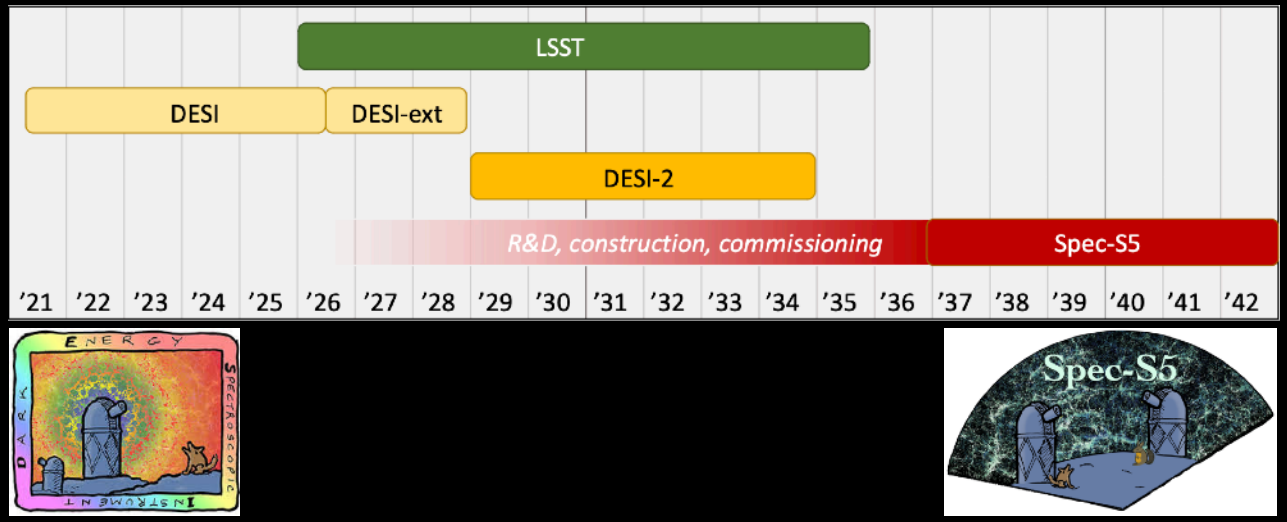
Spec-S5:

exploring the 2 < z < 4.5 Universe



A. Raichoor (LBNL) — Action Dark Energy 2024 — Oct. 30, 2024

Outline

- Context: US Spectroscopic Roadmap
- Spec-S5: Science at z > 2, Instrumental setup
- DESI-2, a Spec-S5 pathfinder

Material

- Snowmass Papers, e.g.:
  - Schlegel+22: https://ui.adsabs.harvard.edu/abs/2022arXiv220903585S
  - Ferraro+22: https://ui.adsabs.harvard.edu/abs/2022arXiv220307506F
  - CF4 report: https://ui.adsabs.harvard.edu/abs/2022arXiv220908049A
  - CF5 report: https://ui.adsabs.harvard.edu/abs/2022arXiv220908265C
  - CF6 report: https://ui.adsabs.harvard.edu/abs/2022arXiv220908654F
  - Overall CF report: https://ui.adsabs.harvard.edu/abs/2022arXiv221109978C
- P5 2023 report: https://www.usparticlephysics.org/2023-p5-report
- HEPAP May 2024 meeting slides: https://science.osti.gov/hep/hepap/Meetings/202405
- Talks at “Future spectroscopic surveys workshop” (Berkeley, May 2024): https://indico.physics.lbl.gov/event/2769/
- Spec-S5 website for instrument infos: https://spec-s5.org

Spectroscopic roadmap on good tracks

- Snowmass:
  - "*identify the most important questions in High Energy Physics and the tools and infrastructure required to address them*"
  - Letters of Intent → White Papers → Panel Reports → Frontier Reports → Final Report

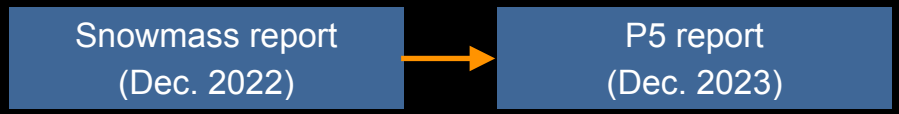
Snowmass report
(Dec. 2022)

Lists all the science cases that could be best done with a Stage V spectroscopic survey

"Continue operation of DESI (via a new DESI-II program) to constrain dark energy in new domains and as a step towards a Stage V spectroscopic facility (Spec-S5)."

Spectroscopic roadmap on good tracks

- Snowmass:
  - "*identify the most important questions in High Energy Physics and the tools and infrastructure required to address them*"
  - Letters of Intent → White Papers → Panel Reports → Frontier Reports → Final Report
- P5: Particle Physics Project Prioritization Panel



"*The proposed next-generation spectroscopic survey, 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.*

Spectroscopic roadmap on good tracks

- Snowmass:
  - "*identify the most important questions in High Energy Physics and the tools and infrastructure required to address them*"
  - Letters of Intent → White Papers → Panel Reports → Frontier Reports → Final Report
- P5: Particle Physics Project Prioritization Panel
- HEPAP: High Energy Physics Advisory Panel

Snowmass report (Dec. 2022) → P5 report (Dec. 2023) ⇢ HEPAP report (meeting in May 2024)

P5 Recommendation 1: we recommend continued support for the following ongoing experiments [...]: DESI

→ DOE fully supports this recommendation and puts it as the highest priority in planning our allocation of funding.

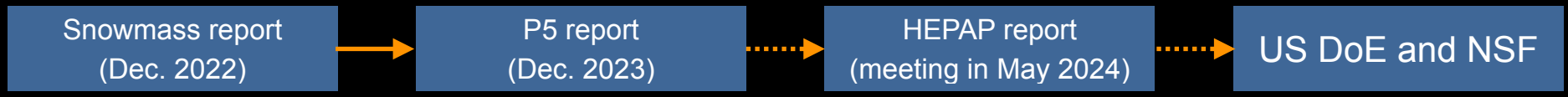
P5 Recommendation 3: Support DESI-II for cosmic evolution

→ DOE will work with the DESI Collaboration to carefully decide a scope, schedule and cost envelope for the DESI-II upgrade

*Scientific assessment: "**absolutely central**" ; Technical readiness: "**ready to initiate construction**"*

Spectroscopic roadmap on good tracks

- Snowmass:
  - "*identify the most important questions in High Energy Physics and the tools and infrastructure required to address them*"
  - Letters of Intent → White Papers → Panel Reports → Frontier Reports → Final Report
- P5: Particle Physics Project Prioritization Panel
- HEPAP: High Energy Physics Advisory Panel

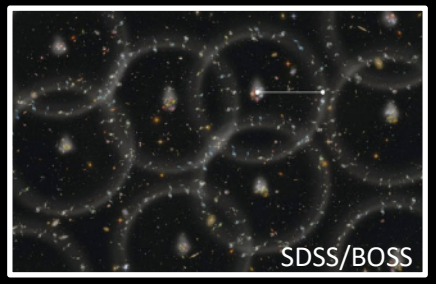


Dark energy & cosmological probes

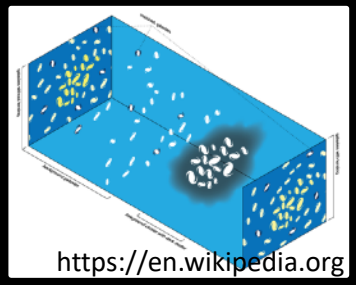
- 1998: Supernovae Ia observations → acceleration of the expansion of the universe
- 2006: DETF (*Dark Energy Task Force*, Albrecht+06):
  - Community should engage in large observational programs
  - Four main cosmological probes

Supernovae Ia (SN Ia)

Baryon Acoustic Oscillations (BAO)



Weak-lensing (WL)



Galaxy clusters (GC)

Dark energy & cosmological experiments

- 1998: Supernovae Ia observations → acceleration of the expansion of the universe
- 2006: DETF (*Dark Energy Task Force*, Albrecht+06):
  - Community should engage in large observational programs
  - Four main cosmological probes (SN Ia, WL, BAO, galaxy clusters)
  - Figure of Merit: 1 / (95% conf. area in the (w_0, w_a) plane)

$$w(z) = \frac{P(z)}{\rho(z)} = w_0 + \frac{z}{1+z} \cdot w_a$$

	Stage II	Stage III	Stage IV
FoM	30	3x FoM(Stage II)	10x FoM(Stage II)
Period	2000's	2010's	2020's
***Some* Experiments**	**SDSS-I, II** SNLS CFHTLS, KiDS …	**SDSS/BOSS + eBOSS** DES, HSC …	**DESI** *Euclid* LSST / Rubin PFS *Roman* …

Dark energy & cosmological experiments

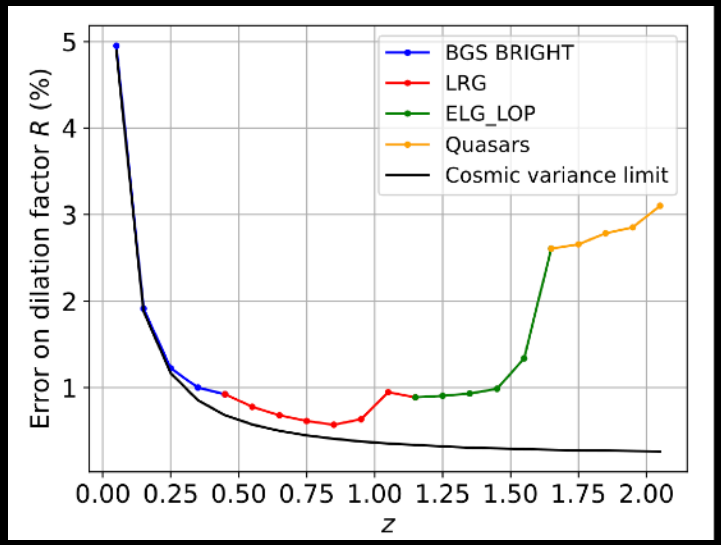
- 1998: Supernovae Ia observations → acceleration of the expansion of the universe
- 2006: DETF (*Dark Energy Task Force*, Albrecht+06):
  - Community should engage in large observational programs
  - Four main cosmological probes (SN Ia, WL, BAO, galaxy clusters)
  - Figure of Merit: 1 / (95% conf. area in the (w_0, w_a) plane)
- Stage V: move beyond the horizon of the DETF:
  - inflation, dark energy, neutrinos, light relics, dark matter

$$w(z) = \frac{P(z)}{\rho(z)} = w_0 + \frac{z}{1+z} \cdot w_a$$

	Stage II	Stage III	Stage IV	Stage V
FoM	30	3x FoM(Stage II)	10x FoM(Stage II)	new FoM, 10x DESI
Period	2000's	2010's	2020's	2030's
***Some* Experiments**	**SDSS-I, II** SNLS CFHTLS, KiDS …	**SDSS/BOSS + eBOSS** DES, HSC …	**DESI** *Euclid* LSST / Rubin PFS *Roman* …	**Spec-S5** WST MSE MUST …

Large unexplored volume at 2 < z < 4.5

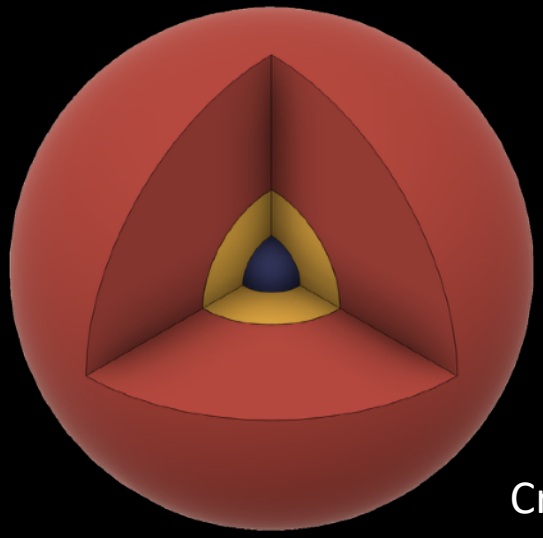
- DESI will have extracted all the BAO information at z < 1.6



DESI+24

Large unexplored volume at 2 < z < 4.5

- DESI will have extracted all the BAO information at z < 1.6
- Going to z > 2:
  - new tracers:
    - LAEs (Lyman Alpha Emitters), LBGs (Lyman Break Galaxies)
    - see last slides on DESI-2
  - large number of modes (maximum volume per solid angle)
  - linear modes well-correlated with initial conditions, less affected by late-time astrophysics
  - larger redshift range: degeneracy breaking, measures early → late Dark Energy



2010's	0 < z < 1	SDSS
2020's	0 < z < 1.6	DESI
2030's	2 < z < 4.5	DESI-2, Spec-S5

Credits: D. Kirkby

New Figure of Merit (FoM)

- Constraining power on much of the fundamental physics: proportional to the number of linear or mildly non-linear modes that are correlated with the initial conditions
- Spectroscopic surveys at 2 < z < 4.5: more constraints than CMB because of third dimension

- New FoM: number of ~linear modes observable
- Spec-S5 goal: 10x FoM(DESI)

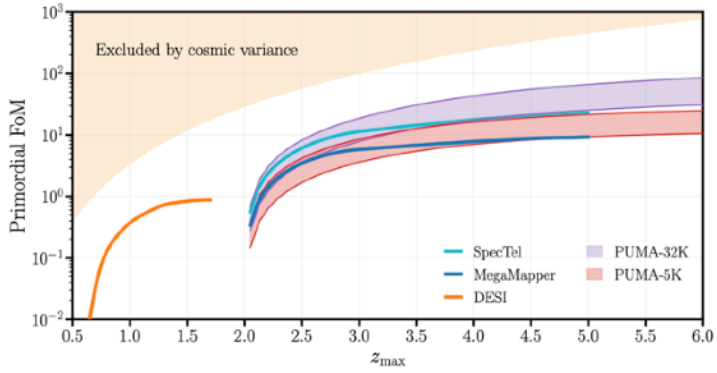


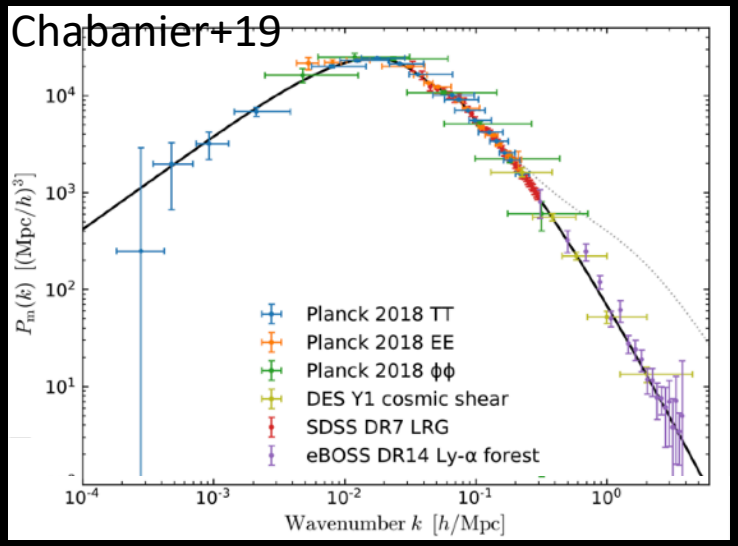
Figure 2: "Figure of Merit" FoM $\equiv 10^{-6}\, N_{\rm modes}$, representing the effective number of "linear" modes observable as a function of $z_{\rm max}$ for DESI, PUMA (-5K and -32K), and MegaMapper and SpecTel, two examples of Stage-5 spectroscopic surveys. For DESI we include only the ELGs. For PUMA, we consider both optimistic and pessimistic foreground models, which are the boundaries of the shaded regions. The boundary of the shaded orange region is the cosmic variance limit for an all-sky survey, assuming $b(z) = 1$. From [3] (see [2] for details about the calculation).

Ferraro+22

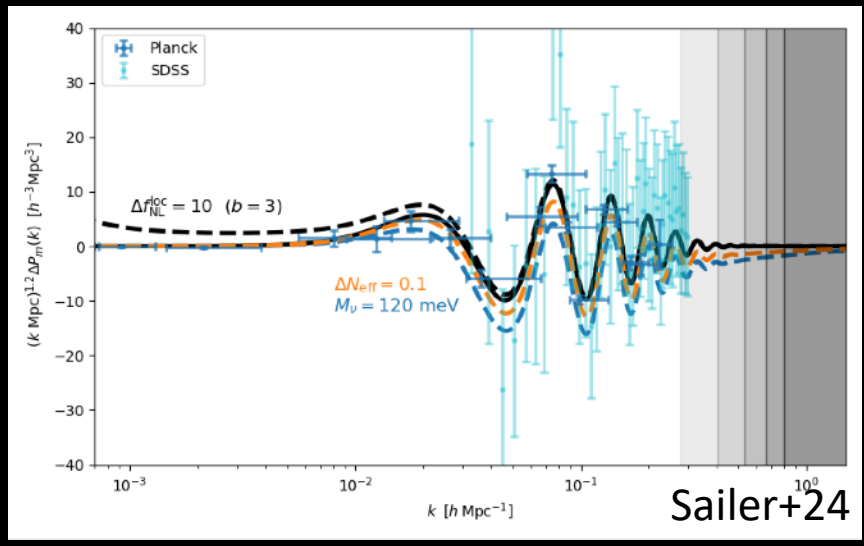
Science driver: primordial physics

- Use the tool of the power spectrum of density fluctuations imprinted from the early universe

Chabanier+19



BAO with SDSS

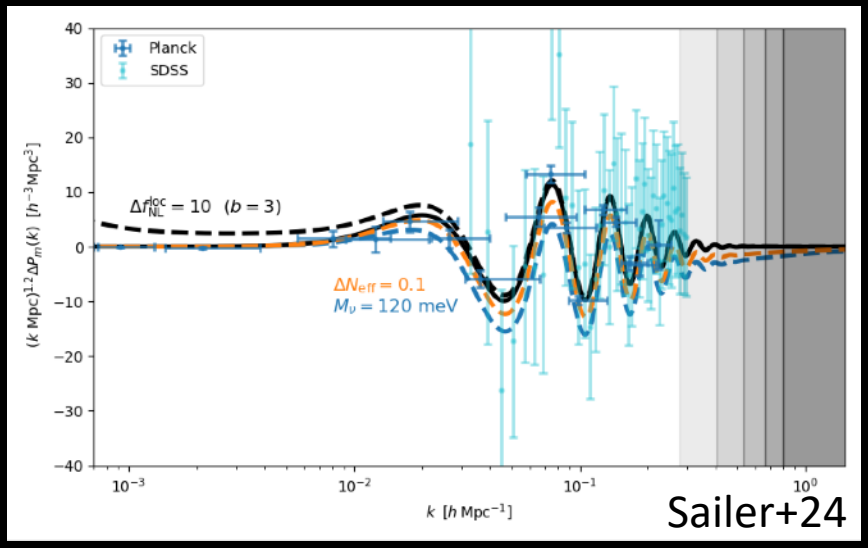


Sailer+24

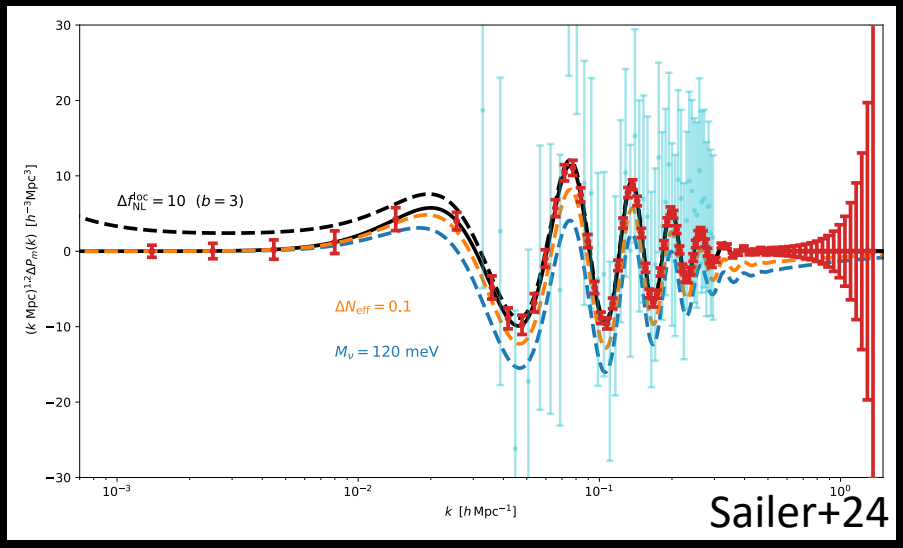
Science driver: primordial physics

- Use the tool of the power spectrum of density fluctuations imprinted from the early universe
- High-precision power spectrum measurements enable:
  - non-Gaussianity induced by inflation (f_{NL})
  - neutrino masses and light relics
  - primordial features
- Further constraining with e.g. bispectrum or cross-correlation with CMB

BAO with SDSS

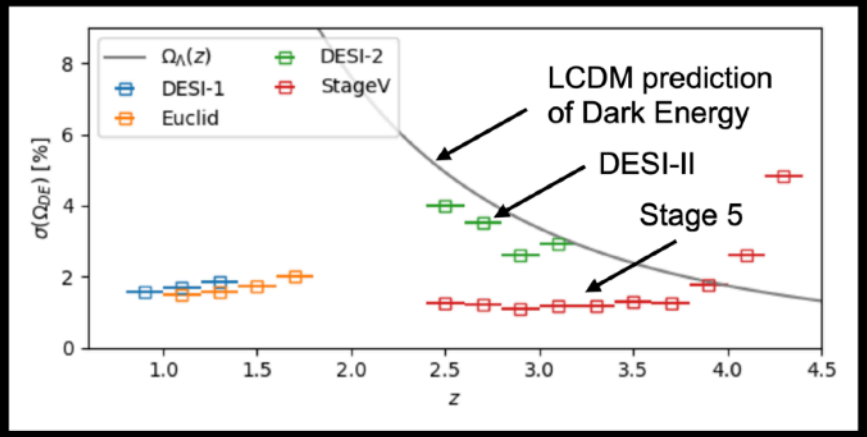


Primordial physics with Spec-S5



Science driver: Dark Energy

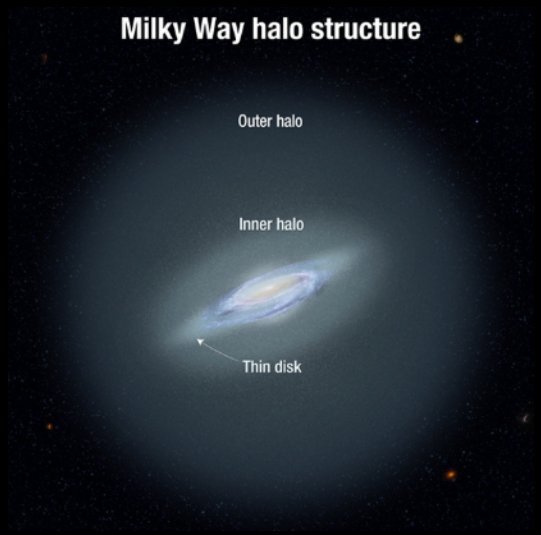
- fully spanning the Dark Energy dominated era and extending well into matter domination.
- BAO at z > 2 (evolving dark energy?)
- Many measurements at 1% accuracy



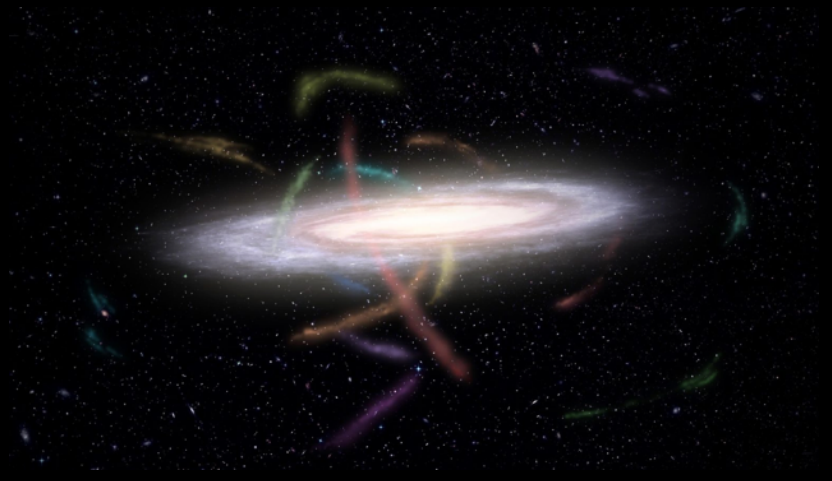
Sailer+24

Science driver: Dark Matter

- All positive evidence of Dark Matter is from cosmological measures
- Map gravitational influence of dark matter-only masses in the outer halo of the Milky Way



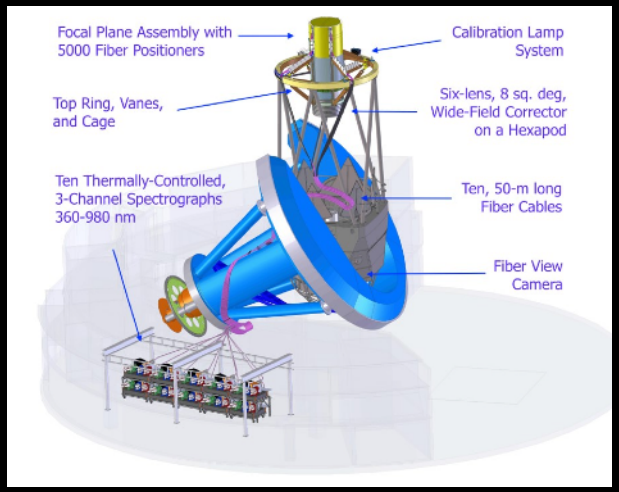
Credits: NASA, ESA, and A. Feild [STScI]



Credits: James Josephides and S5 Collaboration

DESI: the instrument

- Mayall telescope in Arizona, USA
- 4m primary mirror, 8 deg^2 field-of-view, 5000 fiber positioners, 10 optical spectrographs
- High throughput (optics, spectrographs, fibers, CCDs)



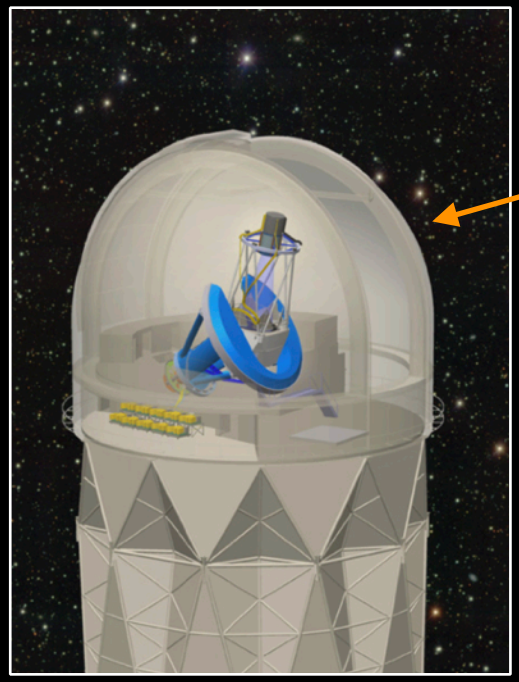
DESI+22

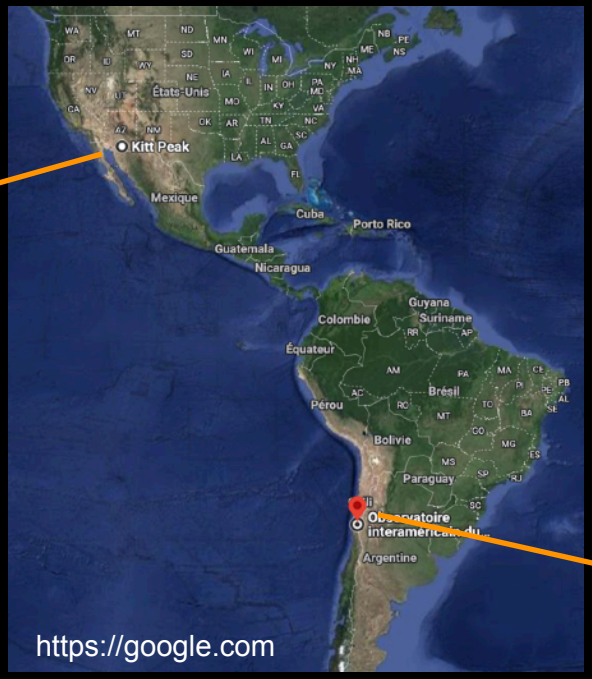
Spec-S5: instrumental setup

- Use two telescopes, Mayall in USA and Blanco in Chile

https://spec-s5.org

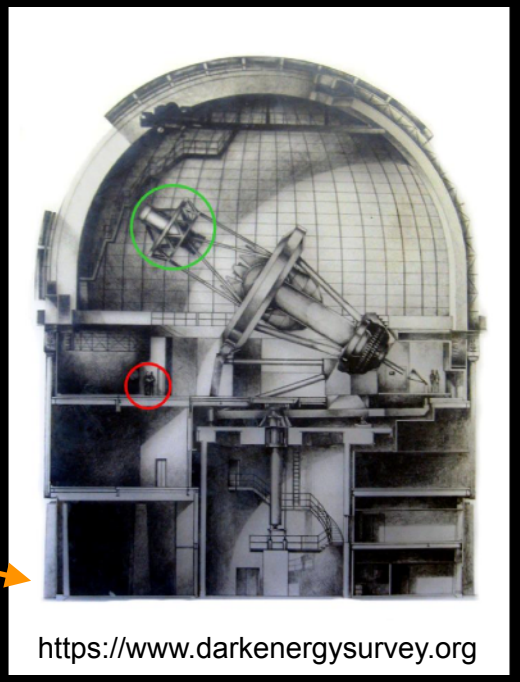
Mayall, KPNO, USA
(DESI)





https://google.com

Blanco, CTIO, Chile
(DECam)



https://www.darkenergysurvey.org

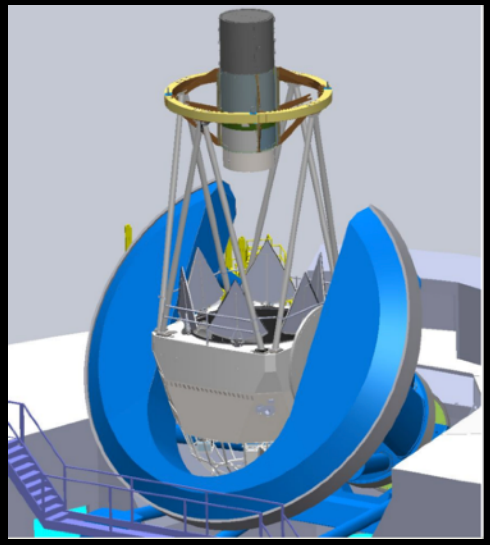
Spec-S5: instrumental setup

- Use two telescopes, Mayall in USA and Blanco in Chile
- Change the mirrors (4m to segmented-6m)

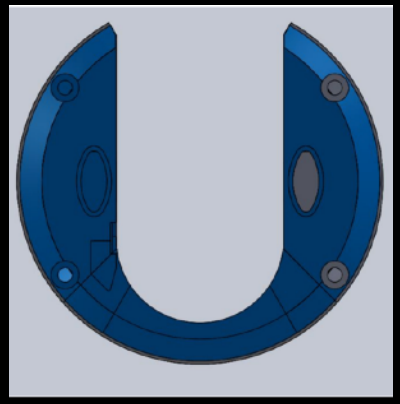
https://spec-s5.org

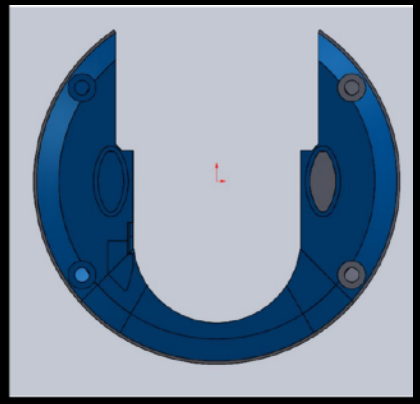
Images credits: B. Besuner

4m mirror

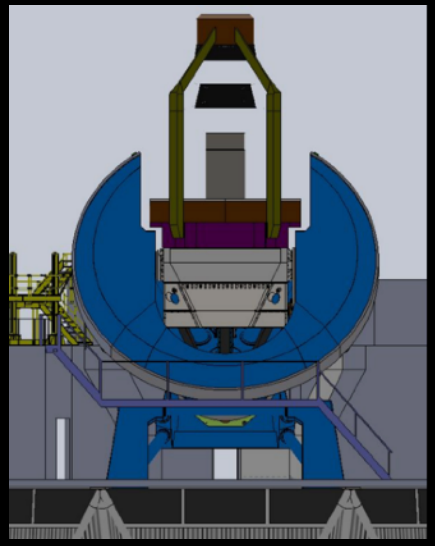


trim “horseshoe”





6m mirror

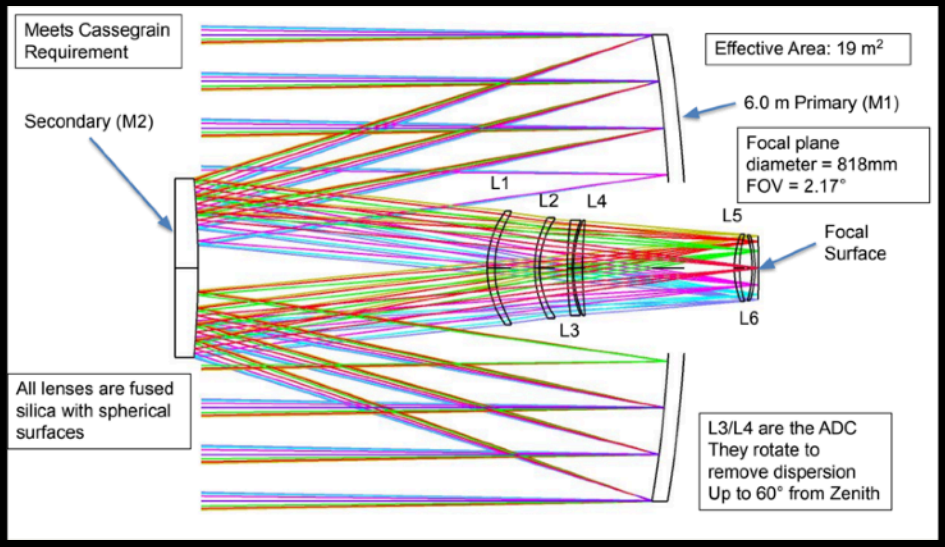


Spec-S5: instrumental setup

https://spec-s5.org

- Use two telescopes, Mayall in USA and Blanco in Chile
- Change the mirrors (4m to segmented-6m)
- Optical corrector: not-too-large, spherical lenses; 3.7 deg^2 field-of-view

Images credits: P. Jelinsky



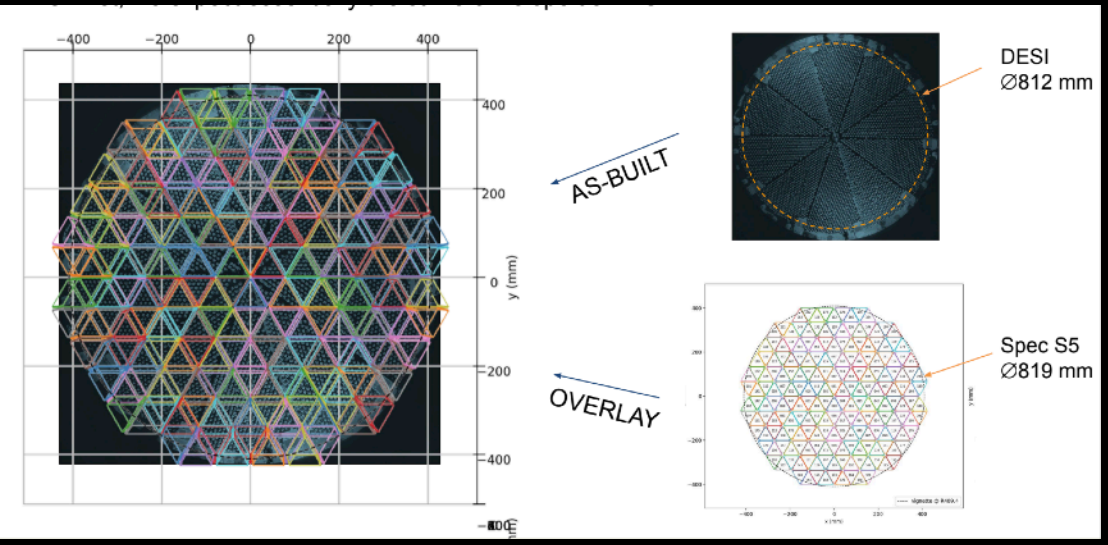
Optic	6m f/3.6 (Final) Diameter (m)	Mass (kg)
M1	6.00	---
M2	2.31	---
L1	1.47	358.0
L2	1.31	237.1
L3 (ADC1)	1.23	251.4
L4 (ADC2)	1.23	184.8
L5	0.87	80.0
L6	0.84	44.4
Focal Plane	0.82	---

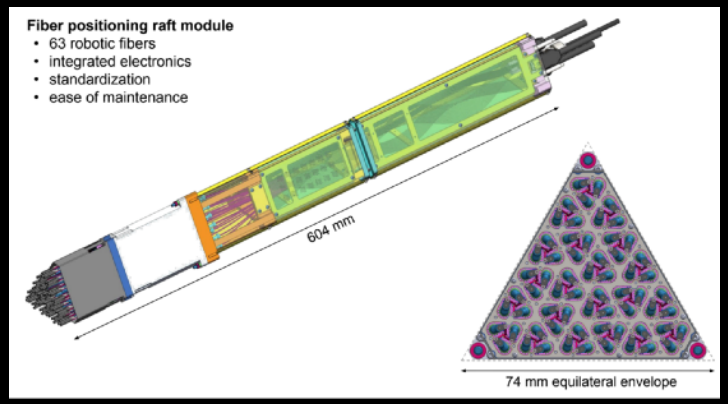
Spec-S5: instrumental setup

https://spec-s5.org

Images credits: J. Silber

- Use two telescopes, Mayall in USA and Blanco in Chile
- Change the mirrors (4m to segmented-6m)
- Optical corrector: not-too-large, spherical lenses; 3.7 deg^2 field-of-view
- Focal plane:
  - 13k positioners on each telescope (vs. 5k for DESI)
  - 204 “rafts” of 63 positioners each — easily removable and serviceable (1.2k each)





Spec-S5: instrumental setup

https://spec-s5.org

Images credits: J. Silber

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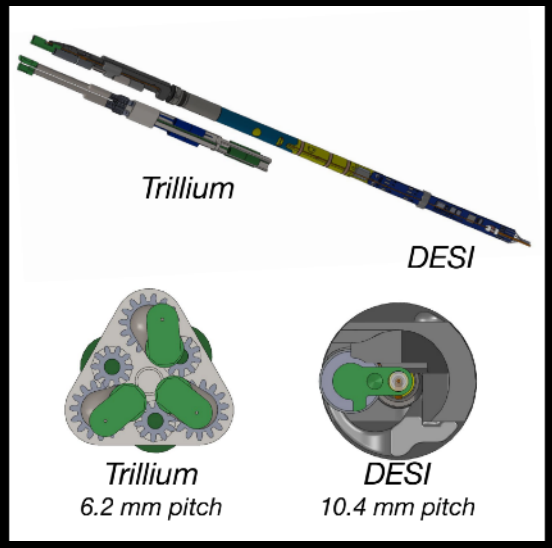

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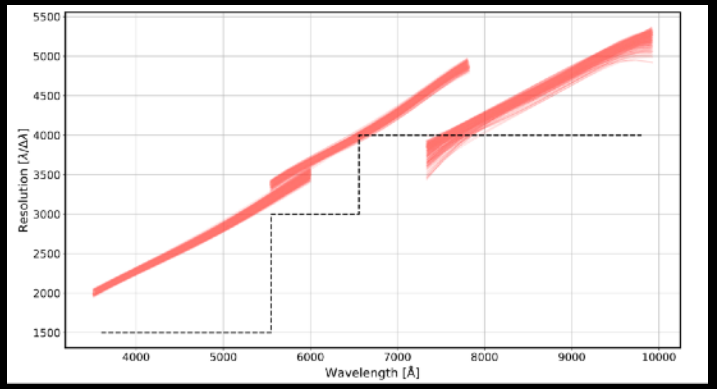
  - 204 “rafts” of 63 positioners each — easily removable and serviceable (1.2k each)
  - Trillium robots: 6.2mm pitch, 3 fiber actuators
- Spectrographs:
  - Close to the DESI ones, (wavelengths: 360 — 980 nm, resolution: 2000 — 5500)
  - 23 spectrographs on each telescope, 8-9 rafts per spectrograph (up to 567 fibers per spectrograph)
  - “Skipper” CCDs with very low read-noise



DESI+16

Spec-S5: instrumental setup

https://spec-s5.org

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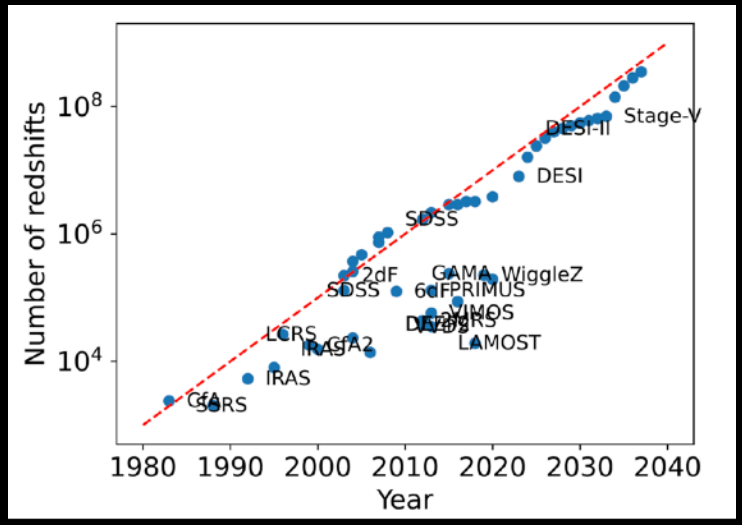
Spec-S5 → **15x faster** than DESI (→ **300x faster** than SDSS)

Spec-S5: notional survey

- Goal: 10x increase w.r.t. DESI new FoM
- Imaging for targets:
  - footprint of 11k deg^2
  - Rubin and possibly future releases of Legacy Surveys
- Targets:



Schlegel+22

2 < z < 4.5 galaxies	60M
z < 1.6 galaxies	130M
stars	50M

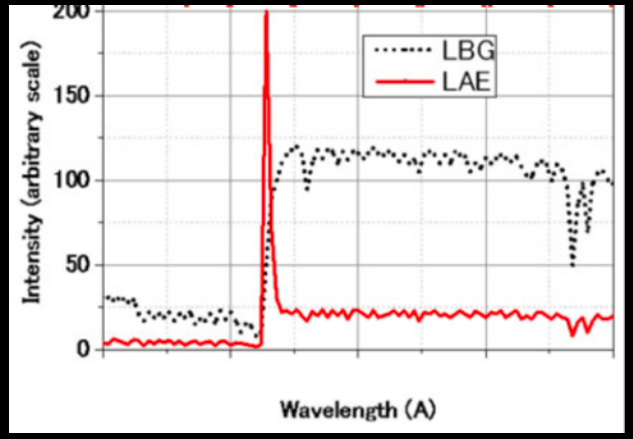
DESI-2: a pathfinder to Spec-S5

- Starts after the proposed DESI-extension (2029 — 2035)
- Footprint: 5000 deg^2 (maybe 10000 deg^2 for the $z < 1$ program?)
- No major instruments upgrade:
  - “Skipper” CCDs would be nice, but not compulsory
- Three programs:
  - probe the $2 < z < 4.5$ Universe with LAEs and LBGs
  - high-density $z < 1$ galaxy sample
  - stars for Dark Matter

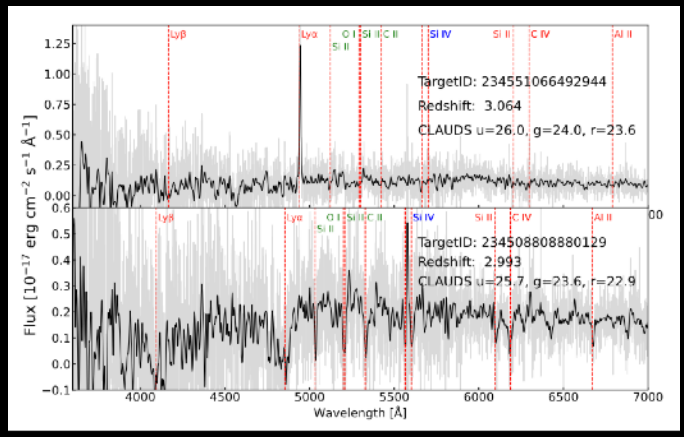
DESI-2: LAEs / LBGs pilot studies

- LAEs (Lyman Alpha Emitters):
  - low-mass star-forming galaxies
  - strong Lya line at 1216 A
  - best-selected with medium- or narrow-band filters

- LBGs (Lyman Break Galaxies):
  - massive, actively star-forming galaxies
  - “Lyman break”: flux bluewards of 912 A absorbed by the neutral hydrogen
  - best-selected with broad-band filters



Credits: D. Schlegel

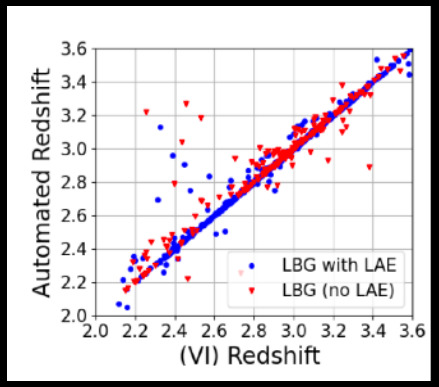


Ruhlmann-Kleider+24

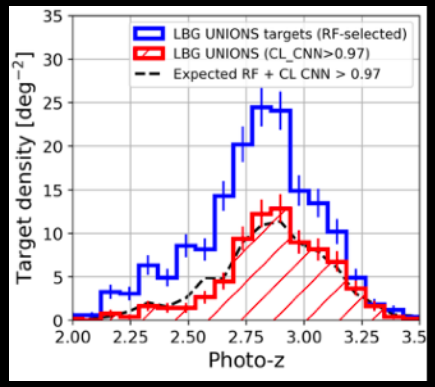
DESI-2: LAEs / LBGs pilot studies

- Several pilot observations done with DESI since Survey Validation:
  - Test various target selections (from broad-band, medium-band, narrow-band photometry)
  - Ruhlmann-Kleider+24, Payerne+24: results for LBGs selected with broad-band photometry (CLAUDS, UNIONS)
  - Raichoor in prep.: results from LAE/LBG selected with medium-band photometry (Suprime)
  - White+24, Dey in prep.: results for LAEs selected with narrow-band photometry (ODIN)

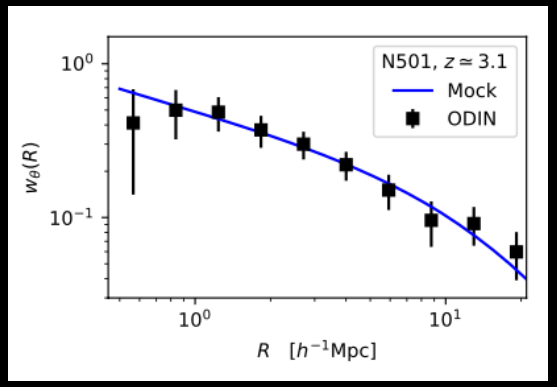
- Very successful!
  - Visual Inspection campaign to build truth table
  - Spectroscopic redshift fitters development
  - Characterization of the observed populations
  - DESI can get redshifts for LAEs/LBGs in a reasonable amount of time



Ruhlmann-Kleider+24



Payerne+24



White+24

DESI-2: medium-band imaging survey

- 5 medium-band filters “within the g-band”
- https://desi.lbl.gov/trac/wiki/DecamLegacy/IBIS
- accepted DECam proposal (DocDB-7853): 90 nights, 1000 deg2 on the Equator
- already started!

Efficiently Mapping the z>2 Universe with Medium-Band Filters **2023B-184194**

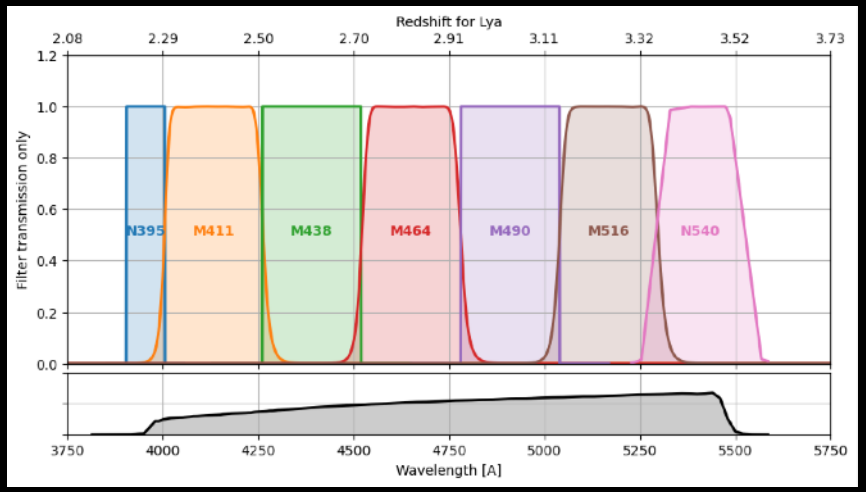
Type: NOIRLab: Survey (NOIRLab Survey 2023B)
Proprietary Period: None

Abstract:
We propose a DECam medium-band imaging survey over 1000 sq deg suitable for a detailed study of the z > 2 universe using DESI spectroscopy. Imaging this footprint with three new, medium-band filters spanning 4224–5036 Ang will allow selection of 0.5 million 2.4 < z < 3.2 Lyman Break Galaxies (LBGs) and 1.6 million Lyman-Alpha Emitters (LAEs). Follow-up spectroscopy with the second phase of the DESI instrument beginning in 2026 will measure dark energy in the matter-dominated regime where theoretical models for dynamic dark energy models differ. These observations will also pilot the primordial physics experiment of Rubin imaging + Stage-5 Spectroscopy in the 2030s.

Investigators:

PI: Arjun Dey, NOIRLab, arjun.dey@noirlab.edu

PI: David Schlegel, Lawrence Berkeley National Laboratory, djschlegel@lbl.gov



Conclusions

- Spectroscopic roadmap DESI → DESI-2 → Spec-S5:
  - Endorsed by the US community (Snowmass, P5, HEPAP)

- Spec-S5:
  - Primordial physics accessible at z > 2
  - Dark Energy and Dark Matter
- New instrumental setup (Mayall+Blanco) to reach 10x DESI new FoM

- DESI-2: Pathfinder for Spec-S5; Use of the DESI instrument