

From Galaxy Maps to Cosmic Acceleration

Uendert Andrade
Leinweber Postdoctoral Fellow
University of Michigan

Leinweber Institutes Postdoctoral Fellows Meeting @ MIT · OCTOBER 21–23, 2026



LSA LEINWEBER INSTITUTE FOR THEORETICAL PHYSICS UNIVERSITY OF MICHIGAN

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UNIVERSITY OF MICHIGAN → ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

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Theoretical cosmologist who likes data and football ⚽ 🇧🇷

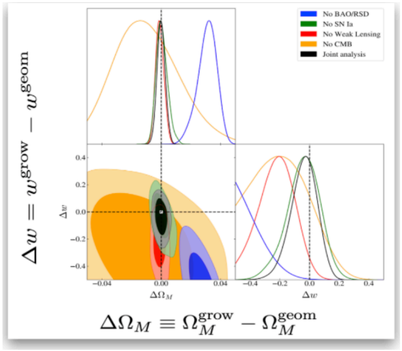
Research focus: *Probing the fundamental hypotheses of the standard cosmology*

PhD highlights (Observatório Nacional, Rio de Janeiro)

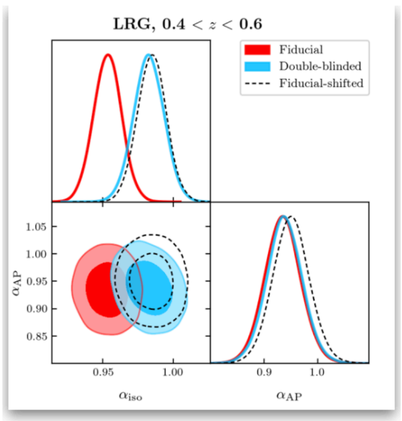
*Tests of **Cosmic Isotropy** with Supernovae and Gamma-ray bursts*

*Measuring the **Cosmic Homogeneity** scale with LSS*

*Empirical Consistency Test of Dark Energy Models: **Growth vs Geometry***



Andrade et al. JCAP 11 (2021) 014



Andrade et al. JCAP 01 (2025) 128

Excited about:

- New methodologies, e.g.,
  - optimized samples
  - advanced techniques
- Consistency checks
- Full-shape, full-sky analyses
- Wide-field surveys: DESI-II, Rubin, Euclid, Roman

Postdoc highlights

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

THE DARK ENERGY SURVEY

DESI DR1 Blinding Validation

Validating the Galaxy and Quasar Catalog-Level Blinding Scheme for the DESI 2024 analysis

DESI DR2 BAO Topical Group Lead

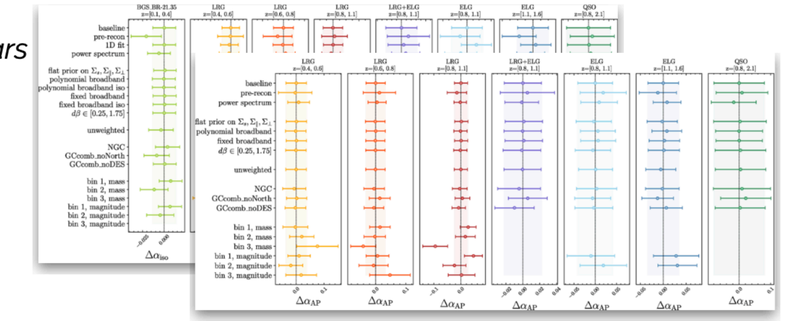
Validation of the DESI DR2 measurements of baryon acoustic oscillations from galaxies and quasars

DESI DR2 BAO Key Project Co-coordinator

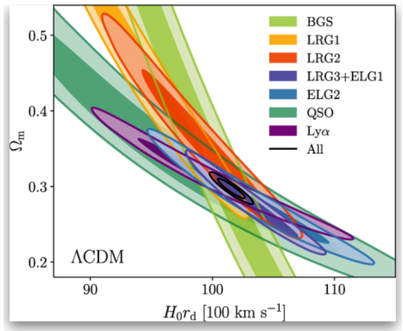
DESI DR2 results. II. Measurements of baryon acoustic oscillations and cosmological constraints

DES Y6 ΛCDM extensions: Geometry-Growth Split

In prep



Andrade et al., 2025. Phys. Rev. D 112, 083512



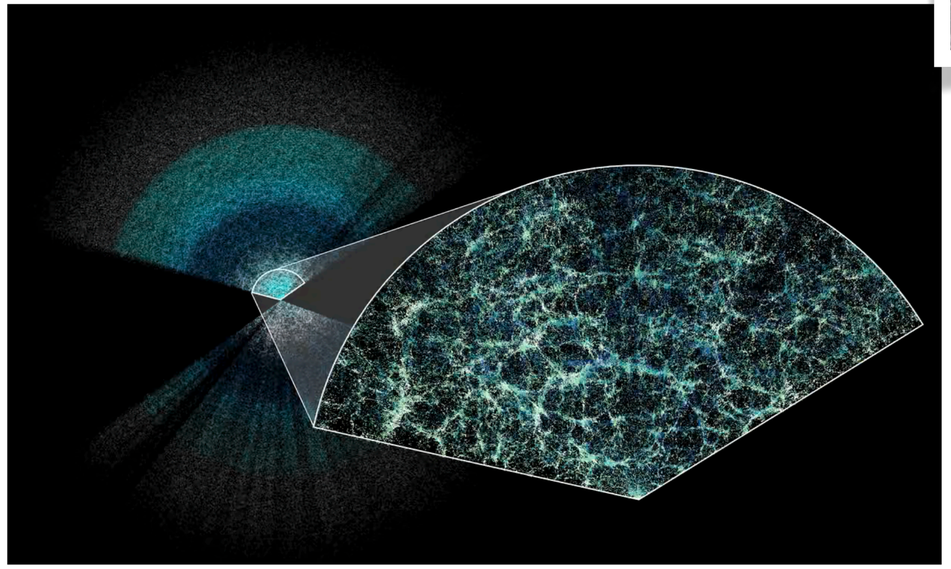
DESI Collaboration 2025. Phys. Rev. D 112, 083515

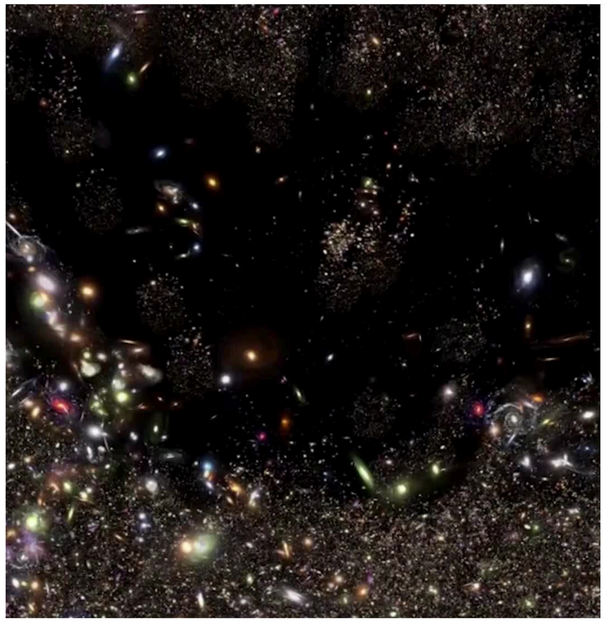
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

New 3D cosmic map raises questions over future of universe, scientists say

Researchers say findings from map with three times more galaxies than previous efforts could challenge standard idea of dark energy





The New York Times

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.



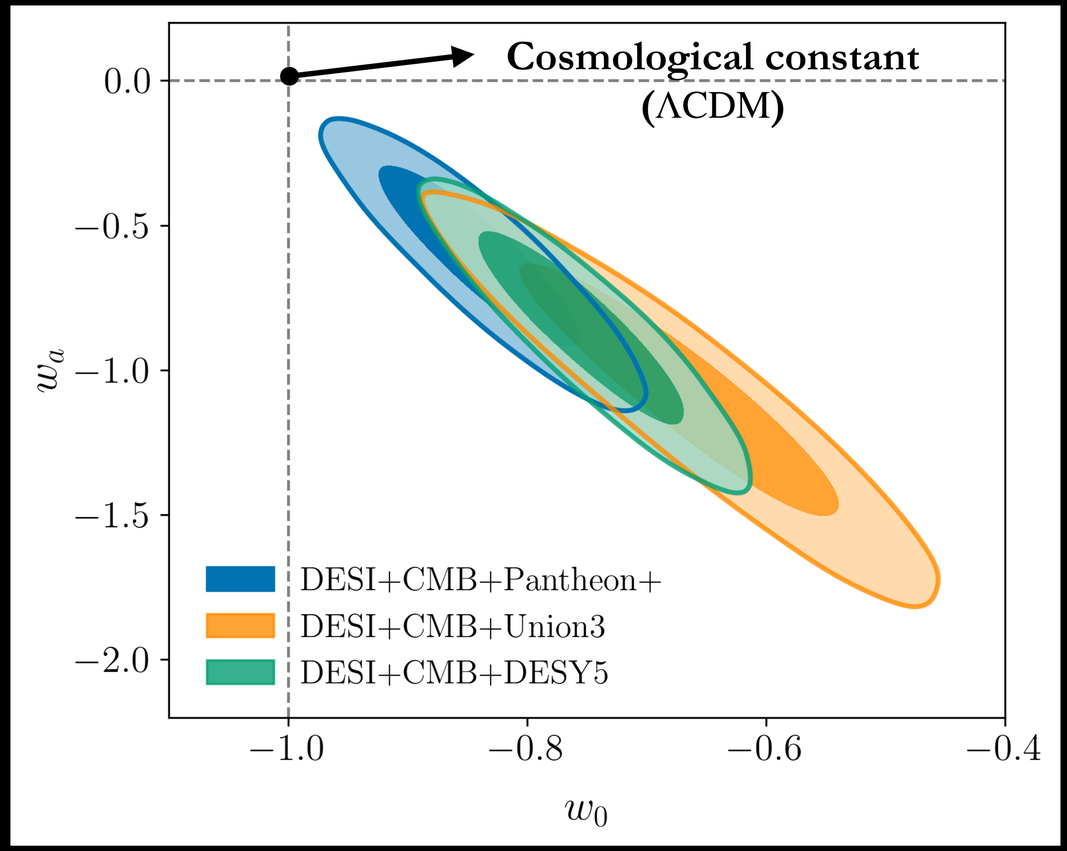
2024 Biggest Breakthroughs in Physics

16:45

Quantamagazine

DR1: Dynamical Dark Energy - (w_0, w_a)

3.9σ tantalizing suggestion of deviations from the standard cosmological model

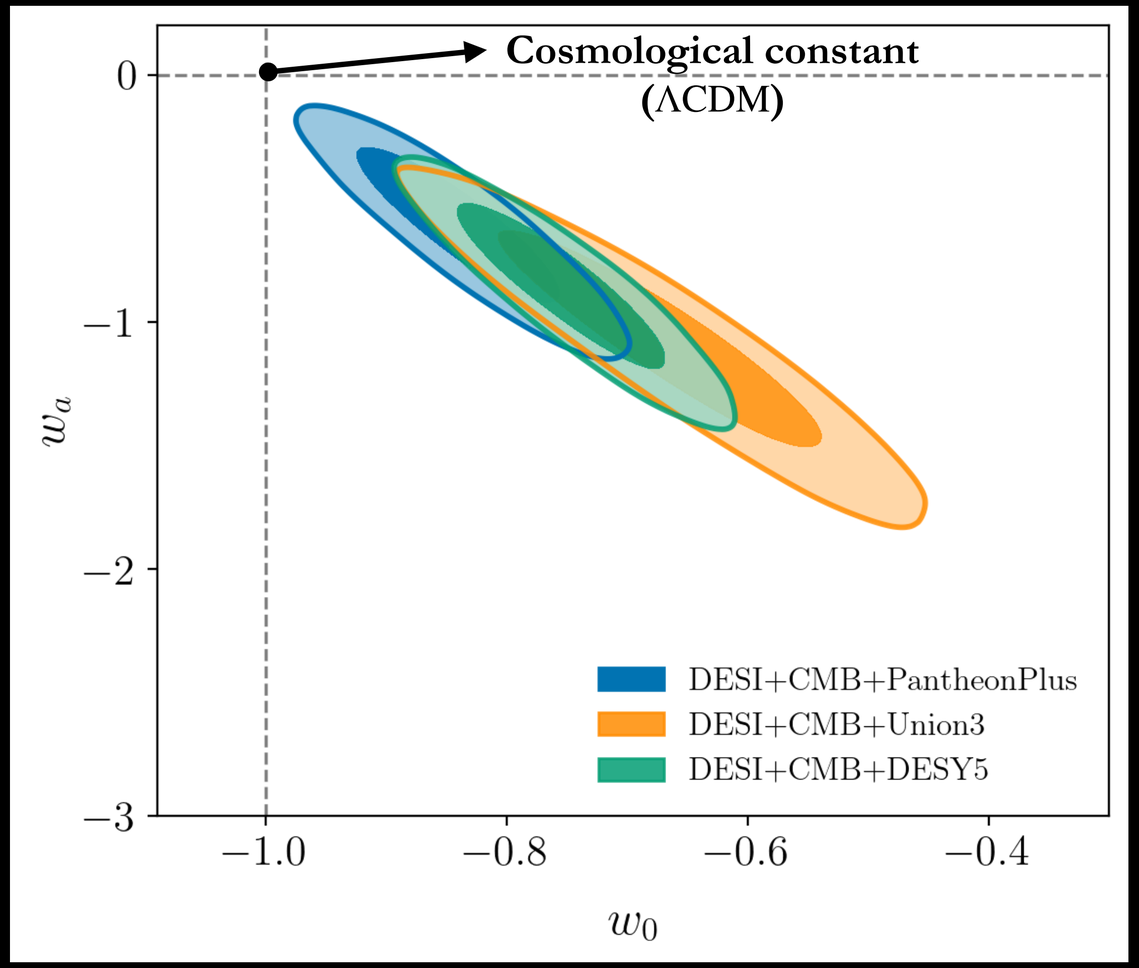


Time evolution of the equation of sate

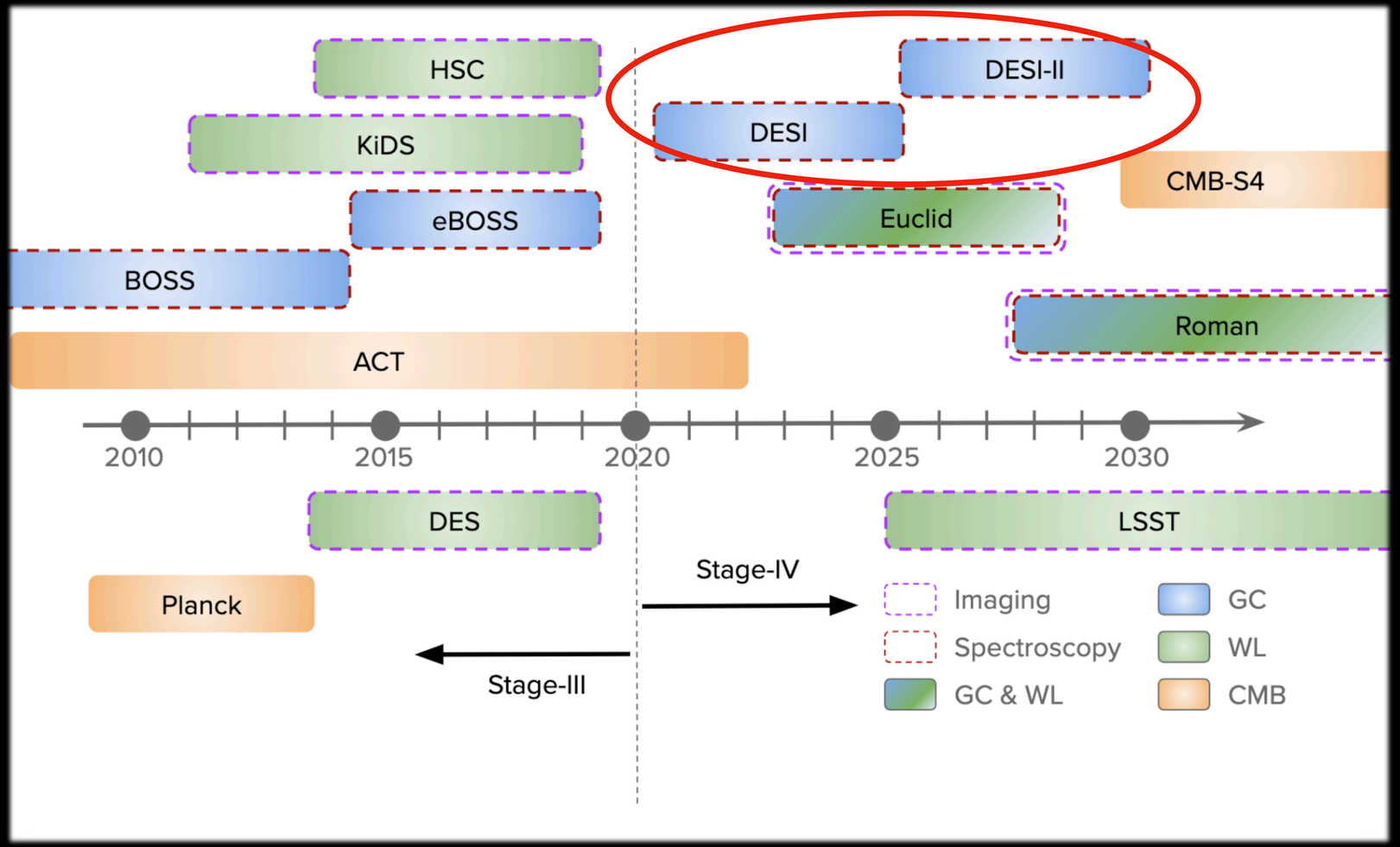
Present-day dark energy equation of state

DR2: Dynamical Dark Energy - (w_0, w_a)

- 4.2σ in favor of Dynamical Dark Energy
- Unless there is an **unknown systematic** error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution



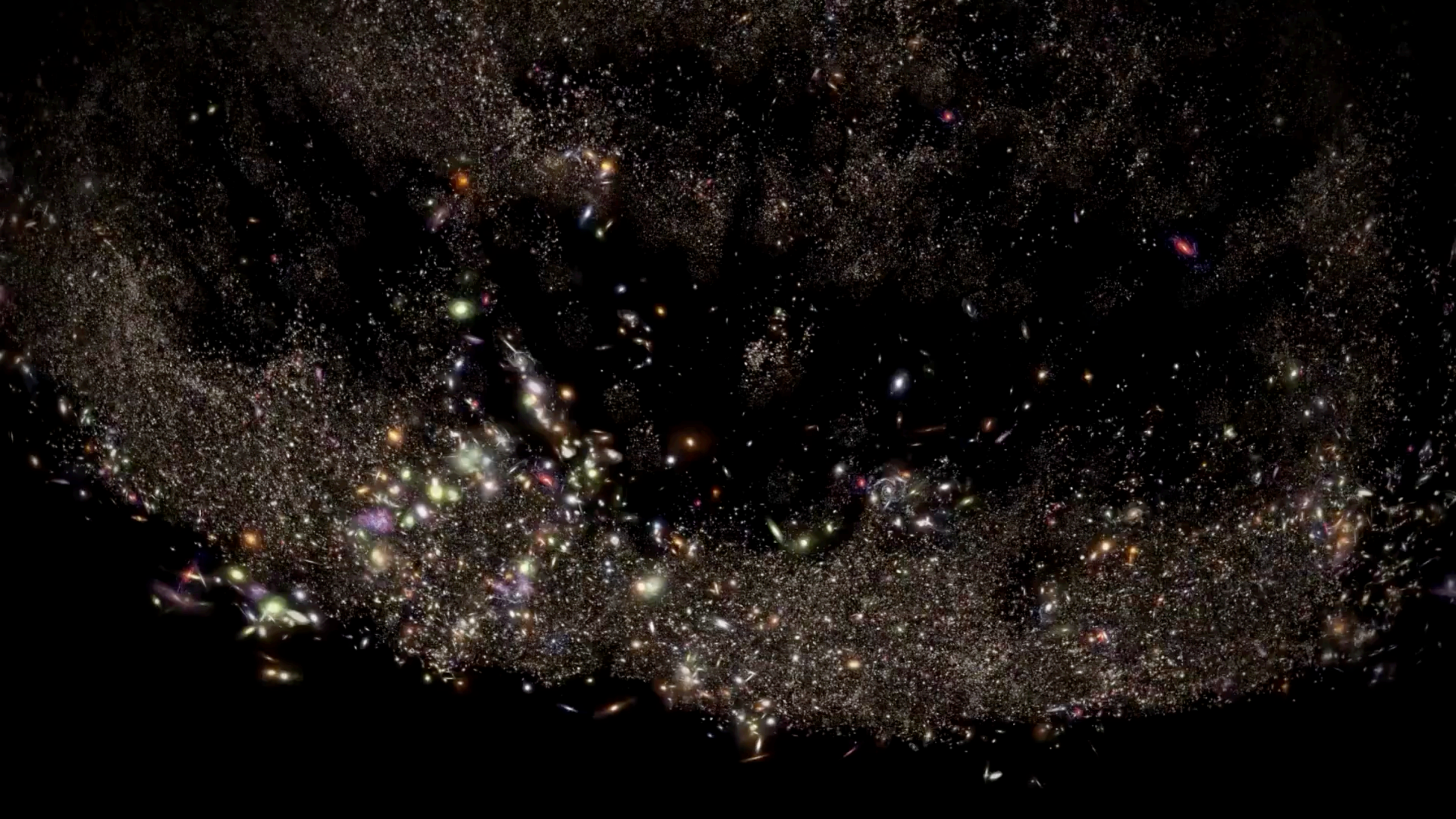
Transitioning from Stage-III to Stage-IV surveys

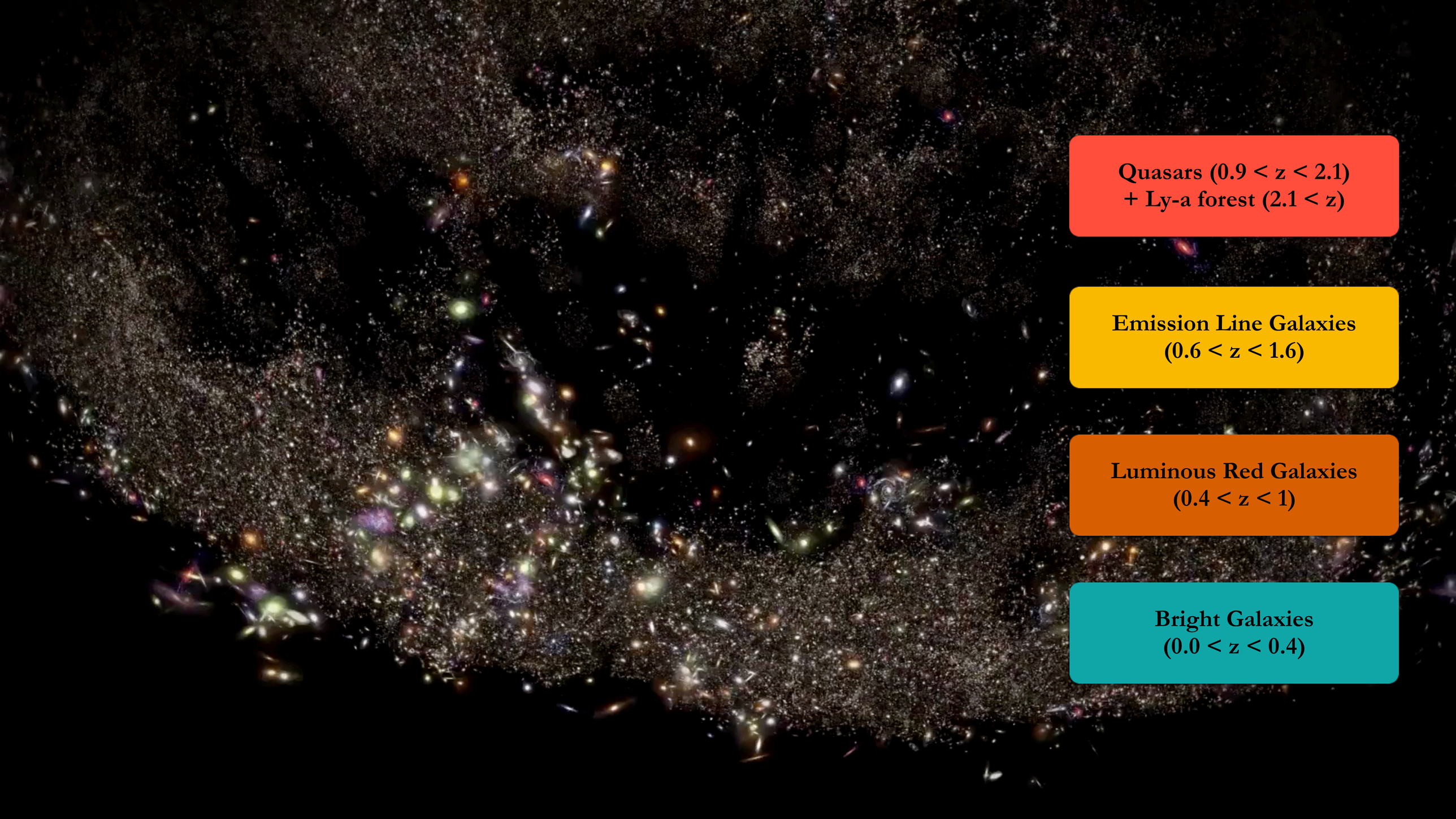


REPORT OF THE DARK ENERGY TASK FORCE 2006

III. We recommend that the dark energy program include a combination of techniques from one or more Stage III projects designed to achieve, in combination, at least a factor of three gain over Stage II in the DETF figure of merit, based on critical appraisals of likely statistical and systematic uncertainties.

IV. We recommend that the dark energy program include a combination of techniques from one or more Stage IV projects designed to achieve, in combination, at least a factor of ten gain over Stage II in the DETF figure of merit, based on critical appraisals of likely statistical and systematic uncertainties. Because JDEM, LST, and SKA all offer promising avenues to greatly improved understanding of dark energy, we recommend continued research and development investments to optimize the programs and to address remaining technical questions and systematic-error risks.




Quasars (0.9 < z < 2.1)
+ Ly-a forest (2.1 < z)
Emission Line Galaxies
(0.6 < z < 1.6)
Luminous Red Galaxies
(0.4 < z < 1)
Bright Galaxies
(0.0 < z < 0.4)

DESI Survey: Making the Largest 3D Map of the Universe

Quasars (0.9 < z < 2.1)
+ Ly-a forest (2.1 < z) [Ming-Feng's talk]

Emission Line Galaxies
(0.6 < z < 1.6)

Luminous Red Galaxies
(0.4 < z < 1)

Bright Galaxies
(0.0 < z < 0.4)



From 2021-end of 2028 DESI will measure precise redshifts to ~50 million galaxies over 17,000 deg2

Main Science Goals of DESI

- Measure the expansion history and constrain dark energy
- Measure the growth of cosmic structure
- Test the standard cosmological model
- Constrain neutrino physics (Hernan's Talk)
- Probe inflation and the primordial Universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Main Science Goals of DESI

- Measure the expansion history and constrain dark energy
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- Probe inflation and the primordial Universe

- Baryon Acoustic Oscillations (BAO)
- Redshift Space Distortions (RSD)

BAO Technical requirement

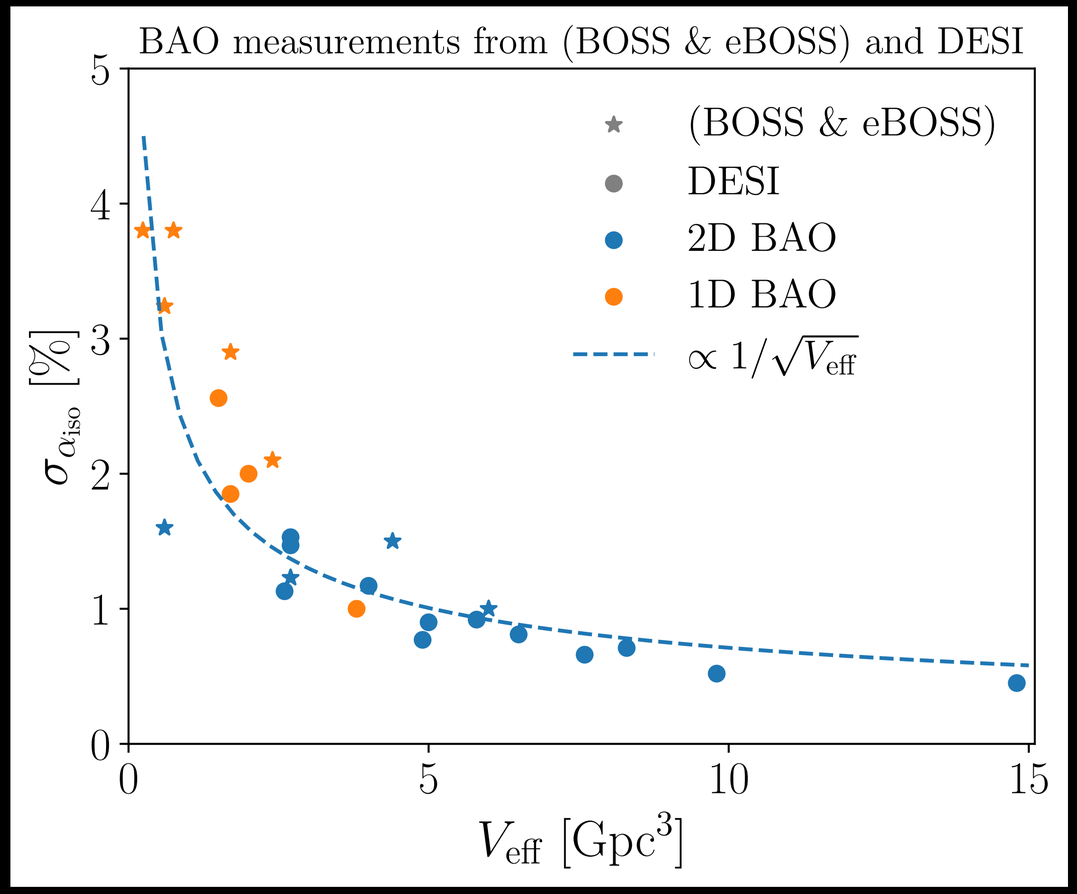
- large-volume spectroscopic survey
- with sufficient sampling density

$$\frac{\sigma_{\rm BAO}}{\rm BAO} \propto \frac{1}{\sqrt{V_{\rm survey}\, k^2\, dk\, d\mu}} \frac{P + P_{\rm noise}}{P_{\rm lin}\, C(k)},$$

$$N_{\rm modes} \propto V_{\rm survey}\, k^2\, dk\, d\mu,$$

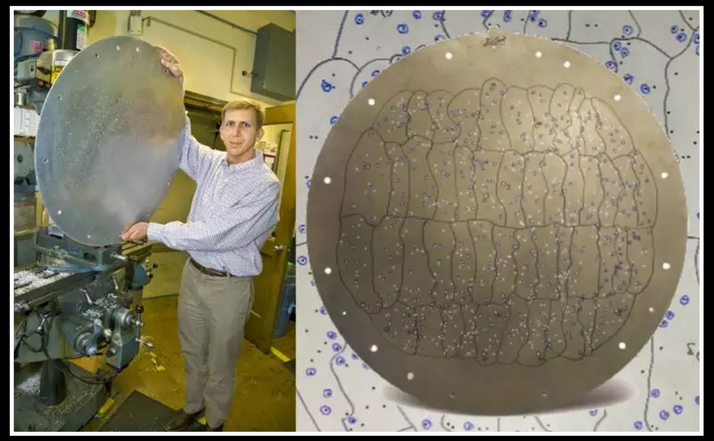
$$P_{\rm noise} \equiv 1/n,$$

$$V_{\rm eff} \propto V_{\rm survey} \left[\frac{n\,P}{1 + n\,P}\right]^2.$$

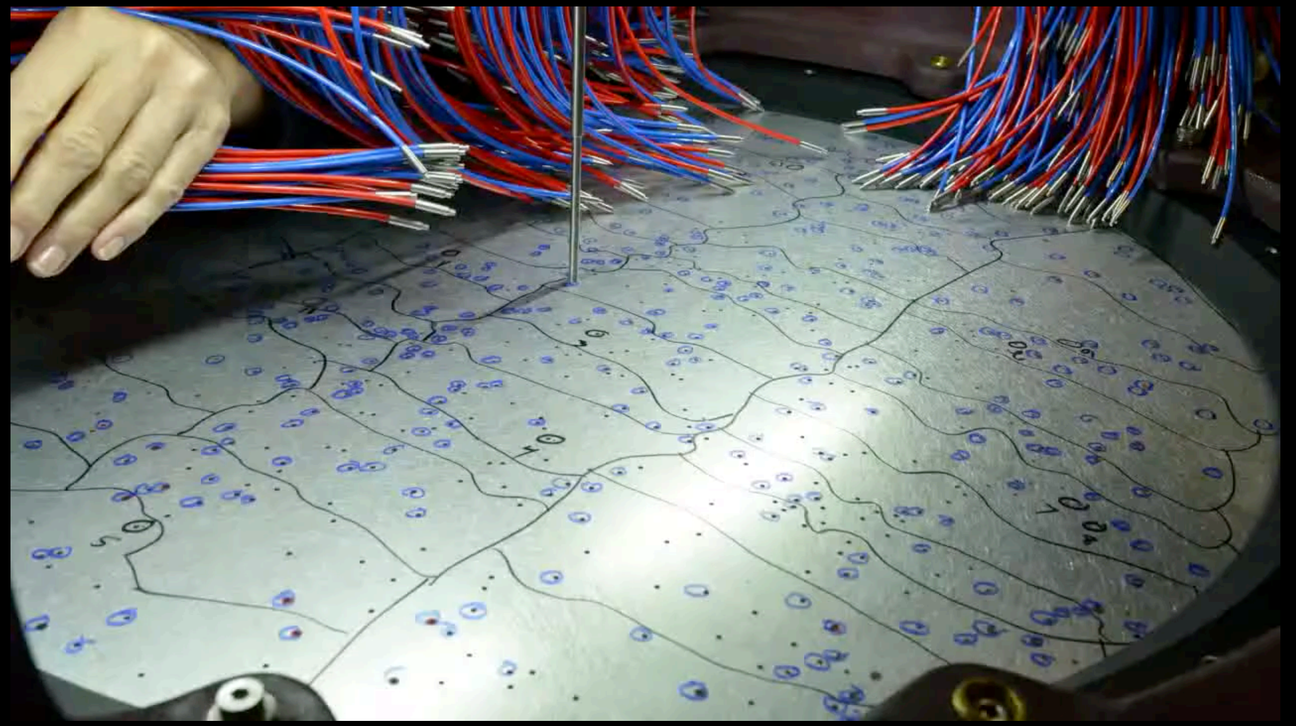


Andrade++ PRD 112, 083512 (2025)

Fiber assignment before DESI





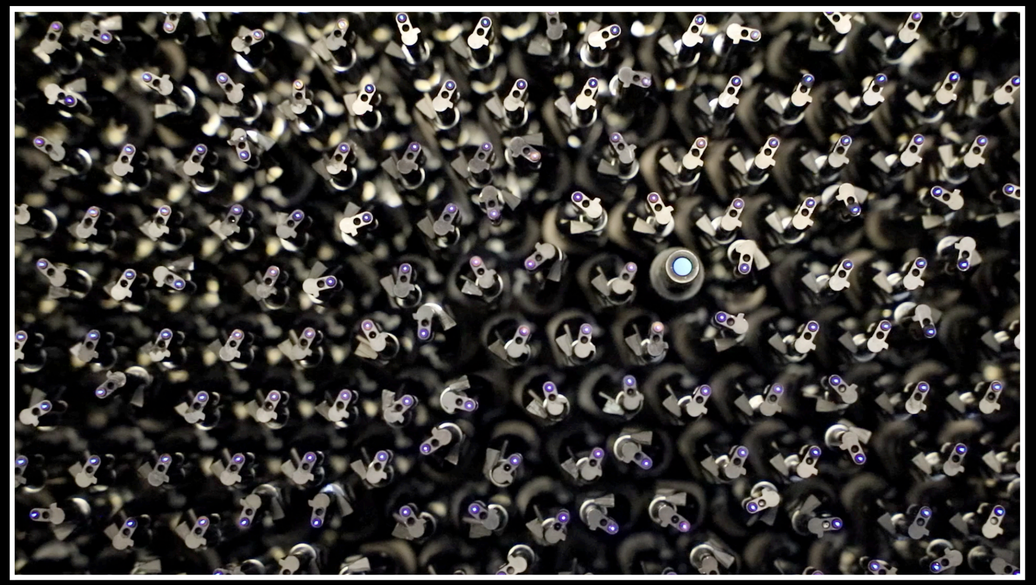


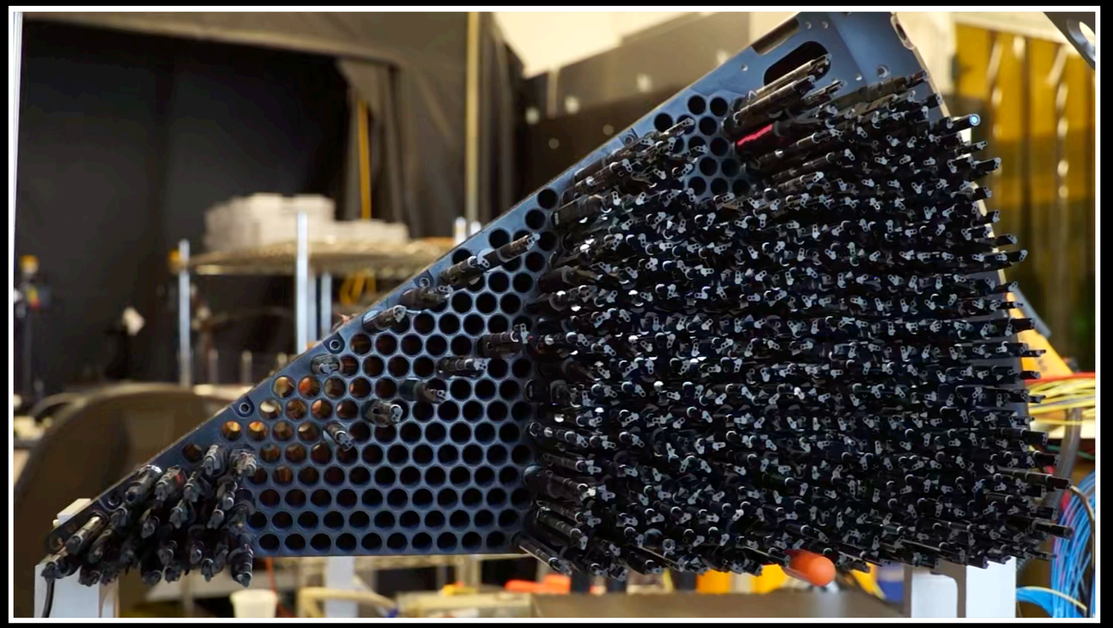
- Process of plugging optical fibers into plates for observations for the Sloan Digital Sky Survey (SDSS)
- Each plate can take anything from 30 mins to several hours to be plugged by the expert SDSS Plate Pluggers

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Automated dance of 5000 robotic positioners







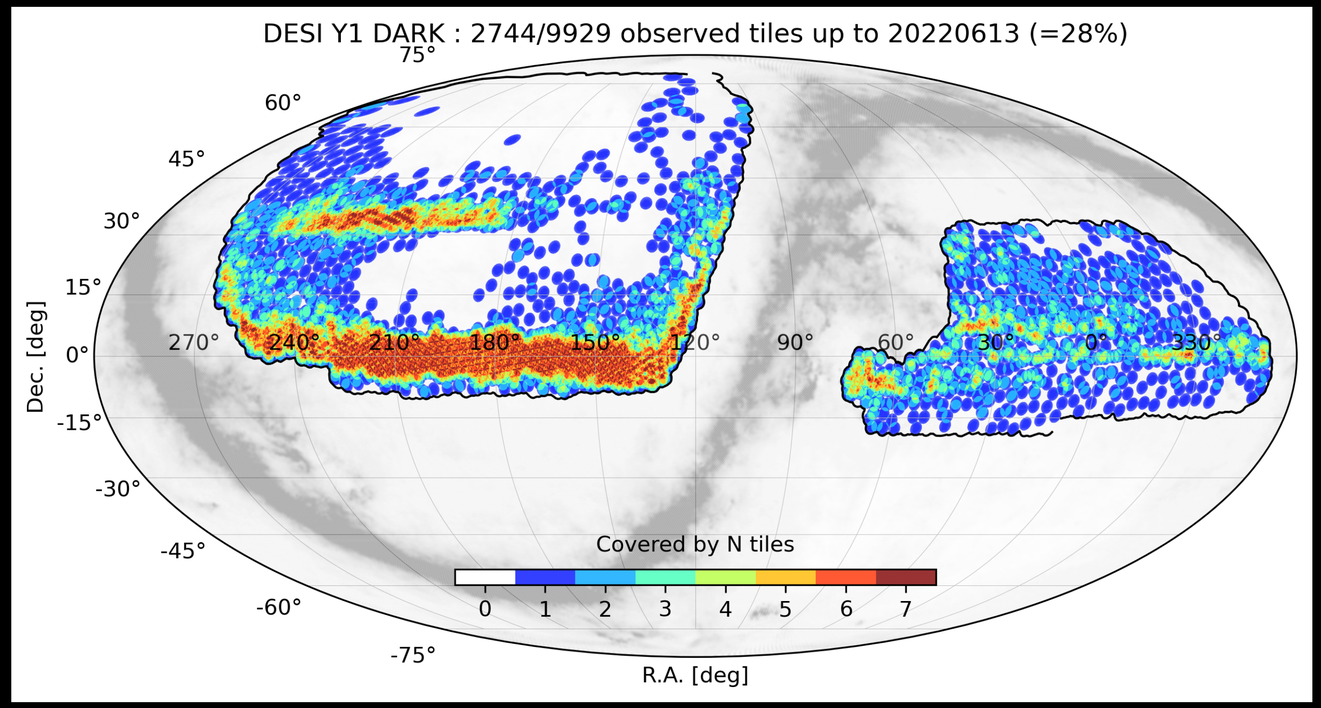


University of Michigan undergraduate Clara Mateju doing a stage 1 assembly

Image credit: Curtis Weaverdyck

From DESI DR1 to DR2 sample

Observations from May 14th 2021 to April 12th 2022



Final survey

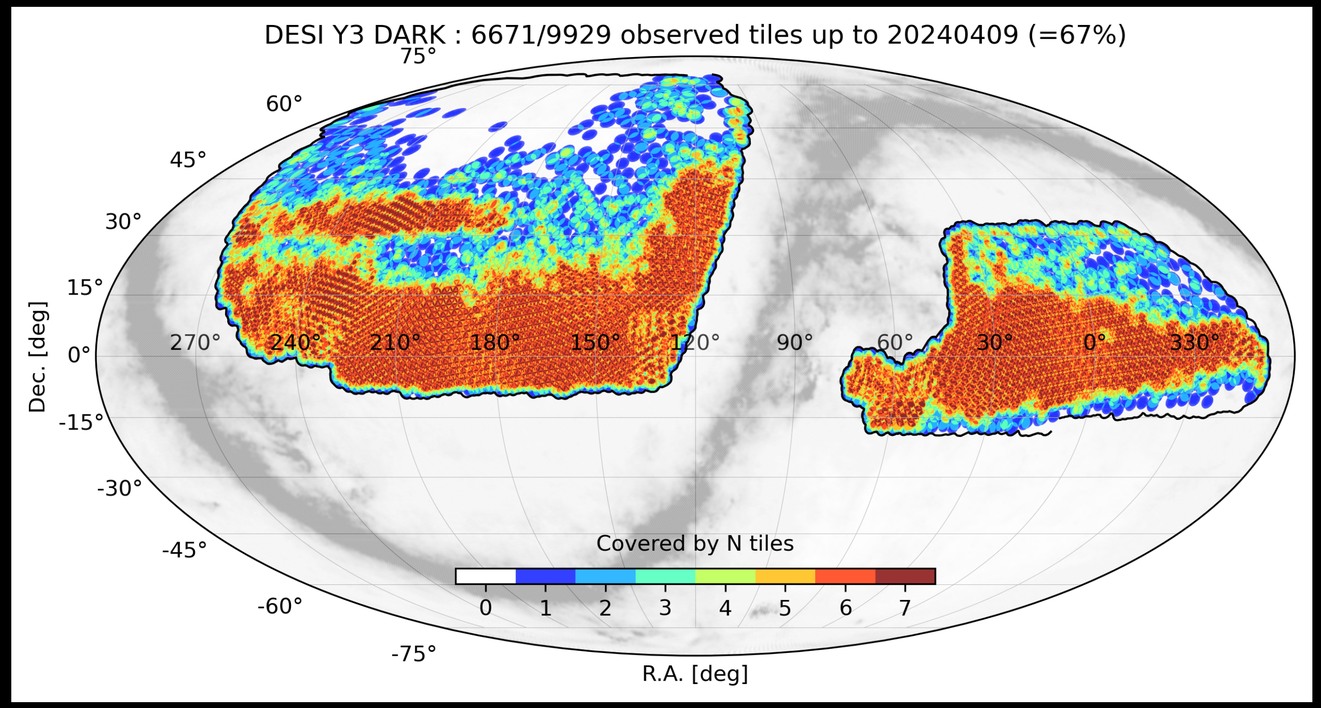
- dark time (LRG, ELG, QSO): 7 visits
- bright time (BGS): 5 visits
- 17,000 deg^2

approved 2015
construction started 2016
2017
2018
first litght 2019
survey started 2020
DR1 data sample 2021
2022
DR1 results 2023
DR2 sample secured 2024
DR2 results 2025
end of the survey... ... DESI-2 2026

From DESI DR1 to DR2 sample

Observations from May 14th 2021 to April 12th 2022

April 9, 2024

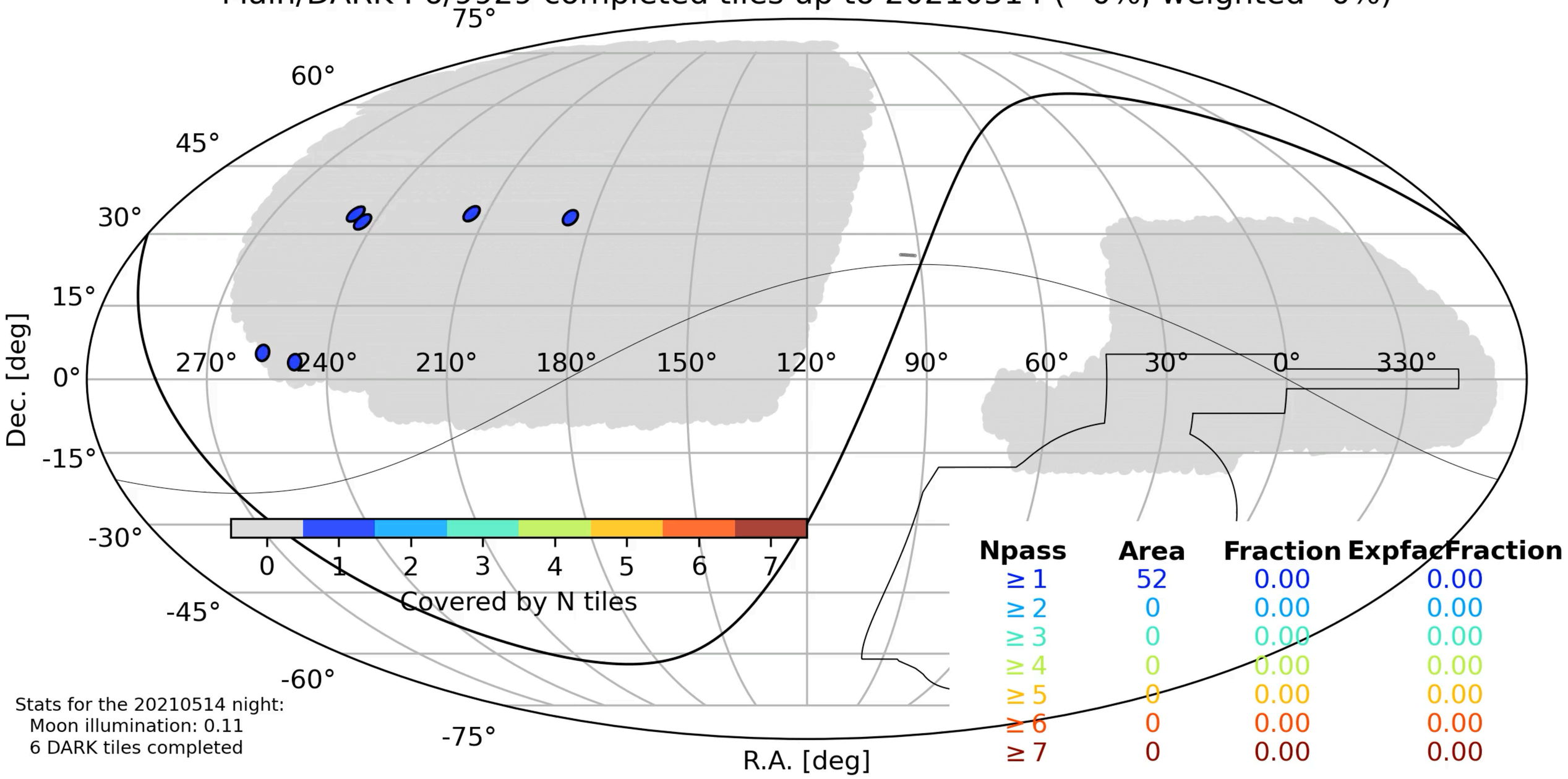


Final survey

- dark time (LRG, ELG, QSO): 7 visits
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approved
construction started
first litght
survey started
DR1 data sample
DR1 results
DR2 sample secured
DR2 results
end of the survey... ... DESI-2

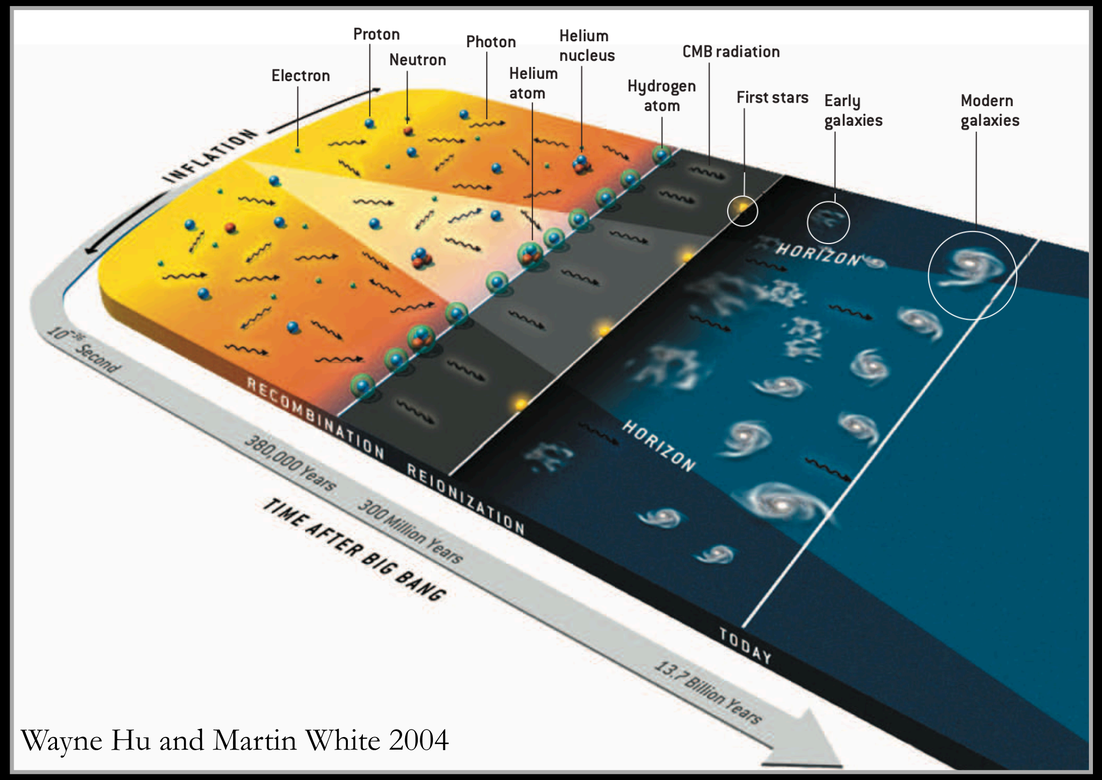
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026


Main/DARK : 6/9929 completed tiles up to 20210514 (=0%, weighted=0%)
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Dec. [deg]
270°
240°
210°
180°
150°
120°
90°
60°
30°
0°
330°
R.A. [deg]
0
1
2
3
4
5
6
7
Covered by N tiles
Npass
Area
Fraction
Expfac
Fraction
≥ 1
52
0.00
0.00
≥ 2
0
0.00
0.00
≥ 3
0
0.00
0.00
≥ 4
0
0.00
0.00
≥ 5
0
0.00
0.00
≥ 6
0
0.00
0.00
≥ 7
0
0.00
0.00
Stats for the 20210514 night:
Moon illumination: 0.11
6 DARK tiles completed

x

Baryon Acoustic Oscillations (BAO)

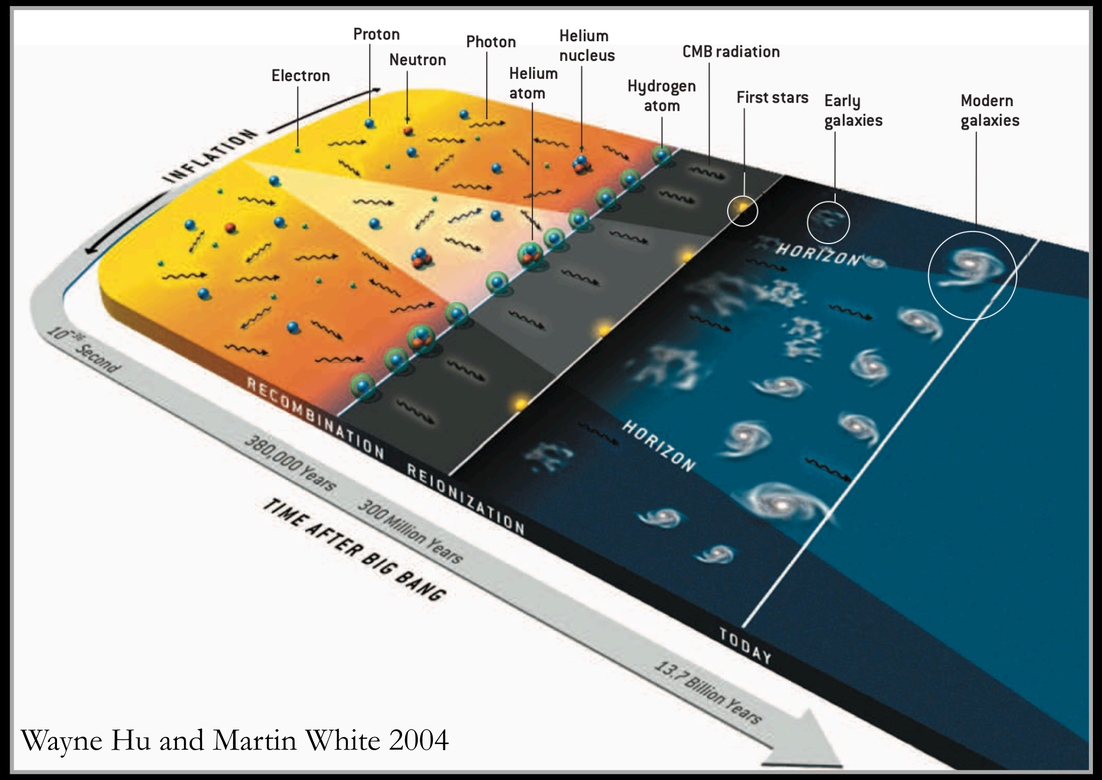
- Gravity and pressure generated sound waves in the primordial plasma
- When baryons and photons decoupled, the sound waves stopped



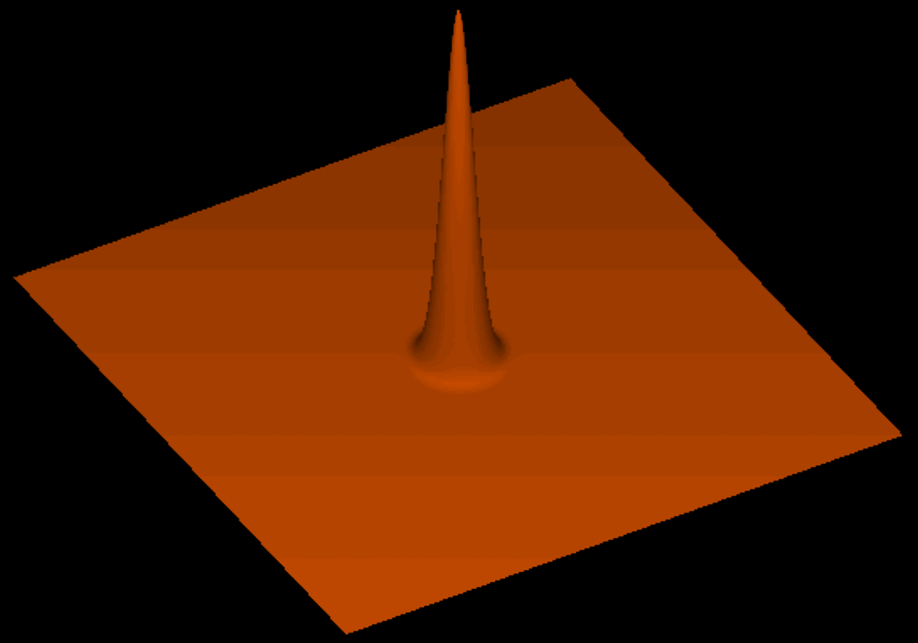
Wayne Hu and Martin White 2004

Baryon Acoustic Oscillations (BAO)

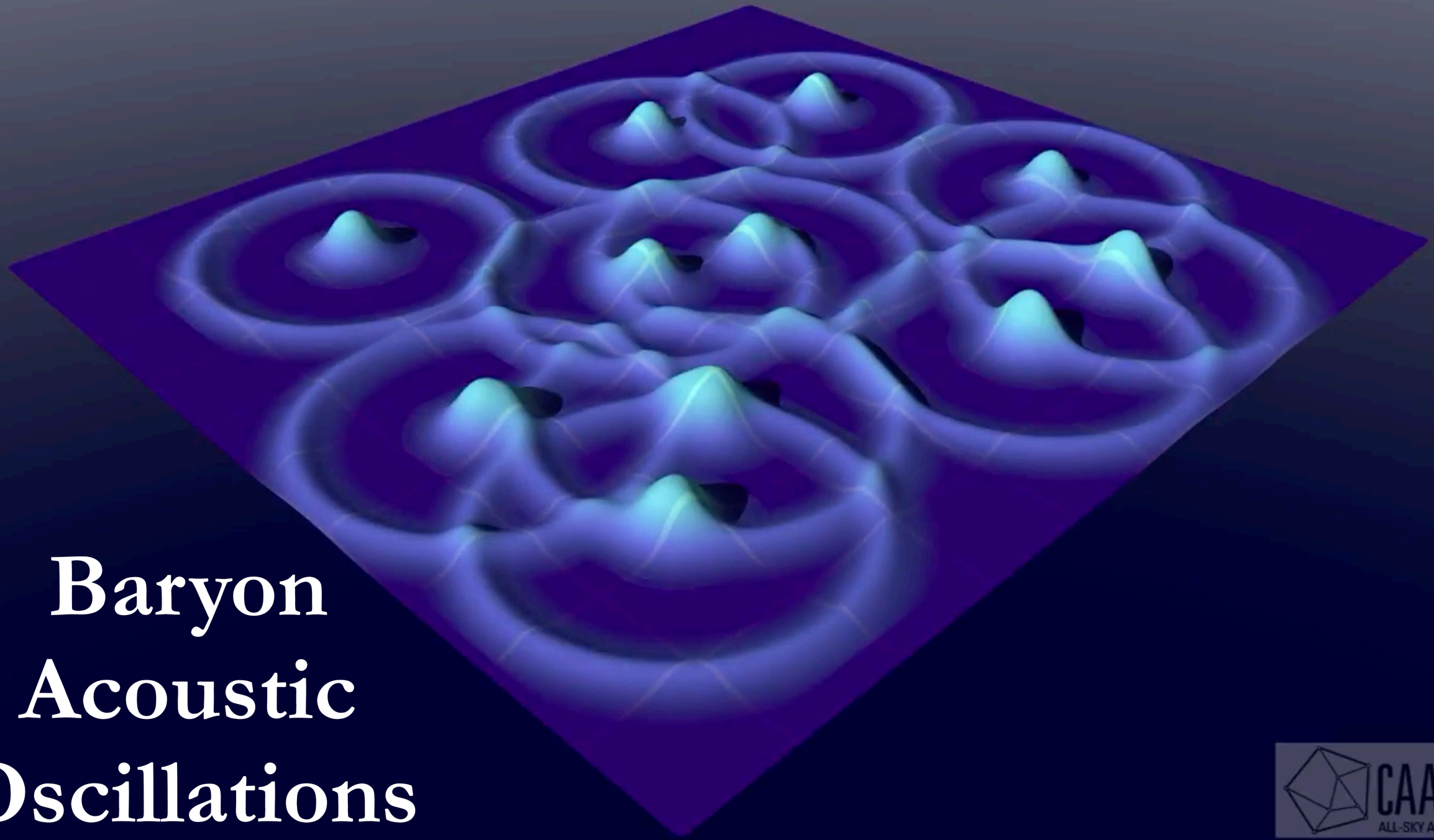
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Wayne Hu and Martin White 2004



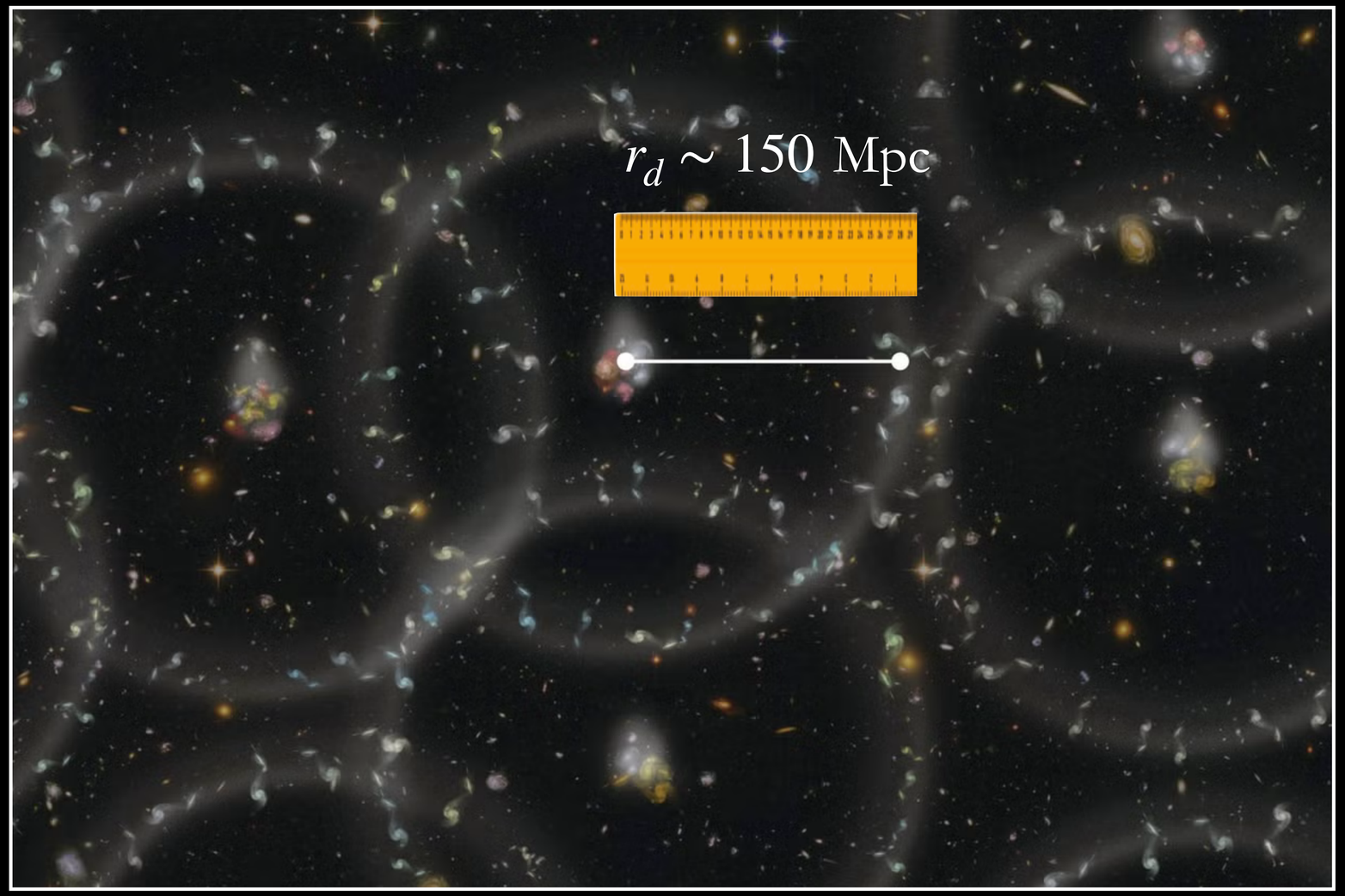
Credit: Daniel Eisentein



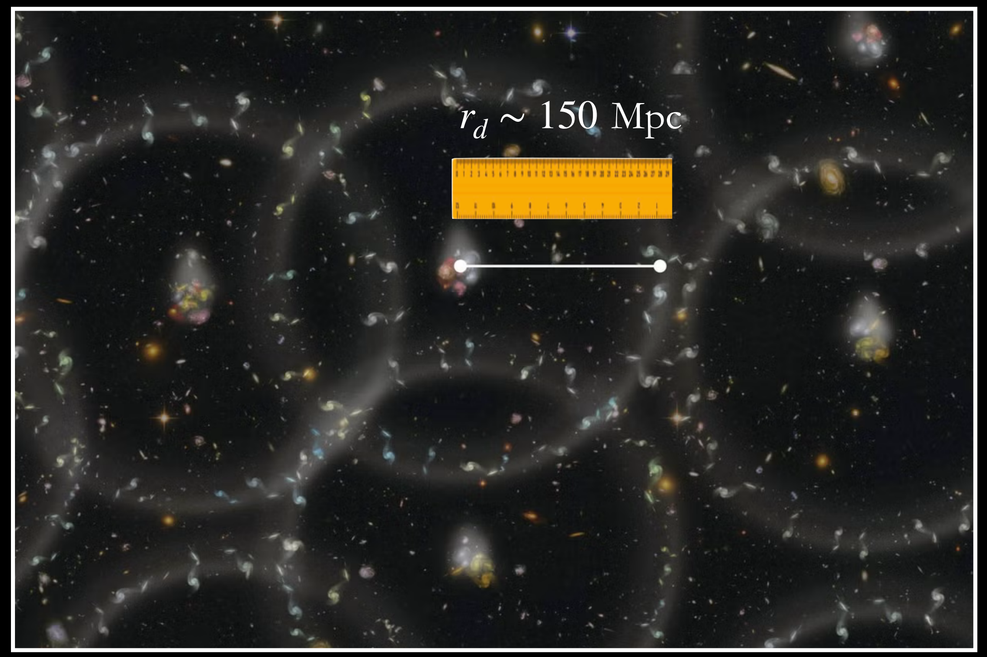
Baryon Acoustic Oscillations

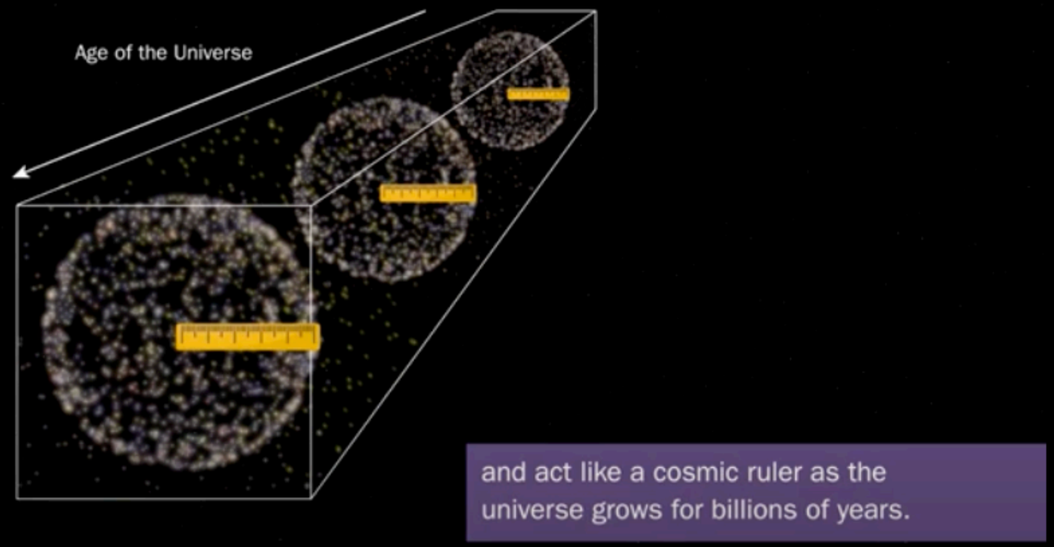
CAASTRO
ALL-SKY ASTROPHYSICS

Baryon Acoustic Oscillations (BAO)

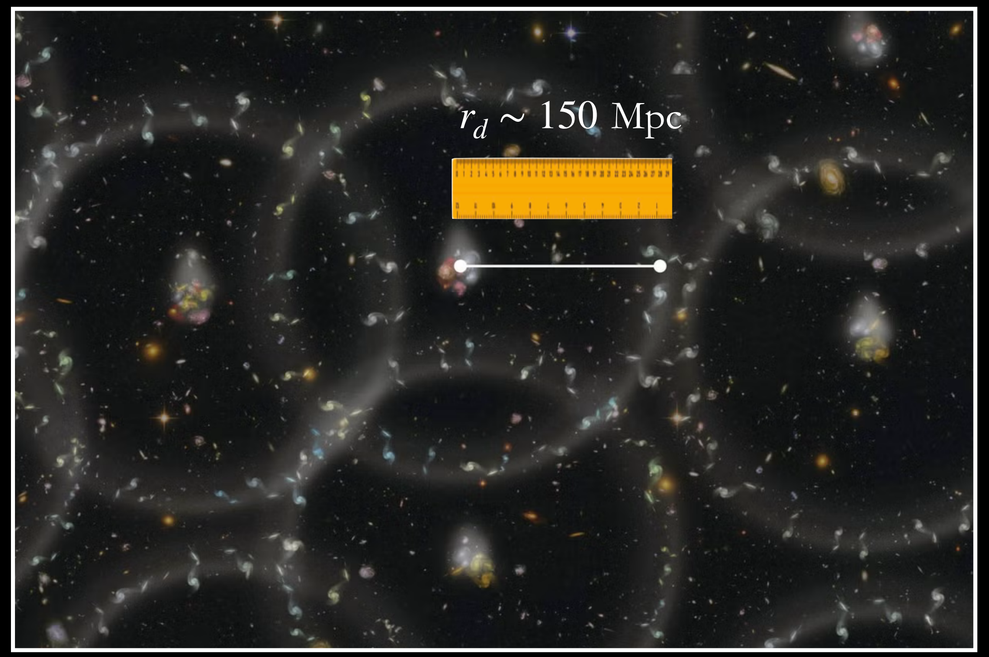


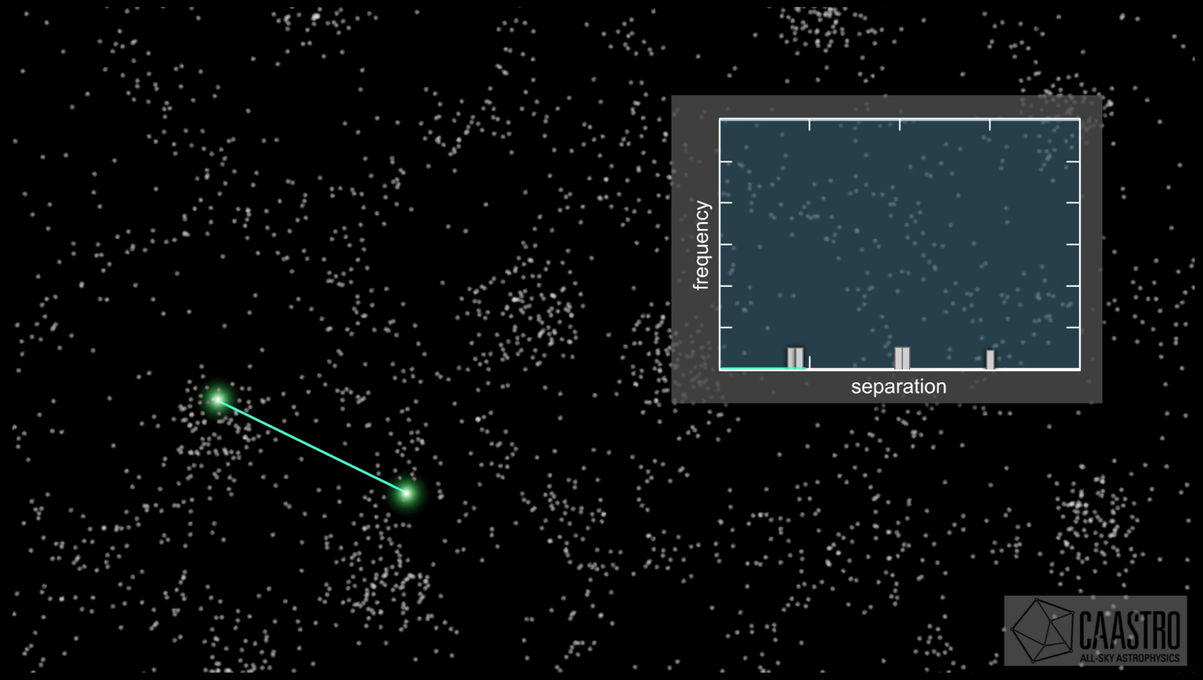
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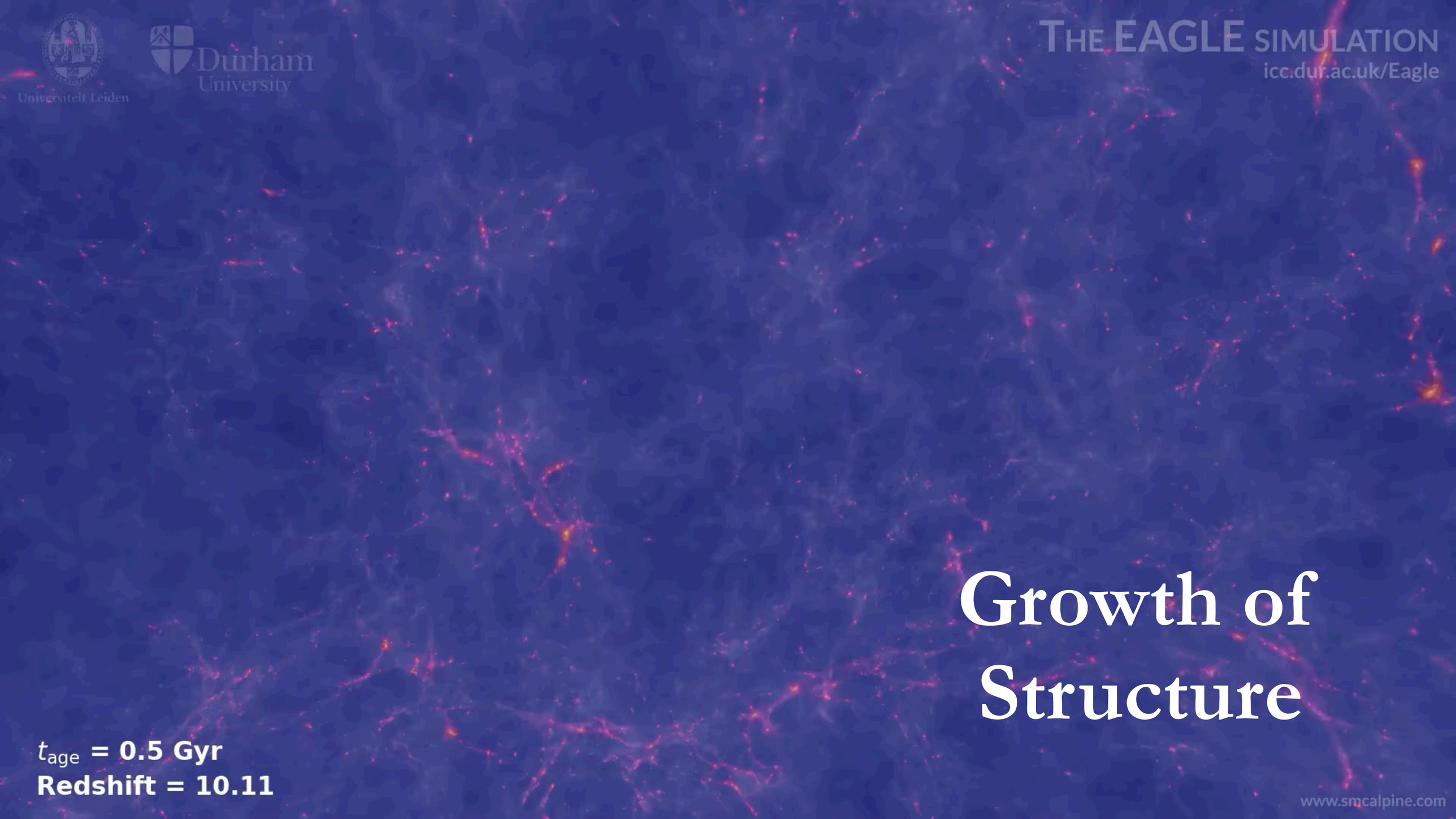


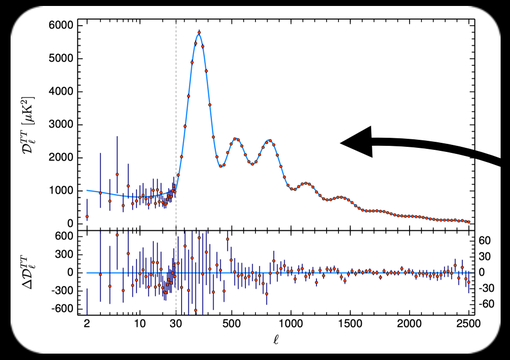


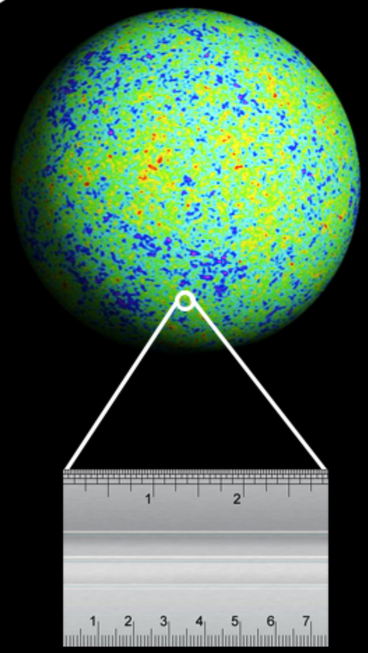
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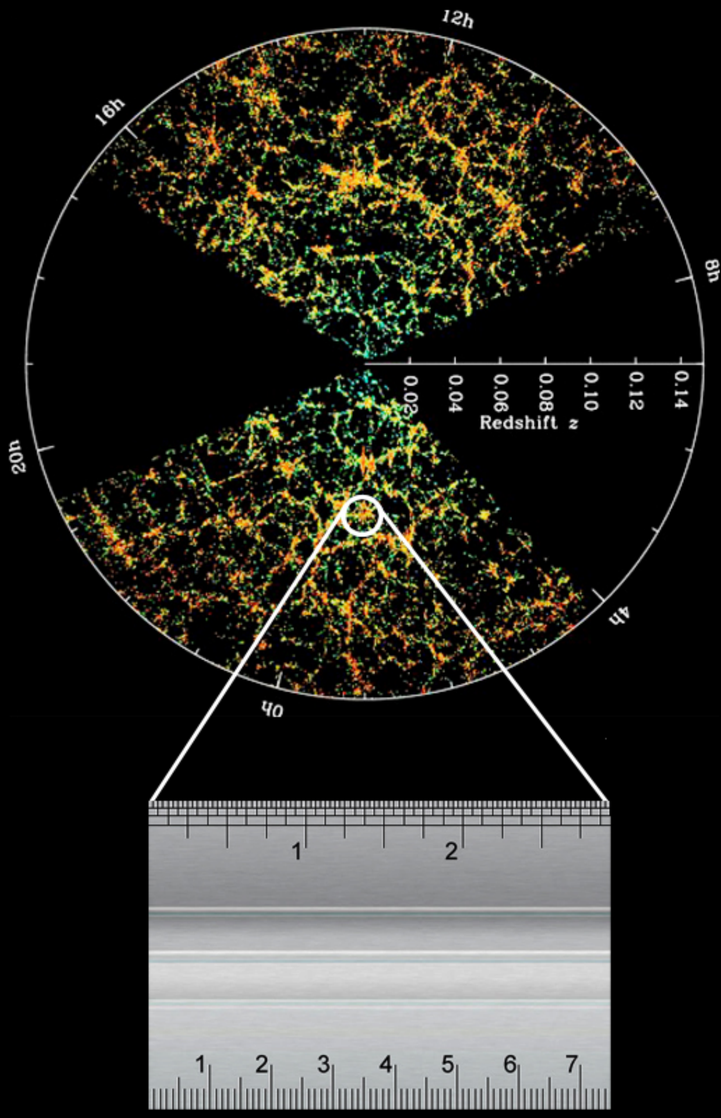





Universiteit Leiden
Durham University
THE EAGLE SIMULATION
icc.dur.ac.uk/Eagle
Growth of Structure
t_{age} = 0.5 Gyr
Redshift = 10.11
www.smcalpine.com







DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

BAO in the matter power spectrum

- BAO is left as an imprint both in the distribution of photons (CMB), but also in the matter distribution
- What ***complicates*** extracting this signal from the matter power spectrum?
  1. Galaxies are biased tracers
  2. Peculiar velocities
  3. Have to assume a fiducial cosmology
  4. Nonlinear gravitational growth

BAO in the matter power spectrum

Putting all together

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} \underbrace{\left[b + f\mu^2\right]^2}_{\text{Bias \& Kaiser RSD}} \times \Bigg[\underbrace{F_{\rm FoG}(k,\mu) \times P_{\rm nw}(k)}_{\substack{\text{Small-scale damping on} \\ \text{broadband (FoG)}}} + \underbrace{e^{-k^2\Sigma_{\rm nl}^2(\mu)} \times P_{\rm w}(k)}_{\substack{\text{Nonlinear BAO damping} \\ \text{(bulk flows, nonlinear growth)}}} \Bigg] \times \mathscr{L}_\ell(\mu)\, d\mu$$

Where:

- b : Linear bias — how galaxies trace the underlying matter.
- $f\mu^2$: Redshift-space distortions (Kaiser effect), anisotropic squashing along LOS.
- $P_{\rm nw}(k)$: Smooth broadband (no-wiggle) power spectrum.
- $P_{\rm w}(k)$: Oscillatory BAO wiggles.
- $F_{\rm FoG}(k,\mu) = \dfrac{1}{1+\frac{1}{2}k^2\mu^2\Sigma_s^2}$: Small-scale damping from random motions (virial velocities).
- $e^{-k^2\Sigma_{\rm nl}^2(\mu)}$: Nonlinear BAO damping from bulk flows + nonlinear growth.
- $\Sigma_{\rm nl}^2(\mu) = \Sigma_\perp^2 + \mu^2\left(\Sigma_\parallel^2 - \Sigma_\perp^2\right)$: Anisotropic damping.
- $\mathcal{L}_\ell(\mu)$: Legendre polynomial for multipole ℓ.

Other effects applied before multipoles:

- **AP distortion:** $k_\parallel^{\rm obs} = \alpha_\parallel k_\parallel$ and $k_\perp^{\rm obs} = \alpha_\perp k_\perp$.
- **BAO template cosmology:** Peak position shifts if assumed r_d differs from true r_d.
- **Broadband marginalization:** Polynomial terms or equivalent.

BAO in the matter power spectrum

Putting all together

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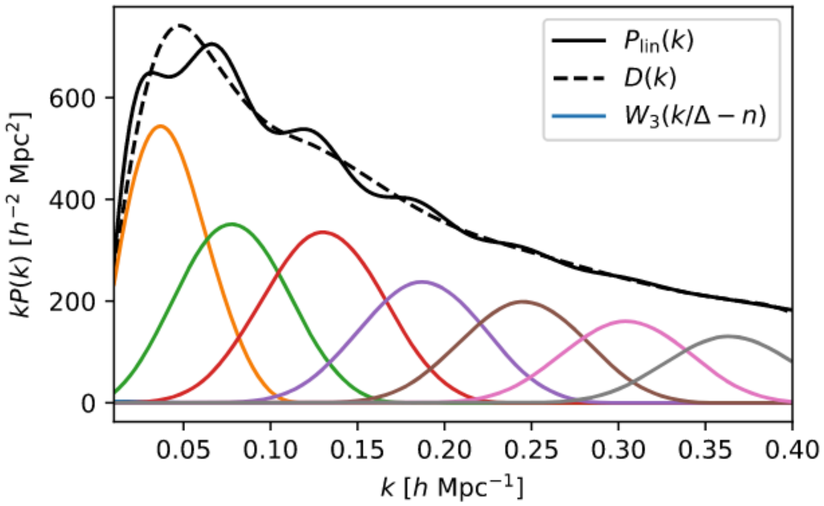
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- **Broadband marginalization:** Polynomial terms or equivalent.

$$P_{\rm g}(k,\mu) = \mathcal{B}(k,\mu)P_{\rm nw}(k) + \mathcal{C}(k,\mu)P_{\rm w}(k) \; + \; \mathcal{D}(k)$$



Broadband modeling:

- D(k) splines: local flexibility, robust to systematics, preserves BAO.

Chen, Howlett et al. 2024

BAO in the matter power spectrum

Putting all together

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} \underbrace{\left[b + f\mu^2\right]^2}_{\text{Bias \& Kaiser RSD}} \times \Bigg[\underbrace{F_{\rm FoG}(k,\mu) \times P_{\rm nw}(k)}_{\substack{\text{Small-scale damping on} \\ \text{broadband (FoG)}}} + \underbrace{e^{-k^2\Sigma_{\rm nl}^2(\mu)} \times P_{\rm w}(k)}_{\substack{\text{Nonlinear BAO damping} \\ \text{(bulk flows, nonlinear growth)}}} \Bigg] \times \mathscr{L}_\ell(\mu)\, d\mu$$

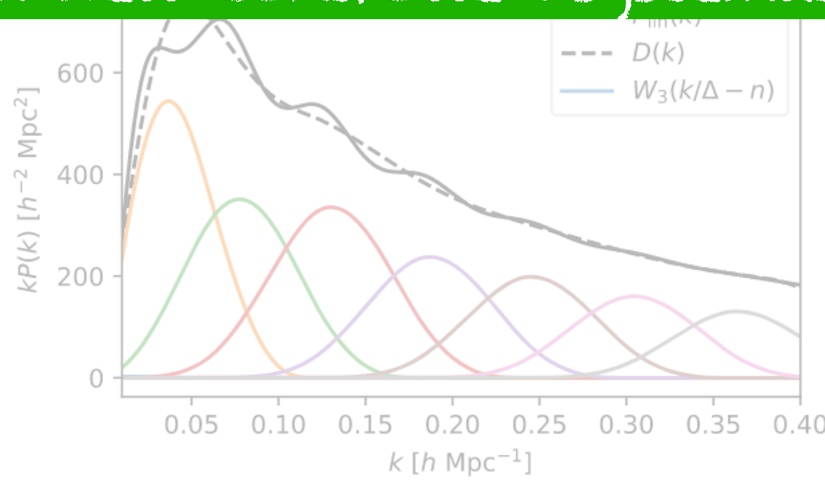
Takeaway:
- BAO is robust and theoretically well understood
- A robust distance probe with well-controlled systematics

Where

- $P_{\rm w}(k)$: Oscillatory BAO wiggles.
- $F_{\rm FoG}(k,\mu) = \dfrac{1}{1+\frac{1}{2}k^2\mu^2\Sigma_s^2}$: Small-scale damping from random motions (virial velocities).
- $e^{-k^2\Sigma_{\rm nl}^2(\mu)}$: Nonlinear BAO damping from bulk flows + nonlinear growth.
- $\Sigma_{\rm nl}^2(\mu) = \Sigma_\perp^2 + \mu^2\left(\Sigma_\parallel^2 - \Sigma_\perp^2\right)$: Anisotropic damping.
- $\mathcal{L}_\ell(\mu)$: Legendre polynomial for multipole ℓ.

Other effects applied before multipoles:

- **AP distortion:** $k_\parallel^{\rm obs} = \alpha_\parallel k_\parallel$ and $k_\perp^{\rm obs} = \alpha_\perp k_\perp$.
- **BAO template cosmology:** Peak position shifts if assumed r_d differs from true r_d.
- **Broadband marginalization:** Polynomial terms or equivalent.



Broadband modeling:

- D(k) splines: local flexibility, robust to systematics, preserves BAO.

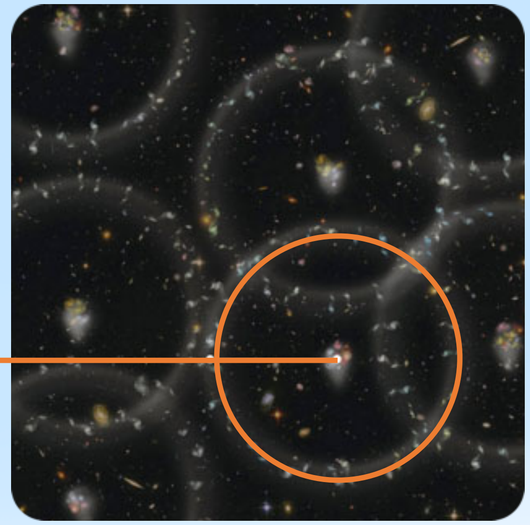
Chen, Howlett et al. 2024

BAO Measurements

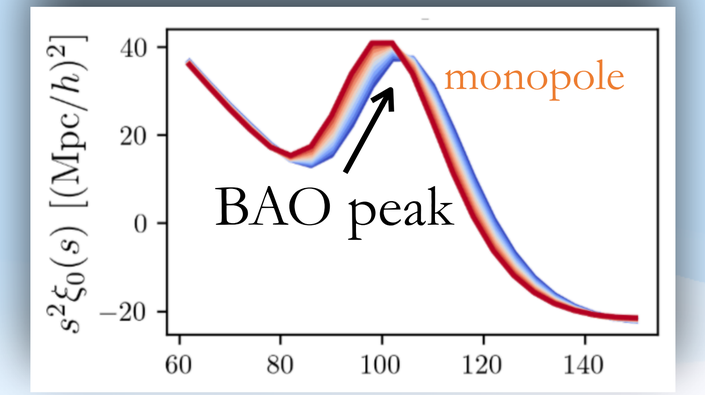
What DESI BAO measures



line of sight



correlation function

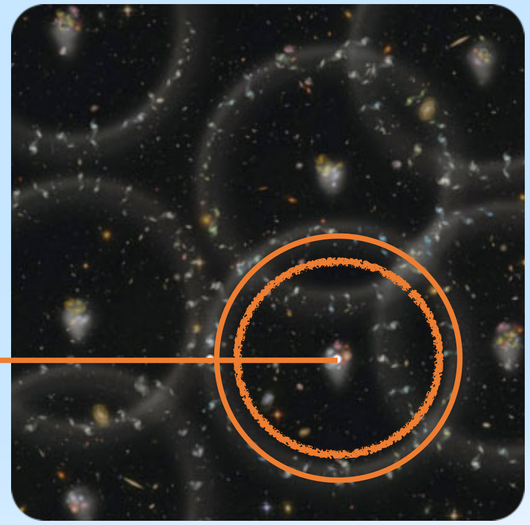


What DESI BAO measures

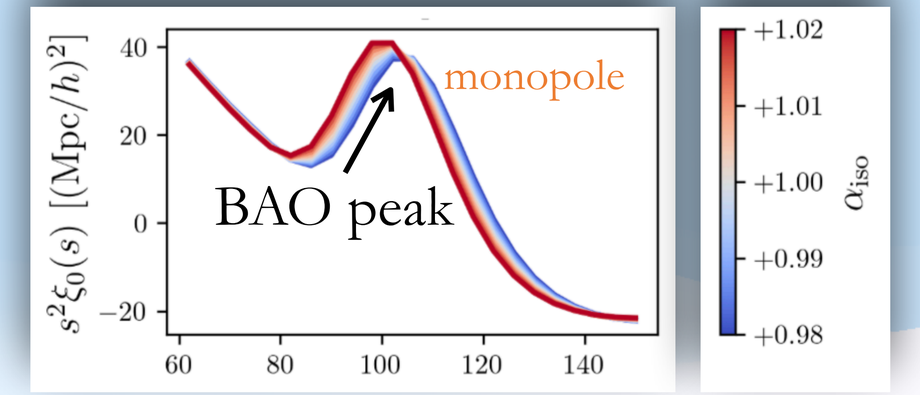
isotropic



line of sight



correlation function



$$\alpha_{\rm iso} \propto (D_{\rm M}^2(z) D_{\rm H}(z))^{1/3} / r_{\rm d}$$

comoving transverse distance

Hubble distance $c/H(z)$

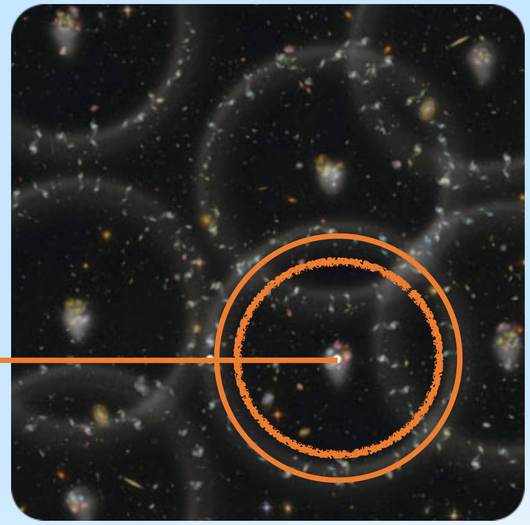
sound horizon (standard ruler)

What DESI BAO measures

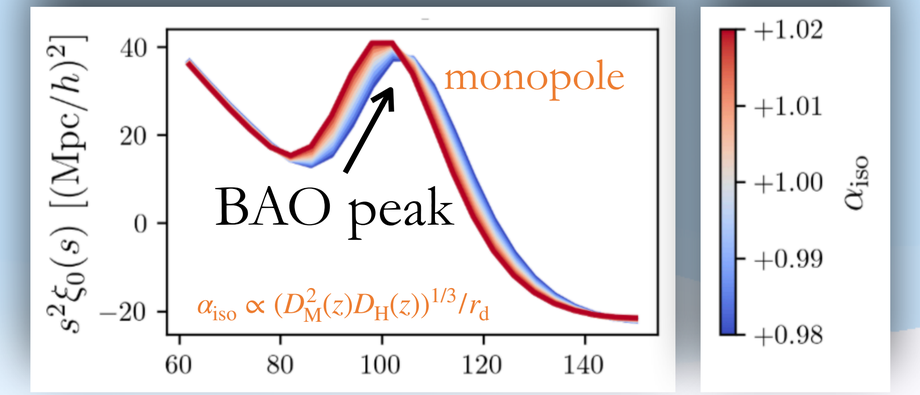
isotropic



line of sight

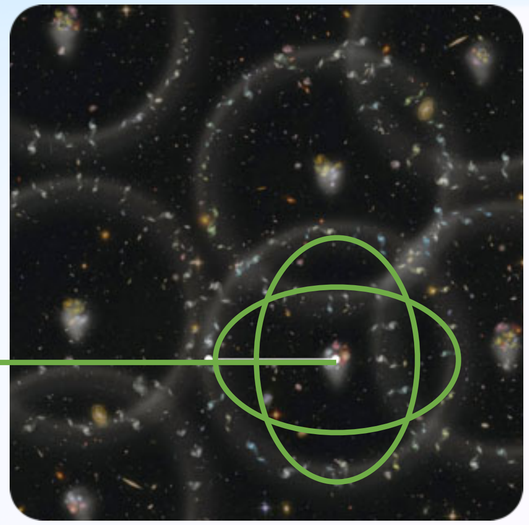


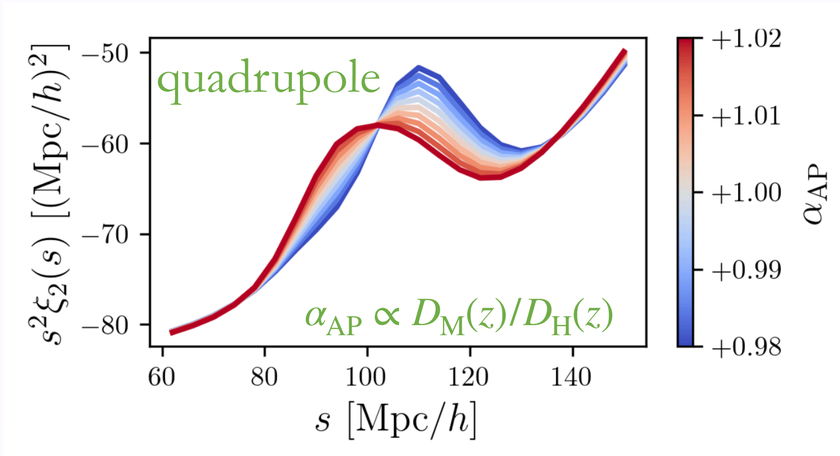
correlation function





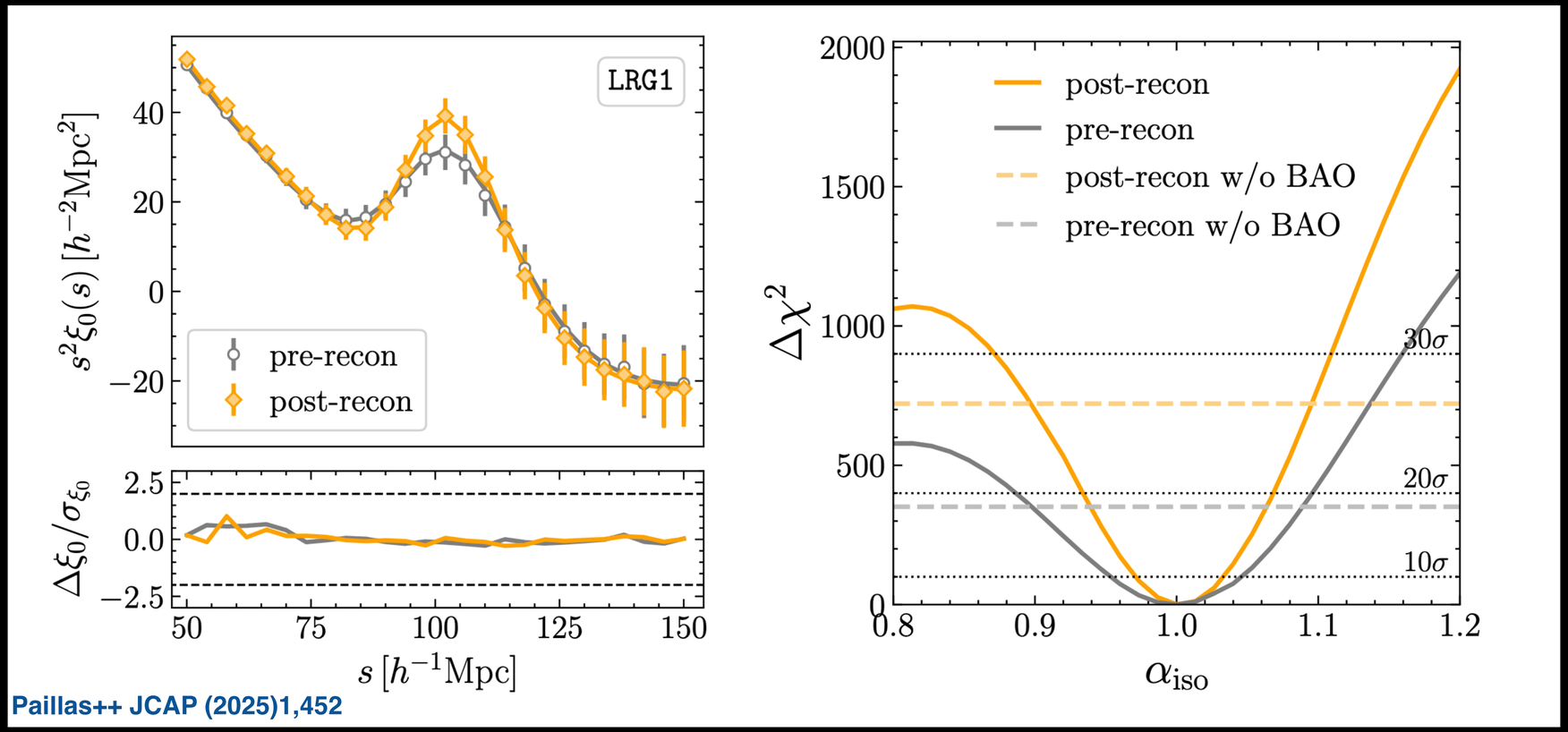
line of sight





Density field reconstruction

1. Reconstruction dramatically increases the BAO detection significance: from ~18σ to ~27σ



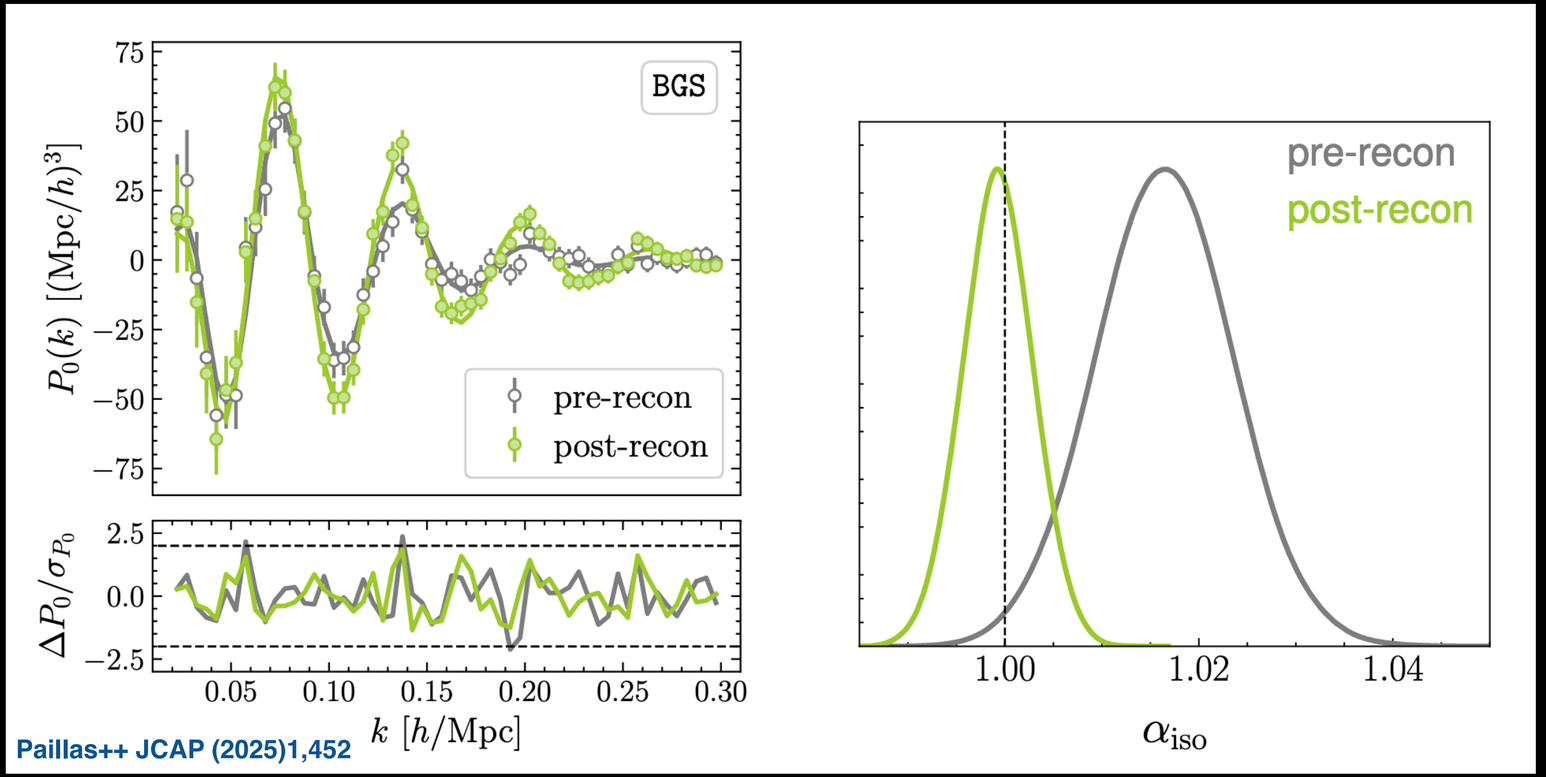
Paillas++ JCAP (2025)1,452

analysis on AbacusSummit mocks

Reconstruction helps to sharpen the BAO peak by partially restoring the linearity of the density field

Density field reconstruction

2. Reconstruction reduces bias in the BAO scale and improves precision

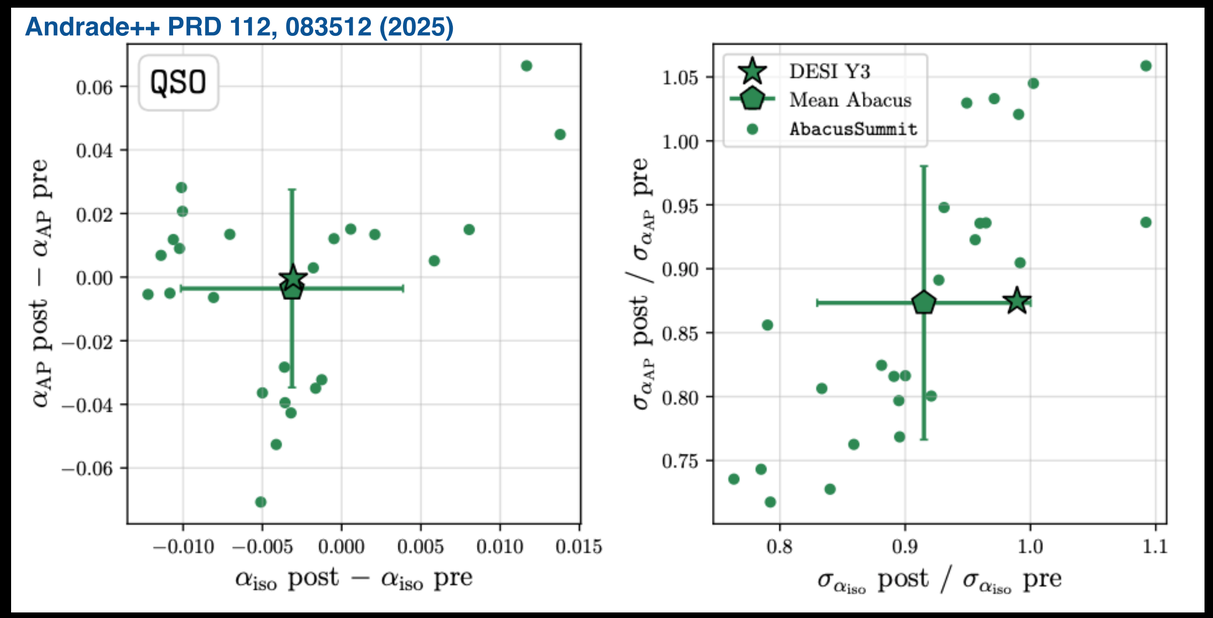


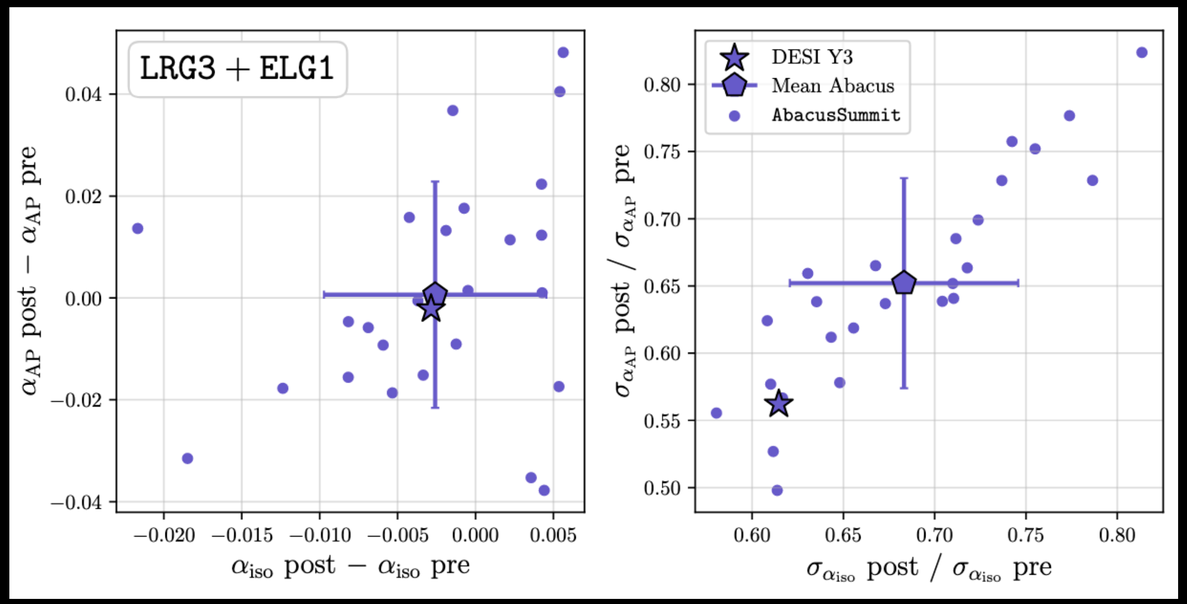
Paillas++ JCAP (2025)1,452

analysis on AbacusSummit mocks

Reconstruction not only sharpens the BAO feature, but can also help removing systematic shifts in the location of the peak due to non-linear evolution and galaxy biasing.

Density field reconstruction





For QSO, reconstruction reduces the uncertainties by 3.7% for $\alpha_{\rm iso}$ and 8.5% for$\alpha_{\rm AP}$

For LRG3+ELG1, reconstruction reduces the uncertainties by 42% for $\alpha_{\rm iso}$ and 47% for $\alpha_{\rm AP}$

This level of improvement from the data finds good agreement with the distribution of mocks

Tests of systematic errors

Considered many possible sources of systematic errors using simulations and data:

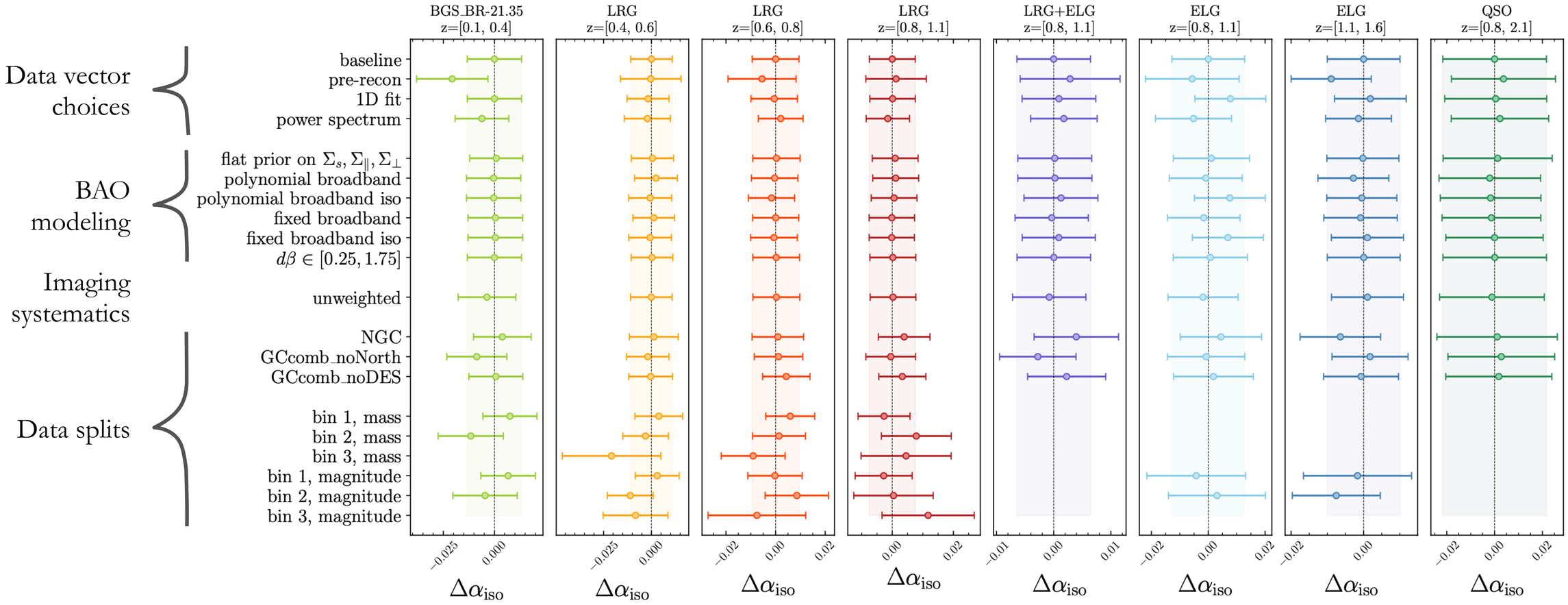
- observational effects (imaging systematics, fiber collisions)
- BAO reconstruction (2 algorithms compared)
- covariance matrix construction
- incomplete theory modeling
- choice of fiducial cosmology
- galaxy-halo (HOD) model uncertainties

No systematics dected

systematics << statistics

Maximum effect: $\sigma_{\text{stat.+syst.}} < 1.06\ \sigma_{\text{stat.}}$

DR2 BAO is robust against different choices



Differences in the isotropic BAO dilation

Andrade++ PRD 112, 083512 (2025)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Validation of the DESI DR2 BAO measurement

PHYSICAL REVIEW D **112,** 083512 (2025)

Editors' Suggestion | Featured in Physics

Validation of the DESI DR2 measurements of baryon acoustic oscillations from galaxies and quasars

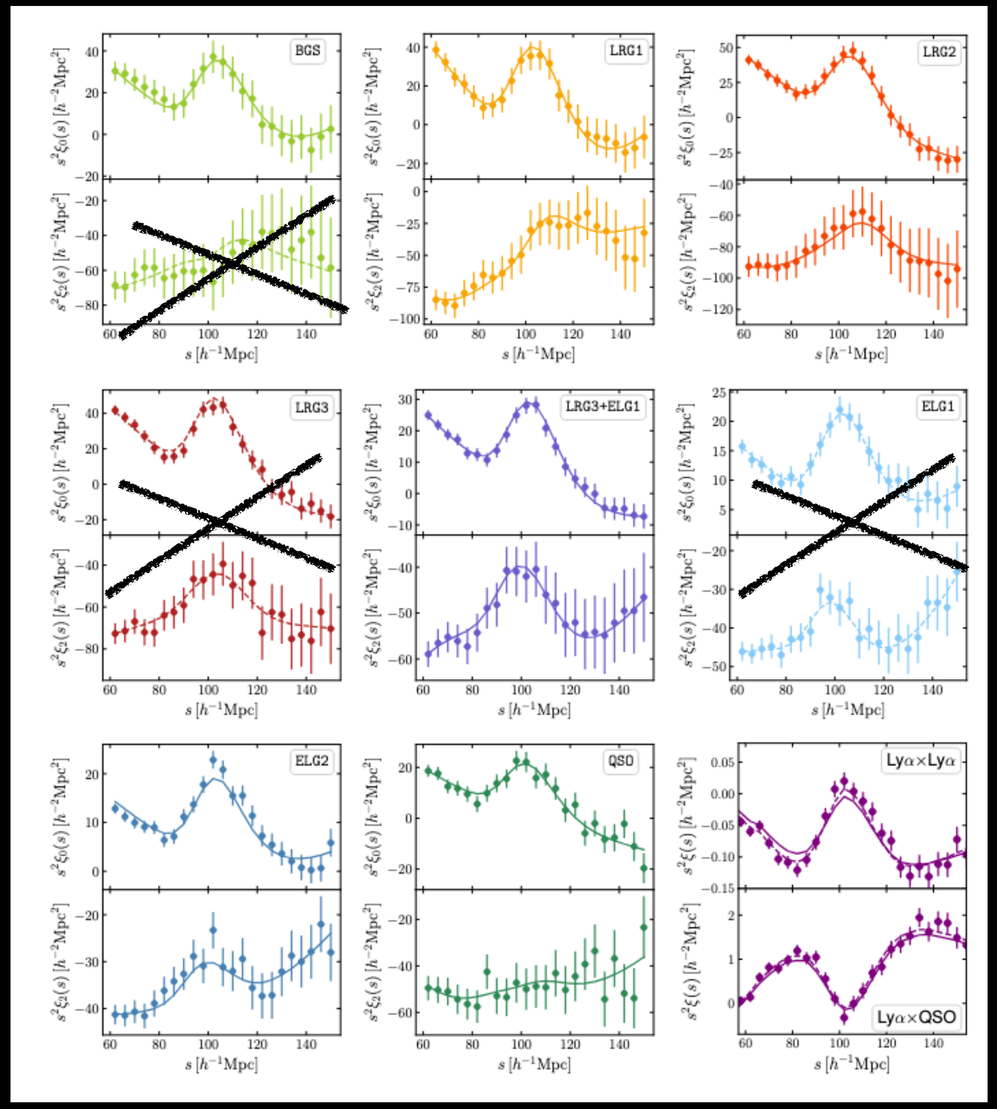
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Final BAO Measurements in DESI DR2: The Most Precise to Date



✅ Clear BAO peak detected in all tracers around ~100 Mpc/h.

✅ Detection significance ranges from 5.6σ (QSO) to 14.7σ (LRG+ELG)

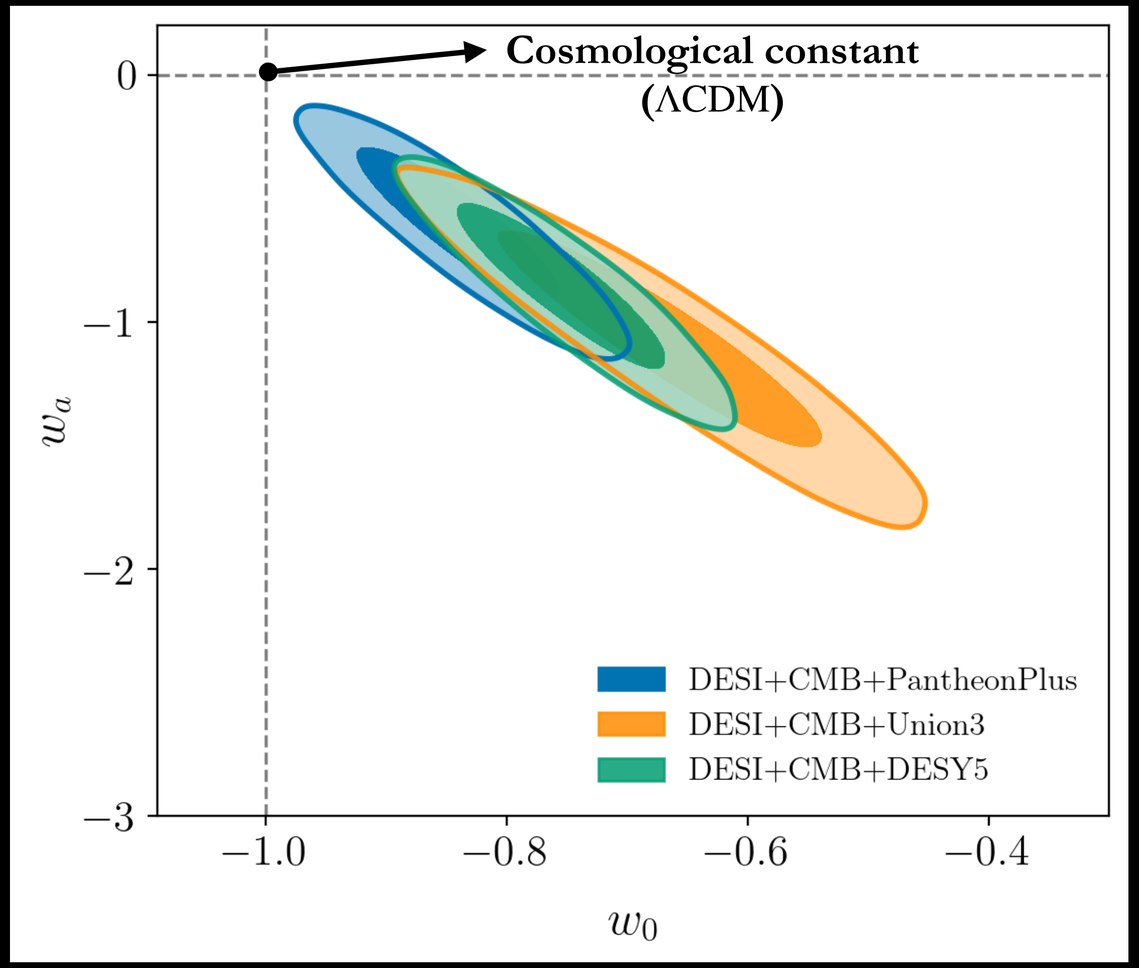
✅ The most precise BAO measurements ever (40% more precise than DR1)

- DESI Collaboration *et al.* (2025), DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints
- DESI Collaboration et al. (2025), DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest

- Andrade et al. (2025), Validation of the DESI DR2 GQC BAO measurements
- Casas et al. (2025), Validation of the DESI DR2 Lyα BAO

DR2: Dynamical Dark Energy - (w_0, w_a)

- 4.2σ in favor of Dynamical Dark Energy
- Unless there is an **unknown systematic** error associated with one or more datasets, it is clear that ΛCDM is being challenged by the combination of DESI BAO with other measurements and that dynamical dark energy offers a possible solution



Blinding of the galaxy catalogs



Blinding of the galaxy catalogs

Journal of Cosmology and Astroparticle Physics
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DARK ENERGY SPECTROSCOPIC INSTRUMENT (DESI) SURVEY YEAR 1 RESULTS

Validating the galaxy and quasar catalog-level blinding scheme for the DESI 2024 analysis

U.S. Department of Energy Office of Science

U. Andrade et al.
Full author list at the end of the paper

E-mail: uendsa@umich.edu



Blinding of the galaxy catalogs

Blinding happens in three steps:

1. Blinding for BAO;
2. Blinding for RSD;
3. Blinding for primordial non-Gaussianity $f_{\rm NL}$.

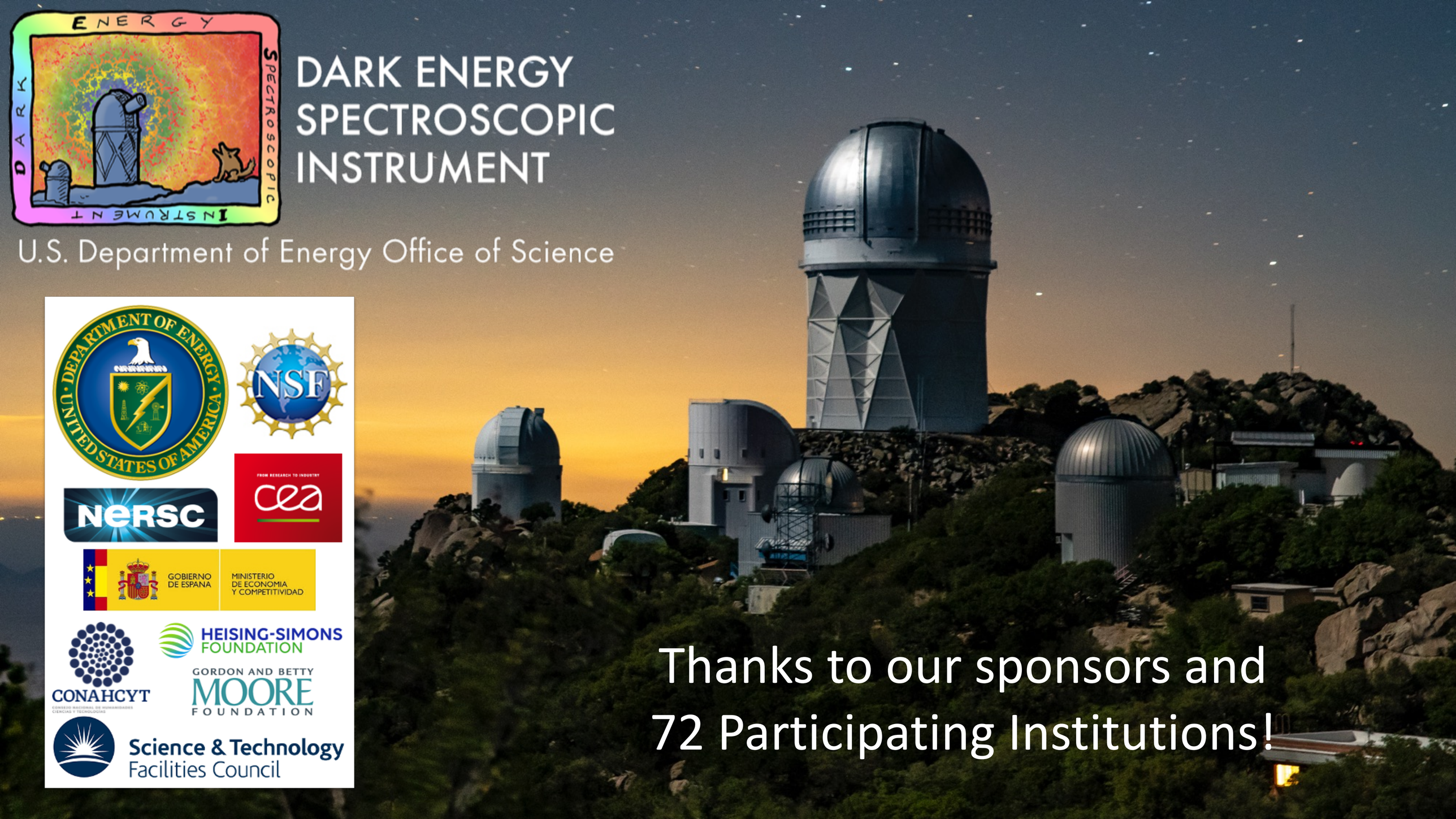


Looking ahead to DR3 BAO

Nothing is carved in stone yet, since we still have some time to decide

But two things I am mostly excited about:

- New reconstruction methodology
- More tracers in the “combined tracer” probe



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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