Dark Energy — New Experiments

Marcelle Soares-Santos
University of Michigan

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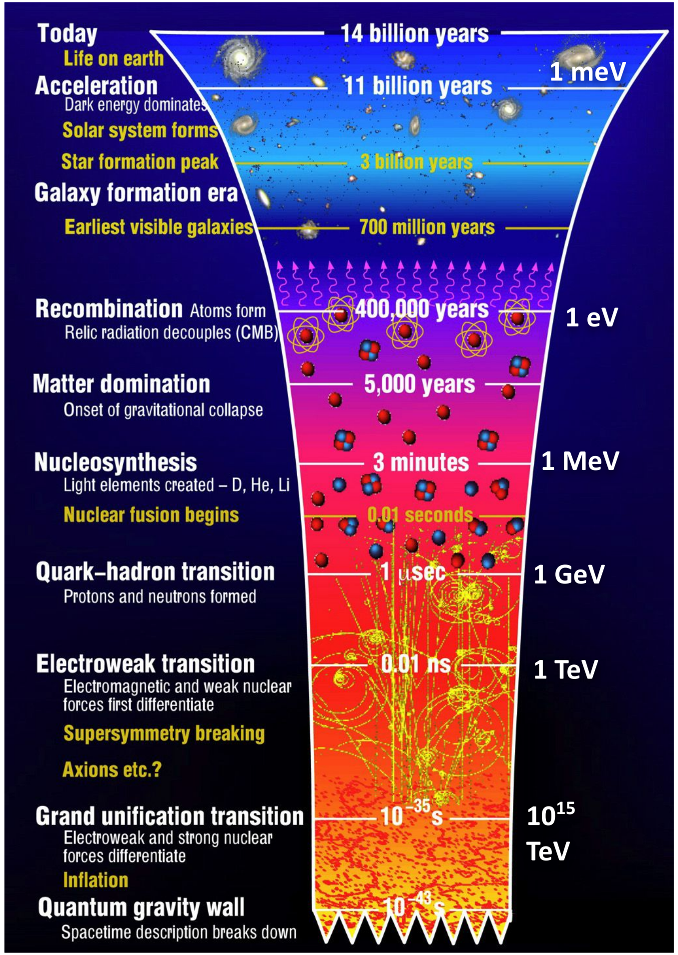
Background image: The Dark Energy Survey

Introduction

The particle physics and cosmology community aims to understand the fundamental constituents of matter and energy, revealing profound connections underlying everything we see, from the smallest to the largest structures in the Universe.

In this talk, I present prospects for future experiments focusing on the new physics driving the accelerated expansion of the universe in the last 5 billion years: **dark energy**.

- Dark energy research is a **discovery-driven, high-visibility, rigorous and bold** program, which has matured and grown over the last few years by both **leveraging and driving new developments across the entire community**. And we have a bright future ahead!

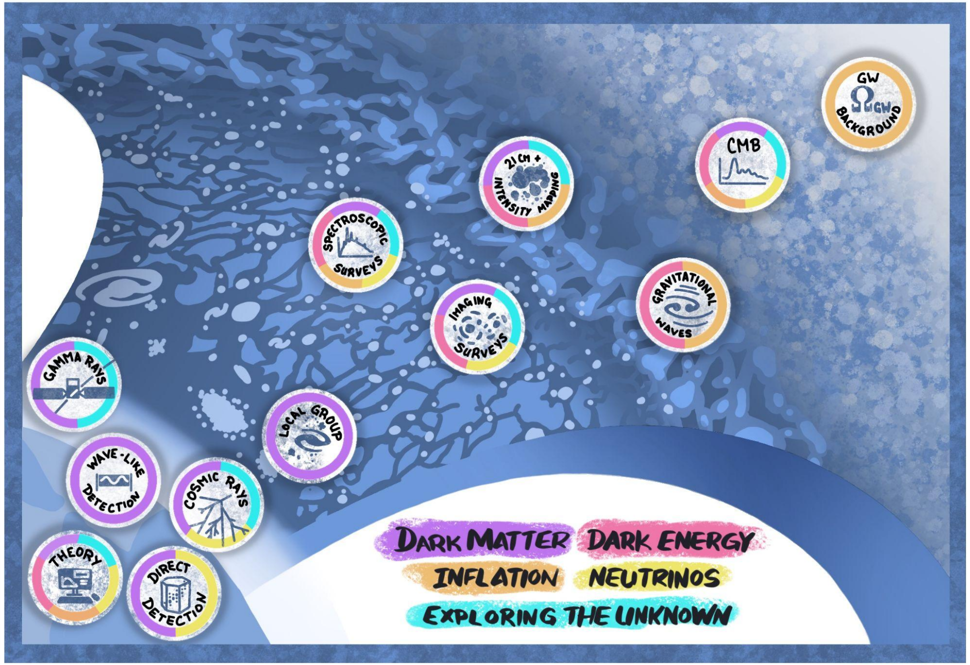


Introduction

The U.S. HEP community has recently completed a study, known as **Snowmass**, in which future (10-20 years timescale) experiments in all areas of HEP were considered.

As one of the co-conveners of the **Cosmic Frontier** group, I helped sheppard the Snowmass process, with a particular focus on **Dark Energy** research.

Much of this talk is based on the **Snowmass Cosmic Frontier Report**: [Chow, Soares-Santos, Tait, et al. 2022, arXiv:2211.09978]



High-impact science

HEP science drivers have been lines of inquiry recognized by multiple Nobel prizes. **Cosmic Frontier is key to four (out of five)** of the science drivers.

- **Dark Energy and Cosmic Acceleration** 2011, 2019
- **Dark Matter**
- Higgs 2013
- **Neutrinos** 2015
- **New Particles, Interactions and Principles**

New breakthroughs are within reach in the upcoming decade.

Our science also lends itself naturally to **powerful public engagement opportunities**.

Fundamental questions

- **Is dark energy the cosmological constant?**
  - Or a new field?
  - Or the result of beyond General Relativity physics?

- **Did BSM degrees of freedom influence the thermal history of the universe?**

- **Is the inflation paradigm realized in nature?**
  - What is the energy scale of the inflaton field?
  - What are the dynamics of inflation?

Thanks to detector technology developments, new discovery windows have just opened up!

Understanding dark energy

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

- **Example parameters to measure:**
  - Equation of state, $w = w_0 + w_a z/(1+z) + \ldots$
  - Amplitude of clustering of galaxies, S_8
  - Rate of cosmic expansion today, H_0
  - Energy density today, Ω_m

- **Test for consistency:**
  - Models that predict the same expansion history may predict different clustering growth rates.
  - Early and late universe analyses should yield consistent results.

Key observables

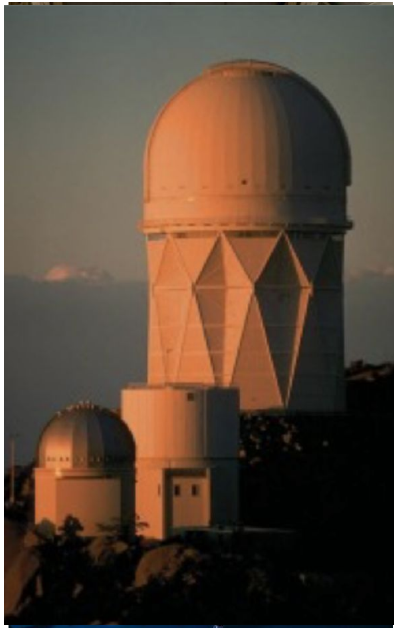
- Cosmic expansion history
- Cosmic microwave background
- Growth of structure
- Gravitational waves

Thanks to an integrated theory program that spans

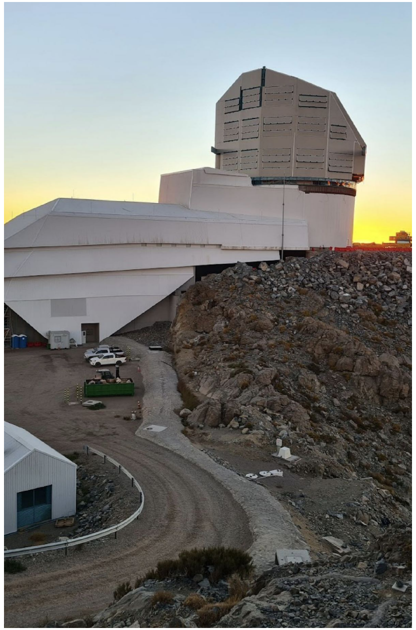
- New models
- New observables & algorithms
- Predictions & forecasting
- Simulations
- Pipeline development

the discovery potential of these key observables is fully realized.

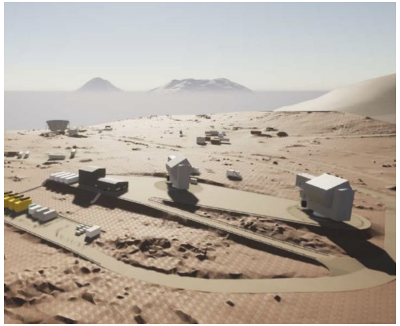
Key facilities



Spectroscopic Surveys



Imaging Surveys

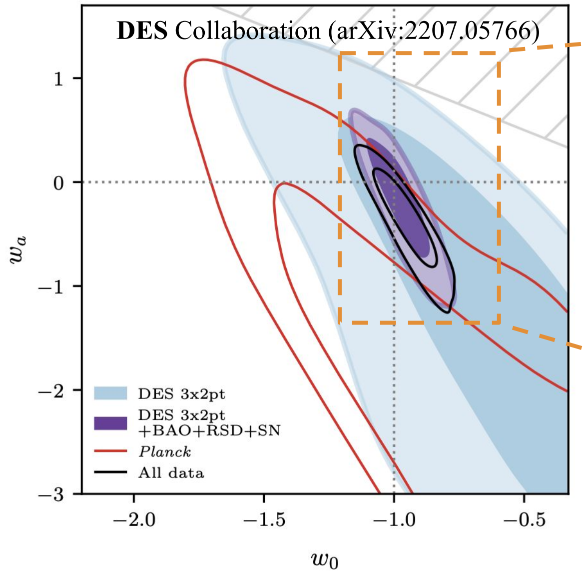


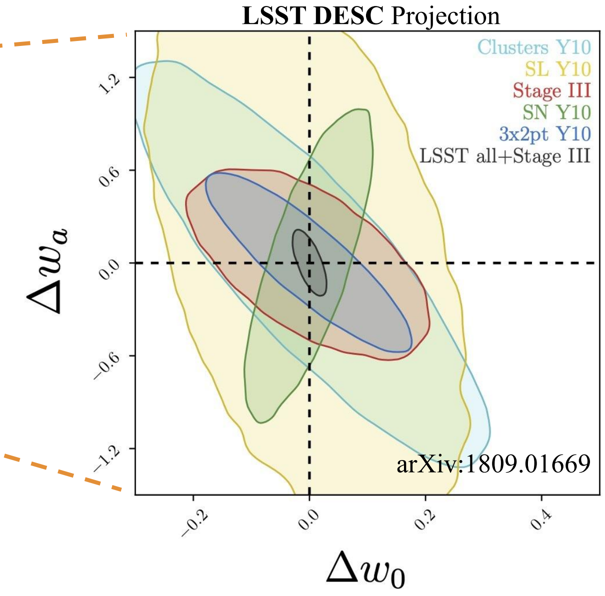
Cosmic Microwave Background

Gravitational Waves

Precision cosmology

The field is advancing in leaps in the era of dark energy precision measurements.





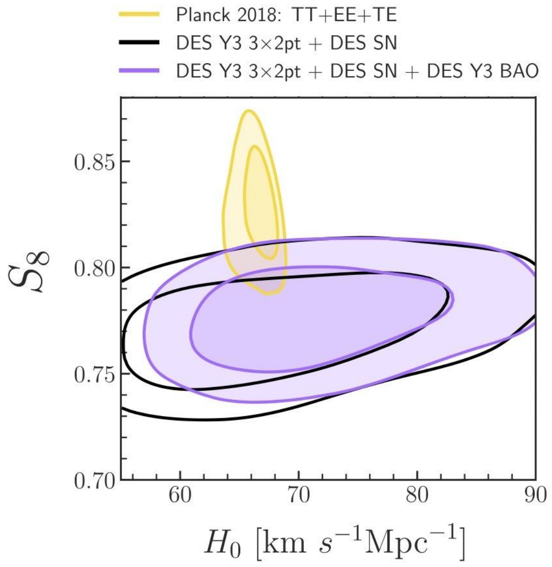
Precision cosmology

Tantalizing "anomalies" between early and late-universe probes of cosmology:

> **Overall, the universe seems to expand faster and be smoother than the cosmological constant prediction.** — Adam Riess, at the Snowmass Public Lecture, July 20 2022.

We may be at the edge of a new discovery.

DES, **PRD** 105, 043512 (2022)

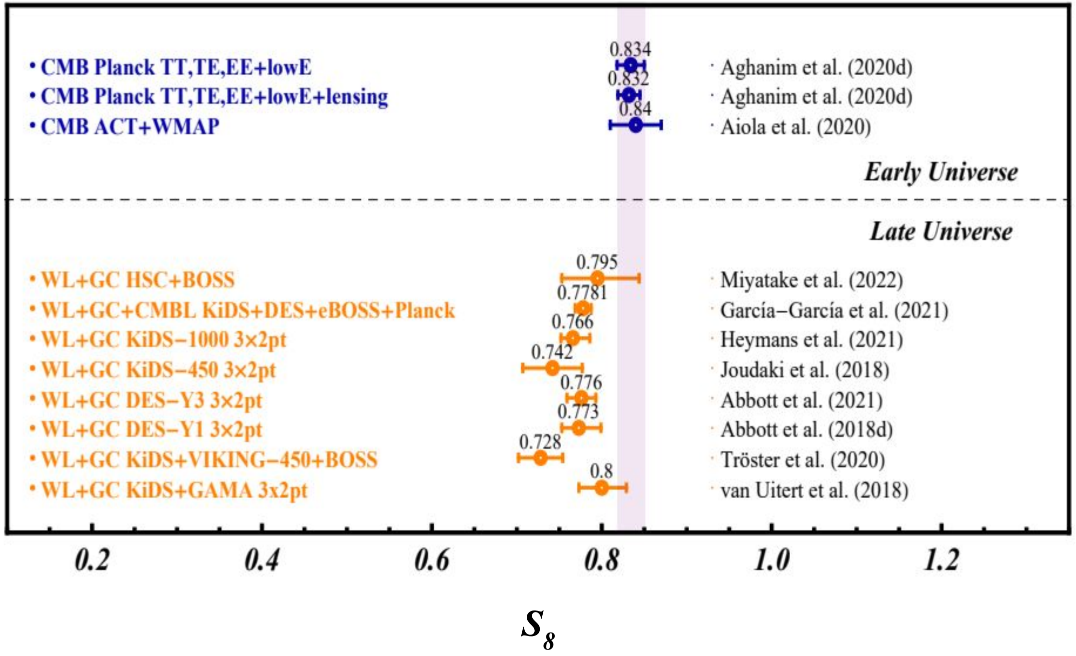


S_8 tension

Growing discrepancy between CMB-based and galaxy-based measurements: **systematics or new physics?**

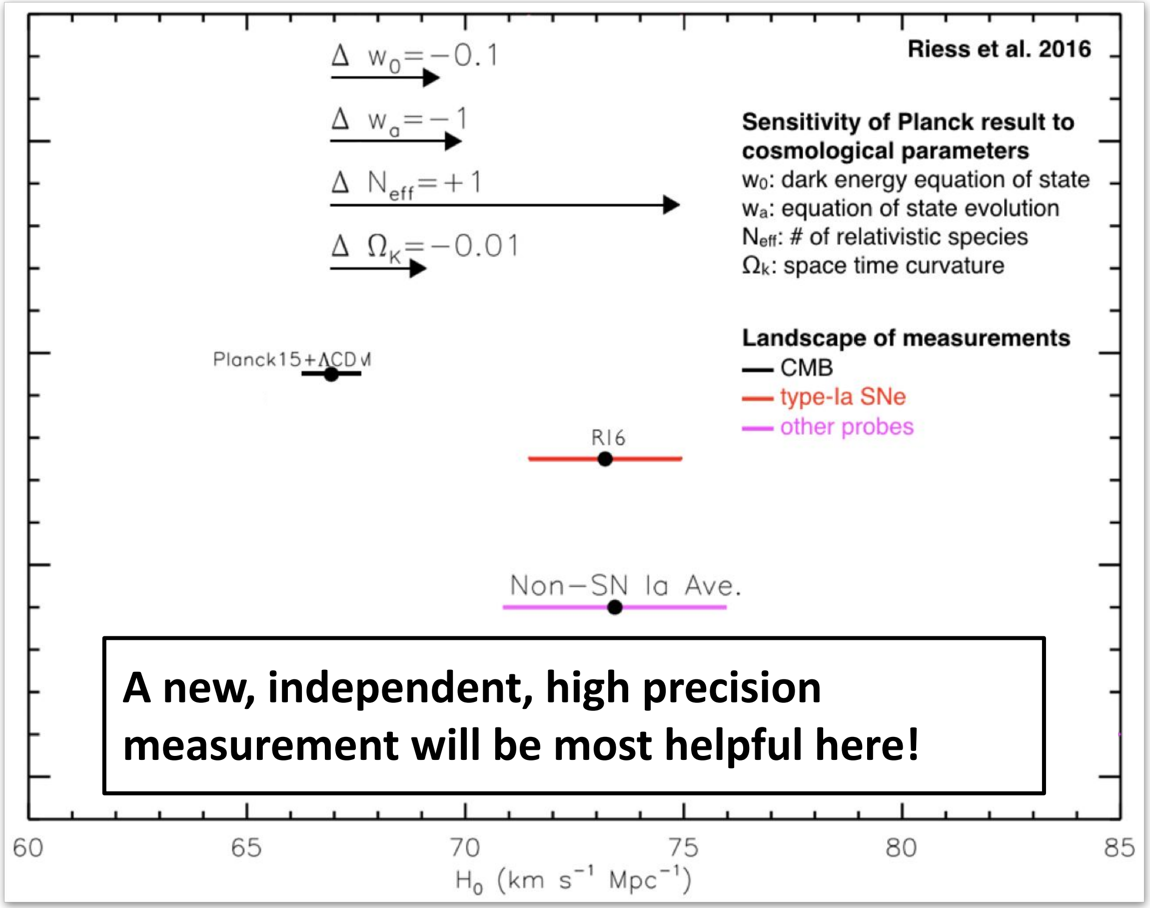
Galaxy clusters are a particularly sensitive observable.

Cosmology Intertwined (a review paper for Snowmass 2021)
Abdalla et al. **JHEAp** 2204, 002 (2022)



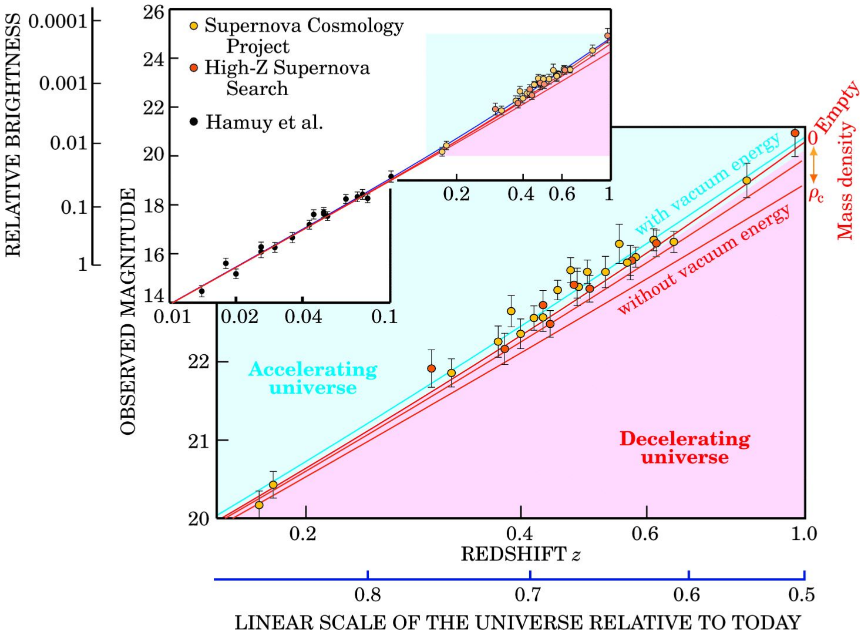
H_0 tension

Growing discrepancy between SNe and CMB-based measurements of the current rate of expansion: **systematic effects, or new physics?**



Distance indicators for cosmology

- Standard observables can be used to determine cosmic distances and measure cosmic expansion rate via the Hubble diagram.
- Examples of “standards” include:
  - **candles**: type-Ia supernovae
  - **rulers**: scale of BAO feature in the CMB maps and galaxy districution
  - **sirens**: merging binary neutron stars and black holes
- Note that two pieces of information are needed: **distance** and **redshift**



Standard Sirens

In a merging binary system, the change in GW signal frequency, gives us the size of the system.

Once we know the size, we can predict the intrinsic amplitude, and compare that with the observed amplitude in our detectors!

NATURE VOL. 323 25 SEPTEMBER 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

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systems with circular orbits[5]. Consider a binary at a distance $100r_{100}$ Mpc, with total mass $m_T M_\odot$ and reduced mass $\mu M_\odot$, emitting waves at frequency $100 f_{100}$ Hz (twice its orbital frequency). The standard 'quadrupole formula' of general relativity[6,7] shows that the waves will have amplitude (r.m.s.-averaged over detector and source orientations)

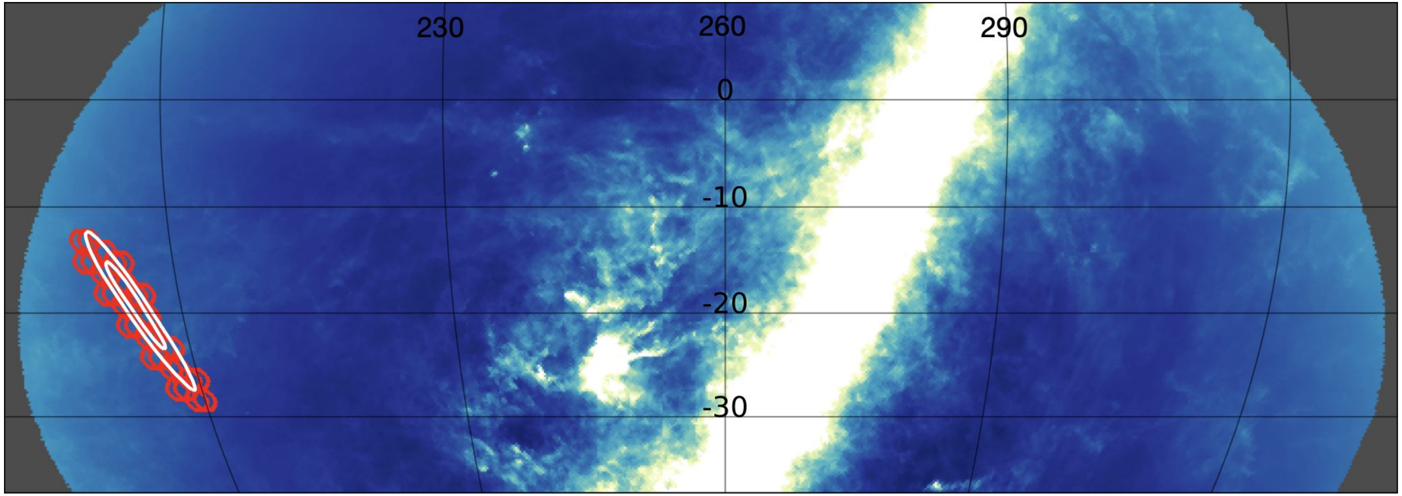
$$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^{2/3} r_{100}^{-1} \quad (1)$$

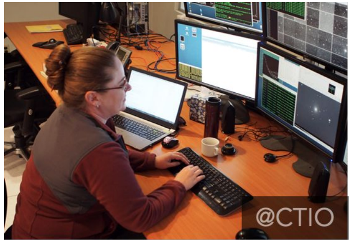
and that their frequency will change on a timescale

$$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3} \text{ s} \quad (2)$$

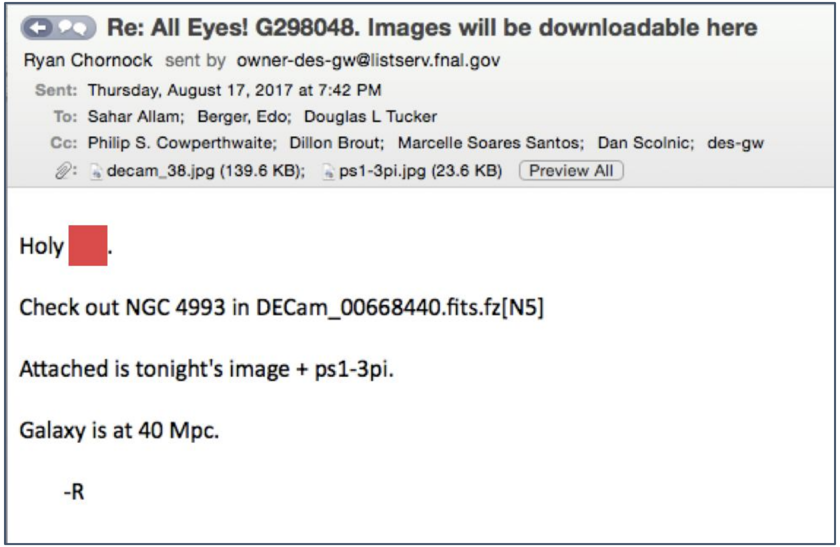
A needle in the haystack

GW170817 localization region was in the far west and set ~1.5 hours after twilight. Observations as soon as it gets dark: 8:13 pm Chile time (23:13 UT), 10.5 h post-merger. Pictured here is my group with people in place to eyeball the images on-site (at CTIO, in Chile) and at Fermilab.





Discovery of GW170817



Re: All Eyes! G298048. Images will be downloadable here

Ryan Chornock sent by owner-des-gw@listserv.fnal.gov

Sent: Thursday, August 17, 2017 at 7:42 PM

To: Sahar Allam; Berger, Edo; Douglas L Tucker

Cc: Philip S. Cowperthwaite; Dillon Brout; Marcelle Soares Santos; Dan Scolnic; des-gw

decam_38.jpg (139.6 KB); ps1-3pi.jpg (23.6 KB) Preview All

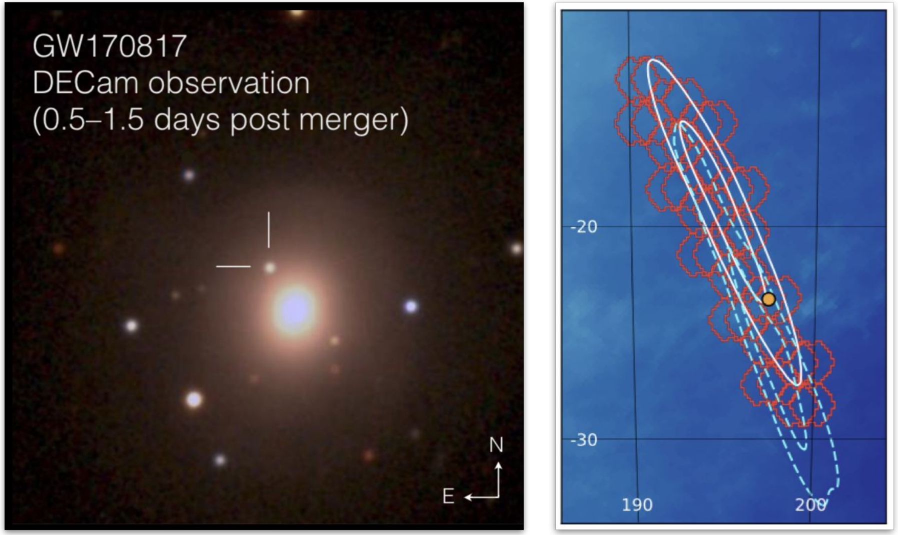
Holy [redacted].

Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

-R

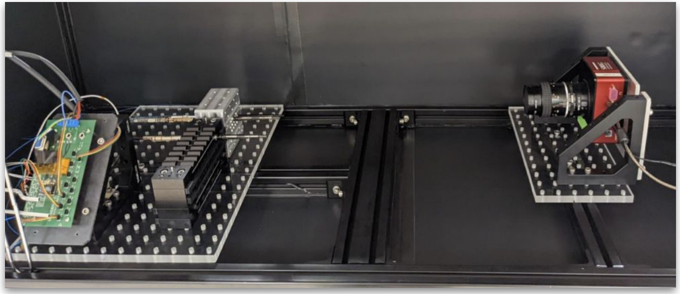


Soares-Santos et al. 2017

We found it! (co-discovery with other groups in the community; we want many more discoveries like this!)

DESI: new ongoing project

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science



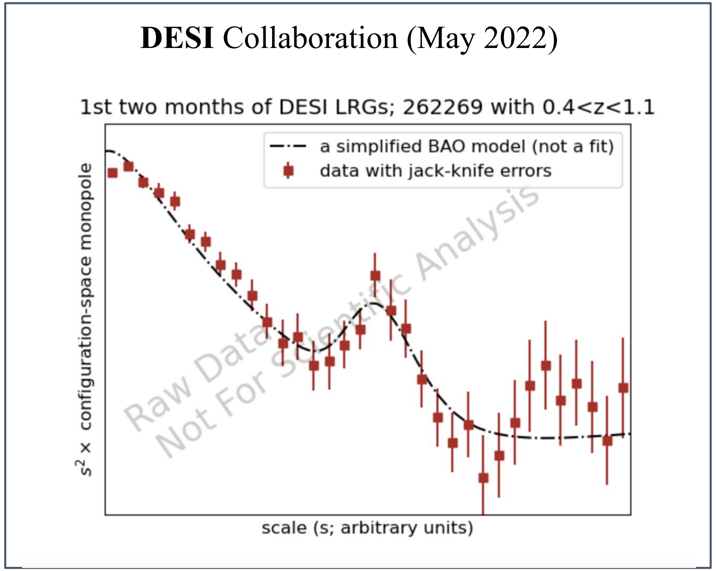
Thanks, in part, to its highly multiplexed focal plane system (arXiv: 2205.09014), DESI has already mapped 75M galaxies, more than all previous spectroscopic surveys combined!

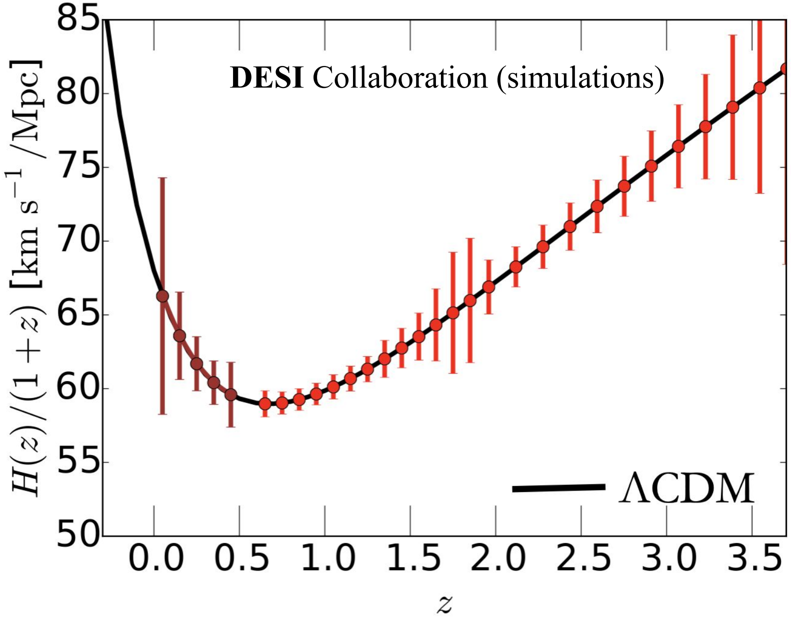
Analyses are going forward as we speak. Focus on BAO (standard ruler) and other measurements of 3D clustering of galaxies.

Pictured here is UM student Ayla Rodriguez, assembling the DESI test stand at the University of Michigan in Summer 2022.

DESI science projections

The field is advancing in leaps in the era of dark energy precision measurements.





LSST: upcoming project

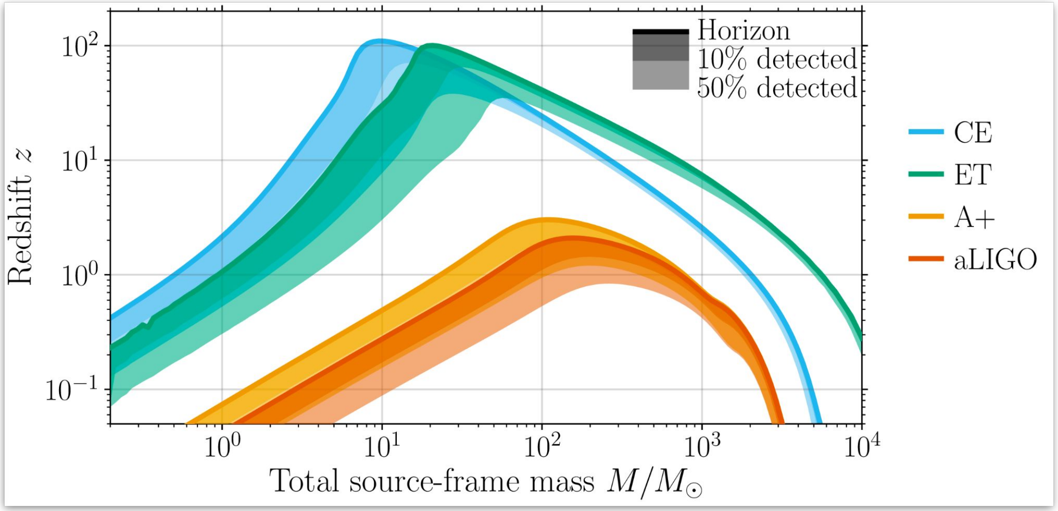
Vera Rubin Observatory
Legacy Survey of Space and Time

Deep, Fast, Wide:
next-generation imaging survey.

Pictured here is UM student Johnny Esteves, working on the camera commissioning in Chile.

Future GW antenna (proposed)

Ground-based 3rd generation GW observatories such as Cosmic Explorer (CE) or Einstein Telescope (ET) would detect standard sirens up to redshift > 20 (!)



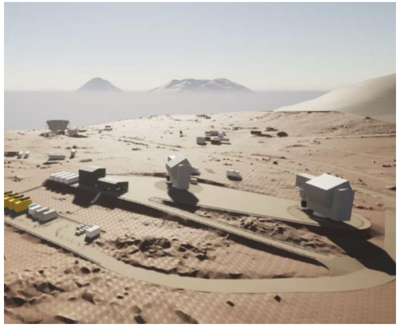
CMB-S4

CMB-S4 is ready to build now:

- CD-0 achieved in 2019
- CD-1 preparations underway

CMB-S4 is at the core of the CF program. It uniquely addresses cosmic inflation and its results will impact the science of many HEP frontiers.

The community consensus is that building and operating CMB-S4 is a **top immediate priority**.



CMB-S4

Spec-S5

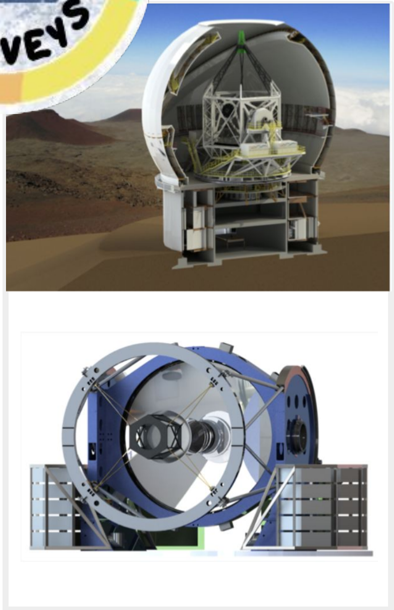
<u>Stage V Spectroscopic Facility</u>
6-10m telescope, 20-50k fiber focal plane
leap in survey power and science reach

Spec-S5 will be ready to build soon:

- Pathfinder small project ready now (DESI-II)
- Target CD-0 well before 2030

Spec-S5 will propel us into a new era of precision cosmology, ensuring that the U.S. community will remain a leader in CF science for decades to come.

The community consensus is that building Spec-S5 is our **<u>top near-term priority</u>**.



Spec-S5

New space-based experiments

JWST — (launched 2021) — Narrow field of view, but great potential for deep high-redshift follow-up observations of selected objects by Euclid and other ground-based surveys.

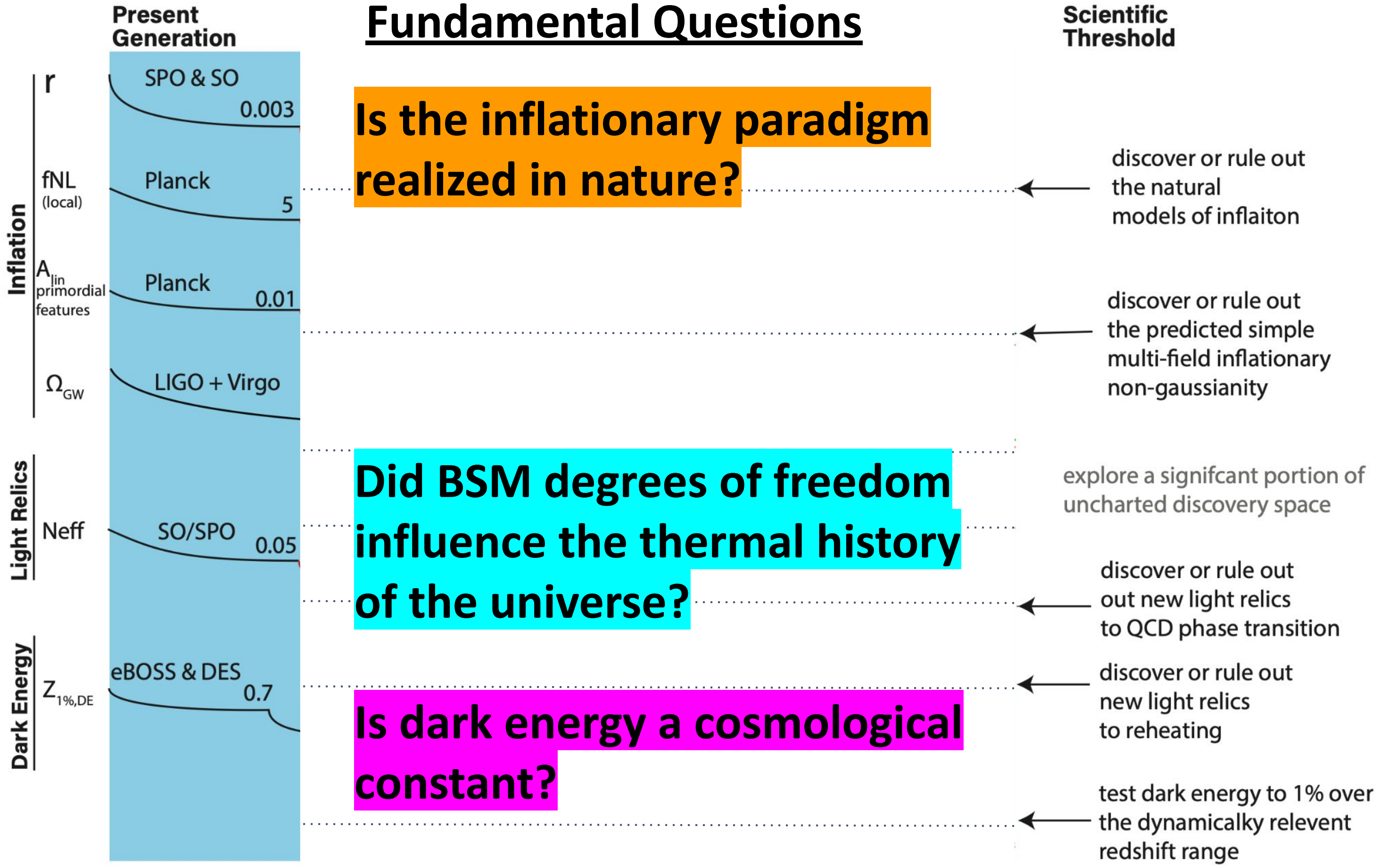
Euclid — (launched 2023) — A space telescope with both imaging and spectroscopic instruments! Aperture is smaller than current and planned ground-based facility, but image quality and IR coverage are superb. It will provide invaluable input complementary to DESI and LSST and will enable many systematic mitigation studies.

Roman — (launch expected in 2027) — Similar aperture as the Hubble space telescope but with 100 times the FOV. Will be a great instrument for supernovae and other dark energy probes.

LISA — (launch expected in the 2030's) — First space-based GW observatory, with sensitivity to longer wavelengths than ground-based detectors. Maybe sensitive to GW signals from inflation which will be revolutionary on their own and complementary to the CMB-S4 program.

The path to discovery

Fundamental Questions

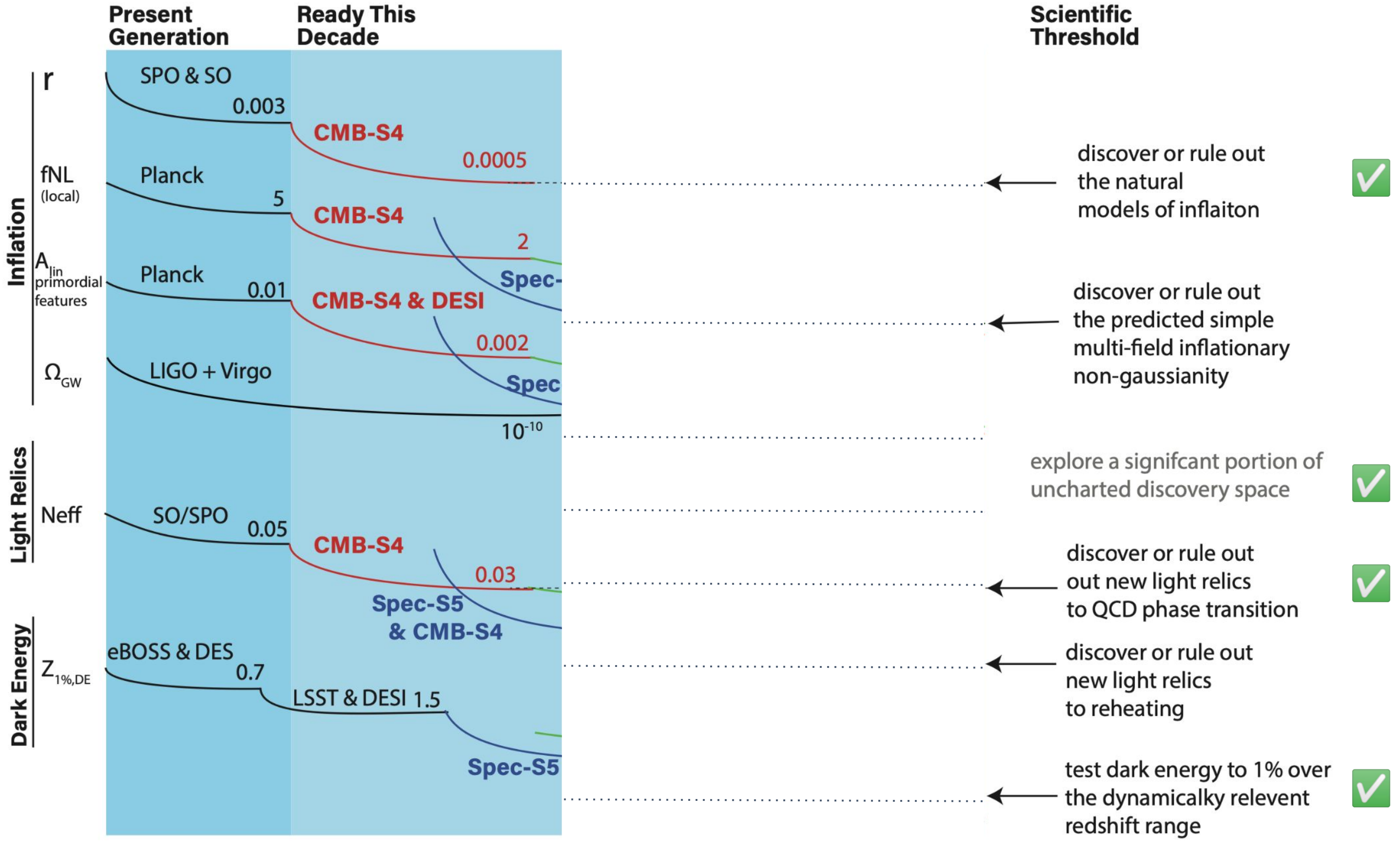


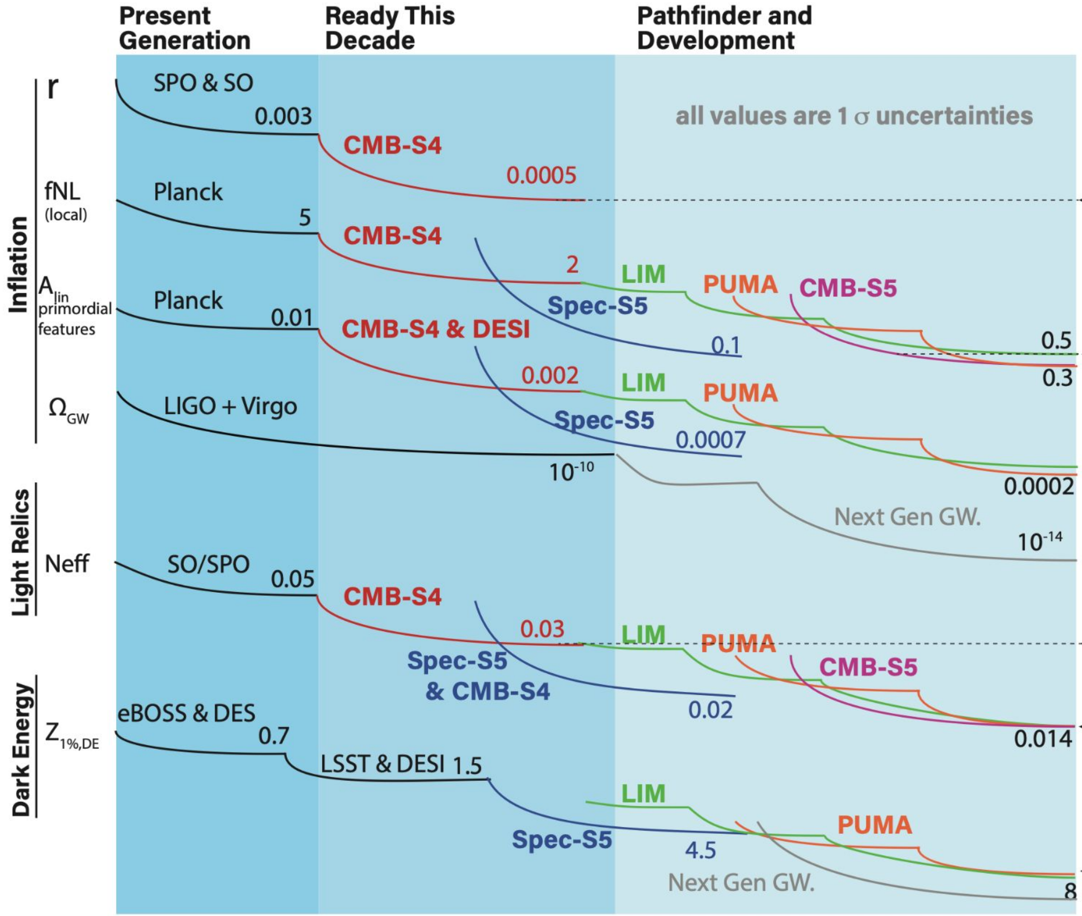
Is the inflationary paradigm realized in nature?

Did BSM degrees of freedom influence the thermal history of the universe?

Is dark energy a cosmological constant?

Not shown:
Neutrinos
Dark Matter


Present Generation
Ready This Decade
Scientific Threshold
Inflation
r
SPO & SO
0.003
CMB-S4
0.0005
fNL (local)
Planck
5
CMB-S4
2
Spec-
A lin primordial features
Planck
0.01
CMB-S4 & DESI
0.002
Spec
Ω GW
LIGO + Virgo
10-10
Light Relics
Neff
SO/SPO
0.05
CMB-S4
0.03
Spec-S5 & CMB-S4
Dark Energy
Z 1%,DE
eBOSS & DES
0.7
LSST & DESI 1.5
Spec-S5
discover or rule out the natural models of inflaiton
discover or rule out the predicted simple multi-field inflationary non-gaussianity
explore a signifcant portion of uncharted discovery space
discover or rule out out new light relics to QCD phase transition
discover or rule out new light relics to reheating
test dark energy to 1% over the dynamicalky relevent redshift range



discover or rule out the natural models of inflaiton ✅

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test dark energy to 1% over the dynamicalky relevent redshift range ✅✅

Community consensus

In the dark energy and cosmic acceleration community, we are pursuing the vision outlined for current experiments while fully engaged in a new vision for this upcoming decade and beyond.

Specific areas with strong community consensus are:

- Carry out cross-survey science and leverage ongoing/planned projects
- Completion of CMB-S4
- Roadmap to Stage-5 spectroscopy project
- Pathfinders for new opportunities: GW and 21cm/LIM

An approximate timeline

- **2023-2036: Build & operate CMB-S4 (current large project)**
- 2023-2036: Science with DESI, LSST, CMB-S4
- 2023-2025: Pathfinder for 21cm (LuSEE-Night)
- 2024-2027: Pathfinder for Spec-S5 target selection (DESI-II)
- **2024: Target date for CD-0 for Spec-S5 (next large project)**
- 2025-2029: Pathfinders for next-generation GW Observatory
- 2027-2029: Pathfinders for 21cm/mm-wave line intensity mapping
- **2029: Begin CD process for LIM, GWO (future large project)**

Summary

This talk presented prospects for dark energy research in the next decade and beyond.

The community approaches the problem with observables that are both well-established (e.g., galaxy clustering, supernovae) and novel (e.g., standard sirens).

Driven by new detectors and instruments, we expect an exponential growth in the impact of this multi-messenger cosmology program in future years.

The future is bright for dark energy research!