ΛCDM and galaxy formation

Simon White
Max Planck Institute for Astrophysics
Is $\Lambda$CDM a predictive theory for galaxy formation?
Is $\Lambda$CDM a predictive theory for galaxy formation?

**The Hot Big Bang:** Set out, 1920’s, confirmed 1960’s
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**Nonbaryonic DM:** Introduced, 1975 – 85, confirmed 1993 –
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The Hot Big Bang: Set out, 1920’s, confirmed 1960’s


Λ: Introduced 1917, resurfaced 1970’s, 80’s, confirmed 1997 –
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Inflationary fluctuations: Introduced ~1980, confirmed 2003 –
Is \( \Lambda CDM \) a predictive theory for galaxy formation?

The Hot Big Bang: Set out, 1920’s, confirmed 1960’s


\( \Lambda \): Introduced 1917, resurfaced 1970’s, 80’s, confirmed 1997 –

Inflationary fluctuations: Introduced \( \sim1980 \), confirmed 2003 –

All critical elements of the \( \Lambda CDM \) model were in place before any of the last three was experimentally confirmed

The first simulation of \( \Lambda CDM \) structure formation dates from 1985
The current CMB evidence for ΛCDM

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>0.02233 ± 0.00015</td>
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<td>$\Omega_c h^2$</td>
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<tr>
<td>100$\theta_{MC}$</td>
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<td>$\tau$</td>
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<td>ln(10$^{10}$A$_S$)</td>
<td>3.043 ± 0.014</td>
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<tr>
<td>$n_s$</td>
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<tr>
<td>$\Omega_m h^2$</td>
<td>0.1428 ± 0.0011</td>
</tr>
<tr>
<td>$H_0$ [km s$^{-1}$Mpc$^{-1}$]</td>
<td>67.37 ± 0.54</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.3147 ± 0.0074</td>
</tr>
<tr>
<td>Age [Gyr]</td>
<td>13.801 ± 0.024</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.8101 ± 0.0061</td>
</tr>
<tr>
<td>$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$</td>
<td>0.830 ± 0.013</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>7.64 ± 0.74</td>
</tr>
<tr>
<td>100$\theta_*$</td>
<td>1.04108 ± 0.00031</td>
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<tr>
<td>$r_{drag}$ [Mpc]</td>
<td>147.18 ± 0.29</td>
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- **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

Planck Collaboration 2018
The current CMB evidence for $\Lambda$CDM

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The $\Lambda$CDM is an \textit{a priori} model which is \textbf{fully} specified by the observed CMB temperature and fluctuations.

All the structural properties of the nonlinear low-z universe are thus zero-parameter predictions.

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- Measurements of all 6 $\Lambda$CDM parameters.

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

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- **Measurements** of all 6 \( \Lambda \)CDM parameters
  - Cosmic properties, \textbf{not} fitting parameters
- Low-z data needed to specify \textit{nature} of the DM
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, $\varepsilon = J / J_{\text{circ}}(r)$ for all stars

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Galaxies from the Auriga project

Grand et al 2017

8/30 “Milky Ways”
Distributions of circularity, $\varepsilon = J/J_{\text{circ}}(E)$ for all stars
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 $\epsilon$ distribution

Gargiulo et al 2019
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 than 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
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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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?

- $\Lambda$CDM is an \textit{a priori} theoretical model with parameters fully specified by CMB measurements.

- Of its basic tenets, only the cold nature of the Dark Matter \textit{requires} data from the low-redshift Universe for justification/validation.

- In principle, $\Lambda$CDM thus predicts \textbf{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 \textit{same} $\Lambda$CDM framework.
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It seems very unlikely that the detailed structural properties of galaxies can be used reliably to infer failings of $\Lambda$CDM.
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Complex simulations of limited realism/fidelity $\leftrightarrow$ Limited observations of a more complex reality