Galaxy Formation
The Big (and Little) Picture

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This is your Universe

Galaxies are our link to the dark sector
Galaxies:

**Ellipticals**
- $M_{\text{halo}}>10^{11}M_\odot$
- $V\sim 350\text{ km/s}$
- Highly Clustered
- Old stars
- Rare-ish

**Spirals**
- $M_{\text{halo}}>10^{10}M_\odot$
- $V\sim 200\text{ km/s}$

**Dwarfs**
- $M_{\text{halo}}>10^8M_\odot$
- $V\sim 30\text{ km/s}$
- Weakly Clustered
- Young stars
- Numerous
Dark Matter
Large scale structure rotation
Structure forms hierarchically

- Dark matter collects into halos
- Small halos form first
- Lots of merging, especially at early times

Scale-free, so galaxy halo similar
Galaxy Clusters

V. Springel

Abell 1689
Galaxy Formation: The Short Course

- Dark matter virializes.
- Gas heats & cools.
- Or it doesn’t.
- Dense gas forms stars.
The slightly longer version:

- Infalling gas shock heats to the virial temperature of the dark matter halo.
• Infalling gas shock heats to the virial temperature of the dark matter halo.
Some gas cools & contracts

- Gas that comes in with high angular momentum forms a rotating disk.
When gas gets dense, it forms stars.
Stars are collisionless

- They tend to preserve the motion with which they were formed.

Courtesy K. Johnston
Gas can be ejected: “Feedback”

Stars

Ionized Gas \( (10^4 \text{K}) \)

Really Ionized Gas \( (5 \times 10^6 \text{K}) \)

Strickland et al 2004
Simulated galaxies are starting to look really promising!

- rotation
- ages
- sizes

20 X 6.5 Kpc. Blue= Gas Red= Stars

F. Governato
Is CDM compatible with our understanding of galaxy formation?

**CDM**
- Heirarchical
- Lots of small scale power
- Small stuff first
- Large stuff last

**Nature**
- *Too Few* low mass galaxies
- Young low mass galaxies & *old* high mass galaxies
- Massive objects at high redshift.
- Anti-Heirarchical?

Surprisingly, yes
Hiding Low Mass Halos:

Milky Way data is "missing" galaxies if $\Lambda$CDM is correct
Making dwarf galaxies disappear:

- "Feedback"
  - Supernova blowout
  - $E_{\text{thermal}} > E_{KE} > E_{\text{grav}}$

- "Squelching"
  - Reionization
  - $E_{\text{thermal}} > E_{\text{grav}}$

- "Tidal Disruption"
  - $E_{\text{grav,host}} > E_{\text{grav}}$

Dwarf galaxies have small gravitational potentials
Similar problems for **massive** galaxies:

- Smaller fraction of baryons wound up in massive galaxies
- Star formation feedback & reionization won’t work for deep potential wells

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van den Bosch et al. 2004
Merging = Gas → BH = Outflow
AGN Feedback:

- Bigger spheroid = Bigger Black Hole
- Feedback stronger in more massive galaxies
- Star formation shuts down earlier and more completely in massive galaxies

van den Bosch et al. 2004

SN Feedback from disks

AGN Feedback from spheroids
AGN Feedback makes galaxies appear “anti-hierarchical”

In massive galaxies:
- Stars form early
- Mass assembles late

Lucia et al. 2005
Putting it all together:

Courtesy G. Stinson & F. Governato
Problems remain

• Predicting internal structure
• Internal kinematics
• Numbers/Masses at high redshift?
• Compatibility with reionization?

But, given our success of making the impossible possible, I’d be optimistic.
But really, this is all a fairy tale.

We’ve proven that $\Lambda$CDM is not necessarily wrong.

This doesn’t mean it’s right!
Why galaxy formation is *not* constraining cosmological models*

Theory starts with $\Lambda$CDM as an *a priori* assumption

Tunes “gastrophysics” to match observations

Moore et al

*in the era of precision cosmology*
Start with predicted dark matter distribution

Adjust star formation and SN “feedback” to suppress the “right number” of galaxies
What are the odds?

Real Gas

Real Outflows

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

Red = ionized

Real Star Formation
Where could non-$\Lambda$CDM physics be lurking?

Not on large (>Mpc) scales

Tegmark

5% normal matter
25% dark matter
70% dark energy
On intermediate (~1-10Mpc) scales?

- Fix shape of the linear power spectrum
- $\sigma_8 \Omega_m^{0.6}$ is lower when measured on small scales, than for CMB+SN

(Note: derived behavior of baryons vs mass is qualitatively similar)

Tinker et al 2005
On smaller (~1 kpc) scales?

Compared to the *real* universe

$\Lambda$CDM simulations have:

- Too many small lumps
- Too high a central density

\[ \rho(< R) \propto \frac{M}{R^3} \propto \left( \frac{V(R)}{R} \right)^2 \]

- Too much small scale power
- Too high initial phase space density
Galaxy formation provides far more freedom than people are exploiting.

CDM is an absurdly minimal description of dark matter.
What to do?

• Don’t ignore theories whose power spectra deviate at small scales.
• Improve constraints on gastrophysics.
• Look for better observational tests.
• Increase dynamic range of simulations.
• Aggressively pursue dark-dark halos