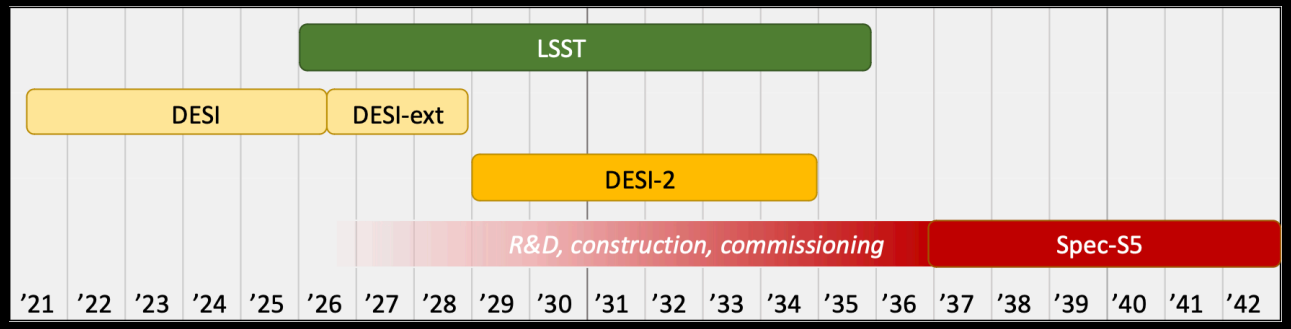
Spectroscopic surveys:

DESI, DESI-2, Spec-S5



A. Raichoor (LBNL)

LPNHE Seminar
July 1st, 2024

Outline

- LSS experiments introduction
- DESI: status update and proposed extension
- Beyond DESI:
  - Science at z > 2
  - DESI-2, a Spec-S5 pathfinder: overview, with focus on high-redshift program
  - Spec-S5: overview

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)."

"New data from other facilities will be needed as a complement to unlock the full constraining power of LSST, including follow-up observations of strong gravitational lenses, supernovae, and gravitational wave standard sirens, as well as measurements of spectroscopic redshifts for deep training samples of objects to enable precision photometric redshift measurements."

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

Snowmass report (Dec. 2022) → P5 report (Dec. 2023)

"*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.*

The balance between these scientific goals, which affects survey design, should be refined in light of early DESI and Rubin Observatory LSST results"

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*"
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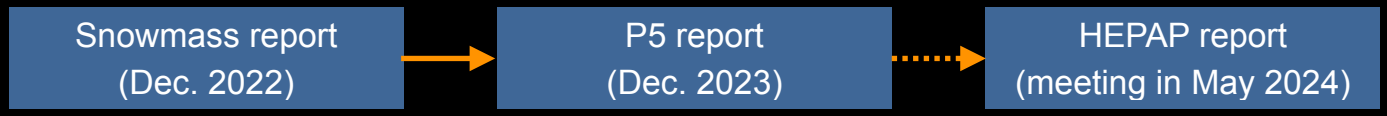
- P5: Particle Physics Project Prioritization Panel
- HEPAP: High Energy Physics Advisory Panel



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

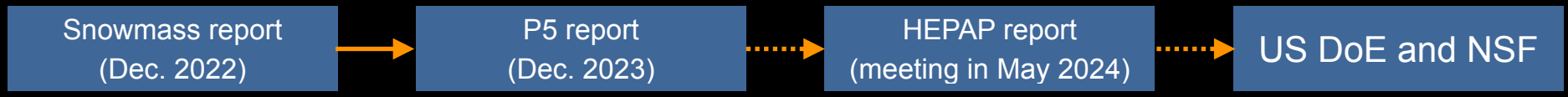
→ DOE fully supports this recommendation and puts it as the highest priority in planning our allocation of funding.

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

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

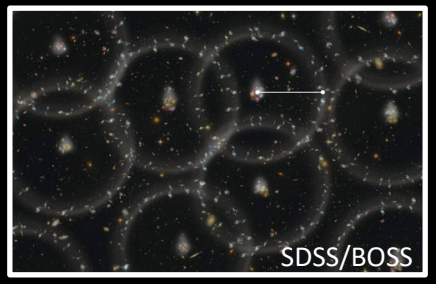


Dark energy & cosmological probes

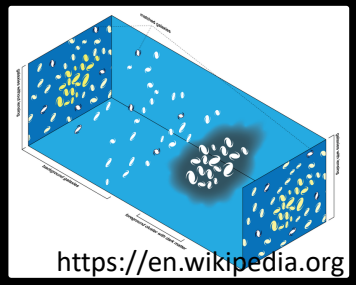
- 1998: Supernovae Ia observations → acceleration of the expansion of the universe
- 2006: DETF (*Dark Energy Task Force*, Albrecht+06):
  - Community should engage in large observational programs
  - Four main cosmological probes

Supernovae Ia (SN Ia)

Baryon Acoustic Oscillations (BAO)



Weak-lensing (WL)



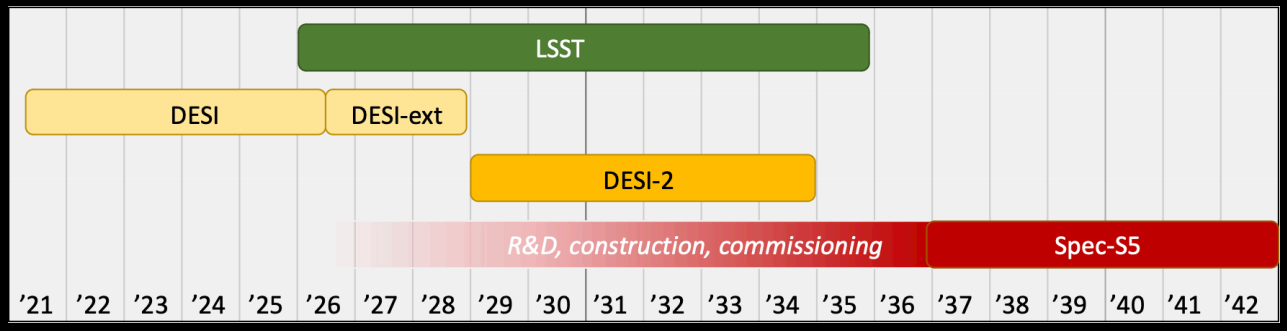
Galaxy clusters (GC)

Dark energy & cosmological 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
  - Figure of Merit: 1 / (95% conf. area in the (w_0, w_a) plane)

	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 …

DESI


LSST
DESI
DESI-ext
DESI-2
R&D, construction, commissioning
Spec-S5
'21
'22
'23
'24
'25
'26
'27
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'30
'31
'32
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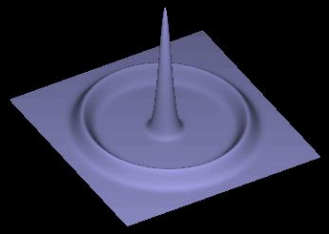
'34
'35
'36
'37
'38
'39
'40
'41
'42

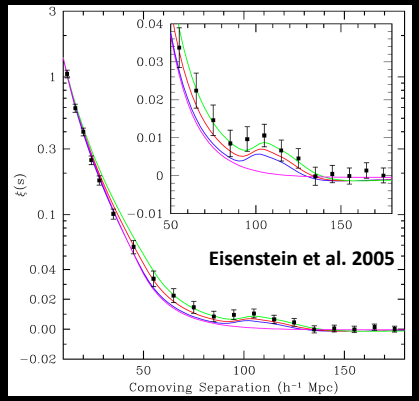
DESI: cosmological probes

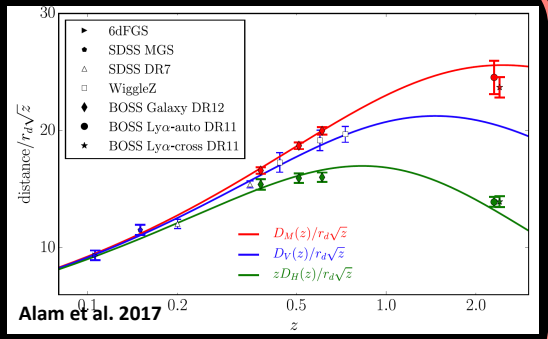
- LSS (*Large-Scale Structures*) experiment: BAO and RSD with spectroscopic redshifts
- **BAO** → Universe expansion [also SNIa]

BAO



https://www.cfa.harvard.edu/~deisenst

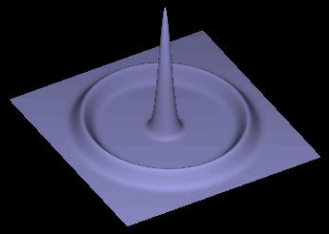




DESI: cosmological probes

- LSS (*Large-Scale Structures*) experiment: BAO and RSD with spectroscopic redshifts
- **BAO** → Universe expansion [also SNIa]
- **RSD** (*Redshift Space Distortions*) → Growth of structure + test of General Relativity [also WL+GC]

BAO



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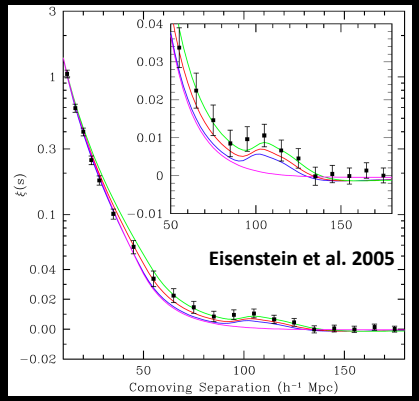
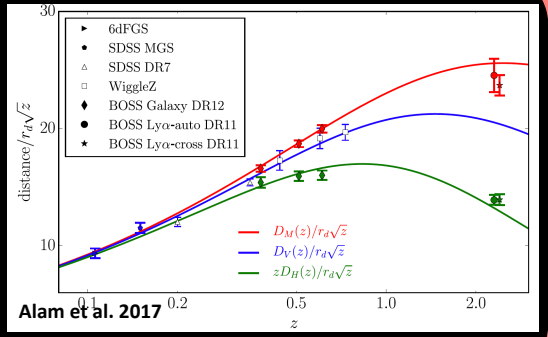
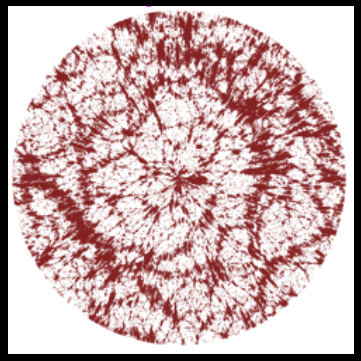
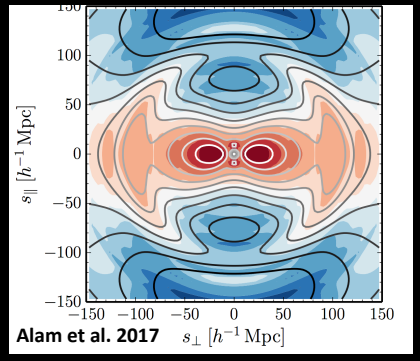
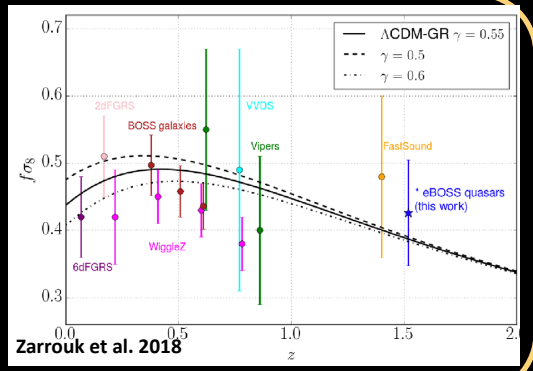




RSD

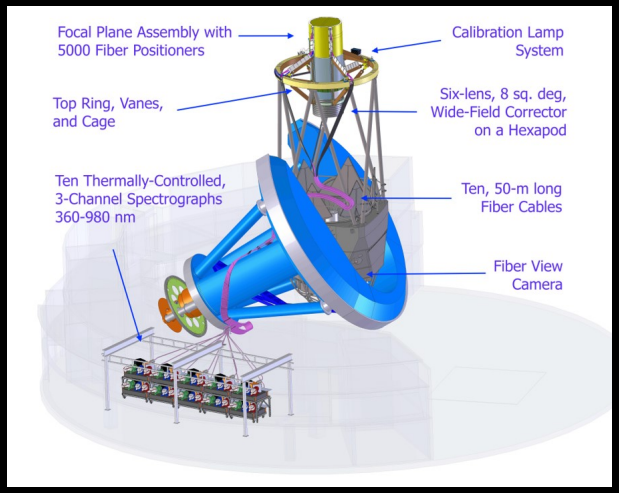






DESI: the instrument

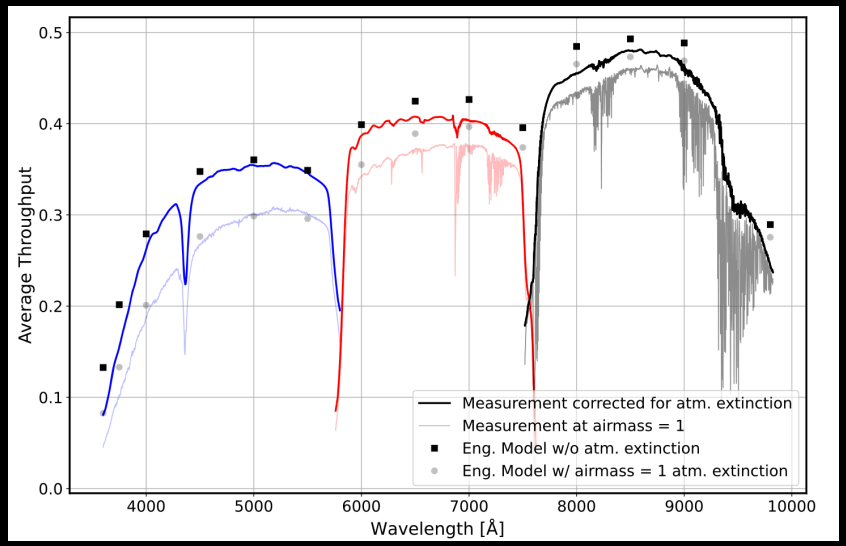
- Mayall telescope in Arizona, USA
- 4m primary mirror, 8 deg^2 field-of-view, 5000 fiber positioners, 10 optical spectrographs



DESI+22

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

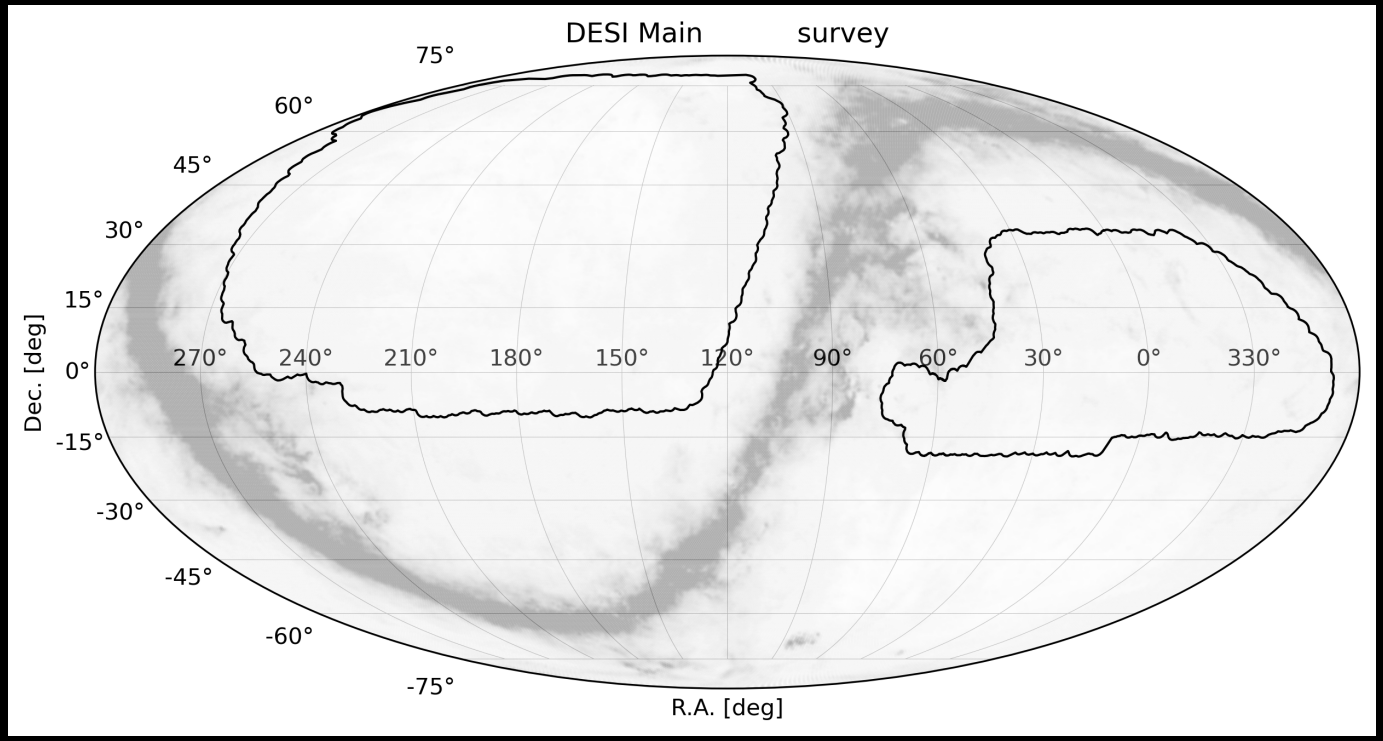
DESI: the instrument

- 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)
- Redshift factory!

SDSS/BOSS-eBOSS: 1k spectra in ~1 hr
DESI: 5k spectra in ~15min → **20x faster**

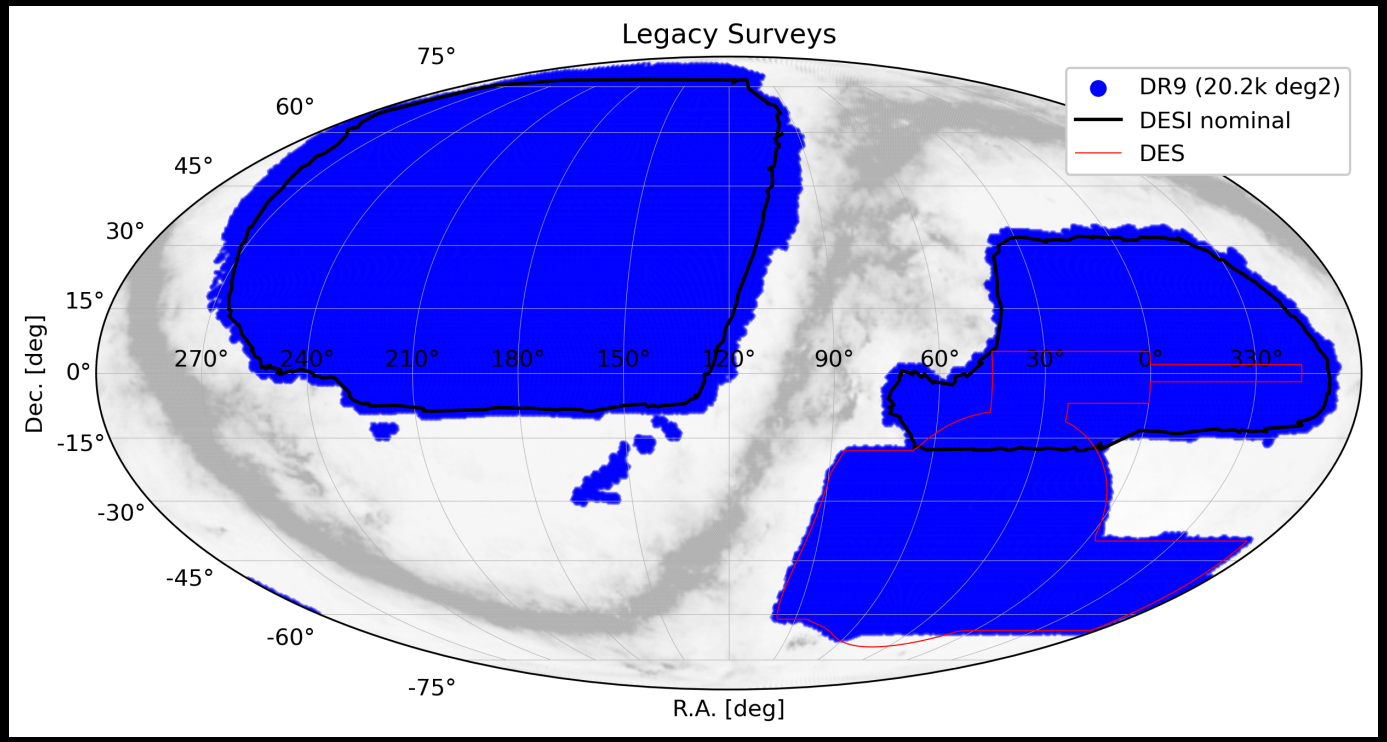
DESI: Main Survey design

- Five years over 14,000 deg^2 (1/3 of the sky), started on May, 14th 2021



DESI: Main Survey design

- Five years over 14,000 deg^2 (1/3 of the sky), started on May, 14th 2021
- Targets selected from the Legacy Surveys DR9 (https://www.legacysurvey.org/dr9/; Dey, Schelgel +19)



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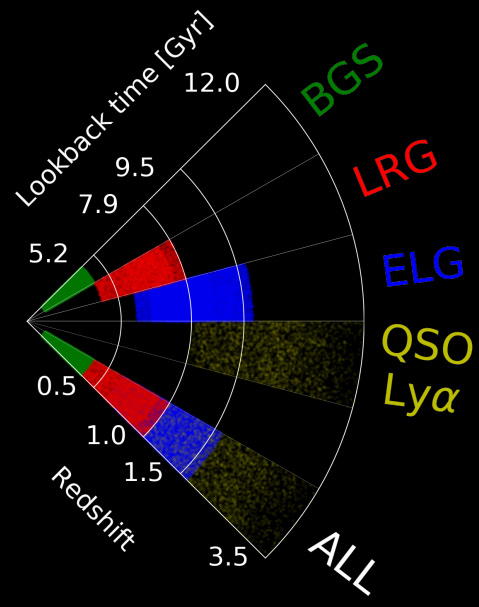
- 40M redshifts (~10x the whole SDSS over 20 years), one tracer optimal for each redshift range

	N	Redshift	Comments
MWS	6M	-	stars
BGS	13.5M	0.05 < z < 0.4	bright galaxies
LRG	8M	0.4 < z < 1.1	luminous red galaxies
ELG	16M	0.6 < z < 1.6	emission line galaxies
QSO + Lyα	3M	0.8 < z < 3.5	quasars

bright time (Moon up)

dark time (Moon down)



DESI: Main Survey design

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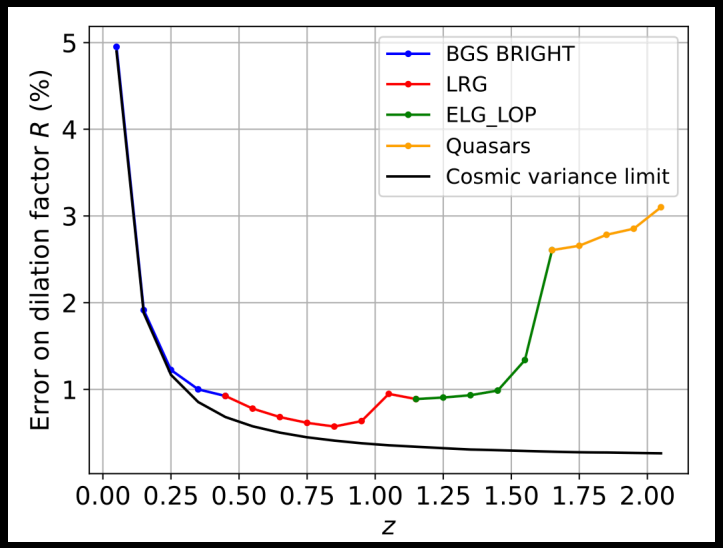
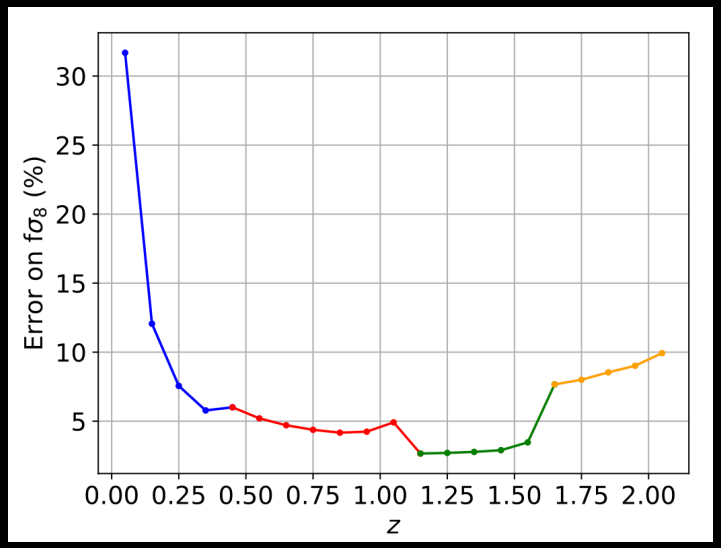
- 40M redshifts (~10x the whole SDSS over 20 years), one tracer optimal for each redshift range
- Sub-percent forecast constraint on R(z) and fσ8

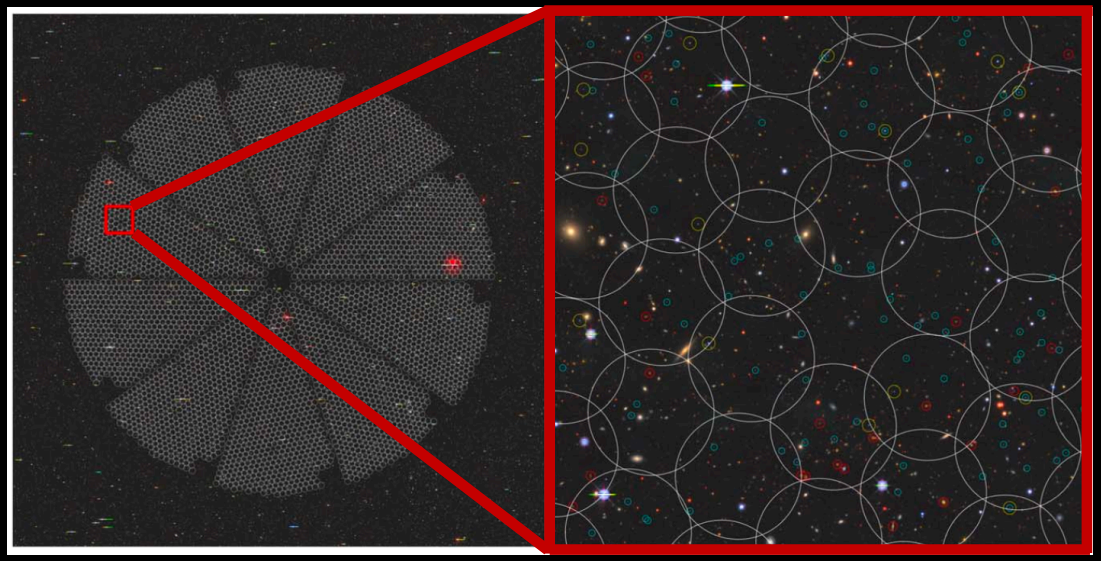




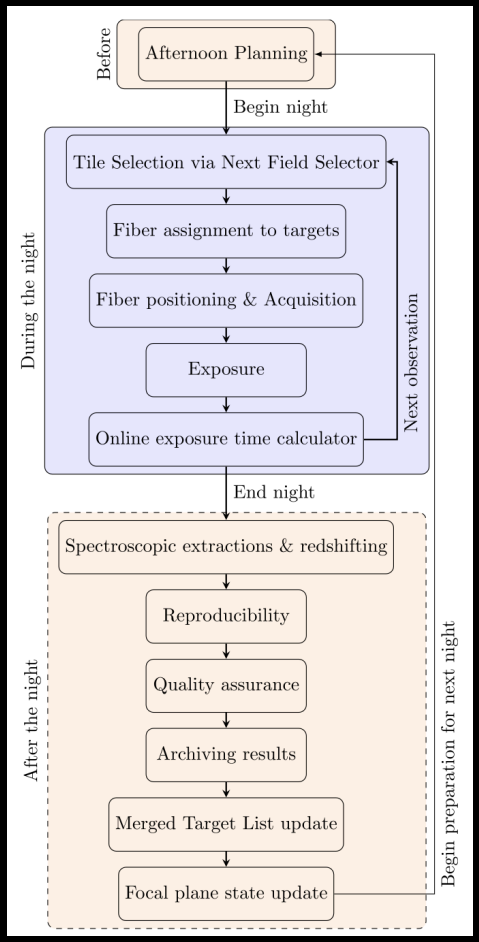
DESI+24

DESI: Main Survey operations workflow

- Optimized operations, very efficient
  - Daily status of the focal plane + survey state
  - Non-overlapping tiles observed during a night



DESI+24



Schlafly+23

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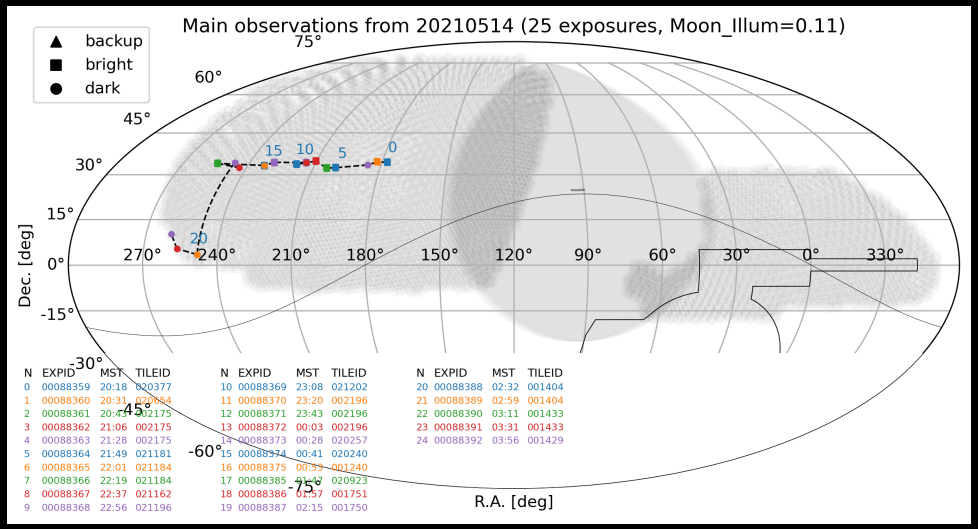
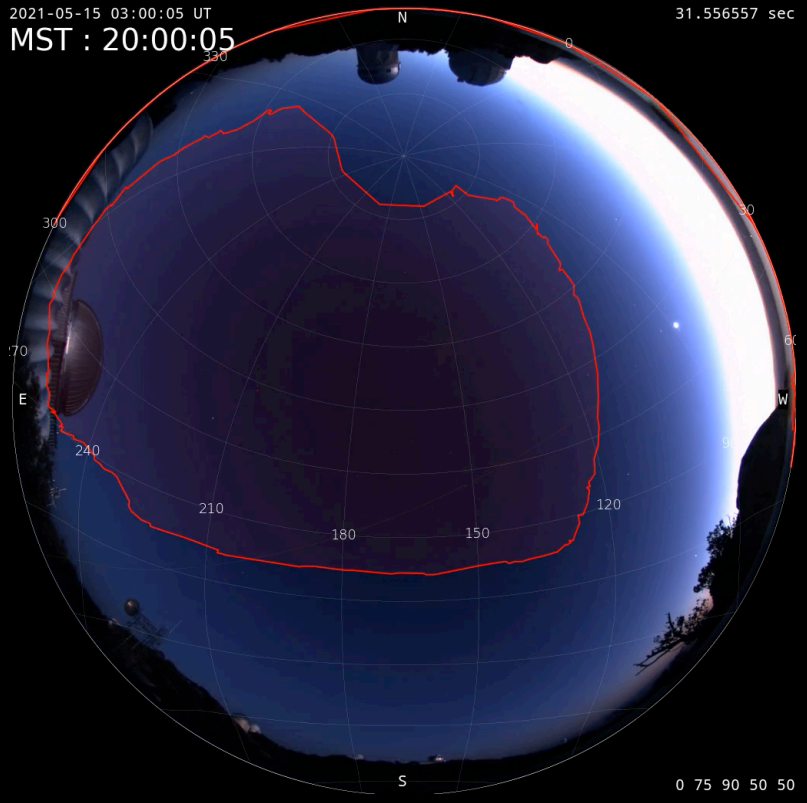
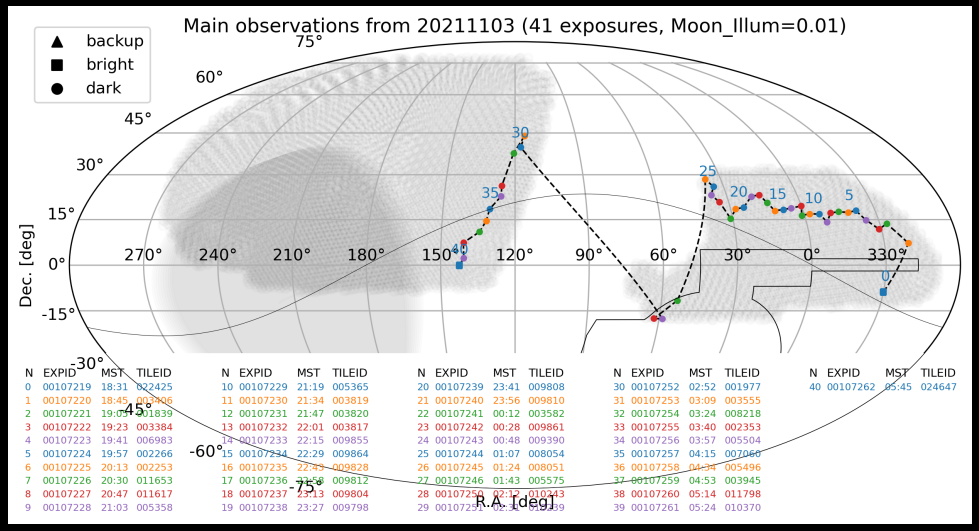




DESI: Main Survey operations workflow

- Optimized operations, very efficient
  - Daily status of the focal plane + survey state
  - Non-overlapping tiles observed during a night
  - Record night: 20211103, 39 dark tiles, ~200k spectra



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1	00107220	18:45	003006
2	00107221	19:03	001839
3	00107222	19:23	003384
4	00107223	19:41	006983
5	00107224	19:57	002266
6	00107225	20:13	002253
7	00107226	20:30	011653
8	00107227	20:47	011617
9	00107228	21:03	005358
10	00107229	21:19	005365
11	00107230	21:34	003819
12	00107231	21:47	003820
13	00107232	22:01	003817
14	00107233	22:15	009855
15	00107234	22:29	009864
16	00107235	22:43	009828
17	00107236	22:58	009812
18	00107237	23:13	009804
19	00107238	23:27	009798
20	00107239	23:41	009808
21	00107240	23:56	009810
22	00107241	00:12	003582
23	00107242	00:28	009861
24	00107243	00:48	009390
25	00107244	01:07	008054
26	00107245	01:24	008051
27	00107246	01:43	005575
28	00107250	02:12	010343
29	00107251	02:30	010339
30	00107252	02:52	001977
31	00107253	03:09	003555
32	00107254	03:24	008218
33	00107255	03:40	002353
34	00107256	03:57	005504
35	00107257	04:15	007066
36	00107258	04:34	005496
37	00107259	04:53	003945
38	00107260	05:14	011798
39	00107261	05:24	010370
40	00107262	05:45	024647

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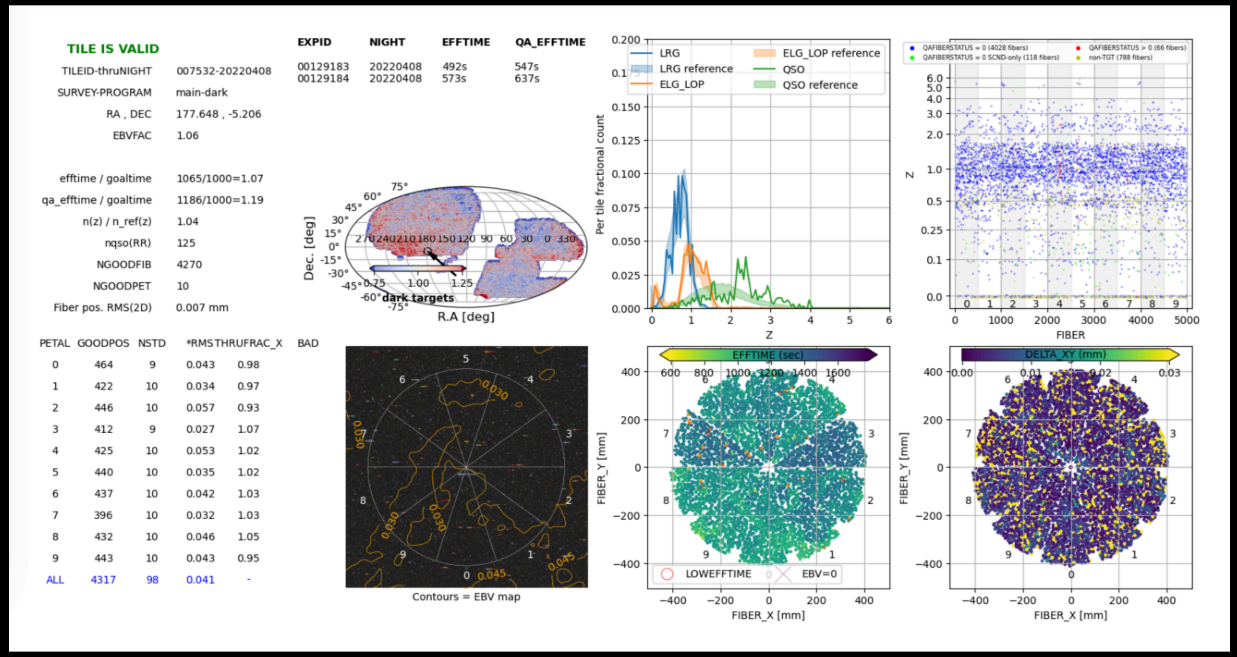
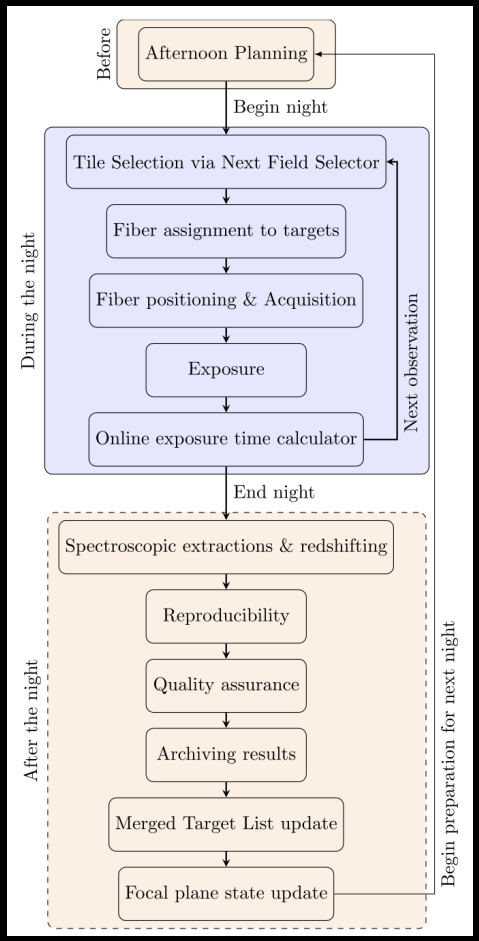
- Optimized operations, very efficient
  - Daily status of the focal plane + survey state
  - Non-overlapping tiles observed during a night
  - Record night: 20211103, 39 dark tiles, ~200k spectra
  - “Redshifts by breakfast”
  - Each tile is QA-validated (~10 persons team)

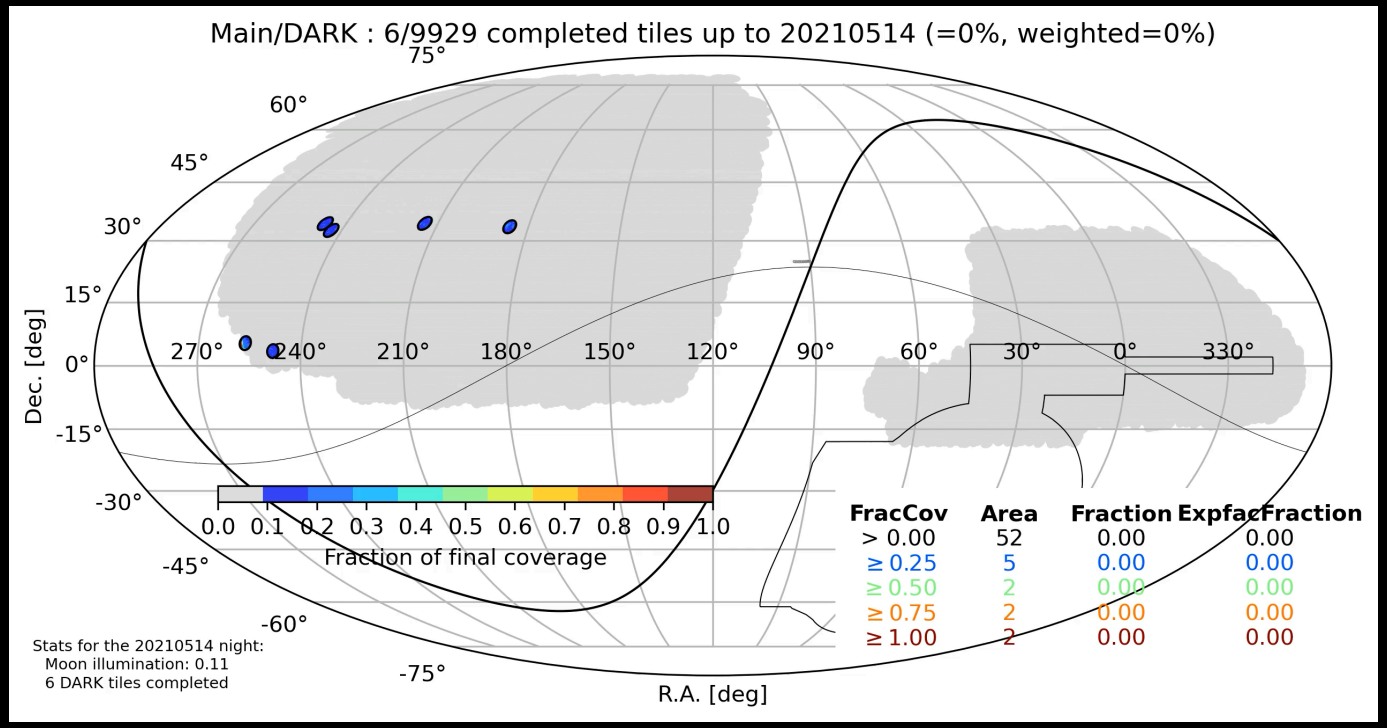




Schlafly+23

DESI: Main Survey observations

- Started on May, 14th 2021
- Survey progress: https://data.desi.lbl.gov/desi/users/raichoor/main-status/main-status.html



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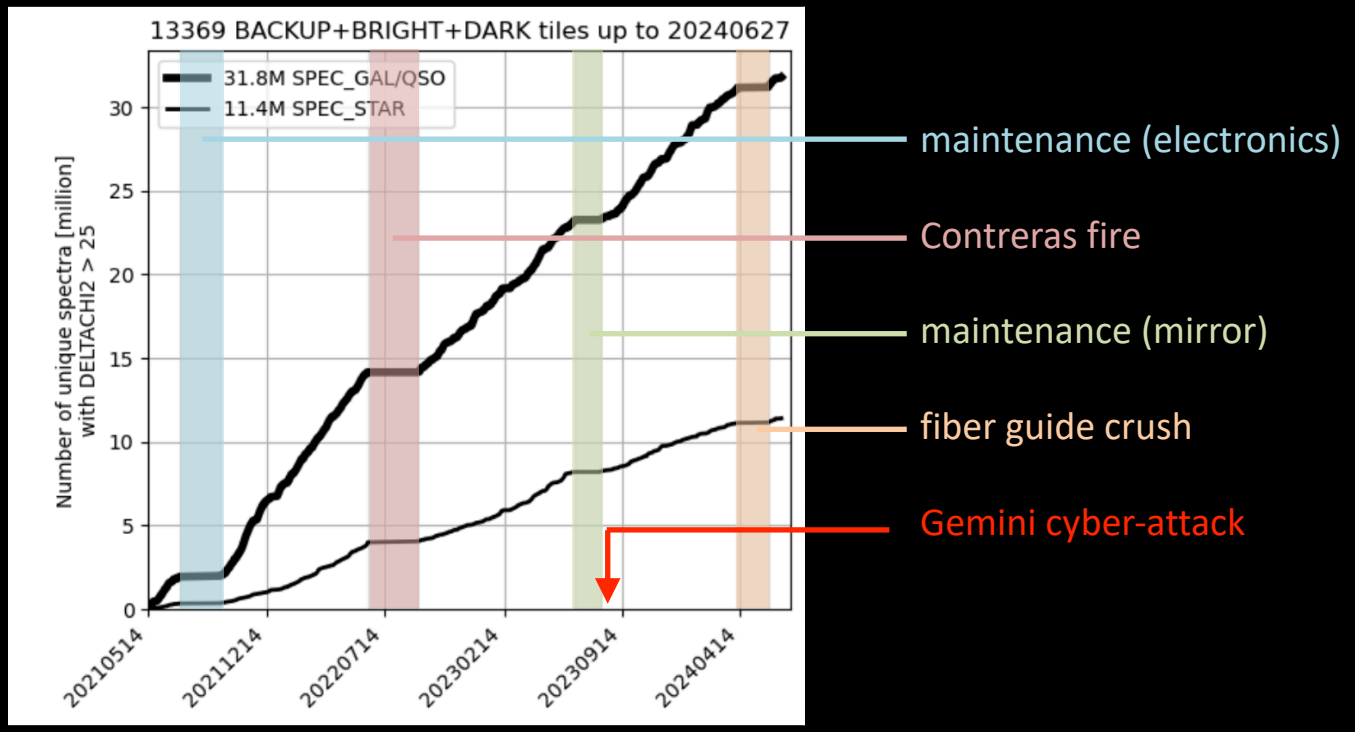

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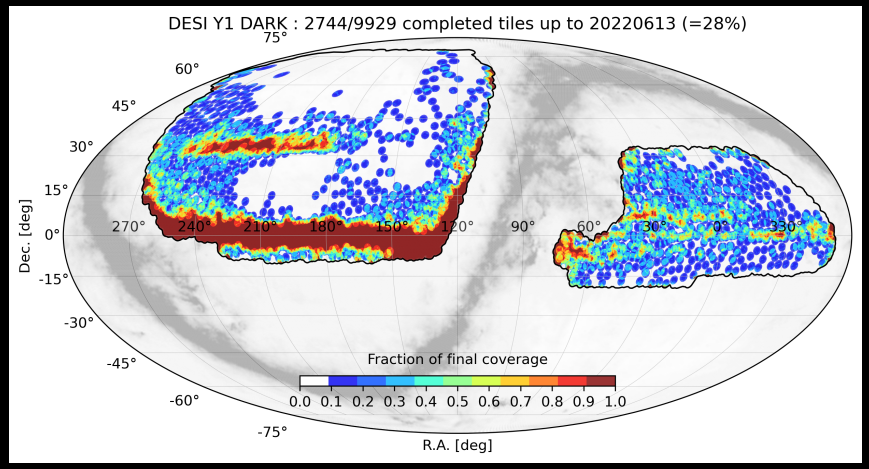

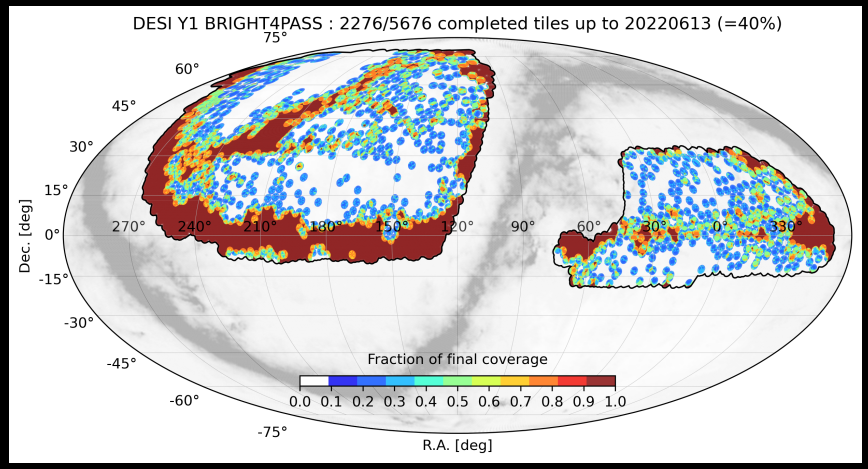

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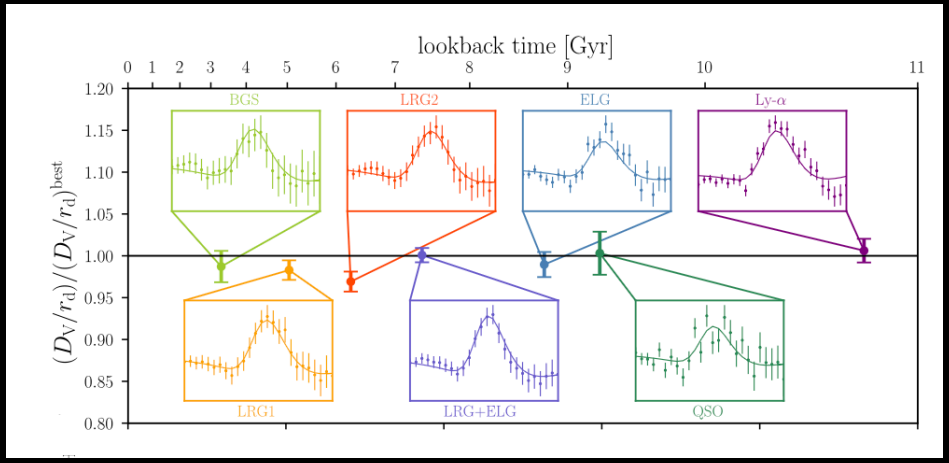
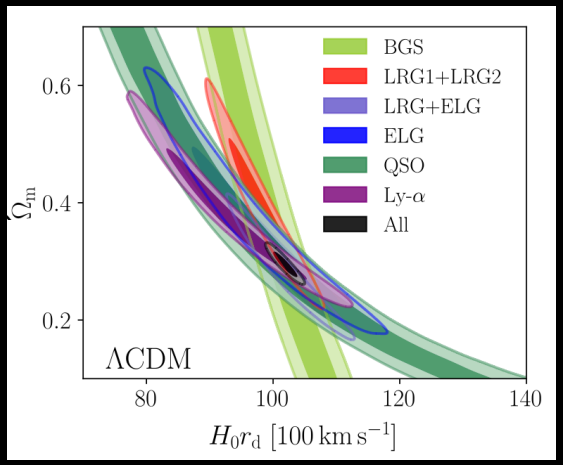
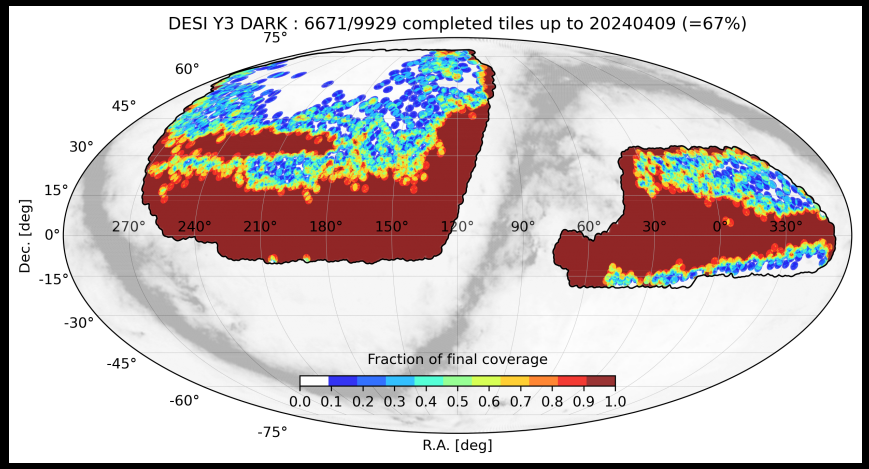
- Shutdowns: planned … and unplanned, but still ahead of schedule!
- DR1 sample:
  - All data up to June 2022 (18M galaxies, 1.5M quasars, 4M stars)
  - Sample used for the DESI 2024 results released in April (5.7M redshifts for BAO, x3 SDSS/ DR16)

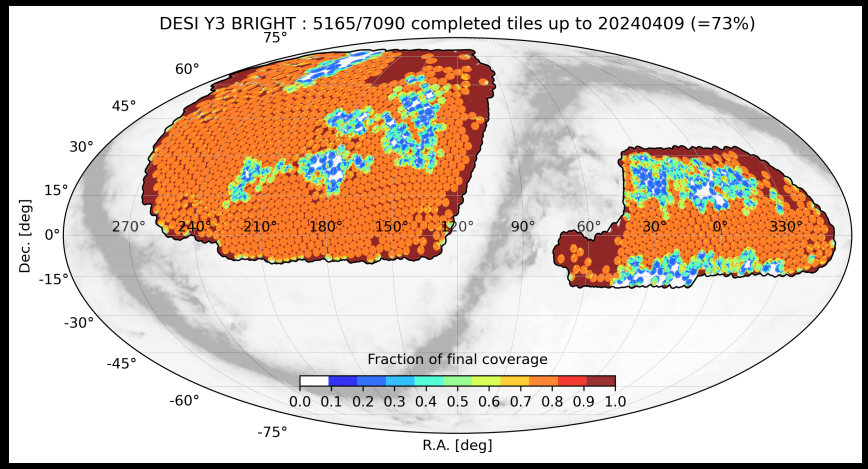




DESI: Main Survey observations

- Started on May, 14th 2021
- Survey progress: https://data.desi.lbl.gov/desi/users/raichoor/main-status/main-status.html
- Shutdowns: planned … and unplanned, but still ahead of schedule!
- DR1 sample:
    - All data up to June 2022 (18M galaxies, 1.5M quasars, 4M stars)
    - Sample used for the DESI 2024 results released in April (5.7M redshifts for BAO, x3 SDSS/ DR16)
- Y3 data:
    - All data up to April 2024
    - Bright program: extra-pass added in September 2023

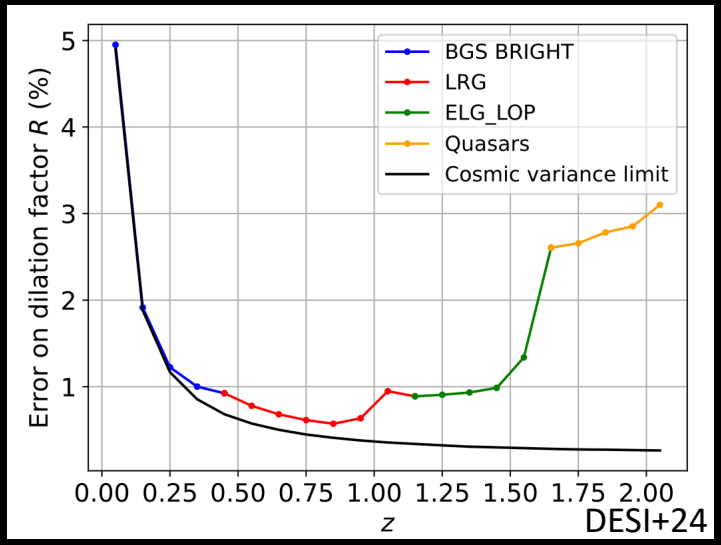


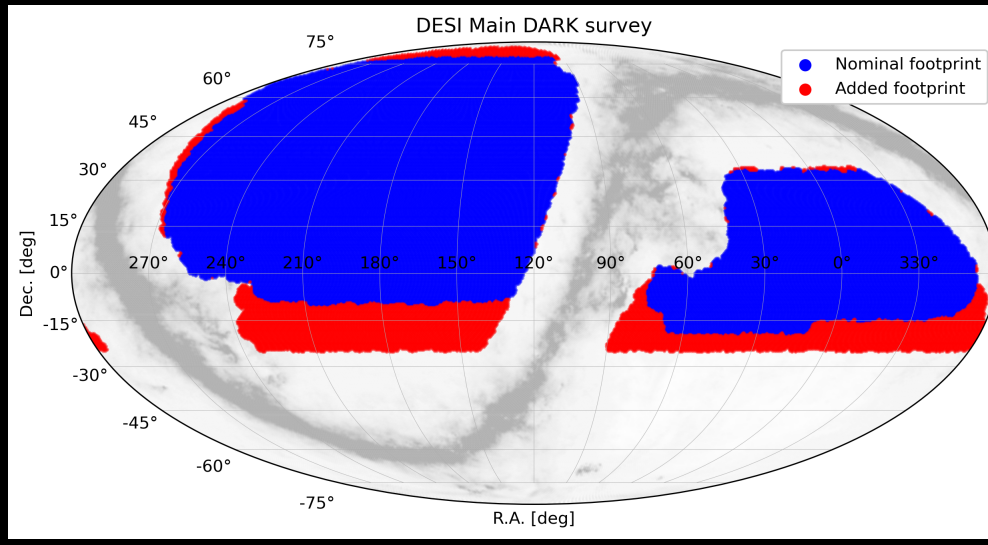


DESI: possible extension

- Goals are to maximize:
  - BAO information
  - Test of non-ΛCDM models independent of SN
  - Synergies with Rubin and CMB surveys in the Southern Sky

- Request to DOE to extend the survey to the end of 2028:
  - Additional LRG targets (300 deg^{-2}) + add two more passes → more LRG + ELG observations
  - Extend the footprint South (will use Legacy Surveys DR11) → more area (14k to 17k deg^{-2}) + overlap with Southern Sky





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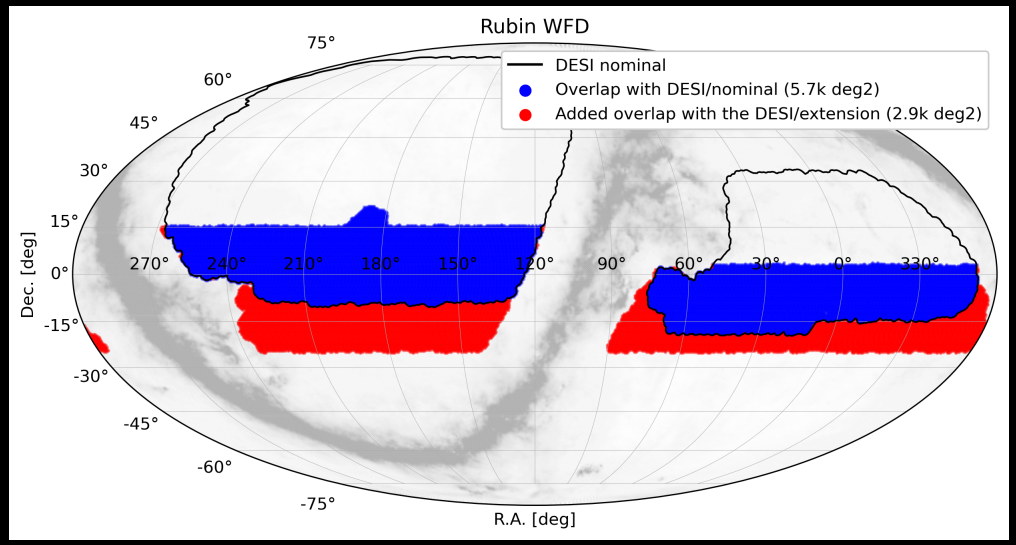
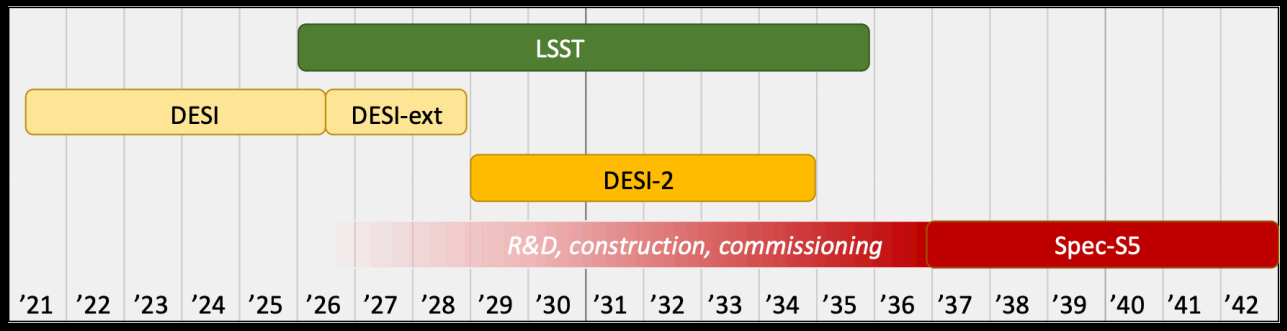
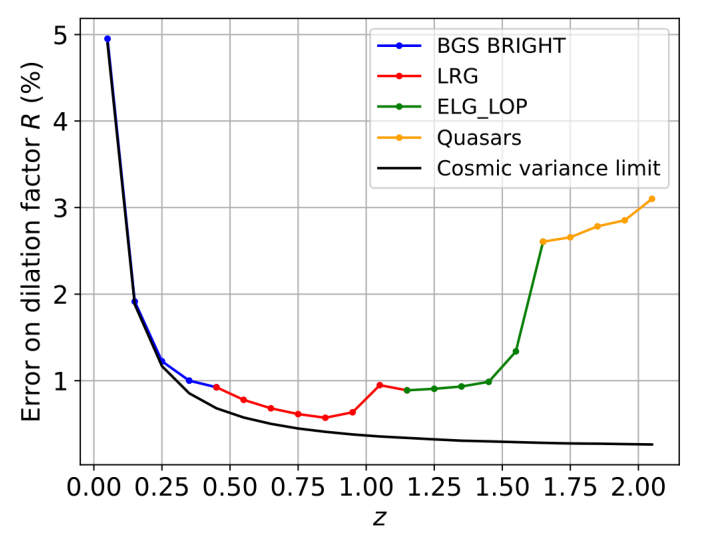


DESI-2 and Spec-S5



Beyond DESI: large unexplored volume

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

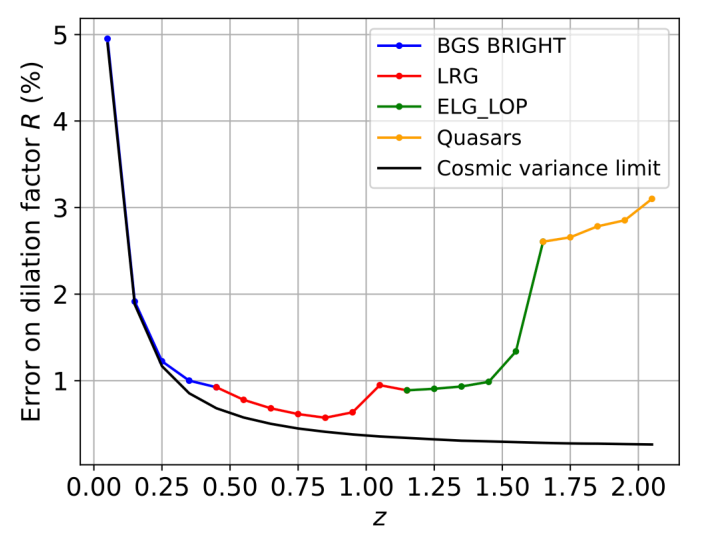


DESI+24

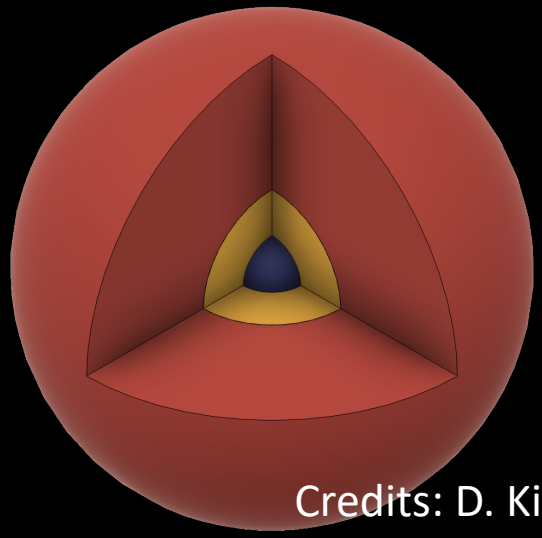
Beyond DESI: large unexplored volume

- DESI will have extracted all the BAO information at z < 1.6
- Going to z > 2:
  - maximum volume per solid angle → large number of modes
  - larger volume: 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



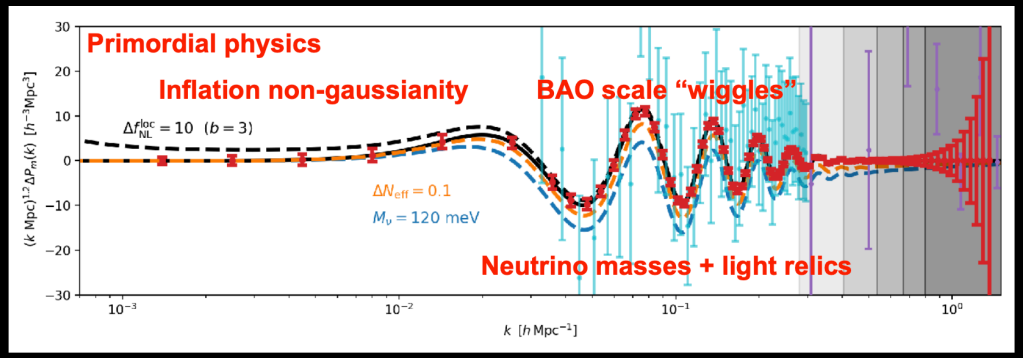
DESI+24

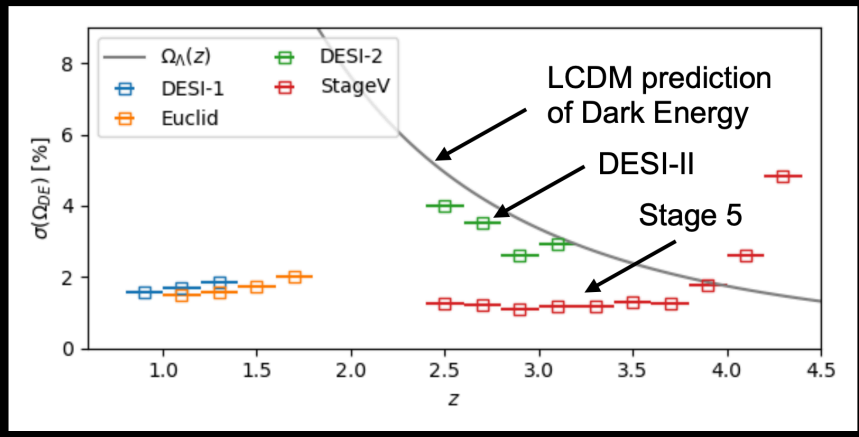


Credits: D. Kirkby

Beyond DESI: z > 2 science

- Inflation and early Universe, thanks to high-precision power spectrum measurements
  - non-Gaussianity induced by inflation (f_{NL})
  - primordial features
  - neutrino masses and light relics
- Dark Energy:
  - BAO at z > 2 (evolving dark energy?)





Credits: D. Schlegel; based on Sailer+22

Beyond DESI: new 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)

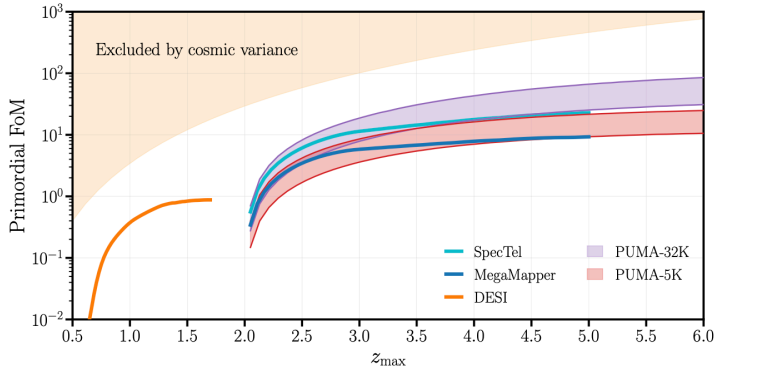
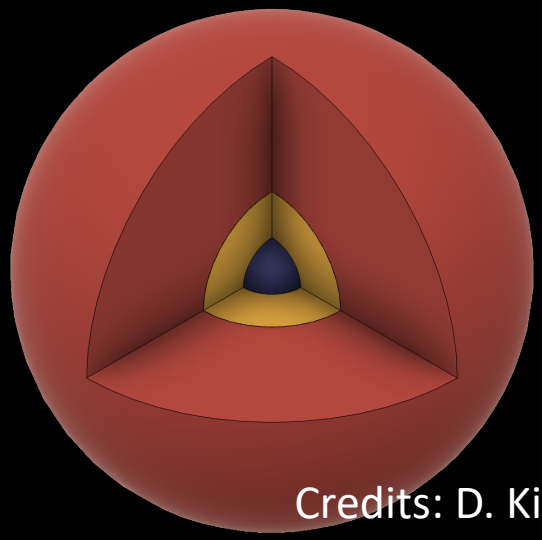


Figure 2: "Figure of Merit" FoM $\equiv 10^{-6}\, N_{\rm modes}$, representing the effective number of "linear" modes observable as a function of $z_{\rm max}$ for DESI, PUMA (-5K and -32K), and MegaMapper and SpecTel, two examples of Stage-5 spectroscopic surveys. For DESI we include only the ELGs. 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).

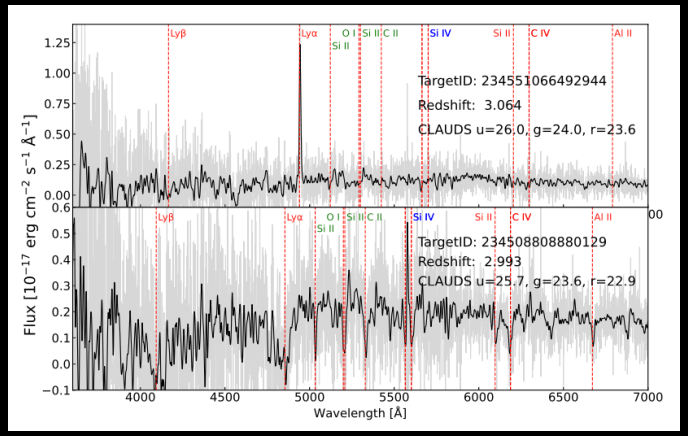
Ferraro+22



Credits: D. Kirkby

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 (Lyman Alpha Emitters) and LBGs (Lyman Break Galaxies)
  - high-density z < 1 galaxy sample
  - stars for Dark Matter

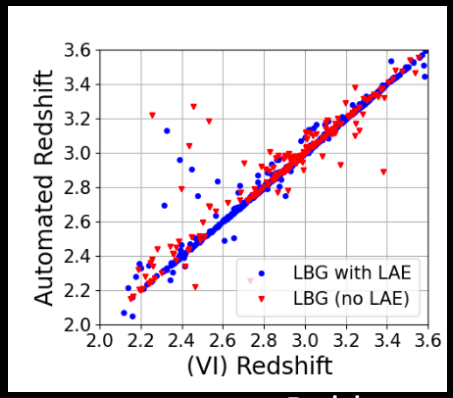


Ruhlmann-Kleider+24

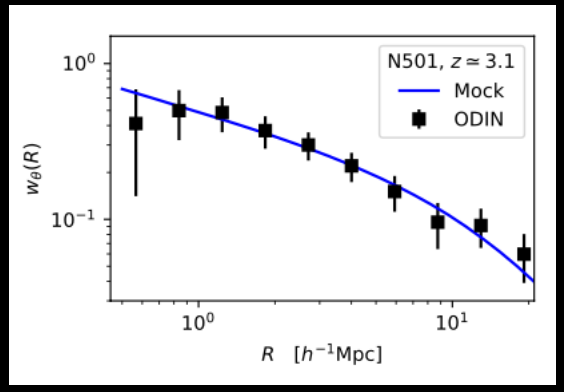
DESI-2: LAEs / LBGs pilot studies

- Several pilot observations done with DESI since Survey Validation:
  - Test various target selections (from broad-band, medium-band, narrow-band photometry)
  - Ruhlmann-Kleider+24: results for LBGs selected with broad-band photometry (CLAUDS)
  - 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



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!
- survey progress: https://data.desi.lbl.gov/desi/users/raichoor/ibis-status/ibis-status.html

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.

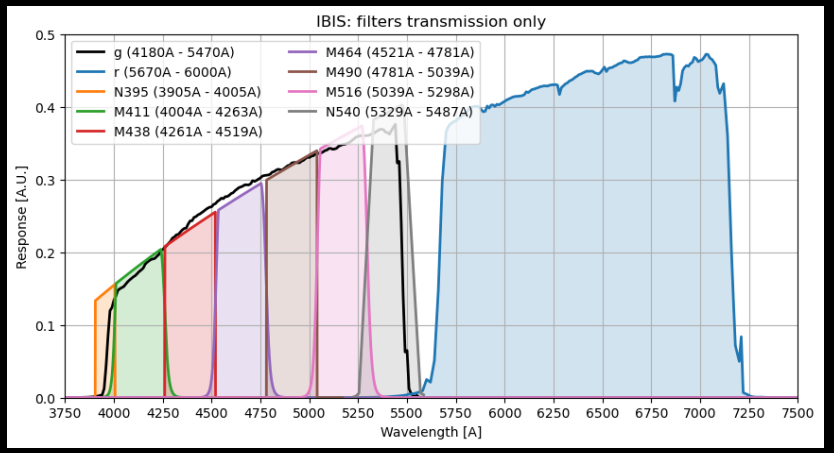
Investigators:

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

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

Scheduled Runs:

Run 1 (2023B): Blanco CT-4m / DECam *Classical (Date TBD)*	**0.10 scheduled nights**
Run 2 (2024A): Blanco CT-4m / DECam *Classical*	**15.00 scheduled nights**
Run 3 (2024B): Blanco CT-4m / DECam *Classical*	**14.00 scheduled nights**



DESI, DESI-2 & Rubin/DESC

- Working groups to coordinate/maximize DESI,DESI-2 x Rubin science:
  - DESI-side: T. Eifler and J. Newman
  - DESC-side: A. Amon and J. DeRose

- Discussion to “front-load” u-band observations in Rubin in DESI-2 footprint

- Lots of Rubin/DESC science cases can benefit from DESI, DESI-2:
  - Photometric redshift calibrations
  - combined LSS and lensing analyses
  - SN1a hosts
  - Galaxy clusters
  - etc

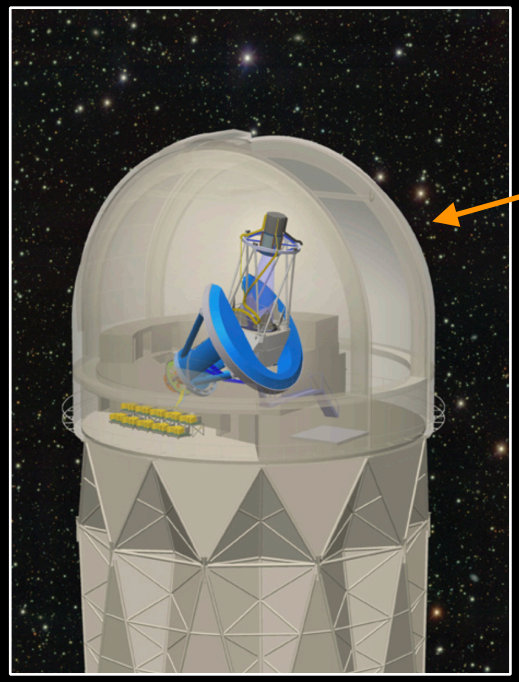
- Possible observations in Rubin Deep Fields, and also spare fibers program

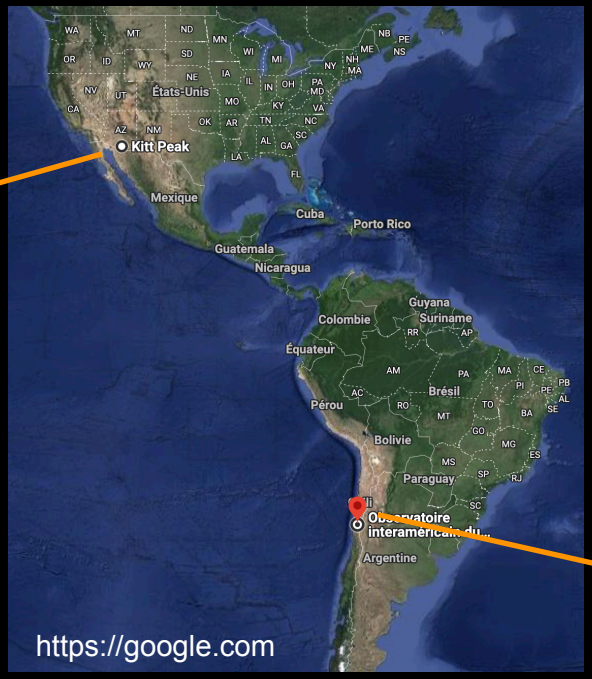
Spec-S5: instrumental setup

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

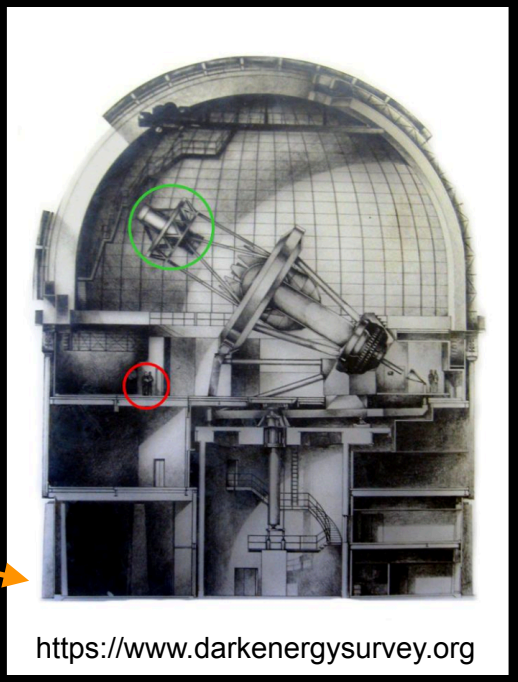
https://spec-s5.org

Mayall, KPNO, USA





Blanco, CTIO, Chile



Spec-S5: instrumental setup

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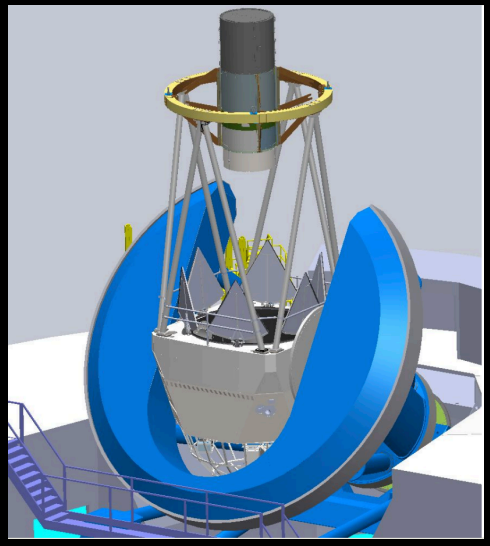
- Change the mirrors (4m to segmented-6m)

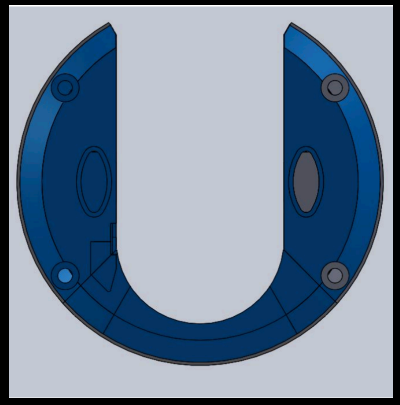
https://spec-s5.org

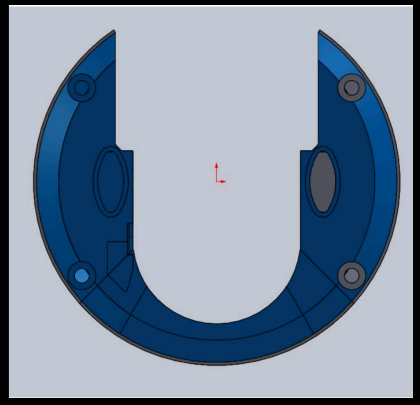
Images credits: B. Besuner

4m mirror

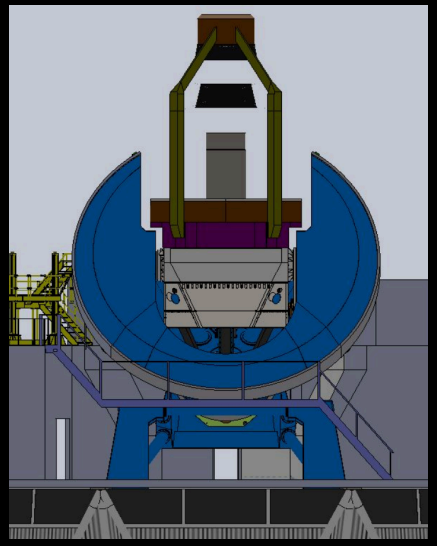


trim “horseshoe”





6m mirror



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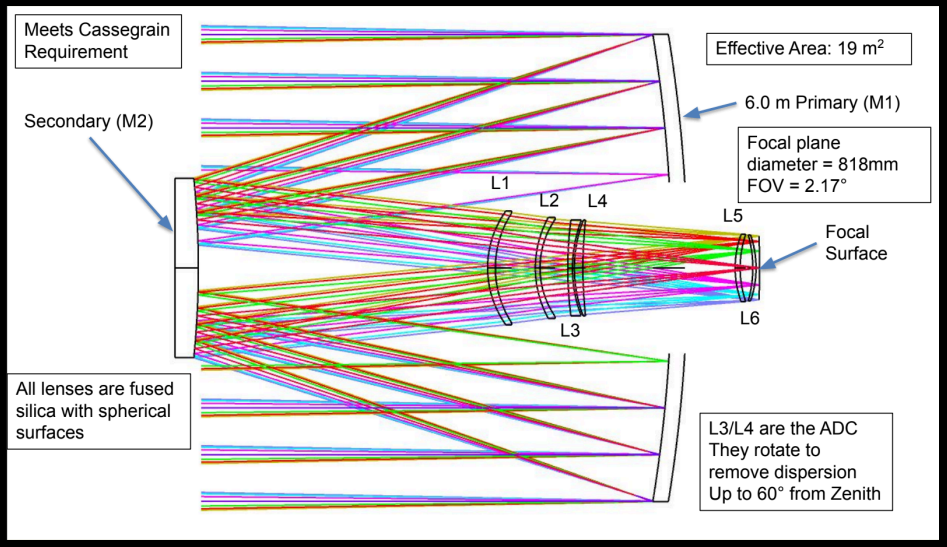
- Optical corrector: not-too-large, spherical lenses; 7 deg^2 field-of-view

https://spec-s5.org

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

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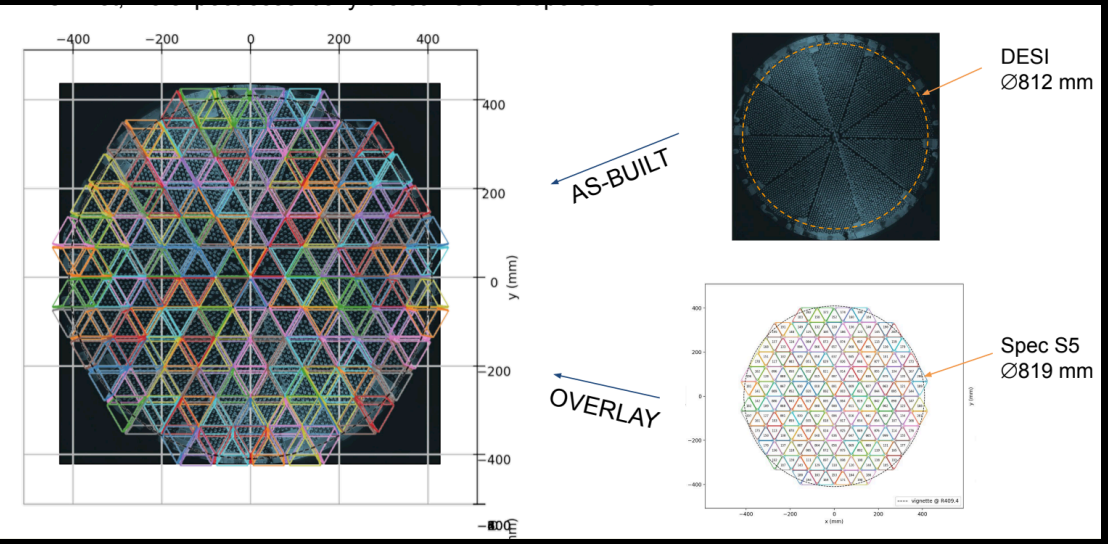
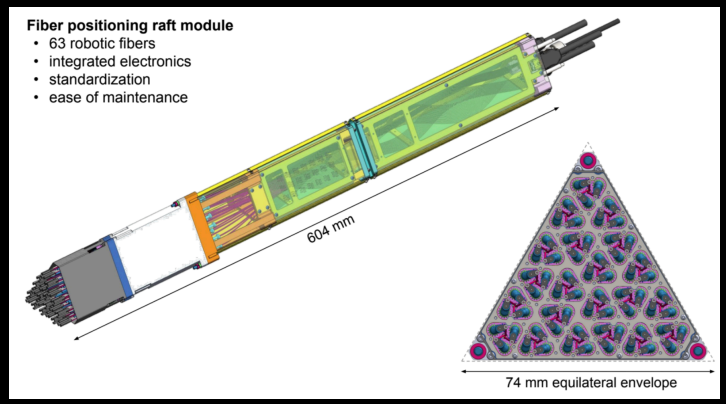
  - 13k positioners on each telescope (vs. 5k for DESI)
  - 204 “rafts” of 63 positioners each — easily removable and serviceable (1.2k each)





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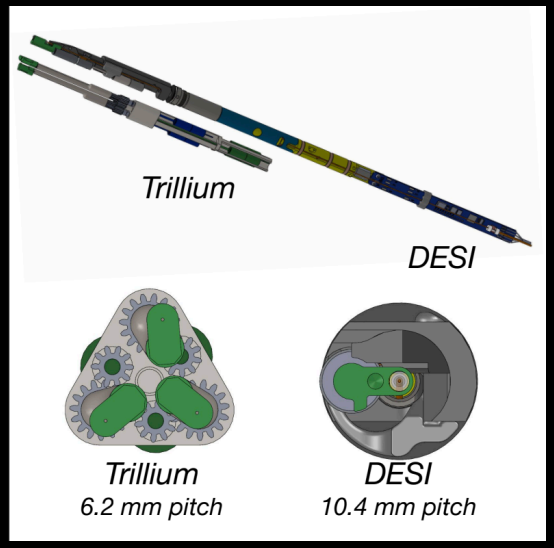
Images credits: J. Silber



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  - 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

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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:
  - z > 2 galaxies : 60M
  - z < 1.6 galaxies :130M
  - stars: 50M

Conclusions

- Spectroscopic roadmap DESI → DESI-2 → Spec-S5:
  - Endorsed by the US community (Snowmass, P5, HEPAP); Synergies with Rubin
- DESI:
  - Y1 results presented in Apr. 2024, Y3 sample data in the can; Extension proposed to DOE
- Beyond DESI:
  - Primordial physics accessible at z > 2; proposed new FoM
  - DESI-2: Pathfinder for Spec-S5; Use of the DESI instrument
  - Spec-S5: New instrumental setup (Mayall+Blanco) to reach 10x DESI new FoM