Feeding High-z Galaxies from the Cosmic Web

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Lecture 1
z=0
z=8
Cosmological simulations

Oxford Dictionary: *simulate*
pretend to be, have or feel,
hide under a false appearance,
feign, put on, dissemble

Toy modeling

Consider a spherical cow...

"Oh, not a computer, Caldwell —
we’re replacing you with a
computer simulation."
Consider a spherical cow...

Oxford Dictionary: simulate

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"Oh, not a computer, Caldwell — we're replacing you with a computer simulation."
Key Concepts at high z

1. **Cold Streams from Cosmic Web**
   co-planar, pancakes, angular momentum, mergers, outflows, detection in Ly\(\alpha\)

2. **Violent Disk Instability (VDI)**
   in-situ clumps, evolution of instability

3. **Instability-Driven Inflow**
   spheroids, black Holes
Lecture 1: Outline

1. Cosmological inflow rate
2. Virial shock heating and cold flows
3. Cold streams from the cosmic web
4. Smooth flows and mergers
5. Stream penetration and fragmentation
6. Observing cold streams in Lyman alpha
7. Angular momentum: transport and exchange
8. Outflows
1. Cosmological Inflow rate

Neistein, van den Bosch, Dekel 2006
Neistein & Dekel 2008
Dekel et al. 2009; 2012

Genel et al. 2008
**Accretion Rate into a Halo at z>1**

**EdS cosmology at z>1**

\[
a = \left(1 + z\right)^{-1} \approx \left(t / t_1\right)^{2/3} \quad t_1 = \left(2 / 3\right)\Omega_m^{-1/2}H_0^{-1} \approx 17.5 \text{ Gyr}
\]

\[
\rho_u = \rho_0 a^{-3} \quad \rho_0 \approx 2.5 \times 10^{-30} \text{ g cm}^{-3}
\]

**Virial relations**

\[
V^2 = GM/R \quad M/(4R^3) = 200\Delta_{200}\rho_u
\]

\[
V_{200} \approx M_{12}^{1/3}(1 + z)_3^{1/2} \quad R_{100} \approx M_{12}^{1/3}(1 + z)_3^{-1}
\]

**From EPS and N-body simulations (5-10% accuracy)**

\[
\frac{\dot{M}}{M} \approx s M_{12}^\beta (1 + z)^\mu \quad s \approx 0.03 \text{ Gyr}^{-1} \quad \beta \approx 0.14 \approx (n + 3) / 6 \quad P \propto k^n
\]

\[
\mu \rightarrow 5/2 \quad \text{PS self-invariant time}
\]

\[
\alpha = \delta / D(a) \quad D \propto a \propto t^{2/3}
\]

\[
\partial M / \partial \omega = \text{const.} \quad \rightarrow \frac{\dot{M}}{M} \propto \dot{\omega} \propto a^{-5/2}
\]

**EPS evolution of main progenitor**

\[
\dot{M} \propto M \quad M_0 = M_1 + \Delta M \quad t_1 \rightarrow t_0
\]

\[
P(M_1 | M_0) = f(M_1 / M_0) g(\sigma(M))
\]

**Toy model**

\[
\frac{\dot{M}}{M} \approx s (1 + z)^{5/2} \quad s \approx 0.03 \text{ Gyr}^{-1}
\]

\[
M(z) \approx M_0 e^{-\alpha(z-z_0)} \quad \alpha = (3 / 2)st_1 \approx 0.79
\]

\[
\left< \dot{M}_{\text{baryon}} \right> \approx 80 M_\odot \text{ yr}^{-1} \quad M_{12}^{1.14} (1 + z)_3^{2.5} \quad f_{0.17}
\]
AMR Cosmological Simulations

Cosmological box, RAMSES (Teyssier), resolution 1 kpc

Zoom-in individual galaxies, ART (Kravtsov, Klypin), RAMSES
Ceverino, Tweed, Dekel, Primack:
  - 50 pc res. (30 galaxies)
  - 25 pc res., lower SFR, stronger feedback

Isolated galaxies, resolution 1-10 pc, RAMSES, Bournaud et al.

Collaborators: Bournaud, Teyssier, Krumholz, ...

HUJI: Ceverino, Goerdt, Mandelker, Tweed, Zolotov, ...

UCSC: Fumagalli, Moody, Mozena, ...
Toy Model vs Simulations

Dekel, Zolotov, Tweed, Cacciato, Ceverino, Primack 2013

\[ \frac{\dot{M}}{M} = s (1 + z)^{5/2} \quad s = 0.03 \text{Gyr}^{-1} \]

\[ M(z) \approx M_0 e^{-\alpha(z-z_0)} \quad \alpha \approx 0.79 \]
Steady State: SFR Governed by Accretion

Mass conservation

\[ \dot{M}_{\text{gas}} = \dot{M}_{\text{acc}} - \dot{M}_* \]

Kennicutt SFR

\[ \dot{M}_* = \frac{M_{\text{gas}}}{\tau_{\text{sfr}}} \]

If \( \dot{M}_{\text{acc}}, \tau_{\text{sfr}}^{-1} \) vary on a timescale \( < \tau_{\text{sfr}} \)

\[ M_{\text{gas}} = \dot{M}_{\text{acc}} \tau (1 - e^{-t/\tau}) \quad \dot{M}_{\text{gas}} = \dot{M}_{\text{acc}} e^{-t/\tau} \quad \dot{M}_* = \dot{M}_{\text{acc}} (1 - e^{-t/\tau}) \]

Steady state after \( \tau_{\text{sfr}} \)

\[ \dot{M}_{\text{gas}} \rightarrow 0 \quad \dot{M}_* \rightarrow \dot{M}_{\text{acc}} \]

Timescale for change of parameters from \( z=4 \) to \( z<1 \)

\[ \frac{\dot{M}_{\text{acc}}}{dM_{\text{acc}} / dt} \geq t \approx 4 \tau_{\text{sfr}} \quad \frac{\tau_{\text{sfr}}^{-1}}{d\tau_{\text{sfr}}^{-1} / dt} \approx t \approx 4 \tau_{\text{sfr}} \quad \tau_{\text{sfr}} \approx \varepsilon_{\text{ff}}^{-1} t_{\text{ff}} \approx 0.75 \text{ Gyr} \]

\[ \frac{t_{\text{ff}}}{t} \approx \frac{t_{\text{ff}}}{t_{\text{disk}}} \frac{t_{\text{disk}}}{t_{\text{vir}}} \frac{t_{\text{vir}}}{t} \approx \frac{1}{3} \times 0.05 \times 0.14 \approx 0.0023 \]
Cosmological Steady State: SFR $\sim$ accretion rate into the disk

Mass conservation:

$$\dot{M}_{\text{gas}} = \dot{M}_{\text{gas,acc}} - \dot{M}_{\text{sfr}}$$

$$\dot{M}_{\text{sfr}} = \frac{M_{\text{gas}}}{\tau_{\text{sfr}}}$$

But gas accumulates in disks at earlier times and in smaller masses.
Star-formation history:

\[ SFR = f_b \langle \dot{M}_{\text{halo}} \rangle \]
2. Virial shock heating and cold flows

Rees & Ostriker 1977; Silk 1977; Binney 1977

Birnboim & Dekel 2003; Dekel & Birnboim 2006
3. Virial Shock Heating

- Critical halo mass $\sim 10^{12} M_\odot$
- Cold streams penetrate the hot medium at $z>2$
Old Standard Picture of Infall to a Disc

Rees & Ostriker 77, Silk 77, White & Rees 78, ...

Perturbed expansion
Halo virialization

Gas infall, shock heating at the virial radius
Radiative cooling
Accretion to disc if $t_{\text{cool}} < t_{\text{ff}}$
Stars & feedback

$M < M_{\text{cool}} \sim 10^{12-13} M_{\odot}$
### Cooling rate

<table>
<thead>
<tr>
<th>Z</th>
<th>log $\Lambda_{\text{mic}}$ [erg cm$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-21</td>
</tr>
<tr>
<td>0.05</td>
<td>-22</td>
</tr>
<tr>
<td>0.3</td>
<td>-23</td>
</tr>
</tbody>
</table>

\[
q = \frac{N_A^2 \chi^2}{\mu^2} \Lambda(T) \rho \quad \text{[erg g$^{-1}$ s$^{-1}$]}
\]

$N_A / \mu$ molecules per g, $\chi$ e$^-$ per particle

**Line emission**

**Bremsstrahlung**

![Graph showing cooling rate with lines for different Z values and labels for log T [K] and log $\Lambda_{\text{mic}}$ [erg cm$^3$/s]]
Brems.

Rees & Ostriker 77; Silk 77; White & Rees 78; Blumenthal et al. 86

Cooling vs Free Fall

log gas density

$T_{\text{cool}} < T_{\text{ff}}$

$H_2$

$H$

CDM

upper bound too big

Brems.

galaxies

clusters

$10^4$ $T$ $10^5$ $10^6$ $10^7$

Virial velocity

$10$ $30$ $100$ $300$ $1000$

O1O3O5

CDM
Consider a spherical cow...
Gas through shock: heats to virial temperature compression on a dynamical timescale versus radiative cooling timescale

Shock-stability analysis: post-shock pressure vs. gravitational collapse

\[ t_{\text{cool}}^{-1} < t_{\text{compress}}^{-1} \]

\[ t_{\text{compress}} = \frac{21 \rho}{5 \dot{\rho}} \approx \frac{4 R_s}{3 V} \]
Shock Stability
post-shock pressure vs. gravitational collapse

adiabatic: \( \gamma = \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s \)

stable: \( \gamma > 4/3 \)

with cooling rate \( q \) (internal energy \( e \)):

\[
\gamma_{\text{eff}} \equiv \frac{d(\ln P)}{d(\ln \rho)} = \gamma - \frac{\rho q}{\dot{\rho} e} = \frac{5}{3} - \frac{21}{5} \frac{t_{\text{comp}}}{t_{\text{cool}}}
\]

\[
\dot{e} = -P \dot{V} - q
\]

\[
t_{\text{comp}} \equiv \frac{21 \rho}{5 \dot{\rho}} \approx \frac{4}{3} \frac{R_{\text{shock}}}{V}
\]

\[
t_{\text{cool}} \equiv \frac{e}{\dot{q}} \propto \frac{T}{\rho \Lambda(T,Z)} \quad T \approx \frac{3}{16} V^2 \quad \rho_{\text{post}} \approx 4 \rho_{\text{pre}}
\]

Stability criterion:

\[
\gamma_{\text{eff}} > \frac{10}{7} \quad \rightarrow \quad t_{\text{cool}}^{-1} < t_{\text{compress}}^{-1}
\]
Growth of a Massive Galaxy

Spherical hydro simulation

Birnboim & Dekel 03
A Less Massive Galaxy

Spherical hydro simulation

Birnboim & Dekel 03
Hydro Simulation: ~Massive $M = 3 \times 10^{11} \, M_\odot$  

Kravtsov et al.

$z = 4$  
$M = 3 \times 10^{11} \, M_\odot$  
$T_{\text{vir}} = 1.2 \times 10^6 \, K$  
$R_{\text{vir}} = 34 \, \text{kpc}$

**virial shock**
Less Massive \( M = 1.8 \times 10^{10} \, M_\odot \)

Kravtsov et al.

cold infall

\( z = 9 \)
\( M = 1.8 \times 10^{10} \)
\( T_{\text{vir}} = 3.5 \times 10^5 \)
\( R_{\text{vir}} = 7 \) kpc
Shock-Heating Scale

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

Birnboim & Dekel 03
Dekel & Birnboim 06

Keres et al 05

- **stable shock**
- **unstable shock**

\[ 6 \times 10^{11} M_\odot \]

- **typical halos**
- **PS**
- **SN 2\sigma 4.7\%**

redshift \( z \)
The Critical Mass: Cosmological Simulations

SPH Keres et al 2005, AMR Kravtsov et al

$M < 10^{12} M_\odot$ cold flows

$M > 10^{12} M_\odot$ virial shock heating
Fraction of Cold Gas in Halos: Cosmological simulations (Kravtsov)

Birnboim, Dekel, Neistein 2007
Virial shock: rapid expansion from the inner halo to $R_{\text{vir}}$.

Necessary condition $M > M_{\text{crit}}$.

Trigger: minor merger.

d(Entropy)/dt
Two Galaxy Types: Bi-modality
Bi-modality in color, SFR, bulge/disk

$0.65 < z < 0.75$

$E/S0/Sa$

Disks and Irregulars

$M_{*\text{crit}} \sim 3 \times 10^{10} M_\odot$

Bell
Color-Magnitude bimodality & B/D depend on environment ~ halo mass

Environment density: low high very high

SDSS: Hogg et al. 03
Galaxy Bi-modality about $M_{\text{crit}}$  

While halos grow by smooth accretion and mergers

$M < M_{\text{crit}}$: The Blue Sequence

- cold gas supply $\rightarrow$ disk growth & star formation
- Stellar feedback regulates SFR $\rightarrow$ long duration mergers & disk instability $\rightarrow$ bulges

$M > M_{\text{crit}}$: The Red Sequence

- shock-heated gas + AGN feedback $\rightarrow$ no new gas supply
- gas exhausted $\rightarrow$ SFR shuts off
- passive stellar evolution $\rightarrow$ red & dead
- further growth by gas-poor mergers
In a standard Semi Analytic Model (GalICS)

Cattaneo, Dekel, Devriendt, Guiderdoni, Blaizot 06

Excess of big blue

No red sequence at $z\approx 1$

Too few galaxies at $z\approx 3$

Star formation at low $z$
With Shutdown Above $10^{12} M_\odot$
Standard
With Shutdown Above $10^{12} M_\odot$
From Blue to Red Sequence by Shutdown

Dekel & Birnboim 06

$M_{\text{vir}} \left[ M_\odot \right]$ vs. redshift $z$

- $z > 2$
  - cold gas supply & SN feedback
  - blue, star-forming discs
  - cold streams in hot media

- $z < 1$
  - cold gas supply & SN feedback
  - red & dead spheroids
  - shutdown gas supply & star formation
  - grouped

$M_{\text{shock}}$

$M_{\text{star,crit}}$

Halo mass $\rightarrow$

SFR $\downarrow$

Age $\uparrow$

Color

$10^{15}$

$10^{14}$

$10^{13}$

$10^{12}$

$10^{11}$

$10^{10}$

$10^{9}$

0 1 2 3 4 5

redshift $z$

all cold

hot
cold in hot

0 1 2 3 4 5

Stellar mass $\rightarrow$
3. Cold Streams from the Cosmic Web

Dekel et al. 2009
Danovich, Dekel, Hahn, Teyssier 2012

Pichon et al. 2012
Kim et al. 2012
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
Mass Distribution of Halo Gas

density

Temperature

disk
cold flows
adiabatic infall
shock-heated

Total Mass (log)
Cold Streams in Big Galaxies at High z

\( M_{\text{vir}} \) [\( M_\odot \)]

- **all hot**
- **all cold**
- **M_{\text{shock}} \sim M_\ast**
- **M_{\text{shock}} \gg M_\ast**
- **cold filaments in hot medium**

Dekel & Birnboim 06

redshift z

10^9
high-sigma halos: fed by relatively thin, dense filaments → cold narrow streams

typical halos: reside in relatively thick filaments, fed ~spherically → no cold streams
Origin of dense filaments in hot halos \((M \geq M_{\text{shock}})\) at high \(z\)

At low \(z\), \(M_{\text{shock}}\) halos are typical: they reside in thicker filaments of comparable density

At high \(z\), \(M_{\text{shock}}\) halos are high-\(\sigma\) peaks: they are fed by a few thinner filaments of higher density

Large-scale filaments grow self-similarly with \(M_*(t)\) and always have typical width \(\sim R_* \propto M_*^{1/3}\)
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
Critical Mass and Cold Streams in Hot Halos: Cosmological Simulations

Ocvirk, Pichon, Teyssier 08

![Graph showing mass and redshift relationship]

- \( M_{\text{stream}} \)
- \( M_{\text{shock}} \)
- Cold filaments in hot medium

Log(halos Mass \([M_{\odot}]\)) vs. redshift \( z \)
Cold Streams at ~1 kpc Resolution

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

Dekel et al 09 Nature
Cold streams through hot halos
Cold streams through hot halos

Diagram showing:
- Density
- Entropy
- Flux per solid angle

Outflows
Flux per solid angle

Dekel et al 09
Streams riding DM filaments of Cosmic Web. High-z massive galaxies form at the nodes.
Cosmic-web Streams feed galaxies: mergers and a smoother component

AMR RAMSES Teyssier, Dekel
box 300 kpc
res 30 pc
z = 5.0 to 2.5
Streams Feeding a Hi-z Galaxy

Tweed, Dekel, Teyssier
RAMSES Res. 50 pc

100 kpc

log ρ (nh/cc)
Streams Feeding a Hi-z Galaxy

Ceverino, Dekel, Primack
ART res. 35-70 pc
Cold Streams Penetrate through Hot Halos

\[ M_v > 10^{12} \, M_\odot \]

Agertz et al. 09

100 kpc
Co-planar Streams and Pancakes

influx $M_{\odot}$ yr$^{-1}$ rad$^{-2}$

1-2$R_{\text{vir}}$
Streams in a Pancake

influx $M_\odot \text{yr}^{-1}\text{rad}^{-2}$
Streams in a Pancake
Flows into pancakes, and along pancakes to filaments

The stream plane extends from $r<0.4R_v$ to $r>5R_v$

Influx at $R_{\text{vir}}$: 70% in streams, 20% in pancakes

Influx in the streams: 55% in 1 stream, 90% in 3 streams

MW4 $z=7$

influx $M_\odot \text{yr}^{-1} \text{rad}^{-2}$
Distribution of Influx in Streams and Pancakes

Influx:
70% in streams
20% in pancakes

>50% in 1 stream
>90% in 3 streams
Origin of Structure near a Node of the Cosmic Web

A dominant filament in a dominant sheet within a smoothing volume

3 major filaments in a plane (Arnold et al. 1982)

A honeycomb:
- maximum volume of voids
- minimum length of filaments
Pancakes of low Entropy

Entropy

MW1

MW4

MW5

Influx

MW1

MW4

MW5
4. Smooth Flows and Mergers

Dekel et al. 2009
Stream Clumpiness - Mergers

Dekel, Teyssier et al 09; MareNostrum RAMSES sims 1kpc res

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

$M=10^{12} M_\odot \quad z=2.5$
Distribution of gas inflow rate

Cosmological hydro simulations (MareNostrum, Dekel et al. 09)

![Graph showing distribution of gas inflow rate with R [kpc] on the x-axis and \( \dot{M}_{\text{in}} [M_\odot \text{yr}^{-1}] \) on the y-axis. The graph includes a histogram of the distribution of gas inflow rates with labeled regions for smooth flows and mergers >1:10. A separate plot shows the probability distribution function \( P(\dot{M}|M) \) with \( M=10^{12}M_\odot \) and \( z=2.5 \).]
Galaxy density at a given gas inflow rate

Dekel et al. 2009, Mare Nostrum Simulation

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

\[ \approx \text{Star-Forming Gal's} \]

\[ \approx \text{Sub-Millimeter Gal's} \]

\[ \text{SFR} \sim \frac{\dot{M}}{M_* \text{ yr}^{-1}} \]
Mergers have a Limited Contribution to SFR

At a given $dM/dt$, $3/4$ galaxies are fed by smooth flows.

SFGs are miniminor mergers, i.e. smooth flows.

Bright SMGs are mergers & smooth flows.
In-situ vs Ex-situ Star Formation

Tweed, Zolotov, Dekel, Ceverino et al. 2012

From $z=4$ to $z=1$
In-situ SFR 77%-57%
Ex-situ mergers 23%-43%
Mass Added in Major vs Minor Mergers

Neistein & Dekel 2008

\[ \omega = \frac{\delta_c}{D(t)} \]

\[ \frac{\dot{M}}{M} = \frac{(dM / d\omega)}{M} \dot{\omega} \]

\[ \dot{\omega} \approx -0.04 (1 + z)^{2.5} \text{ Gyr}^{-1} \]
5. Stream penetration and fragmentation

Dekel et al. 2009
Dekel, Zolotov, Tweed, Ceverino, Primack 2013
Baryon Penetration to the Disk: ~50%

Toy models versus simulations (ART 50 pc): Dekel, Zolotov, Tweed, Cacciato, Ceverino, Primack

EPS approximation:
\[ \dot{M} = 0.03 \text{Gyr}^{-1} M (1+z)^{5/2} \]

\[ M = M_0 e^{-0.8(z-z_0)} \]

A proxy for SFR
Baryon Penetration to the Disk: ~50%

Toy models versus simulations (ART 50 pc):
Dekel, Zolotov, Tweed, Cacciato, Ceverino, Primack

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\[ M = M_0 e^{-0.8(z-z_0)} \]

A proxy for SFR
Streams Break Up - the “Messy” Region

Higher resolution reveals smaller clumps:
- Merging galaxies with DM halos
- Baryonic clumps - hydro and thermal instabilities
Supersonic cold stream in a hot medium (2D)
Supersonic cold stream in a hot medium (2D)
6. Observing Cold Streams in Lyman alpha

Emission:  Goerdt et al. 2010, Kasen et al. 2011
Absorption: Fumagalli et al. 2011, Goerdt et al. 2011

ART code (Klypin, Kravtsov)
Simulations: Ceverino, Dekel, Bournaud 2010
Lyman-alpha Emission (LA Blobs)

Radiative transport of UV & Lyα, fluorescence from stars, dust
Goerdt et al. 10; Kasen, Ceverino, Fumagalli, Dekel, Prochaska, Primack

Extended source of cold H is provided by the inflowing (clumpy) streams

Energy is provided by:
1. inflow down the gravitational potential gradient
2. fluorescence by stars

Yet to be incorporated: AGN, enhanced outflows
Gravity Powers Lyman-alpha Emission

\[ E_{\text{heat}}(r) = f_c \dot{M}_c \frac{\partial \phi}{\partial r} \]

\[ E_{\text{heat}} \approx 1.2 \times 10^{43} \text{ erg s}^{-1} f_c M_{12}^{1.82} (1 + z)^{3.25} \]

In AMR simulations: \( V_{\text{inflow}} \sim V_{\text{vir}} \sim \text{const.} \rightarrow \text{potential gain dissipates to } L_\alpha \)

Half the luminosity outside 0.3\( R_v \)

LABs from galaxies at \( z=2-4 \) are inevitable

Have cold streams been detected?

Gravitational heating is generic (e.g. clusters)
Lyman-alpha from Cold streams

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

\[ T = (1-5) \times 10^4 \text{ K} \quad n = 0.01-0.1 \text{ cm}^{-3} \quad N_{\text{HI}} \sim 10^{20} \text{ cm}^{-2} \quad \text{pressure equilib.} \]

Surface brightness

\[ L \sim 10^{43-44} \text{ erg s}^{-1} \]

100 kpc
Cold streams as Lyman-alpha Blobs

Goerdt, Dekel, Sternberg, Ceverino, Teyssier, Primack 09

Matsuda et al 06-09
Lyman-alpha Luminosity Function

Isophotal area and kinematics also consistent with data
Detection of Inflow in Lya Emission

Kulas, Shapley et al. 2011    Systemic z from Hα
Most are red-shifted → outflows
5% are blue-shifted → inflow

Kasen et al. 12
Cold Streams as Absorption Systems

Fumagalli, Prochaska, Kasen, Dekel, Ceverino, Primack 2011; Goerdt et al. 2012

MFP
15.5-17.2 cm$^{-2}$

LLS
17.2-19.0 cm$^{-2}$

DLA
>20.3 cm$^{-2}$

SLLS
19.0-20.3 cm$^{-2}$

MW3 @ z = 4.0
10 kpc

MW8 @ z = 4.0
10 kpc

MW4 @ z = 4.0
10 kpc

MW1 @ z = 3.2
10 kpc

MW9 @ z = 3.2
10 kpc

MW1 @ z = 1.9
10 kpc
Stacked 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.
Lya Image - radiative transfer

Kasen et al 11: including Lya multiple scattering, UV bkgd, Fluorescence from stars
7. Angular Momentum: Transport and Exchange

Danovich et al. 2012
In-streaming → Extended Rotating Disk

- AM by transverse motion of streams - impact parameter
- Streams transport AM into the inner halo
- One stream is dominant
- Higher J/M at later times → inside-out disk buildup
Disk AM Buildup by Streams
AM Exchange in the Inner Halo

Danovich, Dekel, Hahn, Teyssier 2012

Is AM amplitude conserved to within a factor of 2?

AM is not conserved all the way to the disk!

Torques & AM exchange in the inner halo \(\sim 0.3R_v\)

Ceverino, Dekel, Bournaud 2010
ART 50 pc resolution
Angular Momentum on Halo Scale

Only little alignment between stream plane and AM at $R_v$

Most of the AM in one stream
Disk is not aligned with AM at $r>0.3R_{\text{vir}}$
8. Outflows
What drives the massive outflows in massive galaxies?

How do the outflows affect the inflows?

Need to maintain Inflow + Reservoir = SFR + Outflow
Inflows & Outflows

Tweed, Dekel, Teyssier
RAMSES 70-pc resolution

Outflows find their way out through the dilute medium
no noticeable effect on the dense cold rapid inflows

Gas density
hot
high Z

Metallicity
**Inflows and Outflows**

House, Tweed, Ceverino et al.

Outflow $\eta \sim 0.7$

In-streaming $\sim 1.7\text{SFR}$
Conclusions

Certain robust predictions for high-z galaxies in $\Lambda$CDM cosmology

- Cosmological inflow rate $\dot{M}/M \sim 0.03 \text{ Gyr}^{-1} (1+z)^{2.5} \quad M \propto \exp(-0.8z)$
- Steady state: SFR $\sim$ accretion rate, $M_{\text{gas}} \sim \text{const.}$, as long as $\tau_{\text{sfr}} \sim \varepsilon^{-1}t_{\text{ff}}$
- Shock heating scale $M_v \sim 10^{12} M_\odot$ - cold flows / hot medium - bimodality
- High-z massive galaxies fed by cosmic-web streams, smooth & mergers
- $\sim3$ co-planar streams (70%) in a pancake (20%)
- $\sim50\%$ penetration into the galaxy; instabilities, messy region near disk
- Streams (mostly one) transport AM. AM exchange in the inner halo.
- Cold streams are observable in Ly$\alpha$ emission (LAB) and absorption (LLS)
- Outflows are in harmony with the in-streams (tentative)
Cosmic Web, Cold Streams, Clumpy Disks & Spheroids