Star formation in Low Metallicity Gas

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Motivation

- How does star formation proceed in low-metallicity gas where H_2 is rare?
- Deviations from solar K-S relation
  - Theoretical: Pelupessy+ 2006; Robertson & Kravtsov, 2008; Gnedin & Kravtsov, 2010
  - Observational: Bigiel+ 2010, Bolatto+ 2011
- Potentially reduces of star formation in dwarfs
  - Krumholz & Dekel, 2012; Kuhlen+ 2012; Kuhlen+ 2013; Thompson+ 2013

Gasoline (Wadsley, et al., 2003)

- SPH code with
  - Cosmic UV background radiation
  - H & He ionization
  - Metal line cooling (Shen+ 2010)
  - Metal diffusion
  - Supernovae feedback (blastwave) (Stinson+ 2006)
  - **Non-equillibrium Molecular Hydrogen** (Christensen+ 2012)
  - **Molecular Hydrogen-based star formation** (Christensen+ 2012)

- Which reproduces
  - Damped Lyman-α systems (Pontzen et al., 2008, 2010)
  - Mass-metallicity relation (Brooks et al., 2007)
  - Broken exponential disks in spirals (Roskar et al., 2008)
  - Tully-Fisher relation (Governato et al., 2007)
  - Realistic rotation curves in dwarfs (Governato et al., 2010)
  - Reduced bulge mass in spiral galaxies (Guedes et al., 2011)
  - Change the angular momentum distribution (Brook et al., 2011, Pontzen et al., 2011)
  - …

Implementing Molecular Hydrogen

Formation

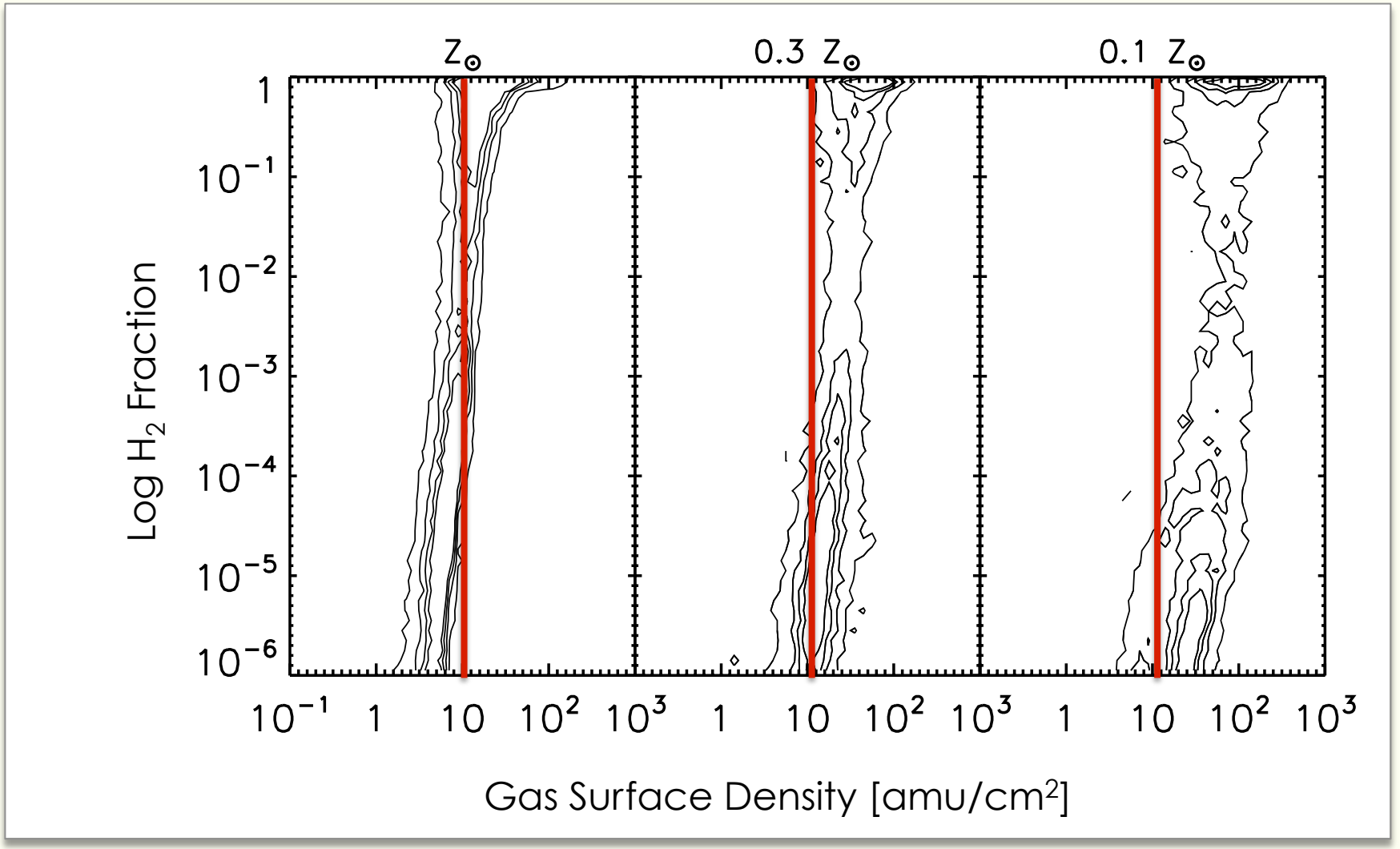
- Forms primarily on dust (metals) (Wolfire et al., 2008)
  - *Metallicity*
  - *Density*
  - Gas *clumpiness* (McKee & Ostriker et al., 2007)
- Also forms in gas-phase through H^- (Abel+ 97)

Based on the work of Gnedin & Kratsov, 2009

Destruction

- Destroyed primarily by LW radiation
  - *Flux* from local young stars
- Self-shielding and shielding by dust (Draine & Bertoldi, 1996)
  - *Surface density* (column length x density)
  - *Metallicity*
  - *(Dust shielding applied to HI)*
- Also destroyed through collisions

HI–H_2 Transition



Christensen et al., 2012

Implementing Molecular Hydrogen

Formation

- Forms on dust (metals) (Wolfire et al., 2008)
  - ***Metallicity***
  - ***Density***
  - Gas *clumpiness* (McKee & Ostriker et al., 2007)

Destruction

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  - ***Metallicity***
  - *(Dust shielding applied to HI)*

Star Formation Recipe

- Probabilistic, based on local gas properties

$$p \propto 1 - e^{-c^* \Delta t / t_{dyn}}$$

  - Formation time: $t_{dyn} \propto \rho^{-1/2}$
  - Efficiency: c^*
  - Threshold density allowed: ρ_{min}
  - Threshold temperature allowed: T_{max}

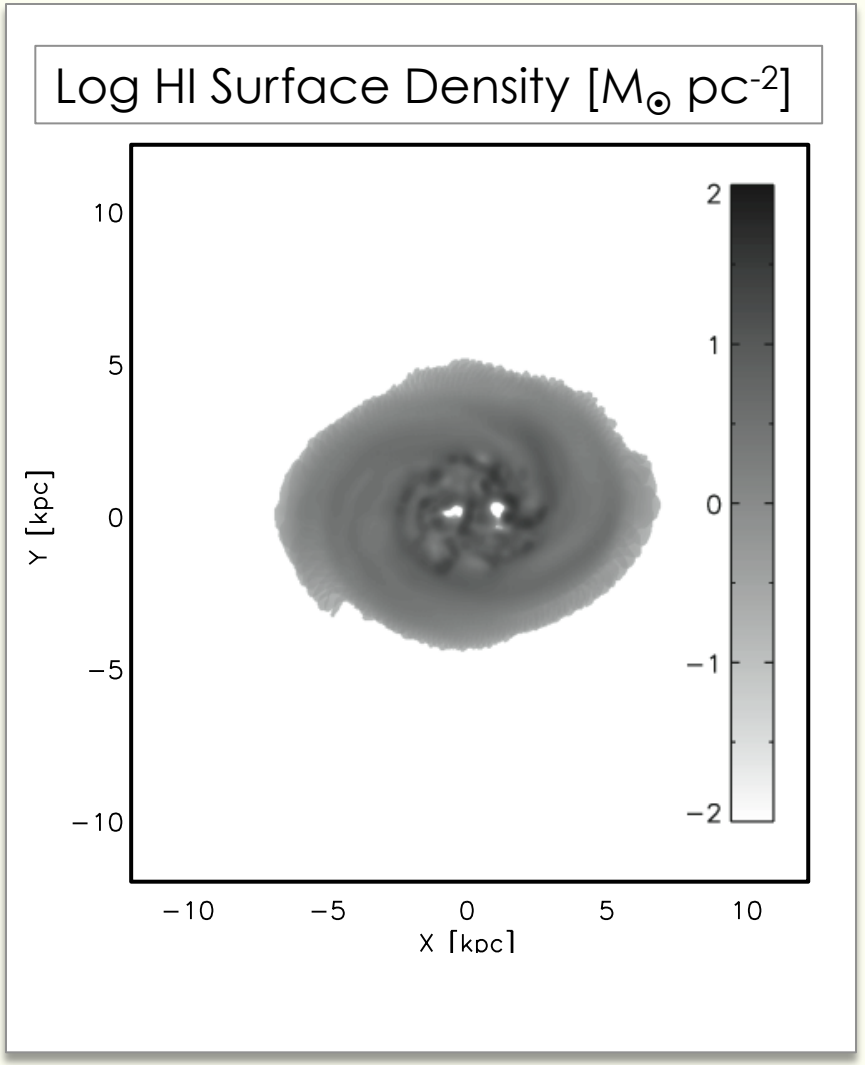
- No H_2–based SF
  - $c^* = 0.1$
  - $\rho_{min} = 100$ amu/cc
  - $T_{max} = 10000$ K
- H_2-based SF
  - $c^* = H_2/(HI + H_2)$ 0.1
  - $\rho_{min} = 0.1$ amu/cc
  - $T_{max} = 1000$ K

Dwarf Galaxy Zoom-in Simulation

- 25^3 Mpc^3 Box
- Resolution
  - DM (10^7): $m_p = 16{,}000 M_\odot$
  - Gas (6×10^6): $m_g = 3300 M_\odot$
  - Star: $m_s = 1000 M_\odot$
  - Force Resolution: 90 pc
- z = 0 properties
  - $M_{vir} = 3.8 \times 10^{10} M_\odot$
  - $V_{200} = 60$ km/s
  - log(O/H) + 12 = 7.8
  - $Mag_i = -16.4$
  - $g - i = 0.42$

Reproducing Kennicutt-Schmidt Relation

- HI
  - Mock THINGS observation
    (Walter et al., 2008)



Reproducing Kennicutt-Schmidt Relation

- HI
  - Mock THINGS observation
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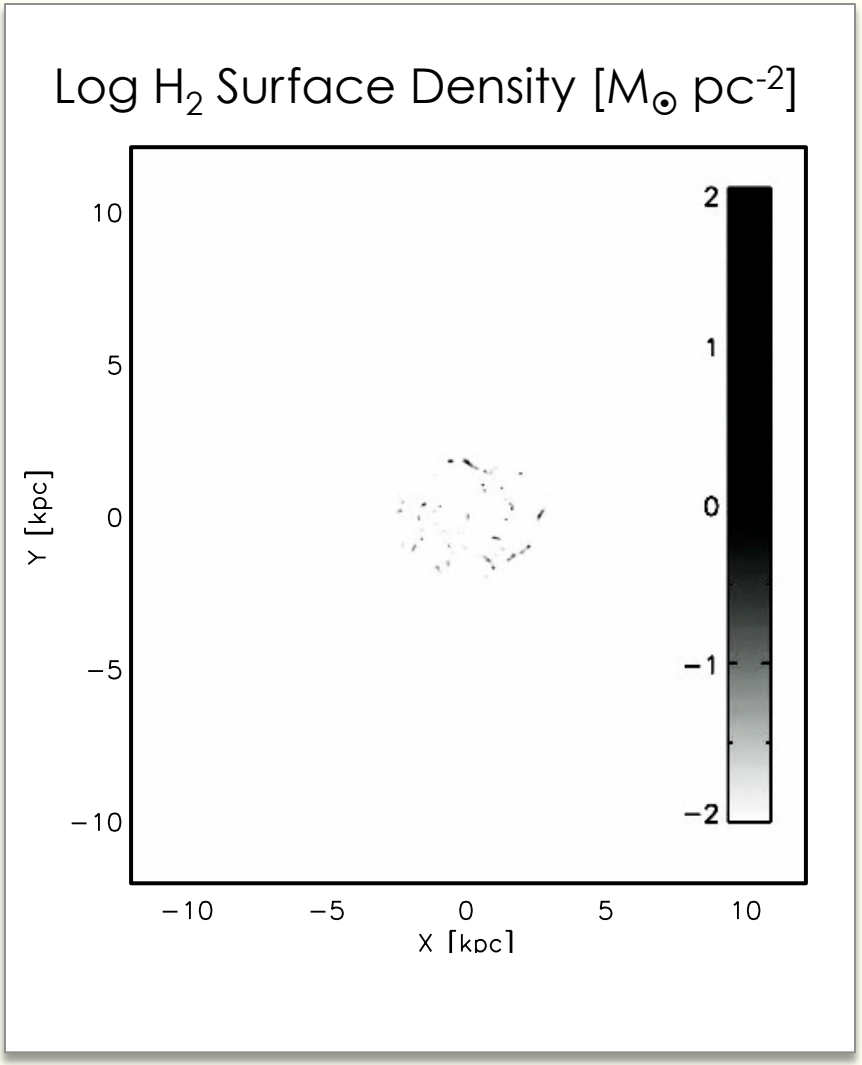
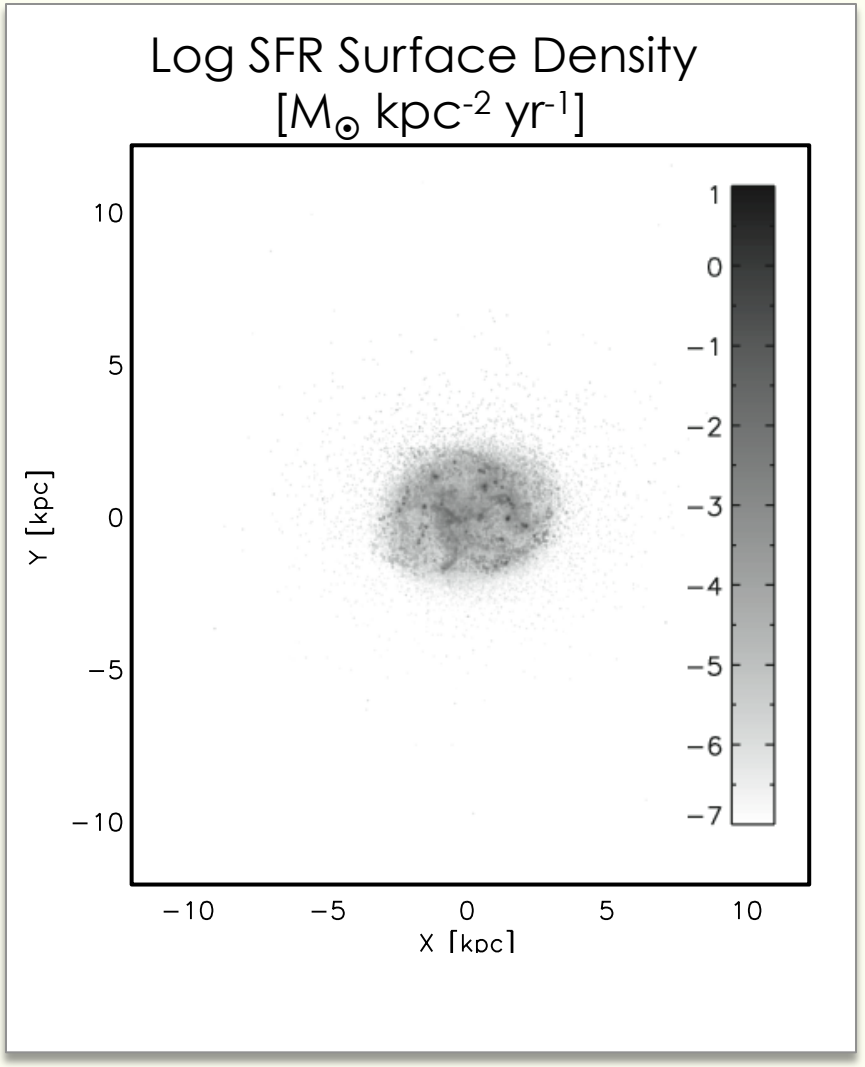
- H_2



Reproducing Kennicutt-Schmidt Relation

- HI
  - Mock THINGS observation
    (Walter et al., 2008)
- H_2
- SFR
  - Mock FUV and 24μm observations
    (Sunrise, Jonsson et al., 2006)



Reproducing Kennicutt-Schmidt Law

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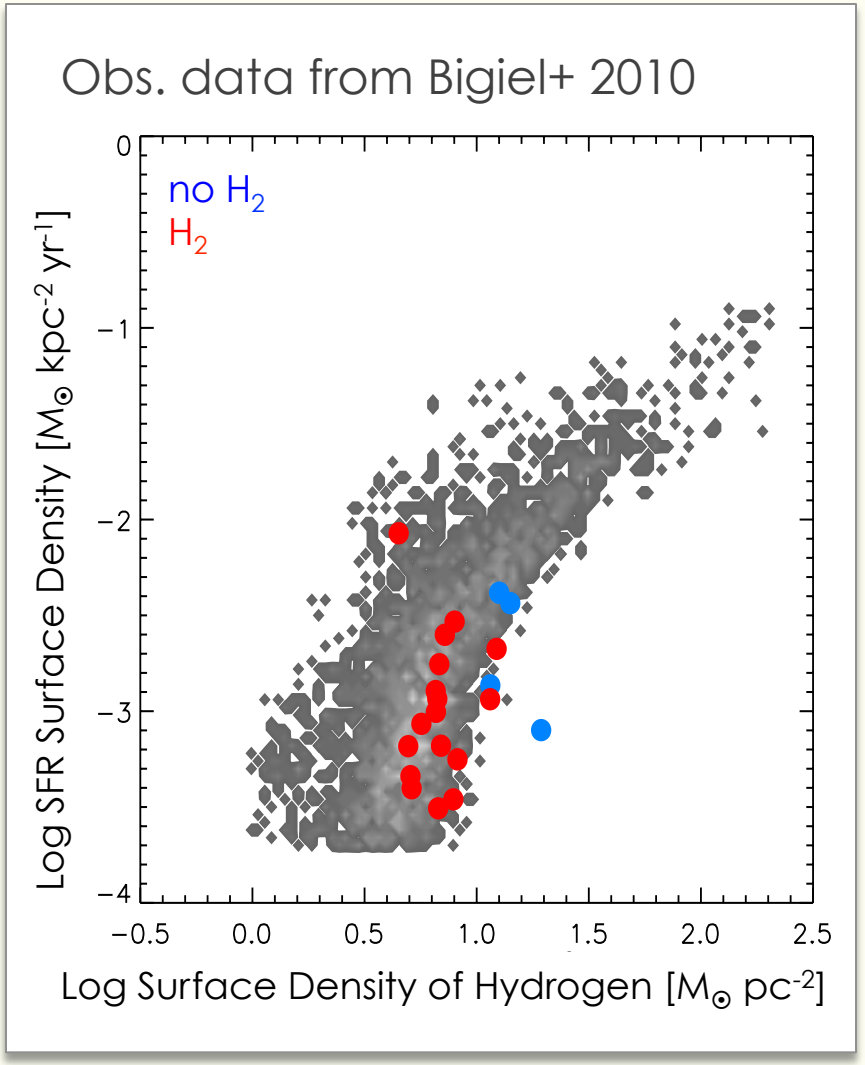
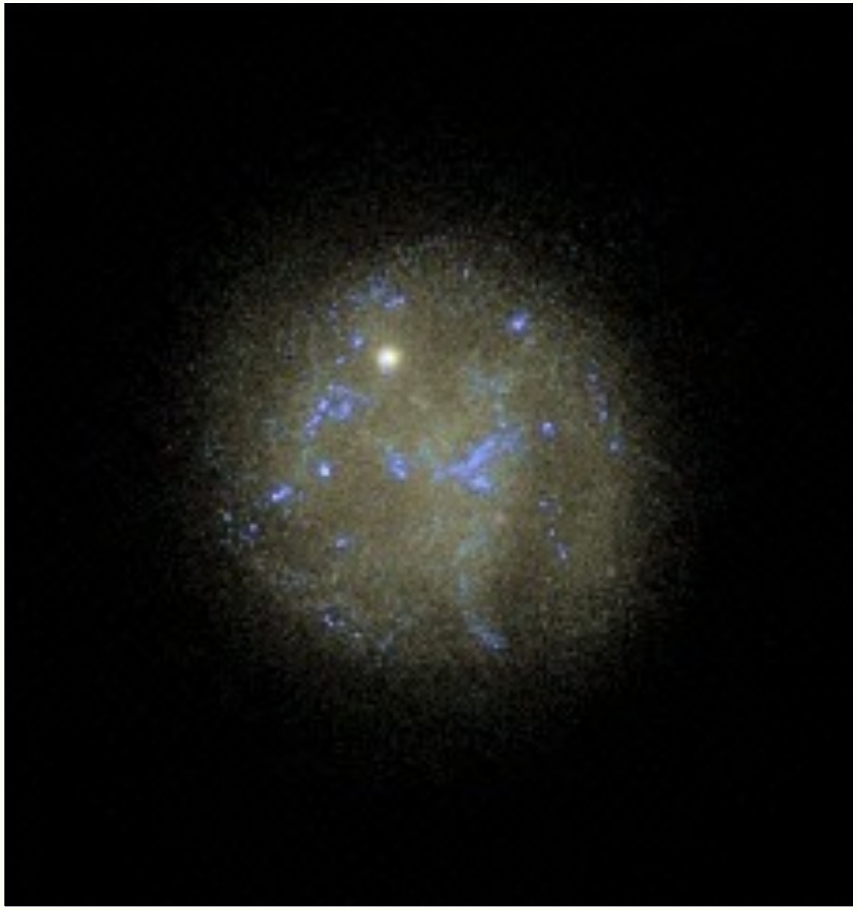


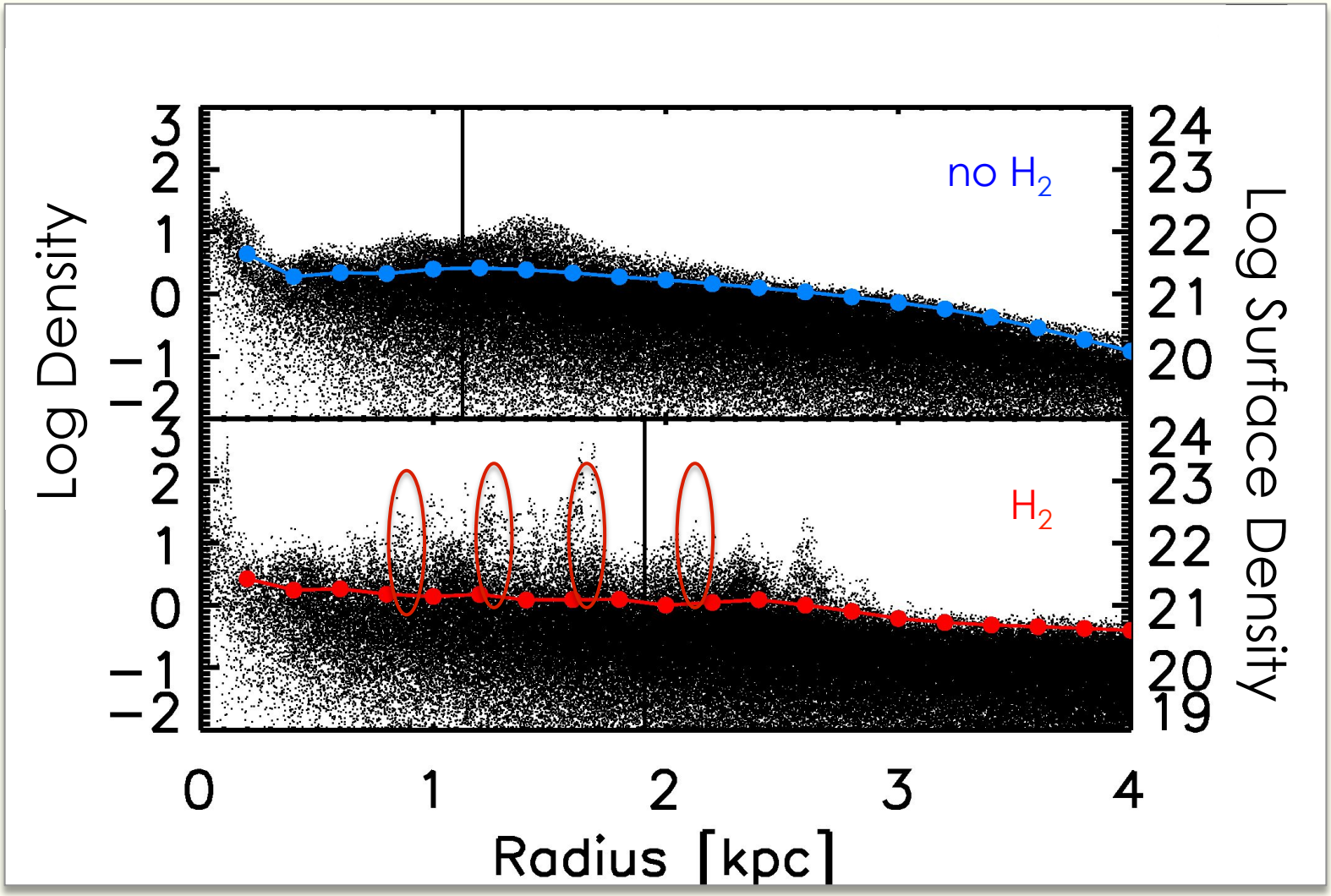
Christensen et al., 2012

Extended Star Formation with H_2

No H_2	H_2



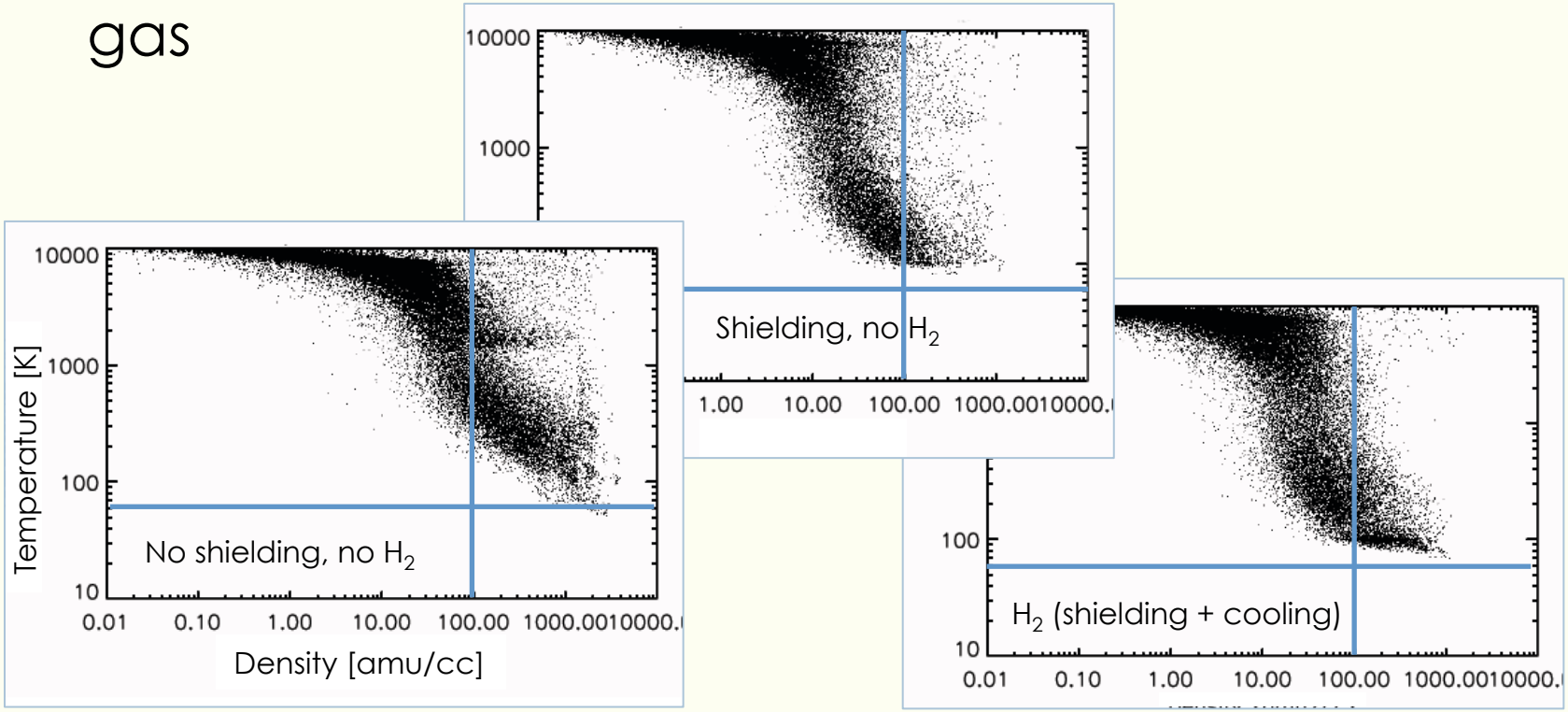
Clumpier Gas with H_2



Christensen et al., 2012

Shielding's Effect on Temperature

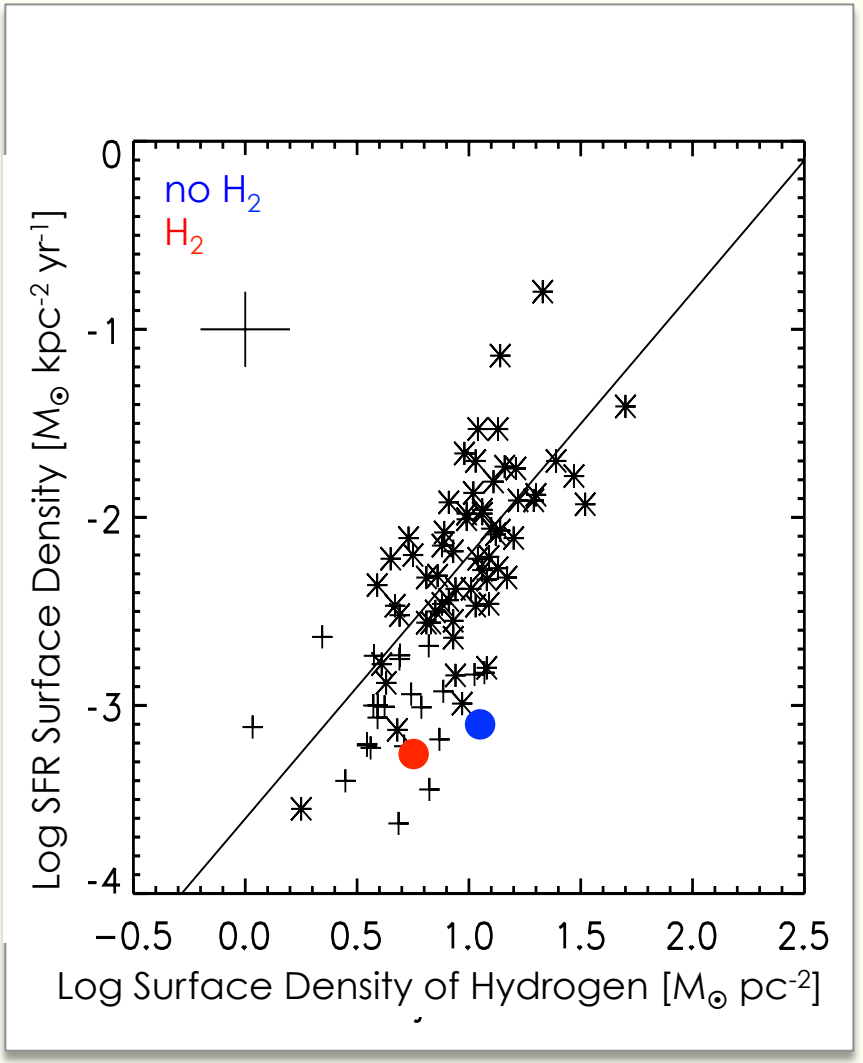
- Dust shielding of HI and H_2 reduces heating of dense gas from UV background/LW
- Results in the increased formation of cold, dense gas



See Glover & Clark, 2012

Reproducing Kennicutt-Schmidt Relation

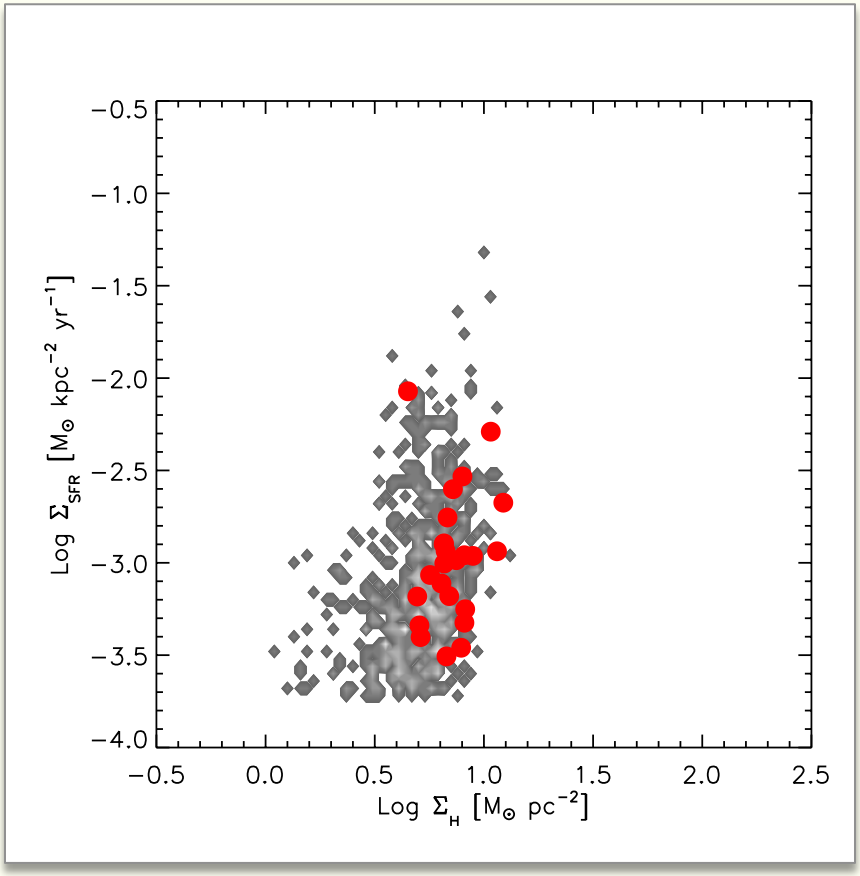
- HI
  - Mock THINGS observation
    (Walter et al., 2008)
- H_2
- SFR
  - Mock FUV and 24μm observations
    (Sunrise, Jonsson et al., 2006)



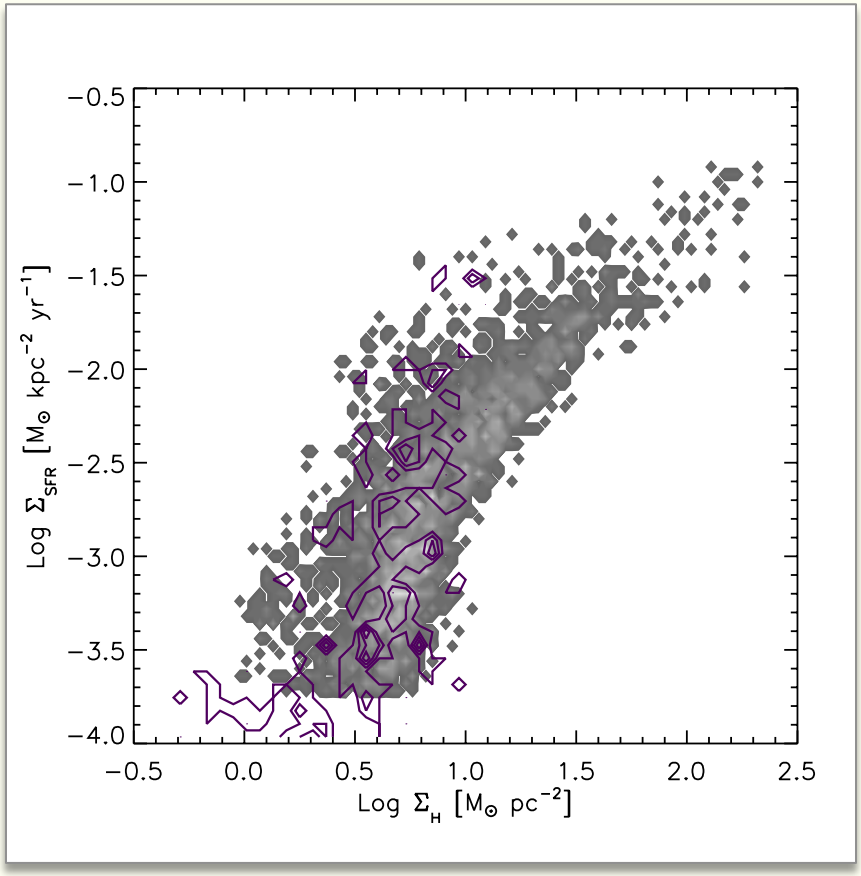
Christensen et al., 2012

Kennicutt–Schmidt Relation at Different Metallicities

Dwarf Galaxies: log(O/H) + 12 = 7.8

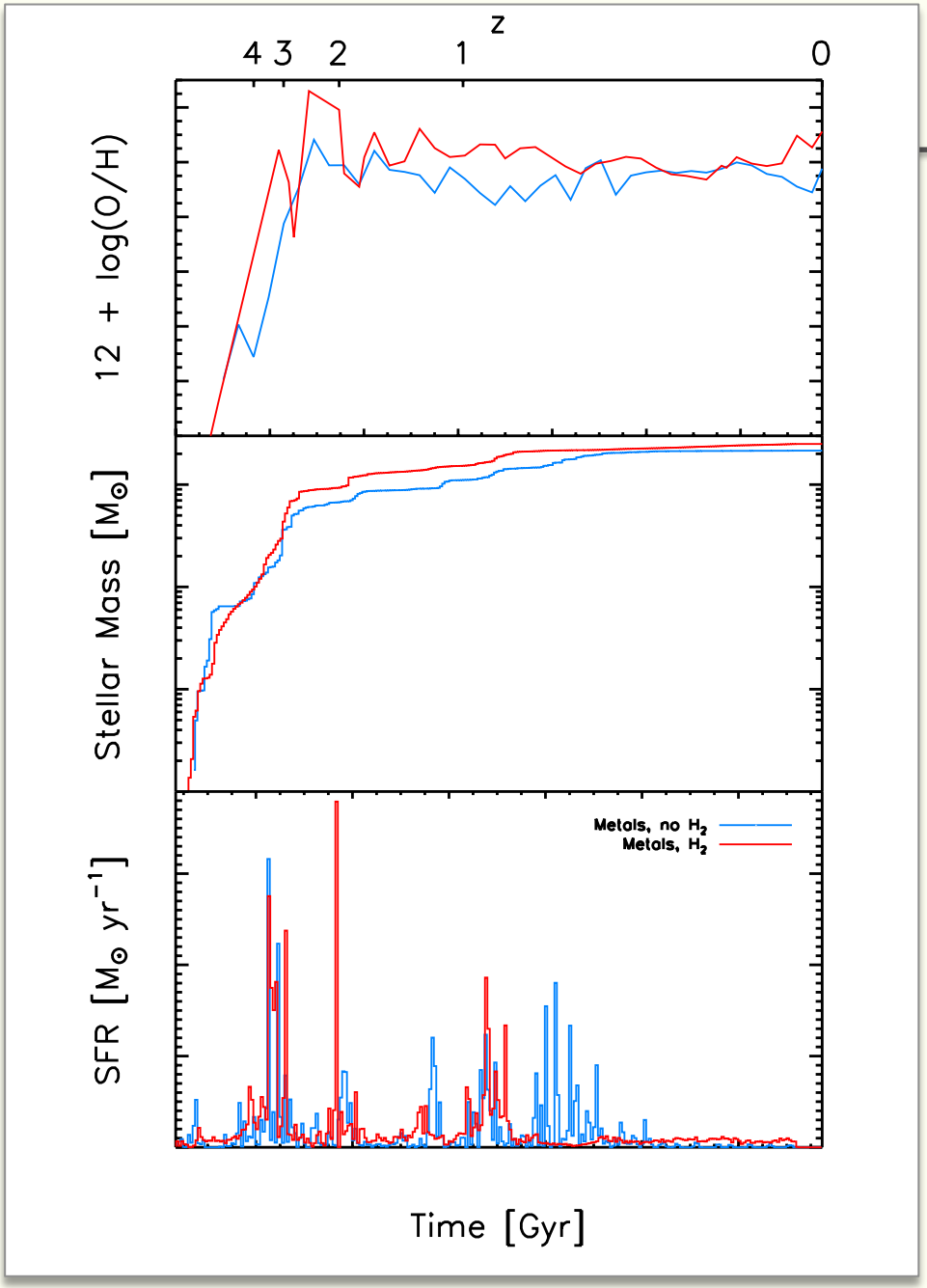


Spirial Galaxies: log(O/H) + 12 = 8.5



Obs. data from Bigiel+ 2010

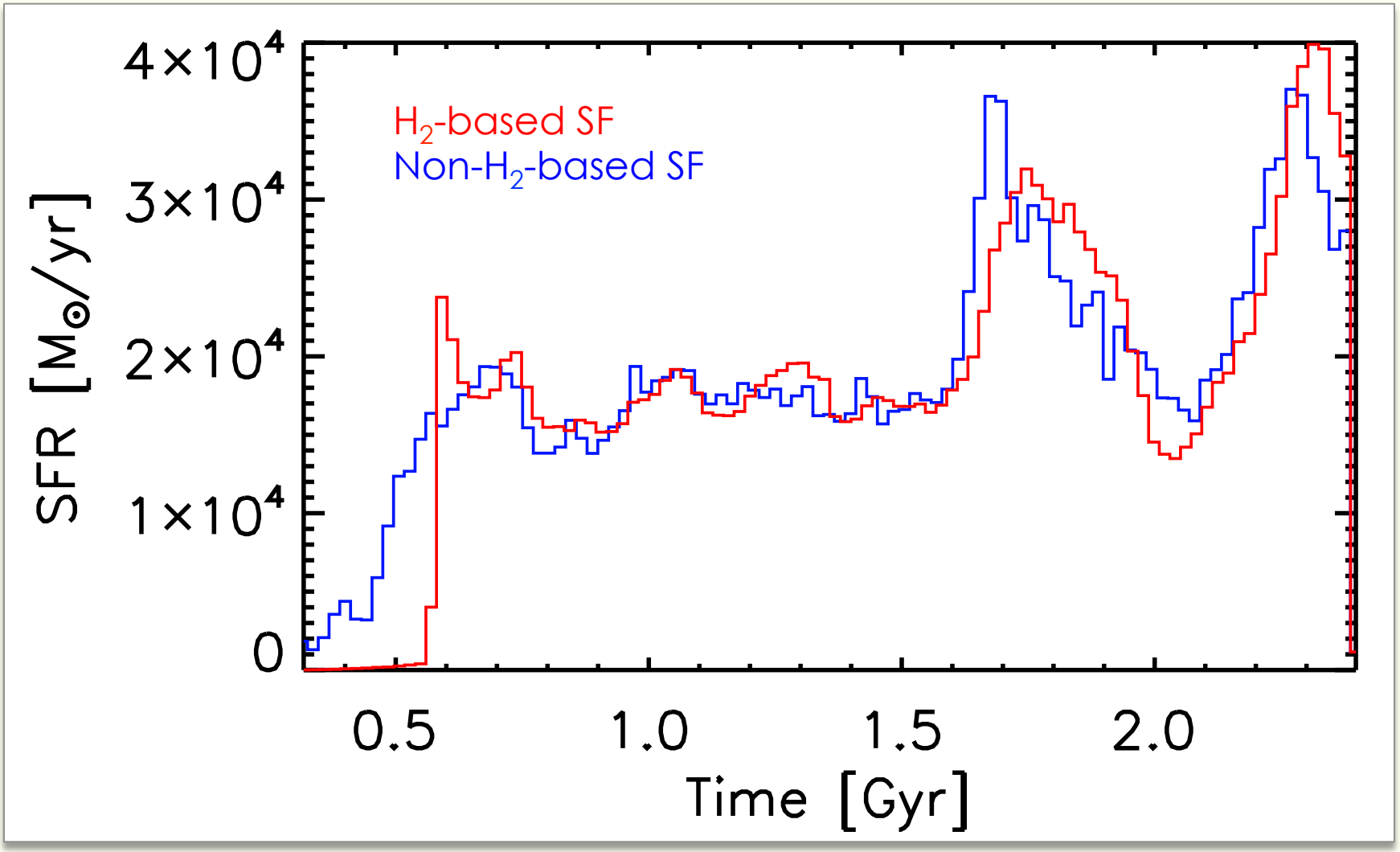
SFHs


z
4 3 2 1 0
12 + log(O/H)
Stellar Mass [M⊙]
SFR [M⊙ yr⁻¹]
Metals, no H2
Metals, H2
Time [Gyr]

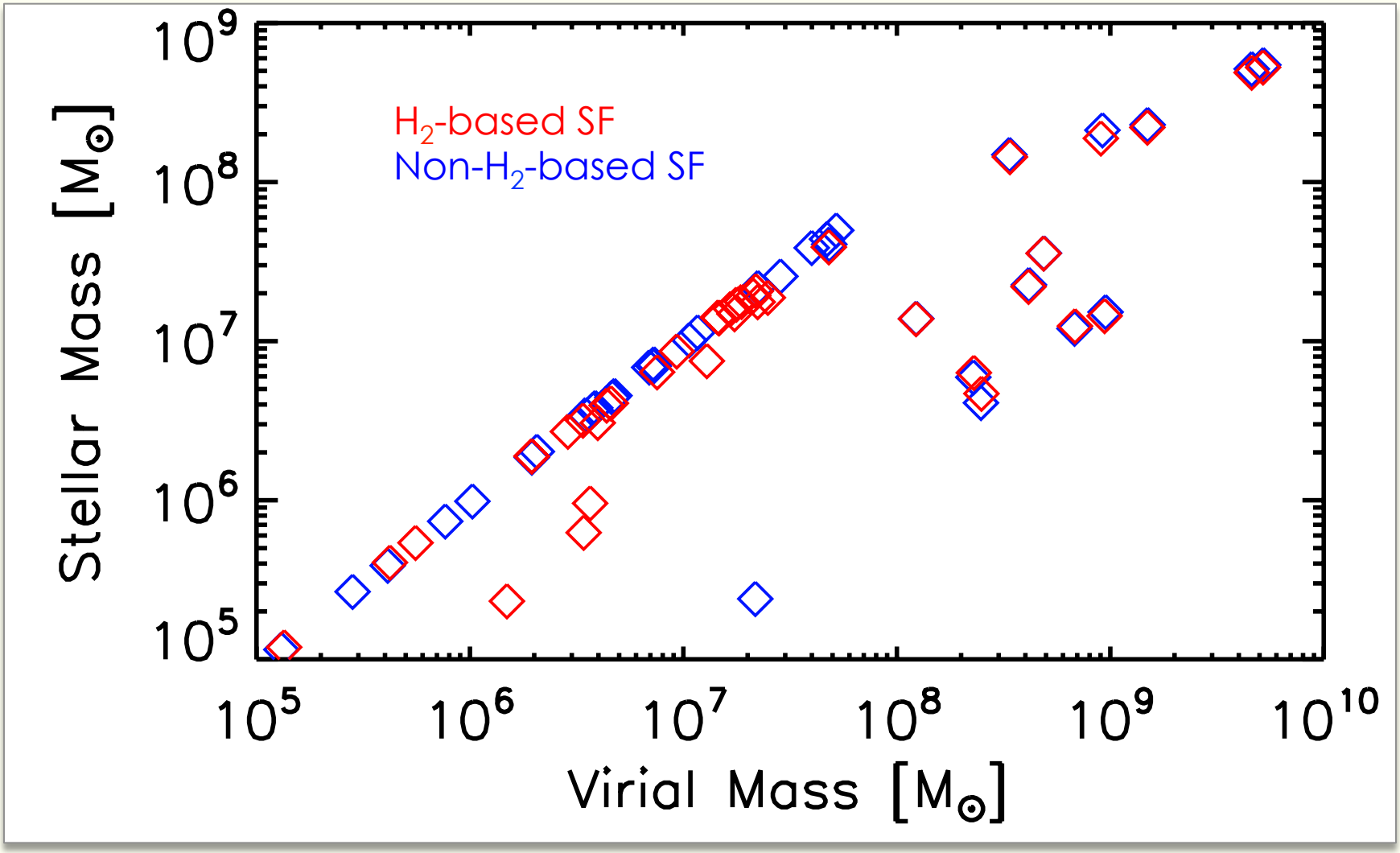
Comparing H_2 & non-H_2 SF

- Dwarf galaxy with H_2 and H_2-based star formation
  - ***No SN Feedback***
- Dwarf galaxy with H_2 and **non**-H_2-based star formation
  - ***No SN Feedback***

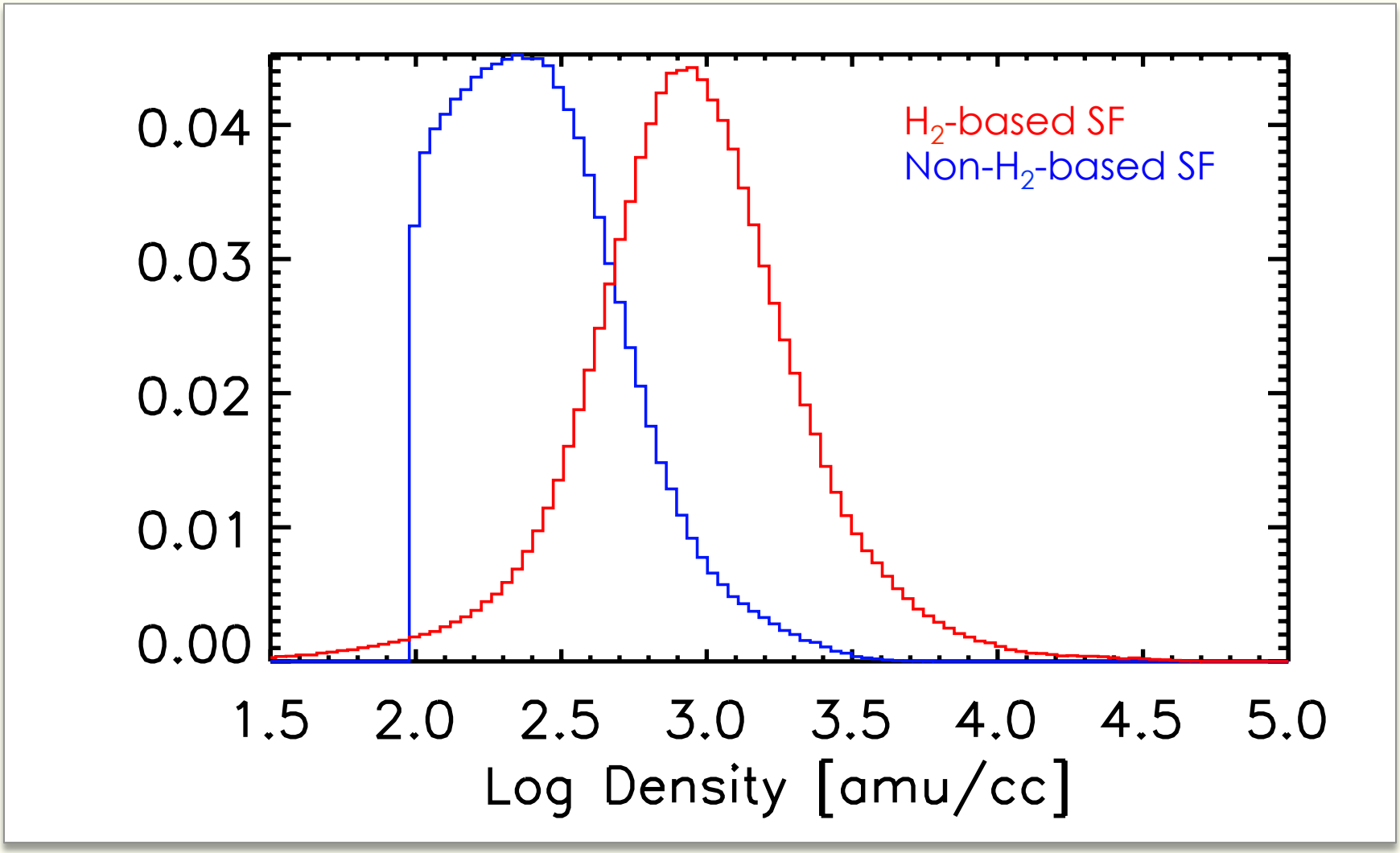
SFHs

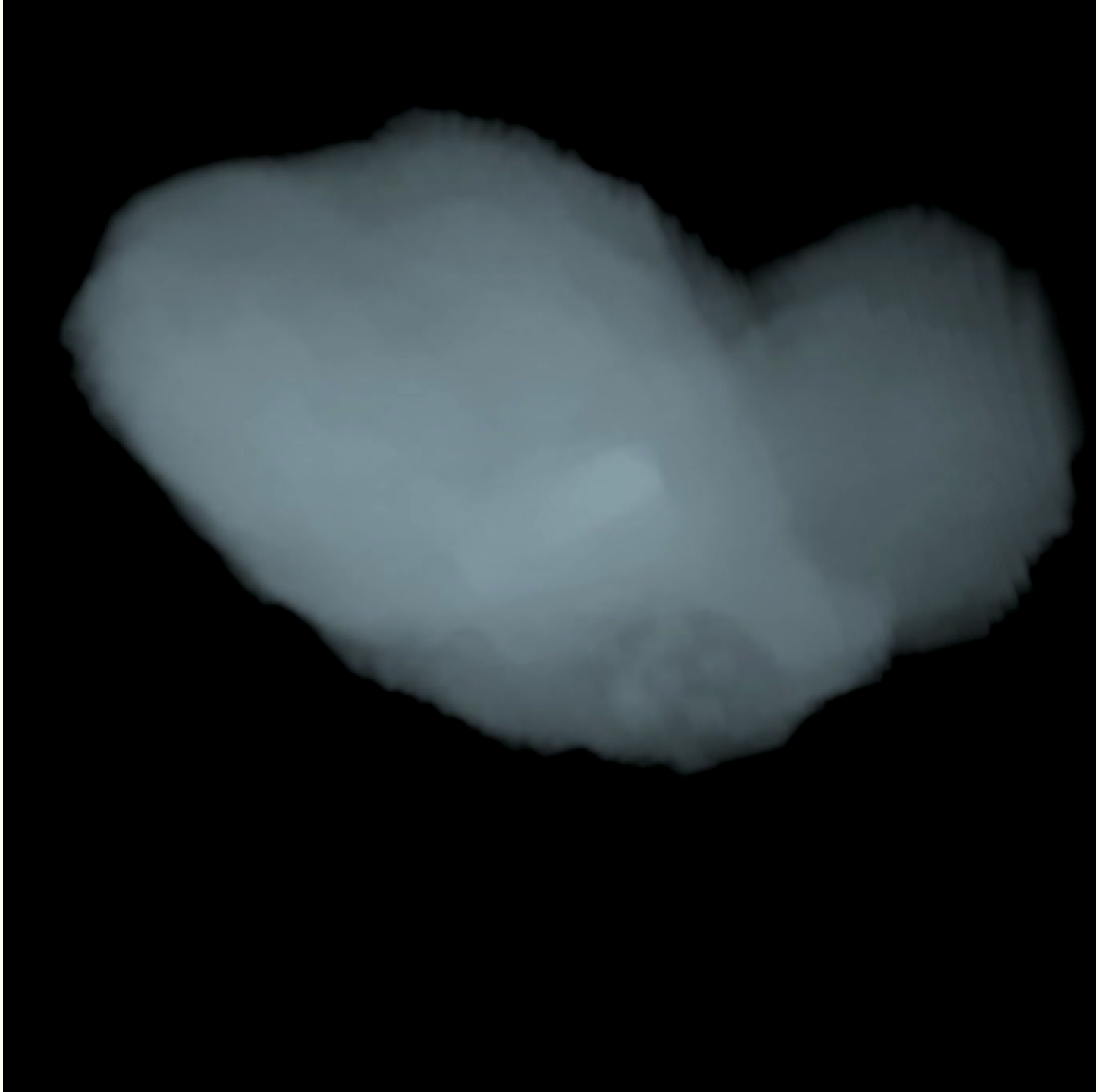

4×10⁴
3×10⁴
2×10⁴
1×10⁴
0
SFR [M⊙/yr]
H2-based SF
Non-H2-based SF
0.5
1.0
1.5
2.0
Time [Gyr]

Stellar Mass -- Halo Mass

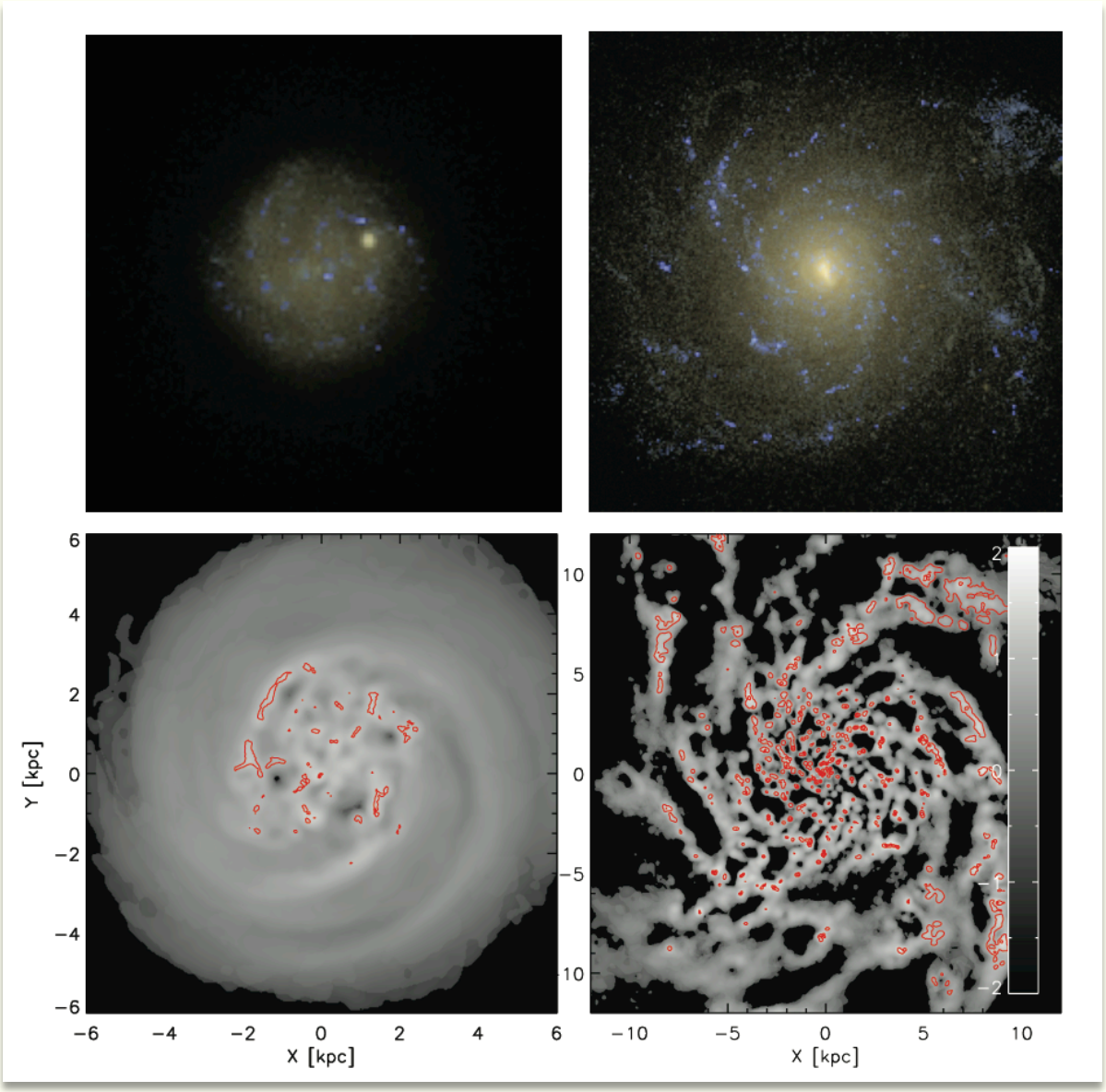


Density of Star Forming Gas





Mock-Observations at z=0

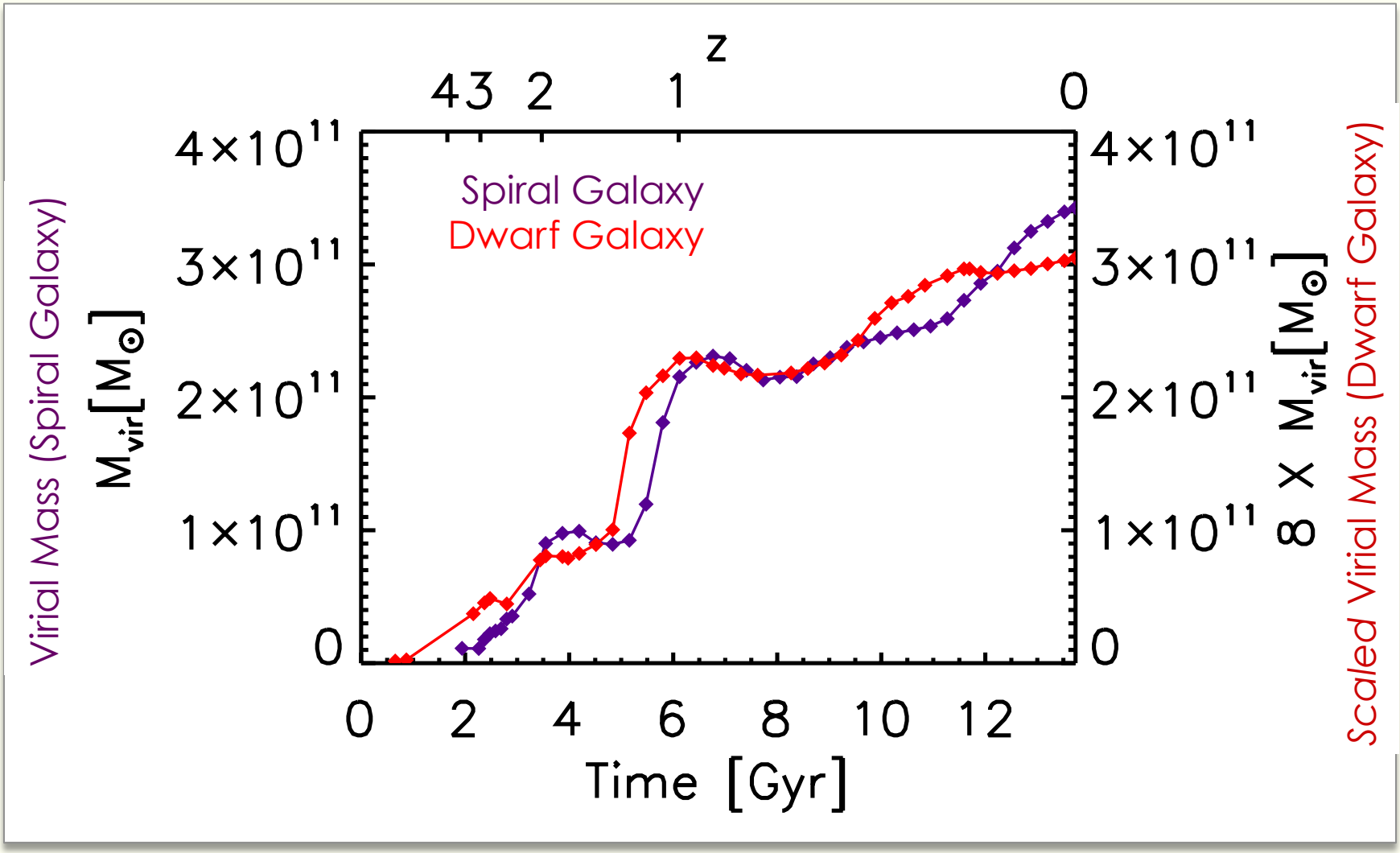


Images from SUNRISE (Jonsson '06)

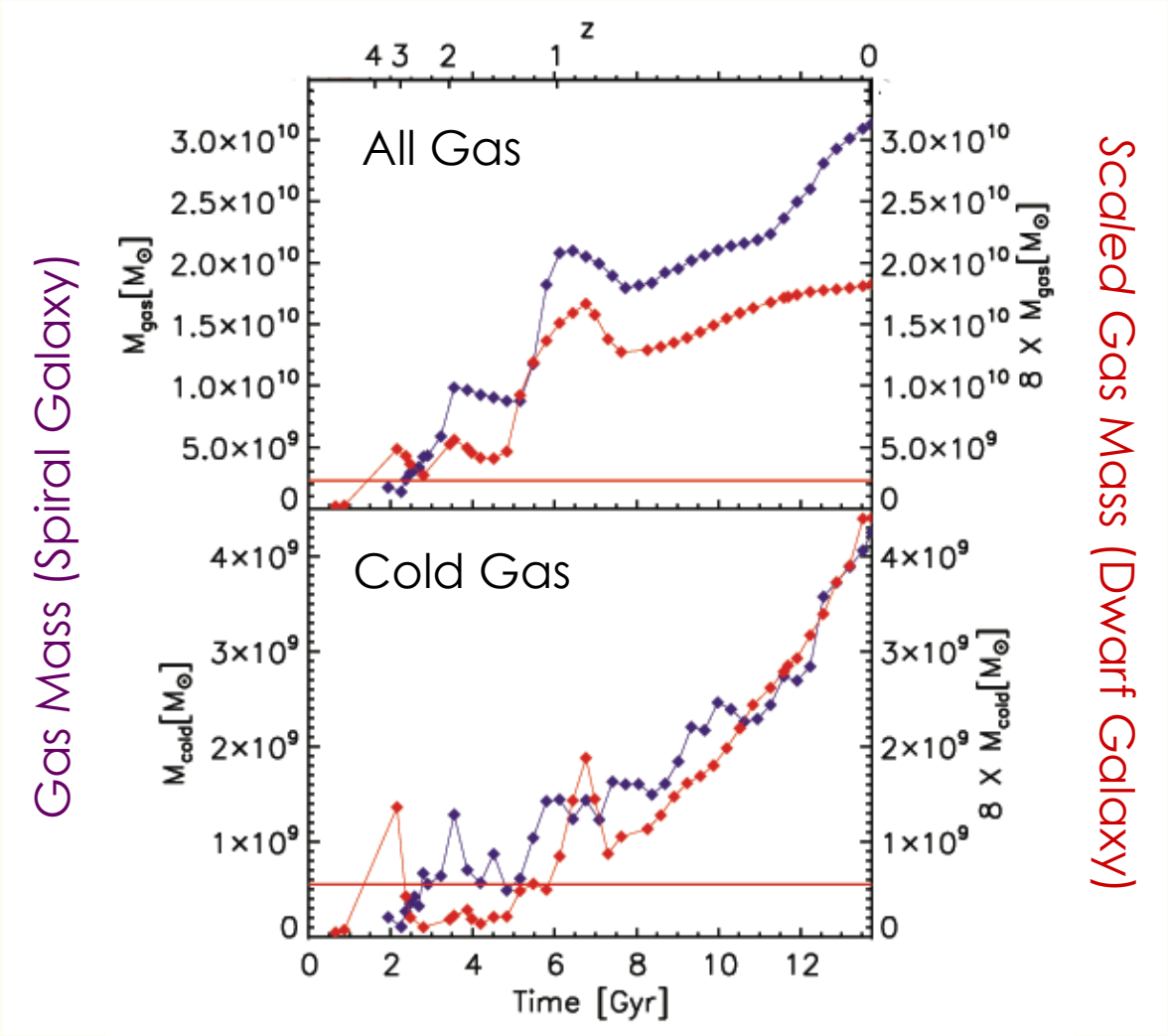
Comparing the Evolution of a Dwarf and Spiral Galaxy

- Simulated "similar" galaxies created from scaled-up initial conditions
- Spiral galaxy is scaled up by 2 spatially and 8 (2^3) is mass
- Same environment, different mass

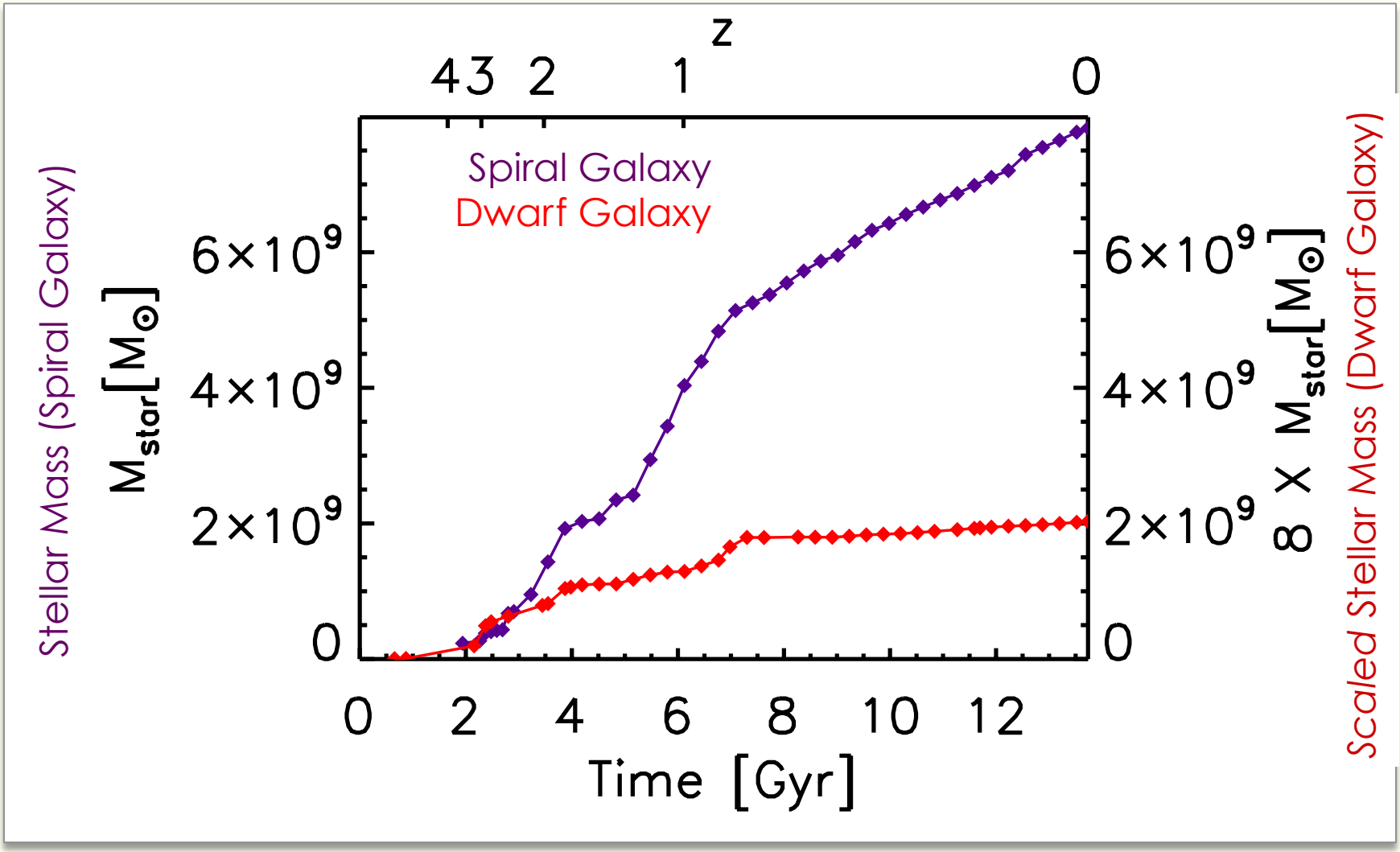
Evolution of Total Mass



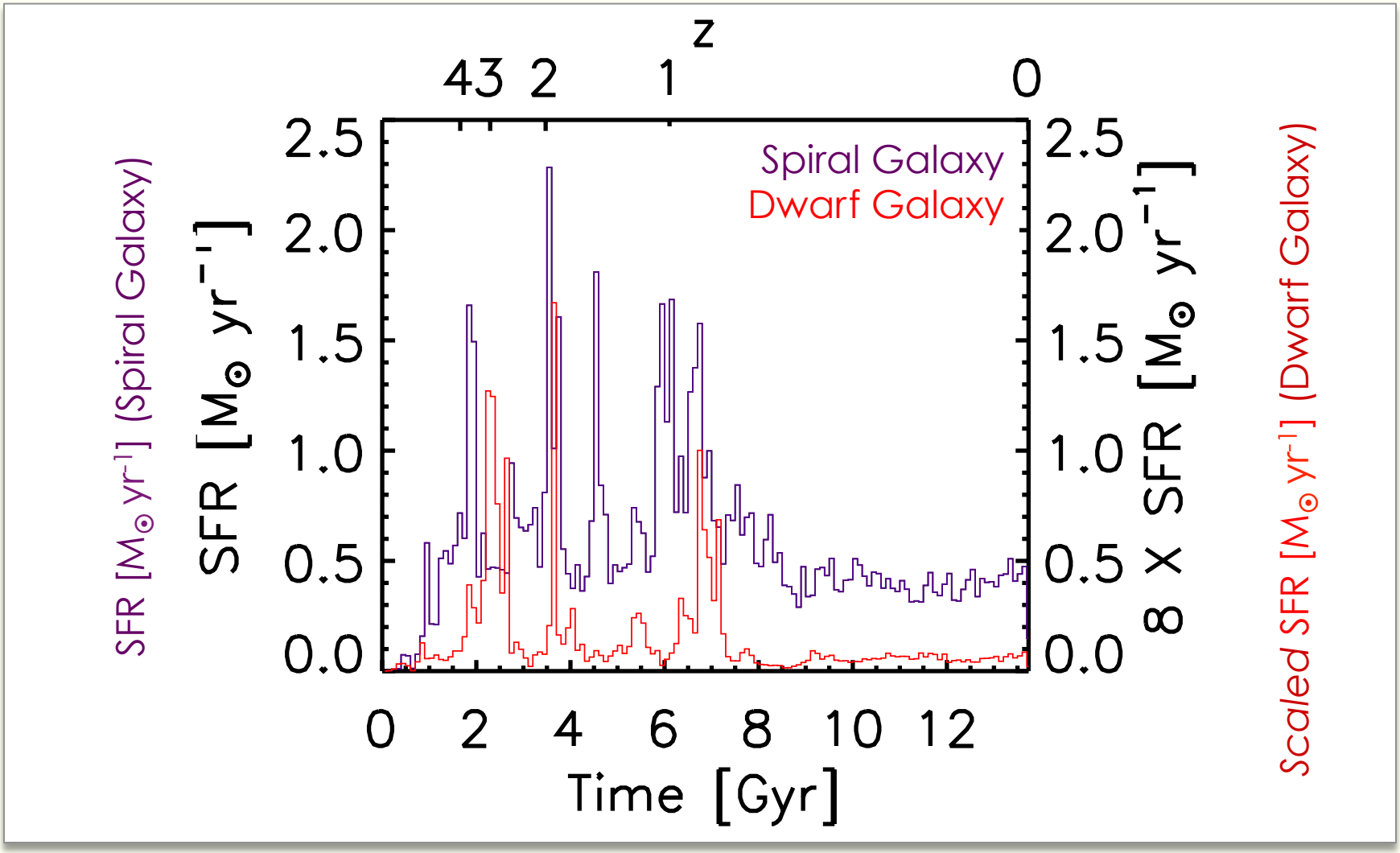
Evolution of Gas Mass



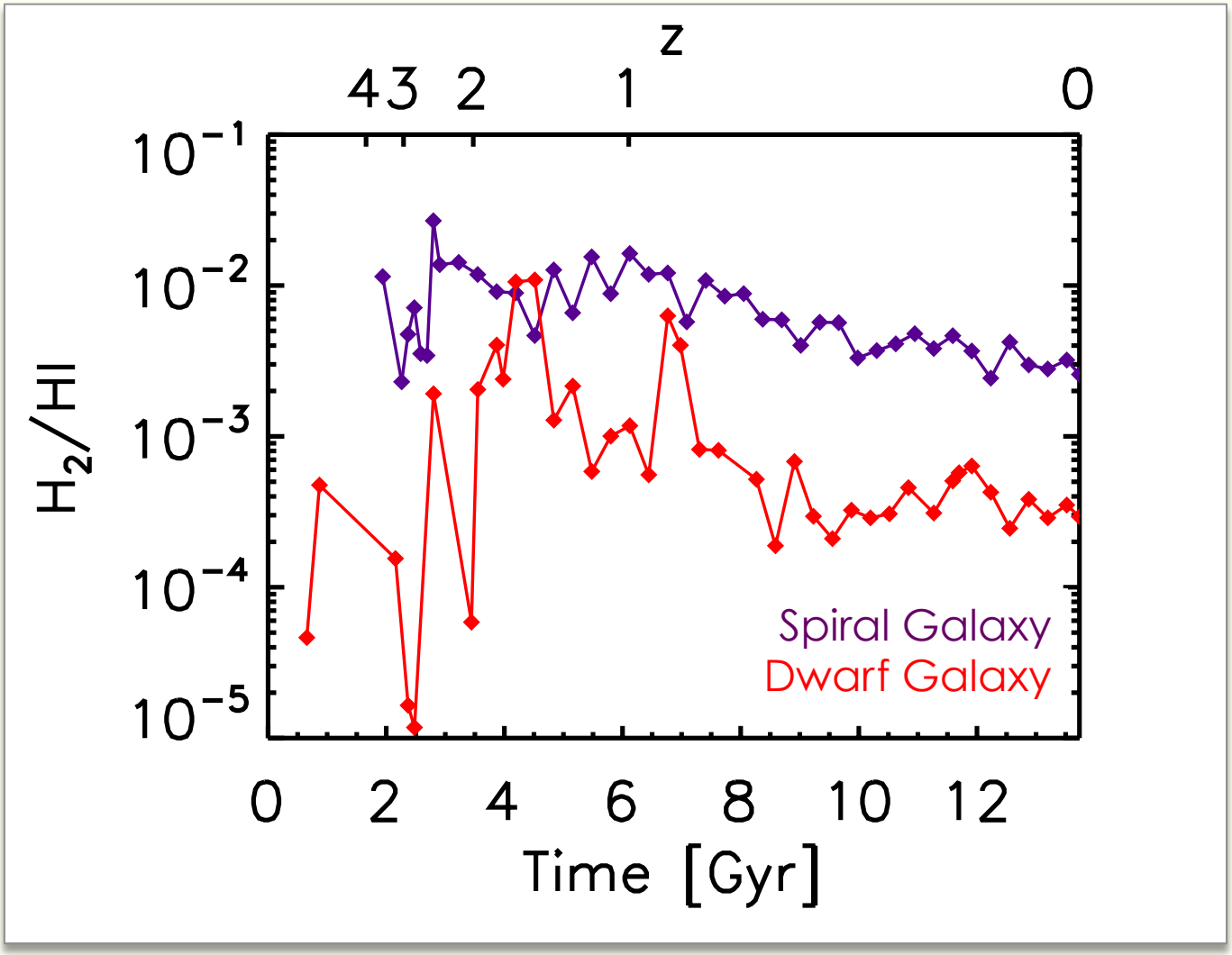
Evolution of Stellar Mass



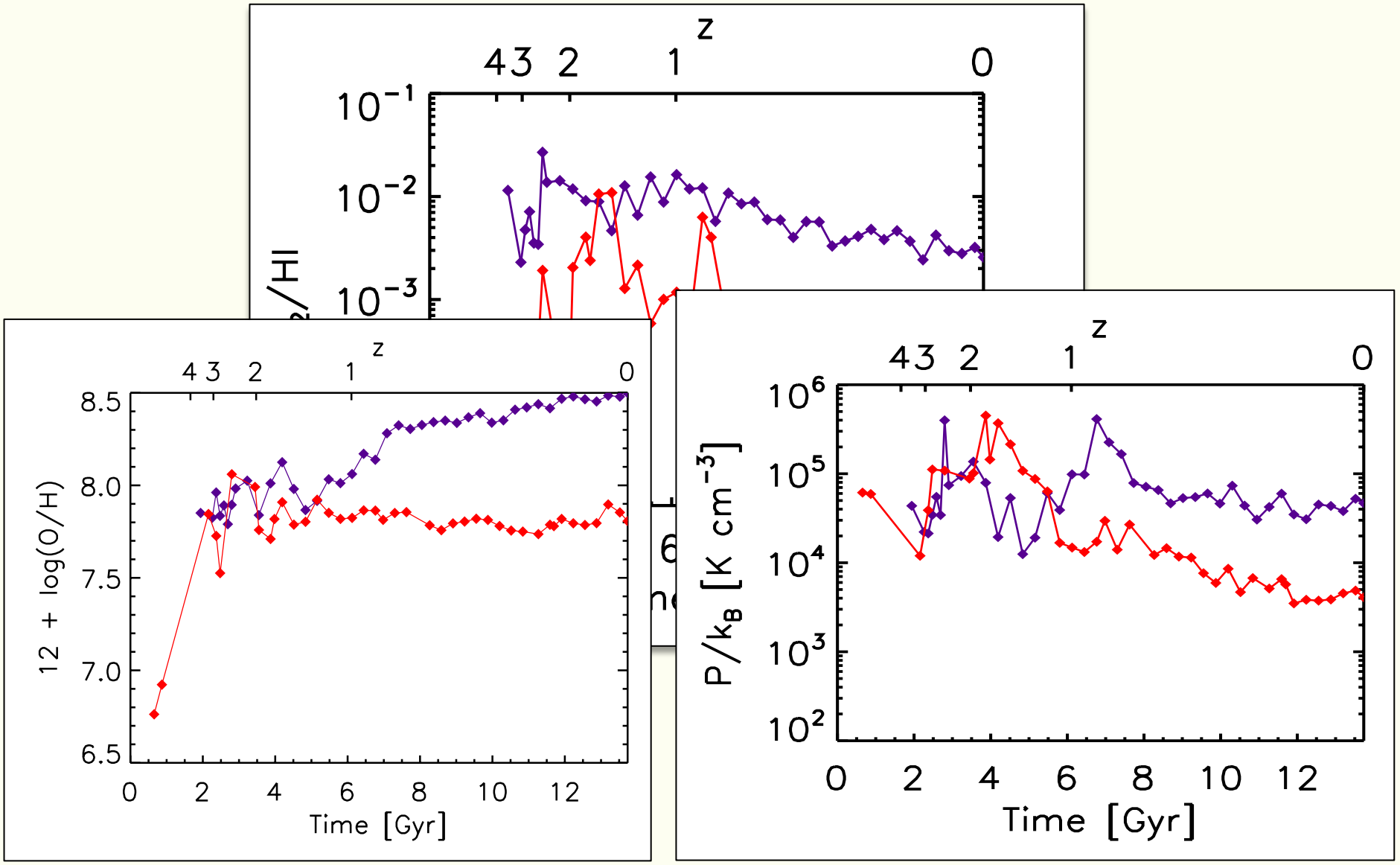
Star Formation Histories



Molecular Hydrogen Over Time



Molecular Hydrogen Over Time



Summary

- Shielded gas produces clumpier and more extended star formation
- H_2-based star formation can reproduced the observed dependency of the resolved K-S relation on metallicity
- Global K-S relation can hide wide variation in the star forming properties
- H_2-based star formation does not limit star formation in dwarf galaxies
- Lower average pressure/surface densities strongly correlated with reduced star formation in dwarf galaxies