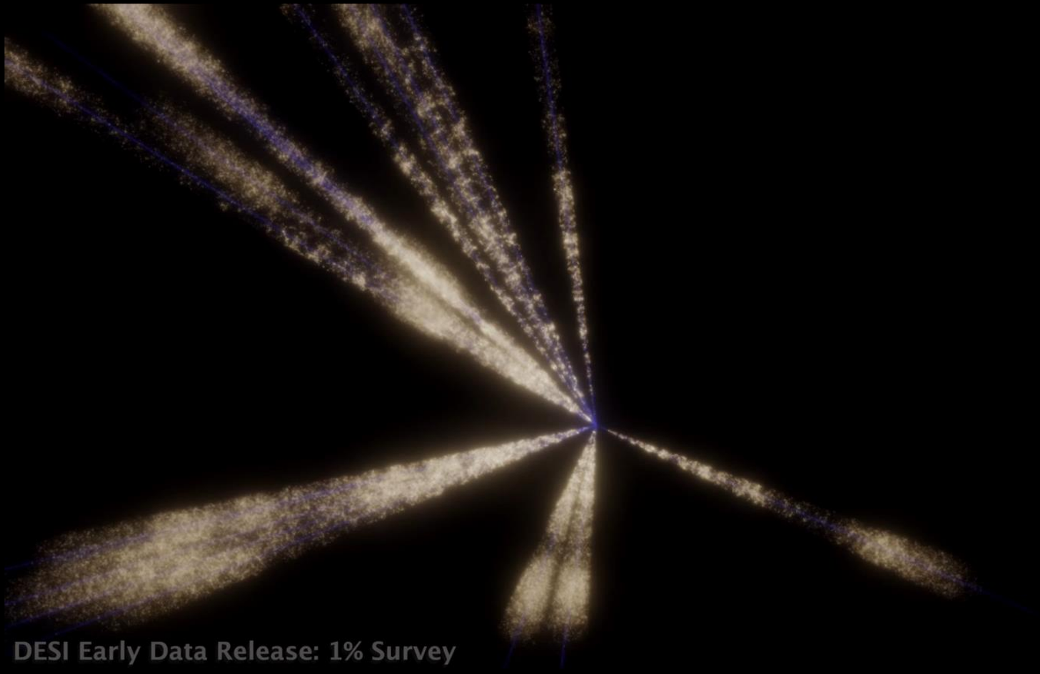


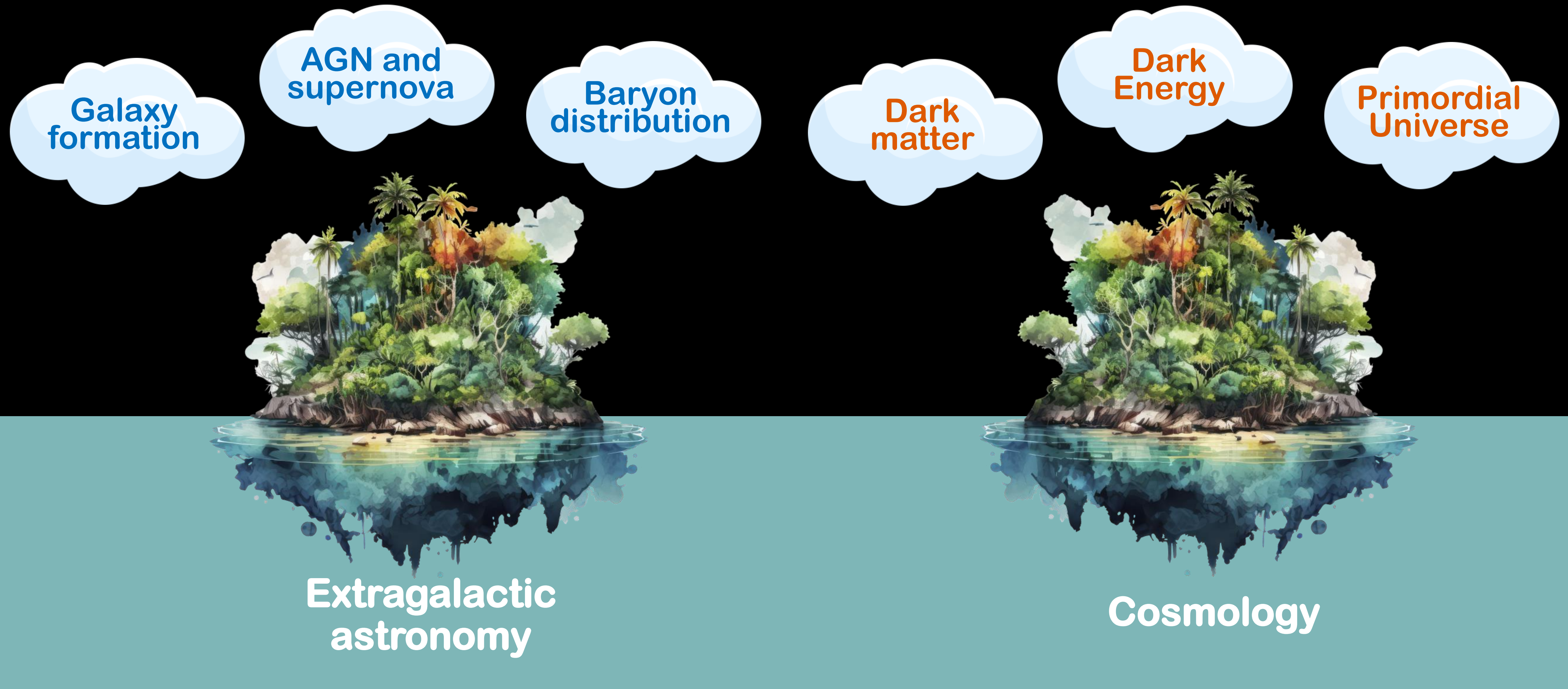
Solving big-scale problems with small-scale physics

Boryana Hadzhiyska

UC Berkeley, Berkeley Lab
Miller & Chamberlain
Postdoctoral Fellow

Colloquium, UC Berkeley

10/17/2024


Galaxy formation
AGN and supernova
Baryon distribution
Dark matter
Dark Energy
Primordial Universe
Extragalactic astronomy
Cosmology


Galaxy formation
AGN and supernova
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Gas (baryon) physics

Galaxy-halo connection

Why care about the baryons (gas) in the Universe?

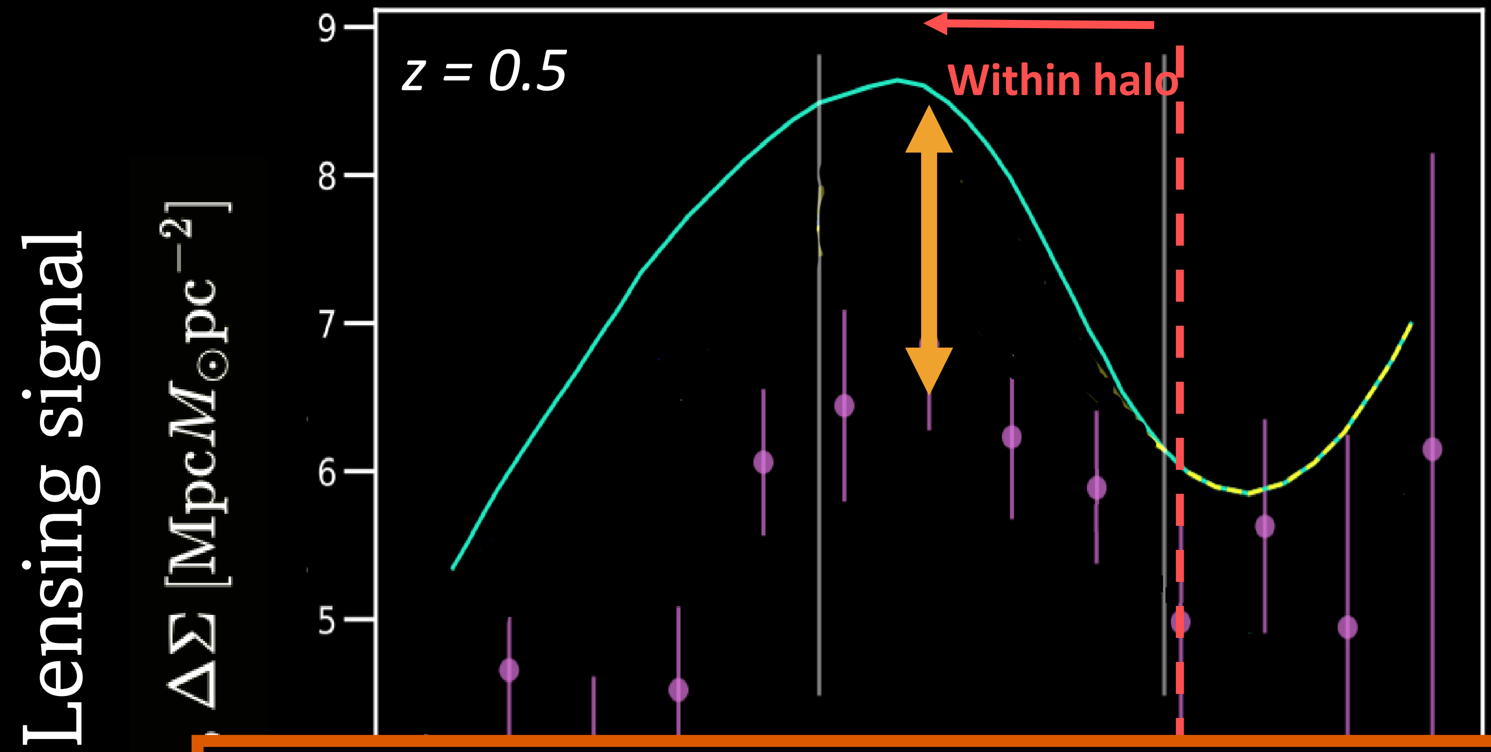
Important in astronomy:

- Inventorying baryons in the Universe (‘missing baryons’)
- Understanding AGN/SN feedback

Important in cosmology:

- Effect on gravitational lensing
- Calibrating cluster masses
- Key to unraveling dark energy, dark matter, neutrinos, etc.

"Lensing is low" tension



Could gas feedback explain the tension?

Leauthaud+ 2017

Ways of measuring gas density

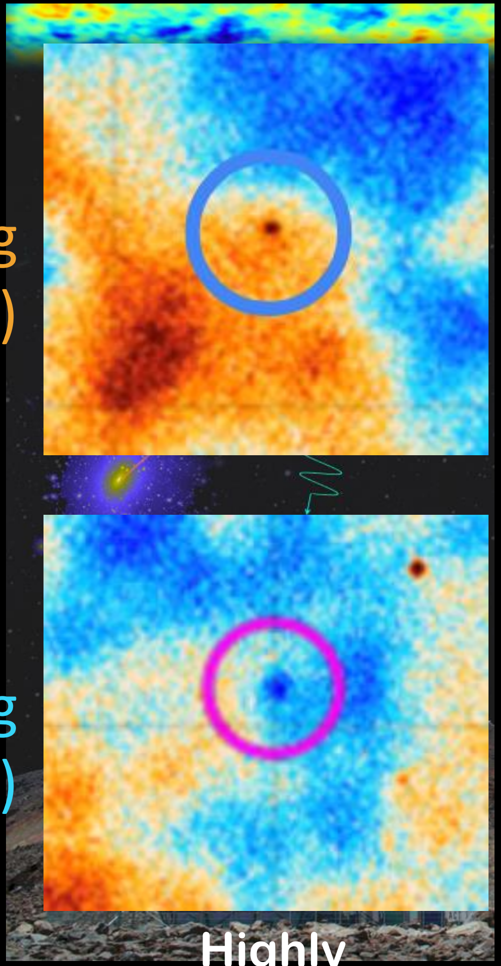
Many quantities sensitive to baryons:

- tSZ, kSZ, X-ray, FRBs, metal lines

Most of them are complicated!

kSZ: scattering of CMB photons off gas in moving galaxy groups and clusters

Cluster moving towards us (+)



Cluster moving away (–)

Highly exaggerated

kSZ is the most promising probe for measuring the gas density*!

Why is the kSZ effect special?

From CMB

$$\frac{T_{\rm kSZ}}{T_{\rm CMB}} = \tau_{\rm halo} \frac{v_{\rm halo}}{c}$$

From galaxy distribution

"Optical depth" =
direct measure of gas density

"Halo velocity" =
key to gravity, dark energy

Astrophysics x Cosmology

Robust to additive contaminants (dust, infrared emission)!

Clean probe of all the "missing baryons"!

Complementary to X-rays, tSZ

Detection of large baryonic feedback with kSZ effect via DESI and ACT

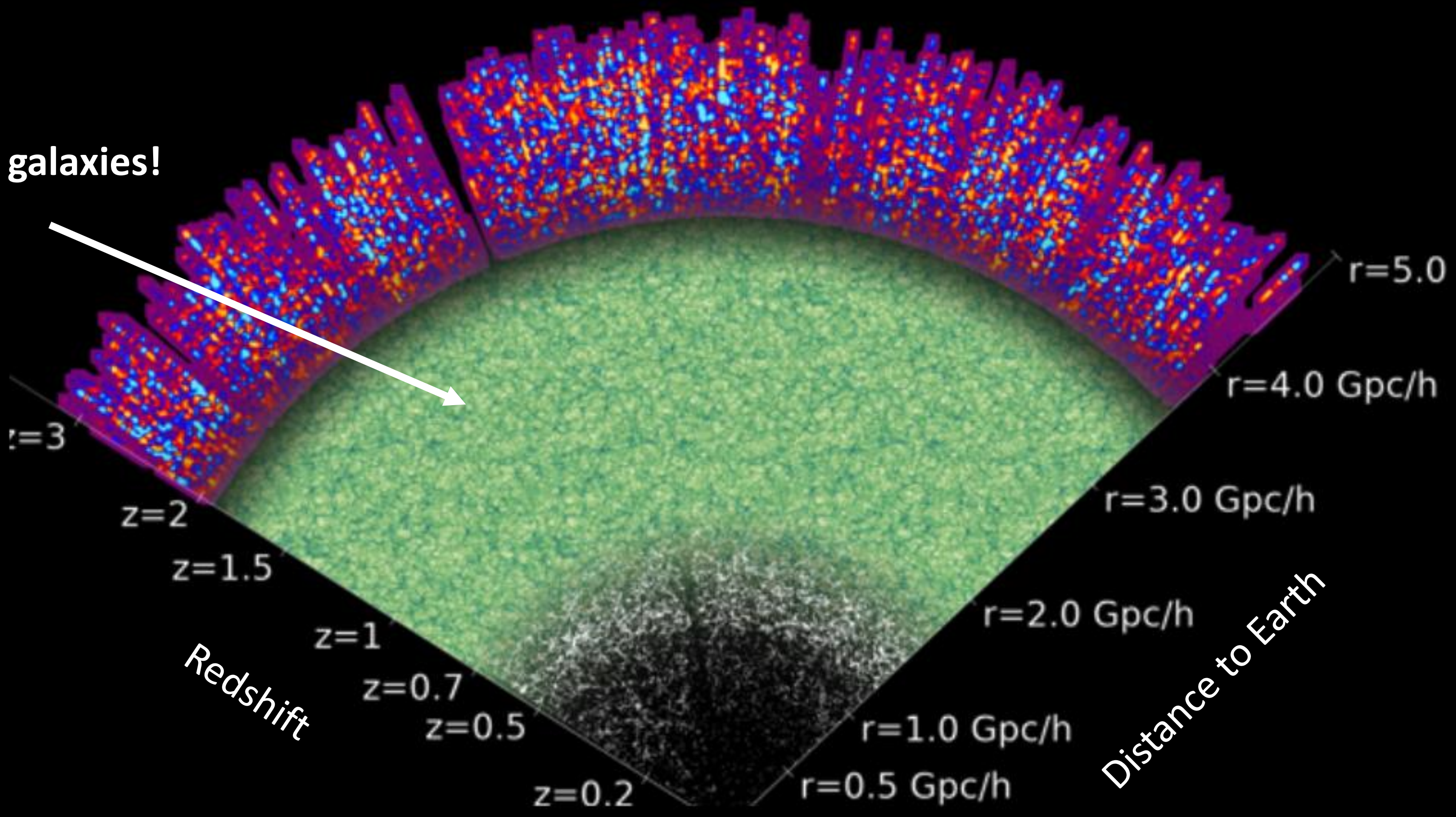
DESI: Galaxy survey experiment

ACT: CMB experiment

B. Ried H. Liu S. Ferraro E.Schaan

Spectroscopic galaxy surveys

Millions of galaxies!



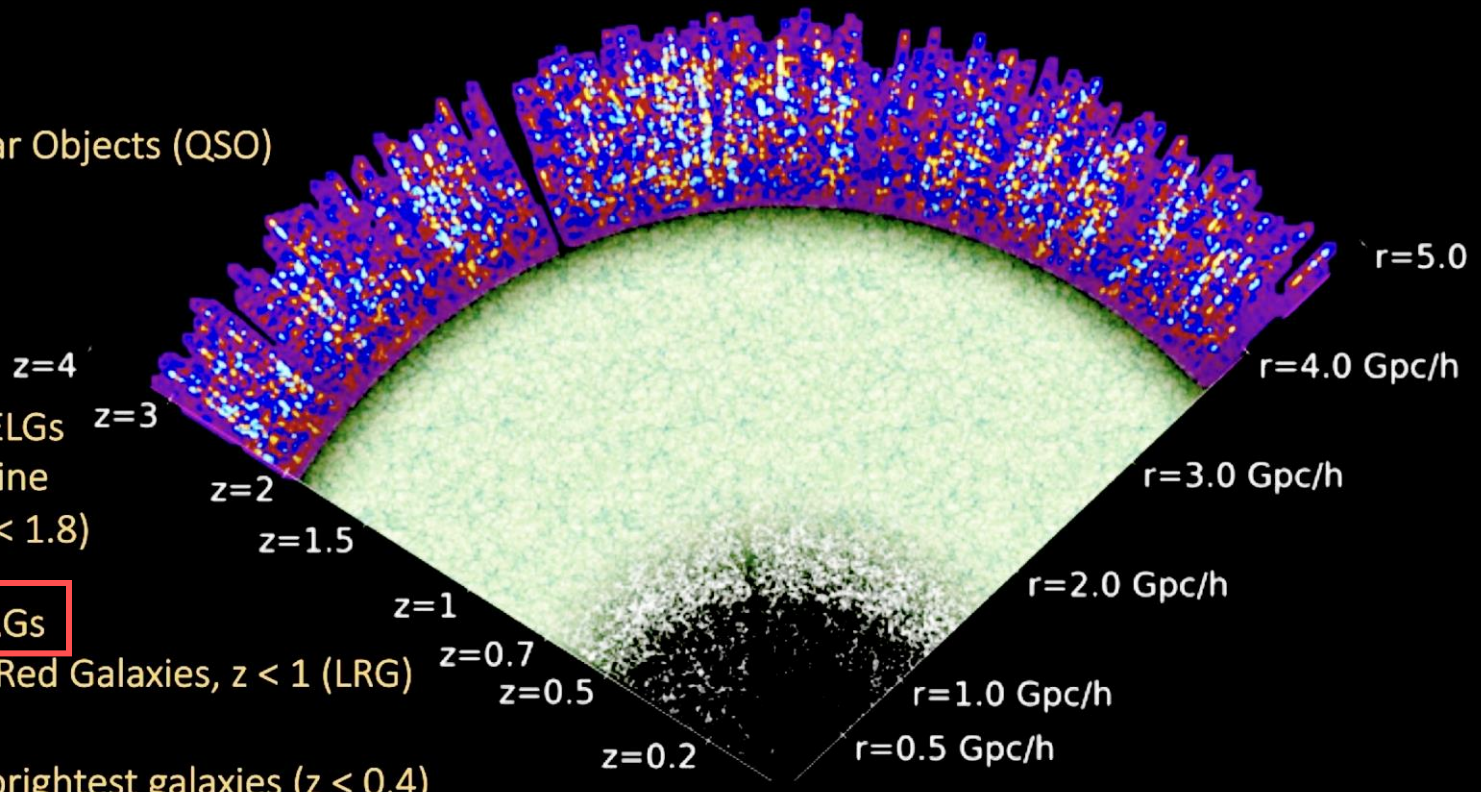
Dark Energy Spectroscopic Instrument (DESI)

$\gtrsim$ **2.7** million Quasi Stellar Objects (QSO)

$\gtrsim$ **13** million ELGs (Emission Line Galaxies, $z < 1.8$)

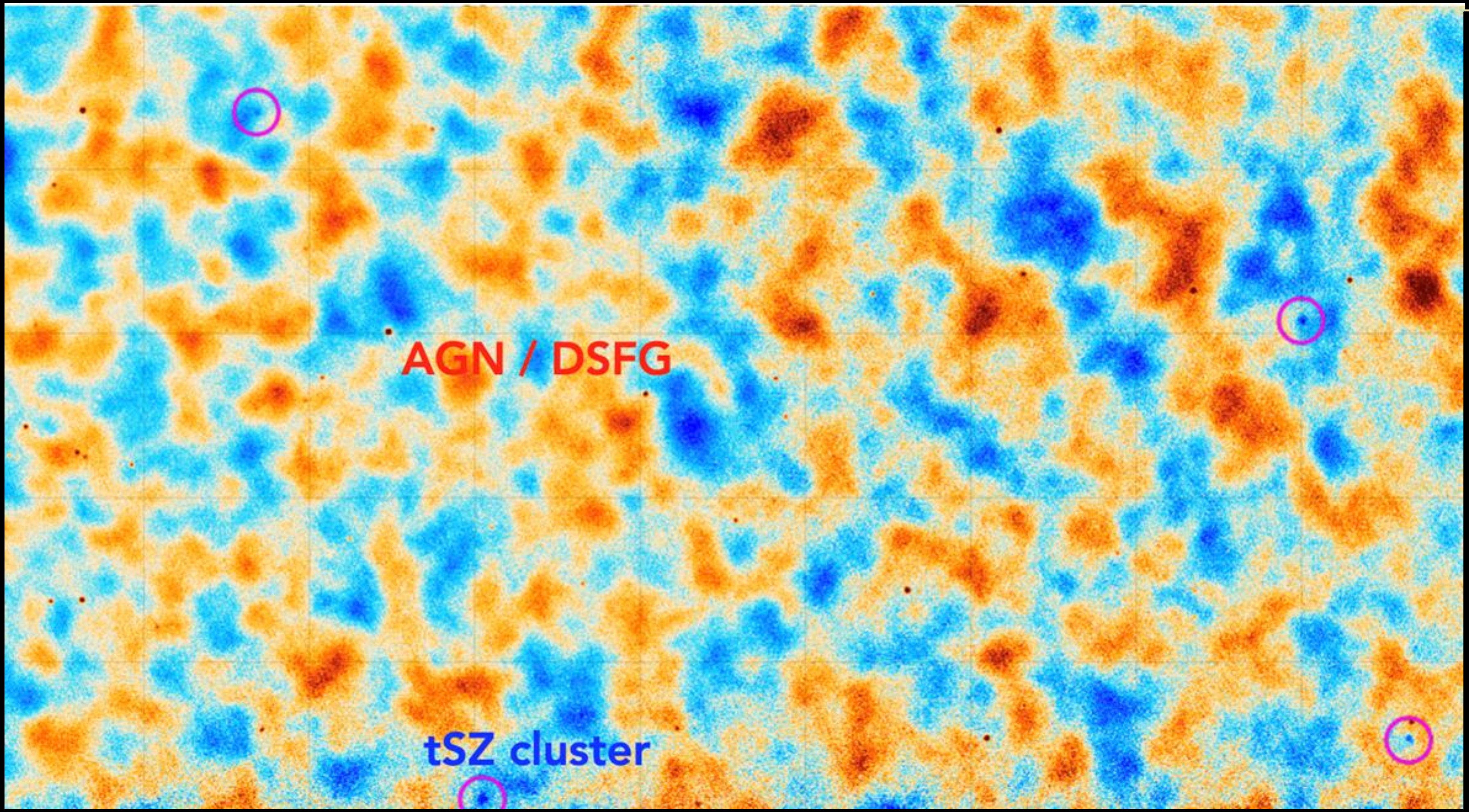
$\gtrsim$ **7.5** million LRGs (Luminous Red Galaxies, $z < 1$ (LRG)

$\gtrsim$ **9** million brightest galaxies ($z < 0.4$)



A factor of ~ 10 improvement compared with previous surveys (SDSS)!

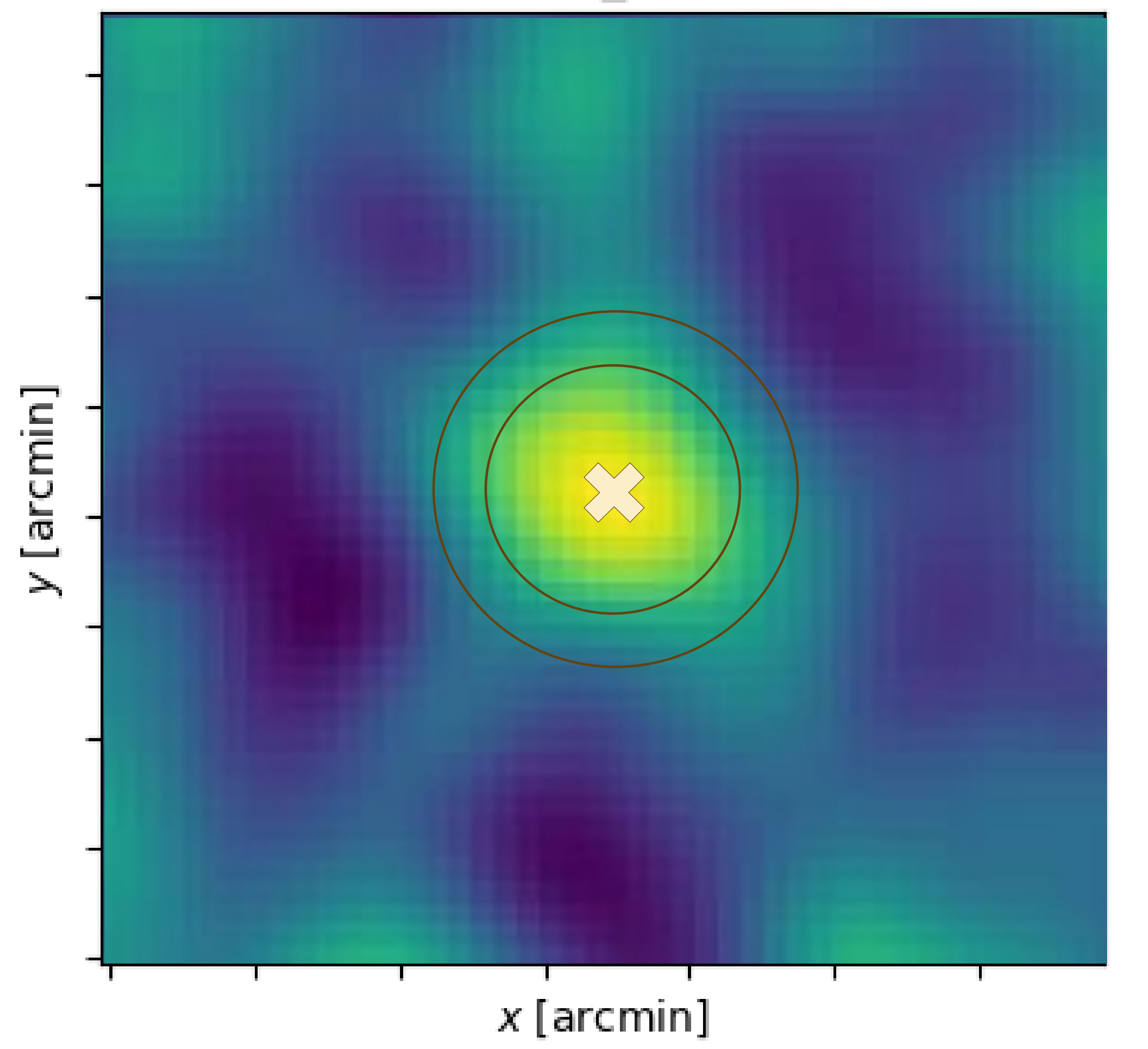
Atacama Cosmology Telescope (ACT) vs. *Planck*



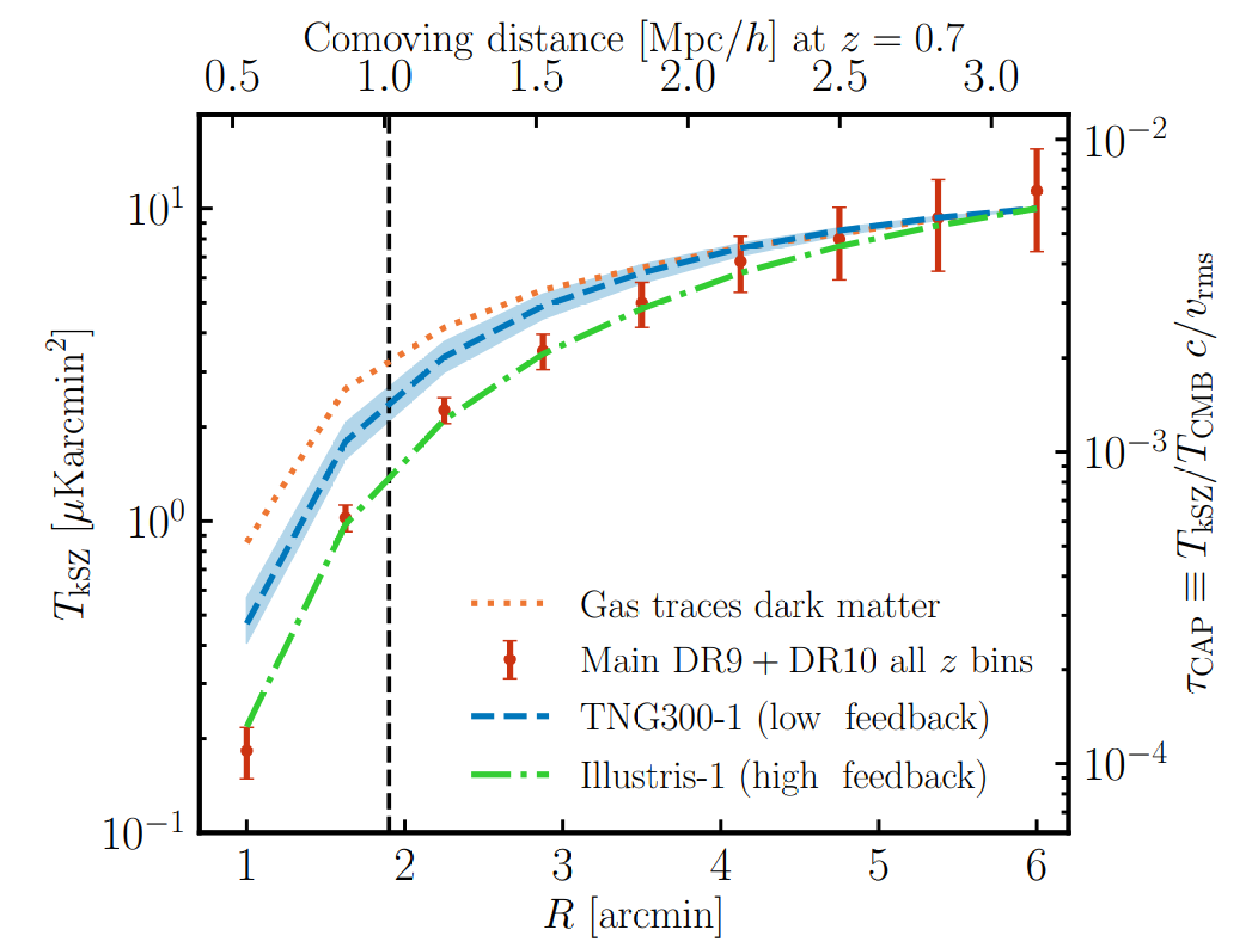
High-res
ACT

Gas feedback in the Universe appears to be strong!

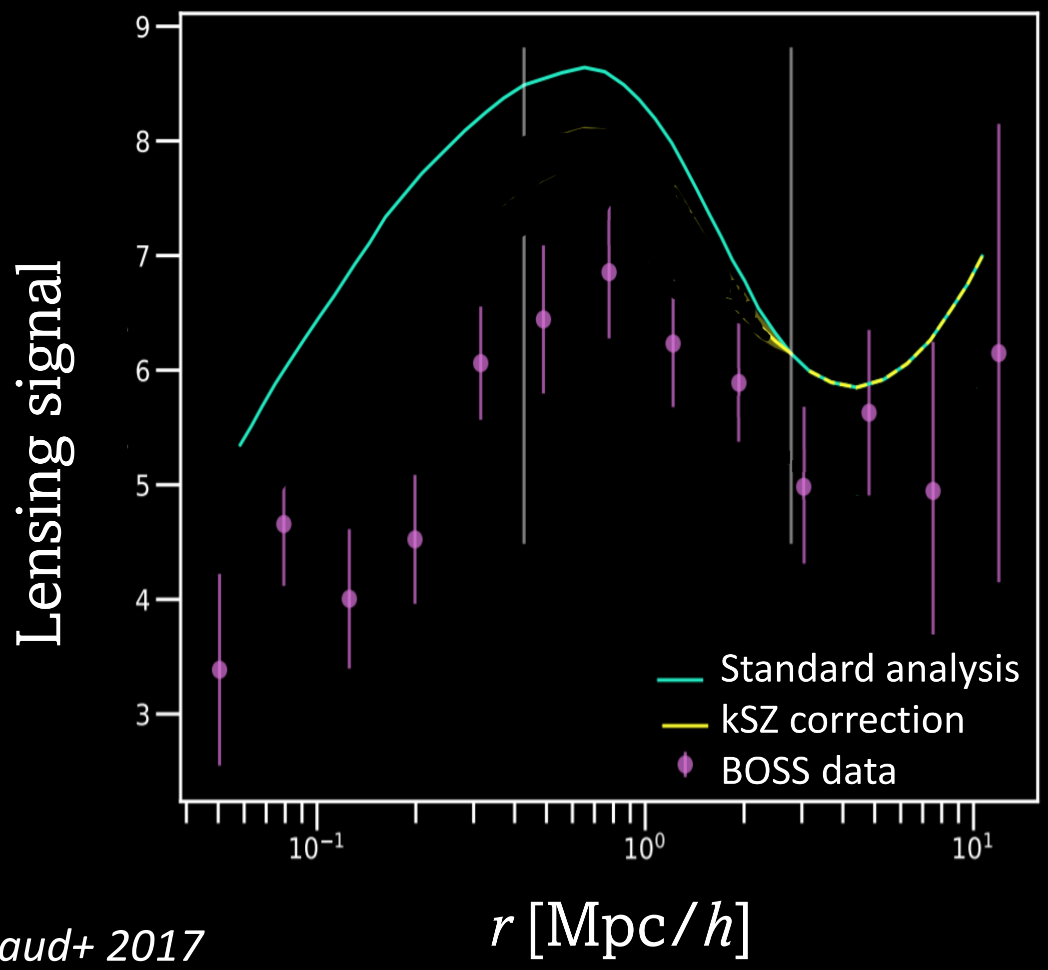
- Highest S/N to date (7.5 mln gals)!
- Large discrepancy between simulation and observations
- AGN feedback in sims is too weak (Hadzhiyska 2023)



Evidence for large baryonic feedback

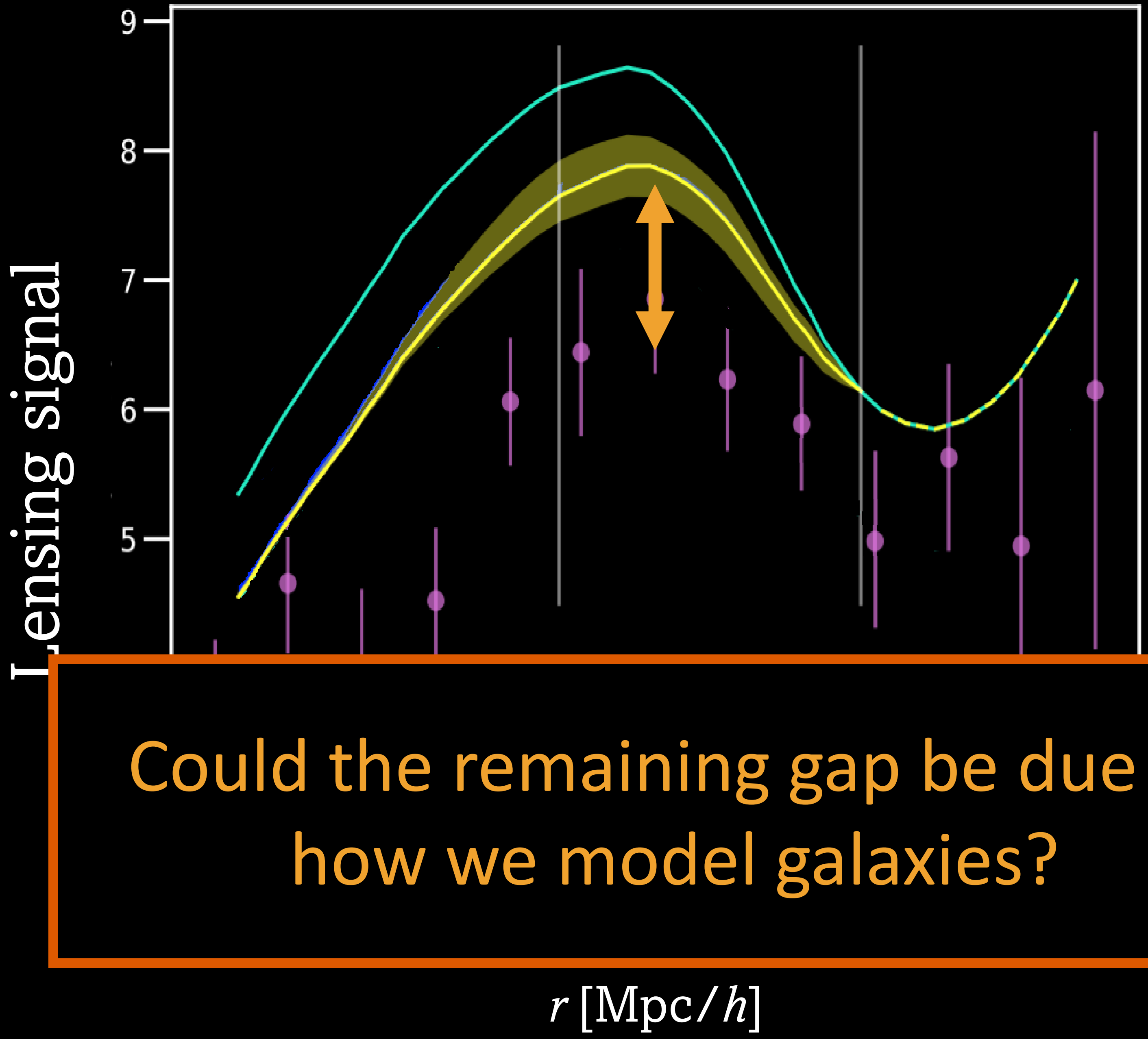


Gas distribution: major unknown in weak lensing



Leauthaud+ 2017
Amodeo & ACT Collab. (2020)

- Can it reduce the "Lensing is low" tension?
- Inevitable consequence of kSZ measurement
- Large feedback could explain "Low σ_8" tension, stay tuned!

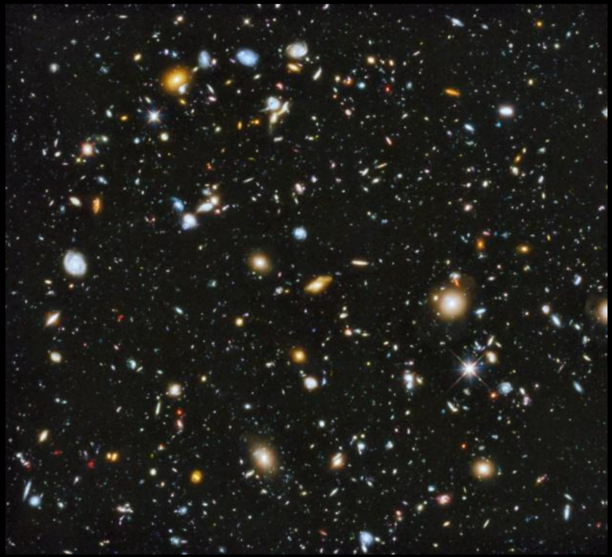


Could the remaining gap be due to how we model galaxies?

Gas (baryon) physics

Galaxy-halo connection

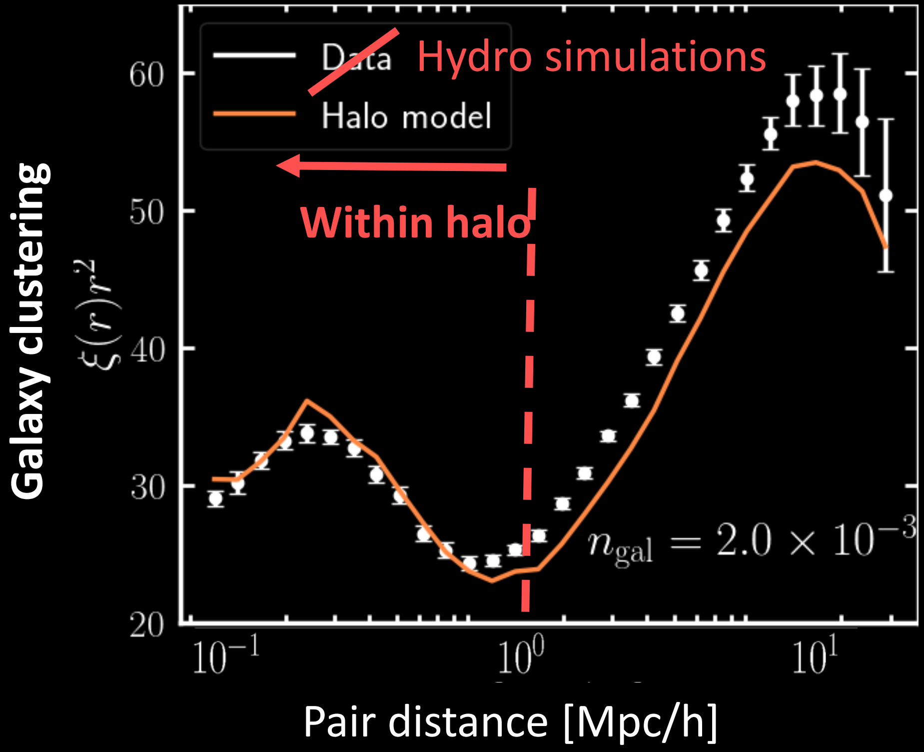
Importance of the galaxy-halo link in cosmology

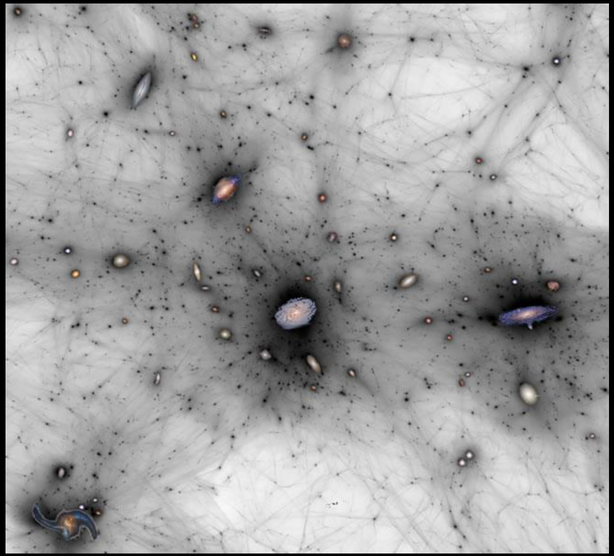


Galaxy distribution (survey)

Summary statistics (clustering)

- Is dark energy a cosmological constant?
- Is general relativity the correct theory of gravity?





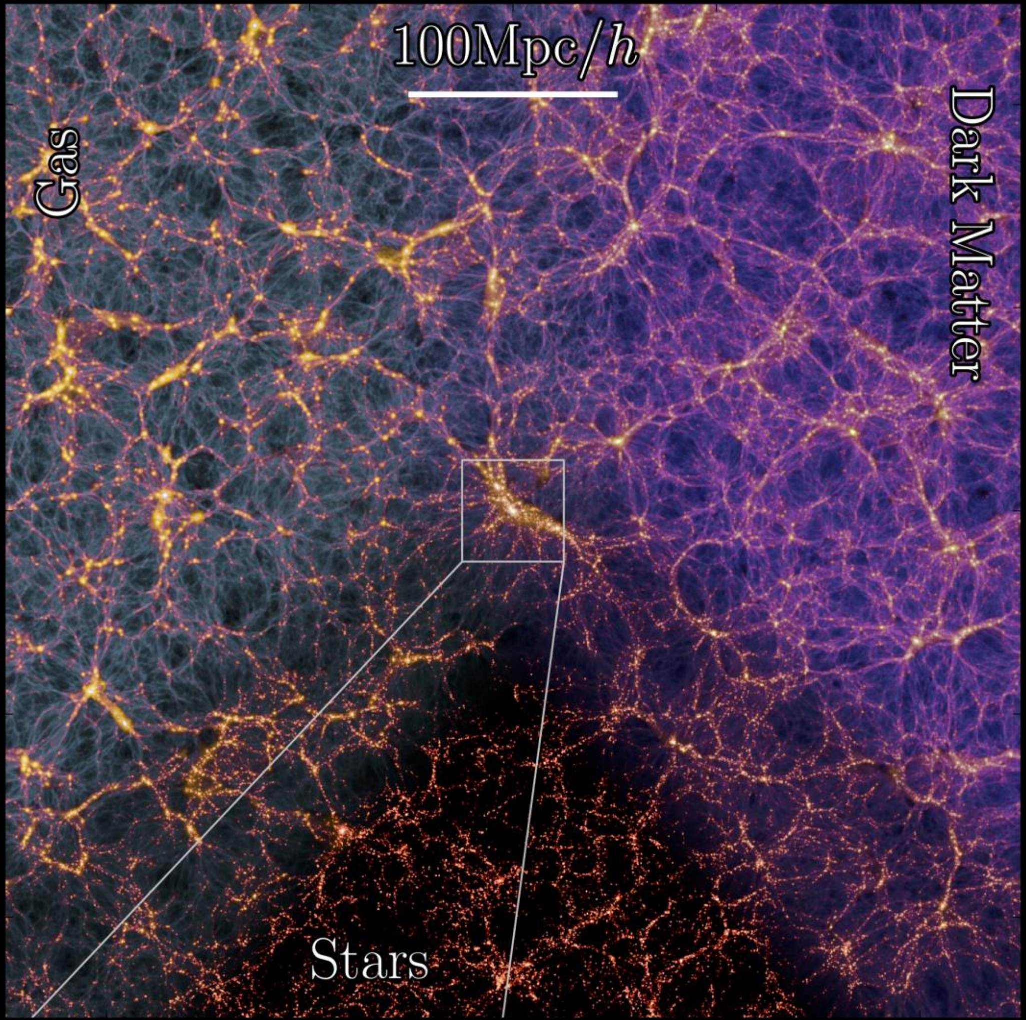
Galaxy-halo model on N-body sims (e.g., AbacusSummit)

Cosmological parameters

Adjust parameters until clustering matches!

Hydrodynamical simulations as plausible reality

MillenniumTNG



Core team of 8 people (incl. BH)
PI: V. Springel, L. Hernquist

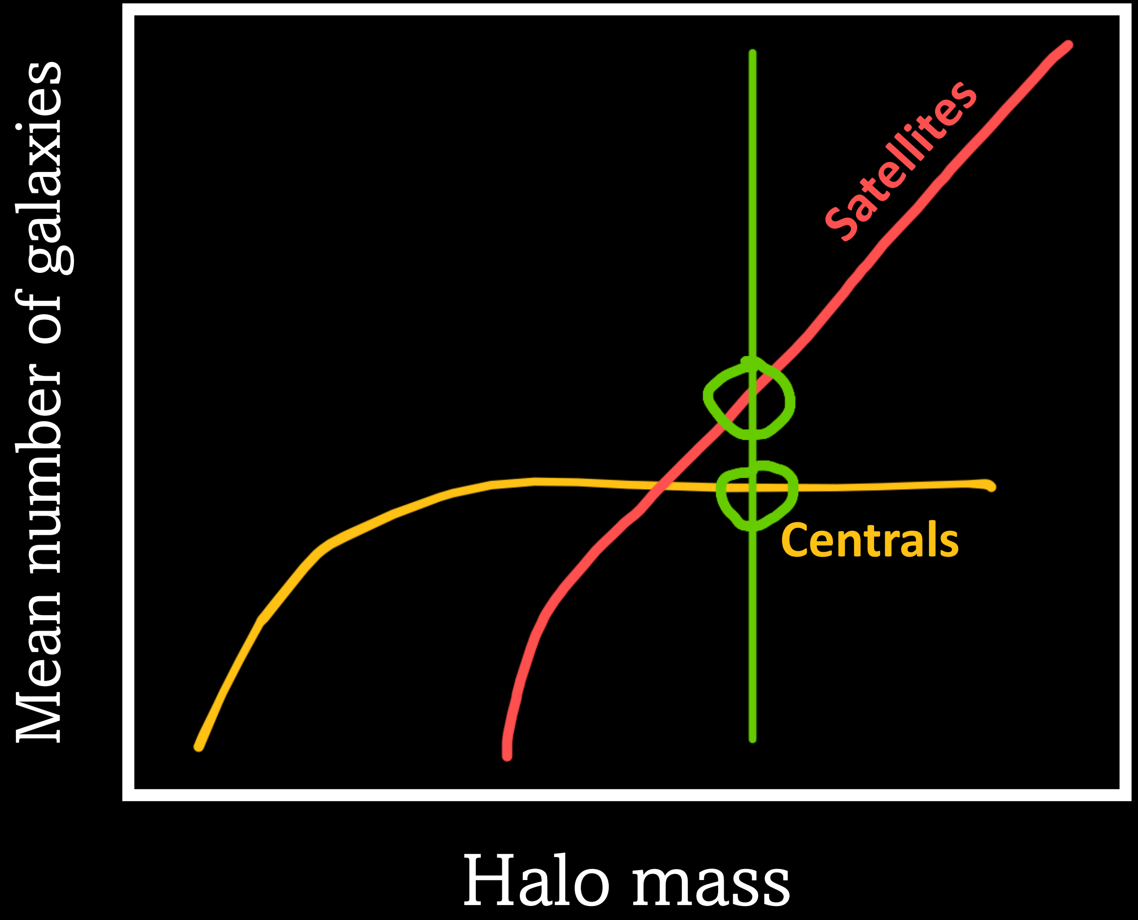
- Realistic large-volume hydrodynamical simulation
- Successfully predicts many observations (why not use in analysis?)
- Lets us test galaxy painting models on realistic data

Does modeling galaxy formation help cosmology and vice versa?

Example 1: Ignoring galaxy environments biases cosmology

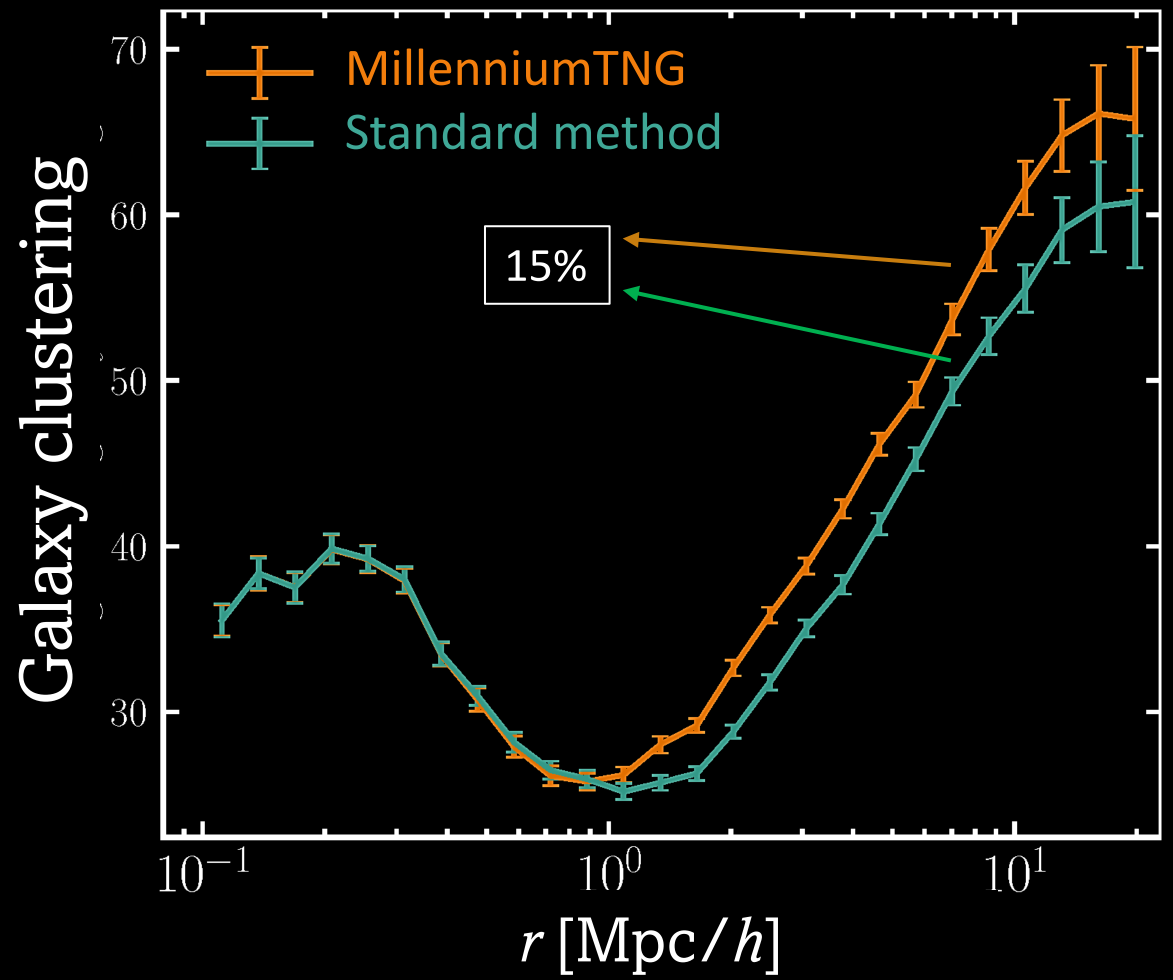
Example 2: Formation of blue galaxies as a cooperative process

Standard galaxy painting technique



- **Halo model: Number of galaxies depends on halo mass**

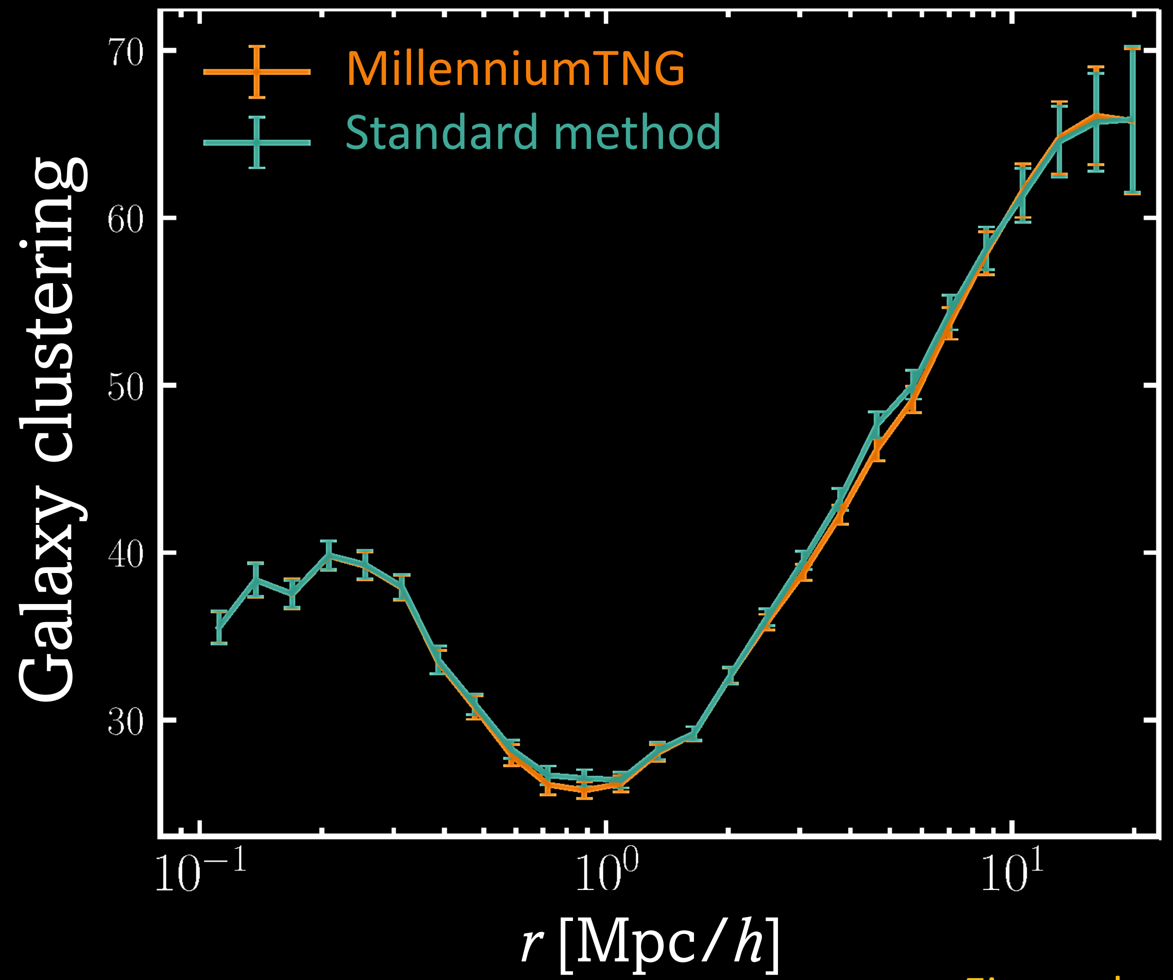
How does it square up against MTNG?



- Differs from MTNG "truth" by 15%
- Difference well above the subpercent precision of DESI
- If unaddressed, leads to bias in the inferred cosmology:
  - cluster mass
  - clumping of matter (σ_8)

Hadzhiyska 2020, Hadzhiyska, MTNG+ 2023a

What are the missing ingredients?



Hadzhiyska 2020, Hadzhiyska, MTNG+ 2023a

- Standard model treats halos in isolation
- In reality, they undergo: mergers, stripping, quenching…
- Can a simple dependence on environment help (assembly bias)?
- How does this bear in reality?

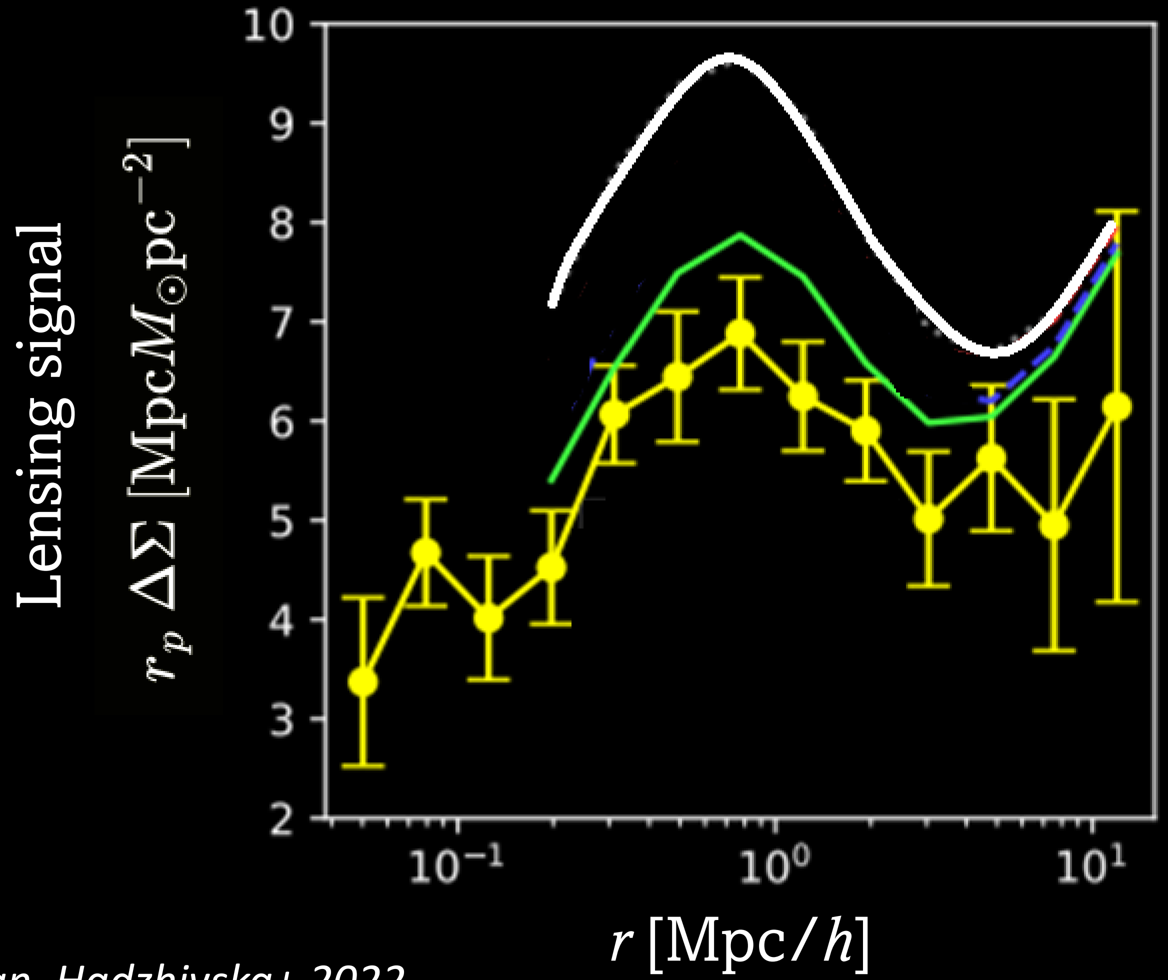
Amount of anisotropic pulling:

$$q_R^2 \equiv \frac{1}{2}\left[(\lambda_2 - \lambda_1)^2 + (\lambda_3 - \lambda_1)^2 + (\lambda_3 - \lambda_2)^2\right]$$

Eigenvalues of:

$$T_{ij} \equiv \partial^2 \phi_R / \partial x_i \partial x_j$$

Applied to “Lensing is low” problem



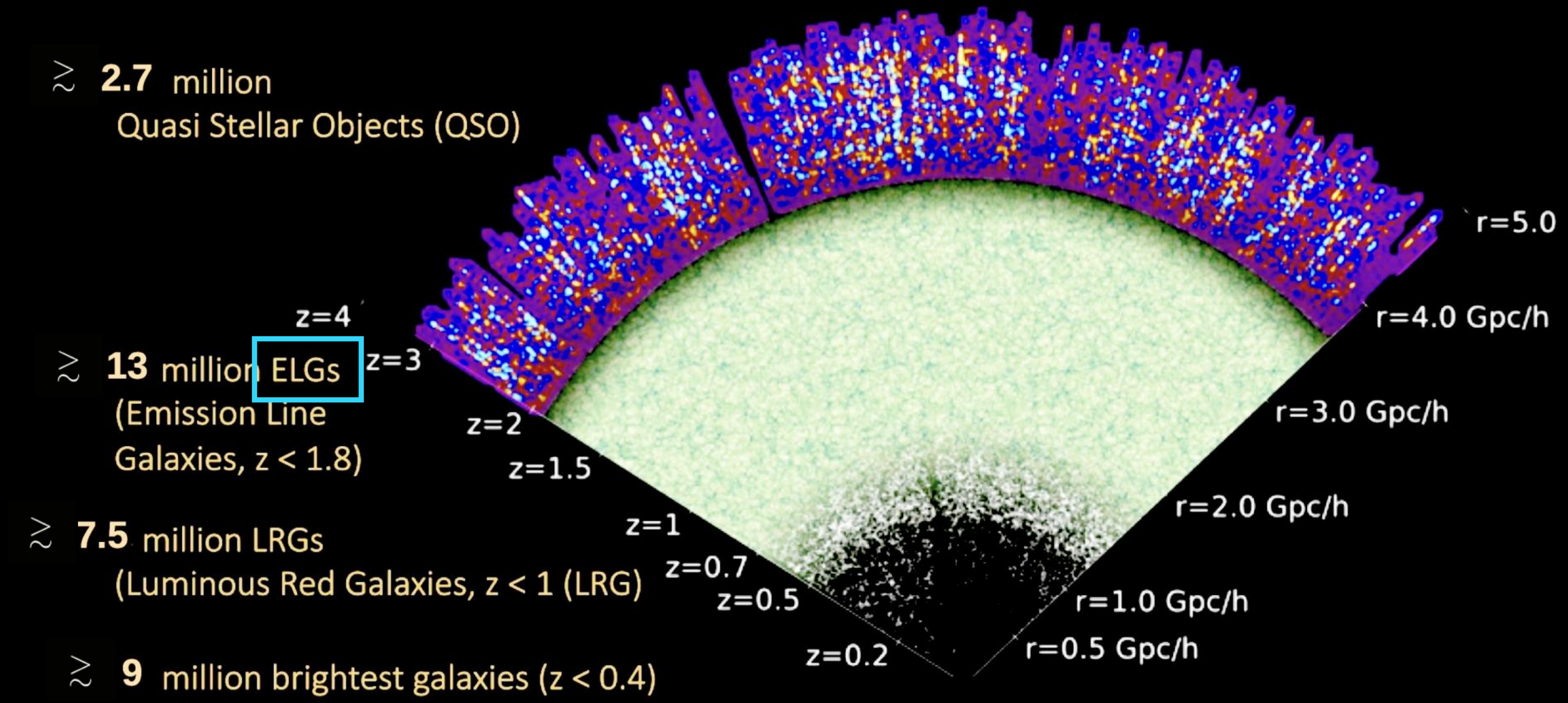
- Standard method
- BOSS data
- Our method (based on environment)
- Independently from baryonic effects reduces tension
- Ongoing joint efforts! Stay tuned

Yuan, Hadzhiyska+ 2022

How does modeling galaxy formation help cosmology and vice versa?

- Example 1: Ignoring galaxy environments biases cosmology
- Example 2: Formation of blue galaxies as a cooperative process

Blue galaxies: main target of DESI, *Euclid*, *Roman*

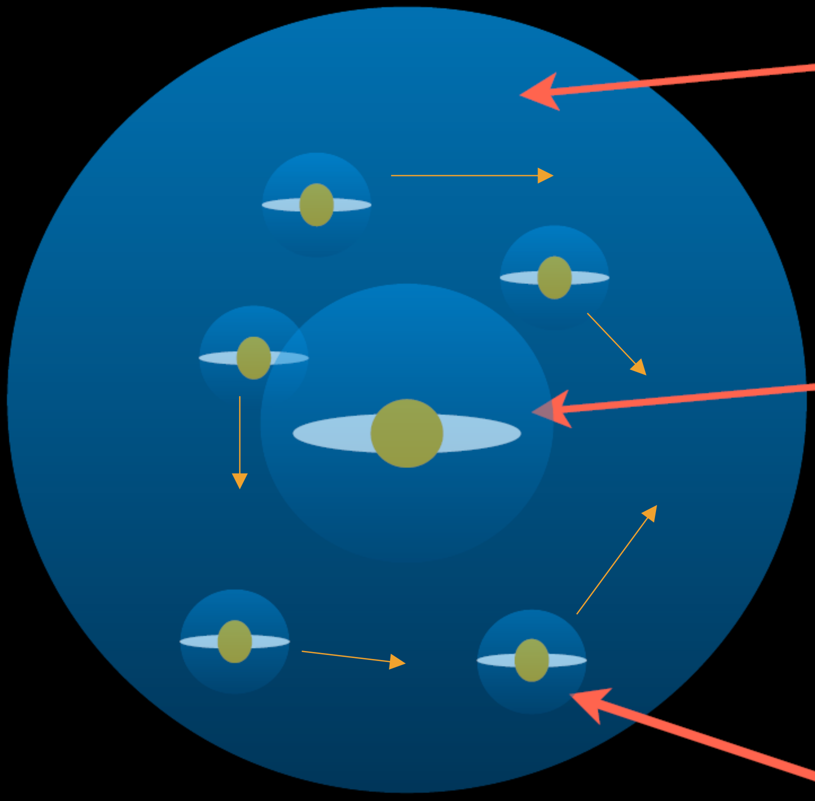


Despite huge number, emission-line galaxies (ELGs) vastly understudied!

Do assumptions about blue galaxies hold?

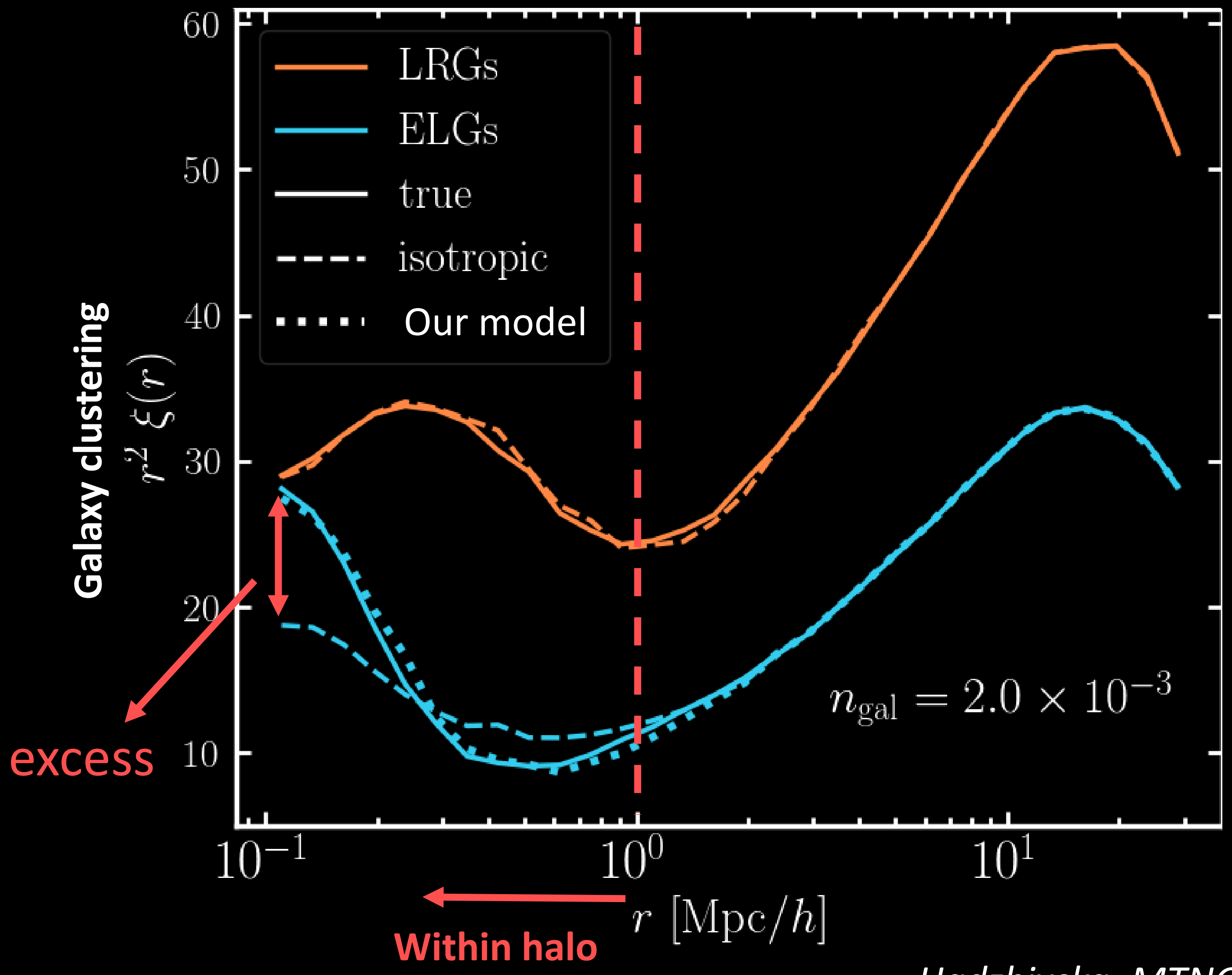
Standard assumptions:

1. # of satellites Poisson distributed
2. Centrals & satellite are independent
3. Satellites are distributed isotropically



Hadzhiyska, Tacchella+ 2022, Hadzhiyska 2023b

Are satellites isotropically distributed?

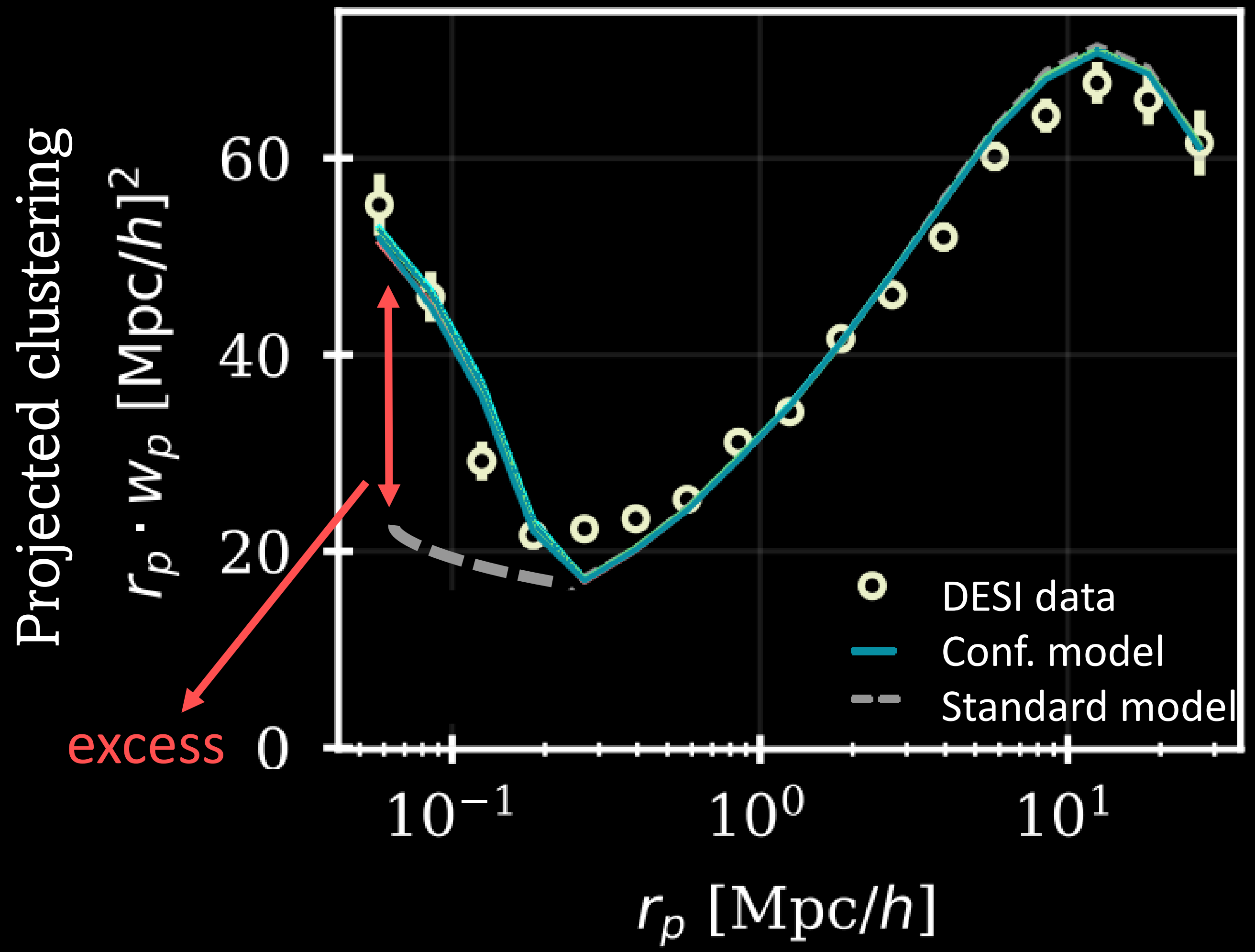


- Holds for red, but not for blue galaxies
- In fact, all three assumptions fail for blue
- What if we allow blue satellites to form doublets and triplets?

Hadzhiyska, MTNG+ 2023b

A couple of months later...

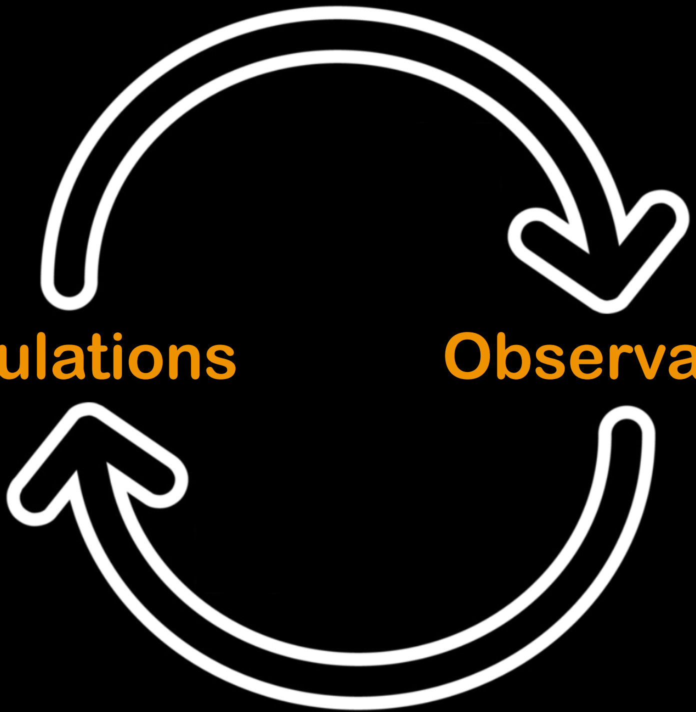
- "Conformity" observed in DESI!
- Sheds light on blue galaxy formation (ex-situ vs. in-situ)
- Allows us to calibrate simulation models



Rocher, DESI+ (incl. Hadzhiyska) 2023

Through intersectional work, we can probe cosmology and astronomy

interpret



MillenniumTNG
AbacusSummit

Simulations

Observations

DESI
ACT

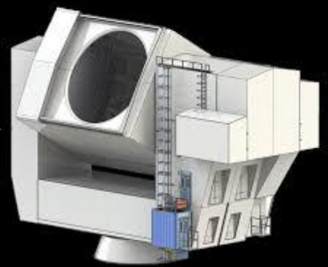
Anything else?

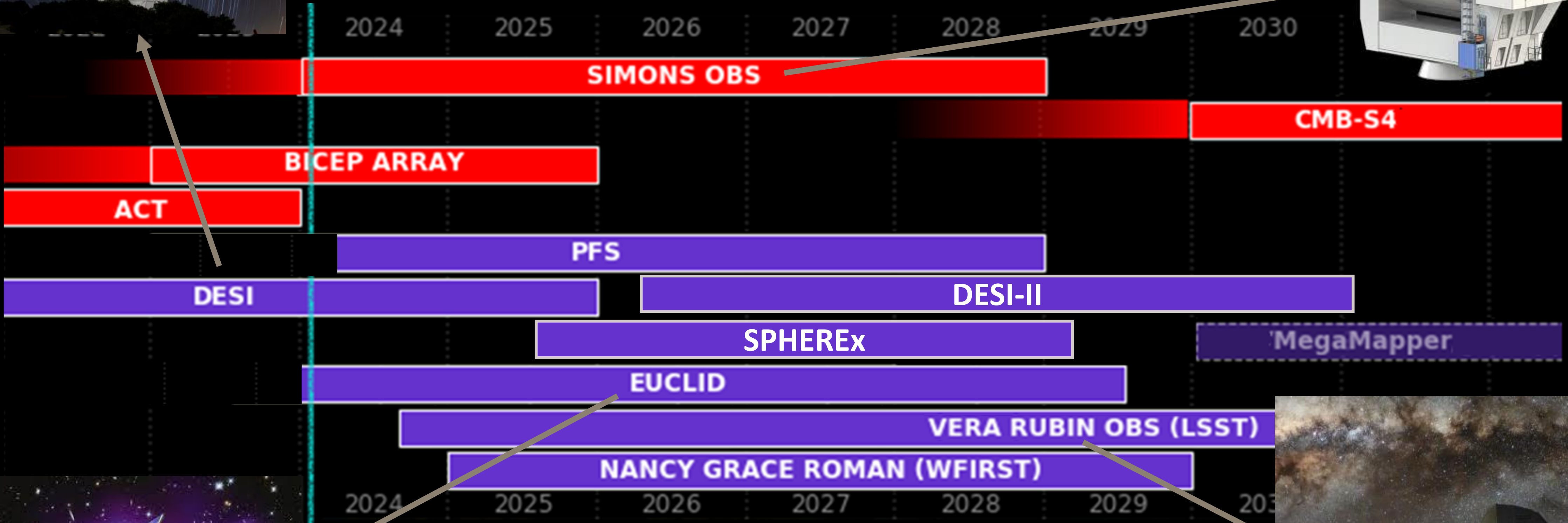
calibrate

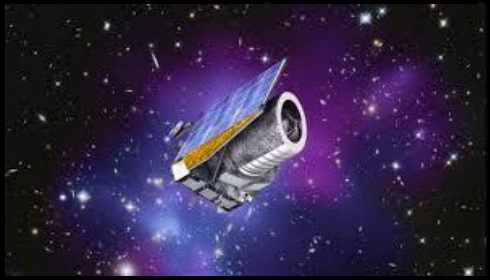
Why is *this* the age of multi-component cosmology?

Pinpoint equation of state of dark energy

First light in 2024!







10s of millions of observed spectra!

100s of millions of photometric galaxies: gas feedback, neutrinos

The better our measurements become, the more accurate our models need to be

Compelling path:

Simultaneous modeling of multiple observables

When perturbation theory meets AI

H. Liu

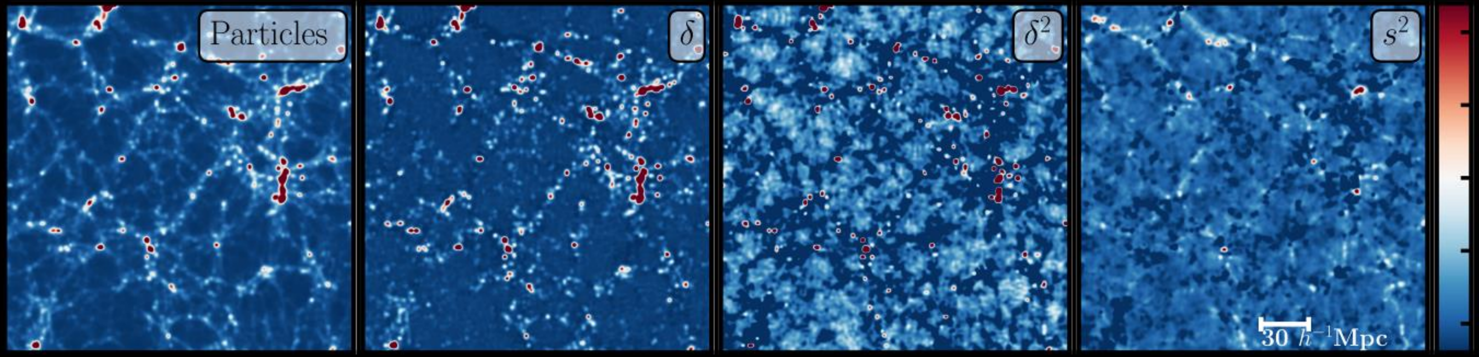
Compute all dark matter fields allowed from symmetry to 2nd order

- Galaxy distribution (Modi+ 2019, Hadzhiyska+ 2021)
- Gas & pressure density (kSZ, tSZ, X-rays, 21cm)
- AI on small scales ideally suited

$$F[\delta(q)] \approx 1 + b_1\delta(q) + b_2(\delta^2(q) - \langle\delta^2\rangle) + b_s(s^2(q) - \tfrac{2}{3}\langle\delta^2\rangle) + b_{\nabla^2}\nabla^2\delta(q) + \dots$$

LSS & CMB surveys:
Euclid, eROSITA, SO, Rubin, SPHEREx…

Advect to present day using gravity-only simulation

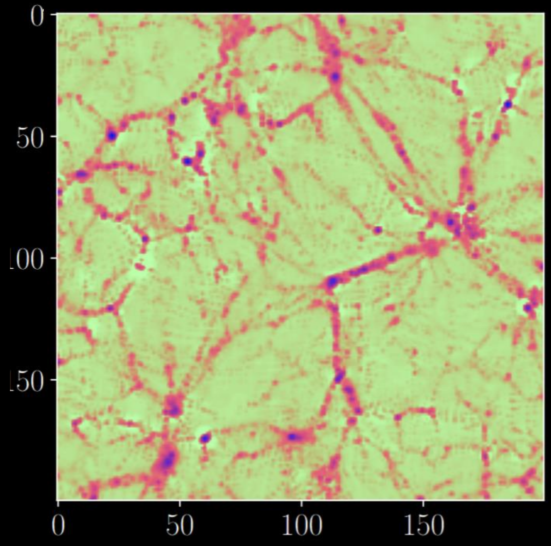


Credit: N. Kokron

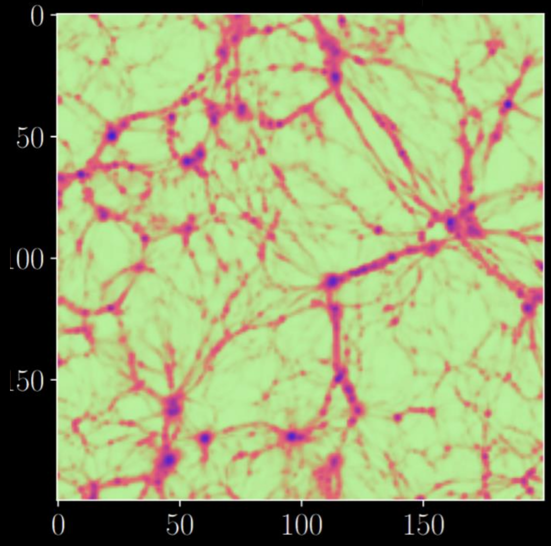
When perturbation theory meets AI

H. Liu

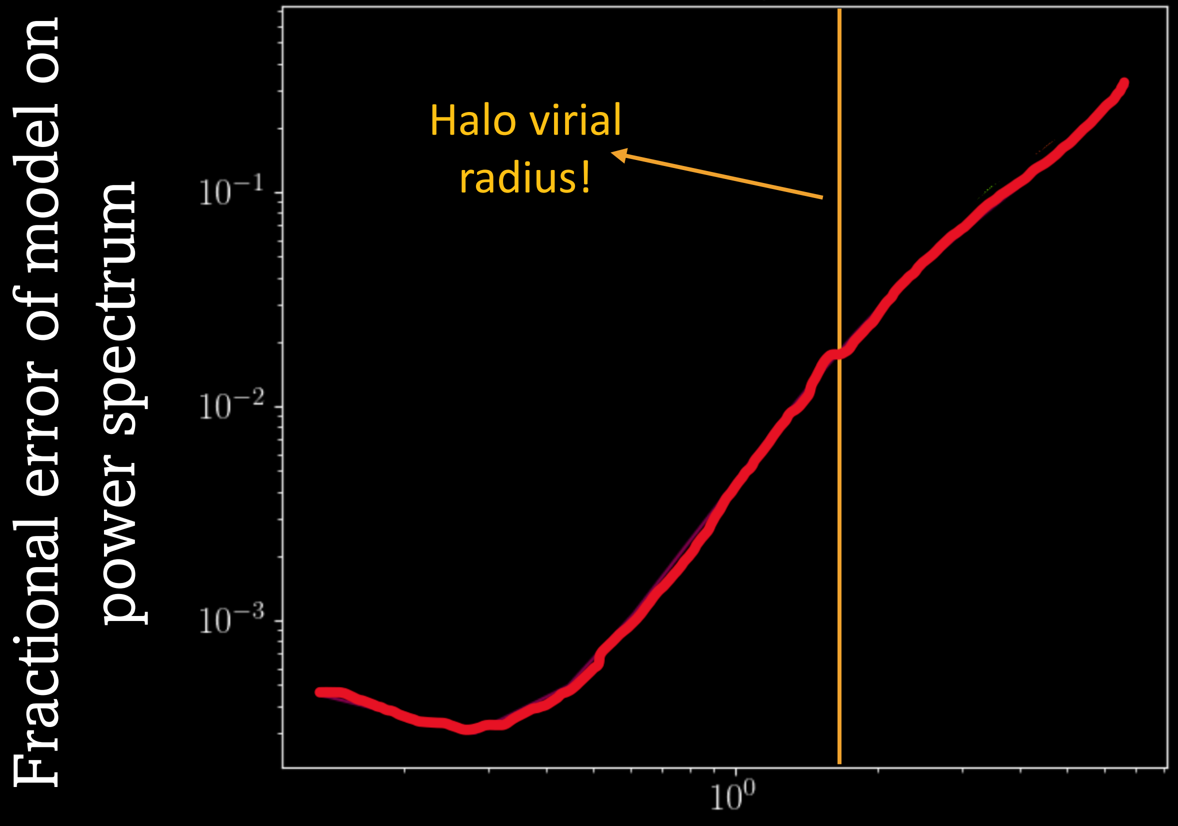
Reconstructed optical depth



True optical depth



Liu+ 2024 (in prep)



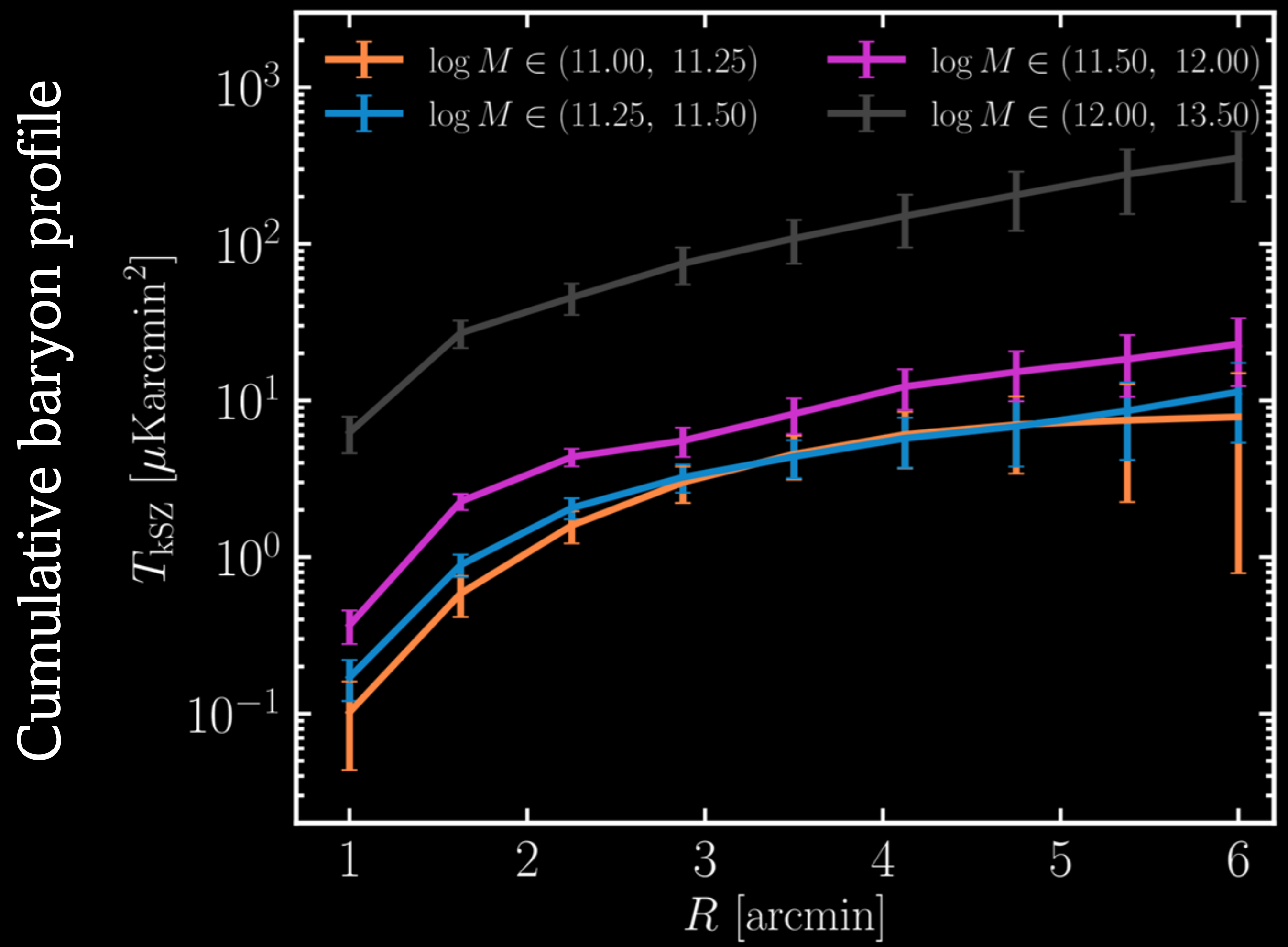
Large-scale k [h/Mpc] Small-scale

Towards obtaining a full multi-scale picture of galaxy thermodynamics

Extending to different galaxy types, redshifts, gas probes

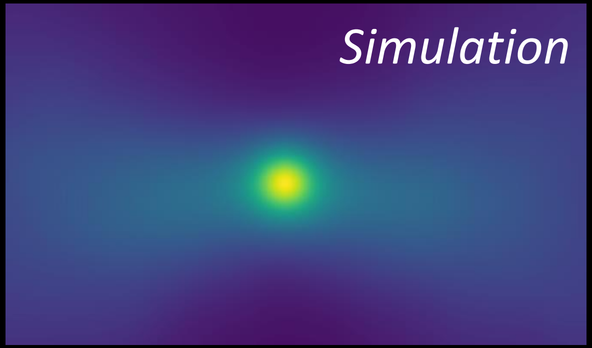
- Already can split into mass bins to understand evolution
- Tracers (preliminary!):
  - Bright Galaxy Sample (z ~ 0.3)
  - LRGs (z ~ 0.7)
  - ELGs (z ~ 0.9)
  - Quasars (z ~ 1.4)
- Probes:
  - kSZ → gas density
  - tSZ → gas pressure
  - + kSZ → gas temperature
  - X-rays → intracluster medium
  - lensing → cluster mass

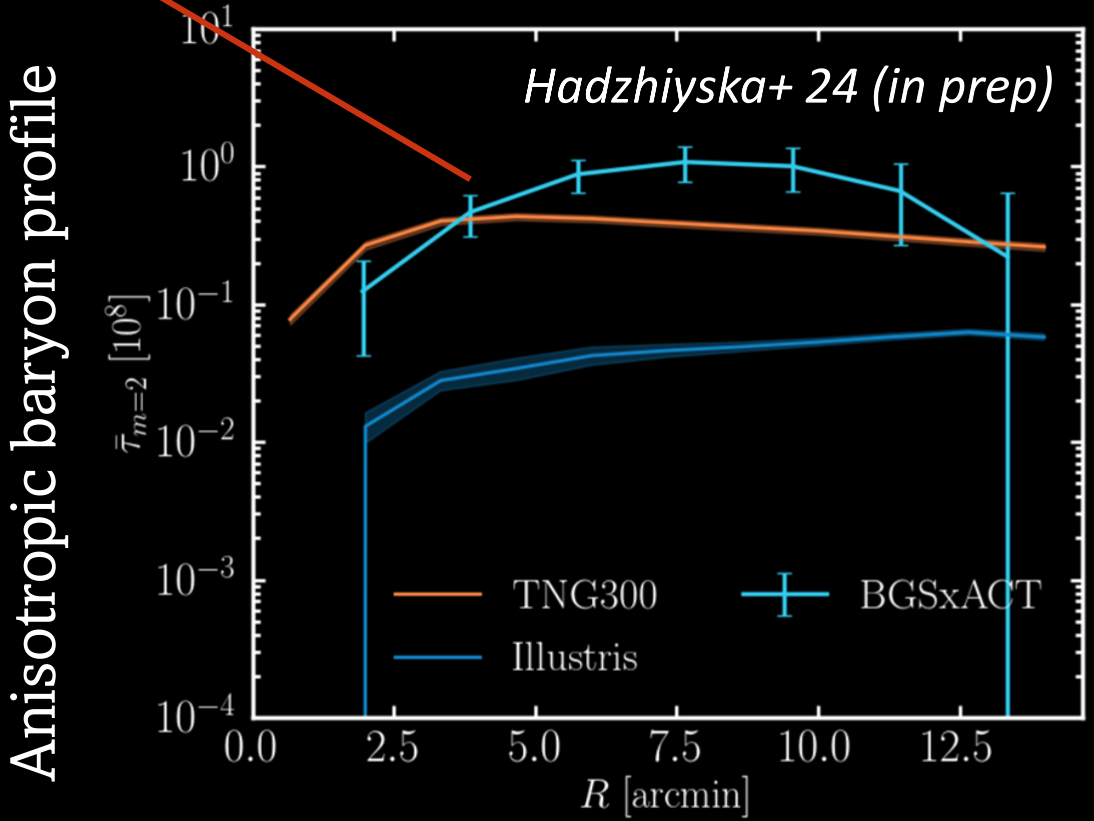
Hadzhiyska & ACTxDESI collaboration 2024

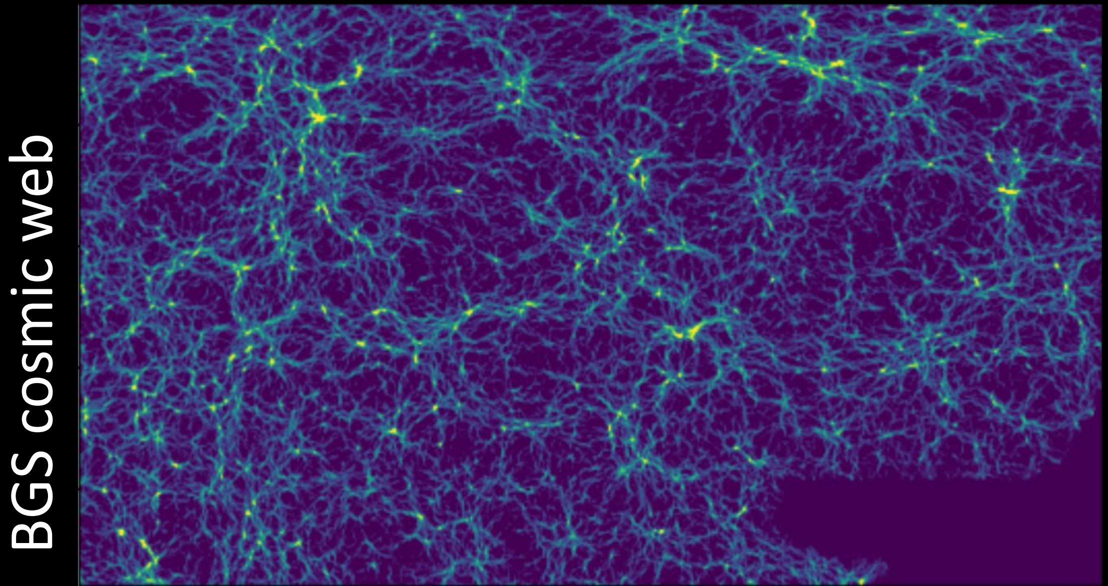


Apart from the isotropic signal… gas-filament alignment!

- Detection of anisotropic signal w/ DESI
- Key for understanding gas flow and feedback
- Stacking on cosmic web of DESI BGS







Summary of science case

- Future of cosmology: intersection with galaxy formation & evolution
  - Galaxy formation
  - AGN activity
  - Baryon distribution

  - Modified gravity
  - Dark sector
  - Primordial Universe

1. kSZ for resolving “missing baryon” problem and calibrating AGN/SN models
2. Small-scale cosmology from galaxy surveys informed by hydro simulations

Next steps:

- Interpretation and optimal extraction of information
- Obtaining a full picture of thermodynamics of galaxy groups & clusters

Backup slides

Apart from the isotropic signal… gas-filament alignment!

- Detection of anisotropic signal w/ DESI
- Key for understanding gas flow and feedback
- Stacking on cosmic web of DESI BGS