

Galaxy-Halo Connection:
*You can have your cake
and eat it too!*

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DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

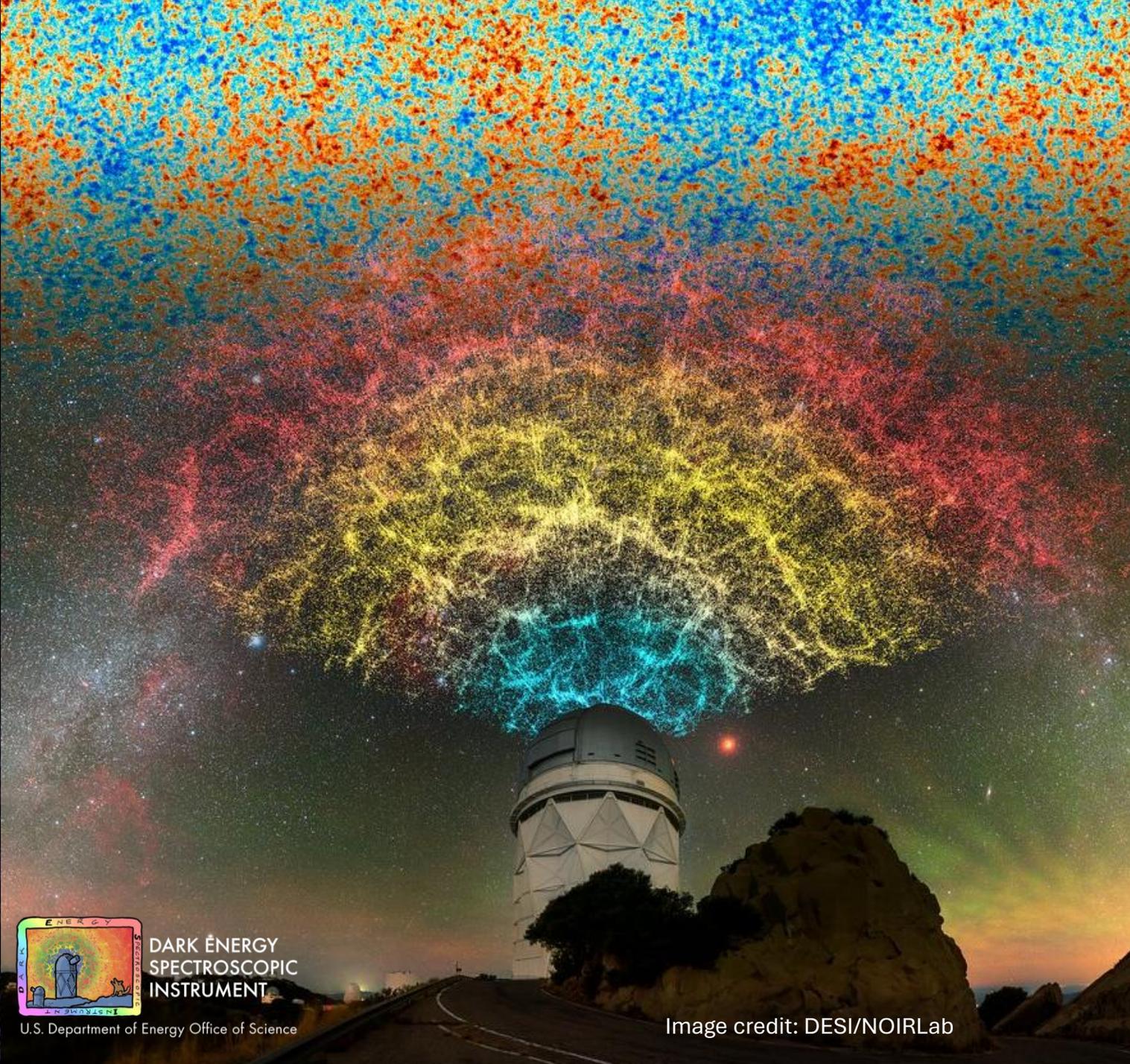


Image credit: DESI/NOIRLab

3 Pillars of Modern Cosmological Measurements

Cosmic Microwave Background

- The light from the moment the universe became neutral, 380,000 years after the **Big Bang**.

Standard Candles

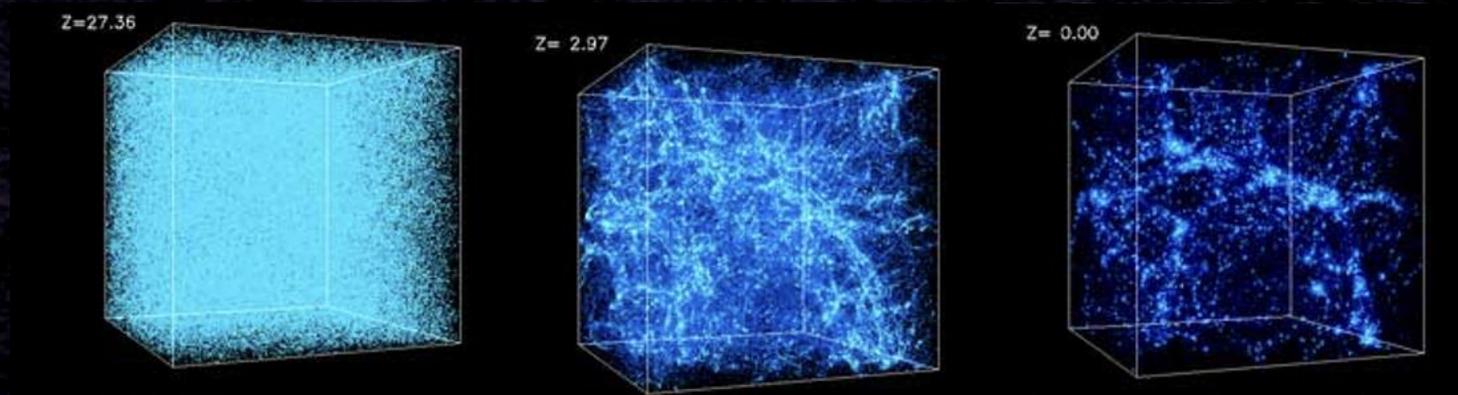
- Objects with constant brightness - known, standard energy output like **Supernovae**

Large-Scale Surveys

- **Surveys** of galaxies use their distribution to probe the expansion of the universe.

Large Scale Structure Surveys

- Observe large regions of space to produce galaxy redshift surveys
- Growth of LSS gives info about time dependence of Gravity, Dark Energy



Simulation Credit: National Center for Supercomputer Applications by Andrey Kravtsov (U Chicago) and Anatoly Klypin (NMSU).



Baryon Acoustic Oscillations (BAO)

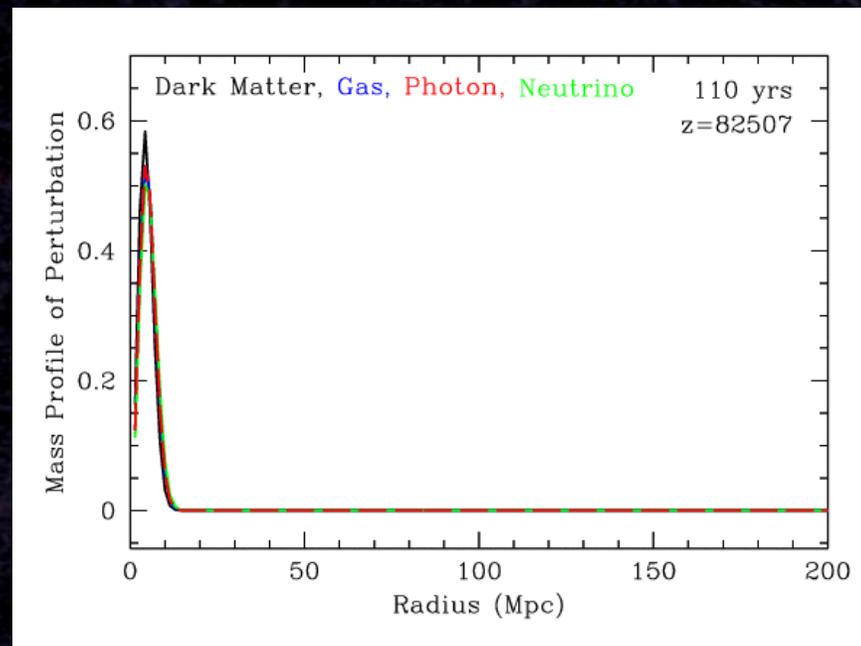
Baryon Acoustic Oscillations come from spherical waves of matter in the very early Universe. Galaxies were more likely to form in the densest regions, creating "bubbles" of galaxies.

We observe these as rings of galaxies on the sky. BAO can tell us what the Universe was like at its beginning and how it's changing.

Credits: Claire Lamann, DESI Member

- Pressure waves emanated from primordial dark matter halos
- Travelled rapidly in the early universe
 - Covering a comoving distance of 150 Mpc (sound horizon r_d) between Big Bang and the epoch of recombination.
- 'Standard ruler' for expansion history

Visualizing the origin of the **acoustic peak**
Credits: Daniel Eisenstein, DESI Member



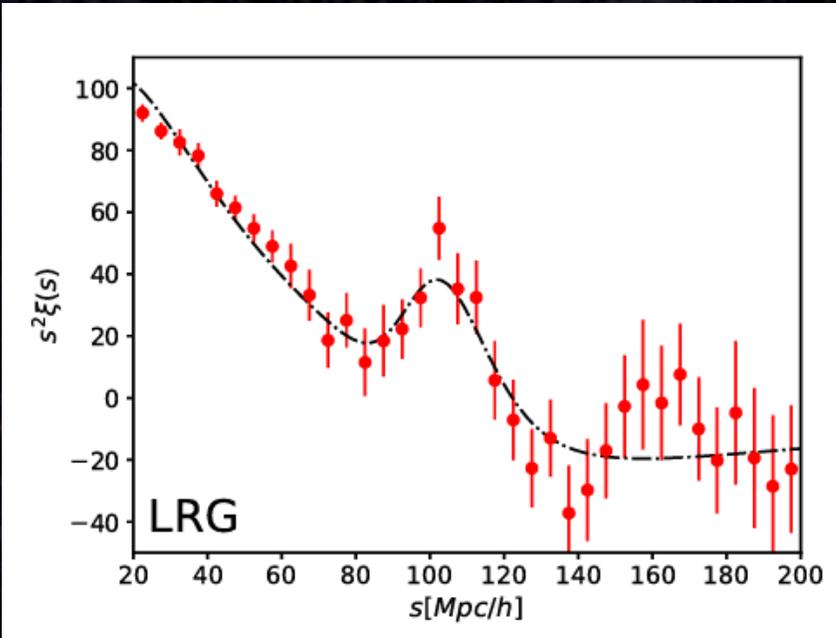
Two-Point Correlation Functions (2PCF)

Excess probability of finding galaxy within given distance of another galaxy

- Most common estimator: Landy - Szalay estimator

$$\hat{\xi}_{LS}(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

- Data(D) – 3D Position coordinates of Galaxies
- Randoms(R) – Position of Galaxies from a Random sample
 - based on the redshift distribution of the Data



First Detection of BAO signal from early DESI data (Arxiv 2304.08427)

****Another handy tool: Power spectrum – the Fourier transform of 2PCF**



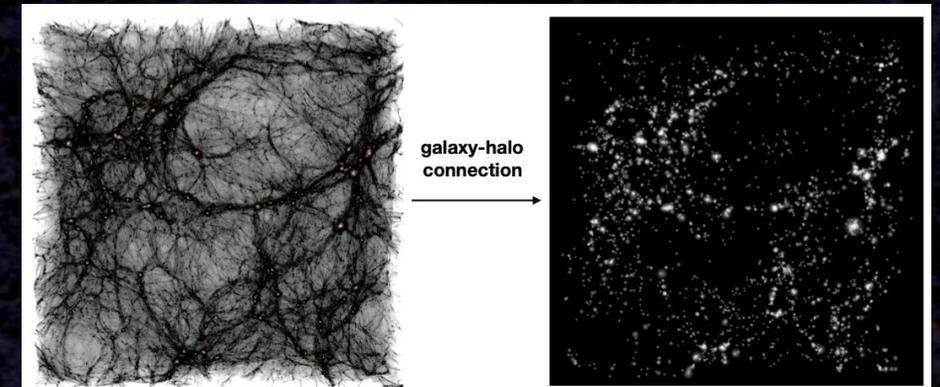
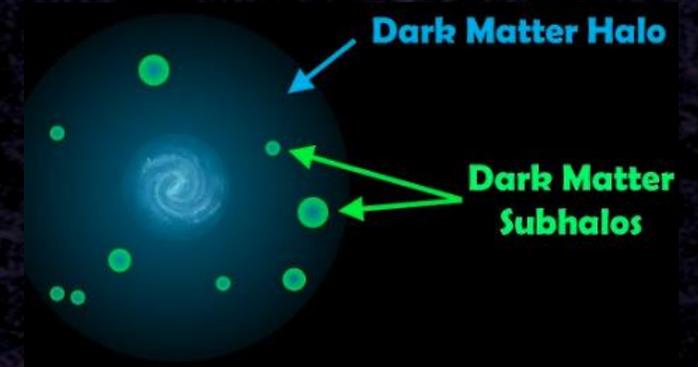
Dark Matter Halos & Galaxies

Dark matter collapses under gravity into dense, \sim spherical structures called *halos*

- Fundamental building blocks of cosmic web
- Gravitational anchors, or "cradles"
 - Characterized by Mass, V_{peak} (Max. circular velocity across accretion history)
- Galaxies form and evolve here

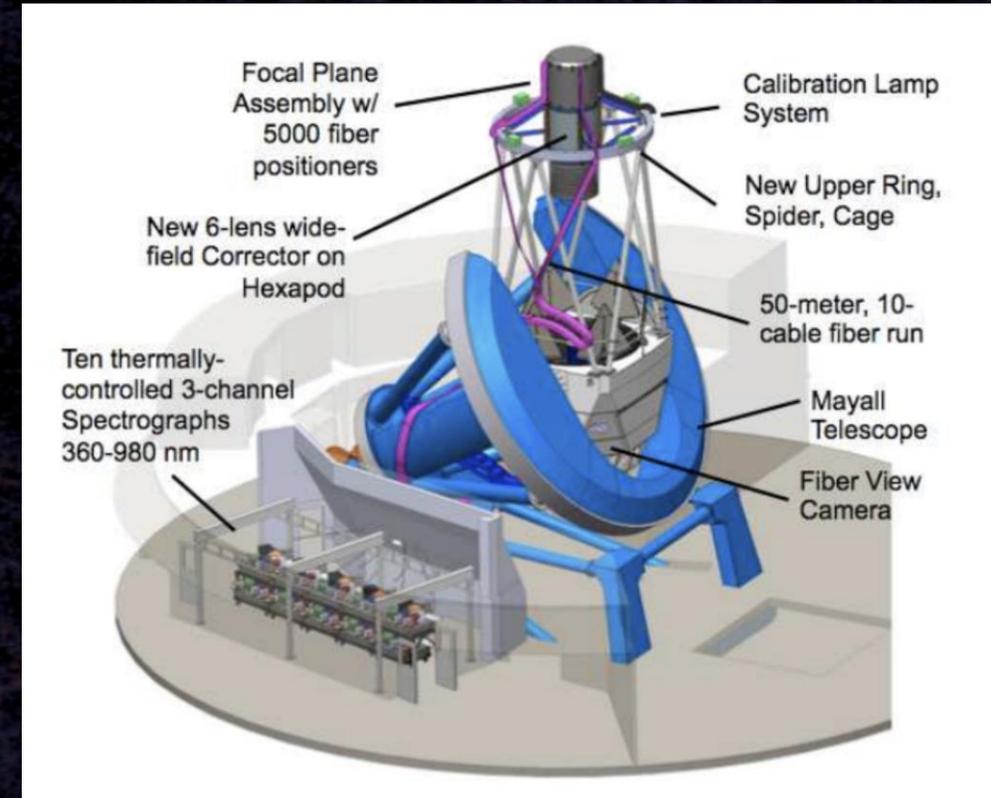
Galaxy Bias: Galaxies form in densest regions of DM distribution

- Provide a **biased** view of underlying matter field



Dark Energy Spectroscopic Instrument (DESI)

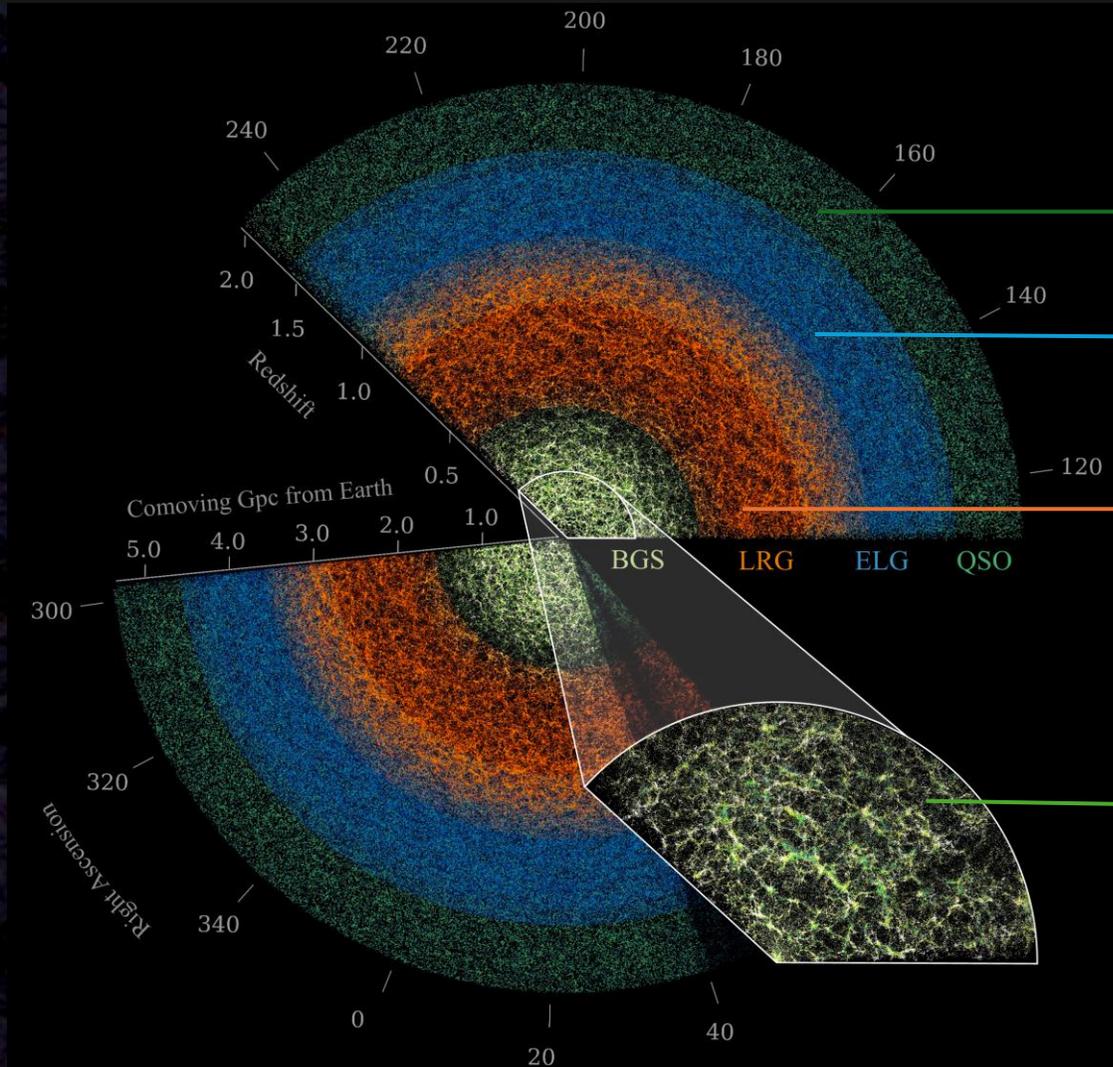
- Probe expansion history of our Universe
- Study the physics of galaxies and quasars
- Construct 3D map - from nearby universe out to 11 billion light years
- At 4m Mayall Telescope, KPNO, Arizona, USA
 - Bandpass: 3,600 – 9,800 Å
 - 10 Spectrographs, 3 CCDs each– **Blue**, **Red**, and **Near IR**.
- 5000 Robotically controlled Positioners (*spectra of galaxies, stars*)



Scan to know more about the DESI robots!



DESI Dark Matter Tracers



Quasars (QSOs)

- Direct tracers ($z < 2.1$)
- Using Lyman- α absorption features ($2.1 < z < 3.5$)

Emission Line Galaxies (ELGs)

- $0.8 < z < 1.6$ (bright forbidden [OII] emissions)

Luminous Red Galaxies (LRGs)

- $0.4 < z < 1.1$ (4000 Å break)

Bright Galaxy Survey (BGS)

- $0.1 < z < 0.4$, magnitude limited



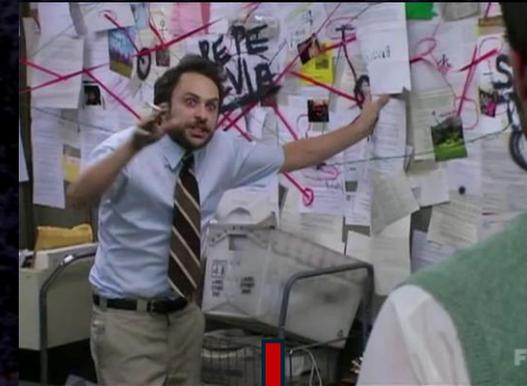
Modelling the *Galaxy-Halo Connection*

Define a mapping : Halo properties \longleftrightarrow Galaxy properties

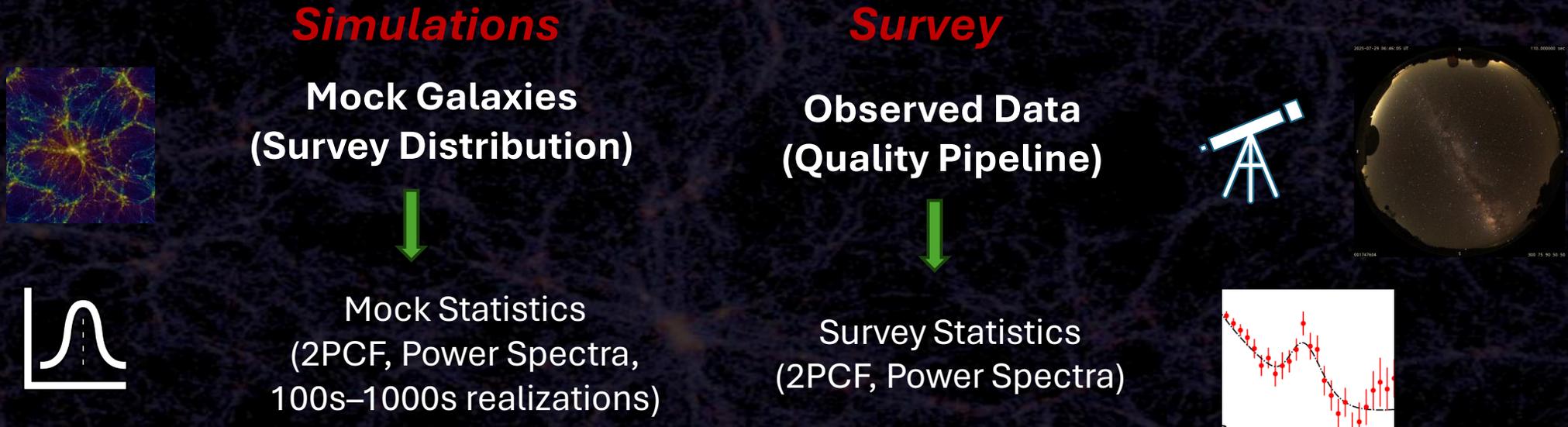
- Hydrodynamic simulations (computationally challenging!)

Large, high-resolution N -body simulations (e.g., *Uchuu*)

- Resolve substructure **down to dwarf galaxies**
- $8 \text{ Gpc}^3 h^{-3}$ cubic box, Multiple snapshots
- Simple statistical prescriptions
 - *Halo Occupation Distribution* (HOD)
- Empirical yet physically-motivated approaches
 - *Subhalo Abundance Matching* (SHAM)



Sequence of Events



- ✓ **Compare Survey vs Mock**
- ✓ **Validate Galaxy-Halo Model**
- ✓ **Covariance Estimation**
- ✓ **Cosmological Interpretation**



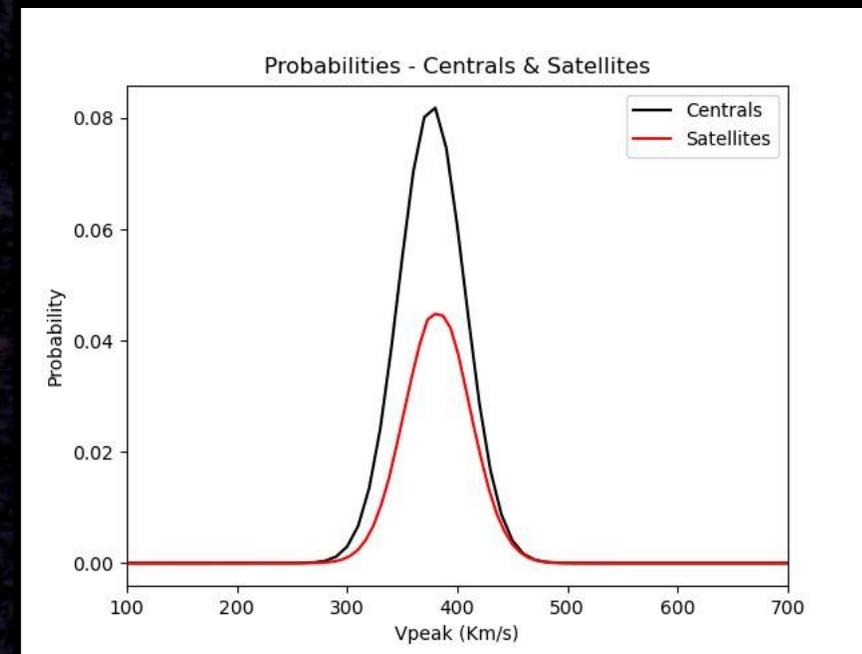
(Sub)halo Abundance Matching (SHAM)

- Physically-motivated
- **Core Assumption:** Galaxy property correlated with (sub)halo property

Modified SHAM - accounts for the incompleteness & selection effects

- Assume scatter in the V_{peak} between galaxies and DM halos
- Gaussian Modeling method:
 - Quantities of Interest: ' V_{mean} ' (mean V_{peak}), ' f_{sat} ' (Satellite fraction), ' σ ' (Std. Deviation)

Works remarkably well with very few free parameters



Further modification in SHAM: ELGs

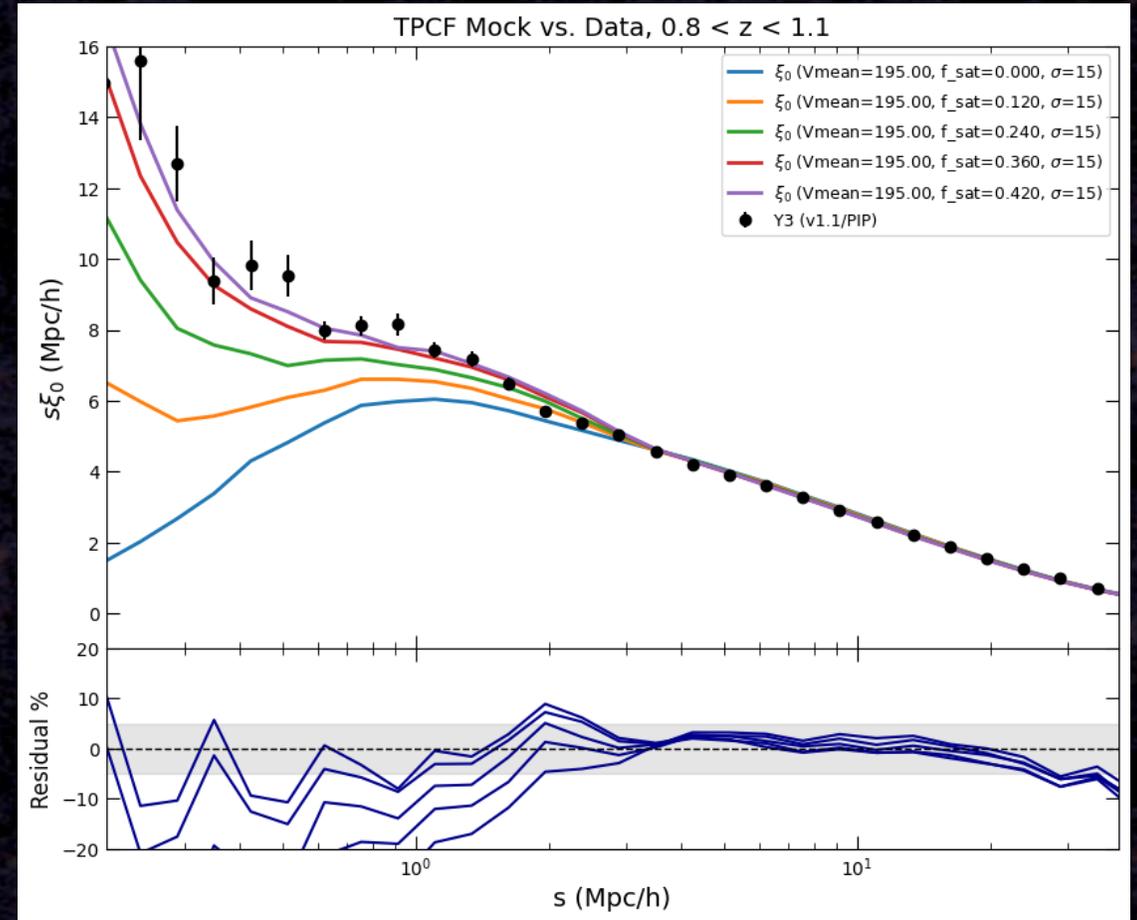
From simulation, select objects

- Avoid major mergers
- Slower moving satellites as ELGs

Satellites with high peculiar velocity -

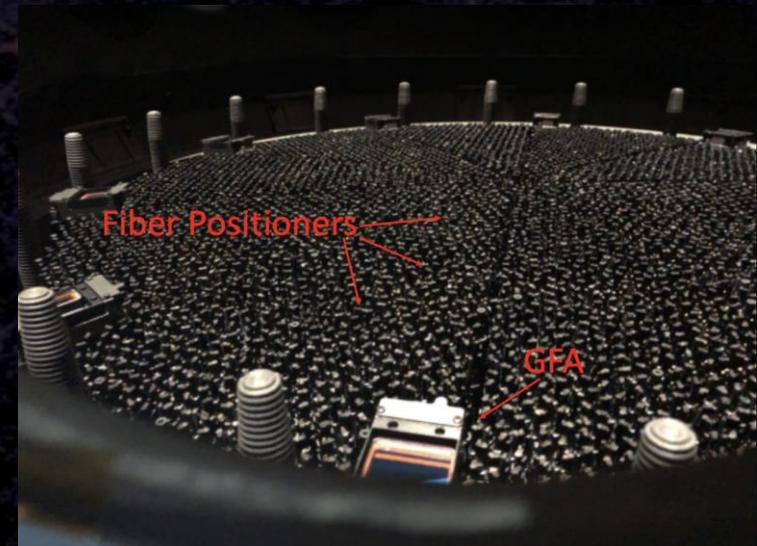
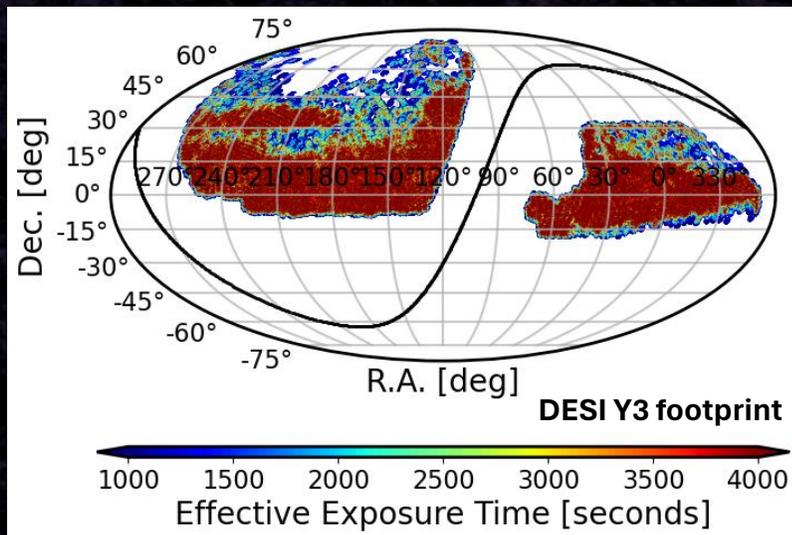
- Subject to ram pressure
- Gas removed from satellite
- Star formation quenched

Generate ELG Mocks using a Gaussian V_{peak} distribution



Survey Realism

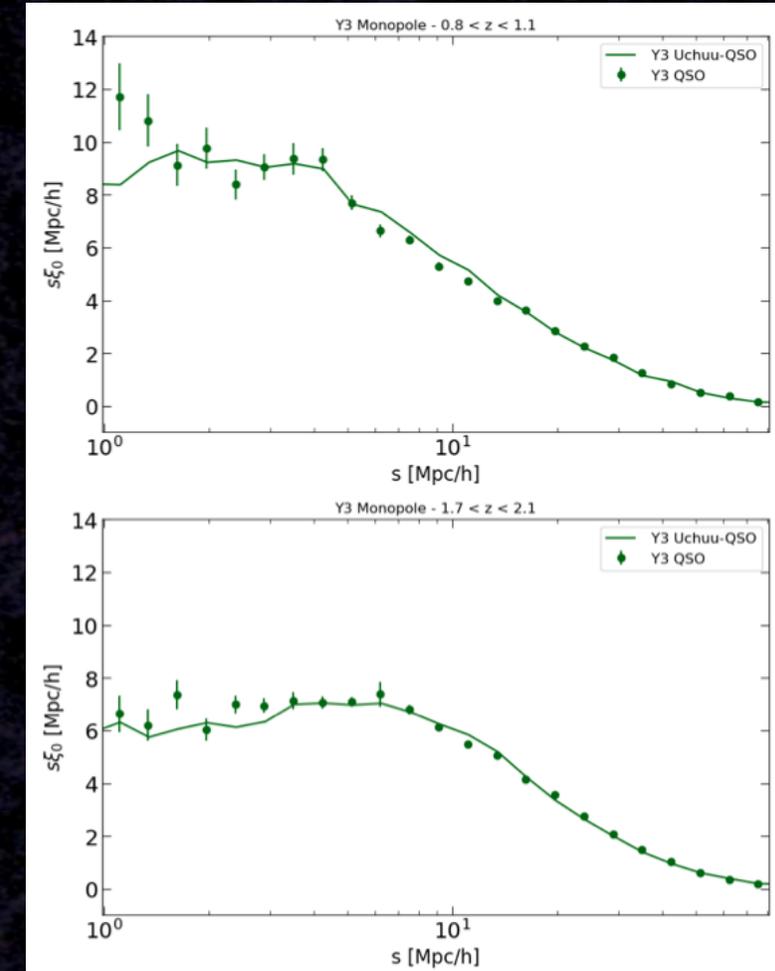
- Must simulate imperfections of real survey
 - **Survey Footprint:** Include galaxies in the parts of DESI observed sky
 - **Target Selection:** Mimic algorithms deciding which objects are bright enough to be targeted
 - **Fiber Collisions:** Robotic positioners can't be placed too close;
 - We miss some close pairs of galaxies; must be modelled



Results: DR2 Reference Mocks - QSOs

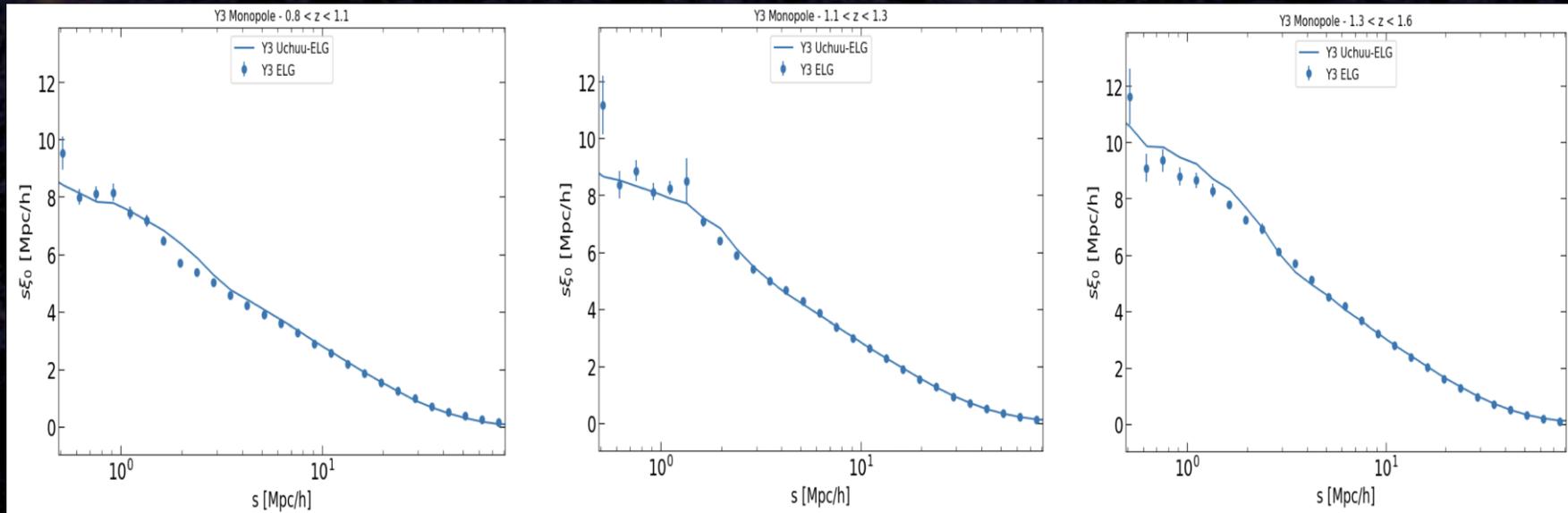
- **Reference Mocks:** High Precision simulations
 - Best estimate of what a given cosmology predicts about clustering properties of DESI tracers
 - Template for training and testing covariance mocks
- ~ 1.5M QSOs
- Clustering evolution with redshift across $z = 0.8 - 1.1$, $1.1 - 1.4$, $1.4 - 1.7$, $1.7 - 2.1$
- Reasonable agreement with Survey data (1 Mpc/h onwards)

Vaisakh, et al (in Collab. Review)



Results: DR2 Reference Mocks - ELGs

- ~6.5M ELGs
- Clustering evolution with redshift across $z = 0.8 - 1.1$, $1.1 - 1.3$, $1.3 - 1.6$
- Reasonable agreement with Survey data (0.5 Mpc/h onwards)



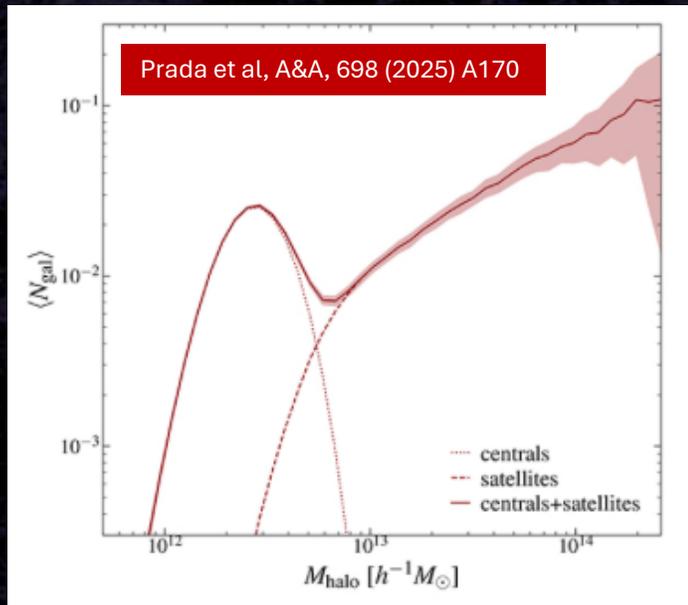
Vaisakh, et al (in Collab. Review)



Halo Occupation & Galaxy Bias

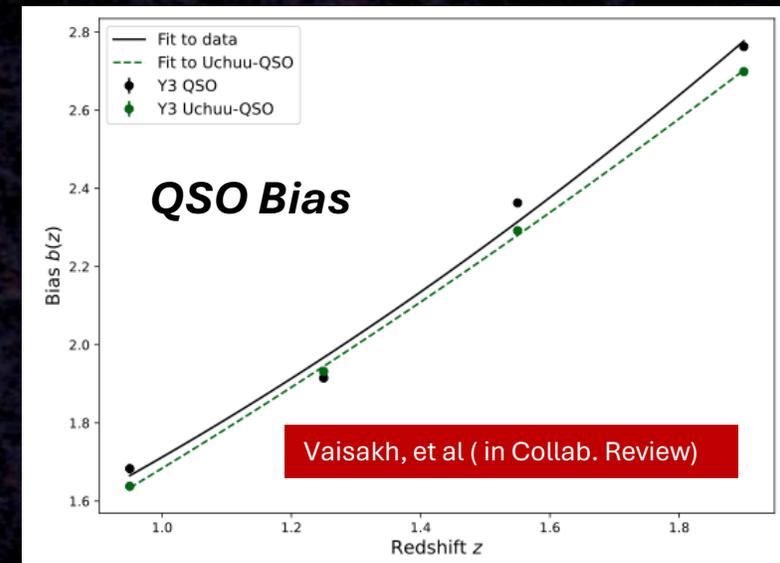
Halo Occupation Distribution (HOD)

- Halo Model – describes DM distribution in terms of halos
- Mass of a gravitationally bound DM halo \leftrightarrow Number of galaxies forming in that halo
- Mean Halo Mass: $2.5 \times 10^{12} M_{\text{sun}}$



Galaxy Bias

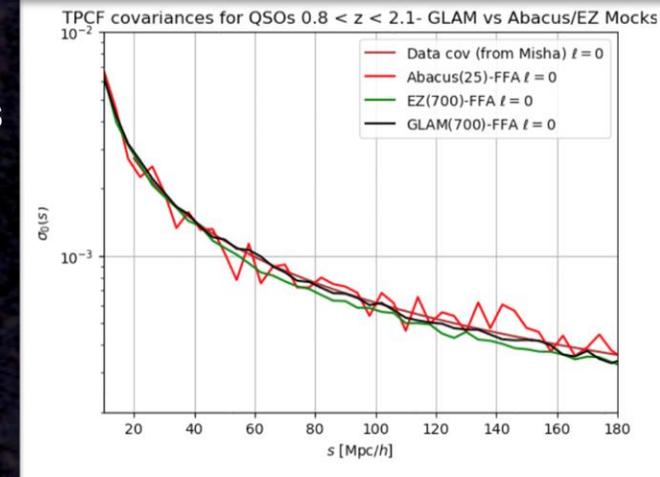
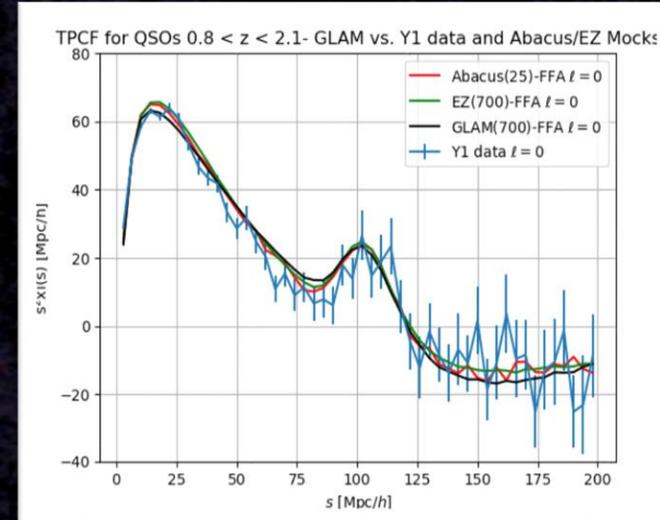
- Galaxy formation effects cause spatial distribution of baryons to differ from that of DM
- Bias $b = (\xi_{\text{gal}} / \xi_{\text{DM}})^{1/2}$



Results: GLAM-Uchuu Covariance Mocks

GLAM (GaLaxy Mocks) Simulation

- N-body code by Klypin & Prada, 2018
- Accurate estimation of covariance errors for N-point clustering
 - Crucial in BAO analysis
 - Massive mock production lowers systematic errors
- Use Uchuu to tune GLAM mocks for Covariances
 - 1000+ Mocks with different box-sizes and cosmologies
 - Produced at MANEFAME3/M3 (SMU), skun6 (Granada) & cosma8 (Durham)



**Performance of GLAM-Uchuu
mocks against other simulations
(AbacusSummit, EZMocks) and
survey data
(Theoretical Covariances provided
by Misha Rashkovetskyi)**



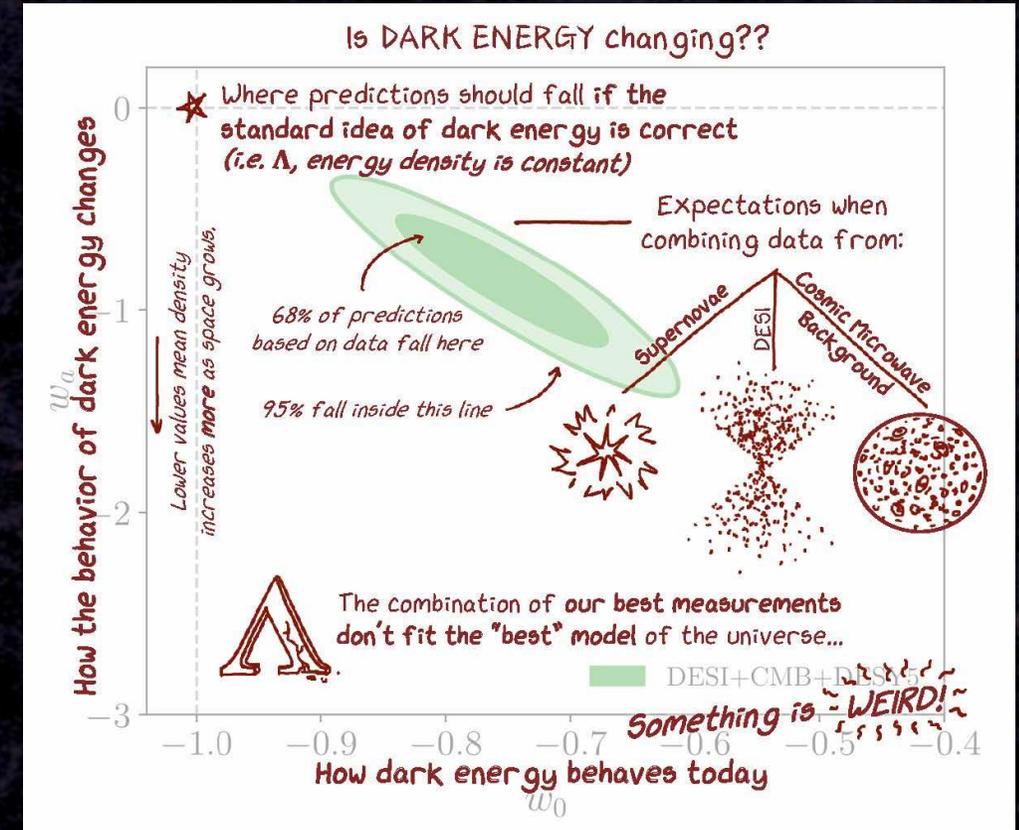
Cosmology Results: DESI DR2

Measured BAO distances from ~15 million galaxies & QSOs across $0.1 < z < 2.1$

- When combined with external probes (CMB, SNe),
 - **$w_0 w_a$ cosmology**: Time-varying dark energy provides a better fit (than LCDM) in some combinations
 - Preference at $\sim 2.8\text{--}4.2 \sigma$ depending on dataset

Where Mocks come into picture:

- Covariance matrices needed to quantify uncertainties
- **Robust Model Testing** under realistic survey conditions
- Disentangle cosmological signals from observational or sample variance effects



Summary & Future

- DESI currently delivering the most precise measurements of our universe's structure
 - Quality of this data demands an equally sophisticated simulation and modelling infrastructure
 - Currently producing reasonable results 0.5 Mpc/h onwards

Continued development of mock catalogs is essential for:

- Testing theories of gravity
- Measuring the mass of the neutrino
- Constraining the nature of dark energy with unprecedented precision

The better our simulations, the more we can learn from our observations

When 95% of the total energy density of the Universe isn't directly observable



No Frodo, let's unravel the secrets!



References & Acknowledgements

- Prada et al, A&A, 698 (2025) A170
- Vaisakh, et al (in Collab. Review)
- **Wechsler, R. H., & Tinker, J. L. (2018).** *The Connection between Galaxies and Their Dark Matter Halos*
- *DESI Collaboration et al. (2025) DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints*

I am looking for Postdoc Opportunities!



SCAN ME

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Thank You!



Team members: Robert Kehoe, James Lasker, Nabendu Khan, Antone Amalbert (SMU) Francisco Prada, Elena Fernandez-Garcia (IAA-Spain), Anatoly Klypin (Uva)

The DESI collaboration is honored to be permitted to conduct scientific research on Iolkam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.
Special thanks to *National Energy Research and Computing Center (NERSC, at LBL, Berkley)*, *CESGA Supercomputing Cluster (IAA, Barcelona, Spain)*, and *SMU HPC – Maneframe III, SMU, Dallas, Texas*, for access to their high-performance computing clusters.

The logo for the Dark Energy Spectroscopic Instrument (DESI) is shown in the top left corner, featuring a colorful illustration of a telescope and a dog. Below the logo, the text 'DARK ENERGY SPECTROSCOPIC INSTRUMENT' is written. The background of the slide is a photograph of the Kitt Peak National Observatory at sunset, showing several large telescope domes on a hillside.

U.S. Department of Energy Office of Science

A collection of logos for the project's sponsors, including the U.S. Department of Energy Office of Science, NSF, NERSC, CEA, Heising-Simons Foundation, Gordon and Betty Moore Foundation, and Science & Technology Facilities Council.

Thanks to our sponsors and
72 Participating Institutions!

Backup



Outline

- Introduction
 - Dark Matter Halos
 - Galaxy Surveys (DESI)
 - Galaxy Halo Connection
- Modelling
 - Empirical models
 - SHAM
- Results



The Dark Matter Halo

Halo Mass Function

Abundance of halos

Exponentially more low-mass halos than high-mass ones!

Density Profile

Halos not uniform spheres

Peaks at the centre and falls off (see NFW profile)

Substructures

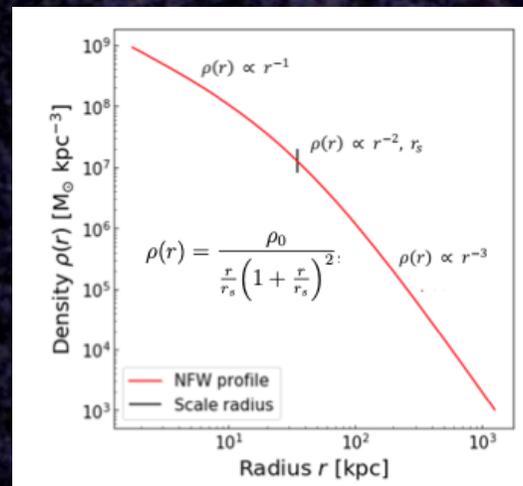
Subhalos - remnants that were accreted and tidally stripped

Host satellites

Assembly History

Same mass Halos can have very different histories

Some are early and dense, others late and more diffuse



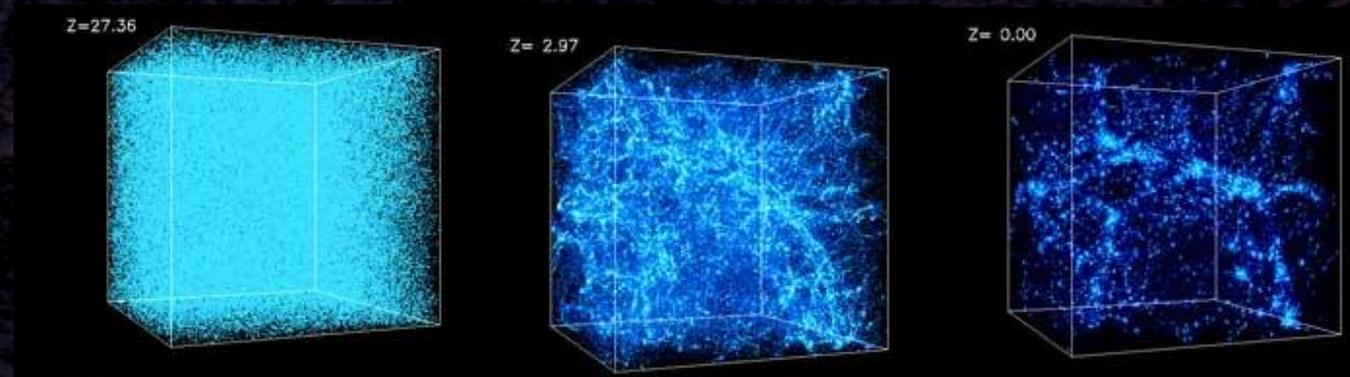
The Halo Mass Function: A Key Prediction

- A cornerstone prediction of the Λ CDM model
- (dn/dM) - number density of halos of a given mass at any cosmic epoch
- **Tells** us how many small halos versus how many rare, giant halos we should expect in each volume of space.
- This prediction from simulations is incredibly robust and serves as the foundation for populating our virtual universes



Large Scale Structure Surveys

- Observe large regions of space to produce galaxy redshift surveys
- Growth of LSS gives info about time dependence of Gravity, Dark Energy



Simulation Credit: National Center for Supercomputer Applications by Andrey Kravtsov (U Chicago) and Anatoly Klypin (NMSU).

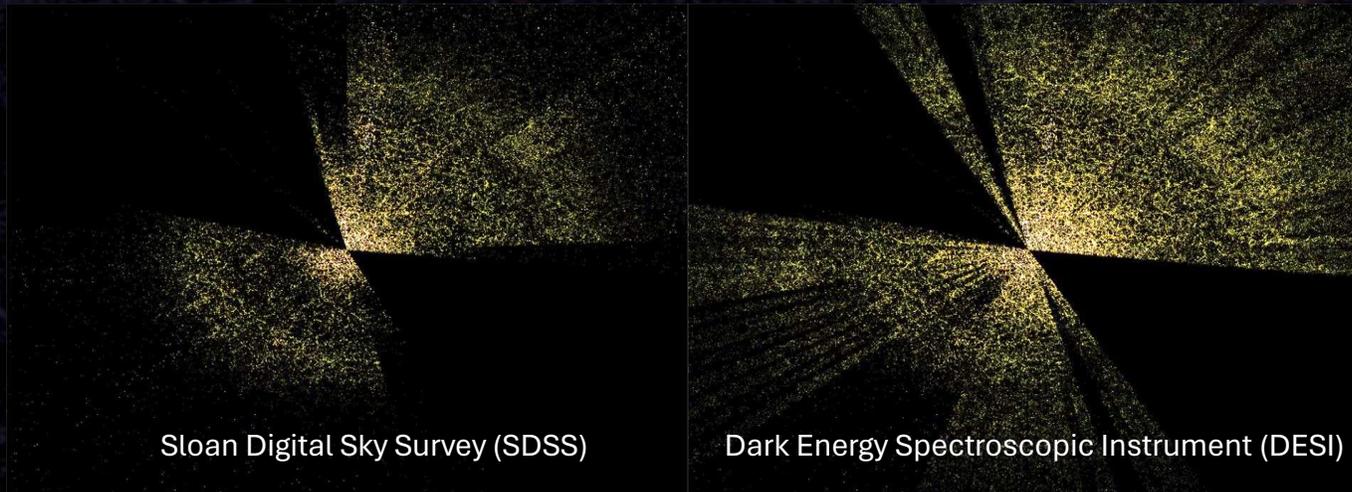


Image Credits: DESI Science Outreach; Institute of Space Sciences (ICE-CSIC) Outreach



DESI Dark Matter Tracers

Milky Way Survey (MWS)

- Stars, $z \sim 0$

Quasars (QSOs)

- Direct tracers ($z < 2.1$)
 - Using Lyman- α absorption features ($2.1 < z < 3.5$)

DESI uses different types of DM tracers

Bright Galaxy Survey (BGS)

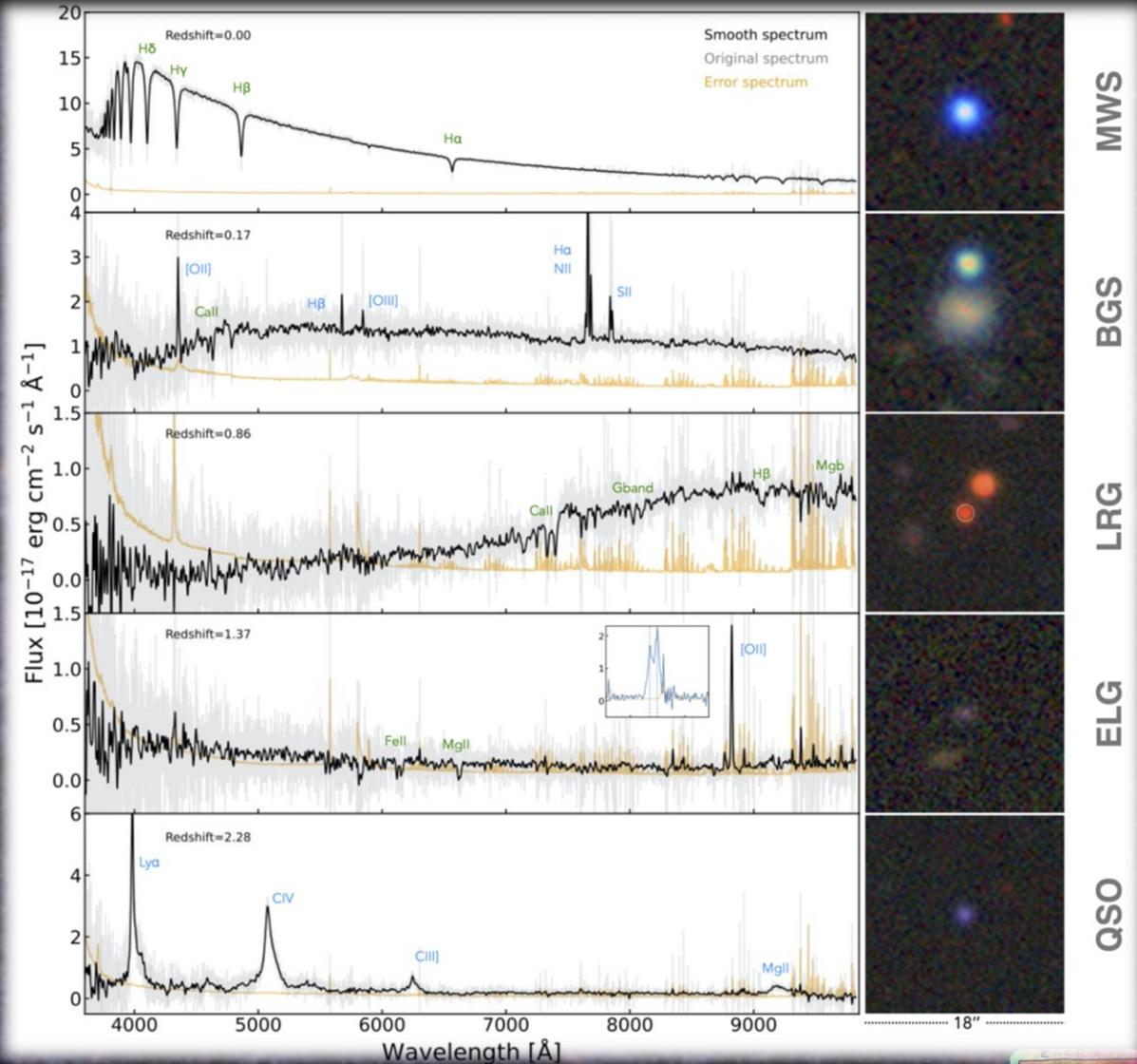
- upto $z \approx 0.4$

Emission Line Galaxies (ELGs)

up to $z = 1.6$ (bright forbidden [OII] emissions)

Luminous Red Galaxies (LRGs)

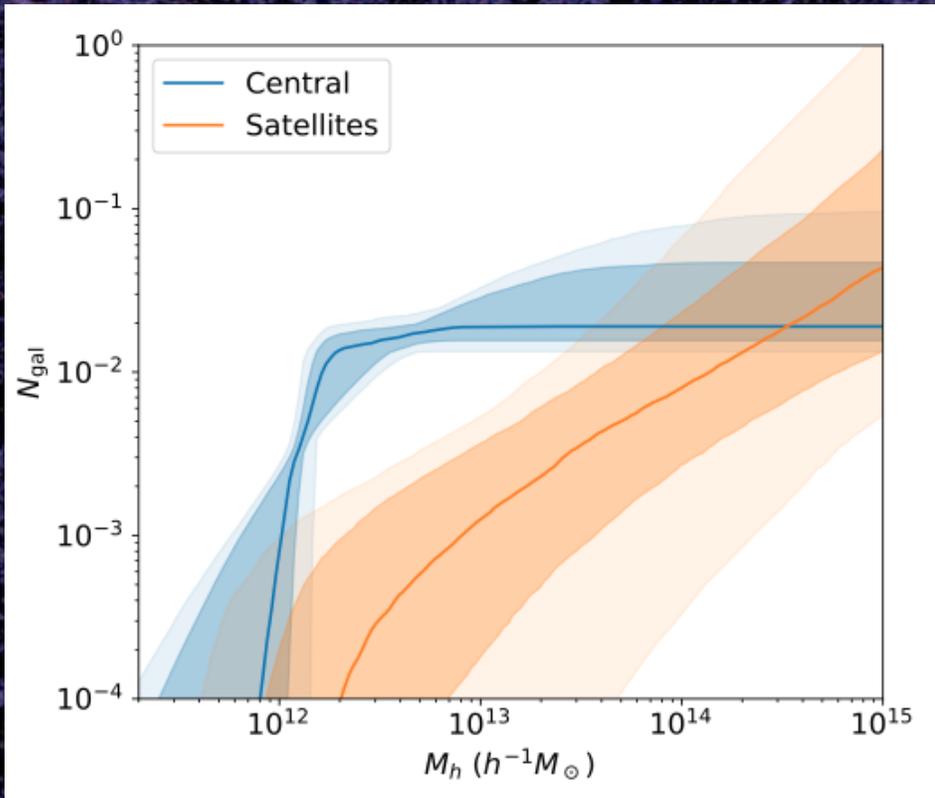
up to Redshift $z = 1.1$ (4000 Å break)



Example spectra for the DESI target classes.
Credit: Ting-Wen Lan, DESI member



Halo Occupation Distribution (HOD)



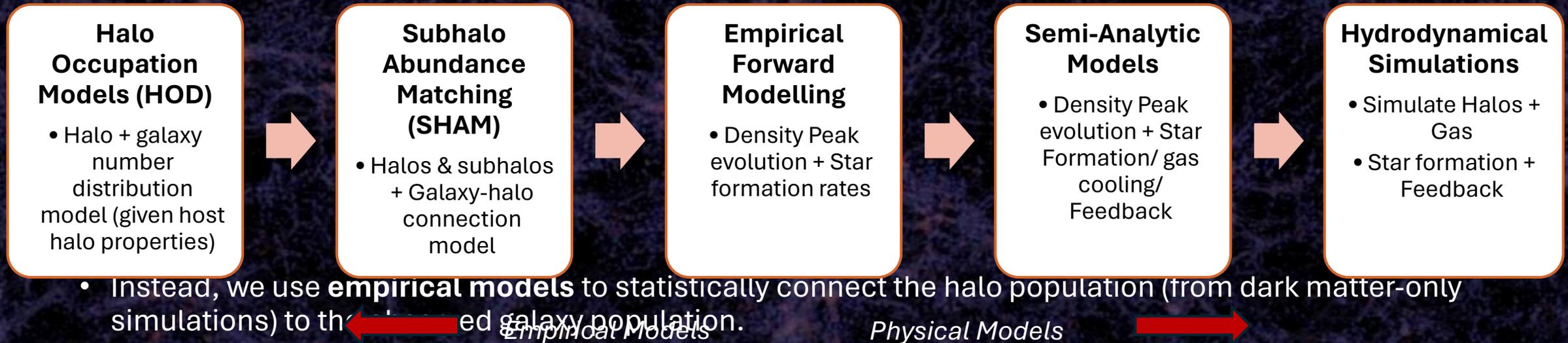
S.Yuan, et al. 2306.06314

- A purely statistical framework
- $P(N|M)$ - probability that a halo of mass M hosts N galaxies
- Modeled as two separate components:
 - **Centrals:** $\langle N_{\text{cen}} \rangle$ is a step-function
 - Below a minimum mass, M_{min} , halos don't host a central galaxy
 - **Satellites:** $\langle N_{\text{sat}} \rangle \propto (M/M_1)^{\alpha}$
 - No. of satellites grows as a power-law with halo mass
- Model parameters (*few too many*) are tuned to match observations

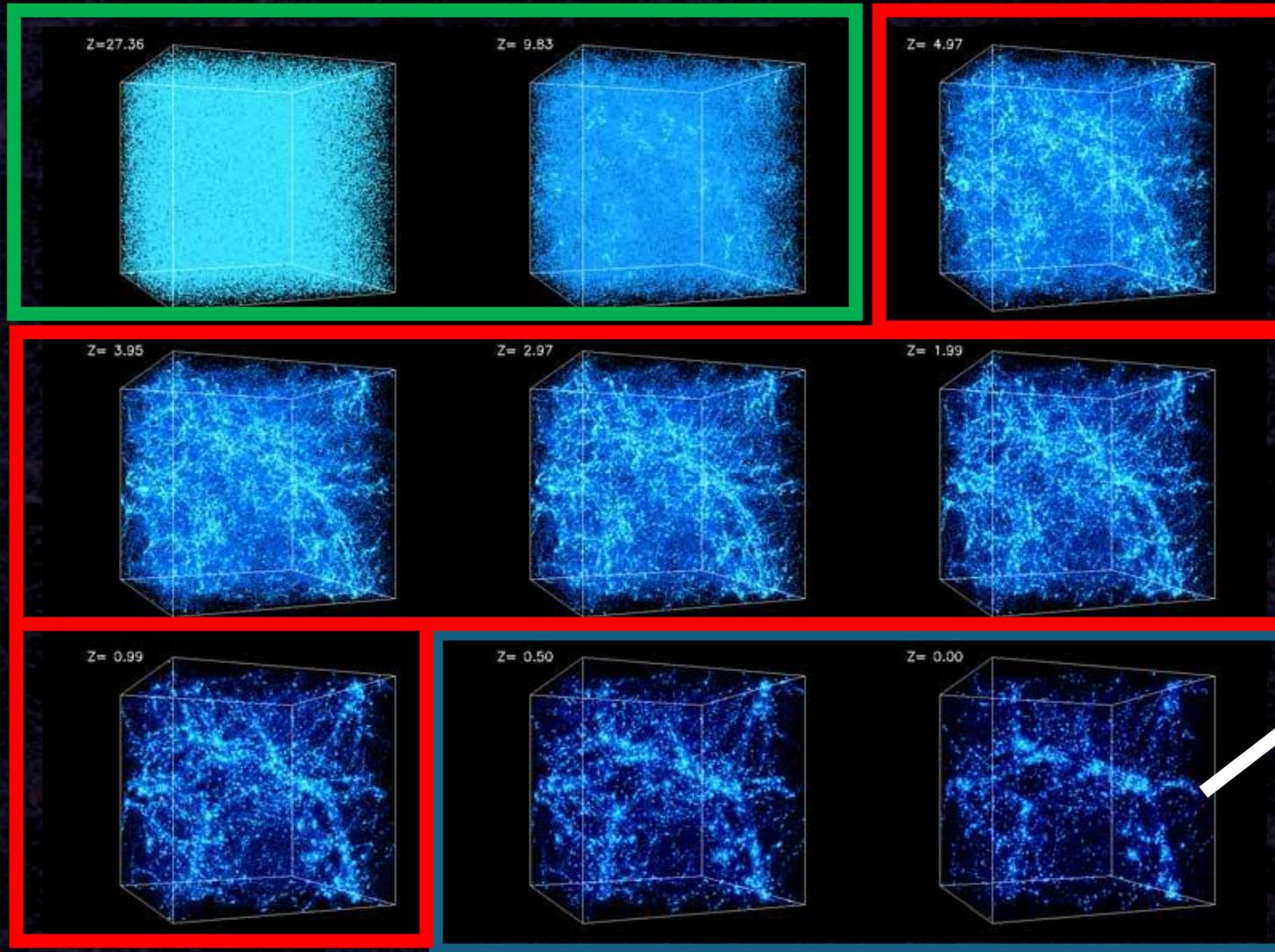


Bridging the gap: *Empirical Models*

Computationally impossible to simulate the entire universe with full galaxy formation physics



Closer to how
it all began!



Distant Universe

We're here now!

Nearby Universe

simulations allow us to compare observational results to the theoretical formation of clusters and large-scale structure, and to explore the role of dark matter and dark energy.



Constructing a Lightcone

Surveys don't see a static cube of the universe

- When we look at distant objects, we **look back in time**: *A lightcone mimics this reality*

