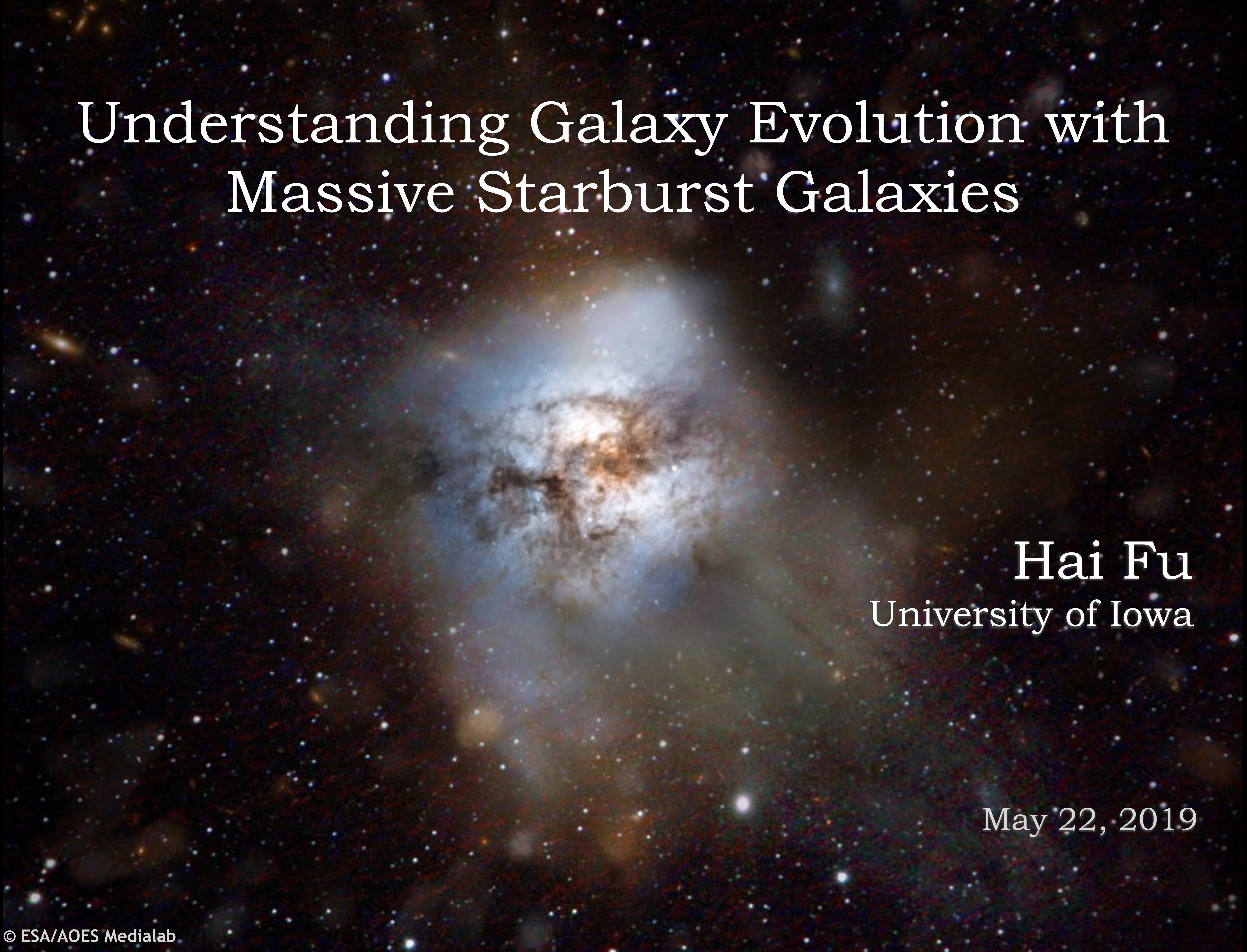
Understanding Galaxy Evolution with Massive Starburst Galaxies



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University of Iowa

May 22, 2019

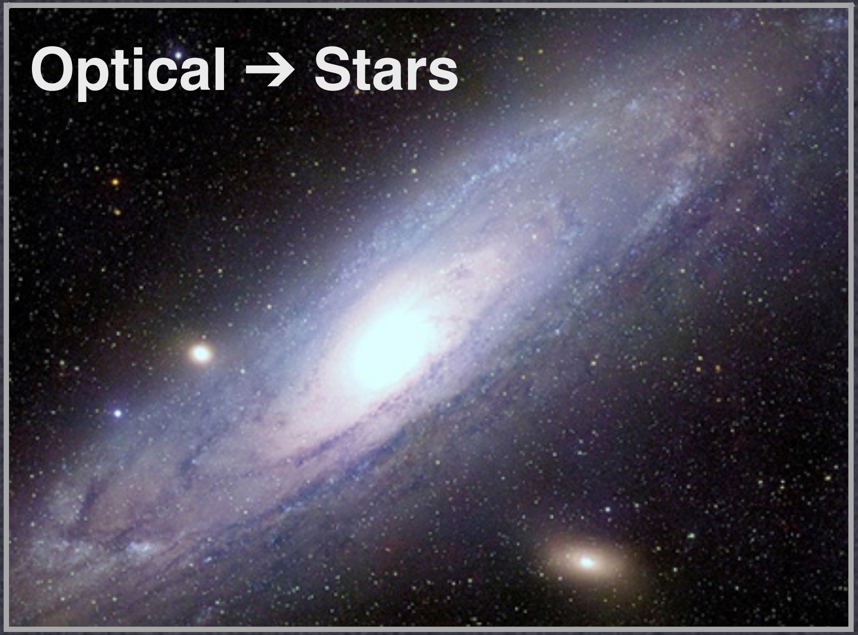
Galaxy 101: The Andromeda Galaxy

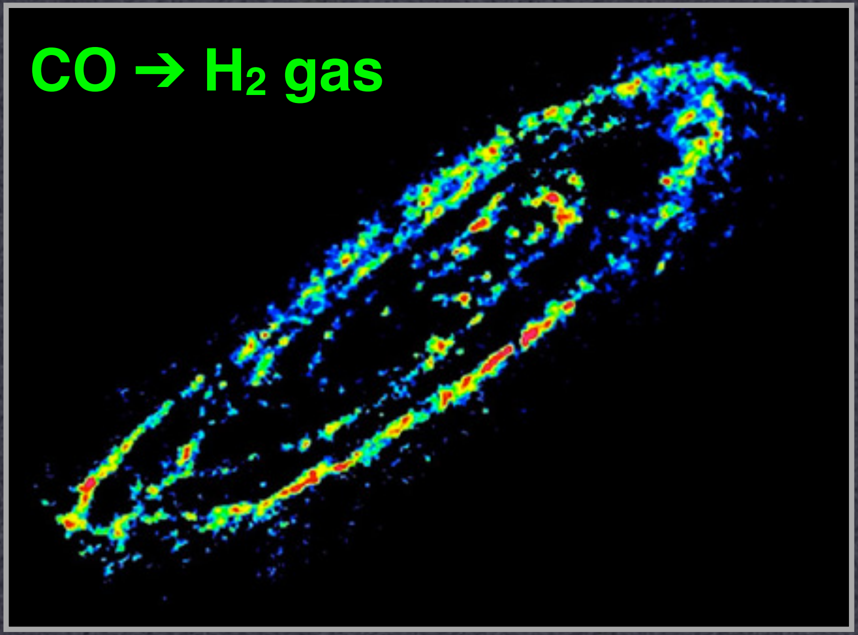
- It is made of stars, gas, & dust
  - Stellar Mass: $1.3\text{x}10^{11}\ M_{\odot}$
  - Molecular Gas Mass: $4\text{x}10^{8}\ M_{\odot}$

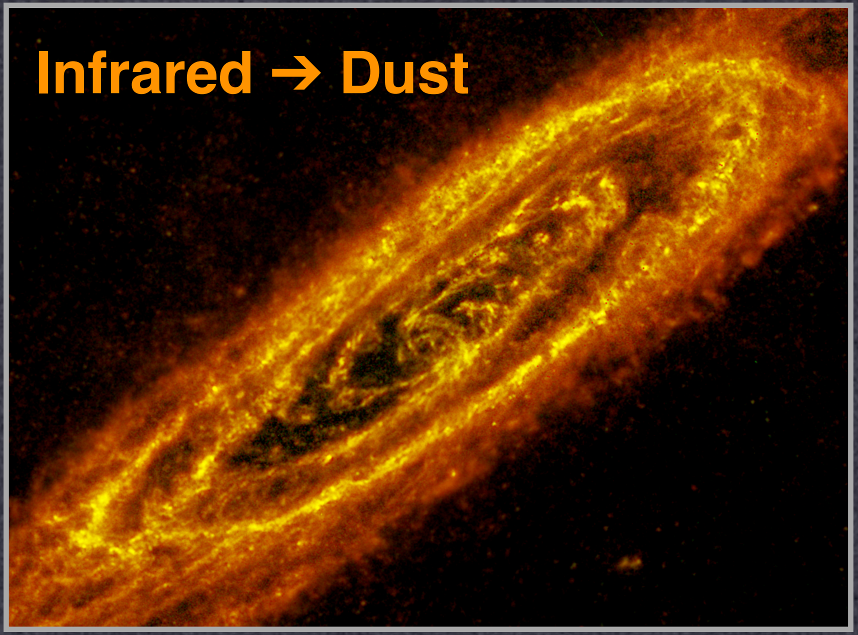
    molecular gas is mostly H_2 but is traced by CO
  - Dust Mass: $8\text{x}10^{7}\ M_{\odot}$

    dust obscures optical light but glows in infrared
- Its star formation rate (SFR) is 1 $M_{\odot}$ per year
- It lives in a dark matter halo
  - Halo Mass: $1.2\text{x}10^{12}\ M_{\odot}$

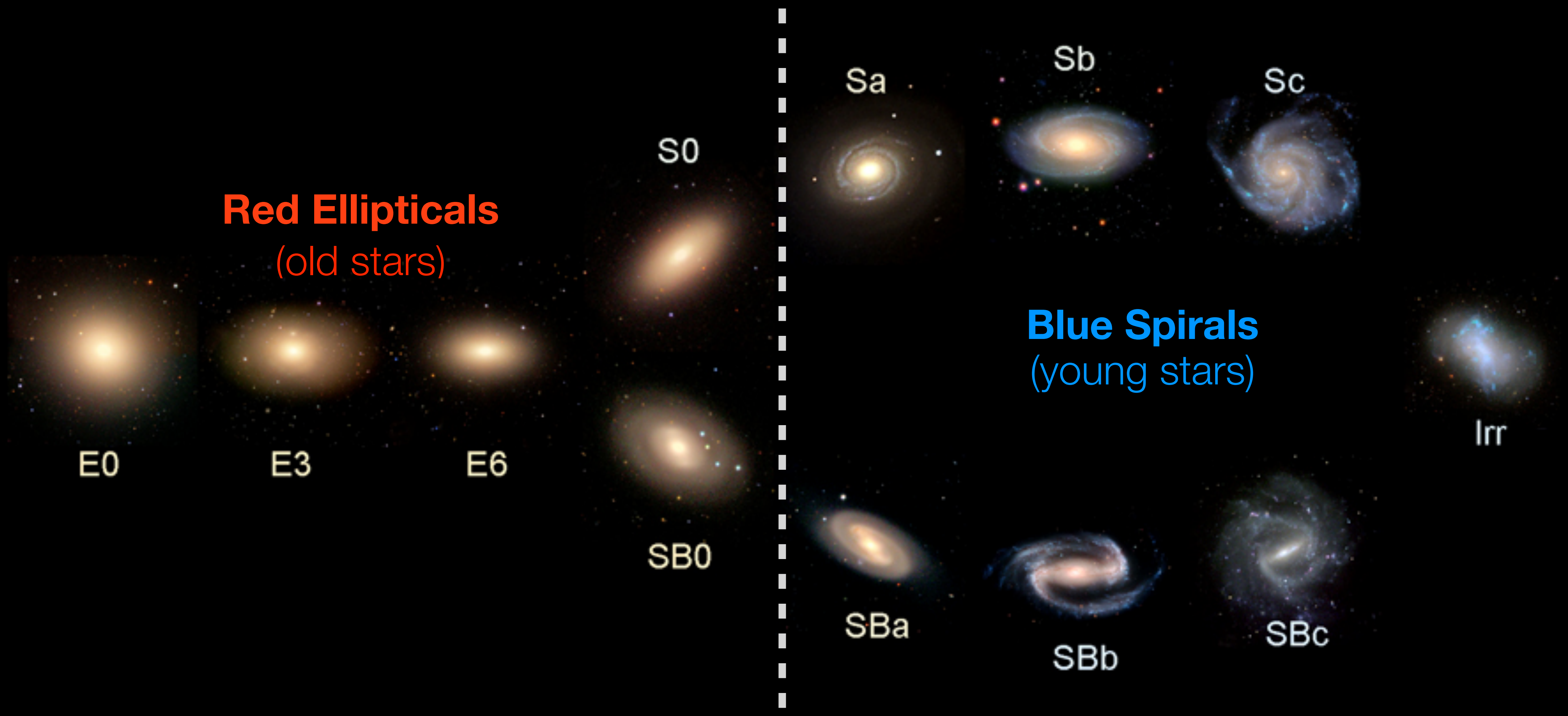
    >10x greater than the visible mass







Galaxy 101: Color Bimodality - Galaxies are either blue or red

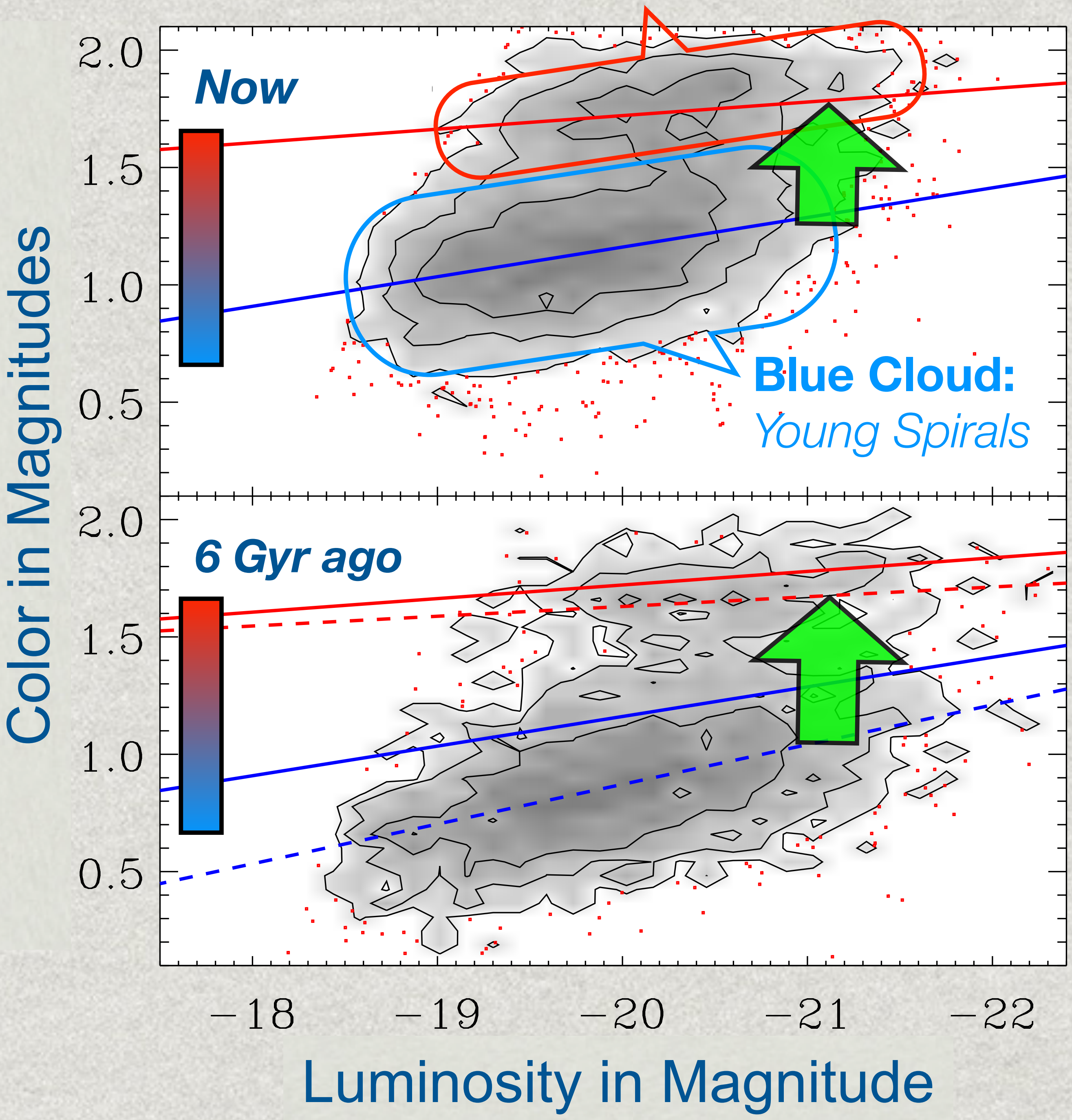


Hubble's Galaxy Classification Scheme

Galaxies in the Current Universe

Galaxy 101: Color Bimodality: Galaxies are either blue or red

Red Sequence: *Old Ellipticals*



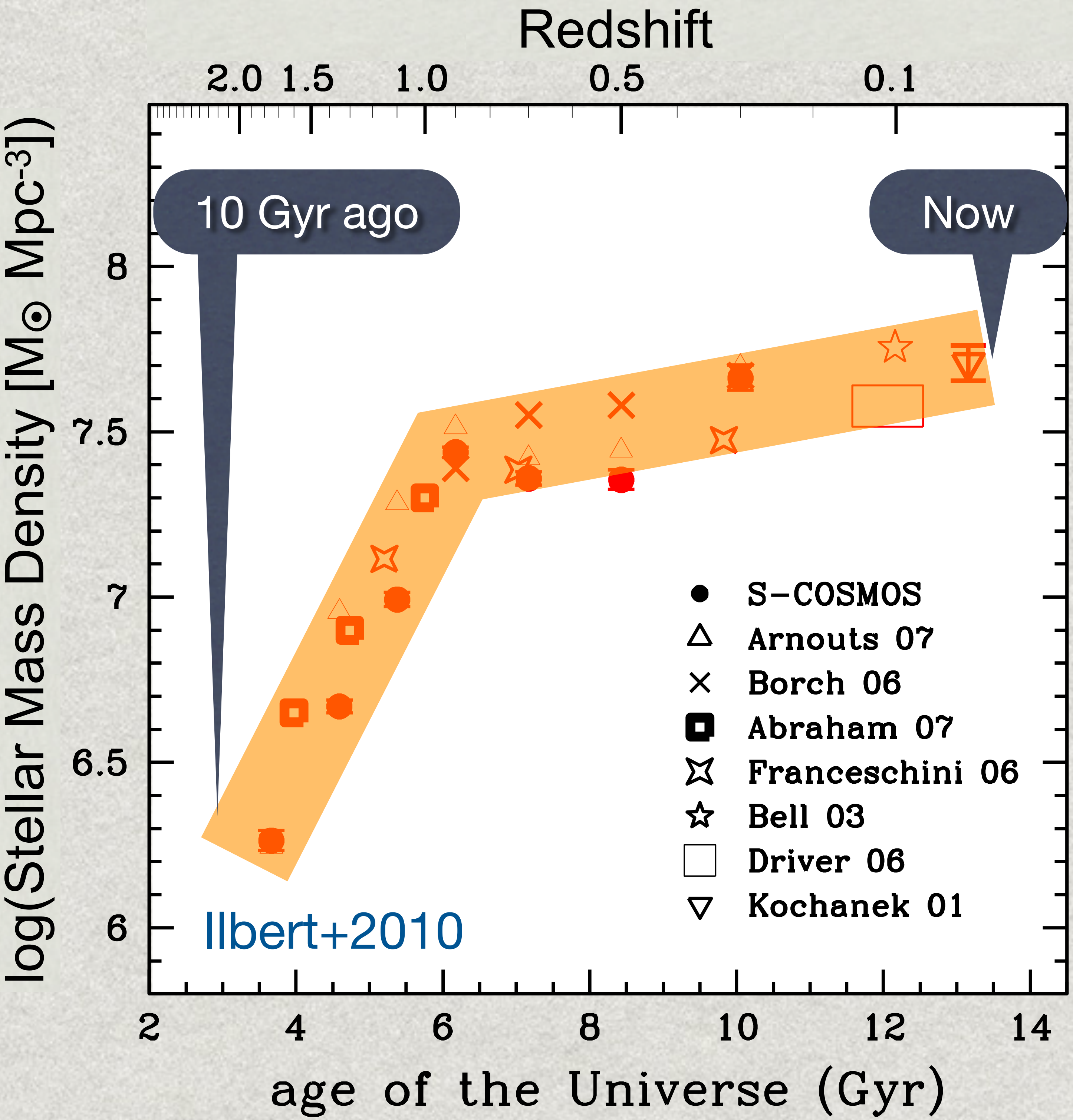
Blue Cloud: *Young Spirals*

Blanton+2006

Rapid build-up of red sequence

Red Galaxy Formation

- **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 10 times in just 2 billion years ($1 < z < 2$).

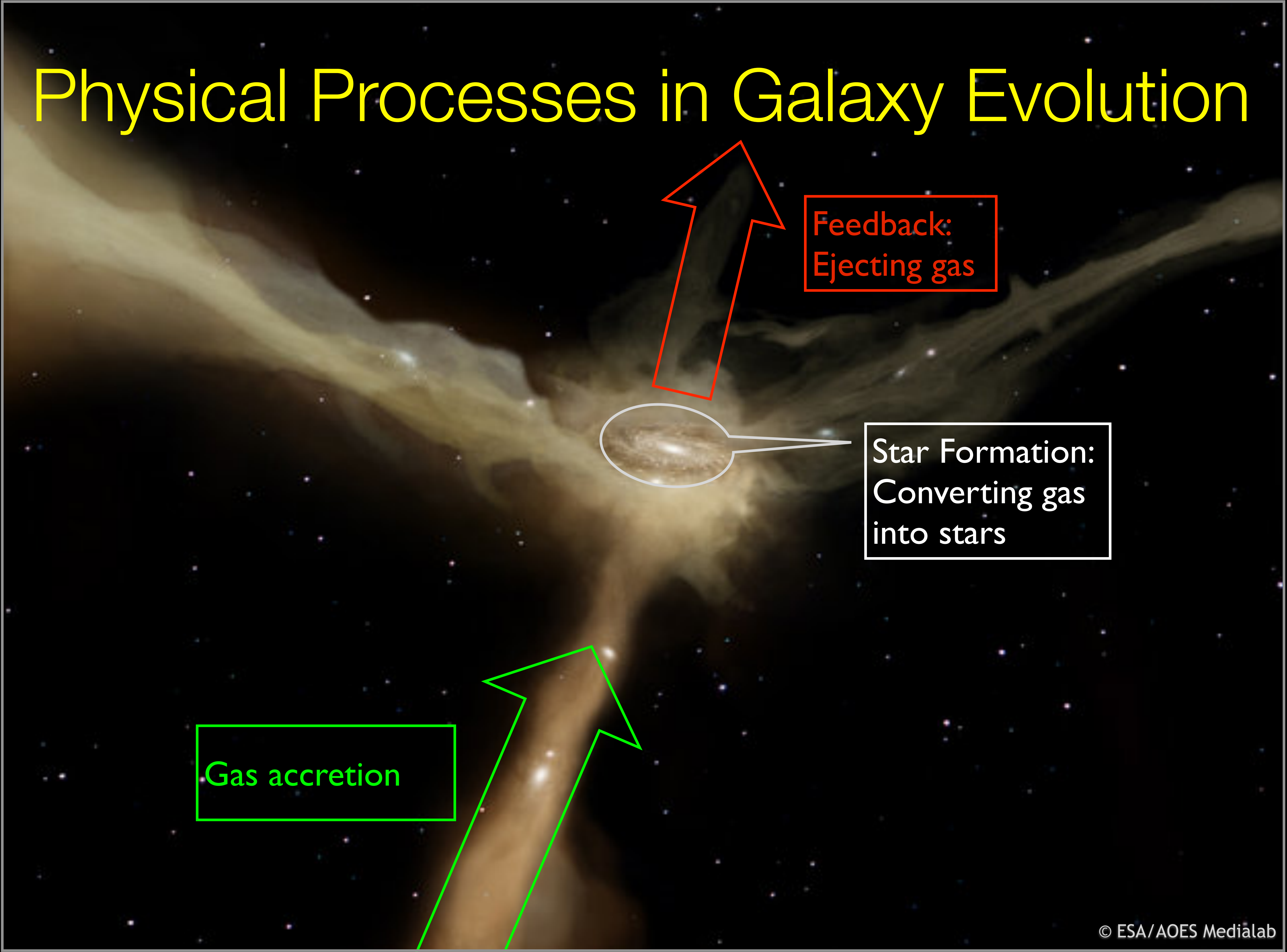


Ilbert+2010

Outline

- Galaxies show two main flavors -- **blue** or **red** -- in the past 10 Gyrs (or 70% of the universe’s life), and **red** galaxies formed early and rapidly.
- A model of galaxy formation & evolution:
  - ✓ the evolution in global star formation level
  - ✗ why galaxies are either blue or red?
  - ✗ dusty galaxies with tremendous star formation rates
- Why dusty galaxies are key to understand the divide between the blue and red galaxies?
- Prospects of a physical understanding of galaxy evolution with future observations

Physical Processes in Galaxy Evolution

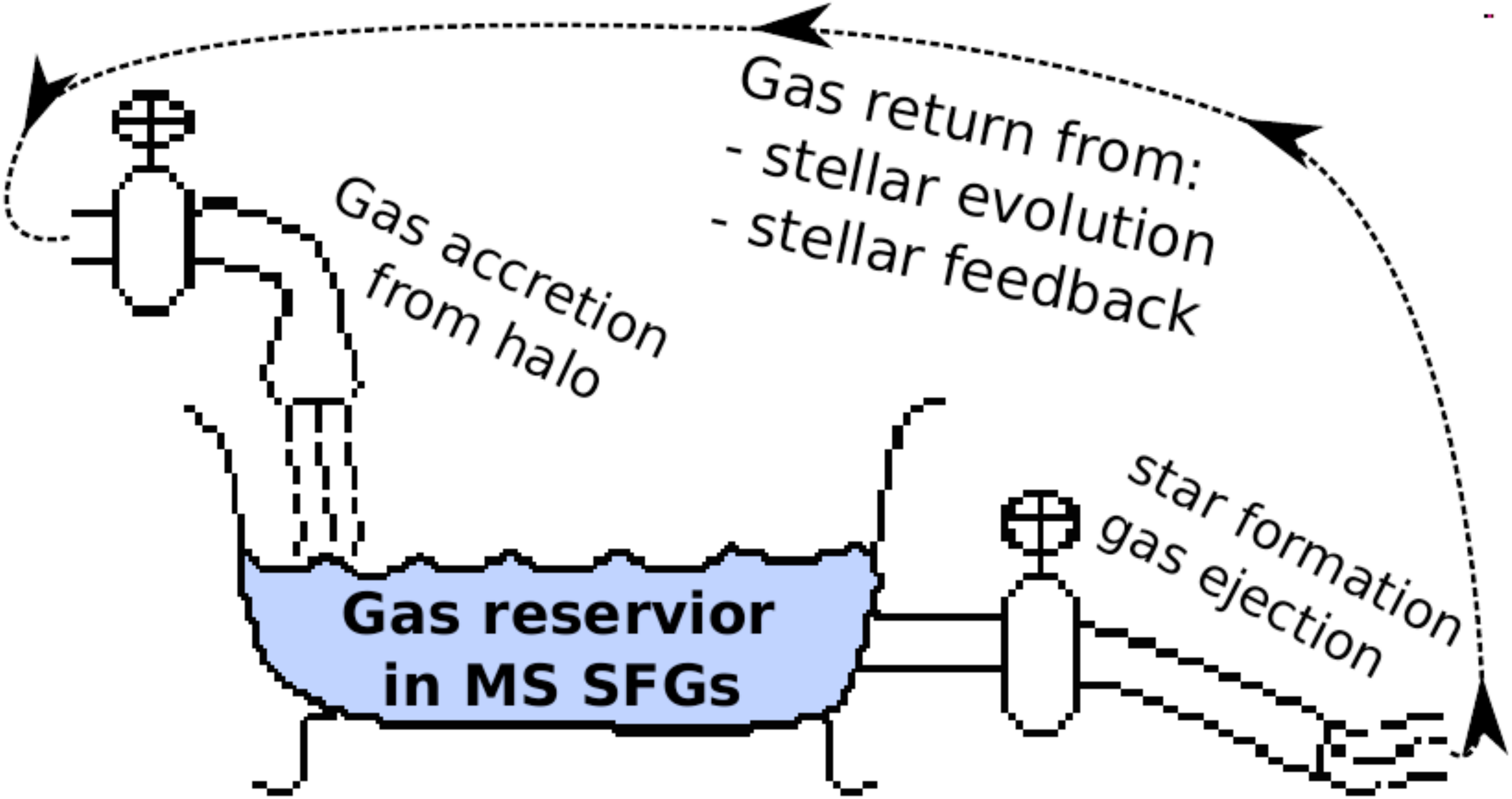


Feedback: Ejecting gas

Star Formation: Converting gas into stars

Gas accretion

The “Bathtub” Model



The “Bathtub” Model

Change in Cold Gas Reservoir

Accretion Rate ∝ Halo Growth Rate

Gas Consumption Rate ∝ Star Formation Rate

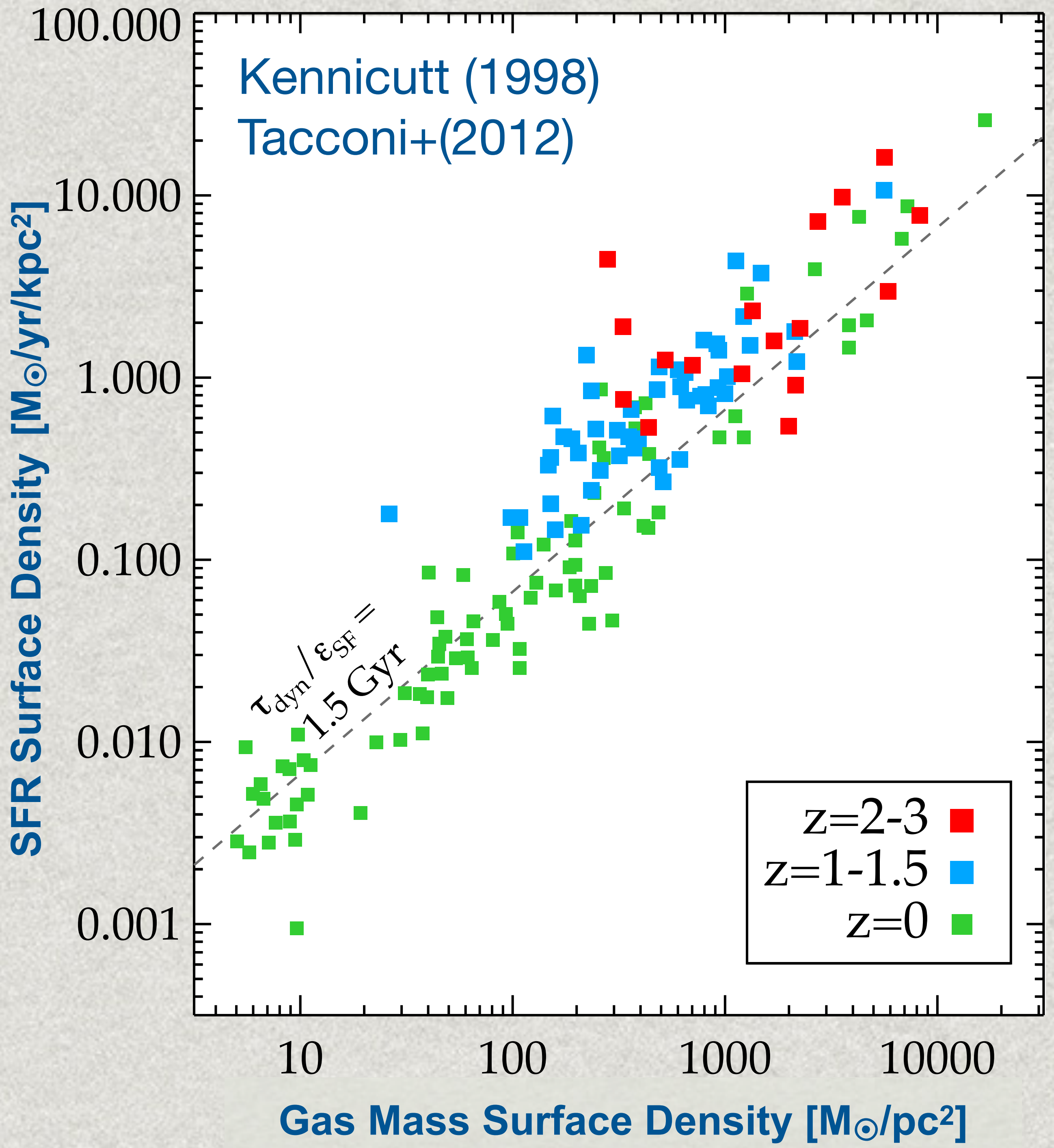
$$\left\{\begin{array}{l} \boxed{\dfrac{dM_{\mathrm{gas}}}{dt}} = \boxed{\epsilon_{\mathrm{cold}} f_{\mathrm{baryon}} \dfrac{dM_{\mathrm{halo}}}{dt}} - \boxed{(1 - f_{\mathrm{recycle}} + f_{\mathrm{outflow}}) \dfrac{dM_{\mathrm{star}}}{dt}} \\ \dfrac{dM_{\mathrm{halo}}}{dt} \propto M_{\mathrm{halo}}^{1.1}(1+z)^{2.2} \\ \dfrac{dM_{\mathrm{star}}}{dt} = \mathrm{SFR} = \epsilon_{\mathrm{SF}} \dfrac{M_{\mathrm{gas}}}{\tau_{\mathrm{dyn}}} \end{array}\right.$$

ejection out of halo

⬅ **Halo Growth Rate from Simulations**

⬅ **Star Formation Law**

Kennicutt-Schmidt Star Formation Relation



- Stars form because of gravitational collapse of gas clouds, hence:

  $$\mathbf{SFR = \epsilon_{SF}/t_{SF}\ M_{gas}}$$

  ϵ_{SF}: fraction of mol. gas involved in SF

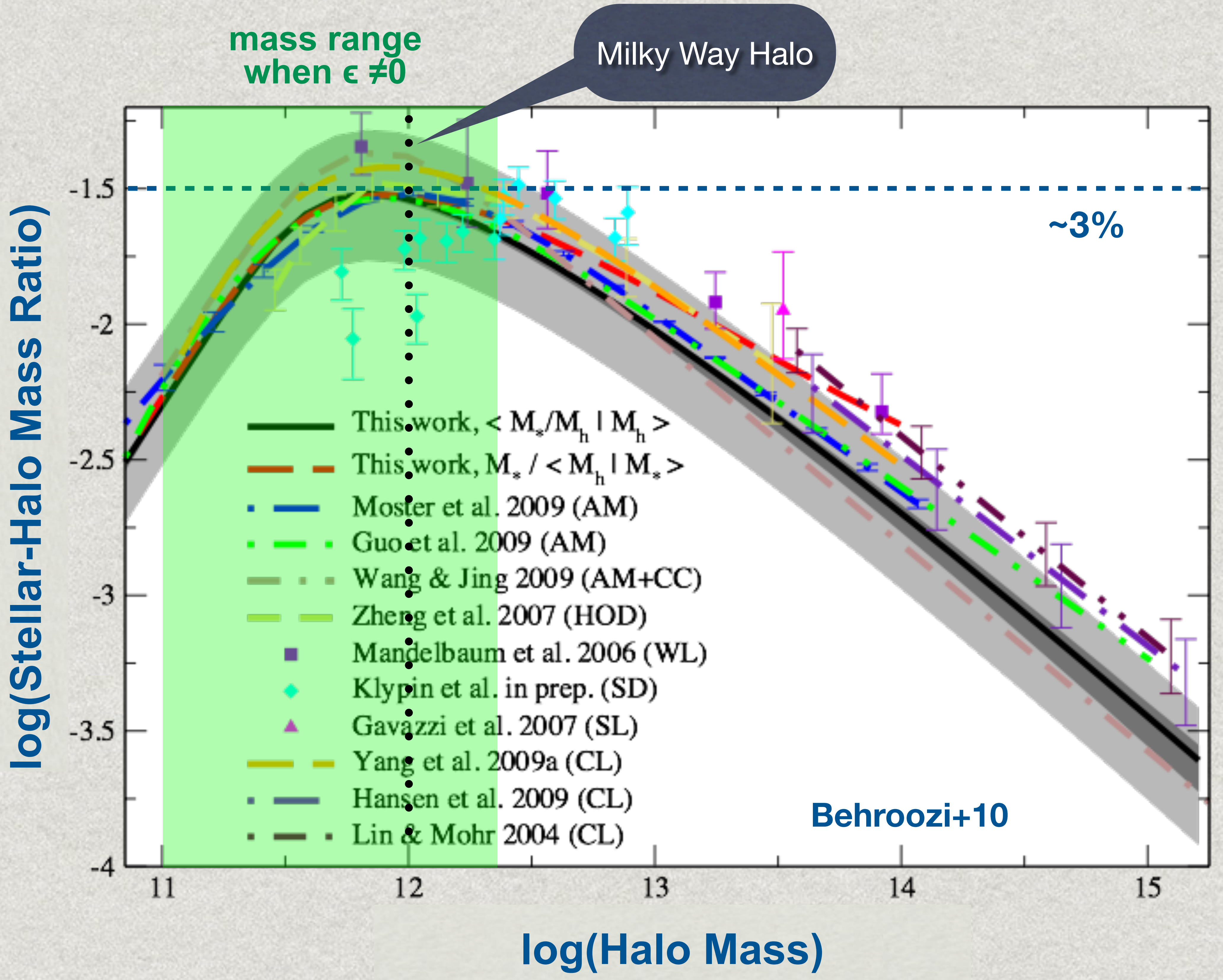
  t_{SF}: SF timescale

- The data on the left show for normal SFGs:

  $$\mathbf{t_{SF}/\epsilon_{SF} \sim 1.5\ Gyr}$$

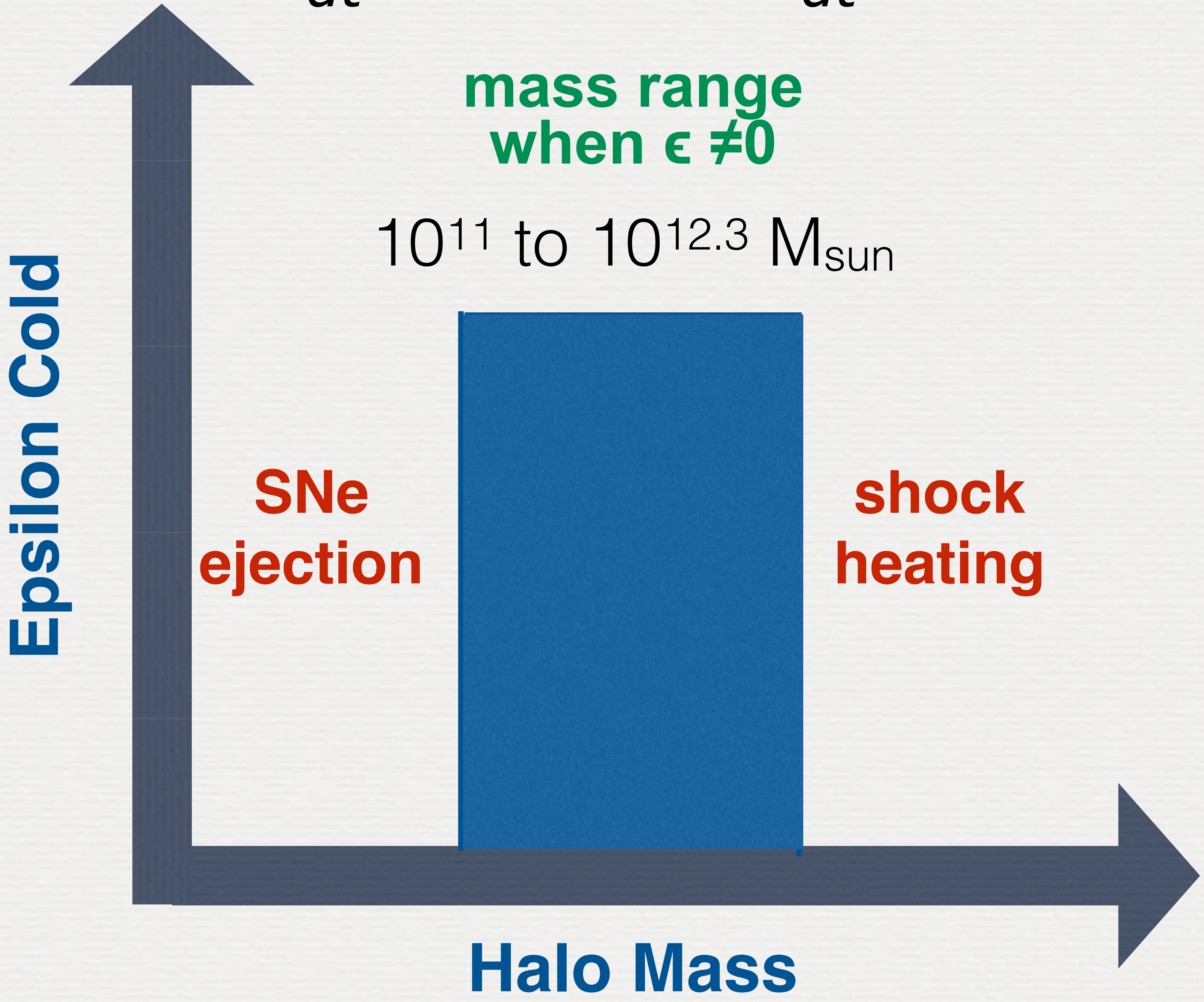
  ($\epsilon_{SF} \approx 0.01$ for $t_{SF} = 15$ Myr)

The Cold Gas Accretion Efficiency



The Cold Gas Accretion Efficiency

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



mass range when ϵ ≠0

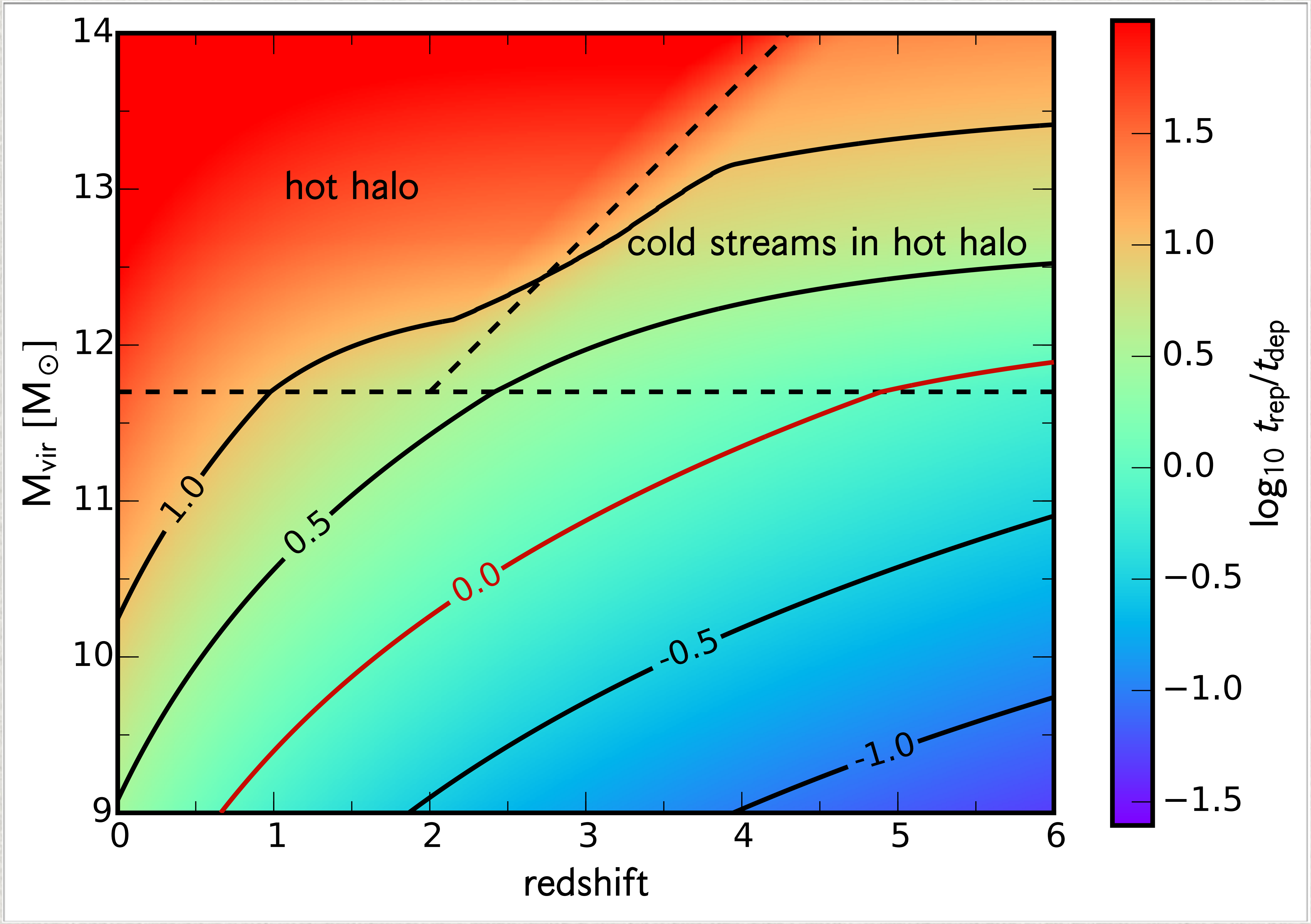
10^{11} to $10^{12.3}$ M_{sun}

SNe ejection

shock heating

The Cold Gas Accretion Efficiency

Tacchella+2015, Dekel & Birnboim 2006



When all the gas come in hot: drain the tub

SFR declines exponentially with a 2-3 Gyr e-folding time

$$\left\{ \begin{array}{l} \dfrac{dM_{\mathrm{gas}}}{dt} = \cancel{\epsilon_{\mathrm{cold}} f_{\mathrm{baryon}} \dfrac{dM_{\mathrm{halo}}}{dt}} - (1 - f_{\mathrm{recycle}} + f_{\mathrm{outflow}})\mathrm{SFR} \\ \mathrm{SFR} = \epsilon_{\mathrm{SF}} \dfrac{M_{\mathrm{gas}}}{\tau_{\mathrm{dyn}}} \ (\mathrm{Kennicutt} - \mathrm{Schmidt\ law}) \end{array} \right.$$

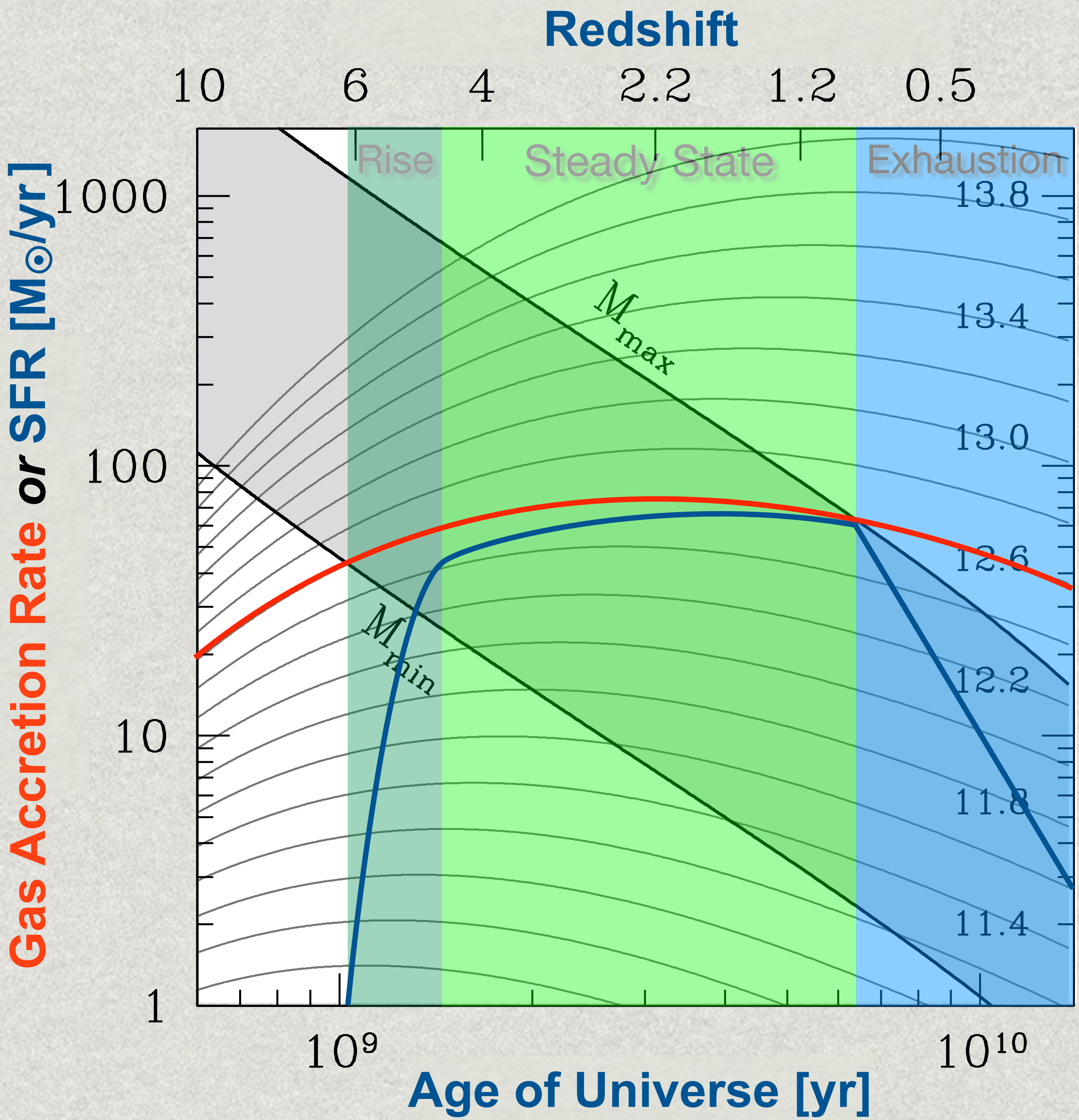
when $\epsilon_{\mathrm{cold}} = 0$ we have :

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

Solving this equation, we get an exponentially declining SFR :

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

Predicted Star Formation History



- **Grey region**: efficient cold gas accretion $10^{11}<M_{Halo}<10^{12.3}\ M_\odot$
- **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_{SF}/ϵ_{SF})**.

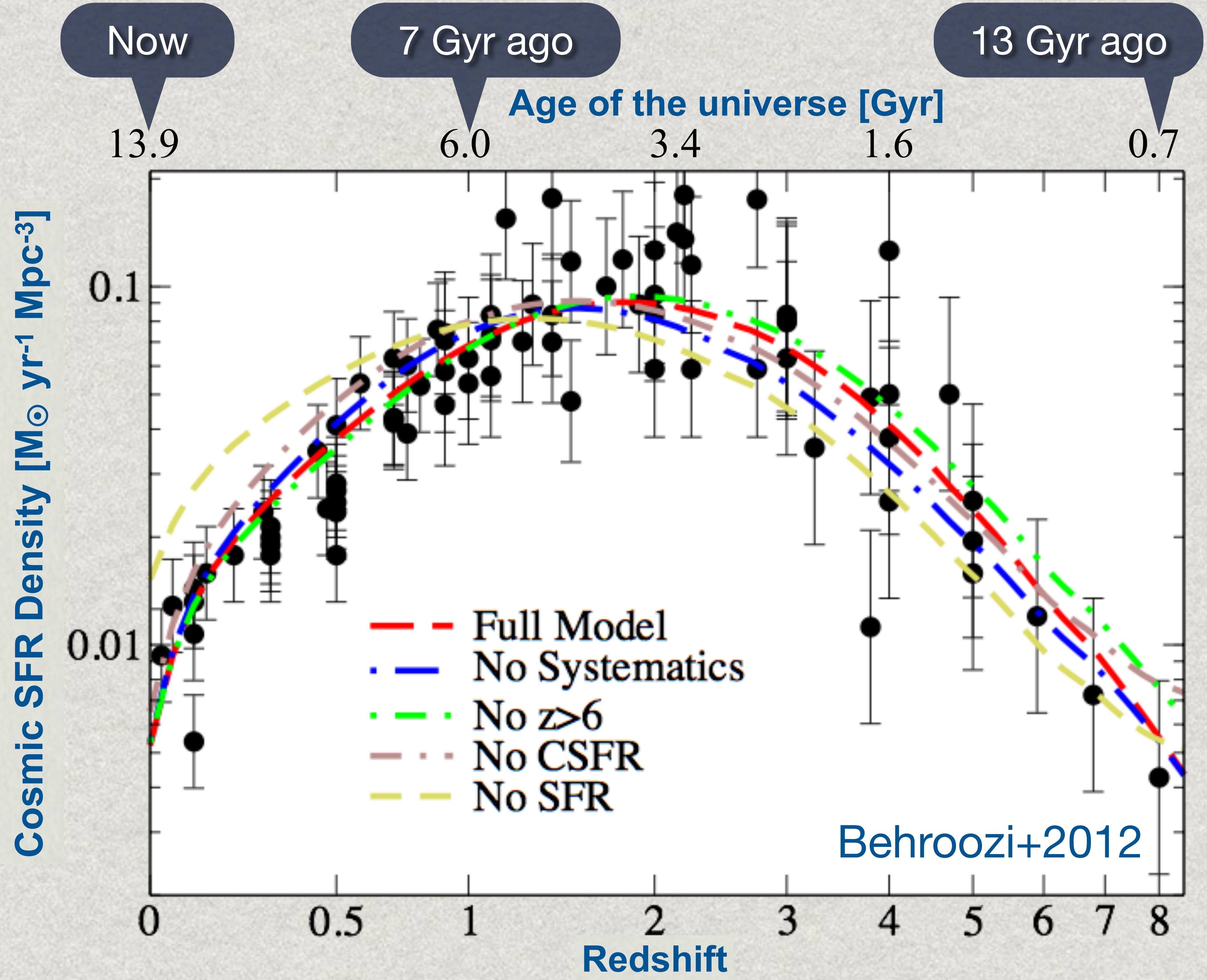
Bouche+2010,Cattaneo+2006
Dekel & Birnboim 2006

The Cosmic Star Formation History

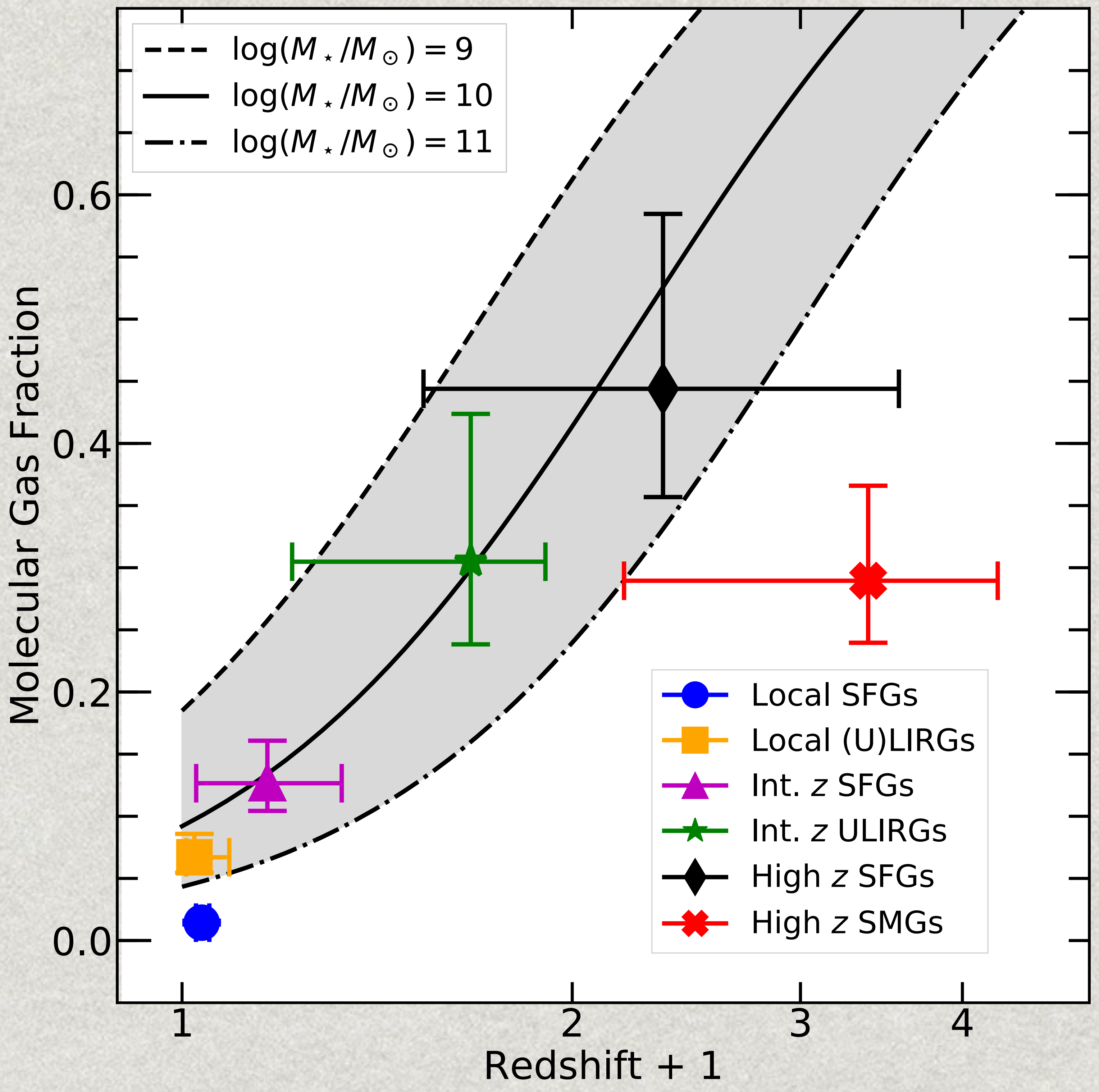
Cosmic star formation

- peaked when the universe was only 3 billion years old.
- declined by 10x in the second half of the universe' life

SFR = Star Formation Rate



The Decline of Molecular Gas Fraction

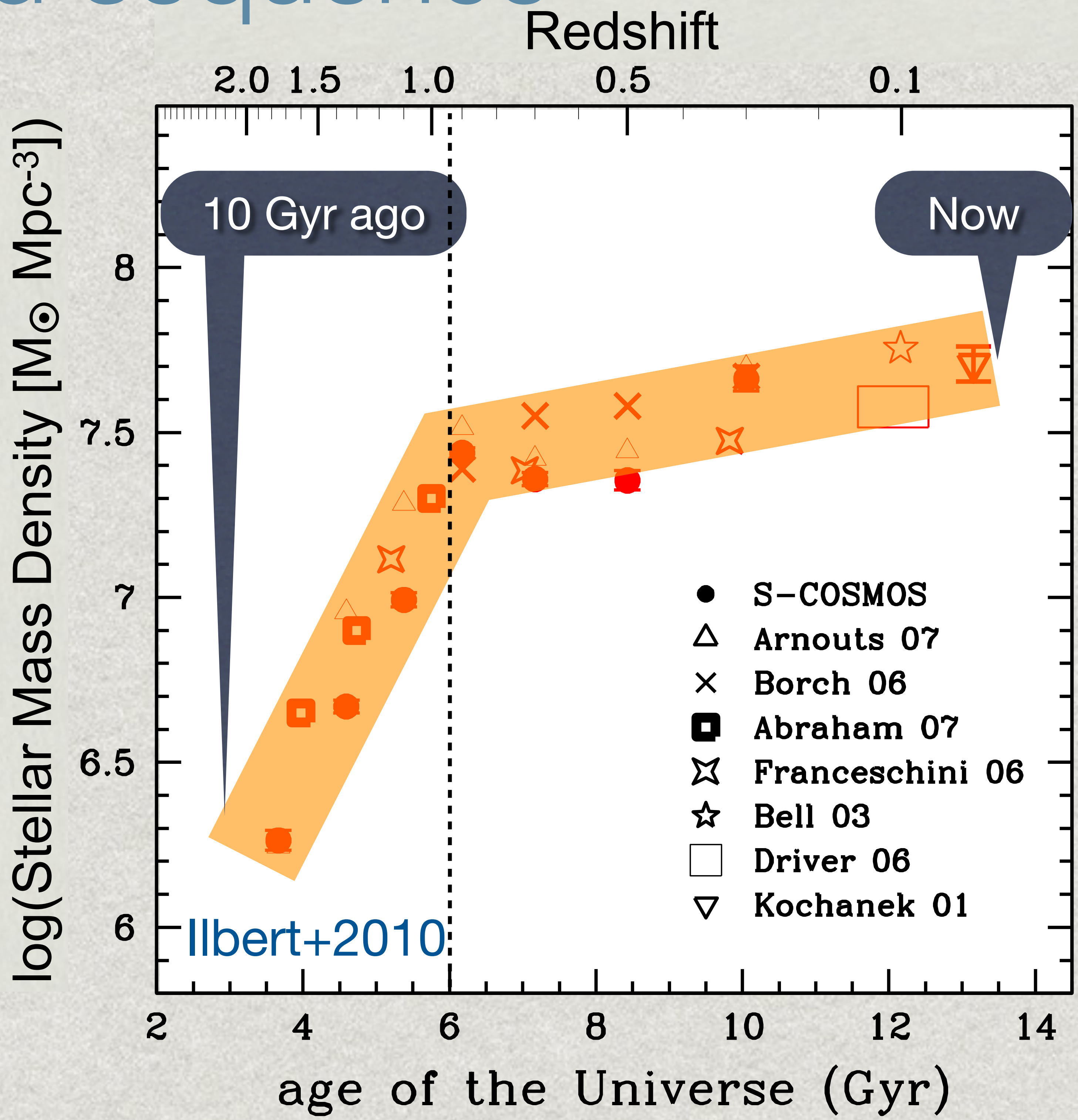


Isbell, Xue, Fu 2018: Using Tully-Fisher Relation to Measure Gas Fractions

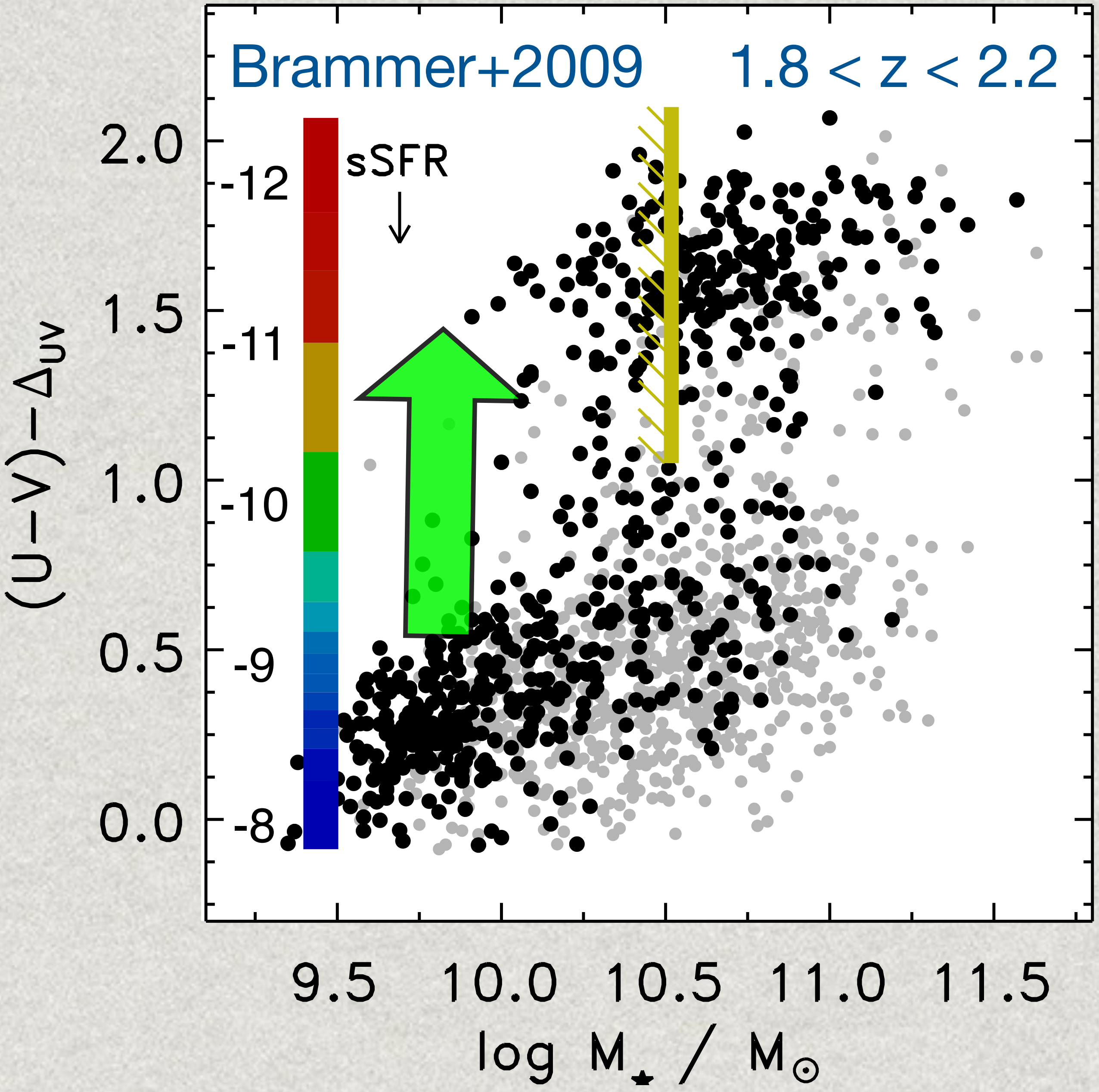
Challenge I: Rapid build-up of the red sequence

Red Sequence Formation

- **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 (= e^3) in just 2.5 Gyr ($1 < z < 2$). So **the e-folding time for the mass growth is 1 Gyr.**



Color bimodality at high-redshift requires rapid quenching



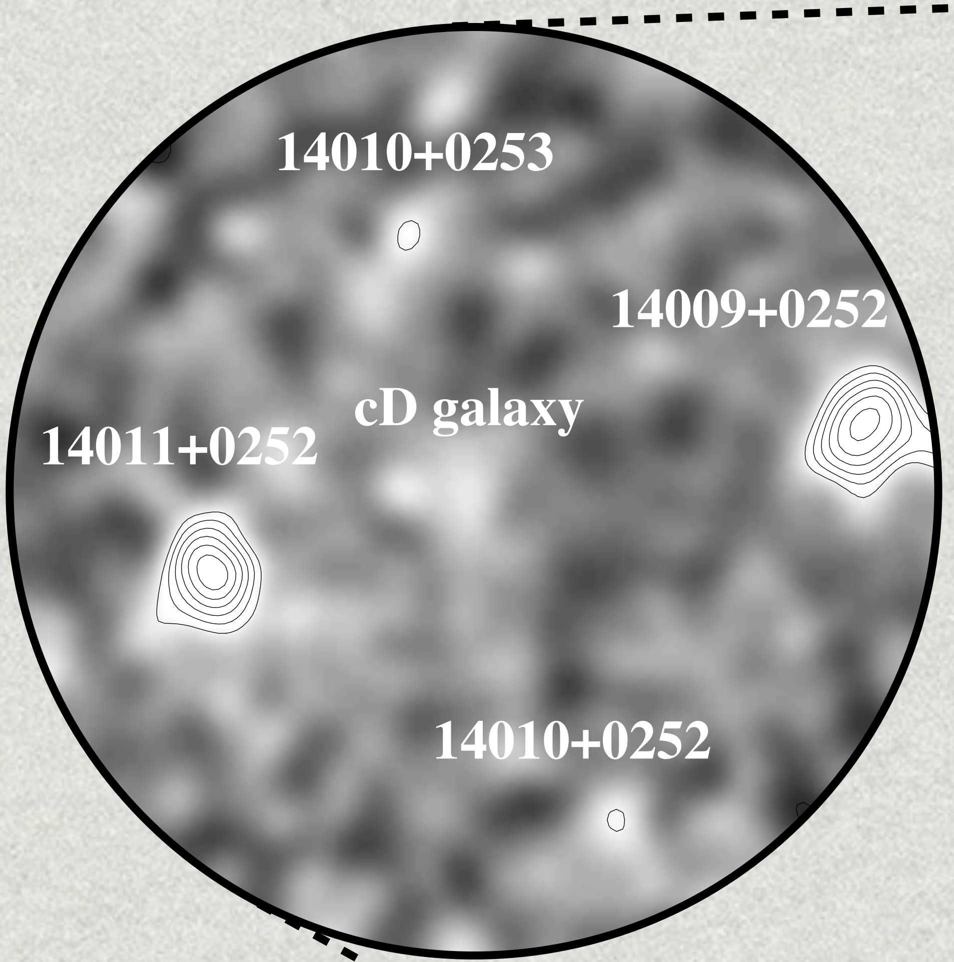
The rapid built-up of the **red sequence** requires rapid decline of SFR:

Red-sequence e-folding timescale of ~**1 Gyr** indicates an SFR e-folding time ~**0.2 Gyr**, because SFR must decline by 100 times (~5 e-folding, **e^5 = 150**) for a galaxy to cross the green valley

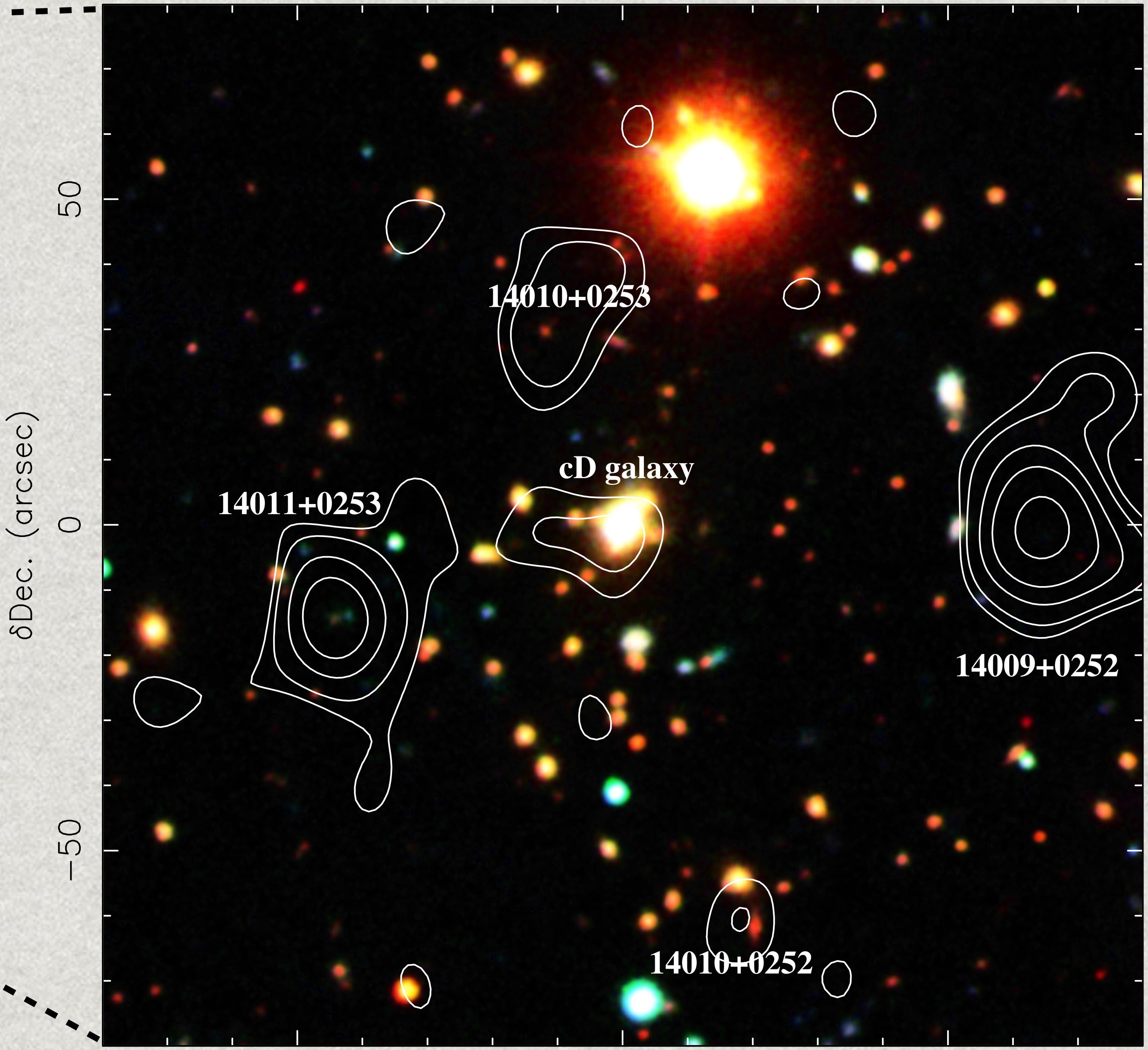
This is **10x** shorter than the gas exhaustion time (~**2 Gyr**)!
This is not draining, but quenching!

Challenge II: Submillimeter Galaxies (SMGs)

Submm (850 μm)

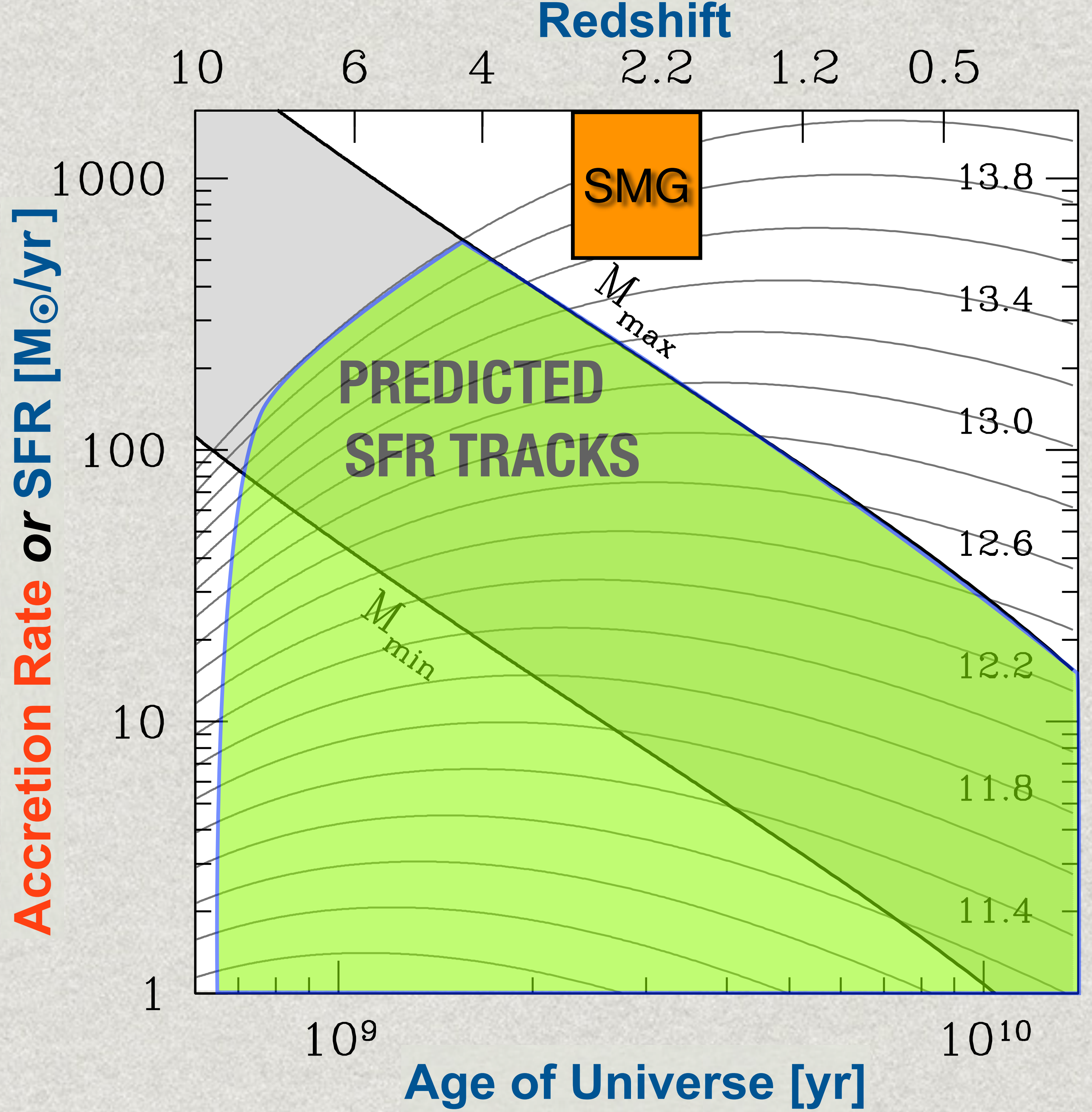


Optical Image overlaid with submm contours



Barger+98,
Smail+98,
Eales+99,
Ivison+00

Challenge II: Submillimeter Galaxies (SMGs)

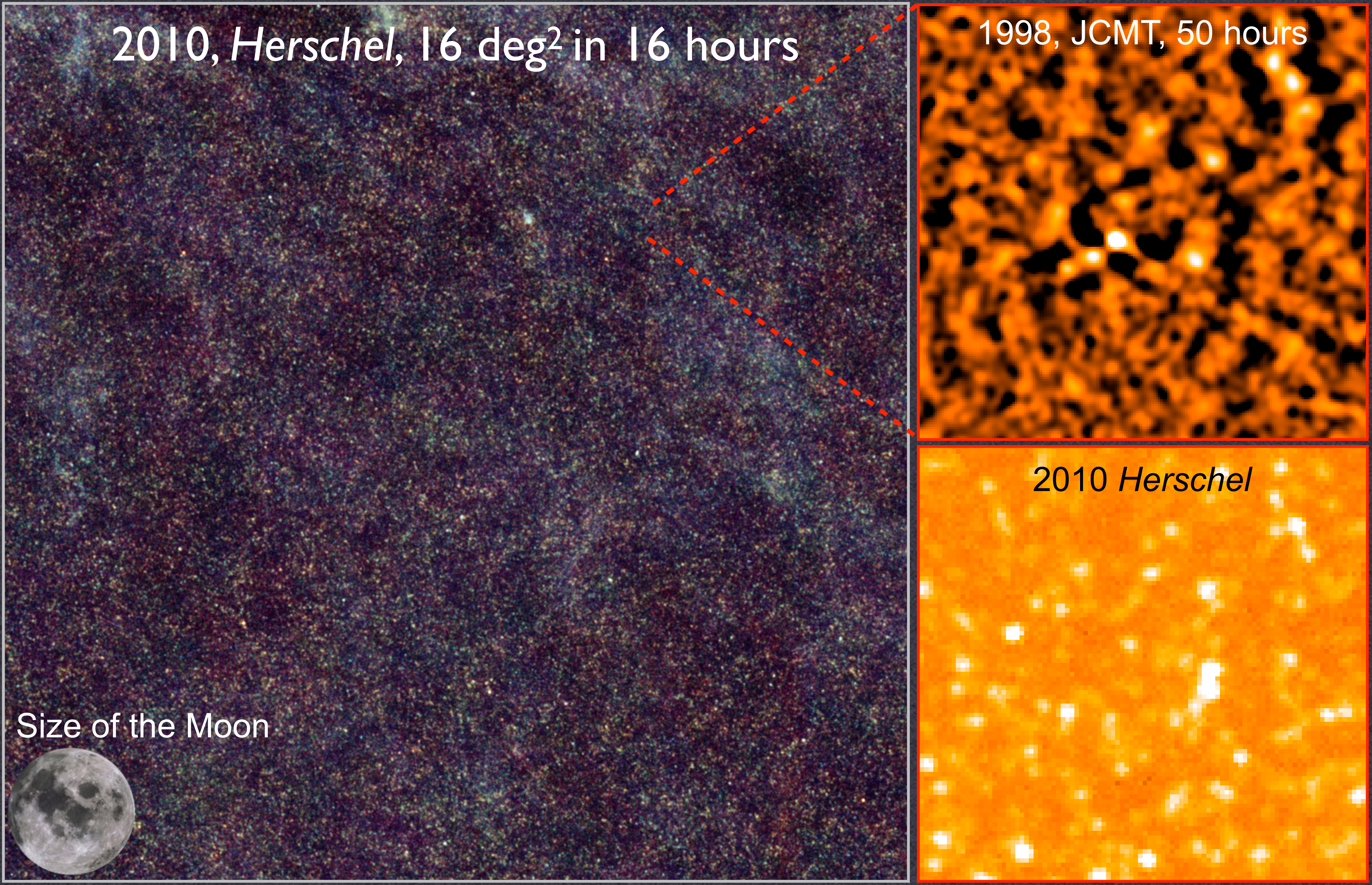


- **SMG = Submillmeter Galaxies**
- **Grey region**: efficient cold gas accretion in halos with $10^{11} < M_{Halo} < 10^{12.3}$ $M_\odot$
- **Green region:** star formation tracks of all halos
- **The SFRs of SMGs appear too high for any halos at their observed epoch.**

How do we solve these problems?

Better and more observations :)

Submm Surveys with Herschel



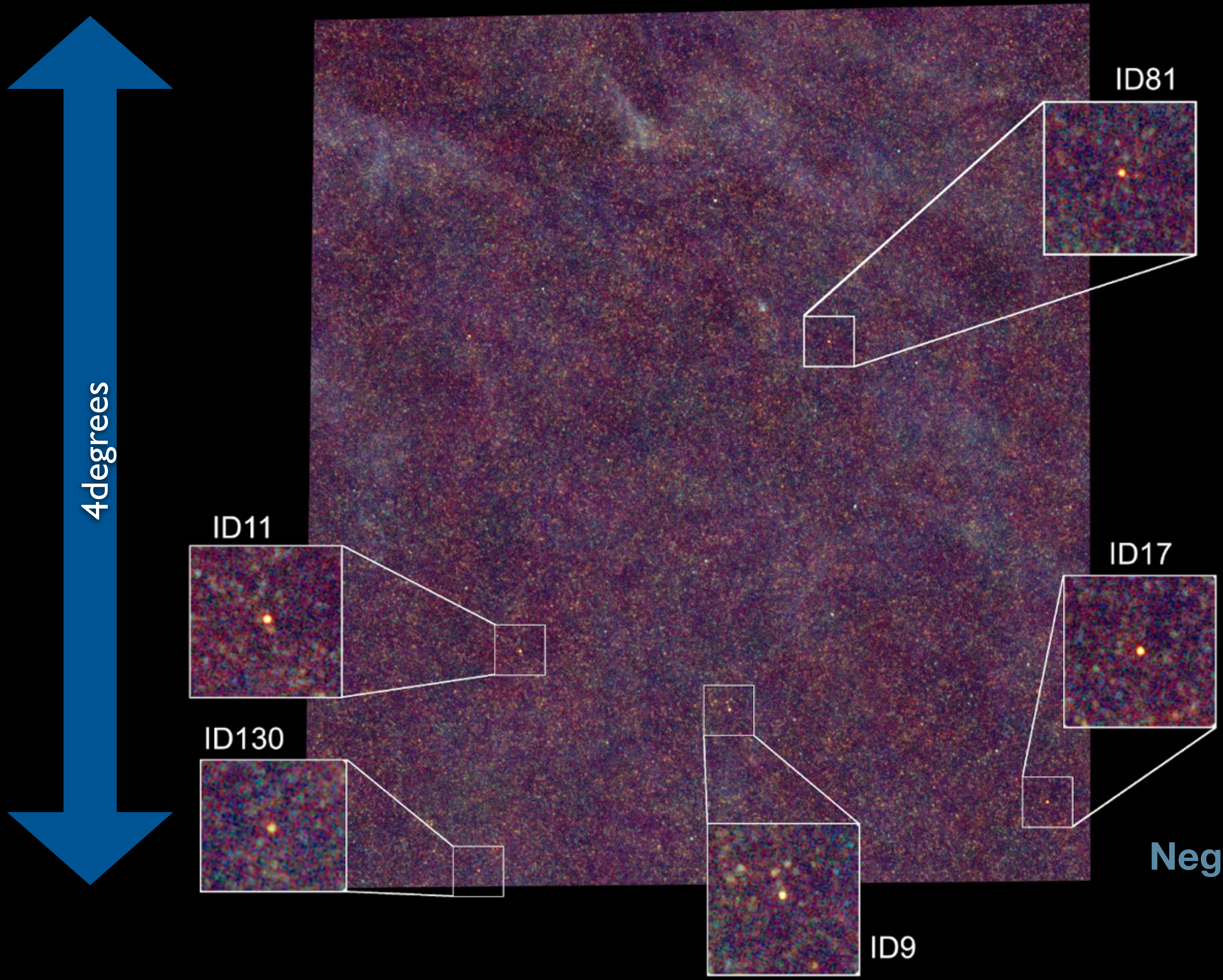
2010, *Herschel*, 16 deg^2 in 16 hours

Size of the Moon

1998, JCMT, 50 hours

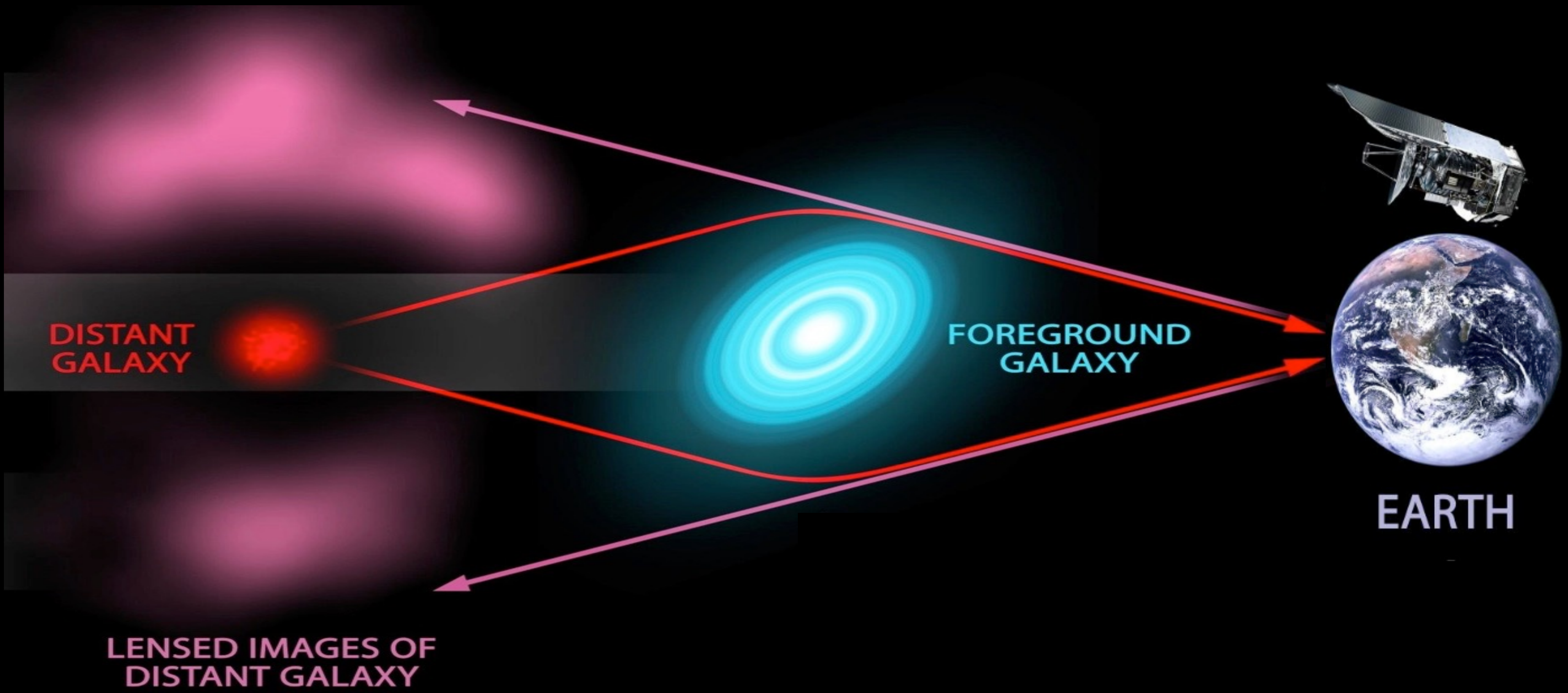
2010 *Herschel*

Brightest Submillimeter Sources are Either Extremely Luminous or Lensed



Negrello+(2010)

Efficient Selection of Strongly Lensed SMGs

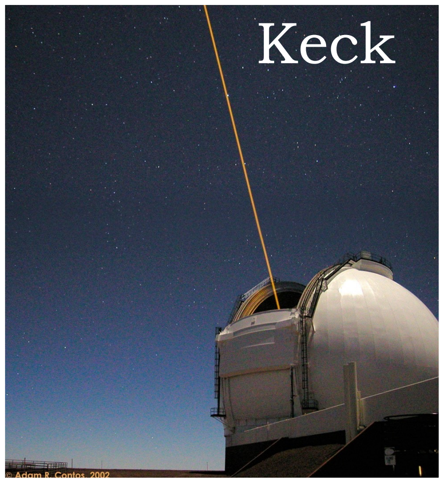


Blain (1996), Negrello et al. (2007), Wardlow et al. (2013)

Multi-wavelength Follow-up Observations

High-Resolution Imaging & Spectroscopy

Herschel



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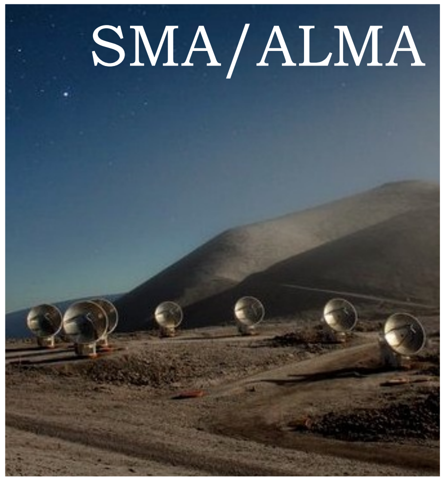

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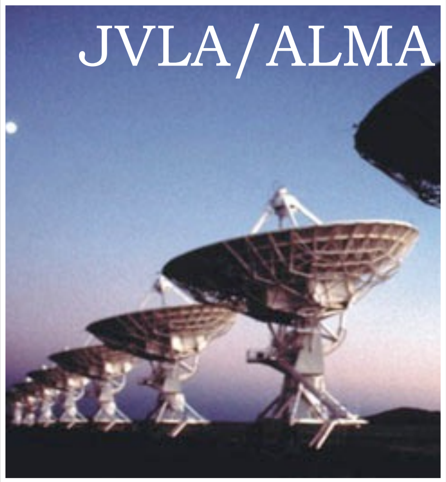
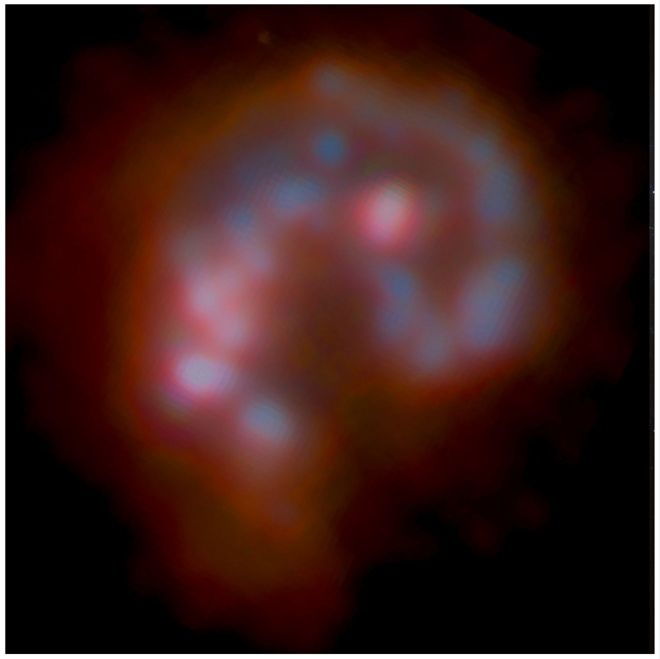


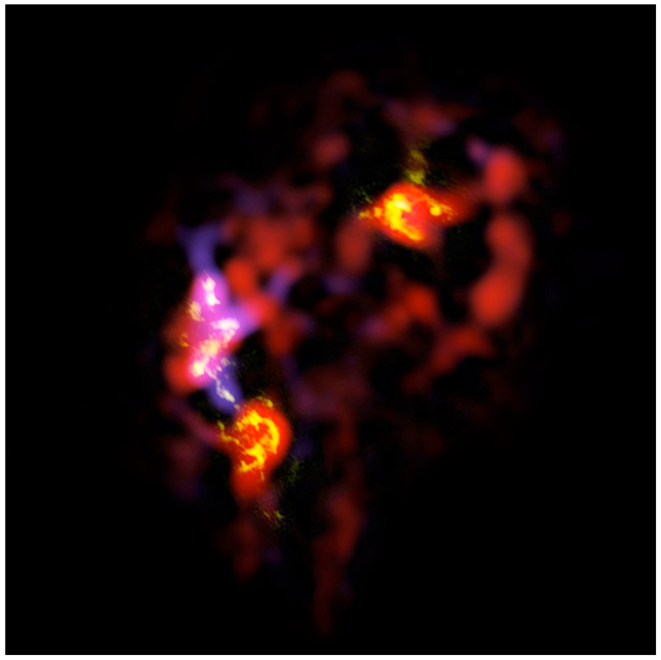
Probing Stars:
previous star formation (SF)

The Antennae Galaxies

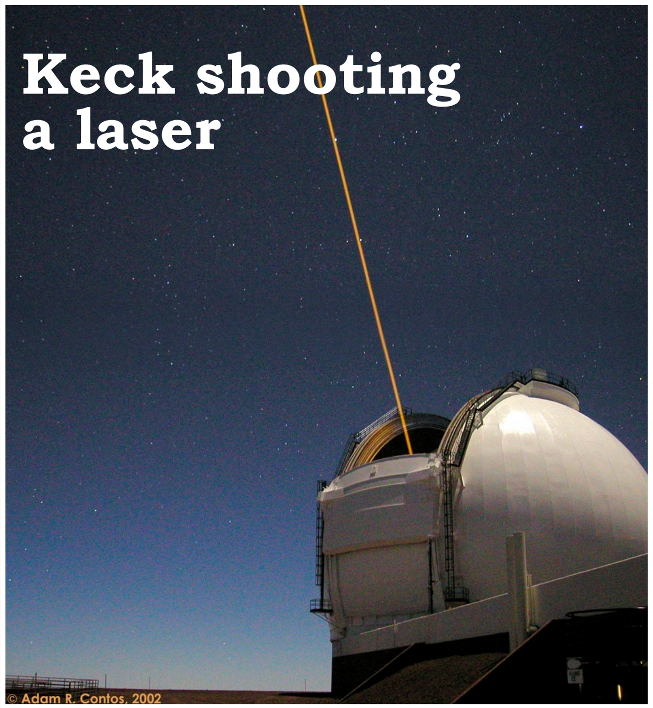
Dust:
current SF



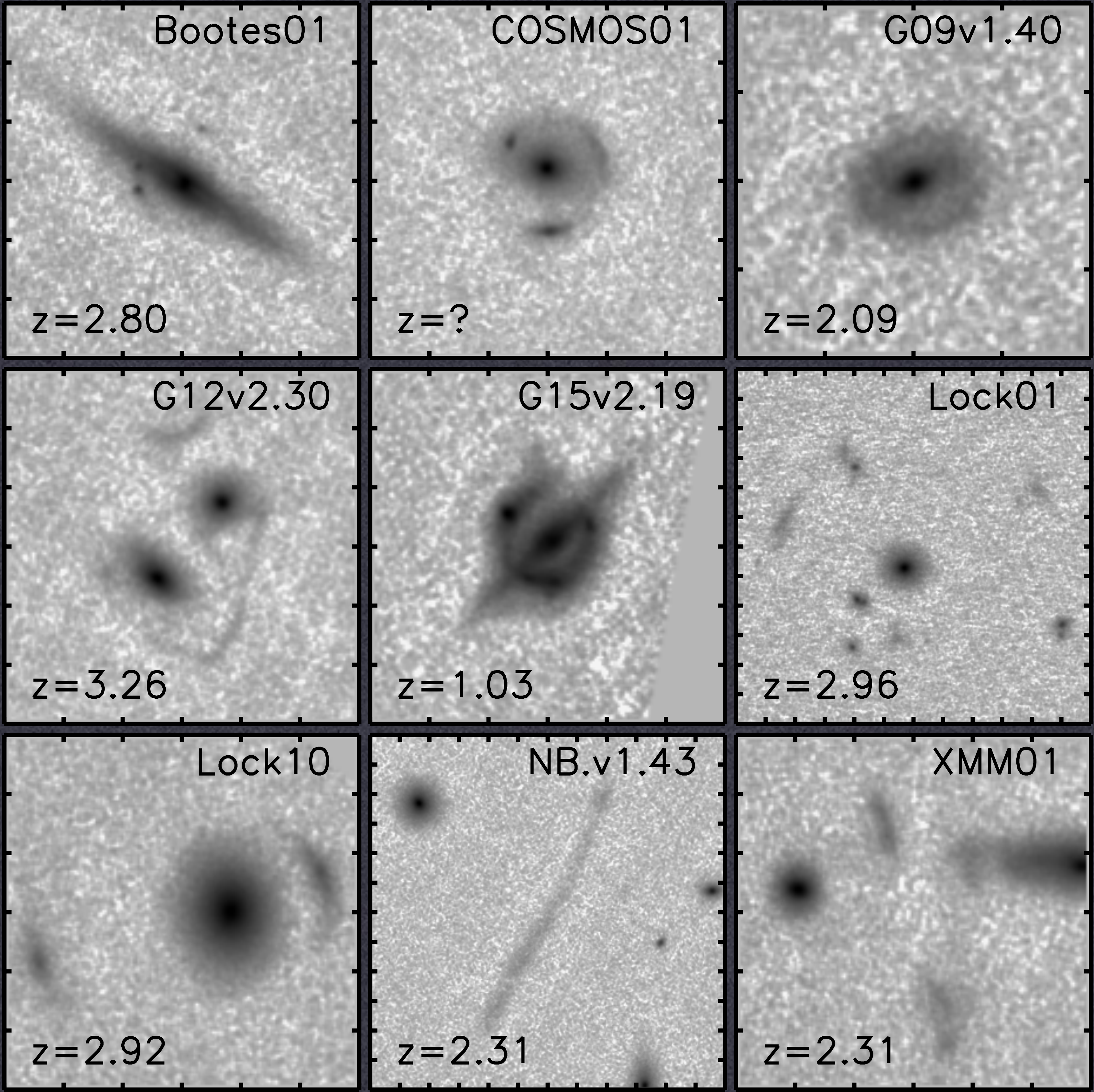
CO → Molecular Gas:
fuel of SF



High-Res Imaging w/ Keck Adaptive Optics (AO)

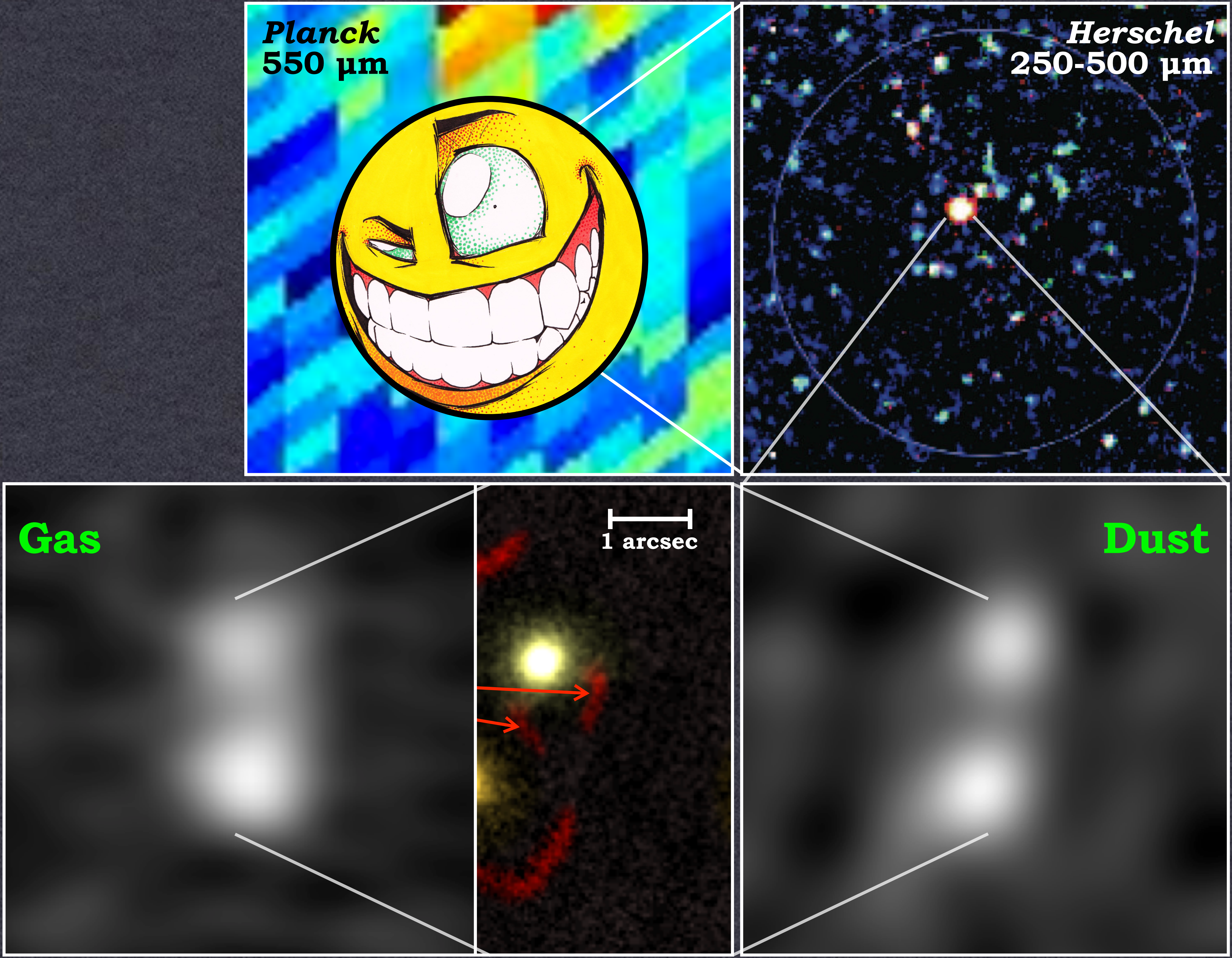


© Adam R. Contos, 2002



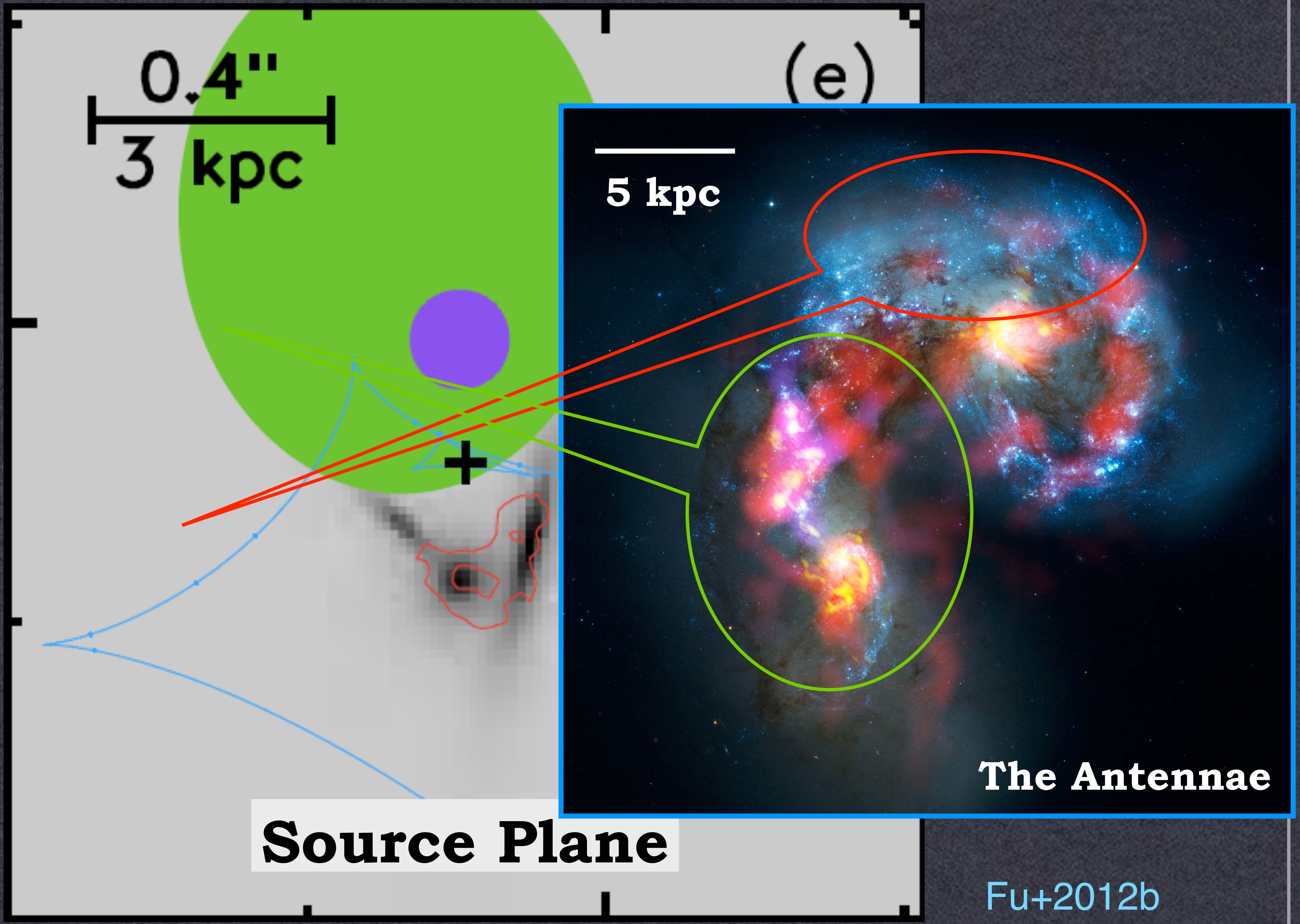
Calanog, Fu, et al. 2014
Bussmann et al. 2015

Observations of a Strongly Lensed SMG: G12v2.30



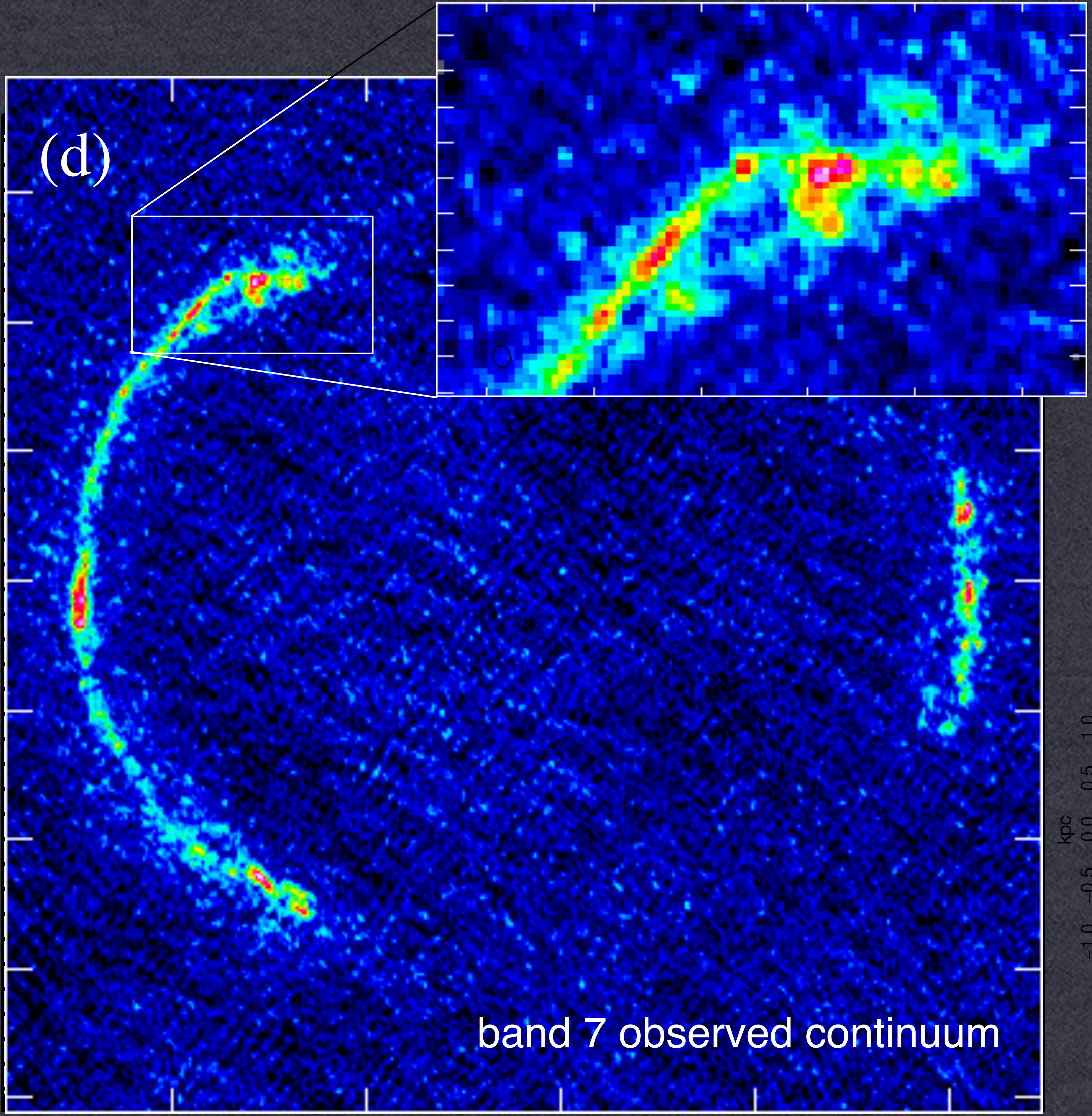
Fu+2012b

Source Plane Morphologies: Molecular Gas, Dust, and Stars

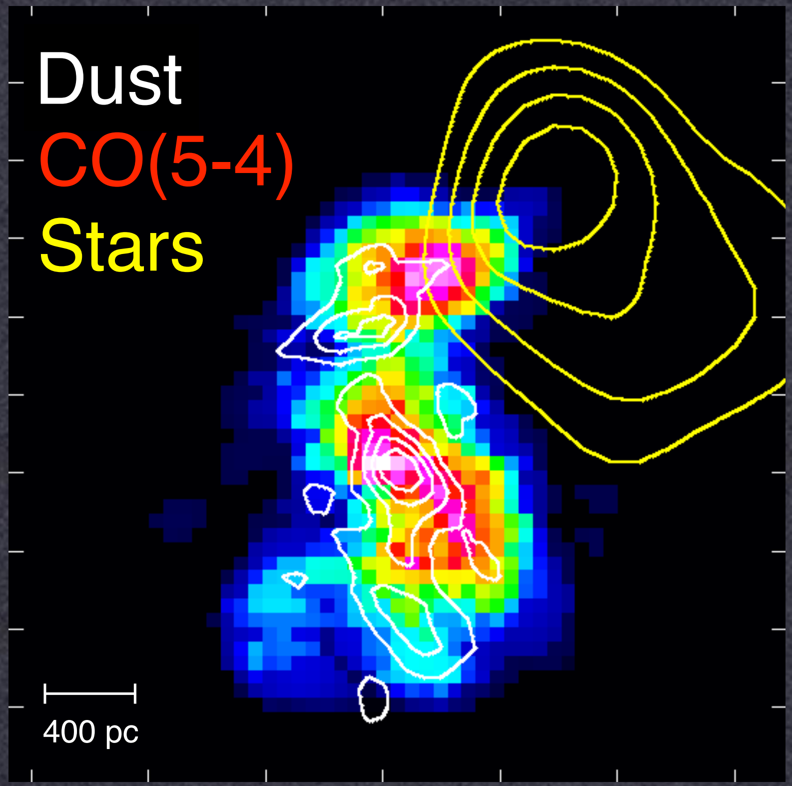


Fu+2012b

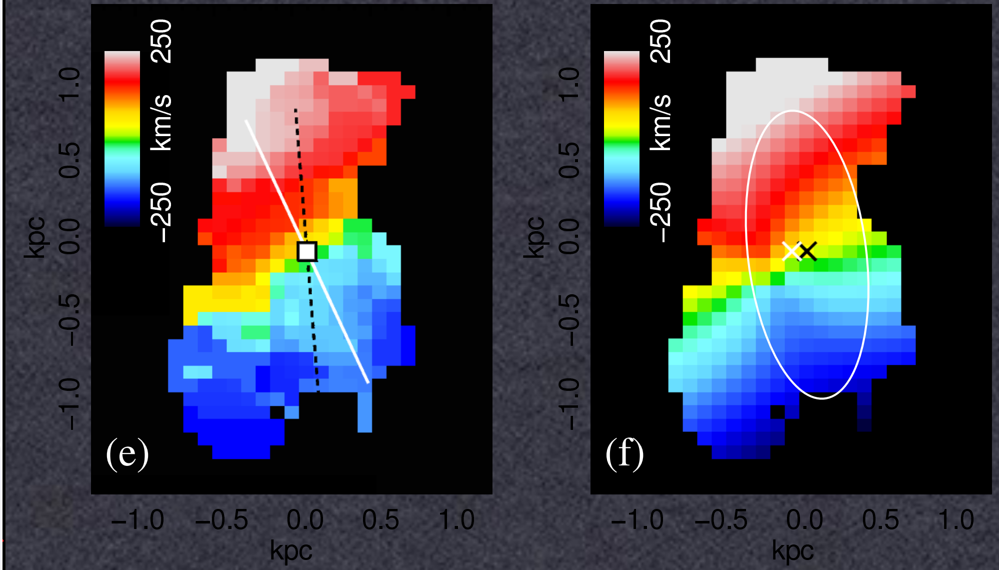
ALMA Long Baseline Campaign: SDP.81 (z = 3.04)



Source Plane

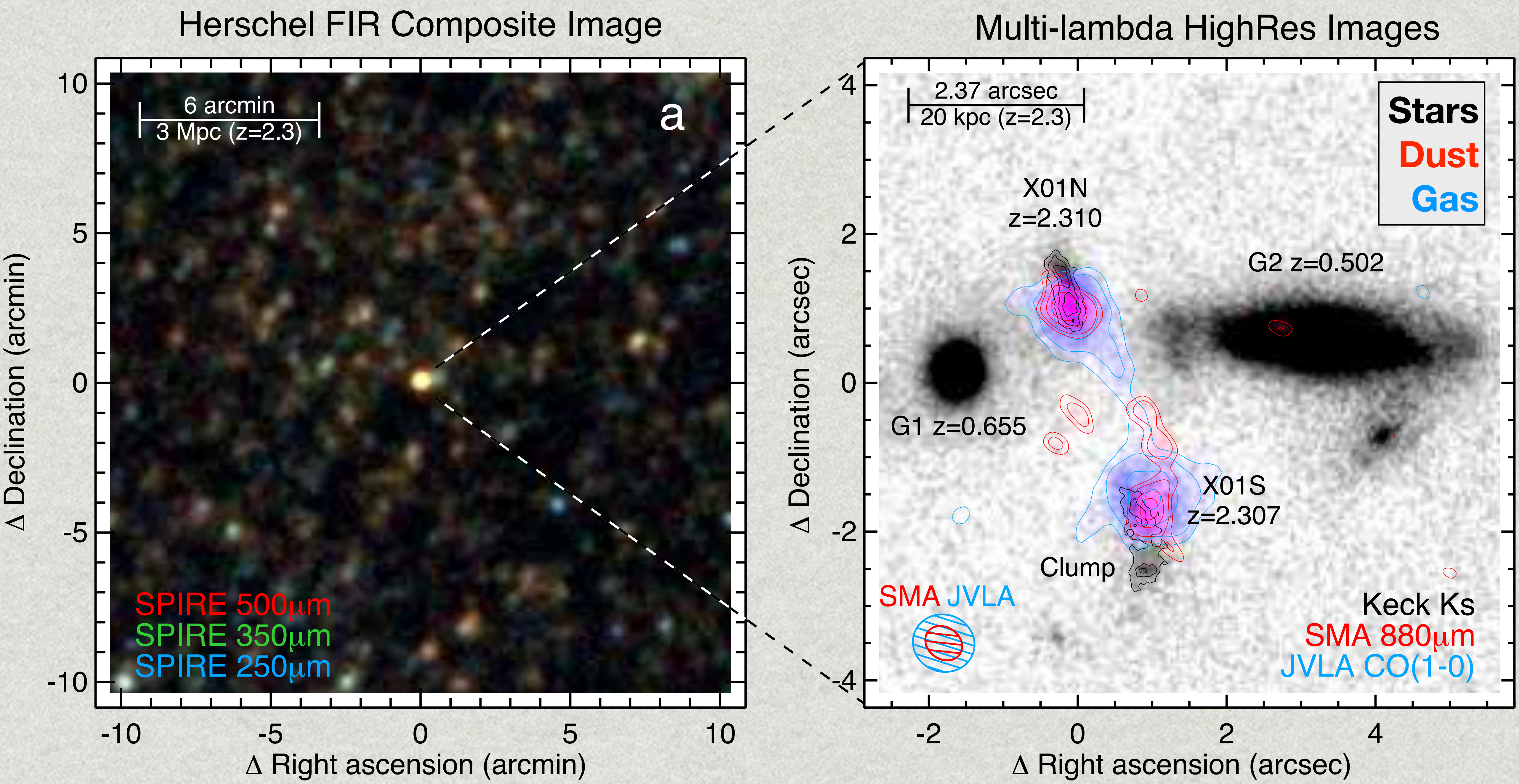


CO(5-4) velocity field



ALMA Partnership 2015
Dye+2015 (23mas=180 pc)

HXMM01: A Hyper-Luminous SMG Merger at z=2.3



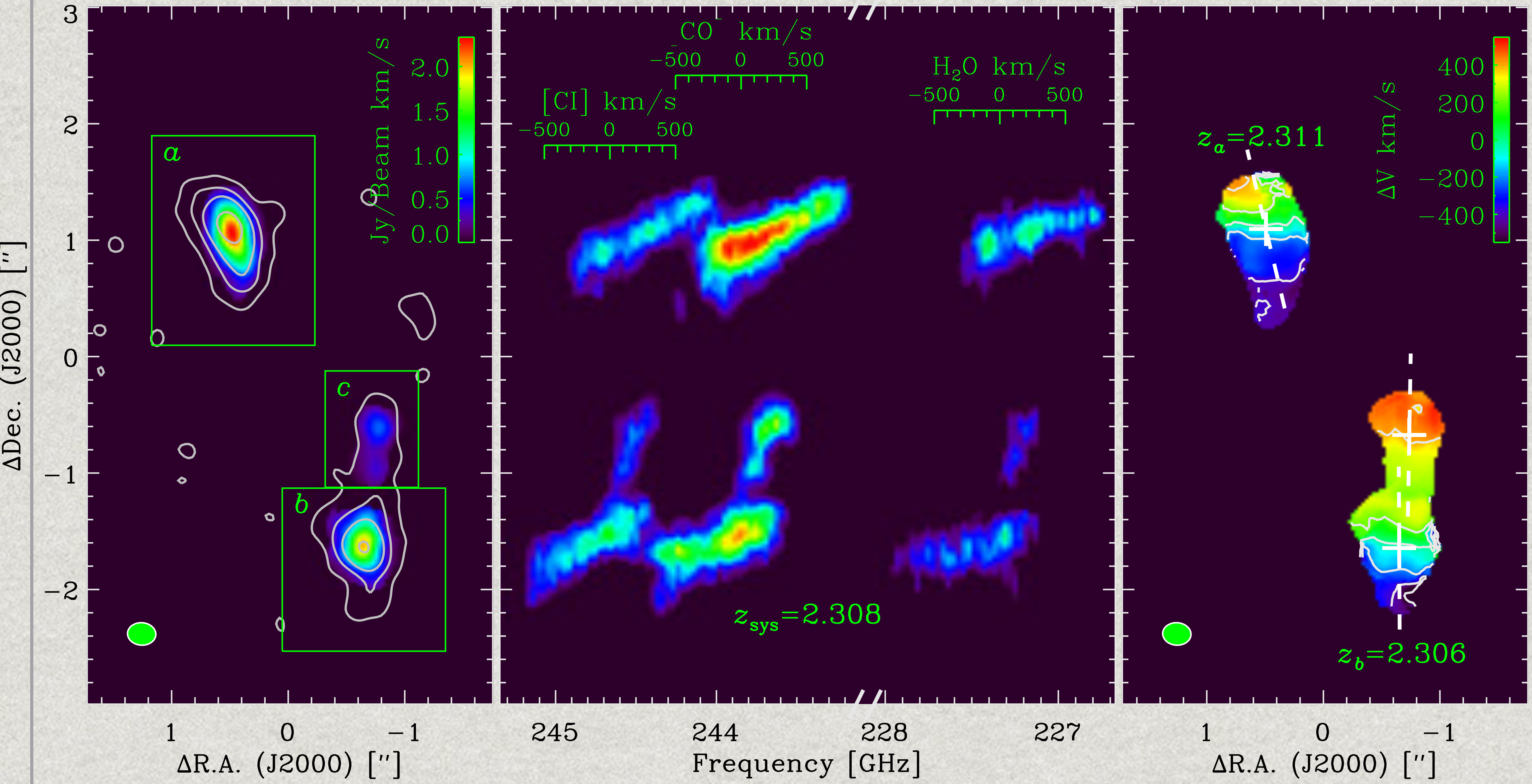
Fu, et al. 2013

SMG reproduced by cosmological zoom-in simulations (Narayanan+16)

Robert Thompson

Deep ALMA Observation of HXMM01

0.2" spatial resolution, 40 km/s spectral resolution, 240 GHz, 2.6 hr on-source

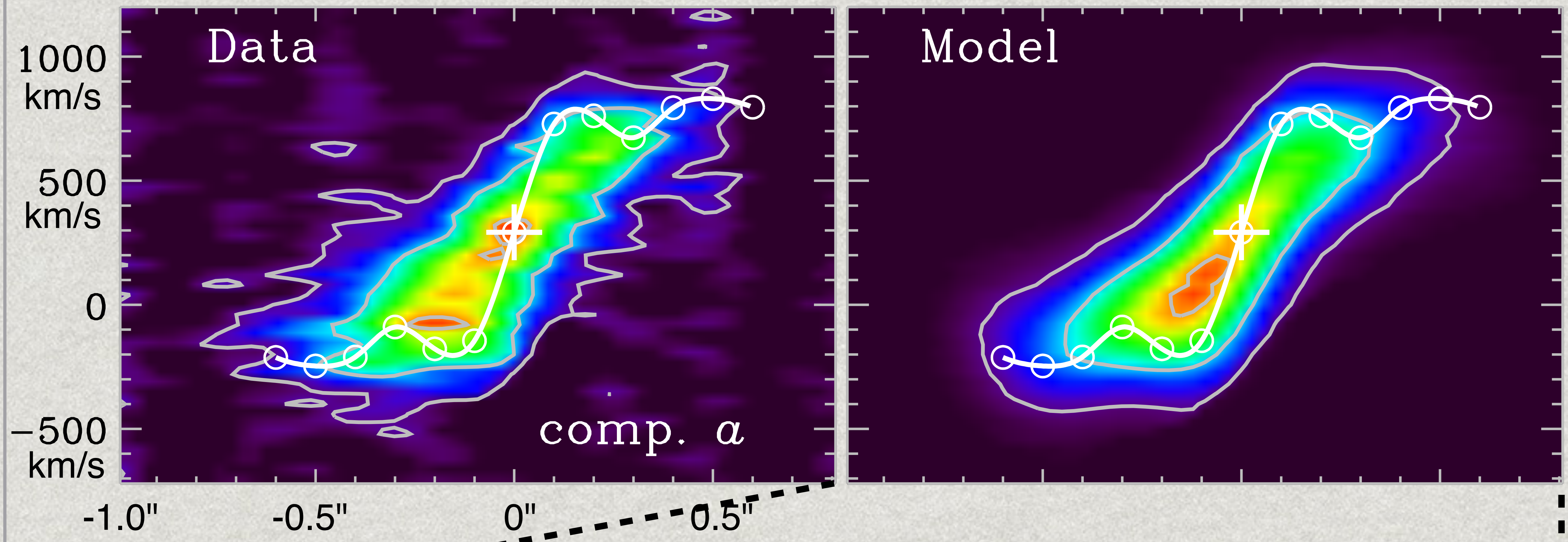


Xue, Fu, et al. 2018

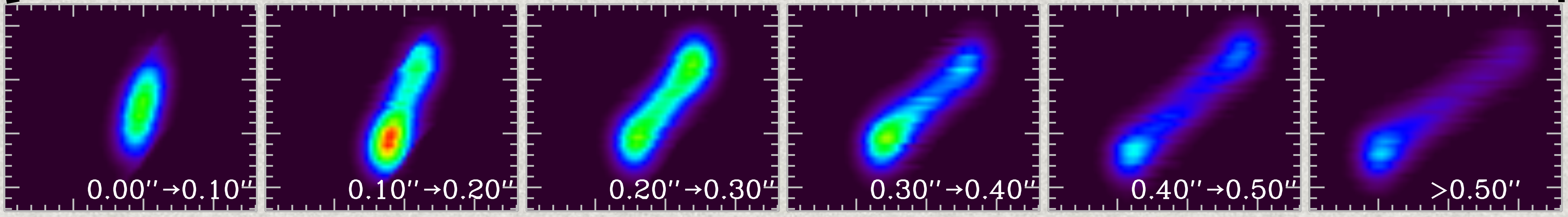
Tilted-Ring Modeling of Gas Kinematics

CO *J*=7-6 Position Velocity Diagram

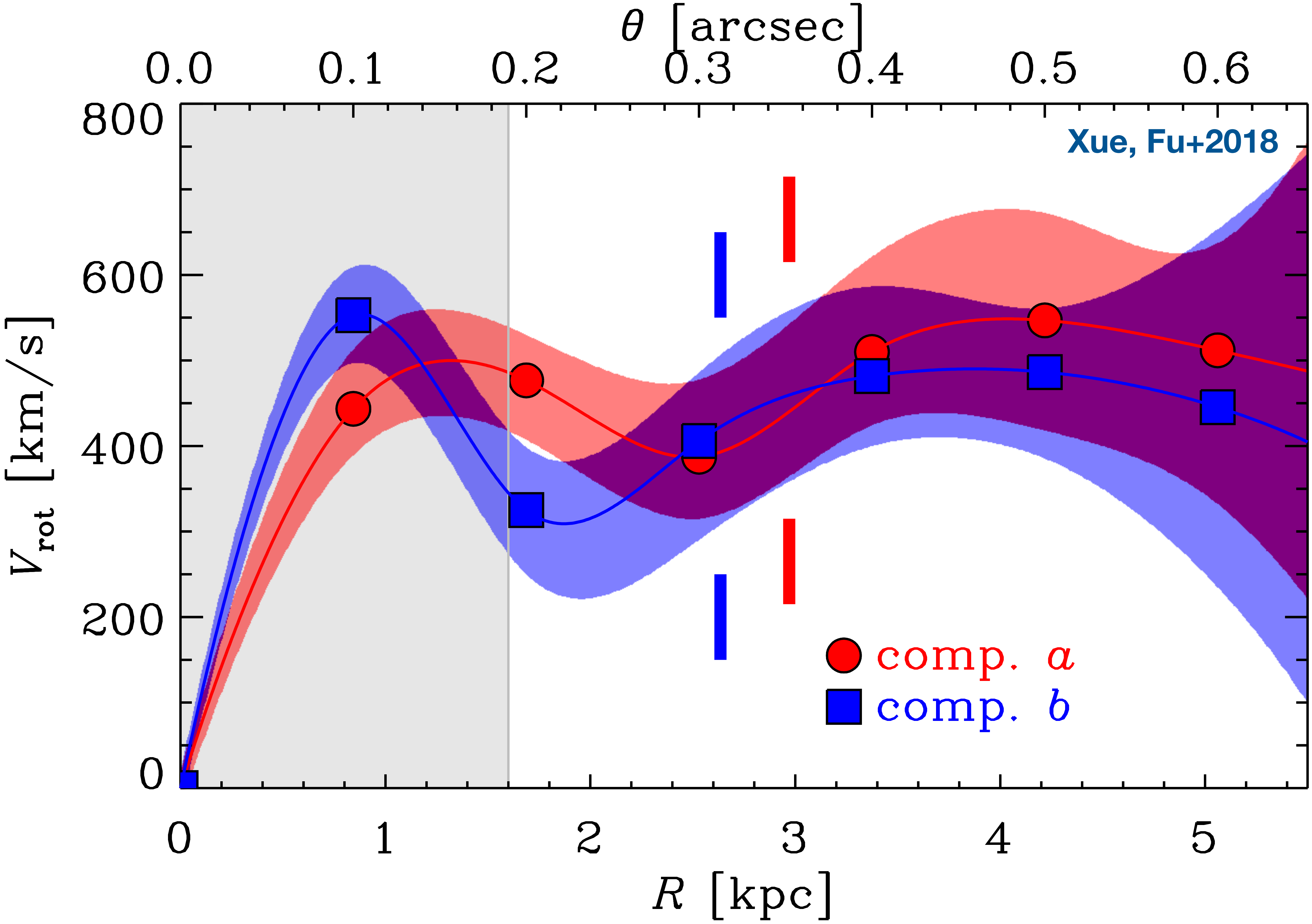
Xue, Fu+2018



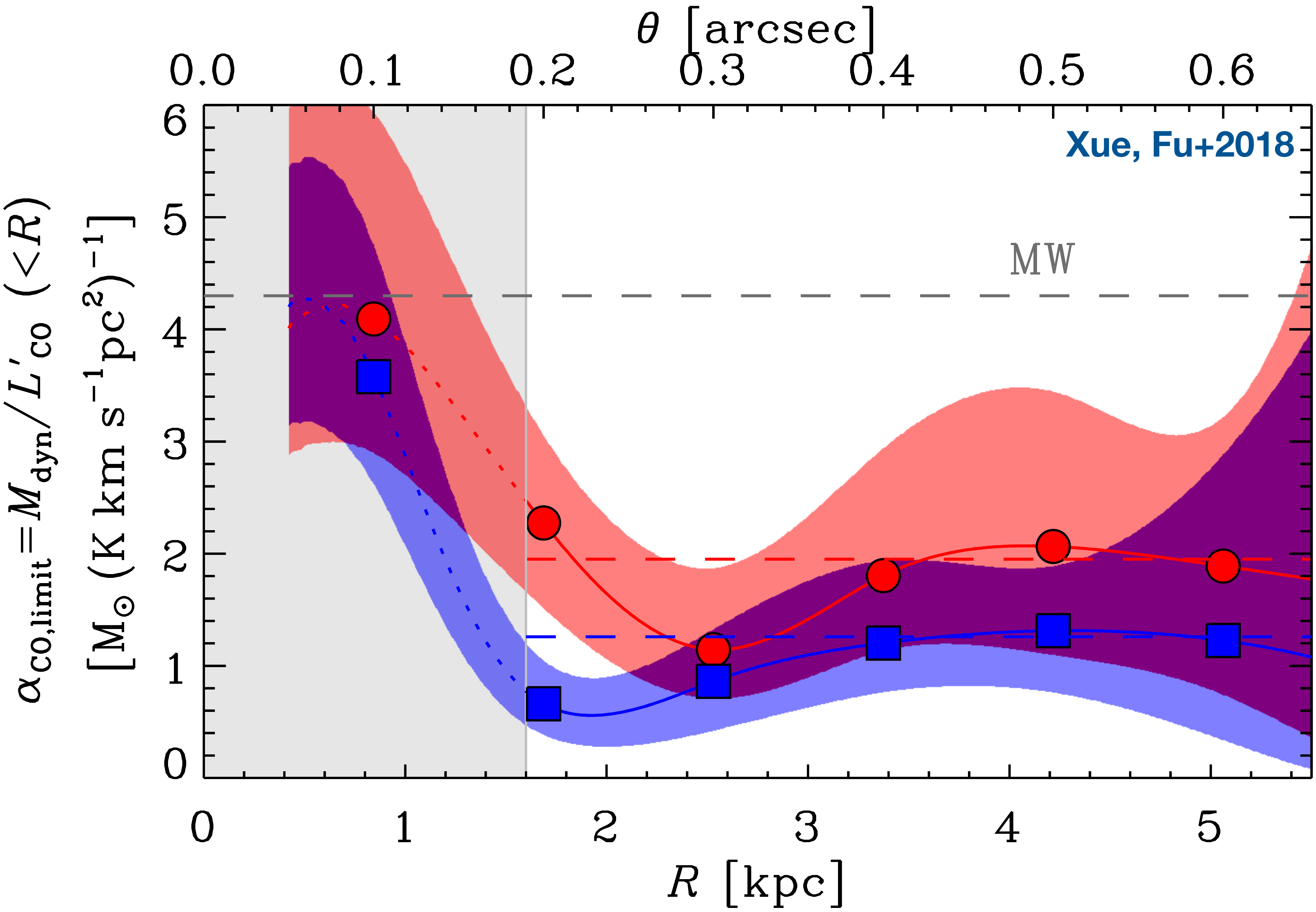
Position Velocity Diagram of Contributing Rings

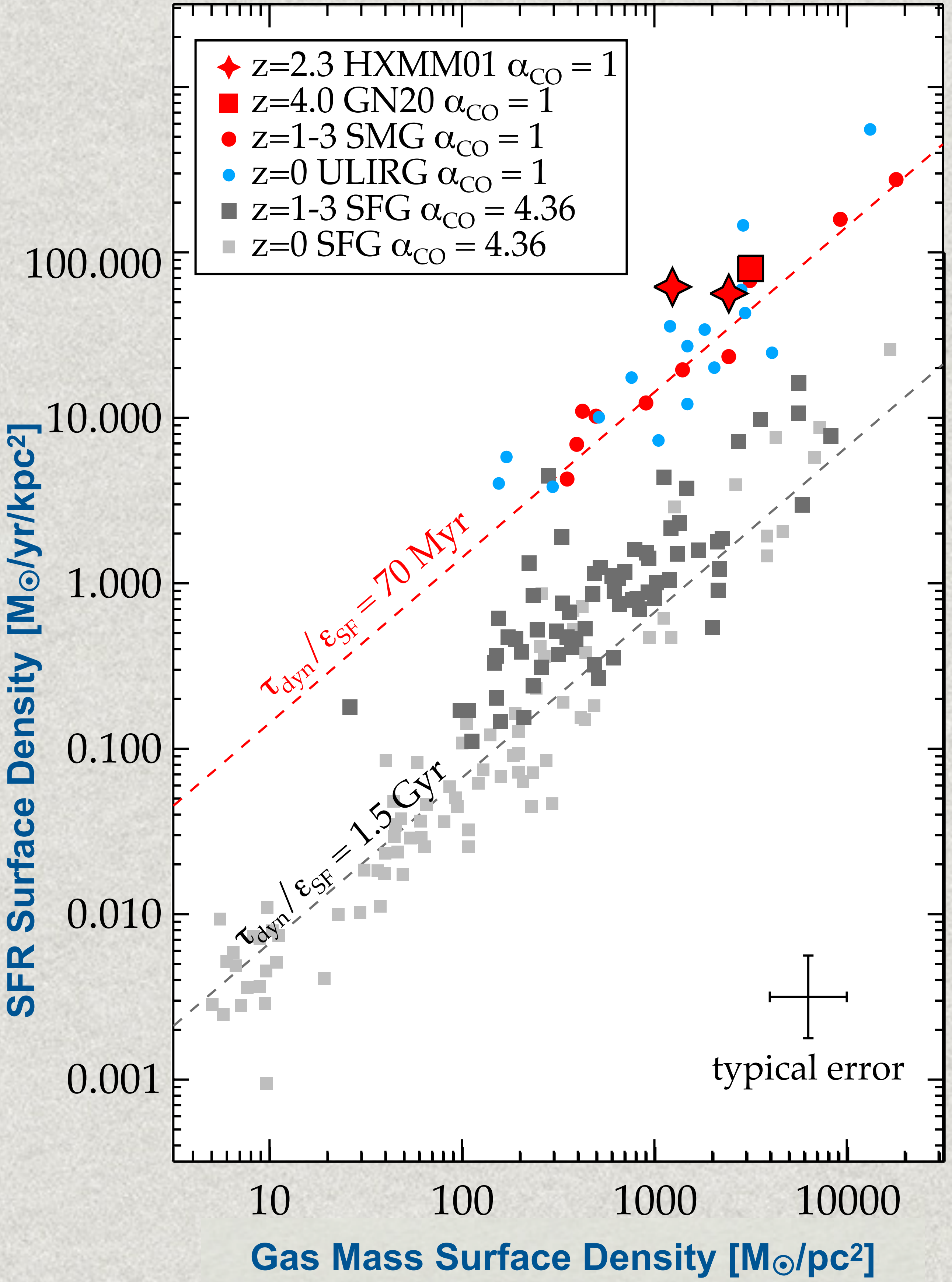


Flat Rotation Curves @ z = 2.3



Dynamical upper limits on the CO-H_2 conversion factor





Kennicutt-Schmidt Relation

- Stars form because of gravitational collapse of gas clouds, therefore:

  $$\Sigma_{SFR} = \epsilon_{SF}/t_{SF}\ \Sigma_{gas}$$

  or:

  $$SFR = \epsilon_{SF}/t_{SF}\ M_{gas}$$

- The data on the left show for normal SFGs:

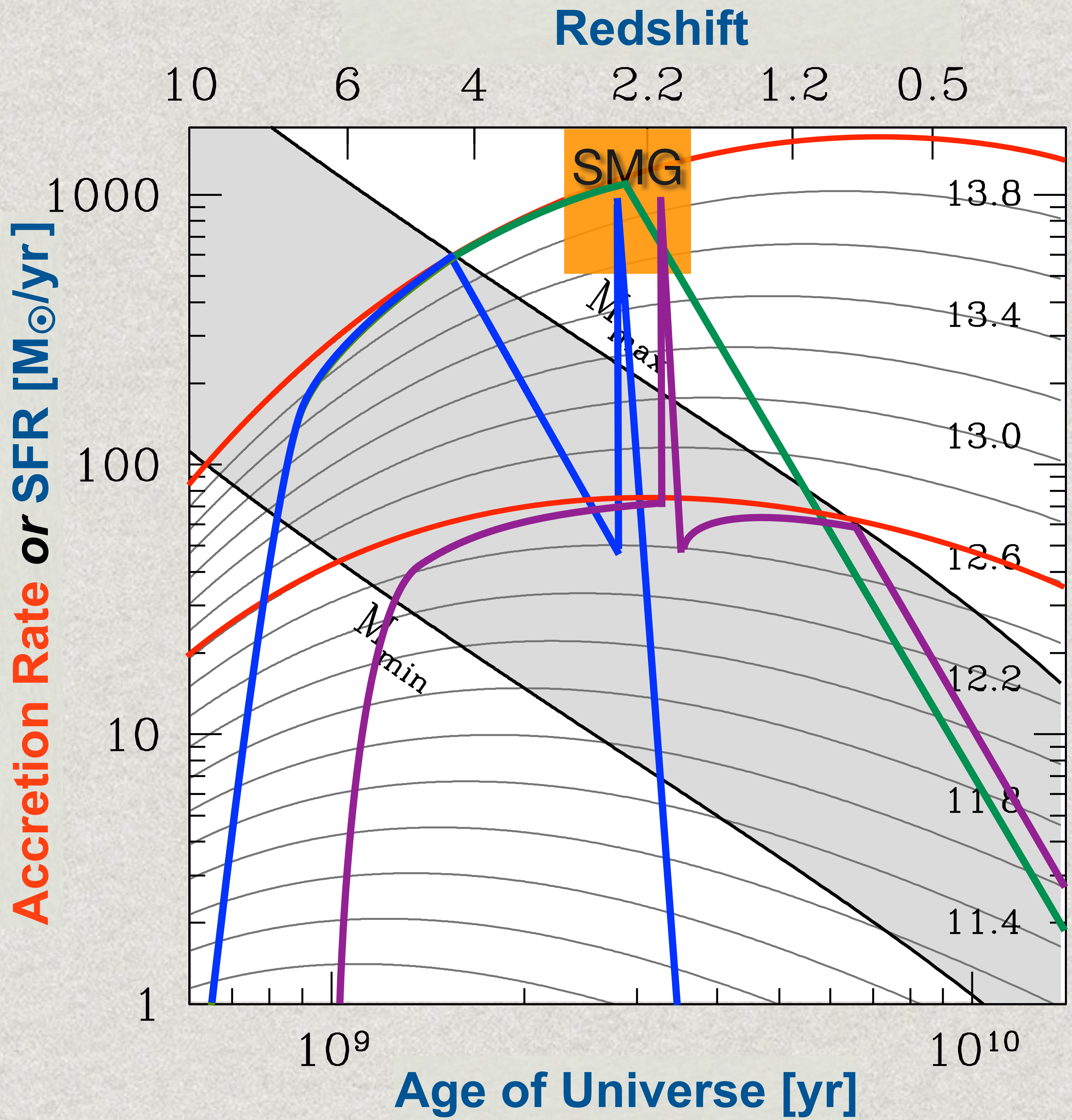
  $$t_{SF}/\epsilon_{SF} \sim 1.5\ \text{Gyr}$$

  for starbursts:

  $$t_{SF}/\epsilon_{SF} \sim 0.1\ \text{Gyr}$$

Fu+13, Daddi+09, Genzel+10, Hodge+12

Solutions to the “SMG” Problem



✘: Efficient cold gas accretion continues in **10^{13}** $M_\odot$ halos.

disagrees w/ hydro-dynamical simulations and over-produce massive galaxies and SMGs

✓: Burst: Star formation efficiency increases 10x in **10^{13}** $M_\odot$ halos.

most likely

✘: Burst: Star formation efficiency increases 10x in **10^{12}** $M_\odot$ halos

disagrees w/ clustering results

Starburst as a Universal Phase in Massive Galaxy Evolution

- Suppose SMGs live in dark matter halos with $12.5 < \log(M_{halo}/M_\odot) < 13.5$ and $2 < z < 3$, the space density of such halos is 1.1×10^{-4} Mpc^{-3}
- Average lifetime of the SMG phase is ~200 Myr (the gas exhausting timescale, 2 M_{gas}/SFR)
- Universe aged by 1.2 Gyr between $2 < z < 3$
- So if every such halo goes through an SMG phase, the expected space density of SMGs is:

  1.8×10^{-5} Mpc^{-3} = $1.1 \times 10^{-4} \times (200/1{,}200)$

  agreeing with the observed space density of SMGs:

  2×10^{-5} Mpc^{-3} at $2 < z < 3$

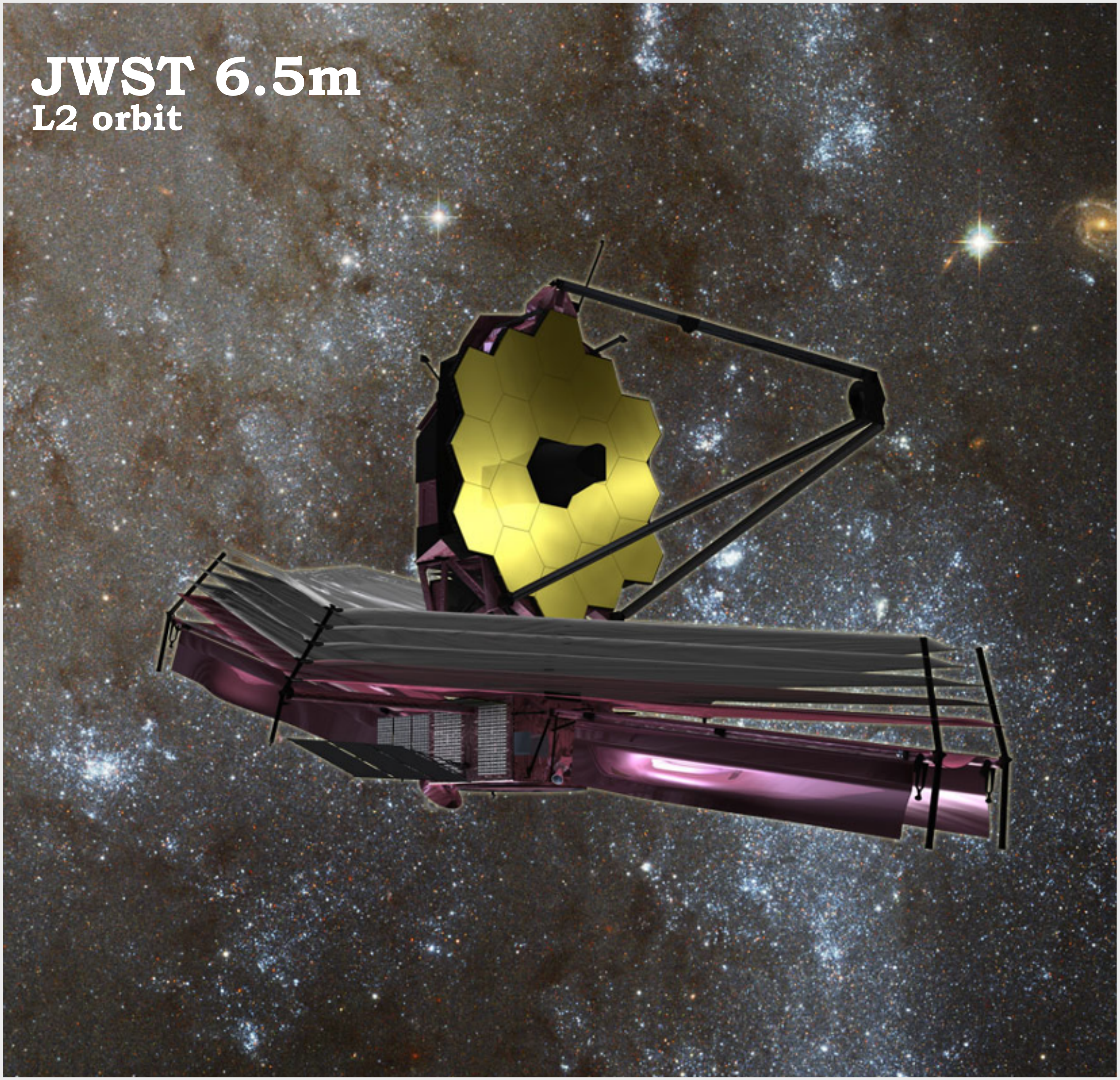
Summary

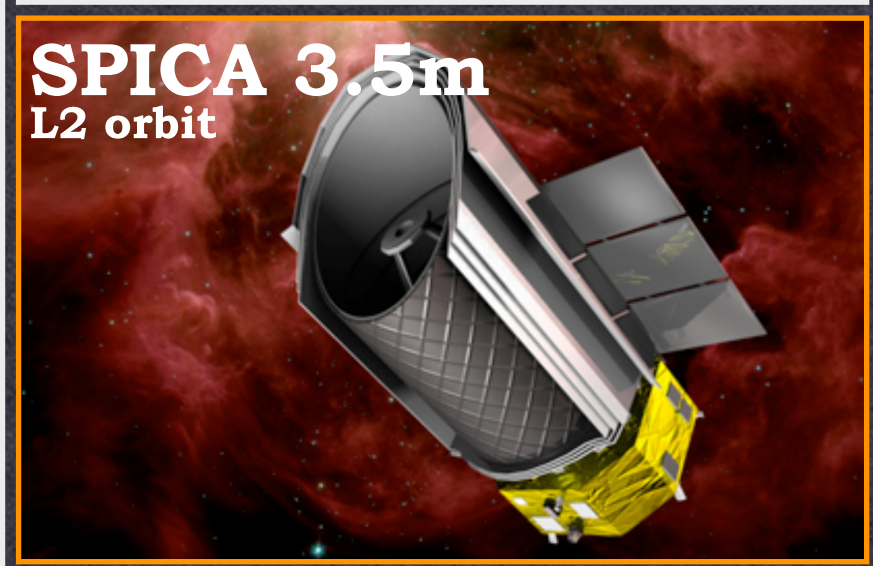
- SMGs have ~10x higher SF efficiency than normal galaxies, i.e., they are massive starbursts
- Starbursts can stop star formation by rapidly exhausting the gas reservoir, providing a quenching mechanism to turn blue starforming galaxies into red passive galaxies.
- Starbursts are a universal phase in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

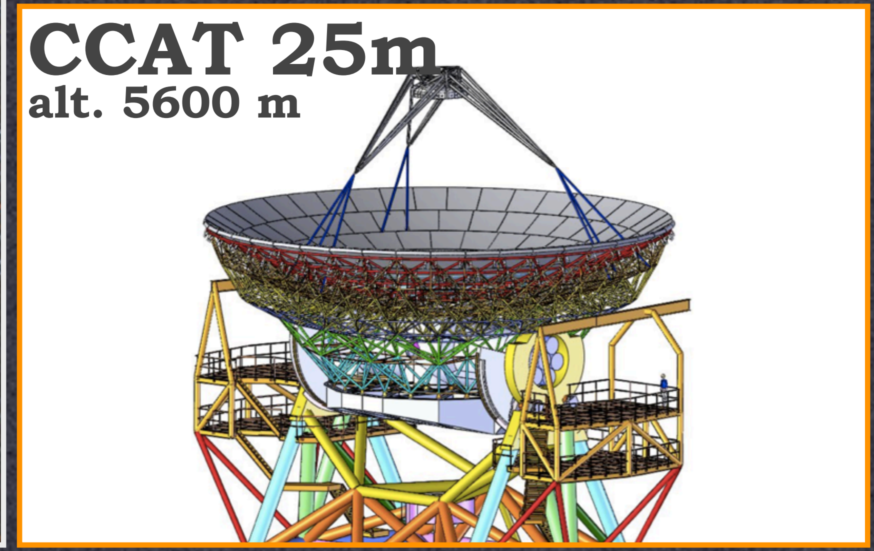
▸ *What triggers the high star formation efficiency? Why every massive galaxy goes through a burst phase?*

How do we solve the remaining problems?

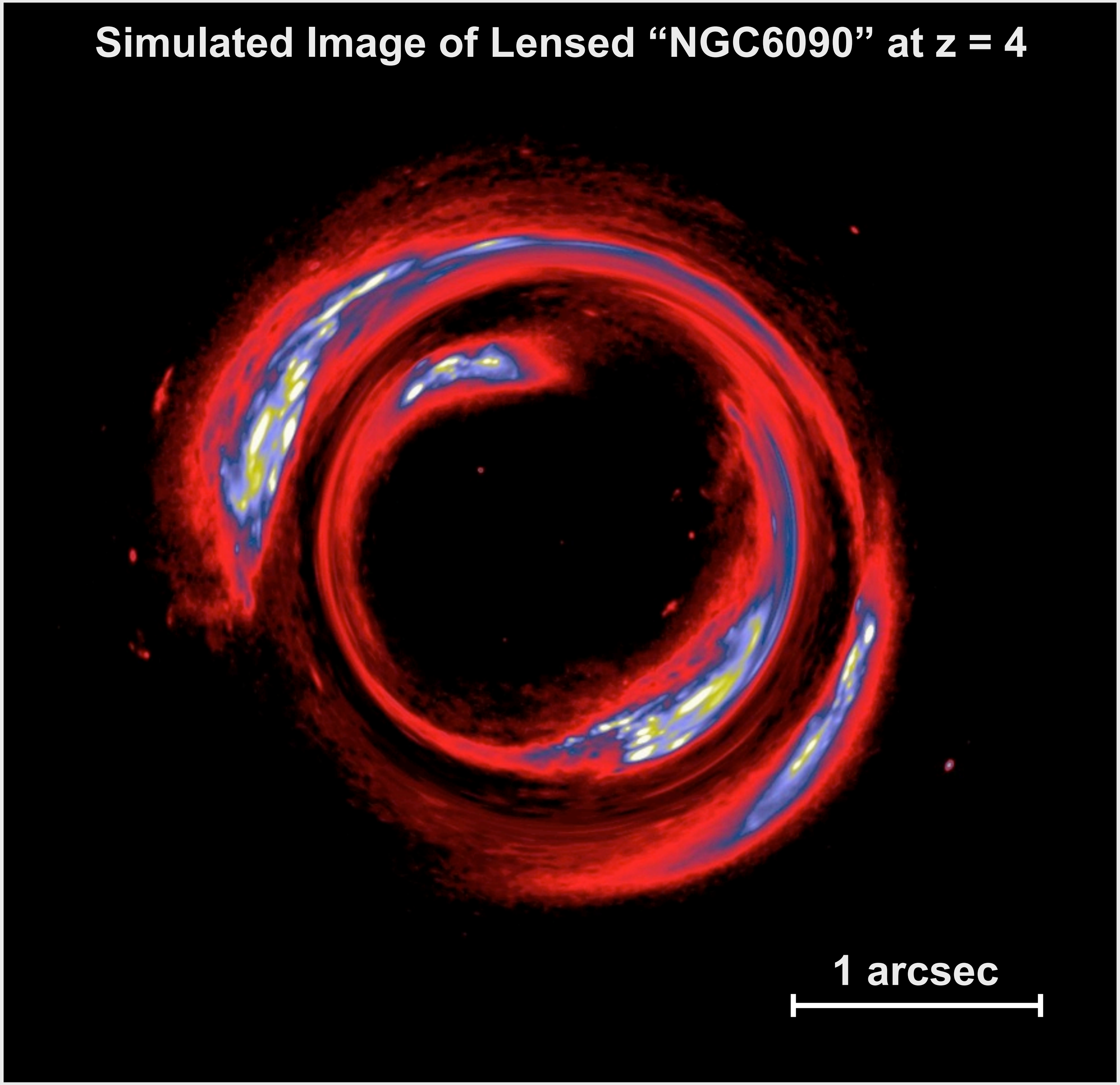
Better and more observations :)

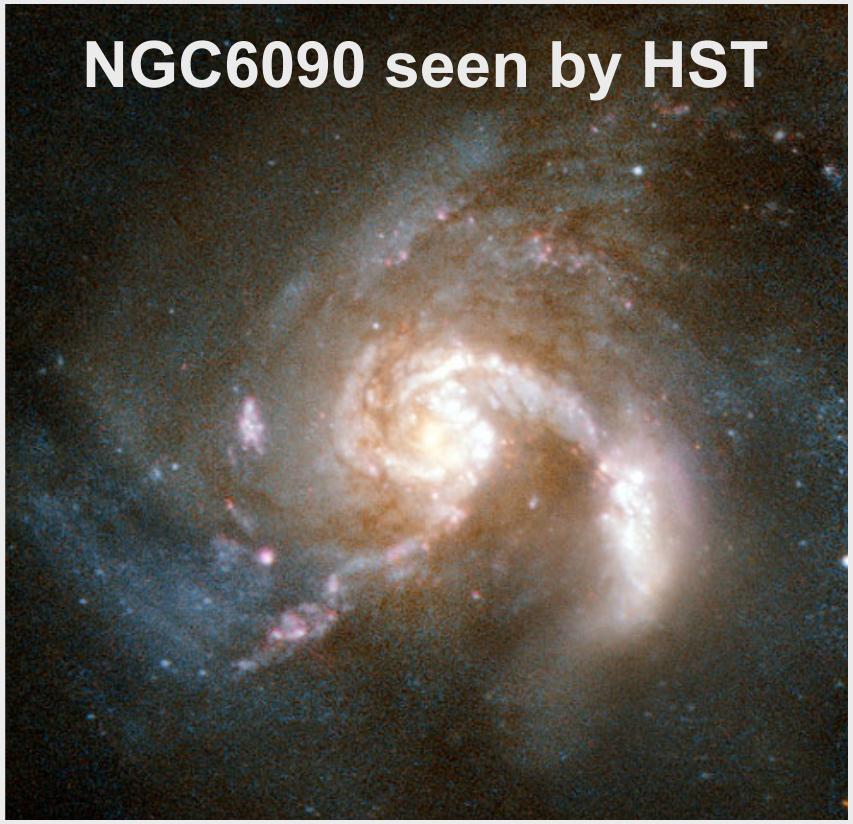






Future IR/Submm Telescopes





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

Power of Lensing + JWST/TMT

Take-Home Messages

- Massive starbursts are critical for our understanding of galaxy evolution: they likely represent a transitional phase between blue star-forming galaxies and red dead galaxies
- Herschel and existing facilities have revolutionized this field, and its legacy will be carried on by ALMA and future observatories like the JWST.
- In the next decade, observations will address the nature of starbursts by resolving star-forming regions and tracing gas accretion through the cosmic web (in both absorption and emission)