Inferring the 3D shapes of galaxies inside halos with UNIONS: preparation for intrinsic alignment studies

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Laboratory: CEA, Paris-Saclay, CosmoStat

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Context and objectives

Galaxy-halo connection for intrinsic alignments

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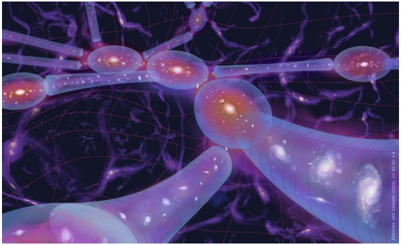
- **Galaxy-halo connection**: the link between galaxies and halos is not clear



Credit: Fortuna & Chisari (2025)

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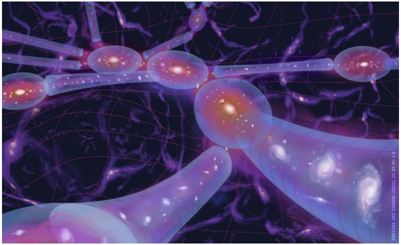
- **Galaxy-halo connection**: the link between galaxies and halos is not clear
- Understanding the **3D morphology** of galaxies inside dark matter halos can give insights about the process of **evolution** of galaxies across the **cosmic web**



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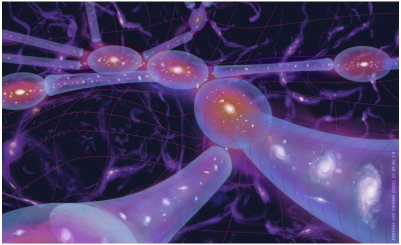

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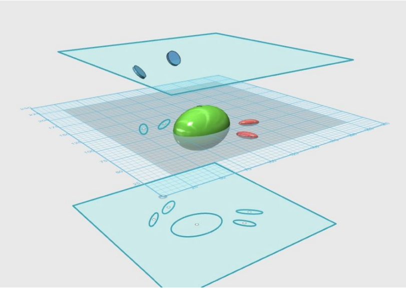

Joachimi et al. 2016

- This is interesting for **intrinsic alignments** (IA): the IA signal depends on the way the **shapes** of galaxies evolved in 3D among the **large-scale structure** of the Universe

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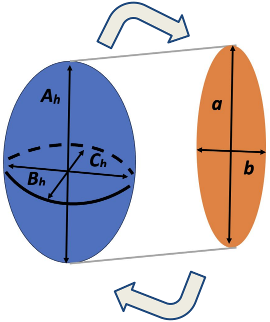
- **Problem:**

  => How to go from projected images to 3D shapes ?



UNIONS (Ultraviolet Near Infrared Optical Northern Survey)

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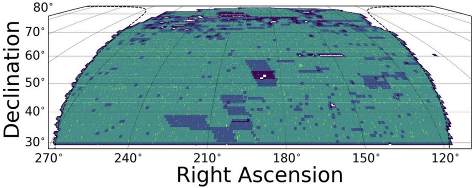

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  ~340 millions of galaxy shapes
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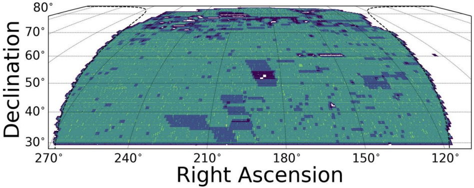

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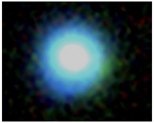
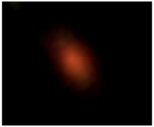
- **Measure** of **intrinsic alignments** by cross-matching UNIONS 2D shapes of galaxies with **spectroscopic** surveys (*Hervas Peters et al. 2025*, see Martin's talk tomorrow*)*

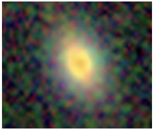
UNIONS x DESI

- **Spectroscopic samples** of galaxies:

  - **ELG**, **LRG** and **BGS**, Dark Energy Spectroscopic Instrument (DESI) DR1







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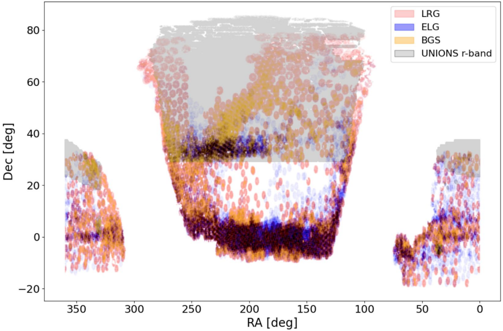

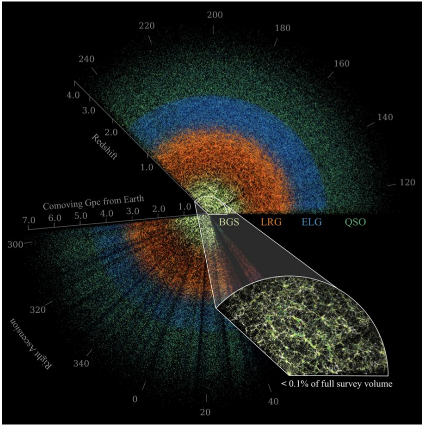

DESI Collaboration 2025

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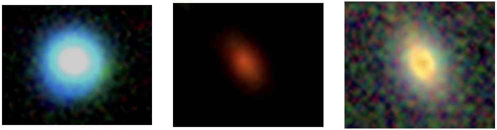

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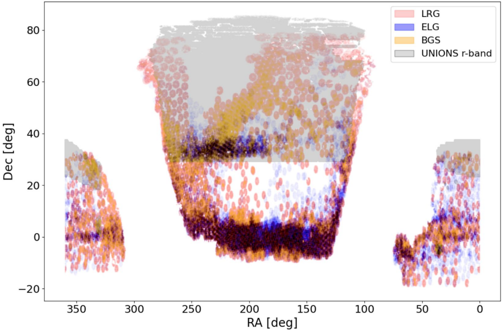
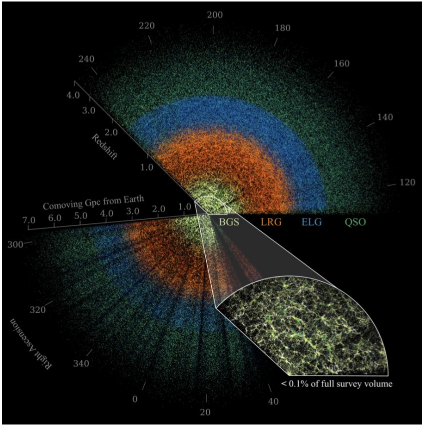


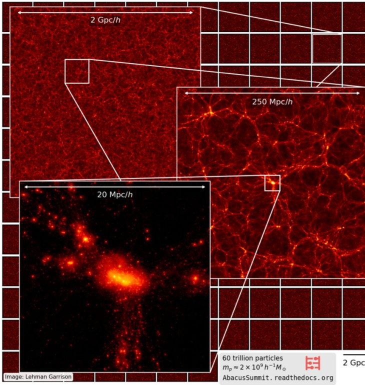


DESI Collaboration 2025

- **Cross-match** with **UNIONS** forms
  . **ELG-UNIONS**: ~360 000 galaxies
  . **LRG-UNIONS**: ~360 000 galaxies
  . **BGS-UNIONS**: ~1 300 000 galaxies

N-body simulations AbacusSummit

- **Simulation suite** designed to meet the requirements of DESI



Maksimova et al. 2021

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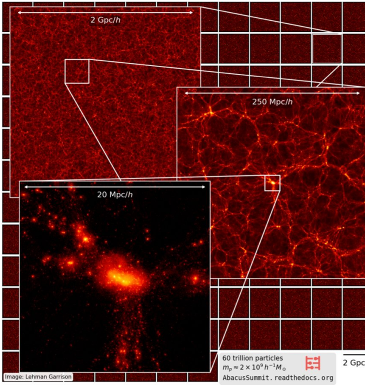

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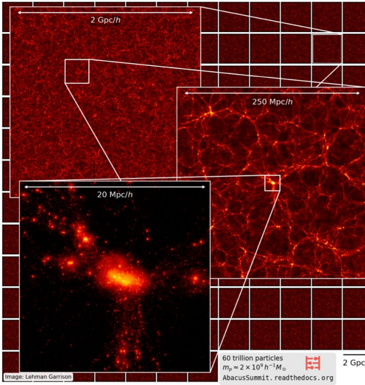

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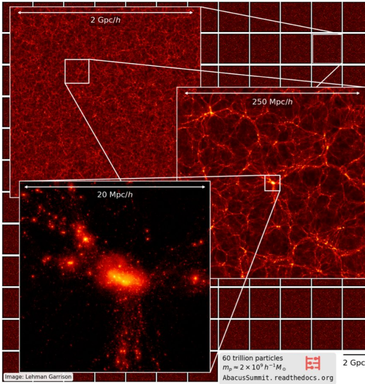

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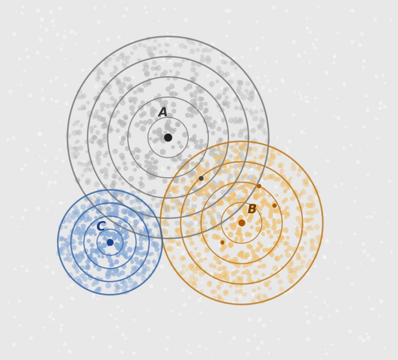

- **Catalogues of halos** identified with the CompaSO (Competitive Assignment to Spherical Overdensities) algorithm (*Hadzhiyska et al. 2021*)

Methodology

I) Getting a halo catalogue per galaxy sample

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IV) Inferring galaxy-halo connection from observations using simulation-based inference (SBI)

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- *Step 1*: Generate a **mock galaxy catalogue** in a simulation box using an **HOD (Halo Occupation Distribution) model** for each galaxy sample

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Example: HOD model for the LRG (*Yuan et al. 2023*)

Mean occupation number of **central** and **satellite** galaxies:

$$\bar{n}_{\rm cent}^{\rm LRG}(M) = \frac{f_{\rm ic}}{2}\,{\rm erfc}\left[\frac{\log_{10}(M_{\rm cut}/M)}{\sqrt{2}\sigma}\right] \qquad \bar{n}_{\rm sat}^{\rm LRG}(M) = \left[\frac{M-\kappa M_{\rm cut}}{M_1}\right]^{\alpha}\bar{n}_{\rm cent}^{\rm LRG}(M)$$

M	mass of the host halo
$M_{\rm cut}$	minimum halo mass to set a central galaxy
$f_{\rm ic}$	incompleteness parameter (by definition: $0 < f_{\rm ic} \leq 1$)
σ	steepness of the transition from 0 to 1 in the number of central
$\kappa M_{\rm cut}$	minimum halo mass to host a satellite galaxy
α	power law index on the number of satellite galaxies
M_1	typical halo mass that hosts one satellite galaxy

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Code: *AbacusHOD* (*Yuan et al. 2021*)

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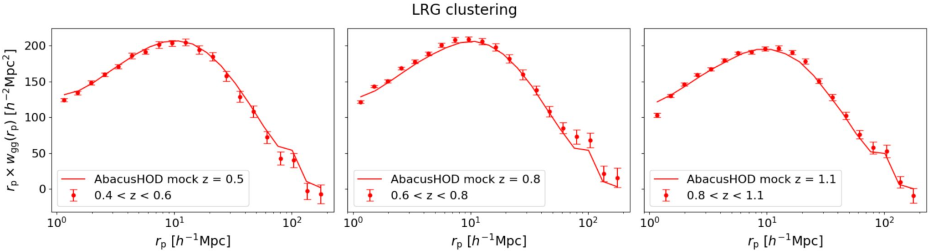

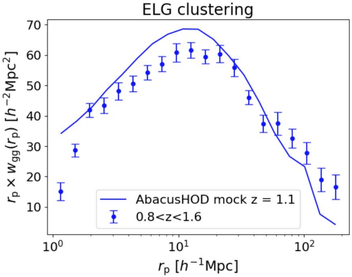

$$\xi_{gg}(r_\mathrm{p},\Pi) = \frac{DD(r_\mathrm{p},\Pi) - 2\,DR(r_\mathrm{p},\Pi) + RR(r_\mathrm{p},\Pi)}{RR(r_\mathrm{p},\Pi)}$$

$$w_{gg}(r_\mathrm{p}) = \int_{-\Pi_\mathrm{max}}^{\Pi_\mathrm{max}} \mathrm{d}\Pi\, \xi_{gg}(r_\mathrm{p},\Pi)$$ *Landy & Szalay 1993*

- Best fit HOD parameters from *Yuan et al. 2023* and *Rocher et al. 2024*

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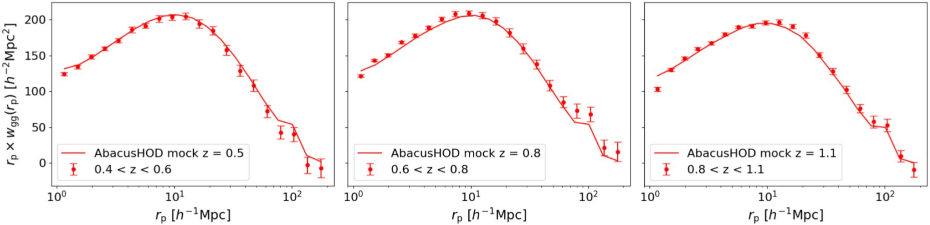
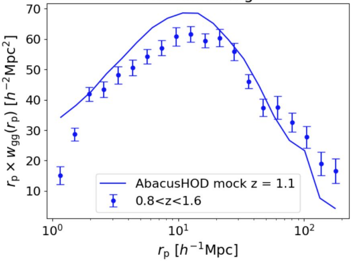
LRG clustering



ELG clustering



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- *Step 3*: Extract the **host halos** of the corresponding galaxies of the mock

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- Simple **inertia tensor**: $I_{ij} = \frac{\sum_n m_n x_{ni} x_{nj}}{\sum_n m_n}$

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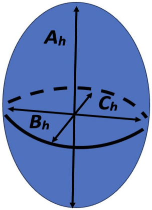

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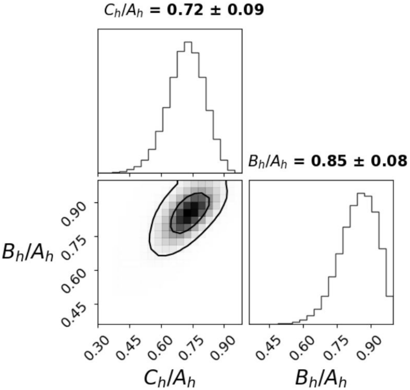
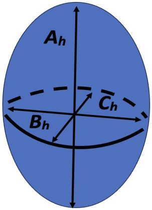
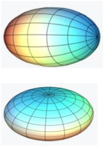
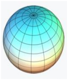






prolate $A_h > B_h \approx C_h$

oblate $A_h \approx B_h > C_h$



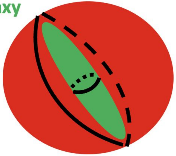
spheroidal $A_h \approx B_h \approx C_h$

Example: Abacus halos at $z = 0.5$

Pandya et al. 2024

III) Modelling the 3D shapes of galaxies inside halos

- **Populating** each halo with a 3D **central galaxy** of axis lengths A_g, B_g, C_g such that:



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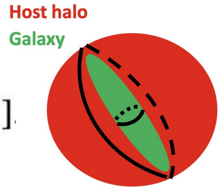

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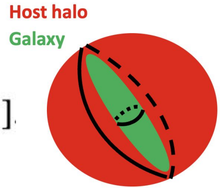

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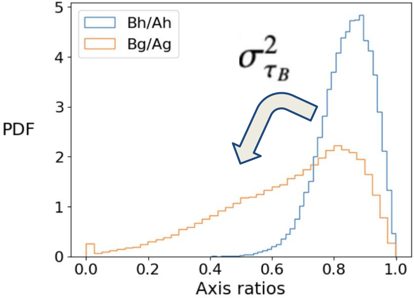

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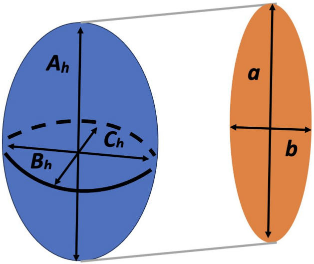
- **Projection** in 2D (*Lamman et al. 2023*) for different μ_{τ_B}, μ_{τ_C} drawn uniformly in $[0;1]$.



IV) Inferring 3D galaxy-halo connection with SBI

PRIORS

INPUT PARAMETERS (3D)

Parameters of 3D galaxy-halo connection θ

FORWARD SIMULATIONS

. **HOD**

. **Model** of galaxy 3D shapes

. **Projection** 3D → 2D

OUTPUT (2D)

Distribution of **galaxy ellipticities** = summary statistics

x = P(e)

TRAINING / INFERENCE

Neural Posterior Estimation (NPE)

. **training** a neural network on simulated pairs (θ, x)

. **estimation** of P(θ|x)

. **inference**: constraints on 3D galaxy-halo connection

DATA

Observed distribution of **ellipticities**

$P_{obs}(e)$

VALIDATION

- Posterior Predictive Check
- Ensemble test
- Coverage test

Analyses

- **(1)** LRG in 3 redshift bins

  $0.4 < z < 0.6$ $\quad$ $0.6 < z < 0.8$ $\quad$ $0.8 < z < 1.1$

  => testing for redshift evolution

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- **(1)** LRG in 3 redshift bins

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  => testing for redshift evolution

  (2) ELG $0.8 < z < 1.6$ and LRG $0.4 < z < 0.6$

  => testing for different types of galaxies

Analyses

- **(1)** LRG in 3 redshift bins

  $0.4 < z < 0.6$ $\quad$ $0.6 < z < 0.8$ $\quad$ $0.8 < z < 1.1$

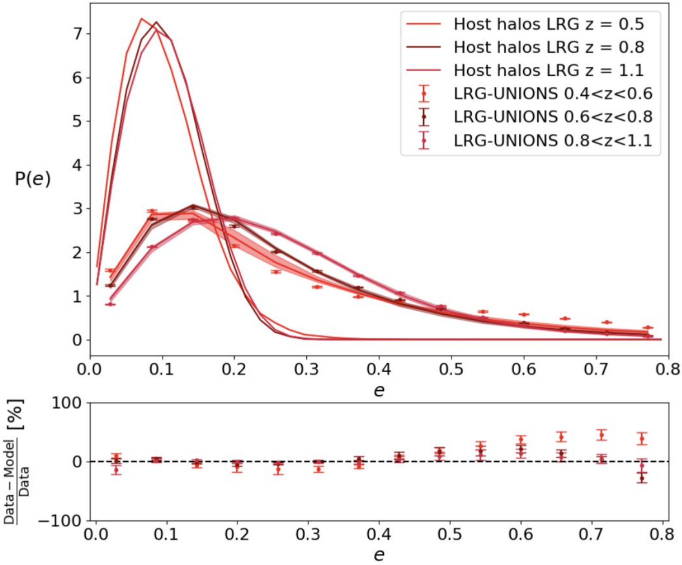
  => testing for redshift evolution

  (2) ELG $0.8 < z < 1.6$ and LRG $0.4 < z < 0.6$

  => testing for different types of galaxies

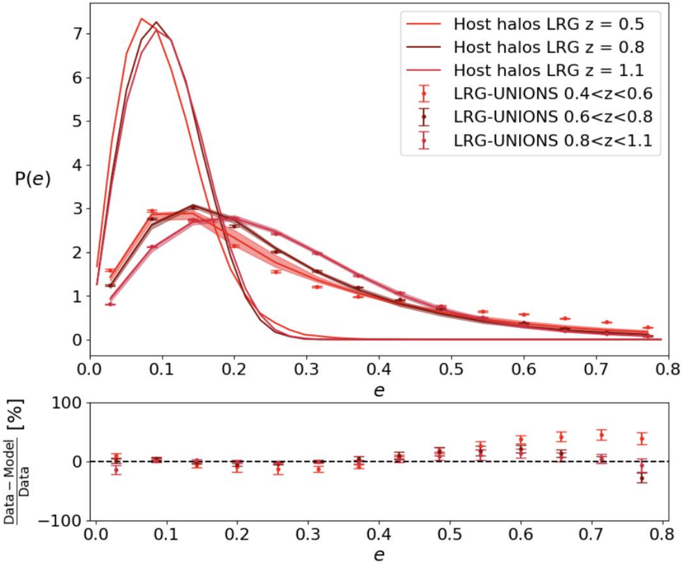
- For each case:
  - distribution of ellipticities
  - galaxy-halo connection
  - constraint on 3D shapes

(1) Redshift evolution: distribution of ellipticities



Preliminary

(1) Redshift evolution: distribution of ellipticities

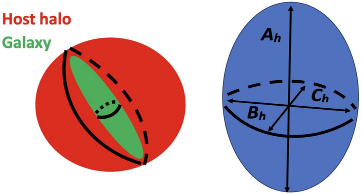


Preliminary

LRG 2D shapes more elongated at higher redshift

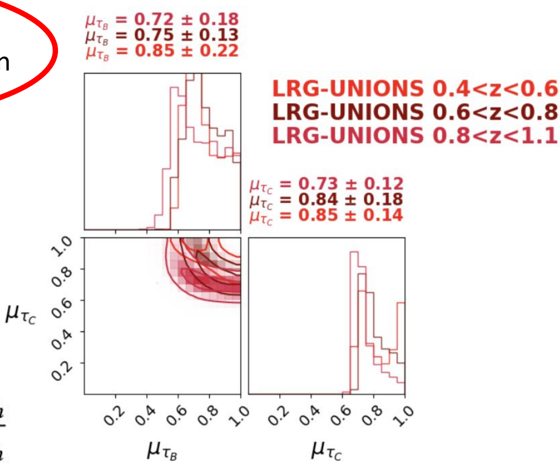
(1) Redshift evolution: galaxy-halo connection

$\mu_{\tau_B}, \mu_{\tau_C}$: means of τ_B, τ_C for the whole halo population



$$\frac{B_g}{A_g} = \tau_B \frac{B_h}{A_h} \qquad \frac{C_g}{A_g} = \tau_C \frac{C_h}{A_h}$$

with $\tau_B, \tau_C \in [0; 1]$



Preliminary

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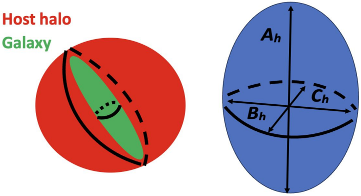

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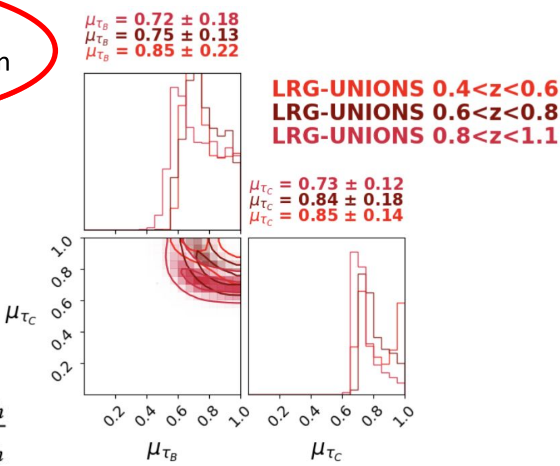
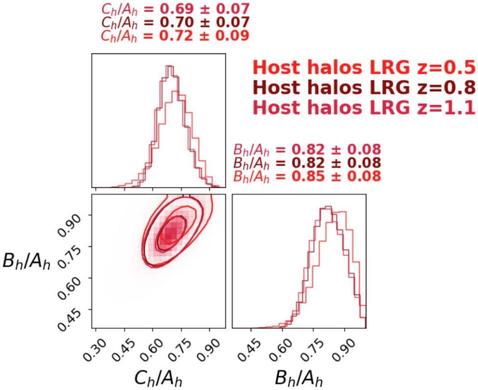


Preliminary

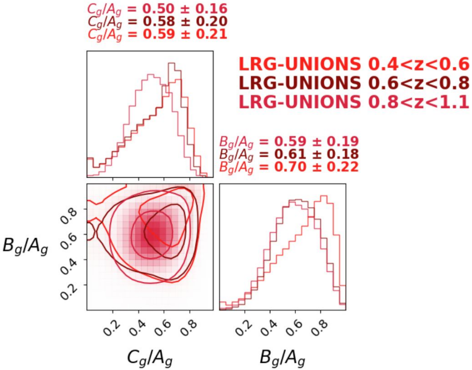
LRG 3D shapes more stretched inside their halos at higher redshift

(1) Redshift evolution: constraints on 3D shapes

Halos



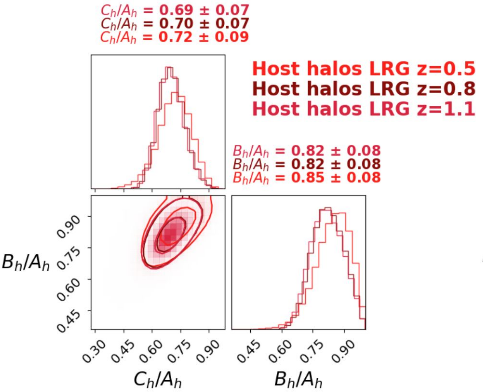
Galaxies



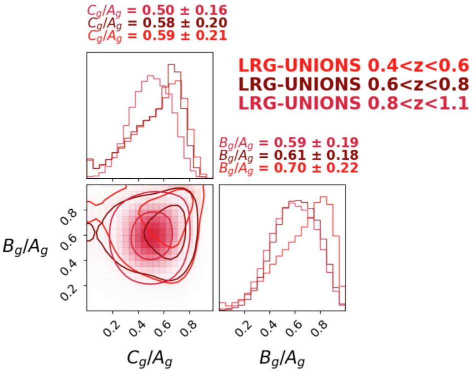
Preliminary

(1) Redshift evolution: constraints on 3D shapes

Halos



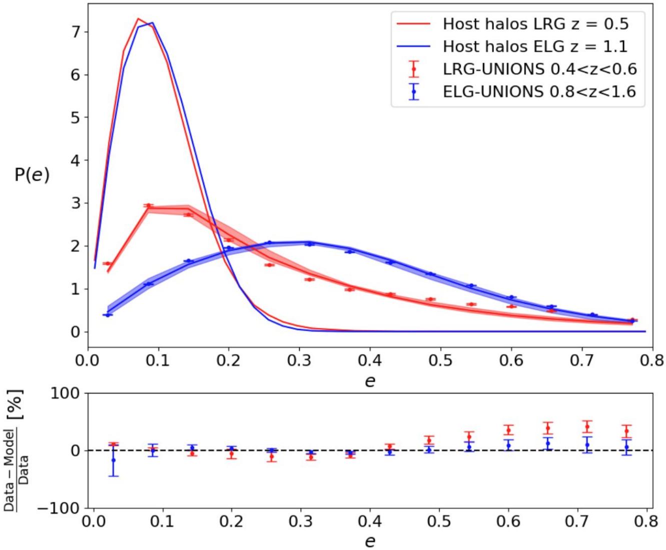
Galaxies



Preliminary

LRG 3D shapes more elongated at higher redshift
Host halos rounder than the galaxies

(2) ELG / LRG: distribution of ellipticities



Preliminary

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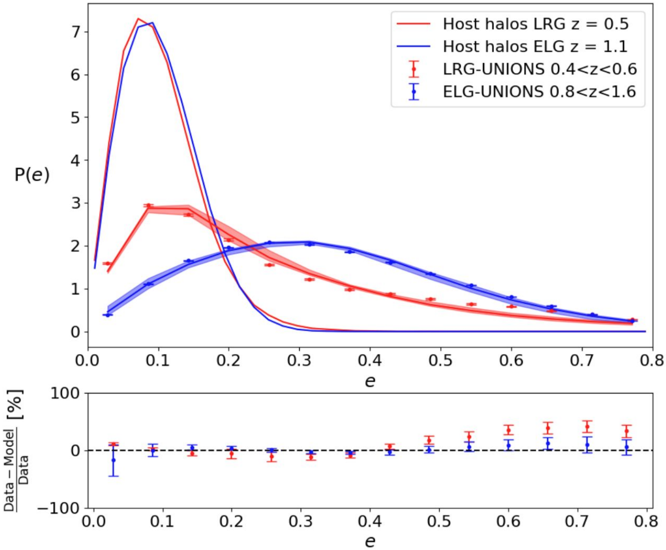
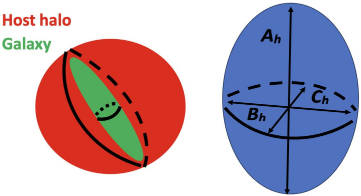


Preliminary

ELG 2D shapes more elongated than LRG

(2) ELG / LRG: galaxy-halo connection

$\mu_{\tau_B}, \mu_{\tau_C}$: means of τ_B, τ_C for the whole population



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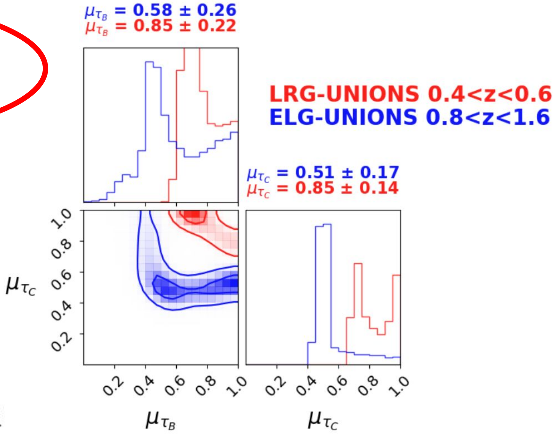

Preliminary

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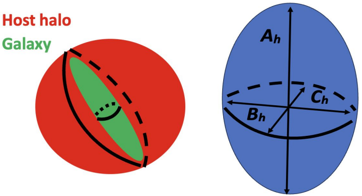

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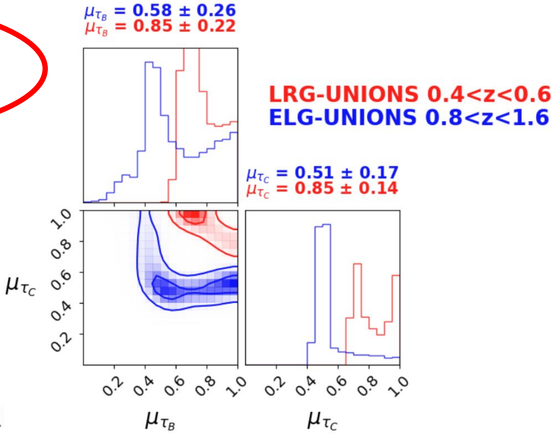
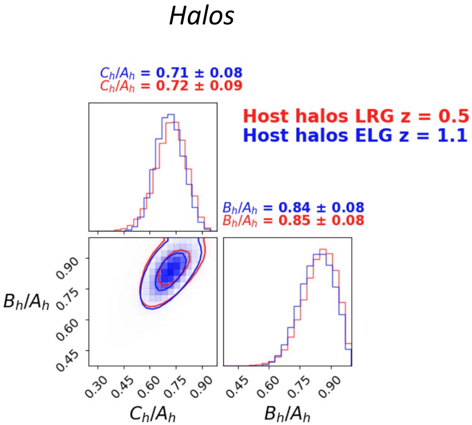
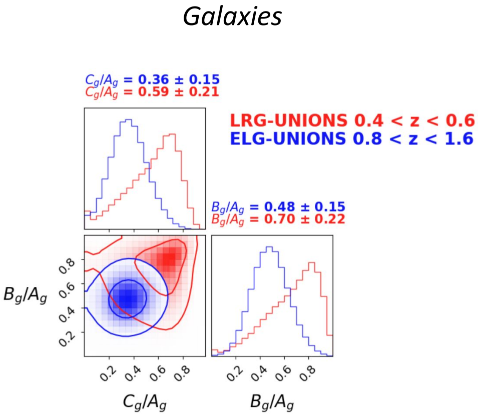


Preliminary

We probe different 3D shapes between LRG and ELG

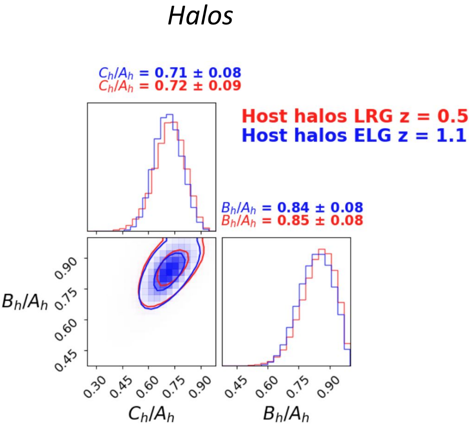
(2) ELG / LRG: constraints on 3D shapes

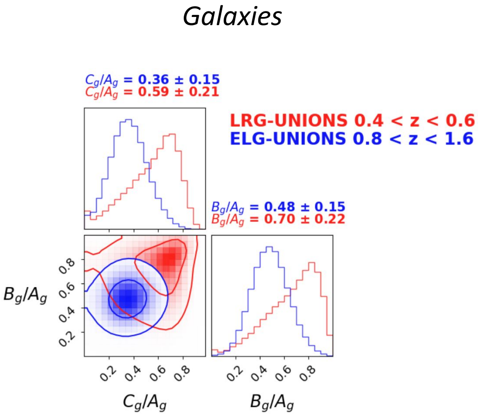




Preliminary

(2) ELG / LRG: constraints on 3D shapes



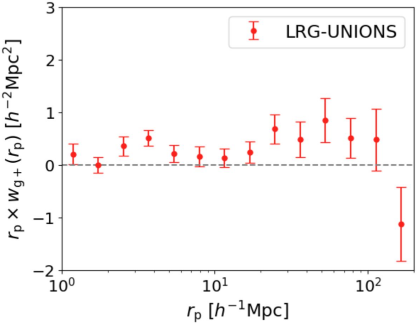


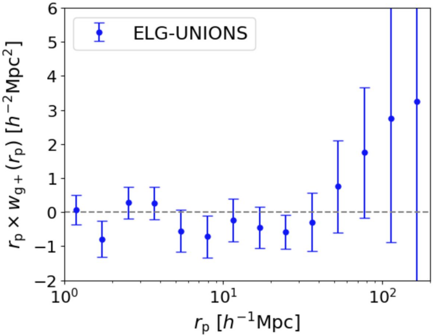
Preliminary

ELG: more elongated objects in 3D than LRG

Towards galaxy intrinsic alignment in 3D…

$$\xi_{g+}(r_p, \Pi) = \frac{S_+D(r_p, \Pi) - S_+R_D(r_p, \Pi)}{R_S R_D(r_p, \Pi)} \qquad w_{g+}(r_p) = \int_{-\Pi_{max}}^{\Pi_{max}} d\Pi\, \xi_{g+}(r_p, \Pi)$$





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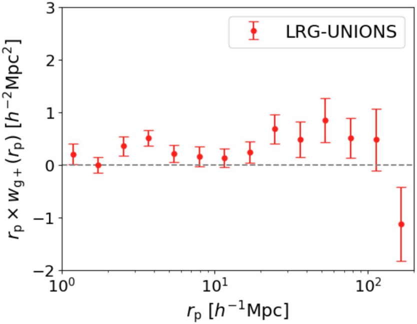
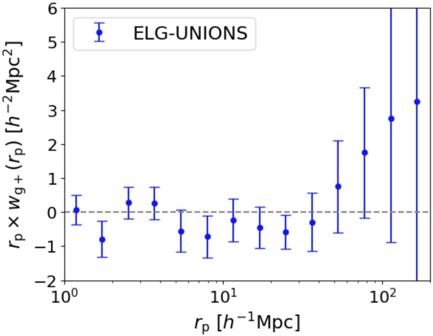
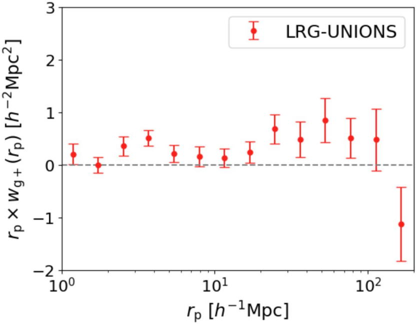


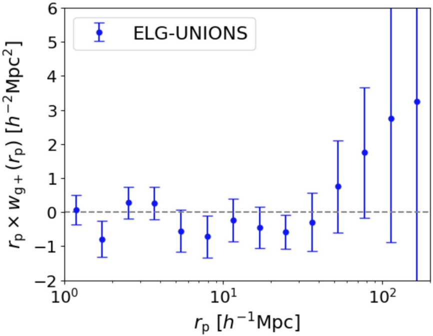


- **Future aim**: make a prediction of intrinsic alignment of galaxy using our model of 3D morphology

Towards galaxy intrinsic alignment in 3D…

$$\xi_{g+}(r_p, \Pi) = \frac{S_+D(r_p, \Pi) - S_+R_D(r_p, \Pi)}{R_S R_D(r_p, \Pi)} \qquad w_{g+}(r_p) = \int_{-\Pi_{max}}^{\Pi_{max}} d\Pi\, \xi_{g+}(r_p, \Pi)$$





- **Future aim**: make a prediction of intrinsic alignment of galaxy using our model of 3D morphology
  => **motivation**: to reveal extra informations to intrinsic alignments about the 3D morphology of galaxies

Conclusion and next steps

- Development of a model of **3D morphology** for central galaxies inside dark matter halos using AbacusSummit N-body simulations

Conclusion and next steps

- Development of a model of **3D morphology** for central galaxies inside dark matter halos using AbacusSummit N-body simulations

- Development of a **simulation-based inference** method to measure the **distribution** of the 3D shapes of galaxies from the distribution of their **projected images**

Conclusion and next steps

- Development of a model of **3D morphology** for central galaxies inside dark matter halos using AbacusSummit N-body simulations

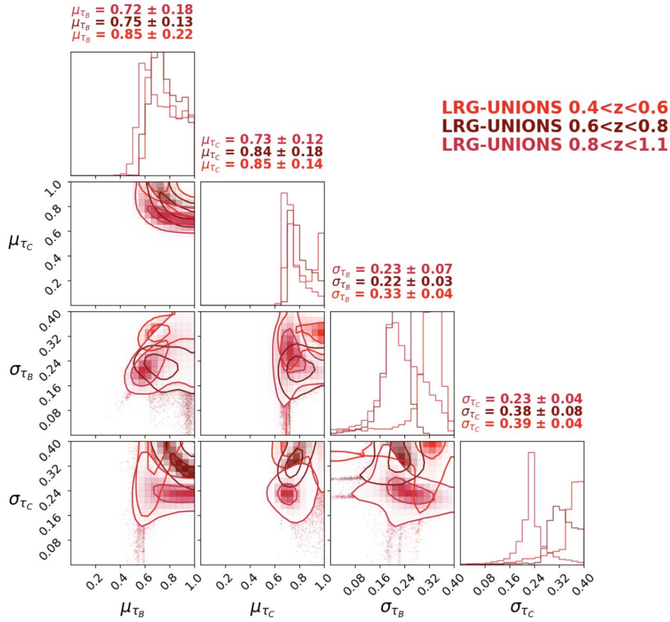
- Development of a **simulation-based inference** method to measure the **distribution** of the 3D shapes of galaxies from the distribution of their **projected images**

- Ongoing works / next steps:
  - applying our pipeline to the DESI **BGS** sample
  - adding a **misalignment** parameter for the central galaxies
  - develop a model of 3D morphology for **satellite** galaxies
  - work with **hydrodynamic simulations**

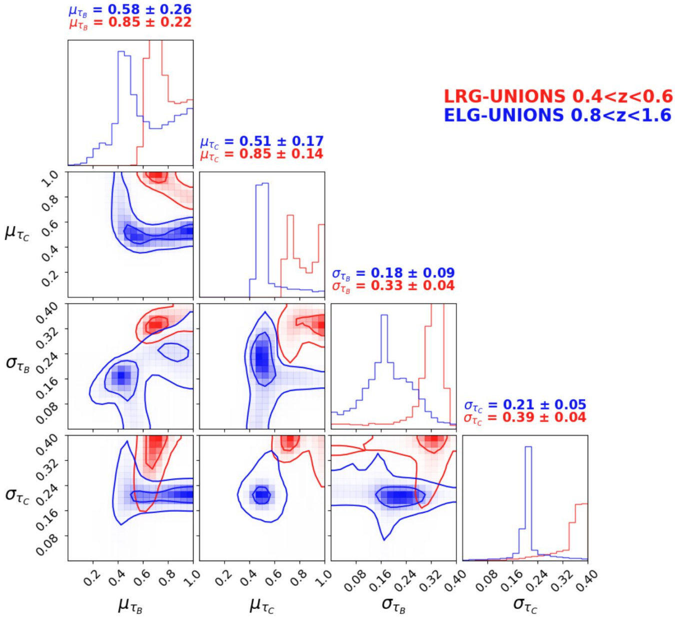
Thank you for your attention !

Back up slides

Redshift evolution: other parameter constraints

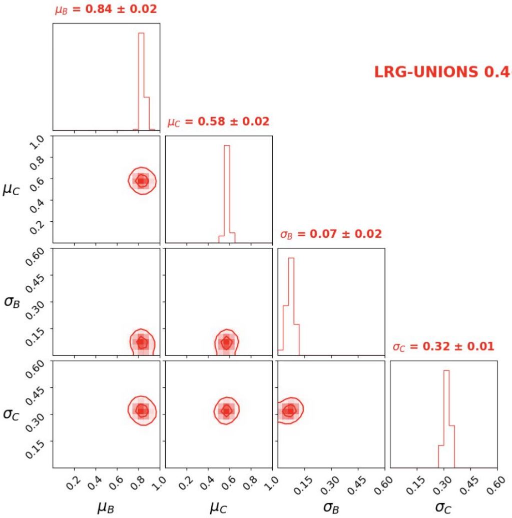


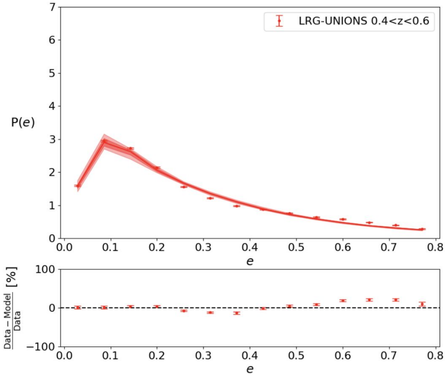
ELG / LRG: other parameter constraints



Toy-model for the LRG

LRG-UNIONS 0.4<z<0.6





Validation: coverage test for the LRG