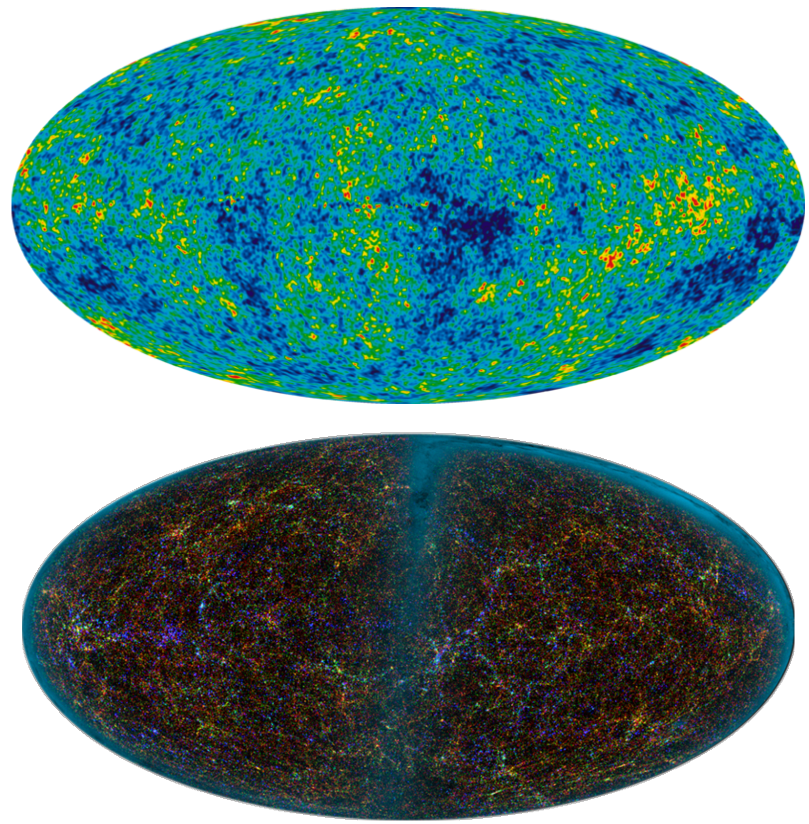
CF04: Dark energy & cosmic acceleration in the modern universe

All Cosmic Frontier Meeting

Jim Annis, Jeff Newman, Anže Slosar

Our questions are simple...



- Is ΛCDM the best model?
- Is GR correct on large scales, or not?
- How did large scale structure arise from the event of inflation?

but our data is extremely rich in science

The US Dark Energy Community

We work in big collaborations studying DE through a staged program of optical surveys

• SDSS I & II: “the survey”	2000-2008
• SDSS III: BOSS	2008-2014
• DES:	2013-2019
• SDSS IV: eBOSS	2014-2020
• DESI:	2021-2026
• Rubin Observatory: LSST/DESC	2024-2034

These collaborations have scientists working on
- instrumentation
- theory
- simulations
- analysis & computation
- machine learning

All doing cosmology

Without vibrant support for all these fields, our experiments could not progress.

Stage IV dark energy: DESI & Rubin's LSST

Snowmass 2021

- The 2013 Snowmass papers are a good overview of the aims
  - Much effort aimed at the ΛCDM expansion history $H(z) = H_0\,[\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_{DE}\,]^{1/2}$ and
  - whether in $\Omega_{DE}\,(1+z)^{1+w}$ the equation of state parameter $w = -1$
- The Snowmass process is future oriented: 10+ year horizon

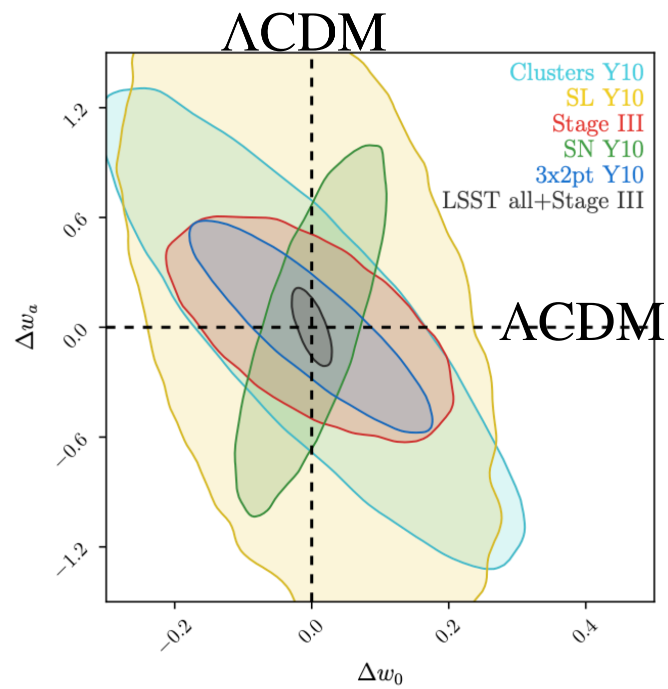
Enabling Flagship Dark Energy Experiments to Reach their Full Potential

Snowmass 2021

CF04 invited white paper

Editors: Dickinson, Kim, Nugent, Newman

- LSST aims at DE to $\Delta w_0 < 0.02$ and $\Delta w_a < 0.14$
- DESC SRD forecasts assume systematics contribute as much to errors on w_0, w_a as random uncertainties:
  - reducing LSST systematics can ~double its DETF Figure of Merit
- **High-multiplex spectroscopy reduces key systematics**
  - photo-z errors, intrinsic alignments systematic reduction
  - cluster membership and velocities, which also helps CMB-S4
- **Targeted follow-up spectroscopy on 2-40m telescopes**
  - strong lensing time delays for H(z)
  - SN peculiar velocities for structure growth



Mandelbaum et al. 2018, LSST DESC SRD

Rubin Observatory after LSST

Snowmass 2021

CF04 contributed white paper

Authors: Blum, Digel, Drlica-Wagner, Habib, Heitmann et al.

See CF03's: *Vera C. Rubin Observatory as a flagship dark matter experiment*

- Rubin Observatory has a world-leading wide field of view camera & large aperture telescope
- LSST will finish in 2034.
- There is flexibility and opportunity in what comes next, but as LSST data hasn't started to flow, it is too early to understand Rubin's next best use.
- New observing strategies and instruments are possible:
  - Observing modes:
    - **Gravitational wave event standard siren follow up to measure H(z) with an exciting new messenger**
    - Strongly lensed AGN and supernova
    - Microlensing
    - Proper motions of dwarf galaxy stellar populations
  - Instruments:
    - A new filter set offset in wavelength from u,g,r,i,z,y
    - Narrow band filters for selecting emission lines at a given redshift
    - Replace LSSTCam with a different instrument, e.g. a camera with NIR sensors or a MOS
- Best strategy is to re-examine the options for the leadership asset at mid-decade.

Real-time cosmology with high precision spectroscopy and astrometry

CF04 invited white paper

Authors: Chakrabarti, Gonzalez et al.

Instrumentation R&D is required

Acceleration measurements

Science

- Cosmic acceleration via dz/dt
- Galactic acceleration - Milky Way dark matter sub-structures to $\sim 10^6 M_\odot$

Key Technologies

- Externally dispersed interferometry
- Actively stabilized spectrographs

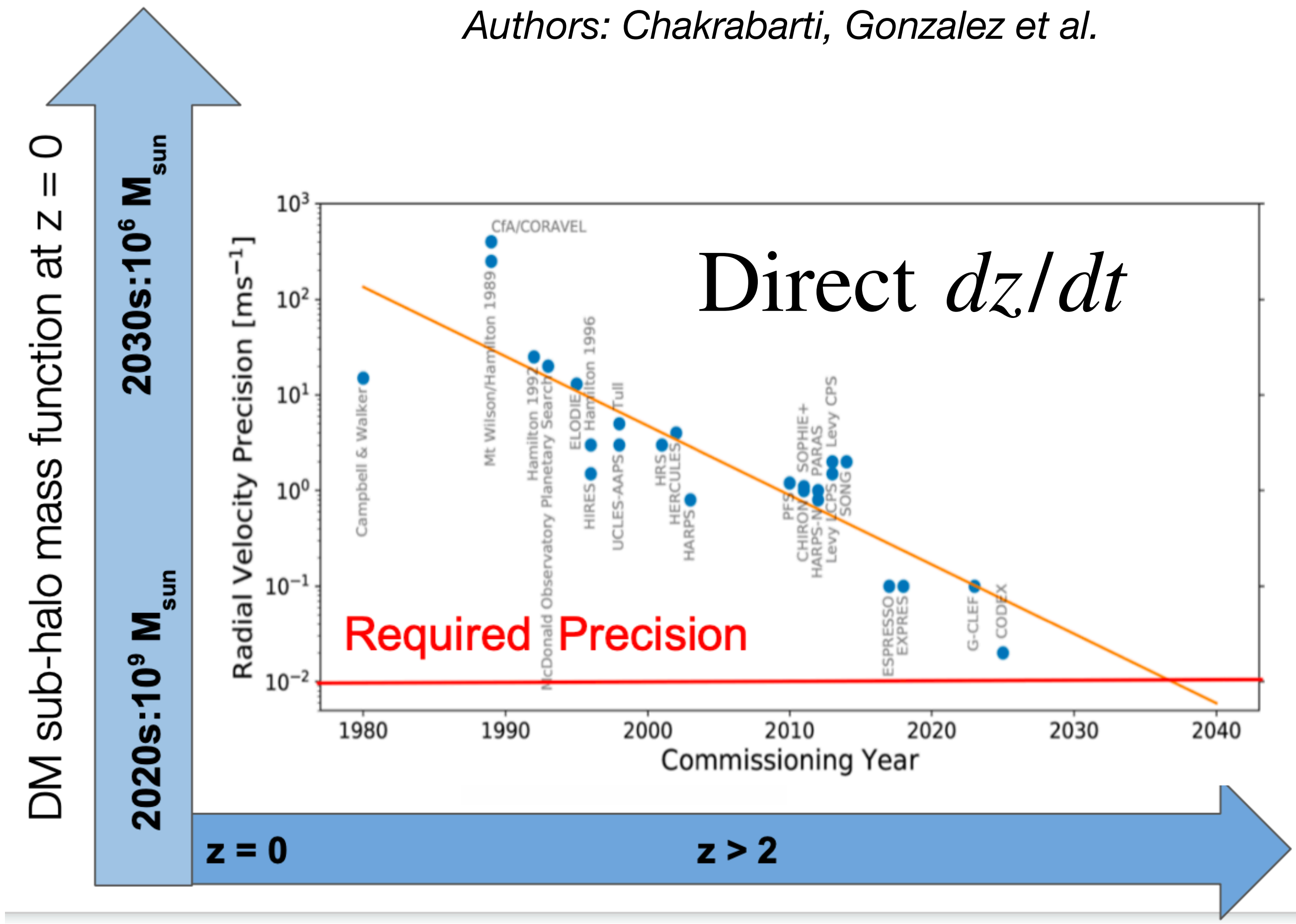
Astrometry

Science

- Parallax at cosmological distances
- Milky Way dark matter substructure

Key Technologies

- Quantum-assisted interferometry



Community Roadmap

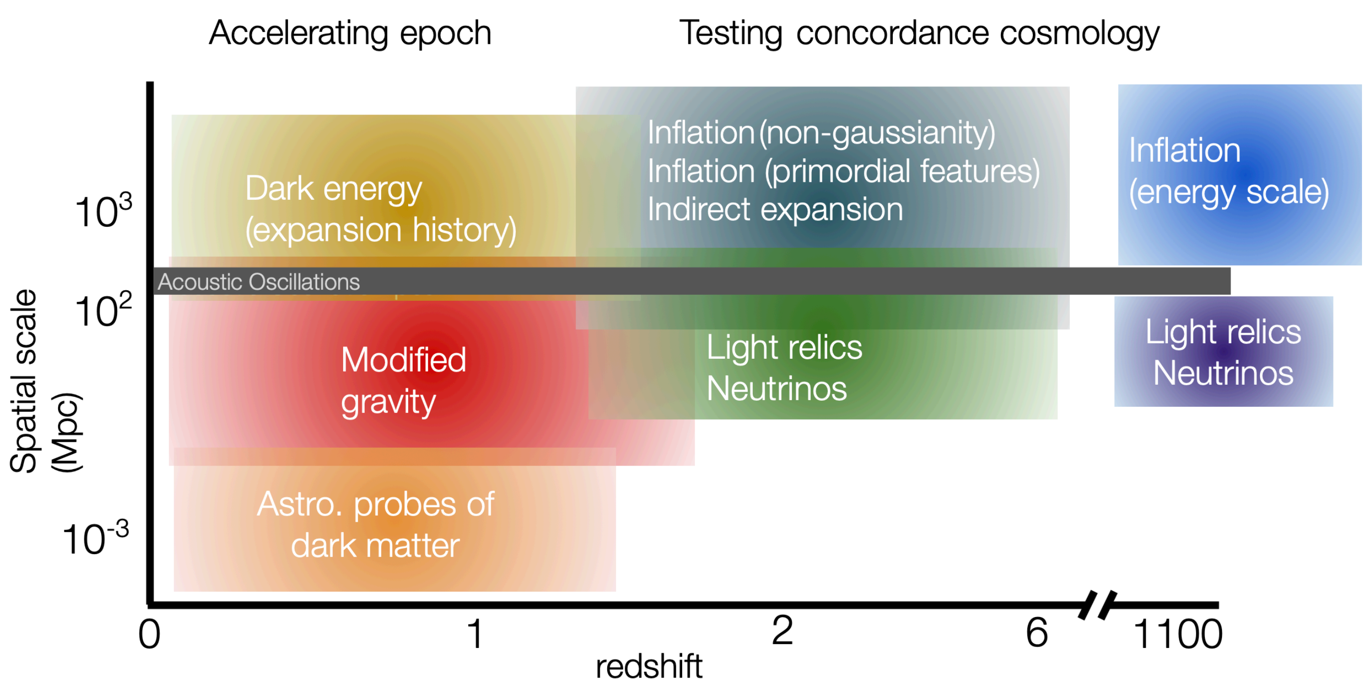
Data Discovery Space

The Snowmass process is future oriented: 10+ year horizon

The community sees open discovery space in our realm for the 2030s

Open questions span many orders of magnitude in scale

The community has developed new ideas that allow us to explore these

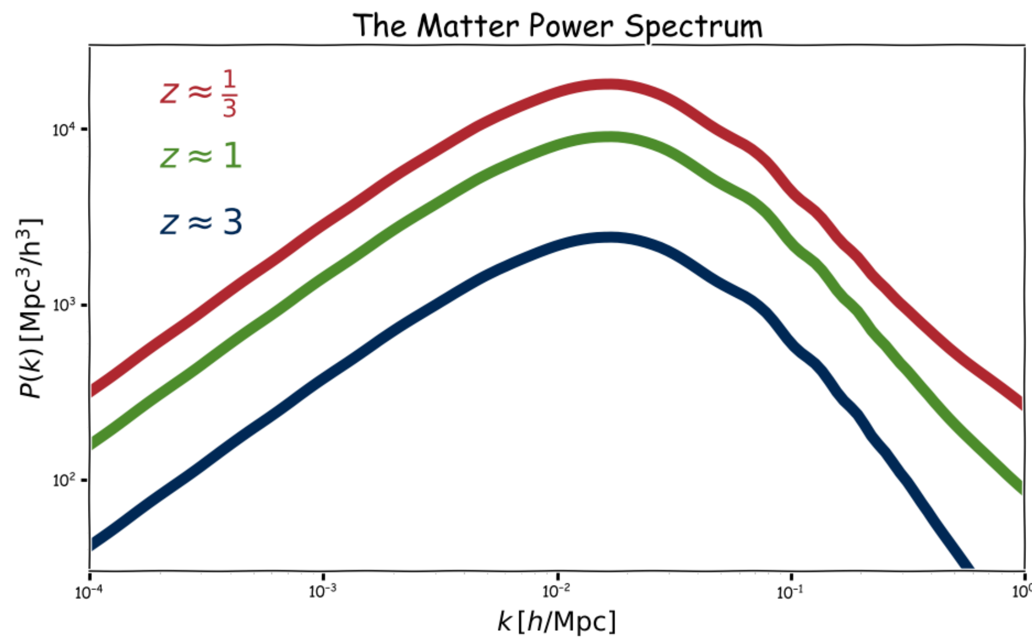


Matter power spectrum

Snowmass 2021

The Snowmass process is future oriented: 10+ year horizon

- The linear matter power spectrum is: $P(k,z) = k^4 T(k)^2 D(z)^2\, P_{init}(k)$
  - *k* is the wavenumber in (h/Mpc)
  - $P_{init}(k)$ is the inflationary power spectrum
  - *D(z)* is the growth factor, determined by GR. Modified gravity:
  - *T(k)* is the transfer function, standard model and astrophysics
- Opportunities in P(k,z), at two *z* ranges
- Advantages of $z \approx 1$
  - Ability to obtain dense sampling
  - Better at studying growth, D(z)
    - $\mathrm{GR} + \Lambda\mathrm{CDM}$ predicts growth very precisely
  - Era of DE domination
- Advantages of $z \approx 3$
  - 3x the volume at $2 < z < 6$ than at $z < 2$
  - T(k) is less important- less theory needed
  - Era of matter domination



High density galaxy clustering in the regime of cosmic acceleration

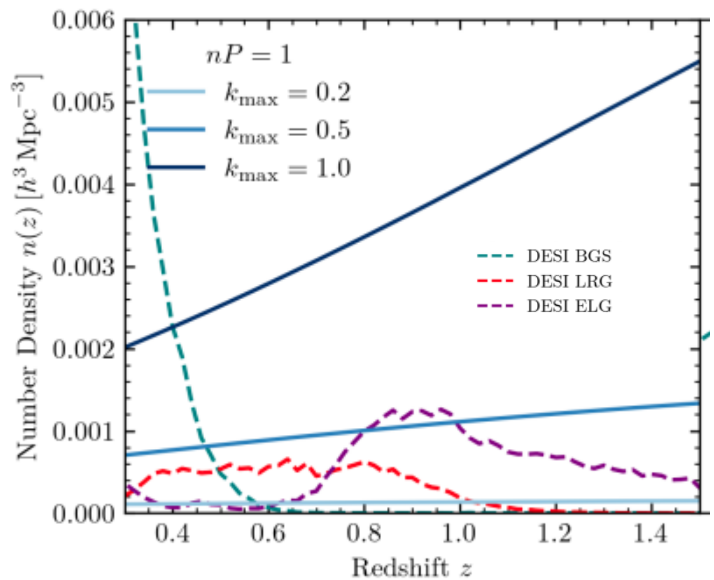
CF04 invited white paper

Authors: Dawson, Hearin, Heitmann, Ishak, Lange, White, Zhou

Snowmass 2021

Physics with a new spectroscopic sample at z<1.5

- *D(z)* measurements on the *H(z)* and *w*.
- Is GR correct on large scales, or not?
- Measure neutrino masses; possibly resolve the question of mass hierarchy.
- Provide tight limits on
  - dark matter interactions,
  - light relic particles,
  - potential features in the primordial power spectrum
- Test late time S_8 versus CMB PS amplitude from the CMB



Potential in new data samples

- DESI exceeds shot noise limit at $z < 1.5$ for $k < 0.2\, h/Mpc$.
- A DESI-2 could reach 5000 galaxies/sq-degee.
- 10,000 galaxies/sq-degree exceeds the shot noise limit for $k < 1\, h/Mpc$.
- Data has potential below $k < 1\, h/Mpc$
  - modeling consistency required at better than 0.1% precision $k < 1\, h/Mpc$
  - R&D in theory and simulations are required to reach the data's full potential

Cosmology and fundamental physics from the three-dimensional large scale structure

Snowmass 2021

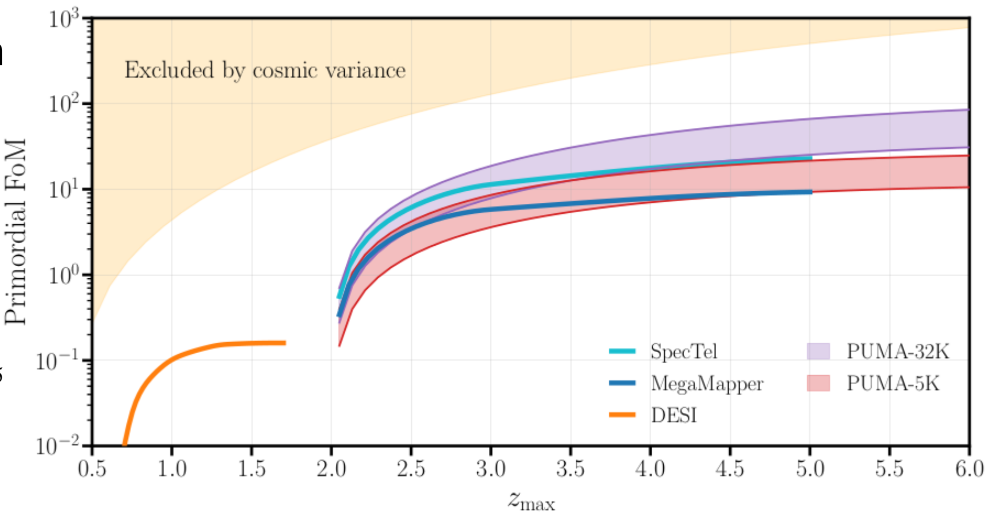
CF04 invited white paper

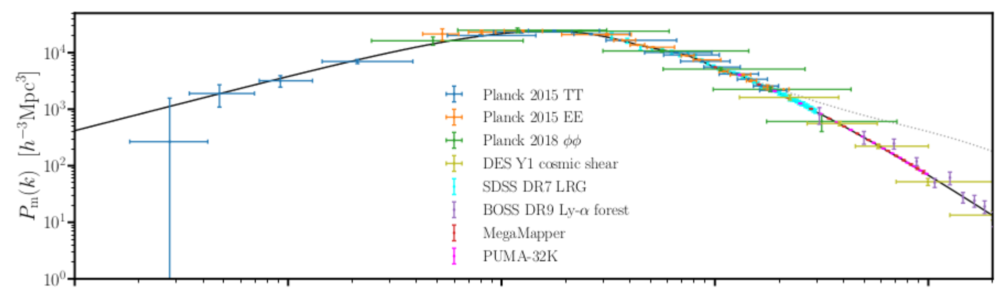
Authors: Ferraro, Sailer, Slosar, White

Physics with a new spectroscopic sample at 2<z<6

Goal: large number of modes linearly correlated with the initial conditions, N_{lin}.

- Most constraints scale as $\sim N_{lin}^{1/2}$
  - increases in FoM by two orders of magnitude
- Early Accelerated Epochs (inflation):
  - $\sigma(f_{nl}) < 1$ from the power spectrum alone (and better with bispectrum).
  - percent-level deviations from expected expansion up to $z \sim 10^5$ though power spectrum imprints
- Dark Energy:
  - Directly measure the Dark Energy density deep into matter domination epoch
  - testing large classes of dynamical DE models.
- Light Relics:
  - Constraints comparable to CMB-S4
    - Helium abundance independent





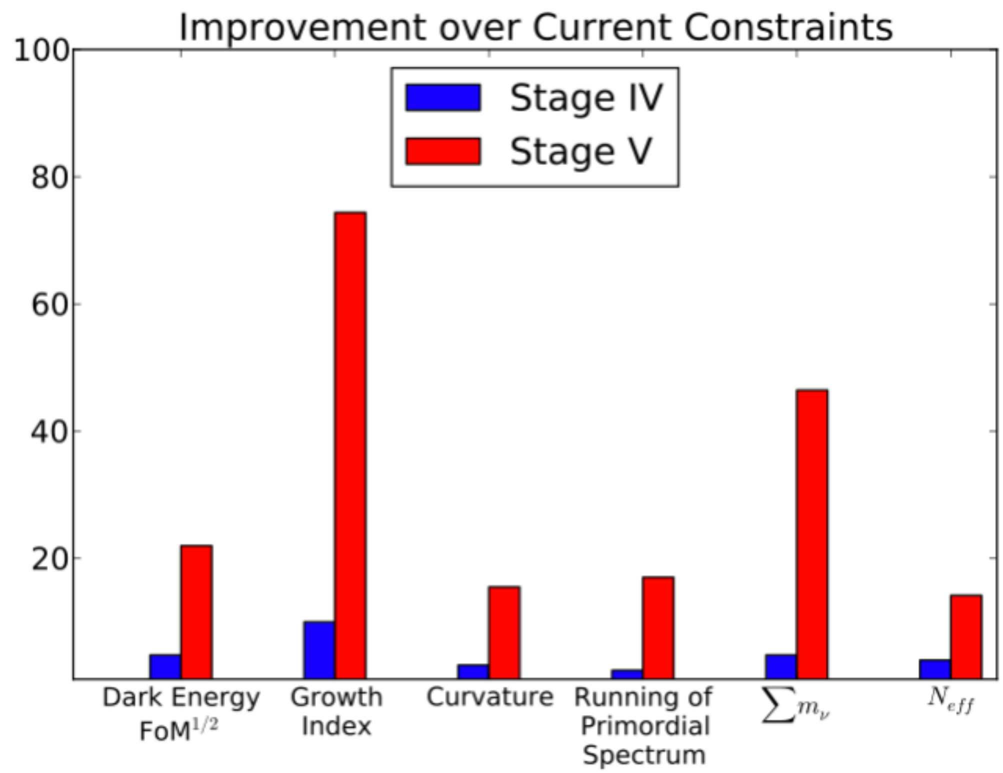
Is ΛCDM the best model?

Cosmological model discovery space

- ΛCDM is a 6 parameter model

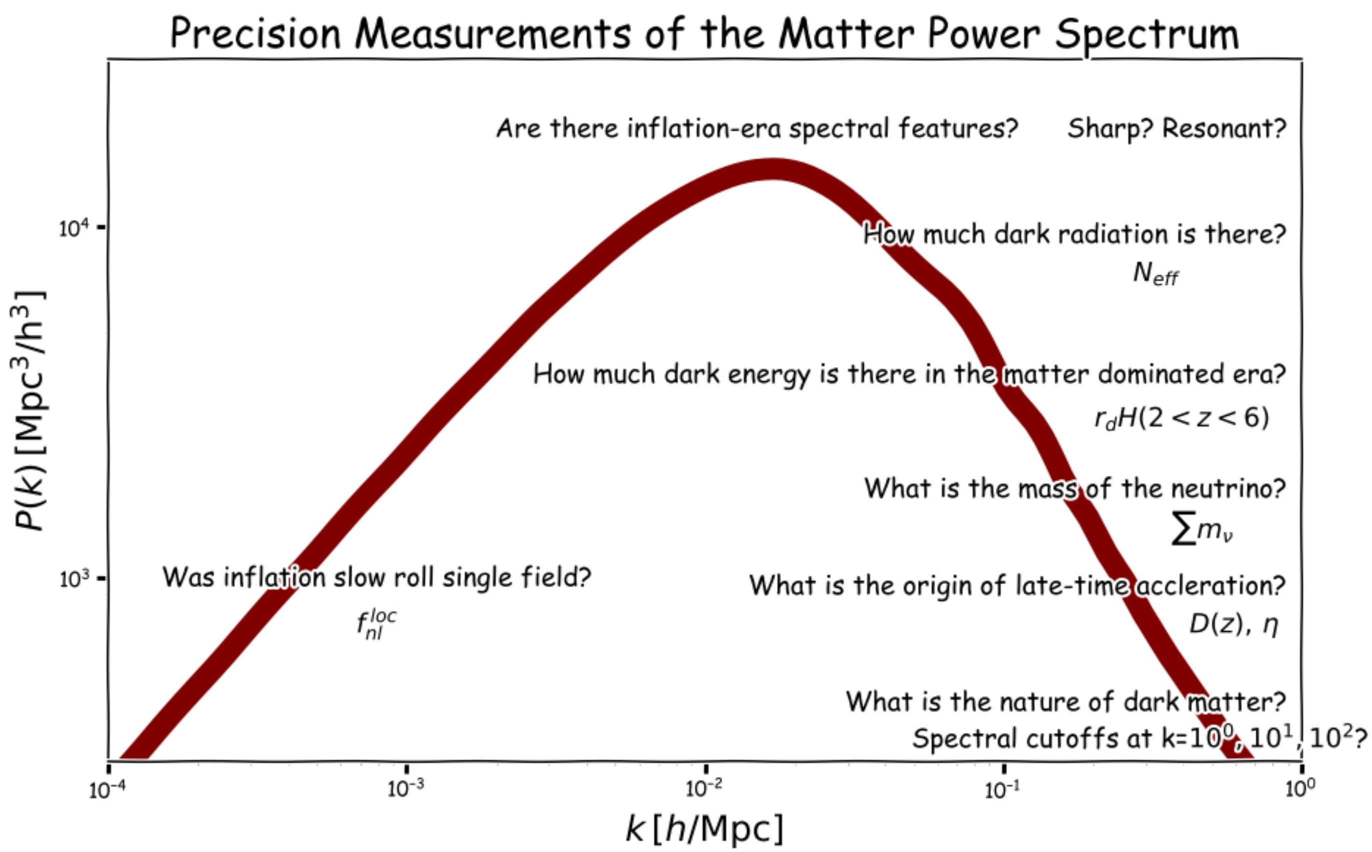
- Projections for Stage V experiments explore discovery space on the six most likely extensions

New experiments are necessary



Community Roadmap

The questions we want to answer

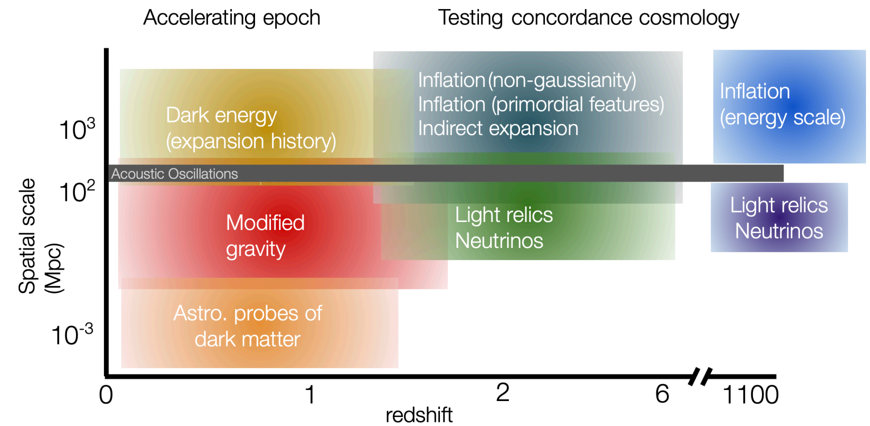


Community Roadmap

A Stage V Spectroscopic Facility

- Clearest opportunities to make gains after Rubin will be spectroscopic.
- **This requires a new spectroscopic facility**
  - Large aperture, high multiplex, wide wavelength coverage, wide field of view
  - Proposals include Mauna Kea Spectroscopic Explorer, MegaMapper, SpecTel, and more
  - This facility would also
    - enable gains in understanding dark matter
    - be complementary to flagship LSST/Euclid/Roman analyses
- Short term needs:
  - Instrumental R&D (fiber positions, precision measurement techniques, simulation advances) and
  - LSST follow-up observations/Northern mini survey at the small project level
- Medium term needs:
  - Review to understand Rubin post-LSST,
  - CD-0 for a new spectroscopic facility

Data Discovery Space



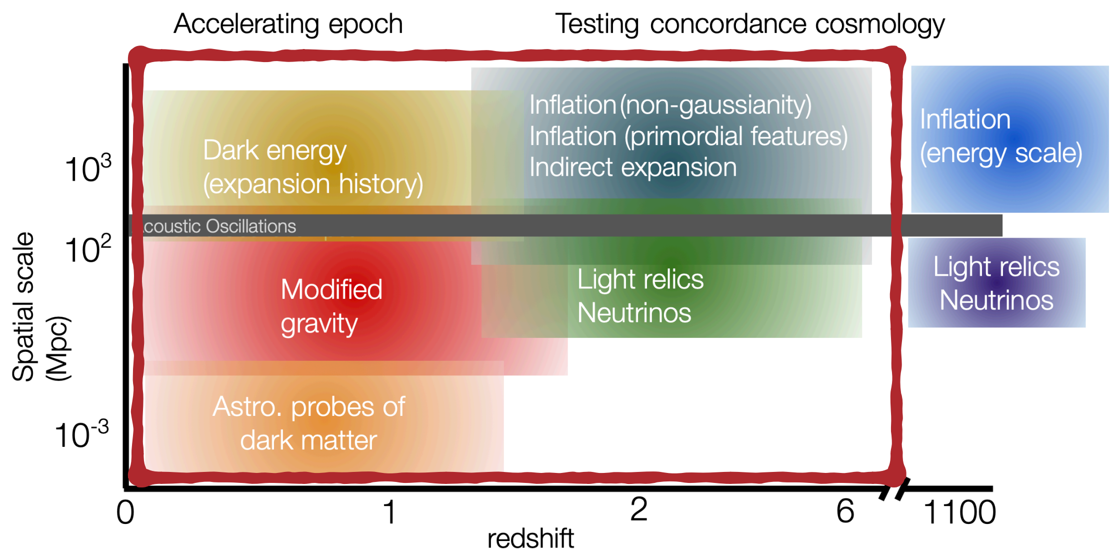
The data obtained will be rich in information: the applications will go beyond what we plan now.

SDSS was designed to measure the shape of the power spectrum, and that is not what it is known for today.

Community Roadmap

Data Discovery Space

- An aspirational next generation spectroscopic facility would enable three interleaved surveys:
  - $z \approx 0$ Milky Way (for DM)
  - $z < 2$ high nP
  - $z > 2$ high N_{lin}
- Massively multiplexed large aperture facility also emerged as a priority in the Astro Decadal survey.
- The community understands the physics reach of this facility would be the entire left side of this diagram



Backup slides

Connections to Dark Matter

Snowmass 2021

Not possible to separate cosmic studies of CDM from the next generation of dark energy studies

- Thus many of the papers in CF03 are closely related to CF04
- In many current theories, DM is part of an extended dark sector that includes dark radiation. Measuring N_{eff} constrains possible dark radiation.
  - CF05: The physics of light relics
- Constraining the $\sum m_\nu$ is measuring the mass of a dark matter, just not the dominant form.
  - CF07: Synergy between cosmological and laboratory searches in neutrino physics

Connections to other CF05/CF07 white papers

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- CF05: Inflation: theory and observations
- CF07: Synergy between cosmological and laboratory searches in neutrino physics
- CF07: Cosmology intertwined: a review of the particle physics, astrophysics, and cosmology associated with with cosmological tensions and anomalies