Semi-Analytic Models are currently the best way to understand the formation of galaxies and clusters within the cosmic web dark matter gravitational skeleton. This lecture will discuss the current state of the art in galaxy formation, and describe the successes and challenges for the best current $\Lambda$CDM models of the roles of baryonic physics and supermassive black holes in the formation of galaxies. I thank my collaborators Avishai Dekel, Sandra Faber, and Rachel Somerville for some of the slides used in this lecture.
What We Know About Galaxy Formation

**Initial Conditions:** WMAP5 cosmology

CMB + galaxy P(k) + Type Ia SNe →

$\Omega_\Lambda = 0.72$, $\Omega_m = 0.28$, $\Omega_b = 0.046$, $H_0 = 70 \text{ km/s/Mpc}$, $\sigma_8 = 0.82$
What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxy properties

Well-studied in Milky Way and nearby galaxies
What We Know About Galaxy Formation

- **Initial Conditions:** WMAP cosmology
- **Final Conditions:** Low-z galaxies
- **Integral Constraints:** Cosmological quantities
  - Star Formation Rate Density (SFRD) vs. redshift (M\(_\odot\)/yr/Mpc\(^3\)) - Madau plot
  - Stellar Mass Density (SMD) vs. redshift (M\(_\odot\)/Mpc\(^3\)) - Dickinson plot
    - SMD should = integrated SFRD: \( \rho_*(t) = \int_0^t dt \frac{d\rho_*}{dt} \)
  - Extragalactic Background Light (EBL) - constrains integrated SFRD
What We Know About Galaxy Formation

- **Initial Conditions:** WMAP cosmology
- **Final Conditions:** Low-z galaxies
- **Integral Constraints:** Cosmological quantities
- **Well-studied galaxy evolution at z<1**
  - SDSS clarified galaxy scaling relations, galaxy color bimodality
  - COMBO-17, DEEP, COSMOS surveys measuring star formation rates, etc.
What We Know About Galaxy Formation

- **Initial Conditions:** WMAP cosmology
- **Final Conditions:** Low-z galaxies
- **Integral Constraints:** Cosmological quantities
- **Well-studied galaxy evolution at** $z<1$
- **Galaxy Zoo Identified at** $z=2-3$

Lyman break galaxies, Lyman alpha emitters, Distant red galaxies, Active Galactic Nuclei, Damped Lyman alpha systems, Submillimeter galaxies

However: Evolutionary sequence unclear. Which (if any) are progenitors of typical galaxies like the Milky Way?

with thanks to Eric Gawiser
Present status of $\Lambda$CDM “Double Dark” theory:

- cosmological parameters are now well constrained by observations
- structure formation in dominant dark matter component accurately quantified
- mass accretion history of dark matter halos is represented by ‘merger trees’ like the one at left

Semi-Analytic Models of Galaxy Formation
Astrophysical processes modeled:

- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

Semi-Analytic Models of Galaxy Formation

Springel et al. 2006
gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures

gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)

cooled gas collapses to form a rotationally supported disk

cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)

massive stars and SNae reheat (and expel?) cold gas and some metals

galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids

White & Frenk 1991; Kauffmann et al. 93; Cole et al. 94; Somerville & Primack 99; Cole et al. 2000; Somerville, Primack, & Faber 01; Croton et al. 06; De Lucia & Blaizot 06; Cattaneo et al. 07; Somerville et al. 08
New Improved Semi-Analytic Models Work!

• Earlier CDM-based galaxy formation models suffered from a set of interlinked problems
  – overcooling/cooling flow problems in galaxies and clusters
  – failure to produce observed color bimodality

• ‘Bright mode’ AGN feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism

• Low-accretion rate ‘radio mode’ feedback is a promising mechanism for counteracting cooling flows over long time scales

• New self-consistent ‘hybrid’ models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/interpret the relationship between galaxies, BH, and AGN across cosmic history

-- Rachel Somerville
Baryons in Dark Matter Halos

- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall, most efficient at $M_{\text{halo}} \sim 10^{11} M_{\odot}$
- baryon/DM ratio must be a strongly non-linear (& non-monotonic) function of halo mass

Dark halo mass growth vs. time: 4 clusters

GALics DM halos by Cattaneo et al. 2006
Dark halos of progressively smaller mass

Cattaneo et al. 2006
A schematic model of average halo mass growth
Key assumption: *star-forming band* in dark-halo mass
Key assumption: **star-forming band** in dark-halo mass
Key assumption: **star-forming band** in dark-halo mass
Implications and Predictions of the Model

1) Each halo has a unique dark-matter growth path and associated stellar mass growth path.

2) Stellar mass follows halo mass until $M_{\text{halo}}$ crosses $M_{\text{crit}}$.

SAMs: \[ M_{\text{star}} \sim 0.05 \, M_{\text{halo}} \]

3) A \textit{mass sequence} comes from the fact that different halo masses enter the star-forming band at different times. A galaxy’s position is determined by its \textit{entry redshift} into the band. More massive galaxies enter earlier. Thus:

\[ z_{\text{entry}} \longleftrightarrow M_{\text{halo}} \longleftrightarrow M_{\text{star}} \]
Implications and Predictions of the Model

Massive galaxies:
- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

Small galaxies:
- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

“Downsizing”

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).
Theories for the **lower** halo star-formation boundary

\[ M_{\text{halo}} \rightarrow \text{time} \rightarrow M_{\text{halo}} \]

\[ M_{\text{thresh}} \]

\( M_{\text{thresh}} \) is the halo mass at the **LOWER** edge of the star-formation band, roughly \( 10^{10} M_\odot \).

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**Not yet well understood**

1. **Supernova feedback (Dekel & Silk 1985):**
   \[ v_{\text{lim}} < 100 \text{ km/sec} \]

2. **Early Universe reionization (e.g., Somerville 2002):**
   \[ v_{\text{lim}} < 30 \text{ km/sec} \]

3. **Plus tidal destruction!**
Theories for the *upper* halo star-formation boundary

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1. Gas in halos above the critical halo mass $M_{\text{crit}} \sim 10^{12} M_\odot$ cannot cool (Ostriker & Rees 1978, Blumenthal et al. 1984, Dekel & Birnboim 2007).

$M_{\text{crit}}$ is the halo mass at the **UPPER** edge of the star-formation band, roughly $10^{12} M_\odot$.  

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**Diagrame**: 
- **Hotter** 
- **Diffuse**
More realistic model of halo-cooling boundary
More realistic model of halo-cooling boundary

Dekel & Birnboim 2006

Submm galaxies?

Star-forming band
Theories for the upper halo star-formation boundary

Merging galaxies trigger BH growth. AGN feedback drives out galaxy gas (Hopkins et al 2006).

\[ M_{\text{crit}} \] is the halo mass at the upper edge of the star-formation band, roughly \( 10^{12} M_{\odot} \).
Why AGN Feedback Can Make Massive Galaxies Red/Dead

- Need mechanism to
  - quench star formation in massive galaxies
  - stop cooling in clusters
- SN feedback inadequate: not enough energy, little star formation in red galaxies
- BH mass closely connected with host galaxy’s spheroid mass
- Bigger BH $\Rightarrow$ more energy ($L_{\text{max}} \sim L_{\text{Edd}} \sim M_{\text{BH}}$)

Magorrian et al. 1998; Gebhardt et al. 2000, Ferrarese & Merritt 2000
The challenge of simulating BH growth and AGN FB in a cosmological context

• dynamic range:
  – Gpc (luminous QSO)
  – few 100 Mpc (LSS)
  – 10’s of kpc (ICM, jets)
  – sub-kpc (star formation, stellar FB)
  – few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  – pc & sub-pc (accretion disk, BH mergers, etc)

• poorly understood physics (B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...)
AGN feedback 1: bright mode

- optical/X-ray luminous AGN/QSO, produced during periods of efficient feeding (mergers?)
- high accretion rates (0.1-1 \( L_{\text{Edd}} \)), fueled by cold gas via thin accretion disk --> BH grows rapidly
- rare-->duty cycle short
- thermal coupling of AGN energy with ISM is probably fairly weak (<5%)

Di Matteo, Springel & Hernquist 2005
Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

- self-regulated BH growth, reproducing $M_{\text{BH}}$-σ relation (di Matteo et al. 2004)

- AGN-driven wind removes residual cold gas at the end of the merger, leading to lower SFR and redder colors in the spheroidal remnant (Springel et al. 2004)
Rest-frame U–B colour is plotted against the B-band absolute magnitude for DEEP2 comparison galaxies (small blue dots) and X-ray sources (filled red circles) in the EGS in the range $0.7 < z < 1.4$. Squares around the symbols indicate hard X-ray sources, and more luminous systems ($L_X > 10^{43}$ erg s$^{-1}$) are plotted with larger symbols. The dashed line separates red and blue galaxies, and the dotted lines show the DEEP2 completeness limits at $z = 1.0$ and $z = 1.4$. (Nandra et al., ApJ Letters, 2007.)
The highest fraction of EGS galaxies hosting AGN are early-types, not mergers. This suggests that the AGN activity is delayed, rather than occurring mainly during and immediately following mergers as the Hopkins et al. simulations predicted. (Christy Pierce et al., ApJ Letters, May 2007).
• some massive galaxies are ‘radio loud’
• radio activity believed to be associated with BH’s in ‘low accretion state’ (low Eddington ratio, $<10^{-3}$)
• jets often associated with cavities visible in X-ray images
• coupling of jet energy with hot gas very efficient
NEW Self-Consistent Model for the Co-Evolution of Galaxies, Black Holes, and AGN

- Top-level halos start with a \( \sim 100 \, M_{\text{sun}} \) seed BH
- Mergers trigger bursts of star formation and accretion onto BH; **efficiency** and **timescale** parameterized based on hydrodynamical merger simulations (\( \mu, B/T, V_c, f_g, z; \) Cox et al., Robertson et al.)
- BH accrete at Eddington rate until they reach ‘critical mass’, then enter ‘blowout’ (power-law decline) phase
  \[
  \frac{dm_{\text{acc}}}{dt} = \frac{m^*_{\text{Edd}}}{1 + (t/t_Q)^\beta}
  \]
- Energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

Somerville, Hopkins, Cox, et al. 2008 MN
quasi-hydrostatic hot gas halo? no

- gas continues to cool
- forms a new disk

no

- in the absence of new fuel, stars evolve passively...

yes

- radio jets form & begin to heat hot gas, offset cooling flow

- accretion onto BH shuts off

- cooling and accretion resumes

- galaxies & BH continue to grow via wet, moist & dry mergers...
Predicted $M_{BH}$-$M_{bulge}$ relationship

in Somerville+08 model, arises from ‘bright mode’ feedback

matches slope & scatter of observed relation

large symbols: Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex
cyan: predicted median, 10th, & 90th percentile
predicted scatter: ~0.15 dex

Somerville et al. 2008
AGN Heating Leads to Galaxy Mass Functions at z~0 in Agreement with Observations

Star Formation Efficiency

\[
M_{\text{star}} \quad \frac{F_{b}M_{\text{halo}}}{M_{\text{star}}}
\]

SN FB

AGN FB

Stellar Mass Function

\[
\log \left( \frac{dN}{d\log M_{\ast}} \right) \quad [\text{Mpc}^{-3} \text{dex}^{-1}]
\]

\[
\log M_{\ast} \quad [M_{\odot}]
\]

Somerville et al. 2008
Luminosity Functions

Somerville et al. 2008
Model produces enough massive galaxies at high redshift

Somerville et al. 2008; see also Bower et al. 2006; Kitzblicher & White 2006

observations:
Borch et al. (COMBO-17)
Drory et al. (GOODS)
Glazebrook et al. (GDDS)
Fontana et al. (K20)
Papovich et al. (GOODS DRGs)
Stellar Mass Function Evolution

data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)

Somerville et al. in prep
We might expect that a more energetic encounter will cause increased tidal stripping and puff up the remnant.

NO! For our simulations, more energetic encounters create more compact remnants.

Why? Dissipative effects cause more energetic encounters to result in smaller remnants. The greater the impulse, the more the gas is disturbed, therefore the more it can radiate and form stars.

A number of physical mechanisms conspire to make this so (e.g., greater tidal effects, lower angular momentum, and more gas disk overlap).
Reff prediction by Cole et al. 2000 dissipationless model, best for dry merging

Reff prediction by Covington et al. 2008

Covington et al. 2008 model takes dissipation into account, also works well for dry and non-equal mass mergers, including minor mergers!

Stellar velocity dispersion also predicted well!
Somerville+08 SAM + Mergers Predict Observed Size-Mass

DISKS
- z ~ 0 observations SDSS
- higher z data Trujillo+06

SPHEROIDS
- z ~ 0 observations SDSS
- higher z data Trujillo+06
The black line is fit to the SAM remnants with $M_{\text{dyn}} \propto M^1 + \alpha$ (1 + $\alpha$ is shown on the figure).

Covington et al. in prep.

Red line is the observed relation at low redshift (Gallazzi et al., 2006).

Fundamental Plane plotted as $M_\ast$ vs. $M_{\text{dyn}}$ for the remnants in the S08 SAM, binned by redshift. Model reproduces observed tilt of the Fundamental Plane.

Observed scaling $M_{\text{dyn}} \propto M_\ast^{1.2}$

Virial scaling

Matt Covington dissertation 08
Flow through the color-mass diagram for “central” galaxies

- **Red sequence**
- **Blue cloud**
- **Dry merging**
- **Wet merging**
- **Quenching band**
Flow through the color-mass diagram for "satellite" galaxies
Flow through the CM diagram versus environment

Hogg et al. 2003: Sloan Survey
$M_i^{0.1} = -19.3$

Transition mass $3 \times 10^{10} M_\odot$

$M_i^{0.1} \sim -21.0$

Satellite/Central wet/dry transition

$M_i^{0.1} > -22.1$

All boxy/dry

All formed by environment

BH not avail?

Some by env, some by wet mergers

All by dry mergers

Sandra Faber
History of Star Formation and Stellar Mass Build-up

Star Formation History

“Madau Plot”

Fit to Data

Fiducial Model

Low Model

SFR in bursts

Stellar Mass Build-up

“Dickinson Plot”

Fiducial Model: WMAP1
$\sigma_8=0.9$

Low model: WMAP3 $\sigma_8=0.75$
or WMAP1 and no cooling if $M_h<10^{11} M_{\odot}$

Discrepancy: SFR indicators or IMF evolution?

Somerville et al. 2008
SFR tracers available for large numbers of galaxies at $z \sim 1$:

1) **Thermal IR 24mum + UV continuum** :

   **Advantage:** In principle, self-correcting for extinction
   **Problems:** Obscured AGN posing as SF (Daddi et al. 2007)
   Are local IR SED templates correct at $z > \sim 1$?
   **Hope:** longer $\lambda$ data (FIDEL, Herschel, LMT, ALMA)

2) **UV continuum**

   **Advantage:** widely available from broad-band imaging to high $z$
   **Problems:** extinction correction (UV slope, ...) uncertain
   **Hope:** SED fits (Salim et al.), calib from other tracers

3) **Emission lines** (Balmer, OII, OIII)

   **Advantage:** Robust extinction correction from Balmer decrement
   **Problems:** Balmer lines need NIR spectroscopy at $z \sim 1$
   OII, OIII depend on T,O/H, calibration problematic
   **Hope:** NIR, massively Multi-Object spectrographs
Both models work well!
Both models work well!
08SAM Fails to Predict Observed 850 μm Number Counts
Luminosity Density at $z \sim 0$

- **Fiducial Model**
- **Low Model**

Primack+08
Extragalactic Background Light

Franceschini et al. 08
Backward Evolution Model

08SAM-Fiducial

Primack et al. 05

08SAM-Low

Primack+08
Buildup of EBL over time.
Upper Limits on EBL from $z \sim 0.2$ Blazars and $z=0.53$ Quasar

Gamma-ray upper limits assuming $\Gamma_{\text{max}} > 1.5$

- Mazin & Raue 07
- Aharonian+06
- MAGIC 3C279
- Franceschini+08
- 08SAM-Fiducial
- 08SAM-Low
- Primack+05
Gamma Ray Attenuation Due to Fiducial and Low Models

Fiducial Model \( \tau = 1 \)

Low Model \( \tau = 1 \)

Low Model is well within observational constraints

Primack+05
Stecker+06
Gilmore, Primack, Somerville 2009

Fiducial Model also looks OK!
Conclusions

• High resolution DM simulations show halo substructure. New hydrodynamic simulations are increasingly able to explain galaxy formation. At $z>2$, even massive halos have cold streams bringing in gas that quickly forms stars. At $z<2$ this only happens for $M_{\text{halo}} < 10^{12}$.

• Spheroids from mergers have the observed size-mass relation and lie in the observed Fundamental Plane.

• New self-consistent semi-analytic galaxy formation models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict and interpret the relationship between galaxies, BH, and AGN across cosmic history.

• Such models accurately predict number counts and luminosity functions in all spectral bands and all redshifts except for sub-mm galaxies.

• The predicted range of EBLs is consistent with the best estimates of EBL evolution inferred from observations.