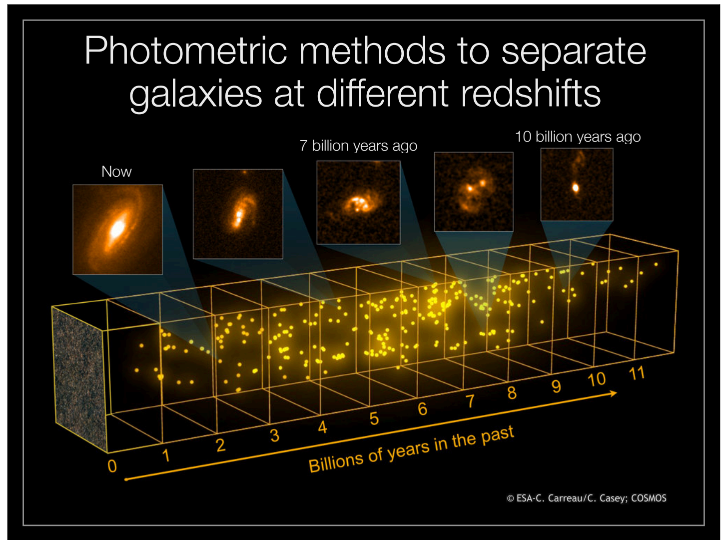
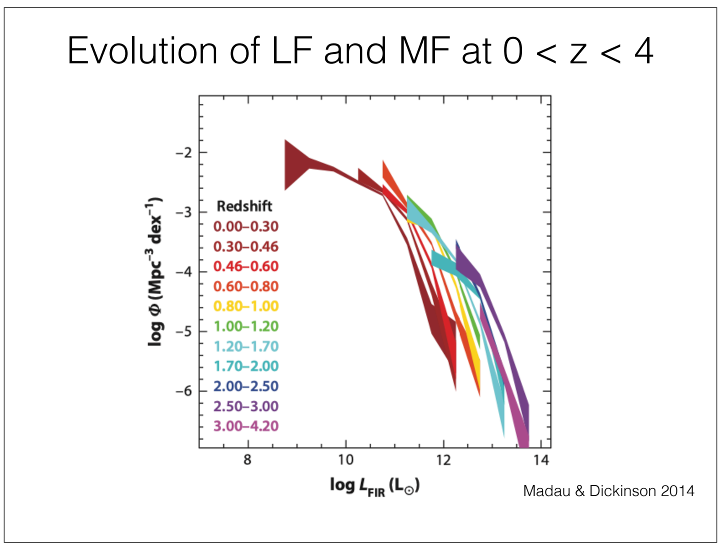
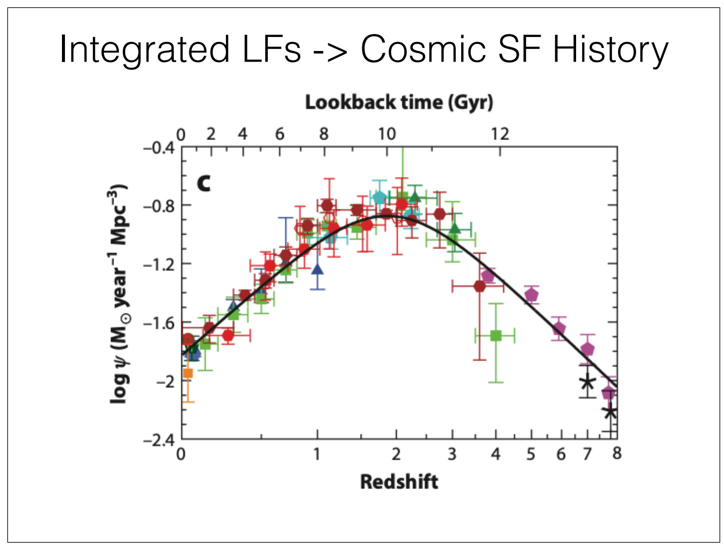
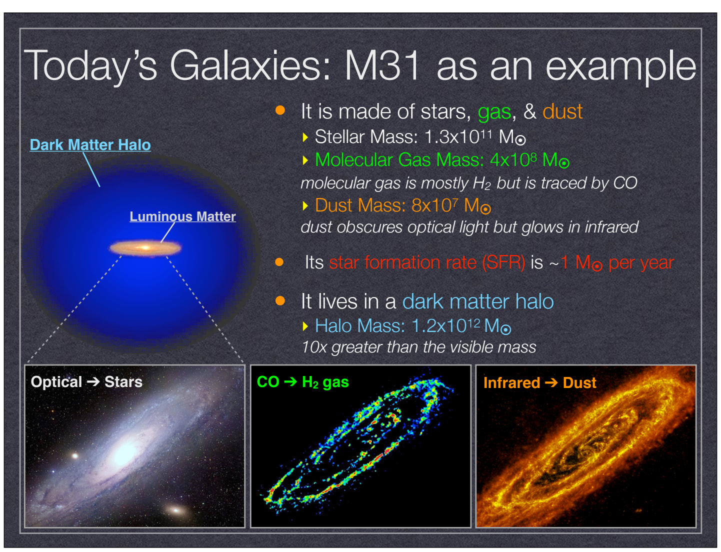
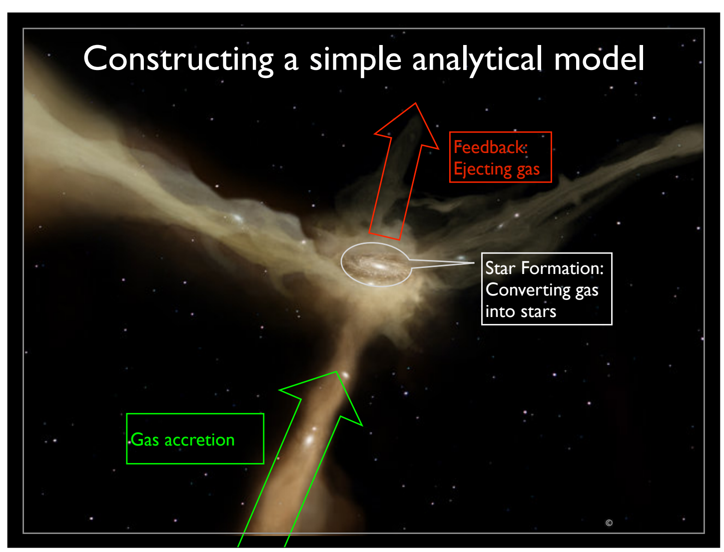

Observed Galaxy Evolution


Photometric methods to separate galaxies at different redshifts
Now
7 billion years ago
10 billion years ago
0 1 2 3 4 5 6 7 8 9 10 11
Billions of years in the past
© ESA-C. Carreau/C. Casey; COSMOS


Evolution of LF and MF at 0 < z < 4
Redshift
0.00–0.30
0.30–0.46
0.46–0.60
0.60–0.80
0.80–1.00
1.00–1.20
1.20–1.70
1.70–2.00
2.00–2.50
2.50–3.00
3.00–4.20
log Φ (Mpc⁻³ dex⁻¹)
log L_FIR (L☉)
Madau & Dickinson 2014


Integrated LFs -> Cosmic SF History
Lookback time (Gyr)
c
log ψ (M☉ year⁻¹ Mpc⁻³)
Redshift


Today's Galaxies: M31 as an example
Dark Matter Halo
Luminous Matter
It is made of stars, gas, & dust
Stellar Mass: 1.3x10¹¹ M☉
Molecular Gas Mass: 4x10⁸ M☉
molecular gas is mostly H₂ but is traced by CO
Dust Mass: 8x10⁷ M☉
dust obscures optical light but glows in infrared
Its star formation rate (SFR) is ~1 M☉ per year
It lives in a dark matter halo
Halo Mass: 1.2x10¹² M☉
10x greater than the visible mass
Optical → Stars
CO → H₂ gas
Infrared → Dust


Constructing a simple analytical model
Feedback: Ejecting gas
Star Formation: Converting gas into stars
Gas accretion

A Simple Analytical Model

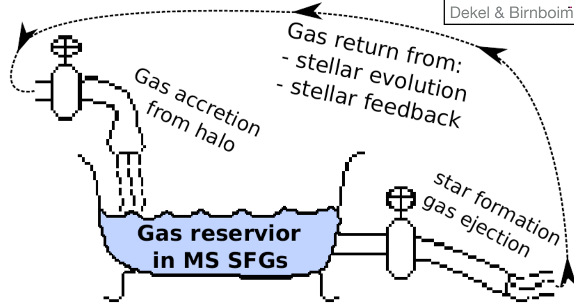
(1) a continuity equation:

Change in Cold Gas Reservoir | **Accretion Rate ∝ Halo Growth Rate** | **Gas Consumption Rate ∝ Star Formation Rate**

$$\frac{dM_{gas}}{dt} = \epsilon_{cold} f_{baryon} \frac{dM_{halo}}{dt} - (1 - f_{recycle} + f_{outflow}) \frac{dM_{star}}{dt}$$

The "Bathtub" Model

Bouche+2010
see also Lilly+2013
Cattaneo+2006
Dekel & Birnboim 2006



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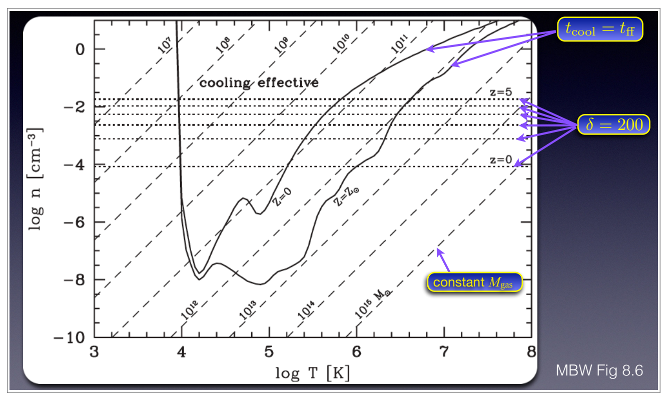
Where stellar growth decouples from halo growth is specified by the cold gas accretion efficiency (ϵ_{cold})

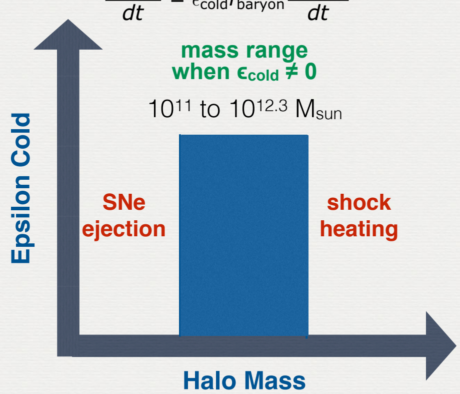
Virialized gas in massive halos cannot cool effectively ($t_{cool} > t_{ff}$)



MBW Fig 8.6

The Cold Gas Accretion Rate

$$\frac{dM_{gas}}{dt} = \epsilon_{cold} f_{baryon} \frac{dM_{halo}}{dt}$$



The "Bathtub" Model

First, a continuity equation:

Change in Cold Gas Reservoir | **Accretion Rate ∝ Halo Growth Rate** | **Gas Consumption Rate ∝ Star Formation Rate**

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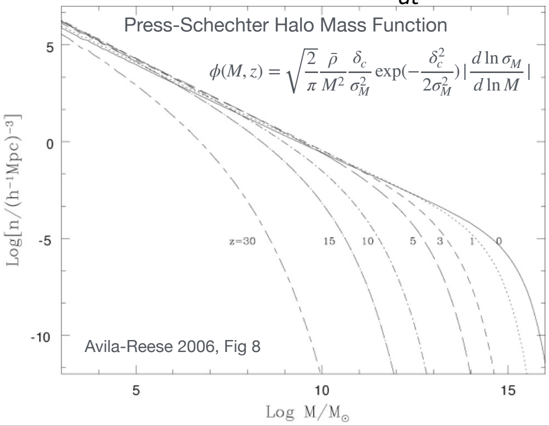
Where stellar growth decouples from halo growth is specified by the cold gas accretion efficiency (ϵ_{cold})

$$\begin{cases} \epsilon_{cold} = 0.0 \text{ if } M_{halo} < 10^{11} M_{\odot} \\ \epsilon_{cold} = 0.7 \text{ if } 10^{11} < M_{halo} < 10^{12.3} M_{\odot} \\ \epsilon_{cold} = 0.0 \text{ if } M_{halo} > 10^{12.3} M_{\odot} \end{cases}$$

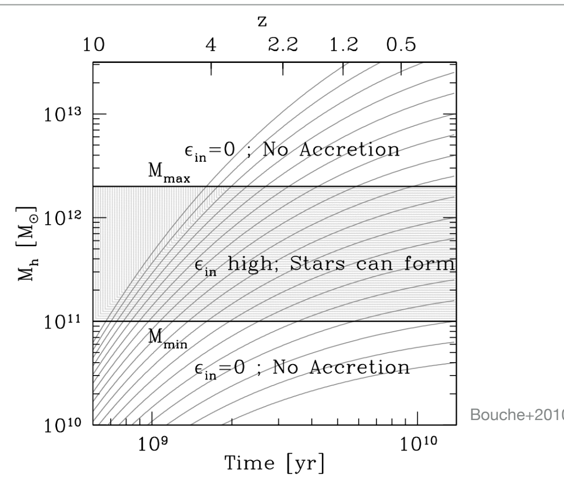
But we need two additional equations to solve the continuity equation.

The ``Bathtub'' Model

(2) halo growth from extended PS formalism: $\frac{dM_{\rm halo}}{dt} \propto M_{\rm halo}^{1.1}(1+z)^{2.2}$

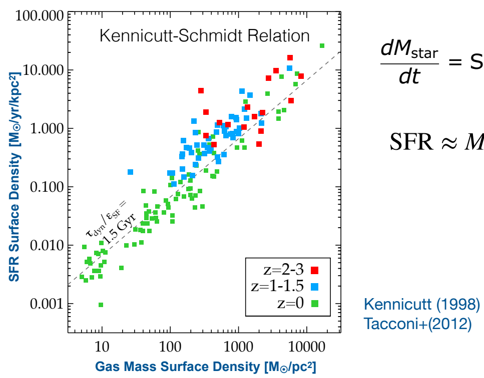


Halo mass vs. redshift & time



The ``Bathtub'' Model

(3) an equation that relates gas mass and star formation:



$$\frac{dM_{\rm star}}{dt} = {\rm SFR} = \epsilon_{\rm SF}\frac{M_{\rm gas}}{\tau_{\rm dyn}}$$

$${\rm SFR} \approx M_{\rm gas}/10^9{\rm yr}$$

Kennicutt (1998)
Tacconi+(2012)

The ``Bathtub'' Model: Accretion-Driven Star Formation

a continuity equation coupled with
a halo growth history and a star formation law

Change in Cold Gas Reservoir | **Accretion Rate ∝ Halo Growth Rate** | **Gas Consumption Rate ∝ Star Formation Rate**

$$\begin{cases} \frac{dM_{\rm gas}}{dt} = \epsilon_{\rm cold} f_{\rm baryon}\frac{dM_{\rm halo}}{dt} - (1 - f_{\rm recycle} + f_{\rm outflow})\frac{dM_{\rm star}}{dt} \\ \frac{dM_{\rm halo}}{dt} \propto M_{\rm halo}^{1.1}(1+z)^{2.2} \\ \frac{dM_{\rm star}}{dt} = {\rm SFR} = \epsilon_{\rm SF}\frac{M_{\rm gas}}{\tau_{\rm dyn}} \end{cases}$$

⬅ **Halo Growth Rate from EPS**
⬅ **Kennicutt-Schmidt Relation**

cold gas accretion efficiency:

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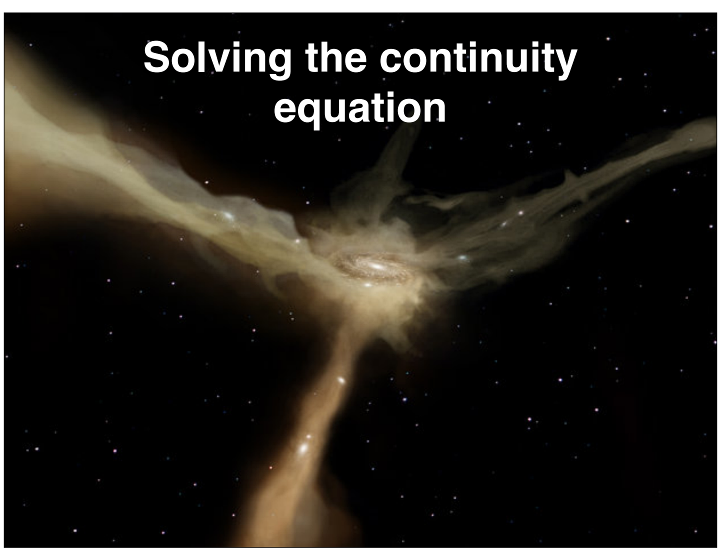
recycle & feedback:

$$\begin{cases} f_{\rm recycle} = 0.5 \\ f_{\rm outflow} = 0.6 \end{cases}$$



The ``Bathtub'' Model: Accretion-Driven Star Formation

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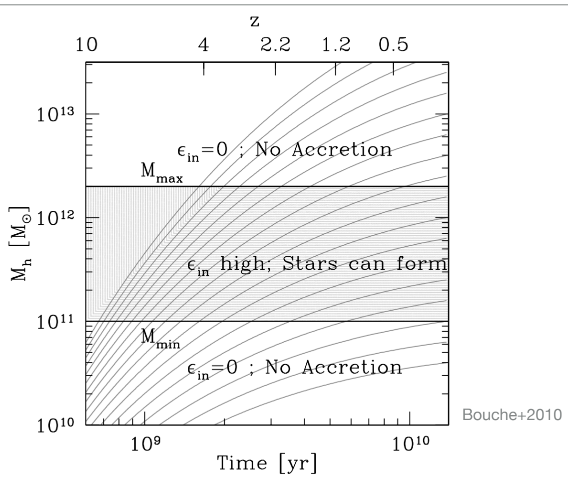
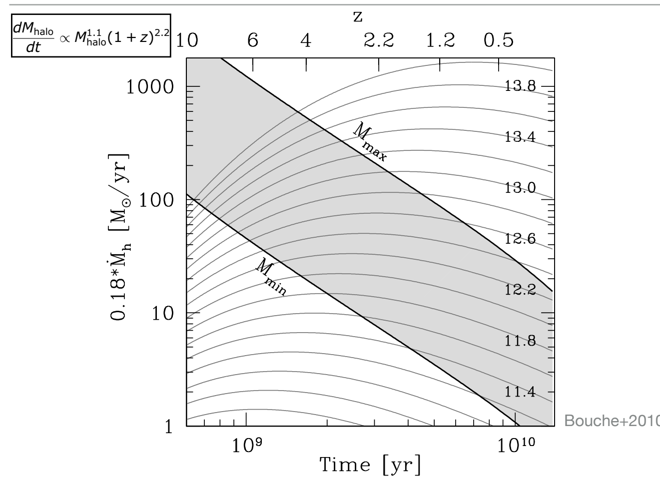
Halo mass vs. redshift & time



Halo growth rate vs. redshift & time



When reservoir stays constant: steady state

- SFR ~ Accretion Rate
- Gas reservoir filled to SFR x 1 Gyr

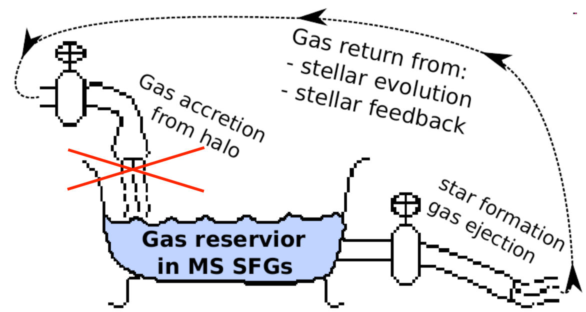
$$\cancel{\frac{dM_{gas}}{dt}} = \epsilon_{cold} f_{baryon} \frac{dM_{halo}}{dt} - (1 - f_{recycle} + f_{outflow})\mathrm{SFR}$$

when $\frac{dM_{gas}}{dt} = 0$ we have :

$$\mathrm{SFR} = \frac{\epsilon_{cold} f_{baryon}}{1 - f_{recycle} + f_{outflow}} \frac{dM_{halo}}{dt} \simeq f_{baryon} \frac{dM_{halo}}{dt}$$

(note the approximation)

When cold gas accretion stops: drain the tub



When cold gas accretion stops: drain the tub

SFR exponentially declines with an e-folding time of 2 Gyr

$$\begin{cases} \frac{dM_{gas}}{dt} = \cancel{\epsilon_{cold} f_{baryon} \frac{dM_{halo}}{dt}} - (1 - f_{recycle} + f_{outflow})\mathrm{SFR} \\ \mathrm{SFR} = \epsilon_{SF} \frac{M_{gas}}{\tau_{dyn}} \end{cases}$$

⇐ **Star Formation Law**

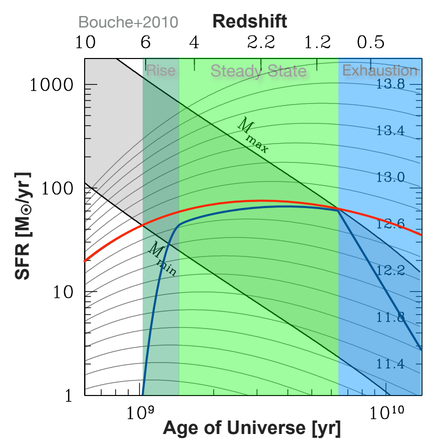
when $\epsilon_{cold} = 0$ we have :

$$\frac{d\mathrm{SFR}}{dt} = -\frac{\epsilon_{SF}(1 - f_{recycle} + f_{outflow})}{\tau_{dyn}} \mathrm{SFR}$$

Solving this equation, we get an exponentially declining SFR :

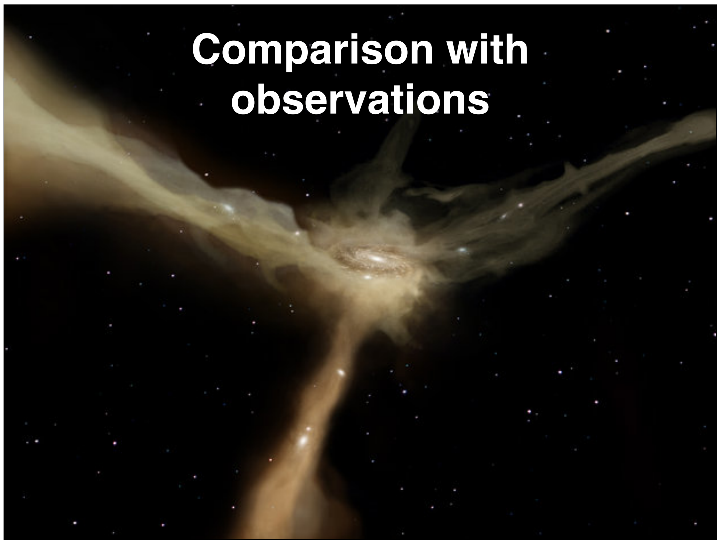
$$\mathrm{SFR} \propto \exp(-\frac{t}{\tau}) \text{ and } \tau = \frac{\tau_{dyn}}{\epsilon_{SF}(1 - f_{recycle} + f_{outflow})} \simeq 2 \text{ Gyr}$$

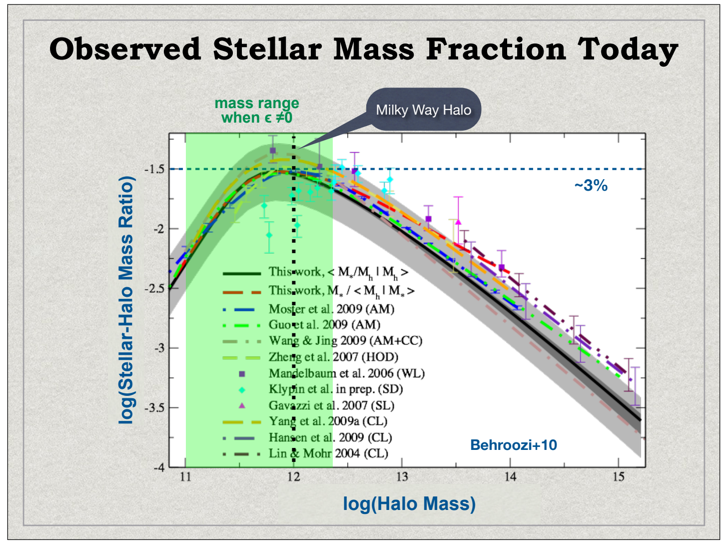
Accretion-Driven Star Formation History

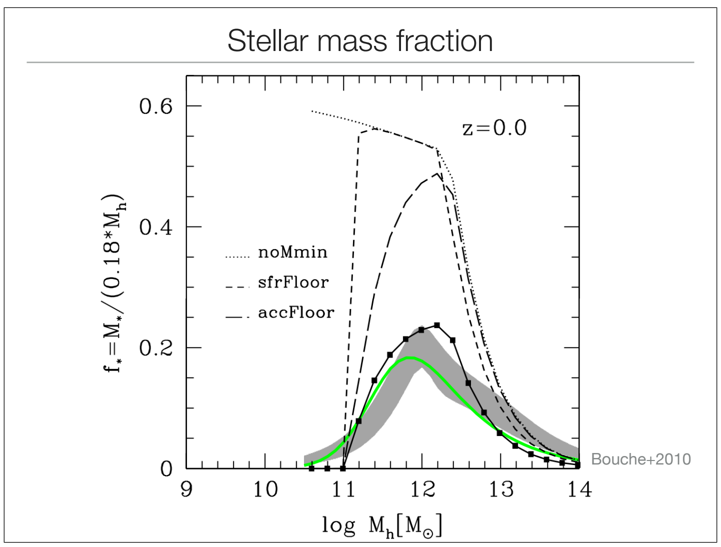


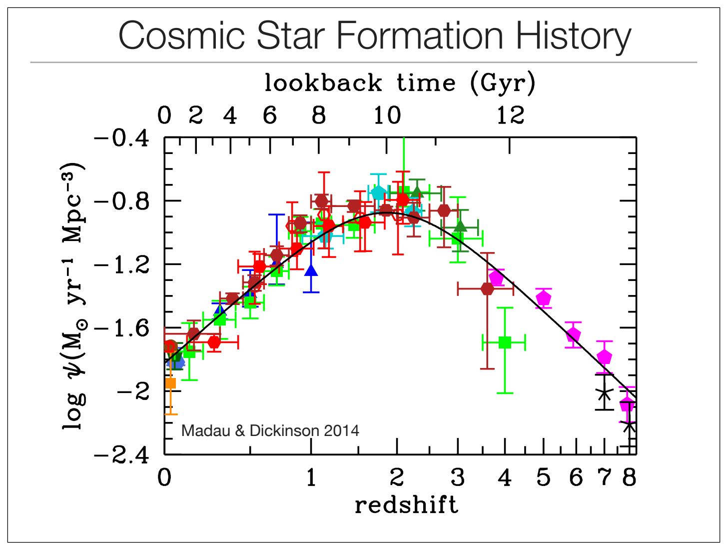
- **Grey region**: efficient cold gas accretion **$10^{11} < M_{Halo} < 1.5 \times 10^{12} M_\odot$**
- **Gas accretion history** of a $10^{12.6} M_\odot$ halo (mass at $z = 0$)
- **Star formation history** from the continuity equation:

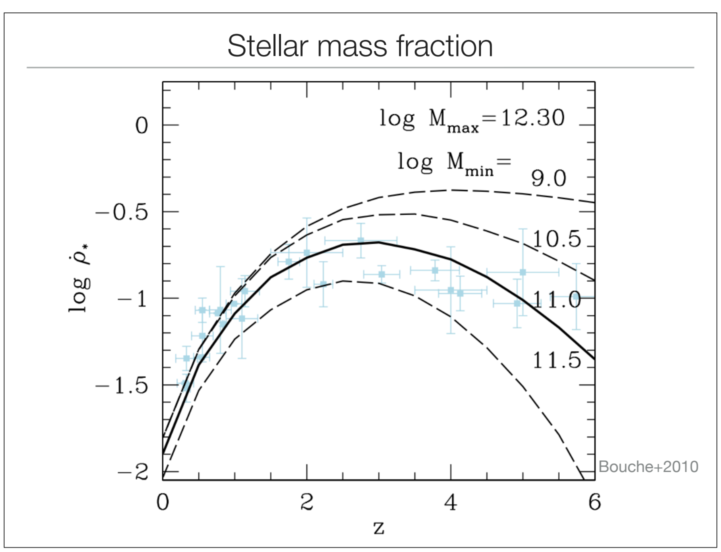
1. Once the halo crosses the minimum mass (**$10^{11} M_\odot$**), the SFR rapidly rises to reach a steady state;
2. As the halo mass reaches **$10^{12.3} M_\odot$**, cold gas accretion is choked and the SFR starts to decline with an *e*-folding time of **2-3 Gyr (=2 τ_{dyn}/ϵ_{SF})**.

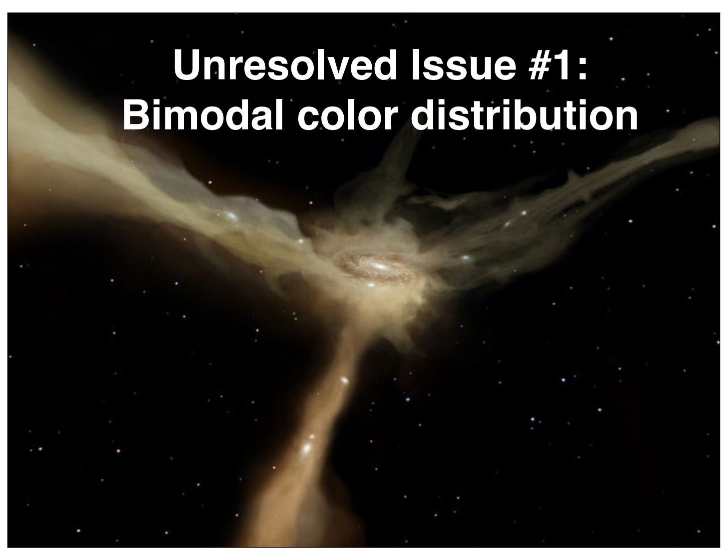

Comparison with observations


Observed Stellar Mass Fraction Today
mass range when ϵ ≠0
Milky Way Halo
~3%
log(Stellar-Halo Mass Ratio)
log(Halo Mass)
This work, < M*/Mh | Mh >
This work, M* / < Mh | M* >
Moster et al. 2009 (AM)
Guo et al. 2009 (AM)
Wang & Jing 2009 (AM+CC)
Zheng et al. 2007 (HOD)
Mandelbaum et al. 2006 (WL)
Klypin et al. in prep. (SD)
Gavazzi et al. 2007 (SL)
Yang et al. 2009a (CL)
Hansen et al. 2009 (CL)
Lin & Mohr 2004 (CL)
Behroozi+10


Stellar mass fraction
z=0.0
noMmin
sfrFloor
accFloor
f*=M*/(0.18*Mh)
log Mh[M⊙]
Bouche+2010

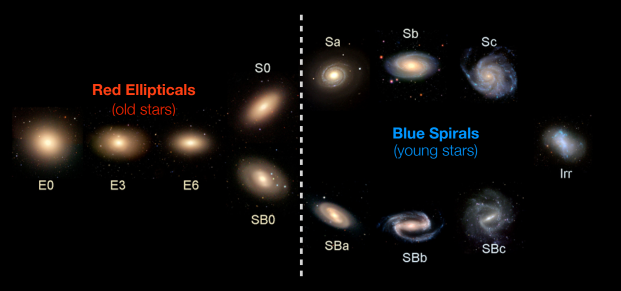

Cosmic Star Formation History
lookback time (Gyr)
log ψ(M⊙ yr⁻¹ Mpc⁻³)
redshift
Madau & Dickinson 2014


Stellar mass fraction
log Mmax=12.30
log Mmin=
9.0
10.5
11.0
11.5
log ρ̇*
z
Bouche+2010


Unresolved Issue #1:
Bimodal color distribution

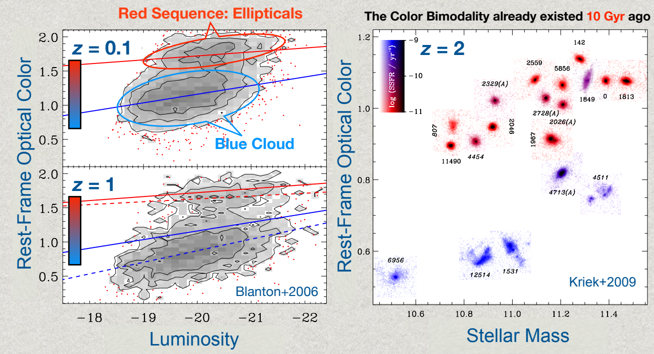
Color Bimodality: Galaxies are either blue or red

Hubble's Galaxy Classification Scheme



Galaxies in the Current universe

Color Bimodality

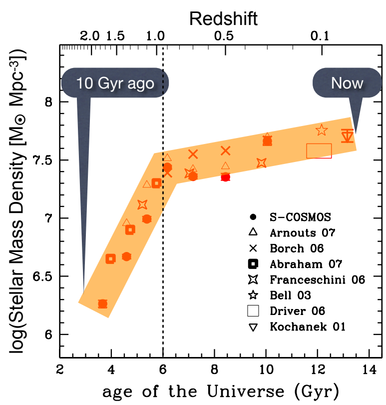


The early & rapid build-up of the red sequence

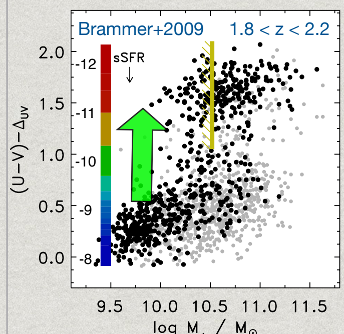
the evolution of the total comoving stellar mass density of quiescent galaxies

- **Early Completion**: Most of the stellar mass in the red sequence is already in place by $z = 1$
- **Rapid Build-Up**: Stellar mass density increased more than 20x in just 2.5 Gyr ($1 < z < 2$).

Ilbert+2010



Color bimodality at high-redshift requires rapid quenching



The lack of galaxies between blue cloud and red sequence requires very rapid transition:

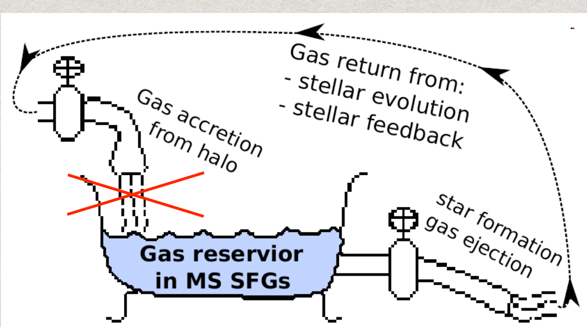
* It takes ~5 e-folding time to cross the green valley ($e^5 = 150$)
* red-sequence e-folding timescale of 1 Gyr indicates an SFR e-folding time **<0.2 Gyr** (consistent w/ Goncalves+2012)

This is 10x shorter than the gas exhaustion time (~**2 Gyr**)!

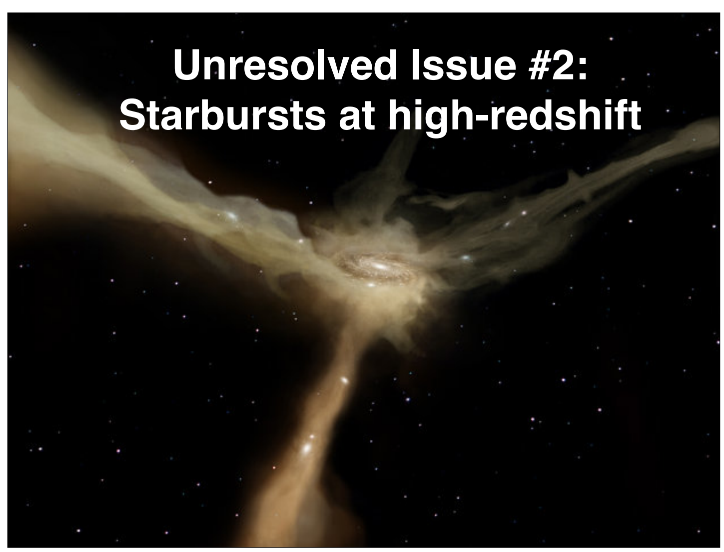
$$\tau = \frac{\tau_{dyn}}{\epsilon_{SF}(1 - f_{recycle} + f_{outflow})}$$

How to quench star formation? (i.e. reduce the e-folding time by 10x)

$$SFR \propto \exp(-\frac{t}{\tau}) \text{ and } \tau = \frac{\tau_{dyn}}{\epsilon_{SF}(1 - f_{recycle} + f_{outflow})} \simeq 2 \text{ Gyr}$$

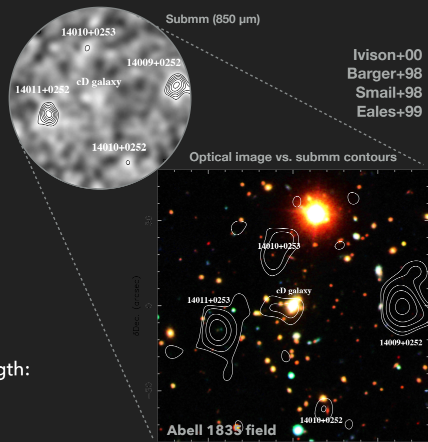


Unresolved Issue #2: Starbursts at high-redshift

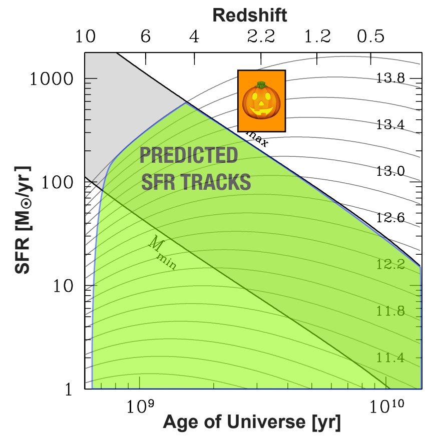


Submm-Bright Galaxies (SMGs) at z ~ 2.5

- SMG definition: S(850um) > 2-3 mJy
- Bright in submm, but extremely faint in optical
- Median properties:
  $<z>$ ~ 2.5
  $<L_{IR}>$ ~ 5×10^{12} $L_\odot$
  $<SFR>$ ~ 500 $M_\odot$/yr
- Strong clustering strength:
  M_{halo} ~ 10^{13} $M_\odot$
  similar to z ~2 QSOs



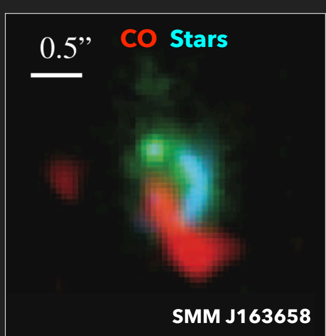
Intense Starburst Galaxies at z ~ 2



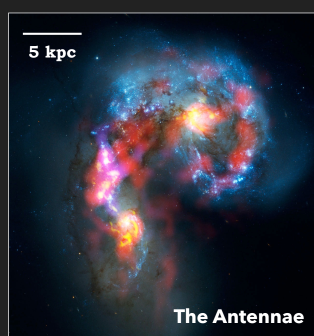
- **Green region:** star formation tracks of all halos less than 10^{14} $M_\odot$ at $z = 0$.
- **Orange: The SFRs of these galaxies appear too high for any halos at their epoch.**

Misaligned stellar and ISM emission

typical offsets: a few kpc (0.5" = 4 kpc @ z = 2.5)



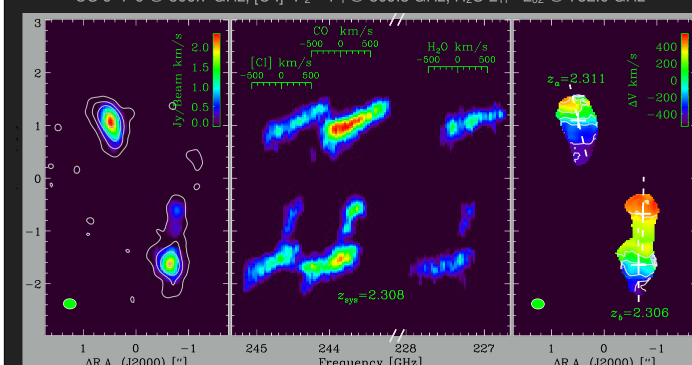
Tacconi+2008



Calistro Rivera+2018

Resolved gas kinematics in an SMG merger

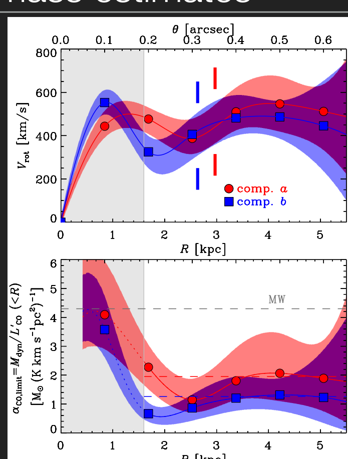
ALMA Cycle 3, 2.6 hr on-source, 0.2" spatial resolution, 240 GHz (band 6, z = 2.308)
CO J=7-6 @ 806.7 GHz, [C I] $^3P_2$ - $^3P_1$ @ 809.3 GHz, H_2O 2_{11} - 2_{02} @ 752.0 GHz



Xue, Fu+2018

Dynamical mass estimates

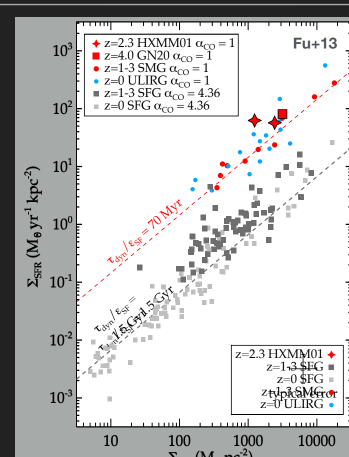
- Rotation velocities reach 500 km/s (inclination corrected), with a dispersion ~ 160 km/s
- Dynamical masses: M_{dyn} ~ 2×10^{11} M_{sun} within 5 kpc
- CO(1-0) luminosity: L'_{co} ~ 1.5×10^{11} K km/s pc^2
- Upper limits on the CO-to-H2 conversion factor: M_{H2}/L'_{co} < 1.5, much lower than the Galactic GMC value of 4.3.



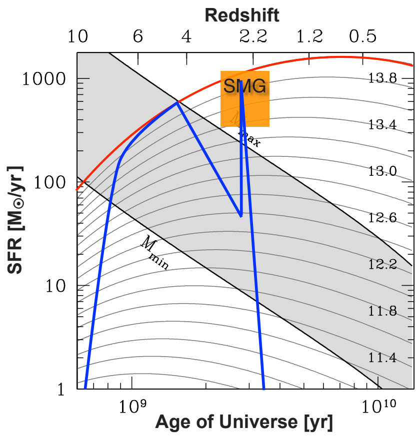
Xue, Fu+2018

The Unsustainable Growth of SMGs

- M_{gas}/SFR ~ 100 Myr
- 10x greater SFR for any given gas mass
- 10x shorter gas depletion timescale than normal star-forming galaxies
- Without continuous gas supply, SFR will decline with an e-folding timescale of ~200 Myr



So, what's up with the SMGs?



✓: Burst: Star formation efficiency increases 10x in **10¹³** M⊙ halos.

Implications:

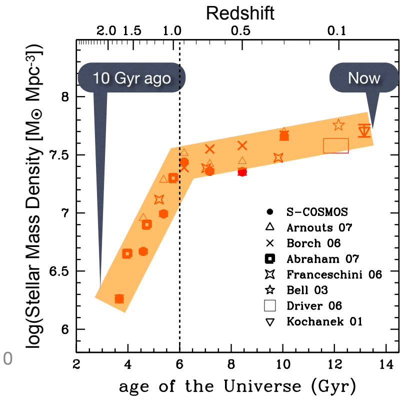
- two distinct populations of SMGs: z > 4 and z ~ 2
- high stellar masses (~2x10¹¹ M_{sun})
- relatively low gas fraction
- helps explain the early, rapid formation of massive quiescent galaxies

The early & rapid build-up of the red sequence

the evolution of the total comoving stellar mass density of quiescent galaxies

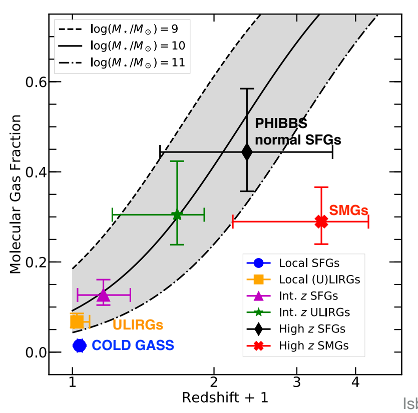
- **Early Completion**: Most of the stellar mass in the red sequence is already in place by $z = 1$
- **Rapid Build-Up**: Stellar mass density increased more than 20x in just 2.5 Gyr ($1 < z < 2$).
- *Not* observed in star-forming galaxies

Ilbert+2010



SMGs have lower gas fraction than normal SFGs?

Data Points: gas fractions measured w/ Tully-Fisher relation & $\alpha_{CO} = 1$
Curves: gas fractions inferred from sSFR(z) of different stellar masses



Isbell, Xue, Fu 2018

one stone two birds

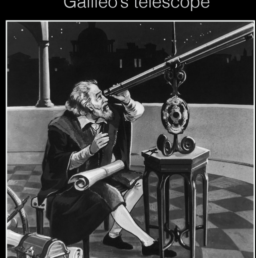
- SMGs have ~10x higher SF efficiency than normal galaxies, i.e., they are massive starbursts
- Starbursts can stop star formation by rapidly exhausting the gas reservoir, providing a quenching mechanism to turn blue starforming galaxies into red passive galaxies.
- Starbursts are a universal phase in the formation of massive red galaxies. All galaxy formation models should be able to reproduce this important phase.
- *What triggers the high star formation efficiency? Why every massive galaxy goes through a burst phase?*

Astronomy originated from and is almost entirely driven by observation, which itself is driven by technological advances!

Tycho's mural quadrant

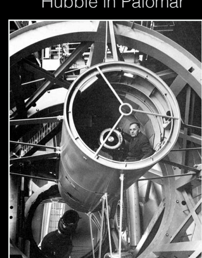
1577

Galileo's telescope



1610

Hubble in Palomar

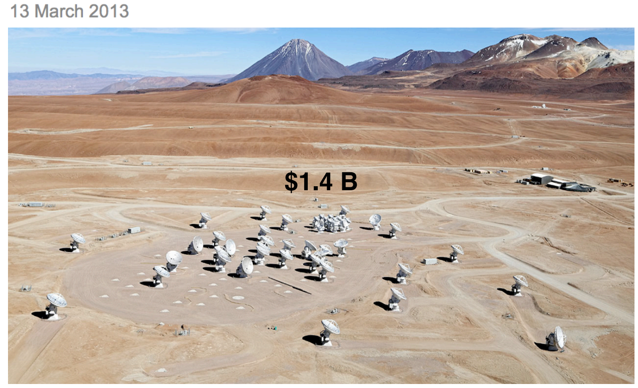


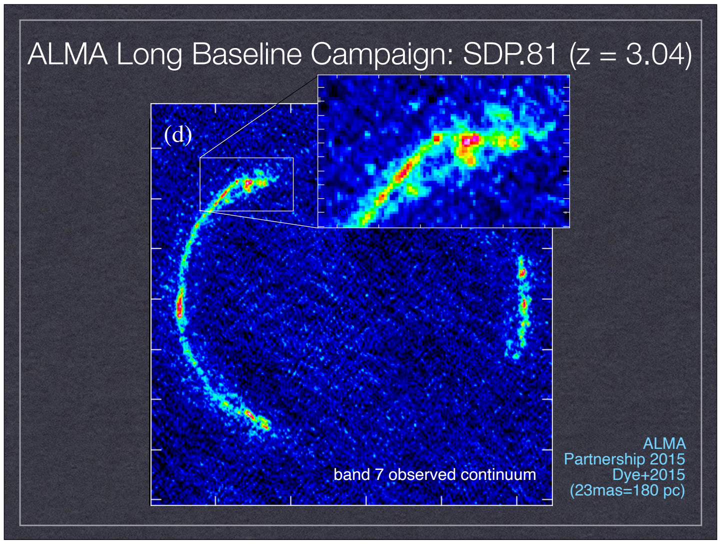
1948

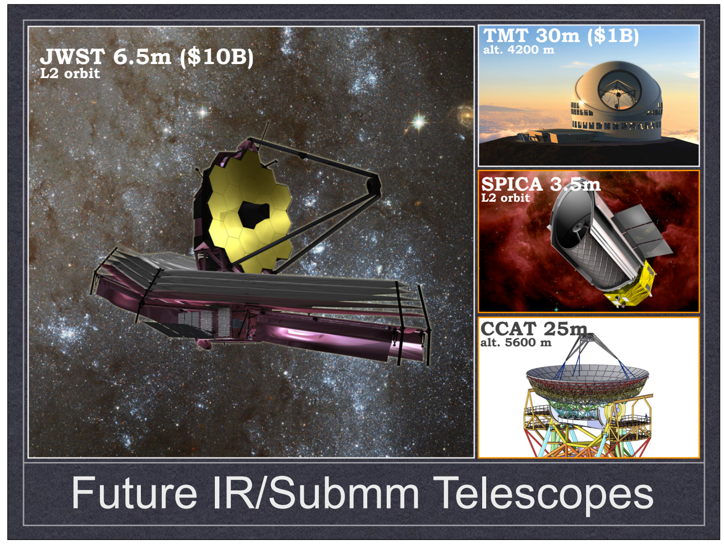
ALMA Inauguration Heralds New Era of Discovery

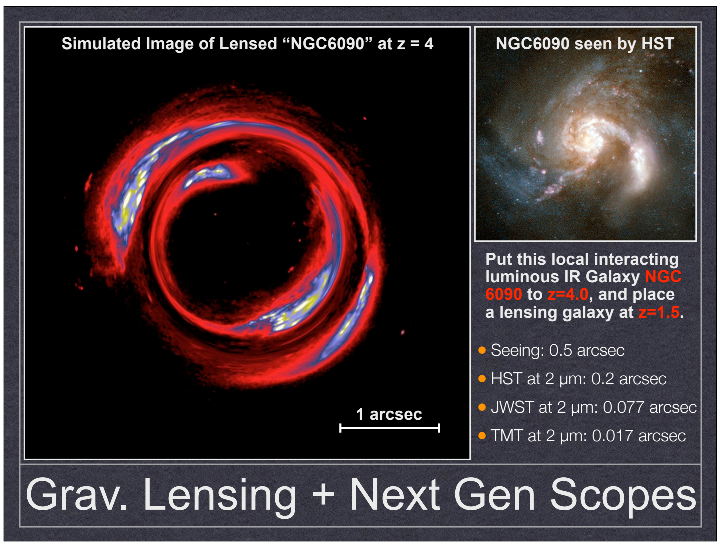
Revolutionary telescope will enable unprecedented views of the cosmos

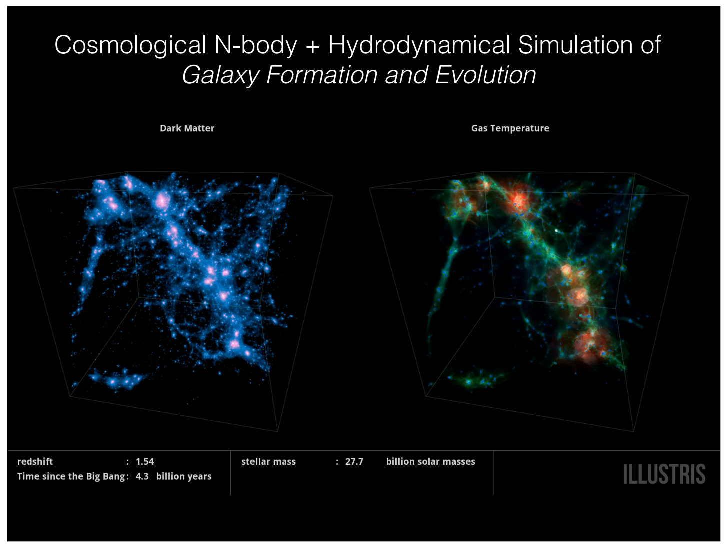
13 March 2013




ALMA Long Baseline Campaign: SDP.81 (z = 3.04)
(d)
band 7 observed continuum
ALMA
Partnership 2015
Dye+2015
(23mas=180 pc)


JWST 6.5m ($10B)
L2 orbit
TMT 30m ($1B)
alt. 4200 m
SPICA 3.5m
L2 orbit
CCAT 25m
alt. 5600 m
Future IR/Submm Telescopes


Simulated Image of Lensed "NGC6090" at z = 4
1 arcsec
NGC6090 seen by HST
Put this local interacting luminous IR Galaxy NGC 6090 to z=4.0, and place a lensing galaxy at z=1.5.
Seeing: 0.5 arcsec
HST at 2 μm: 0.2 arcsec
JWST at 2 μm: 0.077 arcsec
TMT at 2 μm: 0.017 arcsec
Grav. Lensing + Next Gen Scopes


Cosmological N-body + Hydrodynamical Simulation of
Galaxy Formation and Evolution
Dark Matter
Gas Temperature
redshift : 1.54
Time since the Big Bang: 4.3 billion years
stellar mass : 27.7 billion solar masses
ILLUSTRIS