Maunakea Spectroscopic Explorer

Cosmology at MSE

Christophe Yèche
CEA-Saclay

Will Percival
University of Waterloo

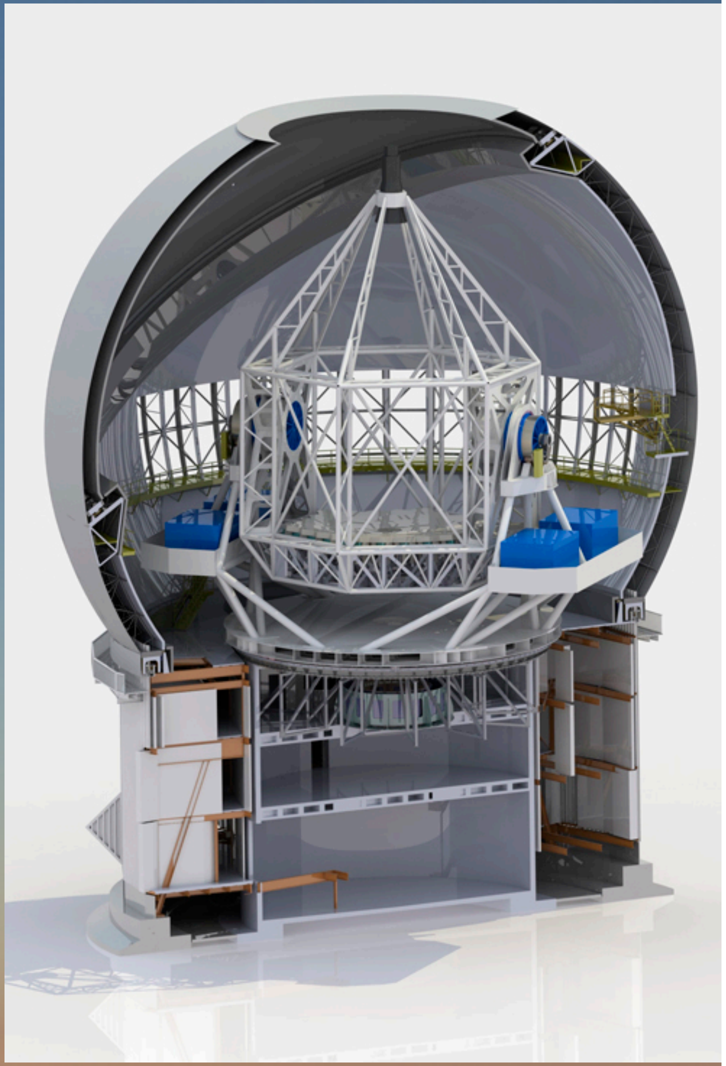
Snowmass2021, CF4 - The Modern Universe, July 15 2020

Maunakea Spectroscopic Explorer

Wide-field, multi-object spectrographs

MSE in a nutshell

- It will replace the 3.6-m Canada-France-Hawaii Telescope
- 11.2 m telescope with 1.5 deg^2 FoV
- Fully dedicated to spectroscopy
- Positioner with 4332 fibers
- Low and moderate resolution:
  R: 2500 → 6000
- Wavelength range:
  Visible + NIR (J and H bands)



Program for cosmology

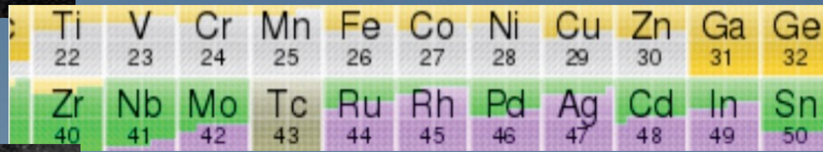
- A large-volume survey of high-redshift galaxies and quasars
- Presentation based on the white paper:
  W. Percival, Ch. Yèche et al., arXiv:1903.03158

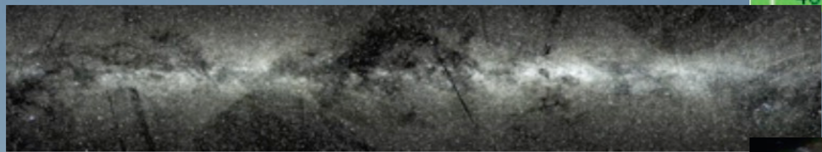
Maunakea Spectroscopic Explorer

Science Working Groups

Exoplanets and stellar astrophysics
Maria Bergemann & Daniel Huber

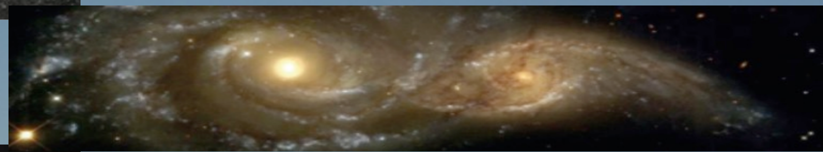
Chemical nucleosynthesis
Sivarani Thirupathi & David Yong

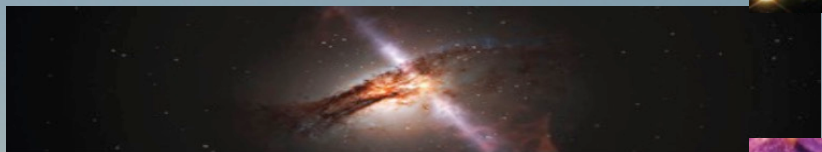




Milky Way and resolved stellar pops
Carine Babusiaux & Sarah Martell

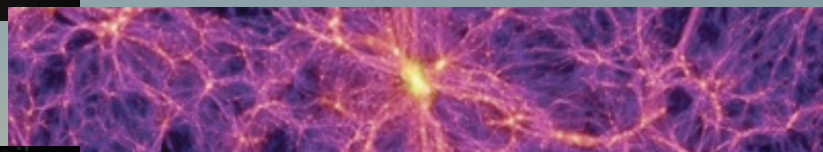
Galaxy Formation and evolution
Kim-Vy Tran & Aaron Robotham

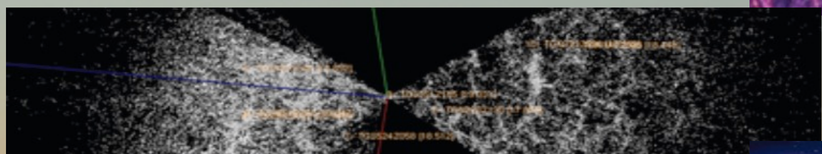




AGN and supermassive black holes
Yue Shen & Sara Ellison

Astrophysical tests of dark matter
Ting Li & Manoj Kaplinghat





Cosmology
Will Percival & Christophe Yeche

Time domain astronomy and transients
Adam Burgasser & Daryl Haggard

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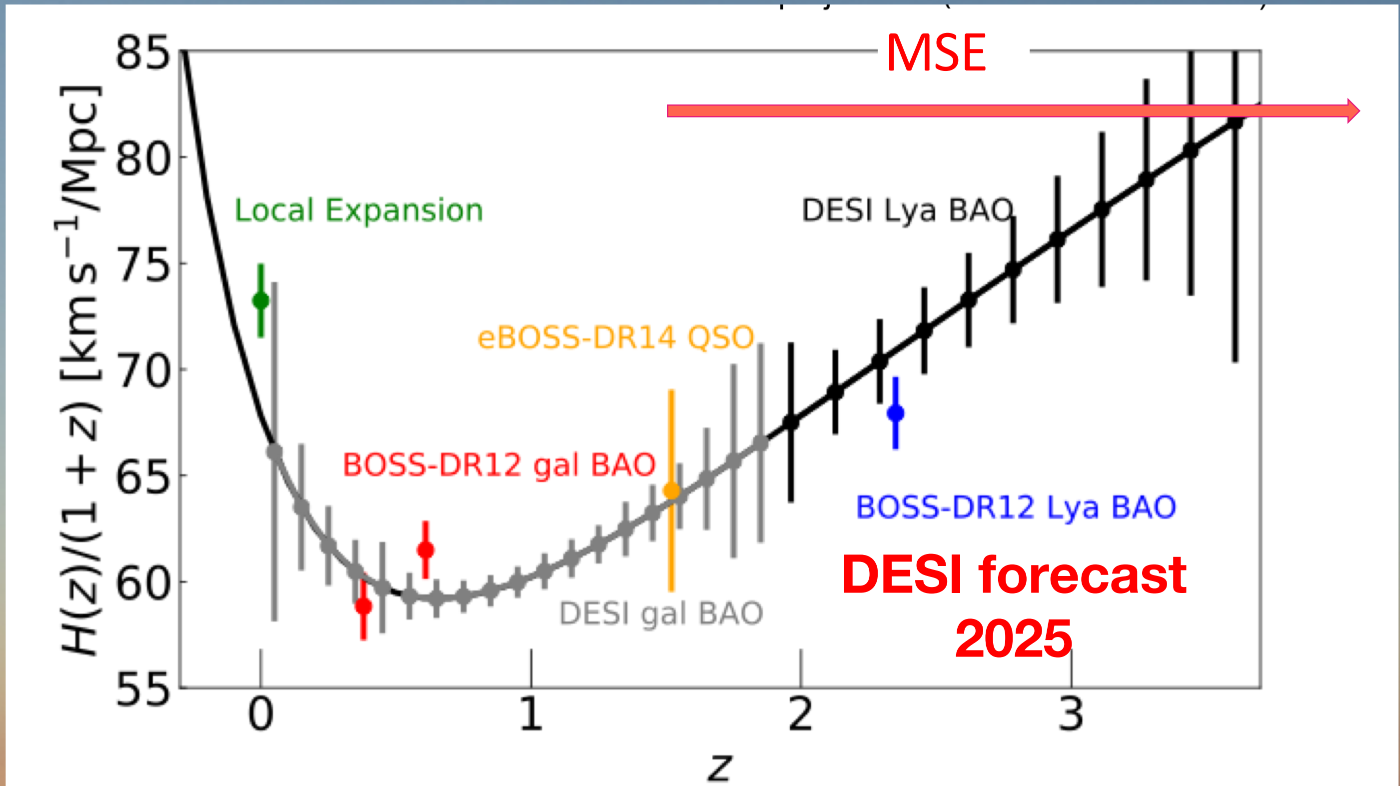
CONTEXT
What cosmology at the time of MSE?

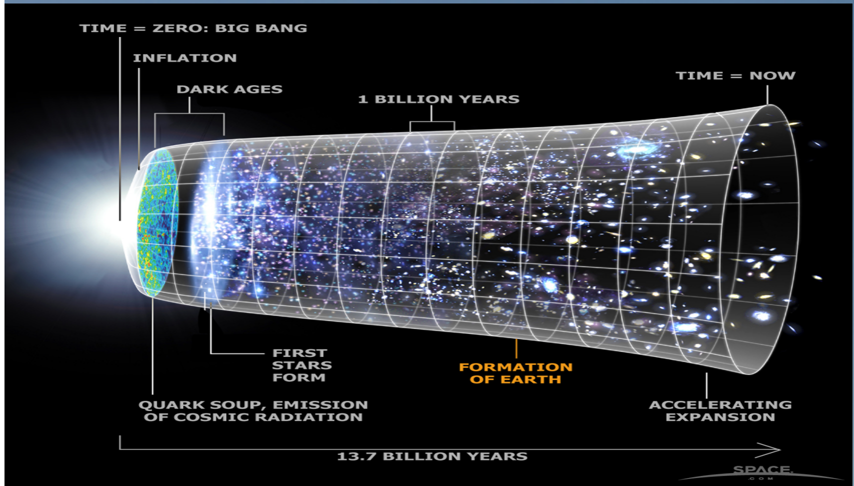
Expected sensitivity on BAO in 2025

DESI 2020-2025

- *Shot noise limited for z>1.5, mainly based on HI absorption in Lya forests for z>2.1*
- *Region partially covered by DESI and Euclid which is in a matter-dominated regime*



Inflation and non-gaussianity



Description of the primordial potential Φ

$$\Phi = \varphi + f_{NL}.\left(\varphi^2 - <\varphi^2>\right)$$

φ : a gaussian random field

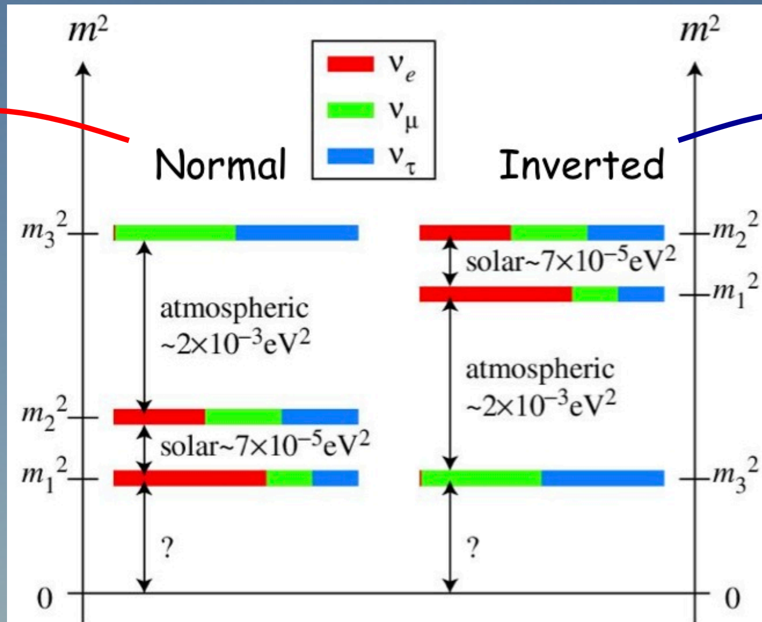
f_{NL} : amplitude of the non-Gaussianity

Primordial non-gaussianities, a test of inflation

- *Primordial fluctuations distributed almost Gaussian with the simplest slow-roll models $f_{NL} \sim O(10^{-3})$*
- *But many alternative inflation models predict $f_{NL} > 1$*
- *CMB is cosmic variance limited : $\sigma(f_{NL}) \sim 5$*
- *Galaxy surveys with a large volume can achieve $\sigma(f_{NL}) \sim 1$*

Neutrino Masses and Hierarchy

Minimum: $\Sigma m > 0.06$ eV



Minimum: $\Sigma m > 0.10$ eV

An answer to mass hierarchy with cosmological neutrinos

- *Particles Physics: atmospheric and solar oscillations*
- *No constraint on absolute masses*
- *2 possible schemes: normal vs inverted hierarchy*
- *With $\sigma(\Sigma m_\nu)$~8 meV, we may measure the mass better than 7σ and have a decision on Mass Hierarchy at 5σ*

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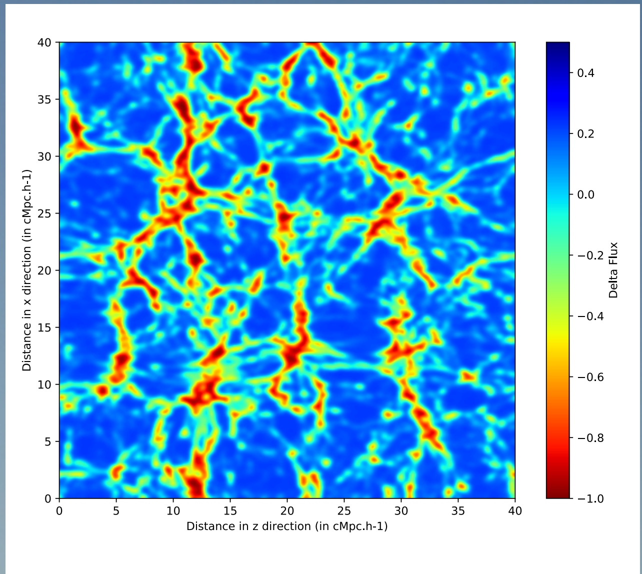
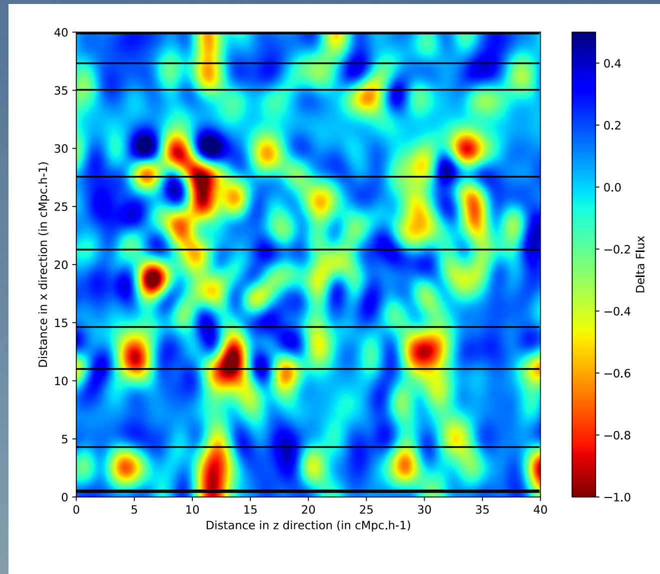
3D-Tomography of IGM





3D map obtained with 500 deg^{-2} backg. sources

3D map with HI absorption in Ly-α Forest

- *Use both QSOs and Lyman Break Galaxies (LBG) as background sources*
- *Science of cosmic voids and proto-cluters*
- *Currently, two very complementary projects:*

1. *CLAMATO: Keck, density: ~1000 deg^{-2}, Area: 1deg^2, QSOs and LBGs, r<25, 2 hours*
2. *eBOSS: Sloan, density: ~35 deg^{-2}, Area: 200 deg^2, QSOs and LBGs, r<25, 2 hours*

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A large-volume survey of high-redshift galaxies and quasars

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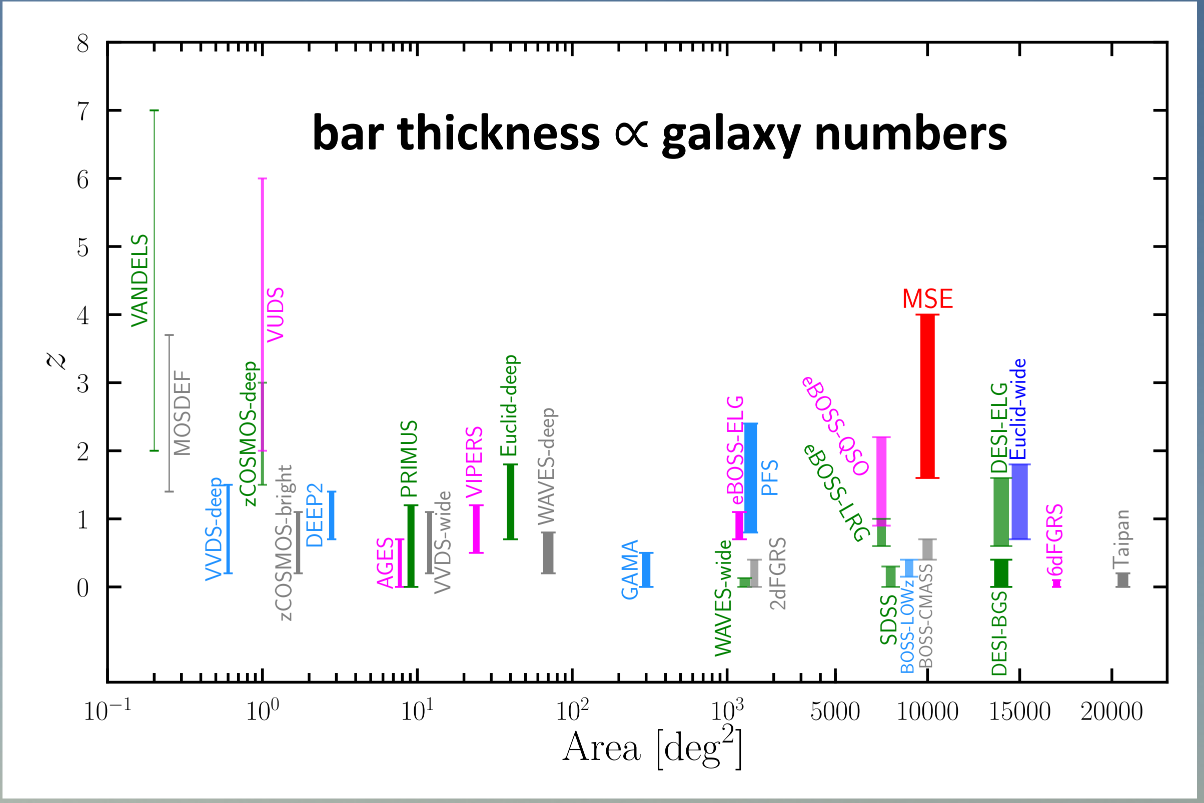
bar thickness ∝ galaxy numbers

Wide survey with SF galaxies and quasars



- Wide survey: 10,000 deg^2
- Three tracers covering 1.6<z<4.0
- 8000 pointings with 30 minute exposure
- 100 nights per year for a 5-year MSE program

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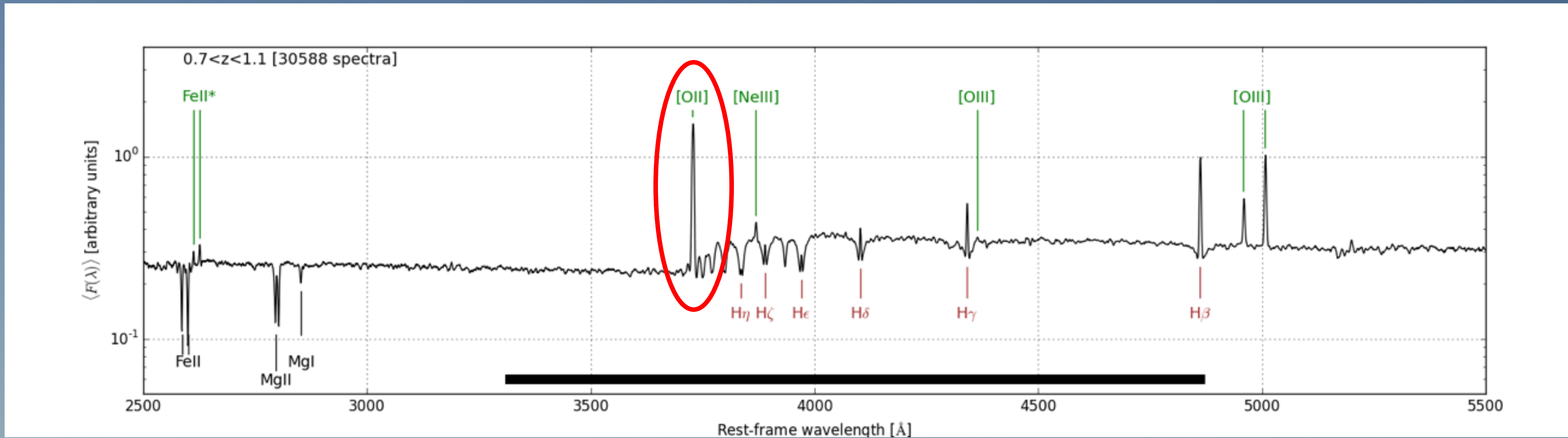
Emission Line Galaxies **1.6<z<2.4**

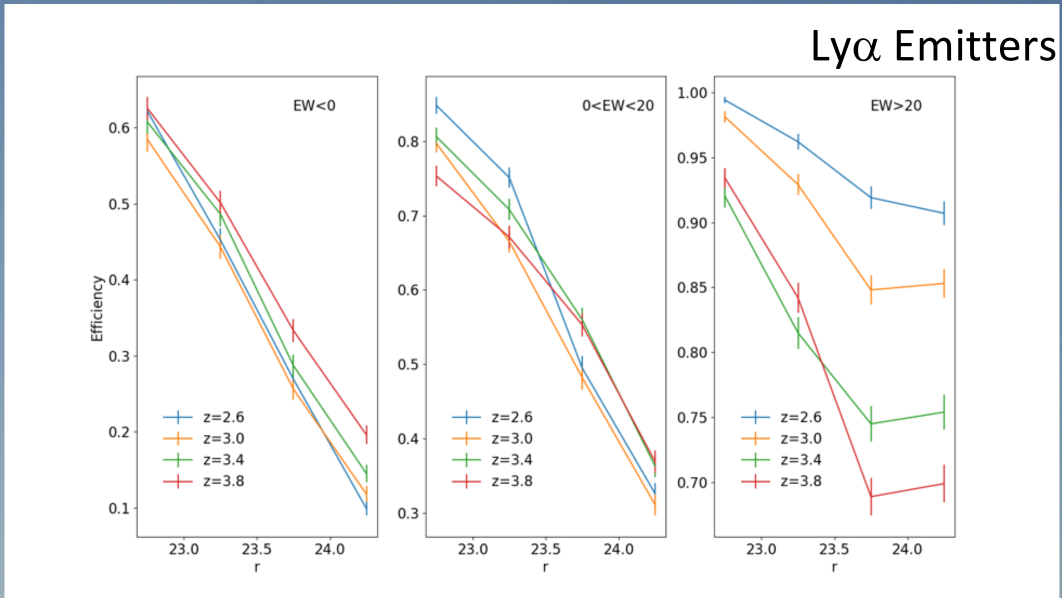


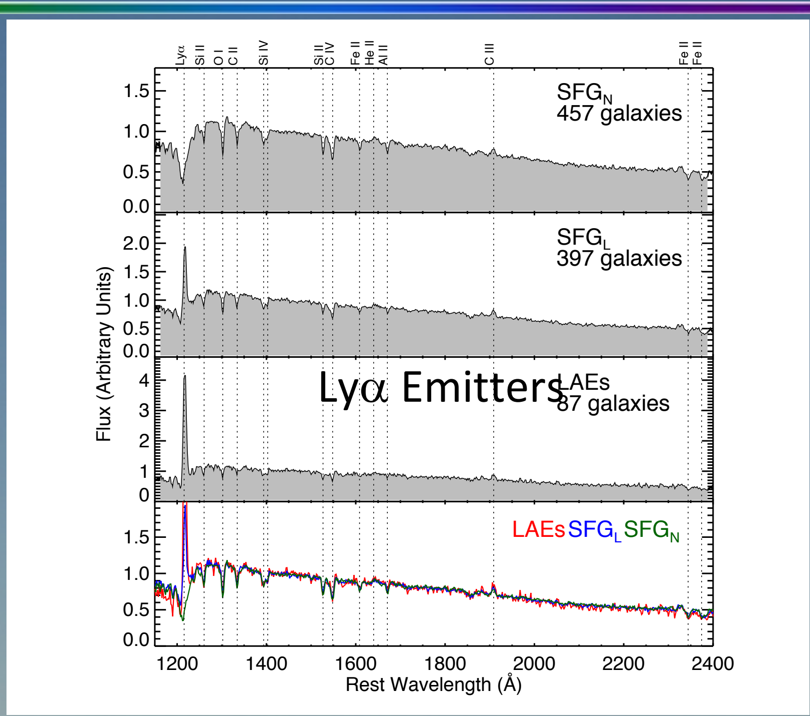
Raichoor et al. 2017

Complementary program to DESI, Euclid and PFS

- *Star-forming galaxies with strong emission lines*
- *Redshift measured with O-II line in NIR arm*
- *600 deg^{-2} targets with 90% redshift efficiencies*
- *Higher redshift compared to DESI/Euclid (z<1.6/1.8)*
- *Wider footprint compared to PFS (Surface~1500 deg^2)*

Lyman Break Galaxies 2.4<z<4.0



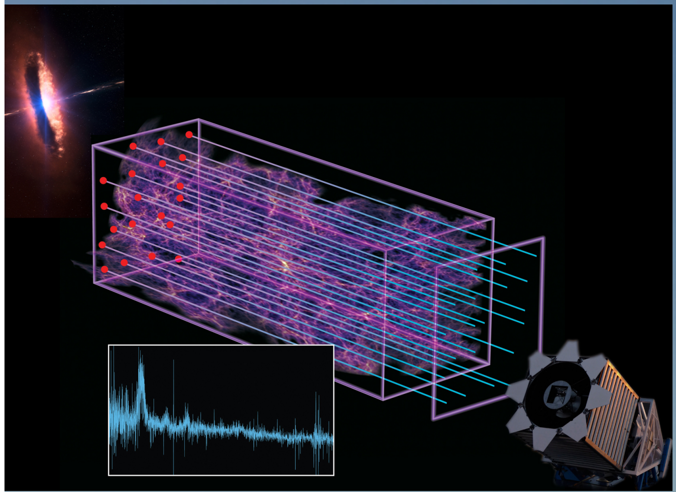


Hathi et al. 2015

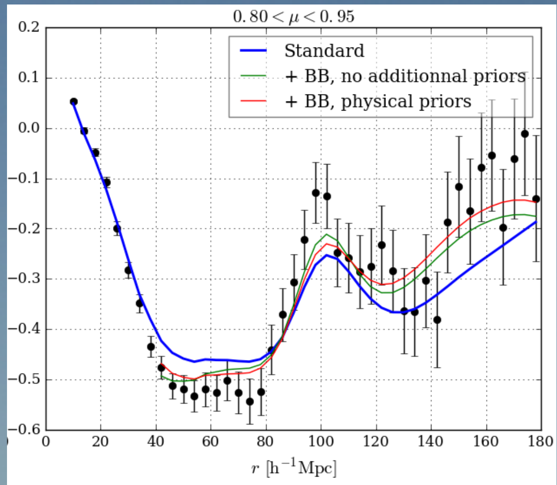
Terra incognita in cosmology

- *Star-forming galaxies with variable Lyα emission line*
- *Selection by well-controlled drop-out techniques*
- *Redshift efficiency varies as a function of Lya strength*
- *1400 deg^{-2} targets with ~50% redshift efficiencies*
- *Very conservative estimate of redshift efficiency*

Lyα forest of quasars **2.1<z<4.0**

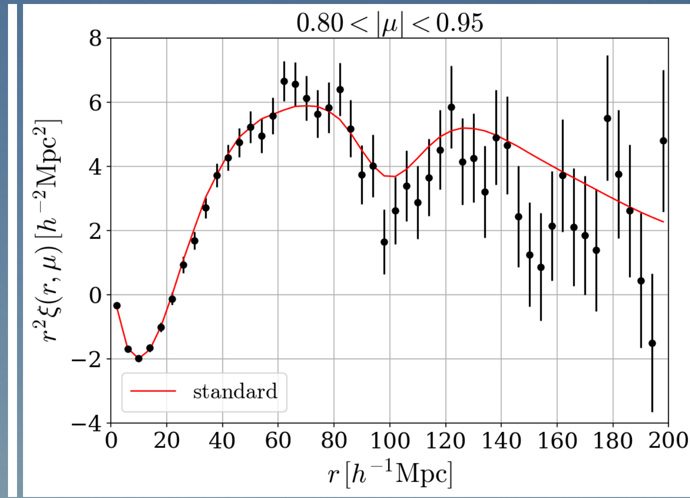


Auto correlation



Sainte Agathe et al. 2019

Cross-correlation Lyα x QSO



Bloomqvitz et al. 2019

A dream for cross-correlations with Lya forests

- *HI absorption in IGM along the line of sight of QSOs*
- *We expect low density gas (IGM) to follow the matter density*
- *Cross-correlation with QSOs, ELGs and LBGs*
- *Method demonstrated by BOSS/eBOSS*
- *170 deg^{-2} expected quasars with r<24 and redshift>2.1*

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bar thickness ∝ galaxy numbers

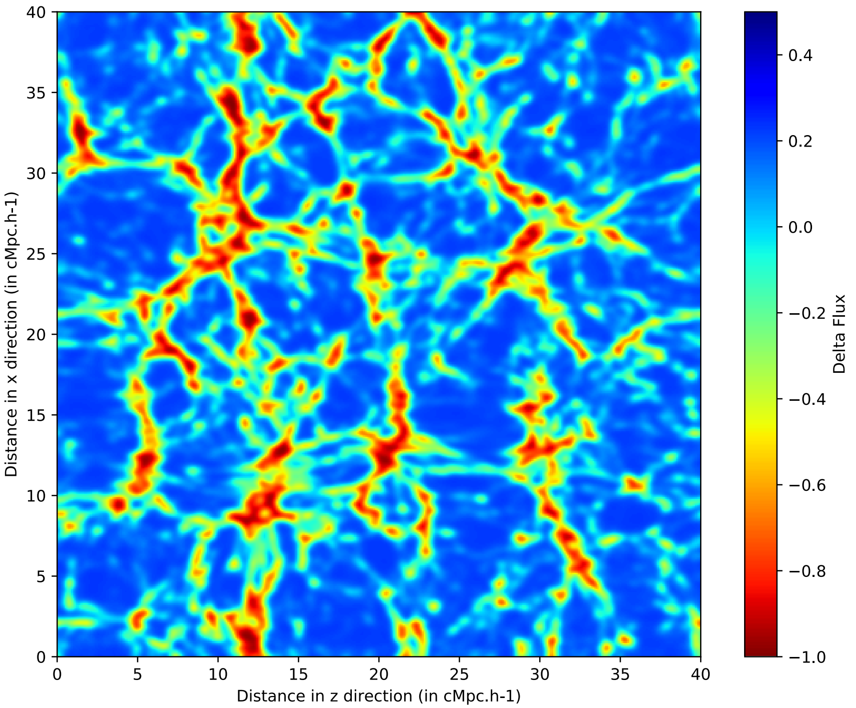
Summary of the tracers

Tracer	Redshift Range	Target Density (deg^{-2})	True Target Density (deg^{-2})	Tracers with redshift
ELG	1.6 – 2.4	600	540	5.4M
LBG	2.4 – 4.0	1400	700	7.0M
QSO (Ly-α)	2.1 – 4.0	200	170	1.7M

Strategy

- *Highest fiber assignment priority given to QSOs*
- *Then to ELGs, with 600 deg^{-2} target density (nP(0.1)~1)*
- *A filler sample with LBGs (700 deg^{-2} with a good redshift, nP(0.1)~0.6)*

Deep Field for 3D Tomography



Strategy

- *Same density as CLAMATO with eBOSS area*
- *Area: 50-100 deg^2*
- *Targets: 200 deg^{-2} Ly-a QSO targets and 200(deg^{-2} LBG targets*
- *Exposure time: 0.5 hour → 2 hours*
- *Total time 10-20% of the full cosmology survey*

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Forecasts

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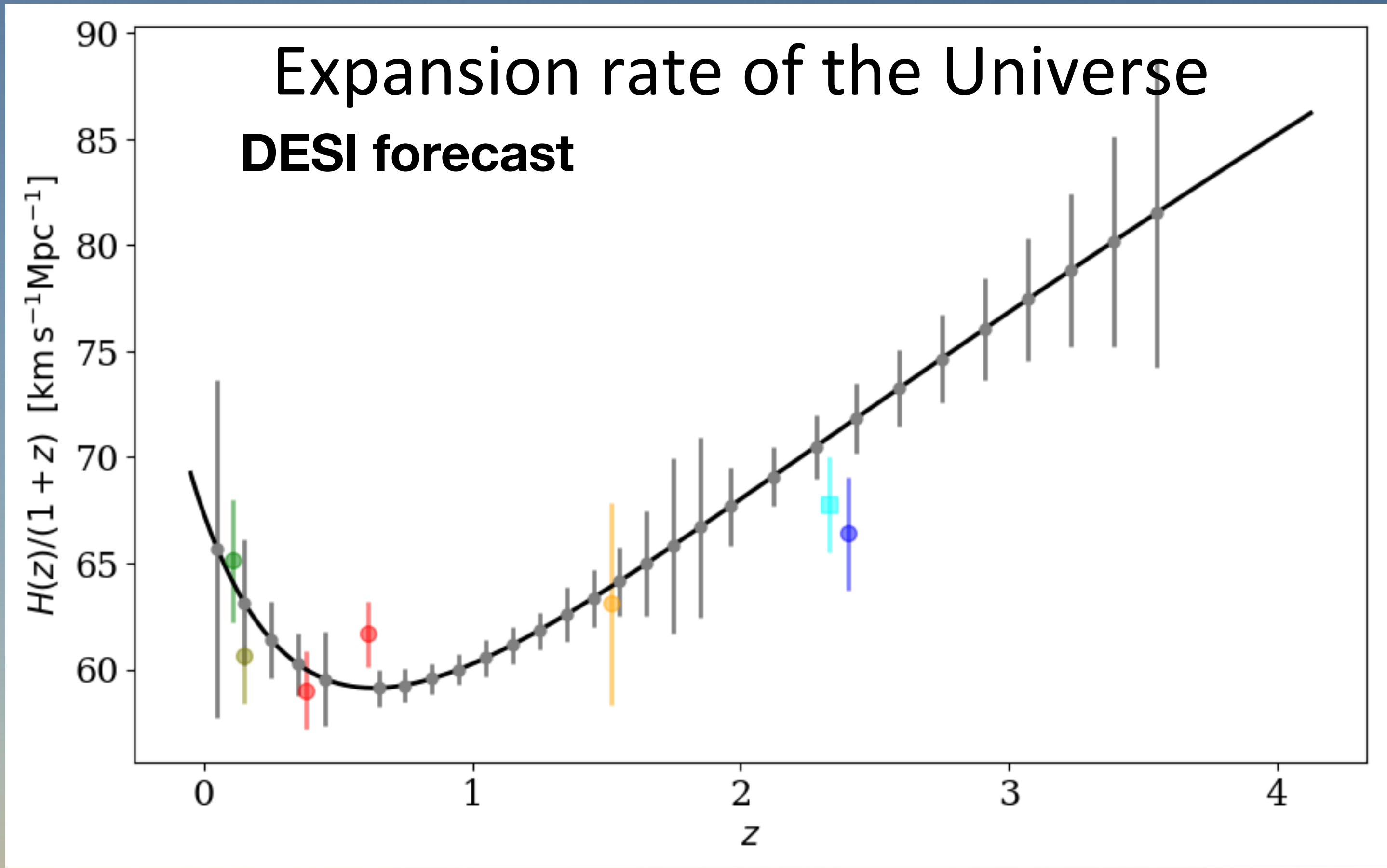
Forecast for BAO



- After DESI in 2025…

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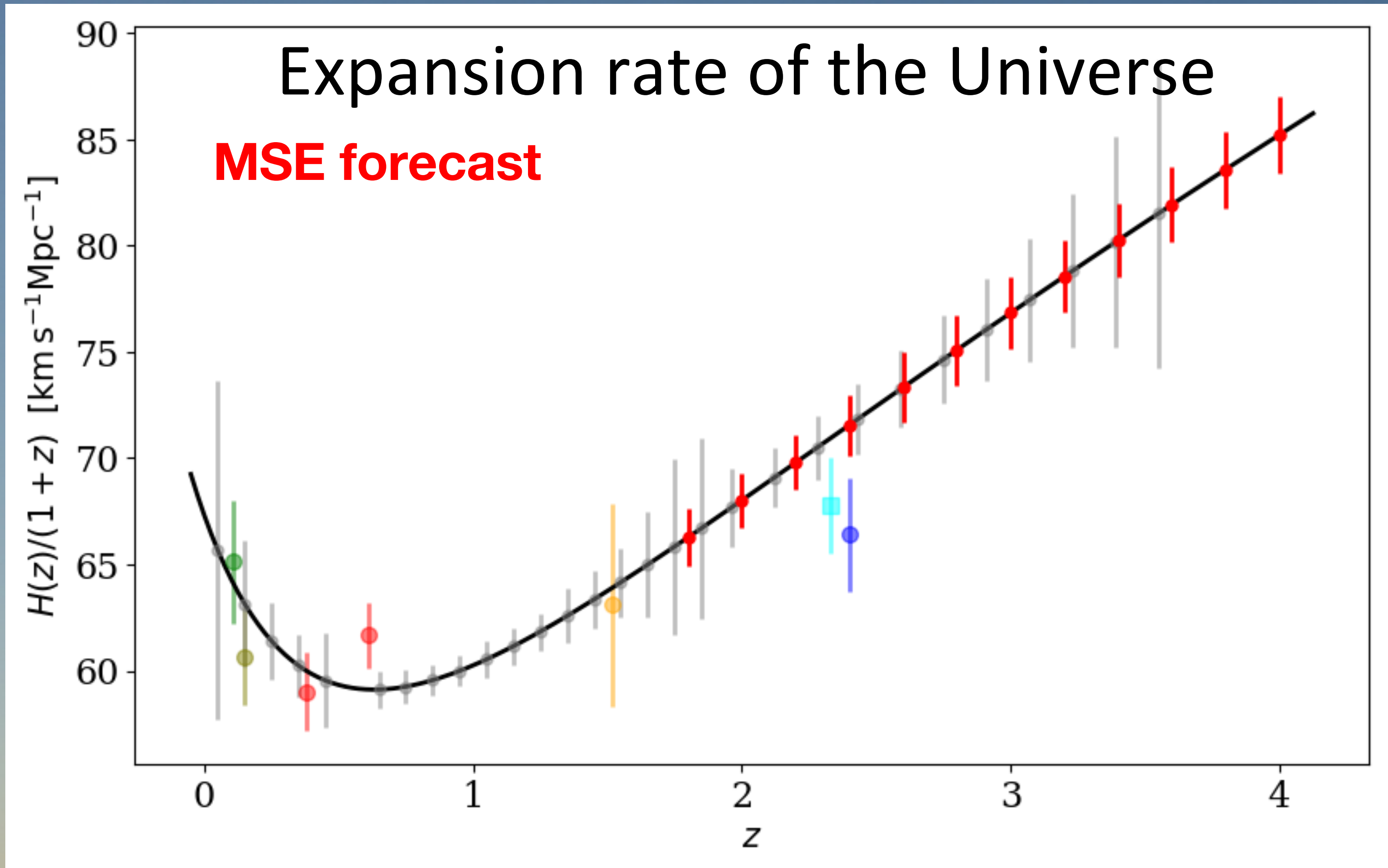
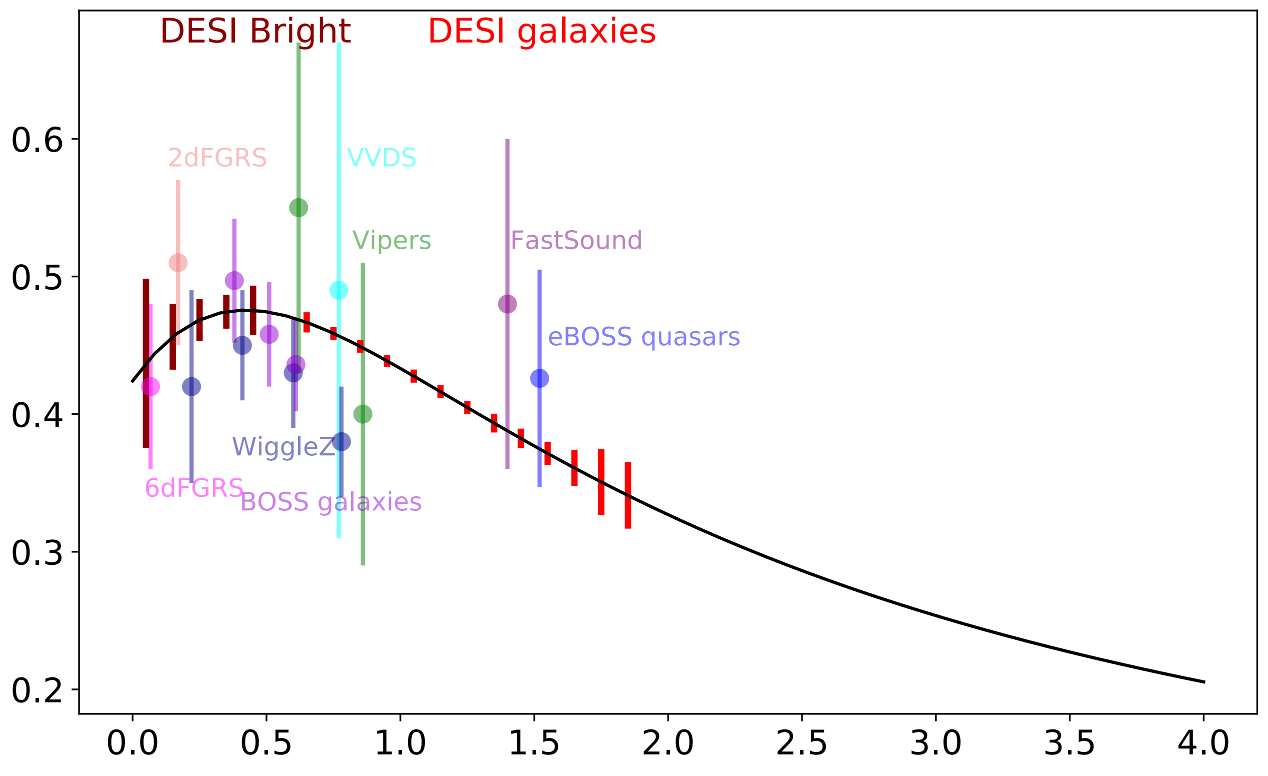
Forecast for BAO



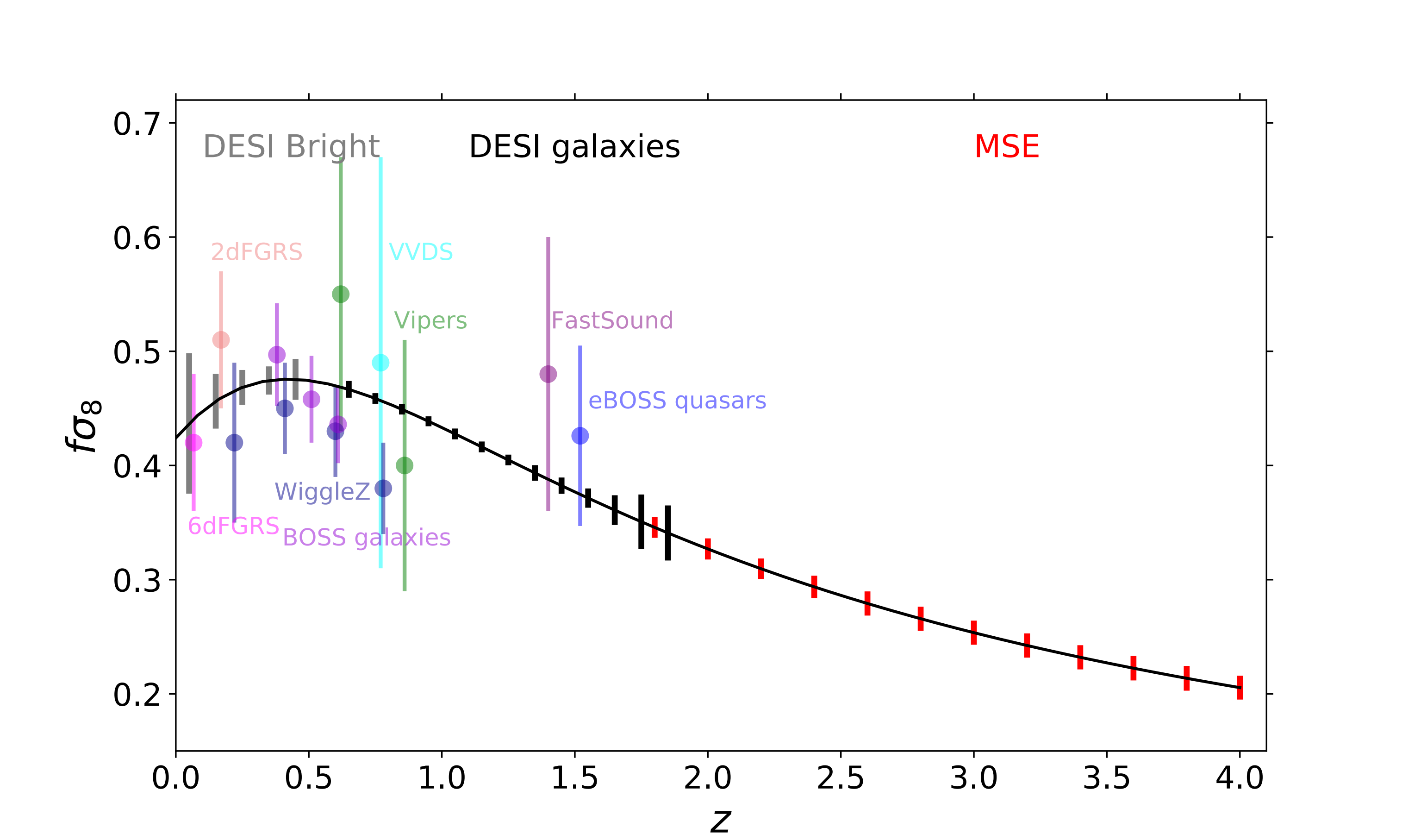
- 12 independent sub-percent measurements of BAO scale
- Benchmark to test exotic early Dark Energy models

Forecast for RSD



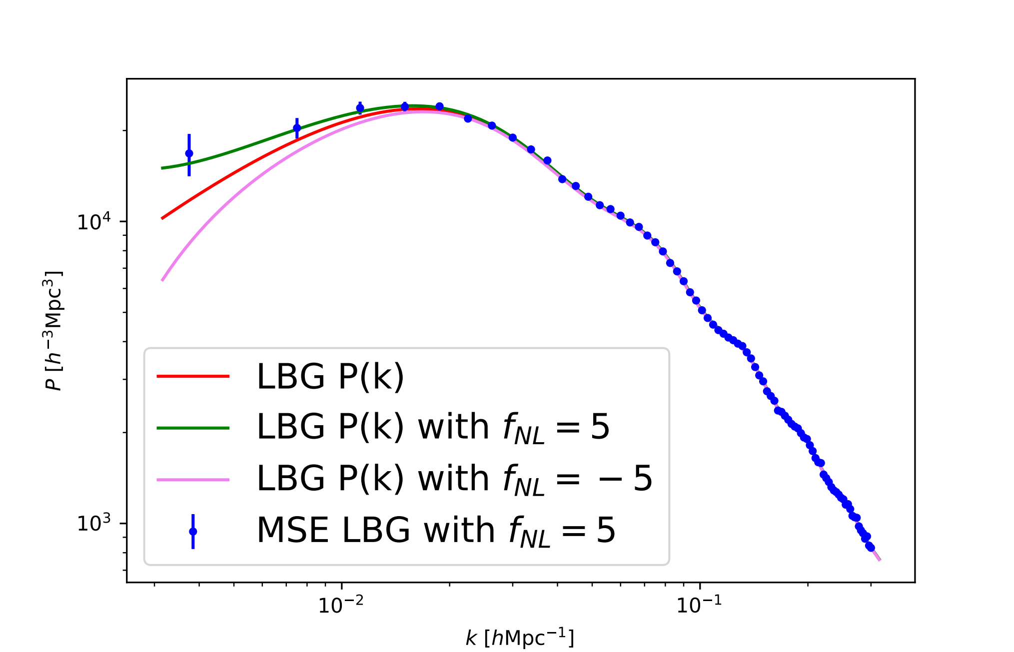
- After DESI in 2025…

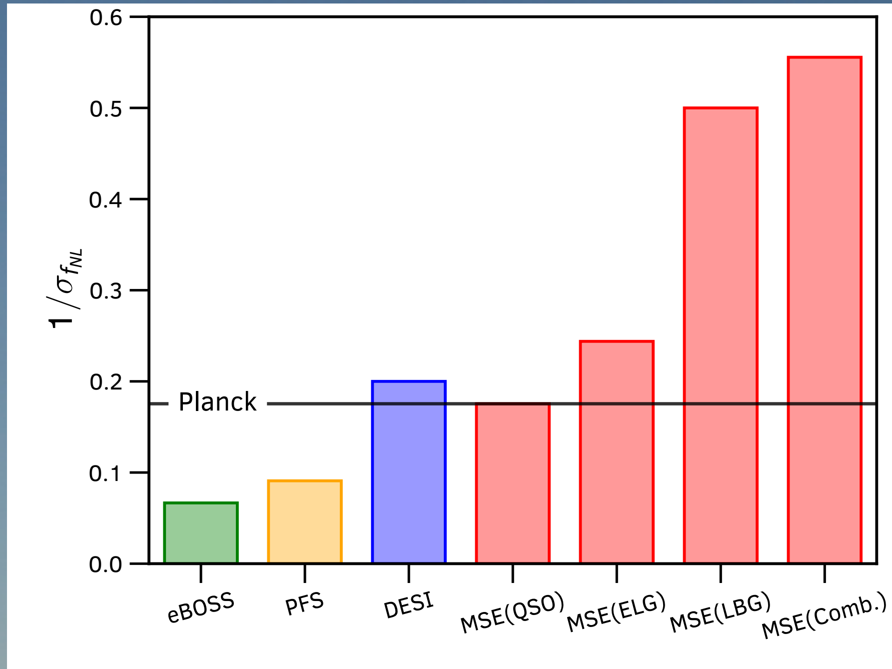
Forecast for RSD



- *RSD measurements from 1.9% to 3.6%*
- *Growth rate f~1 at z=4* → ***Pure measurement of σ_8*** → similar to CMB

Forecast for f_{NL}





A picture of primordial Universe

- *f_{NL} : 3 tracers better or significantly better than CMB alone*
- *Total accuracy **$\sigma(f_{NL})$~1.8 with Power Spectrum***
- *Increasing the redshift success rate to 70% and the redshift range to 2.4<z<5.0 → **$\sigma(f_{NL})$<1** !!!*

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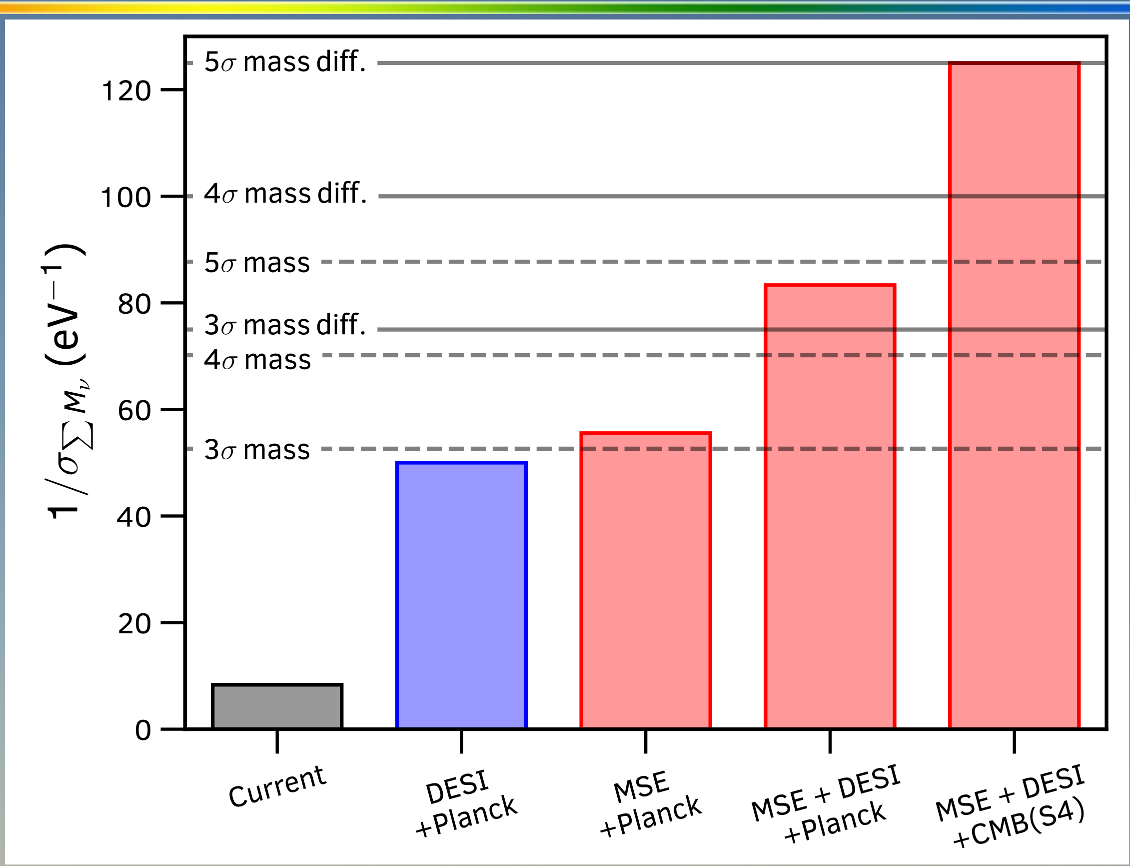
Forecast for Σm_ν



A picture of primordial Universe

- *With CMB(S4), accuracy on neutrino masses $\sigma(\Sigma m_\nu)$~8 meV*
- *Neutrino mass hierarchy at 5σ as precise as DUNE (ν beams)*

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PARTNERSHIP, COST, SCHEDULE

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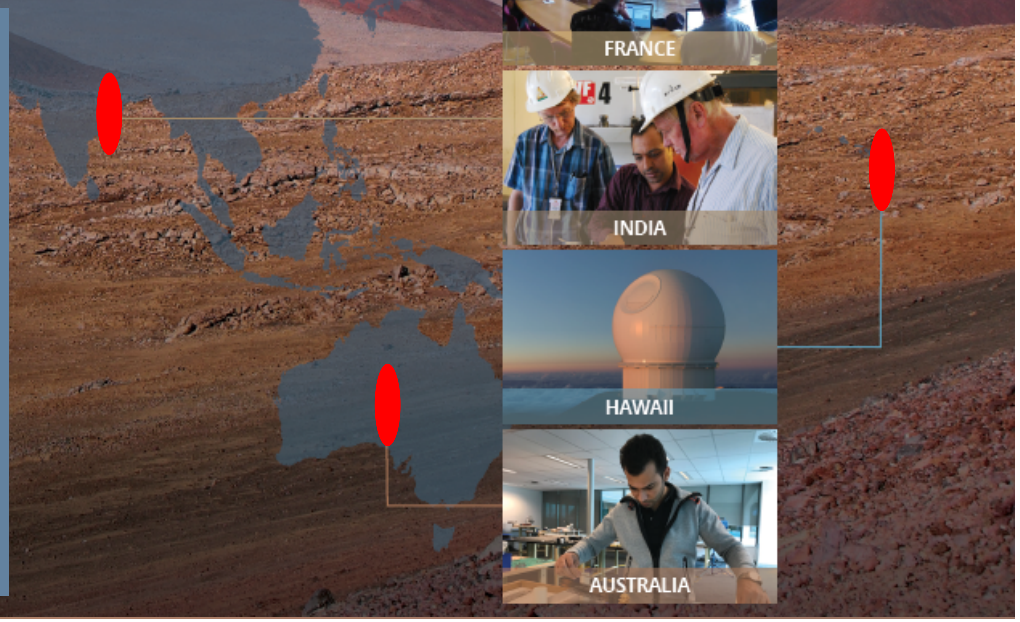
Preliminary Design Phase

The PDP starts in 2019 with participants:

- Australian Astronomical Optics (AAO) Macquarie
- National Research Council (NRC) of Canada
- National Astronomical Observatories (NAOC), Chinese Academy of Sciences
- Centre National de la Recherche Scientifique (INSU) of France
- Institute for Astronomy, University of Hawaii
- India Institute of Astrophysics
- Texas A&M University
- National Optical Astronomy Observatory, UK Participant Group participate as observers



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Science requirements

Accessible sky	30000 square degrees (airmass<1.55)						
Aperture (M1 in m)	11.25m						
Field of view (square degrees)	1.5						
Etendue = FoV x π (M1 / 2)^2	149						
Modes	**Low**		**Moderate**	**High**			**IFU**
Wavelength range	0.36 - 1.8 µm		0.36 - 0.95 µm	0.36 - 0.95 µm ♯			IFU capable; anticipated second generation capability
	0.36 - 0.95 µm	J, H bands		0.36 - 0.45 µm	0.45 - 0.60 µm	0.60 - 0.95 µm	
Spectral resolutions	2500 *(3000)*	3000 *(5000)*	6000	40000	40000	20000	
Multiplexing	>3200		>3200	>1000			
Spectral windows	Full		≈Half	$\lambda_c/30$	$\lambda_c/30$	$\lambda_c/15$	
Sensitivity	m=24 *		m=23.5 *	m=20.0 ♮			
Velocity precision	20 km/s ♪		9 km/s ♪	< 100 m/s ★			
Spectrophotometric accuracy	< 3 % relative		< 3 % relative	N/A			

♯ Dichroic positions are approximate

* SNR/resolution element = 2

♪ SNR/resolution element = 5

♮ SNR/resolution element = 10

★ SNR/resolution element = 30

Simplification and optimization of the low and moderate resolution spectrographs for cosmology and galaxy science

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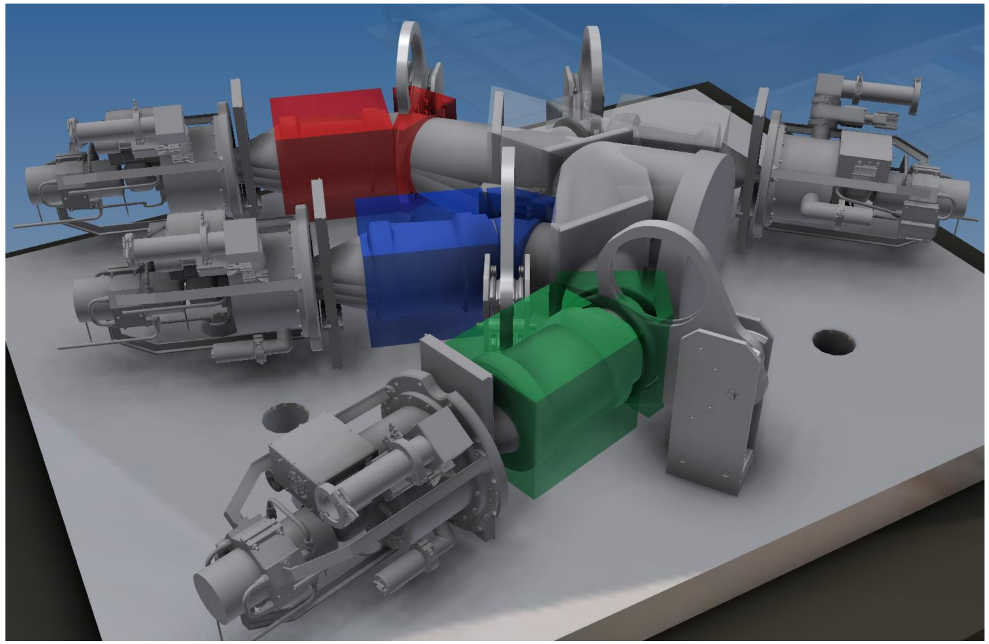
Optimization of spectrographs for cosmology

Current Design

- 6 spectrographs with low and moderate resolution
- Design similar to DESI spectrograph with a additional NIR arm
- LMR spectrograph budget ~$60M (over a total budget ~$400M)
- Winlight company which built DESI spectrographs involved in the design and the construction



New Design in discussion

- 3/4 spectrographs with 4 visible arms equipped with 6k (15mm) detectors
- Full coverage from 360nm to 1000nm with moderate resolution R~5000
- 2 spectrographs with 2 NIR arms (J and H bands)

Gain for cosmology

- Better resolution R: 3000 → 5000
- Better redshift success rate
- H band: ability to observe ELGs in 2.9<z<3.7 redshift range

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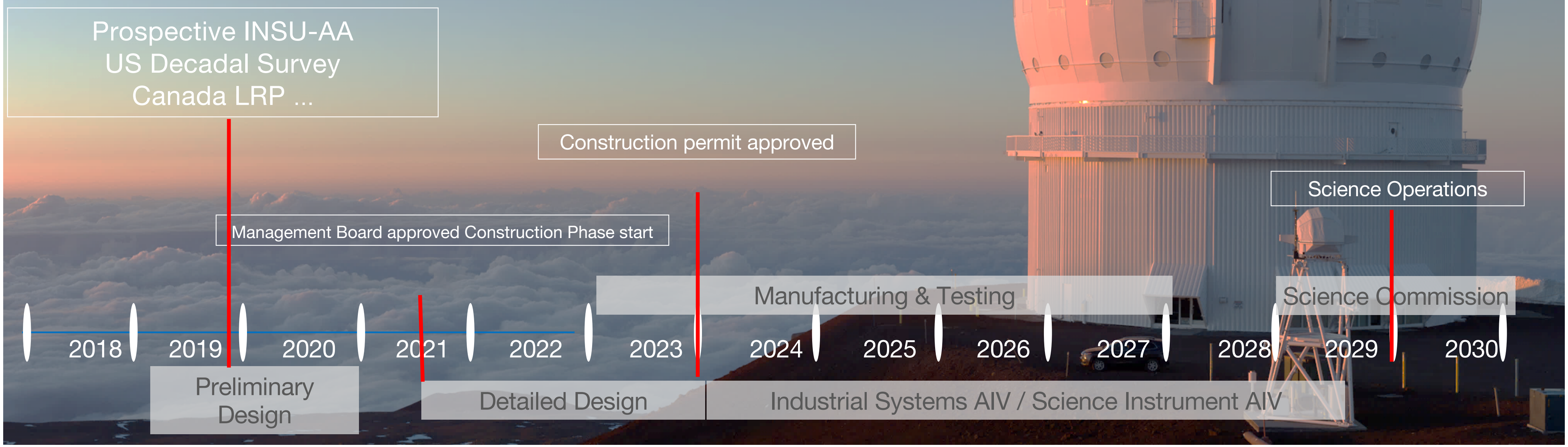
Project Timeline Estimate

Preliminary Design is starting

Science commission will begin in 2029



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Summary

A study of primordial Universe with galaxies and quasars

- *Terra incognita for wide cosmological survey*
- *Precise measurement of non-gaussianity with $\sigma(f_{NL})$~1.8*
- *Neutrino mass hierarchy at 5σ in case of normal hierarchy*

A "generic" program for cosmology

- *3 tracers: ELGs, LBGs (LAE) and QSOs*
- *Redshift: $1.6<z<4.0$*
- *Surface: Wide field 10,000 deg^2 - Deep Field 100 deg^2*
- *Volume: 280 Gpc^3*
- *100 nights per year for a 5-year MSE program*
- *~Half of the dark time during the first 5 years of MSE*

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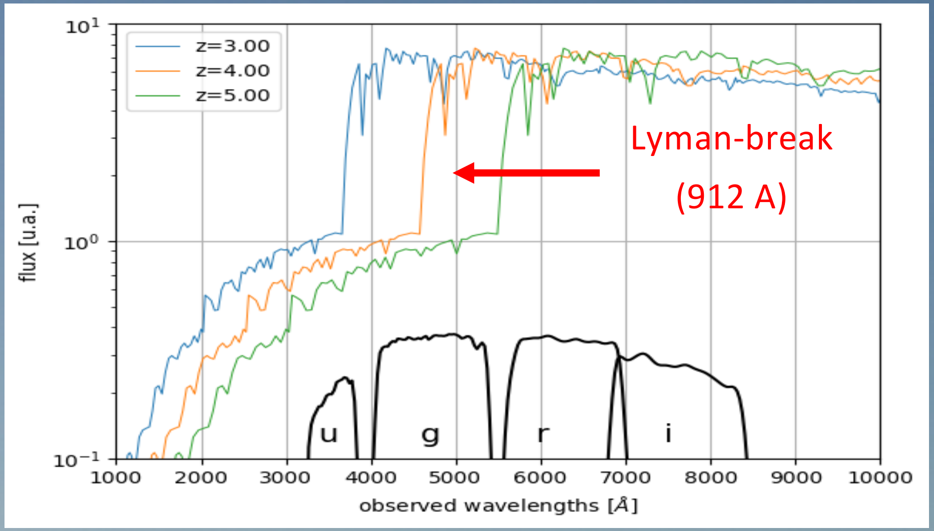
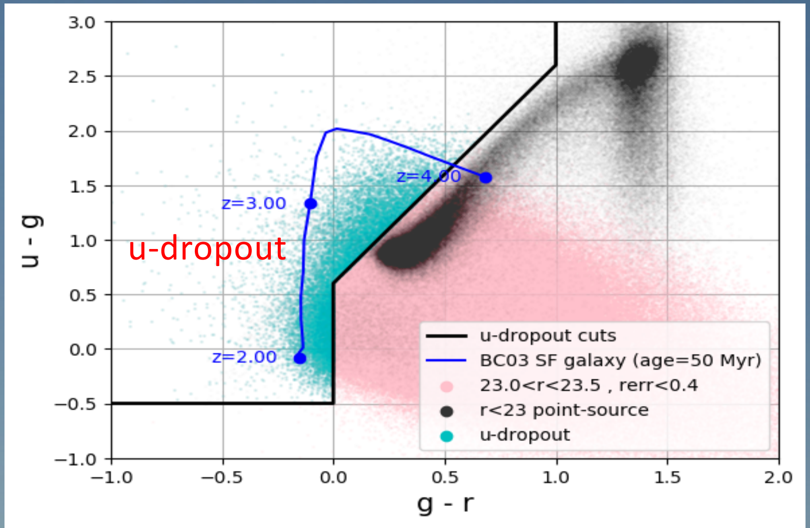
Additional Slides

Target selection of the LBGs





Selection based on dropout techniques

- *By comparing two neighboring bands, we can detect the strong absorption below Lyman-break*
- *For z~3, u-dropout u-g>0*
- *For z~4, g-dropout g-r>0*

Test with KiDS photometric Catalog

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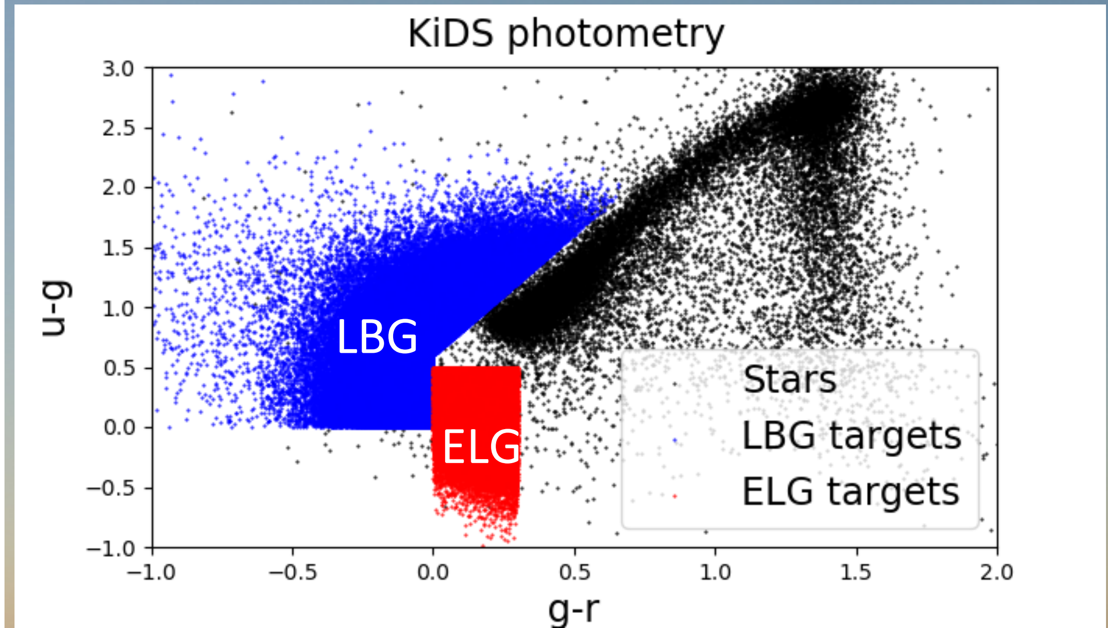
	u	g	r	i	seeing
KiDS	24.2	25.1	25.0	23.6	0.7"
LSST-1 yr	24.1	25.6	25.8	25.1	0.7"
LSST-10 yr	25.3	26.8	27.0	26.4	0.7"

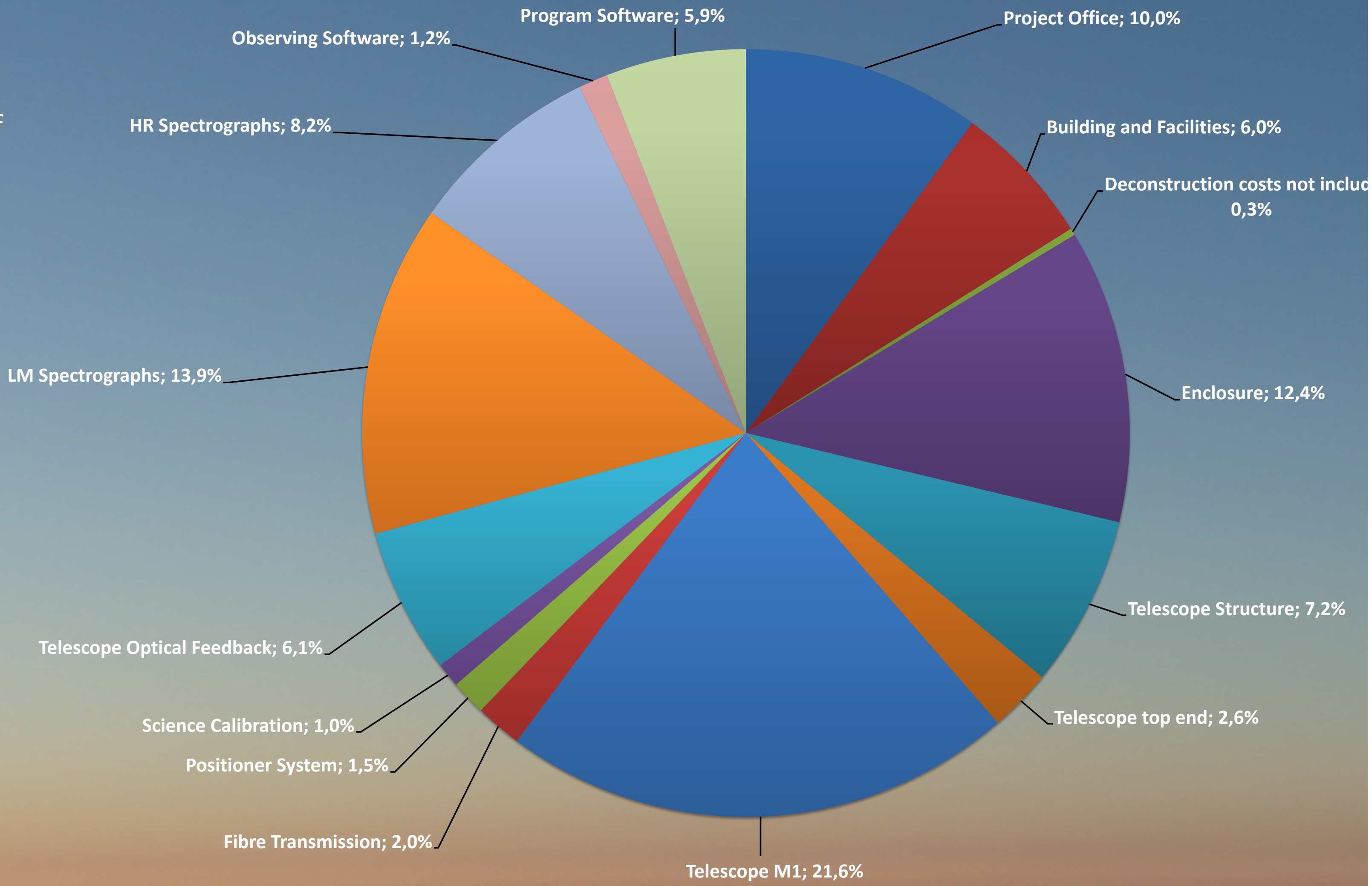


Selection of LBGs and ELGs

- *Based on KiDS photometry*
- *100 deg^2 in equatorial stripe in NG*
- *ugri bands*
- *mag. limit: 23.7/24.5 for ELG/LBG*
- *LBG density: 1400 deg^{-2}*
- *ELG density: 700 deg^{-2}*

Project Cost Estimate

- Risk Adjusted Construction Cost of **$424M**
- Base year 2017
- The PDP cost is estimated to be $25M
- $13M of in-kind contributions have been identified.
- About $9M invested in CoDP



Technical Specifications (Telescope-Positioner)

Site characteristics	
servatory latitude	19.9 degrees
cessible Sky	30,000 square degrees (airmass < 1.55 i.e., δ > -30 degrees)
edian image quality	0.37 arcsec (free atmosphere, zenith, 500 nm)
. length of night adjusted for weather	8 hours
serving efficiency (on-sky, on-target)	80%
pected on-target observing hours	2336 hours / year
pected on-target fiber-hours	10,119,552 fiber-hours / year (total): 7,589,664 (LR & MR) / 2,529,888 (HR)

Telescope architecture	
ucture, focus	Altitude-azimuth, Prime
. aperture / Science field of view	80.8 m^2 / 1.5 square degrees
ectrograph system	6 x LMR spectrographs (4 channels / spectrograph), all identical, each channel seperately switchable to provide LR and MR modes

Fiber positioning system	
ultiplexing	4,332 (total): 3,249 (LR & MR) / 1,083 (HR)
er size	1 arcsec (LR & MR) / 0.75 arcsec (HR)
sitioner patrol radius	90.3 arcsecs
sitioner accuracy	0.06 arcsec rms
sitioner closest approach	Two fibers can approach with 7 arcsecs of each other (three fibers can be placed within 9.9 arcsec diameter circle)
positioning time	< 120 seconds
pical allocation efficiency	> 80 % (assuming source density approximately matched to fiber density)

Science Driven Design