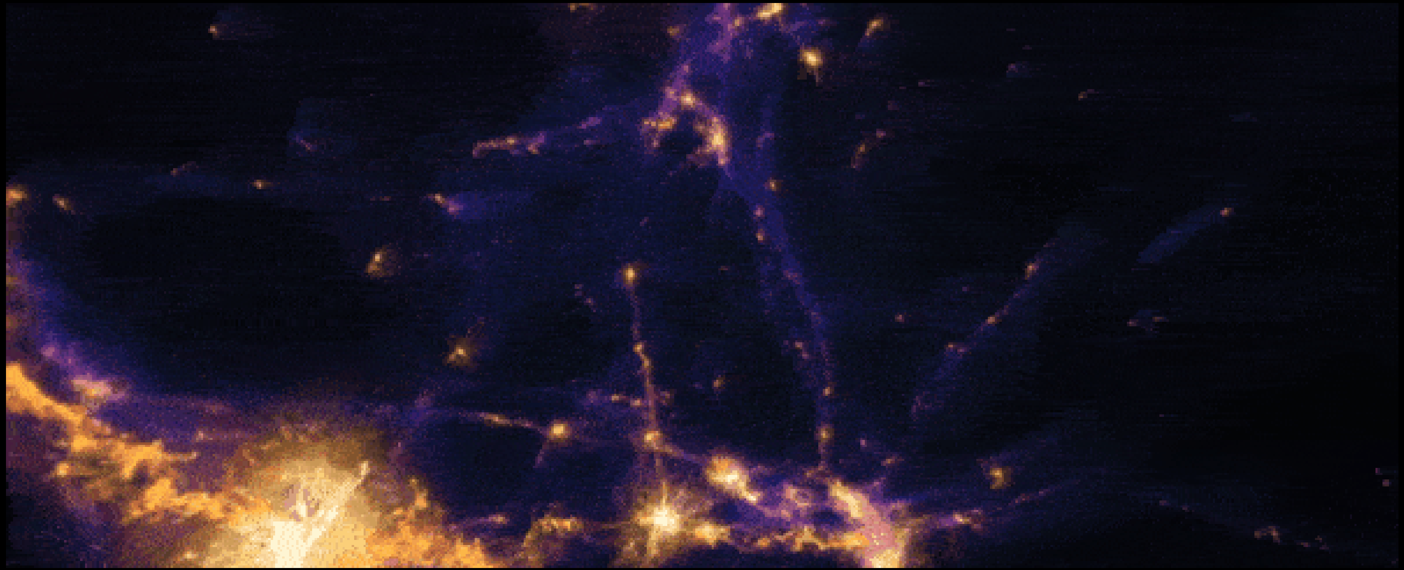
Uncovering physics

from Stage-IV cosmological experiments with accurate galaxy models



Boryana Hadzhiyska, PhD Candidate

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Chamberlain, LBNL

12/1/2021

Acknowledging team effort!

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- Lehman Garrison (CfA, CCA)
- Nina Maksimova (CfA)

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Karim+ (2021, in prep.)

Layout

1. What questions does my research address?
2. How do they relate to efforts at LBNL?
   - Stage-IV galaxy surveys (DESI, Rubin)
   - Stage-III/IV CMB experiments (ACT, CMB-S4)
3. What is my research experience with large-scale structure and CMB?
4. What do I propose to do in the next few years?

What research questions does my program address?

What is the composition of the Universe and what is the nature of dark matter?

What is the mass of the neutrino and its mass hierarchy?

My research

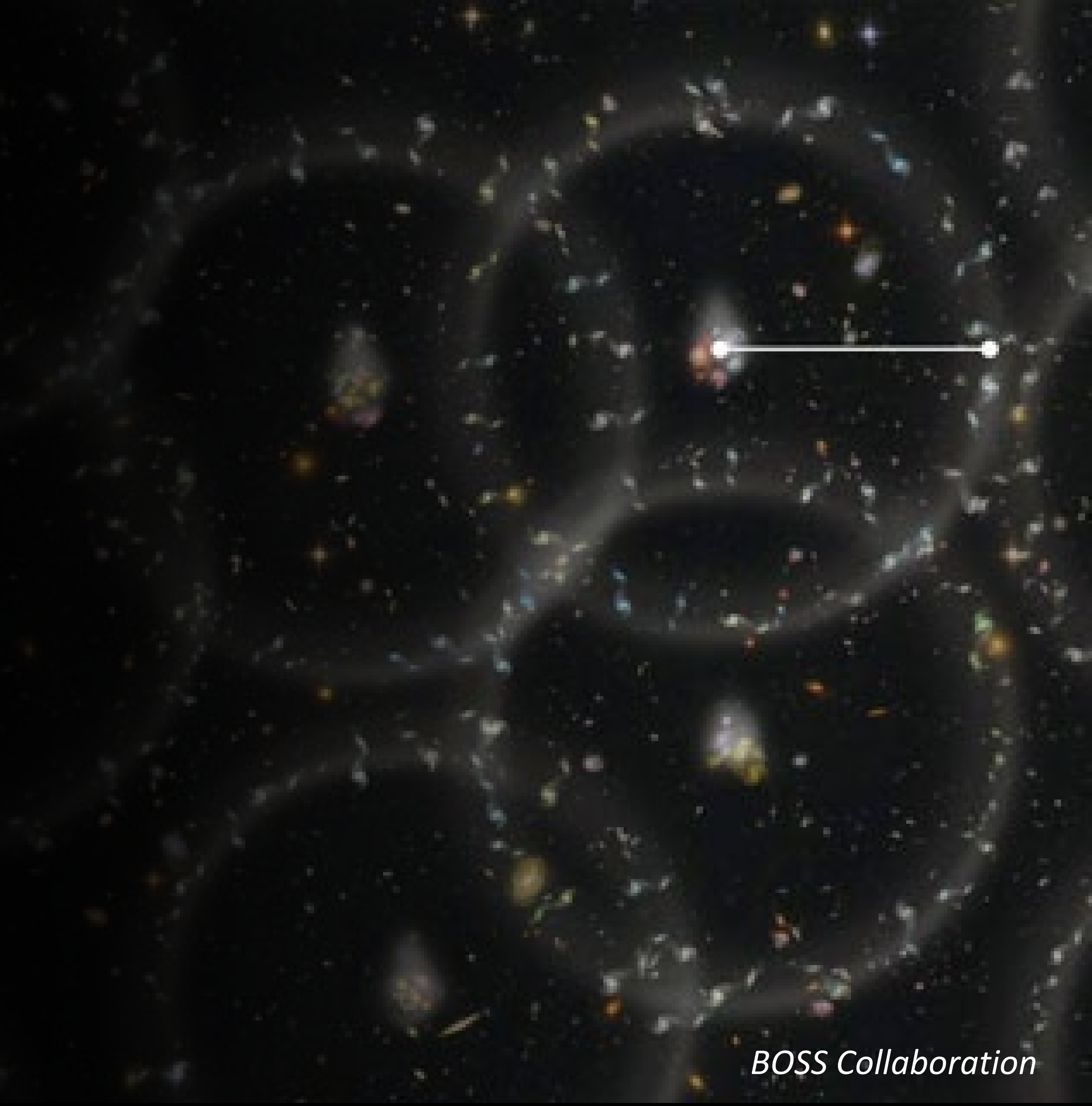
Is dark energy the cosmological constant, a failing of GR, or a new form of energy?

Is inflation the correct explanation for the origin of fluctuations in the Universe?

These questions are also relevant to LBNL research: e.g., DESI, CMB-S4, synergies with Rubin, DUNE, LZ, etc.

Dark energy, growth rate

- DESI’s primary measurements will be of dark energy via growth rate of Universe
- Baryon acoustic oscillations (BAO) provide cleanest probes of expansion history
- Quasars (Ly-α) probe dark energy at earlier times ($z > 2$)
- Supernovae catalogs via Rubin calibrated with DESI redshifts provide independent probes



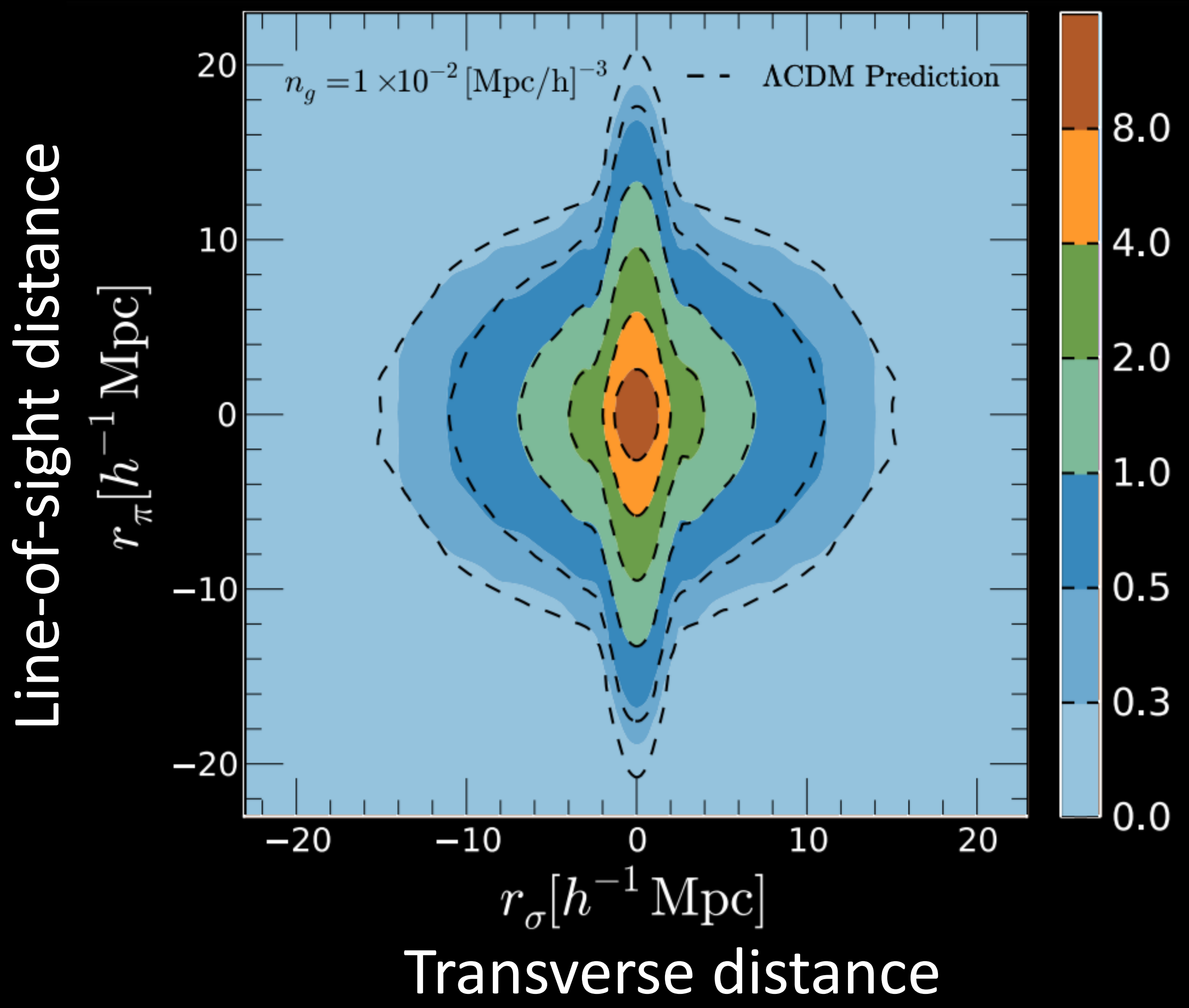
BOSS Collaboration

Dark energy, modified gravity

- DESI will measure redshifts (and thus intrinsic velocities) of nearly 40 million galaxies
- The intrinsic velocities of galaxies give a measurement of gravity at each time epoch
- Shape of galaxy correlation function tests dark energy
- Perturbation theory* connects observations and theory on quasilinear scales
- Galaxy-halo modeling* provides an alternative on small scales

*Part of proposal

SDSS Collaboration



Inflation(?)

- Primordial fluctuations in the density seeded the large-scale structure we observe today
- The clustering of galaxies/clusters & Ly-α forest via DESI constrains the primordial power spectrum

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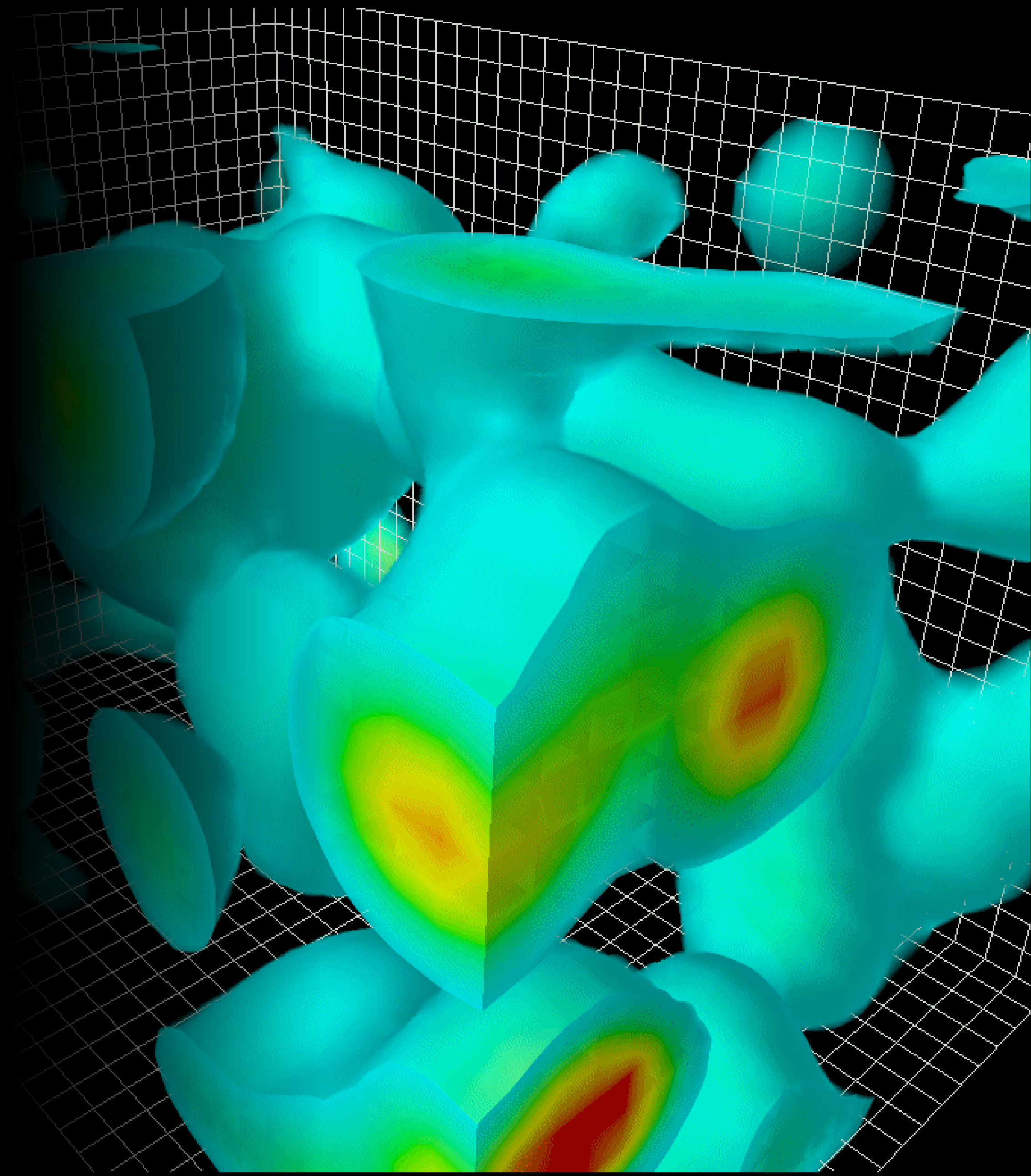
- Primordial non-Gaussianities are predicted by a plethora of models
- Complementary to CMB probes, measuring statistics beyond the two-point clustering* of galaxies allows us to constrain non-Gauss.



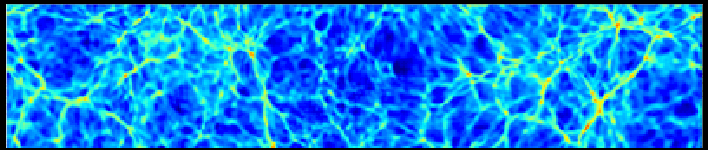
*Part of proposal

Neutrinos

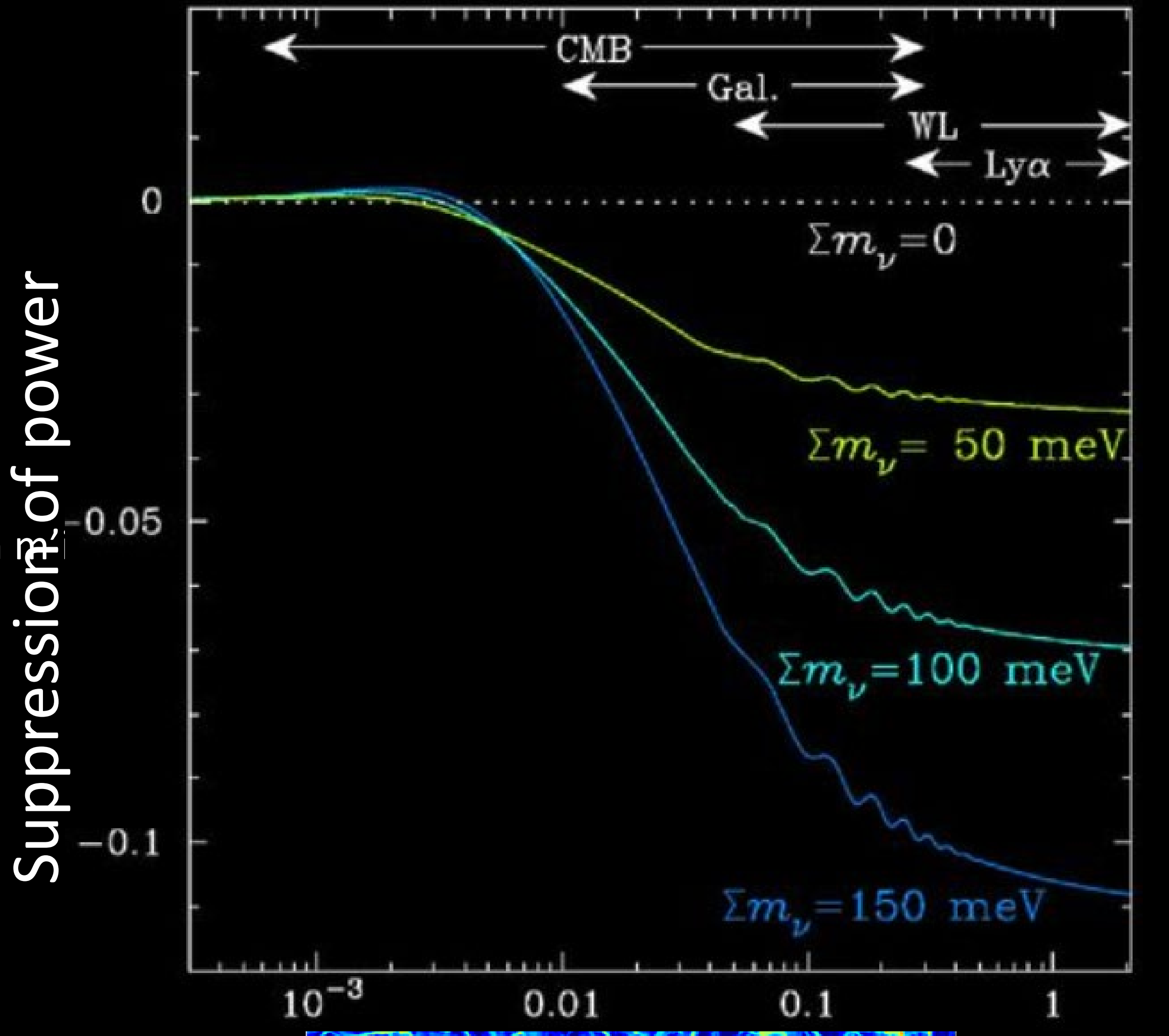
- From neutrino mixing experiments, we know the neutrino mass differences, but not the absolute masses
- Next-generation cosmology experiments (e.g., ACT, DESI, CMB-S4) will improve our sensitivity to neutrino mass
- There are different complementary approaches: CMB, galaxies, weak lensing*, Ly-α forest, etc.

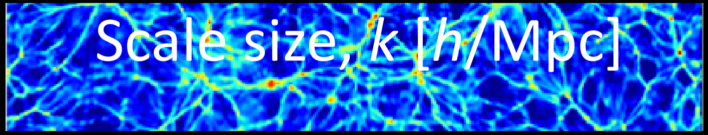
*Part of proposal

With m'less neutrinos



With m...

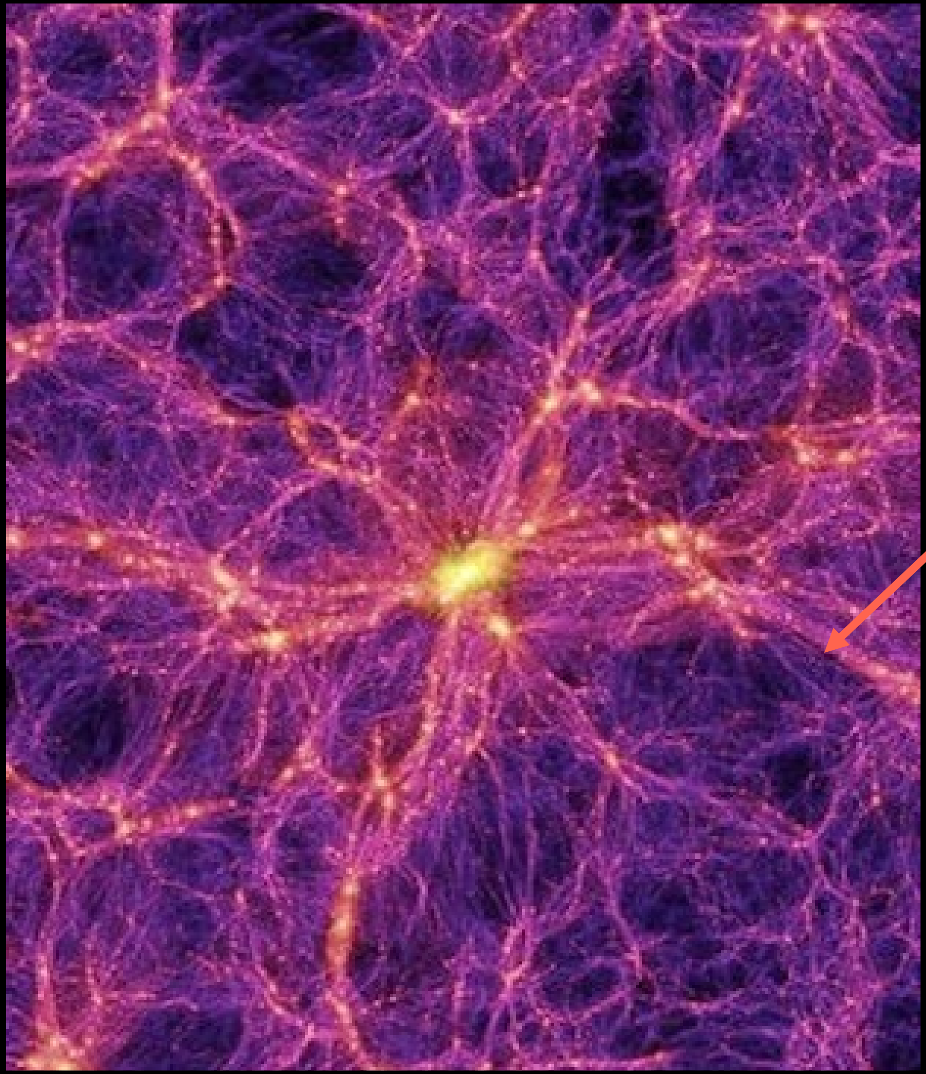


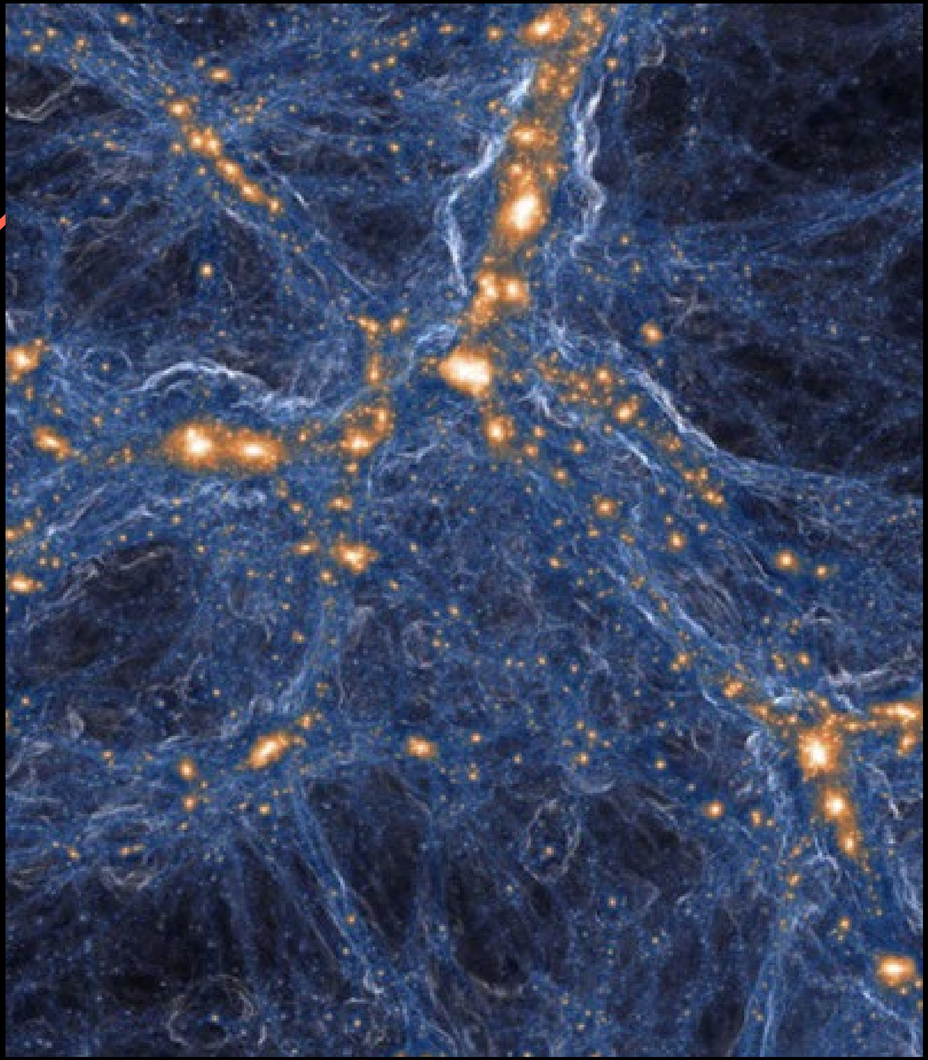


Many of the proposed tools need careful modeling in order to understand potential systematics: e.g. galaxy/cluster bias, baryonic effects, etc.

To meet the goals of next-generation experiments, my research will construct accurate models of the galaxy distribution using state-of-the-art simulations, advancing the science of LBNL

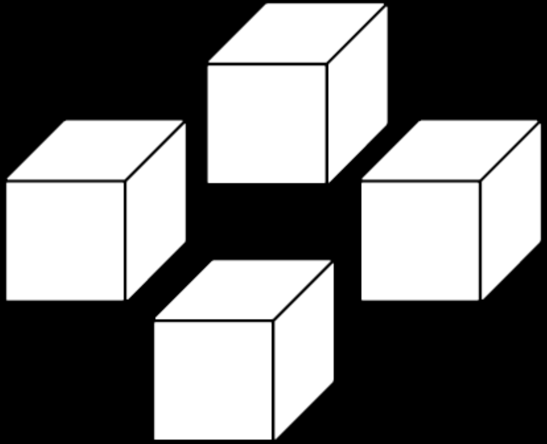
Types of cosmological simulations





Extracting cosmology from DESI with a high-fidelity simulation-informed galaxy model

AbacusSummit



Hydro sim.-informed **model**

Constraining growth of structure, modified gravity, dark energy

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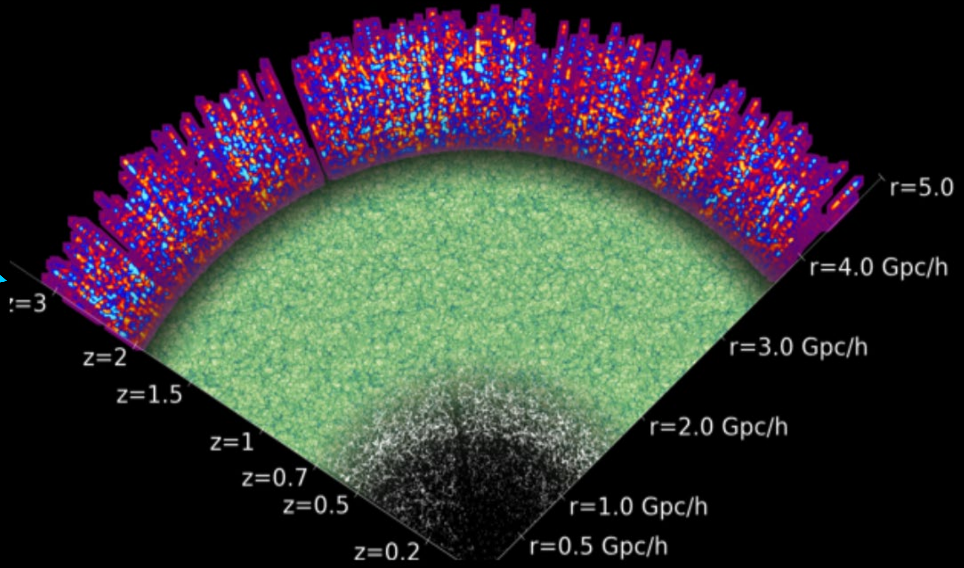

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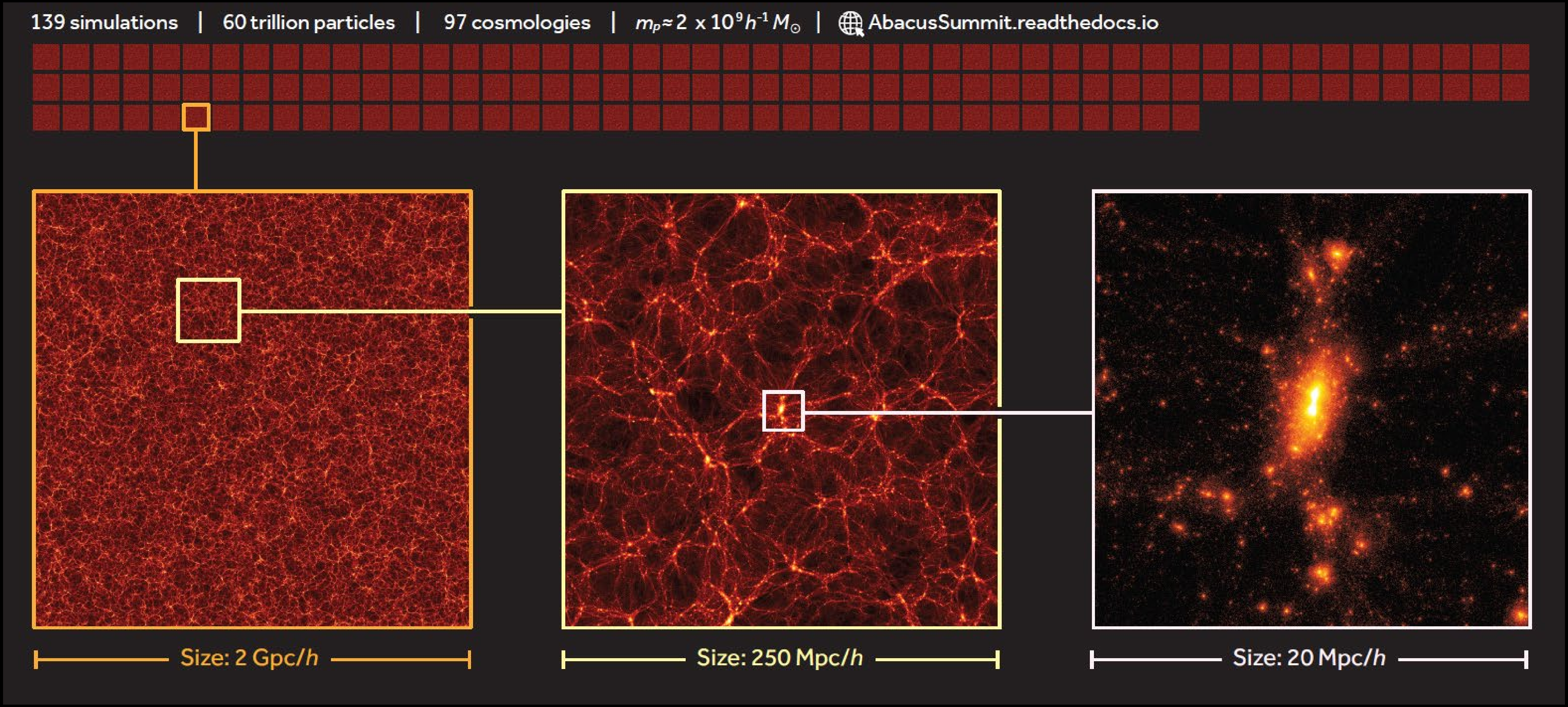
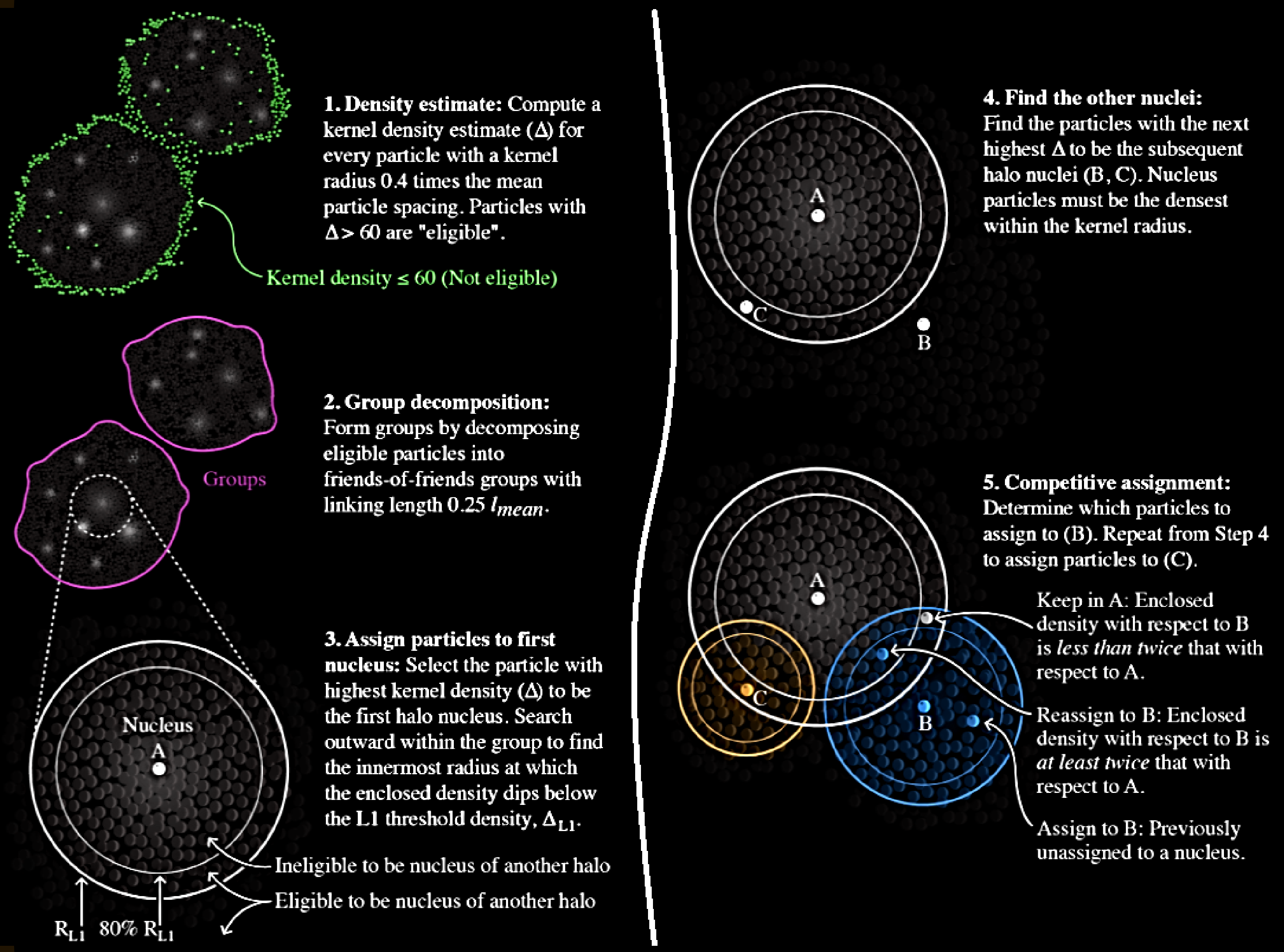
AbacusSummit: largest-yet *N*-body suite

N. Maksimova, L. Garrison, D. Eisenstein, B. Hadzhiyska+, 2021



CompaSO: A new halo finder

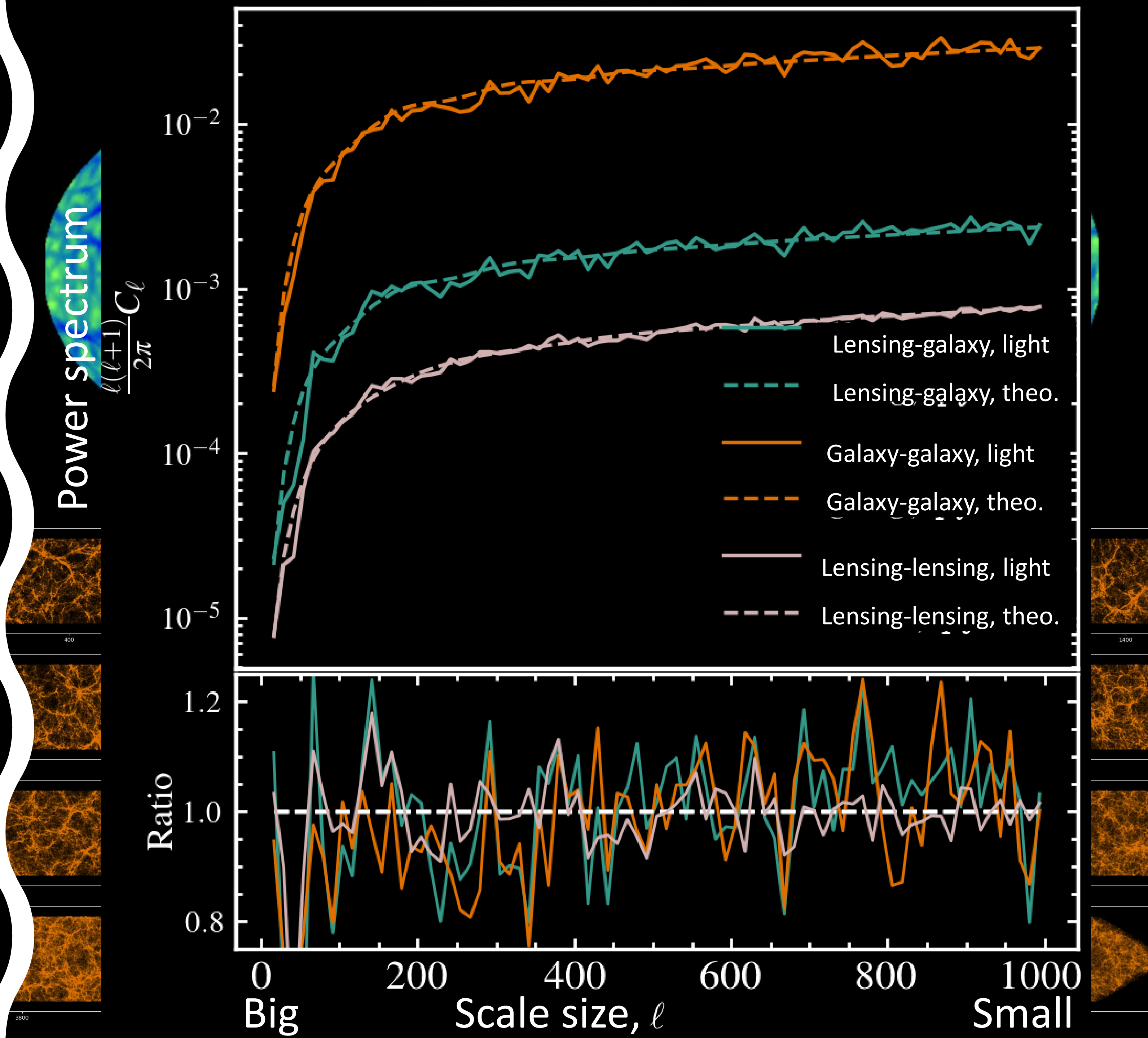
- Halo finding: essential for survey analysis
- Designed + implemented new highly optimized finder CompaSO
- Comparable to more sophisticated finders
- Currently used in analyzing DESI data



Hadzhiyska+ (2021a)

The AbacusSummit halo light cone catalogs

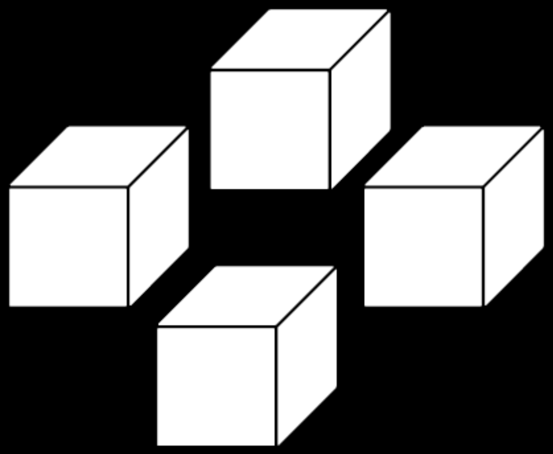
- Publicly available
- 25 simulations cover an octant of the sky and 2 simulations cover the full sky until $z \sim 2$ (10 bln yrs)
- For testing observational effects and performing weak lensing analysis
- Used them to develop the simulation pipeline for the DESI ELGxCMB analysis (Karim+ in prep.)



Hadzhiyska+ (2021b)

Extracting cosmology with a high-fidelity simulation-informed galaxy models

AbacusSummit



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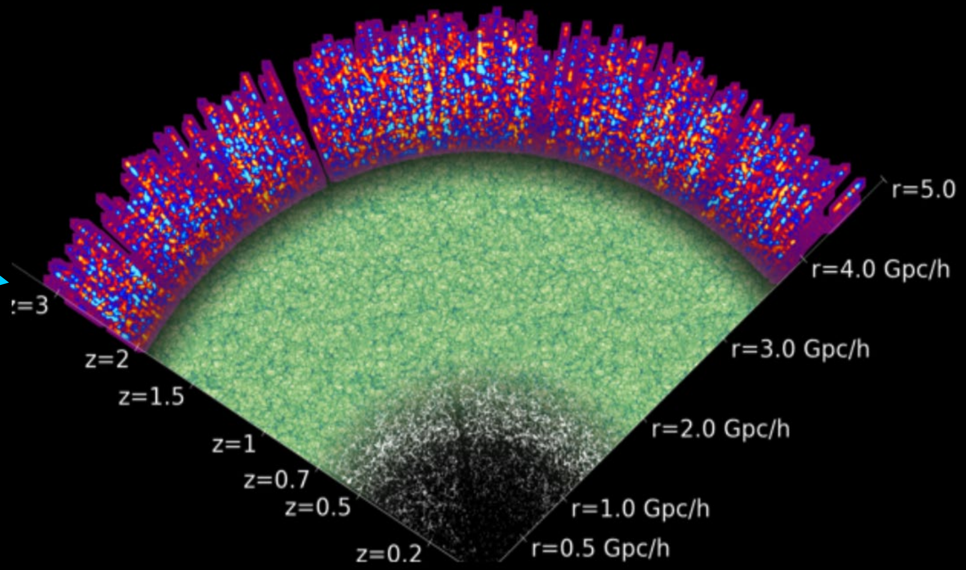

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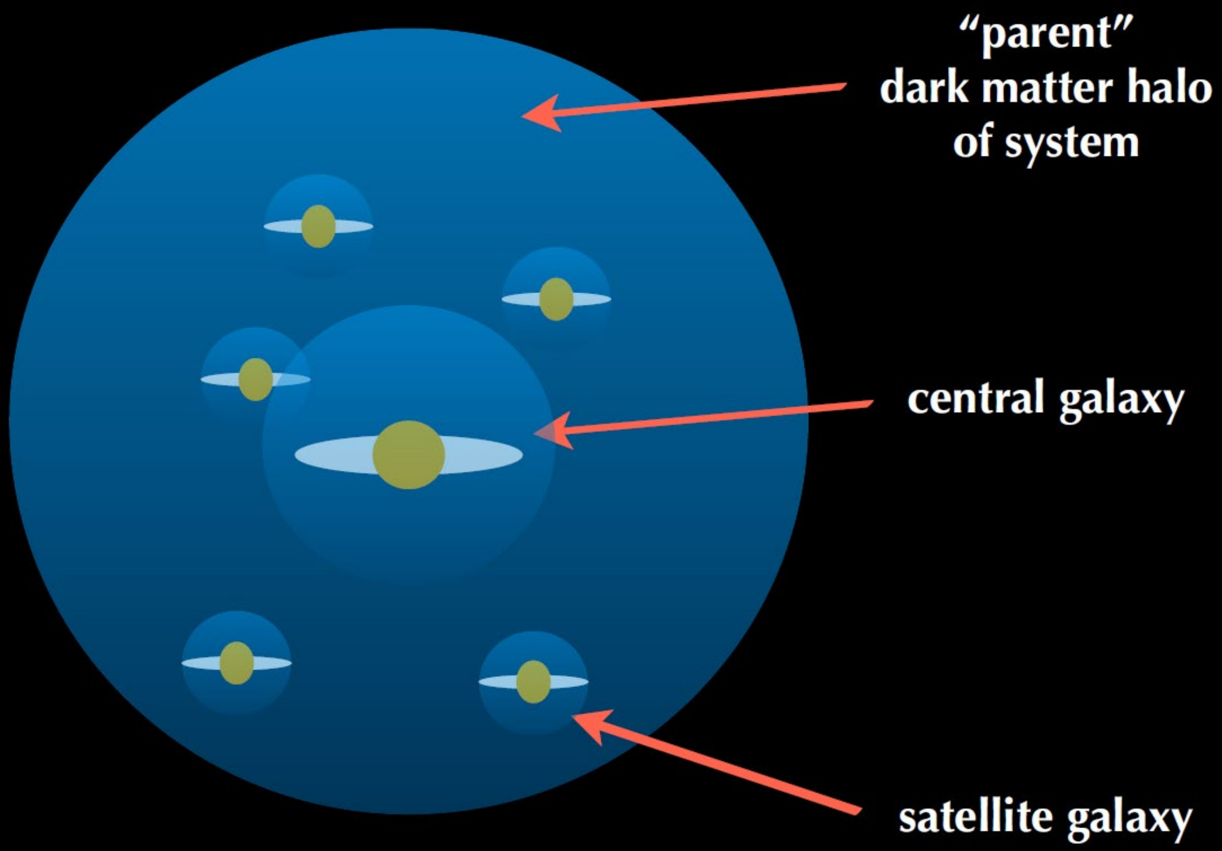
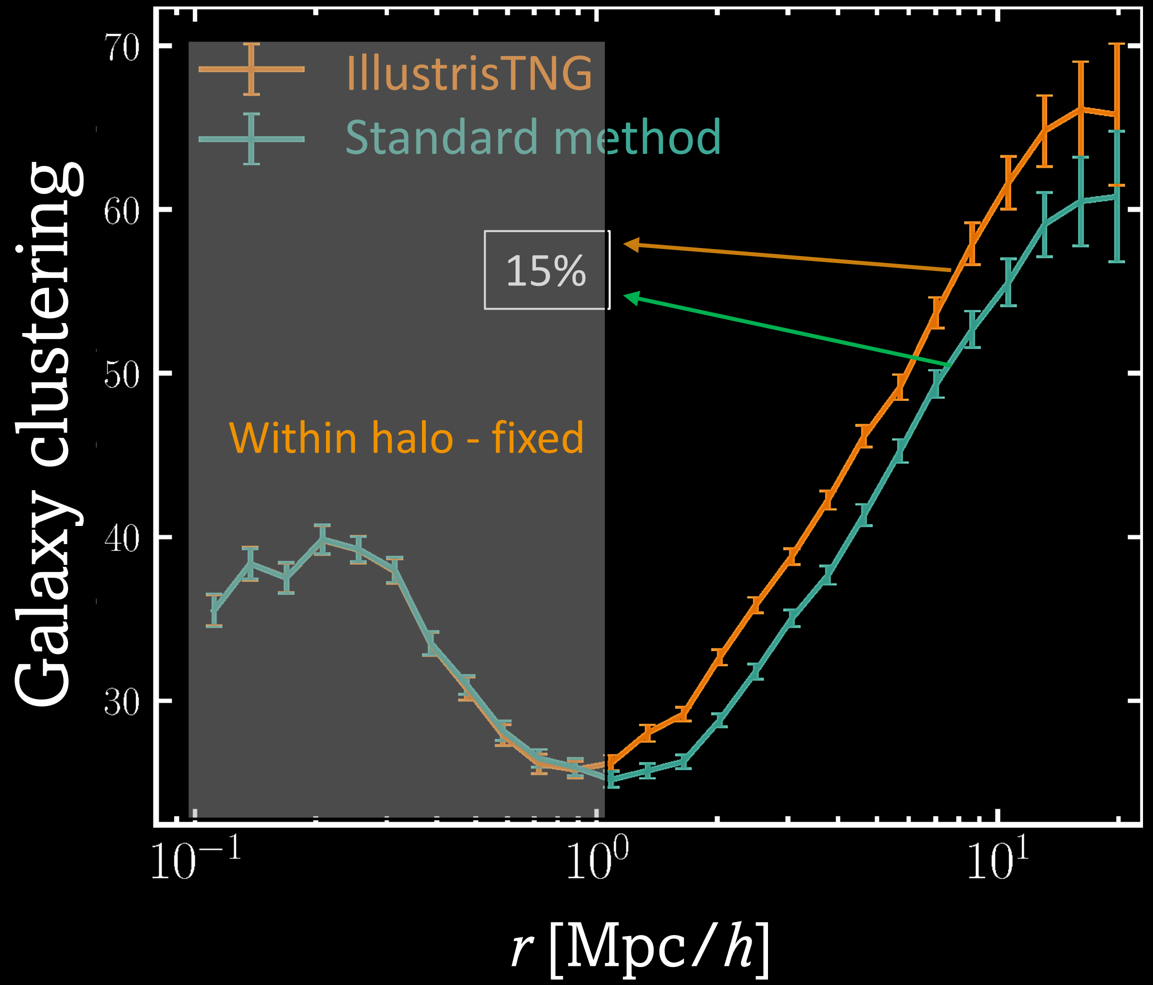
The galaxy-halo model provides a prediction of the galaxy distribution in *N*-body simulations



- **Assumption:** The properties of galaxies are dictated by the properties of the dark-matter halo they reside in.
- Key to the analysis of DESI and galaxy surveys, as it generates realistic galaxy catalogs from cosmological simulations of huge volumes
- Provides galaxy clustering predictions

Predictions of the standard galaxy models



Hadzhiyska+ (2019)

- Most popular method fails to recover galaxy clustering at the 15% level!
- Well above the subpercent level precision of the DESI measurements
- Other empirical methods fail, too
- If unaddressed, could lead to notable bias in the inferred cosmology

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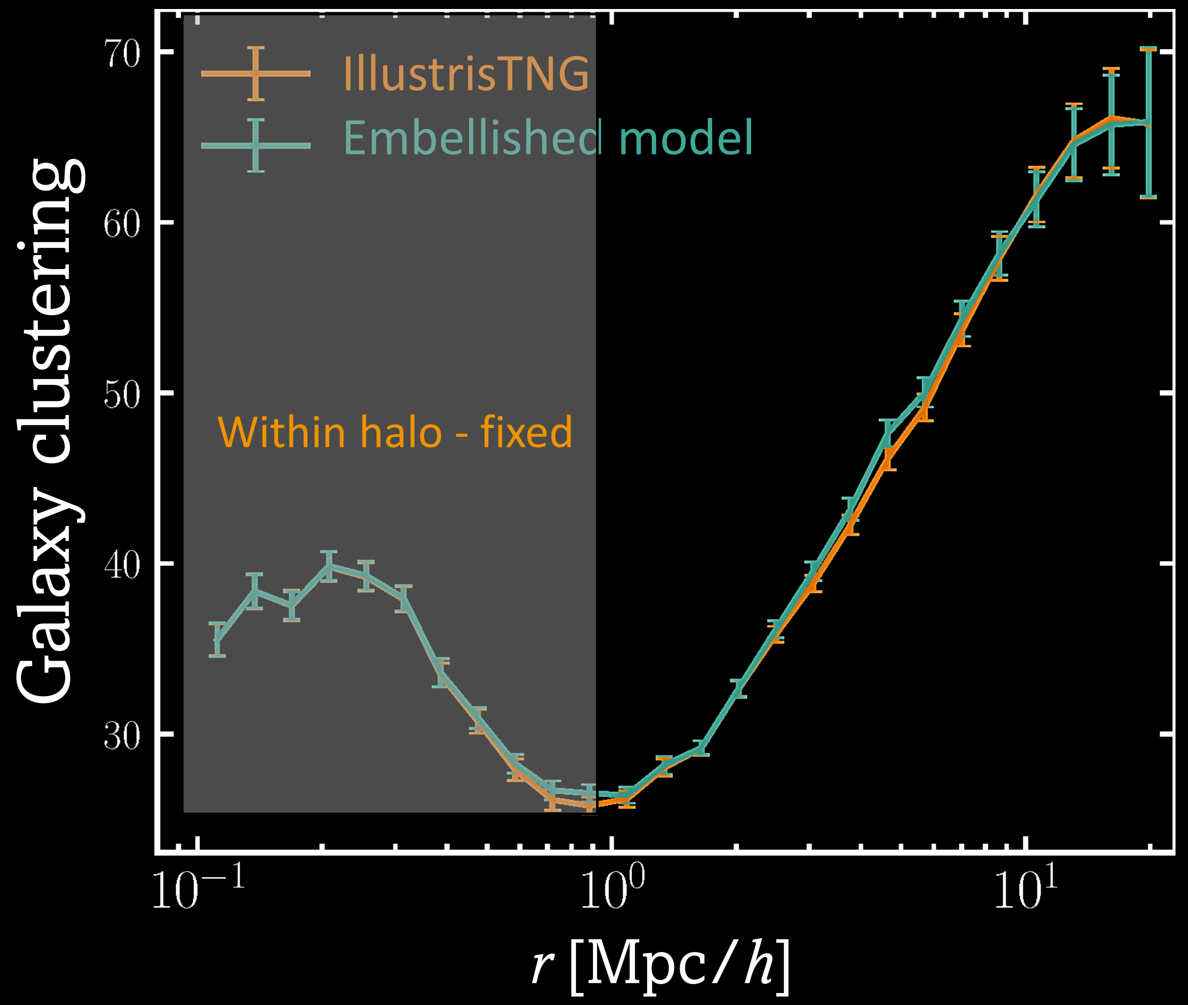
Enhanced models outperform standard ones



Hadzhiyska+ (2021b)

- I have designed physically intuitive modifications to standard methods that predict the correct clustering
- Preliminary work shows that embellished mode reproduces other statistics of the galaxy field
- This model provides a simple, yet accurate path to observational analysis
- Does it work in practice?

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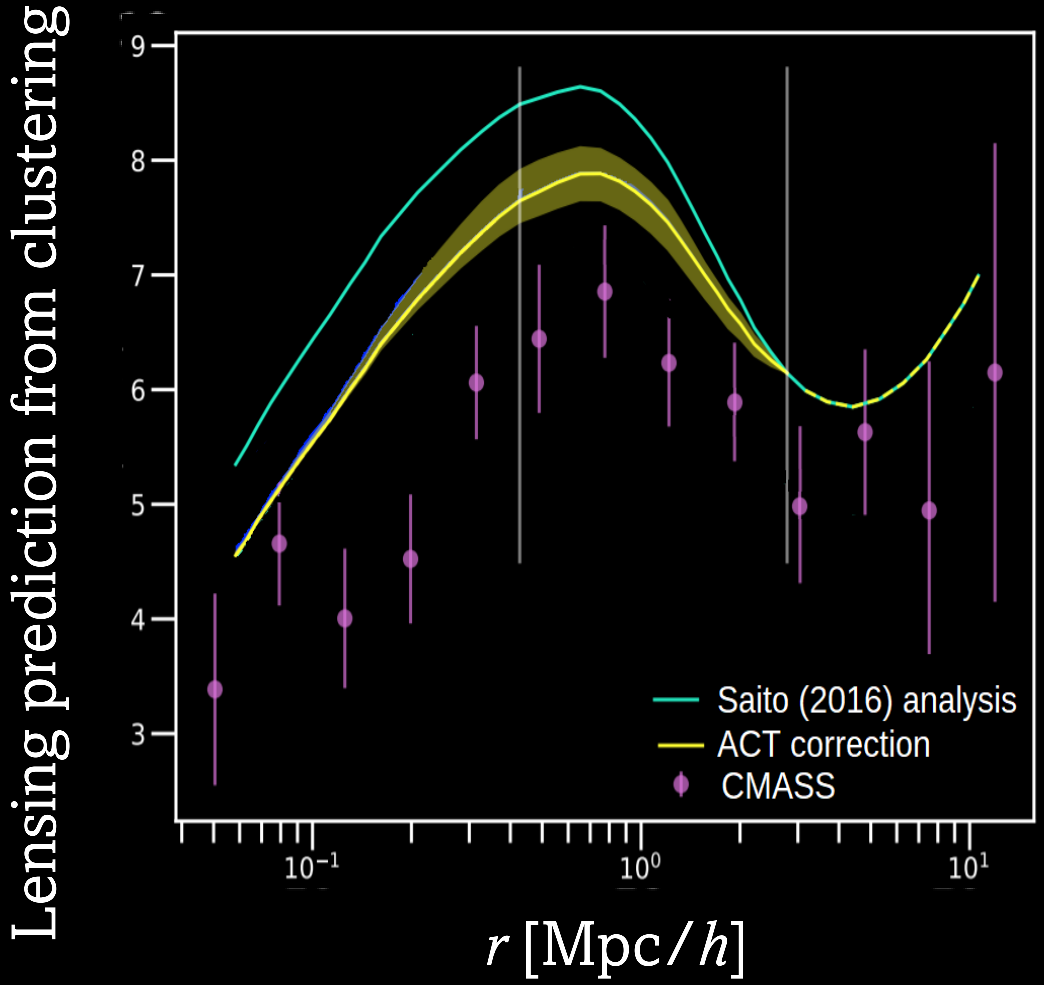
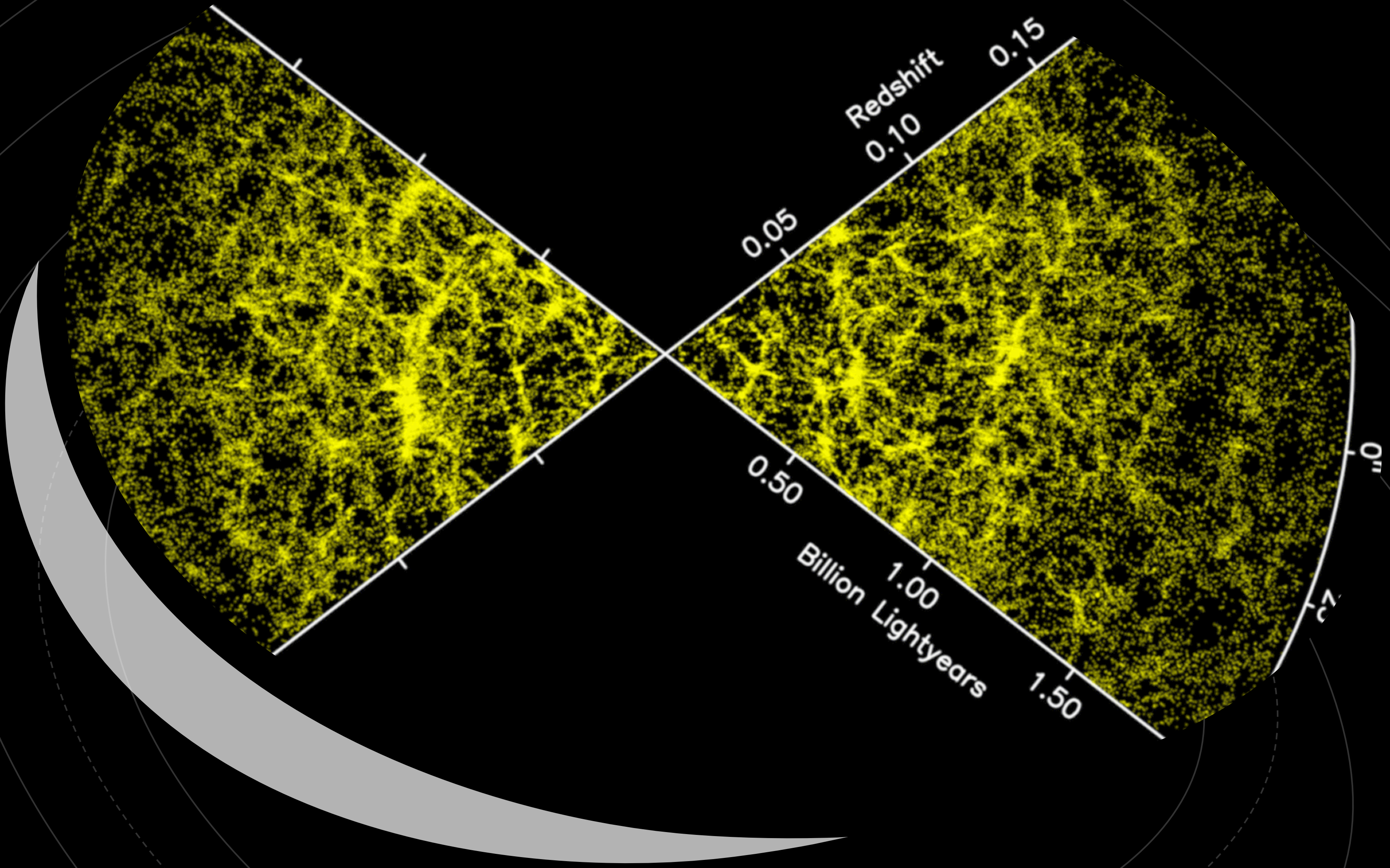
Applying embellished models to data



- We applied my proposed embellishment of the standard method to the CMASS BOSS analysis
- Reduced the tension significantly in the “Lensing is low” effect
- Can this be fully explained by considering also baryonic effects*?

*Part of proposal

Yuan, Hadzhiyska+ (2020)
Amodeo & ACT Collab. (2020)



Future work relevant to redshift surveys

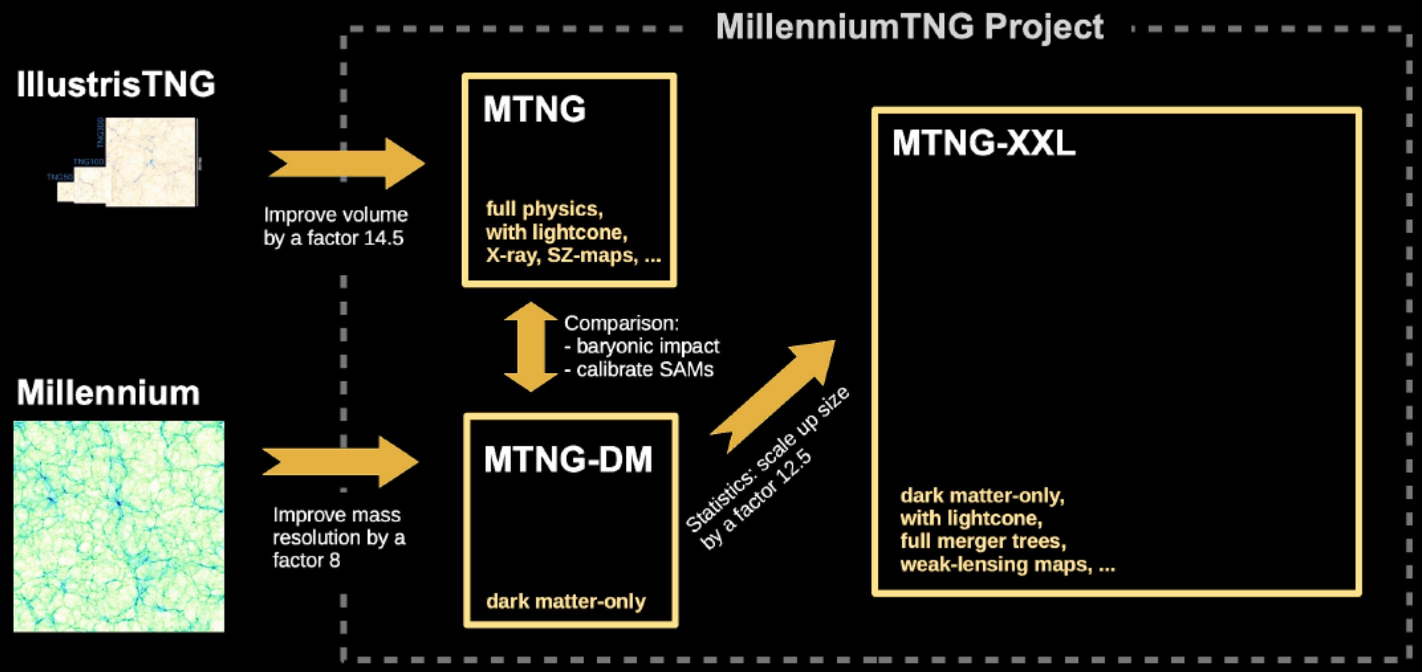
e.g., DESI, *Euclid*

Redshift surveys:
Going forward, I will…

- Extract cosmological constraints on the growth of structure from redshift surveys (DESI, *Euclid*) using high-fidelity galaxy models
- Constrain primordial non-Gaussianities via novel statistical methods

Developing high-fidelity models with the MillenniumTNG (MTNG) hydro simulation

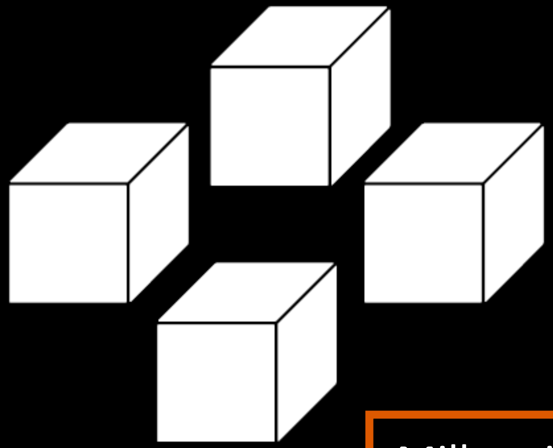
An effort led by:
Volker Springel, Lars Hernquist, Carlos Frenk, Simon White,
Ruediger Pakmor, Sowнak Bose, and myself



- 15 x volume of IllustrisTNG
- Better large-scale statistics
- Can study 3-point correlations, void statistics, counts-in-cell
- Various tracers (luminous red galaxies, emission-line galaxies, X-ray, Sunyaev-Zel’dovich, Ly-α, CMB lensing) observable with Stage-IV experiments

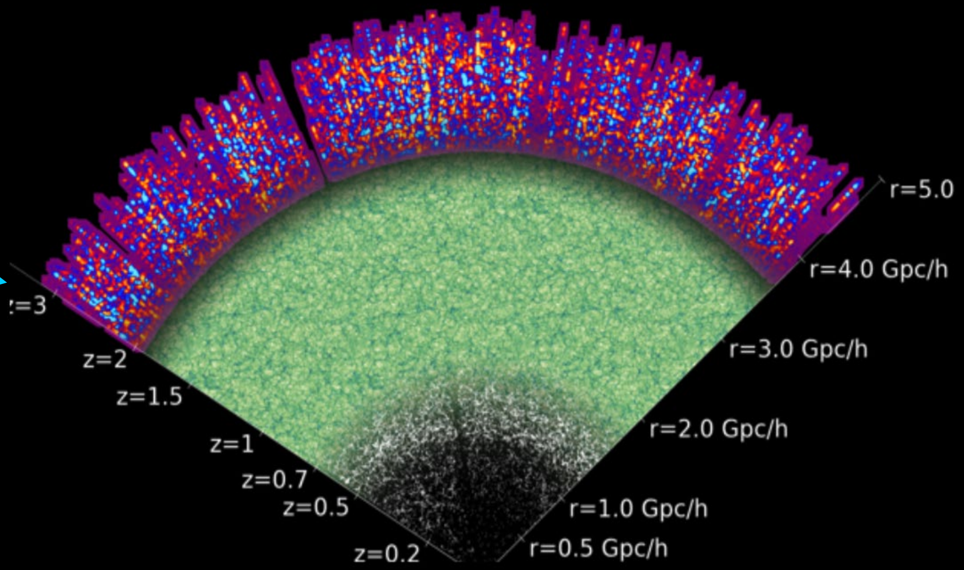
Extracting cosmology with a high-fidelity simulation-informed galaxy models

AbacusSummit → Hydro sim.-informed model → Constraining growth of structure, modified gravity, dark energy



MillenniumTNG!

Galaxy observations from DESI/*Euclid*



Aided by the capabilities of *Perlmutter*

Candidates: Lagrangian Deep Learning (Dai & Seljak, 2020), Semi-analytic models (Hadzhiyska+, 2021f)

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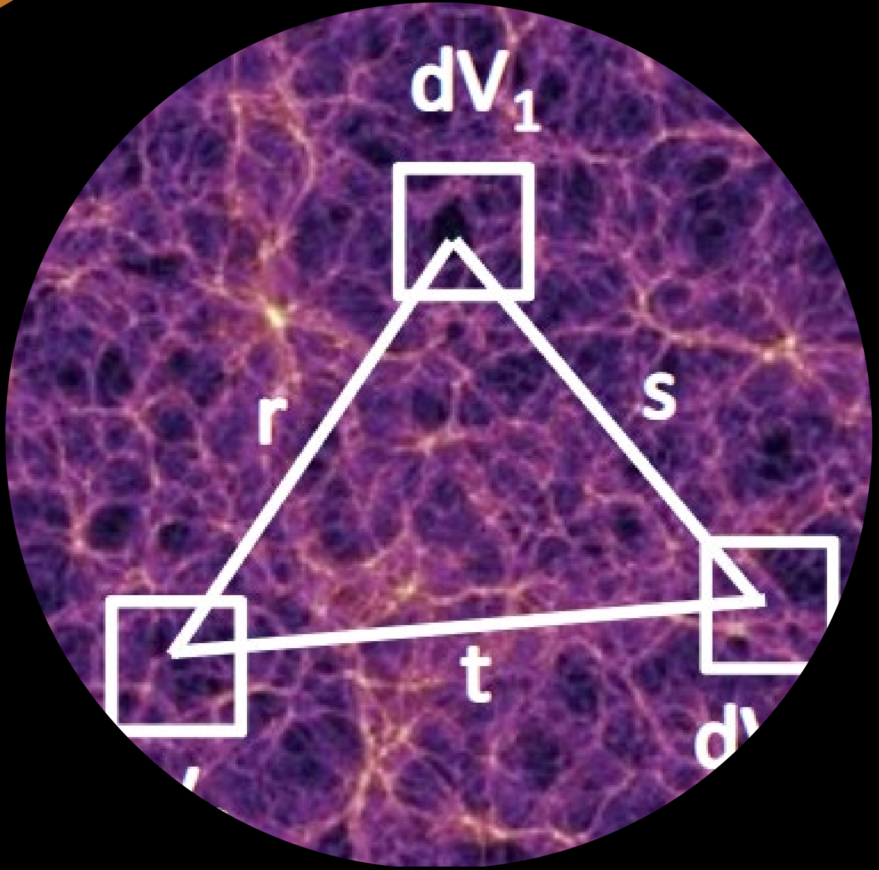
Constraining non-Gaussianities with non-standard statistics

Motivation: Many works have shown theoretically that alternative statistics (higher-order statistics, voids, nearest-neighbor, etc.) can constrain inflationary models, but systematics in real observations are a problem.

I propose a strategy to apply those in practice:

1. Test observational effects on the Abacus light cones
2. Develop a fast emulator that predicts these statistics
3. Measure them on galaxy data from redshift surveys
4. Constrain primordial non-Gaussianities with DESI

Banerjee & Abel 2020



Beyond redshift surveys: Synergies between CMB and large-scale structure

CMB (ACT, CMB-S4), spectroscopic/photometric surveys (DESI, Rubin)

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So far, I have...

- Applied novel models to joint analysis of photometric surveys & CMB
- Developed a CMB lensing estimator optimal on very small scales

Hybrid Effective Field Theory (HEFT)

- Expansion of galaxy field via Lagrangian Perturbation Theory

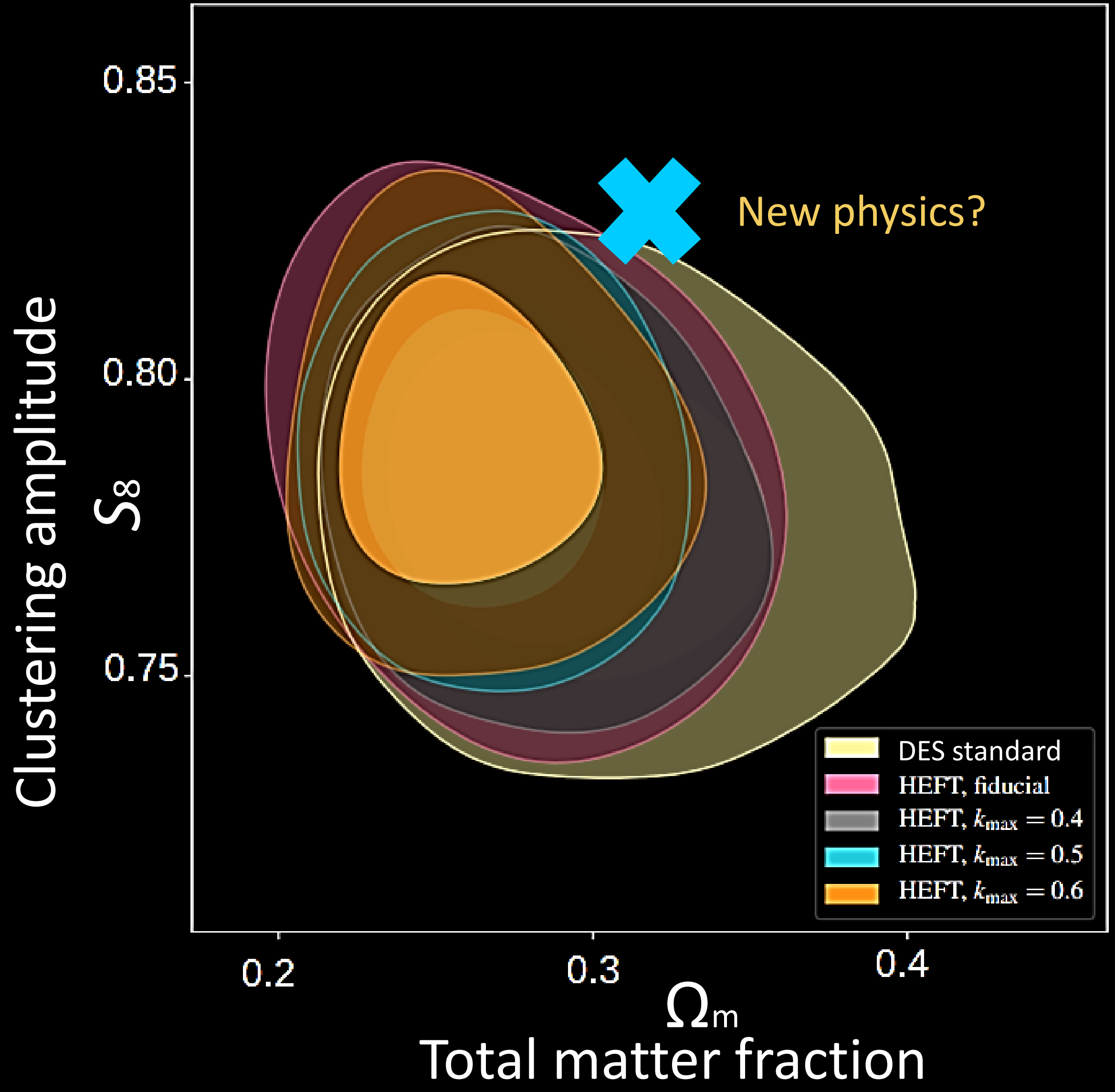
$$1 + \Delta_{g,L} = 1 + b_1\delta_L + b_2(\delta_L^2 - \langle\delta_L^2\rangle) + b_s(s_L^2 - \langle s_L^2\rangle) + b_\nabla \nabla^2\delta_L$$

- Advection from Lagrangian to Eulerian done via simulations

$$1 + \Delta_g(\mathbf{x}) = \int d^3\mathbf{q}\,[1 + \Delta_{g,L}(\mathbf{q})]\,\delta^D(\mathbf{x} - \mathbf{q} - \Psi(\mathbf{q}))$$

- We reanalyzed Dark Energy Survey (DES) Year 1 data and found improved cosmological constraints
- Ongoing work testing tensions with CMB data from *Planck* (blue cross)

Modi+ (2020), Hadzhiyska+ (2021a)



Large-scale structure (LSS) & CMB:
Going forward, I will...

- Combine galaxy-halo and EFT approaches to constrain neutrino mass
- Constrain baryonic effects and cluster mass from DESIxACT data
- Develop CMB lensing reconstruction tools for CMB-S4

So far, I have...

- Applied novel models to joint analysis of photometric surveys, CMB
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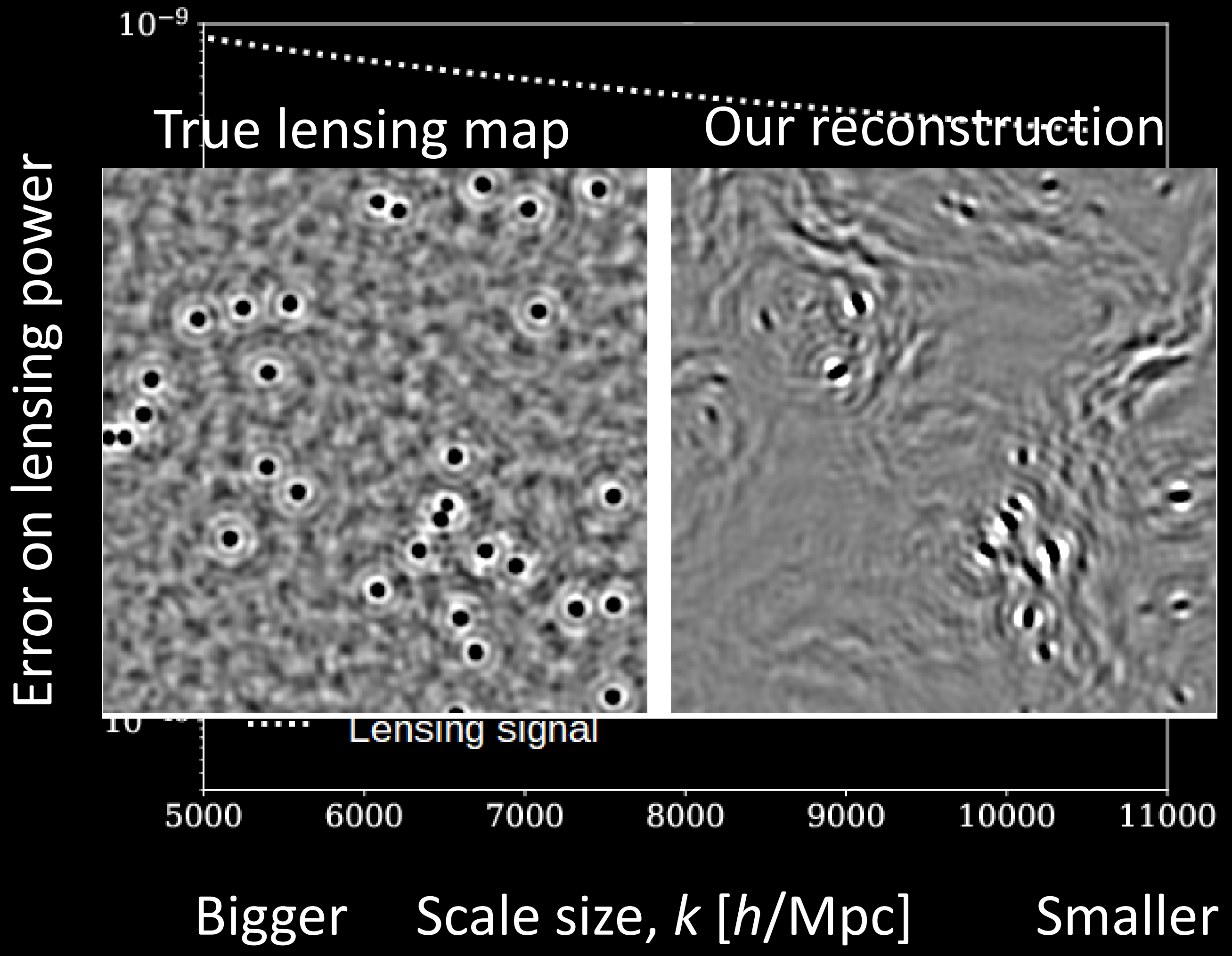
CMB lensing in the small-scale regime

- CMB-S4 will make high-resolution maps, allowing us to measure very small scales, sensitive to neutrinos and DM
- On these scales, the standard (quadratic) lensing estimator is suboptimal
- Along with S. Ferraro & B. Sherwin, developed a new estimator, outperforming the standard in that regime
- But… the search continues

Millea+ (2020)



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- Combine galaxy-halo and EFT approaches to analyze CMBxDESI
- Develop CMB lensing reconstruction tools for CMB-S4
- Constrain baryonic effects and cluster mass from DESIxACT data

In order to unlock information from CMB experiments, we need to understand foregrounds such as the Sunyaev-Zel'dovich effect

… which also offers a wealth of information

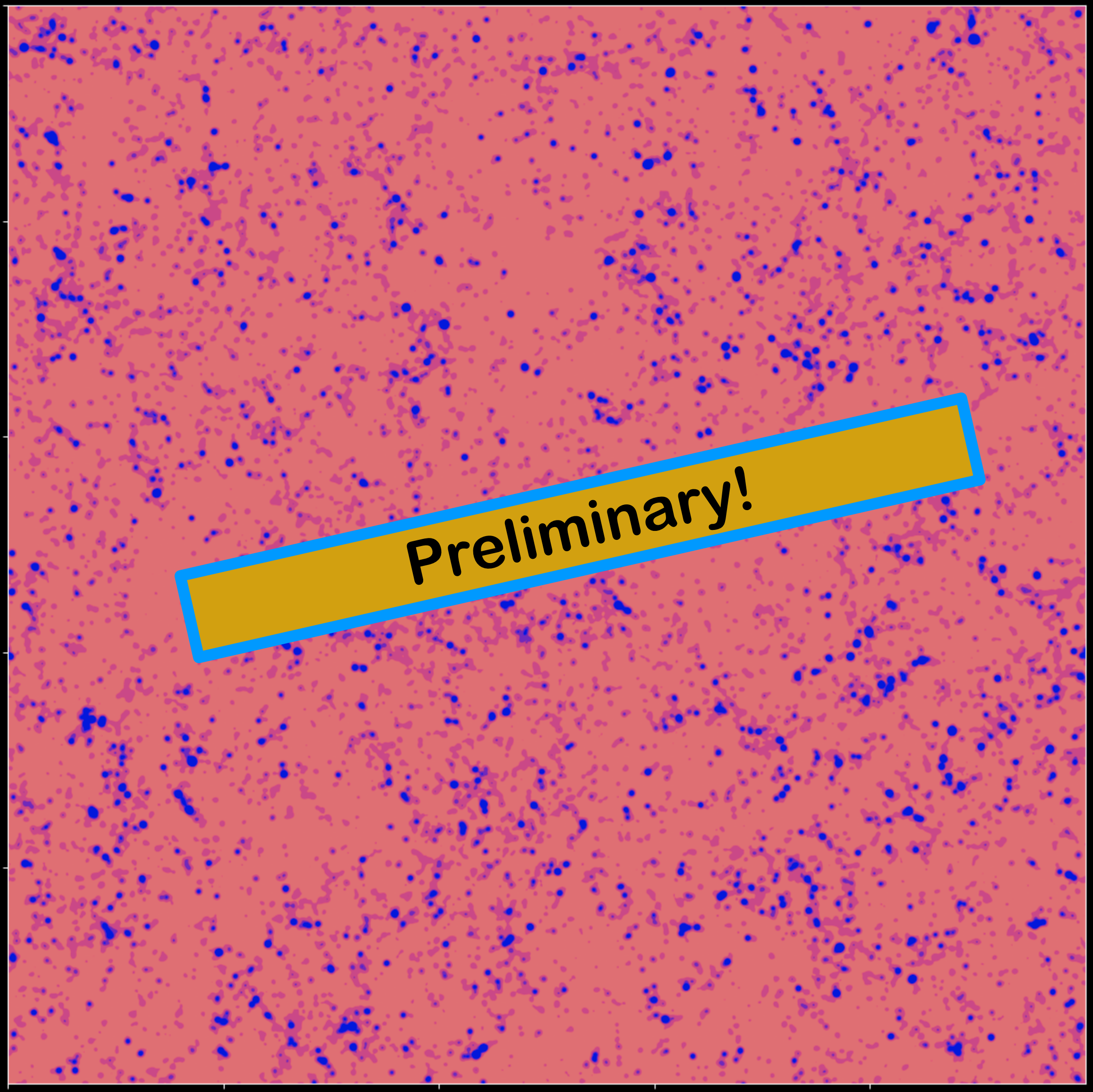
Large-scale structure & CMB:
Going forward, I will…

- Combine galaxy-halo and EFT approaches to analyze CMBxLSS
- Develop CMB lensing reconstruction tools for CMB-S4
- Constrain baryon effects and cluster mass using Sunyaev-Zel’dovich

Constraining baryons w/ Sunyaev-Zel'dovich

- Results from the scatter of CMB photons off electrons in galaxies
- Probes the baryon profile of clusters and their masses, providing a powerful probe of cosmology
- Can also be used to correct weak lensing measures ("Lensing is low") and study baryon systematics (Ly-α)
- Can disentangle neutrino and dark matter from baryonic effects
- Thanks to DESIxACT MoU and MTNG, I will provide constraints on baryonic feedback and inform simulations

Simulated map of Sunyaev Zel'dovich



Amodeo & ACT Collab. (2020)

Summary

- The next decade will see a surge in the volume of cosmological data
- I have developed essential tools for robust and unbiased analysis:
  - Galaxy-halo modeling
  - Cosmological simulations (AbacusSummit, MTNG)
  - Effective field theory and applications to weak lensing
  - Photometric uncertainties and systematics
  - CMB lensing and cross-correlations with galaxies
- The unique resources of LBNL in combination with these tools will allow us to recover the missing pieces in our cosmological model!

☺ ☺ ☺ Thank you for attending ☺ ☺ ☺