The Dark Energy Spectroscopic Instrument (DESI): the survey begins

Julien Guy, LBNL
on behalf of the DESI Collaboration

RPM June 3rd, 2021

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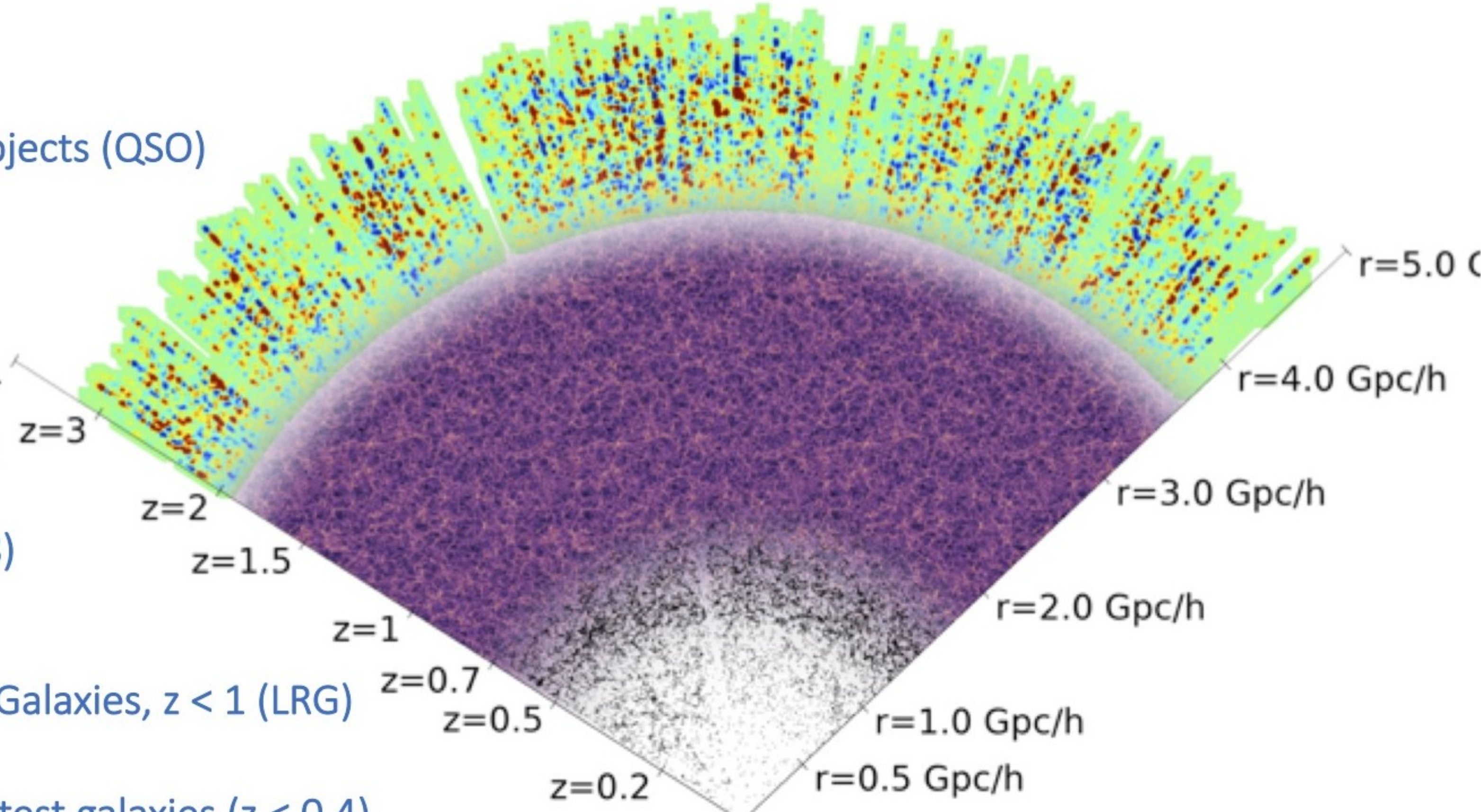
DESI ~~will create~~ a 3D Map of the Universe is creating

2.7 million
Quasi Stellar Objects (QSO)

13 million ELGs
(Emission Line Galaxies, z < 1.8)

7.5 million LRGs
(Luminous Red Galaxies, z < 1 (LRG)

9 million brightest galaxies (z < 0.4)



(numbers based on densities obtained during Survey Validation, assuming a 14,000 deg2 survey)

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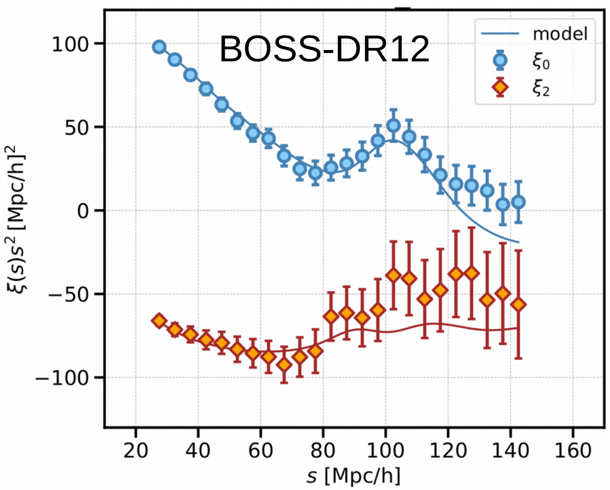
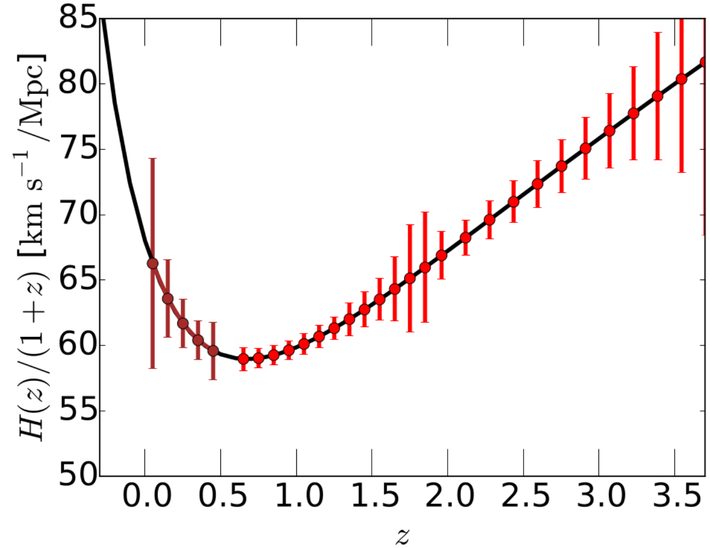
DESI main science goals

Baryon Acoustic Oscillations

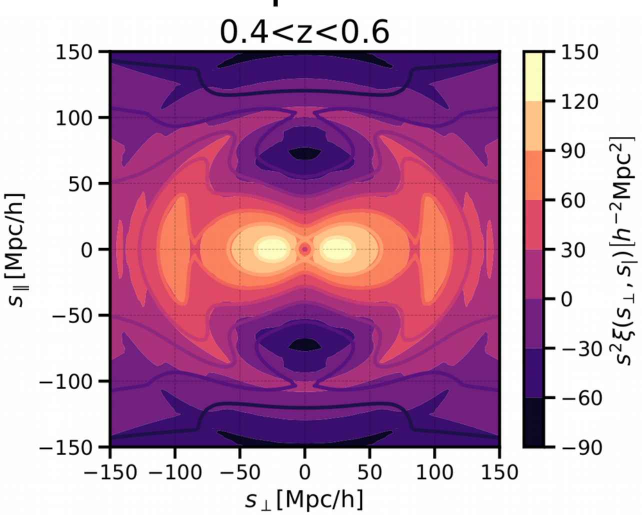


BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)

Expansion history

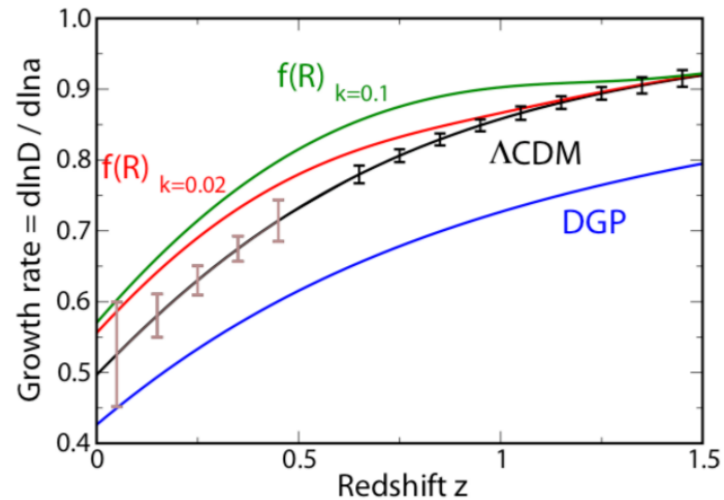


Redshift Space Distortions



BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)

Growth rate of structure



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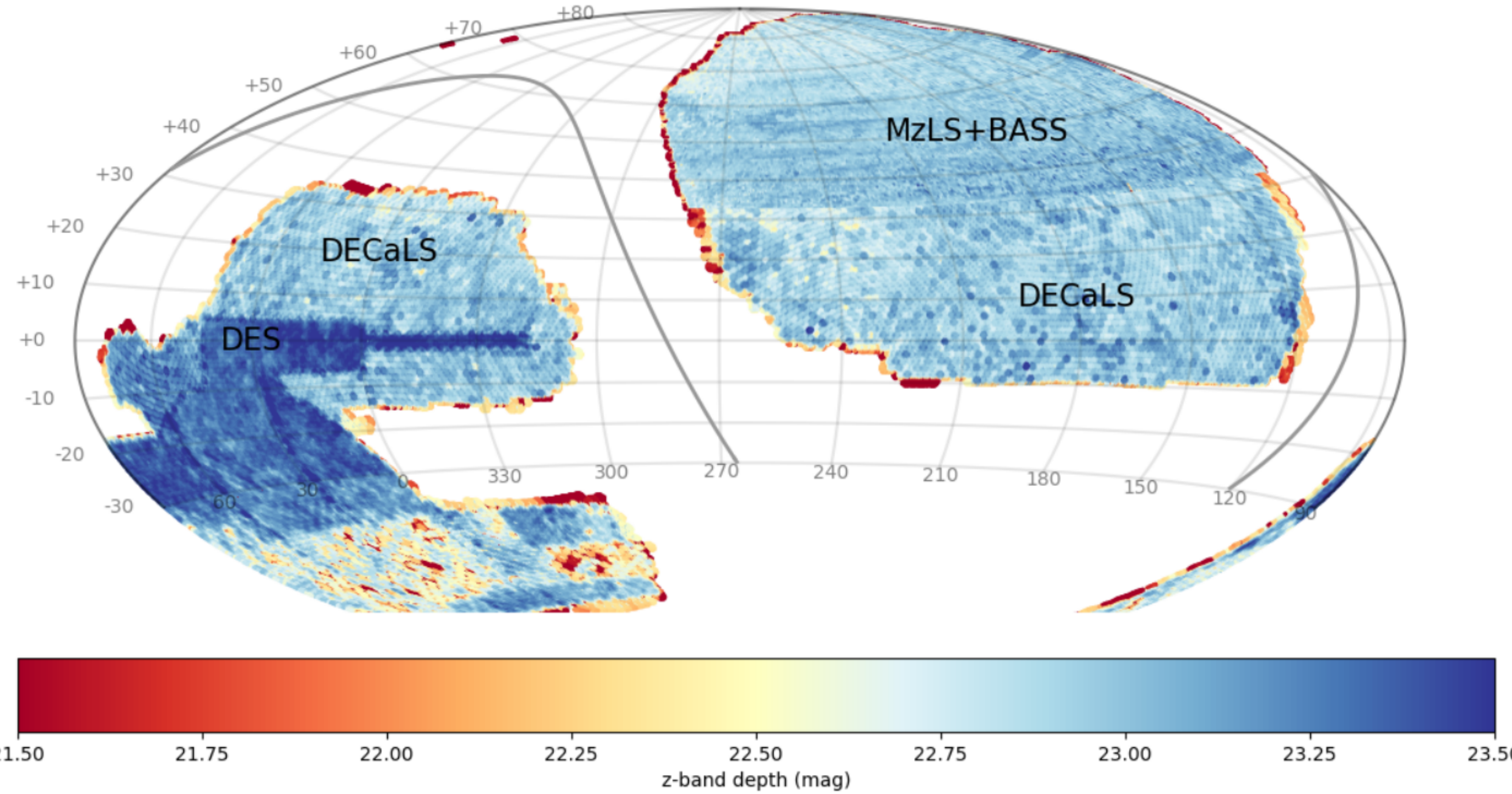
It starts with an imaging survey

https://www.legacysurvey.org/dr9/description/



16k deg.^{2} of grz &W1/2 imaging, Dey ++ (2019). Including public DES images (all) with new Tractor max. likelihood source fitting (Lang ++). 1st lensing by Blazek++.

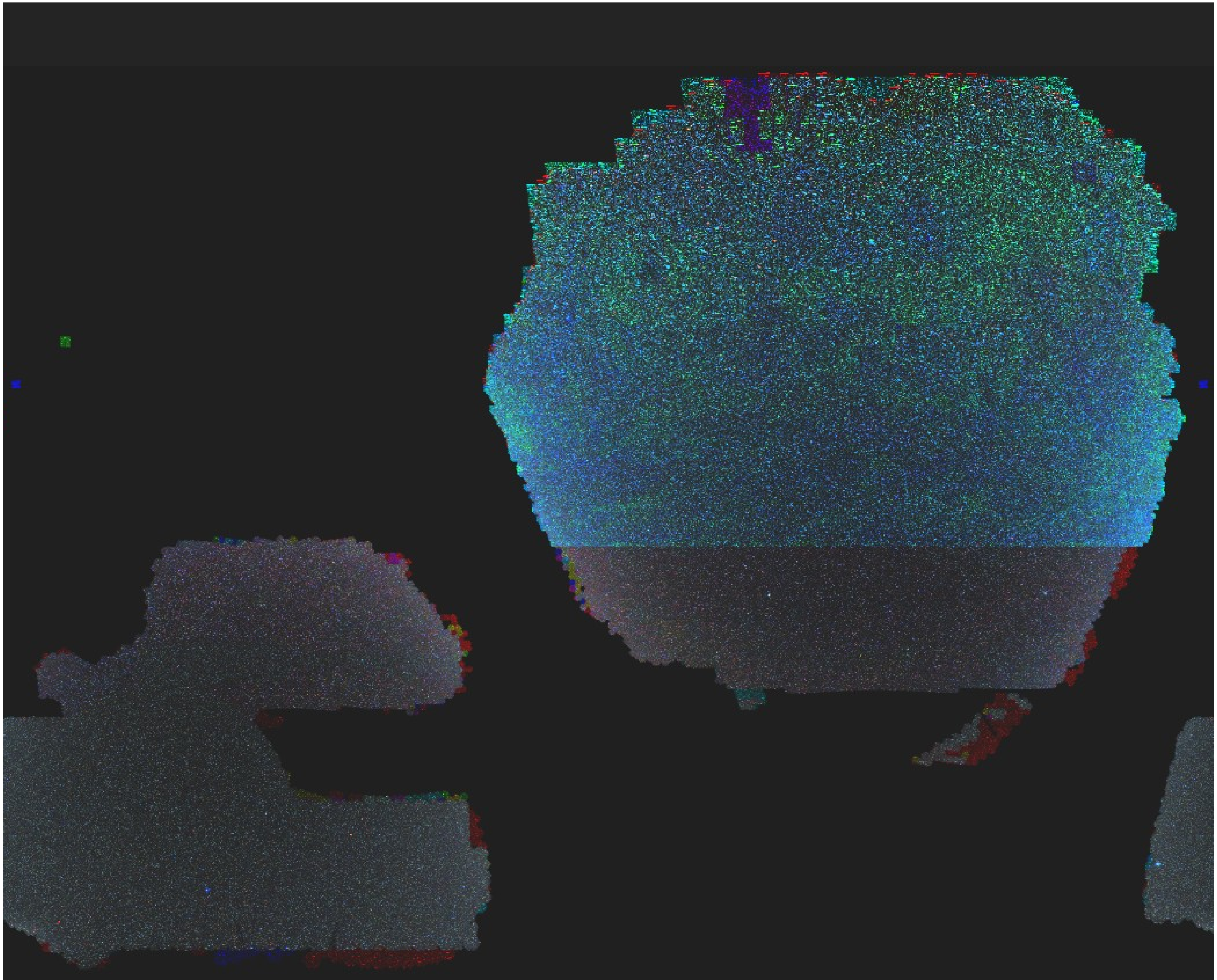
legacysurvey.org/viewer

Survey Name	Single-Frame Depths[1] PSF Depth[2] g	r	z	Galaxy Depth[3] g	r	z	PSF FWHM ["] g	r	z
DECaLS[5]	23.95	23.54	22.50	23.72	23.27	22.22	1.29	1.18	1.11
BASS[6]	23.65	23.08		23.48	22.87		1.61	1.47	
MzLS[7]			22.60			22.29			1.01

(slide from Mike Wilson)

Legacy Survey Data Release 9

https://www.legacysurvey.org/dr9/description/



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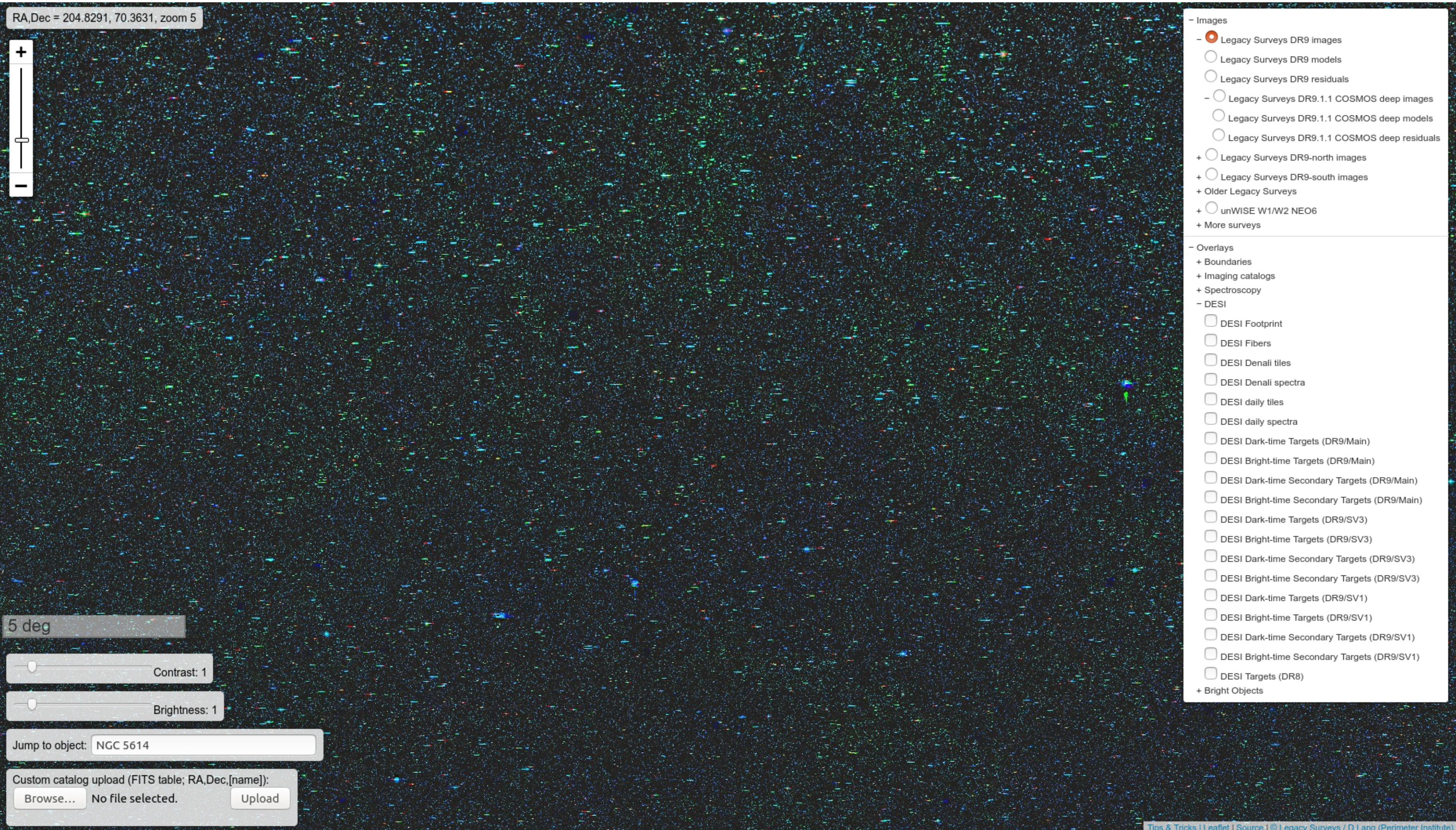
Legacy Survey Data Release 9

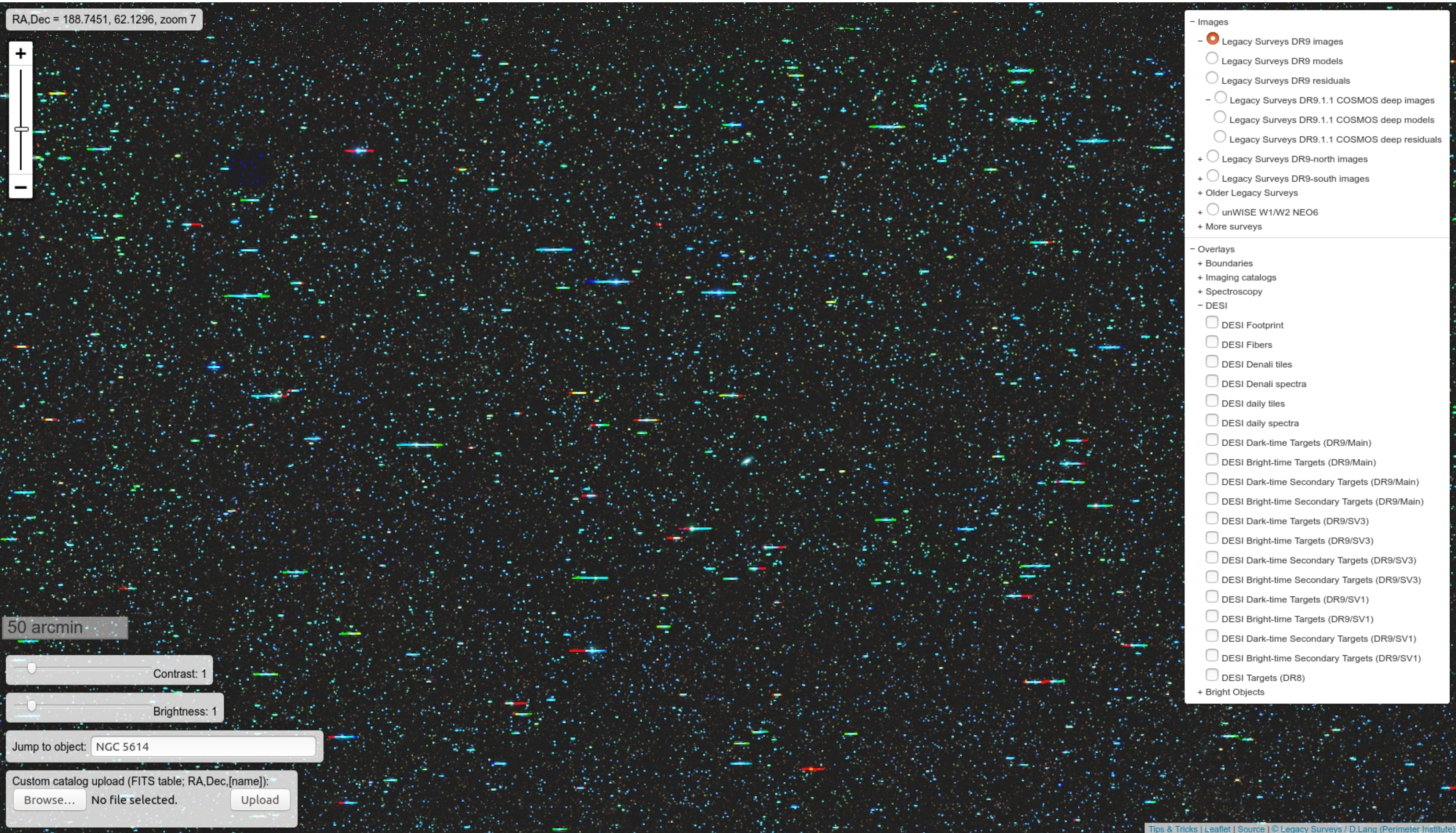
Released in January 2021

Final imaging catalog for DESI targets



Legacy Survey Data Release 9

Released in January 2021
Final imaging catalog for DESI targets



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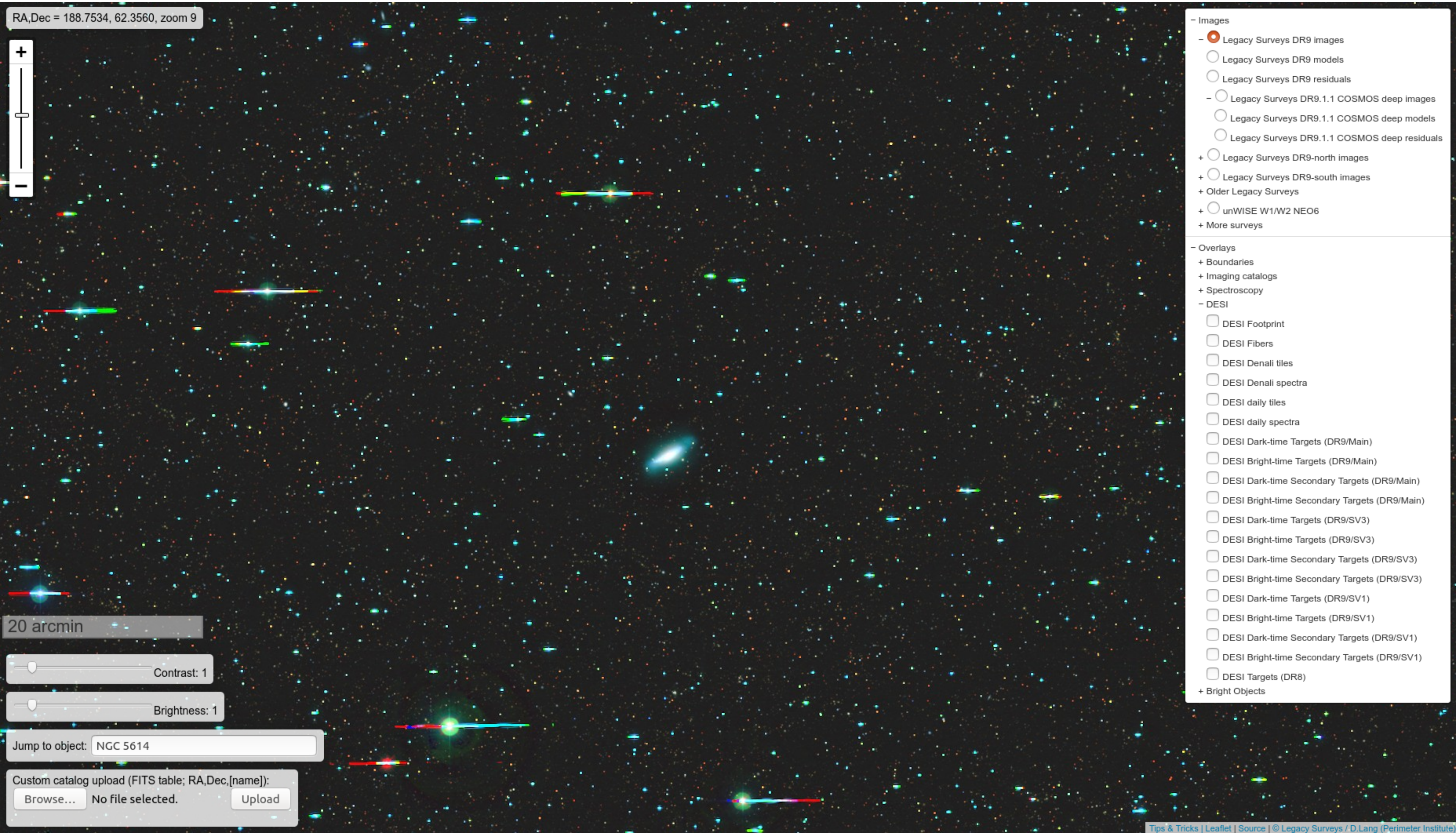

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DESI spectra from Survey Validation

red: star white: galaxy blue: QSO

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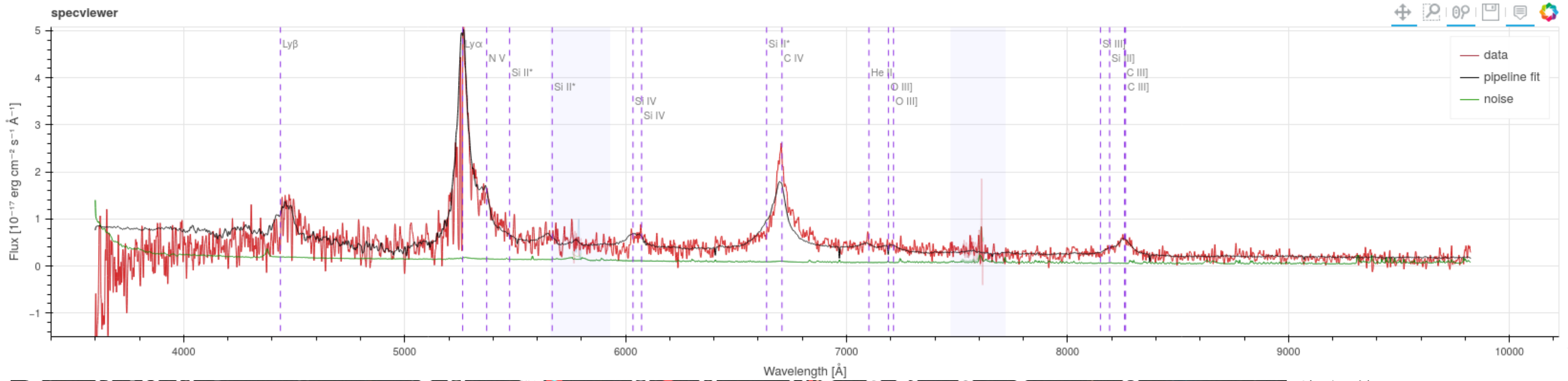
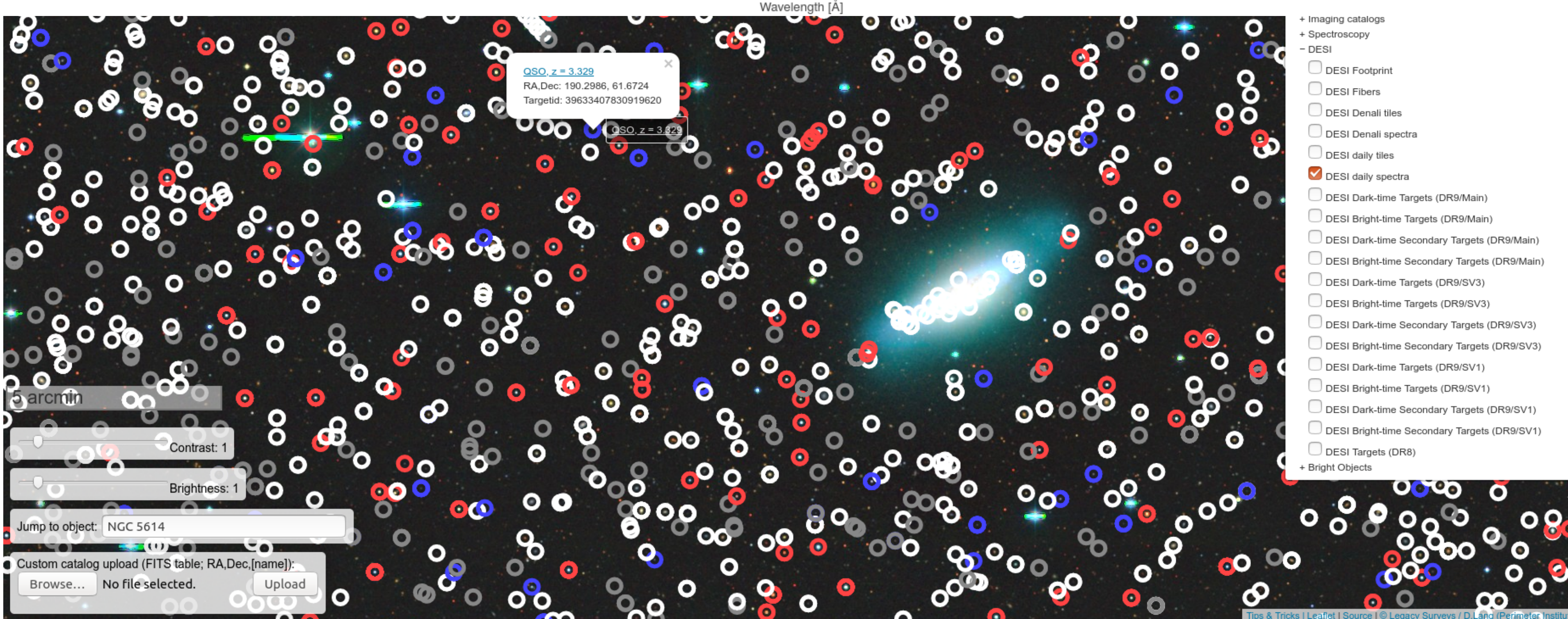
DESI spectra from Survey Validation





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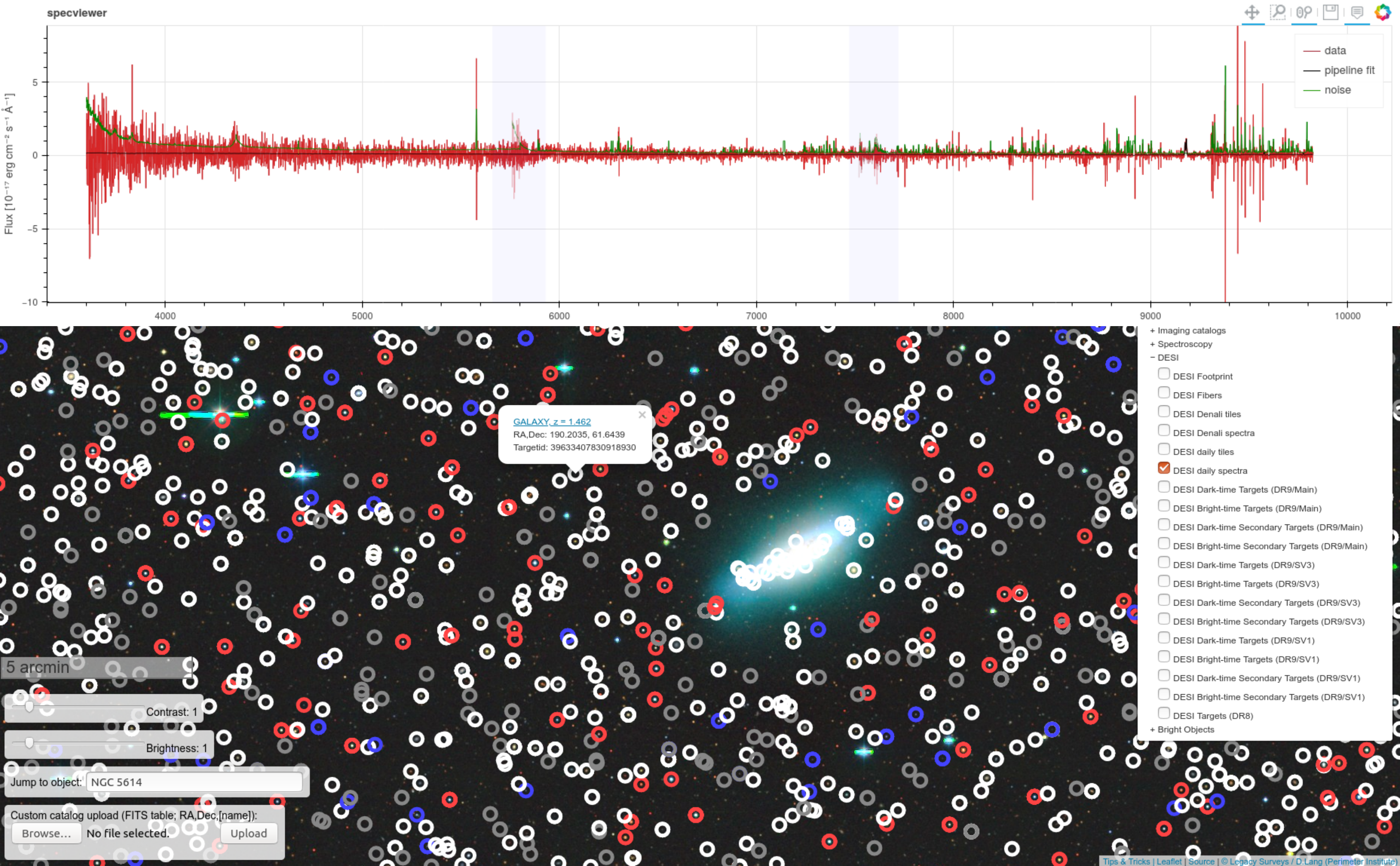
DESI spectra from Survey Validation



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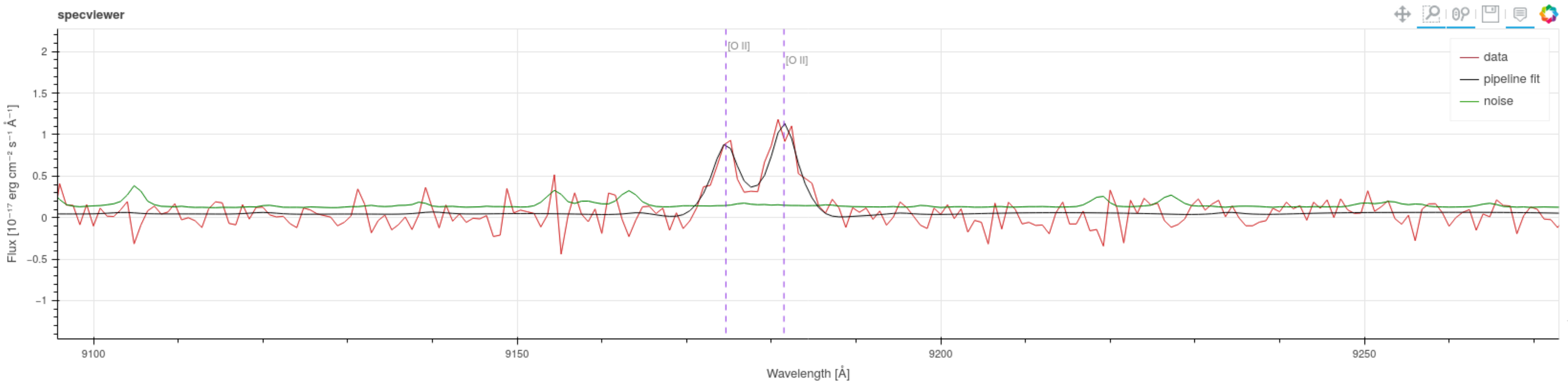
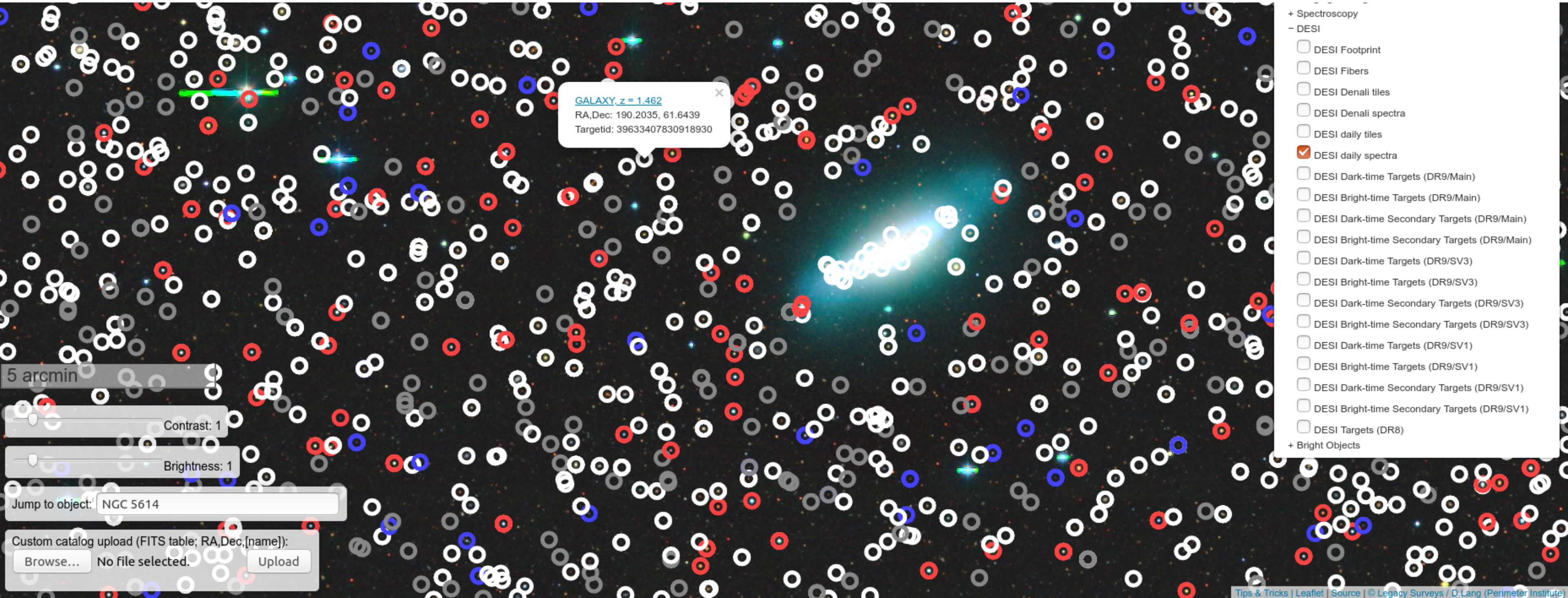
DESI spectra from Survey Validation





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DESI spectra from Survey Validation

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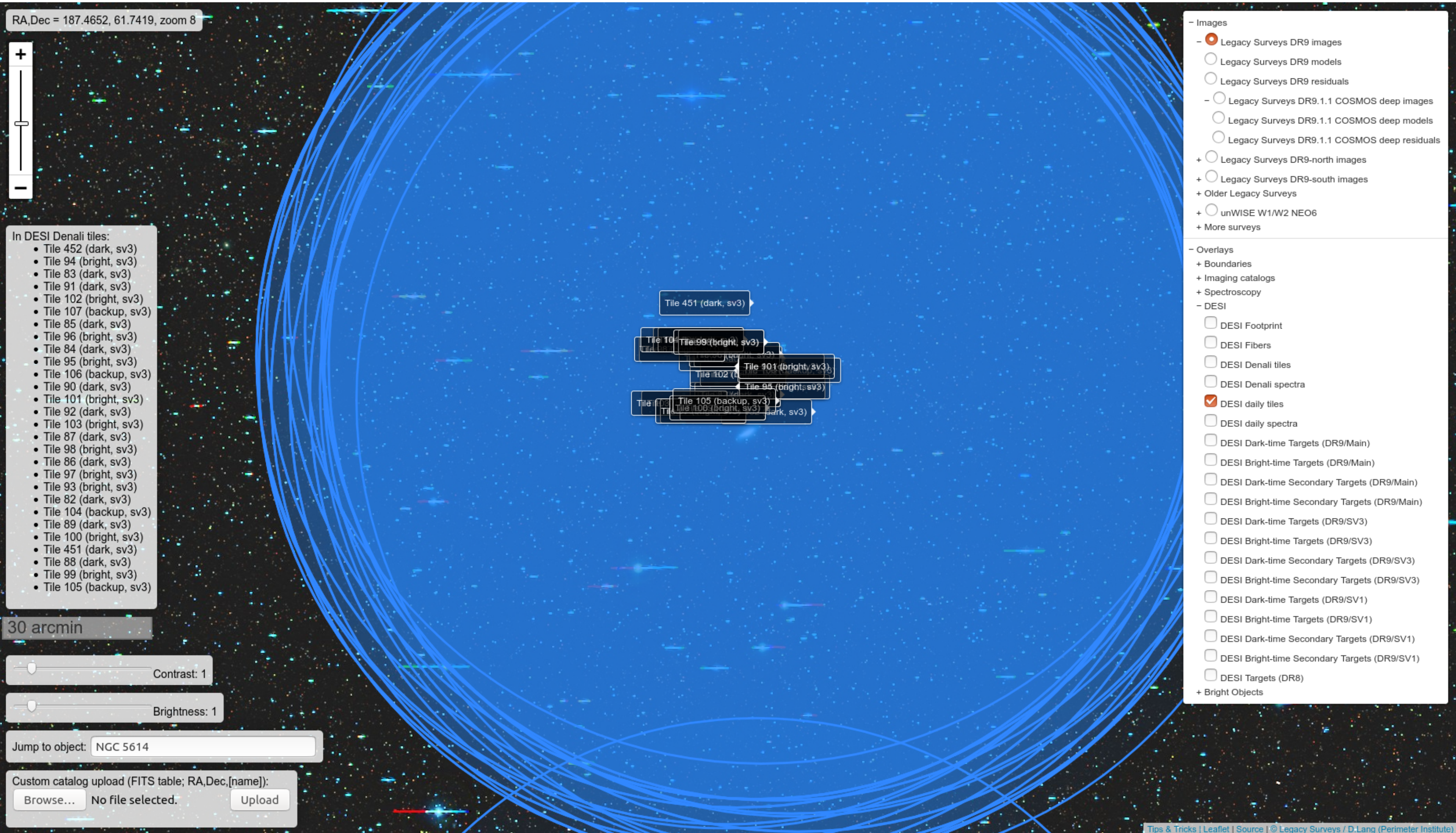
DESI spectra from Survey Validation

One SV3 field : rosette dithering pattern
(full completness on few selected fields)



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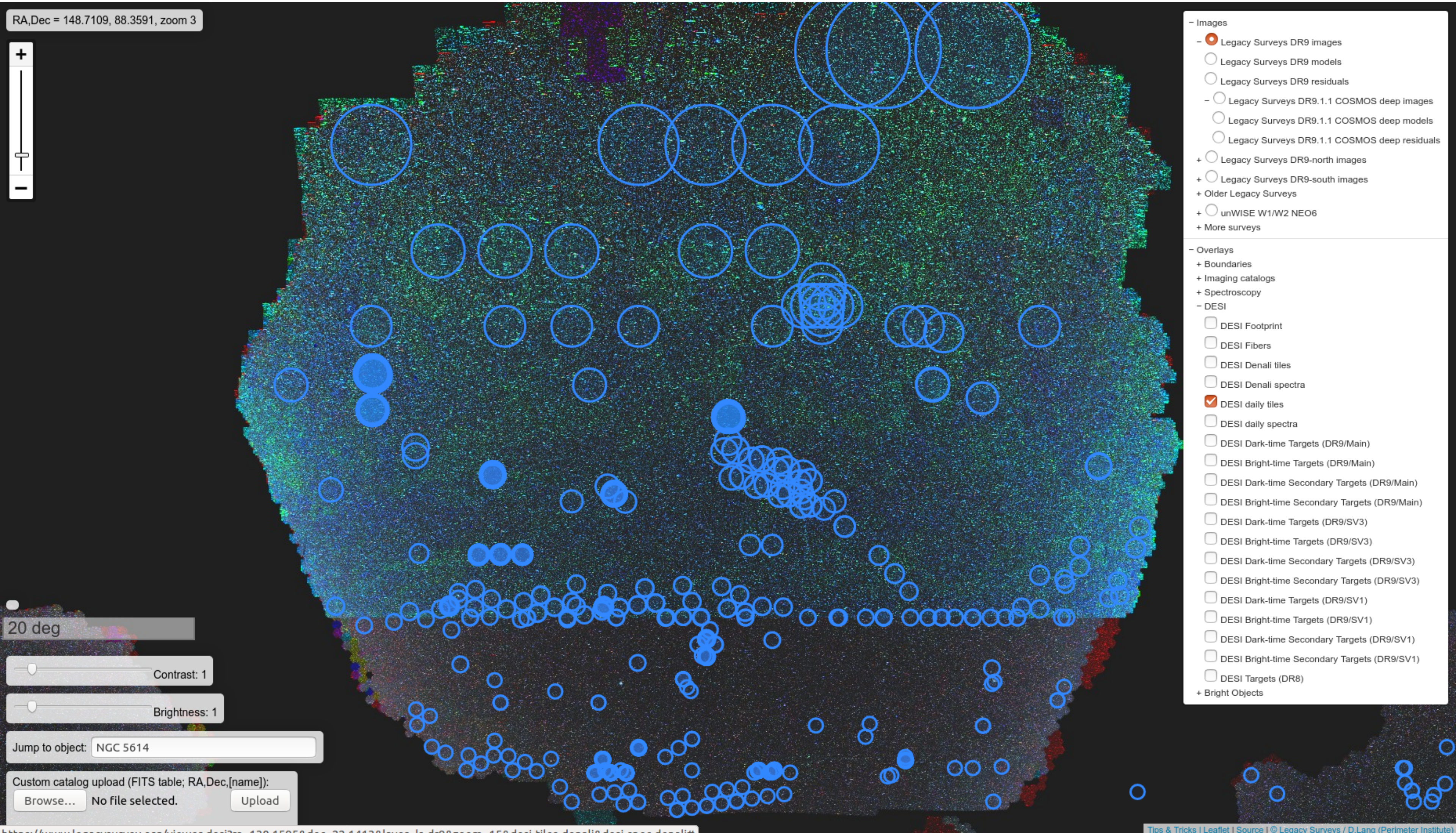
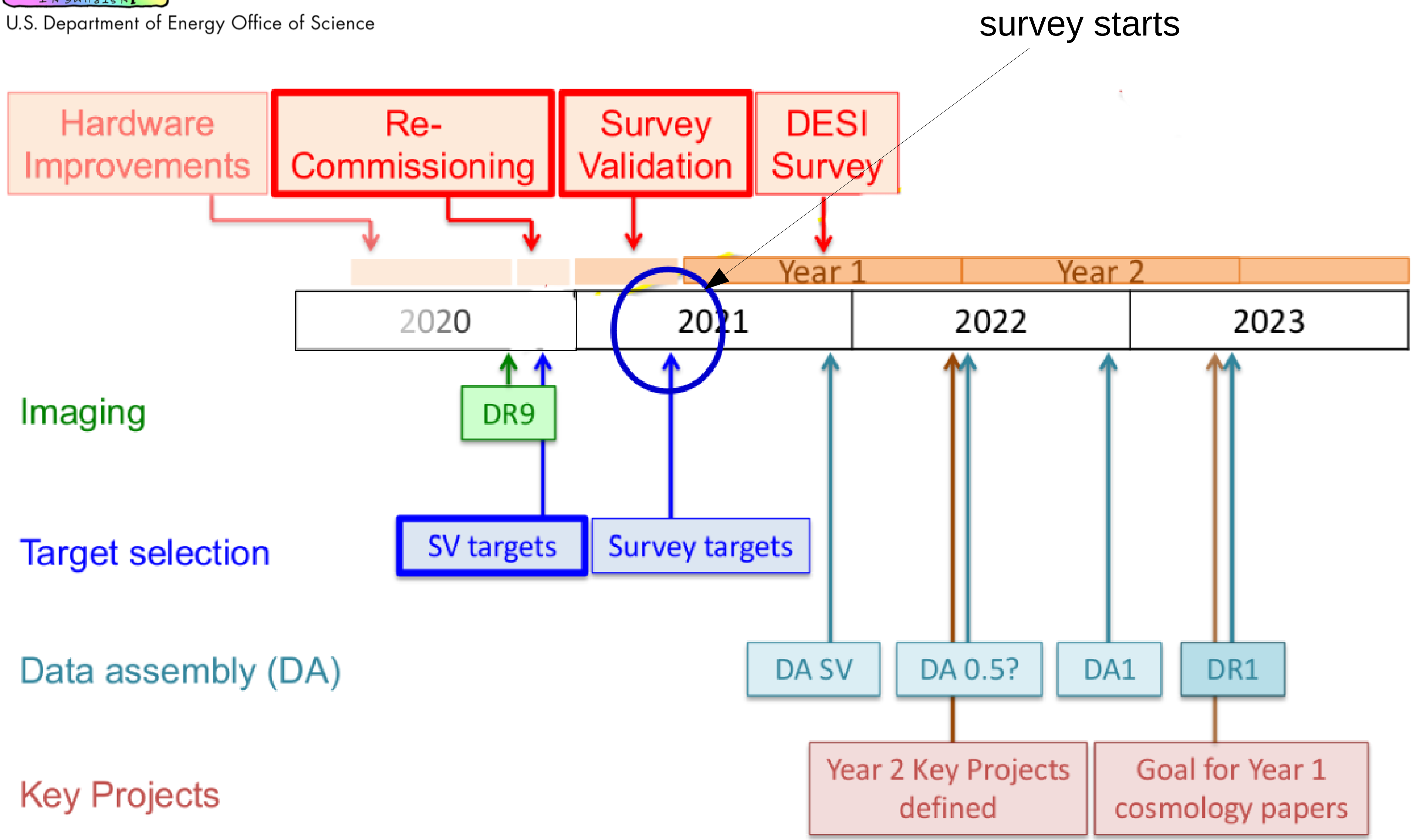
Tiles already observed (as of May 28, 2021) in northern galactic cap



DESI timeline



Checklist for starting the survey

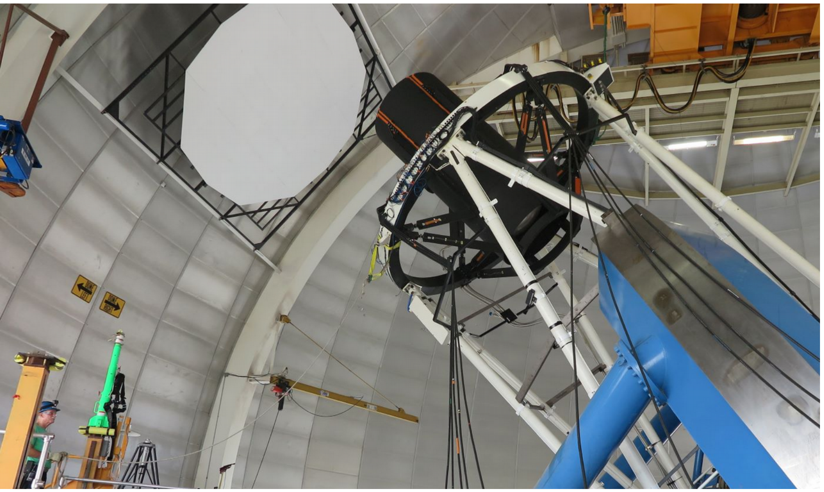
- instrument performance (selection)
    (corrector optics, focal plane, spectrographs, throughput)

- instrument control system and observation performance
    (pointing , guiding , auto-focus , rotation compensation , positioning loop,
    inter-exposure time, exposure time calculator online QA)

- spectroscopic pipeline
    (requirements on efficiency, purity, precision, run time,
    feedback to operations)

- survey validation
    - validation of targeting methods : target densities
    - first science analysis : halo occupation distributions,
      lyman-alpha early studies

DESI instrument overview



Focal plane assembly with 5000 fiber positioners

Calibration Lamp System

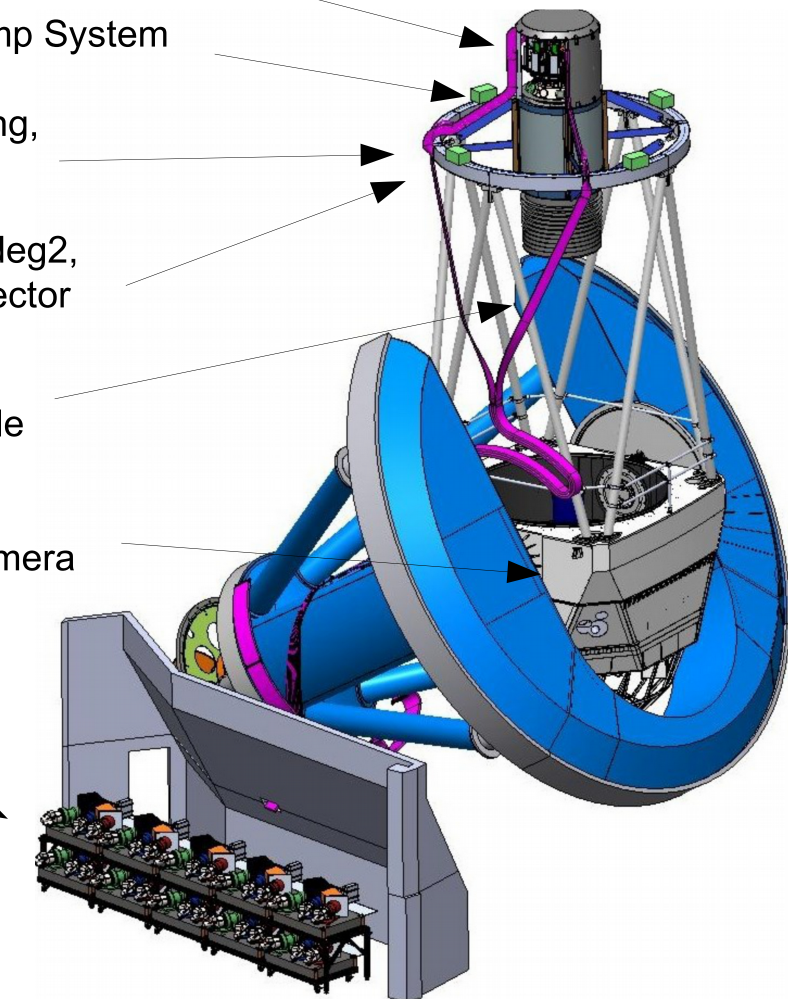
New Upper Ring, Vanes, Cage

New 6-lens 8 deg2, wide field corrector in hexapod

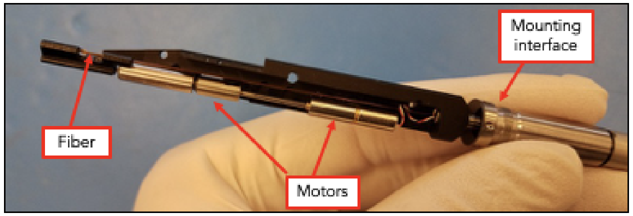
47.5m, 10-cable fiber run

Fiber View Camera

Ten, thermally-controlled 30channel spectrographs 360-980nm



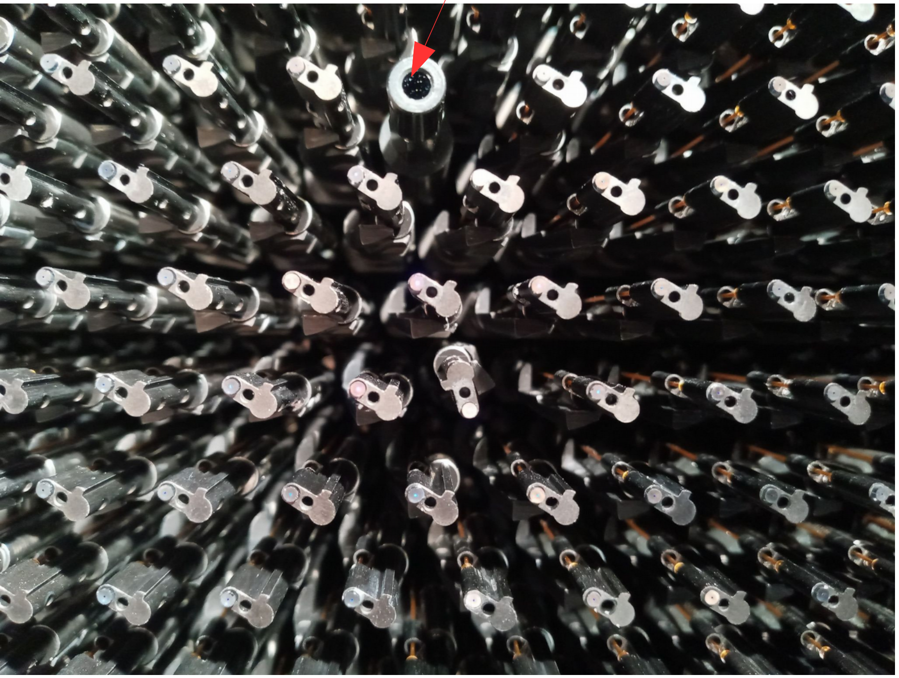
DESI focal plane



5000 positioners
- Two 3-mm long arms
- Pitch 10.4 mm
- Patrol radius 12 mm

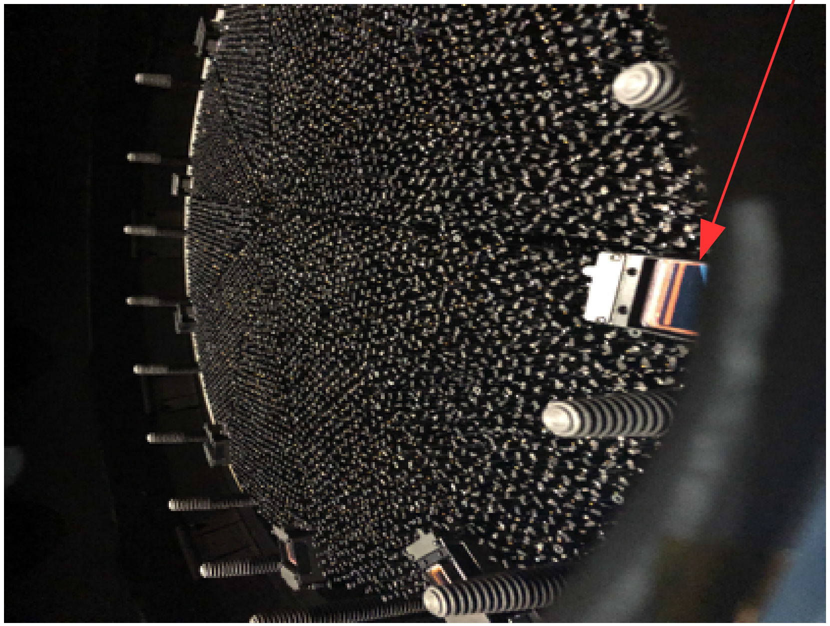
in 10 petals

one fiducial



view of the installed focal plane

one GFA



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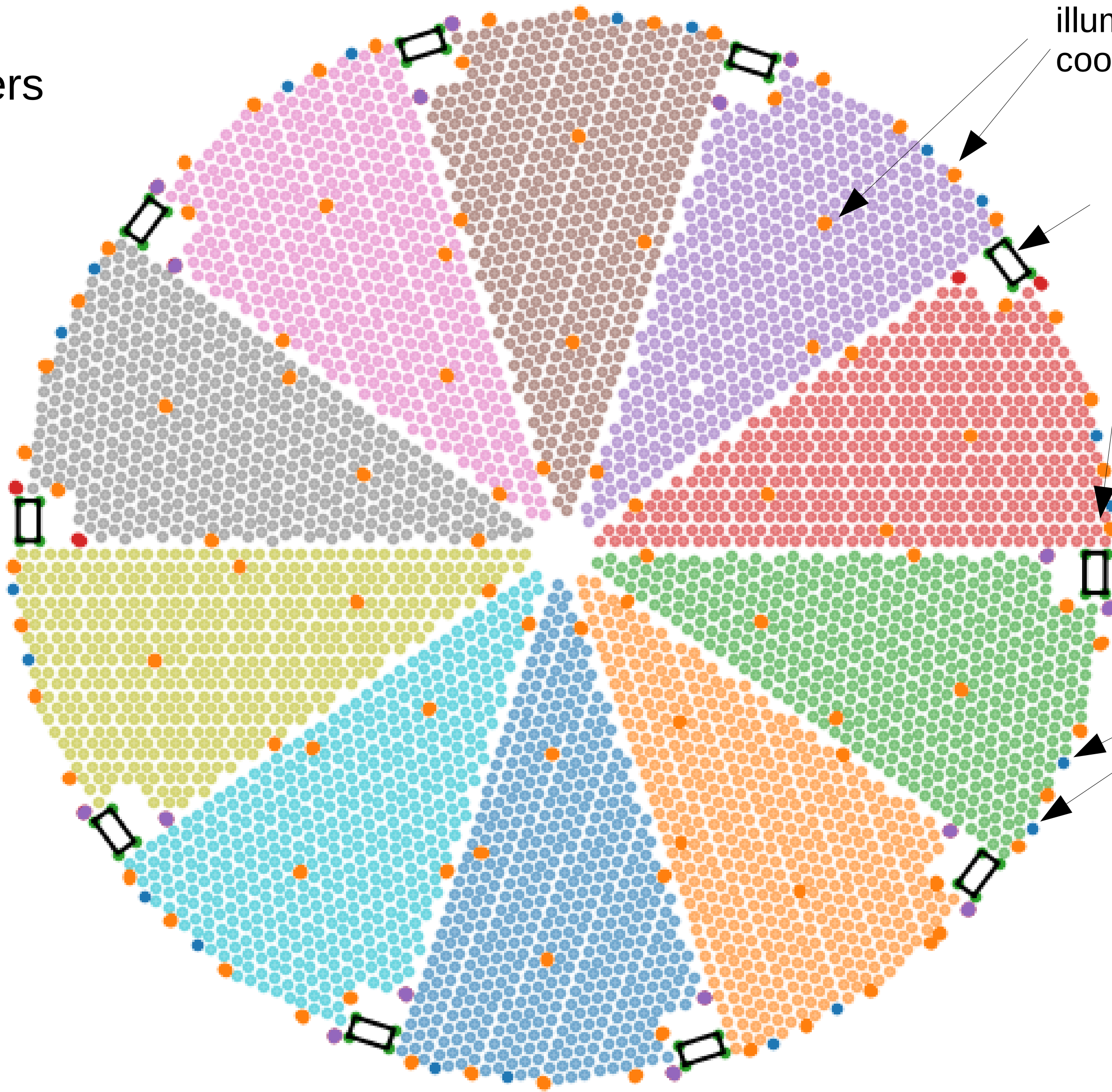
DESI focal plane

5000 positioners
10 petals



120 fiducials (with 4 illuminated pinholes) for coordinates

10 GFAs
CCDs for guiding and auto-focus

20 fibers to monitor the sky level in real-time

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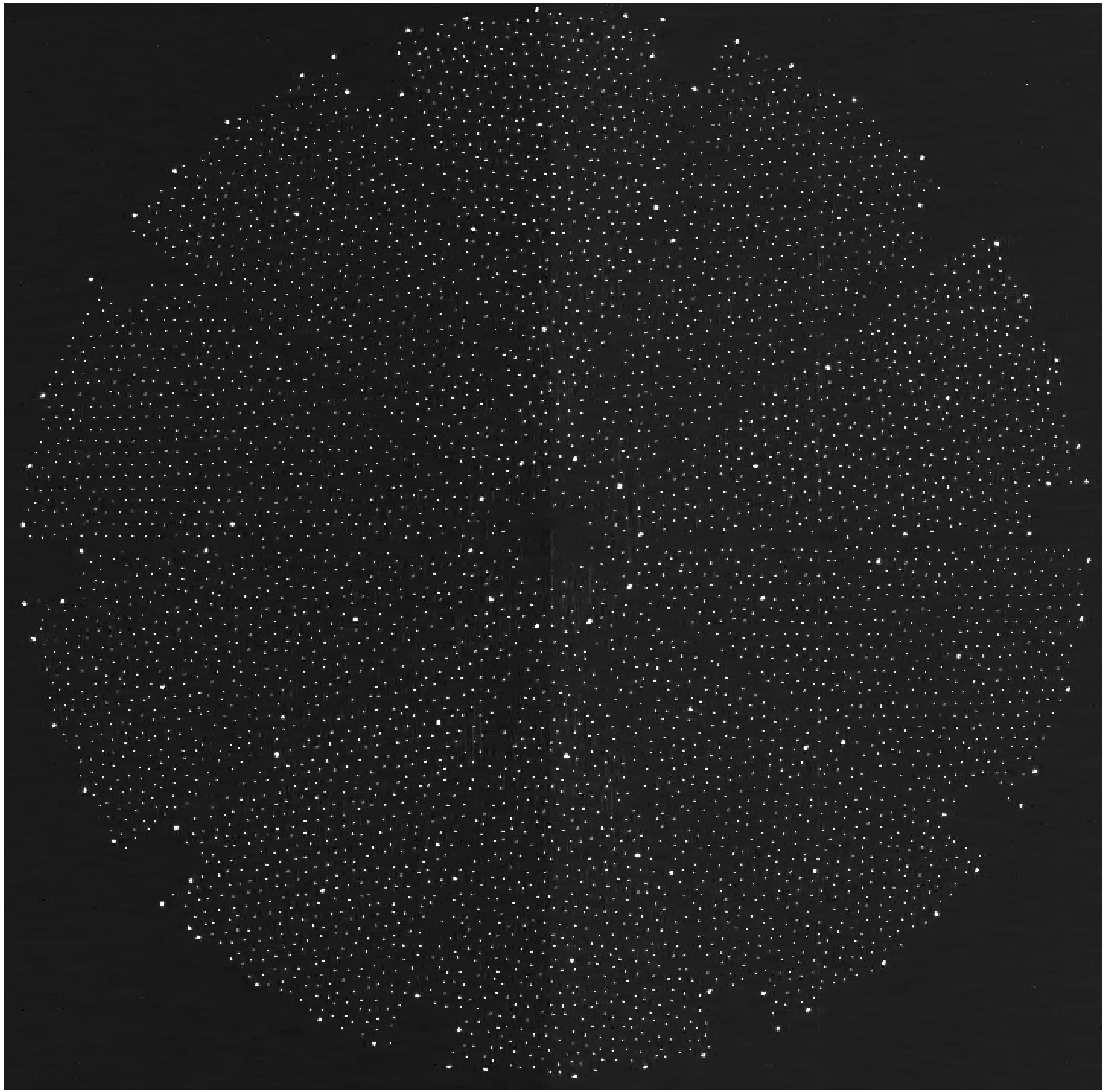
Fiber view camera image
back-illuminated focal plane



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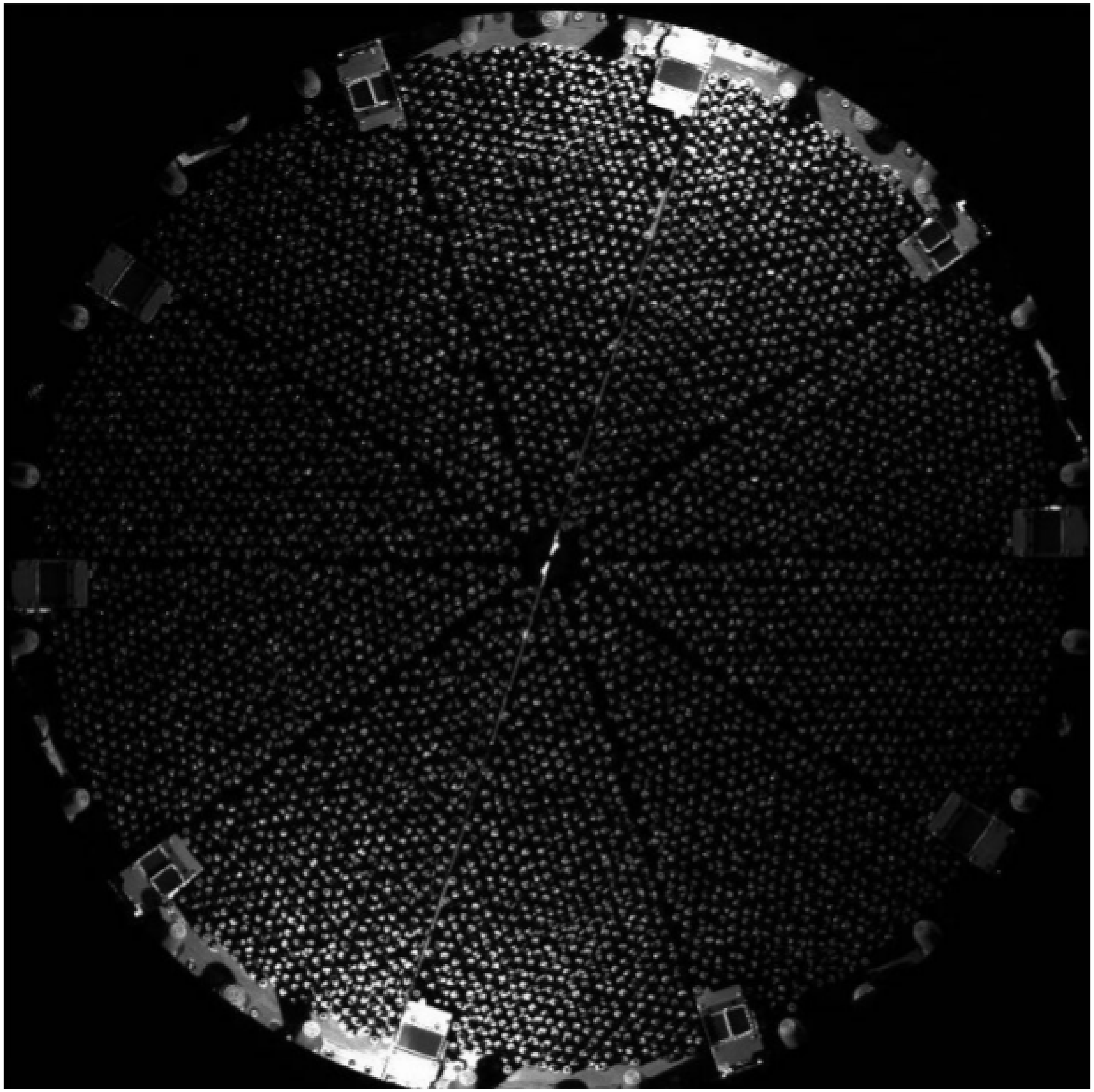
Fiber view camera image
front-illuminated focal plane



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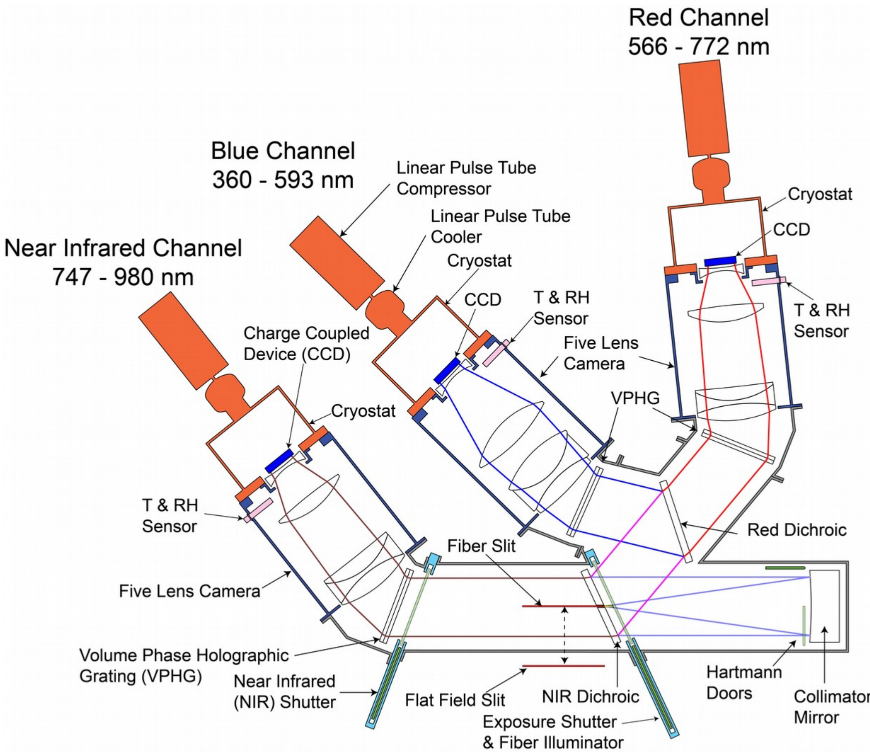
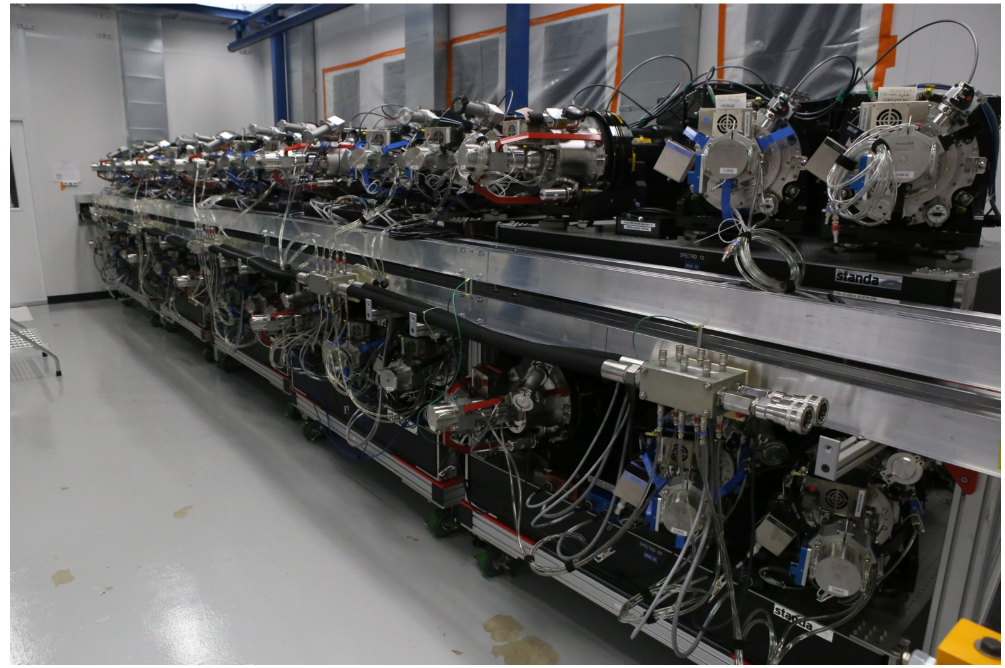
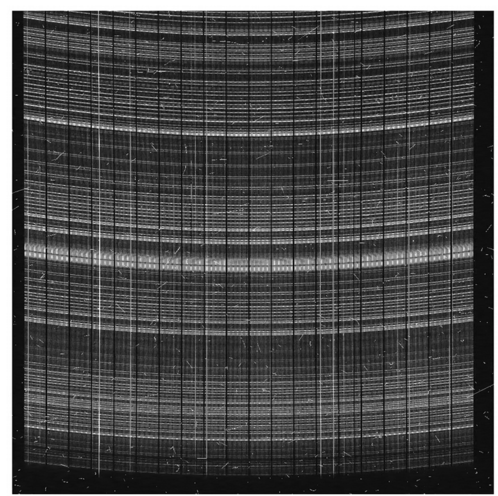
DESI spectrographs



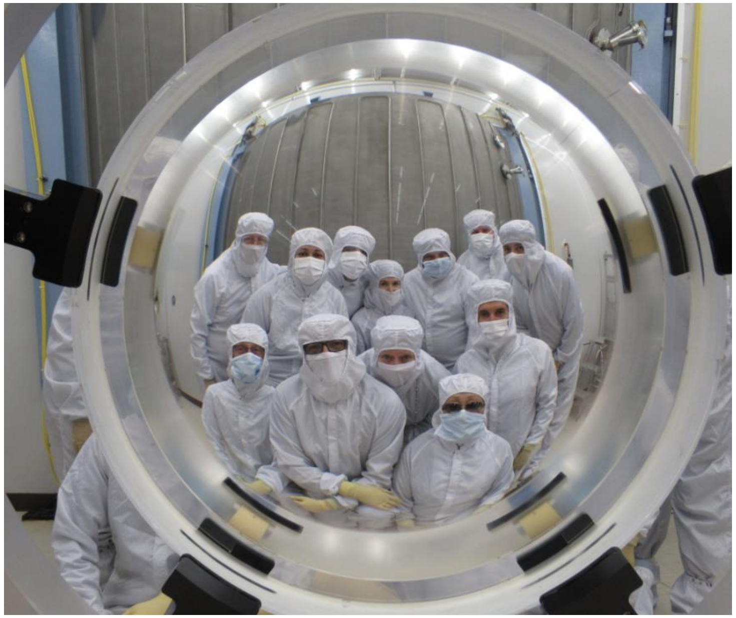


10 spectrographs
- 3 arms : BLUE (ITL CCD)
  RED-NIR (LBNL 250 microns CCD)
- 360-980 nm
- Volume Phase Holographic Gratings
- Resolution adapted to resolve [0II] doublet



Checklist for starting the survey

- instrument performance (selection)
  - corrector optics : seeing
  - focal plane : fiber positioning accuracy
  - spectrographs : optics stability
  - system : throughput



Corrector optics focal plane enclosure performance

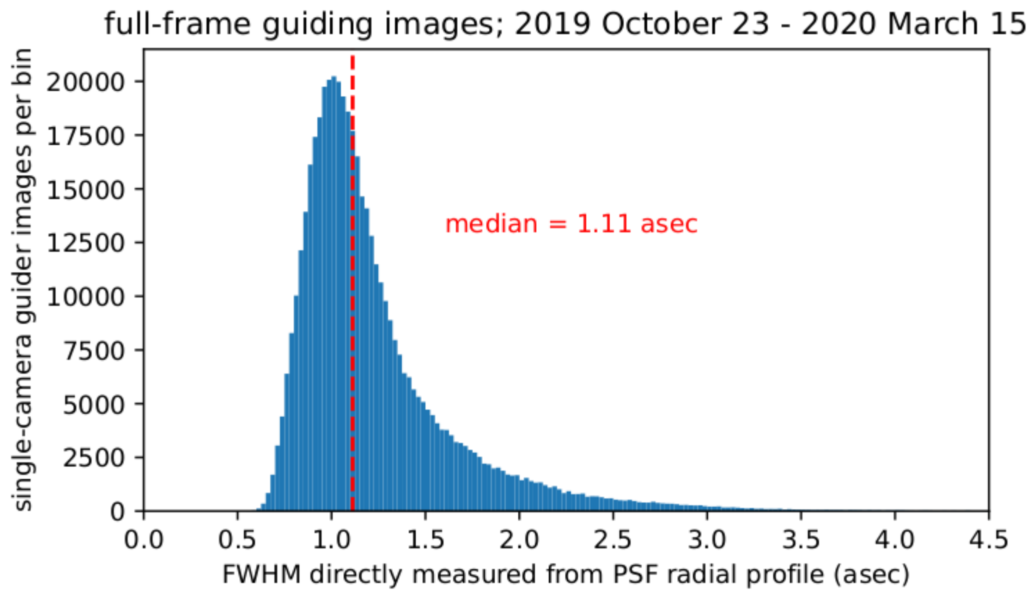
Point Spread Function (PSF) in the Mayall focal plane measured with the guide CCDs.

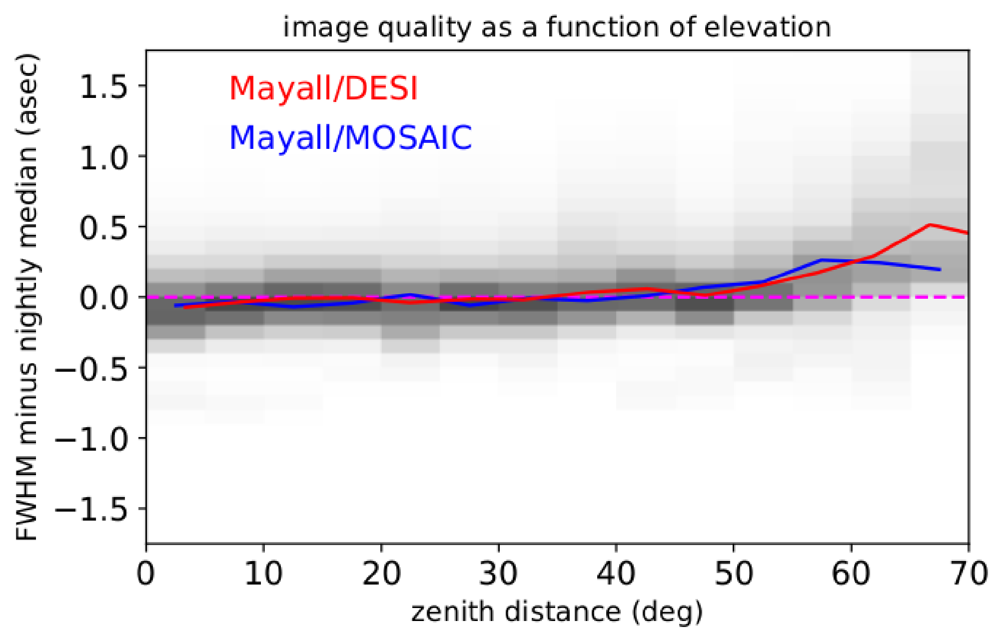
FWHM ~1.1 arcsec consistent with past data (measured with previous instrument on the Mayall)

The focal plane instrument does not introduce extra air turbulence in the dome

(thanks to the thermal isolation and heat exchanger system)

Aaron Meisner, SPIE 2020



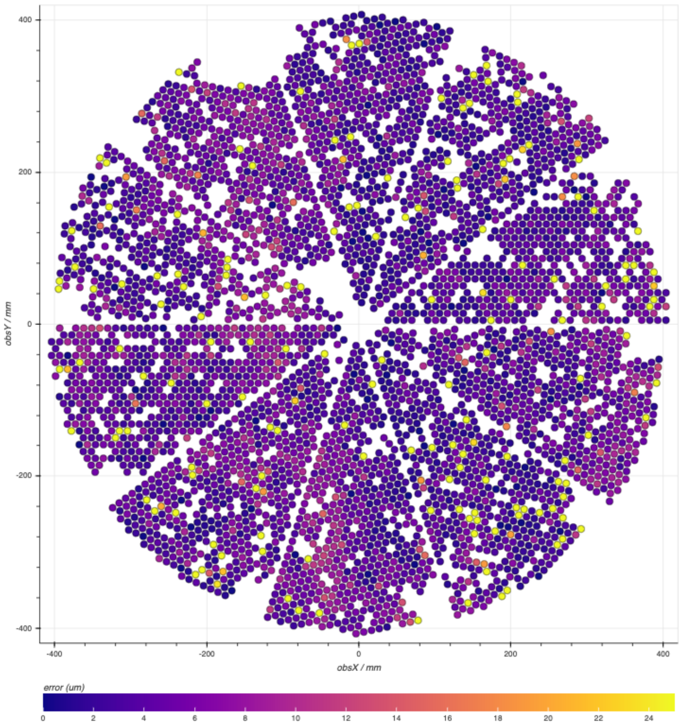


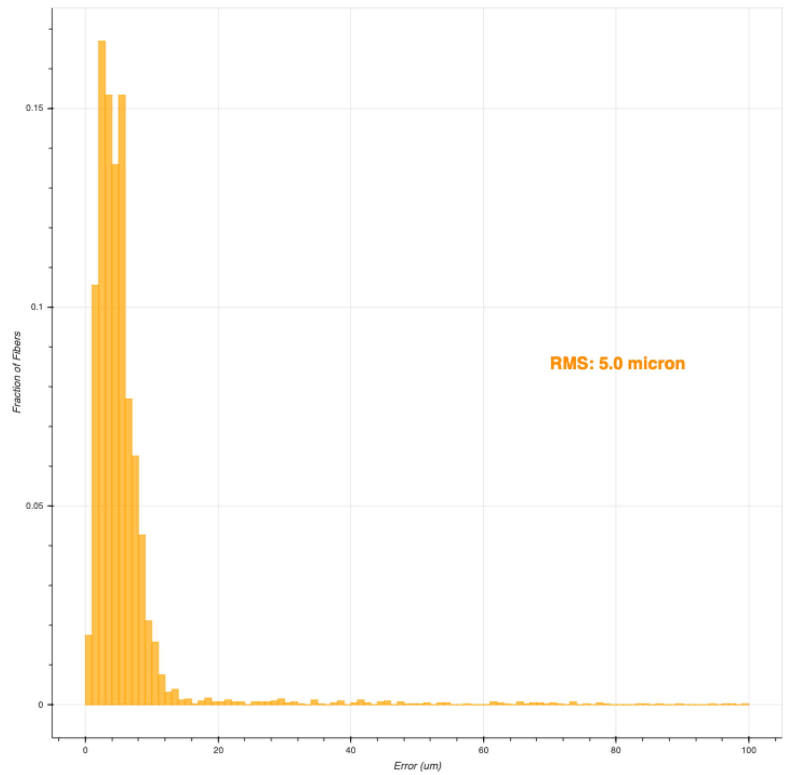
Fiber positioning precision

Fiber positioning performed in two steps :

1) blind move
2) correction move after Fiber View Camera (FVC) analysis

Achieves a precision of 5 microns (rms 2D) (a fiber has a diameter of 107 micros)
Dominant statistical noise source : air turbulence between mirror and focal plane

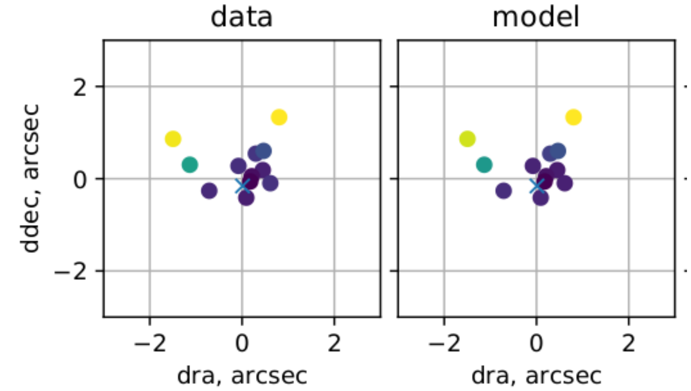




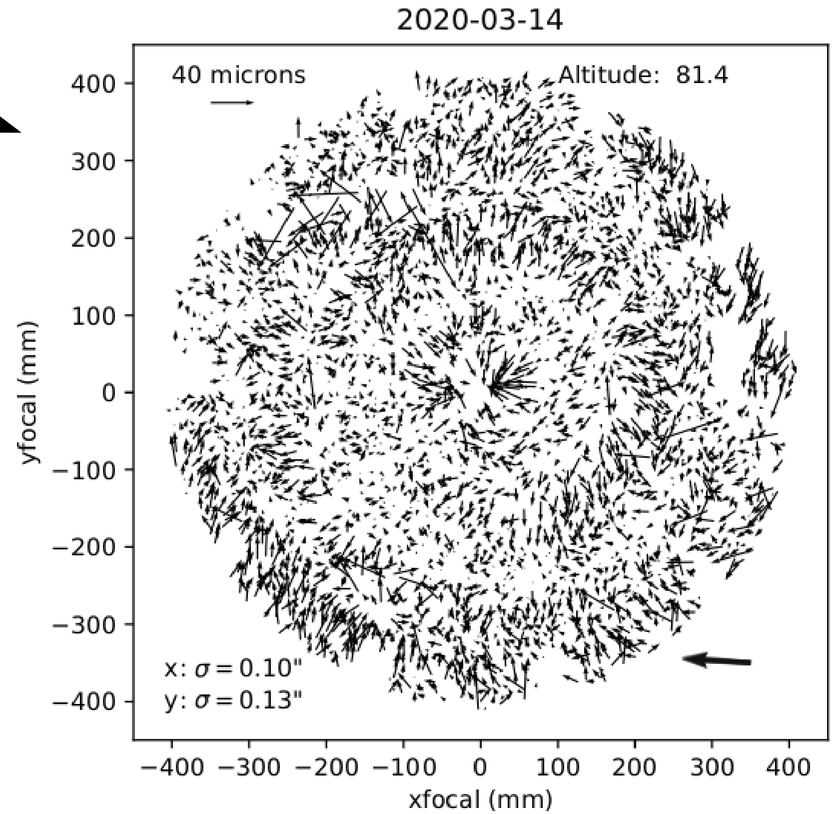
Claire Poppett, APS 2021
(with Kevin Fanning, Michael Schubnell, Joe Silber)

Fiber positioning accuracy

The systematic errors on the fiber positioning are estimated with dedicated **dither sequences** where the fibers are purposefully offset from their target over many exposures.

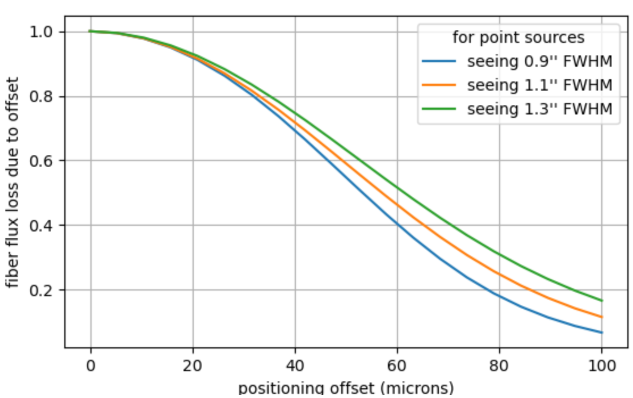


By analysis of the flux recorded in the spectrographs, one can estimate the fiber positioning errors.



After several rounds of improvements a precision of about 0.10 arcsec rms (1D) (or 10 microns 2D) has been achieved.

Flux loss due to imperfect positioning ~3 %



Schlafly, APS 2021

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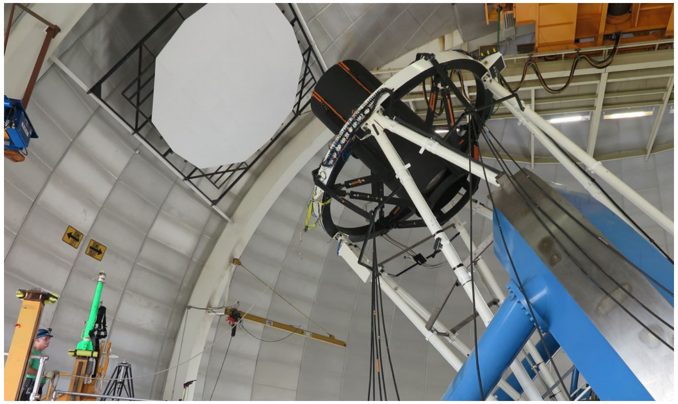
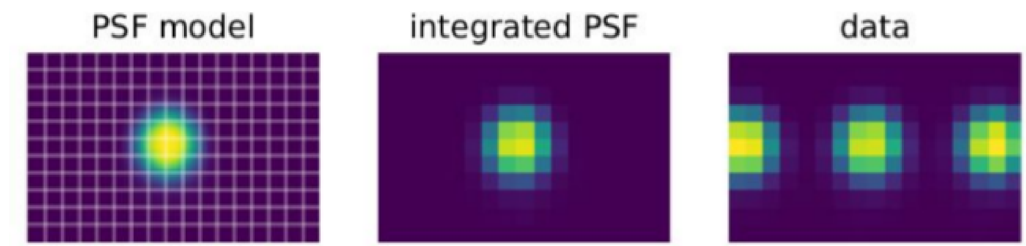
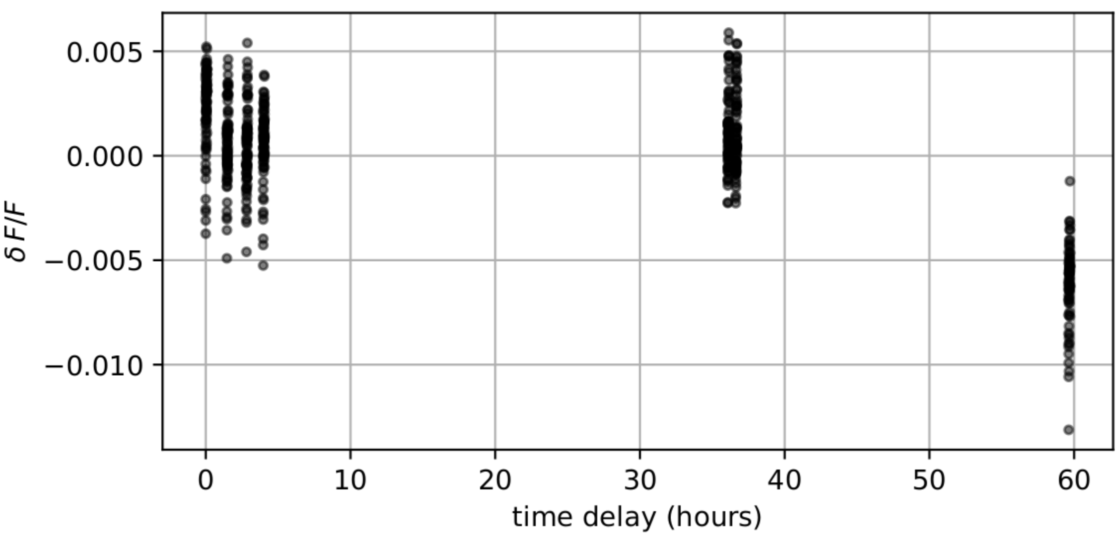
Spectrograph optics stability



Every afternoon :
- sequence of calibration exposures on white spot
- arc lamps for PSF and wavelength calibration
- LED array for flat fielding



PSF stability : better than 1%
in terms of emission line flux bias,
over several hours (inc. positioner and telescope movements)



(here b1 camera, data from March 2020)

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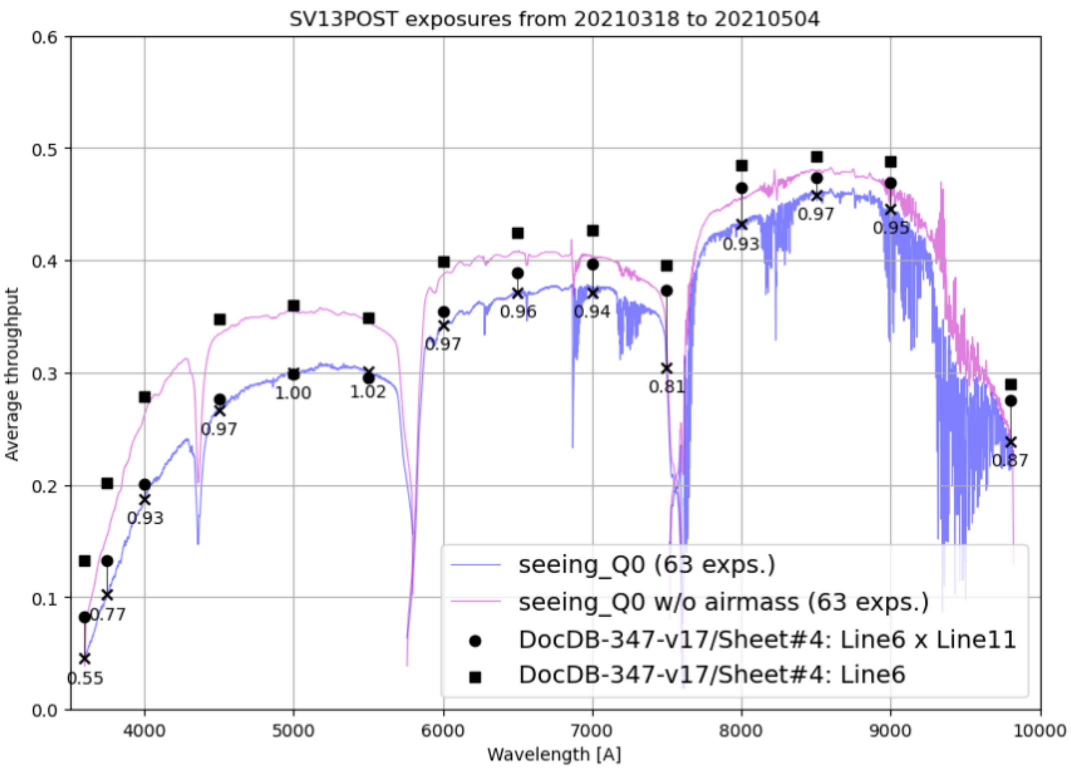
DESI throughput

from astronomical observations

Flux calibration obtained by comparing the observed spectra of standard stars to models (the models are fit on the same data using the shape of absorption lines)



(Anand Raichoor)

Average throughput obtained by
- combining many exposures
- correcting for the fiber aperture loss determined with guide CCDs

Purple curve (without atmosphere) comprises :
- all optics reflectivity/transmission (telescope + spectrographs)
- fiber transmission
- loss due to fiber ratio degration
- CCD quantum efficiency

~ 40% at 7000A

~4% lower than engineering data
but does not include loss due to fiber positioning errors (~3%)

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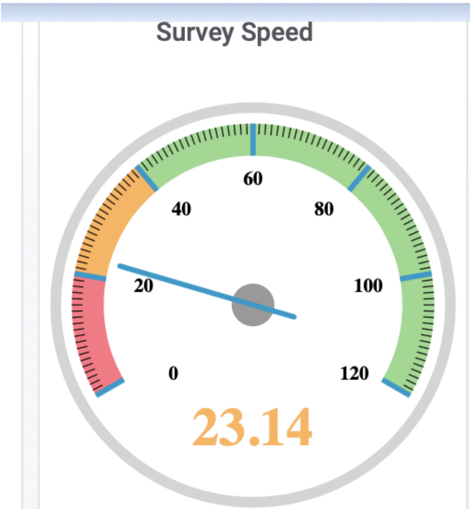
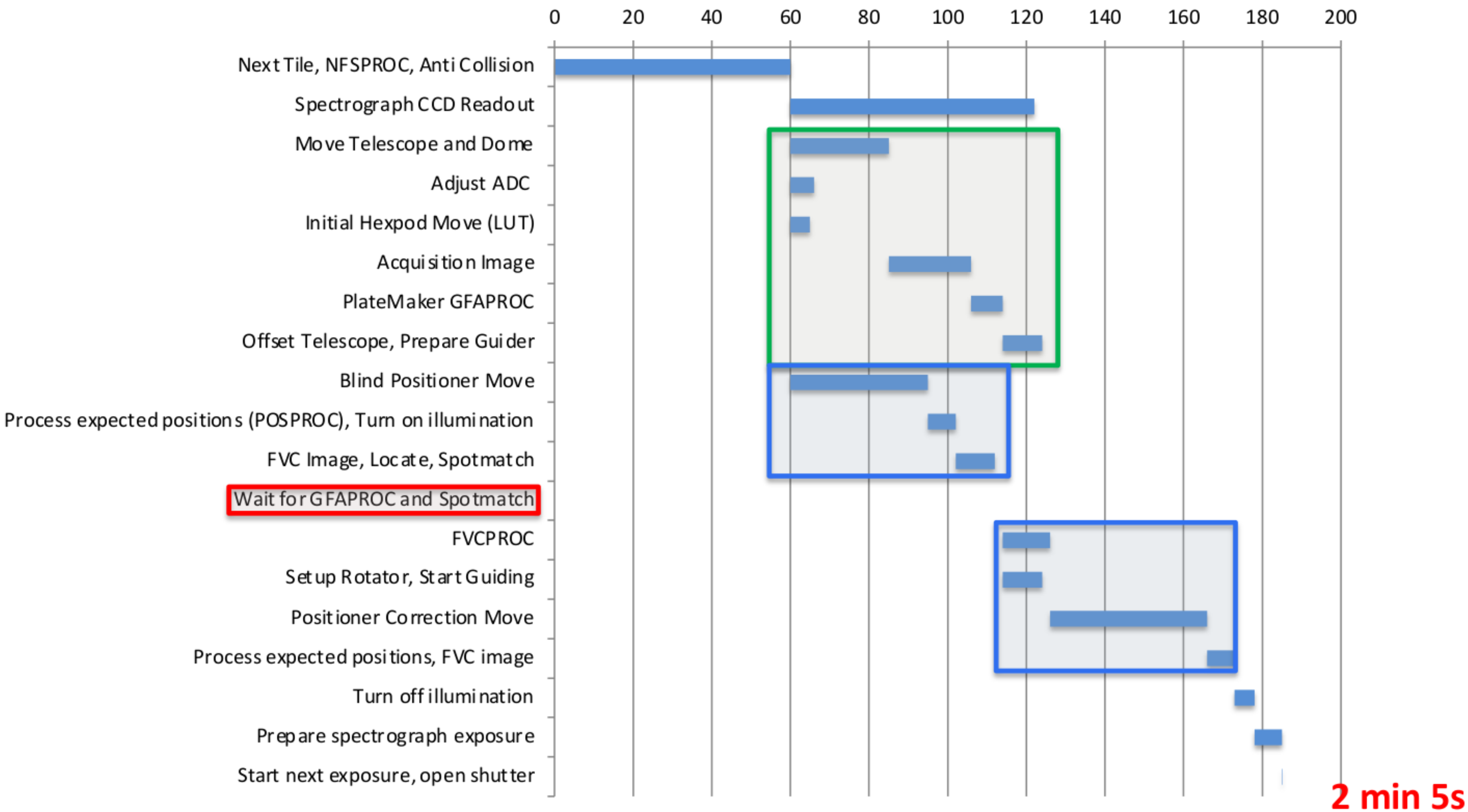
- instrument control system and observation performance
    - (pointing , guiding , auto-focus , rotation compensation , positioning loop)
    - inter-exposure time
    - exposure time calculator
    - online QA



(Klaus Honscheid, Ann Elliott)

Inter-exposure sequence

Overhead ~2min , for typical exposures of 20 min

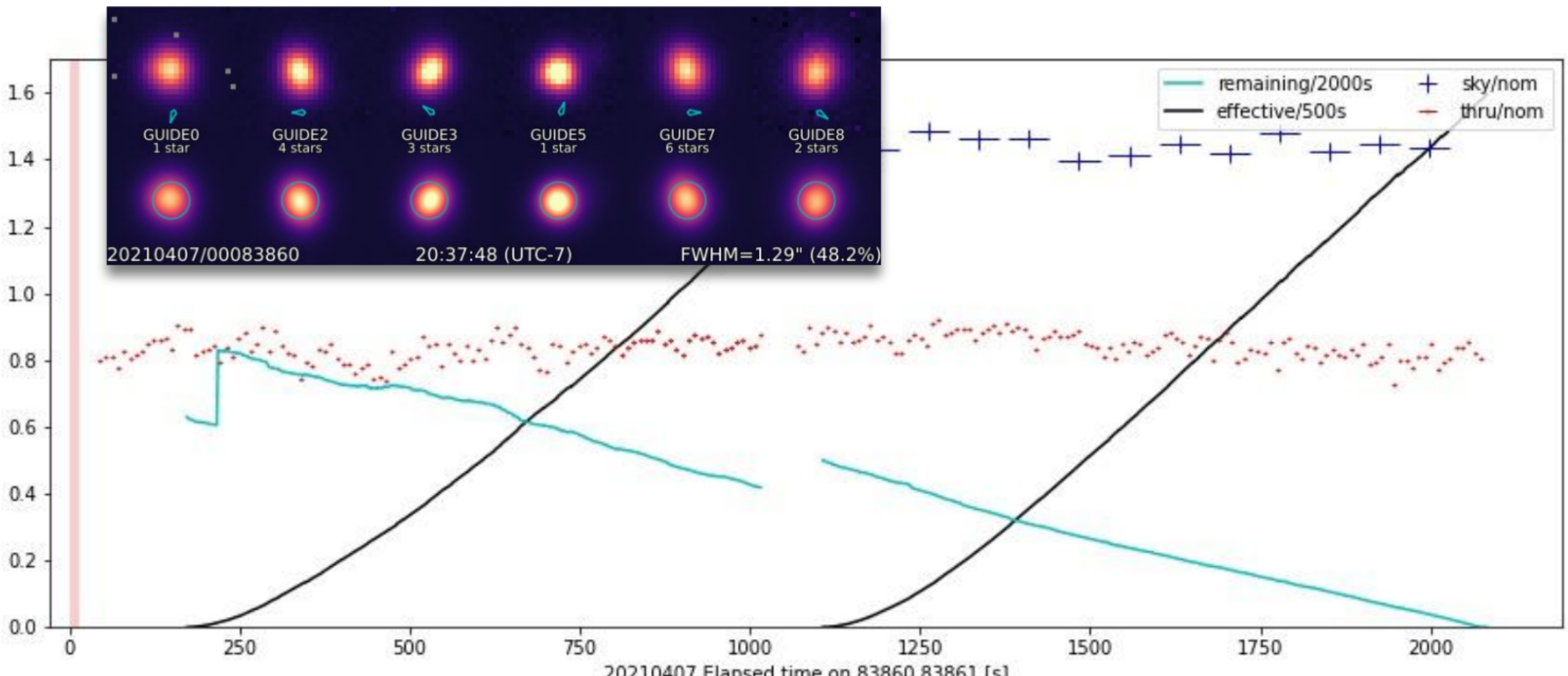


(figure from Klaus Honscheid)

Exposure Time Calculator

Inputs :
- guide images -> throughput , seeing (PSF) -> signal level S
- sky monitor fibers -> sky brightness -> noise level N

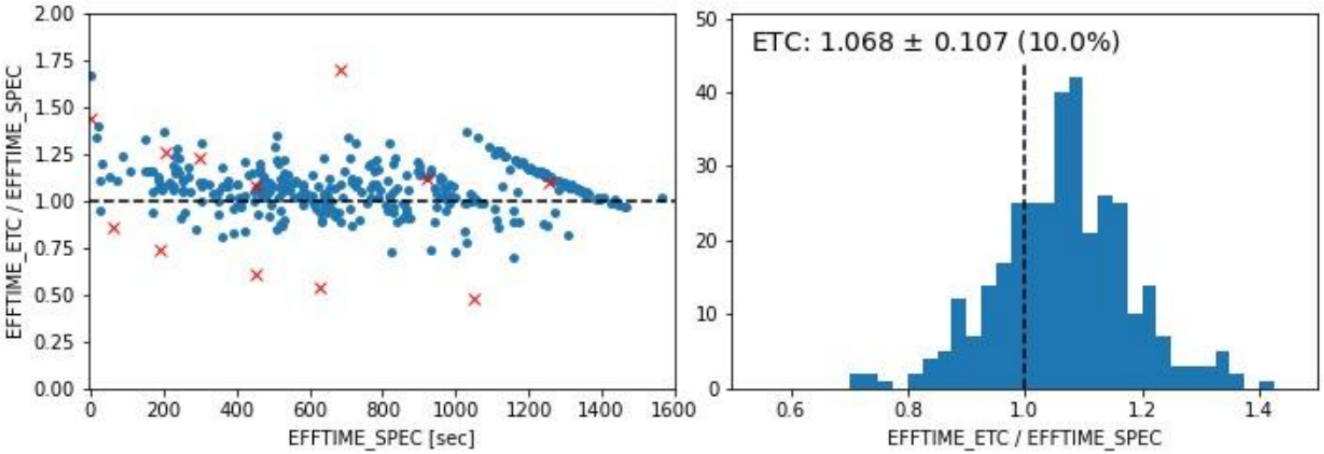
Output :
- **Predicts in real-time the « effective exposure time » ~ (S/N)^2**
- Informs the acquisition system of the remaining observation time



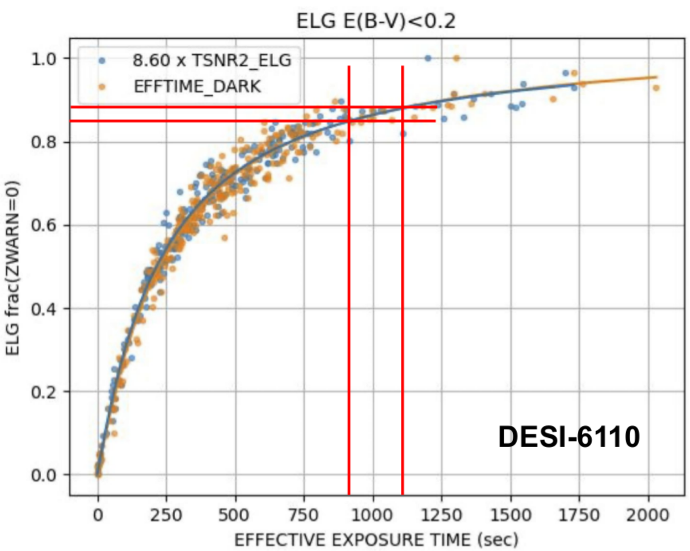
(David Kirkby)

Exposure Time Calculator

~ 10% precision on the effective exposure time (compared to offline spectroscopy)



ELG redshift success as a function of the effective exposure time



~ only few % variation of redshift success rate

Important for survey homogeneity (less systematics for the clustering analysis)

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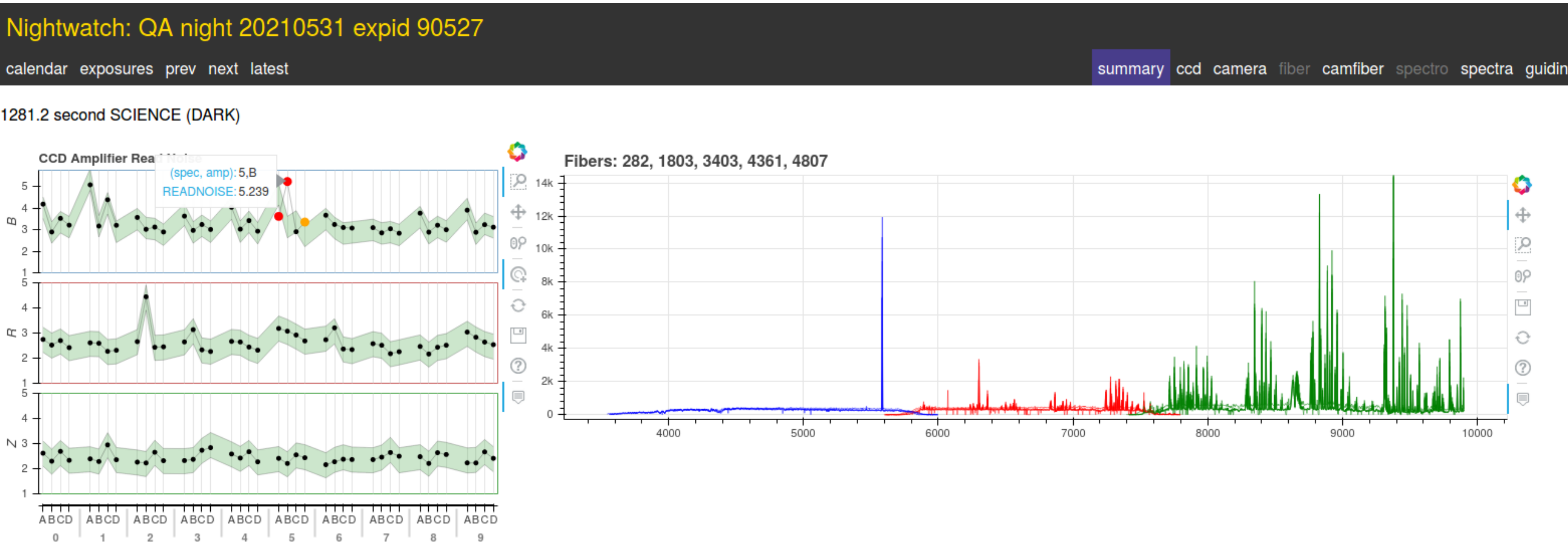
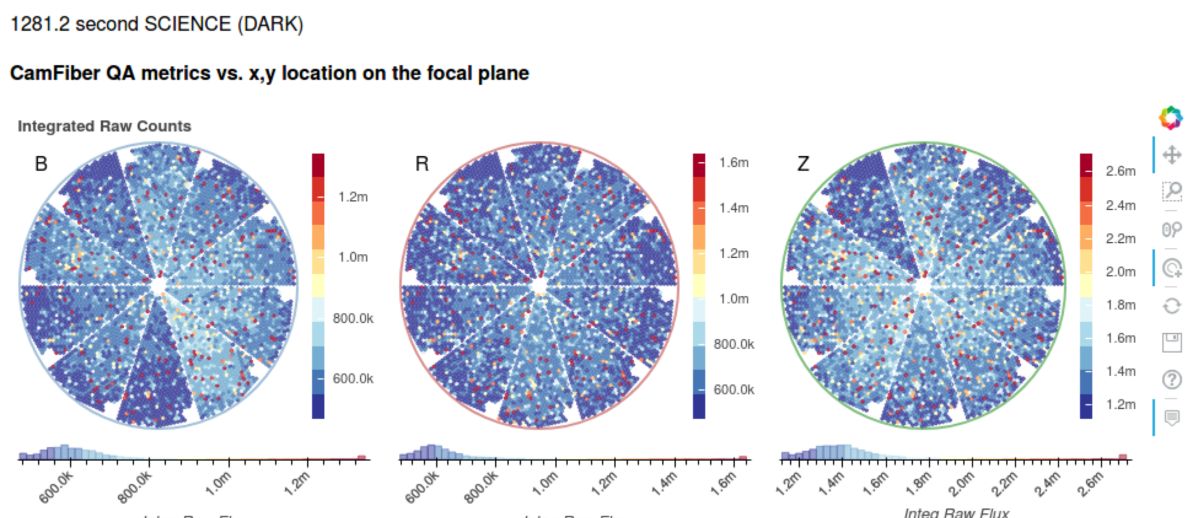
Online spectroscopic Quality Assessment

Used by observers during the night





(Stephen Bailey
with undergrads Ana Lyons,
Ruhi Doshi, and William Sheu)

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- instrument control system and observation performance
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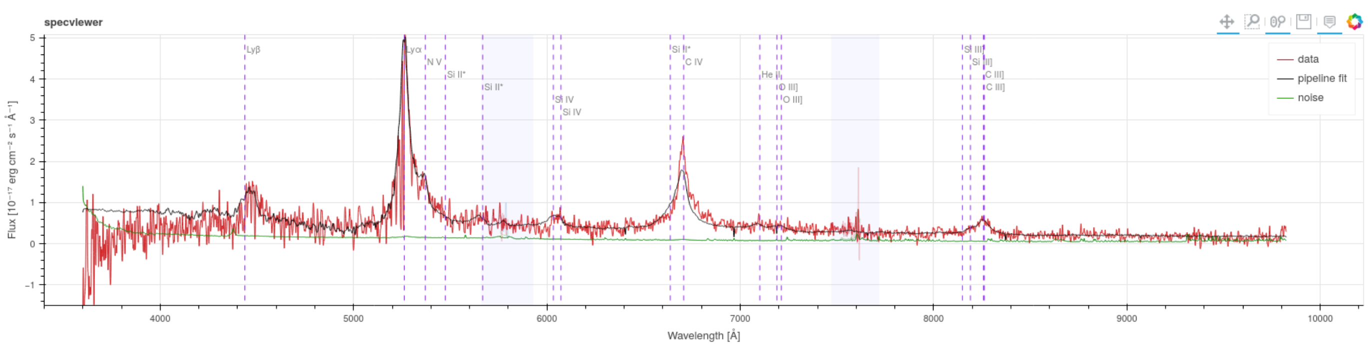
- spectroscopic pipeline
  - requirements on efficiency, purity, precision
  - run time, feedback to operations

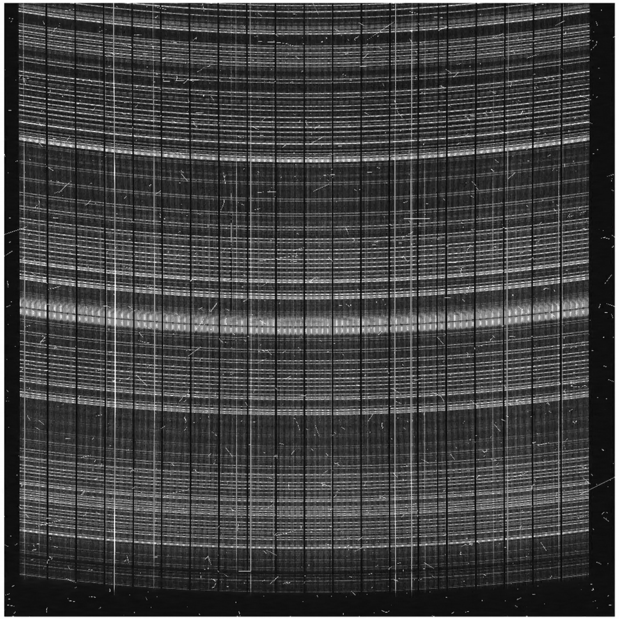


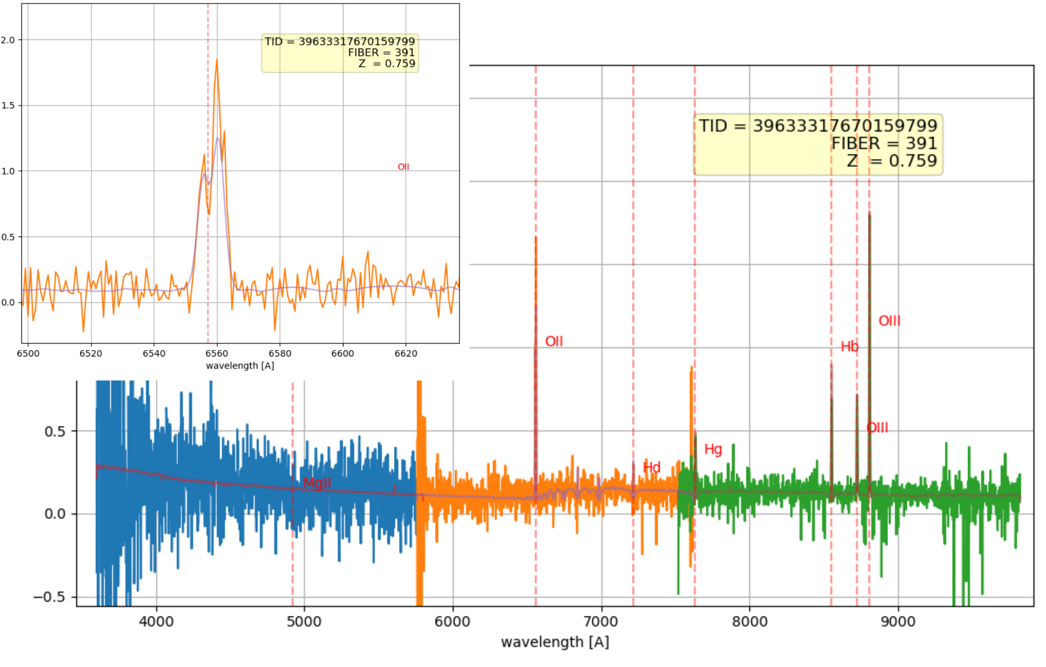
(visualization tool: Eric Armengaud)

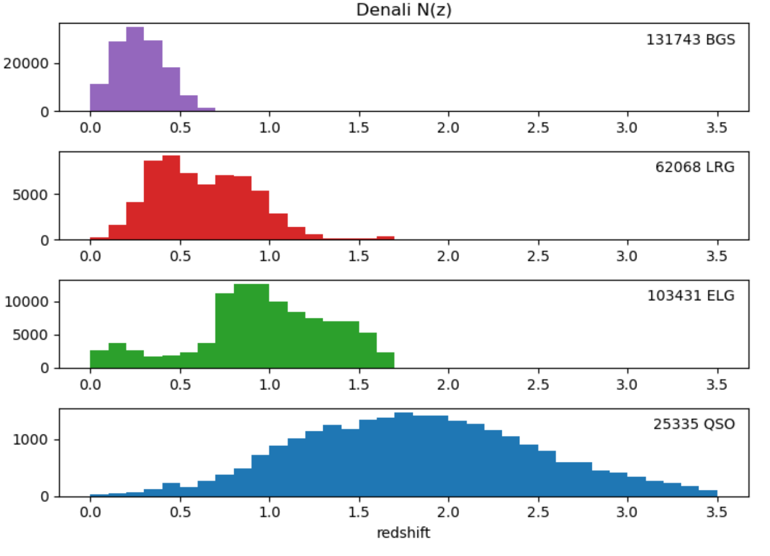
Spectroscopic pipeline

Input for each exposure: 30 CCD images
- 4k x 4k pixels
- BLUE channel: ITL thin CCDs
- RED, NIR channels: LBNL 250 micron thick CCDs

Output:
- 5000 wavelength and flux calibrated spectra
- spectroscopic classification and redshifts



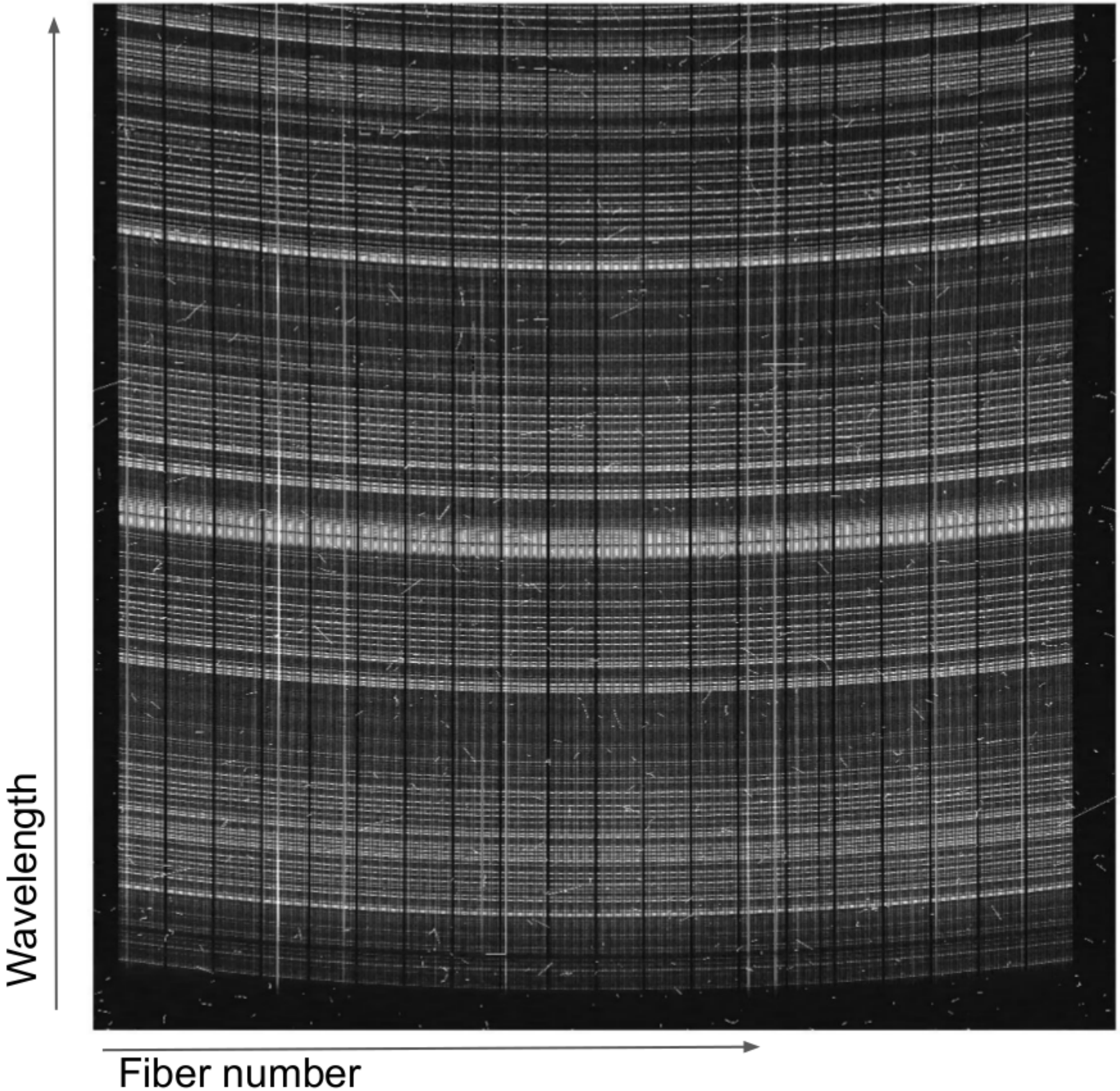




(Stephen Bailey, JG, Anthony Kremin)

Visual illustration

18 min exposure from April 12, one NIR CCD

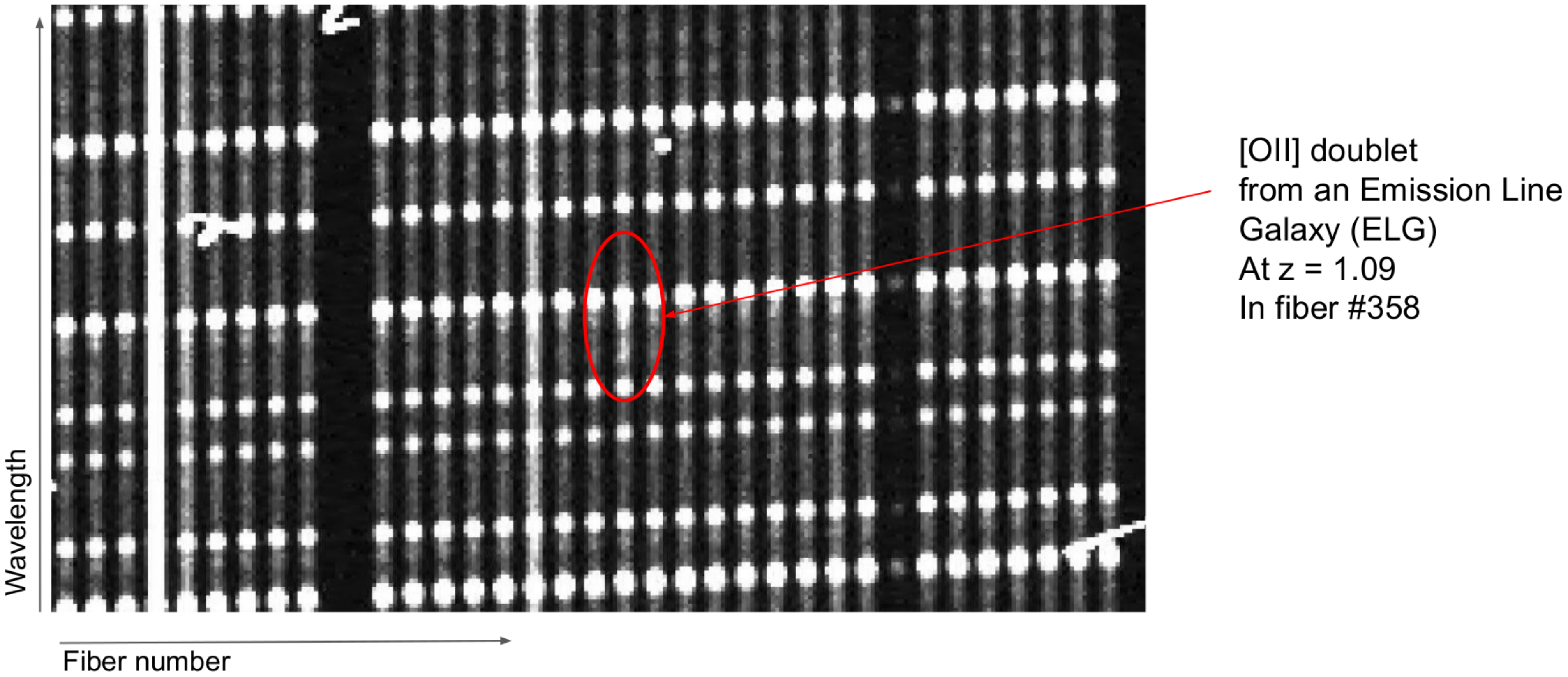


500 vertical fiber traces

Curved horizontal lines are sky lines

Visual illustration

18 min exposure from April 12, one NIR CCD



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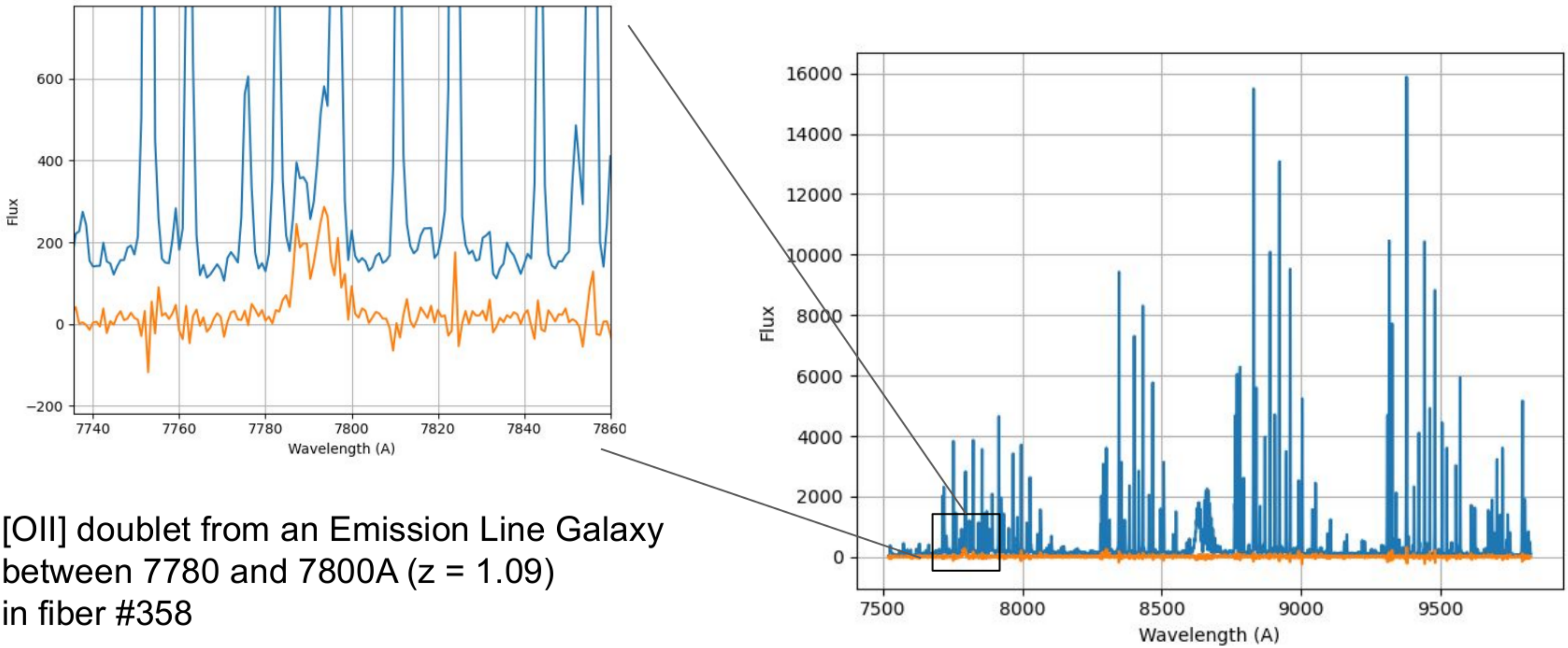
Visual illustration

18 min exposure from April 12, one NIR CCD

Extracted spectrum of fiber #358 for this exposure
before and after the subtraction of the sky background



[OII] doublet from an Emission Line Galaxy
between 7780 and 7800A (z = 1.09)
in fiber #358

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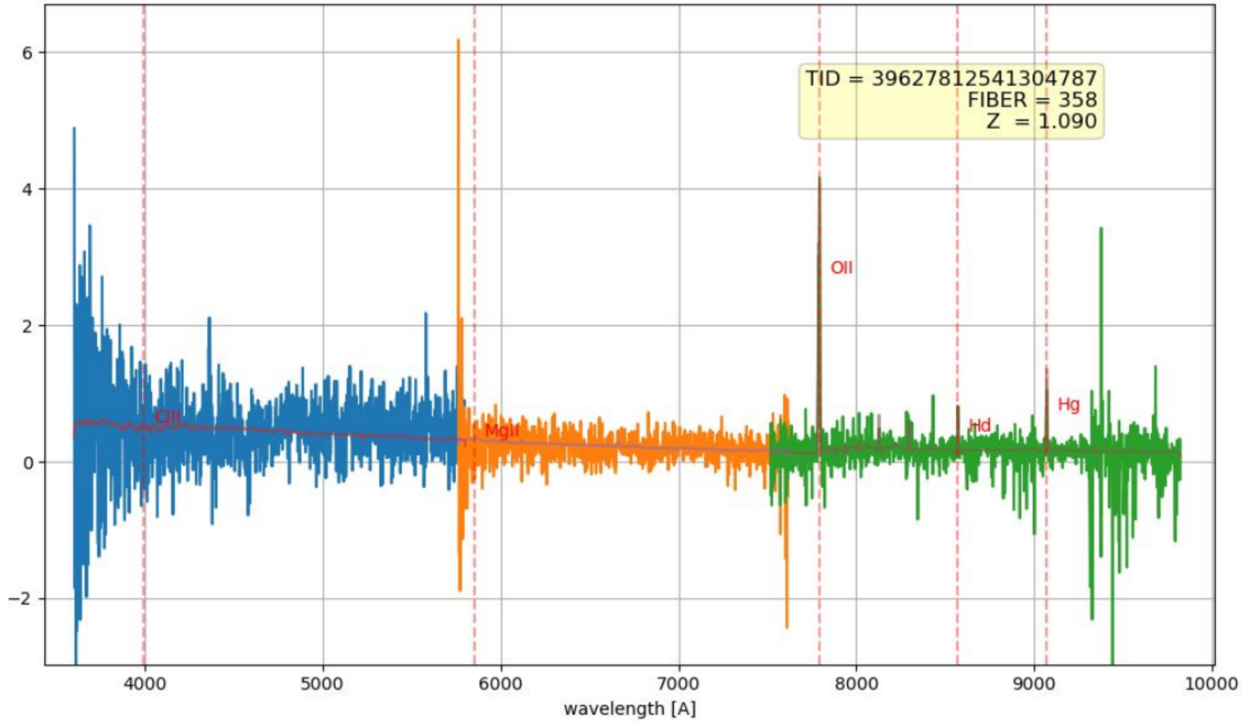
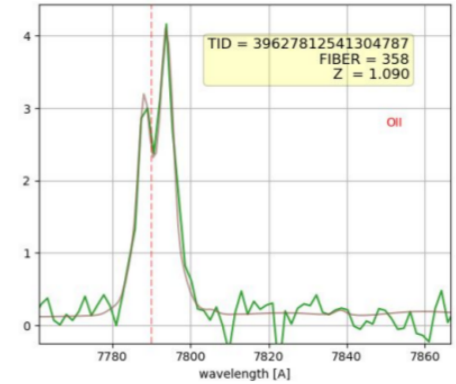
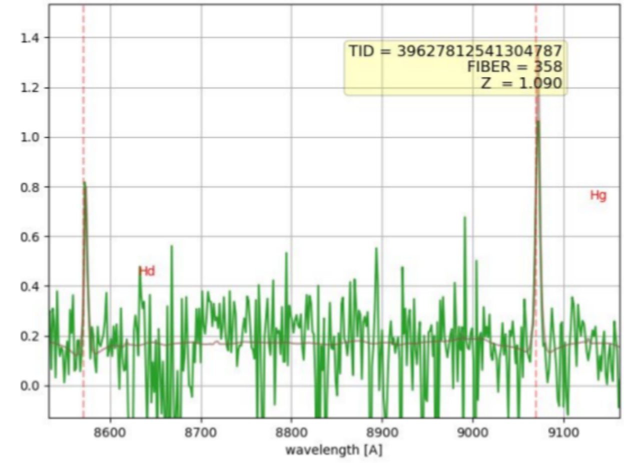
Visual illustration

18 min exposure from April 12, one NIR CCD

Automated spectral classification and redshift fit







Spectroscopic pipeline requirements

- Processing time constraint:
  Daily processing to get redshifts from the previous night before noon in order to plan the observation of the next night (choice to repeat or not the observations of tiles / targets)
  Lot of help from NERSC (NESAP)
  - real time queue with 12 nodes
  - reservations for data release processing
    (max concurrency reached during reprocessing for internal data release with NERSC reservation: 240 nodes; 16,000 cores - 4 month of data processed in 48 hours)

- Requirements on :
  - Redshift efficiency (90-95%, depending on the target class)
  - Redshift failure rate <5%
  - Redshift precision and accuracy (statistical and systematic error)
  - Precision of the noise estimation (for the Lyman-alpha power spectrum)
  - Precision on the flux calibration (for Lyman-alpha, stellar physics)

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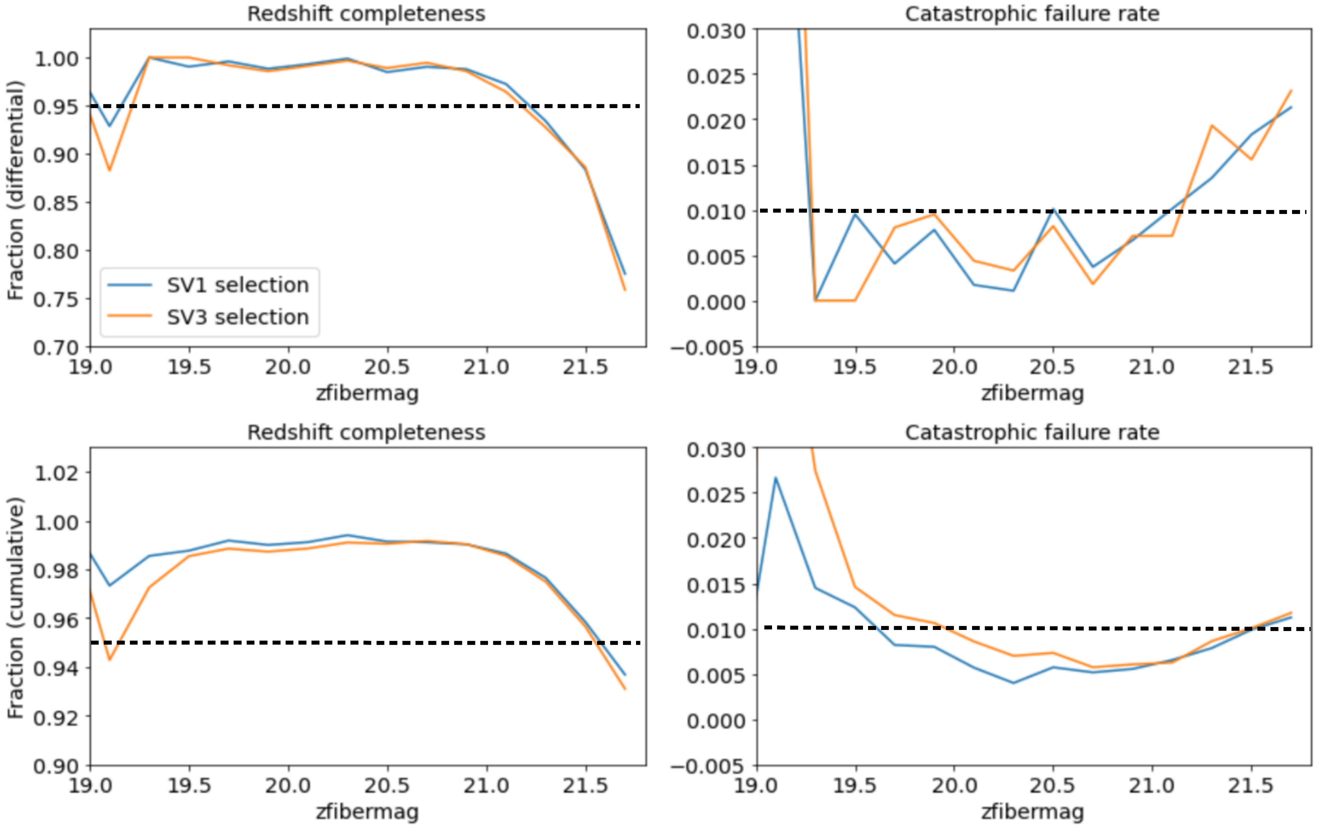
Spectroscopic pipeline requirements validated during SV

(figures from Ting-Wen Lan)

Example : Luminous Red Galaxies

'truth' : either very deep observations or visual inspection



1% << requirement (5%)

1%

redshift completeness > 95 %
redshift (undetected) failures < 5 %
(0.4<z<1.1)

(homogeneity of the survey)
(spurious signal, bias in correlation function)

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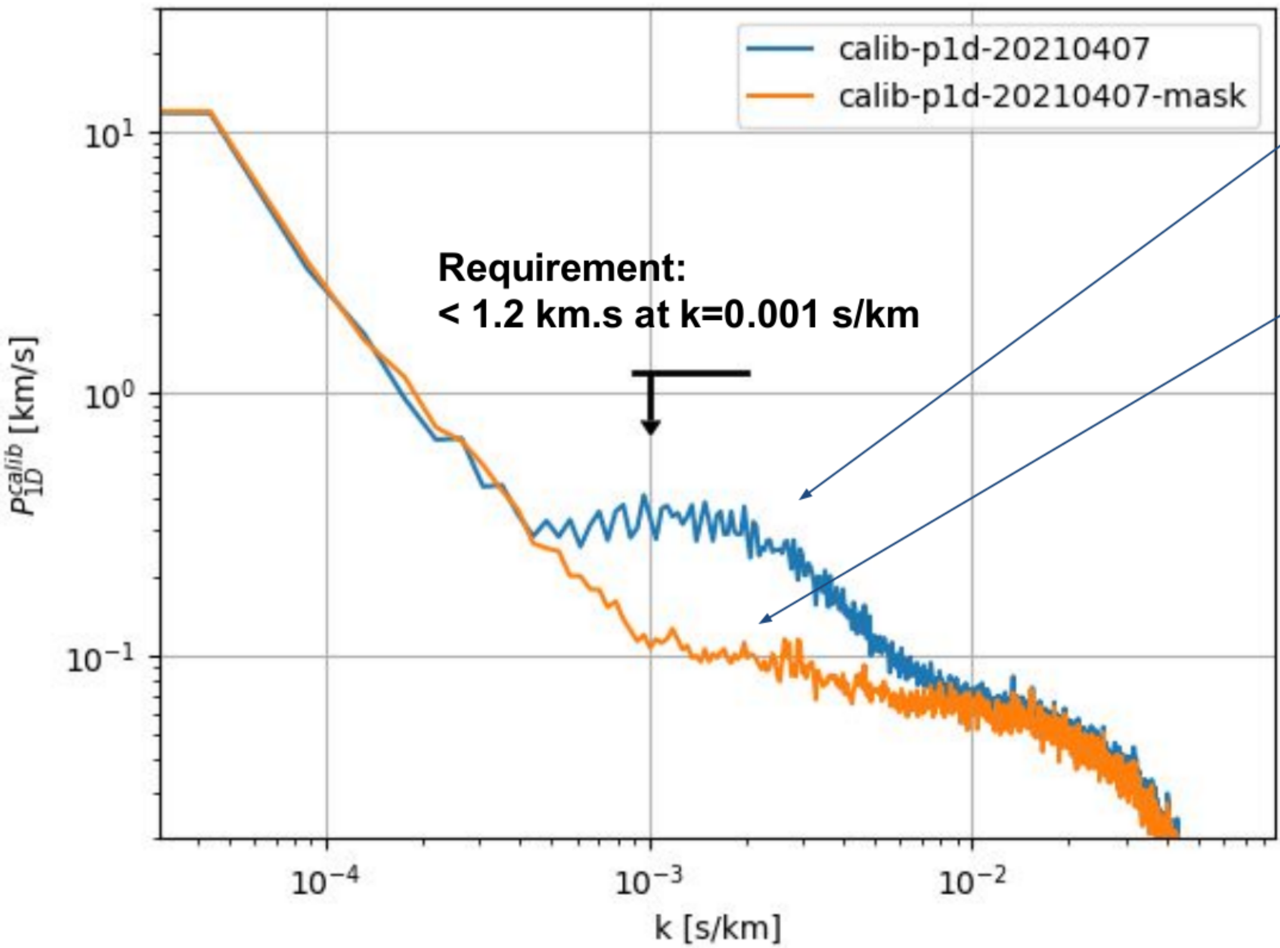
Spectroscopic pipeline requirements validated during SV

Requirement on the flux calibration precision :
The Ly-α QSO fractional flux calibration errors shall have power less than 1.2 km/s at k~0.001 s/km.



Excess calibration noise due to the variation of the collimator low reflectivity feature

Removed by simply interpolating over the feature before computing the Fourier transform.

Spectroscopic pipeline feedback to operations

Every morning

- new calibrated spectra from the past night
- coadded (stacked) with past observations per tile (=pointing)
- new redshift catalog
- measure redshift efficiency, signal to noise per tile, effective time per tile
- run other classifiers (Neural Network)

Possibly every day
(but not necessarily in practice, depending on the overlap of tiles)

- update the list of targets to observe
- assign fibers to targets given the new target list, and the state of the focal plane

Every afternoon

- a new sequence of tiles to observe is prepared for the next night

(not showing here the performance of the fiber assignement code,
tile selector , survey simulations)

Checklist for starting the survey

- instrument performance (selection)
  (corrector optics, focal plane, spectrographs, throughput)

- instrument control system and observation performance
  (pointing , guiding , auto-focus , rotation compensation , positioning loop, inter-exposure time, exposure time calculator online QA)

- spectroscopic pipeline
  (requirements on efficiency, purity, precision, run time, feedback to operations)

- survey validation
  - validation of targeting methods : target densities
  - first science analysis : halo occupation distributions,
    lyman-alpha early studies

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Targets (Final Design Report)

Level 1 requirement on the BAO precision (isotropic distance scale R, aggregated)
sigma_R <0.28% for z<1.1
sigma_R <0.39% for 1.1<z<1.9

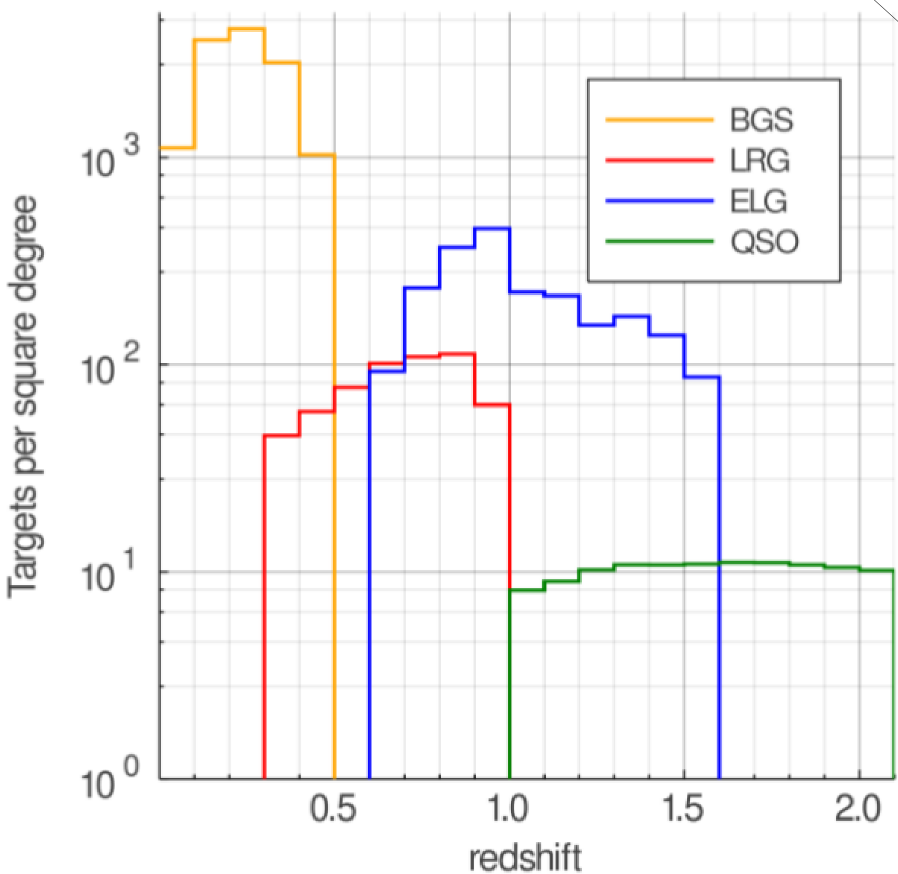
$$\sigma_{BAO} \propto V_{eff}^{-1/2}$$

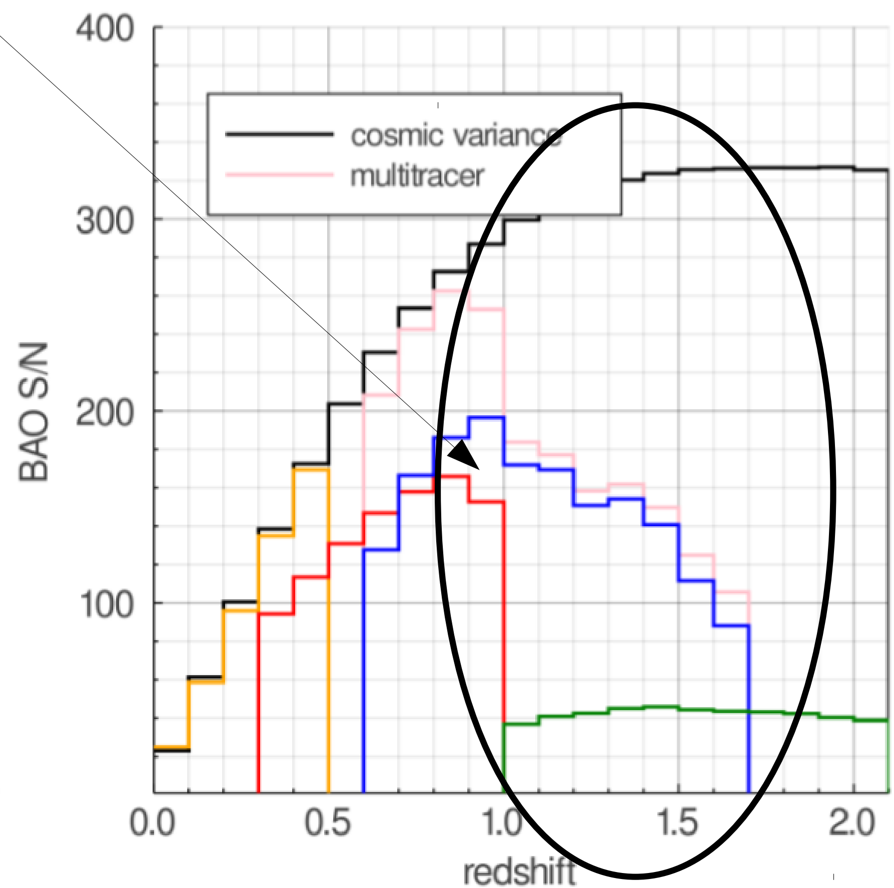
$$V_{eff} \equiv \int d^3r(1 + 1/(nP))^{-2}$$

survey area, redshifts

target density

tracer bias





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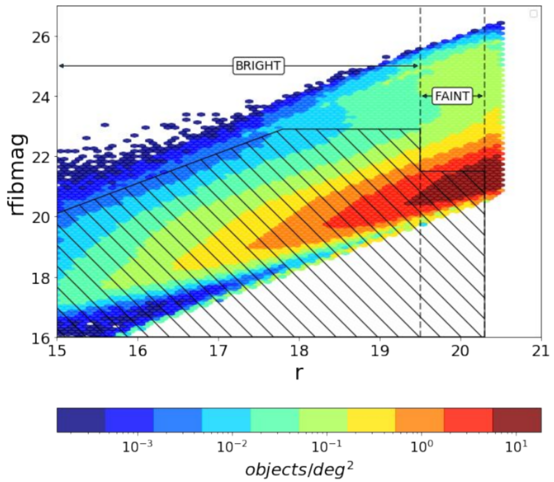
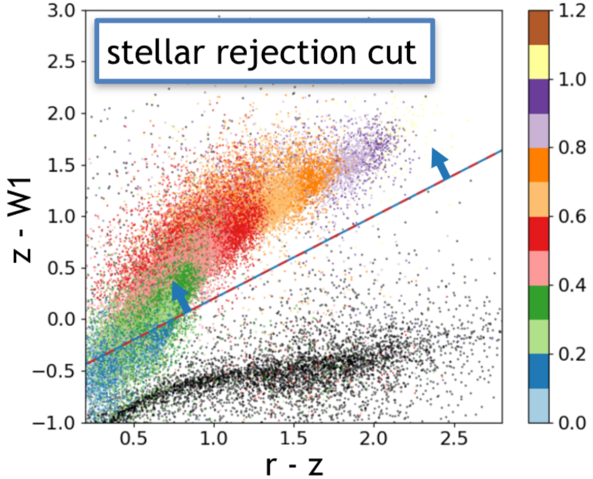
Targets selected from g,r,z,W1

figures from Newman, APS 2021
(with Zhou, Raichoor, Wilson, Yeche ...)

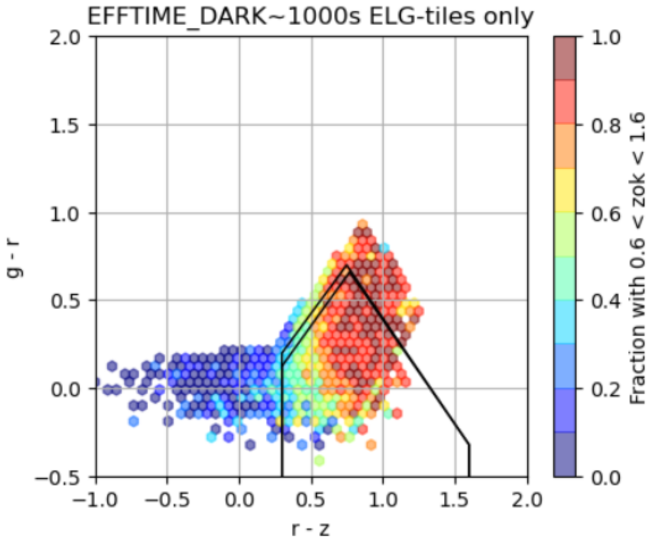
BGS r<19.5



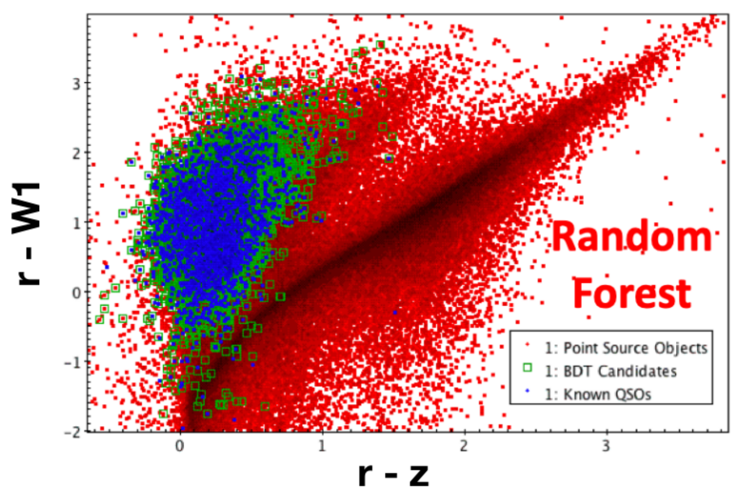
LRG z_fiber<21.7+ g,r,z,W1 color cuts



ELG g<23.5 + g,r,z color



QSO (r<22.7, point source, RF)



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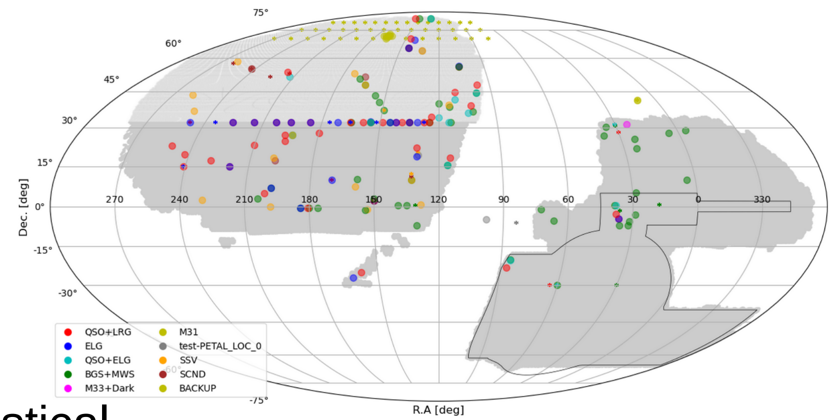
SV1 : optimizing the target selection testing the spectroscopic pipeline

- broader color selection cuts to optimize the target selection

- several very deep tiles
  - obtained with many repeated observations
  - provide « truth » tables
  - used for visual inspection
  - repeated observation to study redshift statistical precision

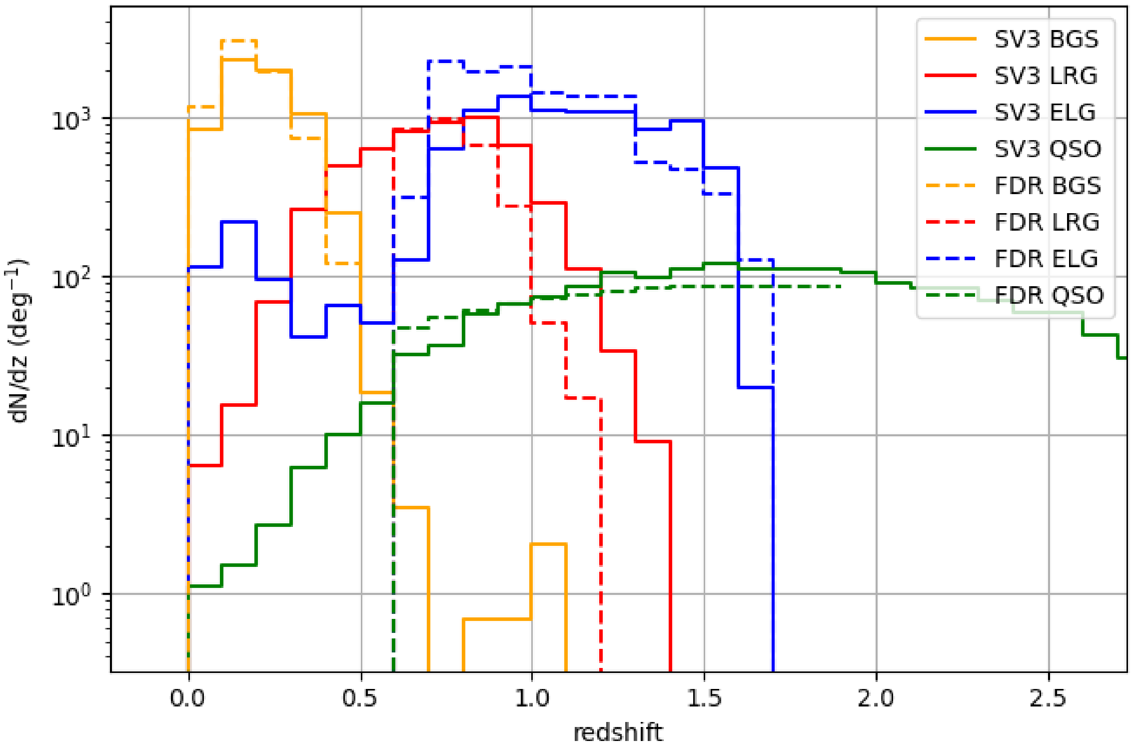


- tiles in various regions
  - north (MzLS+BASS) vs south (DECaLS) vs deep DES region
  - low / high Galactic extinction
  - low / high stellar density

- various observing conditions
  - exposure times
  - low / high airmass
  - seeing
  - sky brightness (moon / twilight)

Targets : achieved densities

Target density at the end of SV (final selection)



<u>integrated number density per square degree</u>

	BGS $z < 0.5$	LRG $0.4 < z < 1.1$	ELG $1.1 < z < 1.6$	QSO $z < 2.1$	QSO $z > 2.1$
Parent sample	860	600	1900	310	
Revised SRD	600	440	400	120	50
Estimated main survey	640	480	440	135	58

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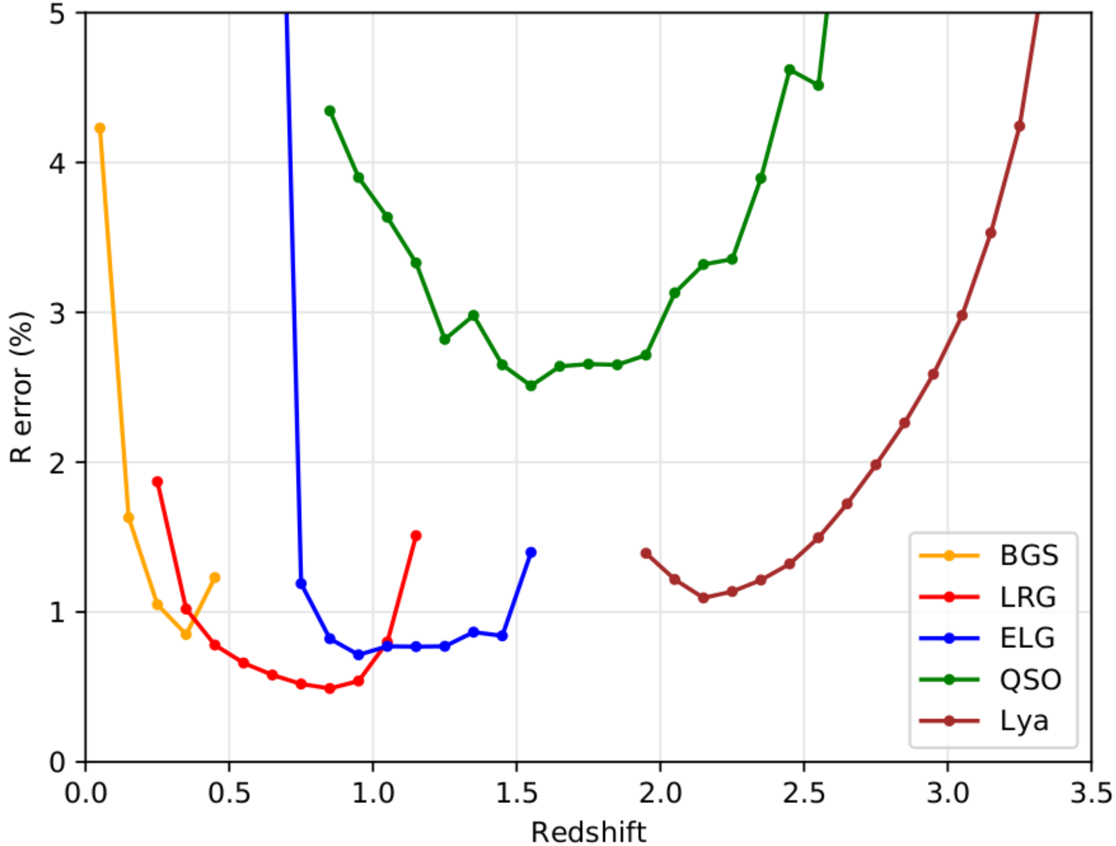
BAO forecast at the end of SV

Forecast assuming 7 passes in dark time, 4 passes for the BGS survey
Includes : targeting algorithm purity, fiber assignment efficiency,
redshift efficiency (assuming 1000s effective exposure time per tile)
achieved S/N in the spectra for Lyman-alpha

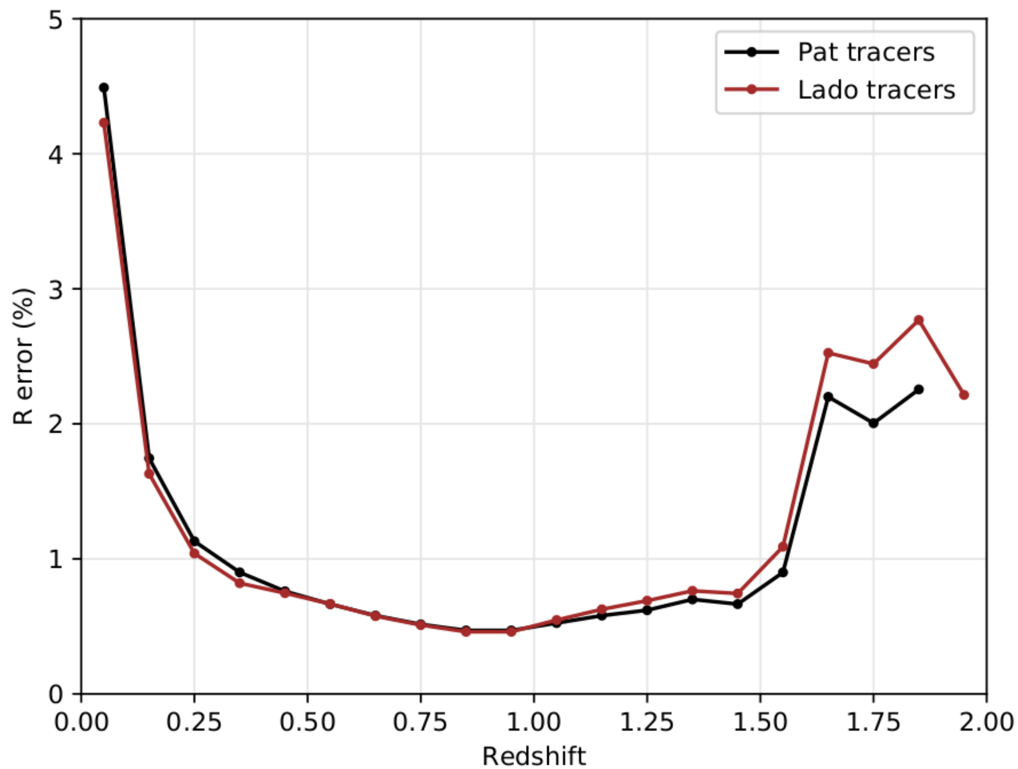
Uncertainty on the BAO isotropic scale R per redshift bin of width 0.1



(per tracer)

BAO forecast at the end of SV

Uncertainty on the BAO isotropic scale R per redshift bin of width 0.1



(combining BGS,LRG,ELG,QSO but without Lya)

(Pat MacDonald, Lado Samushia)

Scenario	σ_R $(0 < z < 1.1)$	σ_R $(1.1 < z < 1.9)$	σ_H $(1.9 < z < 3.7)$
SRD L1 (9k deg^2)	0.28%	0.39%	1.05%
SRD L1 (14k deg^2)	0.22%	0.31%	0.84%
Current status (14k deg^2)	0.194% [0.197%]	0.318% [0.291%]	0.79%

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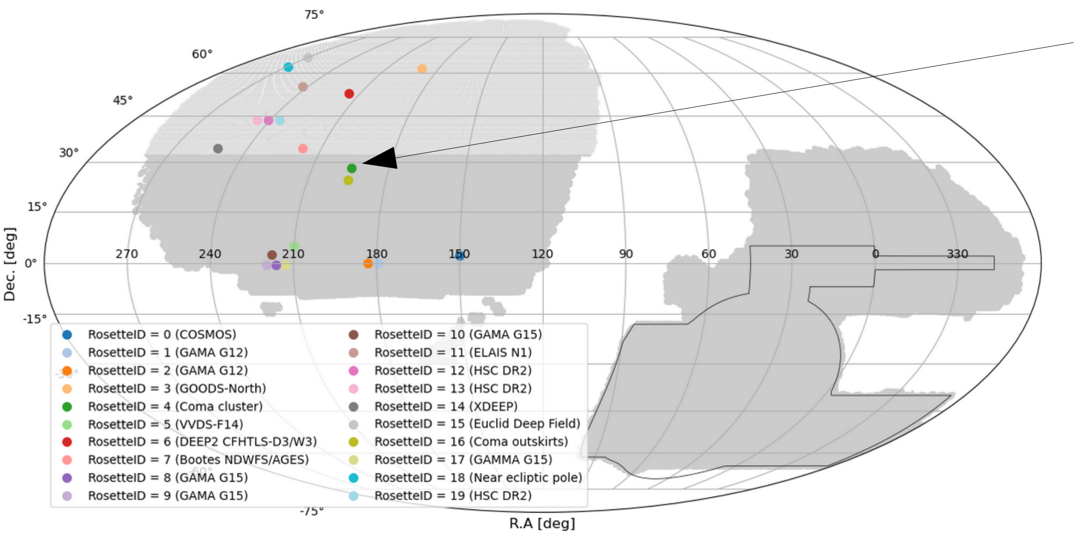
SV3: DESI 1% survey

16 fields with rosette pattern dithering

Reaches 100% fiber assignment (observation) efficiency

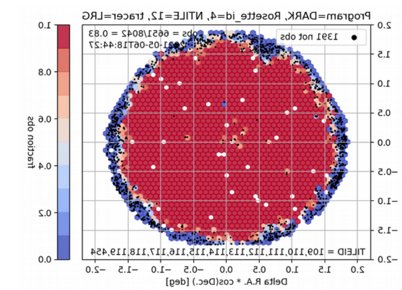
Used to study clustering at small scale

Ex : Rosette #4 on Coma cluster

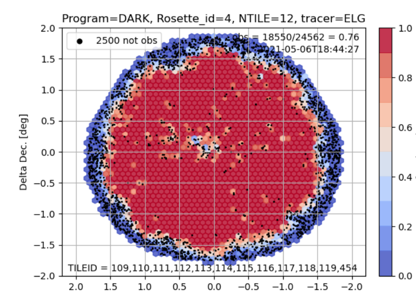


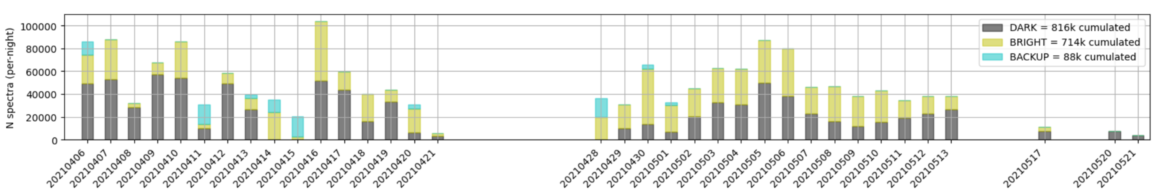
Fraction of observed targets

LRG



ELG

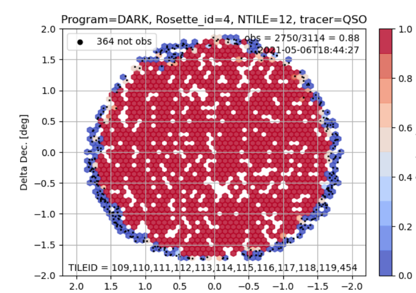




816,000 spectra in dark time

714,000 spectra in bright time

QSO



(figures from Anand Raichoor)

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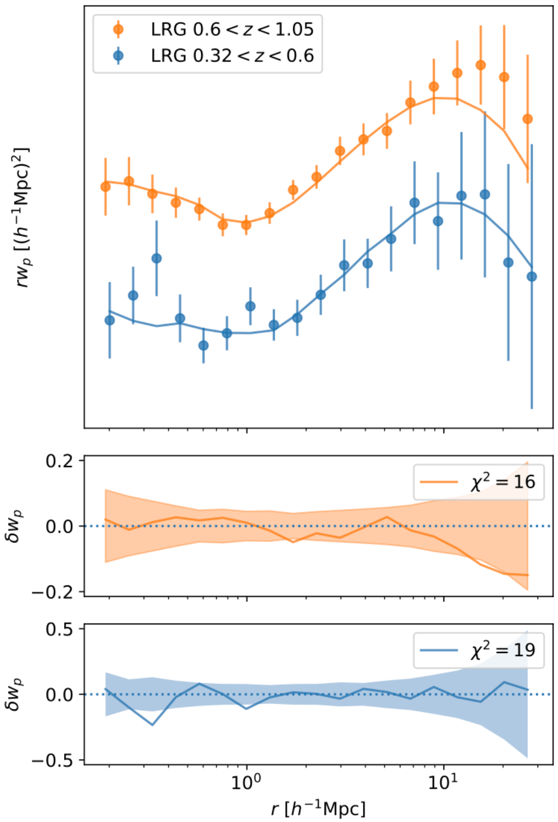
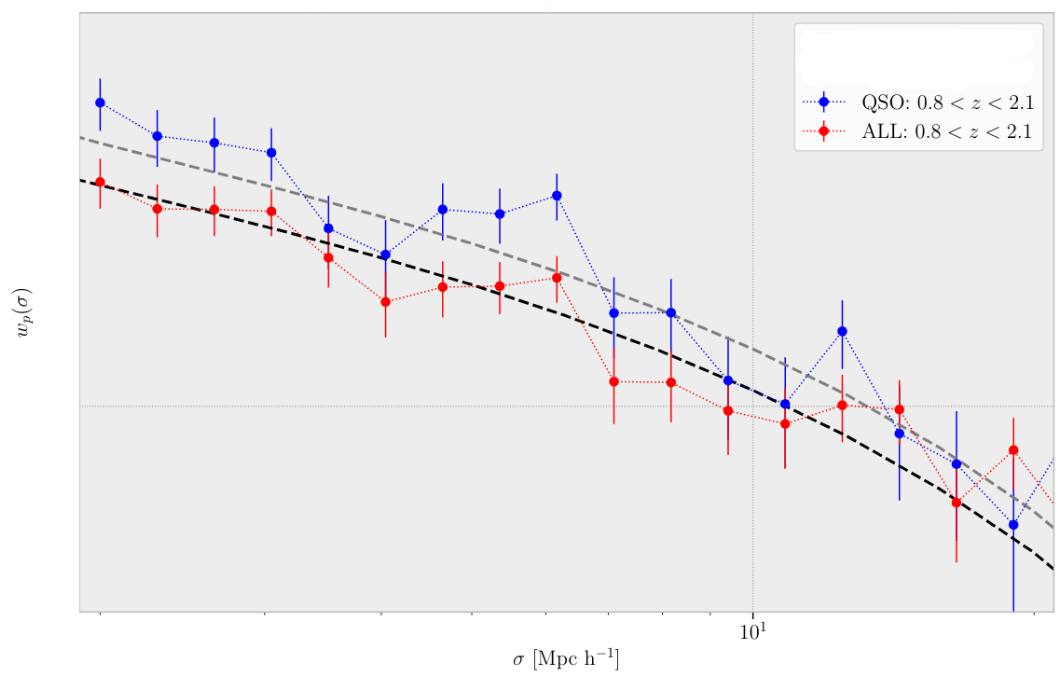
SV3: science analyses have started

Halo Occupation Distribution modeling
(probability to find a galaxy in a halo of a given mass)

Preliminary projected correlation functions from SV3 (1 % survey)



(figure from Sandy Yuan)

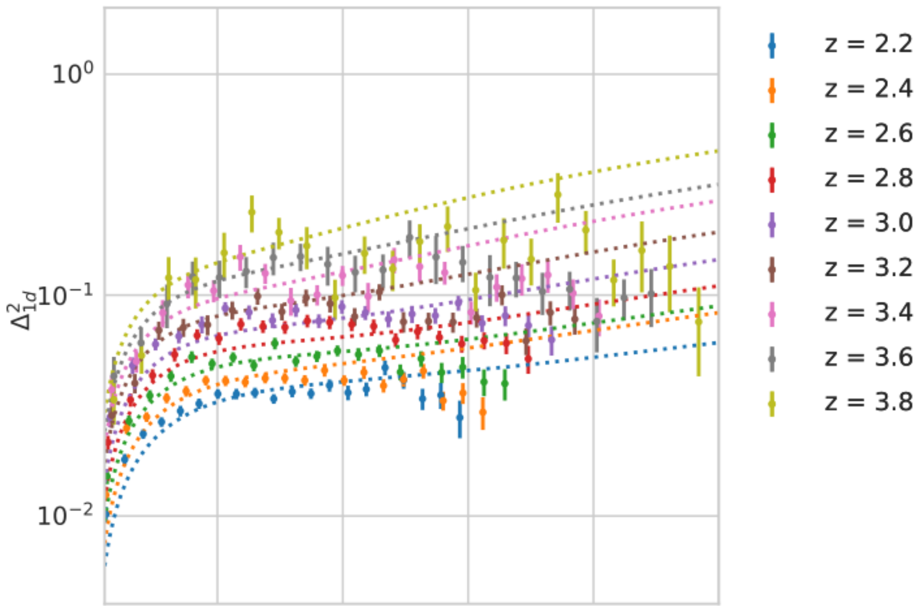


(figure from Edmond Chaussidon)

(axes labels intentionally removed)

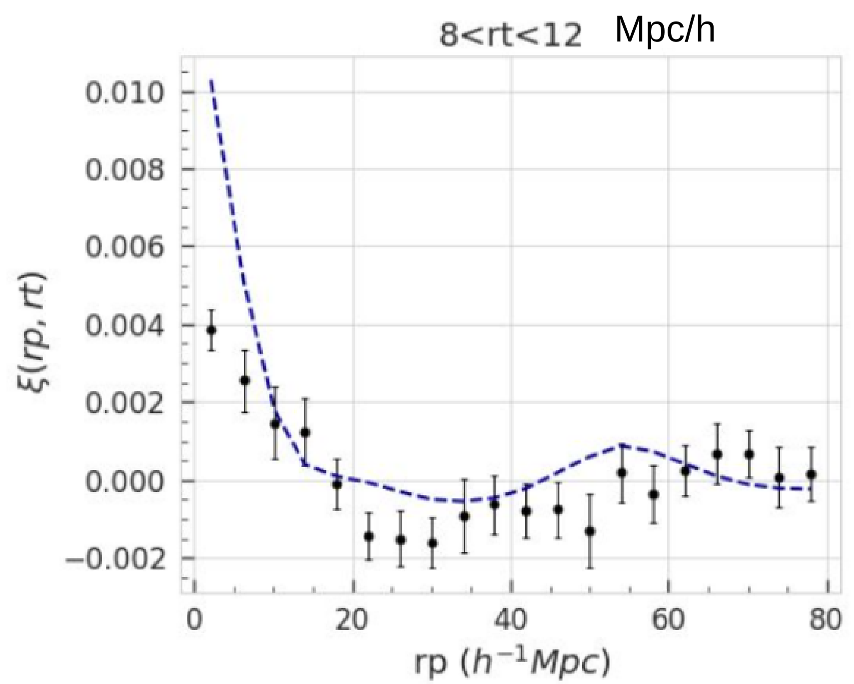
Science analyses have started !

Lya P1D(k) measurement



(figure from Corentin Ravoux and Michael Walther)

Lya auto-correlation function



(Alma Gonzalez, APS 2021)

(very very preliminary
results from SV1)

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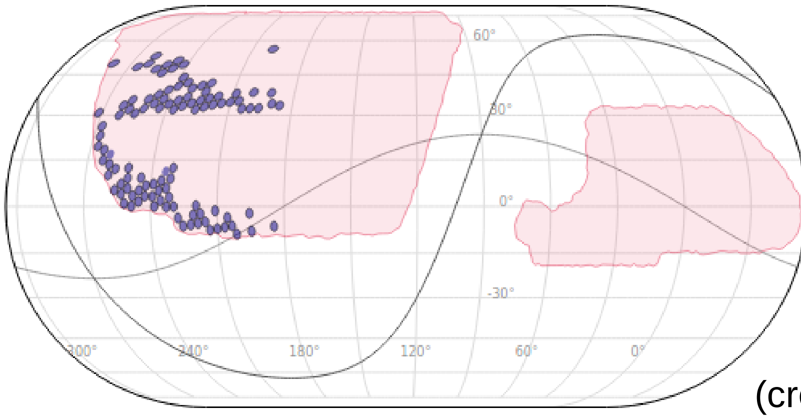
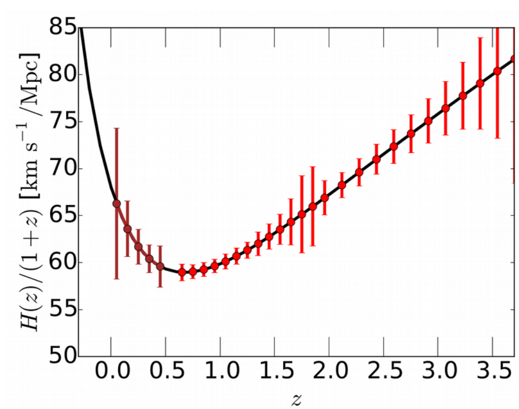
Conclusion

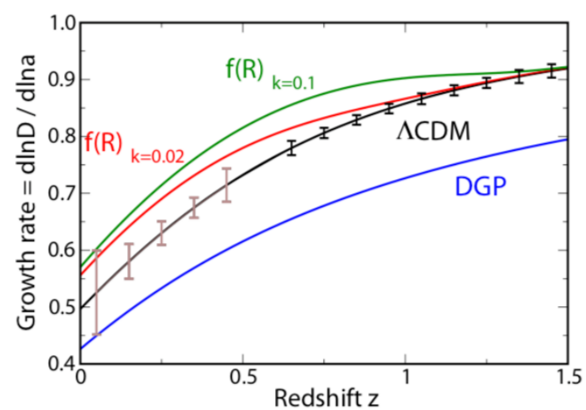
The DESI main survey has started (already 1% done).

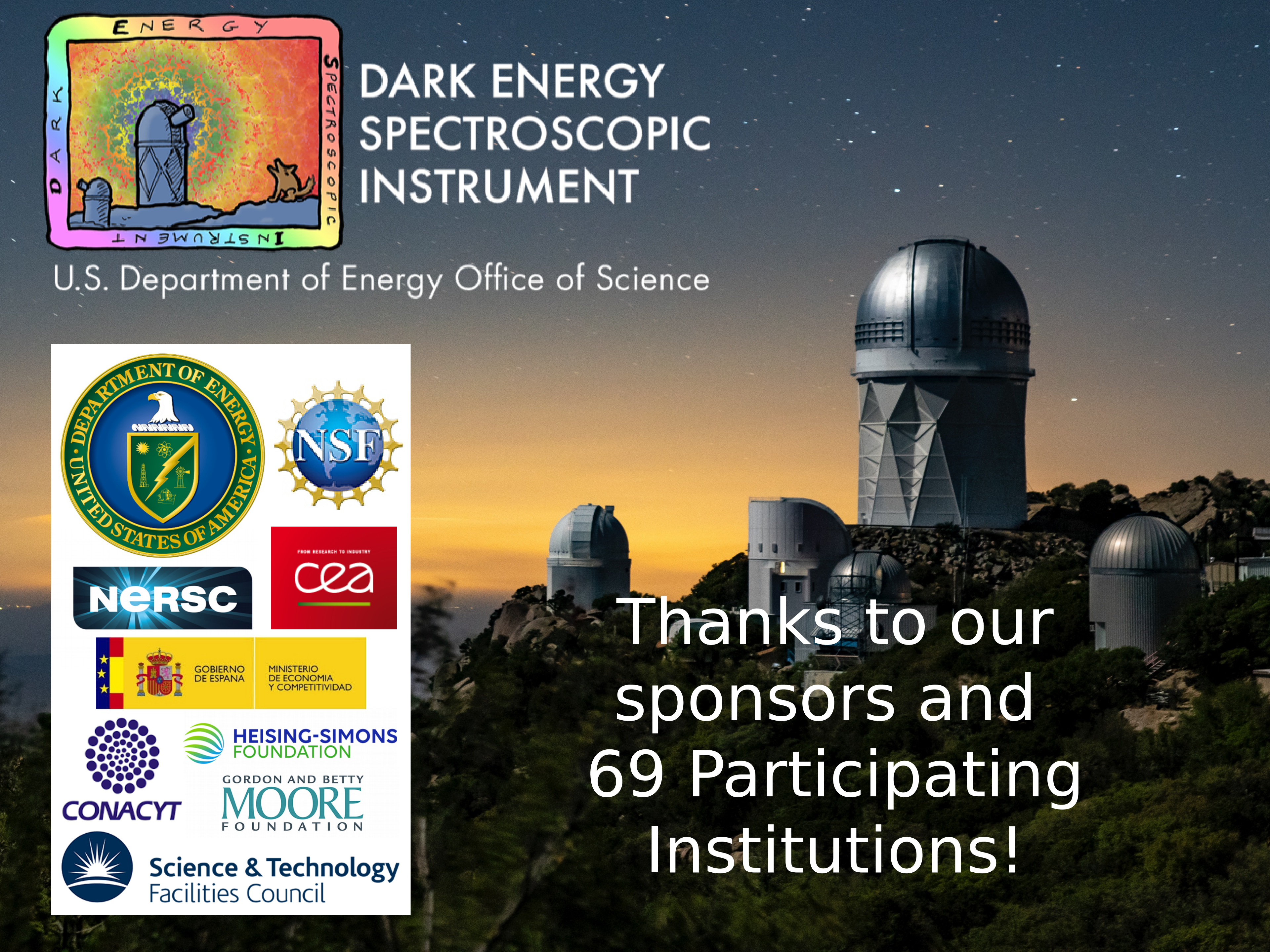


(credit : D. Kirkby)

Forecasts based on the analysis of the Survey Validation data predict we will achieve the project scientific goals in 5 years.
Many scientific results to come !



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