“10 billion years ago things were the same”
- X. Prochaska
LCDM is correct

Halo mass function

Dark matter halos, merger trees, etc. The underlying structure, and its evolution, is known

Cosmological N-body simulations at ever higher resolution and volume (Millennium (I,II,XXL) Bolshoi)
Or not?

Carlos: “CDM rejected at 93.6% confidence level”

Parry, Eke & Frenk ’11
DM profiles in dwarf gals

Walker & Penarrubia 2011
DM profiles in dwarf gals

Walker & Penarrubia 2011
cusps $\rightarrow$ cores

FLATTENING DARK MATTER CUSPS

WITH

Super Nova® FEEDBACK

arXiv:1106.0499
Andrew Pontzen
IoA, Cambridge
Fabio Governato, UW, Seattle
cusps $\rightarrow$ cores
forming bulge-less galaxies

Lucio Mayer, Javiera Guedes
(also Hopkins’ talk)
Galaxies reside in DM halos

- Lots of work establishing this relation
- Talks by Weinberg, Hudson, Primack, Kauffmann, White, etc.

\[ \frac{M_{\text{h}}}{L_{\text{cen}}} \quad (hM_{\odot}/L_{\odot}) \]

\[ 10^{11} \quad 10^{12} \quad 10^{13} \quad 10^{14} \]

\[ 10^2 \quad 10^3 \]

Zehavi, Zheng, Weinberg et al. 2011
The relation between galaxies and halos is “simple” and evolves very slowly with time.

See also Guo et al. 2011, Simon White’s talk

Conroy & Wechsler 2009
“Environment” -> halos

Muldrew, Croton, Skibba, Pearce, et al. 2011
The Continuity Equation

- Lilly’s talk (and Peng’s)

Lilly, Vulcani’s talks
The Continuity Equation

- Lilly’s talk (and Peng’s)

\[ \eta = \mu SFR + \left( \frac{1}{1 - \varepsilon_\rho} \frac{\partial \varepsilon_\rho}{\partial \log \rho} \frac{\partial \log \rho}{\partial t} \right) + \kappa \]

- Overall quenching rate (time$^{-1}$)
- Mass quenching (independent of environment)
- Environment quenching (independent of mass)
- Originally introduced as merging, now understand that it must have specific form
The Continuity Equation

- Lilly’s talk (and Peng’s)

Mass and Environment as Drivers of Galaxy Evolution II: The quenching of satellite galaxies as the origin of environmental effects - Peng et al. 2011
“We don't know what mass quenching is, but at least we identify it as a word”
- Simon Lilly
“Halo mass is all that matters”
- Jeremy Tinker
“Not even halo mass matters”
- Yingjie Peng (also Andrew Wetzel’s poster)
low density

high density

Kauffmann et al 2004
Evolution in cosmic SFR density

Van de Voort, Shaye
Driven by cosmic gas accretion onto the halo and AGN feedback
SF “main sequence”

Elbaz, Genzel, Wuyts

Brinchmann et al. 2004
Daddi et al. 2005
Noeske et al. 2007

Wuyts et al. 2011
The *real* main sequence

NGC 6397

Richer et al. 2008
SFR-Z-Mass

\( \sigma \sim 0.05 \text{ dex} \)

Mannucci, Cresci, et al. 2010
SFR-Z-Mass

Yates et al 2011, submitted

Mannucci, Cresci, et al. 2010
disks are not disks
ellipticals are not elliptical

**SF galaxies:**

**Quiescent galaxies:**

---

Law et al. 2011

van der Wel et al. 2011
Disk galaxy evolution

Miller et al. 2011
“Disks tend to populate the same virial mass halos at any redshift (peak of cooling efficiency/galaxy formation efficiency, Guo et al. 2010)”

- Laura Sales

Miller et al. 2011
Dust properties at $z=2$ and $z=0$
Dust properties at $z=2$ and $z=0$

- mirror and far IR consistent with local SEDs (Chary & Elbaz 01) up to $z\sim 1.5$ (blue, green dots)
- at $z>1.5$: "mid-IR excess" (Daddi +07, Papovich +07) (orange, red dots)

Reddy et al. 2011
Summary of the Summary, part I

• Considering only $M_{\text{star}}$, SFR, $M_{\text{halo}}$, galaxy formation is simple, even boring.

• “10 billion years ago things were the same”
  – Prochaska
SFR laws in total gas density......

“The field is limited by how we measure star formation laws” - R. Kennicutt
SFR laws in total gas density......

.... studies on kpc scales and domination of $H_2$

Bigiel et al
(2008)
SFR laws in total gas density......
 .... studies on kpc scales and domination of H$_2$. ....
 .... even in atomic regime.

Schruba et al. (2011)
A single star formation law......
A single star formation law......

..... two sequences .....


“Main sequence hell and $X_{\text{CO}}$ purgatory” - H.-W. Rix
A single star formation law......
..... two sequences ..... 
..... smoothly varying depletion times.

Saintonge

“I never believe bimodalities in astronomy” - M. Colless
Major mergers dominate galaxy evolution.....
Major mergers dominate galaxy evolution.....
.... role of minor mergers in building up massive galaxies.

The mass growth of LRGs through mergers

- The gap width implies a typical mass ratio of 1:4 between the central galaxy and its most massive satellite
- Mergers of higher mass ratio within the environment unlikely

Tal, Newman, Krabbe, Eliche-Moral, Combes, Martinez-Manso
Major mergers dominate galaxy evolution.....
.... role of minor mergers in building up massive galaxies...
.... Importance of secular processes.

**Two modes to assemble and redistribute mass**

- According to epochs and environment

**Secular evolution**

- Internal slow evolution
- Through bars, spirals, +gas accretion

**Hierarchical scenario**

- Spheroids form through major spiral mergers

- Gas accretion can then reform disks

Combes.
At low redshift, the role of bars for changing stellar populations, star formation rates and metallicities

Combes, Sanchez-Blazquez, Nair, Masters, Lablanche, Swartz
Mergers trigger bars......

Hopkins & Quartert (2010)

Elmegreen et al. (1990).
Mergers trigger bars........

..... mergers don’t trigger bars?!!
Bars formation and destruction

Self-regulated cycle:
⇒ Bar produces gas inflow, and
⇒ Gas inflow destroys the bar

2% of gas infall is enough to transform a bar in a lens
(Friedli 1994, Berentzen et al 1998, Bournaud & Combes 02, 04)

Timescales+orbits for bar formation/destruction in mergers?
Mergers trigger AGN....

Ramos-Almeida, Bessiere, Lietzen, U, Karouzos, Trouille.
Mergers trigger AGN.... 
..... But they are not the only trigger.

Kocevski, Alexander, Heckman, Novak, Schawinski, Mullaney

Genzel paraphrased: “It doesn’t matter how you get the gas to the central few kpc, but then you have to get it to the nucleus”.
Gas rich disks highly unstable, could trigger AGN, but not clear how common this is observationally.

Bournaud et al. (2011)

Wisnioski et al. (2011)
Some high $z$ galaxies have powerful winds....

Pettini et al. (2000)

Shapley et al. (2003)
Some high $z$ galaxies have powerful winds....

...winds are ubiquitous in moderate/high $z$ galaxies.

Kornei, Harrison, Lilly, Martin, Steidel, Weiner, Haehnelt, Dave, Rudie, Oppenheimer, Lehner, Thiart, Harrison, Law, Newman

“Almost everything at high $z$ has an outflow” - C. Steidel
Interpretation of MgII: winds versus disks/halos

**Ubiquitous winds: mass loss ~ SFR**

- Cause of extended MgII absorption haloes at $b < 50$ kpc?
  - Bordoloi et al (2011)
  - (but see also Kacprzak et al 2010)

Stacked spectra of ~ 5200 zCOSMOS $z > 1.2$ galaxies lying behind 4000 $0.5 < z < 0.9$ galaxies with $b < 200$ kpc

[Diagram showing wind models and stellar mass distribution]
Not all MgII is in winds. QSO absorption lines can probe disk.

Kacprzak
The IGM is widely enriched at high $z$ (Pop III?).....

$\Omega$(CIV) ($\times 10^{-8}$)

$Z=0.001$

$Z=0.0001$

The IGM is widely enriched at high z (Pop III?).....
.... High $\Omega_{\text{CIV}}$ does not imply early enrichment

Oppenheimer, Dave.
The IGM is widely enriched at high $z$ (Pop III?).....
.... High $\Omega_{\text{CIV}}$ does not imply early enrichment....
.... Actually, the metals are just in galaxies.

Prochaska, Dave, Oppenheimer
Luminosity-metallicity relation......

Tremonti et al. (2004)
Luminosity-metallicity relation......

..... mass-metallicity relation.....
Luminosity-metallicity relation......
...... mass-metallicity relation.....
.... sequences in size and star formation rate.....

Ellison et al. (2008)
Luminosity-metallicity relation......
..... mass-metallicity relation.....
.... sequences in size and star formation rate.....

Cresci

Mannucci et al. (2010)

.... A plane in SFR-mass-metallicity (FMR).
Can this explain offsets in mass-metallicity relation, e.g. at z>0 (Cresci, but Maier), mergers (Scudder, Krabbe), clusters (Cortese), bars (Ellison, Sanchez-Blazquez, Kauffmann), population extremes (Chun)?
NATO ADVANCED RESEARCH WORKSHOP
"THE EPOCH OF GALAXY FORMATION"
UNIVERSITY OF DURHAM, U.K. JULY 18-22, 1988
Extreme Activity

- Bursting systems (starbursts and AGN)

- Interactions between black holes and their hosts
Bursting systems (starbursts and AGN)
Old view: powerful high-z SFGs are like local analogues – "bursting systems"
New view: high-z SFGs are “quiescent” even to quite high SFRs

Rodighiero +11 (PEP, submitted)
Genzel's talk

- **High duty cycle**
- **Low duty cycle (burst)**
Tacconi’s talk

- projected separation $\sim 4$ kpc
- velocity difference 200 km/s

CO 7-6 (red) on ACS (blue) & NICMOS (green)

300 km/s
A common triggering mechanism for starbursts and quasars? (Hopkins’ talk)

Observational hints: Schawinski’s talk (Treister et al.)
(A few) key questions:

- Does SF really proceed differently in starbursts?
- Are mergers the main triggering mechanism?
- Where does the transition between “quiescent” and “bursting” really occur?
- Is this directly linked to AGN fueling? Is there an evolutionary sequence between starbursts and quasars (esp. at high z)?

Lacey’s talk
Interactions between black holes and their hosts

Donoso et al (2010)
Old view: Black holes not important?
Old view: Black holes not important?

"I'm banned from telescopes for the most part" -- Davé
New-(ish) view: Black holes might be very important

Black holes

Also abundance profiles in the ICM/etc. (McCarthy)
New-(and old) view: AGN (and feedback) take many forms
Black hole accretion modes

Fanidakis, Heckman

Thin disk
- luminous disks
- weak jets

ADAF
- \( \dot{m} = \dot{M} / \dot{M}_{\text{Edd}} < 0.01 \)

“Quasars”

Hot gas
- halo
- quasar

Central engine
- BH
- accretion disk
- \( L_{\text{jet}} \alpha (H/R)^2 B^2 M_{BH} \dot{m} a^2 \)
- \( B_{\text{Blandford & Znajek 1977}} \)

Under-luminous disks
- strong jets

“Radio galaxies”
Moderate-level accretion appears to occur in non-merging systems and are naturally associated with star formation.

Little difference between AGN hosts and non-AGN.
Accretion is **messy** and **stochastic**

“No respectable theorist would touch this...
Thankfully we have a lot of "not-so-respectable" theorists” -- Steidel
McNamara’s talk

Abell 2052

Chandra 500 ksec unsmoothed

Blanton + 11

X-ray

E~10^{59} \text{ erg}

2nd shock

1st shock

N filament

NW loop

NW bubble

S bubble

SE outer bubble

30 kpc

visual
Radiatively-driven feedback expels gas from the galaxy?

Dominant mode of AGN energy input? (e.g. Hopkins)

Some observational evidence for galaxy-scale quasar outflows (Alexander’s talk)

Kauffmann’s talk
"I could have made this movie nicer, but I decided to go to the pub." -- Hopkins
Cosmic time

Gas-rich galaxy(s)

Starburst galaxy

Quasar

Red sequence galaxy

Radiative or mechanical feedback significantly affects the host

Black hole self-regulation?
How do the masses of black holes and galaxies evolve?
How to make the first quasars?

High BH mass at $z > 7$, although rare (Mortlock), but hard to make in simulations (Abel)
(A few) key questions:

- How exactly does AGN radiative or mechanical luminosity couple to gas? How do we properly model this in simulations?

- What is the abundance of galaxy-scale, radiatively-driven quasar outflows?

- Do AGN really govern the entropy in groups at high redshift? What mode of AGN are these?

- How are the first “seed” black holes produced? Do BHs grow faster or slower (on average) than their hosts?
Doktor Professor
Which is the 5th planet in solar system?

- A: Jupiter
- B: Mars
- C: Uranus
What is the dominant gas supply for star formation?

- A: Halo accretion
- B: Cold flows
- C: Mergers
Will we believe this whole paradigm in 20 years?

A: Yes  
B: No  
C: Don’t care