Title: Mapping the Universe with eBOSS

Speakers: Will Percival

Collection: Perimeter Public Lectures

Date: April 07, 2021 - 7:00 PM

URL: https://pirsa.org/21040037

Abstract: In his Perimeter Public Lecture webcast on April 7, 2021, cosmologist Will Percival will aim to help the audience grasp the enormity of space using the latest results from the extended Baryon Oscillation Spectroscopic Survey (eBOSS), which created the largest three-dimensional map of the universe ever made and provided profound insights into the physics of the universe in which we live.

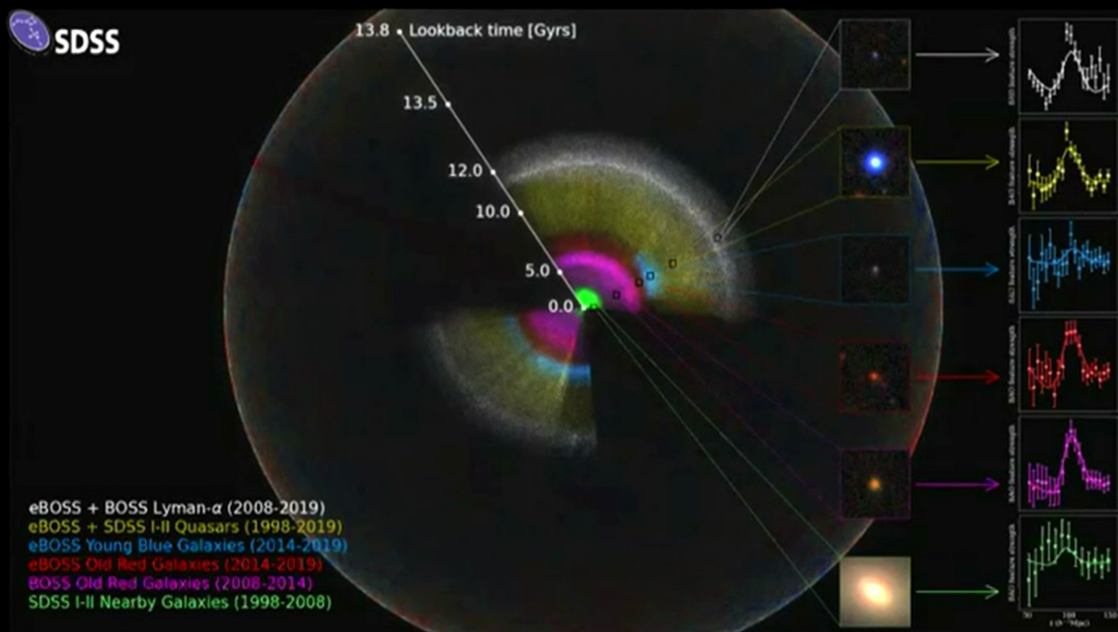
Recording...

PowerPoint Slide Show – [PI-07-04-2021]

Mapping the Universe with eBOSS

Will J. Percival

Director, Waterloo Centre for Astrophysics, University of Waterloo,
Mike and Ophelia Lazaridis Distinguished Chair in Astrophysics
Associate faculty, Perimeter Institute for theoretical physics

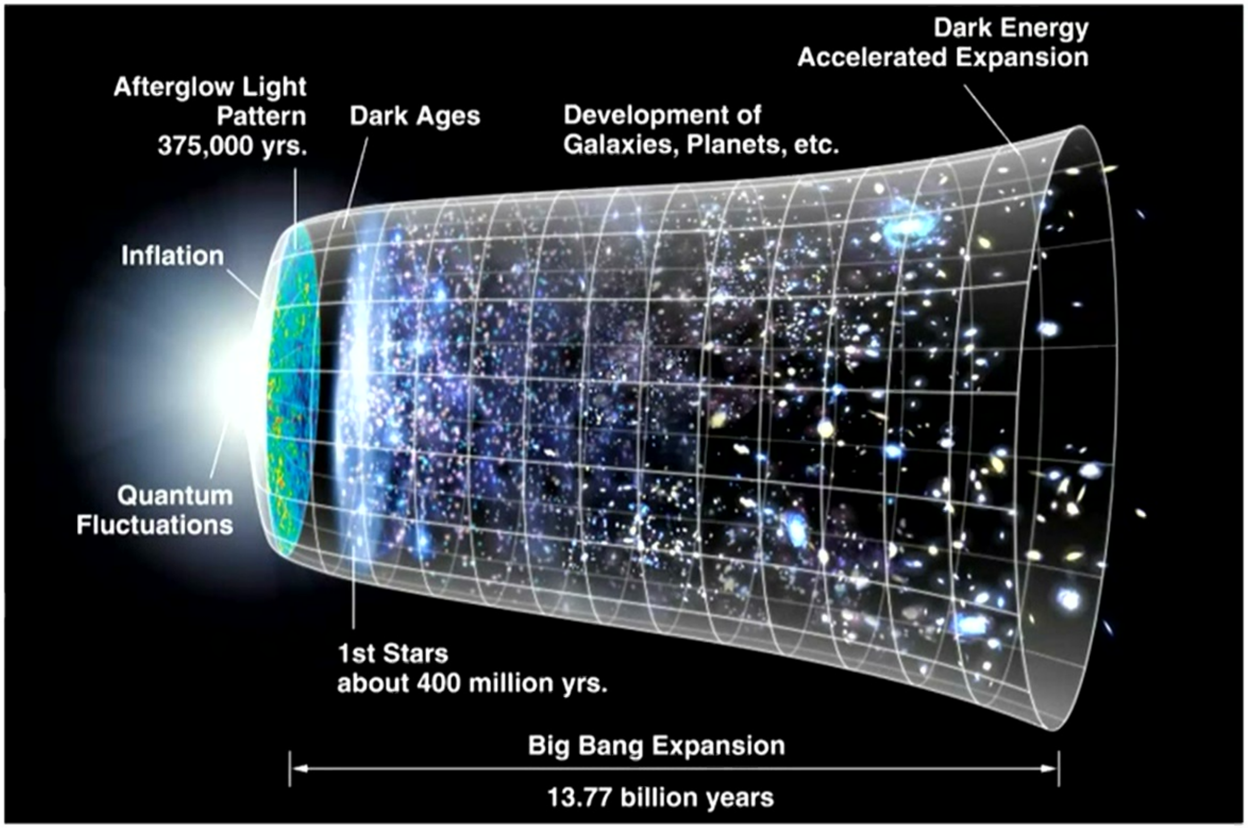


PowerPoint Slide Show – [PI-07-04-2021]

A quick review of modern cosmology

WATERLOO CENTRE FOR ASTROPHYSICS
UNIVERSITY OF WATERLOO

The evolution of the Universe



 https://map.gsfc.nasa.gov/resources/otherimages.html

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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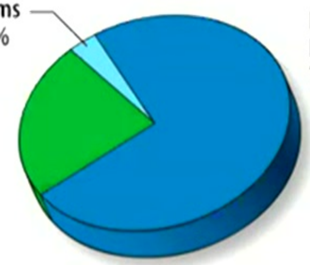
Dark Matter & Dark Energy



Whenever we "weigh" objects on scales larger than the solar system we find more matter than we expect based on the light emission

Models to the early Universe also require a dominant component of matter that does not interact with light: Dark Matter

On cosmological scales we see that the expansion of the Universe is accelerating. But if only gravity was acting on matter, we would expect deceleration. Postulate Dark Energy (just a name given – does not convey information!) to solve this. Can be described by Einstein's cosmological constant Λ (Lambda) in his famous Field equation:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

https://chandra.harvard.edu/photo/2008/bullet/

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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The standard model for cosmology

Rate of growth of the scale factor

Matter density

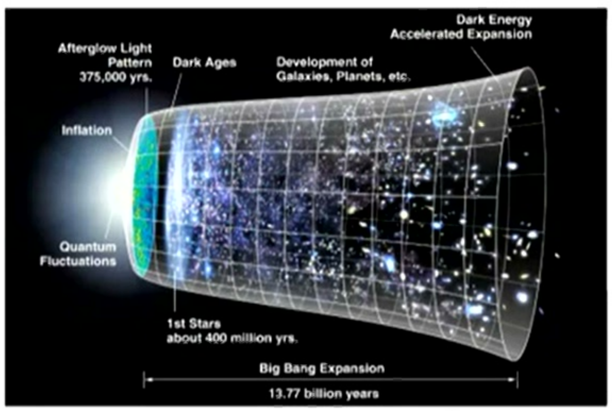
$$\frac{H^2}{H_0^2} = \Omega_M a^{-3} + (1 - \Omega_M)$$

Mathematically simple

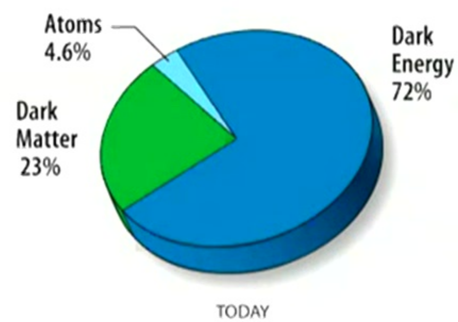
Physically hard to explain:

- What is Dark Matter?
- What is Dark Energy?
- Why do they have the densities that they do?

Scale factor, a



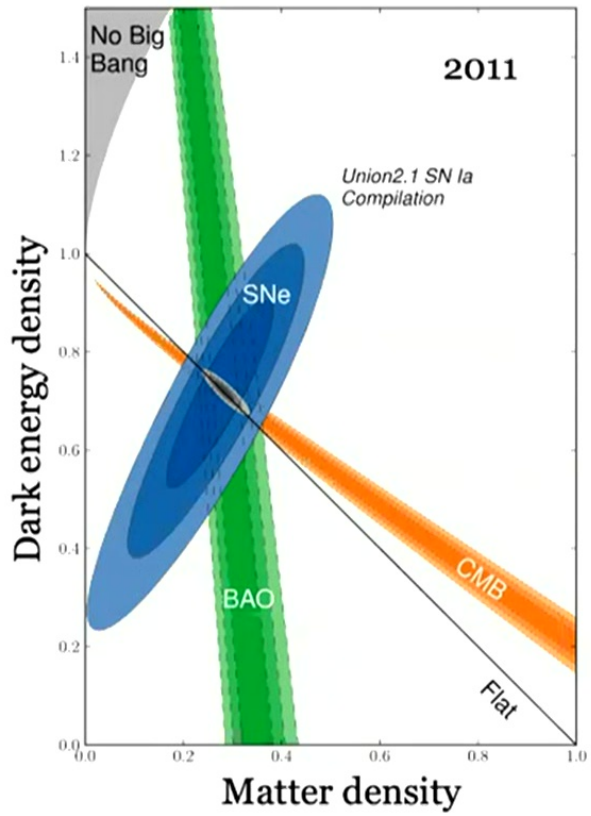
time



https://map.gsfc.nasa.gov/resources/otherimages.html

PowerPoint Slide Show – [PI-07-04-2021]

The standard model for cosmology



 Supernovae cosmology project; http://supernova.lbl.gov/Union/

PowerPoint Slide Show – [PI-07-04-2021]

Recording...

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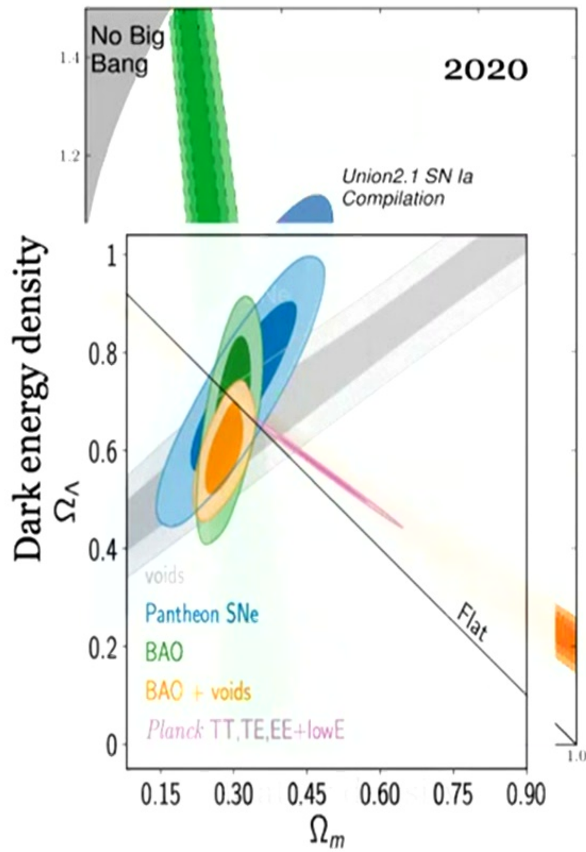
The standard model for cosmology



Mapping the Universe with eBOSS PAGE 7 Nadathur et al. PRL124, 221301 (2020) https://arxiv.org/abs/2001.11044

PowerPoint Slide Show – [PI-07-04-2021]

Recording...

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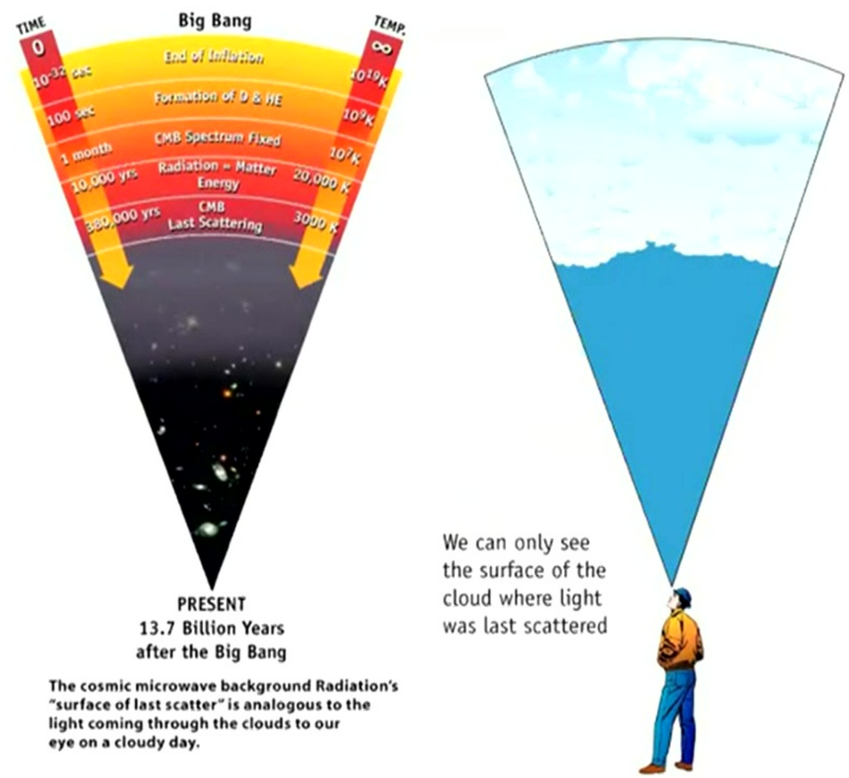
The Cosmic Microwave Background

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

The cosmic microwave background



 https://map.gsfc.nasa.gov/resources/otherimages.html

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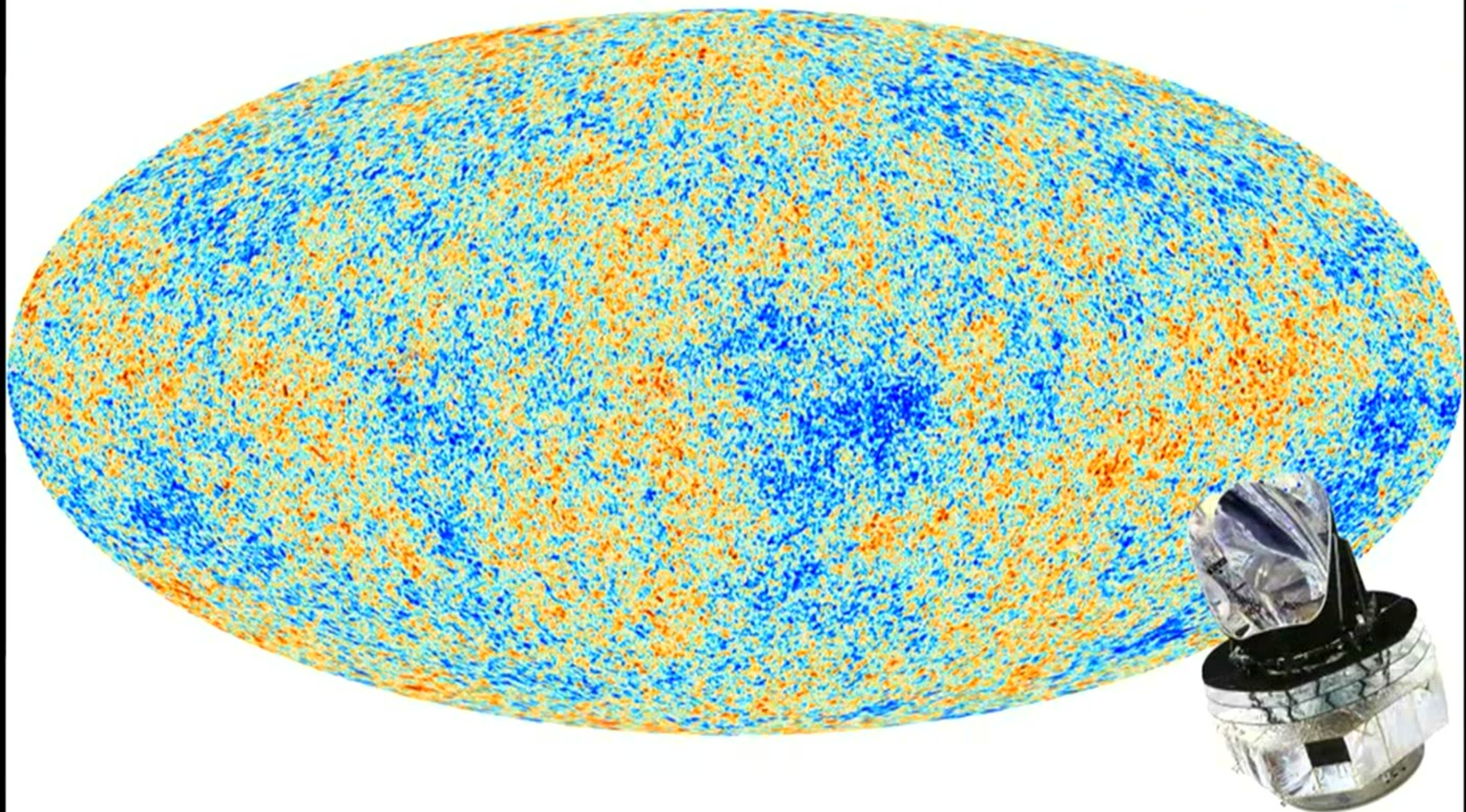
Fluctuations in the CMB



 https://www.cosmos.esa.int/web/planck

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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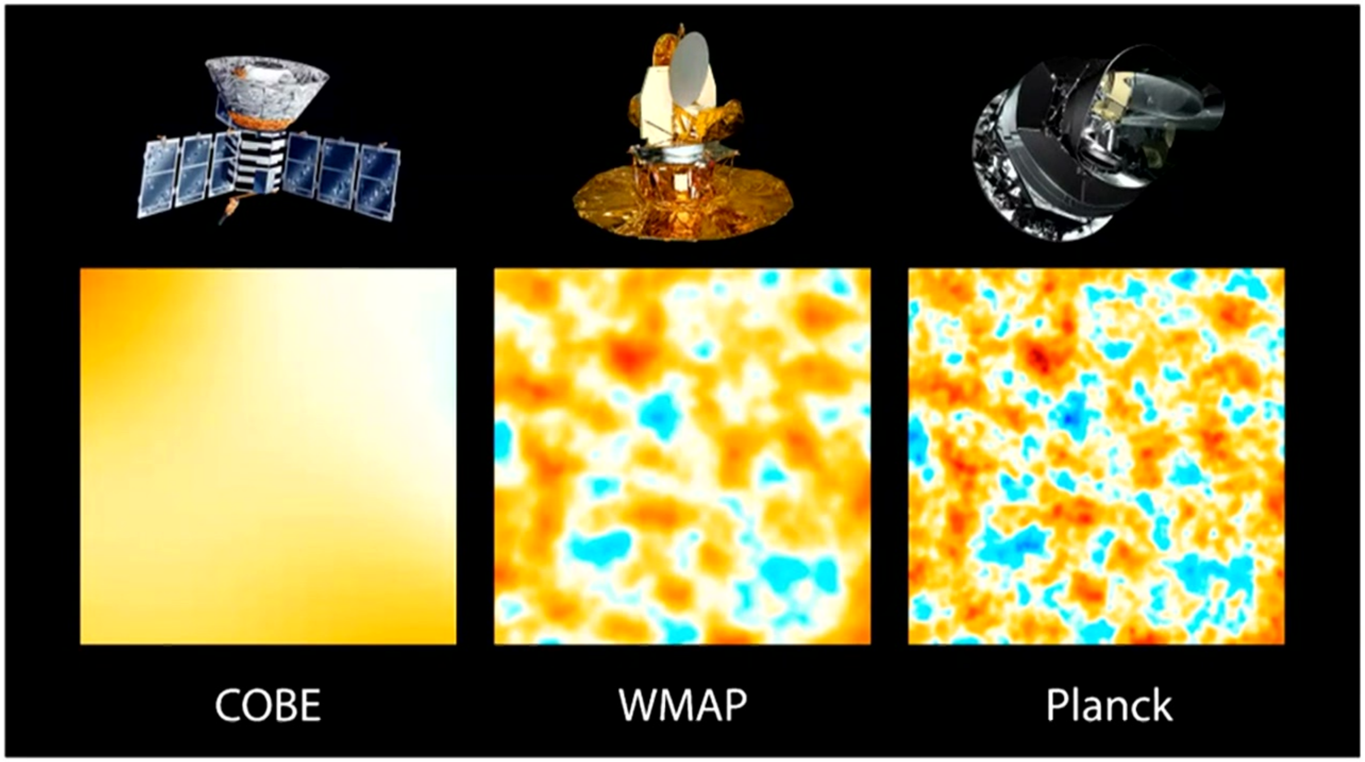
Fluctuations in the CMB

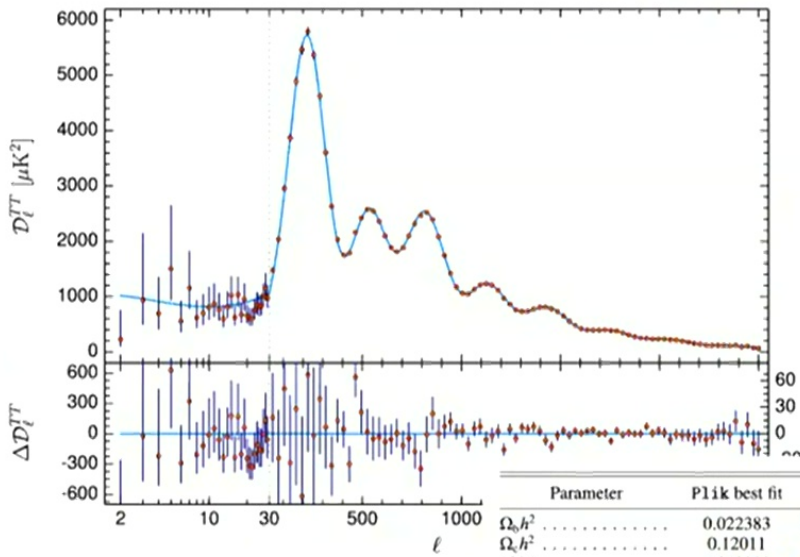


Mapping the Universe with eBOSS PAGE 11 https://www.nasa.gov/mission_pages/planck

PowerPoint Slide Show – [PI-07-04-2021]

Recording...

Parameters from the CMB



Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10}A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

https://arxiv.org/abs/1807.06209

PowerPoint Slide Show – [PI-07-04-2021]

Recording...

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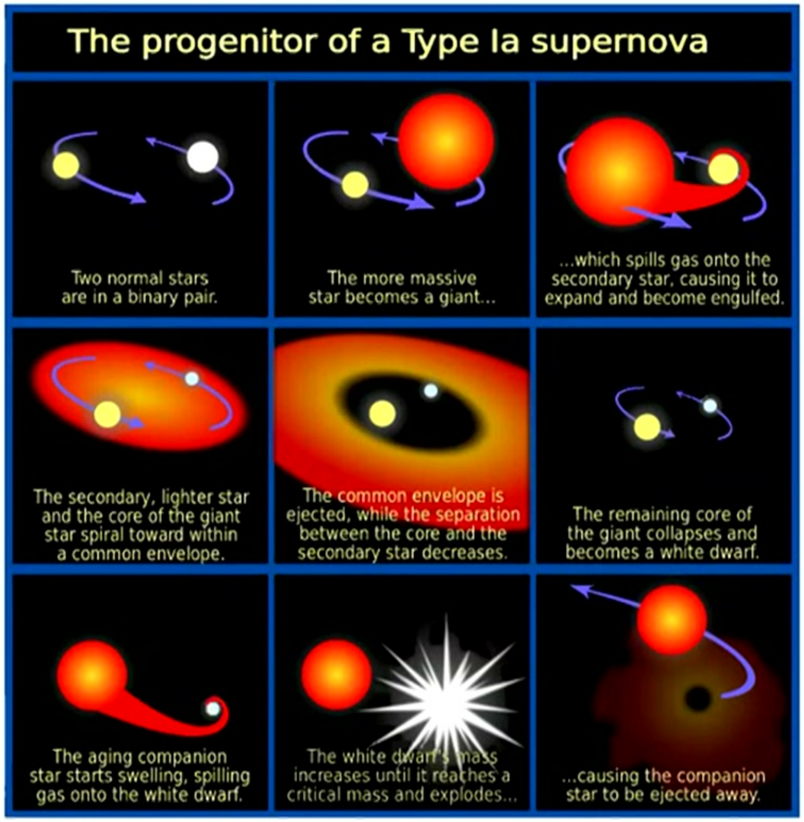
Supernovae as standard candles

PowerPoint Slide Show – [PI-07-04-2021]

Type 1a supernovae

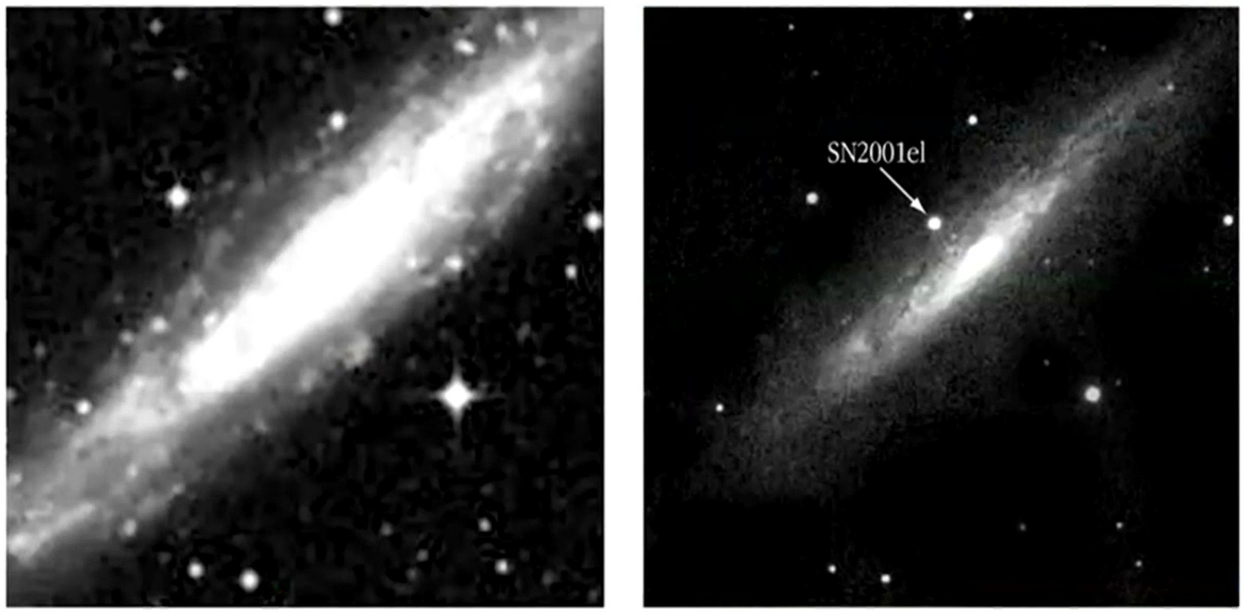


 https://hubblesite.org/image/1620/category/84-supernovae

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

Type 1a supernovae

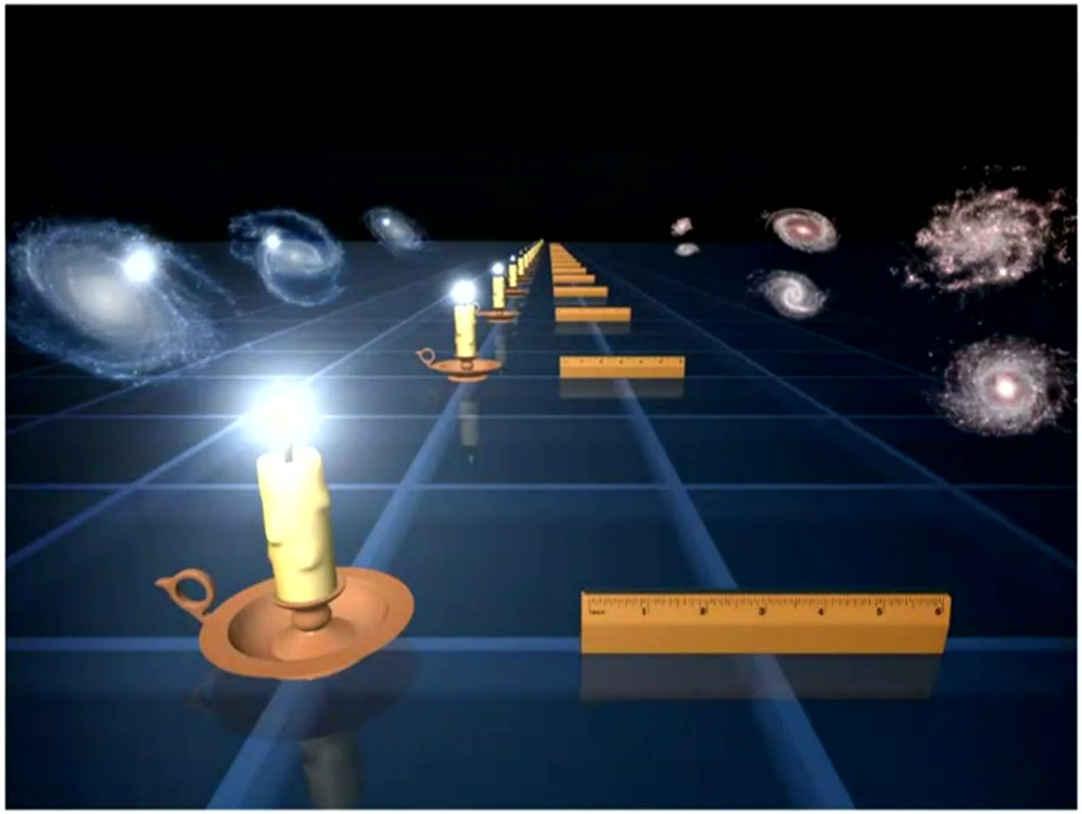


 ESO press release https://www.eso.org/public/news/eso0325/

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

Type 1a supernovae as standard candles

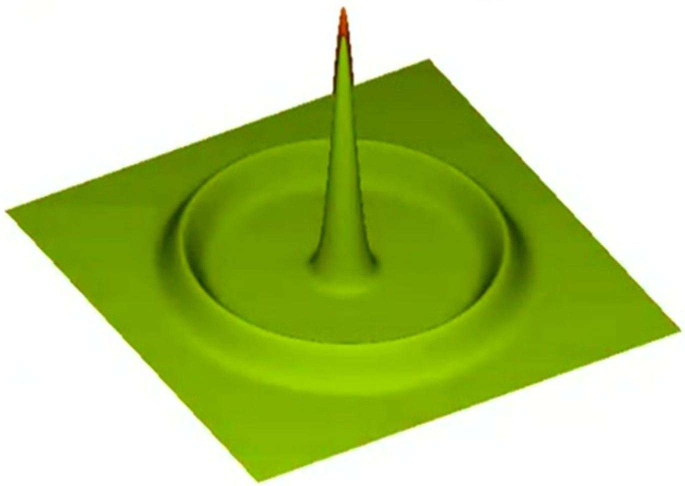


PowerPoint Slide Show – [PI-07-04-2021]

Baryon Acoustic Oscillations as standard rulers

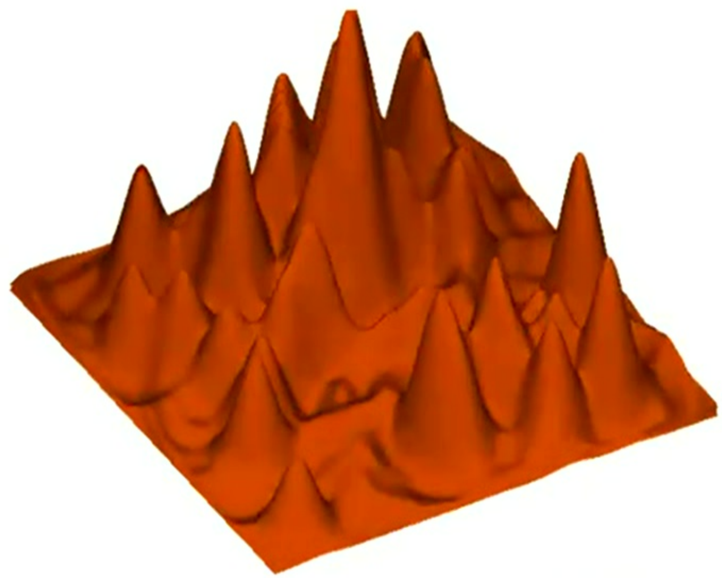
PowerPoint Slide Show – [PI-07-04-2021]

BAO in the early Universe



Single density perturbation in the early Universe (should be in 3D, but hard to plot!)

Sounds wave travels until the Universe cools, and coupling between light and matter ends



A field of perturbations – Peaks are where galaxies grow

 http://galaxies-cosmology-2015.wikidot.com/baryon-acoustic-oscillations

Recording...

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Galaxies

 Hubble XDF www.nasa.gov/mission_pages/hubble/science/xdf.html

Recording...

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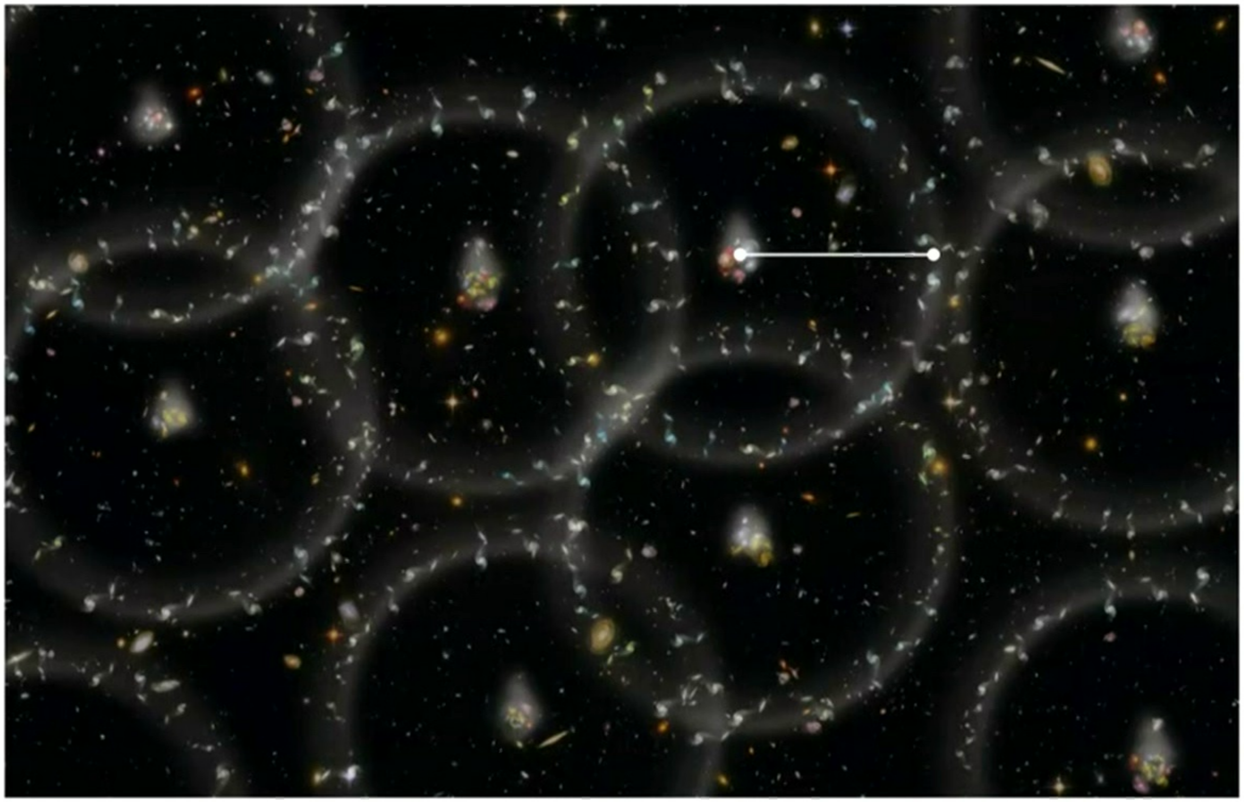
BAO in the late time Universe



Mapping the Universe with eBOSS PAGE 21 Zosia Rostomian, Lawrence Berkeley National Laboratory

BAO as a standard ruler

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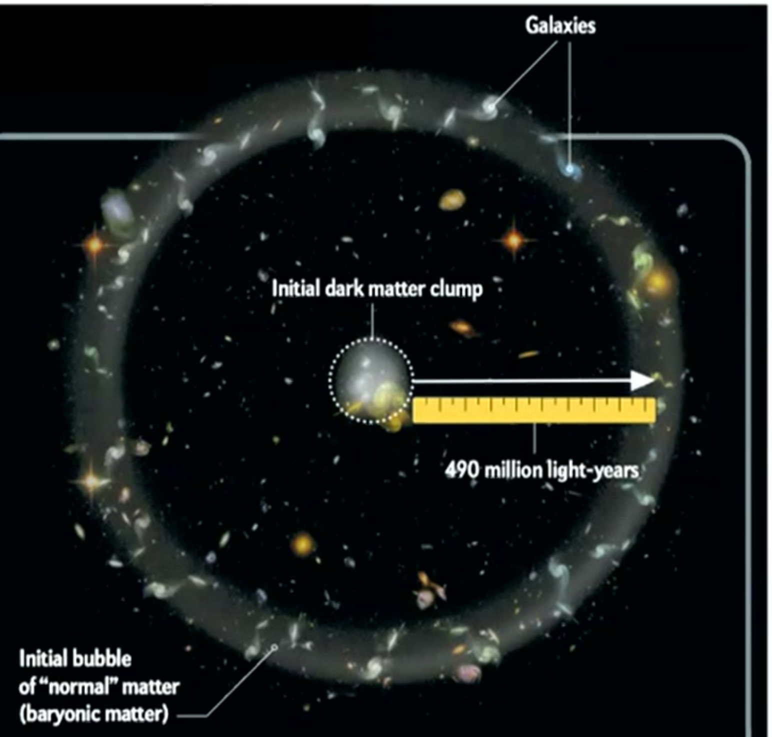
1 START WITH A PATTERN IN SPACE

The eBOSS survey targeted an arrangement seen in galaxies across the universe called baryon acoustic oscillations (BAO). This imprint started with minute fluctuations in the energy throughout spacetime right after the big bang. Because of the way light and matter interacted in the early universe, these fluctuations caused dark matter to form clumps surrounded by spheres of regular matter and light, separated from the dark matter by some 500 million light-years. Over time gravity pulled both types of matter into the clumps of dark matter as well as the spheres of normal matter, leading to a relatively even mixing of dark and normal matter throughout the universe. Eventually galaxies formed everywhere there was matter, resulting in a pattern of cores and shells still seen in the spread of galaxies today.



Mapping the Universe with eBOSS PAGE 22 Dawson & Percival, Scientific American, May 2021

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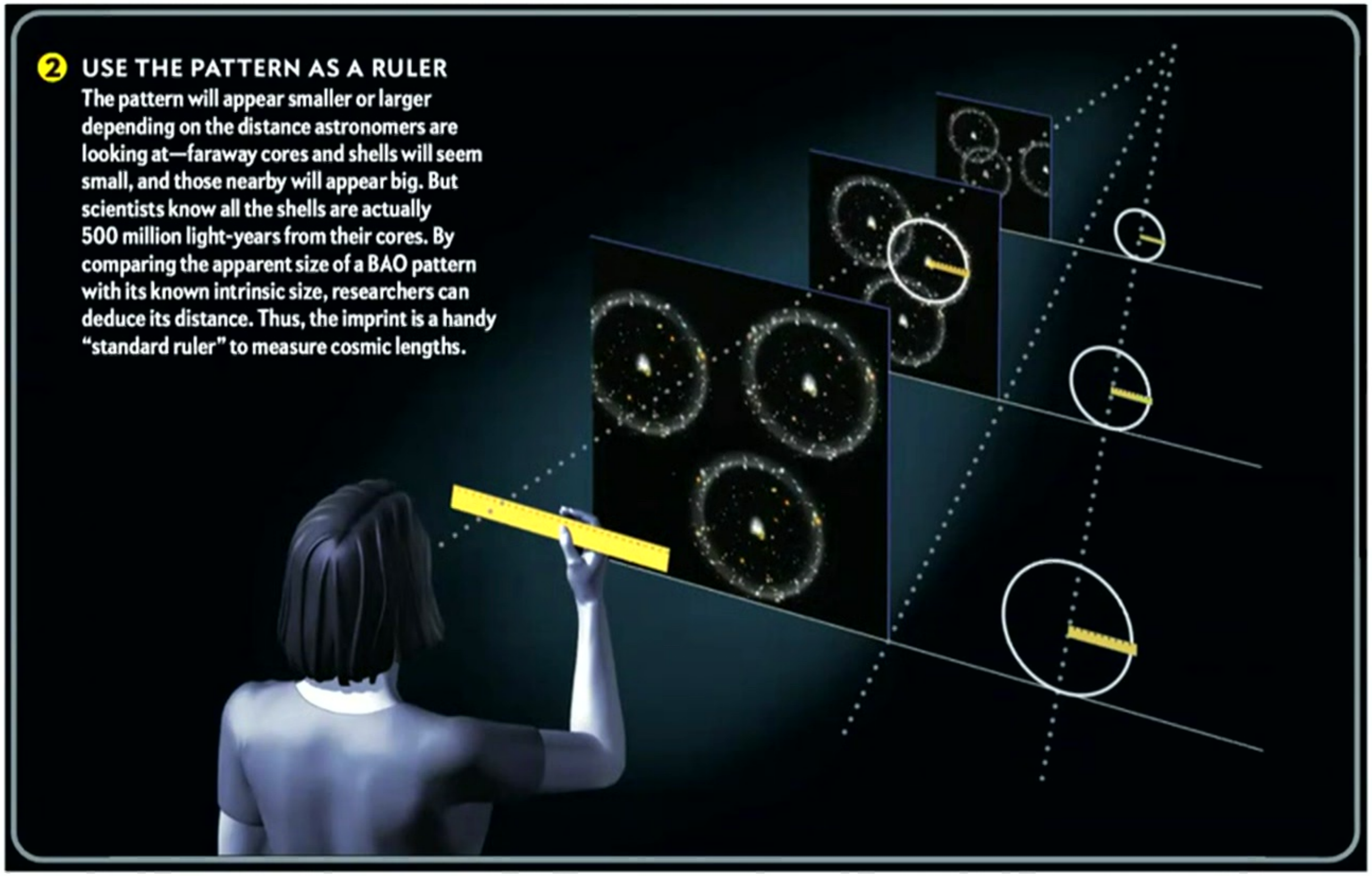
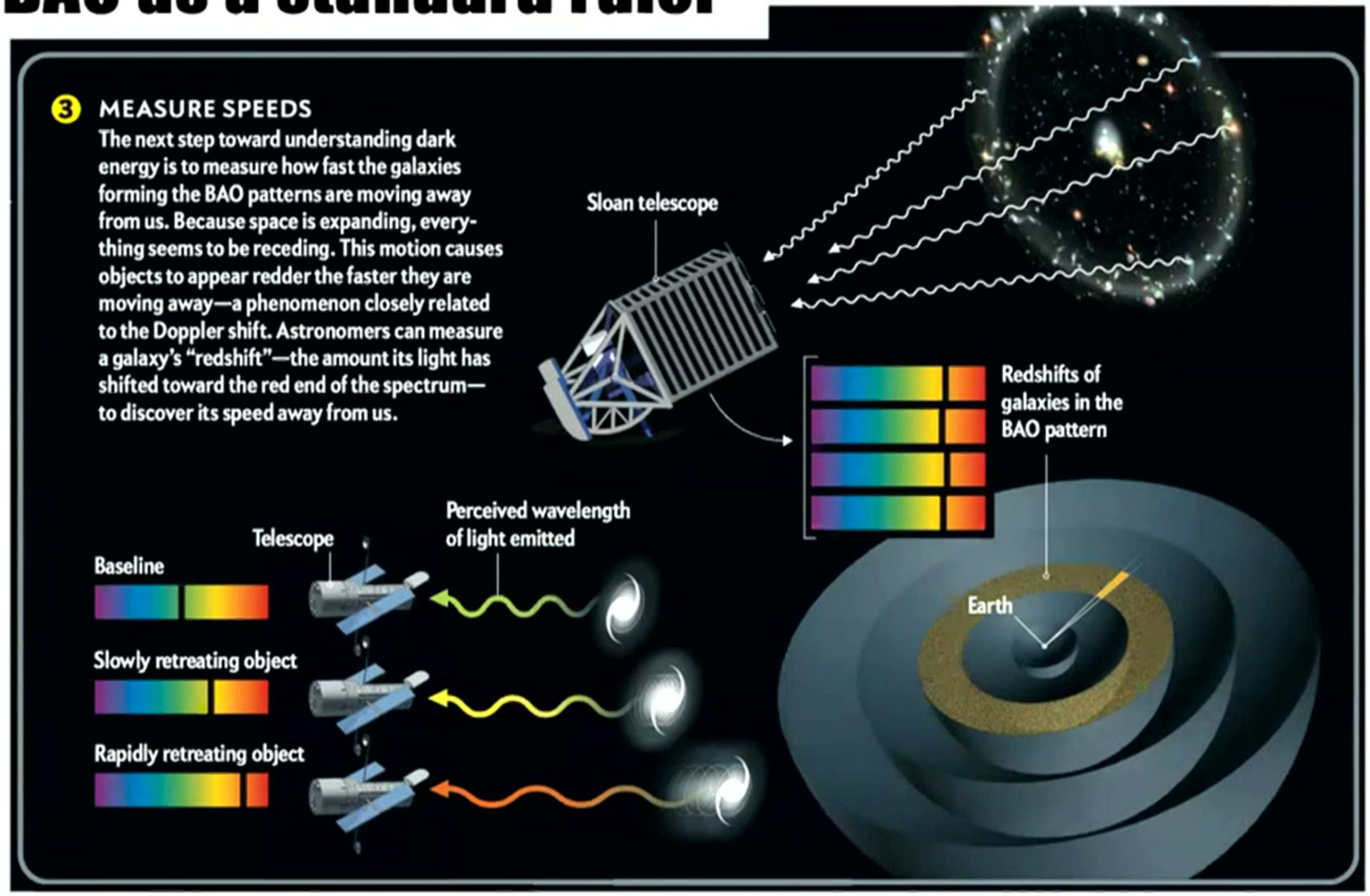
BAO as a standard ruler



PowerPoint Slide Show – [PI-07-04-2021]

BAO as a standard ruler



Mapping the Universe with eBOSS PAGE 24 Dawson & Percival, Scientific American, May 2021

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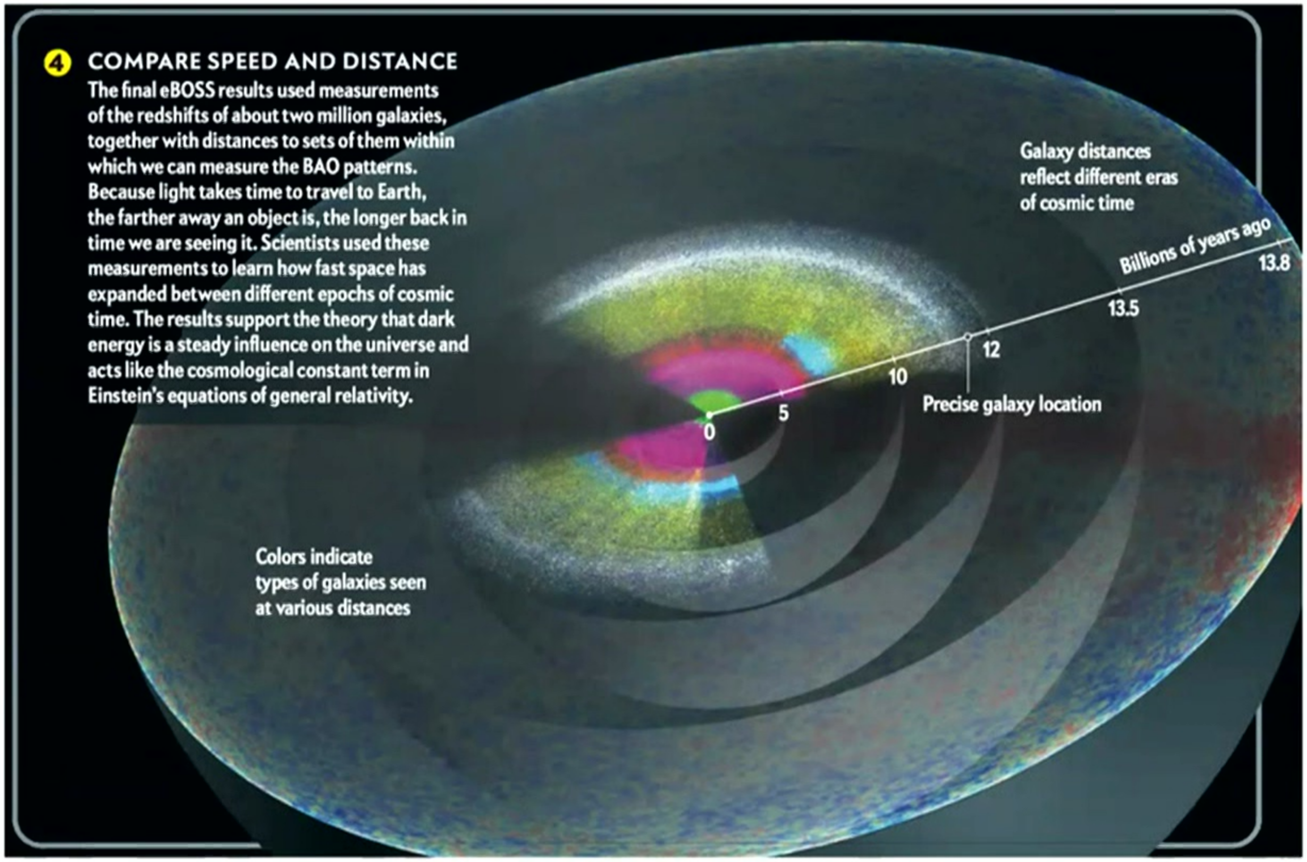
BAO as a standard ruler

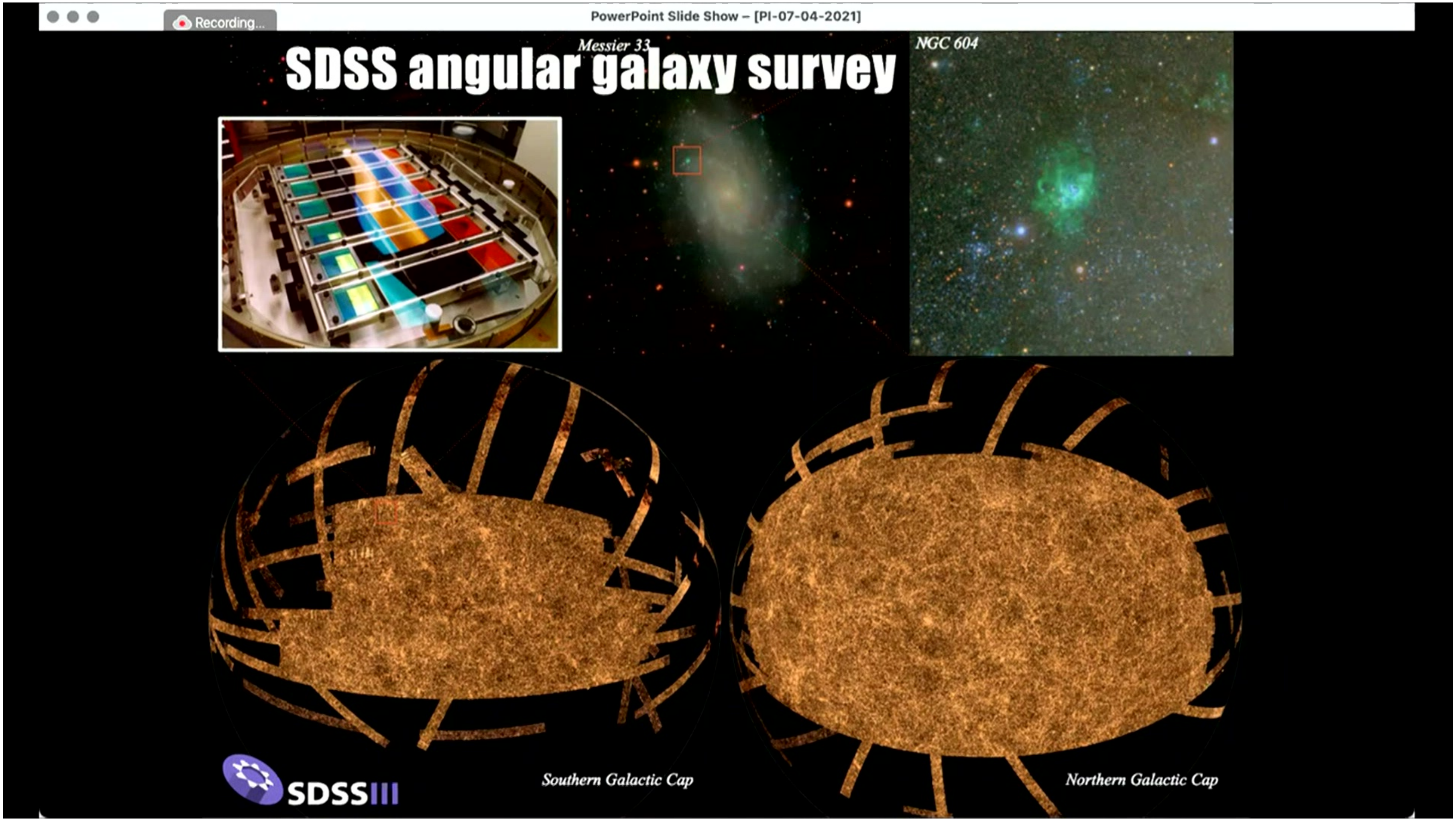


Mapping the Universe with eBOSS PAGE 25 Dawson & Percival, Scientific American, May 2021

PowerPoint Slide Show – [PI-07-04-2021]

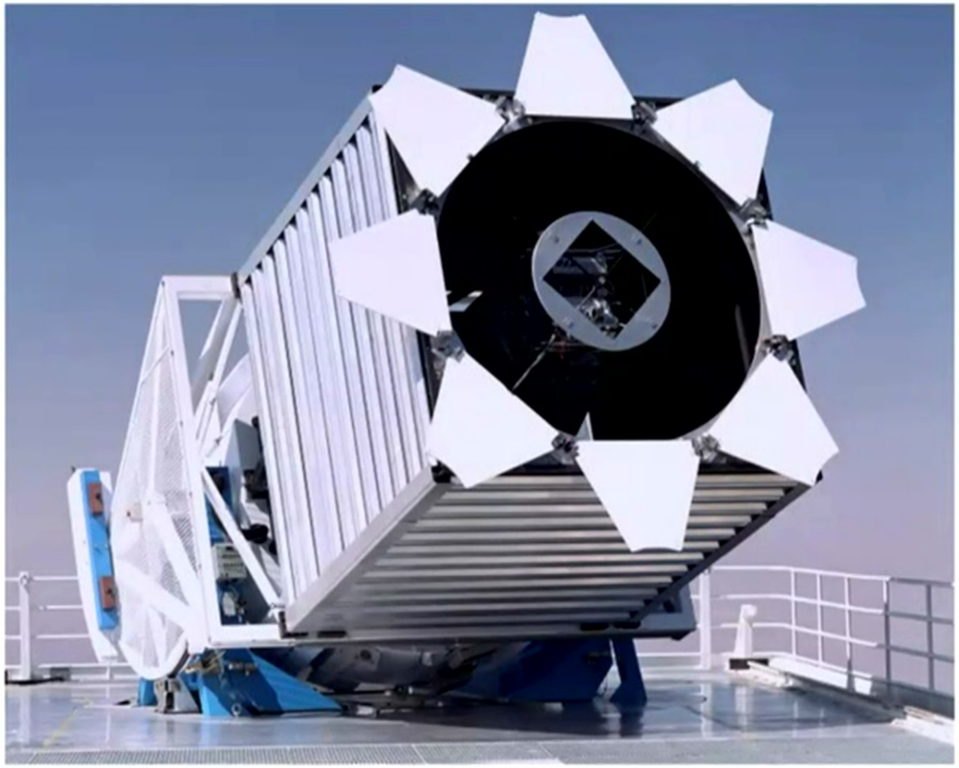
eBOSS (and earlier) experiments

Mapping the Universe with eBOSS PAGE 26


PowerPoint Slide Show – [PI-07-04-2021]
Recording...
SDSS angular galaxy survey
Messier 33
NGC 604
SDSS III
Southern Galactic Cap
Northern Galactic Cap

PowerPoint Slide Show – [PI-07-04-2021]

The Sloan telescope

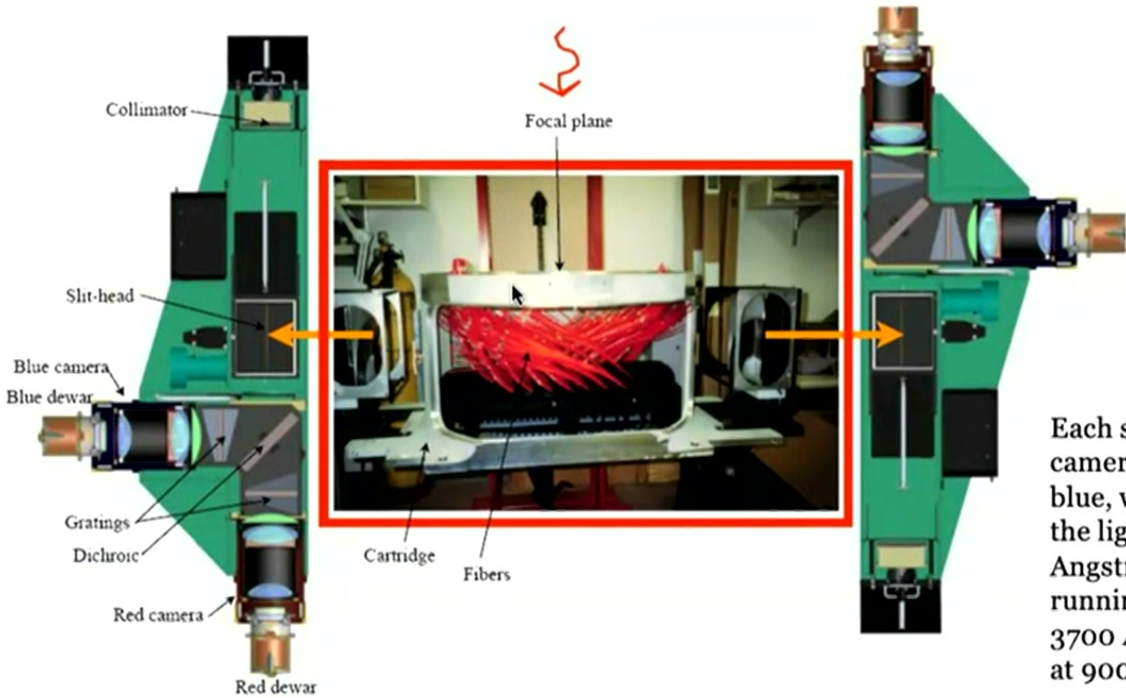


We used a dedicated 2.5m telescope located at Apache Point Observatory, in south east New Mexico. A 1.08 m secondary mirror and two corrector lenses result in a 3° distortion-free field of view.

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

The BOSS spectrographs



Each spectrograph has two cameras, one red and one blue, with a dichroic splitting the light at roughly 6000 Angstroms. The resolution running from R = 1560 at 3700 Angstroms to R = 2650 at 9000 Angstroms.

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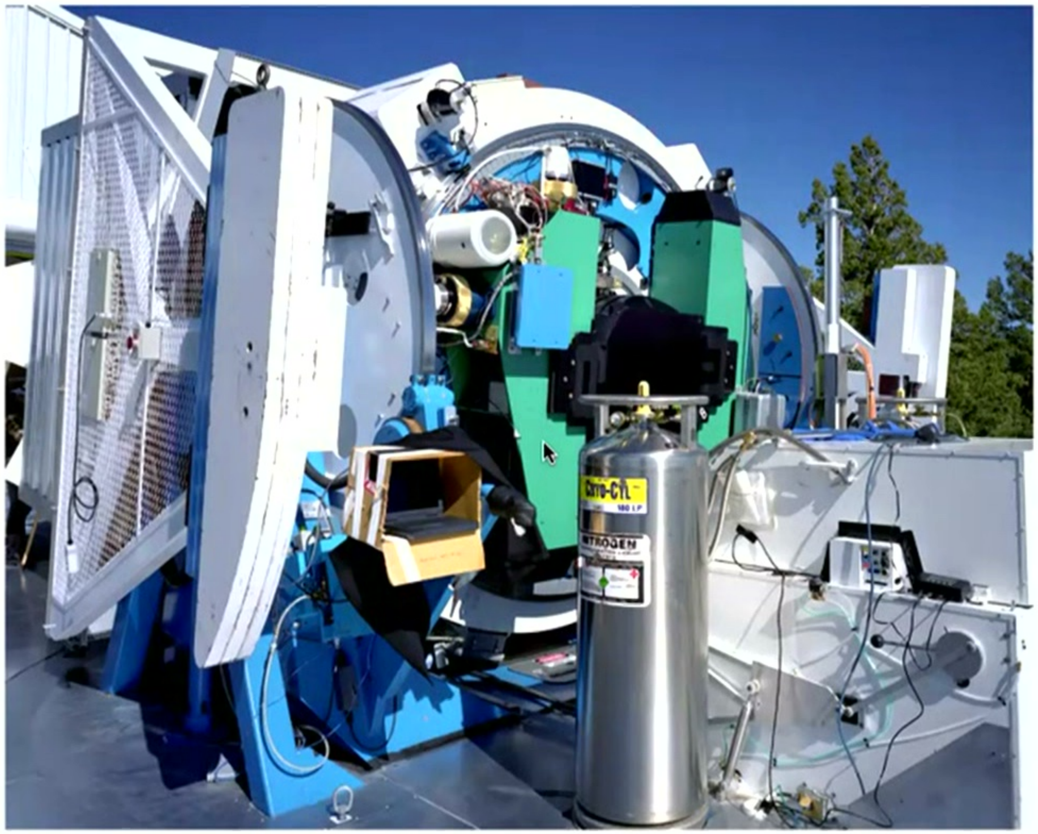
On the telescope



Mapping the Universe with eBOSS PAGE 30 https://www.sdss.org/instruments/boss_spectrograph/

PowerPoint Slide Show – [PI-07-04-2021]

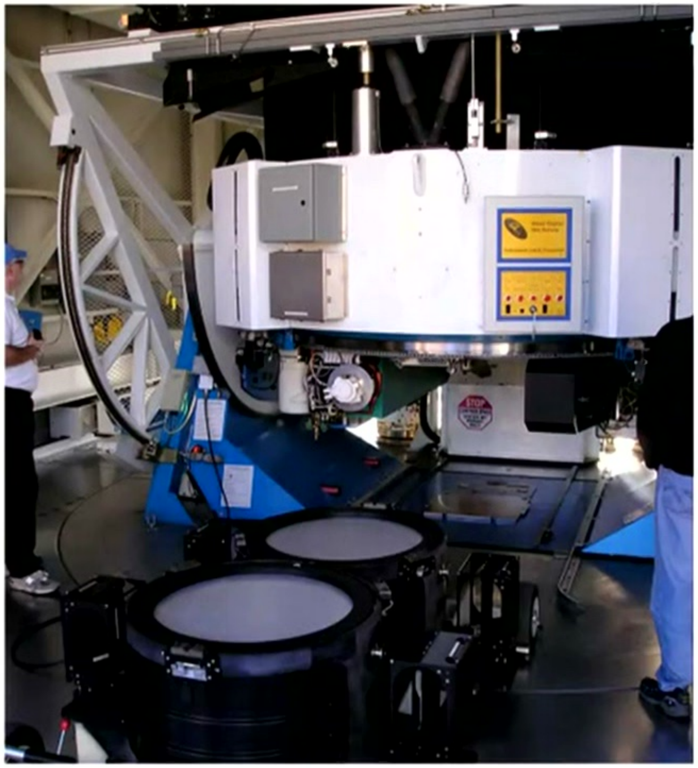
Plug-plates

For eBOSS, for every observation, 1,000 holes are drilled in an aluminum plate (a plug plate, which subtends 3 degrees on the sky), each hole corresponding to an astronomical object such as a quasar, a galaxy, a standard star, or a random blank area on the sky (to measure and subtract the foreground sky emission).

The plug plate is then mounted on a cartridge that can be quickly affixed to the telescope. 1,000 optical fibers with 2 arcsec diameters are plugged into the holes. The fibers send the light from each object into the spectrographs

PowerPoint Slide Show – [PI-07-04-2021]

Night-time operations



Mapping the Universe with eBOSS PAGE 32 https://www.sdss.org/instruments/boss_spectrograph/

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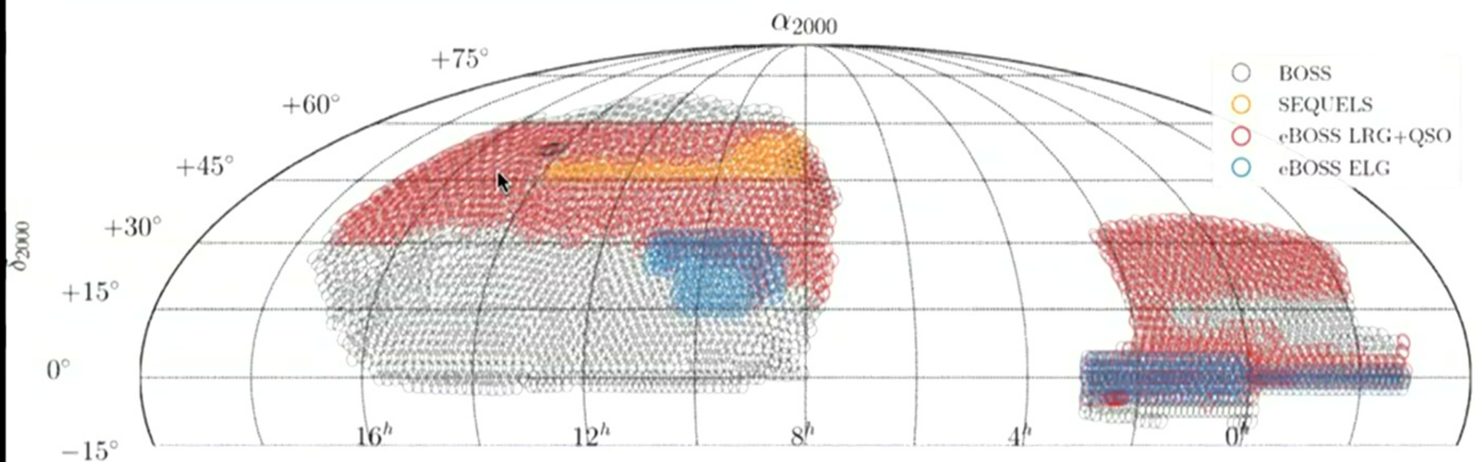
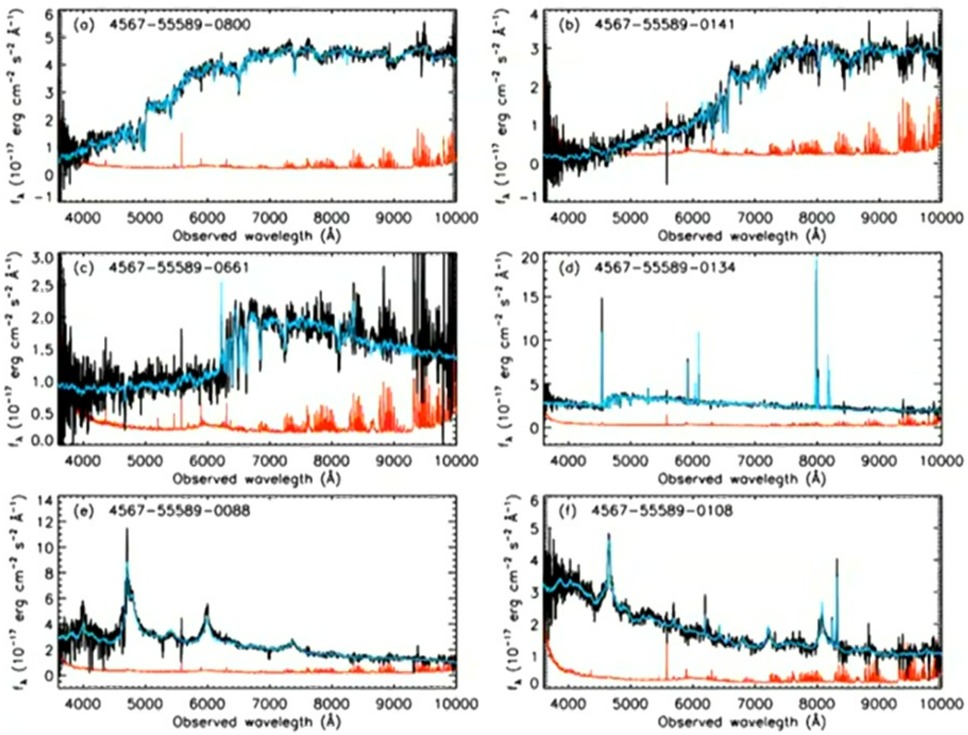
eBOSS sky coverage



eBOSS spectroscopic coverage in equatorial coordinates. Each symbol represents the location of a completed spectroscopic plate scaled to the approximate field of view.

WATERLOO CENTRE FOR ASTROPHYSICS

Galaxy spectra gives recession velocities



Bolton et al. 2012, AJ 144, 20; https://arxiv.org/abs/1207.7326

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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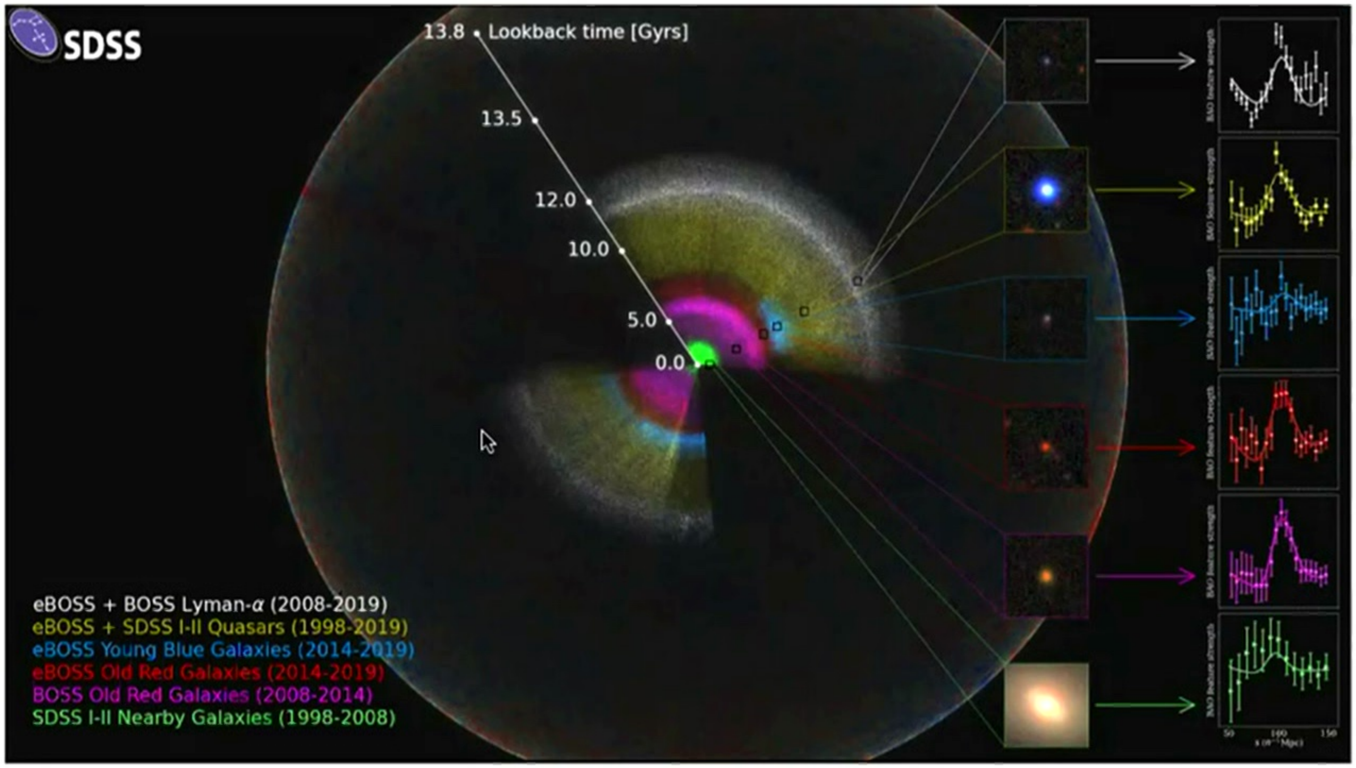
Recession velocity gives distance



Mapping the Universe with eBOSS PAGE 35

Recording...

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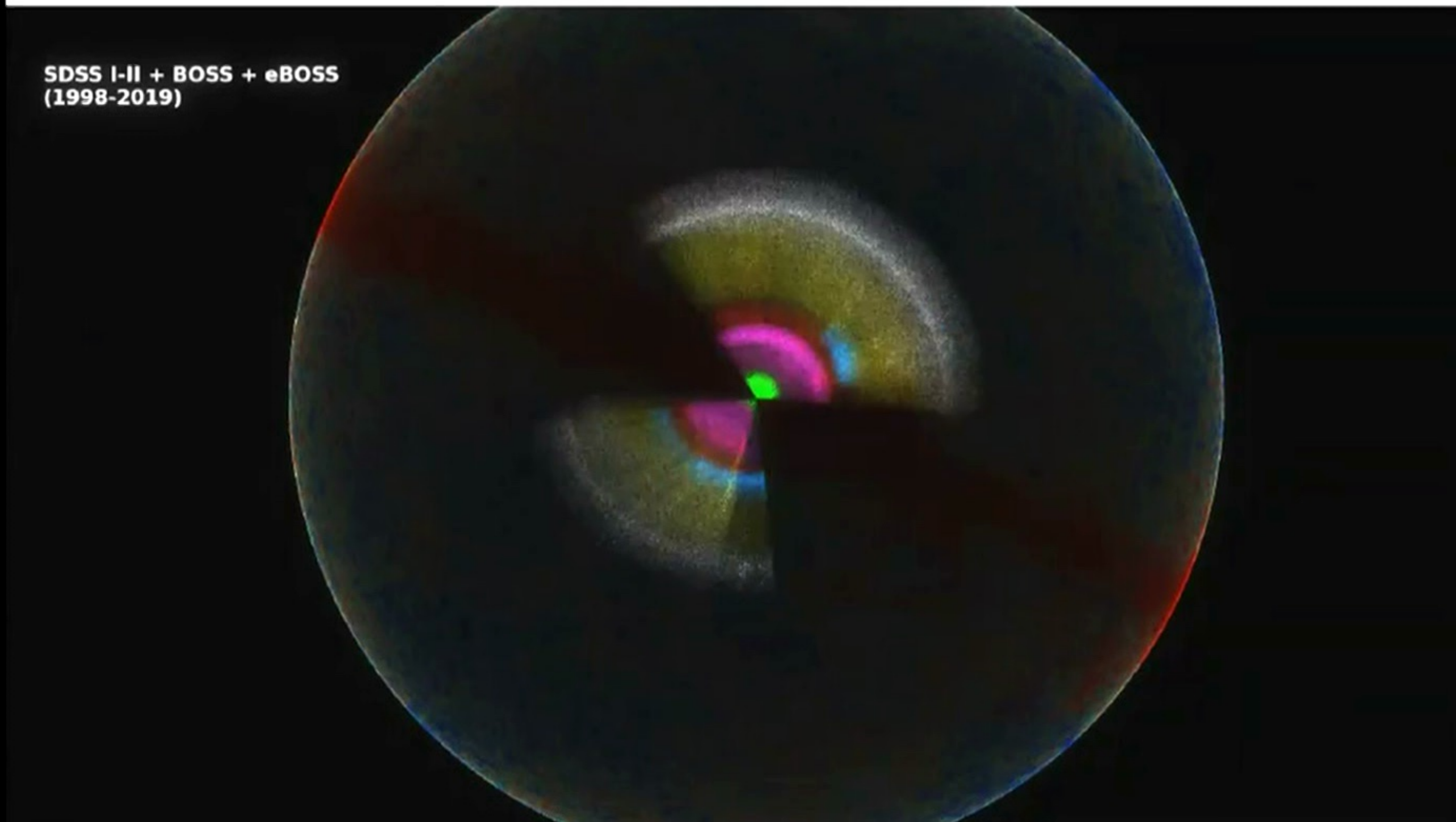
The resulting map



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Recording...

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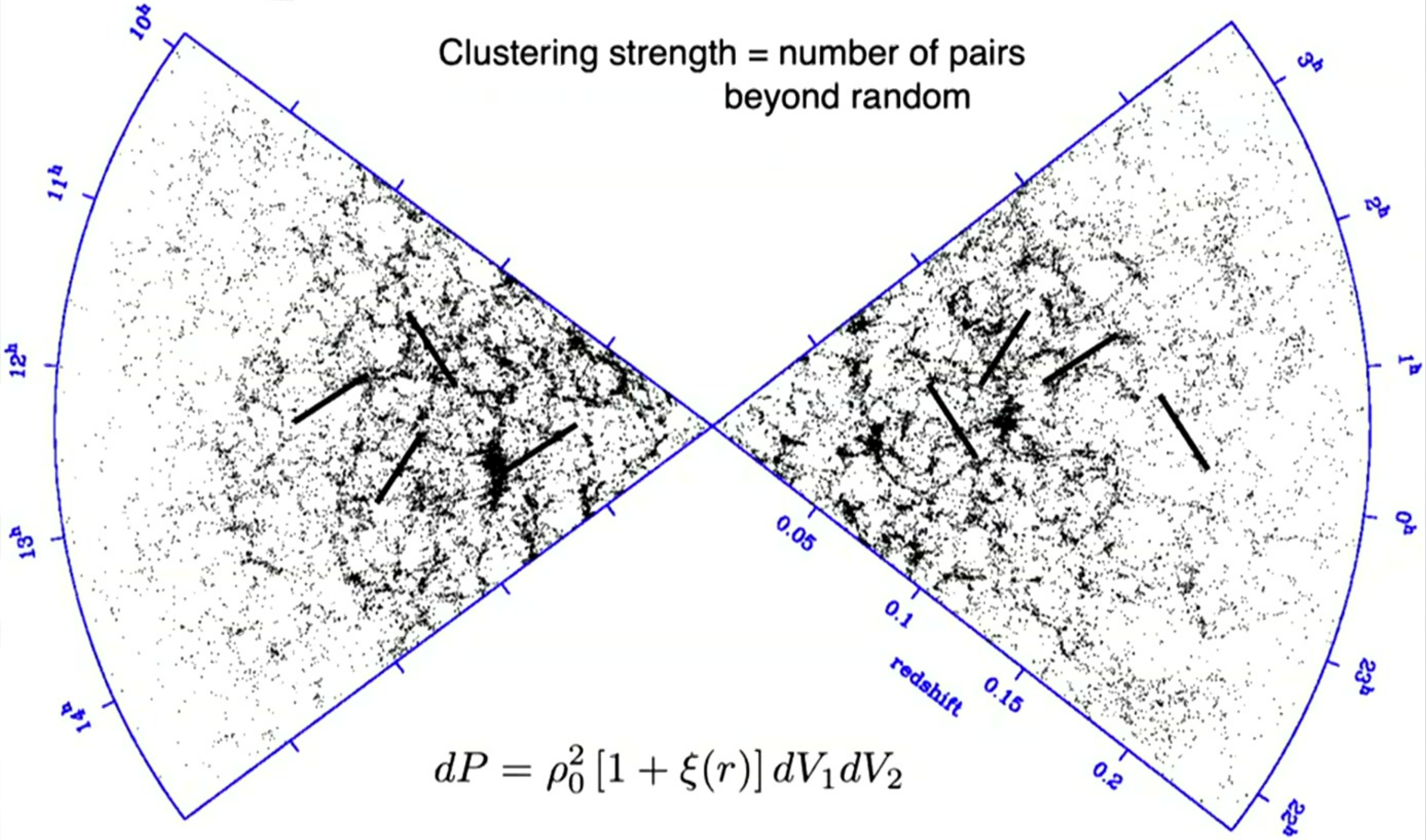
Locating the BAO feature

Clustering strength = number of pairs beyond random



$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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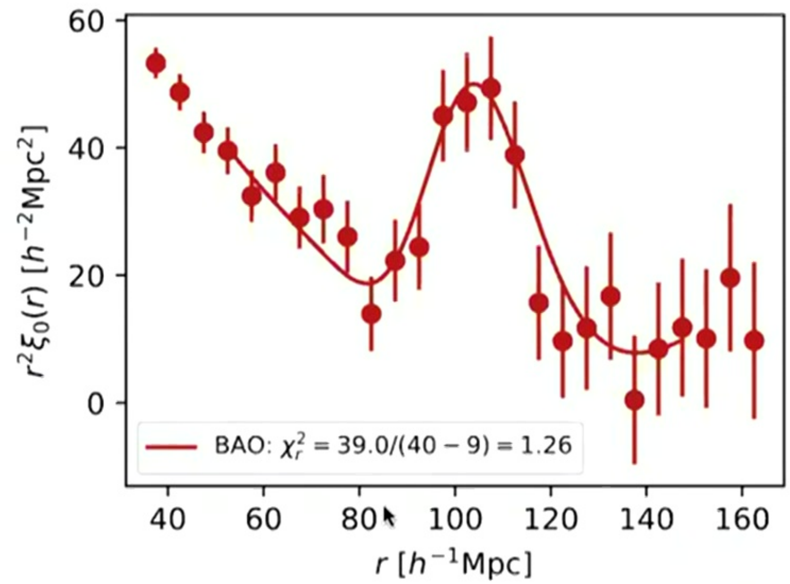
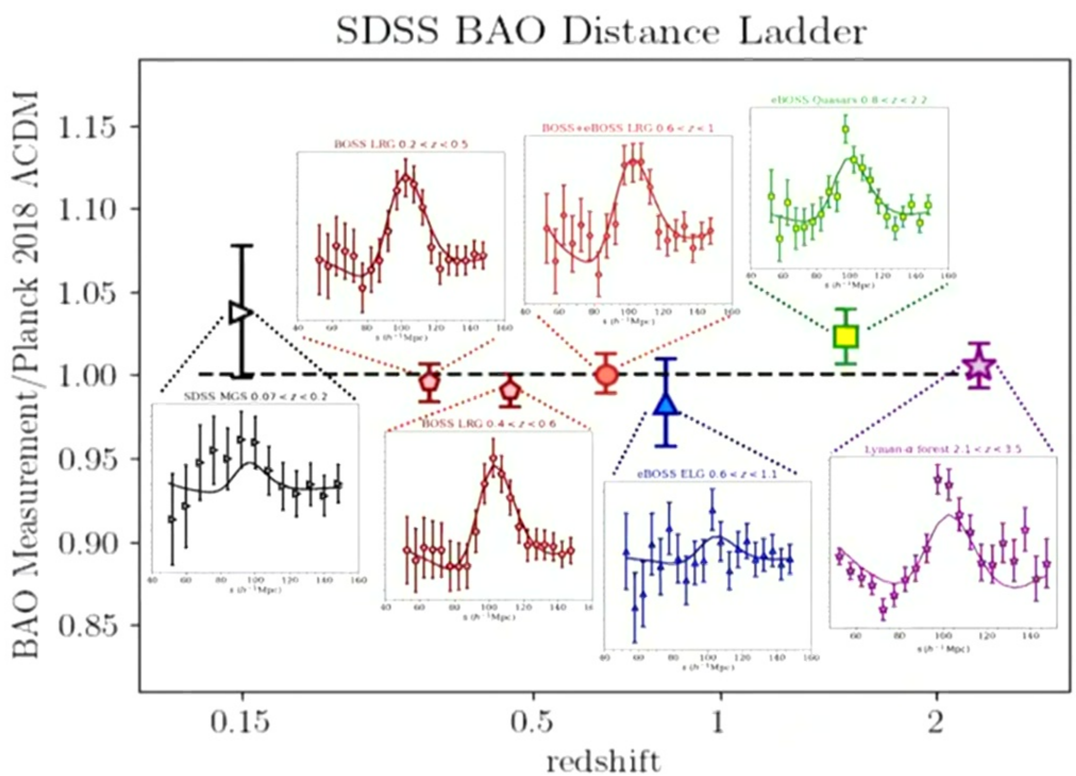
Locating the BAO feature



 Bautista et al. 2020, MNRAS 500, 736; https://arxiv.org/abs/2007.08993

PowerPoint Slide Show – [PI-07-04-2021]

The eBOSS BAO constraints



Mapping the Universe with eBOSS

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The future ...

Recording...

PowerPoint Slide Show – [PI-07-04-2021]

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Dark Energy Spectroscopic Instrument

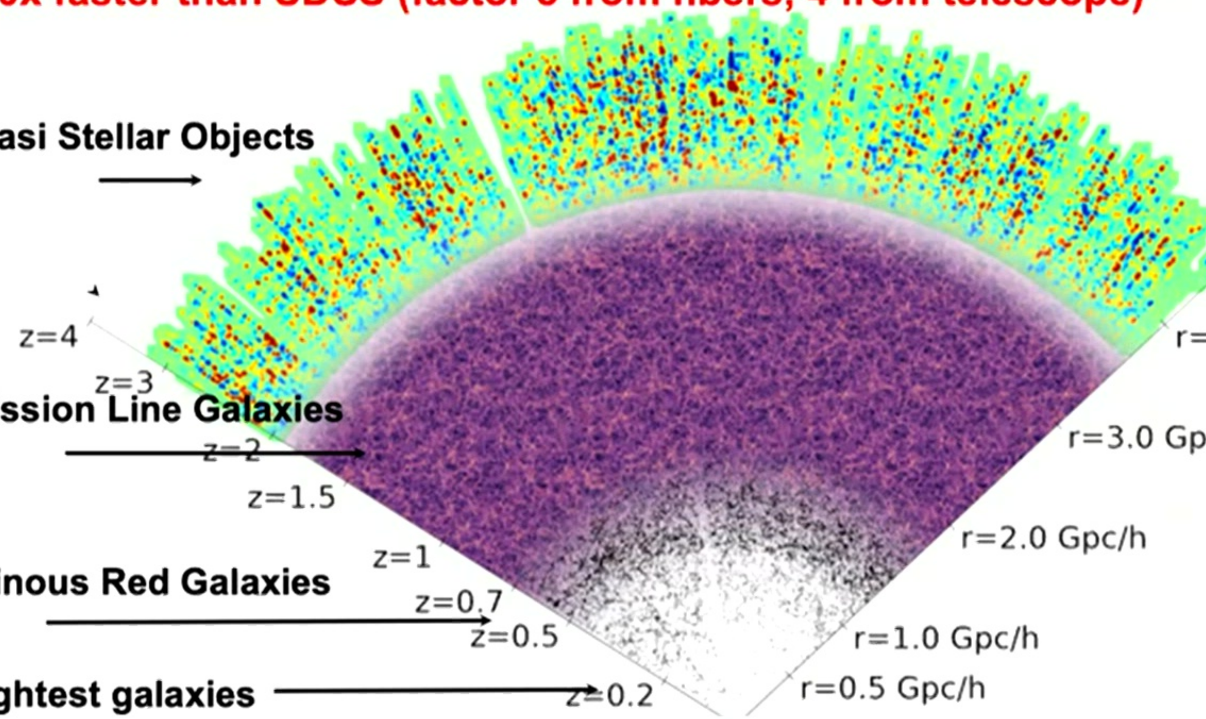
DESI is > 20x faster than SDSS (factor 5 from fibers, 4 from telescope)

2.4 million Quasi Stellar Objects (QSO)

17 million Emission Line Galaxies (ELG)

6 million Luminous Red Galaxies (LRG)

10 million brightest galaxies



PowerPoint Slide Show – [PI-07-04-2021]

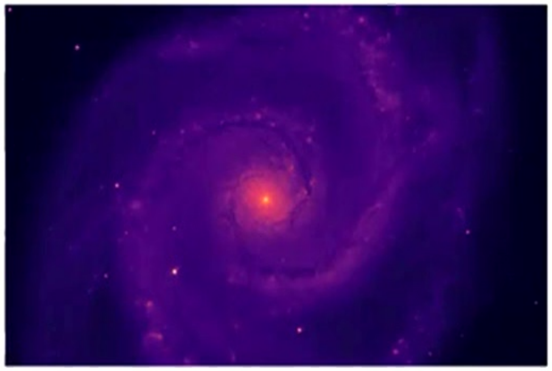
The Mayall telescope

Mapping the Universe with eBOSS PAGE 43 https://en.wikipedia.org/wiki/Nicholas_U._Mayall_Telescope

PowerPoint Slide Show – [PI-07-04-2021]

Optical corrector and focal plane

- 6 lenses, largest ~1m in diameter
- First light of corrector images was measured to be 0.7 arcsec (April 1, 2019)
- Whirlpool galaxy as viewed by Commissioning Instrument



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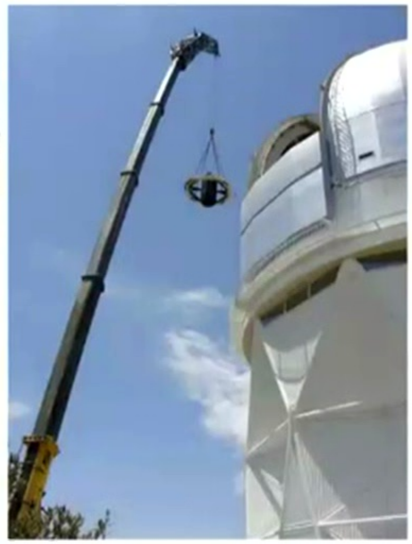
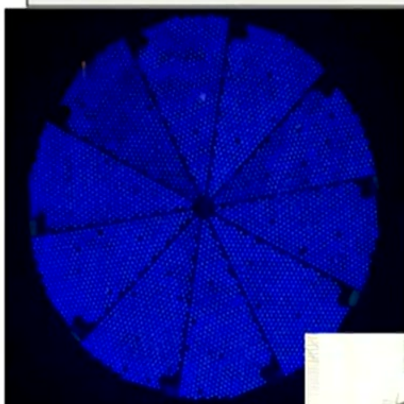
Installation and commissioning

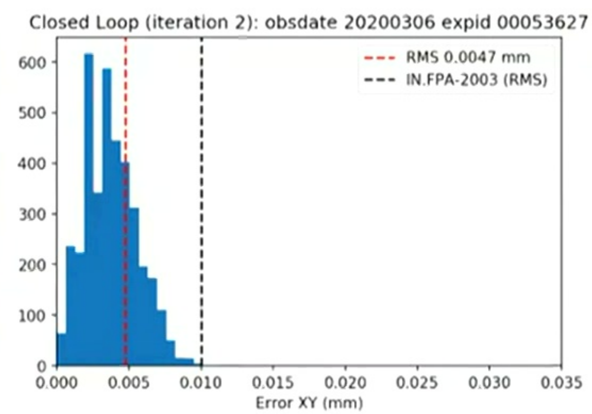


PowerPoint Slide Show – [PI-07-04-2021]

Ten petals constructed



<5 μm rms typical positioning accuracy as-installed



 https://www.desi.lbl.gov/

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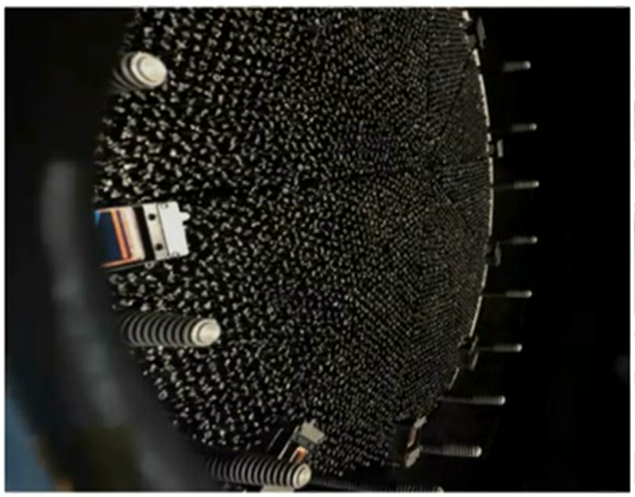
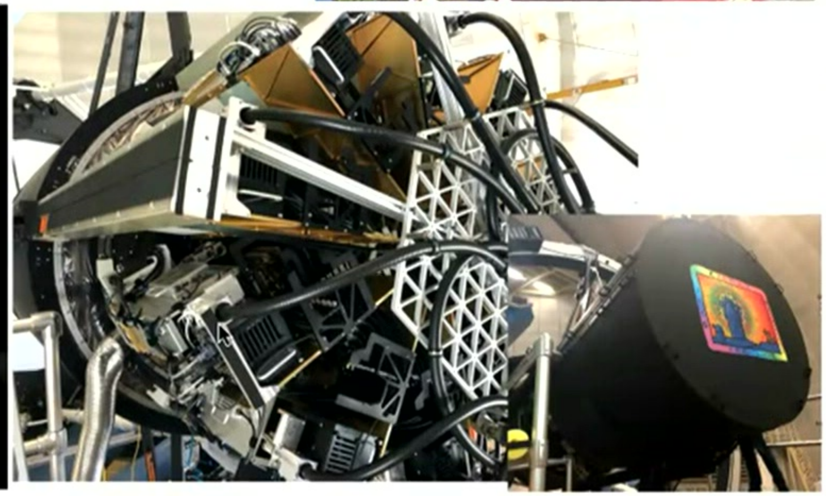
Ten petals installed

Installation of the focal plane instrument was completed in August 2019. The picture below shows the fiber ends of the 5,000 robotic positioners on the focal plane.





Recording...

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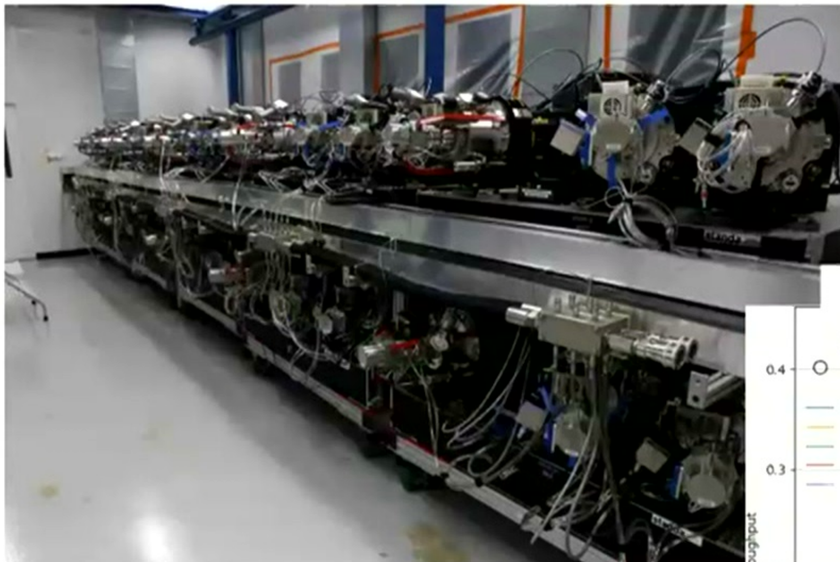
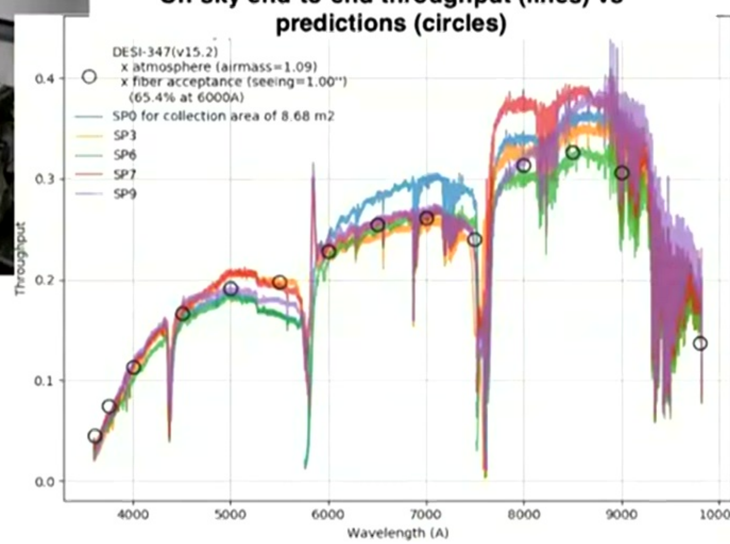
Ten spectrographs installed



10 DESI spectrographs
30 cryostats, 30 CCDs
500 million pixels!!

On-sky end-to-end throughput (lines) vs predictions (circles)



 https://www.desi.lbl.gov/

Recording...

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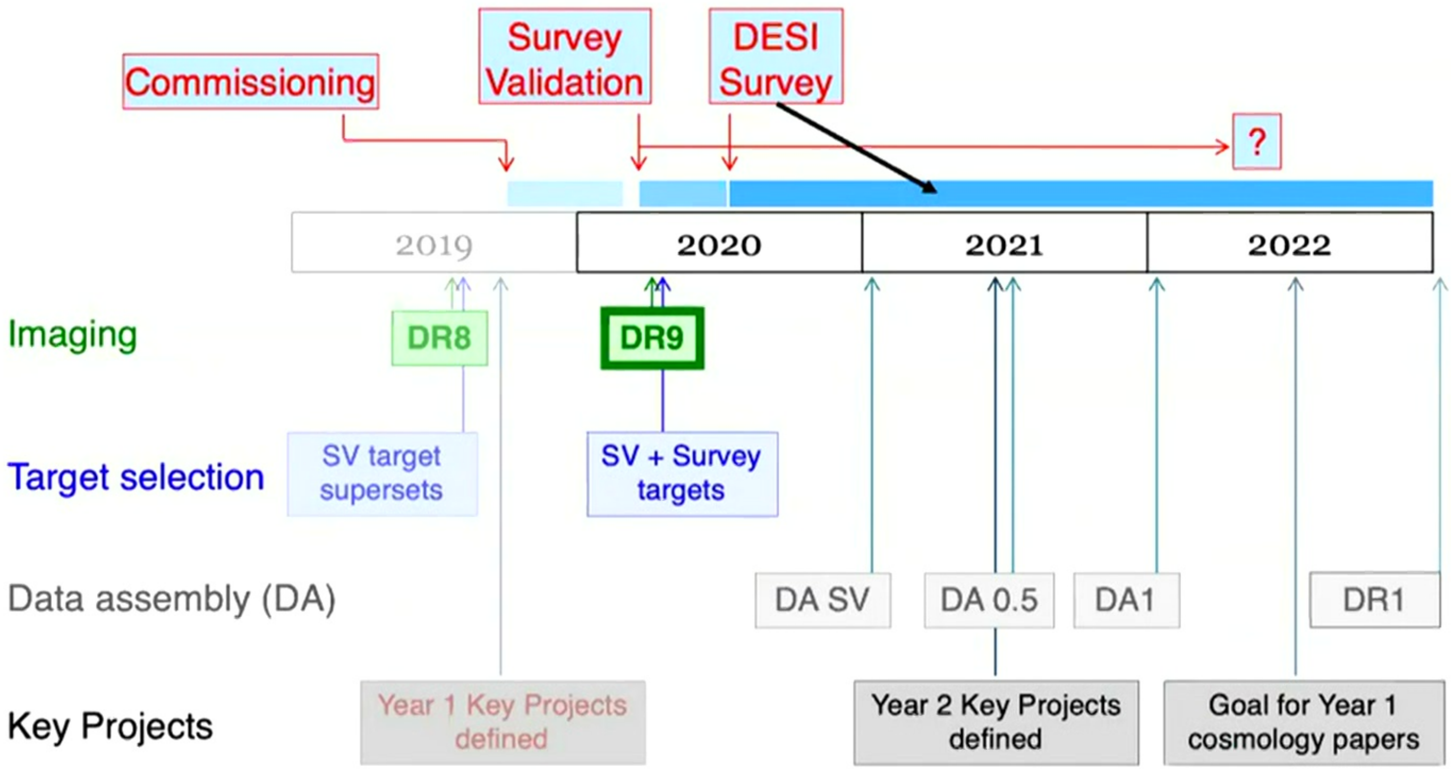
Science started this week!



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Euclid (2022-2028)

PowerPoint Slide Show – [PI-07-04-2021]

Euclid

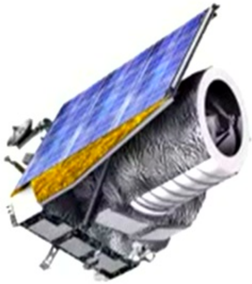
Satellite mission led by ESA, due to launch 2022/3

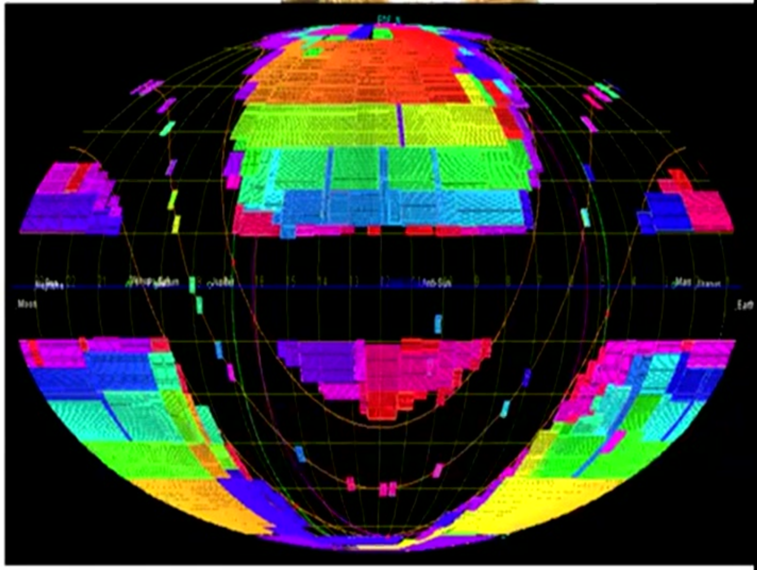
Wide survey:

- $15{,}000\text{deg}^2$
- Works in the Near-Infra Red & Visible

Deep survey:

- 40deg^2
- 12 passes, as for wide survey





https://www.euclid-ec.org

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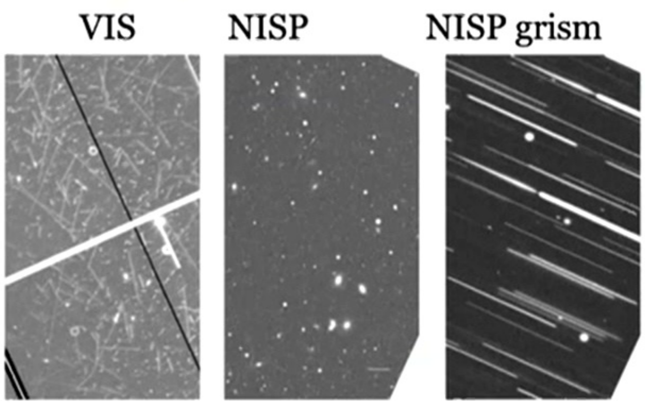
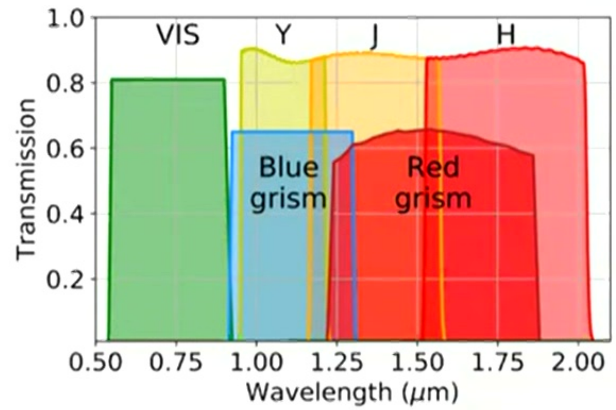
A panchromatic survey



* NISP simulation does not include cosmic rays



	VIS	Y	J	H	GRISM
Wide	24.5	24	24	24	$2x10^{-16}$ erg/s/cm^2
Deep	26.5	26	26	26	$2x10^{-17}$ erg/s/cm^2

Recording...

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Late construction stage

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The Maunakea Spectroscopic Explorer

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Maunakea Spectroscopic Explorer

- Proposed as replacement for Canada-France-Hawaii-Telescope
- New 11.25m diameter primary mirror telescope
- 4332 fibres, 1.5deg² FOV
  - 3249 fibres
    - R~2500 (optical, J, H)
    - R~6000 spectroscopy (optical)
  - 1083 fibres
    - R~20,000 – 40,000 optical windows)
- Many science cases from stars to cosmology

https://mse.cfht.hawaii.edu

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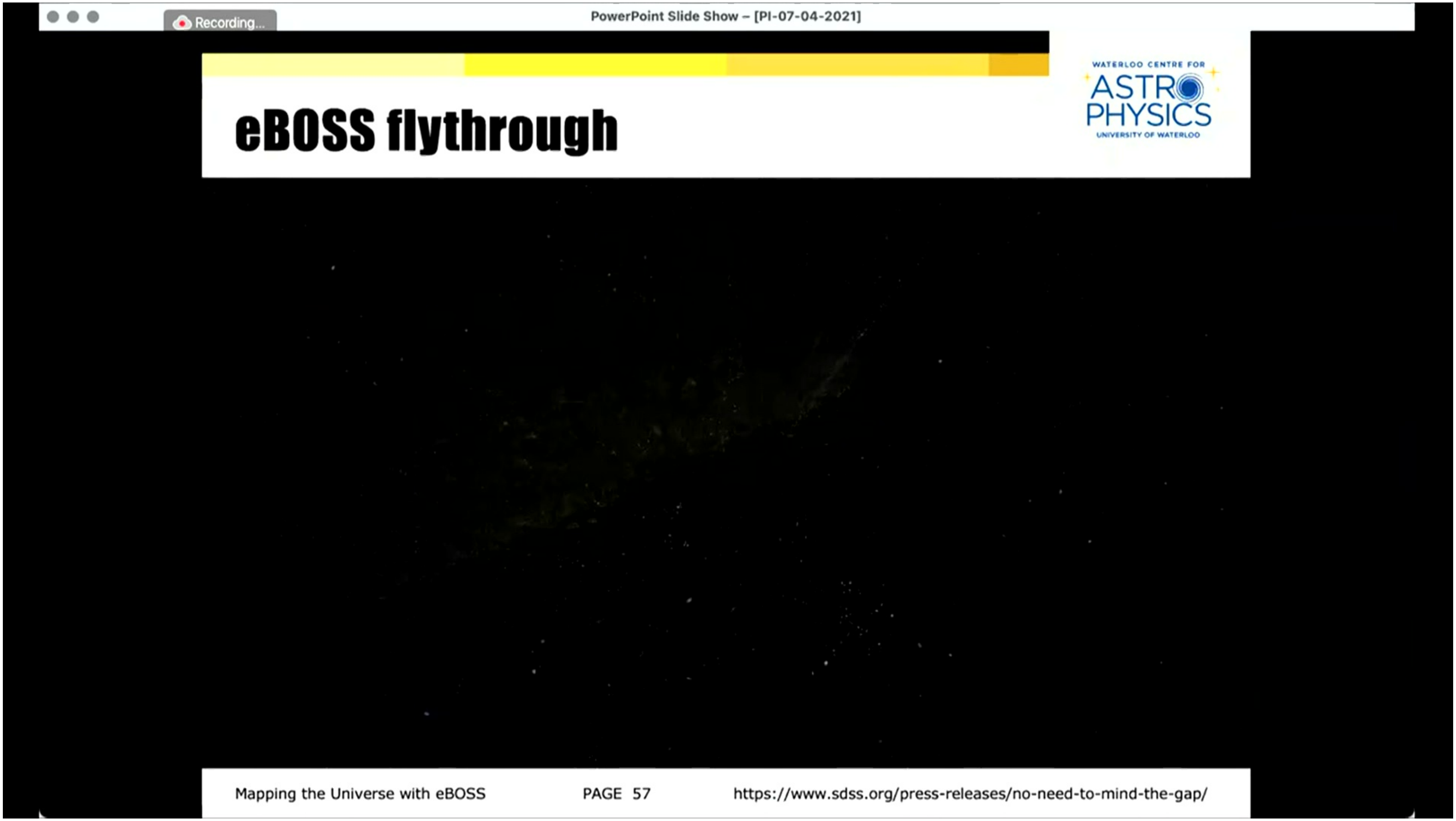
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eBOSS flythrough
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https://www.sdss.org/press-releases/no-need-to-mind-the-gap/