Lecture 14
Numerical simulations of galaxy formation
What do we want from the hydrodynamic simulations?

- Formation and evolution of stellar systems on all scales and epochs (still problematic)
- Evolution, chemical enrichment and reionization of the intergalactic medium (good)
Big Achievement

Incredibly good modelling of the intergalactic gas!
Failure

Formation of galaxies with observed properties!
A successful theory of galaxy formation must self-consistently explain a growing set of multi-wavelength data across much of cosmic time:

- Cosmic star formation history, as a function of color and mass.
- Luminosity functions of galaxies, from UV to NIR, from z~0→5+.
- Clustering of galaxies and properties as a function of environment.
- The Hubble sequence, its establishment and evolution.
- Color-magnitude diagrams.
- X-Ray observations of clusters & groups.
- Sub-mm/FIR sources and the amount of dust-enshrouded SF.
- The appearance of large central AGN, particularly at early times.
Good and bad:

• Fundamental predictions:
  – Plenty of early, massive galaxies; plenty of early star formation.
  – Big galaxies form stars fast & early in small units, then dry merge.
  – Early galaxies are highly biased and clustered; reduces with time.

• Predictions that seem to disagree with observations:
  – Overcooling: Without feedback, too many stars form.
  – Luminosity function: Too many bright galaxies, faint steep end.
  – Angular momentum problem: Can’t form Sc/d galaxies (easily).
  – Color problem: Can’t get a red sequence of “dead red” galaxies.
Star formation history:

By including feedback the models can get a reasonable approximation to the star formation history....

but remember we have free parameters in both the star formation recipe and the feedback model!
Star Formation Cosmic History

![Graph showing star formation rate (SFR) vs. redshift and cosmic time (t [Gyr]).]
Global SFR

Cosmic SFH agrees reasonably well, with a peak at $z>5$. Perhaps too much early SF? Data uncertain.

Simulations show that universe was brighter in past in U and (less so) in V, by roughly the observed factors.

Overall broad agreement in evolution of stellar mass and SFR in massive galaxies at least at lower $z$. 
Actual Galaxy Formation

• How does gas get *into* galaxies?
  – CDM + shock heating + cooling
  –

• How does gas get *out* of galaxies?
  – Feedback, winds, AGN, jets, etc.

• *How do we make disks and can we get the size right?*
Modeling Galaxy Formation

- Infall from IGM
- Disk
- Shock

Cooling, dynamics and fragmentation of gas clouds

- Adiabatic
- Isothermal
- Bound Clouds
- No Condensation
- $M_j (no\ heat\ input)$
- $M_j (T = 10^4 K)$
- No Quasi-Static Phase
- Cannot Cool

$R_{vi} \quad R_{cool}$
Large objects never cool

The largest gravitational structures heat the gas to temperatures ($10^8$ K) where they don't have time to cool:

rich clusters of galaxies have most of their baryons in hot gas
Missing Baryons at z=0

• Galaxies in local universe account for only 10% of baryons we know exist due to three independent measurements, which all agree to $2\sigma$
  – Big bang nucleosynthesis
  – CMB anisotropies
  – IGM absorption at high redshift

• Where are the baryons now?
Whereabouts of the missing baryons:
Warm-Hot intergalactic gas

Cen & Ostriker (1998)

N=512^3
Global Accretion in Hot & Cold Modes

- Accretion rate shows two distinct modes, based on maximum temperature reached by gas.
- Cold mode dominates at $z>2$. At $z \sim 3$, 95% of gas has never reached $T_{\text{vir}}$ before forming into stars.
- Global $T_{\text{thresh}} \approx 2.5 \times 10^5 \text{K}$.
- Clearest separation in halo mass, with dividing mass of $\sim 10^{11.4} M$ (depends on $\Omega_b/\Omega_m$).
Accretion in a Growing Halo

- Left panels: $z=5.5$, right panels: $z=3.2$.
- Halo grows from $M \sim 10^{11}M \rightarrow 10^{12}M$, changes from cold $\rightarrow$ hot mode dominated.
- Left shows cold mode gas as green; Right shows hot mode as green.
- Cold mode filamentary, extends beyond $R_{\text{vir}}$; hot mode quasi-spherical within $R_{\text{vir}}$. Filamentarity enhances cooling.
Detecting Cold Accretion

- Should be detectable as faint Ly$\alpha$ blobs around high-z galaxies.
- Many blobs (~40) seen by Matsuda et al 2004; largest (Steidel’s & Dey’s) likely fueled by outflows/AGN, but most exceed $E_{\text{SF}}$.
- Potential energy of infalling gas emitted in HI and HeII lines.
Downsizing in Simulations

• Hierarchical models predict big halos form late, but galaxy formation not simply related.
• “Hierarchical” means big halos form late, but the subunits collapse early.
• Star formation begins on collapse, so halo and star formation times are anti-correlated.
• Thus “downsizing” or “anti-hierarchical” behavior is actually a natural prediction of CDM.
• Nevertheless, still require increased efficiency of SF at early times – happens naturally in simulations but it all doesn't quite work properly.
• Downsizing is a problem!
Major Merging vs. Smooth Accretion

- *Halos* grow by merging, but in general *galaxies* don’t!
- Jeans mass for baryons is large (compared to dark matter), so gas gets “smoothed” prior to falling into galaxy.
- Galaxies get most of their mass by smooth accretion or minor mergers, *not* major mergers.
- Minor mergers contribute little at lower redshifts.
- Globally follows smooth accretion rate.

Fig. 14. Star formation rate per unit volume (dashed line) for all resolved galaxies in the simulation compared to smooth gas accretion (solid line) and merger accretion rates (dotted line). The merger mass accretion rates include the accretion of stars.
Massive Galaxy Evolution

- NIR Surveys: Massive galaxies are in place at z~2 ⇒ Early epoch of stellar mass growth in the Universe.
- Number densities seen to z~2 agrees with models: Big galaxies form stars early, then “dry merge”.
- Downsizing is a natural consequence of galaxy formation processes (i.e. it is hierarchical, not anti-hierarchical!). High-σ perturbations collapse first, start forming stars, then get too hot and reduce their birthrate ⇒ Stellar ages inversely correlated with halo ages.
Correlations of Physical Properties

- SFR and M* closely tied: Big galaxies are forming stars fastest. Slope is $\sim 1$, so birthrates similar.
- Formation epoch loosely anti-correlated with mass: Big galaxies are older.
- Environmental dependence very weak
But no Red & Dead galaxies!

- Simulations show no red sequence, no trend with $M_V$.
- Clusters & field ellipticals lie along red sequence, at $U-V \approx 1.5$, with brighter galaxies redder.
- Truncating SF on bulge mass in seems to work OK
- What causes truncation (AGN)? When does this happen?
Birthrates of Simulated Galaxies

Birthrate = $t_{\text{Hubble}} \times \text{SFR}/M_*$

Trend to lower birthrates in larger galaxies – GOOD.
Massive galaxies show large birthrates at $z=0$ – BAD.
Need truncated SFR in massive galaxies: AGN?

When are birthrates of massive galaxies truncated in real universe?
Bright-end Excess in NIR LF

- Excess evident at $z\sim0$ (vs. 2MASS), but not so evident vs. K20 data at $z=0.5\rightarrow1.5$.
- Simulated K-band LF bright end doesn’t evolve much from $z=2\rightarrow0$, while data shows substantial passive evolution.
- Simulation evolution a balance between new stars forming and old stars fading, plus lots of dry merging.
- What stops growth? (AGN? Superwinds?) Does dry merging occur or is it numerical overmerging?

Squares, triangles, diamonds: G6 simulation results at $z=0, 1, 2$. Line with errorbars: 2MASS @ $z\sim0$ Line with circles: K20 @ $z\sim1$. 
Also not enough bright Submm sources

- Lots of bright sub-mm galaxies at z>2, with SFR~1000 M/yr.
- Using simulated SFR→F_{850} (for various dust models) yields deficit at bright end
- Lack of merger-induced bursts?

Fardal et al. 2001
Cooling flows in clusters

But the dense centers of the clusters do have time to cool (cooling flows)

But often these are suppressed: current thinking is by AGN in the central galaxy
Cluster Bubbles: Smoking Gun?

- Cooling flows not seen in accord with expectations: Need central heat source.
- “Bubbles” seen in radio & X-ray maps contain hot, tenuous gas. Adding ~1/3 keV/bary to ICM.
- Intermittent AGN heating can prevent cooling flows.
- How much energy does this add to ICM? When does “pre-heating” occur?

Figure 4. Temperature map of the central $200 \times 200$ arcsec of the cluster, colors indicate hotter temperatures. The logarithmically spaced contours show surface brightness from $1\sigma = 1.0^{-4}$ cnt s$^{-1}$ cm$^{-2}$ pix$^{-2}$ to $100\sigma$, showing the cavities. The hottest regions are at the tips of the cavities, where the strongest.
Yet another problem:

Making disk galaxies with the correct size and shape.
Angular Momentum and Galaxy Formation

Angular momentum plays a key role in disk galaxy formation.

Low $j$: infall into the inner regions → central starburst
       formation of galactic bulges and central black holes

High $j$: infall into galactic disk → self-regulated star formation
         $j$ determines size of disk and column density and hence
         star formation rate

Models of elliptical galaxy formation by major mergers require
a reasonable scenario for the formation of disk galaxies.
Initially the gas has the same specific angular momentum as the dark halo.

Dark halos have a universal mean spin parameter produced by torques between neighboring collapsing regions

\[ \lambda = \frac{J |E|^{1/2}}{GM^{5/2}} = 0.04 - 0.05 = \frac{R_{\text{disk}}}{R_{\text{halo}}} \]

If angular momentum were conserved, the size distribution of galactic disks would be in agreement with observations.
The Cosmological Angular Momentum Problem

Prediction of the simple model

Disks retained about half the available angular momentum.

However:

Simulated disk galaxies have scale radii that are a factor of 10 smaller than observed bulges instead of disks.
General solution to suppressing star formation in large galaxies?

Maybe the AGN can solve the problems of too much late large galaxy formation by suppressing cooling in these objects.
Conclusions

• We are still not quite able to simulate the observed population of galaxies arising from primordial density perturbations.
• Clustering, LSS, Lyα forest, etc, all point to ΛCDM being successful on large scales (>100 kpc). [Perhaps issues on small scales?]
• Basic predictions of current simulations:
  – Plenty of big early galaxies, due to “cold mode” path for galaxy growth.
  – Major merging is a subdominant growth mode overall, though big galaxies grow by dry merging.
  – Trend of downsizing is a fundamental, but strength is not predicted correctly.
• Simulations are able to match the cosmic star formation history, luminosity density, luminosity functions, and other properties at high redshifts.
• Feedback is the dominant issue that remains to be solved. AGN feedback offer best hope to solve a host of problems concurrently, but is it viable? Better understanding of supernova feedback, particularly superwinds, also required.
End