

# Galaxies: Structure, Dynamics, and Evolution

Cosmic Star Formation History  
and Later Galaxy Assembly

Baryon Cycle

# Layout of the Course

## Lectures

Feb 2: Course Introduction, Overview, and Galaxy Formation Basics

Feb 9: Disk Galaxies (I)

Feb 12: Disk Galaxies (II)

Feb 16: Disk Galaxies (III) / Collisionless Stellar Dynamics

Feb 23: Collisionless Stellar Dynamics + Vlasov/Jeans Equations

Feb 26: Vlasov/Jeans Equations / Elliptical Galaxies (I)

Mar 9: Elliptical Galaxies (II)

Mar 23: Dark Matter Halos

Mar 30: Connecting Galaxies to Dark Matter Halos

Apr 13: Galaxy Stellar Populations + Lessons from Galaxies at  $z < 0.2$

Apr 20: Lessons from Galaxy Samples at  $z < 0.2$  + Evolution with Redshift

Apr 23: Evolution of Galaxies with Redshift + Pushing to  $z > 1.5$

May 4: Cosmic Star Formation History + Galaxy Evolution at  $z > 6$

May 11: Galaxy Evolution with JWST / Review for Final Exam



# Paper Presentations Now Online

## GALAXIES: STRUCTURE, DYNAMICS, AND EVOLUTION (SPRING 2026)

### PAPER PRESENTATIONS

#### Semester Timeline

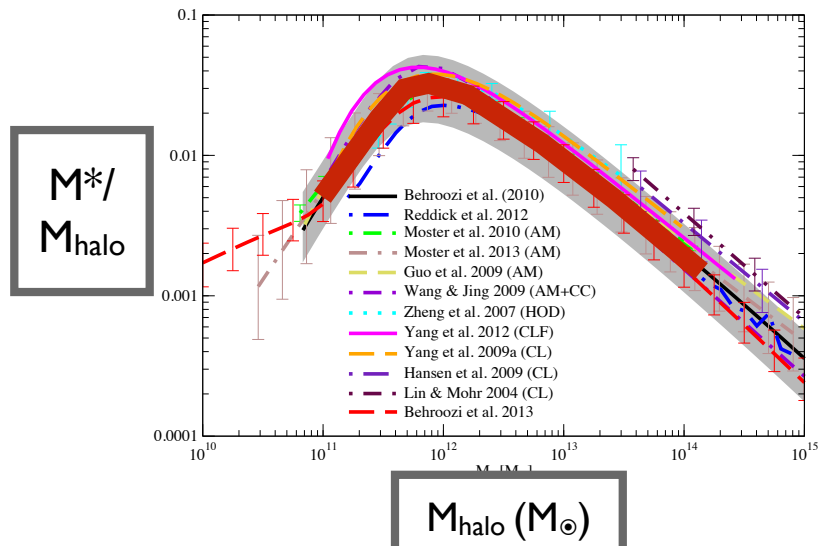
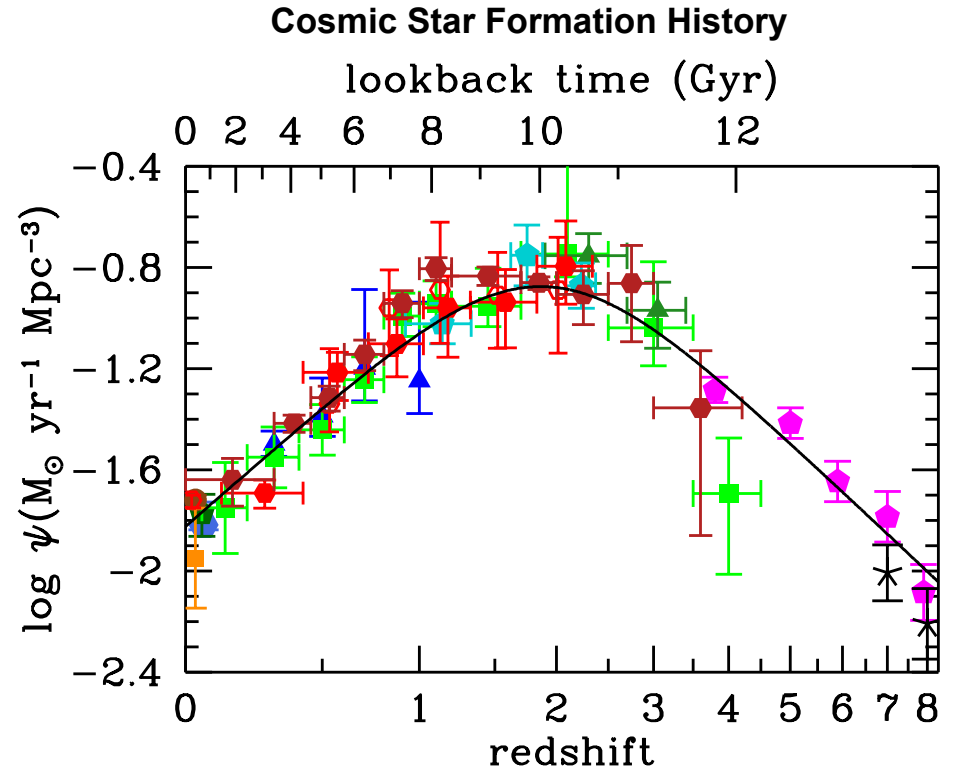
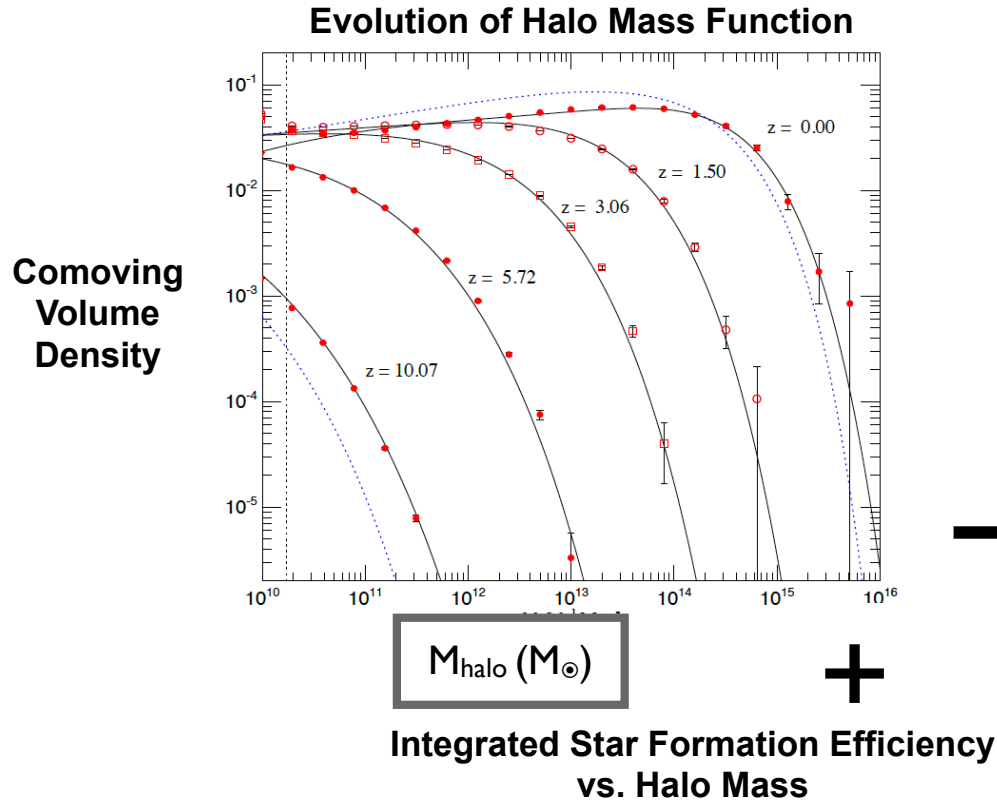
Date	Topic	Students	pdf of presentation	
March 26	Mergers which Formed Milky Way Halo	Chakawri & Besseling	<a href="#">Here</a>	
	Mergers which Formed Milky Way Halo	Kaijser & Gonzalez	<a href="#">Here</a>	
	Mergers which Formed Milky Way Halo	Bercuk & Iconaru	<a href="#">Here</a>	
April 2	Lindblad Resonances, Spiral Density Waves	Beekhuizen & van der Zwet	<a href="#">Here</a>	
	Elliptical Galaxy Scaling Relations	Nieuwstraten & Stoot	<a href="#">Here</a>	
	Gas, Dust in Spiral Galaxies	Heitor & Fonseca	<a href="#">Here</a>	
	Disk Galaxy Scaling Relations	Coey & Ladopoulos	<a href="#">Here</a>	
	Mapping Dark Matter Using Jeans Relations	Langerak & Ferro	<a href="#">Here</a>	
	Elliptical Galaxy Scaling Relations	Gavran & Beran	<a href="#">Here</a>	
	April 16	Mass of Milky Way from Gaia	Ryduchowska & Corcoran	<a href="#">Here</a>
		Core & Cusps in Elliptical Galaxies	Zanello & Zirotti	
Milky Way Satellite Review		Zandbergen & van Holk		
April 30	Age-Metallicity Degeneracy & Metallicities	Tejero & Ntova		
	Using clustering to Infer Masses	Tsioutsia & Fistos		
	Metallicities of $z>6$ Galaxies with JWST	Garg & Suta		
May 7	Mass & Environmental Quenching	van Beek & Schutte		
	Spectroscopy of early quiescent galaxies	Li & Baydar	<a href="#">Here</a>	
	Stellar Population Analyses	Carneiro & Gilibaro	<a href="#">Here</a>	



Some people appear not to have sent me their presentations

**First, let's review the important  
material from last week**

# Can we understand the diagram to the right?



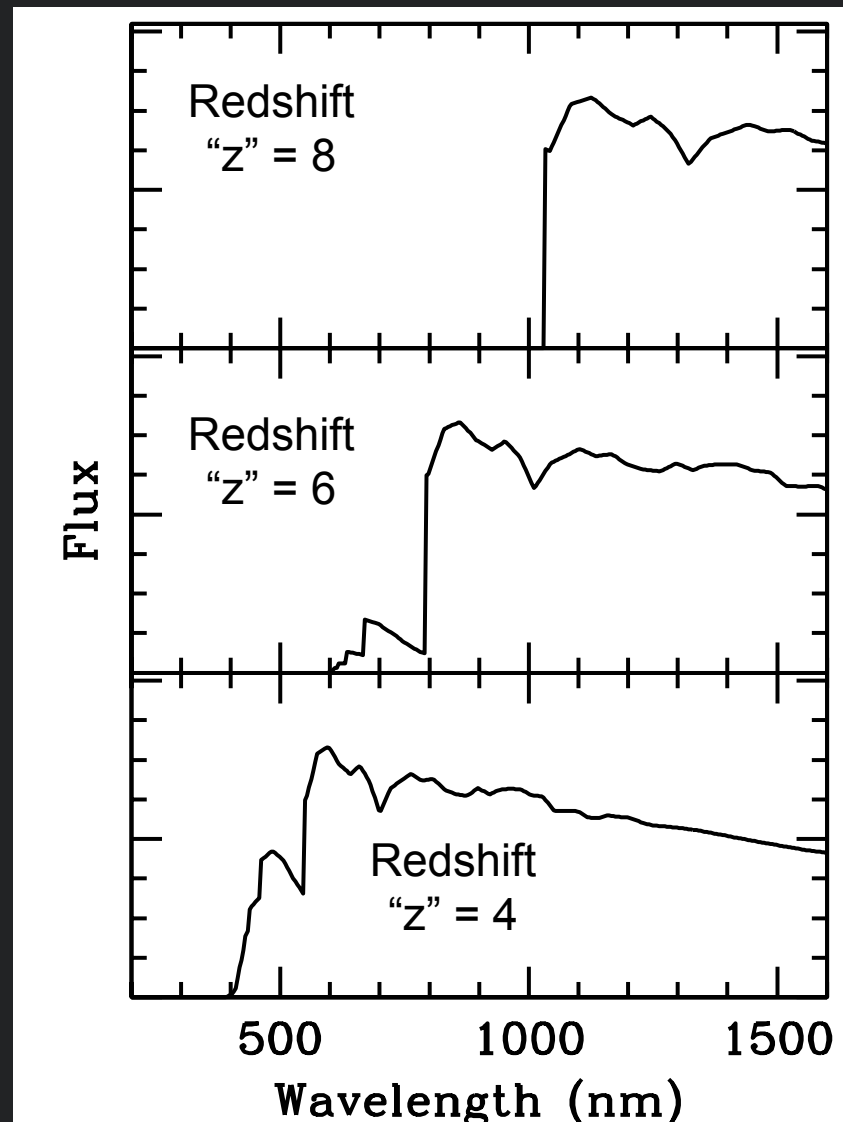
# How can we determine which galaxies on deep images come from the most distant galaxies?

There is a sharp break in spectrum of distant galaxies due to neutral hydrogen in the universe.

As the universe expands, this break in the spectrum is shifted to redder wavelengths (“redshifted”)

By looking for sources with breaks at very red wavelengths, we identify the most distant galaxies.

## Spectra of Distant Galaxies

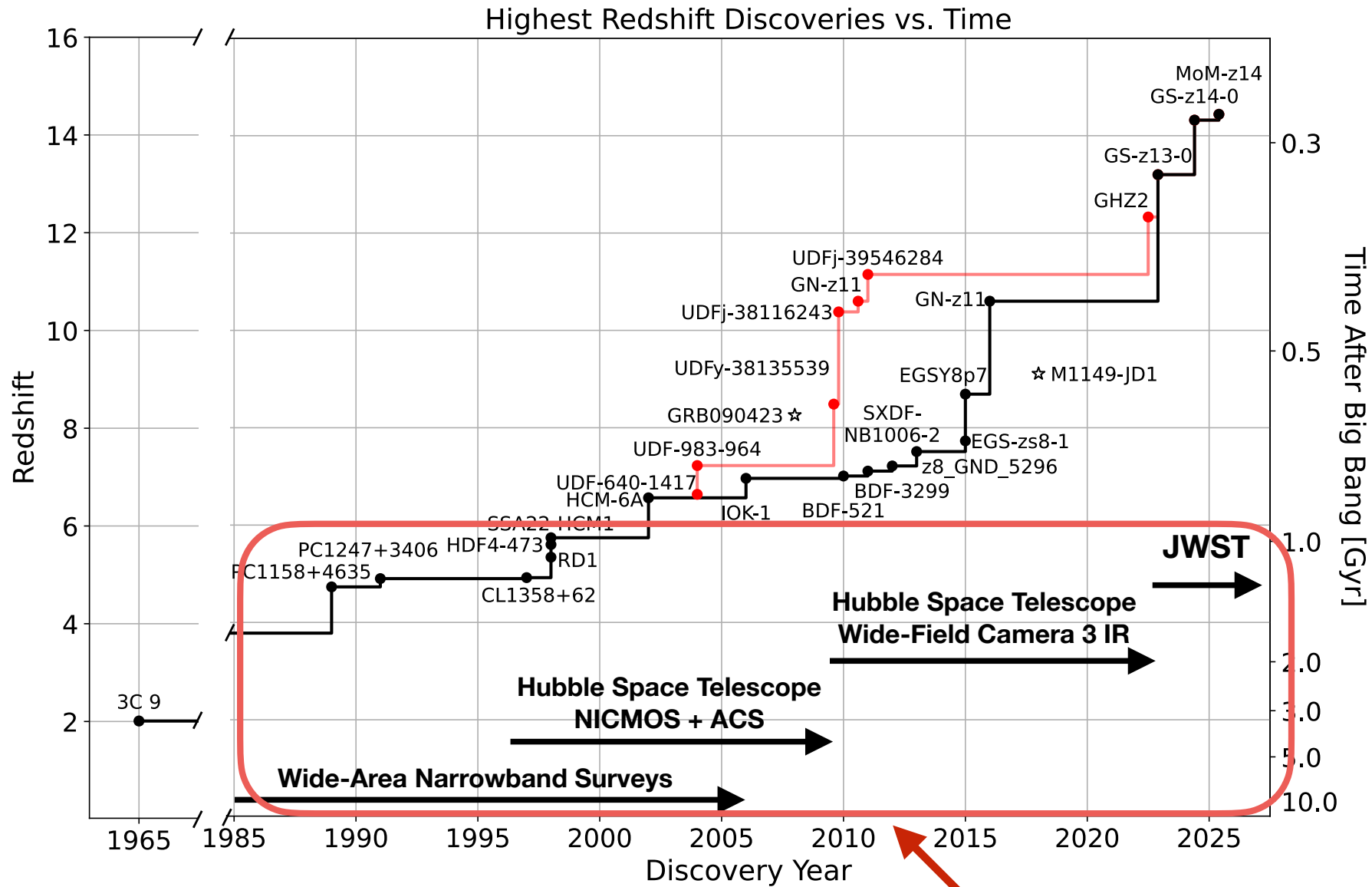


Most Distant  
@ 850 Myr  
after Big Bang

@ 1000 Myr  
after Big Bang

Least Distant  
@ 1800 Myr  
after Big Bang

# Here is the evolution of the redshift record



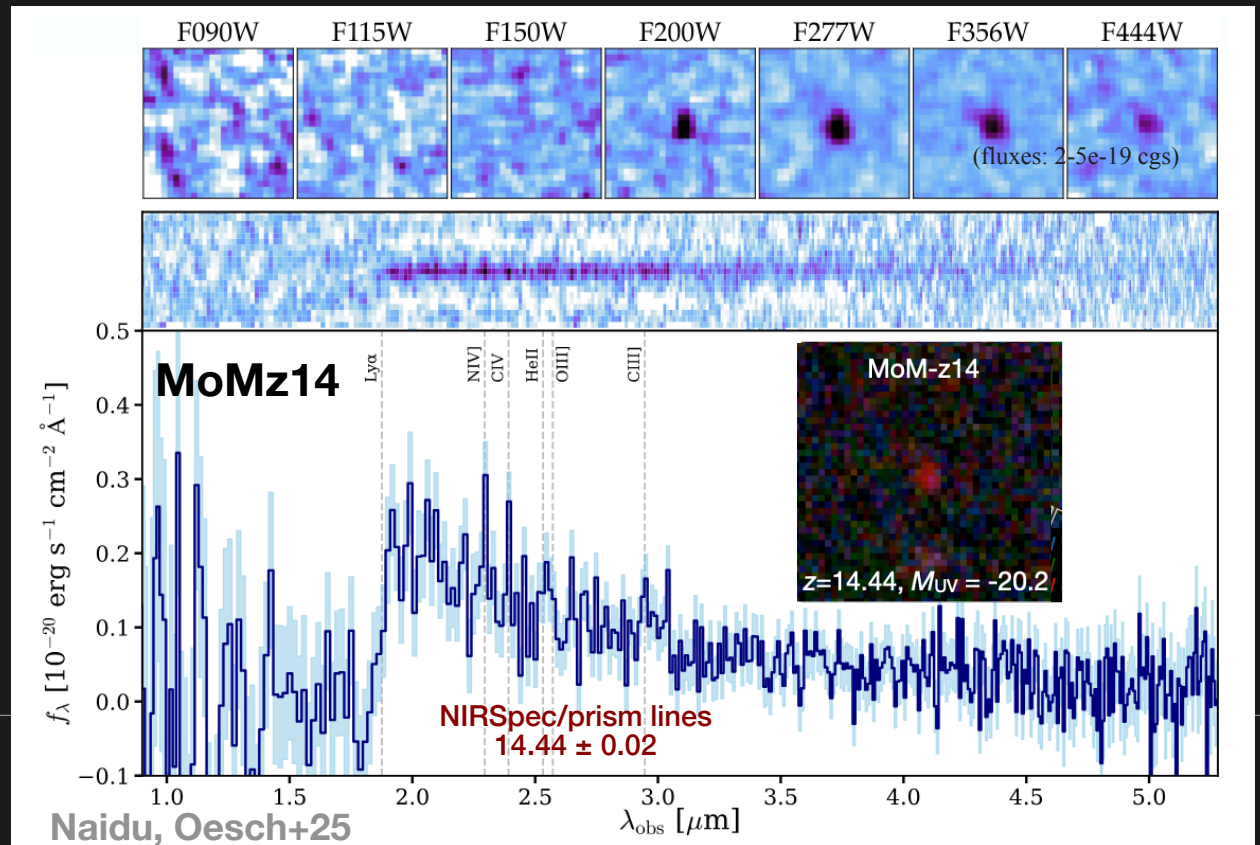
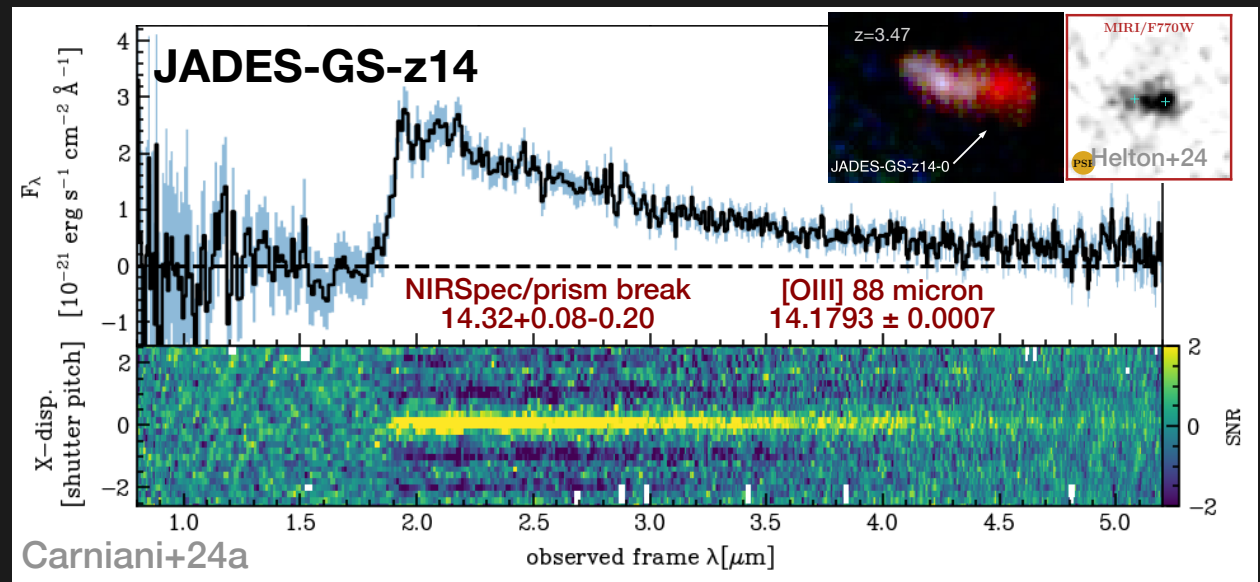
Bouwens+2026, in prep

Technology played a major role

# Spectroscopic High-Redshift Frontier

- ▶ Obtaining spectroscopic redshift confirmations is critical
- ▶ The spectroscopic record holder was broken several times over the past three years

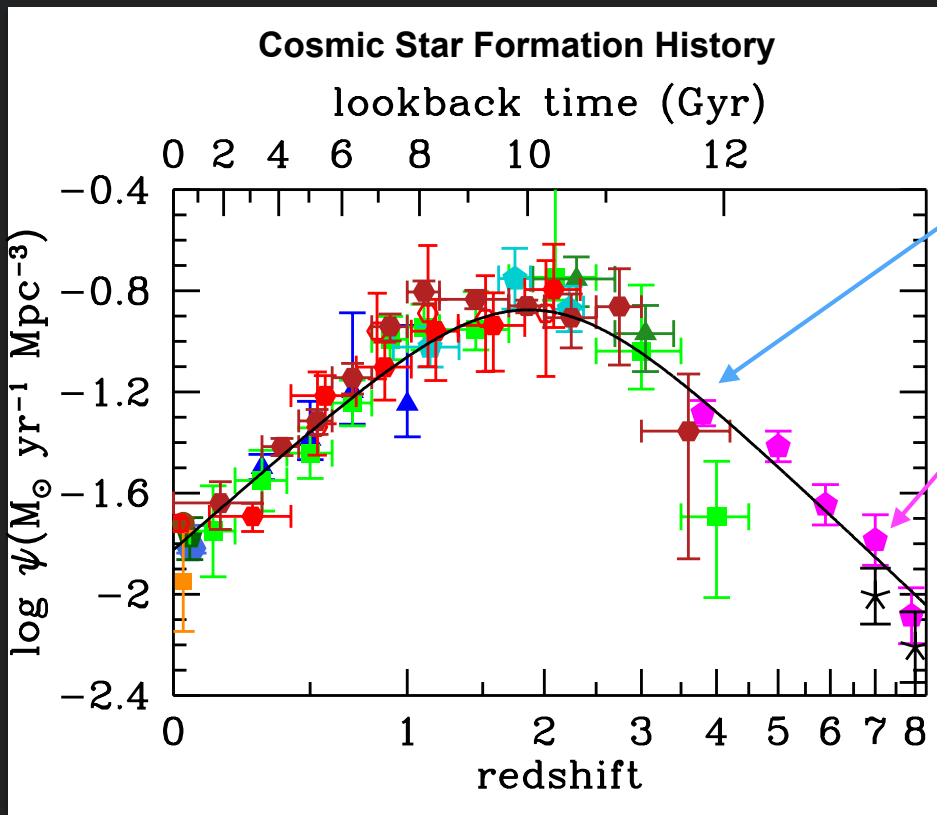
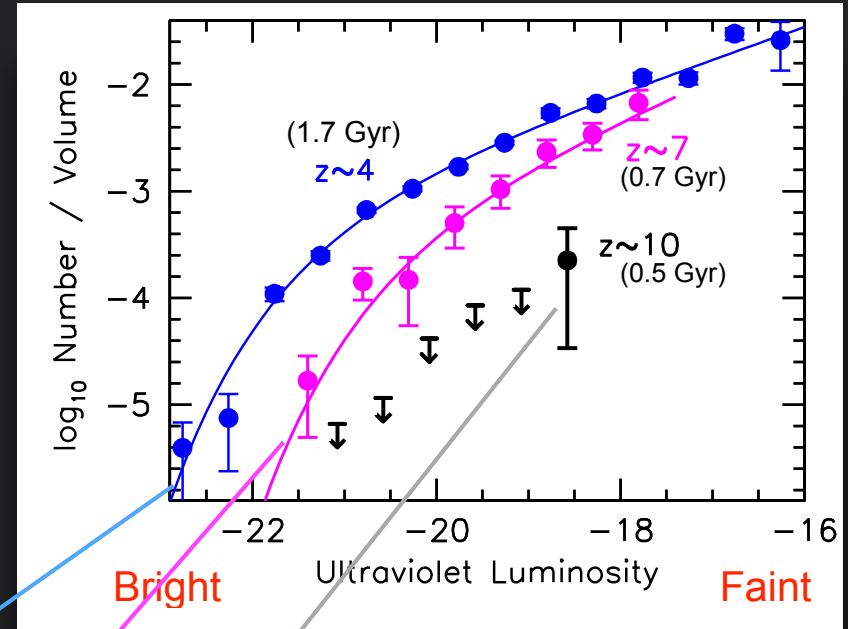
*JWST* obtained a spectrum of the  $z_{\text{spec}}=14.44$  galaxy in only  $\sim 4.5$ hrs



# Can Calculate SFR Density from UV Luminosity Function

UV Luminosity is from newly formed O+B stars in last 100 Myr

$$\text{SFR} = L_{\text{UV}} \times \text{conversion factor}$$



Integrate Luminosity Functions to Derive SFR Density

# Which galaxies would we expect to contain the most dust?

i.e. those with the most metals (i.e., the mass ones):

From lecture 11:

## Relationship between the Gas-Phase Metallicity in a Galaxy and Its Mass

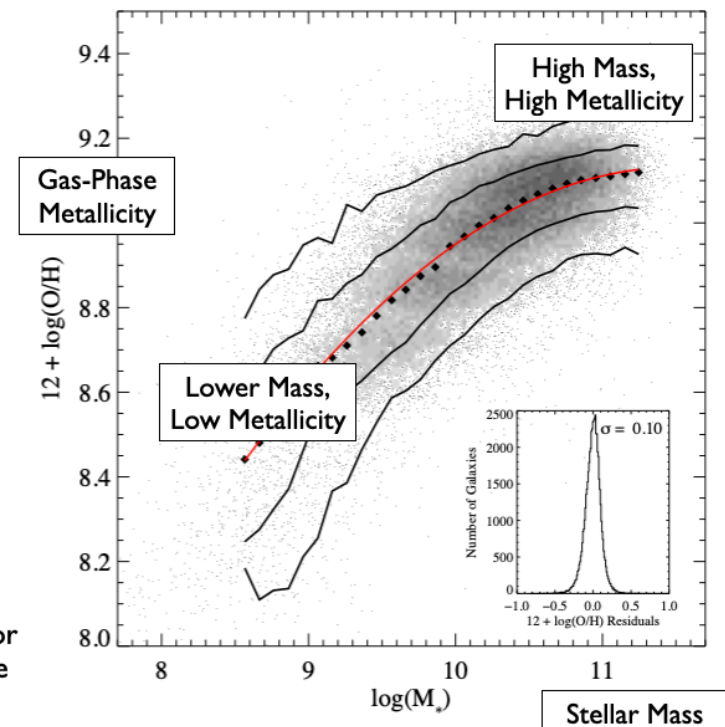
Two primary explanations for this:

### 1) Low Mass Galaxies Form Stars Less Efficiently

As such, only a small percentage of the gas turns into SNe (which adds more metals to the mix)

### 2) Metals can escape more easily from low-mass galaxies due to SNe winds

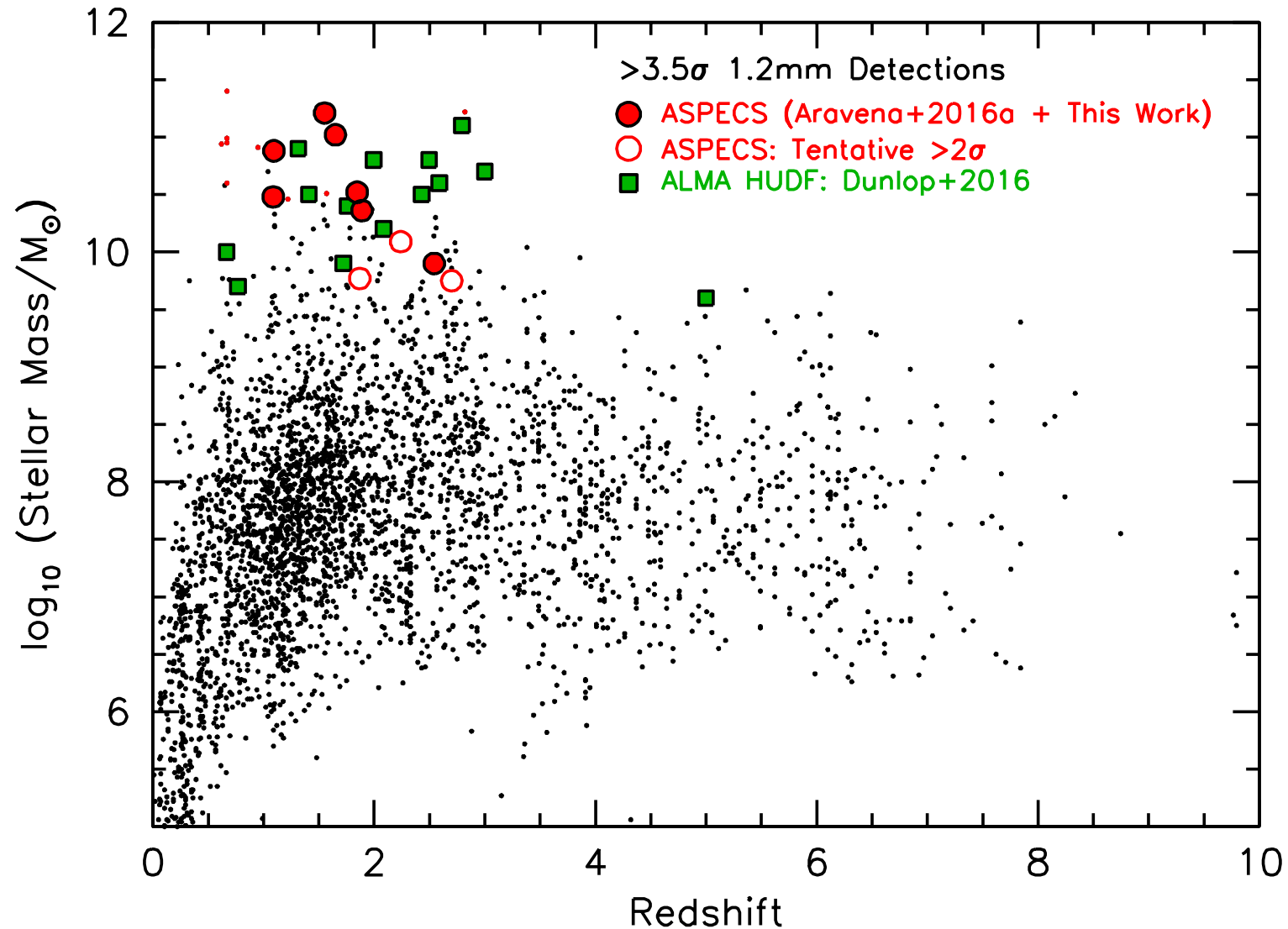
The escape velocity for lower mass galaxies is lower and hence it is easier for metals to escape from such galaxies due to SNe winds



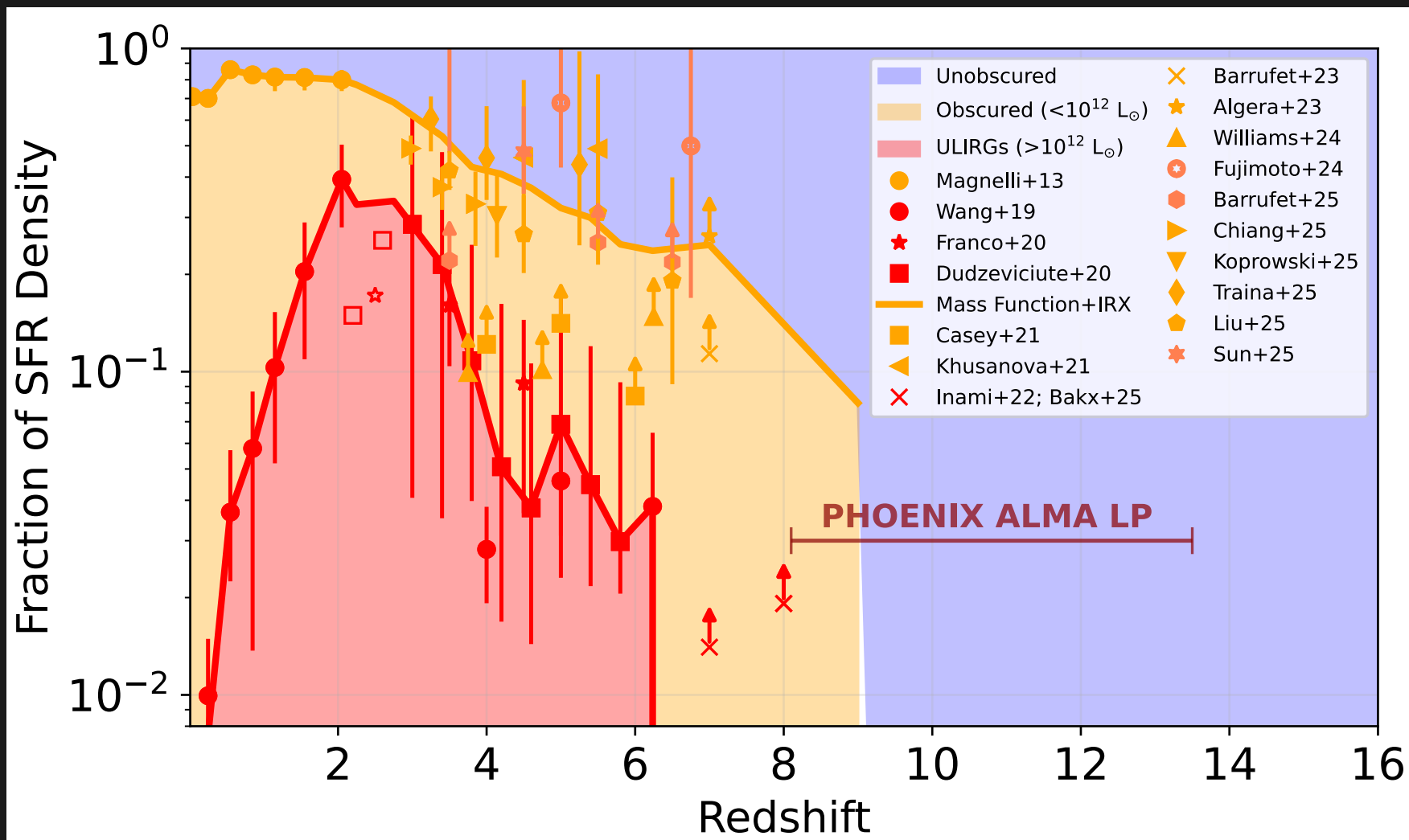
Tremonti+2004

# ALMA UDF

Only the highest-mass sources are individually detected!



# Contribution of Obscured Star Formation to SFR Density



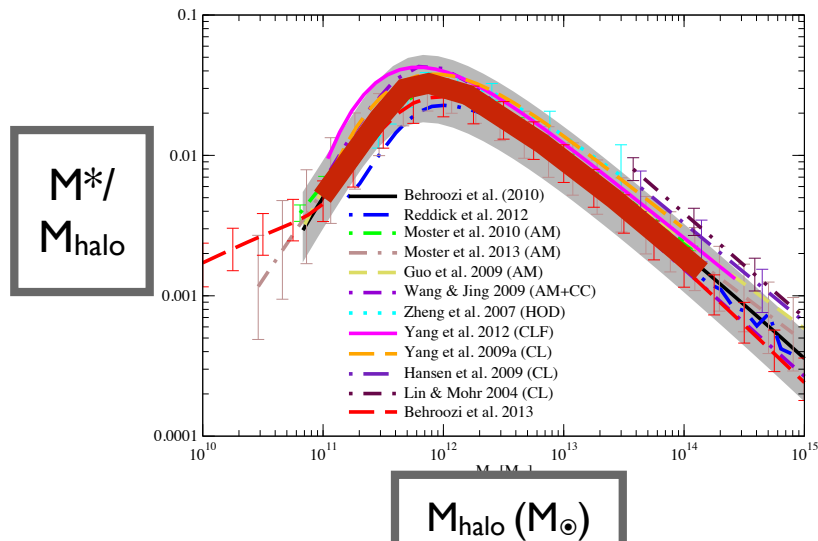
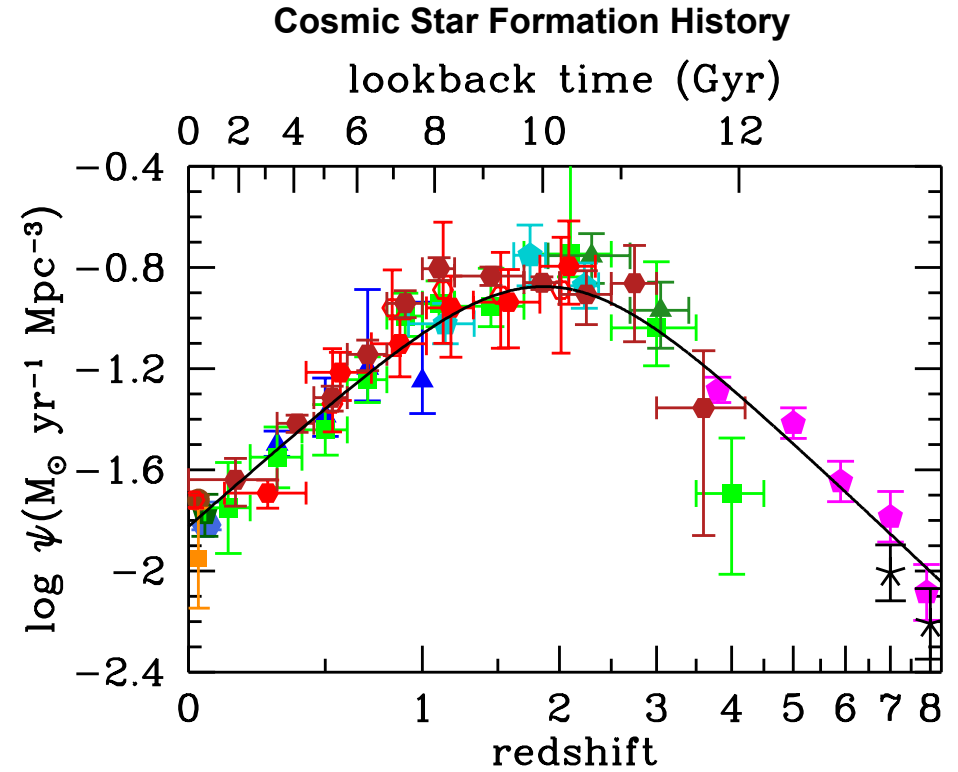
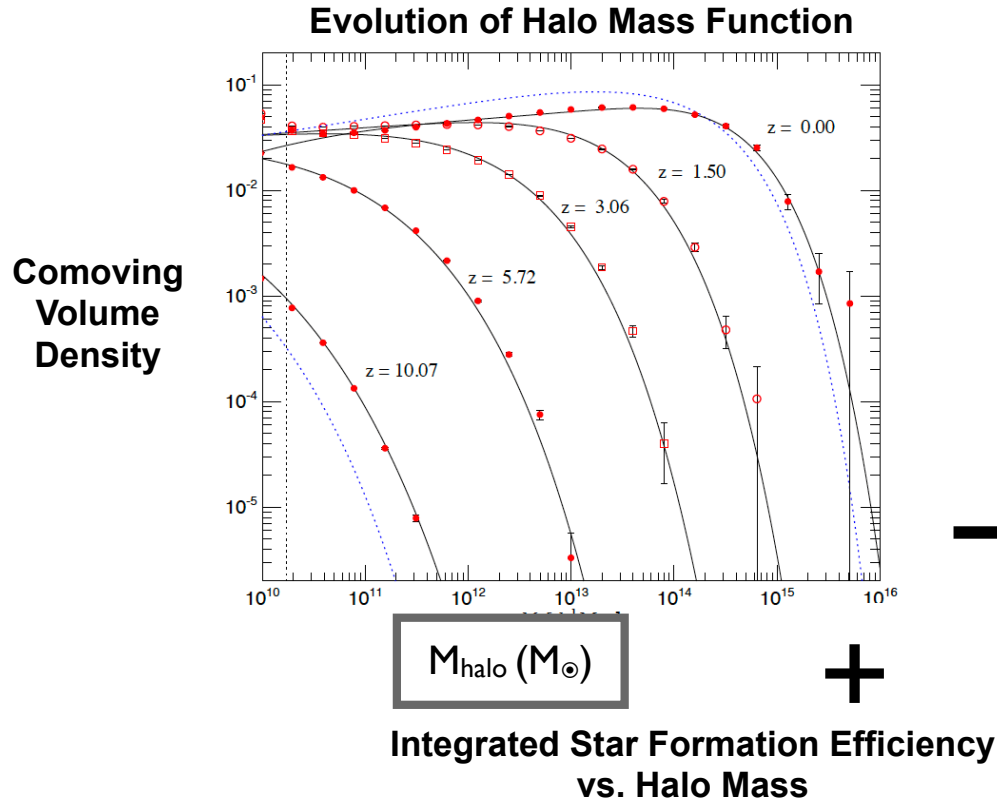
Compilation of  
Many Exciting  
Independent  
Efforts

**NOW** new material for this  
week

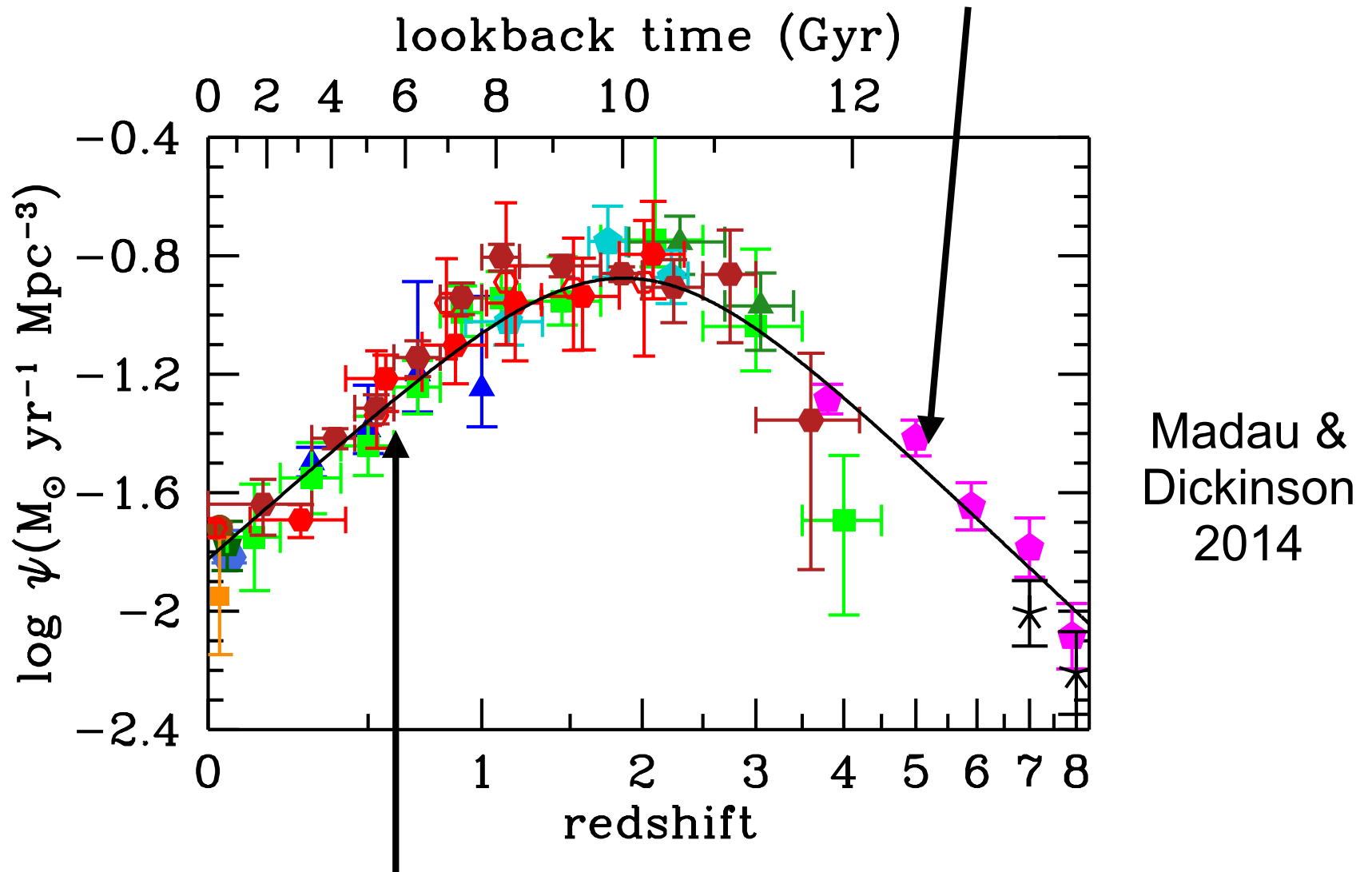
Can we construct a picture  
of how galaxies form and  
evolve across cosmic time?

When do galaxies / does the  
universe form most of its  
stars?

# Can we understand the diagram to the right?



**Last week - we discussed why the cosmic star formation rate density of universe rises at early times...**



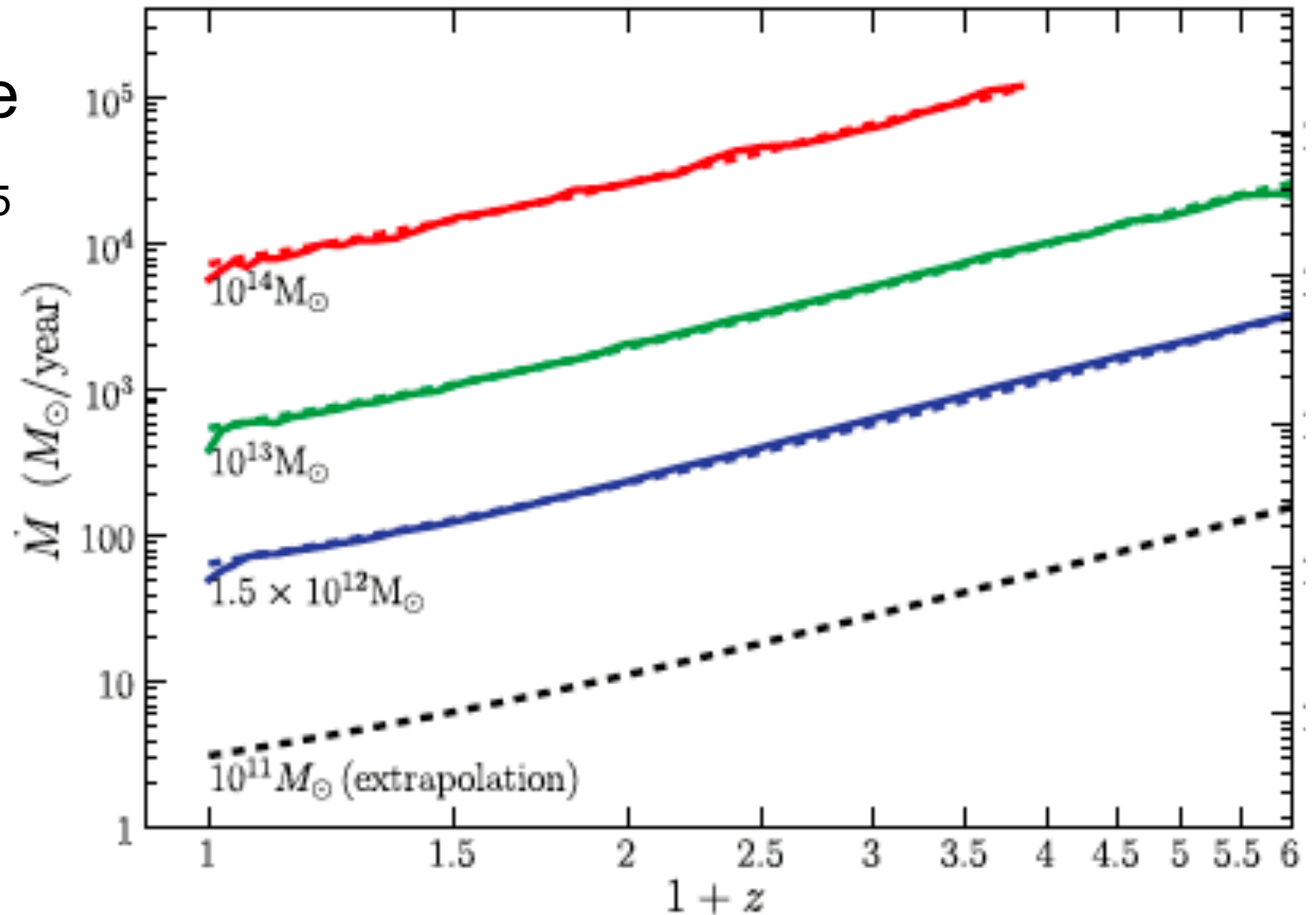
**Why does the cosmic star formation density fall at late times?**

# Consideration #1: Accretion of cold gas onto galaxies slows

Accretion Rate

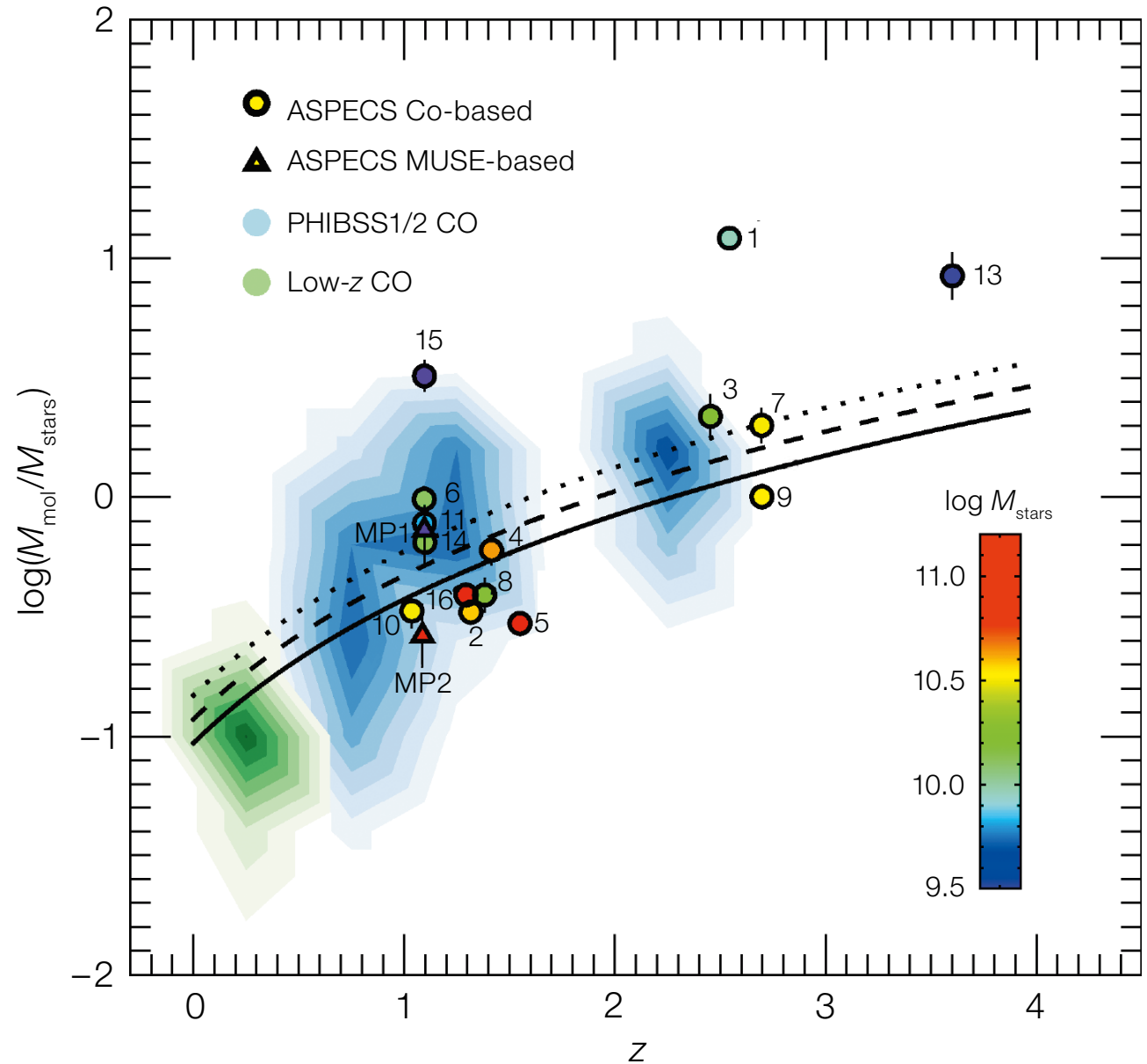
$$dM/dt \sim (1+z)^{1.5}$$

Steeper at high redshifts

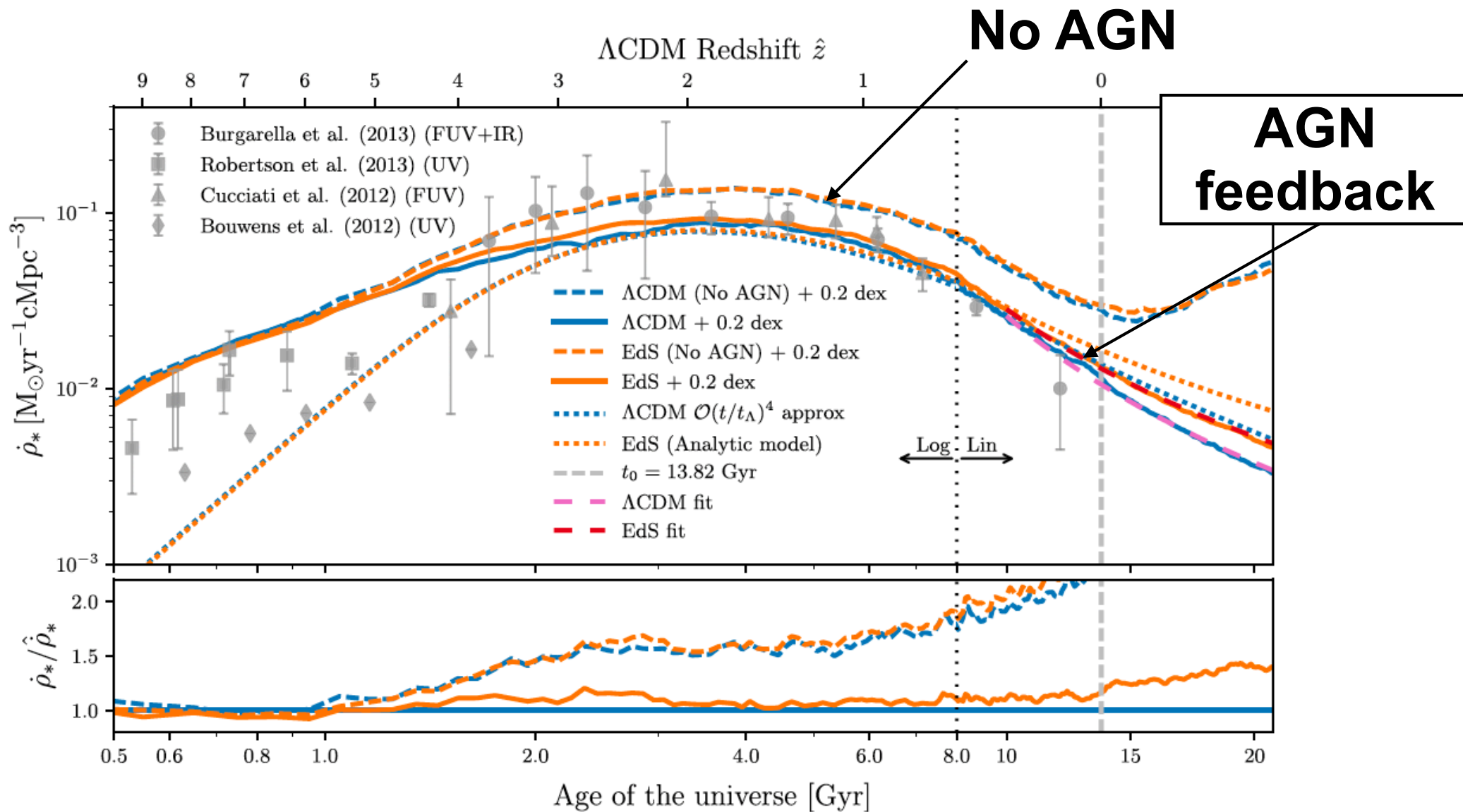


# Consideration #1: Accretion of cold gas onto galaxies slows

As also evident in the evolution of the ratio of gas mass to stellar mass



# Consideration #2: Mass Quenching from an AGN can prevent gas cooling in most massive halos

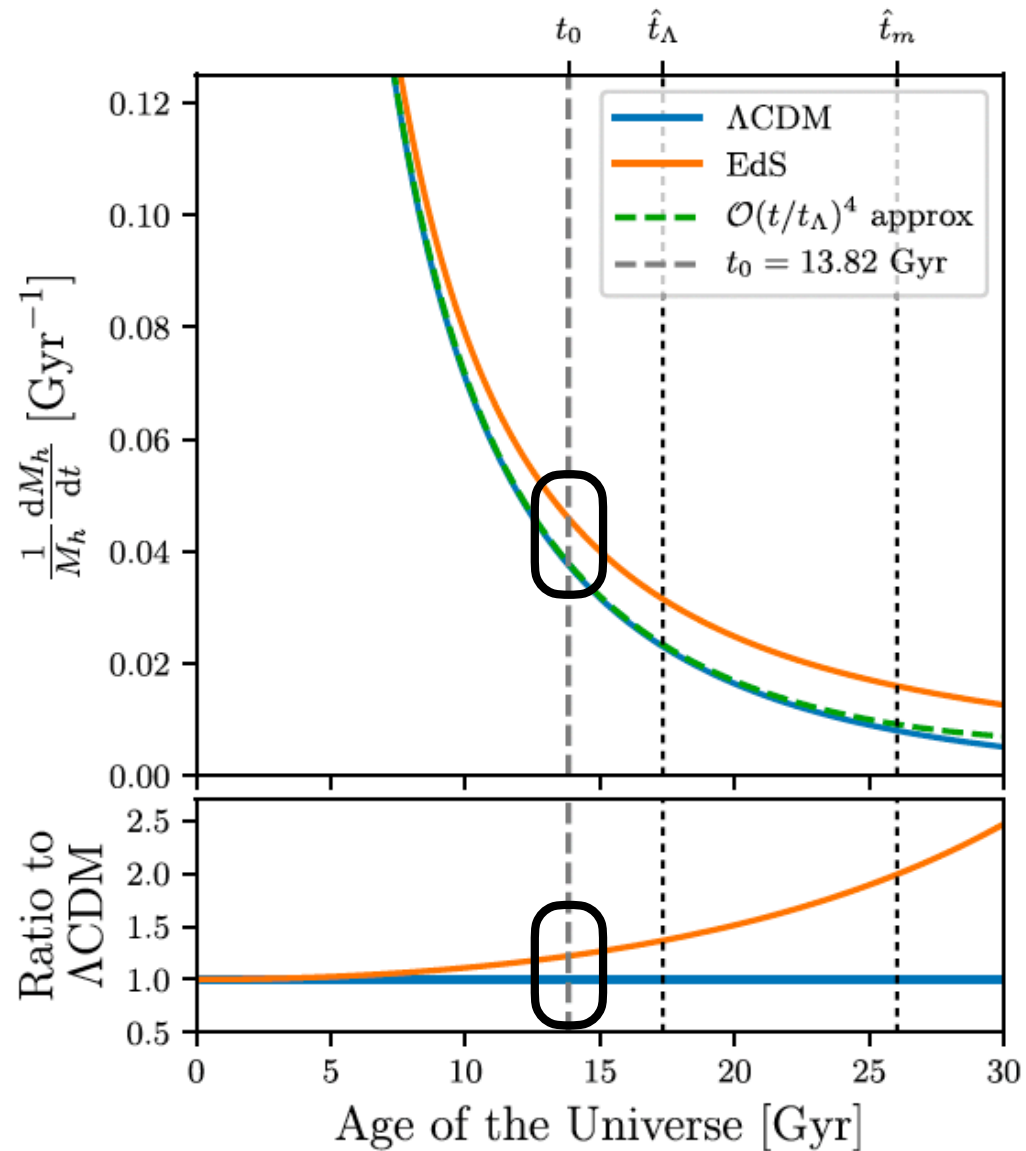


# Consideration #3: Dark Energy slows accretion of matter onto collapsed halos

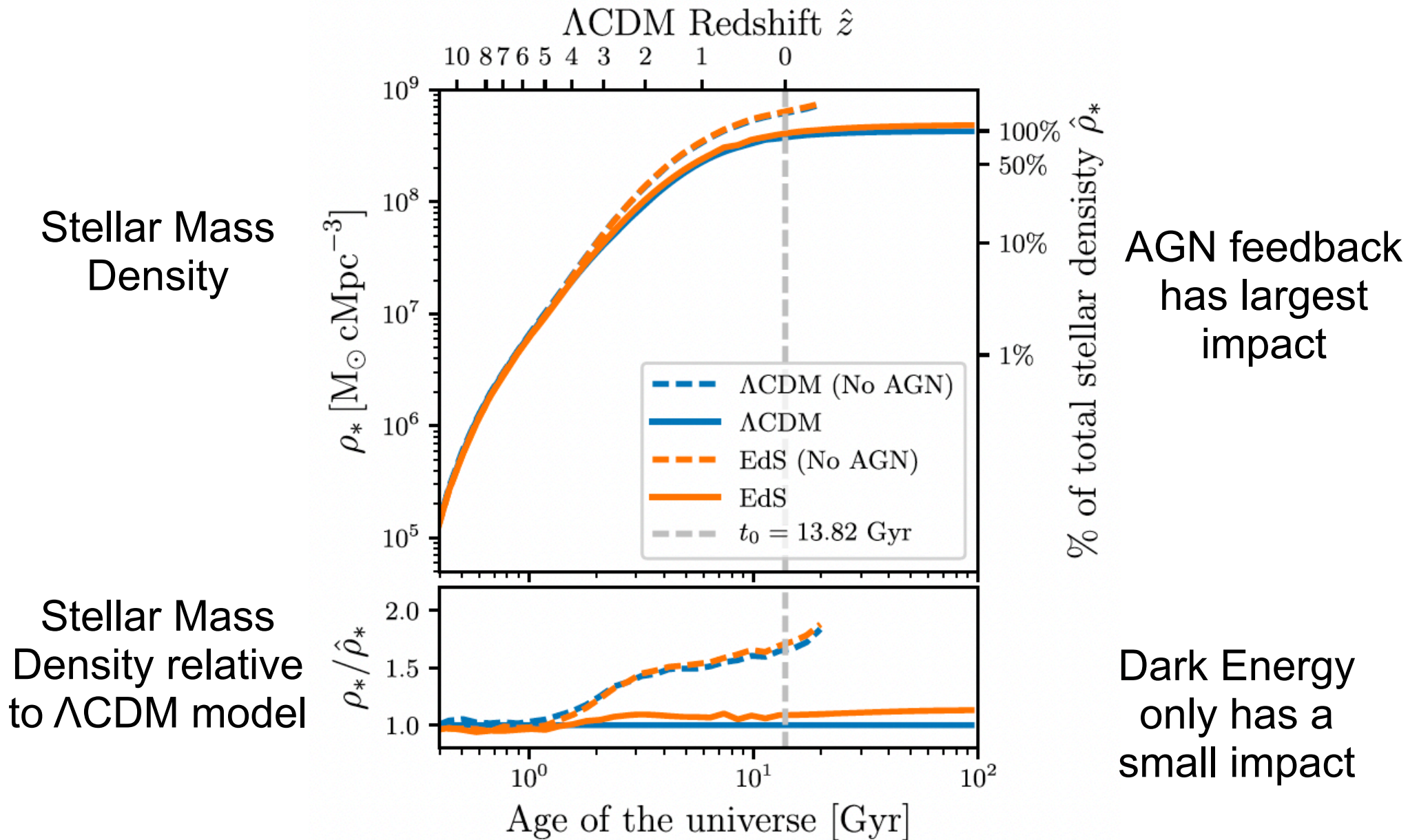
Specific Accretion Rate  
onto Halos

$$(dM_{\text{halo}}/dt)/M_{\text{halo}}$$

But the impact of this is  
much less than the other  
two factors

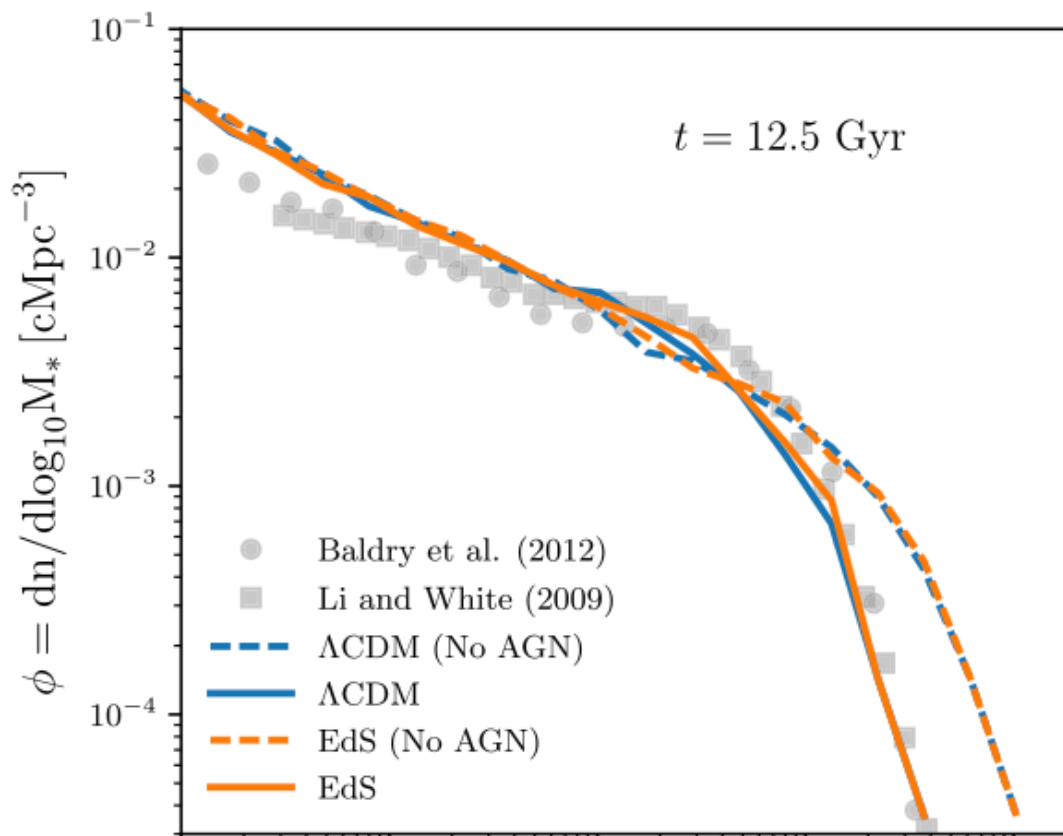


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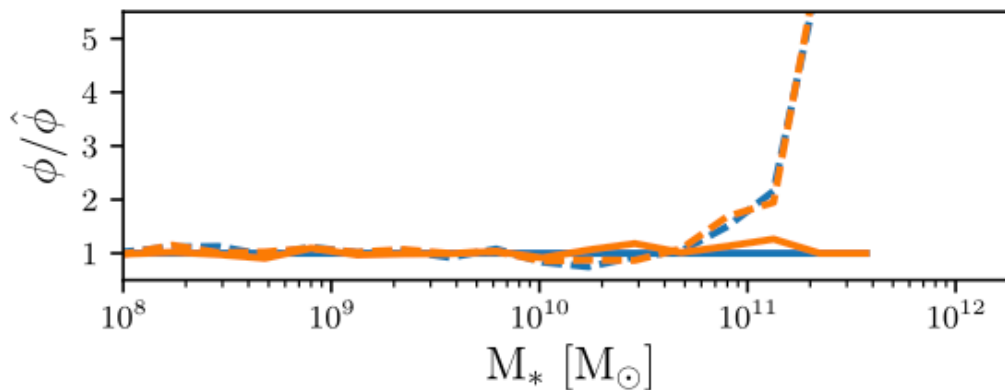
# Impact of AGN feedback + $\Lambda$ CDM on Mass Distribution of Galaxies

Volume  
Density



AGN feedback  
has largest  
impact

Volume Density  
relative to  
 $\Lambda$ CDM model

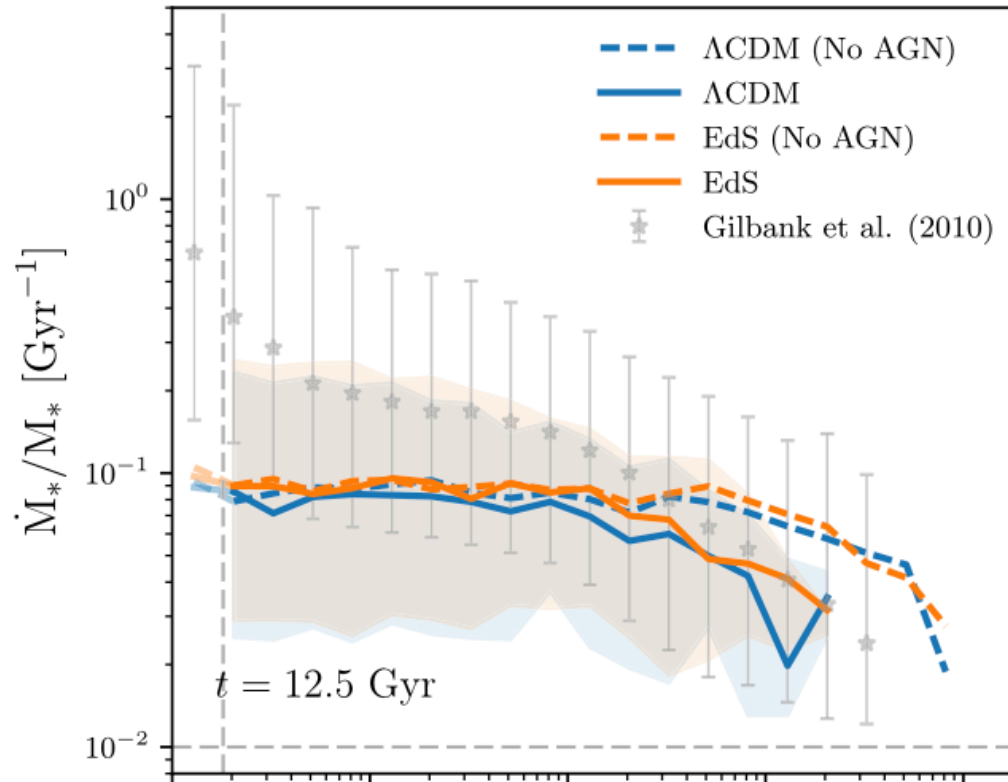


Dark Energy  
only has a  
small impact

# Impact of AGN feedback + $\Lambda$ CDM on Specific Star Formation Rate of Galaxies

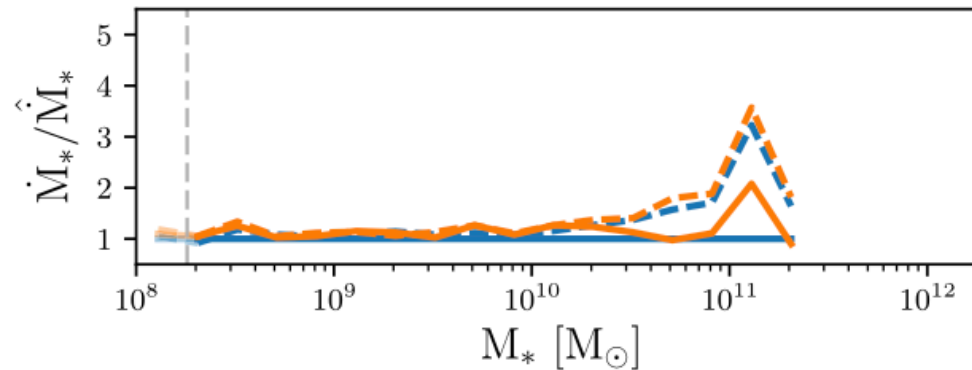
Specific Star Formation Rate

SFR / Stellar Mass



AGN feedback has largest impact

sSFR relative to  $\Lambda$ CDM model

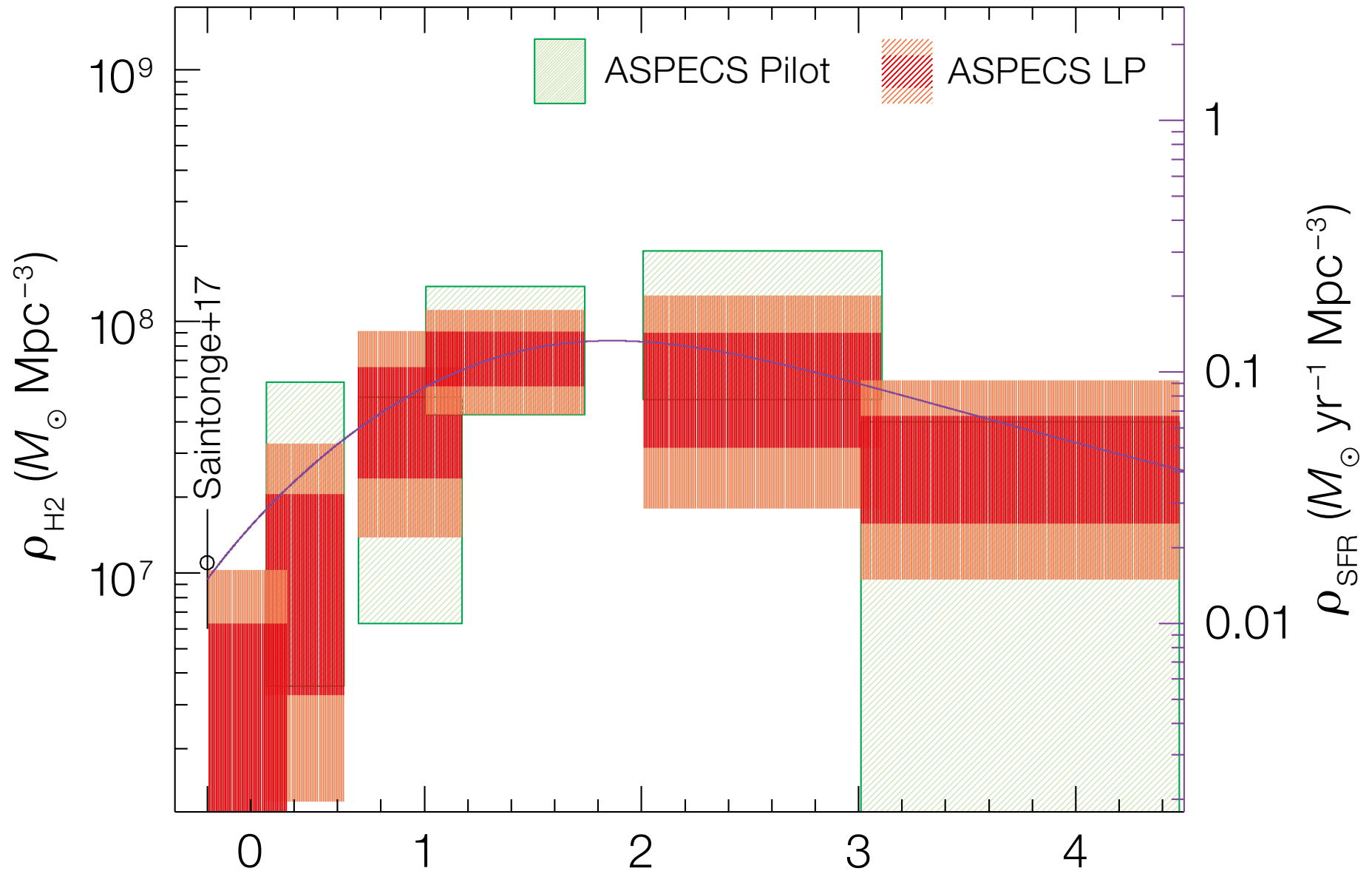


Dark Energy only has a small impact

Galaxy Stellar Mass

How is the evolution of  
galaxies impacted by gas?

# Molecular Gas Mass Density vs. Redshift

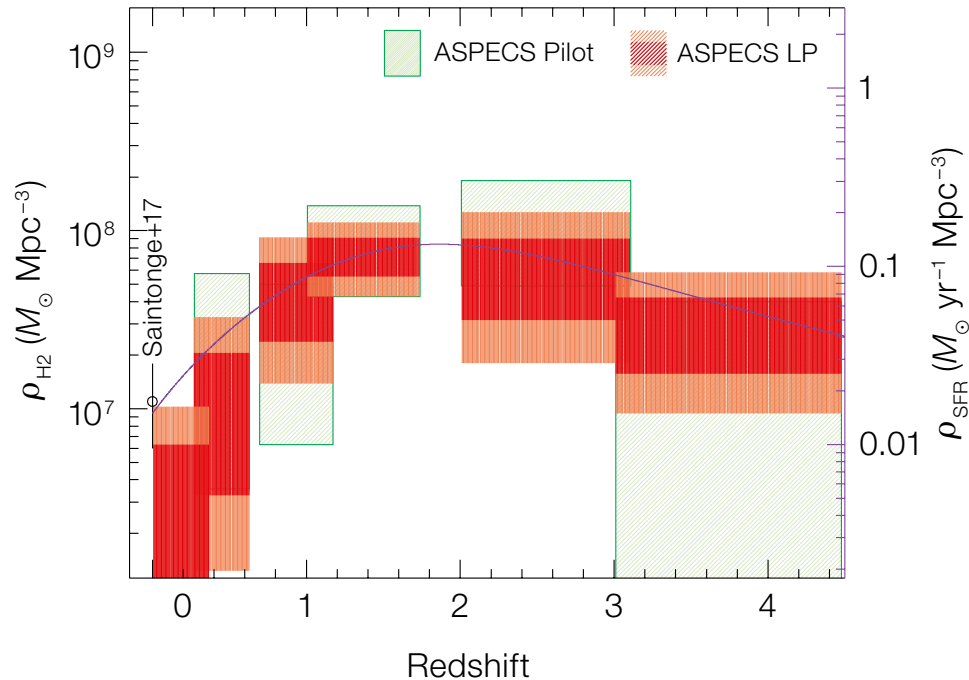


Decarli+2019

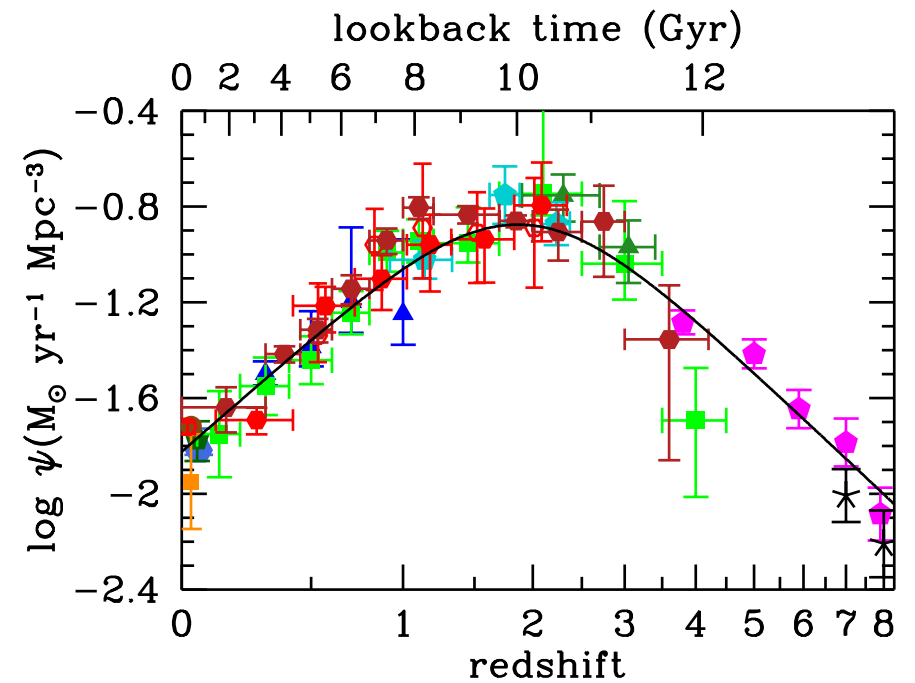
Redshift

# Gas Density vs. SFR Density Evolution

Cosmic Gas Density Evolution



Cosmic Star Formation History



Note the similarities!

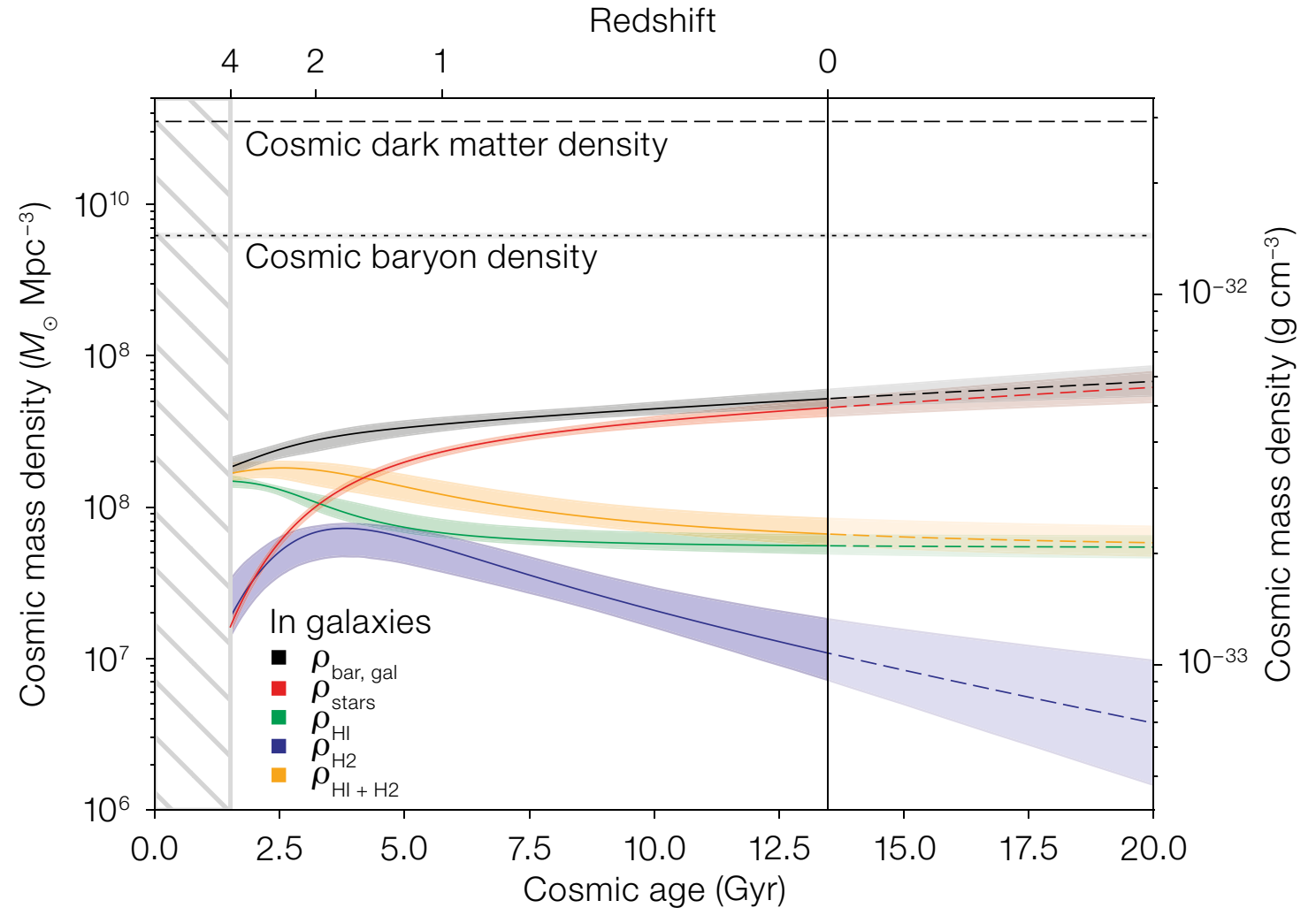
# How Baryon Redistribute themselves vs. Cosmic Time

Initially, baryons in atomic gas

Some baryons go into molecular gas + form stars

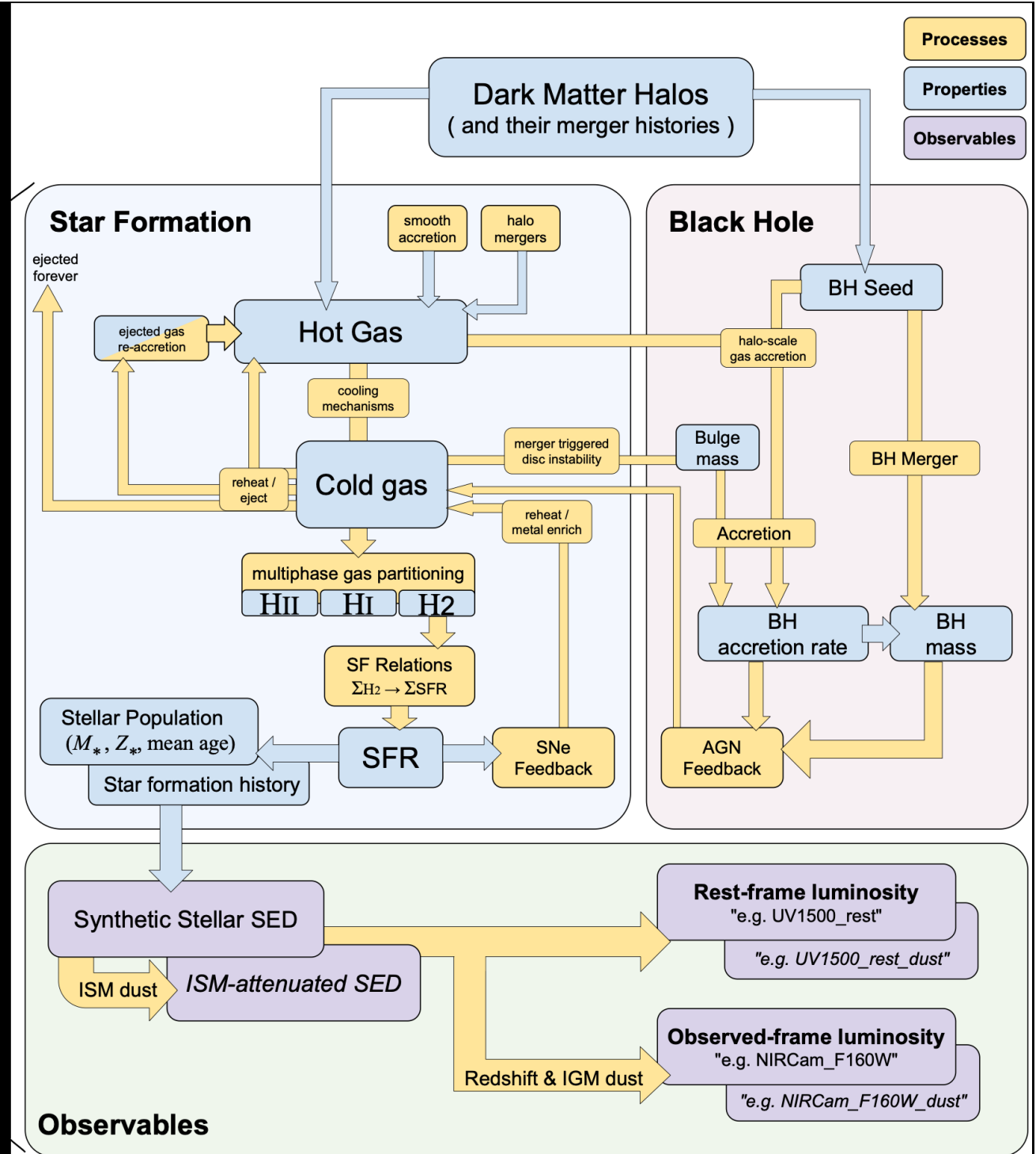
Fraction of Baryons in Stars increases vs. Cosmic Time

Fraction of Baryons in Molecular + Atomic Gas Decreases with Time



L-galaxies, GAEA,  
 SAGE/DARK SAGE  
 GALFORM, GALACTICUS,  
 SHARK  
 CAT  
 Delphi, ASTRAEUS  
 MERAXES  
 Santa Cruz SAM

(again, an incomplete list,  
 in no particular order)

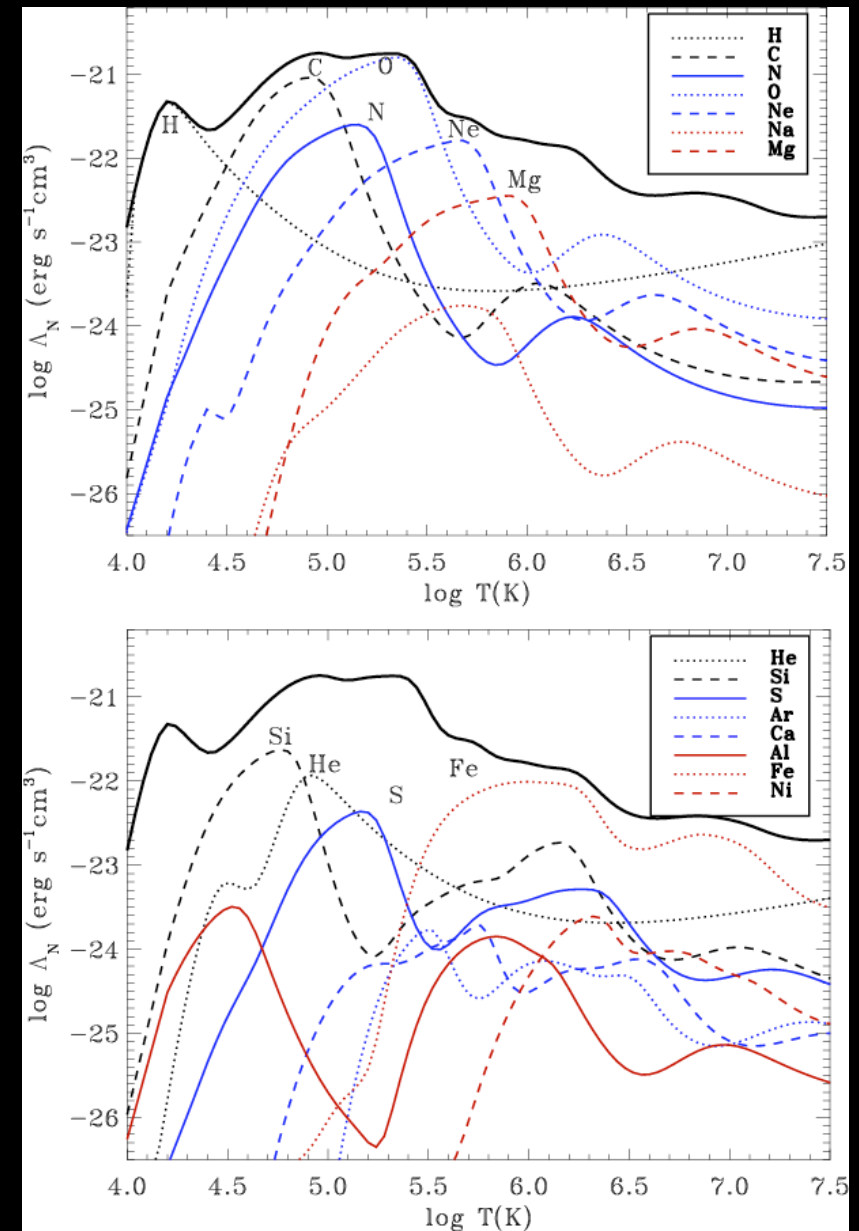
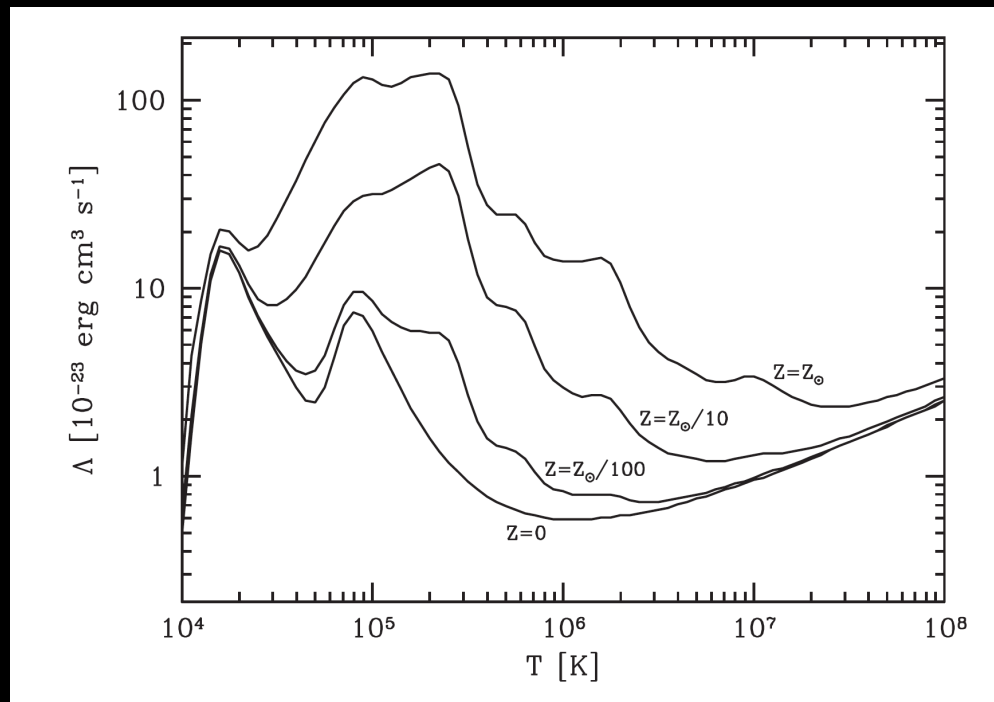


Yung et al. 2019

Credit Somerville

# cooling function

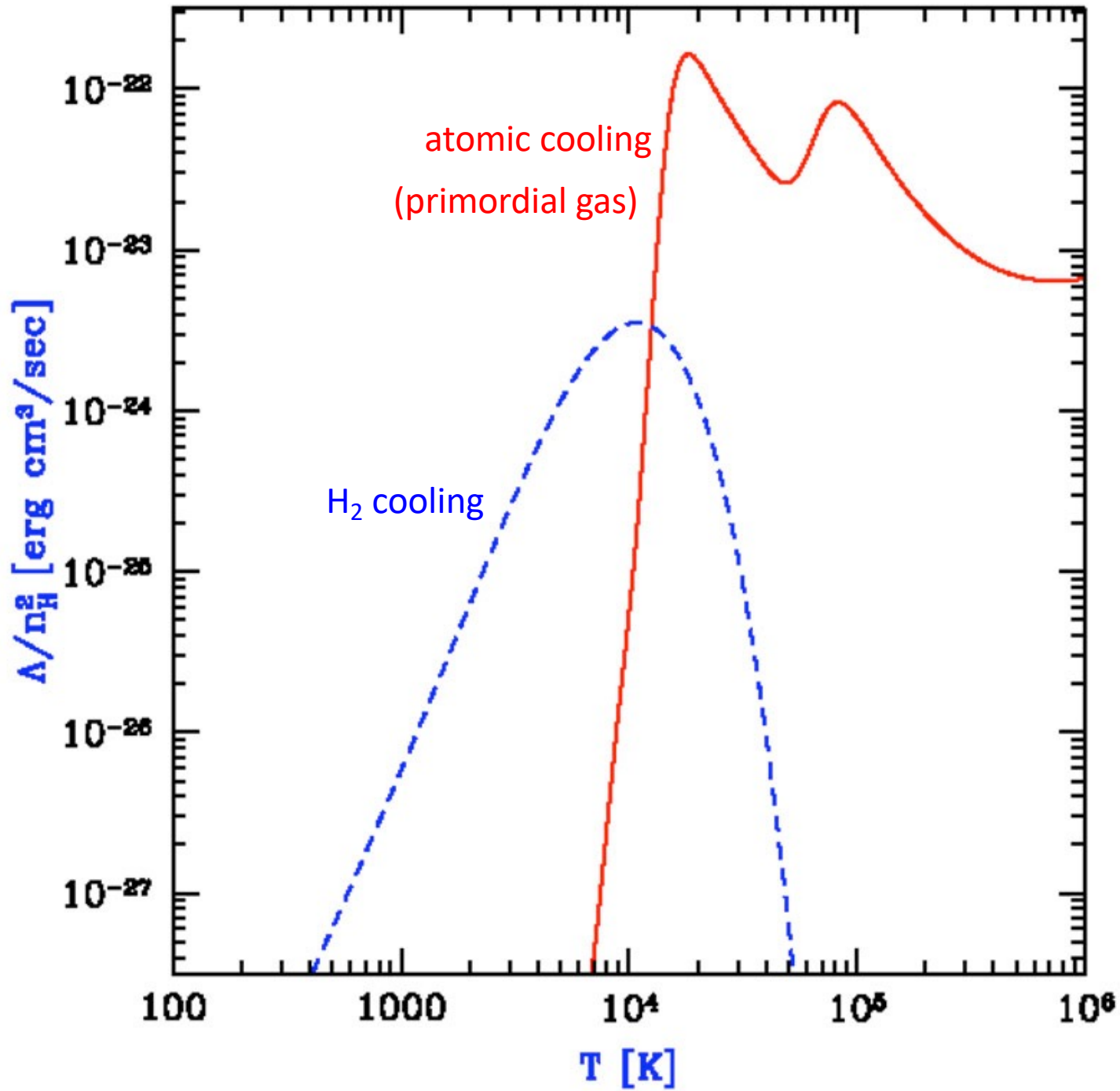
$$\Lambda(T) \equiv \frac{\mathcal{C}}{n_{\text{H}}^2},$$



Sutherland & Dopita 1995

[independent of gas density for optically thin gas]

Credit Somerville

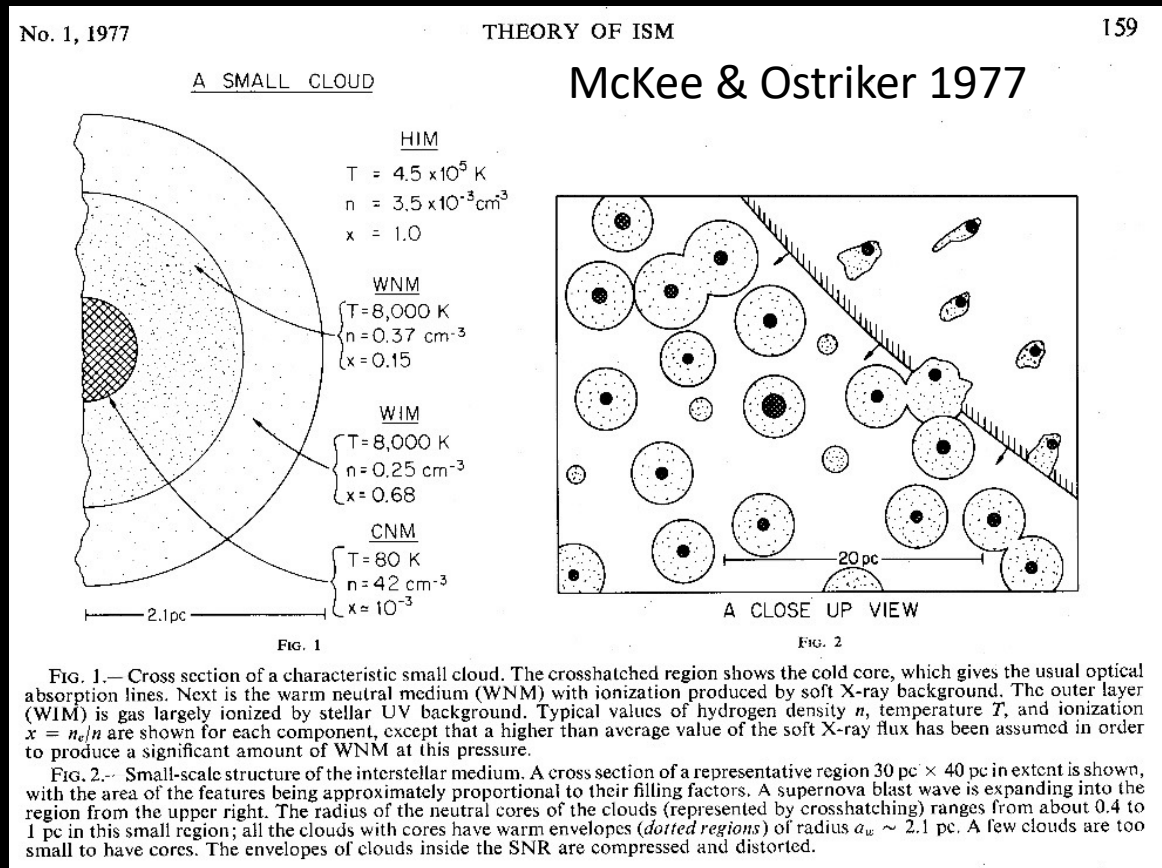
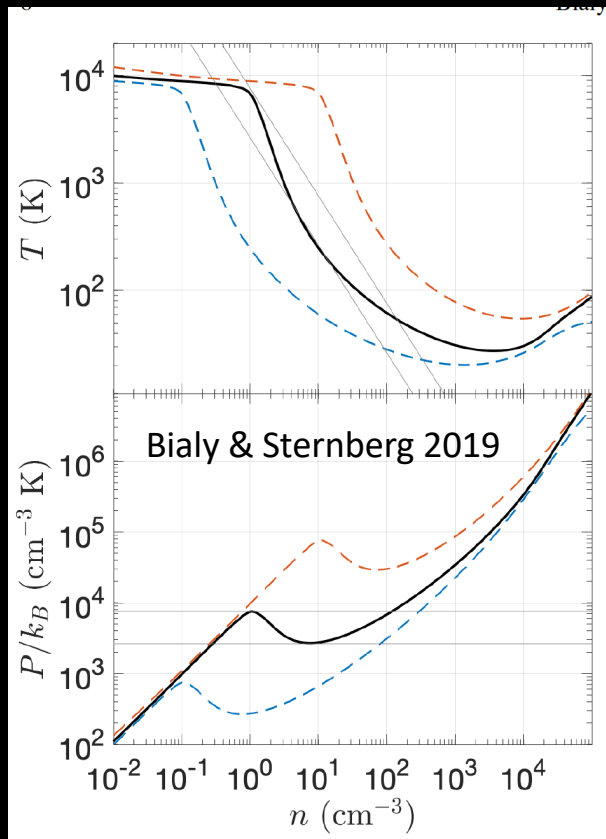


A. Loeb

Credit Somerville

# Interstellar medium (ISM) comes in different phases with wildly different physical conditions:

- from coolest to hottest:
- cold neutral medium (CNM)
- warm neutral medium (WNM)
- warm ionized region (WIM)
- hot ionized medium (HIM)

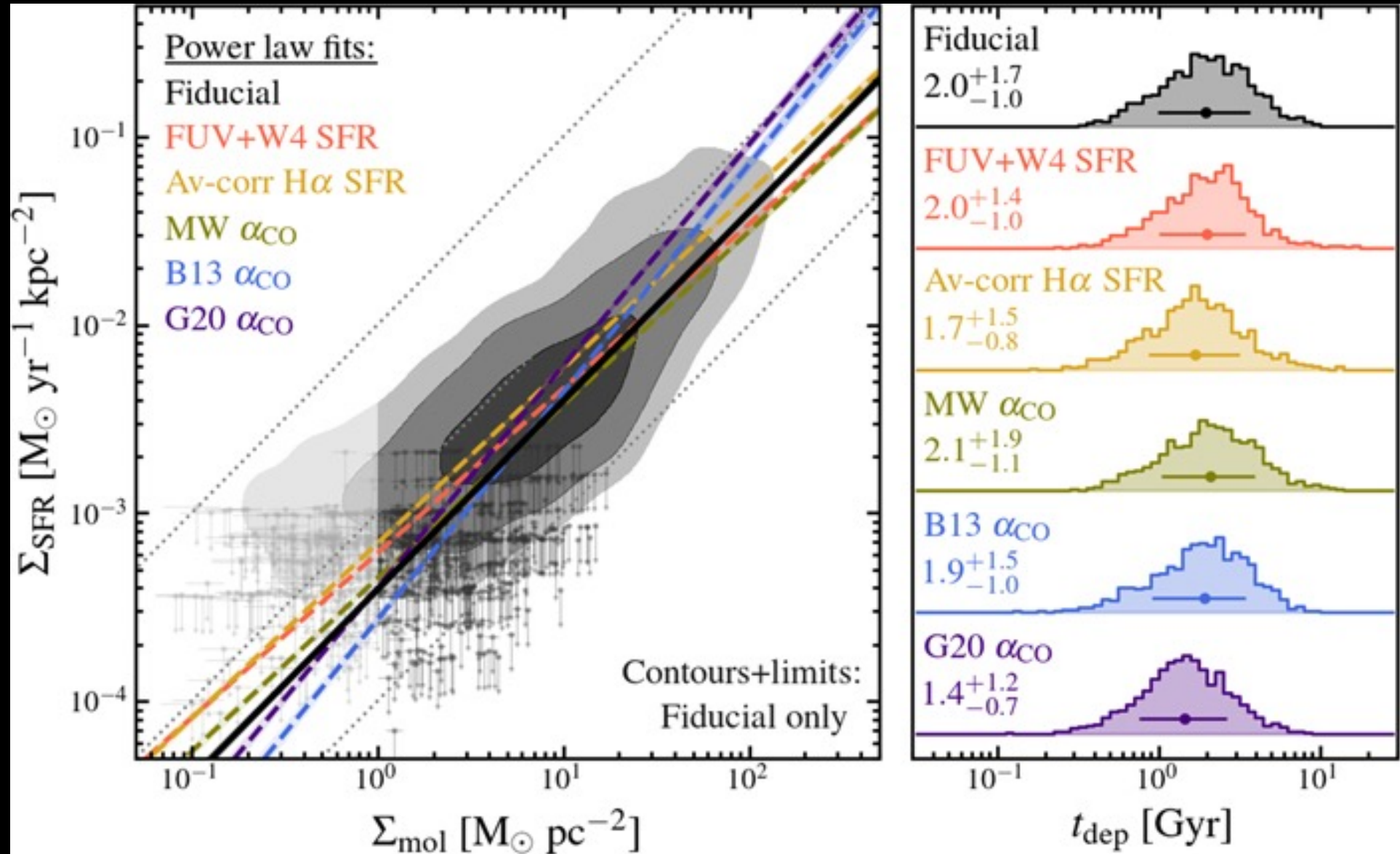


# how efficiently can stars form in GMC?

- free-fall time of GMC

$$\tau_{\text{ff}} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} \simeq 3.6 \times 10^6 \text{ yr} \left( \frac{n_{\text{H}_2}}{100 \text{ cm}^{-3}} \right)^{-1/2}$$

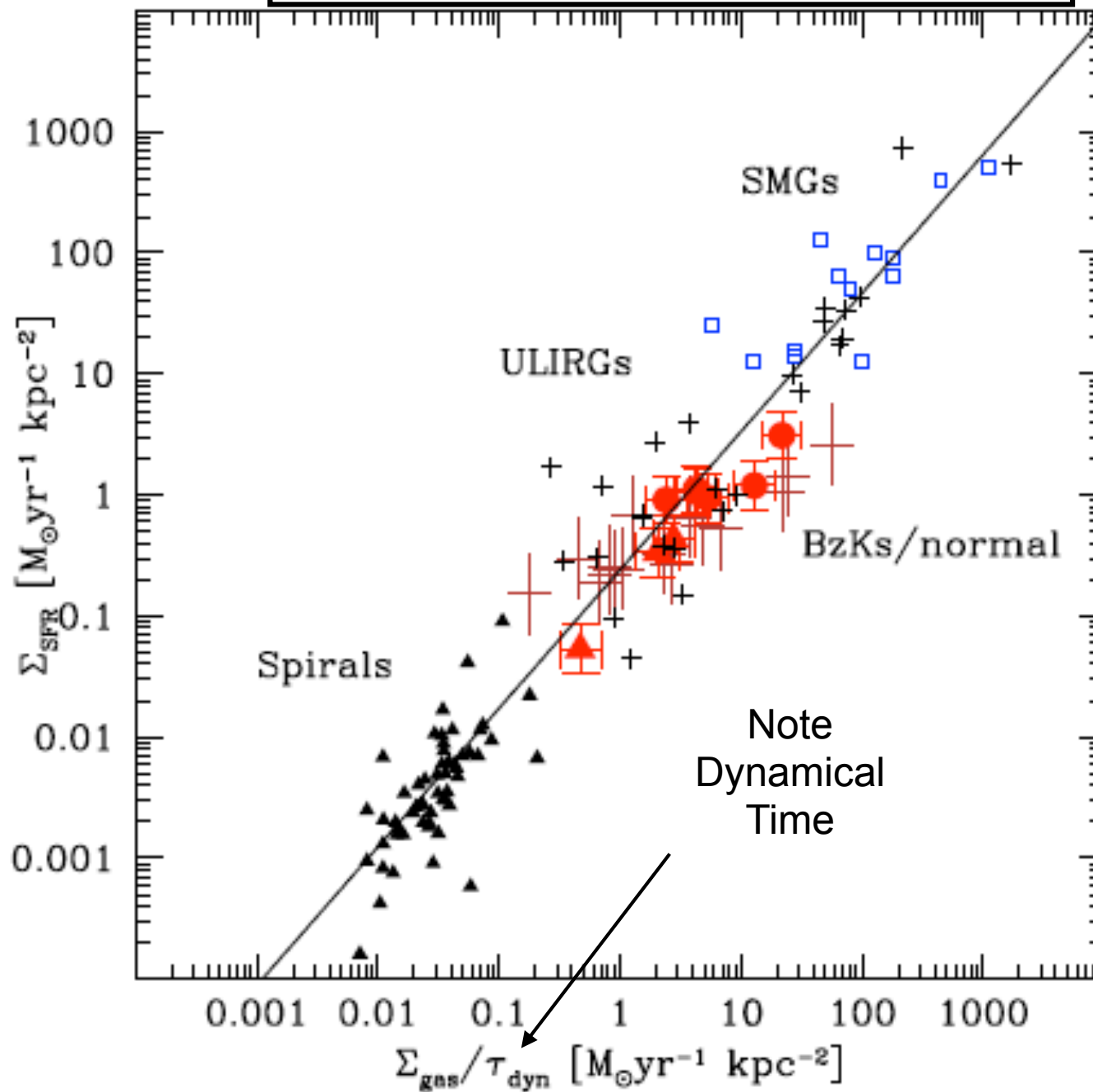
# Kennicutt-Schmidt Relationship



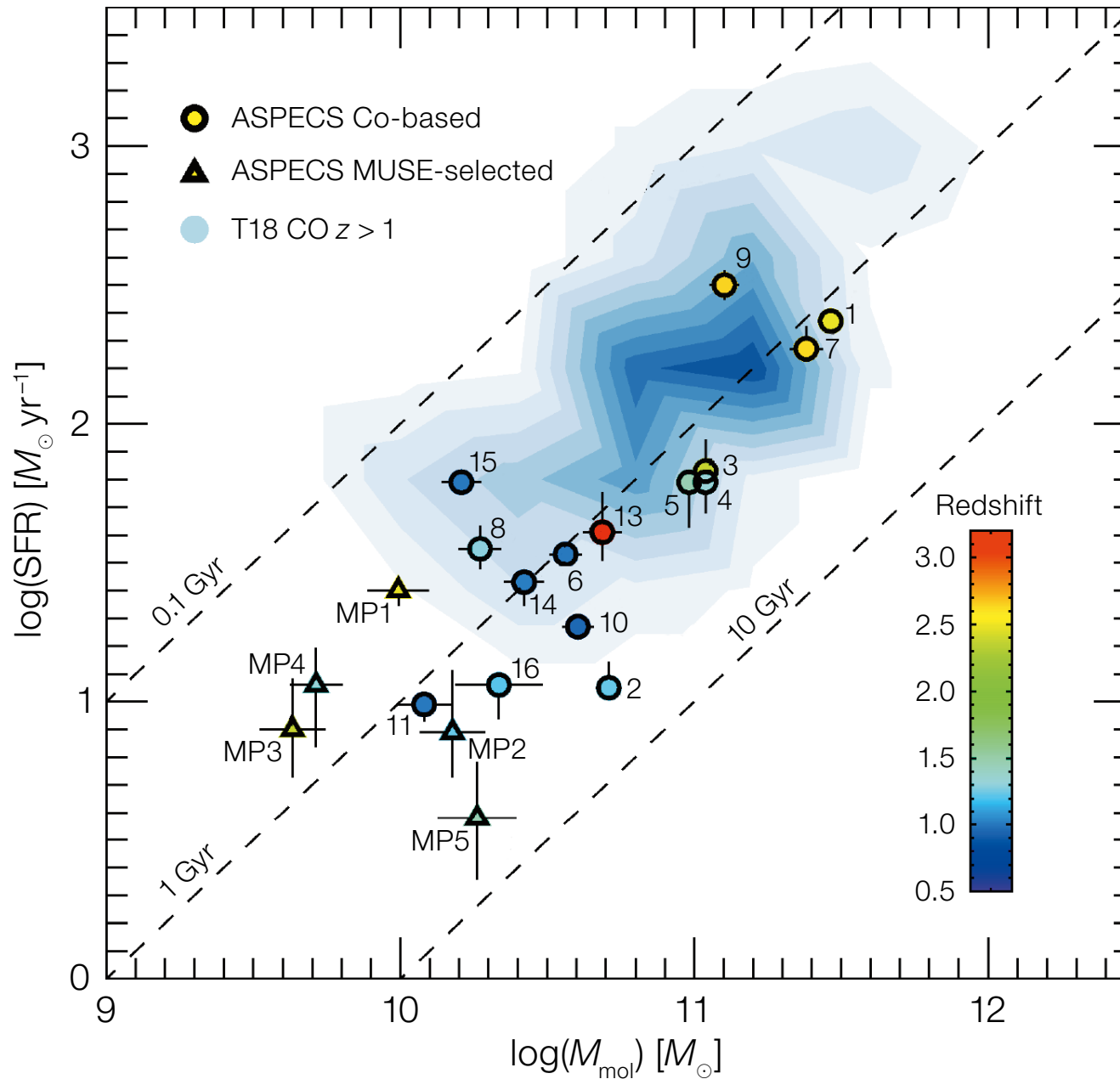
Sun et al. 2023

Credit Somerville

# Kennicutt-Schmidt Relationship



# Kennicutt-Schmidt Relationship at $z \sim 1-3$

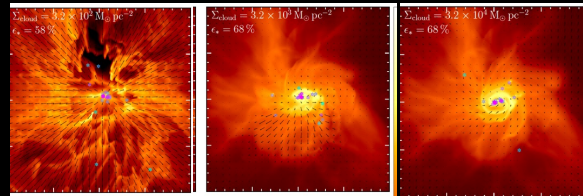


# cloud scale SF efficiency increases with surface density



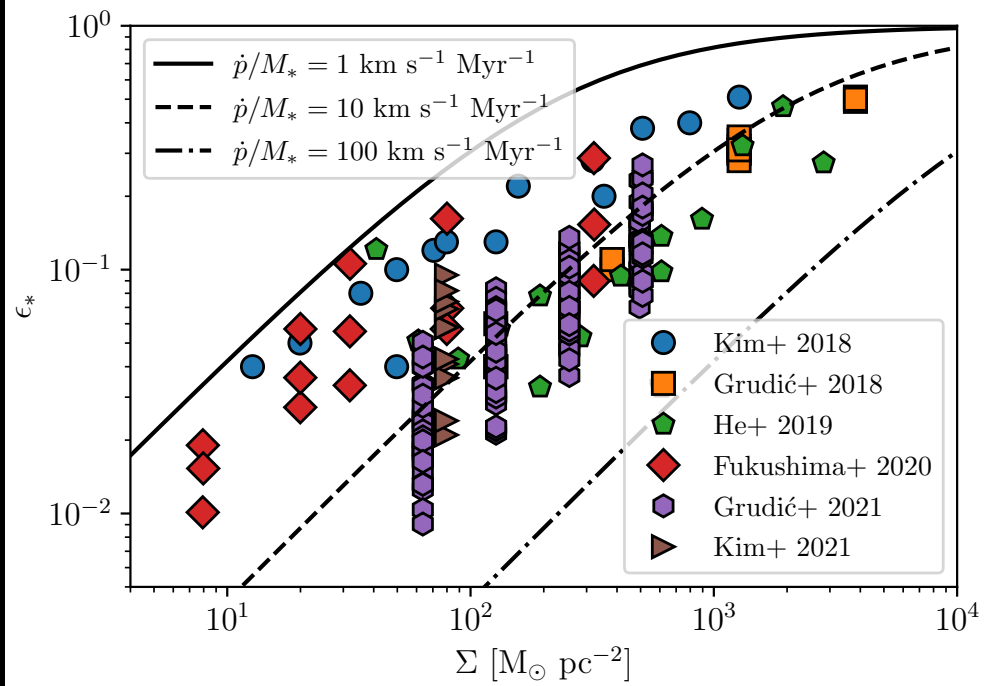
observed super star clusters:  
 $\Sigma \sim 10^4\text{-}10^5 M_{\text{sun}} \text{pc}^{-2}$   
 SFE  $\sim 70\%$  (e.g. Emig+'20)

Menon+23, 24



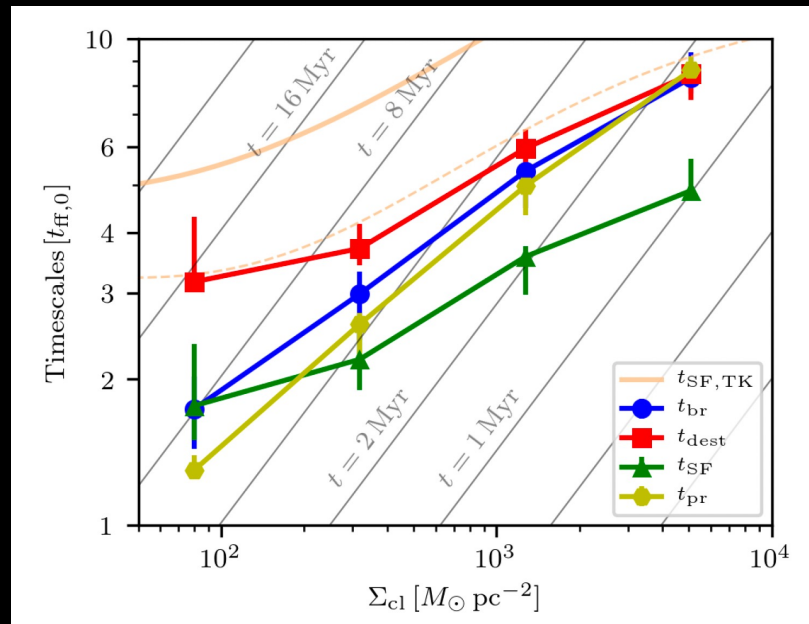
Chevance et al. 2022

fraction of gas turned into stars

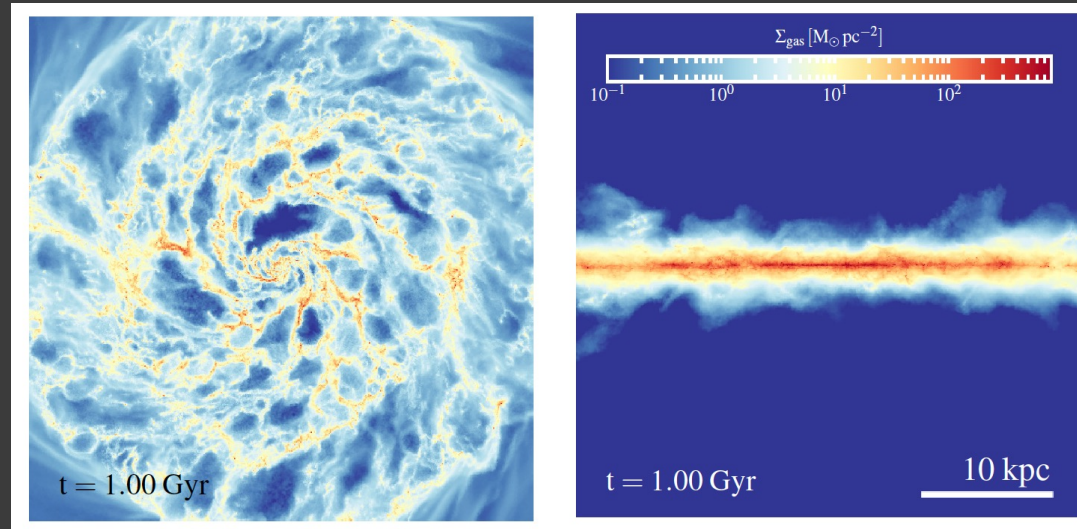
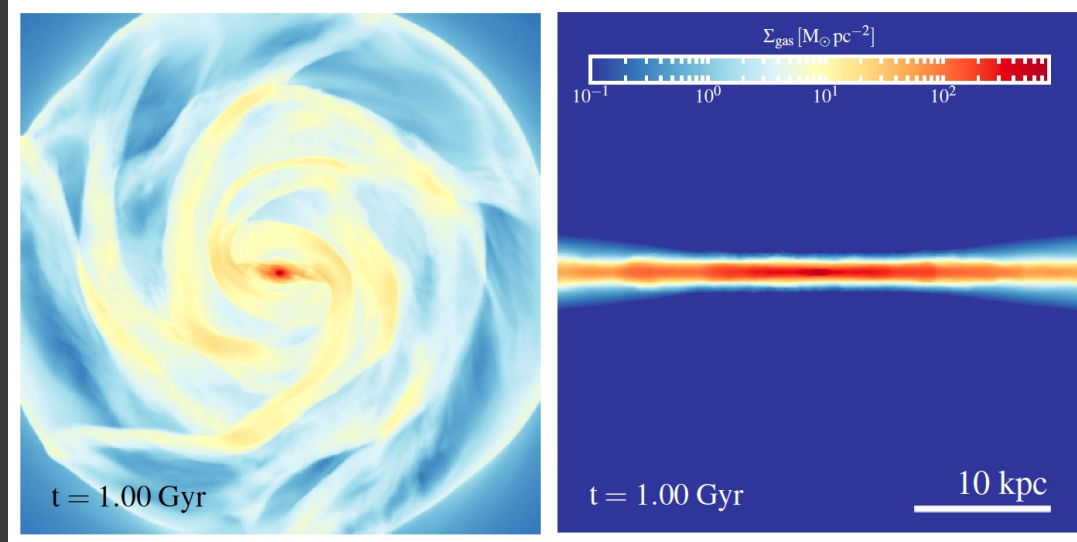
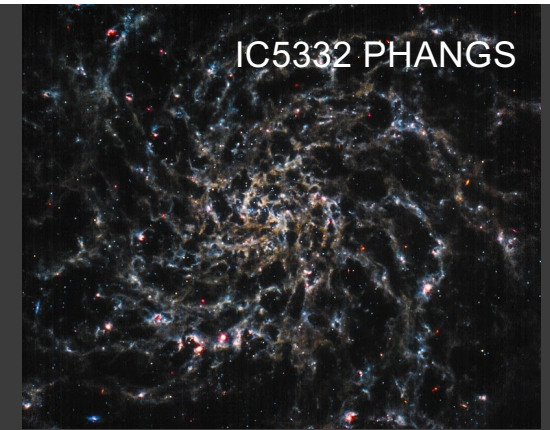


cloud scale surface density

denser clouds survive longer  
 (in units of ff time)  
 before they are dispersed



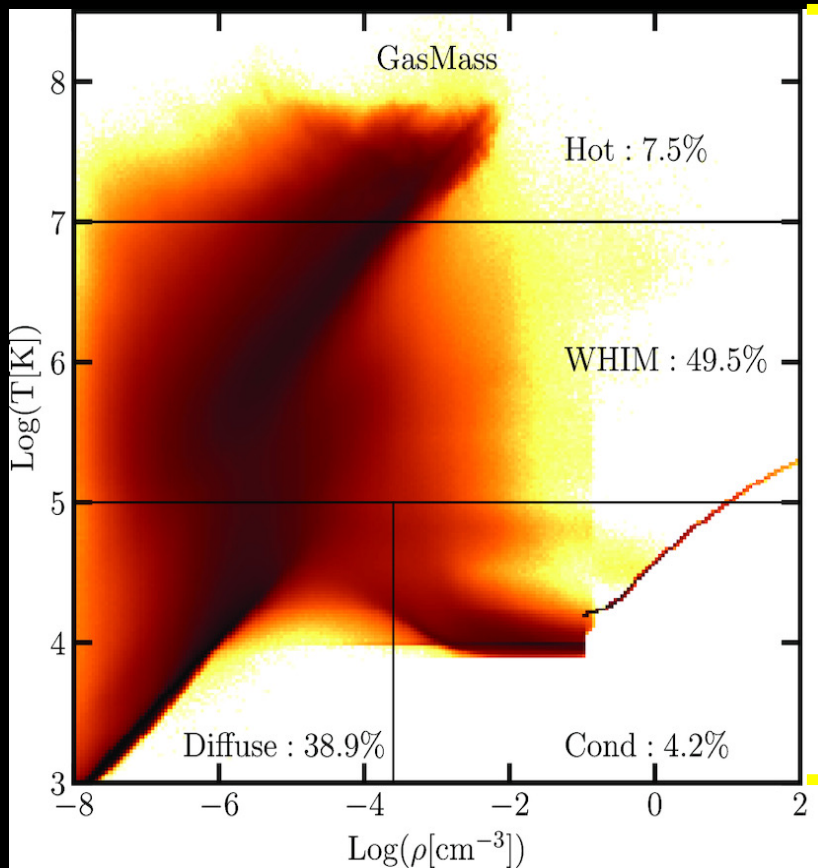
Lancaster et al. 2021



most large volume cosmo sims  
adopt an 'effective equation of  
state';  
artificially pressurizes and  
'smooths' ISM –  
many consequences

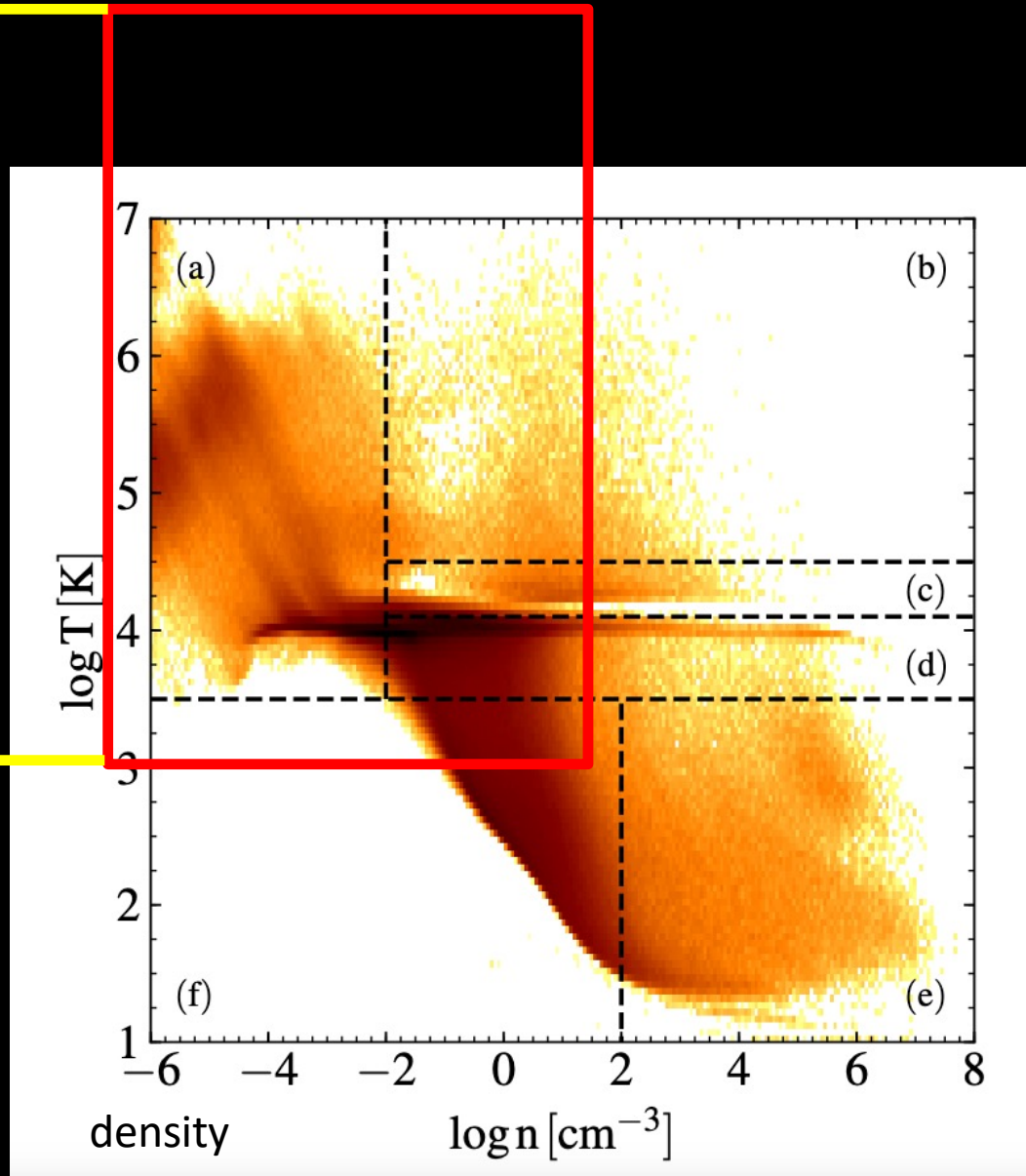
Marinacci et al. 2019

Credit Somerville



Torrey et al. 2019  
 TNG (effective EoS)

Temperature



Marinacci et al. 2019 – SMUGGLE (no eEoS)

# conditions for star formation

- density threshold
- temperature threshold
- molecular gas (SFR based on  $\rho_{\text{H}_2}$ )
- self-gravitating (virial parameter  $<1$ )
- Jeans unstable ( $m_{\text{J}} < m_{\text{cell}}$ )
- convergent flow

typically used in  
'lower res' sims

used in  
'higher res'  
sims

+ an assumed value of  $\varepsilon_{\text{ff}}$  (or a model for it)  
on the smallest resolved scale  
 $\varepsilon_{\text{ff}}$  = star formation efficiency per ff time

# stellar feedback

## Protostellar Outflows



## Stellar Winds



Credit: Chuck Ayoub



Credits: X-ray: NASA/SAO/  
GSFC/M. Corcoran et al; HST:

## Radiation

ionization & heating



Credit: Hui Yang (University of Illinois)

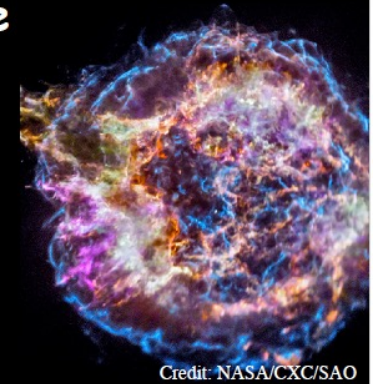


Credit: Jimmy Walker

## Supernovae



Credit: NASA, ESA, CSA, STScI, Teo



Credit: NASA/CXC/SAO

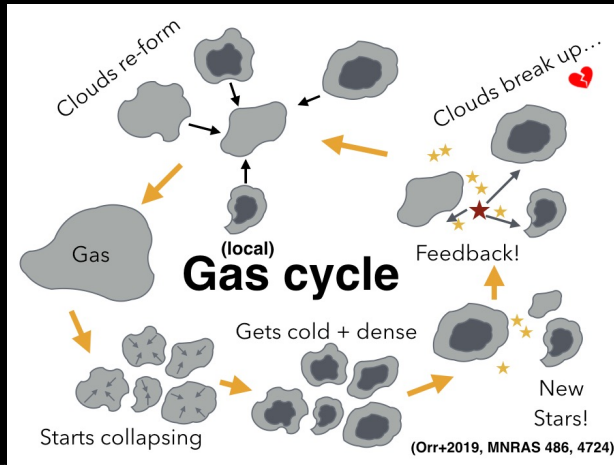
# what physics determines the star formation efficiency in galaxies on different scales?

cloud scale

galaxy scale

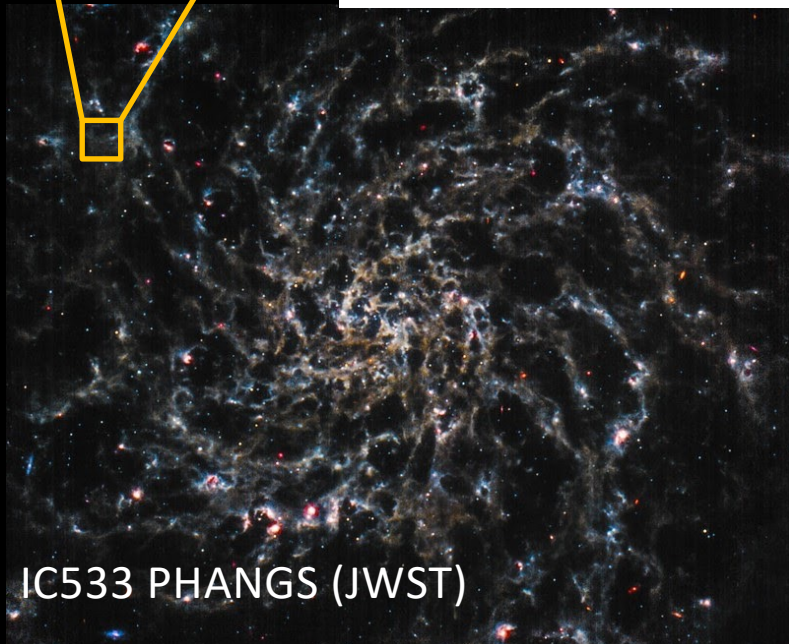


Carina Nebula, HST



*galactic winds eject mass from ISM & inject energy into CGM*

Crab Nebula, HST



IC533 PHANGS (JWST)

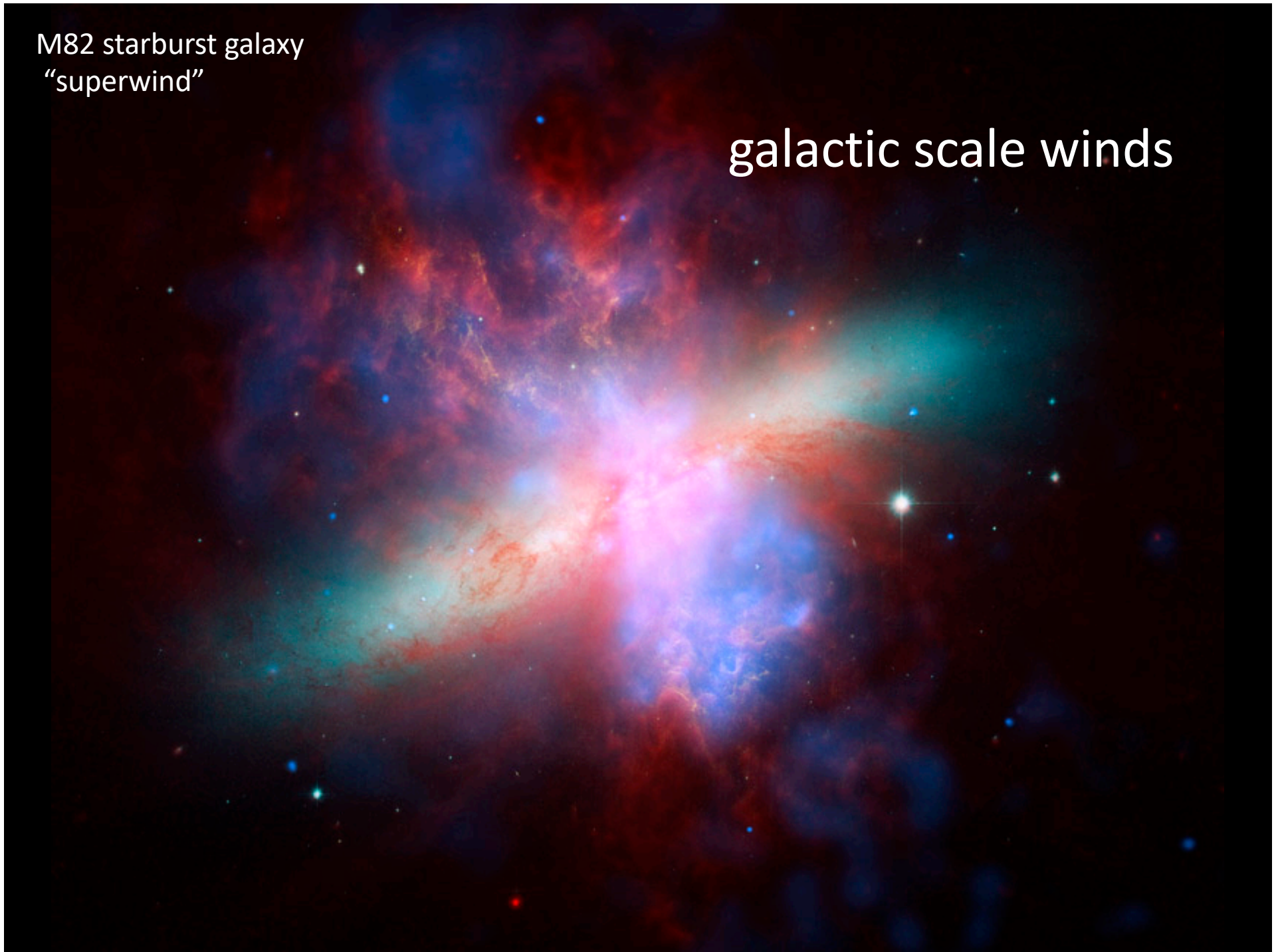
(ejective/preventative feedback)

NASA, ESA and the Hubble Heritage Team (STScI/AURA)

Credit Somerville

M82 starburst galaxy  
"superwind"

galactic scale winds



Credit Somerville

**“mass loading factor”  
of galactic winds**

$$\eta_M = \frac{\dot{M}_{\text{wind}}}{\text{SFR}}$$

**“energy loading factor”  
of galactic winds**

$$\eta_E = \frac{\dot{E}_{\text{wind}}}{e_{\text{SN}} \text{SFR}}$$

**$\Rightarrow \frac{\eta_E}{\eta_M}$  is the specific energy of the wind**

# How are galactic winds launched?

emergent winds are *multiphase*, with a broad distribution of velocities

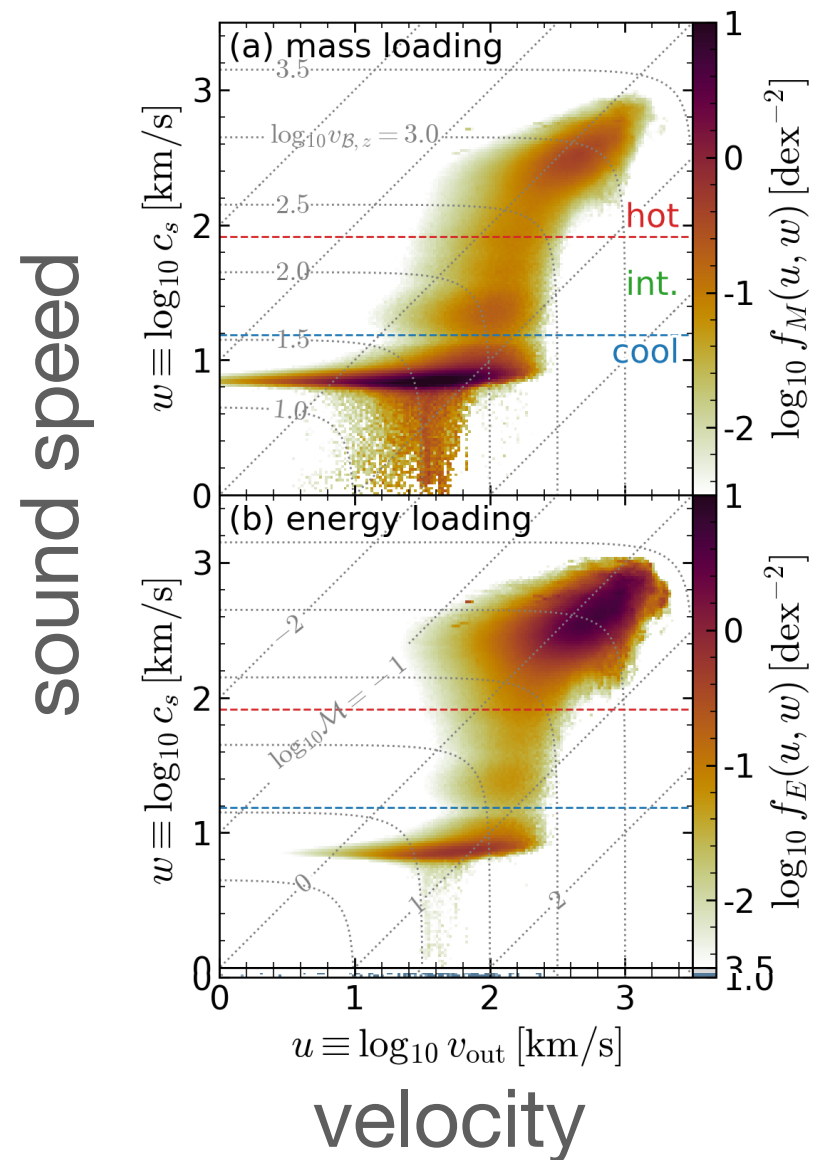
## Mass loading

dominated by cold/warm slow moving material

## Energy loading

dominated by hot, fast, metal enriched outflow

TIGRESS: Kim & Ostriker 2017  
Kim, Ostriker & SMAUG 2020a,b



# Mass Metallicity Relation →

## Fundamental Metallicity Relation

### Relationship between the Gas-Phase Metallicity in a Galaxy and Its Mass

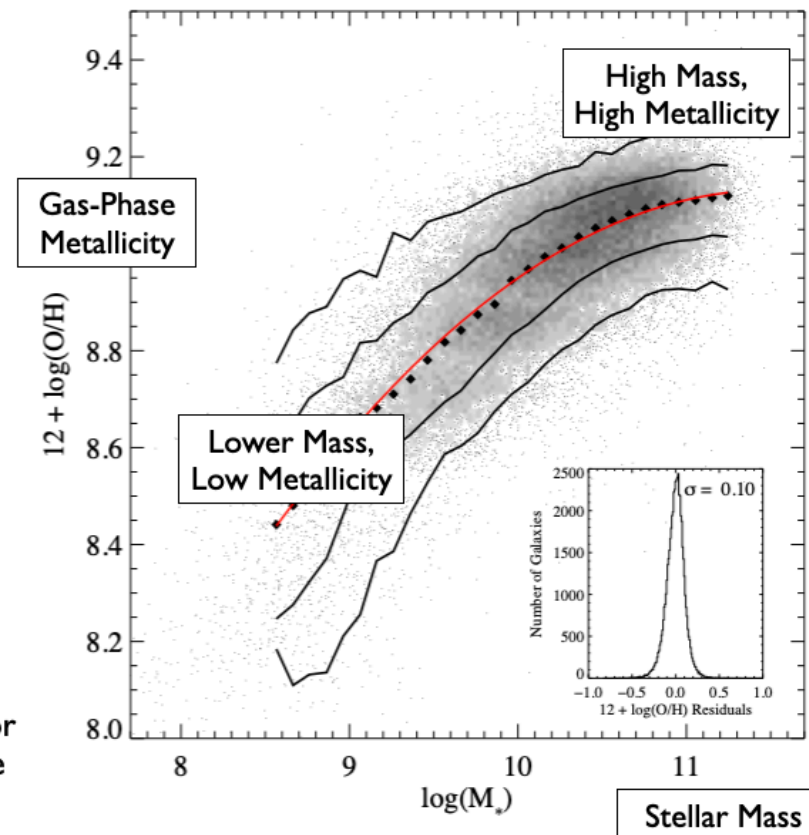
Two primary explanations for this:

#### 1) Low Mass Galaxies Form Stars Less Efficiently

As such, only a small percentage of the gas turns into SNe (which adds more metals to the mix)

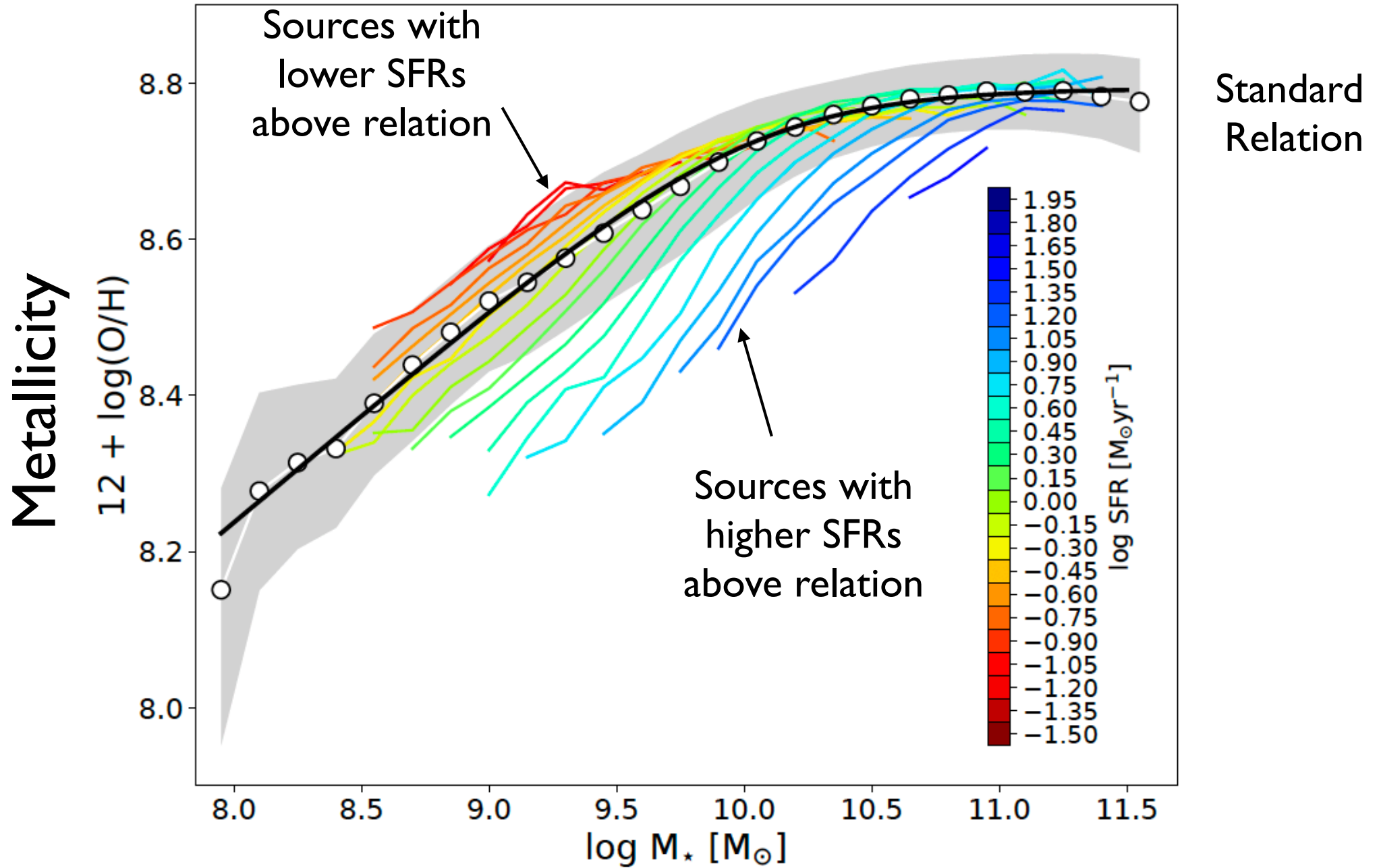
#### 2) Metals can escape more easily from low-mass galaxies due to SNe winds

The escape velocity for lower mass galaxies is lower and hence it is easier for metals to escape from such galaxies due to SNe winds

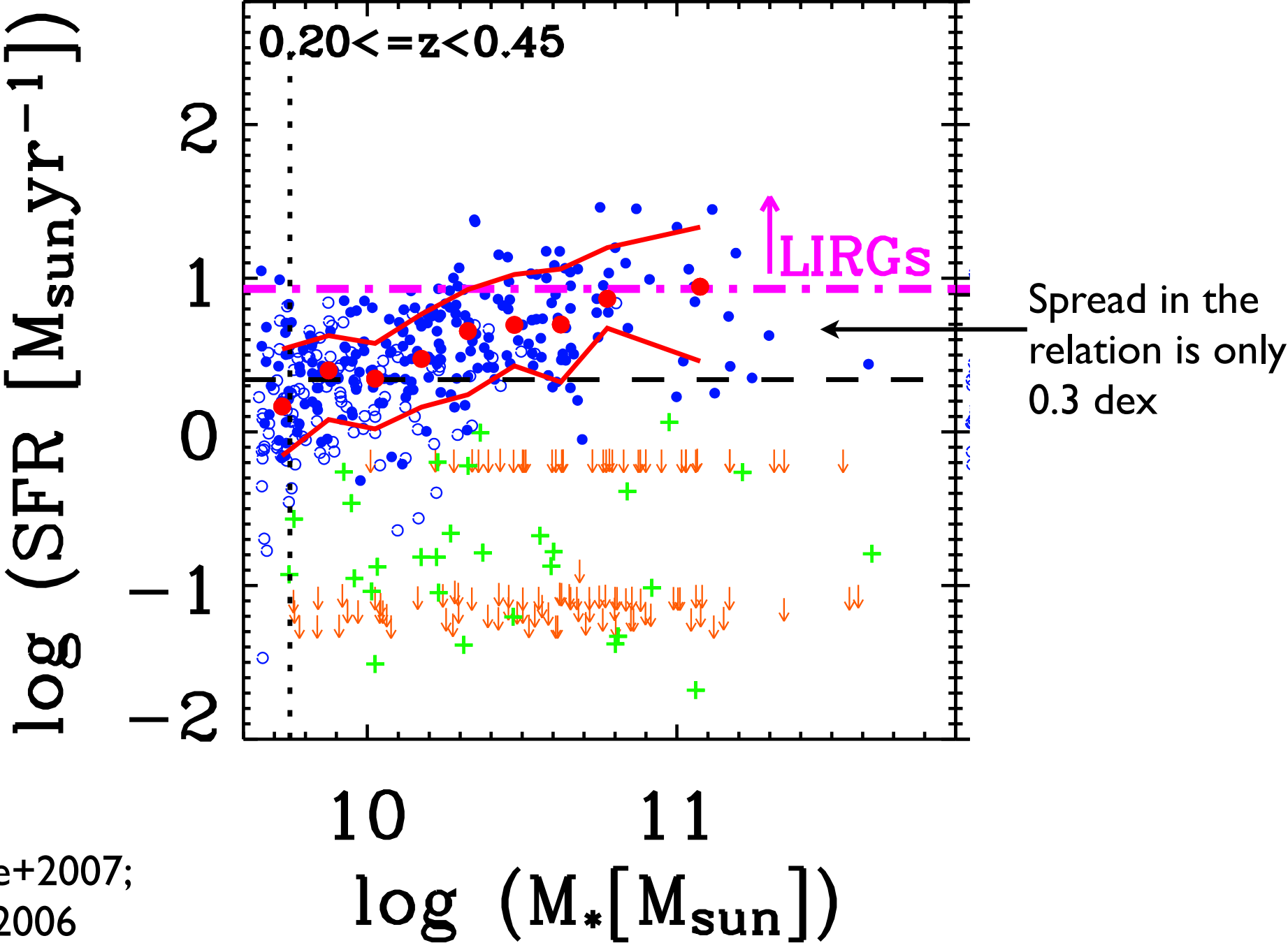


Tremonti+2004

# Fundamental Metallicity Relation

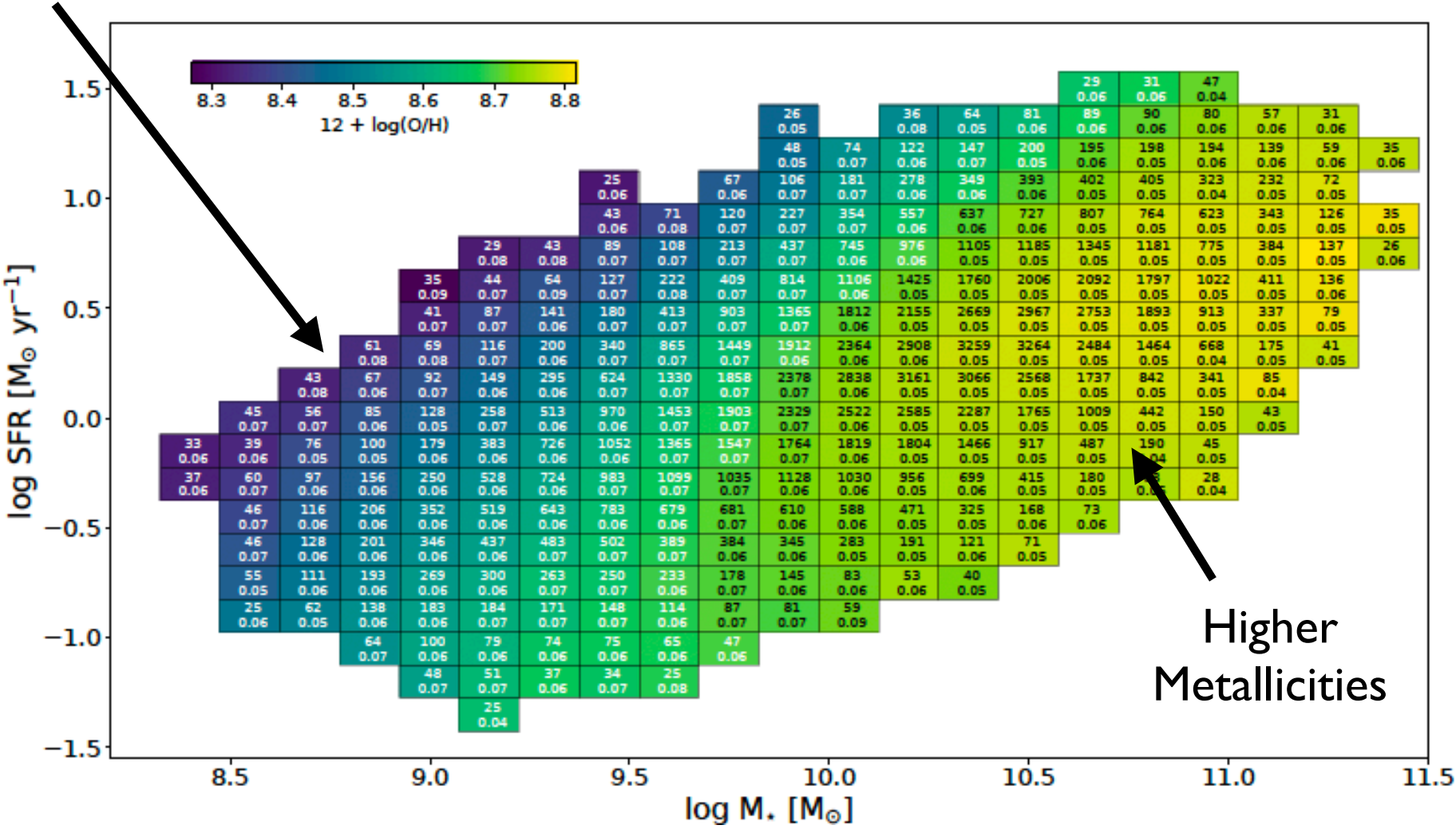


# Star Formation Rate vs. Stellar Mass Relation



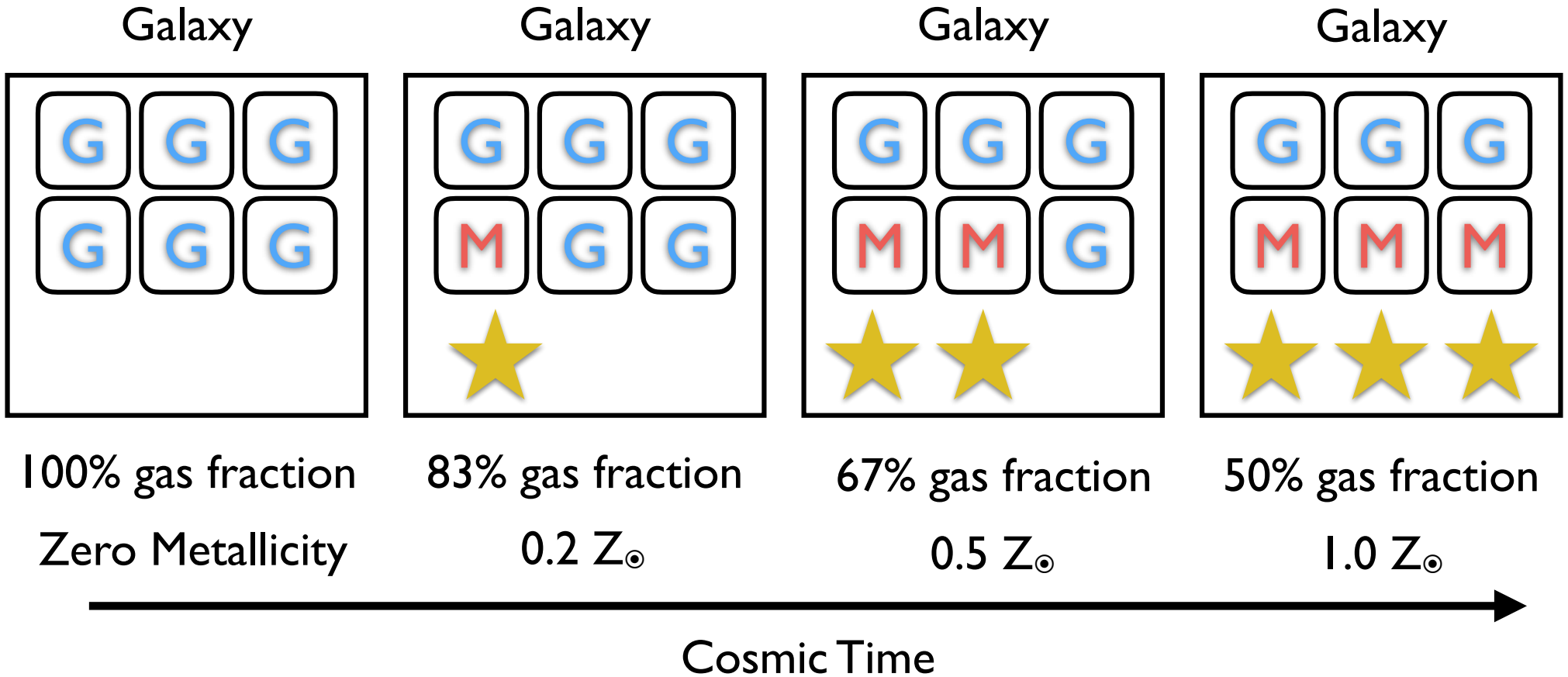
# Star Formation Rate vs. Stellar Mass Relation

Lower  
Metallicities



# What explains Fundamental Metallicity Relation?

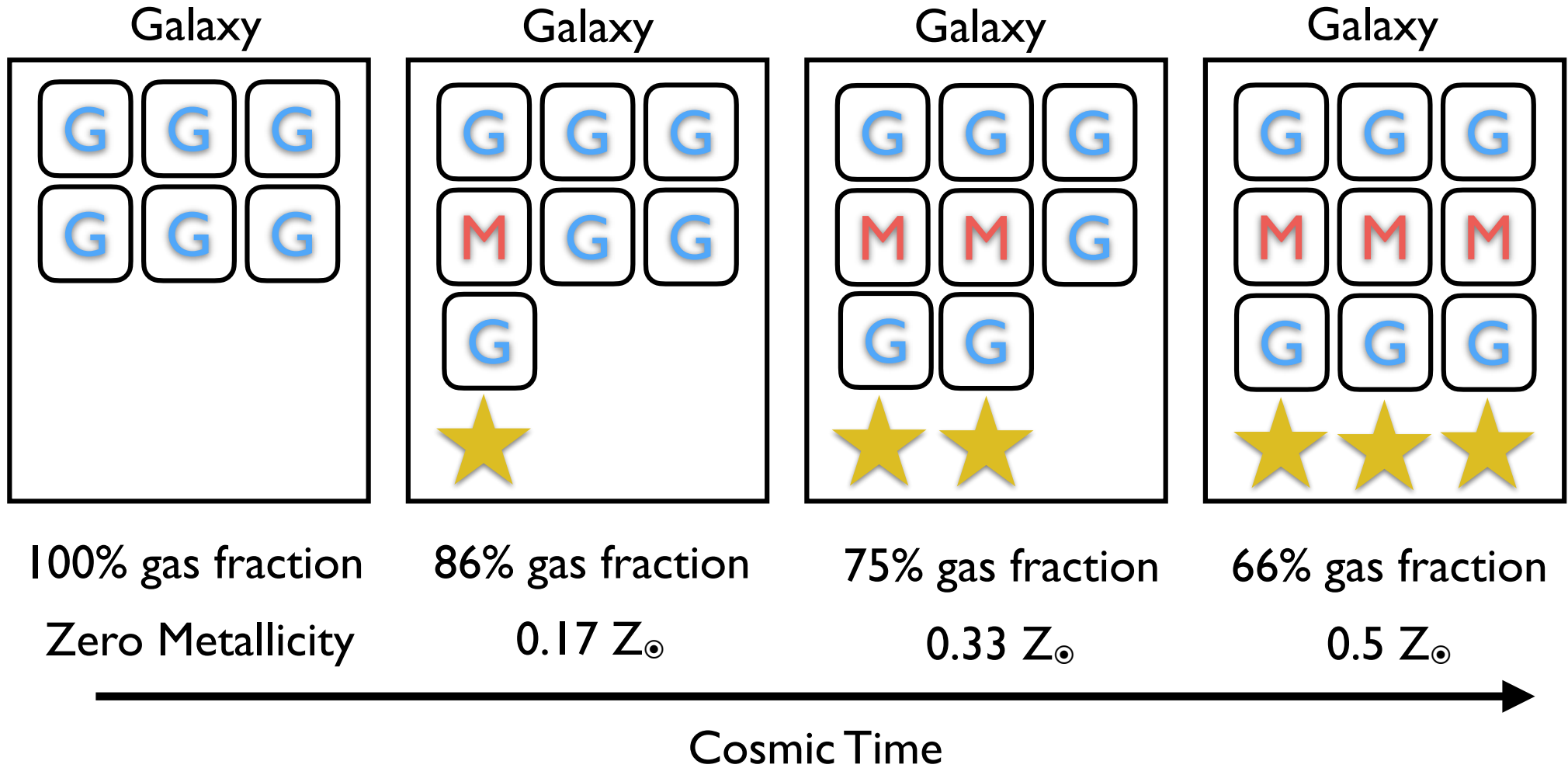
Let's first consider closed box model



As gas fraction decreases, metallicity increases

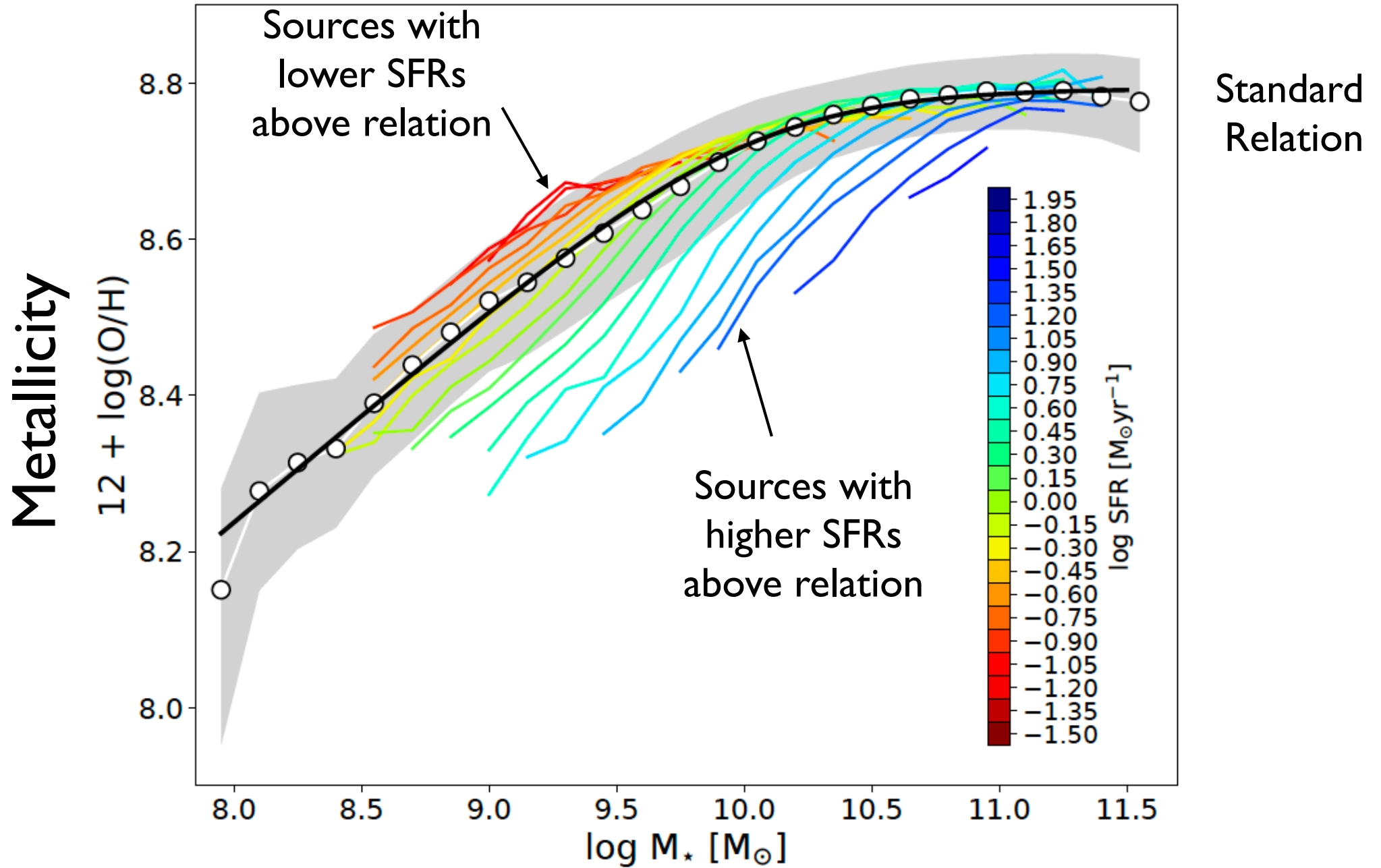
# What explains Fundamental Metallicity Relation?

How will model change if there are gas inflows — which will increase SFR?

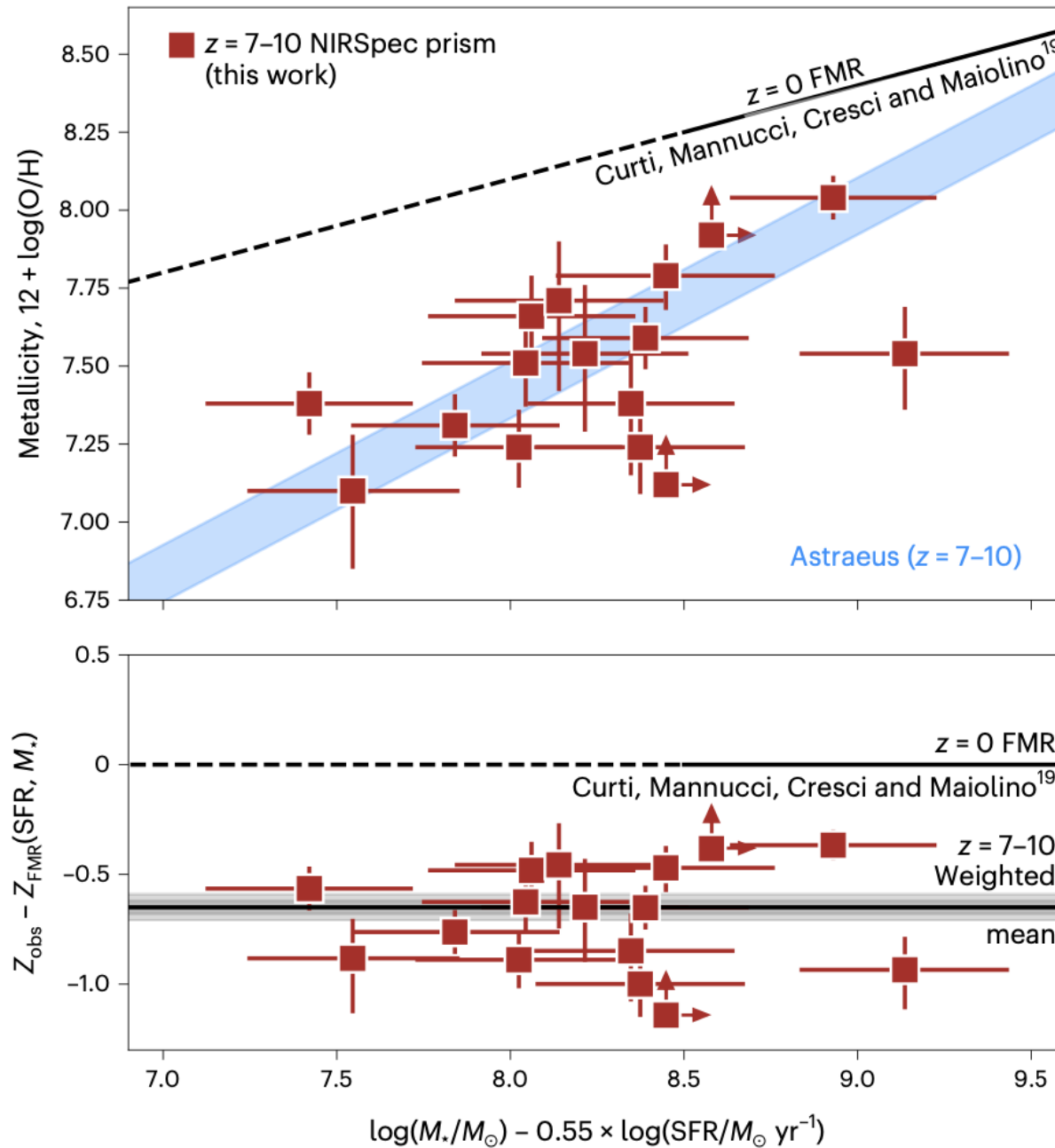


Similar trends to previous, but metallicities are lower

# Fundamental Metallicity Relation



# Do galaxies at $z > 7$ follow the FMR ?



Suggests that gas inflow in  $z > 7$  galaxies may place them even below the FMR

# Key Points to Know in Reviewing for the Final Exam

1. In general, for the exam, please have a basic understanding of everything discussed in lecture.
2. Familiarize yourself with all the homework problems and solutions to these problems given on the course web site; expect to find 1-2 problems on the exam that are similar to homework problems.
3. One of the best guides to what I consider important material for the exam is the summary I provide of the previous lecture. You could be tested on any of those concepts.
4. Understand what is meant by integrals of motion and have a sense of how to determine this number for particles in different potentials.
5. Please know a little about the impact technology, different instruments on Hubble, and the impact JWST has had on the search for galaxies in the early universe.
6. Understand the general constraints an equilibrium solution for a general stellar dynamical system must satisfy. Please be able to summarize briefly how the Schwarzschild method attempts to provide a solution. Please also be aware of the alternate strategy for solving these equations using Jean's theorem.

7. Be able to explain briefly how the Jeans equations are constructed and why they are more useful for astronomers than the Collisionless Boltzman Equation. Be aware of one well known application of those equations.
8. Understand how the Tully-Fisher and Faber-Jackson formulas can be derived.
9. Understand how dynamical friction operates and how it depends on various physical variables.
10. Be familiar with the cooling rate vs. temperature diagram and why this is important for setting the mass scale for galaxy formation.
11. Be familiar with the two steps that are necessary for galaxies to form, i.e., gravitational collapse and gas cooling to the center of a collapsed halo.
12. Please be able to explain how spiral galaxies form and elliptical galaxies likely form.
13. Please be aware of all the basic photometric properties of elliptical galaxies, i.e., how the surface brightness depends on radius, isophotal structure, boxy versus disky, etc.

14. Please have a good understanding of the overall shape of the Sersic profile for different Sersic parameters. Understand how galaxy profiles with Sersic parameters of  $n=1$  are different from galaxies with  $n=4$ . Know the typical Sersic parameters found for elliptical galaxies and for Spiral galaxies. As galaxies become older (and merge, etc.), how does the Sersic parameter change? What drives the effective changes in the Sersic parameters?
15. Be able to sketch what the surface brightness profile looks like for a core/cuspy elliptical versus a power-law elliptical. Please be able to explain why some ellipticals may show cores while others may show cusps.
16. Be capable of explaining how astronomers measure the velocity dispersion for elliptical galaxies.
17. Know which types of ellipticals are consistent with being rotationally supported and which appear more consistent with being supported by their velocity dispersion.
18. Please be capable of spelling out all the properties of the two different types of elliptical galaxies and being able to justify why they have these observed properties.
19. Know the many different forms the virial relation can take and be able to use this relation for short derivations.

20. Please be able to briefly explain why violent relaxation occurs so quickly relative to other relaxation processes like collisional relaxation. What effect does violent relaxation have on the surface brightness profile of the galaxy (i.e., its Sersic parameters)?
21. Please have a quantitative understanding of the winding problem for spiral galaxies. Also understand how we determine whether spiral arms are leading or trailing.
22. Please understand quantitatively why stars undergo epicyclic oscillations when orbiting within an axisymmetric potential.
23. Please understand how the coupling that goes on between the epicyclicular motion and the pattern speed/frequency for the spiral density waves in spiral galaxies.
24. Please understand what isophotal twist is and be able to sketch a simple diagram to illustrate the concept and explain it.
25. Please have a rough understanding of the composition of a spiral arm in a galaxy and which material (e.g. old stars, young stars, high-density gas/dust) leads or trails other material.
26. Please have an understanding of what sets the approximate minimum and maximum masses of galaxies.

27. Please have an understanding on what sets the size of a spiral galaxy and how the size is related to radius of the dark matter halo.

28. Please have a general knowledge of the relations which constrain the structural properties of spiral and elliptical galaxies. How many degrees of freedom do spiral and elliptical galaxies have in their structural properties?

29. Please be familiar with the basic relations regarding the collapse of dark matter halos, i.e., what is the density of a dark matter halo when it first collapses? Know how the critical density of the universe and the Hubble parameter depend on redshift for an Einstein-de Sitter universe. Also know the formula for the critical density. Also know what will eventually happen to a region of the universe which is overdense or which is underdense relative to the critical density.

30. Please ensure you have a good understanding of why the observed velocity dispersion of stars in our own galaxy might correspond with the apparent age of a star, why there might be a relation between the metallicity of a star and its age, and why the abundance ratio of stars would also depend on the age of a star.

31. Please have a sense where molecular hydrogen is distributed in galaxies relative to atomic hydrogen gas.

32. Please have a sense of the structure of our own galaxy, i.e., bulge, halo, thin disk, thick disk.
33. Know how the mass profile of a galaxy scales as a function of radius, both at large and small radii. Please have a rough understanding of the different observational techniques used to probe the mass profile of a dark matter halo.
34. Be able to compute the relative bias from a plotted correlation function. Please know how the bias and clustering depend on the halo mass of a galaxy.
35. Be able to explain why clustering is a valuable tool for astronomers to use to study galaxy evolution.
36. Have an understanding of the rough principles of resolved and unresolved stellar population analyses. Know about the age-metallicity degeneracy and how astronomers try to break it.
37. Be thoroughly familiar with the structure of the basic color-magnitude diagram for galaxies, as seen in the Sloan Digital Sky Survey.
38. Be aware of what we can conclude from the small scatter in the color-magnitude relation of galaxies in nearby clusters.
39. Be aware of the general properties associated with galaxies in either mode of the bimodal distribution.

40. Know that the environment of a galaxy can also affect the properties of a galaxy. Know what the effect will be and why.
41. Be familiar with the mass-metallicity relation. What is the correlation and what are some explanations as to why the correlation exists?
42. Be able to explain what the challenges are in studying galaxies in the nearby universe versus at great distances. How are those challenges overcome?
43. Have an understanding of how the red sequence galaxies evolve with time or redshift. How do the blue sequence galaxies evolve with time?
44. Have a sense for the general picture of galaxy evolution in terms of objects moving from the blue cloud to the red sequence and the role that wet and dry mergers play in building up elliptical galaxies on the red sequence.
45. Be familiar with the Lyman-break technique and be able to explain it briefly.

46. Know the answer to a bunch of questions on galaxies in the early universe, i.e., what are the physical sizes of the galaxies that were found at redshift 3? What do they likely evolve into at lower redshift? How was this latter conclusion drawn? To which redshift have astronomers been able to probe approximately? What differences are there between the population of galaxies seen in the very early universe and those seen at much later times (like today)?

47. Be familiar with the different techniques astronomers use to estimate the star formation rate in distant galaxies and how this is probed.

48. Look over the paper presentations provided on the course website and ~3 sentence summaries provided by the course lecturer. Please be familiar with the presentations at the level of the short summaries and be able to answer short answer questions.

49. Be familiar with Eggen-Lynden-Bell-Sandage and Searle-Zinn models for the formation of the halo for disk galaxies and be able to explain what the observational predictions of those models would be for halo stars.

50. Please be familiar with the integrated star formation efficiency vs. halo mass diagram and understand how it connects with the evolution of the cosmic star formation rate density with cosmic time. Be able to explain why the cosmic star formation rate density increases at early times and then decreases at later times.

51. Please know how the sizes of star-forming galaxies roughly depend on redshift and how this relates to scalings based on the size of collapsed halos with redshift. Please also be aware of how the specific star formation rates of galaxies roughly scale with redshift.

52. Please know how the approximate dust obscuration scales with galaxy mass and how this relates to the mass-metallicity relation. Also be aware of the fundamental metallicity relation and how you might expect the SFR of galaxies to impact the mass-metallicity relation.