High-z Galaxy Formation in LCDM

Theory Challenges

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LCDM makes certain solid theoretical predictions for the most active phase of galaxy formation: massive galaxies ($\sim10^{11}M_\odot$) at high $z$ ($\sim2-3$).

Theory seems consistent with observations, introducing a coherent picture.

Open questions: SFR & feedback.
Cosmic Web, Cold Streams, Clumpy Disks & Spheroids
Bimodality of Stream-Fed Galaxies

- cold streams
- thick disk
- hot halo
- clumpy streams (mergers) build a spheroid & generate turbulence → disk stabilization & quenching of SFR
- smooth streams

The main mode of galaxy formation

$M_v > 10^{12}$

$z > 2$
Theory Challenges

- Galaxies from the cosmic web
- Cold streams in Lyman alpha
- Outflows
- Stream-disk interaction
- Wild clumpy disks
  - angular momentum
  - driving the turbulence
  - clump support
  - clump disruption
- Bulge-less disks
- Fate of wild disks - stabilization
Galaxies emerge from the Cosmic Web

- Halos $M \gg M_{PS}$ - high-sigma peaks at the nodes of the cosmic web
- Typically fed by 3 big streams
- Streams are co-planar
Three Streams: filament mergers

AMR RAMSES
Teyssier, Dekel
box 300 kpc
res 30 pc
z = 5.0 to 2.5
Accretion Rate into a Halo

Neistein, van den Bosch, Dekel 06; Neistein & Dekel 07, 08; Genel et al 08

From N-body simulations/EPS in LCDM (<10% accuracy):

$$\left\langle \dot{M}_{\text{baryon}} \right\rangle = 80 \, M_\odot \, yr^{-1} \, M_{12}^{1.14} \, (1 + z)^{2.4} \, f_{0.17}$$

Almost all penetrate to the inner halo in cold streams

The accretion rate governs galaxy growth & SFR - can serve for successful simple modeling
- Critical halo mass $\sim 10^{12} M_\odot$
- Cold streams penetrate at $z > 2$
At High $z$, in Massive Halos: Cold Streams in Hot Halos

in $M>M_{\text{shock}}$

Totally hot at $z<1$

Cold streams at $z>2$

Dekel & Birnboim 2006

Kravtsov et al
Cold Streams in Big Galaxies at High $z$

$M_{\text{vir}}$ [$M_\odot$]

$M_{\text{shock}} \approx M_*$

$M_{\text{shock}} \gg M_*$

$M_*$

$M_{\text{shock}}$

$10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$

redshift $z$

0 1 2 3 4 5

all hot

cold filaments in hot medium

all cold

Dekel & Birnboim 06
high-sigma halos: fed by relatively thin, dense filaments → cold narrow streams

typical halos: reside in relatively thick filaments, fed ~spherically → no cold streams
Narrow dense gas streams at high $z$ versus spherical infall at low $z$

$M = 10^{12} M_\odot \gg M_{PS}$

$M = 10^{12} M_\odot \sim M_{PS}$

Ocvirk, Pichon, Teyssier 08
Cold Stereoams

\[ \langle \dot{M}_{\text{baryon}} \rangle = 80 M_{\odot} \text{yr}^{-1} M_{12}^{1.14} (1+z)^{2.4} f_{0.17} \]

- >90% of influx in cold streams
- Penetration: \( V \sim V_{\text{vir}} \), \( dM/dt(r) \sim \text{const} \)
- Hot accretion negligible
- recycled outflows

Neistein et al 06, 07, 08; Genel et al 08

Talks by Keres, Stewart, Leitner

Dekel et al 09 Nature
Inflow rate through the halo into the disk

Cosmological hydro simulations MareNostrum, Dekel et al. 09

The flow rate is constant with radius: deep penetration
Galaxy density at a given gas inflow rate

\[ n(\dot{M}) = \int_{0}^{\infty} P(\dot{M} | M) n(M) dM \]

\( P(\dot{M} | M) \) from cosmological hydro simulations (MareNostrum)

\( n(M) \) by Sheth-Tormen

Dekel et al 09, Nature

\[ \text{SFR} \approx (1/2) \text{ inflow rate} \]

\[ \dot{M} \approx 2 \dot{M}_* \]

Star-Forming Gal's

Sub-Millimeter Gal's

SFR = \[ \dot{M} \ [\text{M}_\odot \text{ yr}^{-1}] \]
Lyman-alpha from Cold streams

Fardal et al 01; Furlanetto et al 05; Dijkstra & Loeb 09
Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 10

\[ T = (1-5) \times 10^4 \text{ K} \quad n = 0.01-0.1 \text{ cm}^{-3} \quad N_{\text{HI}} \sim 10^{20} \text{ cm}^{-2} \]
\[ L \sim 10^{43-44} \text{ erg s}^{-1} \]

- Extended cold gas is provided by the incoming streams
- Lya is powered by gravitational infall into halo potential well
Cold streams as Lyman-alpha Blobs

Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 10

Matsuda et al 06-09
**Lyman Alpha Emission (LABs)**

Radiative transfer, ionization from stars, dust

Kasen, Fumagalli, Ceverino, Dekel, Prochaska, Primack

<table>
<thead>
<tr>
<th>100 kpc</th>
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<tbody>
<tr>
<td><strong>no UV</strong></td>
<td><strong>UVB</strong></td>
</tr>
<tr>
<td><strong>UVB + stars</strong></td>
<td><strong>UVB + stars thermal only</strong></td>
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- Lya emission from gravitationally infalling streams is inevitable in high-z massive halos
- Also from outflows and ionization by stars or AGN
Massive Outflows Observed

Steidel et al. 2010

Stacked line profiles of Lya and metal absorption

\[ \dot{M}_{\text{out}} \approx \dot{M}_{\text{sf}} \rightarrow \dot{M}_{\text{in}} \approx \dot{M}_{\text{sf}} + \dot{M}_{\text{out}} \approx 2\dot{M}_{\text{out}} \]

Weak inflow absorption features in the average line profile → small sky coverage → narrow cold streams

Talks by Koo, Prochaska
Neutral Hydrogen Column Density
Radiative transfer, ionization from stars, dust
Kasen, Fumagalli, Ceverino, Dekel, Prochaska, Primack

Talk by Fumagalli
Absorption line profile is weak because of low sky coverage.

Inflow signal consistent with observations (Steidel et al. 10)

Inflow undetectable in metals because of low Z and coverage.
Inflow and Outflow

- What drives the massive outflows in massive galaxies?
- Are the cold streams unaffected?
Stream Clumpiness - Mergers

Mass input to galaxies (all along streams)
- Major mergers >1:3 <10%
- Major+minor mergers >1:10 ~33%
- Miniminors and smooth flows ~67%

Dekel et al 09, Nature

Talk by Teyssier
Angular Momentum

- Streams bring in the angular momentum
- Disk spin & size are determined by one stream
- Clumpy streams generate turbulence

Open issues:
- Origin of extra-large disk sizes?
- Origin of “dispersion-dominated” galaxies $V/\sigma<2$?
  Angular momentum? Stream clumpiness? Feedback? Stage of evolution?

Talk by Bouche

Agertz et al 09
A Disk Fed by Cold Streams

Violent Disk Instability

High gas density $\rightarrow$ disk wildly unstable

Giant clumps and transient features

\[ Q \approx \frac{\sigma \Omega}{\pi G \Sigma} < 1 \]
\[ R_{\text{clump}} \approx \frac{7 G \Sigma}{\Omega^2} \]

Violent Disk Instability

5 kpc

Self-regulation at $Q \sim 1$ with high $\sigma/V \sim 1/4$

Star formation and feedback in the clumps

Rapid migration of massive clumps and mass inflow $\rightarrow$ bulge formation

Noguchi 99
Immeli et al. 04
Bournaud, Elmegreem, Elmegreem 06, 08
Dekel, Sari, Ceverino 09
Ceverino, Dekel, Bournaud 09
Agertz et al. 09

Talks by Cacciato, Ceverino, Teyssier, Genel
What Drives the Turbulence?

- Gravity: accretion, migration

\[
\dot{E} \approx \frac{GM \dot{M}}{R}
\]

- Feedback: SN, radiative, AGN

Talks by Genel, Cacciato
Clump Support: The Clumps are Spinning

Jeans equation for an isotropic rotator

Rotation support, induced by disk rotation and AM conservation during clump collapse, but the spin can be tilted

\[ V_{\text{circ}}^2 = \frac{GM}{R} = V_{\text{rot}}^2 + 2\sigma^2 \]

\[ \frac{V_{\text{rot}}^2}{V_{\text{circ}}^2} \approx 0.2 \left( \frac{\Sigma_{\text{clump}}}{\Sigma_{\text{disk}}} \right)^{1/2} \]

Talk by Ceveriono
Rotating Clumps in a Wildly Unstable Disk

Naab
Clump Disruption by Stellar Radiation Pressure

Murray et al. 10; Krumholz & Dekel 10

Giant clumps in high-z disks survive if the SFR obeys the Kennicutt law

\[
\mathcal{E} \equiv \frac{\dot{\Sigma}_*}{\Sigma_g / t_{ff}} \approx 0.01 -- \text{Kennicutt law}
\]

\[
t_{ff} \approx 15 \text{Myr} M_9^{-1/2} R_1^{3/2}
\]

If \( t_{ff} > 3 \) Myr, the mass fraction ejected is

\[
f_{eject} \approx 0.08 \mathcal{E}_{-2} (\Sigma_{-1} M_9)^{-1/4}
\]

Giant clumps in high-z disks survive if the SFR obeys the Kennicutt law

If \( \mathcal{E} \sim 0.1 \), “fireworks”: clumpy disk in steady state: the clumps are disrupted before they migrate to the center as new clumps form
A Fireworks Model of Clumpy Disks

Clumpy disk in steady state: the clumps are disrupted before they migrate to the center as new clumps form.

SFR efficiencies
\[ \eta = \frac{M_{c^*}}{M_c} \approx 0.1 \]
\[ \varepsilon = \frac{\dot{M}_{c^*}}{M_c / t_{ff}} \]
\[ \eta = \varepsilon \frac{t_{dis}}{t_{ff}} \]

Simulations:
\[ \alpha = \frac{\sum M_c}{M_{disk}} \approx 0.2 \]
\[ \beta = \frac{\sum \dot{M}_{c^*}}{M_*} \approx 0.5 \]
\[ \eta = \frac{\beta \dot{M}_* t_{dis}}{\alpha M_{disk}} \]
\[ \varepsilon = 0.1 \beta \alpha^{-1} (\dot{M}_*/M_d)_{Gyr^{-1}} t_{ff,20} \approx 0.1 \]
\[ t_{dis} \approx t_{ff} \]

Simulation steady state:
\[ t_{form} \approx t_{mig} \approx 16 t_{ff} \]

Duty cycle
\[ \mu = \frac{t_{dis}}{t_{mig}} \approx 0.06 \frac{t_{dis}}{t_{ff}} \]
but should be \( \sim 1 \)
Wildly Unstable Disk: Migration into a Bulge

Formation of an exponential spiral disk and a central bulge from the evolution of a gas-rich primordial disk evolving through a clumpy phase

Models from Bournaud, Elmegreen & Elmegreen 2007

Noguchi 99; Immeli et al. 04; Bournaud, Elmegreen, Elmegreen 06, 08
Clump Formation & Migration to a Bulge
\[ \gamma = 0 - 0.33 - 0.6 \]

Cosmological Steady State

Dekel, Sari, Ceverino 09

\[ \dot{M}_{\text{disk}} = (1 - \gamma) \dot{M}_{\text{acc}} - \dot{M}_{\text{evac}}(\delta) \]
\[ \dot{M}_{\text{bulge}} = \gamma \dot{M}_{\text{acc}} + \dot{M}_{\text{evac}}(\delta) \]
\[ \delta = \frac{M_{\text{disk}}}{M_{\text{tot}}} \]

Steady state for a few Gyr: draining disk is replenished by cold streams, bulge \~disk \~dark matter

Talks by Cacciato, Genel
Wild Disk Instability $\rightarrow$ Bulge

gas

young stars

dark matter

stars
Observations vs. Simulations

Elmegreen et al

2 kpc
UDF 9759

Galaxy C

2 kpc
UDF 9974

Galaxy A

Talk by Mozena
Stellar Images of Clumpy Disks $z=2$
A typical star-forming galaxy at z=2: clumpy, rotating, extended disk & a bulge

Hα star-forming regions
color-code velocity field

Genzel et al. 08
Clumpy Disks with Massive Bulges?

A bulge-less disk ???
- A young clumpy disk that will soon form a bulge?
- Bulge removed by feedback (SN, radiative, AGN)?

Clump coalescence into the bulge = wet mergers. If SFR efficiency in mergers is 10xKennicutt then stellar radiative feedback could disrupt the bulge

Genzel et al. 08; Förster Schreiber et al. 10

$\frac{M(\leq 3 \text{ kpc})}{M(\leq 15 \text{ kpc})} \sim 0.2-0.4$
Simulation of Clump Rotation Dispersion

Hα rotation dispersion
Sub-structure in the disk giant clumps

Caution: high-res $\rightarrow$ substructure $\rightarrow$ less dissipation $\rightarrow$ smaller collapse factor $\rightarrow$ less spin-up

Caution: MW molecular clouds are not spin-supported

Bournaud, Teyssier 10  AMR 2 pc resolution
Stabilization by stream clumps

Dekel, Sari, Ceverino 09

\[ Q \approx \frac{M_{\text{tot}}}{M_{\text{disk}}} \frac{\sigma}{V} \]

- Stabilization \( Q > 1 \) due to bulge growth & turbulence driven by clumpy streams
- Stable disk in steady state for \( M_{\text{disk}}/M_{\text{tot}} < 0.3 \)
  → Bimodality at high \( z \): blue disks and red spheroids
12. Disk Stabilization - SF Quenching

- Dominant bulge - Morphological quenching
- Excessive turbulence by external sources: clumpy streams, feedback
- Low accretion rate (e.g. at late times)
- Low gas fraction (e.g. today’s spirals)

Relation to today’s galaxies?

- The descendants of the high-z clumpy disks are probably S0s and rotating Es, or thick disks of spirals
- Thin disks form later by slow accretion

Martig et al 09

\[ Q \approx \frac{M_{tot}}{M_{disk}} \frac{\sigma}{V} \]
Conclusion

LCDM makes certain solid theoretical predictions for how massive galaxies form at high z, consistent with observations, together suggesting a coherent picture:

- Galaxies are fed by cold streams from the cosmic web
  Streams include major & minor mergers and smooth flows
  Streams radiate as Lyman-alpha blobs

- Gas-rich disks form, develop violent instability, self-regulated
  Giant clumps form stars (?) and migrate to a bulge. Disruption (?)
  Cosmological steady state with bulge ~ disk. Bulge disruption (?)
  Angular momentum versus dispersion (?)

- Spheroids form by mergers and by violent disk instability

- Disks are stabilized (SFR quenched) by bulge, external turbulence,
  low accretion rate, gas consumption & stellar dominance

- Main open issues: star formation & feedback
Cosmic Web, Cold Streams, Clumpy Disks & Spheroids