Future Facilities: The Stage 5 Spectroscopic Survey (Spec-S5)

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What is a Stage 5 Spectroscopic experiment?

Dark Energy Task Force (DETF) in 2005 advised DOE, NSF, NASA on the future of Dark Energy research

REPORT OF THE

DARK ENERGY TASK FORCE

Four stages of spectroscopic experiments:

- Stage 1 & 2: SDSS — confirms Dark Energy
- Stage 3 SDSS/(e)BOSS — Establish BAO as key cosmological probe
- Stage 4: DESI — precision Dark Energy z=0->3

Stage 5 Spectroscopy moves us beyond the horizon of DETF, addressing Dark Energy, **inflationary physics**, neutrinos, light relics, dark matter

—> All of this is physics beyond the standard model

Spec-S5 will explore the observables of **INFLATION** physics.

These are the highest energy scales in physics at ~10^{16} GeV

Spec-S5 will address physics Beyond the Standard Model:

DARK ENERGY & **DARK MATTER**

Spec-S5 will do this with the largest **3-dimensional map** of the Universe

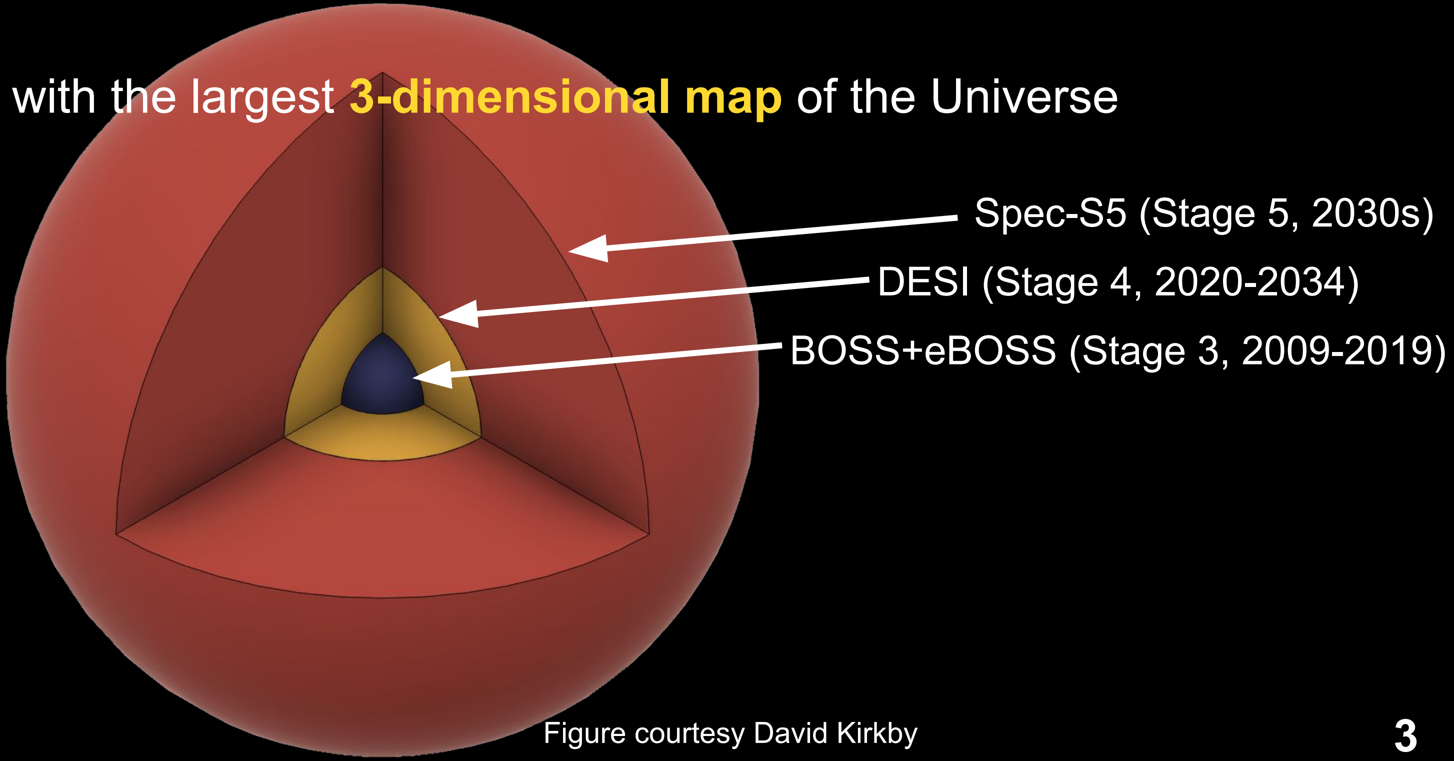


Figure courtesy David Kirkby

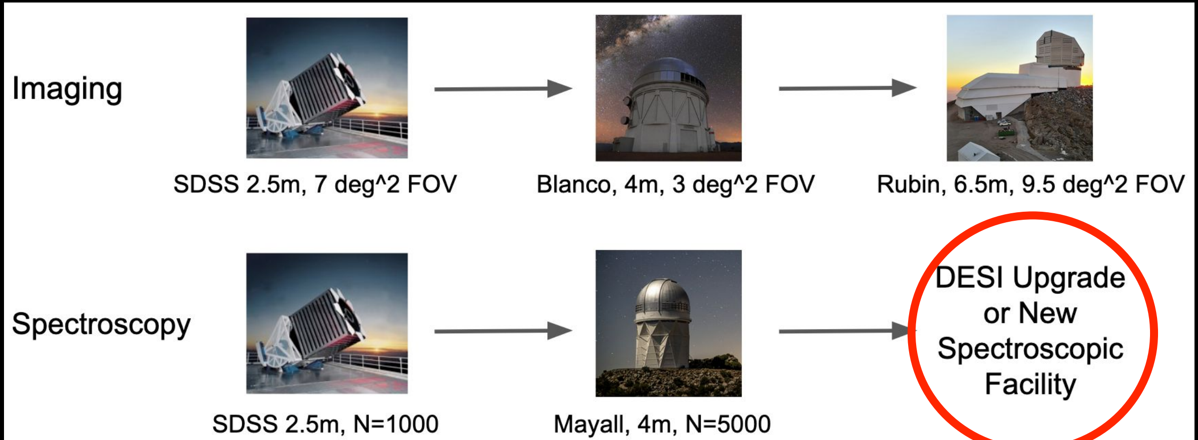
The Opportunities of Stage 5 Spectroscopy

Next-generation will probe both epochs of accelerated expansion

- Direct Dark Energy density measurements to z=4.5
- Improved sensitivity to initial conditions imposed by inflation

- 10-fold increase in survey power (Stage 5) relative to DESI (Stage 4)
- Theory development for signature of BSM physics in large-scale structure (e.g. this conference)

Snowmass report: “CMB-S4 and Spec-S5 are ready to be immediately implemented”



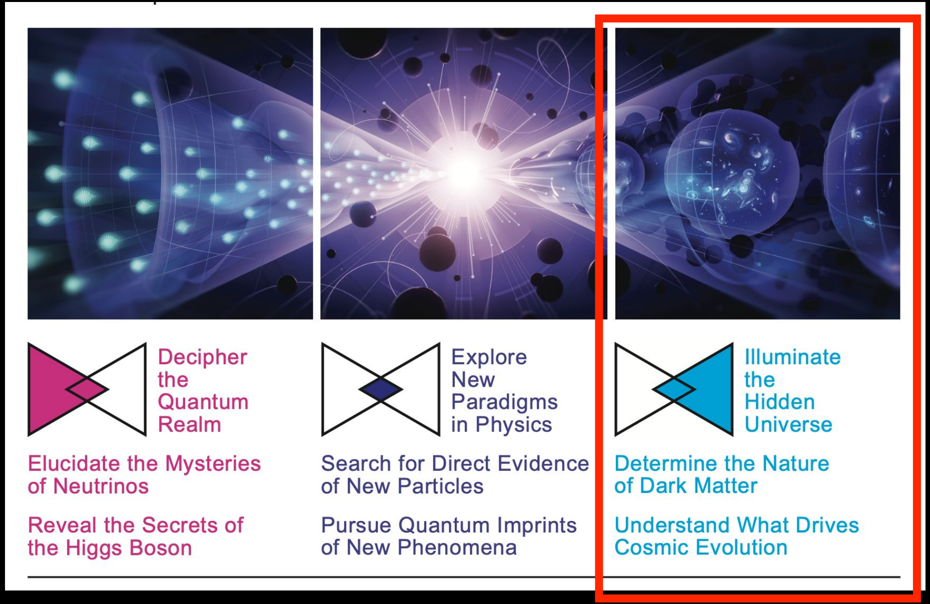
Snowmass CF6 report

Snowmass Cosmic Frontier report:

" **Cosmic observations are exclusively responsible for our knowledge of the need to extend the Standard Model** to describe dark matter, dark energy, and cosmic inflation. "

P5 recommends Spec-S5 to address key questions of the hidden universe:

" **Spec-S5, holds great promise to advance our understanding and reach key theoretical benchmarks** in several areas: inflationary physics via the statistical properties of primordial fluctuations, late-time cosmic acceleration, light relics, neutrino masses, and dark matter. "



P5: Endorses road map from DESI → DESI-II → Spec-S5

"The DESI-II program (Recommendation 3c) is a first step at going beyond the galaxy surveys constructed as a result of the previous P5 report. Besides providing an opportunity for testing technology for next-generation spectroscopic surveys, its scientific goals include constraining cosmic acceleration by extending DESI dark energy constraints deeper into the matter-dominated regime, and complementing/enhancing dark energy and dark matter science with Rubin Observatory LSST by leveraging the power of overlapping spectroscopic and imaging surveys."

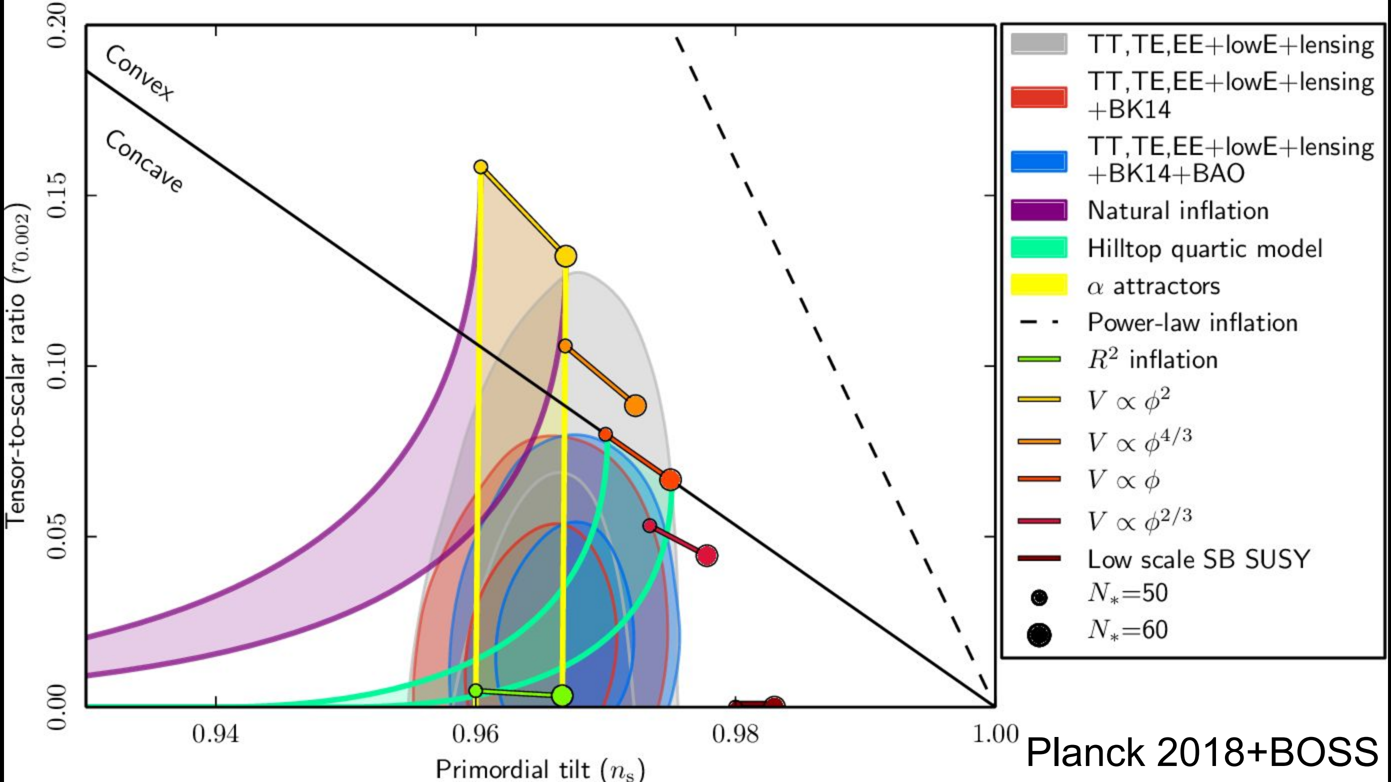
Spec-S5 goals

Spec-S5 science drivers

1. Inflation and Early Universe
2. Dark energy
3. Dark matter

Science driver 1: Inflation physics

Stage 3 experiments (Planck, BOSS) have shown that energy fluctuations at the end of inflation were not exactly scale-free (n_s=0.97), gravity waves were small (r), ruling out the simplest (ϕ^2) inflation models



Planck 2018+BOSS

Science driver 1: Inflation and Early Universe Physics

Spec-S5 will extensively explore inflation by measuring its non-gaussianity and primordial features, complementary to CMB-S4's measurement of B-modes from gravity waves

1. **Tensor-to-scalar ratio**: energy scale of inflation → best measured by CMB-S4 in B-modes
   - insight into rate of expansion during inflation
   - detection provides evidence that gravity is quantized

2. **Non-gaussianity**: physics of the inflaton field → best measured by Spec-S5 and CMB-S4
   - number of fields responsible for inflation
   - excited state of the inflaton field
   - interactions between particles and the inflaton field

3. **Primordial features:** deviations in scale invariance from well-motivated particle physics
   - early universe particle production
   - periodic corrections to the inflationary potential
   - changes to the power-law power spectrum on small scales
   - ***best measured by Spec-S5***

Science driver 1: Inflation and Early Universe Physics

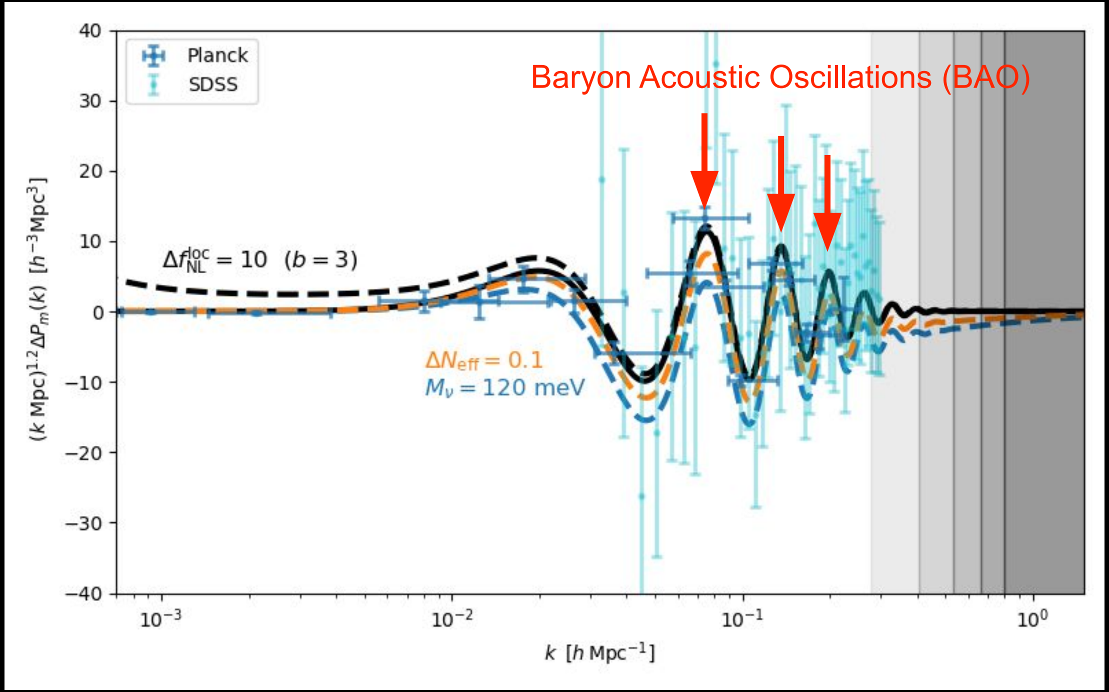
Spec-S5 will provide insights into very early cosmic history by measuring the effective number of neutrino species and other aspects of new physics that alter the clustering of matter

1. **Light Relics**: Well-motivated BSM particles
    - Low mass, very weakly interacting particles
    - detection provides evidence that gravity is quantized
    - Δ Neff > 0.027, depending on time of decoupling and other factors
    - Measured in CMB and Spec-S5

2. **Other Physics:** LSS captures evolutionary history since end of inflation
    - ***What is best measured by Spec-S5?***

Science driver 1: Inflation physics

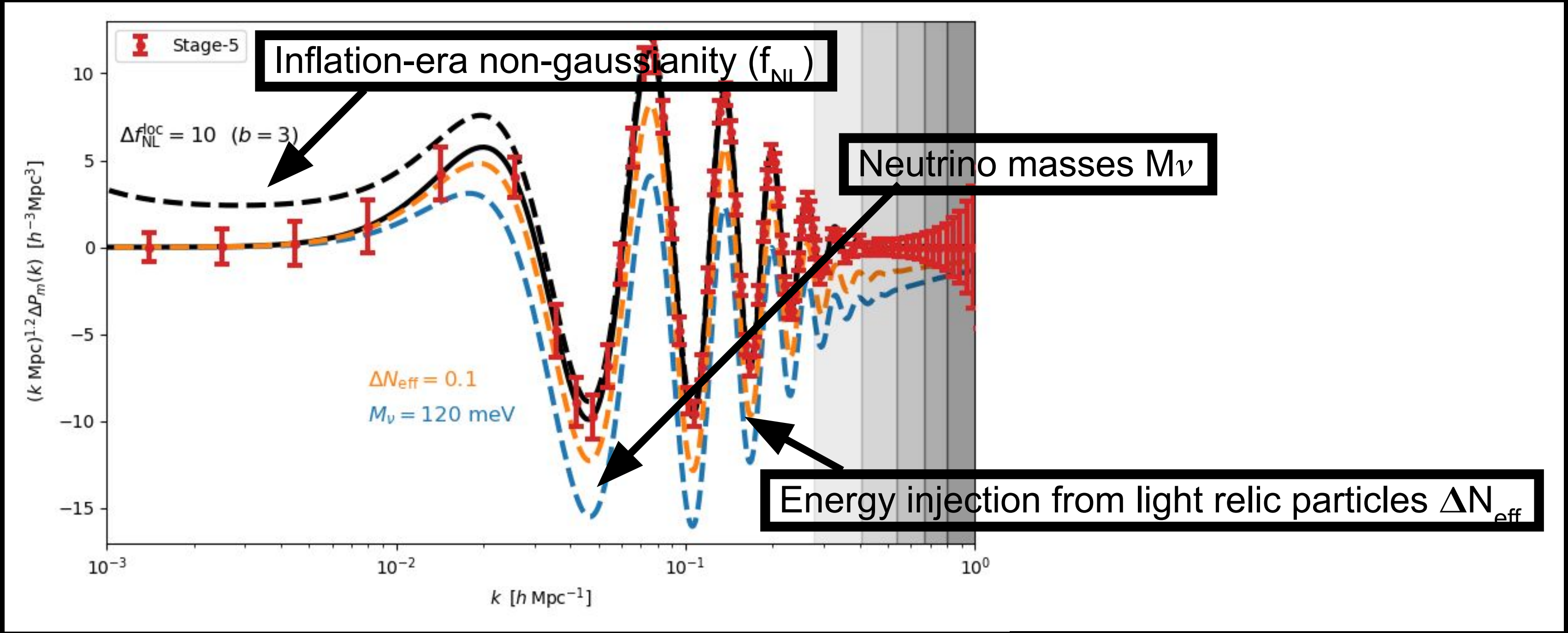
Spec-S5 uses the tool of the power spectrum of density fluctuations imprinted from the early universe, rapidly matured technology from BOSS (Stage 3) -> DESI (Stage 4) -> SpecS5 (Stage 5)



Science driver 1: Inflation physics

Spec-S5 unlocks new physics with a next generation of accuracy across a vast range of scales

Spec-S5 will extensively explore inflation by measuring its non-gaussianity and primordial features



Why Use Galaxies?

1. **Early Universe clustering statistics**:
   - CMB: advantage of linear physics and well-controlled tracers
   - Galaxies: advantage is in shear information content due to three-dimensional clustering

2. **Galaxies over $2<z<4.5$ as optimal tracers**:
   - Roughly maximum volume per solid angle → large number of modes
   - Reduced processing of density field relative to lower redshift DESI sample
   - Closer representation of initial conditions

3. **Challenges in Galaxies over $2<z<4.5$:**
   - Limits of imaging, target selection, and spectroscopy from ground-based telescopes
   - Increasing bias with increasing redshift partially mitigating benefits of linear modeling
   - Uncertain impact in precision from higher order statistics

Science driver 2: Dark energy

Spec-S5 BAO will confidently measure dark energy at z>2,
many measurements with 1% accuracy
when the universe was transitioning from dark matter-dominated to dark-energy dominated

Current hints of time-varying dark energy equation of start will be confidently confirmed or ruled out by Spec-S5 BAO

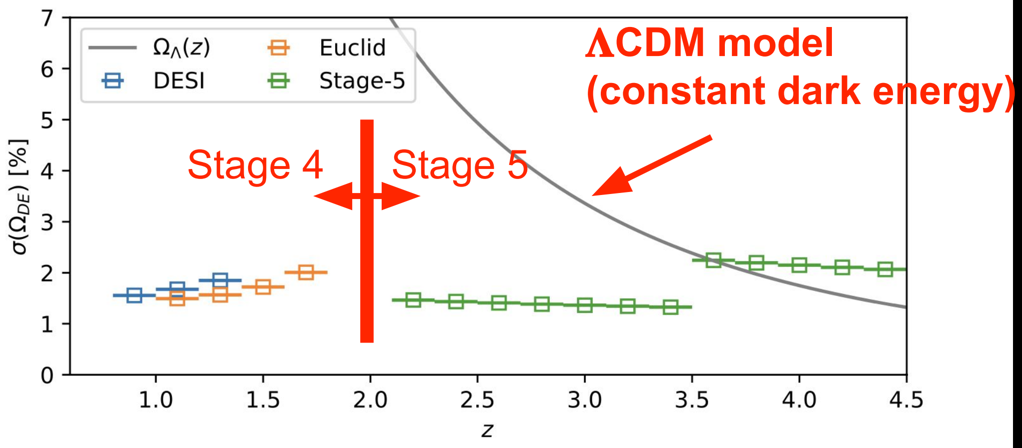


Figure 1: Predicted precision on the absolute error on the dark energy fraction ($\Omega_{\rm DE}$) as a function of redshift. The solid curve presents the relative energy density of dark energy under the fiducial ΛCDM model.

Science driver 3: Dark matter

All **positive** evidence of dark matter is from cosmological measures
Spec-S5 will map gravitational influence of dark matter-only masses in the outer halo of the Milky Way

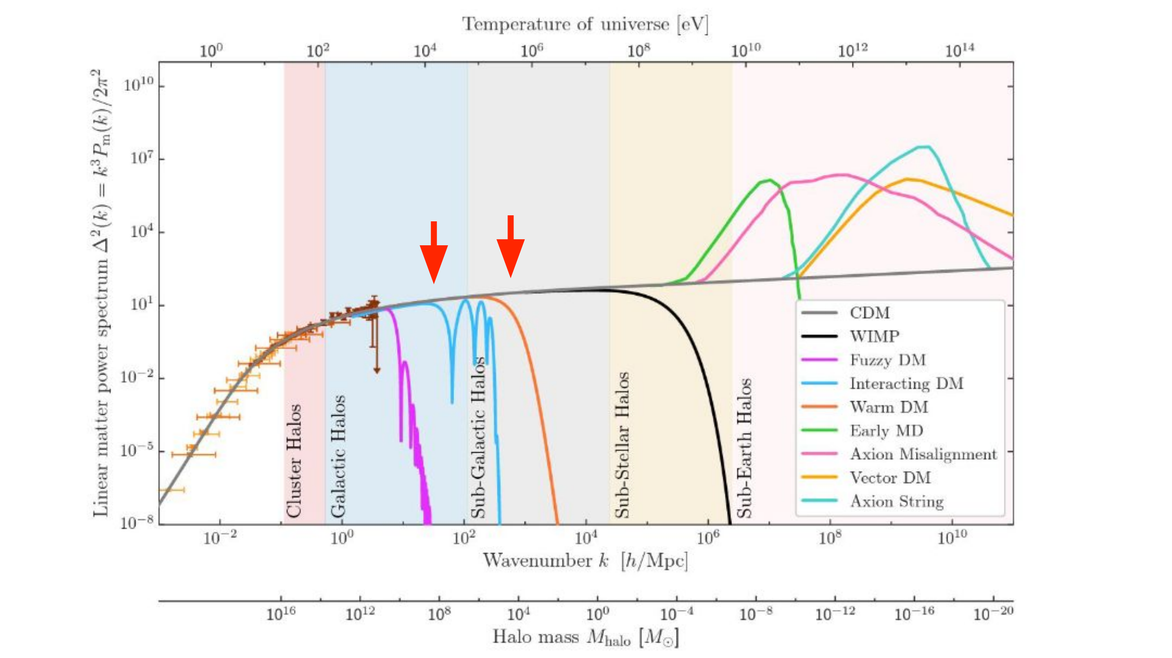
S. Payne-Wardenaar / K. Malhan, MPIA

Science driver 3: Dark matter

Spec-S5 will detect the gravitational influence of clumps of dark matter

Spec-S5 will test hidden-sector dark matter models: axions, interacting DM, warm DM, even in cases that would be inaccessible to direct detection

In the 2030s, breakthrough discoveries of dark matter could come from direct direction or cosmological (gravitational) detections



Predictions for 8 models for dark matter models that modify the power spectrum relative to Cold Dark Matter (Bechtol et al 2022)

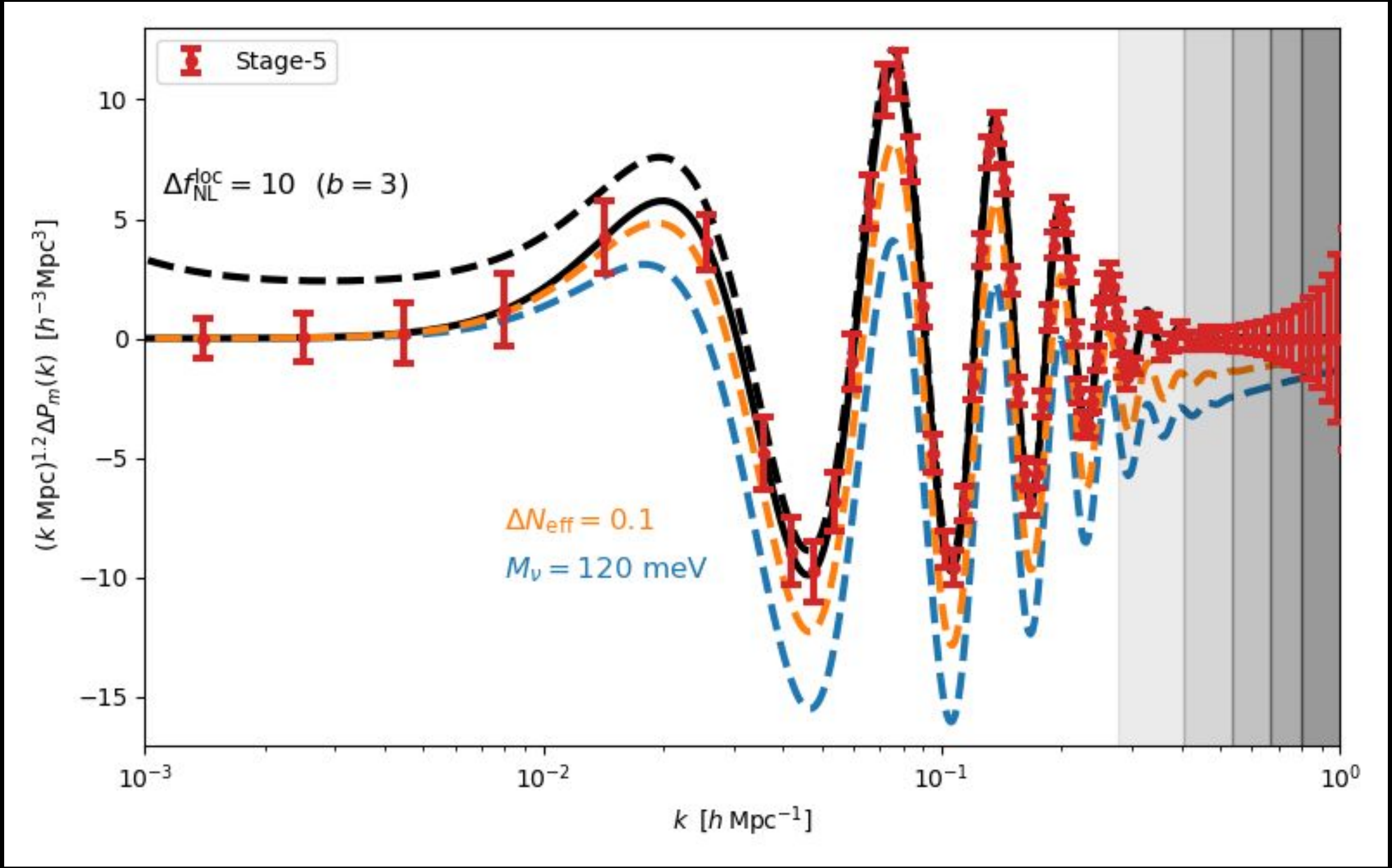
Today's Sessions: Opportunities in Next Generation LSS

1. **2nd Morning Session**: Theoretical Modeling and Higher Order Statistics
   - Applications of EFT to LSS
   - Physics beyond the power spectrum

2. **1st afternoon session:** Inflationary Physics - non-Gaussianity
   - Introduction to non-Gaussianity
   - Panel discussion on what we know and don't know about non-Gaussianity

3. **Closing session:** Particle Physics and LSS
   - Perspectives from particle physics, dark matter, and European community

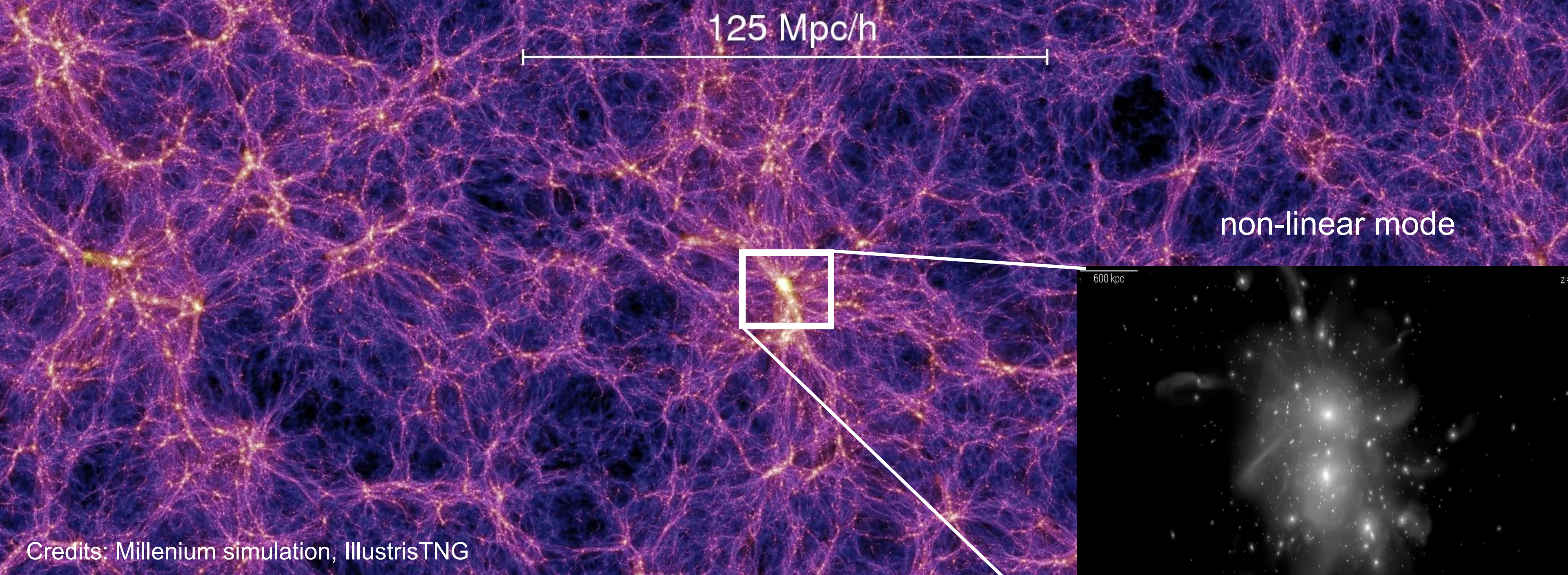
Expected Precision on Power Spectrum



Spec-S5 requirements

Spec-S5 conceptual design designed for 10x "Primordial Figure of Merit" by mapping 10x more linear modes than DESI

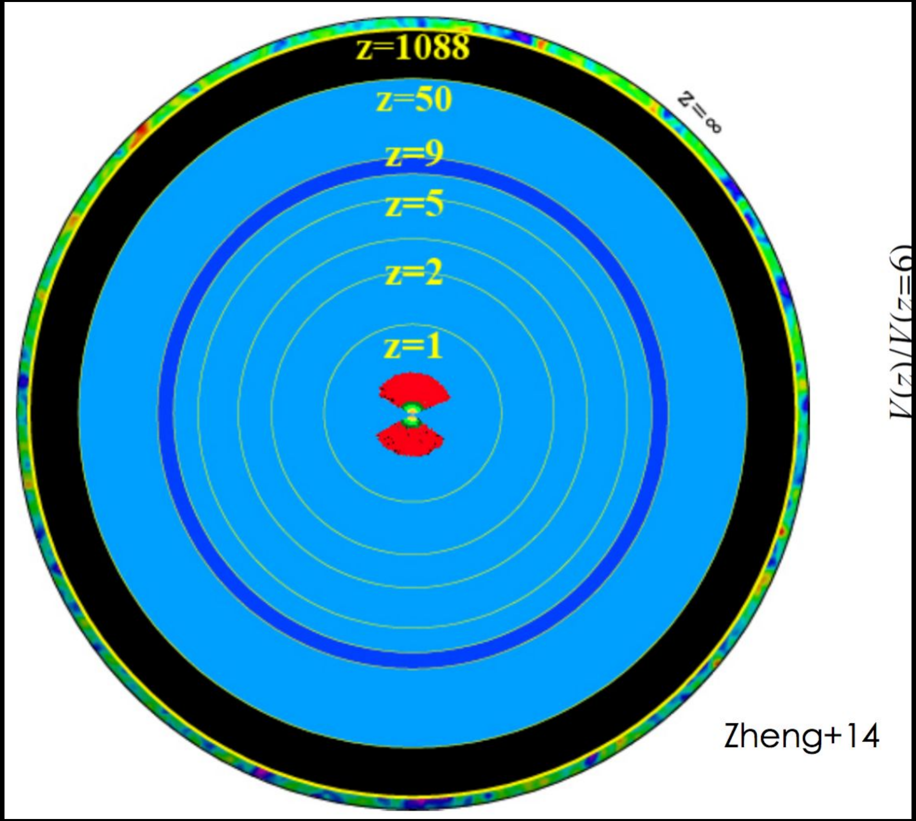
More modes achieved with
- more volume
- smaller non-linear scales at high redshift

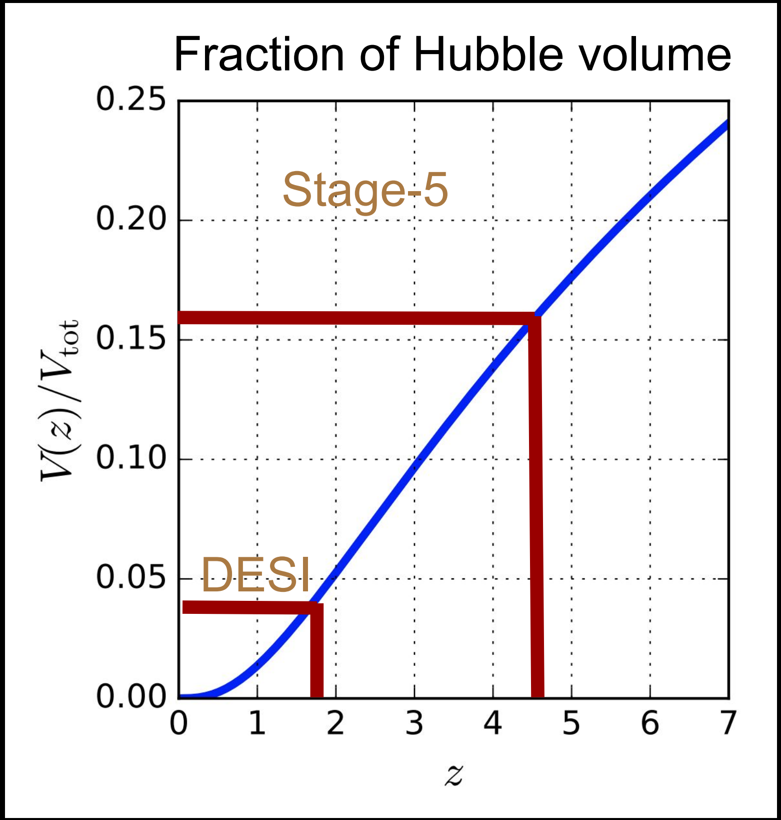


Credits: Millenium simulation, IllustrisTNG

Map more galaxies -> more linear modes -> Primordial Figure of Merit

- 2 < z < 4.5 enormous volume only accessible with spectroscopy (Stage 5)
- 4.5 < z < 20 comparable volume from future radio surveys (Stage 6)

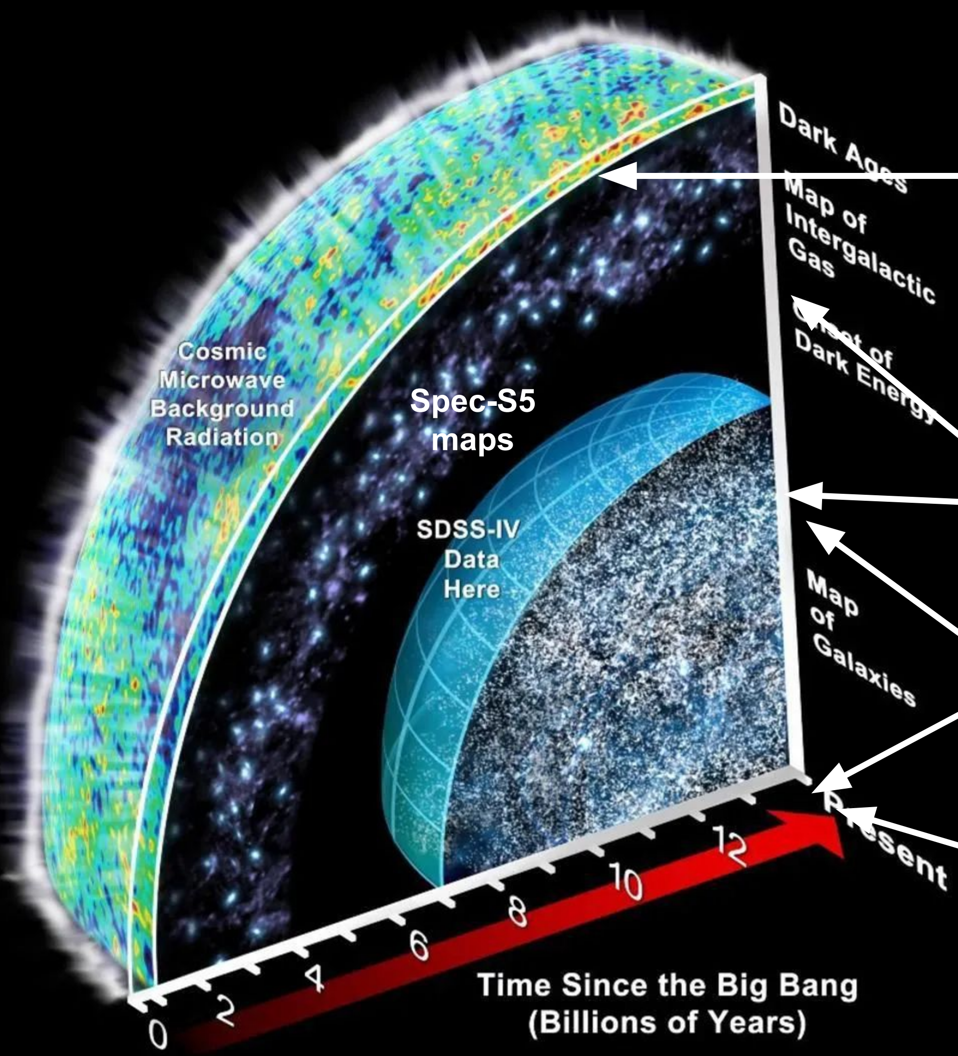




Science Requirements (Statistical Precision)

1. **Spec-S5:** Multi-dimensional science drivers
   - Motivated by comprehensive study of inflation and early universe physics
   - Level One Requirement based on information contena
     - Level 1 requirement: 10-fold increase in number of Fourier modes relative to DESI
   - Flow-down to Level 2 requirement: number density of galaxies and area
     - Level 2 requirement: survey area of 11,000 square degrees
     - Level 2 requirement: $n>8.0 \times 10^{-4}\ h^3/\mathrm{Mpc}^3$ over $2.1<z<3.5$ (4698 per sqdeg)
     - Level 2 requirement: $n>2.0 \times 10^{-4}\ h^3/\mathrm{Mpc}^3$ over $3.5<z<4.5$ (716 per sqdeg)

Draft based on pilot studies of target selection and science case!



CMB is a limited number of modes by being 2-dimensional

Spec-S5 will map 62 million galaxies at z>2 for use in inflation + dark energy

Spec-S5 will map 130 million galaxies at z<2 for use in late-time dark energy

Spec-S5 will map 50 million stars for dark matter physics

Forecasts

1. **Number densities and area**:
   - $2.1<z<3.5$: $n>8.0 * 10^{-4}\ h^3/Mpc^3$ (4698 per sqdeg)
   - $3.5<z<4.5$: $n>2.0 * 10^{-4}\ h^3/Mpc^3$ (716 per sqdeg)
   - 11,000 sqdeg

2. **Assumptions:** Conservative? Realistic?
   - Single tracer
   - Power spectrum only (based on Sailer, Castorina, Ferraro & White, arXiv:2106.09713)

3. **Cosmology parameters:**
   - Measurements of Neff to a precision of 0.040 independent of CMB constraints
   - Constraints on the Local form of primordial non-Gaussianity to a precision of 1.4
   - No constraints on other forms of primordial non-Gaussianity
   - BAO (0.1% precision) and RSD (0.6% precision) at $2.1<z<4.5$
   - 4X improvement on primordial features relative to DESI

Spec-S5 implementation

Spec-S5 rebuilds two existing telescopes to be 15X faster than DESI

- Mayall Telescope at Kitt Peak, Arizona (northern site)
- Blanco Telescope at Cerro Tololo, Chile (southern site)

Both host DOE HEP experiments (DESI, Dark Energy Camera)

Mayall Telescope (Arizona)

Blanco Telescope (Chile)

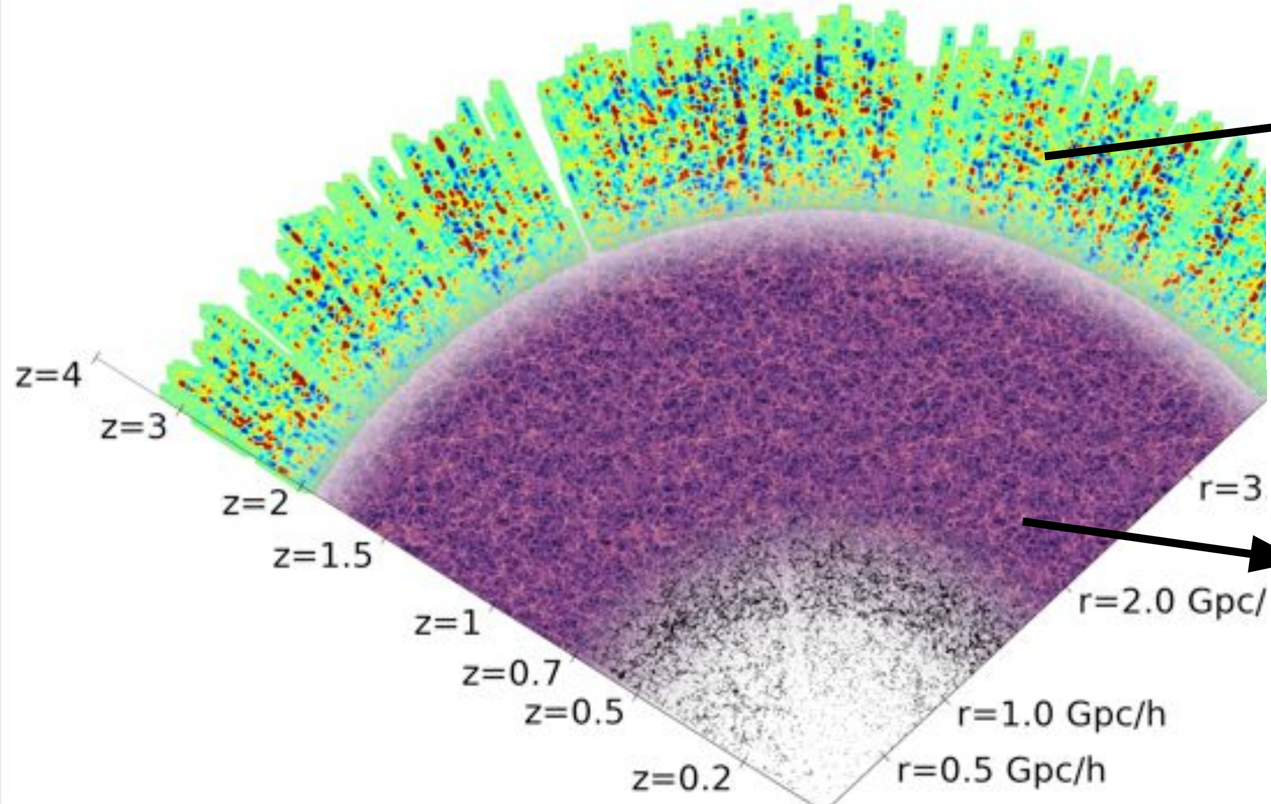
Survey Design Considerations

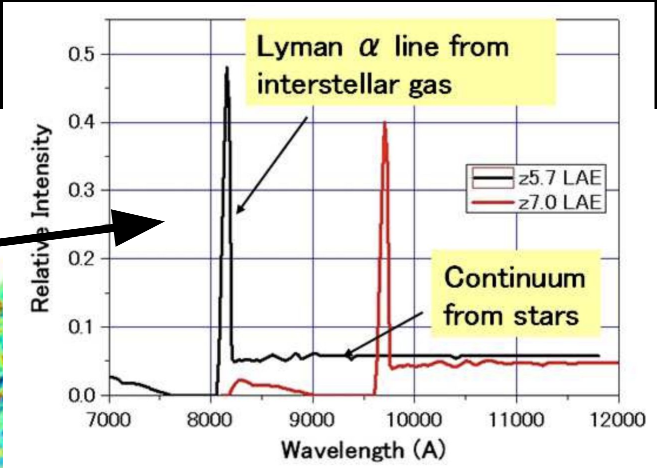
1. **Redshift reliability**
   - Design must allow confirmation of z>2 galaxies
   - Typically favors either high bias tracer or emission line galaxies

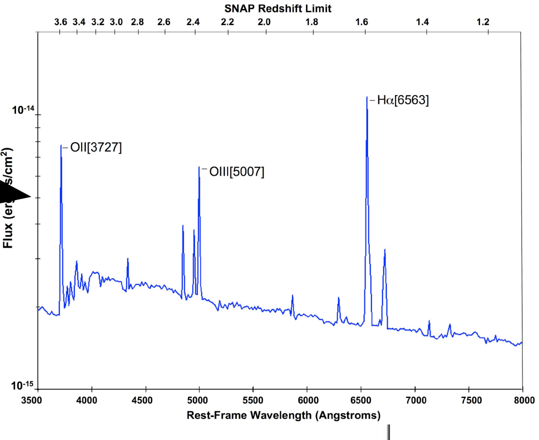
2. **Instrument constraints:**
   - Optics, fiber count, detectors, etc all within umbrella budget
   - >10X survey speed within reach

3. **Tracer bias:** Possible to trade number density and survey area, within reason
   - Consider information content as function of scale in power spectrum
   - Consider information content in higher order statistics
   - Consider effect of bias on modeling of power spectrum at smaller scales

The Universe has been kind providing compact galaxies at all redshifts







Spec-S5 has developed a survey plan in “Spec-S5 Reference Design”
Pilot studies for all target classes have been successfully conducted using the DESI instrument over the past year, with those data published or in the process of publication

- 62 million high redshift (z>2) galaxies
- 130 million galaxies at z<2
- 50 million dark matter tracer stars

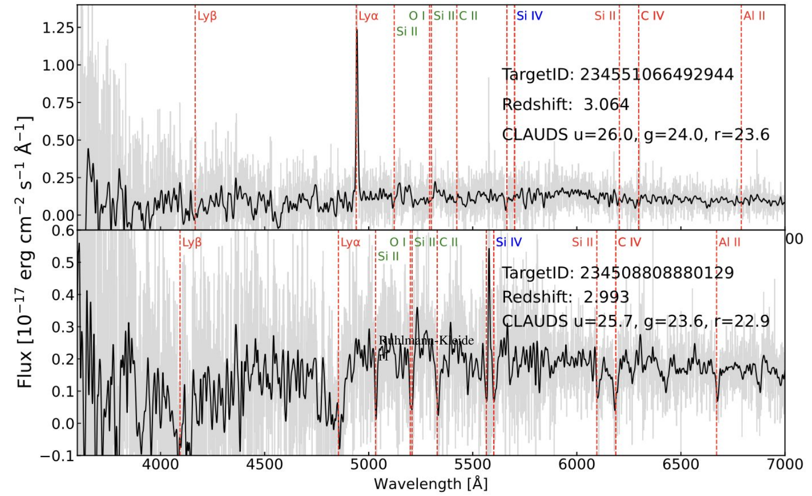


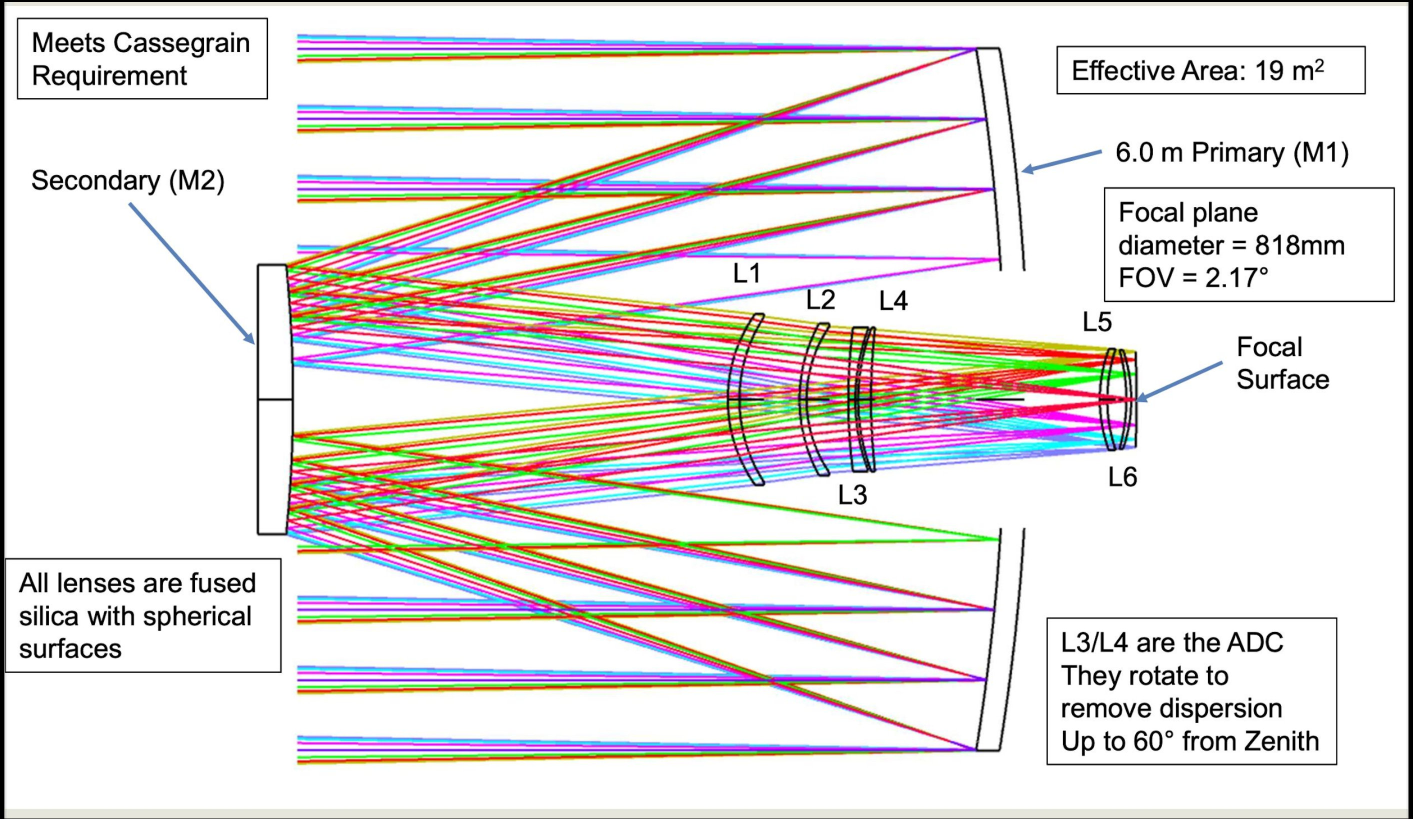
Figure 3. Two spectra of LBG targets from the u-dropout TMG selection measured during the pilot survey of 2021 on the COSMOS field. The raw spectra are in grey, the smoothed ones are in black. A Gaussian smearing with a standard deviation of 4 pixels is used. *Top:* a significant Lyα emission is present, hence absorption lines are weak. *Bottom:* a broad Lyα absorption is present as well as a sequence of quite visible absorption lines redward from the Lyα line. Lines labelled in green (resp. blue) are low (resp.high) ionization interstellar metal lines which are used as main redshift indicators during visual inspection.

Ruhlmann-Kleider et al 2024, submitted

Spec-S5 will upgrade 2 existing telescopes: Mayall (KItt Peak), Blanco (Chile)
to each have 6-meter collecting mirror, 26,000 fiber robots (total), 46 spectrographs (total)

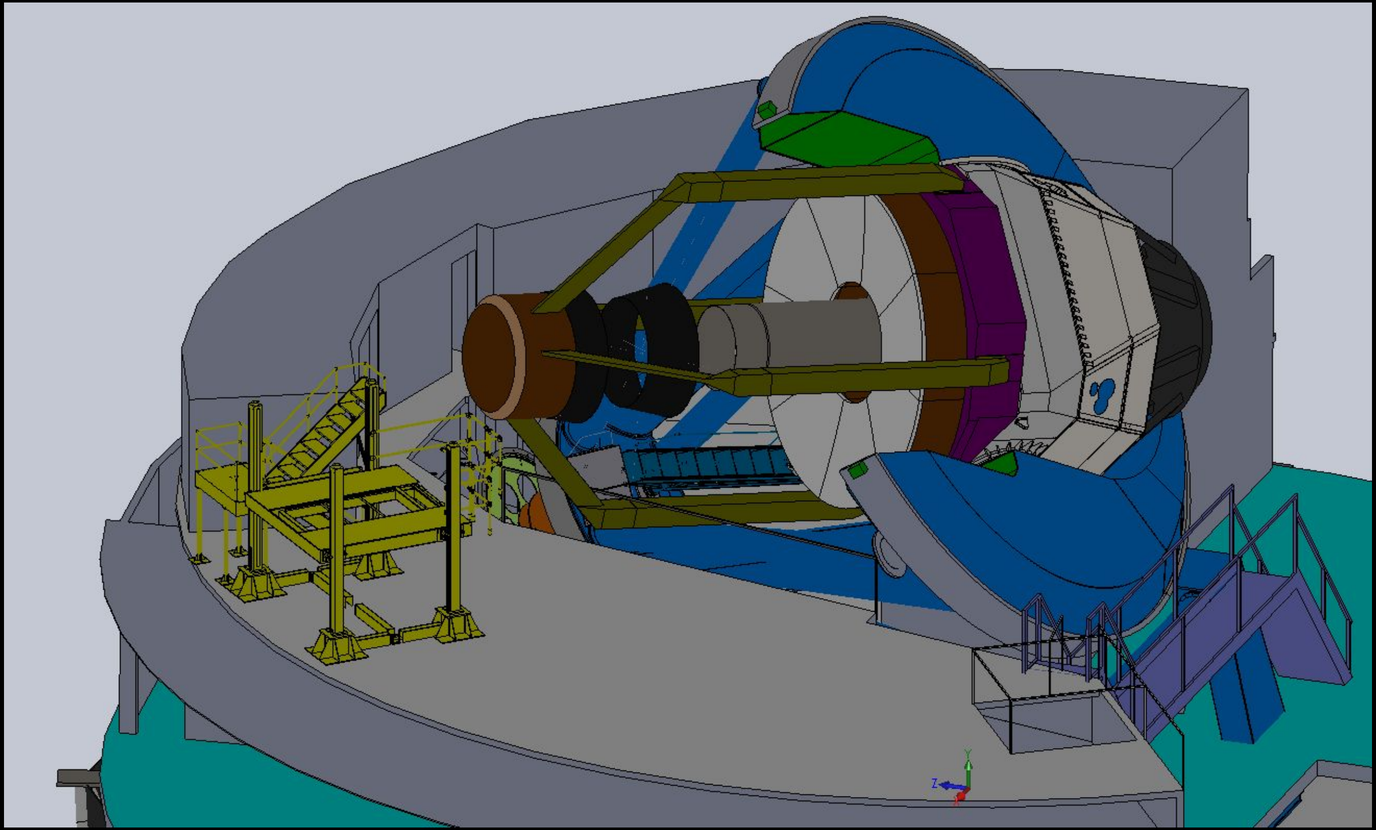
Spec-S5 optical design

6-meter diameter primary mirror is in-family with other telescopes
6-element optical corrector lenses all < 1.47-m diameter (LSST is 1.55-m),
simpler to manufacture than DESI & LSST as all surfaces are spherical



Spec-S5 mechanical design

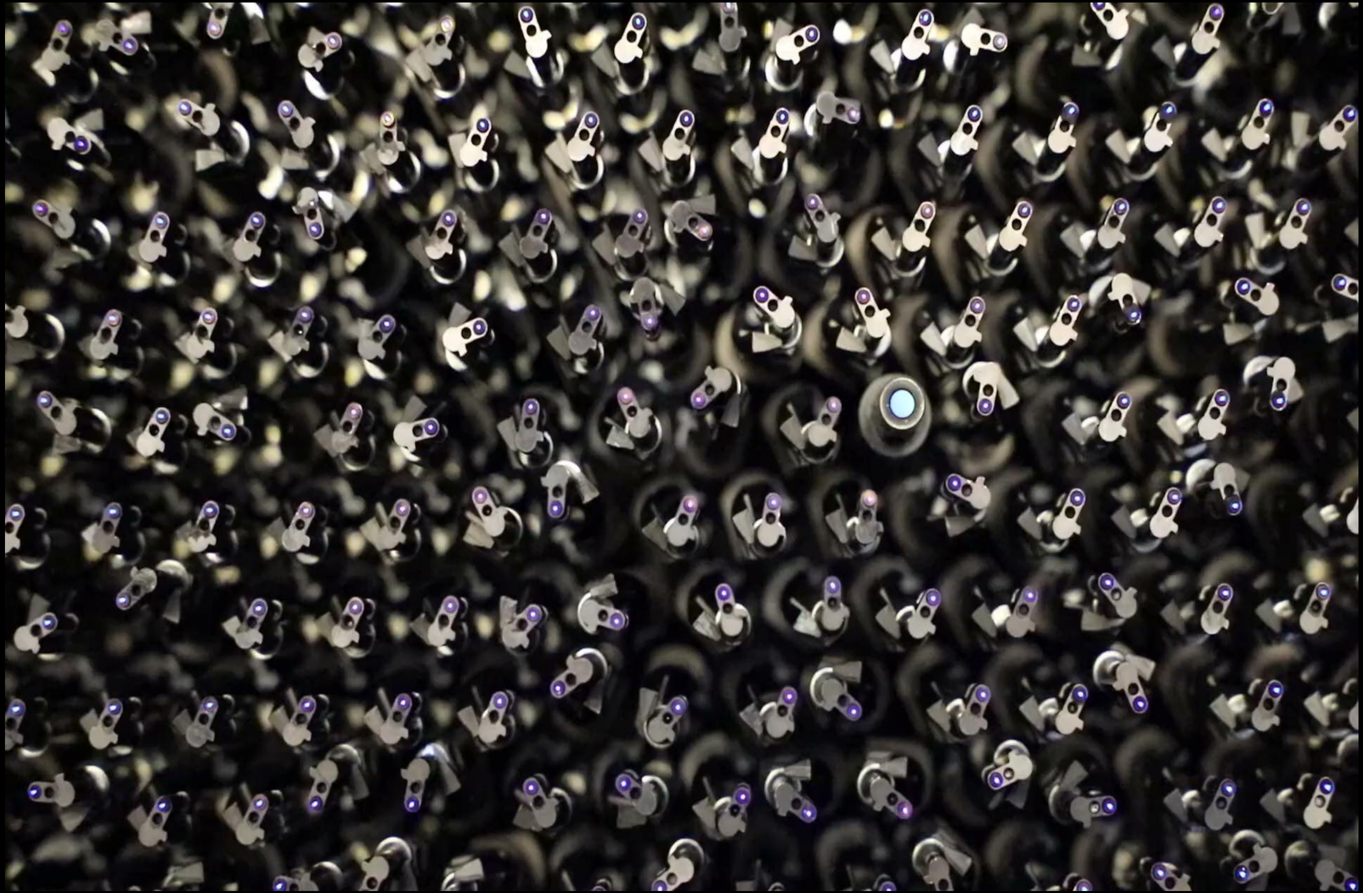
Requires modifications to one portion of the telescope mount (the “horseshoe”), resulting structure is 1.3-m shorter than existing DESI, 6 tons less mass



Spec-S5 focal plane

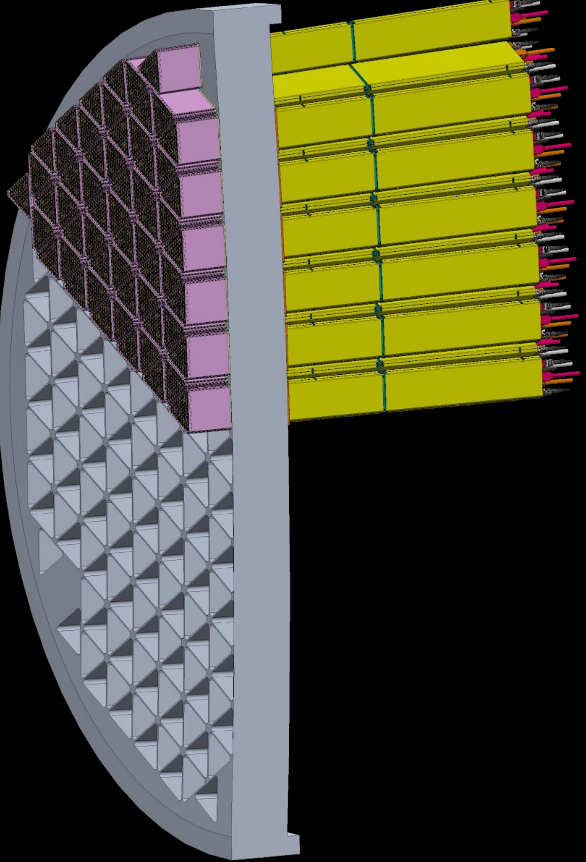
Currently DESI has the highest multi-plexing with 5000 fiber robots
Spec-S5 requires 13,000 fiber robots on each of 2 telescopes

10.4 mm pitch



Spec-S5 focal plane

R&D on **miniaturized** fiber robots (LBNL, U Michigan, EPFL Switzerland)
63-robot "rafts" will be commercially manufactured



Prototype Spec-S5 raft from commercial vendor (Orbray)

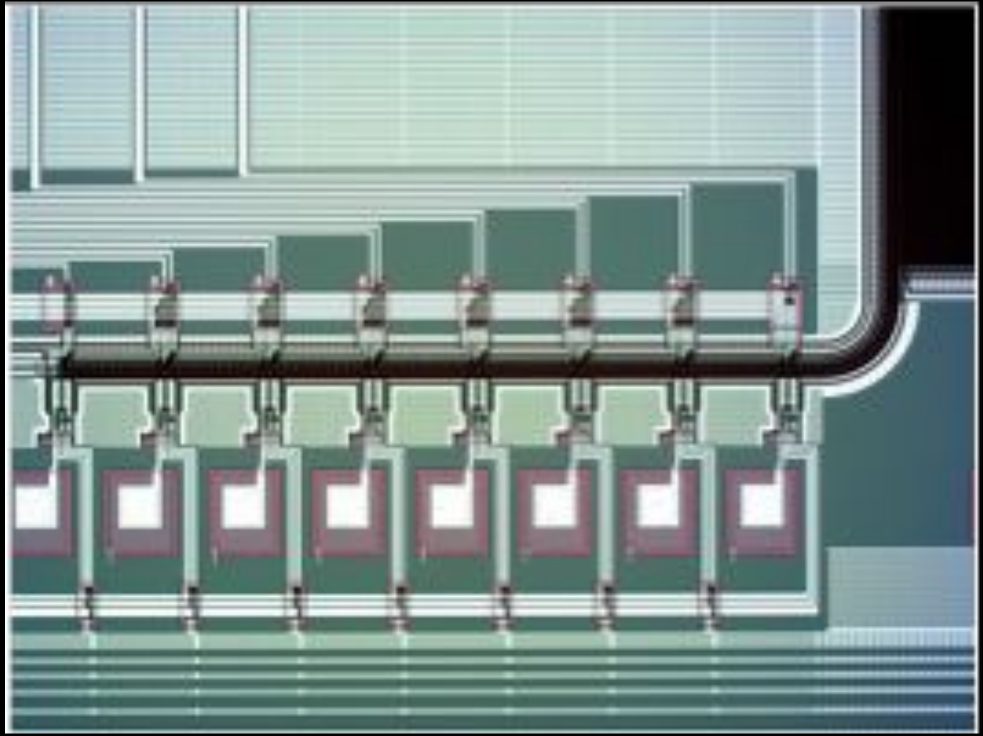
Spec-S5 spectrographs

Spec-S5 could construct **"build-to-print" copies of the DESI spectrographs**

Spec-S5 detectors

Spec-S5 will use **multi-amplifier sensing** CCDs with <1 e- read noise

Spec-S5 may have the opportunity to use Germanium CCDs to also map $1.6 < z < 2.0$
(currently only possible with very costly spectrographs+detectors, i.e. Prime Focus Spectrograph)



Status of Spec-S5

2022: Endorsed by the US Snowmass Community Process
2023: Recommended by the Particle Physics Project Prioritization Panel (P5)
2024: Presented to the High Energy Physics Facilities Subpanel (HEPAP)
2026: Requested project start
2035: First Light

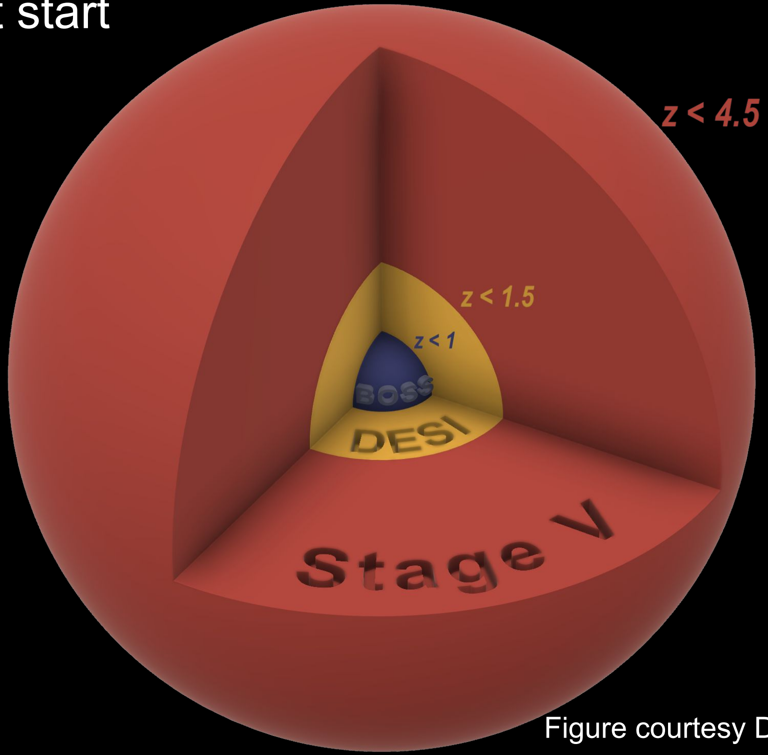
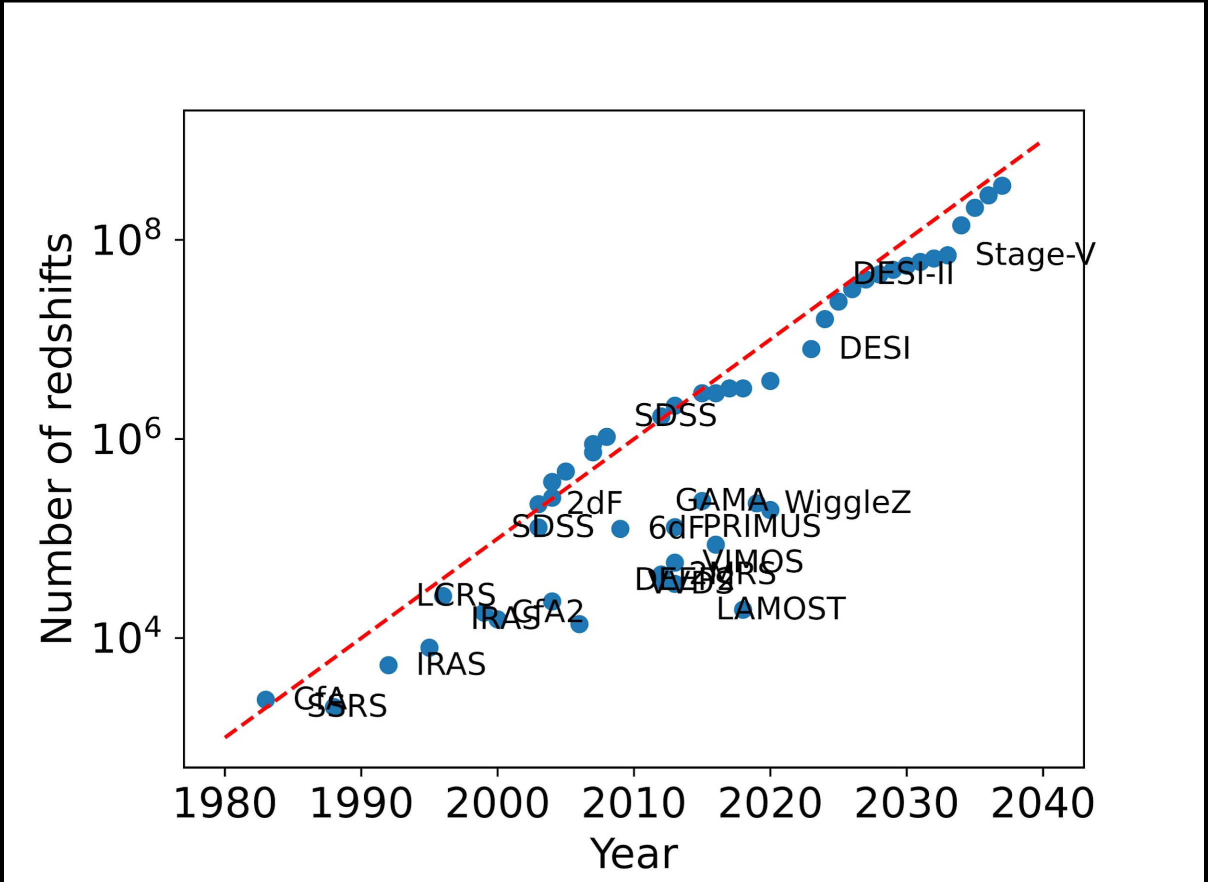


Figure courtesy David Kirkby

Redshift surveys increasing 10X every 10 years

All linear modes at z<4 mapped by 2043 — 2 billion galaxies
All detectable galaxies mapped by 2061 — 140 billion galaxies



The universe has been kind allowing us to map the primordial perturbations… carpe noctum (seize the night)