Intrinsic Alignments with Galaxy Formation Hydrodynamical Simulations

New frontiers in cosmology with the intrinsic alignments of galaxies
YITP, Kyoto University; 08/12/2022

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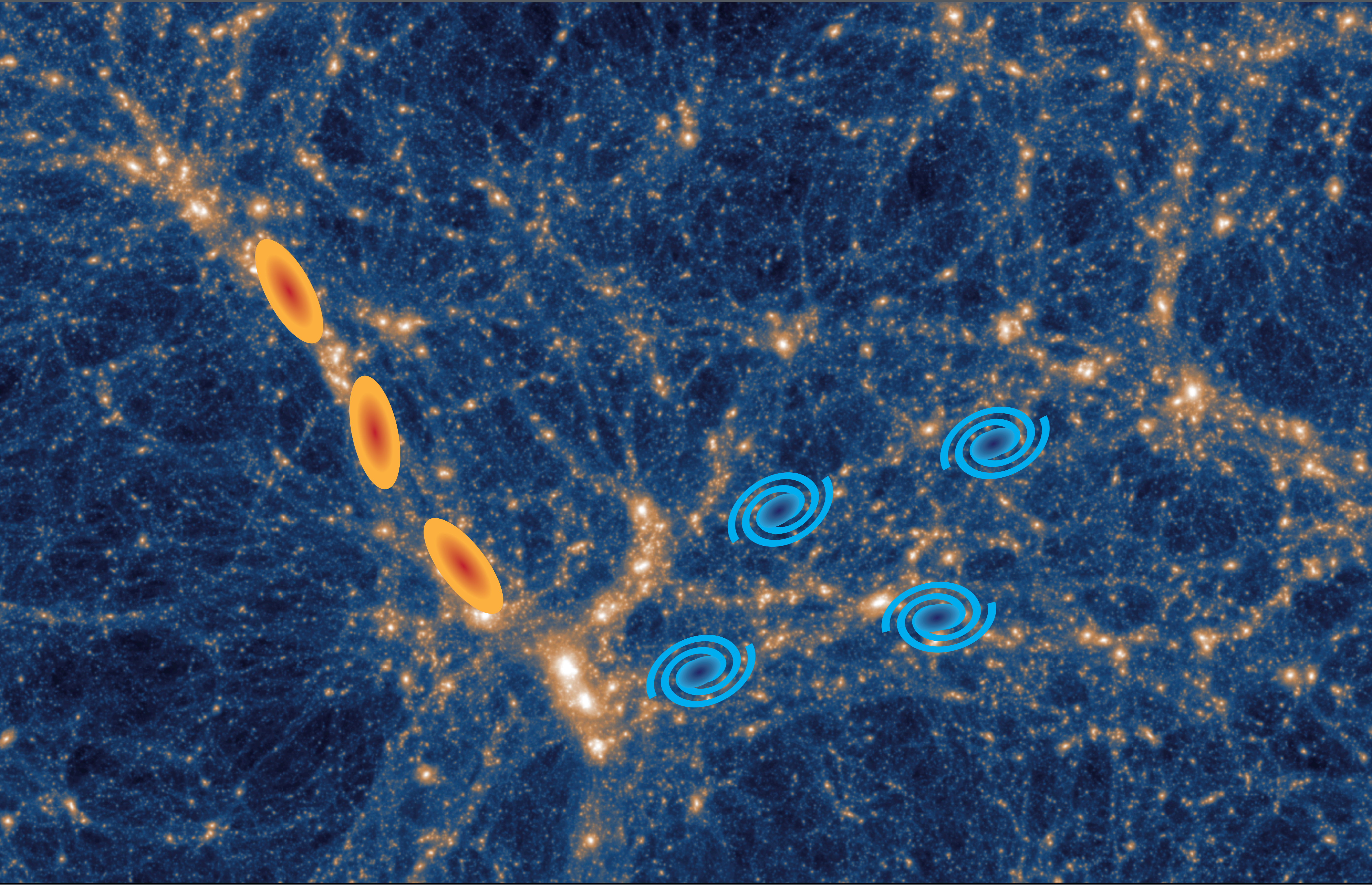
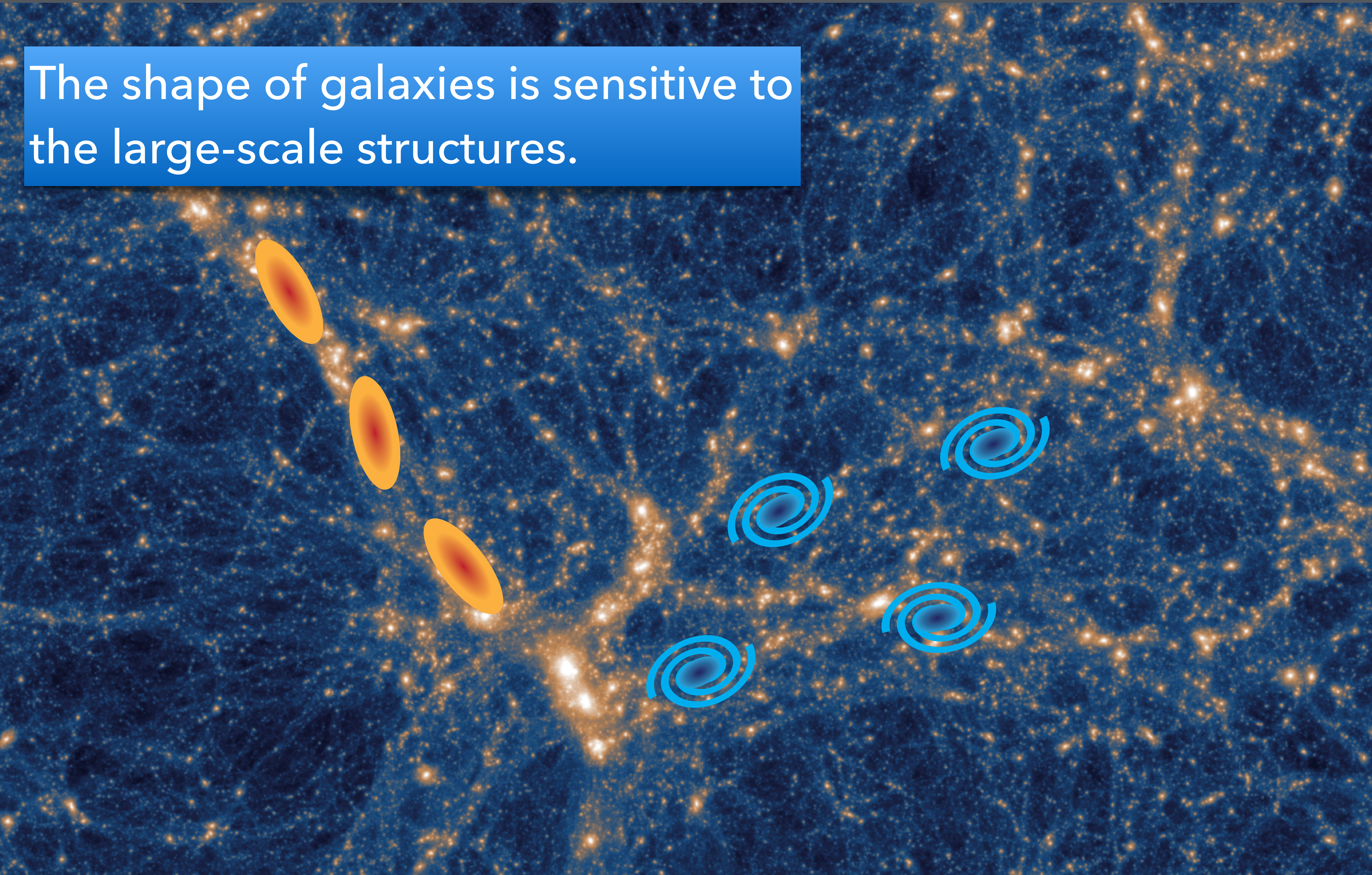
Intrinsic Alignments

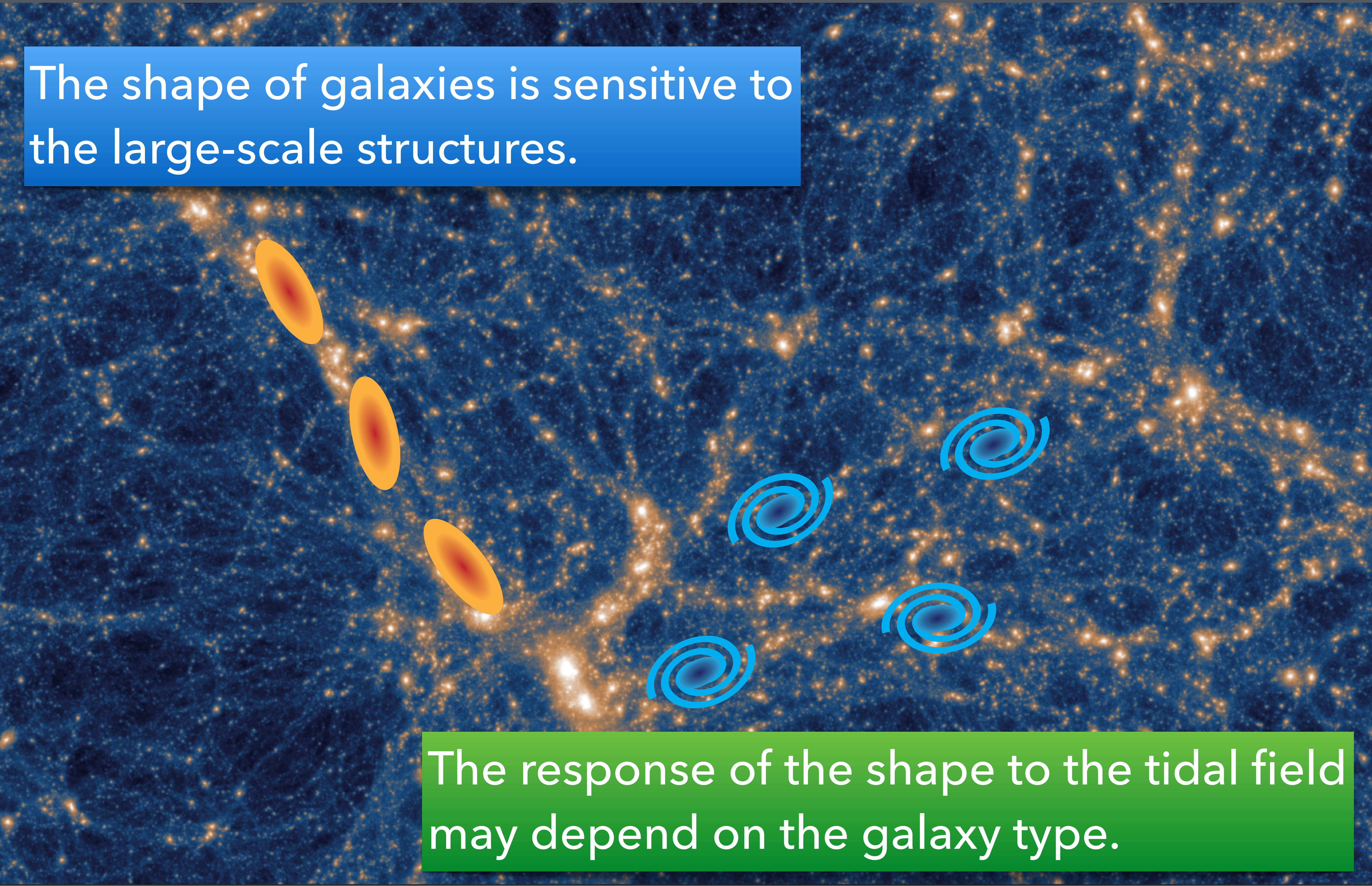


Intrinsic Alignments

The shape of galaxies is sensitive to the large-scale structures.



Intrinsic Alignments



The shape of galaxies is sensitive to the large-scale structures.

The response of the shape to the tidal field may depend on the galaxy type.

Theoretical Modelling of IA

- Intrinsic alignments are thought to be a dominant systematics in weak lensing but also convey cosmological information.

  (Catelan+, 2001; Hirata & Seljak, 2004)

  constant (depends on galaxy sample)

  ➡ ***Linear Alignment:***

  $$\gamma^I = -\frac{C_1}{4\pi G}(\partial_x^2 - \partial_y^2, 2\partial_x\partial_y)\mathcal{S}[\Psi_P]$$

  Gravitational potential

  ➡ ***Quadratic Alignment:***

  $$\gamma^I = C_2(T_{x\mu}^2 - T_{y\mu}^2, 2T_{x\mu}T_{y\mu})$$

  $$T_{\mu\nu} = \frac{1}{4\pi G}\left(\partial_x\partial_y - \frac{1}{3}\delta_{\mu\nu}\partial^2\right)\mathcal{S}[\Psi_P]$$

- The models beyond these have been proposed (incomplete list);

  Nonlinear Linear Alignment (NLA; Bridle & King, 2007):

  Replacing density field with non-linear one

  Tidal Alignment and Tidal Torquing (TATT; Blazek+, 2015, 2019):

  Higher order expansion as in galaxy biasing

  Effective Field Theory (EFT; Vlah+, 2020, 2021):

  The small-scale physics is integrated out and described by a set of free parameters.

N-body Simulation for IA

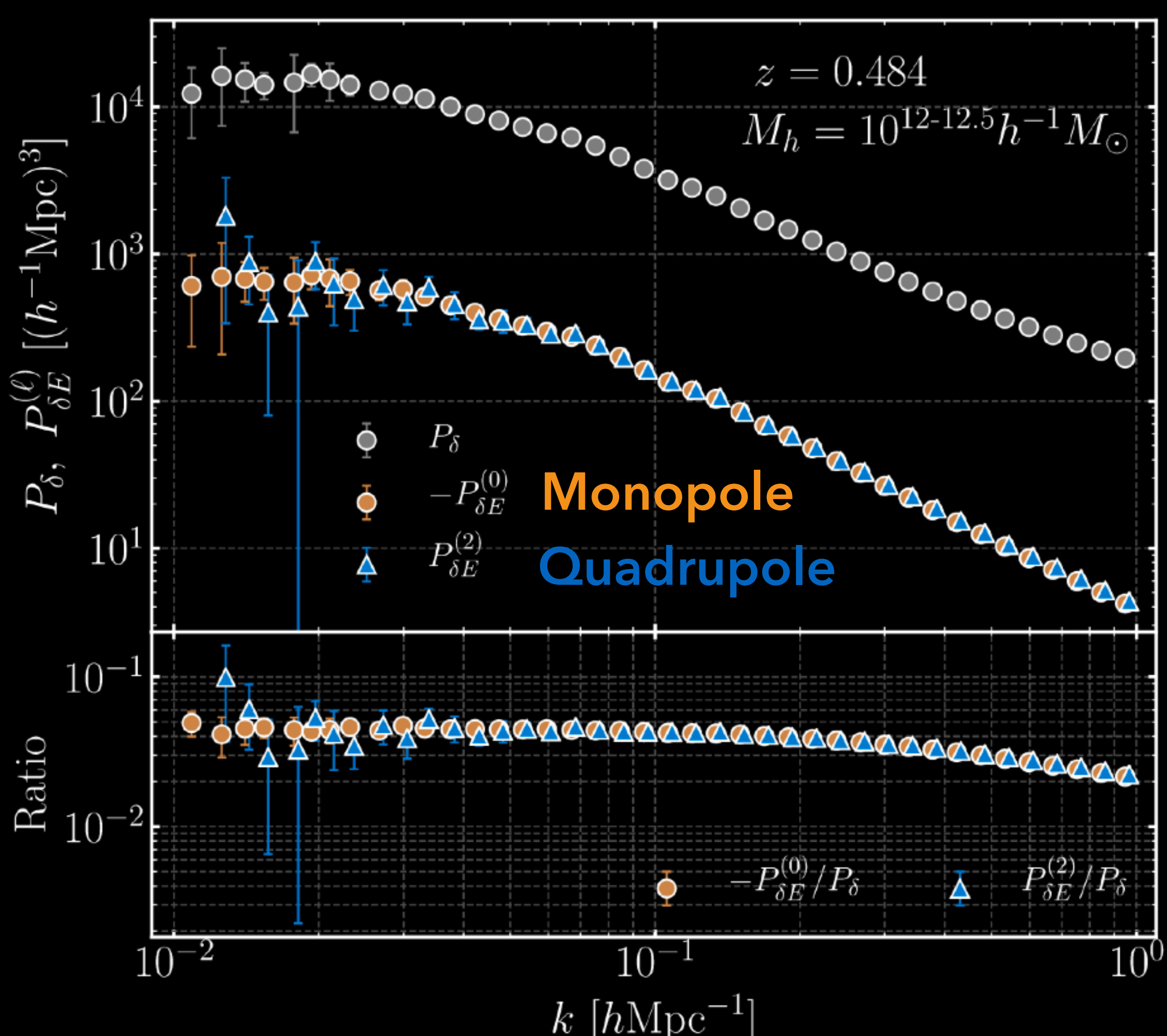
✦ ***Intrinsic alignment power spectra in DM only simulations:***

The underlying shear field is represented by ***shape of halos***.

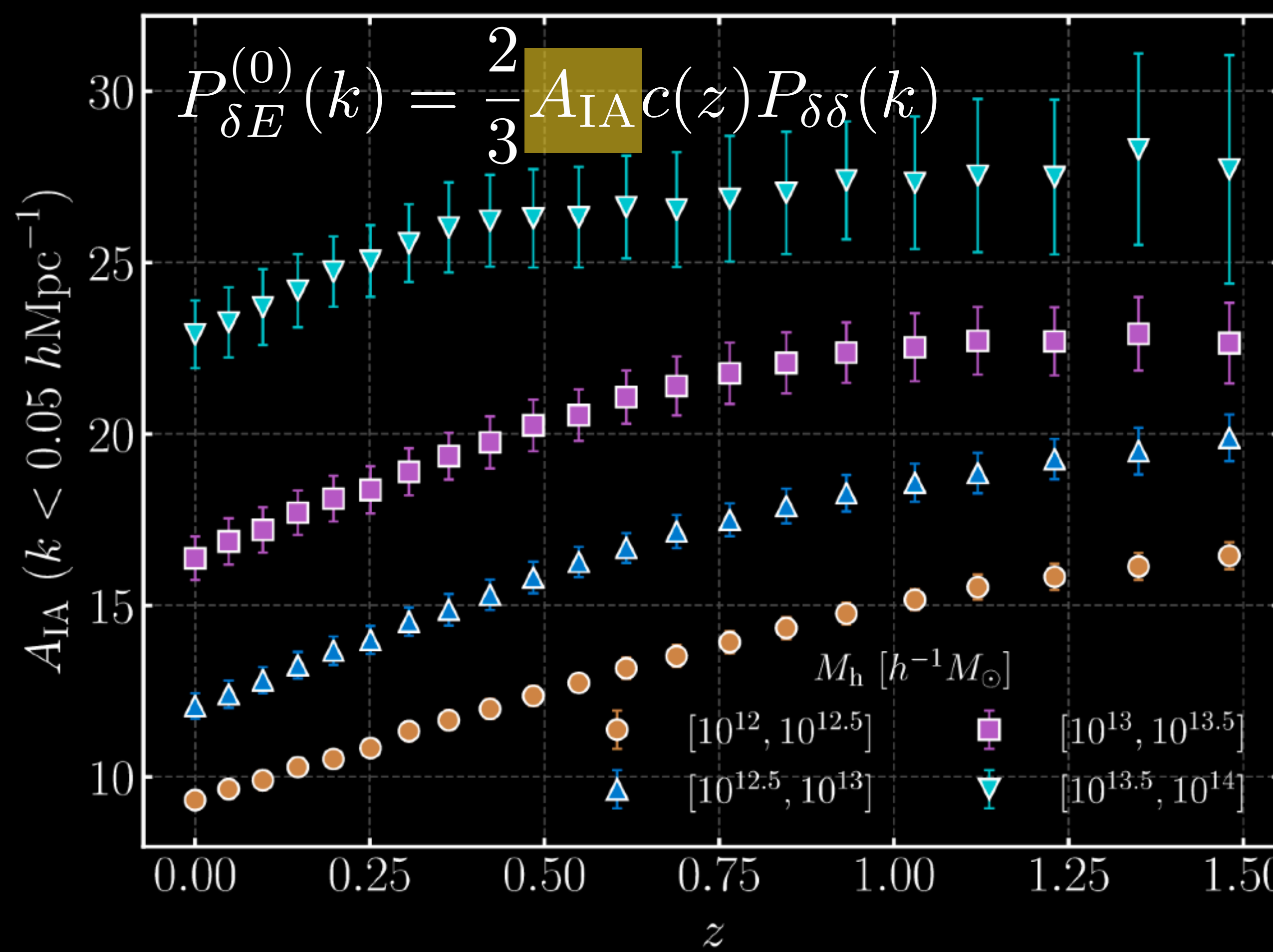
Inertia tensor of halo — **Ellipticity** — **Shear**

$$I_{ij} = \sum_p m_p \frac{\Delta x_p^i \Delta x_p^j}{r_p^2} \rightarrow \epsilon_+ = \frac{I_{11} - I_{22}}{I_{11} + I_{22}},\ \epsilon_+ = \frac{2I_{12}}{I_{11} + I_{22}} \rightarrow \gamma_{(+,\times)} = \frac{1}{2\mathcal{R}} \epsilon_{(+,\times)}$$

***E*-mode and density cross-power spectra**



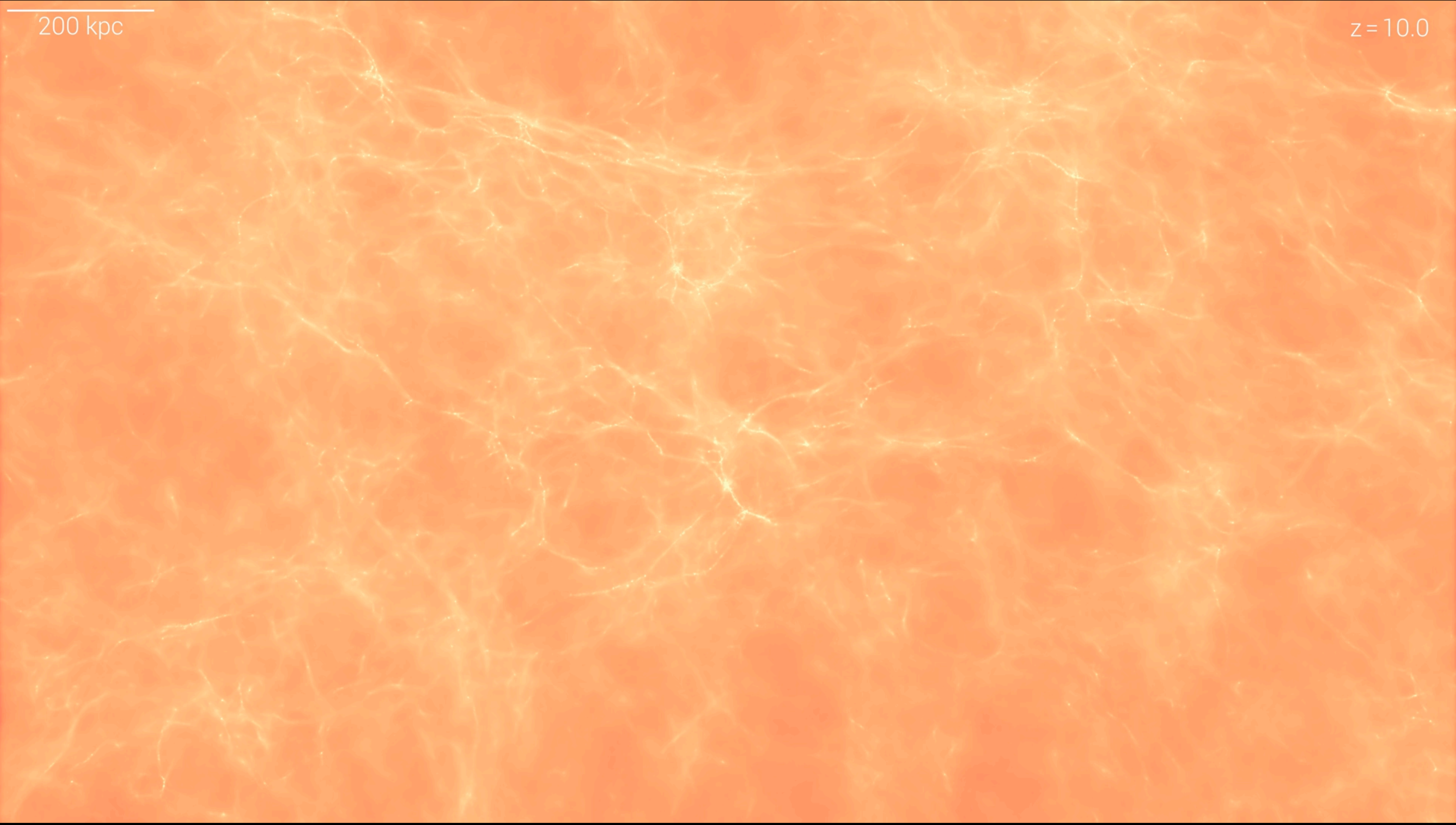
Redshift evolution of IA amplitude



Kurita, Takada, Nishimichi, Takahashi, KO, Kobayashi (2021)

Galaxy Formation Hydrodynamical Simulations

✦Hydrodynamical simulations give access to *stellar mass*, *luminosity*, *colors of galaxies*.



Credit: IllustrisTNG team

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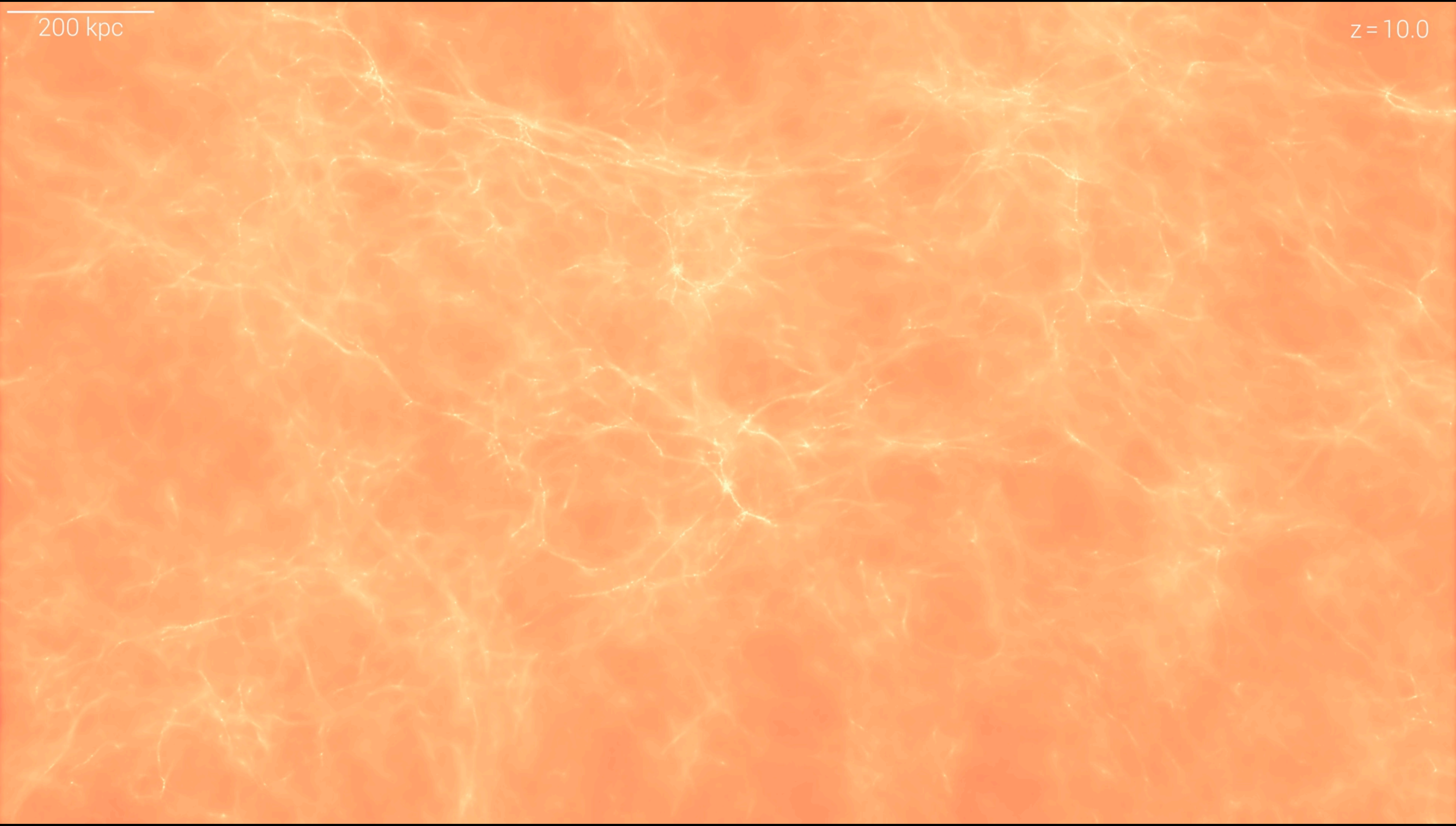


Credit: IllustrisTNG team

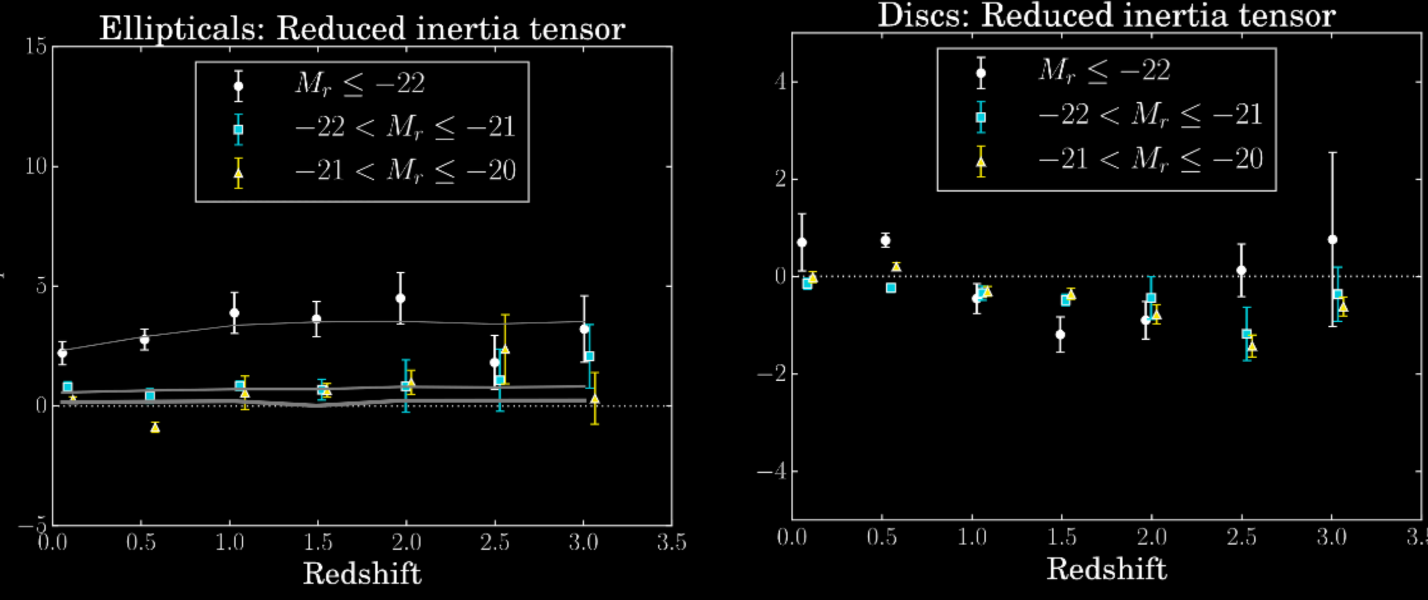
Hydrodynamical Simulations for IA

✦ ***Hydro simulations***: The dependence of IA amplitude on ***galaxy type*** can be directly addressed.

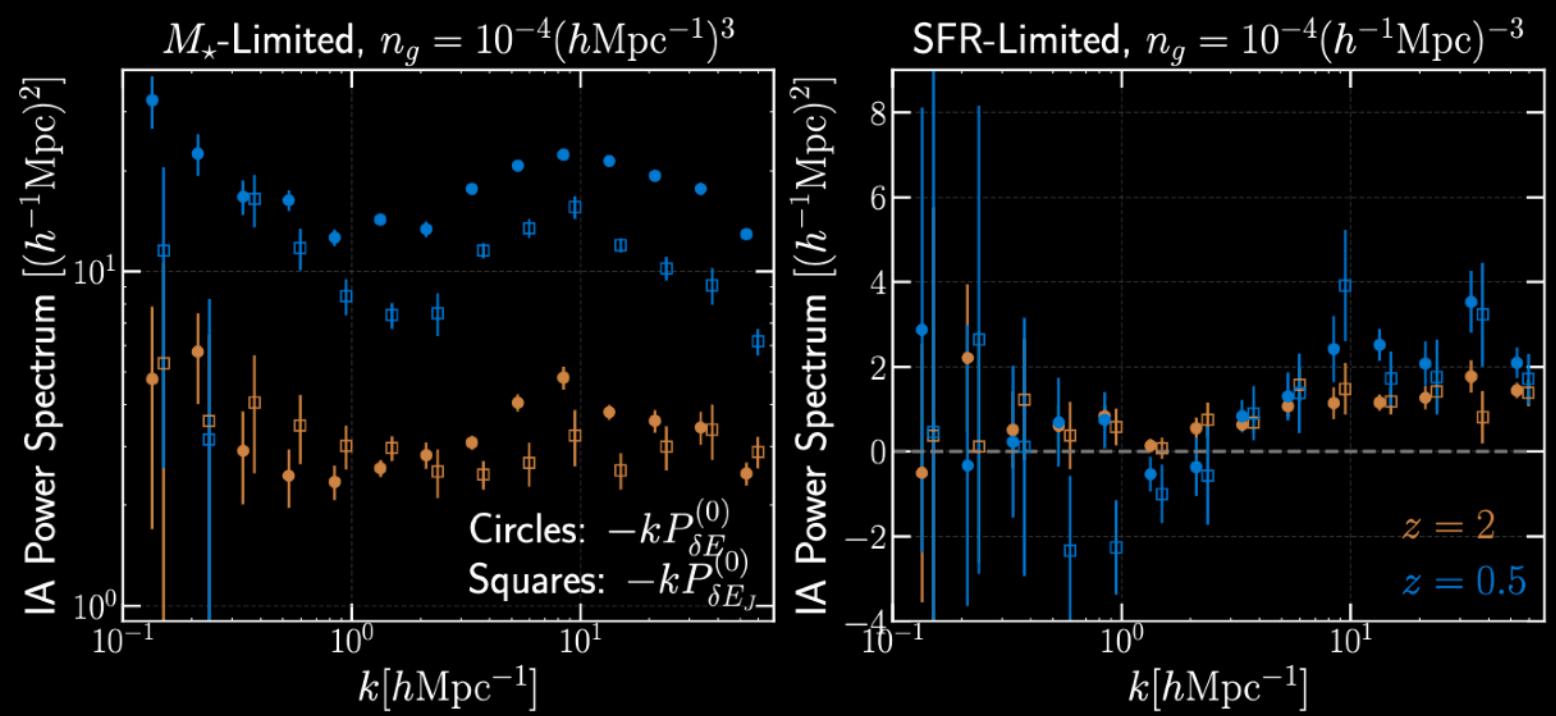
➡ **Horizon-AGN** (Chisari+, 2016)
IA measurements for two galaxy samples (discs/ellipticals) divided based on kinematics.

LRG-like **ELG-like**

IA amplitude (NLA assumed)

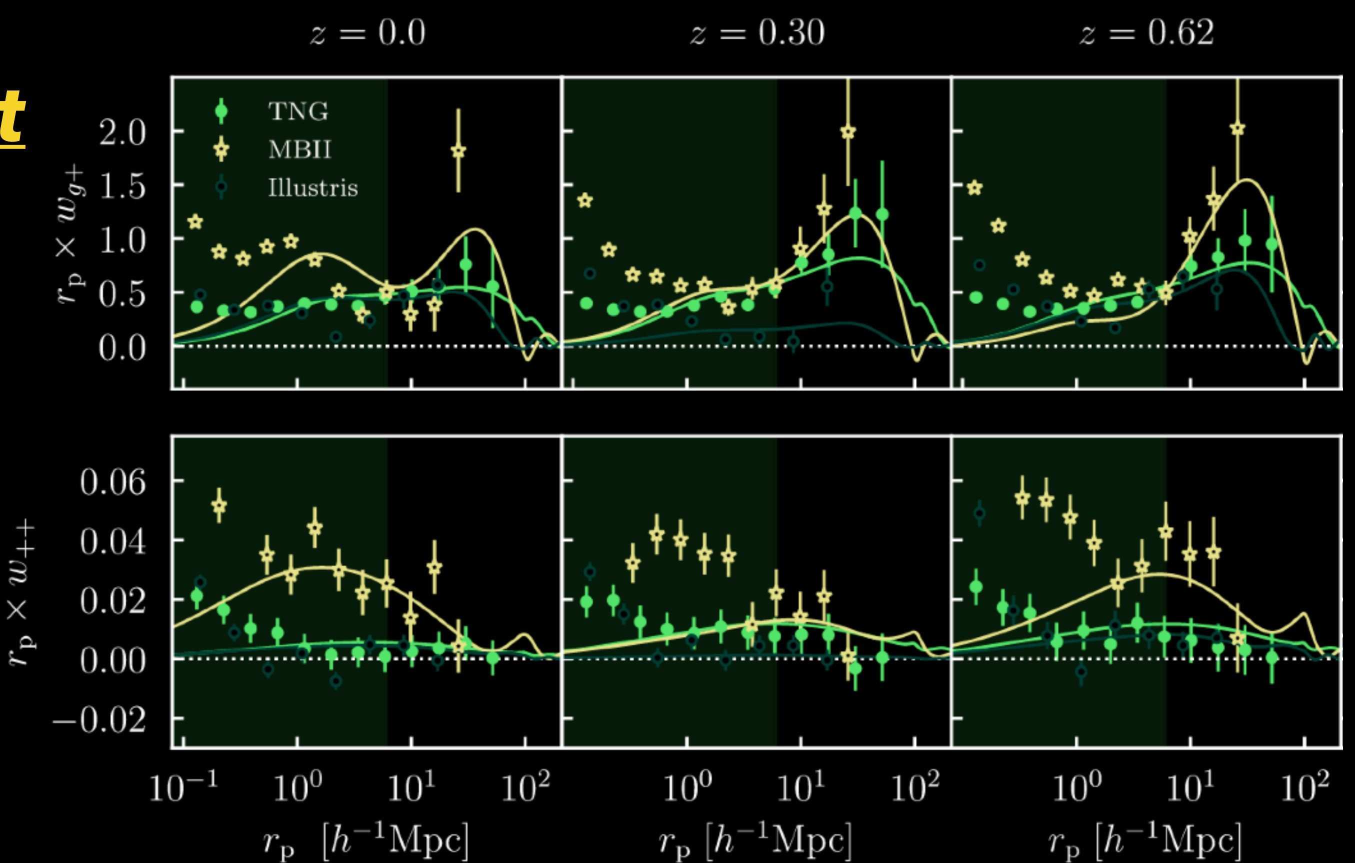


➡ **IllustrisTNG** (Shi+, 2021)
For M_*-limited samples, significant correlation is detected and for SFR-limited sample, the signal is consistent with null signal.

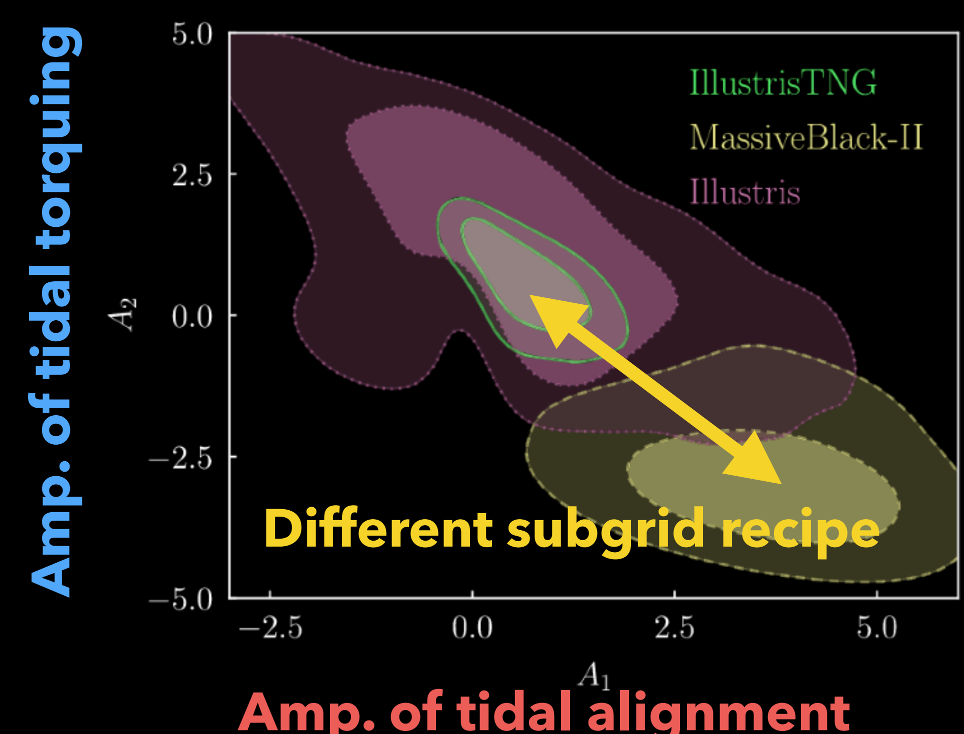


Hydrodynamical Simulations for IA

✦ ***Inconsistency between different galaxy formation simulations:***
The IA power spectra for *stellar mass selected* galaxy samples ($M_* > 1.6 \times 10^9$ Msun/*h*) with Illustris, IllustrisTNG, and MB-II.



➡ This inconsistency propagates to the estimated IA amplitudes;
IA of Illustris(TNG) galaxies can be explained with NLA and tidal torquing is zero consistent.
On the other hand, there is non-zero tidal torquing contribution for MB-II galaxies.



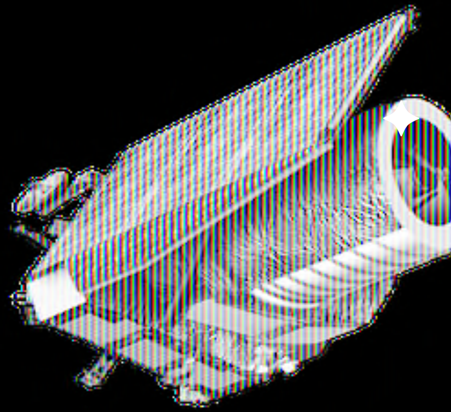
Samuroff, Mandelbaum, and Blazek (2021)

Observations of Emission Line Galaxies

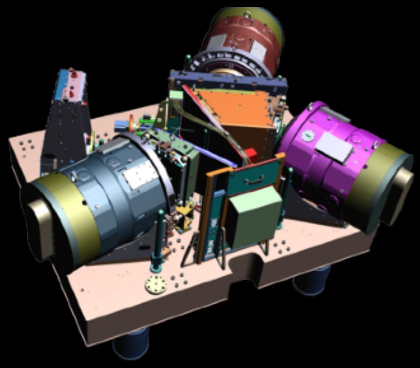
- ✦ Upcoming surveys will target ***emission line galaxies (ELGs)***. ELGs are characterised by strong emission line (Hα, [O II], etc.) from nebular emission irradiated by **short-lived massive stars**.
- ➡ ELGs are **blue spiral galaxies** and the response of the shape to large-scale structures can be different from **red elliptical galaxies**.
  - ***Tidal alignment*** vs ***Tidal torquing***

✦Future spectroscopic surveys

	Redshift	Survey coverage (deg^2)
PFS	0.6-2.4	1,200
DESI	0.6-1.6	14,000
Euclid	0.89-1.82	15,000



Euclid (in 2023 Q2)
coverage: 15,000 deg^2
Hα ELGs ($0.89 < z < 1.82$)



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

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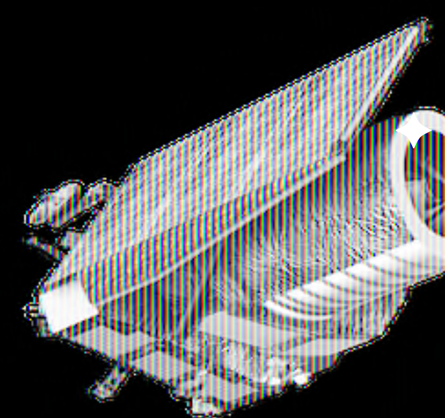

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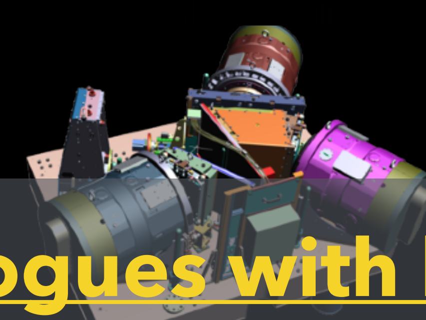

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coverage: 1,200 deg^2
[O II] ELGs ($0.6 < z < 2.4$)

✦ **High-fidelity mock ELG catalogues with hydrodynamical simulations are required to investigate the IA of ELGs!**

Construction of Mock ELG Catalogue

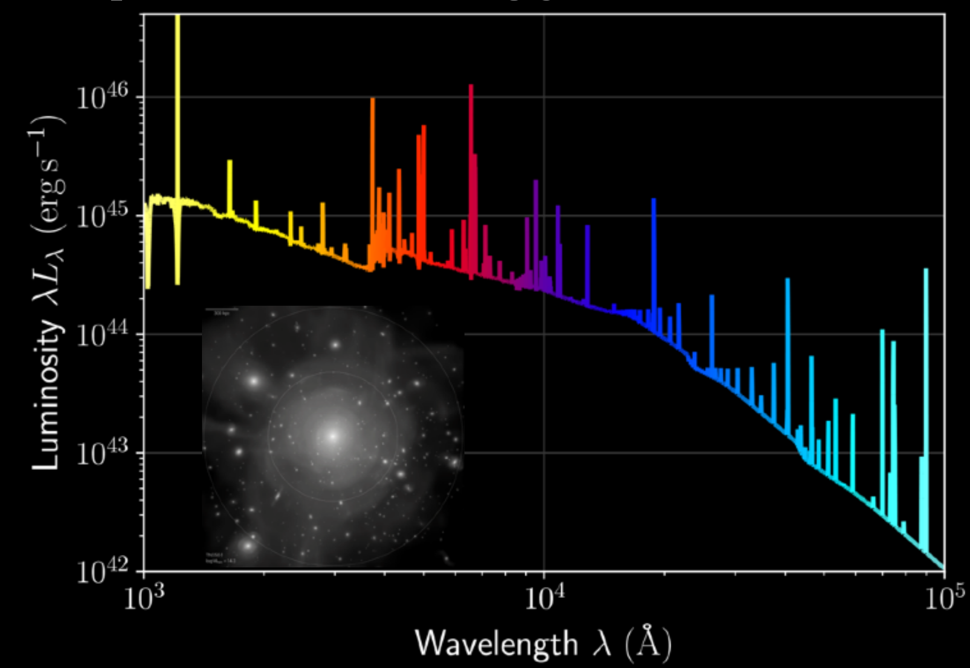
IllustrisTNG (Nelson+, 2019):

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, …

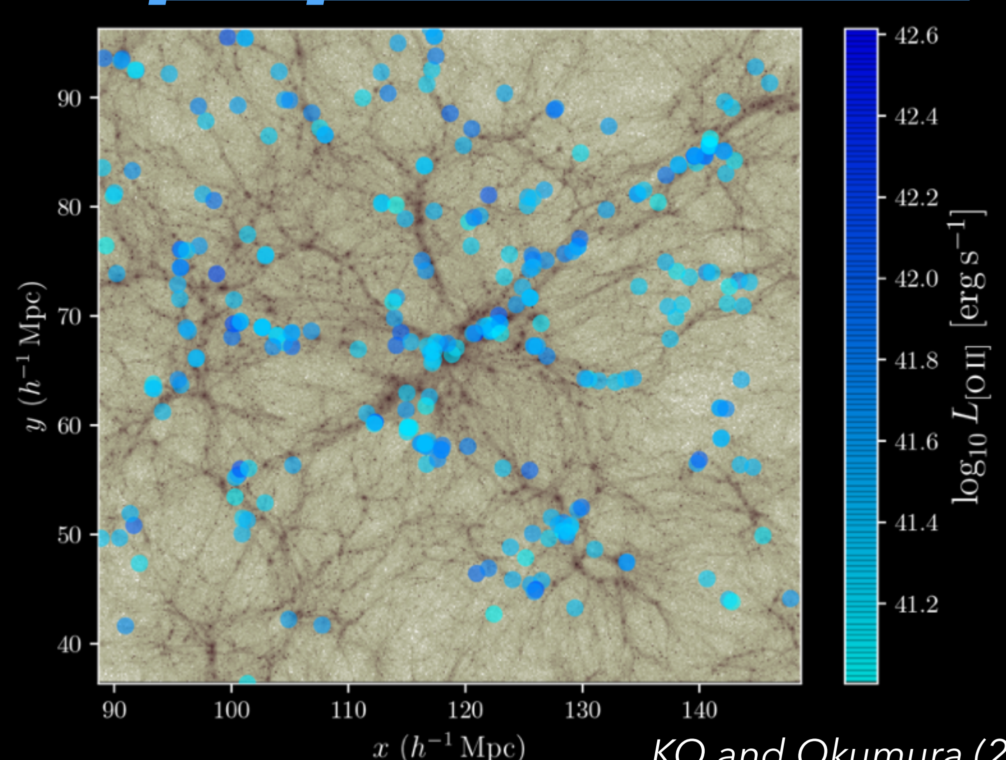
Stellar population synthesis:

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

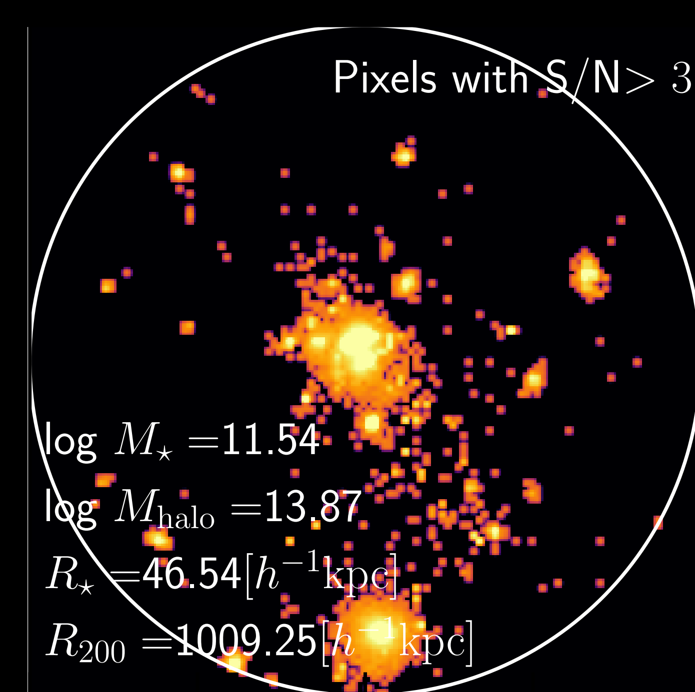


[O II] ELG distribution



KO and Okumura (2022)

HSC i-band luminosity

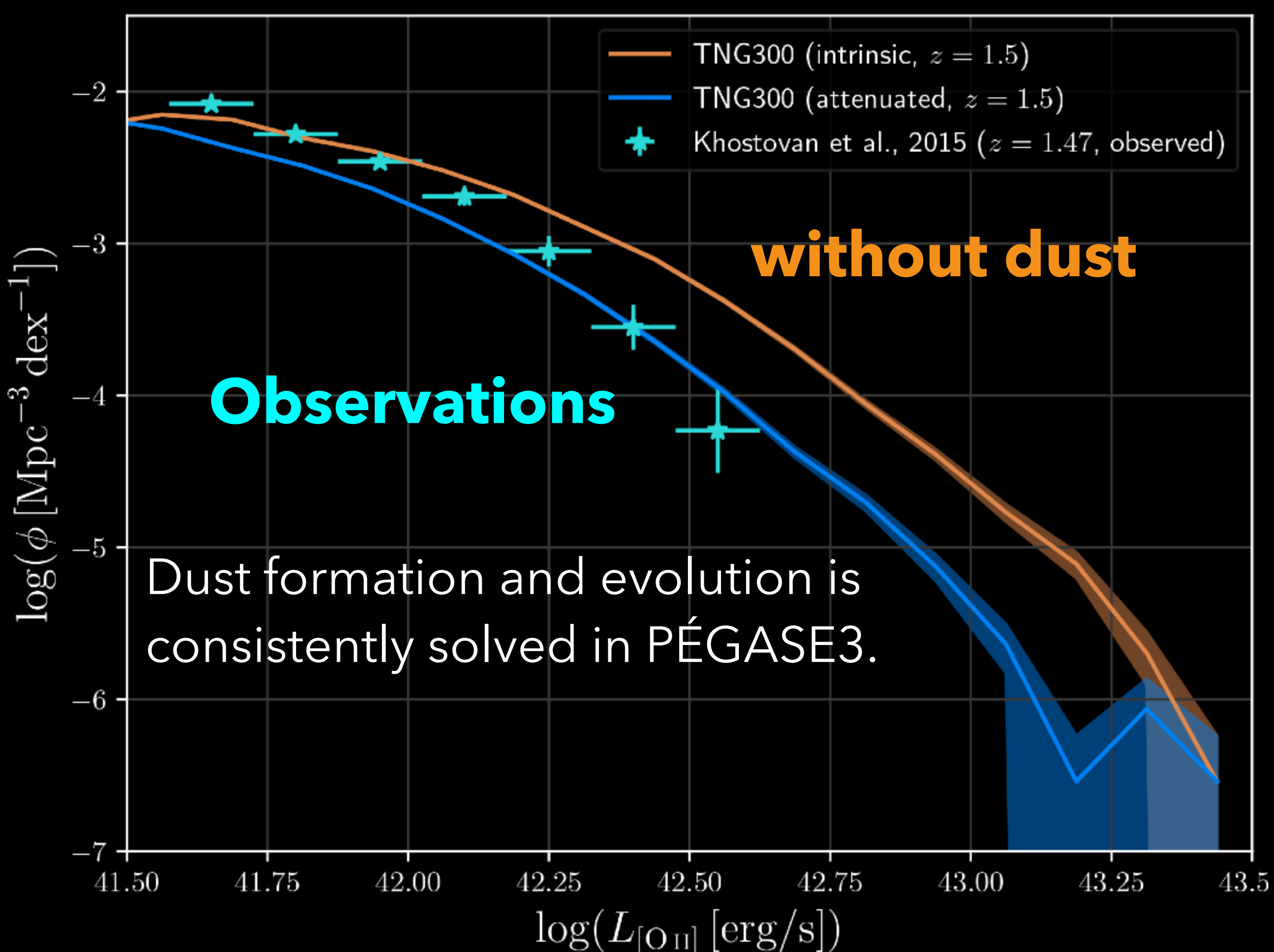


Shi, KO, Kurita and Takada (2021)

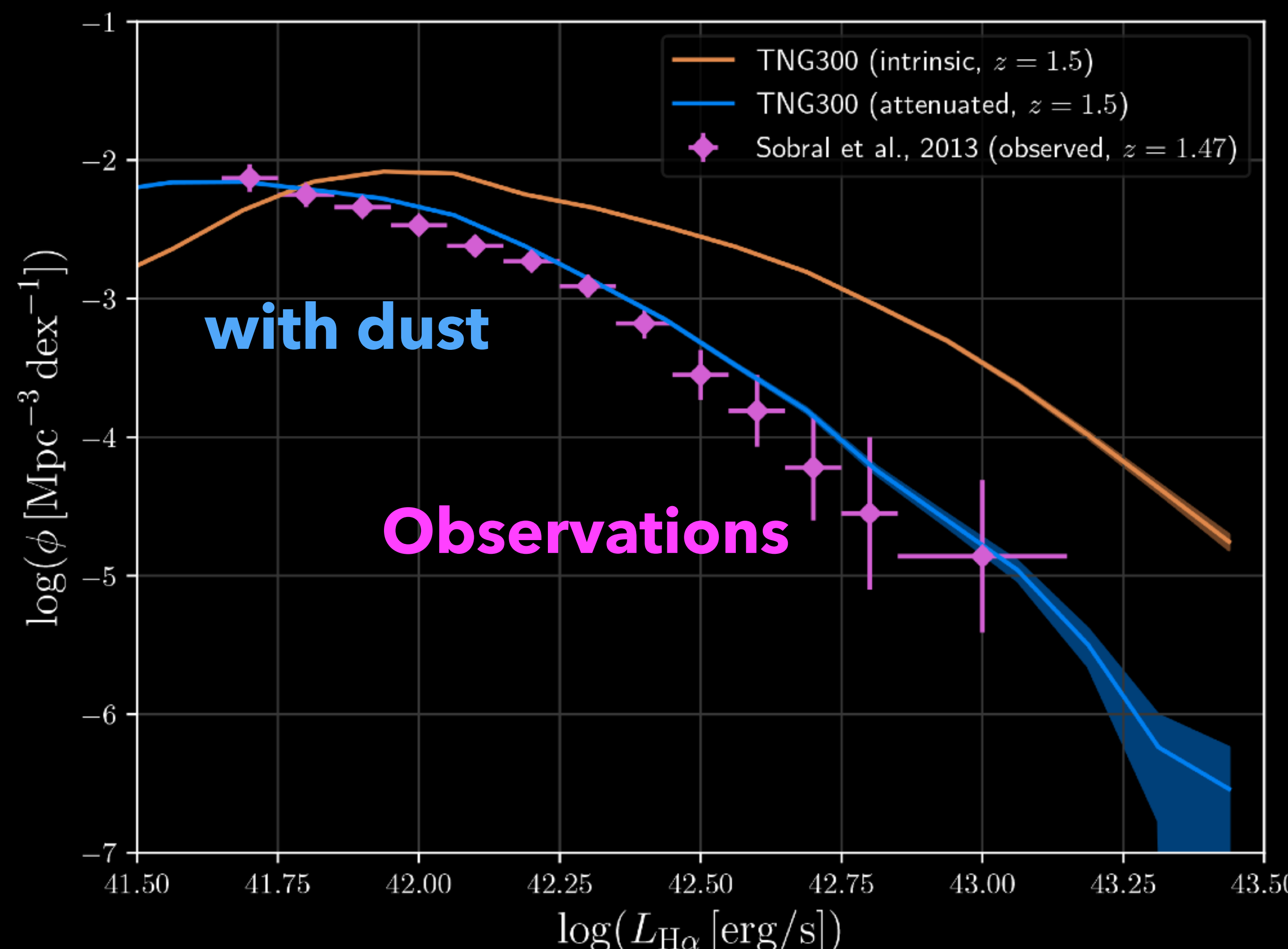
Luminosity Function of Hα and [O II] ELGs

- ✦ 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 additional tuning of parameters***.

Hα ELGs



[O II] ELGs



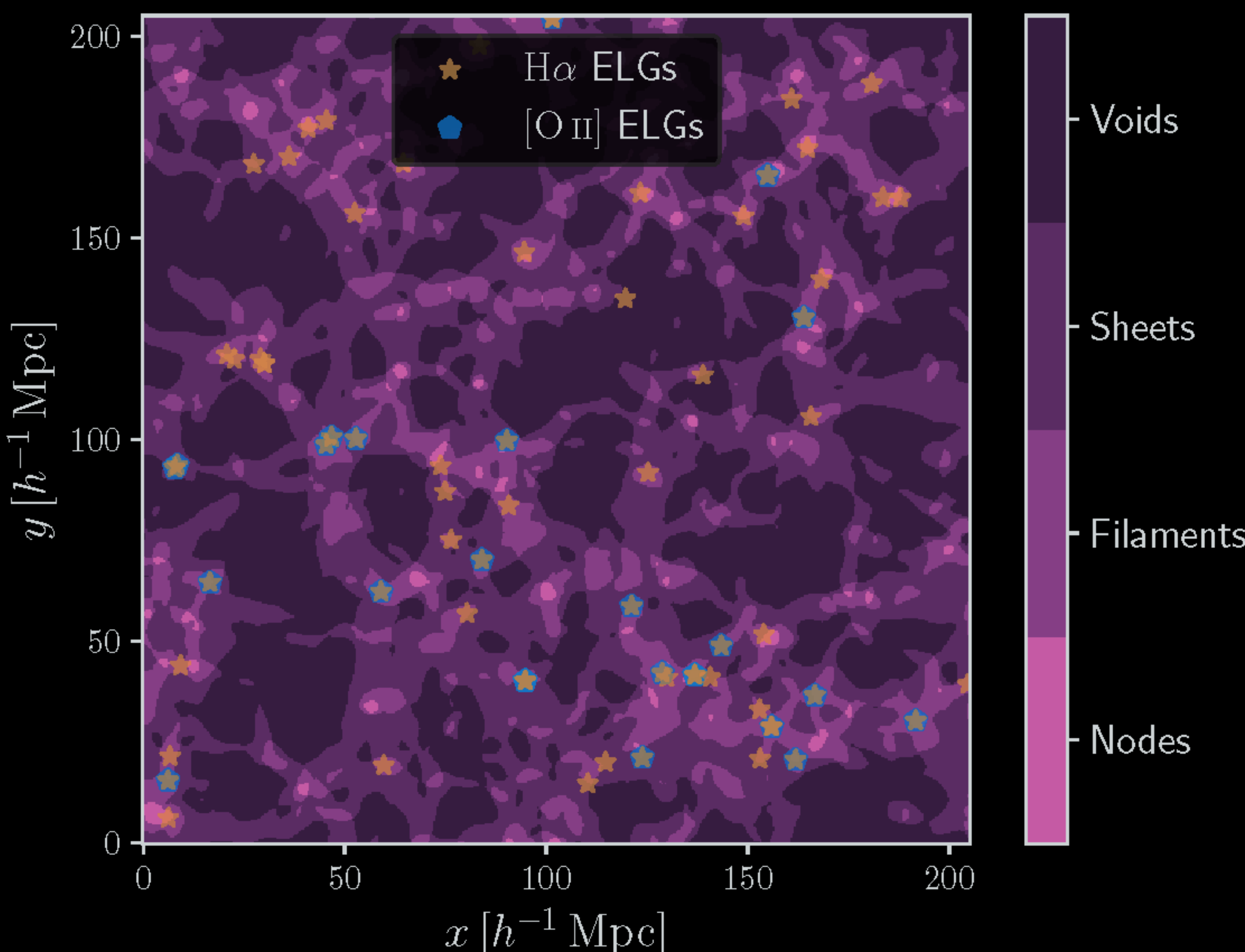
KO and Okumura (2022)

Environments: Cosmic Web

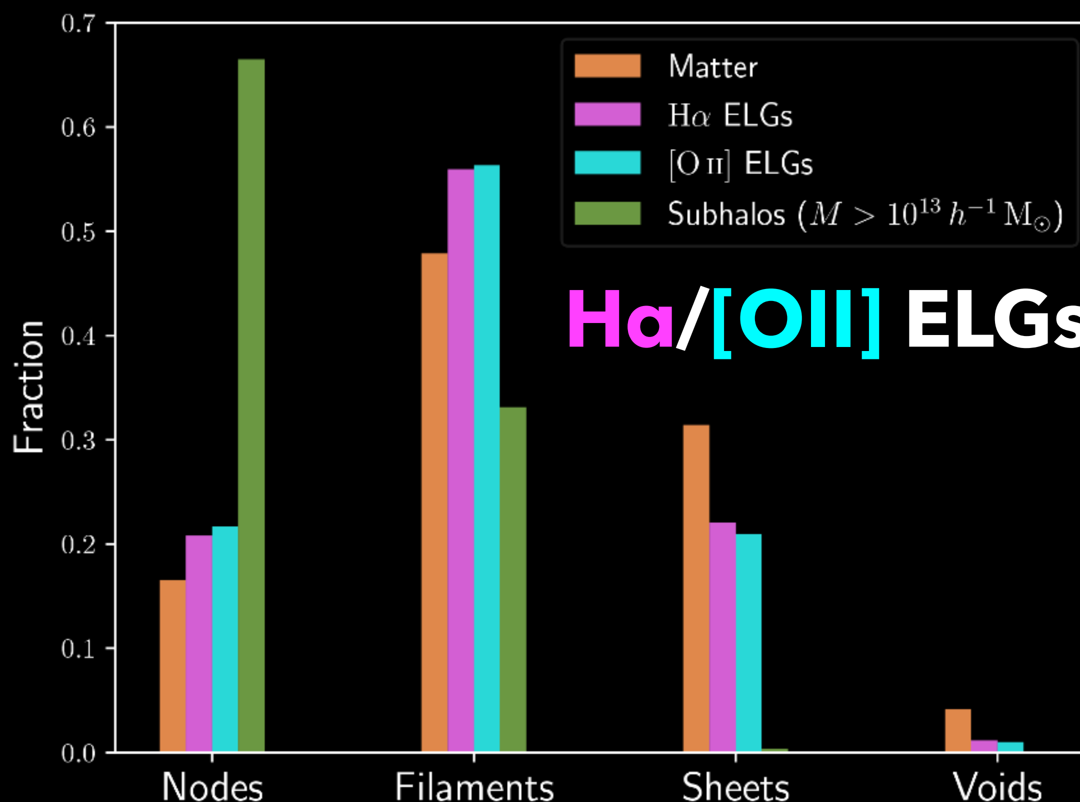
- ***Where are ELGs in cosmic web structures?***
  ELGs are likely to infall towards massive halos along filamentary structures
- ➡ Classification based on the tidal tensor (Hahn+ 2007, Libeskind+, 2018).

$$T_{ij} \equiv \frac{\partial^2 \phi}{\partial x_i \partial x_j}$$

ϕ : (scaled) gravitational potential



LRG-like (mass-limited sample)



- **ELGs are more likely to be found in filaments!**

KO and Okumura (2022)

IA Power Spectra of ELGs

- ***ELG shape cross-power spectrum:***

  [OII] ELGs ($L_{[\mathrm{OII}]} > 10^{41}$ erg/s) at z = 1.5

gg auto

gE cross

$b_1 = 1.97$

Dashed: NLA predictions

$A_{\rm IA} = 4$

$$P_{gE}(k,\mu;z) = -b_1 A_{\rm IA} C_1 \rho_{\rm cr0} \frac{\Omega_{\rm m}}{D(z)} (1-\mu^2) P_{\rm NL}(k)$$

IA Power Spectra of ELGs

shape-ELG cross power

IA amplitudes

Preliminary

IA Power Spectra of ELGs

shape-ELG cross power

IA amplitudes

Preliminary

- Future plan:
  constrain IA amplitudes and cosmological parameters from measured power spectrum

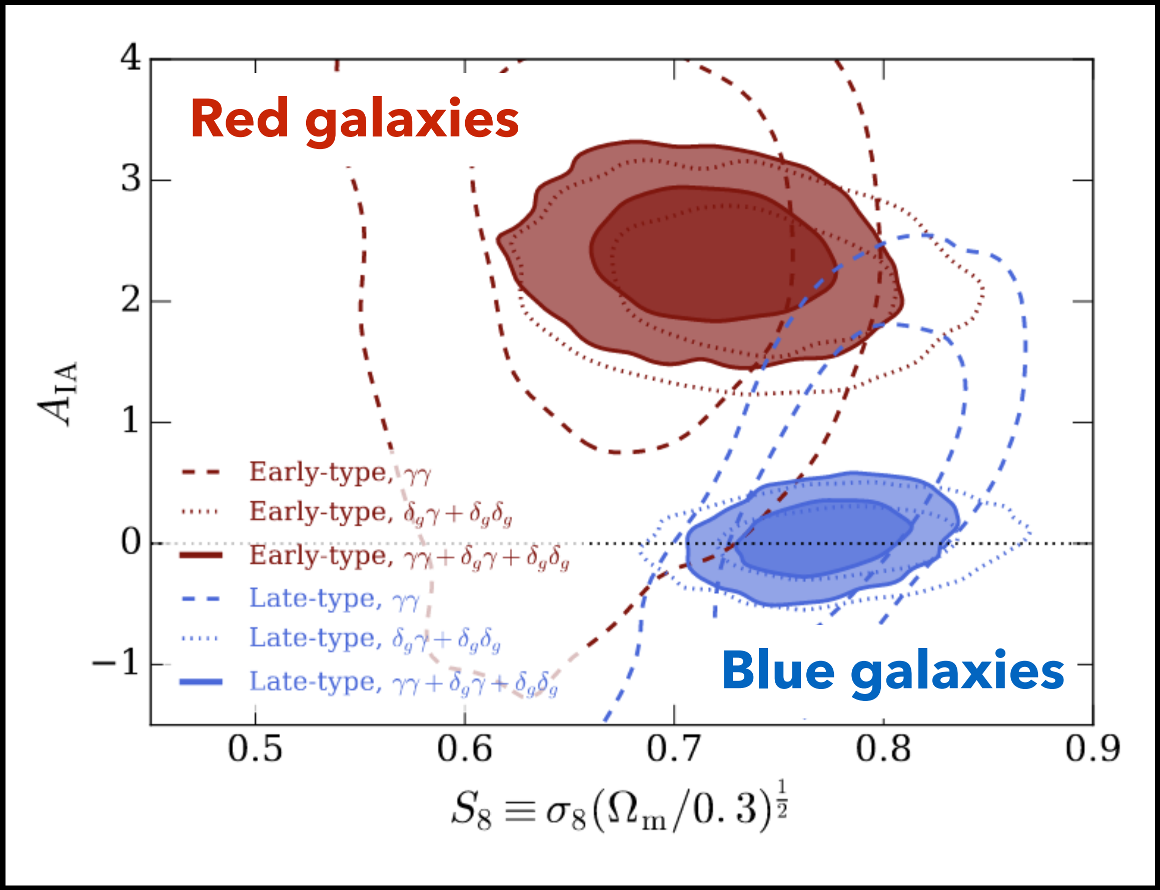
➡Cosmology challenge analysis

IA with mock ELG catalogues

- ***Detectability with future surveys***:
  Selection of ELGs and measurement error must be taken into account.

- ***Luminosity and redshift dependence***:
  How does IA amplitude of ELGs depend on luminosity and redshift?
  (*c.f. Benjamin Joachimi's talk*)

- ***Theoretical modelling***:
  NLA or TATT with non-zero tidal torquing?
  TATT works better for ELGs?



Samuroff+ (2019)

See also Simon Samuroff's talk slides for IA measurements of blue galaxies

Summary

- Hydrodynamical simulations are a powerful tool for IA because growth of large-scale structures and galactic properties (colour/luminosity) are traced simultaneously.

- The NLA model works for red elliptical galaxies and significant detections have already been reported. So far, there is no significant detection of IA for ELGs, but **IA of ELGs has potential to be detected by future surveys**.

- We have measured the shape power spectra of ELGs. We will perform challenge analysis to recover the cosmological parameters and investigate which IA modelling can reproduce the measured power spectrum.