Dwarf elliptical galaxies
as
ancient tidal dwarf galaxies

Jörg Dabringhausen
University of Bonn
Dwarf galaxies in the $\Lambda$CDM-model

Primordial dwarf galaxies form in haloes of cold dark matter (CDM).
Dwarf galaxies in the $\Lambda$CDM-model

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Tidal dwarf galaxies (TDGs) are created by the interaction between primordial galaxies. TDGs cannot contain significant amounts of CDM (Bournaud 2010).
Dwarf galaxies in the $\Lambda$CDM-model

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The Universe contains two types of dwarf galaxies of different origin and with different composition (e.g. Kroupa et al. 2010).
Galaxy interactions and tidal tails

Mice galaxies
Galaxy interactions and tidal tails

Mice galaxies

Tadpole galaxy
Galaxy interactions and tidal tails

- Mice galaxies
- Tadpole galaxy

Star formation in the tidal tails!
Young tidal dwarf galaxies
Young tidal dwarf galaxies
Young tidal dwarf galaxies
Young tidal dwarf galaxies

Some TDGs are expected to survive for more than a Gyr - what will they look like then?
The TDGs in mass-radius parameter space

Radii and masses of objects that observers have identified as TDG-candidates have been collected from the literature.

Dabringhausen & Kroupa (2013)
The TDGs in mass-radius parameter space

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Radii and masses are available only for a small number of the known TDG-candidates.

Dabringhausen & Kroupa (2013)
The effect of ageing

Star formation & evolution in the TDG-candidates

Dabringhausen & Kroupa (2013)
The effect of ageing

Star formation & evolution in the TDG-candidates
→ Mass-loss though feedback

Dabringhausen & Kroupa (2013)
The effect of ageing

Star formation & evolution in the TDG-candidates

Mass-loss through feedback

Expansion of the TDG-candidate

Dabringhausen & Kroupa (2013)
The effect of tidal fields

TDGs form near their progenitor galaxies

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The vicinity of a major galaxy implies that a dwarf galaxy is within a tidal field

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The effect of tidal fields

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The vicinity of a major galaxy implies that a dwarf galaxy is within a tidal field

The tidal field limits the maximum radius of a TDG

Dabringhausen & Kroupa (2013)
Comparison with actual old stellar systems

The TDG-candidates evolve onto the mass-radius sequence defined by dwarf ellipticals (dEs) and dwarf spheroidals (dSphs).

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The origin of dE-galaxies

Massive extended objects forming in tidal tails evolve into dEs

dwarf elliptical galaxy
The origin of dE-galaxies

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The origin of dE-galaxies

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In a $\Lambda$CDM universe, dEs should also form in dark matter haloes

To which extent do these two formation channels contribute to the total population of dE-galaxies?
The dEs in parameter space
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Only one sequence of dwarf galaxies in parameter space
The dEs in parameter space

- Projected half-light radius vs. stellar mass
- 

\[
\text{projected half-light radius [pc]} \quad \text{stellar mass [M}_\odot\text{]}
\]

- \[\ell_{\text{halo}}\]

- 

\[
\sigma_{\text{los}} \quad \text{[pc/Myr]} \quad L_V \quad \text{[L}_\odot\text{]}
\]

- E
- 

\[
10^2 \quad 10^4 \quad 10^6 \quad 10^8 \quad 10^{10} \quad 10^{12}
\]

- L
- 

\[
10^2 \quad 10^4 \quad 10^6 \quad 10^8 \quad 10^{10} \quad 10^{12}
\]
The dEs in parameter space
The single sequence of dwarf galaxies in parameter space suggests that there is only one type of dwarf galaxy.
The spatial distribution of dE-galaxies

Dwarf satellite galaxies of tidal origin are expected to form *rotating disks* around their host galaxies.

Wetzstein et al. 2007
The spatial distribution of dE-galaxies

Dwarf satellite galaxies of tidal origin are expected to form **rotating disks** around their host galaxies.

Primordial dwarf satellite galaxies are expected to be distributed **isotropically** around their host galaxies.
All satellite galaxies of the Milky way lie within a disk (Pawlowski et al.)
The spatial distribution of dE-galaxies in the Local Group

All satellite galaxies of the Milky way lie within a disk (Pawlowski et al.)

At least half of the satellite galaxies of M 31 lie within a disk (Ibata et al. 2013)
The origin of dE-galaxies

There is a single sequence of dE-galaxies in parameter space
The origin of dE-galaxies

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There is a dominating channel for the formation of dE-galaxies
The origin of dE-galaxies

- There is a single sequence of dE-galaxies in parameter space
- All dE-galaxies orbiting around the Milky Way lie within a single plane
- There is a dominating channel for the formation of dE-galaxies
The origin of dE-galaxies

There is a single sequence of dE-galaxies in parameter space

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There is a dominating channel for the formation of dE-galaxies

The satellites of the Milky Way formed within a tidal tail instead of CDM-haloes
The origin of dE-galaxies

There is a single sequence of dE-galaxies in parameter space

There is a dominating channel for the formation of dE-galaxies

All dE-galaxies orbiting around the Milky Way lie within a single plane

The satellites of the Milky Way formed within a tidal tail instead of CDM-haloes

Tidal interactions are the dominating (if not the only) channel for the formation of dE-galaxies
All dE galaxies are created as TDGs. Such dEs cannot contain significant amounts of cold dark matter (Bournaud 2010).
The origin of dE-galaxies

**All** dE galaxies are created as TDGs. Such dEs cannot contain significant amounts of cold dark matter (Bournaud 2010).

**NO** dE galaxies form as primordial dwarf galaxies in haloes of cold dark matter.
The origin of dE-galaxies

**All** dE galaxies are created as TDGs. Such dEs cannot contain significant amounts of cold dark matter (Bournaud 2010).

**NO** dE galaxies form as primordial dwarf galaxies in haloes of cold dark matter.

But how can the internal dynamics of dEs be explained without dark matter ??
The internal dynamics of dE galaxies

Stellar masses are estimated from the luminosities and the colours assuming 13 Gyr old stellar populations.
The internal dynamics of dE galaxies

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The velocity dispersions can be estimated from the stellar masses and the radii.
The internal dynamics of dE galaxies

Assuming virial equilibrium and Newtonian dynamics:

\[ \sigma_{\text{los}} = \sqrt{\frac{G M_*}{4 r_e}} \]
The internal dynamics of dE galaxies

The discrepancy between the predicted $\sigma_{\text{los}}$ and the observed $\sigma_{\text{los}}$ is usually interpreted as unseen mass.
The internal dynamics of dE galaxies

The discrepancy between the predicted $\sigma_{\text{los}}$ and the observed $\sigma_{\text{los}}$ is usually interpreted as unseen mass.

Since TDGs cannot contain CDM, there must be another reason for the high $\sigma_{\text{los}}$ of the dEs if they are old TDGs.
MOND to the rescue!

- MOND: MODified Newtonian Dynamics
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• MOND: Modified Newtonian Dynamics

• Introduced by Milgrom (1983).

• Compared to the Newtonian prediction, the gravitational force in MOND is increased in the limit of very weak space-time curvature.
MOND to the rescue!

- MOND: Modified Newtonian Dynamics
- Compared to the Newtonian prediction, the gravitational force in MOND is increased in the limit of very weak space-time curvature.

For stellar systems with shallow potentials, MOND predicts higher velocity dispersions than Newtonian dynamics.
The internal dynamics of dE galaxies

Assuming MOND instead of Newtonian dynamics:

Dabringhausen et al., in prep.
The M/L-ratios of dE galaxies

Assuming Newtonian dynamics:

\[ M = 4 \frac{r_e \sigma_{\text{los}}^2}{G} \]

The masses that enter the M/L ratios are calculated from the predicted \( \sigma_{\text{los}} \) as well as from the observed \( \sigma_{\text{los}} \) with

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Assuming MOND:

Non-equilibrium dynamics?

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Many objects younger than 13 Gyr

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The M/L-ratios of dE galaxies

Assuming MOND:

Non-equilibrium dynamics?

Bottom heavy IMFs? (van Dokkum & Conroy 2010)

Many objects younger than 13 Gyr.

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The M/L-ratios of TDGs

Bournaud et al. 2007: The combined mass of all baryons in galaxies forming out of the tidal debris around NGC 5291 is too small to explain their internal dynamics...
The M/L-ratios of TDGs

Bournaud et al. 2007: The combined mass of all baryons in galaxies forming out of the tidal debris around NGC 5291 is too small to explain their internal dynamics...

...however, their internal dynamics is consistent with MOND. (Milgrom 2007)
Conclusions

• All dEs and dSphs may in fact be old TDGs.
• The high internal velocity dispersions of dEs and dSphs must then be a consequence of MOND and non-equilibrium dynamics.

The $\Lambda$CDM-model of cosmology would then have to be revised.