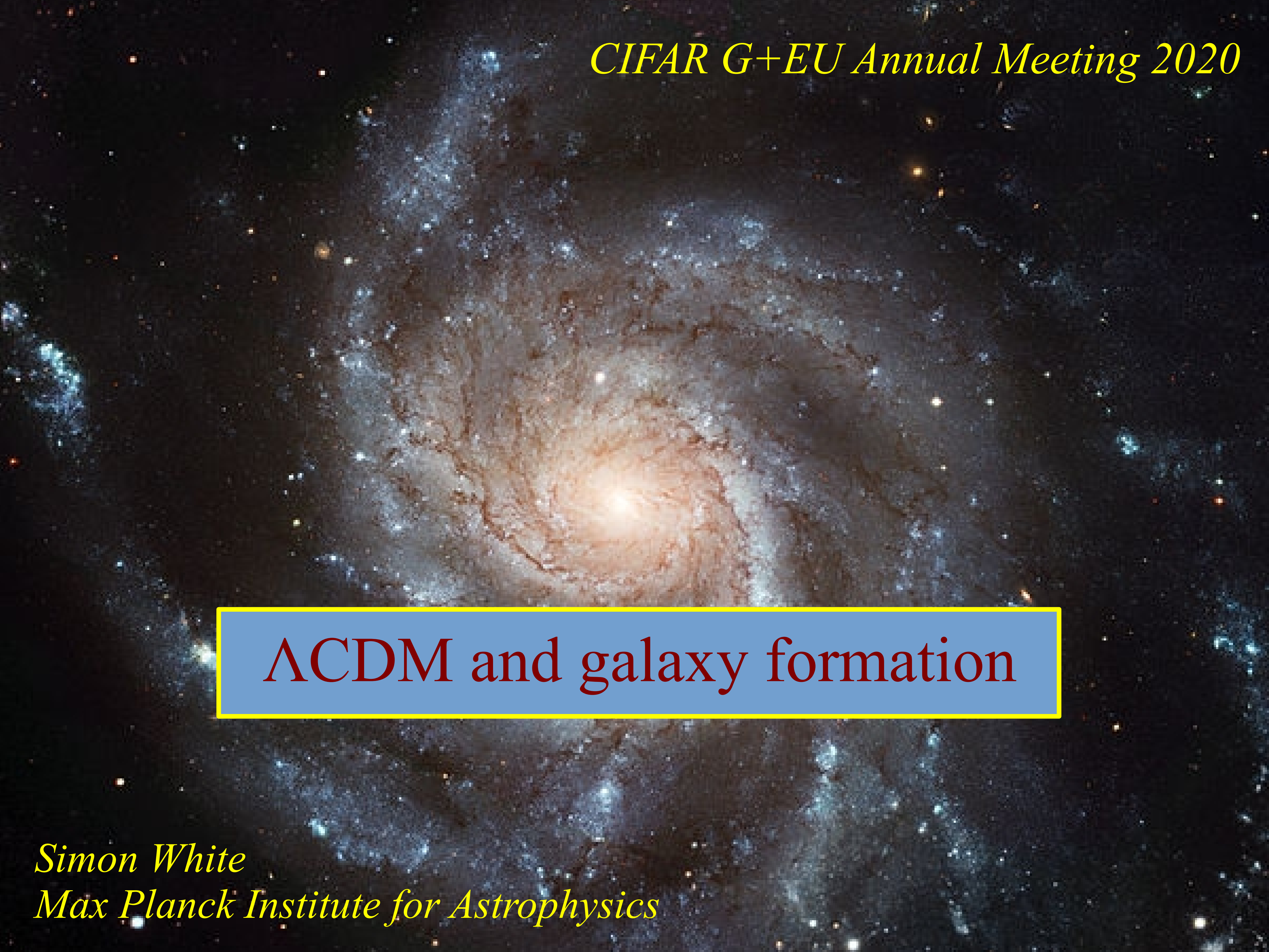

CIFAR G+EU Annual Meeting 2020

ΛCDM and galaxy formation

Simon White
Max Planck Institute for Astrophysics

Is ΛCDM a predictive theory for galaxy formation?

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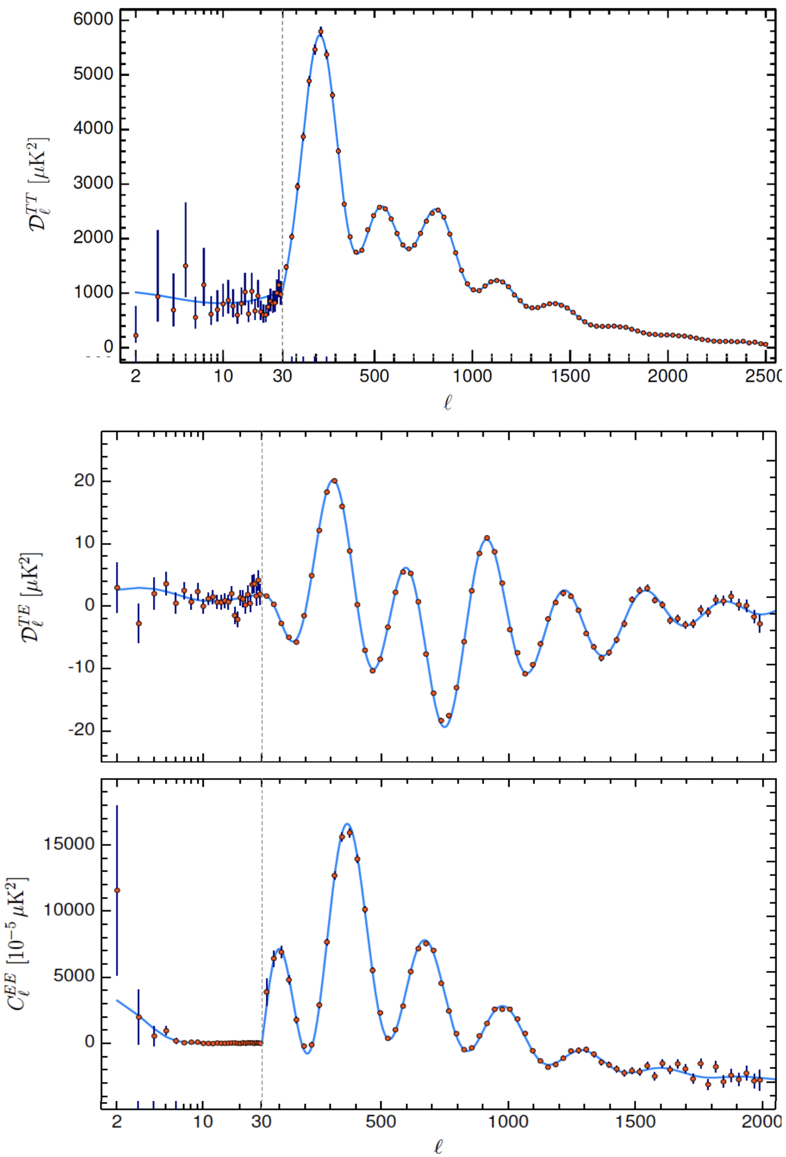
All critical elements of the ΛCDM model were in place before *any* of the last three was experimentally confirmed

The first simulation of ΛCDM structure formation dates from 1985

The current CMB evidence for ΛCDM



Planck Collaboration 2018

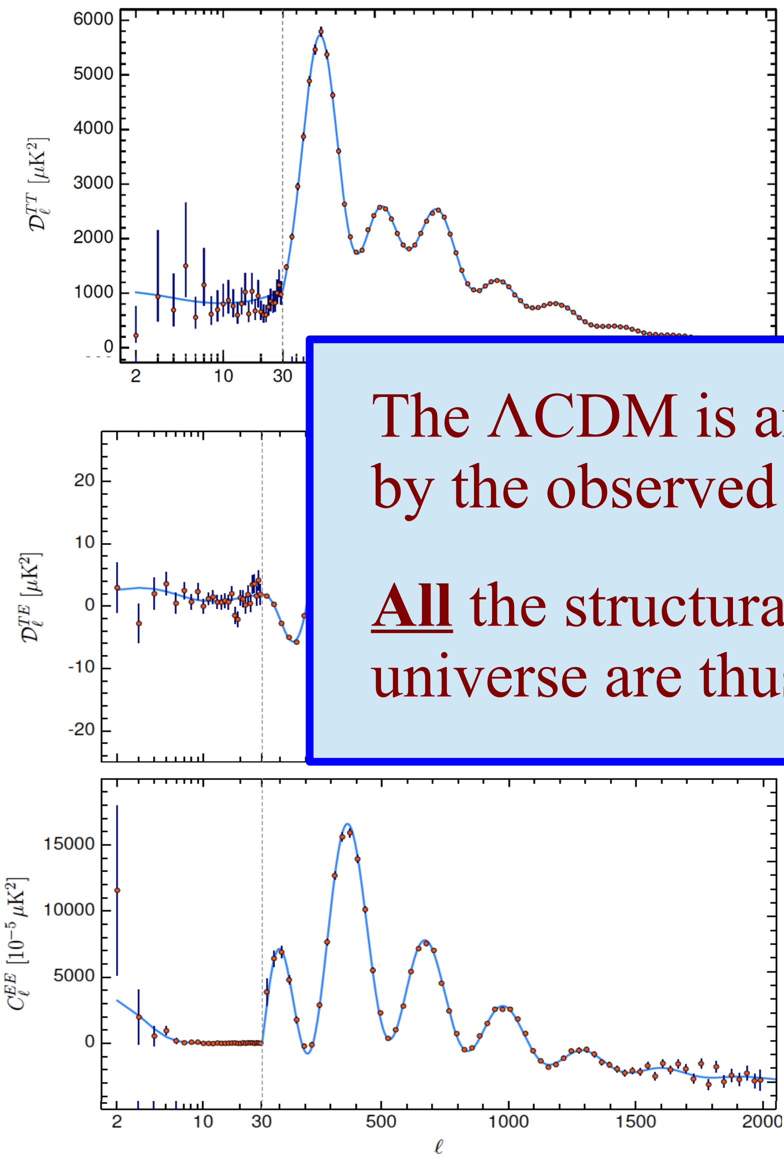
Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{drag} [Mpc]	147.18 ± 0.29

- **No** local/low-redshift data are used

→ **Measurements** of all 6 ΛCDM parameters
Cosmic properties, **not** fitting parameters

- Low-z data needed to specify nature of the DM

The current CMB evidence for ΛCDM



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<u>All</u> the structural properties of the nonlinear low-z universe are thus zero-parameter predictions

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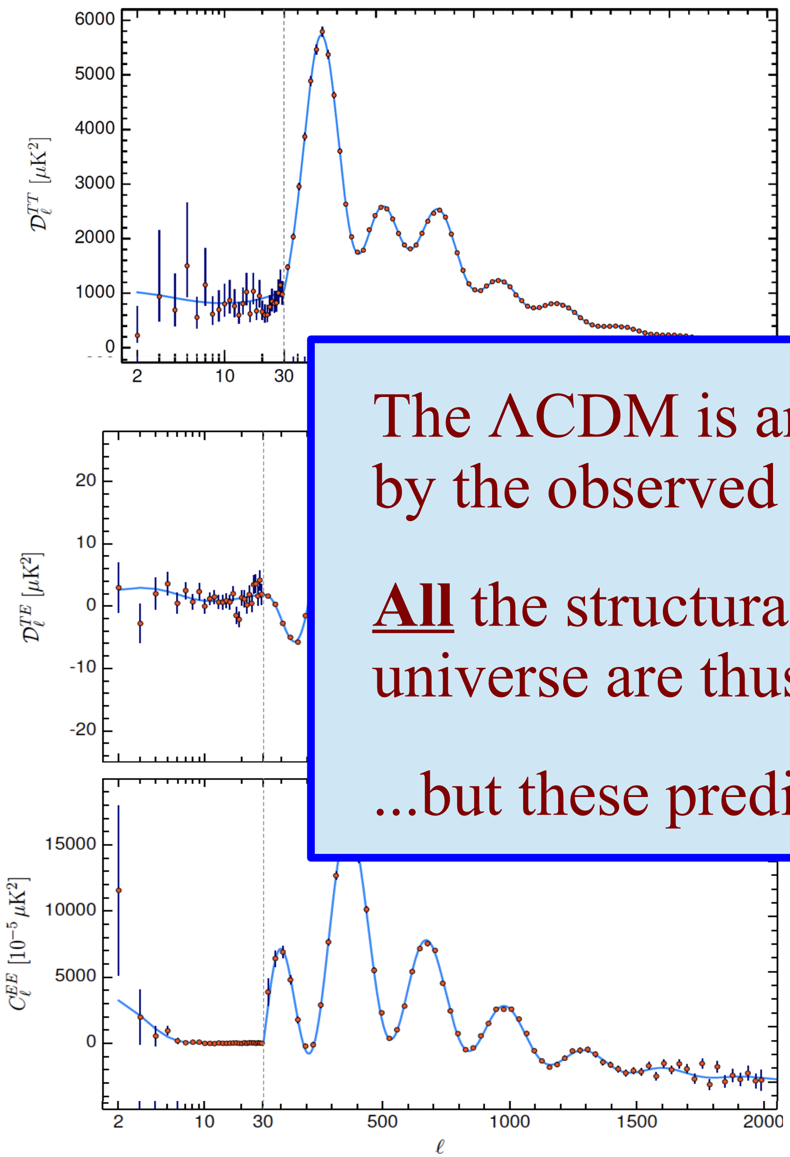

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<u>**All**</u> the structural properties of the nonlinear low-z universe are thus zero-parameter predictions

...but these predictions can be very hard to calculate!

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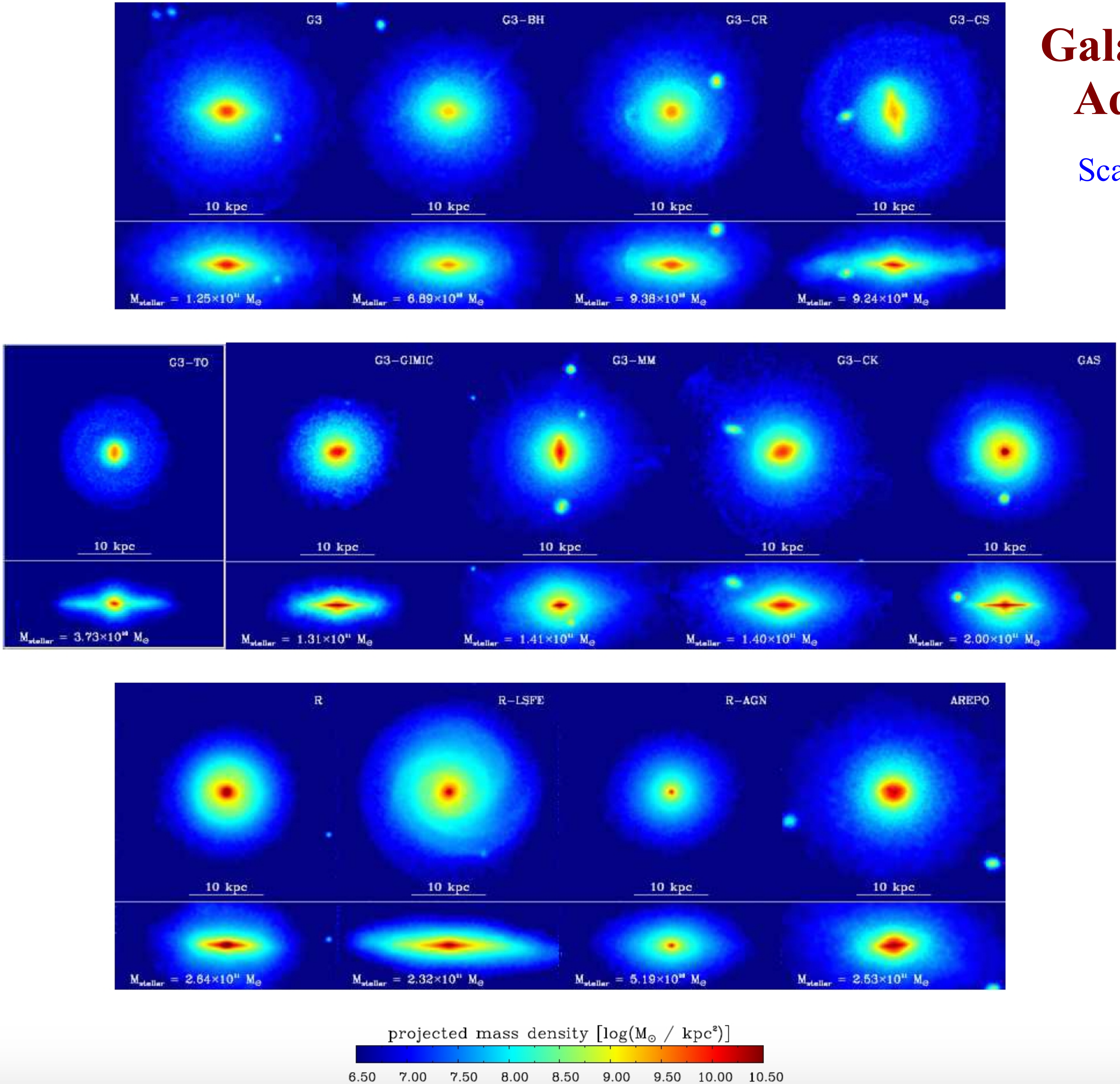

Galaxies from the Aquila project

Scannapieco et al 2012

13 simulations with 9 different codes, all from the same IC's

Each group was asked to use their "best" astrophys. models/params.

The results were all analysed in a uniform way

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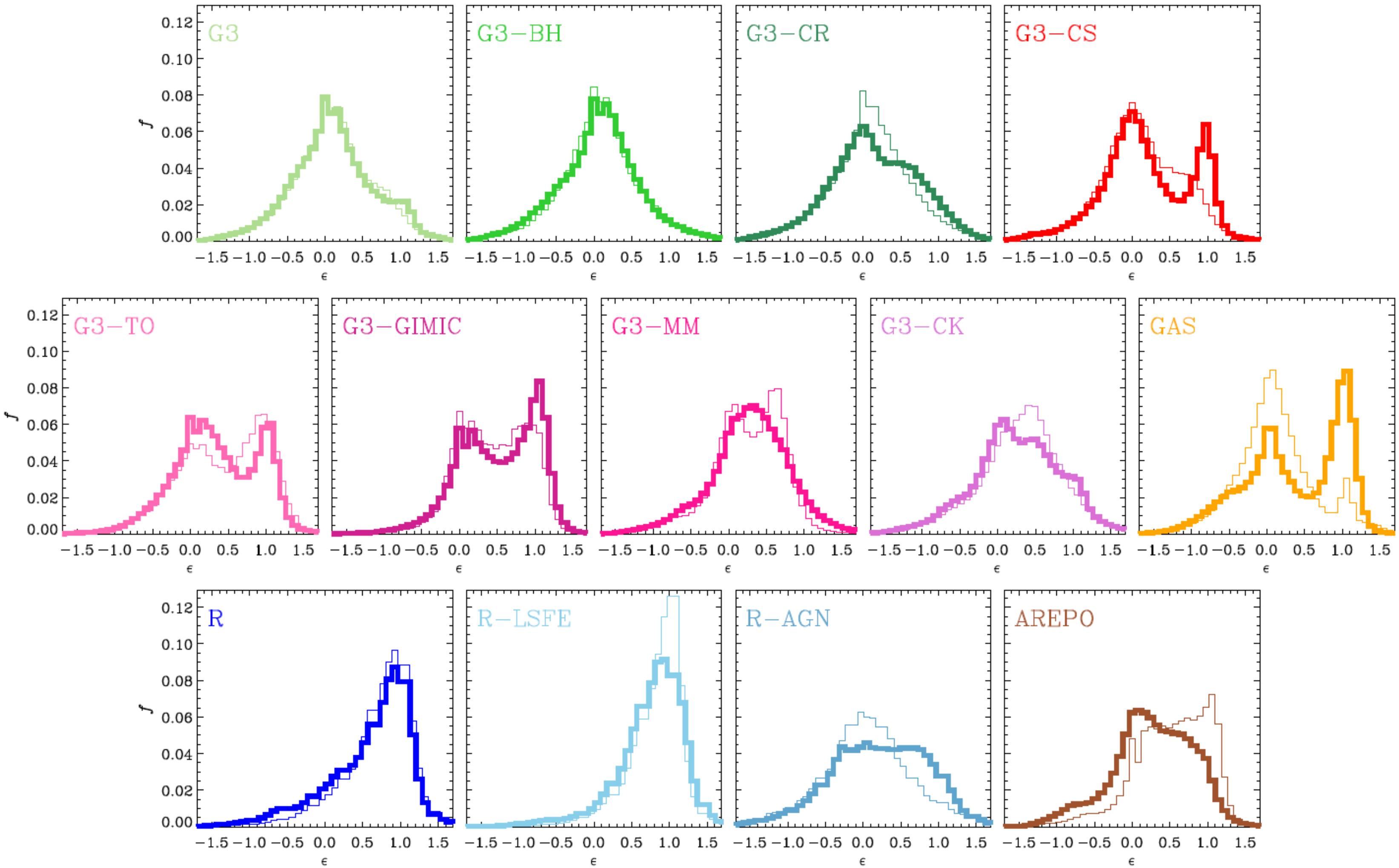
Distributions of circularity, $\varepsilon = J/J_{circ}(r)$ for all stars



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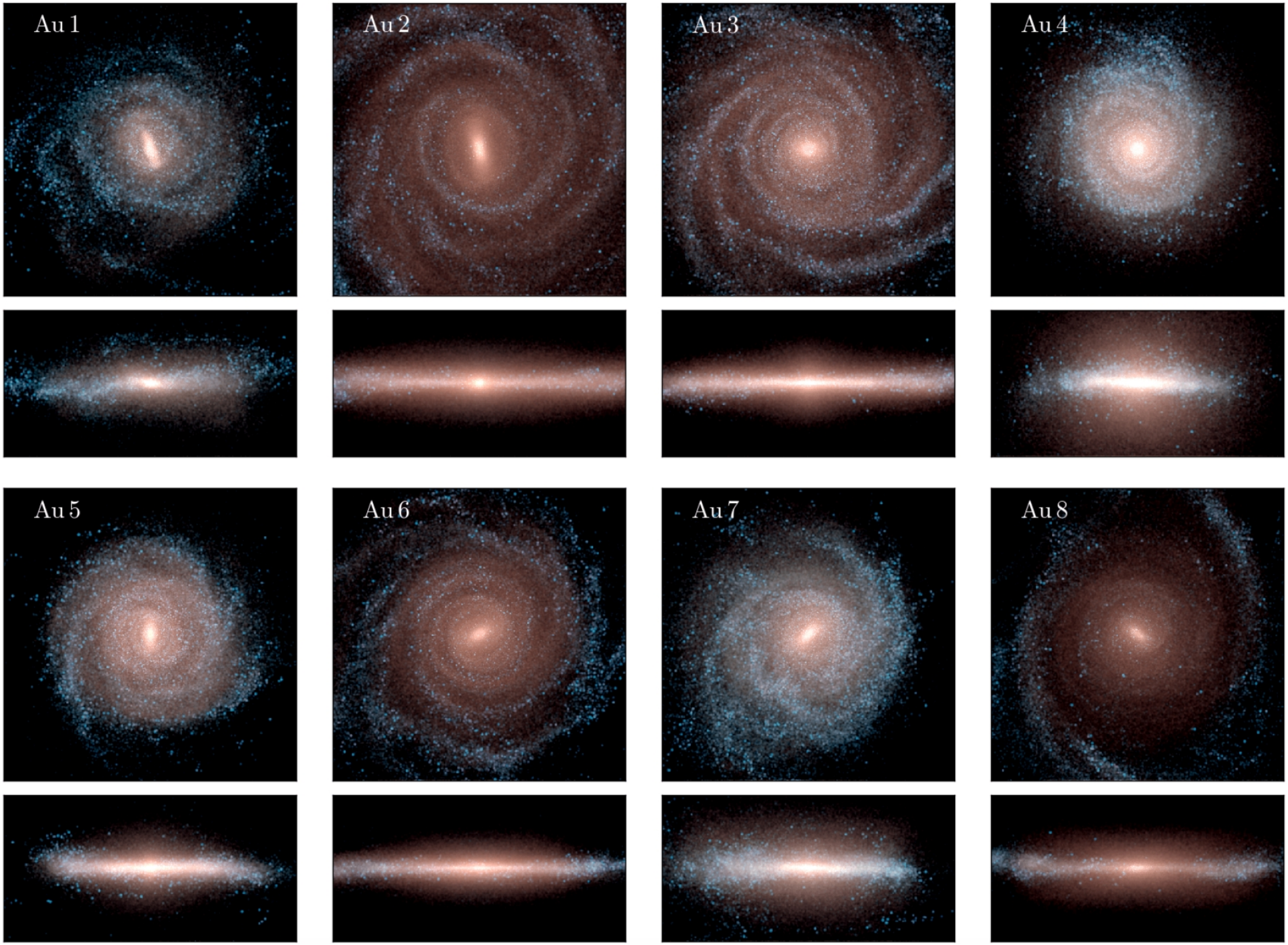
Galaxies from the Auriga project

Grand et al 2017

8/30 “Milky Ways”

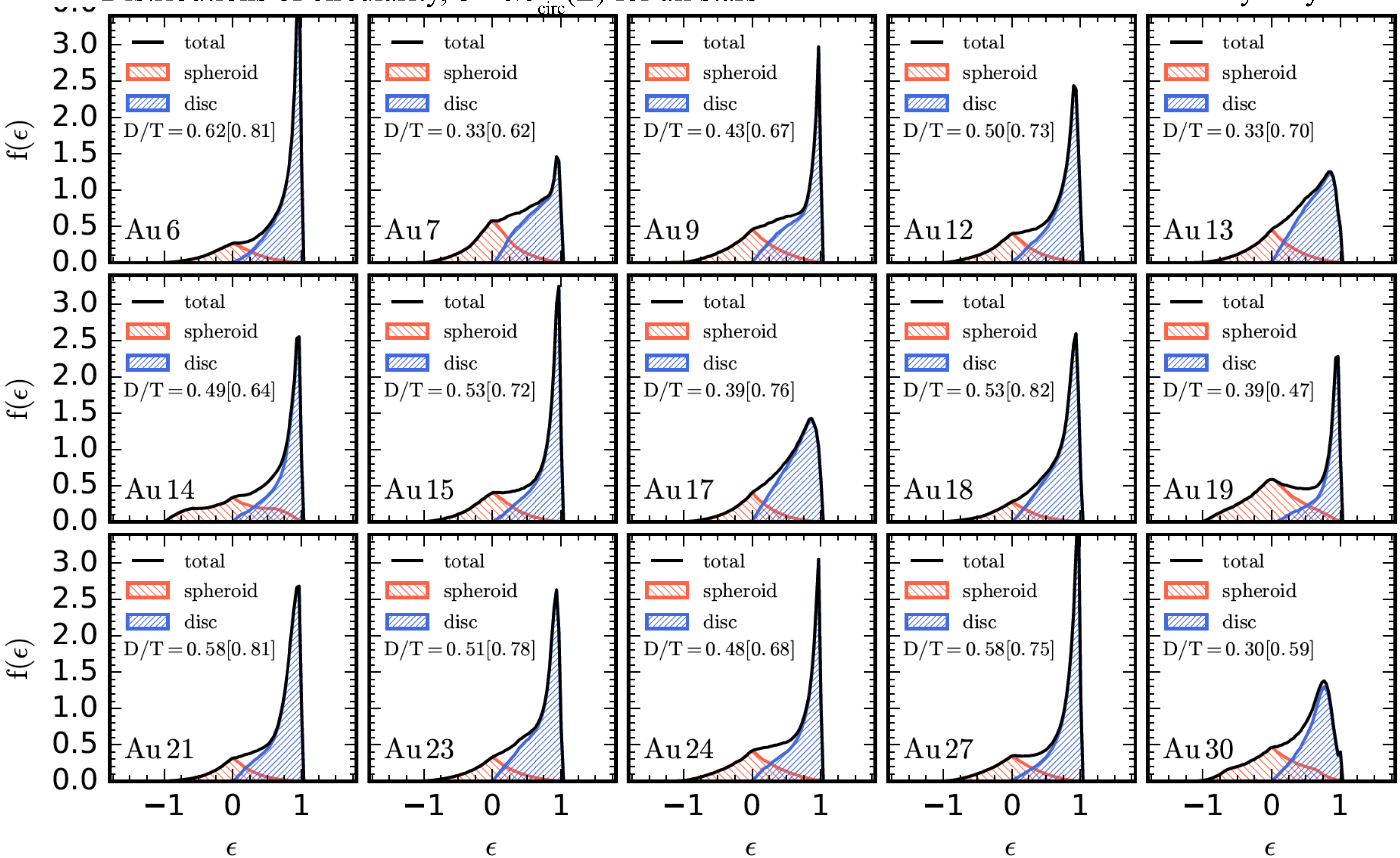


Galaxies from the Auriga project

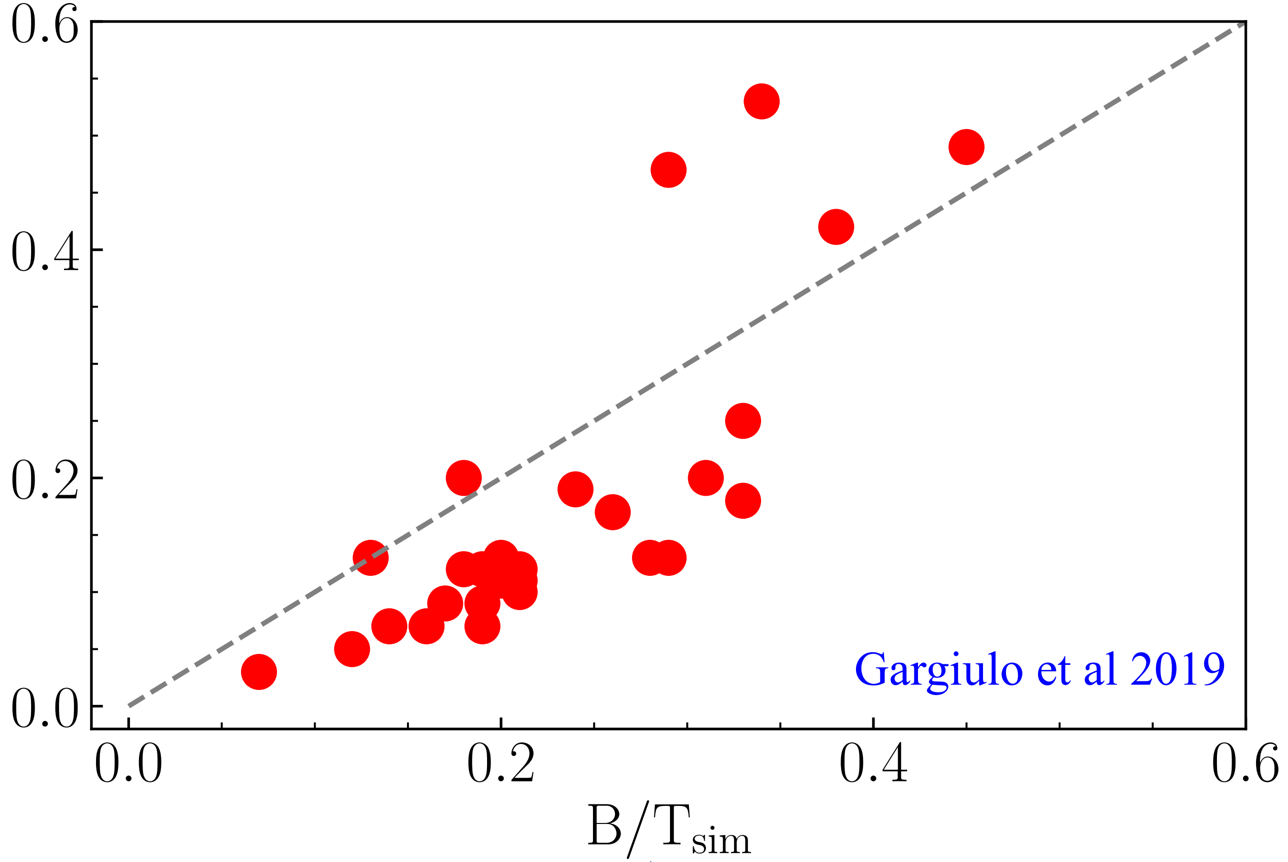
Grand et al 2017

Distributions of circularity, $\varepsilon = J/J_{circ}(E)$ for all stars

15/30 "Milky Ways"

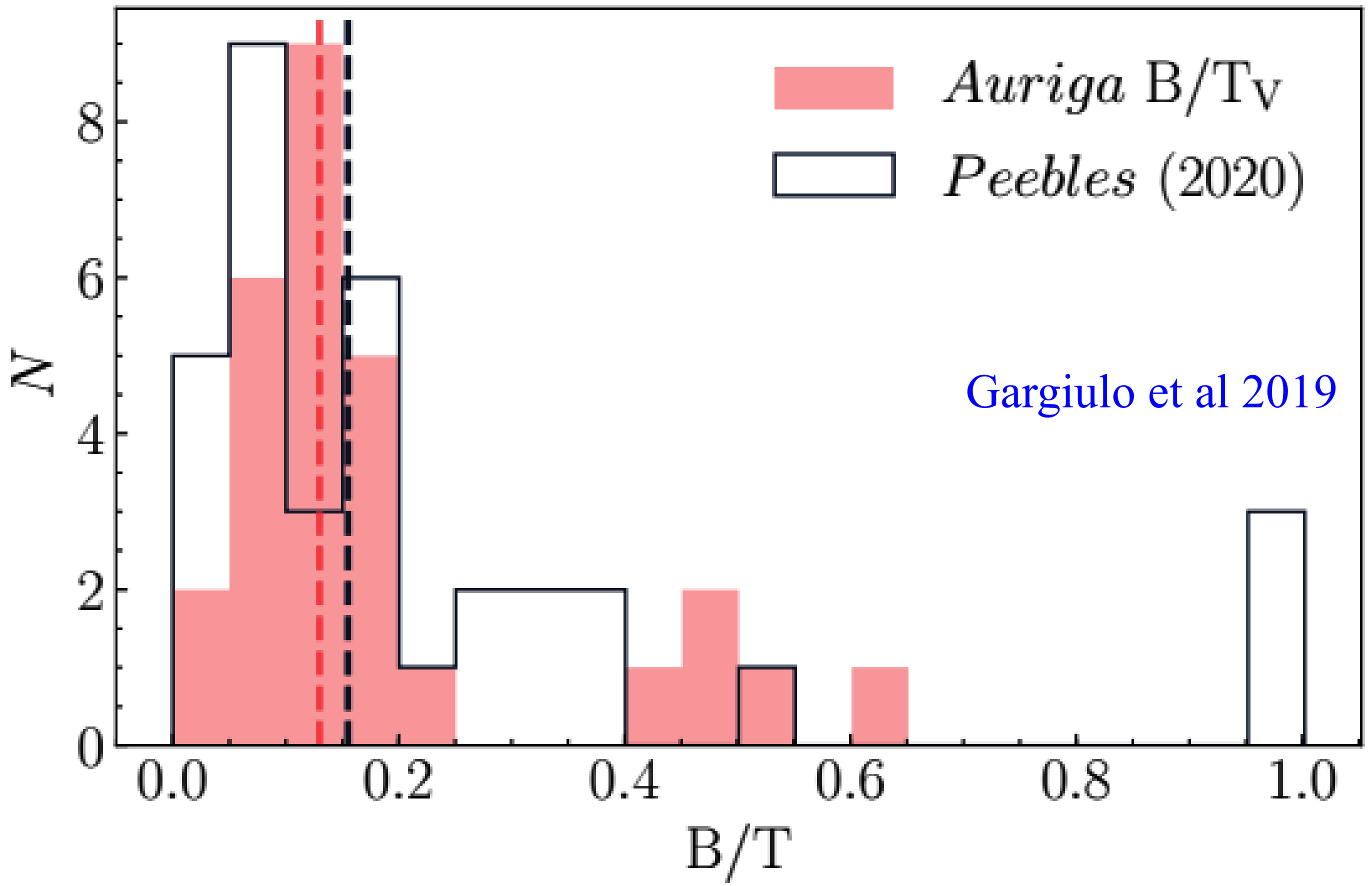


For Auriga galaxies the fraction of all stars inferred to be the bulge varies systematically with measurement method



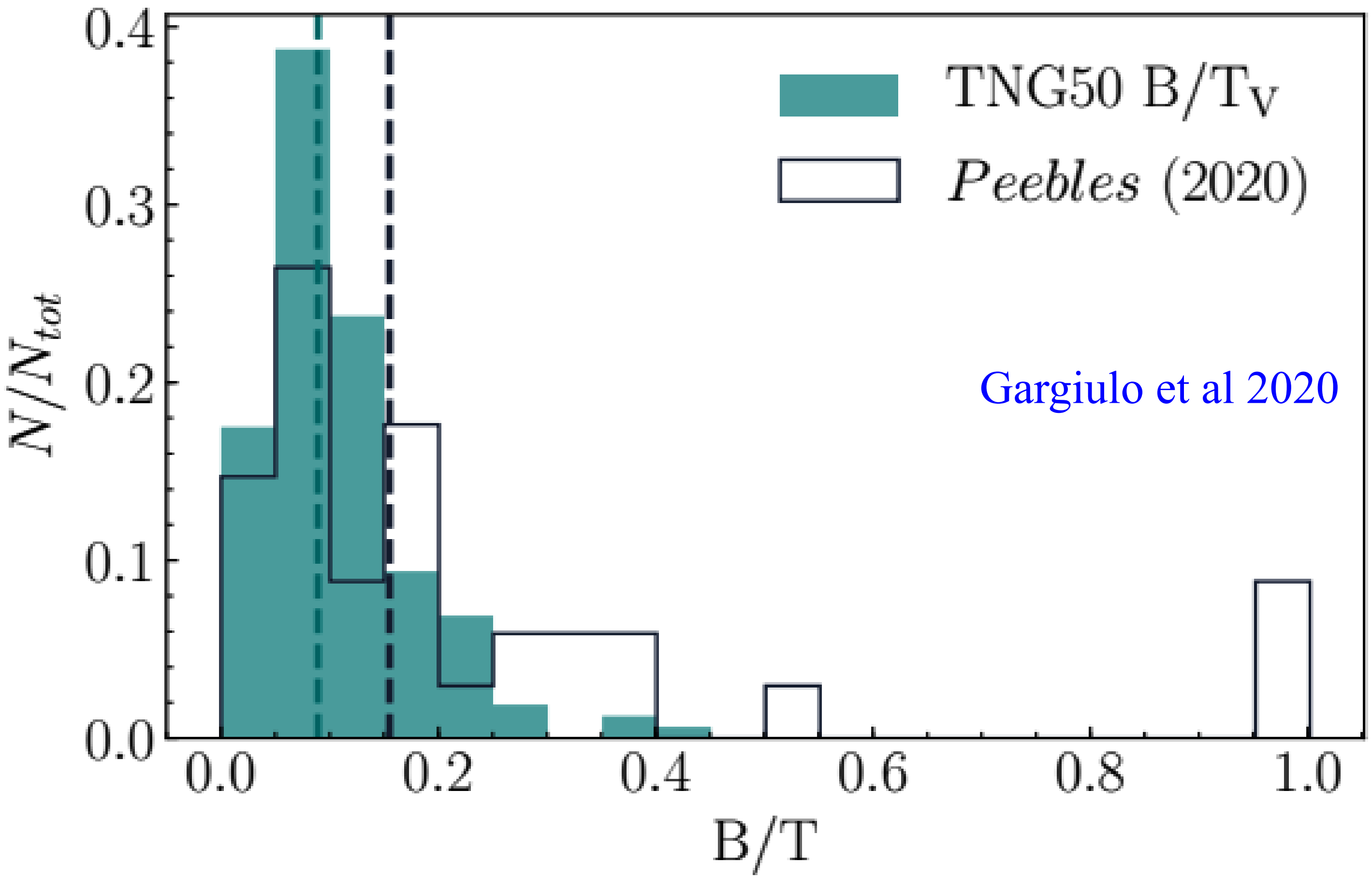
Estimated photometrically from the face-on V-band image

estimated kinematically from the ε distribution



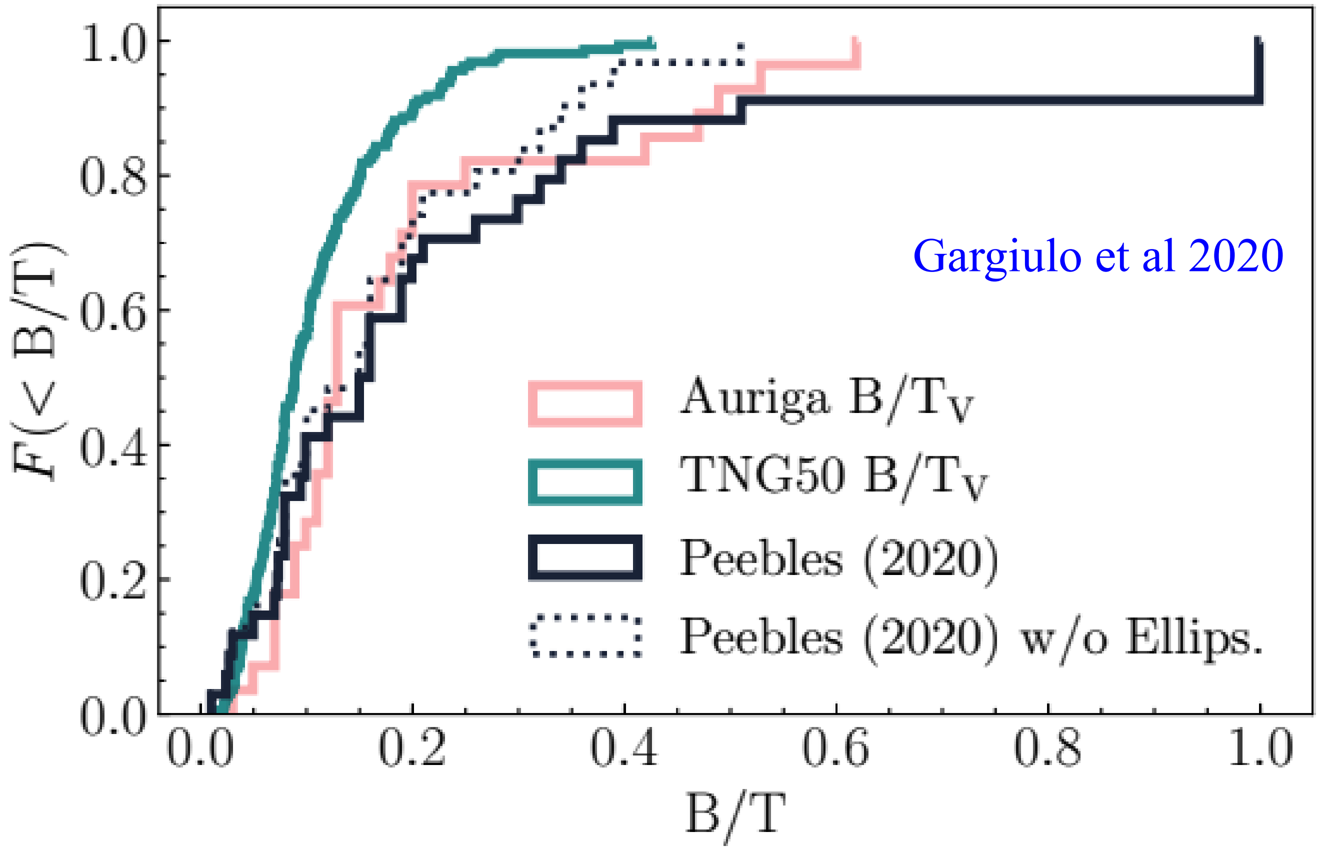
The distribution of B/T estimated photometrically for 28 Auriga galaxies is similar to that estimated (also photometrically) for 34 nearby massive galaxies in the sample assembled by Peebles (2020).

There are no E's in Auriga, but 3 in the observed sample (bigger halos?)



The distribution of B/T estimated photometrically for 160 TNG50 galaxies is skewed to *smaller* values that estimated (also photometrically) for 34 nearby massive galaxies in the sample assembled by Peebles (2020).

However, the TNG galaxies were selected to have disk-like star distributions

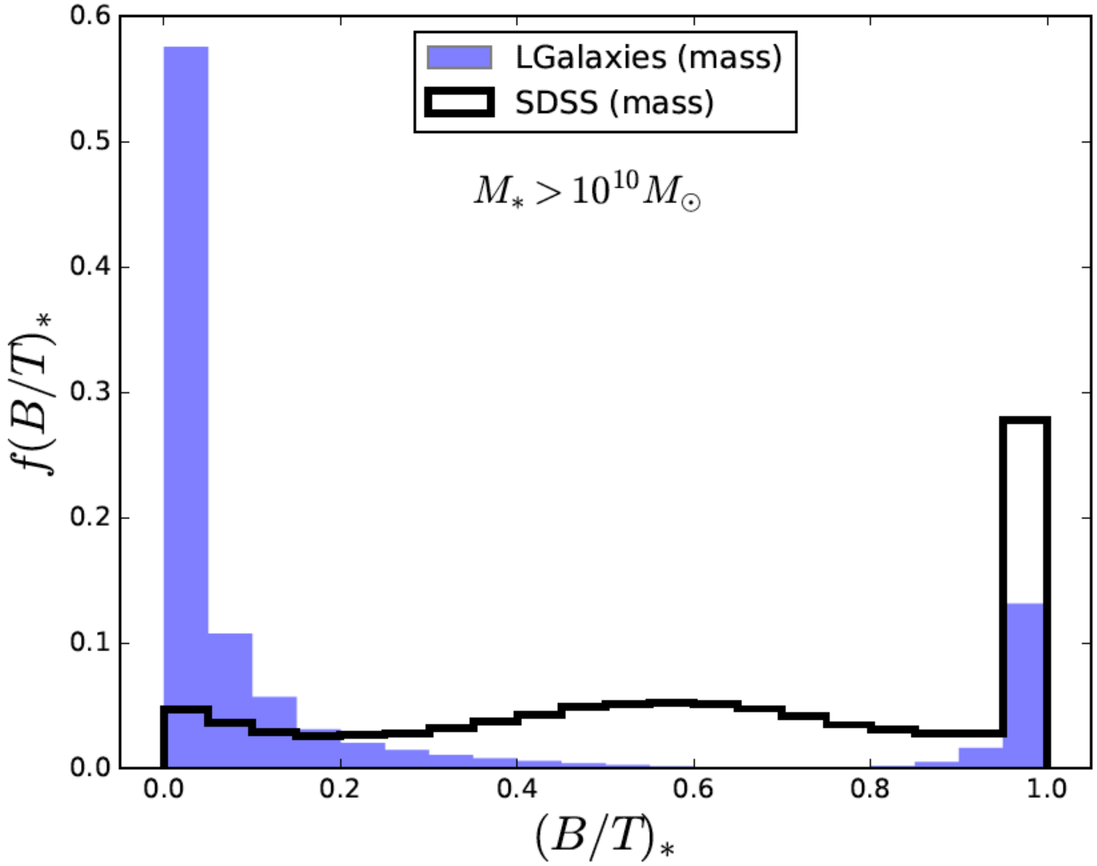


The Auriga B/T values are consistent with observation, with or without E's

TNG50 gives smaller bulges than either the observations or Auriga, but this may be due partly to the sample selection

Photometric B/T distributions for large samples

Bluck et al 2019



The distribution in a recent Millennium Simulation semi-analytic model is more strongly bi-modal than in SDSS ($0.02 < z < 0.2$)

The samples are dominated by galaxies ~0.5 the mass of the Milky Way

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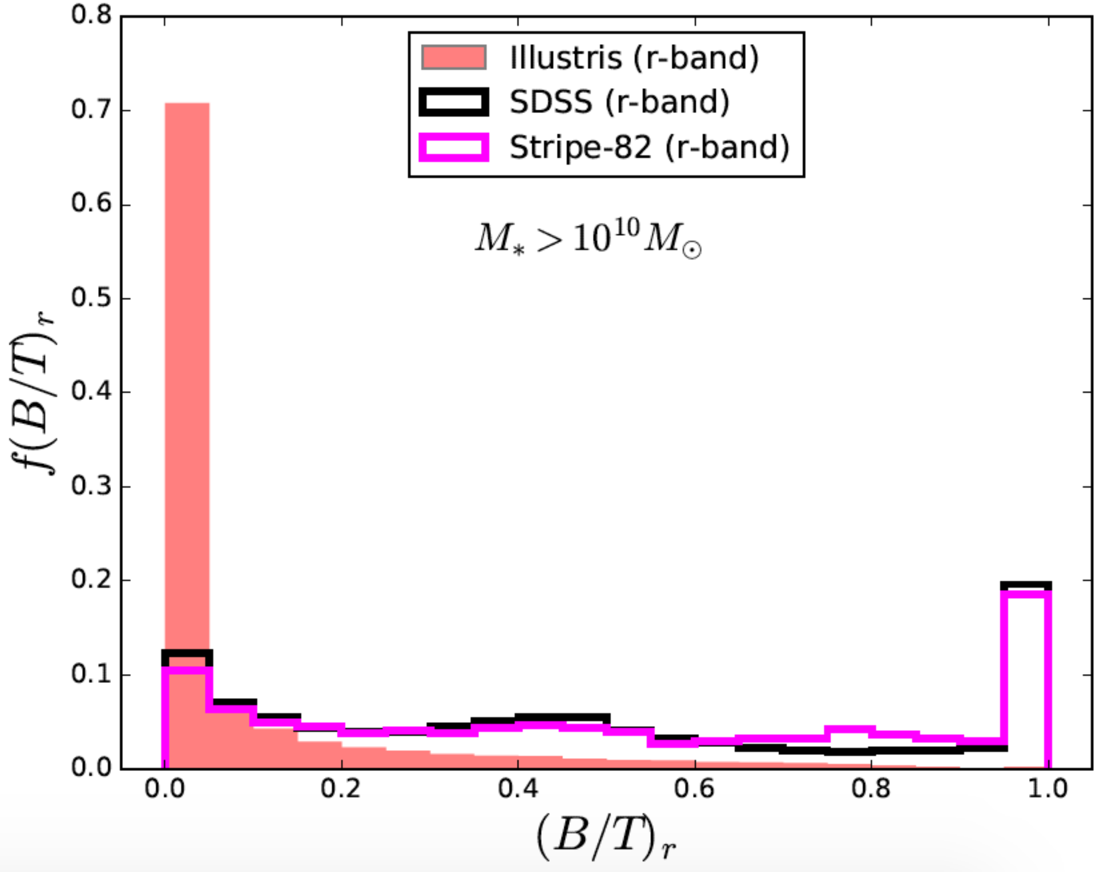

The distribution in the Illustris simulation has almost no E's or intermediate values of B/T over this mass range.

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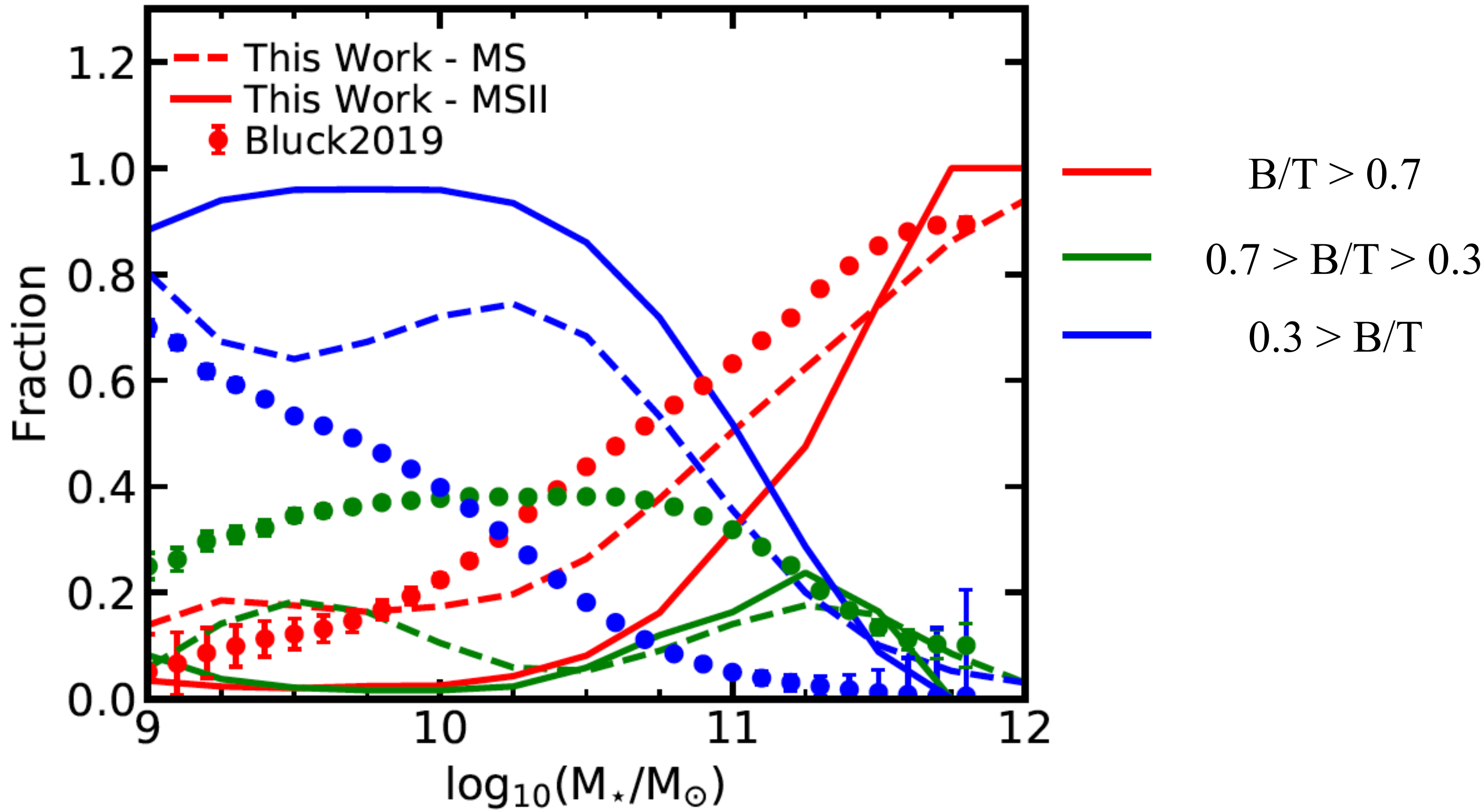
Photometric B/T as a function of stellar mass

Henriques et al 2020



At all stellar masses the SDSS sample has more galaxies with intermediate B/T than a semi-analytic model based on the Millennium Simulations

Summary points?

- ΛCDM is an *a priori* theoretical model with parameters fully specified by CMB measurements
- Of its basic tenets, only the cold nature of the Dark Matter *requires* data from the low-redshift Universe for justification/validation
- In principle, ΛCDM thus predicts **all** properties of the nonlinear, late-time universe (e.g. all galaxy properties) with no further freedom
- In practice, it can be very hard to calculate these predictions reliably.
- Different (uncertain) treatments of astrophysical processes can lead to very different galaxy properties within the *same* ΛCDM framework

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It seems very unlikely that the detailed structural properties of galaxies can be used reliably to infer failings of ΛCDM

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Complex simulations of limited realism/fidelity ↔ knowledge? ↔ Limited observations of a more complex reality