CF04: Dark Energy and Cosmic Acceleration in the Modern Universe

SnowMass2021

Conveners: Jim Annis, Jeff Newman, Anze Slosar

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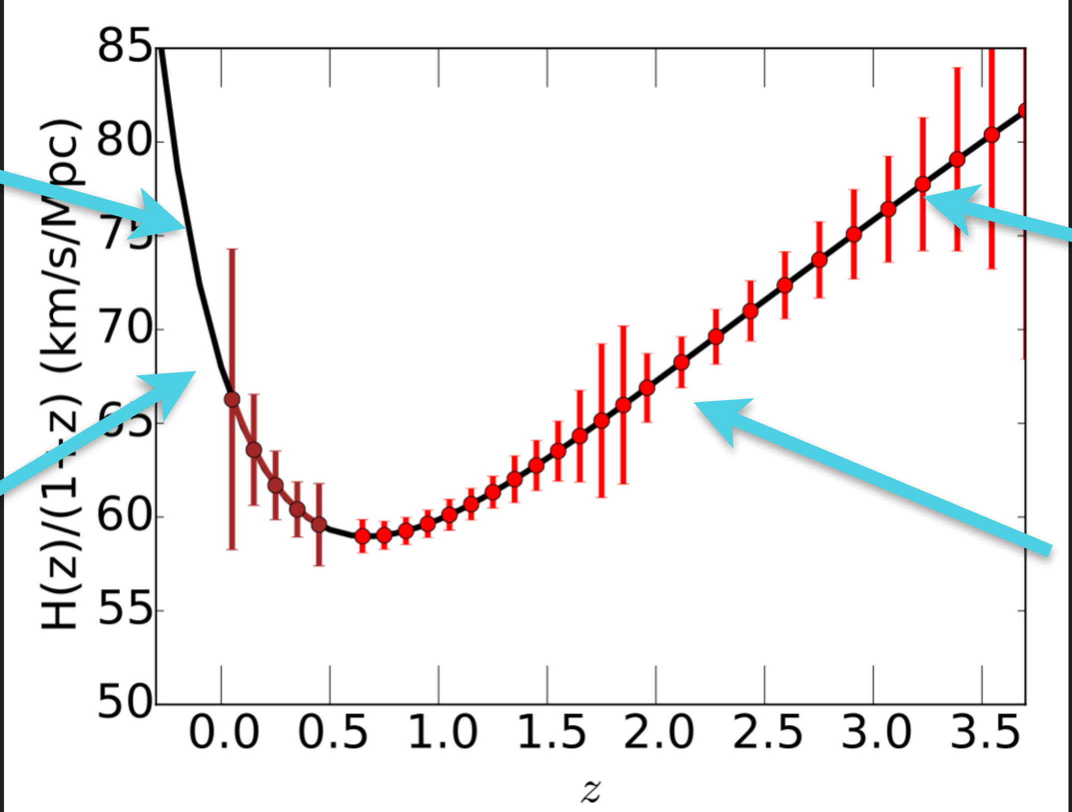
Snowmass 2021

Acceleration in the Modern Universe

- Simple questions
  - Is ΛCDM the best model?
  - Is GR correct on large scales, or not?
  - How was the current large scale structure seeded from the event of inflation?

- The DE program is vibrant and progressing rapidly:
  - (DOE/NSF) DES, DESI, Rubin/LSST
  - (other) SphereX, Euclid, Roman
  - Growing out of the 2013 Snowmass!
  - In the late 2020's we'll have data from all 6
    - There are a variety of opportunities to build on this!

The program is built around providing definitive measurements of Dark Energy, through both expansion rate and the growth of structure.



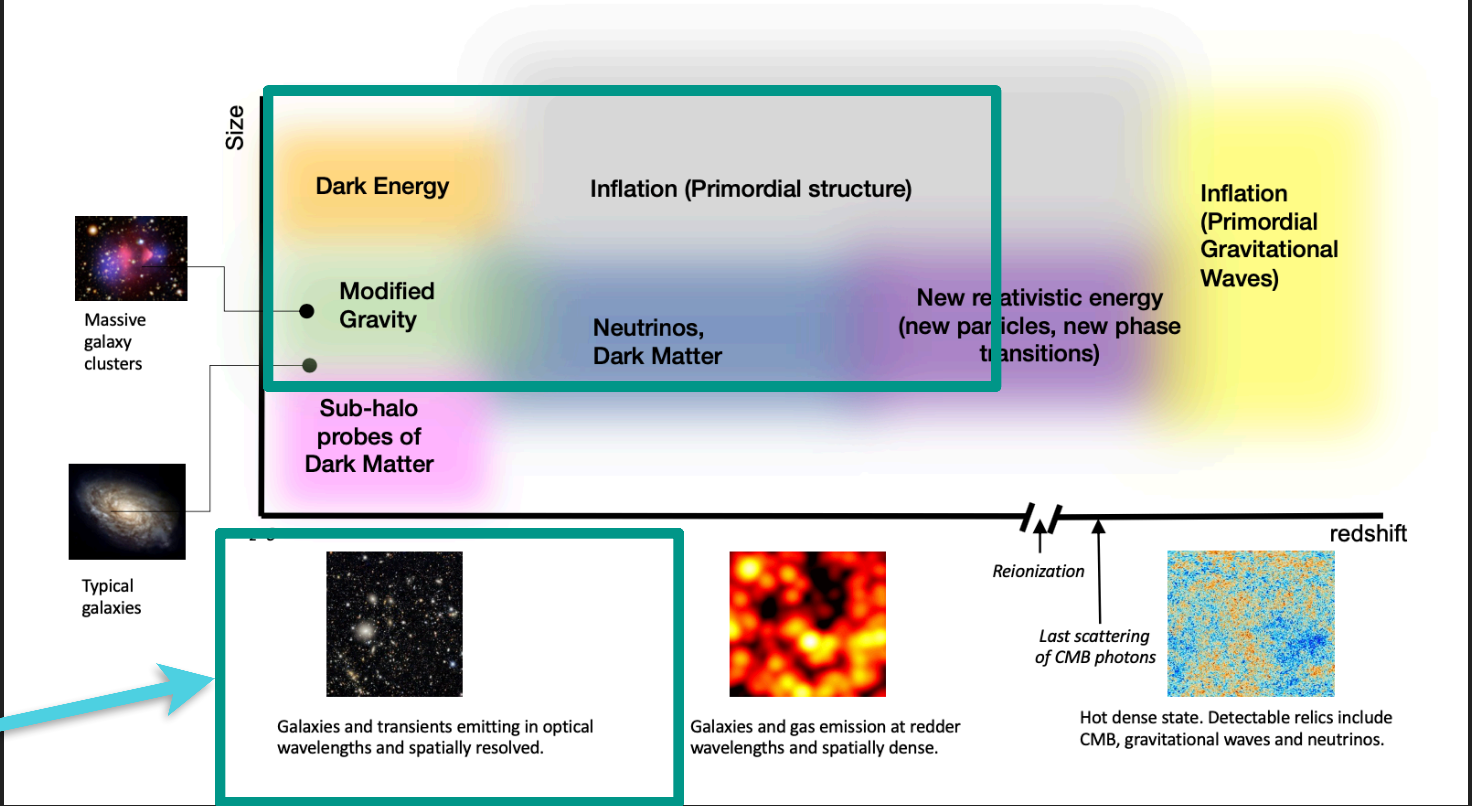
Add LSST SN constraints at low z?

Show effects of shifting H_0?

Show Stage 5 spectroscopic facility constraints at higher z?

Add family of curves from w_0/ w_a MCMC chains for DES or eBOSS?

These measurements simultaneously provide precision tests of dark energy, gravity and other cosmophysics: inflation, neutrinos, dark matter, etc.



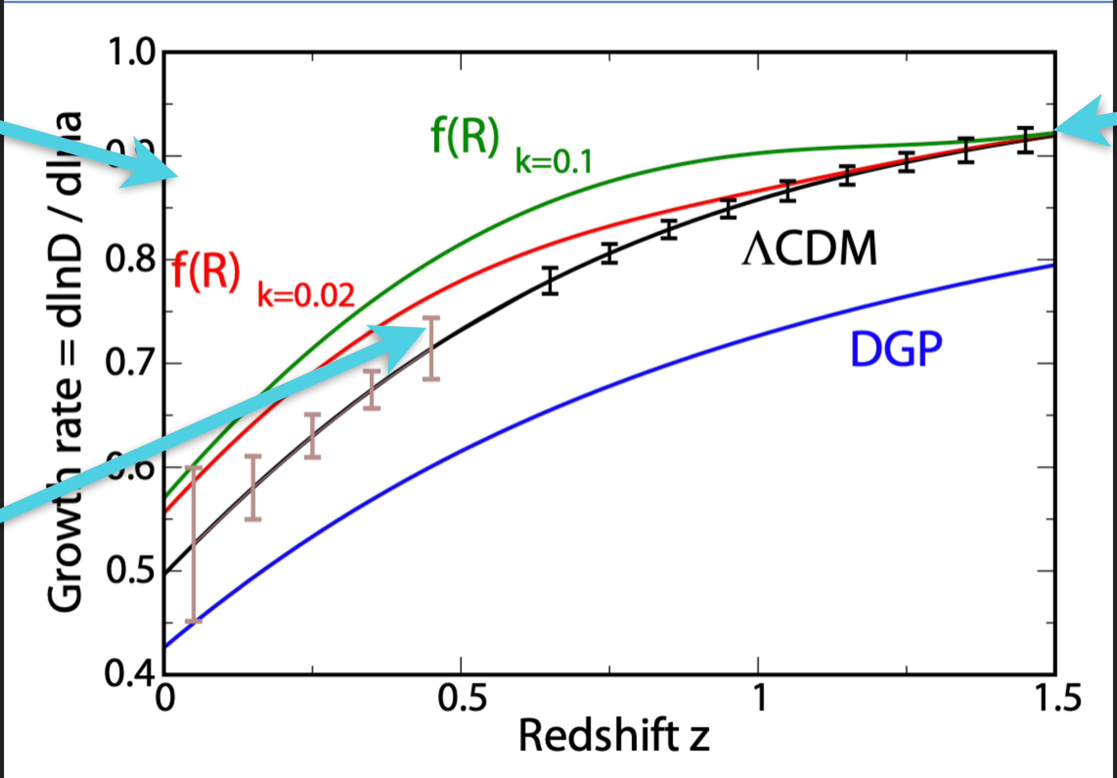
Galaxies and transients emitting in optical wavelengths and spatially resolved.

Galaxies and gas emission at redder wavelengths and spatially dense.

Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

Highlight H(z)/ targeted studies?

The tests of gravity evaluate whether DE manifests as a energy density or a change in GR. ΛCDM assumes GR.



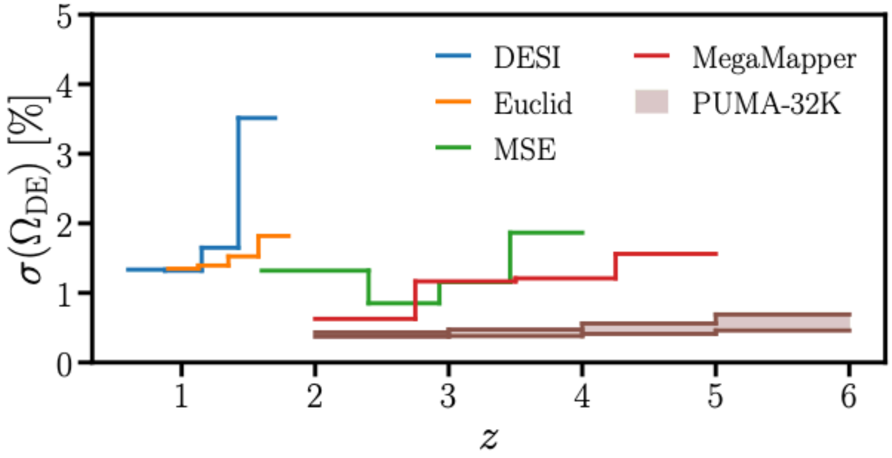
Add SN peculiar velocity constraints at low z?

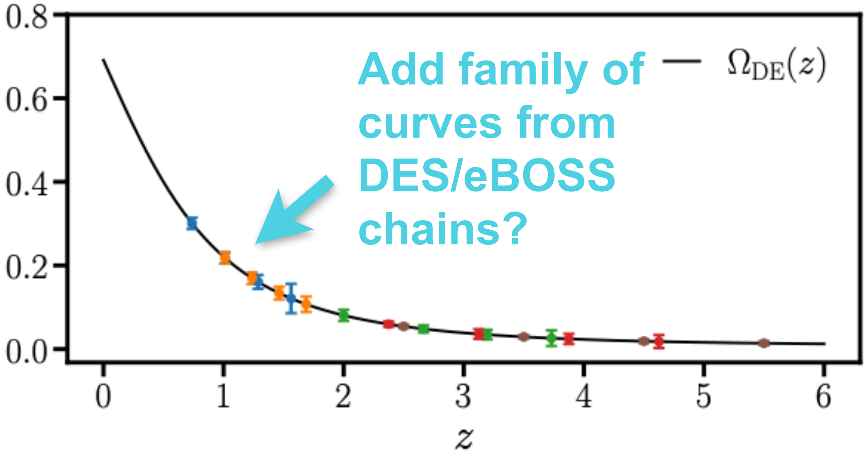
Add LSST WL constraints at intermediate z?

Show Stage 5 spec. facility constraints at higher z?

A next generation, stage V spectroscopic experiment goes wide at high-z and deep at lower-z

- Wide maximizes the number of linear modes on the matter power spectrum surveyed
- Deep is maximizing the number density of targets at lower-z to capture wealth of non-linear information
- The wide program aims to measure Ω_{DE} at $2<z<5$ as a discovery potential.

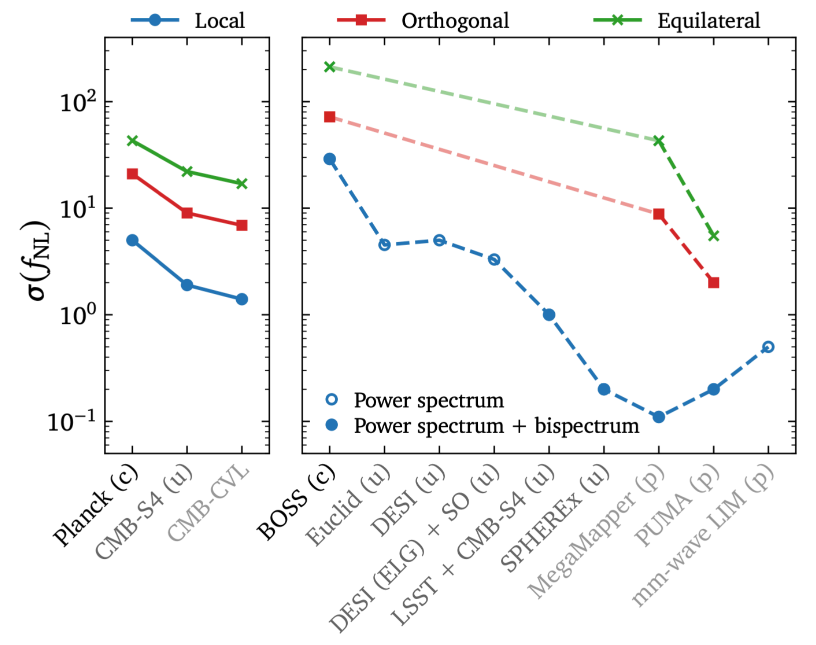




Add family of curves from DES/eBOSS chains?

In typical DE models Ω_{DE} goes to zero at high redshift -- can test for unconventional DE by measuring expansion to higher z

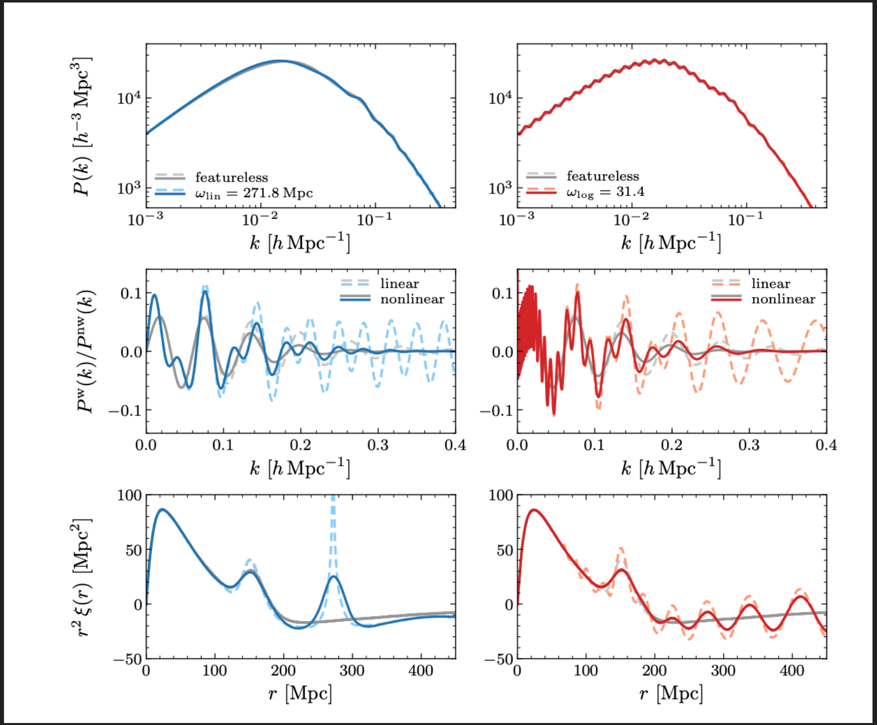
These same measurements have discovery potential on primordial non-Gaussianities due to inflation

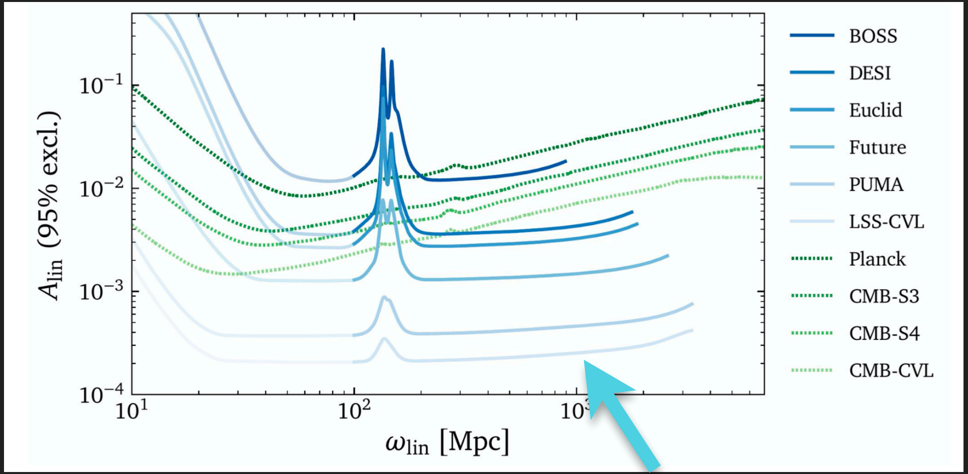


Single field, slow roll inflation models predict f_{NL}~1.

Searching for signatures of inflationary scales

- Stage V spectroscopic facility is particularly powerful as a probe of inflation -- potential 10-20x gain in sensitivity to features in inflation power spectrum (tied to energy scales!)





Remove ~half the curves?

Future experiments can greatly expand our inflation discovery potential

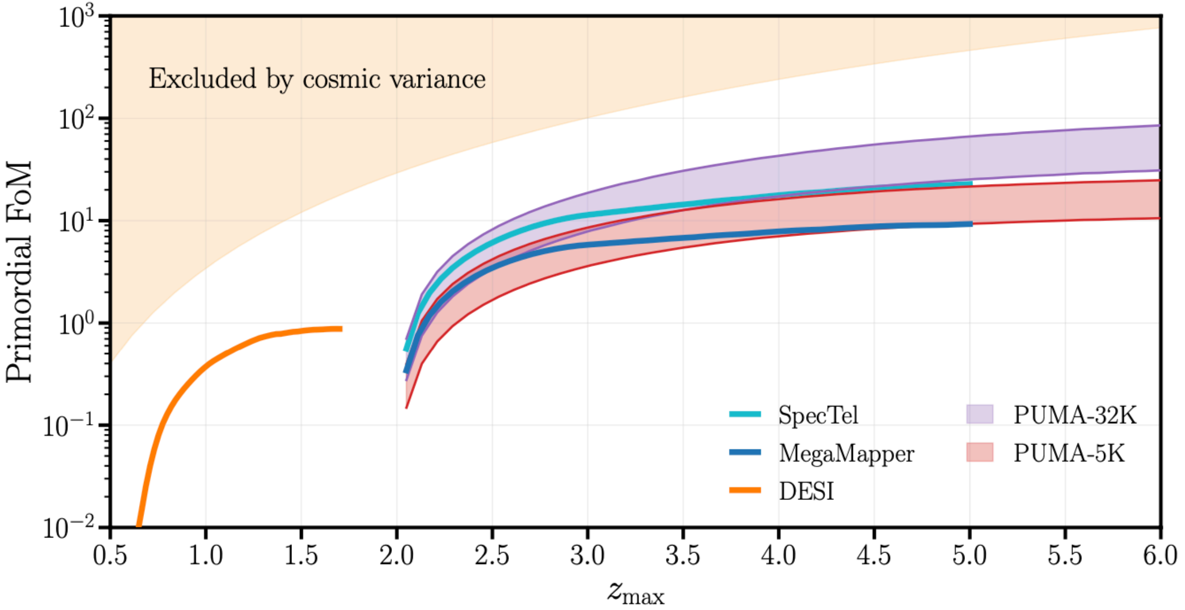
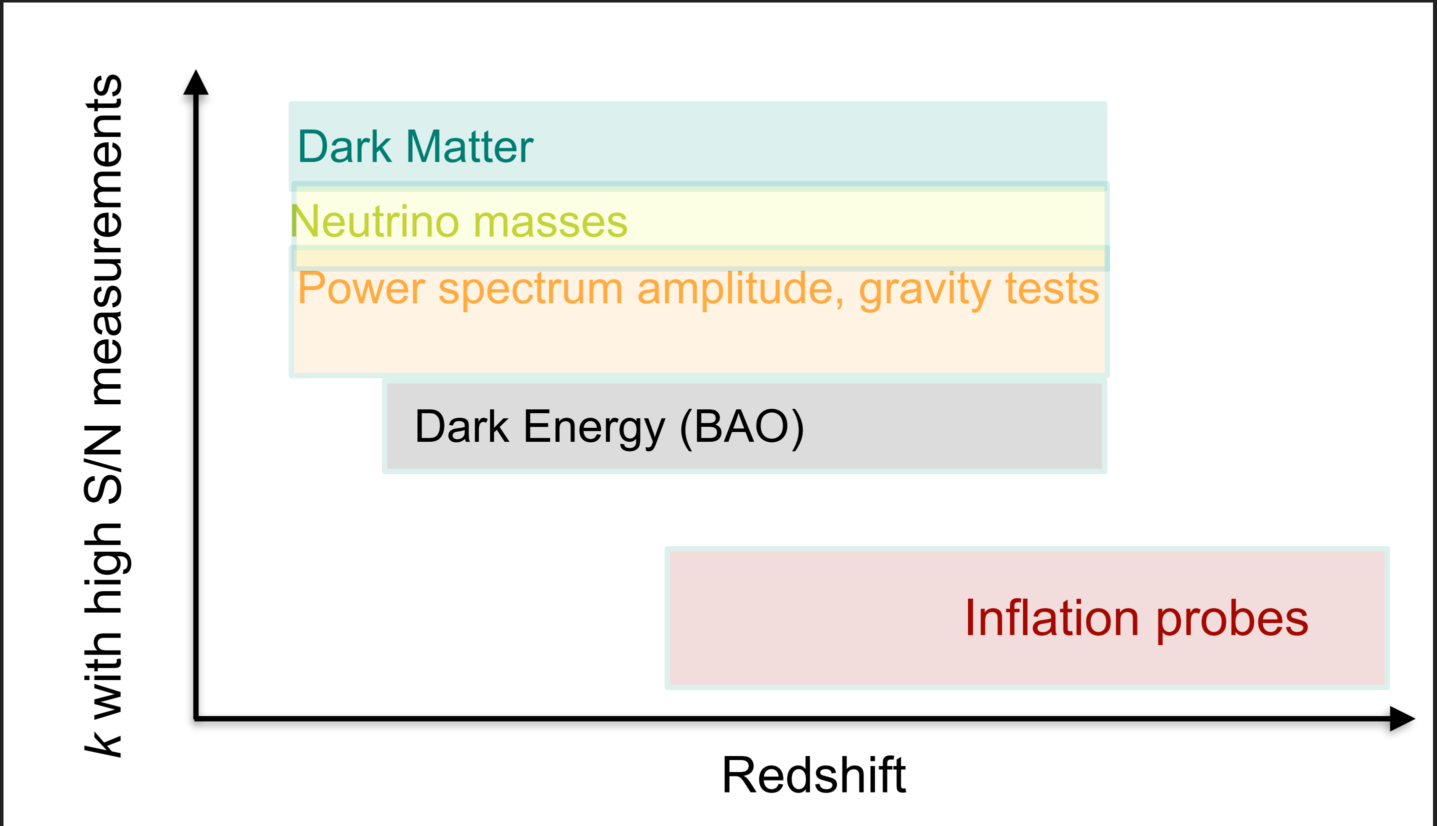


Figure 4-1 Primordial FoM $\equiv 10^{-6}\, N_{\mathrm{modes}}$ as a function of z_{max} for the DESI Emission Line Galaxy sample, as well as estimates based on strawman designs for PUMA (-5K and -32K), MegaMapper and SpecTel surveys. For PUMA, we consider both optimistic and pessimistic foreground models, which correspond to the boundaries of the shaded regions. The boundary of the shaded orange region is the cosmic variance limit for an all-sky survey, assuming $b(z) = 1$. Reproduced from [7].

Measurements in the modern universe can test the contributions of dark energy and test gravity across z=0-5... and constrain fundamental physics in many other ways at the same time



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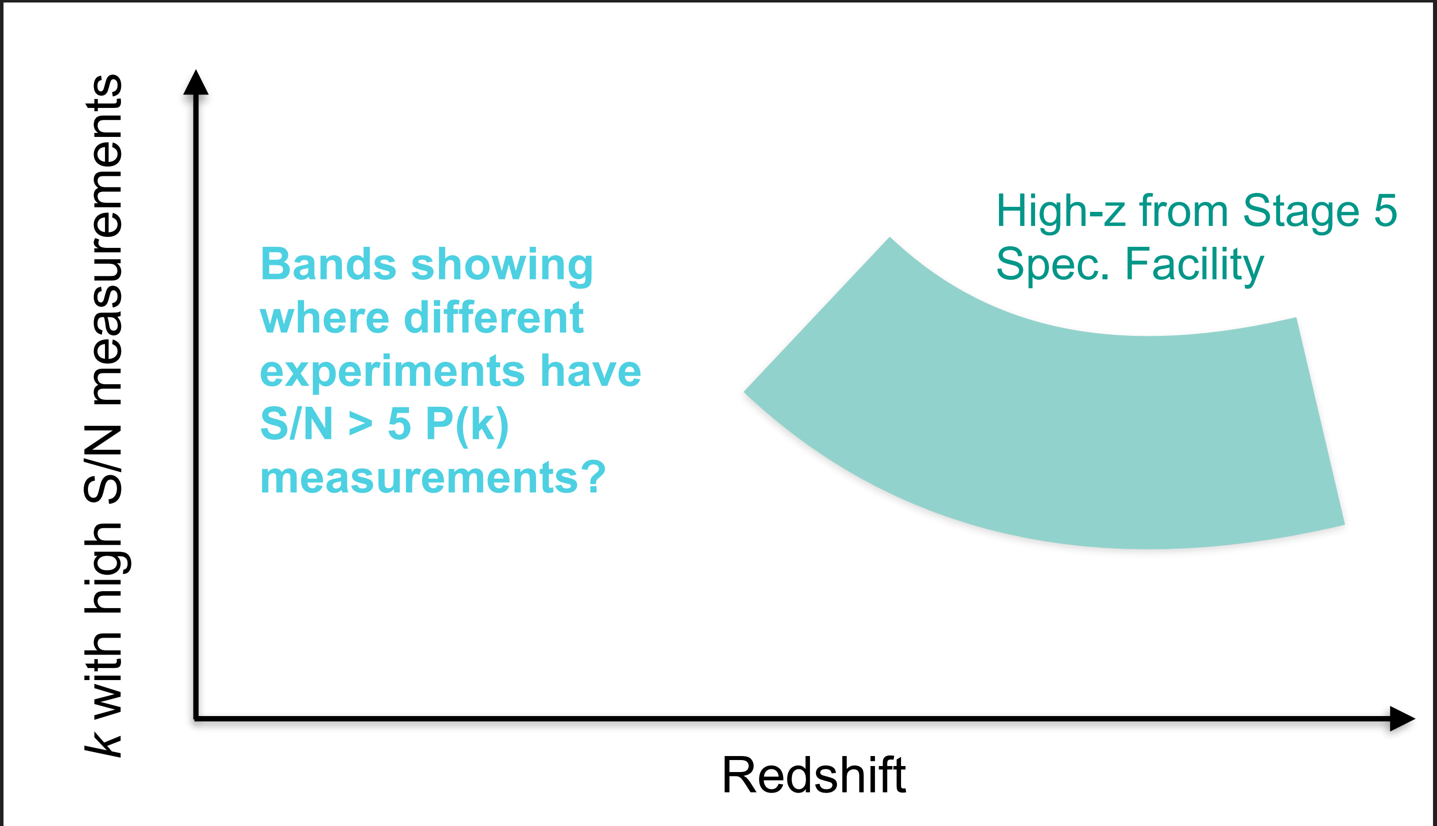
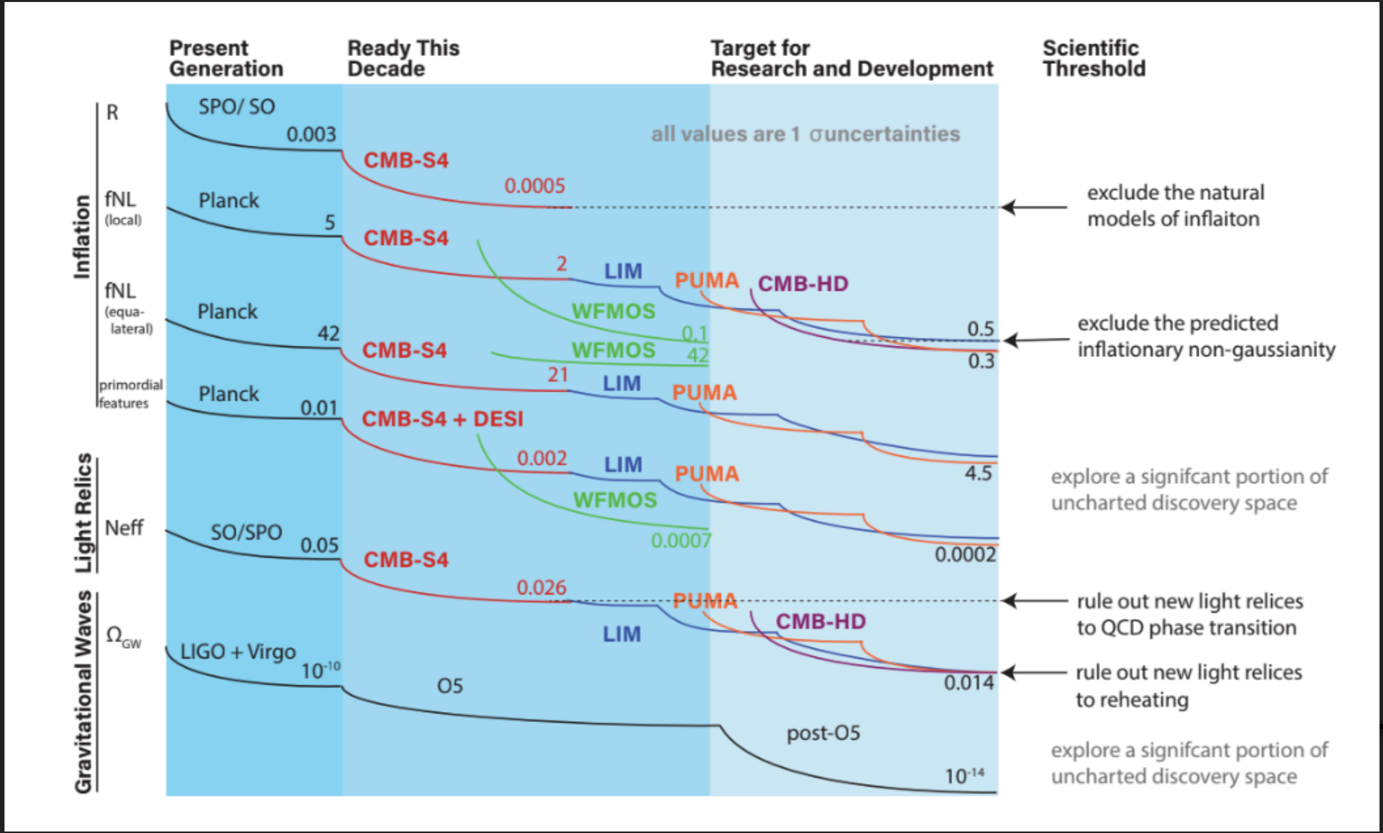


Measurements in the modern universe can test the contributions of dark energy and test gravity across z=0-5... and constrain fundamental physics in many other ways at the same time



Change quantities plotted:

f_{NL}, N_{eff} , max z for Ω_{DE}, something relating to sensitivity to power spectrum features (1/ FOM?), something relating to power spectrum amplitude?

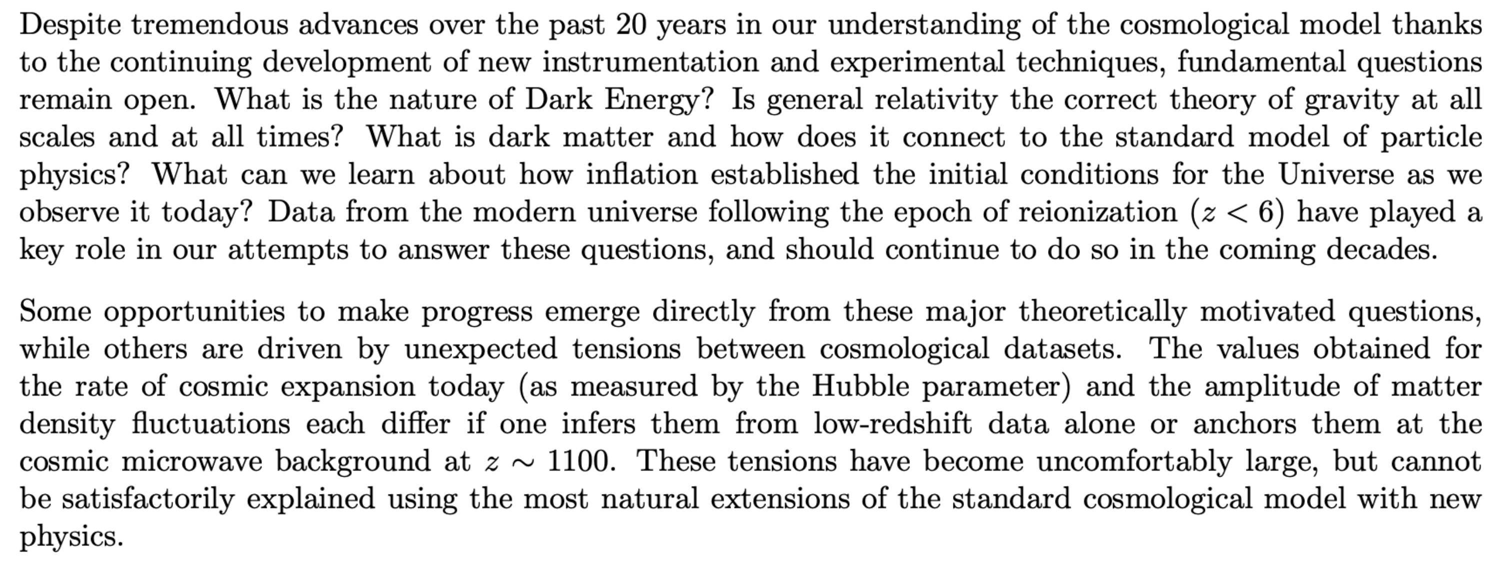
Summary of our findings:

- Key questions we address begin with measuring **dark energy** - both through new experiments and new data to strengthen planned ones - but extend far beyond.
    - tests of gravity, measurement of neutrino masses, constraints on dark radiation, early dark energy, general constraints on inflation models, exploring σ_8 tensions...
- The field is vibrant and progressing rapidly:
    - DES, DESI, Rubin/LSST, complemented by SphereX, Euclid, Roman
    - Growing out of the 2013 Snowmass!
    - Need to evaluate future of Rubin in ~5 years after first LSST results

- The Community believes our roadmap is:
- In the long run - A Stage V spectroscopic facility
- In the short run - A spectrum of exciting programs on telescopes small to ELT
- Always needed - Instrumental R&D

Report Executive Summary: Key questions

- **Key open questions in the modern Universe extend far beyond Dark Energy**
    - Tests of gravity, measurement of neutrino masses, inflation models, early dark energy tests, constraints on dark radiation, exploring σ_8 tensions...
- Proposed experiments could address many of them simultaneously
    - Ideas further described in section 4.2



Despite tremendous advances over the past 20 years in our understanding of the cosmological model thanks to the continuing development of new instrumentation and experimental techniques, fundamental questions remain open. What is the nature of Dark Energy? Is general relativity the correct theory of gravity at all scales and at all times? What is dark matter and how does it connect to the standard model of particle physics? What can we learn about how inflation established the initial conditions for the Universe as we observe it today? Data from the modern universe following the epoch of reionization ($z < 6$) have played a key role in our attempts to answer these questions, and should continue to do so in the coming decades.

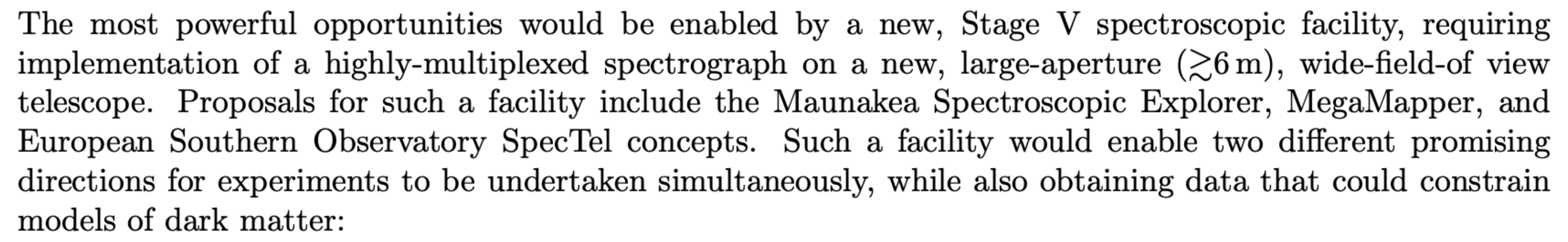
Some opportunities to make progress emerge directly from these major theoretically motivated questions, while others are driven by unexpected tensions between cosmological datasets. The values obtained for the rate of cosmic expansion today (as measured by the Hubble parameter) and the amplitude of matter density fluctuations each differ if one infers them from low-redshift data alone or anchors them at the cosmic microwave background at $z \sim 1100$. These tensions have become uncomfortably large, but cannot be satisfactorily explained using the most natural extensions of the standard cosmological model with new physics.

Report Executive Summary: Context

- **The field is vibrant and progressing rapidly!**
- Section 4.3 summarizes the landscape of current and near-future experiments for context:
  - Dark Energy Survey
  - BOSS, eBOSS and DESI
  - Vera C. Rubin Observatory LSST
  - SphereX, Euclid, Nancy Grace Roman Space Telescope

Report Executive Summary: Stage V spectroscopic facility

- Much community input focused on science that could be done with large spectroscopic surveys
    - Lower-redshift ($z < 1.5$), high-density spectroscopic surveys tracing non-linear scales
    - High-redshift ($z \gtrsim 2$), high-volume spectroscopic surveys tracing linear scales
- **A Stage V spectroscopic facility could undertake these simultaneously** (and do CF3 science, and potentially also strengthen constraints from Rubin Observatory...)
    - Continuing roles for DESI as a bridge to next-generation facilities
- Described in Section 4.4



The most powerful opportunities would be enabled by a new, Stage V spectroscopic facility, requiring implementation of a highly-multiplexed spectrograph on a new, large-aperture ($\gtrsim$6 m), wide-field-of view telescope. Proposals for such a facility include the Maunakea Spectroscopic Explorer, MegaMapper, and European Southern Observatory SpecTel concepts. Such a facility would enable two different promising directions for experiments to be undertaken simultaneously, while also obtaining data that could constrain models of dark matter:

Figure 2 - Dark Energy constraining power

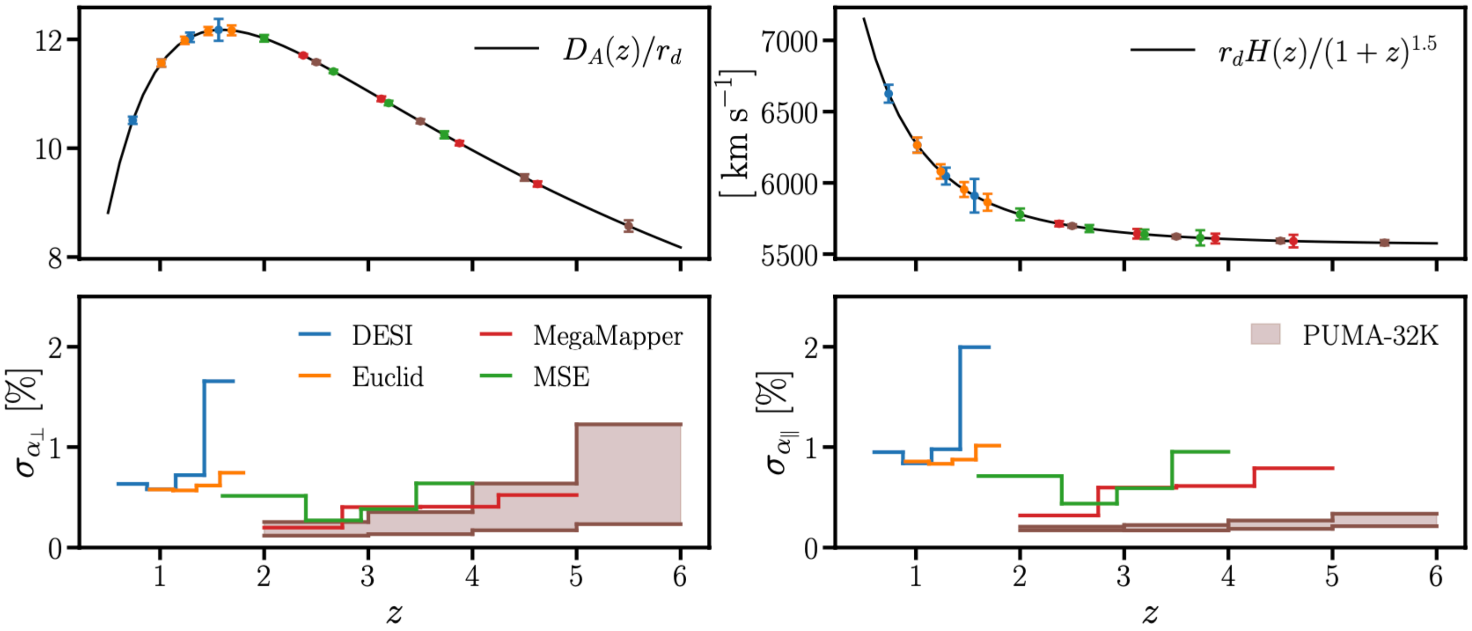
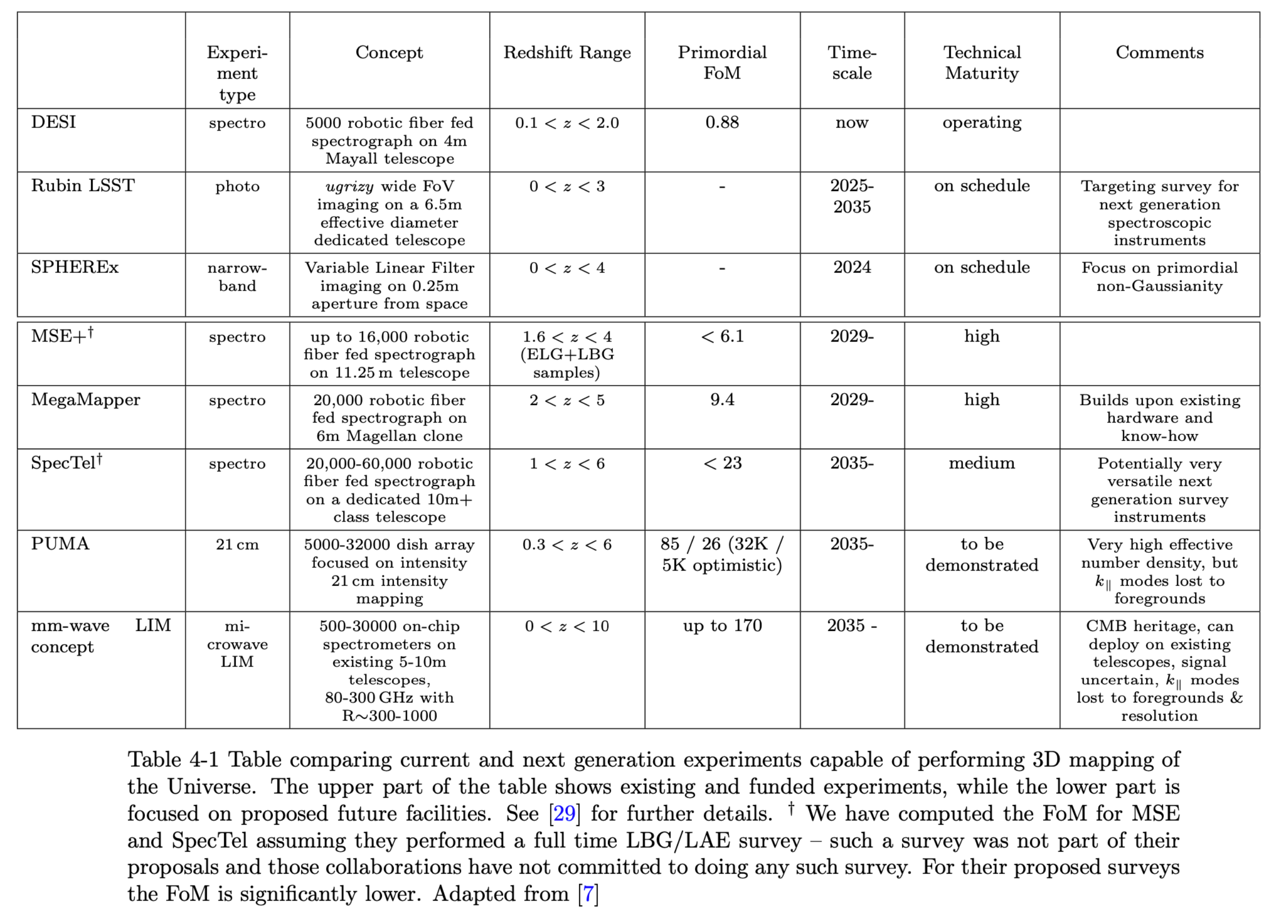


Figure 4-2 Error on the parameters $\alpha_\perp, \alpha_\parallel$ from the reconstructed power spectrum, which can be interpreted as relative errors on $D_A(z)/r_d$ and $r_d H(z)$ respectively. The line for DESI includes constraints from the ELG sample only. The boundaries of the shaded regions denote optimistic/pessimistic foreground assumptions for the 21-cm surveys. In the top panels we show the error bars for the optimistic case. Reproduced from [7].

Table 1 - Key experiments



	Experiment type	Concept	Redshift Range	Primordial FoM	Time-scale	Technical Maturity	Comments
DESI	spectro	5000 robotic fiber fed spectrograph on 4m Mayall telescope	$0.1 < z < 2.0$	0.88	now	operating	
Rubin LSST	photo	*ugrizy* wide FoV imaging on a 6.5m effective diameter dedicated telescope	$0 < z < 3$	-	2025-2035	on schedule	Targeting survey for next generation spectroscopic instruments
SPHEREx	narrow-band	Variable Linear Filter imaging on 0.25m aperture from space	$0 < z < 4$	-	2024	on schedule	Focus on primordial non-Gaussianity
MSE+†	spectro	up to 16,000 robotic fiber fed spectrograph on 11.25 m telescope	$1.6 < z < 4$ (ELG+LBG samples)	< 6.1	2029-	high	
MegaMapper	spectro	20,000 robotic fiber fed spectrograph on 6m Magellan clone	$2 < z < 5$	9.4	2029-	high	Builds upon existing hardware and know-how
SpecTel†	spectro	20,000-60,000 robotic fiber fed spectrograph on a dedicated 10m+ class telescope	$1 < z < 6$	< 23	2035-	medium	Potentially very versatile next generation survey instruments
PUMA	21 cm	5000-32000 dish array focused on intensity 21 cm intensity mapping	$0.3 < z < 6$	85 / 26 (32K / 5K optimistic)	2035-	to be demonstrated	Very high effective number density, but $k_{\parallel}$ modes lost to foregrounds
mm-wave LIM concept	microwave LIM	500-30000 on-chip spectrometers on existing 5-10m telescopes, 80-300 GHz with R∼300-1000	$0 < z < 10$	up to 170	2035 -	to be demonstrated	CMB heritage, can deploy on existing telescopes, signal uncertain, $k_{\parallel}$ modes lost to foregrounds & resolution

Table 4-1 Table comparing current and next generation experiments capable of performing 3D mapping of the Universe. The upper part of the table shows existing and funded experiments, while the lower part is focused on proposed future facilities. See [29] for further details. † We have computed the FoM for MSE and SpecTel assuming they performed a full time LBG/LAE survey – such a survey was not part of their proposals and those collaborations have not committed to doing any such survey. For their proposed surveys the FoM is significantly lower. Adapted from [7]

Figure 3 - matter power spectrum

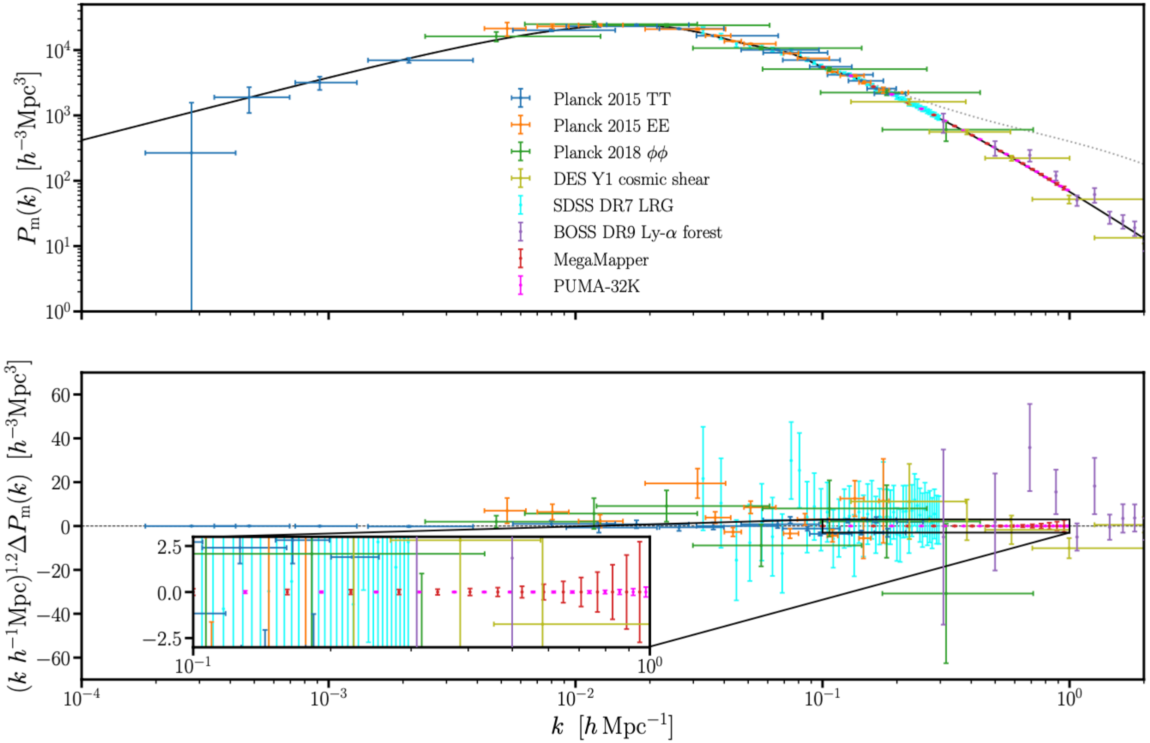


Figure 4-3 Measurements of the linear matter power spectrum at $z = 0$. For both MegaMapper and PUMA-32K we show projected constraints for 15 linearly spaced k-bins between $0.1\ h\,\mathrm{Mpc}^{-1} \lesssim k \lesssim 1\ h\,\mathrm{Mpc}^{-1}$. This figure is reproduced from [7] and adapted from refs. [?, ?, 29].

Add something to show where linear scales / sensitivity to inflation is?

Sensitivity to Early Dark Energy

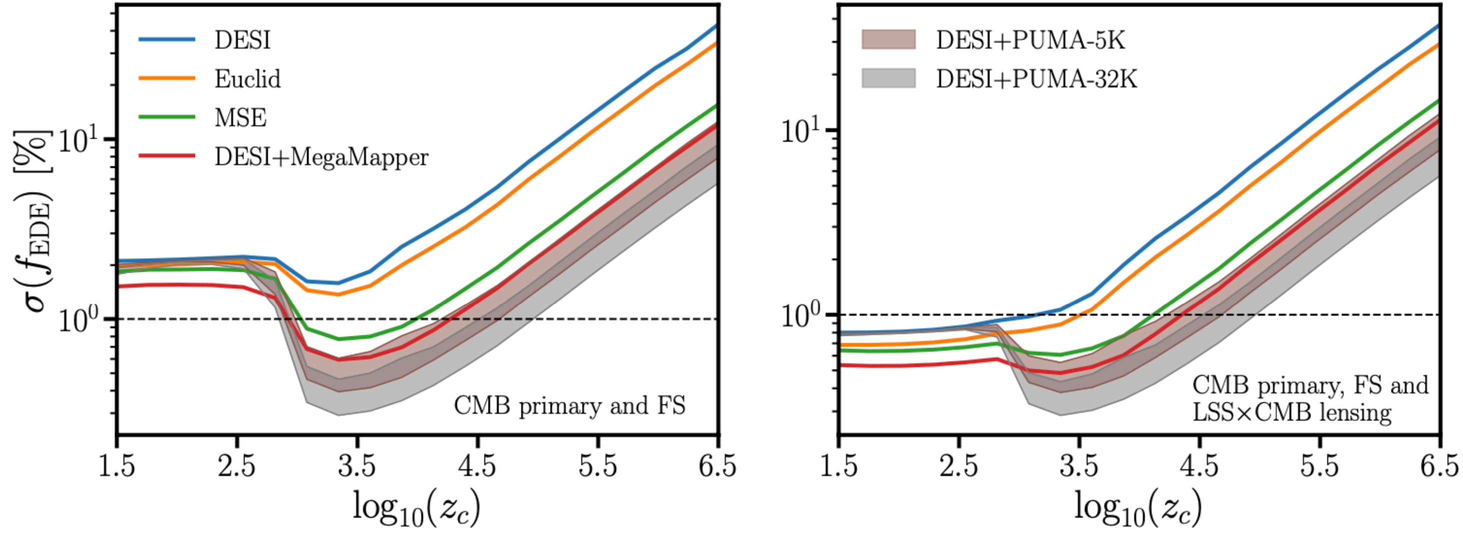
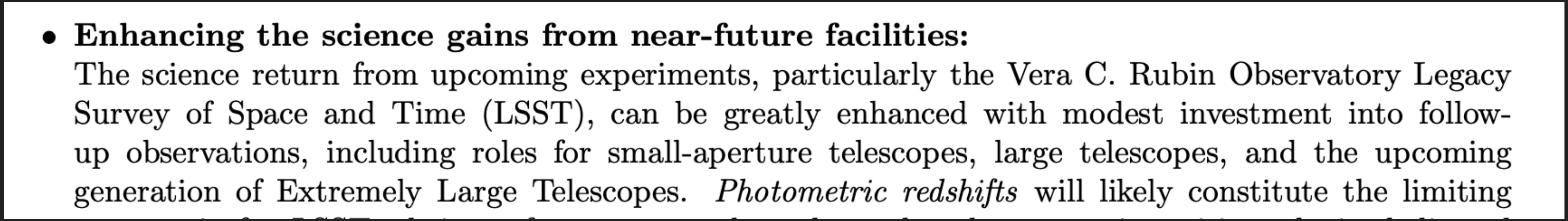


Figure 4-4 Constraints on the maximum amplitude of early dark energy ($f_{\rm EDE}$) as a function of the time at which EDE peaks z_c, assuming $\theta_i = 2.83$. We include a Planck+SO prior on ΛCDM for all experiments. In the left panel we show constraints from full shape (FS) measurements only, while in the right panel we include a prior on ΛCDM and nuisance parameters from SO lensing and cross-correlations with the respective galaxy surveys. Reproduced from [7].

Report Executive Summary: smaller programs

- **Small, exciting, programs** exploiting small telescopes up to ELTs can increase the constraining power of Stage IV imaging surveys:
  - Photometric redshift training/calibration spectroscopy (+Intrinsic Alignment)
  - Supernova follow-up (especially beyond span of 5-year 4MOST/TiDES)
  - Strong lensing follow-up
  - Low-redshift supernova peculiar velocity studies
  - Standard siren followup
  - Later this decade resolve role of Vera C. Rubin Observatory post-LSST
  - Described in sections 4.5, 4.6, and 4.7



- **Enhancing the science gains from near-future facilities:**
  The science return from upcoming experiments, particularly the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), can be greatly enhanced with modest investment into follow-up observations, including roles for small-aperture telescopes, large telescopes, and the upcoming generation of Extremely Large Telescopes. *Photometric redshifts* will likely constitute the limiting

Photometric redshift training spectroscopy improves Rubin LSST science gains

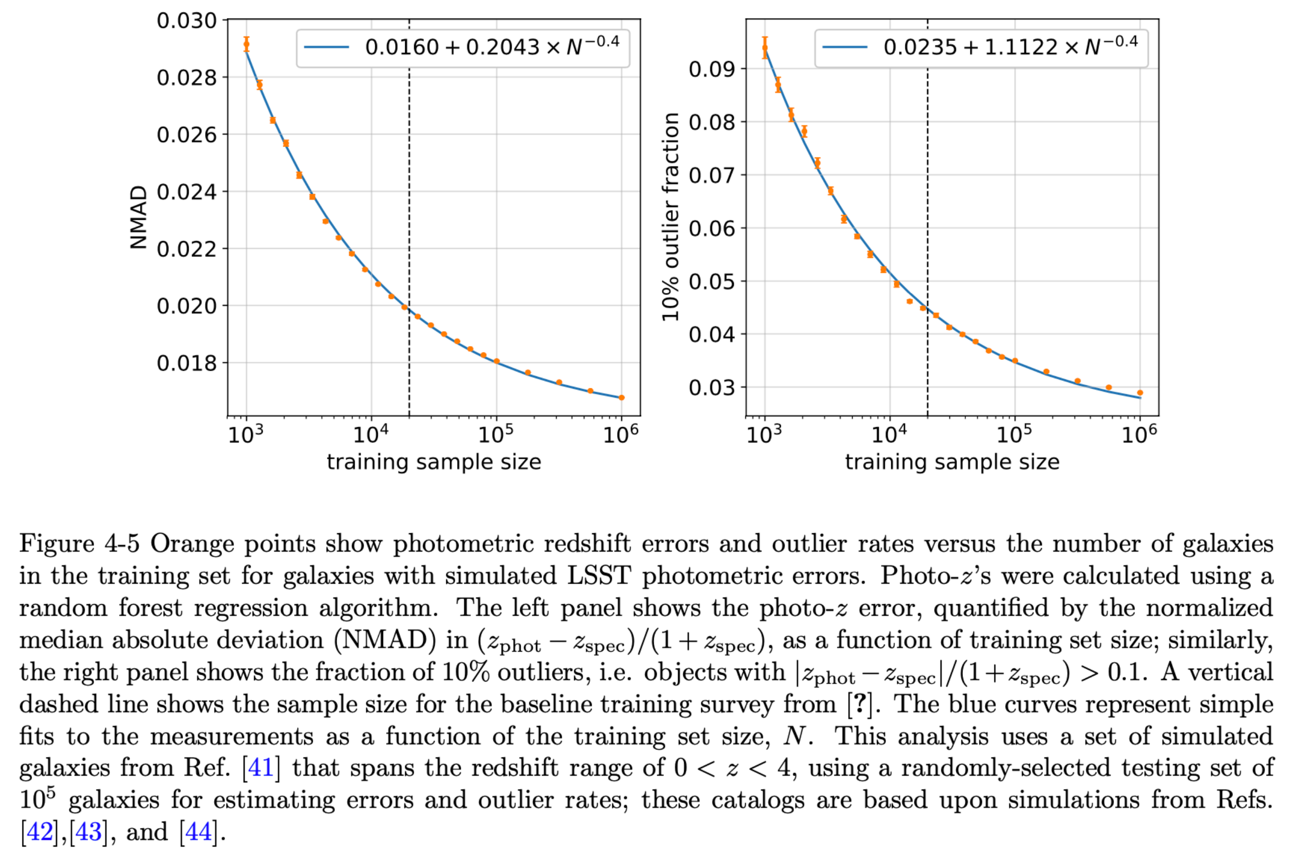


Figure 4-5 Orange points show photometric redshift errors and outlier rates versus the number of galaxies in the training set for galaxies with simulated LSST photometric errors. Photo-z's were calculated using a random forest regression algorithm. The left panel shows the photo-z error, quantified by the normalized median absolute deviation (NMAD) in $(z_{\mathrm{phot}} - z_{\mathrm{spec}})/(1 + z_{\mathrm{spec}})$, as a function of training set size; similarly, the right panel shows the fraction of 10% outliers, i.e. objects with $|z_{\mathrm{phot}} - z_{\mathrm{spec}}|/(1 + z_{\mathrm{spec}}) > 0.1$. A vertical dashed line shows the sample size for the baseline training survey from [**?**]. The blue curves represent simple fits to the measurements as a function of the training set size, N. This analysis uses a set of simulated galaxies from Ref. [41] that spans the redshift range of $0 < z < 4$, using a randomly-selected testing set of 10^5 galaxies for estimating errors and outlier rates; these catalogs are based upon simulations from Refs. [42],[43], and [44].

Table 2: Photo-z training spectroscopy can utilize many facilities

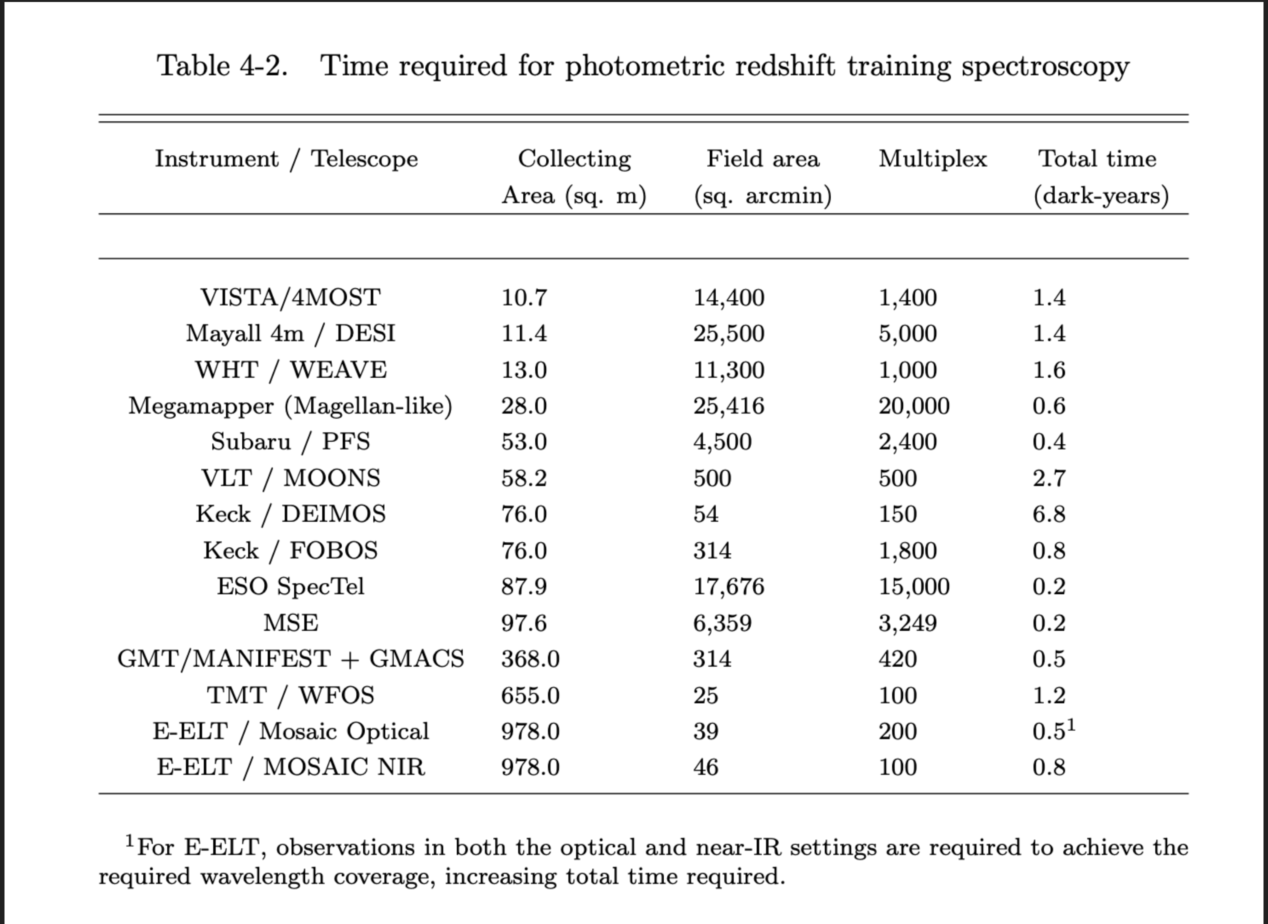


Table 4-2. Time required for photometric redshift training spectroscopy

Instrument / Telescope	Collecting Area (sq. m)	Field area (sq. arcmin)	Multiplex	Total time (dark-years)
VISTA/4MOST	10.7	14,400	1,400	1.4
Mayall 4m / DESI	11.4	25,500	5,000	1.4
WHT / WEAVE	13.0	11,300	1,000	1.6
Megamapper (Magellan-like)	28.0	25,416	20,000	0.6
Subaru / PFS	53.0	4,500	2,400	0.4
VLT / MOONS	58.2	500	500	2.7
Keck / DEIMOS	76.0	54	150	6.8
Keck / FOBOS	76.0	314	1,800	0.8
ESO SpecTel	87.9	17,676	15,000	0.2
MSE	97.6	6,359	3,249	0.2
GMT/MANIFEST + GMACS	368.0	314	420	0.5
TMT / WFOS	655.0	25	100	1.2
E-ELT / Mosaic Optical	978.0	39	200	0.5[1]
E-ELT / MOSAIC NIR	978.0	46	100	0.8

[1] For E-ELT, observations in both the optical and near-IR settings are required to achieve the required wavelength coverage, increasing total time required.

Table 3 (Section 4.5 on small projects): SN spectroscopy can be cheap!

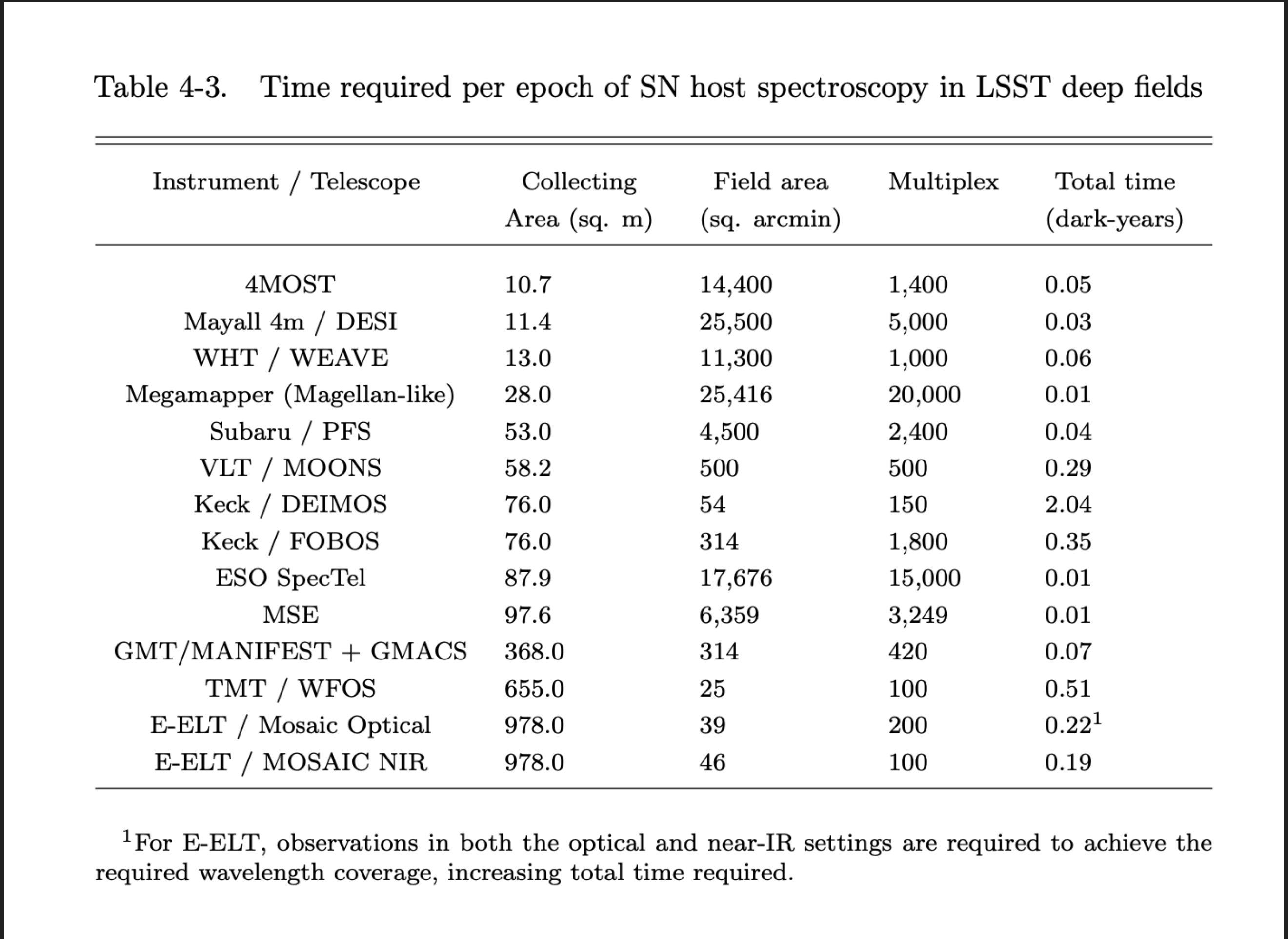


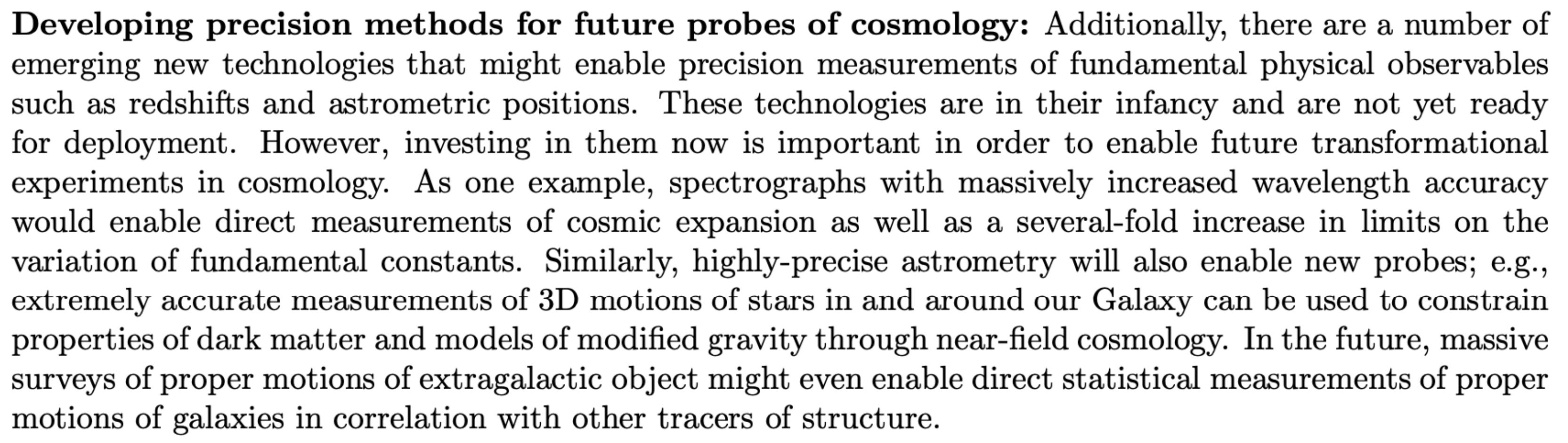
Table 4-3. Time required per epoch of SN host spectroscopy in LSST deep fields

Instrument / Telescope	Collecting Area (sq. m)	Field area (sq. arcmin)	Multiplex	Total time (dark-years)
4MOST	10.7	14,400	1,400	0.05
Mayall 4m / DESI	11.4	25,500	5,000	0.03
WHT / WEAVE	13.0	11,300	1,000	0.06
Megamapper (Magellan-like)	28.0	25,416	20,000	0.01
Subaru / PFS	53.0	4,500	2,400	0.04
VLT / MOONS	58.2	500	500	0.29
Keck / DEIMOS	76.0	54	150	2.04
Keck / FOBOS	76.0	314	1,800	0.35
ESO SpecTel	87.9	17,676	15,000	0.01
MSE	97.6	6,359	3,249	0.01
GMT/MANIFEST + GMACS	368.0	314	420	0.07
TMT / WFOS	655.0	25	100	0.51
E-ELT / Mosaic Optical	978.0	39	200	0.22[1]
E-ELT / MOSAIC NIR	978.0	46	100	0.19

[1] For E-ELT, observations in both the optical and near-IR settings are required to achieve the required wavelength coverage, increasing total time required.

Report Executive Summary: R&D for the future

- **Instrumental R&D is needed** in the shorter term to enable new techniques for exploring acceleration and other cosmological questions:
  - Smaller fiber positioners for Stage V spectroscopic facilities
  - Precision wavelength measurements to enable redshift drift measurements
  - Precision astrometry measurements to enable tests of DM and gravity
  - Development of intensity-mapping methods at a range of wavelengths
  - Described in section 4.8



Developing precision methods for future probes of cosmology: Additionally, there are a number of emerging new technologies that might enable precision measurements of fundamental physical observables such as redshifts and astrometric positions. These technologies are in their infancy and are not yet ready for deployment. However, investing in them now is important in order to enable future transformational experiments in cosmology. As one example, spectrographs with massively increased wavelength accuracy would enable direct measurements of cosmic expansion as well as a several-fold increase in limits on the variation of fundamental constants. Similarly, highly-precise astrometry will also enable new probes; e.g., extremely accurate measurements of 3D motions of stars in and around our Galaxy can be used to constrain properties of dark matter and models of modified gravity through near-field cosmology. In the future, massive surveys of proper motions of extragalactic object might even enable direct statistical measurements of proper motions of galaxies in correlation with other tracers of structure.

Technology could enable redshift drift measurements as a future probe of cosmology

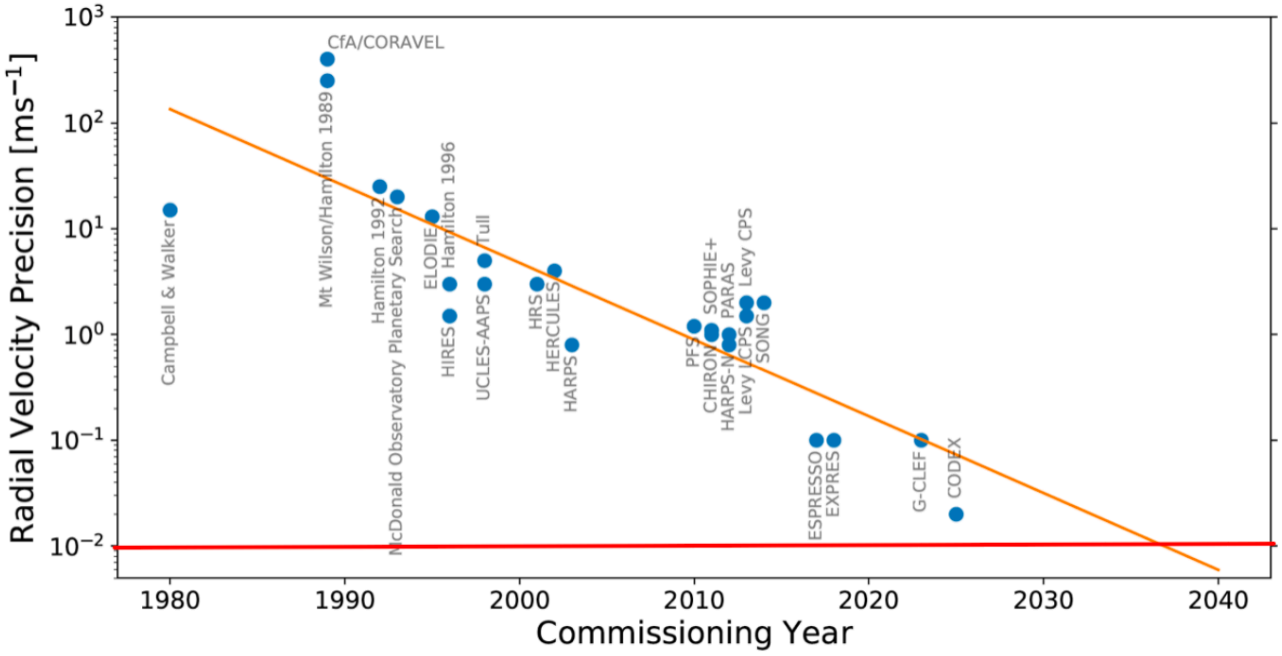


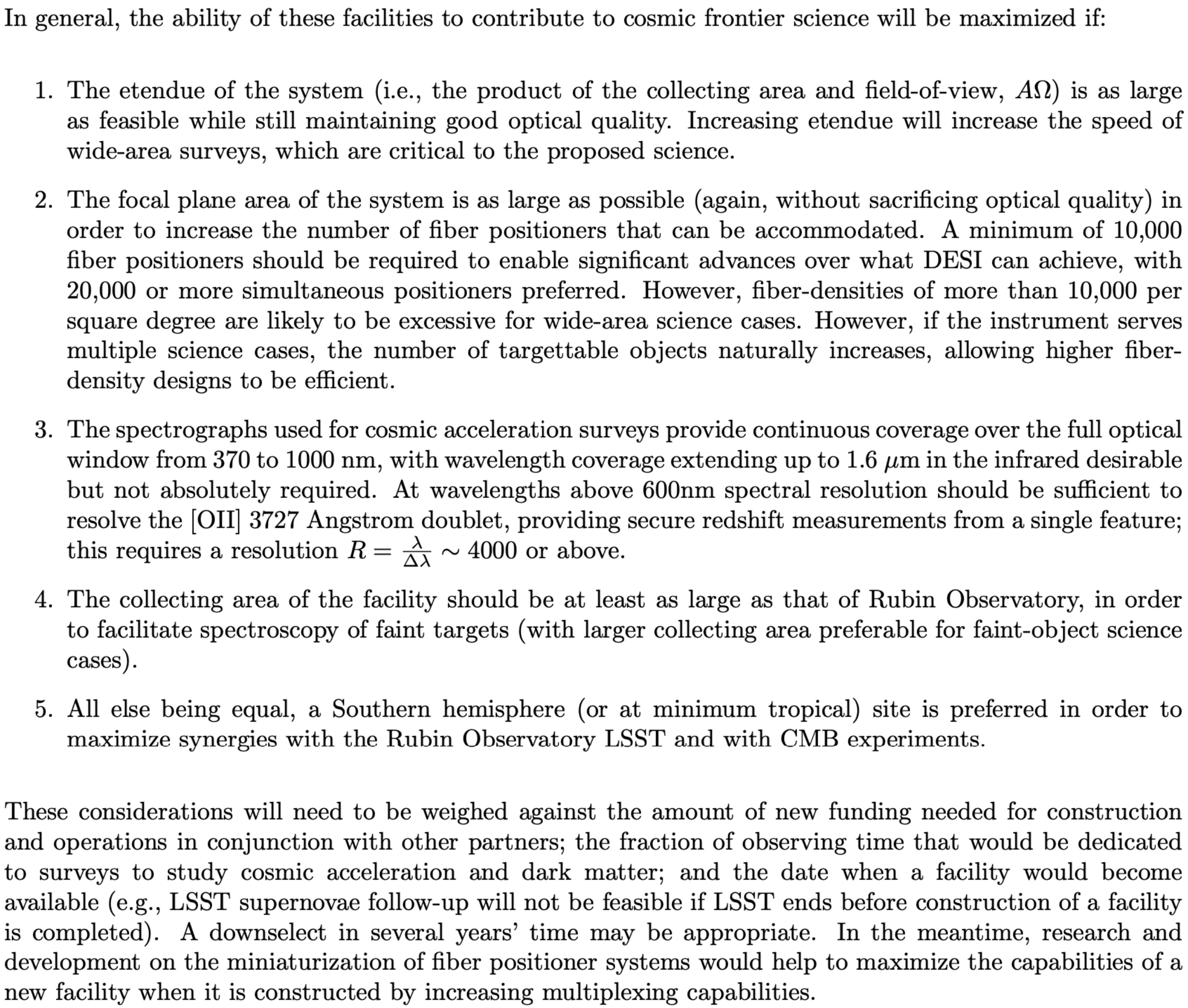
Figure 4-6 Improvements in RV precision for various upcoming instruments (adapted from Silverwood & Easther 2019 and taken from [62]). Cosmological redshift drift requires ∼ 1 cm s^{-1} precision (red line) with stability of years to decades.

Summary of our findings:

- Key questions we address begin with measuring **dark energy** - both through new experiments and new data to strengthen planned ones - but extend far beyond.
  - tests of gravity, measurement of neutrino masses, constraints on dark radiation, early dark energy, general constraints on inflation models, exploring σ_8 tensions...
- The field is vibrant and progressing rapidly:
  - DES, DESI, Rubin/LSST, complemented by SphereX, Euclid, Roman
  - Growing out of the 2013 Snowmass!
  - Need to evaluate future of Rubin in ~5 years after first LSST results

- The Community believes our roadmap is:
- In the long run - A Stage V spectroscopic facility
- In the short run - A spectrum of exciting programs on telescopes small to ELT
- Always needed - Instrumental R&D

How to evaluate Stage V spectroscopic facility options?



In general, the ability of these facilities to contribute to cosmic frontier science will be maximized if:

1. The etendue of the system (i.e., the product of the collecting area and field-of-view, $A\Omega$) is as large as feasible while still maintaining good optical quality. Increasing etendue will increase the speed of wide-area surveys, which are critical to the proposed science.
2. The focal plane area of the system is as large as possible (again, without sacrificing optical quality) in order to increase the number of fiber positioners that can be accommodated. A minimum of 10,000 fiber positioners should be required to enable significant advances over what DESI can achieve, with 20,000 or more simultaneous positioners preferred. However, fiber-densities of more than 10,000 per square degree are likely to be excessive for wide-area science cases. However, if the instrument serves multiple science cases, the number of targettable objects naturally increases, allowing higher fiber-density designs to be efficient.
3. The spectrographs used for cosmic acceleration surveys provide continuous coverage over the full optical window from 370 to 1000 nm, with wavelength coverage extending up to 1.6 μm in the infrared desirable but not absolutely required. At wavelengths above 600nm spectral resolution should be sufficient to resolve the [OII] 3727 Angstrom doublet, providing secure redshift measurements from a single feature; this requires a resolution $R = \frac{\lambda}{\Delta\lambda} \sim 4000$ or above.
4. The collecting area of the facility should be at least as large as that of Rubin Observatory, in order to facilitate spectroscopy of faint targets (with larger collecting area preferable for faint-object science cases).
5. All else being equal, a Southern hemisphere (or at minimum tropical) site is preferred in order to maximize synergies with the Rubin Observatory LSST and with CMB experiments.

These considerations will need to be weighed against the amount of new funding needed for construction and operations in conjunction with other partners; the fraction of observing time that would be dedicated to surveys to study cosmic acceleration and dark matter; and the date when a facility would become available (e.g., LSST supernovae follow-up will not be feasible if LSST ends before construction of a facility is completed). A downselect in several years' time may be appropriate. In the meantime, research and development on the miniaturization of fiber positioner systems would help to maximize the capabilities of a new facility when it is constructed by increasing multiplexing capabilities.