Galaxy Formation and Evolution: What is Simple and What Remains Mysterious

S. M. Faber

Subaru 20th Anniversary Celebration

Nov. 23, 2019

“Reverse Engineering” Galaxy Evolution

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Subaru Telescope 20th Anniversary

GALAXY FORMATION

NAUPAKA IV

KAIA•HÖ•KÜ: TOWARDS UNDERSTANDING THE ORIGIN OF THE COMPLEXITY AND DIVERSITY

SOC: Chair - Masayuki Tanaka (NAOJ), Kate Whitaker (UConn), Mariska Kriek (UC Berkeley), Masato Onodera (Subaru), Pascal Oesch (Yale U.), Yuichi Matsuda (NAOJ)

NOV 19 (TUE) – NAUPAKA IV

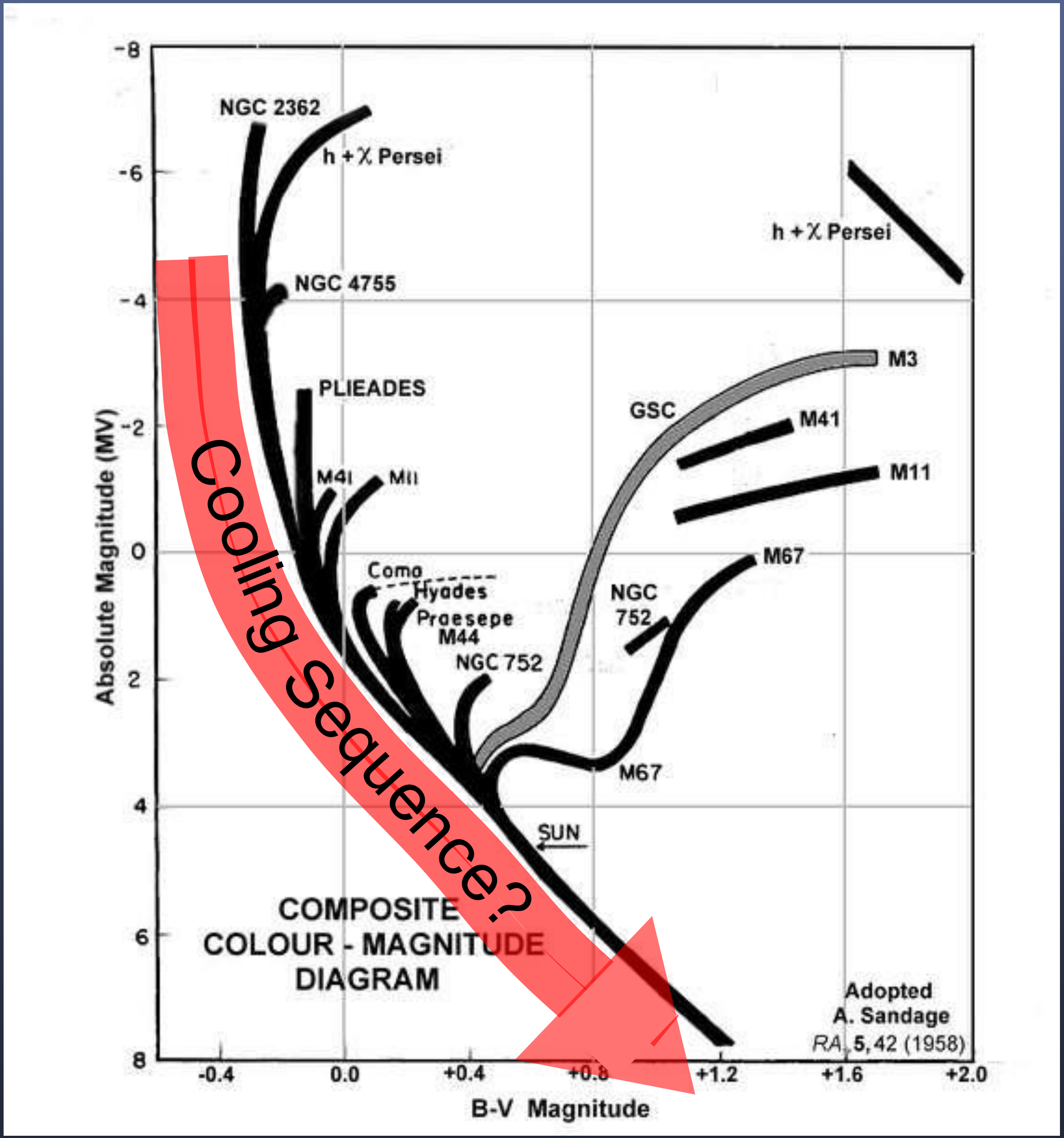
09:00 (I) Ivo Labbe (Swinburne U. of Technology)
The first billion years of galaxy formation
09:25 Daichi Kashino (ETH Zurich)
Exploring the end tail of cosmic reionization with Subaru/HSC
09:40 Satoshi Yamanaka (Waseda U.)
CHORUS: Candidates of Lyman continuum galaxies at z=3.3...
09:55 Shotaro Kikuchihara (U. of Tokyo)
Early Low-Mass Galaxies and Star-Cluster Candidates at z~6-9

NOV 21 (THU) – NAUPAKA IV

09:00 (I) Gwen Rudie (Carnegie Obs.)
The Circumgalactic Medium of Star-Forming Galaxies at...
09:25 Yuma Sugahara (U. of Tokyo)
Fast Outflows Identified in Early Star-Forming Galaxies at...
09:40 (I) Annalisa Pillepich (MPIA)
Universe(s) in a box: insights from the TNG simulations and...

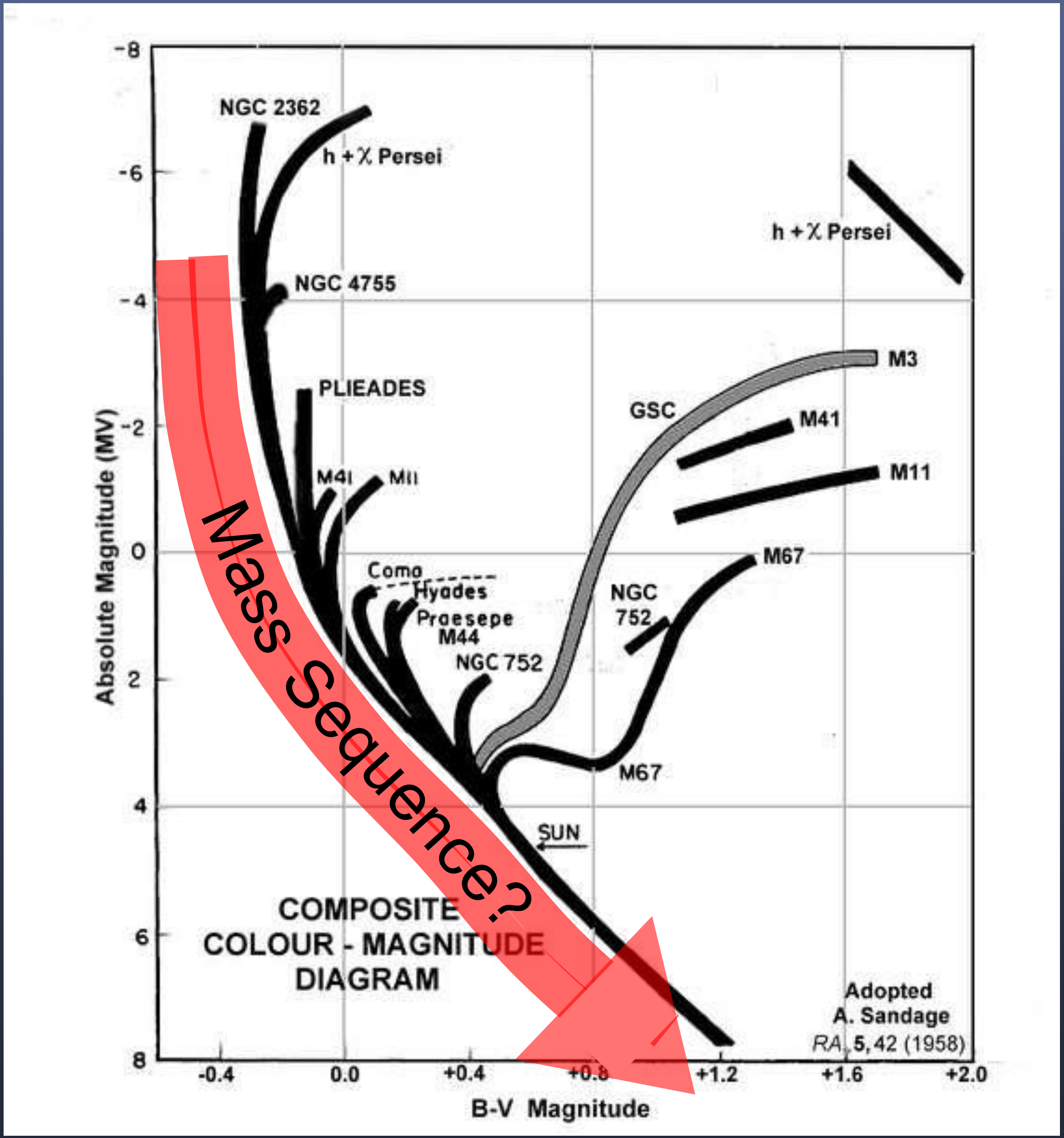
10:20 (I) Camilla Pacifici (STScI)

Sandage: Composite Star Cluster HR diagrams



Sandage 1958

Sandage: Composite Star Cluster HR diagrams



Sandage 1958

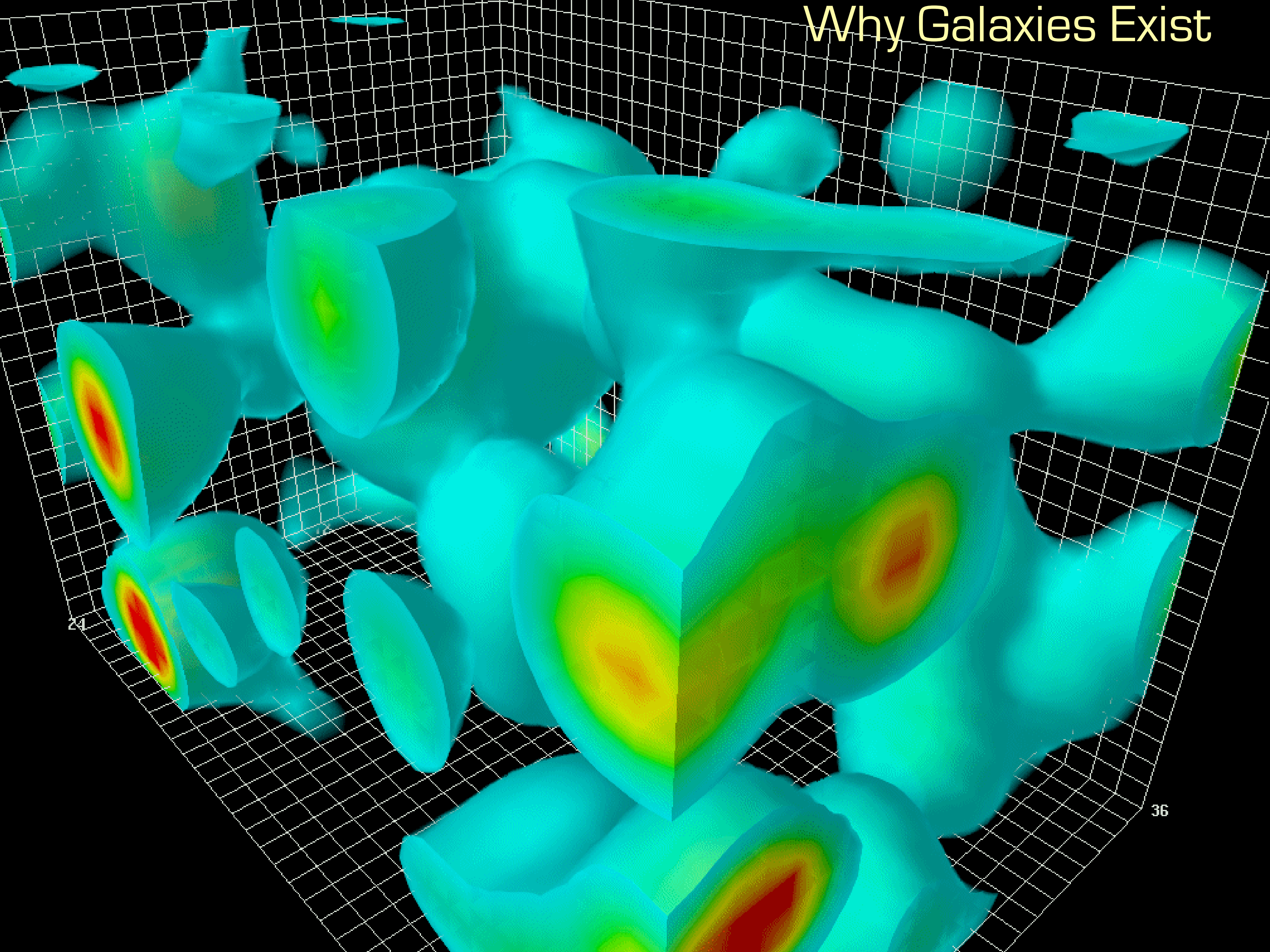
Phenomena to be explained

- Why do galaxies exist?
- Scaling relations
- Star-formation histories
- Characteristic upper stellar mass: $10^{10\text{-}11}\ M_\odot$
- Quenching

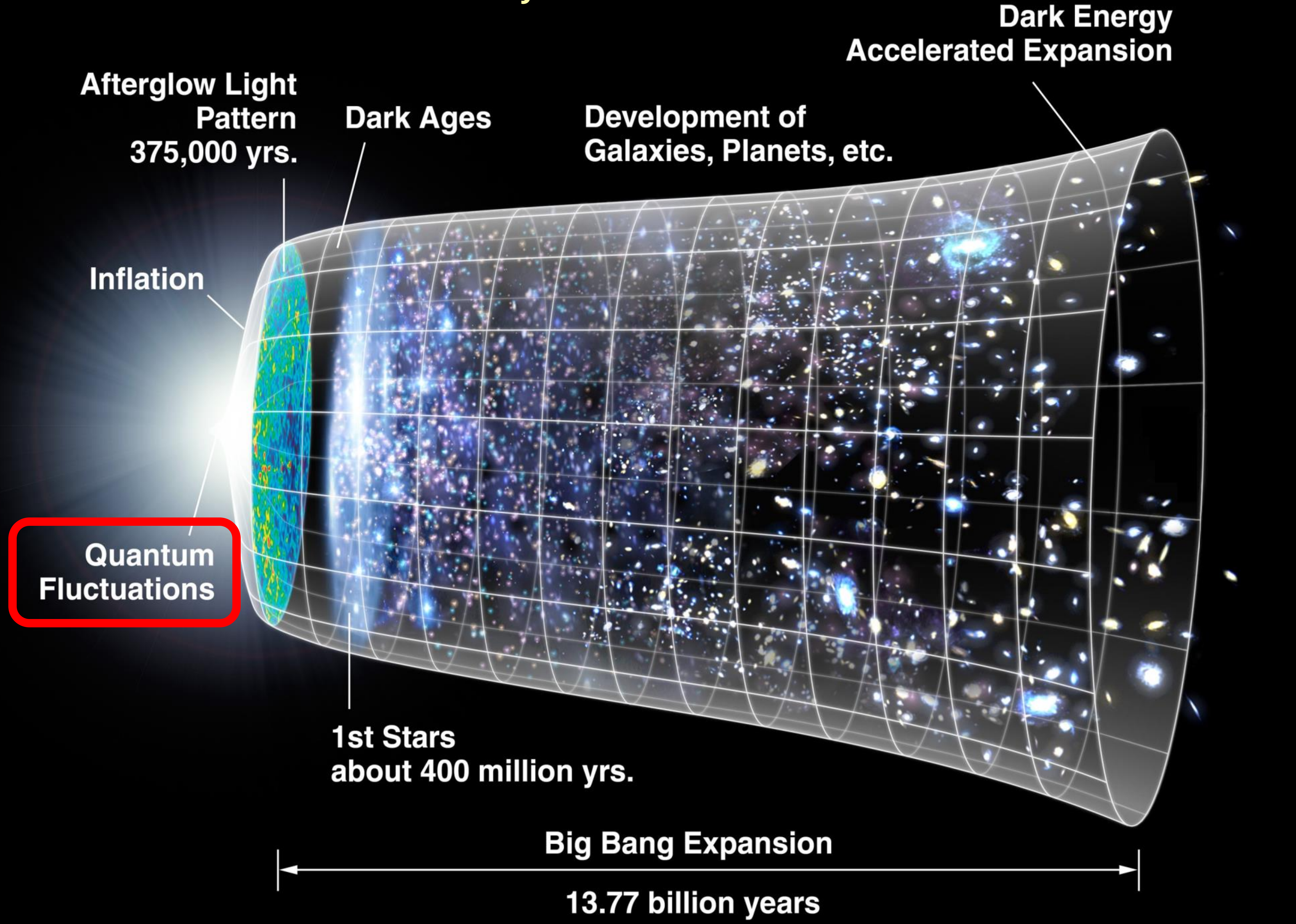
Not discussed for lack of time or personal knowledge:

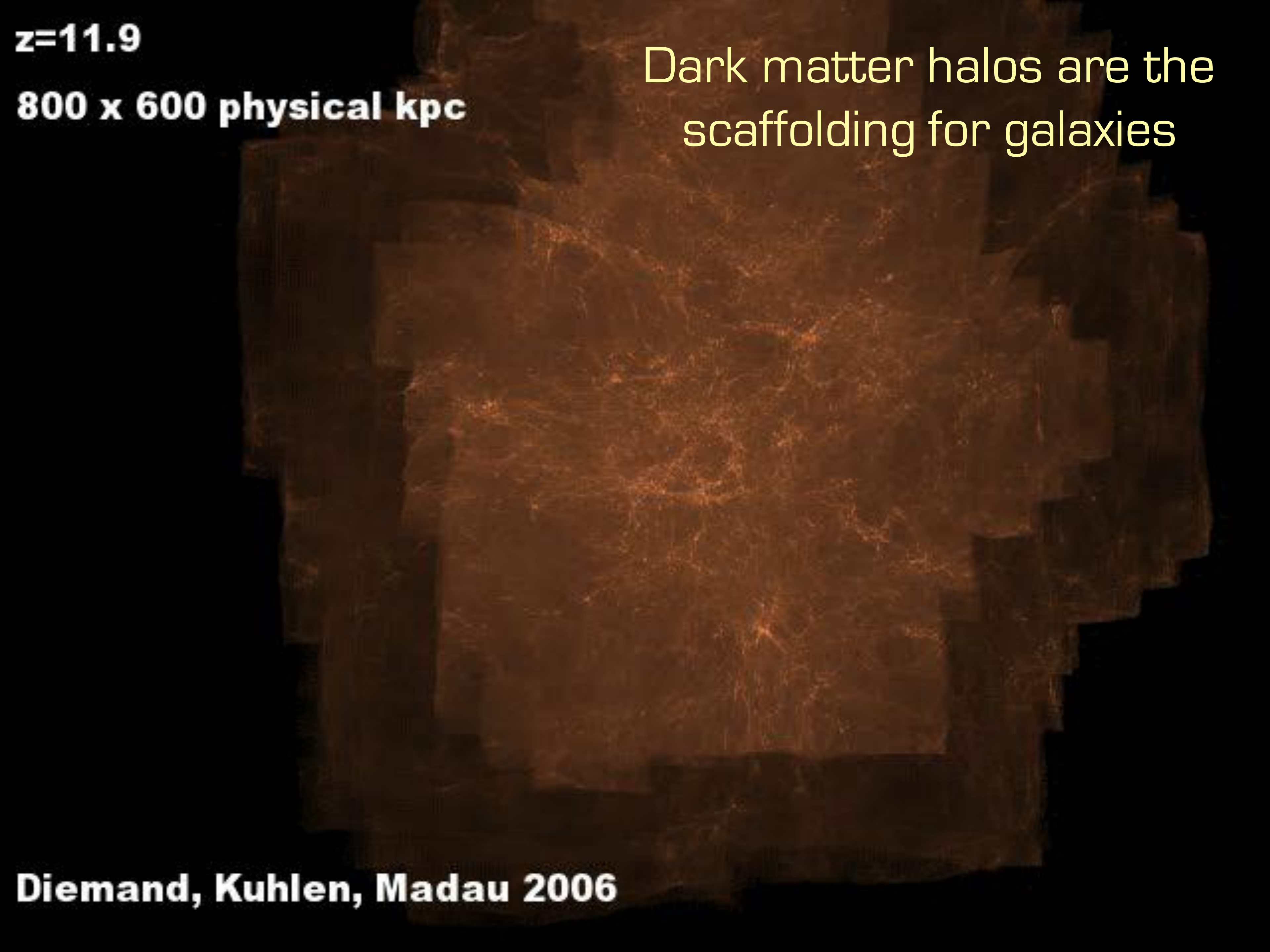
- Morphology: disks, spheroids, bars, Hubble sequence
- Dwarf galaxies below $10^9\ M_\odot$
- Environment effects; effects of mergers
- Early galaxies before $z = 3$

Why Galaxies Exist

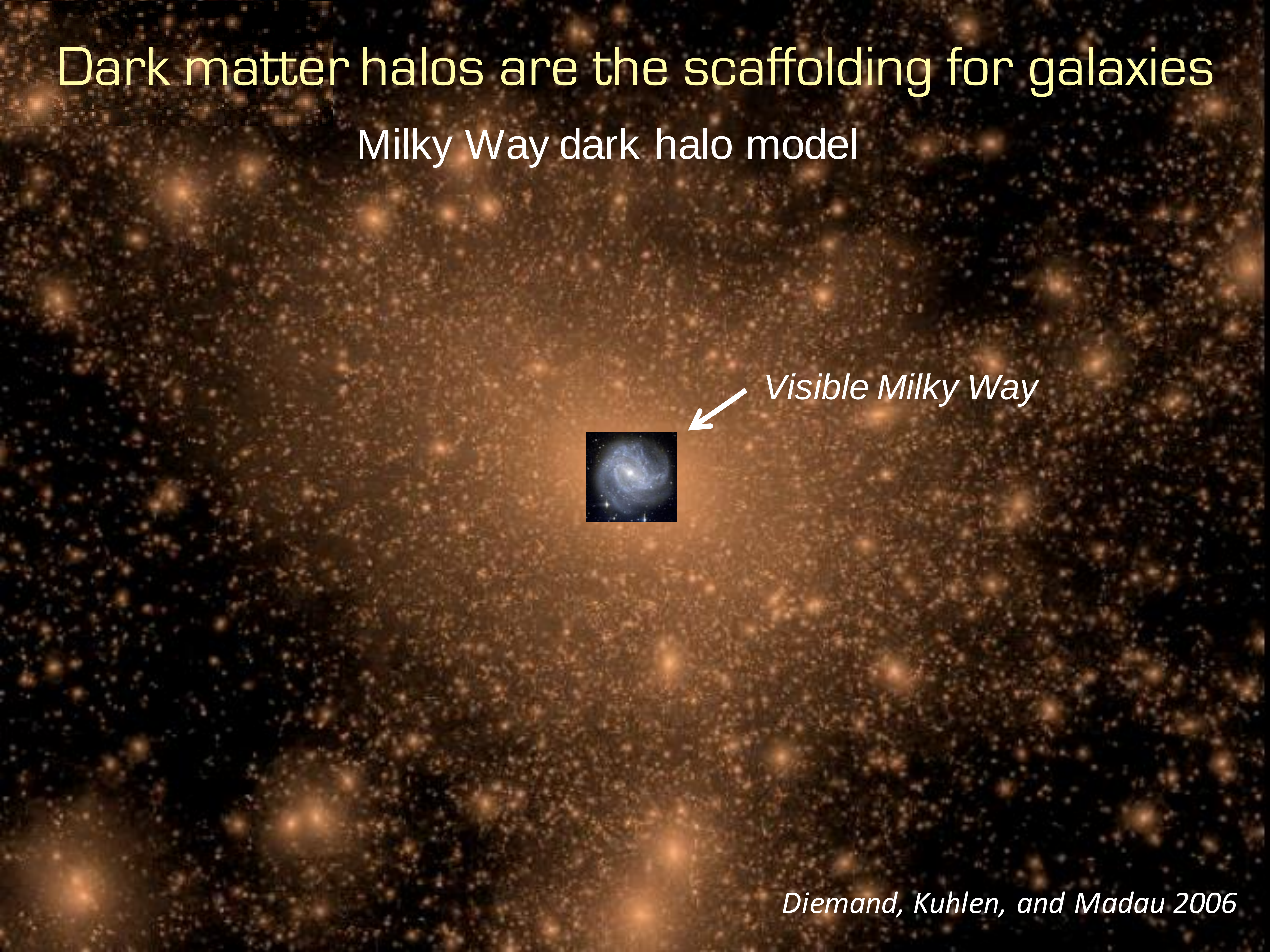


Why Galaxies Exist

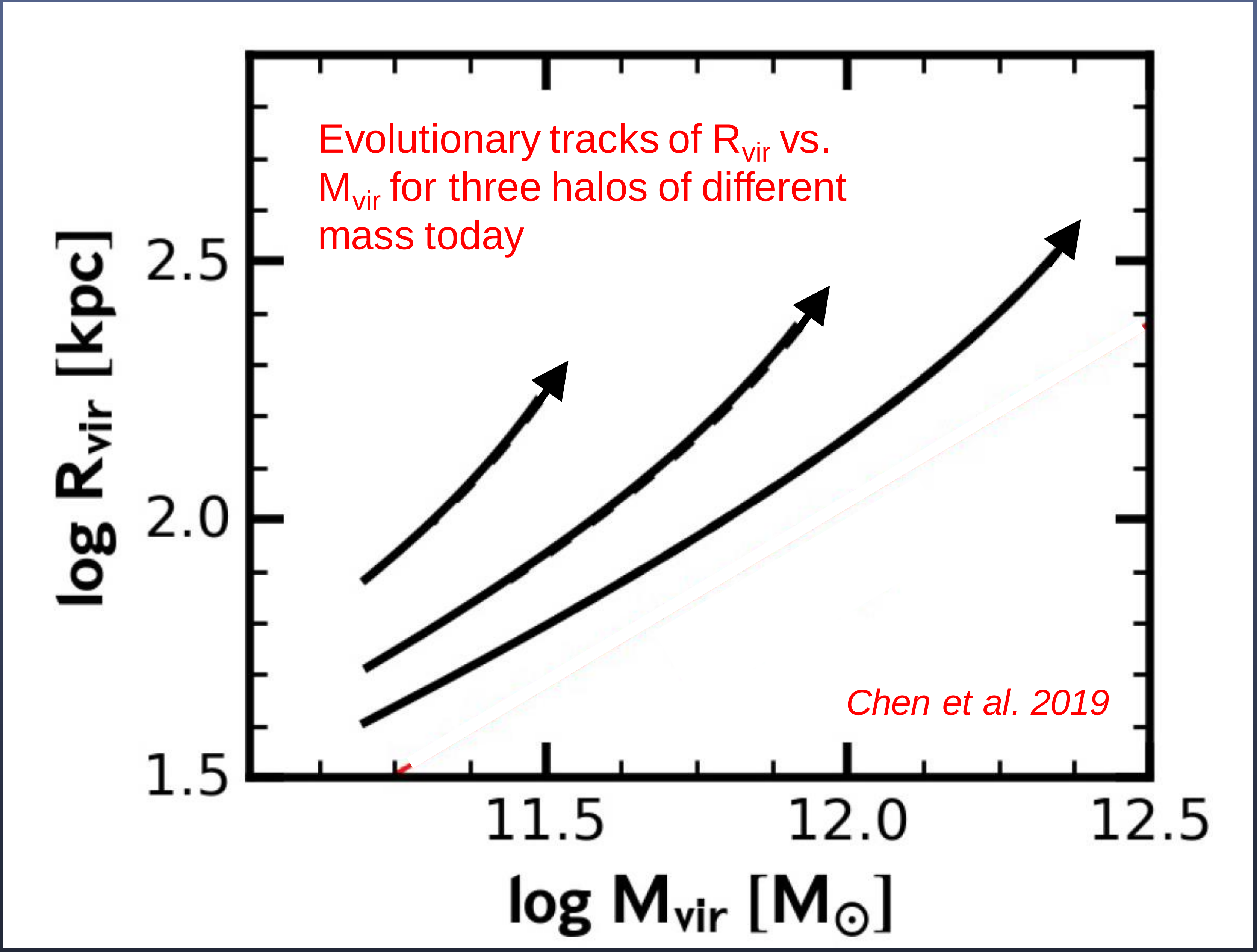



z=11.9
800 x 600 physical kpc
Dark matter halos are the scaffolding for galaxies
Diemand, Kuhlen, Madau 2006

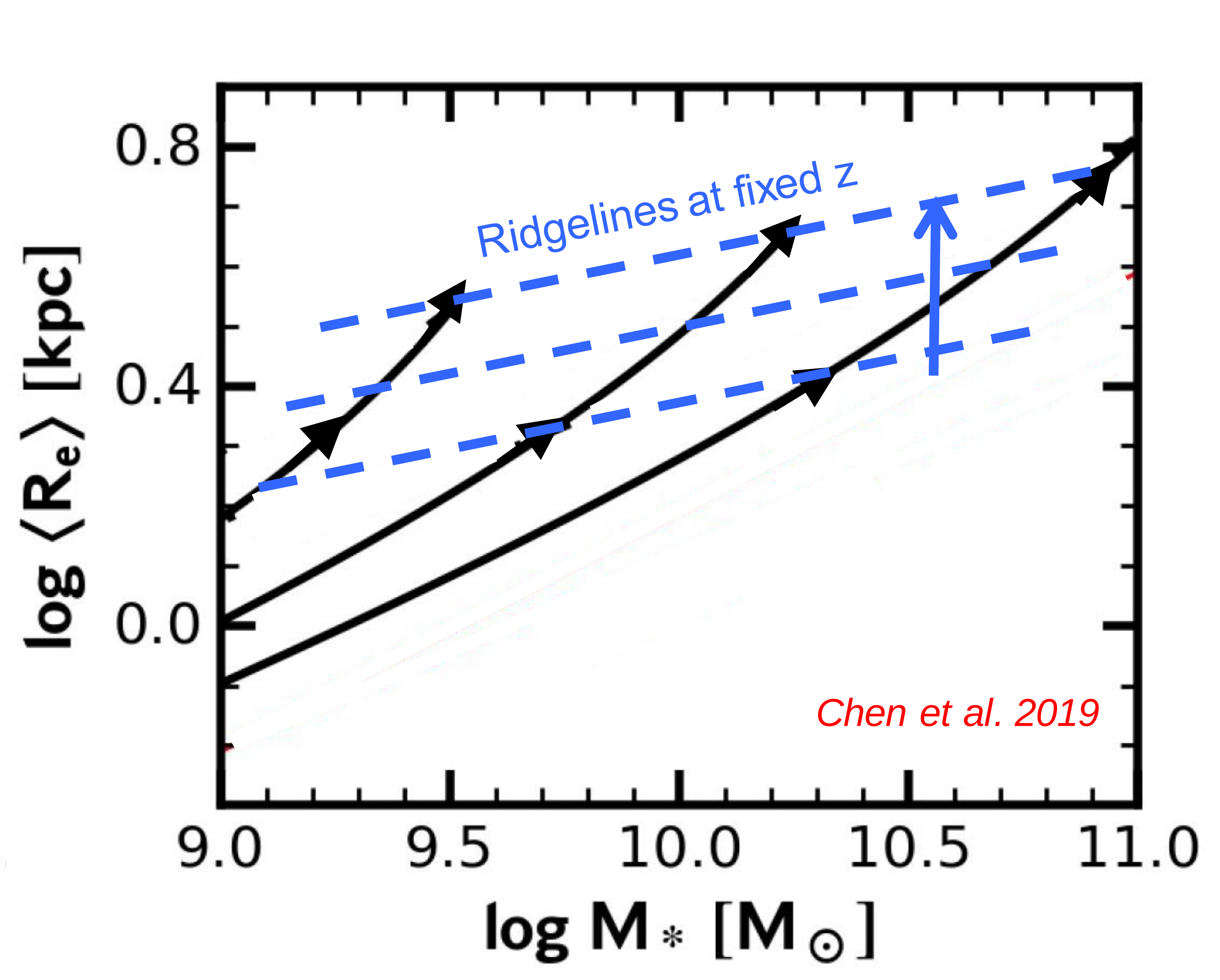
Dark matter halos are the scaffolding for galaxies



Dark matter halos have their own scaling laws

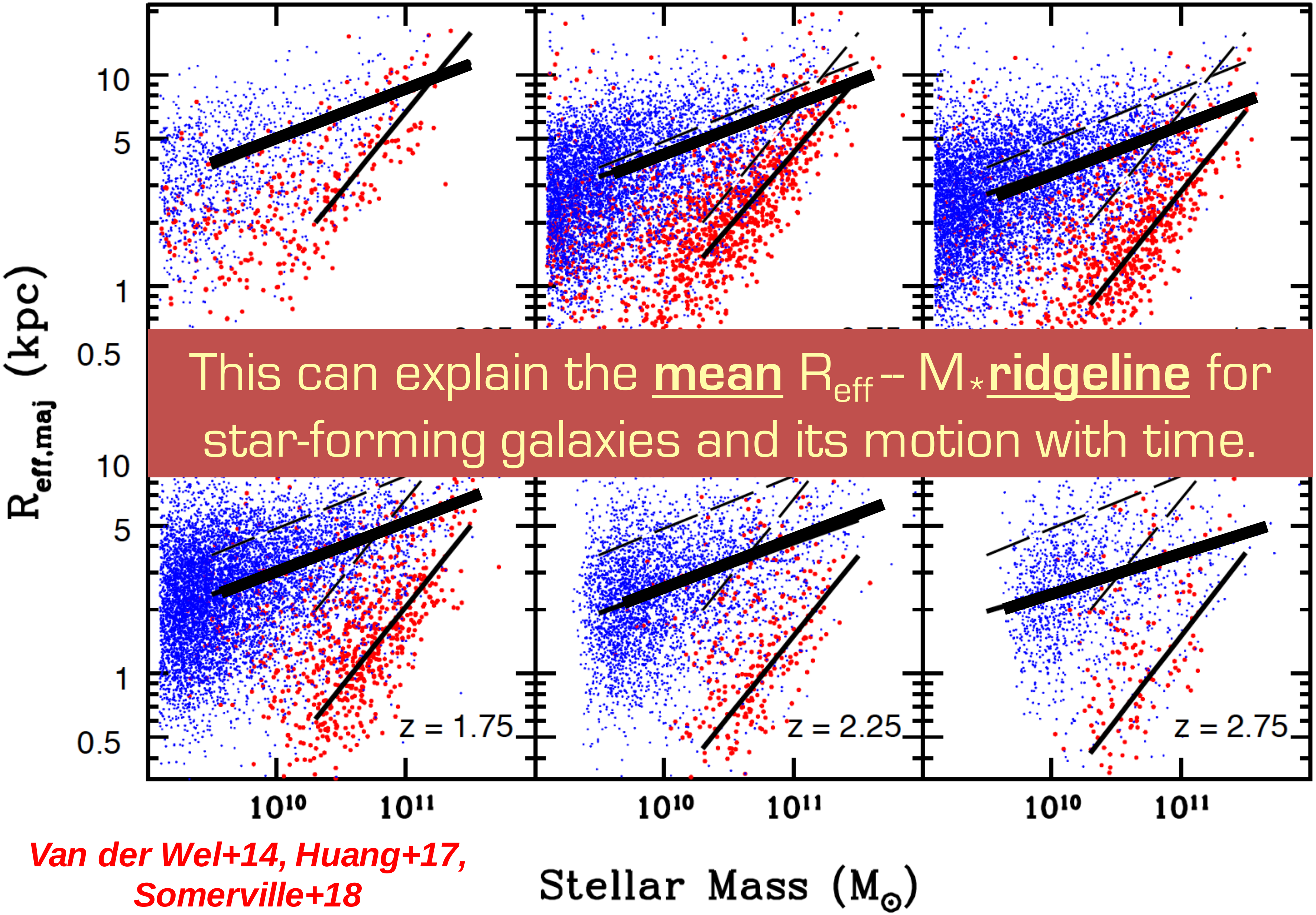


We can match the scaling laws for visible galaxies by painting galaxies into halos in the right way



Link R_{eff} of SF galaxies to the virial radii R_{vir} of their dark halos:

Assume: $R_{eff} = 0.02\, R_{vir}$ on average.

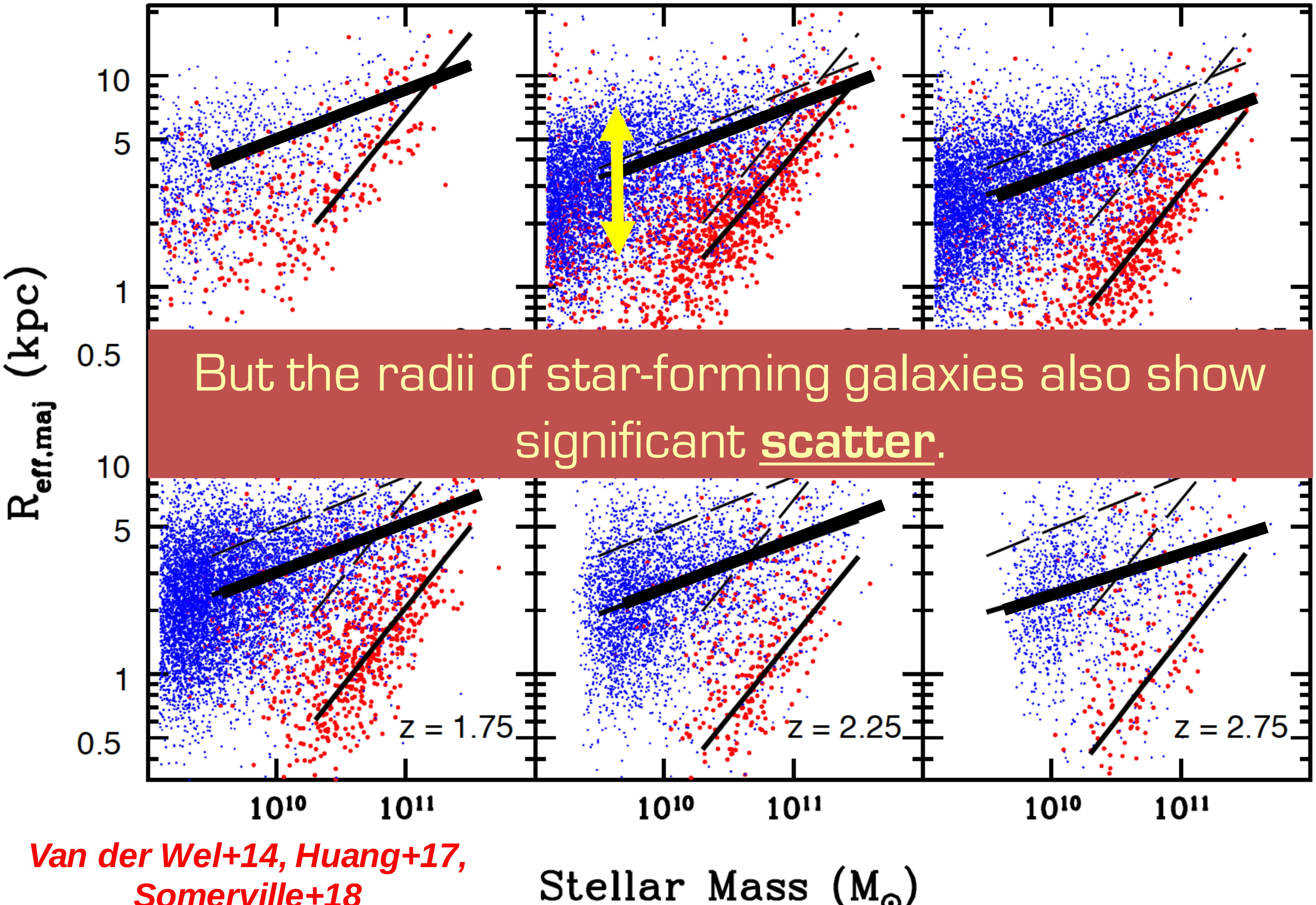


This can explain the **mean** R_{eff} – M_* **ridgeline** for star-forming galaxies and its motion with time.

Van der Wel+14, Huang+17, Somerville+18

Link R_{eff} of SF galaxies to the virial radii R_{vir} of their dark halos:

Assume: R_{eff} = 0.02 R_{vir} on average.

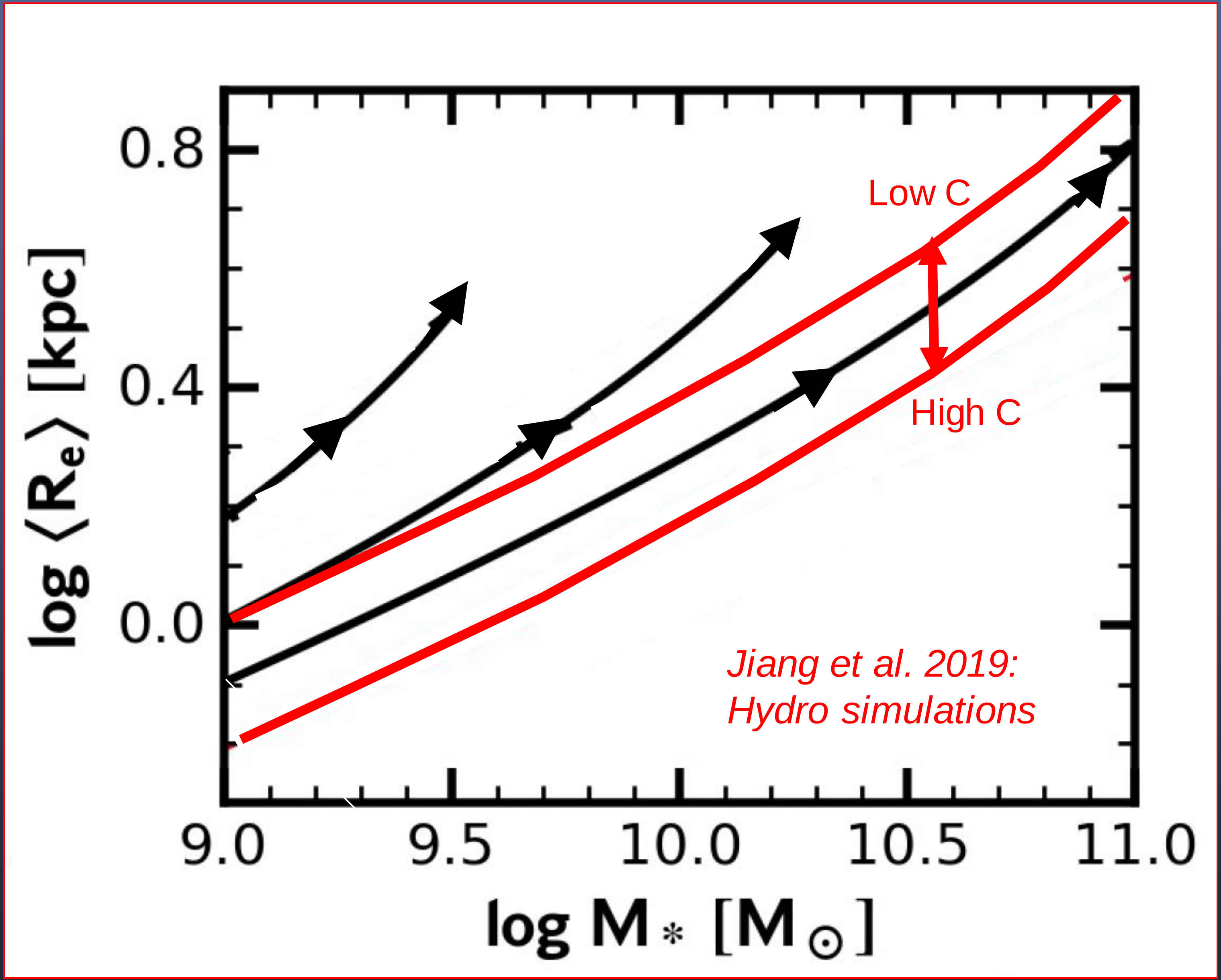


But the radii of star-forming galaxies also show significant **scatter**.

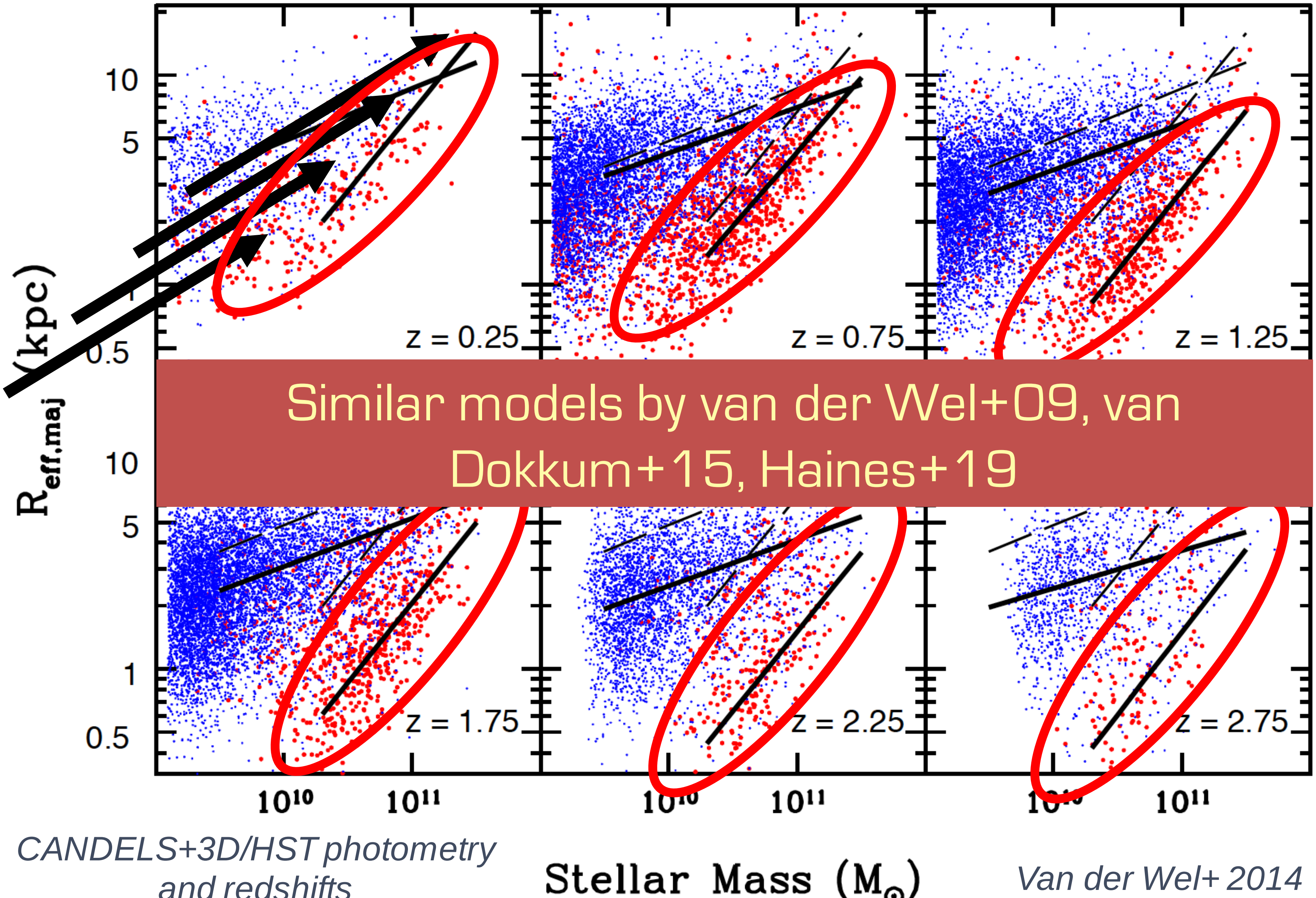
Van der Wel+14, Huang+17, Somerville+18

Changing halo concentration changes R_{eff}

$$R_{eff} = 0.02\ R_{vir} \times (C/10)^{-0.7}$$



SF galaxies evolve in R_{eff} – M_* along parallel tracks until they cross a "quenching boundary"

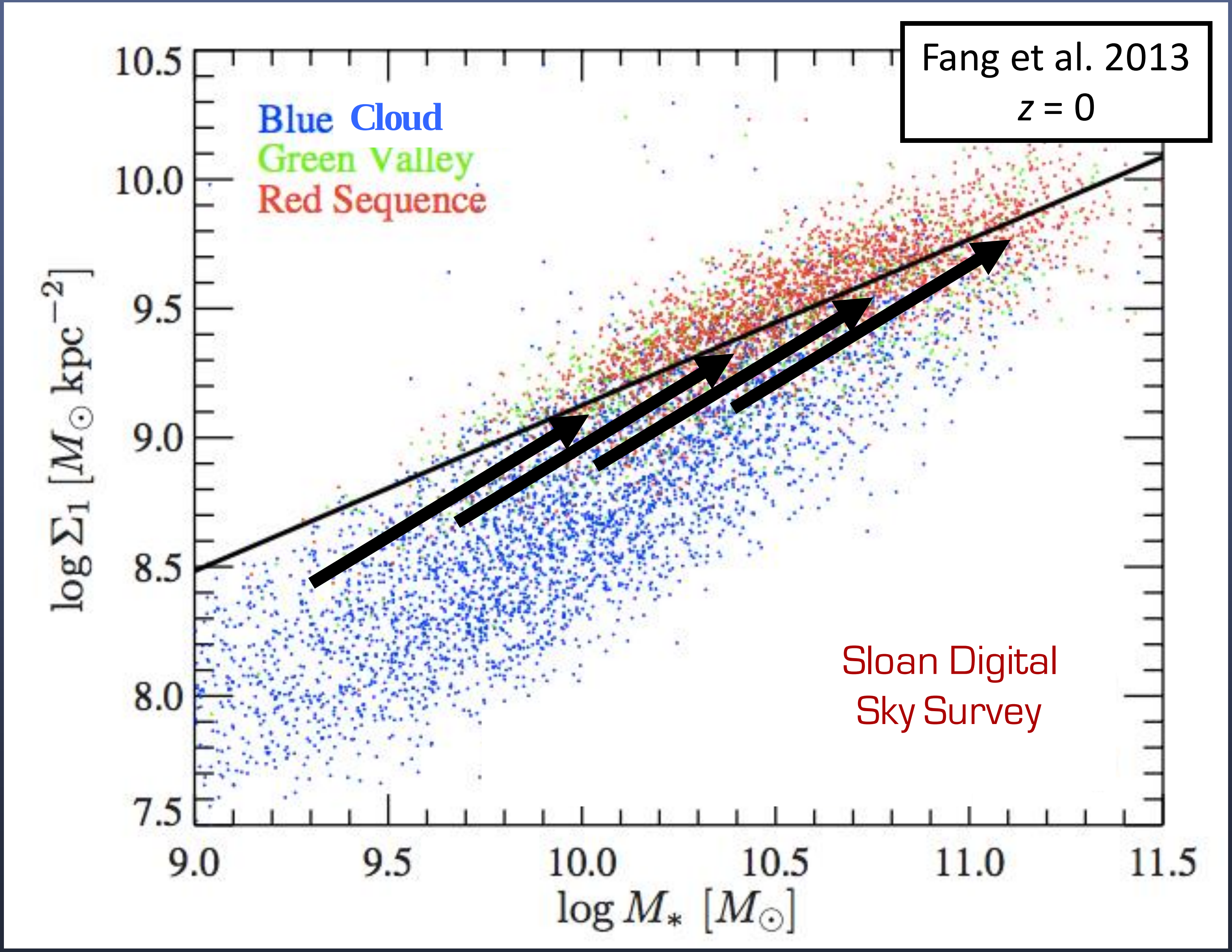


Similar models by van der Wel+09, van Dokkum+15, Haines+19

CANDELS+3D/HST photometry and redshifts

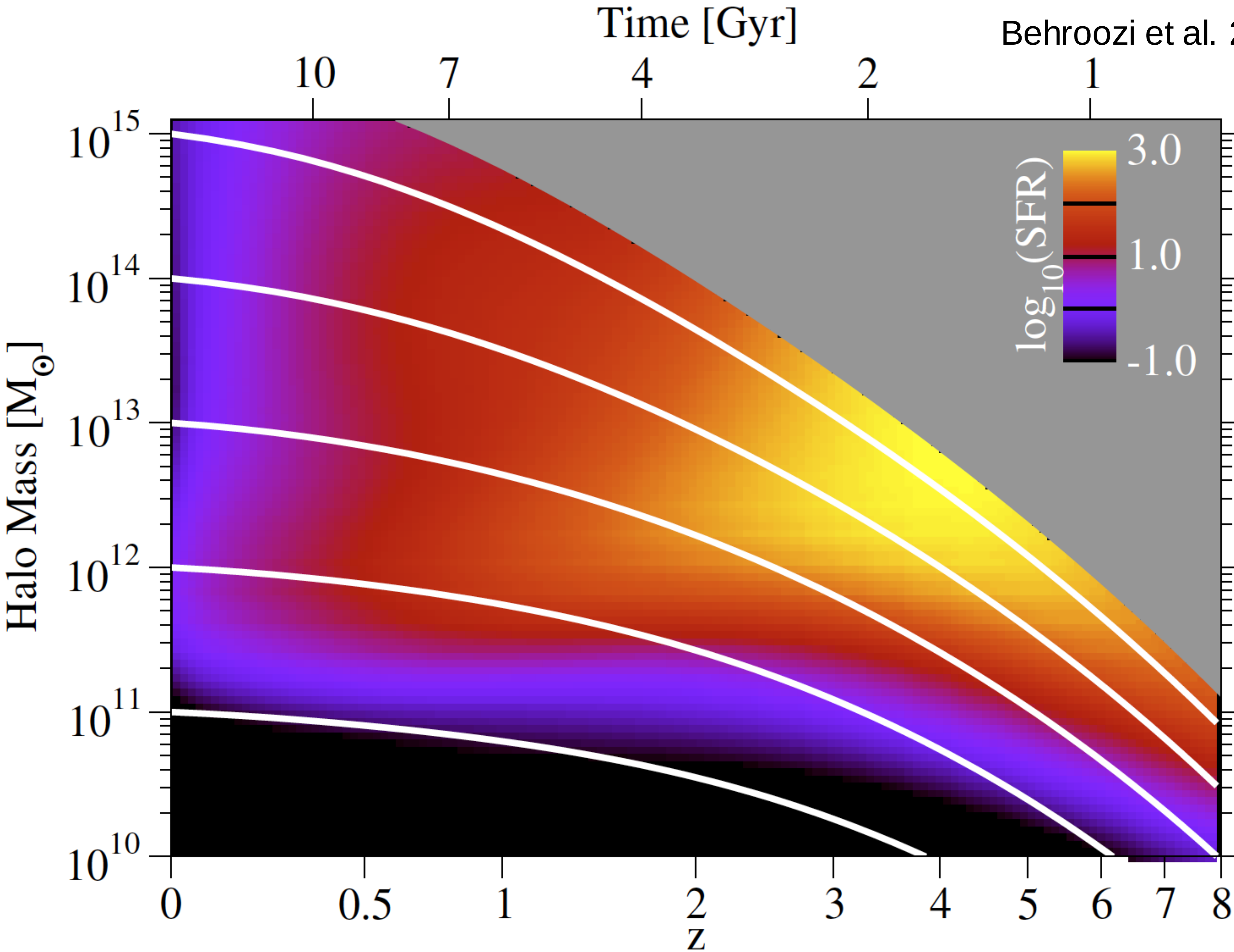
Van der Wel+ 2014

Exponential disks map $R_{eff} - M_*$ into $\Sigma_1 - M_*$

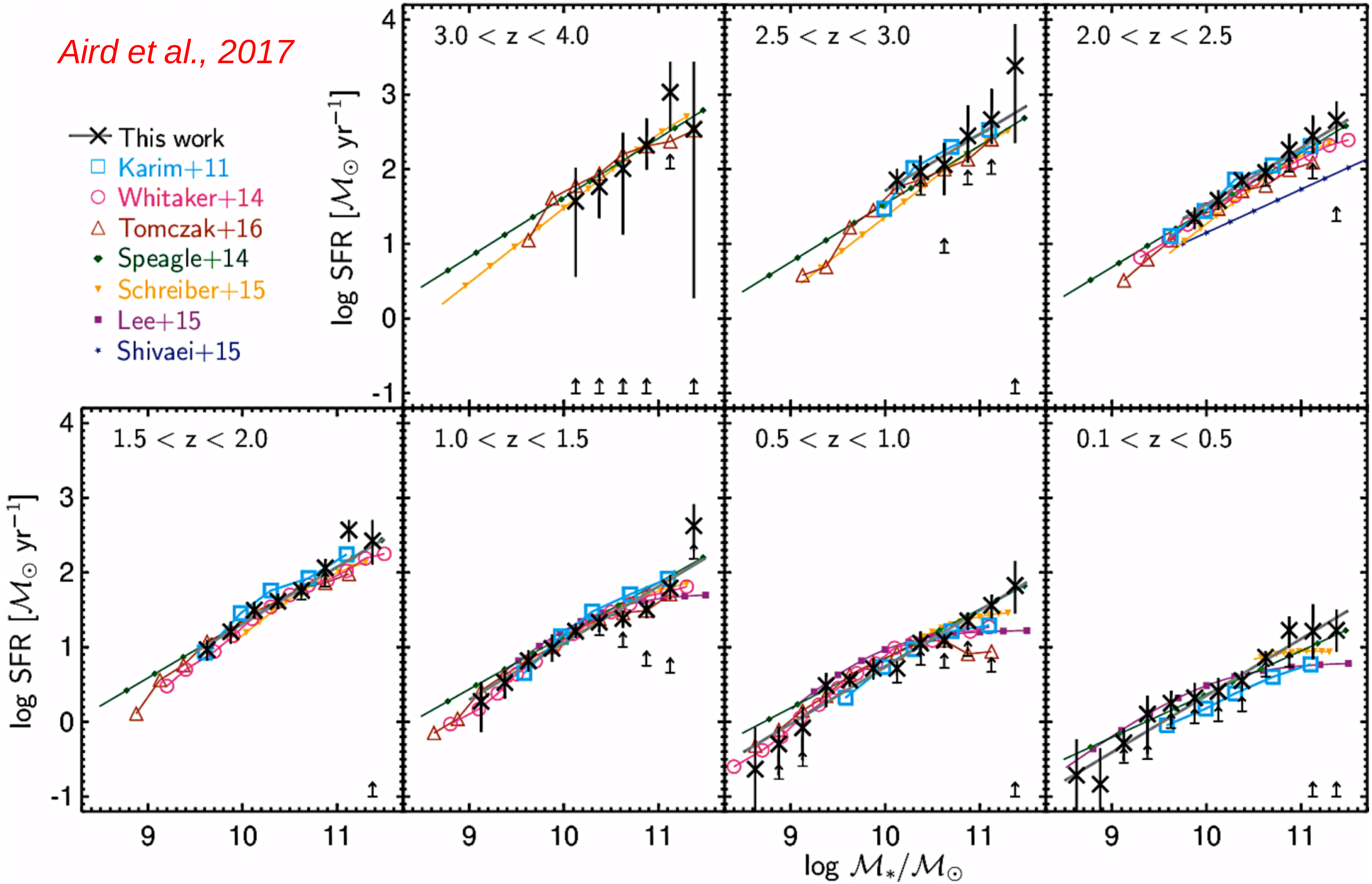


Star-formation histories of dark matter halos

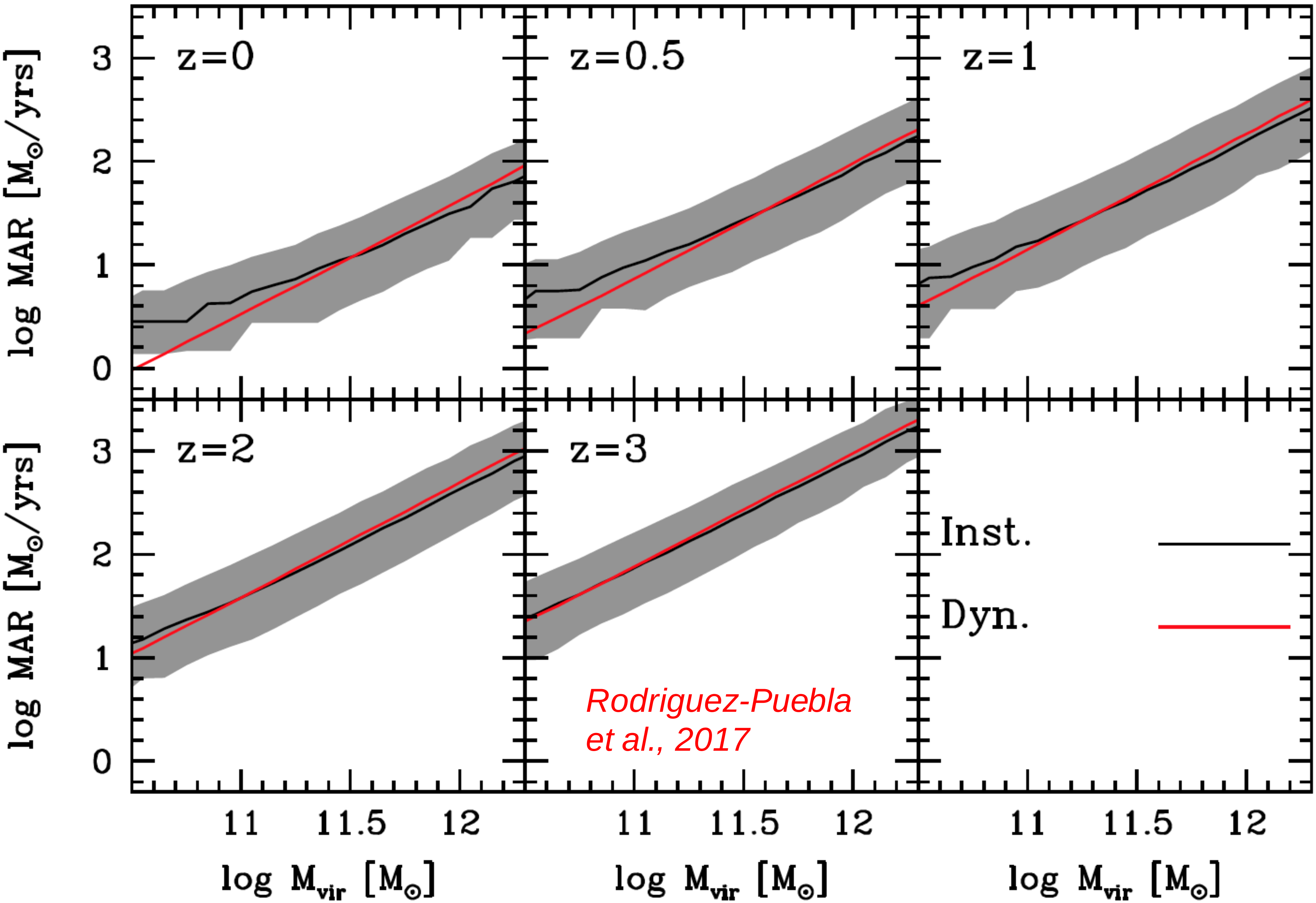
Behroozi et al. 2013



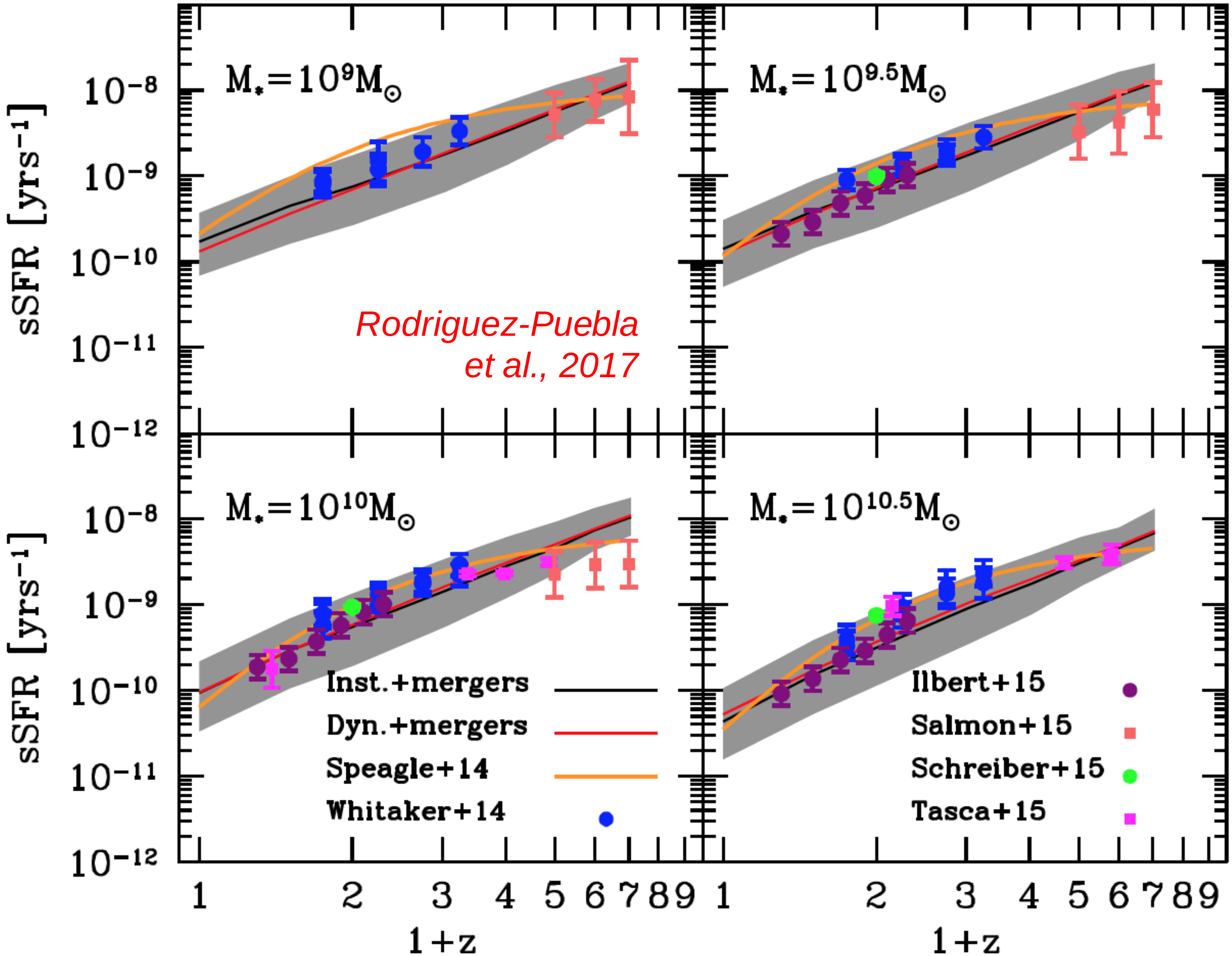
A star-forming main-sequence compilation



Dark halos have their own mass-accretion “main sequence”



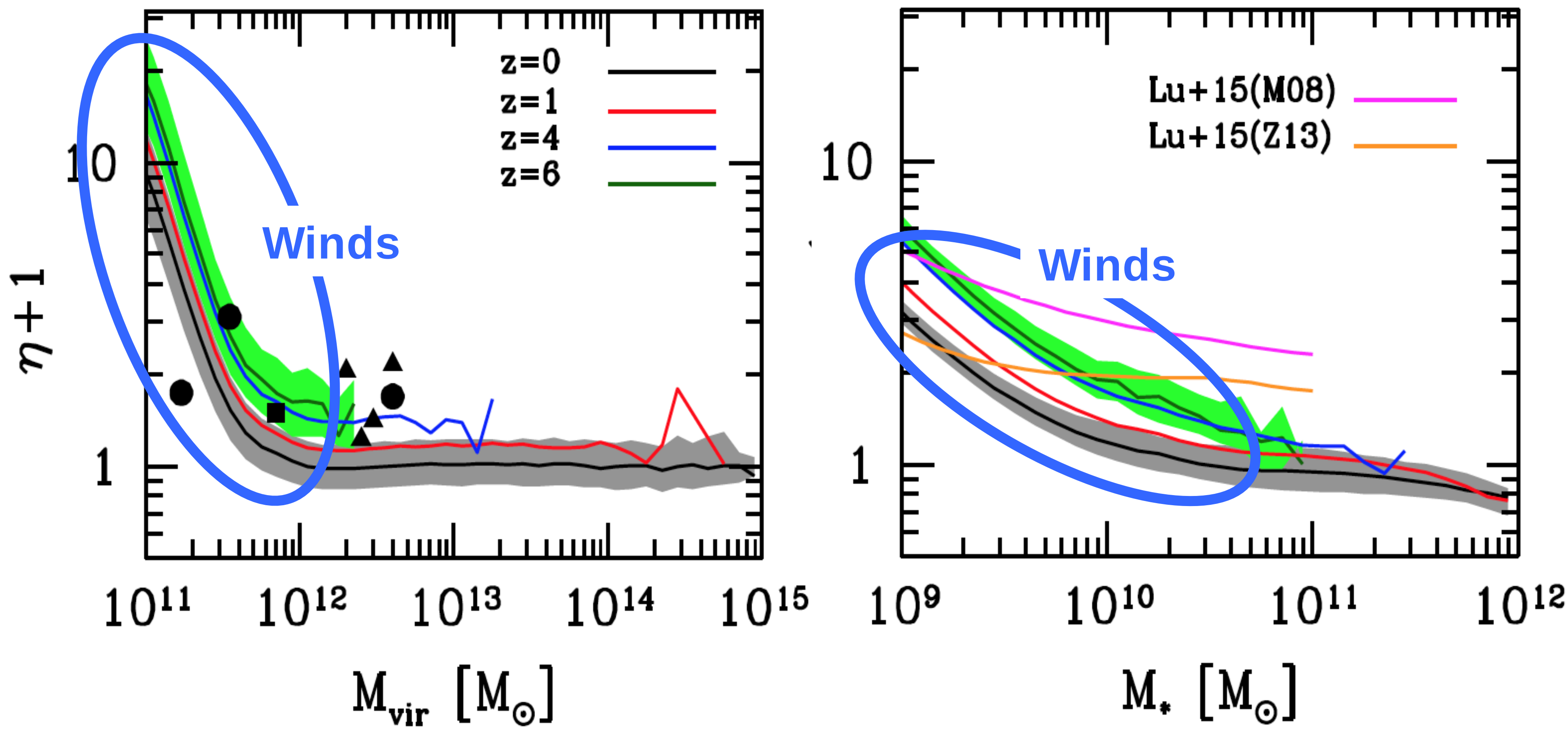
You can get the star-forming main sequence....



....by assuming the right mass-loading factor, η

Needed: a physical theory of stellar winds, which we do not have

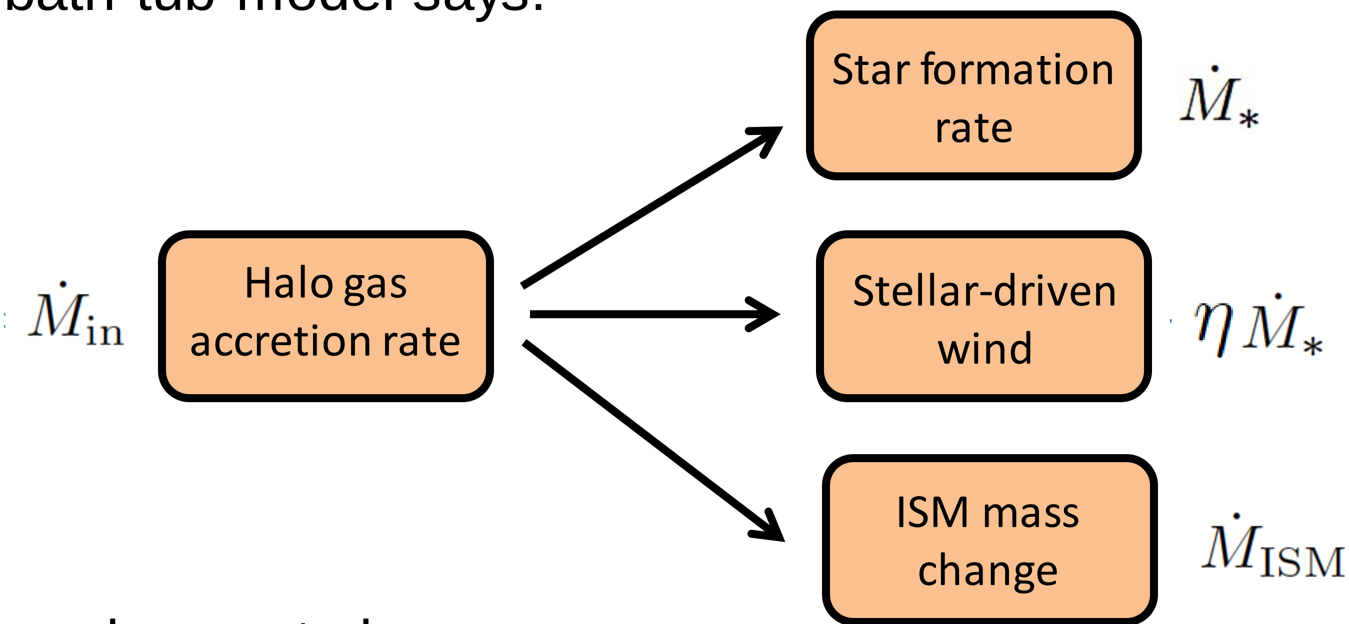
An empirical expression for η based on the "bath-tub model"



Rodriguez-Puebla et al., 2017

Knowing η tells you the star-formation history

The bath-tub model says:

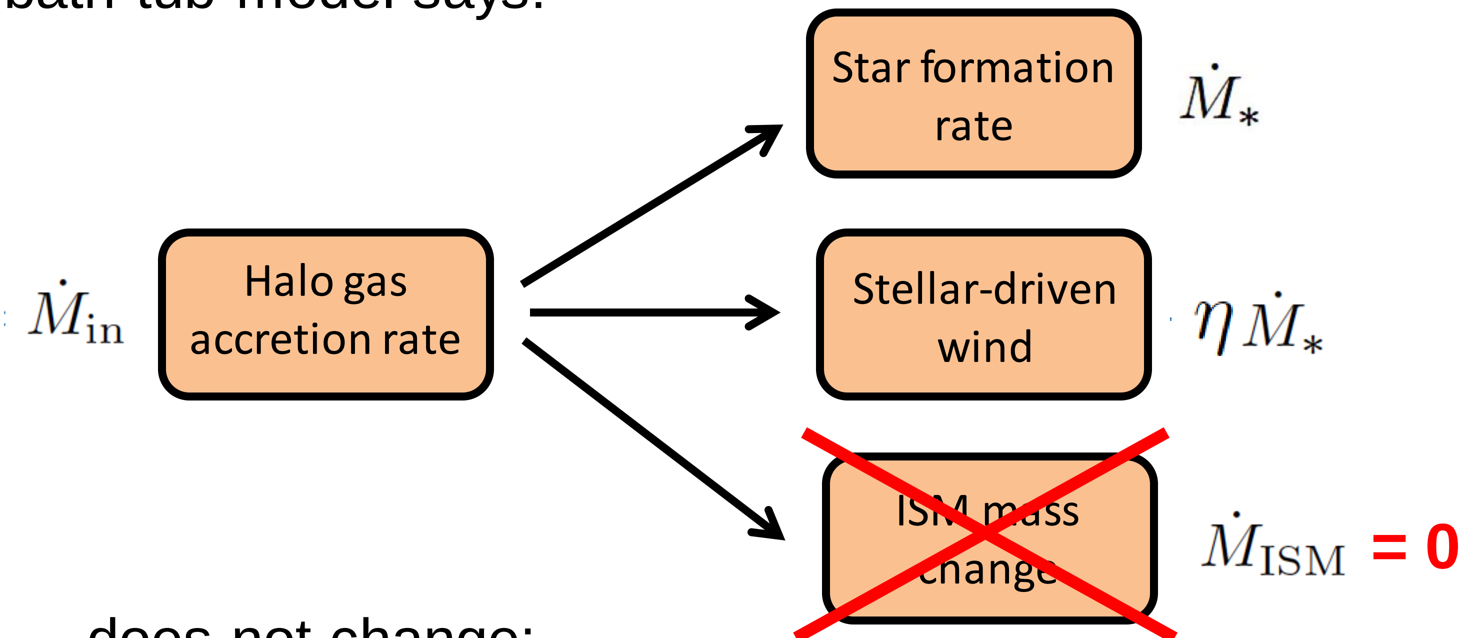


If M_{ISM} does not change:

$$\dot{M}_{\rm in} = (1+\eta)\dot{M}_*$$

Knowing η tells you the star-formation history

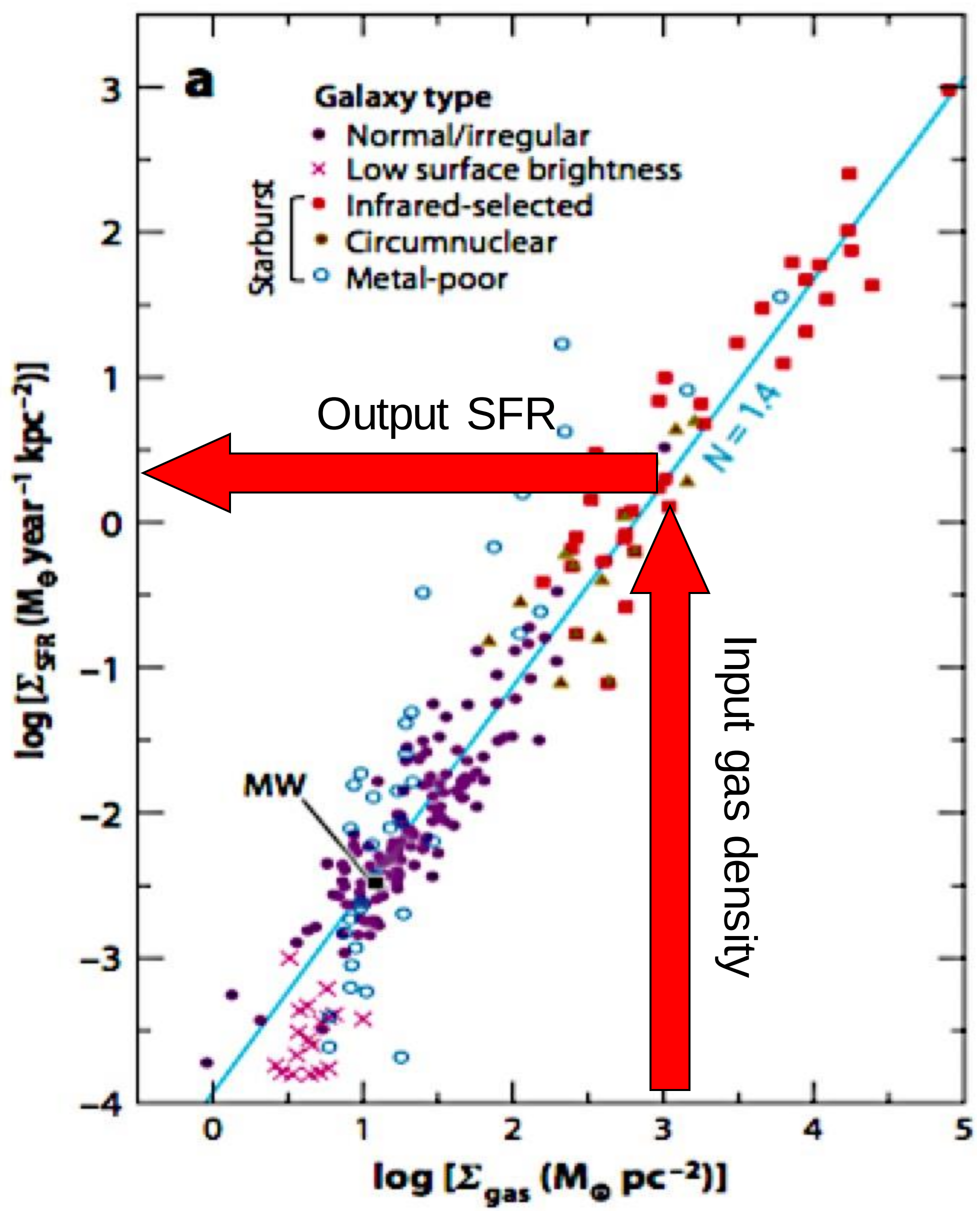
The bath-tub model says:



If M_{ISM} does not change:

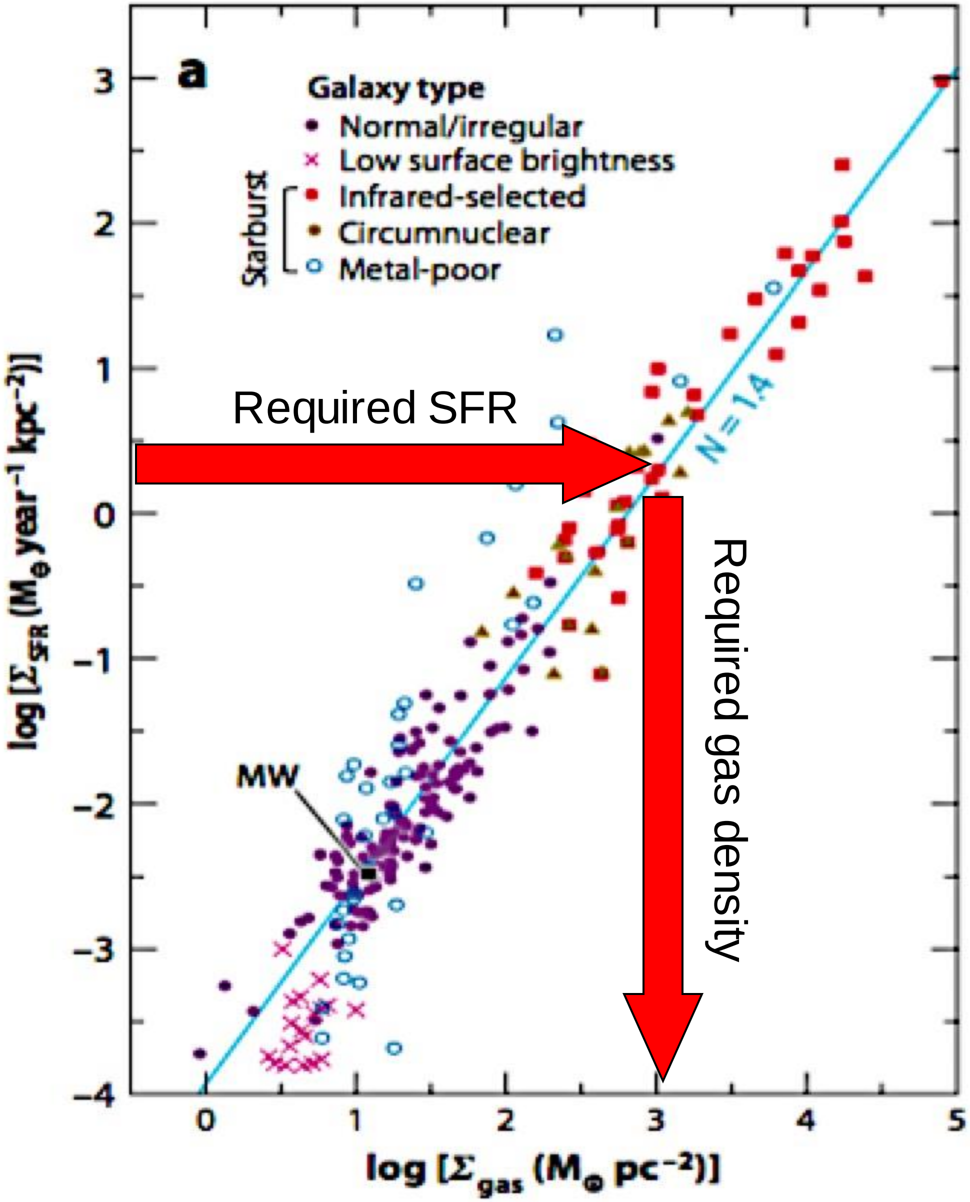
$$\dot{M}_{\rm in} = (1+\eta)\dot{M}_*$$

A different interpretation of the Schmidt-Kennicutt law



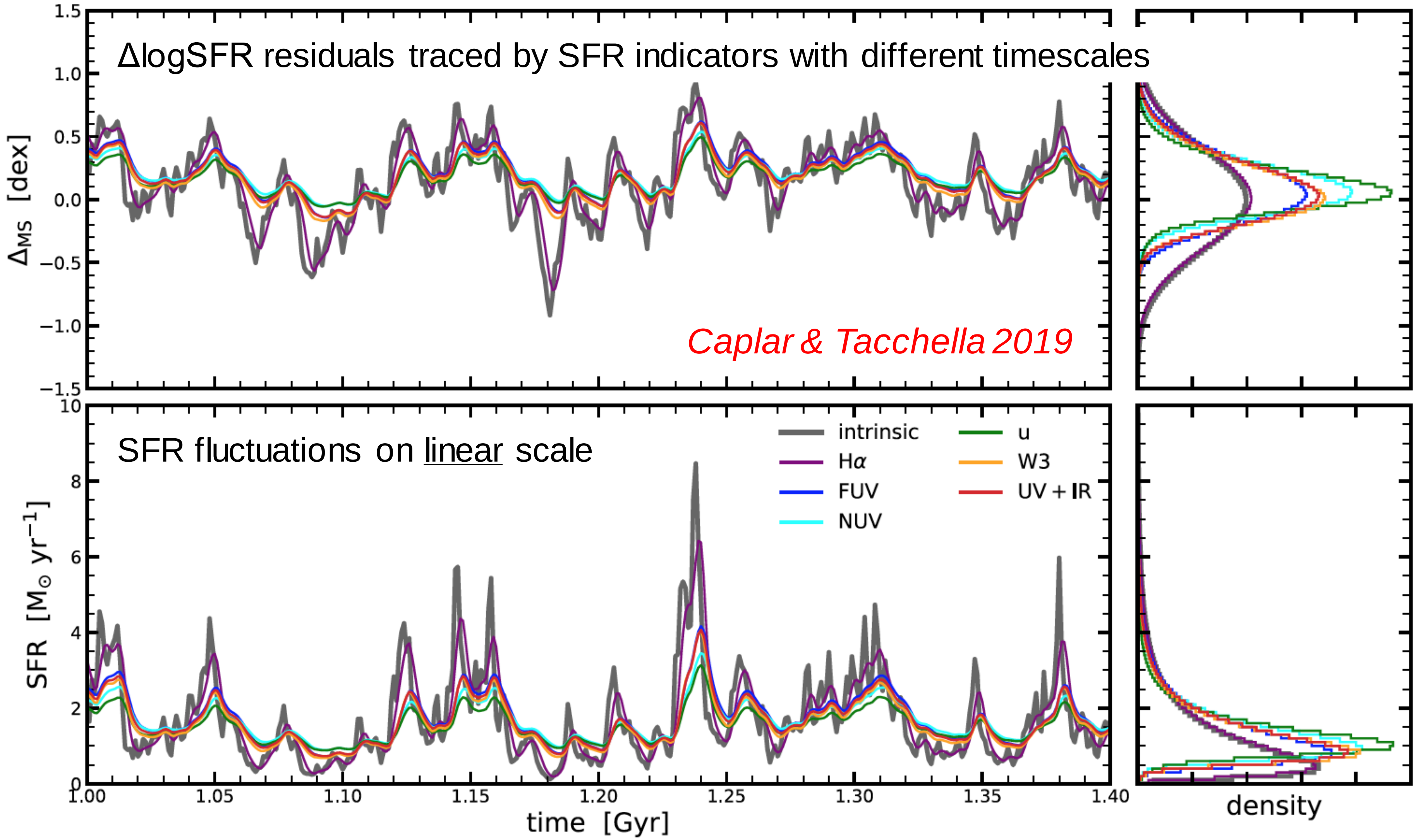
A different interpretation of the Schmidt-Kennicutt law

- Cosmic infall minus wind losses determines the star-formation rate.
- The gas density in the galaxy ***responds*** according to the law in order to make stars at the required rate.
- The causality arrow in the SK law should be read backwards from normal.

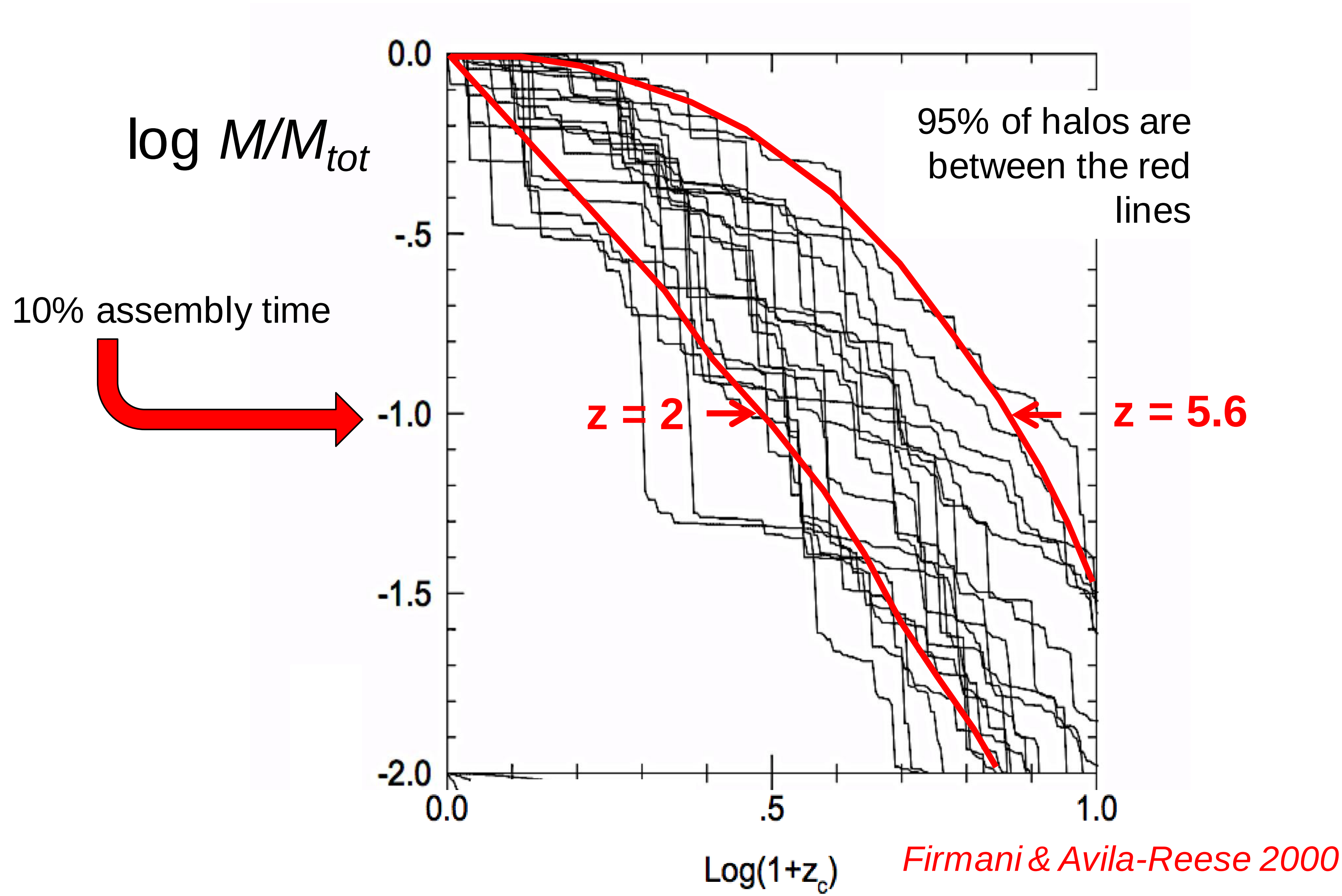


Major unknowns are the origin of ΔSFR residuals and the power spectrum of ΔSFR variations

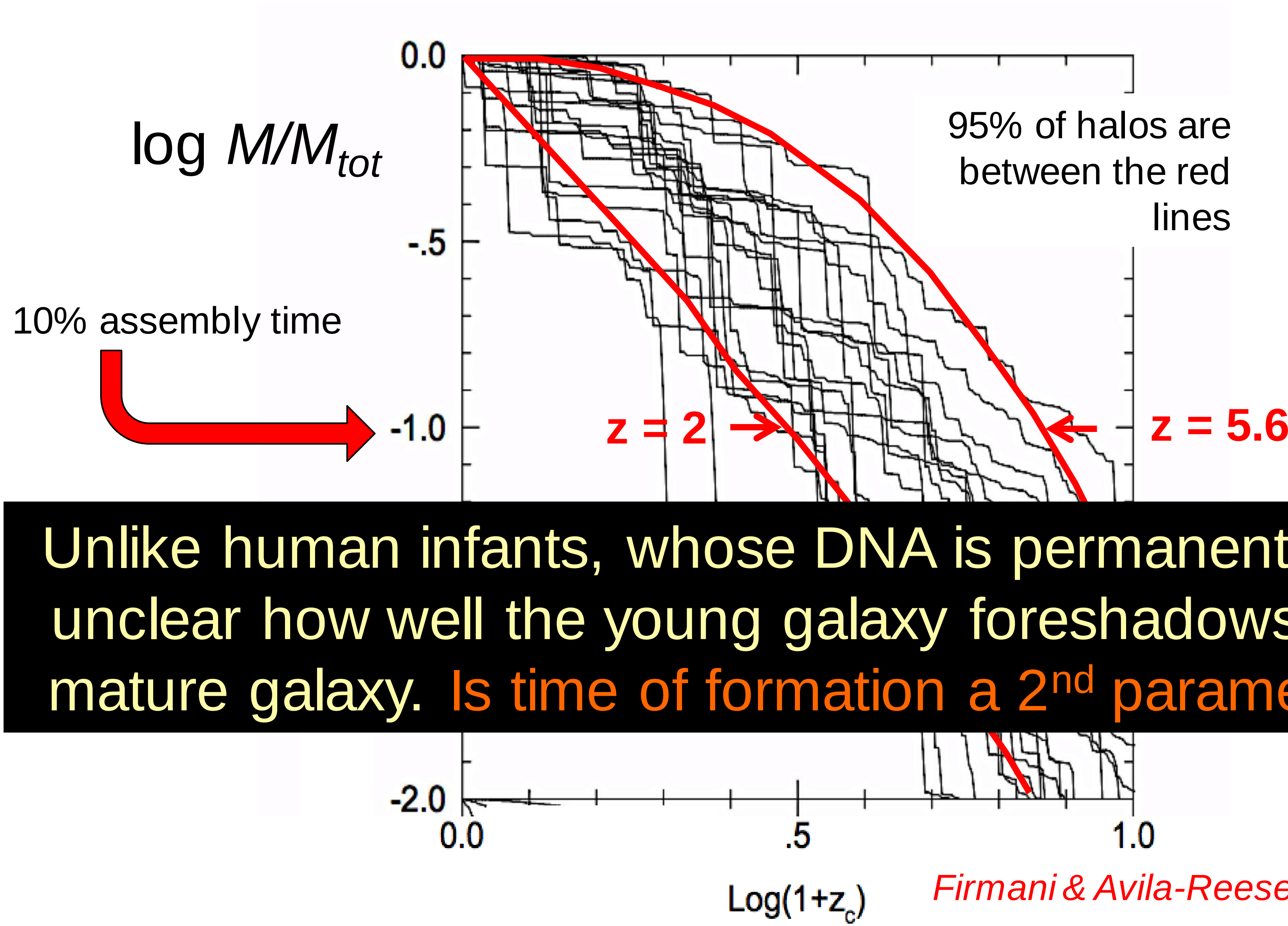
<u>Long-term trends</u> and their effect on galaxy structure are largely unexplored



Assembly histories of dark matter halos with $5 \times 10^{11}\ M_\odot$ today



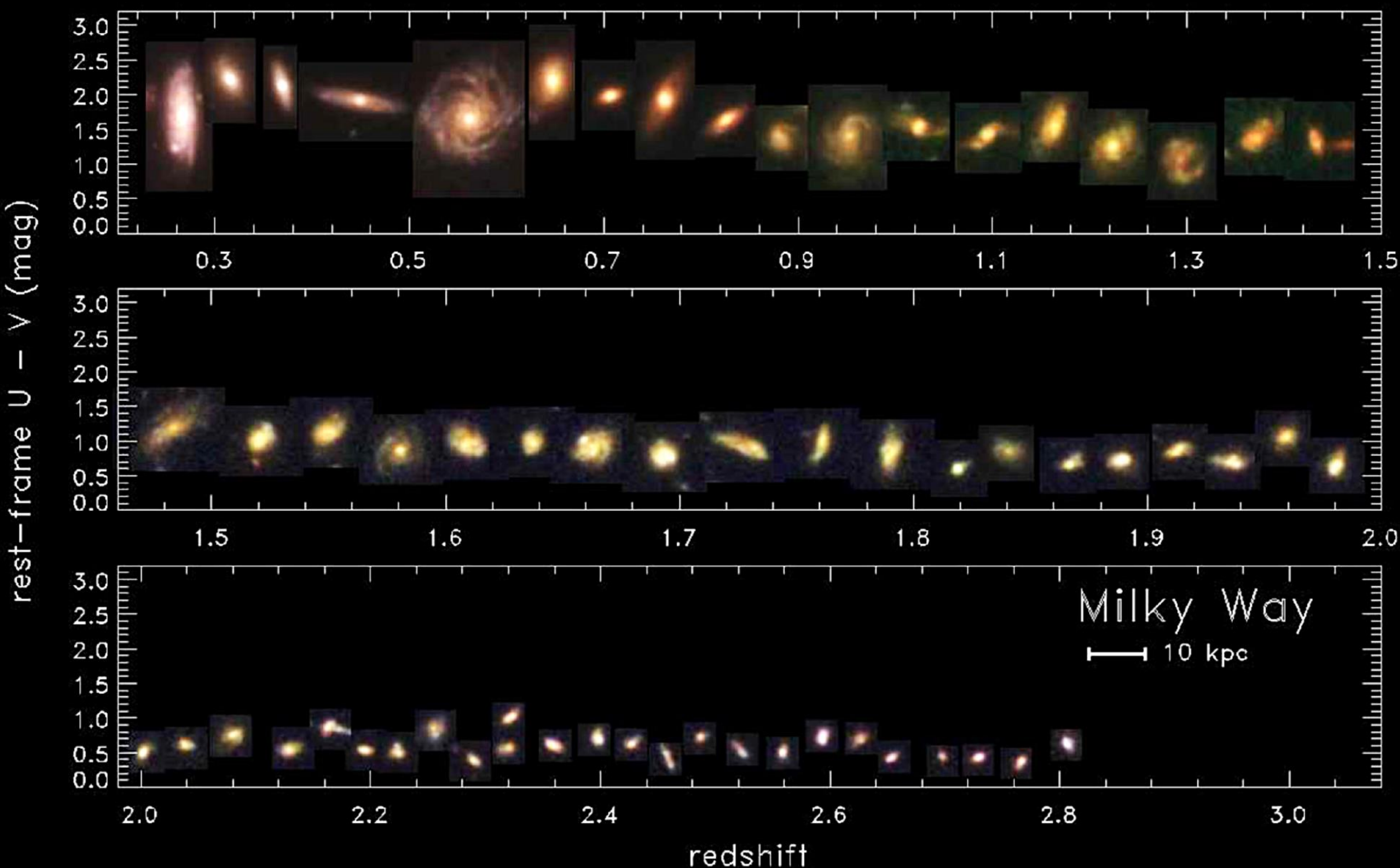
Assembly histories of dark matter halos with 5 x 10^{11} $M_{\odot}$ today



Unlike human infants, whose DNA is permanent, it is unclear how well the young galaxy foreshadows the mature galaxy. Is time of formation a 2nd parameter?

Firmani & Avila-Reese 2000

A mean progenitor history of the Milky Way from abundance matching

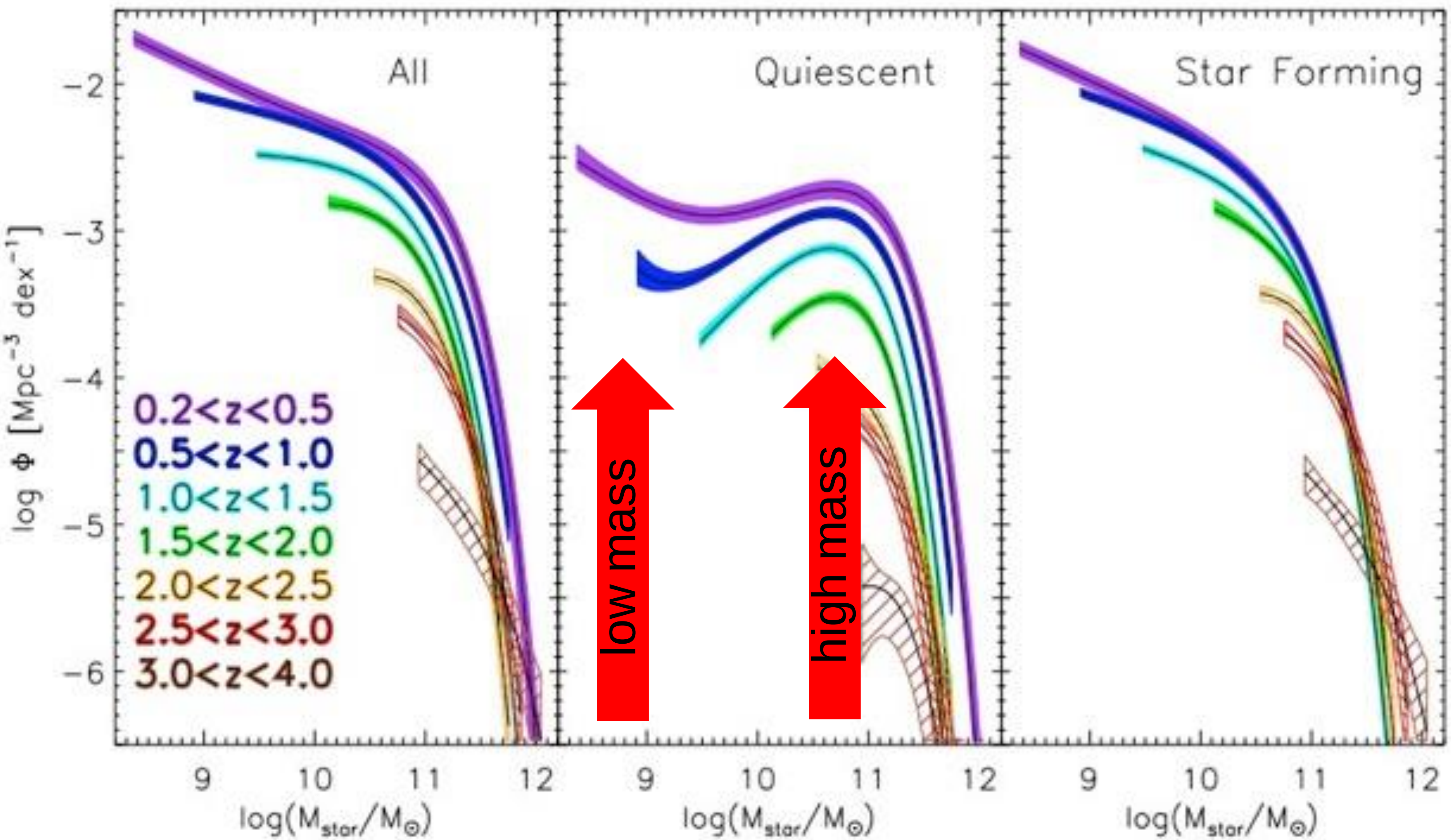


Papovich et al. 2016

There are two quenching channels: high-mass and low-mass

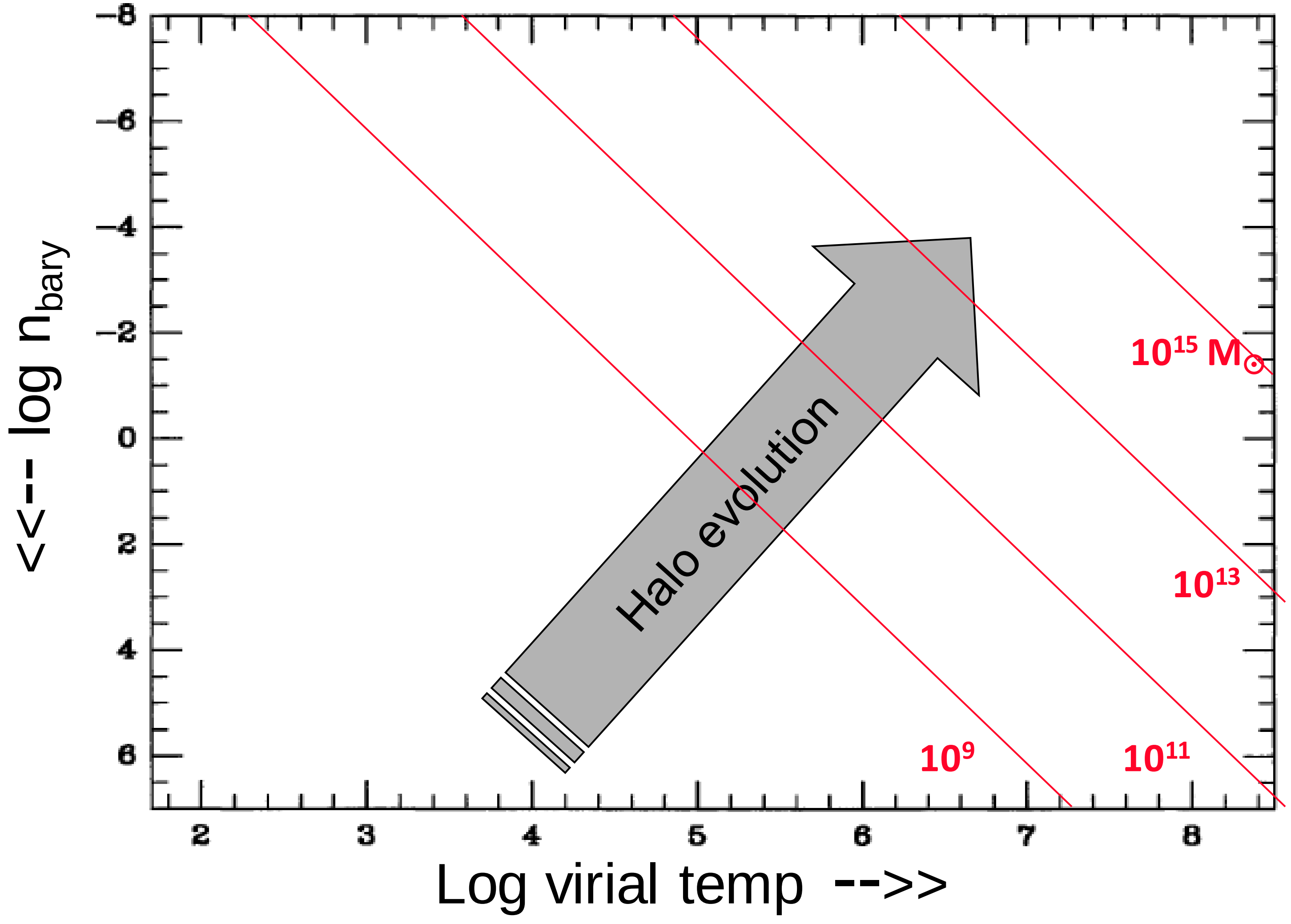
Low-mass channel appears z ~ 1; environmentally caused (Guo et al. 2017)

High--mass channel is early; often identified with **“halo quenching”**



Muzzin et al. 2013; also Ilbert et al. 2010, 2013, Huang et al. 2013

Cooling predicts a dividing line between galaxies and clusters at halo mass $M_{crit} \sim 10^{12}\ M_{\odot}$



Blumenthal et al. 1984; also Rees and Ostriker 1977, Silk 1977

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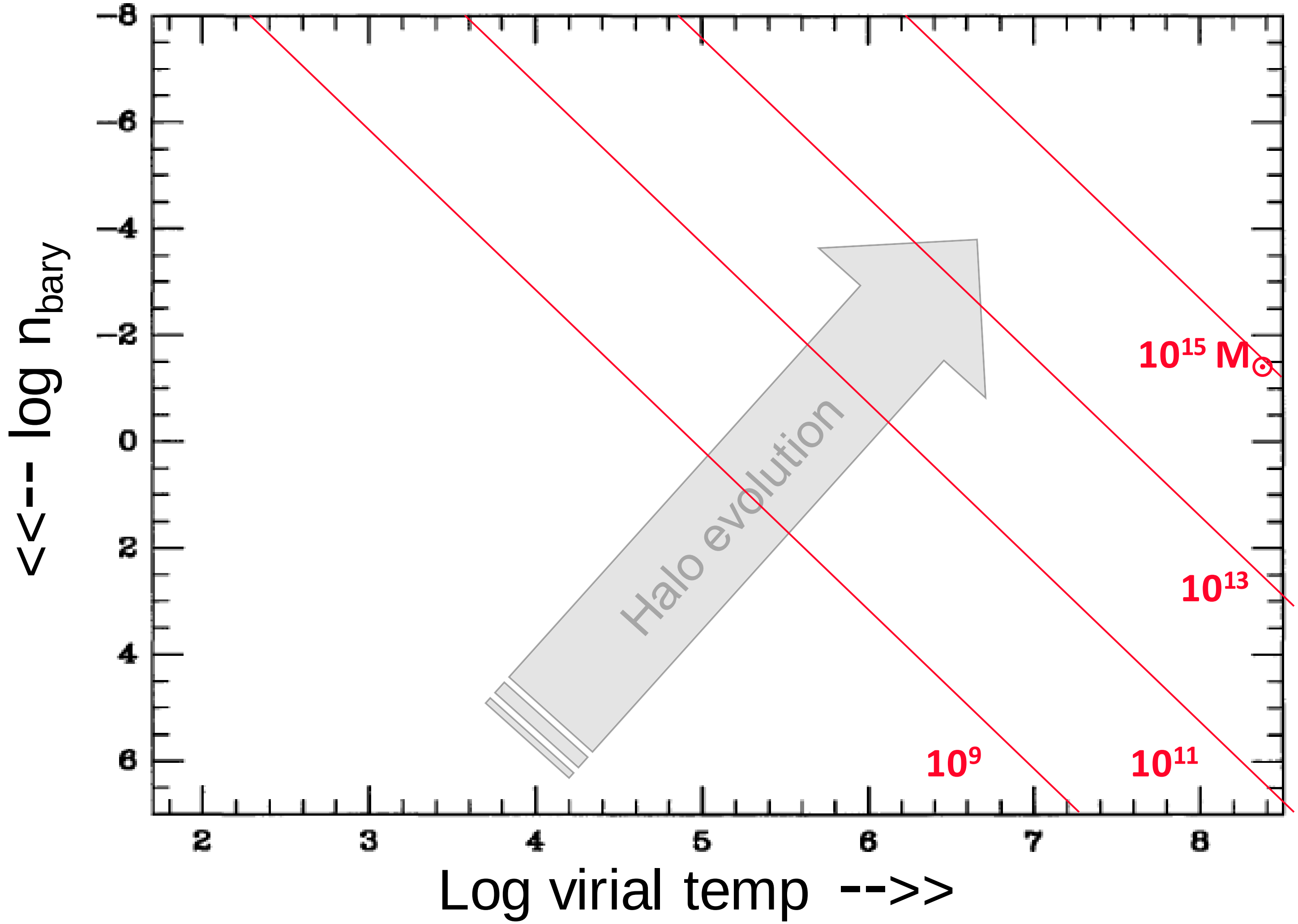

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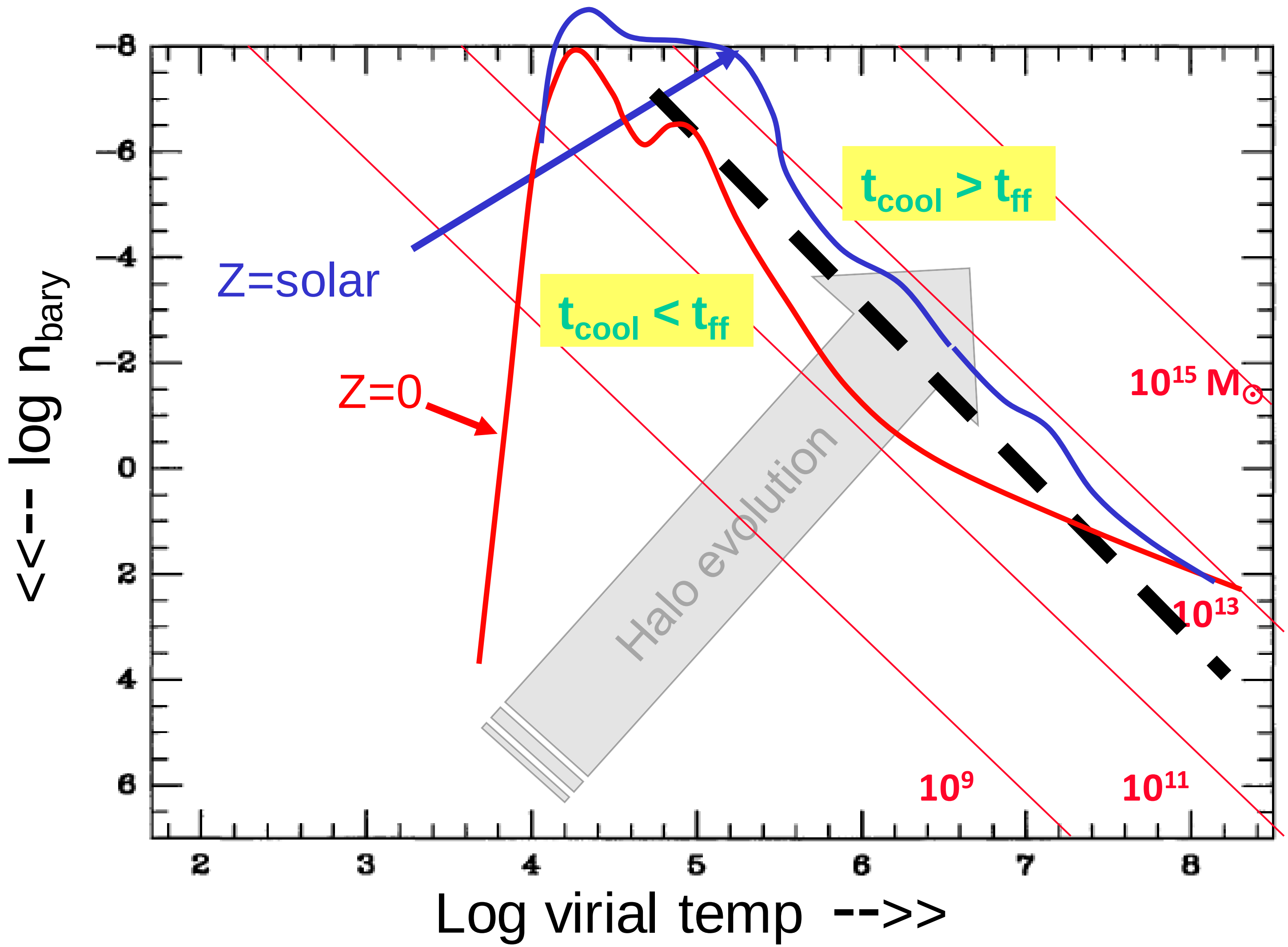
Cooling predicts a dividing line between galaxies and clusters at halo mass $M_{crit} \sim 10^{12} M_\odot$



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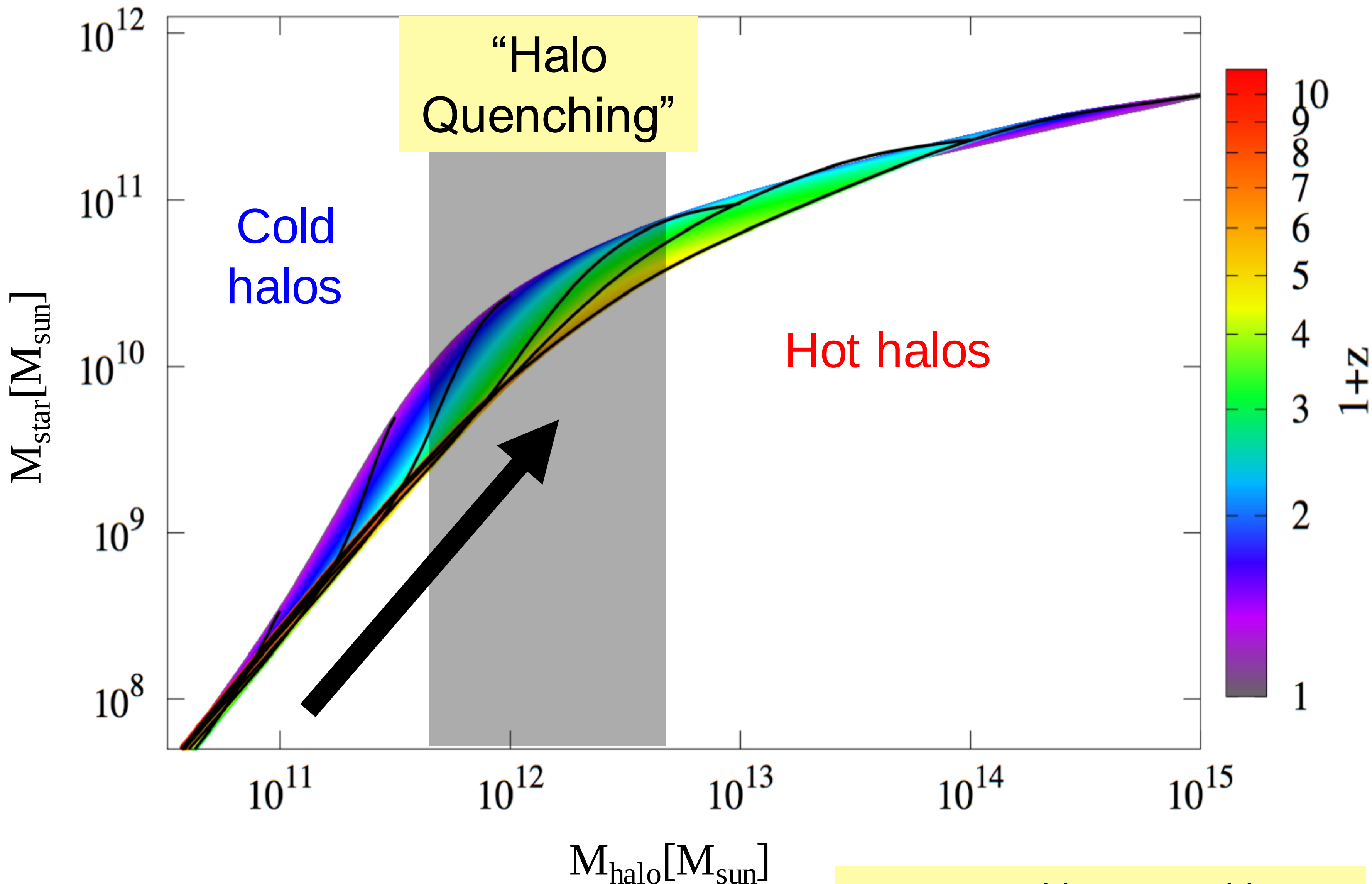
The stellar-mass/halo-mass relation from SHAM



SHAM: Rodriguez-Puebla+17

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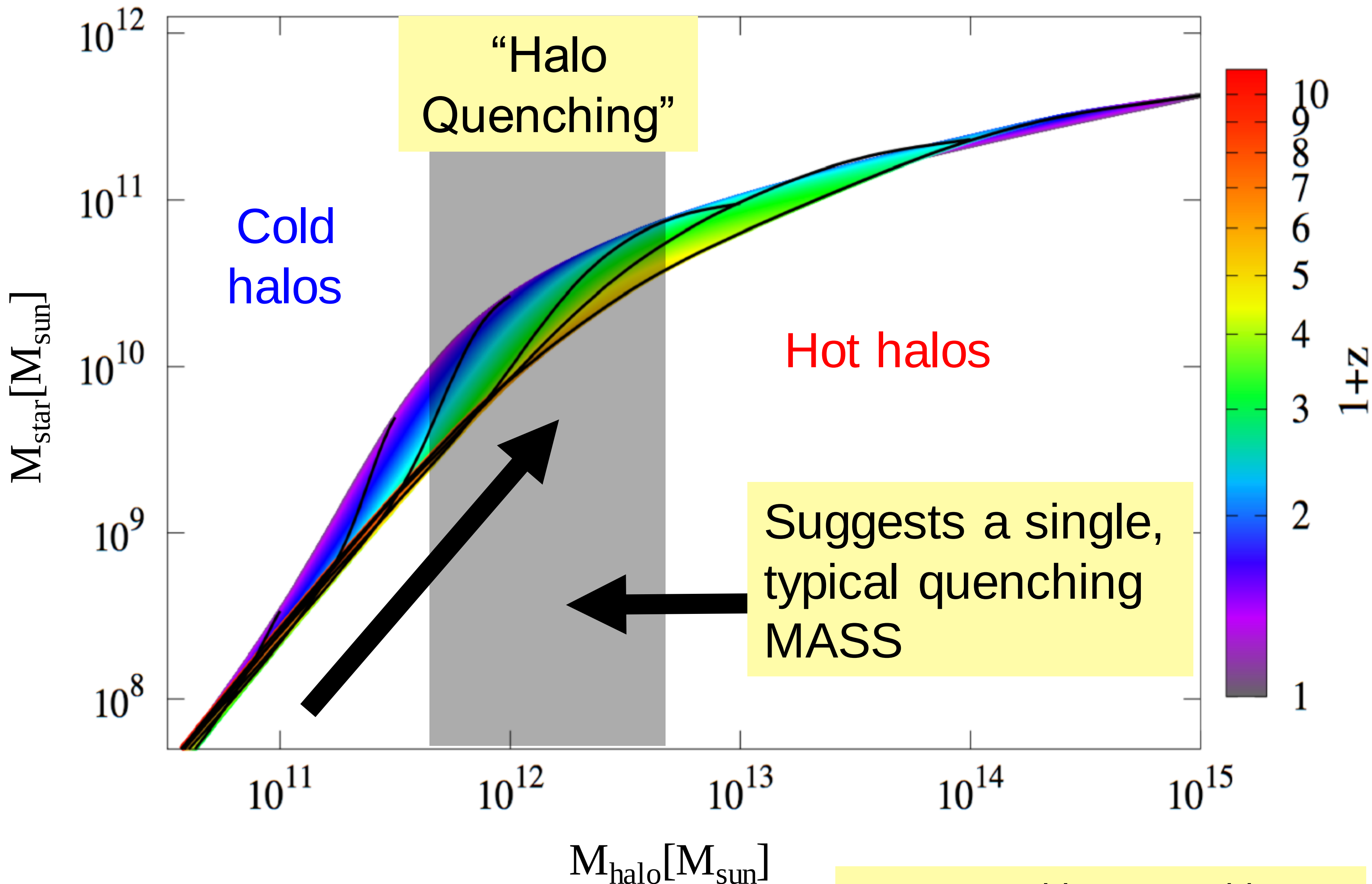

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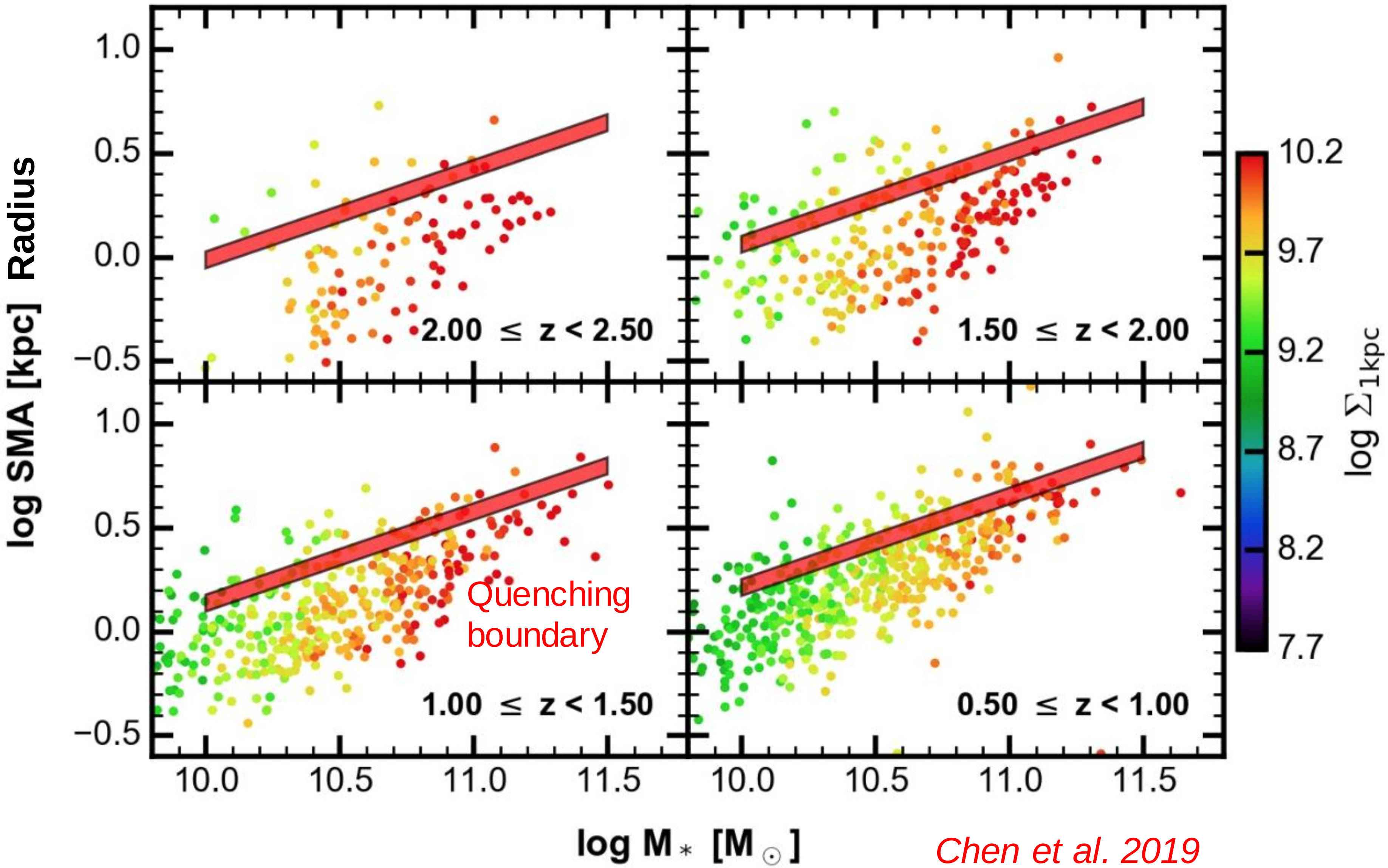
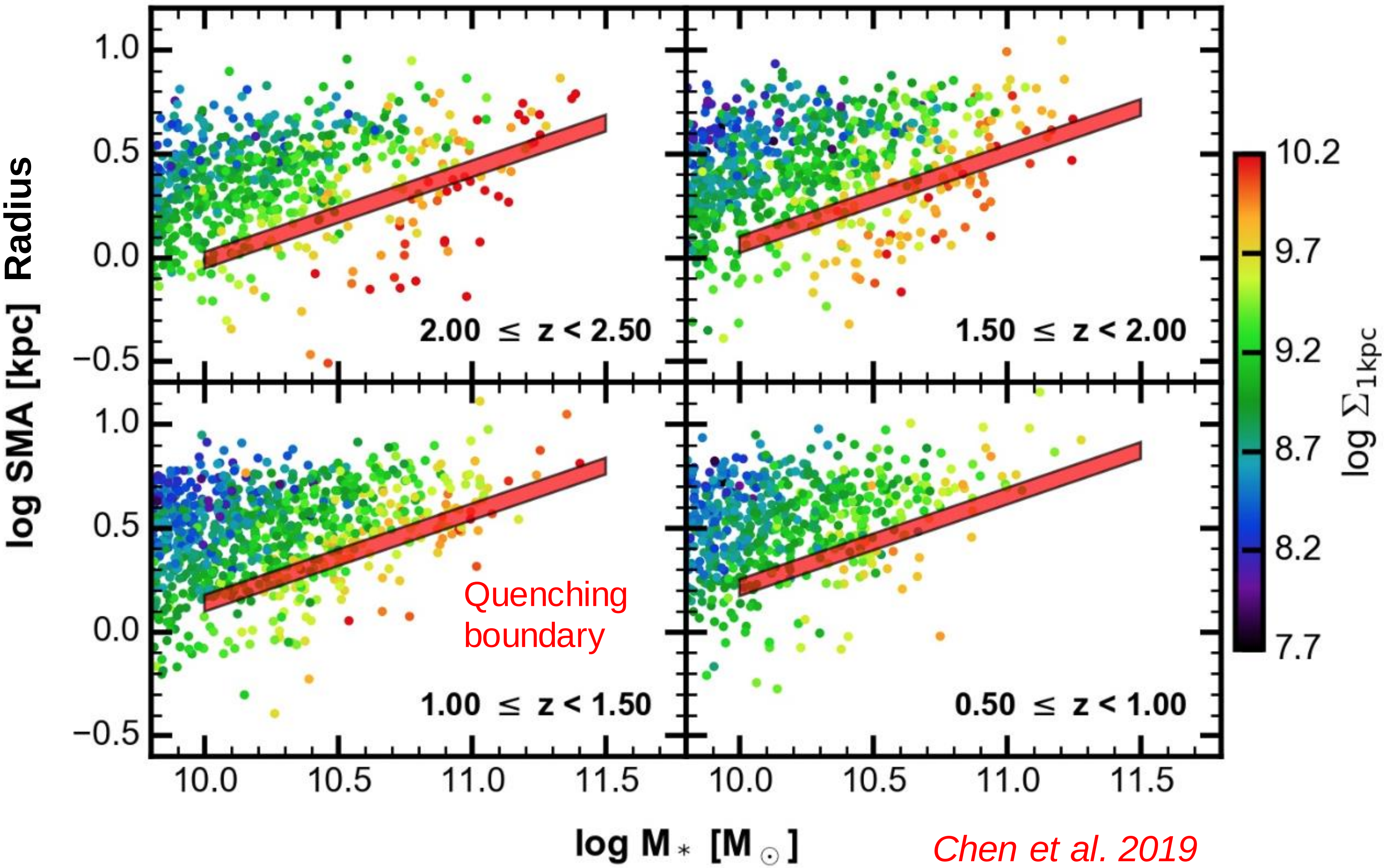
R_{eff} vs. M_*: Quenched galaxies



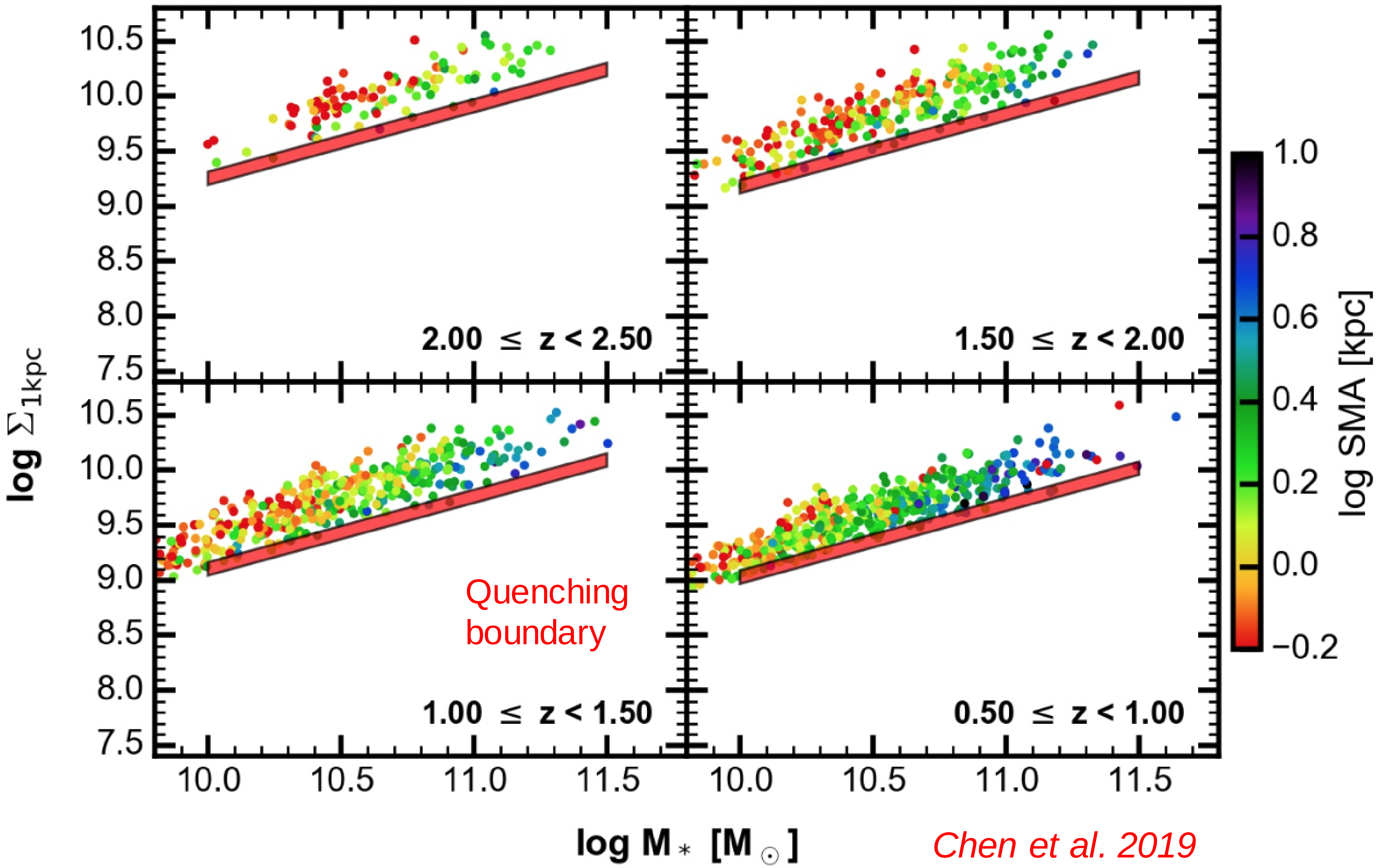
Chen et al. 2019

R_{eff} vs. M_*: Star-forming galaxies



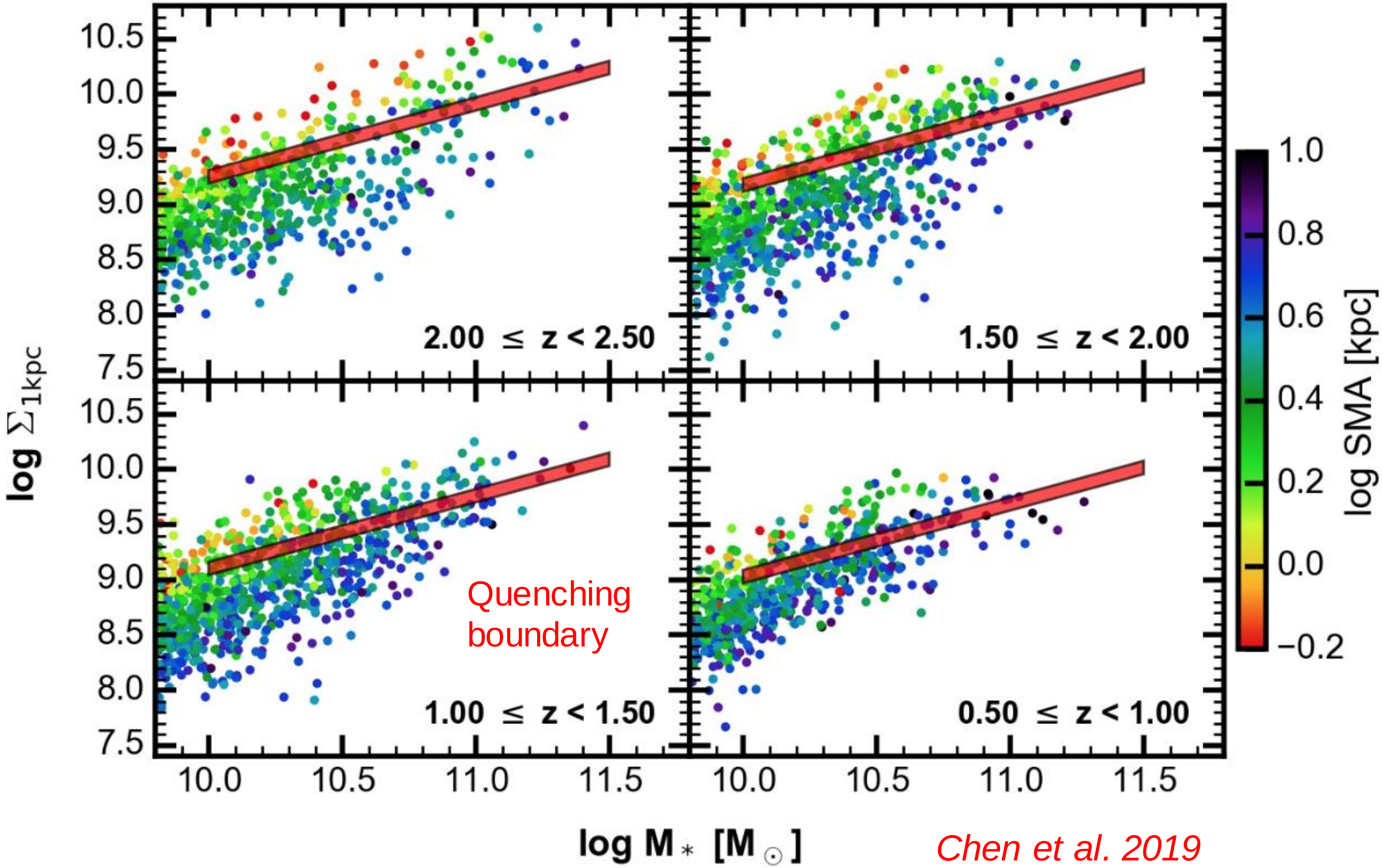
Chen et al. 2019

Σ_1 vs. M_*: Quenched galaxies



Chen et al. 2019

Σ_1 vs. M_*: Star-forming galaxies



Chen et al. 2019

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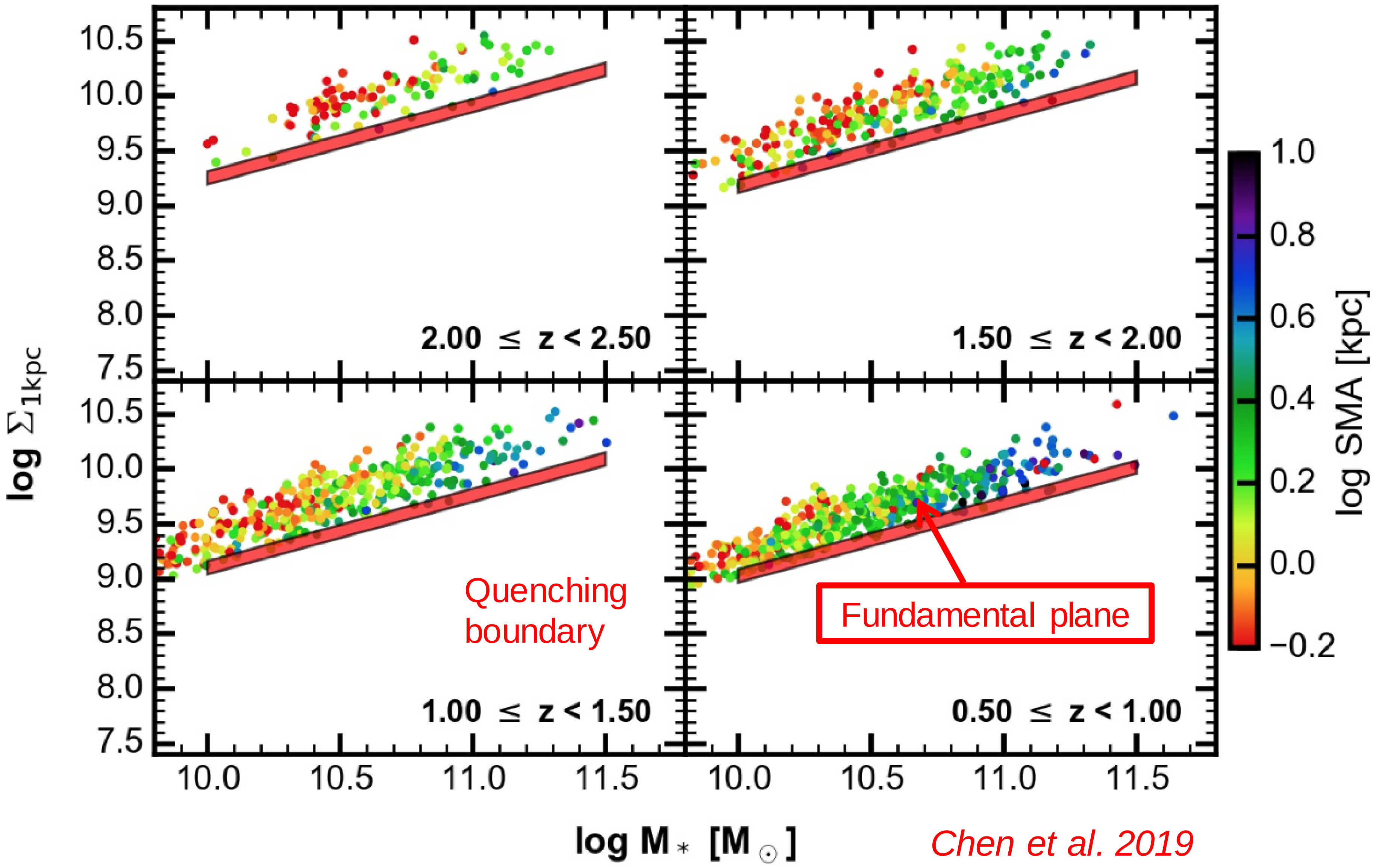
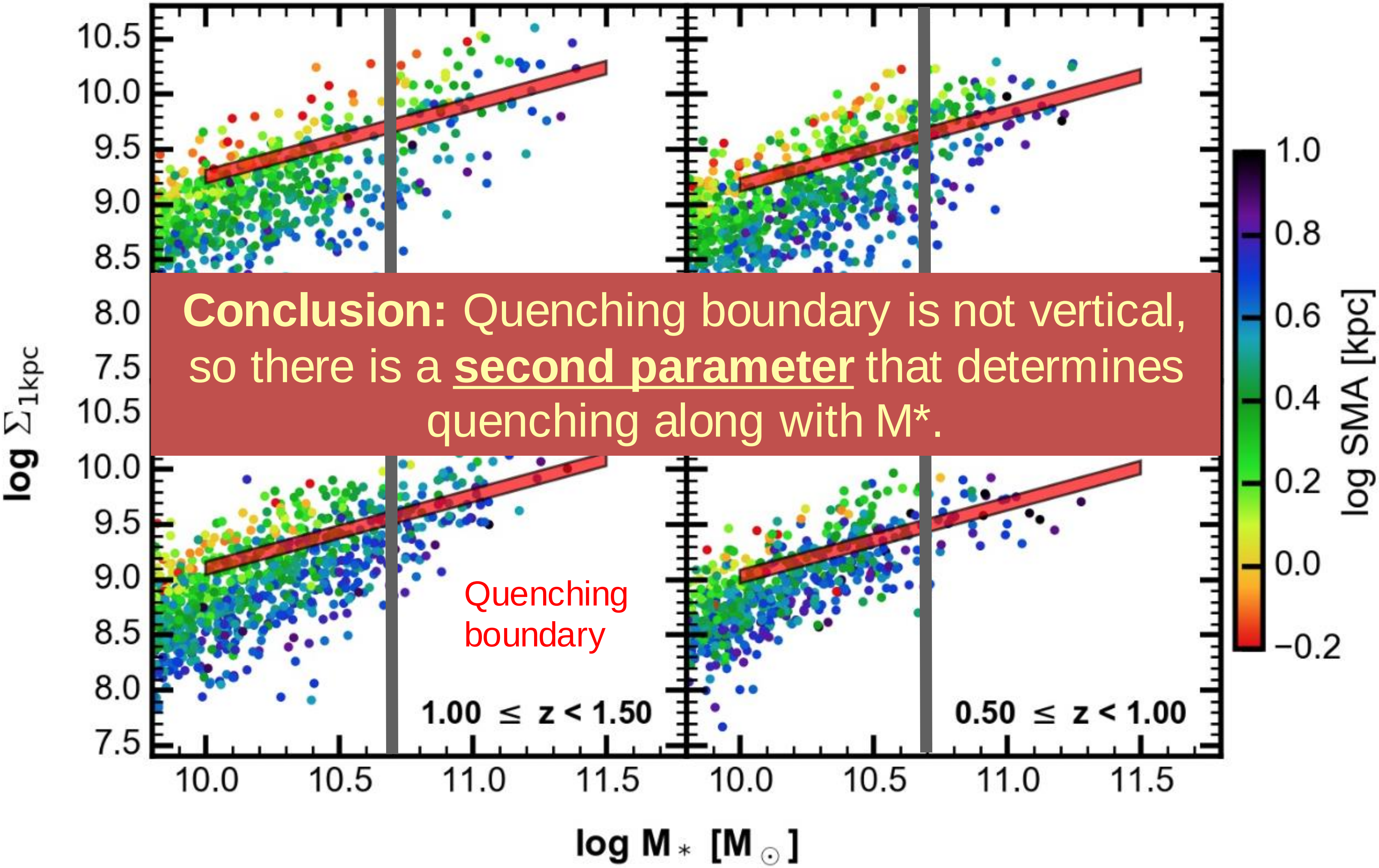


Chen et al. 2019

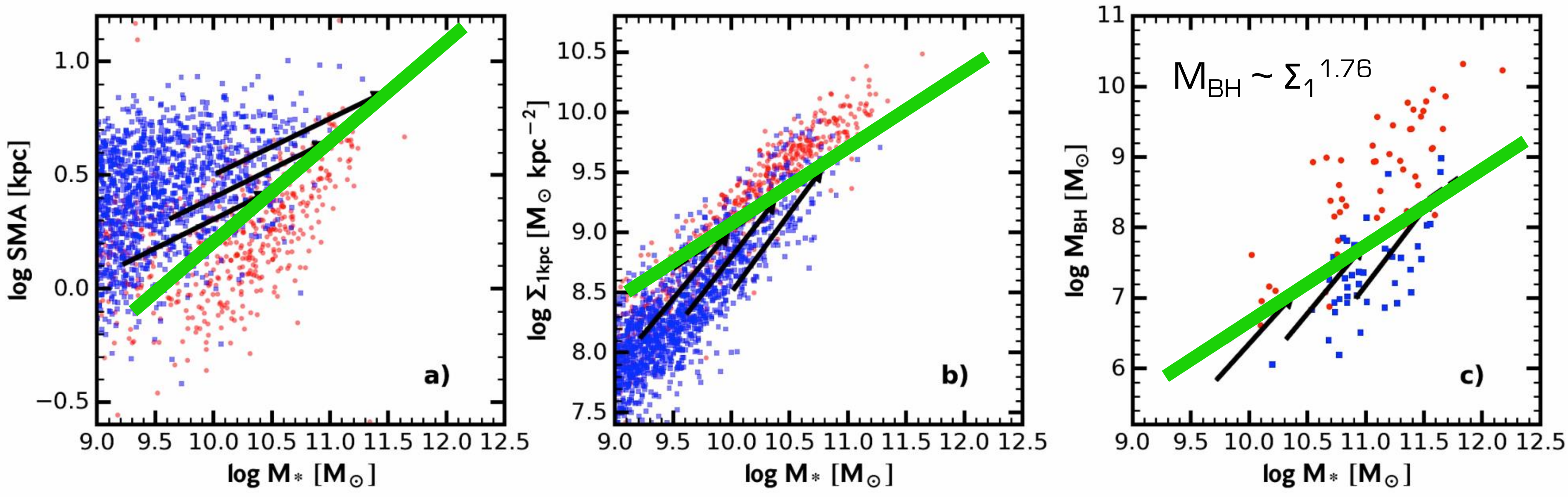
Σ_1 vs. M_*: Star-forming galaxies



Conclusion: Quenching boundary is not vertical, so there is a **second parameter** that determines quenching along with M*.

A single 4-D space: Σ_1, R_e, M_{BH}, M_*

Star-forming galaxies evolve along power-law tracks until they encounter a boundary, where they **enter the green valley**.



R_e vs. M_* Σ_1 vs. M_* M_{BH} vs. M_*

Chen et al. 2019

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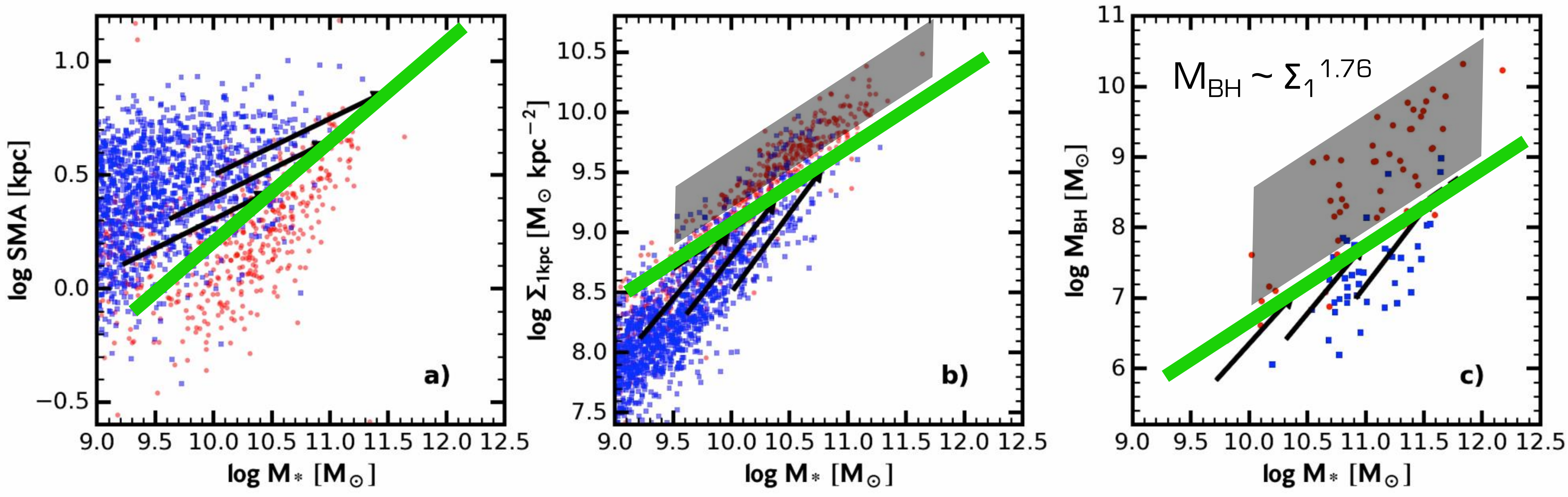
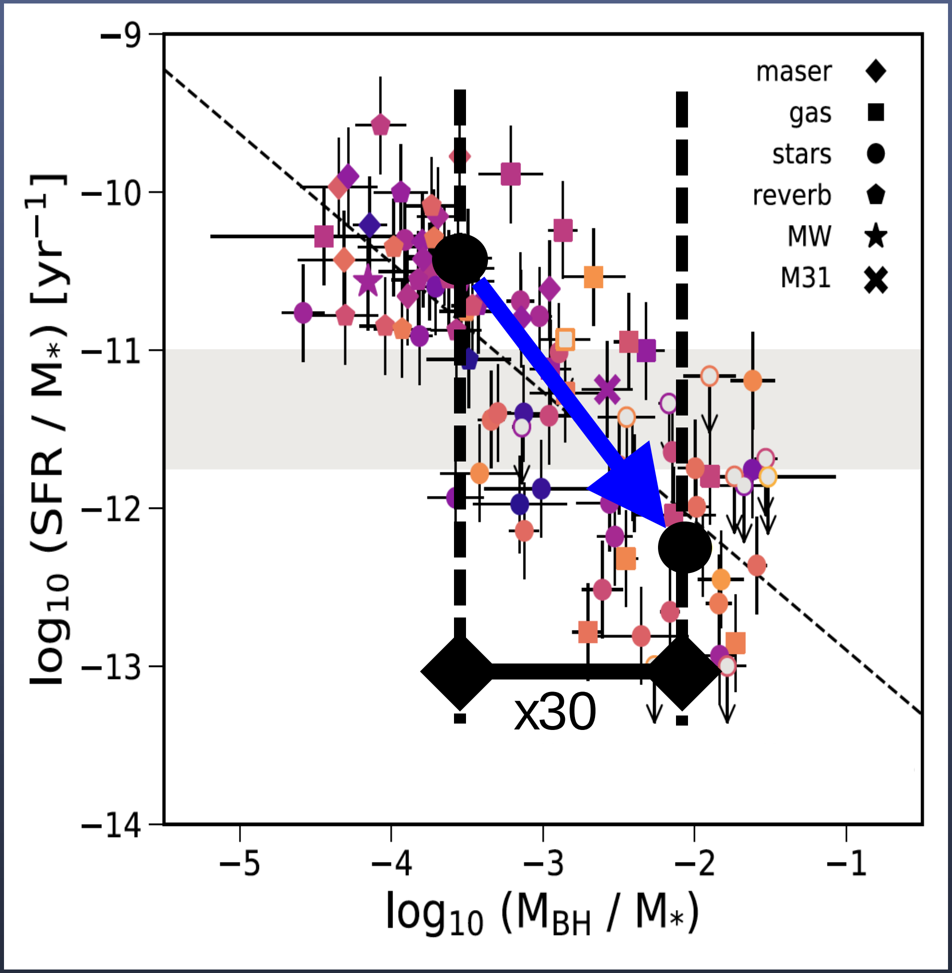


R_e vs. M_* Σ_1 vs. M_* M_{BH} vs. M_*

Chen et al. 2019

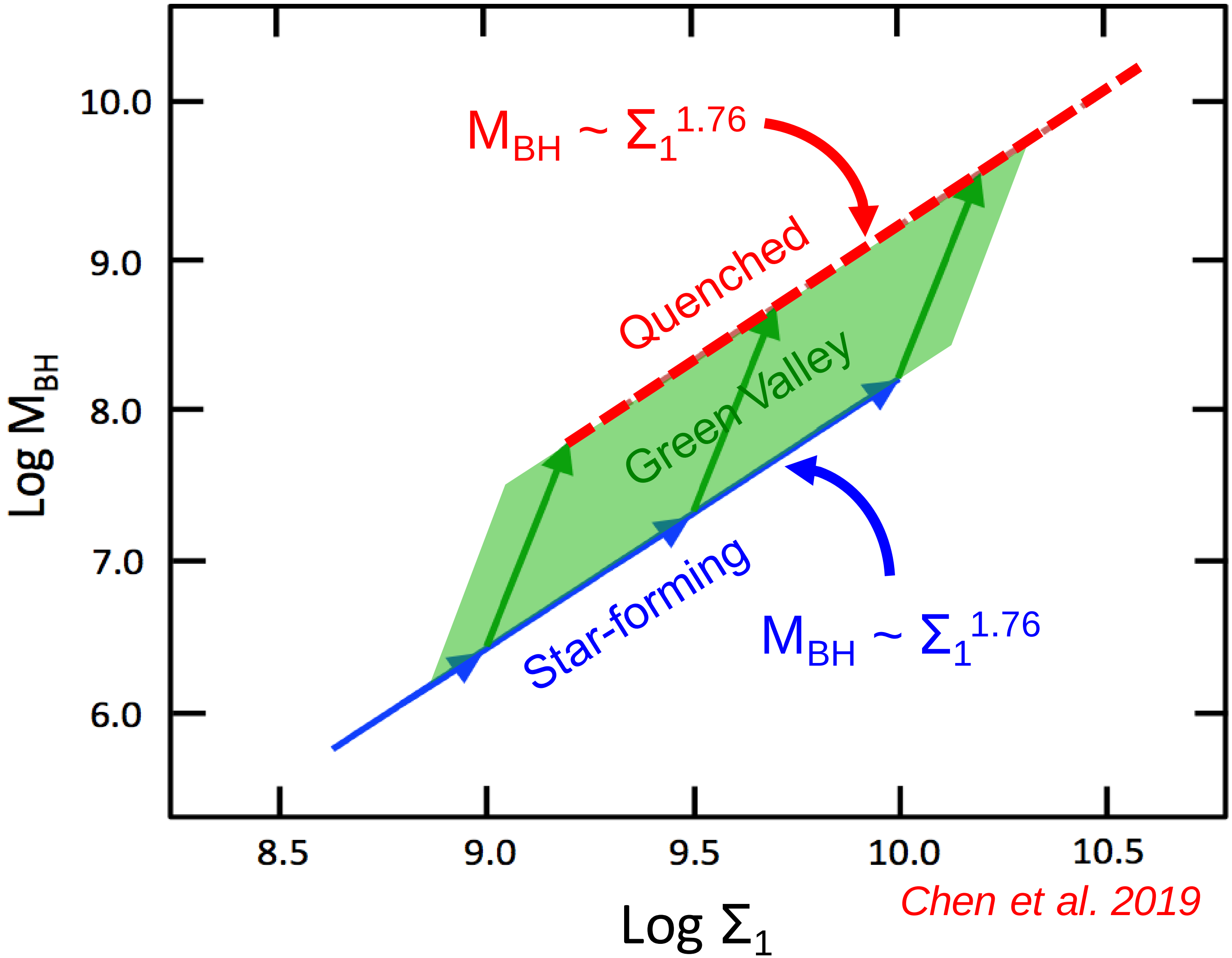
Δ log M_{BH} vs. Δ log SSFR through the green valley

At least 90% of BH growth takes place in the GV

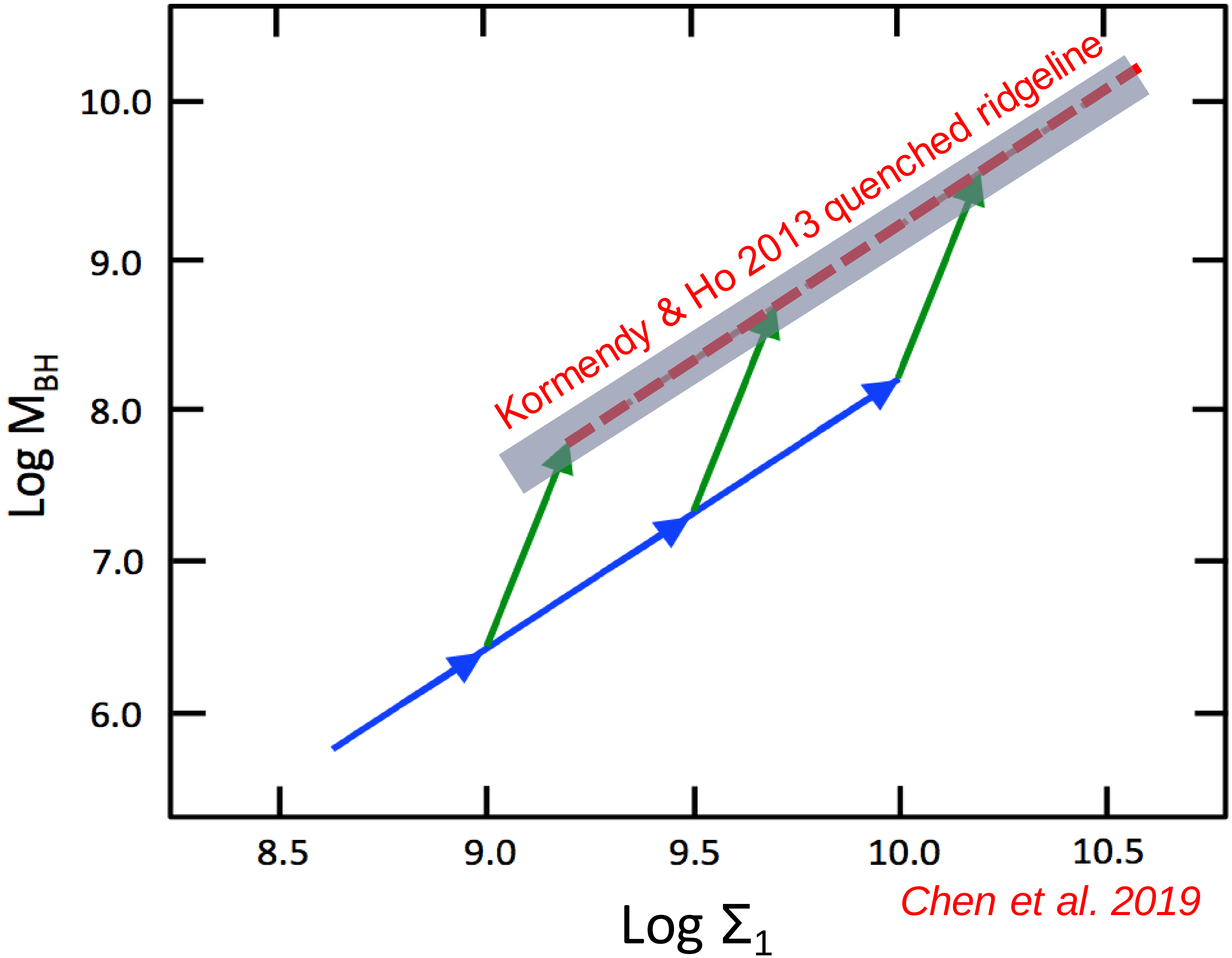


Terrazas et al. 2017

BH growth in star-forming galaxies and in the green valley



Comparison of assumed scaling laws to data



Chen et al. 2019

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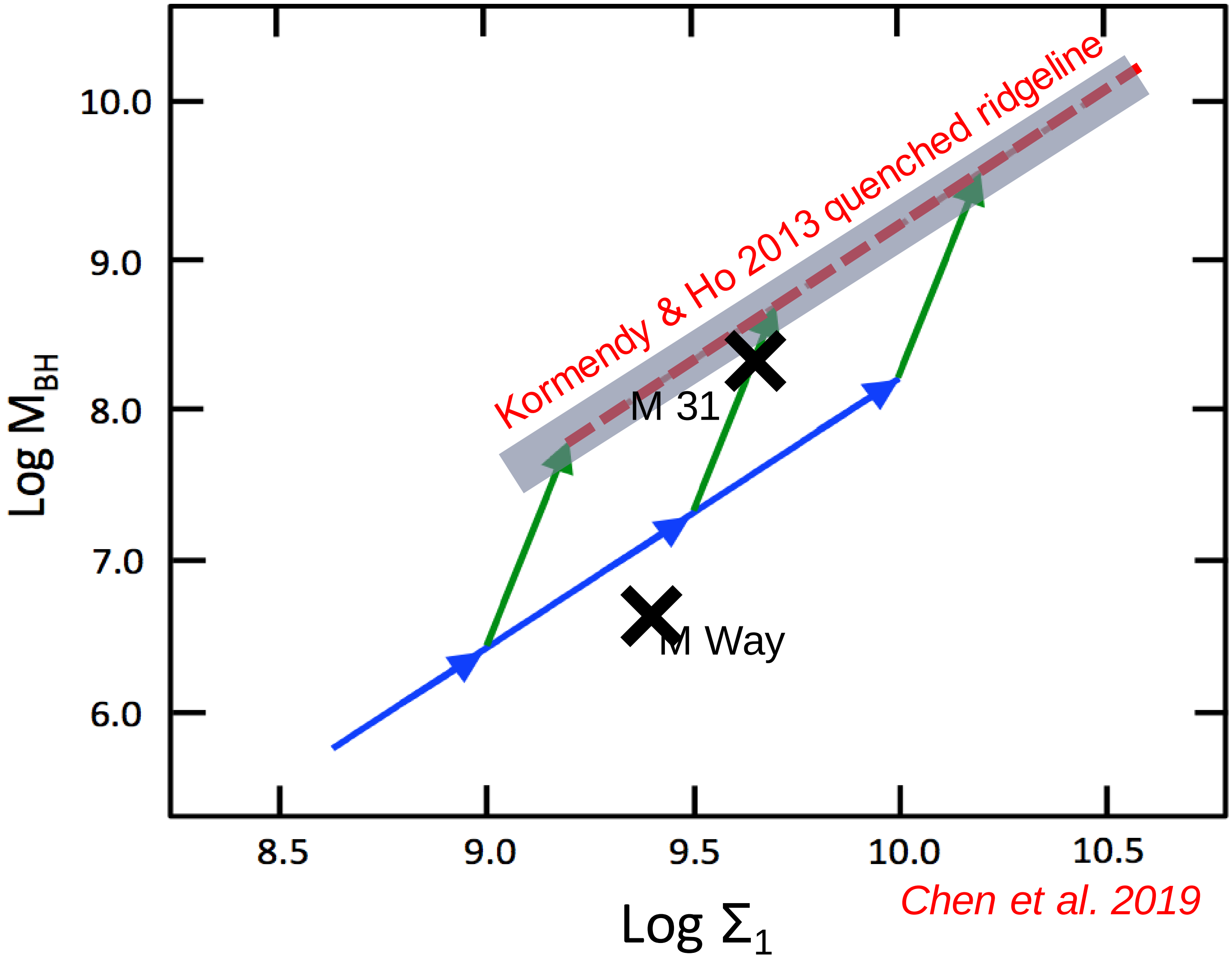
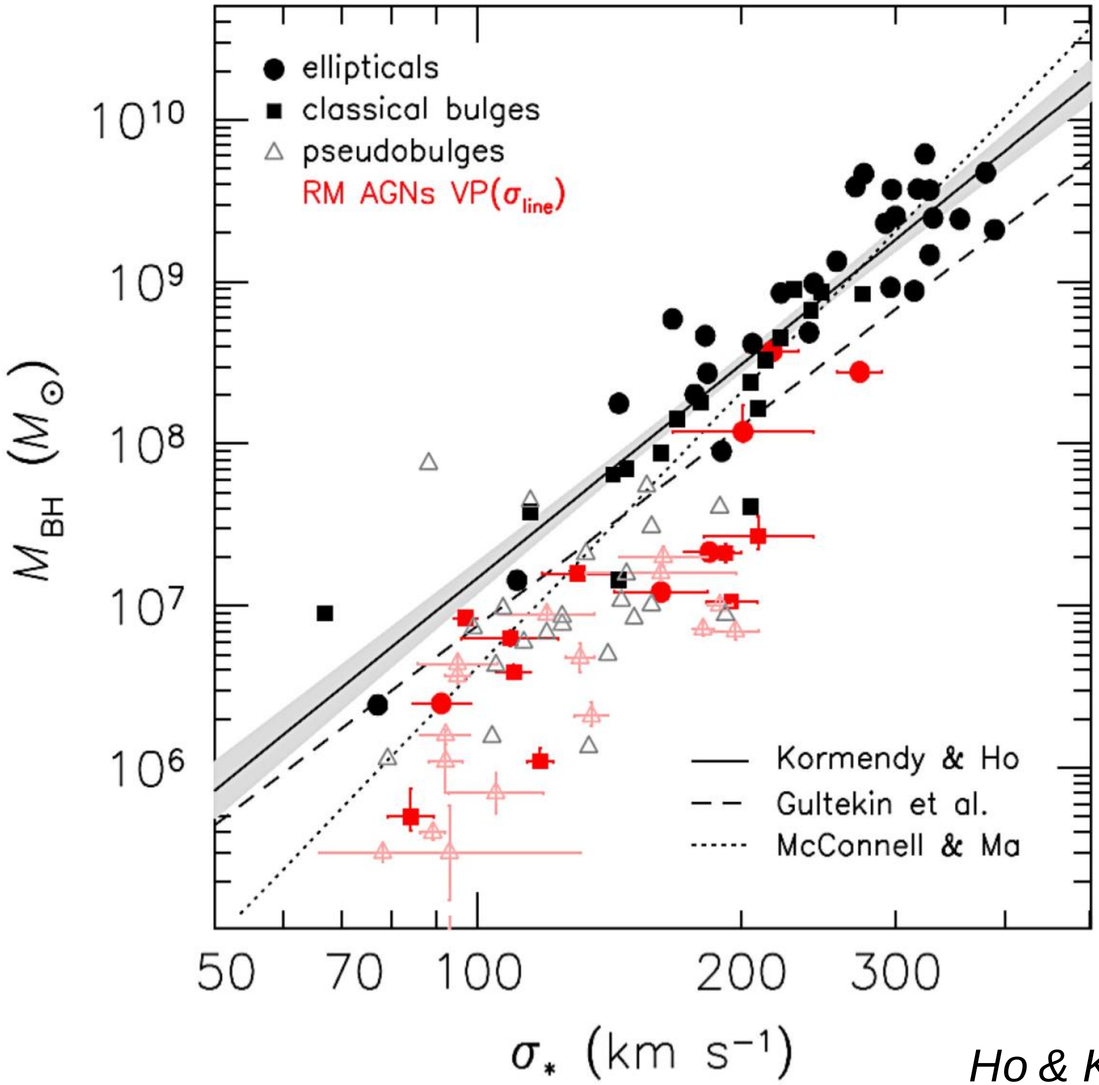


Pseudobulges have small BHs b/c they have not yet crossed the green valley



Ho & Kim 2014

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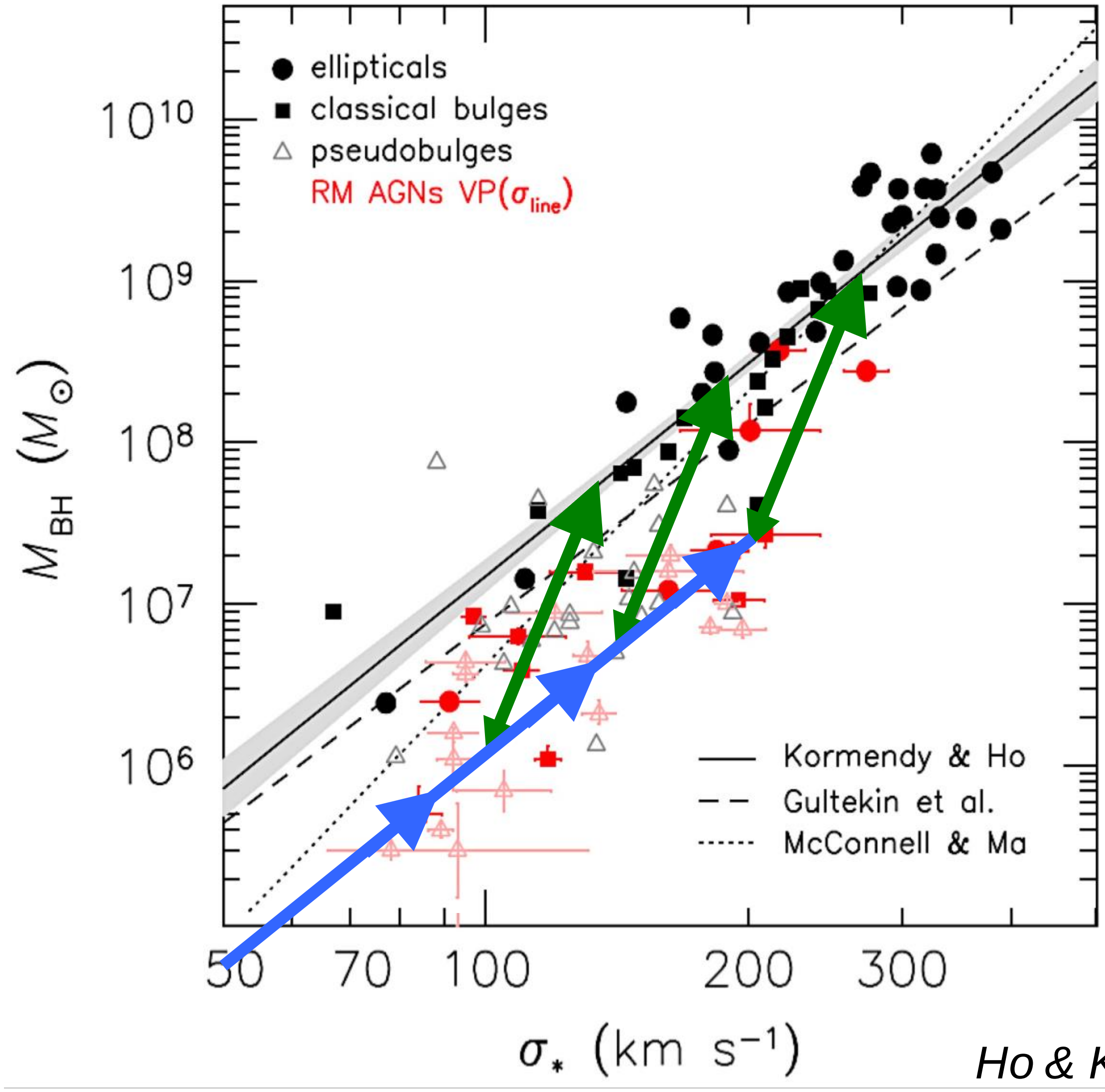
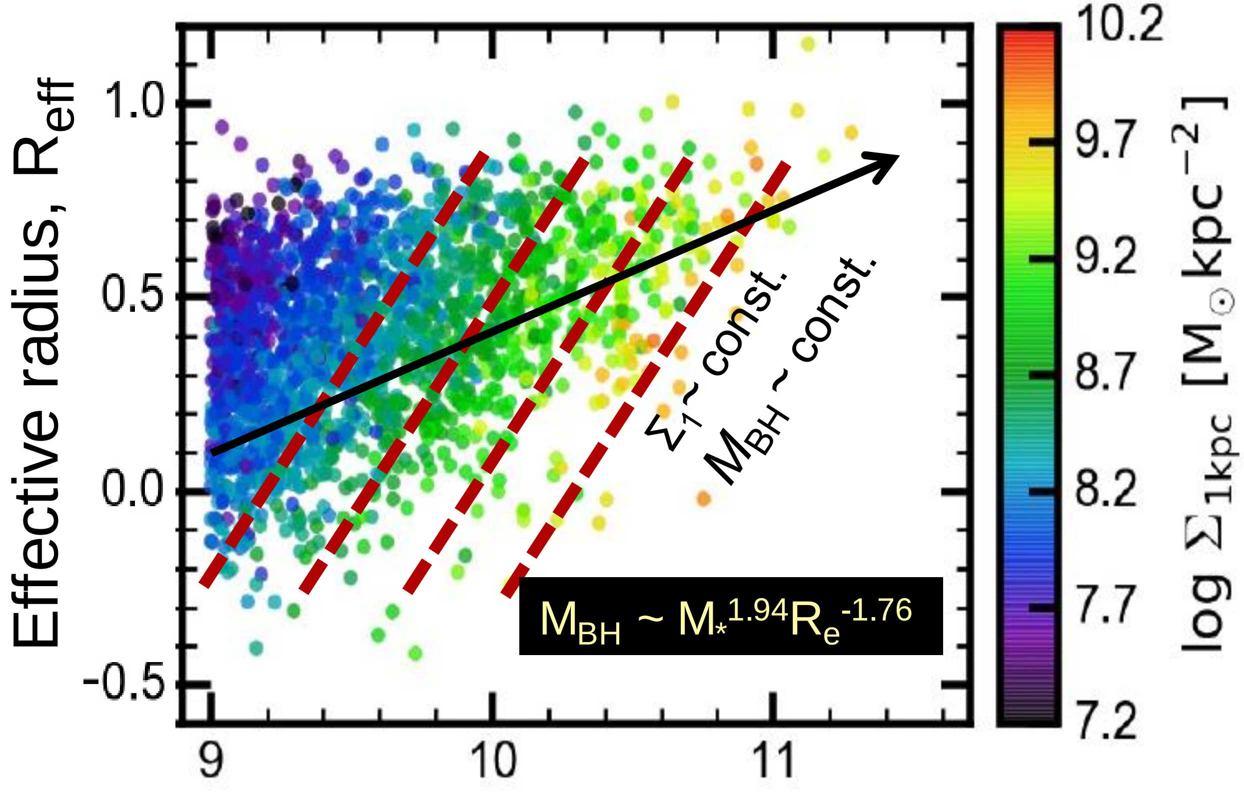


Ho & Kim 2014

Lines of constant Σ_1 are lines of constant M_{BH}

Read Σ_1 and M_{BH} directly from R_{eff} and M*

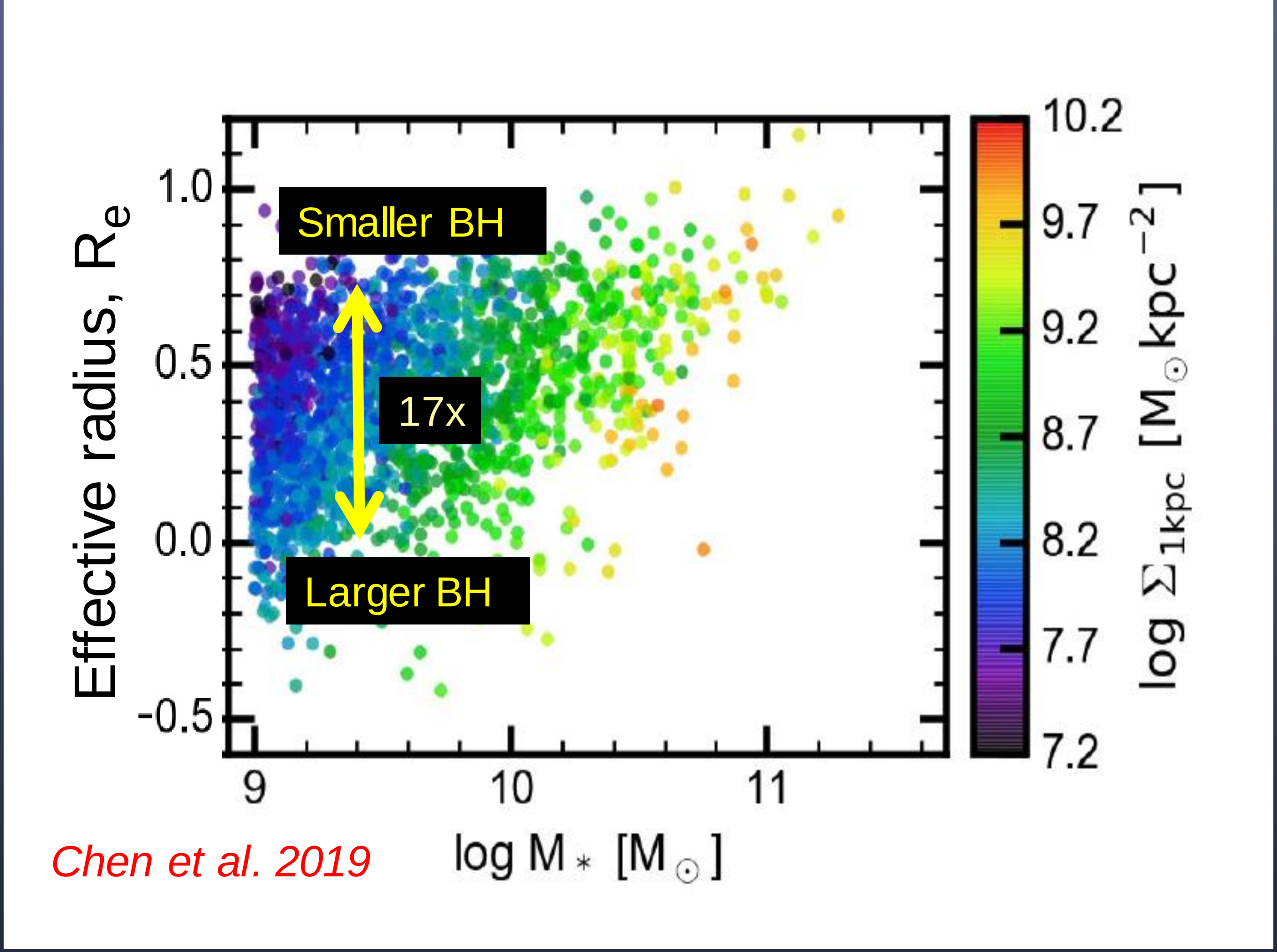


Chen et al. 2019

Also van den Bosch 2016, Krajnovich+18

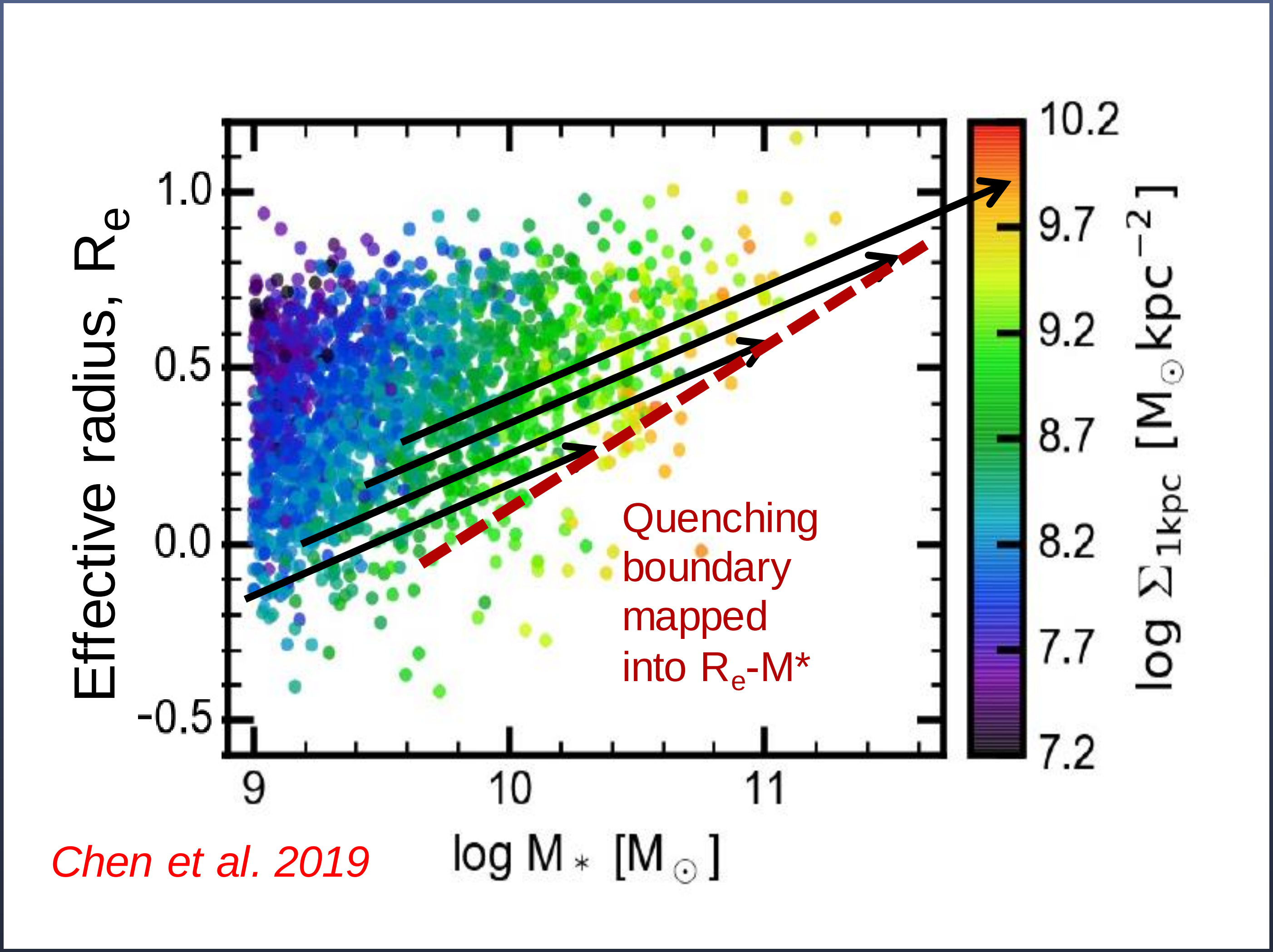
Larger galaxies at same M_* have smaller BHs

BH mass differences are substantial



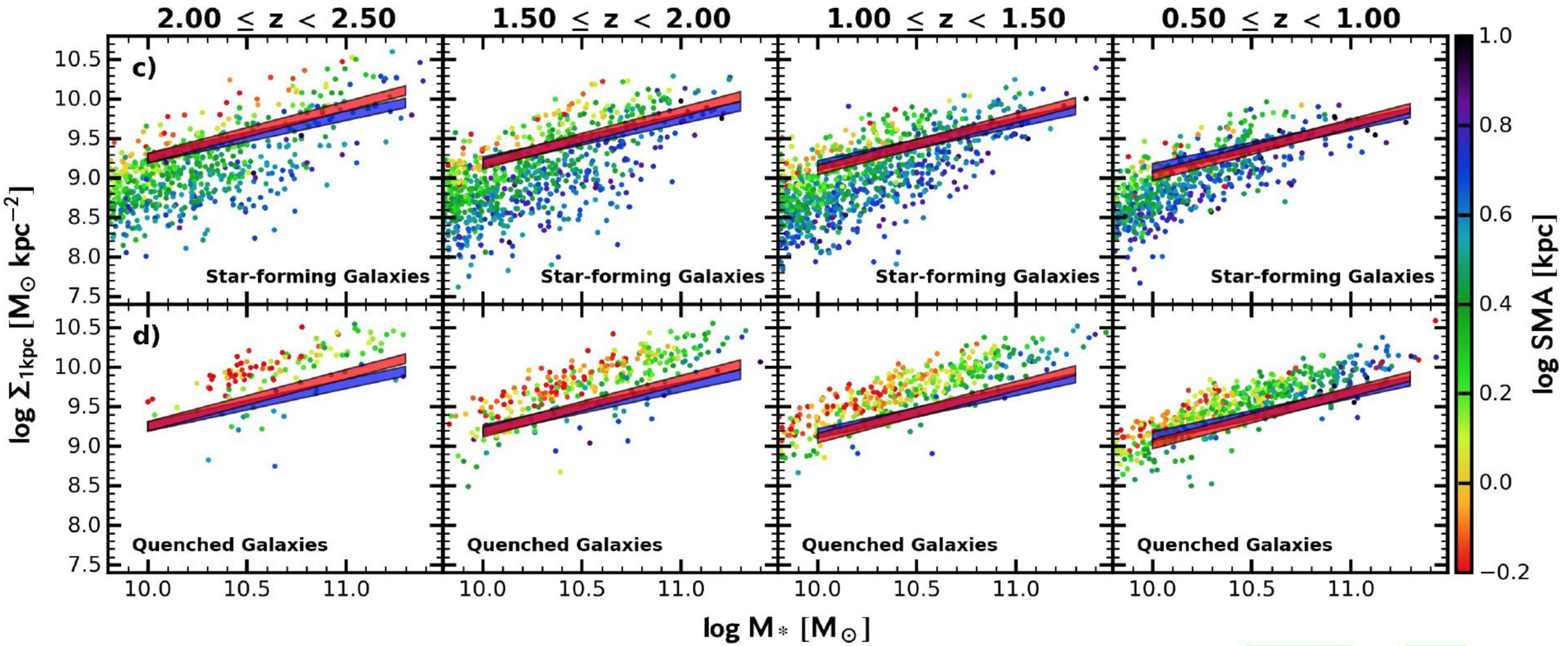
Larger-radii galaxies must have higher M* to quench

This causes the range (1 dex) in M* of quenching galaxies



Green valley entry: E_{BH} = 4x halo gas binding energy

The **red lines** are the observed quenching boundaries.
When galaxies cross, they enter the GV.

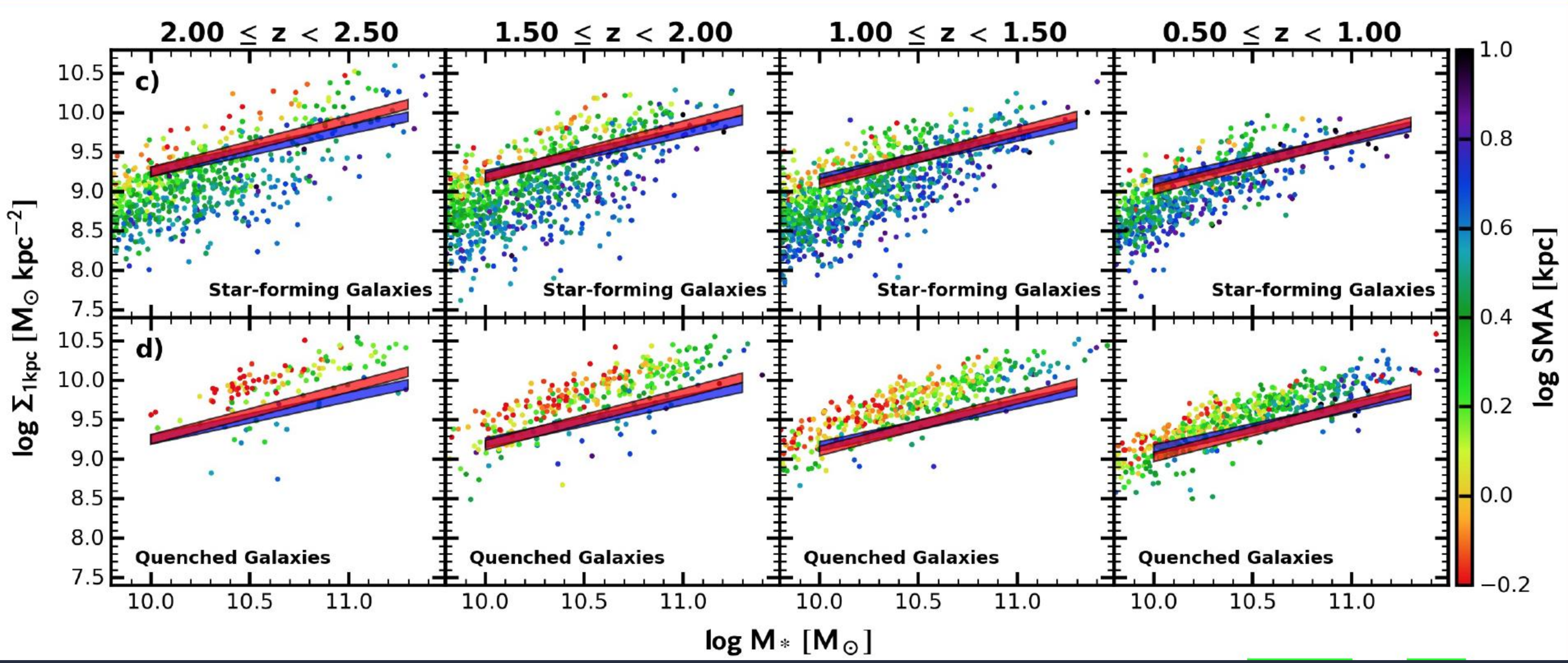


Chen et al. 2019

Green valley entry: E_{BH} = 4x halo gas binding energy

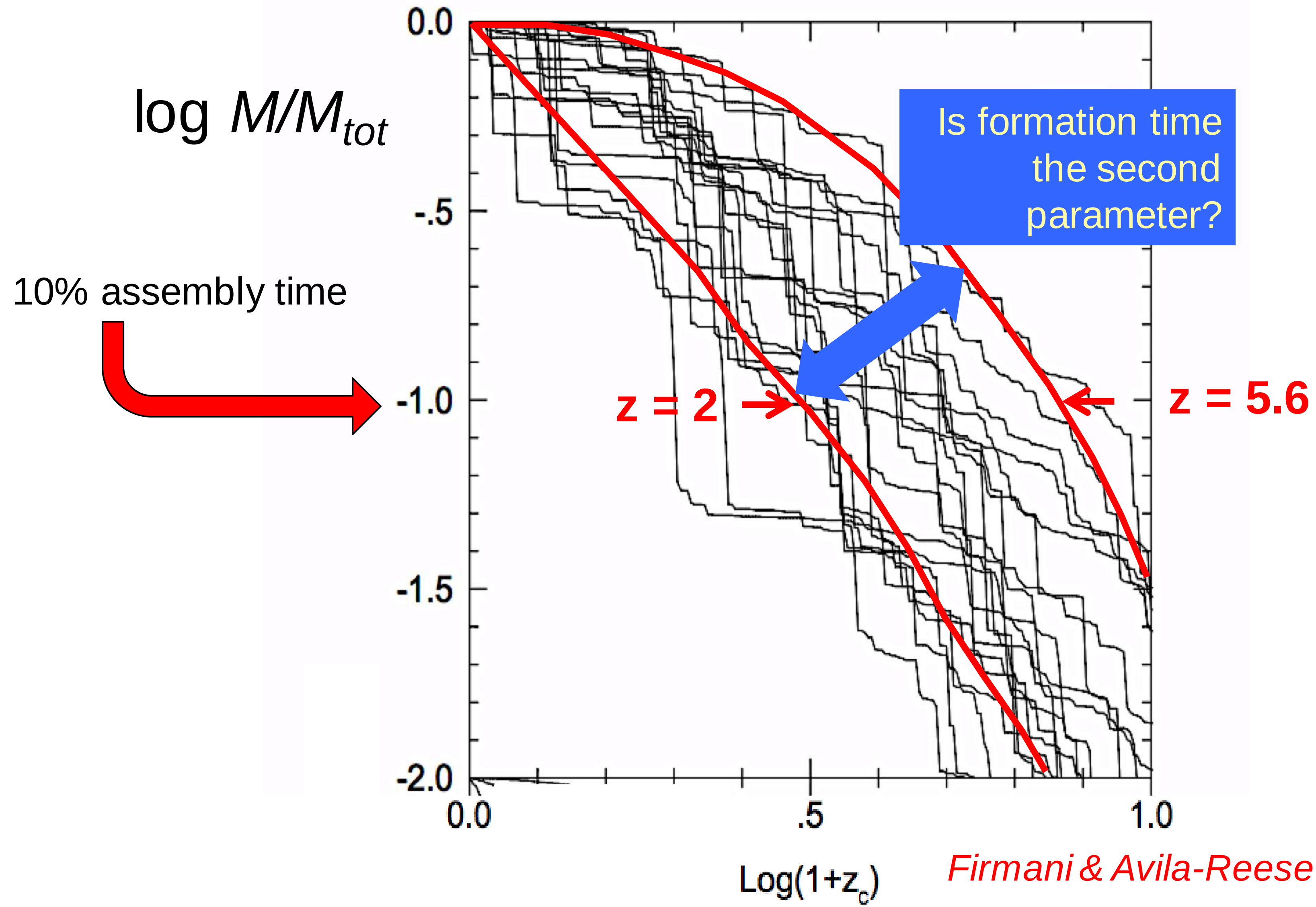
The **blue lines** are the new halo-gas model.

$$0.01 \times M_{BH}c^2 \cong 4 \times E_{bind} = 4 \times \tfrac{1}{2} M_{gas} V_{vir}^2$$



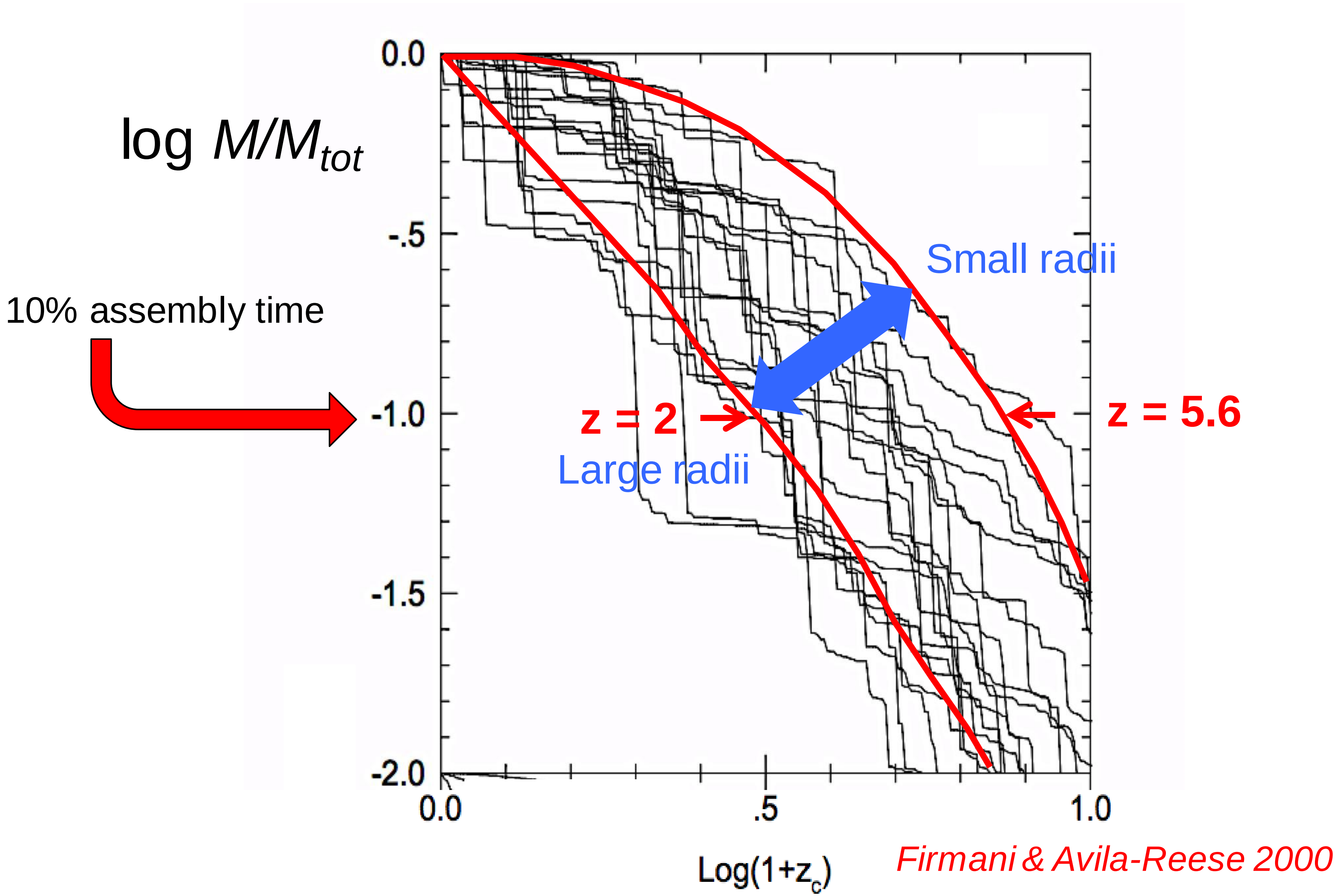
Chen et al. 2019

Assembly histories of dark matter halos with 5 x 10^{11} $M_\odot$ today



Firmani & Avila-Reese 2000

Assembly histories of dark matter halos with 5 x 10^{11} $M_\odot$ today



Phenomena to be explained

Major progress:

✓ Why do galaxies exist?	Inflation + DM
✓ Scaling relations for star-forming gal	Imprinted by halos
✓ Time-smoothed star-formation histories	Imprinted by halos
✓ Maximum stellar mass: $10^{10\text{-}11}\ M_\odot$	Quenching boundary
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✓ Scaling relations for quenched gal	BH-halo contest

Phenomena to be explained

Major progress:

✓	Why do galaxies exist?	Inflation + DM
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Subaru specialties

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