Galaxy Formation Simulations for Cosmology with Emission Line Galaxies

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Refs.

KO and Okumura (2021; in prep.)

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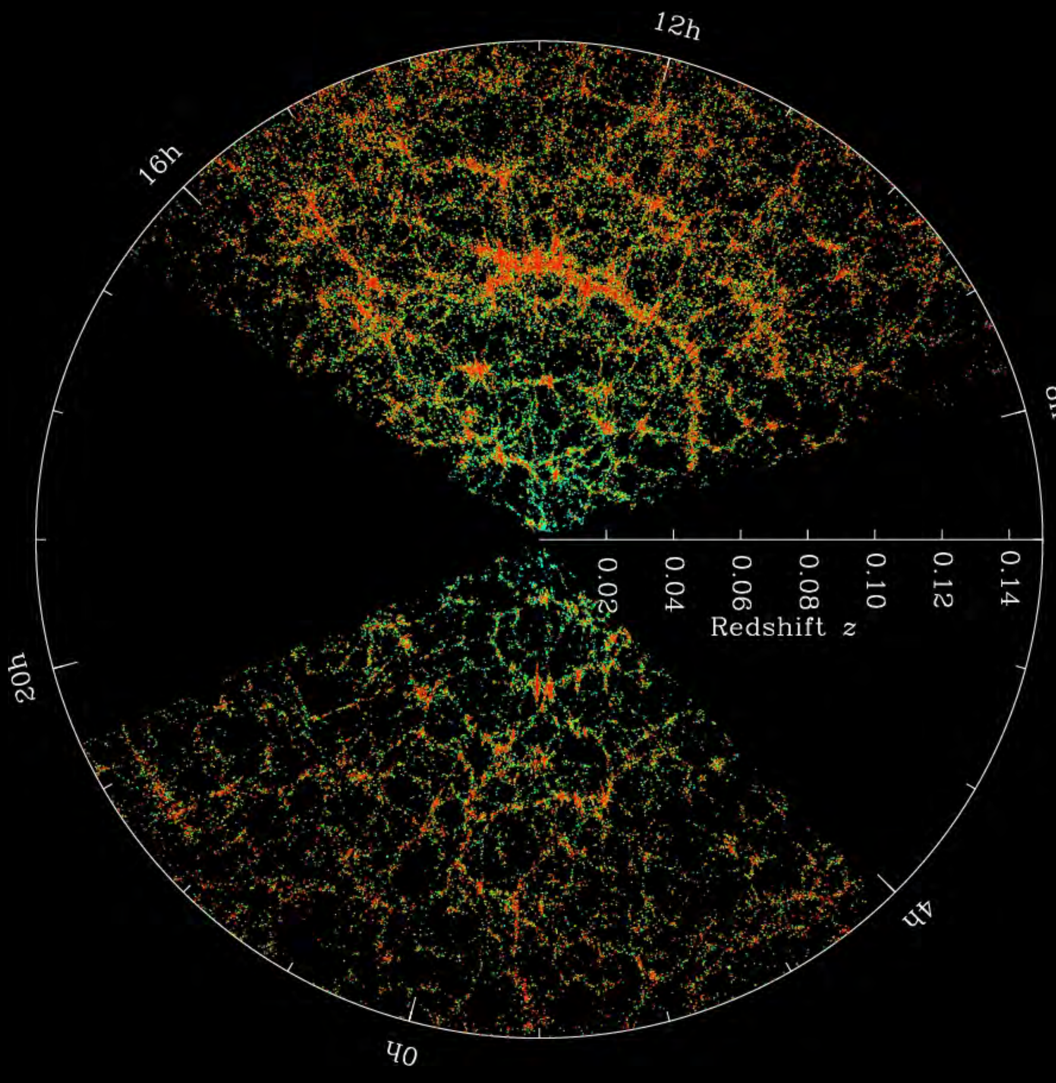
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Cosmology with Galaxy Clustering

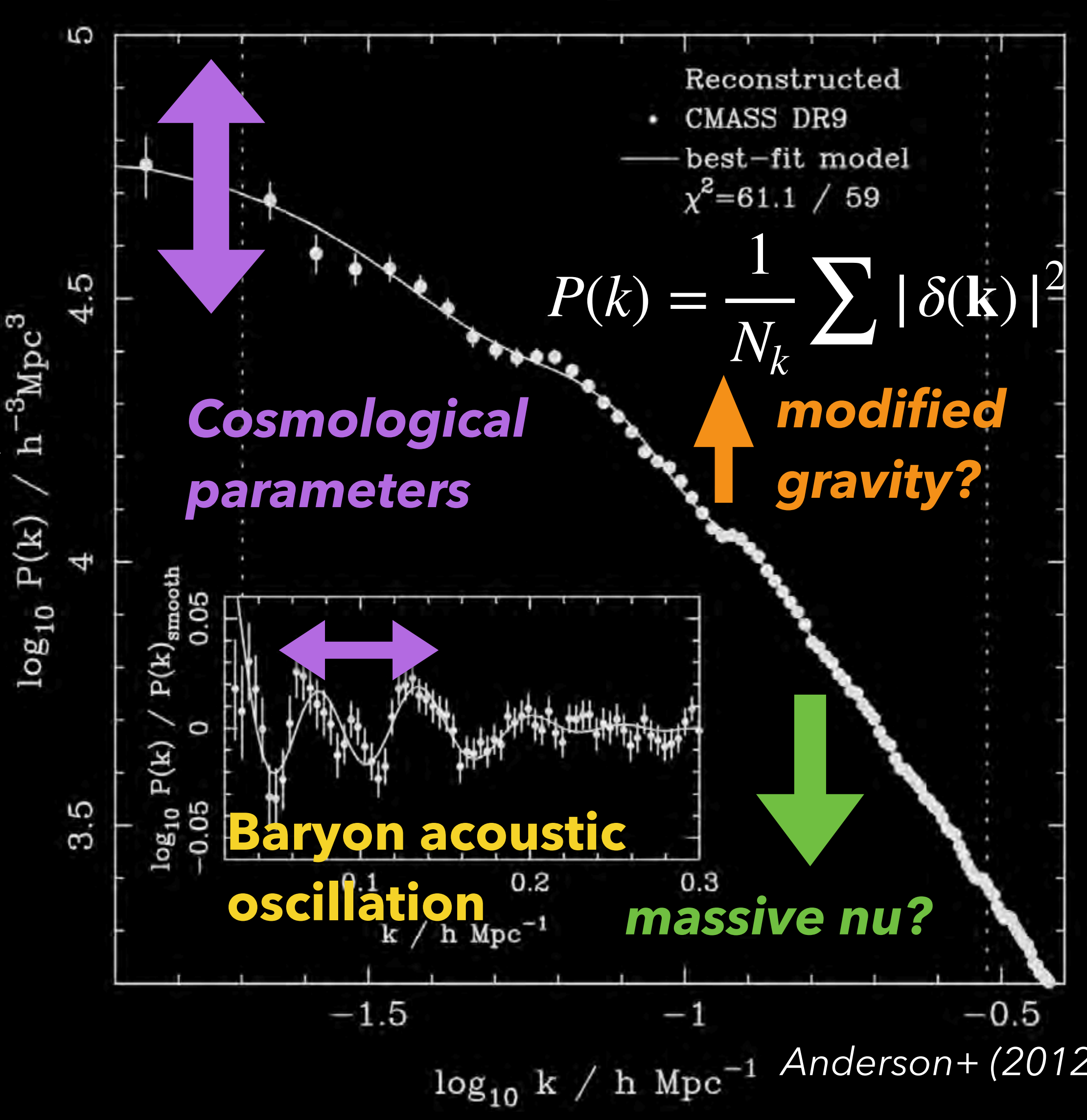
- ✦ The matter distribution, ***large-scale structures***, reflects cosmological models (***modified gravity***, ***massive neutrinos***…).
- ➡ This information is imprinted onto ***power spectrum*** and it is measured from spectroscopic surveys of galaxies.



SDSS Galaxy Map

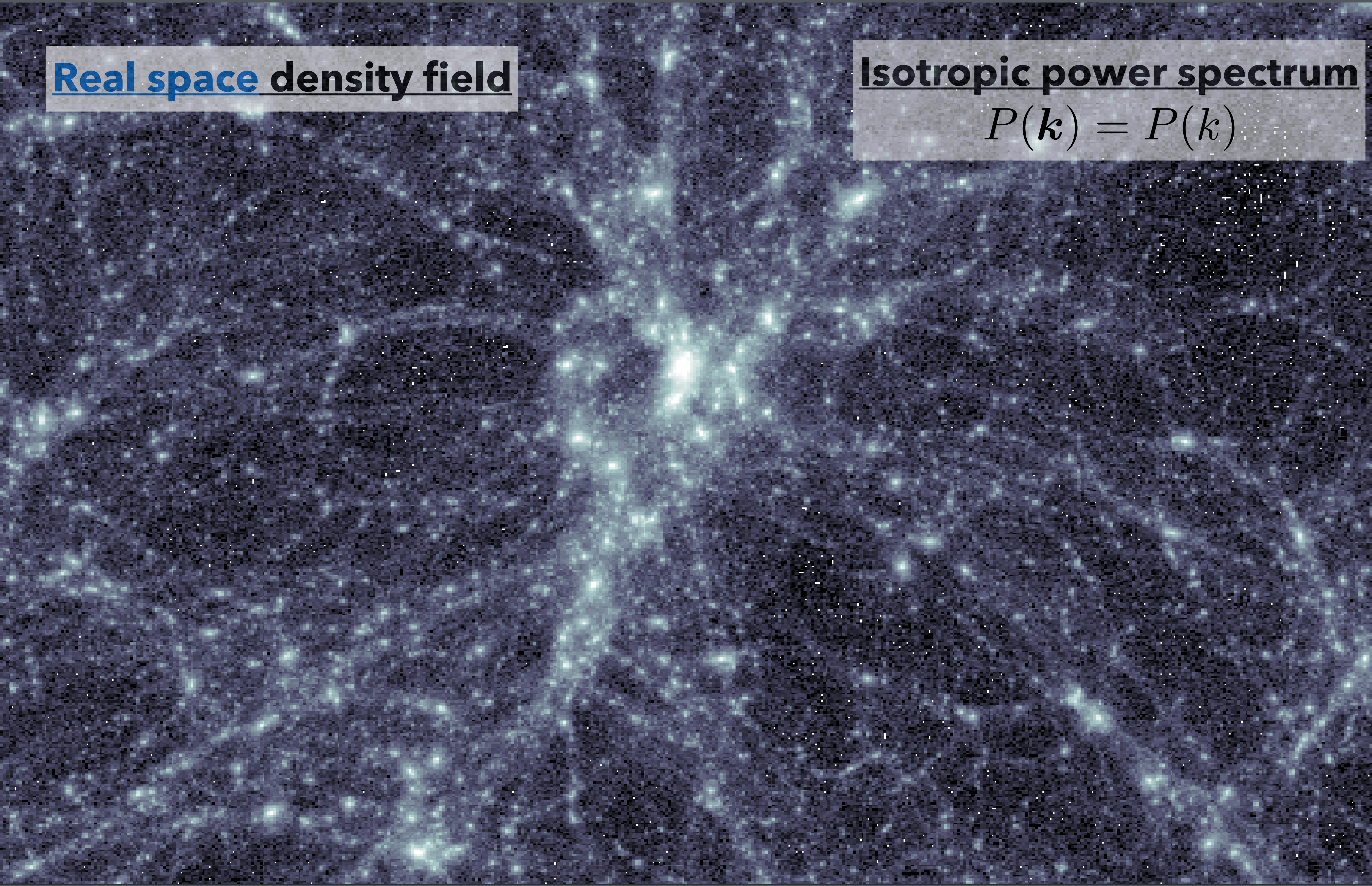
Statistical analysis ➡

Power spectrum

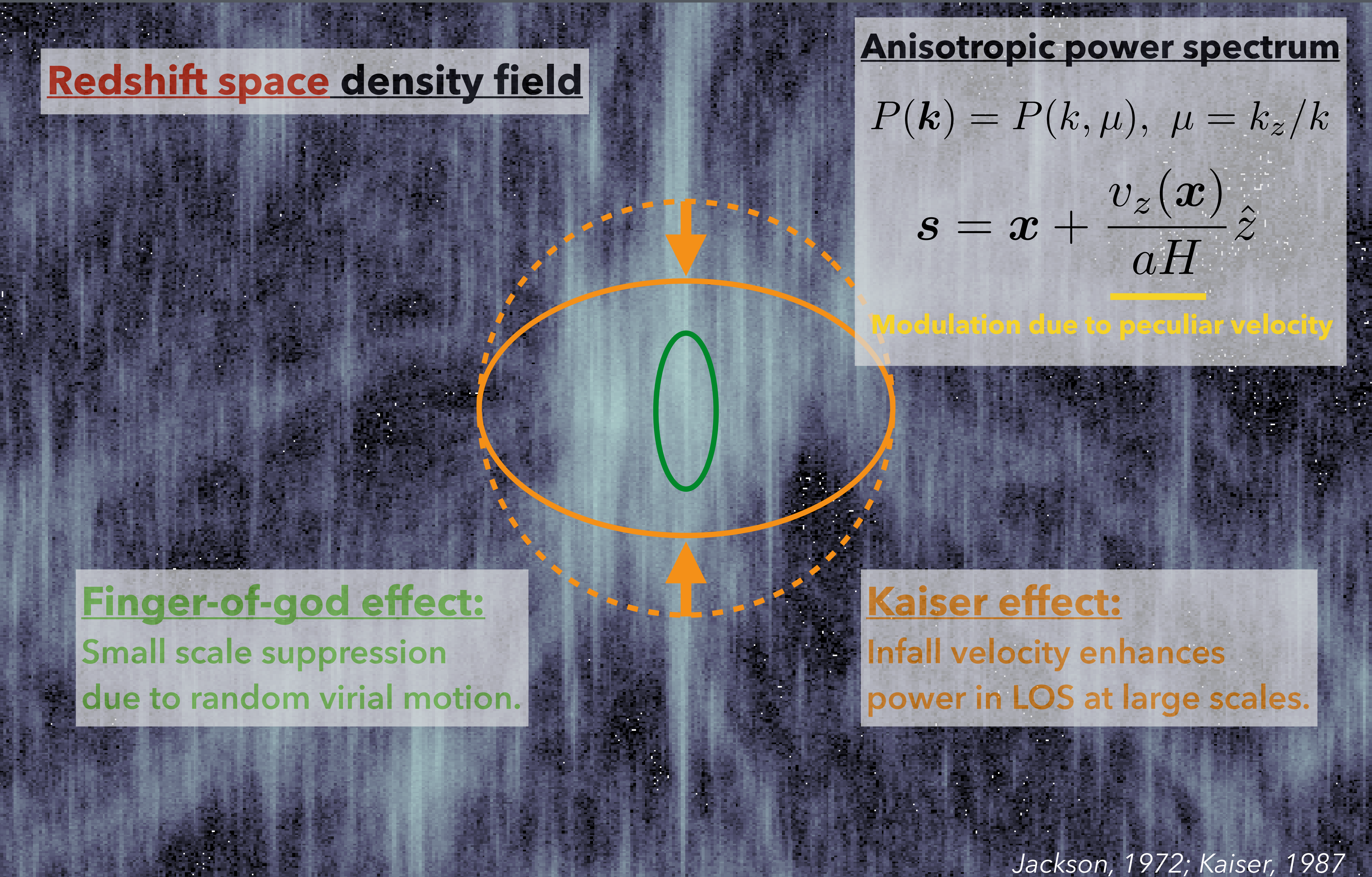


Anderson+ (2012)

Redshift Space Distortion



Redshift Space Distortion



Redshift space density field

Anisotropic power spectrum

$$P(\boldsymbol{k}) = P(k, \mu), \;\; \mu = k_z/k$$

$$\boldsymbol{s} = \boldsymbol{x} + \frac{v_z(\boldsymbol{x})}{aH}\hat{z}$$

Modulation due to peculiar velocity

Finger-of-god effect:
Small scale suppression due to random virial motion.

Kaiser effect:
Infall velocity enhances power in LOS at large scales.

Jackson, 1972; Kaiser, 1987

Redshift Space Distortion

Redshift space density field

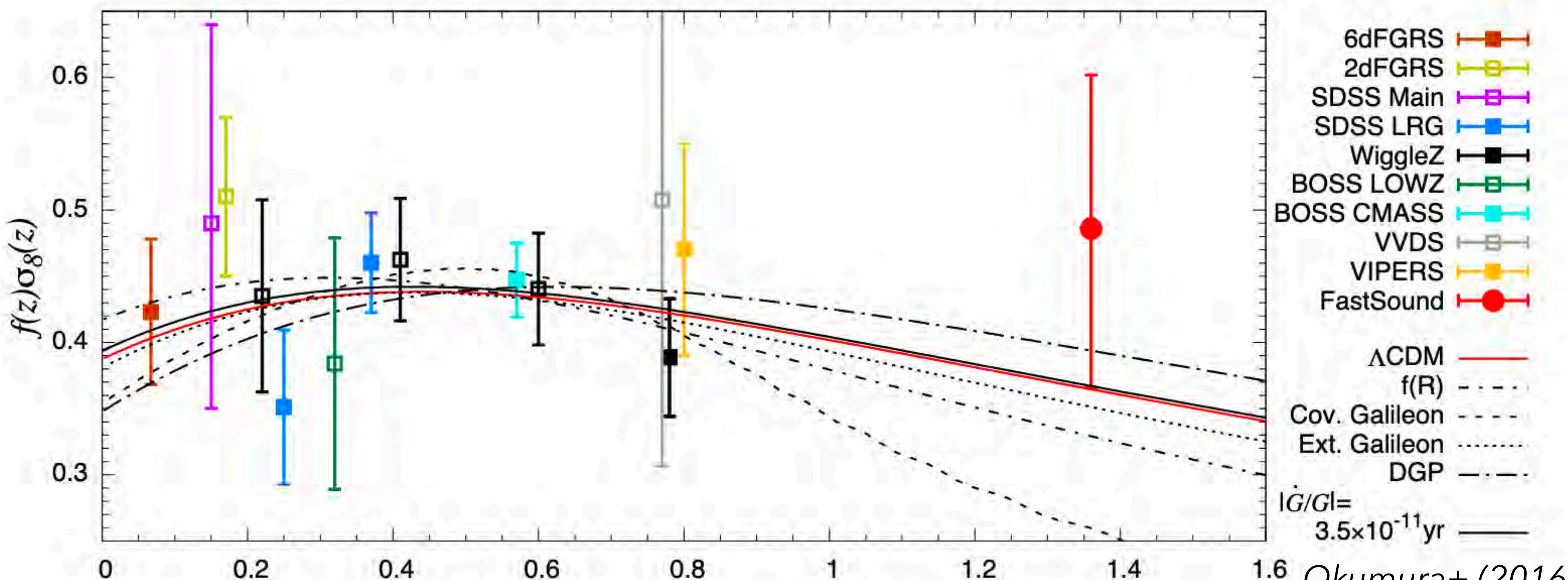
Anisotropic power spectrum

$$P(\boldsymbol{k}) = P(k, \mu), \ \ \mu = k_z/k$$

$\hat{z}$

velocity

Growth rate: $f = \dfrac{\ln D_+}{\ln a} \simeq \Omega_m^\gamma$ **For GR with Λ** $\gamma \simeq 0.55$



Okumura+ (2016)

Fing

Sma

due to random virial motion.

power in LOS at large scales.

Jackson, 1972; Kaiser, 1987

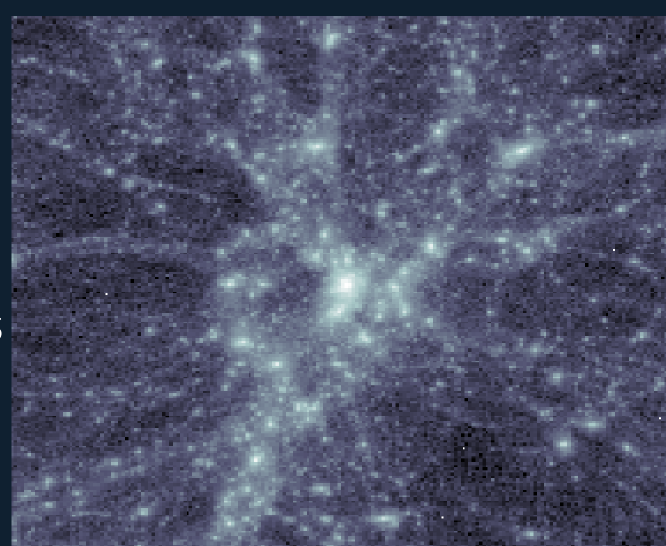
Galaxy Bias: Matter vs Galaxy

- We observe **galaxy distribution**, not matter (baryon+DM) distribution.
  The galaxy distribution follows background matter distribution at some level
  but the relation (***galaxy bias***) is governed by complex astrophysics
  and thus challenging to model it analytically.

- The galaxy formation simulations numerically solve
  gravitational growth and **formation and evolution of galaxies** simultaneously.

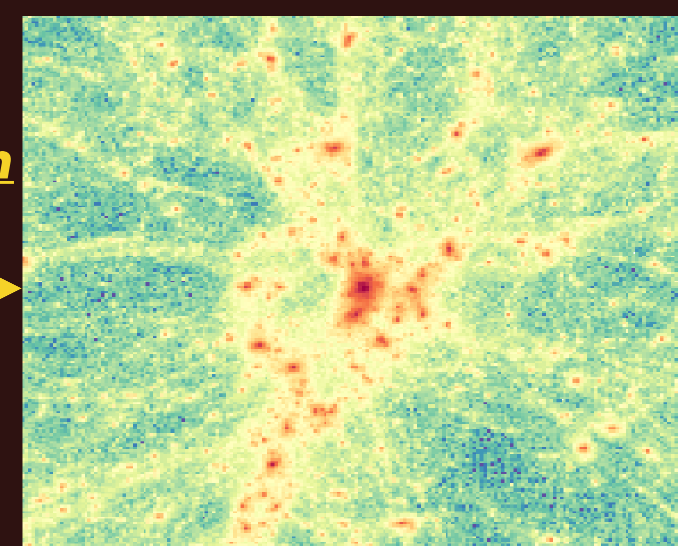
Matter

Density/velocity fields
Halo catalogues
Merger history of halos
…



Direct comparison

Galaxy

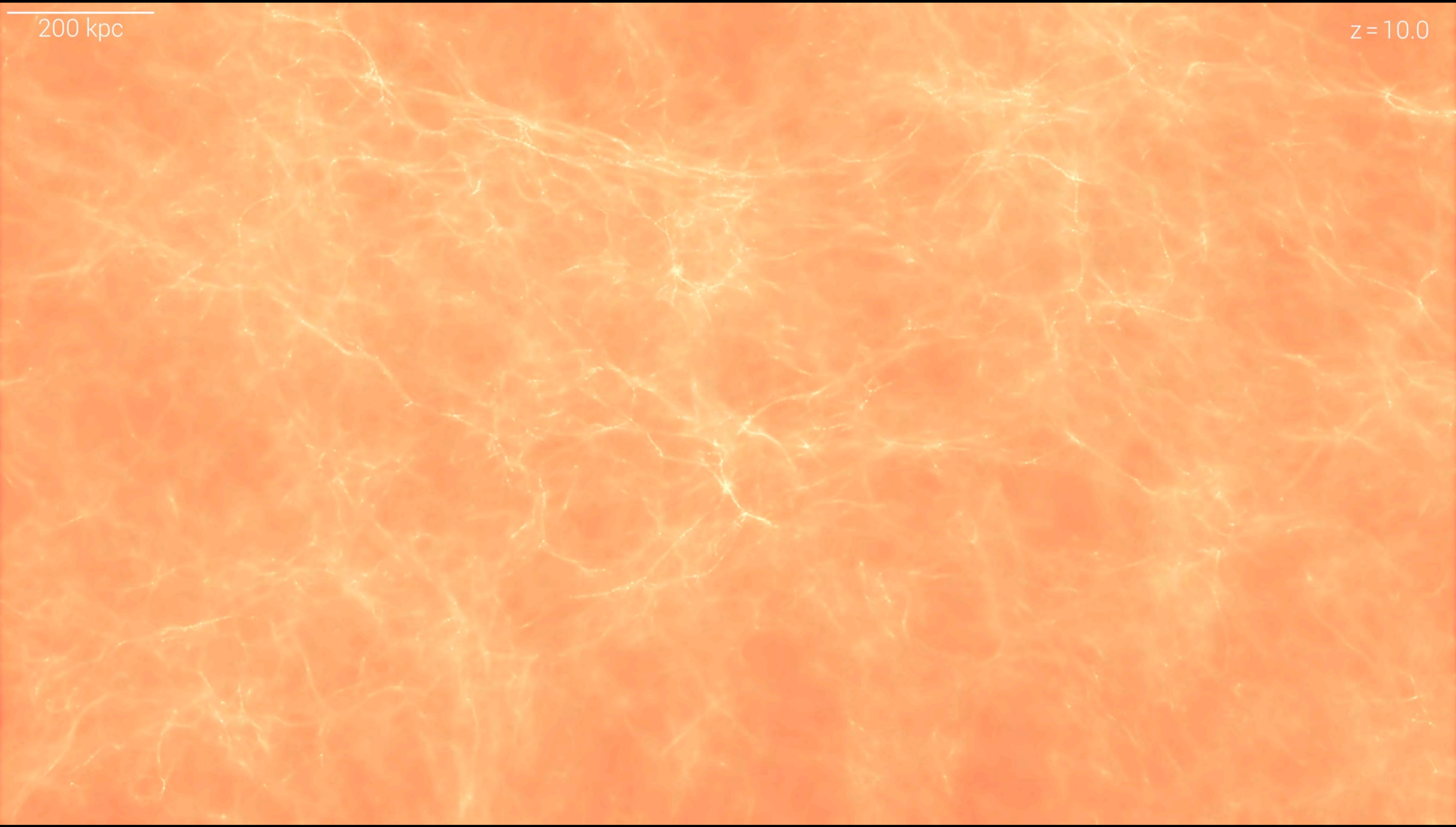


Luminosity
Galaxy catalogues
Star formation rate
Age
Metallicity
…

➡ ***The ideal tool to dissect the galaxy-matter relation!***

Galaxy Formation Hydrodynamical Simulations

✦Numerical simulations are the powerful tool to address the **multi-scale physics**

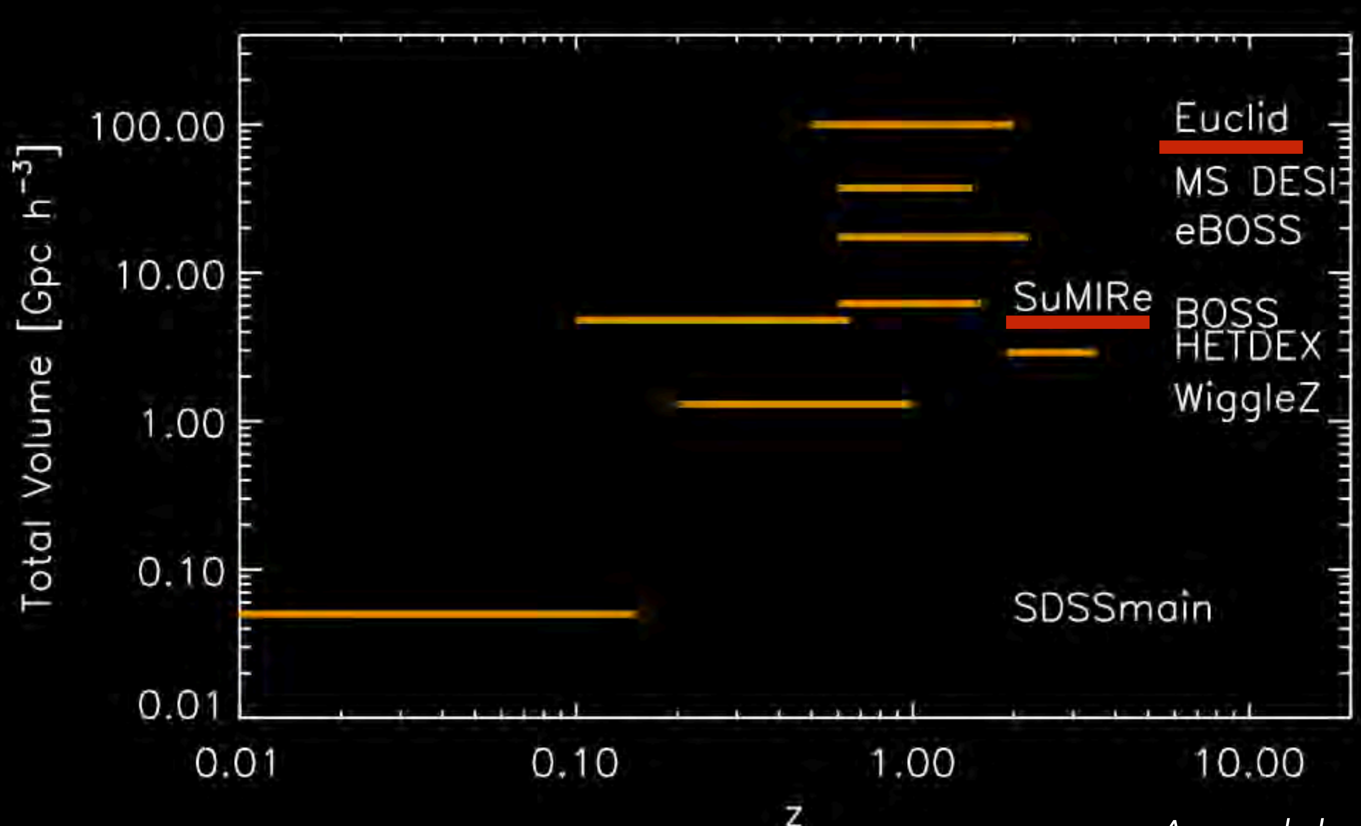


Credit: IllustrisTNG team

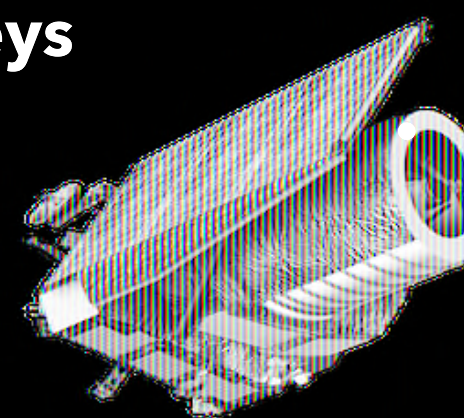
Observations of Emission Line Galaxies

- ✦ Upcoming surveys will target ***emission line galaxies (ELGs)***. ELGs are characterised by strong emission line (Hα, [O II], etc.) from nebular emission. The emission is sourced by **short-lived massive stars**.
- ➡ ELGs are **blue star-forming galaxies** and thus likely to be found in **young halos**.

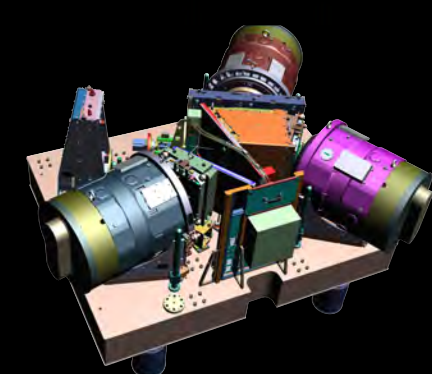
✦Current and future spectroscopic surveys



Amendola+ (2011)



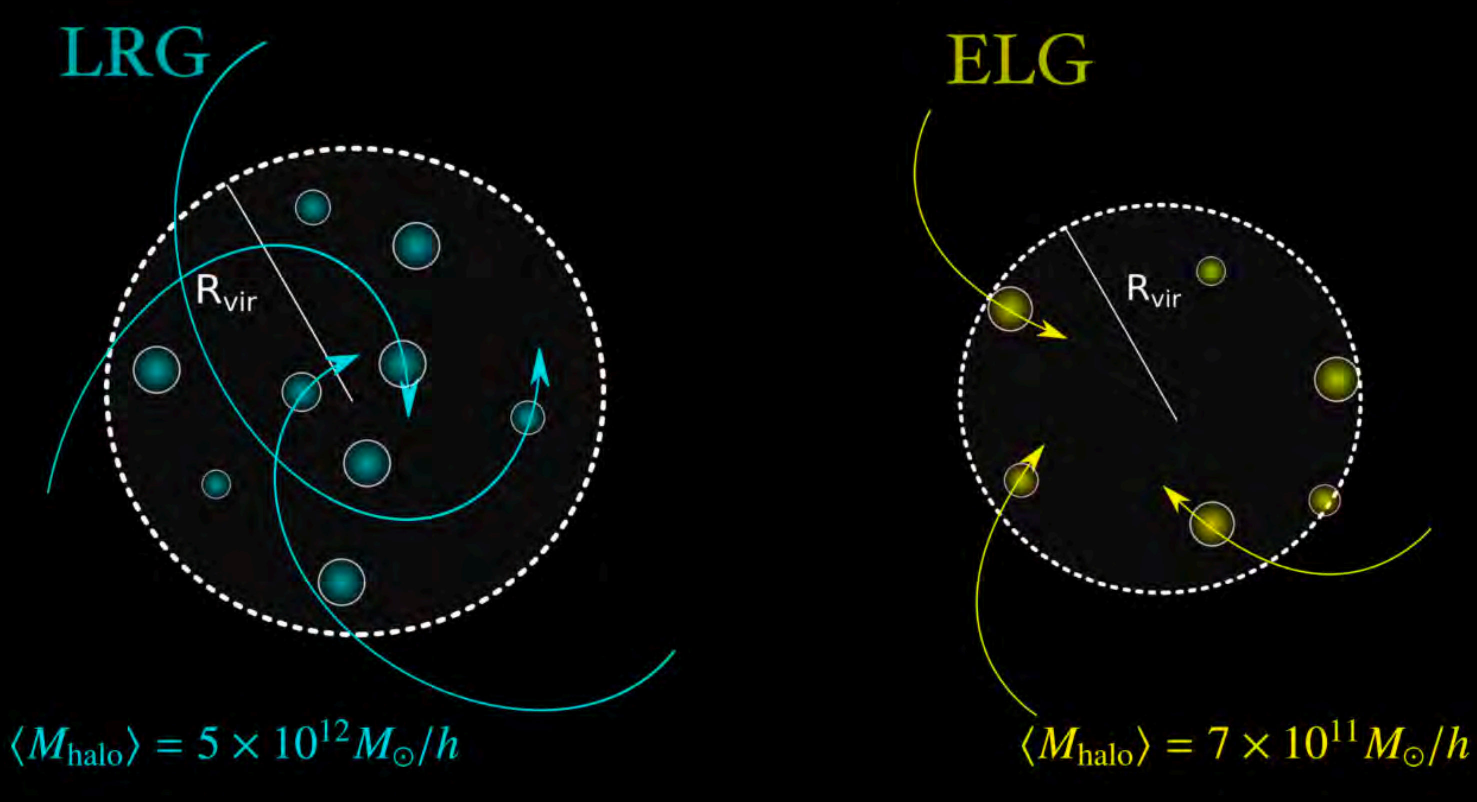
Euclid (in 2023 Q1)
coverage: 15,000 deg^2
Hα ELGs ($0.89 < z < 1.82$)



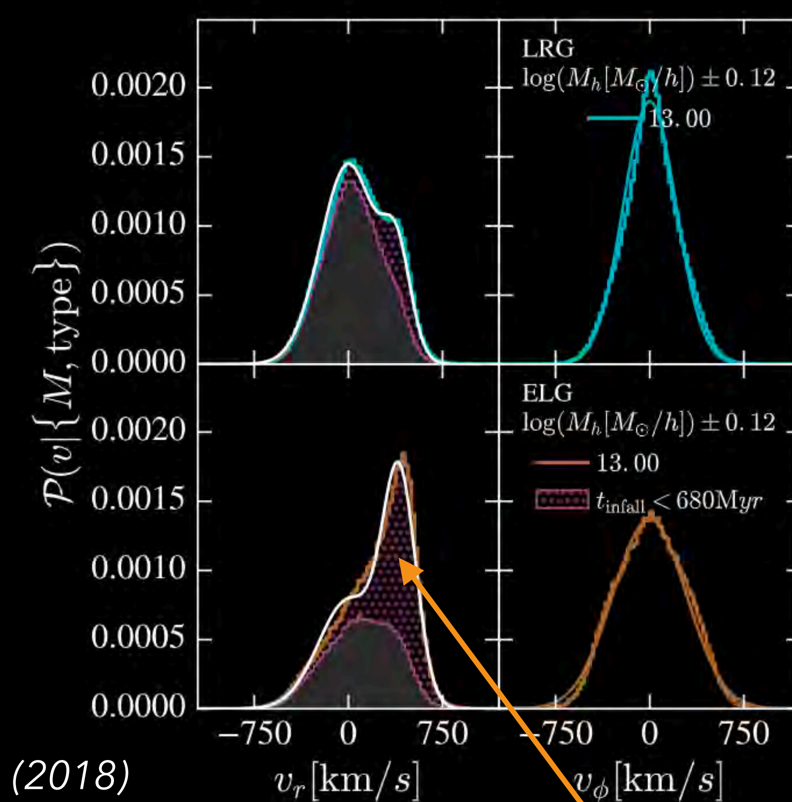
- ***PFS*** (in 2023)
  coverage: 1,200 deg^2
  [O II] ELGs ($0.6 < z < 2.4$)

LRG vs ELG

✦ ***Luminous red galaxies (LRGs)***, which are widely used in cosmological context, are populations complementary to ELGs.



✦Velocity distribution



Orsi+ (2018)

Coherent infall of ELGs

- LRGs are located close to the centre and their kinematics is virialized. On the other hand, ELGs are undergoing infall from outskirts.

➡ This coherent motion directly affects redshift space power spectrum.

Motivation

Fundamental question:
Is the current standard analysis still applicable to ELGs?

In contrast to LRGs, …

- The hosting halos are younger and the halo bias also depends on the age (**assembly bias**).
- ELGs infall towards the halo centre, which might lead to **velocity bias**.
- ELGs are star-forming galaxies. Abundance matching in terms of mass may not work.

➡ **This study: Leveraging hydrodynamical simulations, we investigate properties of ELGs and carry out cosmological analysis of ELG clustering.**

Construction of Mock ELG Catalogue

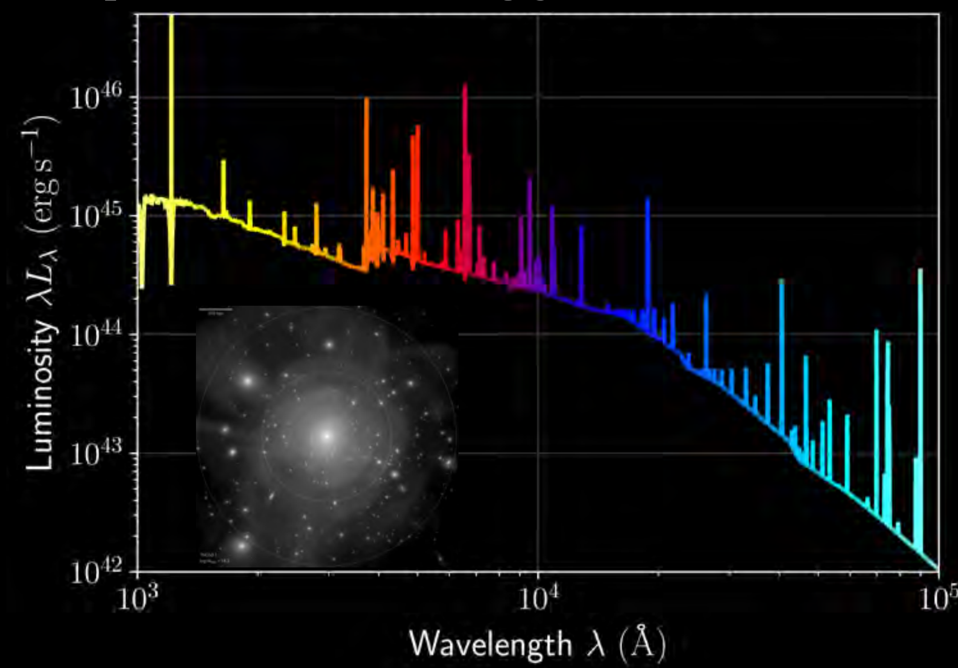
IllustrisTNG (Nelson+, 2019):

Run by moving-mesh code AREPO (Springel, 2010)
L = 205 Mpc/h, N = 2 x 2500^3
Various baryonic processes implemented:
Radiative cooling, star formation, stellar wind, stellar feedback, BH formation/evolution, AGN feedback, MHD, …

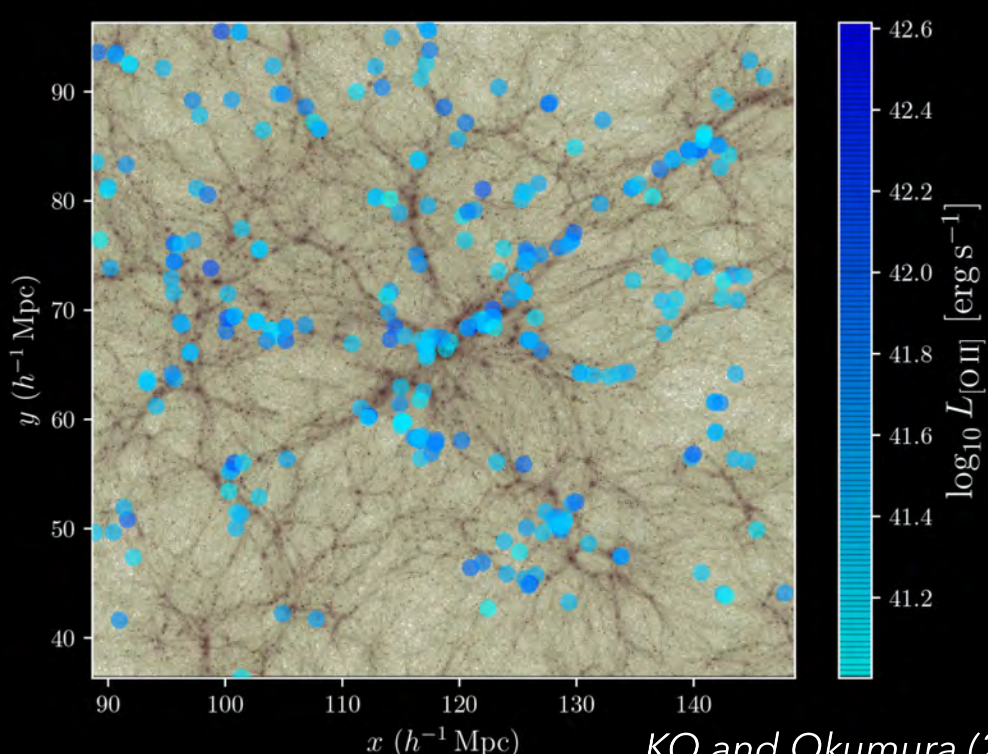
Stellar population synthesis:

For each star particle, we compute SED based on its metallicity and age with PÉGASE.3 (Fioc+, 2019) code coupled with photo-ionization code CLOUDY (Ferland+, 2017).

Spectral energy distribution

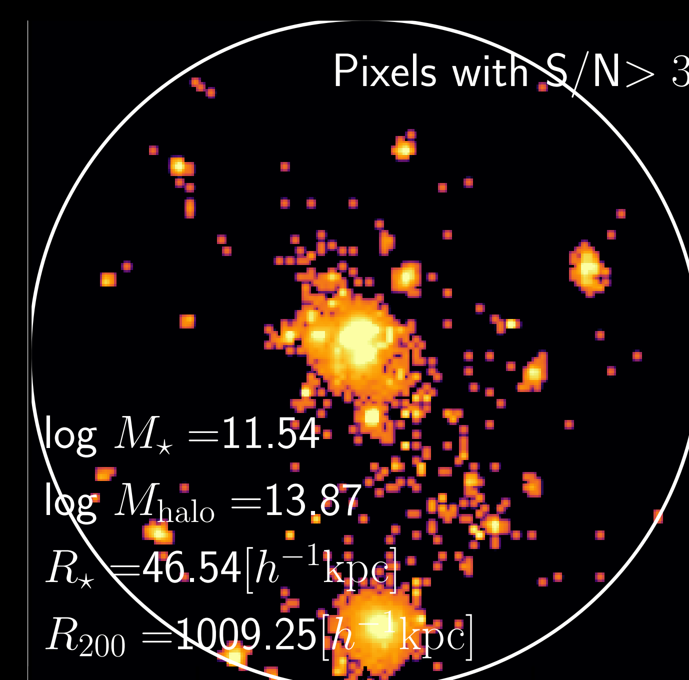


[O II] ELG distribution



KO and Okumura (2021)

HSC i-band luminosity



Shi, KO, Kurita and Takada (2021)

Luminosity Function of Hα and [O II] ELGs

- ✦ As validation of our mock ELG catalogues, luminosity functions of Hα and [O II] ELGs are compared with observations.
- ➡ When dust attenuation is taken into account, the results are consistent ***without tuning parameters***.

Hα ELGs

[O II] ELGs

without dust

with dust

Observations

Observations

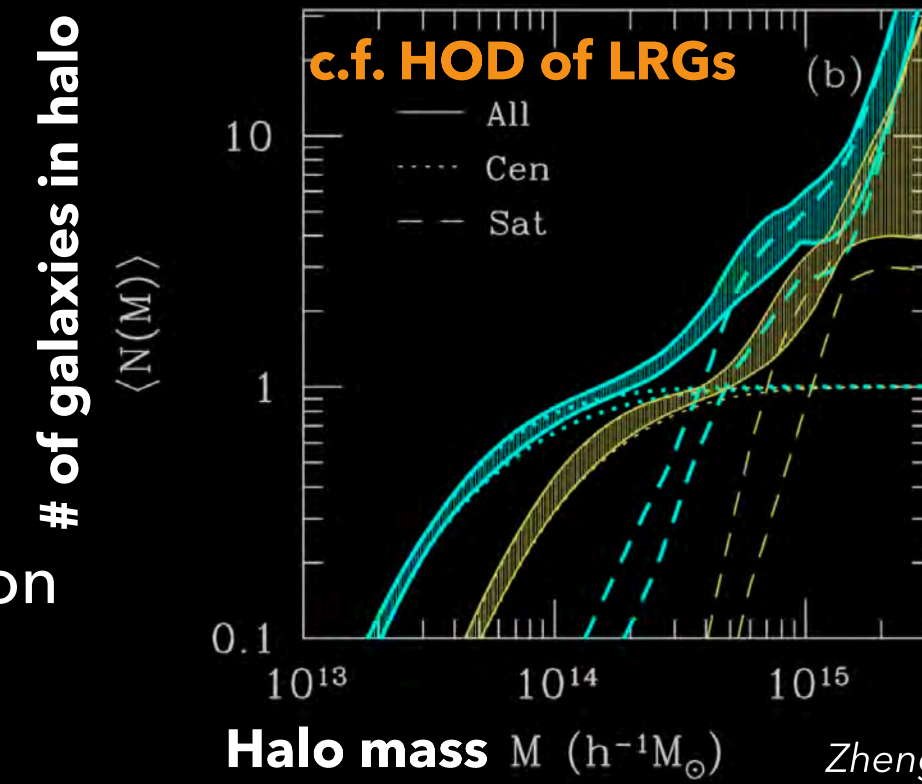
Dust formation and evolution is consistently solved in PÉGASE3.

KO and Okumura (2021)

Halo Occupation Distribution

- ***Halo Occupation Distribution (HOD)***: The mean number of galaxies as a function of halo mass. The most common way to relate galaxies with halo.

- **Central** = gradually growing step-like function
- **Satellite** = power-law function



Zheng+ (2009)

Hα ELGs

[O II] ELGs

# of galaxies

- The small bump represents a distinct population hosting ELGs.

➡ ***Infalling low-mass halos***

Halo mass

KO and Okumura (2021)

Anisotropic Correlation Function

✦ We can measure anisotropic correlation function ***as in real observations***.

➡ Weak FoG suggests coherent infall of ELGs.

- Multipole moments:

$$\xi_\ell(s) = \frac{2\ell + 1}{2} \int_{-1}^{+1} \mathrm{d}\mu \, \xi(s, \mu) \mathscr{P}_\ell(\mu)$$

Monopole (l = 0)

Quadrupole (l = 2)

Solid lines are theoretical predictions with best-fit parameters.

Separation

KO and Okumura (2021)

Inference of Growth Rate

✦ ***Cosmology challenge***: direct comparison between inferred and input values.

- Theoretical model: galaxy power spectrum

Linear bias

$$P_{gg}(k,\mu) = e^{-(k\mu\sigma_v)^2}\left[b_1^2 P_{\delta\delta}(k) + 2b_1 f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right]$$

Halofit fitting formula (Takahashi+, 2012)

Velocity fitting formula (Hahn+, 2015)

Growth rate

LRG

- Parameter space:
  Linear bias, ***growth rate***, velocity disp.
  NOTE: other cosmological parameters are fixed as ones in IllustrisTNG.

ELG

Velocity dispersion

- Inferred growth rate:

True *f*

KO and Okumura (2021)

Summary

- Hydrodynamical simulations are the ideal tool to scrutinise the galaxy-matter relation to improve modelling of ELG clustering.

- We directly measured HOD and anisotropic correlation function of ELGs. **Both show appreciable deviation from the case for the mass-limited sample (LRGs).**

- As in realistic measurements, growth rate is inferred from correlation function. **The inferred value is biased due to incomplete modelling of dynamics of ELGs.**

- Our mock ELG catalogue has potential to evaluate the significance of the cross-correlation with ELGs:
  ELGs (*Euclid*, PFS) **x** 21cm IM (HIRAX, SKA)
  ELGs **x** tSZ (AdvACT, SO, CMB-S4)
  and more!