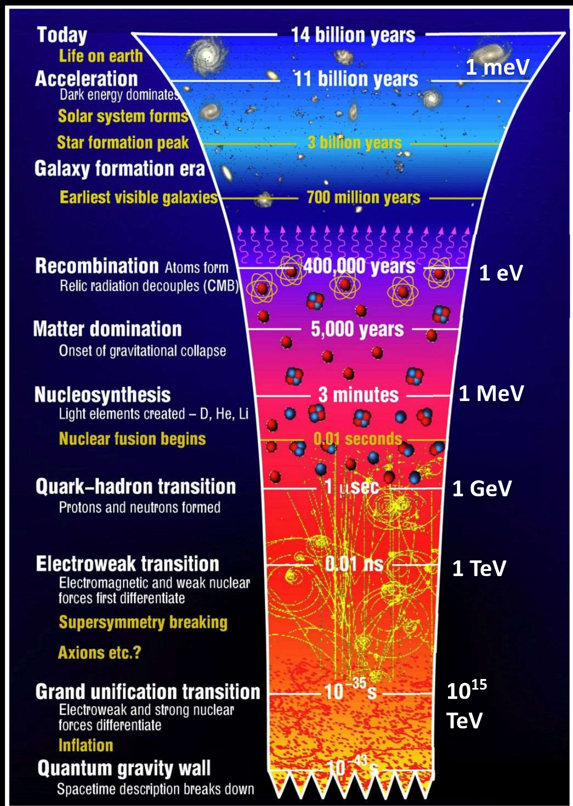
Captions here, please.

Snowmass Cosmic Frontier: Science Highlights

Tim M.P. Tait

University of California, Irvine

EPP: Progress & Promise
November 29, 2022



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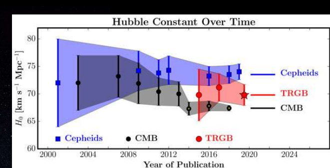
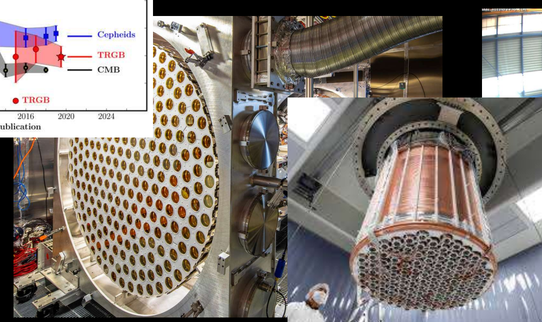
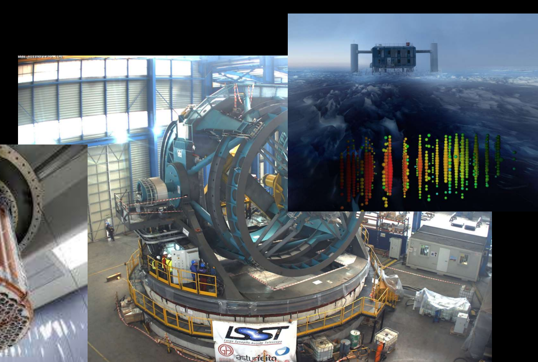
The Cosmic Frontier seeks to understand the fundamental physics that governs the behavior of the Universe and its constituents.



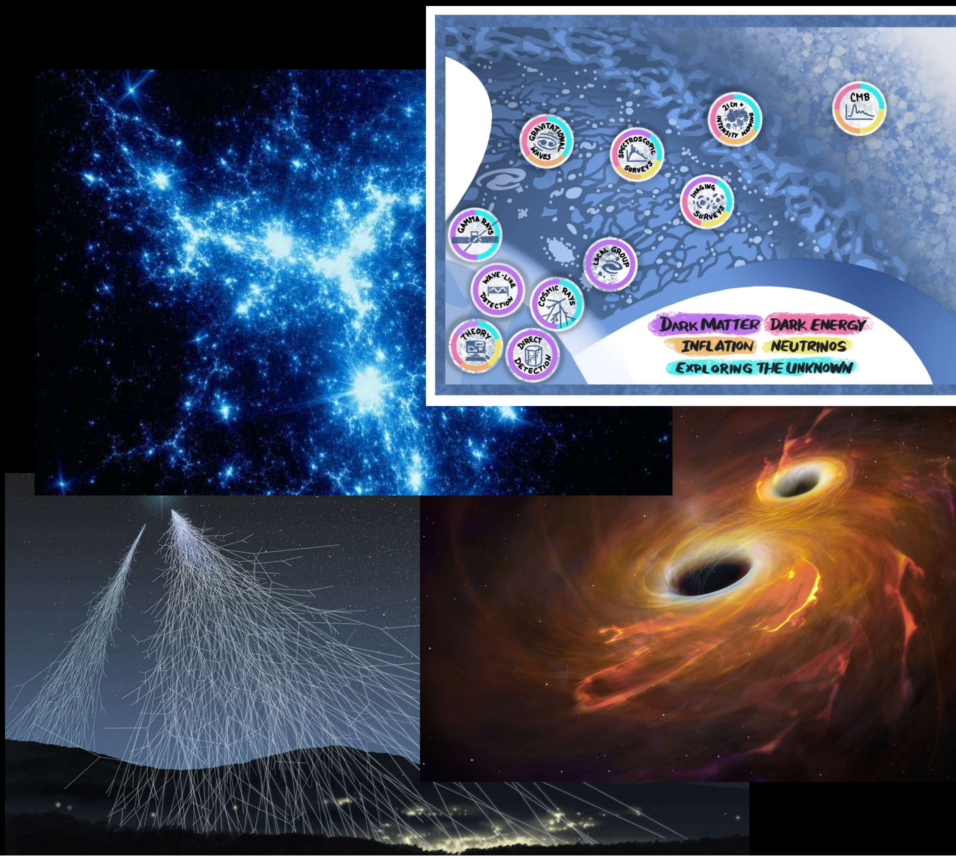




Cosmic Frontier

Captions here, please

- The Cosmic Frontier hosts a wide range of research, spanning new cutting-edge detectors to novel analyses of data that touch on astroparticle physics and astronomy.
- It encompasses the interface between particle physics and cosmology and astrophysics.
- With the exception of neutrino masses, all of the current incontravertible evidence for physics beyond the Standard Model (dark matter, cosmic inflation, dark energy, and the baryon asymmetry of the Universe) are the direct result of Cosmic Frontier research.



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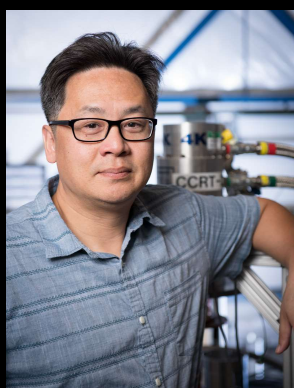
Cosmic Frontier Conveners



Aaron Chou
Fermilab

Marcelle Soares-Santos
University of Michigan

Tim Tait
UC Irvine

Topical Subgroups & Conveners

Captions here, please

Topical Group	Co-conveners				
CF1: Particle DM	Jodi Cooley SMU	Tracy Slatyer MIT	Hugh Lippincott UCSB	Tien-Tien Yu Oregon	
CF2: Wavelike DM	Joerg Jackel Heidelberg	Gray Rybka UW	Lindley Winslow MIT		
CF3: DM Astro Probes	Alex Drlica-Wagner Fermilab	Chanda Prescod-Weinstein UNH	Haibo Yu UC Riverside		
CF4: DE & CA The Modern Universe	James Annis Fermilab	Jeff Newman Pittsburgh	Anze Slosar BNL		
CF5: DE & CA Cosmic Dawn & Before	Clarence Chang ANL	Laura Newburgh Yale	Deirdre Shoemaker Georgia Tech		
CF6: Dark Energy Complimentarity	Vivian Miranda Stony Brook	Brenna Flaugher Fermilab	David Schlegel LBNL		
CF7: Cosmic Probes	Rana Adhikari Caltech	Luis Anchordoqui CUNY	Ke Fang UW Madison	B.S. Sathyaprakash Penn State	Kirsten Tollefson MSU

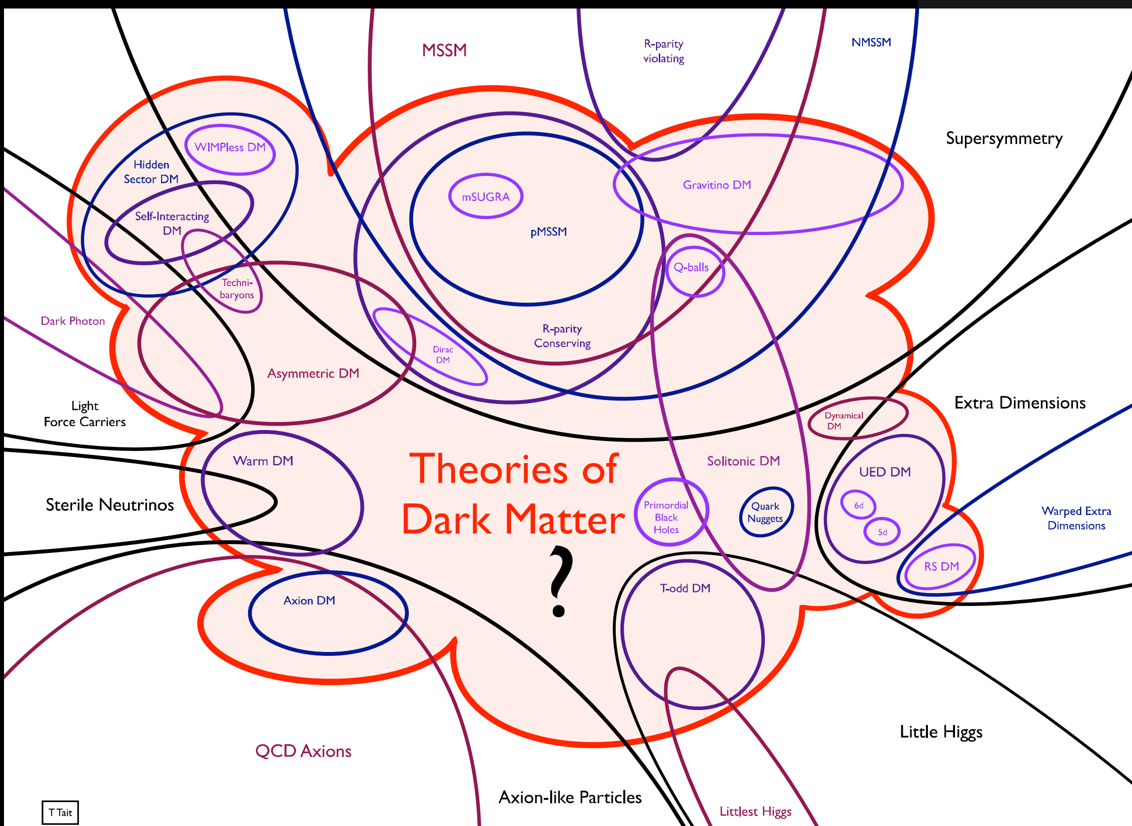
Big Questions

Captions here, please

- What is the fundamental nature of the dark matter? How does it fit in with the Standard Model and what would we learn by detecting it ?
  - Does it manifest as individual quanta (CF1)…or as collective waves (CF2) ?
  - Can we further refine our understand of its properties based on cosmic observations (CF3) ?
- What is the nature of dark energy and cosmic acceleration (CF4 & CF5) ?
  - Is the dark energy dynamical? What is the physics of cosmic inflation? Are there other cosmological transitions whose existence we can infer ?
  - Can we constrain or discover ultra-weakly interacting or super-heavy components of the Universe ?
  - How can we use our existing and planned facilities to extract information that is more than the sum of the individual parts (CF6) ?
- How can we use cosmic probes to learn about fundamental physics (CF7) ?

Dark Matter

Captions here, please



The space of dark matter models encompasses a dizzying array of possibilities, representing many orders of mass and couplings.

Snowmass 2013 organized the space of possibilities in terms of particle physics models, many of which have common features.

Dark Matter

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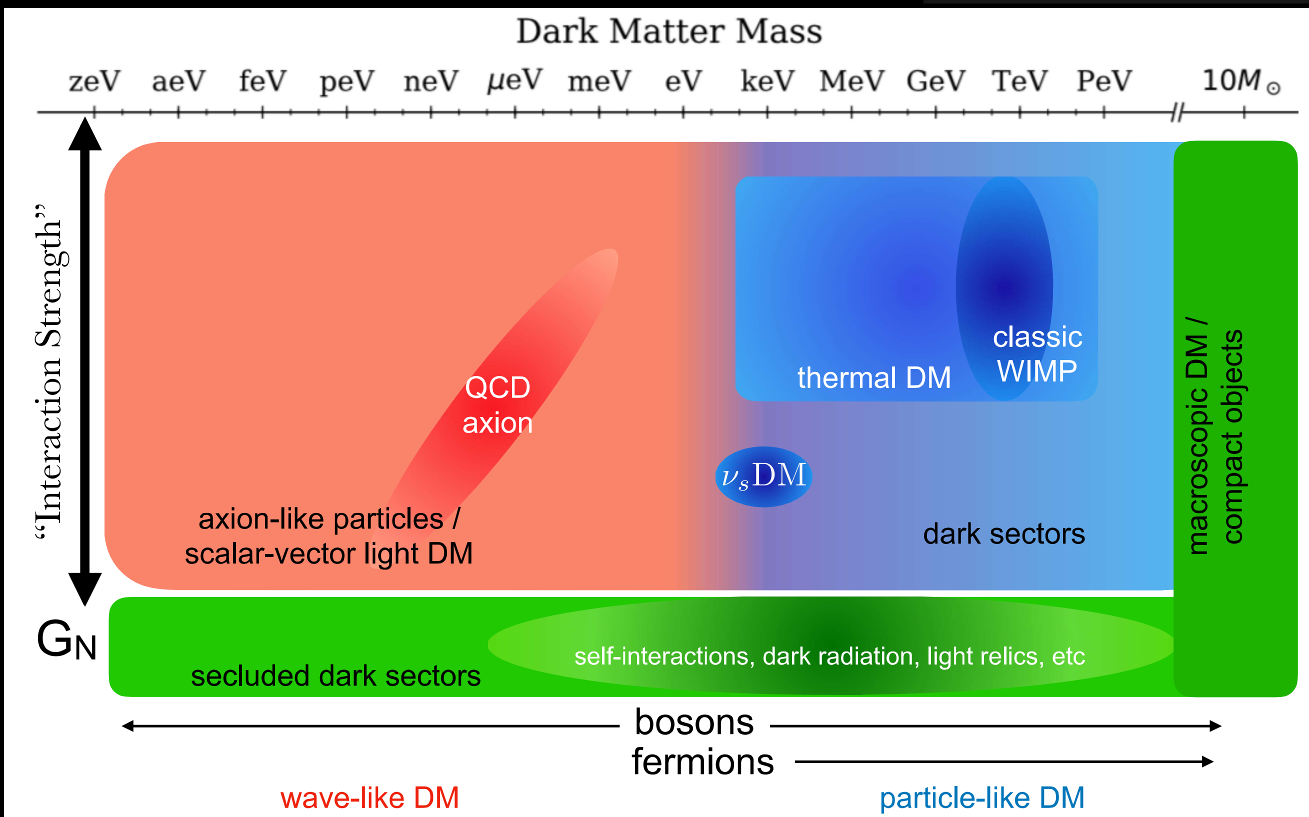

Since Snowmass 2013, there has been something of a reorganization of the way we think about models of dark matter, to classify them more based on their common shared predictions for phenomena.

This 'cartoon' encapsulates a broad brush parameter space of DM mass versus coupling to the Standard Model.

Dark Matter

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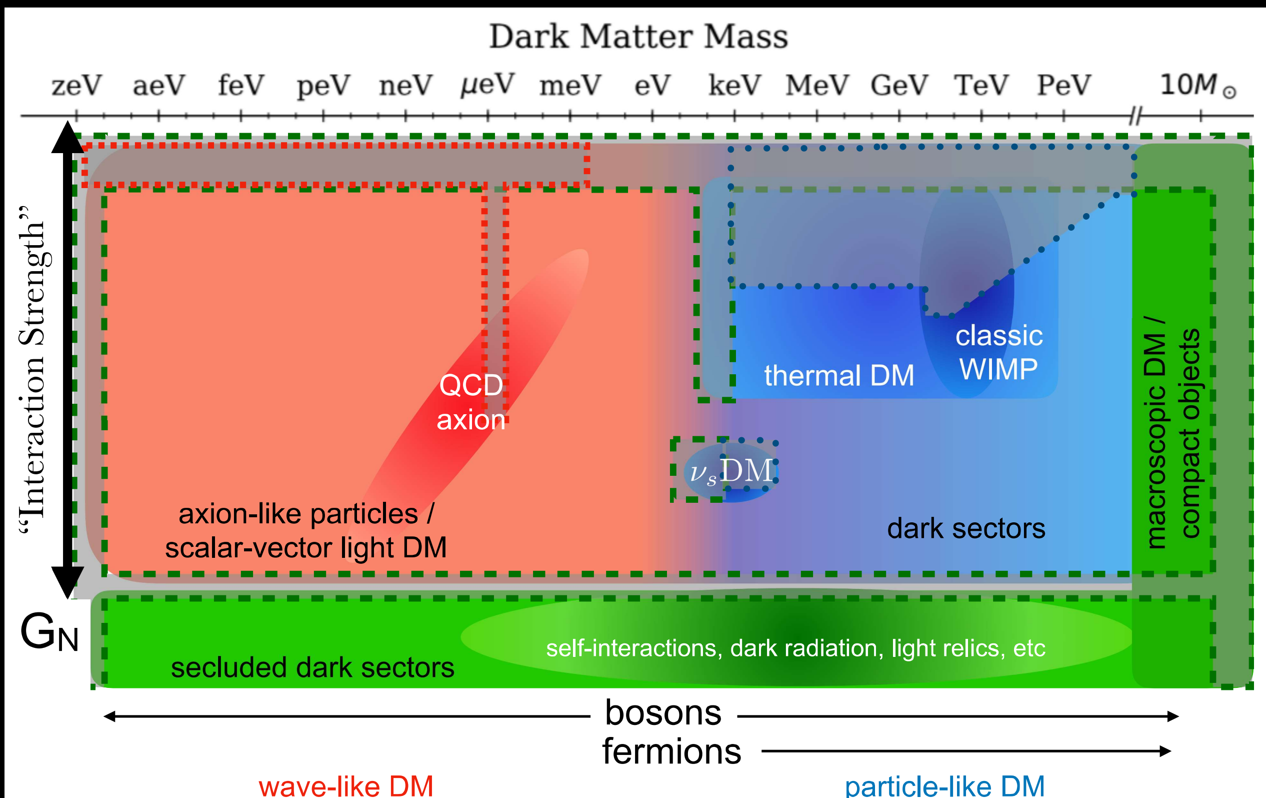

The current situation has seen excellent exploration of some of the best-motivated candidates, including portions of parameter space corresponding to WIMPs, sterile neutrinos, and QCD axions.

Interesting parameter space in these well-defined models remains unexplored, and there are also vast unexplored regions.

Dark Matter

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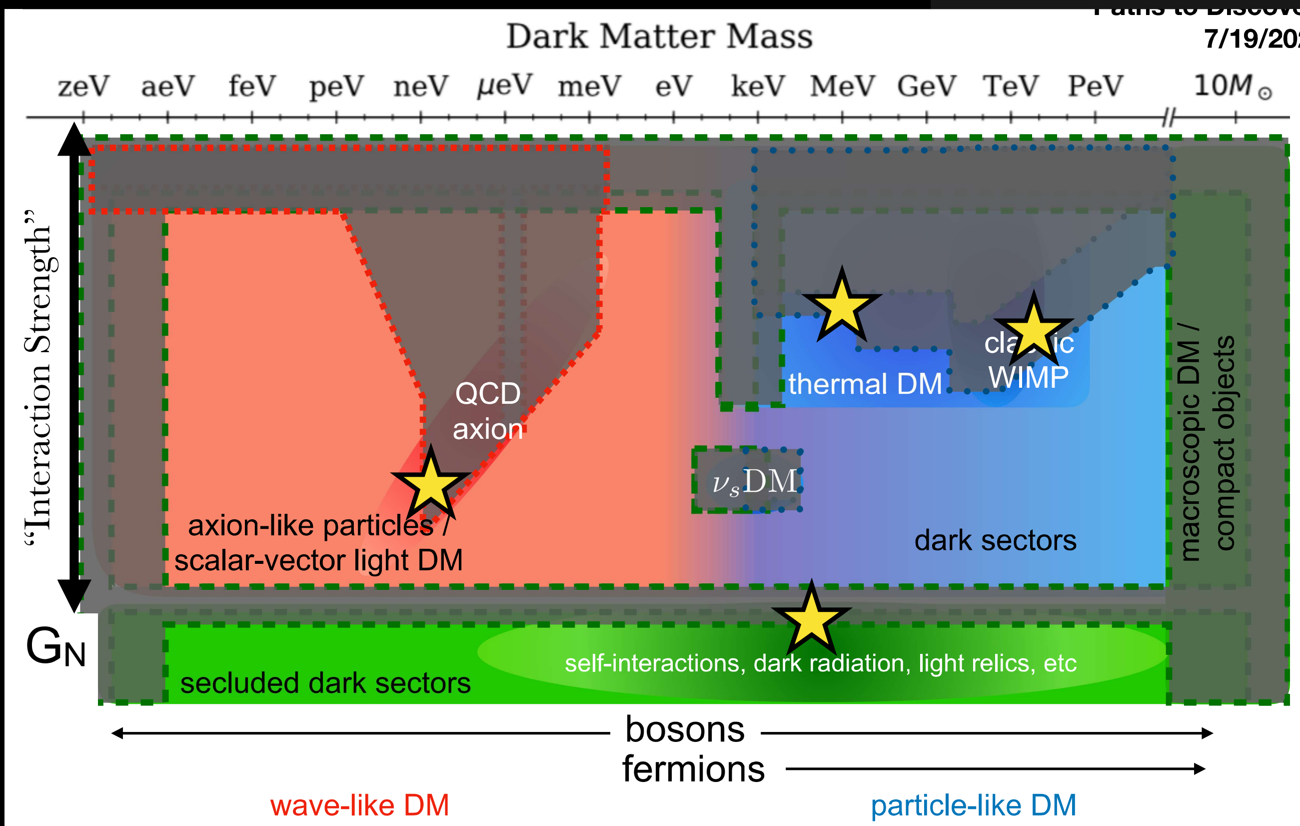

And we have a plan!

'Delve Deep, Search Wide' employs a range of direct searches for WIMPs interacting with targets on Earth, indirect searches for annihilation products, and cosmic probes based on structure, to scrutinize priority targets such as WIMPs and QCD axions, while broadly scanning parameter space, leaving no stone unturned.

Dark Matter

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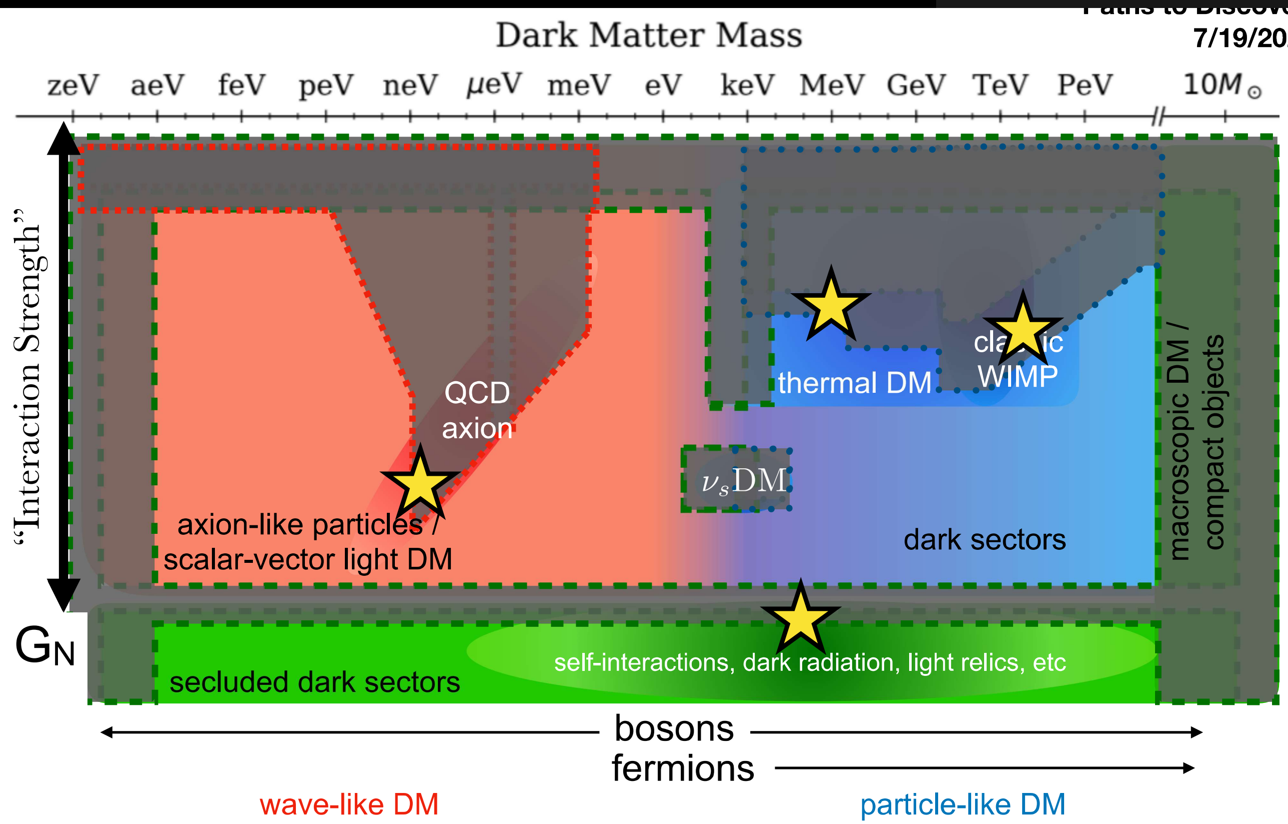


The next 10 years, including future Generation 3 direct searches for WIMPs and axions, combined with future indirect observatories, a program of smaller scale experiments, and key inputs from cosmic probes, results in broad coverage.

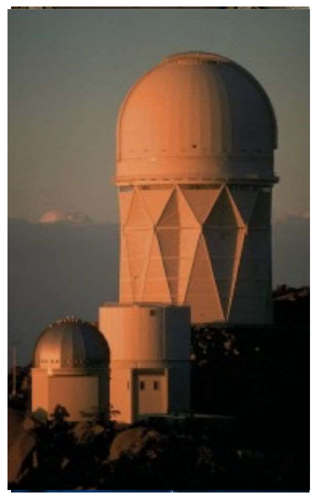
...or transformational discoveries!

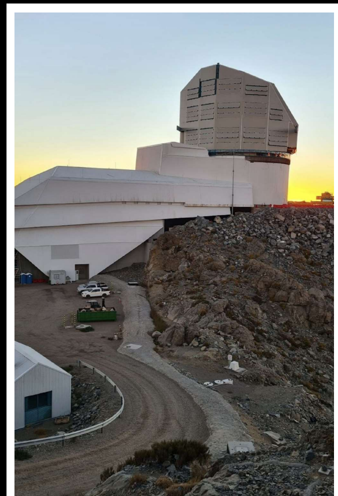
Cosmological Probes

Captions here, please

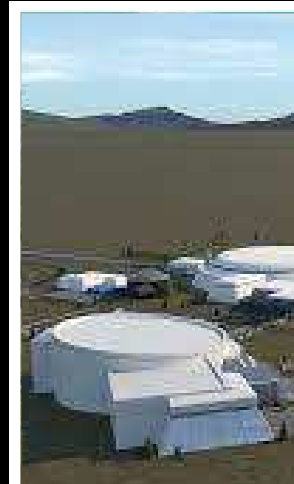
Thanks to investments recommended by the previous P5, we are on the threshold of a dramatic expansion of available cosmological data, able to inform the deepest mysteries of fundamental physics.

Cosmic Expansion History
Cosmic Microwave Background
Growth of Structure
Gravitational Waves


DESI

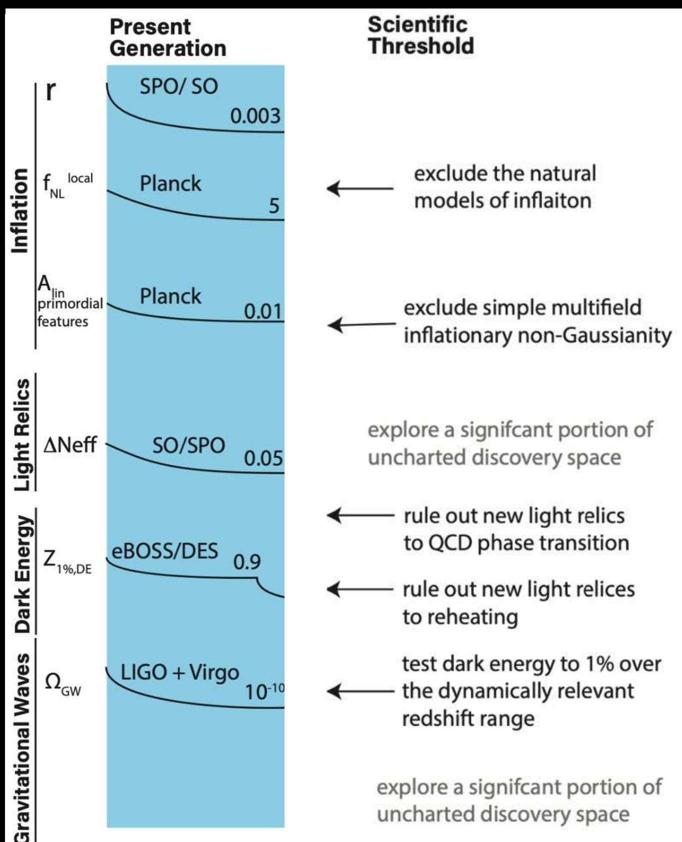

LSST


CMB-S4


Cosmic Explorer

Cosmological Probes

Captions here, please



Current observations have revealed key properties of the Universe and its fundamental constituents. But there is still much left to learn.

Cosmological Probes

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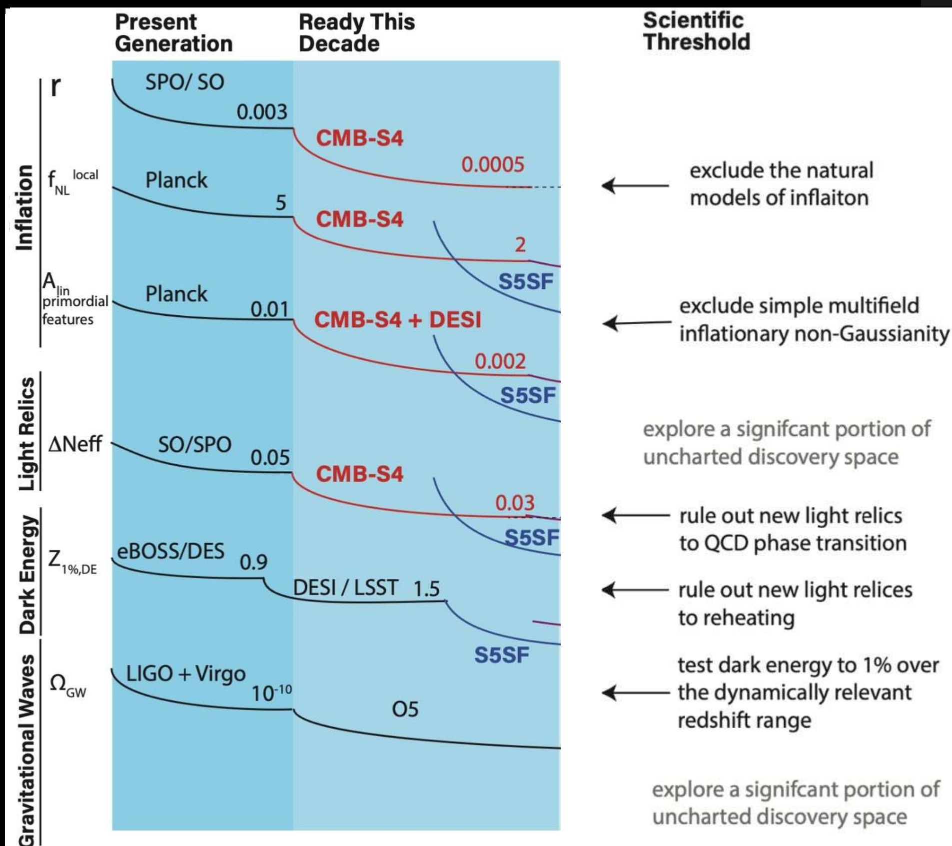


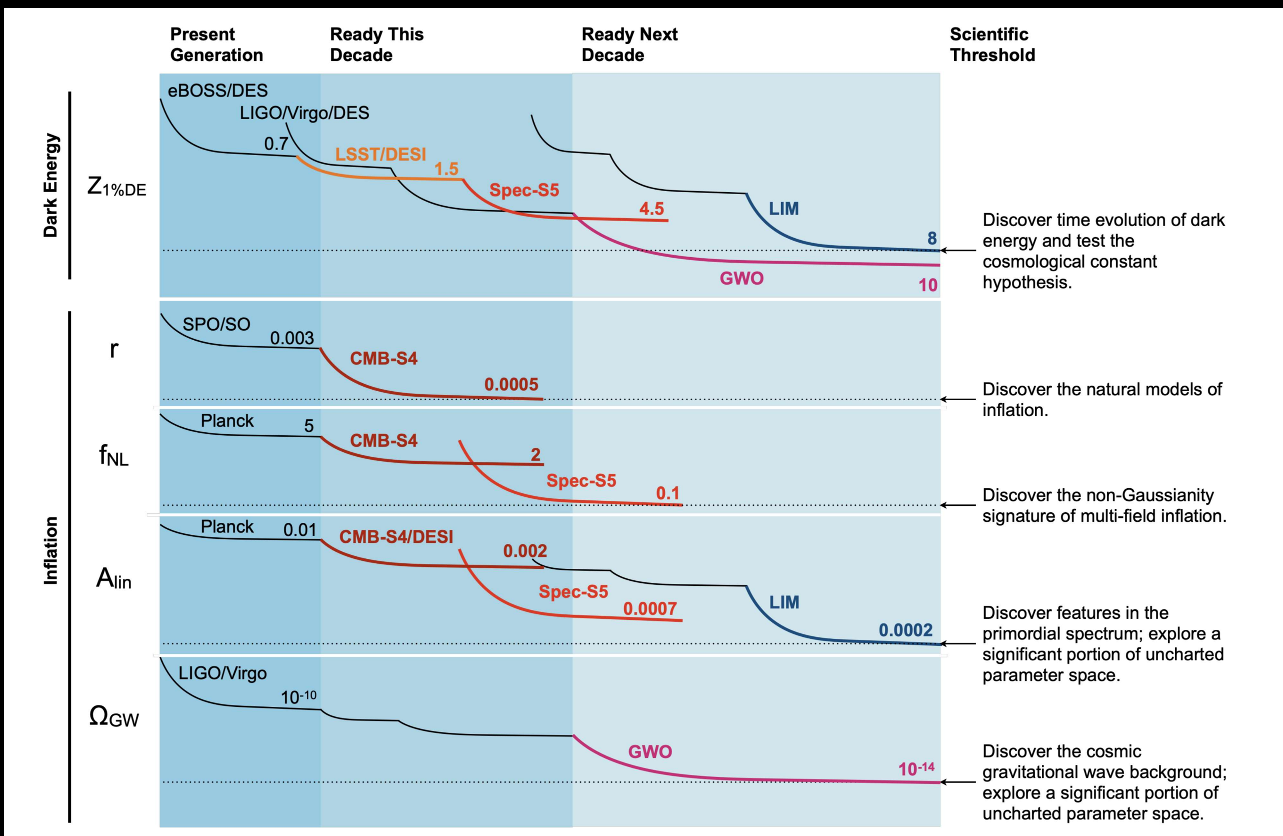
'Search Wide, Aim High'

The near term future will be collecting the data from DESI, completing and executing Rubin/LSST, and constructing CMB-S4, currently on track with CD0.

This program will make unparalleled progress toward understanding the dynamics of cosmic inflation and search for new physics.

Cosmological Probes

Captions here, please

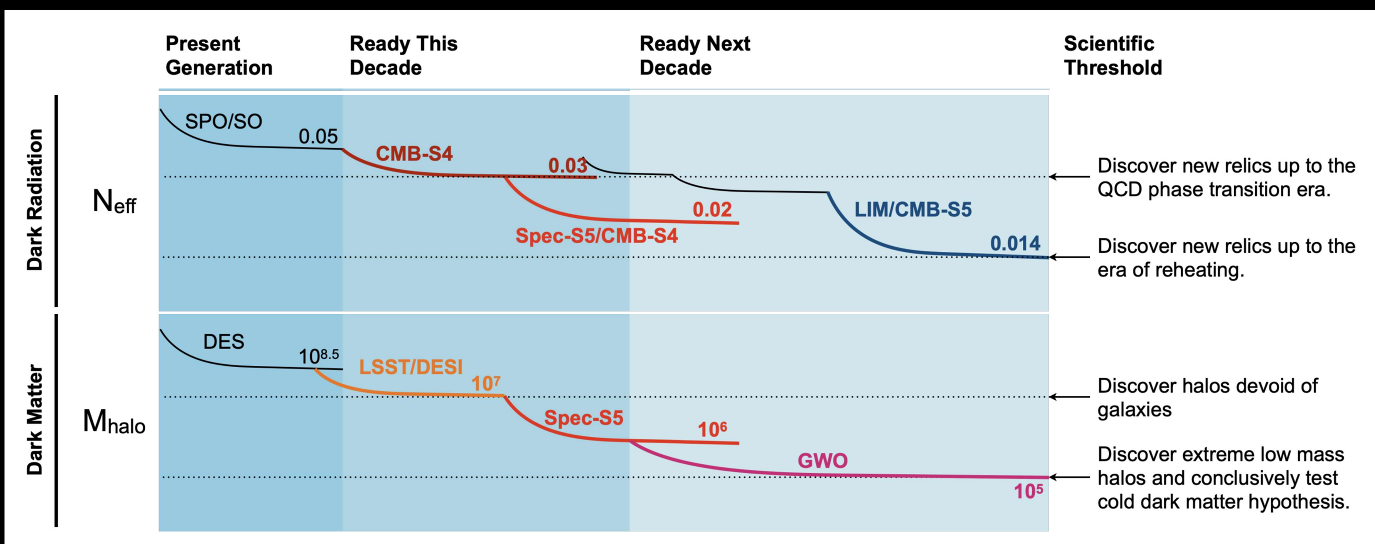


Longer term priorities are the roadmap to a future **Stage V Spectroscopic Facility**, and small projects and pathfinders toward new opportunities such as gravitational waves, 21cm, and Line-Intensity Mapping.

They offer unparalleled views on dark energy and inflation.

Cosmological Probes

Captions here, please



This program also offers unique opportunities to search for new physics and to understand the physics of the dark sector.

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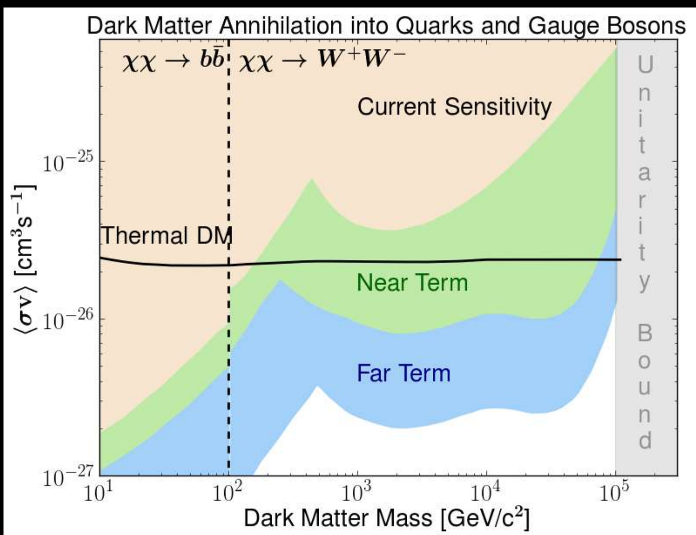
2014 P5 Science Drivers

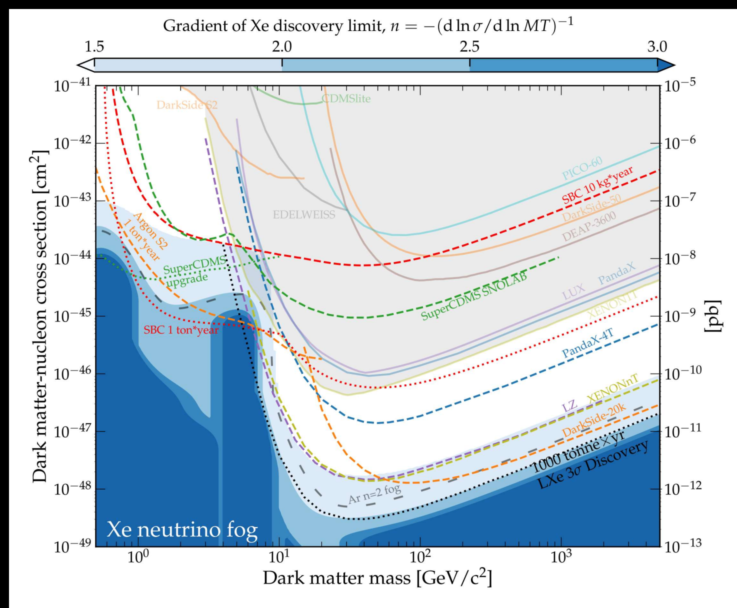
Identify the new physics of dark matter.

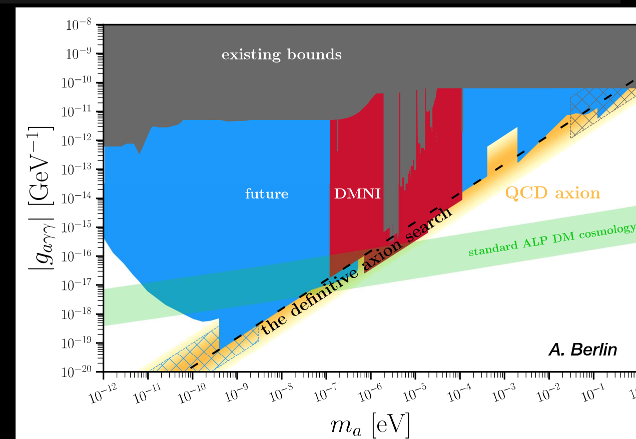
Captions here, please

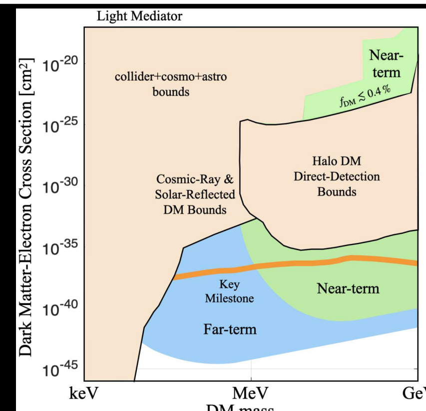


The Cosmic Frontier is *required* to verify that any candidate new physics we discover is *actually* making up the dark matter we see.

Delve deep, search wide!







Identify the new physics of dark matter.

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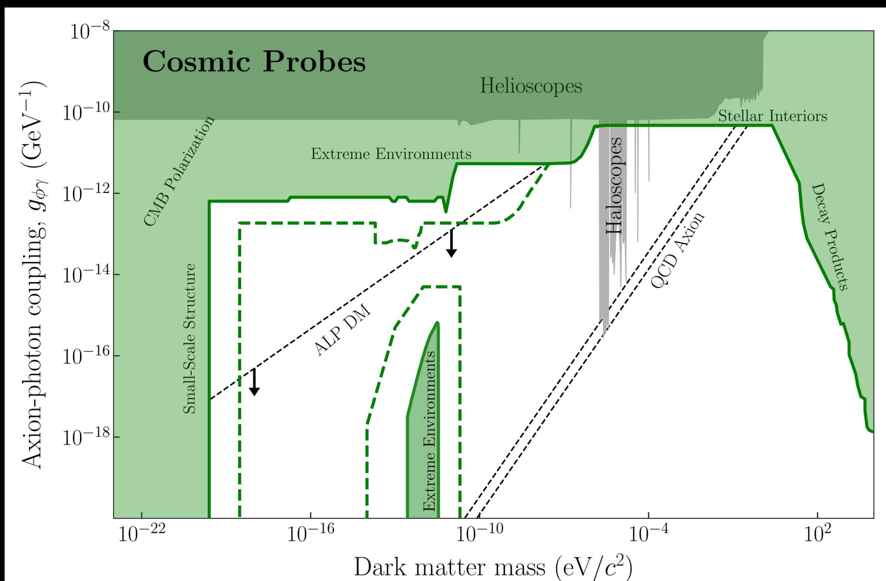
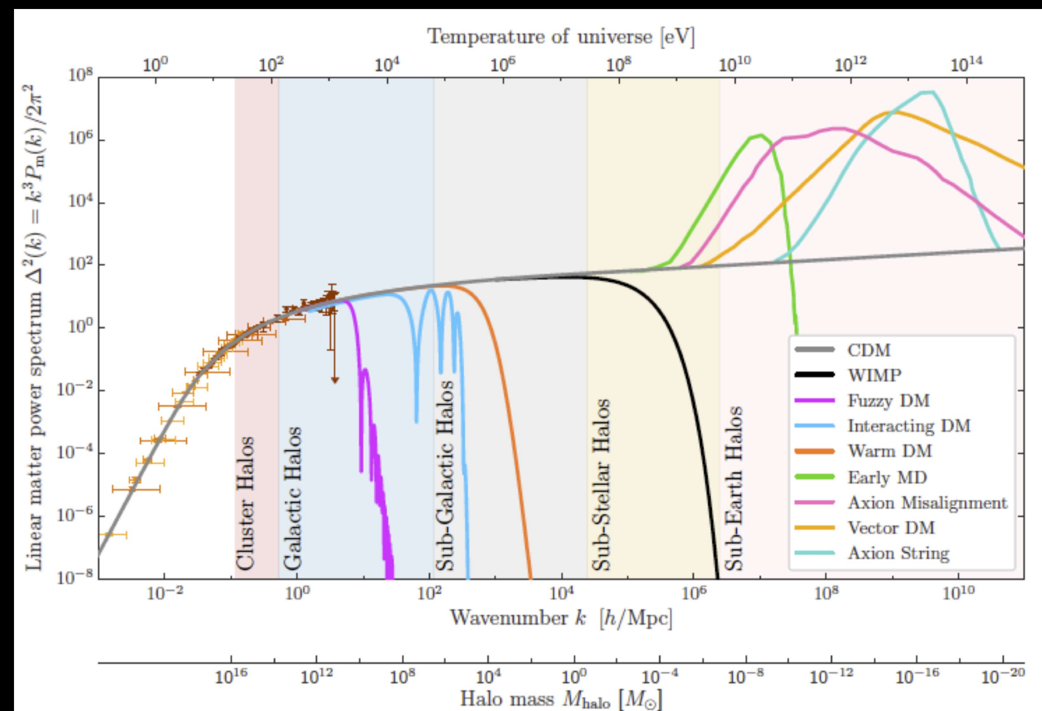
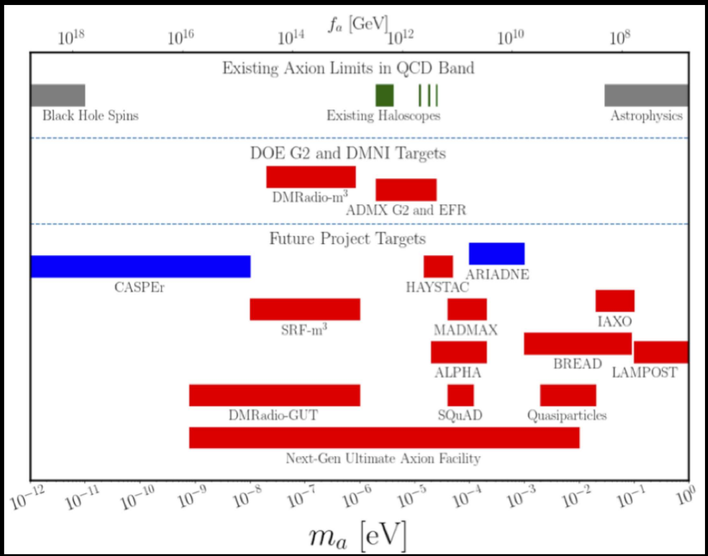


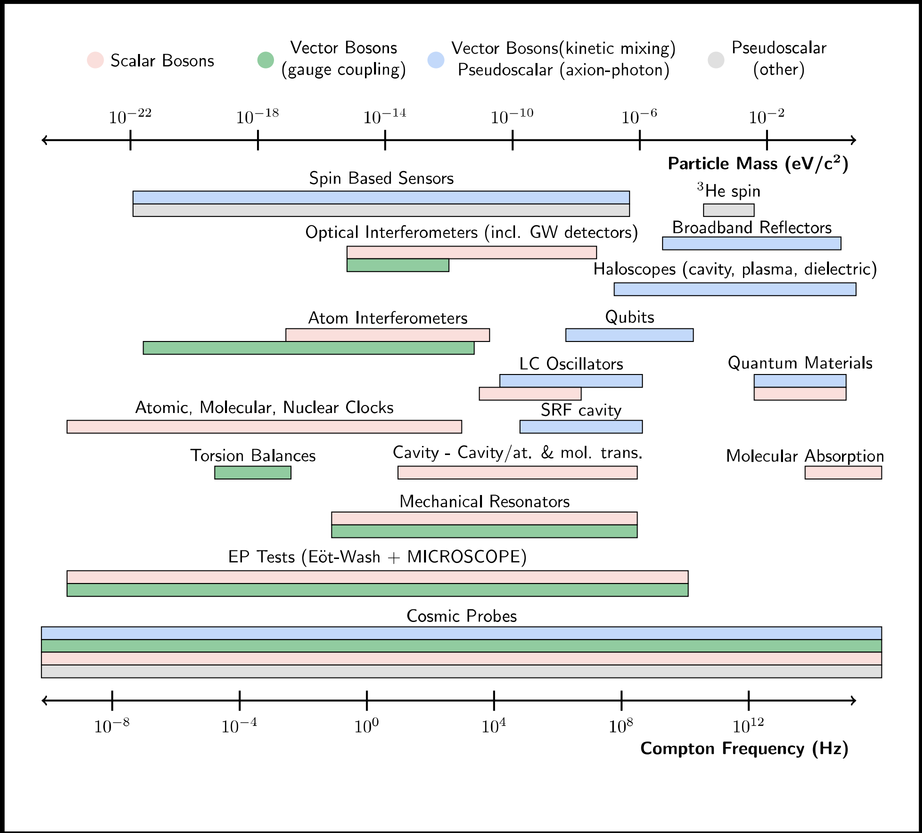


At the lightest allowed masses, ultralight bosonic dark matter is expected to manifest coherently as waves. The smallest scales of structure provide important tests of its mass and production mechanism.

Identify the new physics of dark matter.

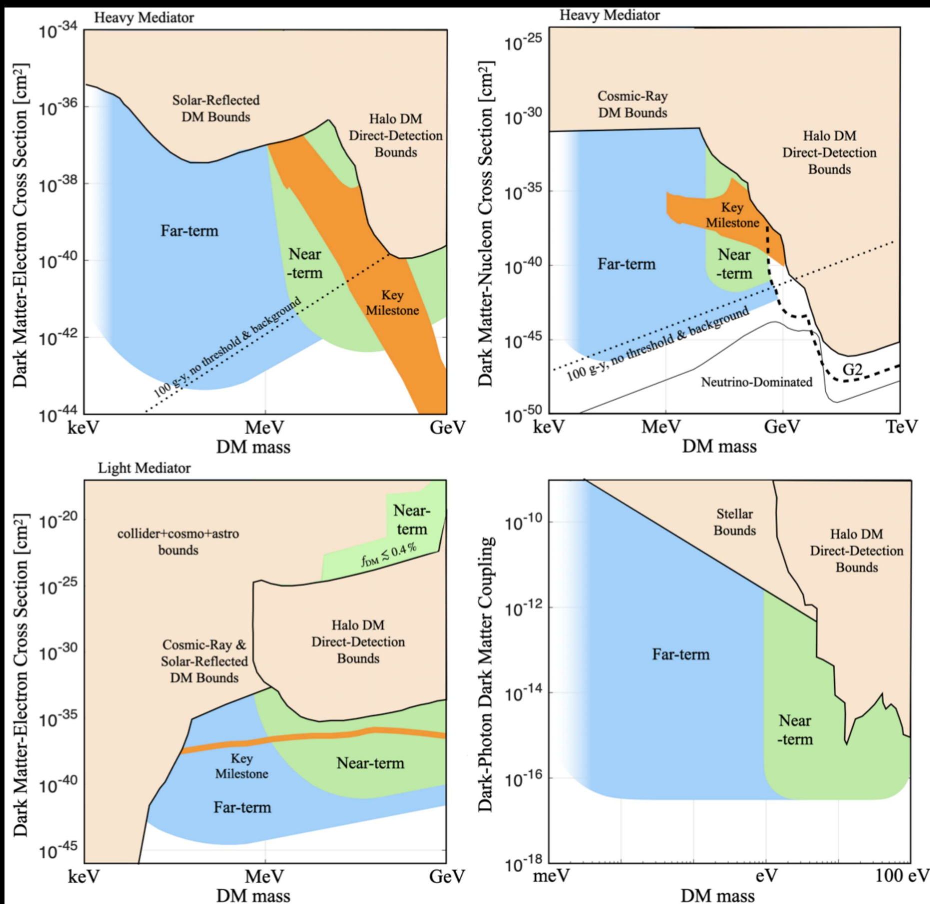
Captions here, please





A variety of experiment can search for waves of dark matter. The QCD axion provides an important target, via both its coupling to photons and to gluons.

Identify the new physics of dark matter.



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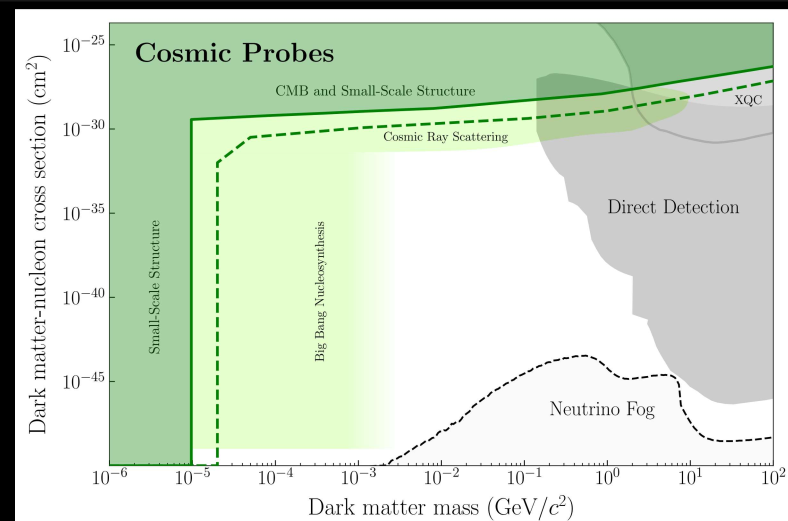
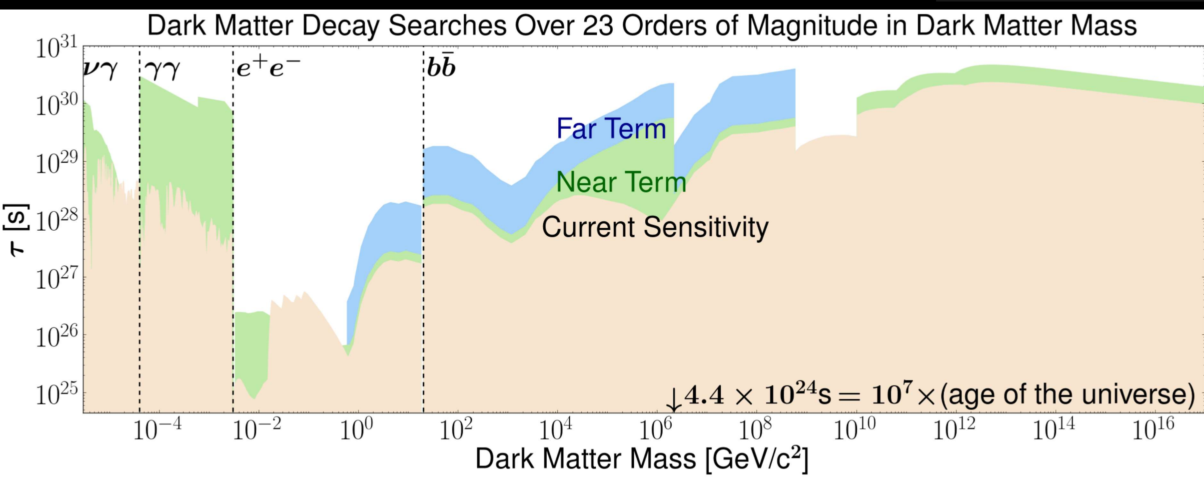


Light particle dark matter (up to ~ GeV) is challenging to detect because of its limited energy deposition. Electron scattering and scattering off of collective excitations are key.

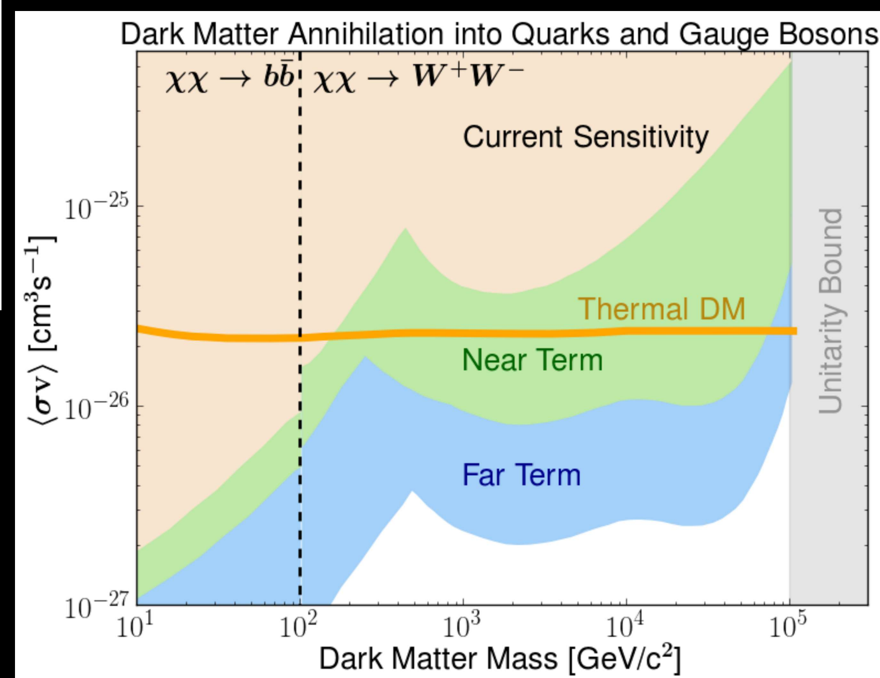
Identify the new physics of dark matter.

Captions here, please



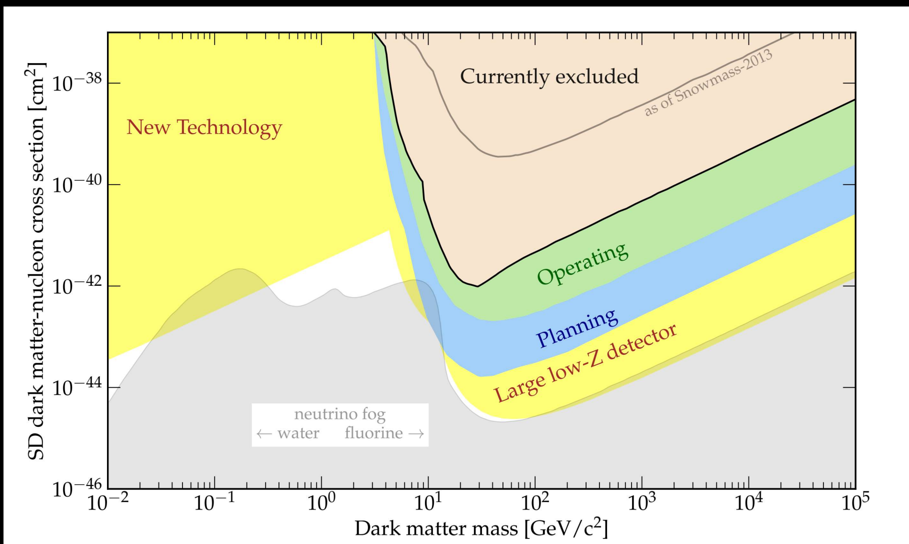
Annihilation into heavy particles results in key probes of the WIMP paradigm.

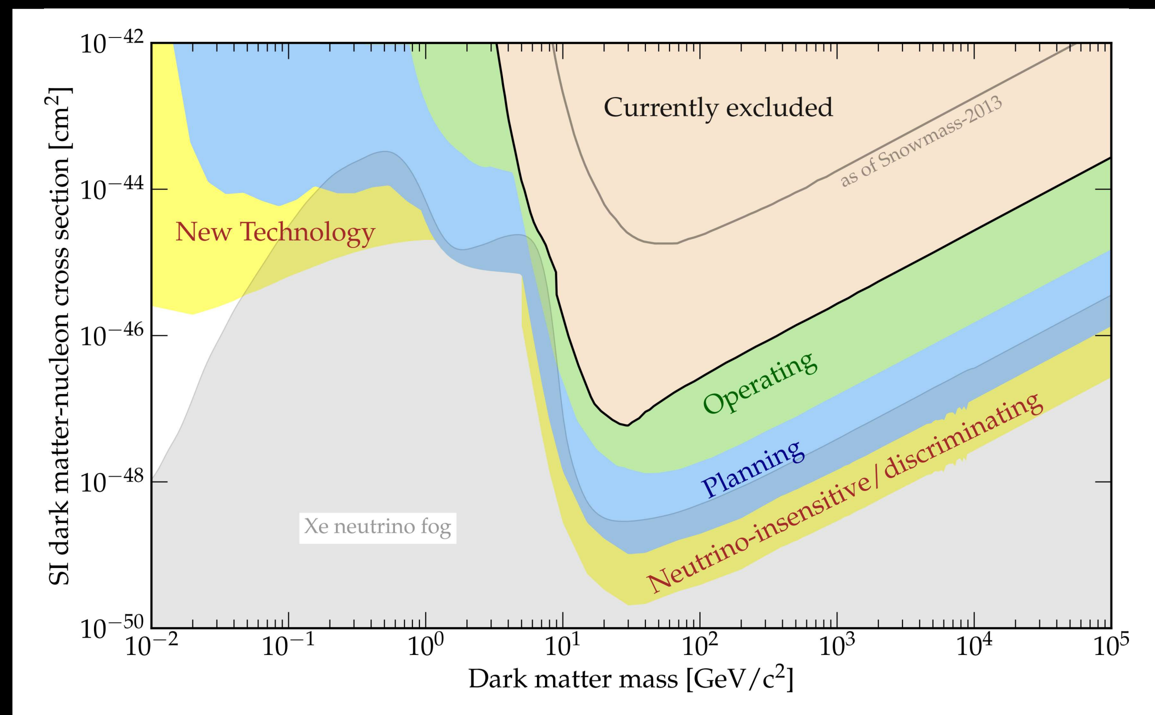
Indirect searches for dark matter decay products constrain the lifetime of the dark matter over a wide range of masses.



Identify the new physics of dark matter.

Captions here, please





Direct searches for WIMPs have made incredible strides over the past two decades, and are now approaching the `neutrino fog'.

Identify the new physics of dark matter.

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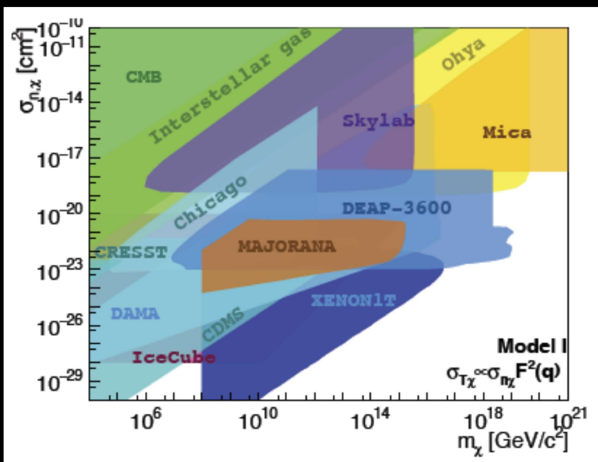
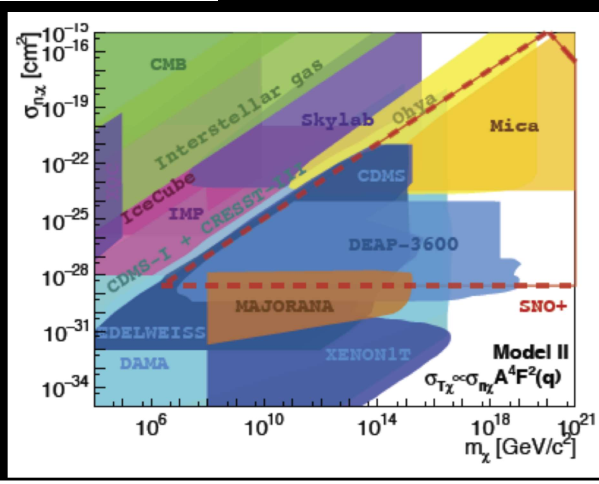
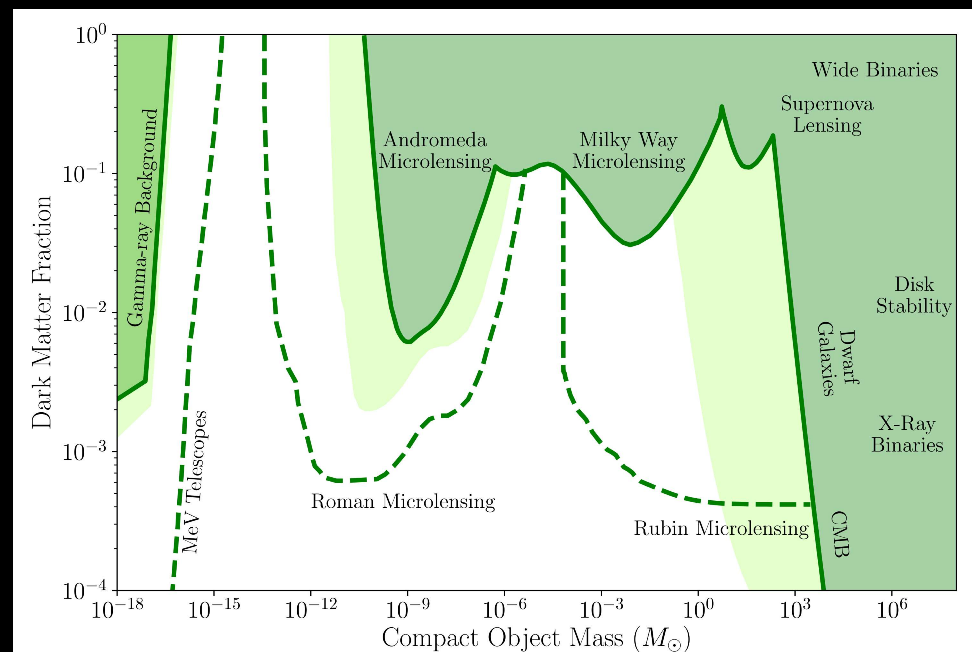


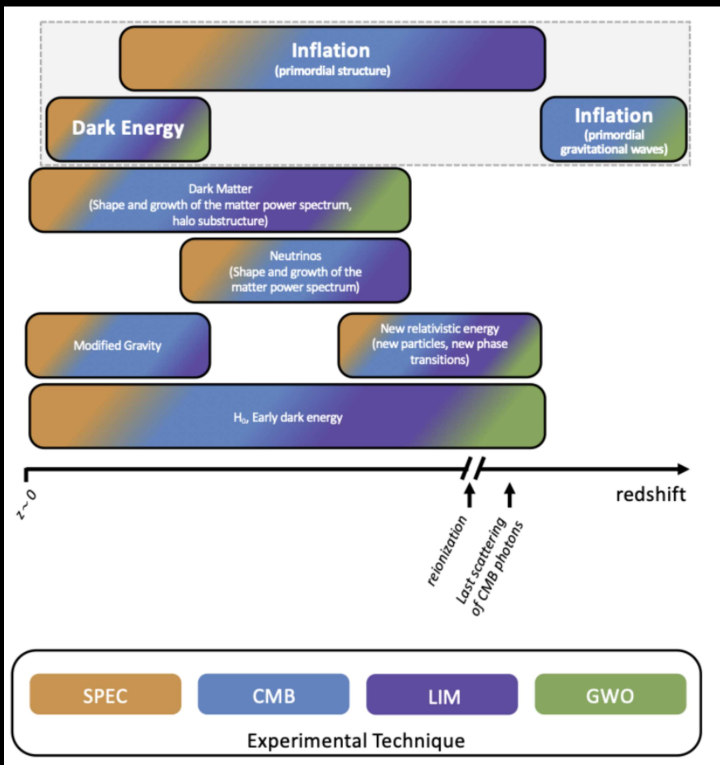
At the largest masses, dark matter could take the form of dark blobs or primordial black holes. Novel detection strategies are required.





Understand cosmic acceleration: dark energy and inflation.

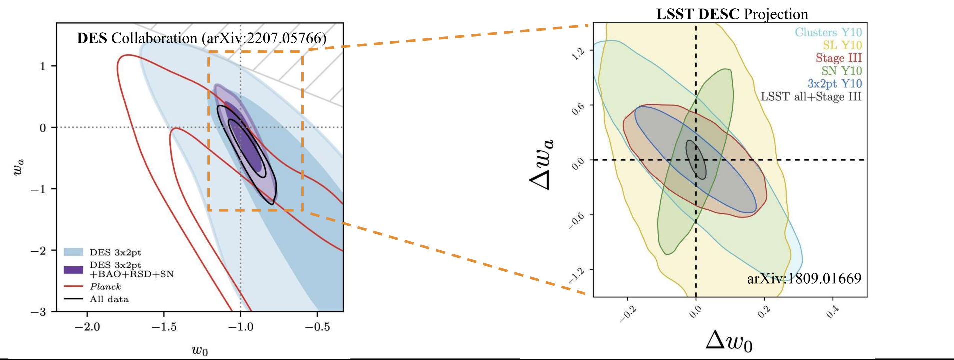
Captions here, please



Search wide, aim high!

Precision cosmology

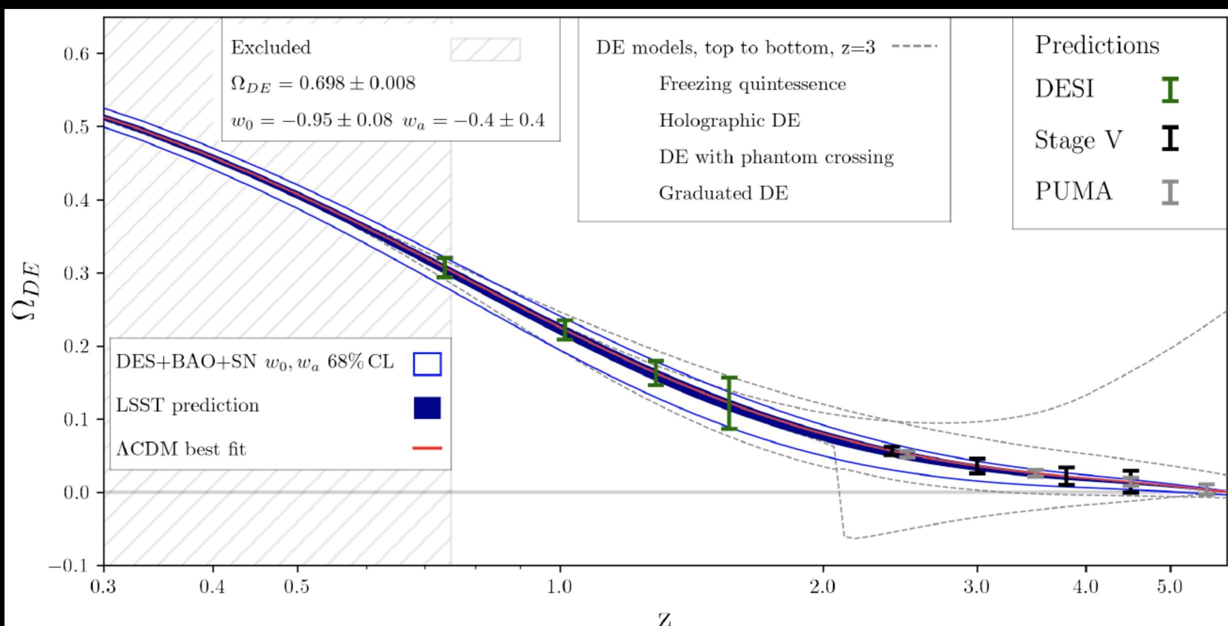
The discovery of **dark energy** led to a **precision measurement program** to understand its physics.

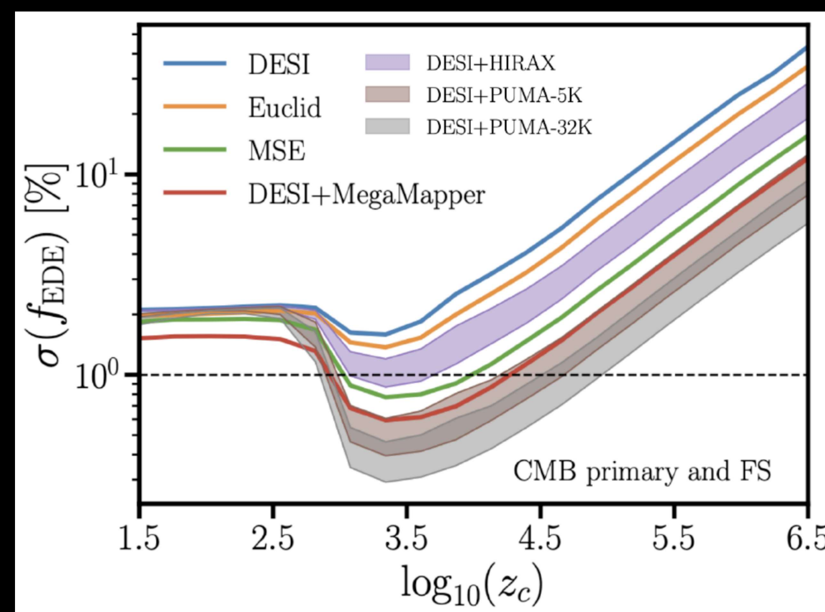


The Cosmic Frontier offers *unique* handles on the physics of inflation and to search for ultra-weakly interacting particles.

Understand cosmic acceleration: dark energy and inflation.

Captions here, please

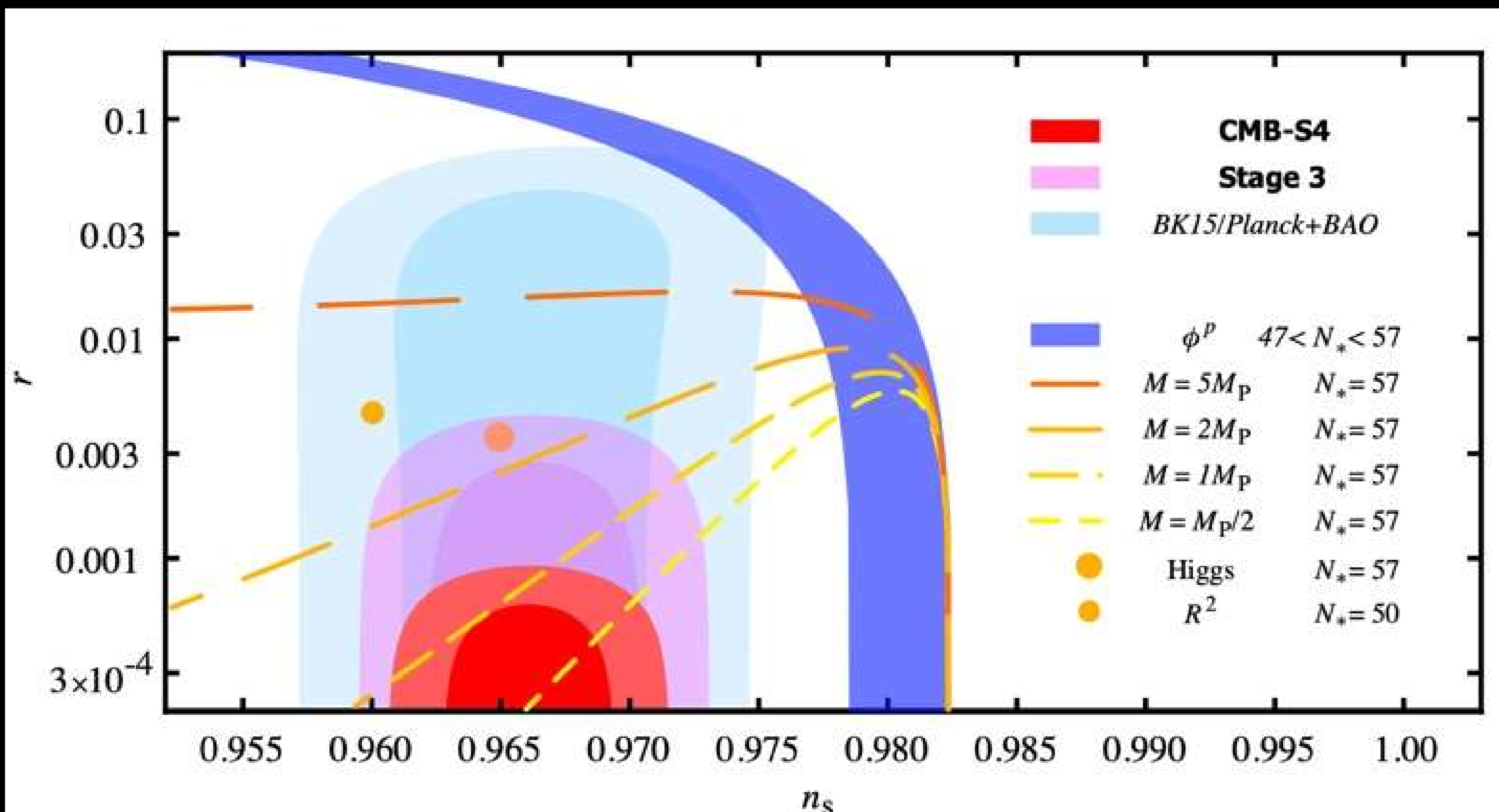


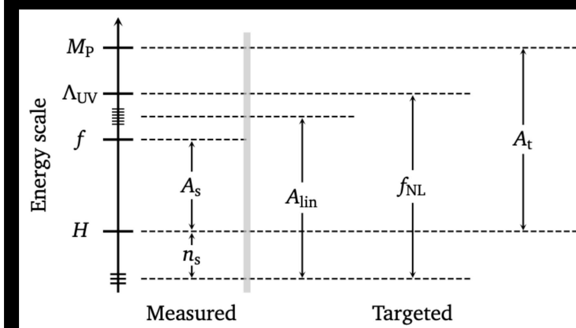


Precise measurements of dark energy in different epochs could shed light on models of Early Dark Energy aimed at resolving the Hubble tension.

Understand cosmic acceleration: dark energy and inflation.

Captions here, please

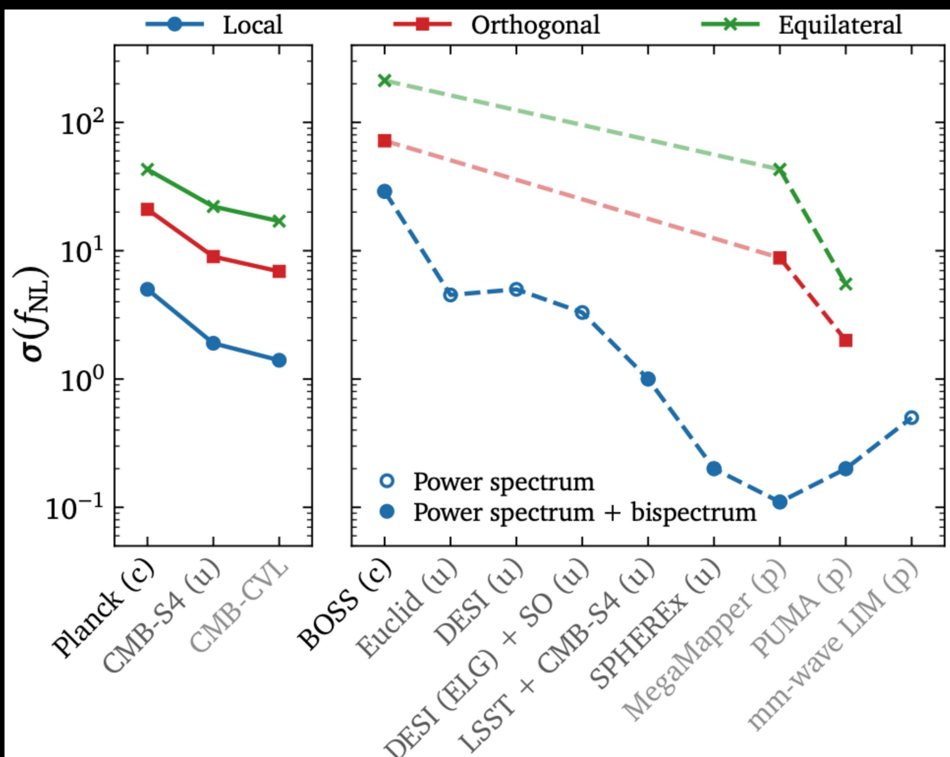


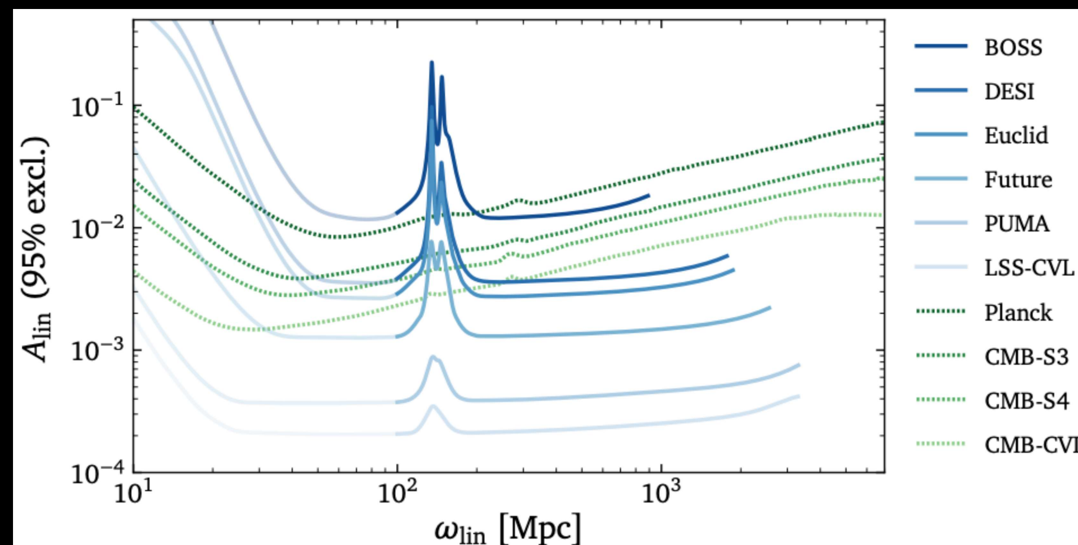


CMB-S4 offers a unique opportunity to access the Physics of inflation.

Understand cosmic acceleration: dark energy and inflation.

Captions here, please

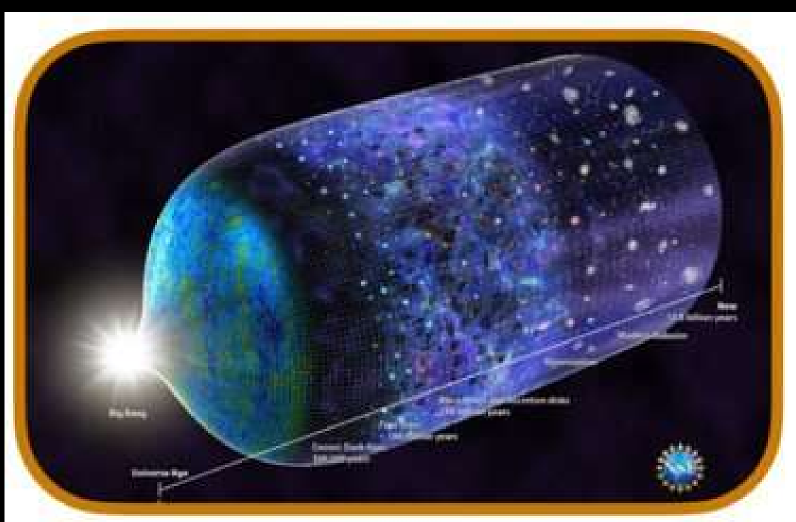


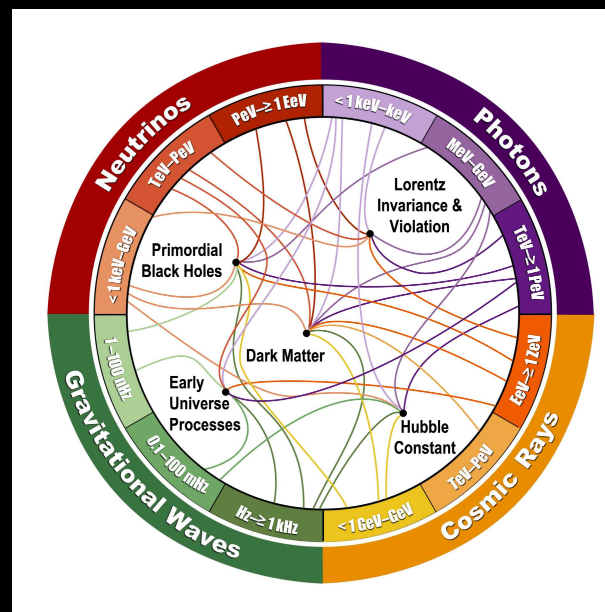


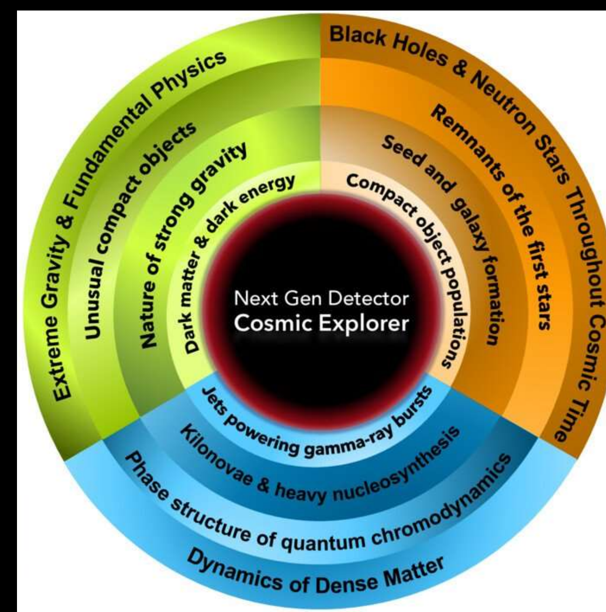
Features in the matter power spectrum, as revealed by template shapes or sharp local features can reveal new high energy dynamics probed via inflation.

Explore the unknown: new particles, interactions, and physical principles.

Captions here, please







Explore the unknown: new particles, interactions, and physical principles.

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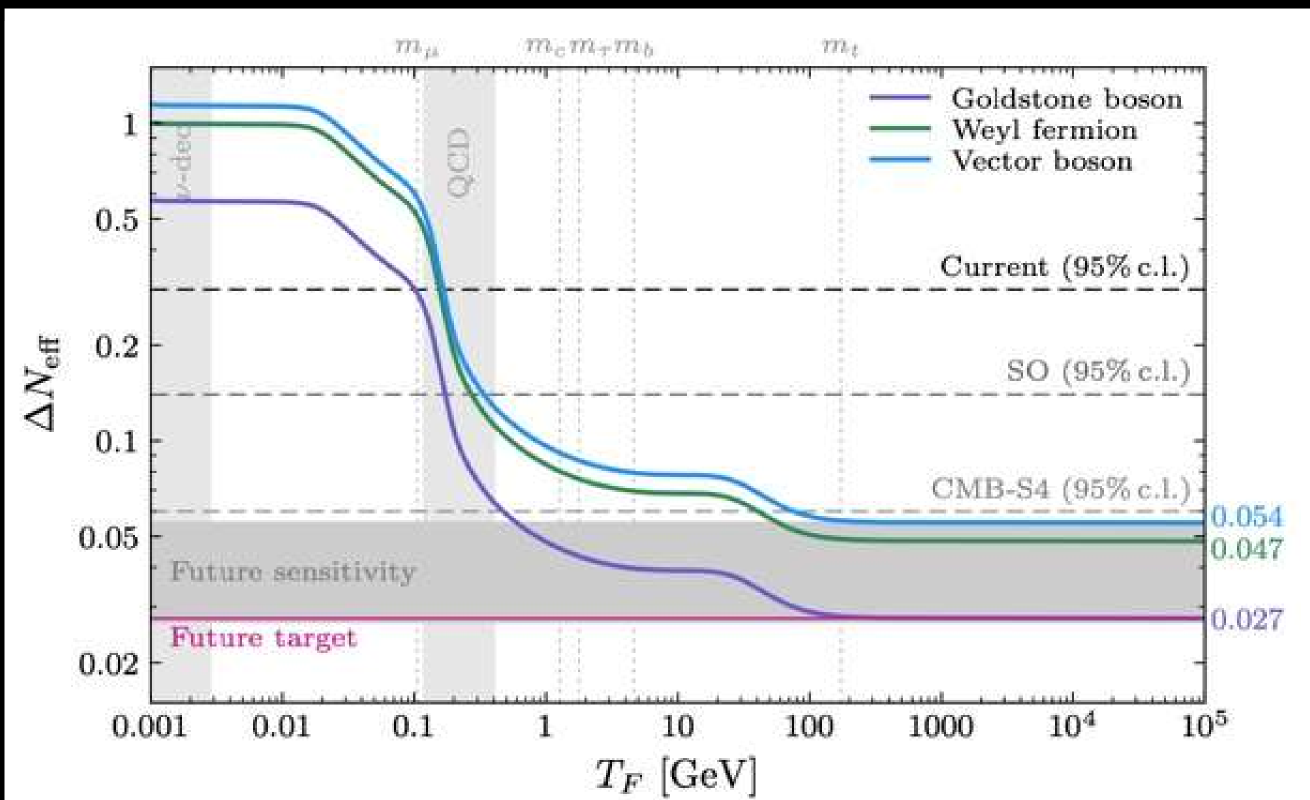
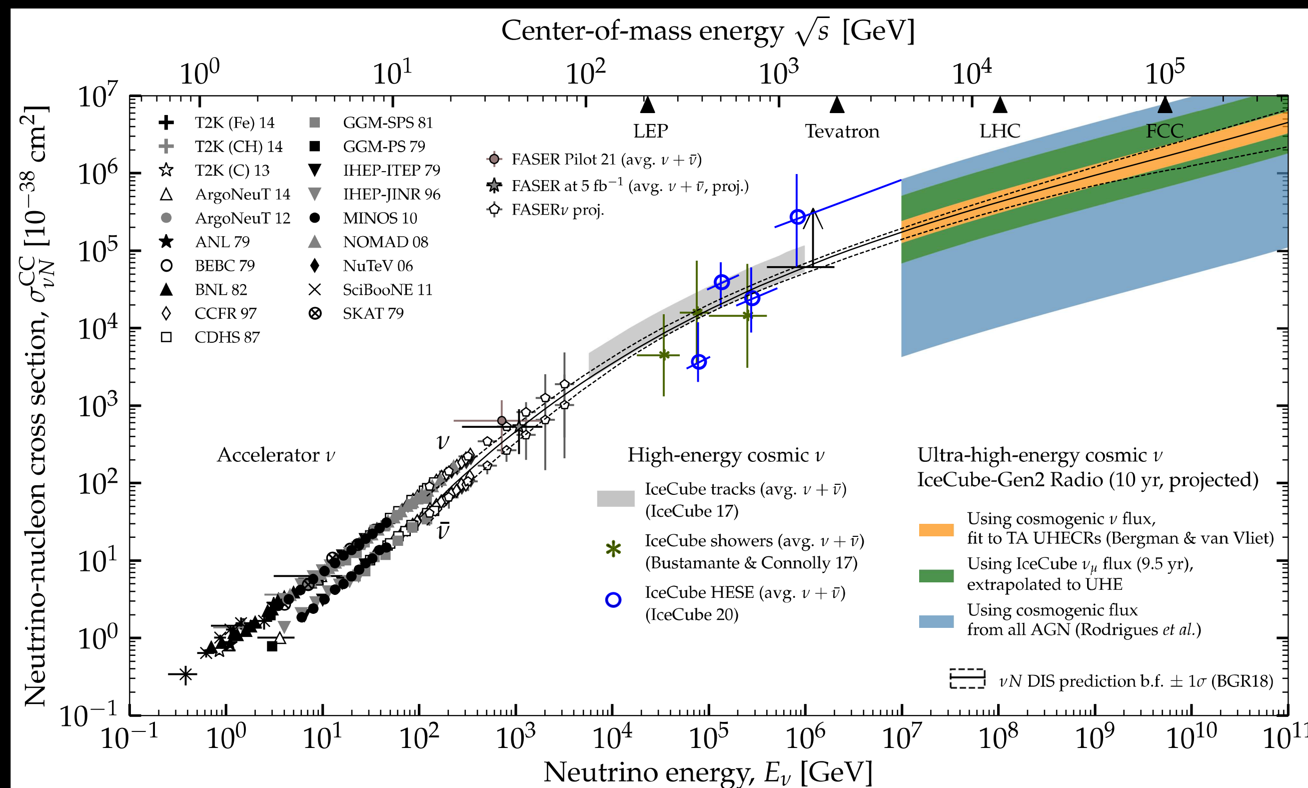


Cosmological probes offer unique ways to infer the existence of particles too weakly interacting for terrestrial probes, but present in the early Universe.

Explore the unknown: new particles, interactions, and physical principles.

Captions here, please

Natural high energy cosmic accelerators provide access to particles and interactions at the very highest energies.



Explore the unknown: new particles, interactions, and physical principles.

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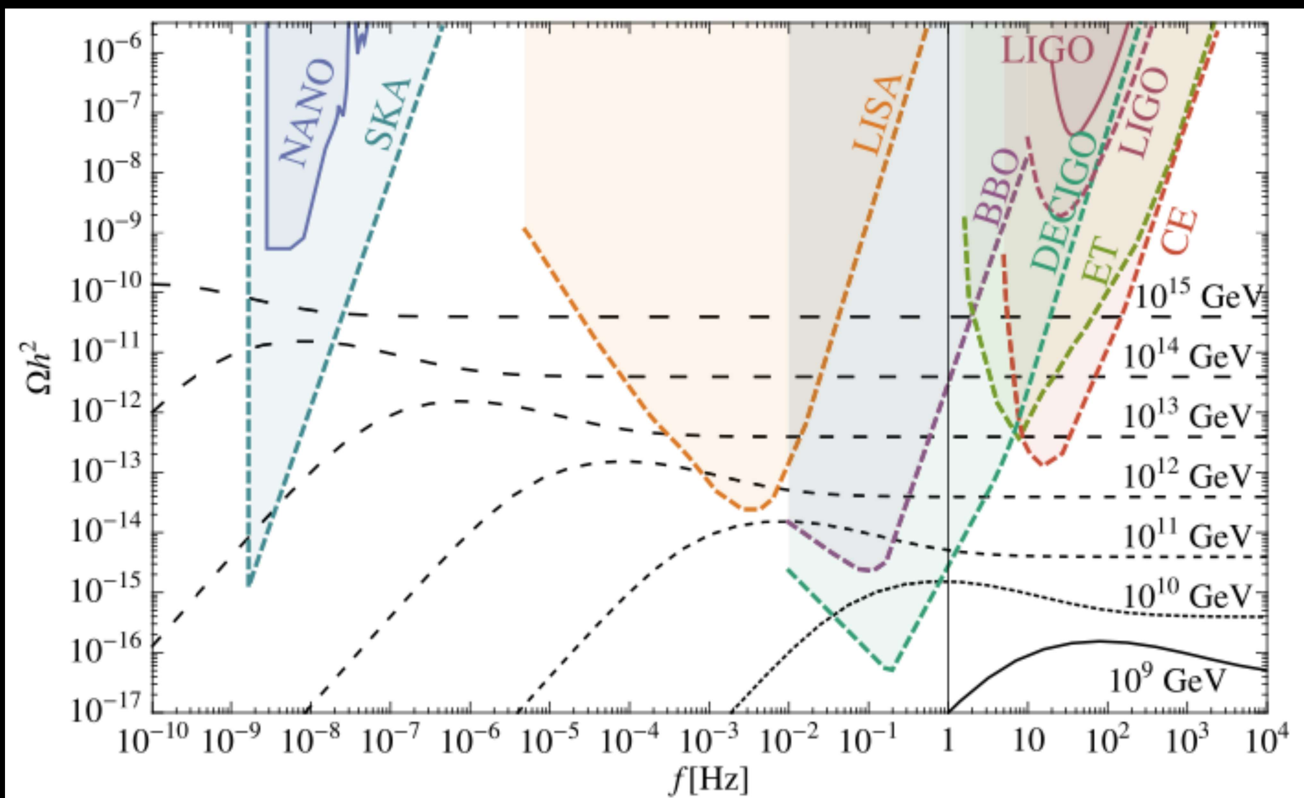

The background of stochastic gravitational waves provides a window sensitive to early phase transitions.

E.g. Leptogenesis & Seesaw
Dror, Hiramatsu, Kohri, Murayama, White 1908.03227 & PRL

Use the Higgs boson as a new tool for discovery.

Captions here, please

Higgs in Space!

C. B. Jackson[a], Géraldine Servant[b], Gabe Shaughnessy[a,c],
Tim M.P. Tait[a,c,d] and Marco Taoso [b,e]

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[b] *CERN Physics Department, Theory Division, CH-1211 Geneva 23, Switzerland*
[c] *Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA*
[d] *Department of Physics and Astronomy, University of California, Irvine, CA 92697. USA*
[e] *IFIC (CSIC-Universitat de València), Ed.Instituts, Apt. 22085, 46071 Valencia, Spain*

jackson@hep.anl.gov, geraldine.servant@cern.ch, ttait@uci.edu,
g-shaughnessy@northwestern.edu, marco.taoso@ific.uv.es

The Higgs may not be the ‘go to’ tool for disovery in the Cosmic Frontier, but it has its important role to play!

Higgs inflation

Javier Rubio

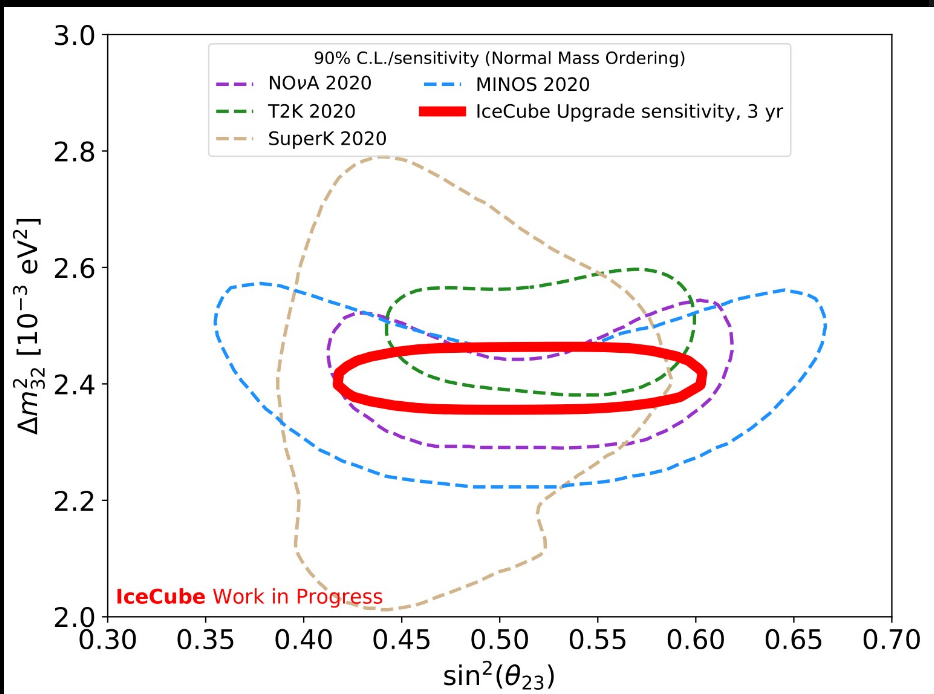
Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany

Abstract

The properties of the recently discovered Higgs boson together with the absence of new physics at collider experiments allows us to speculate about consistently extending the Standard Model of particle physics all the way up to the Planck scale. In this context, the Standard Model Higgs non-minimally coupled to gravity could be responsible for the symmetry properties of the Universe at large scales and for the generation of the primordial spectrum of curvature perturbations seeding structure formation. We overview the minimalistic Higgs inflation scenario, its predictions, open issues and extensions and discuss its interplay with the possible metastability of the Standard Model vacuum.

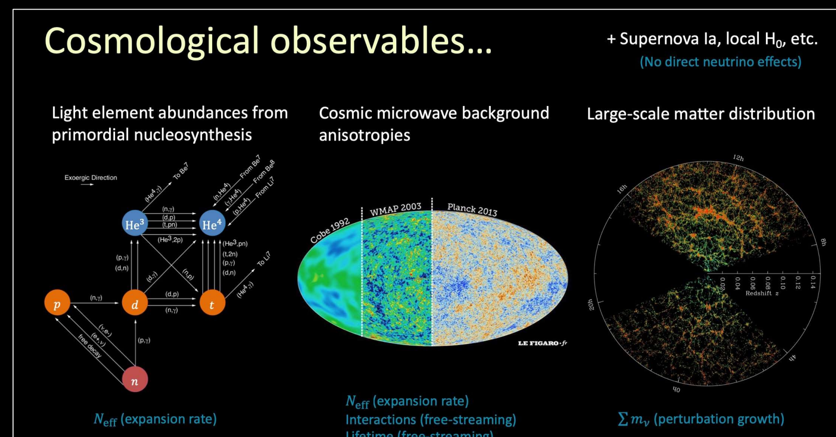
Pursue the physics associated with neutrino mass.

Captions here, please



Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium



Kate Scholberg, Snowmass CSS

Planck TTTEEE+lowE +lensing+BAO; 7-parameters

$N_{\rm eff} = 2.99 \pm 0.34$ (95% CL)

Aghanim et al. [Planck] 2021

Remarkably consistent with Standard Model prediction $N_{\rm eff} \approx 3$

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$\sum m_\nu < 0.12$ eV (95% CL)

Aghanim et al. [Planck] 2021

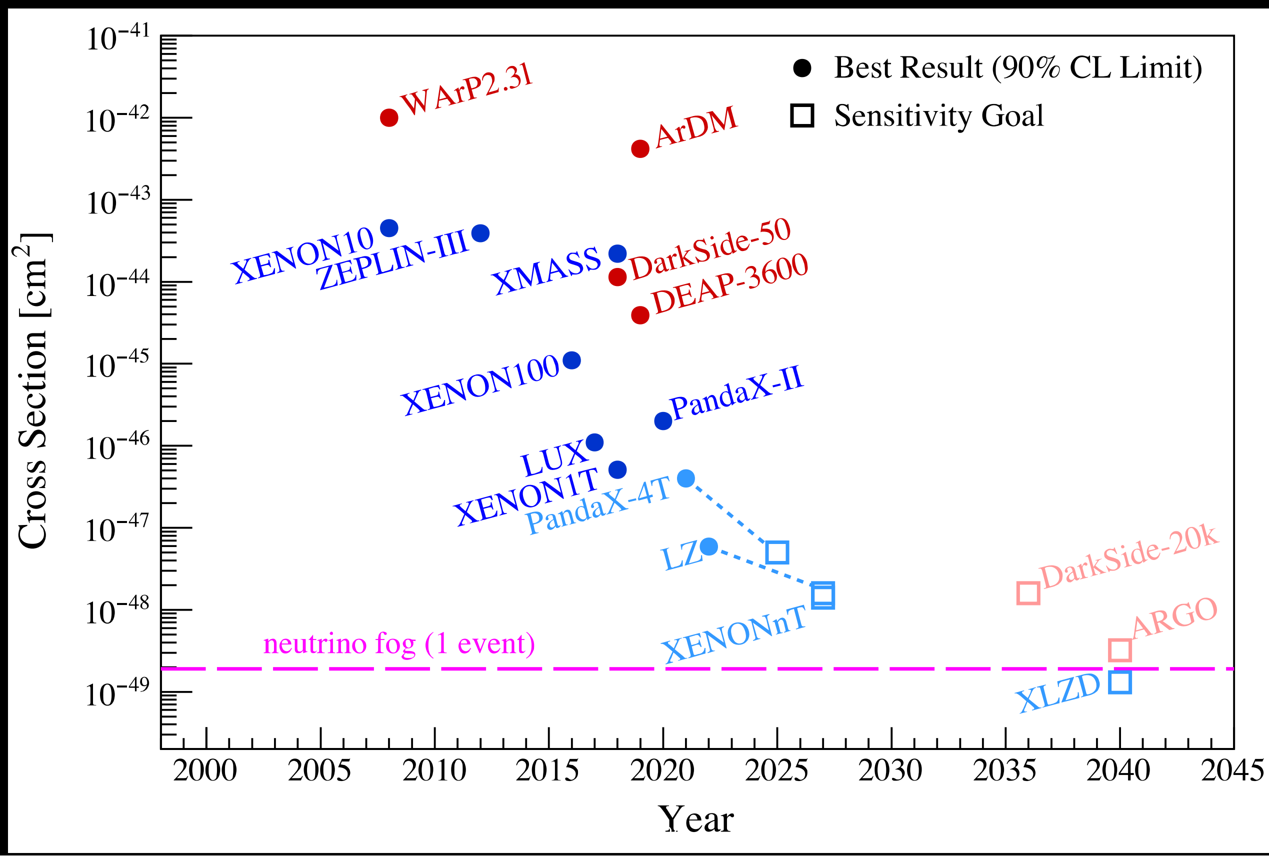
At face value a factor of 30 tighter than current lab bound from KATRIN, $\sum m$ <2.4 eV (90% C.L.) Aker et al. [KATRIN] 2022

Cosmic Frontier observations offer unique and important perspectives on the parameters describing neutrino masses which can inform terrestrial searches.

Captions here, please

Timelines

Captions here, please

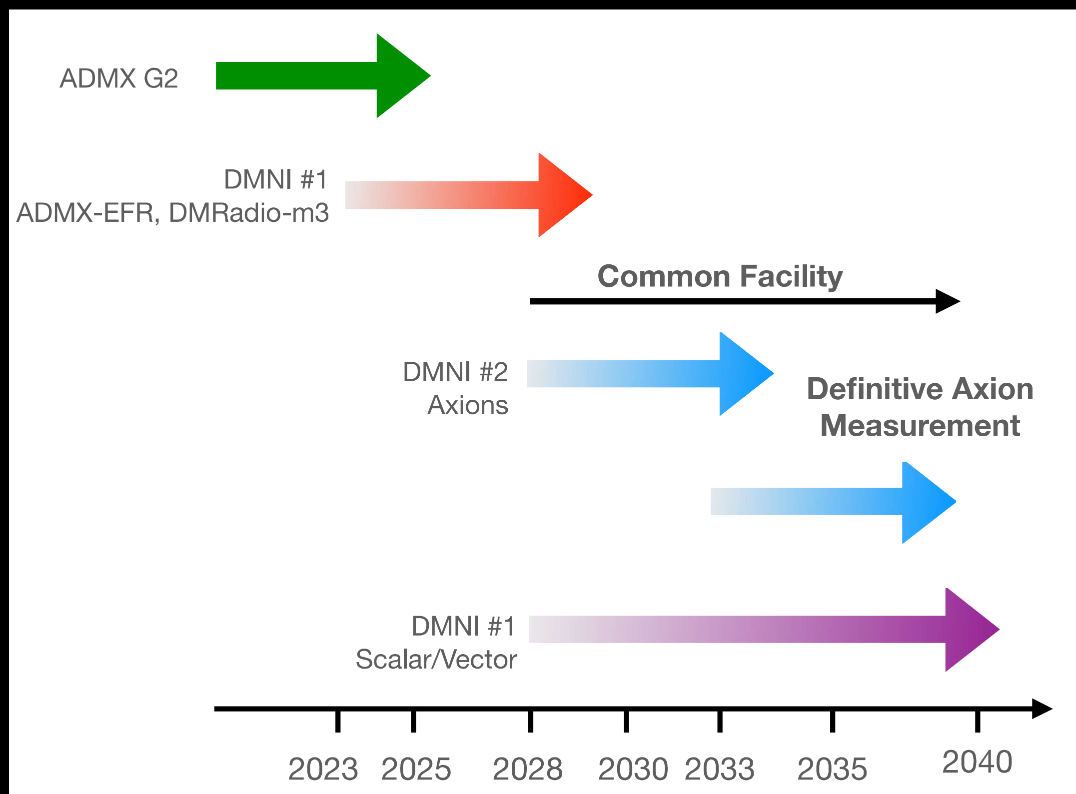


CF1 Report

Liquid nobel DM Searches

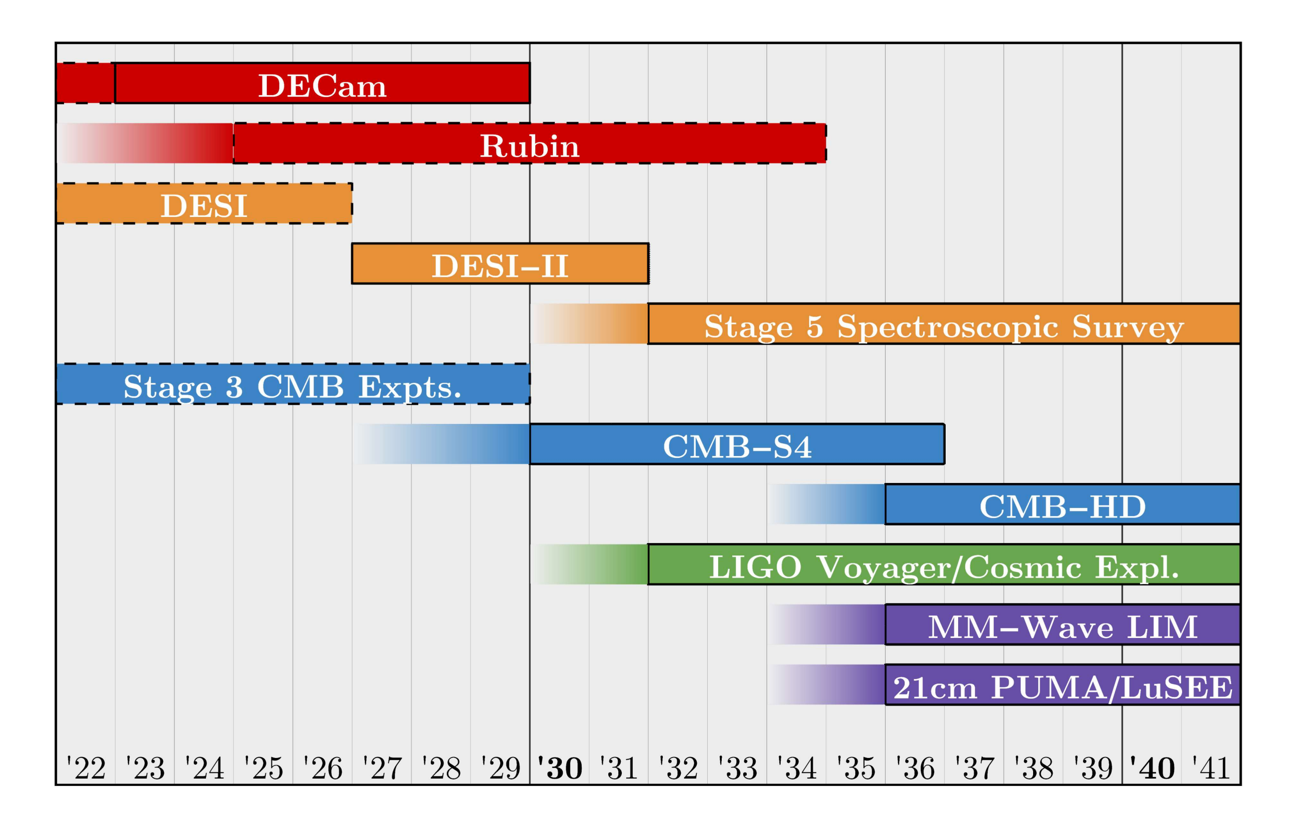
Captions here, please

CF2 Report



Wave DM Searches

Captions here, please

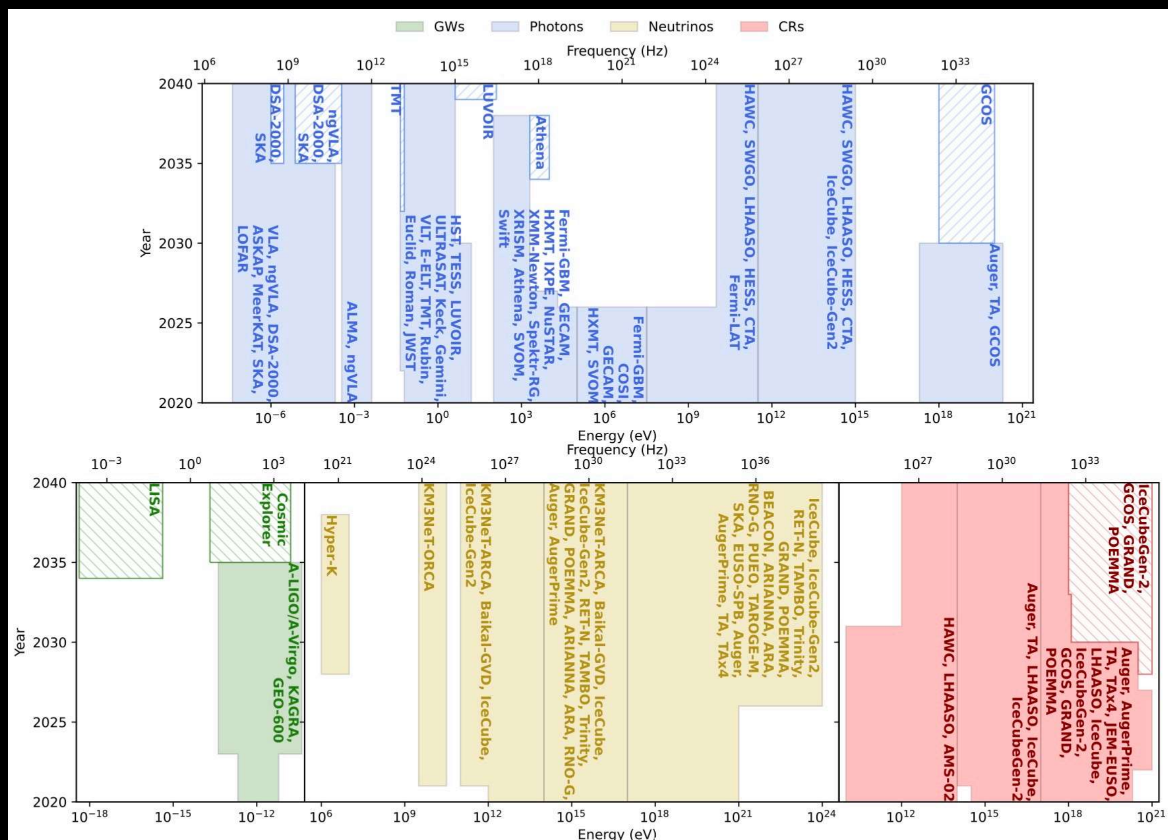


Cosmic Surveys

CF6 Report

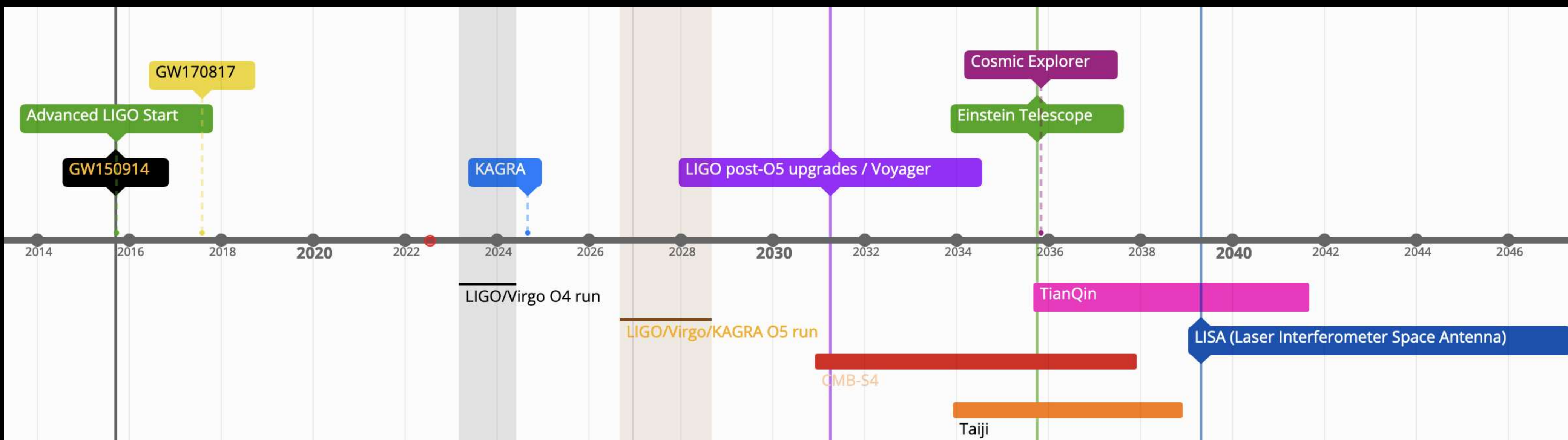
Captions here, please

High energy Cosmic particle Detectors



CF7 Report

Captions here, please



Gravitational wave observatories

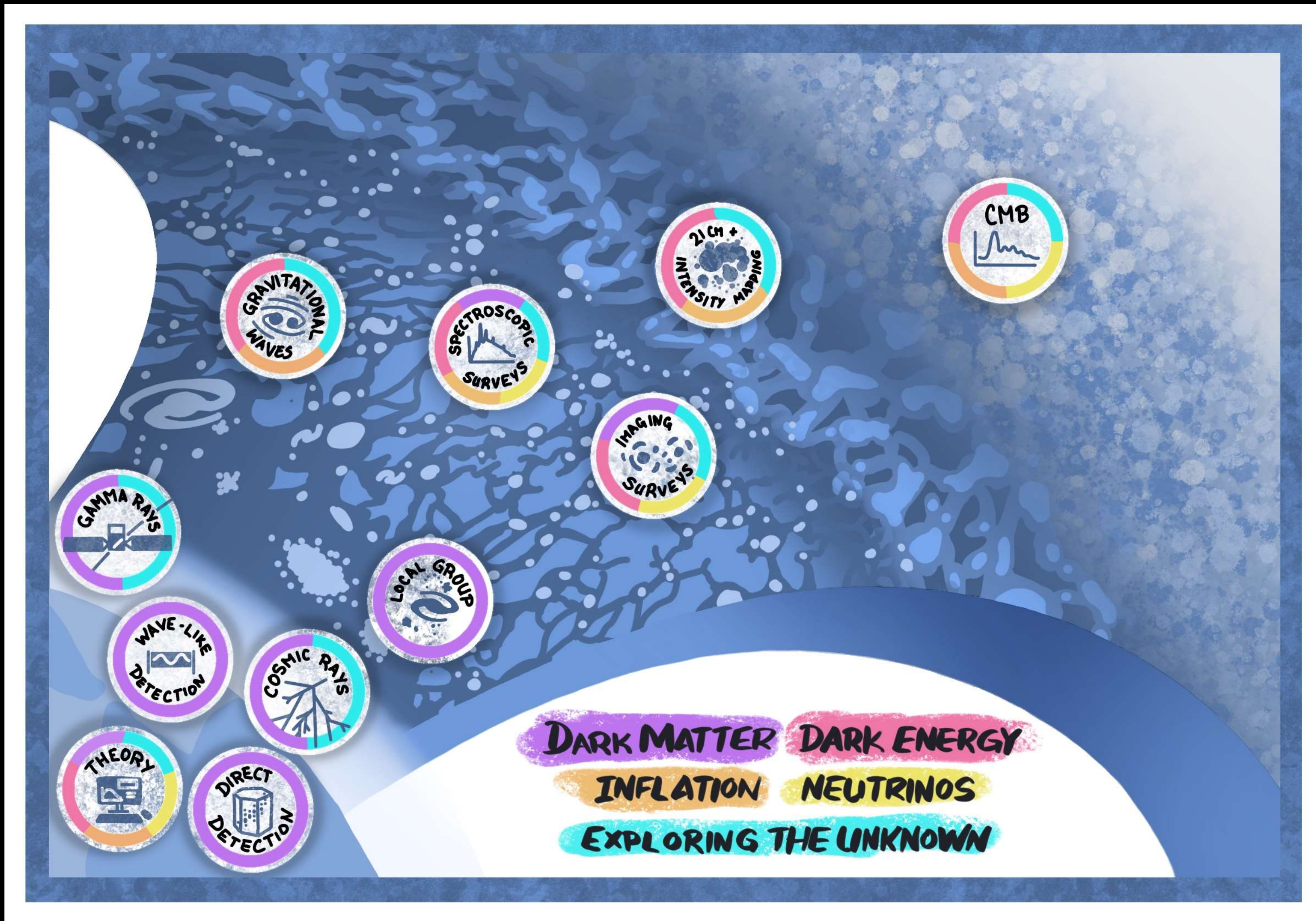
CF7 Report

Captions here, please

Delve Deep. Search Wide. Aim High.

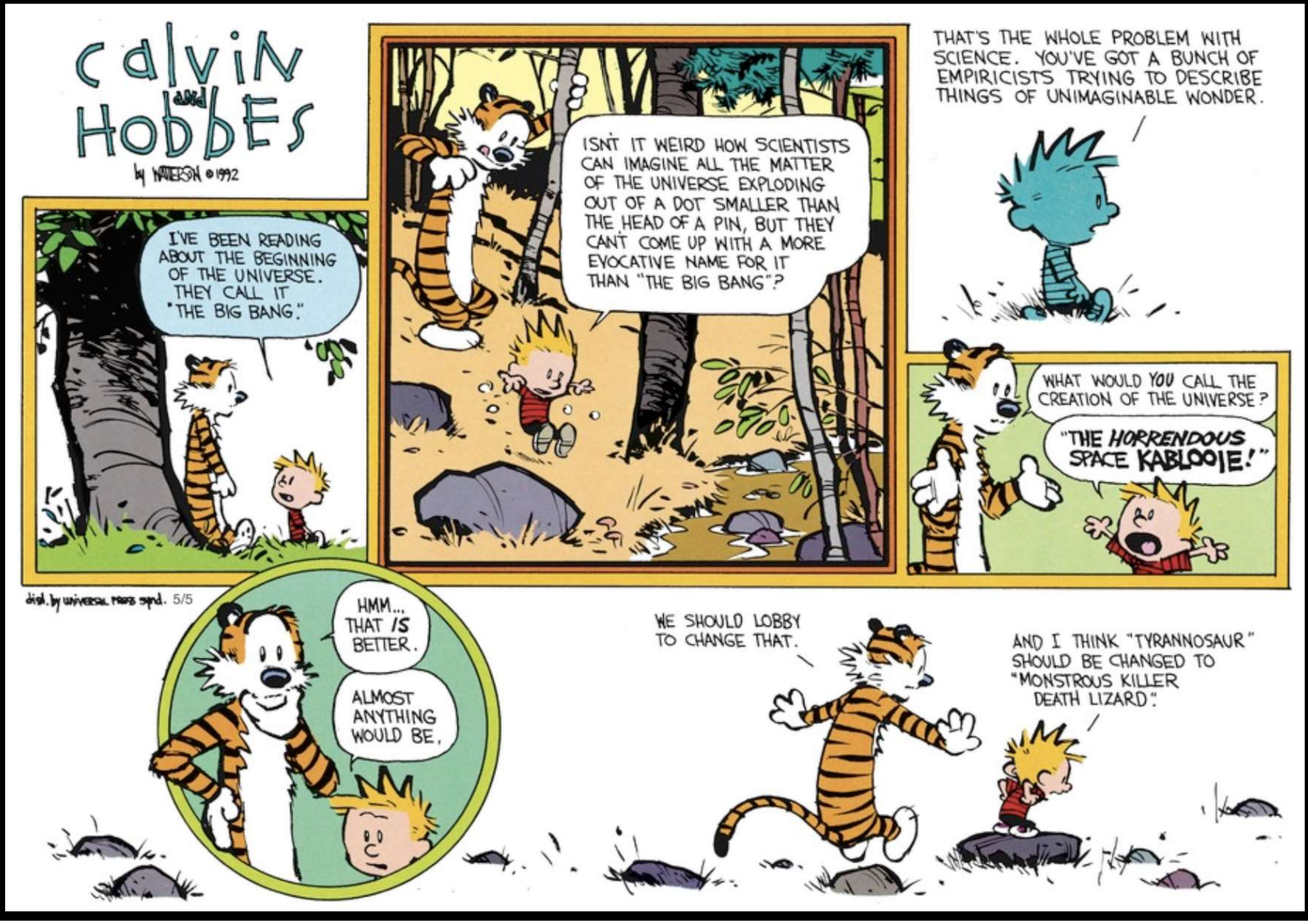
The Cosmic Frontier contributes unique opportunities to the pursuit of fundamental physics.

It has strong synergies with the Energy, Neutrino, and Rare Processes Frontiers, benefits from *essential* connections with the Theory, Computational, Instrumentation, and Underground Facilities Frontiers. It also offers interesting opportunities for the Community Engagement Frontier.



CMB
21 CM + INTENSITY MAPPING
GRAVITATIONAL WAVES
SPECTROSCOPIC SURVEYS
IMAGING SURVEYS
GAMMA RAYS
LOCAL GROUP
WAVE-LIKE DETECTION
COSMIC RAYS
THEORY
DIRECT DETECTION
DARK MATTER
DARK ENERGY
INFLATION
NEUTRINOS
EXPLORING THE UNKNOWN

THANK YOU


Calvin and Hobbes
by WATTERSON © 1992
I'VE BEEN READING ABOUT THE BEGINNING OF THE UNIVERSE. THEY CALL IT "THE BIG BANG."
ISN'T IT WEIRD HOW SCIENTISTS CAN IMAGINE ALL THE MATTER OF THE UNIVERSE EXPLODING OUT OF A DOT SMALLER THAN THE HEAD OF A PIN, BUT THEY CAN'T COME UP WITH A MORE EVOCATIVE NAME FOR IT THAN "THE BIG BANG"?
THAT'S THE WHOLE PROBLEM WITH SCIENCE. YOU'VE GOT A BUNCH OF EMPIRICISTS TRYING TO DESCRIBE THINGS OF UNIMAGINABLE WONDER.
WHAT WOULD YOU CALL THE CREATION OF THE UNIVERSE?
"THE HORRENDOUS SPACE KABLOOIE!"
dist. by universal press synd. 5/5
HMM... THAT IS BETTER.
ALMOST ANYTHING WOULD BE.
WE SHOULD LOBBY TO CHANGE THAT.
AND I THINK "TYRANNOSAUR" SHOULD BE CHANGED TO "MONSTROUS KILLER DEATH LIZARD."