Understanding Dwarf Galaxies in order to Understand Dark Matter

Hot gas explodes out of young dwarf galaxies

Simulation by Andrew Pontzen, Fabio Governato and Alyson Brooks on the Darwin Supercomputer, Cambridge UK.

Simulation code Gasoline by James Wadsley and Tom Quinn with metal cooling by Sijing Sheng.

Visualization by Andrew Pontzen.

Alyson Brooks
Rutgers, the State University of New Jersey

In collaboration with the University of Washington’s N-body Shop™ makers of quality galaxies
Starting Assumption:
There is No Small Scale "Crisis"
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*see arXiv:1407.7544 for a review*
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Key Problems

We need baryons in alternative DM models. Is there a smoking gun that points to a given DM model?

Can we understand the formation and evolution of dwarf galaxies?
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Can we understand the formation and evolution of dwarf galaxies?
WDM: Walking a Fine Line
A Testable Prediction of Delayed Structure Formation

Figure 4. Left: The cumulative SFH (i.e., the fraction of total stellar mass formed by a given lookback time) as a function of redshift. Different lines represent different simulations: green for CDMg3, black for CDMg5, and red for WDMg5. The redshift range is shown on the x-axis.

Figure 5. Right: The cumulative SFH as a function of aperture of our sample (see text for details). Different panels show different simulations: (a) CDM G5, (b) CDM G1, (c) WDM G5, and (d) LGS3. The shaded area represents the ANGST sample, and the red line indicates the rapid rise and the subsequent linear growth of the ANGST sample. The LGS3 CMD (at a color of 24.7) is also shown for comparison.

The CMDs have been designed to mimic the observed color-magnitude diagrams (CMDs) of real galaxies. The MS (main sequence), RGB (red giant branch), SGB (sub-giant branch), HB (horizontal branch), and MSTO (most massive star on the turnoff) are indicated.

References:
Governato et al. (2014)
SIDM: the Constraints Are Weakening

results for a $9\times 10^9$ $M_{\text{Sun}}$ halo

Elbert et al. (2015)
But... baryons win

Bastidas-Fry et al. (2015)
If galaxies in this mass range are observed to have large cores, then something beyond CDM is necessary.
Key Problems

We need baryons in alternative DM models. Is there a smoking gun that points to a given DM model?

Can we understand the formation and evolution of dwarf galaxies?
The Marvel-ous Volumes

Captain Marvel
Elektra
Rogue
Storm

Force resolution: 60pc
SPH resolution: 6pc
$M_{\text{star}}: 400$ Msun
$M_{\text{dm}}: 6000$ Msun
$z \sim 129$ to 0

Many flavors:
- DM only
- With H2 + Black Holes
- Metal cooling + self shielding
- SIDM
The DC Justice League
4 volumes centered on MW-mass halos

Sonia  Sandra  Ruth  Elena

Force resolution: 170 & 85pc
SPH resolution: 17 & 9pc

$M_{\text{star}}$: $8000/1000$ $M_{\odot}$
$M_{\text{dm}}$: $1.3\times10^5/1.6\times10^4$ $M_{\odot}$
z~to 0
The Stellar Mass — Halo Mass Relation

\[ \log M_{\text{star}} [M_{\odot}] \]

\[ \log M_{\text{halo}} [M_{\odot}] \]

-3 -5 -7 -9 -11 -12 -14 -16 -18

V-band Magnitude

- Moster et al. (2013)
- Brook et al. (2014)
- Behroozi et al. (2013)
- Sawala et al. (2015)
Does Star Formation Prescription Matter?

![Graph showing the relationship between log M_{star} [M_{sun}] and log M_{halo} [M_{sun}], with different data points and lines representing different studies, including Moster et al. (2013), Brook et al. (2014), Behroozi et al. (2013), and Sawala et al. (2015). The graph indicates that SF: H$_2$-based.](image-url)
Does Star Formation Prescription Matter?

V-band Magnitude

log $M_{\text{star}}$ [$M_{\odot}$] vs. log $M_{\text{halo}}$ [$M_{\odot}$]

- Moster et al. (2013)
- Brook et al. (2014)
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- Sawala et al. (2015)

SF: Metal Cooling
Interlude: Why We All Claim to Make Realistic Galaxies

“Resolving” Star Formation Regions

High threshold

Low threshold

Feedback becomes more efficient (more outflows per unit mass of stars formed)
Interlude: Why We All Claim to Make Realistic Galaxies

Benincasa et al. (2016)
Towards a more realistic population of bright spiral galaxies in cosmological simulations

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ABSTRACT
We present an update to the multiphase SPH galaxy formation code by Scannapieco et al. We include a more elaborate treatment of the production of metals, cooling rates based on individual element abundances, and a scheme for the turbulent diffusion of metals. Our SN feedback model now transfers energy to the ISM in kinetic and thermal form, and we include a prescription for the effects of radiation pressure from massive young stars on the ISM. We calibrate our new code on the well studied Aquarius haloes and then use it to simulate a sample of 16 galaxies with halo masses between $1 \times 10^{11}$ and $3 \times 10^{12} M_\odot$. In general, the stellar masses of the sample agree well with the stellar mass to halo mass relation inferred from abundance matching techniques for redshifts $z = 0 - 4$. There is however a tendency to overproduce stars at $z > 4$ and to underproduce them at $z < 0.5$ in the least massive haloes. Overly high SFRs at $z < 1$ for the most massive haloes are likely connected to the lack of AGN feedback in our model. The simulated sample also shows reasonable agreement with observed star formation rates, sizes, gas fractions and gas-phase metallicities at $z = 0 - 3$. Remaining discrepancies can be connected to deviations from predictions for star formation histories from abundance matching. At $z = 0$, the model galaxies show realistic morphologies, stellar surface density profiles, circular velocity curves and stellar metallicities, but overly flat metallicity gradients. 15 out of 16 of our galaxies contain disk components with kinematic disk fraction ranging between 15 and 65 %. The disk fraction depends on the time of the last destructive merger or misaligned infall event. Considering the remaining shortcomings of our simulations we conclude that even higher kinematic disk fractions may be possible for ΛCDM haloes with quiet merger histories, such as the Aquarius haloes.
Interlude: Why We All Claim to Make Realistic Galaxies

$M_{\text{star}} \sim 10^8 M_\odot$

Christensen et al. (2014)
Interlude: Why We All Claim to Make Realistic Galaxies

\[ M_{\text{star}} \sim 4 \times 10^9 M_\odot \]

Christensen et al. (2014)
Does Star Formation Prescription Matter?

Munshi, Brooks, et al. (in prep)
Implications for LSST

Munshi, Brooks, et al. (in prep)
**Impact on Expected Satellite Fraction in Dwarfs**

![Graph showing the fraction of isolated dwarfs with more than N substructures](image)

- **MC**
- **H2**
- **Wheeler+ 2015**

Munshi, Brooks, et al. (in prep)
Conclusions

To constrain the Dark Matter model, we must understand dwarf galaxy formation!

Future observations of dwarf galaxies ($M_{\text{star}} < 10^7 M_{\odot}$) are best probes to constrain dark matter properties/model.