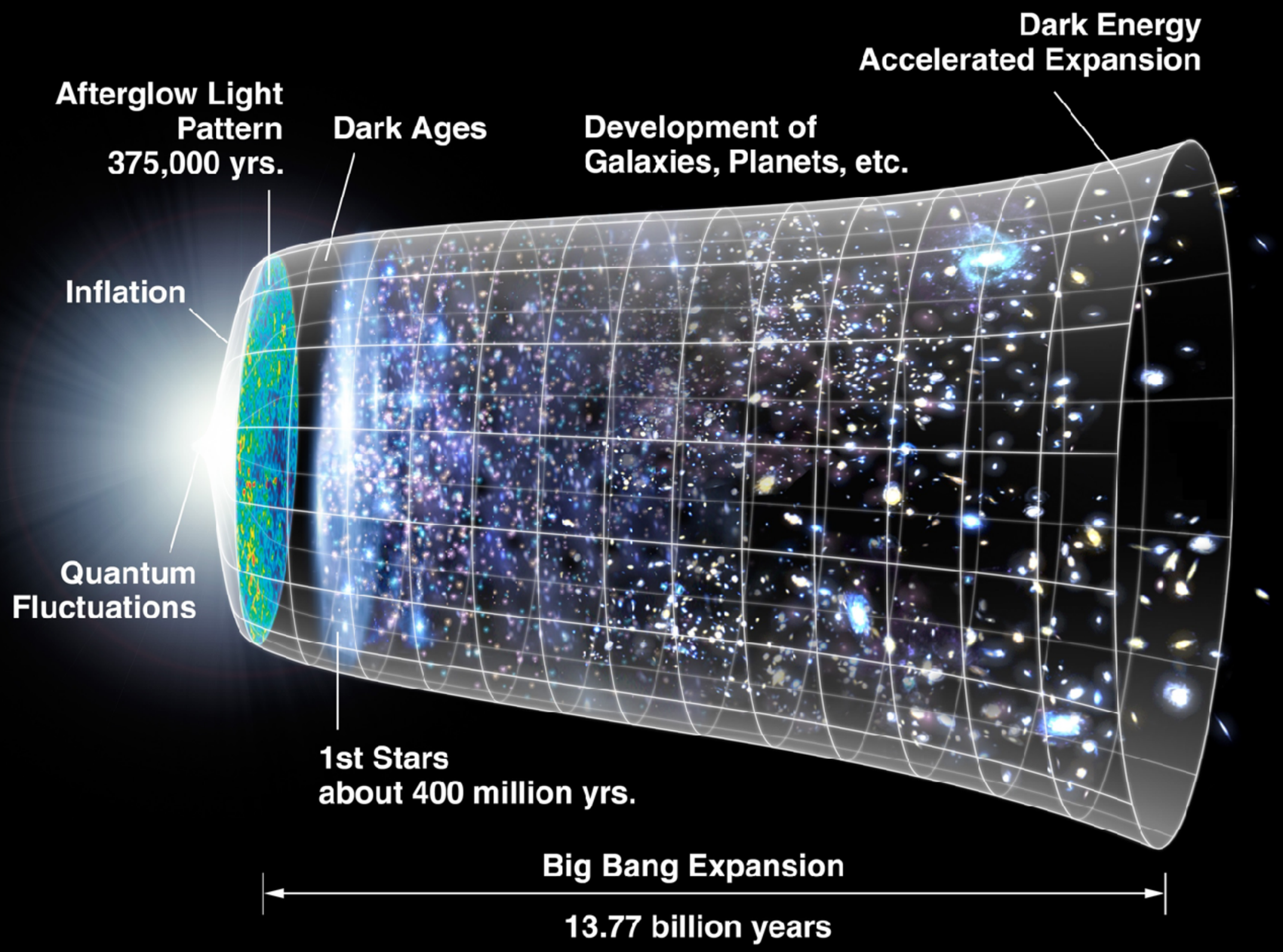
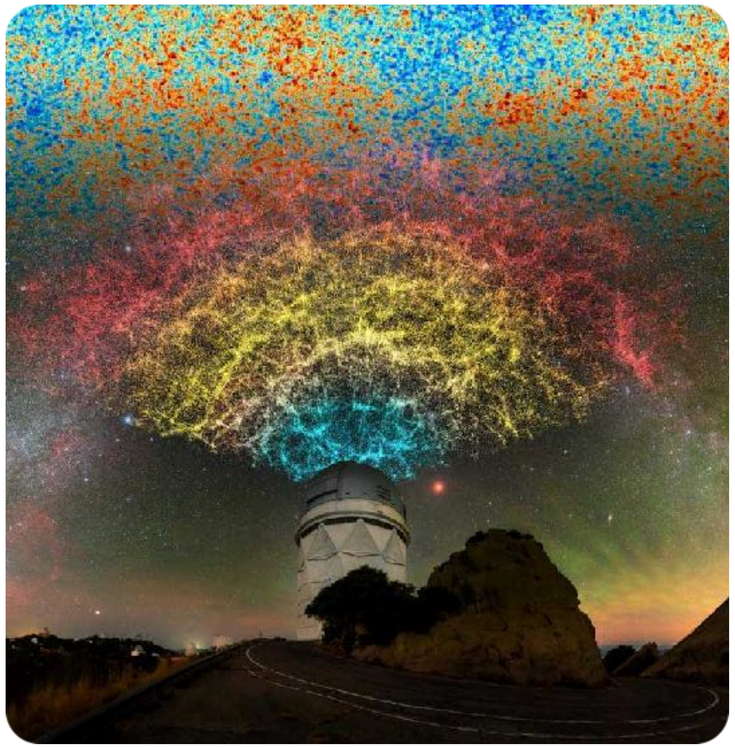
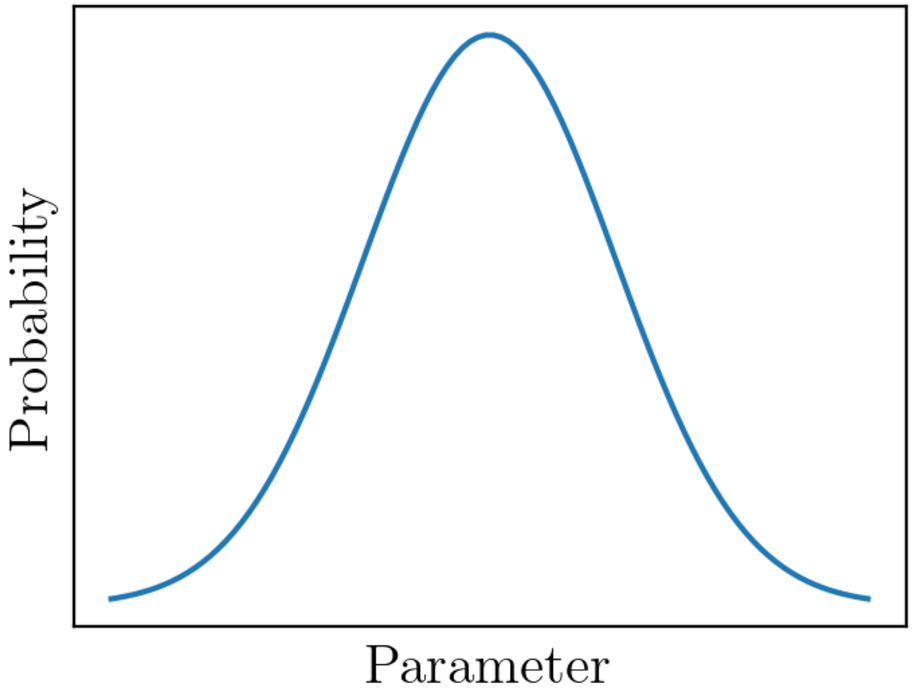
Probing Fundamental Physics with Galaxy Surveys

Enrique Paillas
Postdoctoral Associate
Steward Observatory Prize Fellow
University of Arizona


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Observational Cosmology





$\Omega_{\rm m}, \Omega_{\rm b}, \sigma_8, n_s, H_0, \ldots$

How can we learn about physics from a cosmological experiment?

Image credits: NOIRLab
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

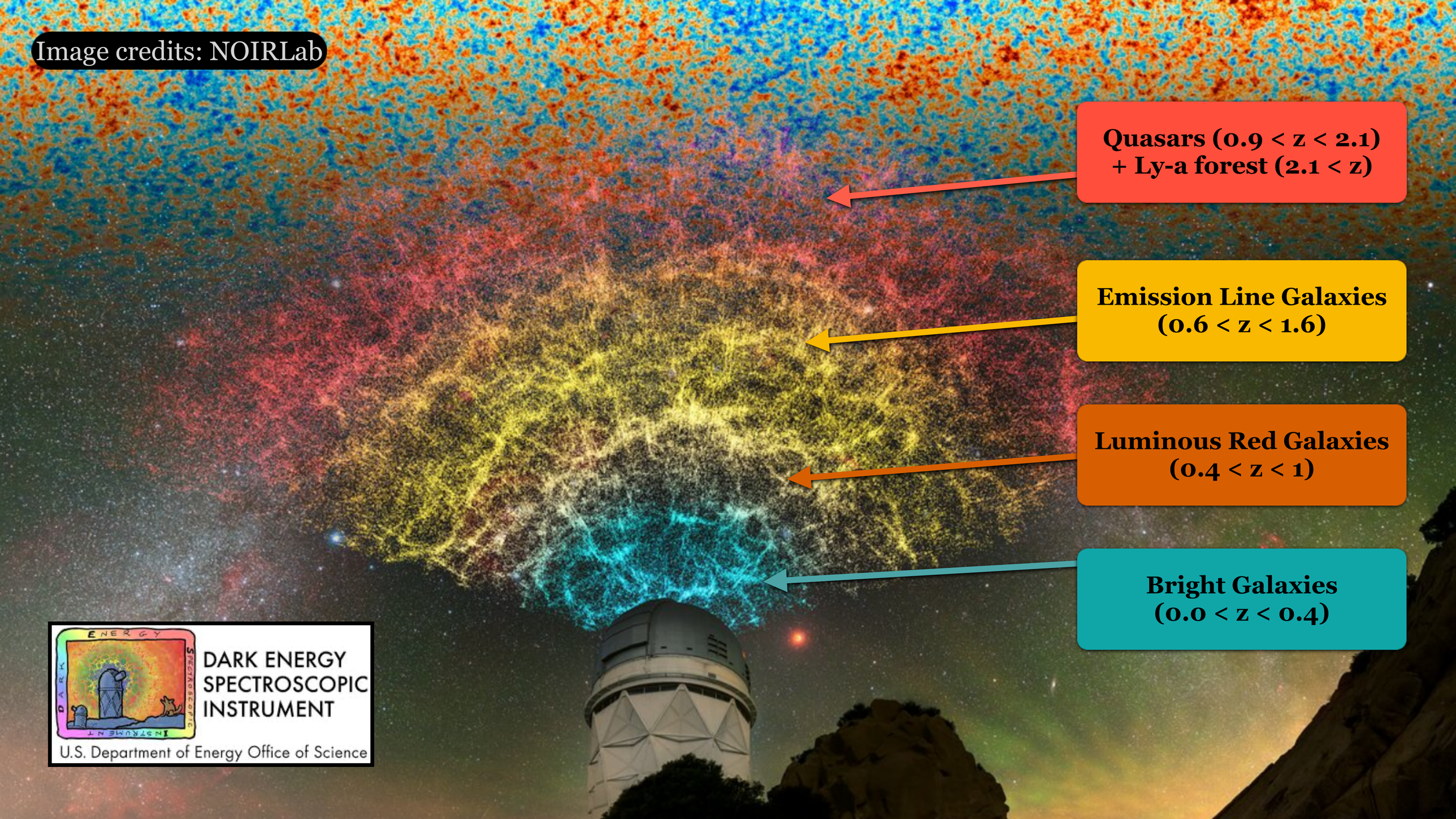
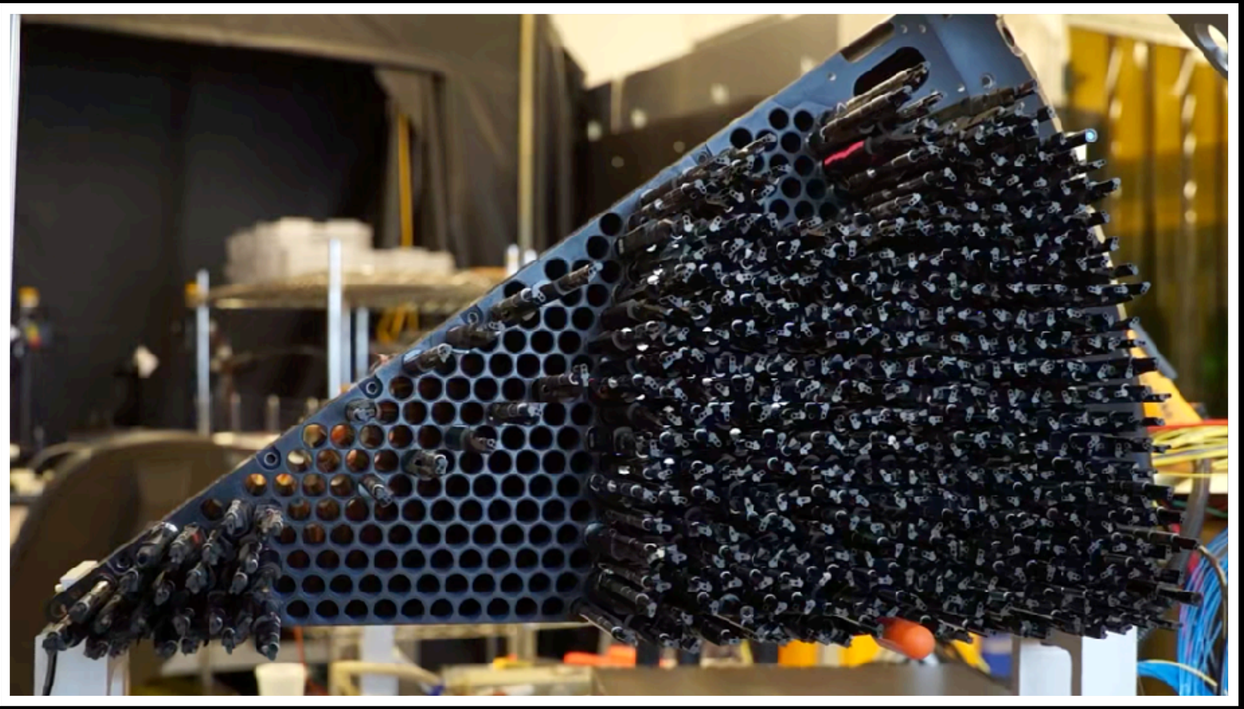
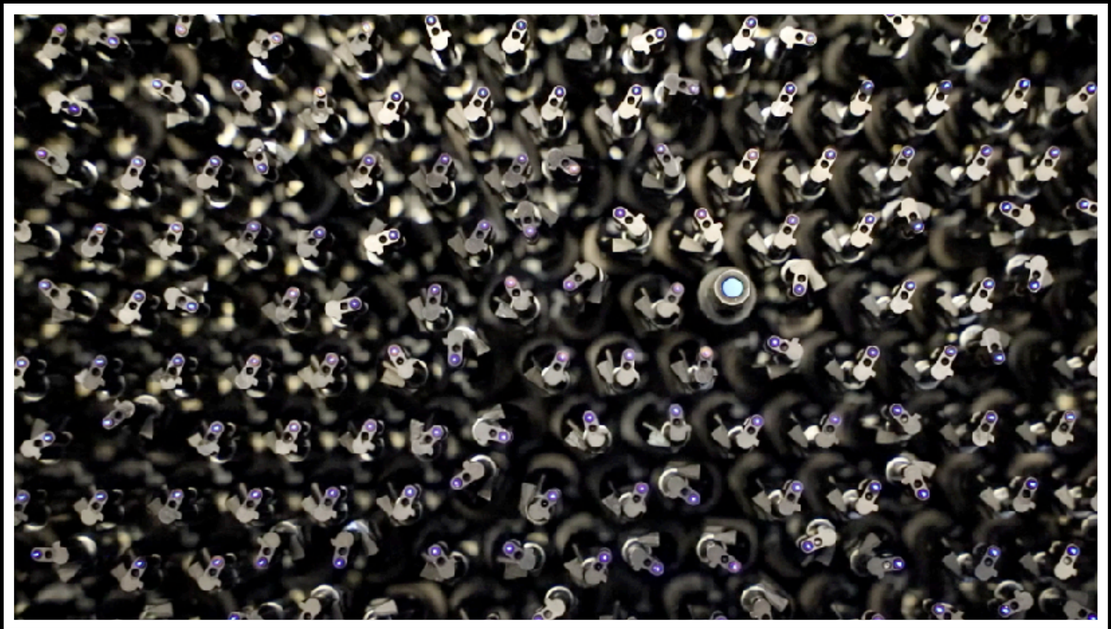
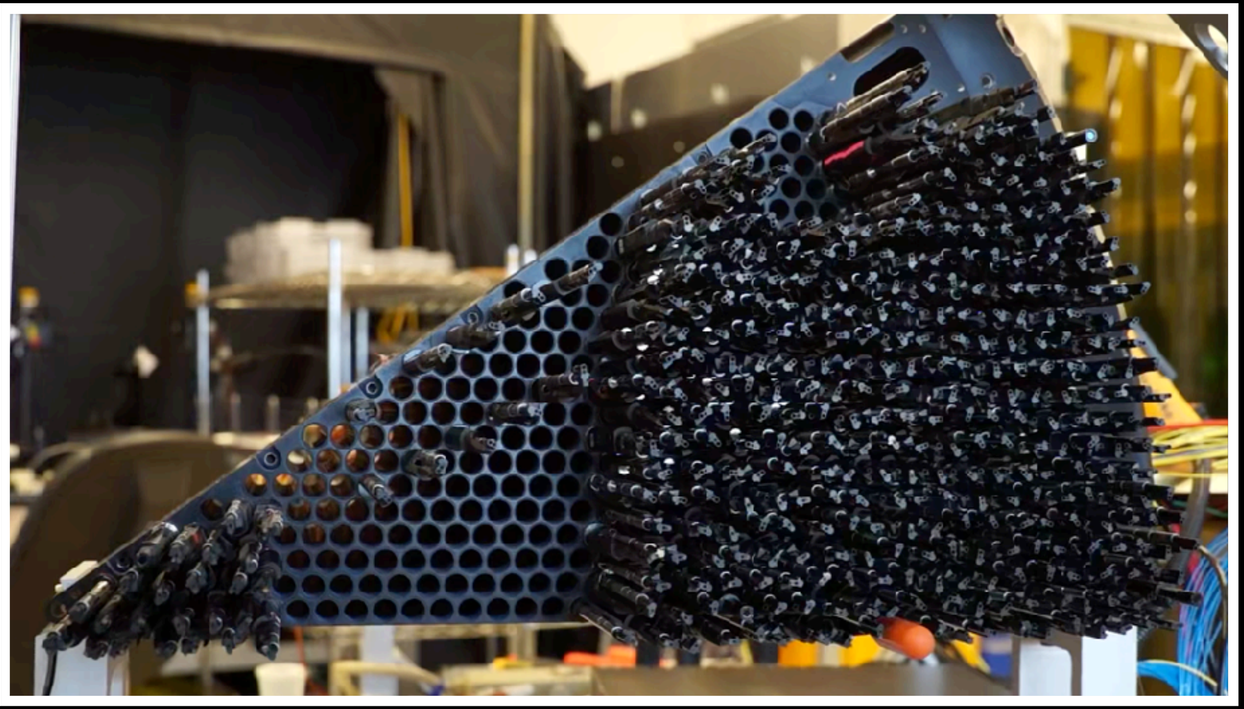
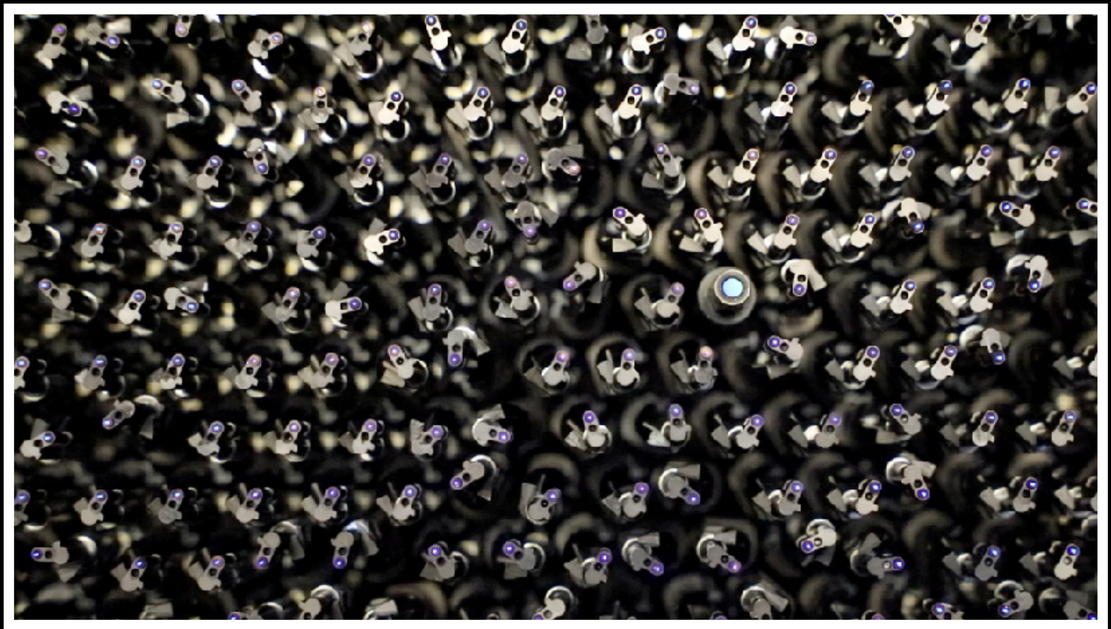


Image credits: NOIRLab
Quasars (0.9 < z < 2.1)
+ Ly-a forest (2.1 < z)
Emission Line Galaxies
(0.6 < z < 1.6)
Luminous Red Galaxies
(0.4 < z < 1)
Bright Galaxies
(0.0 < z < 0.4)
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science





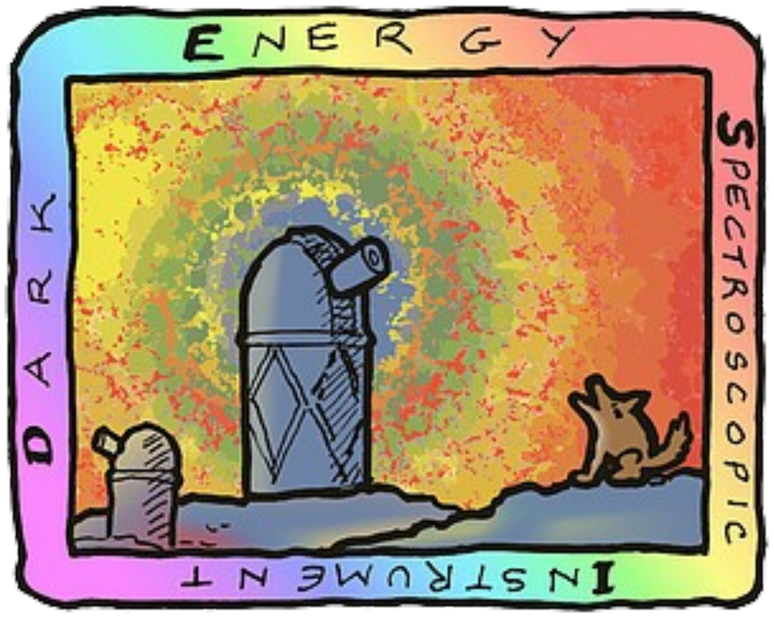




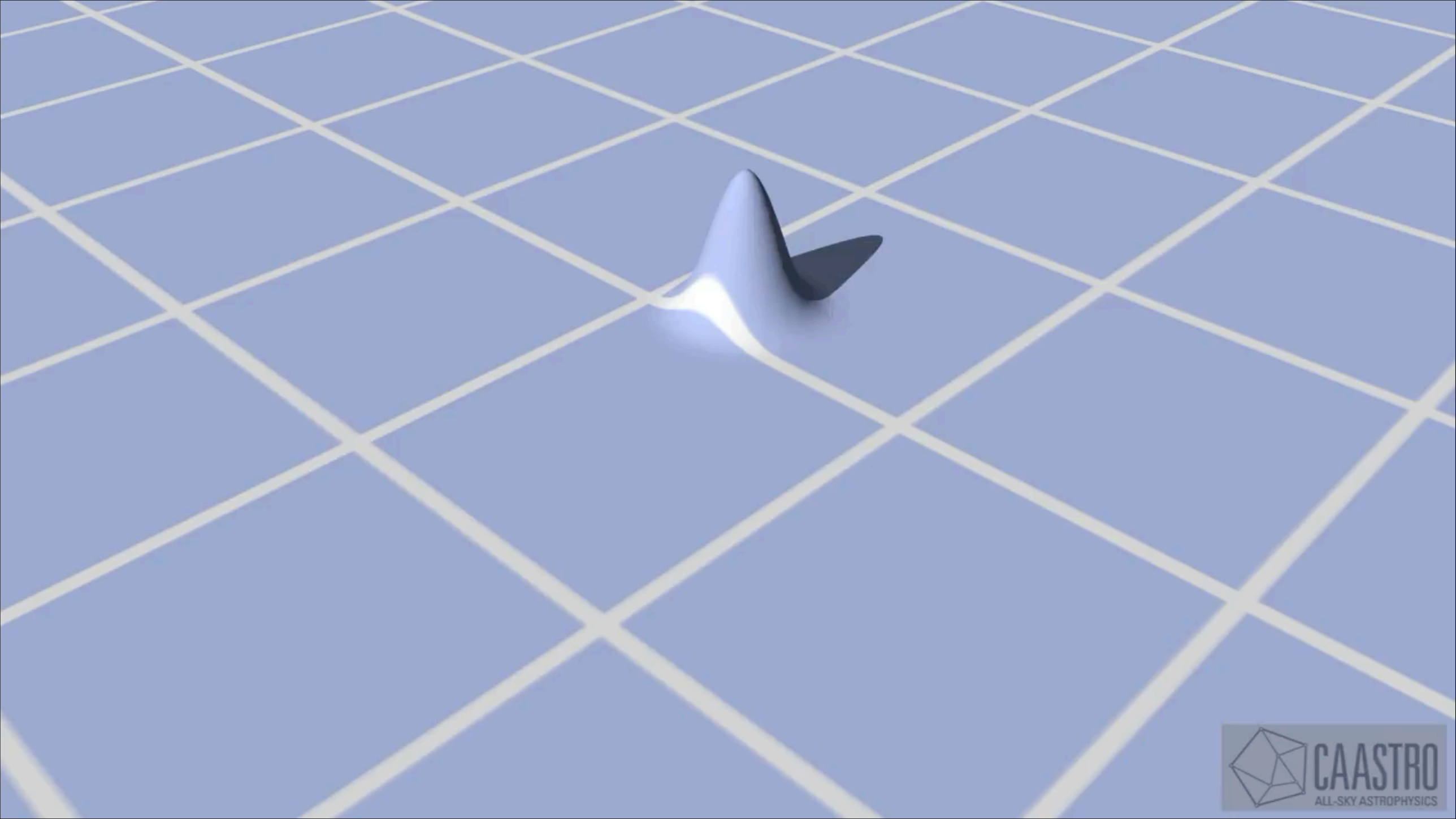
Astronomy & Steward Observatory

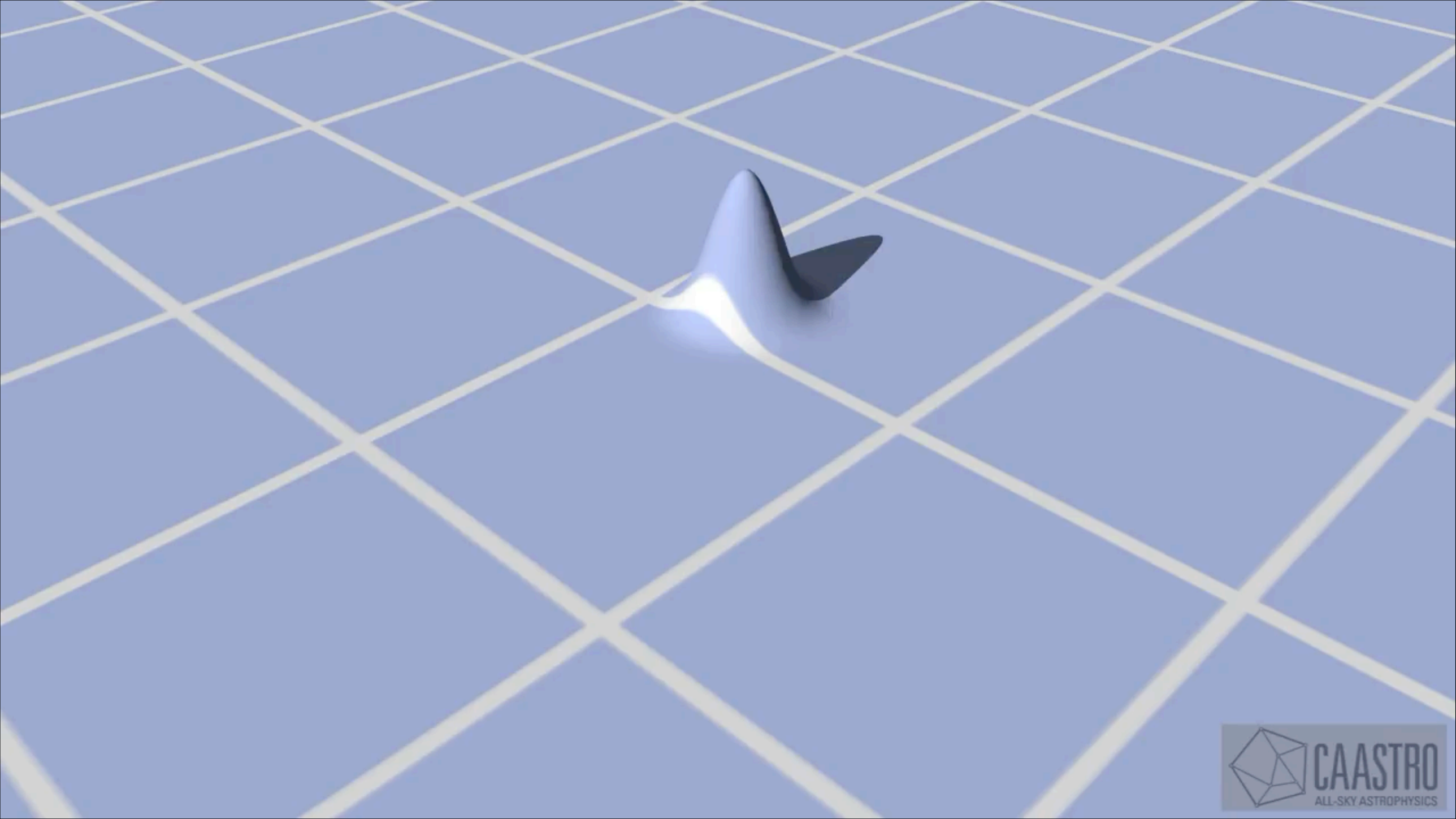
Galaxy & Quasar Clustering working group
(co-chair since 2024)

- Measure the **expansion history** of the Universe through baryon acoustic oscillations.
- Measure the **growth rate of cosmic structure** through the analysis of redshift-space distortions.
- Place upper bounds on the sum of **neutrino masses**.
- Shed light onto the primordial Universe through constraints on **primordial non-Gaussianity**.



Dark Energy


CAASTRO
ALL-SKY ASTROPHYSICS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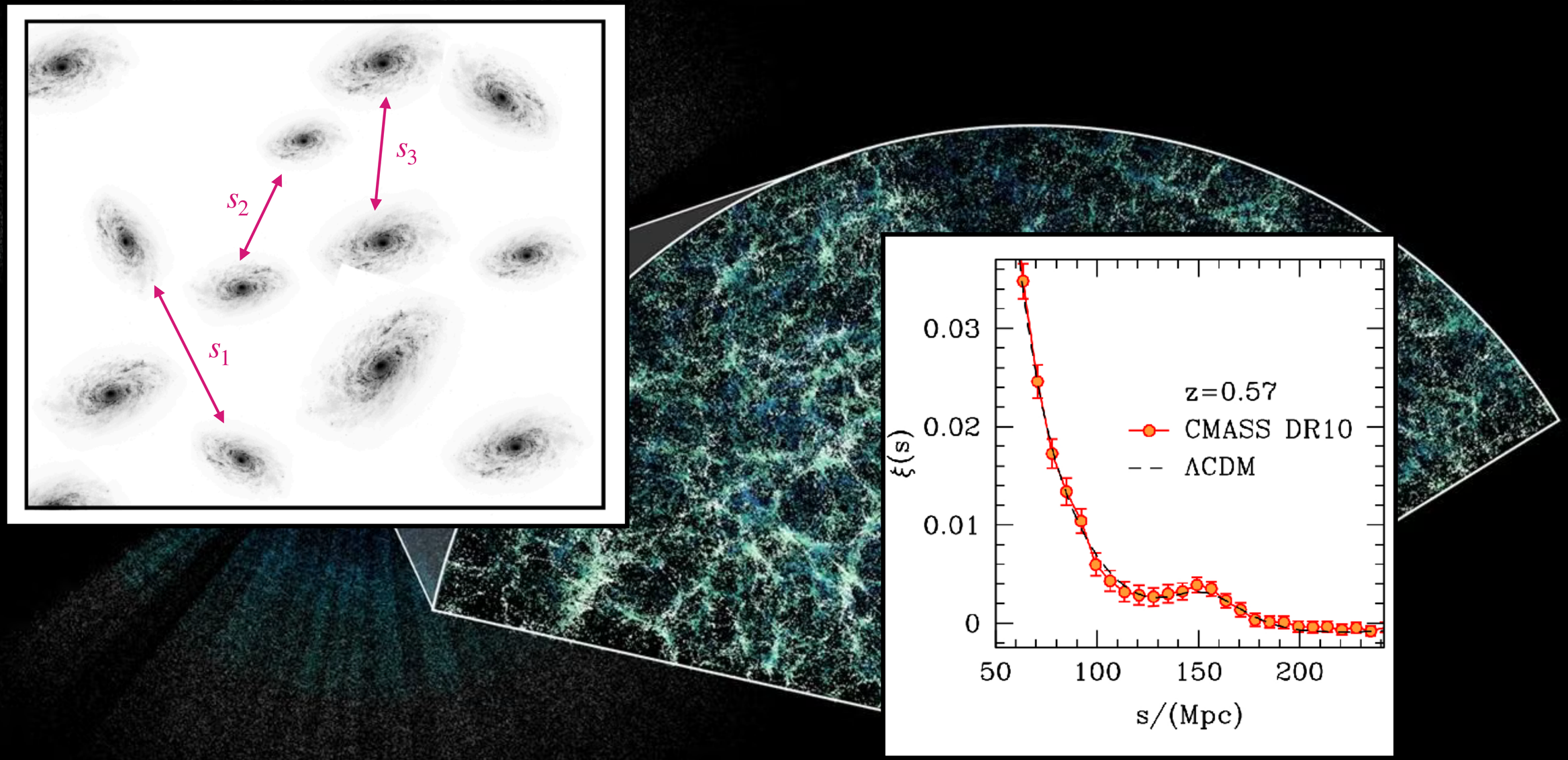
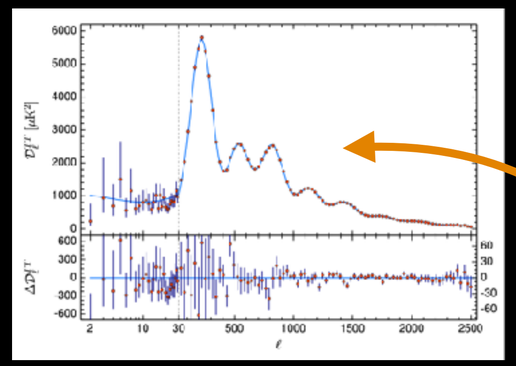
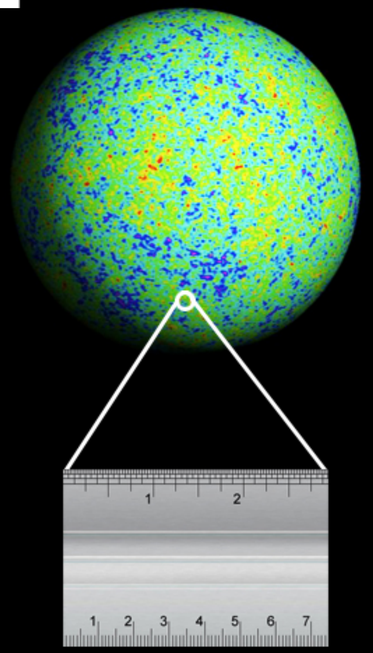
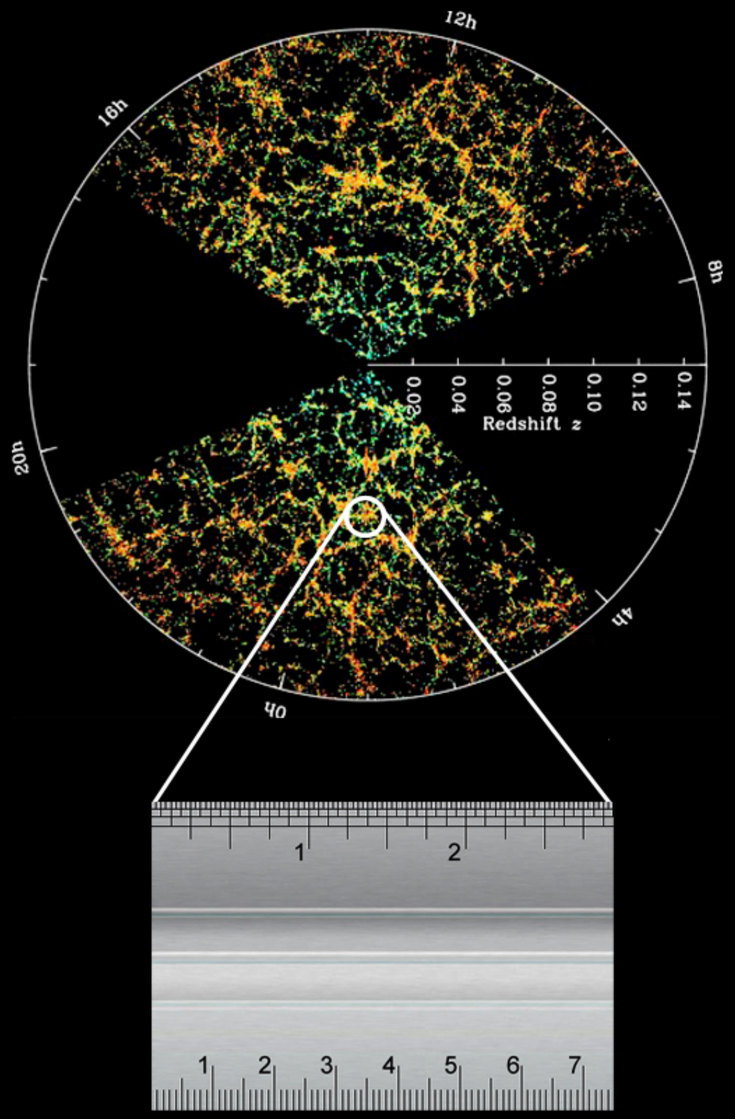

s_1
s_2
s_3
0.03
0.02
0.01
0
$\xi(s)$
z=0.57
CMASS DR10
ΛCDM
50
100
150
200
s/(Mpc)

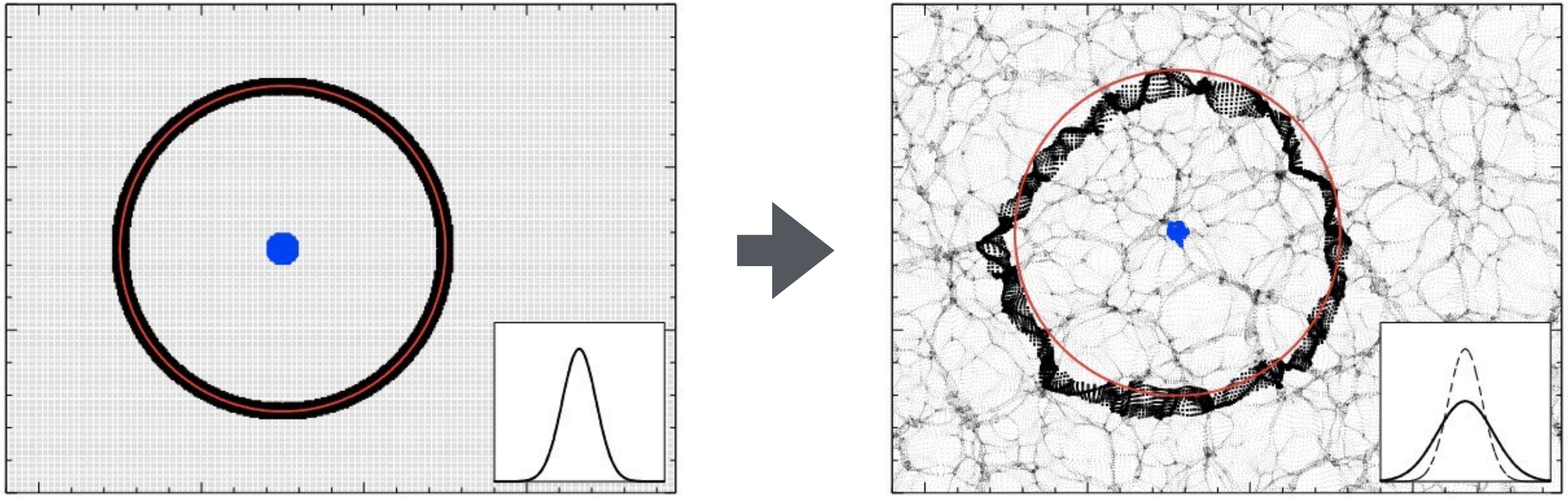






An external calibration on r_d allows us to e.g. break the H_0-r_d degeneracy.

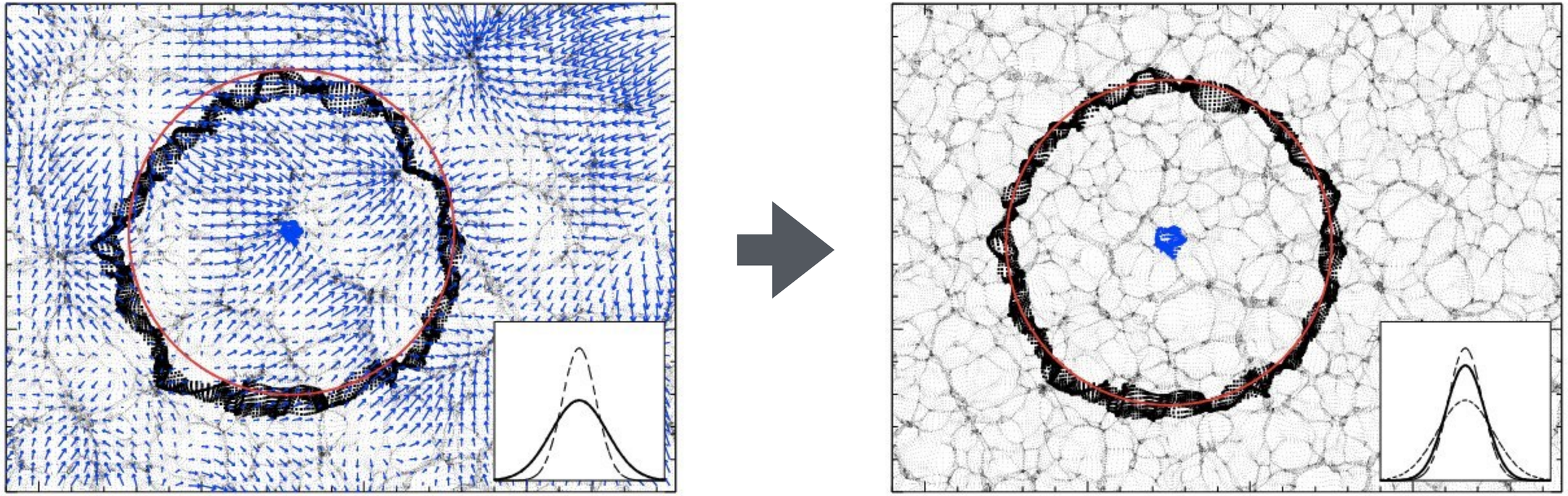
BAO Reconstruction



Non-linear gravitational evolution blurs out the acoustic feature, degrading the precision and accuracy of the BAO ruler.

Padmanabhan+2012

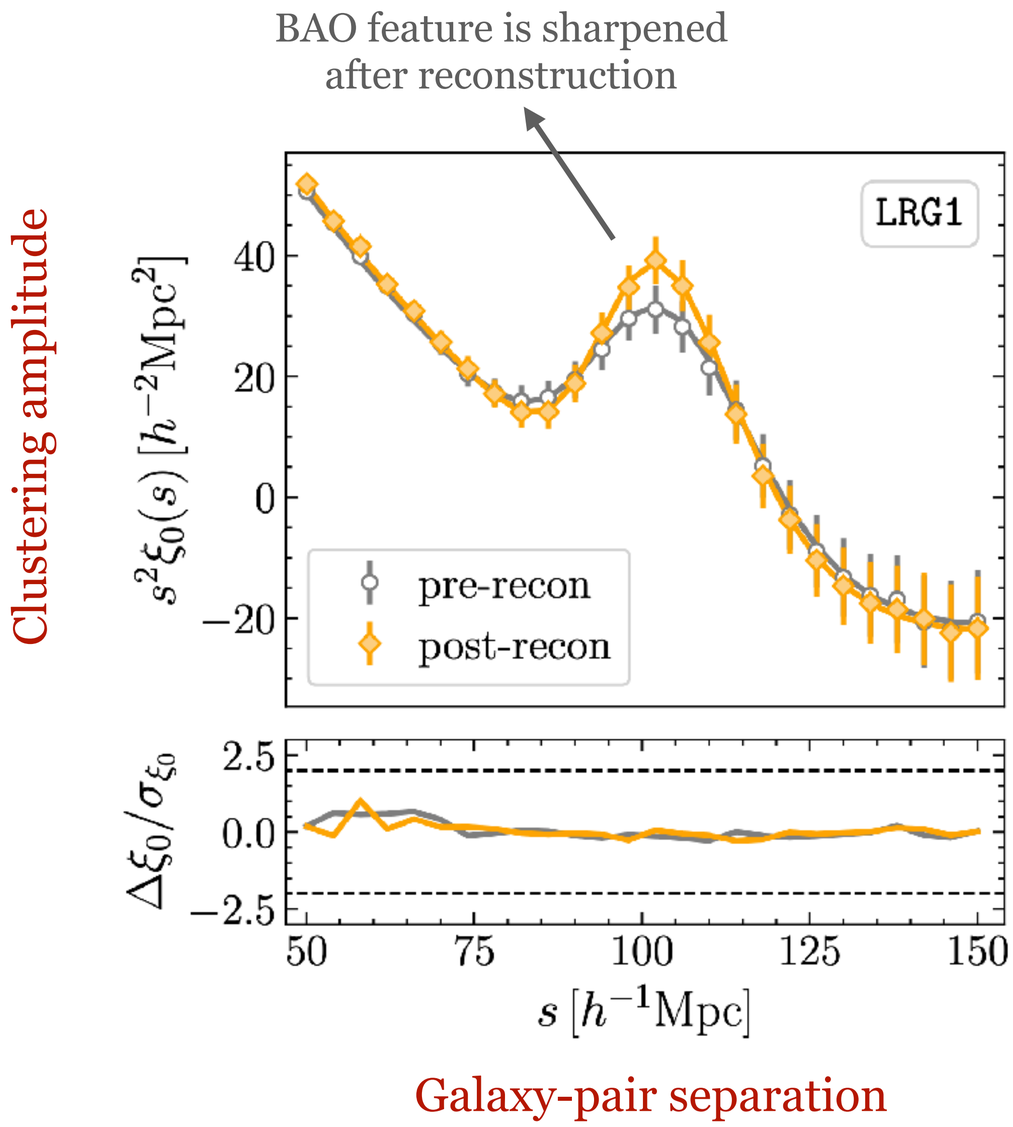
BAO Reconstruction



We can refurbish the ruler using **density-field reconstruction**, which estimates Zel'dovich displacements from the galaxy field to undo non-linear motions.

Padmanabhan+2012

BAO Reconstruction



- Reconstruction **improves the precision** of the BAO detection and **removes systematic biases** due to non-linear evolution.

- Up to **40% improvement** in DESI BAO measurements from our work:

Paillas, Ding, Chen et al. (2024)
Chen, Ding, **Paillas** et al. (2024)

The Nature of Dark Energy

Astronomy & Steward Observatory

- For a cosmological constant, the dark energy **equation of state** is given by

$$w = \frac{p}{\rho c^2} = -1$$

- We can parameterize its **time evolution** by (Chevalier & Polanski 2001, Linder 2003)

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

DESI Collaboration (including **Paillas**), 2024

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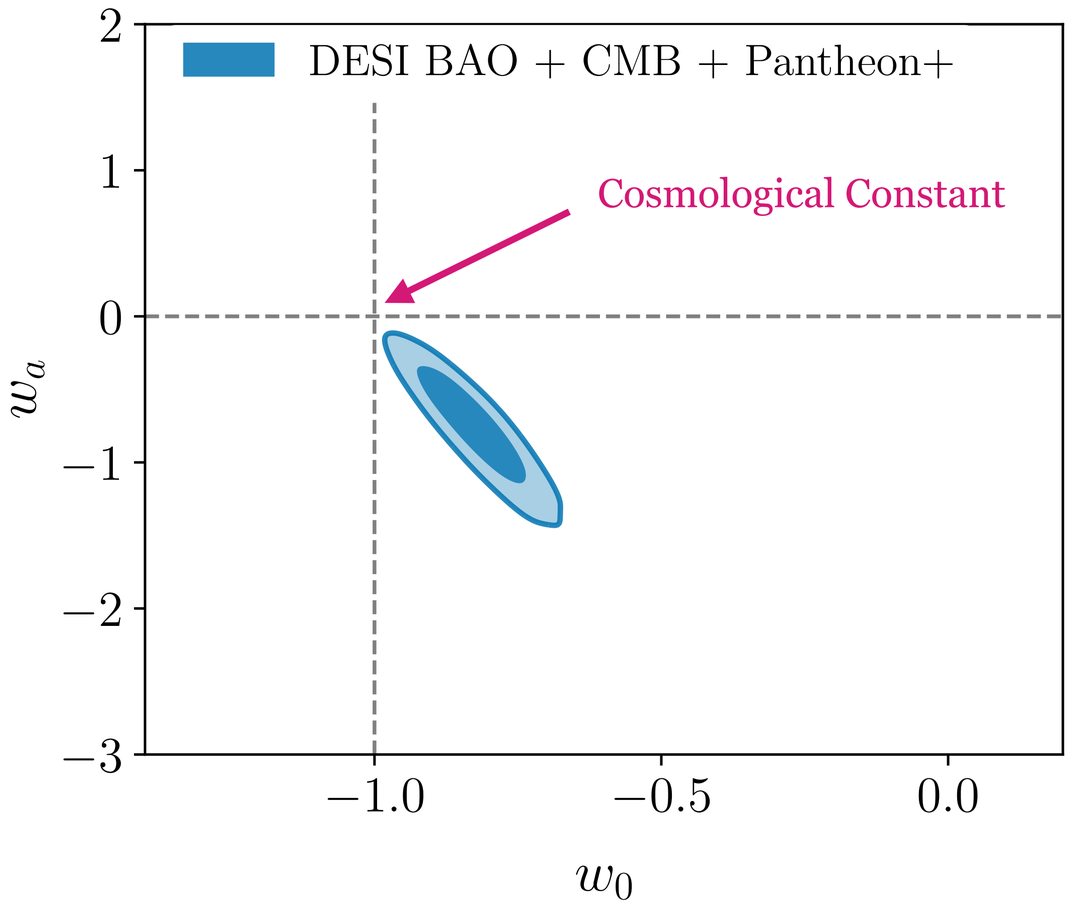
- DESI finds a preference for **dynamical dark energy** (3.9σ significance) when combined with CMB and SNe experiments.



DESI Collaboration (including **Paillas**), 2024

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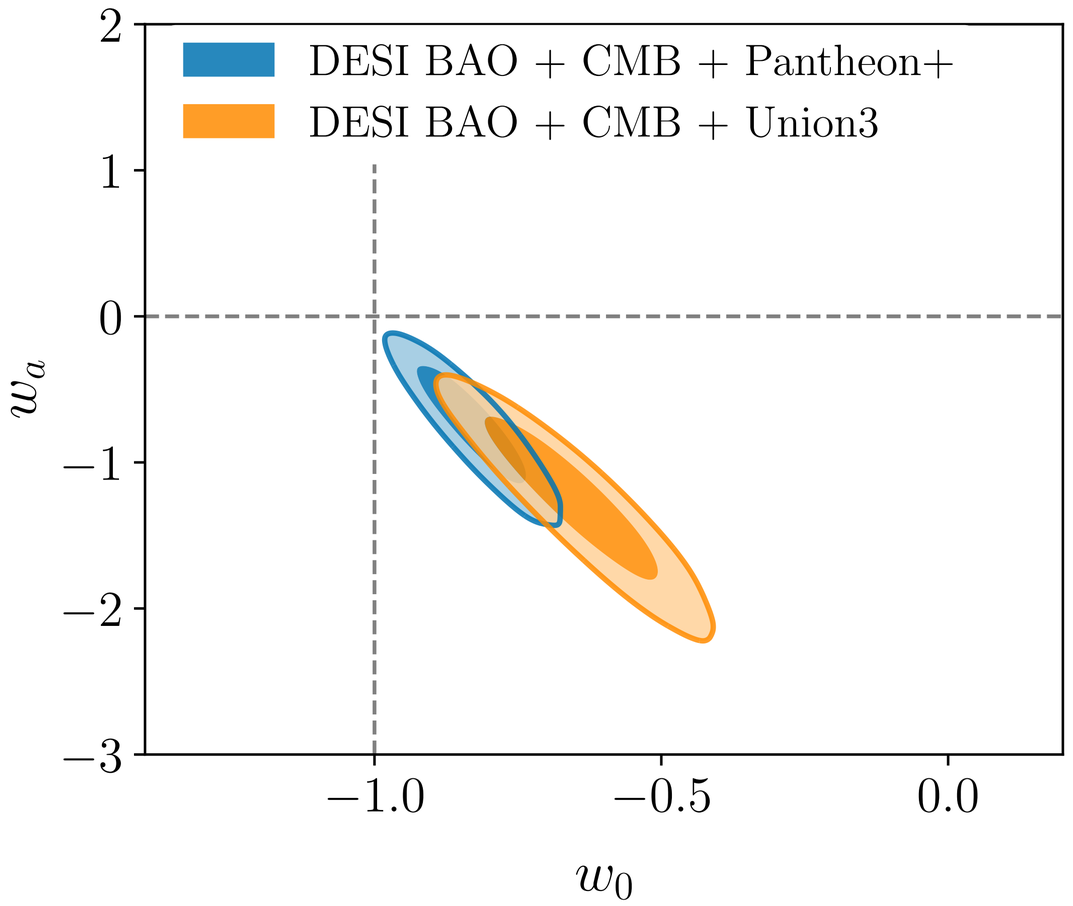

DESI Collaboration (including **Paillas**), 2024

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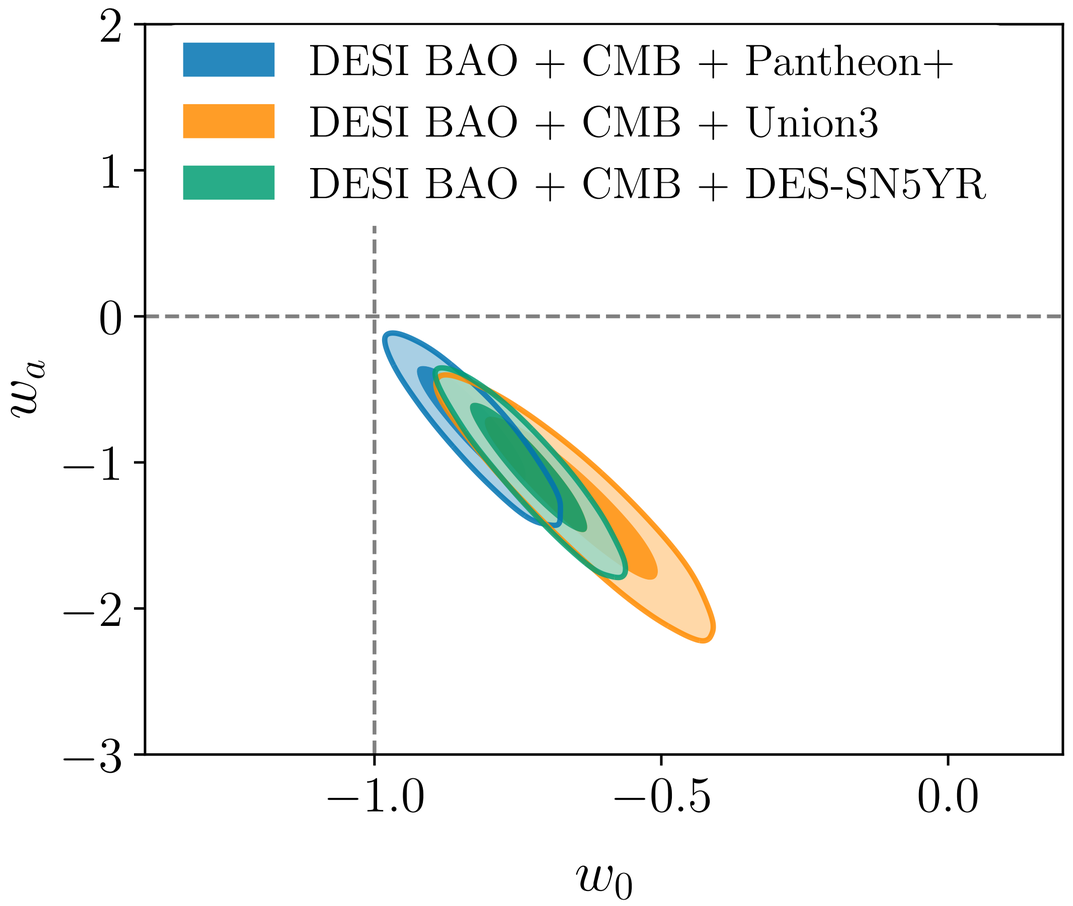


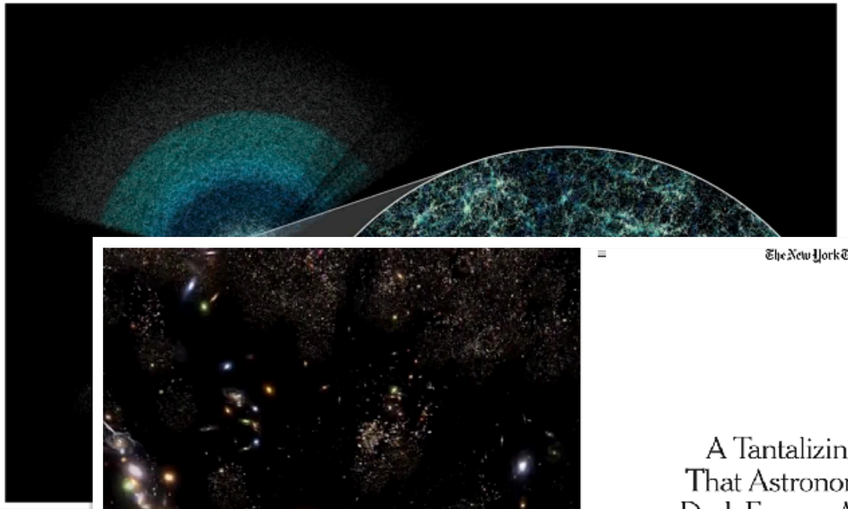
DESI Collaboration (including **Paillas**), 2024

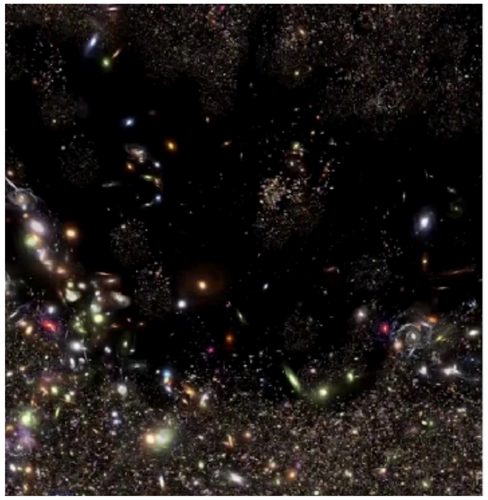
DESI in the Media

Astronomy & Steward Observatory

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

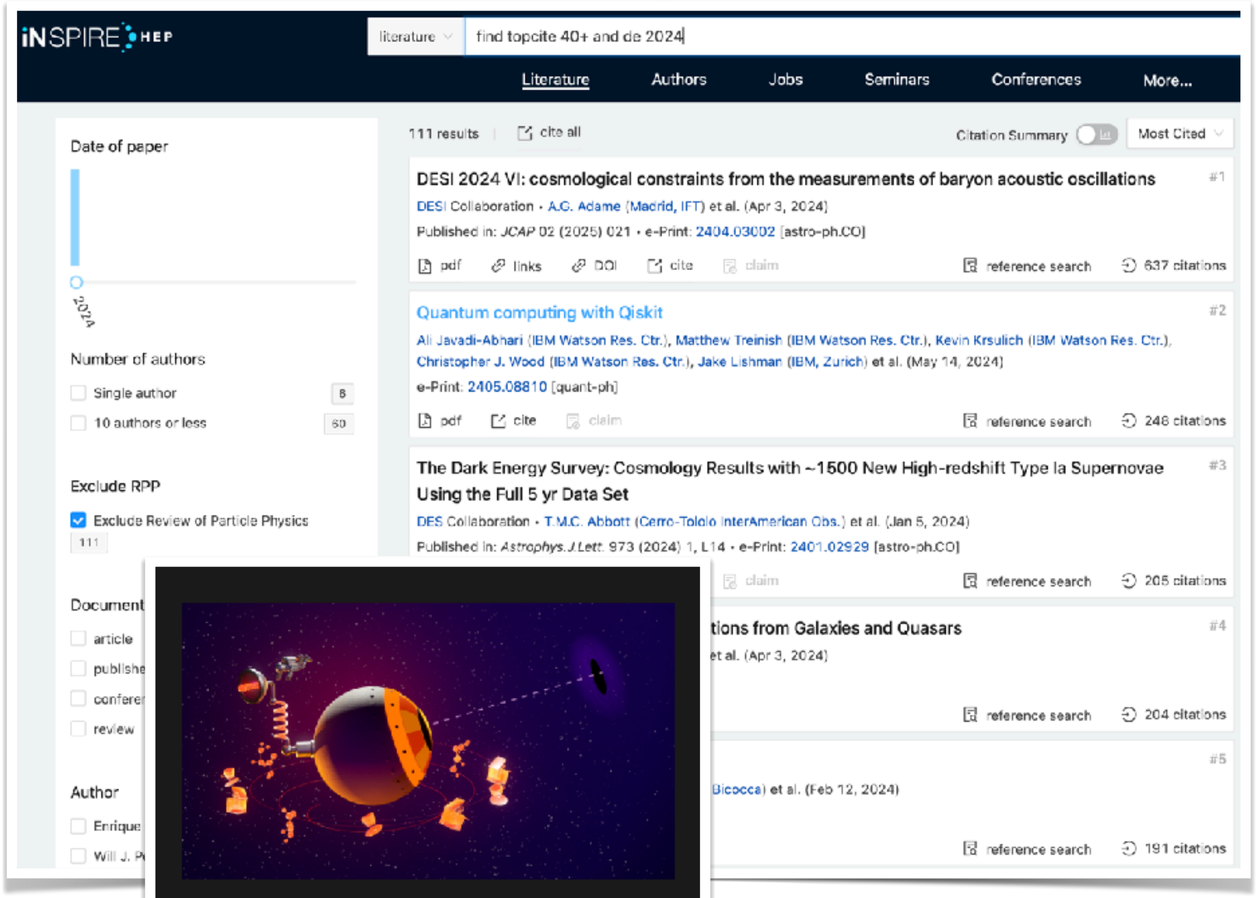




The New York Times

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.



Invited Session April

Latest Results from the Dark Energy Spectroscopic Instrument

1:30 pm – 3:18 pm, Wednesday March 19 // Session APR-R08 // Anaheim Marriott,Grand Ballroom Salon F

Save Add

Chair: Alexie Leauthaud, University of California, Santa Cruz

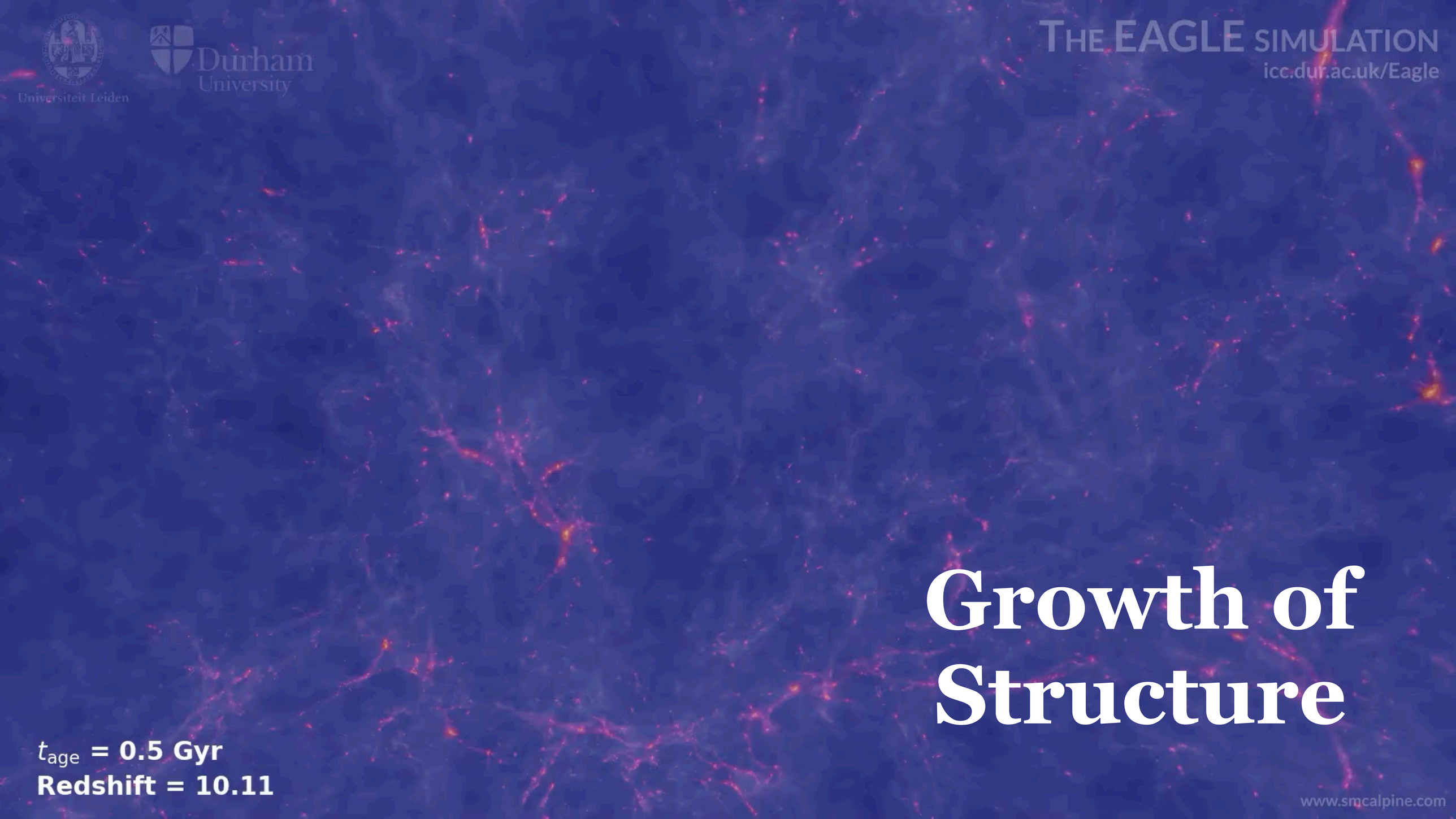
Topics: Astrophysics; Cosmology; Dark Energy; Surveys; Lensing; Measurements; Baryons

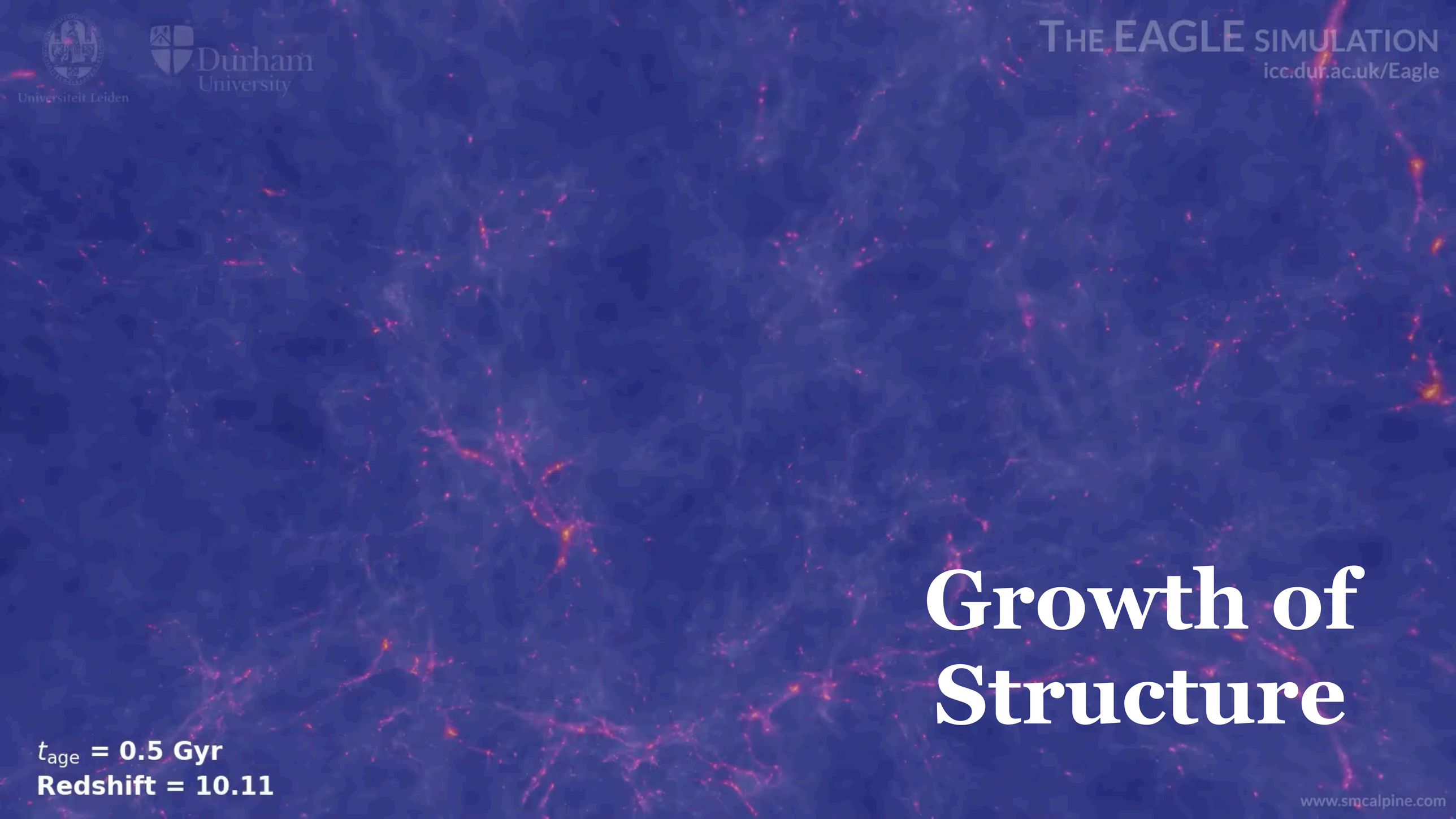
Sponsored by DAP

APS | JOINT MARCH MEETING AND APRIL MEETING

Global Physics Summit

March 16–21, 2025, Anaheim, CA and virtual


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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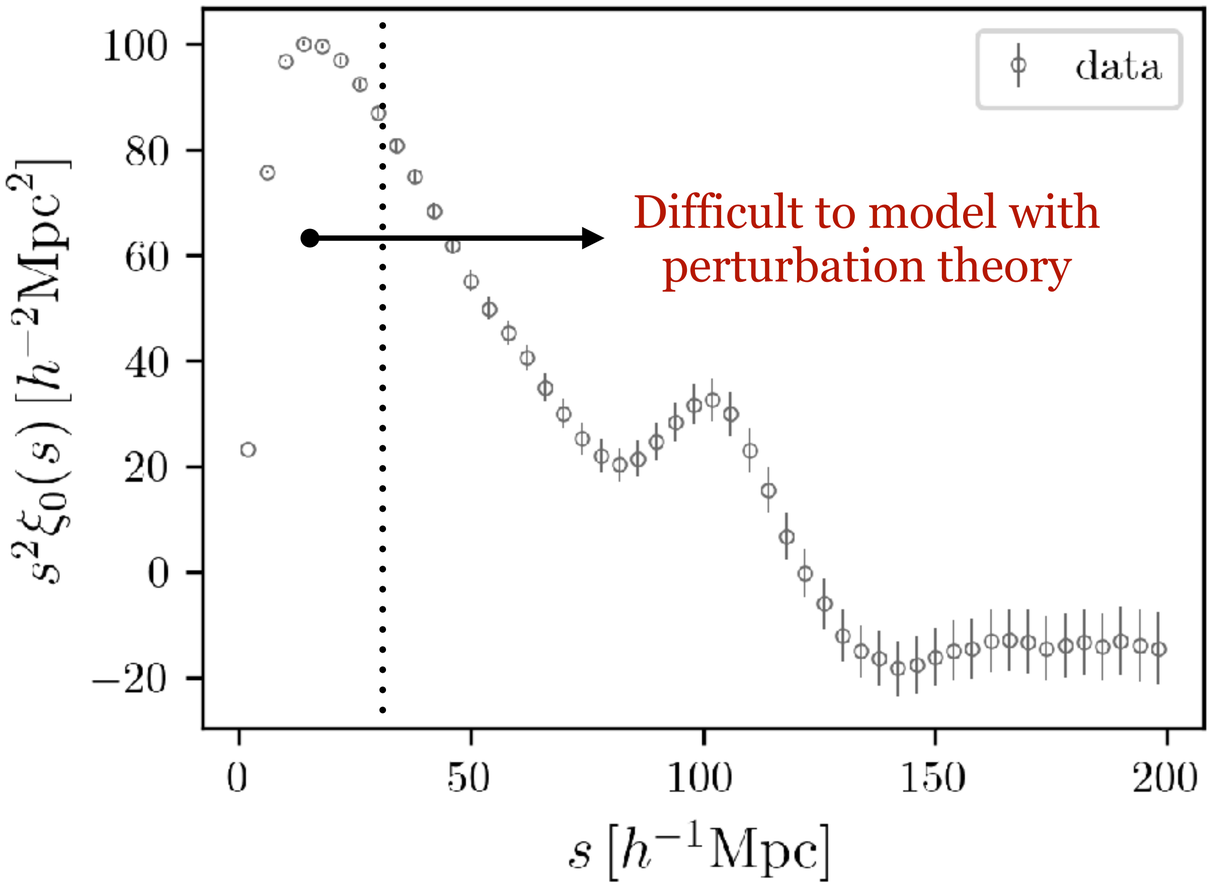
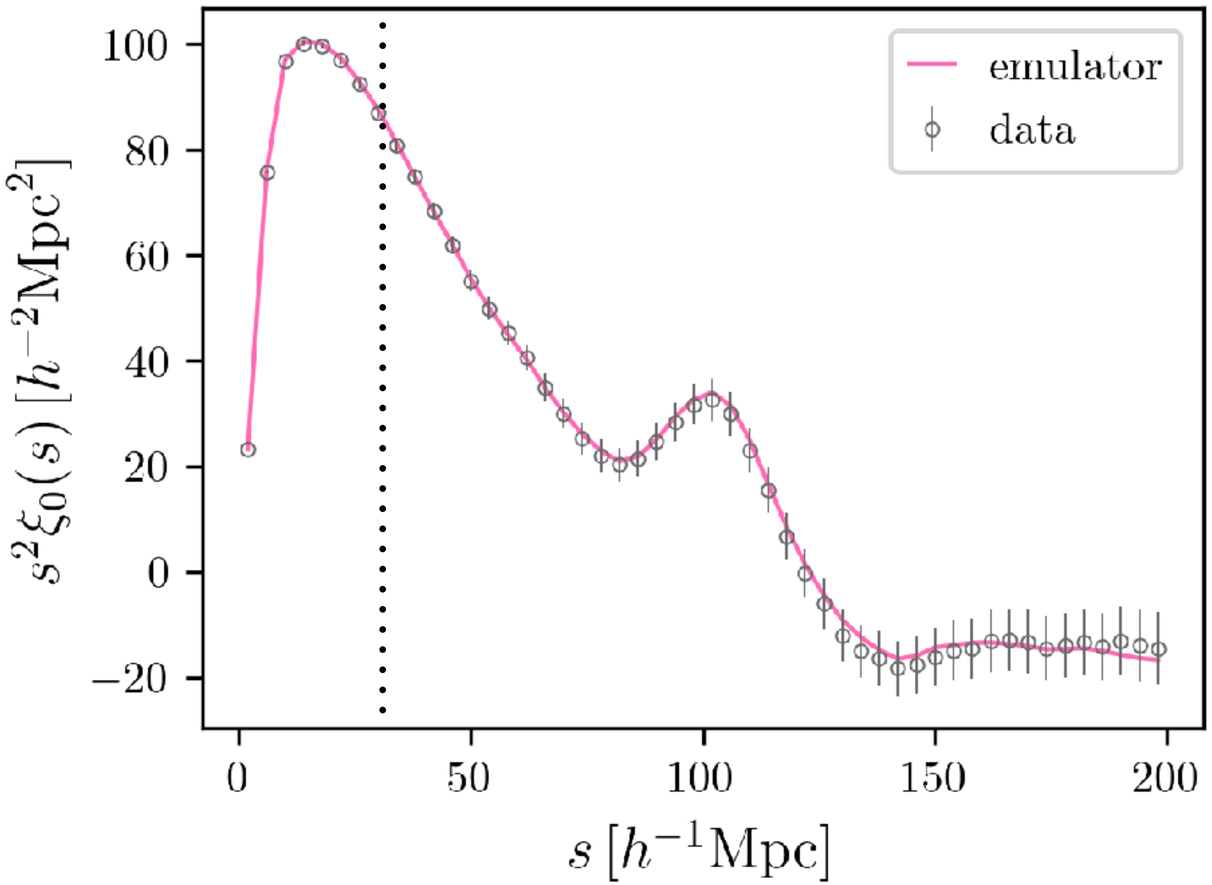
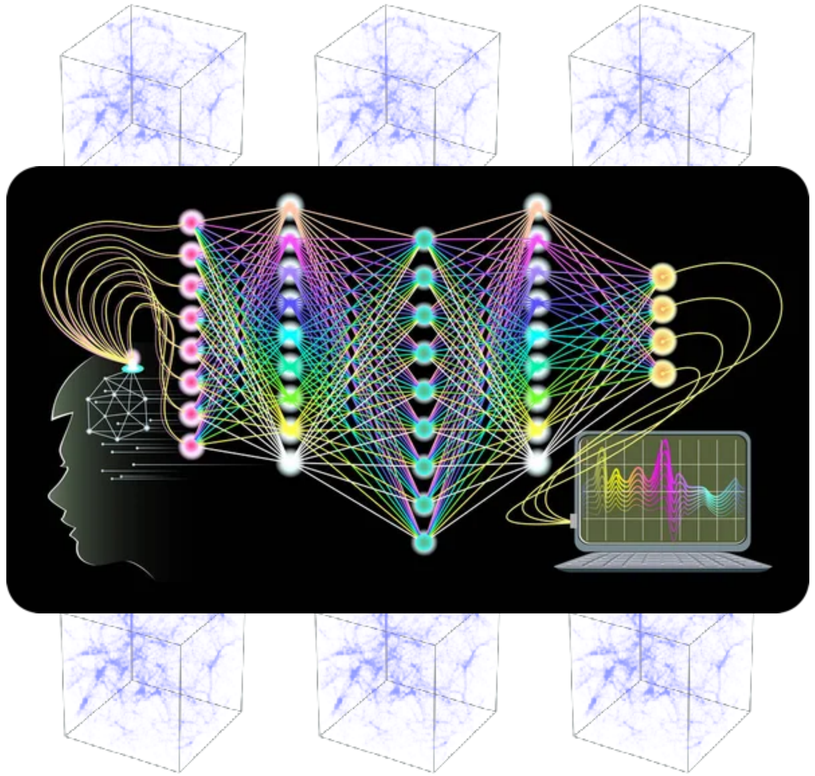
The Growth of Cosmic Structure



- By modeling the full shape of the galaxy clustering signal, we can put tight constraints on the growth rate of cosmic structure.
- Models based on perturbation theory break down on non-linear scales ($\lesssim 20\,h^{-1}\mathrm{Mpc}$).

The Growth of Cosmic Structure





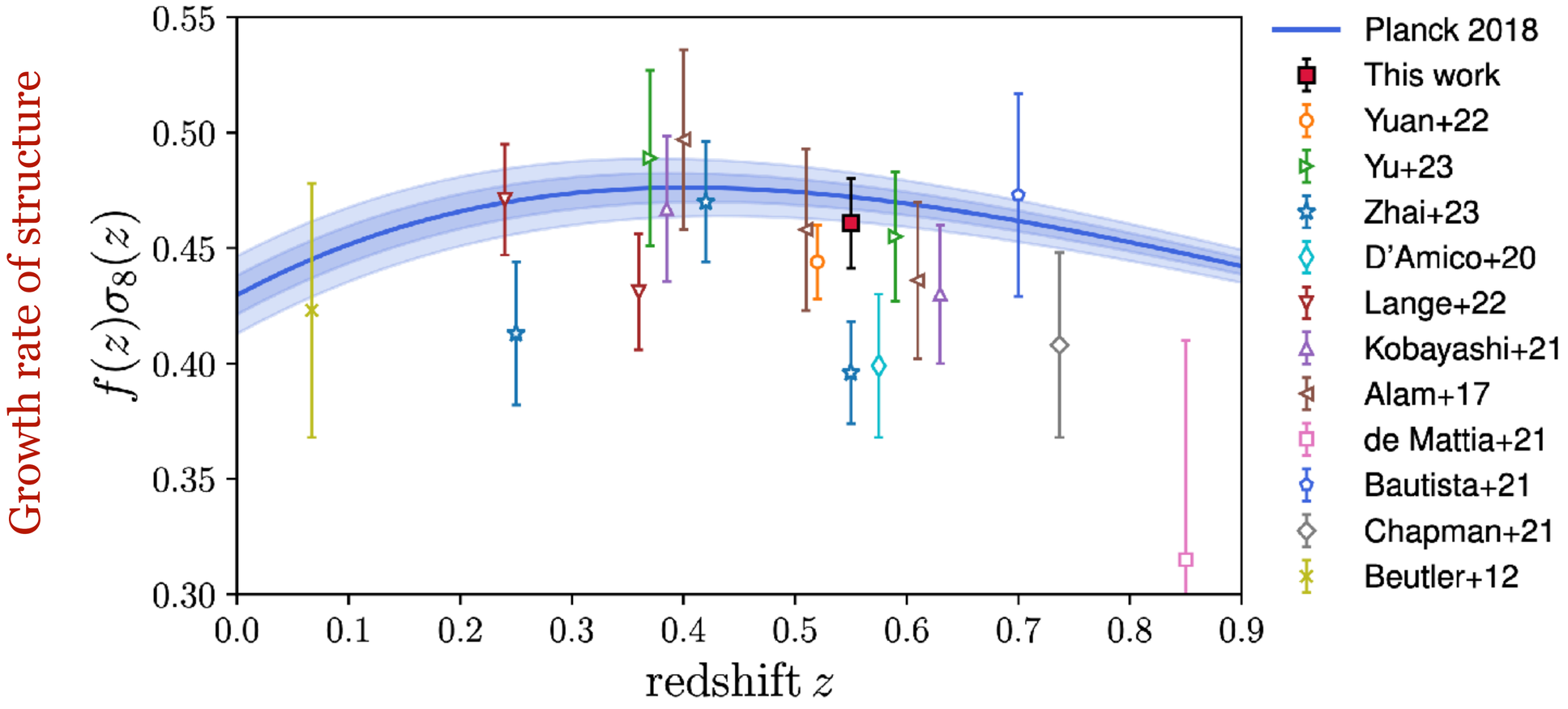
In collaboration with
Carolina Cuesta-Lázaro
(MIT & Harvard)

Paillas+2024 , Cuesta-Lazaro, Paillas+2024

Galaxy Clustering & AI

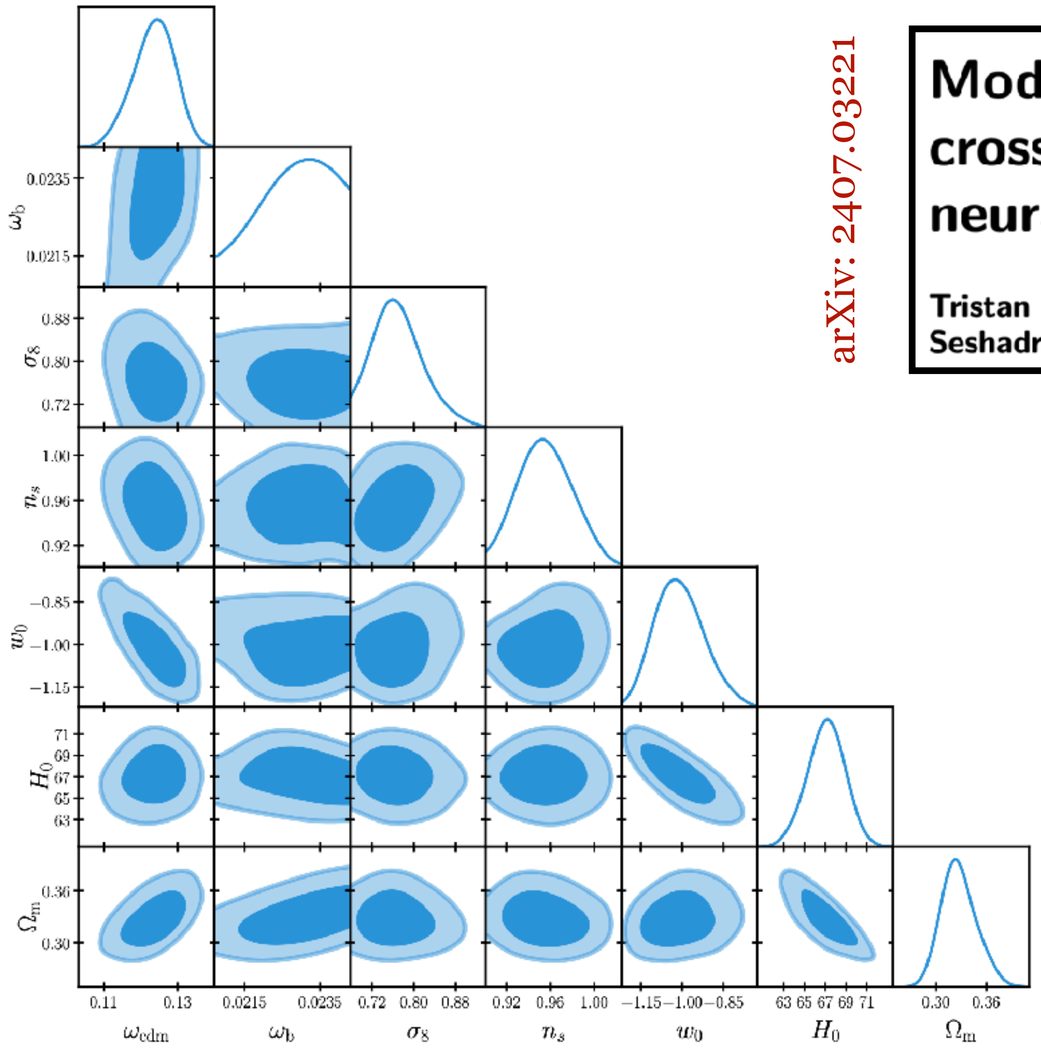
Astronomy & Steward Observatory

Paillas et al. (2024a)



Galaxy Clustering & AI

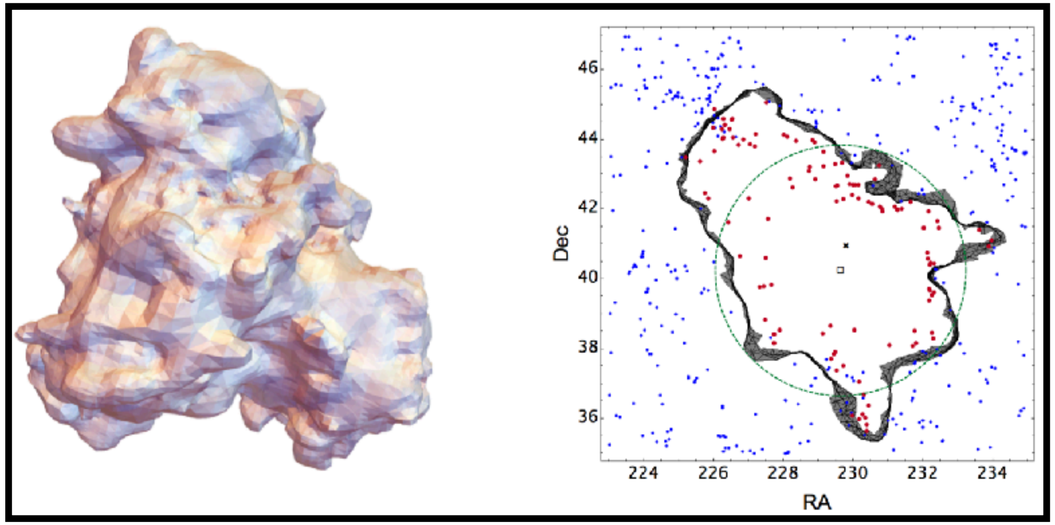
Astronomy & Steward Observatory



arXiv: 2407.03221

Modelling the BOSS void-galaxy cross-correlation function using a neural-network emulator

Tristan S. Fraser,[a,b,1] Enrique Paillas,[a,b] Will J. Percival,[a,b,c] Seshadri Nadathur,[d] Slađana Radinović,[e,f] and Hans A. Winther[e]



Fraser, Paillas+2024

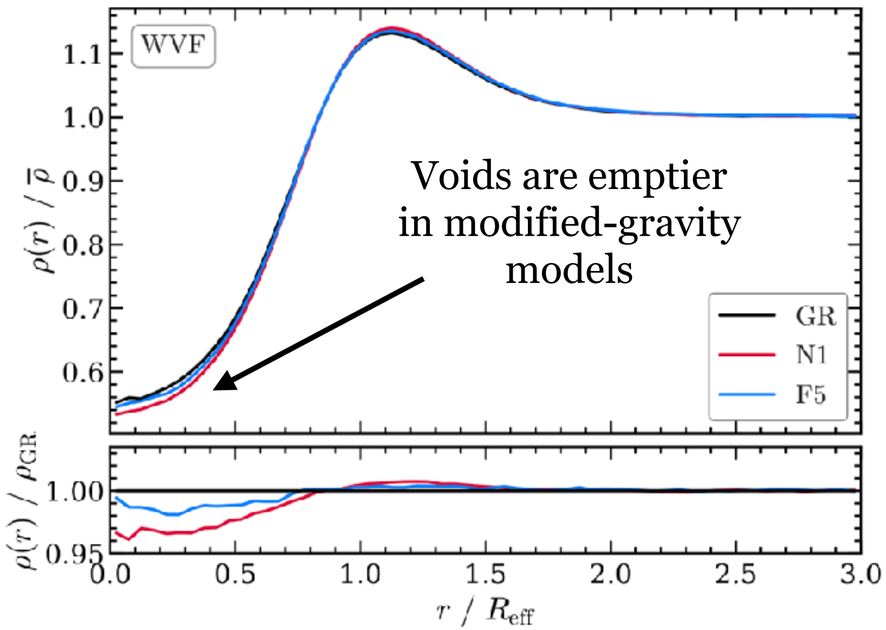
Nadathur (2016)

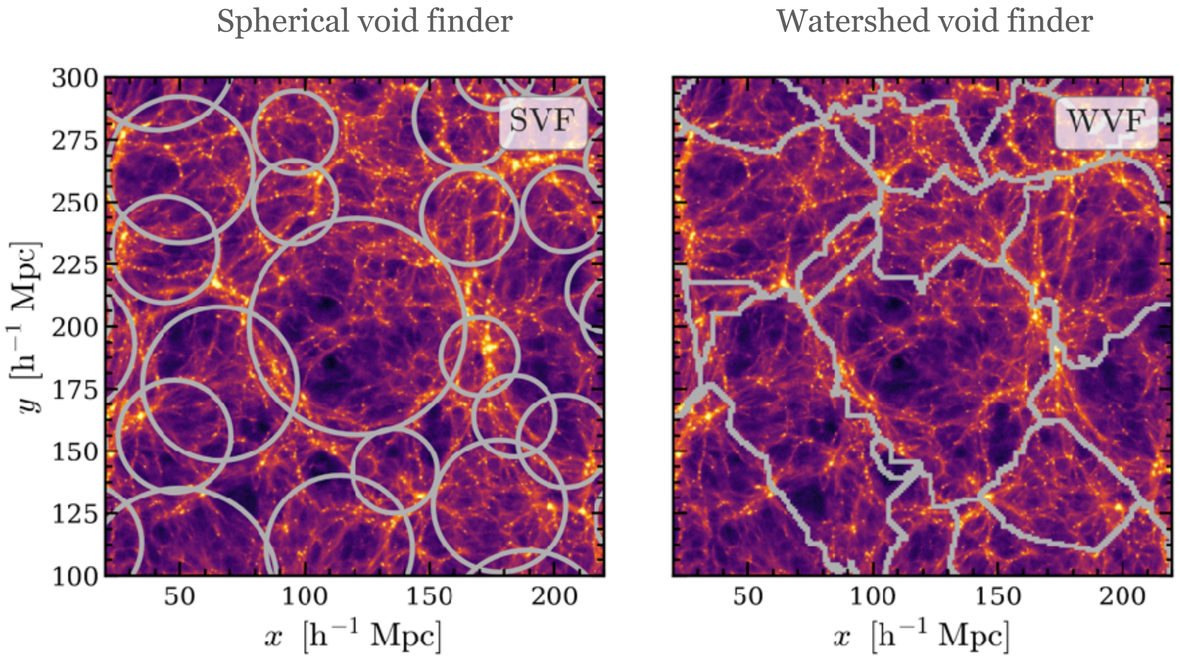
Modifications to Gravity

Astronomy & Steward Observatory

The distribution of matter around cosmic voids is a powerful probe of the theory on gravity on cosmological scales

Cautun, **Paillas** et al. 2018
Paillas et al. 2019
Davies, **Paillas** et al. 2021
Davies et al. (including **Paillas**) 2024





Neutrinos and the early Universe

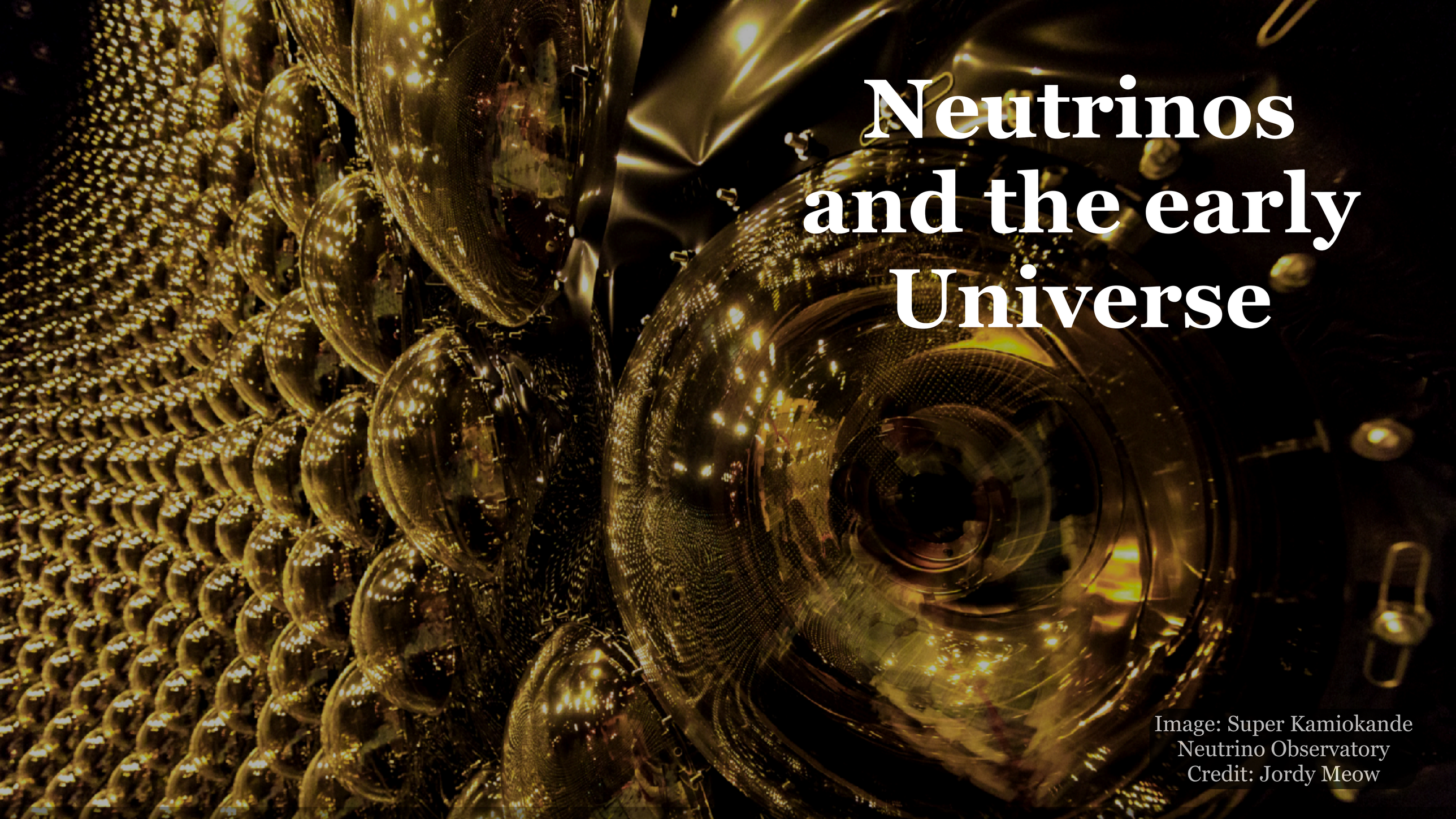


Image: Super Kamiokande Neutrino Observatory
Credit: Jordy Meow

Neutrinos and the early Universe

Image: Super Kamiokande Neutrino Observatory
Credit: Jordy Meow

Massive Neutrinos

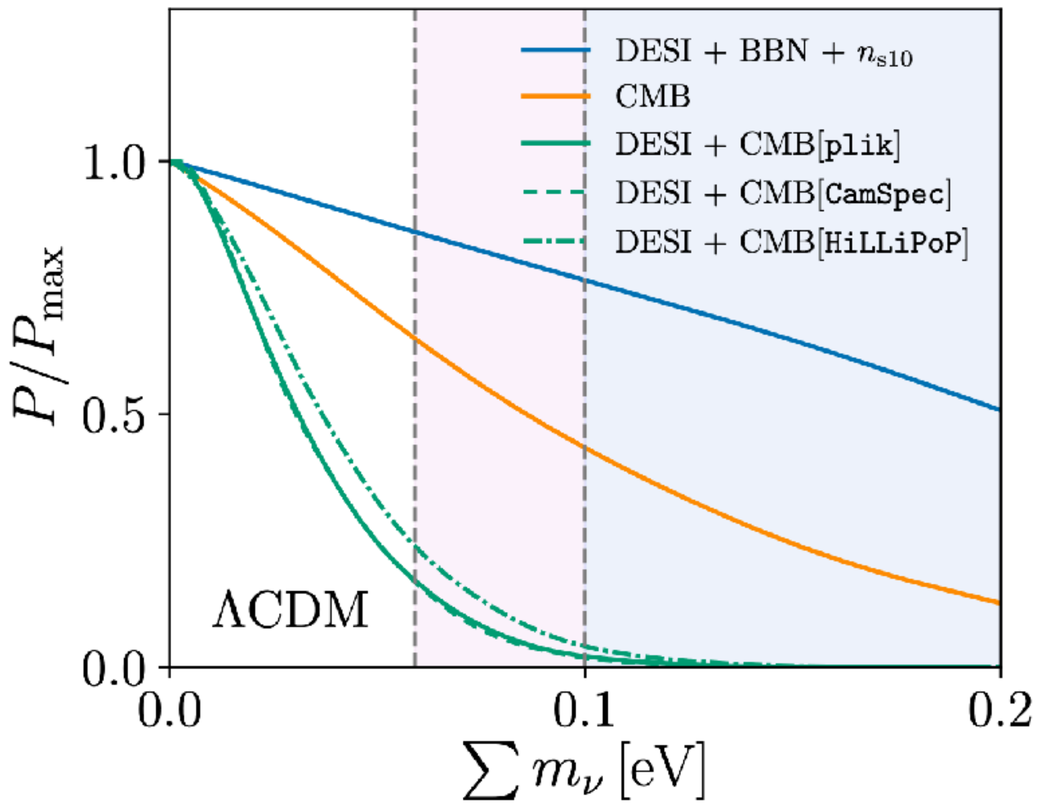
Galaxy surveys can constrain the sum of **neutrino masses** via:

- Contribution to the **expansion history** of the Universe.
- Loss of growth of structure on small scales due to neutrino **free streaming**.

Massive Neutrinos

DESI Collaboration (including **Paillas**), 2024

Probability density



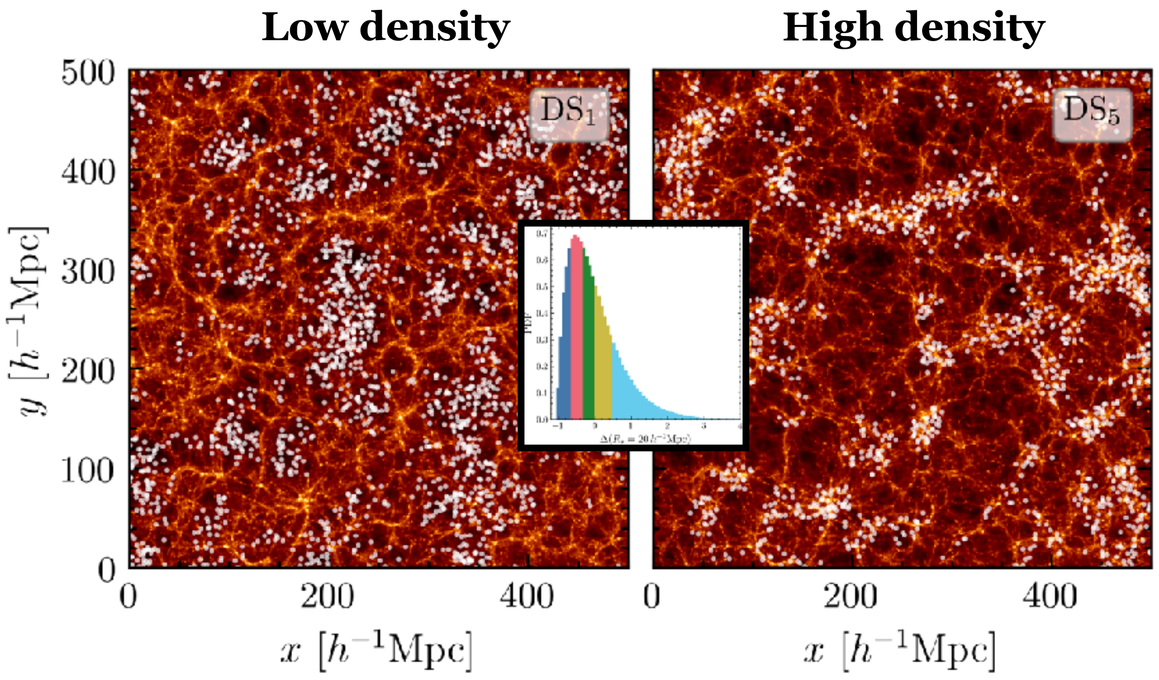
Sum of neutrino masses

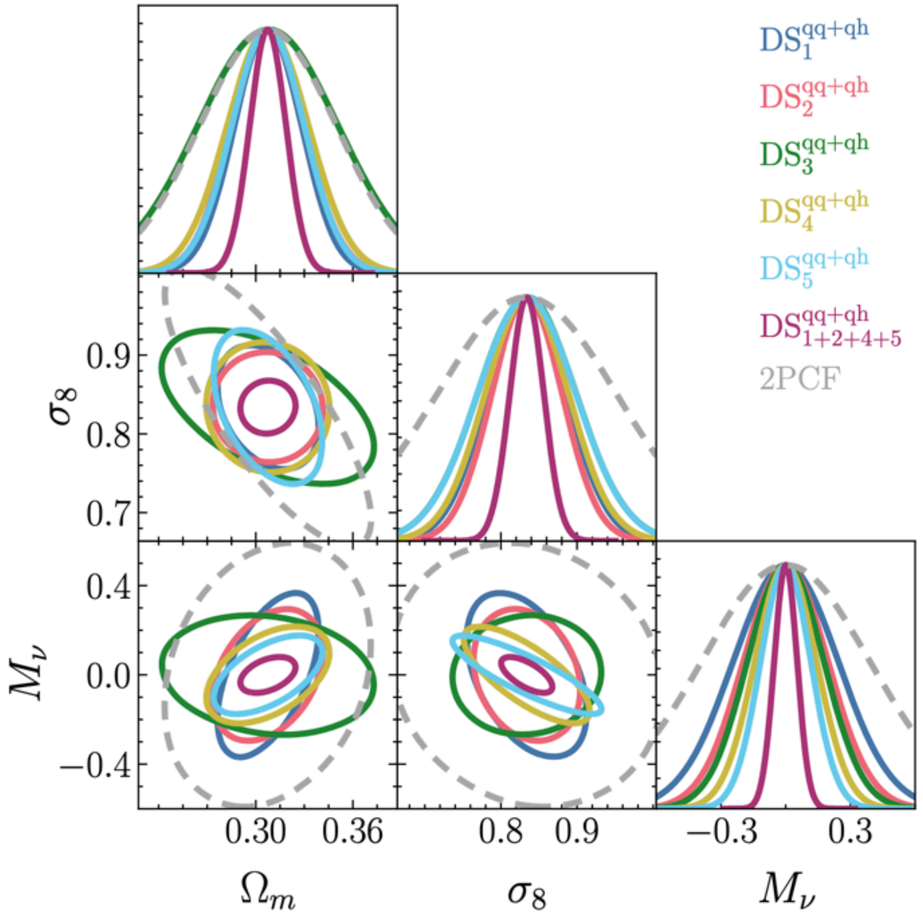
$\sum m_\nu < 0.071$ eV (95%, DESI (FS+BAO)+CMB)

Massive Neutrinos

Astronomy & Steward Observatory

Measuring the clustering signal in different environments of the cosmic web, we can place tight constraints on the sum of neutrino masses, much more precisely than with standard clustering methods.



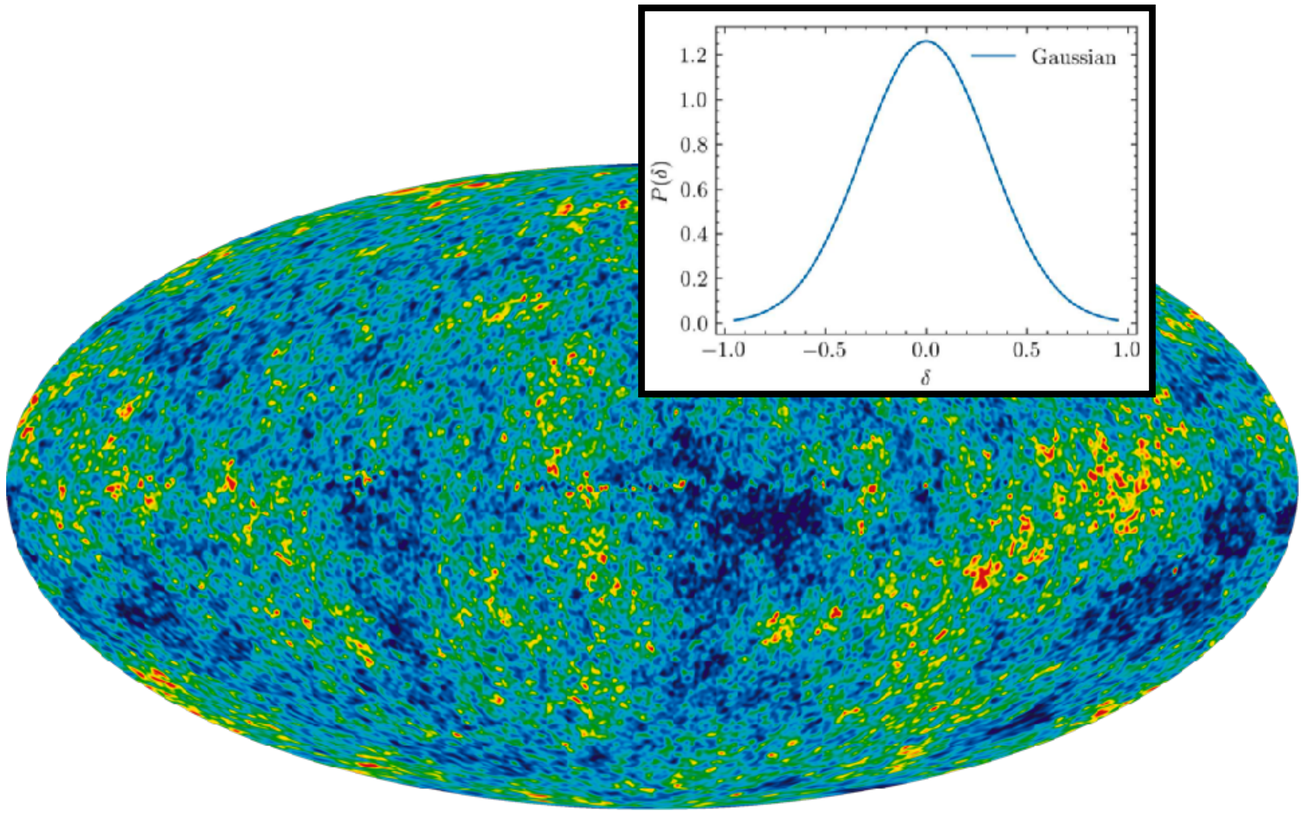


Paillas et al. (2023)

Primordial Non-Gaussianity

Astronomy & Steward Observatory

- Even the simplest inflationary models predict a certain degree of primordial non-Gaussianity (PNG).
- Measuring f_{NL}, which quantifies PNG of the local type[1], is a major target of modern cosmological surveys.



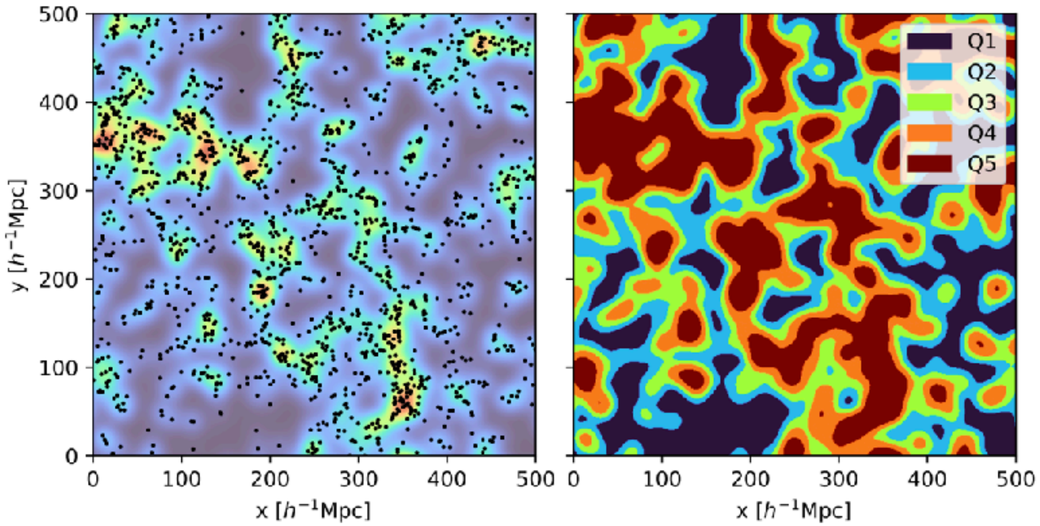
[1]Local-type non-Gaussianity implies that the non-Gaussian contribution is local in real space, meaning it depends on the square of the Gaussian field at the same point in space.

Primordial Non-Gaussianity

Astronomy & Steward Observatory

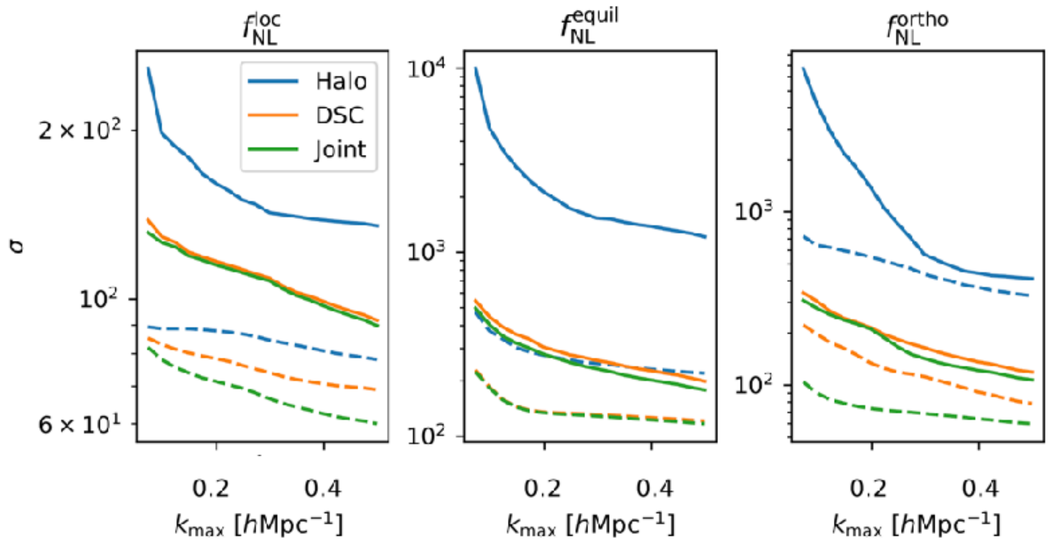
Constraining Primordial Non-Gaussianity with Density-Split Clustering arXiv: 2409.13583

James Morawetz[a,b] Enrique Paillas[a,b,c] Will J. Percival[a,b,d]



Type of PNG

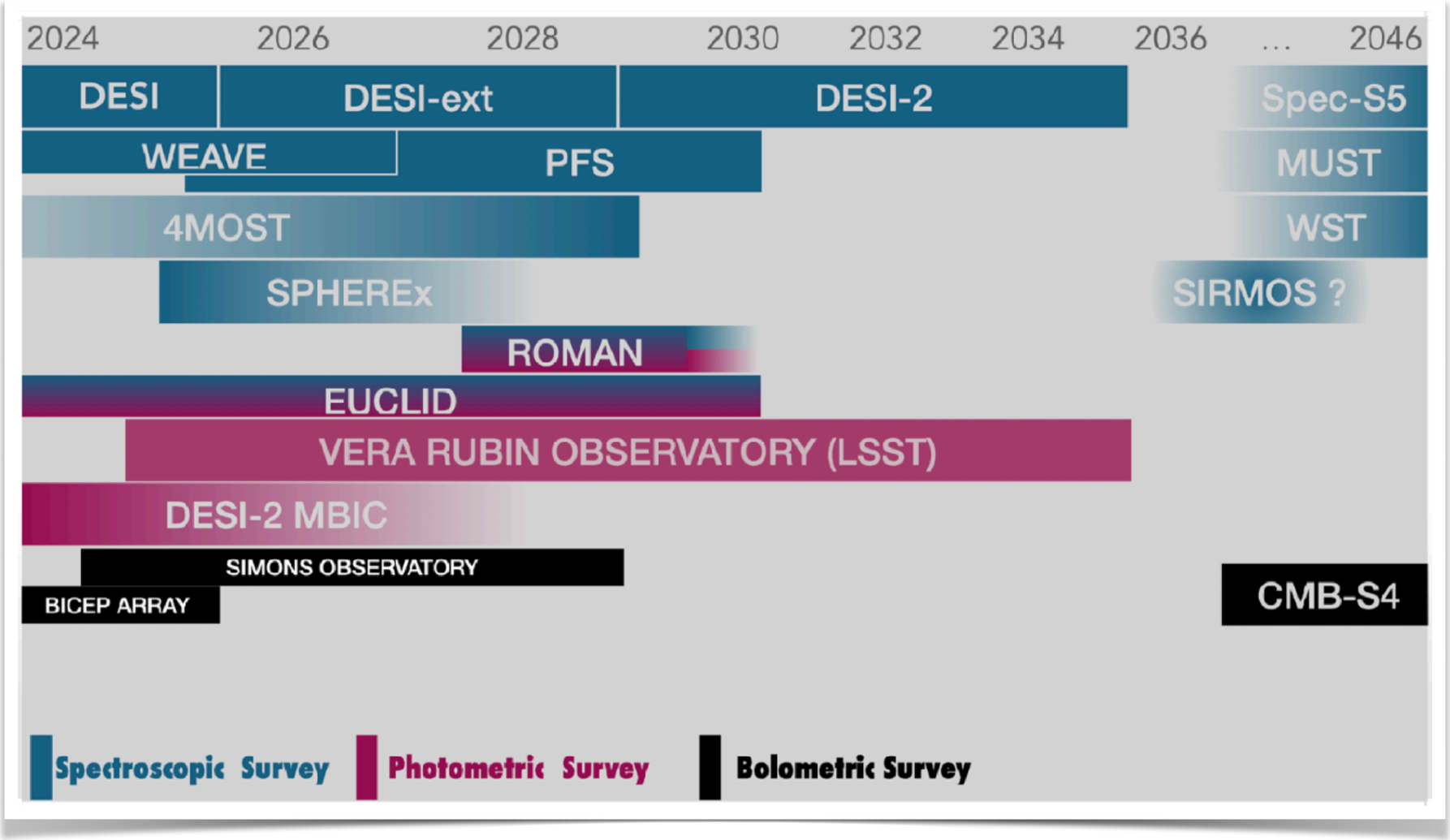
Parameter error



Maximum wavenumber
(larger k = smaller scales)

Future roadmap

Landscape of Cosmological Surveys



Credit: Satya Gontcho A. Gontcho (LBNL)

Recommendation by the P5

Astronomy & Steward Observatory

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion in more favorable budget situations

Science Experiments

Timeline 2024 – 2034

	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
	Science Drivers						
LHC		P	P		P	P	
LZ, XENONnT			P				
NOvA/T2K	P				S		
SBN	P				S		
★ DESI/DESI-II	S		S	P			P
Belle II			S		S	P	
IceCube	P		S				P
SuperCDMS			P				
★ Rubin/LSST & DESC	S		S	P			P
Mu2e						P	
DarkSide-20k			P				
HL-LHC		P	P		P	P	
DUNE Phase I	P				S	S	S
★ CMB-S4	S		S	P			P
CTA			S				P
G3 Dark Matter §	S		P				
IceCube-Gen2	P		S				P
DUNE FD3	P				S	S	S
DUNE MCND	P				S	S	
Higgs factory §		P	S		P	P	
DUNE FD4 §	P				S	S	S
★ Spec-S5 §	S		S	P			P
Mu2e-II						P	
Multi-TeV §		P	P		P	S	
LIM	S		P	P			P

DEMONSTRATOR

- The P5 panel strongly endorsed the funding for the continuation of the DESI survey — DESI-II — as well as Rubin LSST and CMB-S4.

The Future of Cosmology in Chile

Astronomy & Steward Observatory

Columna de Opinión

https://www.elmostrador.cl/cultura/critica-opinion/2024/01/09/observatorios-de-chile-seran-los-mayores-laboratorios-de-fisica-de-particulas/

Columna de Opinión

https://www.biobiochile.cl/noticias/opinion/columnas-bbcl/2024/04/17/la-energia-oscura-y-la-posibilidad-de-que-los-chilenos-resolvamos-sus-misterios.shtml

Spec-S5: Absolutely Central

Blanco Telescope in Cerro Tololo Interamerican Observatory, Chile.

- P5 panel: "We rate Spec-S5 as *absolutely central*."
- "Given the recent design and R&D progress we rate Spec-S5 as "*ready to initiate construction*" within the next decade assuming success of the near-term R&D, and once formal agreement is reached with NOIRlab and NSF for use of the Mayall and **Blanco telescopes**."