Perspectives and Vision

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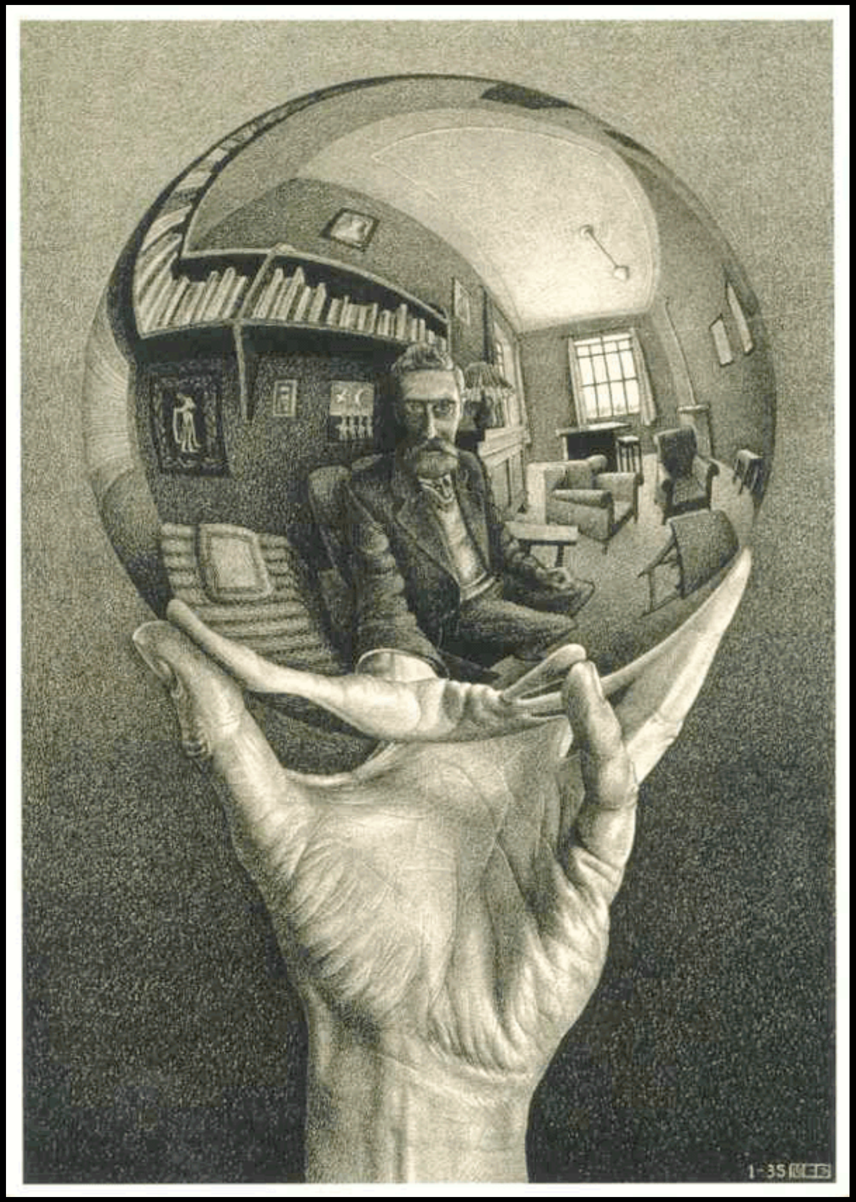
May 19, 2023

Where is the New Physics?

- Particle Physics is in an interesting cross roads.
- The LHC is wildly successful and has established the Higgs as the primary agent of Electroweak Symmetry-Breaking.
- But now the SM does an exquisite job of describing all of its data, with deviations largely at the level one would expect from an instrument with such a large dynamic range of measurements.
- Some people respond to this situation with angst or ennui.
- I don't really understand this perspective.



New Physics is all around us!

(We've been hearing about it all week!)

Where is the New Physics?

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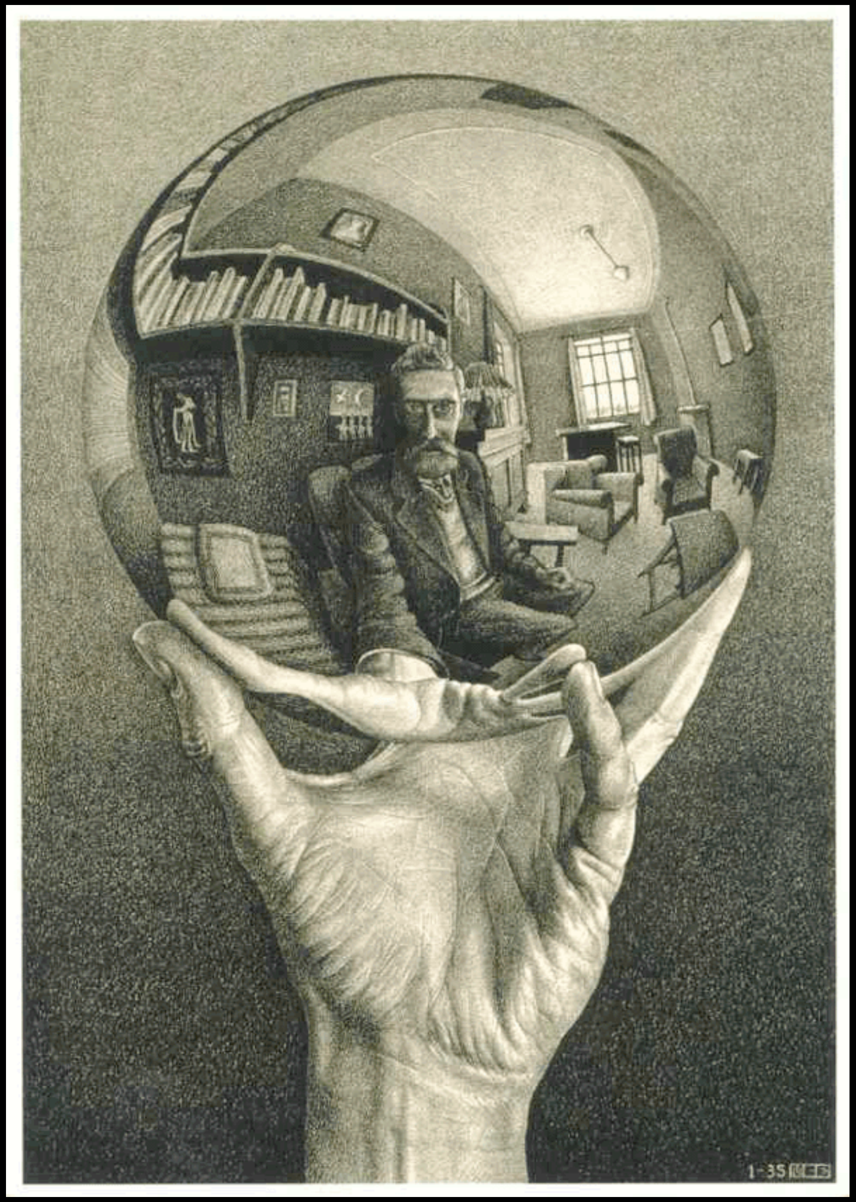
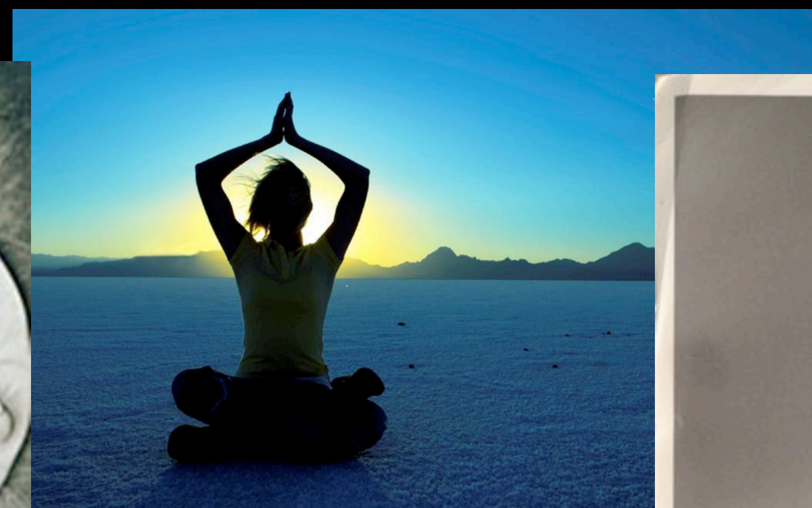
- But now the SM does an exquisite job of describing all of its data, with deviations largely at the level one would expect from an instrument with such a large dynamic range of measurements.
- Some people respond to this situation with angst or ennui.
- I don’t really understand this perspective.
- I am reminded that my favorite crystal ball is the one by MC Escher to the right. It reminds me that often predicting the future tells us more about who we are ourselves than what is likely to happen.



Where is the New Physics?



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!

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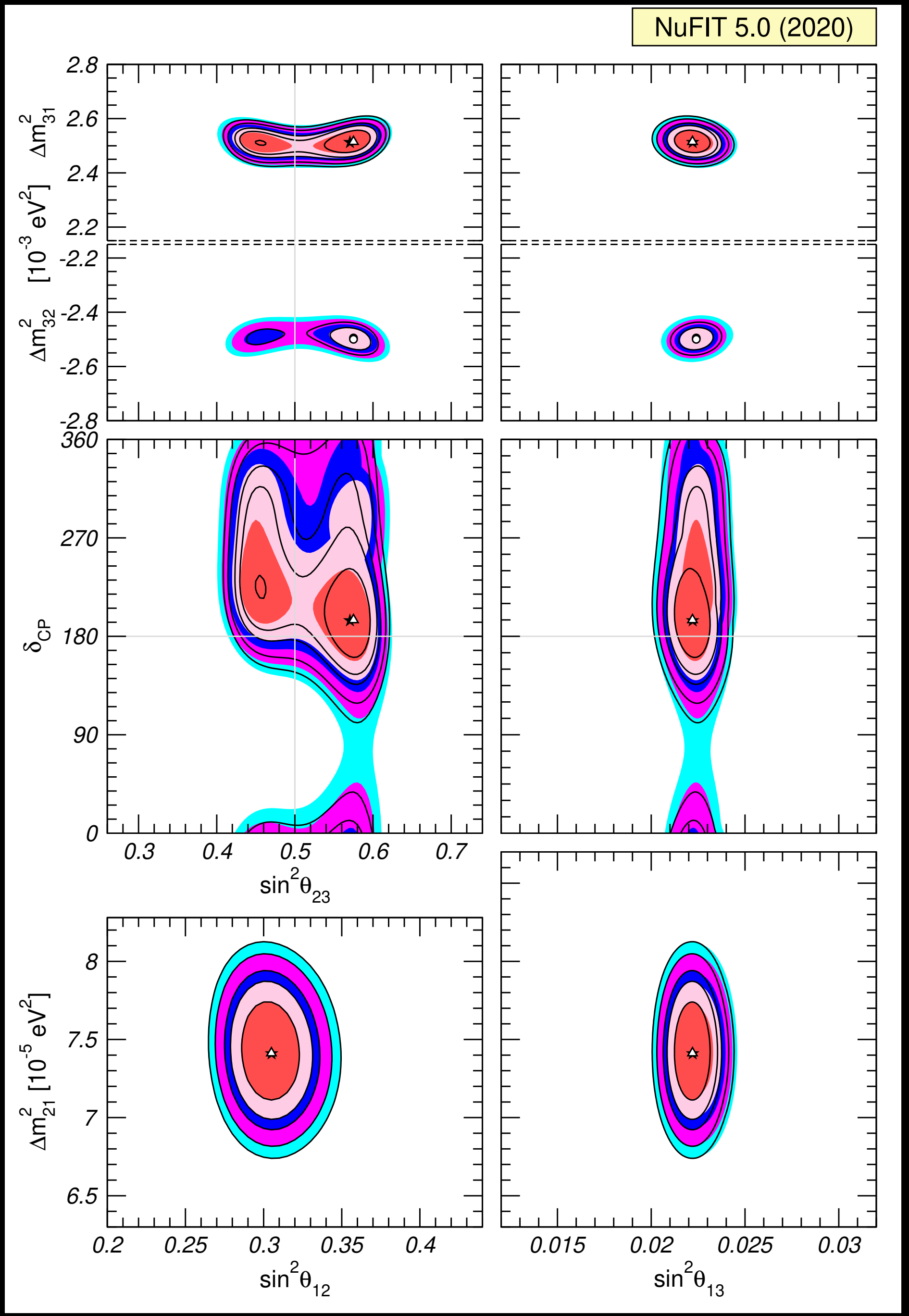
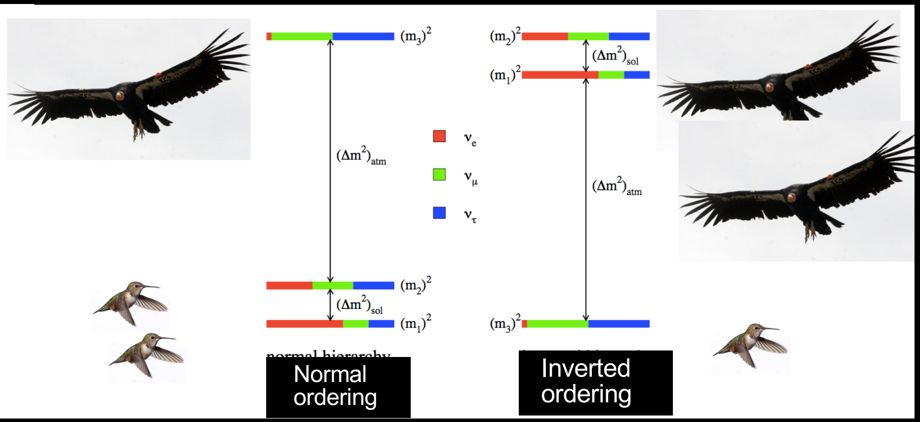
Neutrino Masses

- 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:

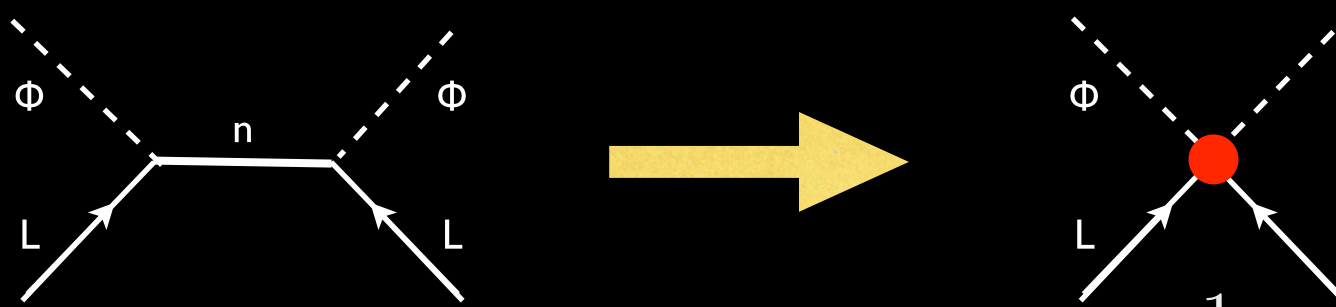
$$\frac{1}{\Lambda_{ij}} \left(\bar{L}_i \Phi\right) \left(L^c_j \Phi\right) + H.c.$$

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

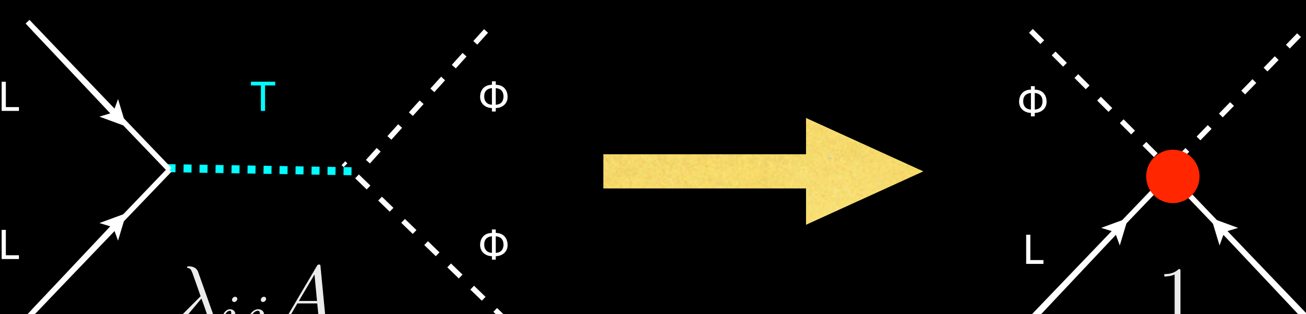
$$(i\sigma_2\Phi^*)Y^\nu_{ij}\bar{L}_i n_j + M\bar{n}n^c + H.c.$$



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

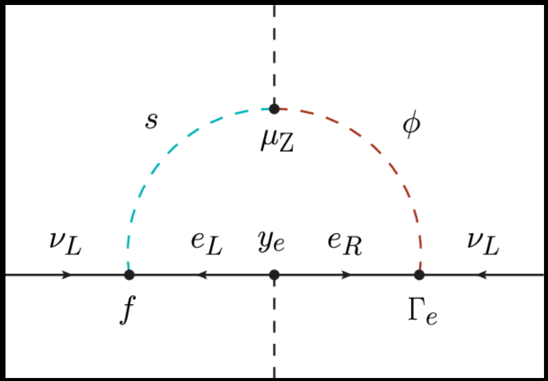
  - We can generate it by integrating out an SU(2)-triplet Higgs-like field:

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



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

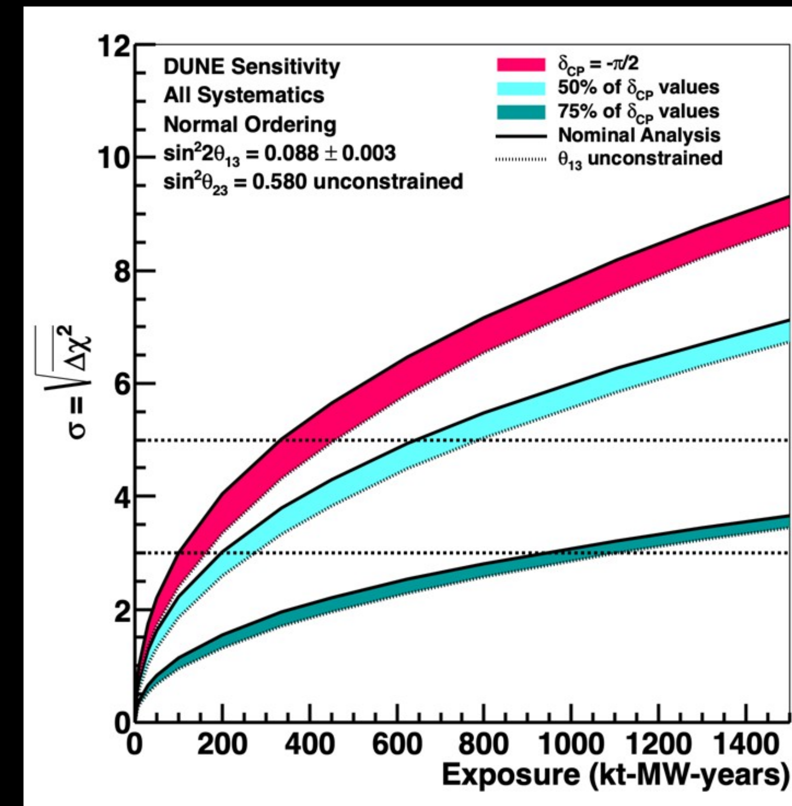
"Zee Model"



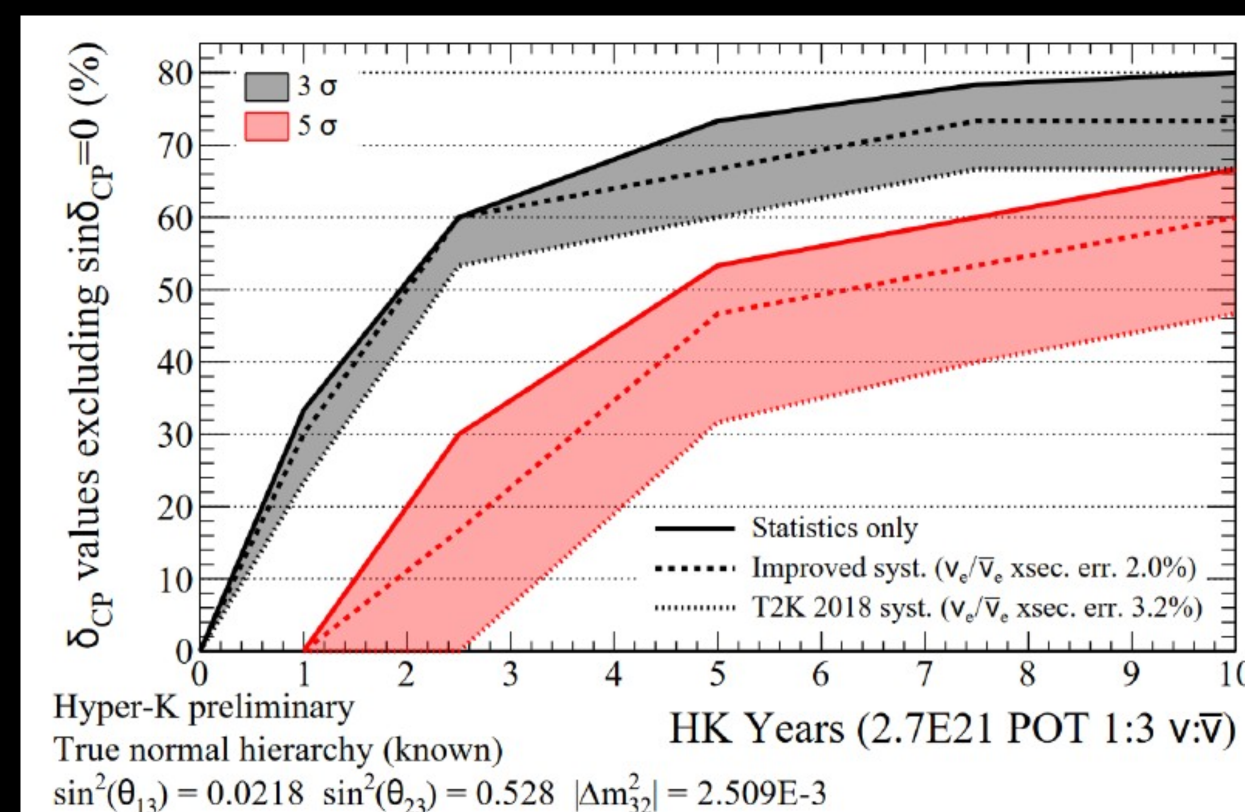
  - There are others ways, such as for example via loop diagrams.

Future Long Baseline

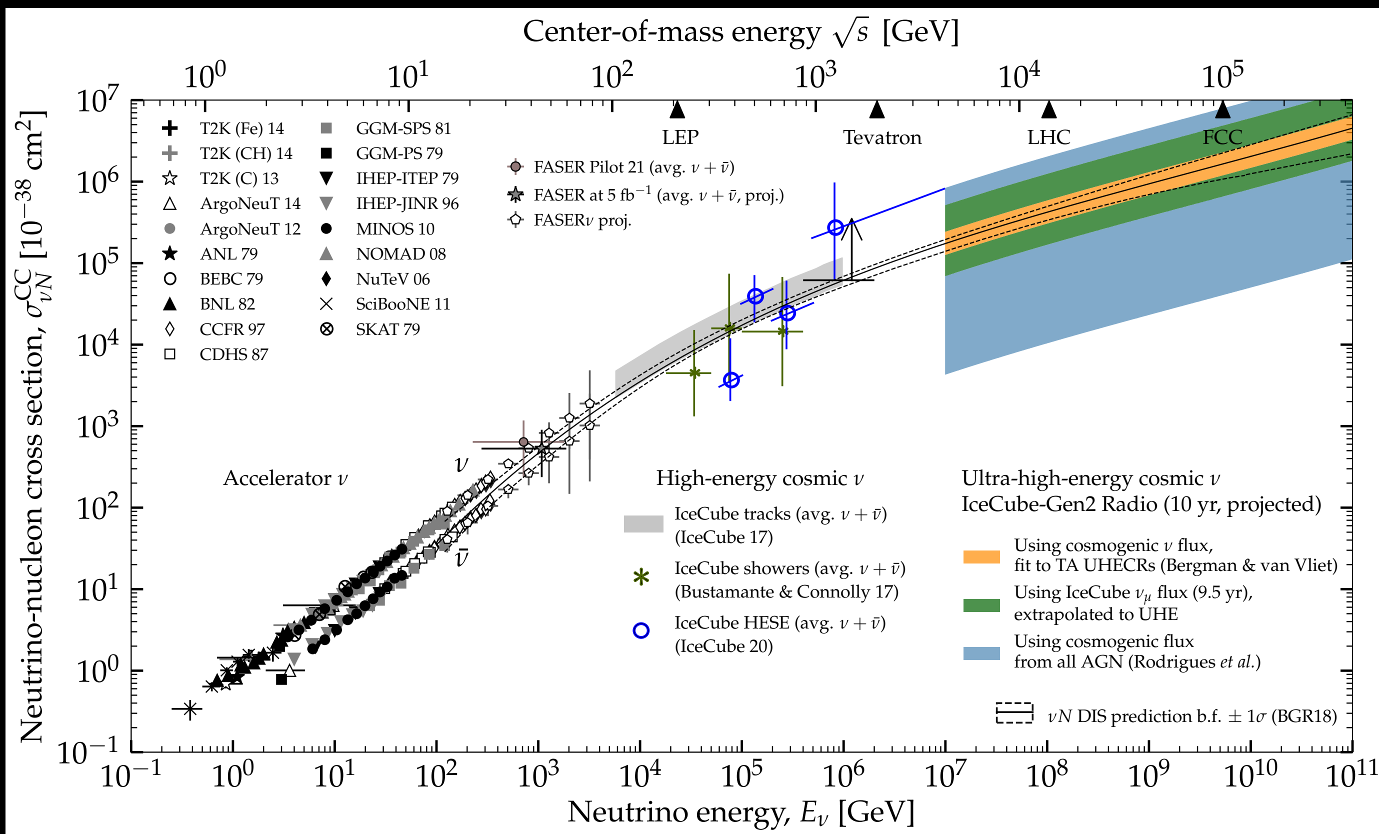
- There are vigorous upcoming programs to pin down the remaining unknowns in the oscillation parameters, centered in the US and Japan.
- These experiments will eventually measure every parameter, but will not significantly over-constrain the PMNS matrix.
- It seems unlikely that oscillation data will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

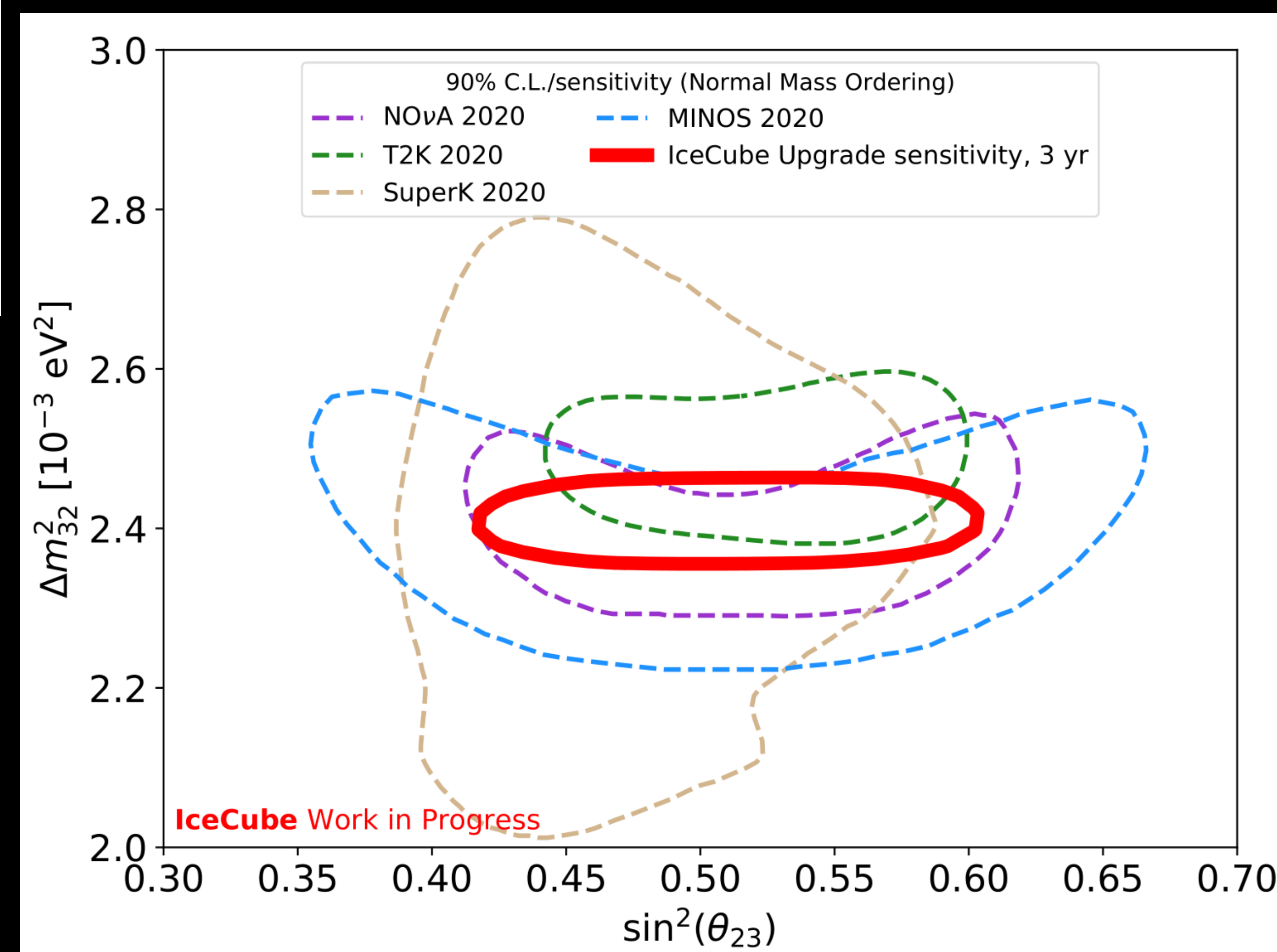


Chris Marshall, P5 Town Hall



High Energy Neutrinos

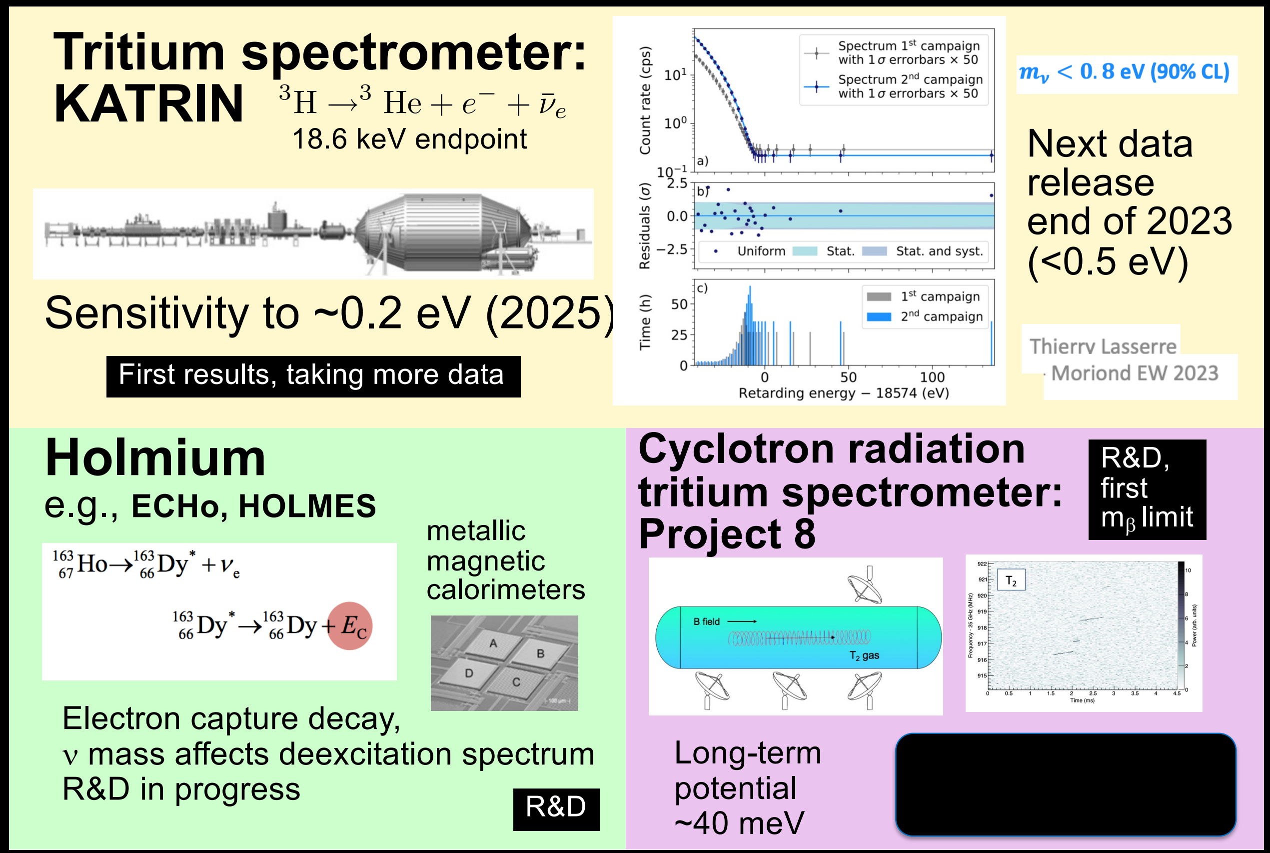




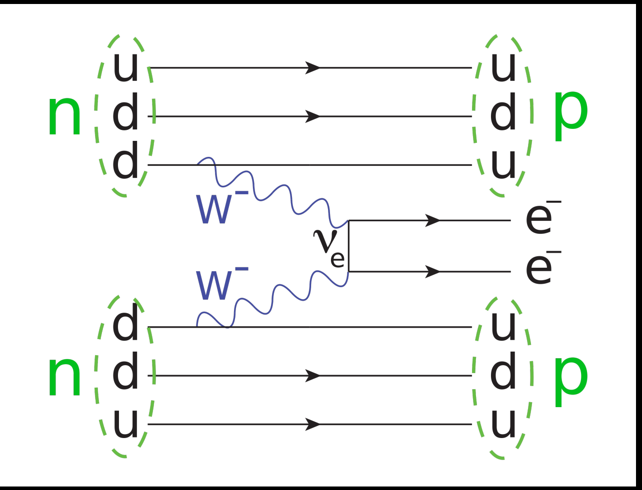
- High energy neutrinos offer an interesting opportunity to test whether oscillations work the same at high energies as they do at the ~GeV energies where neutrino beams operate.

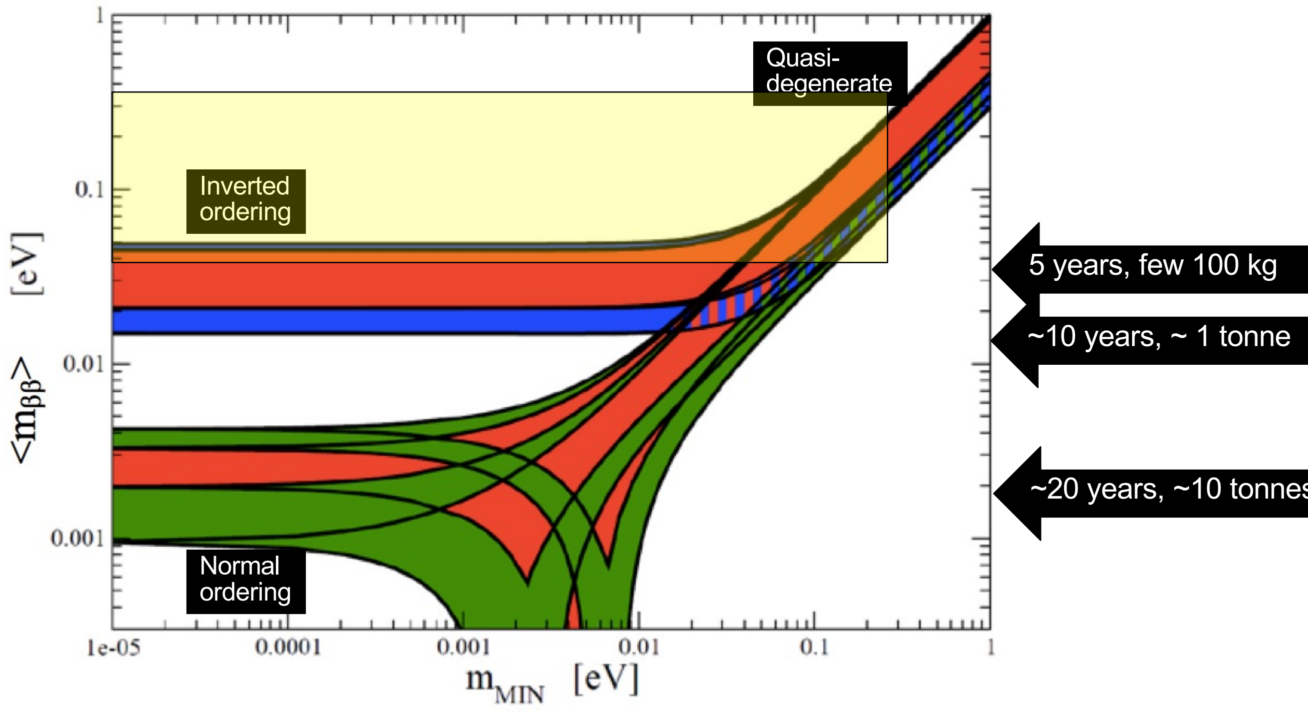
Neutrino Masses

- 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





Precision SM & Beyond

- There is enormous progress in understanding the SM at LHC energies, and how to parameterize deviations.
- There is a beautiful dance between the exquisitely precise experimental results and advances in theoretical predictions.
- For example, the SMEFT provides a language to search for any small deviation in a SM observable induced by heavy new physics.
- We're finally entering an era in which we can systematically explore its effects via inclusive fits.

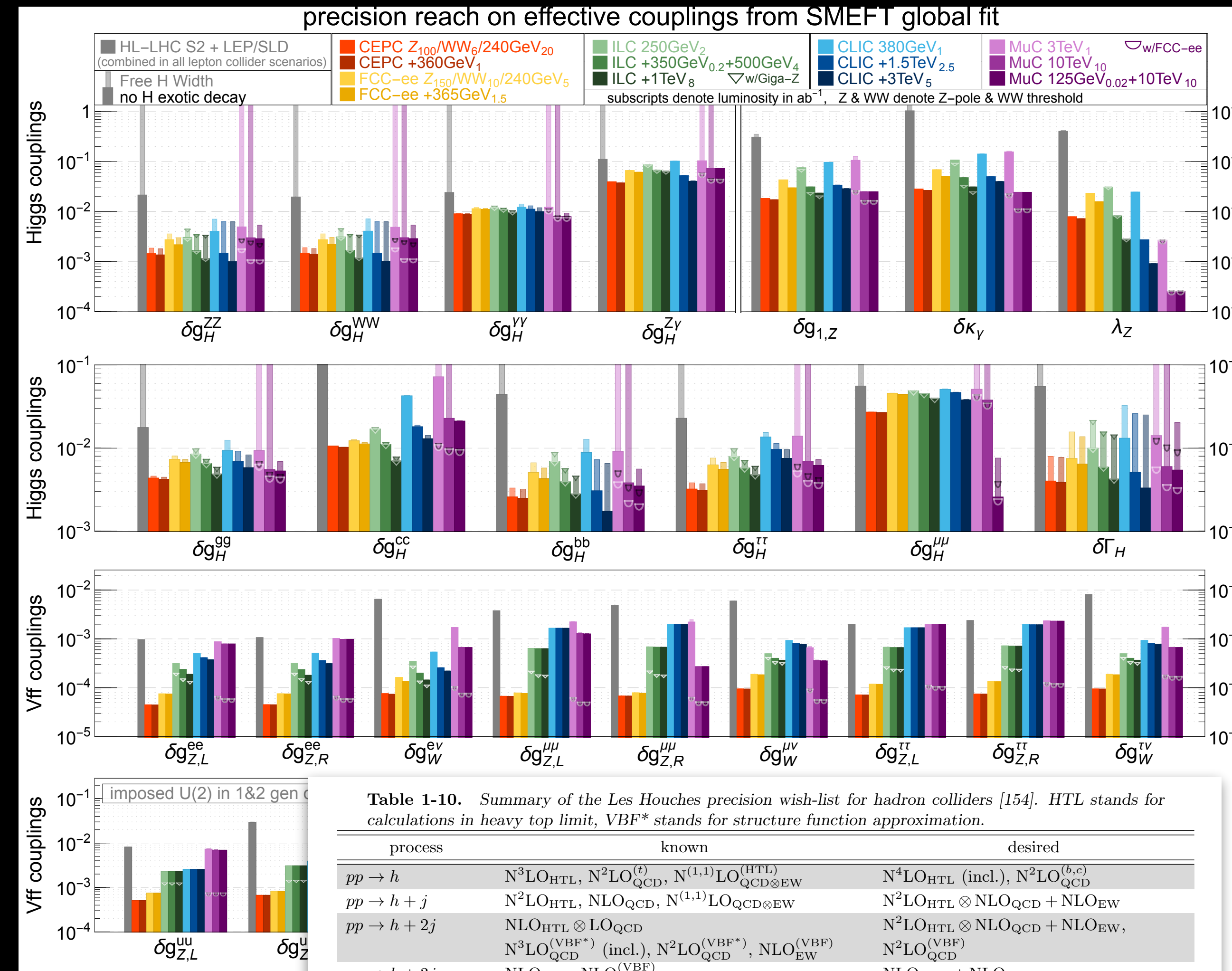


Table 1-10. *Summary of the Les Houches precision wish-list for hadron colliders [154]. HTL stands for calculations in heavy top limit, VBF* stands for structure function approximation.*

process	known	desired
$pp \to h$	N^3LO_{HTL}, $N^2LO^{(t)}_{\text{QCD}}$, $N^{(1,1)}LO^{(\text{HTL})}_{\text{QCD}\otimes\text{EW}}$	N^4LO_{HTL} (incl.), $N^2LO^{(b,c)}_{\text{QCD}}$
$pp \to h + j$	N^2LO_{HTL}, NLO_{QCD}, $N^{(1,1)}LO_{\text{QCD}\otimes\text{EW}}$	$N^2LO_{\text{HTL}} \otimes NLO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to h + 2j$	$NLO_{\text{HTL}} \otimes LO_{\text{QCD}}$ $N^3LO^{(\text{VBF}^*)}_{\text{QCD}}$ (incl.), $N^2LO^{(\text{VBF}^*)}_{\text{QCD}}$, $NLO^{(\text{VBF})}_{\text{EW}}$	$N^2LO_{\text{HTL}} \otimes NLO_{\text{QCD}} + NLO_{\text{EW}}$, $N^2LO^{(\text{VBF})}_{\text{QCD}}$
$pp \to h + 3j$	NLO_{HTL}, $NLO^{(\text{VBF})}_{\text{QCD}}$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to Vh$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$, $NLO^{(t,b)}_{gg \to HZ}$	
$pp \to Vh + j$	N^2LO_{QCD}	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to hh$	$N^3LO_{\text{HTL}} \otimes NLO_{\text{QCD}}$	NLO_{EW}
$pp \to h + t\bar{t}$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$, N^2LO_{QCD} (off-diag.)	N^2LO_{QCD}
$pp \to h + t/\bar{t}$	NLO_{QCD}	N^2LO_{QCD}, $NLO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to V$	N^3LO_{QCD}, $N^{(1,1)}LO_{\text{QCD}\otimes\text{EW}}$, NLO_{EW}	$N^3LO_{\text{QCD}} + N^{(1,1)}LO_{\text{QCD}\otimes\text{EW}}$, N^2LO_{EW}
$pp \to VV'$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$, $+ NLO_{\text{QCD}}$ (gg)	NLO_{QCD} (gg,massive loops)
$pp \to V + j$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$	hadronic decays
$pp \to V + 2j$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$, NLO_{EW}	N^2LO_{QCD}
$pp \to V + b\bar{b}$	NLO_{QCD}	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to VV' + 1j$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$	N^2LO_{QCD}
$pp \to VV' + 2j$	NLO_{QCD} (QCD), $NLO_{\text{QCD}} + NLO_{\text{EW}}$ (EW)	Full $NLO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to W^+W^+ + 2j$	Full $NLO_{\text{QCD}} + NLO_{\text{EW}}$	
$pp \to W^+W^- + 2j$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $NLO_{\text{QCD}} + NLO_{\text{EW}}$	
$pp \to VV'V''$	NLO_{QCD}, NLO_{EW} (w/o decays)	$NLO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to W^{\pm}W^+W^-$	$NLO_{\text{QCD}} + NLO_{\text{EW}}$	
$pp \to \gamma\gamma$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$	N^3LO_{QCD}
$pp \to \gamma + j$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$	N^3LO_{QCD}
$pp \to \gamma\gamma + j$	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$, $+ NLO_{\text{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	N^2LO_{QCD}	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to 2$ jets	N^2LO_{QCD}, $NLO_{\text{QCD}} + NLO_{\text{EW}}$	$N^3LO_{\text{QCD}} + NLO_{\text{EW}}$
$pp \to 3$ jets	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$	
$pp \to t\bar{t}$	N^2LO_{QCD} (w/ decays)+ NLO_{EW} (w/o decays) $NLO_{\text{QCD}} + NLO_{\text{EW}}$ (w/ decays, off-shell effects) N^2LO_{QCD}	N^3LO_{QCD}
$pp \to t\bar{t} + j$	NLO_{QCD} (w/ decays, off-shell effects) NLO_{EW} (w/o decays)	$N^2LO_{\text{QCD}} + NLO_{\text{EW}}$ (w/ decays)
$pp \to t\bar{t} + 2j$	NLO_{QCD} (w/o decays)	$NLO_{\text{QCD}} + NLO_{\text{EW}}$ (w/ decays)

Snowmass EF Report

Precision SM & Beyond

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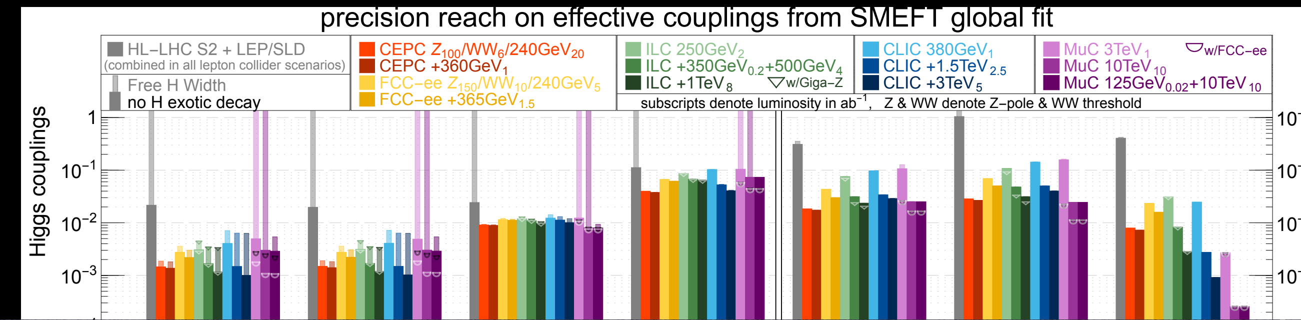
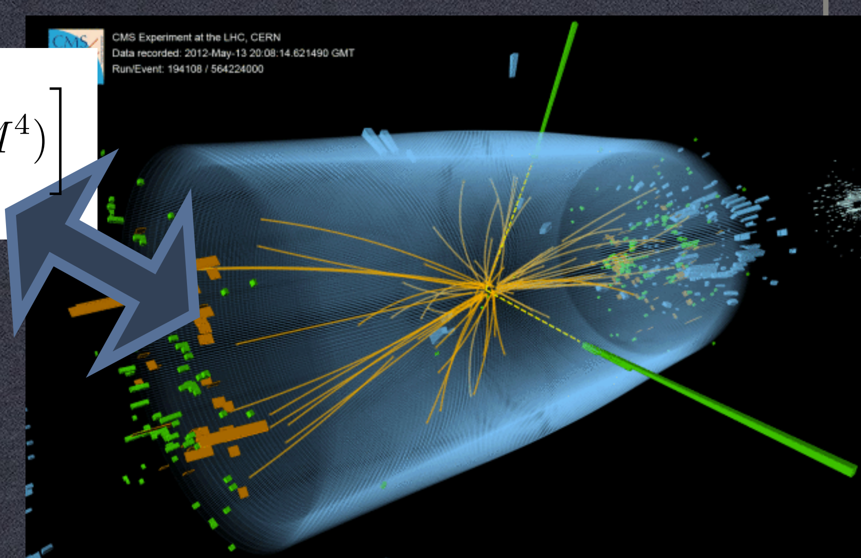


X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		[illegible]	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	[illegible]
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	[illegible]
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu$ [illegible]
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu$ [illegible]
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma$ [illegible]
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$$\frac{c_1^{hZ\bar f f}}{v}(\bar u_{L2}\not\epsilon_3^* u_{L1})\left[1+\alpha_1\frac{s}{M^2}+\beta_1\frac{t}{M^2}+O(E^4/M^4)\right]$$



Spencer Chang
Blois 2023

- We're finally entering an era in which we can systematically explore its effects via inclusive fits.

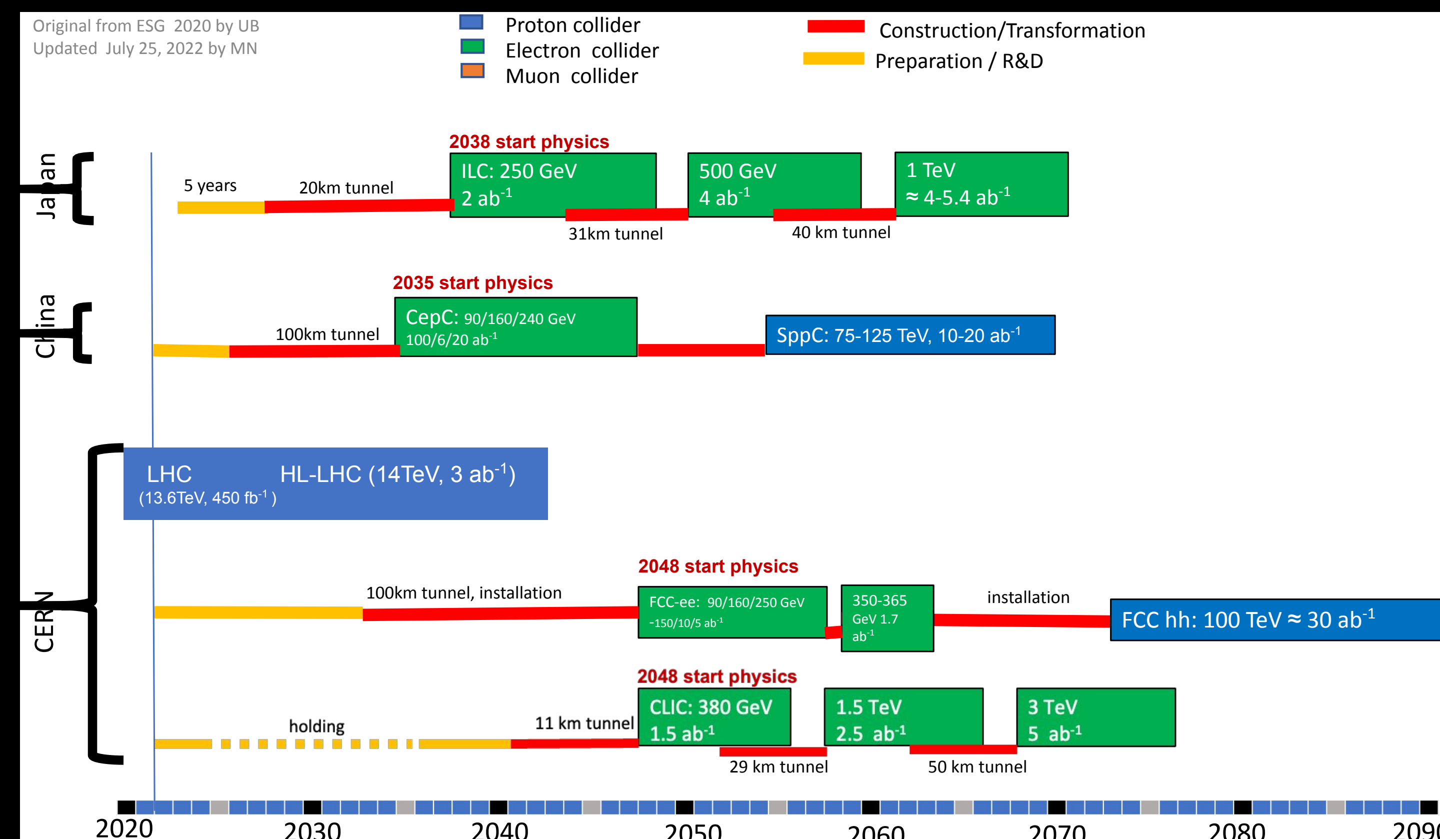
- New ideas can suggest even more general observables!

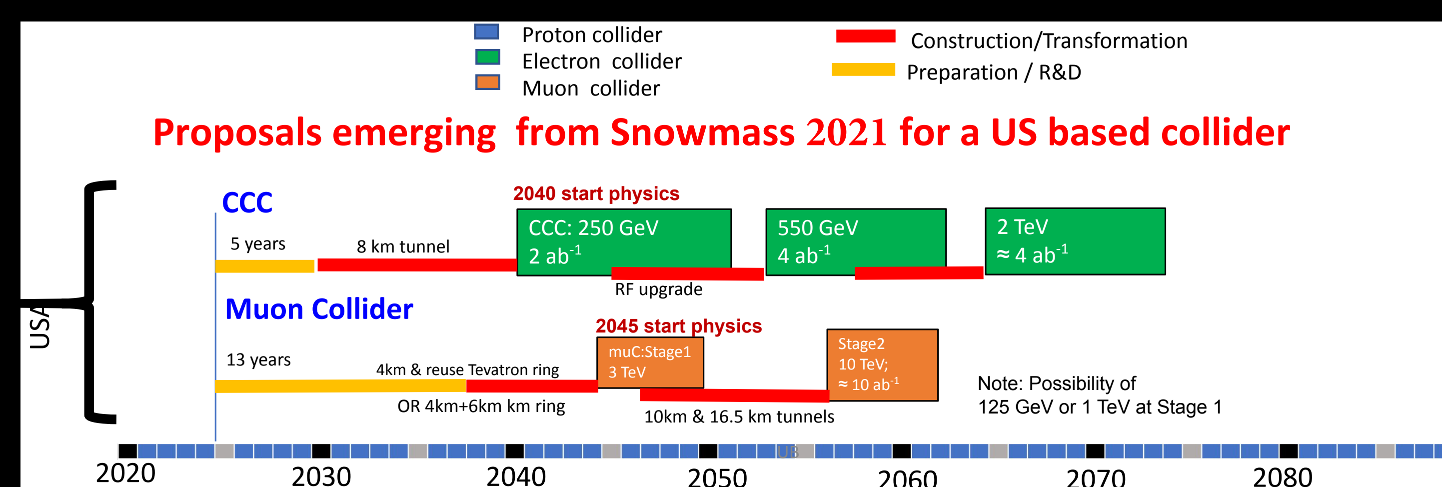
$pp\to V+2j$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp\to V+b\bar b$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$
$pp\to VV'+1j$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp\to VV'+2j$	$\mathrm{NLO_{QCD}}$ (QCD), $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ (EW)	Full $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
$pp\to W^+W^++2j$	Full $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$	
$pp\to W^+W^-+2j$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ (EW component)	
$pp\to W^+Z+2j$	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ (EW component)	
$pp\to ZZ+2j$	Full $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$	
$pp\to VV'V''$	$\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$
$pp\to W^\pm W^+W^-$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$	
$pp\to\gamma\gamma$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp\to\gamma+j$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp\to\gamma\gamma+j$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg channel)	
$pp\to\gamma\gamma\gamma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$
$pp\to$ 2 jets	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}+\mathrm{NLO_{EW}}$
$pp\to$ 3 jets	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$	
$pp\to t\bar t$	$\mathrm{N^2LO_{QCD}}$ (w/ decays)+ $\mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ (w/ decays, off-shell effects) $\mathrm{N^2LO_{QCD}}$	$\mathrm{N^3LO_{QCD}}$
$pp\to t\bar t+j$	$\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD}}+\mathrm{NLO_{EW}}$ (w/ decays)
$pp\to t\bar t+2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD}}+\mathrm{NLO_{EW}}$ (w/ decays)

A Future Collider?

- The LHC will continue to provide even more information about the Higgs and BSM physics, but there are great reasons to eventually go beyond its capabilities.
- Higher precision would allow us to probe loop level modifications of the Higgs couplings, and is a clear milestone to reach for BSM physics.
- Higher energy would allow direct searches for more massive states under controlled environments.
- While any such facility is obviously rather far away, NOW is the time to explore and do the R&D that will pave the way for the future!

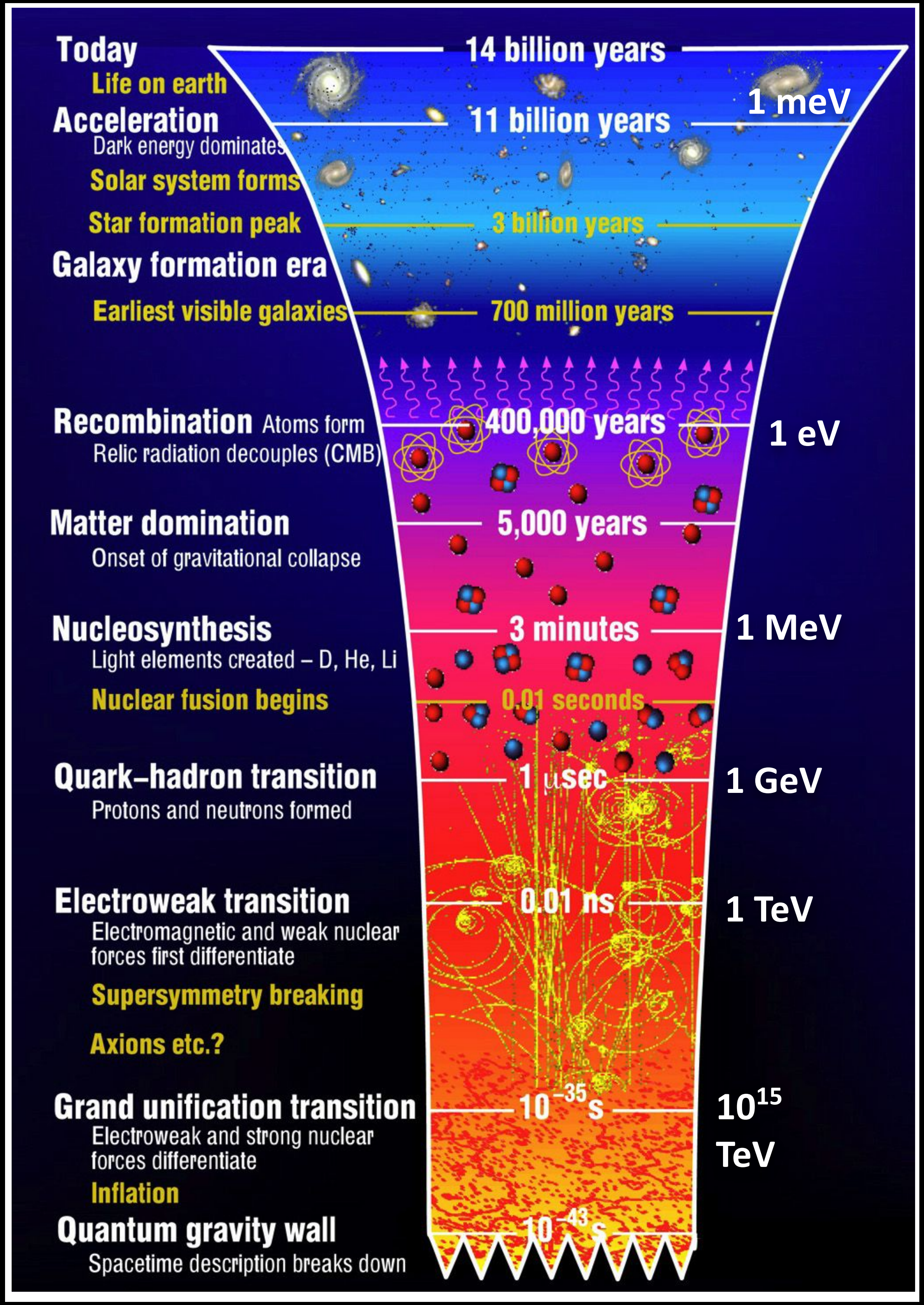
Snowmass EF Report



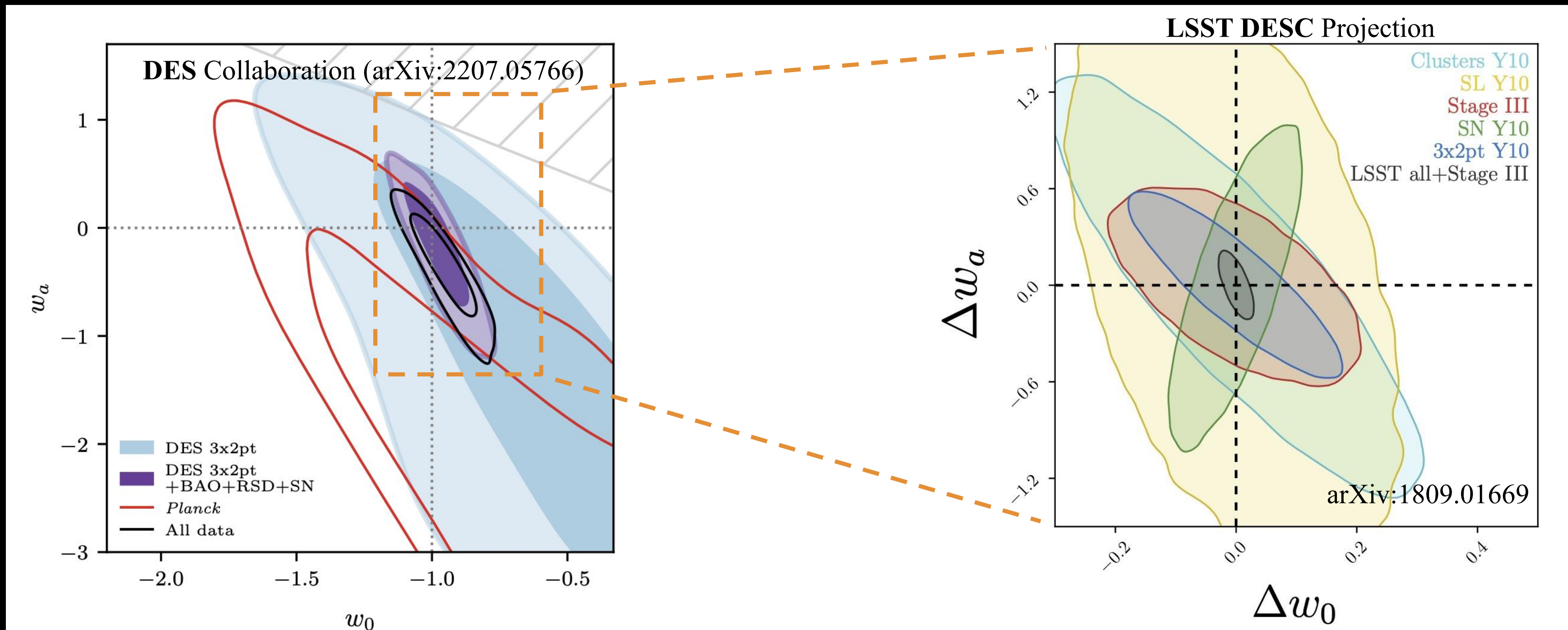


Cosmic Acceleration

- 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.



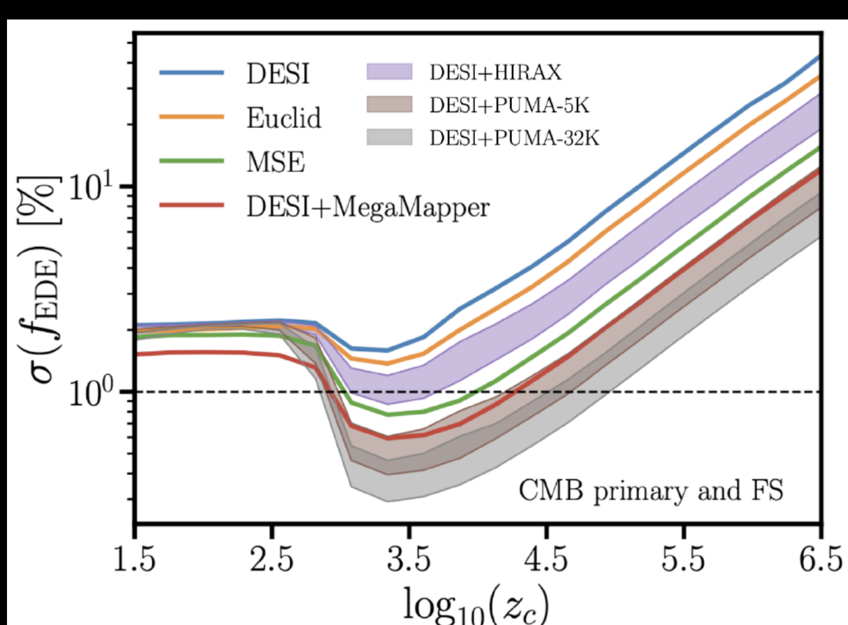
Dark Energy

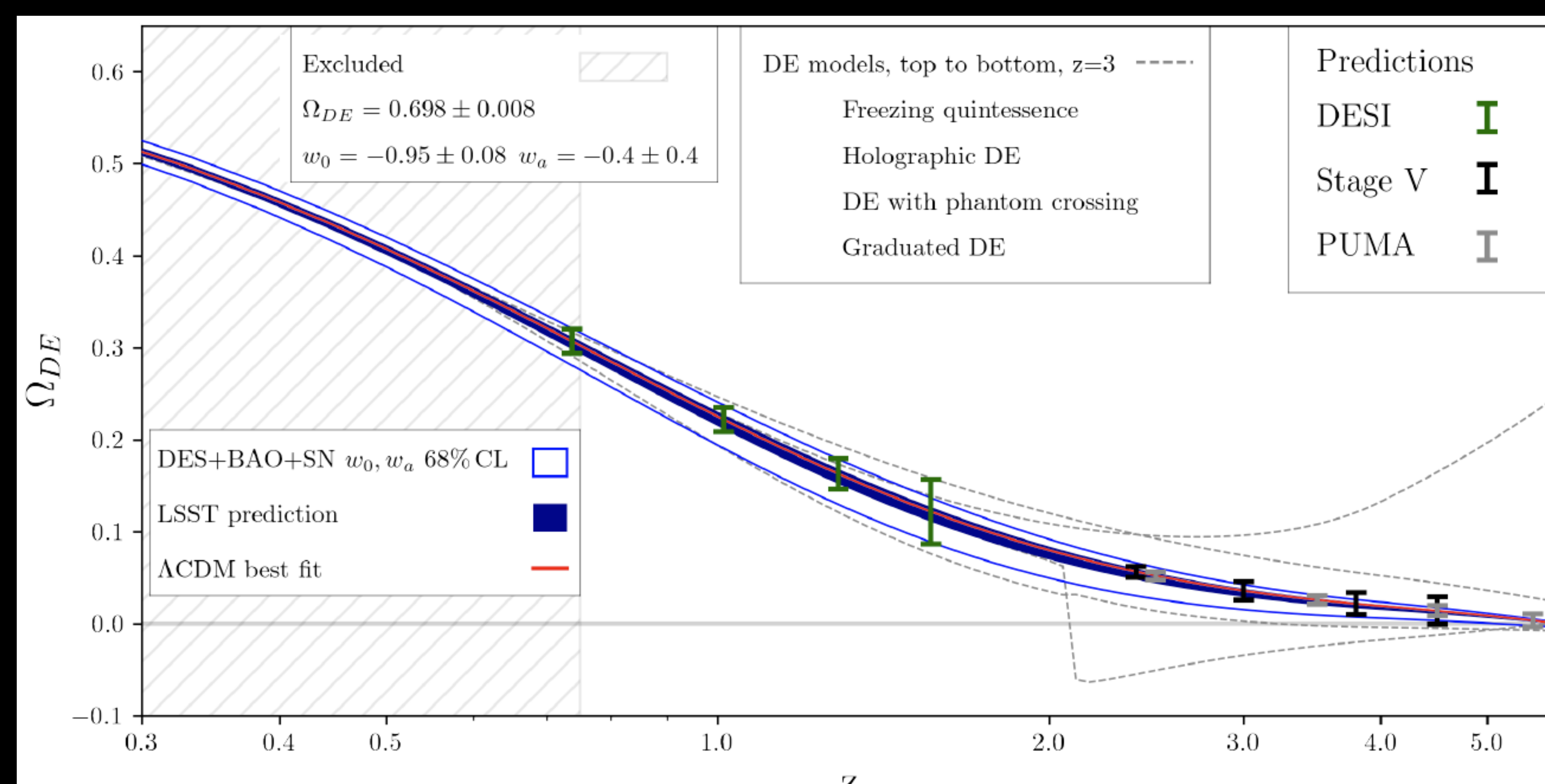


- Modern cosmic surveys will pin down the equation of state parameters for dark energy to the ~ % level.

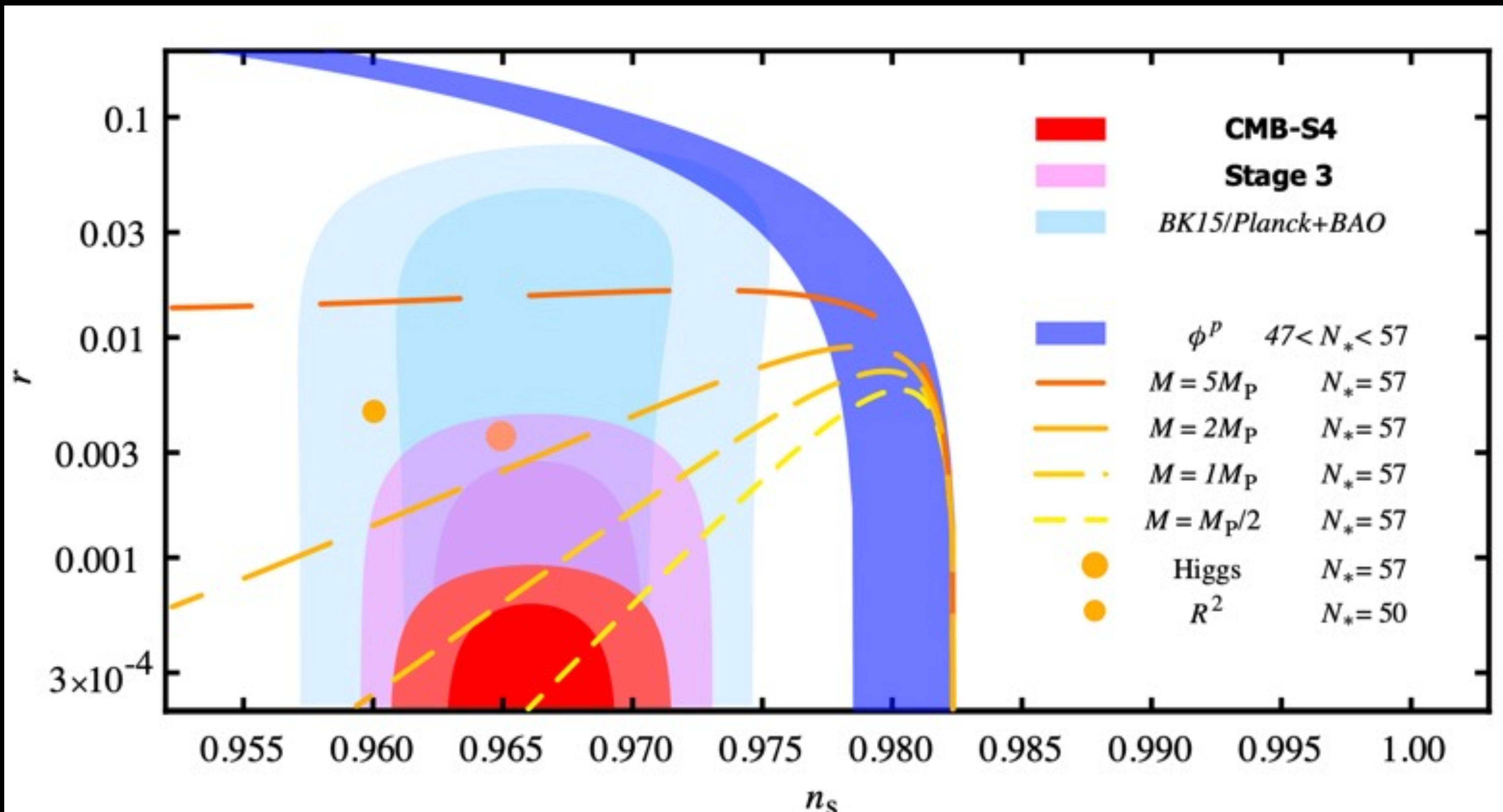
- Future surveys will be able to track the influence of dark energy back to early times, providing direct determination of its cosmic evolution.

Snowmass CF Report





Cosmic Inflation



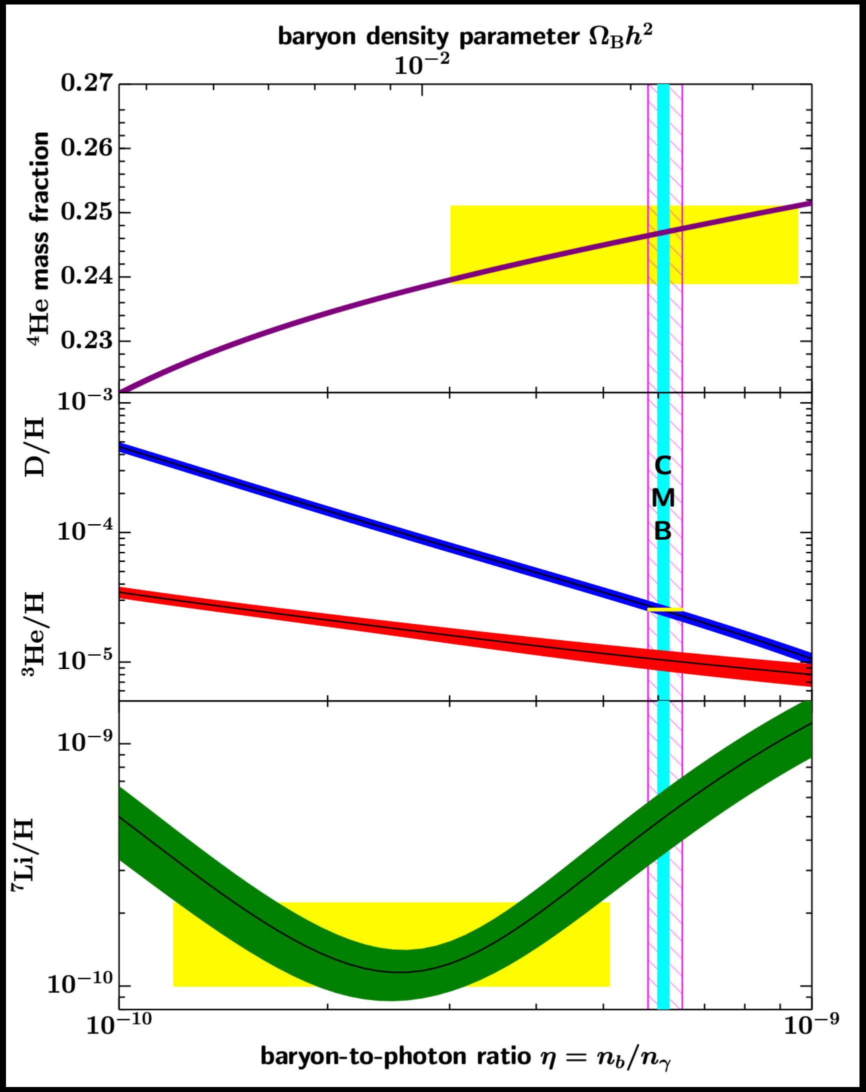
Snowmass CF Report

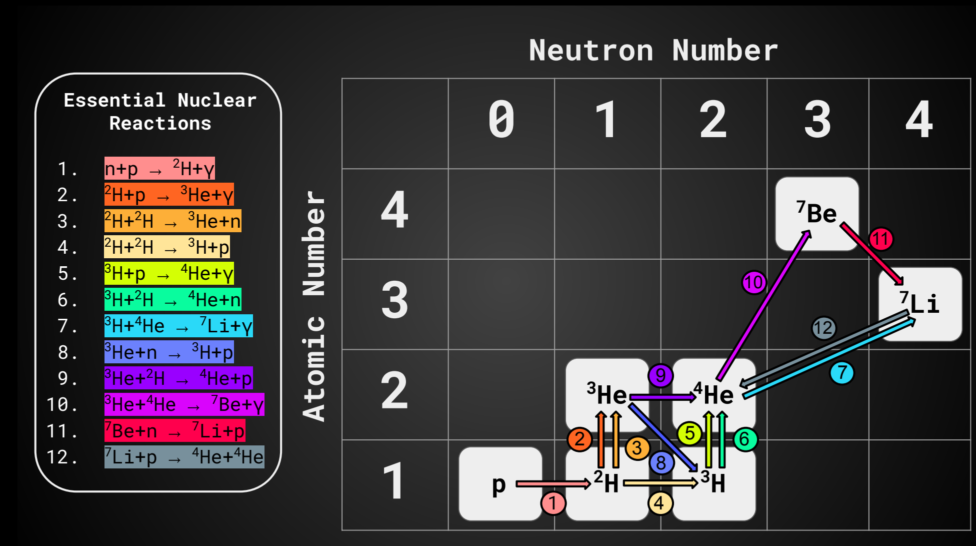
- Cosmic inflation leaves its imprints on the CMB and matter spectrum. Future measurements can distinguish models of inflation and reconstruct the energy scale at which inflation took place.

Baryon Asymmetry

- Our Universe is made of matter and not anti-matter! That is surprising because the laws of physics mostly 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

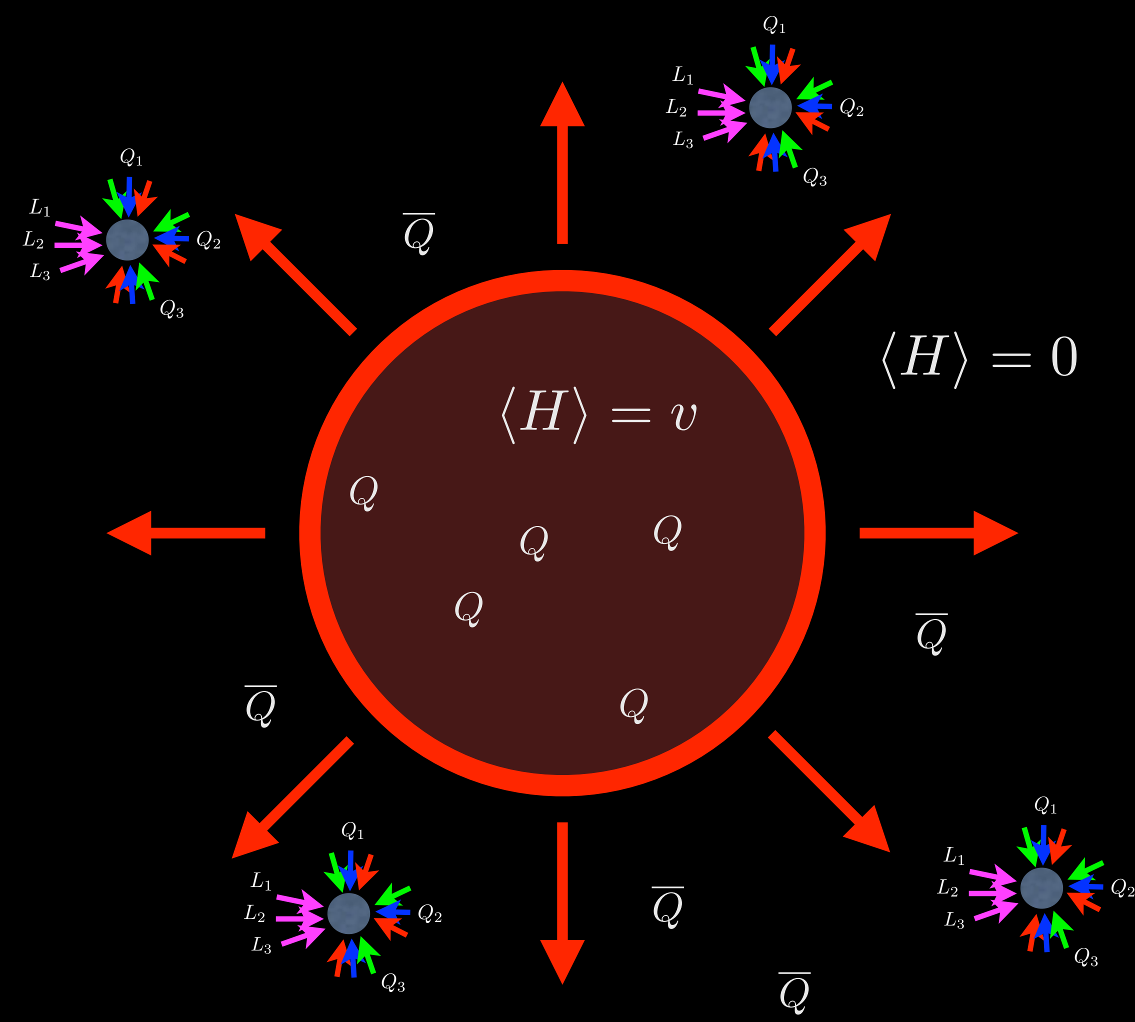




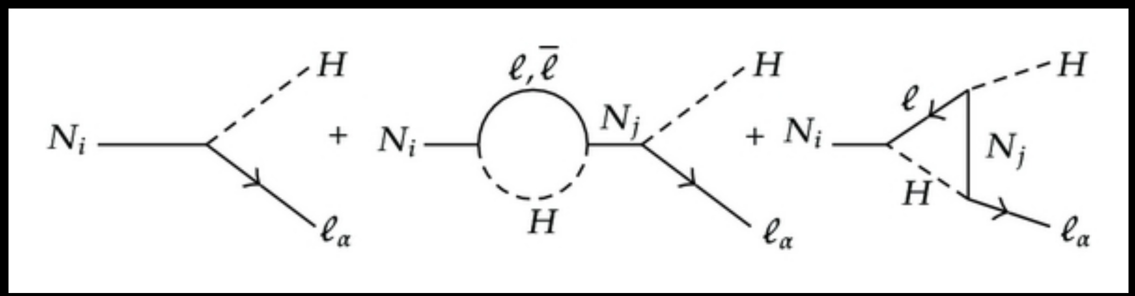
“Prymordial” (Python Code:) Burns, TMPT, Valli 2305.xxxxx

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.



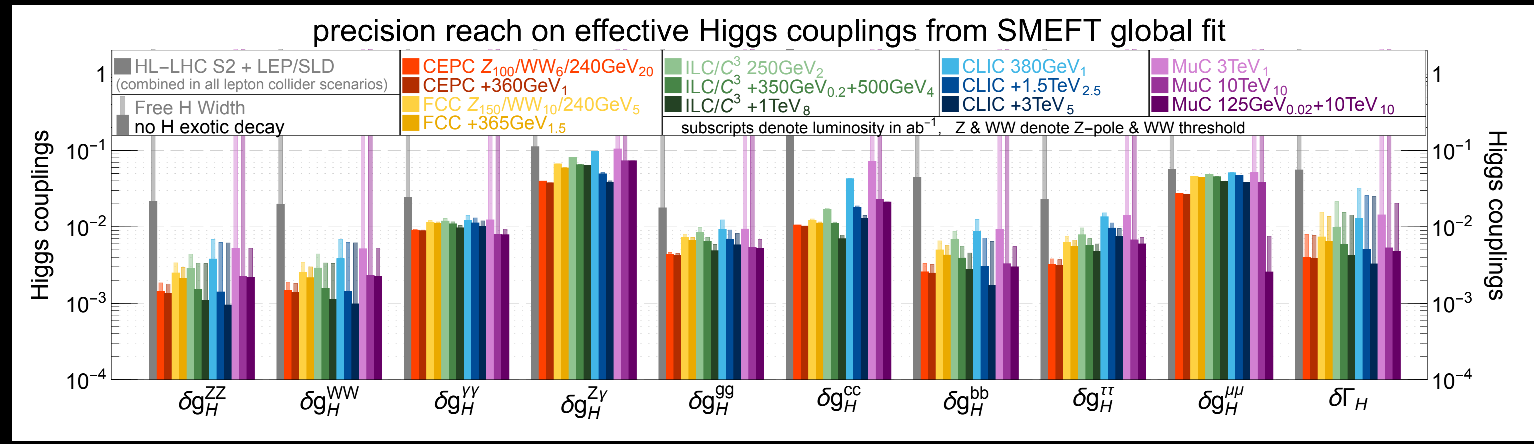
Schematic of the EW Phase Transition

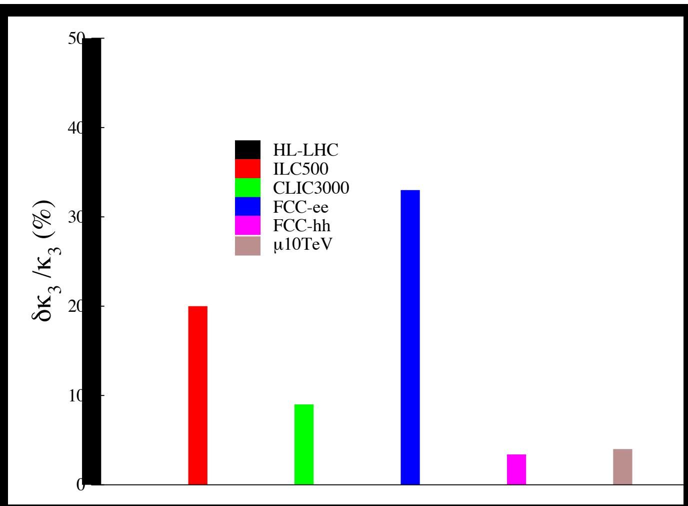


CP-violation in Leptogenesis

Testing Baryogenesis?

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

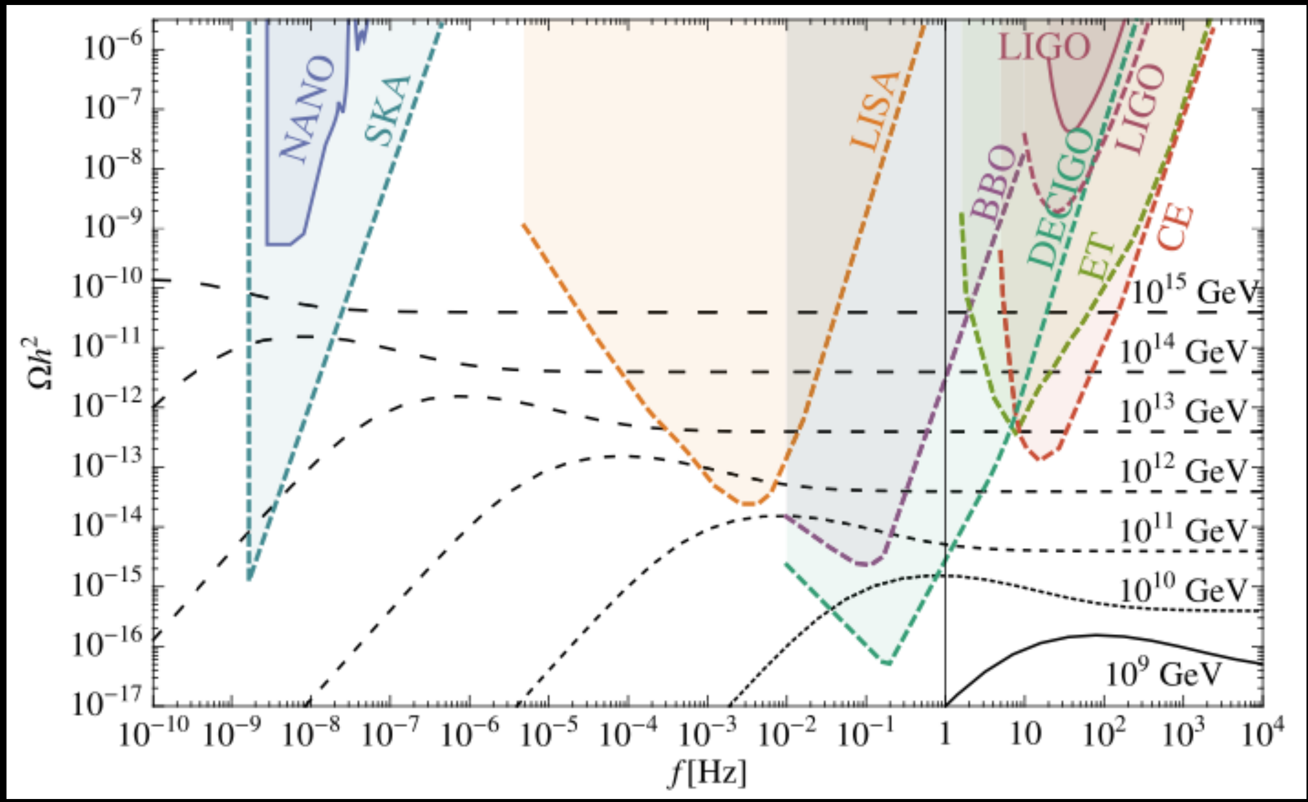




Snowmass EF01+02 Report

- 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.

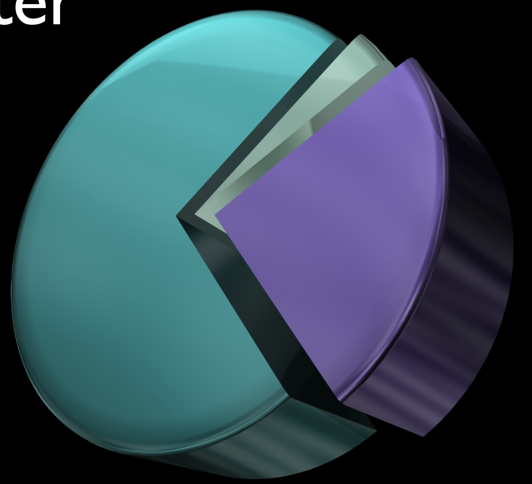
Dror et al 1908.03227



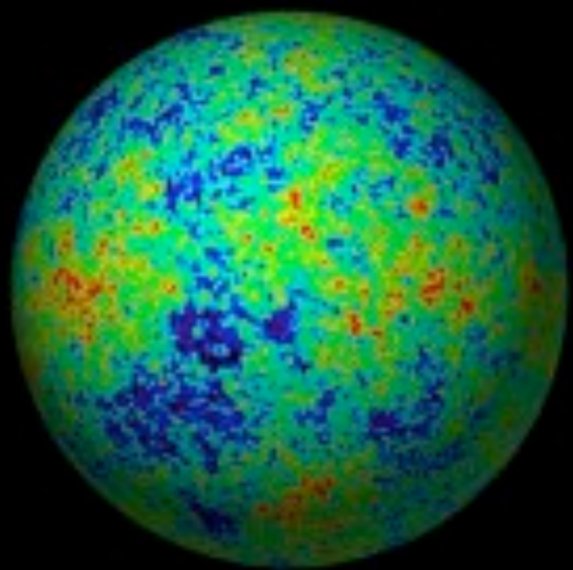
- A stochastic background of gravitational waves can reveal the presence of a phase transition in the early Universe.

Dark Matter

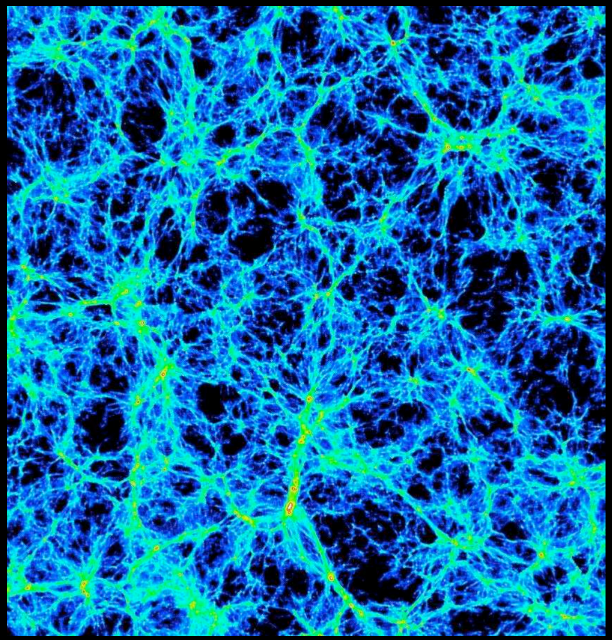
- Ordinary Matter
- Dark Matter
- Dark Energy



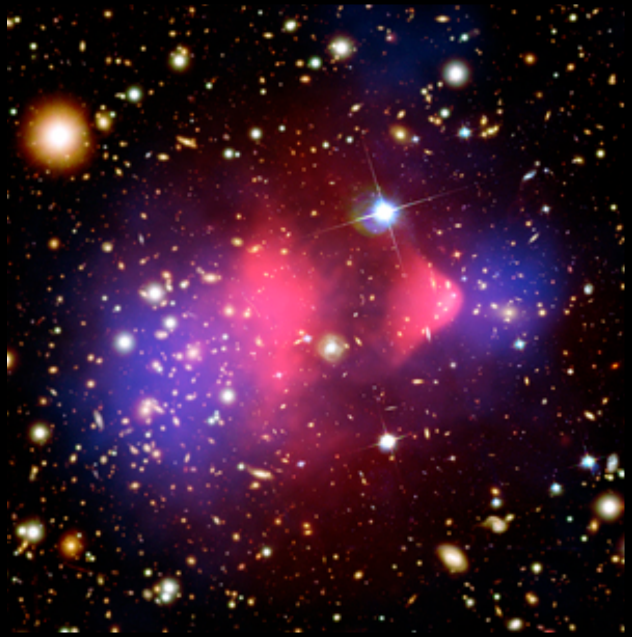
CMB



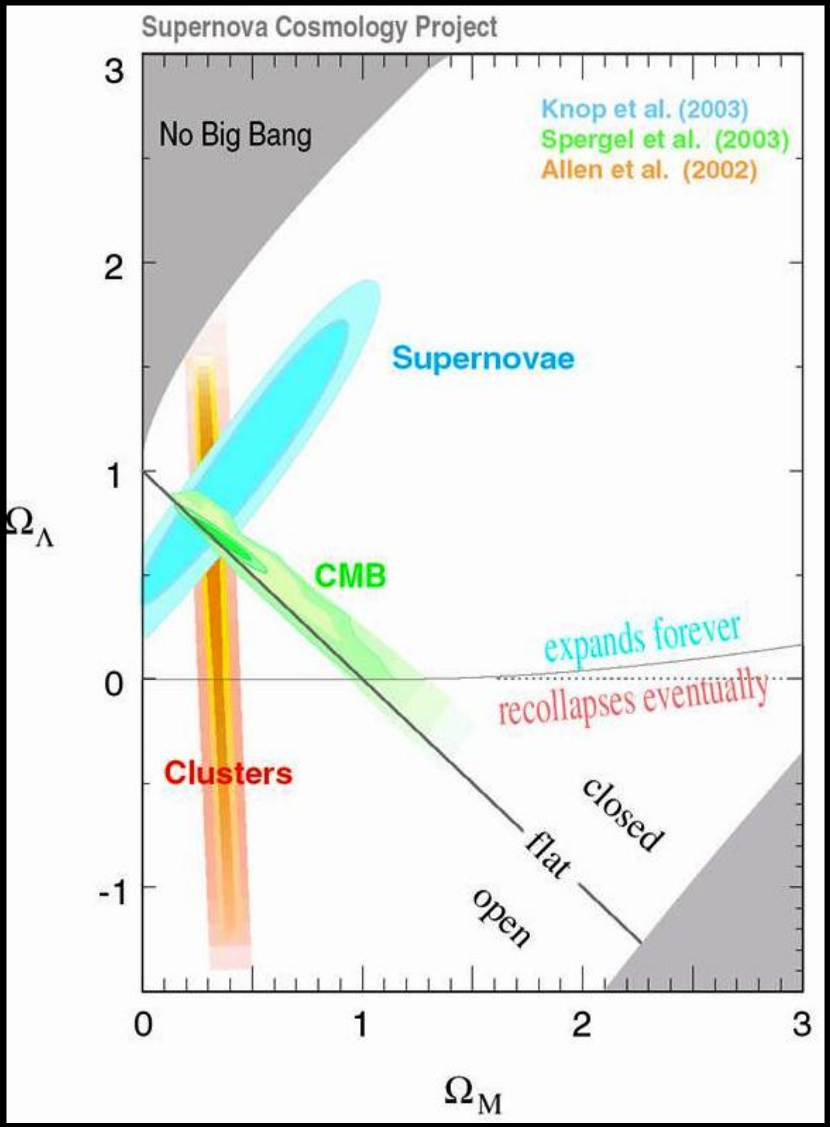
Supernova



Structure

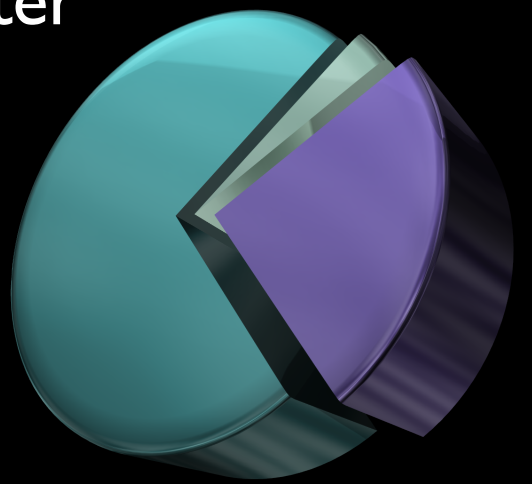


Lensing

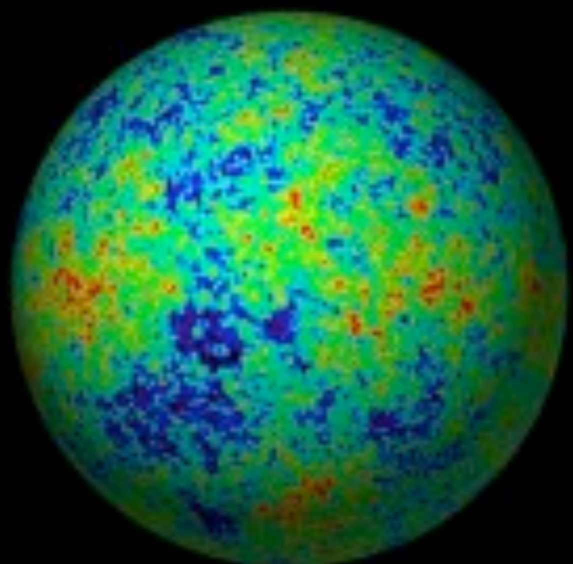


Dark Matter

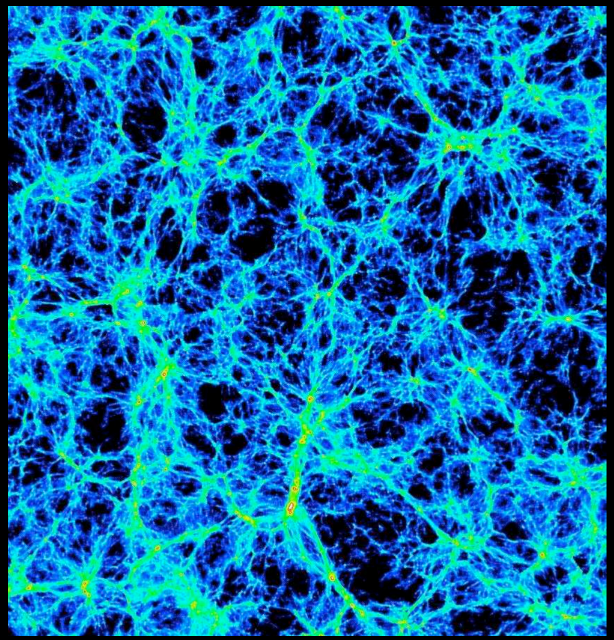
Ordinary Matter
Dark Matter
Dark Energy



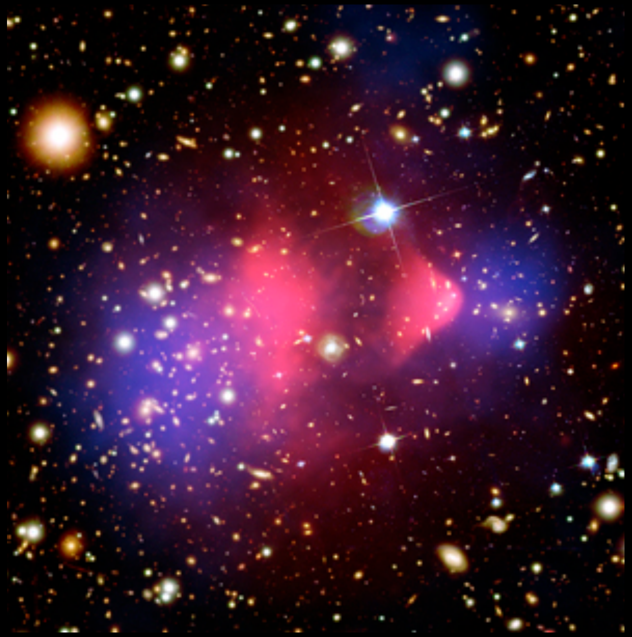
CMB



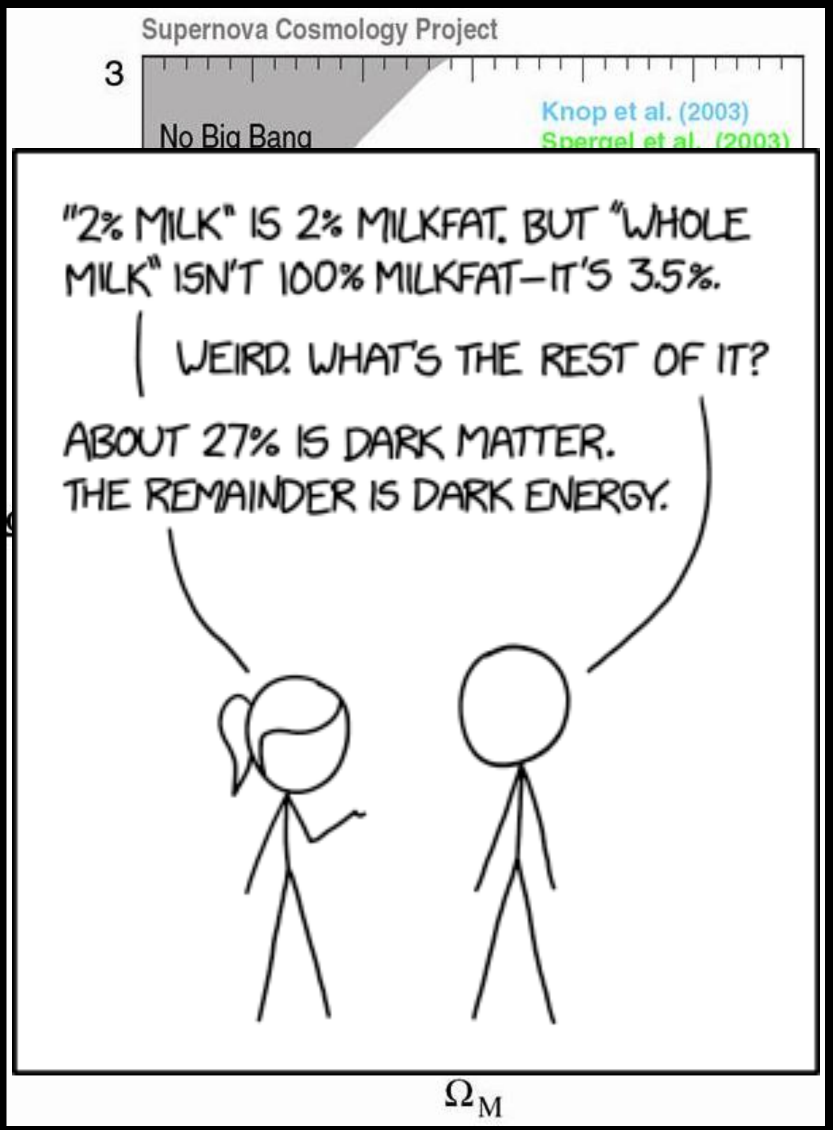
Supernova



Structure

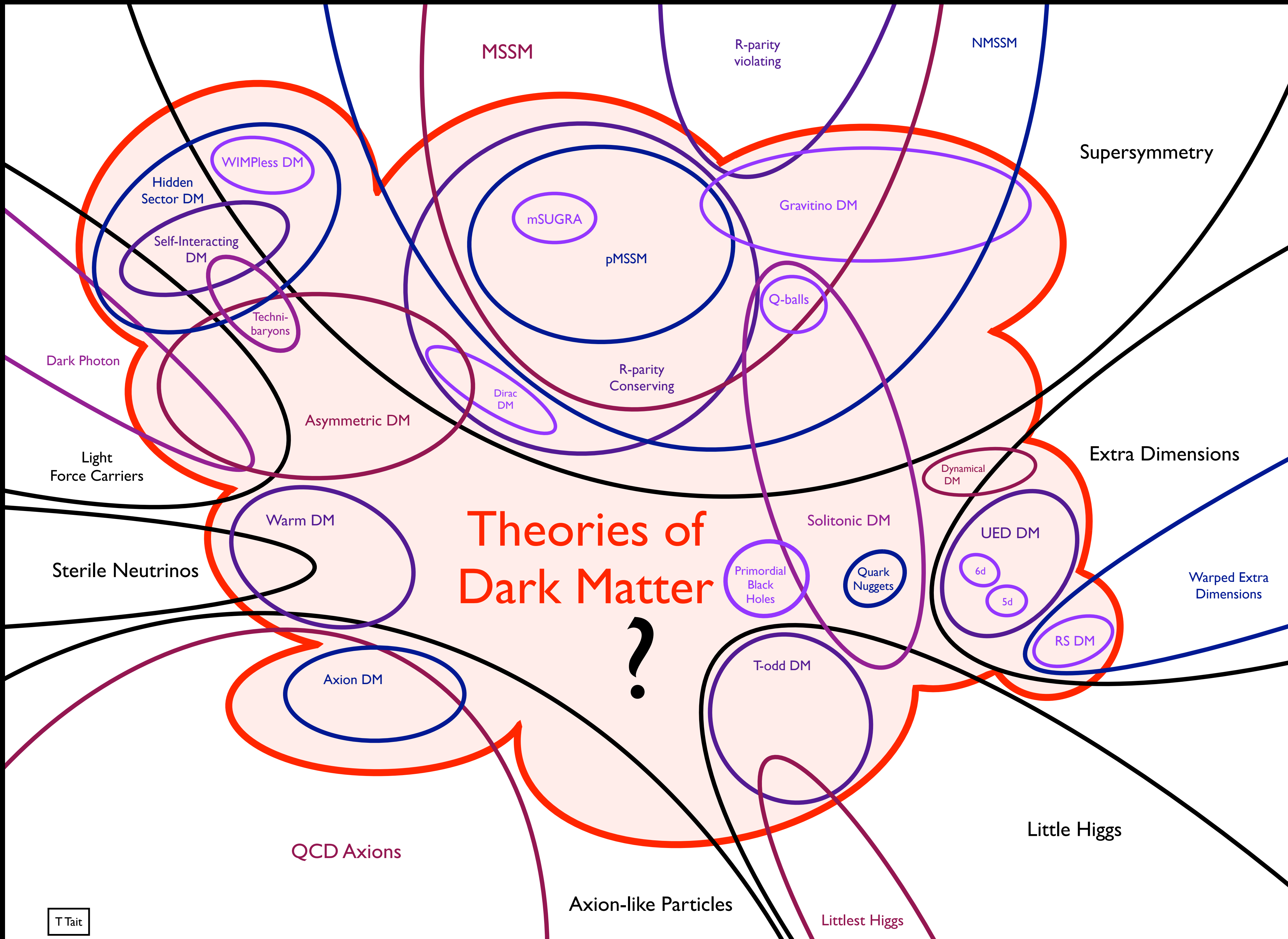


Lensing



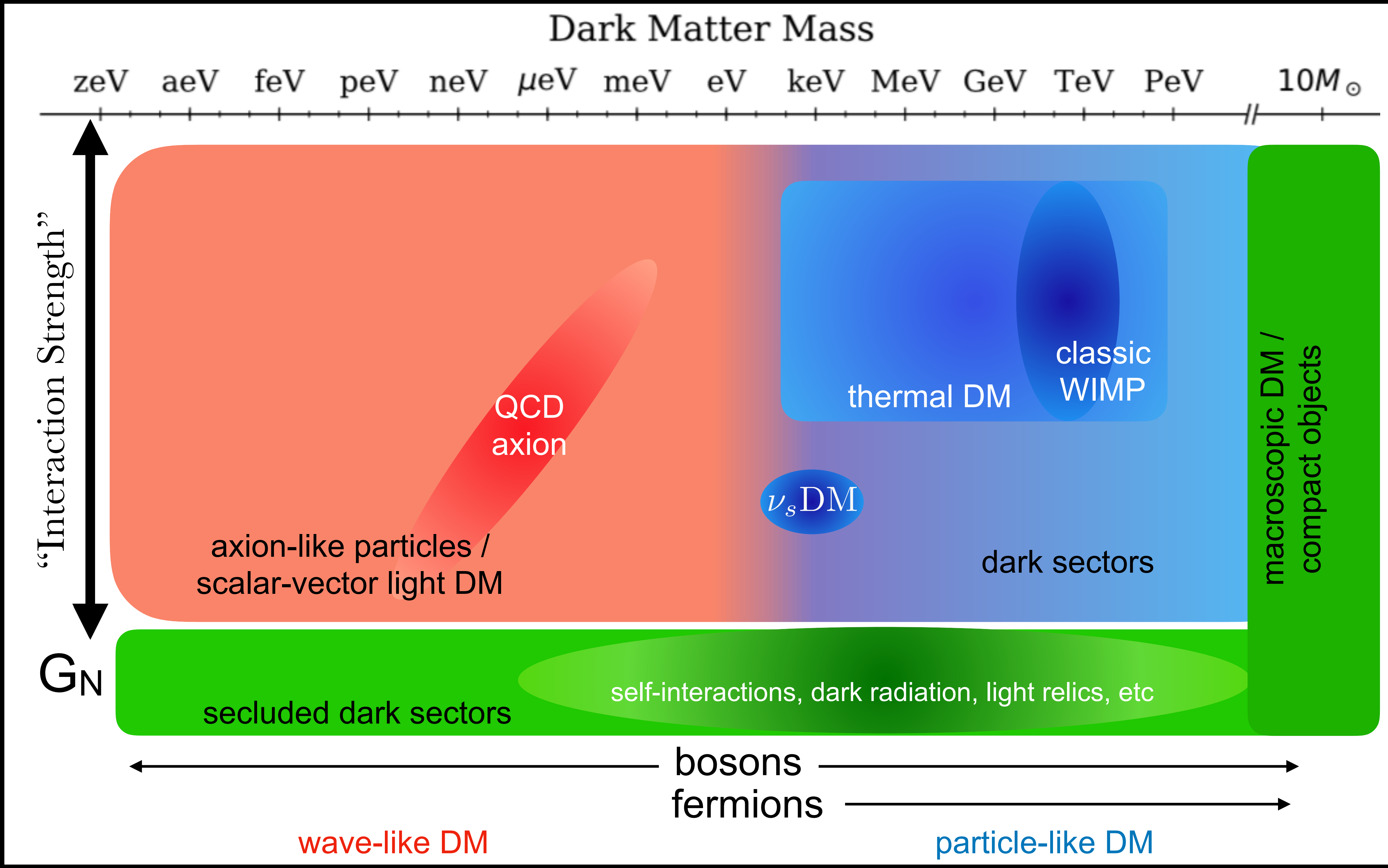
Xkcd

Dark Matter



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

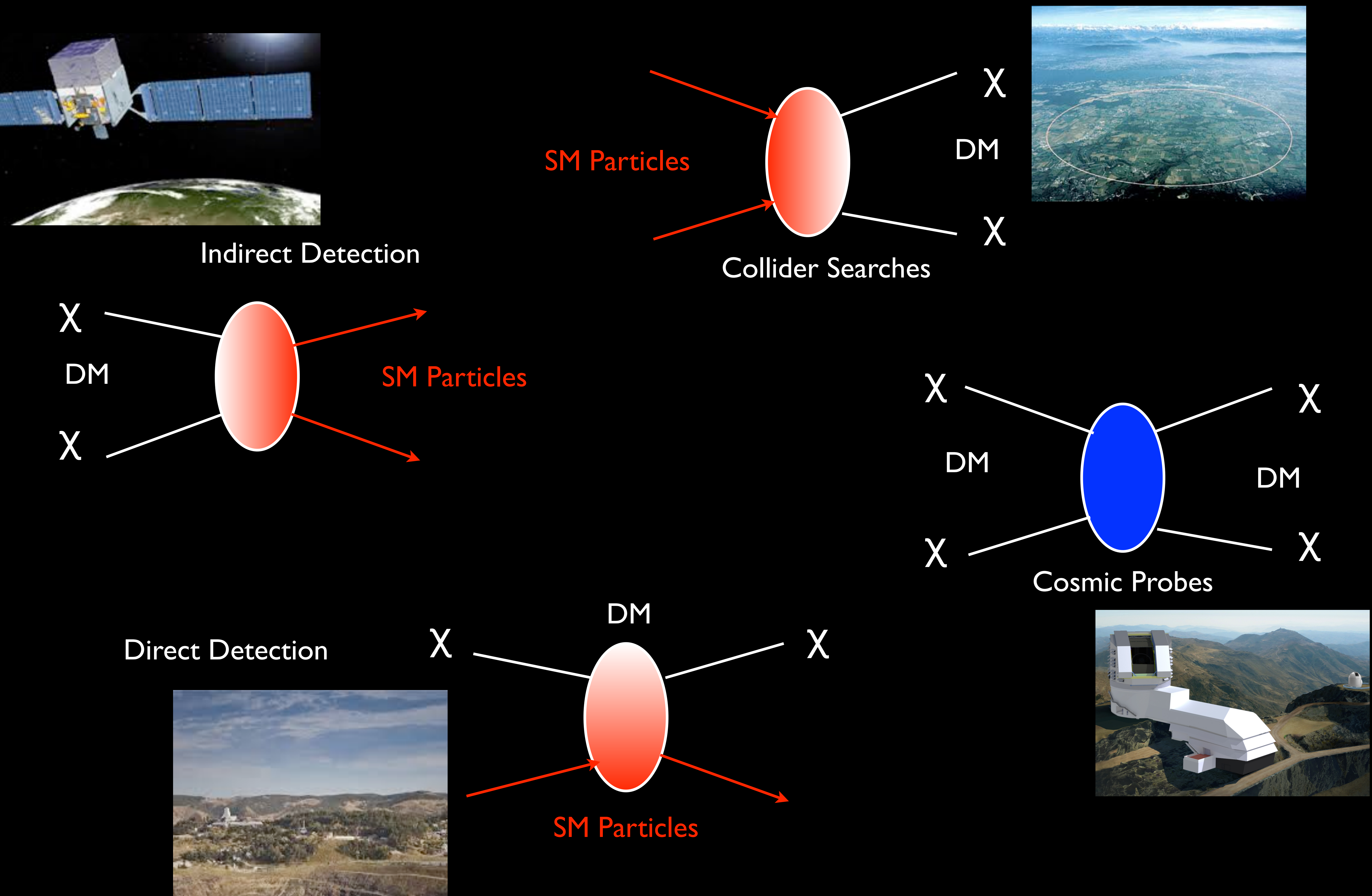
A Vast Landscape



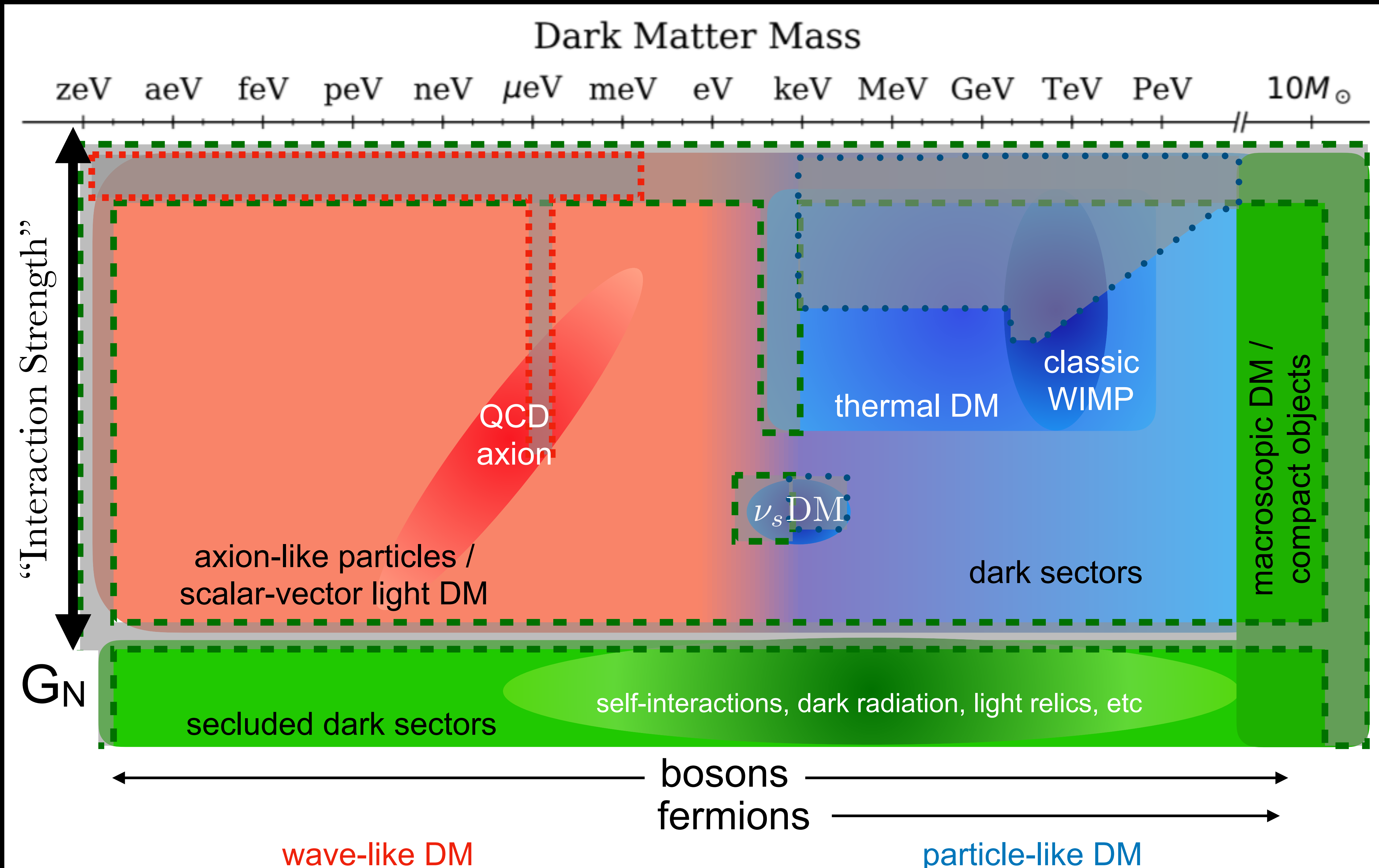
Snowmass CF Report

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

Probes of DM


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

The Current Progress

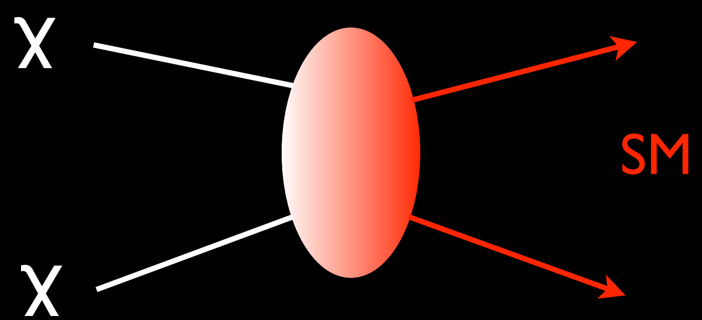


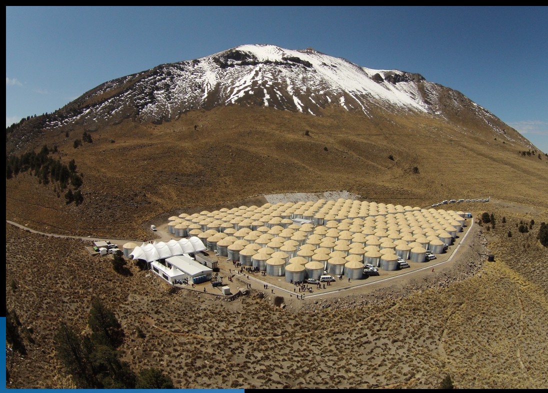
Snowmass CF Report

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

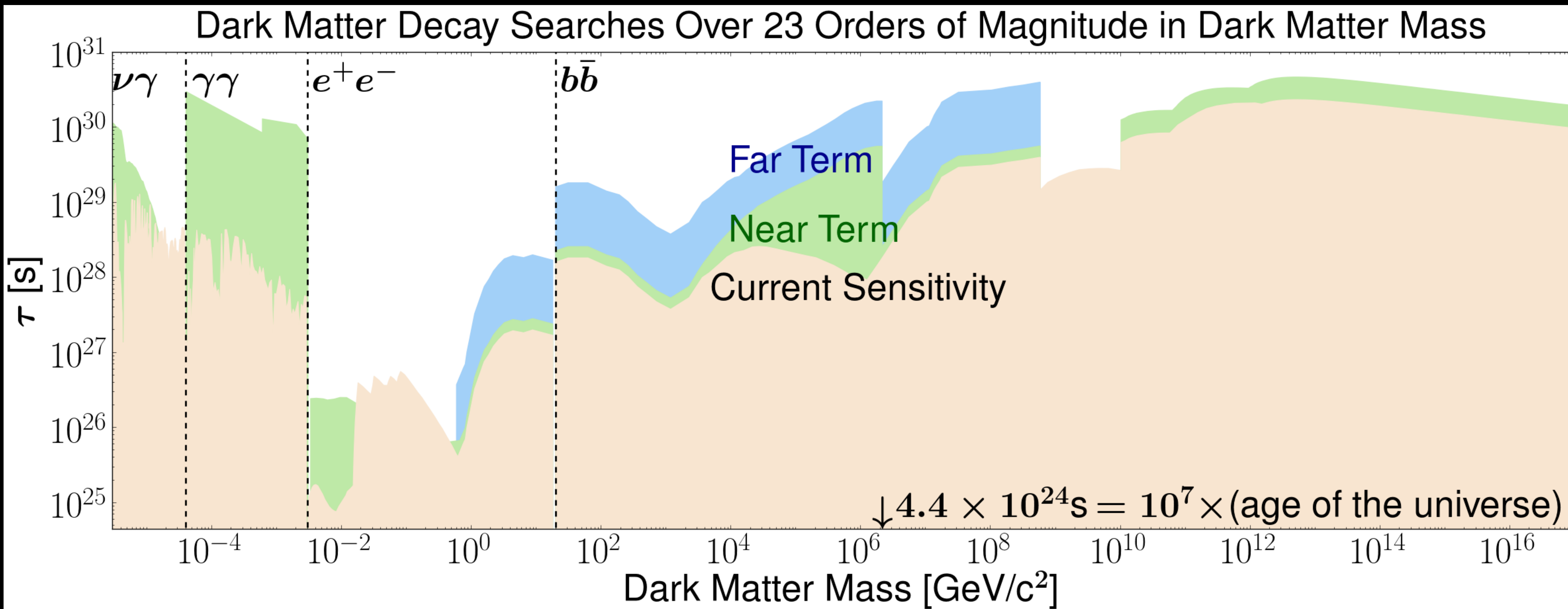
- Indirect detection tries to see dark matter annihilating.
- Dark Matter particles in the galaxy can occasionally encounter one another, and annihilate into SM particles which can make their way to the Earth where we can detect them.
- In particular, photons and neutrinos interact sufficiently weakly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

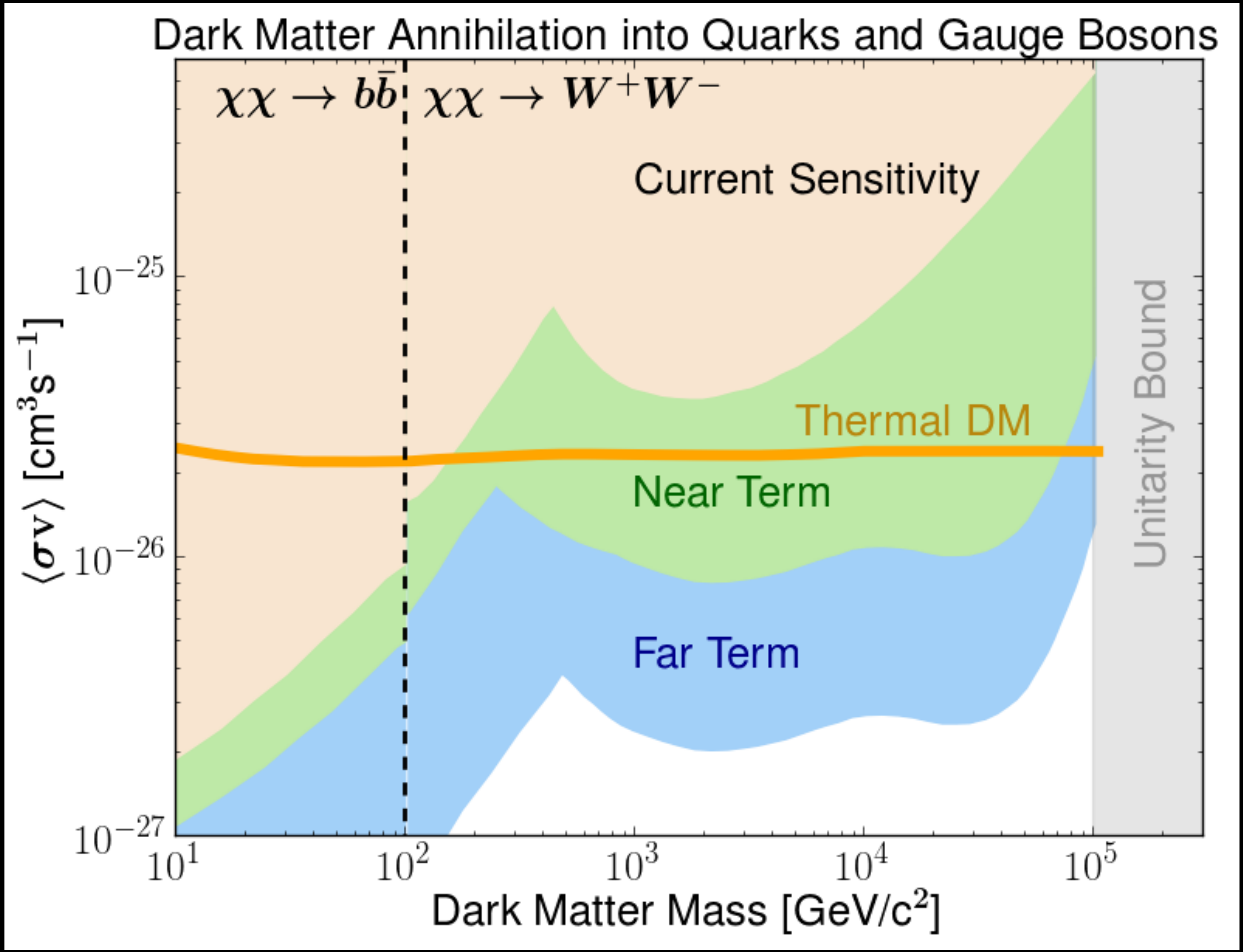
Snowmass CF1 Report



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 decay products bound the DM lifetime to be more than many times the age of the Universe.

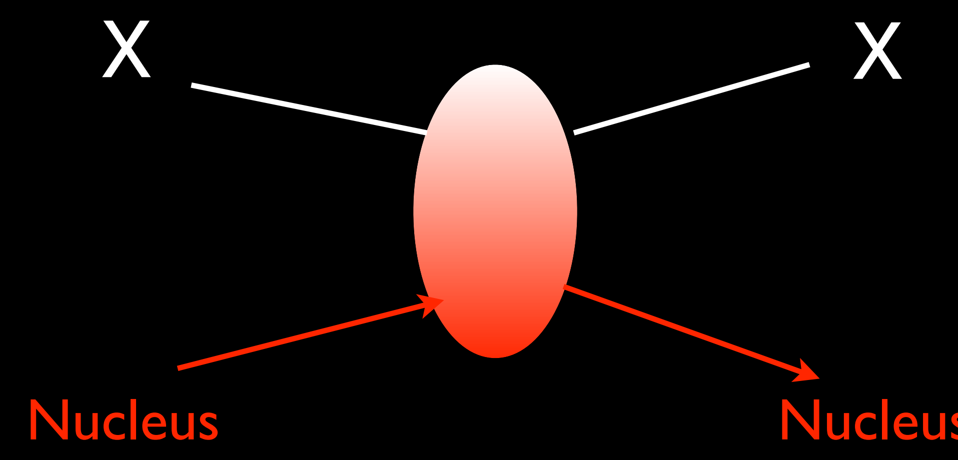
Indirect Detection



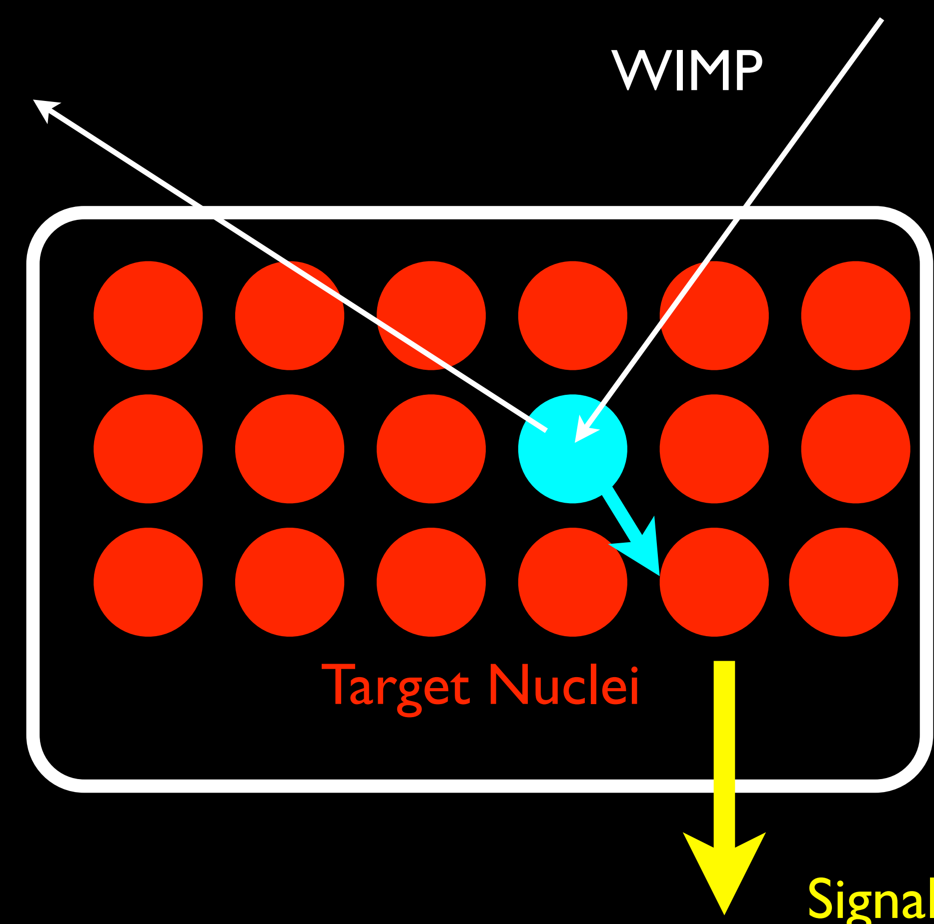
Indirect searches are sensitive to thermal relic dark matter with masses well beyond the reach of particle accelerators.

Snowmass CF1 Report

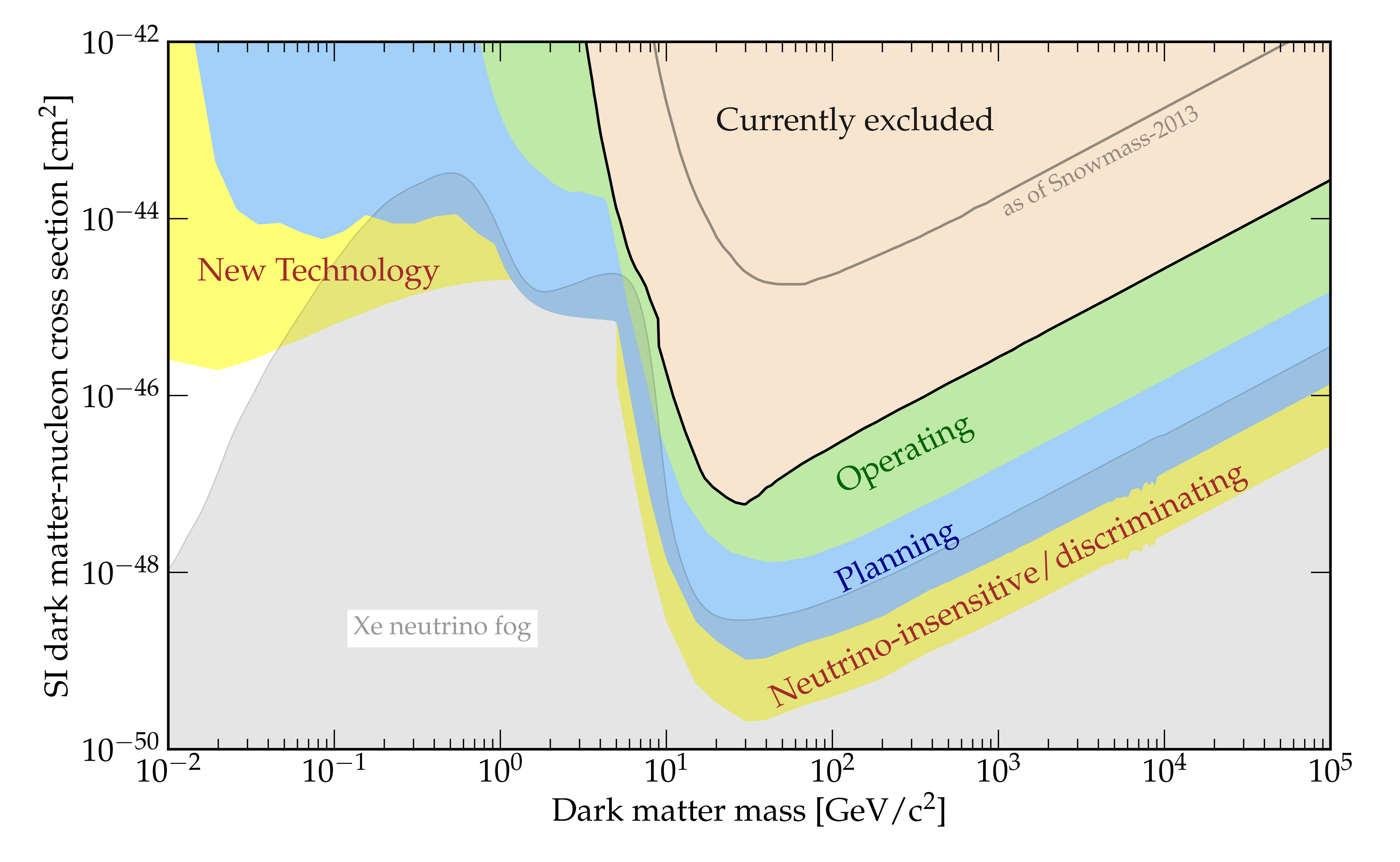
Direct Detection



- The basic strategy of direct detection is to look for the low energy recoil of a heavy nucleus, electron, or collective excitation in the detector material 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!

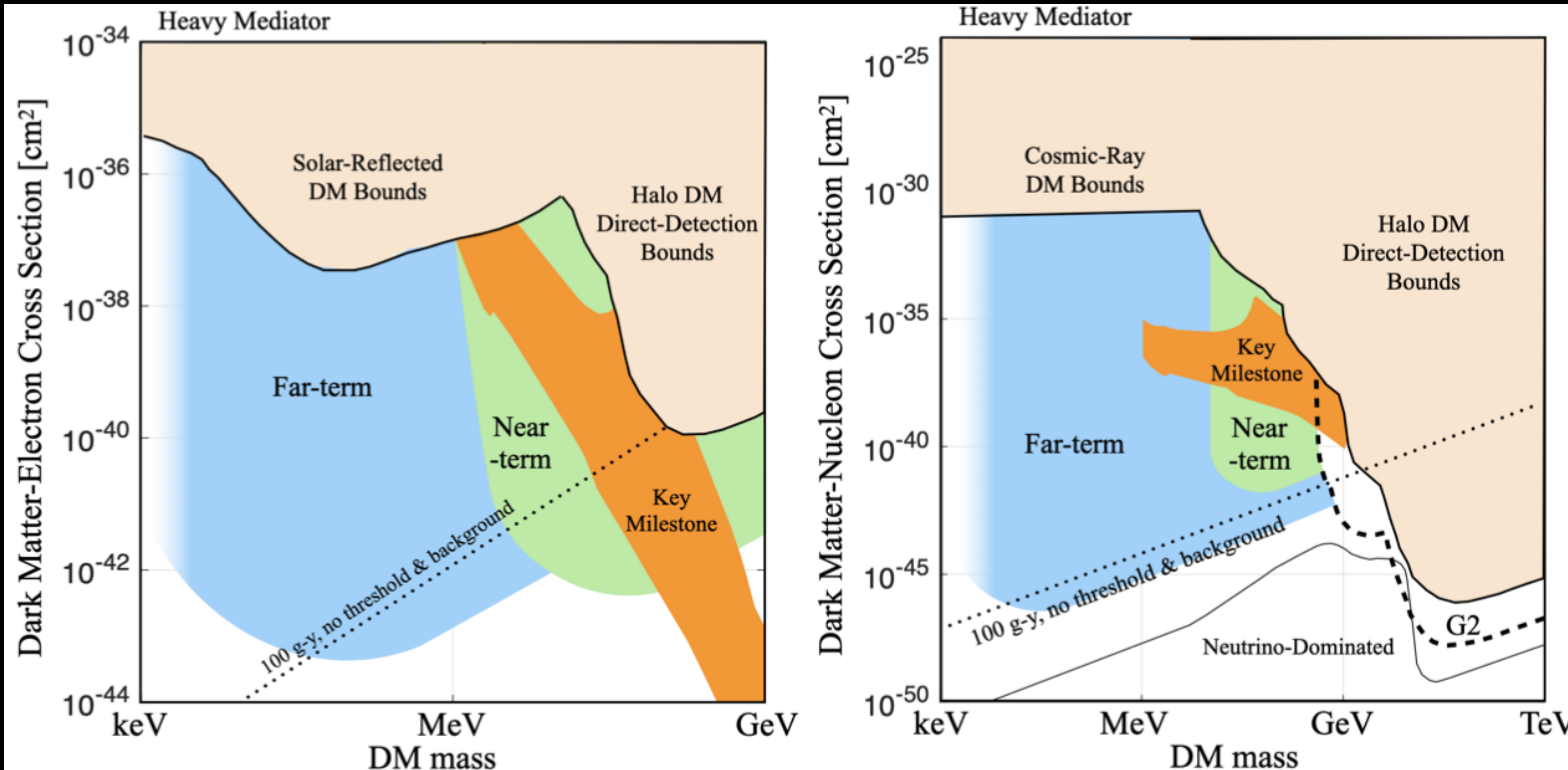


Racing to the Neutrino Fog



Snowmass CF1 Report

Exploring Lower Masses

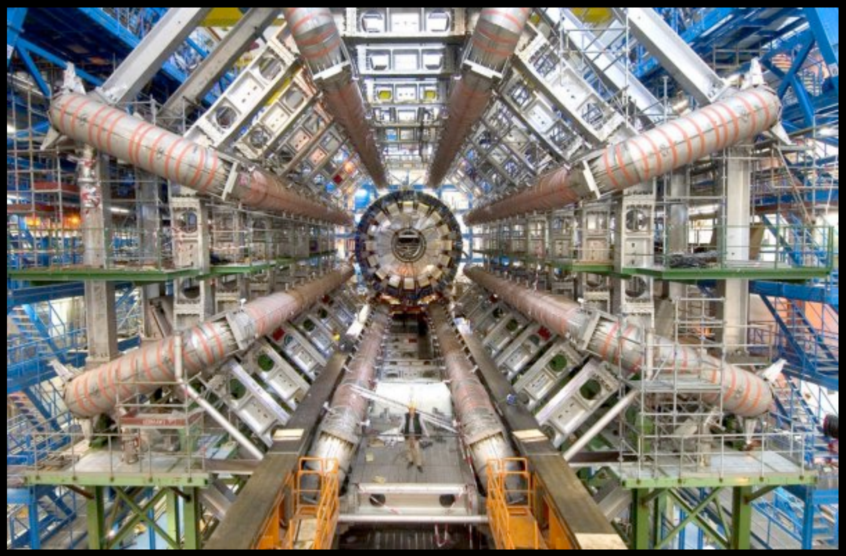


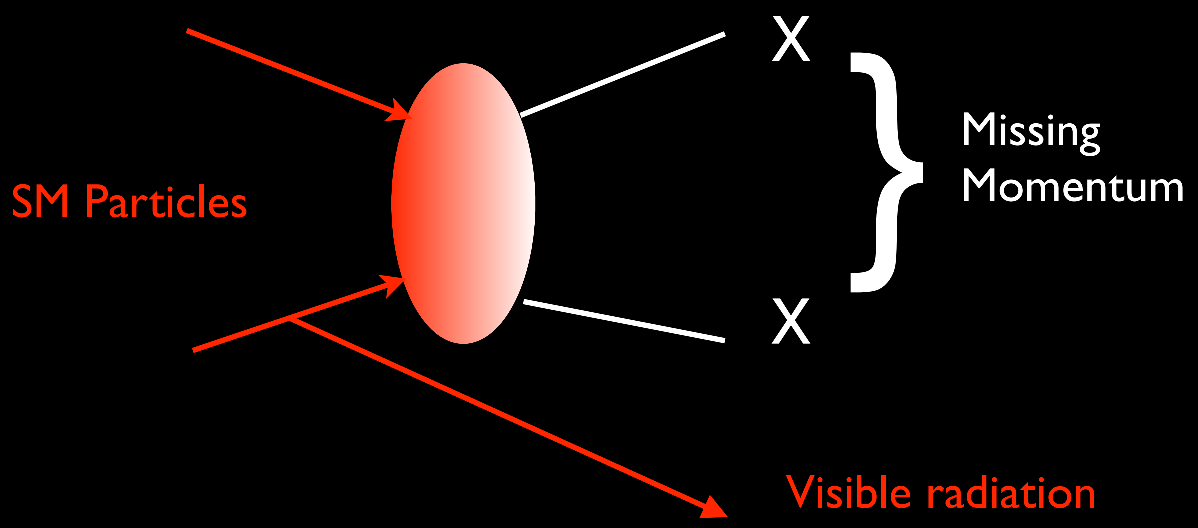
Going to lower DM masses is a challenge, because the ambient dark matter carries very little energy/momentum. Scattering with electrons or collective excitations in the detector offer opportunities to explore the ~MeV mass regime.

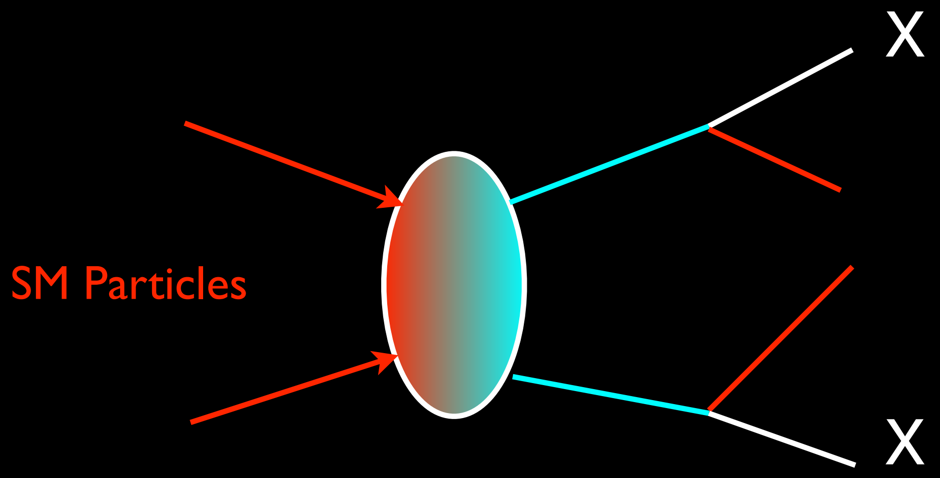
Snowmass CF1 Report

Collider Production

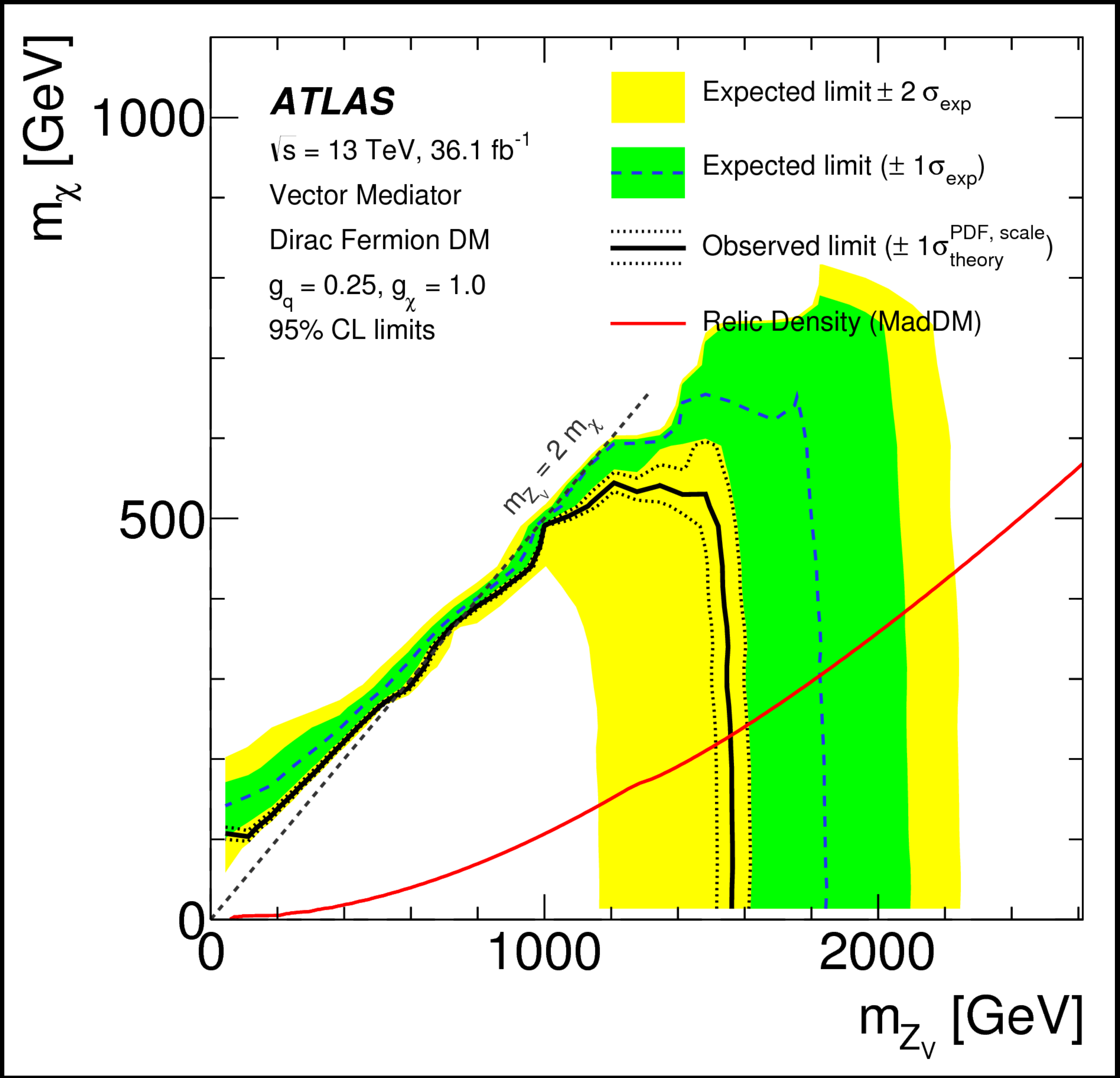
- If dark matter couples to quarks or gluons, we should also be able to produce it at high energy colliders.
- Since the DM is expected to interact very weakly, it is likely to pass through the detector and manifests as an imbalance in momentum.
- Provided they have enough energy to produce them, colliders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

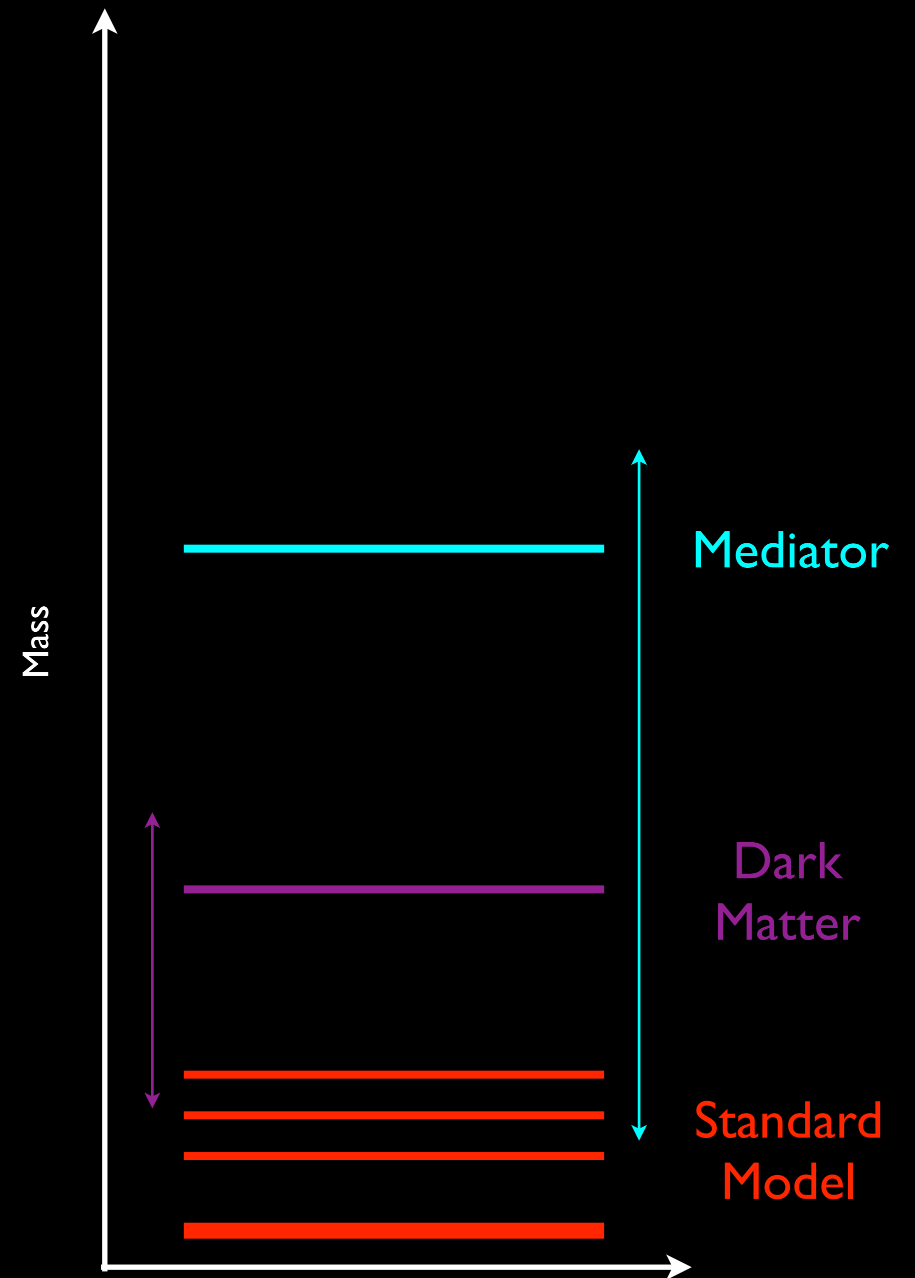


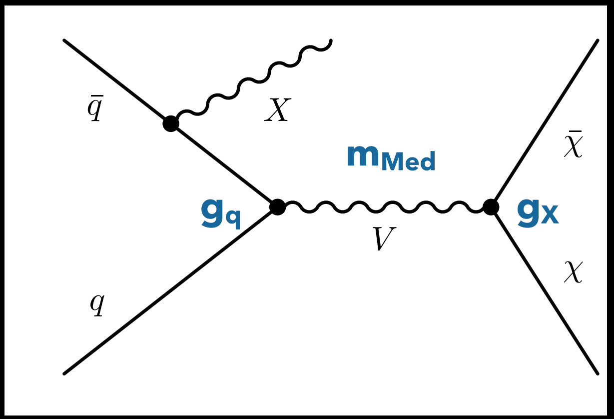




Mono-jet Searches



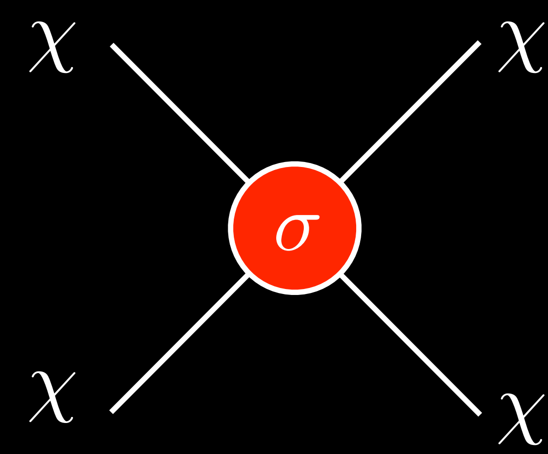




Searches for dark matter (missing momentum) plus a jet of hadrons places limits on the masses and couplings of the dark matter to mediator particles and quarks.

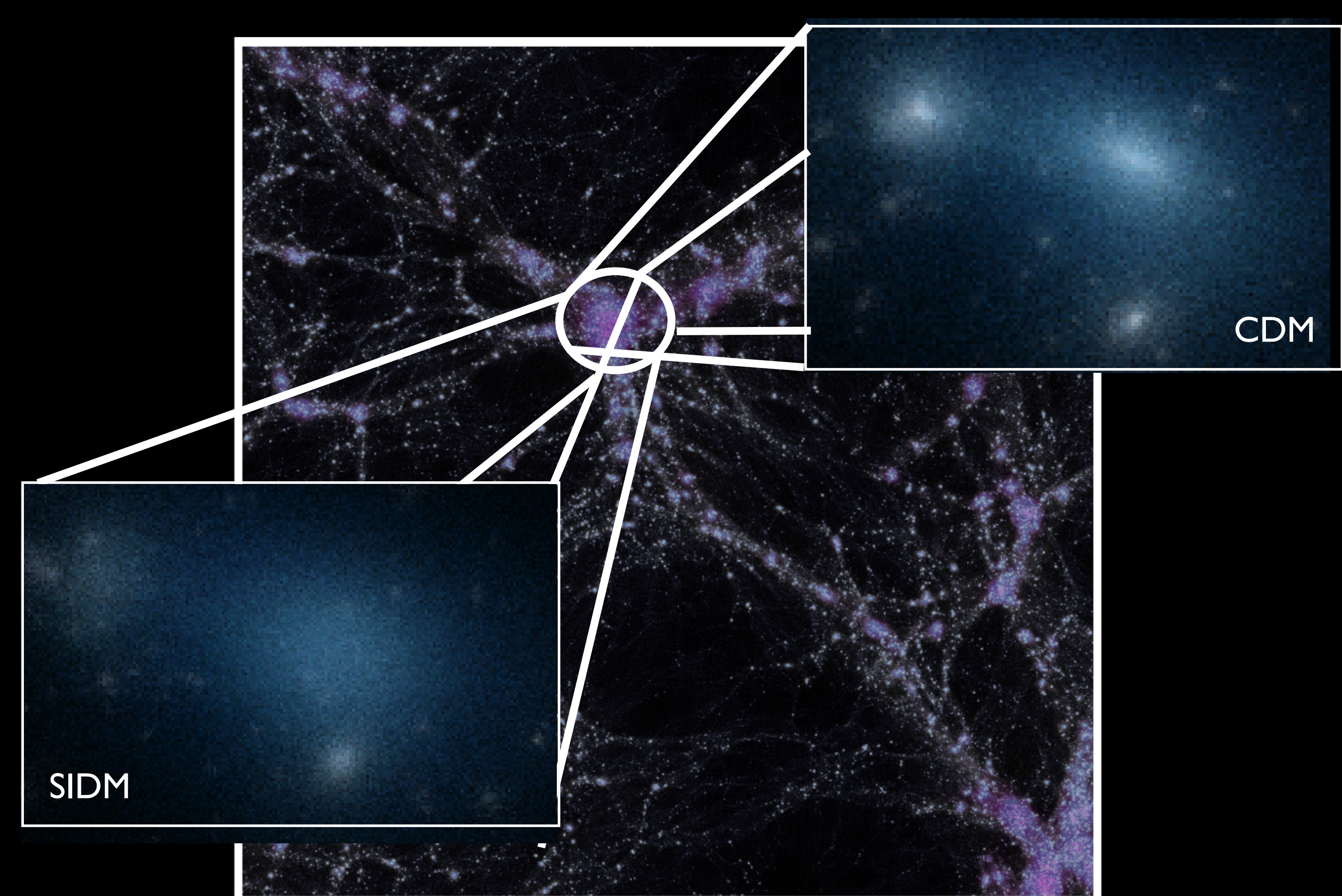
Cosmic Probes of DM

- 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.

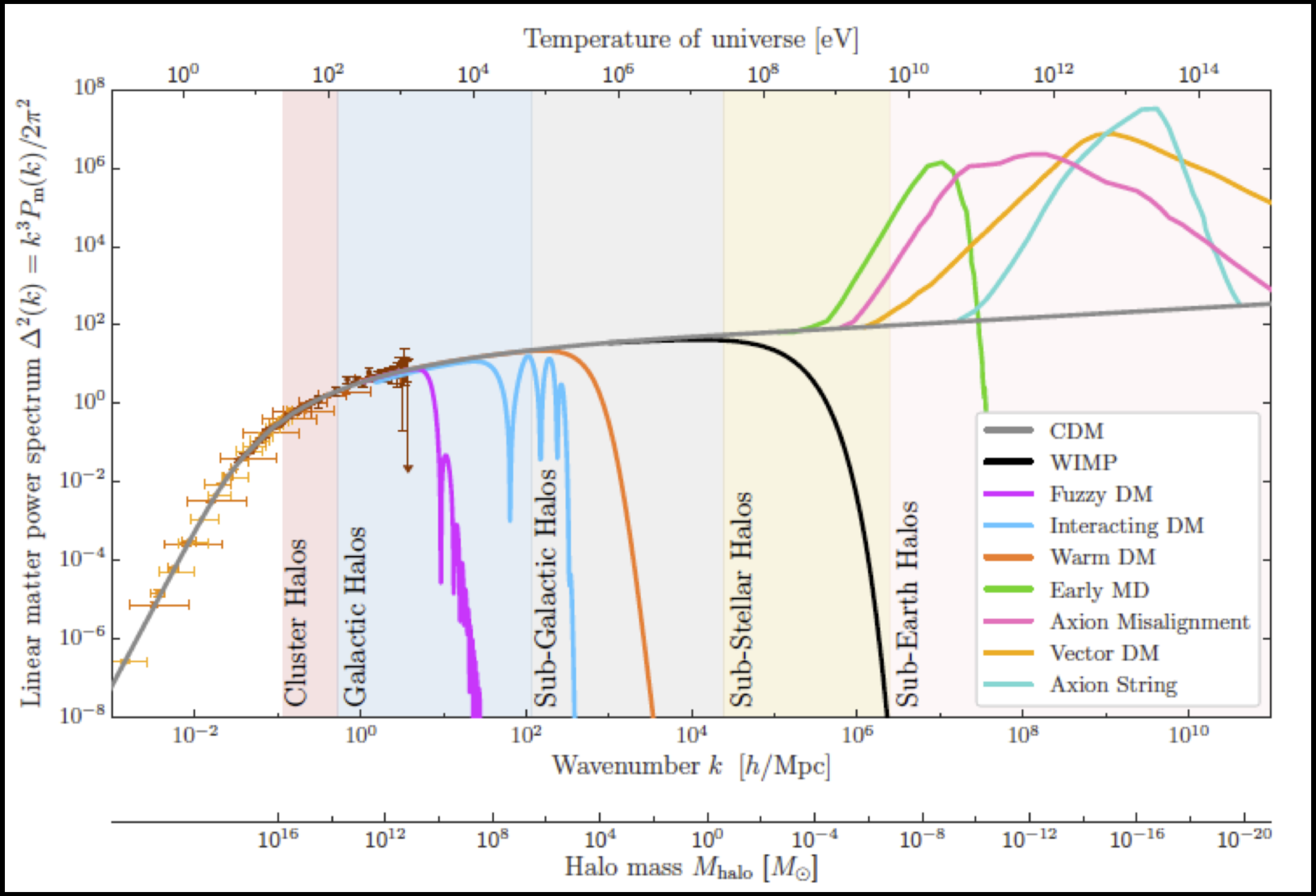


Markevitch et al; Clowe et al

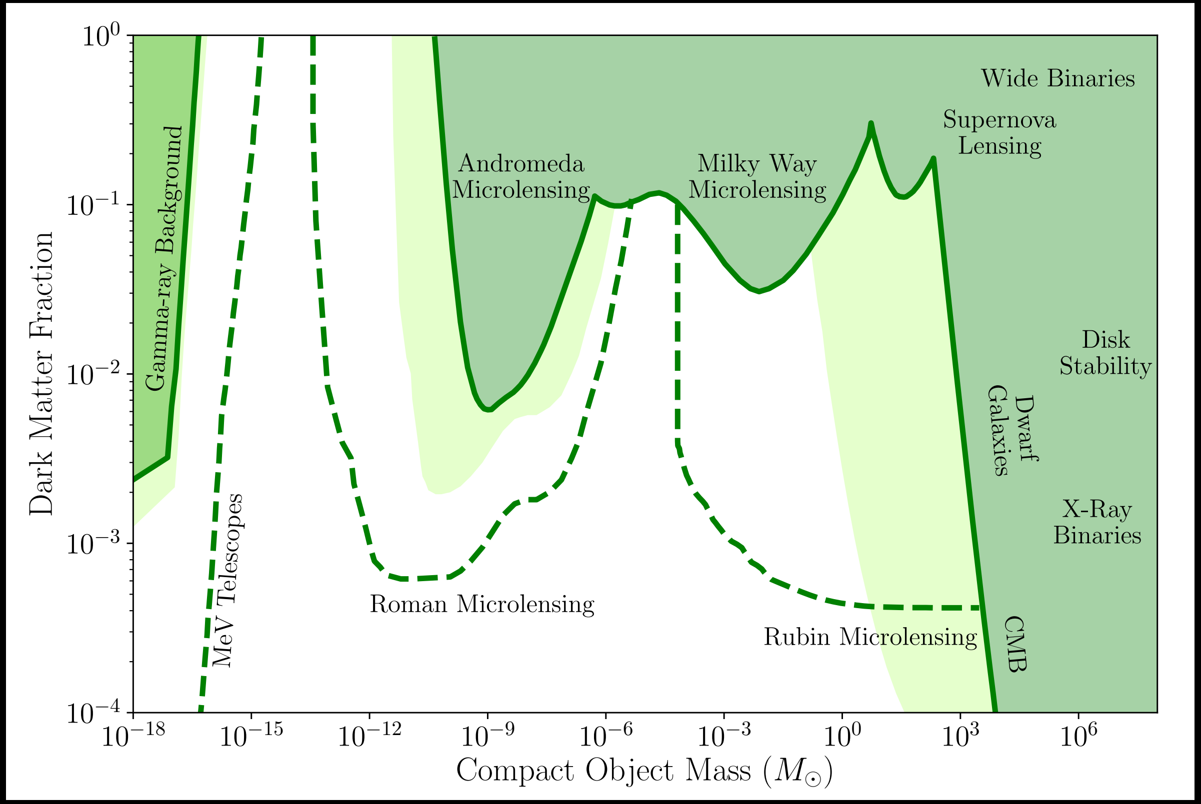
$$\sigma / m < 0.7 \ \mathrm{cm}^2 / \mathrm{g}$$



Astronomical Probes

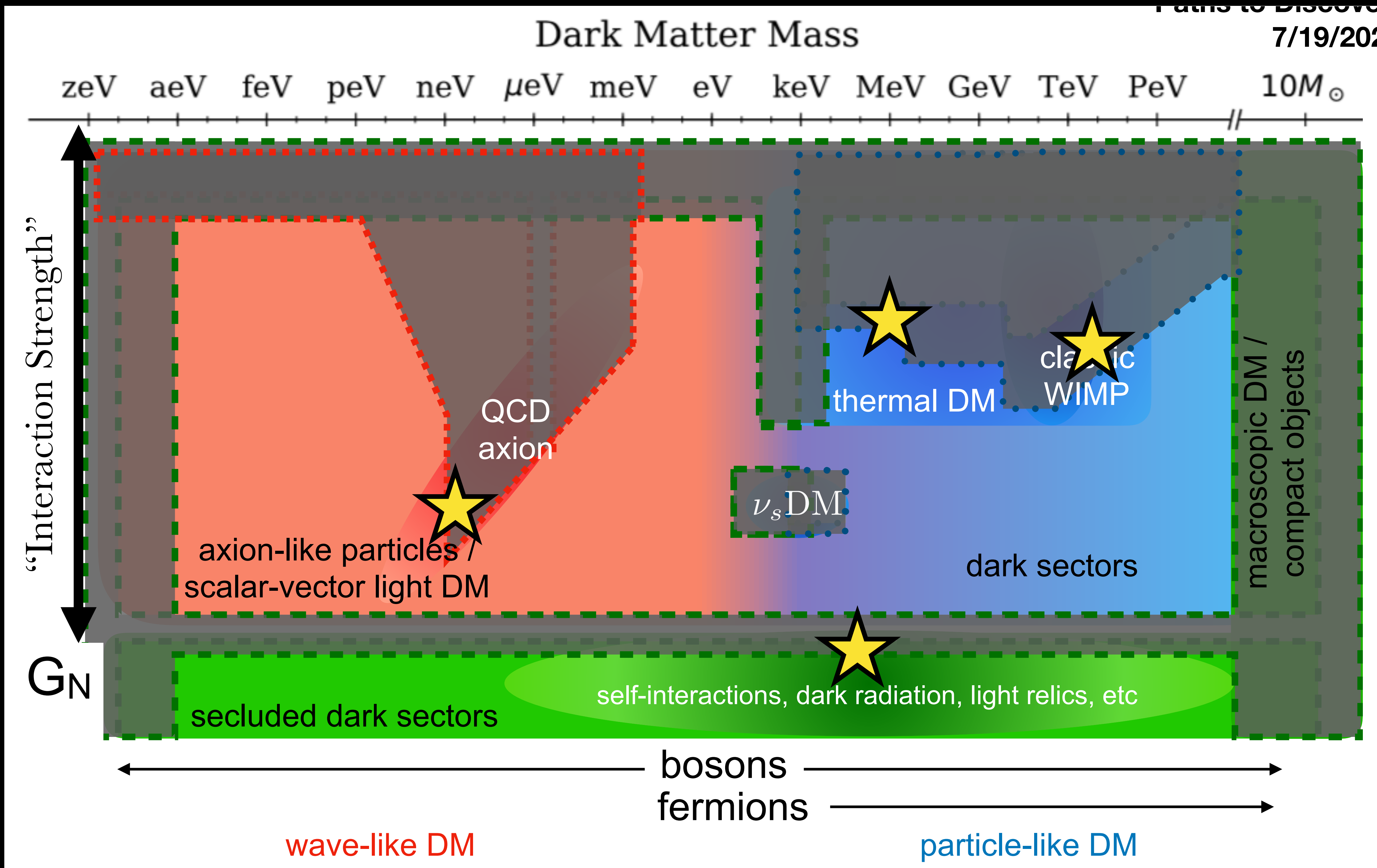


Snowmass CF3 Report



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



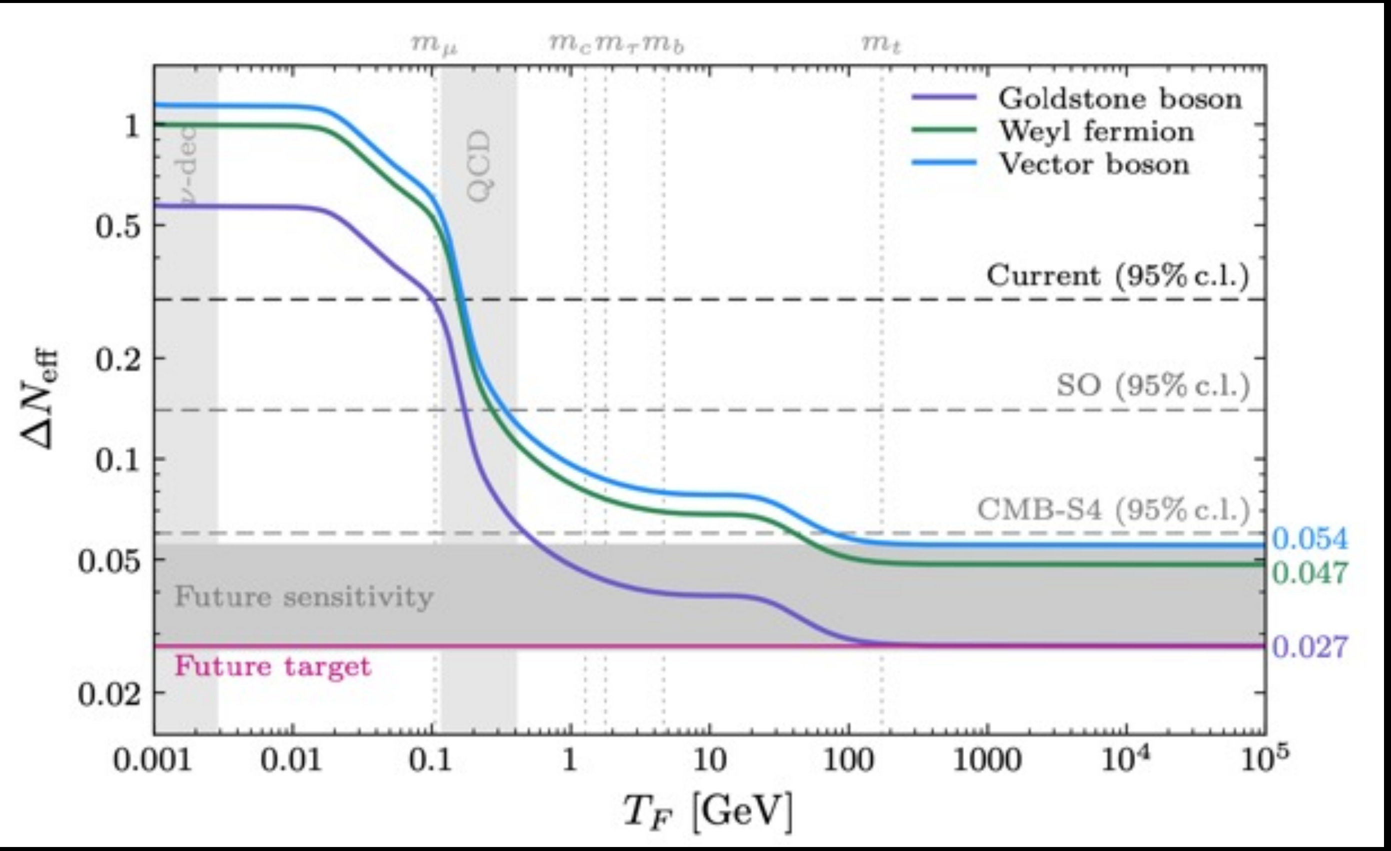
Snowmass
CF Report

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.

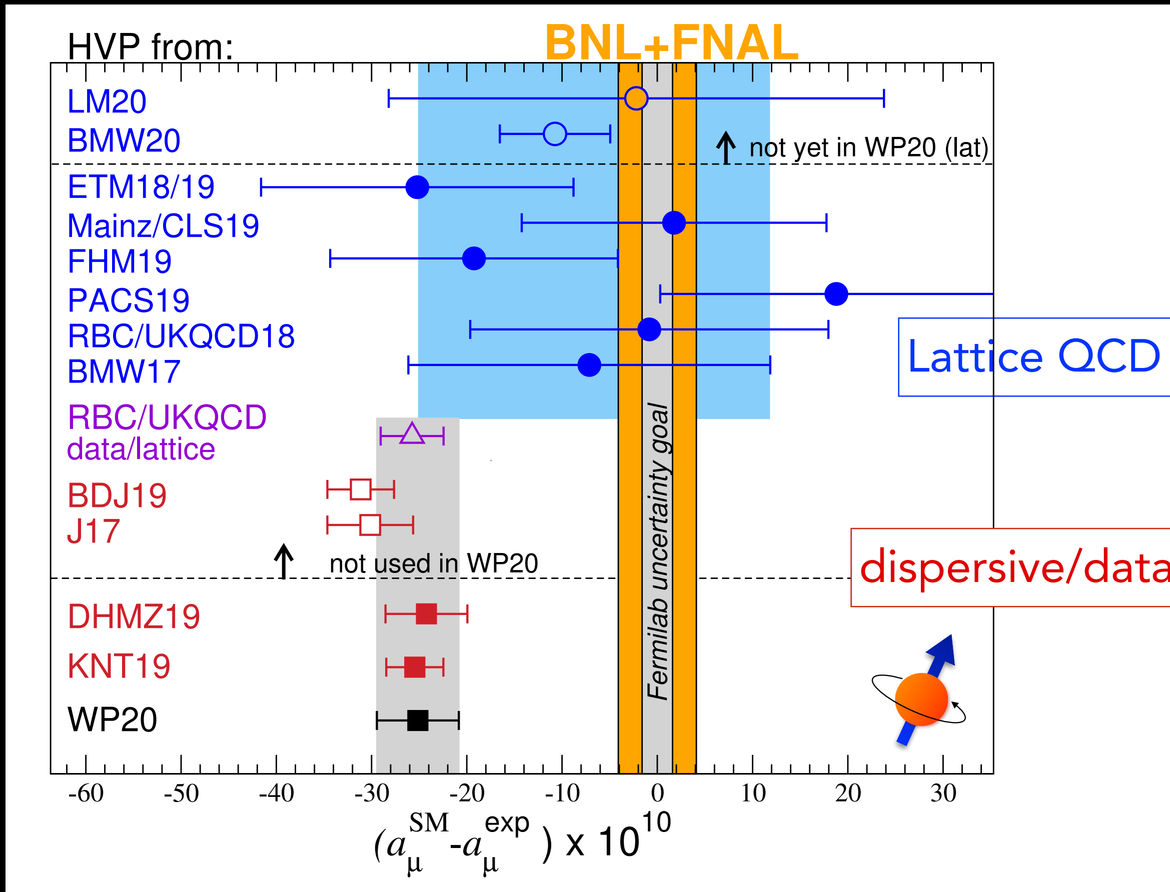


Snowmass CF Report

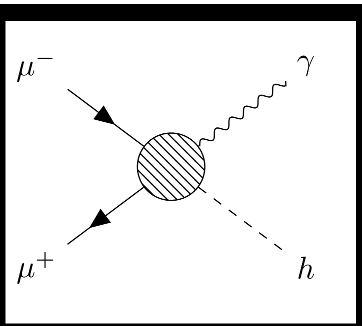
G-2

Aida El-Khadra, P5 Town hall

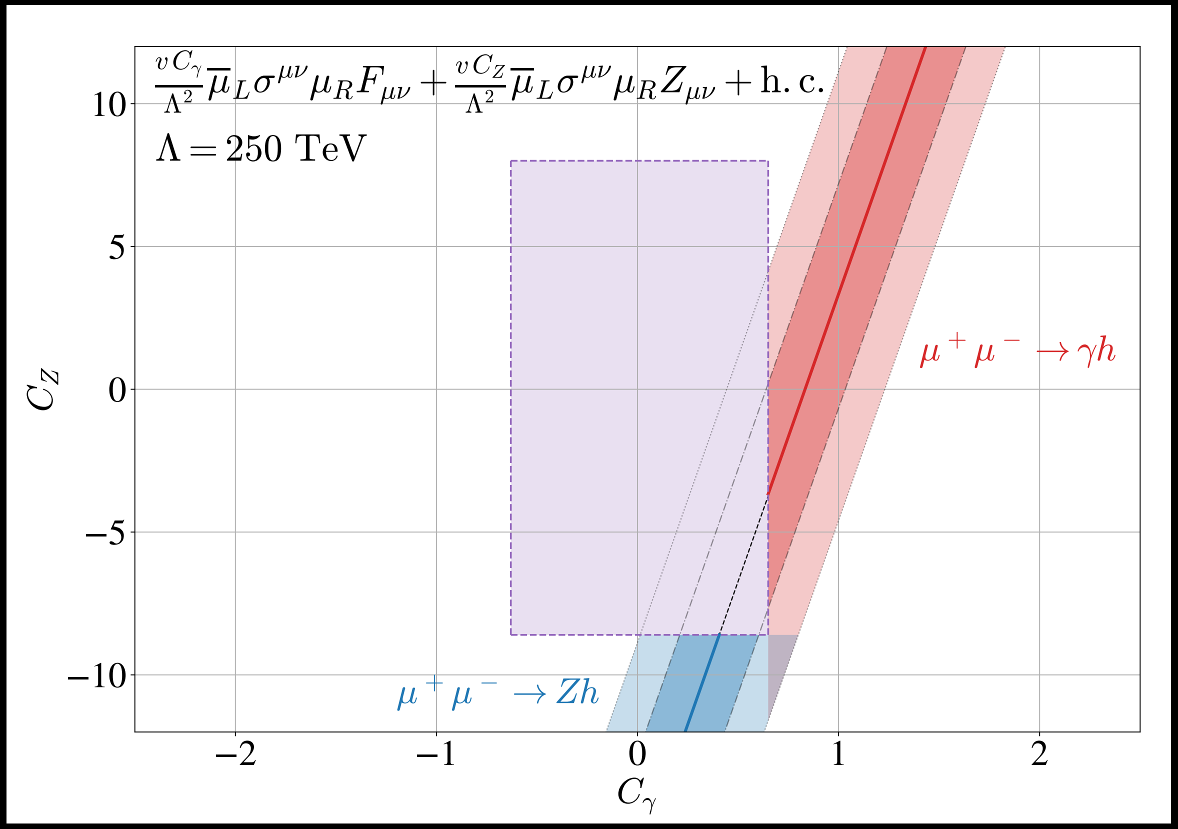
- It may also be that precision measurements will turn out to lead the way. For example, the longstanding discrepancy in the muon's g-2 might be a hint for new physics.
- Currently there are tensions between the best lattice determinations of the hadronic contribution to the vacuum polarization and data-driven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



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



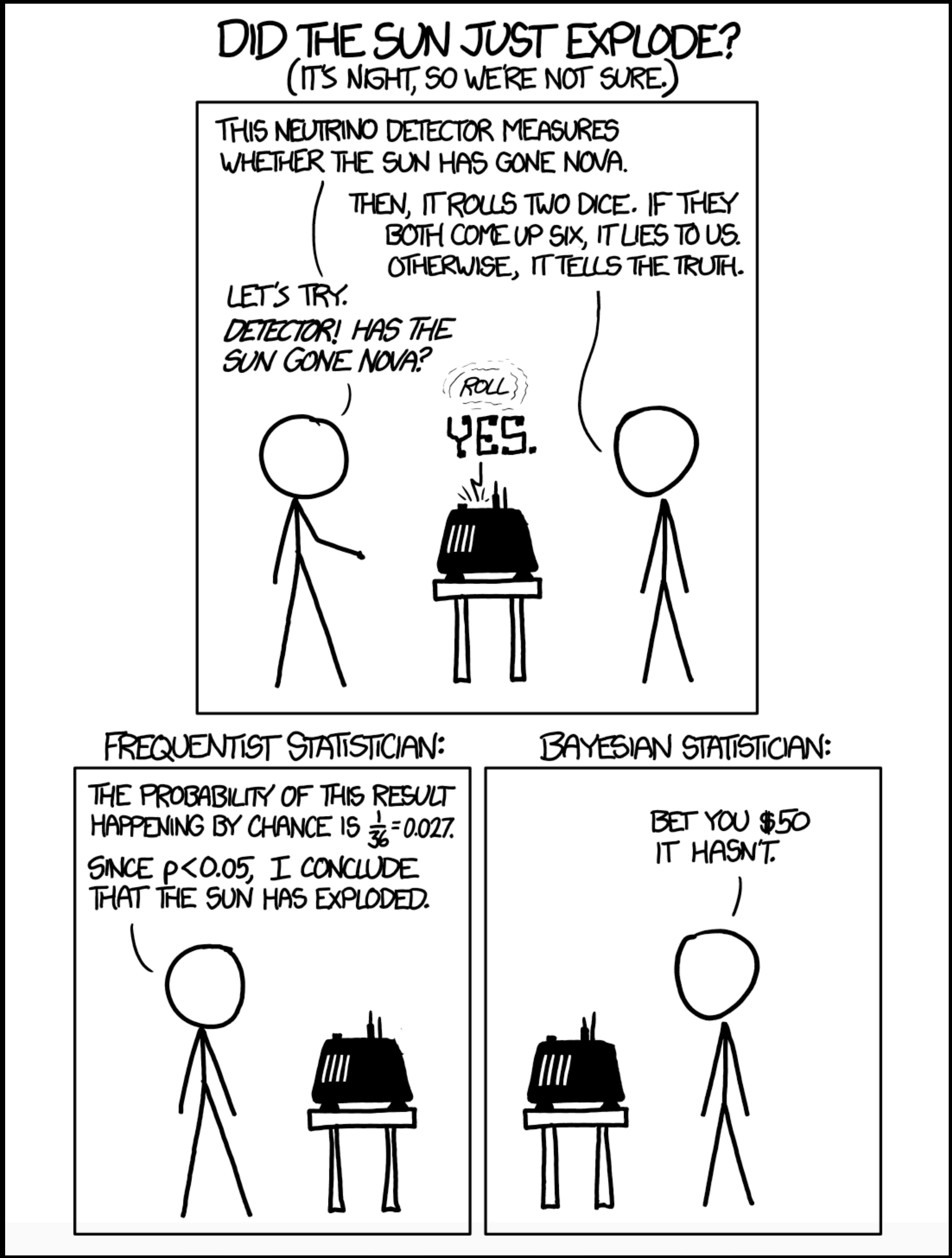
Arakawa, Rajaraman, Sui, TMPT 2208.14464



Discoveries from LHC?

- I would also not buy in to the argument that the LHC will not produce exciting discoveries as we head into the high luminosity running.
- These arguments are essentially boil down to a prior that the mass scale of new physics is log-distributed.
- But there is no reason to think this prior is correct. In fact, the radiative stability of the Higgs would argue that the multi-TeV scale is a special place to look for new physics!
- The LHC has made amazing progress understanding rare processes, and this will continue!

Xkcd



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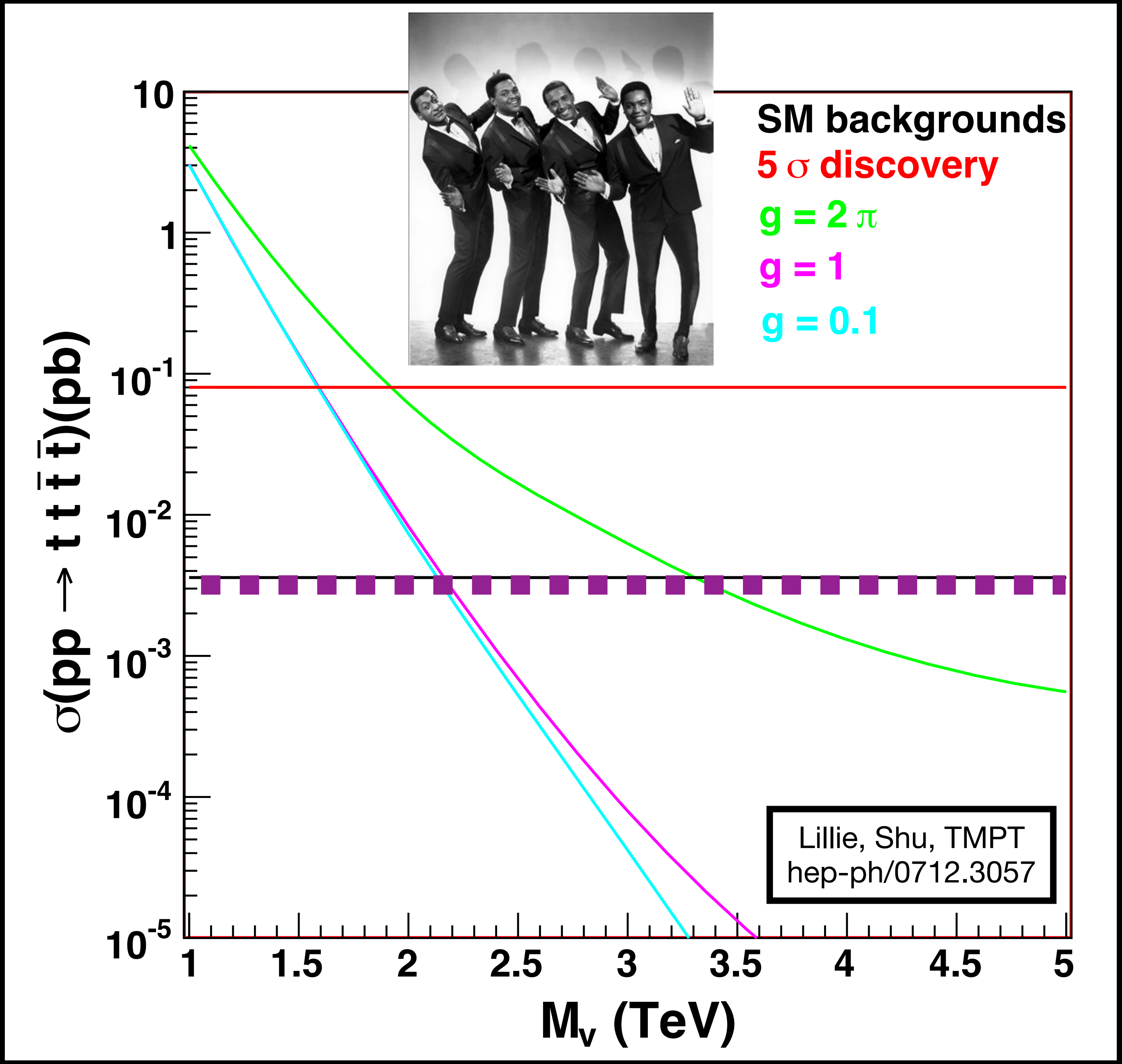
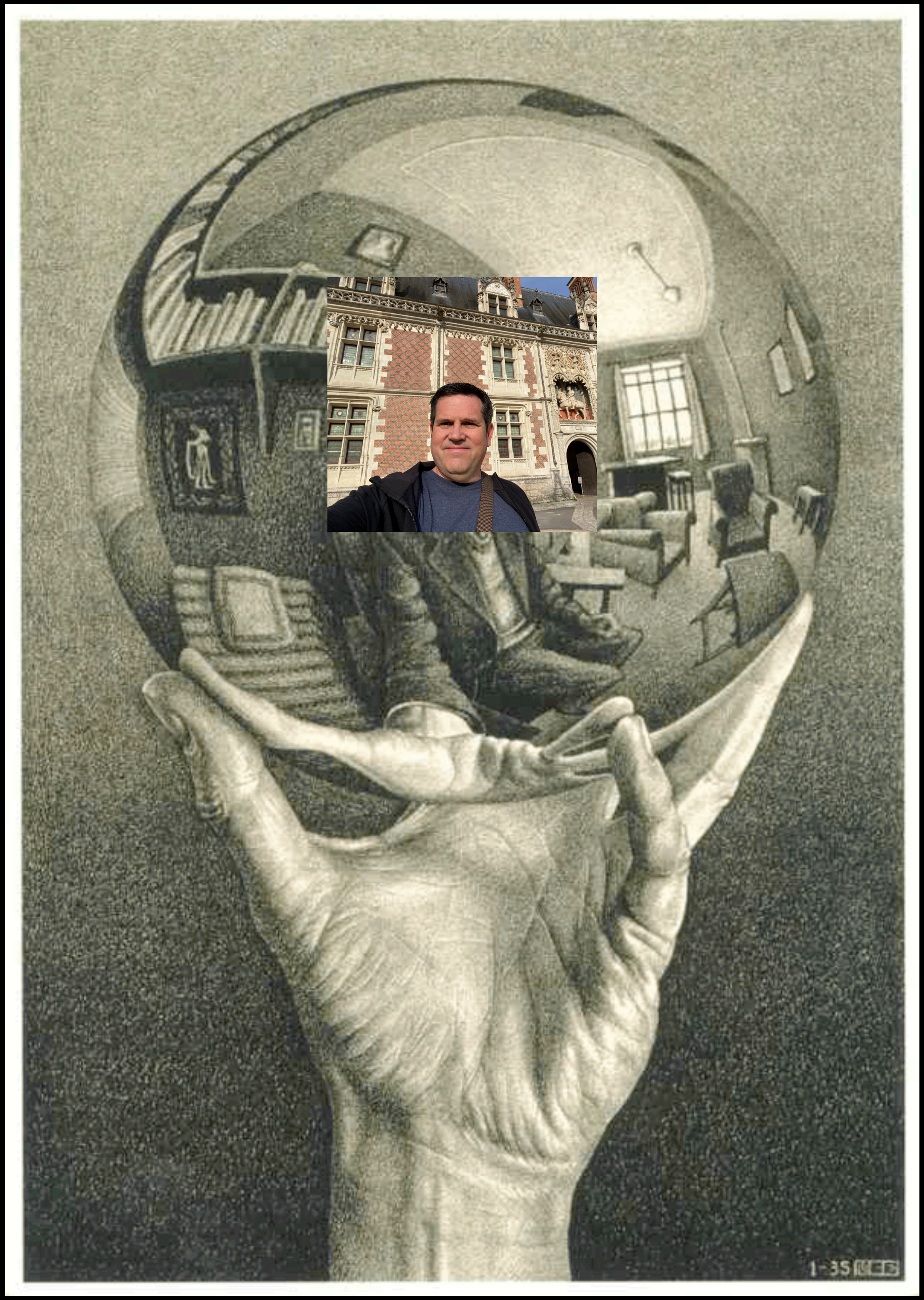
- These arguments are essentially boil down to a prior that the mass scale of new physics is log-distributed.
- But there is no reason to think this prior is correct. In fact, the little hierarchy we observe would argue that the multi-TeV scale is a special place to look for new physics!
- The LHC has made amazing progress understanding rare processes, and this will continue!

E.g. Production of four tops



So Where am *I* headed?



Cosmo-varied Couplings

EW Phase Transition?

QCD Phase Transition?

MeV

eV

Baryogenesis?

BBN

CMB

Today

Before BBN, most of what we know about the physics in the early Universe is an extrapolation based on the Standard Model + ingredients such as dark matter.

This gives license for particle theorists to play.

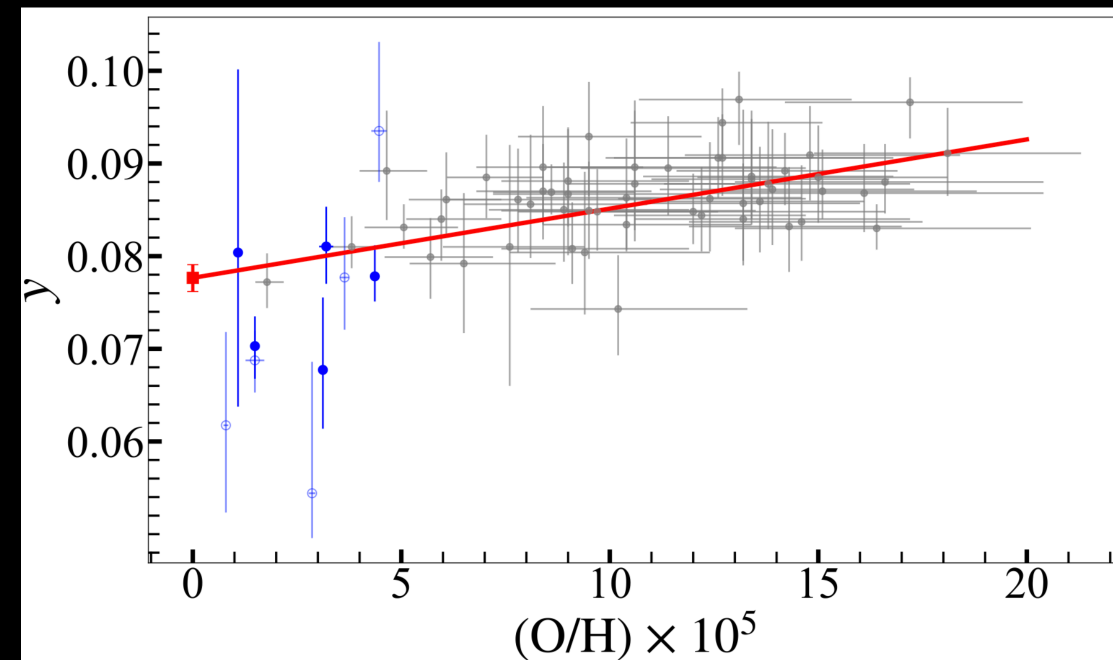
(However, I won't say more here. Please ask me afterwards or look at the extra slides if you are interested…)

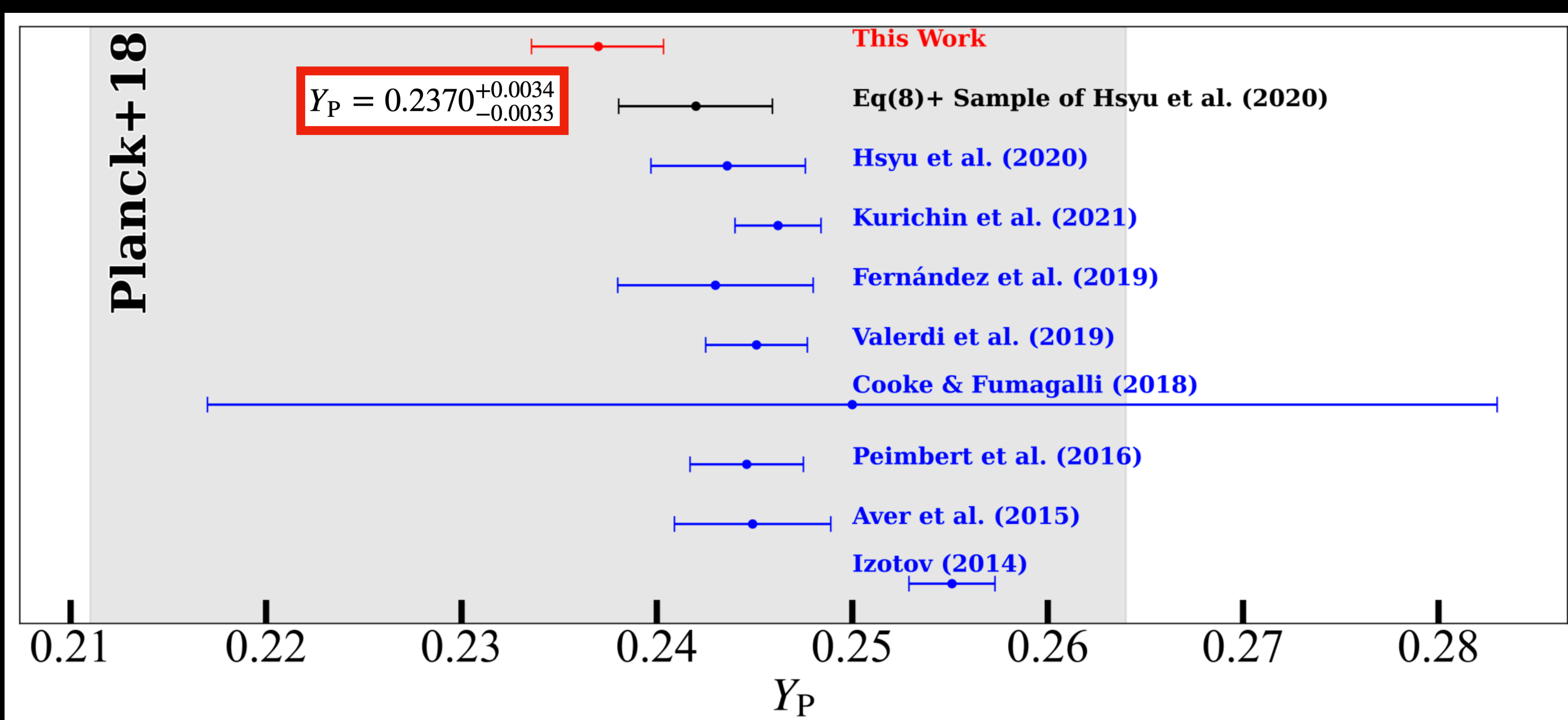
A New ^{4}He Measurement

Extremely metal-poor galaxies (EMPGs) provide pristine environments for primordial ^{4}He measurements.

2021: 51 metal-poor galaxies + 3 EMPGs

2022: deep NIR spectroscopy from Subaru Telescope adds 10 new EMPGs!





Matsumoto et al
arXiv:2203.09617v3
Astrophys.J. 941 2, 167 (2022)

$$Y_P = 0.2370^{+0.0034}_{-0.0033}$$

Compare with PDG 2021:

$$Y_P = 0.245 \pm 0.003$$

~2.5 sigma difference…

Hints for a Lepton Asymmetry?

- The primordial abundance of ^{4}He is sensitive to an asymmetry in the lepton sector.
- Charge neutrality forbids us from having a large asymmetry in the charged leptons, but still allows an asymmetry between neutrinos and anti-neutrinos.
- A chemical potential for neutrinos would impact the total energy density, and contribute to ΔN_{eff}, but this is negligible for the CMB as long as:

$$|\xi_\nu| \lesssim \mathcal{O}(0.1)$$

- But in the BBN era, it also impacts the neutron-to-proton ratio, and thus production of ^{4}He!
- Helium-4 is a very sensitive *leptometer*…

$$e^- + e^+ \leftrightarrow 2\gamma \,,\, 3\gamma$$

↓

$$\mu_\gamma = 0 \,,\, \mu_{e^-} = -\mu_{e^+} \equiv \mu_e$$

$$n_{e^-} - n_{e^+} = n_p$$

↓

$$\eta_e \propto \mu_e / T_\gamma \lesssim \eta_B \sim 10^{-10}$$

$$n + \nu_e \leftrightarrow p + e^-$$

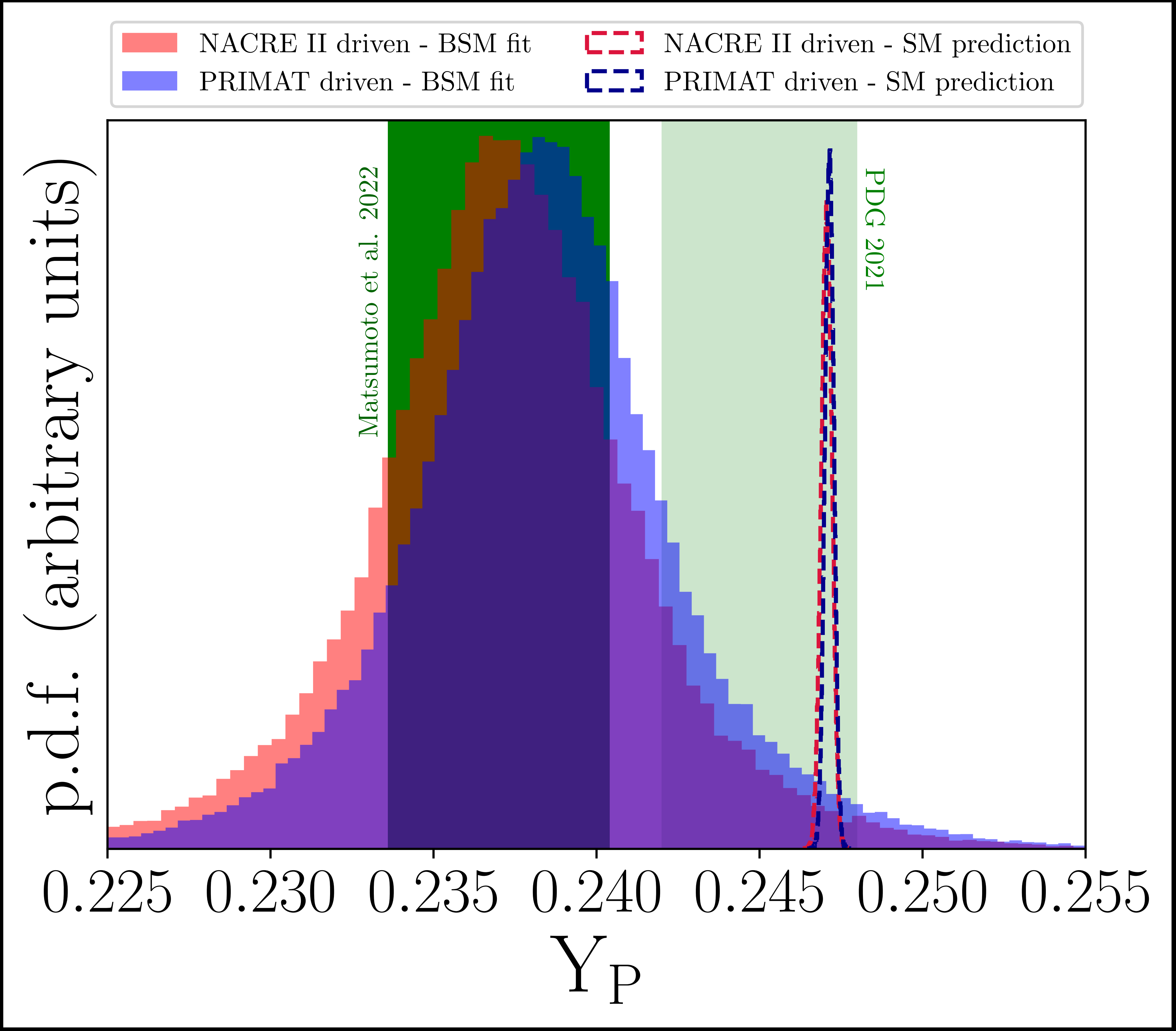
$$\mu_n + \mu_\nu \simeq \mu_p$$

↓

$$(n_n/n_p)|_{eq.} \simeq \exp(-Q/T - \xi_\nu)$$

Results: Helium-4

Burns, TMPT, Valli, 2206.00693 (& PRL)



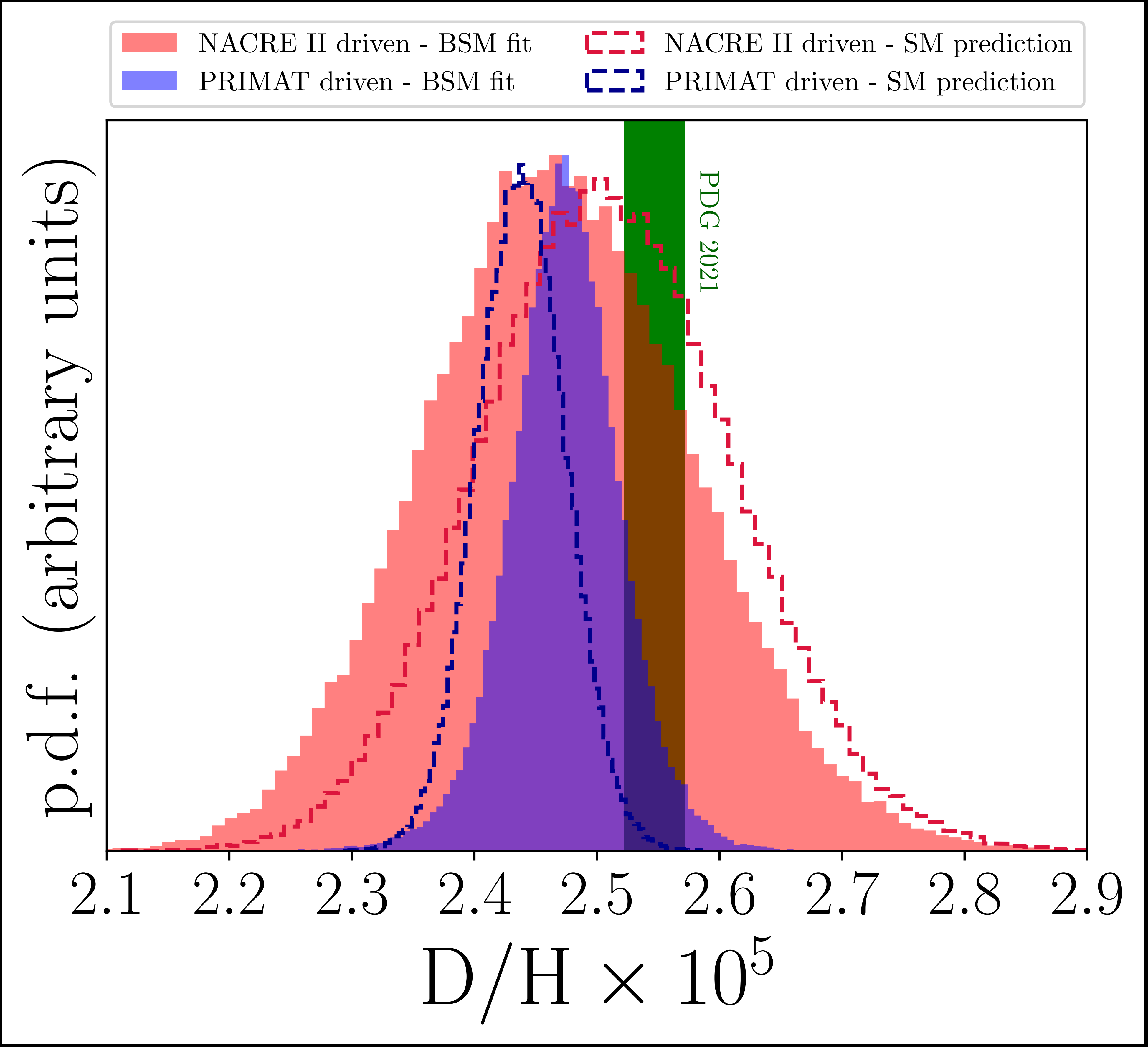
BSM:

Lepton asymmetry

+

N_{eff} Floats

Results: Deuterium



Burns, TMPT, Valli, 2206.00693 (& PRL)

BSM:
Lepton asymmetry
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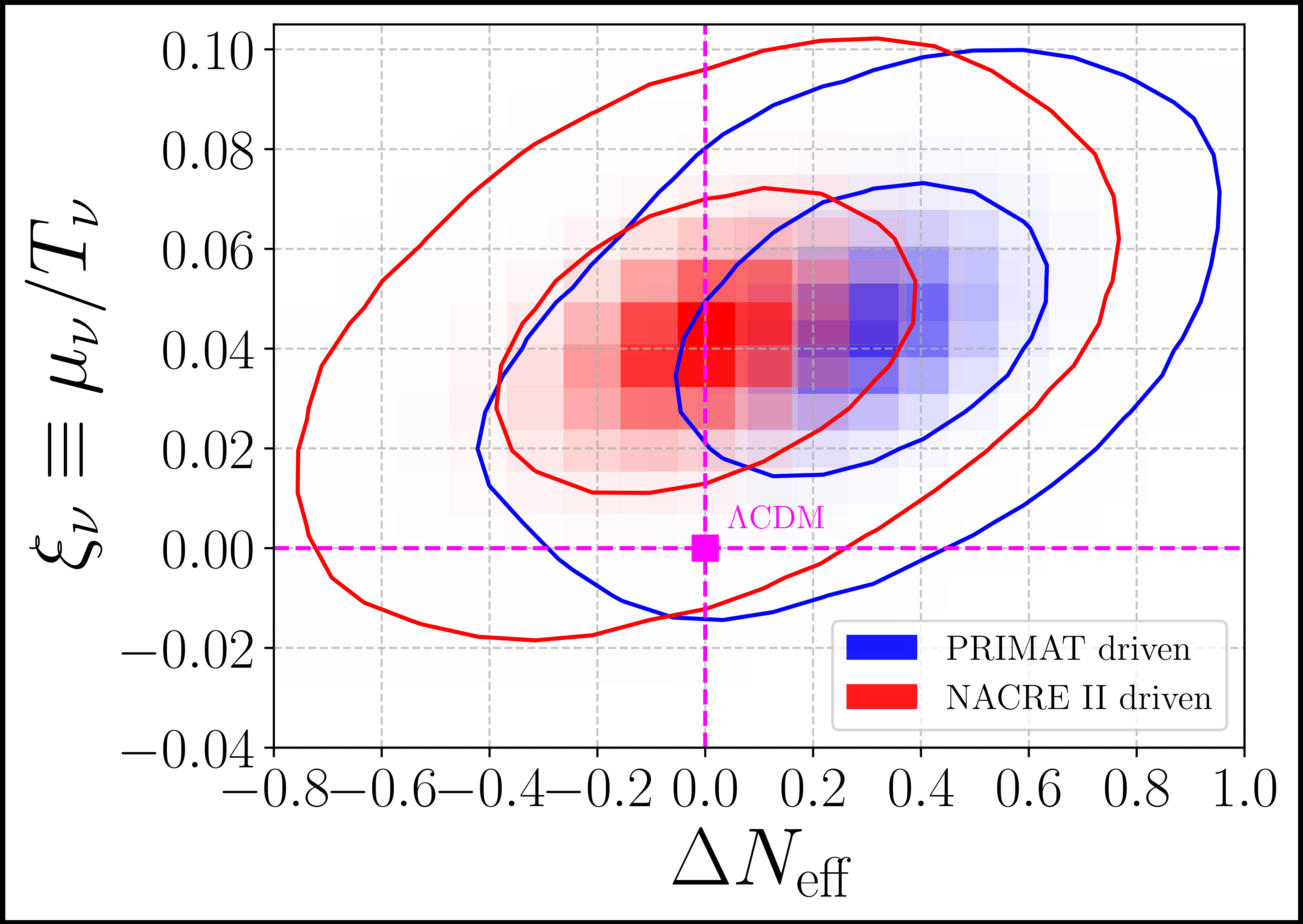
BBN 2022: New Physics Inference



Burns, TMPT, Valli, 2206.00693 (& PRL)

A non-zero lepton asymmetry is detected at the ~2σ level. The central value of the fit is ~ 0.04, independent of the implementation of the nuclear reaction network.

Implications

What does the inferred $\overline{\xi_\nu} \simeq 0.04$ imply!?

Our inference *a priori* **only** involves the electron-flavor neutrino.

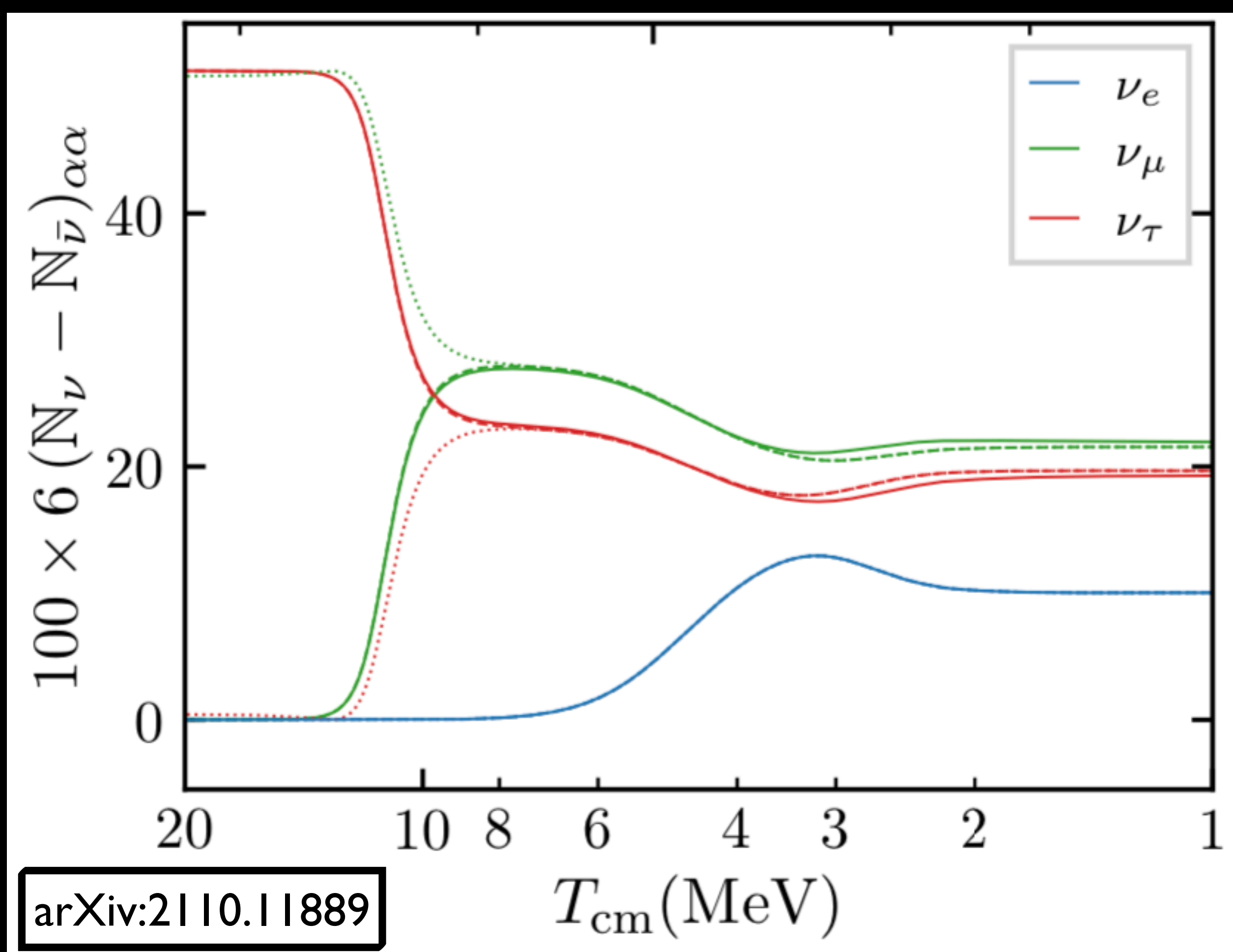
$$\eta_L \simeq \sum_{i=e,\mu,\tau} \frac{n_{\nu_i} - n_{\bar{\nu}_i}}{n_\gamma} \simeq \frac{\pi^2}{12\zeta(3)} \sum_{i=e,\mu,\tau} \left(\frac{T_{\nu_i}}{T_\gamma}\right)^3 \xi_{\nu_i} \quad \Rightarrow \quad \eta_L^0 \in (\,10^{-2}, 1/4\,)$$

LOWER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\,,\ \xi_{\nu_{\mu,\tau}} = 0$

UPPER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\,,\ \xi_{\nu_{\mu,\tau}} = 0.5$

$(\Delta N_{eff} \sim 0.1)$

Initial conditions: $\xi_{e,\mu,\tau} = (\,0\,,0\,,0.5\,)$

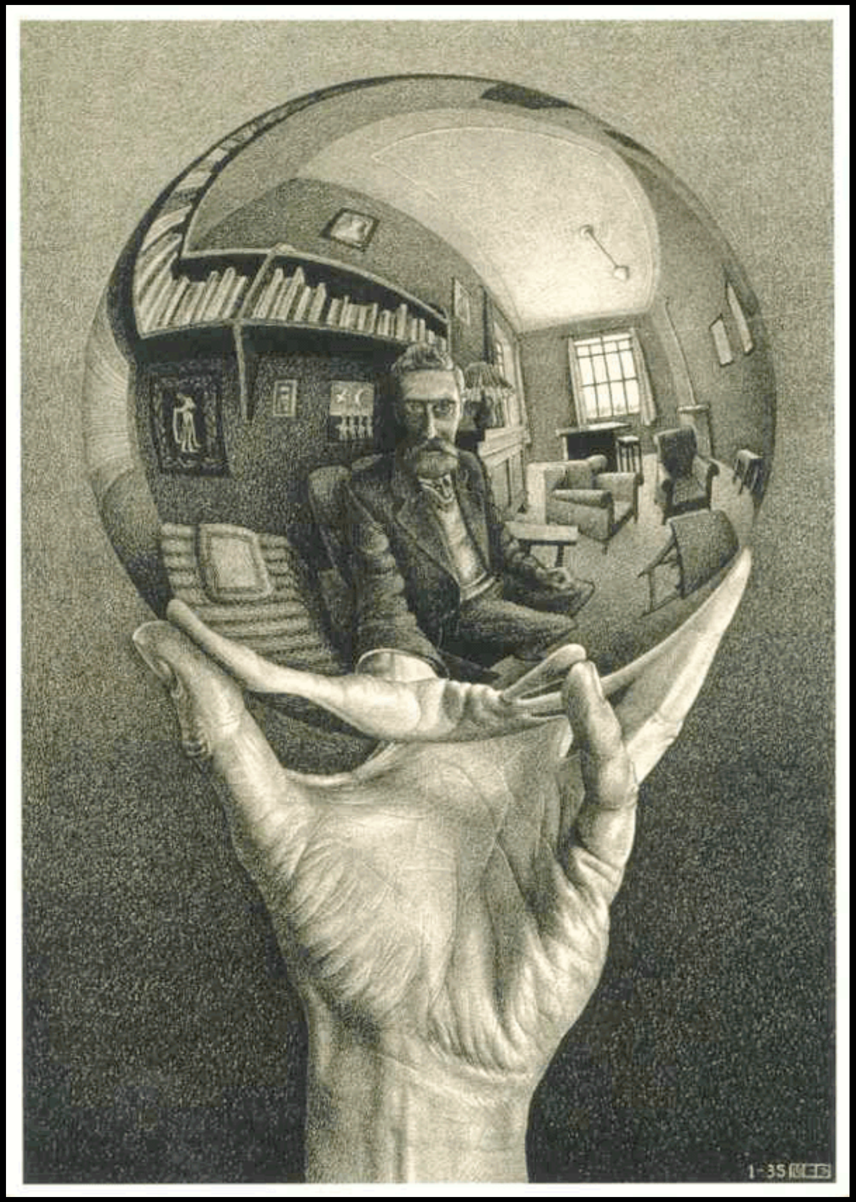


The muon & tau sectors mix efficiently @ ~ 10 MeV [astro-ph/0203442]

The lepton asymmetry today depends on the initial asymmetries and details of PMNS matrix.

Outlook

- Particle physics is vibrant and healthy. This past week has been a celebration of that fact.
- There are plenty of signs of BSM physics already at hand. We need to keep looking for the clues that will tell us how to explain it!
- They are interesting signposts to new ideas and new directions.



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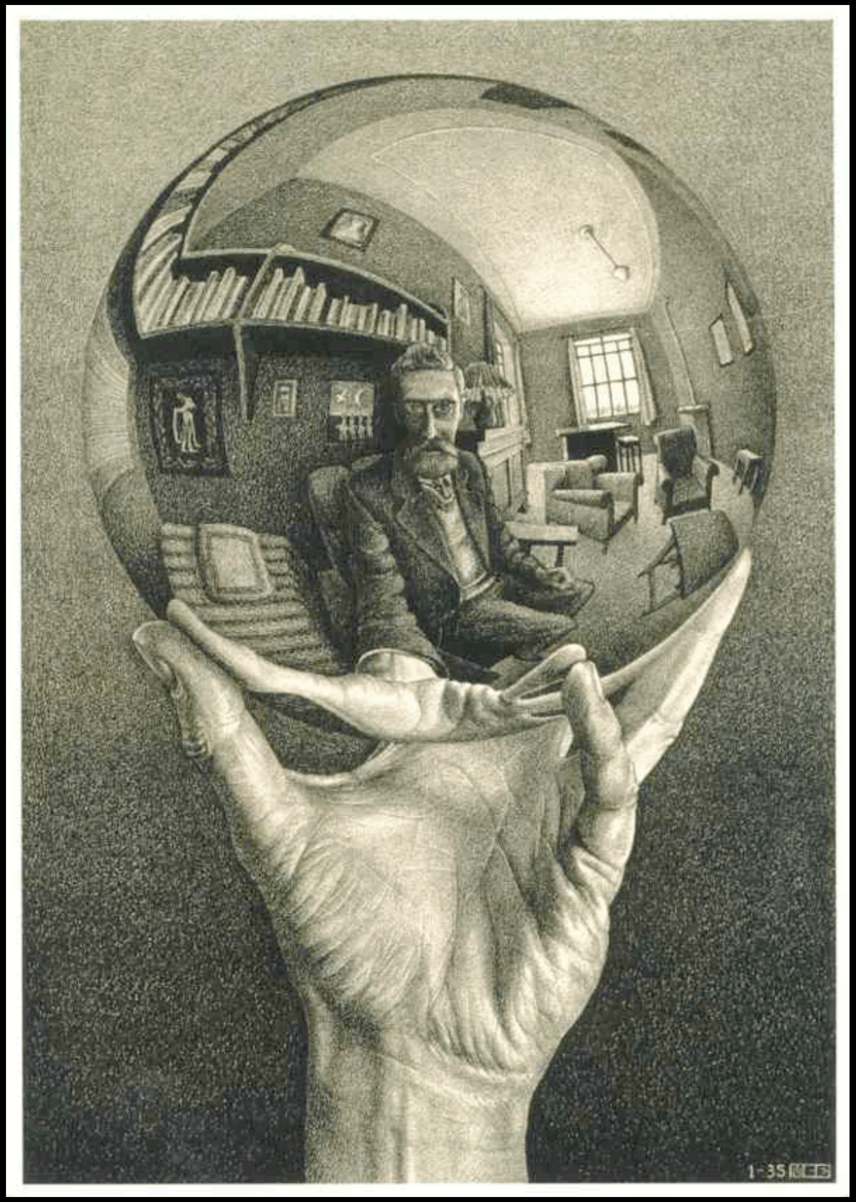

Inspiration:

"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."

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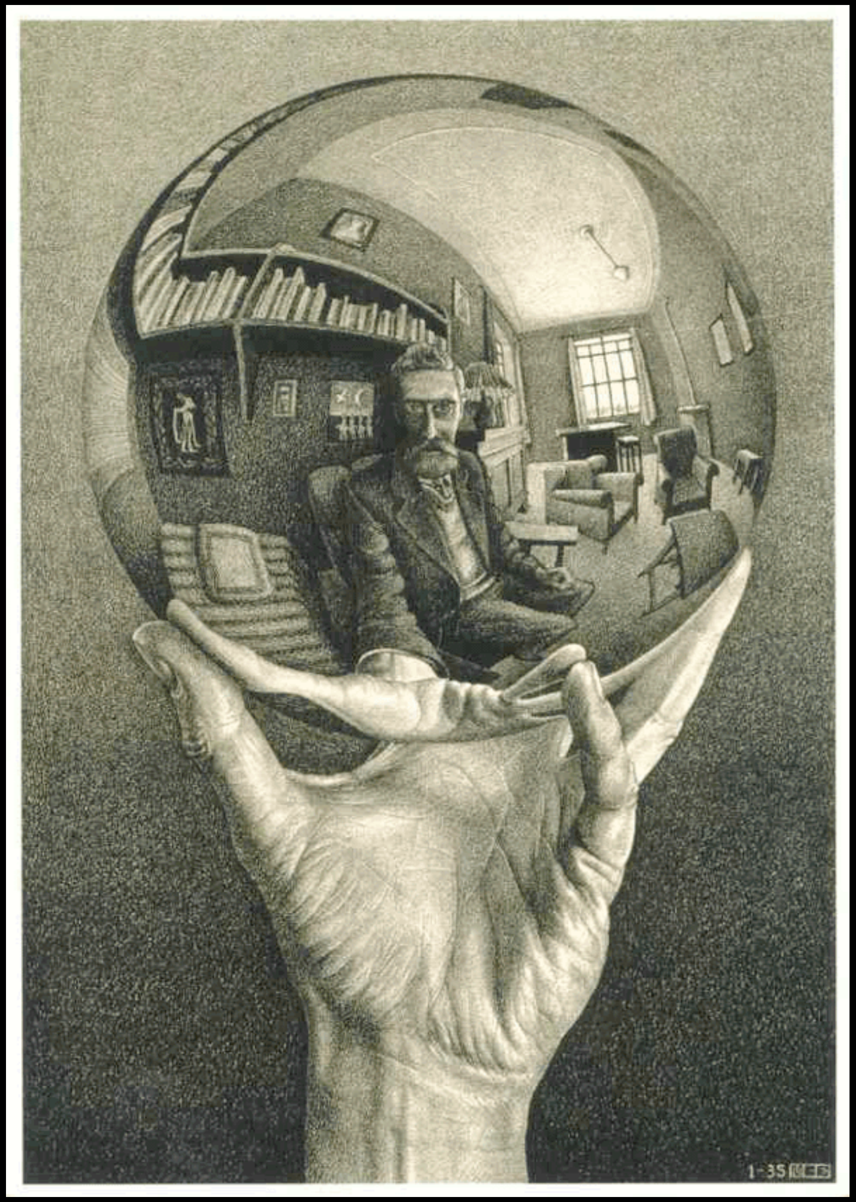

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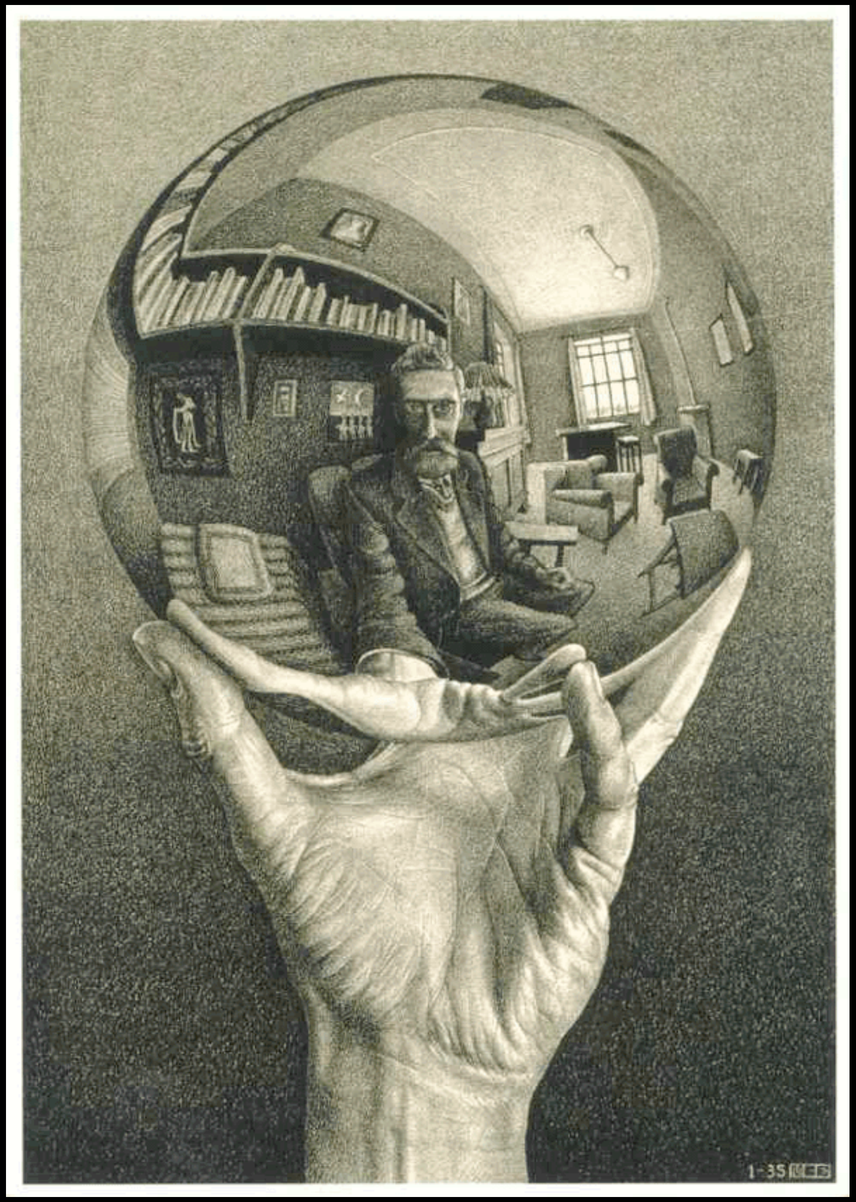

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Caution:

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

— Yogi Berra

Thank you!

And a big thank you to the organizers for a great week!

Image credit: Chateau de Blois

Bonus

Cosmo-varied Couplings

EW Phase Transition?

QCD Phase Transition?

MeV

eV

Baryogenesis?

BBN

CMB

Today

Before BBN, most of what we know about the physics in the early Universe is an extrapolation based on the Standard Model + ingredients such as dark matter.

This gives license for particle theorists to play.

Strong Coupling

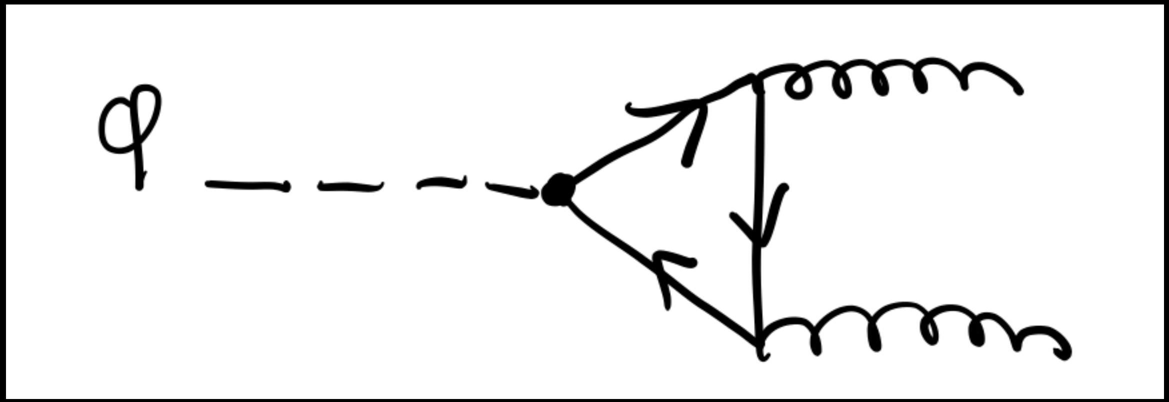
- We introduce dynamics promoting the strong coupling to a dynamical field (denoted by ϕ or S):

Ipek, TMPT PRL

$$-\frac{1}{4}\left(\frac{1}{g_0^2}+\frac{\phi}{M_*}\right)G^{\mu\nu}G_{\mu\nu}$$

$$g_{\text{eff}}^2\left(\langle\phi\rangle\right)=\frac{g_0^2}{1+g_0^2\frac{\langle\phi\rangle}{M_*}}$$

- Φ could be something like a dilation, or a radion in a theory with extra dimensions. It could also have a coupling induced radiatively.



(e.g. via vector-like quarks)

- g_0 is the strong coupling in the absence of a ϕ VEV. It runs just like in ordinary QCD.

Strong Coupling

- At one loop:

$$\frac{1}{\alpha_{\rm eff}} = \frac{1}{\alpha_0} + \frac{33-2n_f}{12\pi}\ln\left(\frac{\mu^2}{\mu_0^2}\right) + 4\pi\frac{\langle\phi\rangle}{M_*}$$

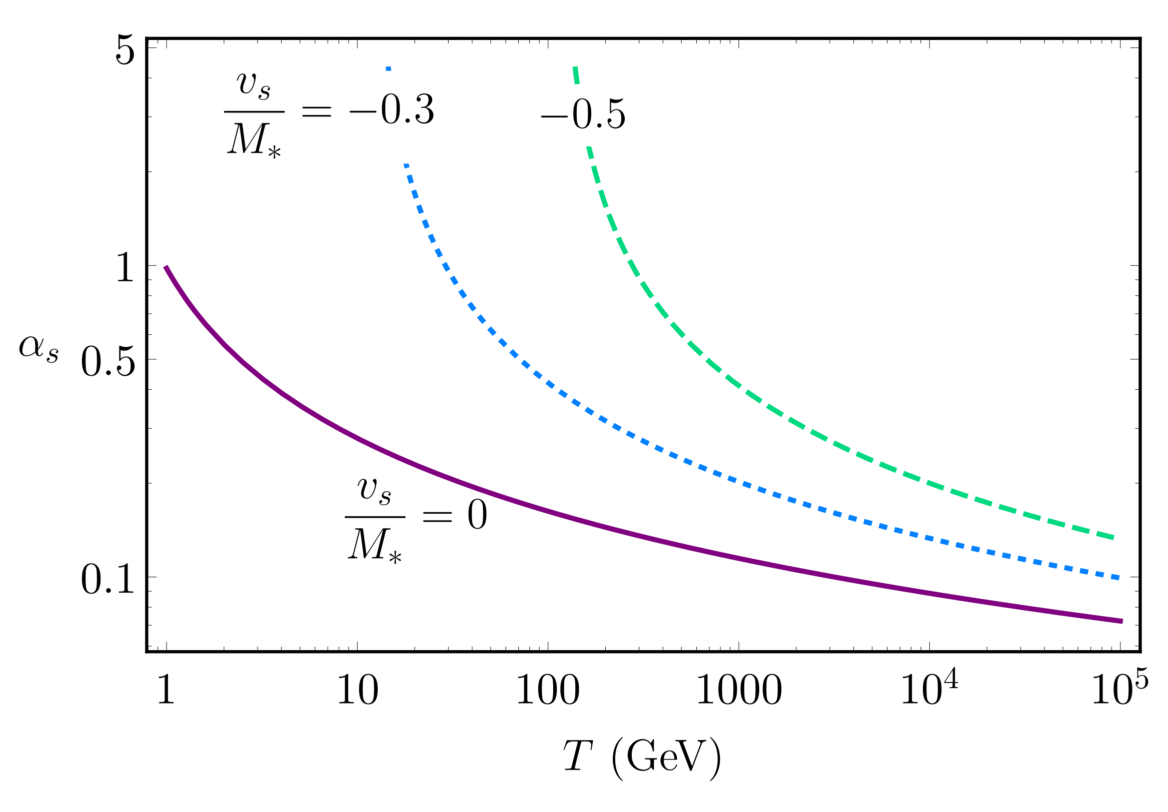
- The scale at which QCD gets strong is about:

$$\Lambda \simeq \Lambda_0 \times {\rm Exp}\left(\frac{24\pi^2}{2n_f-33}\frac{\langle\phi\rangle}{M_*}\right) \equiv \xi\Lambda_0$$

- For $n_f = 6$, to get $\Lambda \sim$ TeV:

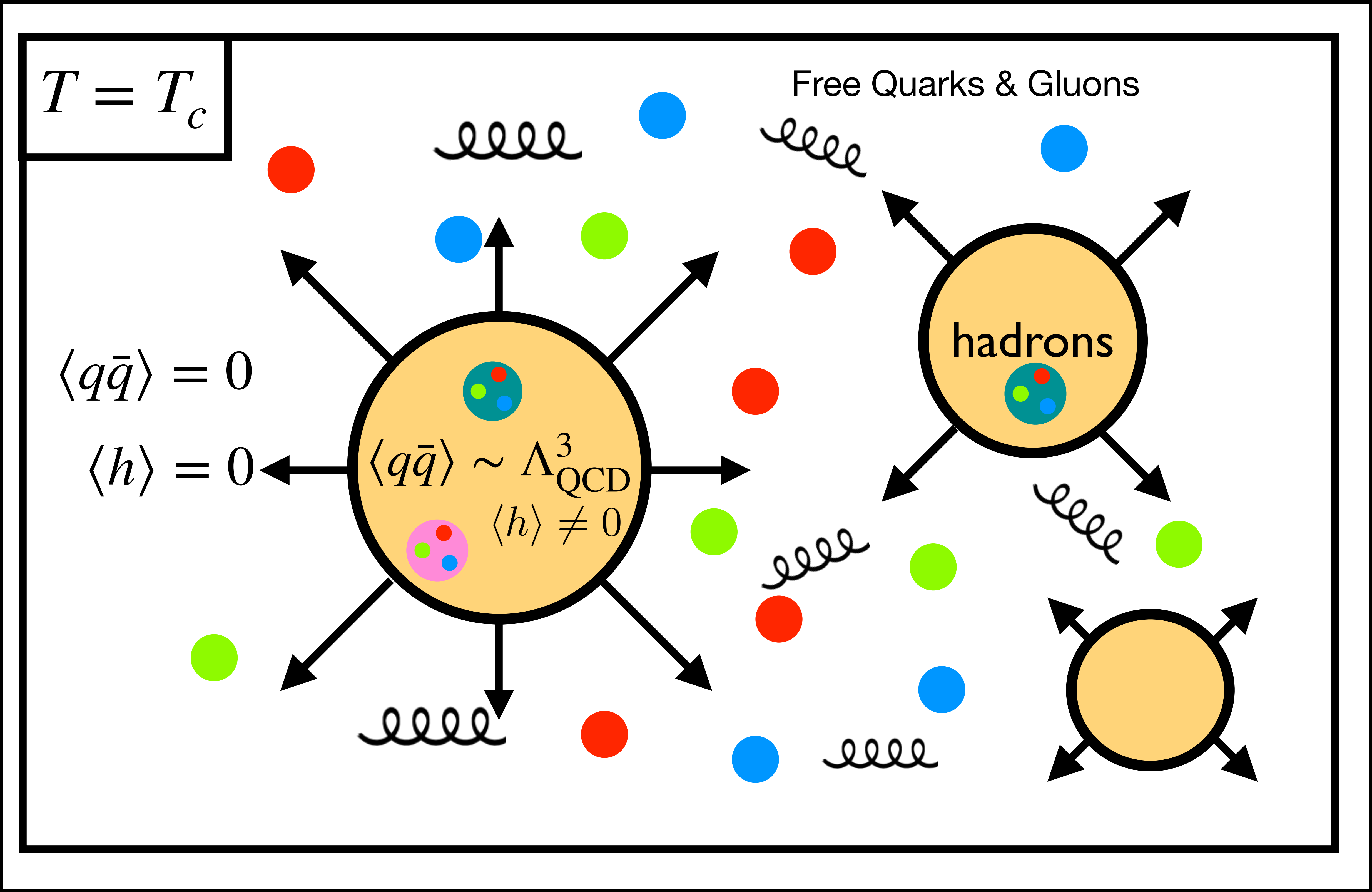
$$\frac{\Delta\langle\phi\rangle}{M_*} \simeq -0.8$$

- This is pushing the EFT, a bit. If induced radiatively, it would require ~10 vector-like quarks at M_*.



2004.06727

QCD Phase Transition

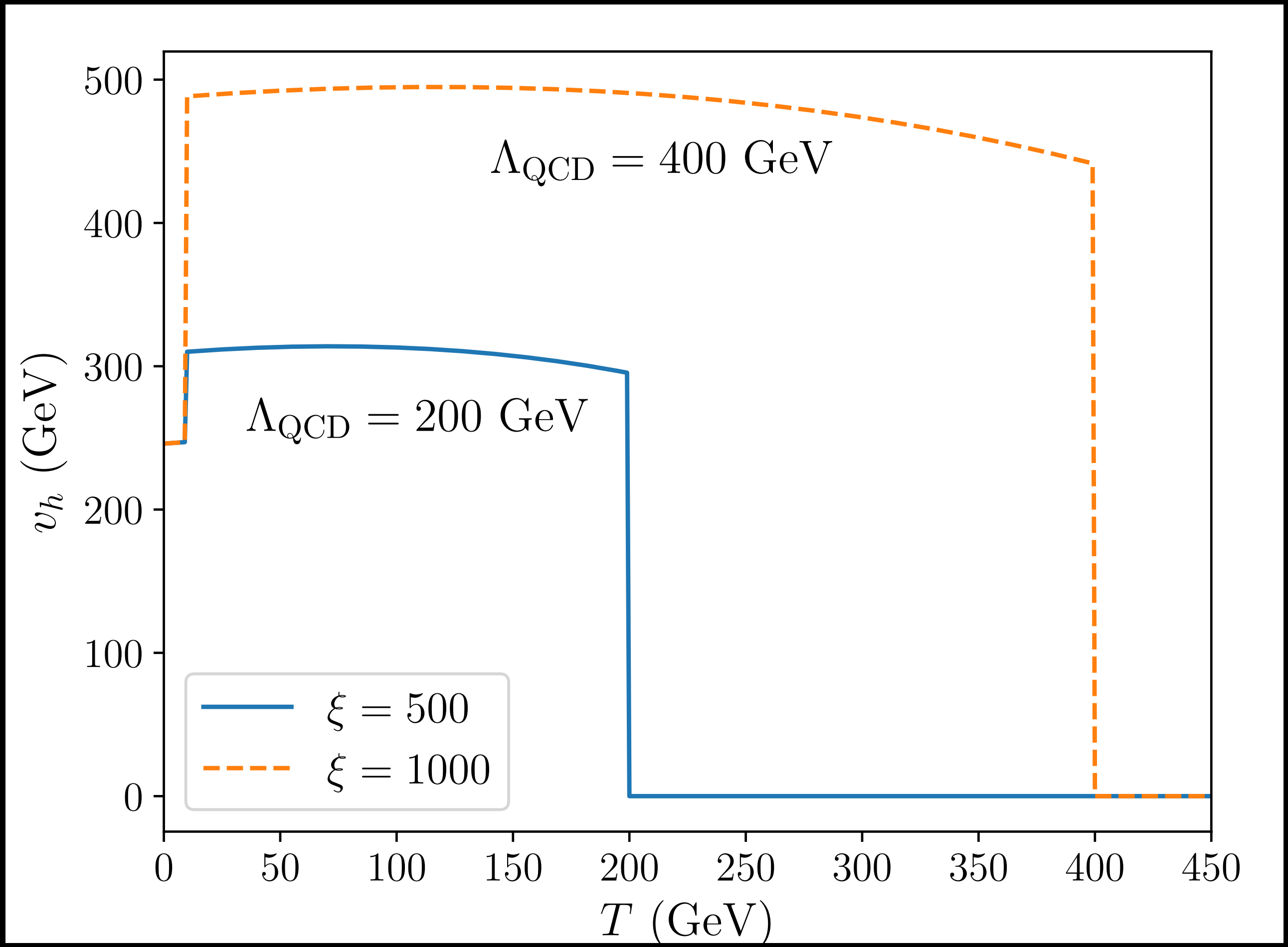


1911.01432

Confined Universe

- In the confined phase, the important active degrees of freedom are the ~35 pNGB mesons.
  - Their properties are described by chiral perturbation theory, with parameters matched to low energy QCD data, and dimensionful quantities scaled up to the high scale confinement scale.

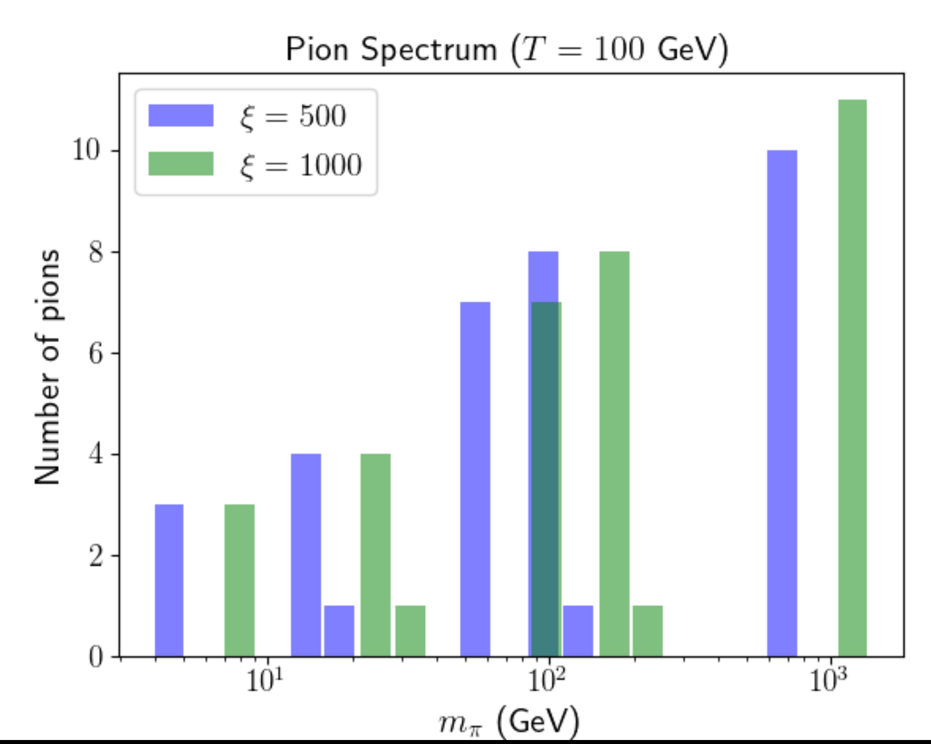
$$\kappa \simeq (220\text{ MeV})^3\,\xi^3\,, \quad f_\pi \simeq 94\text{ MeV}\,\xi, \quad m_\pi^2 \simeq m_{\pi 0}^2\,\xi\,v_h/v_h^0,$$



- The thermal corrections to the Higgs potential are dominated by the top-flavored (or bottom-flavored) mesons rather than top/bottom quarks.

- The chiral condensate acts as a tadpole for the Higgs doublet.

$$\kappa\ \text{tr}(UM_q^\dagger + M_q U^\dagger) \longrightarrow \sqrt{2}\kappa\, y_t\, h - \frac{\kappa}{f_\pi^2}\,\text{tr}[\{T^a, T^b\}M]\,\pi^a\pi^b\,,$$



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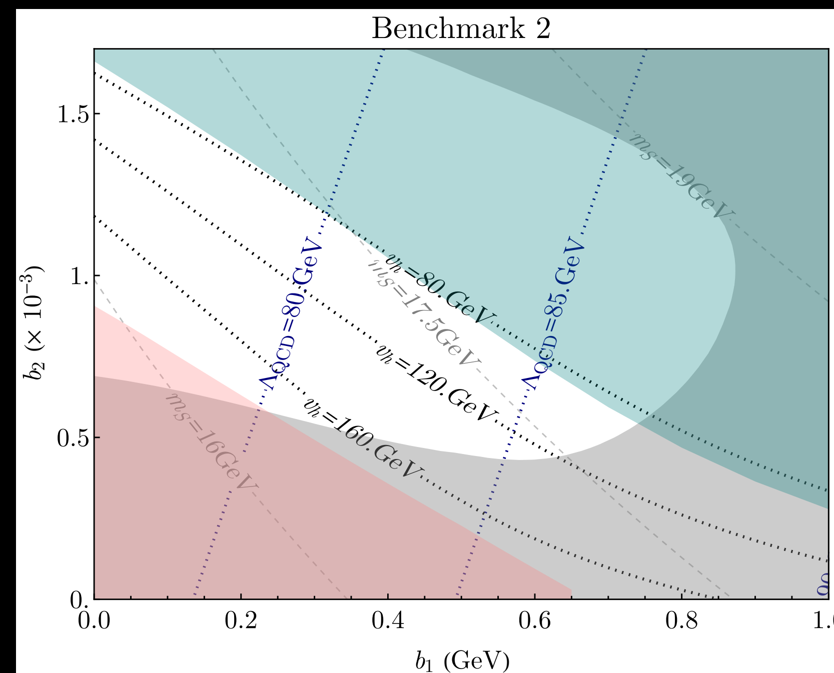
Applications

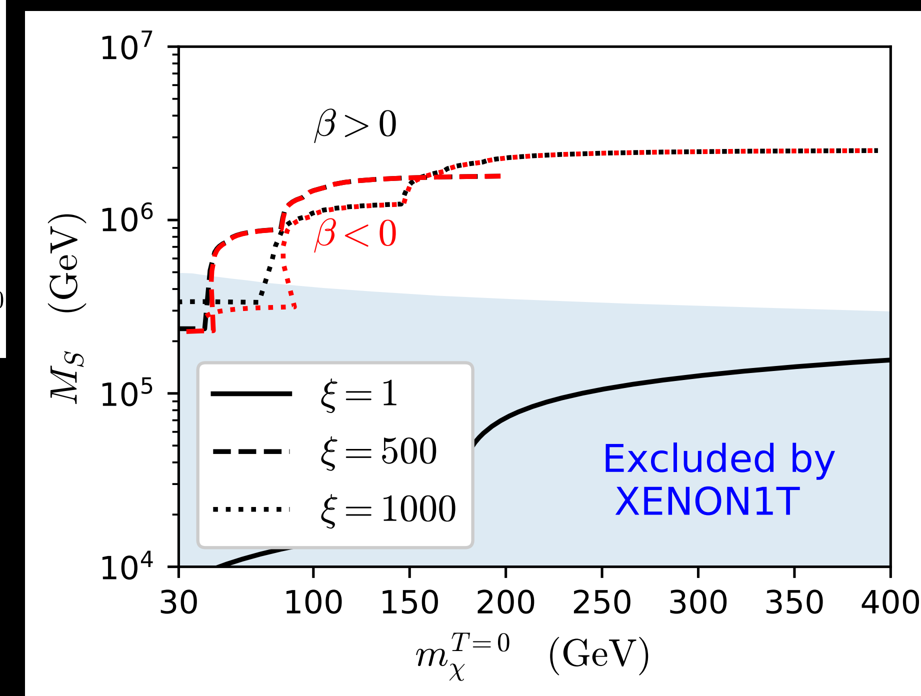
- It turns out such an early period of confinement can be useful!



Croon, Howard, Ipek
TMPT 1911.01432

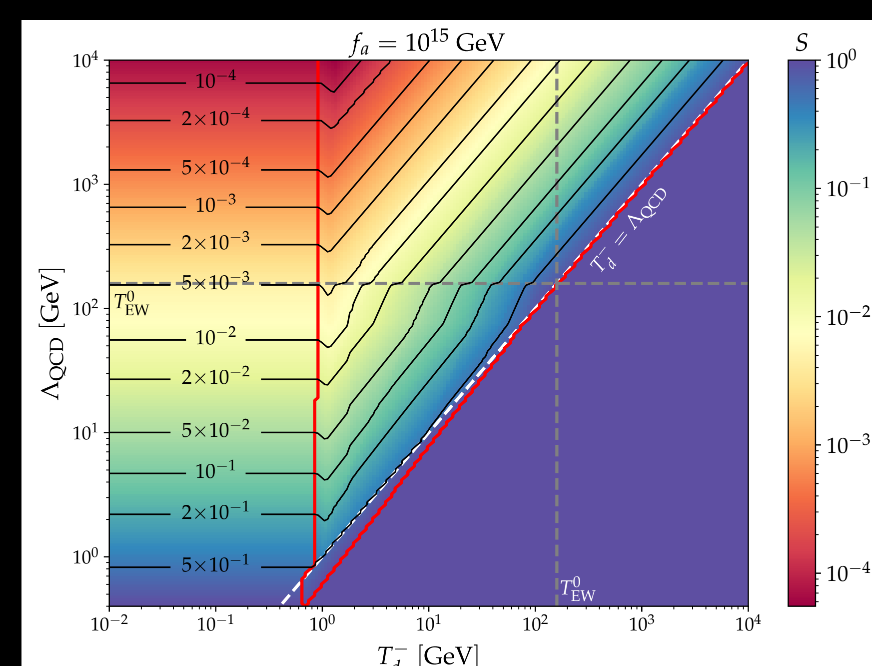
- It can revive spontaneous baryogenesis as an explanation for the baryon asymmetry…

Berger, Ipek, TMPT,
Waterbury 2004.06727



- It can modify dark matter freeze-out…

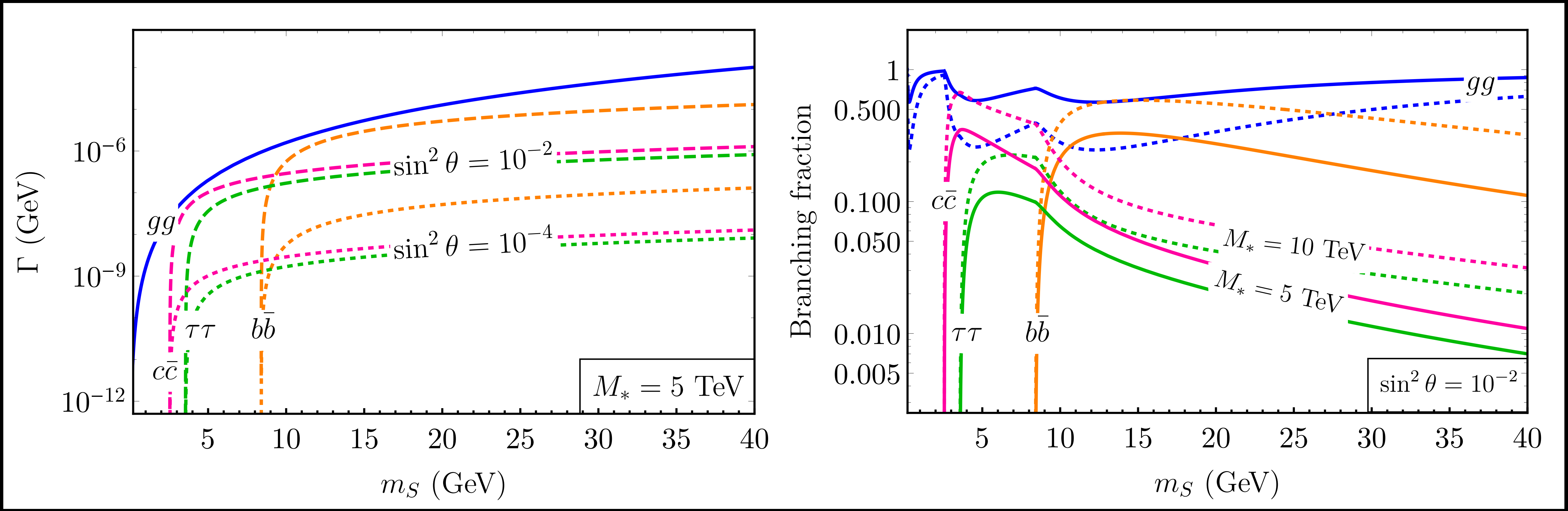
- It can modify axion production…



Heurtier, Huang,
TMPT 2104.13390

Scalar Properties

- The true hallmark of these dynamics is the presence of the singlet scalar field.
  - It couples to gluons through the dimension 5 interaction characterized by scale M_*.
  - It also picks up scaled down Higgs interactions through mixing with the SM Higgs
  - But in this parameter space, the mixing is $\theta < 10^{-3}$ or so. This is too small for the LHC to see a deviation in the SM-like Higgs properties.
  - There could be additional dark decay modes.



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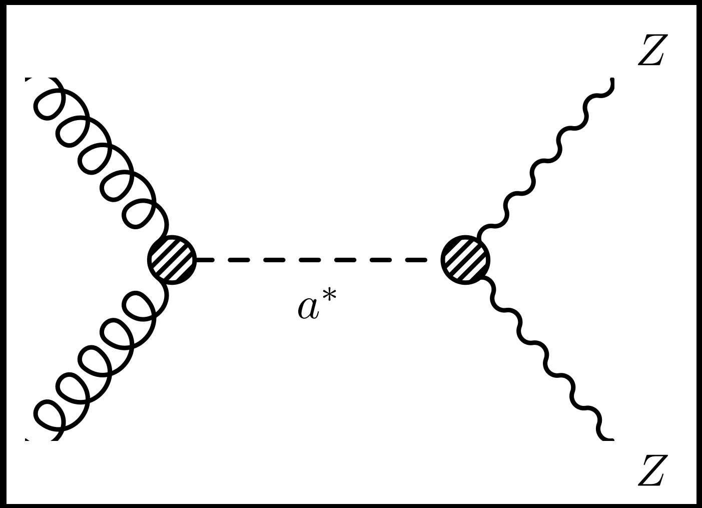
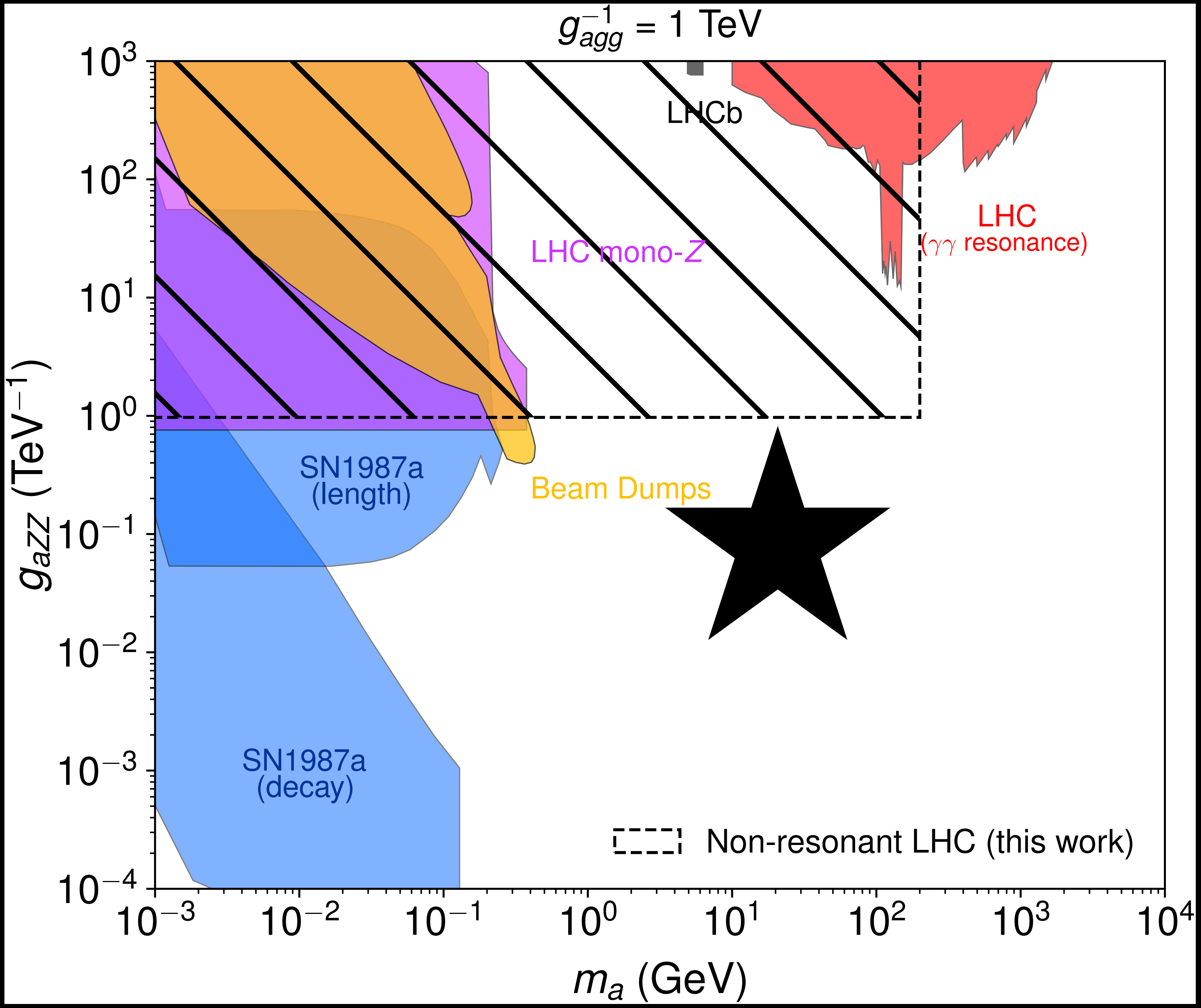
LHC Prospects

The scalar can be produced off-shell at the LHC through gluon fusion.

Usually it decays to dijets, which have large backgrounds.

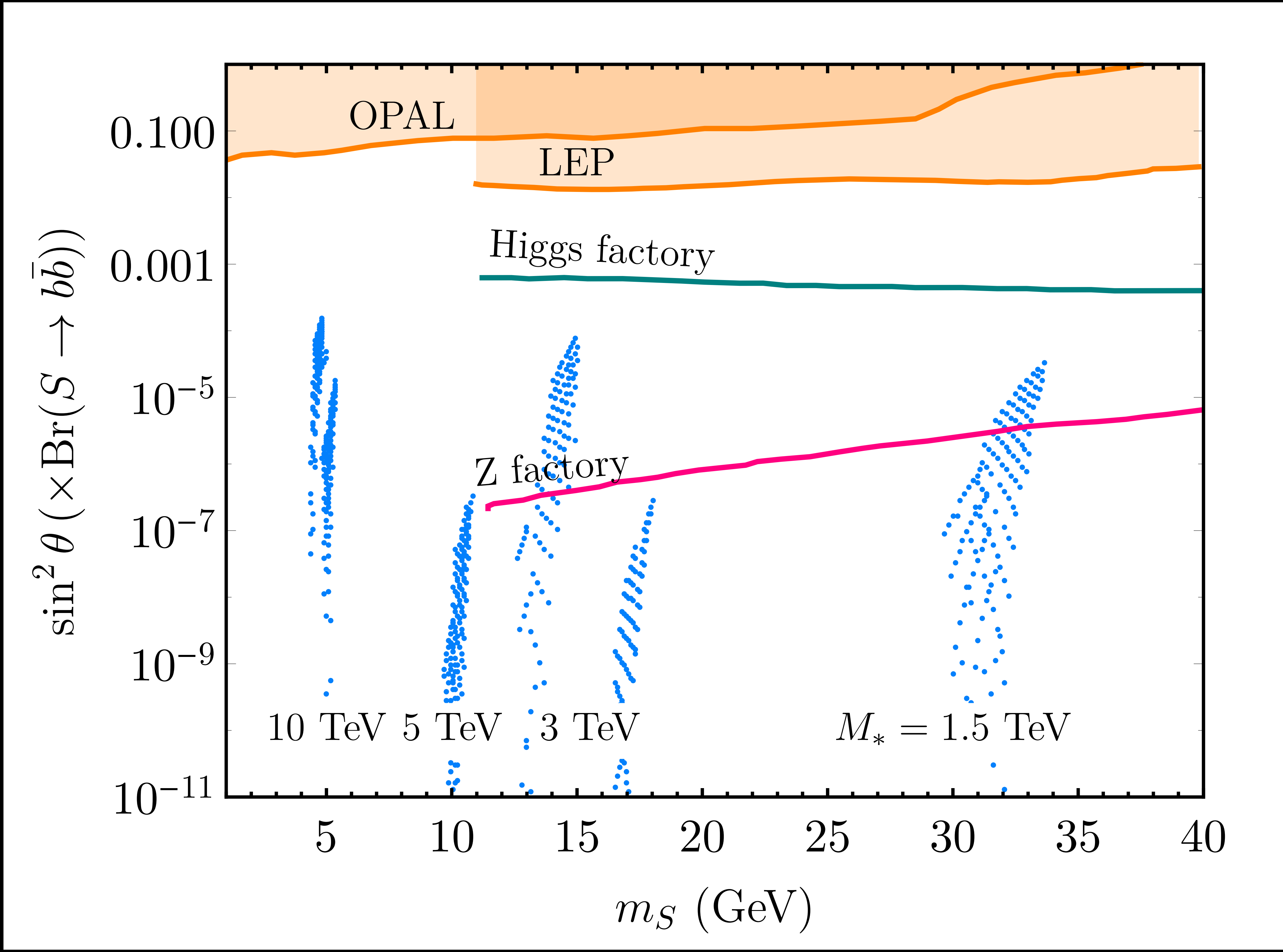
Through mixing with the Higgs, it can also decay into more interesting signatures such as dibosons.





Gavela, No, Sanz, Troconiz 1905.12953

Future Colliders



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