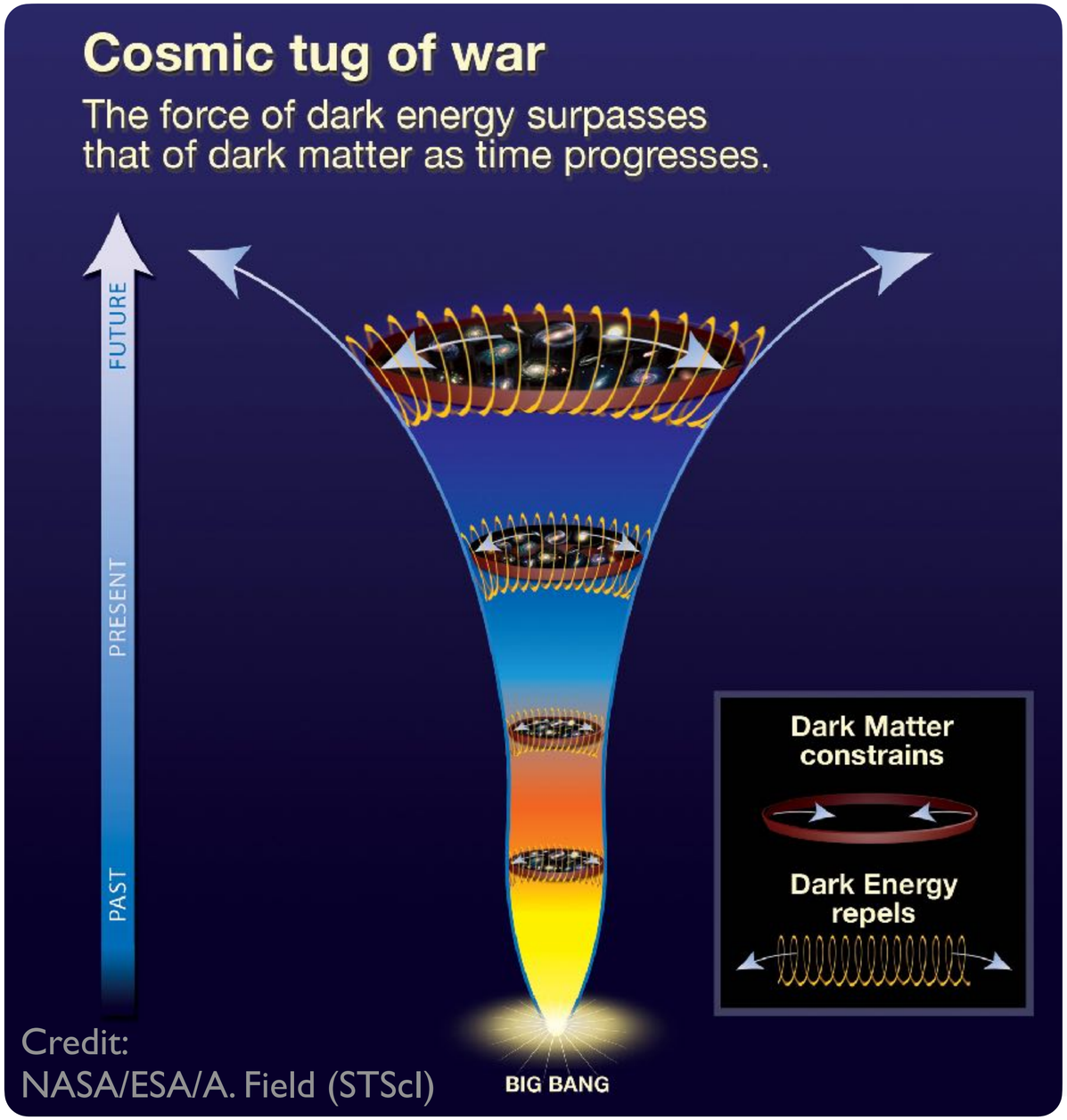
# From DESI to MUST

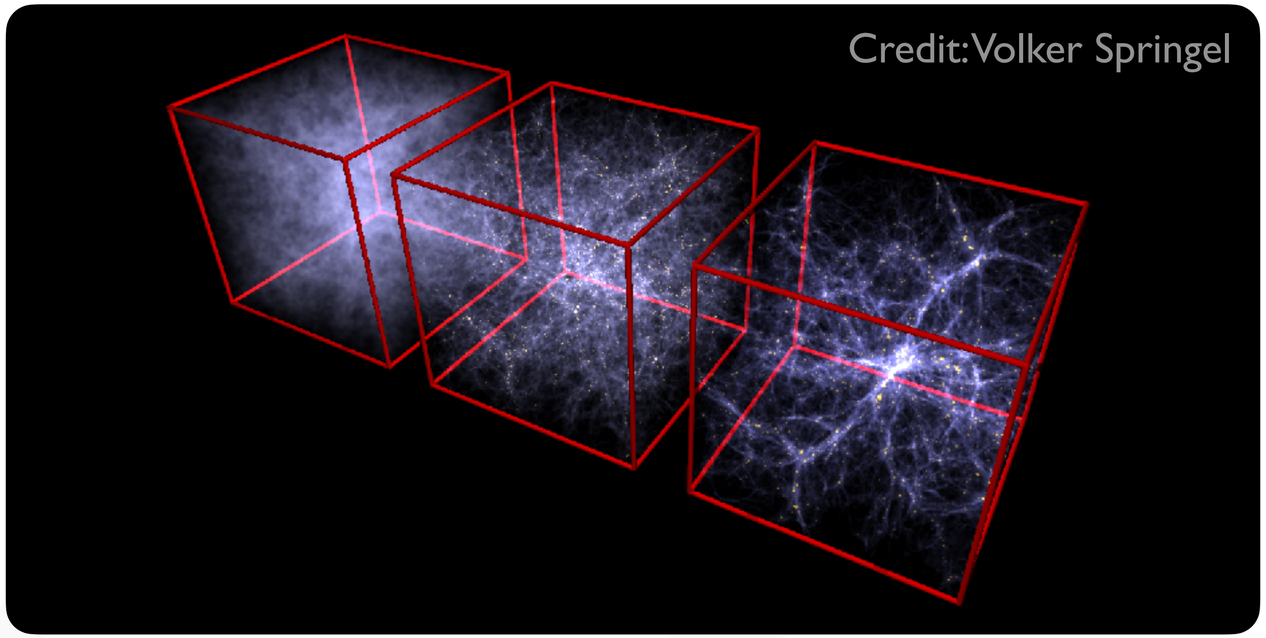
## Fundamental Physics with Large-Scale Galaxy Surveys

Cheng Zhao (赵成)
Department of Astronomy, Tsinghua University
24 July, 2025

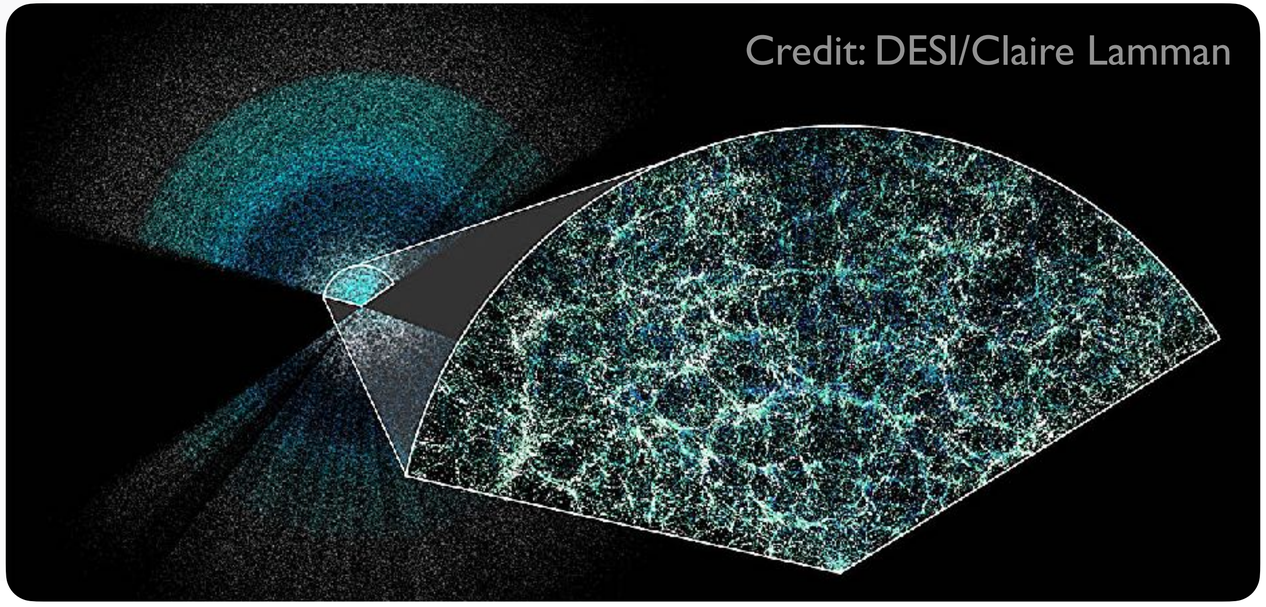
# Large-Scale Structures




Credit:
NASA/ESA/A. Field (STScI)

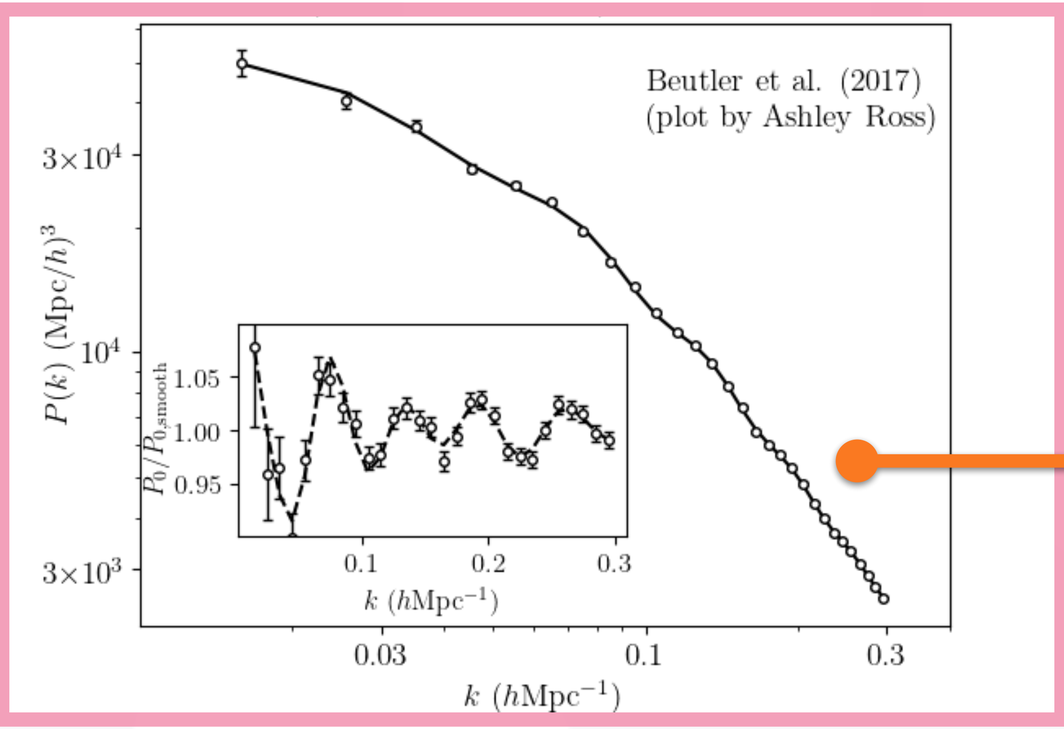


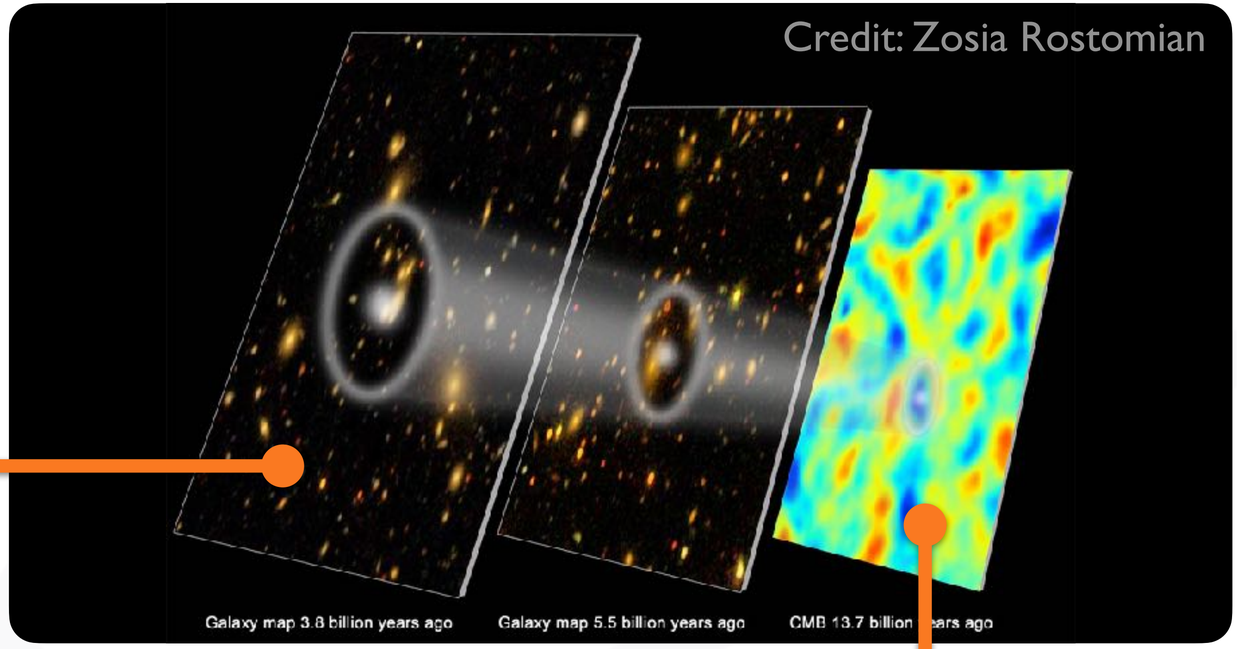
Credit: Volker Springel

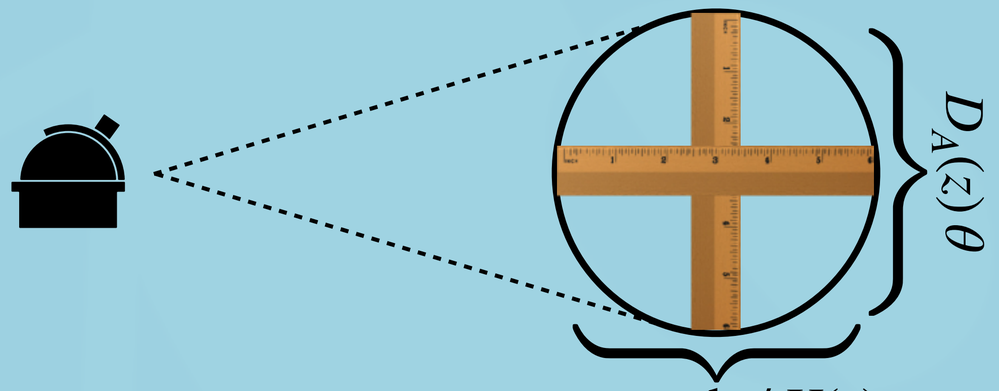


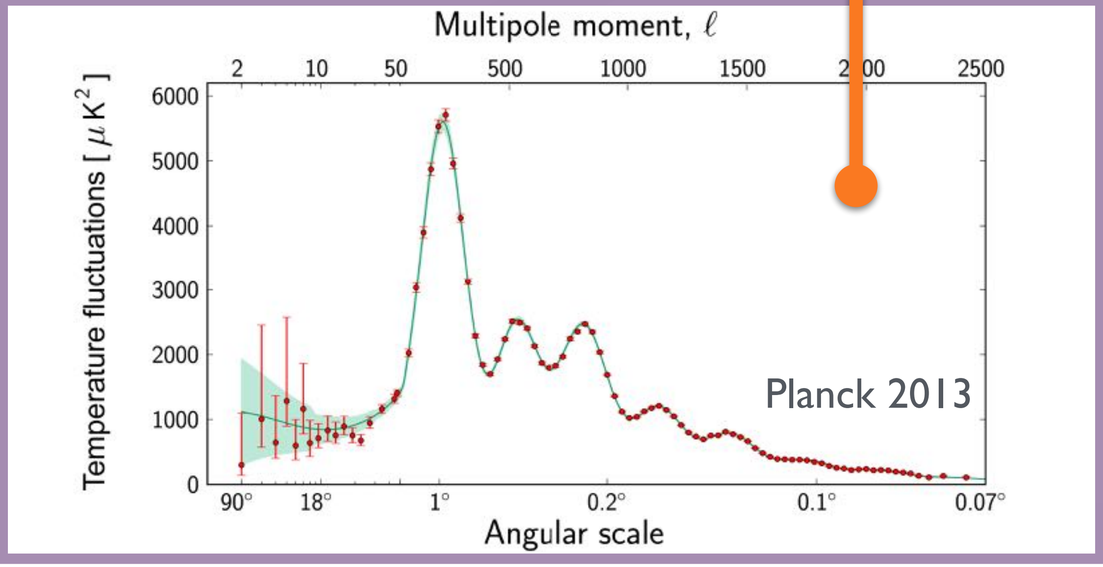
Credit: DESI/Claire Lamman

# MUST Baryon Acoustic Oscillation: Standard Ruler



# Matter Clustering: Power Spectrum

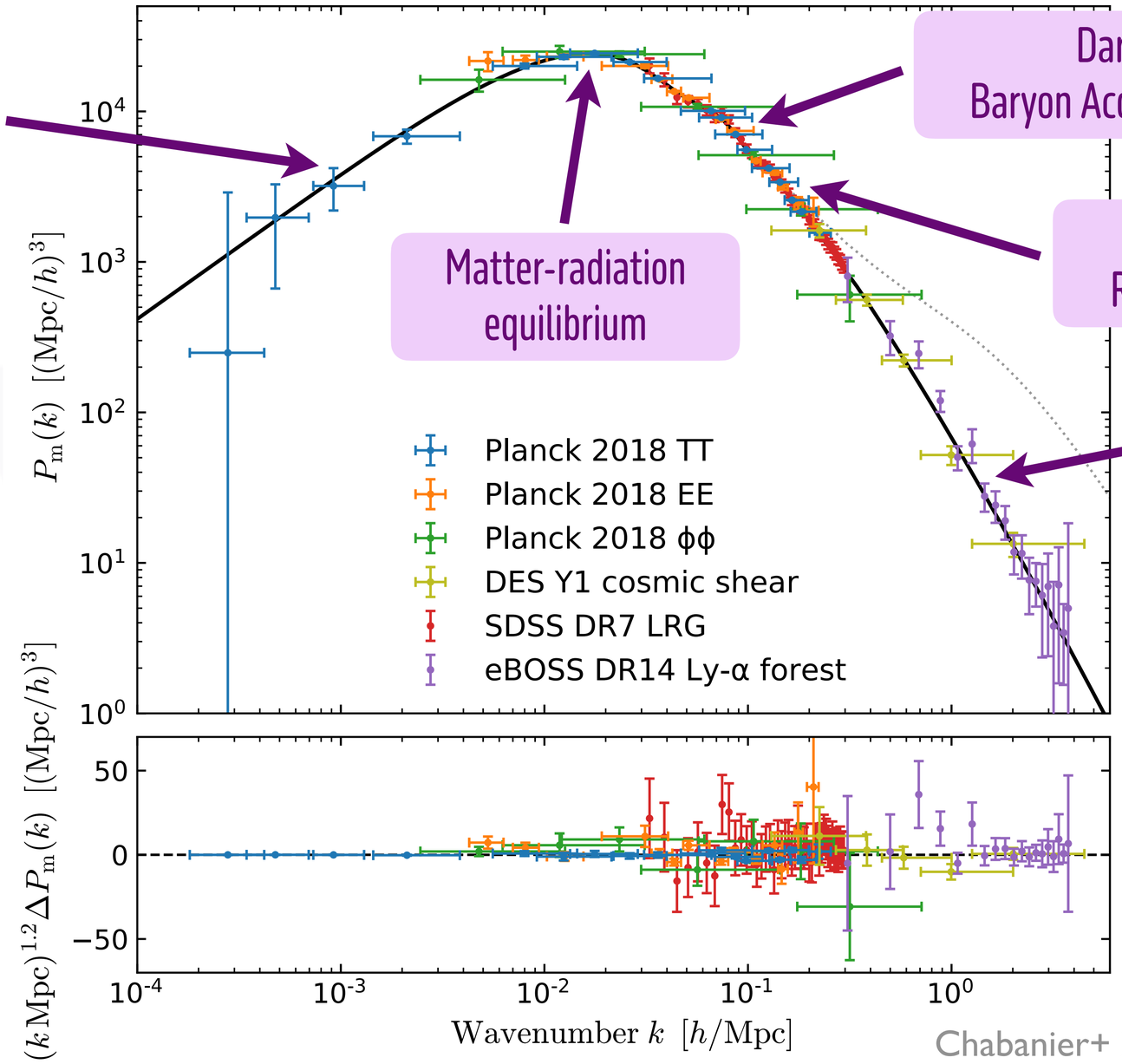
Primordial non-Gaussianity

Dark energy: Baryon Acoustic Oscillation

Matter-radiation equilibrium

Structure growth: Redshift-Space Distortion

Property of dark matter particle




large scale

small scale

Chabanier+ 2019

# MUST Science Cases with Large-Scale Structures

## Dark Energy

- Equation of State
- Time evolution
- Early dark energy

## Light Relics

- Total neutrino mass
- Effective number of relativistic species
- Axion-like particles

## Dark Matter

- Particle mass
- (Self) interaction
- Dynamical dark matter and dark radiation

## Inflation Physics

- Single- vs. Multi-field inflation
- Cosmological collider signals
- Isocurvature perturbations

## Modified Gravity

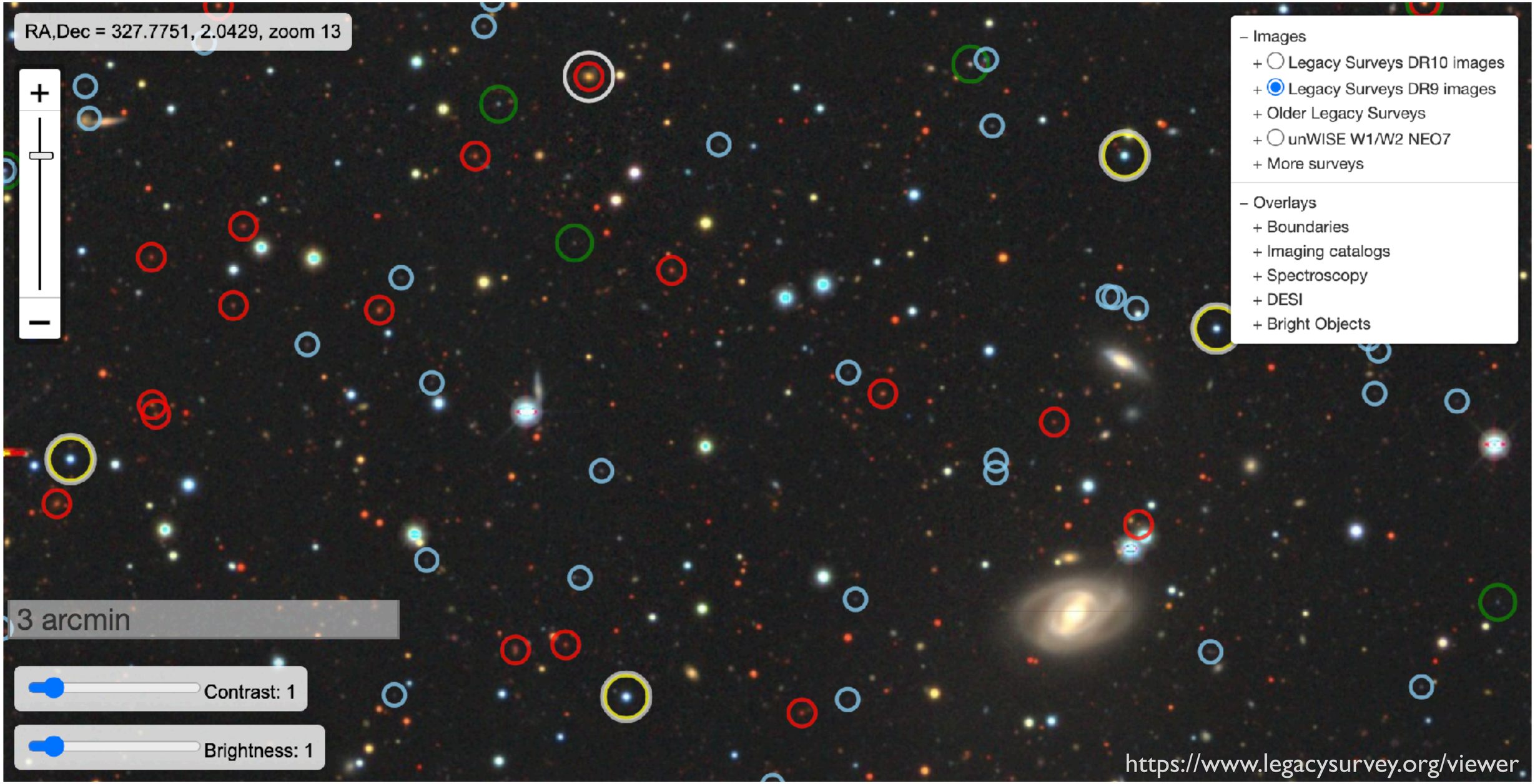
- Scale-dependent growth
- Screening mechanisms
- Gravitational slip

## And more (Beyond Standard Model) . . .

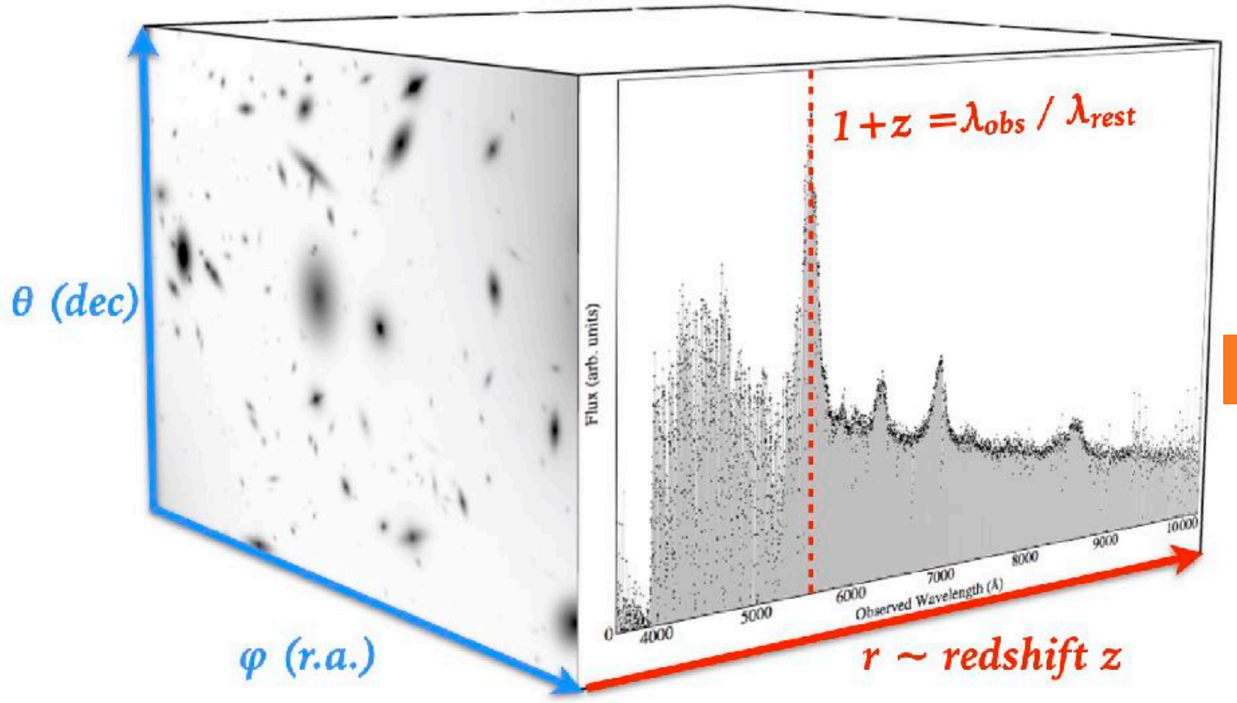
- Parity violation
- Fifth force and new scalar fields
- Lorentzian invariance

MUST

# Galaxy Spectroscopic Survey

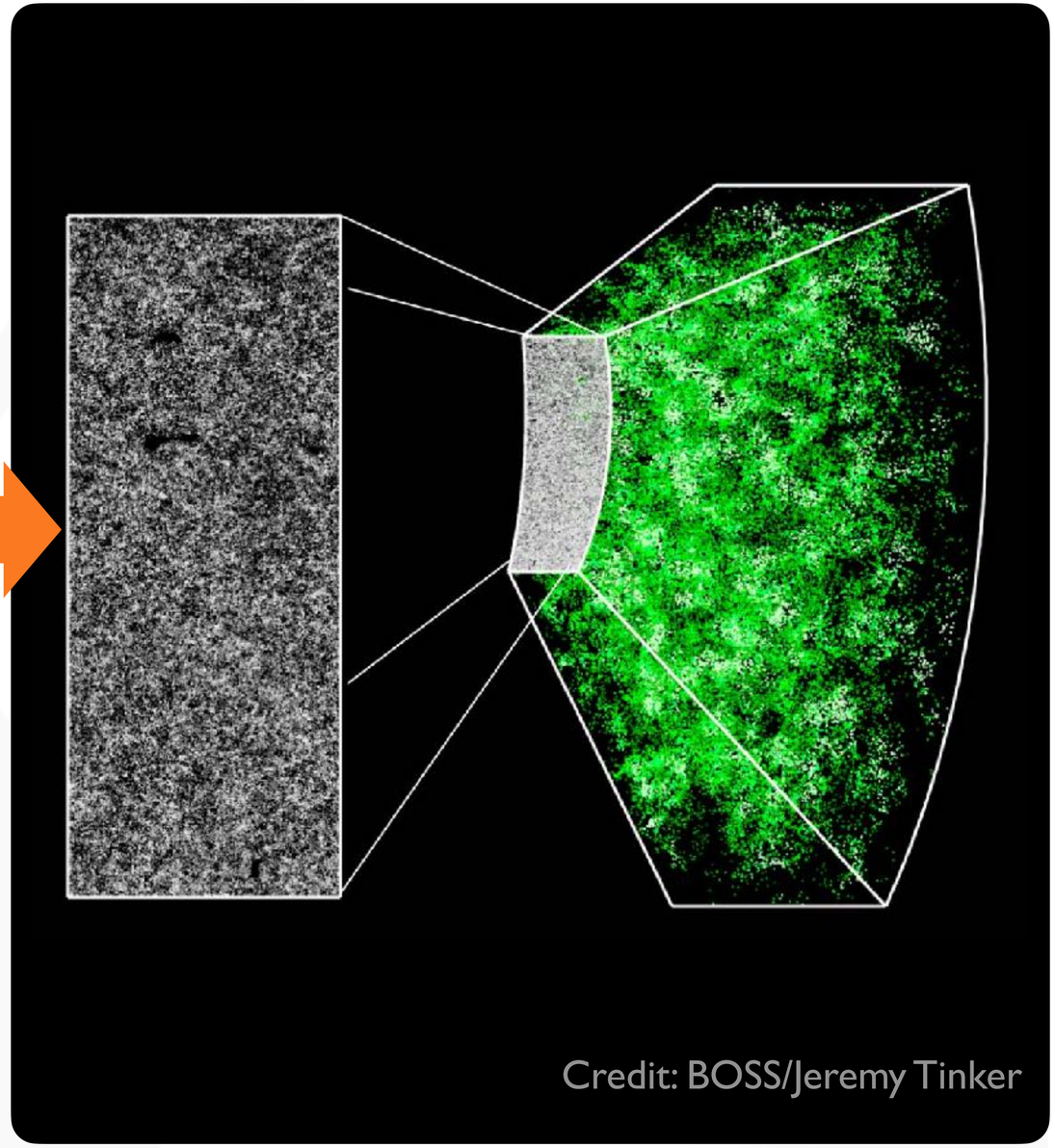


# 3D Galaxy Map




The optical sky is a data cube: $\theta \times \varphi \times r$

Credit: David Kirkby

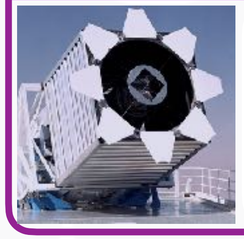


Credit: BOSS/Jeremy Tinker

# MUST Galaxy Spectroscopic Surveys – Stage I/II

## Stage I/II

### SDSS I/II: confirm DE



- Duration: 2000 – 2008
- Aperture: 2.5 m
- Fibers: 800
- Spectra: 100k

## Stage III

### BOSS/eBOSS: precise DE @ z<1



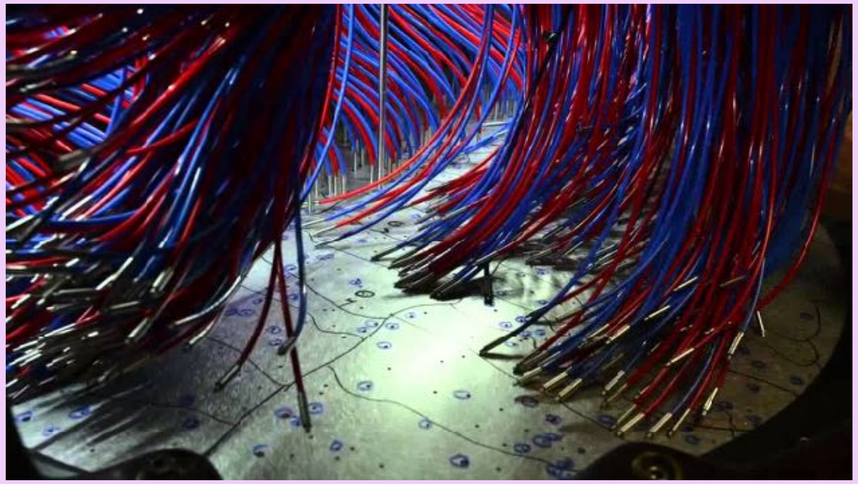
- Duration: 2009 – 2019
- Aperture: 2.5 m
- Fibers: 1,000
- Spectra: 2.5 million

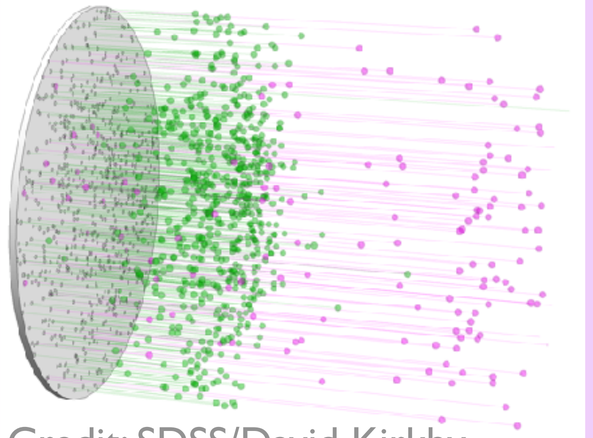
## Stage IV

### DESI: precise DE @ z<3



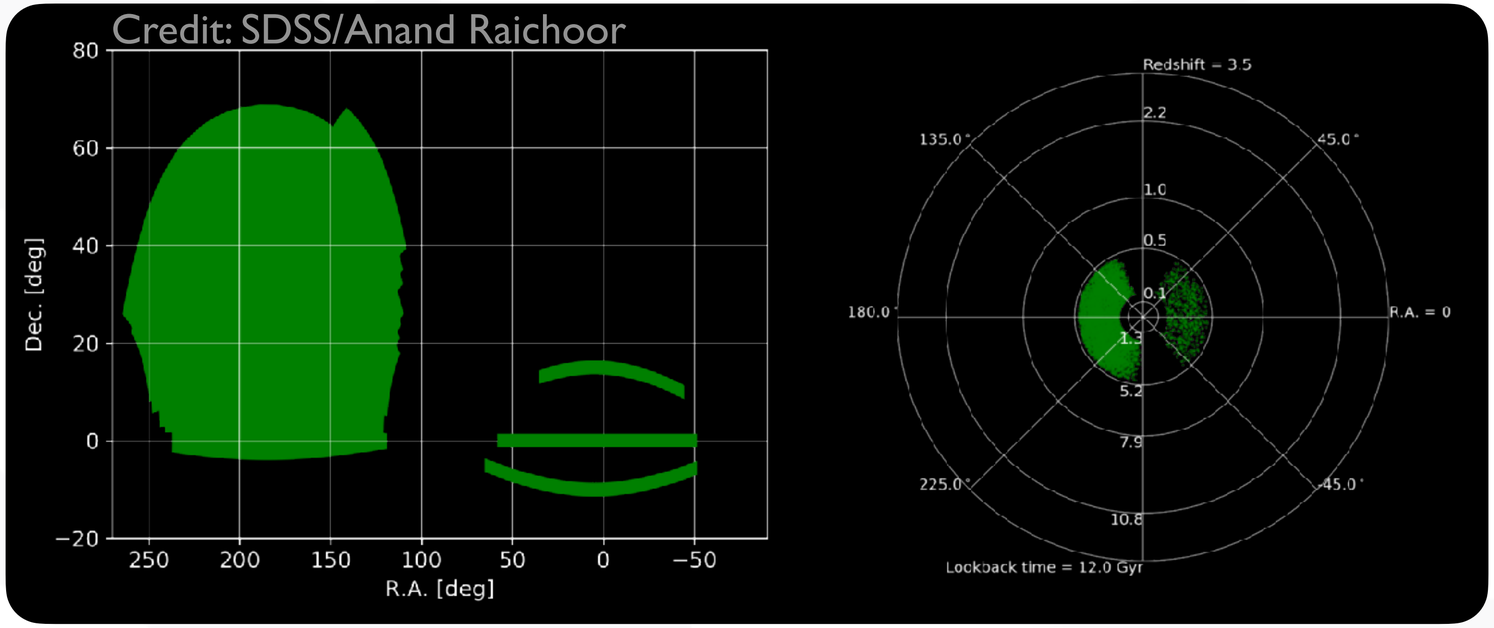
- Duration: 2020 – 2029
- Aperture: 4 m
- Fibers: 5,000
- Spectra: 50 million





Credit: SDSS/David Kirkby

Credit: SDSS/Anand Raichoor



# MUST Galaxy Spectroscopic Surveys – Stage III

## Stage I/II

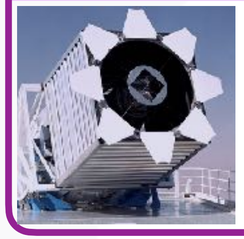
SDSS I/II: confirm DE



- Duration: 2000 – 2008
- Aperture: 2.5 m
- Fibers: 800
- Spectra: 100k

## Stage III

BOSS/eBOSS: precise DE @ z<1



- Duration: 2009 – 2019
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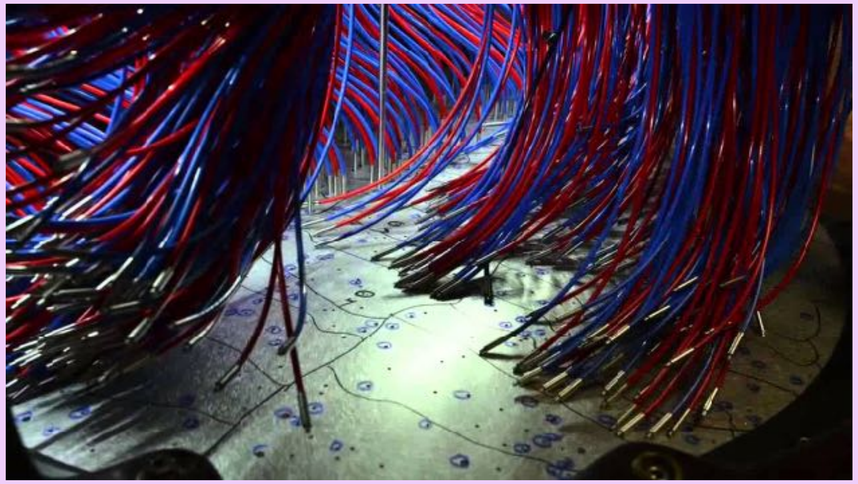
- Spectra: 2.5 million

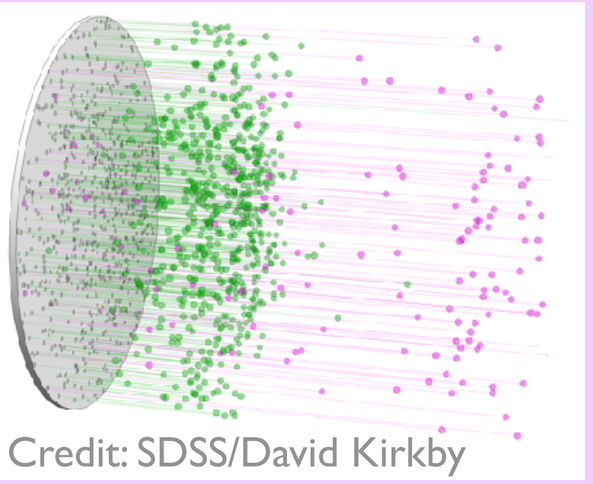
## Stage IV

DESI: precise DE @ z<3

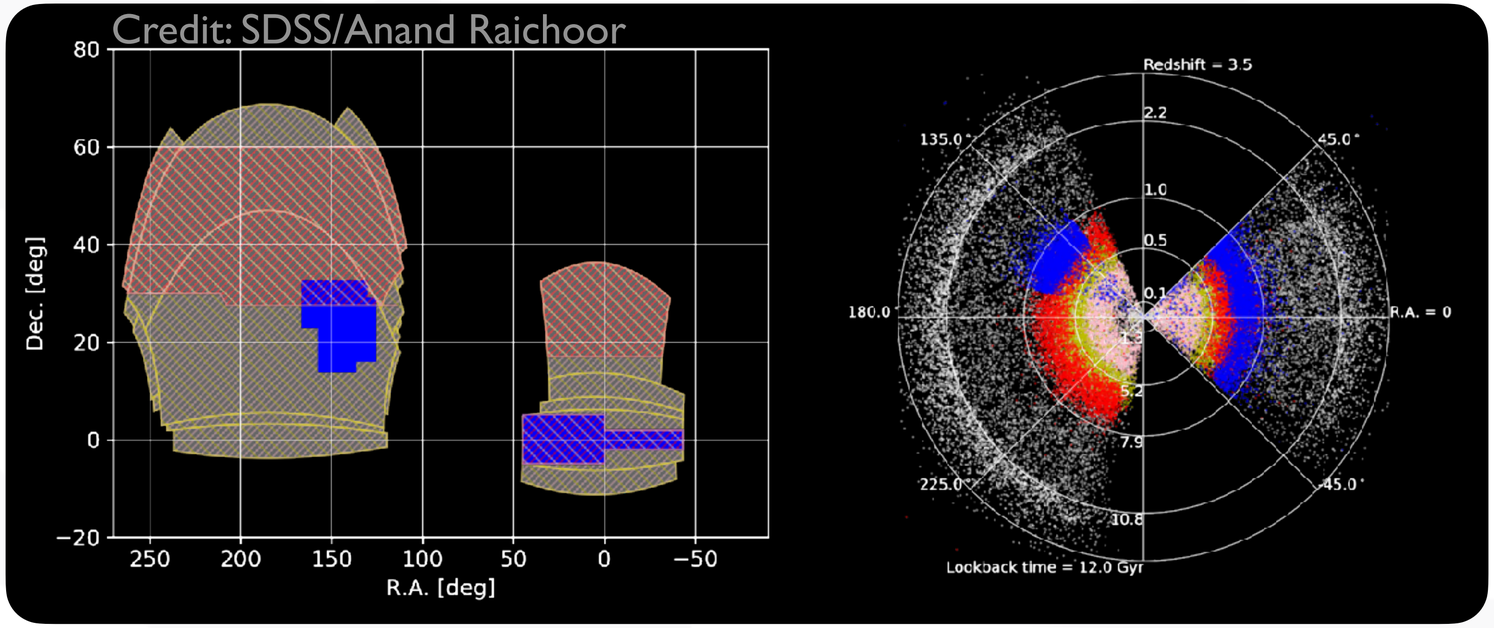


- Duration: 2020 – 2029
- Aperture: 4 m
- Fibers: 5,000
- Spectra: 50 million





Credit: SDSS/David Kirkby



# MUST Galaxy Spectroscopic Surveys – Stage IV

## Stage I/II

SDSS I/II: confirm DE



- Duration: 2000 – 2008
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- Spectra: 100k

## Stage III

BOSS/eBOSS: precise DE @ z<1



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- Aperture: 2.5 m
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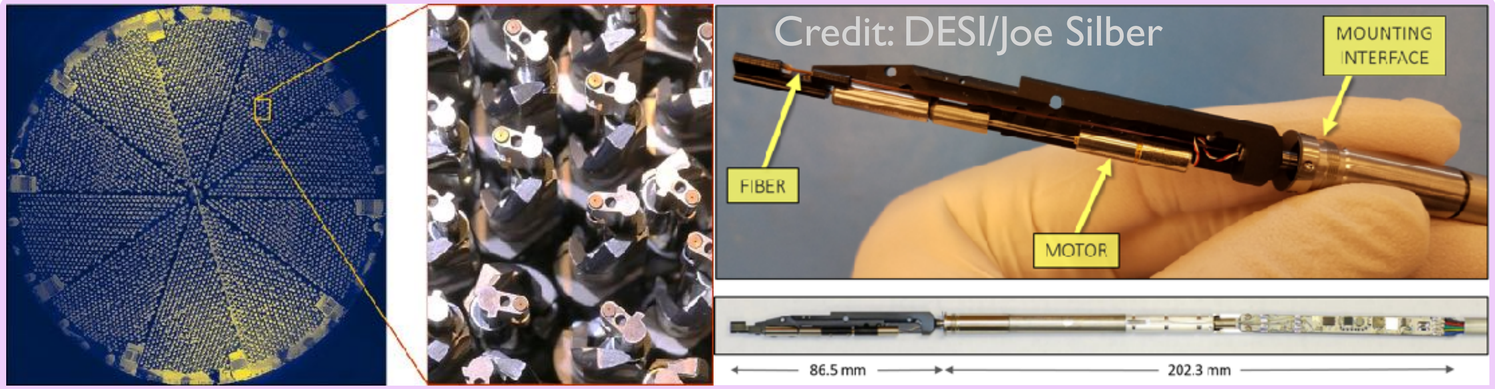
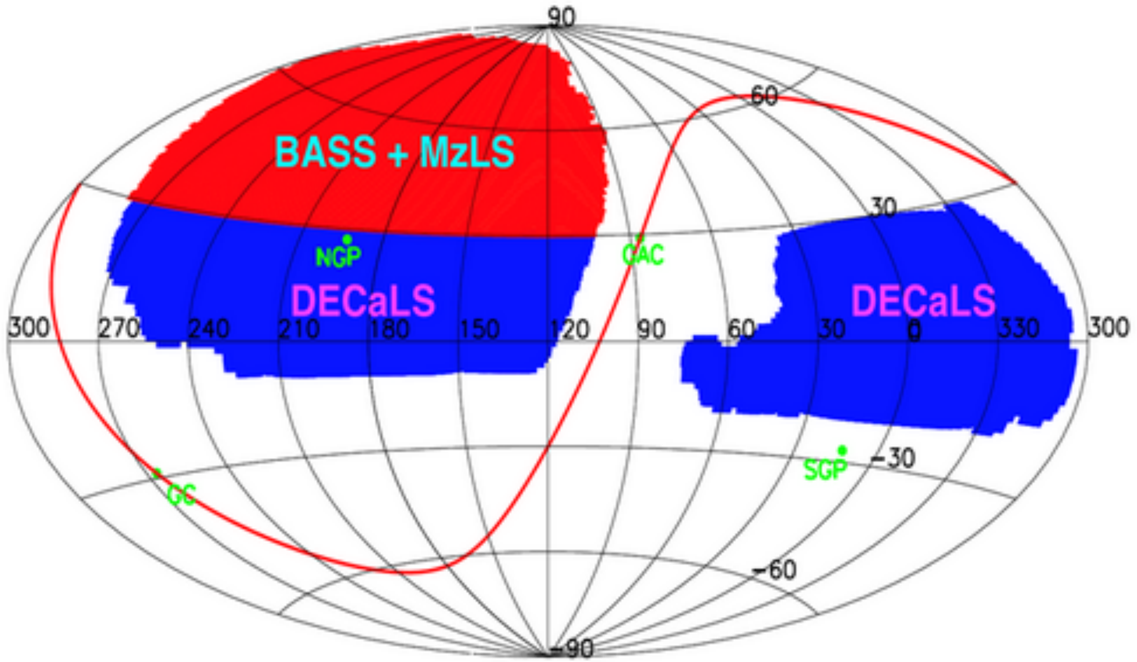
## Stage IV

DESI: precise DE @ z<3

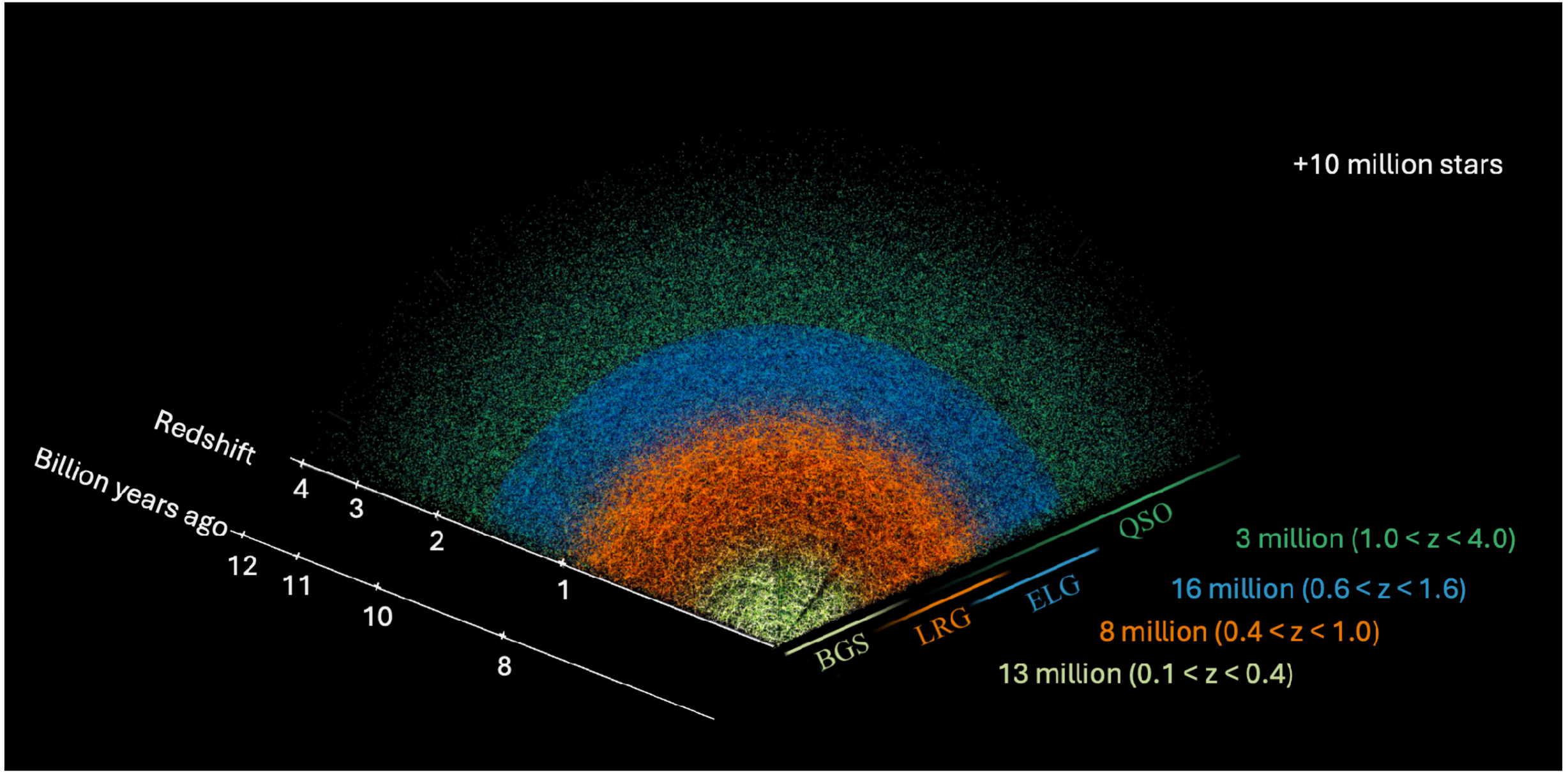
- Duration: 2020 – 2029
- Aperture: 4 m
- Fibers: 5,000
- Spectra: 50 million



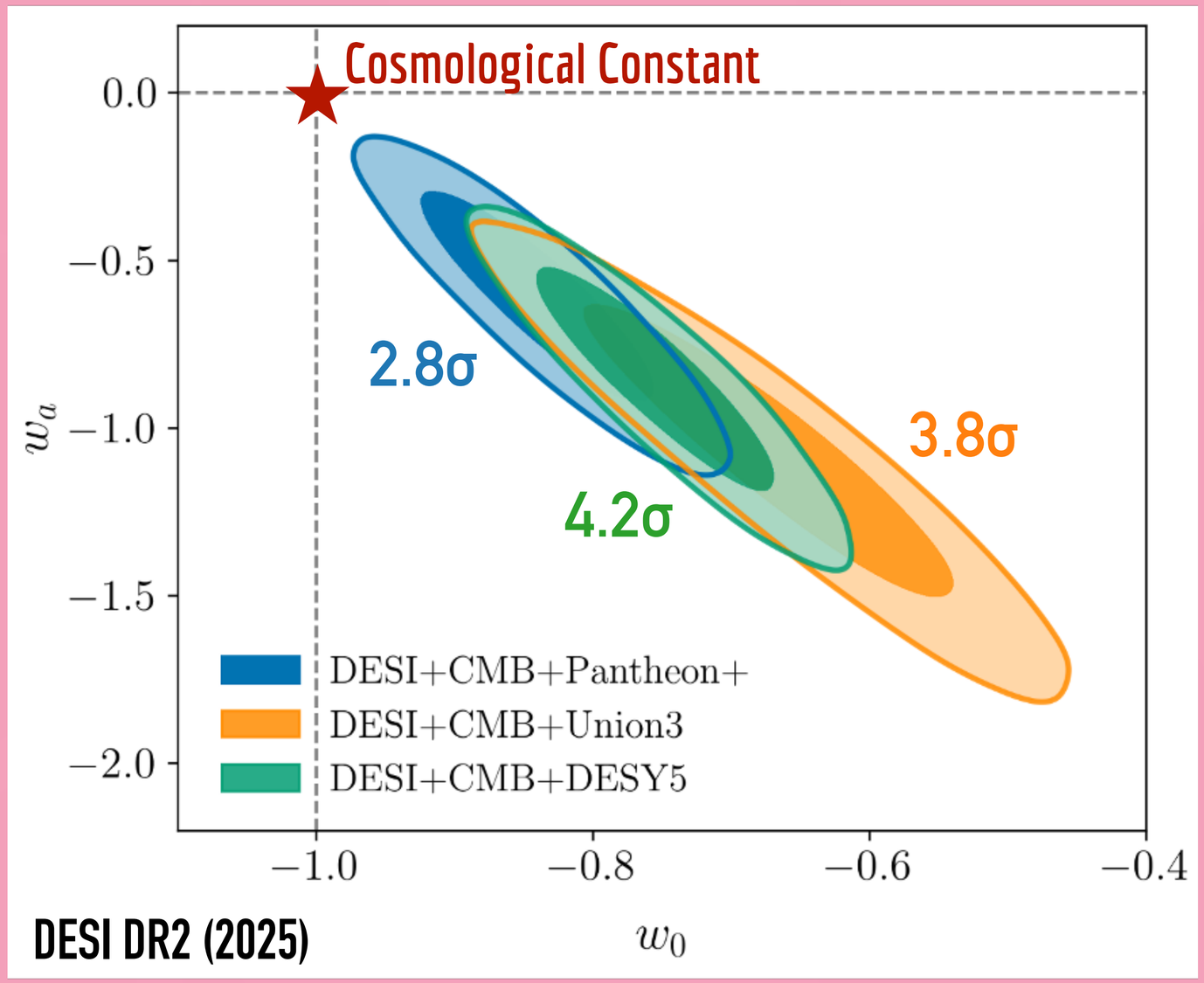




Credit: DESI/Anand Raichoor

# DESI DR2


+10 million stars
Redshift
Billion years ago
4
3
2
1
12
11
10
8
BGS
LRG
ELG
QSO
3 million (1.0 < z < 4.0)
16 million (0.6 < z < 1.6)
8 million (0.4 < z < 1.0)
13 million (0.1 < z < 0.4)

# DESI Results: Evolving Dark Energy




DESI DR2 (2025)

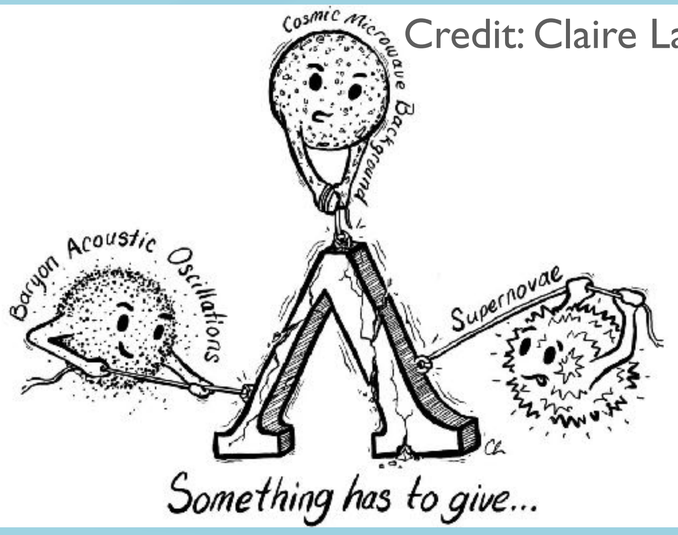
- Dark Energy Equation of State:

$$w = \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

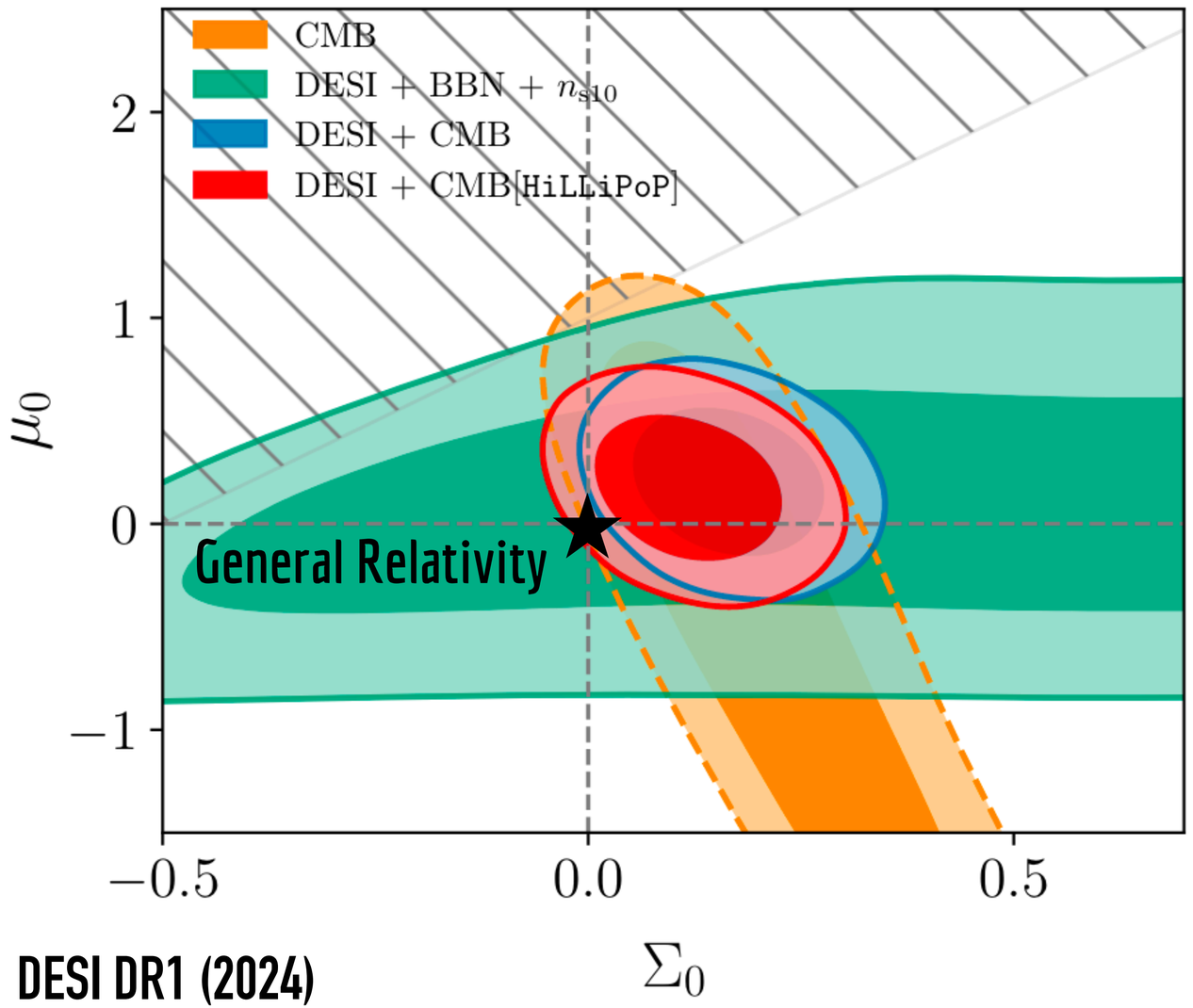
$$w(a) = w_0 + w_a(1 - a)$$

- Evidence of Dynamic Dark Energy

Credit: Claire Lamman



# DESI Results: Modified Gravity




DESI DR1 (2024)

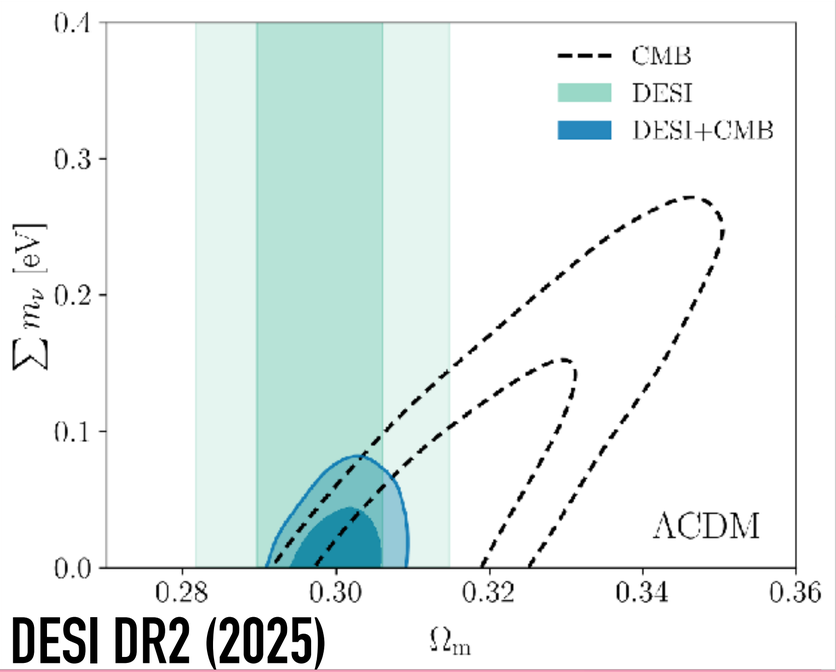
- Parameterization of gravitational potentials

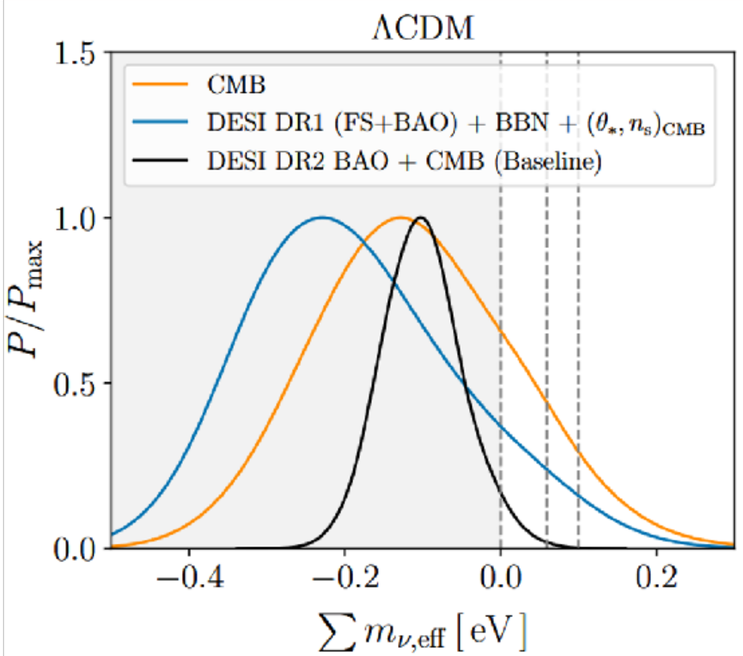
$$k^2\Psi = -4\pi G a^2 \left[1 + \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda 0}}\mu_0\right]\rho\delta$$

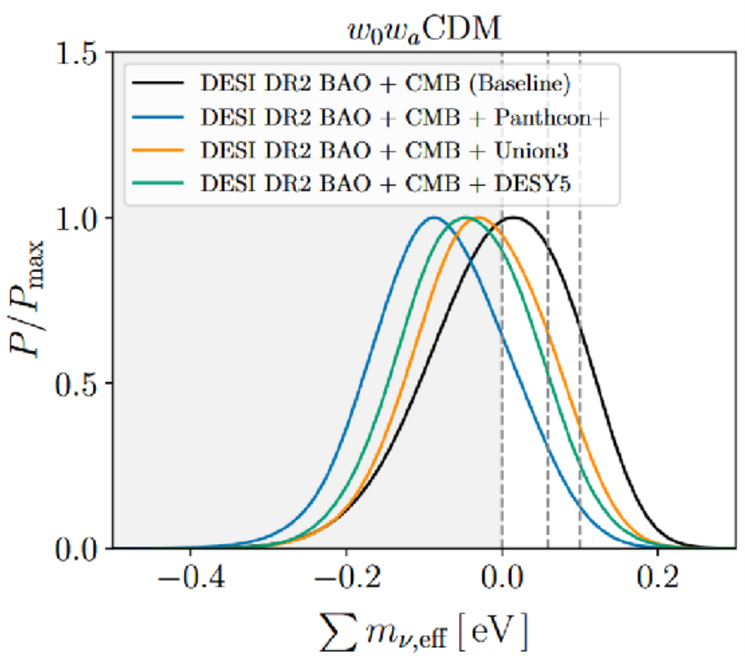
$$k^2(\Psi + \Phi) = -8\pi G a^2 \left[1 + \frac{\Omega_\Lambda(a)}{\Omega_{\Lambda 0}}\Sigma_0\right]\rho\delta$$

- General Relativity is still safe with the combined DESI + CMB constraints

# DESI Results: Total Neutrino Mass

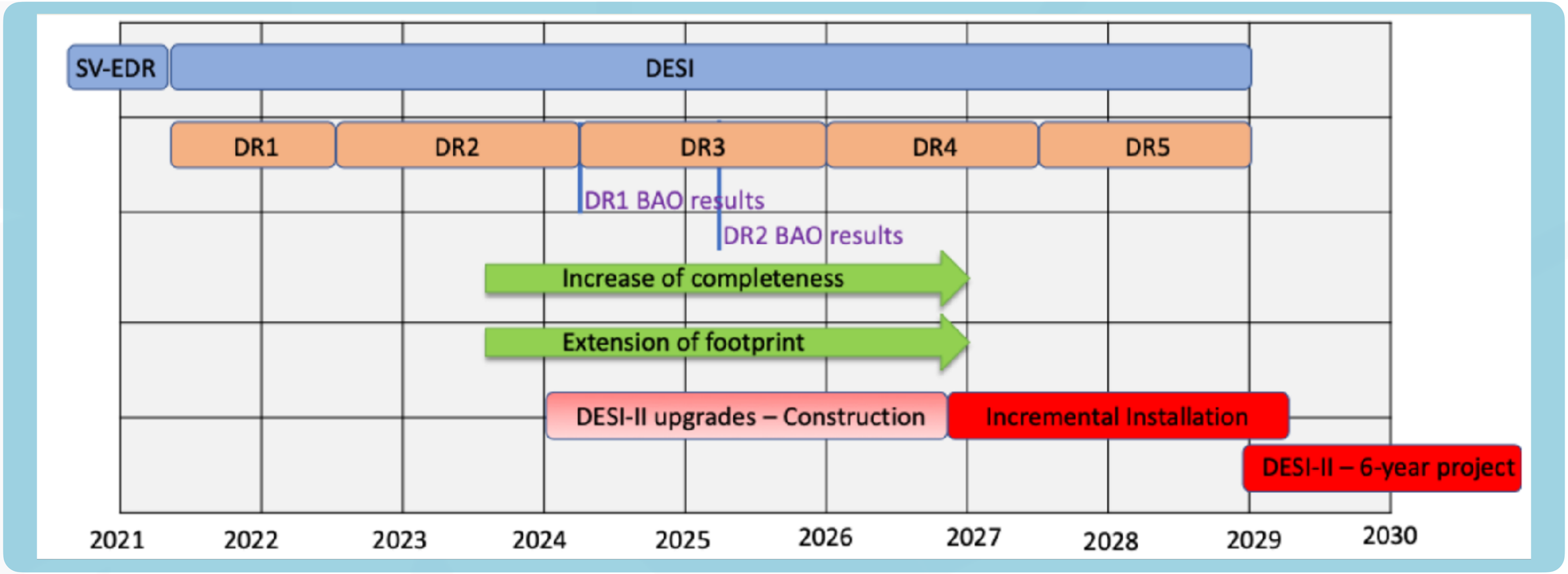



- Normal Hierarchy preferred in ΛCDM: $\sum m_\nu < 0.064\,\mathrm{eV}$ (95% CL)
- "Negative" neutrino mass: hint of tension between cosmology and neutrino oscillation experiments

# DESI Timeline




- Big success (extraordinary high throughput)
- DESI extension approved: 2026 – 2029 with 2 additional data releases
- DESI-II: planned 2029 – 2035 with minimal instrumental upgrades

# MUST: Next Generation Cosmological Survey

An International

Early-2030s

Credit: Iris Long

## Collaboration

Led by

## Tsinghua University

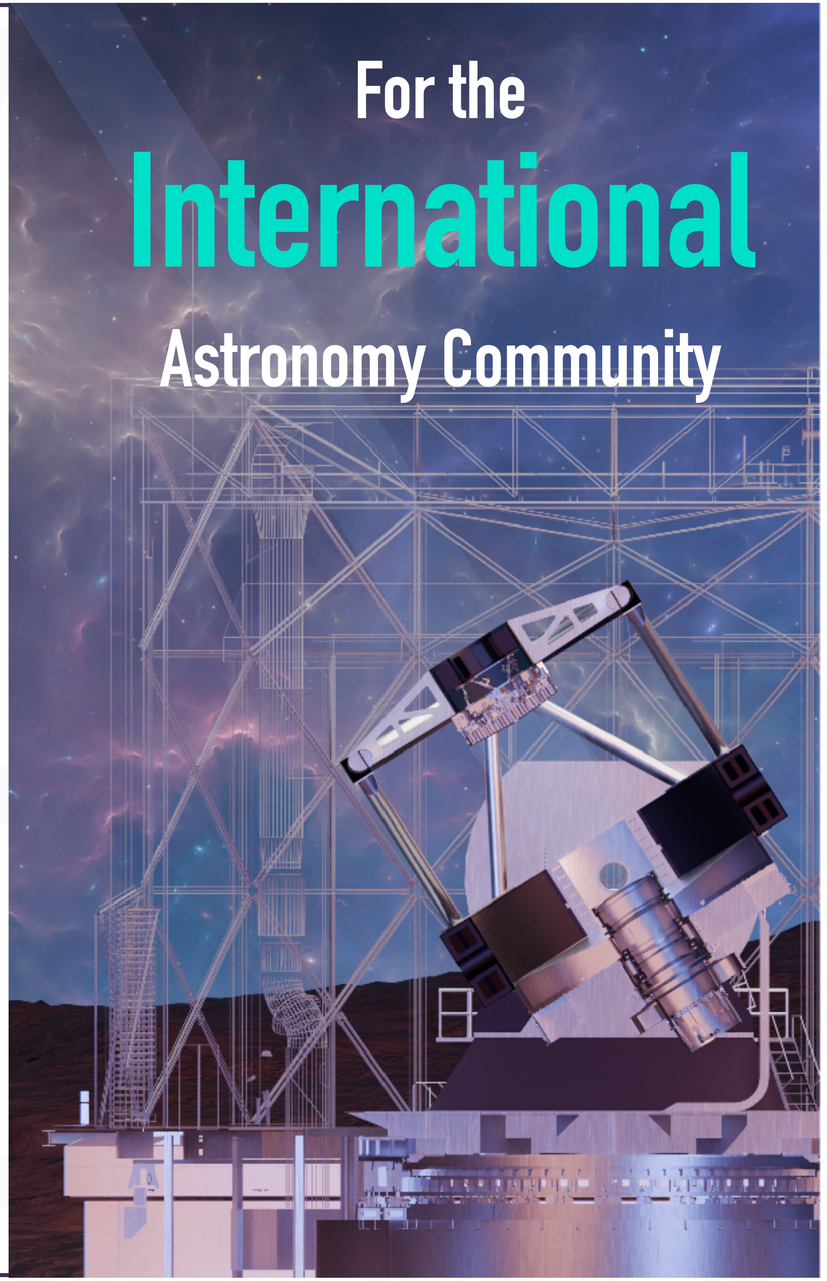
A dedicated

**Survey** Telescope

For the

## International

Astronomy Community



MUST

# Overview of MUST

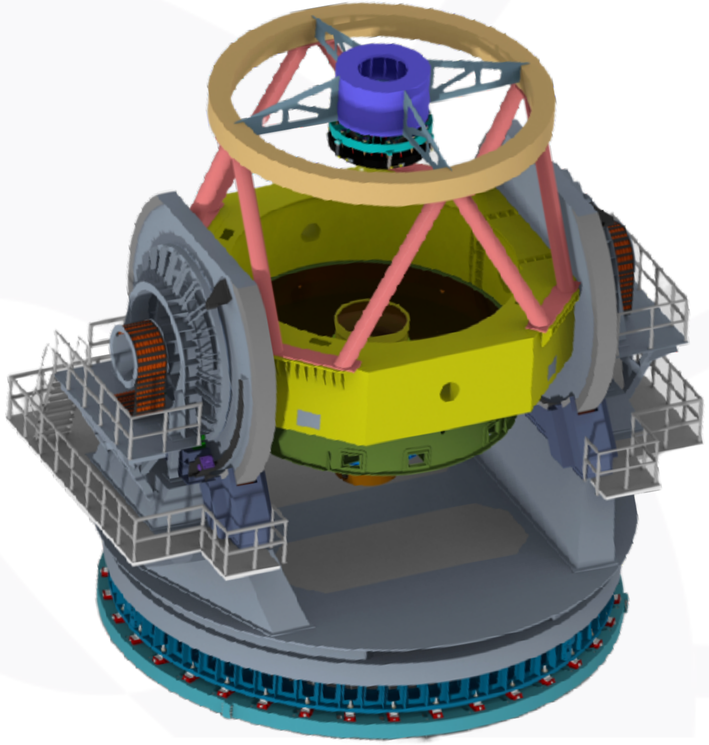
- MUST aims to carry out the world's First Stage-V spectroscopic survey for Cosmology and create the Largest 3-D Map of the Universe.
- MUST will constrain cosmological models with unprecedented precision and strive for breakthroughs in Fundamental Physical Problems, such as the primordial condition of the Universe, the origin and evolution of Dark Energy, and the nature of Dark Matter.

**6.5m** Primary

**2.4m** Secondary

**1.6m** Lens for WFC

**7deg²** FoV



**20,000** Fiber Positioners

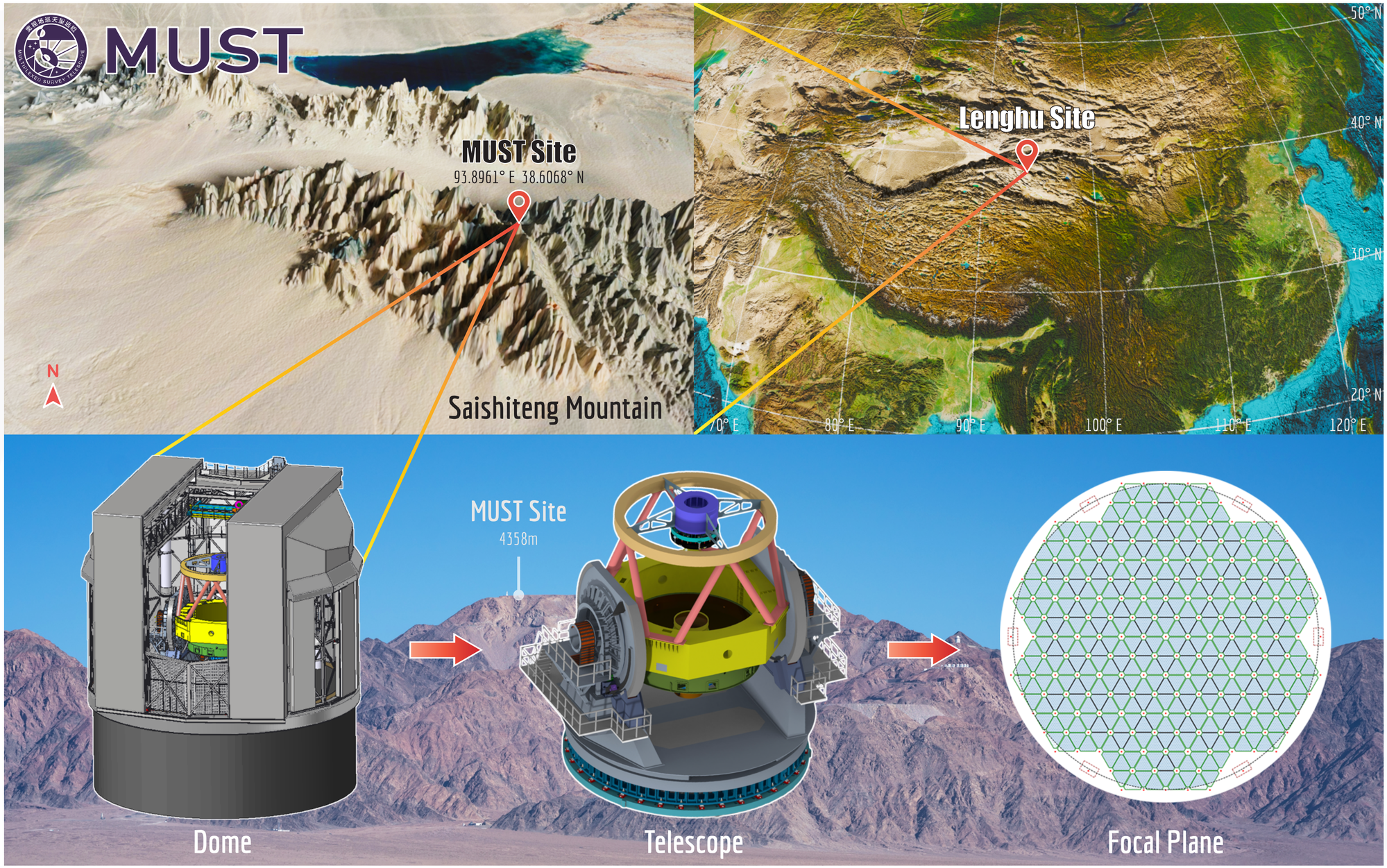
**MODULAR** Focal Plane

**40** Spectrographs

**0.37–0.98** micron

**R~2000–4000**

# Overview of MUST



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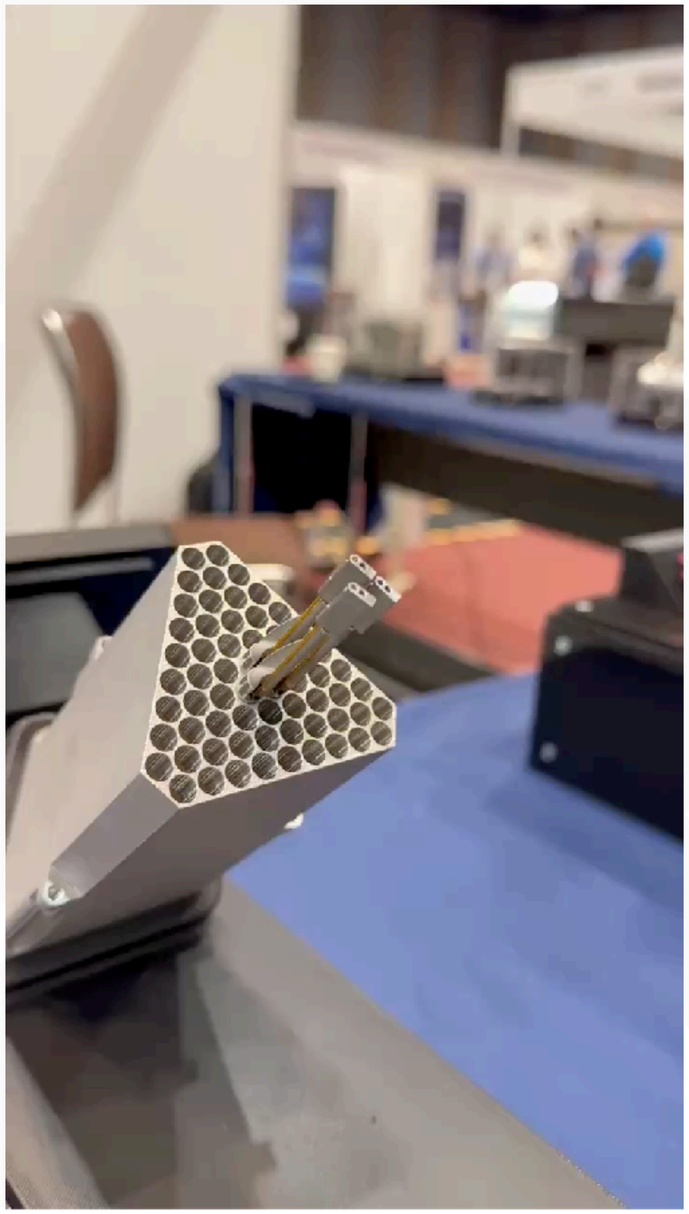
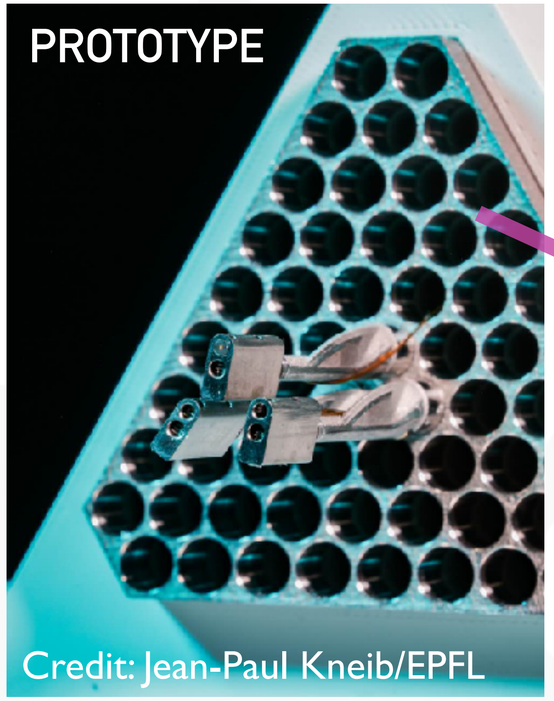
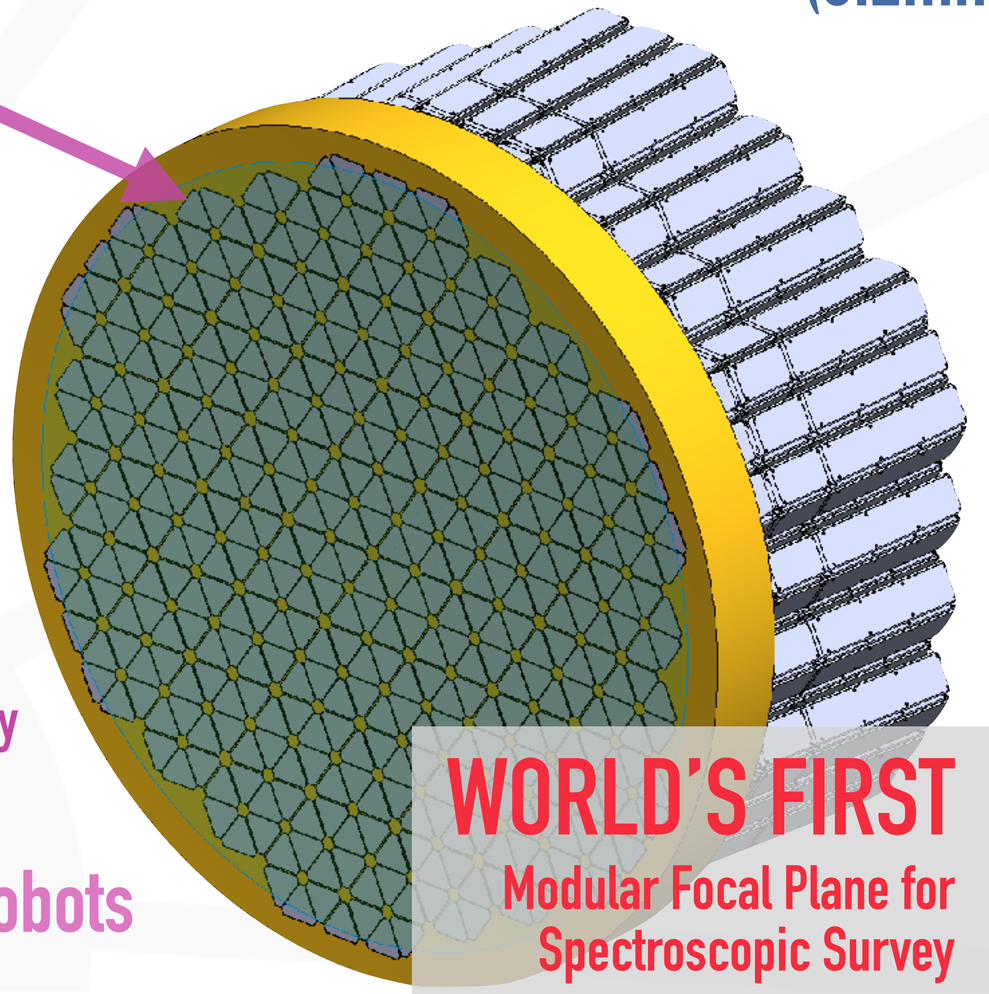
# Focal Plane






## SMALLEST theta-phi fiber positioning robot

- To allow high target density of the Stage-V survey. (6.2mm)



## MOST POWERFUL

### multi-fiber spectroscopic capability

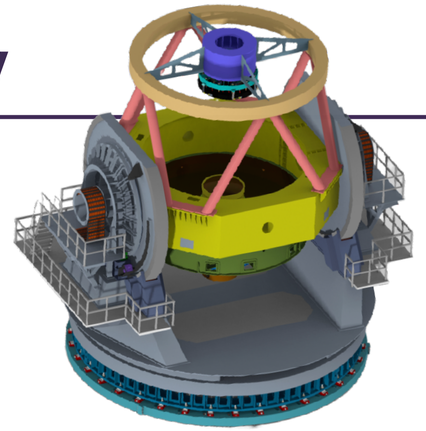
- Enabling high survey efficiency

>20,000 Robots

## WORLD'S FIRST

Modular Focal Plane for Spectroscopic Survey

# MUST Advancements: Moore's Law in Spectroscopy



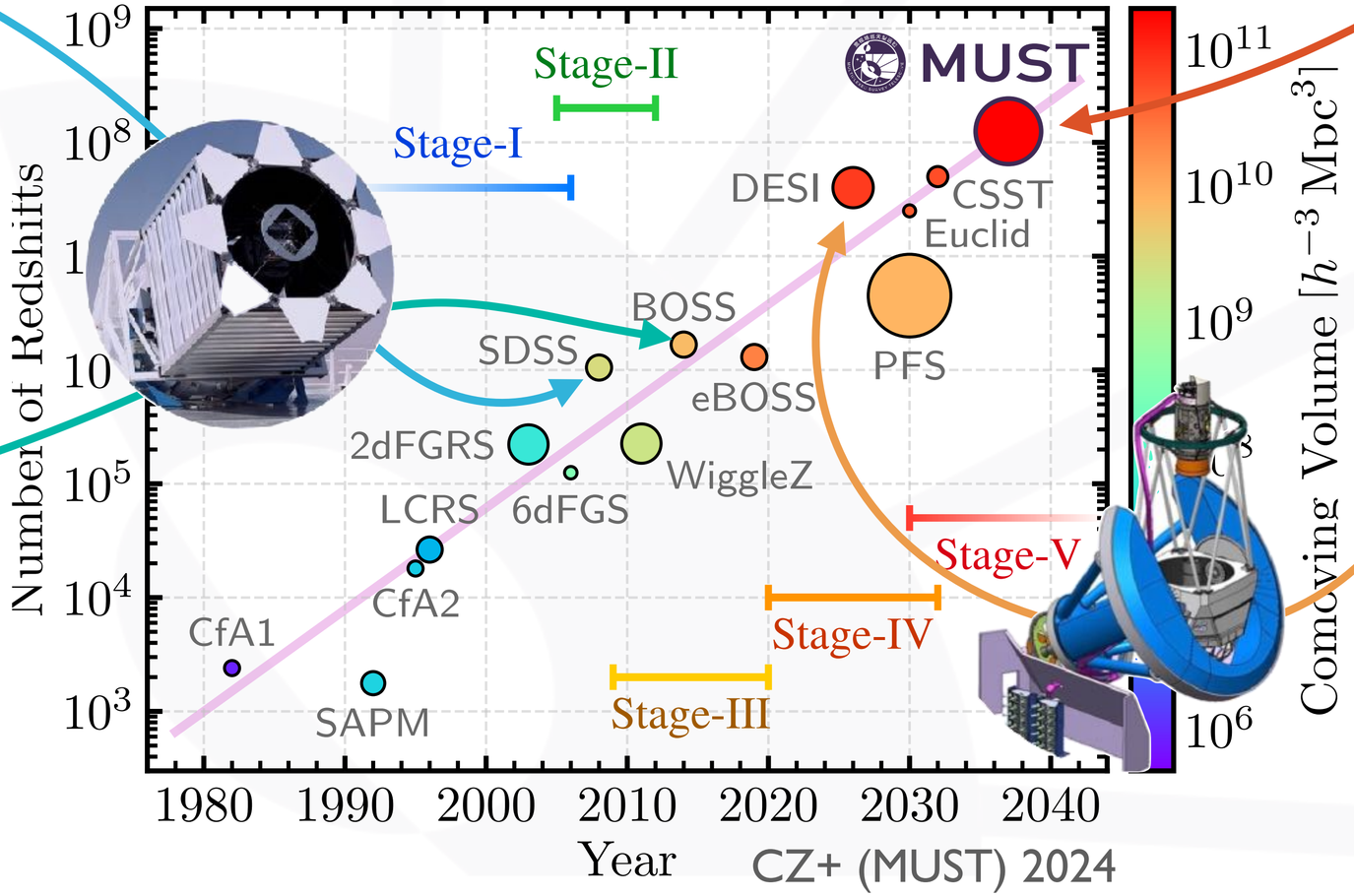
- Over the past 4 decades, spectroscopic surveys have mapped the 3D structures of the nearby Universe and yielded many significant cosmological insights, such as the properties of dark energy.

## Stage I/II: SDSS

- Aperture: 2.5m
- Fibers: 800
- Focal Plane: Metal plate
- Duration: 2000–2008
- Spectra: 100k

## Stage III: BOSS

- Aperture: 2.5m
- Fibers: 1000
- Focal Plane: Metal plate
- Duration: 2008–2019
- Spectra: 2.5 million




## Stage V: MUST

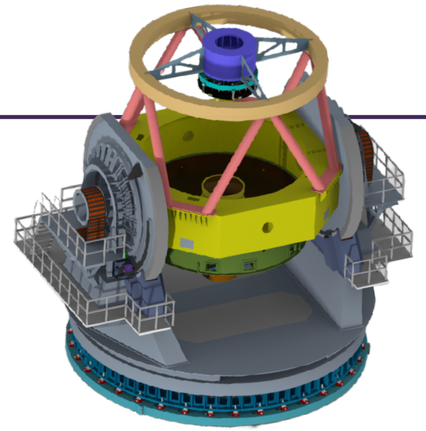
- Aperture: 6.5m
- Fibers: 20,000
- Focal Plane: Modular robots
- Duration: 2030–2040
- Spectra: over 200 million

## Stage IV: DESI

- Aperture: 4.0m
- Fibers: 5000
- Focal Plane: Robots
- Duration: 2020–2029
- Spectra: 50 million

# Advancements: A Deeper Universe

- Over the past 4 decades, spectroscopic surveys have mapped the 3D structures of the nearby Universe and yielded many significant cosmological insights, such as the properties of dark energy.



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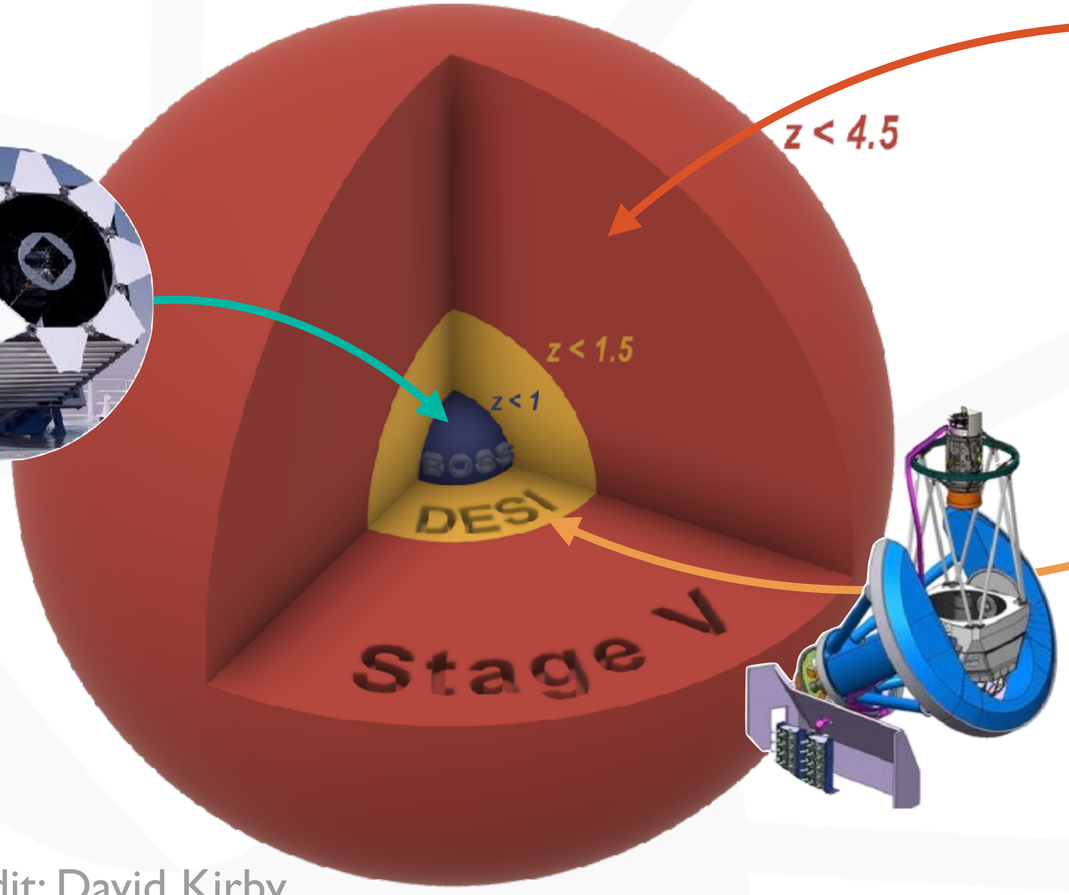


Credit: David Kirby

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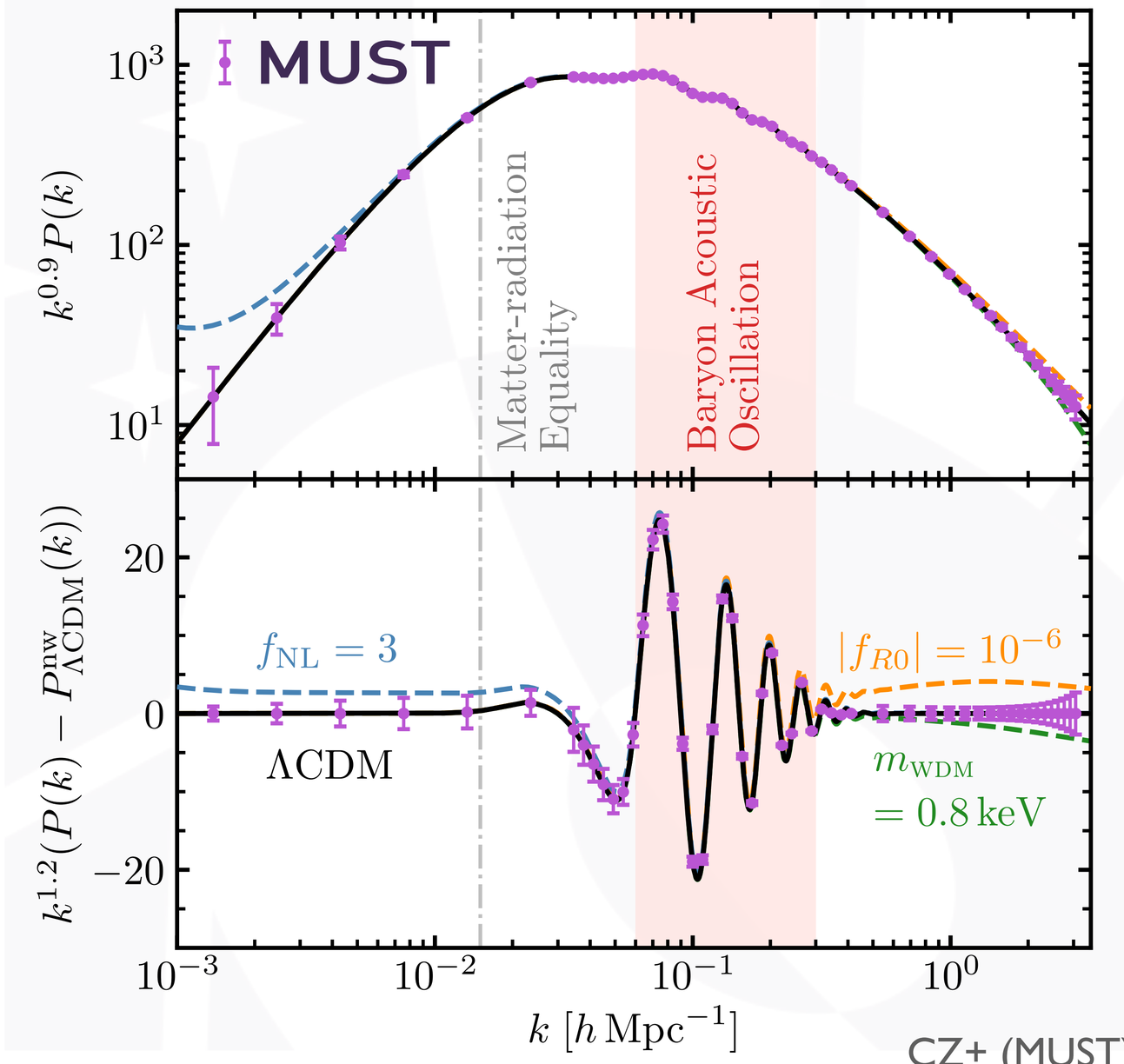
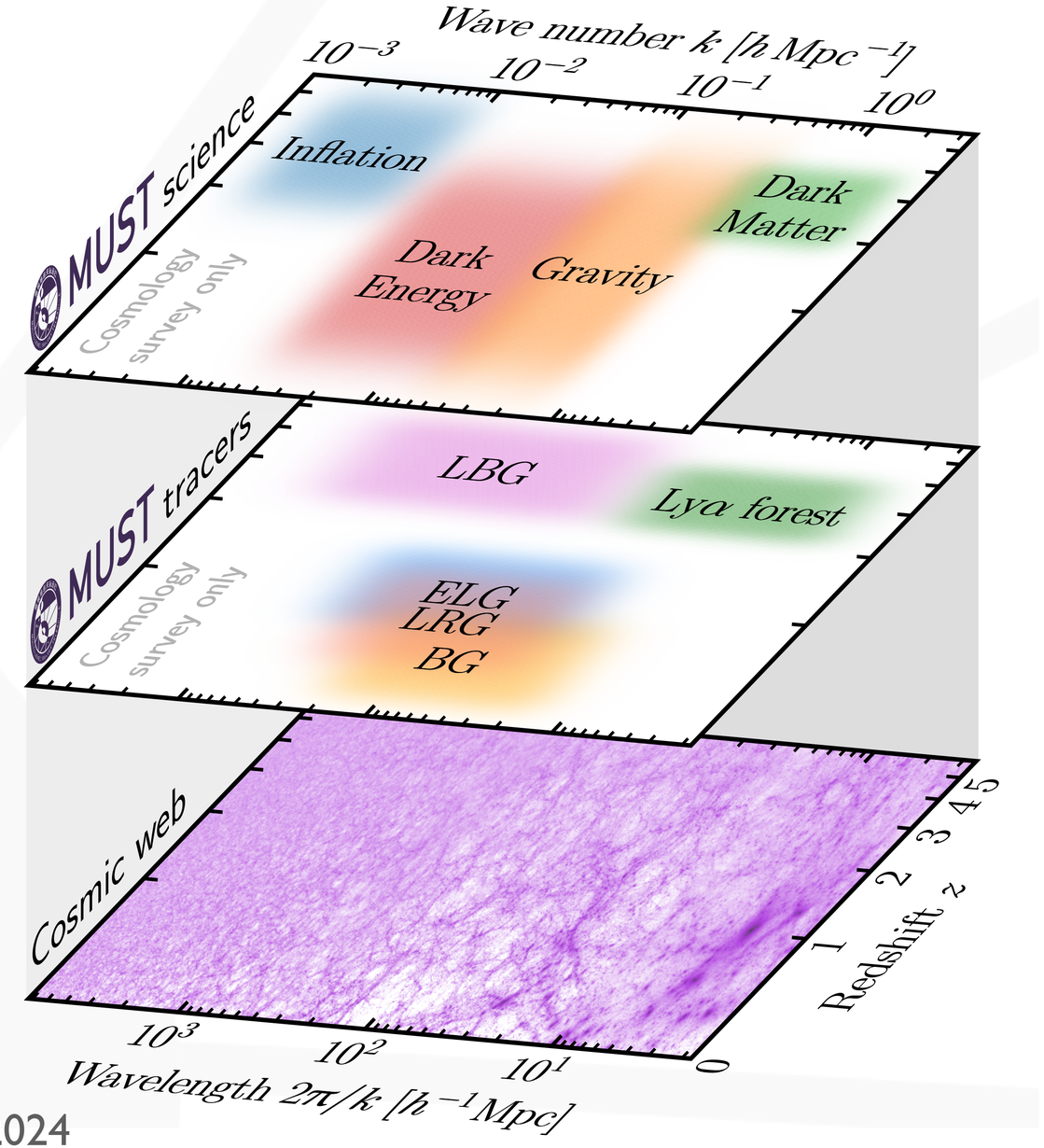
# Scientific Potential




CZ+ (MUST) 2024

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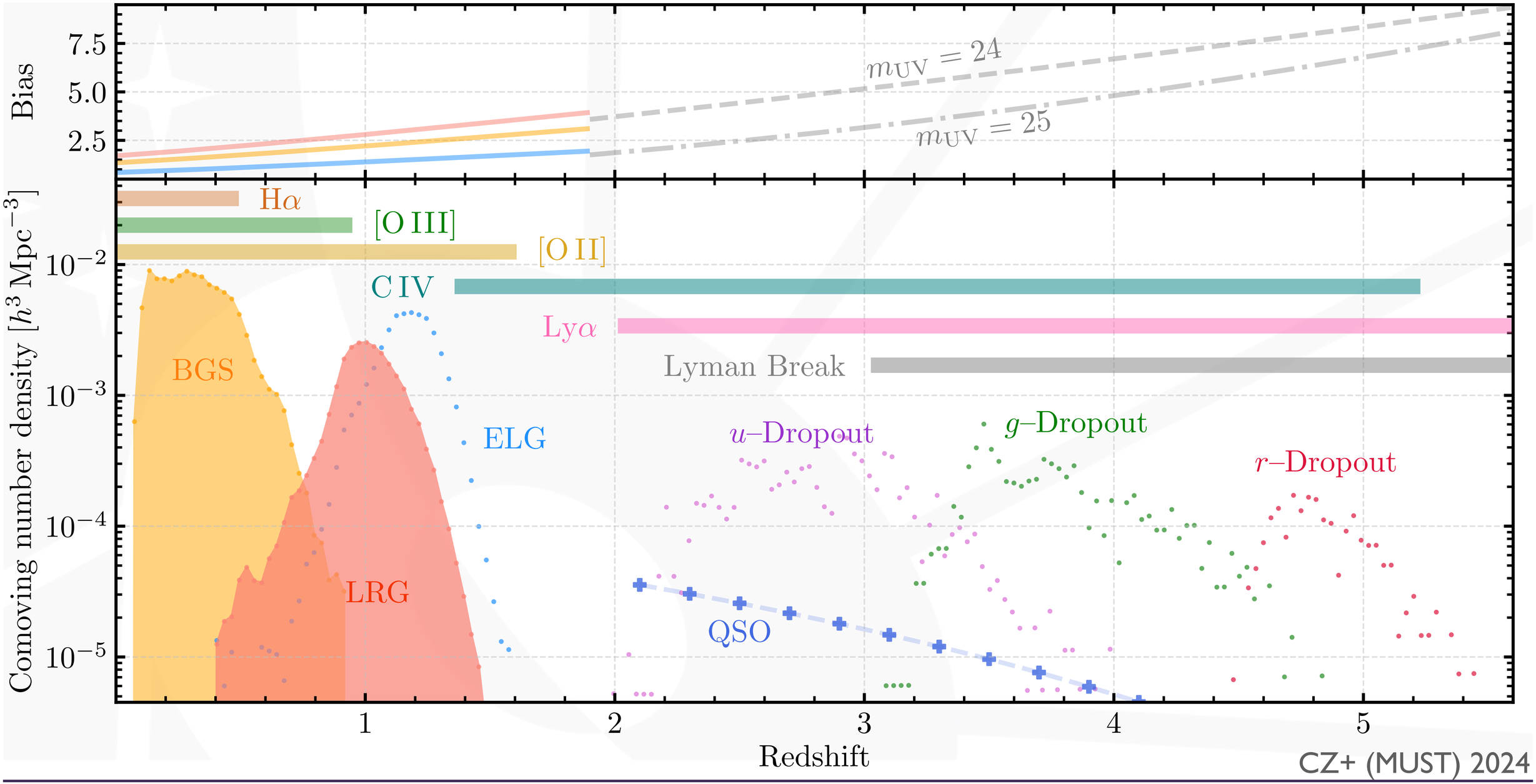
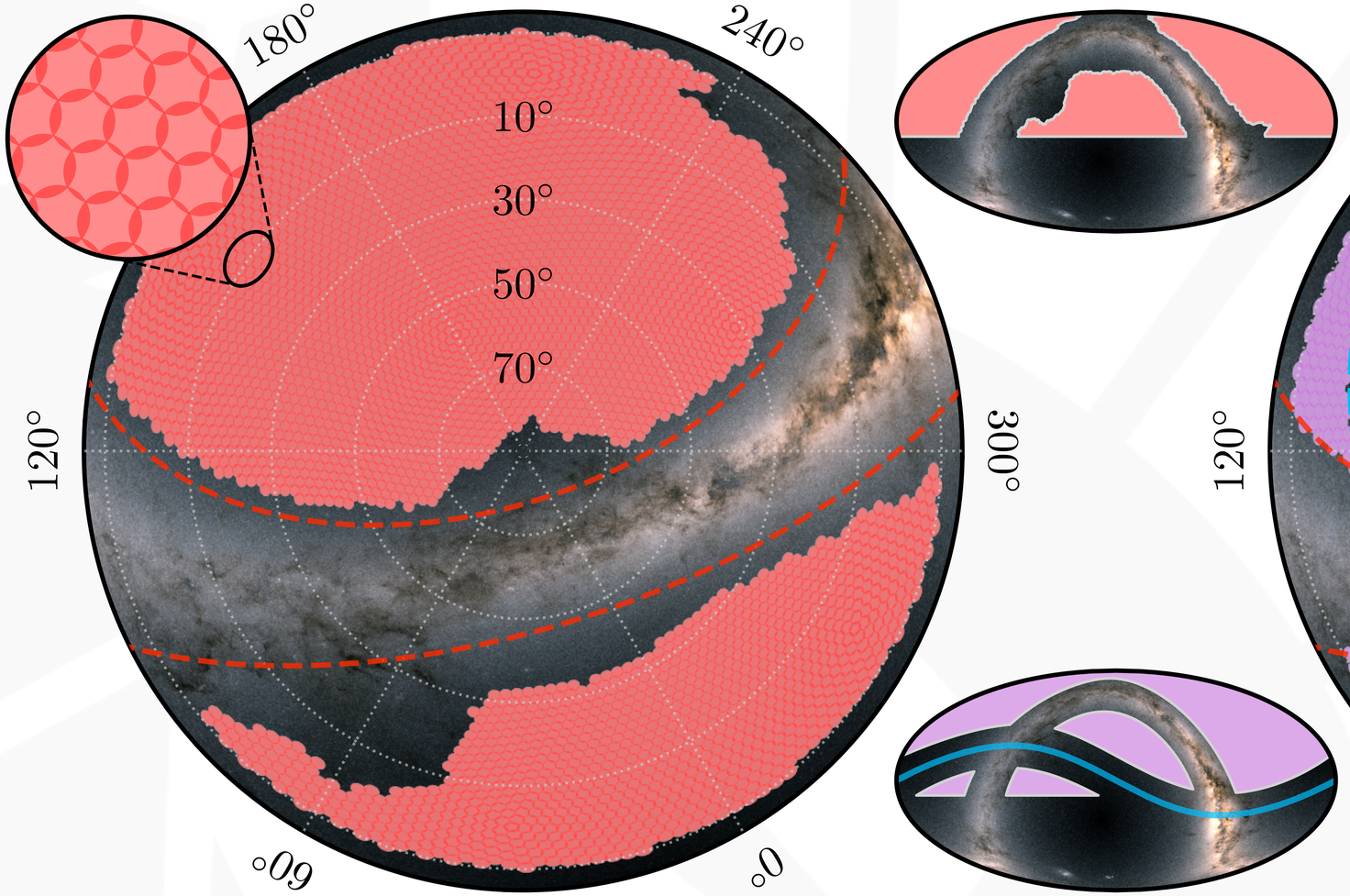
# Target Selection



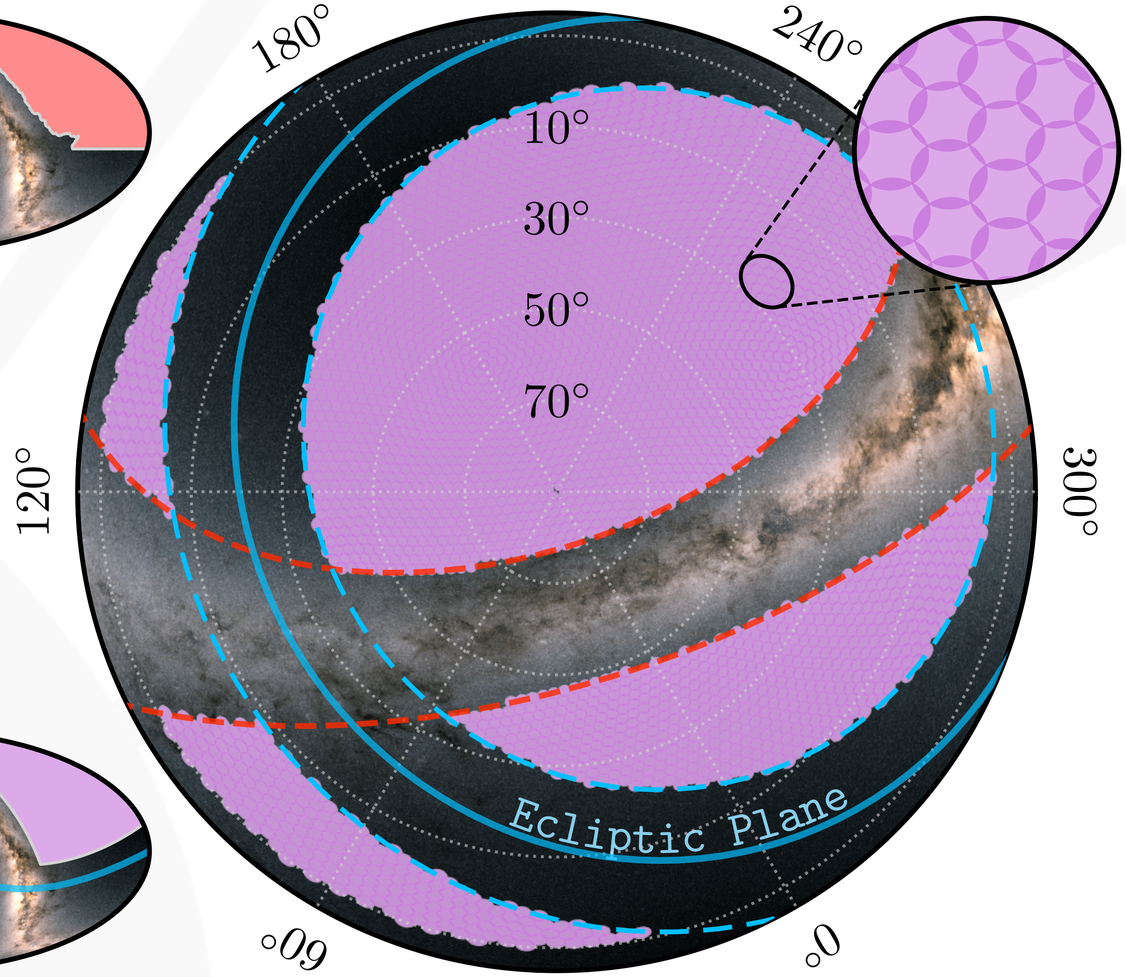

CZ+ (MUST) 2024

# Survey Strategy

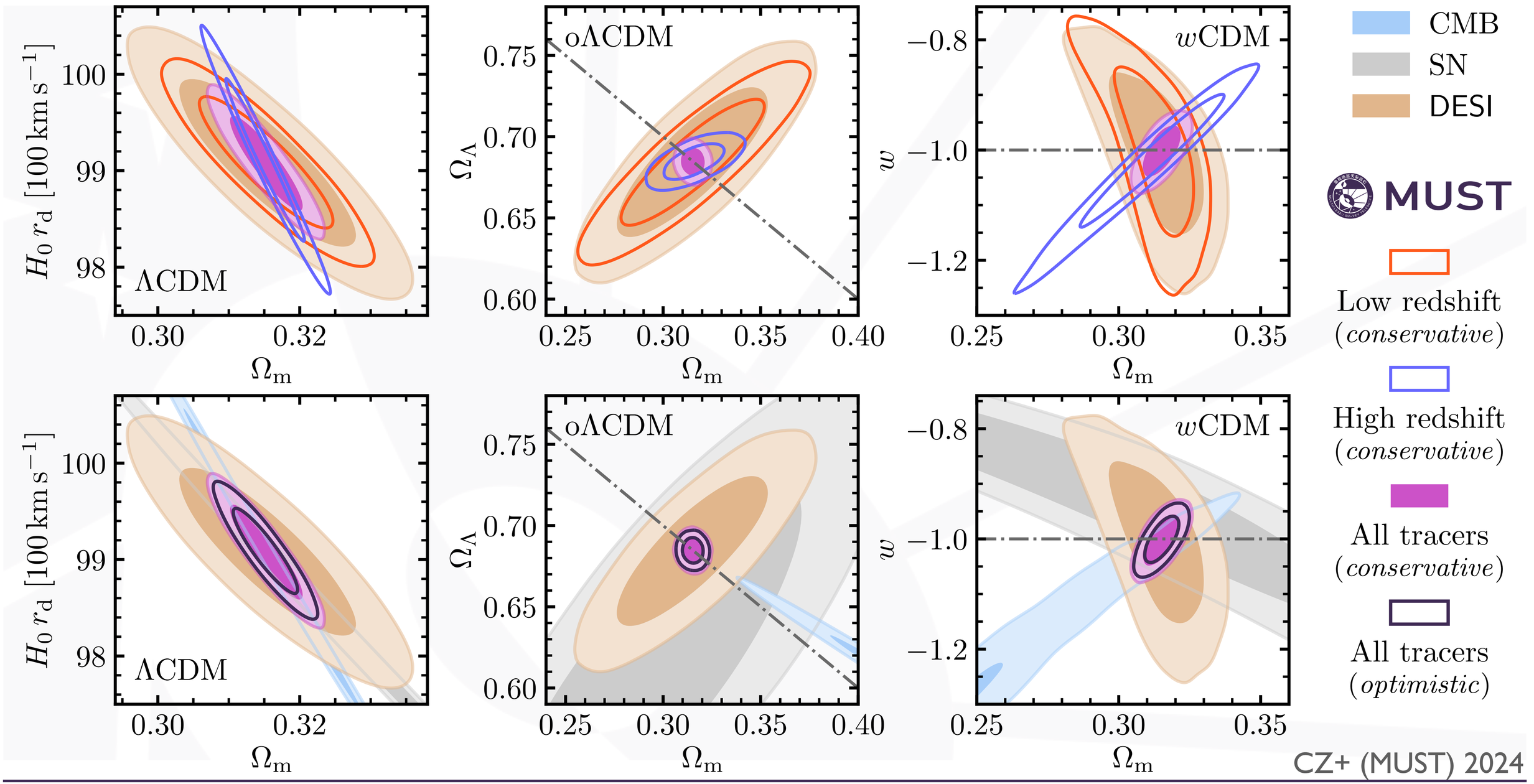
## MUST Gray Time




## MUST Dark Time



# Cosmological Forecasts: BAO

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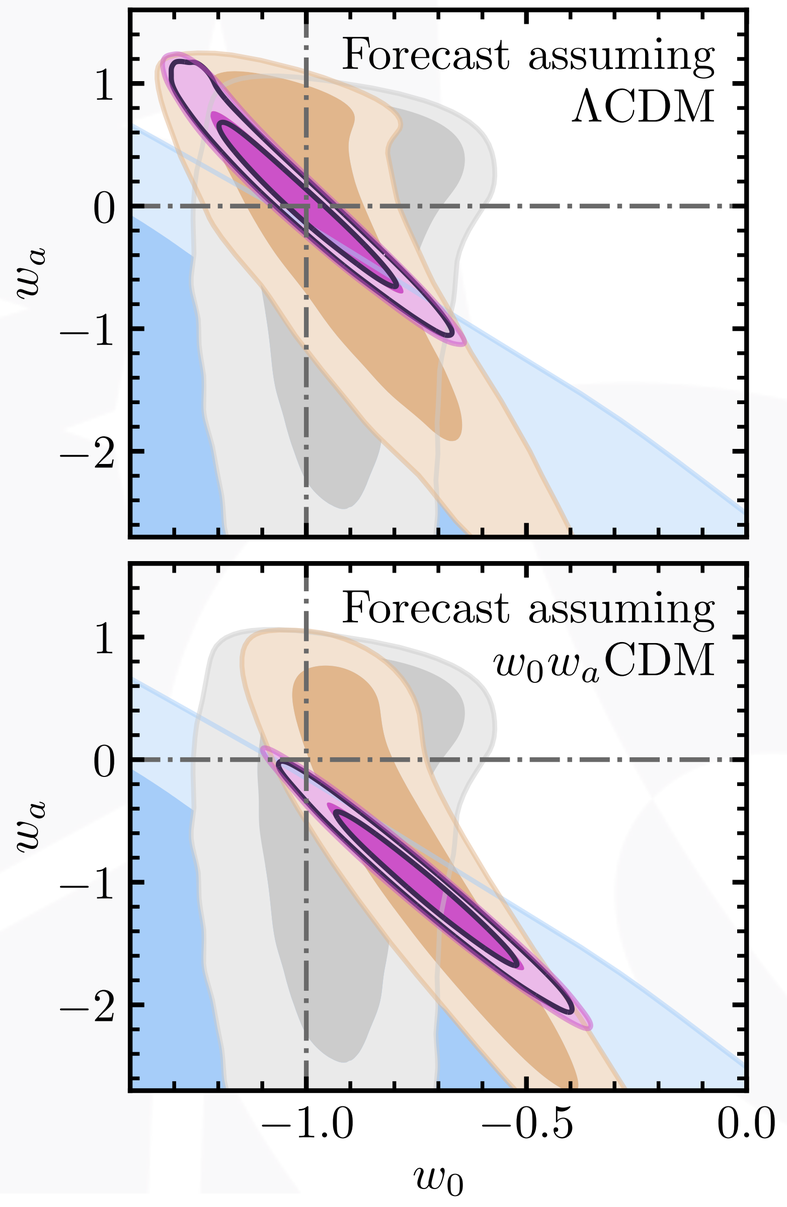
# MUST Cosmological Forecasts: DE & Modified Gravity

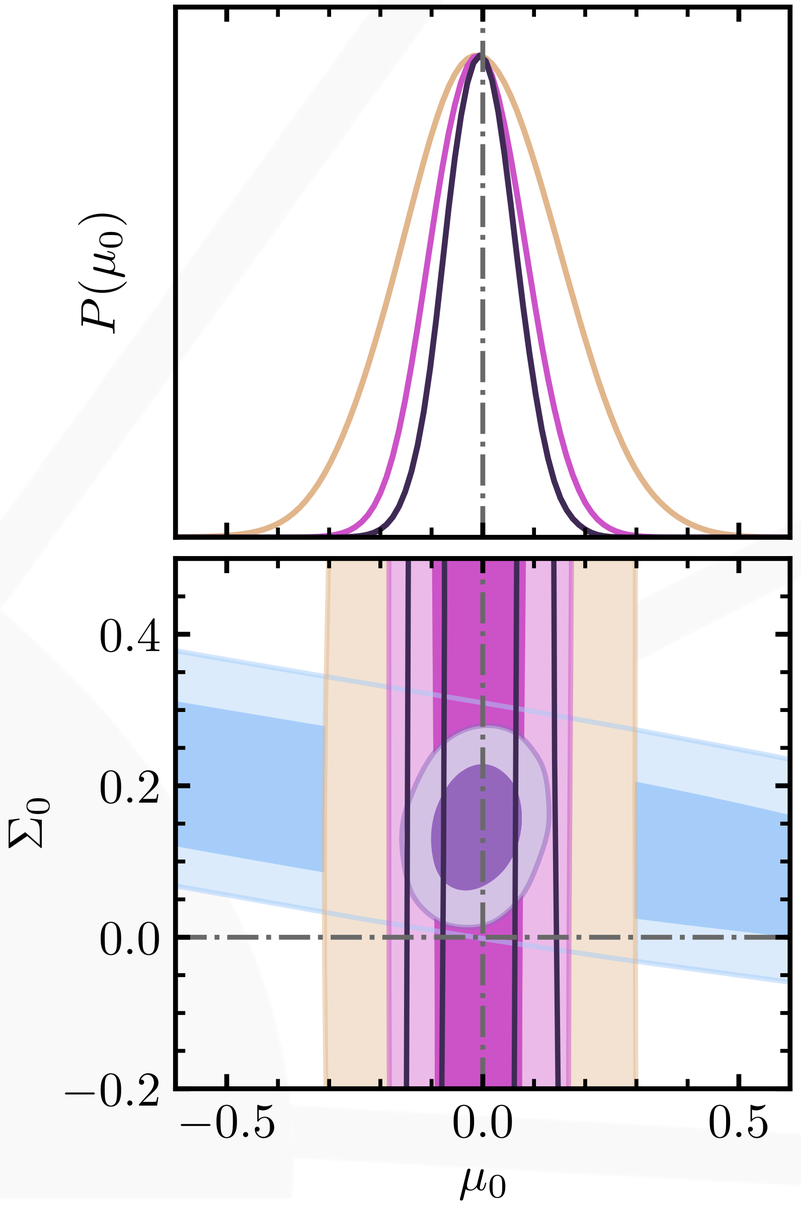



CMB
SN
DESI

MUST

MUST
(*conservative*)

MUST
(*optimistic*)




CMB
DESI

MUST

MUST
(*conservative*)

MUST
(*optimistic*)

MUST + CMB
(*optimistic*)

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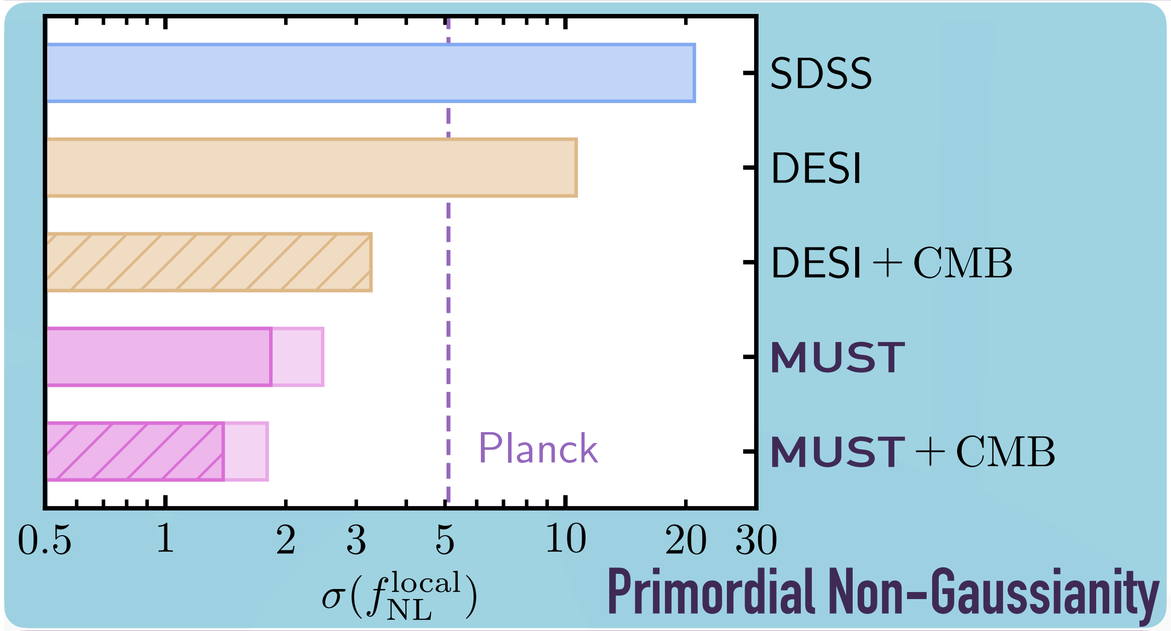
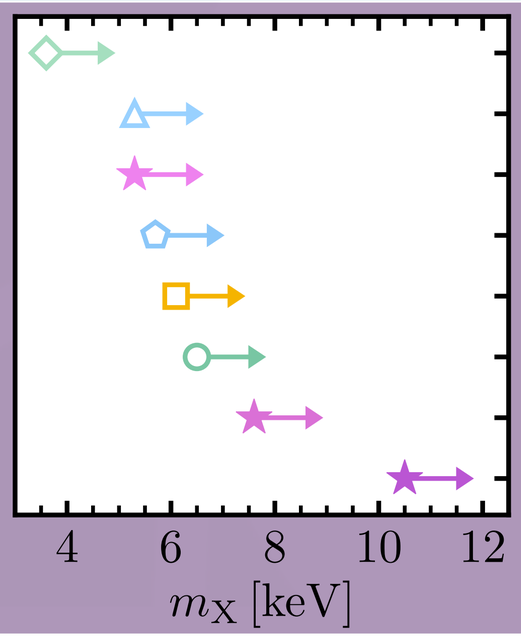
# MUST Cosmological Forecasts

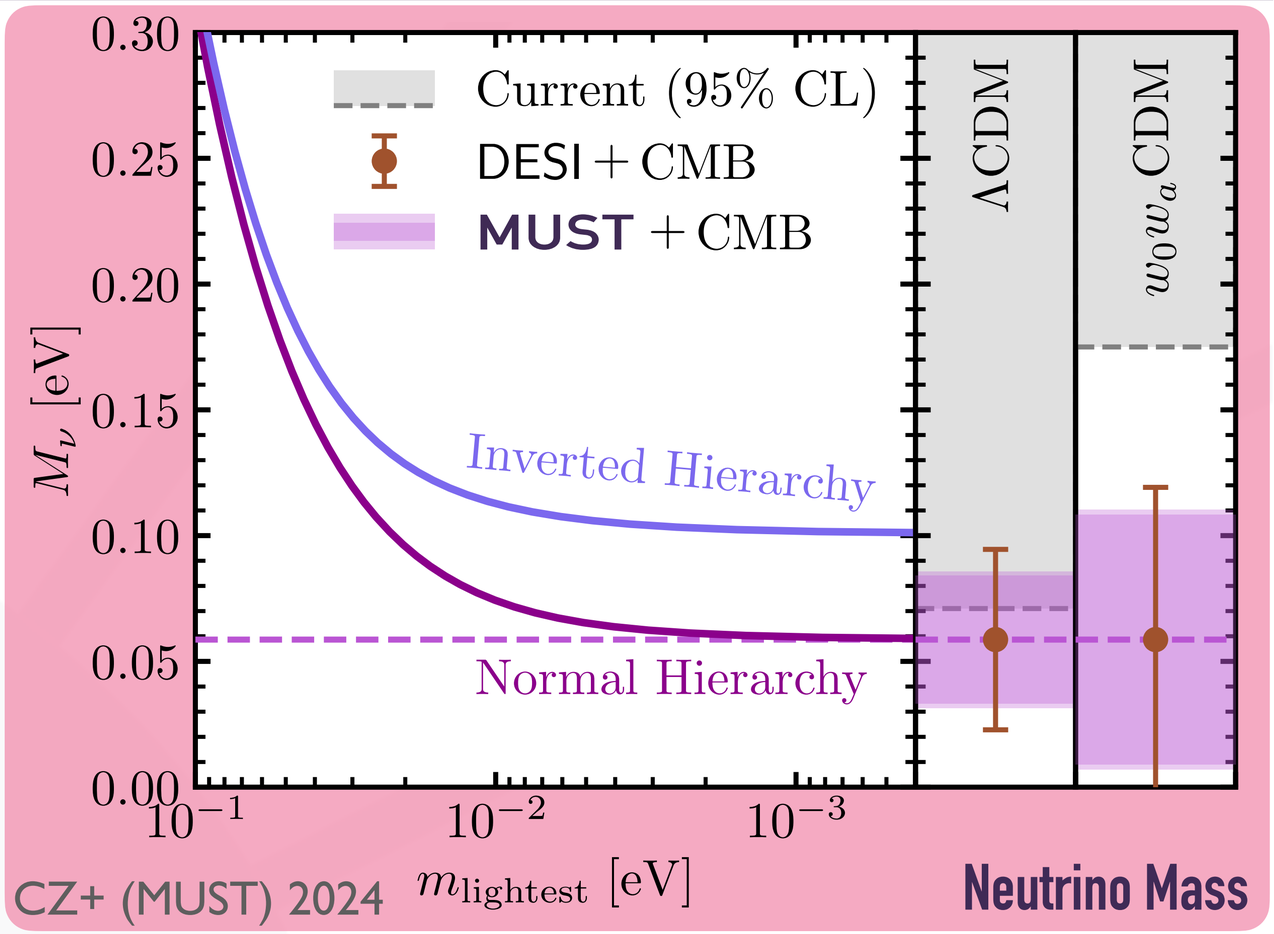



**Primordial Non-Gaussianity**




Stellar stream: GD–1 + Pal 5
Lyα: SDSS + XQ–100
Lyα: **MUST** [5,000 deg$^2$]
Lyα: HIRES + UVES
Lensed quasar: JWST
MW satellite: DES + PS1
Lyα: **MUST** [10,000 deg$^2$]
Lyα: **MUST** [14,000 deg$^2$]

**Warm Dark Matter**

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**Neutrino Mass**

- Significant improvements than DESI
- Call for more science cases
- Mock challenge in progress

# Acknowledgement

**MUST** Scientific Vision:

- To play a major role in the Stage-V spectroscopic cosmology endeavor.
- To conduct large time-domain spectroscopic surveys.
- To become an international astronomical platform for decades to come.

# Thank You!

## We MUST Broaden Our Collaboration!