



MULTIplexed
Survey
Telescope
宽视场巡天望远镜



清华大学
Tsinghua University

From DESI to MUST

Fundamental Physics with Large-Scale Galaxy Surveys

Cheng Zhao (赵成)

Department of Astronomy, Tsinghua University

On behalf on the MUST team

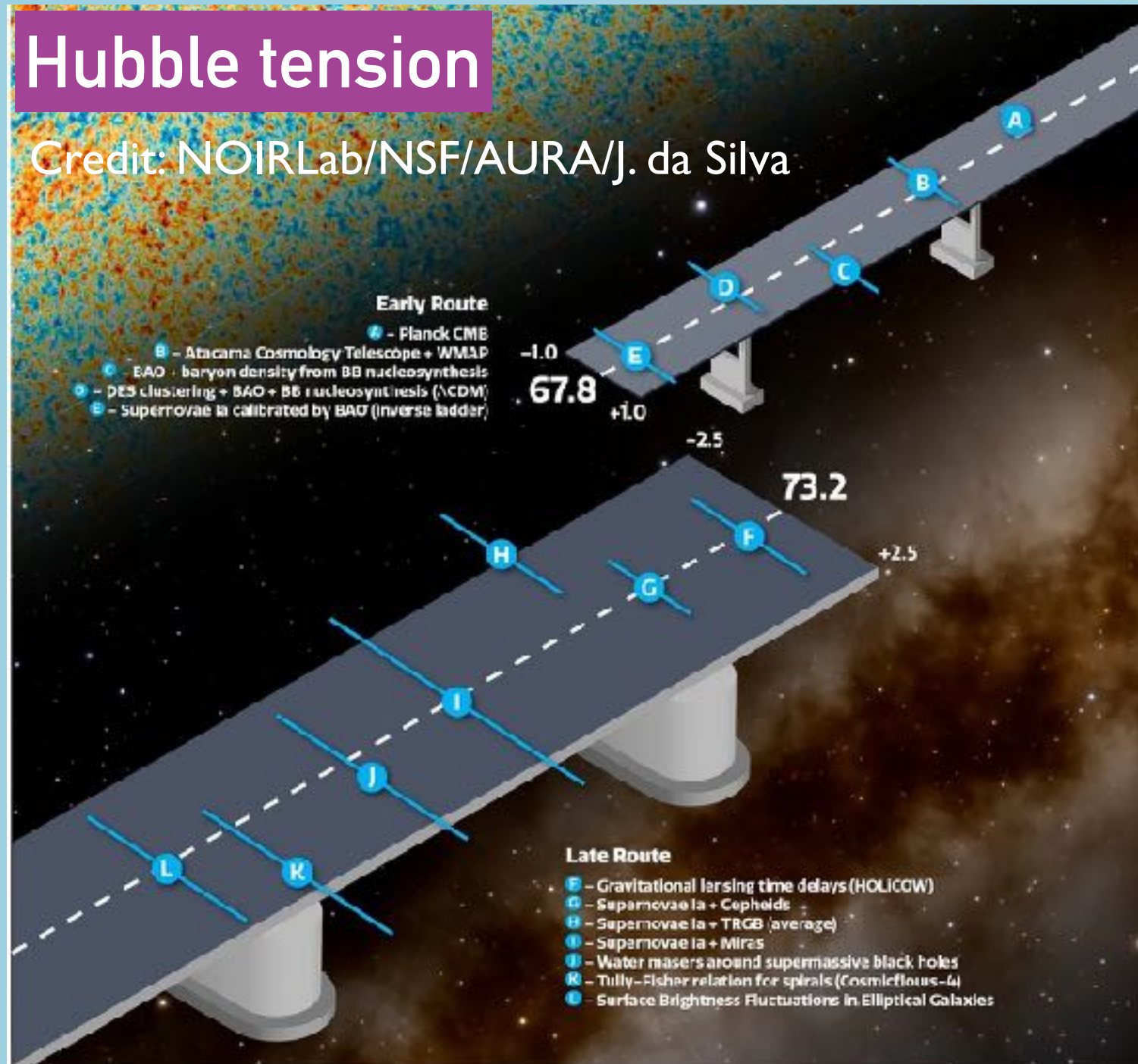
FCPPN/L Workshop 2026, Lyon

Cosmological Problems

Cosmic expansion

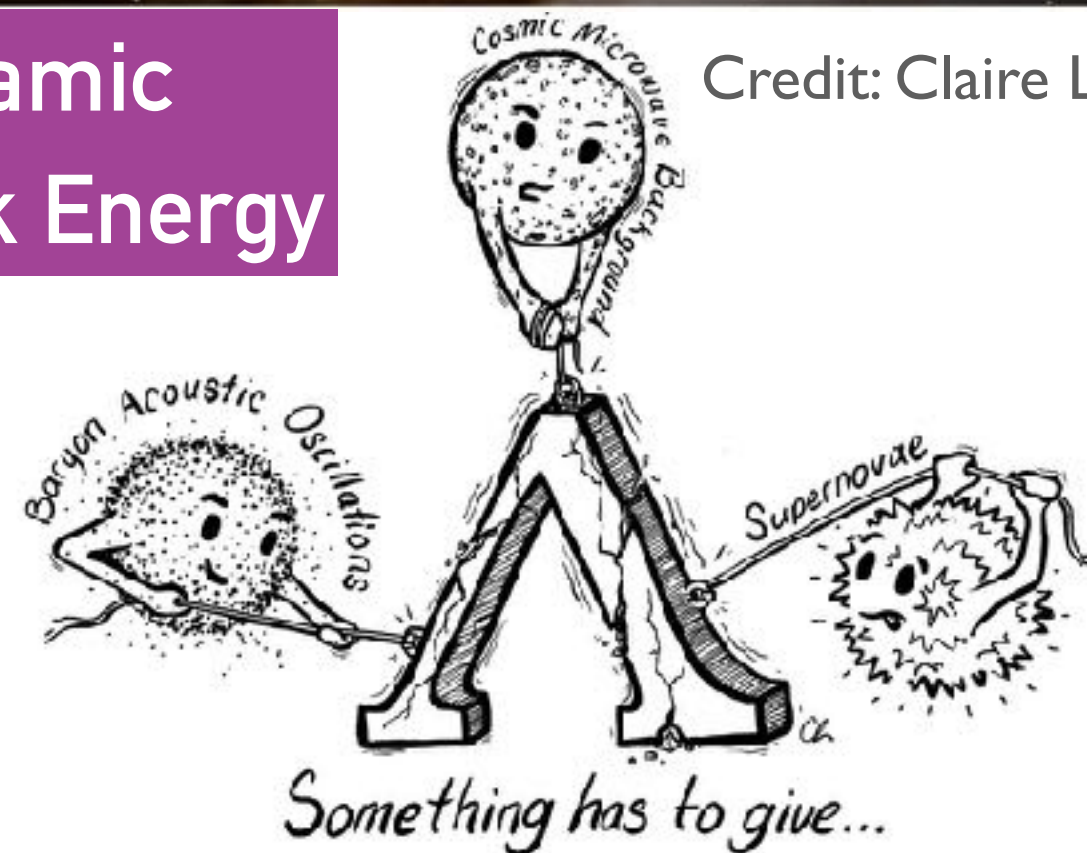
Hubble tension

Credit: NOIRLab/NSF/AURA/J. da Silva

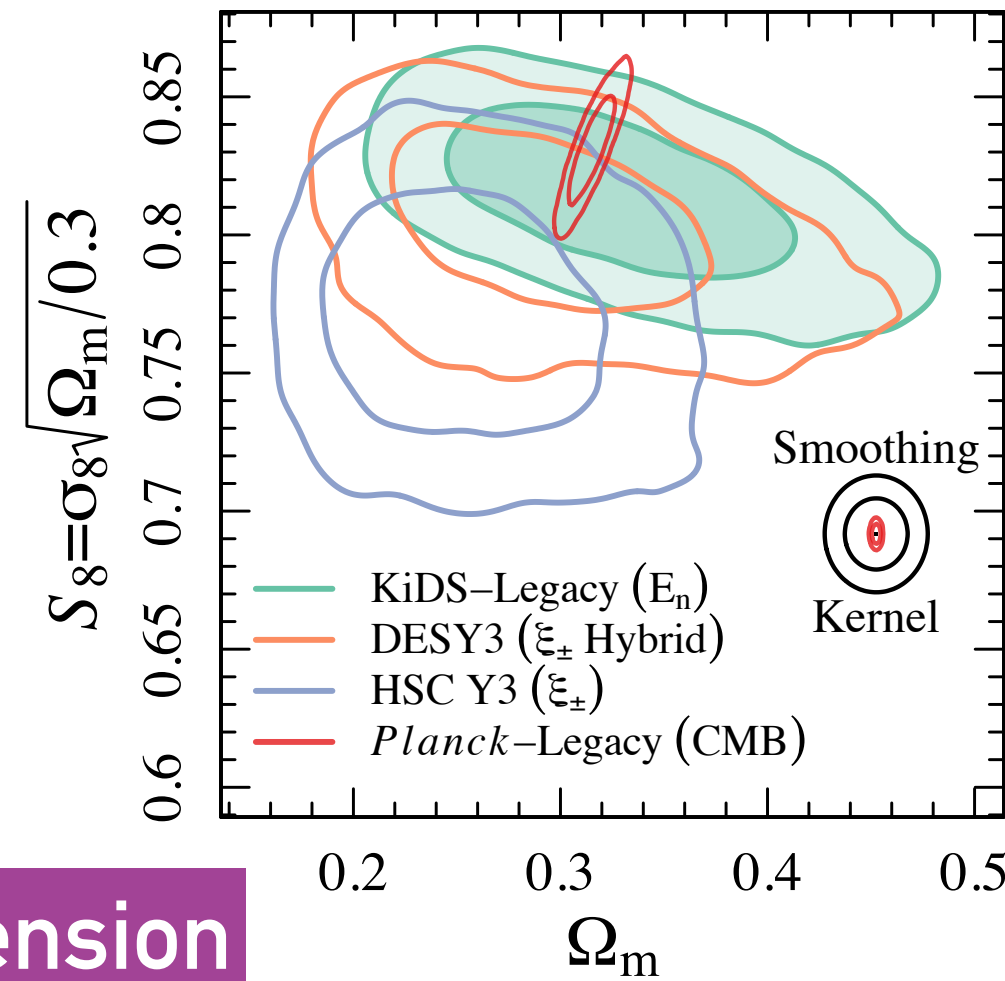


Dynamic Dark Energy

Credit: Claire Lamman



Structure growth



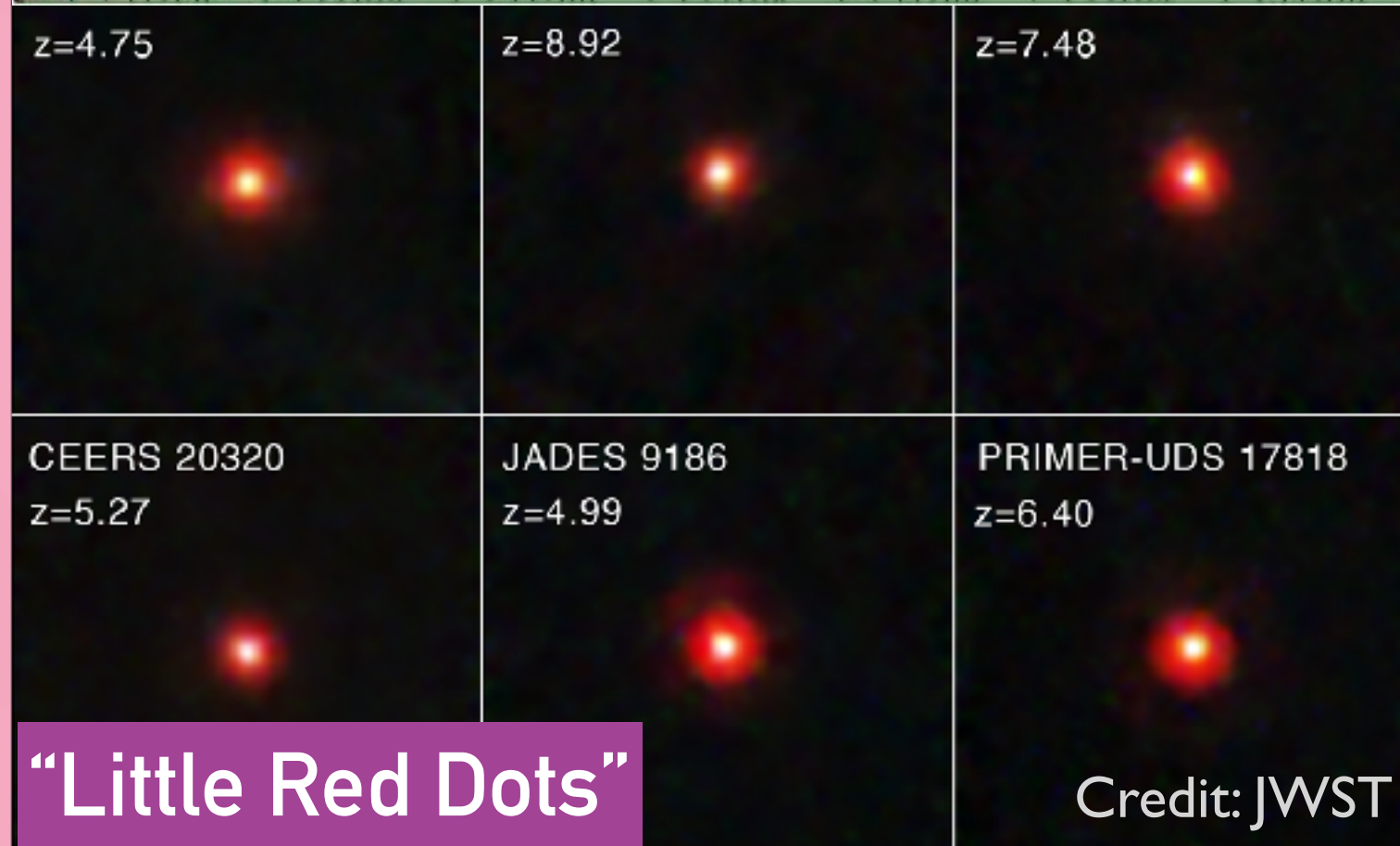
S8 tension

KiDS 2025

missing baryons in Λ CDM

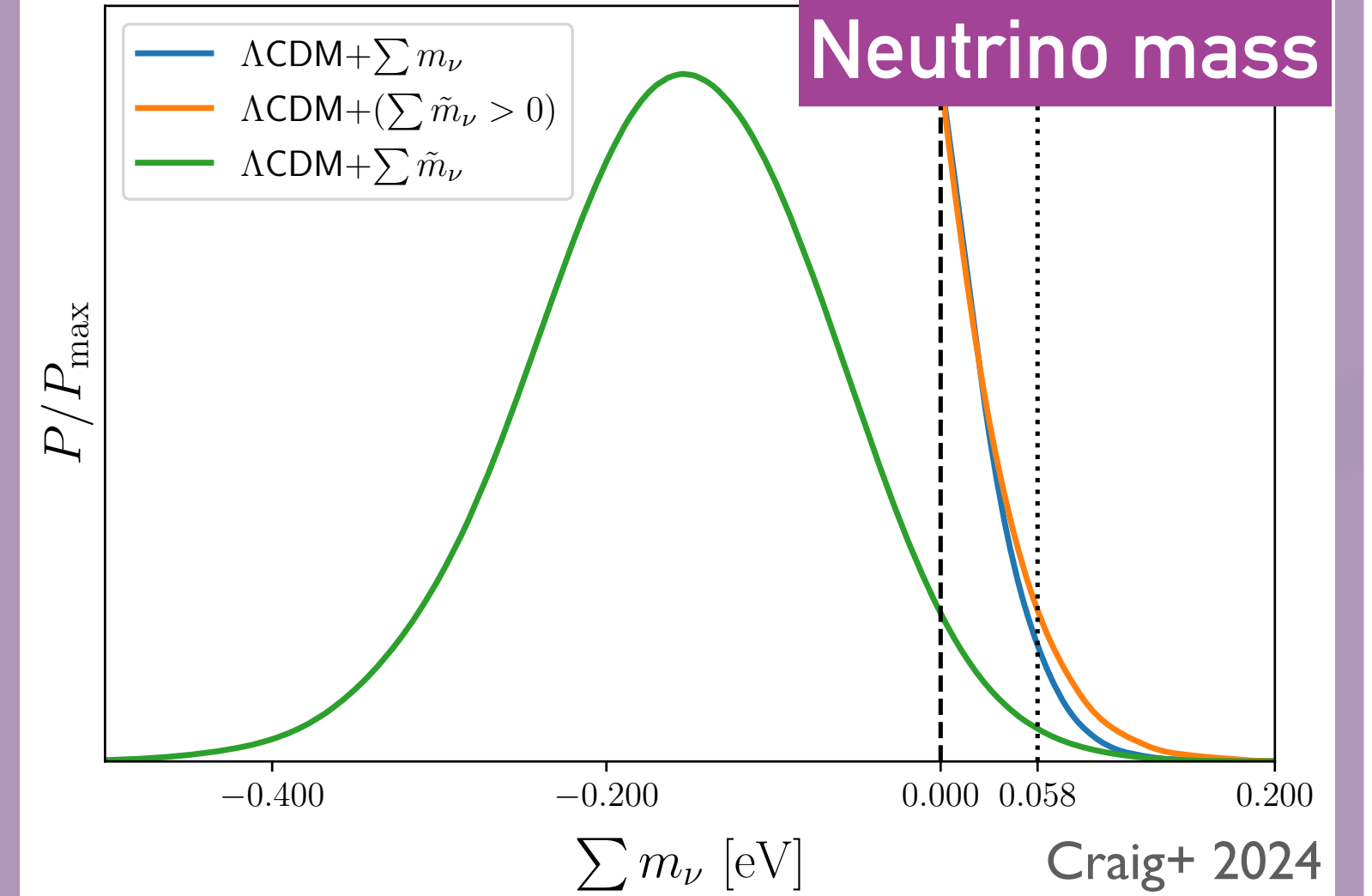
Missing Baryon

detected baryons

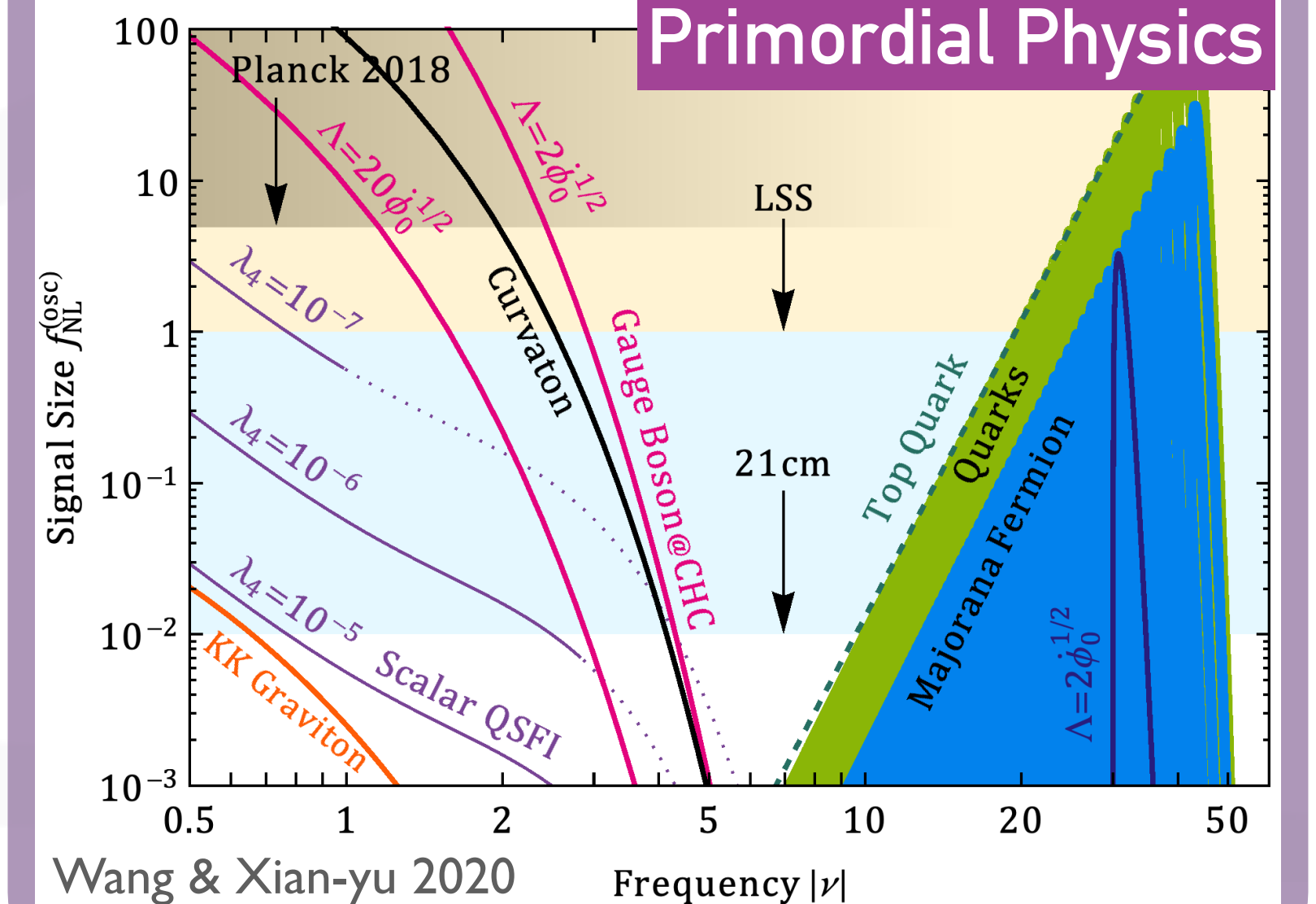


Fundamental Physics

Neutrino mass



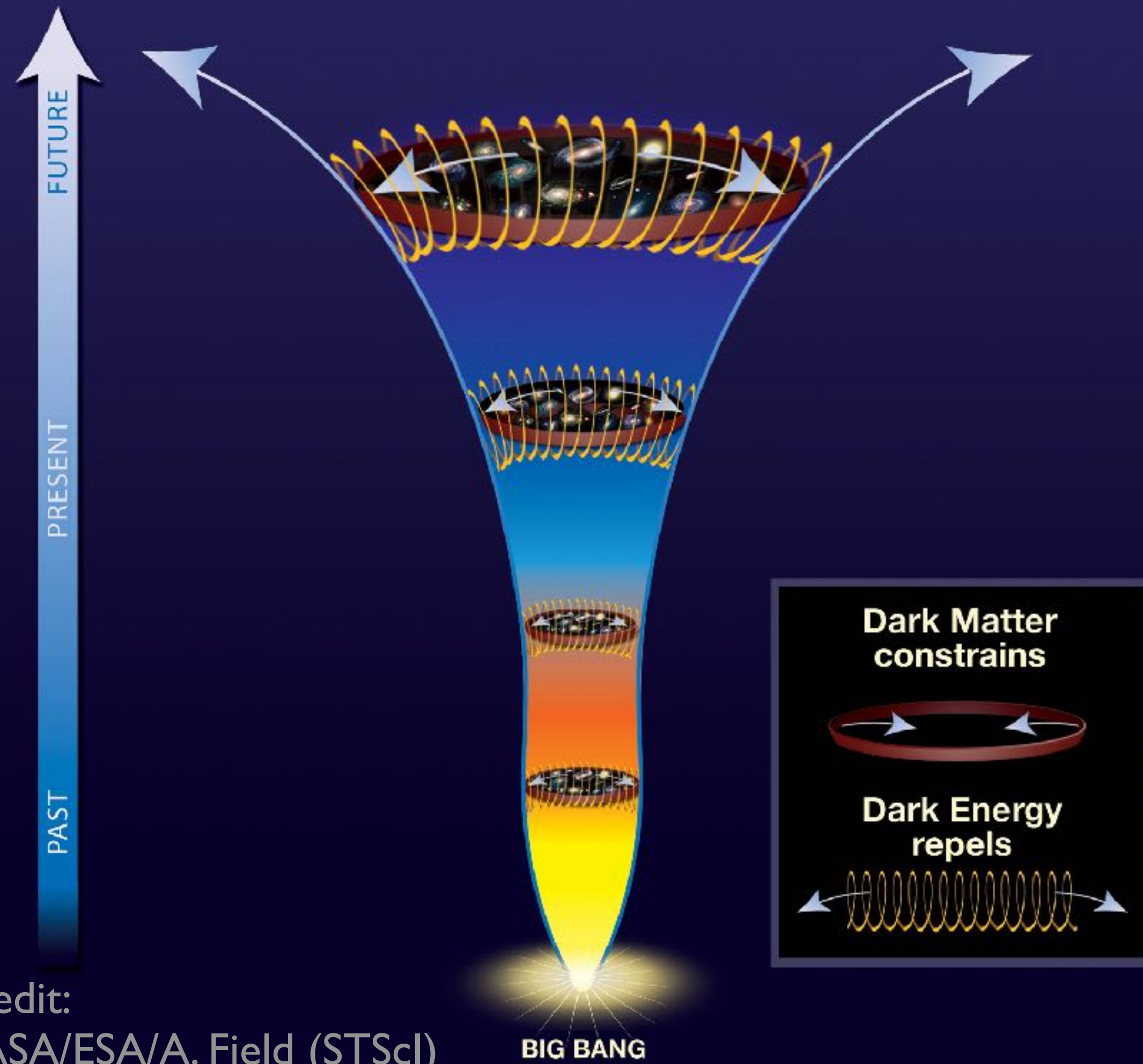
Primordial Physics



Large-Scale Structures: A “Dynamic” Universe

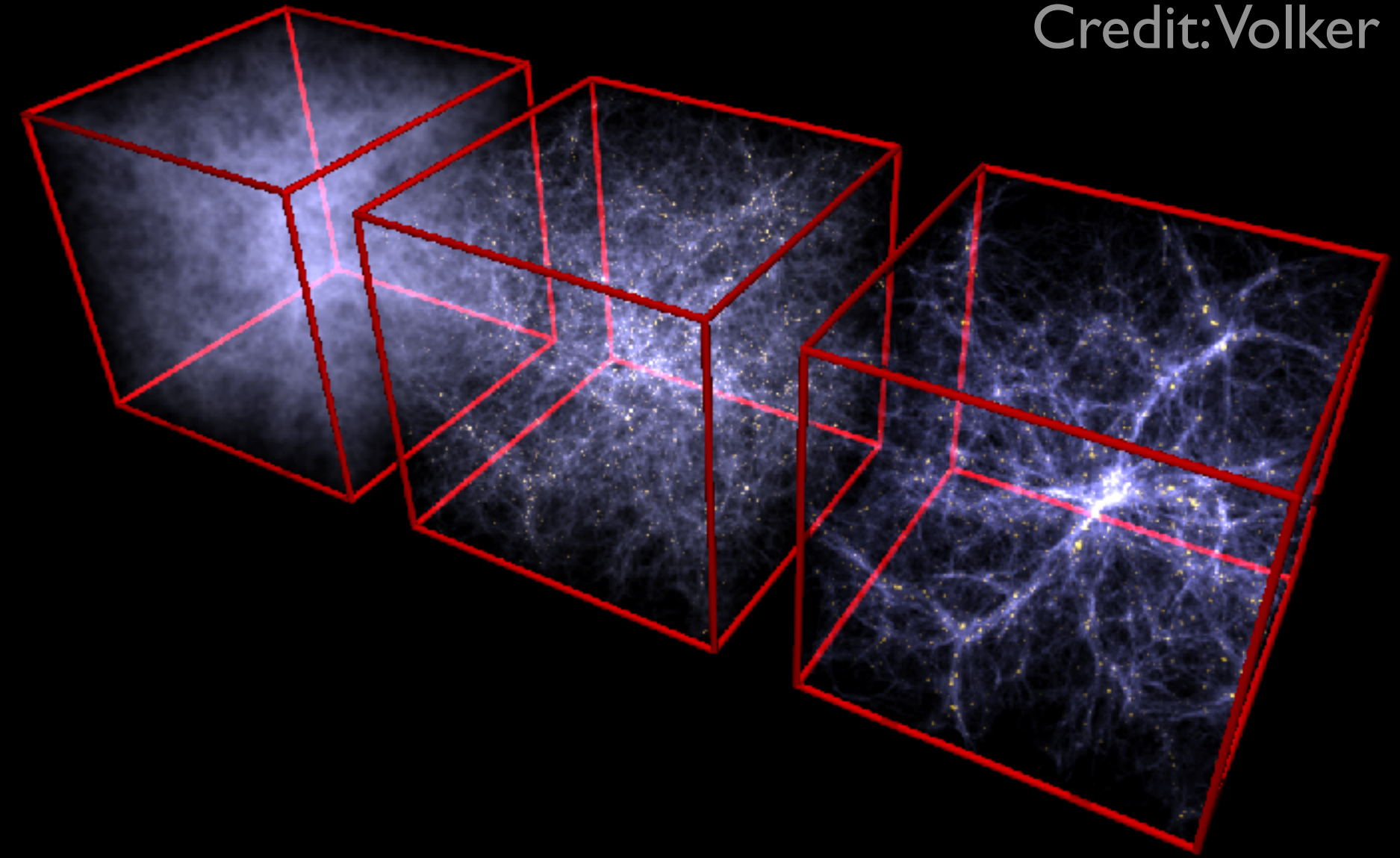
Cosmic tug of war

The force of dark energy surpasses that of dark matter as time progresses.

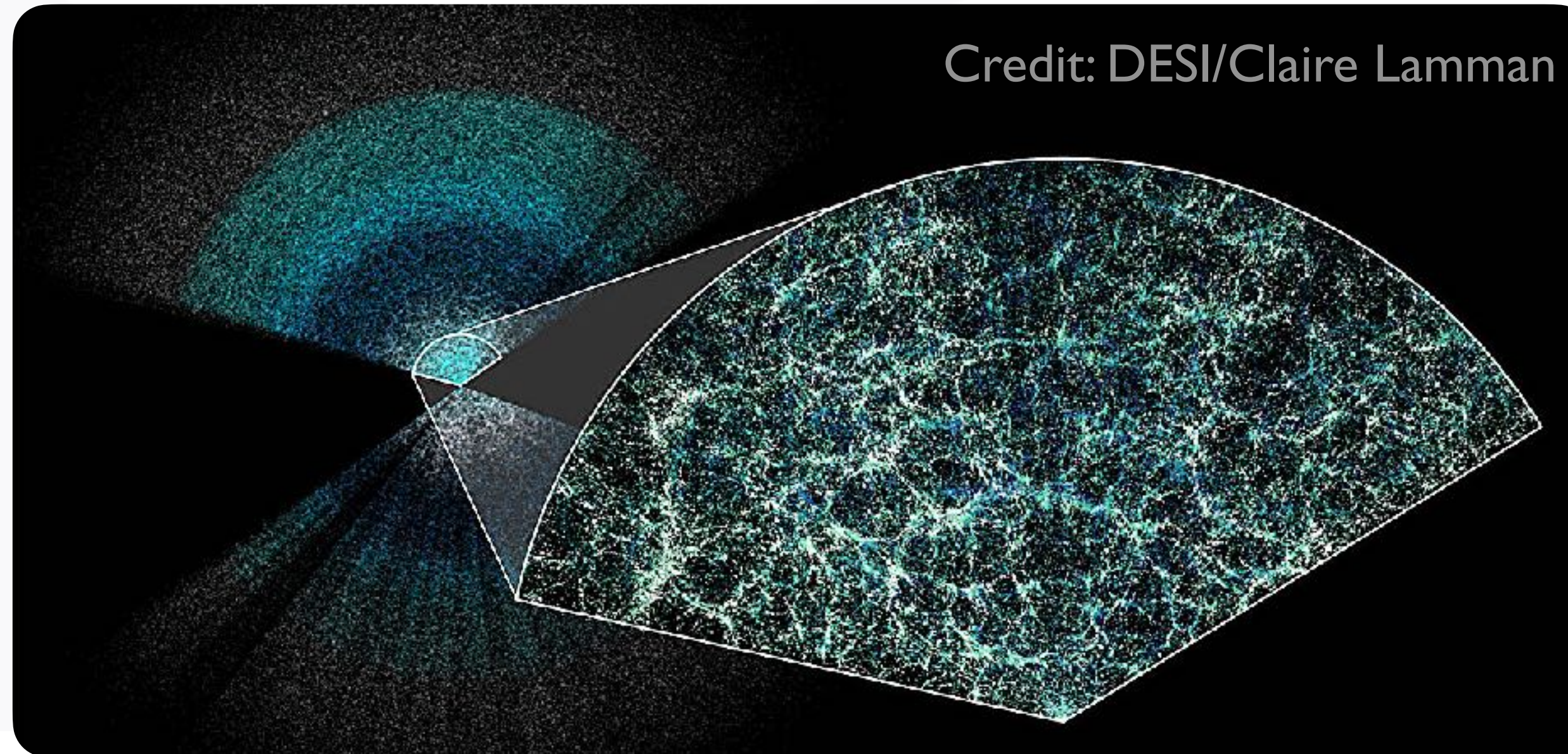


Credit:
NASA/ESA/A. Field (STScI)

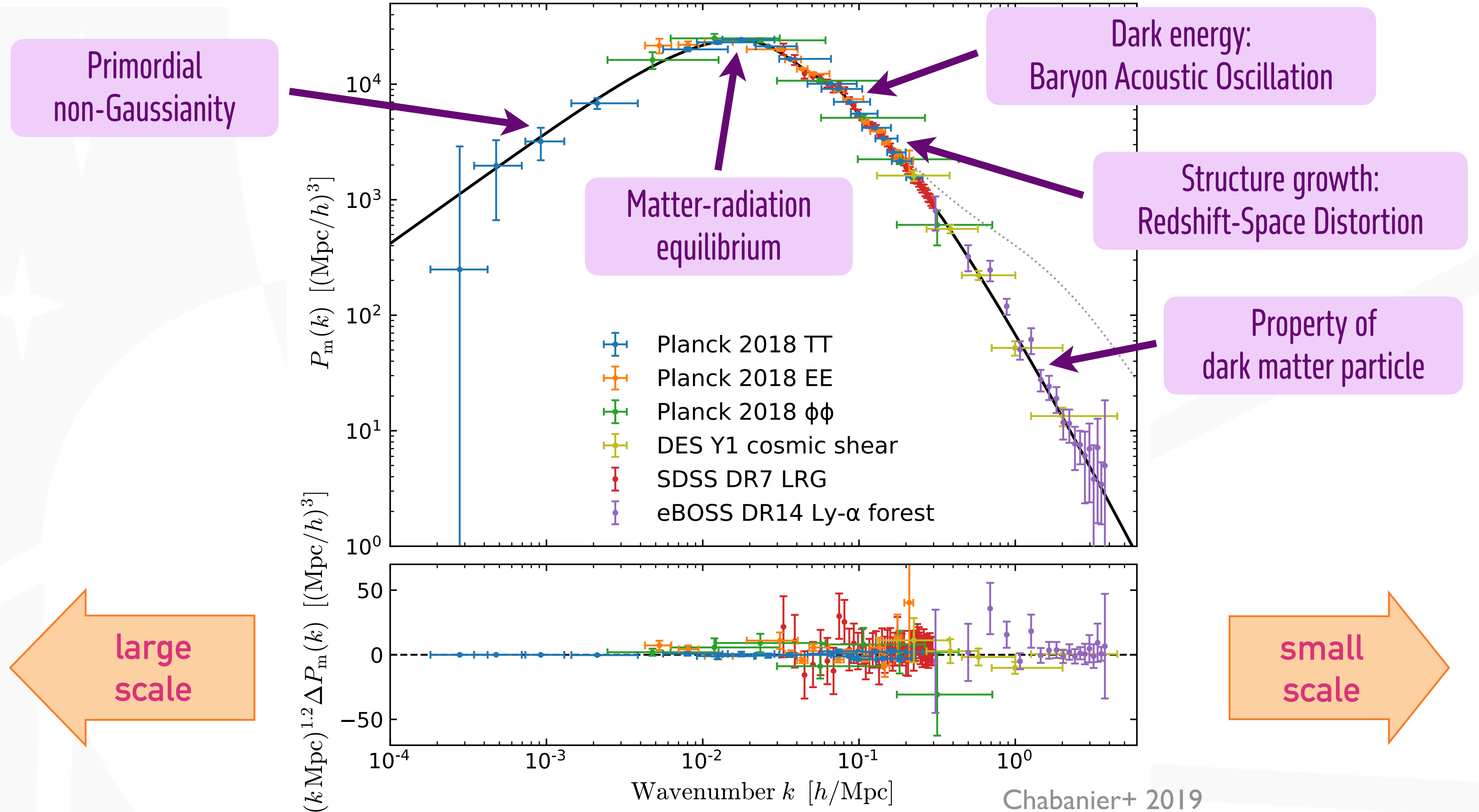
Credit: Volker Springel



Credit: DESI/Claire Lamman



Matter Clustering: Power Spectrum

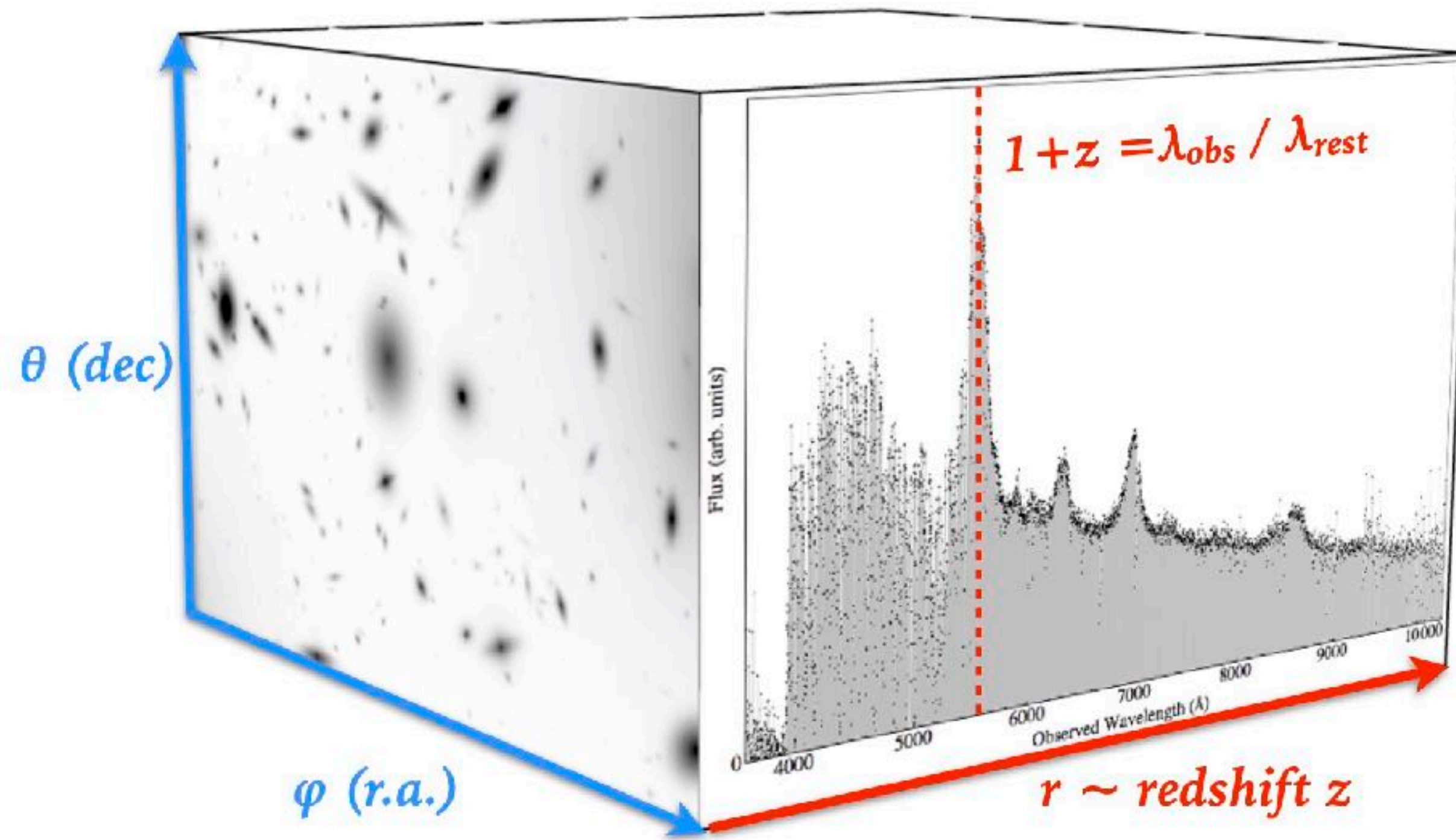


Cosmological Probes



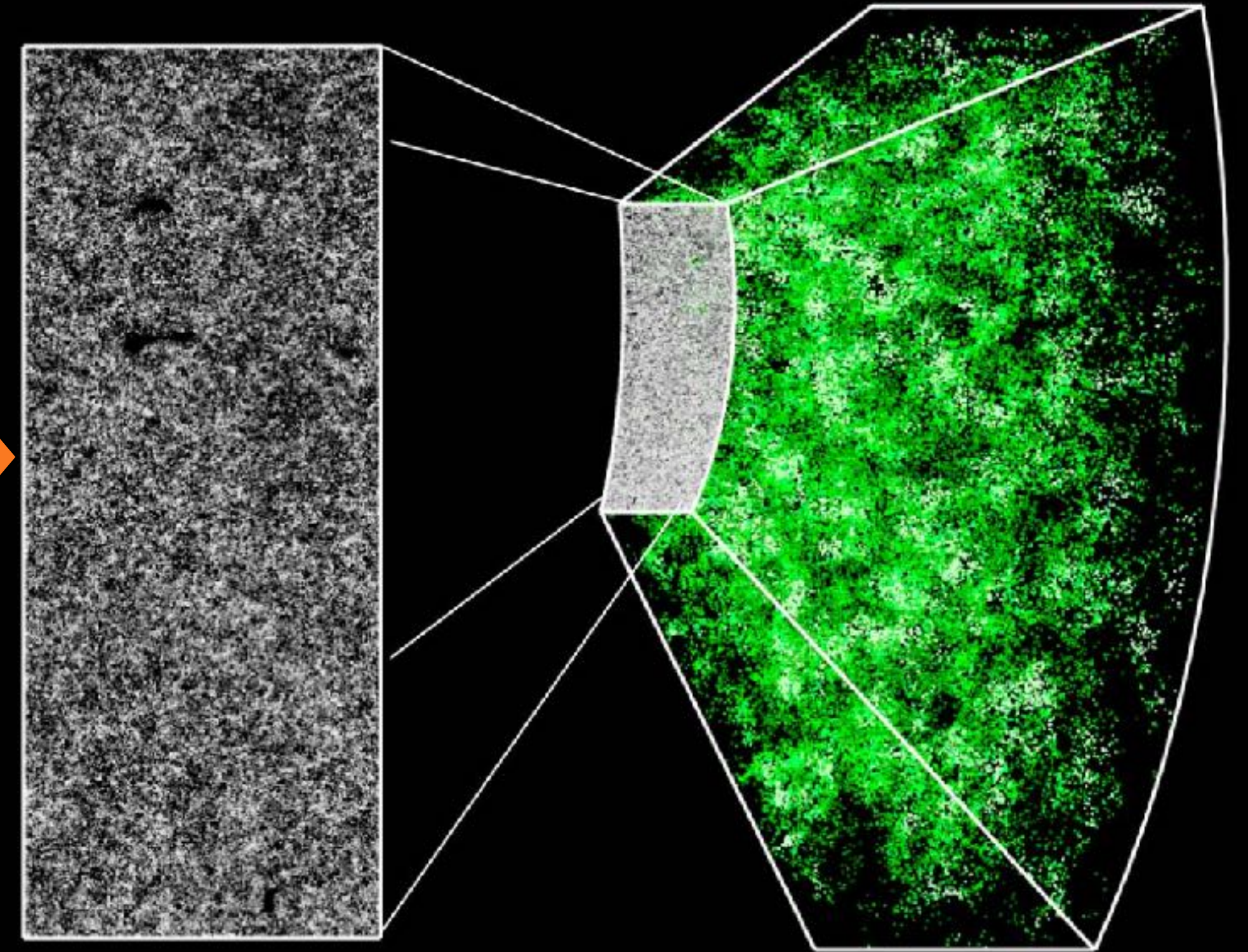
Snowmass report
2021

3D Galaxy Map



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

Credit: David Kirkby

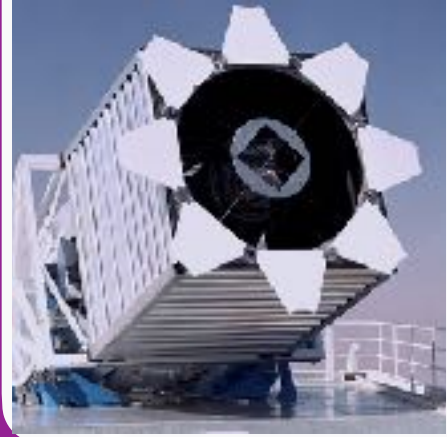


Credit: BOSS/Jeremy Tinker

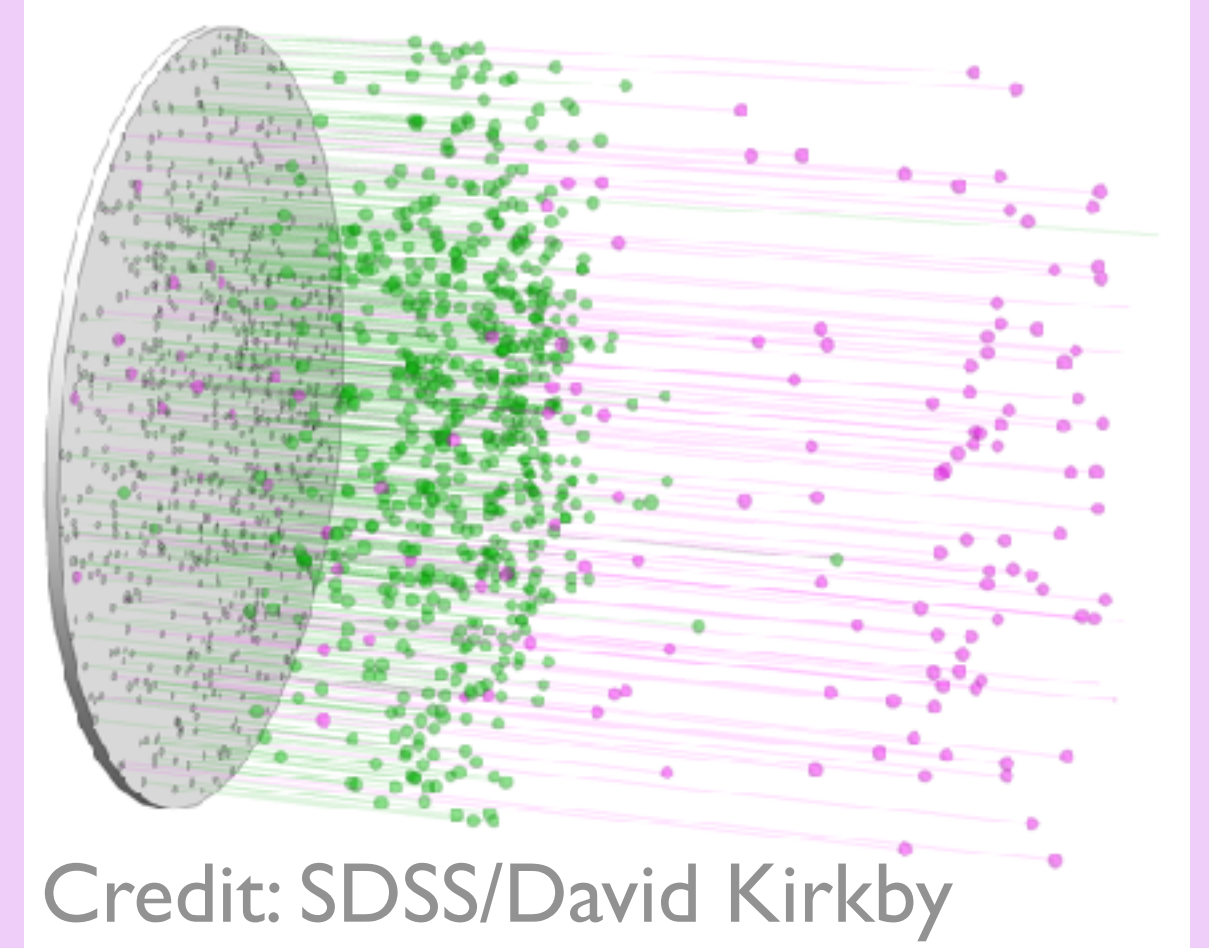
Galaxy Spectroscopic Surveys – Stage I/II

Stage I/II

SDSS I/II: confirm DE



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



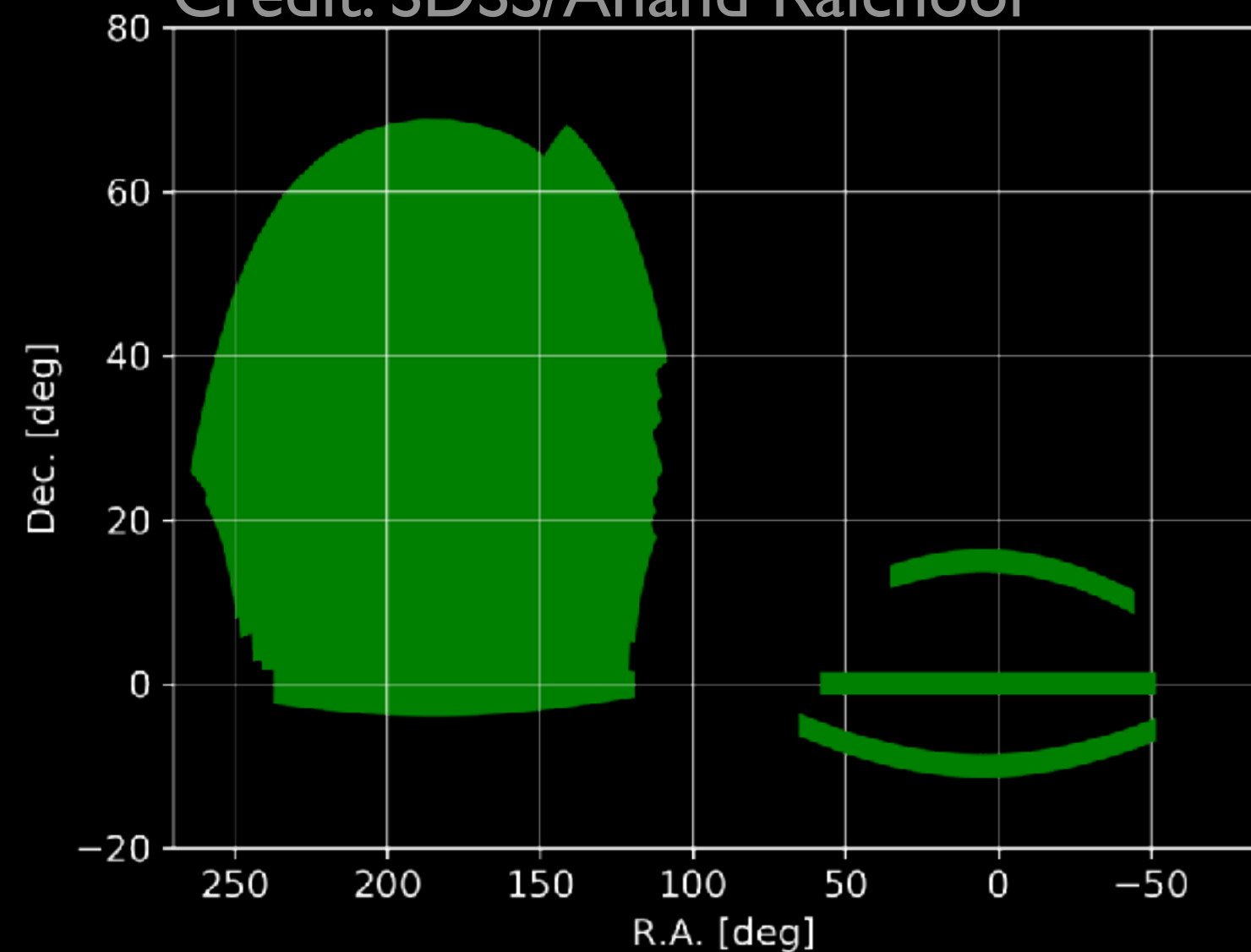
Stage III

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



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

Credit: SDSS/Anand Raichoor

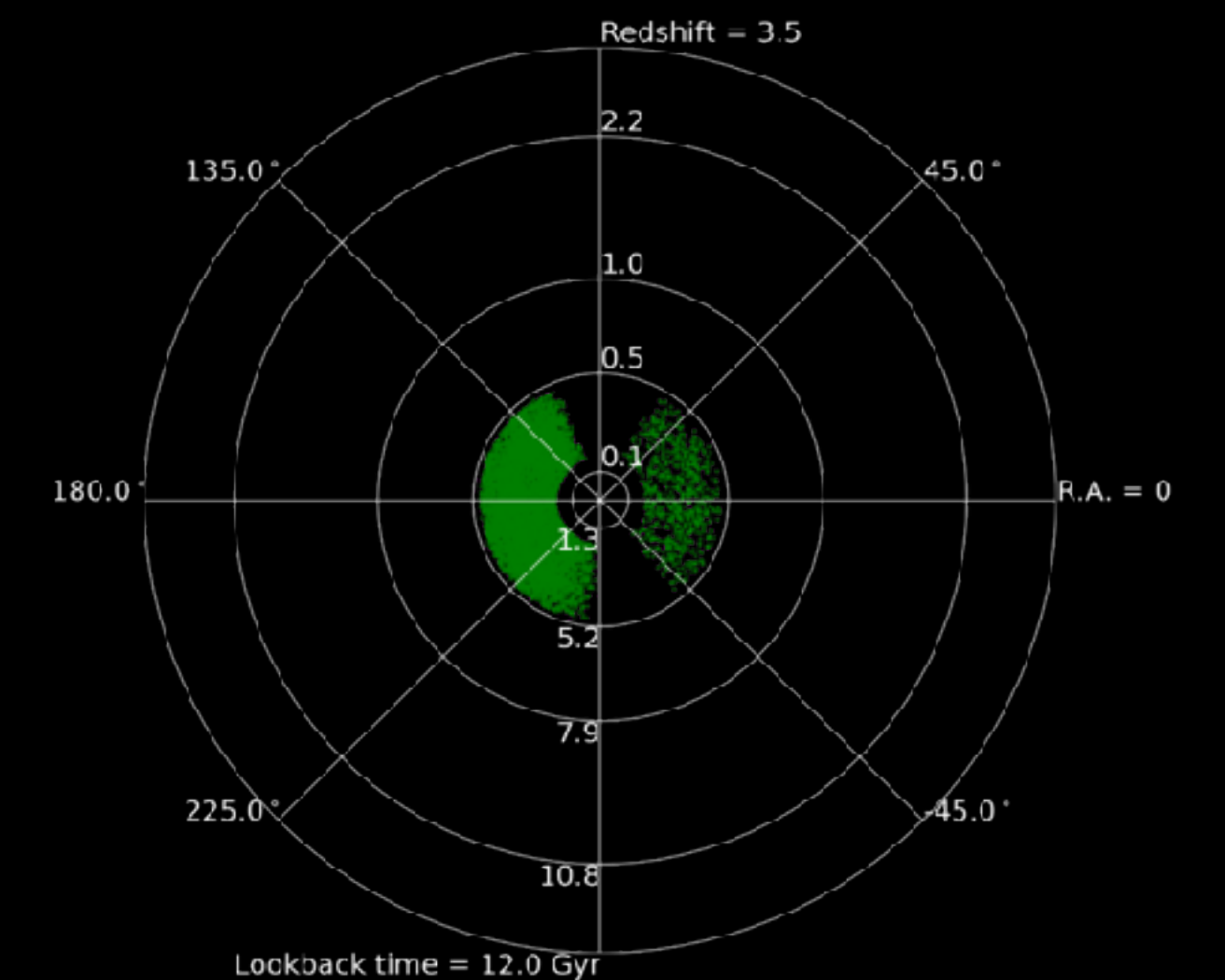


Stage IV

DESI: precise DE @ $z < 3$



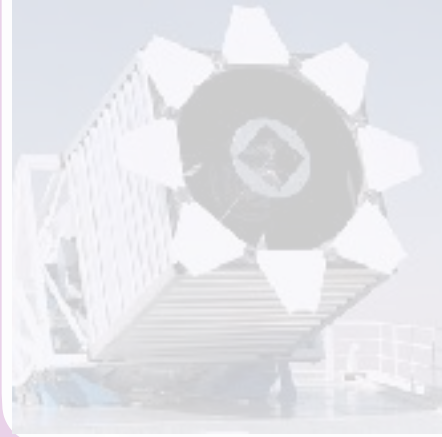
- Duration: 2020 – 2029
- Aperture: 4 m
- Fibers: 5,000
- Spectra: 50 million



Galaxy Spectroscopic Surveys – Stage III

Stage I/II

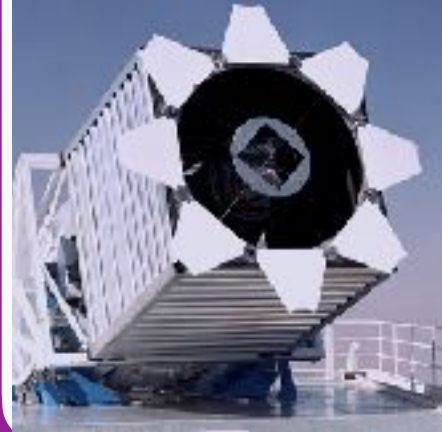
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Stage III

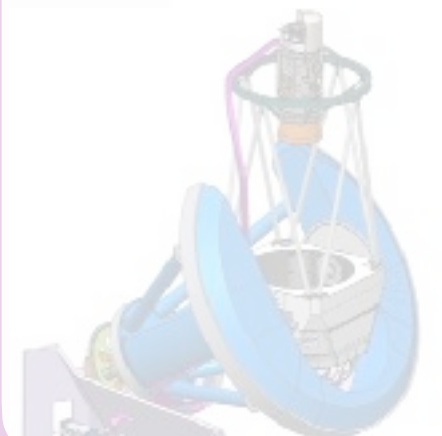
BOSS/eBOSS: precise DE @ $z < 1$



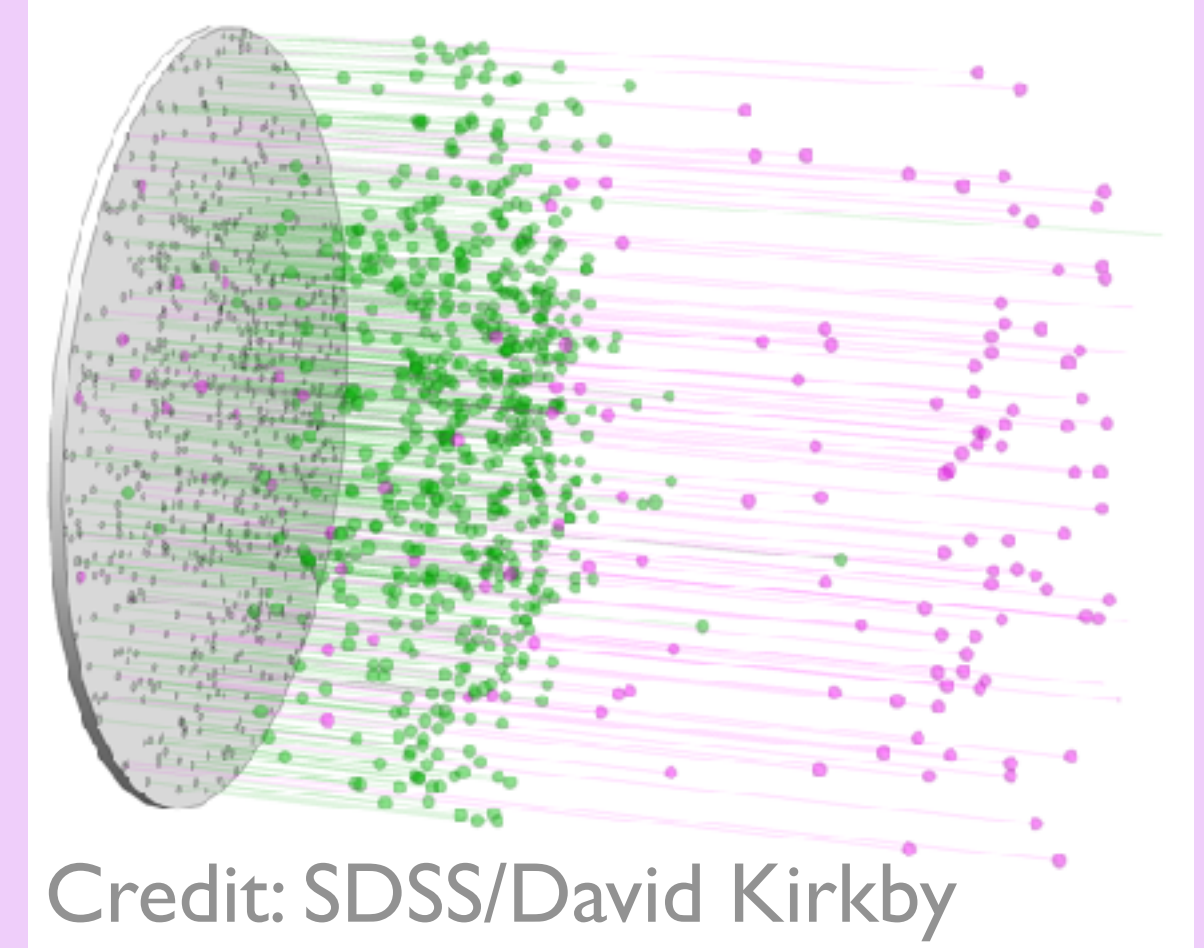
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Stage IV

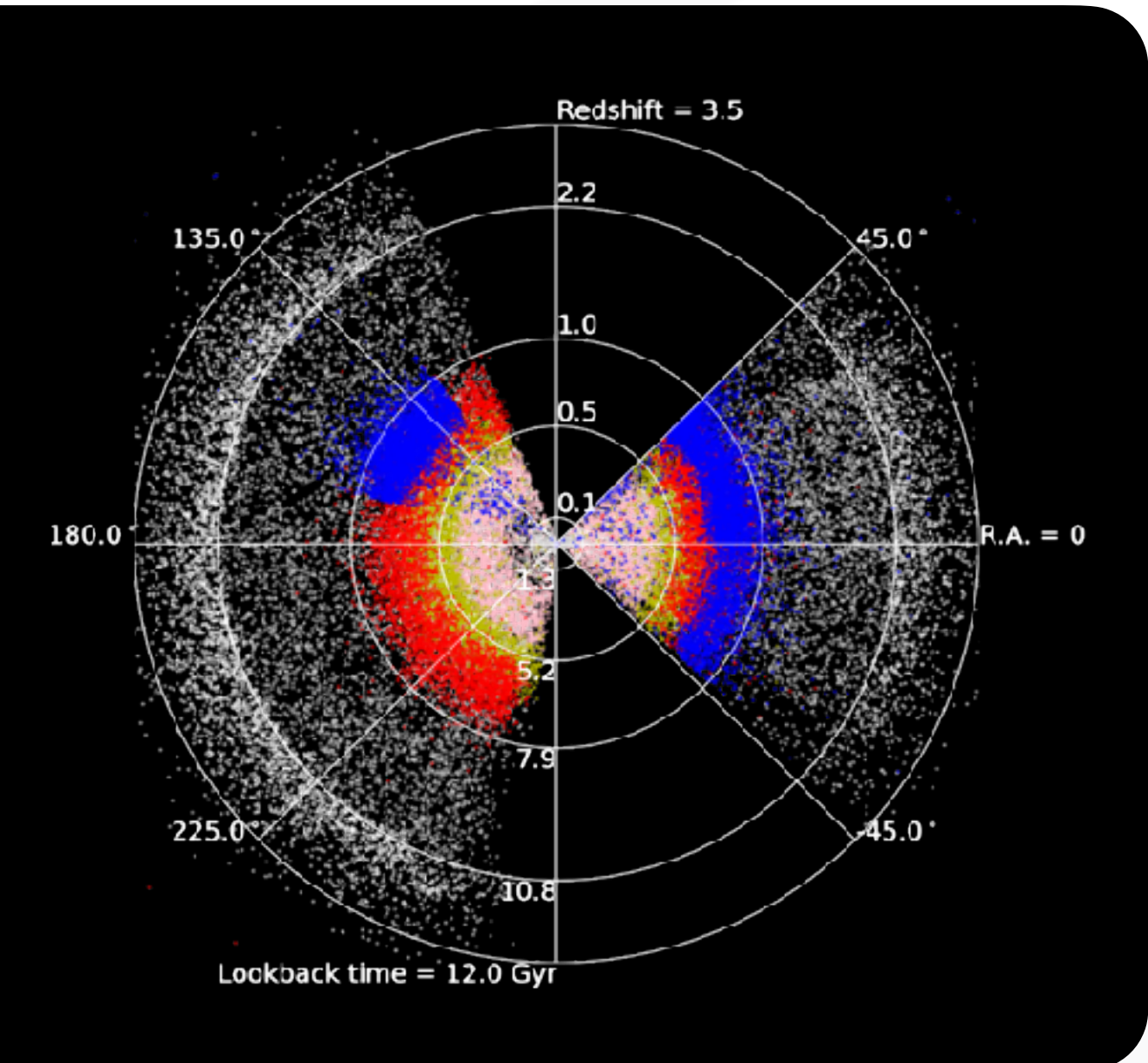
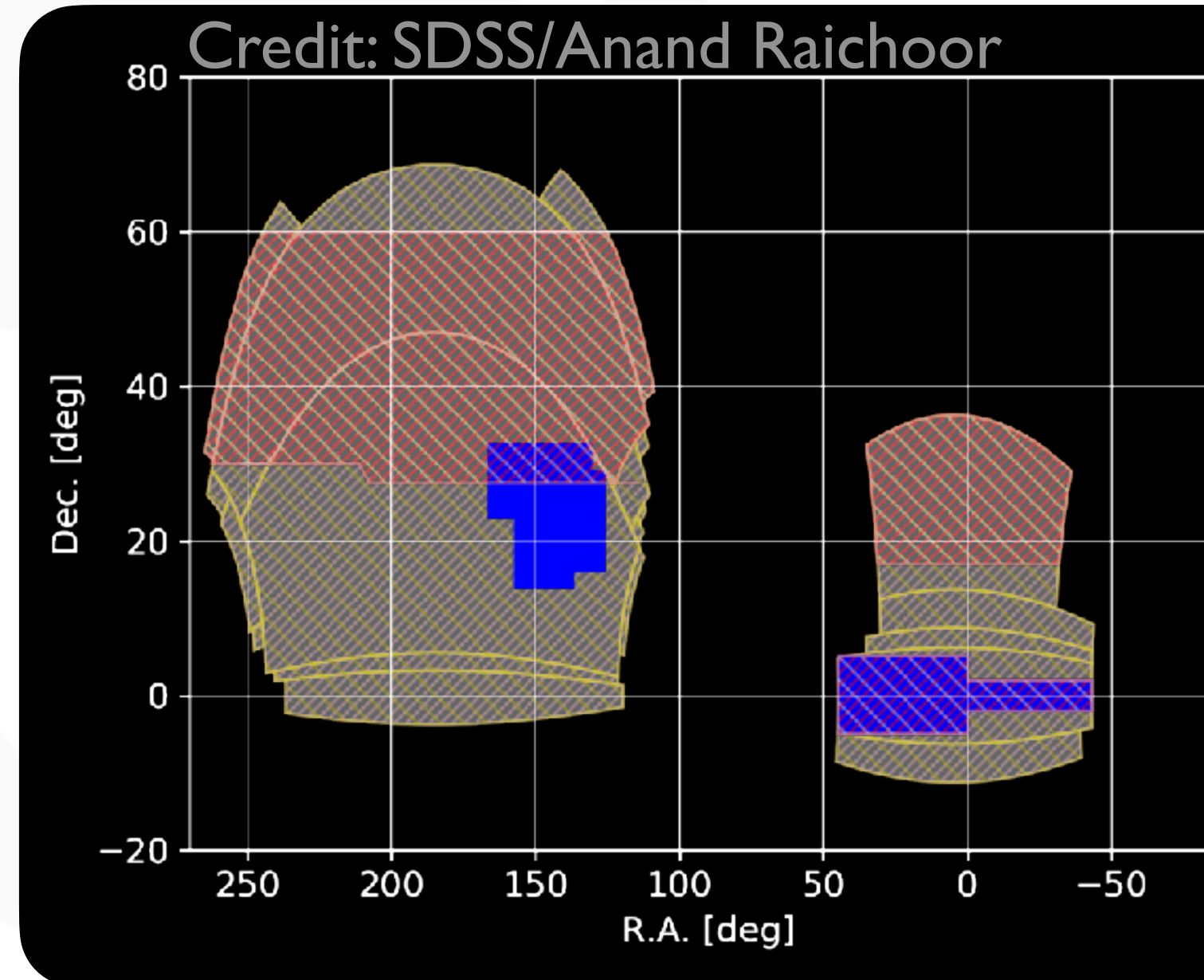
DESI: precise DE @ $z < 3$



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



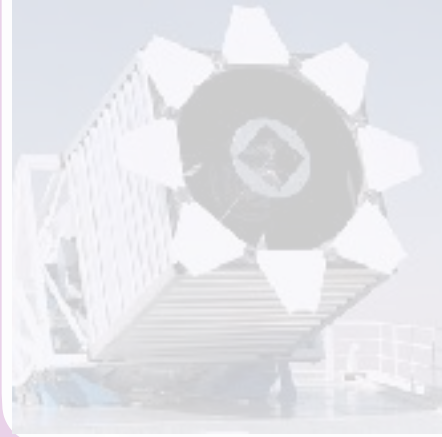
Credit: SDSS/David Kirkby



Galaxy Spectroscopic Surveys – Stage IV

Stage I/II

SDSS I/II: confirm DE



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- Aperture: 2.5 m
- Fibers: 800
- Spectra: 100k

Stage III

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



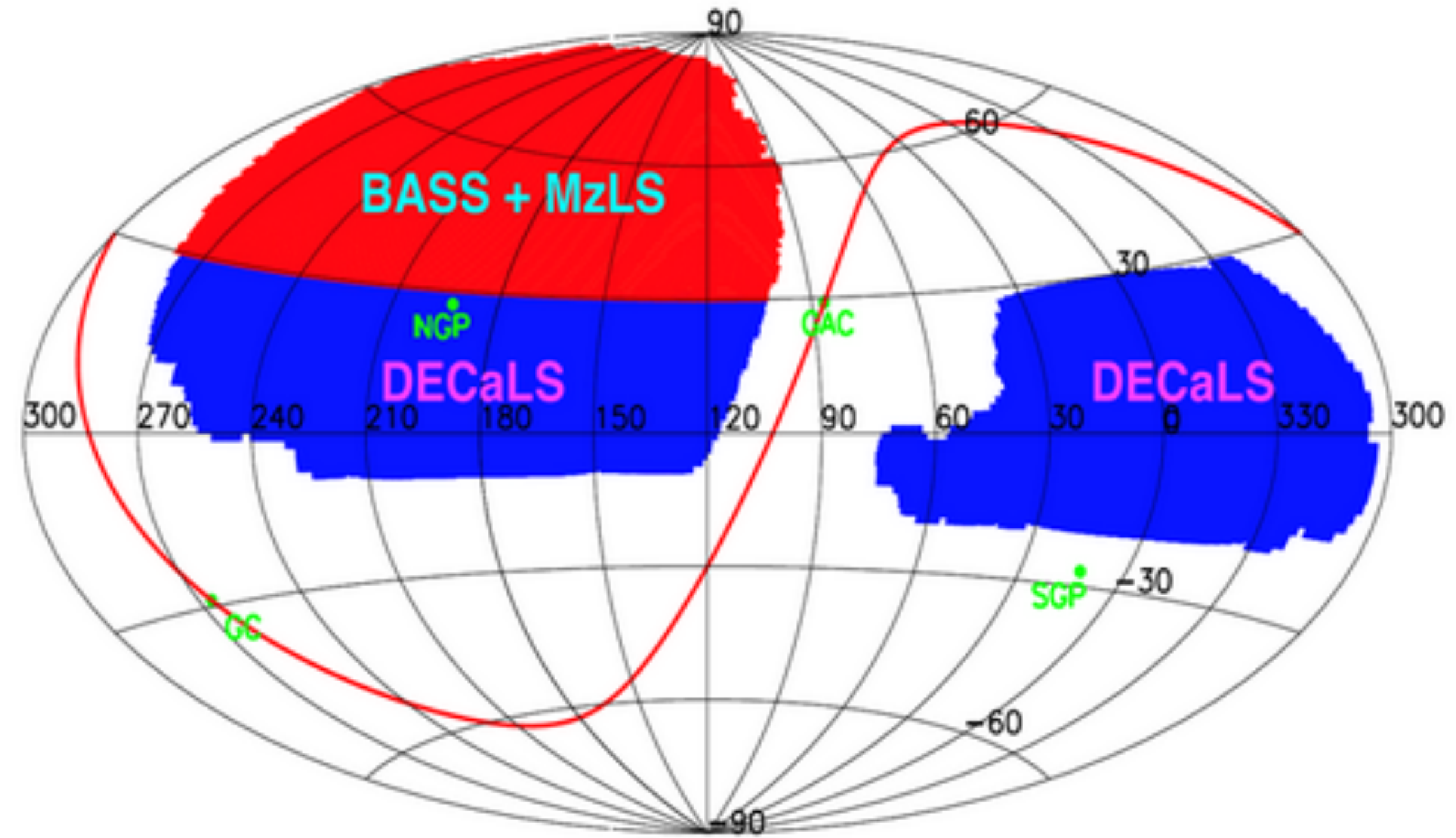
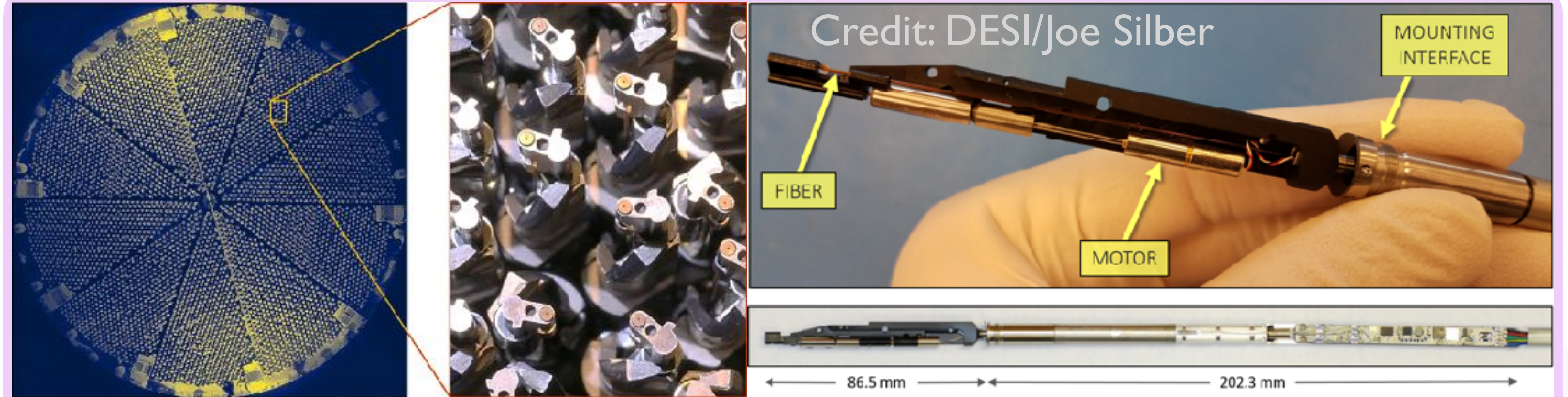
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Stage IV

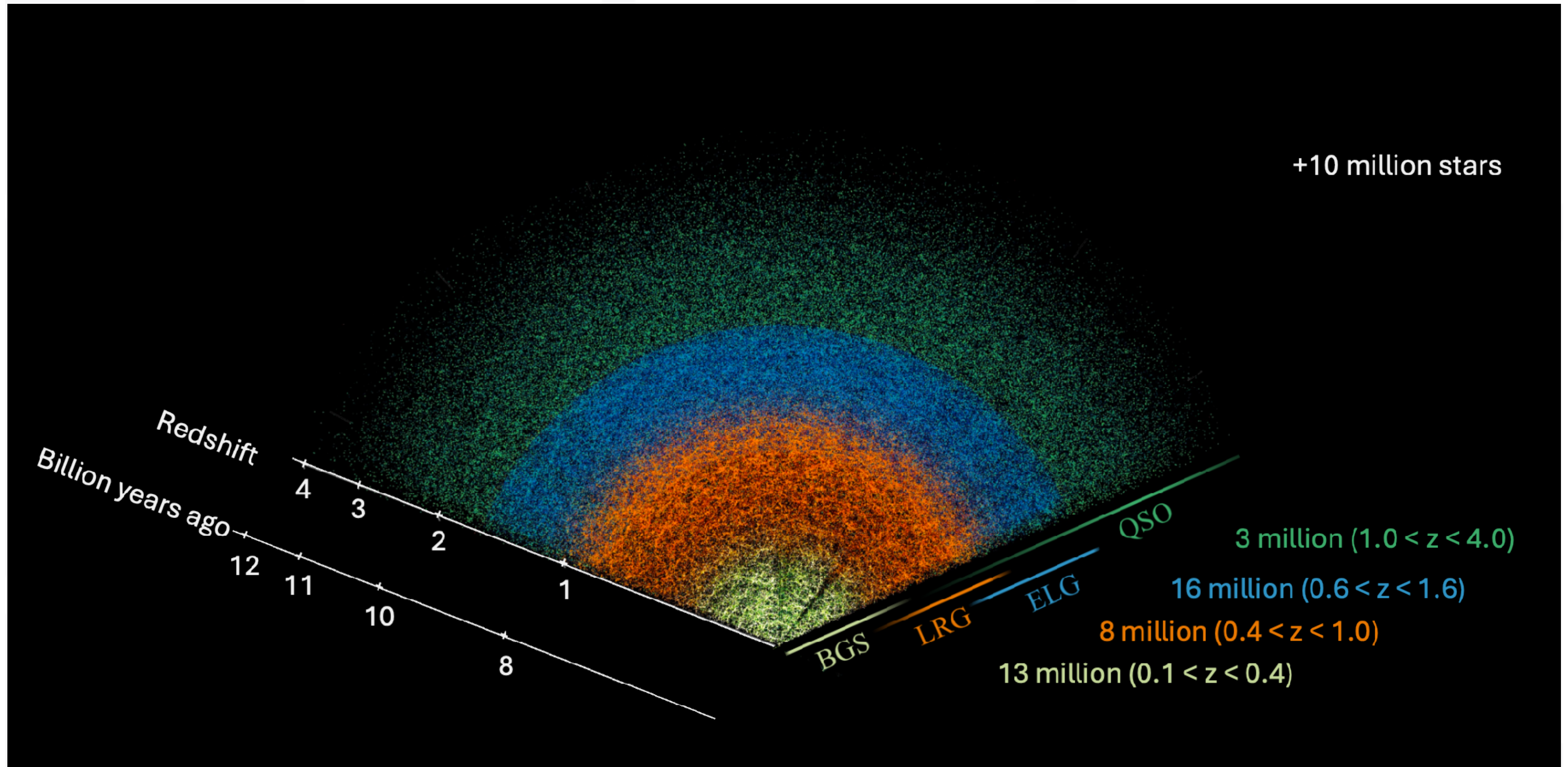
DESI: precise DE @ $z < 3$



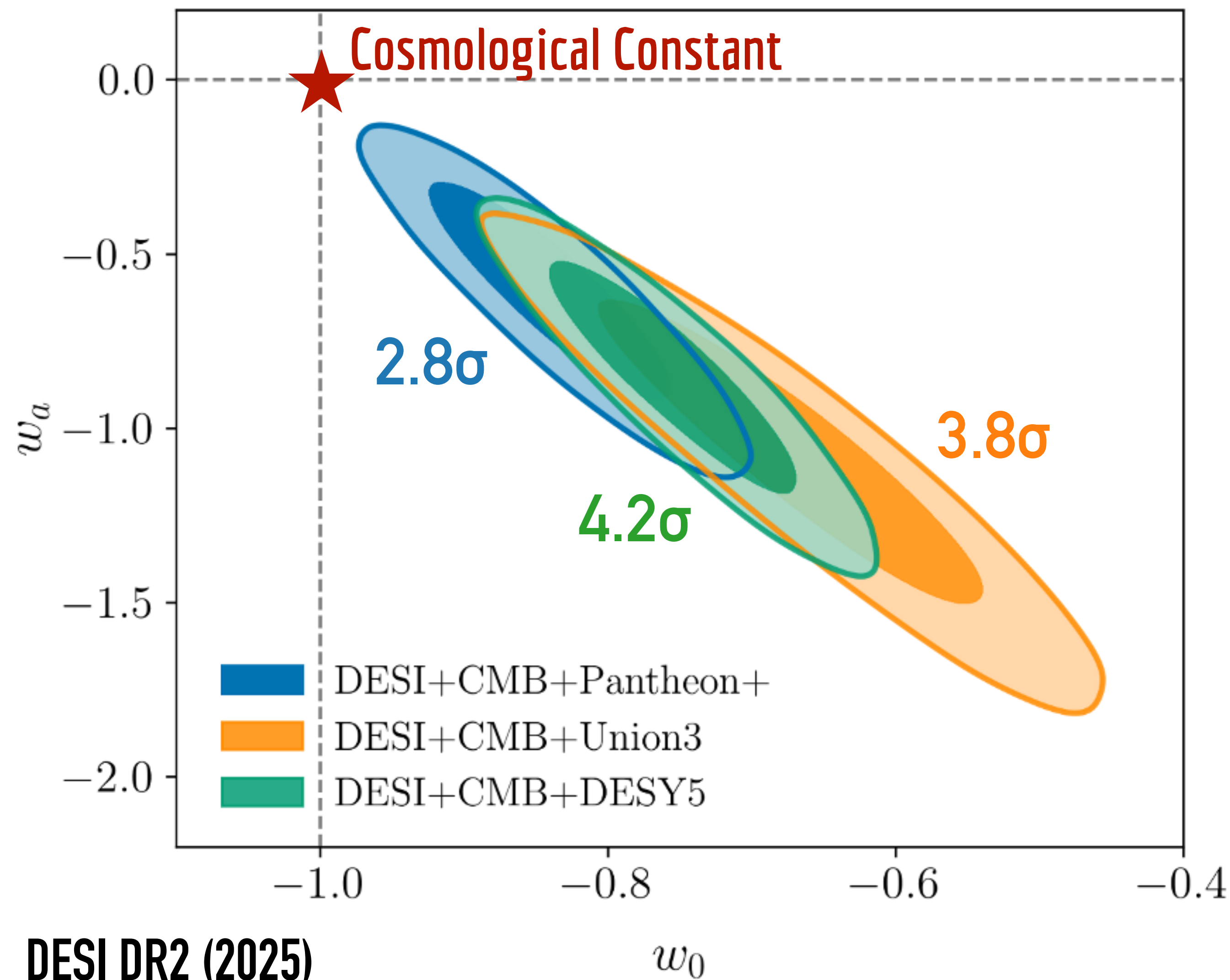
- Duration: 2020 – 2029
- Aperture: 4 m
- Fibers: 5,000
- Spectra: 50 million



Credit: DESI/Anand Raichoor



DESI DR2 Results: Evolving Dark Energy



DESI DR2 (2025)

- Dark Energy Equation of State:

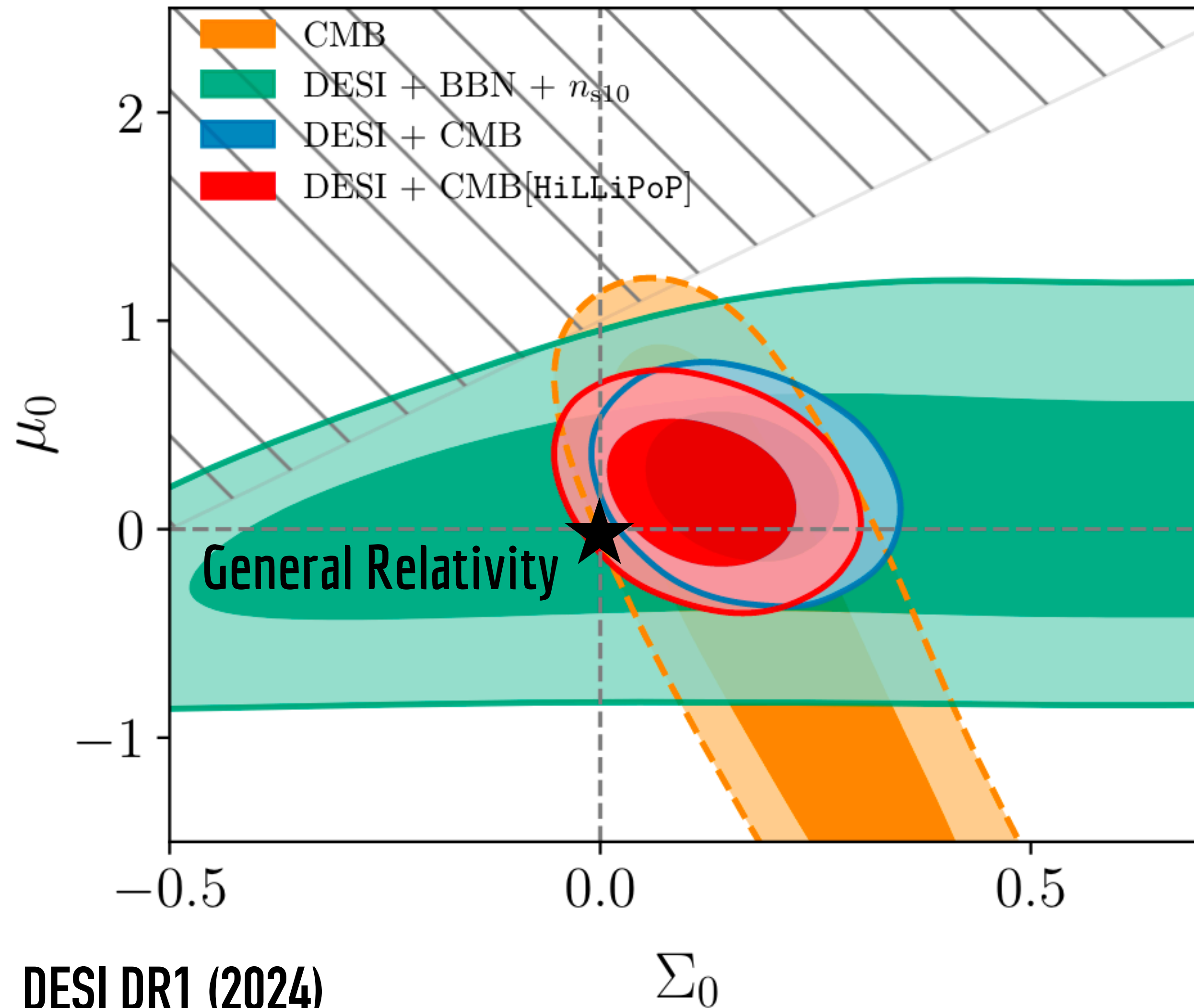
$$w = \frac{p_{\text{DE}}}{\rho_{\text{DE}}}$$

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

- Evidence of Dynamic Dark Energy



DESI DR1 Results: Modified Gravity



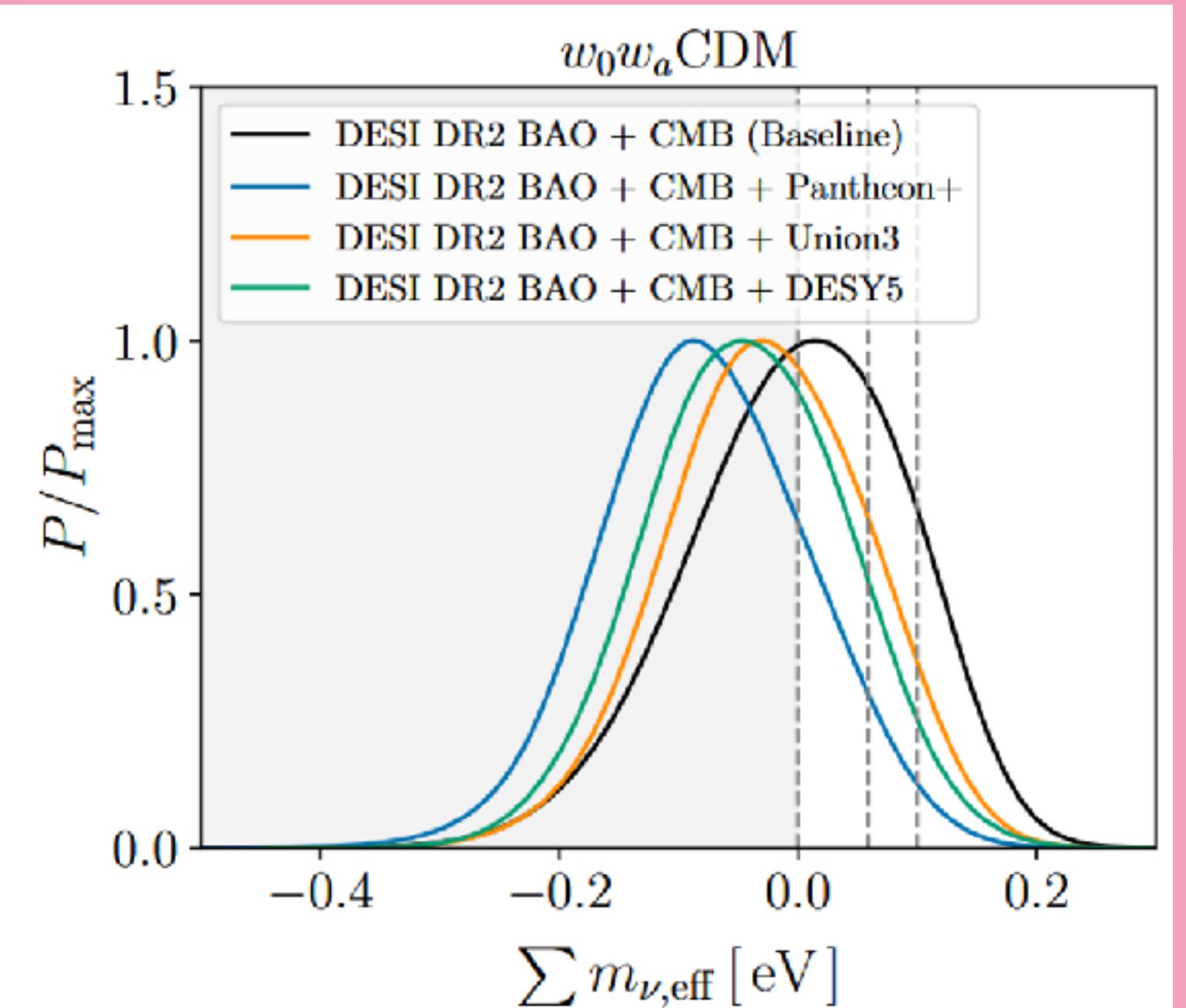
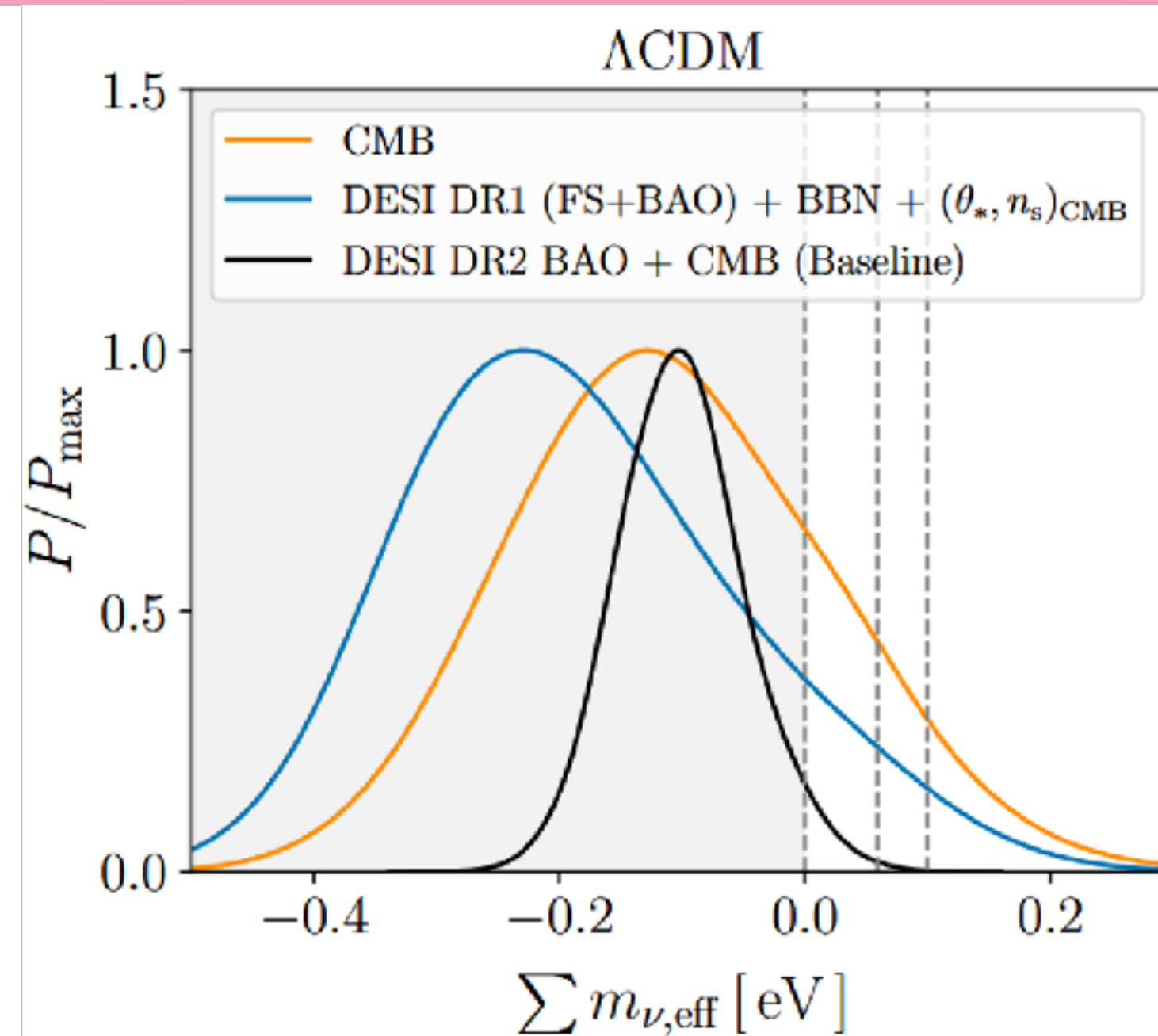
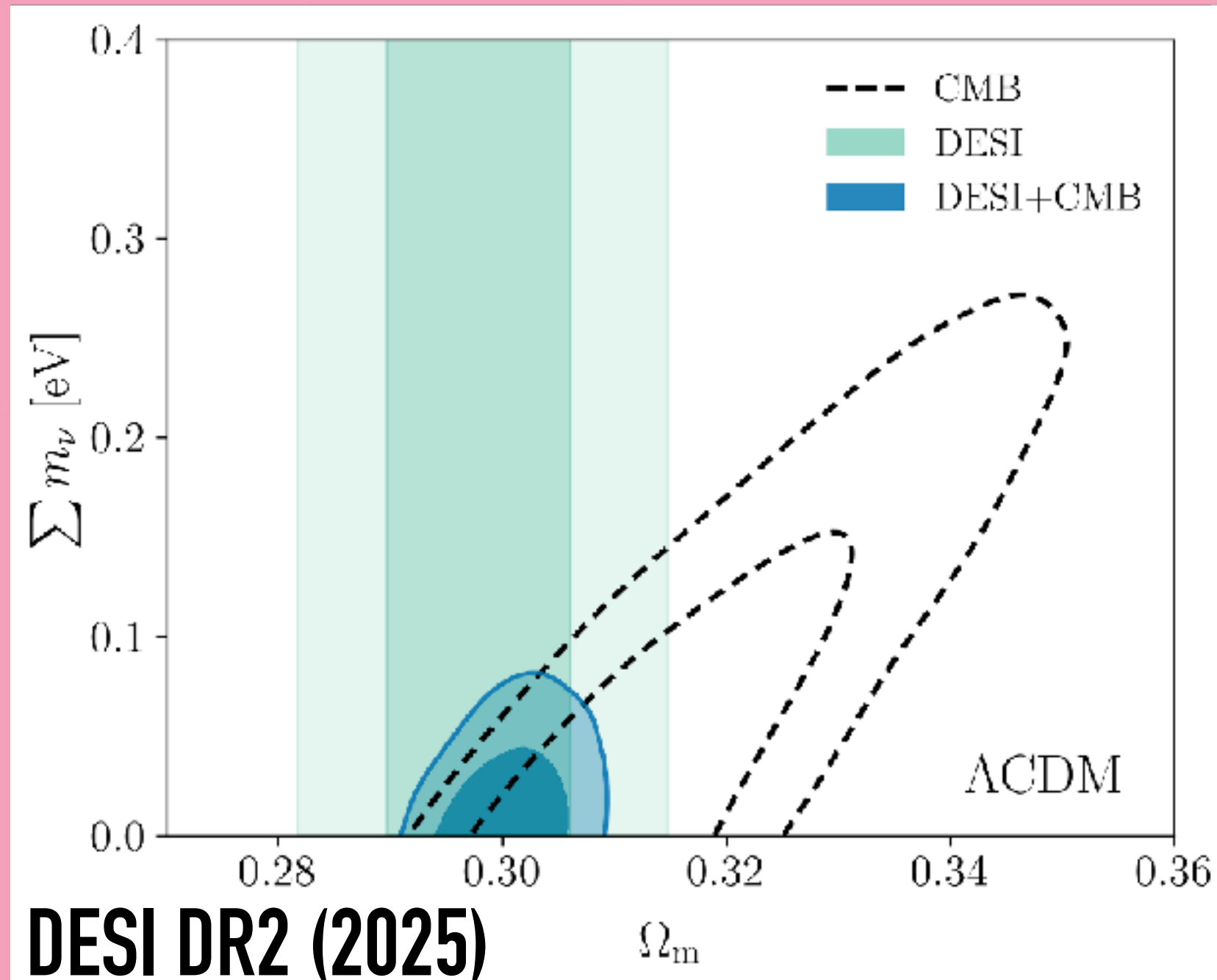
- Parameterization of gravitational potentials

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

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

- General Relativity is still safe with the combined DESI + CMB constraints
- DR2 results to be released soon in this year

DESI Results: Total Neutrino Mass



- Normal Hierarchy preferred in Λ CDM: $\sum m_\nu < 0.064 \text{ eV}$ (95% CL)
- “Negative” neutrino mass: hint of tension between cosmology and neutrino oscillation experiments

Galaxies with Spectroscopy

RA,Dec = 327.7751, 2.0429, zoom 13



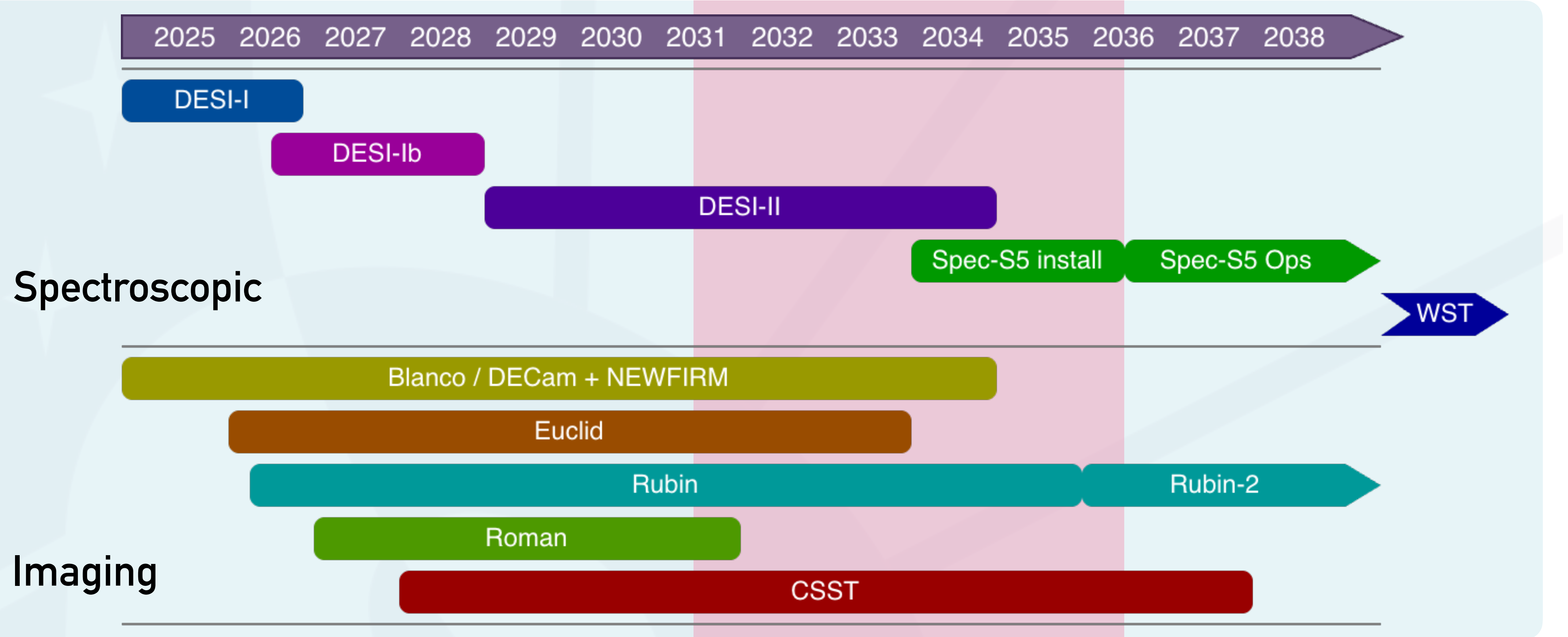
3 arcmin

Contrast: 1

Brightness: 1

- Images
 - + Legacy Surveys DR10 images
 - + Legacy Surveys DR9 images
 - + Older Legacy Surveys
 - + unWISE W1/W2 NEO7
 - + More surveys
- Overlays
 - + Boundaries
 - + Imaging catalogs
 - + Spectroscopy
 - + DESI
 - + Bright Objects

Galaxy Survey Timeline



- Major opportunities in cosmology: massive galaxy surveys and datasets
- A critical 5-6 year window for us

MUST: Next Generation Cosmological Survey

An International
Early-**2030s**

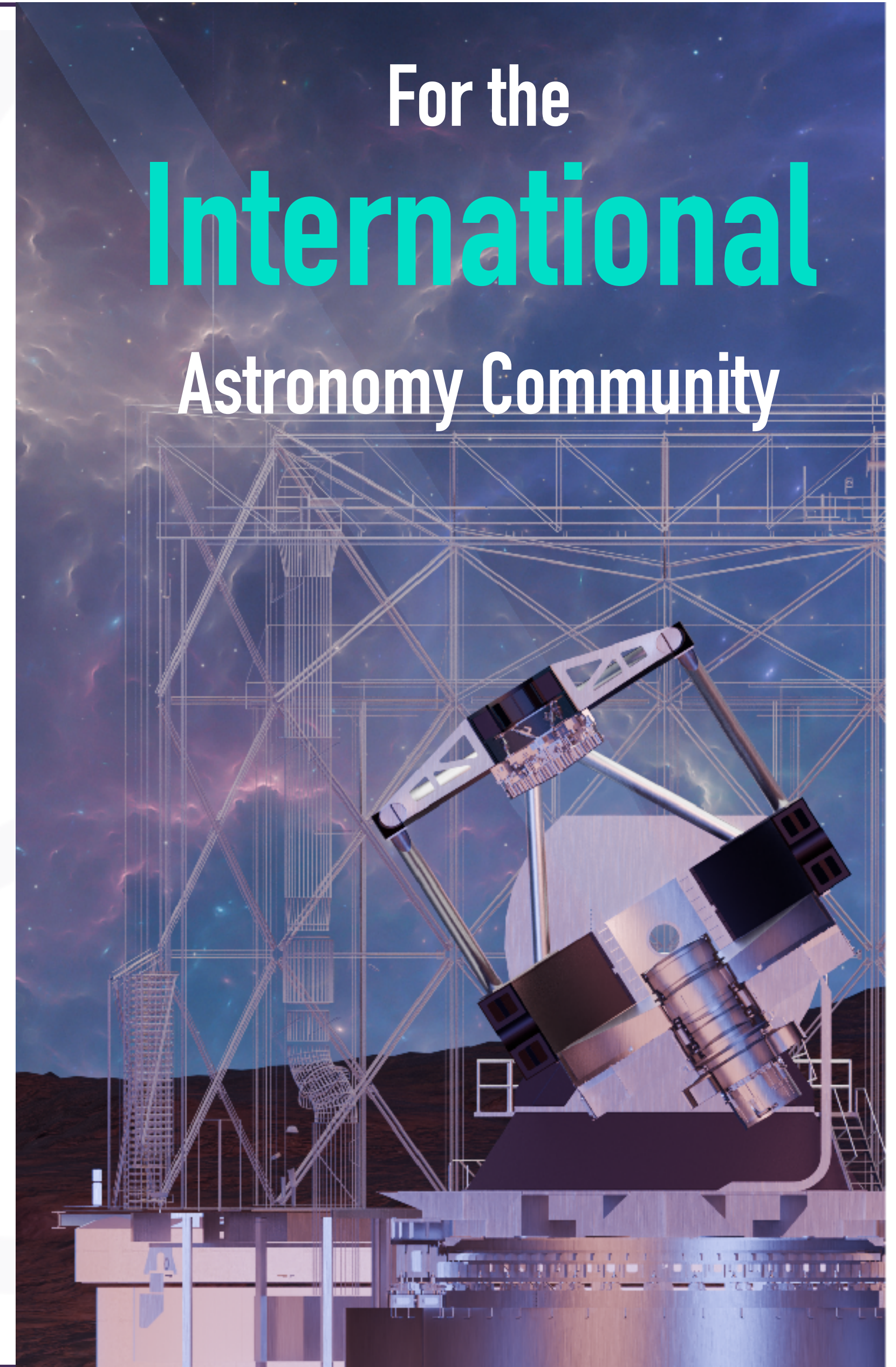
Collaboration

Led by
**Tsinghua
University**

A dedicated
Survey Telescope

Credit: Iris Long

For the
International
Astronomy Community



Overview of MUST

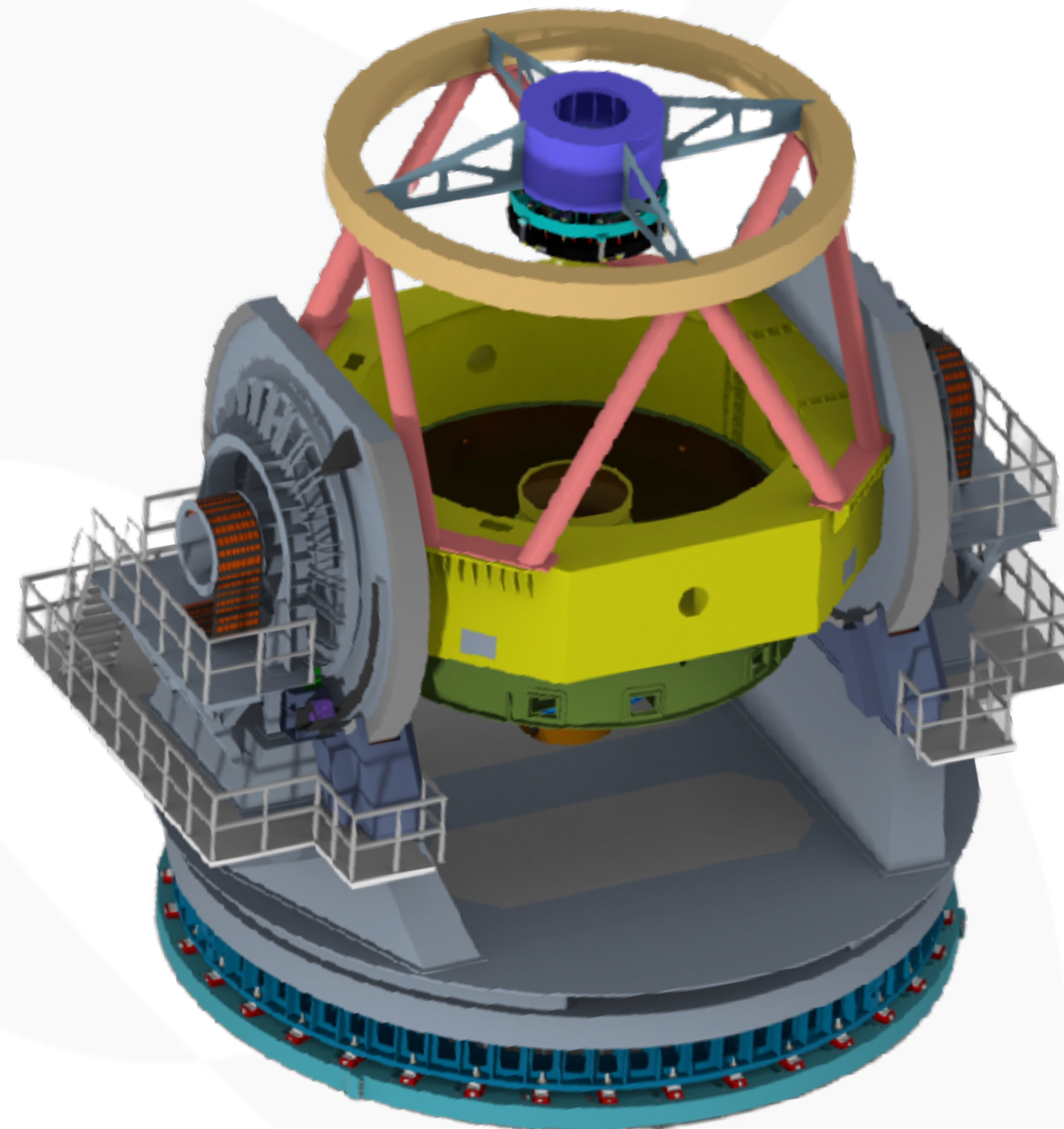
- MUST aims to carry out the world's **First Stage-V** spectroscopic survey for Cosmology and create the **Largest 3-D Map of the Universe**.
- MUST will constrain cosmological models with unprecedented precision and strive for breakthroughs in **Fundamental Physical Problems**, such as the primordial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

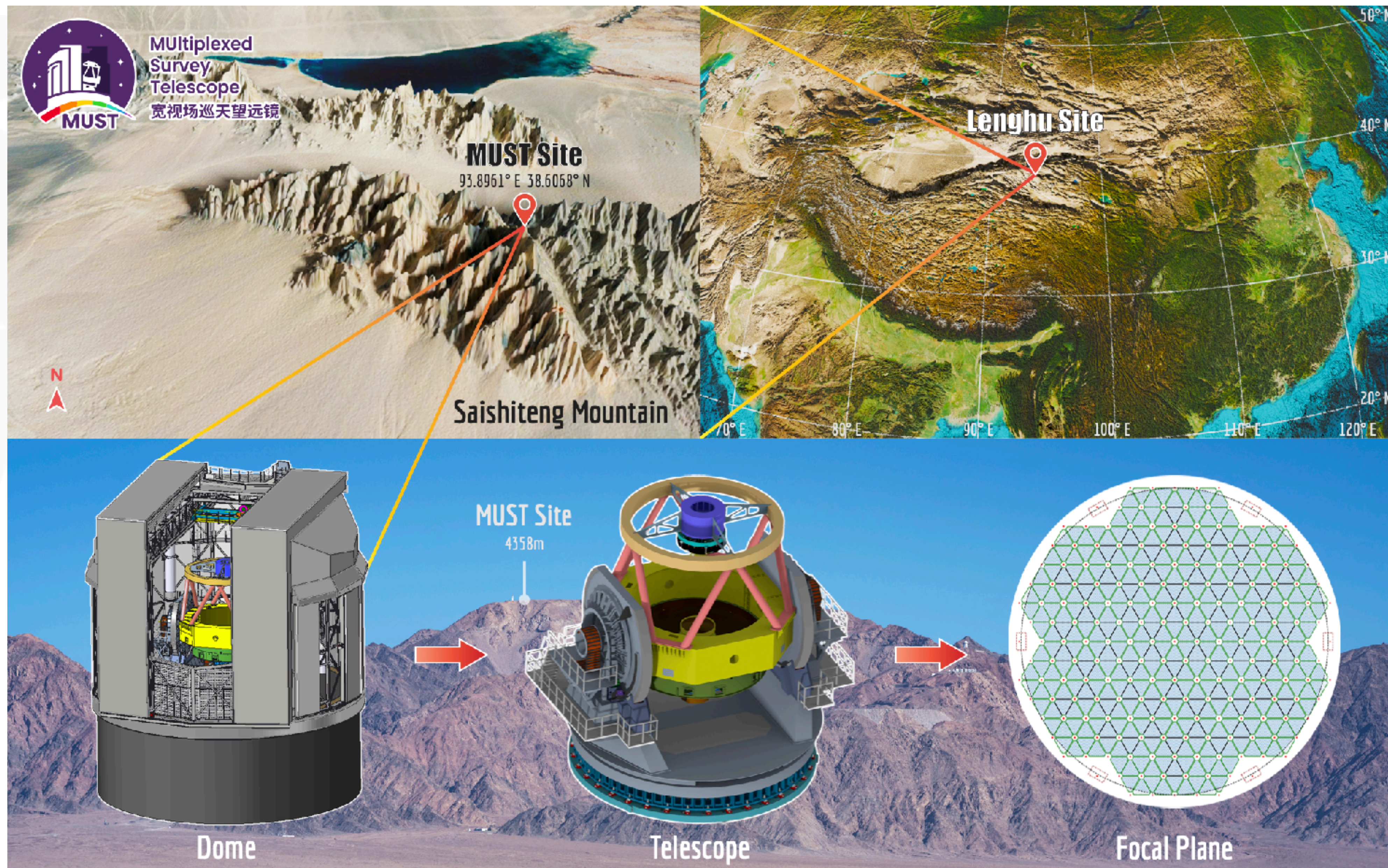
MODULAR Focal Plane

40 Spectrographs

0.37–0.98 micron

R~2000–4000

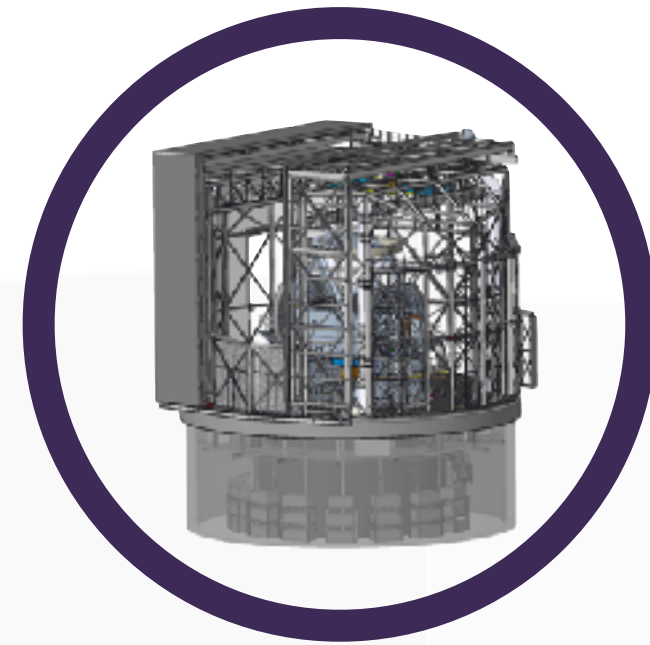
Overview of MUST



Project Progress

Preliminary design completed for all critical sub-systems; contracts signed or partners secured. Some sub-systems are entering **fabrication**.

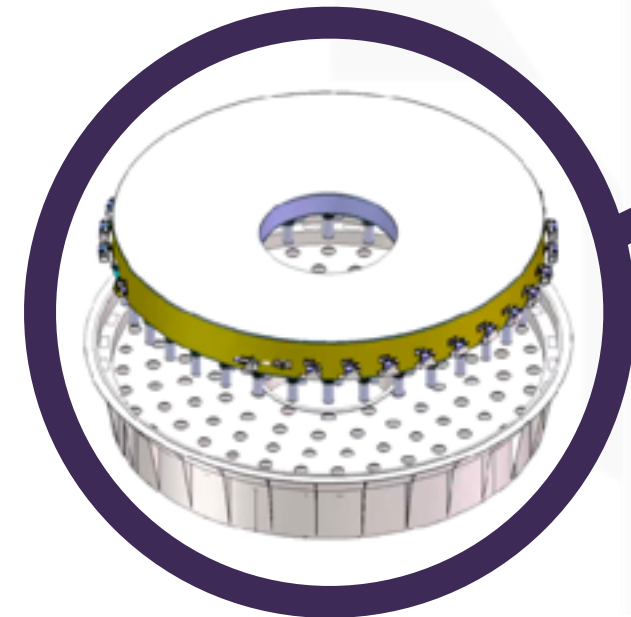
Dome



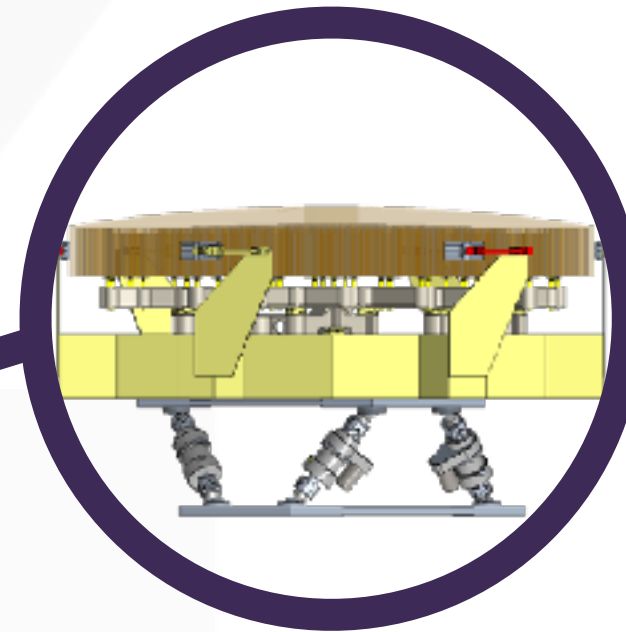
Mount



Primary Mirror



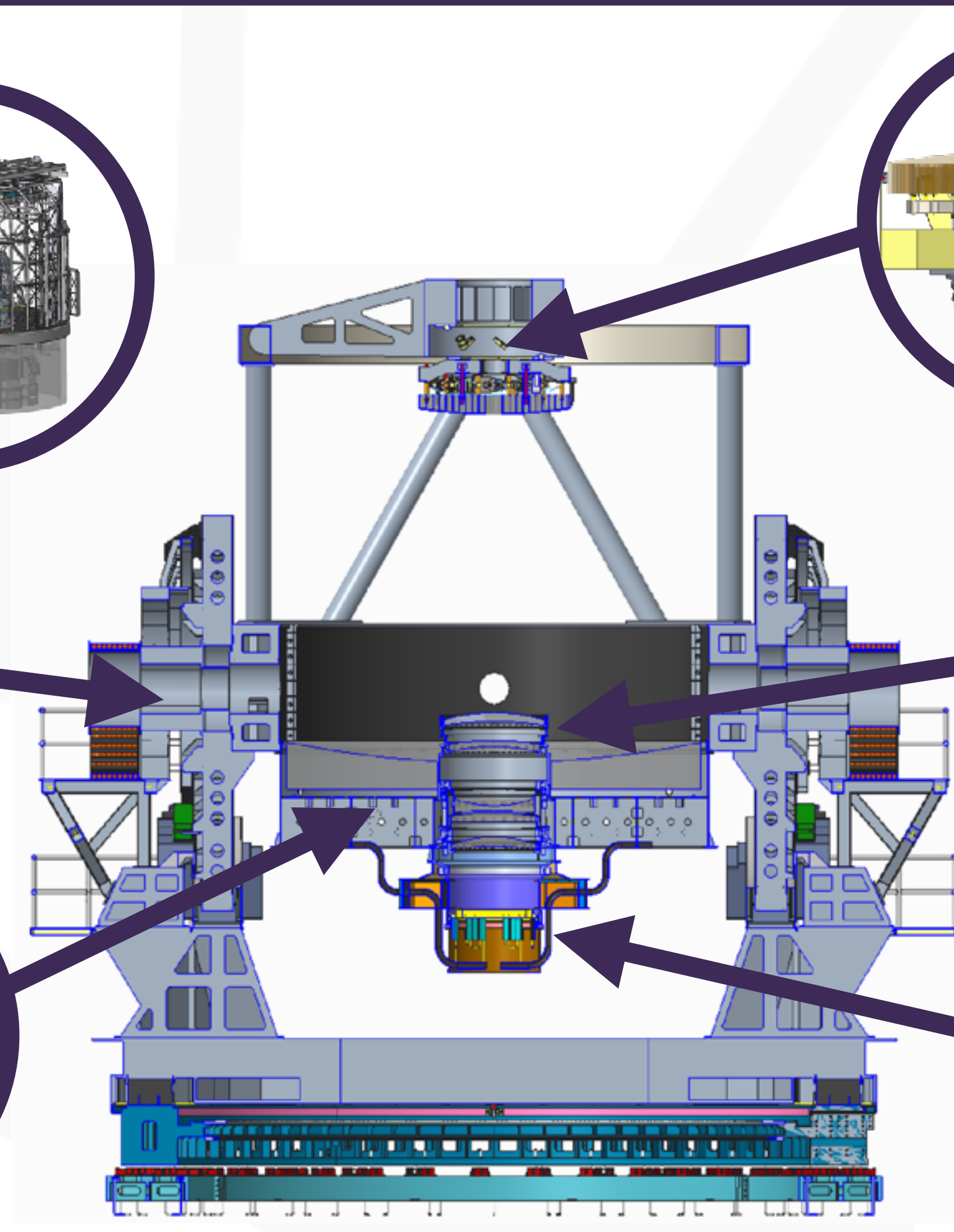
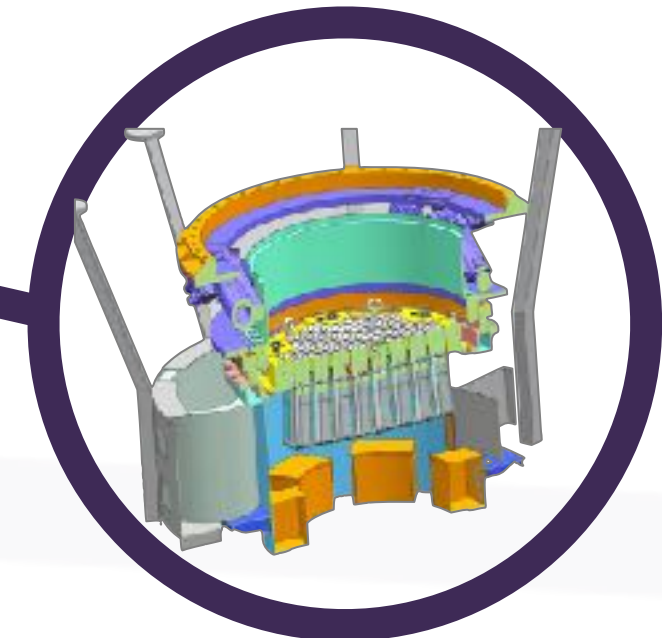
Secondary Mirror



Wide-Field
Corrector



Focal System



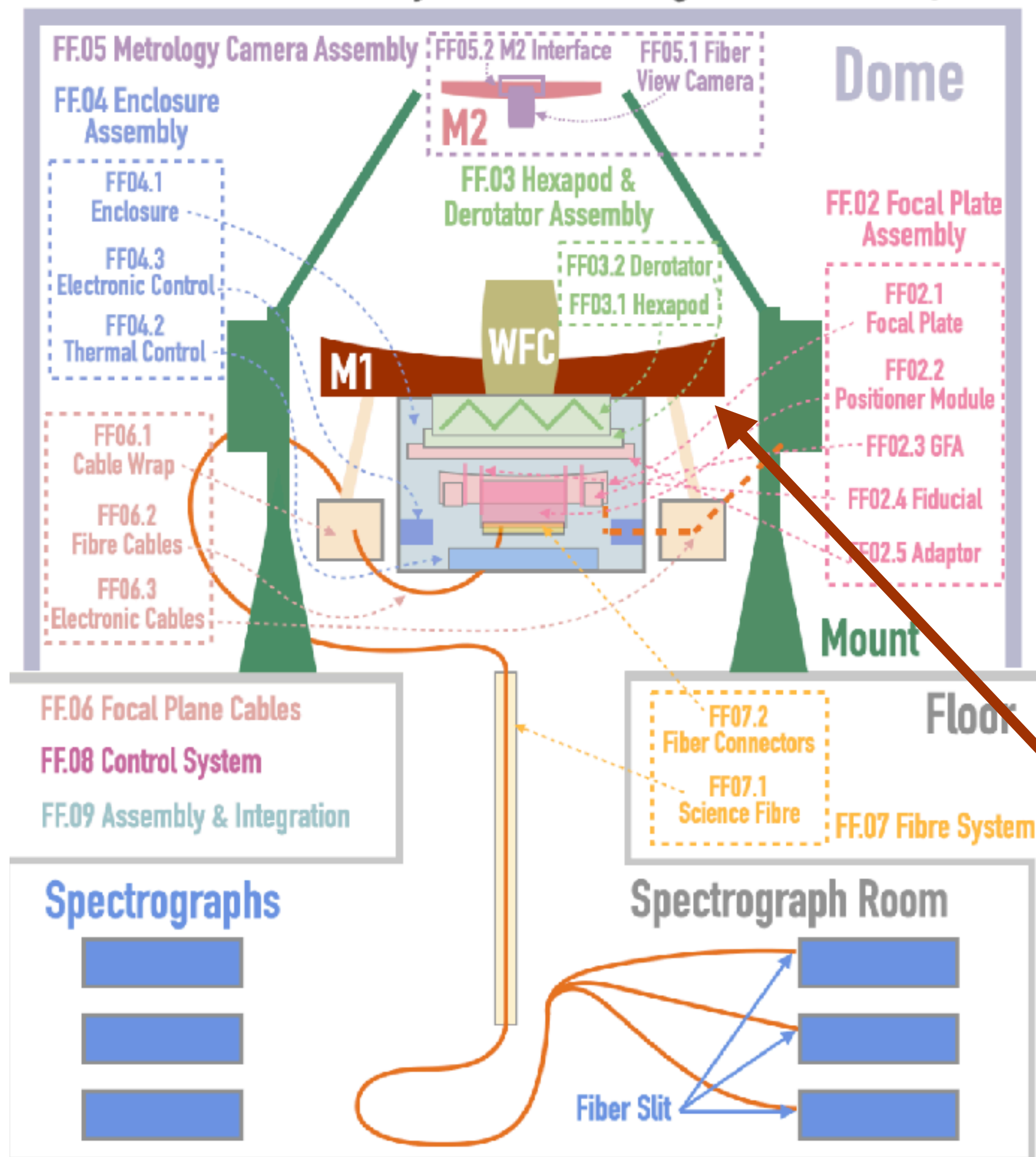
Project Progress

Assembly workshop in Jiangyin in operation

- Finished and already put to use.
- Will become a full optical-mechanical assembly center.



MUST Focal Plane (FF) System Block Diagram NOT To Proportion

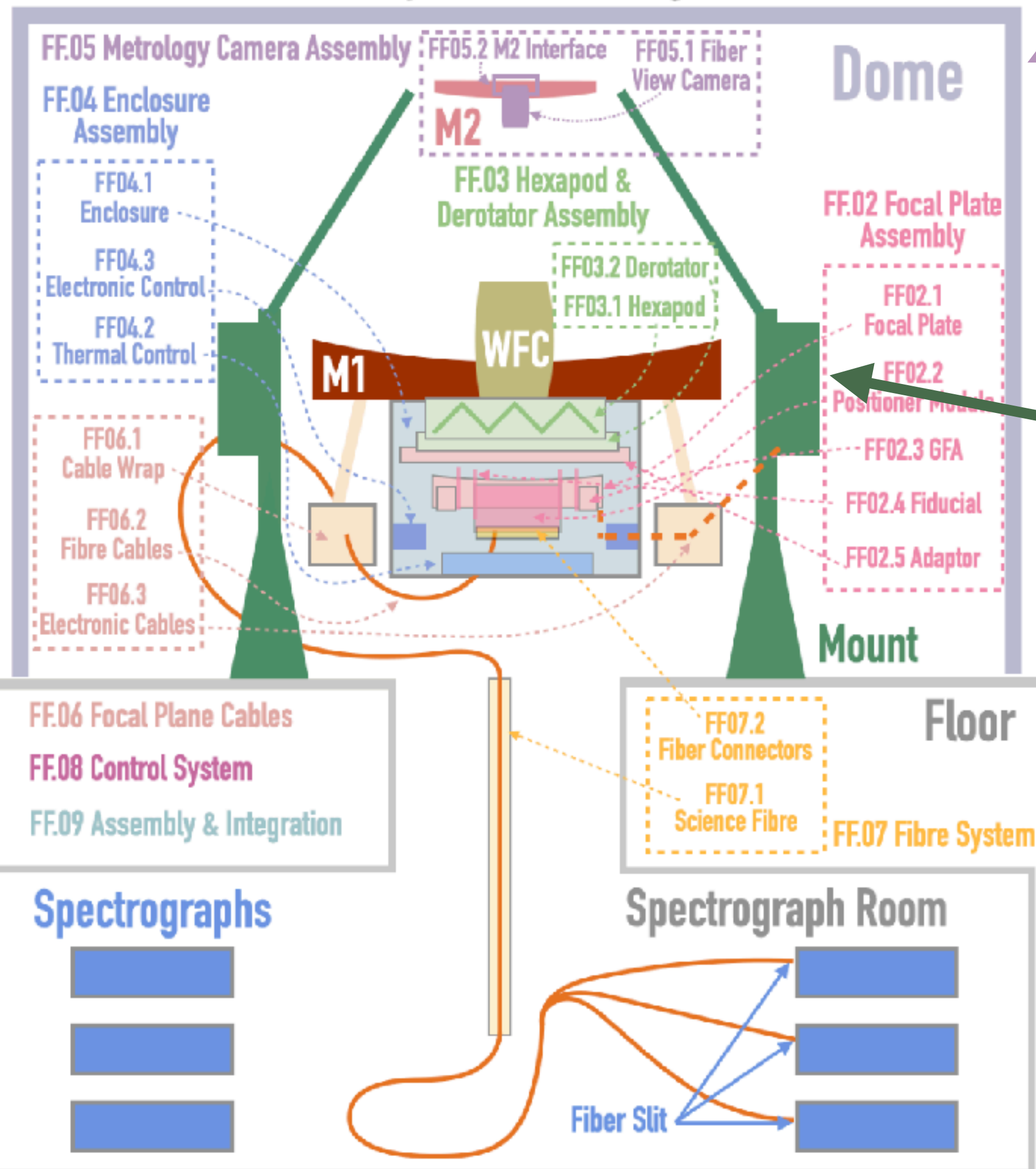


Primary mirror

- **6.5m SiC mirror**: passed the preliminary design review and is being prepared for casting.
- Collaborating to design and test the reflective coating and the protection & cleaning procedures.

Project Progress

MUST Focal Plane (FF) System Block Diagram NOT To Proportion

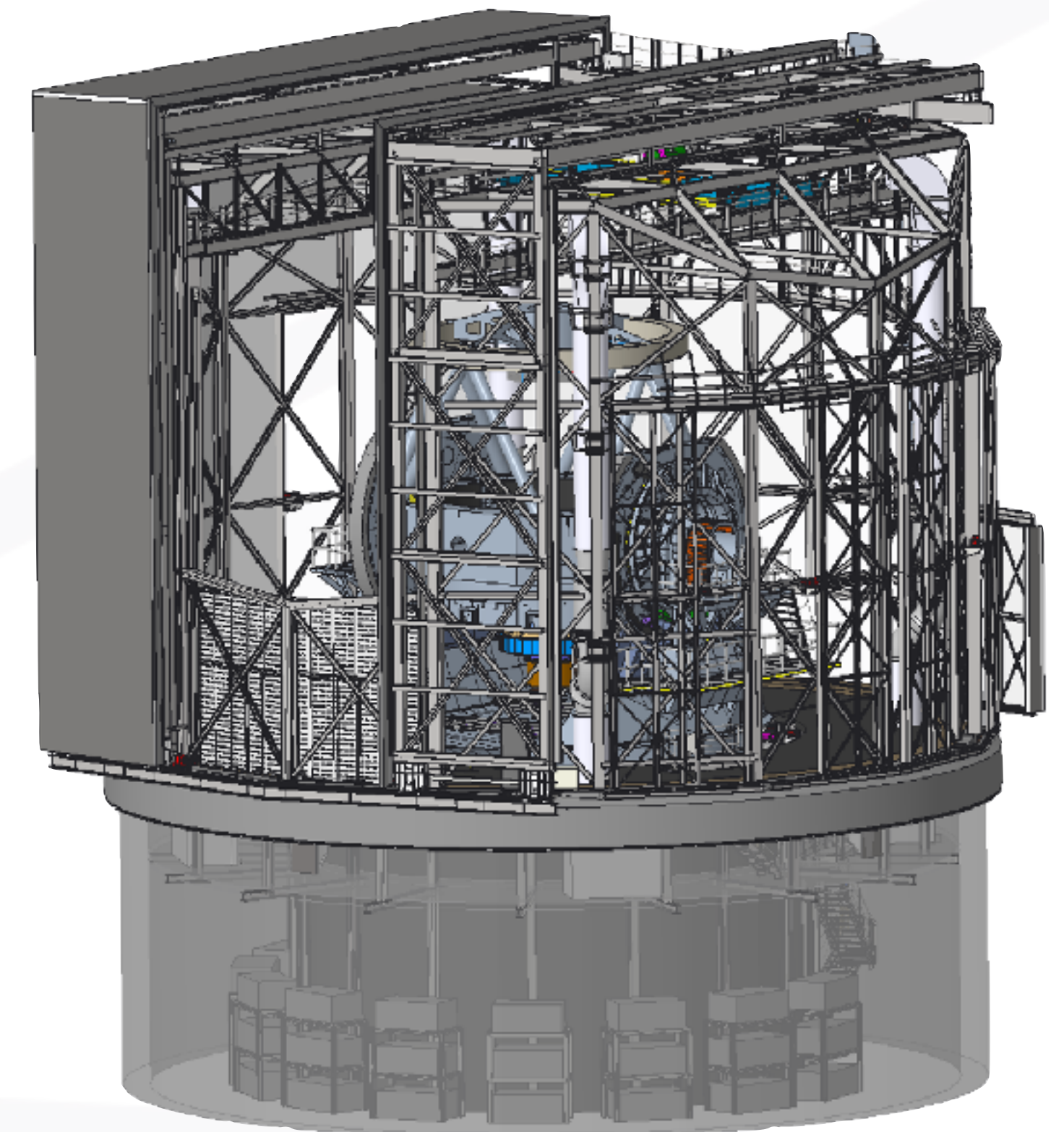


Dome

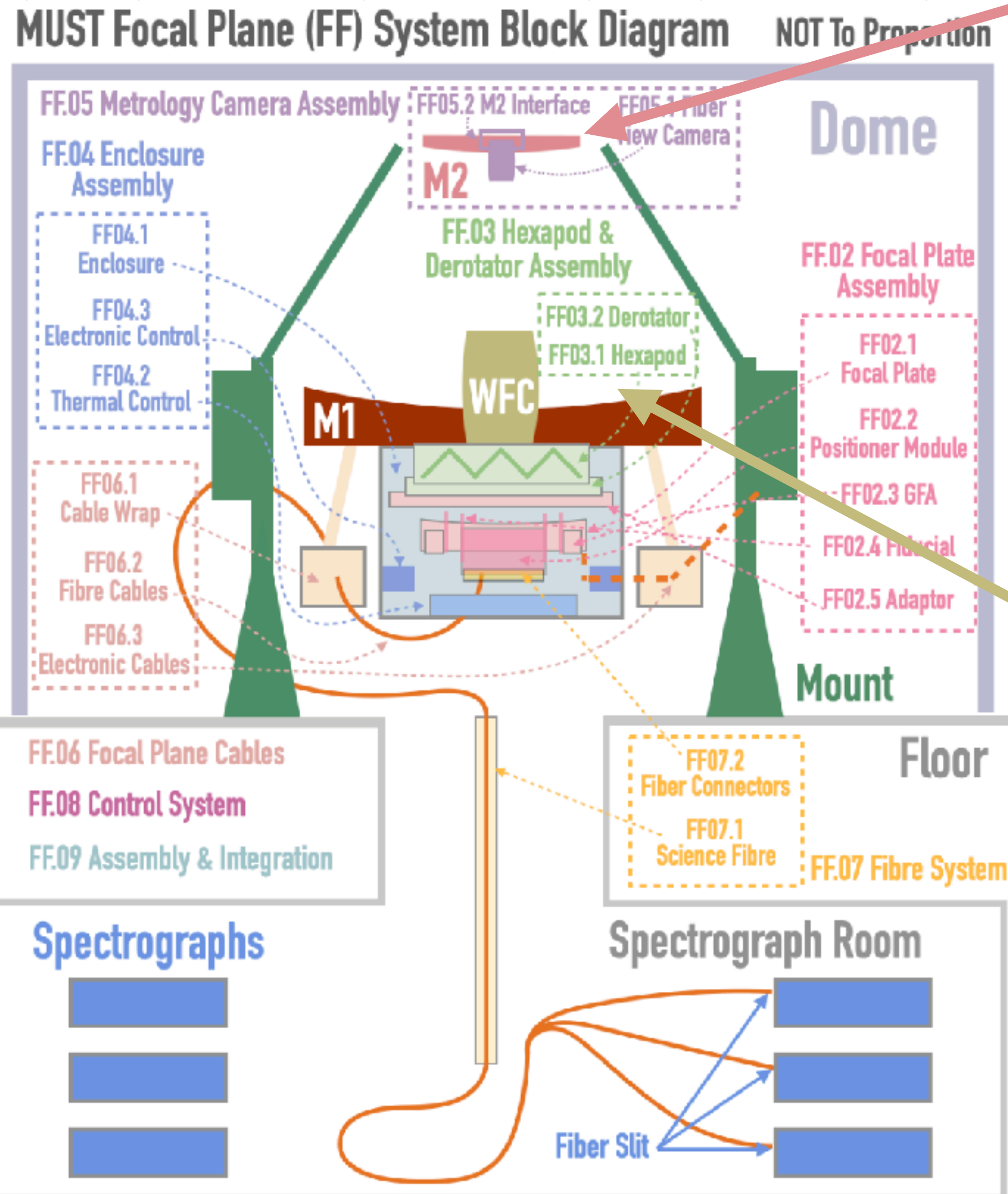
- Iterating the design with EIE, especially the requirements for the spectrograph rooms.
- Now, MUST's dome will be part of a **summit facility** with another telescope.

Mount & tracking system

- Passed the **PDR**.
- Identified a few critical interface issues with the Focal Plane Systems (mostly the fiber route). Will focus on them next year.
- Low on-site temperatures are a significant challenge.



Project Progress



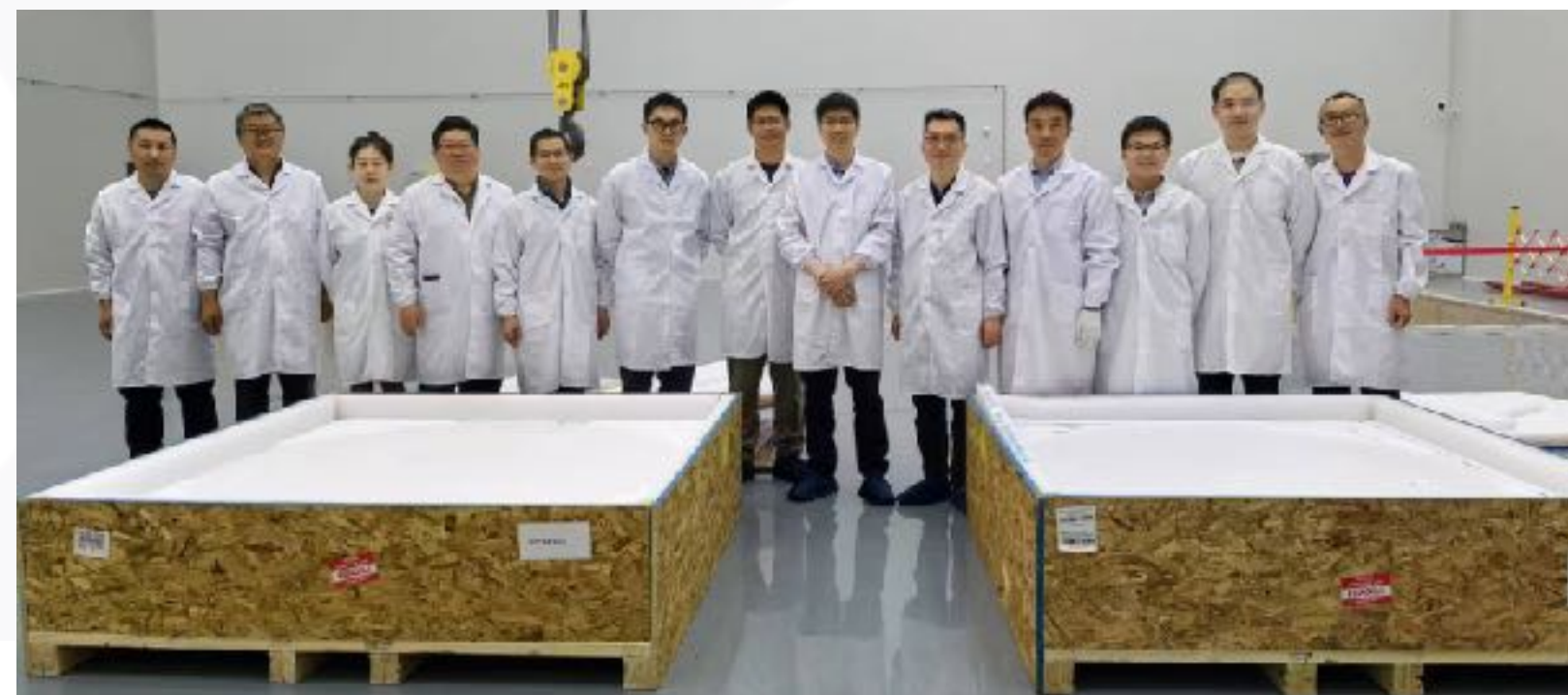
Secondary mirror

- Lightweight processing has begun at our Jiangyin facility.
- The design for the supporting structure has finished.



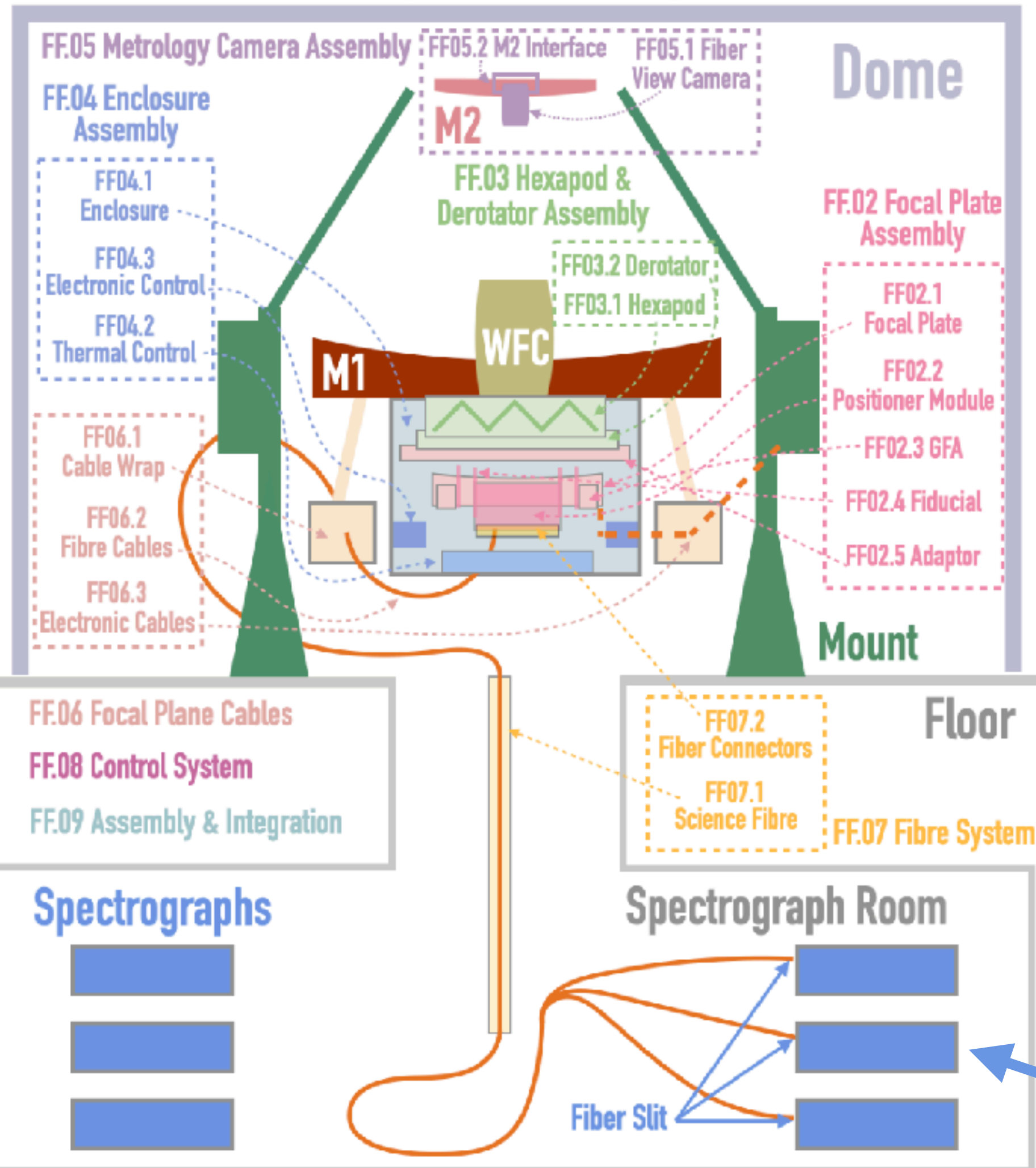
Wide-field corrector

- Lens blanks have arrived; Begun to shape 2 lenses.
- Entering a more detailed design phase.



Project Progress

MUST Focal Plane (FF) System Block Diagram NOT To Proportion



Optical efficiency

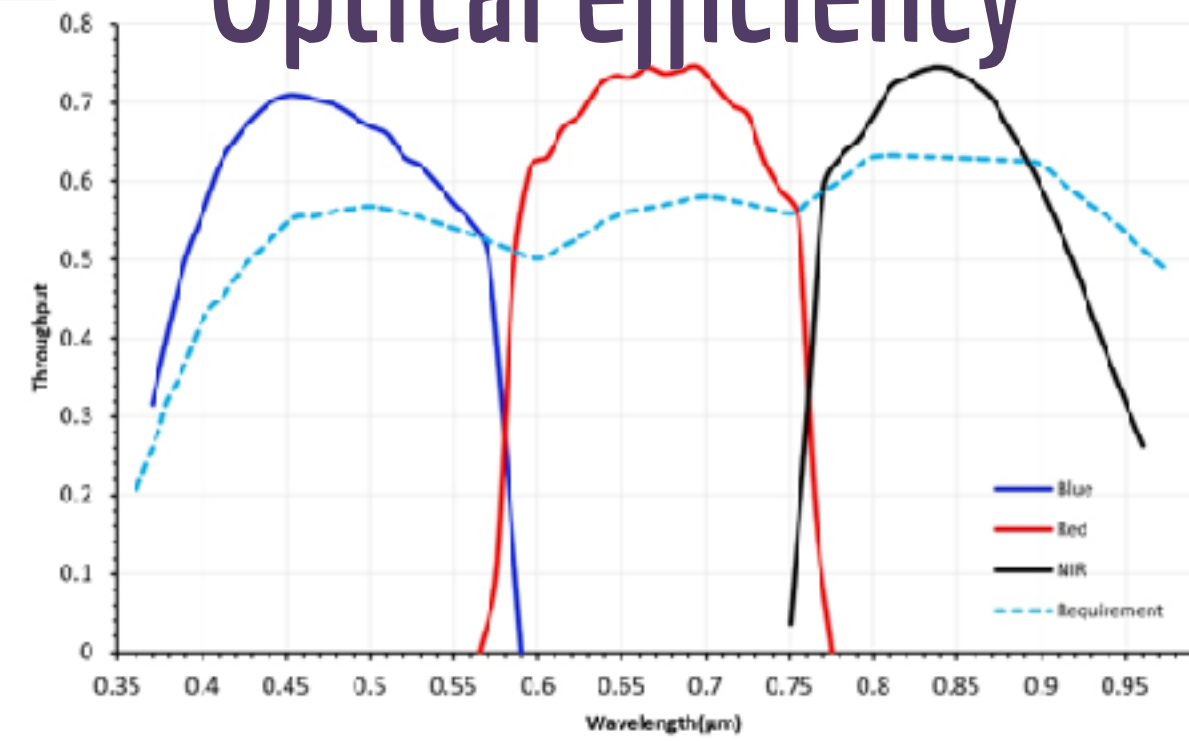


Figure 31 End-to-End throughput of the spectrograph system.

Spectral resolution

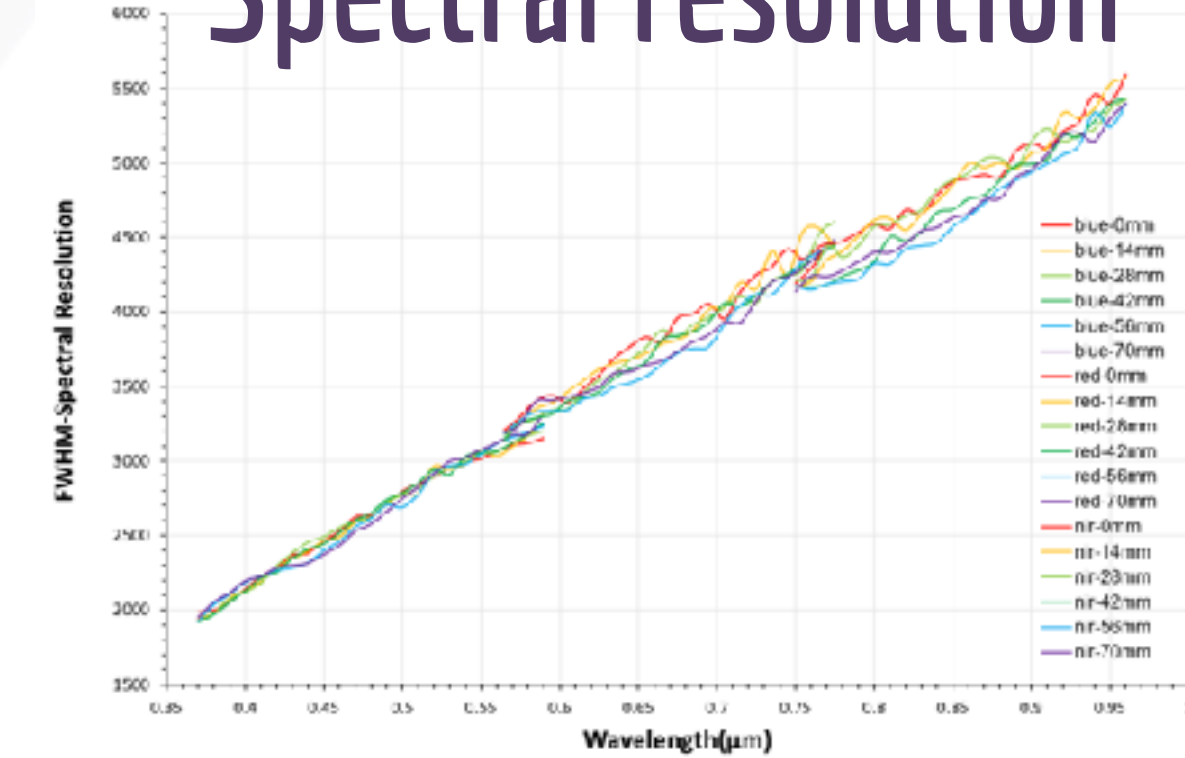
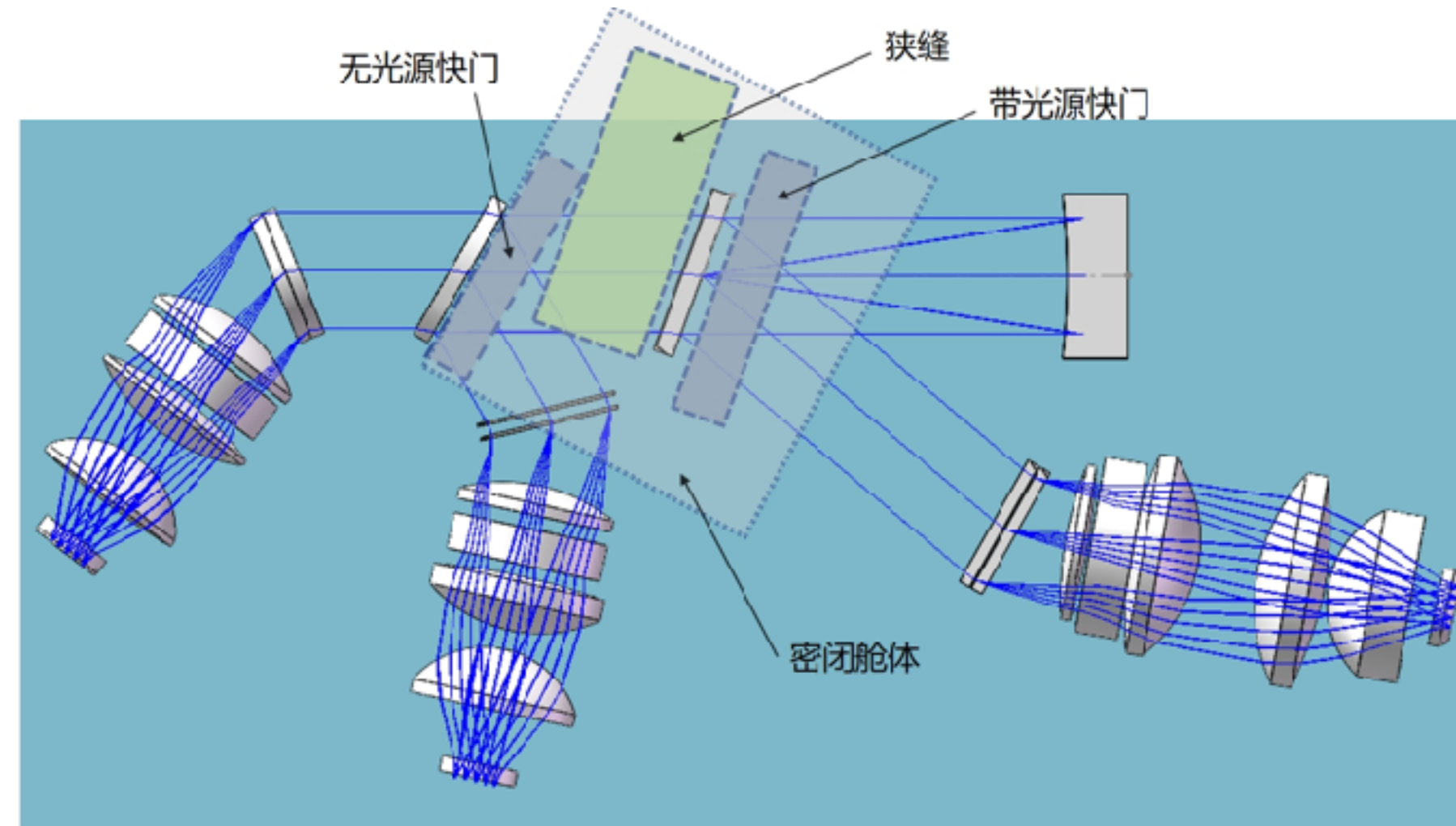


Figure 29 FWHM spectral resolution for the ideal system of different FOV.



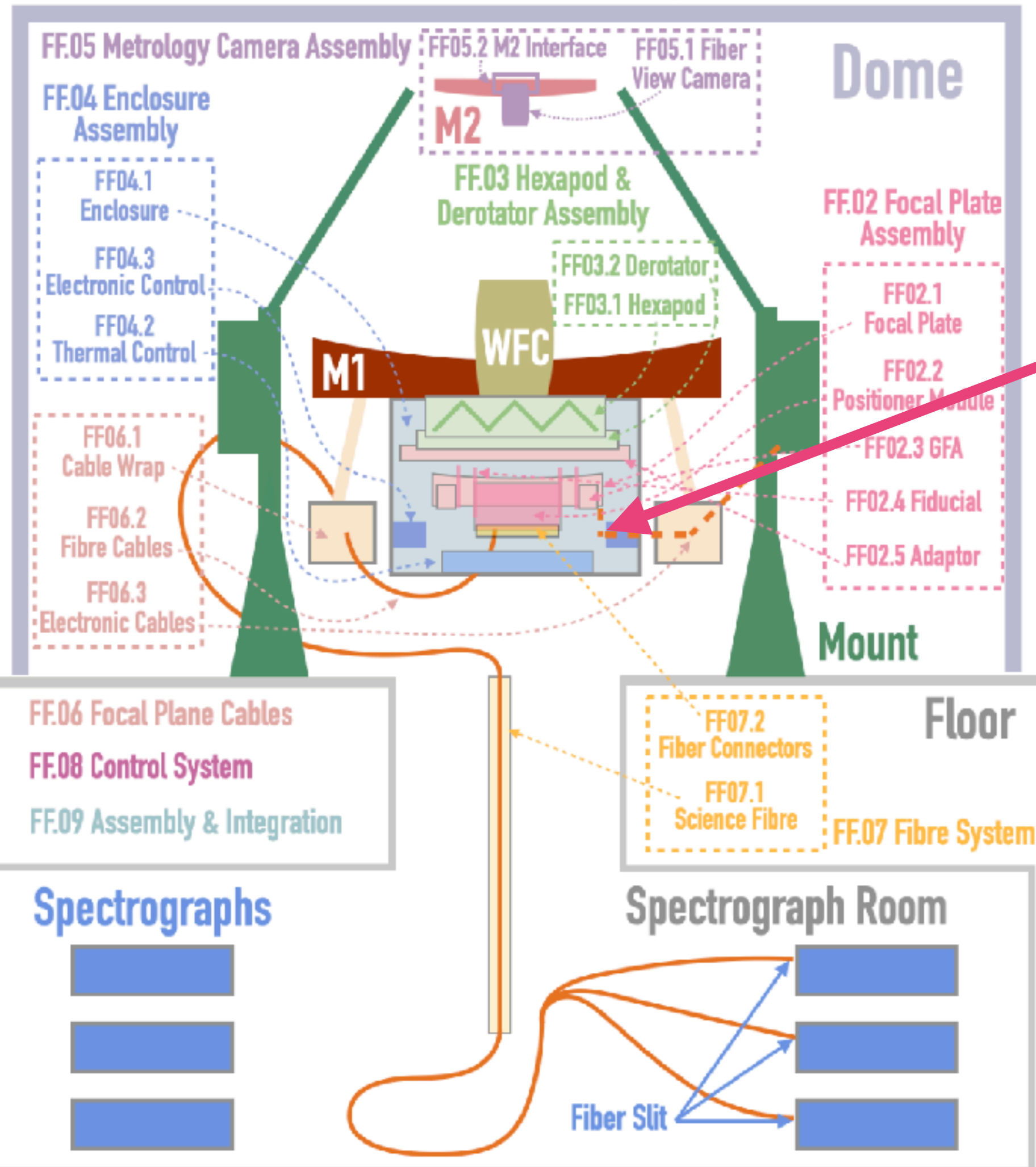
- **Detectors**
 - Purchased for 12 spectrographs.
- **Cryostats**
 - Identified potential collaborators in China; Bidding starts soon.
 - Using a state-of-the-art cryocooler.
- **Need Help:**
 - Fiber Slit; ATI; etc

Spectrograph

- Come up with an independent design; Finished the Conceptual Optical-Design Review

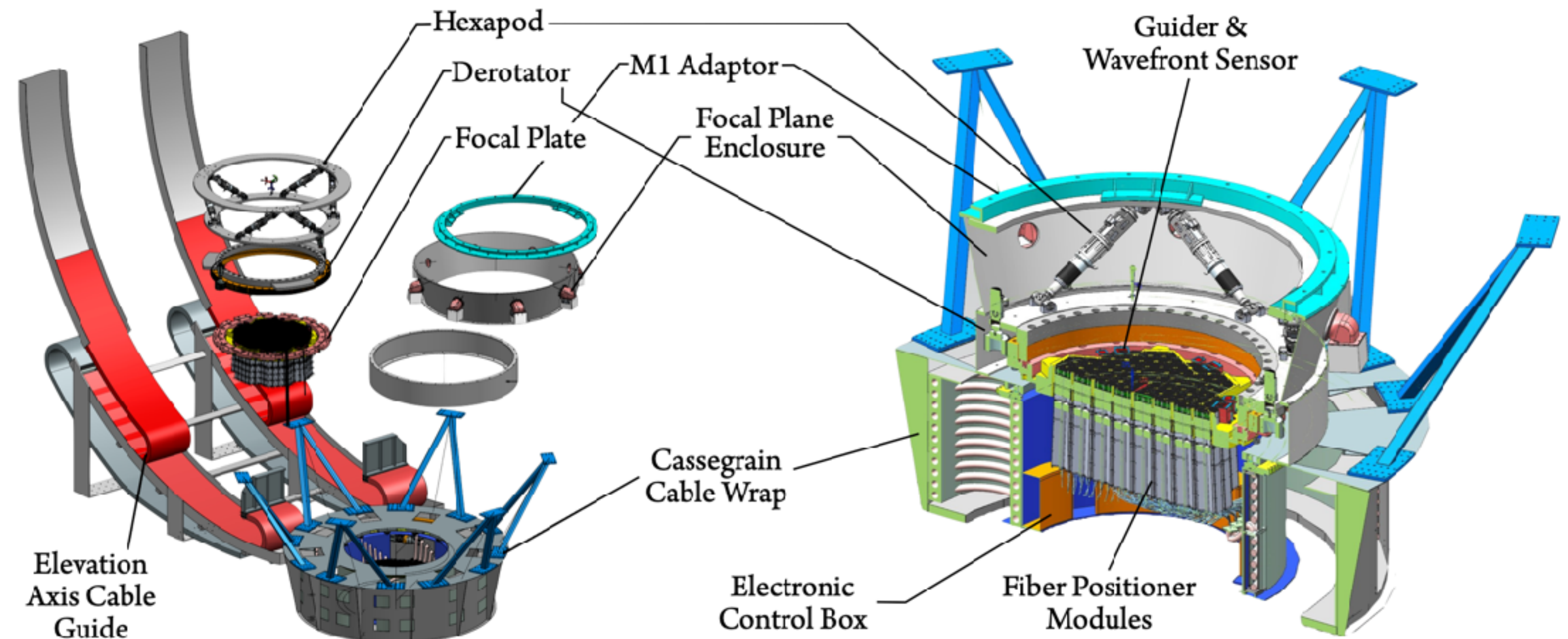
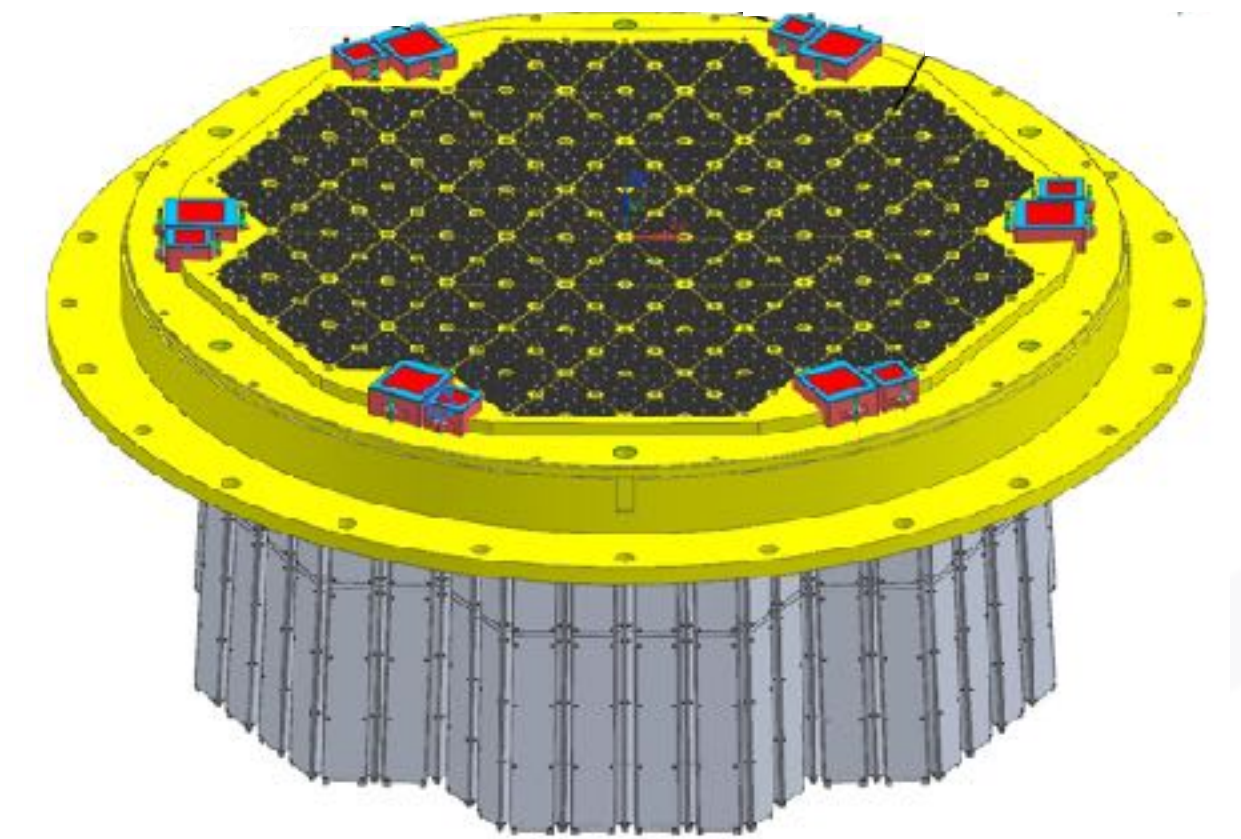
Project Progress

MUST Focal Plane (FF) System Block Diagram NOT To Proportion



Starting from the **Telescope Interface** and the **Fiber Positioning Module**, we now have a conceptual design of the **Focal Plane System**

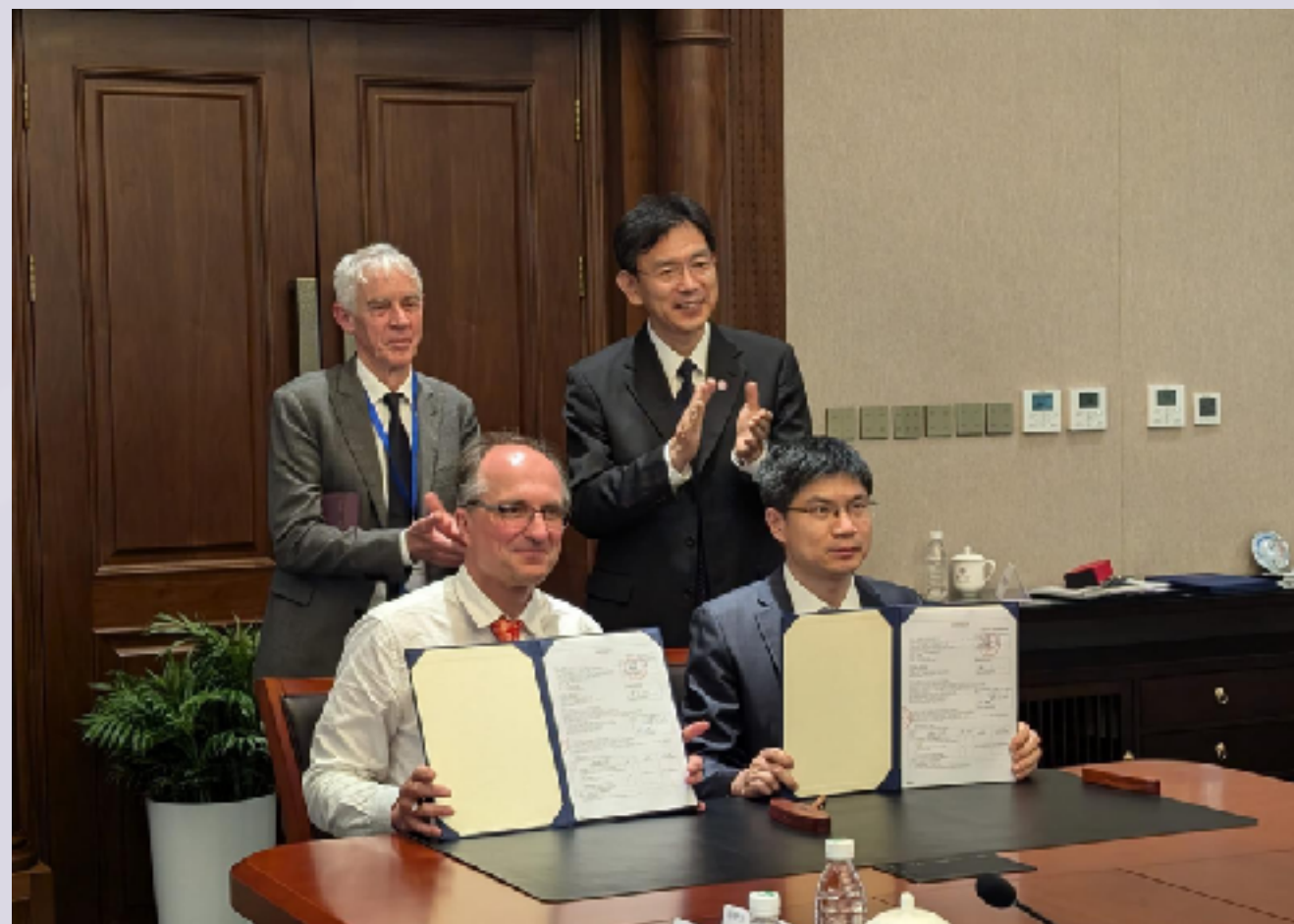
Focal system



Robotic Fiber Positioner

A FRUITFUL COLLABORATION

- We aim to build an international collaboration around **MUST**.
- We are thrilled with the scientific and technical collaborations with **EPFL**.



Credit: Jean-Paul Kneib/EPFL

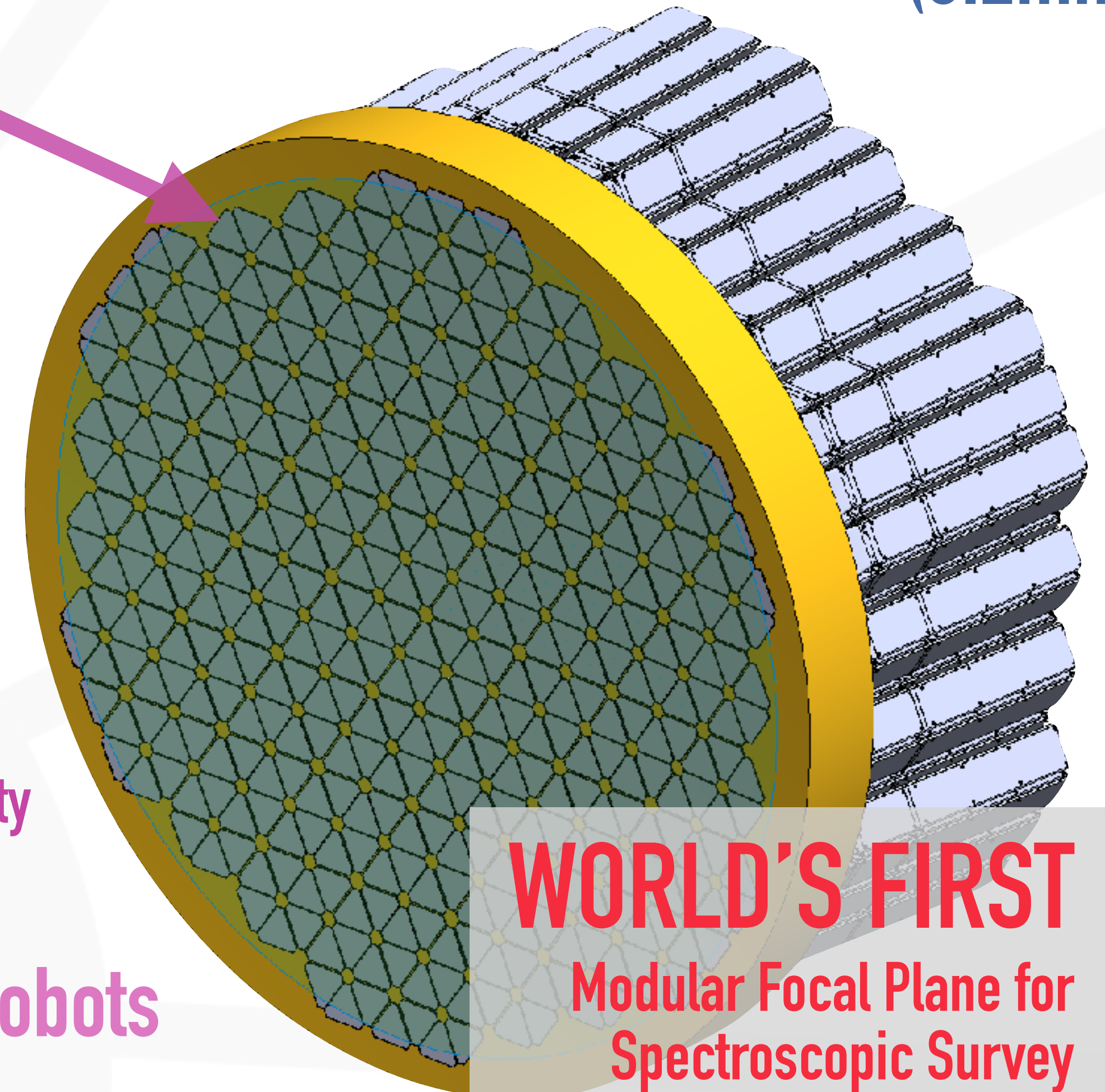
SMALLEST theta-phi fiber positioning robot

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

MOST POWERFUL
multi-fiber spectroscopic capability

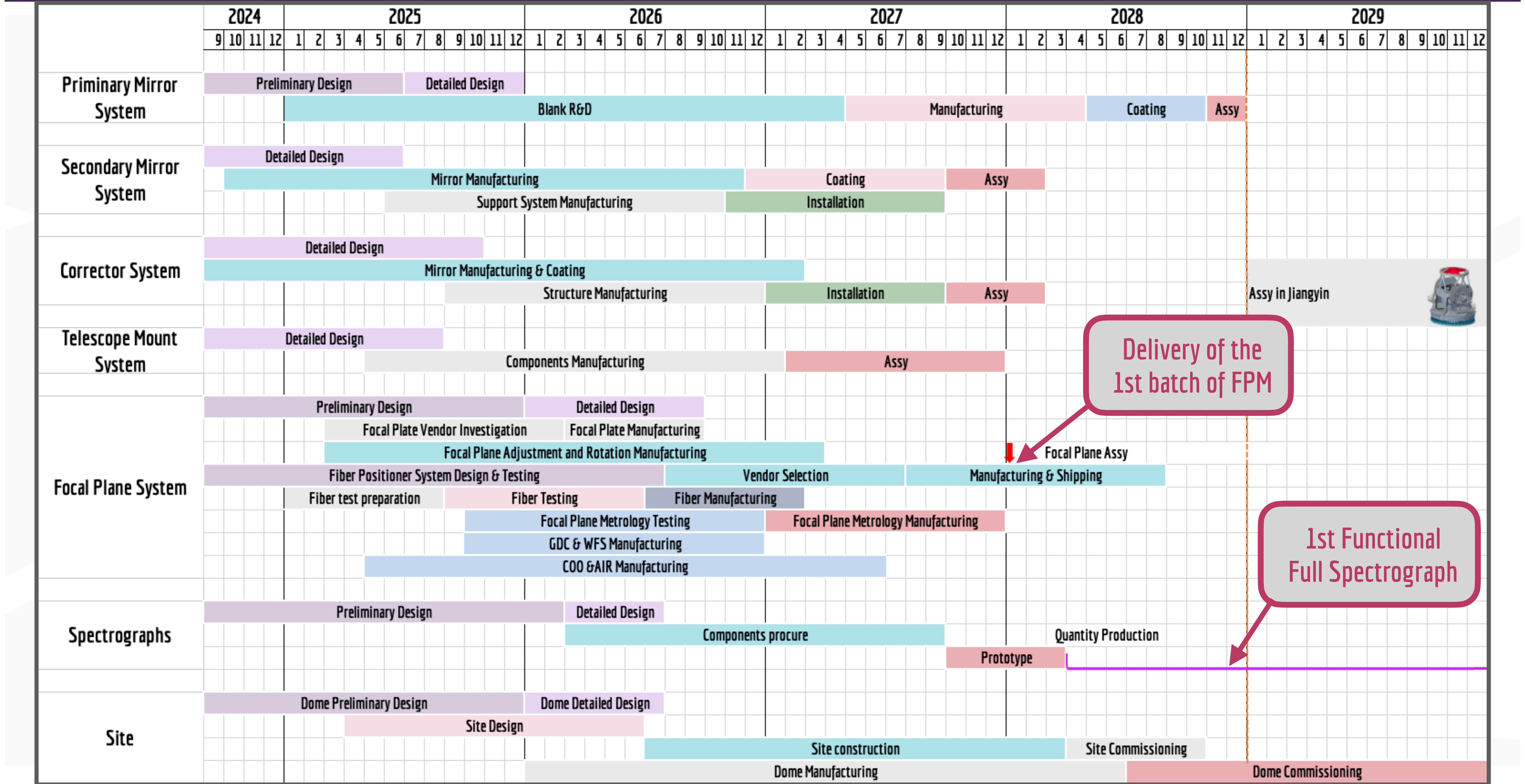
- Enabling high survey efficiency

>20,000 Robots



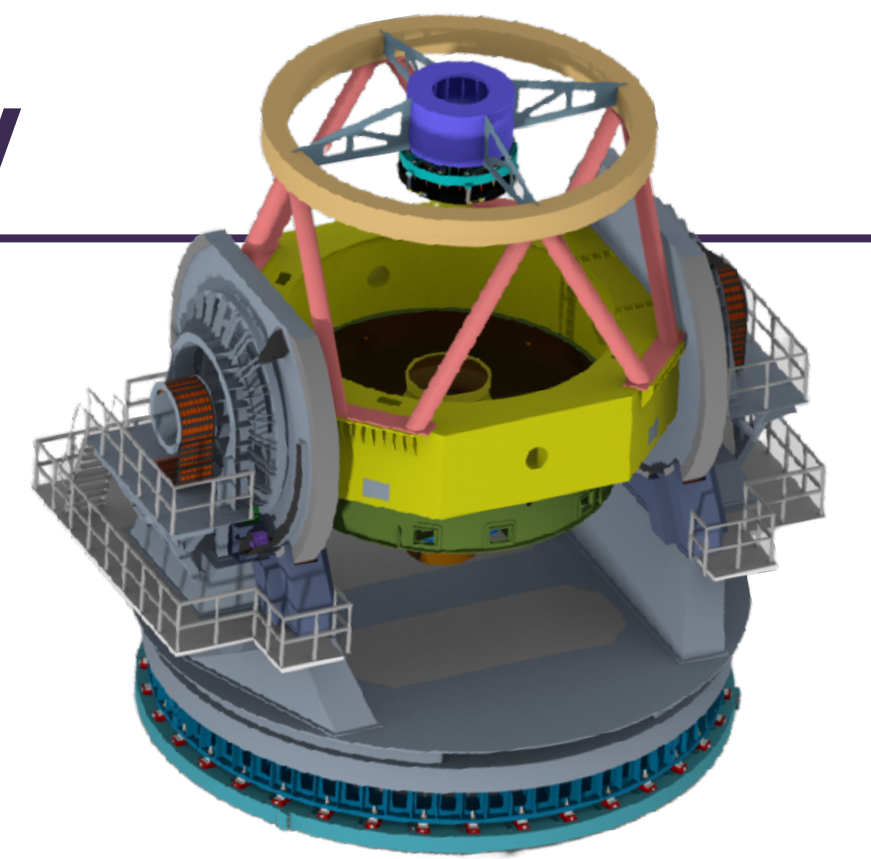
WORLD'S FIRST
Modular Focal Plane for
Spectroscopic Survey

MUST Project Timeline



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.

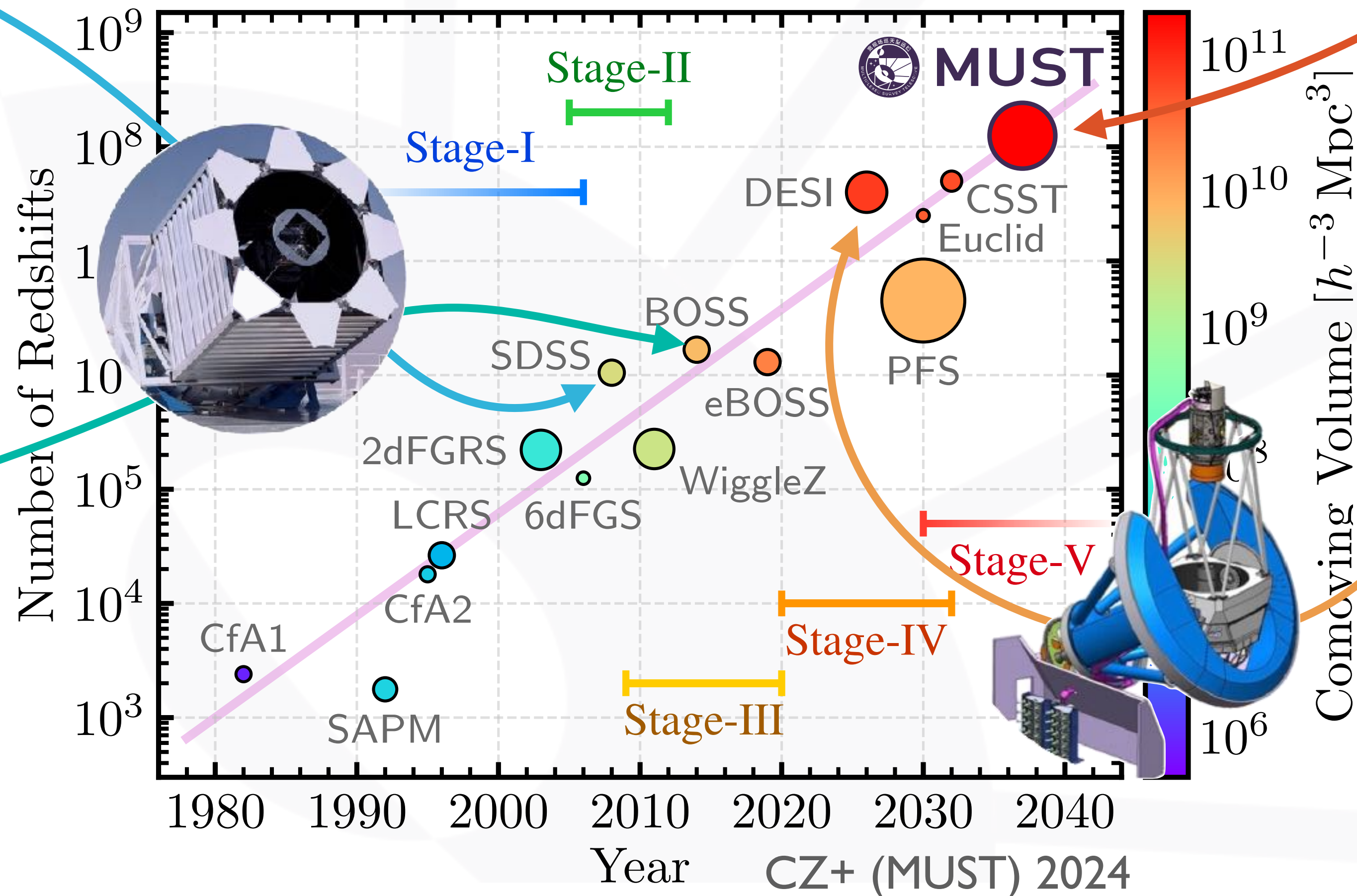


Stage I/II: SDSS

- 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

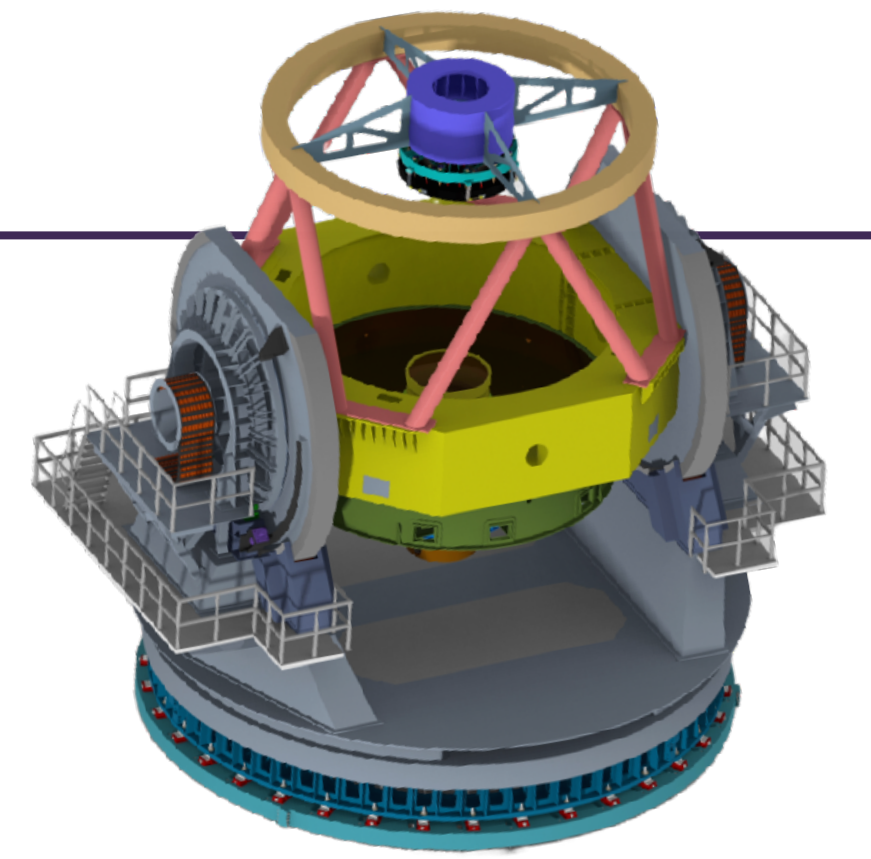
- Aperture: 6.5m
- Fibers: 20,000
- Focal Plane: Modular robots
- Duration: 2030–2040
- Spectra: over 200 million

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.



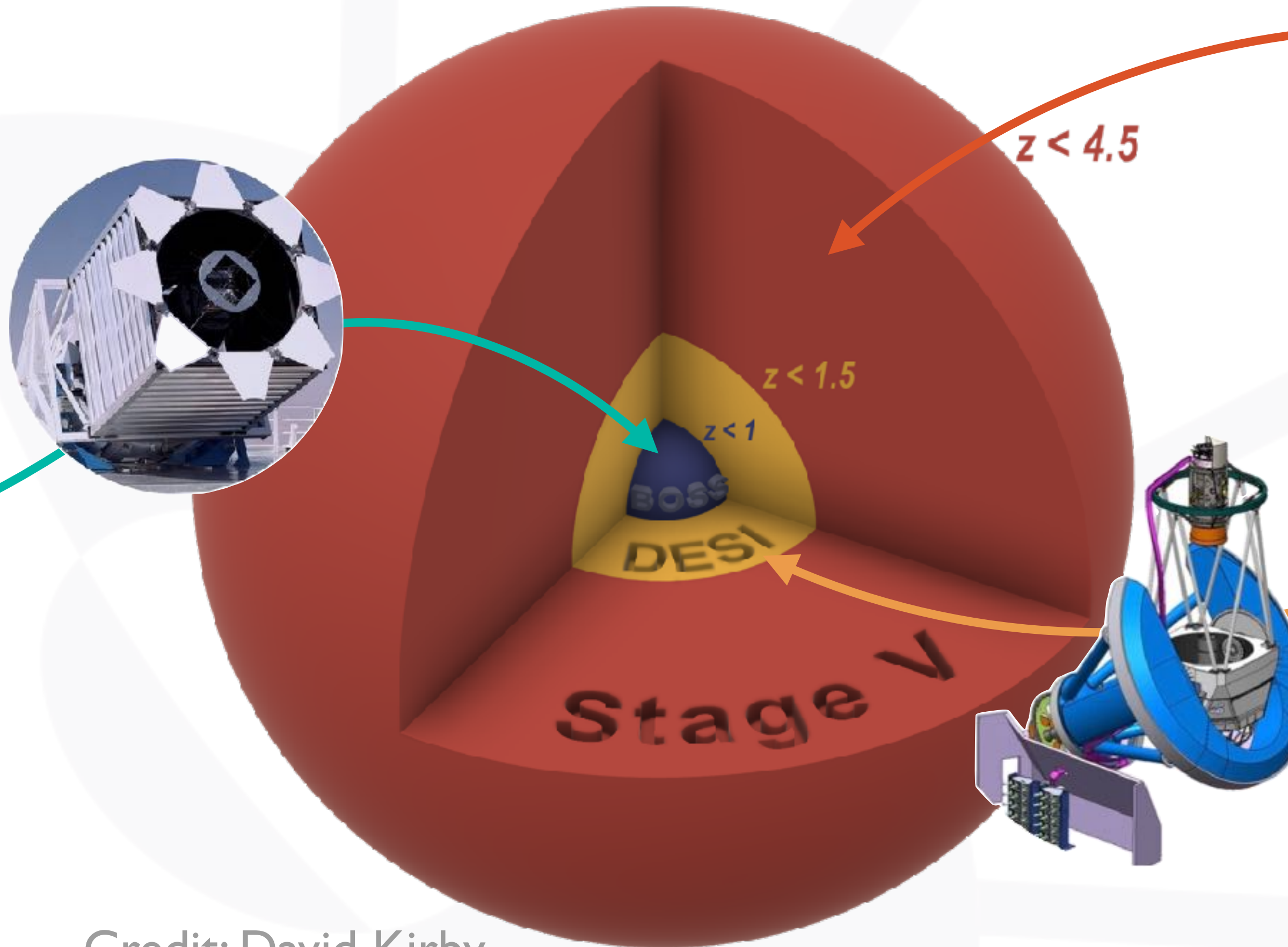
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- Fibers: 1000
- Focal Plane: Metal plate
- Duration: 2008–2019
- Spectra: 2.5 million



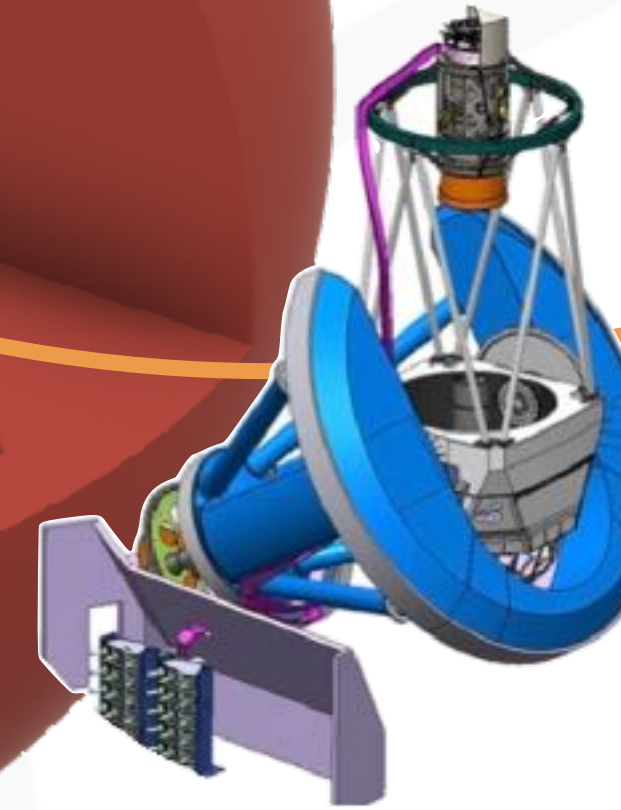
Credit: David Kirby

Stage V: MUST

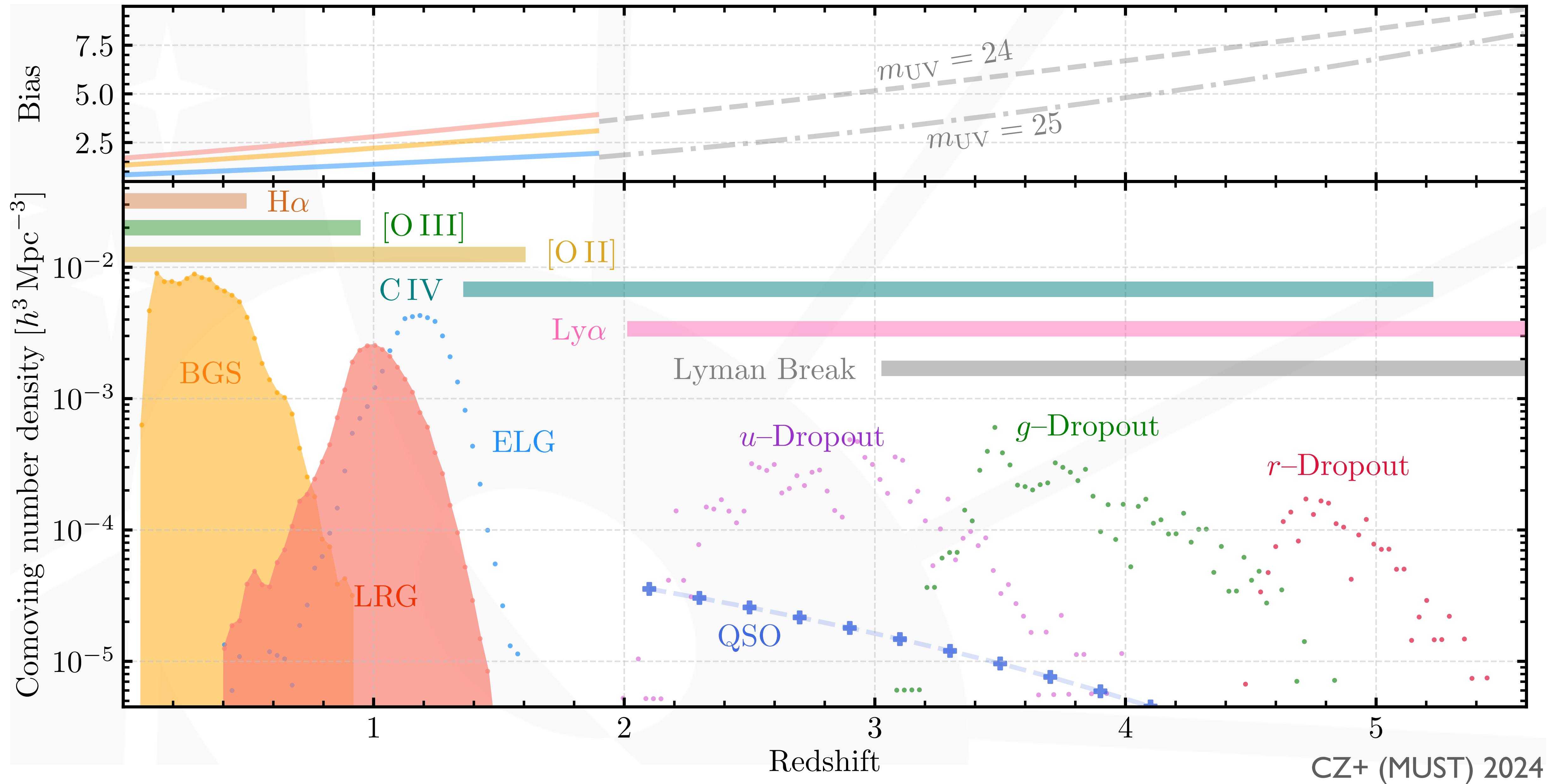
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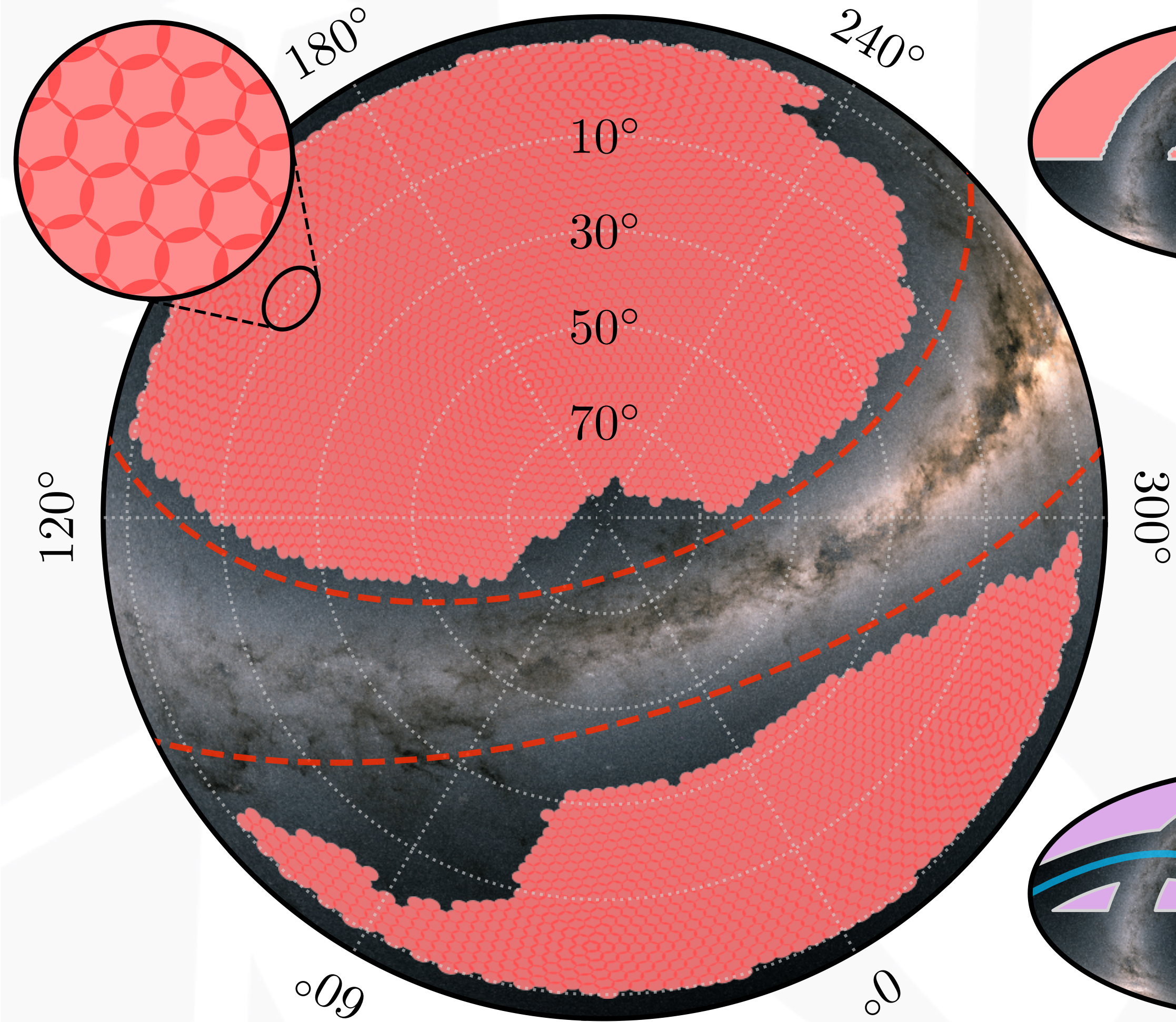
Target Selection



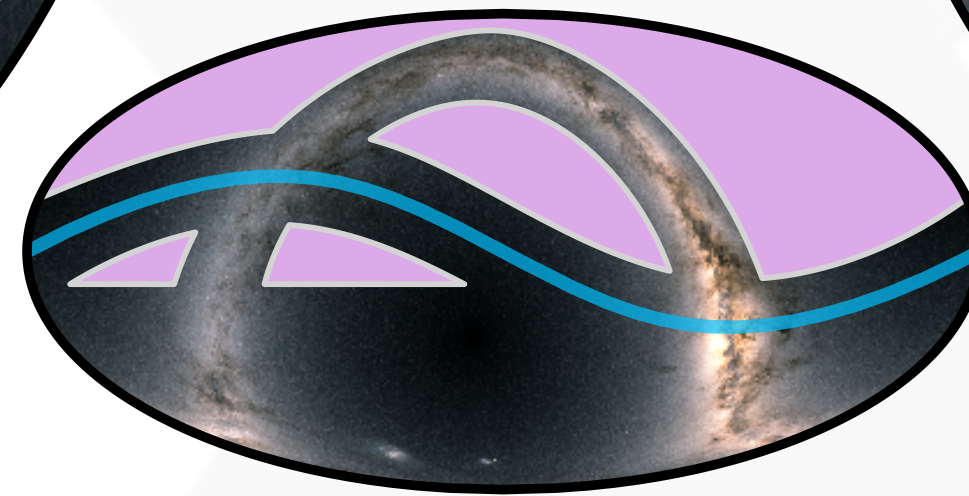
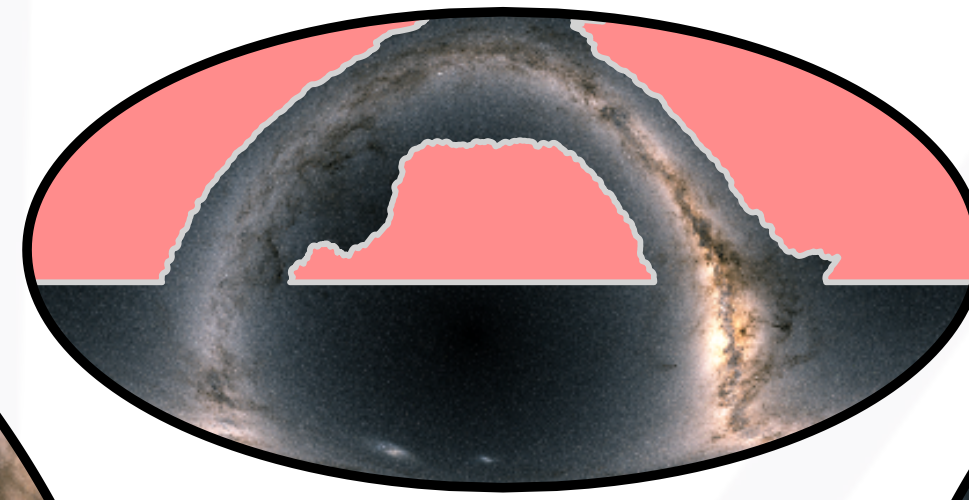
Survey Strategy



MUST GRAY TIME



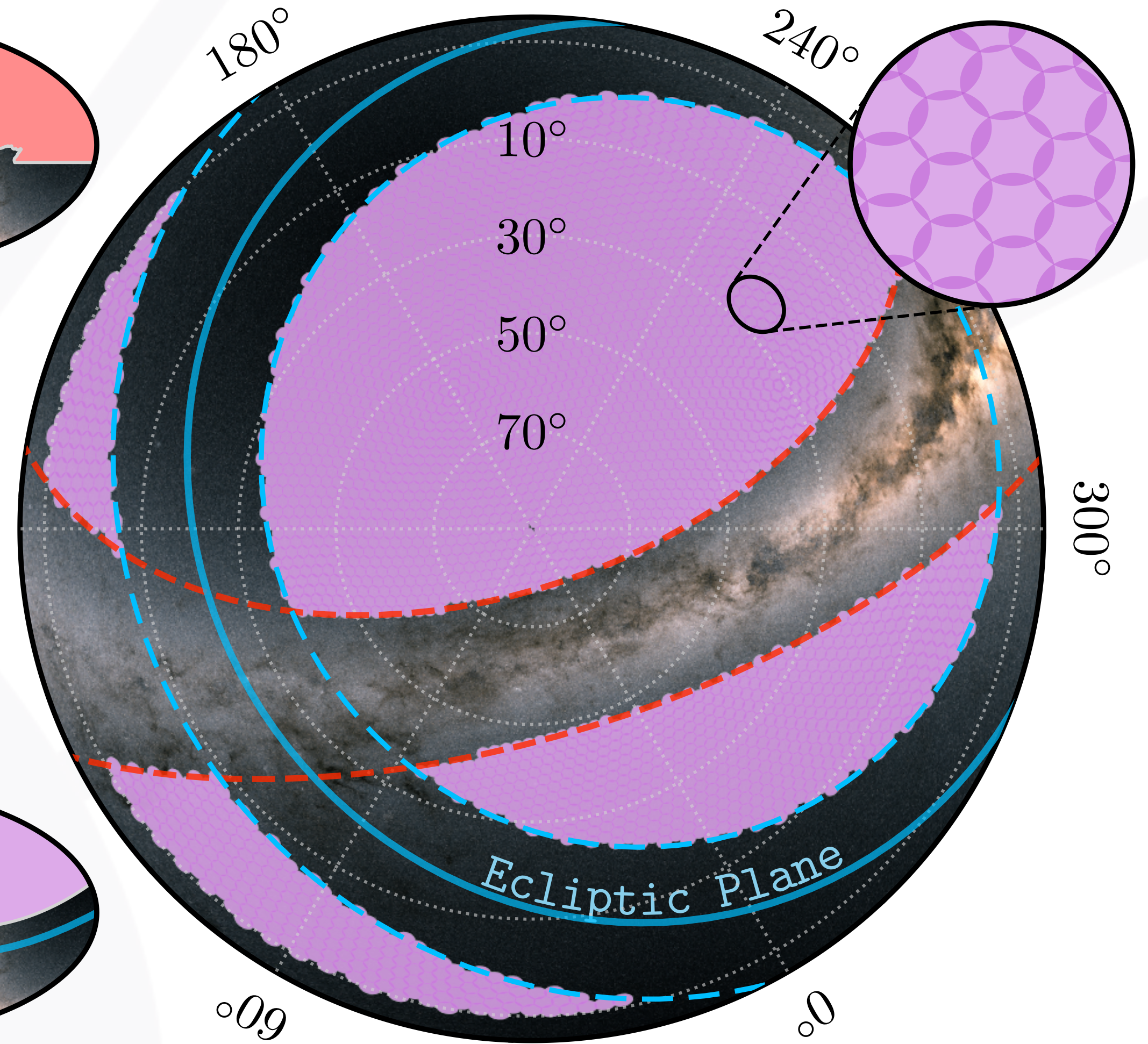
Right Ascension



CZ+ (MUST) 2024



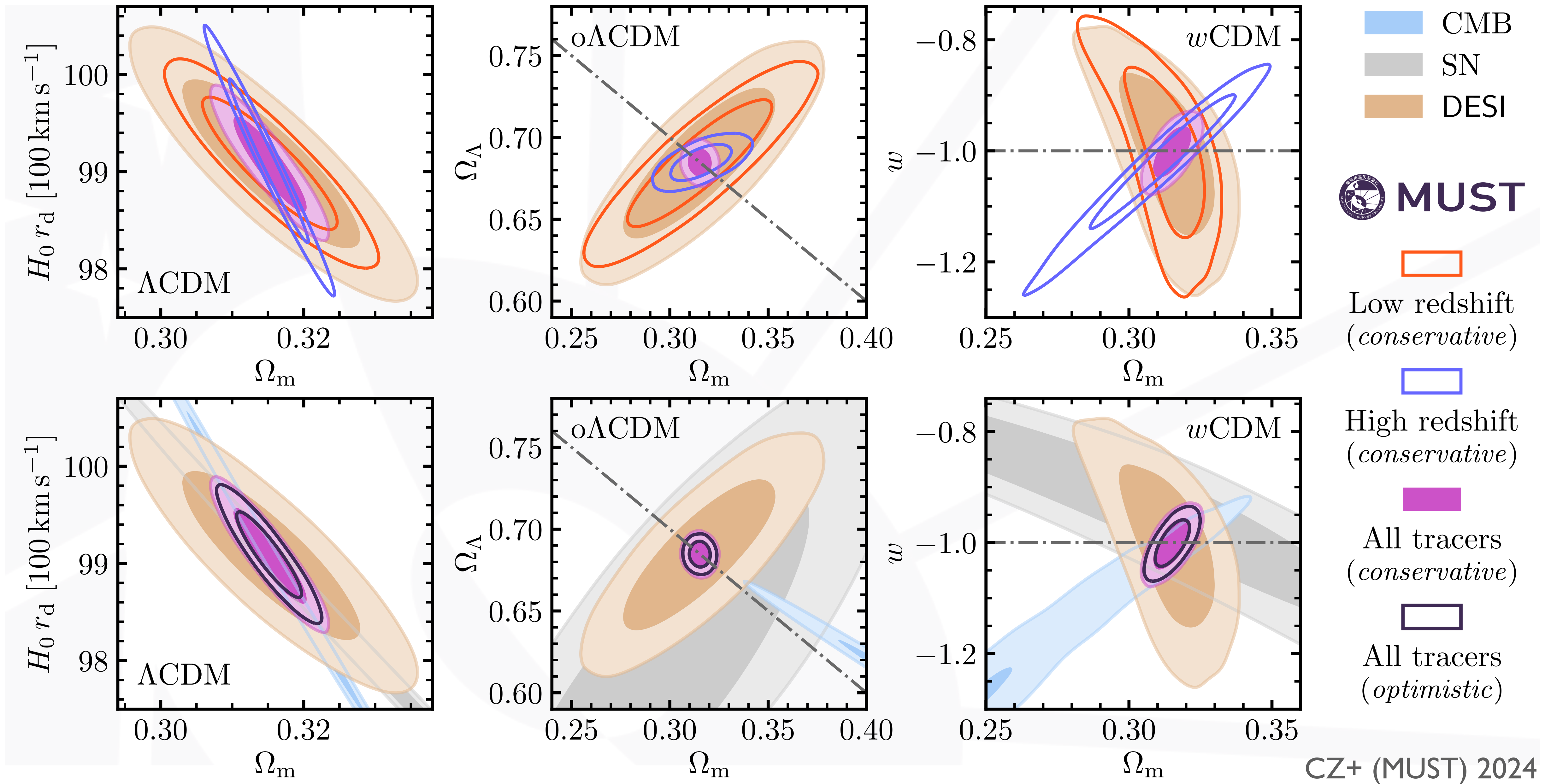
MUST DARK TIME



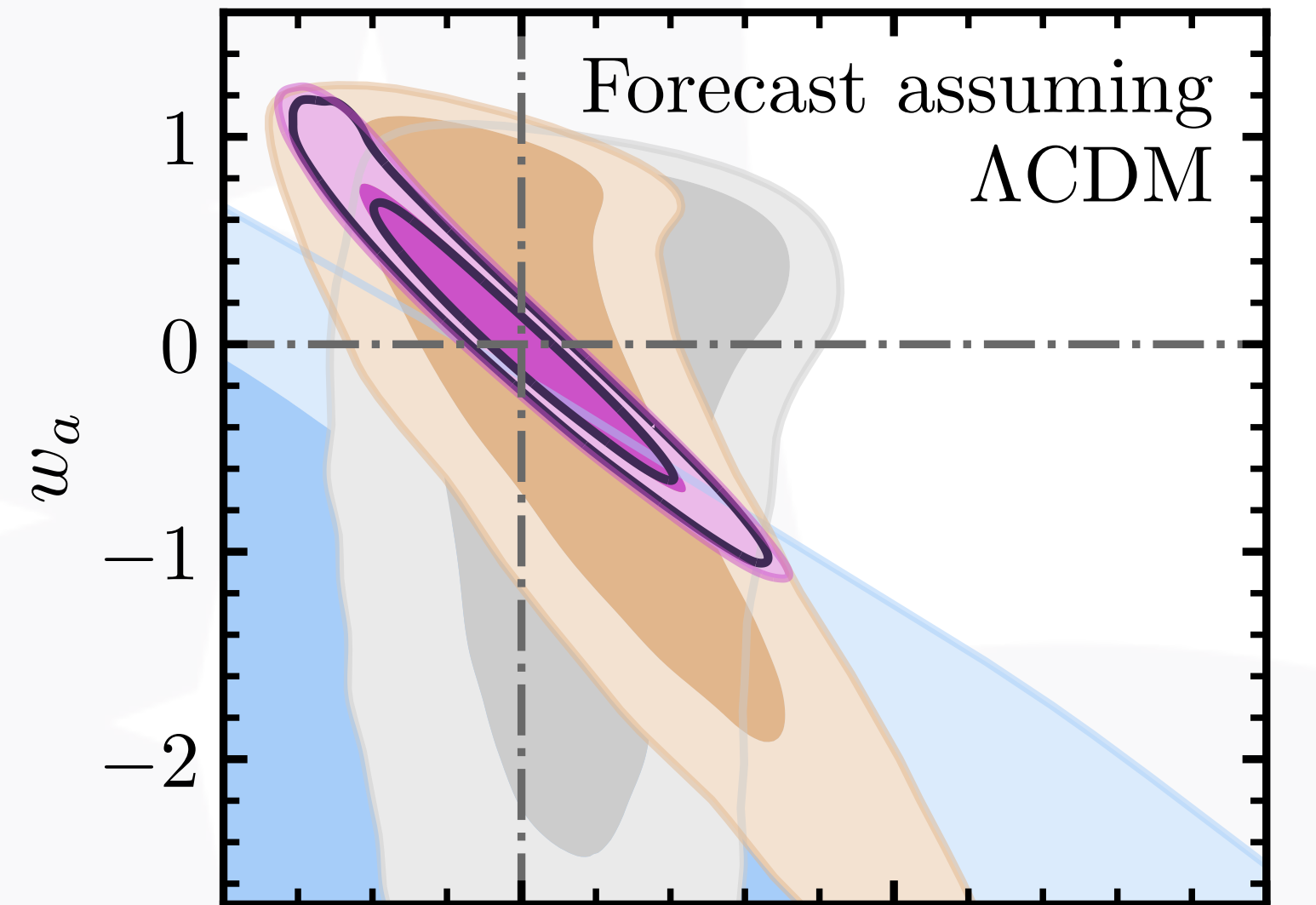
Right Ascension

Ecliptic Plane

Cosmological Forecasts: BAO

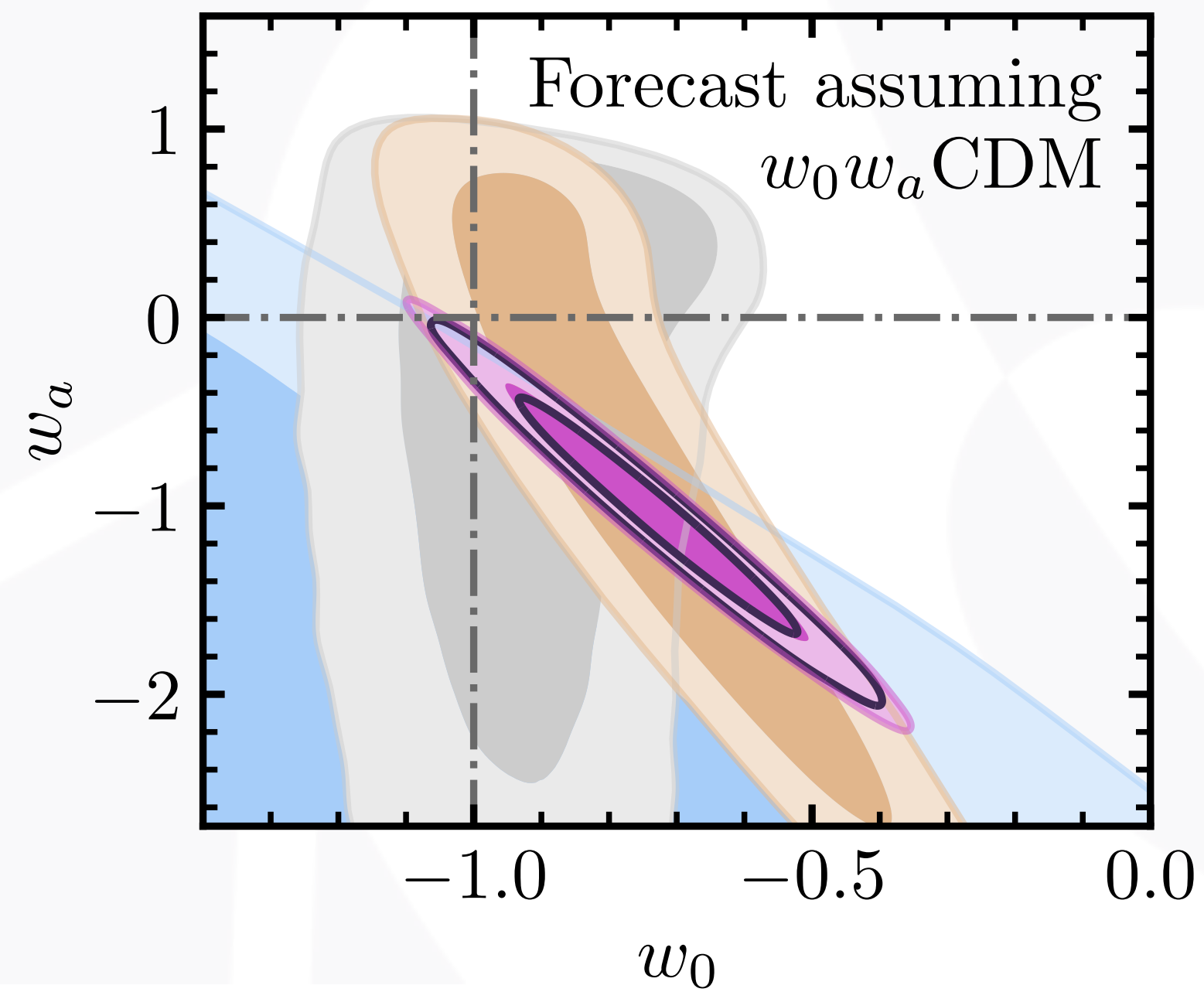


Cosmological Forecasts: DE & Modified Gravity



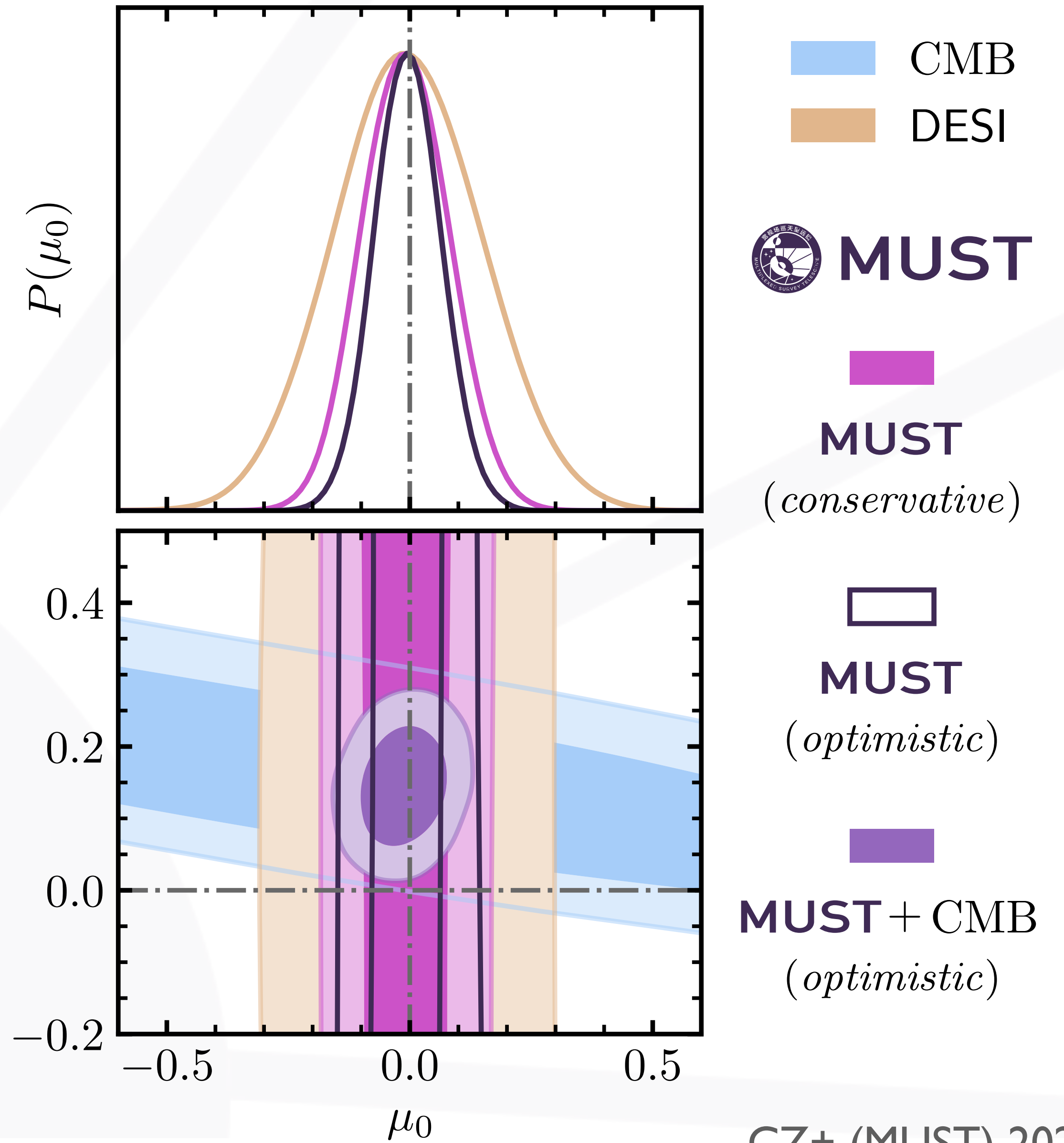
CMB
SN
DESI

MUST

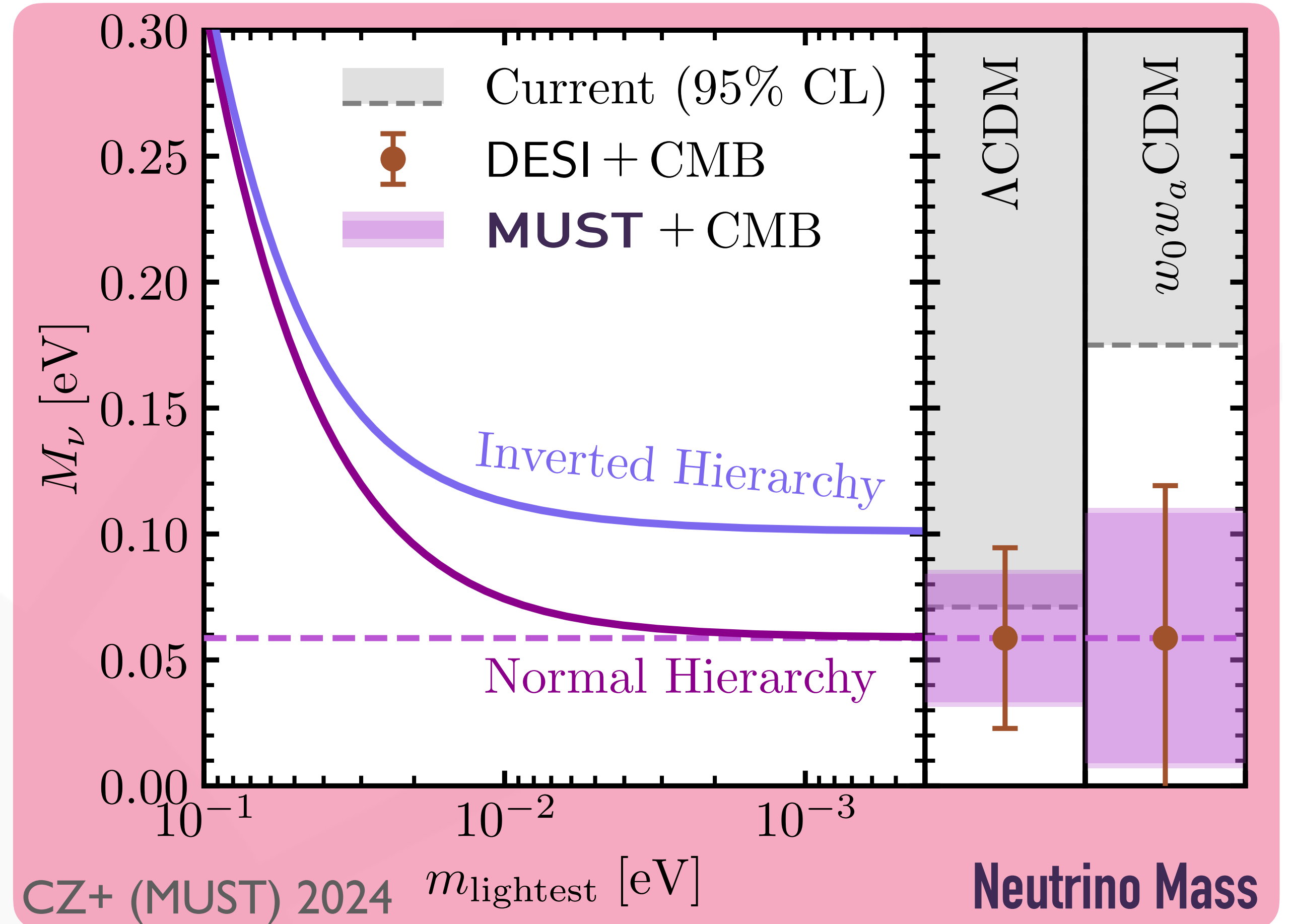
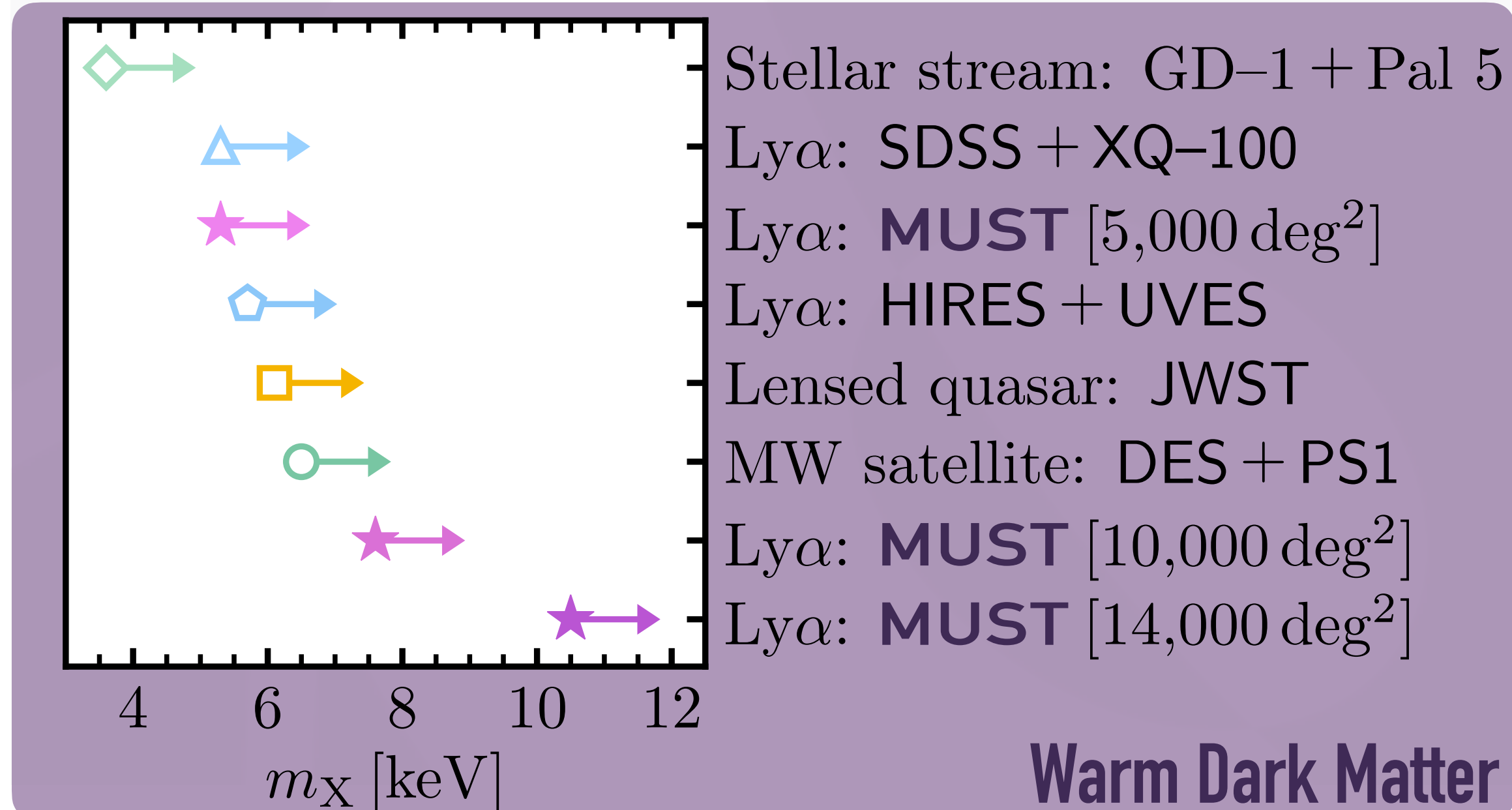
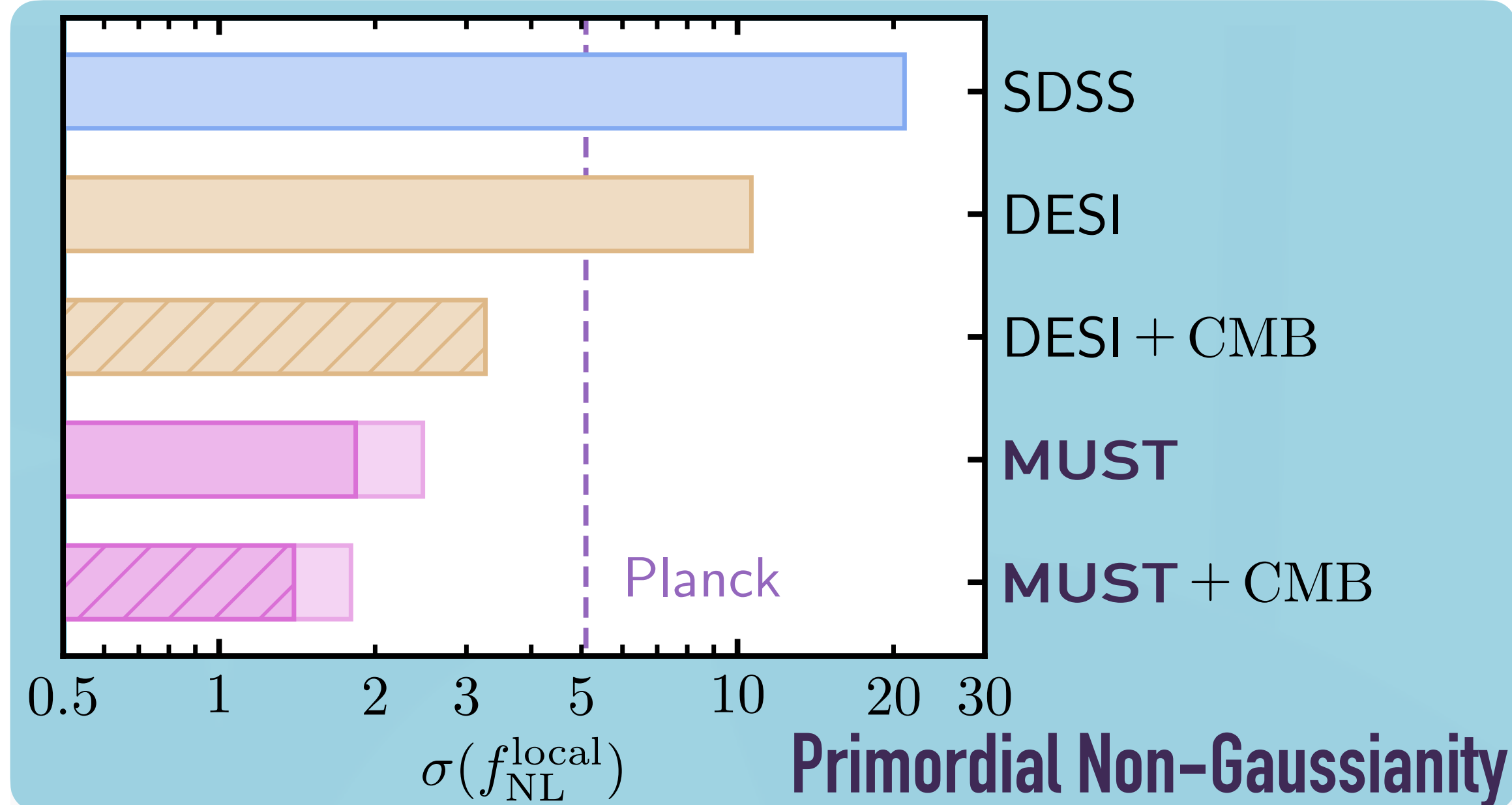


MUST
(conservative)

MUST
(optimistic)



Cosmological Forecasts



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

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!