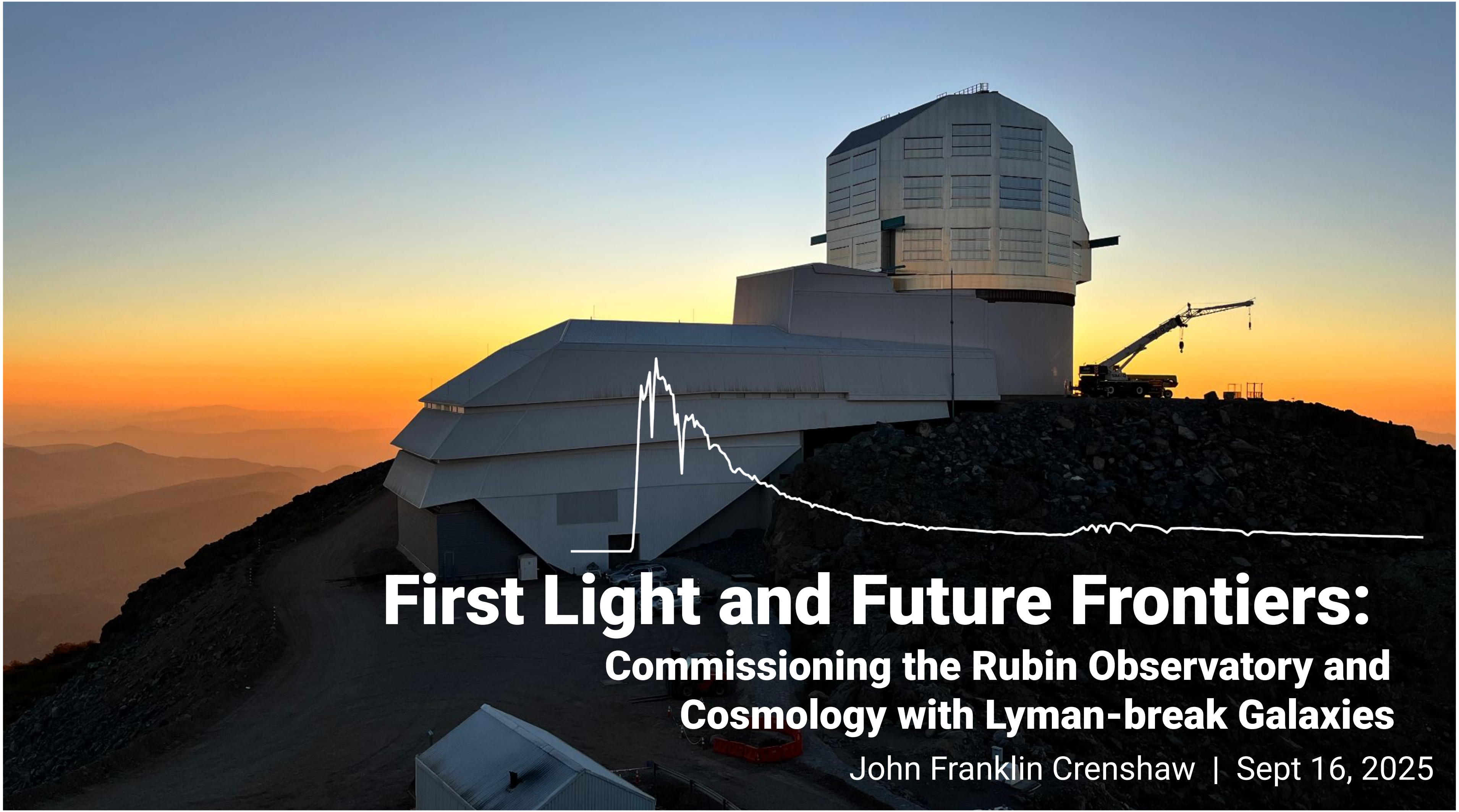


First Light and Future Frontiers:

Commissioning the Rubin Observatory and Cosmology with Lyman-break Galaxies

John Franklin Crenshaw | Sept 16, 2025

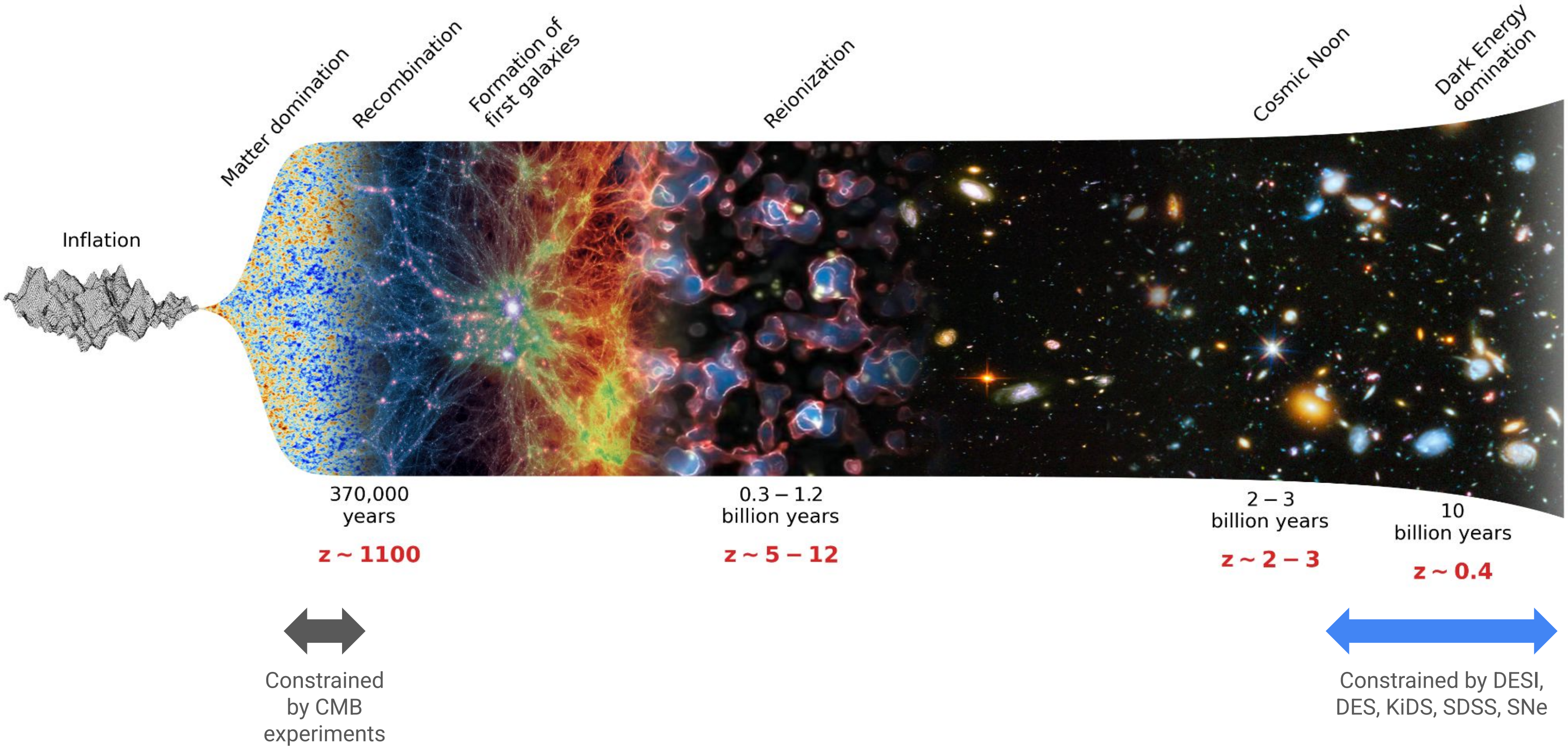

VERA C. RUBIN
LSST

VERA C. RUBIN
FILM

Outline

1. **Cosmology with Lyman-break galaxies**
    - Introduction
    - Forecasts with Rubin
    - Early results from DP1
2. **Commissioning the Rubin Observatory's Active Optics System**
    - Introduction
    - Using AI for wavefront estimation
    - Controlling degeneracies in the system
3. **Current status of commissioning**

Cosmology with Lyman-break Galaxies



Inflation
Matter domination
Recombination
Formation of first galaxies
Reionization
Cosmic Noon
Dark Energy domination
370,000 years
z ~ 1100
0.3 – 1.2 billion years
z ~ 5 – 12
2 – 3 billion years
z ~ 2 – 3
10 billion years
z ~ 0.4
Constrained by CMB experiments
Constrained by DESI, DES, KiDS, SDSS, SNe

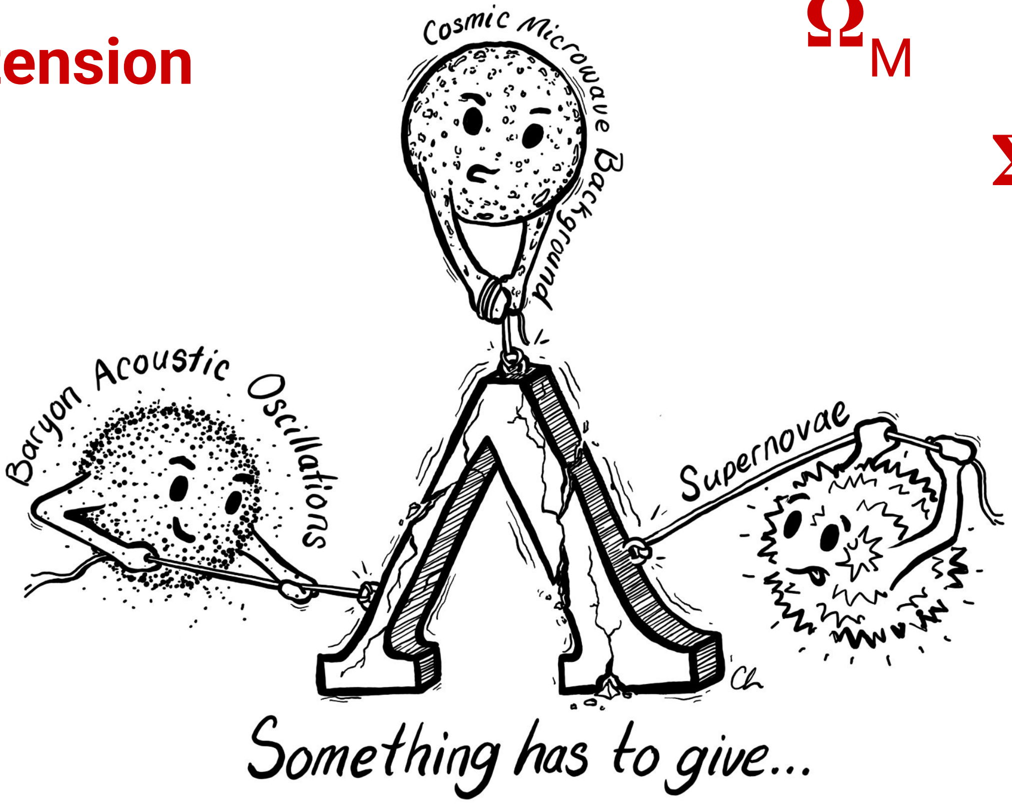
H_0 tension

S_8 tension

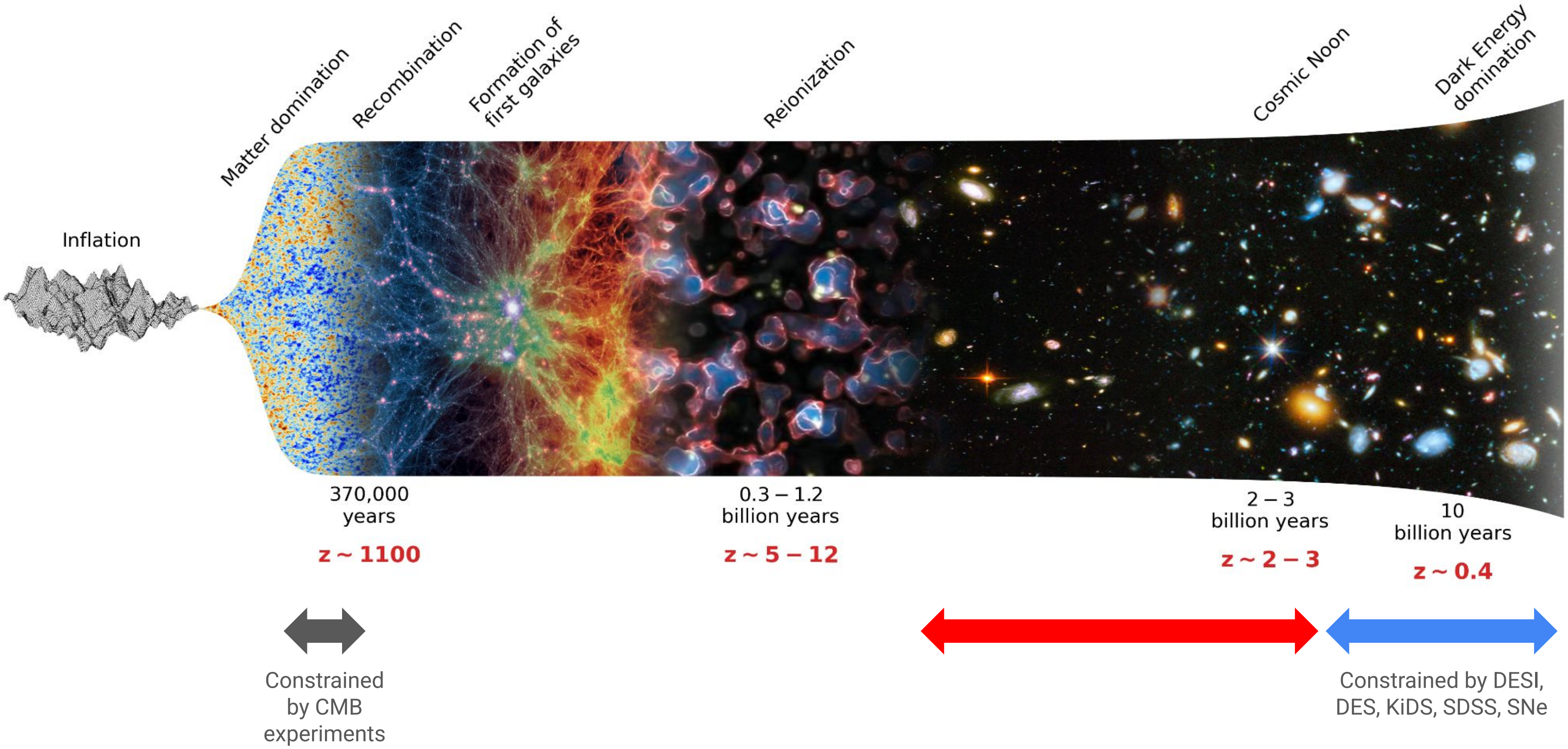
Ω_M

Σm_ν

Evolving dark energy



credit: Claire Lamman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Matter domination
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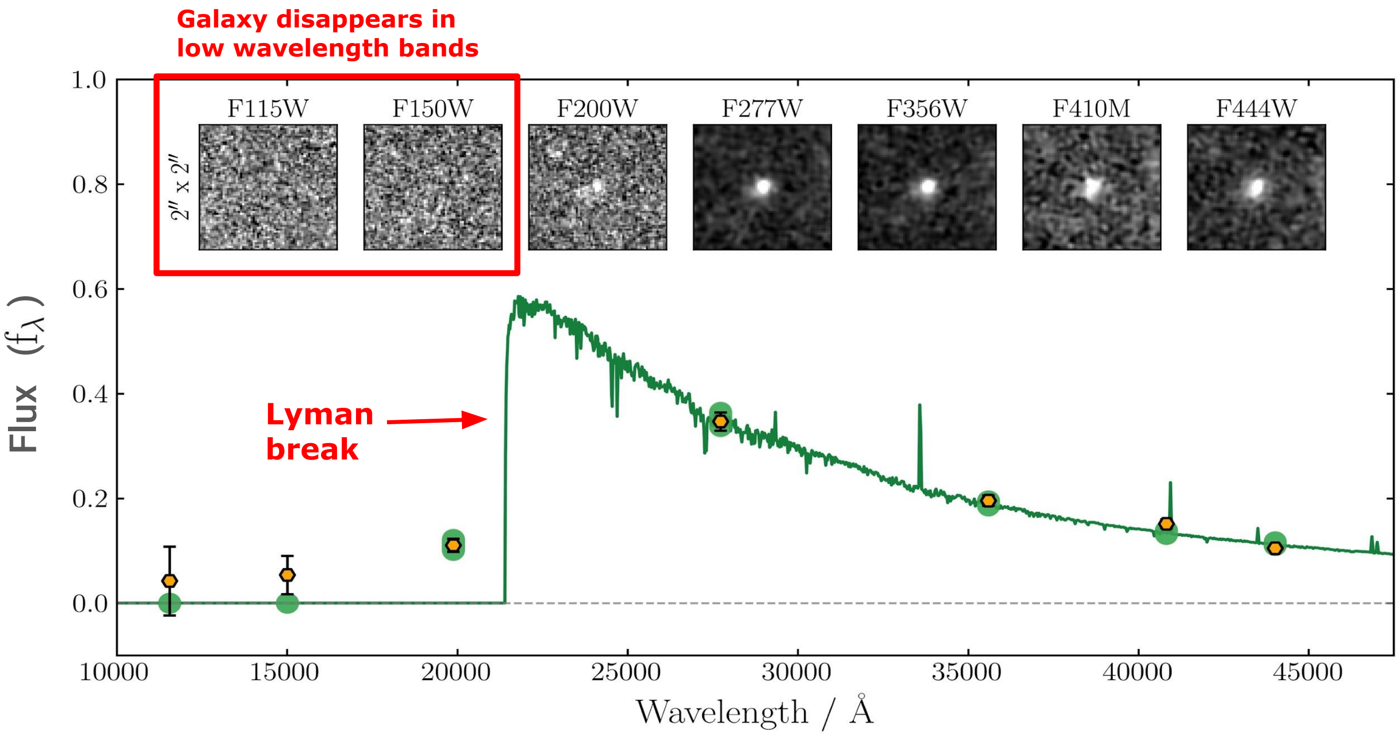
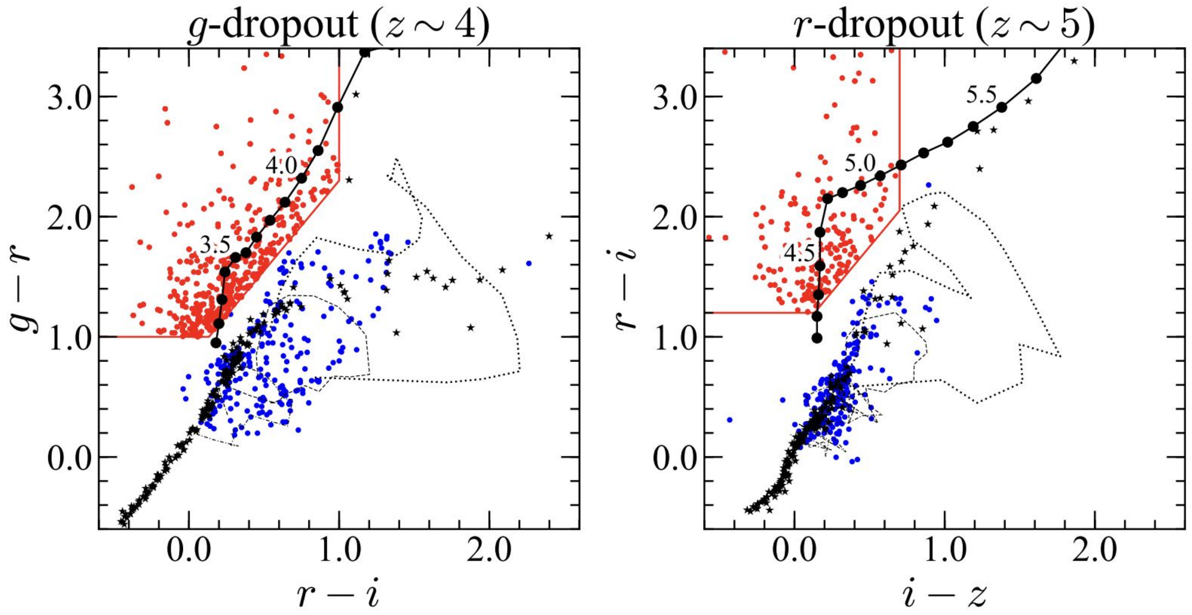
Constrained by CMB experiments
Constrained by DESI, DES, KiDS, SDSS, SNe

High-redshift Lyman-break galaxies (LBGs)



LBG selection with color cuts

Red at short wavelengths due to Lyman break



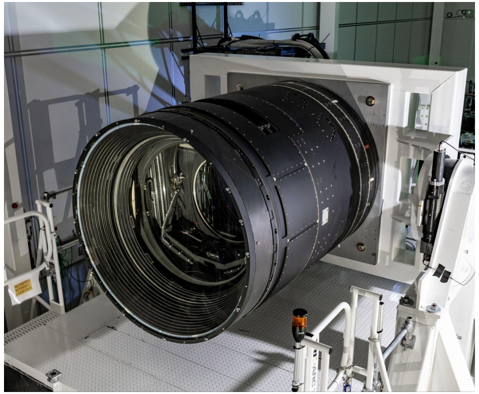
Blue at long wavelengths (star-forming)

Harikane 2021

The Vera Rubin Observatory

Primary mirror: 8.4m
Field of view: 9.6 sq deg
Median seeing 0.67 arcsec
Largest digital camera ever built: 3.2 Gigapixels

LSST Survey: 18,000 deg^2 for 10 years



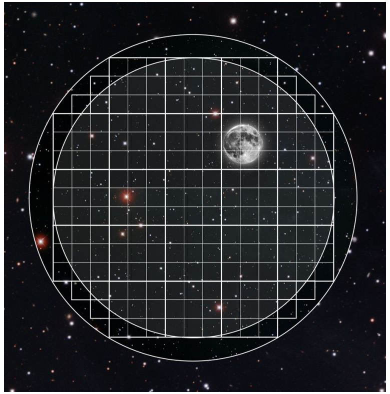
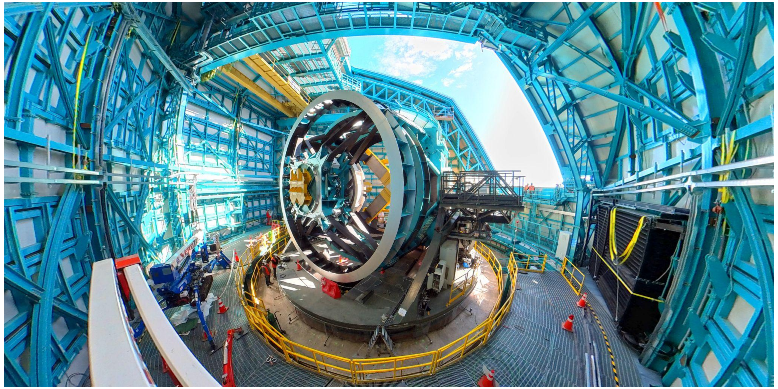


Illustration of the Rubin Camera and focal plane (Credit: SLAC / LSST Project Office)

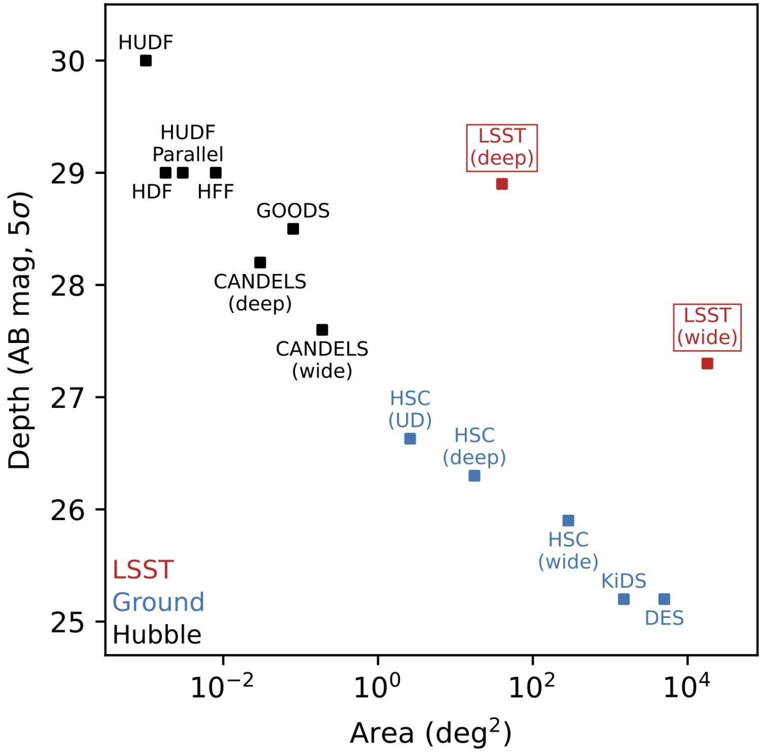


Rubin Observatory in June 2022 (Credit: Rubin Obs/NSF/AURA)

The Legacy Survey of Space and Time (LSST)

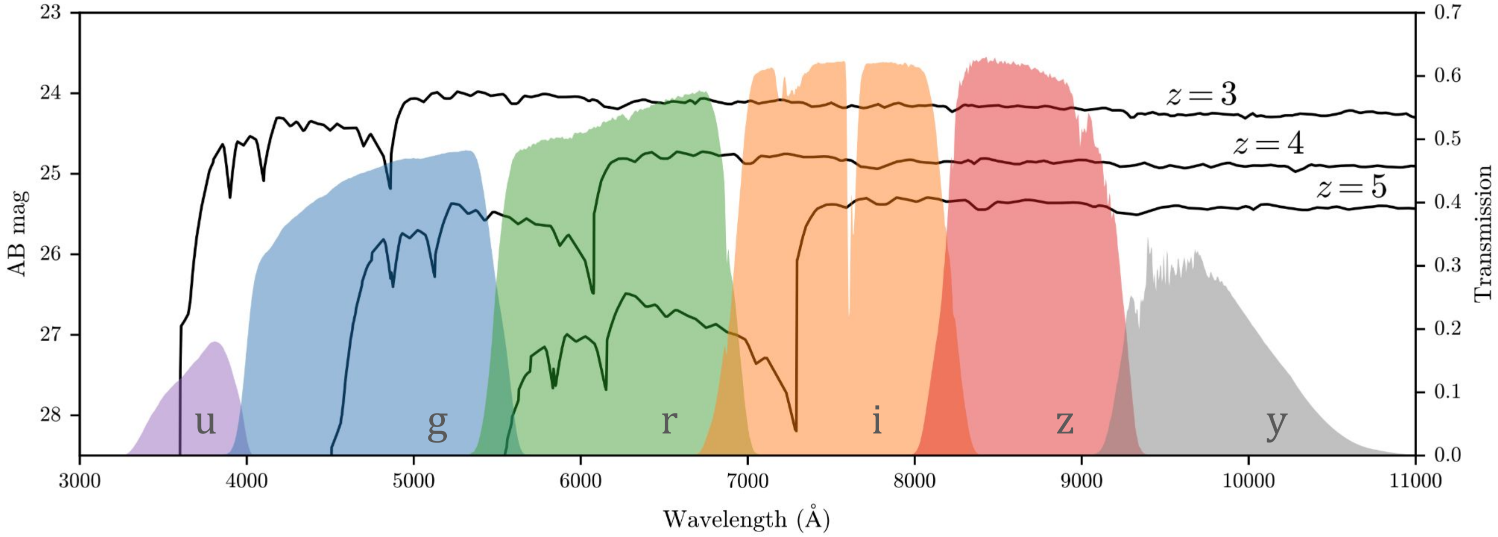
Imaging entire southern sky for 10 years, resulting in a survey of unprecedented width and depth

Transformational for cosmology, extragalactic astrophysics, time-domain astronomy, solar system science, galactic astronomy, and more



Detecting LBGs with LSST

Deep imaging in 6 photometric bands will enable detection of ***150 million*** LBGS between *2 < z < 8*

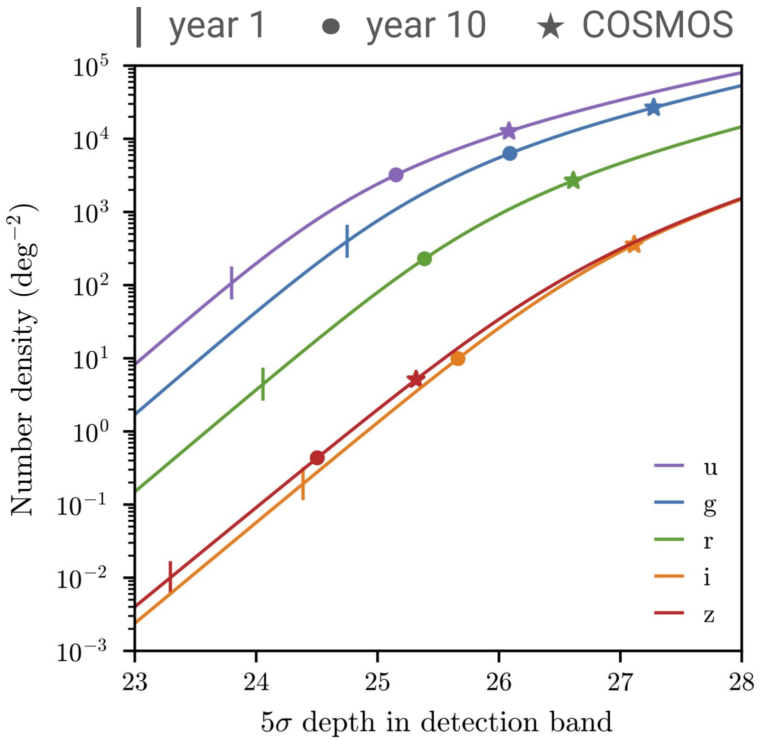


LSST will detect ~150 million high-redshift LBGs

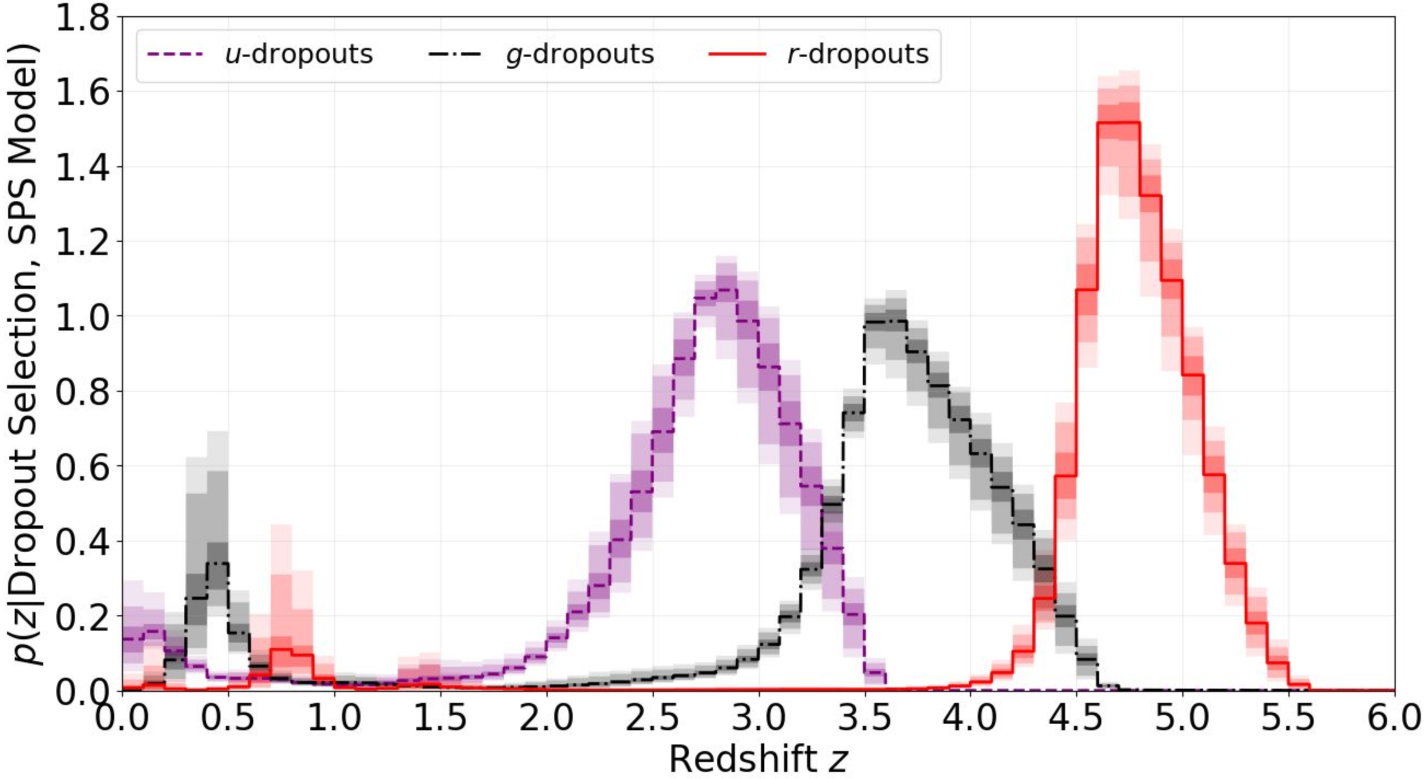
Forecast LSST number densities:

	y1	y10	COSMOS
$z \sim 3$	110	3200	13,000
$z \sim 4$	400	6300	27,000
$z \sim 5$	4.4	230	2,700

all numbers are deg^{-2}



Crenshaw 2025


u-dropouts
g-dropouts
r-dropouts
p(z|Dropout Selection, SPS Model)
Redshift z
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Petri 2025

Cosmology with dropout selection: Straw-man surveys & CMB lensing

M. J. Wilson[a,b] **and Martin White**[a,b,c]

[a]Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
[b]Berkeley Center for Cosmological Physics, UC Berkeley, CA 94720, USA
[c]Department of Physics, University of California, Berkeley, CA 94720, USA

Parameter constraints from cross-correlation of CMB lensing with galaxy clustering

Marcel Schmittfull[1] and Uroš Seljak[2,3,4]

[1]*Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*
[2]*Berkeley Center for Cosmological Physics, University of California, Berkeley, CA 94720, USA*
[3]*Department of Astronomy and Department of Physics, University of California, Berkeley, CA 94720, USA*
[4]*Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 93720, USA*

Clustering of high-z galaxies can constrain evolution of σ_8, neutrino mass, f_{NL}, evolution of dark energy, and more!

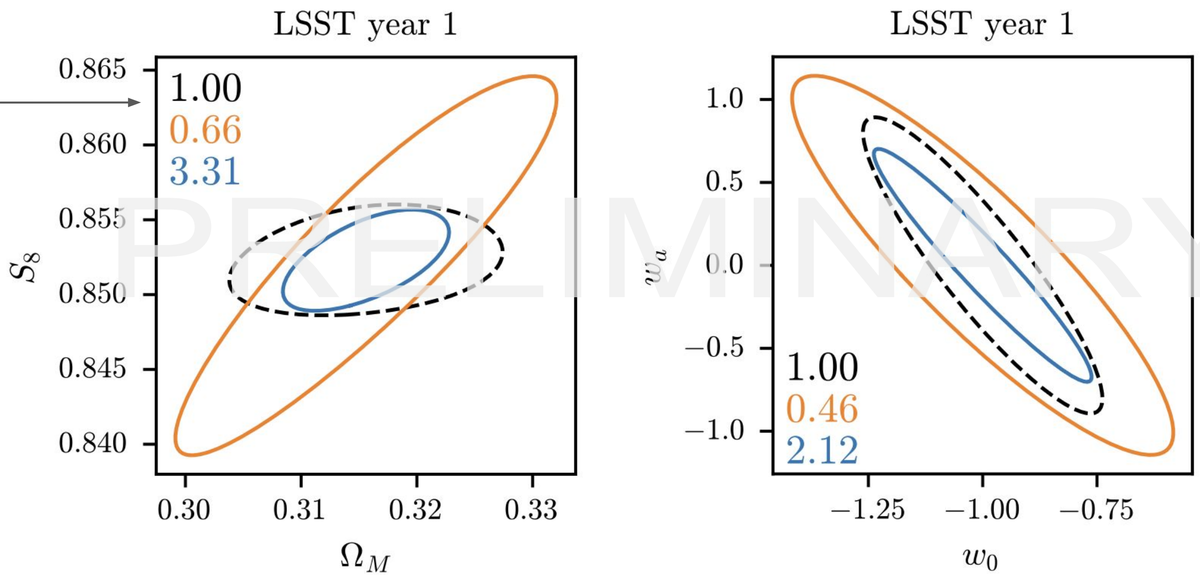
Towards Neutrino Mass from Cosmology without Optical Depth Information

Byeonghee Yu,[1] Robert Z Knight,[2] Blake D. Sherwin,[3,4] Simone Ferraro,[1,5] Lloyd Knox,[2] and Marcel Schmittfull[6]

[1]*Berkeley Center for Cosmological Physics, Department of Physics, University of California, Berkeley, CA 94720, USA*
[2]*Physics Department, University of California, Davis, CA 95616, USA*
[3]*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge CB3 OWA, UK*
[4]*Kavli Institute for Cosmology Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[5]*Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720, USA*
[6]*Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*

Even in year 1, LBGs have potential to dramatically improve LSST constraints

Relative Figure of Merit



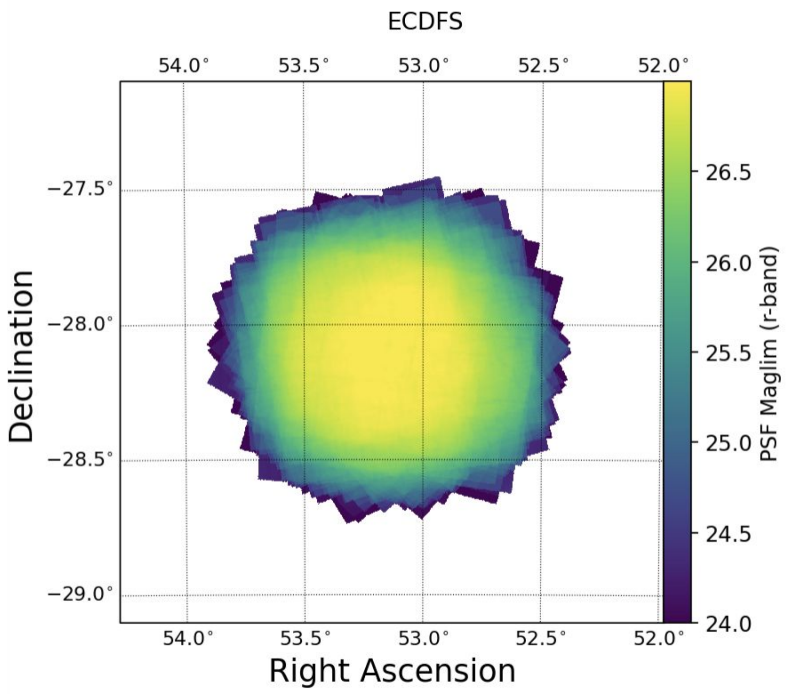
low-z 3x2pt

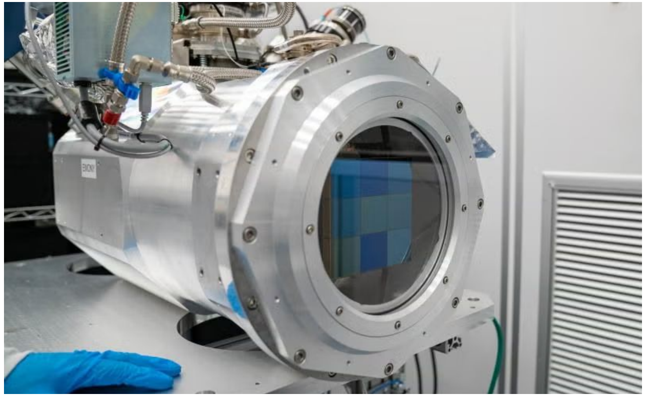
high-z 3x2pt

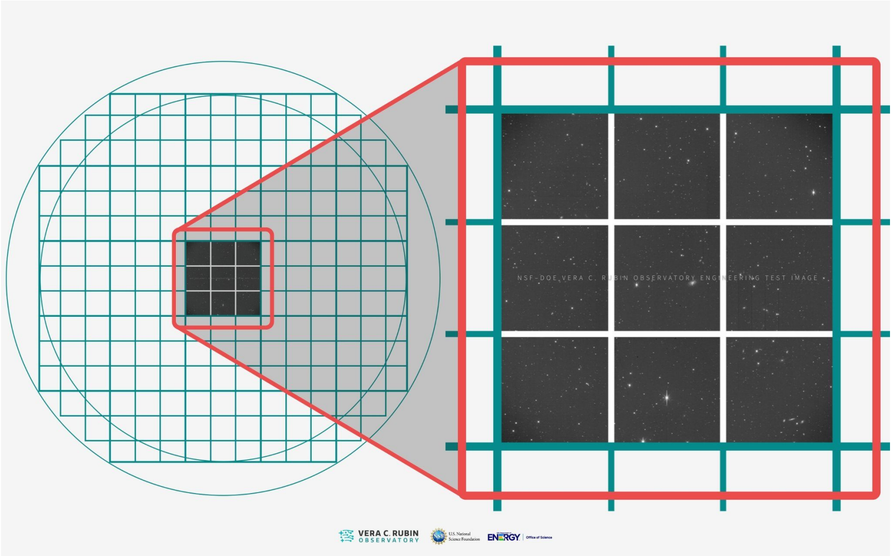
joint forecast

*Cross-correlation with Simons Obs CMB lensing; includes marginalizing over interloper fraction, mean redshift of LBG population, galaxy bias of LBGs and interlopers, magnification bias; includes a model for LBG non-uniformity

DP1 with ComCam

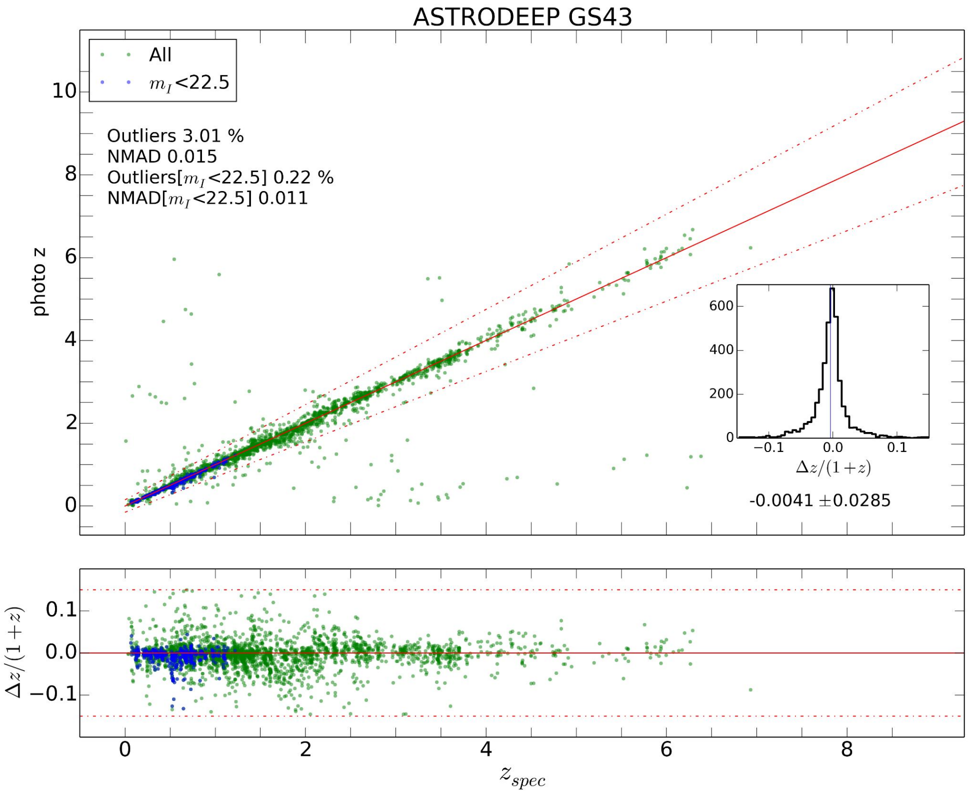






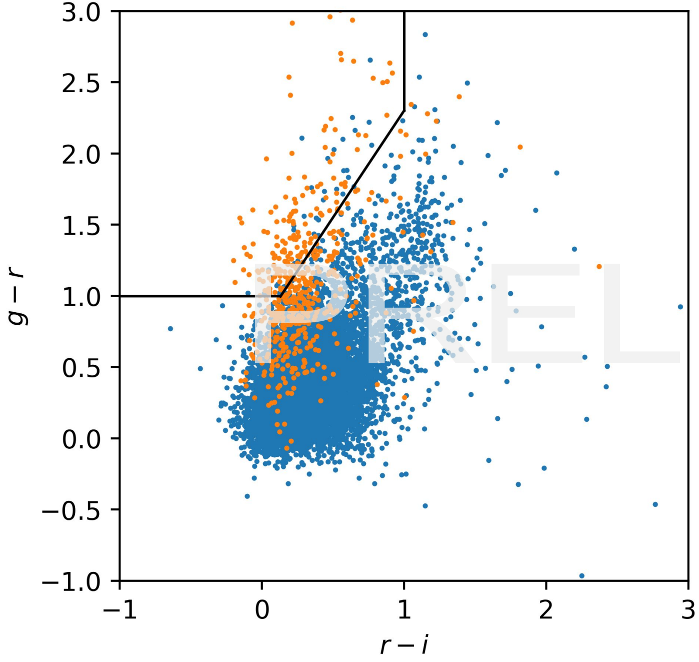
Testing LBG selection by cross-matching to ASTRODEEP many-band survey

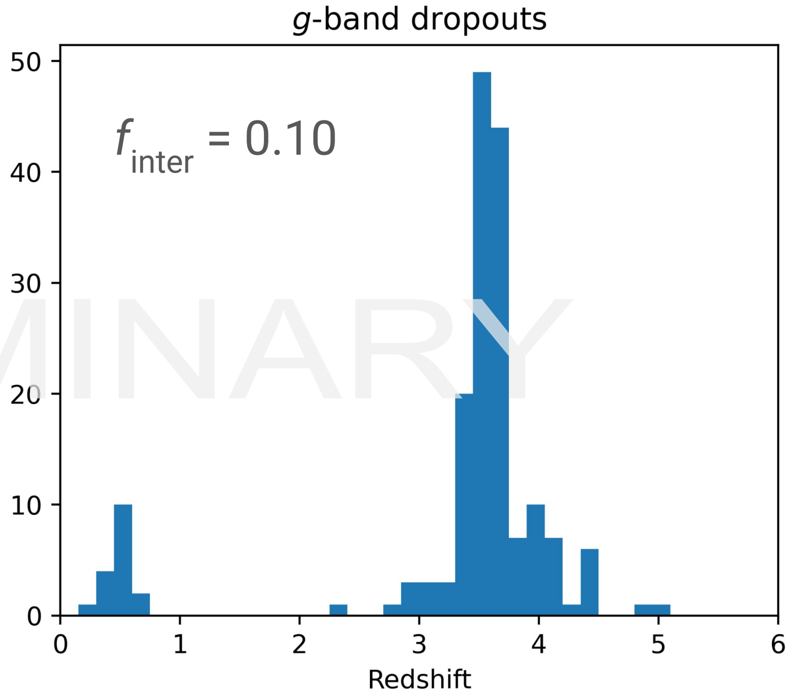
25 wide bands + 18 medium bands including HST, CTIO, Subaru, Spitzer, VIMOS, Magellan, VLT



Merlin 2021

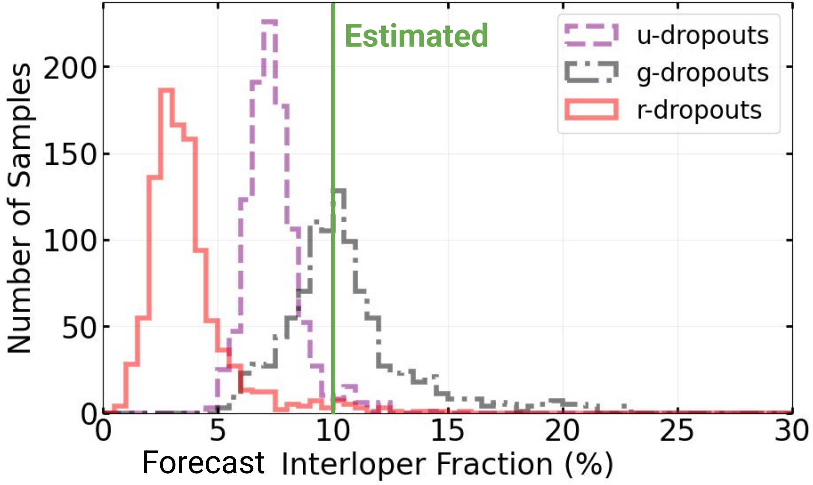
DP1 *g*-dropouts





Good match with forecasts!

- Year 10 g-dropout number density:
  - Forecast ~ 6000/deg^2 (*Crenshaw 2025*)
  - Estimated ~ 5000/deg^2 (including reduction by 10% for interlopers)
- Year 10 g-dropout interloper fraction:

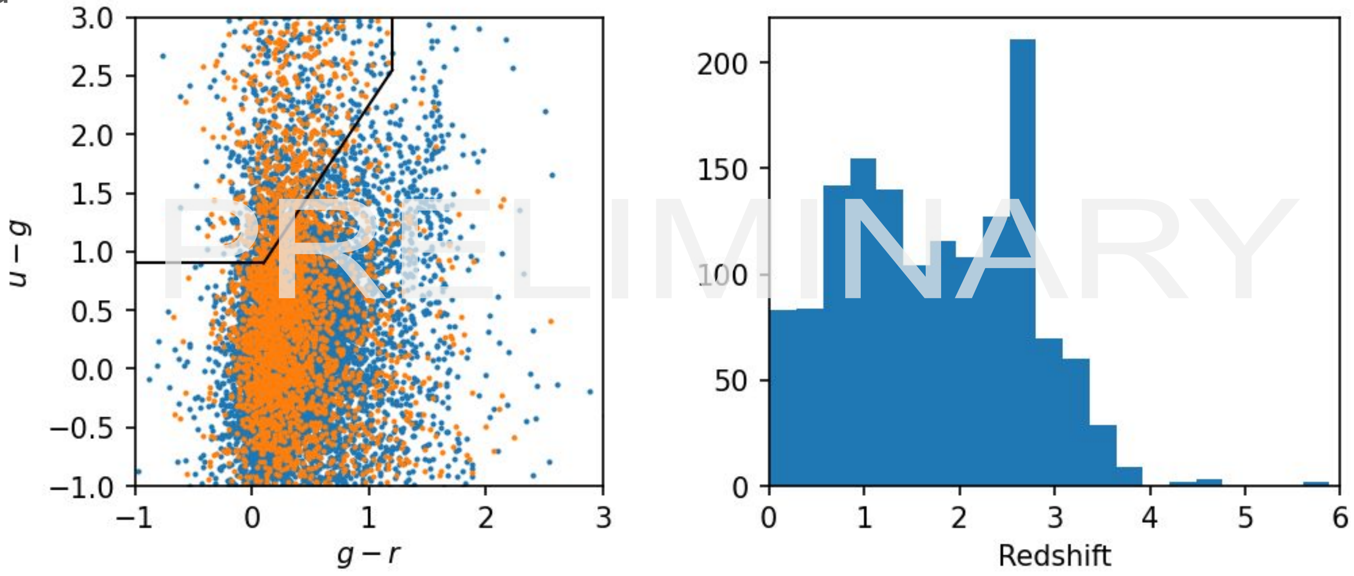


Petri 2025

DP1 *u*-dropouts…

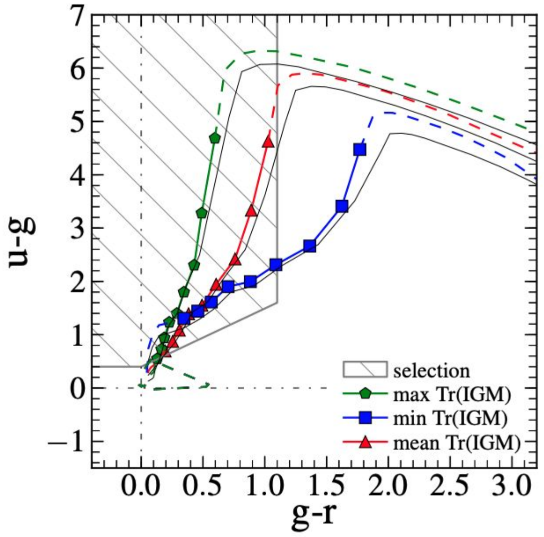
ComCam *u* band is… not great!

Luckily LSSTCam *u* band photometry in COSMOS looks much better (not yet public)



Where do we go from here?

- Early results from DP1 are consistent with LBG forecasting!
- Need to start preparing for analysis with LSST year 1 (data release in late ‘27/early ‘28)
- My biggest concern is photo-z calibration:
    - What can we accomplish with spec-z’s DESI-II pilot surveys?
    - What can we accomplish with deep multiband surveys?
    - How precise does our photo-z calibration need to be to get interesting science out? (not as precise as low-z 3x2pt)
    - How to angle photo-z anisotropies due to varying depth of the IGM?



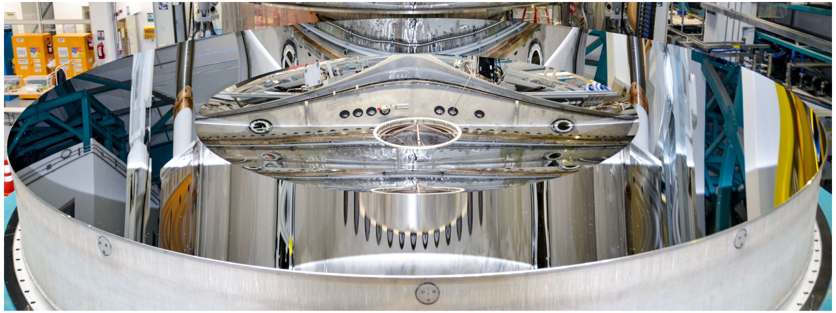
Thomas 2021

Commissioning the Active Optics System

Gravitational and thermal perturbations

- Rubin carefully designed to deliver high image quality across wide field of view
- Gravitational and thermal perturbations destroy image quality
    - Everything bends under gravity; depends on telescope position
    - Bulk temperature and thermal gradients modulate bending
    - Raising temperature expands metal

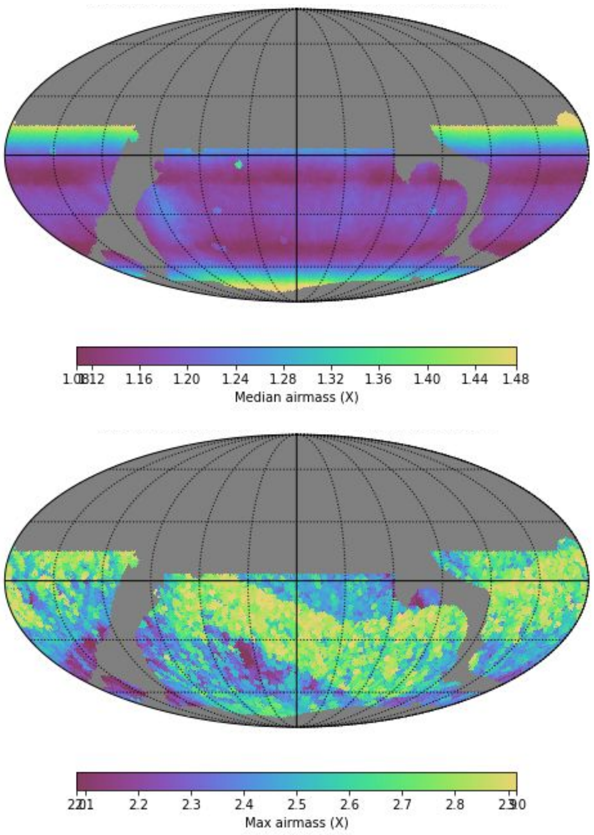
Joint primary-tertiary mirror (M1M3)



Telescope mount

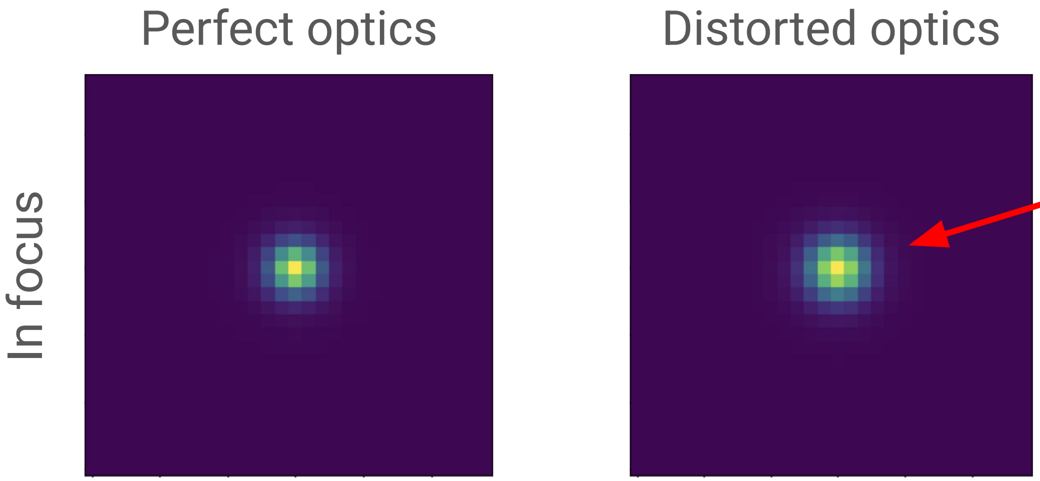
Impact on Cosmology

- Degrades PSF; reduces survey depth
- Correlated with elevation angle and temperature, both correlated with position on sky
- **If uncorrected, reduces number and quality of high-redshift galaxies; non-trivial correlations contaminate cosmology signal!**



Credit: Lynne Jones

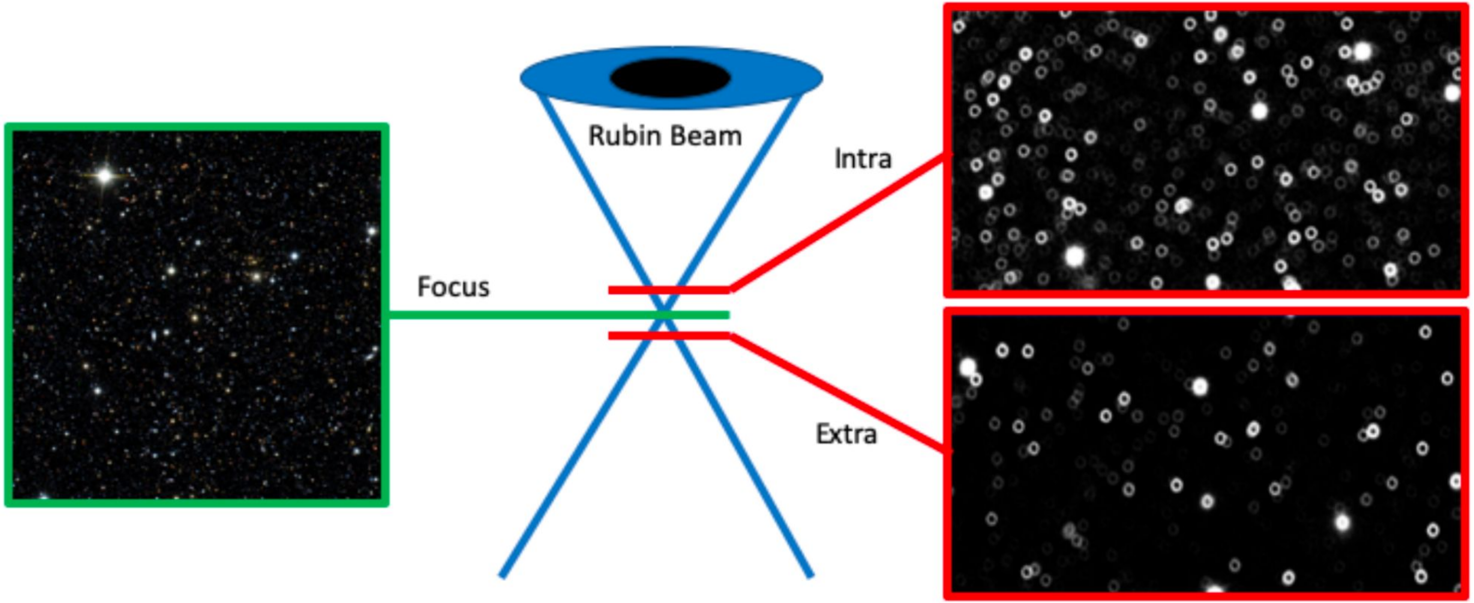
Why out of focus?



The PSF is bigger

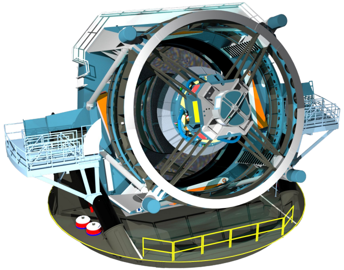
Why?

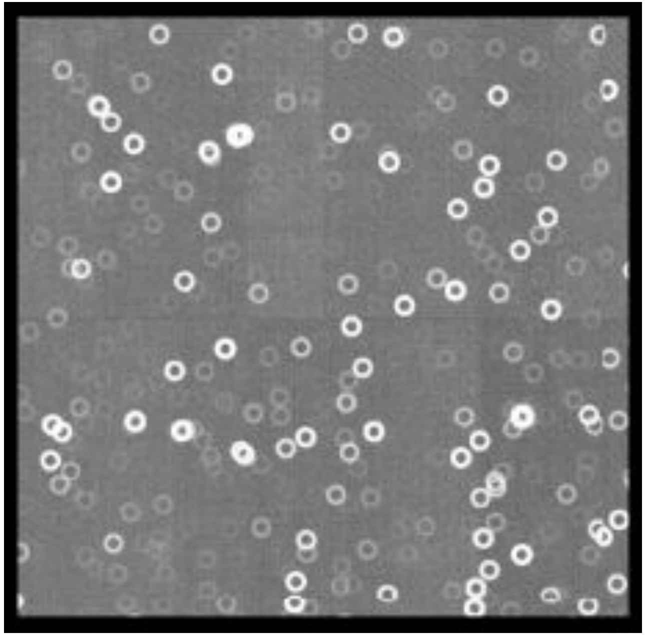
atmosphere?



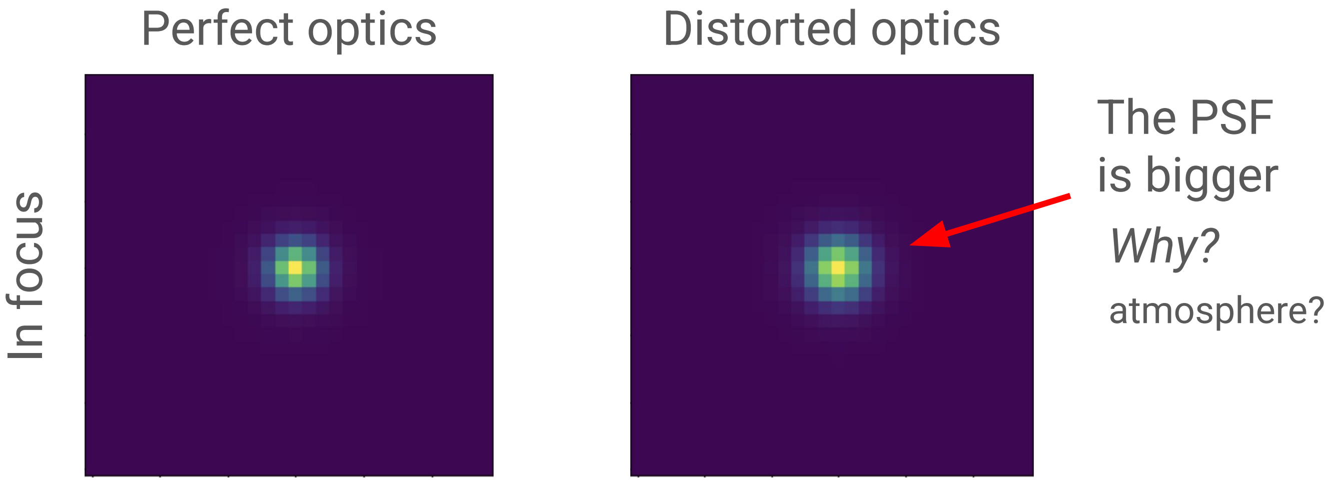
Credit: Thomas 2021

Bokeh





Why out of focus?



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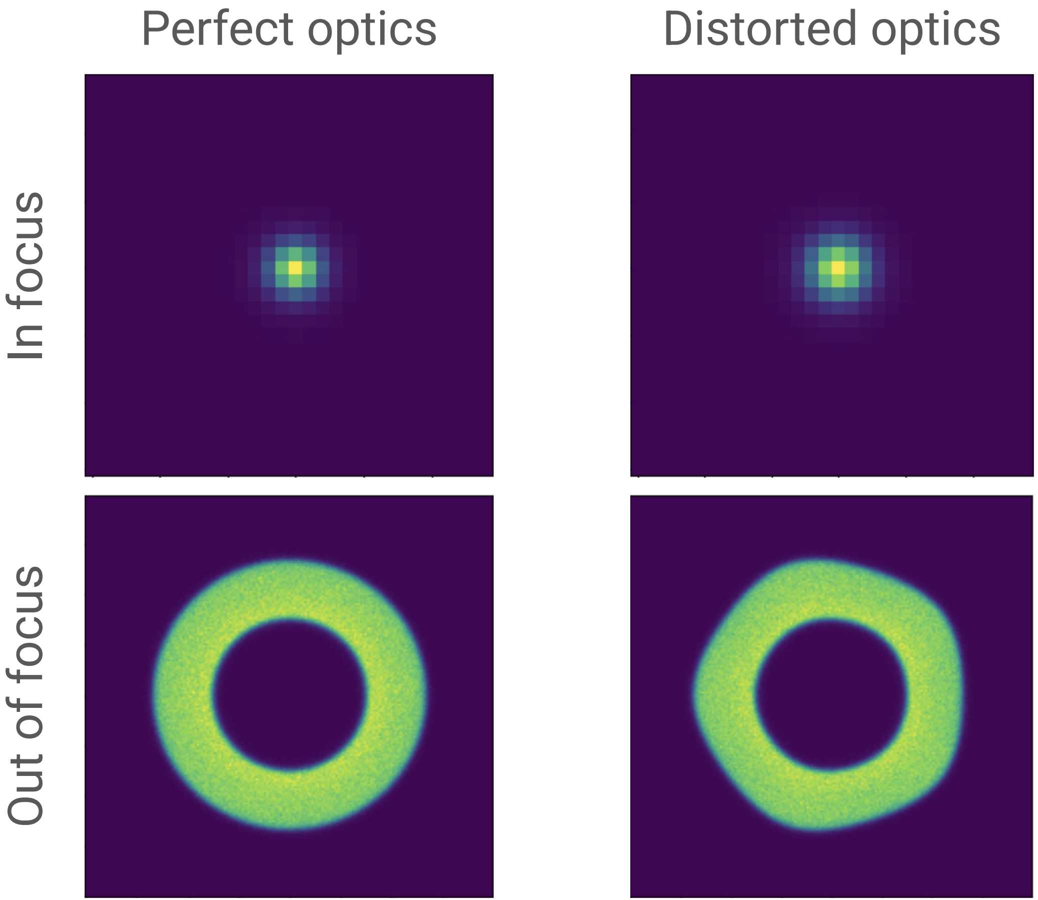
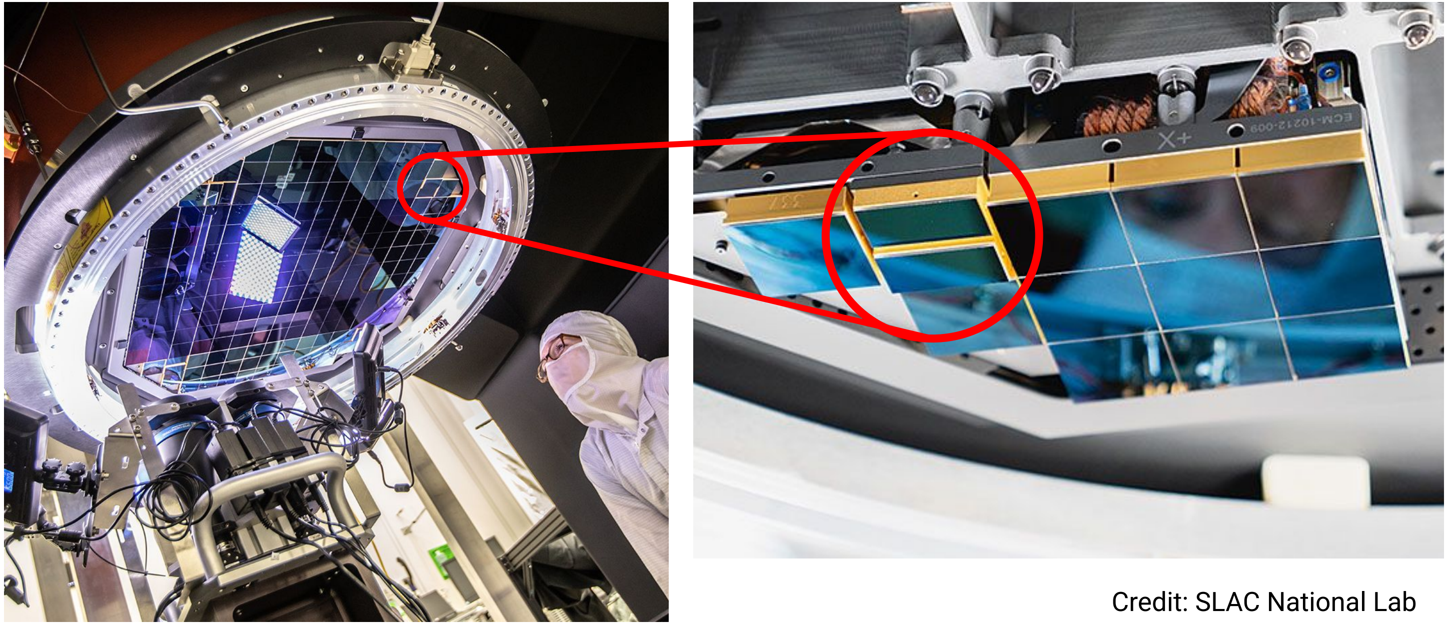


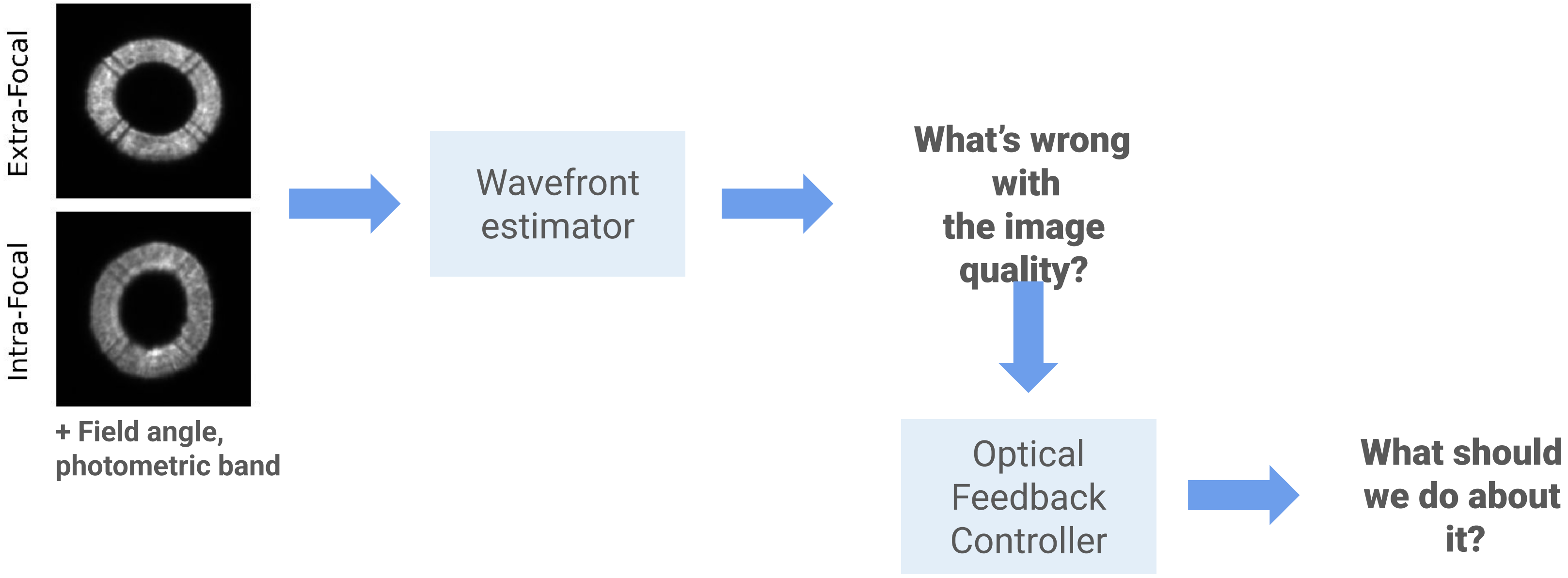
Pentafoil!

Wavefront sensors

Out-of-focus sensors at corners provide information about optical aberrations



Credit: SLAC National Lab



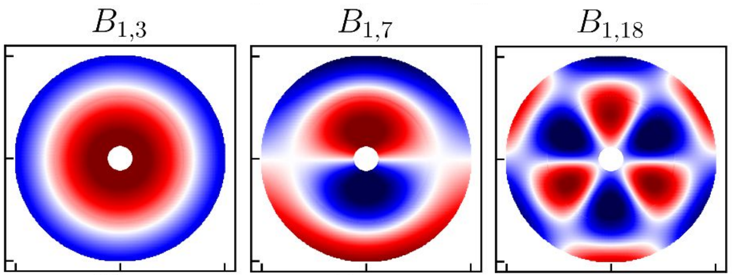
Extra-Focal
Intra-Focal
+ Field angle, photometric band
Wavefront estimator
What's wrong with the image quality?
Optical Feedback Controller
What should we do about it?

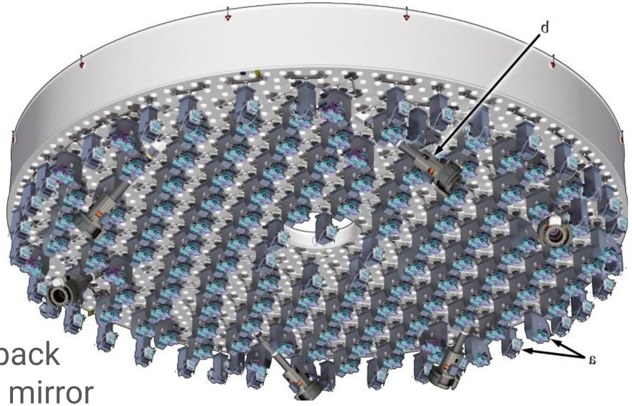
Active Optics

- Active optics correct optical alignment and mirror figures
- Hexapods control positions and angles of M2 and camera
- 228 actuators control shapes of mirrors
- Used to control 50 eigenmodes of the system
  (cf. 5 modes on DECam 😳)

Camera hexapod

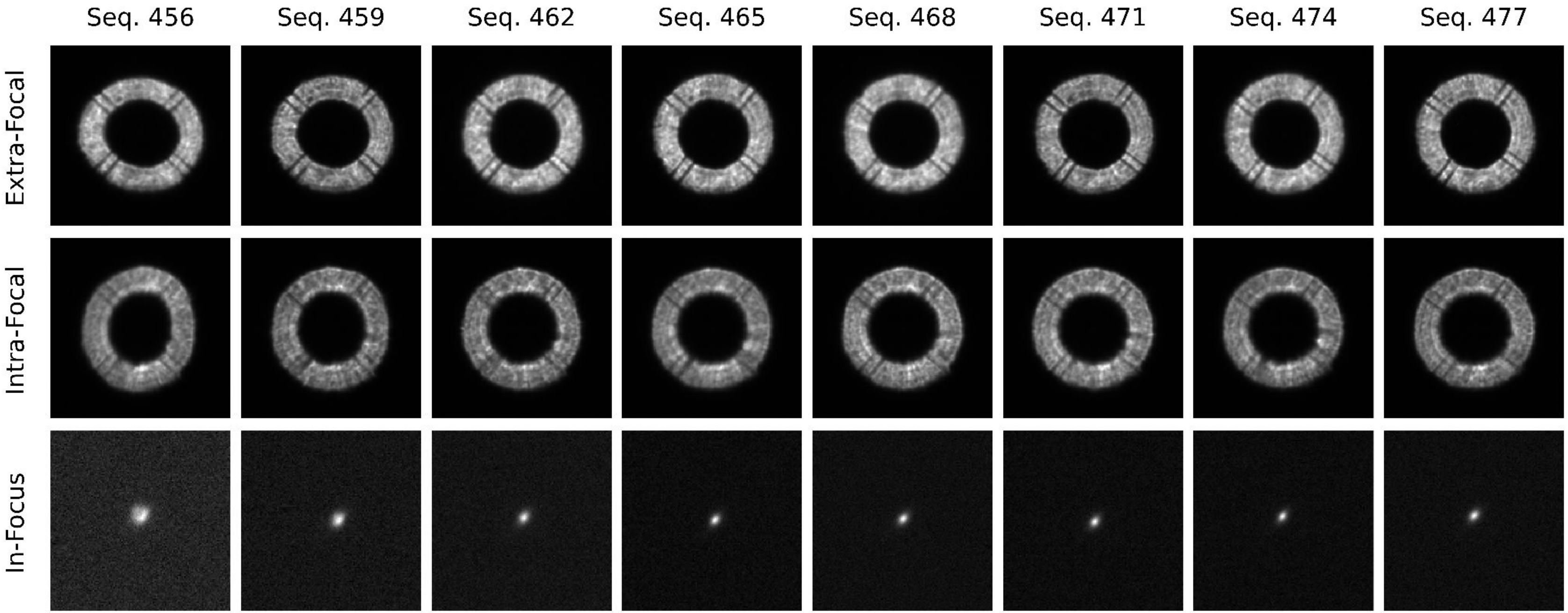
Example bending modes





Actuators on back of the primary mirror

Example with real data



Credit: Guillem Megias Homar

Current status

- Active optics working well!
    - Can put telescope in focus and deliver decent image quality
    - Were able to achieve sub-arcsecond imaging very quickly!
- Challenges
    - Wavefront estimation (i.e. “what’s wrong with the optics) is noisy
    - Imperfect interpolation of the full focal plane from the wavefront sensors
    - Need to speed the system up
    - Decide which degrees of freedom (out of 50) to control

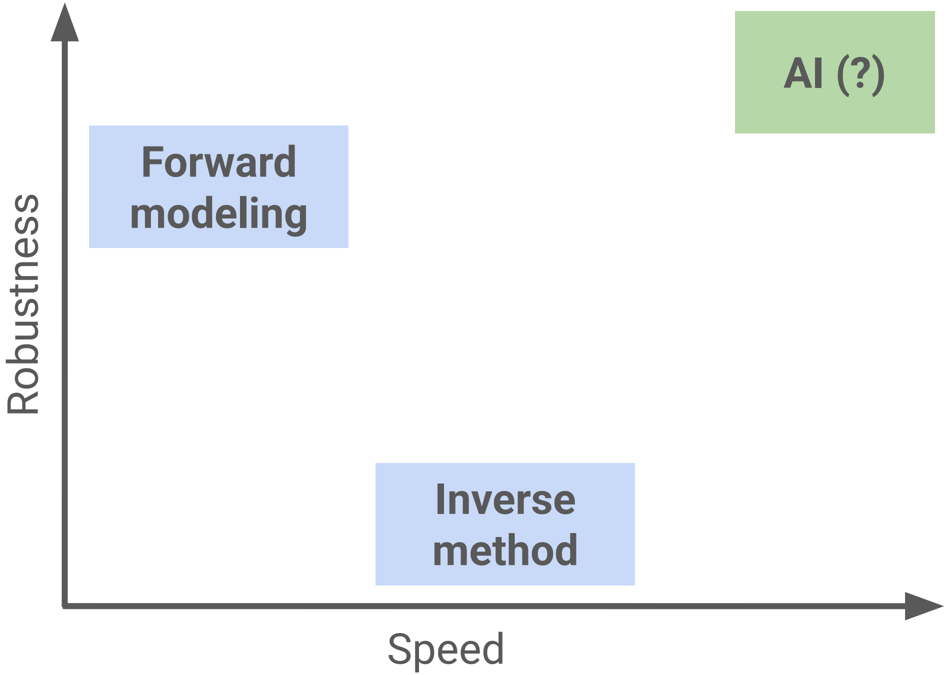
Wavefront estimation

Fractional changes in beam intensity are sourced by curvature in wavefront

$$\nabla^2 W = \frac{1}{I}\frac{\partial I}{\partial z}$$

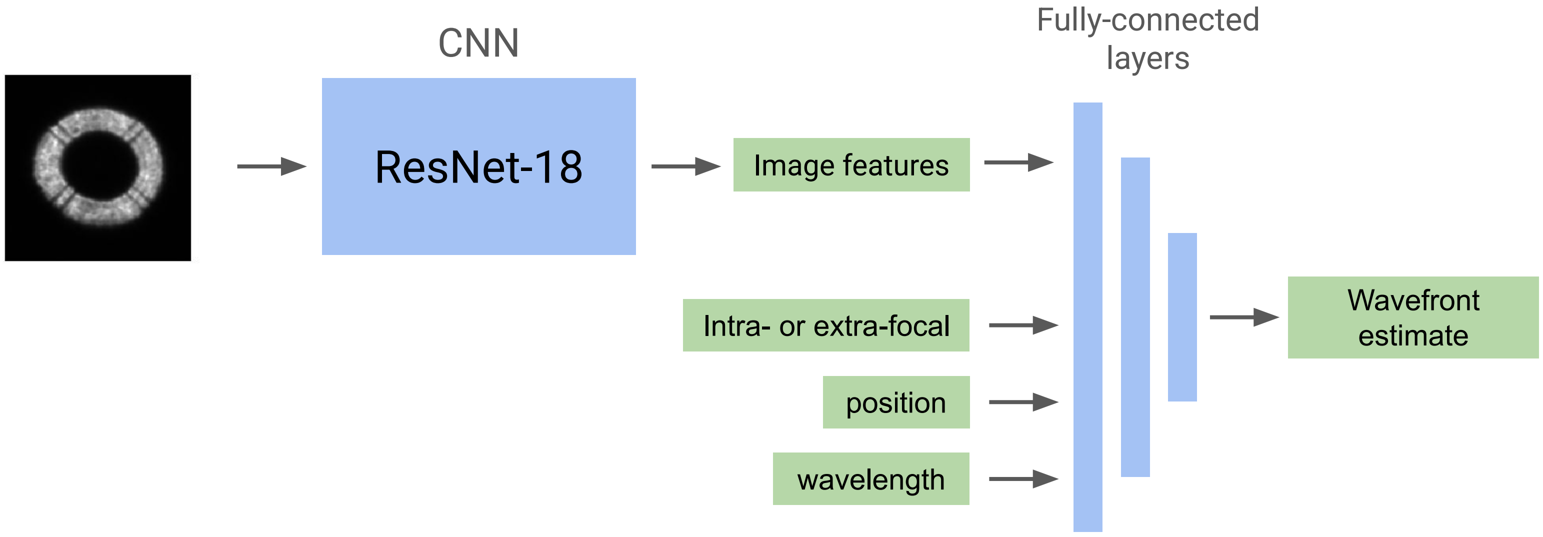
Methods:

1. Forward modeling: robust to any features you can model; slow
2. TIE Solver: not as robust; faster
3. **AI: potentially most robust; fastest**



AI wavefront estimator

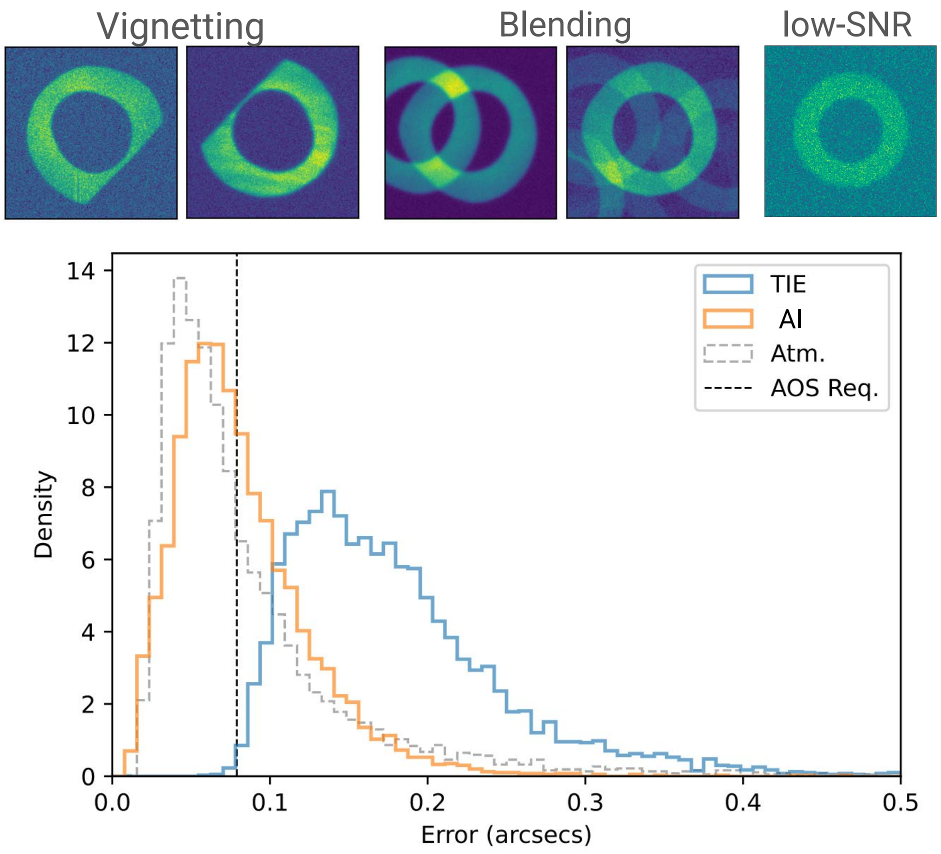
Adapting a “foundation model” trained on images of real-world objects outperformed specially-designed networks



Trained on Rubin simulations

The AI estimator:

- median error 2x lower
- 5x better with vignetting
- 14x better with blending
- 40x faster!



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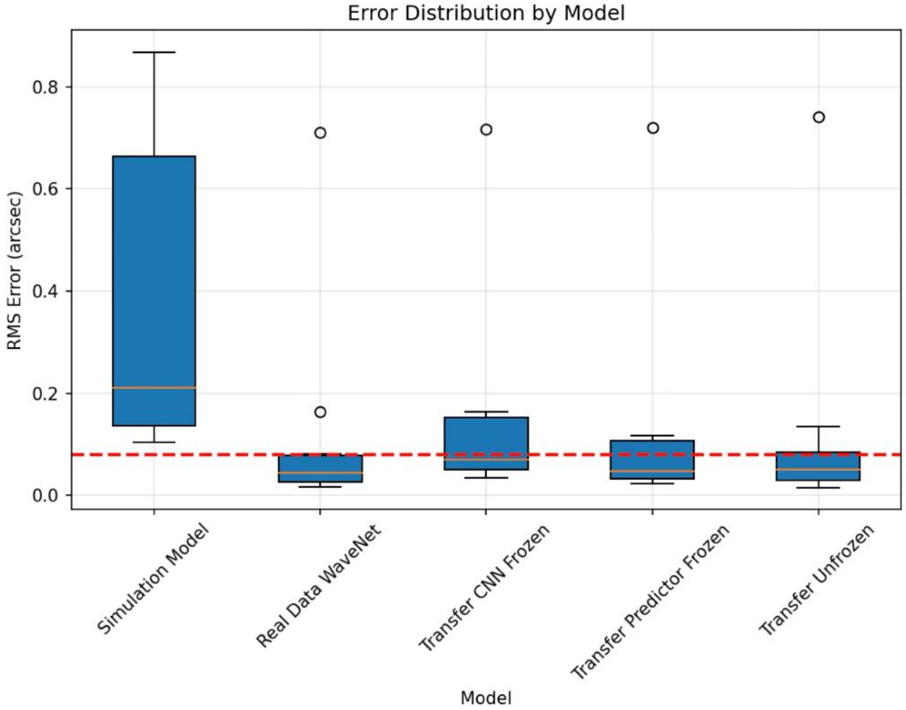
Hurum Tohfa
3rd year PhD @ UW

Adapting to real data

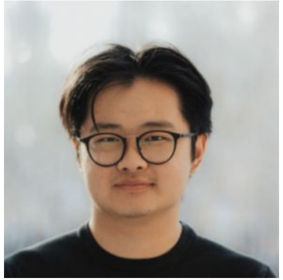
- Model trained on simulations struggles with real data
- Used real commissioning data for transfer learning
- Tested different strategies
- Testing on telescope tomorrow evening!



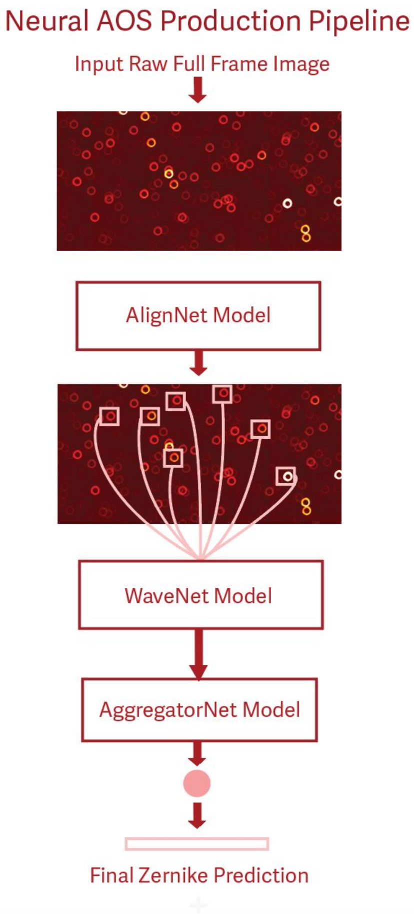
Testing alternative architectures

- Peter and Josh working on an AI model that incorporates more of the AOS pipeline
- Trained on newer, more sophisticated simulations – will be interesting to see if that brings improvements
- Hopefully will be tested after 1 month engineering shutdown

Peter Ma
Berkeley PhD student

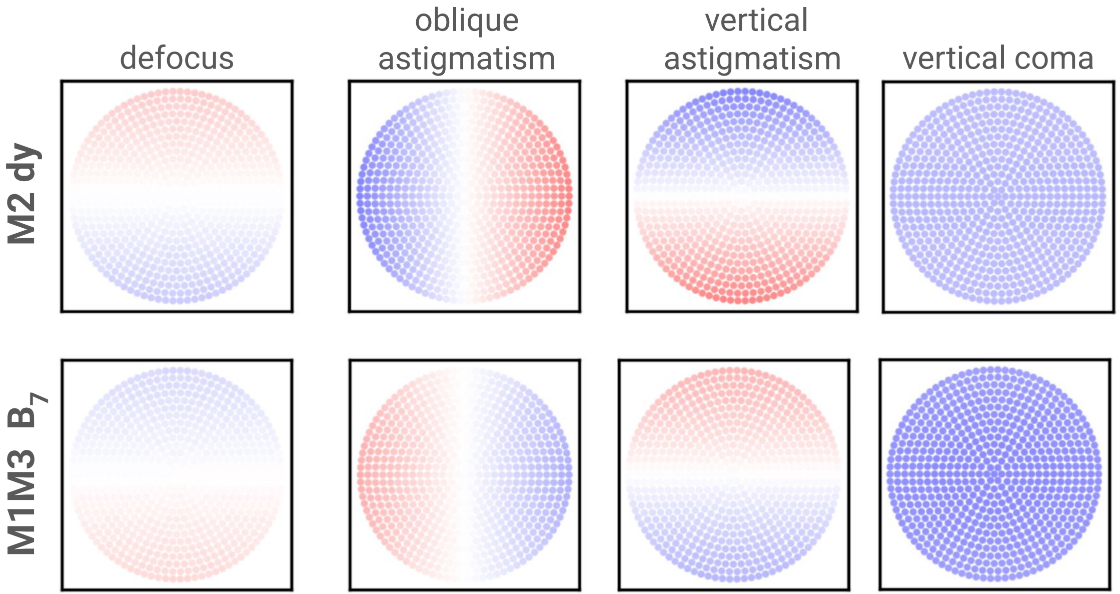


Josh Bloom
Berkeley faculty



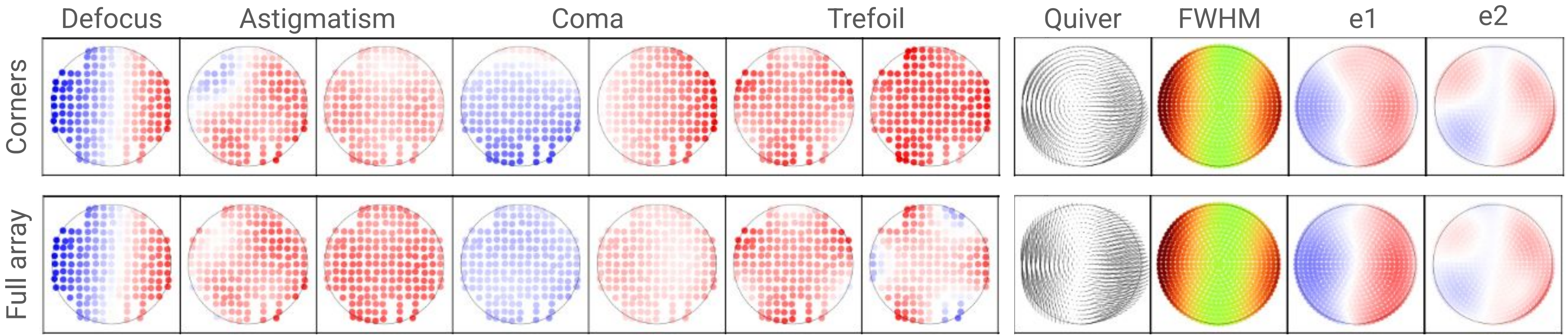
Future for AI in the AOS

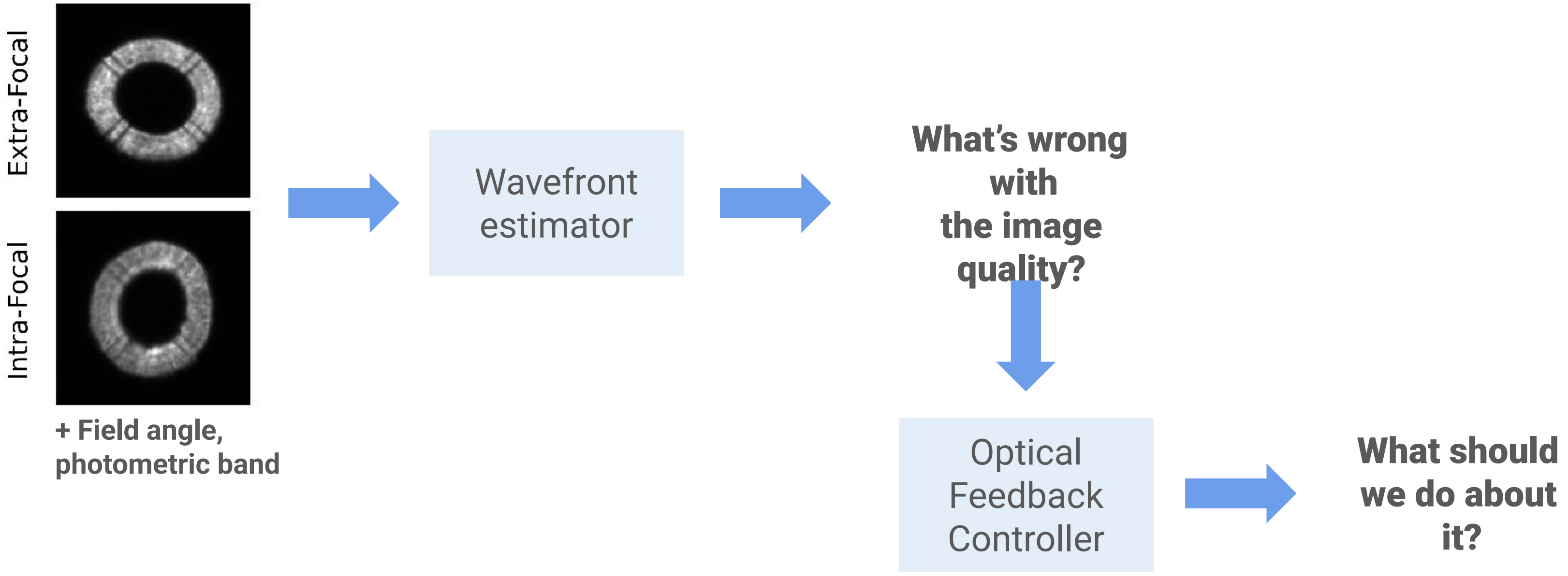
- Fitting entire field at once to take advantage of natural modes of the system



Future for AI in the AOS

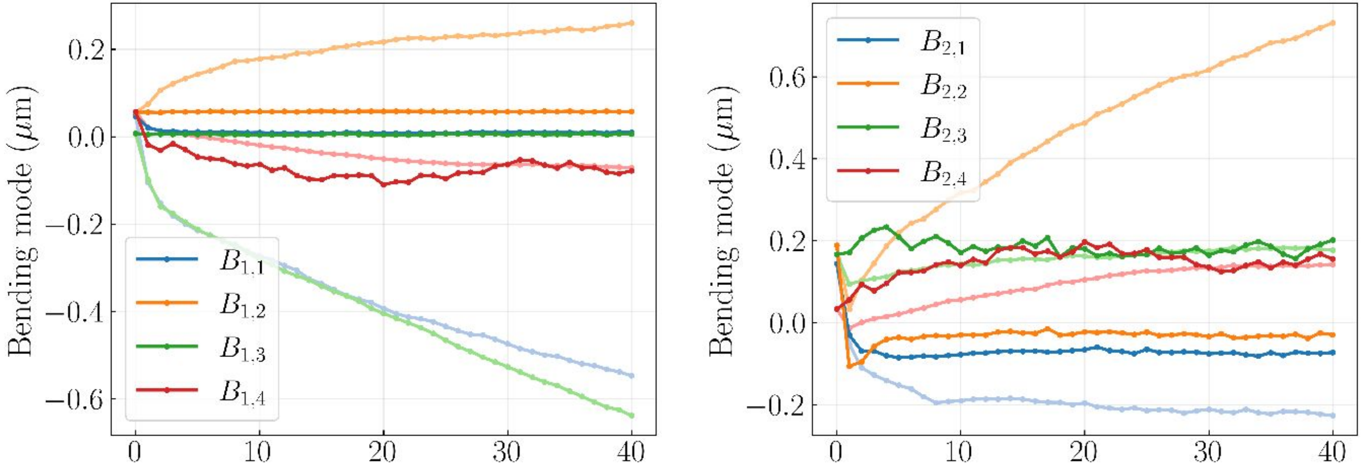
- Fitting entire field at once to take advantage of natural modes of the system
- Leveraging speed of AI to process *as much information as possible*




Extra-Focal
Intra-Focal
+ Field angle,
photometric band
Wavefront estimator
What's wrong with
the image quality?
Optical Feedback Controller
What should we do about it?

Degeneracies in the control system

- Large and complex system – 50 degrees of freedom to control! (cf. DECam only had 5)
- Need to be careful – some modes are degenerate (i.e. don't measurably change image quality)
- How many modes are (effectively) degenerate depends on noise level



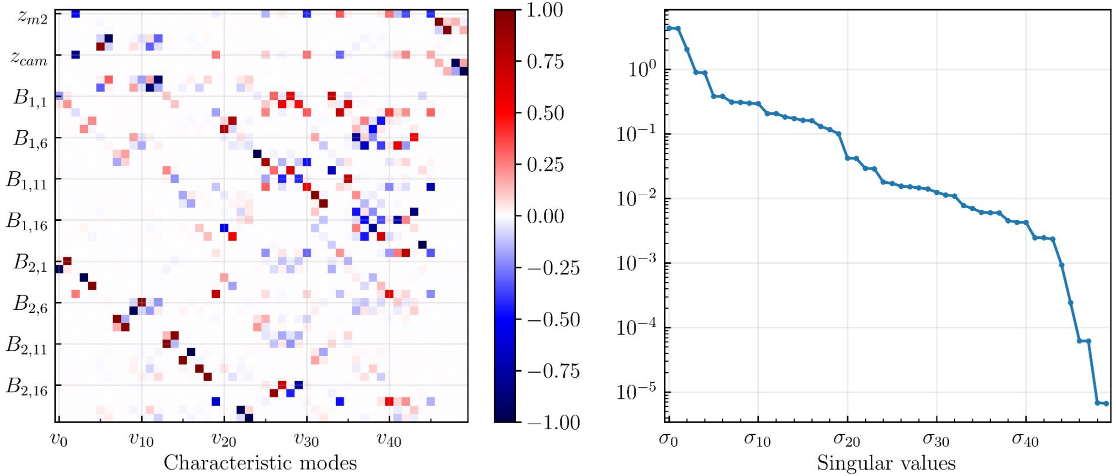
Megias Homar + Crenshaw 2024

Strategy: control system in different basis

Reweight degrees of freedom to

- favor combinations with largest impact on image quality
- favor combinations that require the least movement
- favor system components with largest operational range (e.g. M2 is more flexible than M1M3)

Truncate modes based on noise level

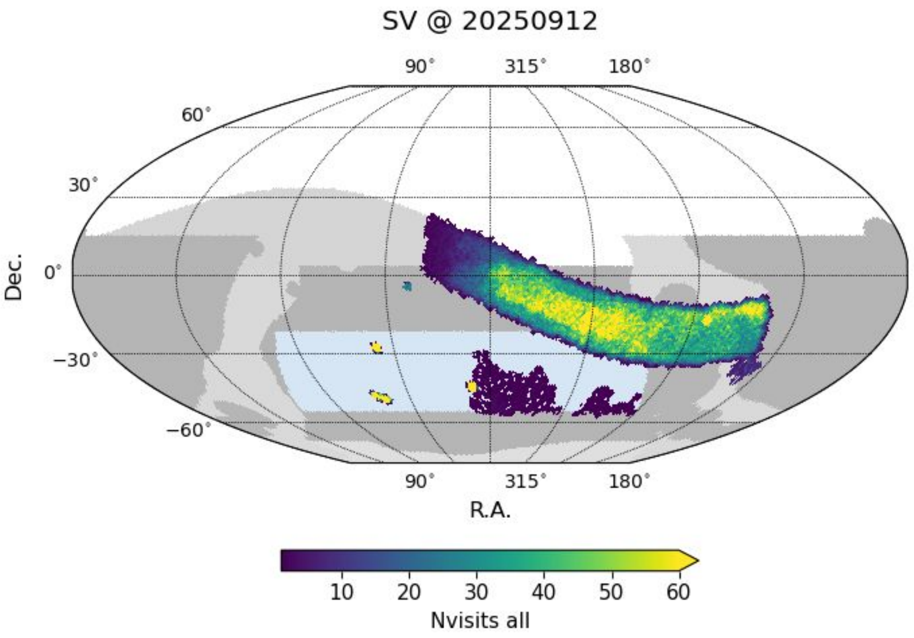


Megias Homar + Crenshaw 2024

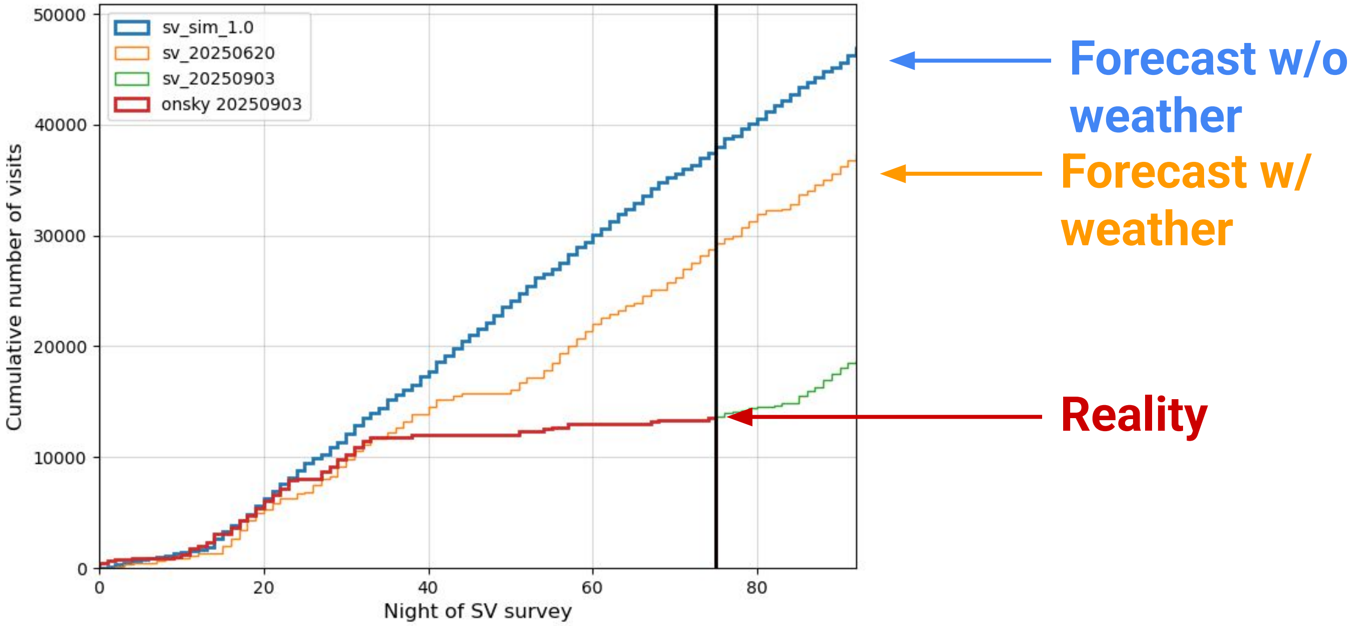
Current Status of Commissioning

Science Validation Surveys

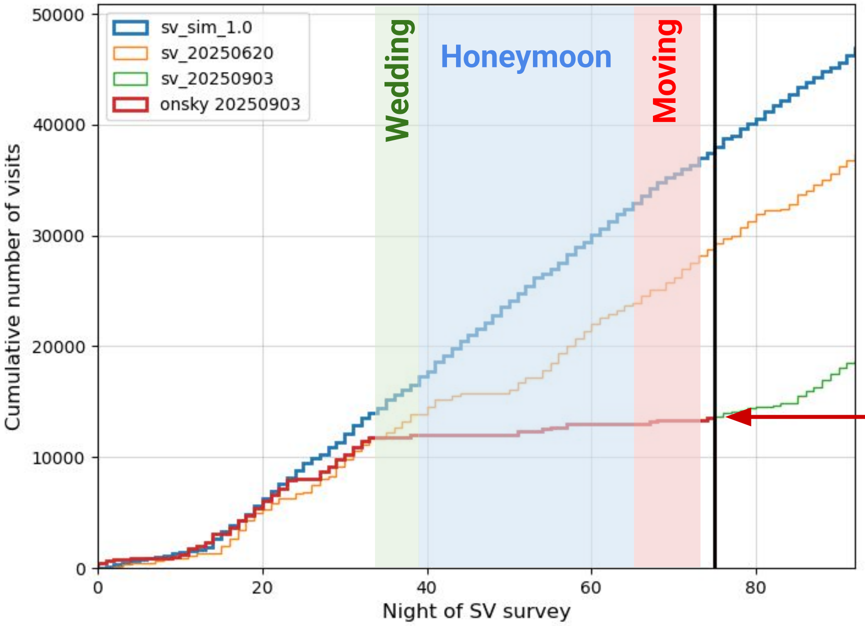
- Working hard to deliver best optical quality possible across entire field of view!
- Exercising system during the science validation survey
- Initial 3000 deg^2 goal impeded by terrible weather; now focusing on 300 deg^2
- Month-long shutdown for engineering starts at end of week



Progress of the survey



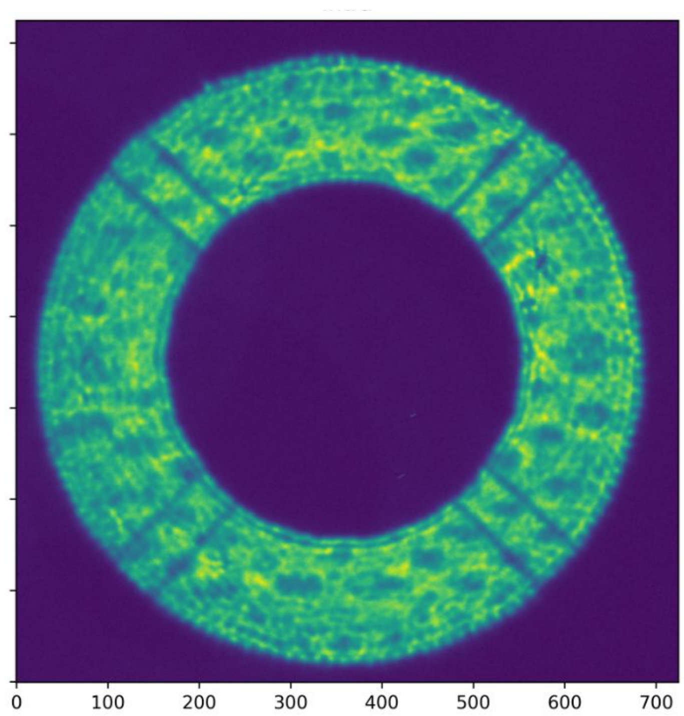
Progress of the survey



Forecast w/o weather

Forecast w/ weather

Reality


0
100
200
300
400
500
600
700

Near future dates

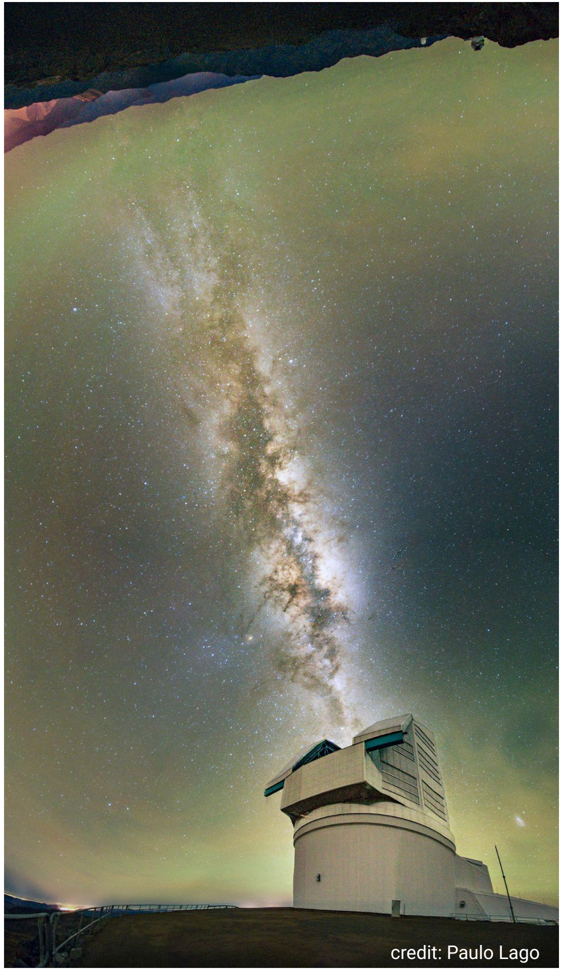
1. End of this week – shutdown for month of engineering time
2. Late October – Operations Readiness Review
3. **December – Start of LSST!**

Legacy Survey of Space and Time

Due	Name	Previously
02-Feb-2024	M1M3 Lift Test	**Completed**
08-Feb-2024	TMA Final Testing Begins	**Completed**
16-Feb-2024	M1M3 Glass Lift Prep	**Completed**
19-Feb-2024	Pathfinder Testing starts	**Completed**
20-Mar-2024	M1M3 Glass Installed	**Completed**
25-Apr-2024	TMA Final Testing Complete	**Completed**
29-Apr-2024	M1M3 Coating Begins	**Completed**
29-Apr-2024	LSSTCam Arrival Allowed	**Completed**
10-May-2024	LSSTCam Pack and Transport	**Completed**
16-May-2024	LSSTCam Received @ Summit	**Completed**
24-May-2024	ComCam Removed from TMA	**Completed**
20-Jun-2024	M2 Cell Removed from TMA	**Completed**
10-Jul-2024	M2 Glass Installed	**Completed**
25-Jul-2024	M2 Glass on TMA	**Completed**
15-Aug-2024	LSSTCam Reverification Start	**Completed**
19-Aug-2024	ComCam Installed on TMA	**Completed**
04-Oct-2024	ComCam First Photon	**Completed**
04-Oct-2024	M1M3 Glass on TMA	**Completed**
02-Dec-2024	LSSTCam L3 Checkout Done	**Completed**
06-Dec-2024	LSSTCam Reverification End	**Completed**
12-Dec-2024	ComCam off Sky	**Completed**
20-Dec-2024	ComCam off TMA	**Completed**
05-Feb-2025	LSSTCam on Top End Assembly	**Completed**
06-Mar-2025	LSSTCam on TMA	**Completed**
14-Apr-2025	TMA Aligned	**Completed**
15-Apr-2025	Rubin First Photon	**Completed**
30-Apr-2025	TMA Pointing Models Complete	**Completed**
30-Jun-2025	TMA AOS Ready	**Completed**
01-Jul-2025	Rubin First Light	**Completed**
01-Jul-2025	Rubin SV1 Start	**Completed**
01-Jul-2025	Rubin SV2 Start	**Completed**
25-Sep-2025	Rubin Eng Prep for OPS Start	11-Sep-2025
24-Oct-2025	Rubin Operations Readiness Review	18-Sep-2025

Summary

- **The Rubin Observatory is in final stages of commissioning; LSST is imminent!**
- LSST will discover hundreds-of-millions of LBGs which will be a powerful probe of high-redshift cosmology
- Early results from DP1 are consistent with LBG forecasting
- We are deploying AI systems to better control Rubin's image quality
- Lots of testing and thought dedicated to controlling the telescope's large, partially degenerate parameter space

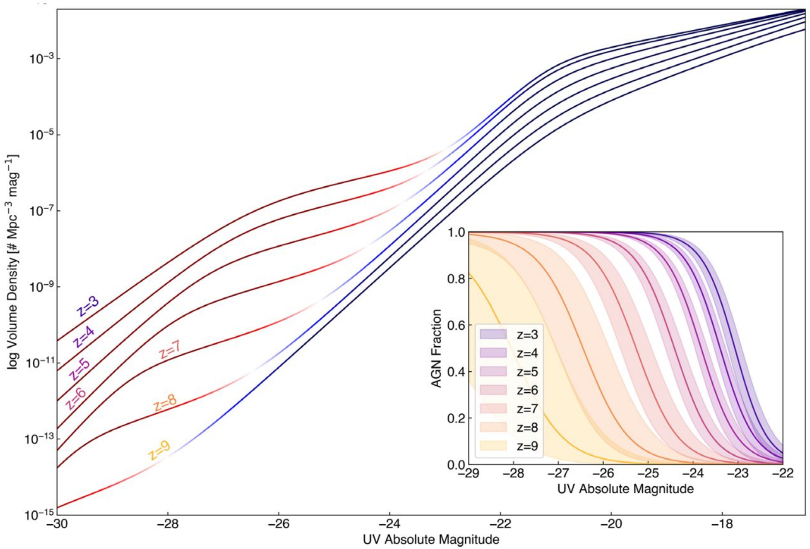


credit: Paulo Lago

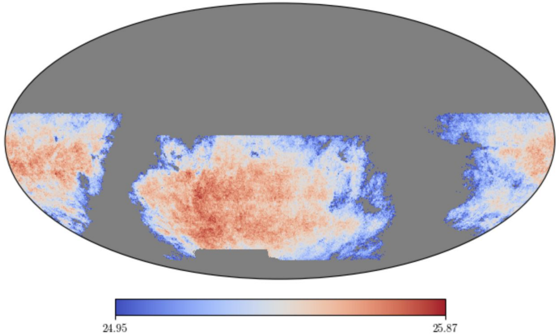
Backup slides

Forecasting LBG population

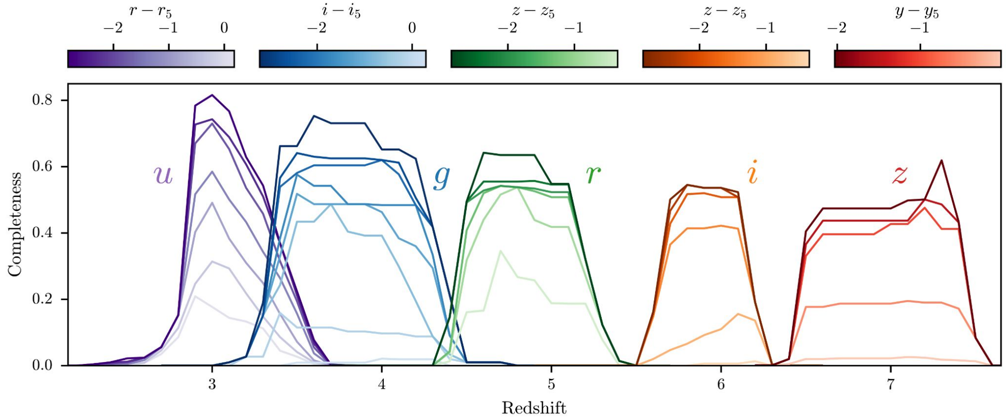
Luminosity functions from HSC + HST + others

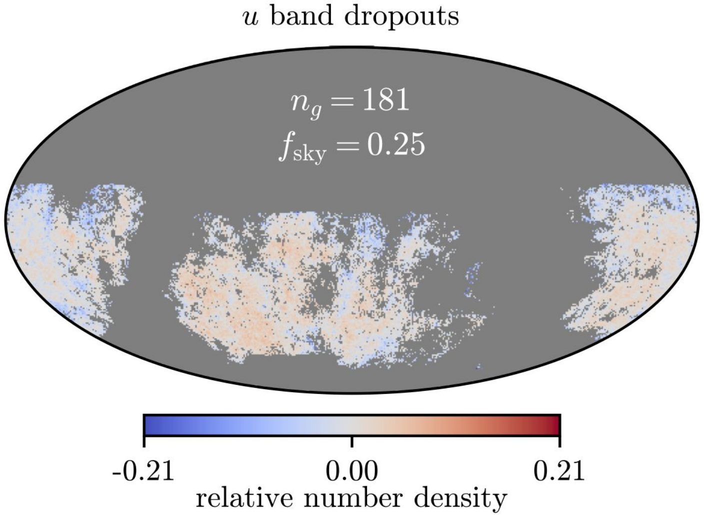


LSST forecast depth maps

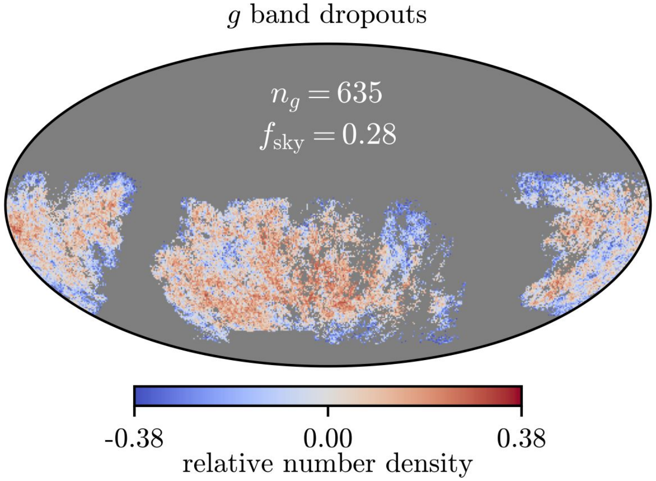


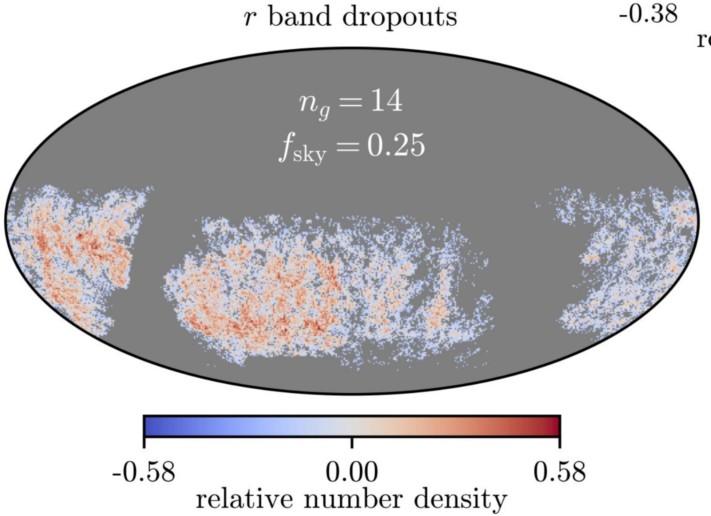
HSC completeness curves





Year 1

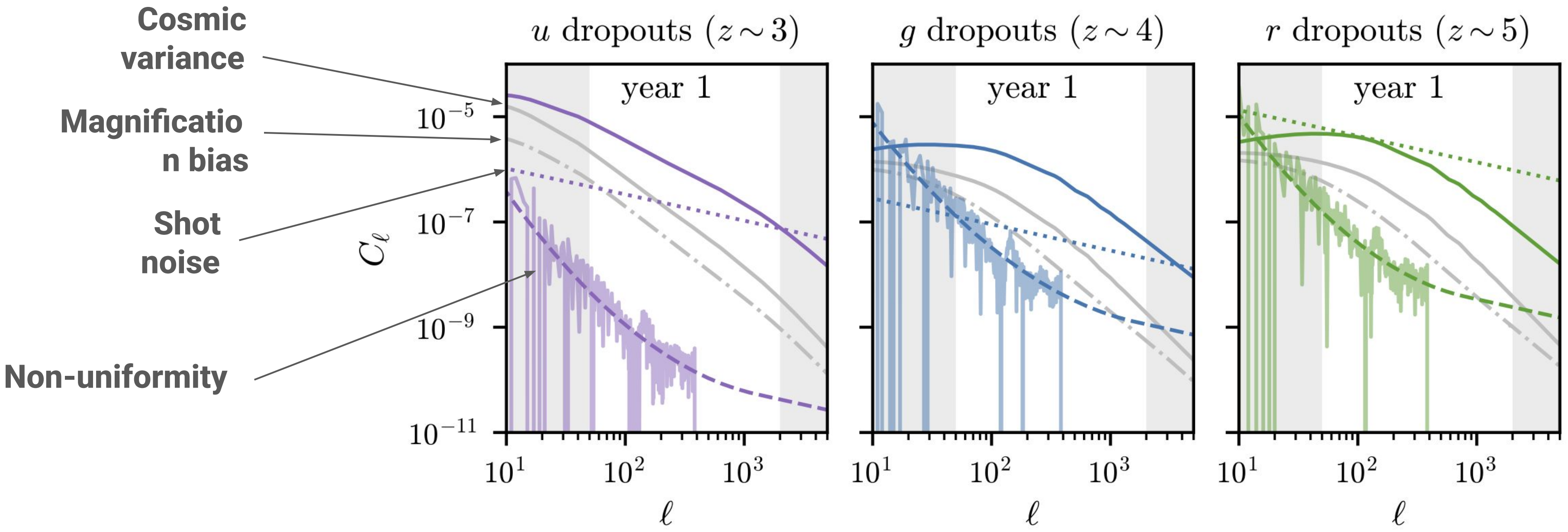




Optimize depth and LBG cuts to maximize 2pt SNR

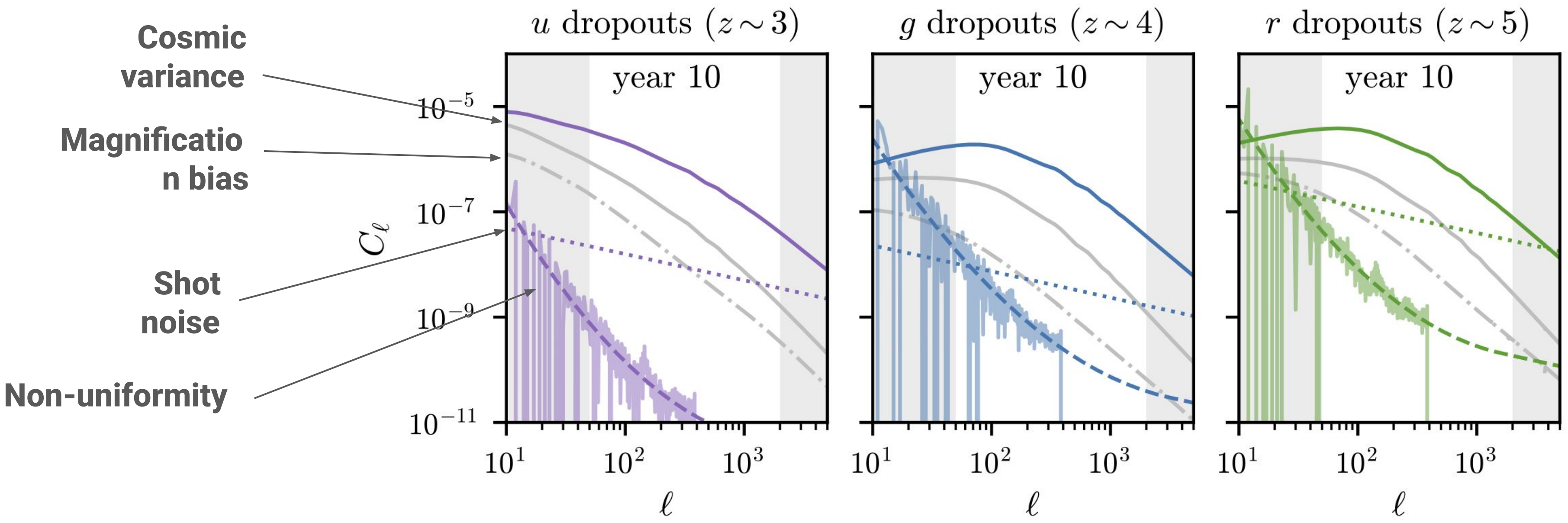
Forecasts for clustering and error sources

Year 1 u & g will be cosmic variance limited at $\ell \lesssim 200$, shot noise limited at $\ell \gtrsim 200$



Forecasts for clustering and error sources

Year 10 *u* & *g* will be cosmic variance limited at $\ell \lesssim 2000$! (and *r* at $\ell \gtrsim 400$)



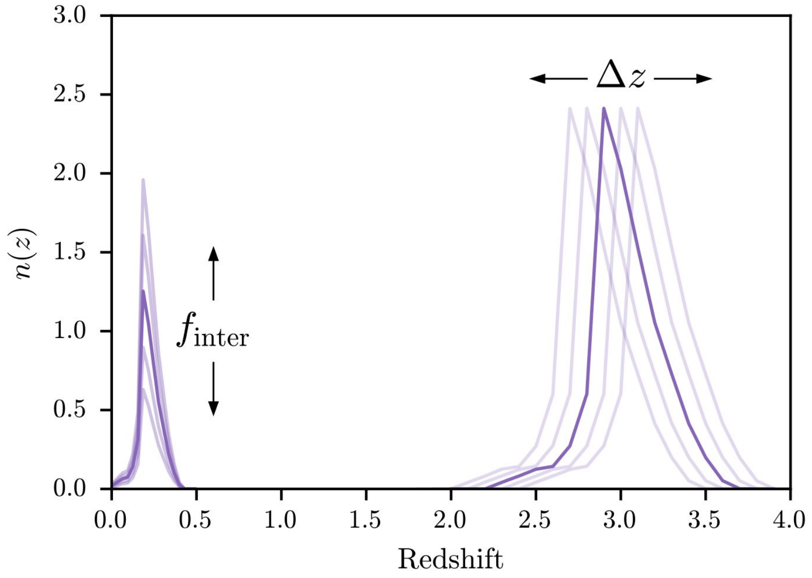
Impact of systematic errors

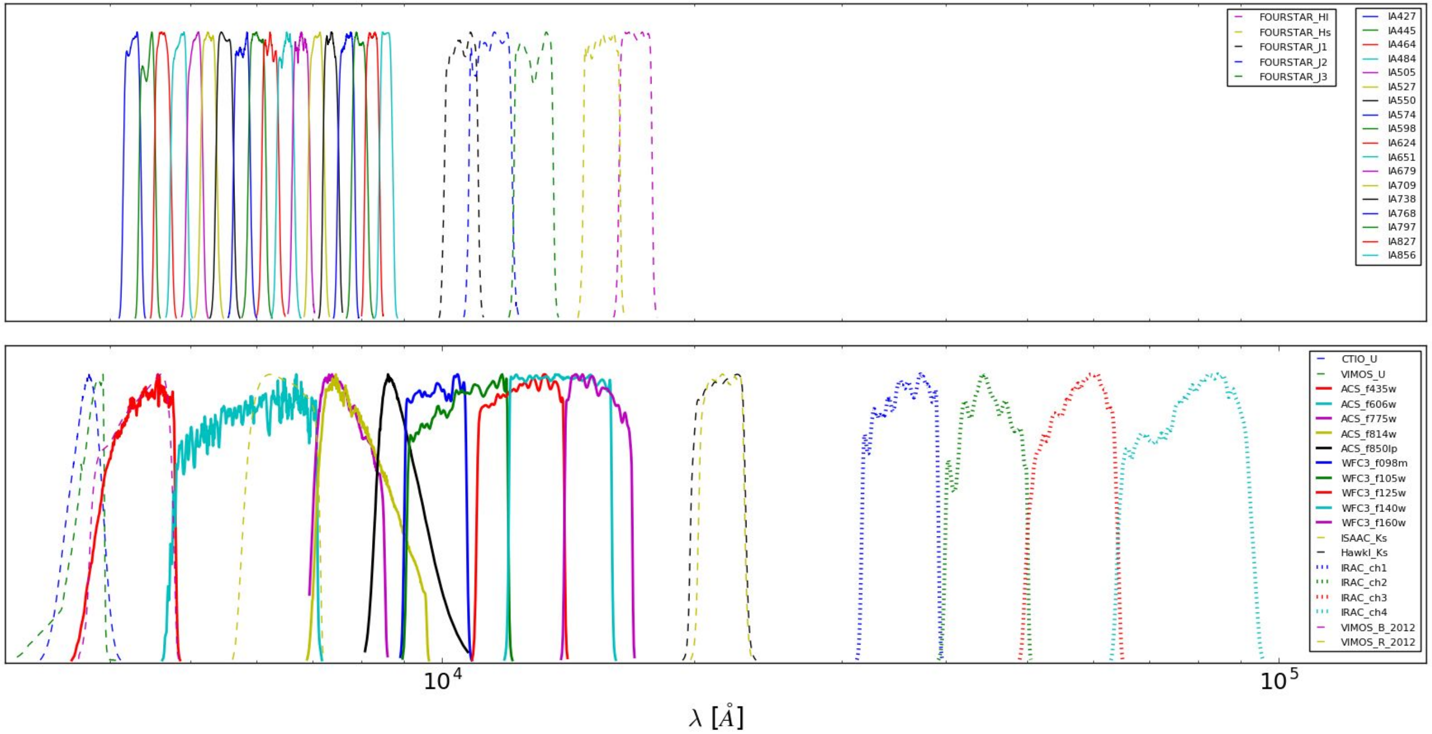
Like most of LSST cosmology, we will be systematics limited

What is the impact on constraints?

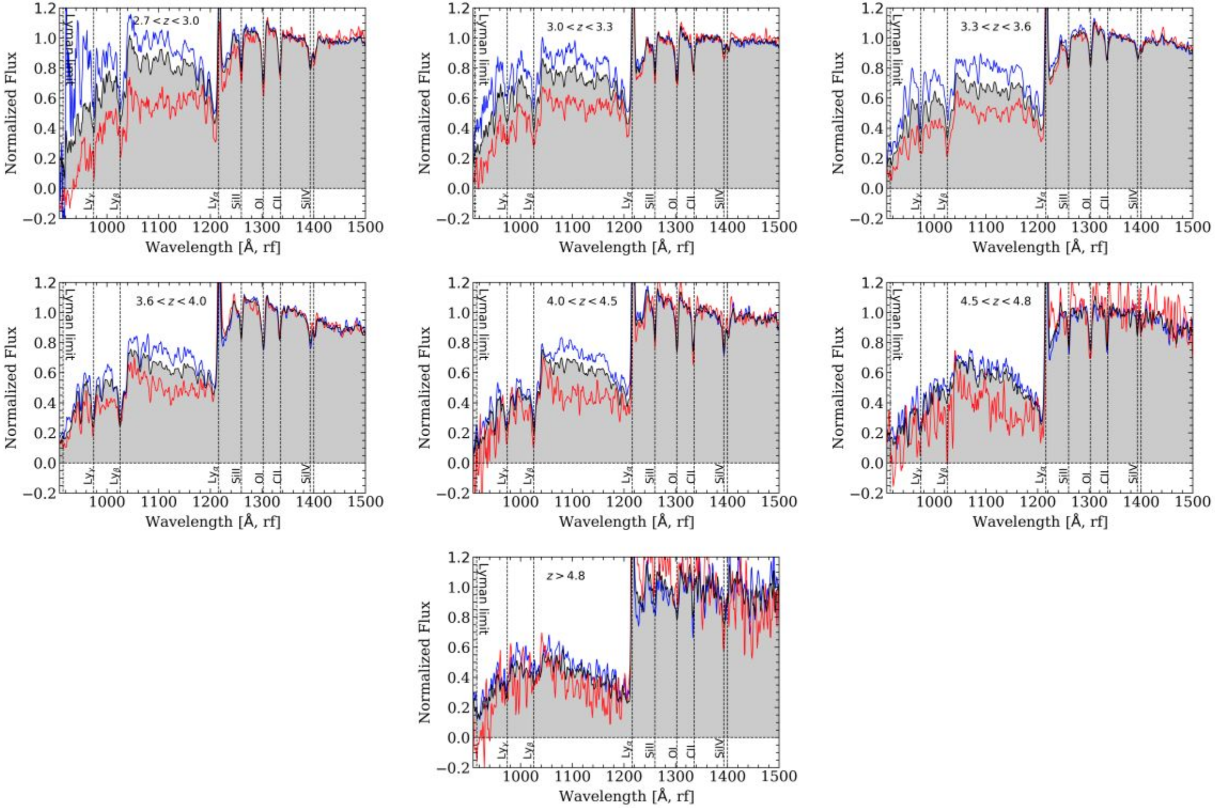
Systematics considered:

- Low-z interlopers
- Mean redshift calibration
- LBG galaxy bias (previously included)
- Interloper bias
- Magnification bias

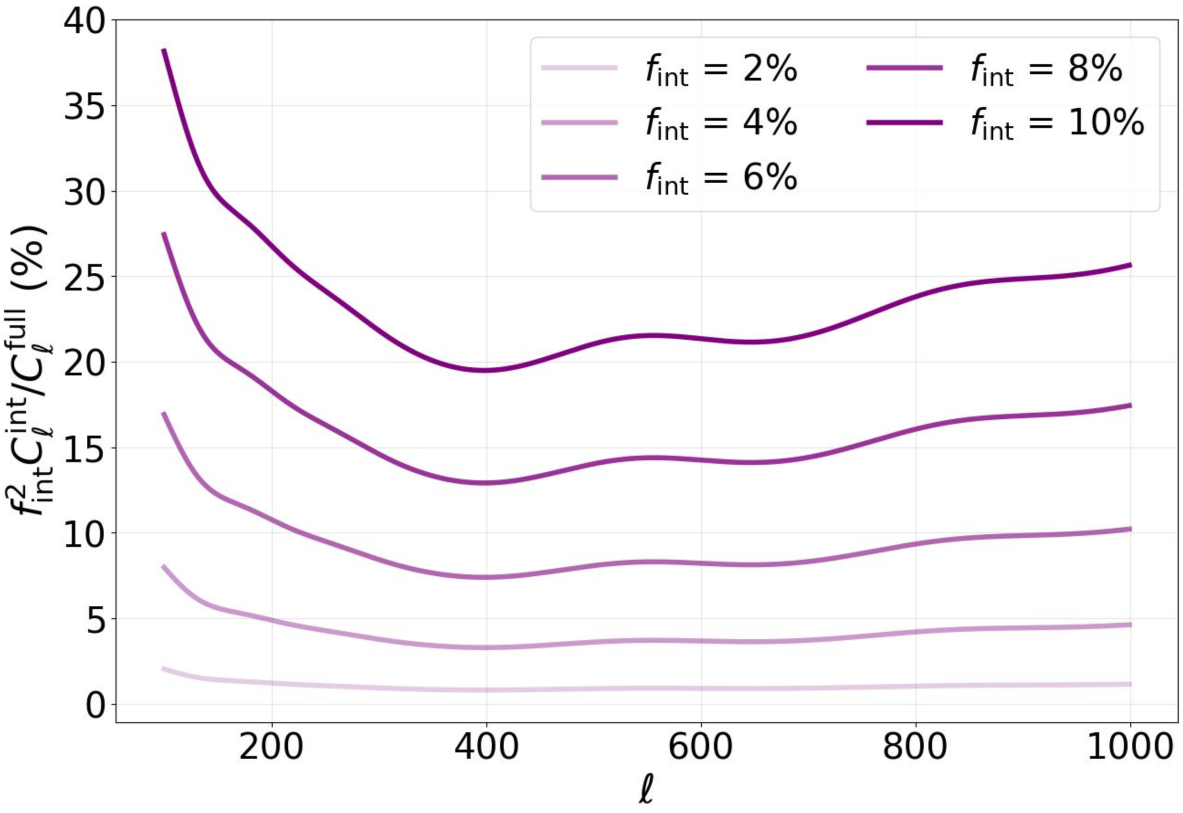



FOURSTAR_HI
FOURSTAR_Hs
FOURSTAR_J1
FOURSTAR_J2
FOURSTAR_J3
IA427
IA445
IA464
IA484
IA505
IA527
IA550
IA574
IA598
IA624
IA651
IA679
IA709
IA738
IA768
IA797
IA827
IA856
CTIO_U
VIMOS_U
ACS_f435w
ACS_f606w
ACS_f775w
ACS_f814w
ACS_f850lp
WFC3_f098m
WFC3_f105w
WFC3_f125w
WFC3_f140w
WFC3_f160w
ISAAC_Ks
HawkI_Ks
IRAC_ch1
IRAC_ch2
IRAC_ch3
IRAC_ch4
VIMOS_B_2012
VIMOS_R_2012
10^4
10^5
λ [Å]

Merlin 2021


2.7 < z < 3.0
3.0 < z < 3.3
3.3 < z < 3.6
3.6 < z < 4.0
4.0 < z < 4.5
4.5 < z < 4.8
z > 4.8
Lyman limit
Normalized Flux
Wavelength [Å, rf]
SiII
OI
CII
SiIV

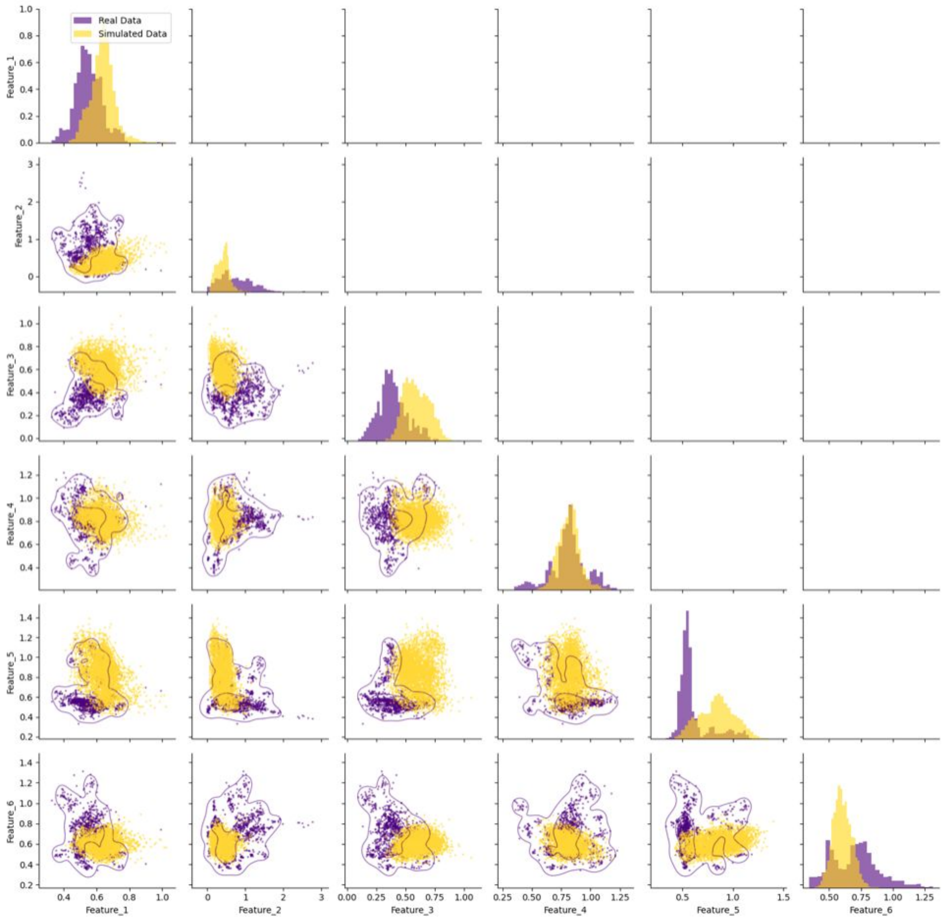
Thomas 2021

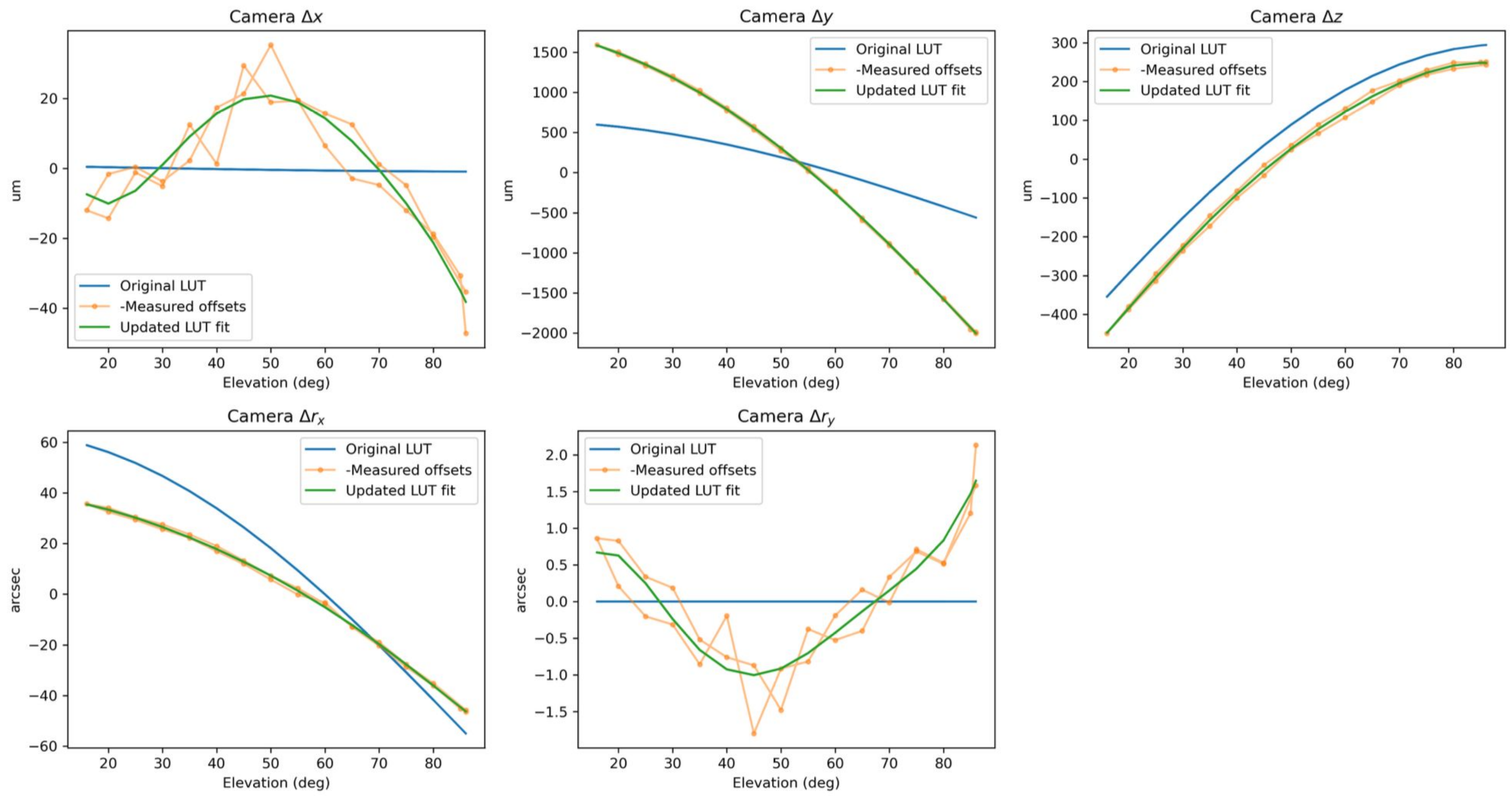


$f_{\rm int}^2 C_\ell^{\rm int}/C_\ell^{\rm full}$ (%)
ℓ
0
5
10
15
20
25
30
35
40
200
400
600
800
1000
$f_{\rm int}$ = 2%
$f_{\rm int}$ = 4%
$f_{\rm int}$ = 6%
$f_{\rm int}$ = 8%
$f_{\rm int}$ = 10%

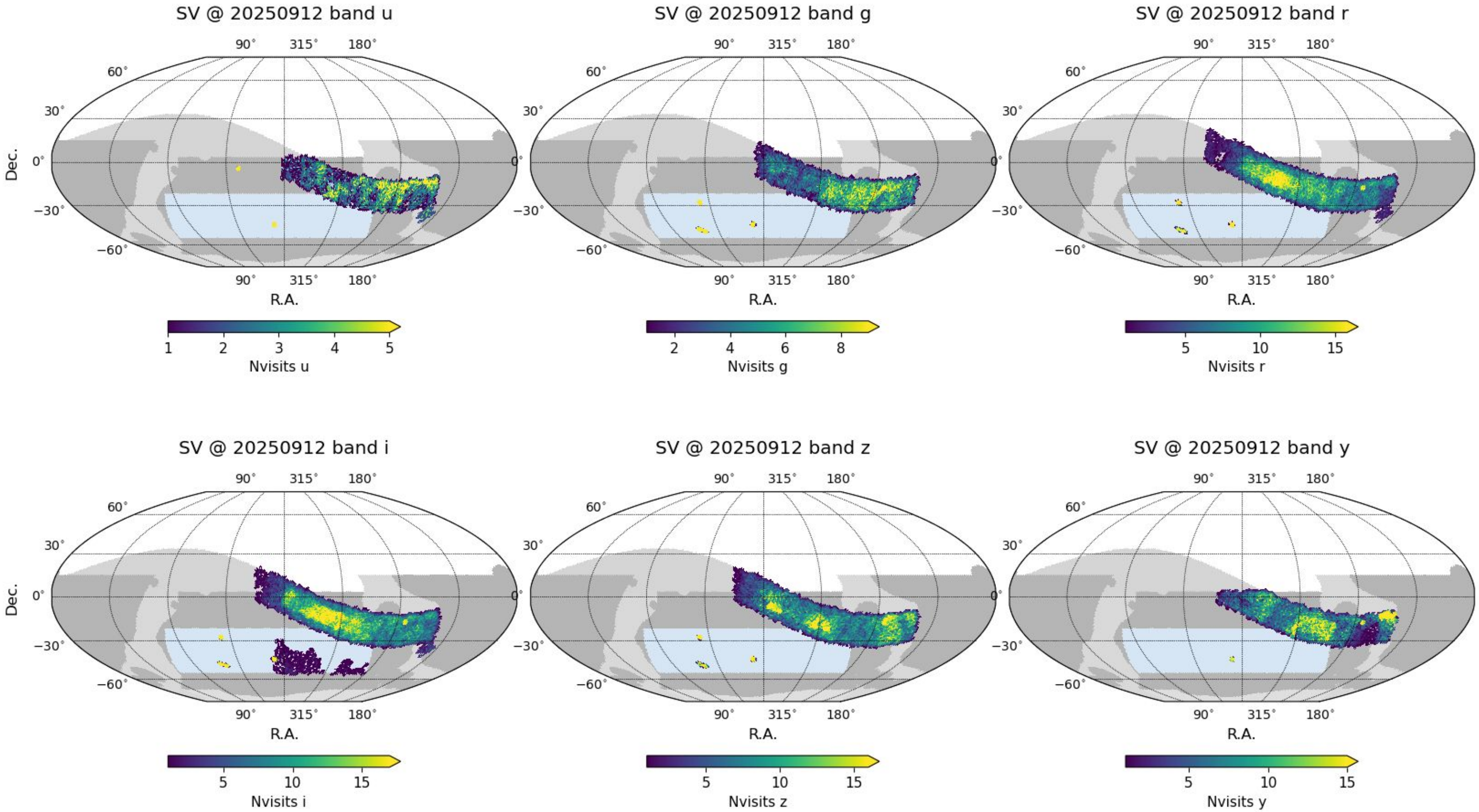
Petri 2025

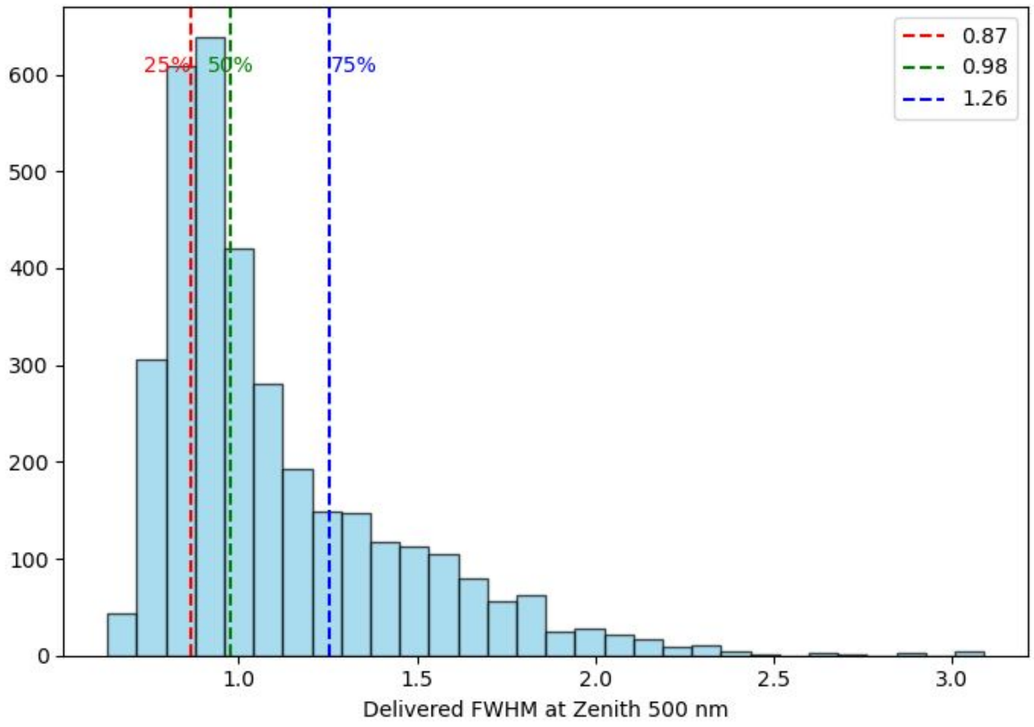
year	u	g	r	i	z	y
1	24.21	25.33	25.50	25.06	24.38	23.54
4	24.86	26.17	26.35	25.89	25.21	24.29
7	25.18	26.41	26.60	26.14	25.48	24.55
10	25.36	26.60	26.79	26.32	25.66	24.73


Real Data
Simulated Data
Feature_1
Feature_2
Feature_3
Feature_4
Feature_5
Feature_6

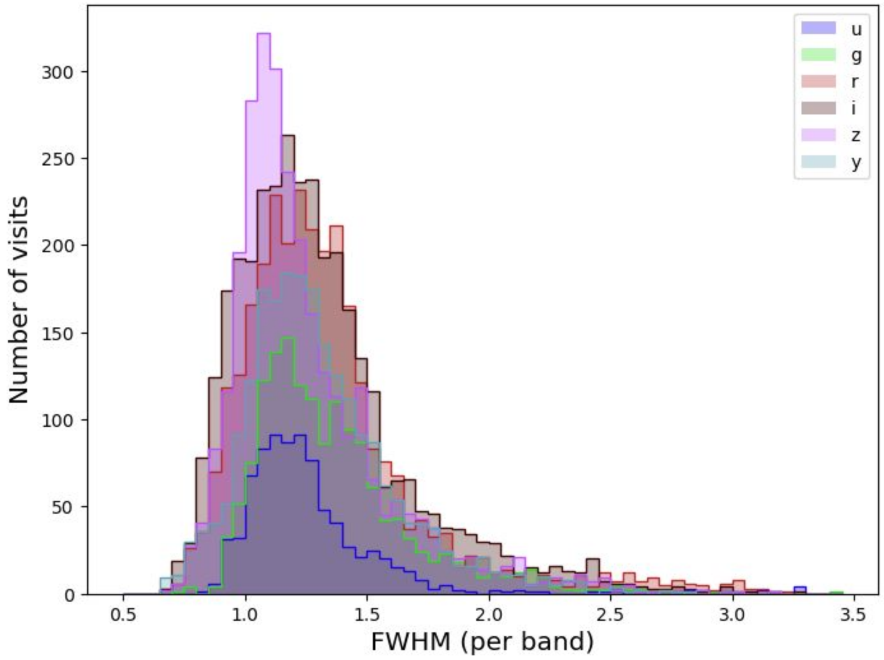


Camera Δx
Original LUT
-Measured offsets
Updated LUT fit
um
Elevation (deg)
Camera Δy
Camera Δz
Camera Δr_x
arcsec
Camera Δr_y

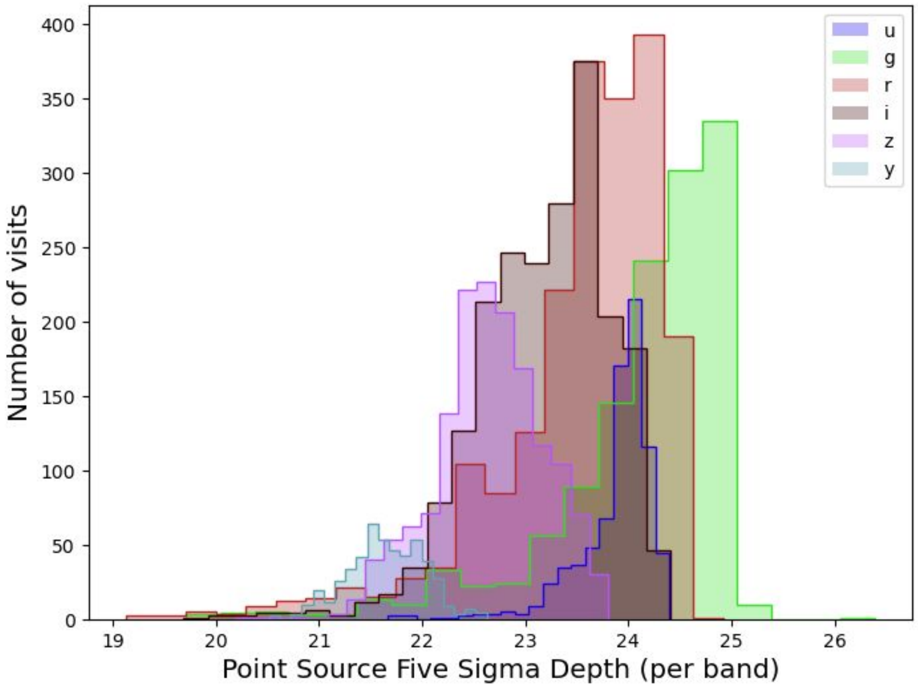

SV @ 20250912 band u
SV @ 20250912 band g
SV @ 20250912 band r
SV @ 20250912 band i
SV @ 20250912 band z
SV @ 20250912 band y
90°
315°
180°
60°
30°
0°
−30°
−60°
Dec.
R.A.
Nvisits u
Nvisits g
Nvisits r
Nvisits i
Nvisits z
Nvisits y



0.87
0.98
1.26
25%
50%
75%
0
100
200
300
400
500
600
1.0
1.5
2.0
2.5
3.0
Delivered FWHM at Zenith 500 nm



Number of visits
FWHM (per band)
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
250
300
u
g
r
i
z
y



Number of visits
Point Source Five Sigma Depth (per band)
19
20
21
22
23
24
25
26
0
50
100
150
200
250
300
350
400
u
g
r
i
z
y