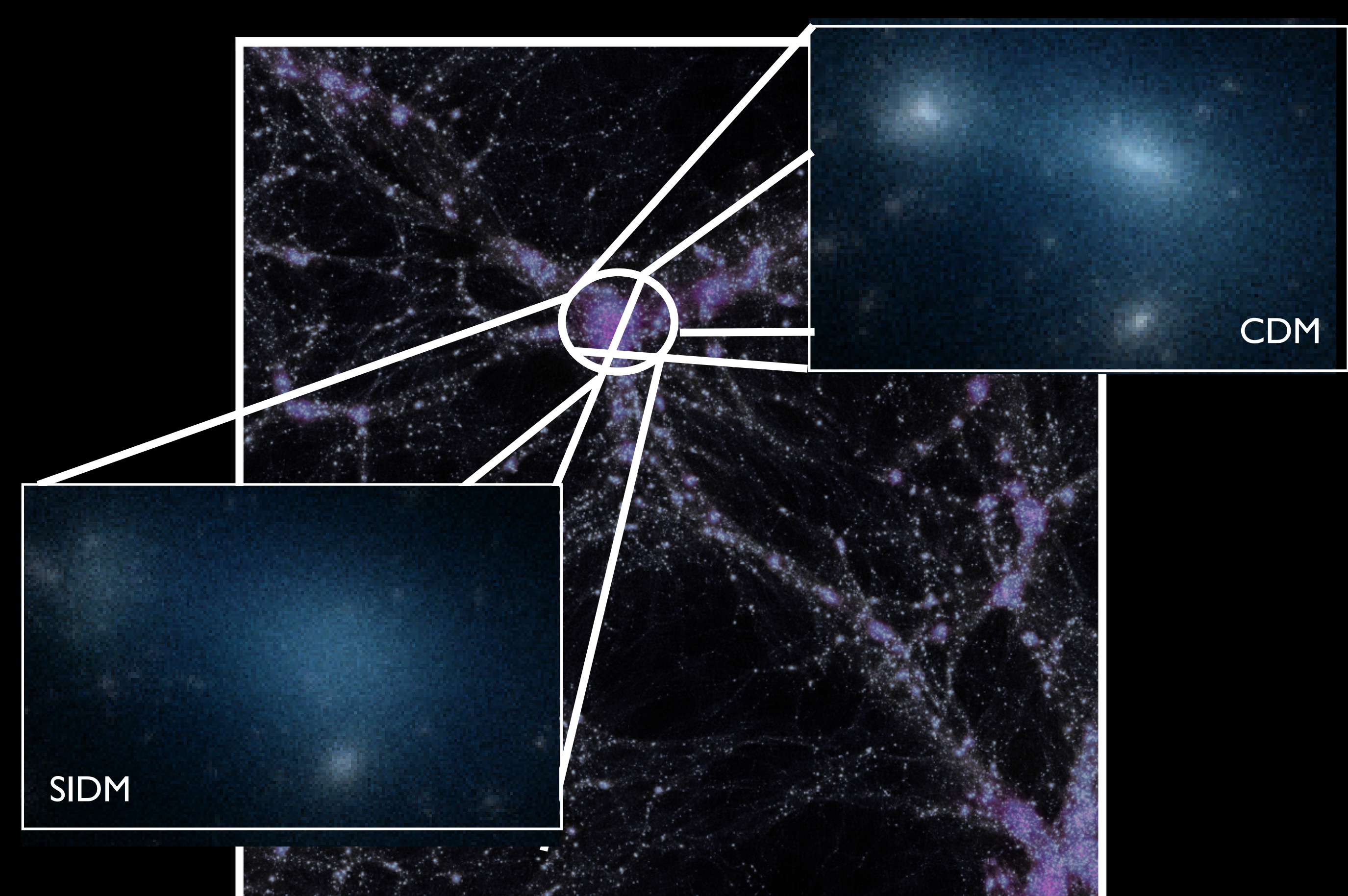
- Cosmic probes of dark matter can access properties of it that are otherwise inaccessible.
- For example, dark matter with large enough self-interactions could retain the successes describing large scale structure, but show measurable differences at the smallest scales.
- This highlights some of the points where simulations benefit from improvement, and both guides their evolution as well as providing a signpost to where there may be surprises lurking in the data.



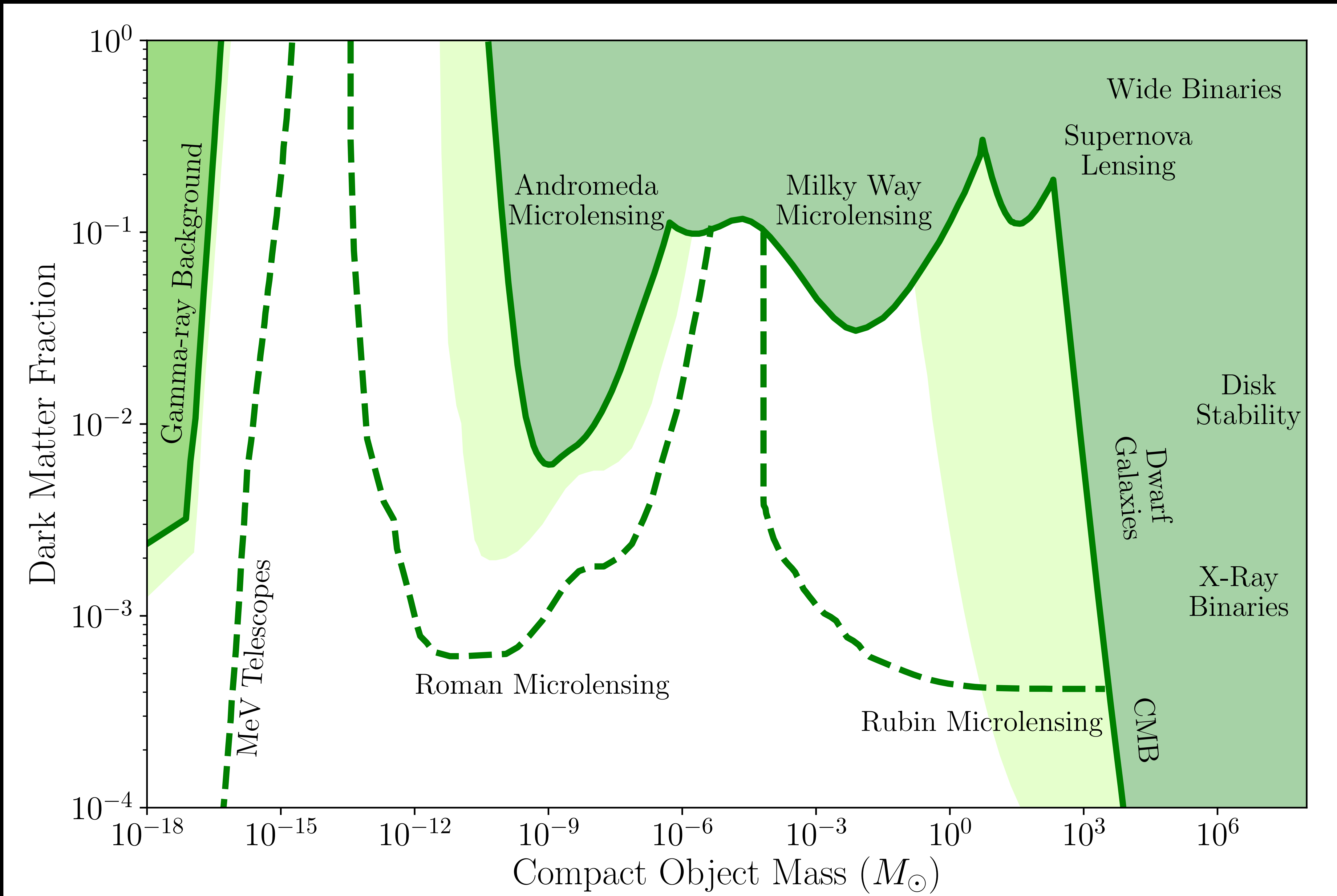


Markevitch et al; Clowe et al

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



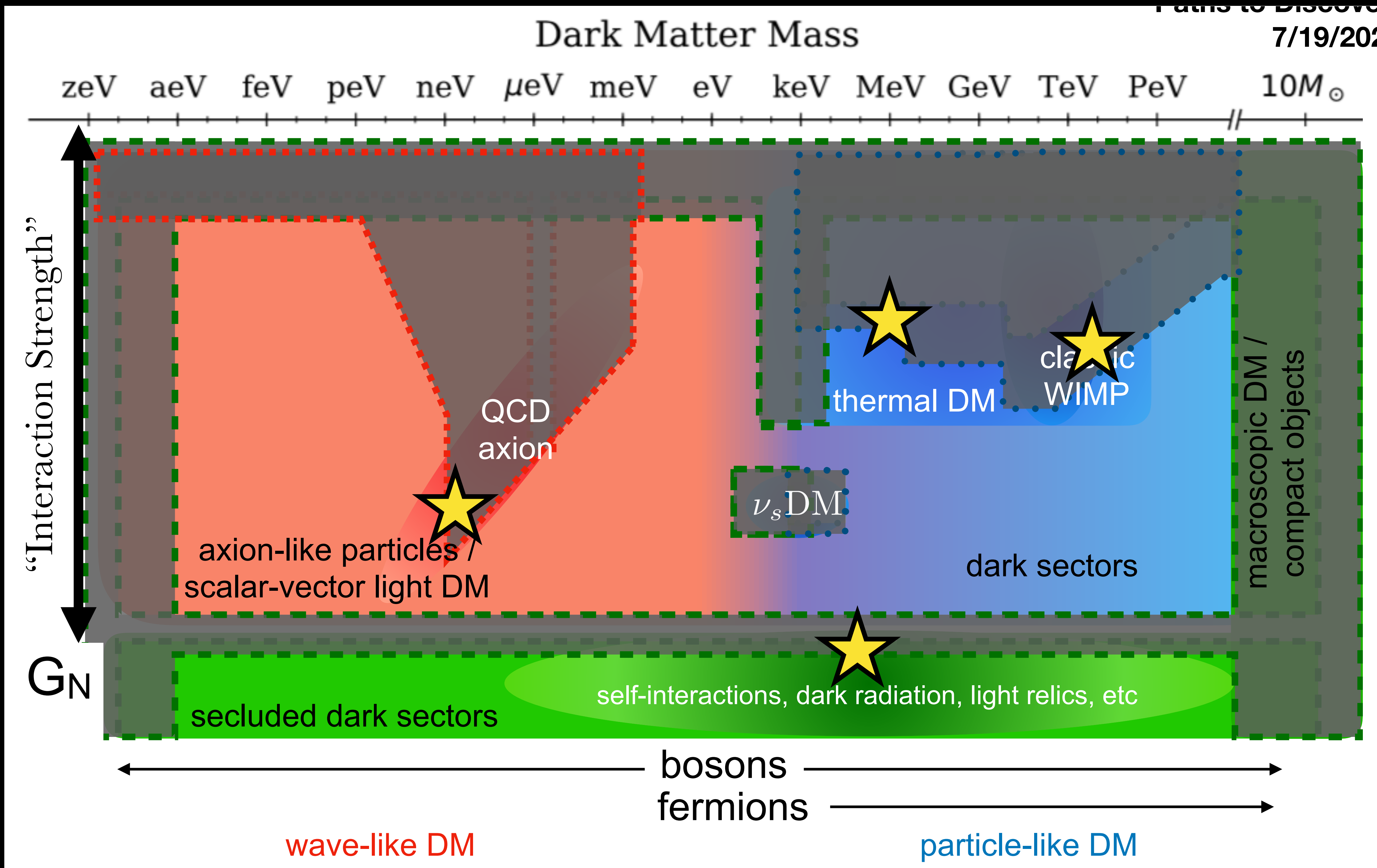
Astronomical Probes



Snowmass CF3 Report

Cosmic probes such as substructures (detected by gravitational lensing) place important constraints on some of the heaviest DM candidates and probe theories leading to unusual distributions of dark matter structure formation.

The Future



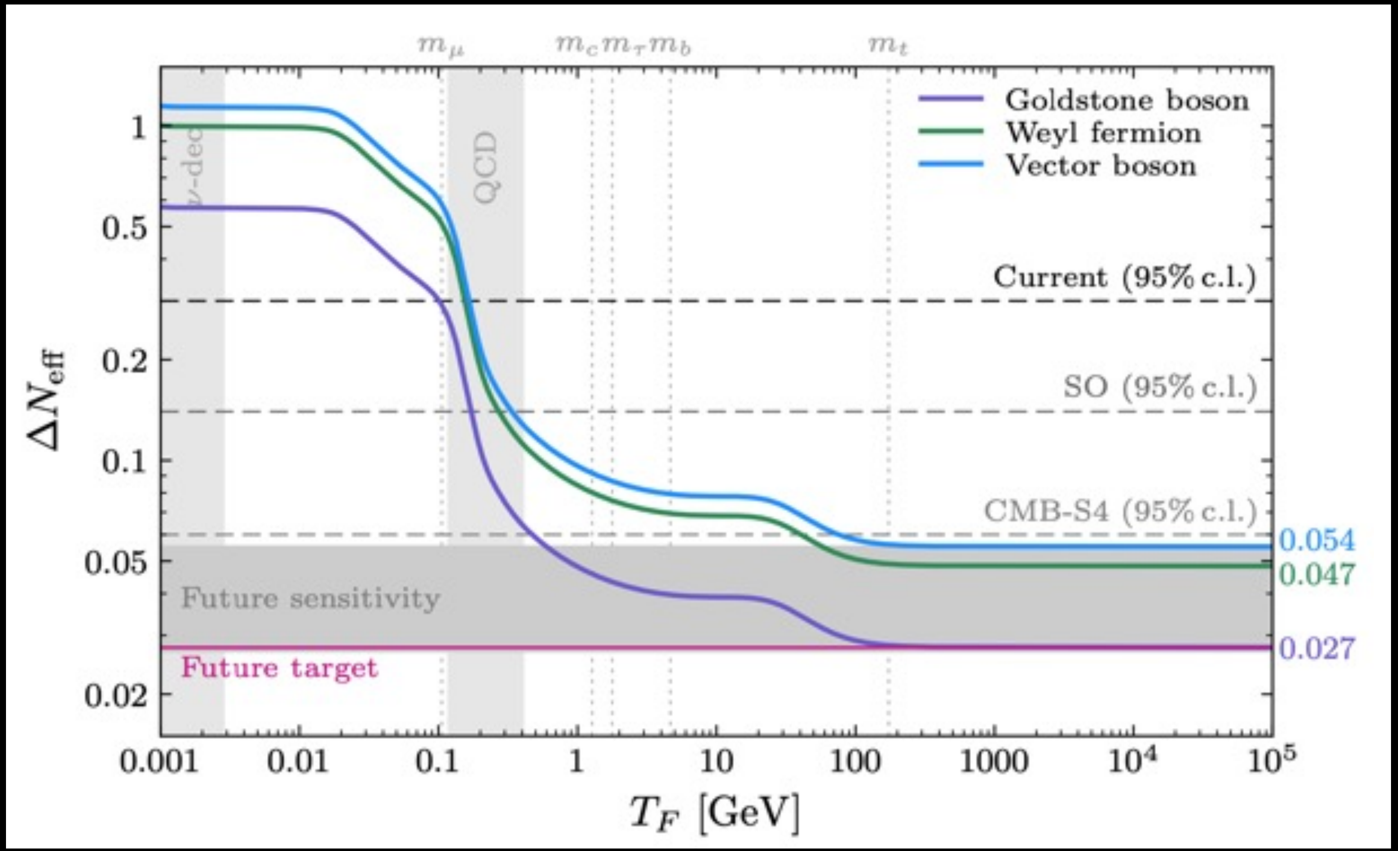
Snowmass
CF Report

The parameter space is broad, but there are plans to explore significant regions of the landscape in the near future.

Exploring the Unknown

- Of course, it may be that the next discovery is not foretold by the hints we have at hand. There could be something around the corner that represents a complete surprise.
- There are many places where could imagine discoveries coming out of the blue. For example, measurements of the expansion of the Universe could reveal the existence of new light degrees of freedom that are too weakly coupled for us to produce them in any rate on the Earth.
- Independent determinations of neutrino masses help maximize the impact of such measurements.

ΔN_{eff} parameterizes the existence of new light particles as a shift in the effective number of SM neutrinos.

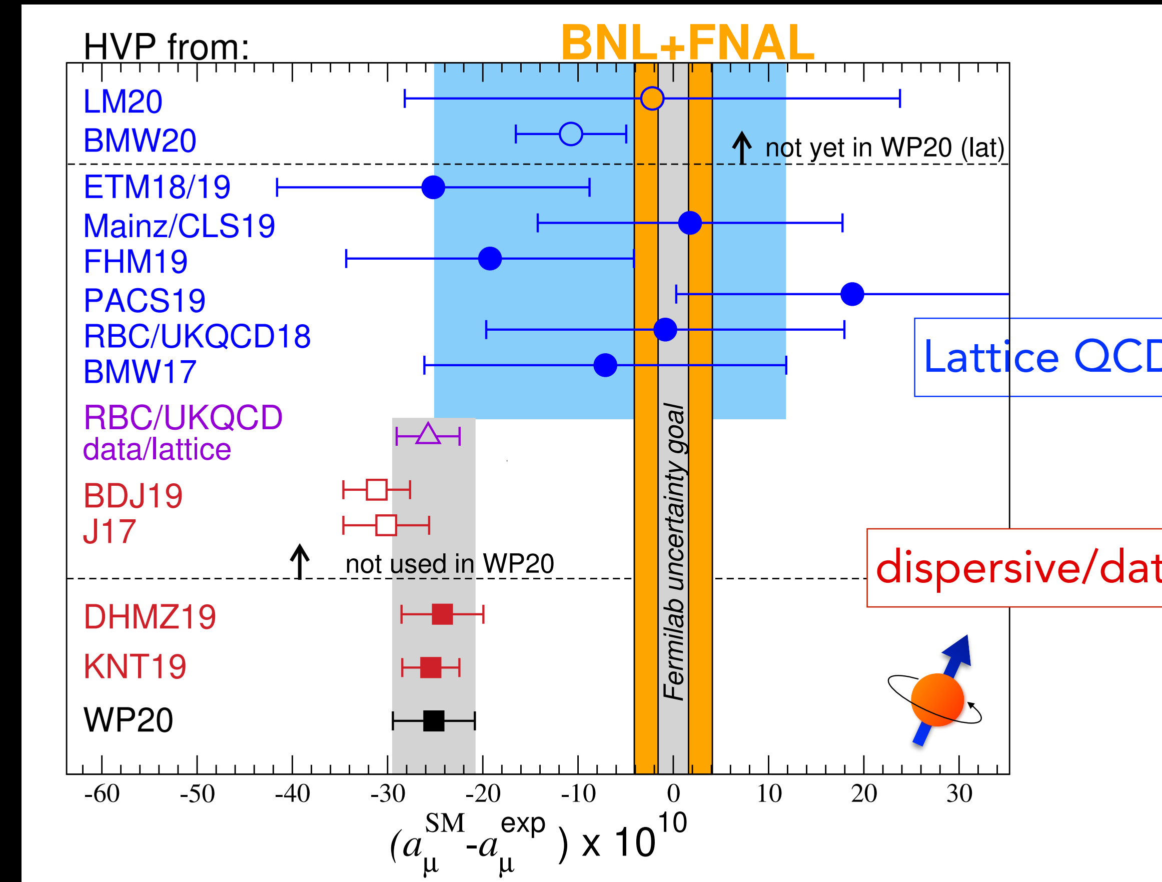


Snowmass CF Report

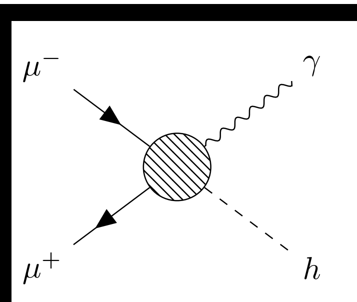
G-2

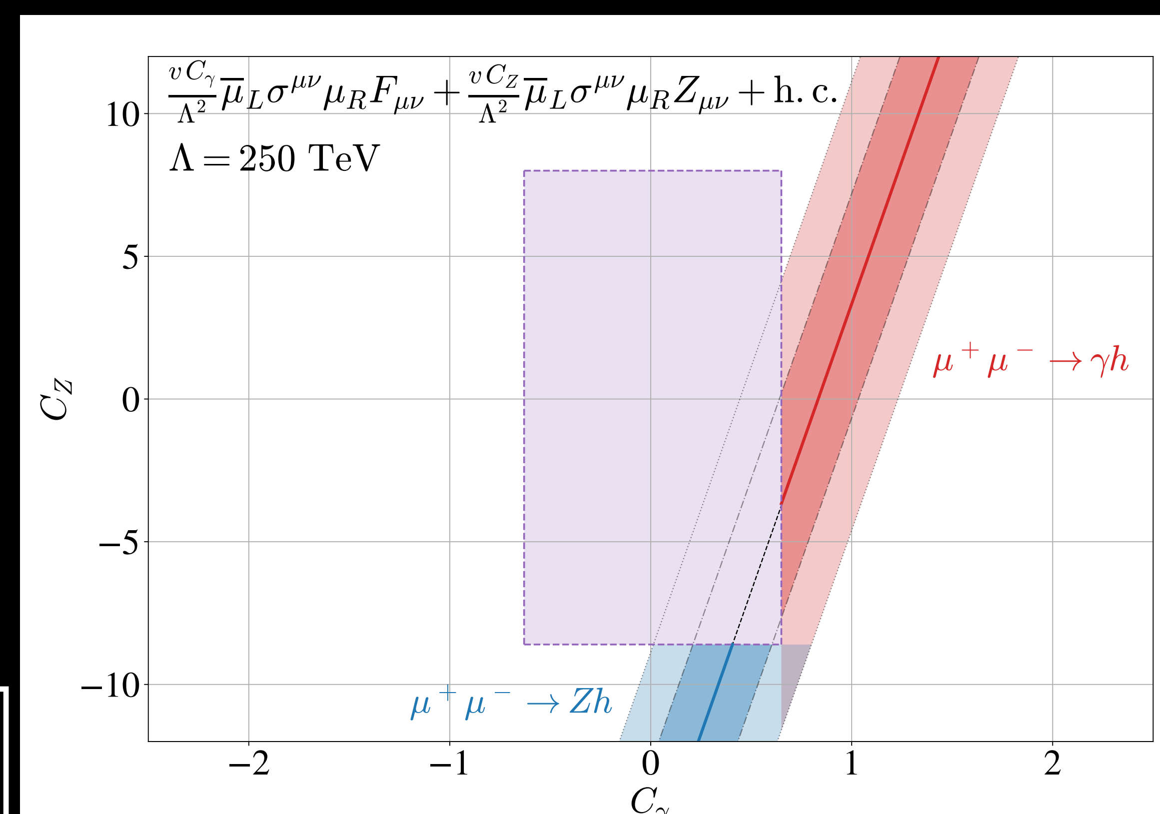
Aida El-Khadra, P5 Town hall

- It may also be that precision measurements will turn out to lead the way. For example, the longstanding discrepancy in the muon's g-2 might be a hint for new physics.
- Currently there are tensions between the best lattice determinations of the hadronic contribution to the vacuum polarization and data-driven estimates.
- A future muon collider could look for complementary signals expected if this is the impact of heavy new physics!



$$\frac{C_\gamma}{\Lambda^2}(H\overline{L}_2)\sigma^{\mu\nu}\mu_R F_{\mu\nu} \to \frac{v\,C_\gamma}{\Lambda^2}\overline{\mu}_L\sigma^{\mu\nu}\mu_R F_{\mu\nu}$$

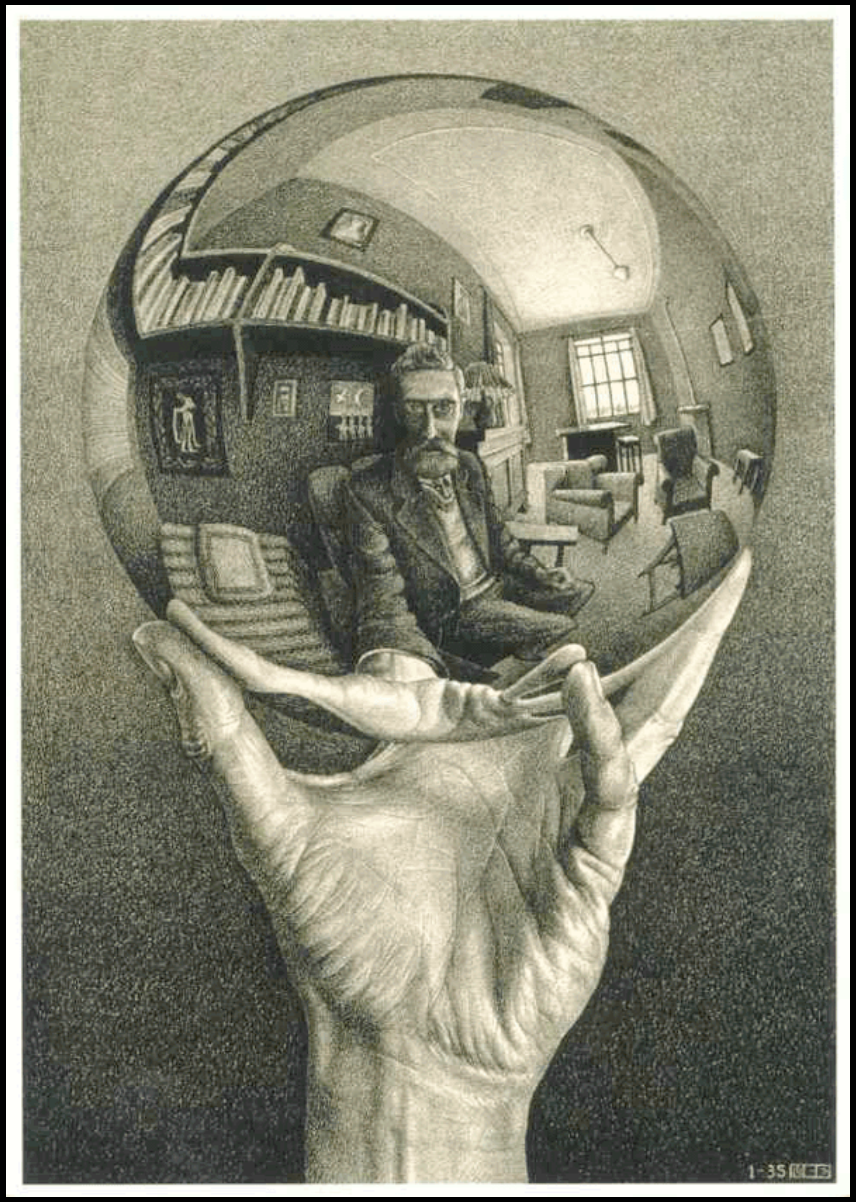




Arakawa, Rajaraman, Sui, TMPT 2208.14464

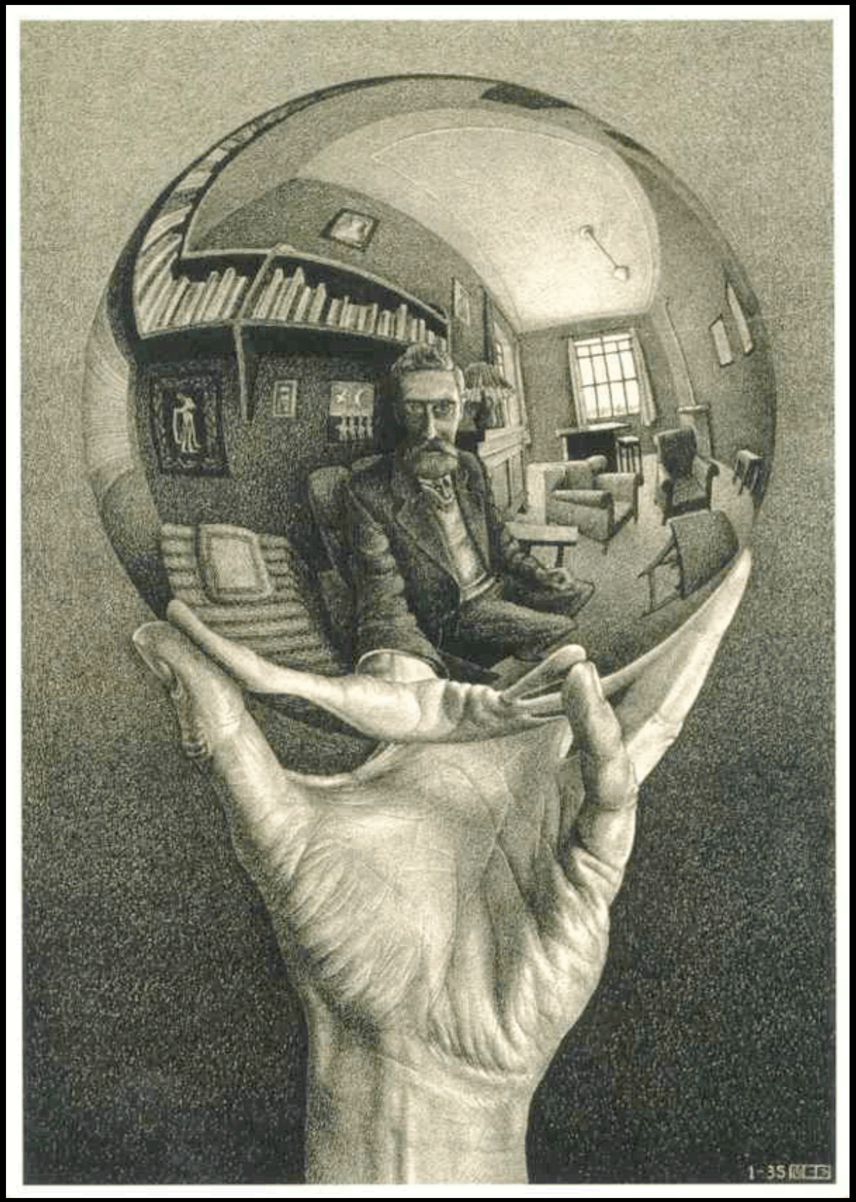
Outlook

- There are plenty of signs of BSM physics already at hand.
- Many are incontrovertible like neutrino masses, while others may disappear with more data or better theoretical understanding.
- All are interesting signposts to new ideas and new directions.



Outlook

- There are plenty of signs of BSM physics already at hand.
- Many are incontrovertible like neutrino masses, while others may disappear with more data or better theoretical understanding.
- All are interesting signposts to new ideas and new directions.



Inspiration:

"If you want your children to be intelligent, read them fairy tales. If you want them to be more intelligent, read them more fairy tales."

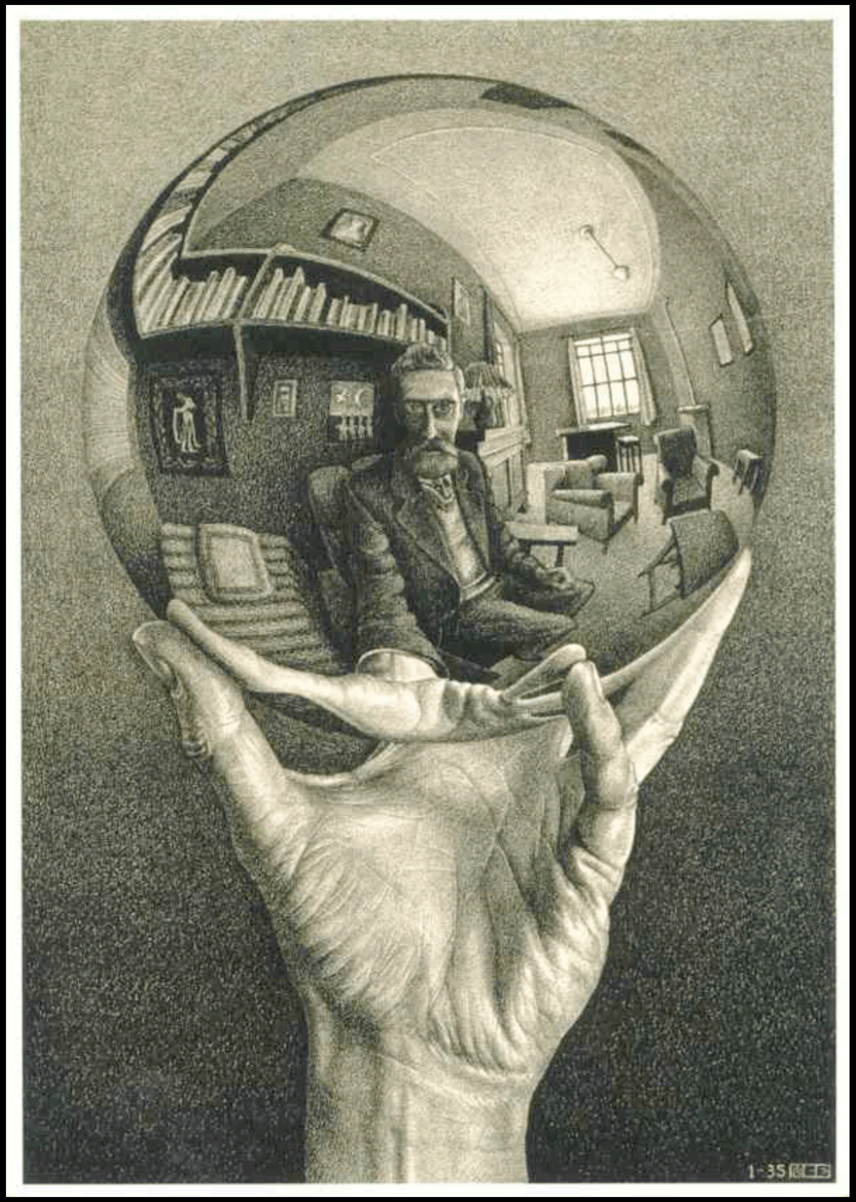
Outlook

- There are plenty of signs of BSM physics already at hand.
- Many are incontrovertible like neutrino masses, while others may disappear with more data or better theoretical understanding.
- All are interesting signposts to new ideas and new directions.

Inspiration:

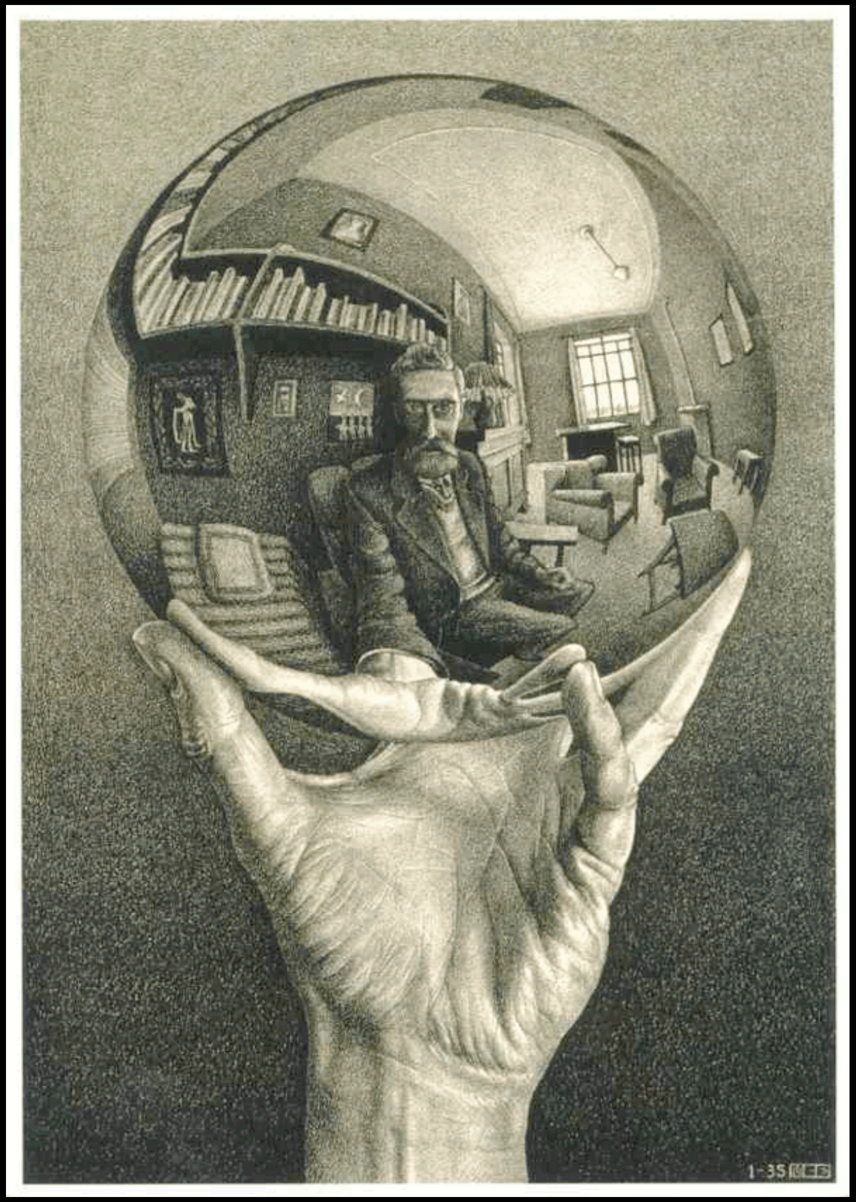
"If you want your children to be intelligent, read them fairy tales. If you want them to be more intelligent, read them more fairy tales."

— Albert Einstein



Outlook

- There are plenty of signs of BSM physics already at hand.
- Many are incontrovertible like neutrino masses, while others may disappear with more data or better theoretical understanding.
- All are interesting signposts to new ideas and new directions.



Inspiration:

"If you want your children to be intelligent, read them fairy tales. If you want them to be more intelligent, read them more fairy tales."

— Albert Einstein

Caution:

"It's tough to make predictions, especially about the future."

— Yogi Berra