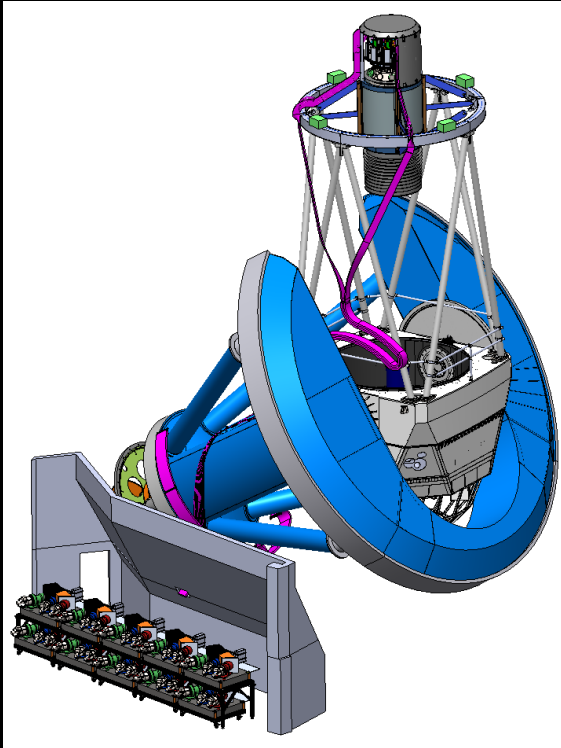


Introduction to Dark Energy Spectroscopic Instrument



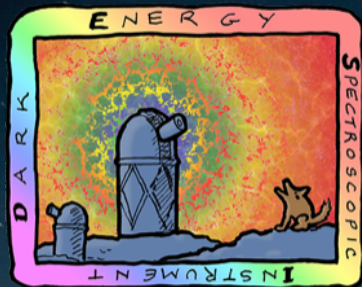
A. Raichoor (LBNL)
on behalf of the DESI collaboration

Cosmic Revelations: A Joint DESI and eROSITA Symposium

May 22nd, 2024



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Lawrence Berkeley National Laboratory



DARK ENERGY SPECTROSCOPIC INSTRUMENT

Thanks to our sponsors and 72 Participating Institutions!

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Outline

- Context:
 - Redshifts
 - Dark energy and cosmological probes
 - Large-Scale Structure (LSS) experiments
- DESI:
 - The instrument
 - The targets
 - The Survey Validation (SV1), the One Percent Survey (SV3), and the Main Survey
 - Data Releases
- Post-DESI:
 - Requested extension
 - DESI-2

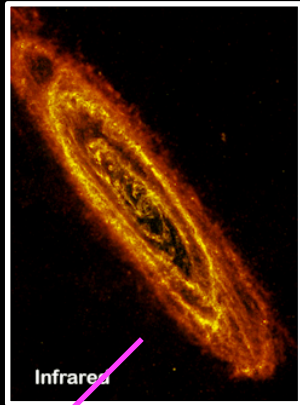
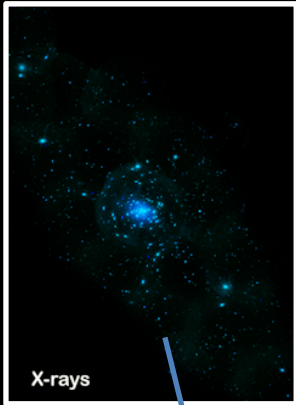


Foreword: astrophysical observations

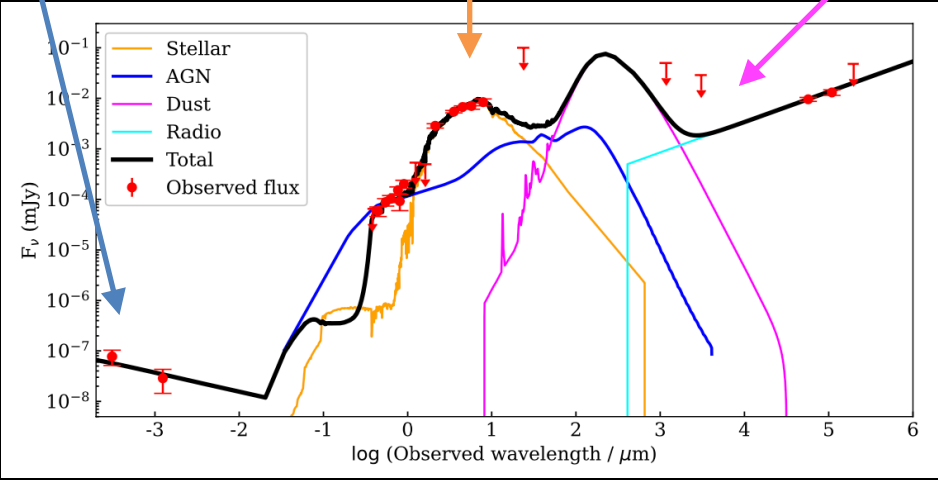
- Typically: X-rays: AGN, optical: stars, infrared: dust

Andromeda galaxy (credits: NASA)

Images



Spectra



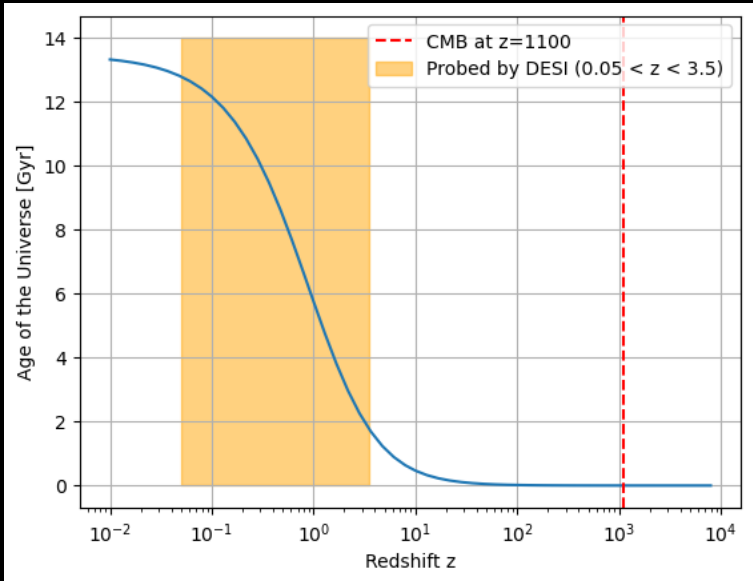
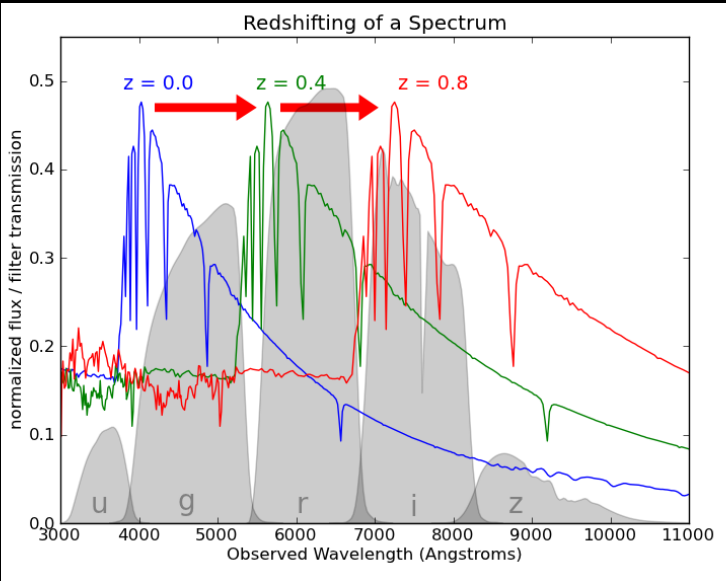
Kubo+22



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Foreword: astrophysical observations

- Redshift:
 - cosmological effect (~Doppler-like): $\lambda_{\text{observed}} = (1 + z) \cdot \lambda_{\text{emission}}$



<https://ogrisel.github.io/scikit-learn.org/sklearn-tutorial/tutorial/astronomy/regression.html>

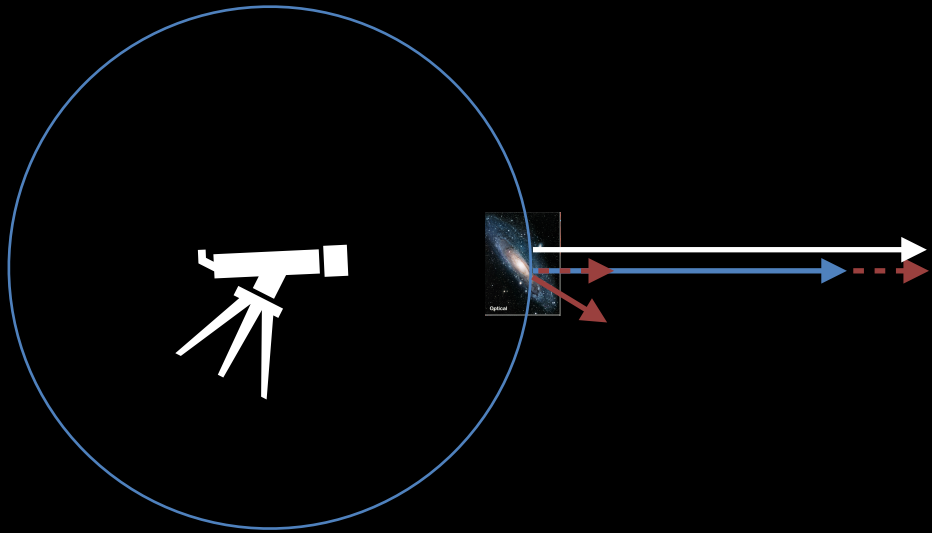


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Foreword: astrophysical observations

- Redshift:
 - cosmological effect (~Doppler-like): $\lambda_{\text{observed}} = (1 + z) \cdot \lambda_{\text{emission}}$
 - measured redshifts: cosmological redshift + galaxy peculiar velocity along line of sight

$$z_{\text{spec}} = z_{\text{Hubble}} + \vec{v}_{\text{pec}} \cdot \vec{los}$$

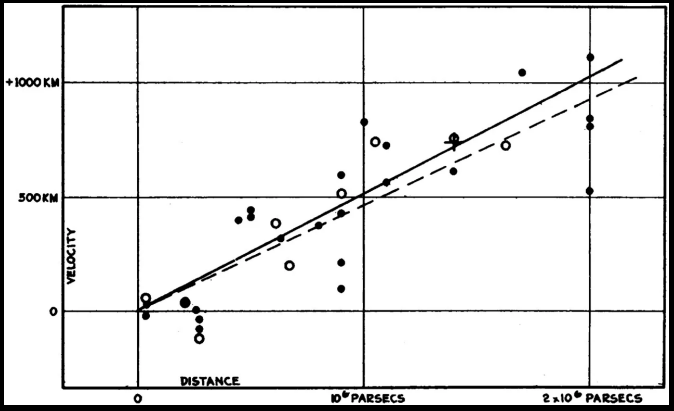


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Dark energy & cosmological probes

- 1930 ~ 1960: Big-bang, universe in expansion, three observational pillars (Hubble's law, CMB, BBN)

Galaxy radial velocity



Galaxy distance

Hubble+29

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

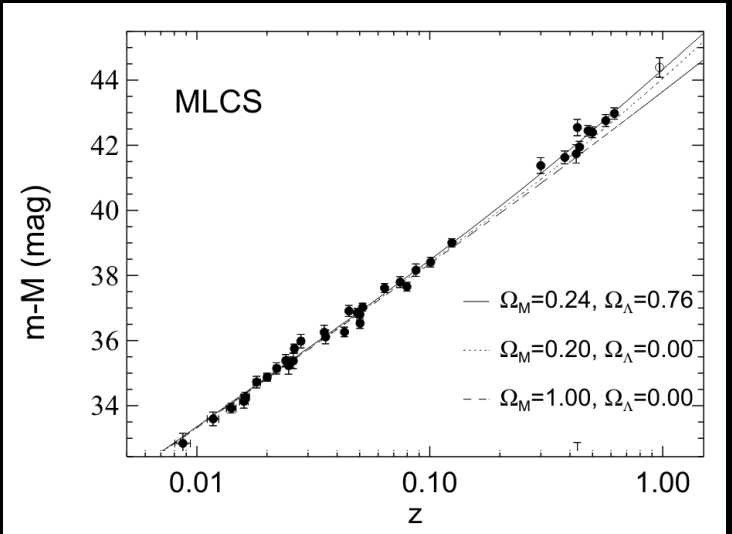
Penzias & Wilson+65



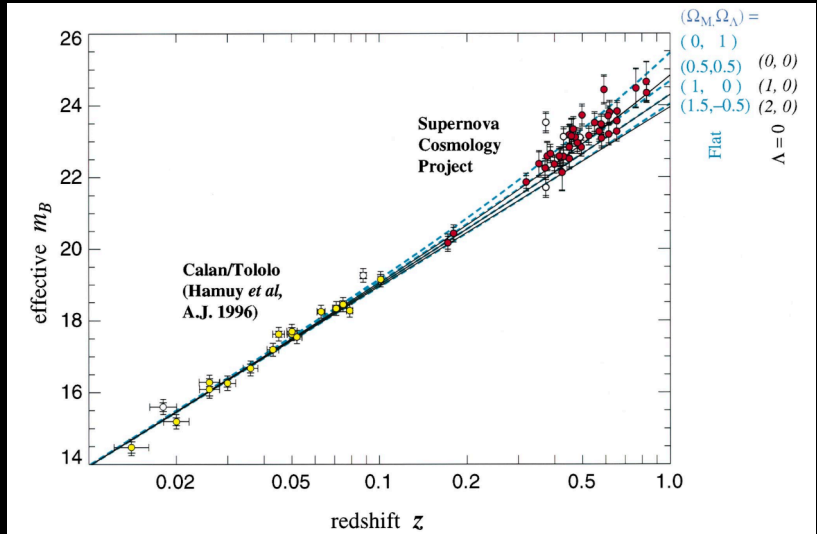
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Dark energy & cosmological probes

- 1930 ~ 1960: Big-bang, universe in expansion, three observational pillars (Hubble's law, CMB, BBN)
- 1998: Supernovae Ia observations → acceleration of the expansion of the universe



Riess+98



Perlmutter+99

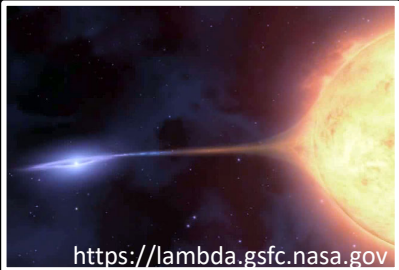


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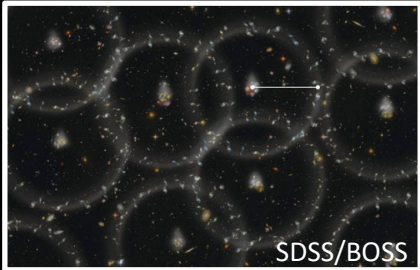
Dark energy & cosmological probes

- 1930 ~ 1960: Big-bang, universe in expansion, three observational pillars (Hubble's law, CMB, BBN)
- 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

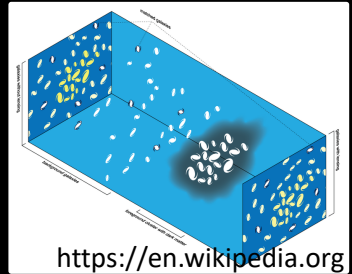
Supernovae Ia (SN Ia)



Baryon Acoustic Oscillations (BAO)



Weak-lensing (WL)



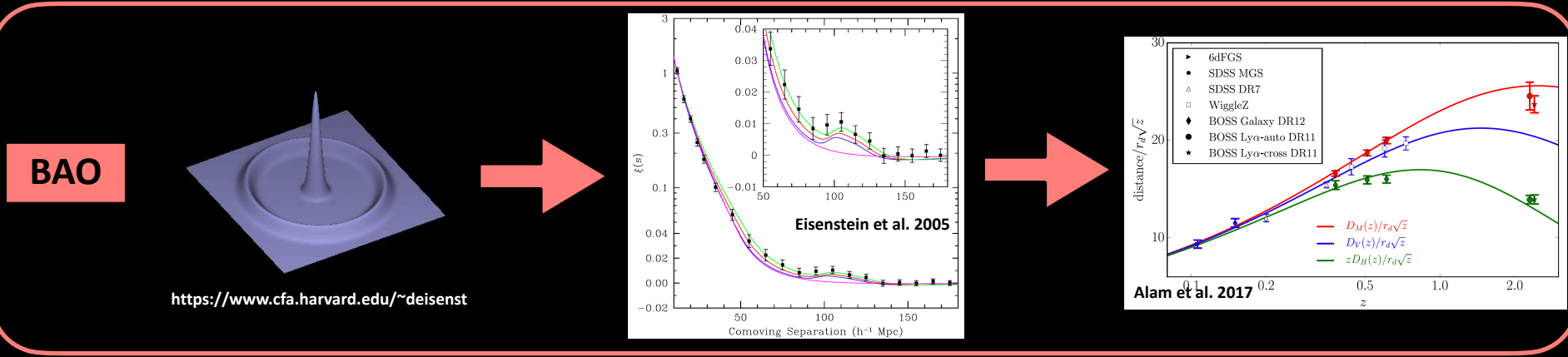
Galaxy clusters (GC)



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LSS experiments: cosmological probes

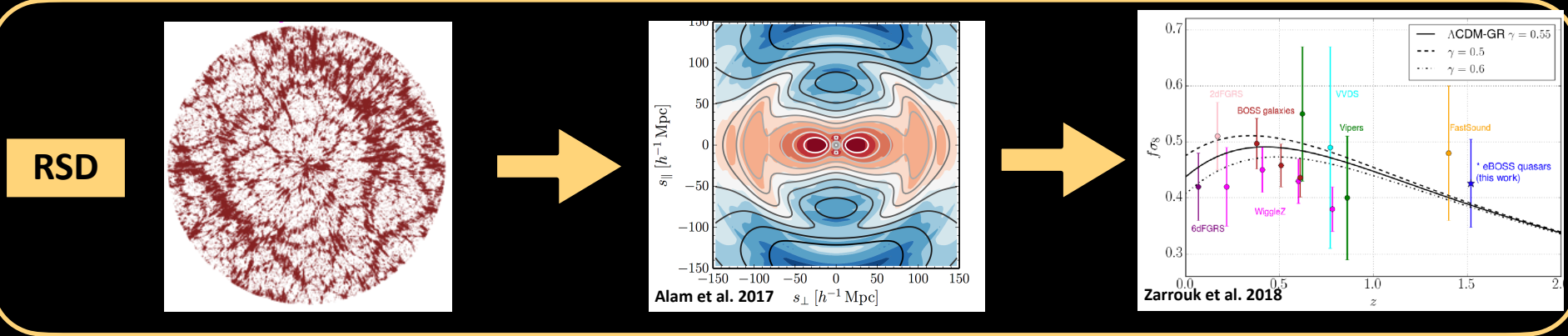
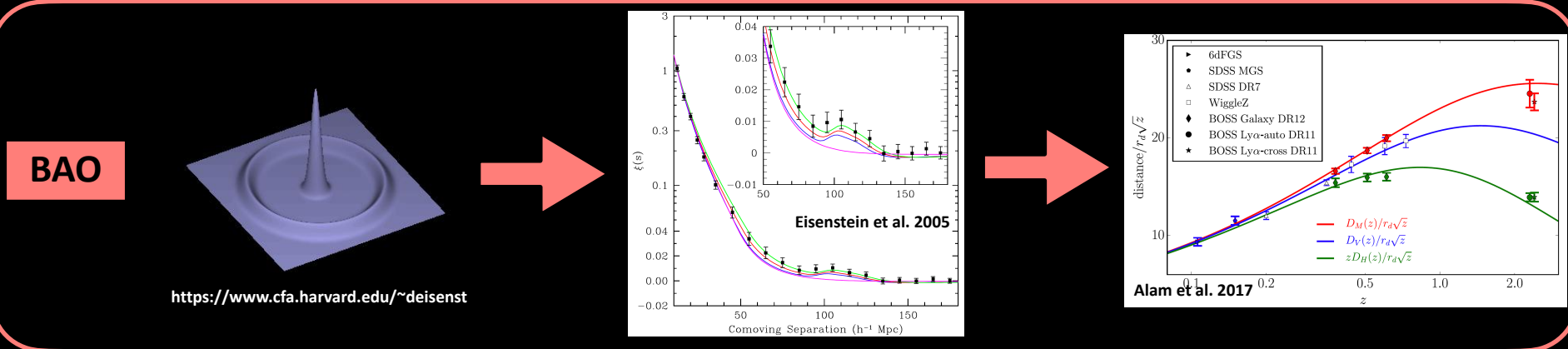
- LSS (*Large-Scale Structures*) experiment: BAO and RSD with spectroscopic redshifts
- **BAO** → Universe expansion [also SNIa]



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LSS experiments: cosmological probes

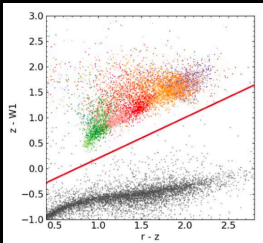
- LSS (*Large-Scale Structures*) experiment: BAO and RSD with spectroscopic redshifts
- **BAO** → Universe expansion [also SNIa]
- **RSD** (*Redshift Space Distortions*) → Growth of structure + test of General Relativity [also WL+GC]



LSS experiments: steps

- **Survey design:** sky footprint, imaging, target selection, tiling/fibre assignment

1. Survey design

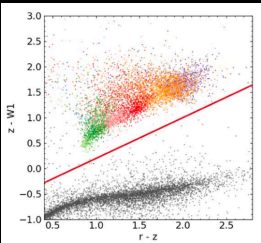


Zhou+23

LSS experiments: steps

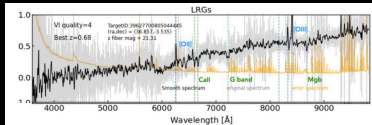
- **Survey design:** sky footprint, imaging, target selection, tiling/fibre assignment
- **Get redshifts:** spectroscopic observations, 1D-spectrum reduction, redshift fitting

1. Survey design



Zhou+23

2. Get redshifts



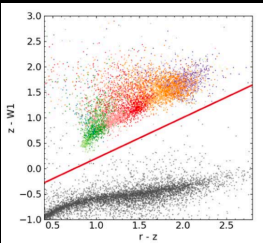
Lan+23



LSS experiments: steps

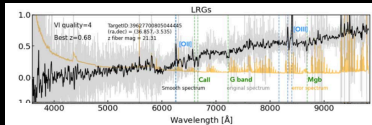
- **Survey design:** sky footprint, imaging, target selection, tiling/fibre assignment
- **Get redshifts:** spectroscopic observations, 1D-spectrum reduction, redshift fitting
- **Clustering:** LSS catalogues, correlation function / power spectrum

1. Survey design



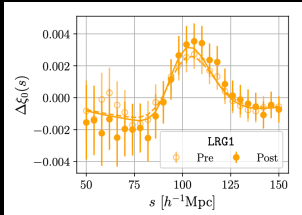
Zhou+23

2. Get redshifts



Lan+23

3. Clustering

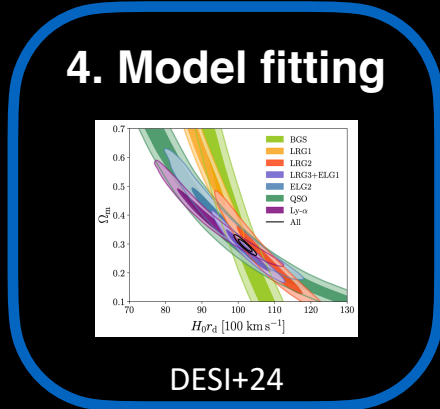
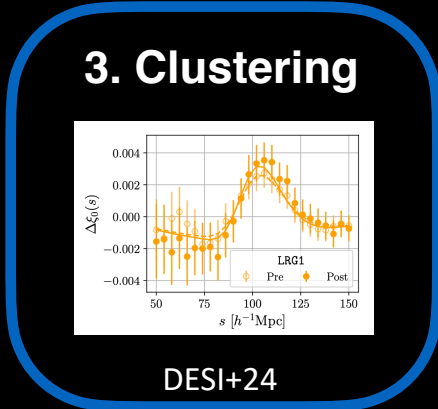
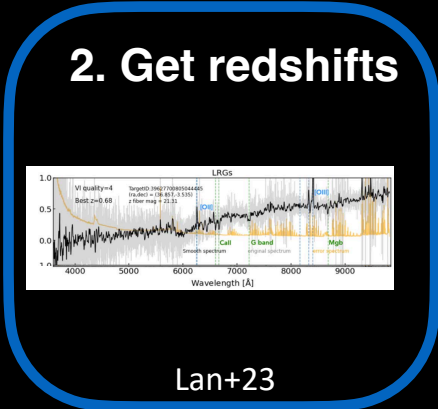
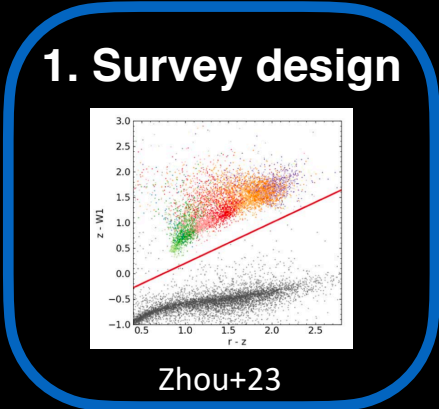


DESI+24



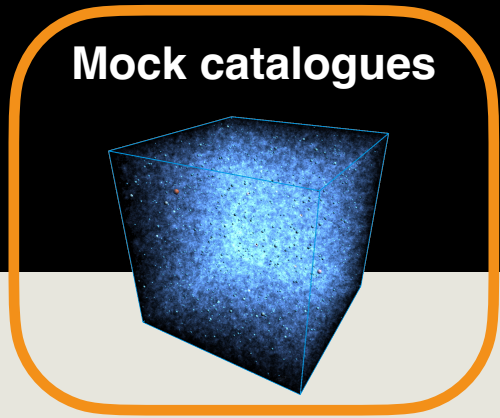
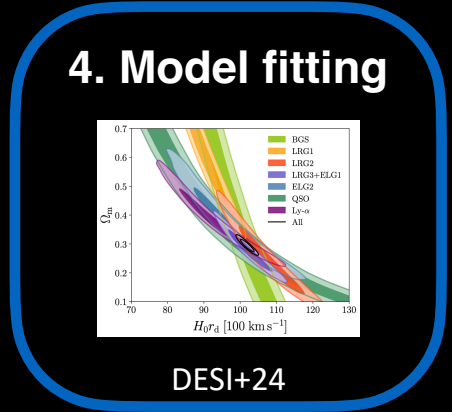
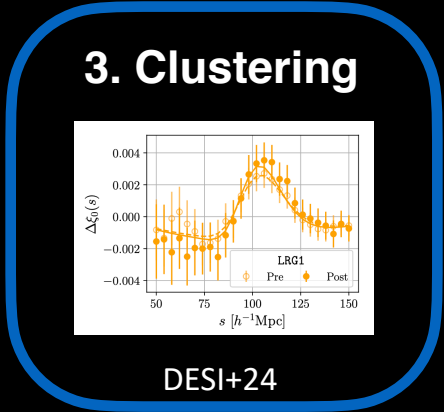
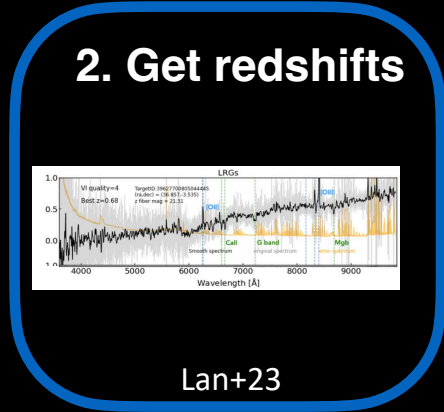
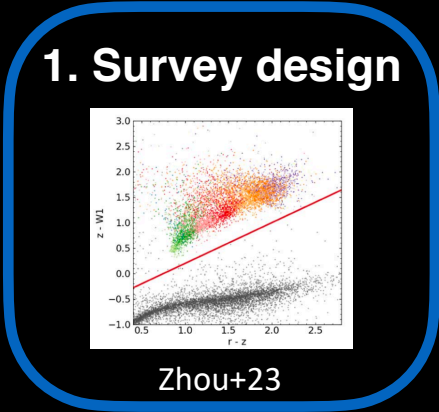
LSS experiments: steps

- **Survey design:** sky footprint, imaging, target selection, tiling/fibre assignment
- **Get redshifts:** spectroscopic observations, 1D-spectrum reduction, redshift fitting
- **Clustering:** LSS catalogues, correlation function / power spectrum
- **Model fitting:** analysis validation, systematics estimation, cosmological parameters



LSS experiments: steps

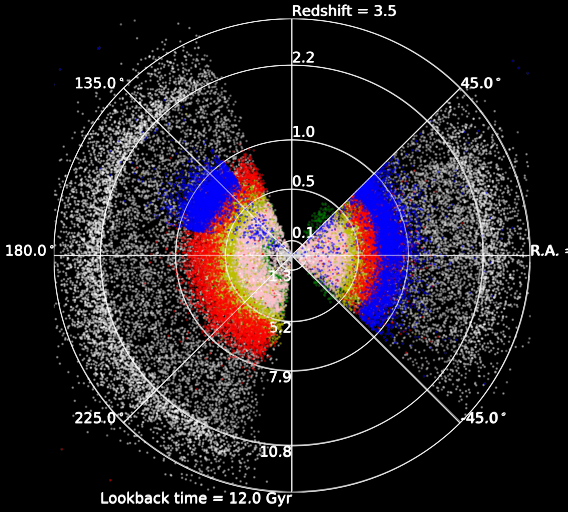
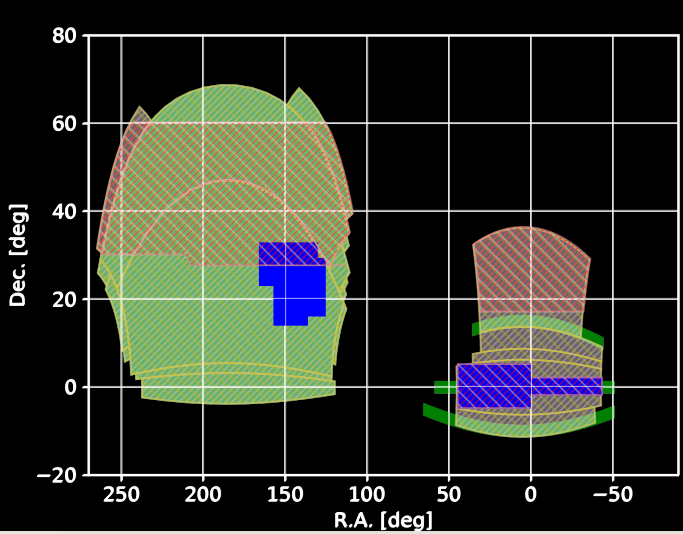
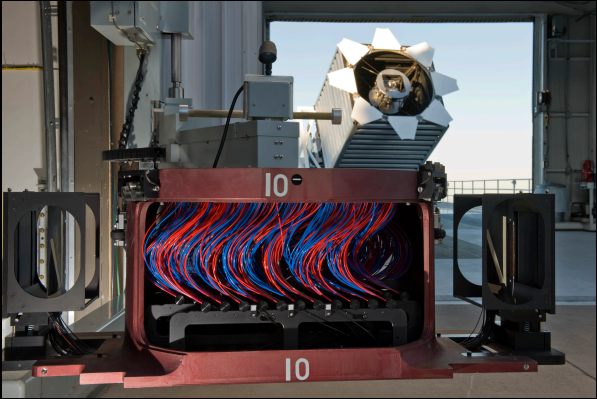
- **Survey design:** sky footprint, imaging, target selection, tiling/fibre assignment
- **Get redshifts:** spectroscopic observations, 1D-spectrum reduction, redshift fitting
- **Clustering:** LSS catalogues, correlation function / power spectrum
- **Model fitting:** analysis validation, systematics estimation, cosmological parameters
- **Mock catalogues:** covariance matrix, analysis validation



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LSS experiments: SDSS

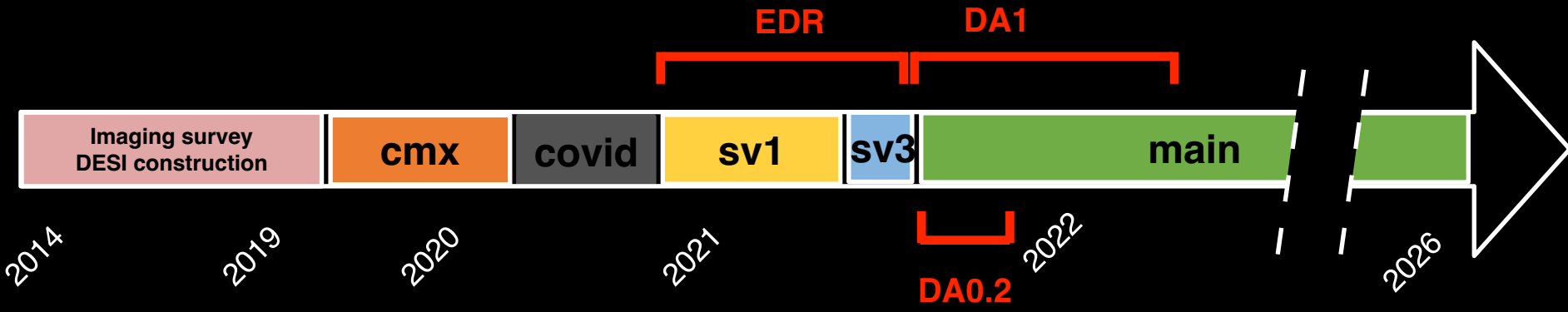
- New Mexico, USA, 2.5-meters, field-of-view 7 deg² (“28x Moons”), 1000 fibres
- SDSS, BOSS, eBOSS: two decades of LSS (2000 — 2019), 5M redshifts
- SDSS+21 : [Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory](#)



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DESI: timeline & releases

- A decade-long effort!



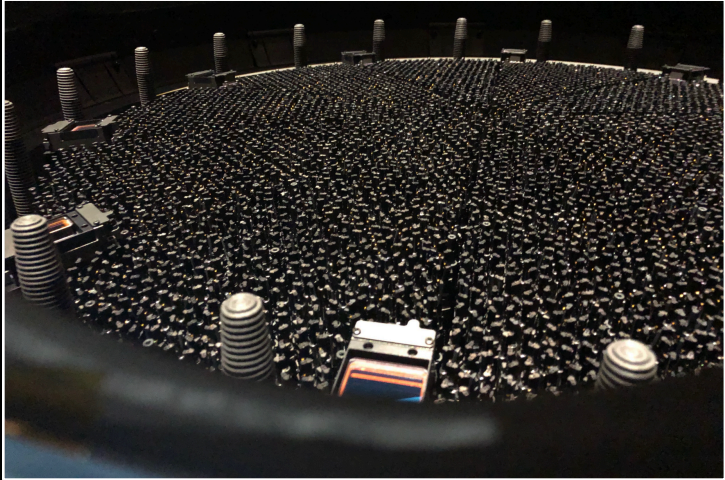
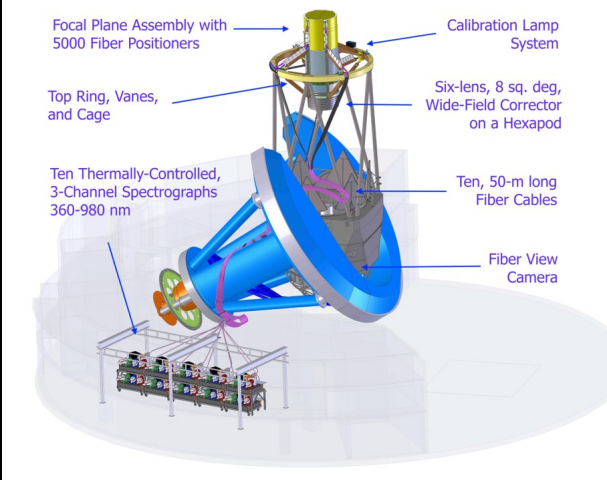
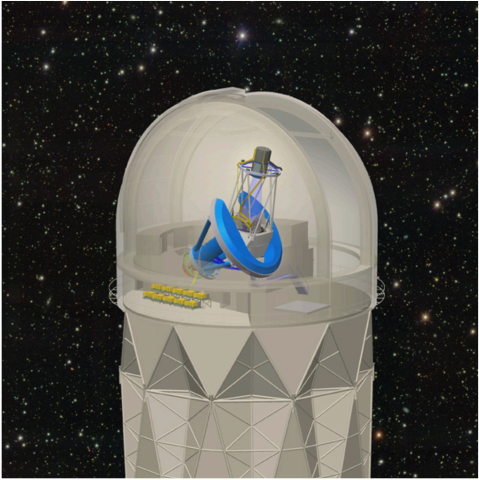
Release	Internal	Public	Content
EDR	2022 Feb.	2023 May	mostly sv1 + sv3
DA0.2	2022 Feb.	along DA1	main: first 2 months
DA1	2023 Feb.	when science analyses done	main: first 13 months



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DESI: the instrument

- Mayall telescope in Arizona, USA
- 4m primary mirror, 8 deg² field-of-view, 5000 fiber positioners, 10 optical spectrographs



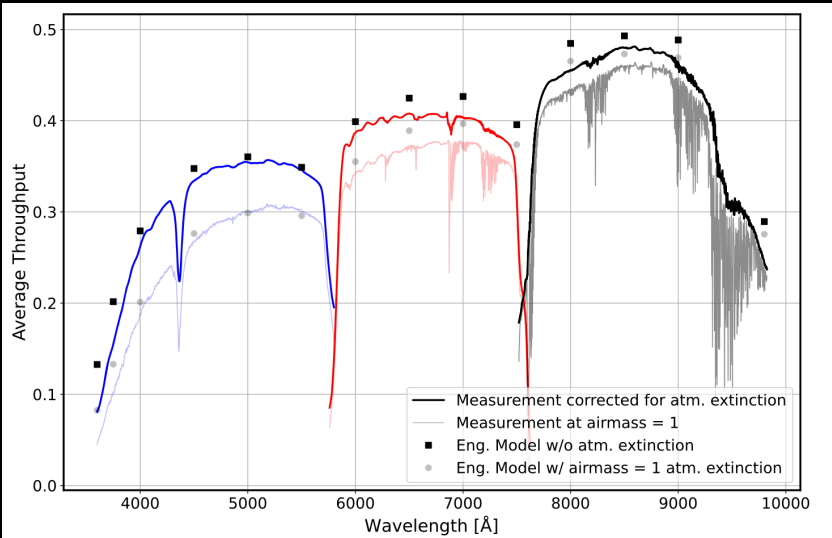
DESI+22

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DESI: the instrument

- Mayall telescope in Arizona, USA
- 4m primary mirror, 8 deg² 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 deg² field-of-view, 5000 fiber positioners, 10 optical spectrographs
- high throughput (optics, spectrographs, fibers, CCDs)
- redshift factory!

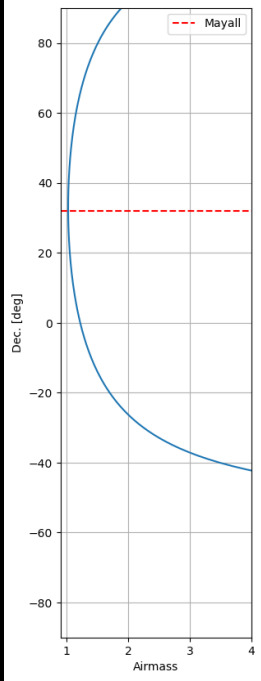
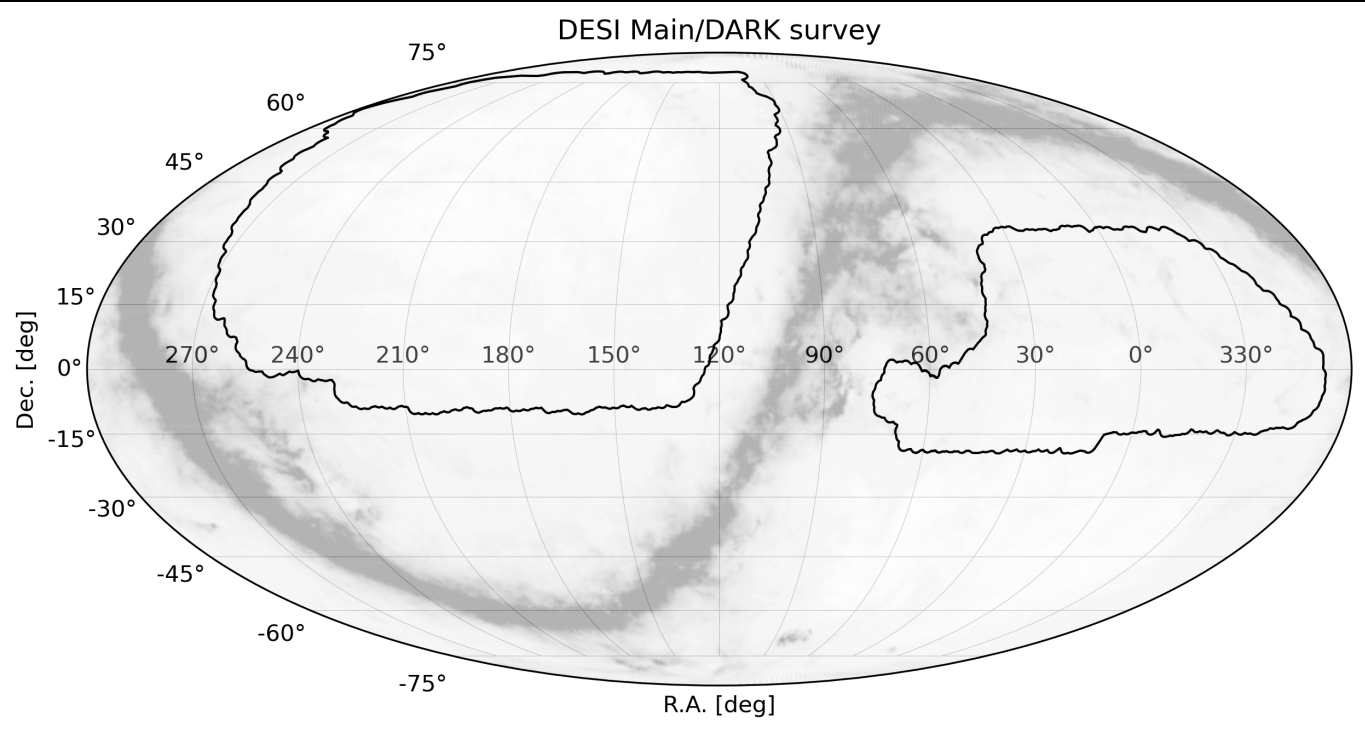
SDSS/BOSS-eBOSS: 1k spectra in ~1 hr

DESI: 5k spectra in ~15min → **20x faster**



DESI: the Main Survey

- Five years over 14,000 deg² (1/3 of the sky), started on May, 14th 2021



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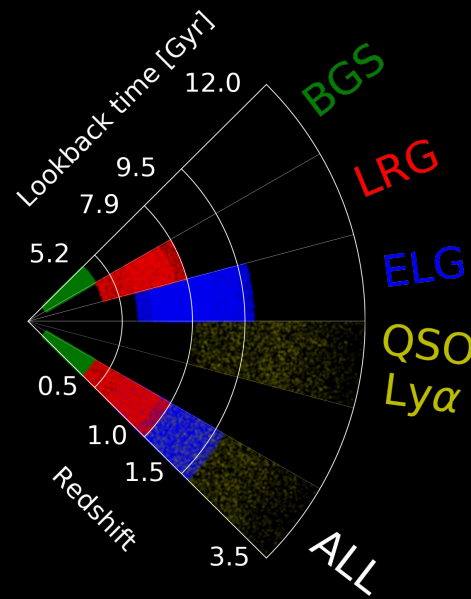
DESI: the Main Survey

- Five years over 14,000 deg² (1/3 of the sky), started on May, 14th 2021
- 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



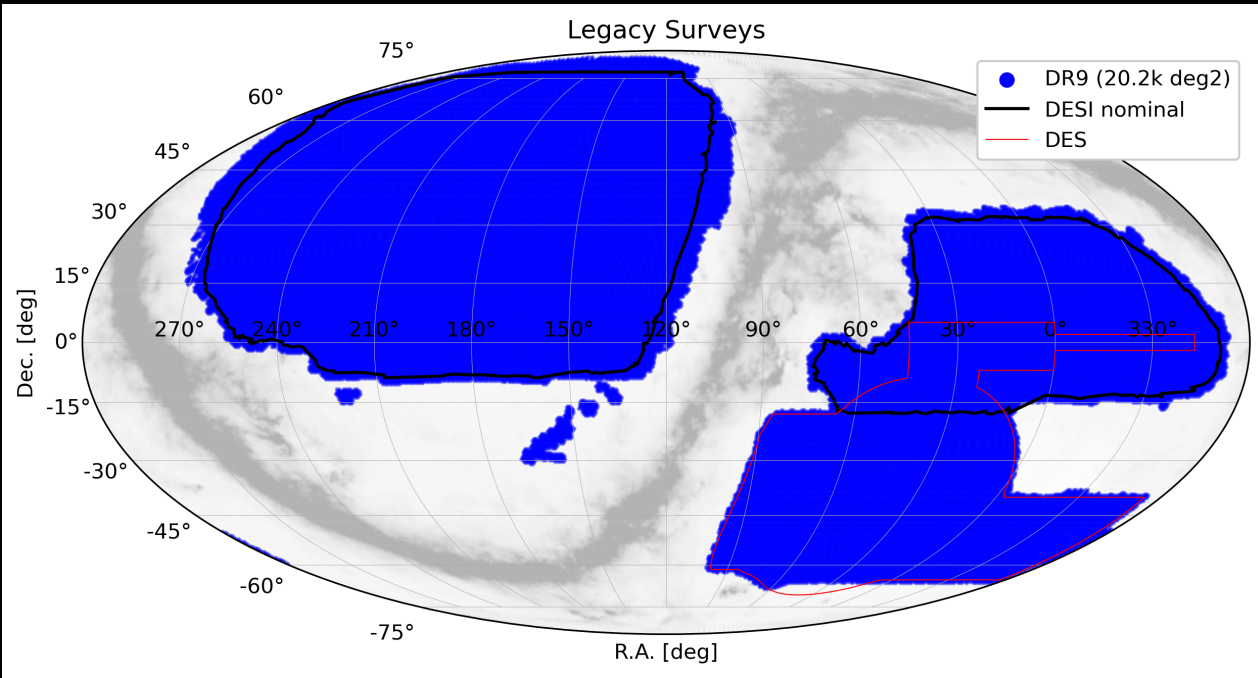
bright time
dark time



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DESI: the imaging

- Legacy Surveys DR9 (<https://www.legacysurvey.org/dr9/>; Dey, Schelgel +19)
- 20k deg² imaged in *grz*-bands + forced-photometry in near-infrared (*WISE*) + *Gaia* info.
- Data coming from three telescopes
- Largest cosmological imaging survey

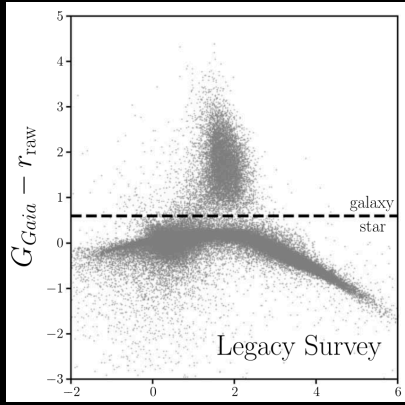


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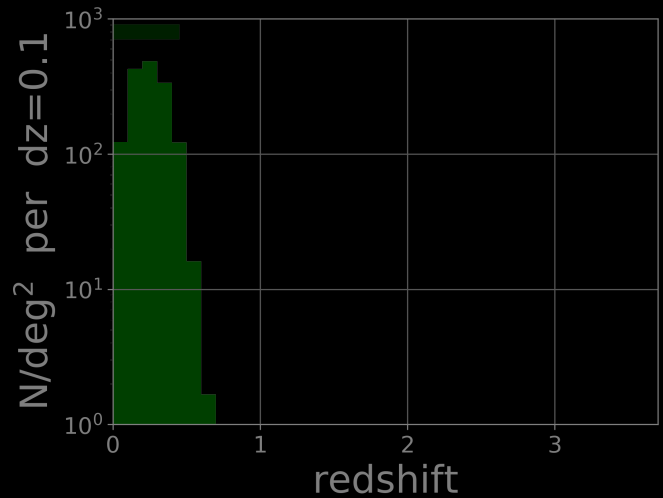
DESI: BGS targets

- Same spirit as the SDSS Main Galaxy Sample, all types of galaxies at $z < 0.4$
- Selection: $r < 19.5-20$ + morphology cut with Gaia

	N	Redshift	Density [deg ⁻²]	Obs. cond.	Comments
BGS	13.5M	$0.05 < z < 0.4$	700	Bright	bright galaxies



Hahn+23

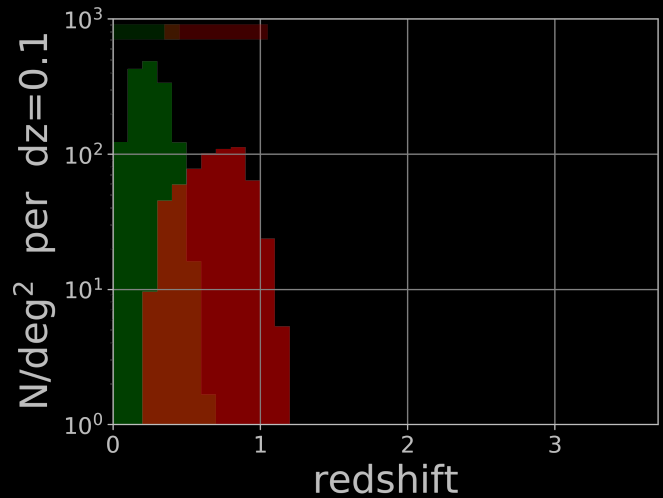
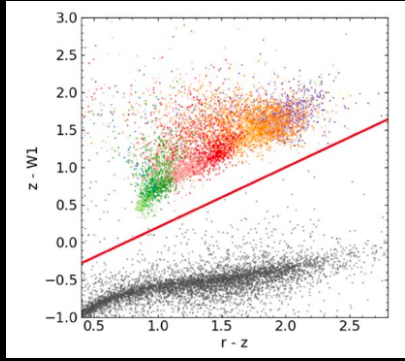


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DESI: LRG targets

- Massive galaxies, with strong clustering bias
- Selection: $z_{\text{fiber}} < 21.6 + \text{grzW1 cuts}$

	N	Redshift	Density [deg ⁻²]	Obs. cond.	Comments
LRG	8M	$0.4 < z < 1.0$	350	Dark	luminous red galaxies



Zhou+23

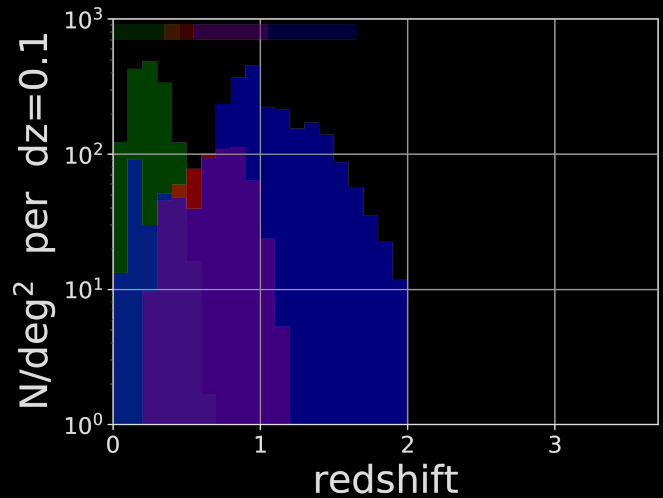
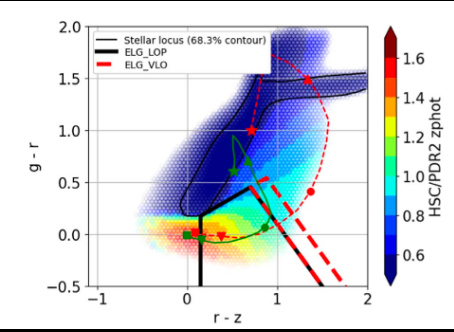


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DESI: ELG targets

- « Faint » star-forming galaxies, with strong emission lines ([OII] doublet)
- Selection: $g_fiber < 24.1$ + grz box

	N	Redshift	Density [deg ⁻²]	Obs. cond.	Comments
ELG	16M	$0.6 < z < 1.6$	2400	Dark	emission line galaxies



Raichoor+23

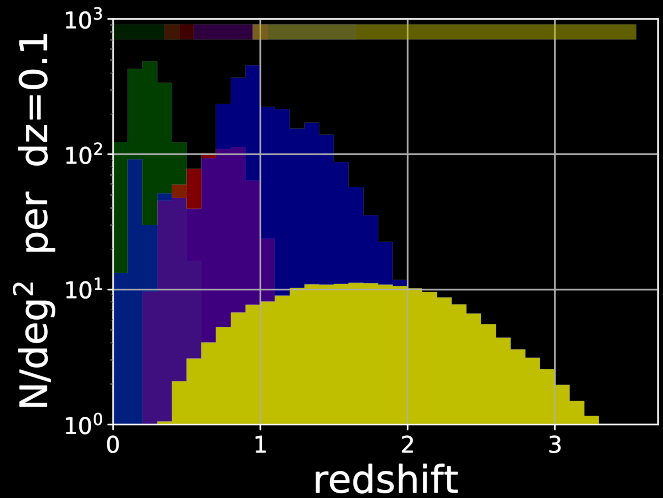
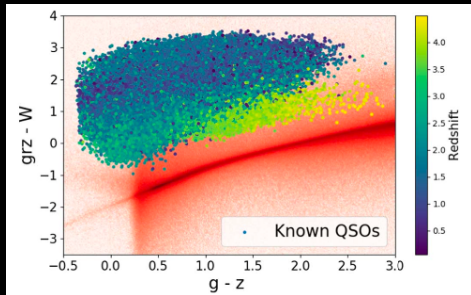


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DESI: QSO targets

- Point-source, luminous, high-redshift objects with AGN activity
- Ly- α forest for $z > 2.1$ QSOs
- Selection: $r < 23.0$, point-source morphology + Random Forest with grzW1W2

	N	Redshift	Density [deg ⁻²]	Obs. cond.	Comments
QSO + Ly α	3M	0.8 < z < 3.5	260	Dark	quasars



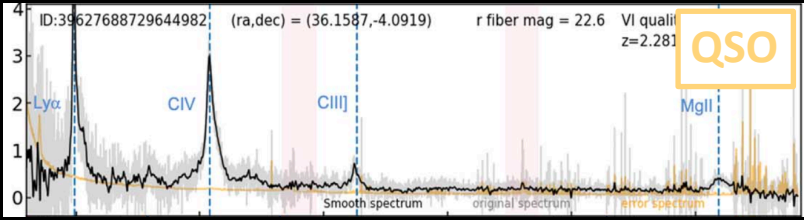
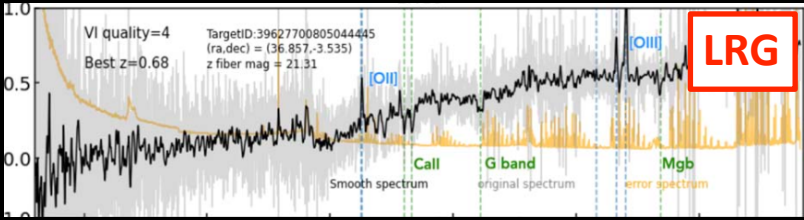
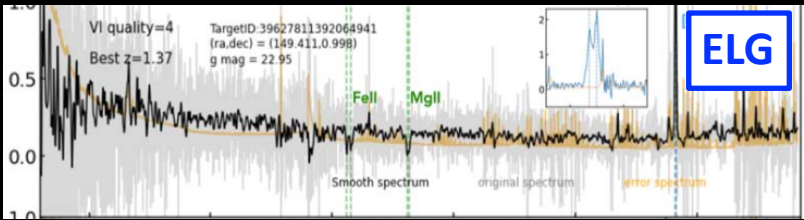
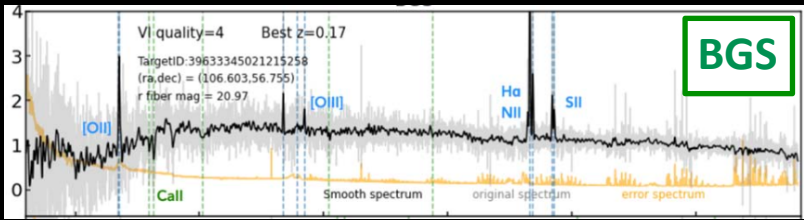
Chaussidon+23



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DESI: Survey Validation (SV1)

- Dec. 2020 — Apr. 2021
- DESI observations of extended target selections
- Goals:
 - Validate target selections properties
 - Build truth table from very deep observations (via Visual Inspections)
 - Validate DESI performances for nominal exposure times



Alexander+23, Lan+23



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- Dec. 2020 — Apr. 2021
- DESI observations of extended target selections
- Goals:
 - Validate target selections properties
 - Build truth table from very deep observations (via Visual Inspections)
 - Validate DESI performances for nominal exposure times

No.	Requirement	Performance
L2	Survey Data Set Requirements	
L2.2	Luminous Red Galaxies	
L2.2.1	The average density with redshift $0.4 < z < 1.0$ shall be at least 300 deg^{-2} .	The average density with redshift $0.4 < z < 1.1$ is 478 deg^{-2} .
L2.2.2	The random redshift error shall be less than $\sigma_z = 0.0005(1 + z)$.	The typical random redshift error is $\sigma_z = 0.00014(1 + z)$.
L2.2.3	The systematic in the mean redshift shall be less than $\Delta z = 0.0002(1 + z)$.	The systematic error in the mean redshift is $\Delta z = 0.00001(1 + z)$.
L2.2.4	The catastrophic redshift failures exceeding 1000 km s^{-1} shall be $< 5\%$.	The rate of catastrophic redshift failures exceeding 1000 km s^{-1} is 0.2% .
L2.2.5	The redshift completeness shall be $> 95\%$ for each pointing averaged over all fibers with targets.	The fraction of targets confirmed as galaxies is 96% over all fibers that receive targets.

LRG requirements (see for all tracers: DESI+24)



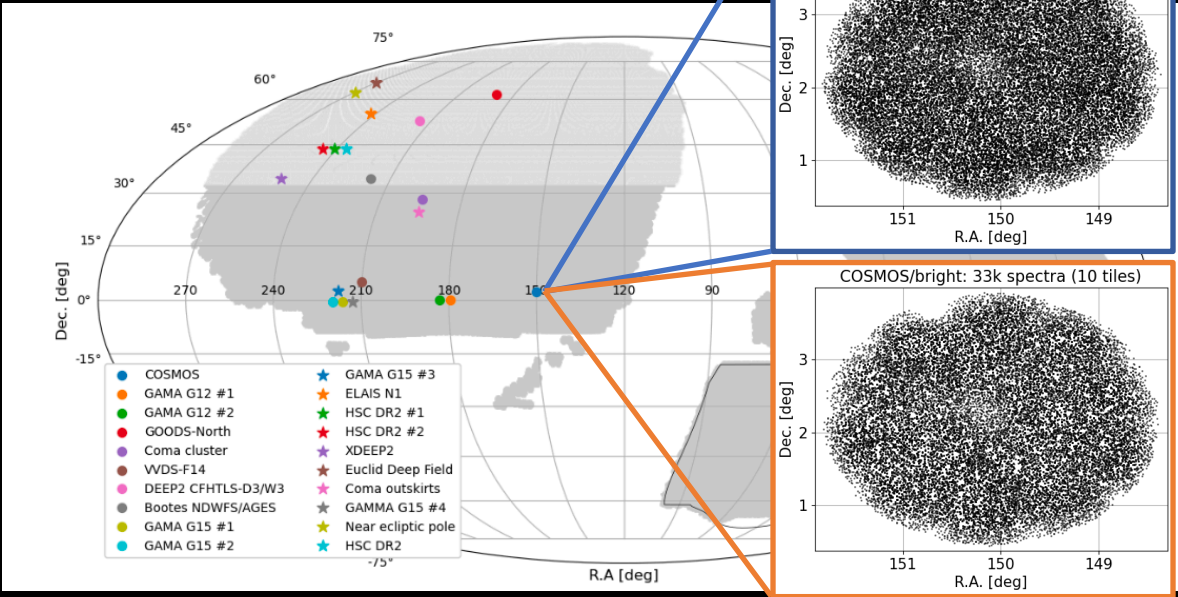
DESI: Survey Validation (SV1)

- Coordinated analysis and release of eight papers in 2023:
 - Myers+23: The Target-selection Pipeline for the Dark Energy Spectroscopic Instrument
 - Cooper+23: Overview of the DESI Milky Way Survey
 - Hahn+23: The DESI Bright Galaxy Survey: Final Target Selection, Design, and Validation
 - Zhou+23: Target Selection and Validation of DESI Luminous Red Galaxies
 - Raichoor+23: Target Selection and Validation of DESI Emission Line Galaxies
 - Chaussidon+23: Target Selection and Validation of DESI Quasars
 - Lan+23: The DESI Survey Validation: Results from Visual Inspection of BGSs, LRGs, ELGs
 - Alexander+23: The DESI Survey Validation: Results from Visual Inspection of the QSO Spectra



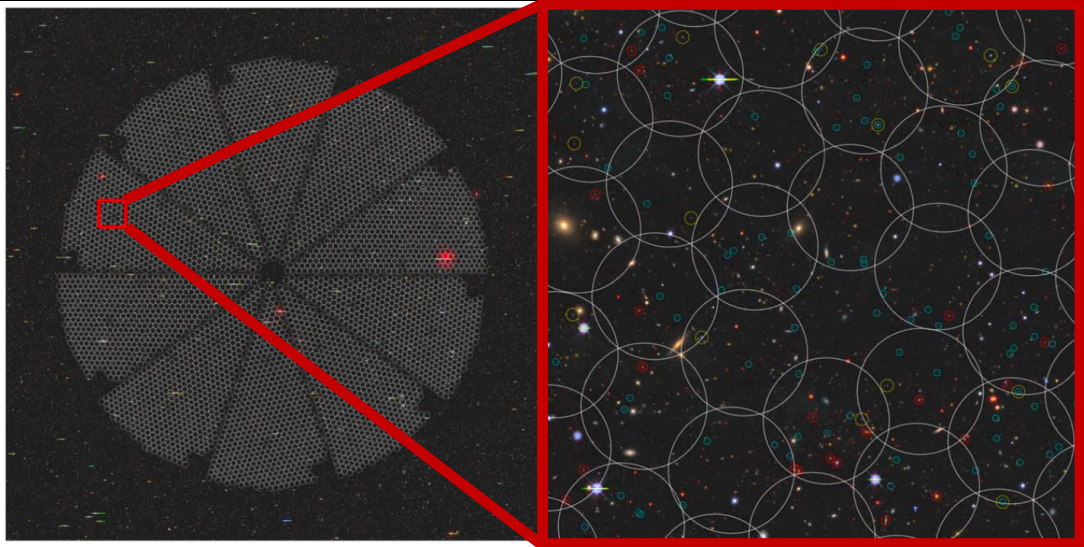
DESI: One Percent Survey (SV3)

- Apr. 2021
- Goal:
 - observations to calibrate halo-galaxy models
 - refine operations procedure
- DESI Main-like targets, 20 reference fields, observed in dark + bright
- Each field: dense tiling of ~12 tiles (“rosette”), 30k+ spectra
- Very high-fiber assignment completeness, high spectroscopic success rate

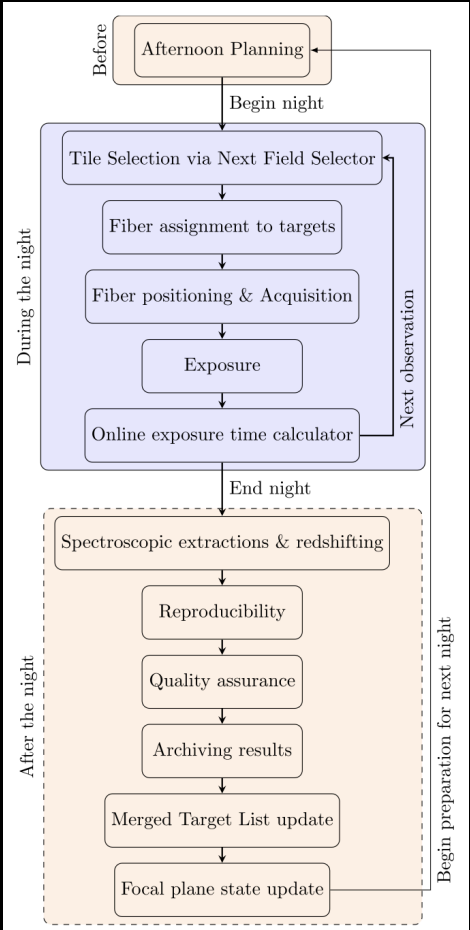


DESI: Main Survey

- Started on May, 14th 2021
- Optimized operations, very efficient
(record night: 20211103, 39 dark tiles, ~200k spectra)



DESI+24



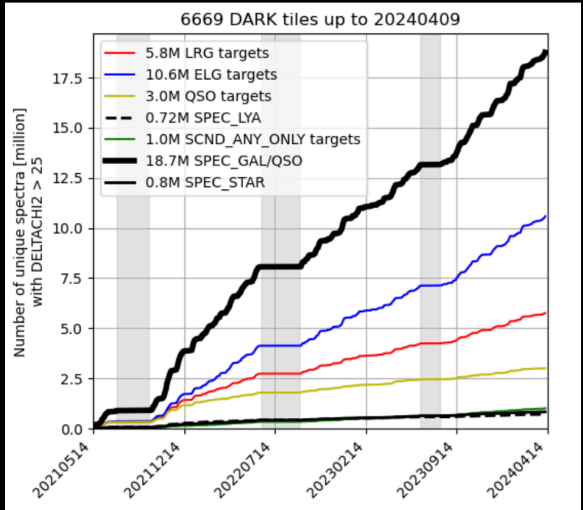
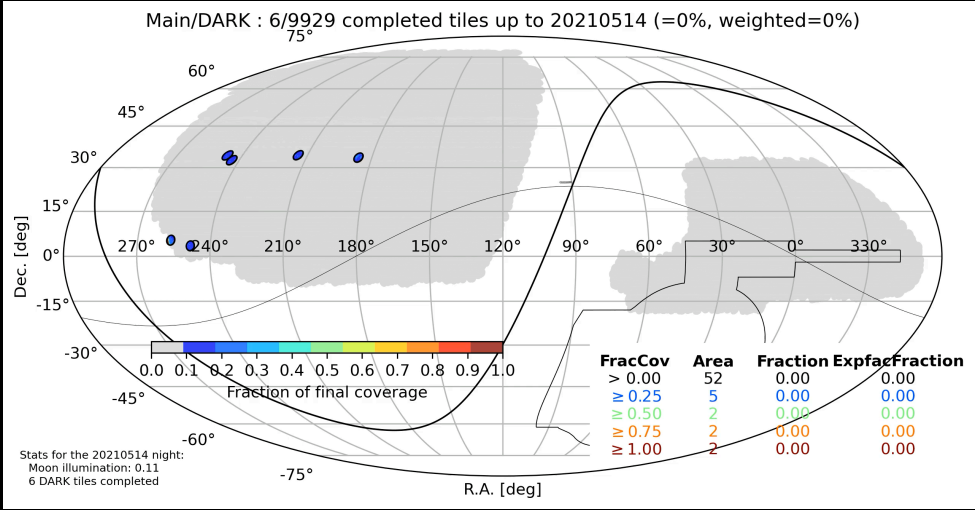
Schlafly+23



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DESI: Main Survey

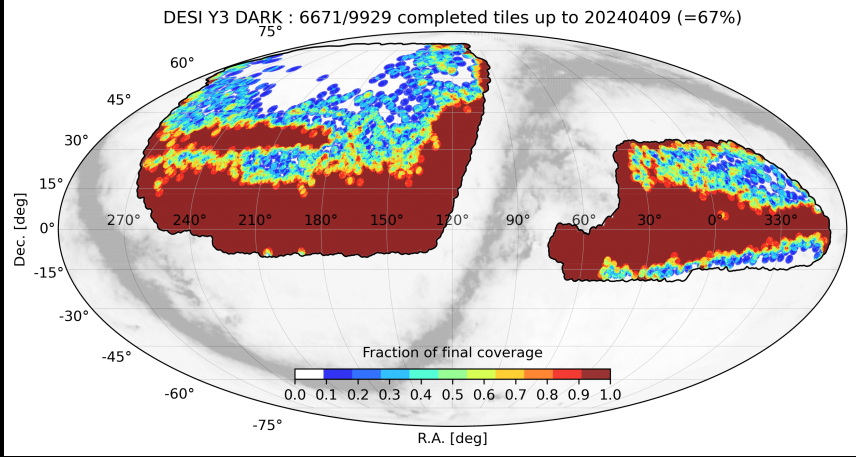
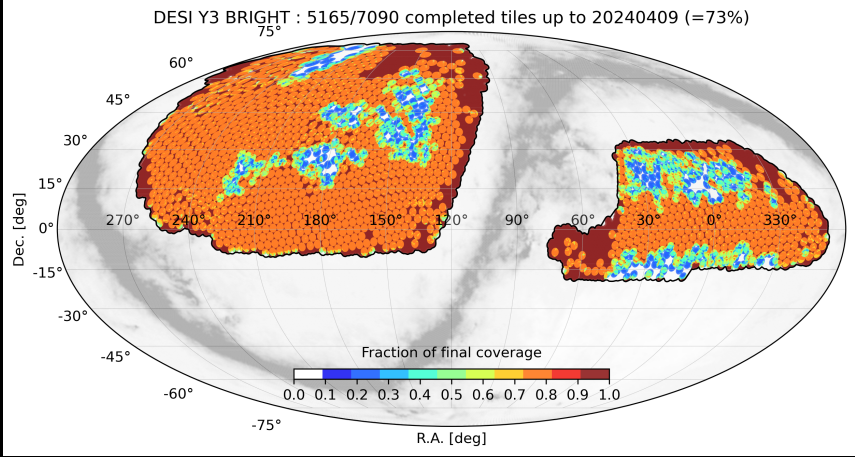
- Started on May, 14th 2021
- Optimized operations, very efficient
(record night: 20211103, 39 dark tiles, ~200k spectra)
- Shutdowns: 2021 (maintenance), 2022 (Contreras fire), 2023.. but still ahead of schedule!



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DESI: Main Survey

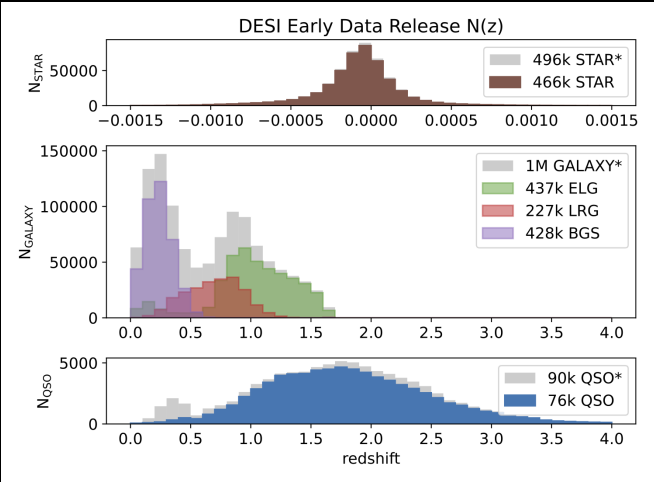
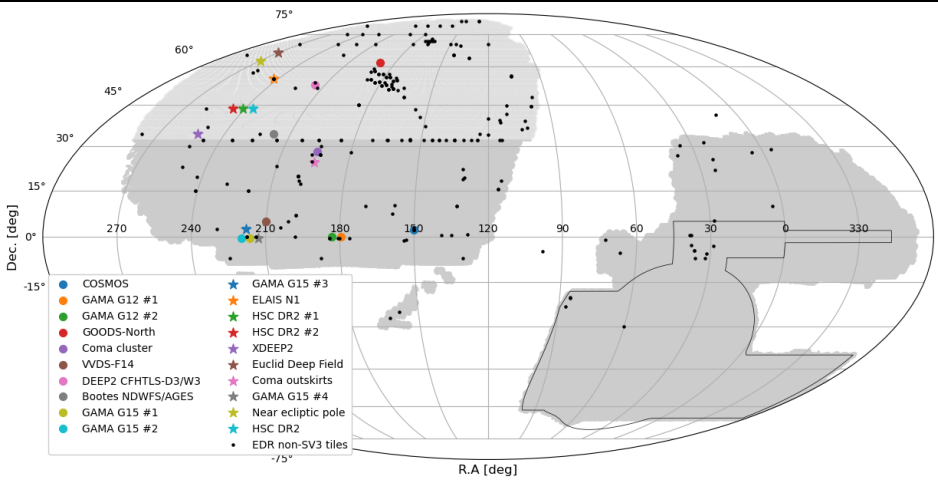
- Started on May, 14th 2021
- Optimized operations, very efficient
(record night: 20211103, 39 dark tiles, ~200k spectra)
- Shutdowns: 2021 (maintenance), 2022 (Contreras fire), 2023.. but still ahead of schedule!
- Y3 coverage



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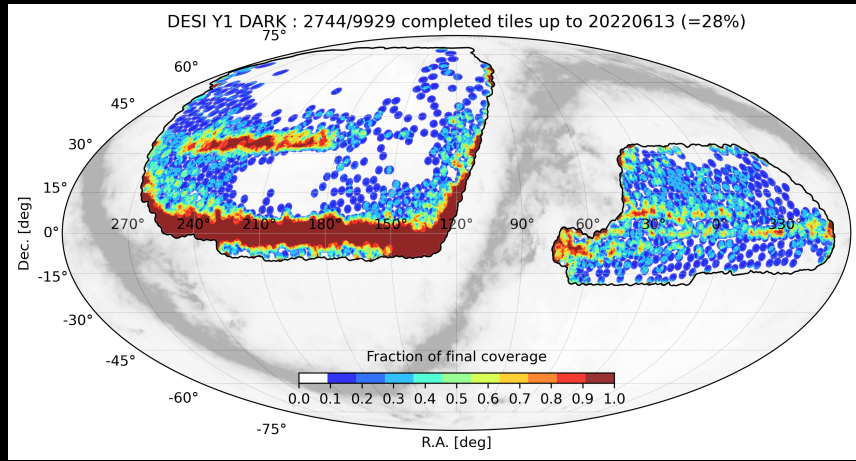
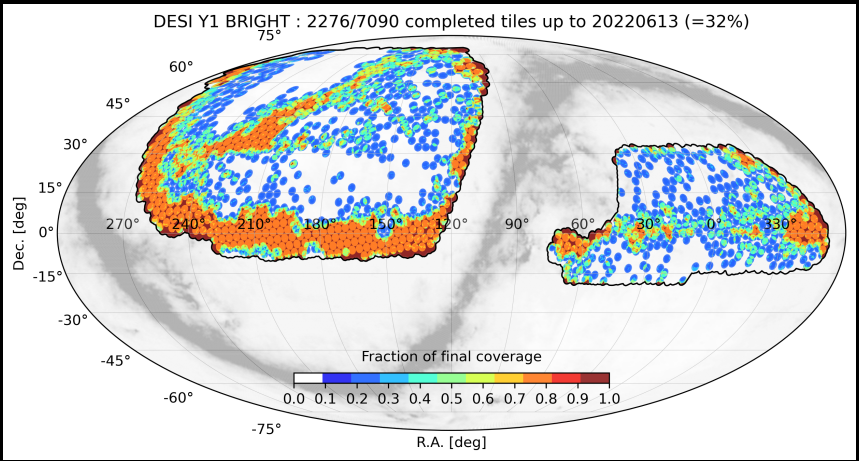
DESI: EDR release

- 2023, May, Survey Validation (SV1) + One percent Survey (SV3)
- Lots more than just redshifts! <https://data.desi.lbl.gov/doc/>
- Various data products:
 - raw data, sky-subtracted flux-calibrated spectra, redshifts measurements (+classification)
 - value added catalogs (more will come after, not tied to the EDR)
 - documentation, datamodel, tutorials
 - papers (overview, data release, spectro. pipeline) + supporting papers (target selection, visual inspection, imaging)



DESI: DR1 sample

- Internal only for now, first 13 months of the Main Survey
- Sample used for the DESI 2024 results released last month

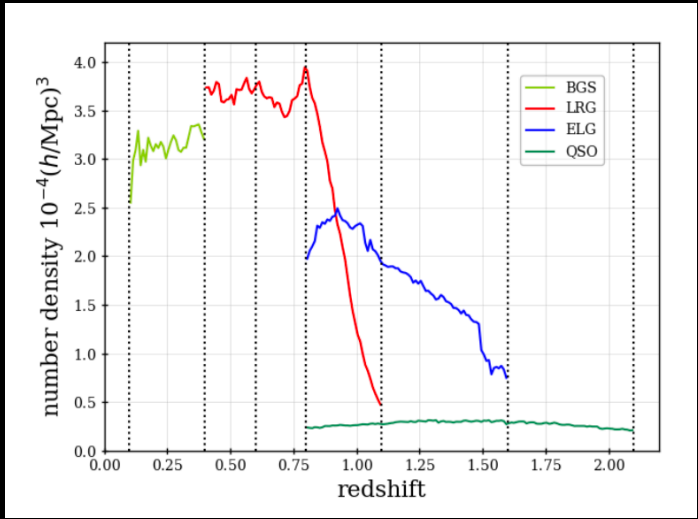


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DESI: DR1 sample

- Internal only for now, first 13 months of the Main Survey
- Sample used for the DESI 2024 results released last month
- 5.7M redshifts used for BAO measurements (x3 SDSS/DR16)

Tracer	redshift range	N_{tracer}	z_{eff}	$P_0(k = 0.14)$	$V_{\text{eff}} (\text{Gpc}^3)$
BGS	0.1 – 0.4	300,017	0.30	$\sim 9.2 \times 10^3$	1.7
LRG1	0.4 – 0.6	506,905	0.51	$\sim 8.9 \times 10^3$	2.6
LRG2	0.6 – 0.8	771,875	0.71	$\sim 8.9 \times 10^3$	4.0
LRG3	0.8 – 1.1	859,824	0.92	$\sim 8.4 \times 10^3$	5.0
ELG1	0.8 – 1.1	1,016,340	0.95	$\sim 2.6 \times 10^3$	2.0
LRG3+ELG1	0.8 – 1.1	1,876,164	0.93	$\sim 5.9 \times 10^3$	6.5
ELG2	1.1 – 1.6	1,415,687	1.32	$\sim 2.9 \times 10^3$	2.7
QSO	0.8 – 2.1	856,652	1.49	$\sim 5.0 \times 10^3$	1.5



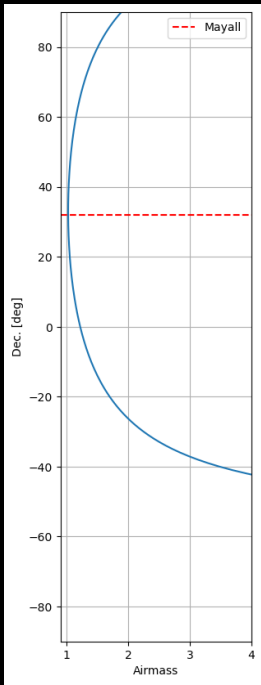
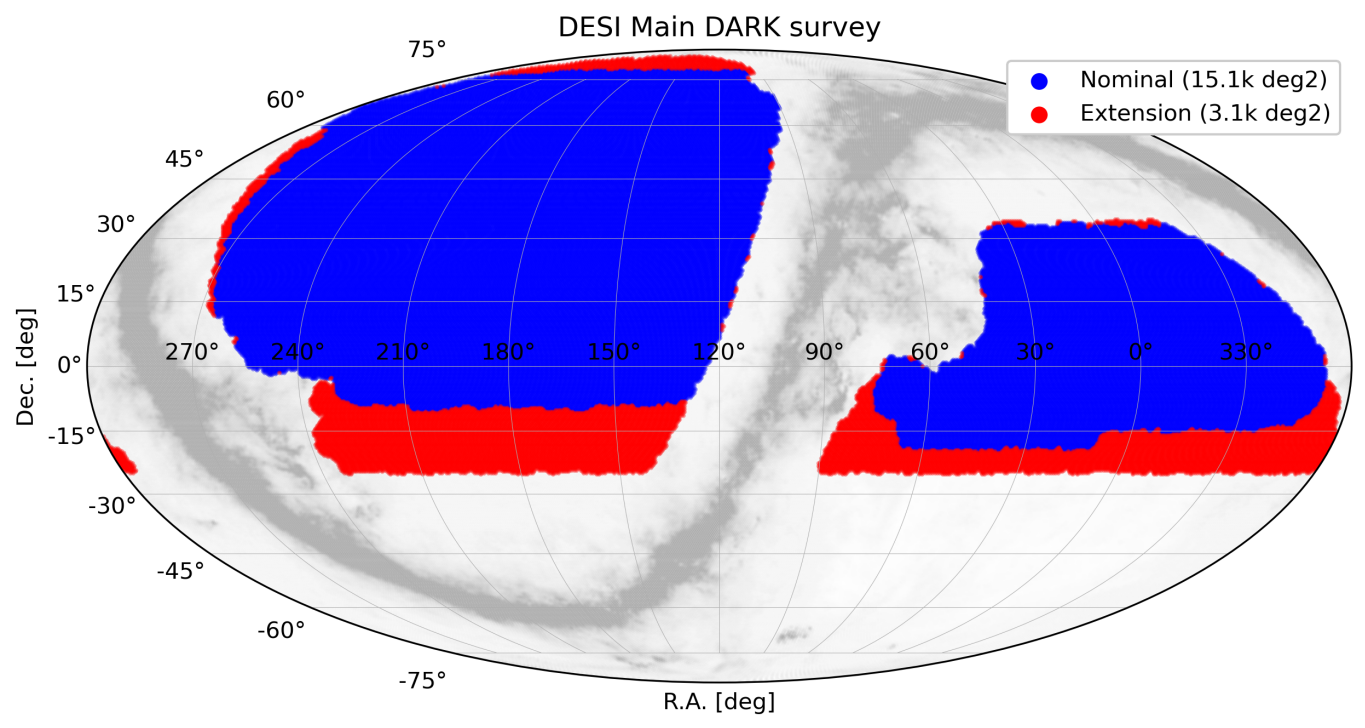
DESI+24



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DESI: possible extension

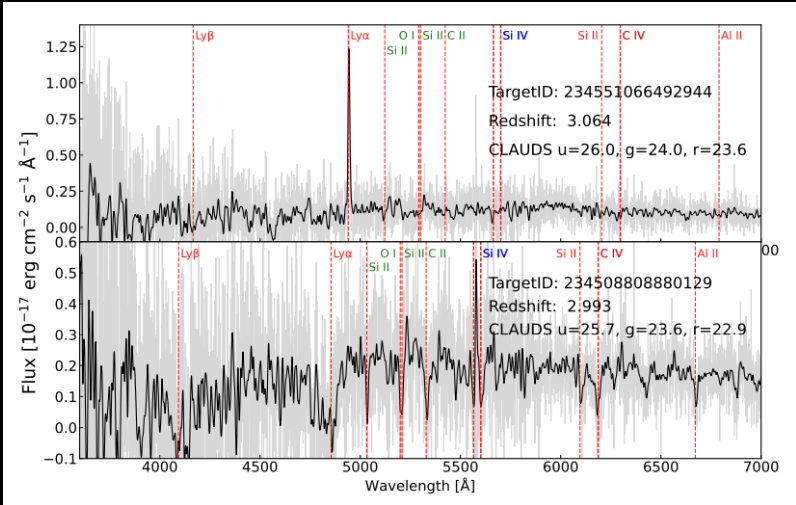
- Main Survey observations ahead of schedule, DR1 results very encouraging
- Request to extend the survey:
 - add two more passes, with new, additional LRG targets
 - extend the footprint South (will use Legacy Surveys DR11)



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DESI-2

- Principle:
 - No major instruments upgrade
 - Core program: probe the $2 < z < 4.5$ Universe with LAEs (Lyman Alpha Emitters) and LBGs (Lyman Break Galaxies)
- Several pilot observations done with DESI since Survey Validation:
 - Test various target selections (from broad-band, medium-band, narrow-band photometry)
 - Very successful, DESI can get redshifts for LAEs/LBGs in a reasonable amount of time
 - Results from LBG selected with broad-band photometry in Ruhlmann-Kleider+24



Ruhlmann-Kleider+24



Conclusions

- DESI:
 - Decade-long efforts now fruitful
 - EDR data public since one year
 - State-of-the-art results with DR1 data, which already has 3x more redshifts than SDSS/DR16
 - Y3 sample data in the can
- Futures:
 - DESI is ahead of schedule
 - Requested extension (denser coverage, more footprint)
 - DESI-2: probing the $2 < z < 4.5$ Universe, pilot studies promising!

