Cosmic Evolution: Late Universe

Rachel Mandelbaum (Carnegie Mellon University)
May 2024

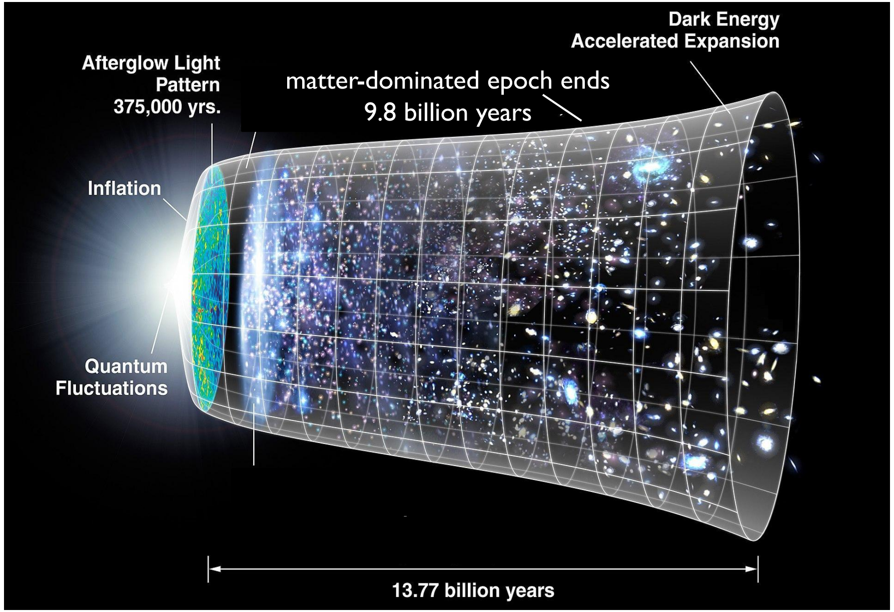
How do cosmological measurements tell us about fundamental physics?

We want to understand the fundamental physics describing the Universe.

Current cosmological paradigm describes a broad range of cosmological observations at the ~10% level. It includes

- initial conditions created by inflation,
- dark matter & dark energy to describe expansion history and growth of structure,

which are all beyond standard model physics.



adapted from NASA/WMAP

Using cosmic surveys as a probe of fundamental physics

The standard cosmological model in simplest form assumes:

- General Relativity (GR) is the correct theory of gravity on cosmic scales
- Dark matter is weakly interacting and cold
- Dark energy is constant in space and time
- Primordial fluctuations come from single-field, slow-roll inflation with a simple potential
- The only "light" degrees of freedom are 3 neutrino species.

Departures from any of these assumptions = major breakthrough in fundamental physics.

Observations to refine & stress-test these assumptions are essential: sharpen precision, extend to new epochs of the universe or distance scales, and/or measure new phenomena.

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P5: Determine the Nature of Dark Matter

P5: Understand What Drives Cosmic Evolution

P5: Elucidate the Mysteries of Neutrinos

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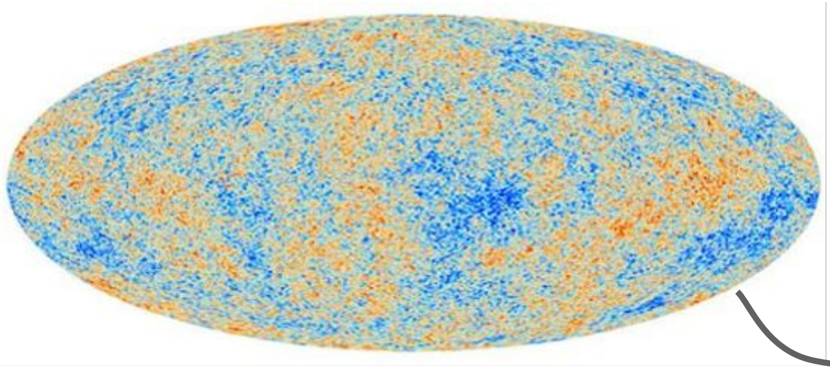
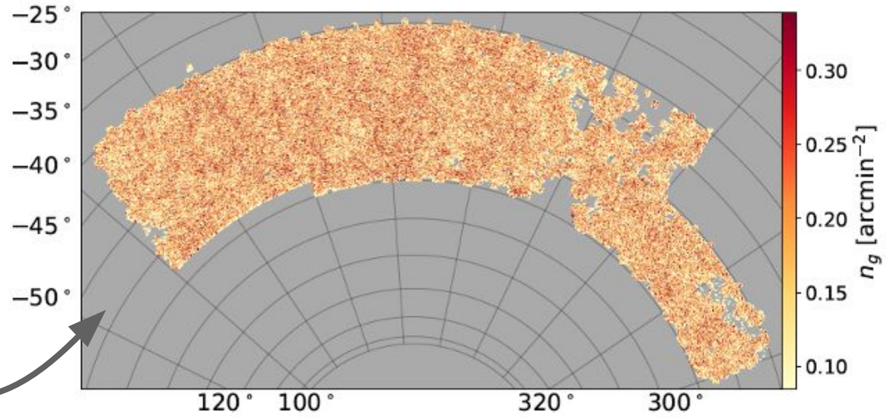
Early vs. late Universe observations are *broadly* explainable in a consistent way

Uniform to 1 part in 10^5, can treat through linear perturbation theory

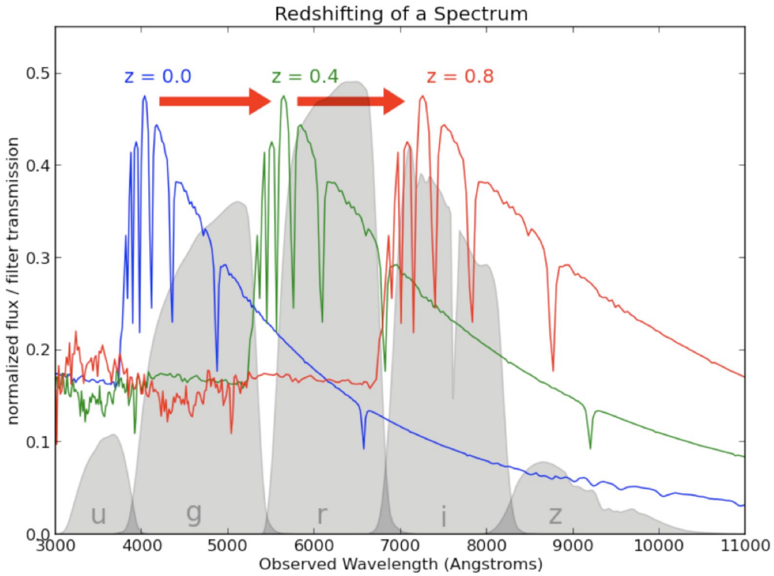


Highly inhomogeneous; nonlinear



As Universe expanded, gravity amplified small overdensities into the rich structure seen today

Late Universe measurements & redshift



http://www.astroml.org/sklearn_tutorial/regression.html

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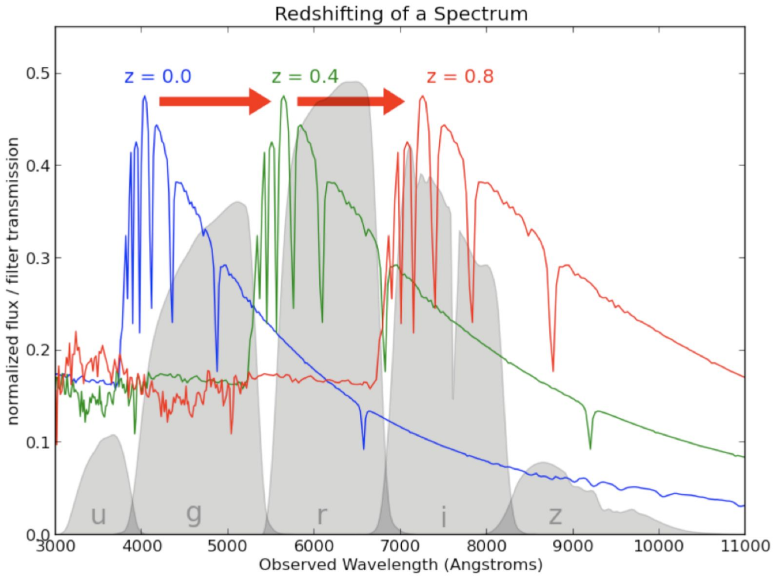

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Redshift in an expanding Universe connects to distances, given a cosmological model.

Measuring spectra (“spectroscopy”):

- Precise, expensive redshift estimates
- Surveys are multiplexed (observe 100s-1000s of galaxies at once)

Measuring images in broad passbands/filters:

- Imprecise redshift estimates…
- …but many more galaxies per unit time

Two flavors of late Universe measurements

Direct measurement of distance-redshift relation (e.g., "standard candles", "standard rulers")

Two flavors of late Universe measurements

Standard ruler: angle subtended by known scale.

- *Cosmic Microwave Background (CMB):* angular scale of sound horizon in early Universe.
- *Baryon Acoustic Oscillations (BAO):* angular scale of sound horizon imprinted in the late-time galaxy distribution.

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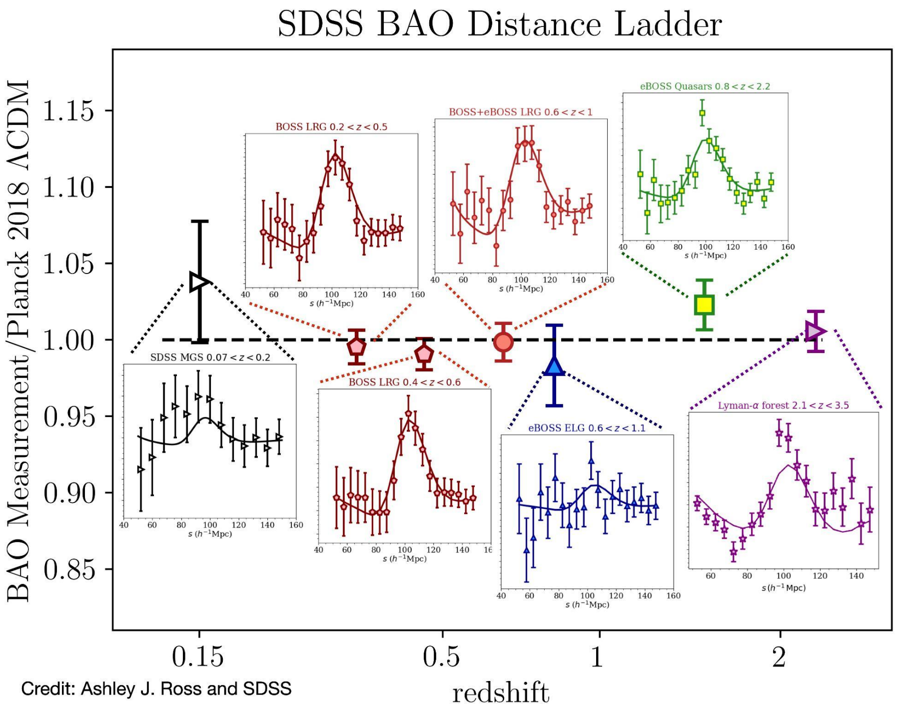
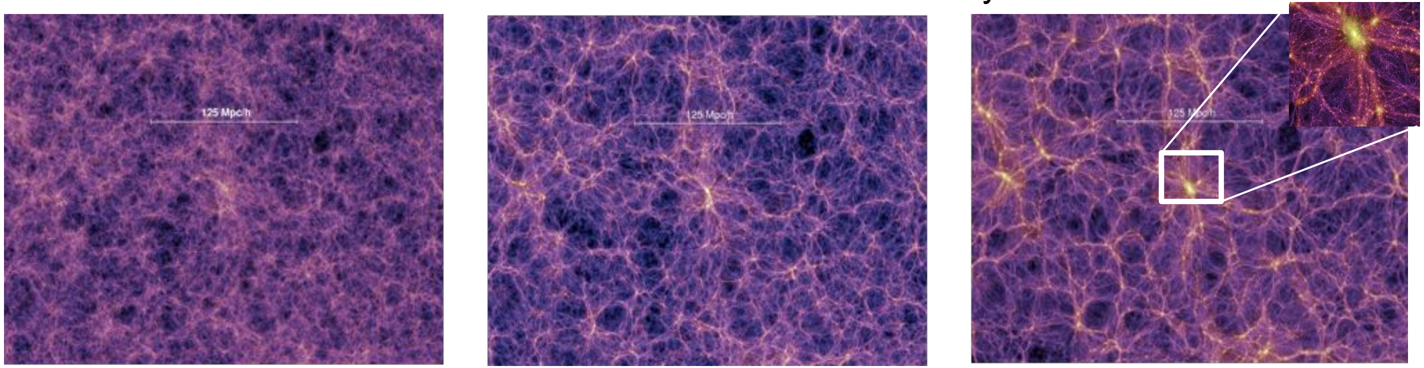


Credit: Ashley J. Ross and SDSS

Two flavors of late Universe measurements

simulated evolution of dark matter density



t = 1.0 Gyr   t = 4.7 Gyr   t = 13.6 Gyr

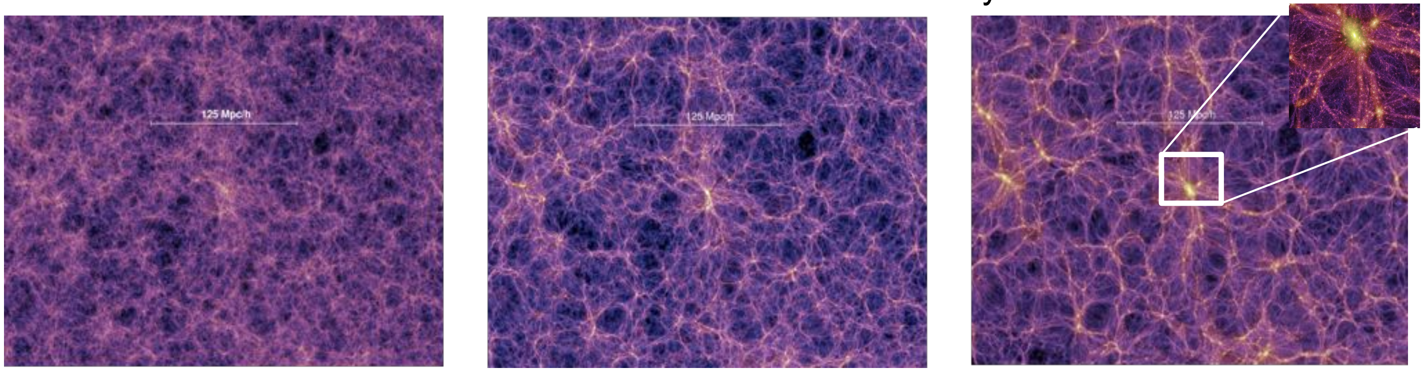
Springel et al. 2006

Two flavors of late Universe measurements

Gravity drives **cosmic structure growth**, while dark energy slows it down.

- Massive neutrinos, inflation impart characteristic scale dependences.
- Non-linear structure: powerful test of dark energy/nature of gravity, enables astrophysical probes of dark matter; simulations essential for interpretation.

simulated evolution of dark matter density



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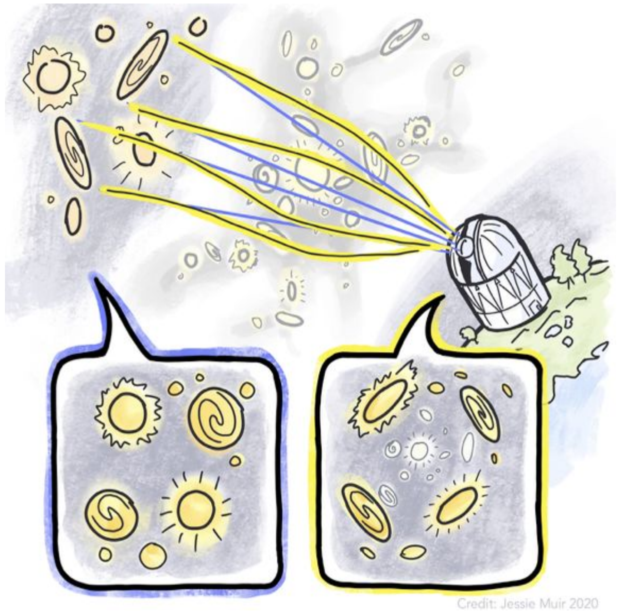
Example: measuring cosmic structure growth

Weak Lensing: deflection of photons by large-scale tidal field ➔ coherent distortion of background galaxies’ shapes (or of CMB field!) probes total foreground matter distribution.



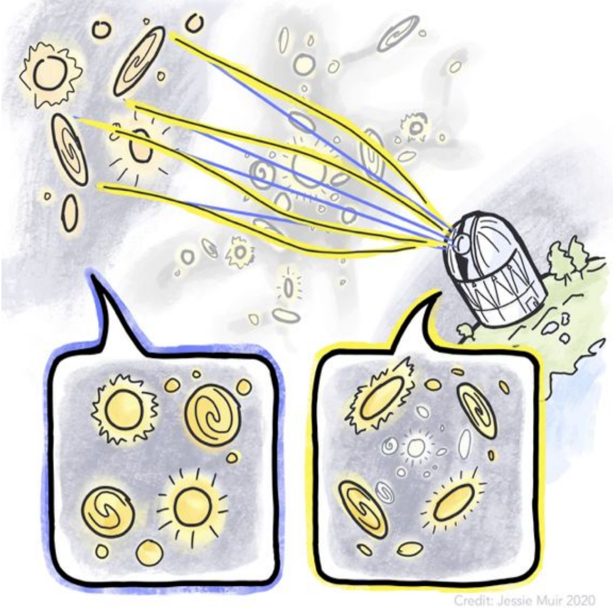
Jessie Muir/DArchive

Example: measuring cosmic structure growth

Weak Lensing: deflection of photons by large-scale tidal field → coherent distortion of background galaxies' shapes (or of CMB field!) probes total foreground matter distribution.

- Total is dominated by dark matter
- Per galaxy S/N << 1 → average over very large numbers of galaxies.
- Requires multi-band imaging for redshifts.

Current surveys (DES, HSC, KiDS) measure **amplitude of cosmic structure fluctuations, S_8**, to ~5%, will reach 0.5% precision with Rubin.



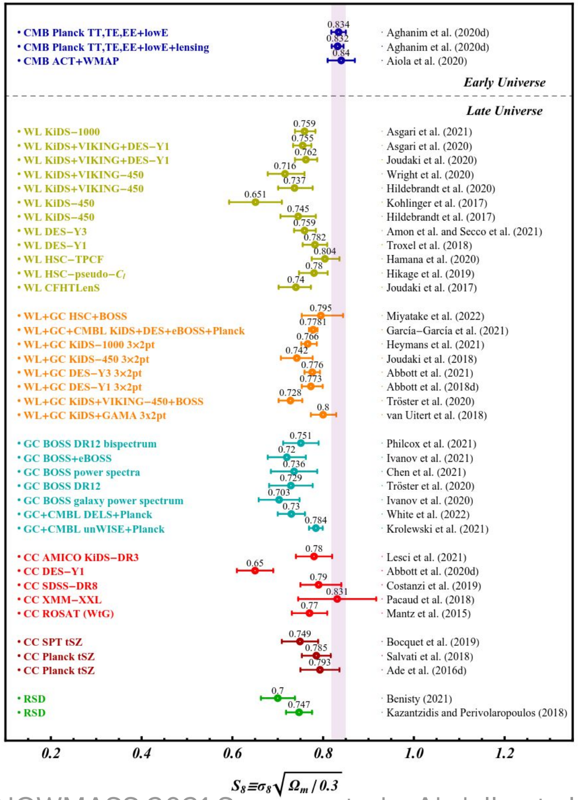
Jessie Muir/DArchive

Galaxy surveys and cosmological probes

Galaxy surveys are generally designed to enable precise measurements of *at least two cosmological probes*:

- Different dependence on cosmological model ➜ increased constraining power, degeneracy breaking
- Different dependence on observational systematics and theoretical uncertainties brings robustness

Early vs. late Universe tensions



CMB

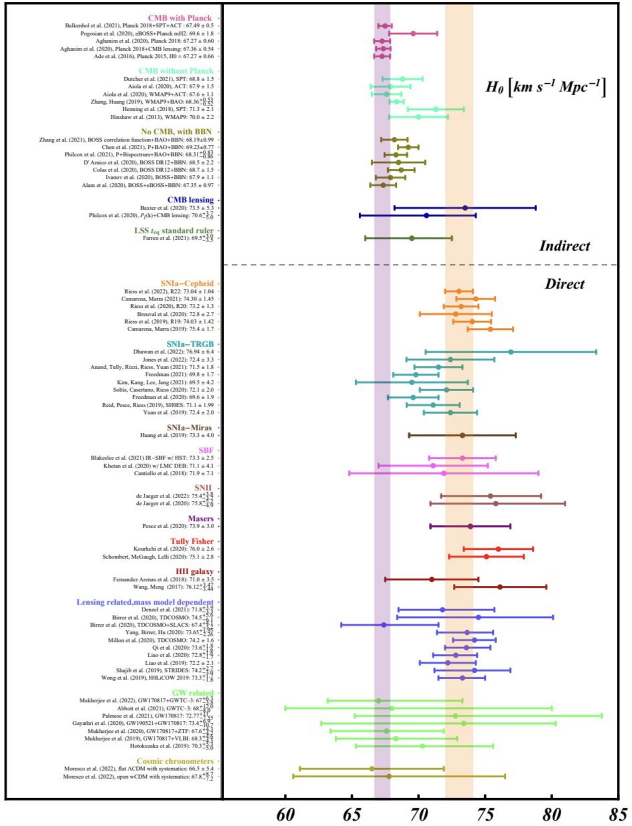
Late Universe

Takeaway: when interpreted within ΛCDM, early and late-time measurements of the amplitude of matter fluctuations are modestly in tension.

SNOWMASS 2021 Summer study: Abdalla et al. (2022)

Early vs. late Universe tensions

Takeaway: when interpreted within ΛCDM, early and late-time measurements of the Hubble parameter are in tension.



Early Universe observations + ΛCDM

Late Universe direct measurements

Early vs. late Universe tensions

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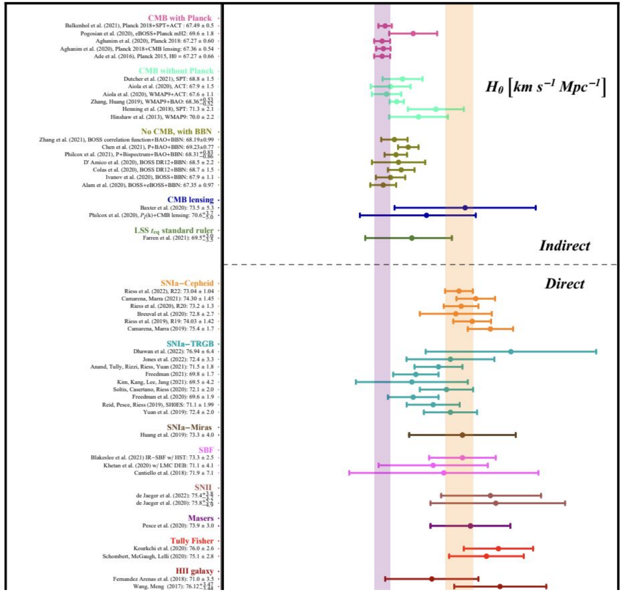
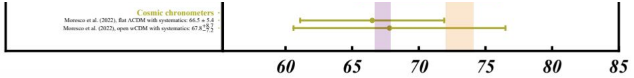


Early Universe observations + ΛCDM

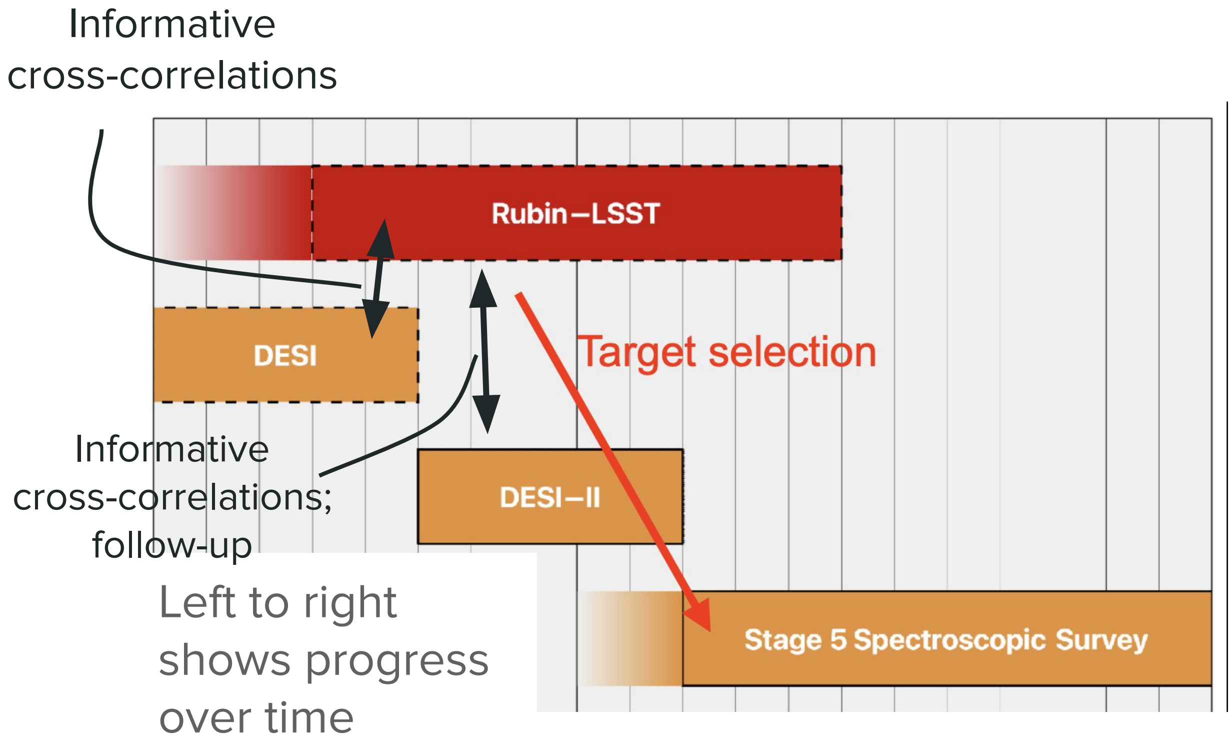
Late Universe direct measurements

Ongoing and upcoming program of galaxy surveys will determine whether this tension is due to real physics, systematics, or statistical fluctuations.



Spectroscopic surveys

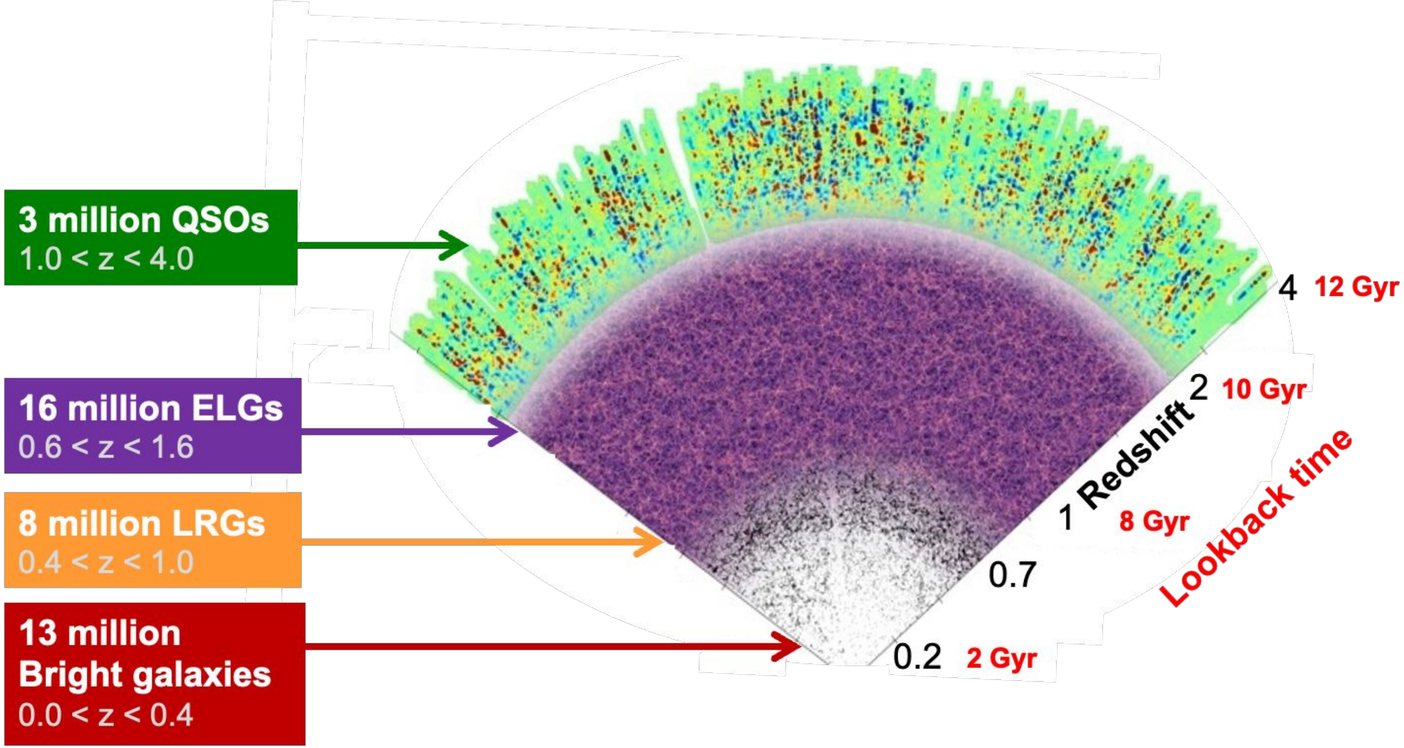
Current & future spectroscopic surveys



Adapted from Snowmass CF6 report

- A sequence of spectroscopic surveys is planned
- Connected to concurrent imaging surveys in a few ways

DESI: Dark Energy Spectroscopic Instrument – and its 40+ million galaxies and quasars

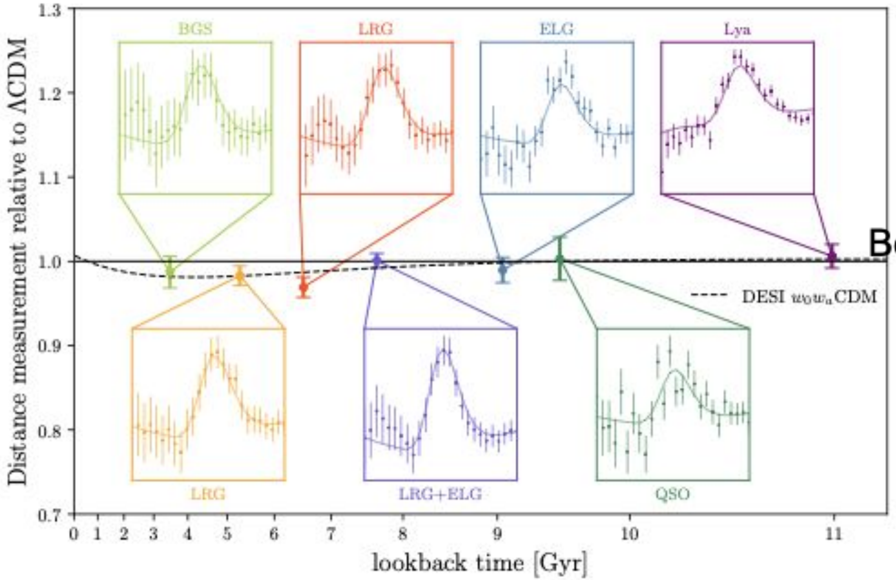


Precision of measured distances from baryon acoustic oscillations will be <0.5% for z<2, <1% for 2<z<4

DESI year 1 baryon acoustic oscillations

BAO data $\Delta\theta$ and $\Delta z \rightarrow D_M / r_d$ and D_H / r_d ➡ Ω_M and $H_0 r_d$

$$D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$



Best ΛCDM fit

Figures from https://data.desi.lbl.gov/doc/papers/

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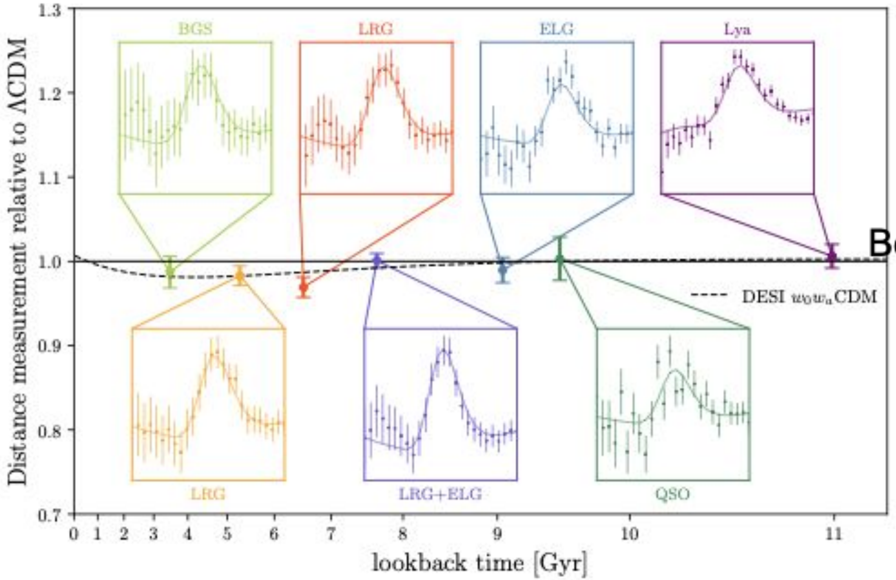

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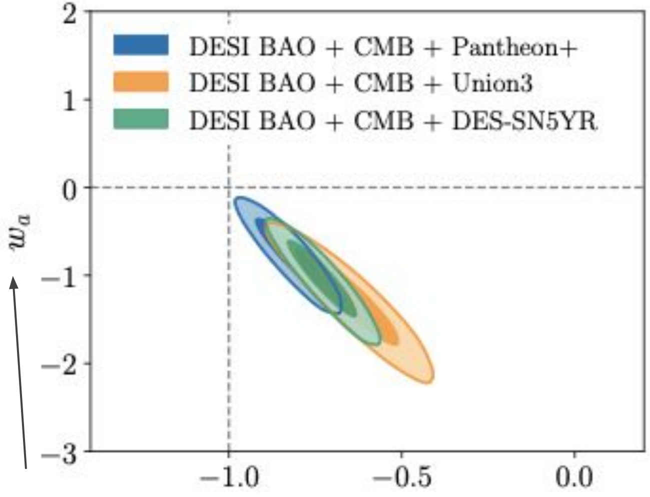
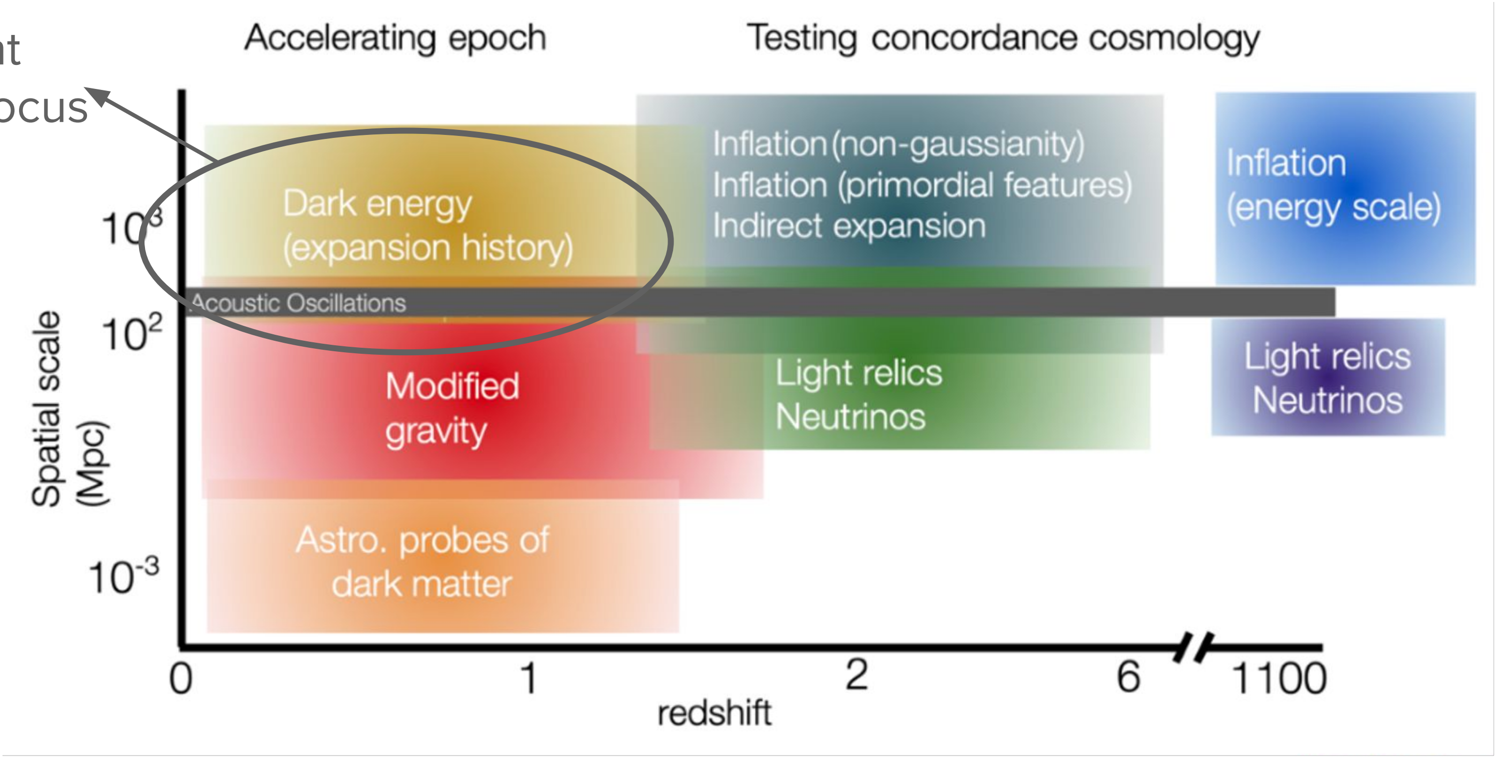
Few-σ tension with ΛCDM when combined with other datasets:



Dark energy equation of state parameters

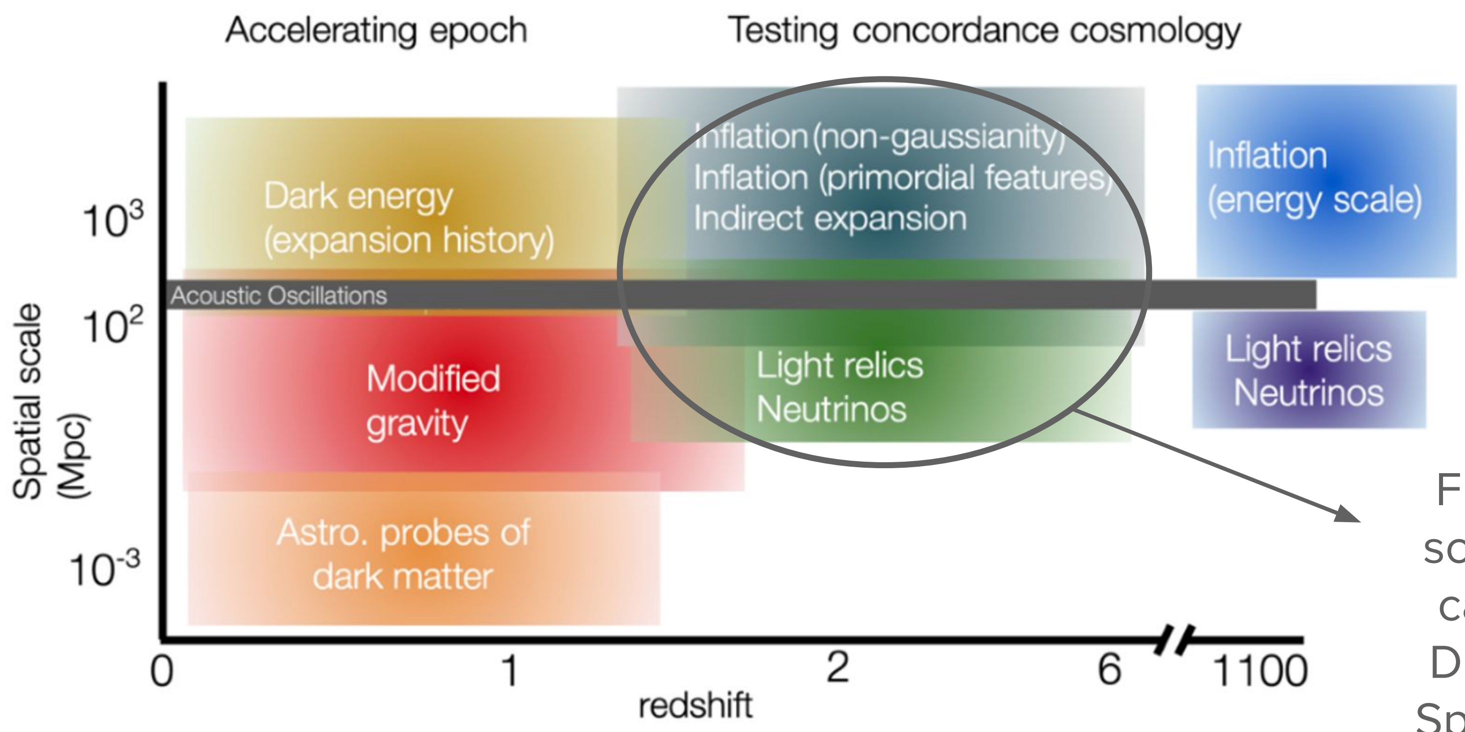
Spectroscopic survey science cases will evolve

Current DESI focus



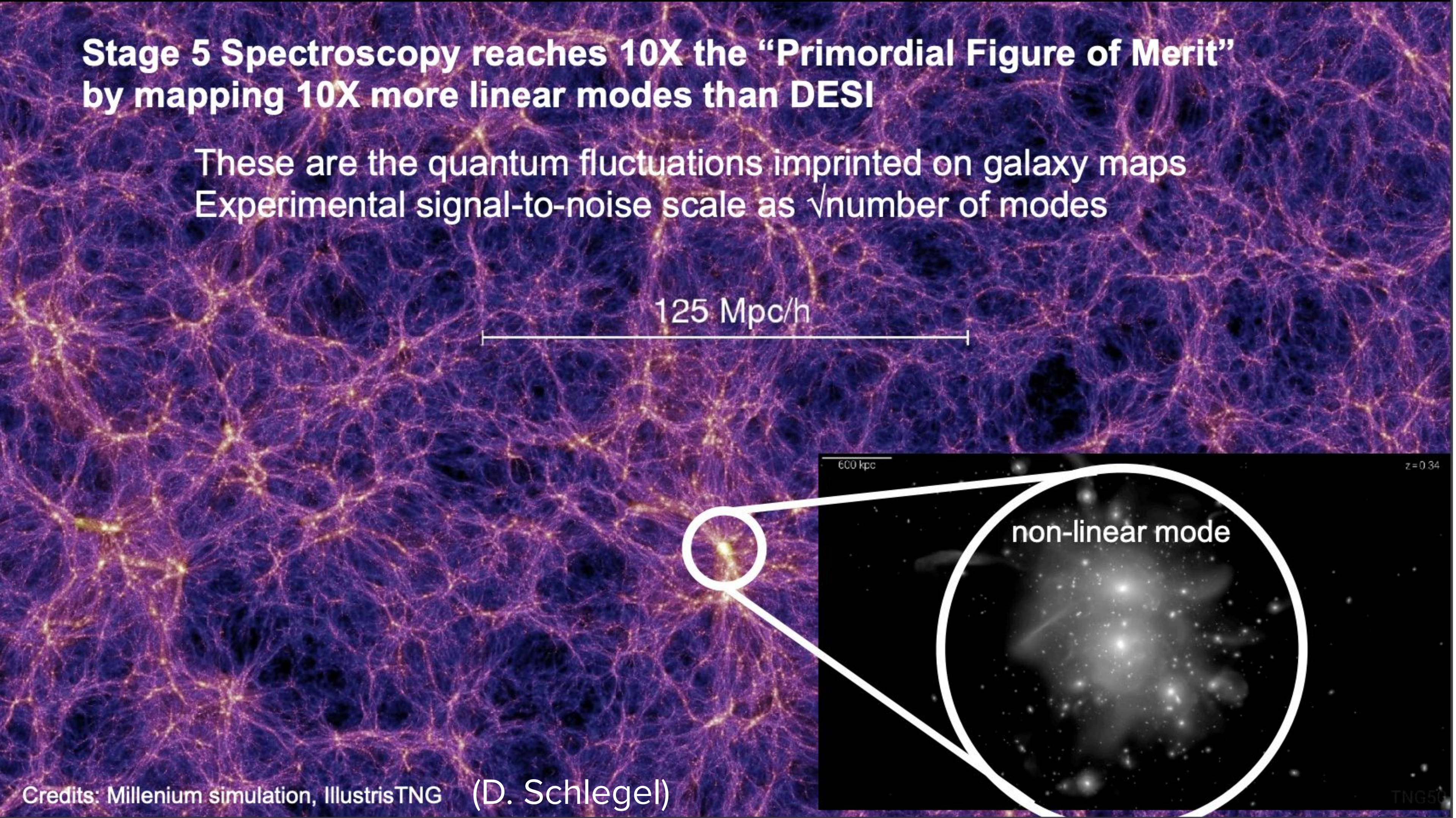
From Kyle Dawson

Spectroscopic survey science cases will evolve



Future science cases: DESI-II, Spec-S5

From Kyle Dawson


Stage 5 Spectroscopy reaches 10X the "Primordial Figure of Merit"
by mapping 10X more linear modes than DESI
These are the quantum fluctuations imprinted on galaxy maps
Experimental signal-to-noise scale as √number of modes
125 Mpc/h
600 kpc
z = 0.34
non-linear mode
Credits: Millenium simulation, IllustrisTNG
(D. Schlegel)

How future spectroscopic surveys expand scientific reach of these observations

Stage 5 Spectroscopy extends to more volume + smaller scales + longer redshift range than DESI

Modes reflect initial conditions, less affected by late-time astrophysics

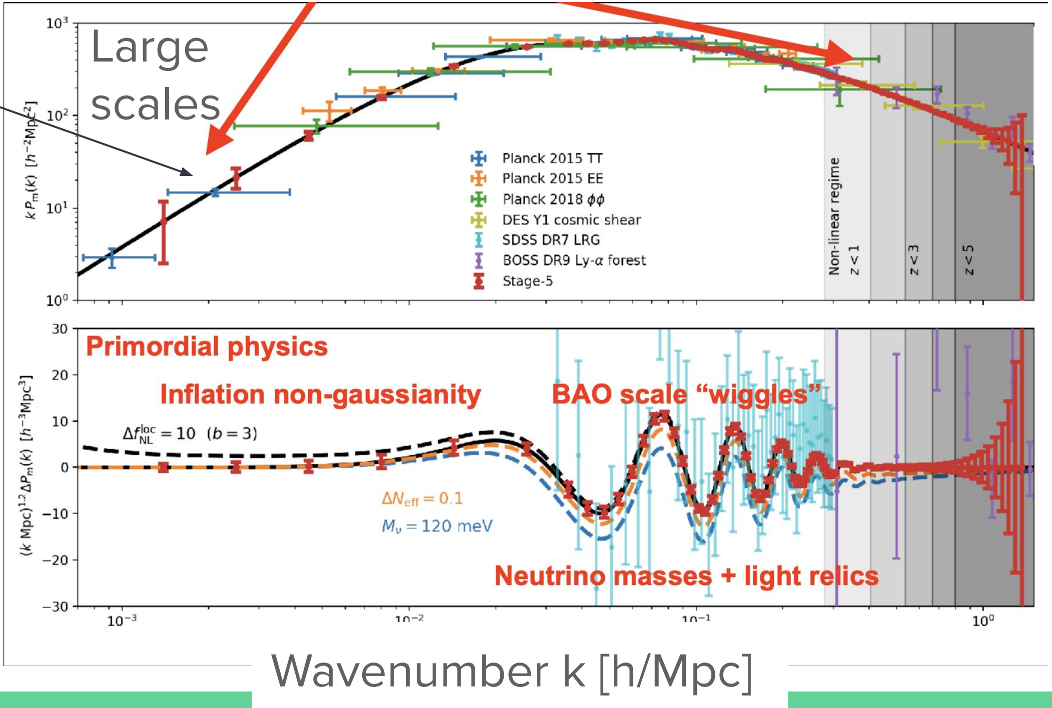


Figure credit: David Schlegel, adapted from Sailer+21

Imaging surveys

The landscape of imaging surveys

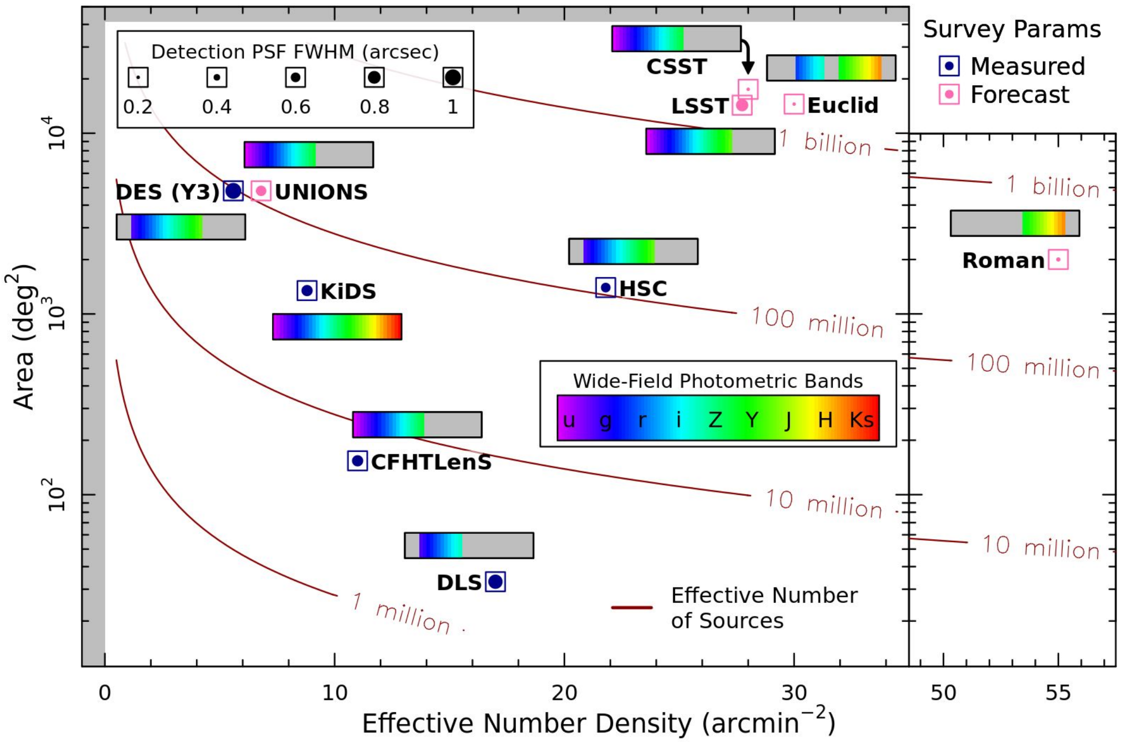


Figure credit: Angus Wright (GCCL)

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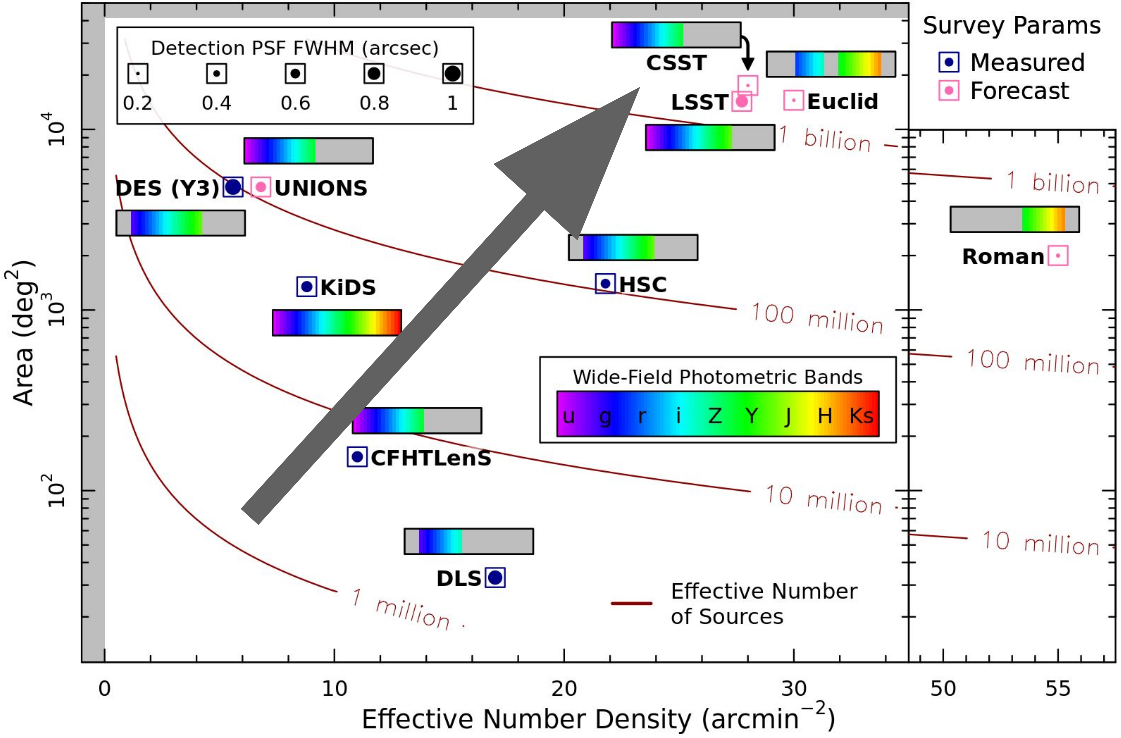

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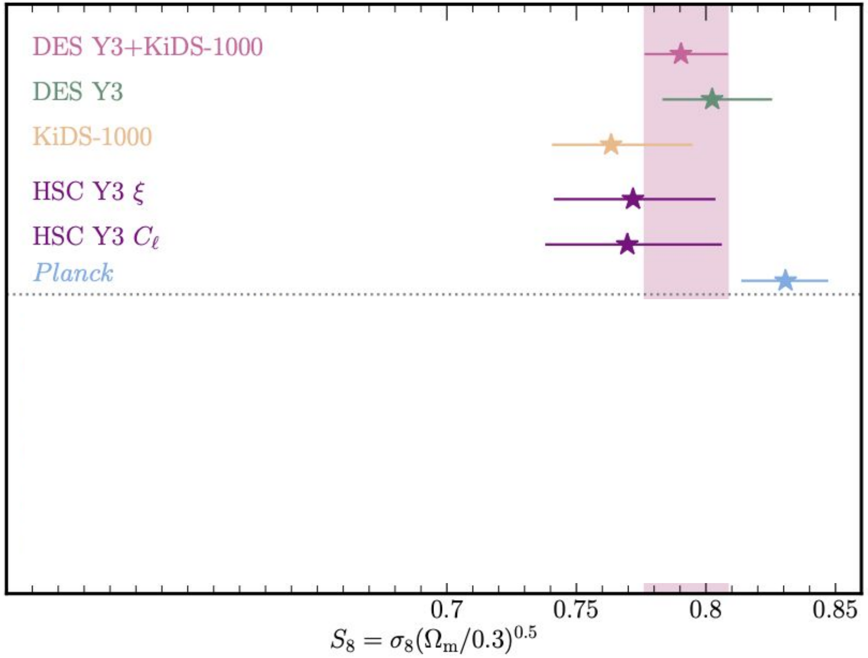
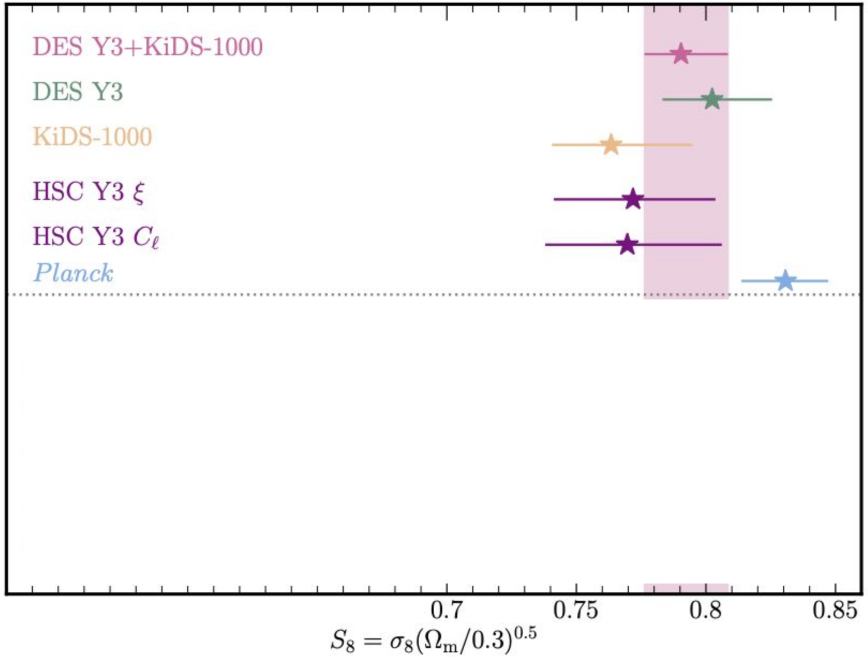
Structure growth measurements in current imaging surveys



Dark Energy Survey and Kilo-Degree Survey Collaboration (2023)

Structure growth measurements in current imaging surveys



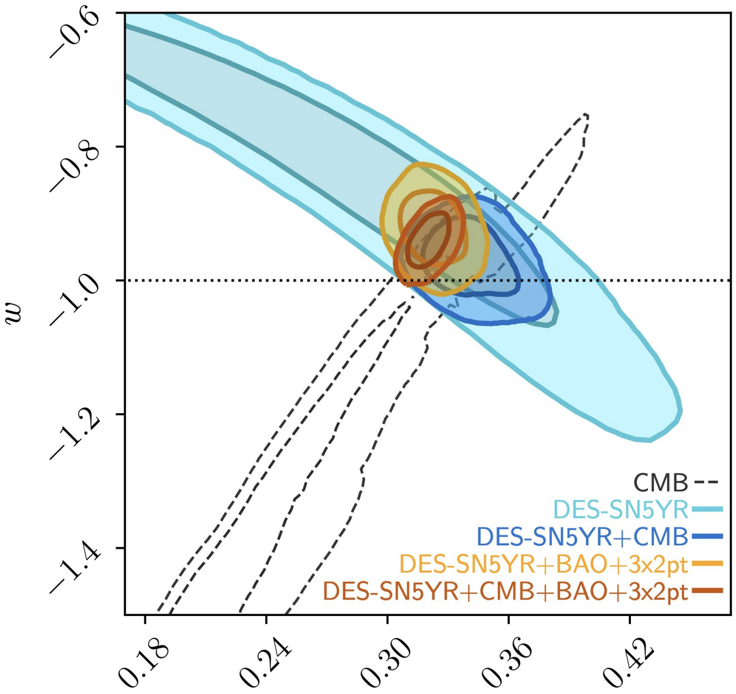
Dark Energy Survey and Kilo-Degree Survey Collaboration (2023)

- Current survey datasets have few-% uncertainties in amplitude of matter fluctuations
- Individual survey measurements are not fully independent & have different model assumptions; are just starting to be meaningfully combined

Example from DES: probing distances

Supernovae (SNIa) as standard candles:

- ~1600 photometrically classified SN with host redshifts
- DES collaboration (2024), arxiv:2401.02929
- All dataset combinations (SN+other) consistent with ΛCDM at 2σ



Matter density parameter Ω_m

Example from DES: structure growth

3x2pt (weak lensing and clustering)

- Galaxies as:
  - **Tracers** of structures,
  - **Background** light: shape affected by structures on the light of sight.
- DES Y3: 4% precision on cosmology

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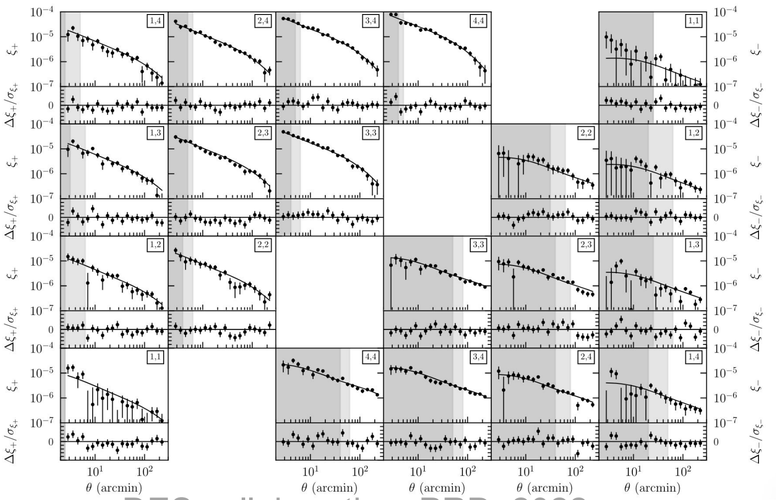

DES collaboration, PRD, 2022

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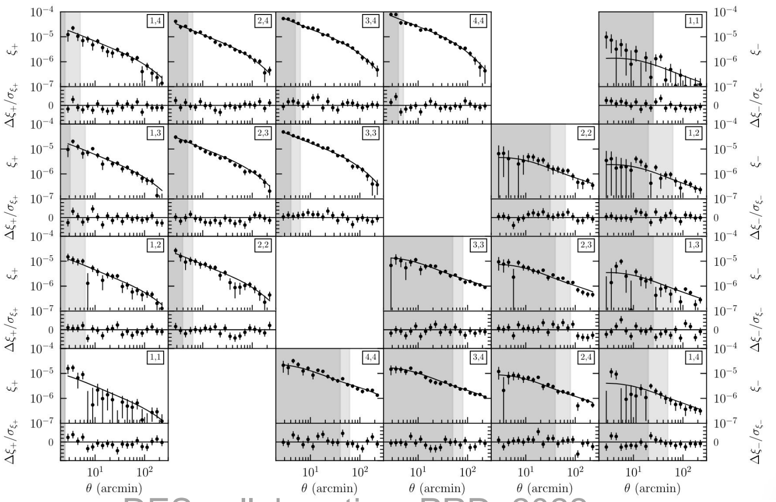

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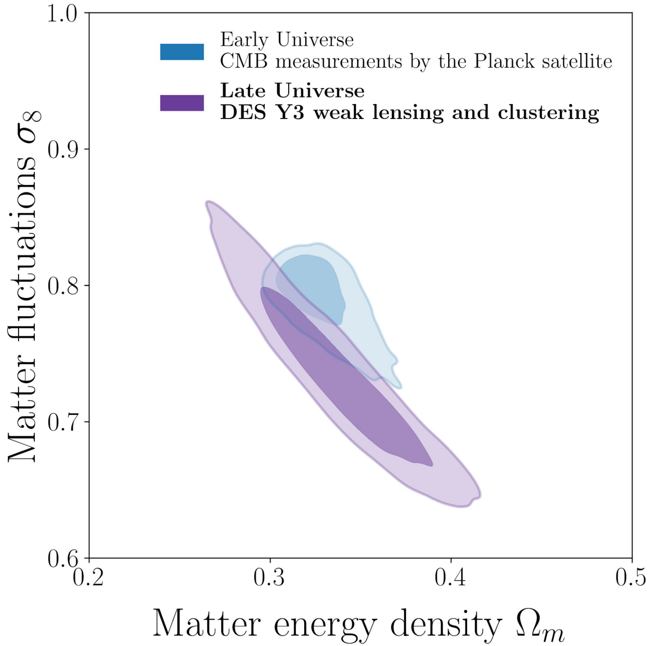

Looking towards the Vera C. Rubin Observatory

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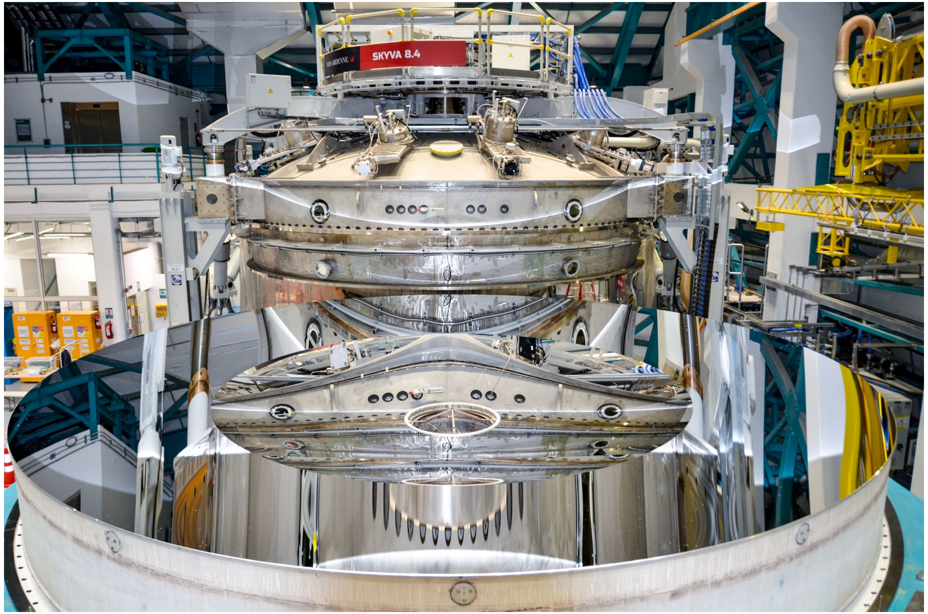
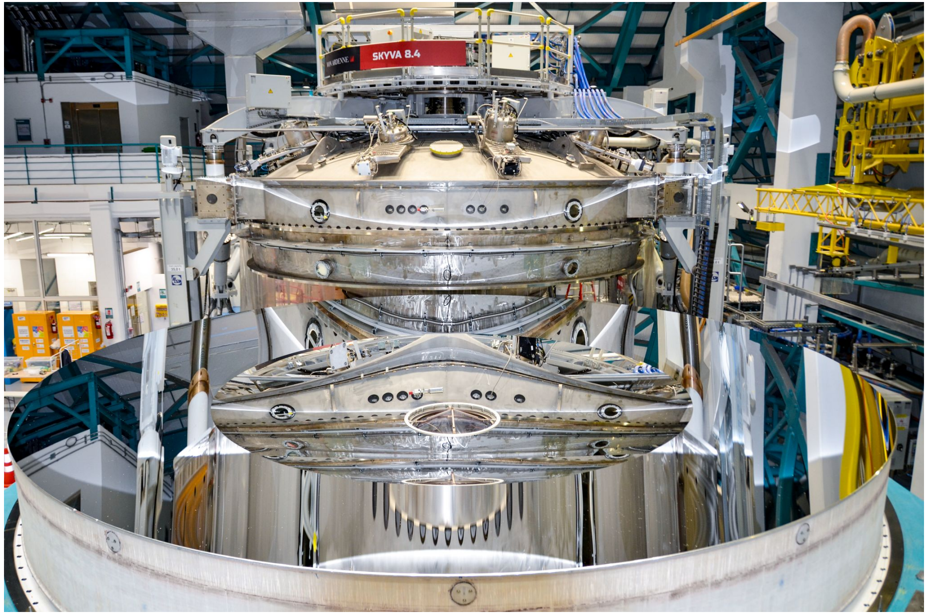


Image credit: Rubin Observatory

Looking towards the Vera C. Rubin Observatory

The Legacy Survey of Space and Time (LSST):

- 10 years of operation.
- ~1000x repeated imaging of the visible sky to produce a 10-year long color movie
- 10 million “alerts” each night
- 30 trillion observations
- 40 billion stars, galaxies, asteroids



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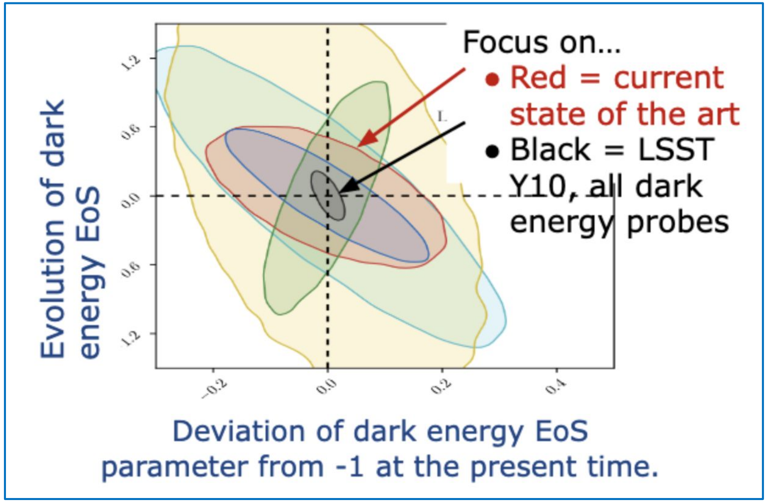
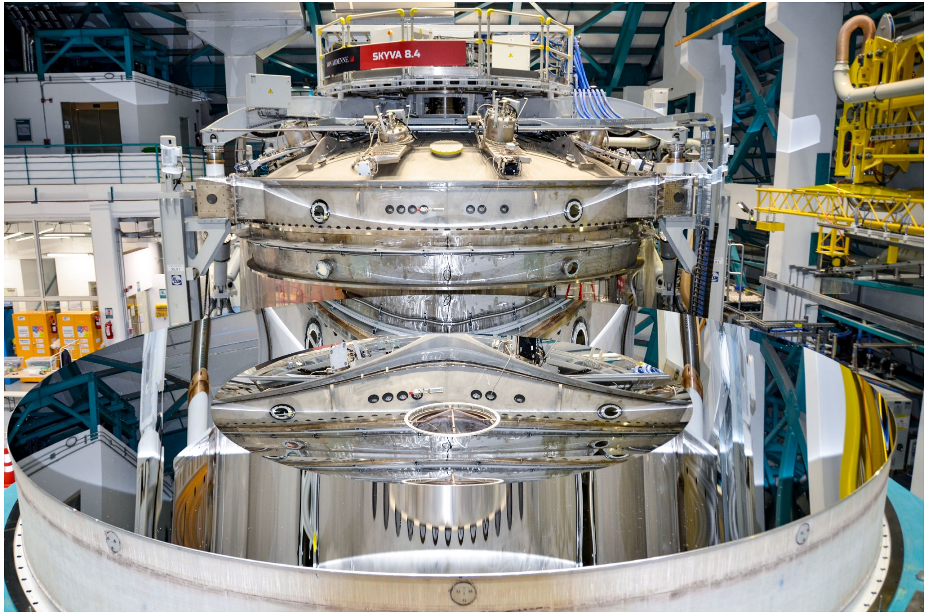


LSST DESC Science Requirements Document, arXiv:1809.01669



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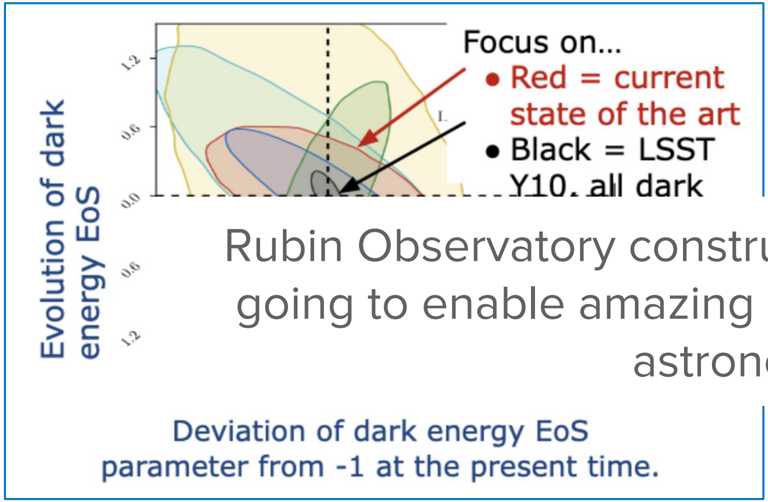

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Rubin Observatory construction is progressing rapidly – and it is going to enable amazing advances in fundamental physics and astronomy more broadly!

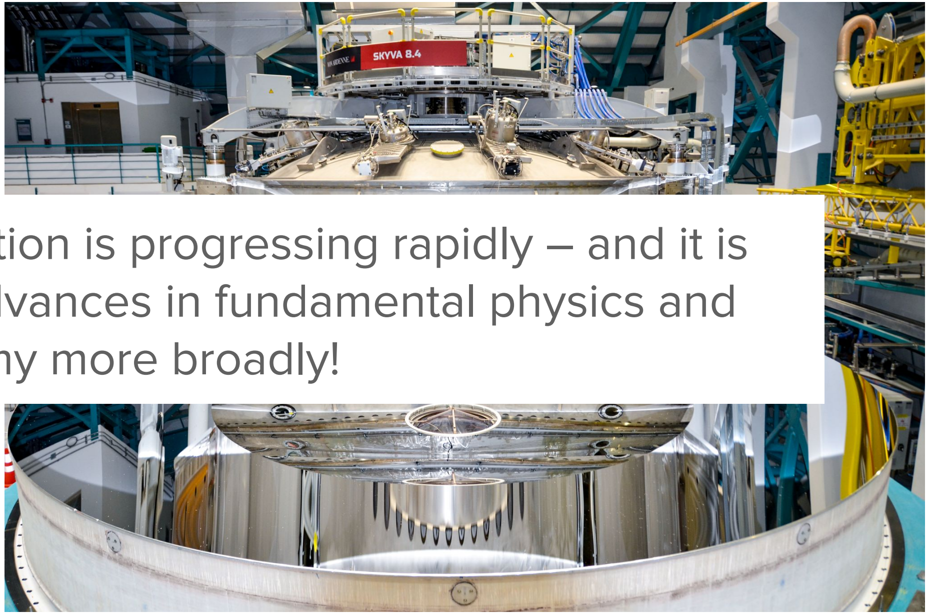
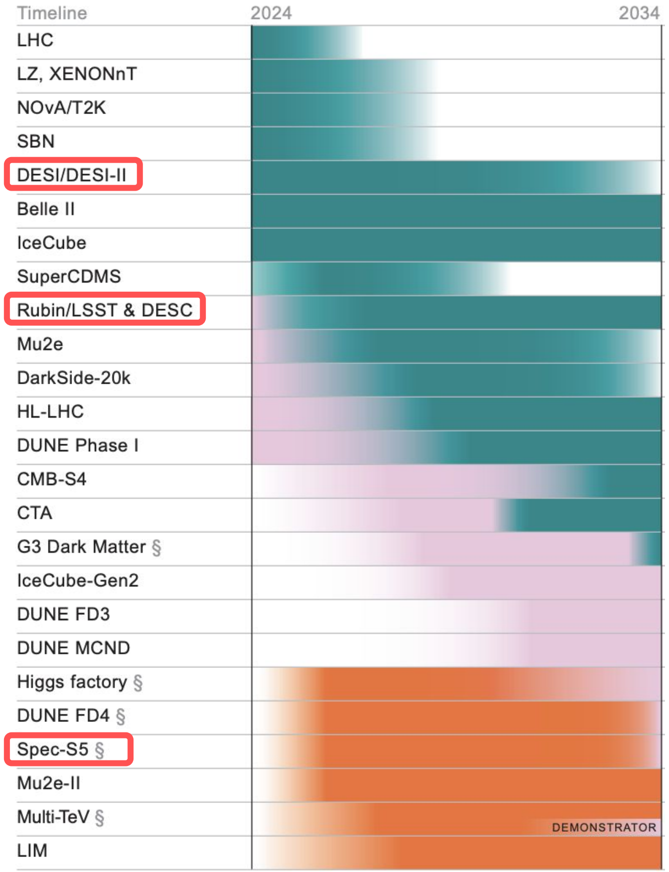


Image credit: Rubin Observatory

Fundamental physics with surveys of the late Universe



operations

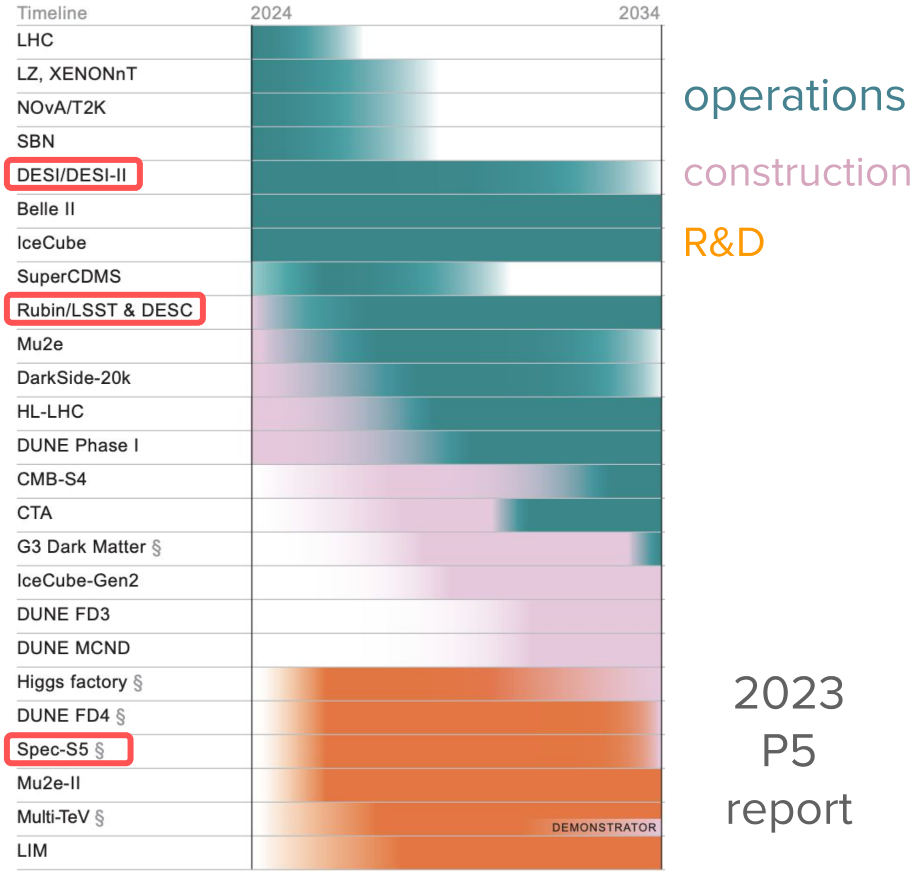
construction

R&D

2023
P5
report

Fundamental physics with surveys of the late Universe

- A comprehensive survey program covers the late Universe
- Current surveys have shown great power & future promise of combining multiple cosmological probes
- There has been enormous progress in systematics mitigation and modeling/simulation development; more is needed for future surveys
- These surveys are especially powerful probes of fundamental physics when combined with early Universe data



2023 P5 report

Acknowledgements

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