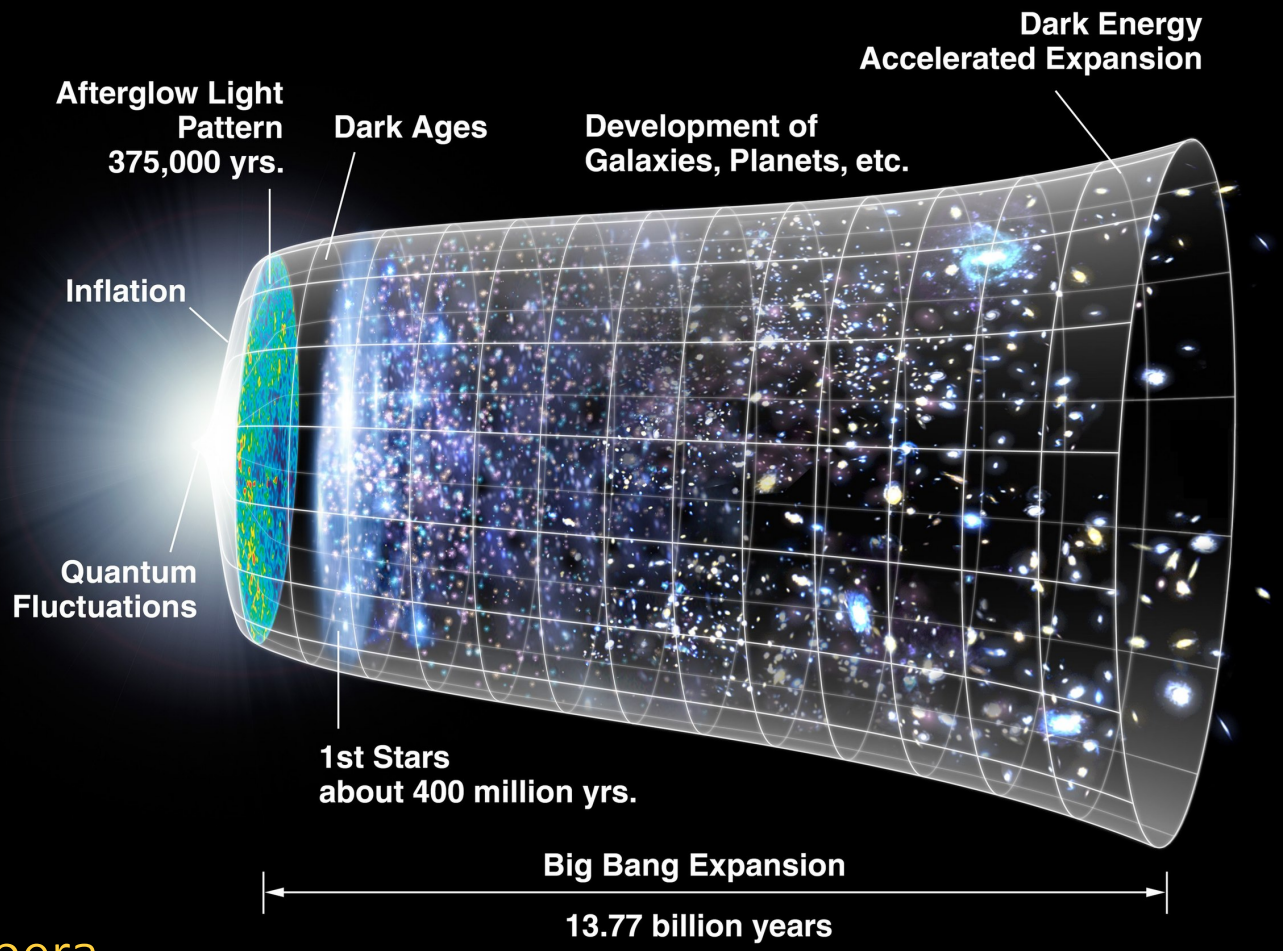
Observational Cosmology: Overview

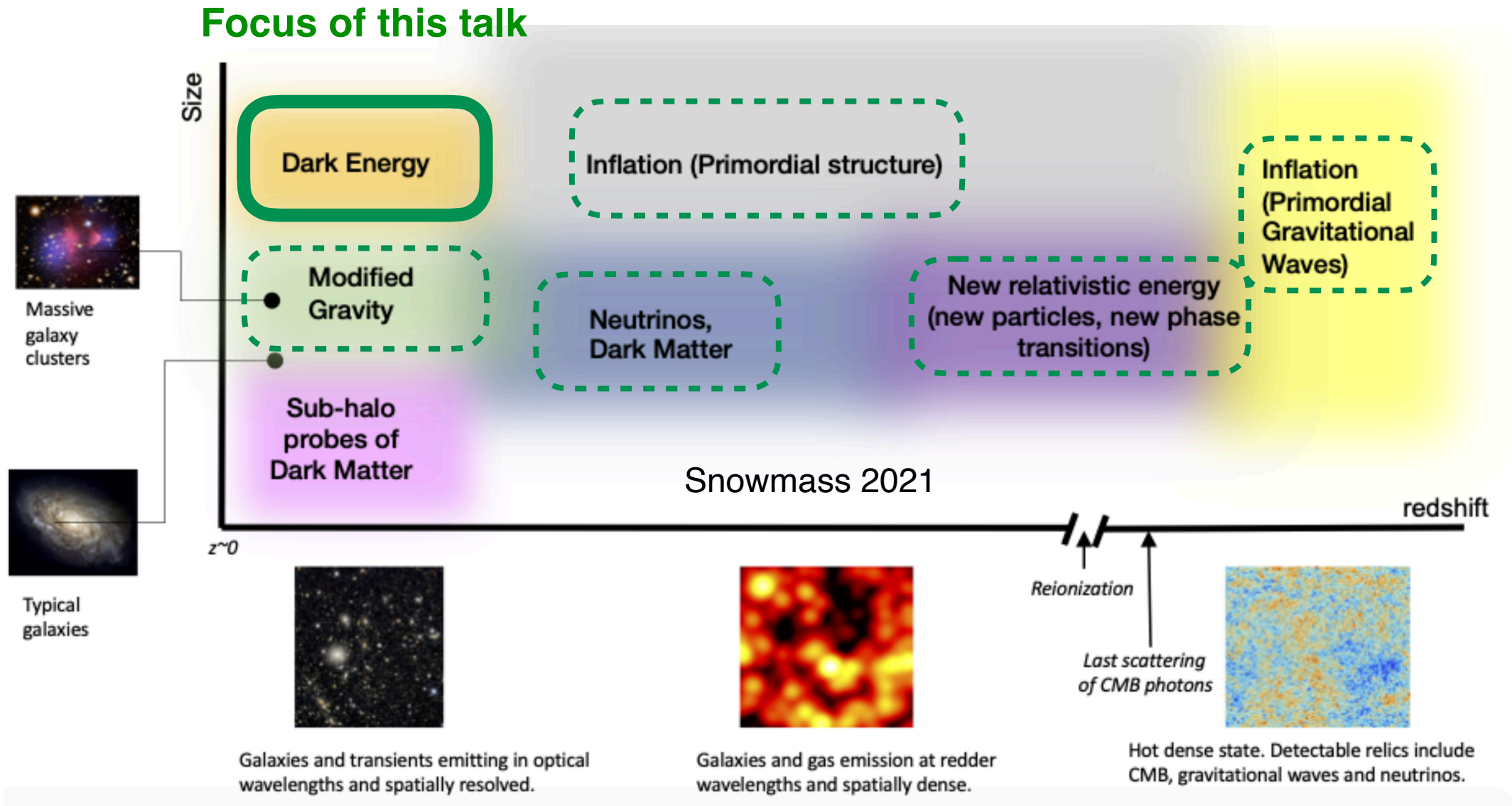


Andreu Font-Ribera
Institut de Física d'Altes Energies (IFAE, Barcelona)
CPAN and IMFP conferences, Santander, October 6th 2023

AGENCIA ESTATAL DE INVESTIGACIÓN

European Research Council

Why am I here?


Focus of this talk
Size
Dark Energy
Inflation (Primordial structure)
Inflation (Primordial Gravitational Waves)
Modified Gravity
Neutrinos, Dark Matter
New relativistic energy (new particles, new phase transitions)
Sub-halo probes of Dark Matter
Massive galaxy clusters
Typical galaxies
Snowmass 2021
redshift
z~0
Reionization
Last scattering of CMB photons
Galaxies and transients emitting in optical wavelengths and spatially resolved.
Galaxies and gas emission at redder wavelengths and spatially dense.
Hot dense state. Detectable relics include CMB, gravitational waves and neutrinos.

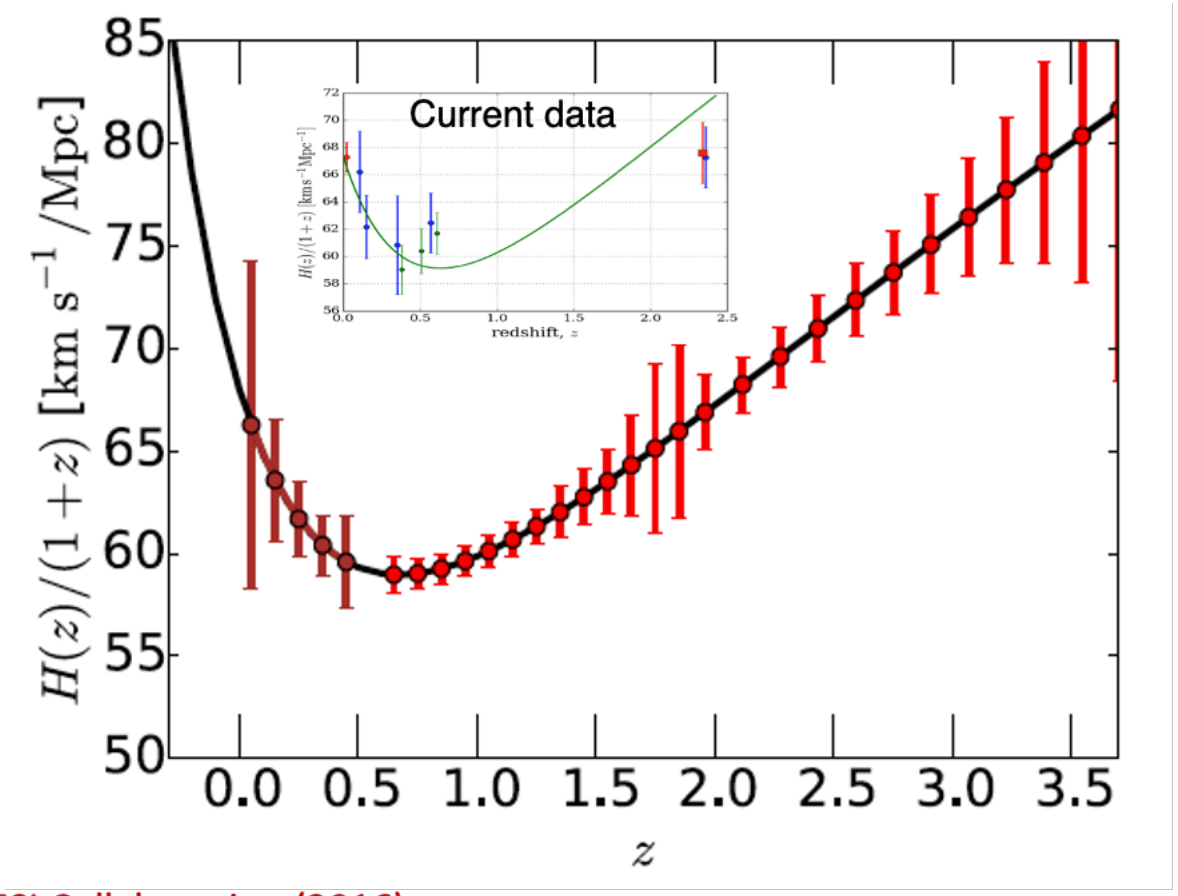
Overview

- Science goals: dark energy, modified gravity and massive neutrinos
- Cosmological probes and survey of surveys (CMB, SNe, galaxies)
- Cosmology with spectroscopic galaxy surveys
- The Dark Energy Spectroscopic Instrument (DESI)

Science Goals: Dark Energy

- The accelerated expansion of the Universe is now confirmed by independent cosmological probes
- Its cause is one of the biggest questions in physics, and a main science case for ongoing and future experiments
- The Dark Energy Spectroscopic Instrument (DESI) will measure the expansion history and constrain the equation of state of dark energy

$$w = p/\rho$$



arXiv:1611.00036 - DESI Collaboration (2016)

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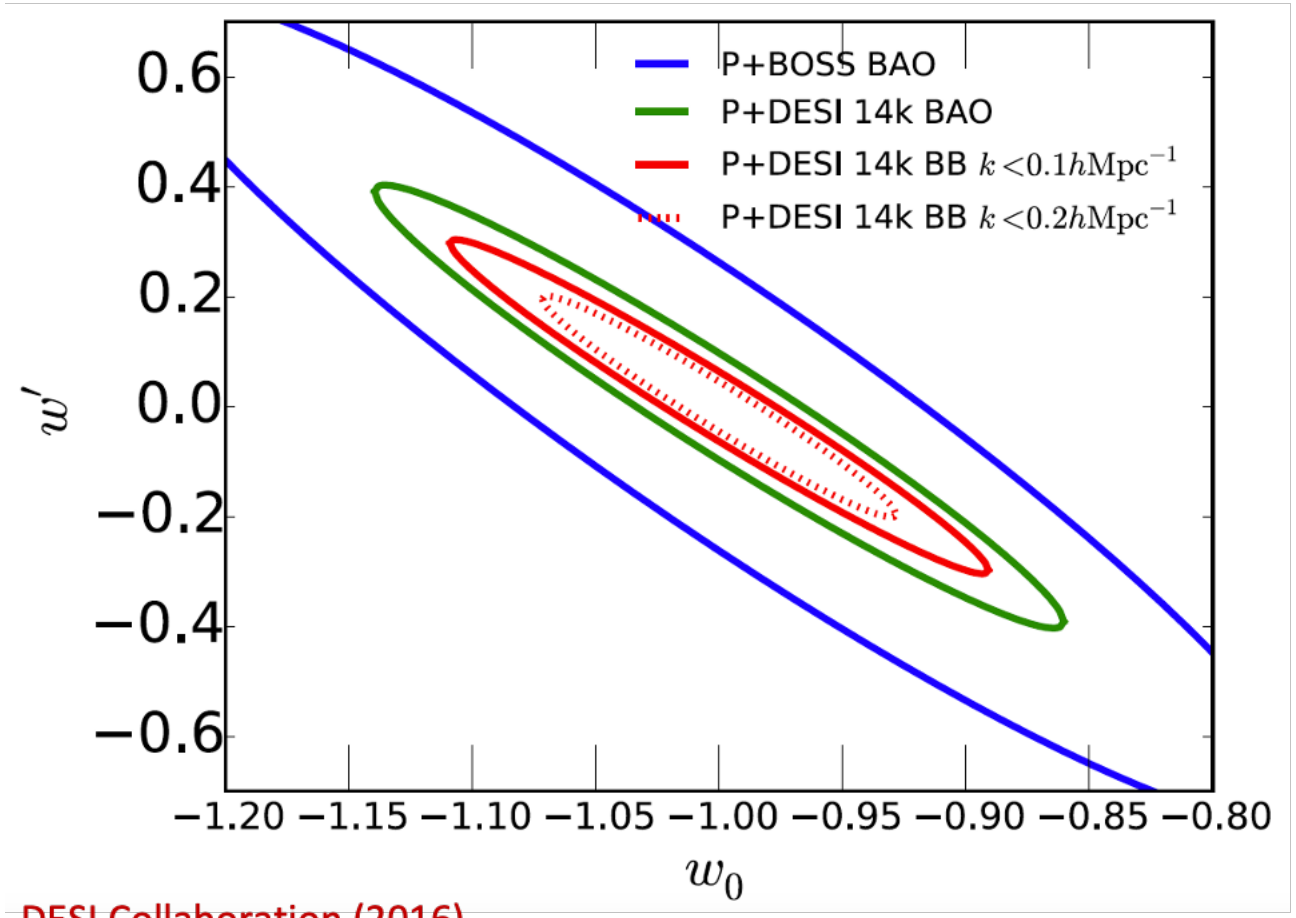
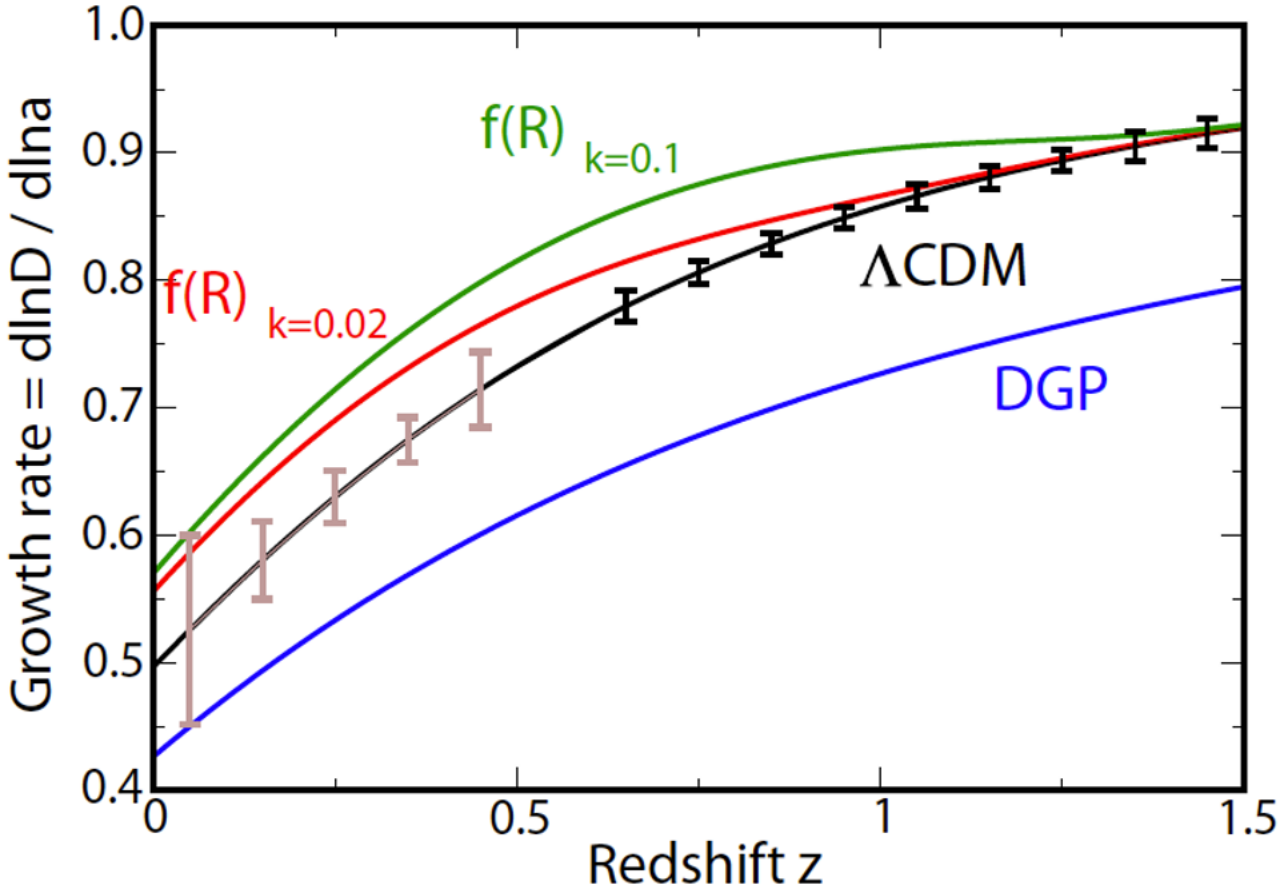


arXiv:1611.00036 - DESI Collaboration (2016)

Science Goals: Modified Gravity

- Modified gravity (MG) models can mimic the expansion of dark energy (DE) models
- One can distinguish between MG and DE by also measuring the growth of structure
- DESI will study the anisotropy in the distribution of galaxies to provide accurate measurements of the growth rate



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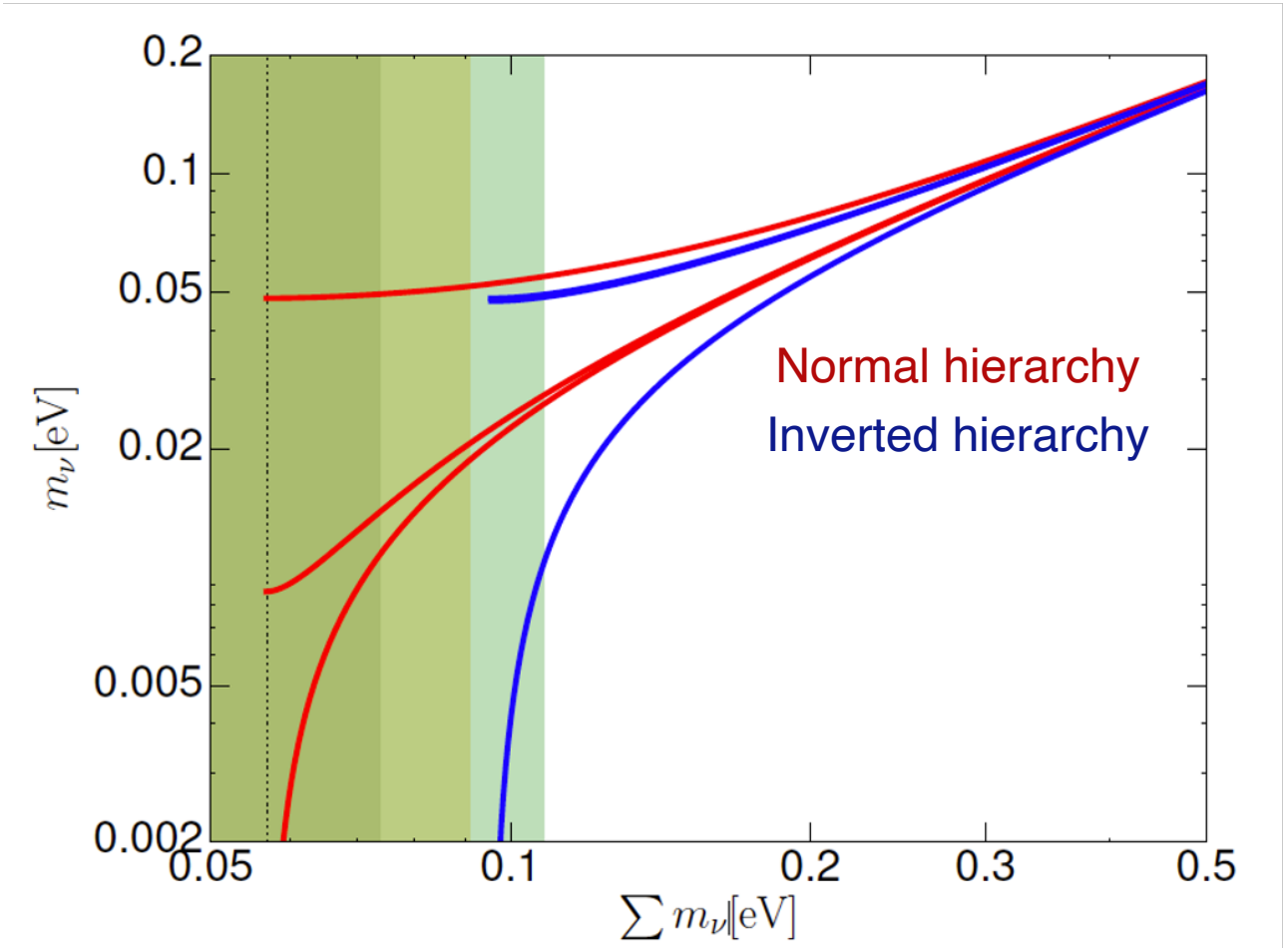
Science Goals: Massive Neutrinos

- Massive neutrinos leave an imprint in the distribution of matter, affecting both its expansion and growth
- In combination with Planck, DESI will be able to accurately measure the sum of the neutrino masses within 0.02 eV
- Depending on the true masses, we might be able to distinguish between the different neutrino hierarchies



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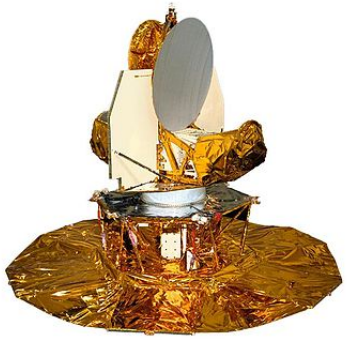
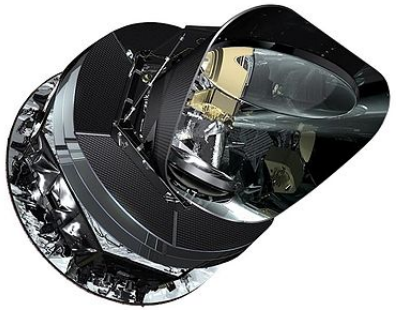
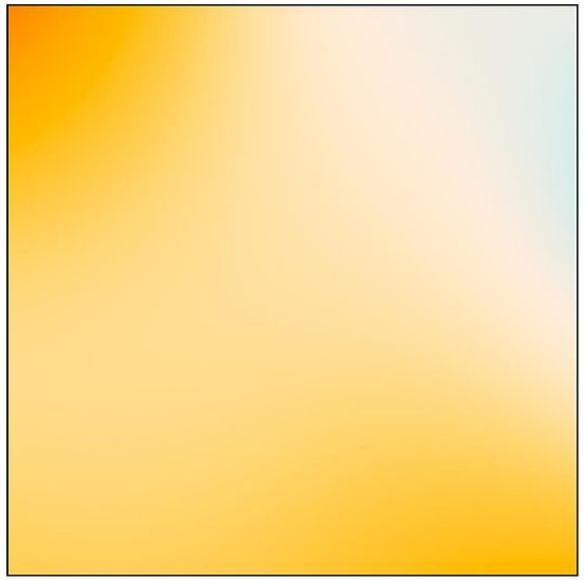
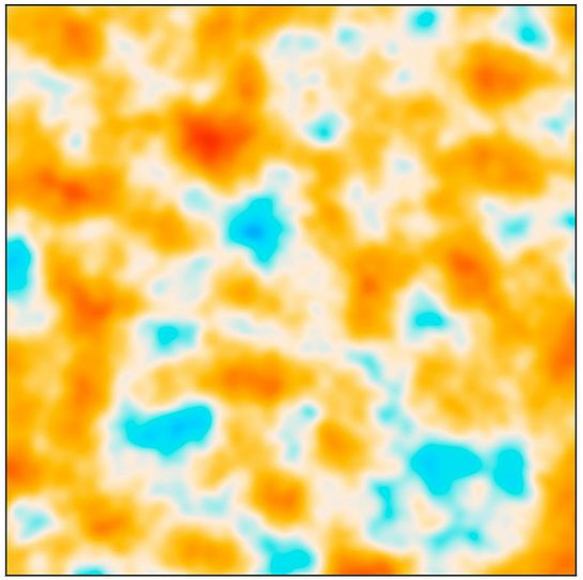
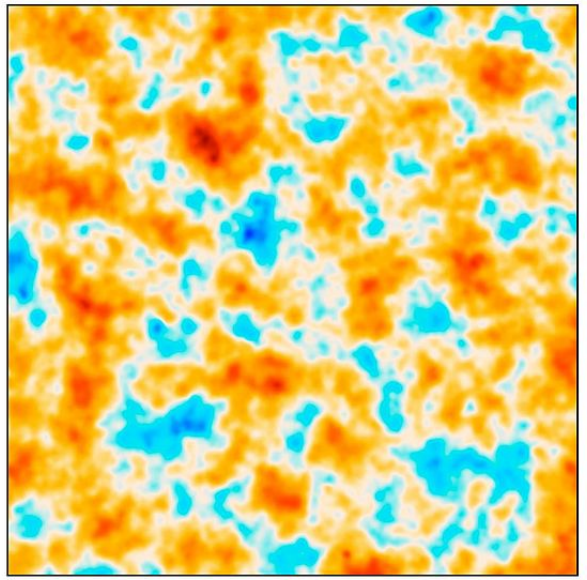
Cosmic Microwave Background (CMB): Present









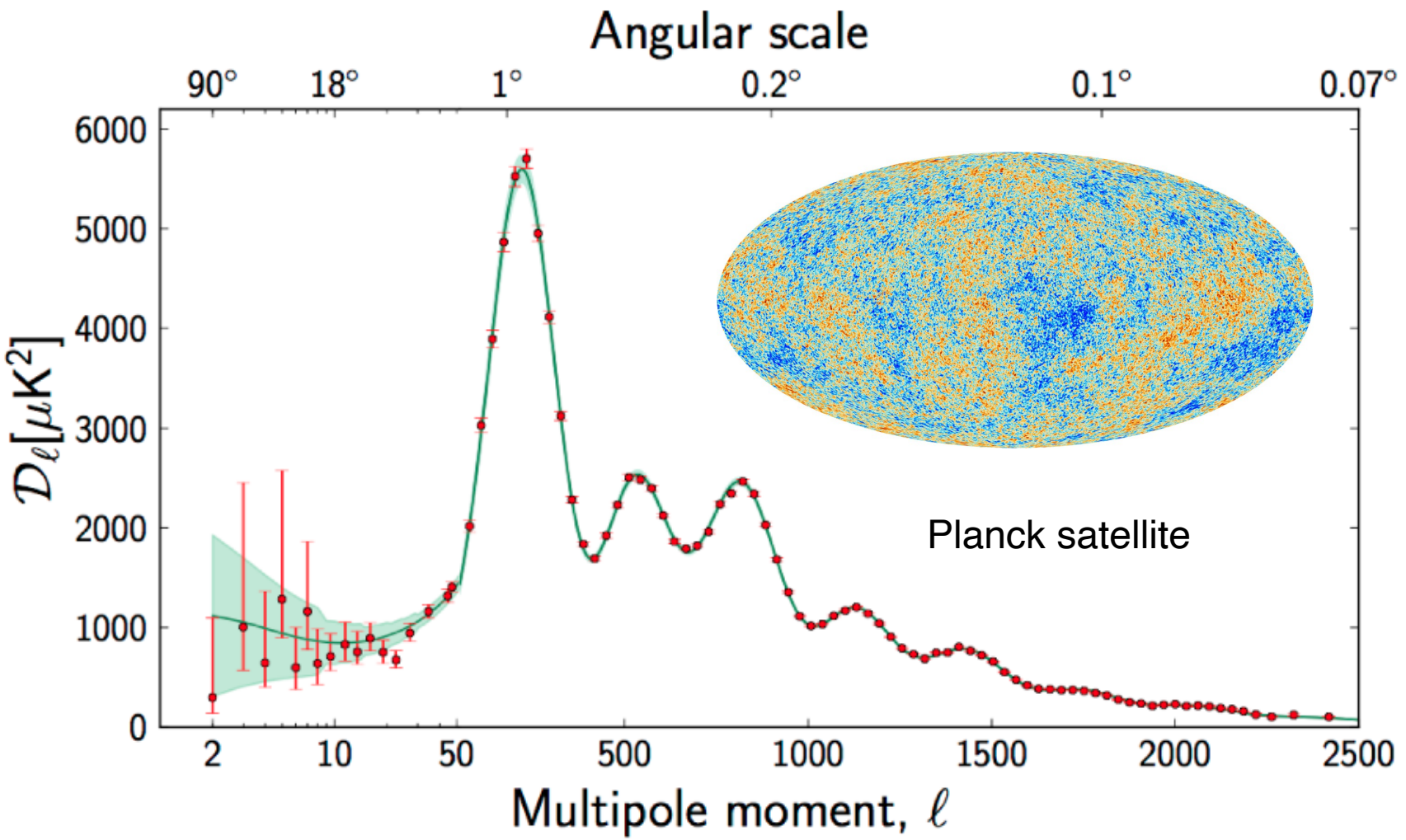


COBE (1989)

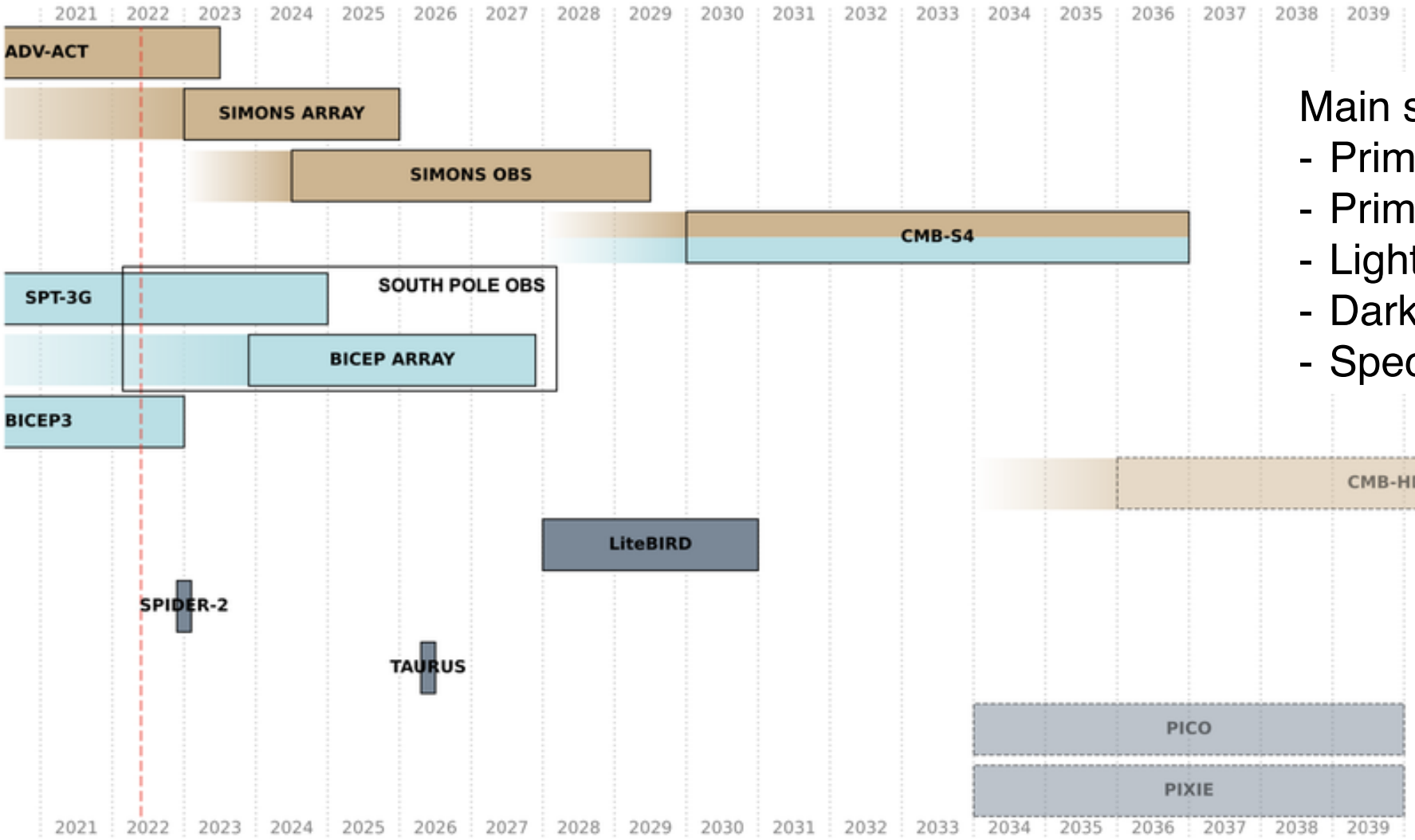
WMAP (2001)

Planck (2009)

Cosmic Microwave Background (CMB): Present



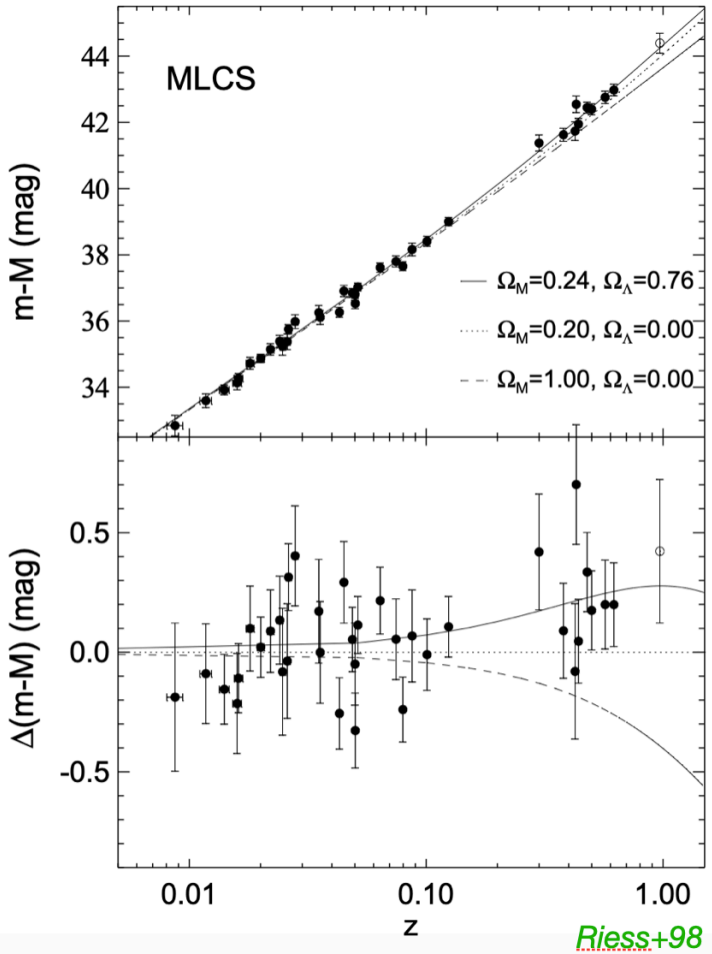
Cosmic Microwave Background (CMB): Future



Main science cases:
- Primordial GW (B modes)
- Primordial power (running)
- Light relics (Neff)
- Dark Energy (CMB lensing)
- Spectral distortions

Supernovae (SN) Surveys: Past

High-z SN Search

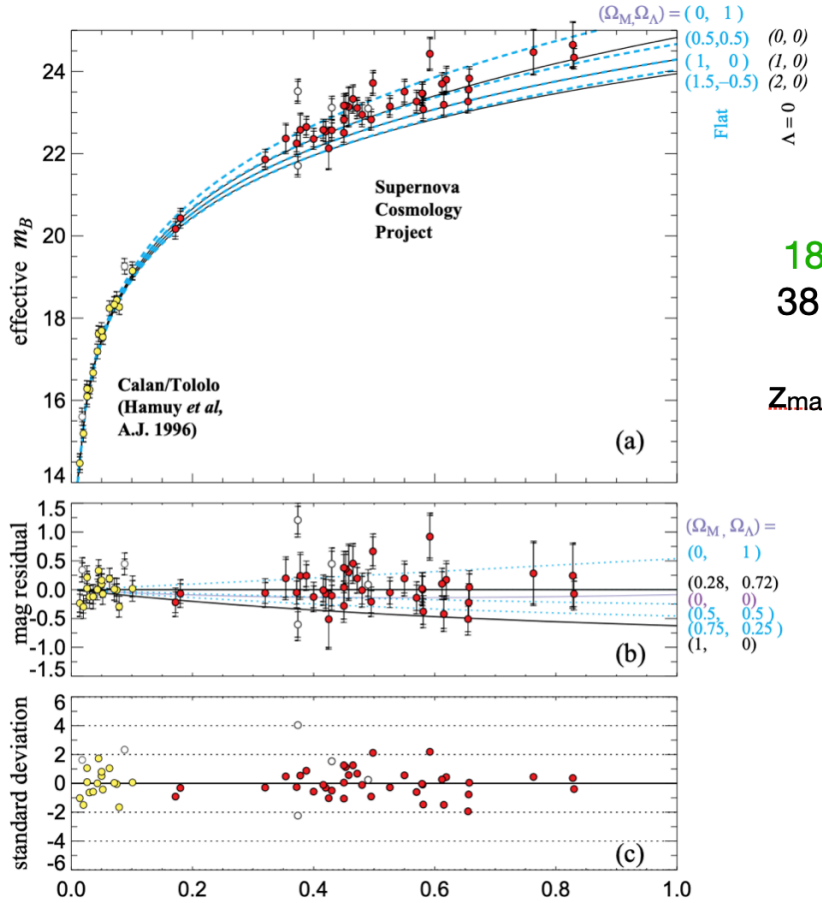


28 low-z
9 high-z

z_{max} ~1.0

Riess+98

SN Cosmology Project

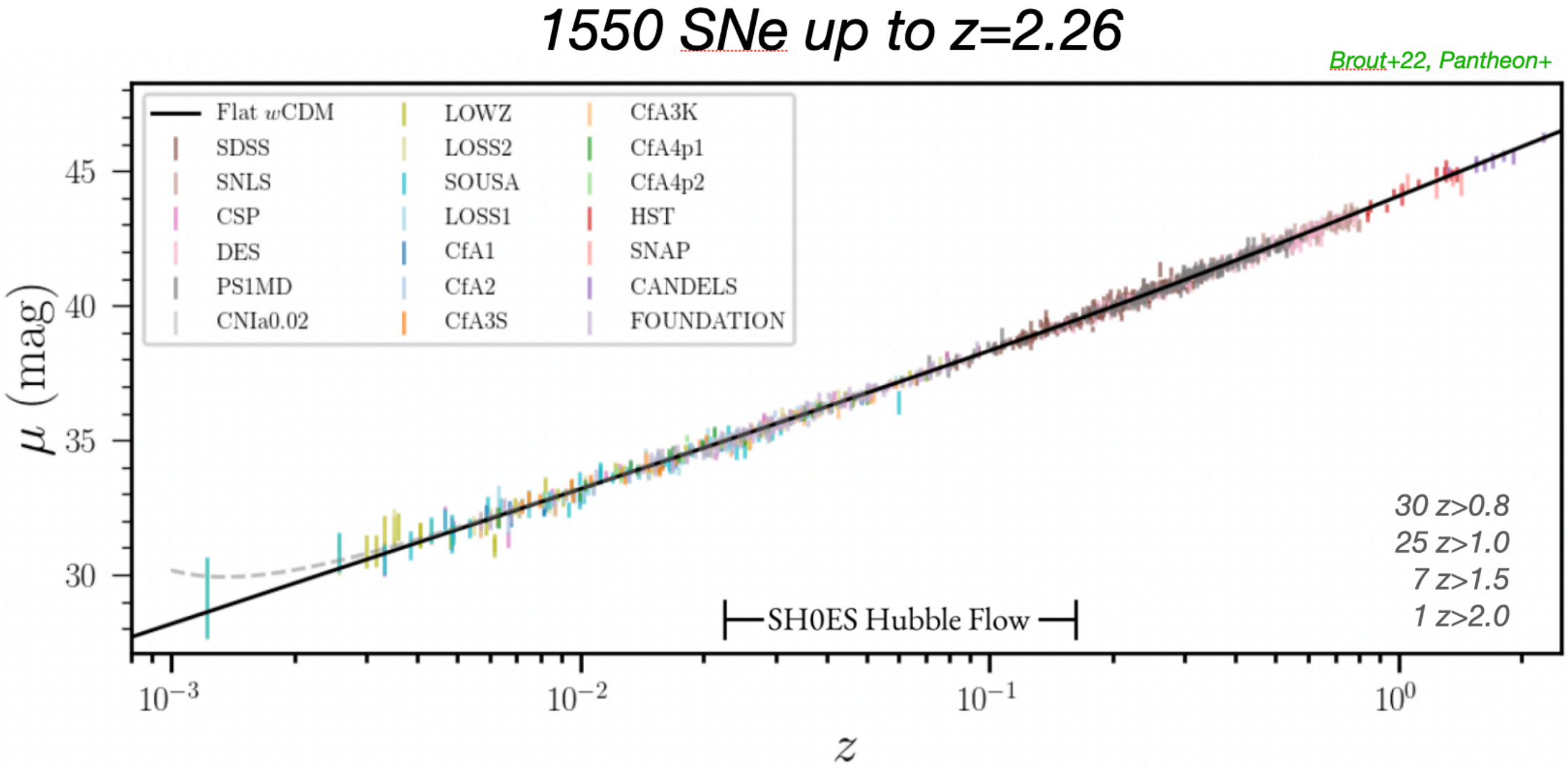


18 low-z
38 high-z

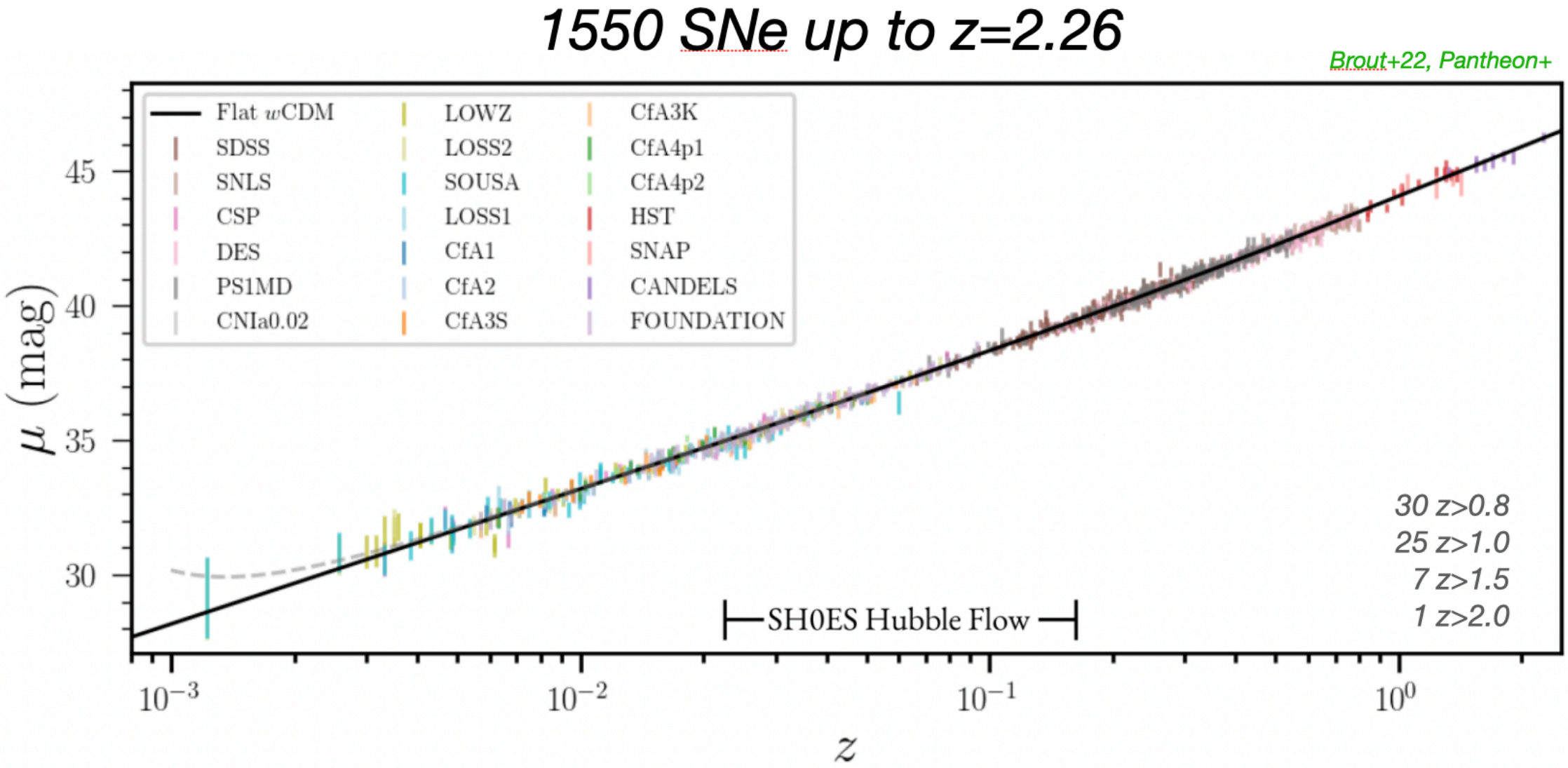
z_{max} ~0.85

Perlmutter+99

Supernovae (SN) Surveys: Present



Supernovae (SN) Surveys: Future



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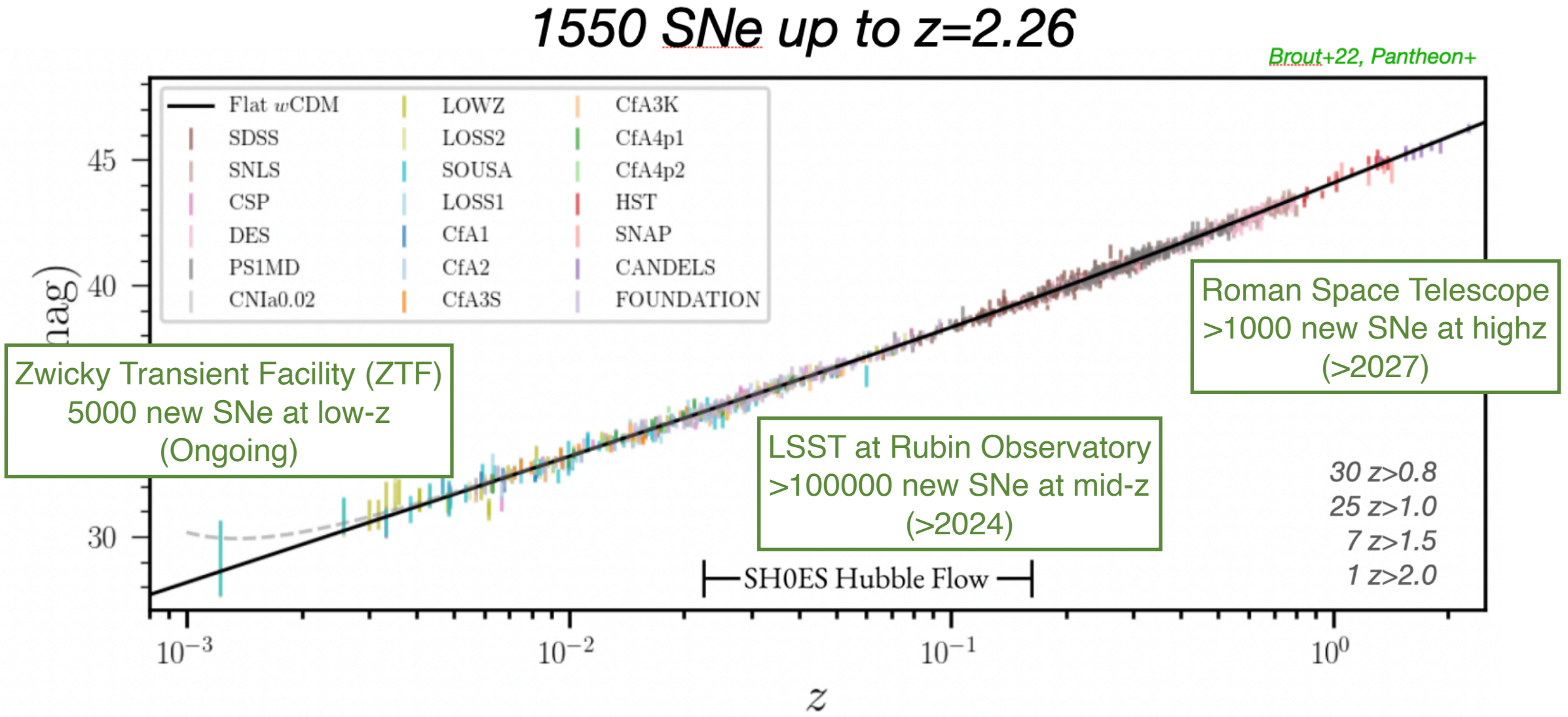

Zwicky Transient Facility (ZTF)
5000 new SNe at low-z
(Ongoing)

Roman Space Telescope
>1000 new SNe at highz
(>2027)

LSST at Rubin Observatory
>100000 new SNe at mid-z
(>2024)

Imaging Galaxy Surveys: Present

Several Stage-3 Dark Energy experiments:
- Hyper Suprime Cam (HSC)
- Kilo Degree Survey (KiDS)
- Dark Energy Survey (DES)

Mainly Weak Lensing (WL), but also large-scale structure (LSS) and cross-correlations


HSC (Subaru, Hawaii)


KiDS (VLTS, Chile)


DES (Blanco, Chile)

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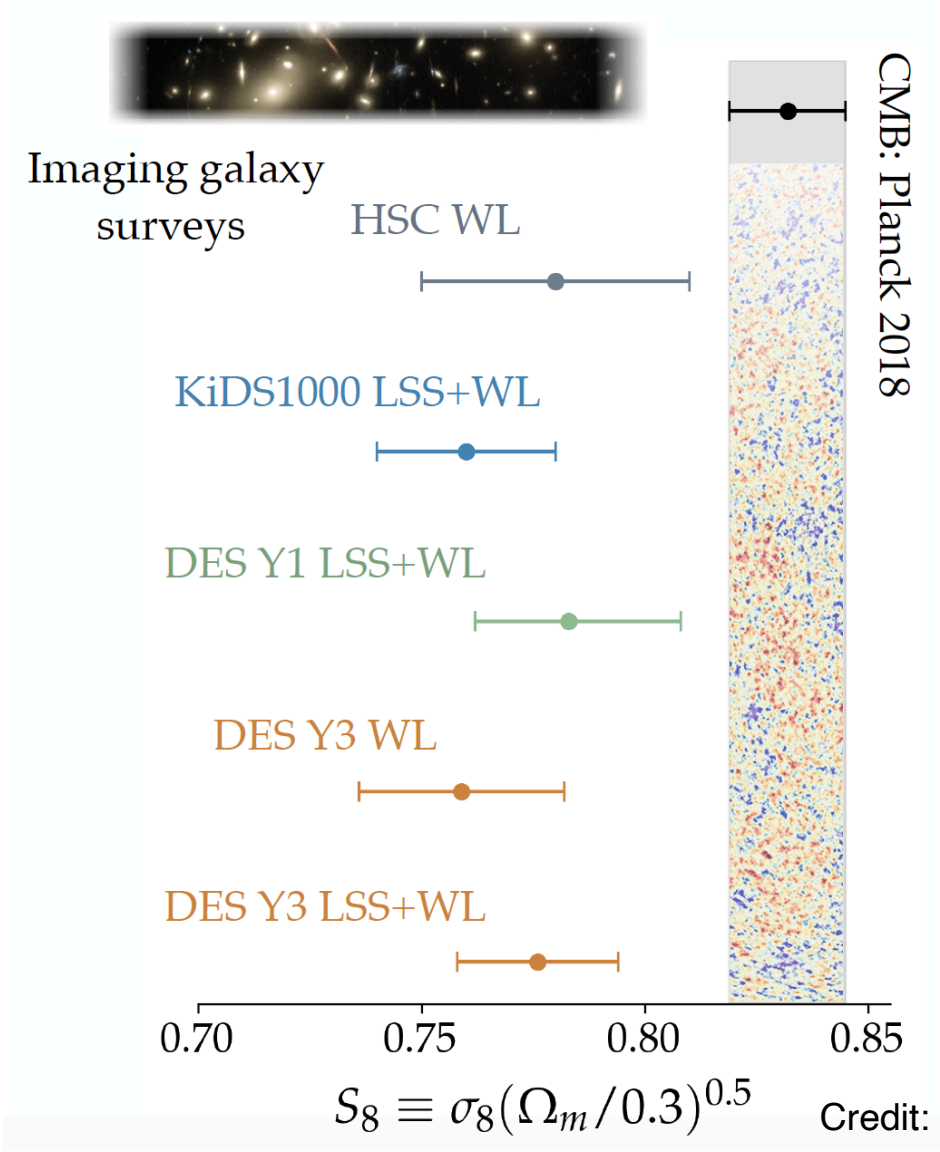
Mild tension between amplitude of matter fluctuations in CMB and in WL (S_8 tension)

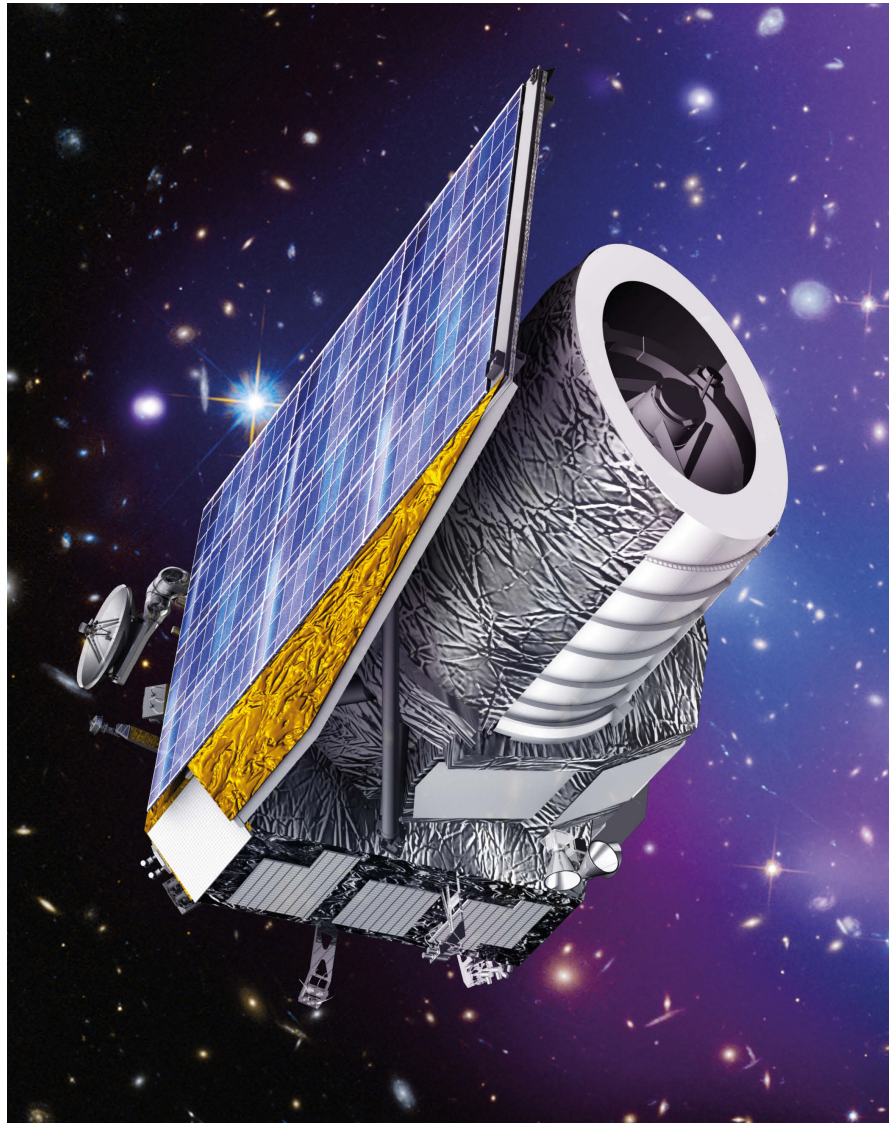


Credit: C. Sanchez

Imaging Galaxy Surveys: Future

The Euclid ESA mission

- ESA medium-size astronomy and astrophysics space mission
- Will survey 15,000 sq. deg.
- Weak lensing in optical focal plane with 1.5 billion galaxies
- And slit-less spectroscopy in infrared for 30 million galaxies
- Photometry for photo-z in infrared focal plane (YJH)
- **Successfully launched in July 2023!**



Imaging Galaxy Surveys: Future

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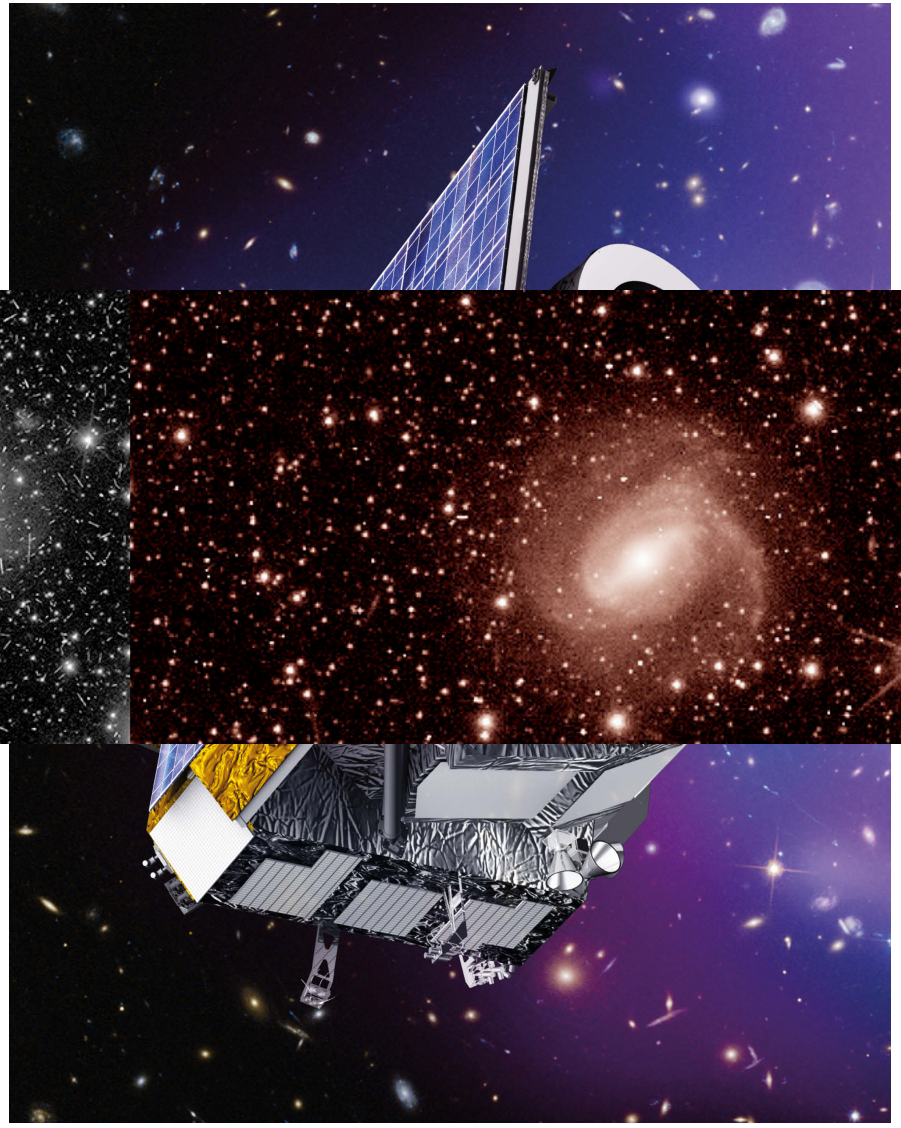

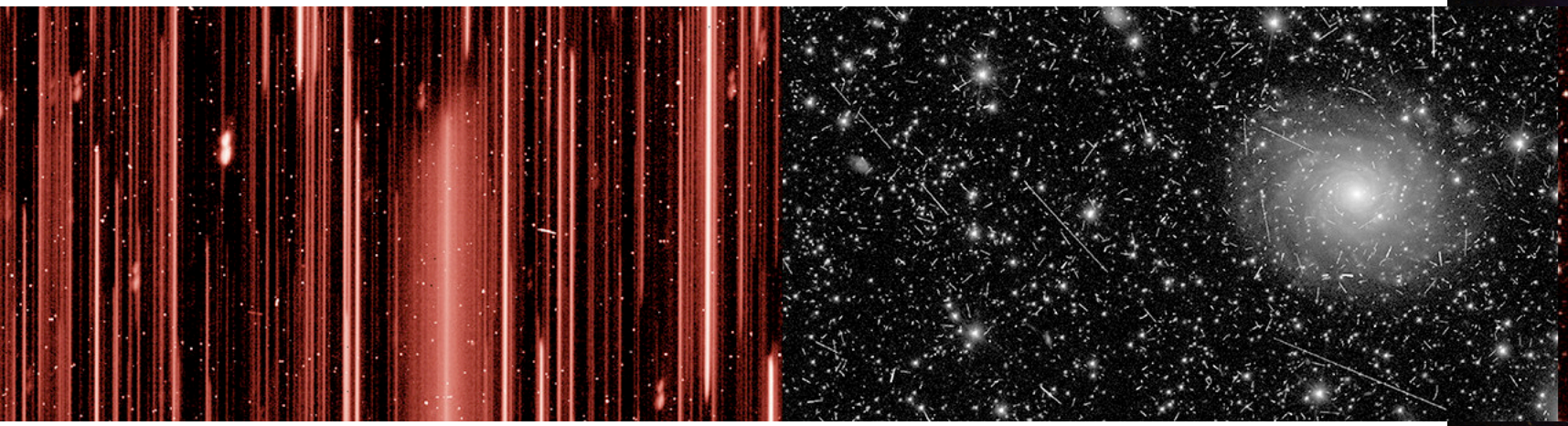

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Imaging Galaxy Surveys: Future

Legacy Survey of Space and Time (LSST)

FASTER (2×15s exp.), WIDER (20k deg2), DEEPER (i ~ 26.8)

DES: 90s exp. 5k deg^2 i ~ 23.8

- 8.4 m diameter mirror
- 9.6 deg^2 field of view
- 825 visits per pointing
- **10 million alerts per night**
- 40 billion objects
- 500 PB of images
- 10-year survey
- Commissioning ongoing
- Survey to start in 2025
- **Weak lensing with 4 billion galaxies**

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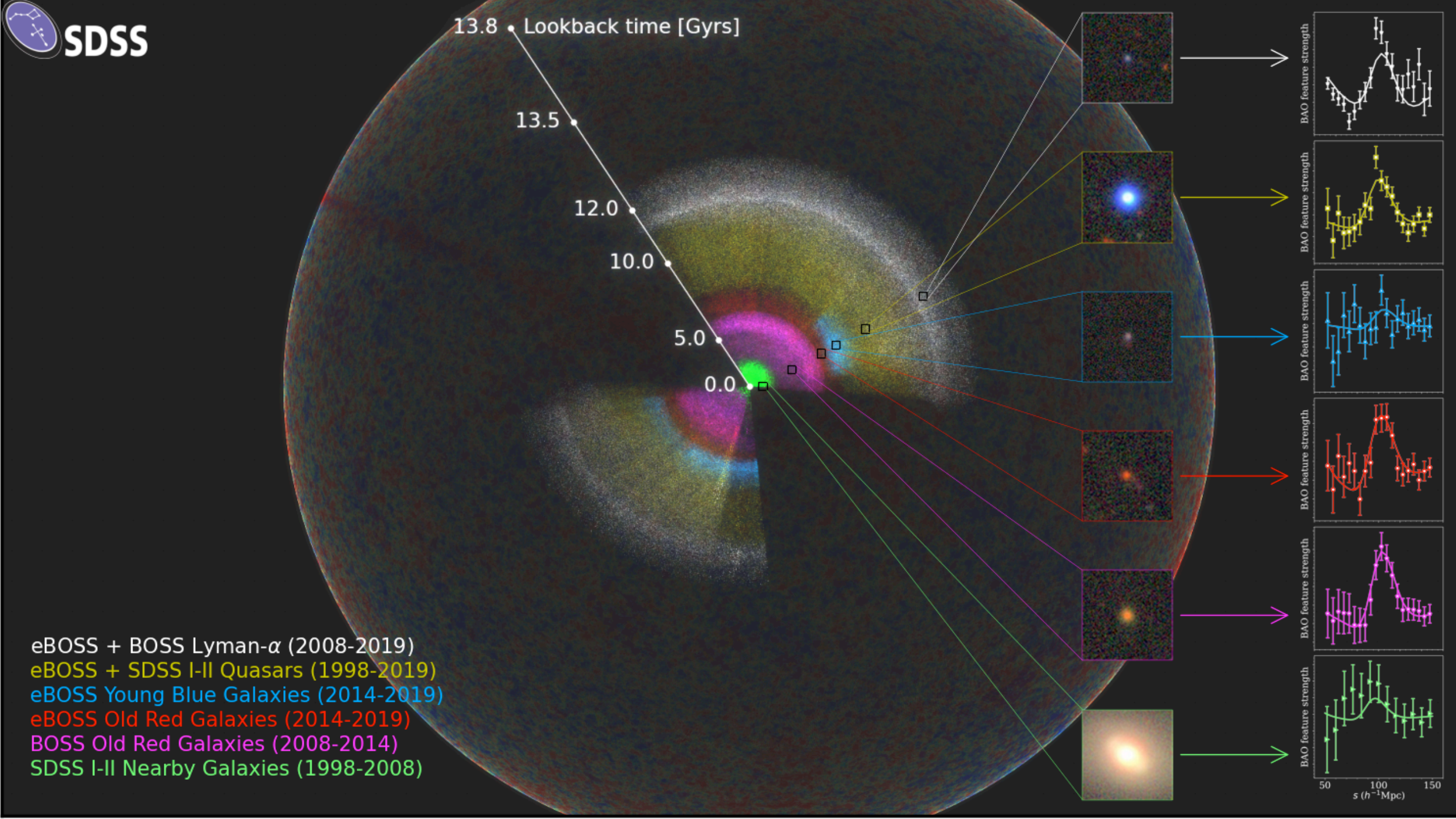

SDSS
13.8 Lookback time [Gyrs]
13.5
12.0
10.0
5.0
0.0
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)
BAO feature strength
BAO feature strength
BAO feature strength
BAO feature strength
BAO feature strength
BAO feature strength
50
100
150
s (h⁻¹Mpc)

Baryon Acoustic Oscillations (BAO)

To study the expansion we want to measure the distance to different redshift

Standard candle (SNe Ia)

known luminosity

+

measure flux

↓

distance

Standard ruler (BAO)

known size

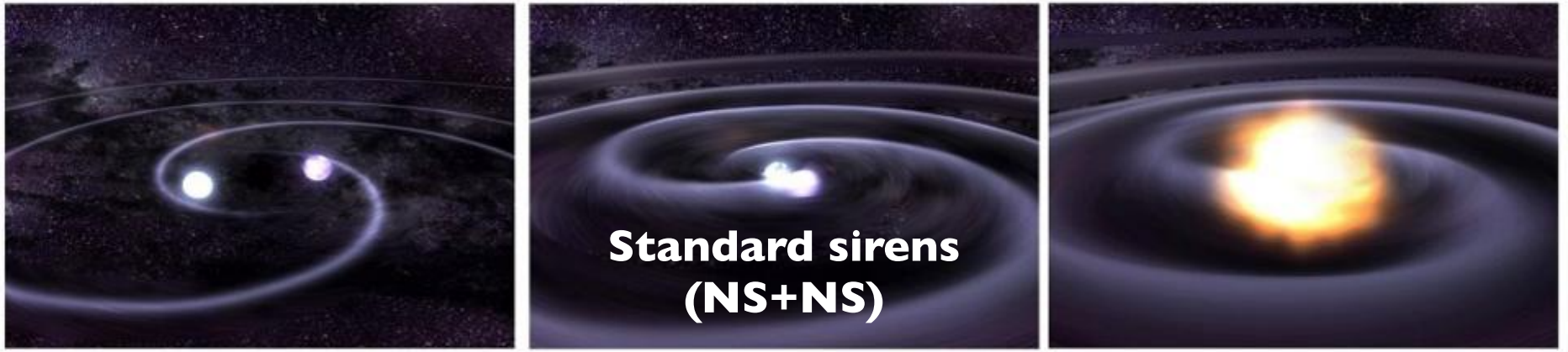
+

measure angle

↓

distance

Baryon Acoustic Oscillations (BAO)



Standa **d ruler**

(SNe Ia) **(BAO)**

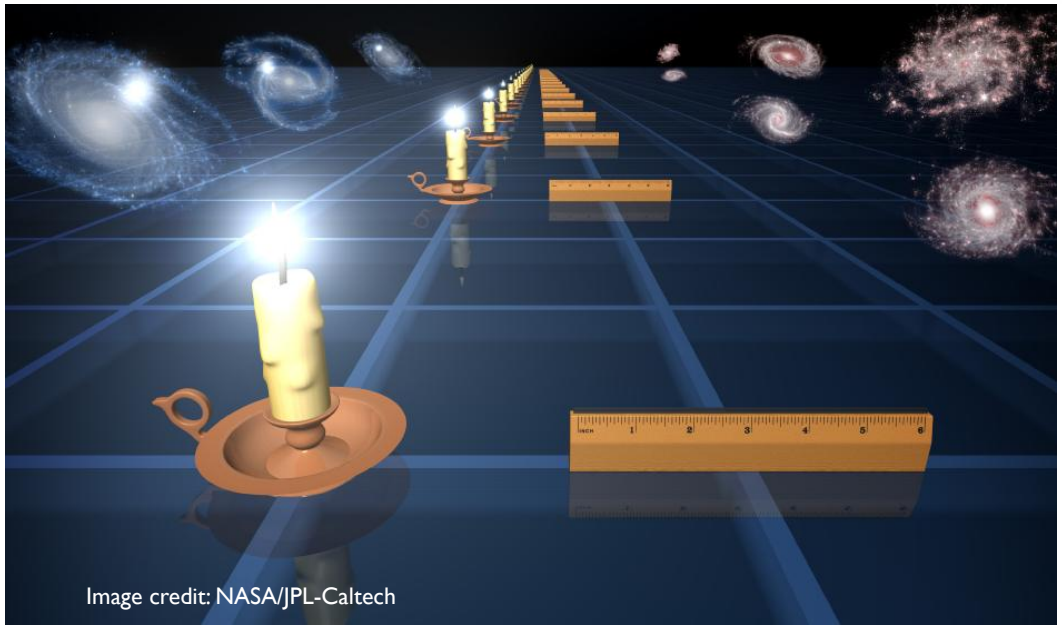
known luminosity

+

measure flux

↓

distance



known size

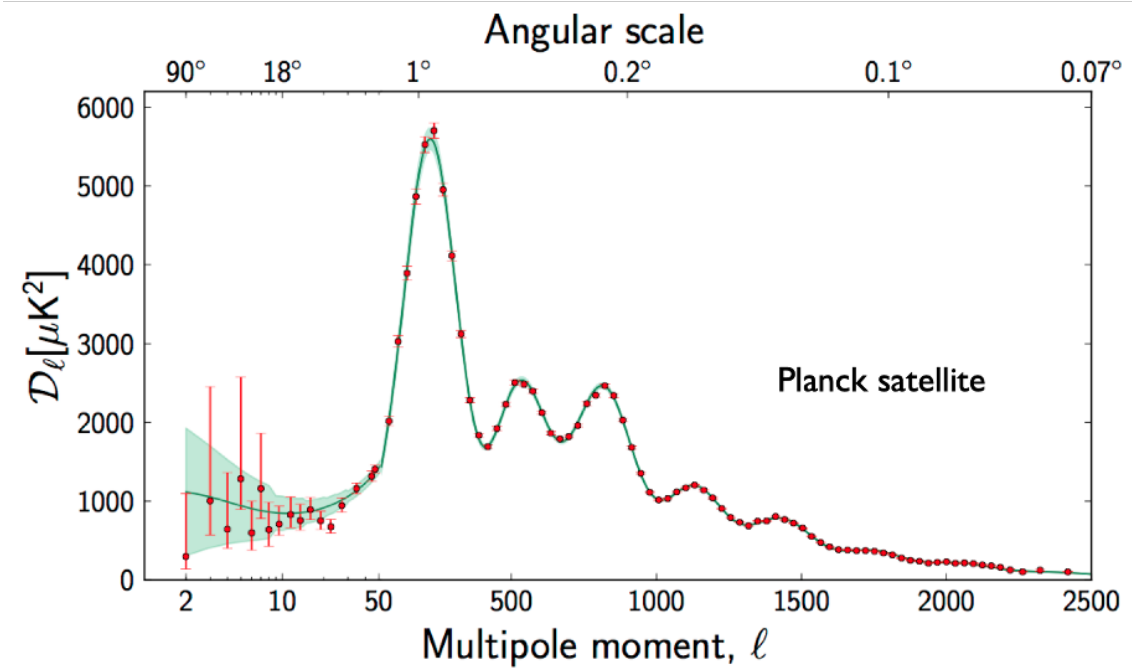
+

measure angle

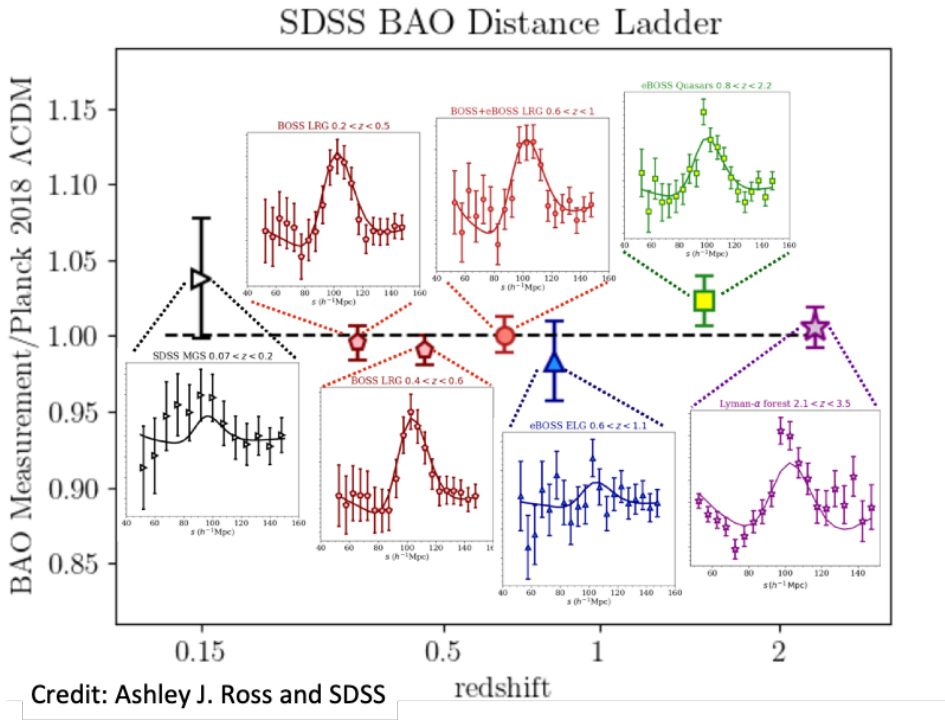
↓

distance

Baryon Acoustic Oscillations (BAO)



Acoustic waves in the photon-baryon plasma in the early Universe left an imprint in the CMB, at a well-known scale known as the *sound horizon*

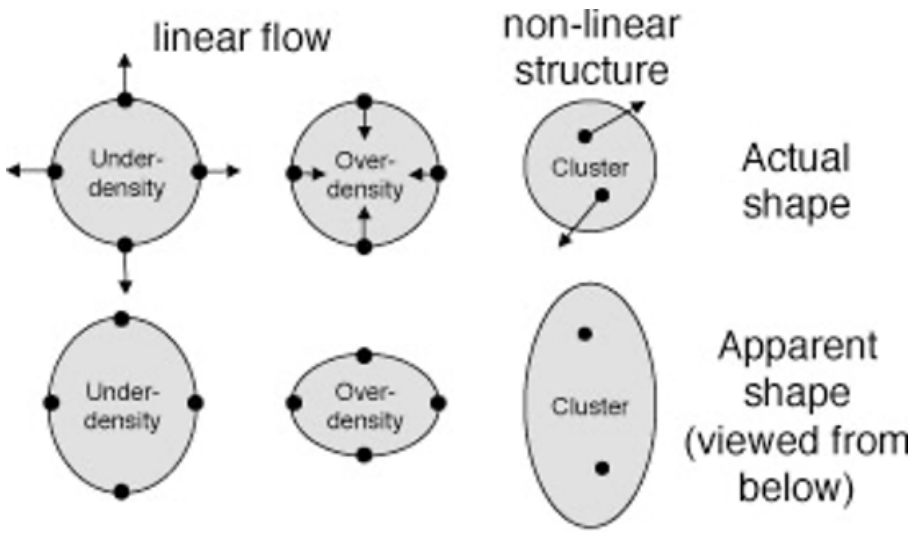


BAO have also been detected in the distribution of matter at low redshift, and can be used as a standard ruler to measure distances to galaxies

Redshift Space Distortions (RSD)

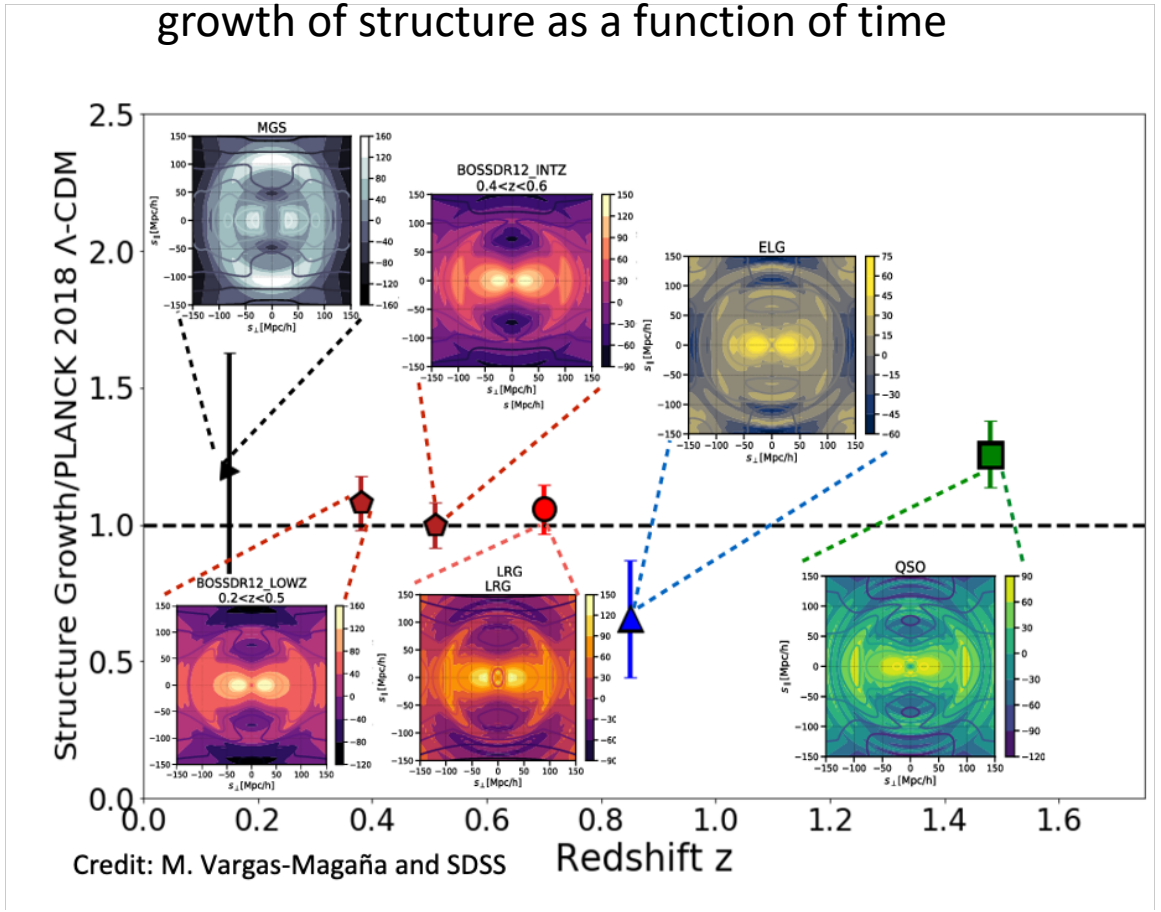
Our galaxy maps are distorted, since our radial coordinate is inferred from its redshift (velocity)

On large (linear scales), the anisotropy in the galaxy correlations depends on the amplitude matter fluctuations and the theory of gravity



Credit: Will Percival

RSDs can therefore be used to measure the growth of structure as a function of time



Cosmology from 20 years of SDSS

eBOSS Collaboration 2021 (arXiv:2007.08991)

"The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory"

Interpretation of 23-paper arXiv submission from July 20, 2020

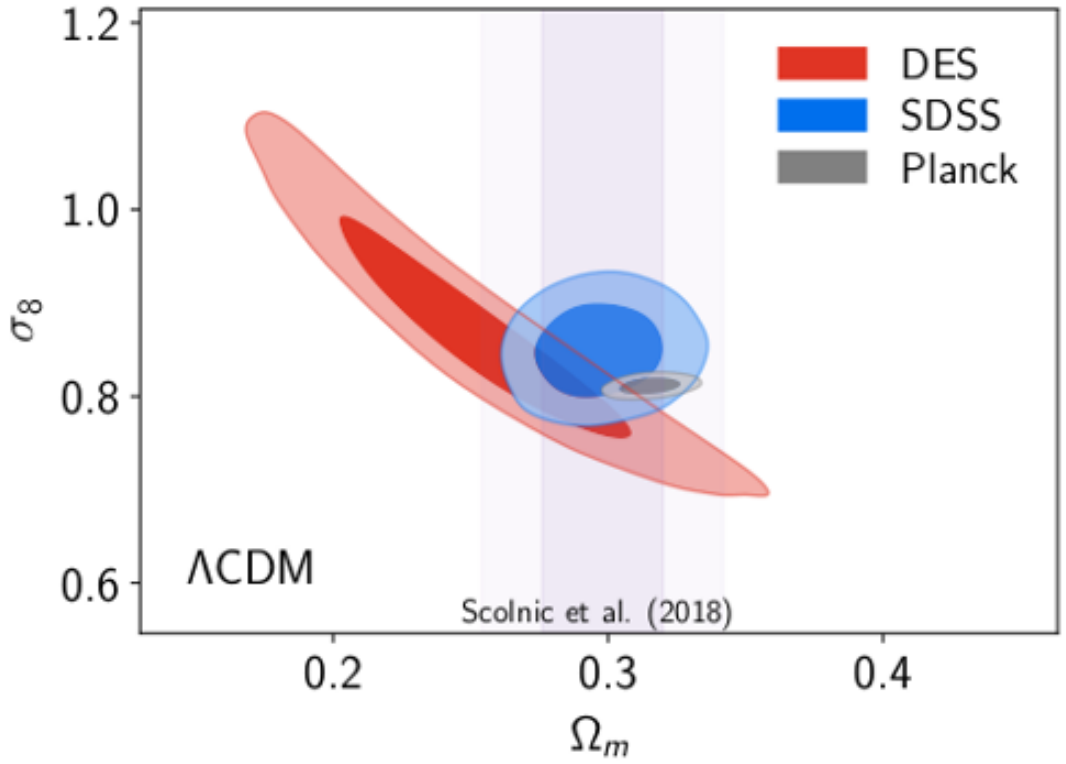
Collaboration paper co-led by (left to right): Eva-Maria Mueller (Oxford), Kyle Dawson (Utah), Andreu Font-Ribera (IFAE), Zheng Zheng (Utah) and Anze Slosar (BNL)

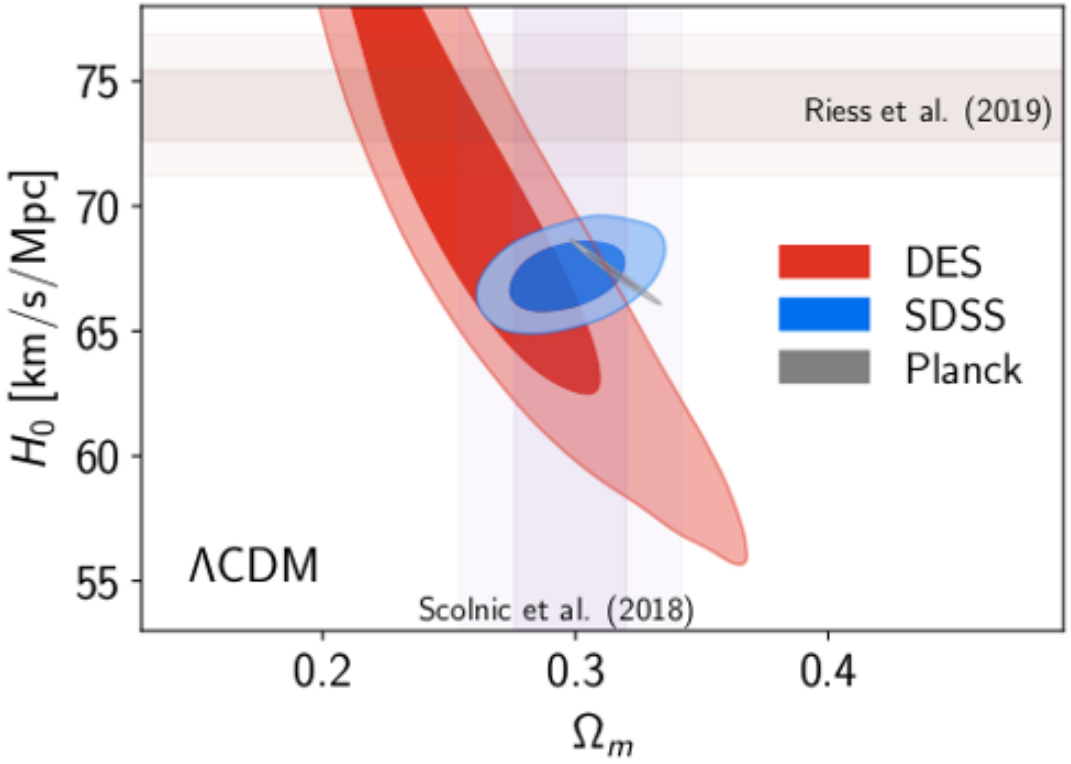




Tension in the flat ΛCDM model?

- SDSS fully consistent with Planck CMB, Pantheon SNe and DES 3x2
- Clear H_0 tension with SHOES distance ladder (more latter)

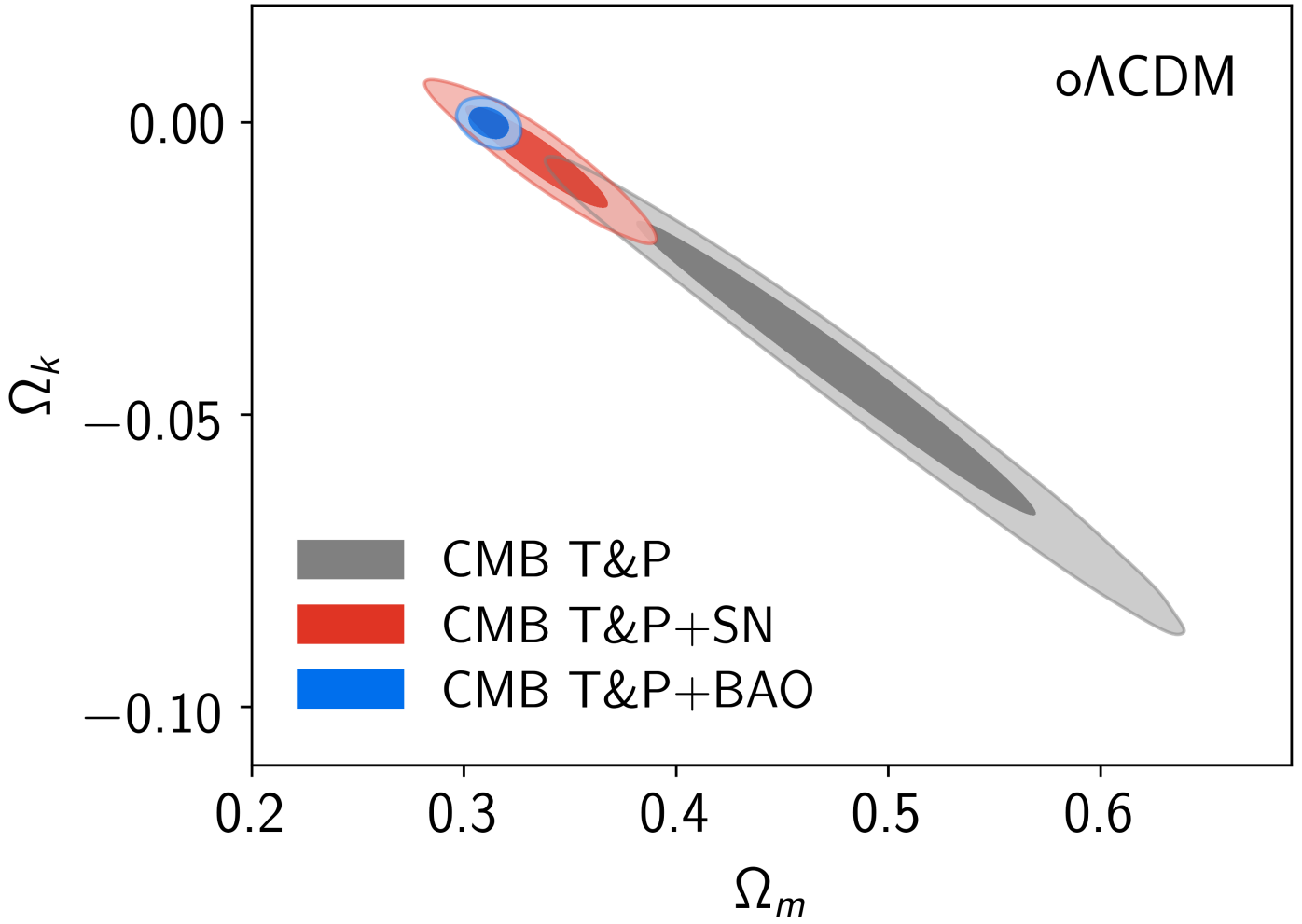




Extended models: curvature

CMB alone can not constraint the curvature of the Universe

BAO + CMB has a clear preference for a flat Universe

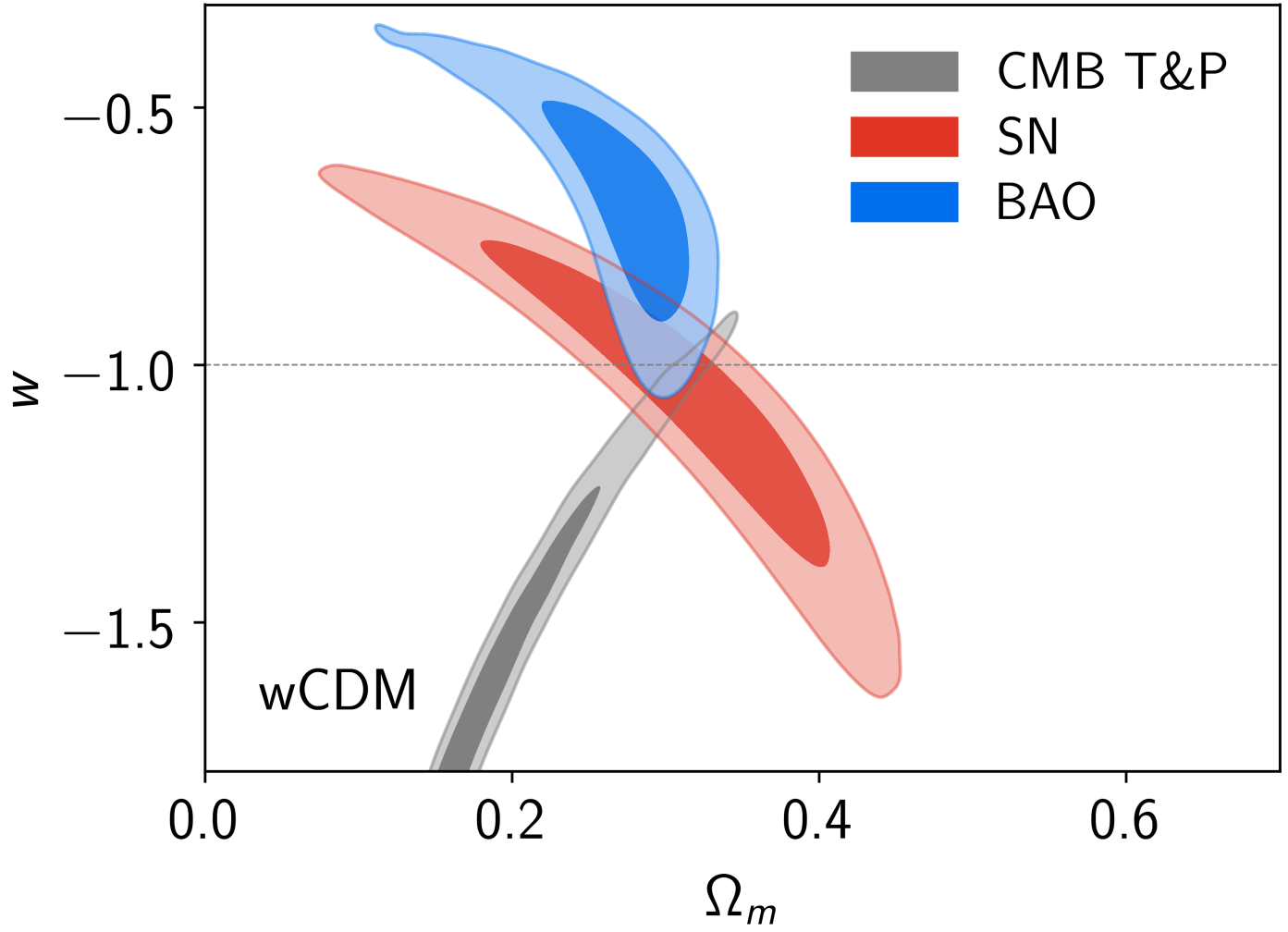


Extended models: dark energy

Equation of state of Dark Energy

$$w = p_{\rm DE}/\rho_{\rm DE}$$

BAO + CMB + SN point to
a cosmological constant

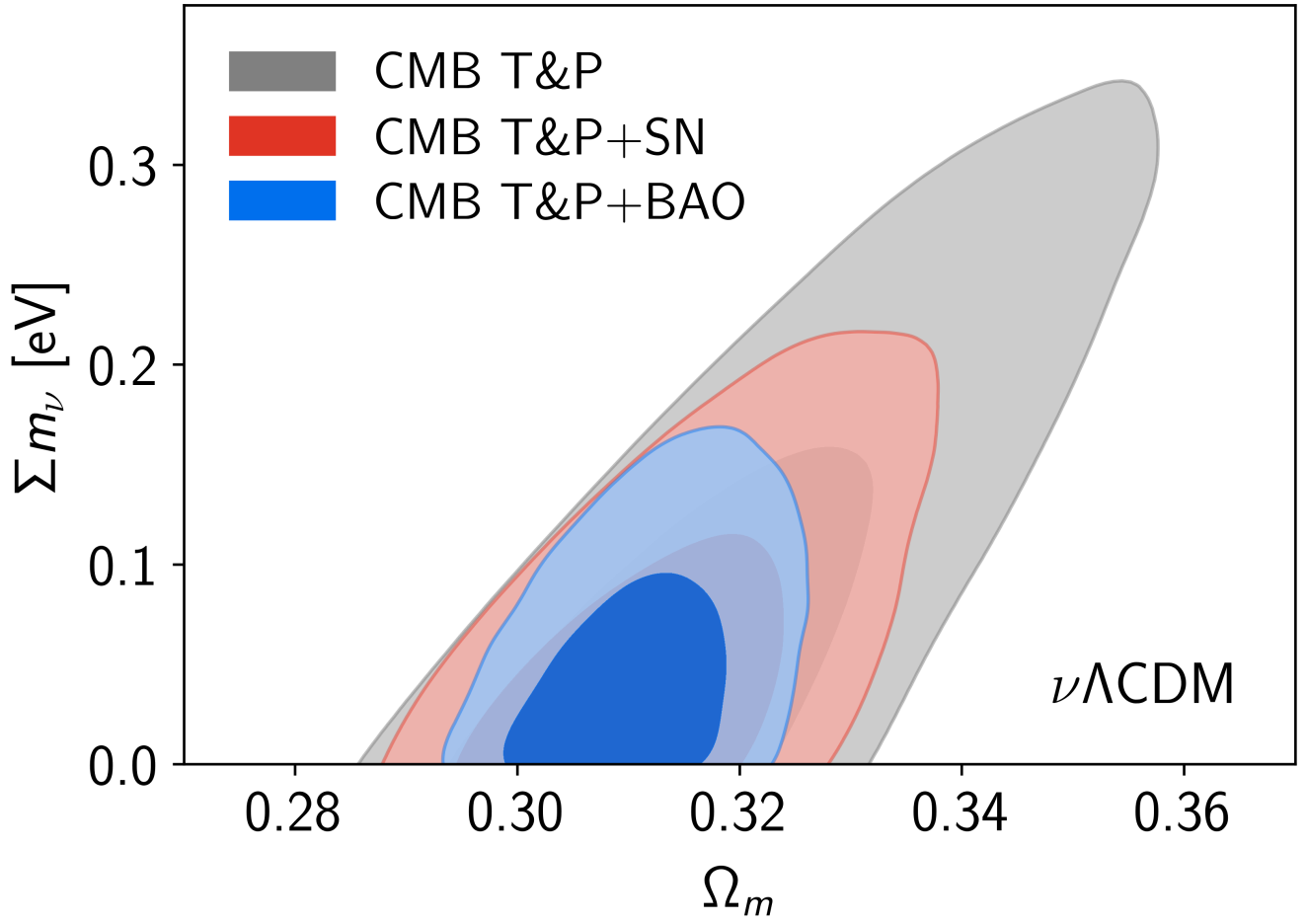


Extended models: massive neutrinos

Lower limits from
neutrino oscillations

$$\sum m_\nu > 0.0588\,\mathrm{eV} \qquad \text{normal hierarchy,}$$
$$\sum m_\nu > 0.0995\,\mathrm{eV} \qquad \text{inverted hierarchy.}$$

BAO breaks degeneracy
with matter density in CMB



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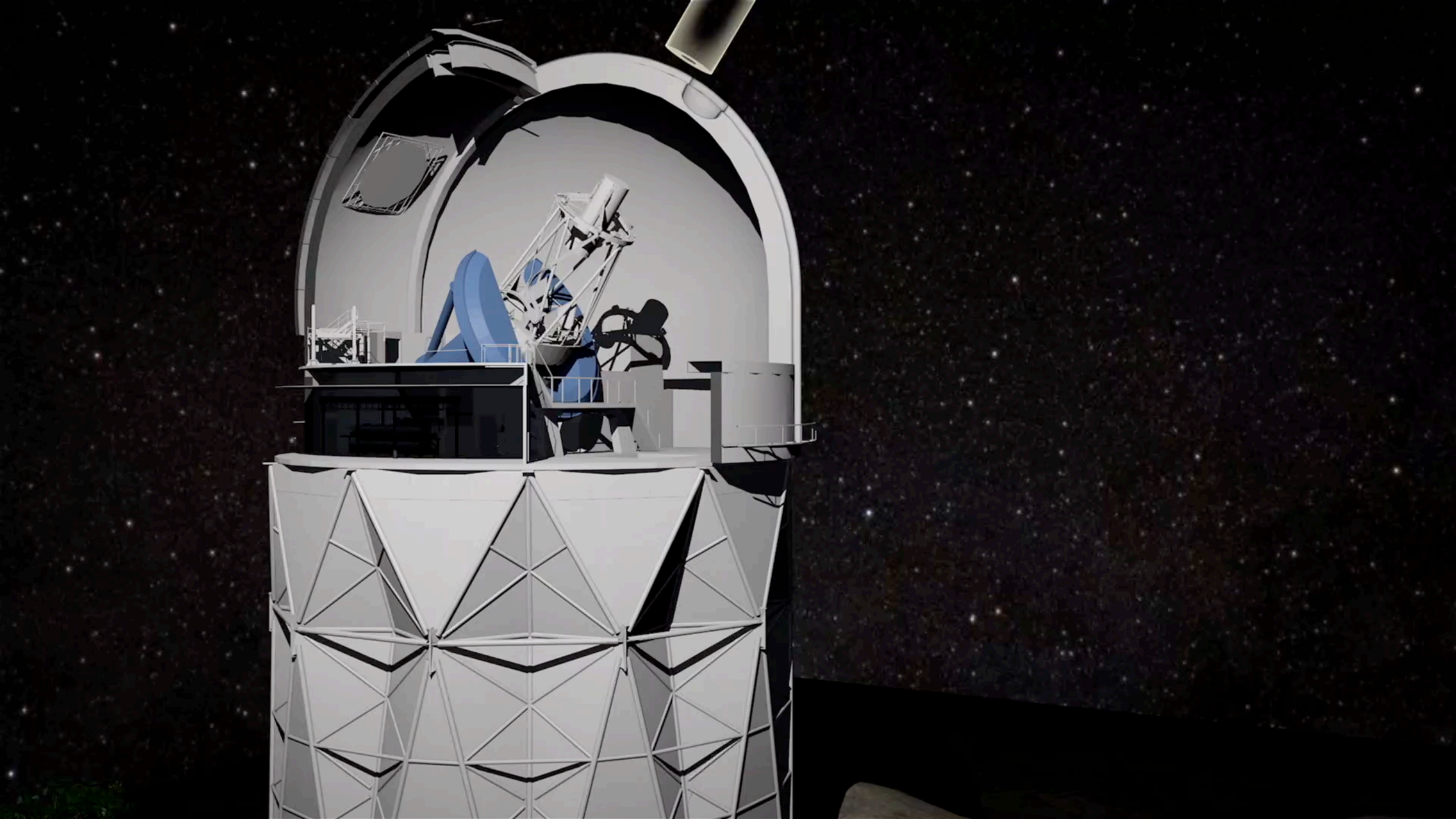
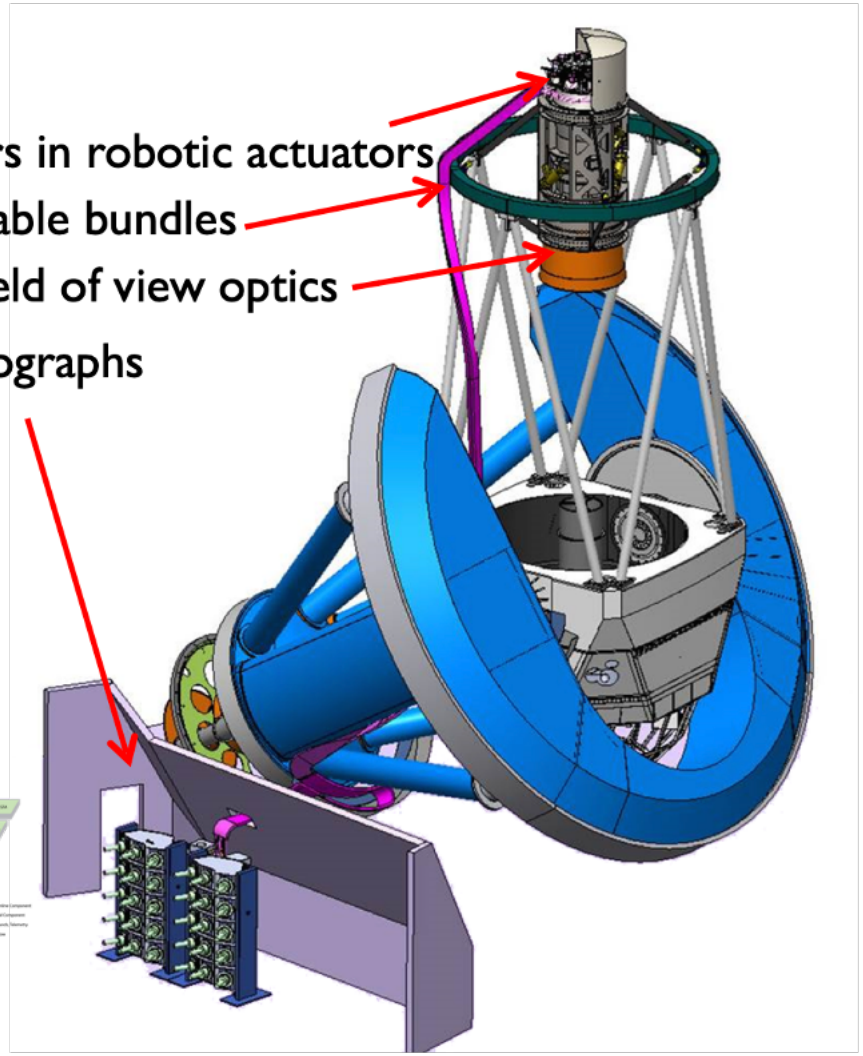
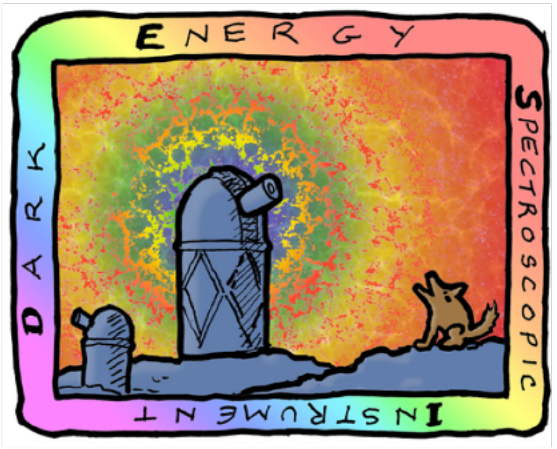


Instrument Overview

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



Readout & Control



Mayall 4m Telescope
Kitt Peak (Tucson, AZ)

Increase BOSS/eBOSS datasets by an order of magnitude

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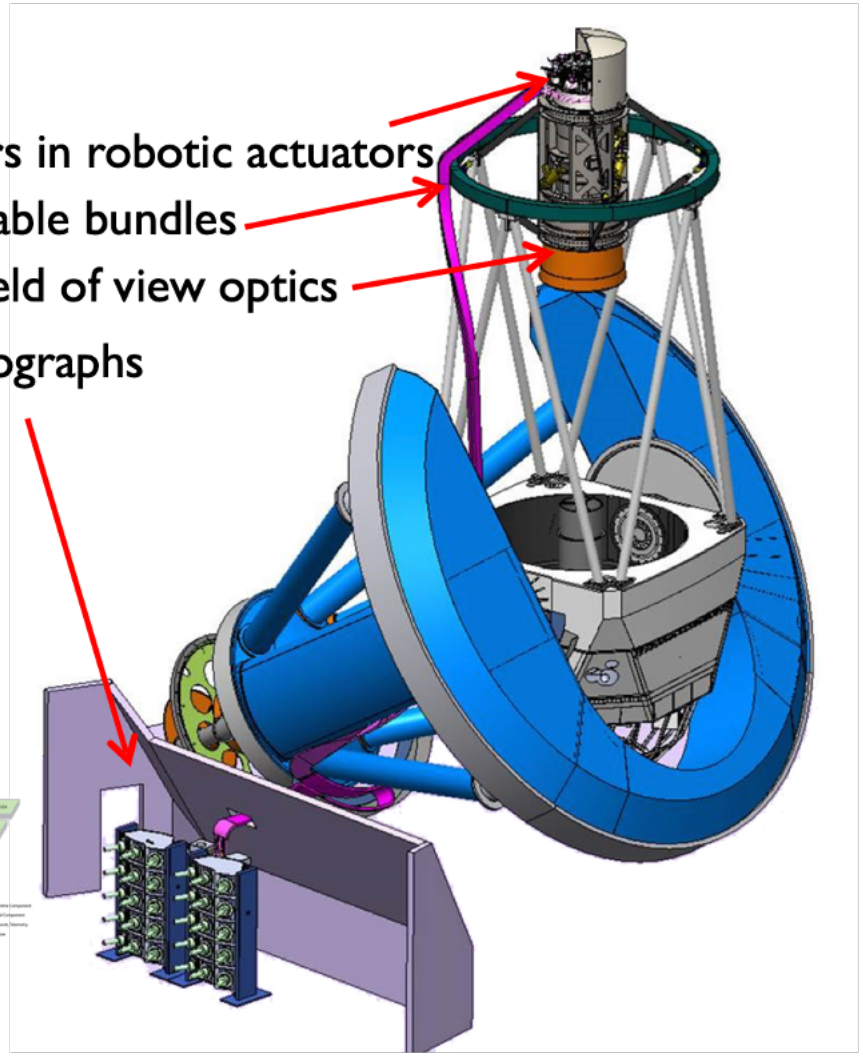

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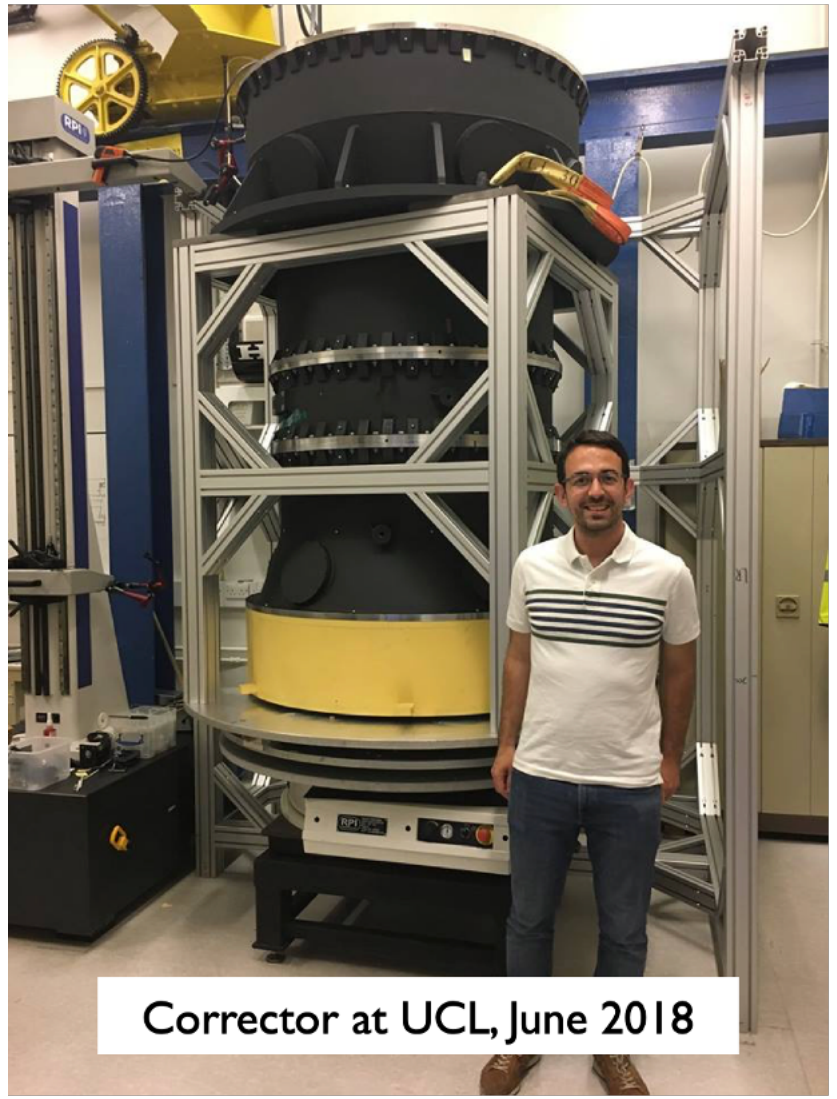

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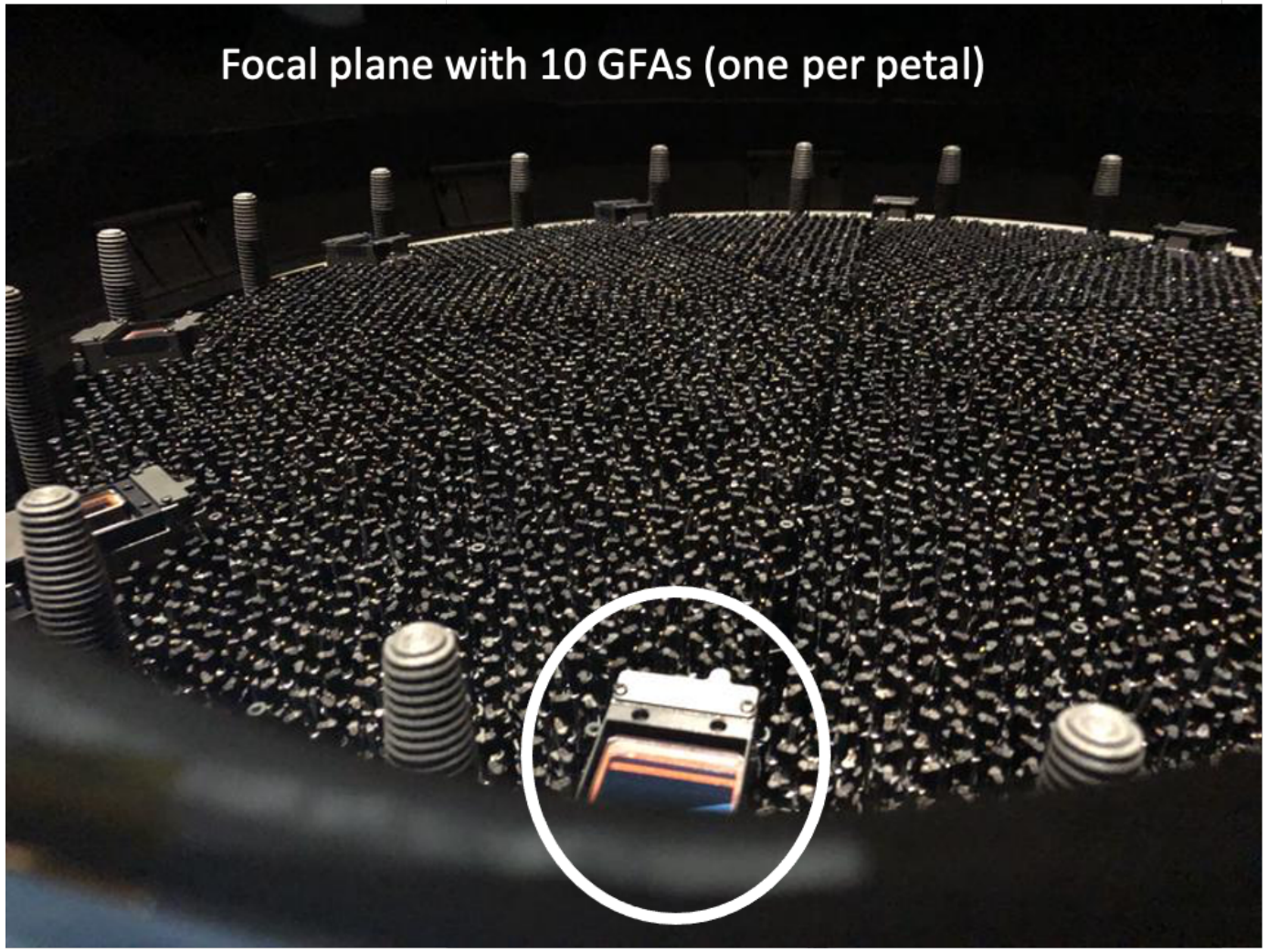
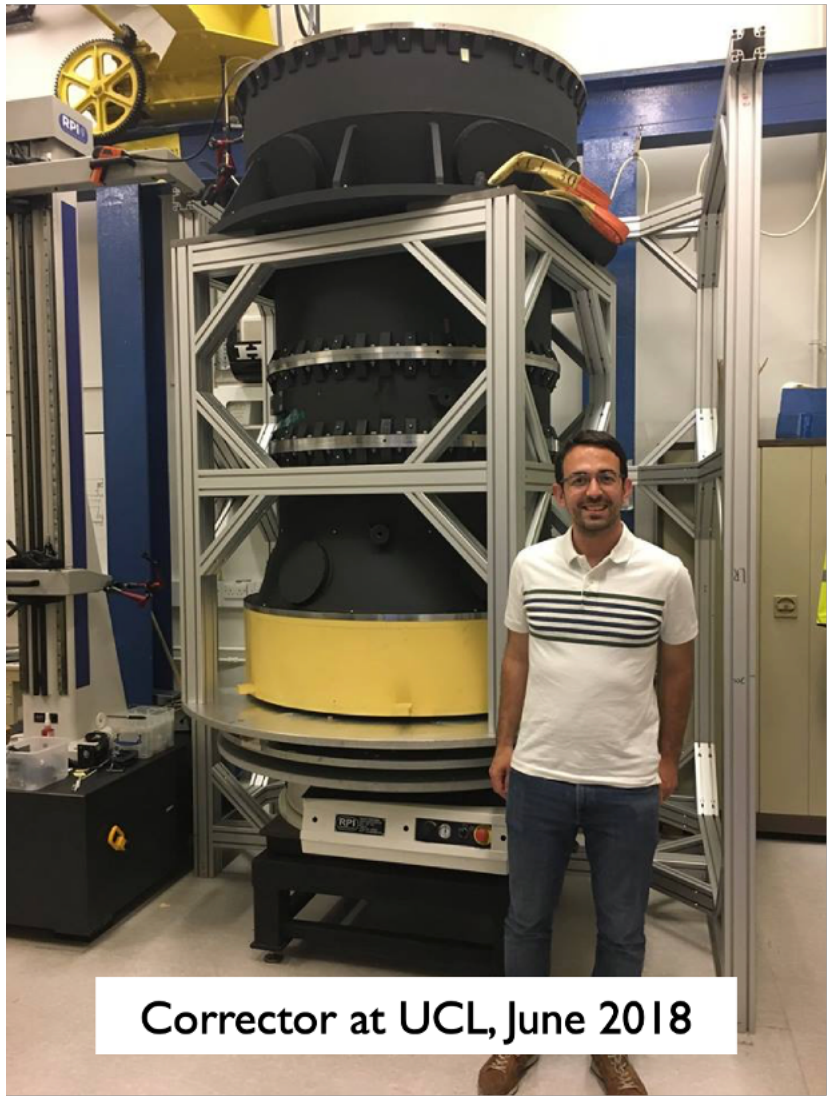
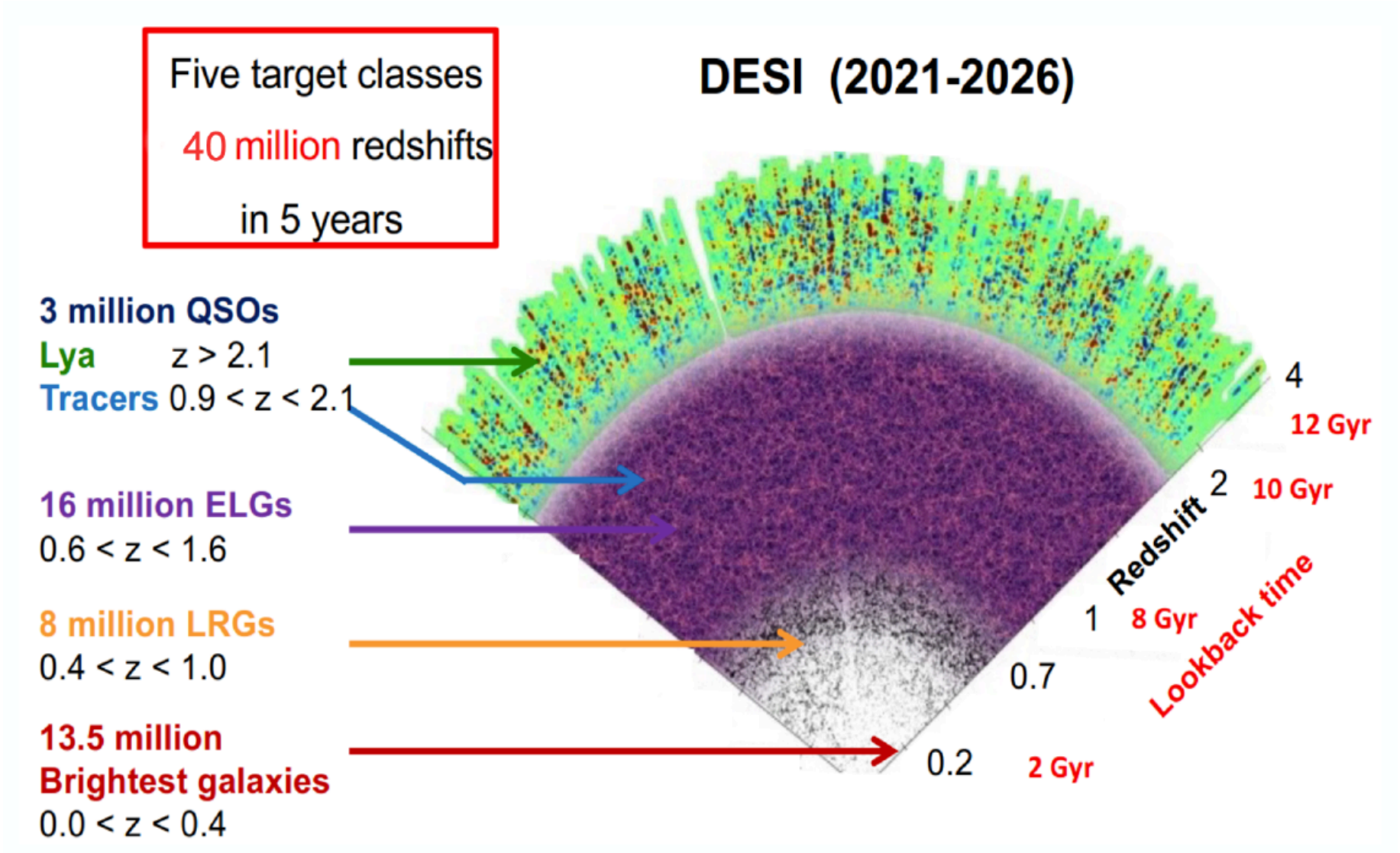




Instrument Overview

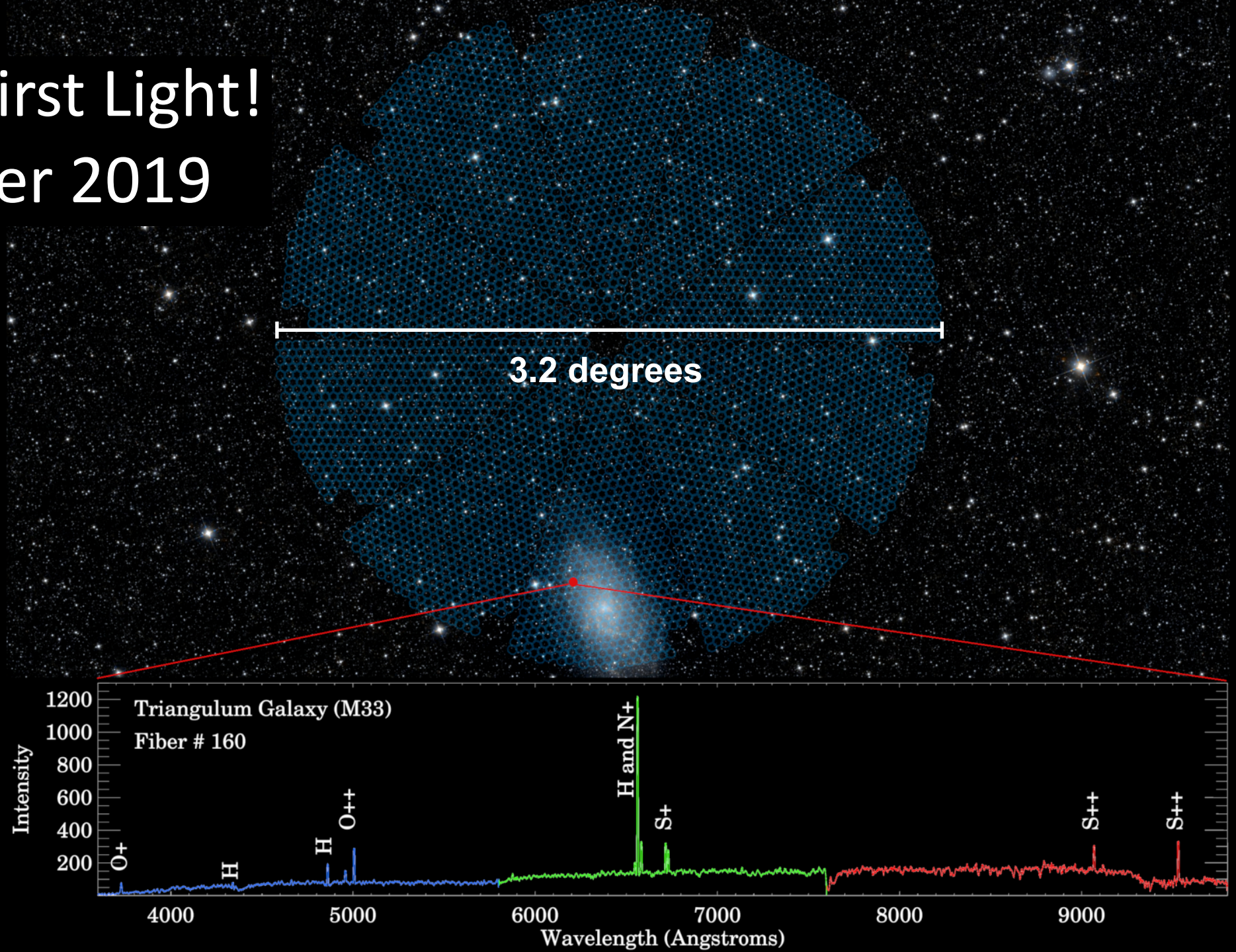
Survey Overview



And now…

… a bumpy road to Dark Energy!

DESI First Light!
October 2019



DESI Survey Validation started in March 2020…

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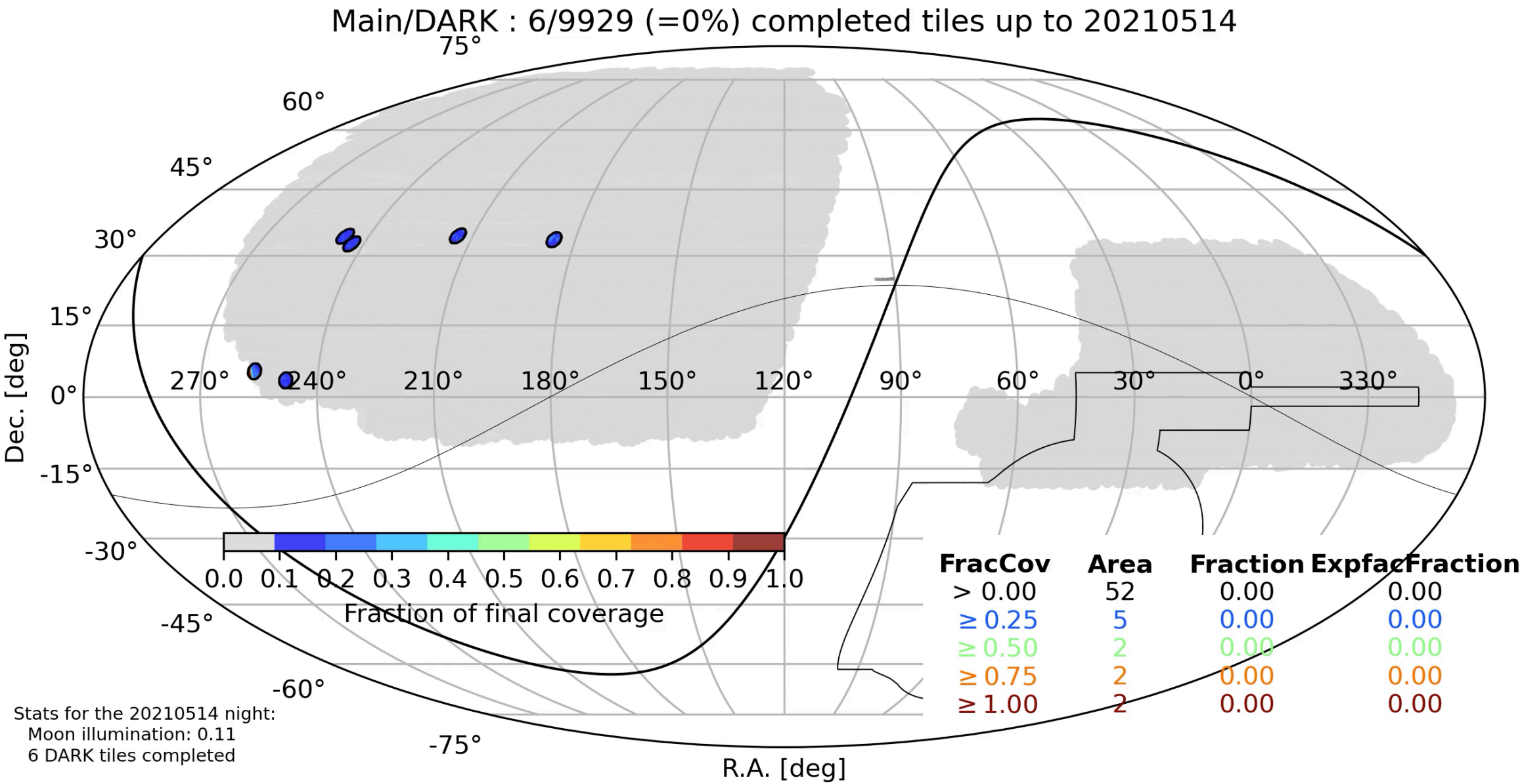
… and lasted 2 days (COVID shutdown until Nov 2020)

Main survey started in May 2021!




… Contreras Fire shutdown June 14, 2022 … until Sep 10, 2022
Z:16
2022-06-16 18:37:17
KPNO Mayall 4m

Hackers in 2023!

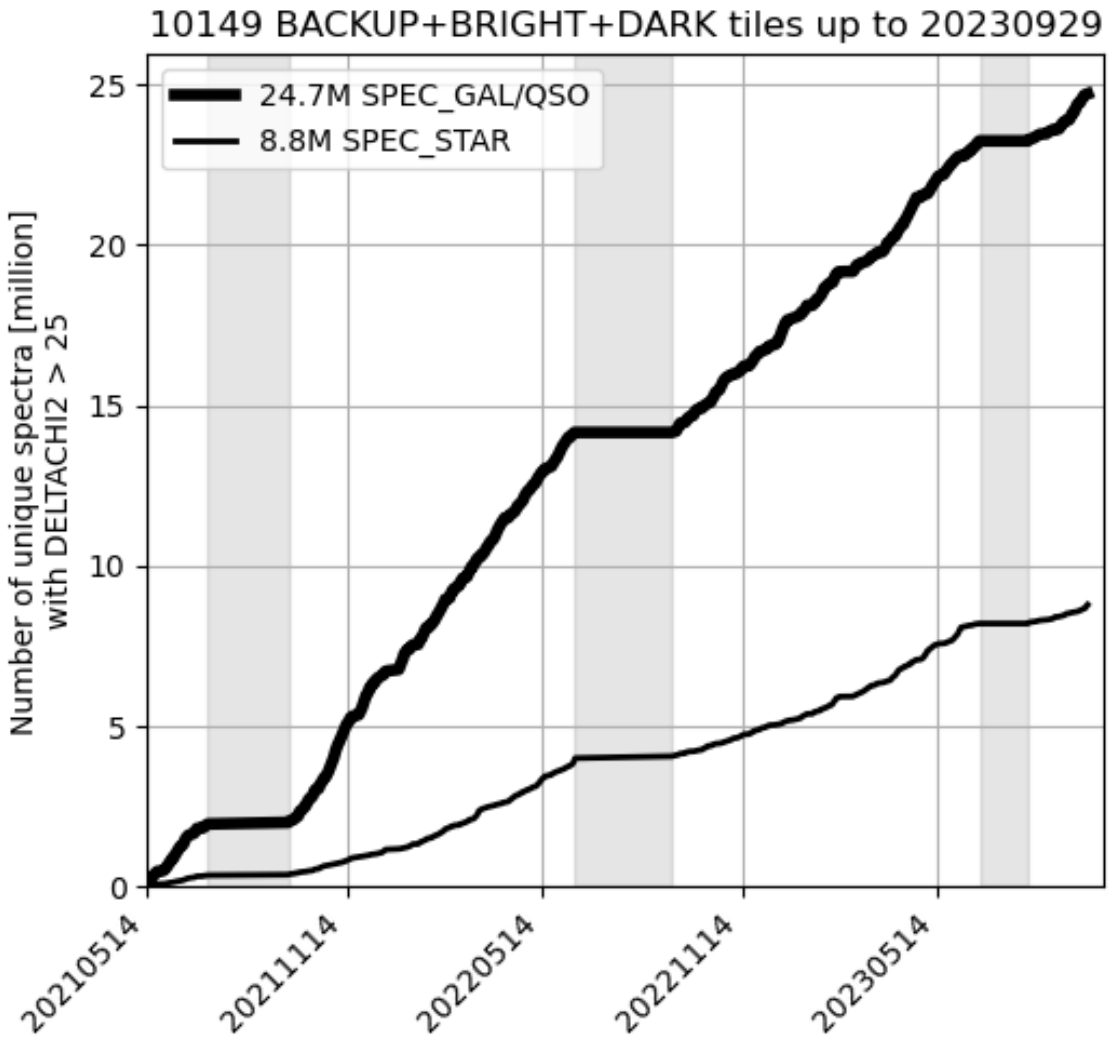
Hackers shut down 2 of the world's most advanced telescopes

By Brett Tingley published August 30, 2023

It's unclear exactly what the nature of the cyberattacks were or from where they originated.

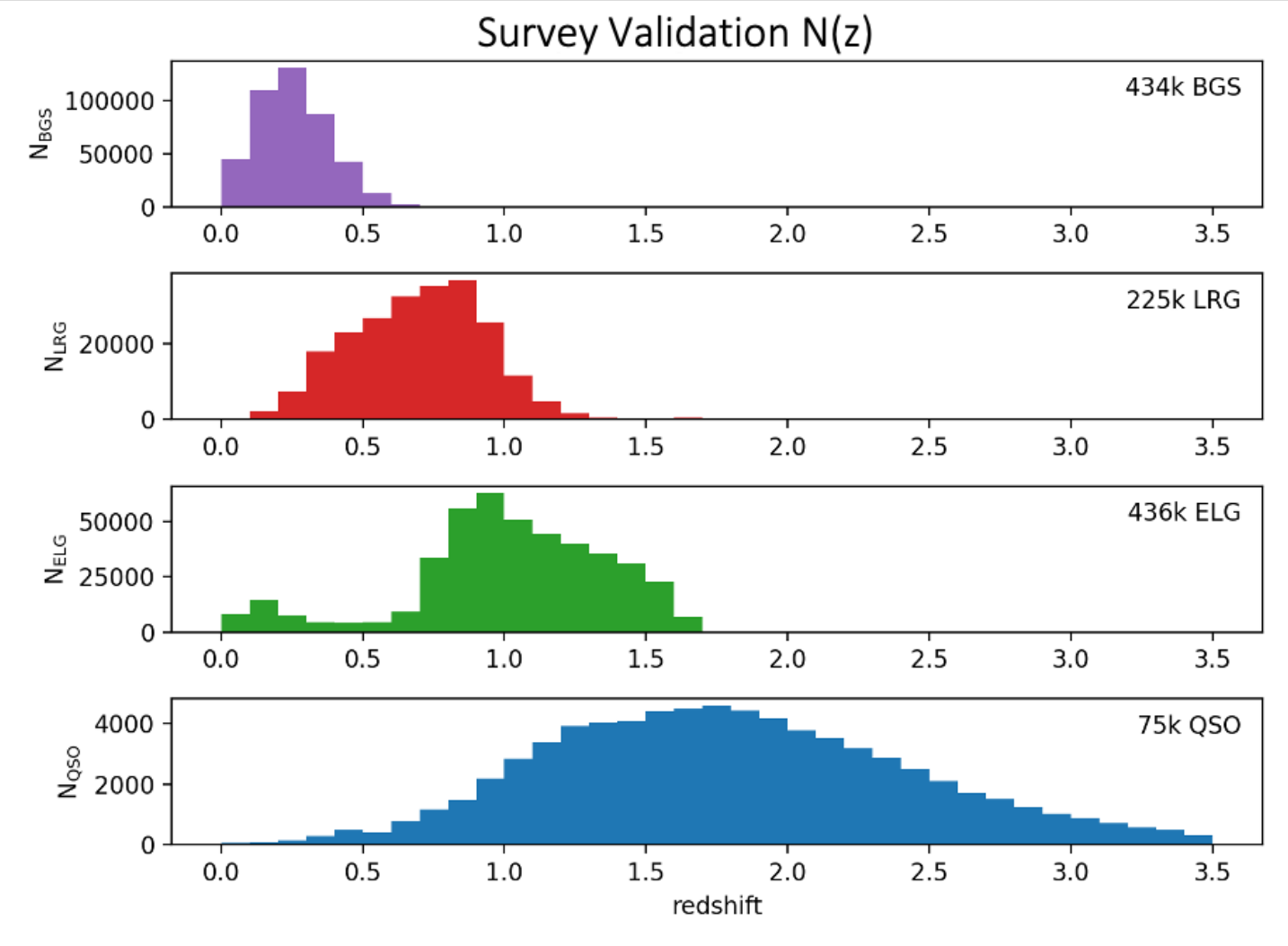
DESI is now 50% complete!

- In spite of covid, fire and pirates, the main survey of DESI is already 50% complete!
- Thanks to a great instrument and survey operations team, we are now 3 months ahead of schedule
- Terminology:
  - DESI-EDR (Early Data Release)
  - DESI-M2 (first two months)
  - DESI-Y1 (up to June'22)
  - DESI-Y3 (up to June'24), DESI-Y5 (final, 2026)

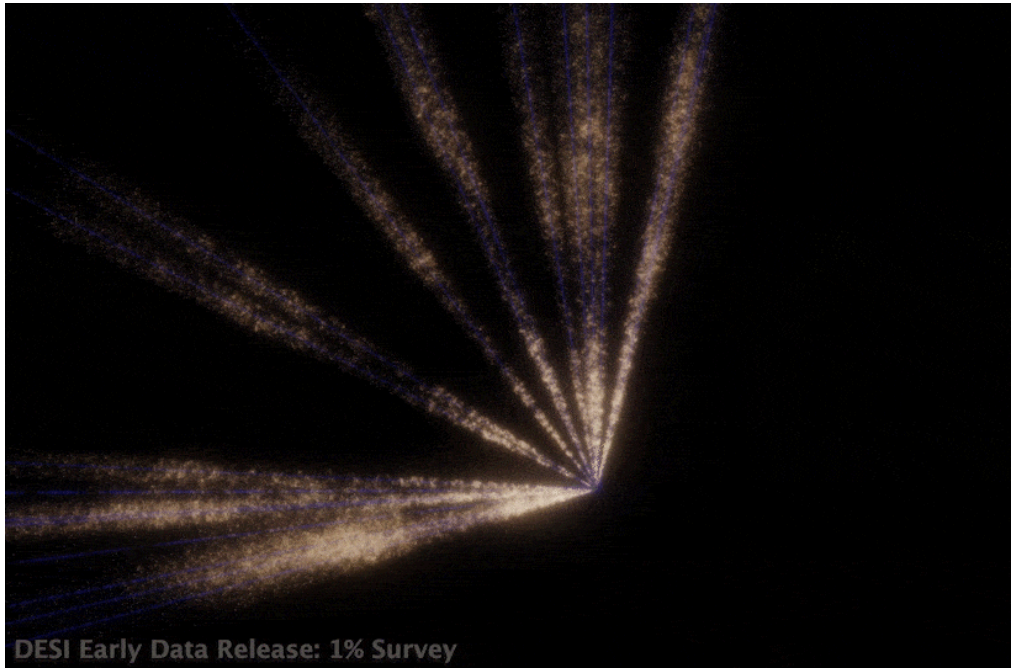


DESI Early Data Release (EDR)

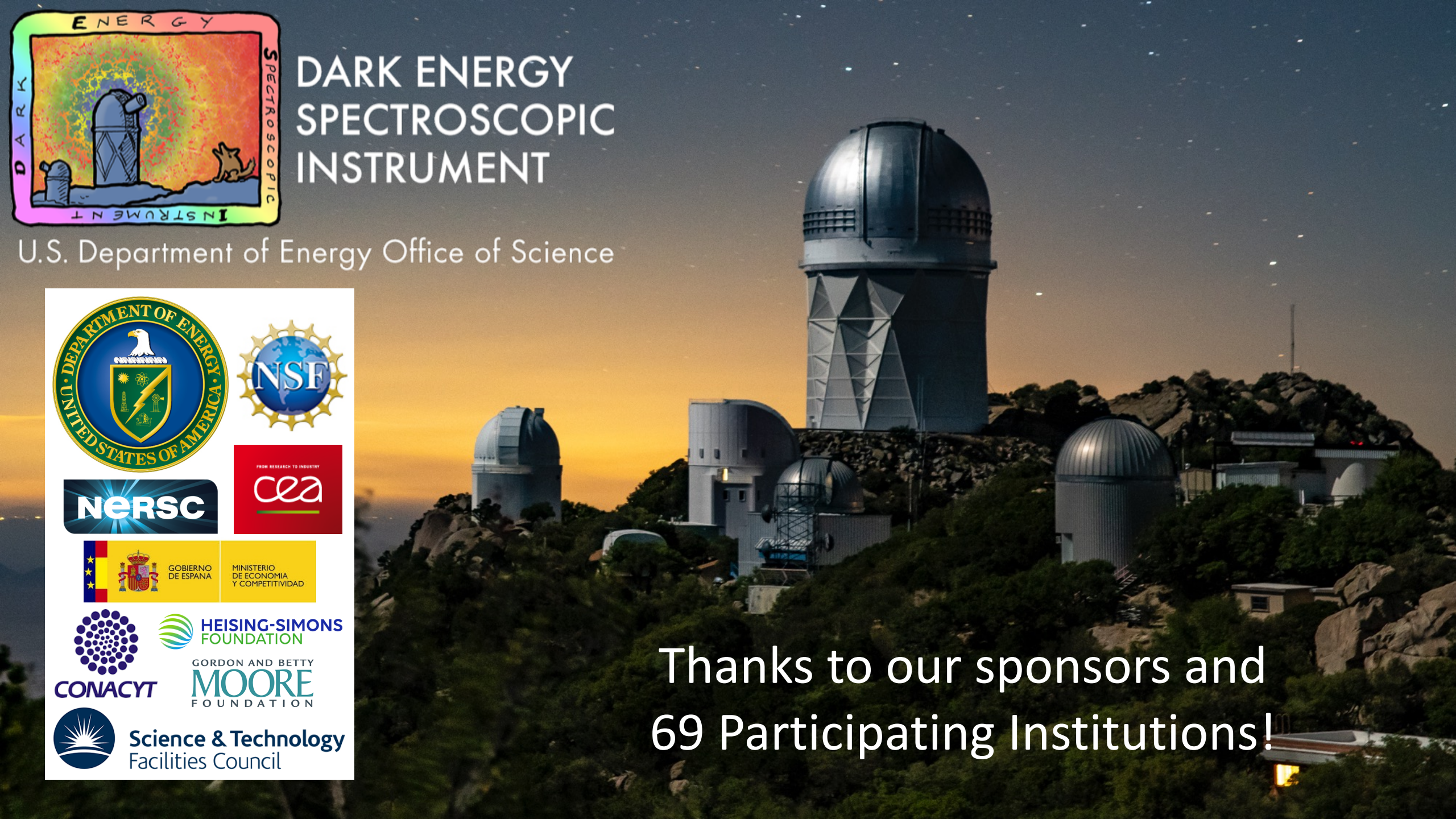
- Over 1 million redshifts obtained during Survey Validation (SV, Dec 2020– May 2021)
- Includes 4 different tracers to cover a wide redshift range, but also lots of stars!
- Redshifts and spectra were made public in June 2023: the Early Data Release (EDR)
- See https://data.desi.lbl.gov/doc



Summary



- Open questions in fundamental physics can be addressed with cosmology
- Dark Energy can be constrained by measuring both expansion and growth
- Combining cosmological probes is the only way forward
- The Dark Energy Spectroscopic Instrument is observing at full speed!
- New state of the art for dark energy, modified gravity and neutrinos masses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Baryon Acoustic Oscillations (BAO)

We can relate redshift to distance if we have a cosmological model

Comoving distance $$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

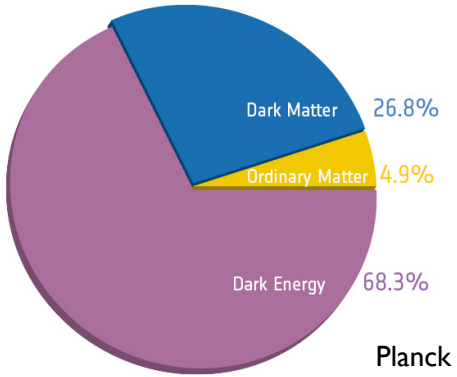
H_0: Hubble constant (current expansion rate)

$H(z')$: Hubble parameter (expansion rate)

$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2$$

Radiation **Dark Energy**

Matter (baryonic or dark) **Curvature**



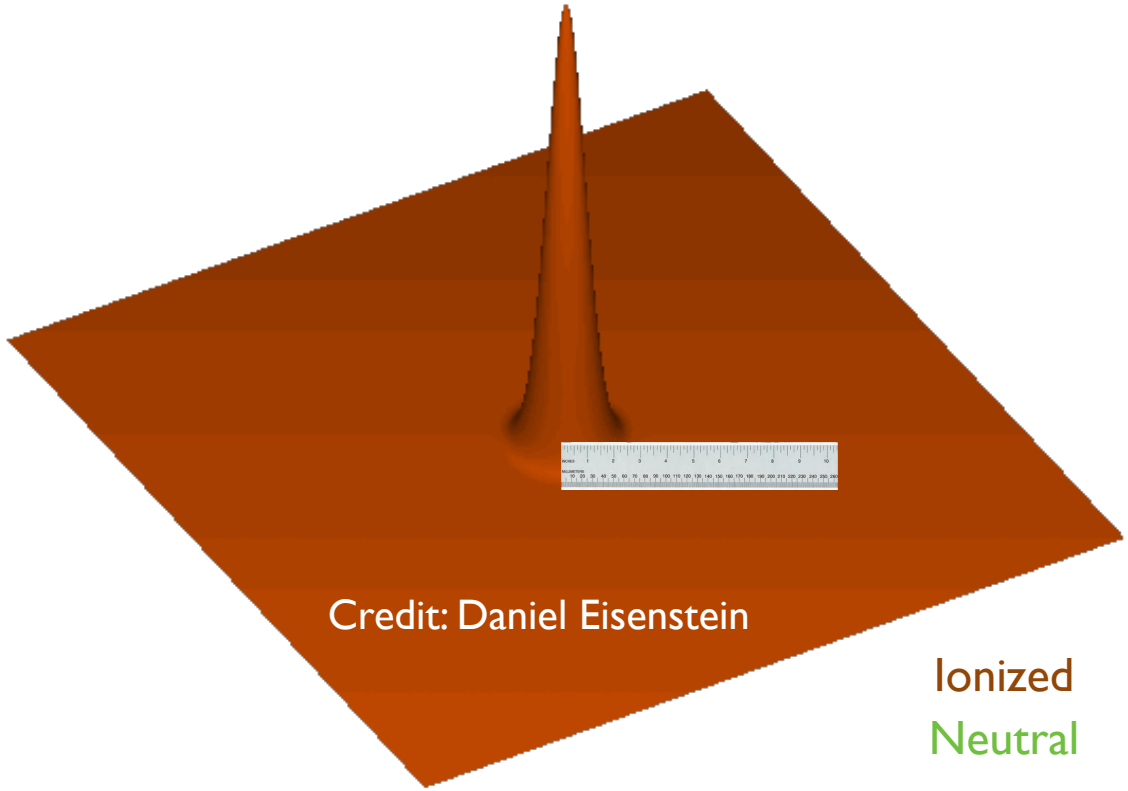
Planck satellite

Baryon Acoustic Oscillations (BAO)

Before recombination (z >1100), photons and ionized matter were tightly coupled

Primordial density fluctuations generated sound waves in the plasma

These waves froze out at recombination, leaving an imprint at a characteristic scale



Sound horizon at recombination (from Planck): $r_d = 147.6 \pm 0.3$ Mpc

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \qquad c_s(z) = 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

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We measure BAO peak in the transverse direction in BOSS: $\Delta\theta_{BAO} = \frac{r_d}{1+z} \boxed{\frac{1}{D_A(z)}}$

We can study the expansion!

We measure BAO peak along the line of sight in BOSS: $\Delta v_{BAO} = \frac{r_d}{1+z} \boxed{H(z)}$