Galaxies

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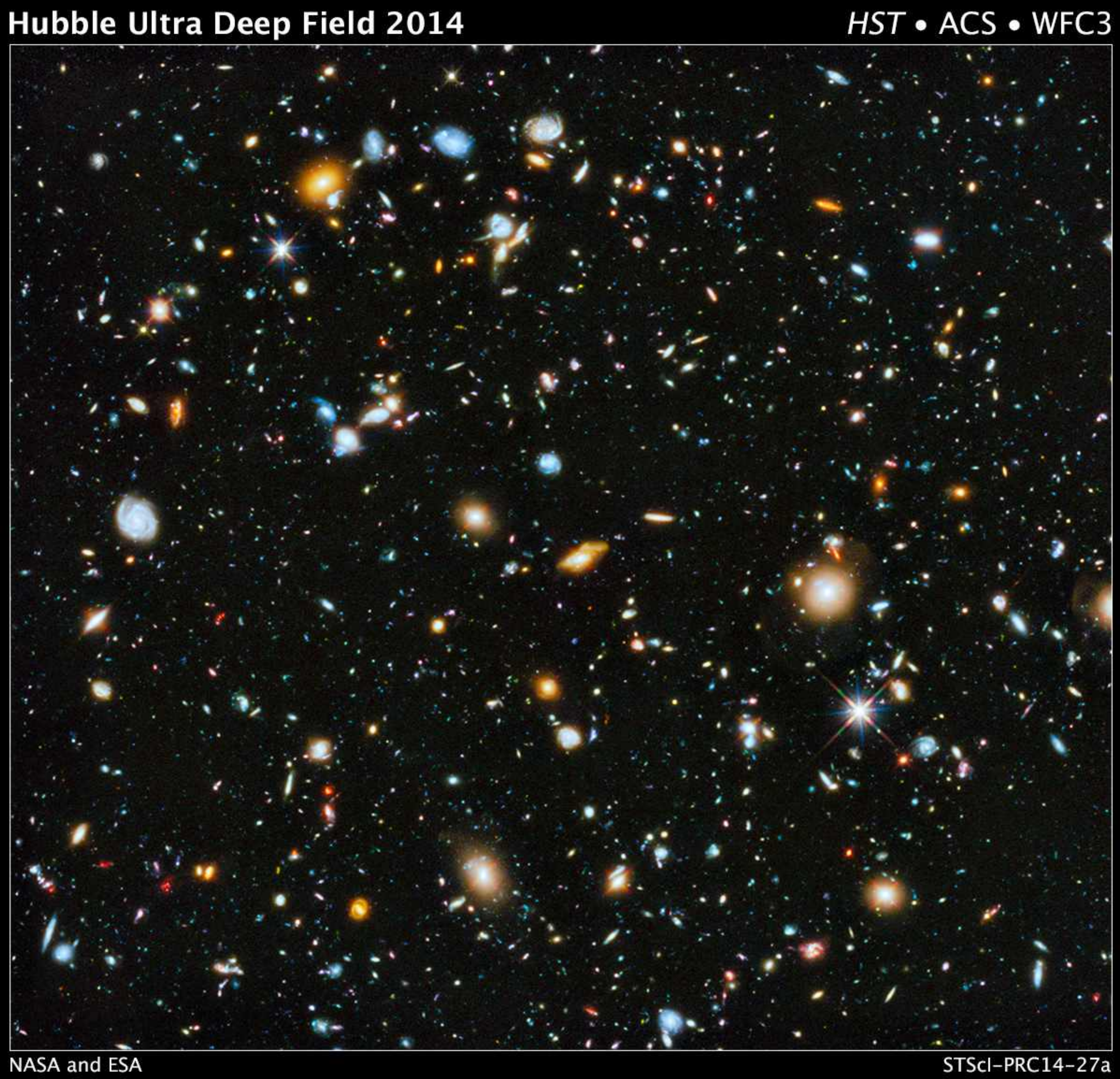
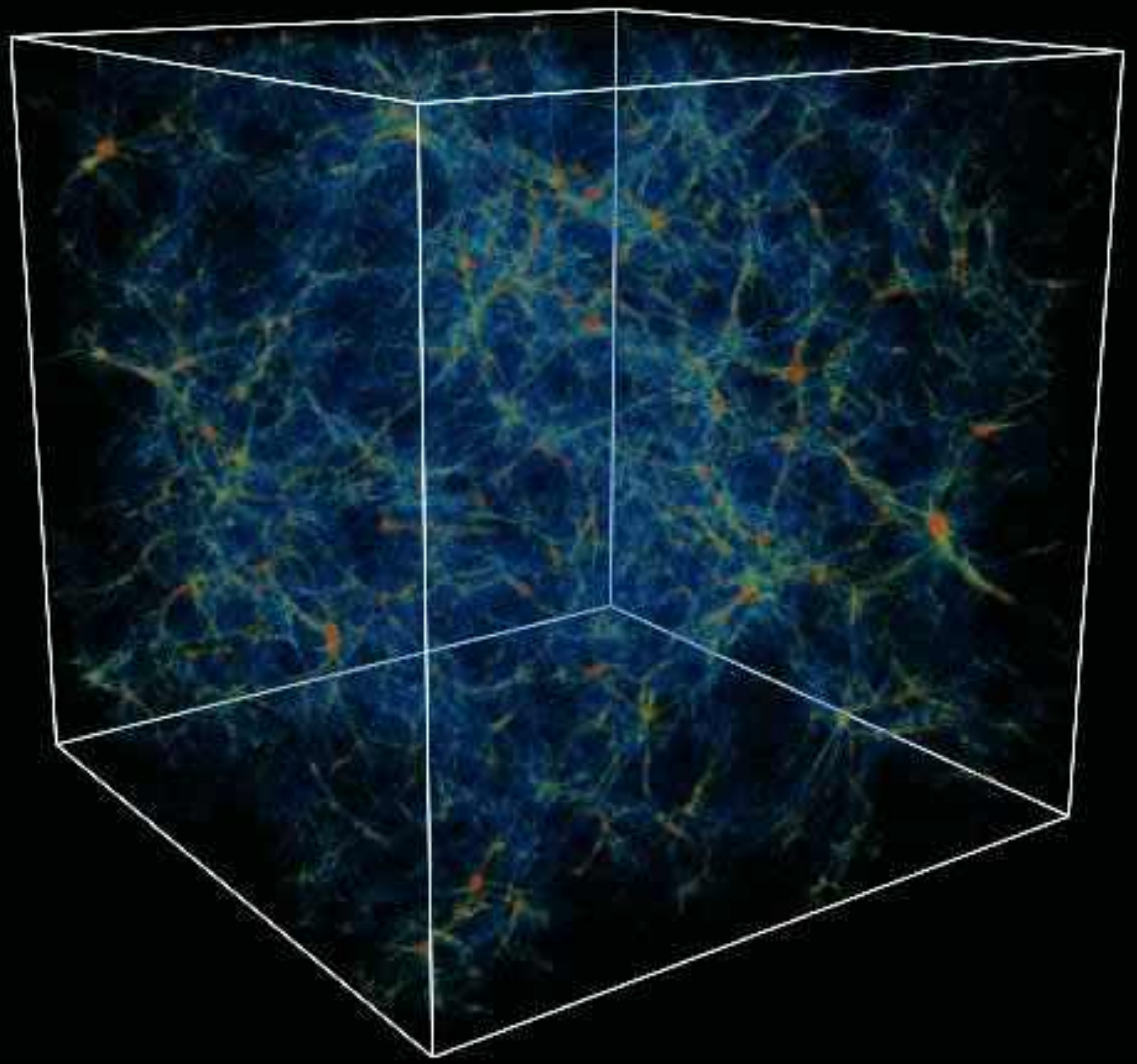
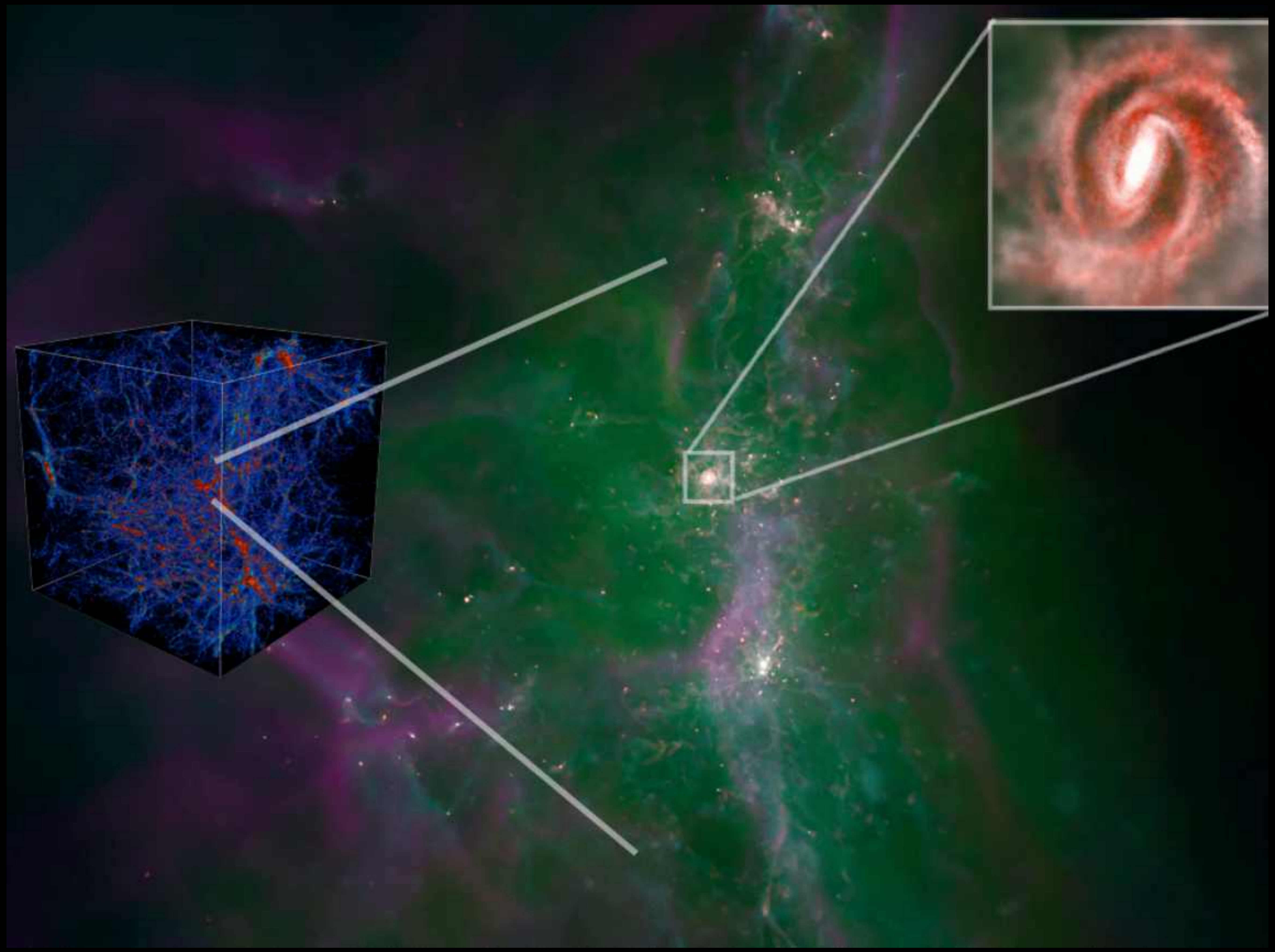
(ASIAA)







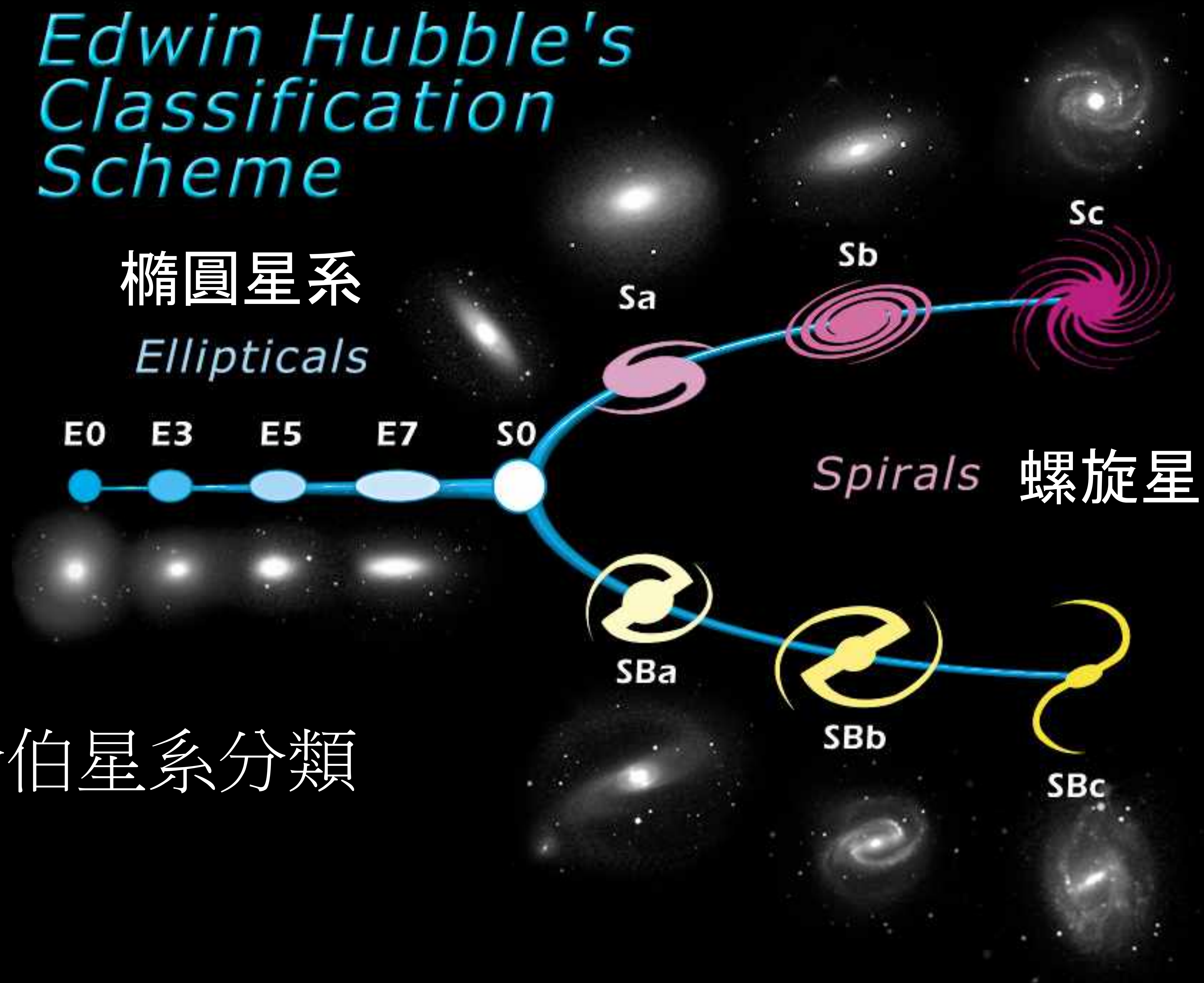
Credit: GADGET3-Osaka SPH code (Shimizu et al. 2019)

OUTLINE

- Star-forming main sequence
- The role of molecular gas
- The resolved star formation scaling relations

Basic properties of galaxies

- Morphology
- Kinematics
- Environment
- Star formation rate
- Stellar mass
- Molecular gas mass

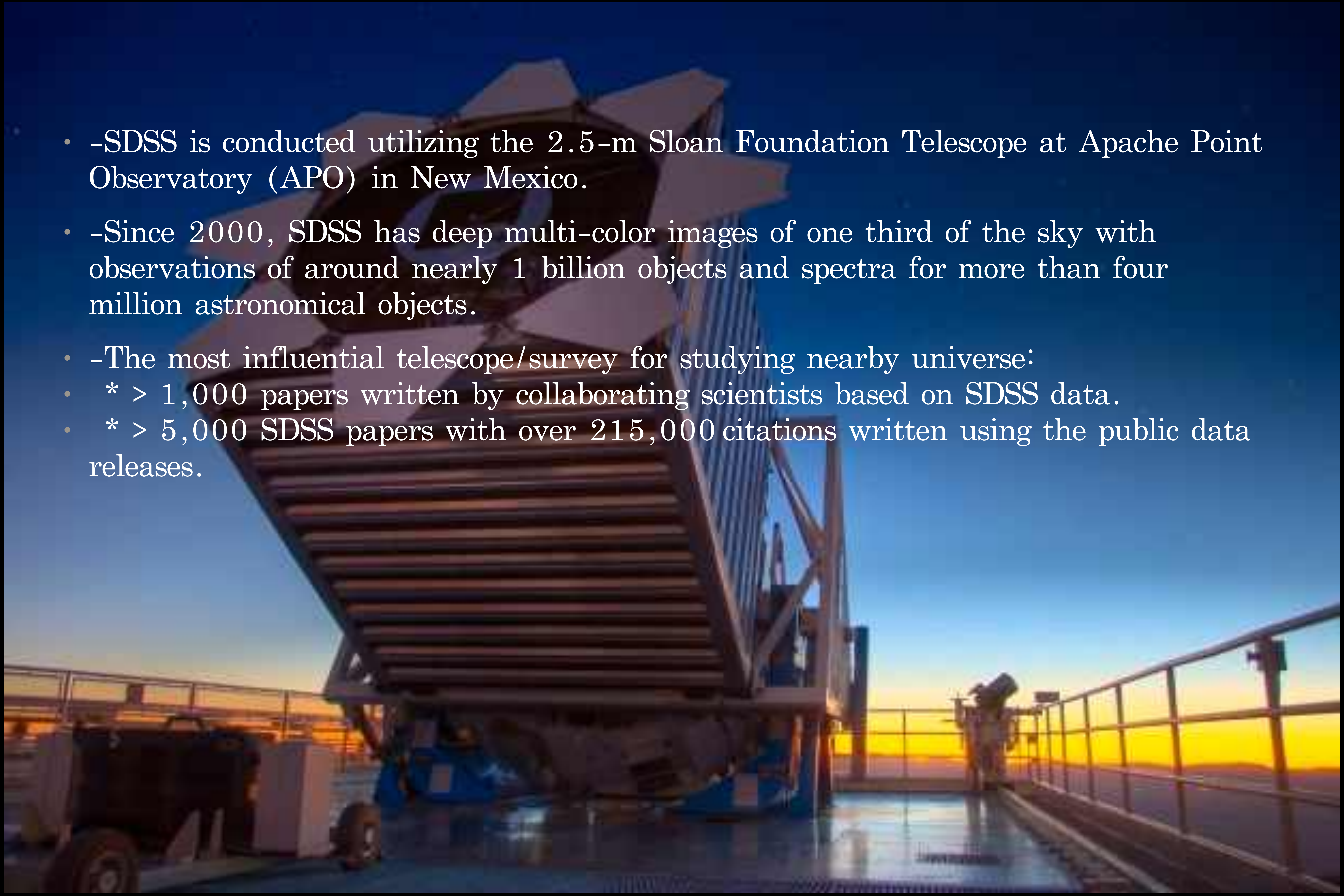


橢圓星系

螺旋星系

哈伯星系分類

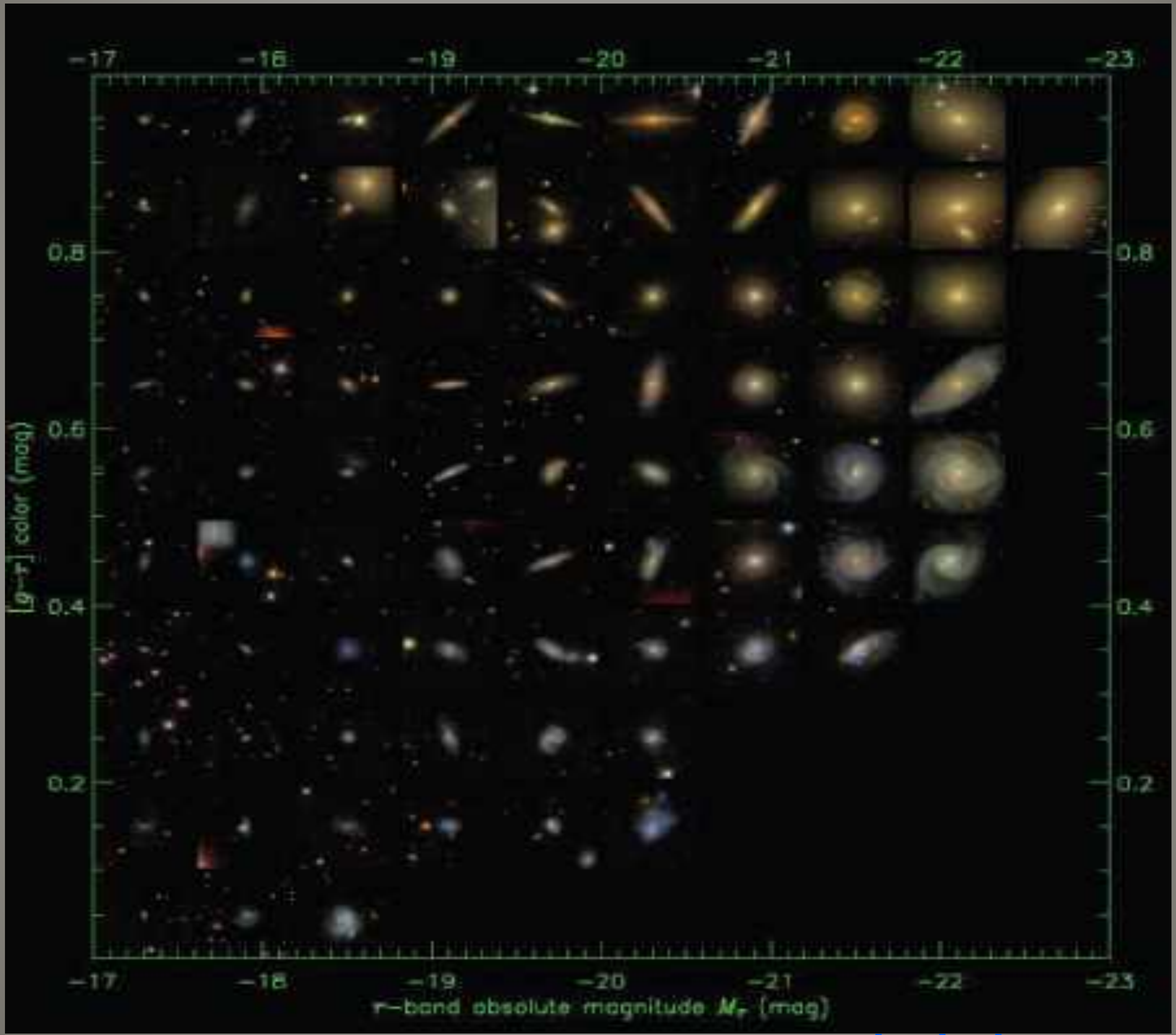
SDSS —SLOAN DIGITAL SKY SURVEY

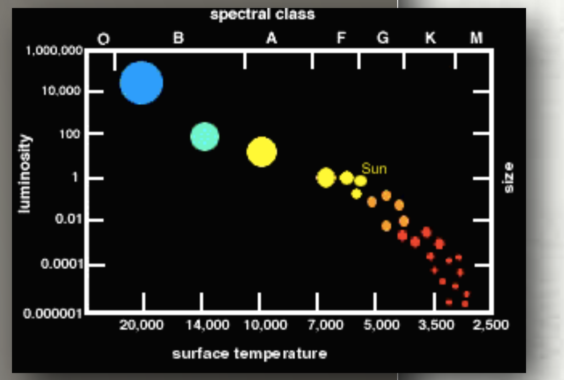


- -SDSS is conducted utilizing the 2.5-m Sloan Foundation Telescope at Apache Point Observatory (APO) in New Mexico.
- -Since 2000, SDSS has deep multi-color images of one third of the sky with observations of around nearly 1 billion objects and spectra for more than four million astronomical objects.
- -The most influential telescope/survey for studying nearby universe:
- * > 1,000 papers written by collaborating scientists based on SDSS data.
- * > 5,000 SDSS papers with over 215,000 citations written using the public data releases.

Galaxy images from SDSS

redder





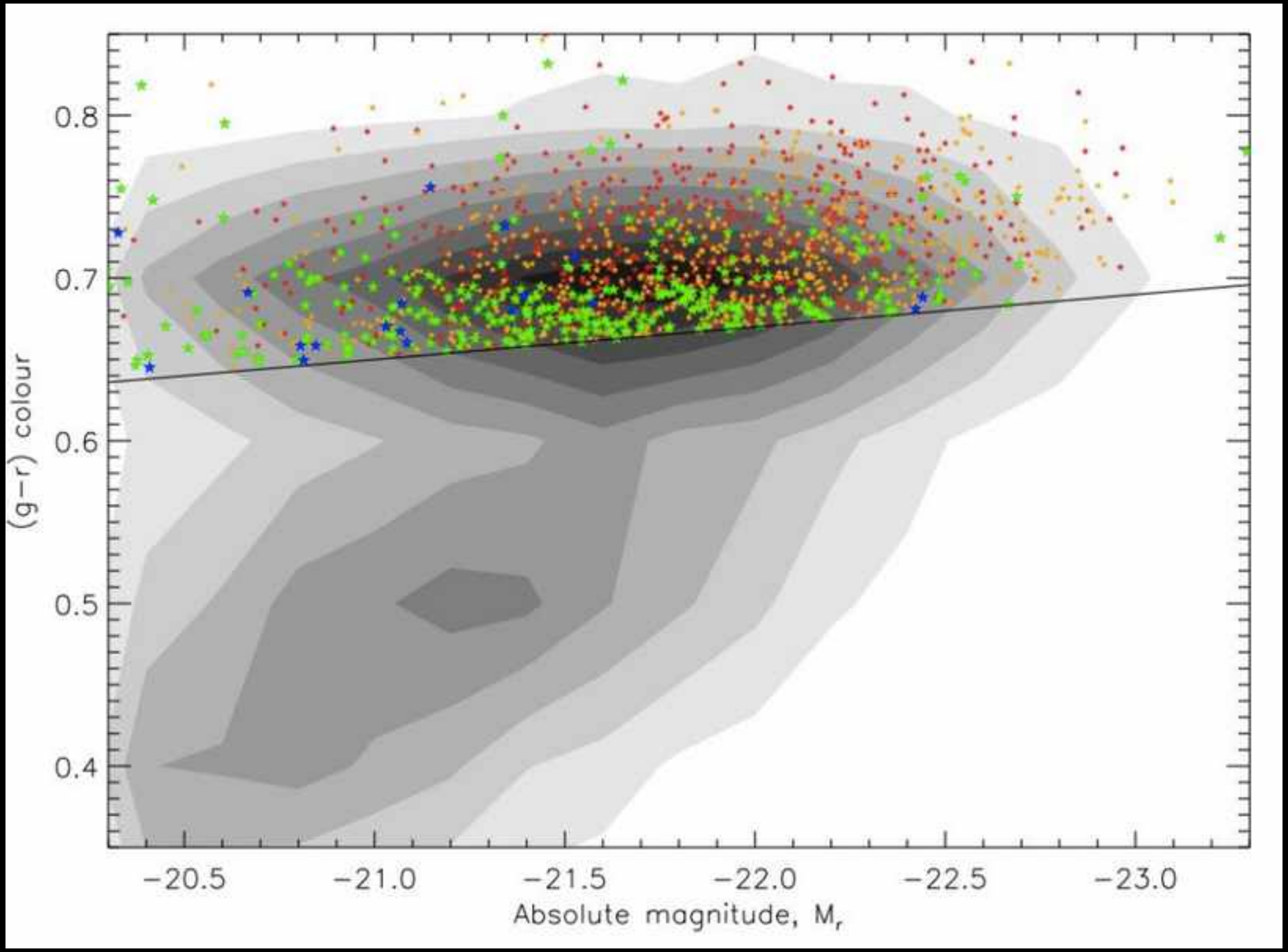
Blanton et al. 2006

brighter

Color Bimodality

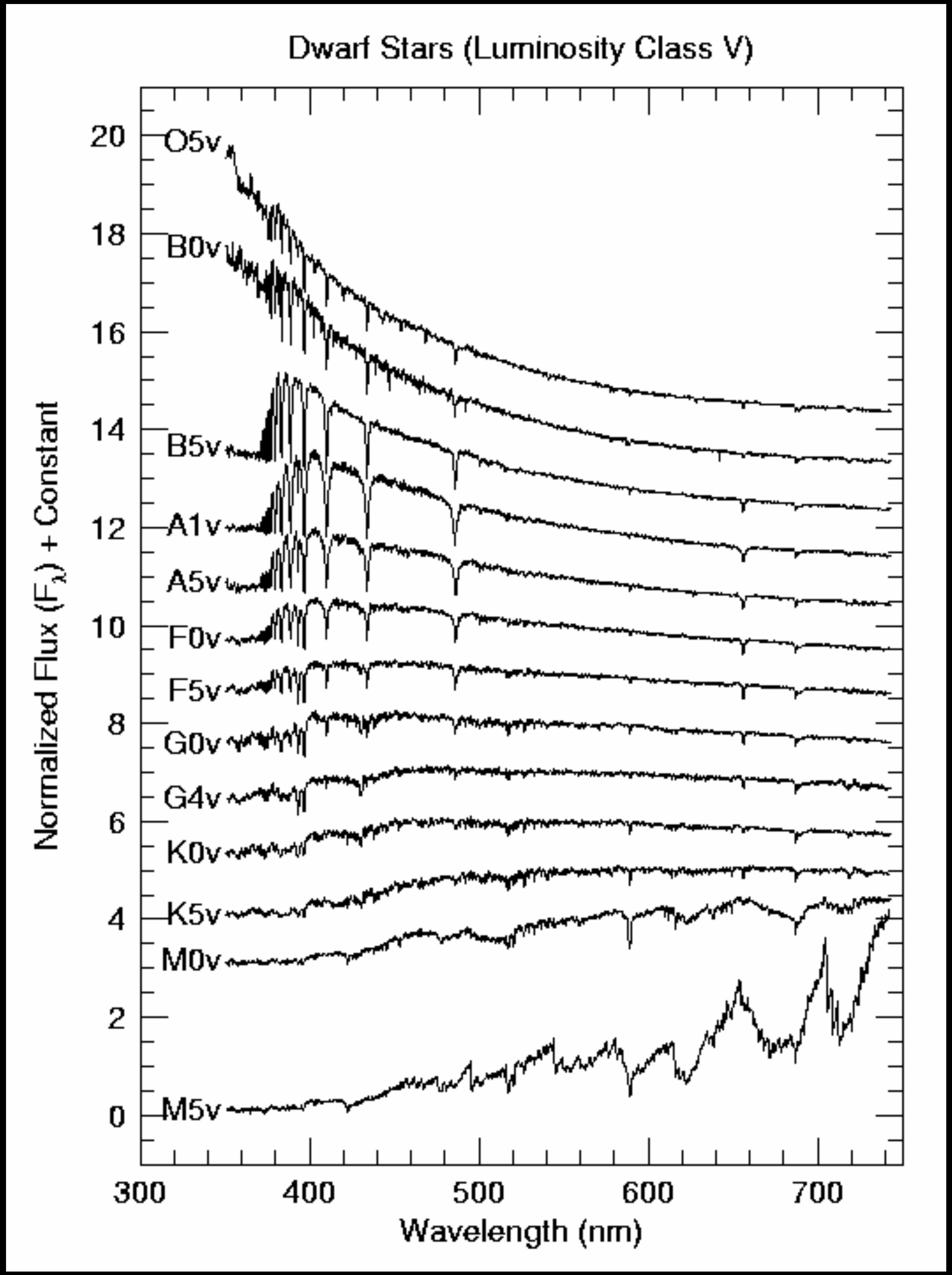
Redder

Masters et al. 09

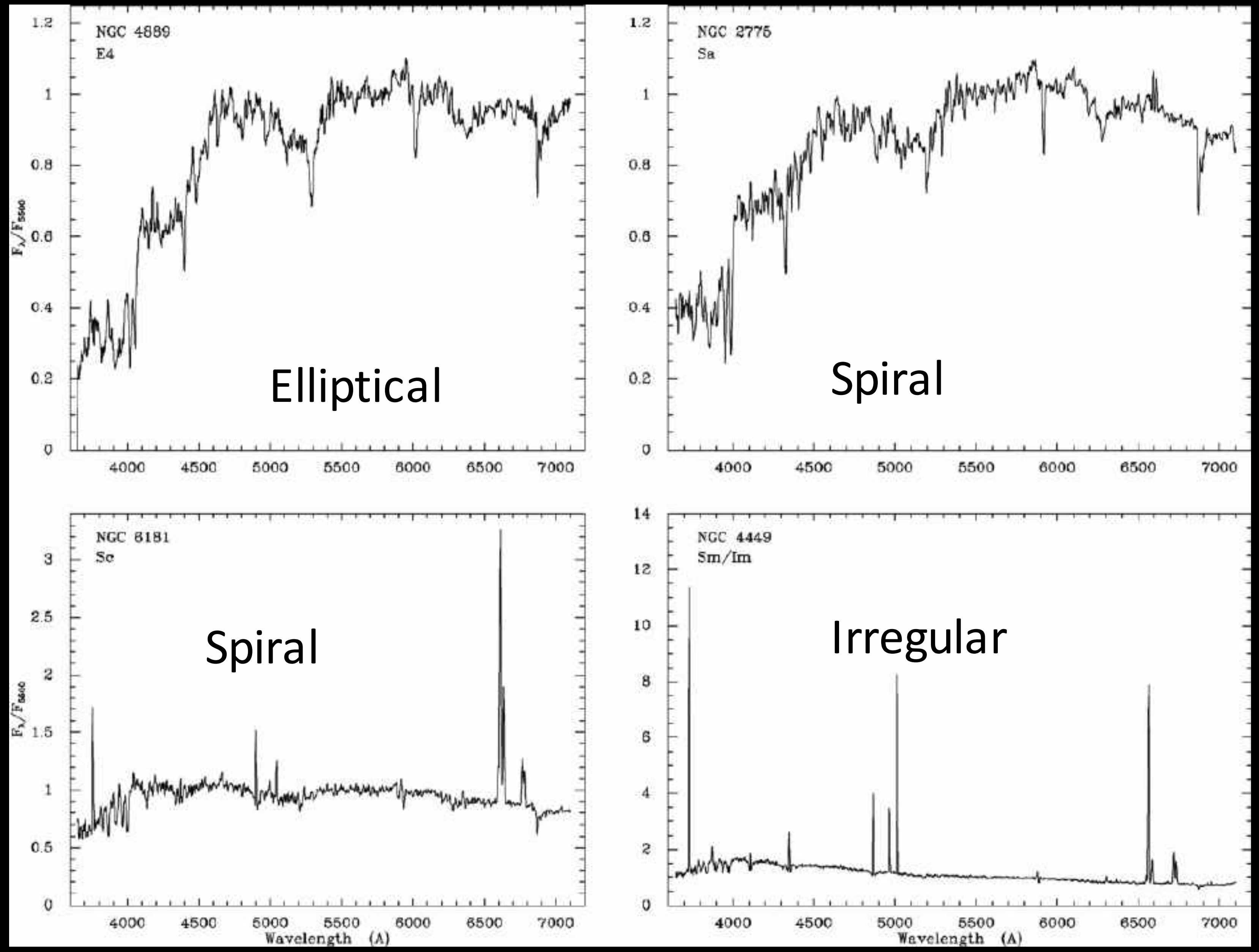


Brighter

INFORMATION FROM SPECTRA



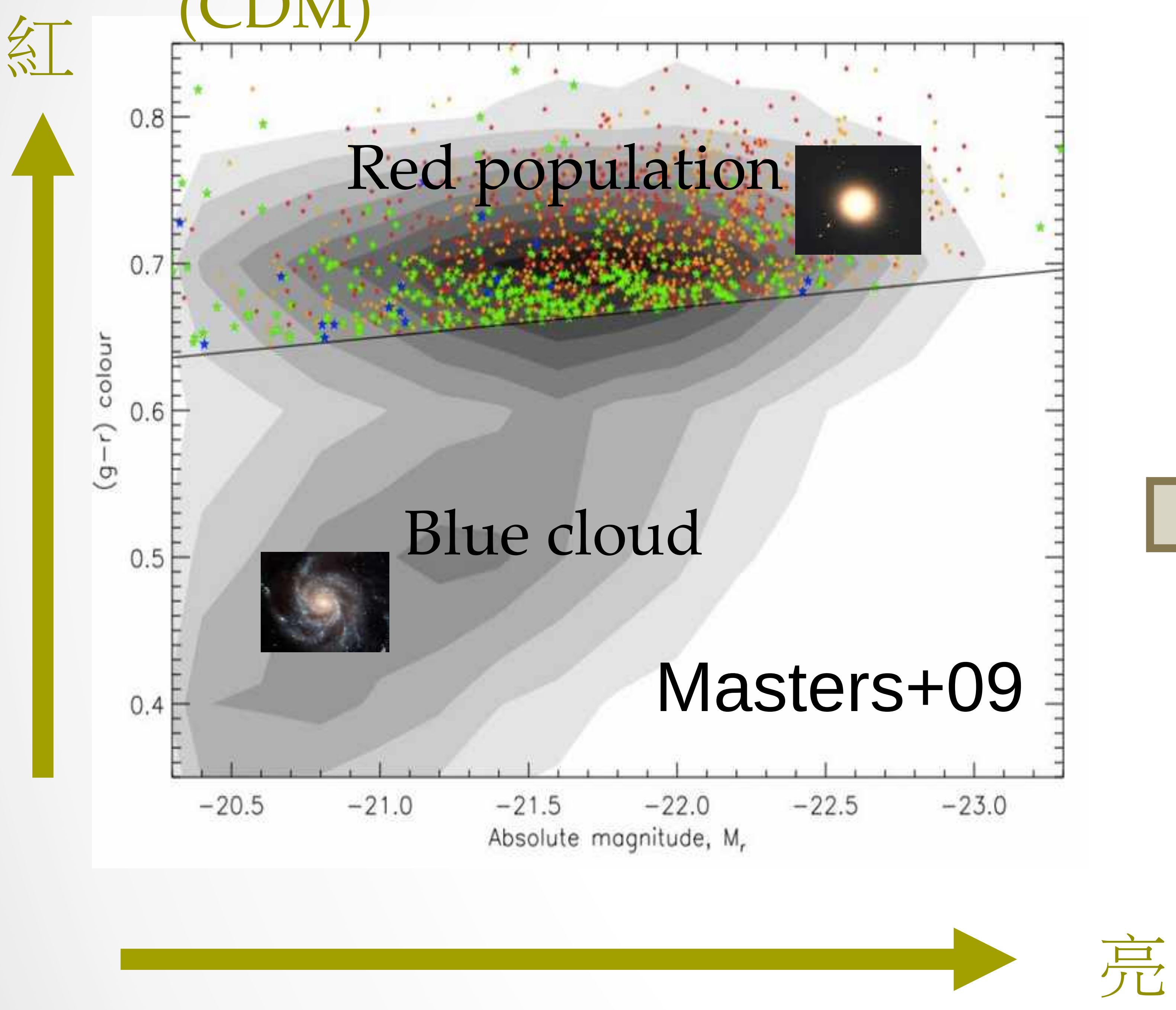
- Stellar Population
- Age
- Star formation Rate (SFR); SF history (SFH)
- Stellar Masses
- Metallicities



Kennicutt 1996

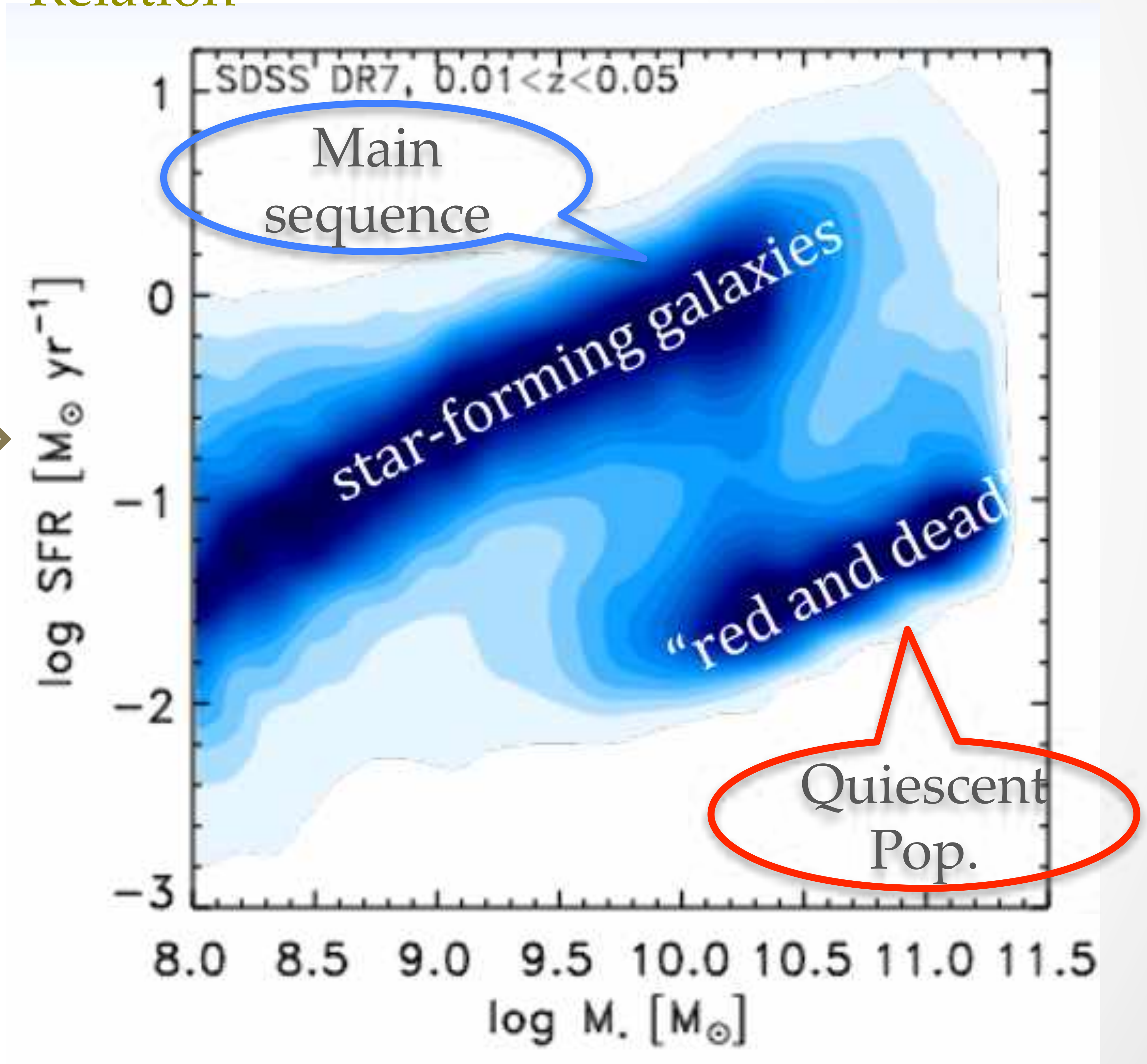
Bimodality

Color-Magnitude Diagram (CDM)



$$M_* = \int SFR\, dt$$

Star Formation Rate (SFR)-Stellar Mass (M_*) Relation



(figure credit: Amelie Saintonge)

Star Forming Main Sequence (SFMS)

SFR

M*

Image credit: CANDELS

Star Formation vs. Quenching

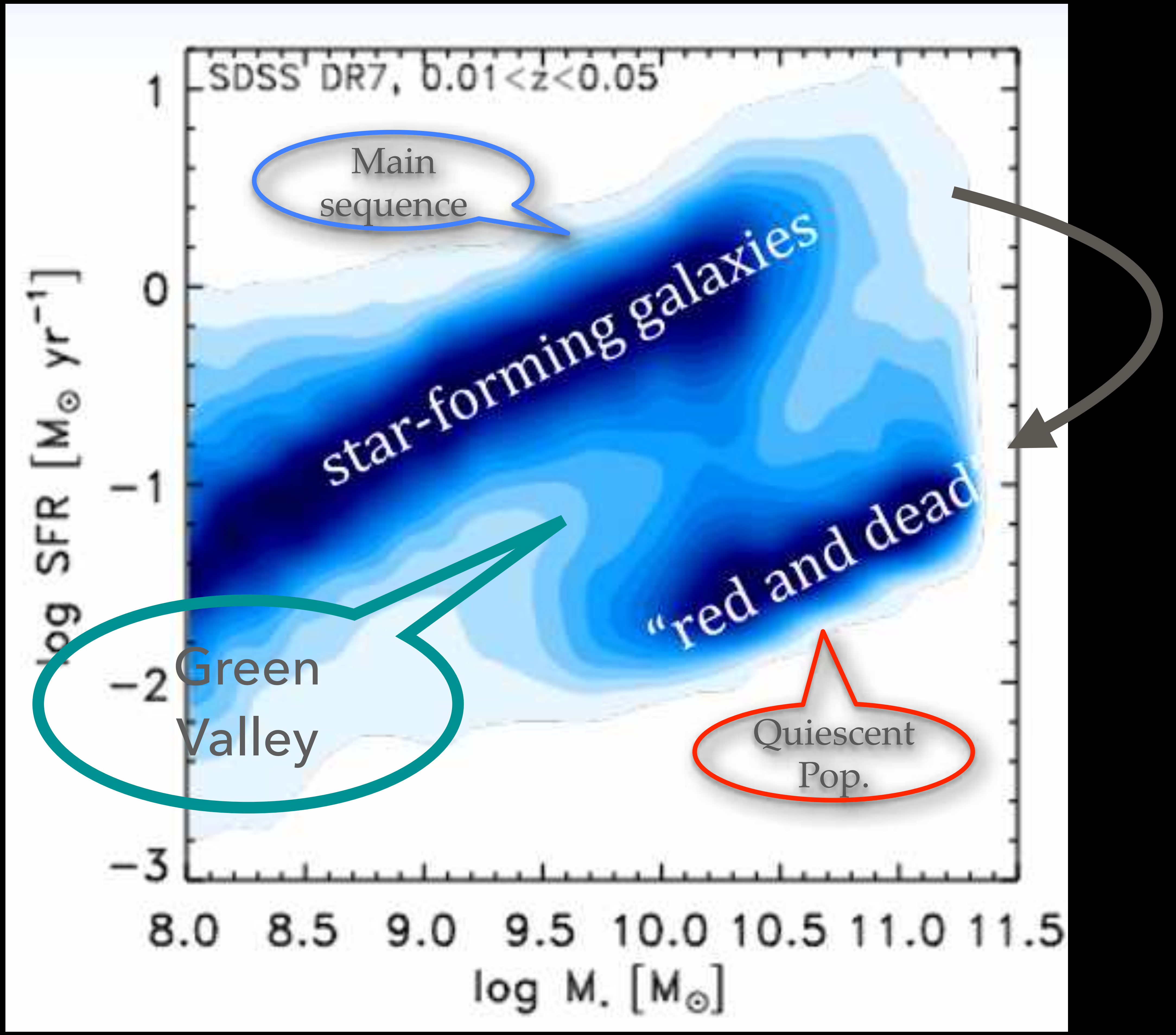
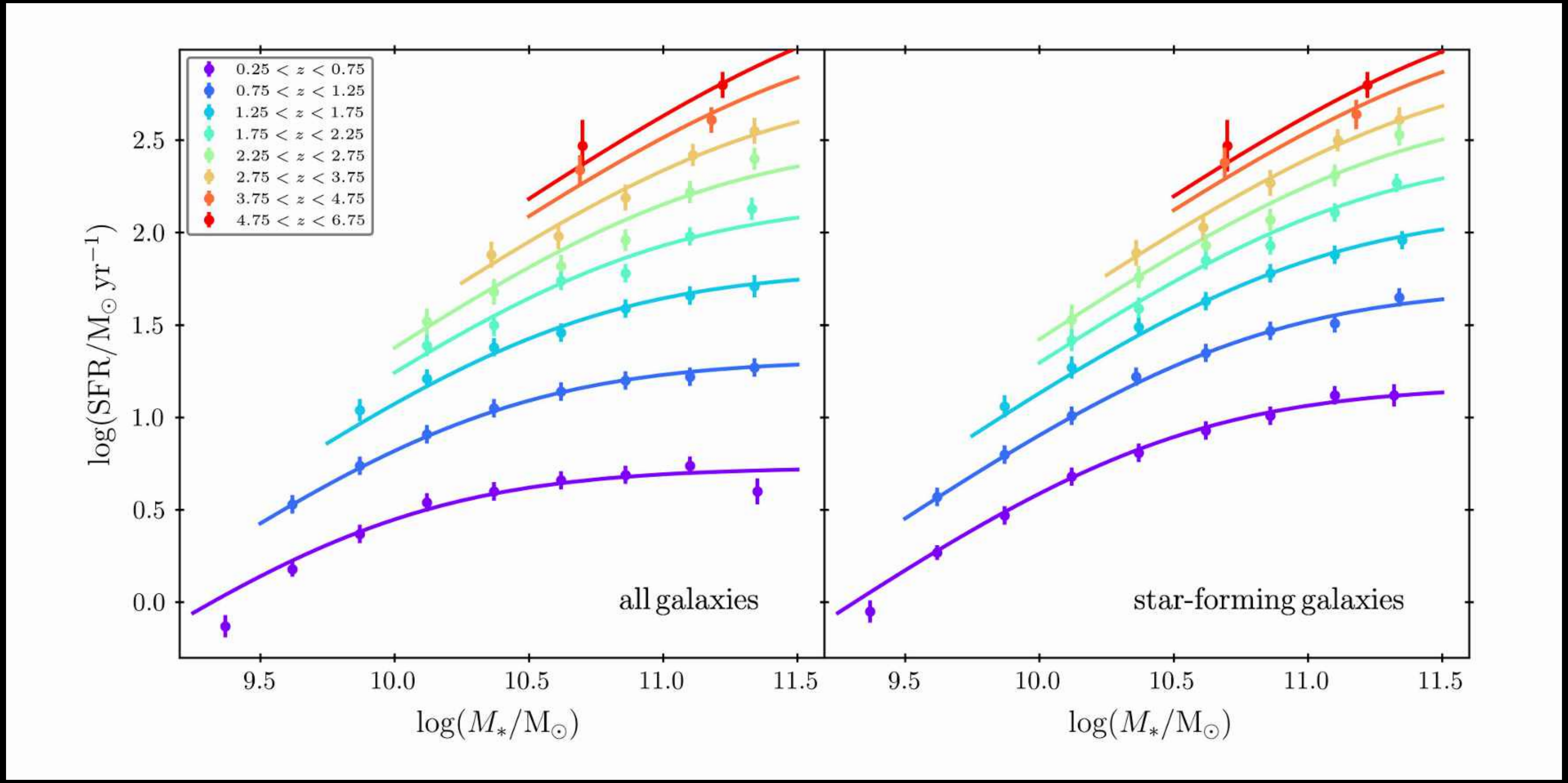


Image credit: Amelie Saintonge

1. Why there is star-forming main sequence (SFMS) with a scatter ~ 0.3dex
   (e.g., Brinchmann+04; Daddi+07;; Noeske+07; Salim+07; Whitaker+12; Lin+12; Lin+14)

2. How does the star formation get quenched?

Redshift Evolution of Star-Forming Main Sequence



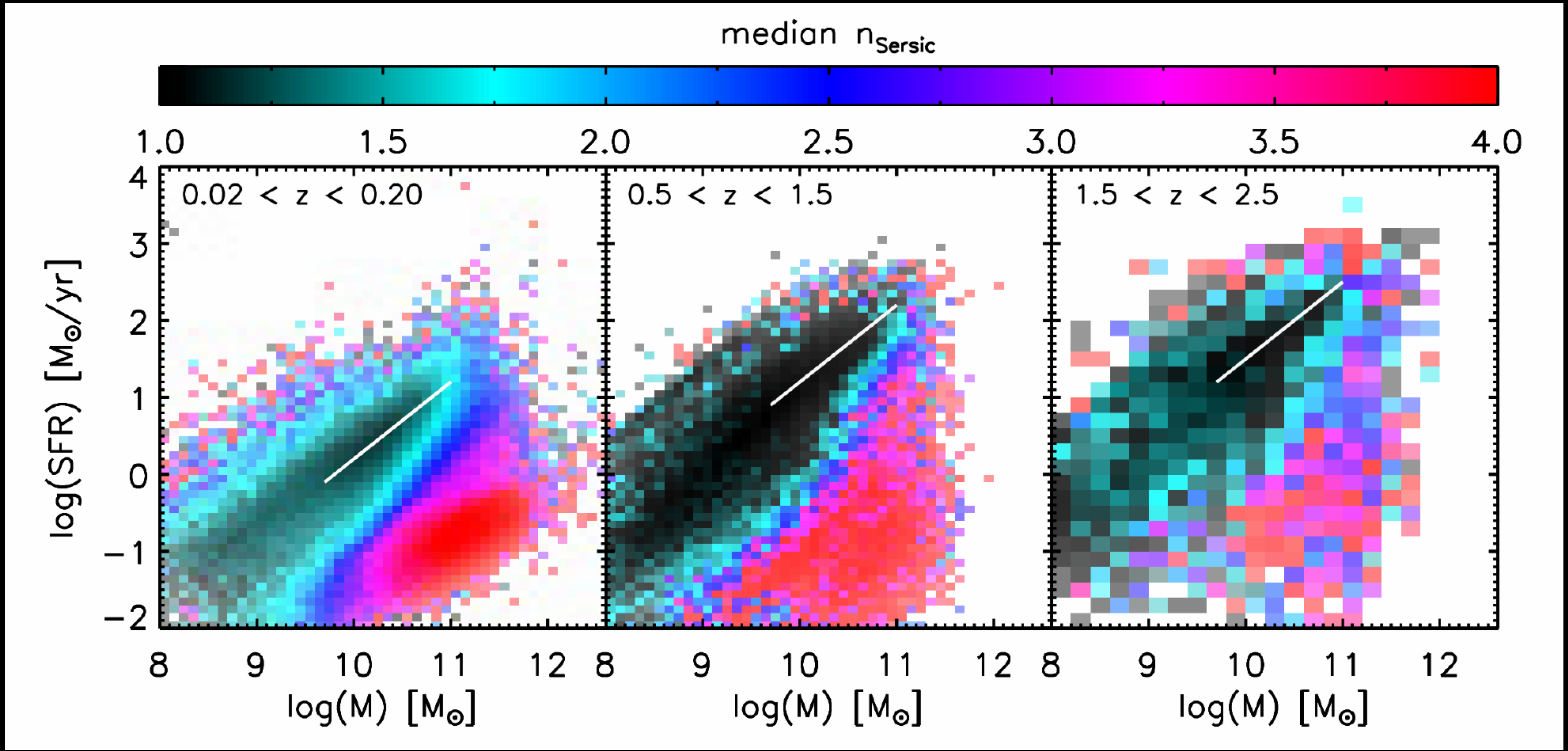
1. The presence of star-forming main sequence (SFMS) is present out to z~7

2. The amplitude of SFMS increases with increasing redshifts (10 times higher at z~2 than at z~0)

e.g., Noeske+07; Elbaz+07; Whitaker+12; Lin+12; Speagle+14; Koprowski+24

Morphologies of Star-Forming Main Sequence

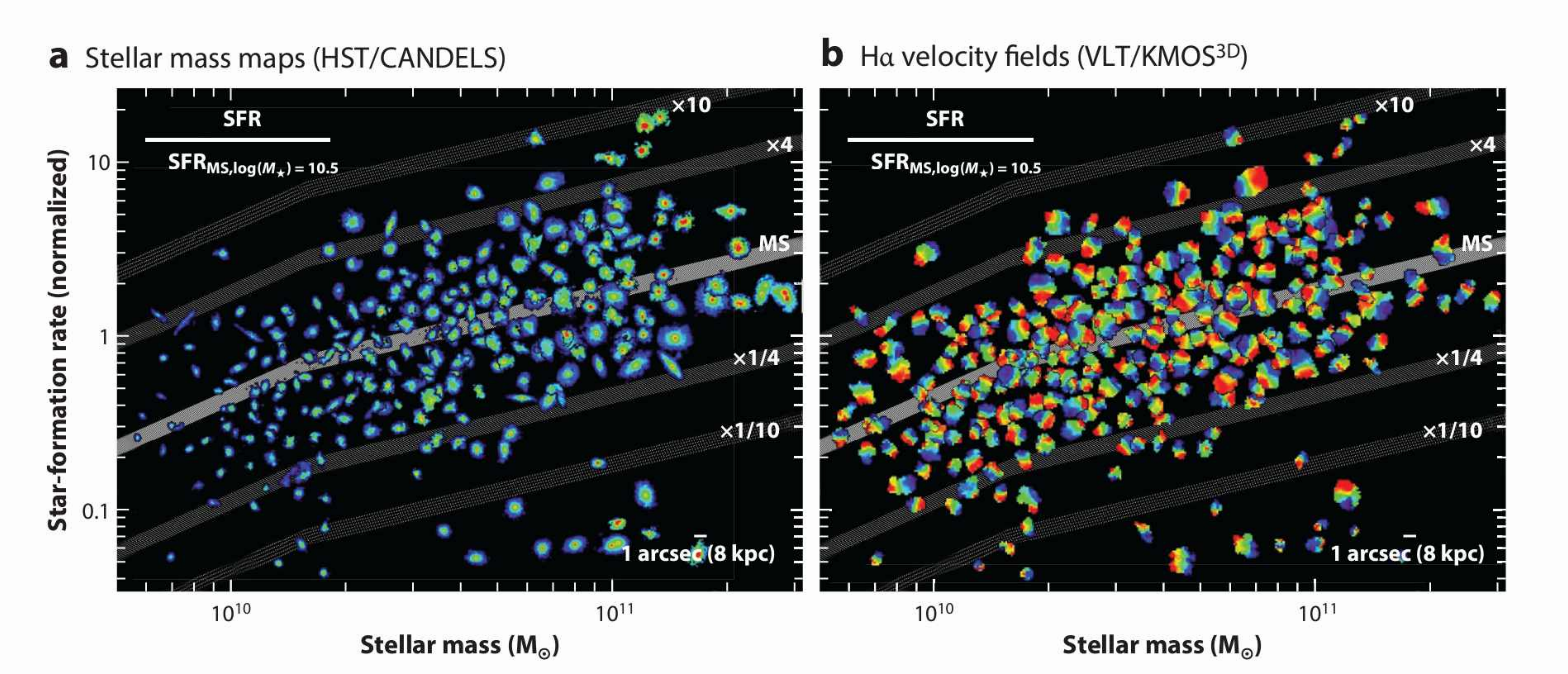
Wuyts+11



- Galaxies on the main seuqence are dominated by disk-like galacis while quiescent galaxies are domინted by bulge-like morephologies

Kinematics of Star-Forming Main Sequence

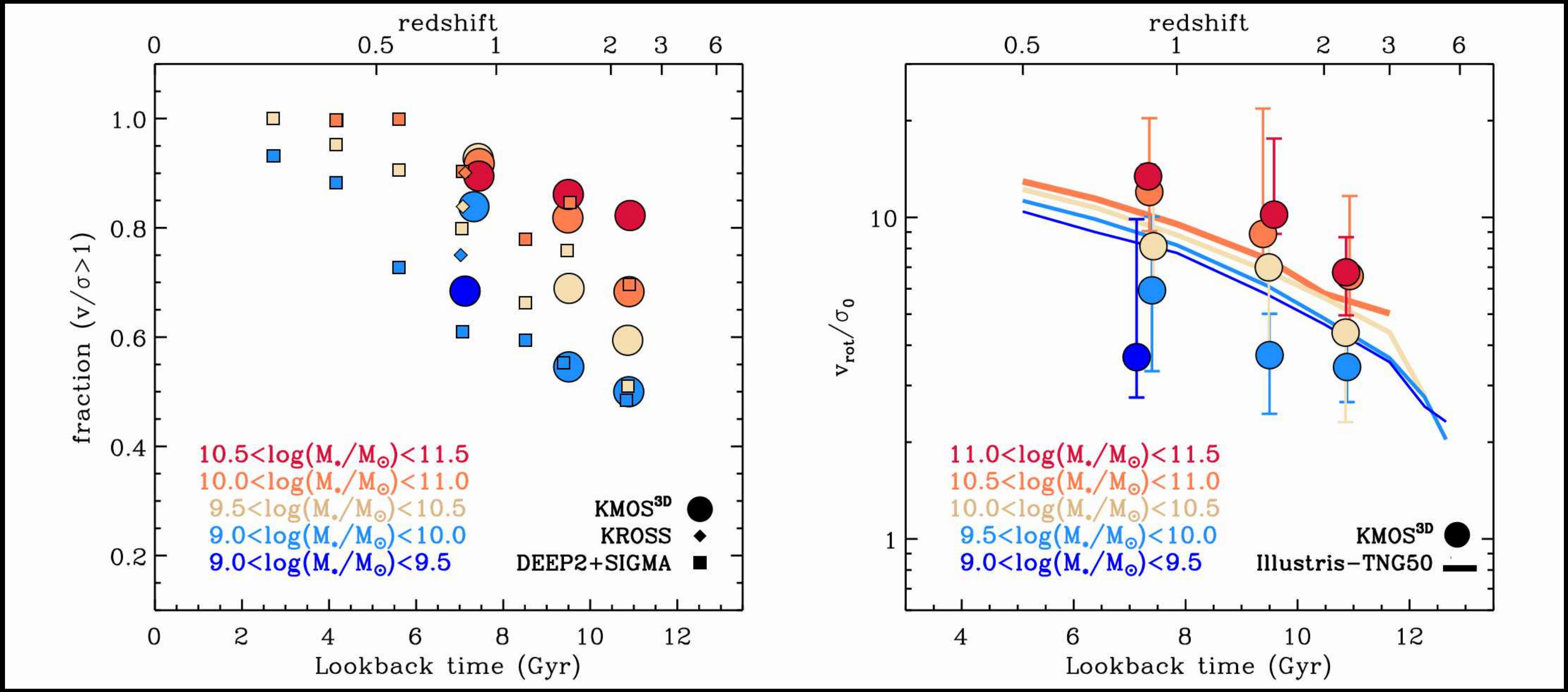
Forster-Schreiber & Wuyts 21



- $v_{rot}/\sigma > 1\text{–}3$ => rotational support
- v_{rot}/σ increases with stellar mass in the MS and decreases with redshift

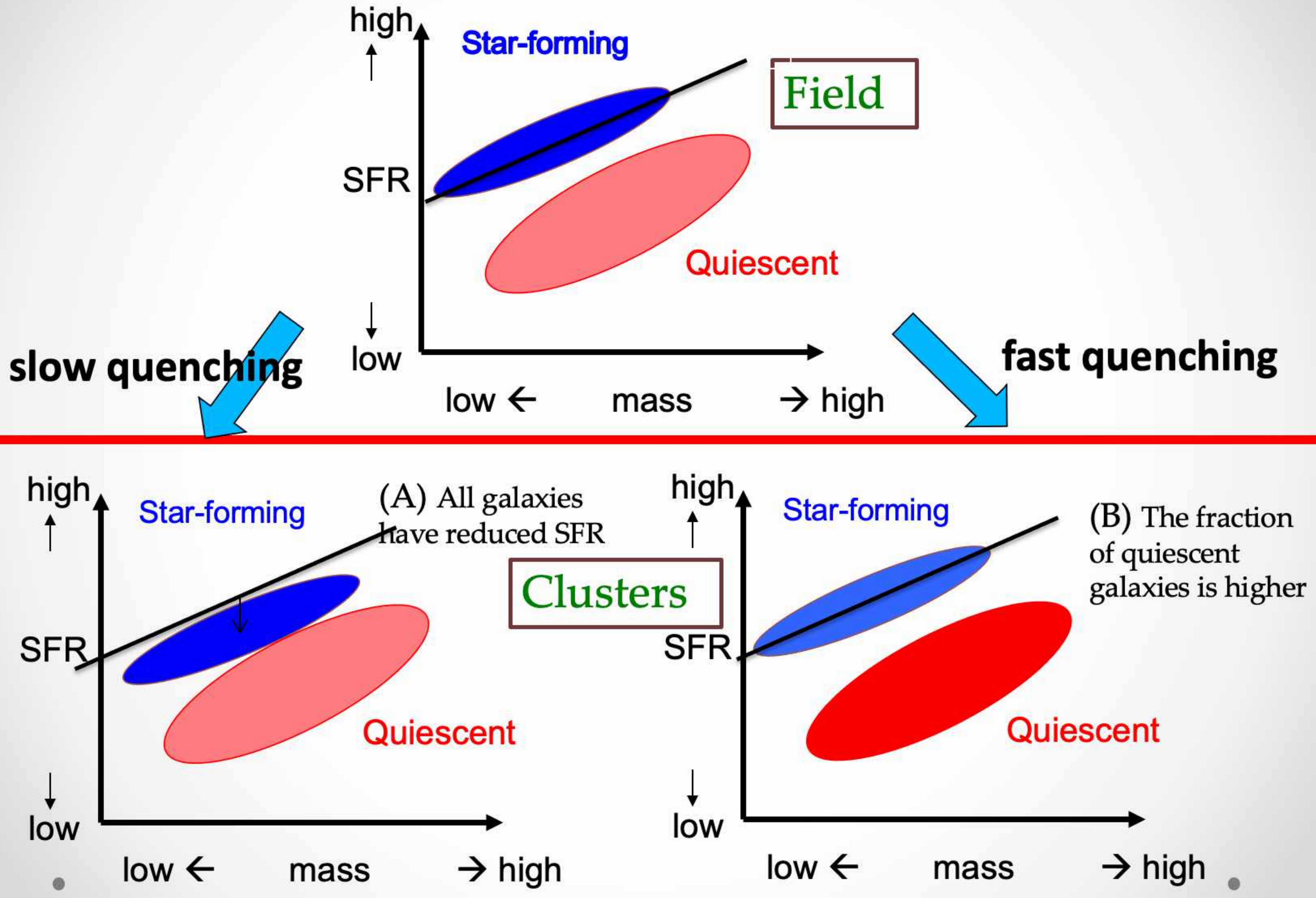
Kinematics of Star-Forming Main Sequence

Wisnioski+19

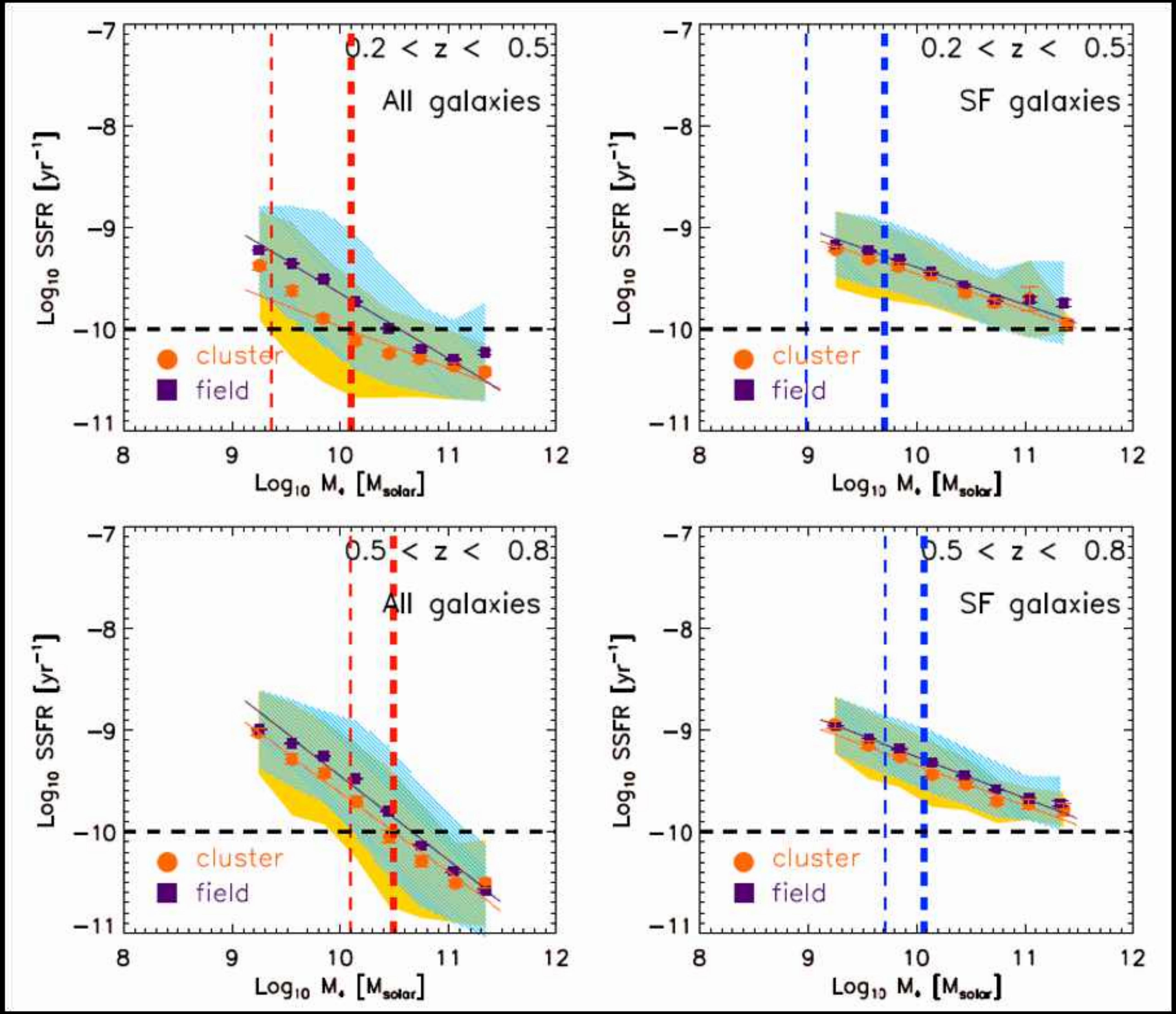


- v_{rot}/σ increases with stellar mass in the MS and decreases with redshift

The SFR-mass relation as a timescale probe



Environment of Star-Forming Main Sequence

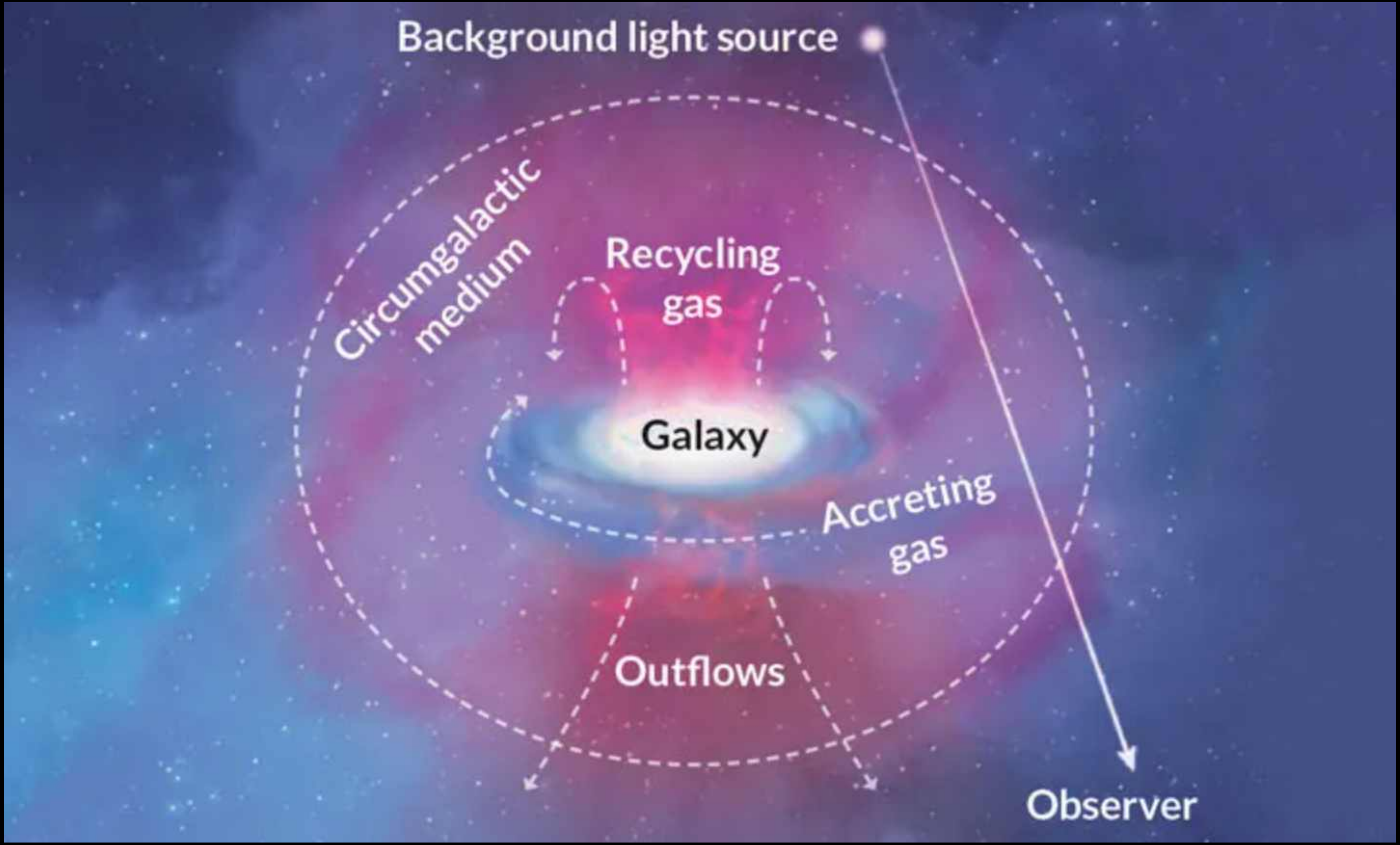


sSFR of the star-forming sequence in clusters is ~20% lower than that in the field

Slow quenching may also play a role!

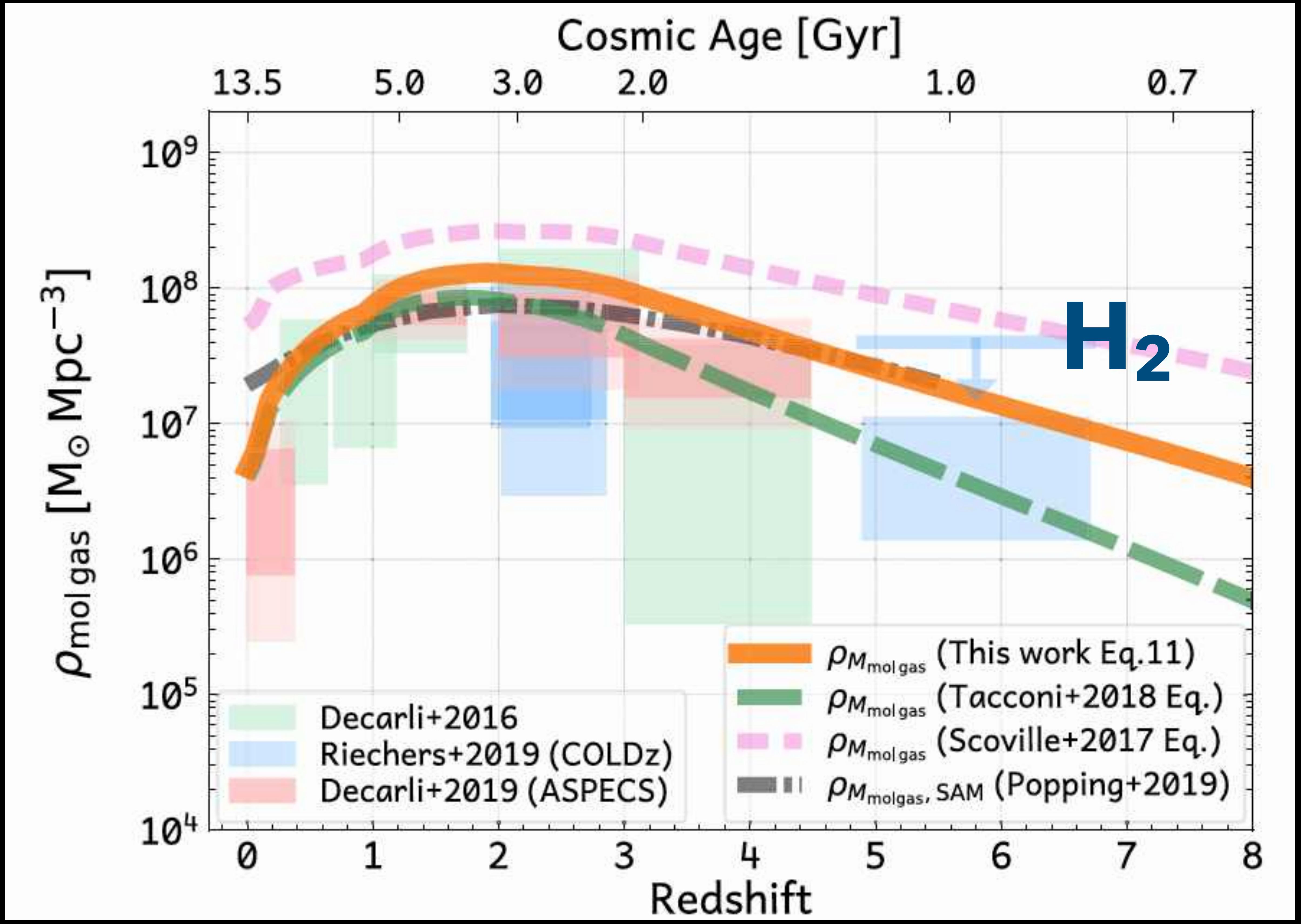
Lin+14; Koyama+13; Jian, Lin+17, 18

Circumgalactic medium (CGM)

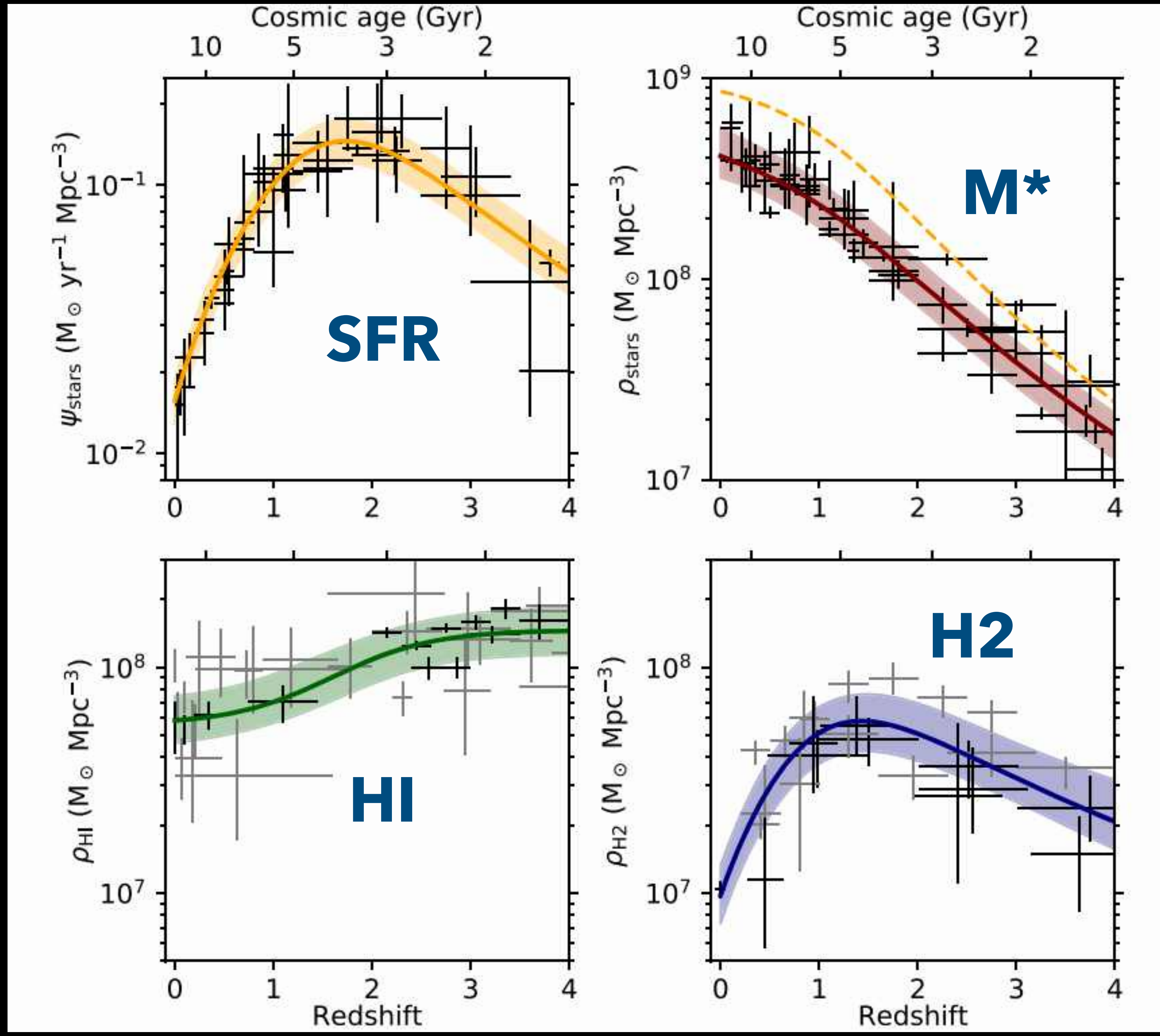


*Sources: J. Tumlinson, M.S. Peeples and J.K. Werk/*Annual Review of Astronomy and Astrophysics *2017; M.S. Peeples/*Nature *2015*

Cosmic star formation rate density directly trace the molecular gas density



Liu+19



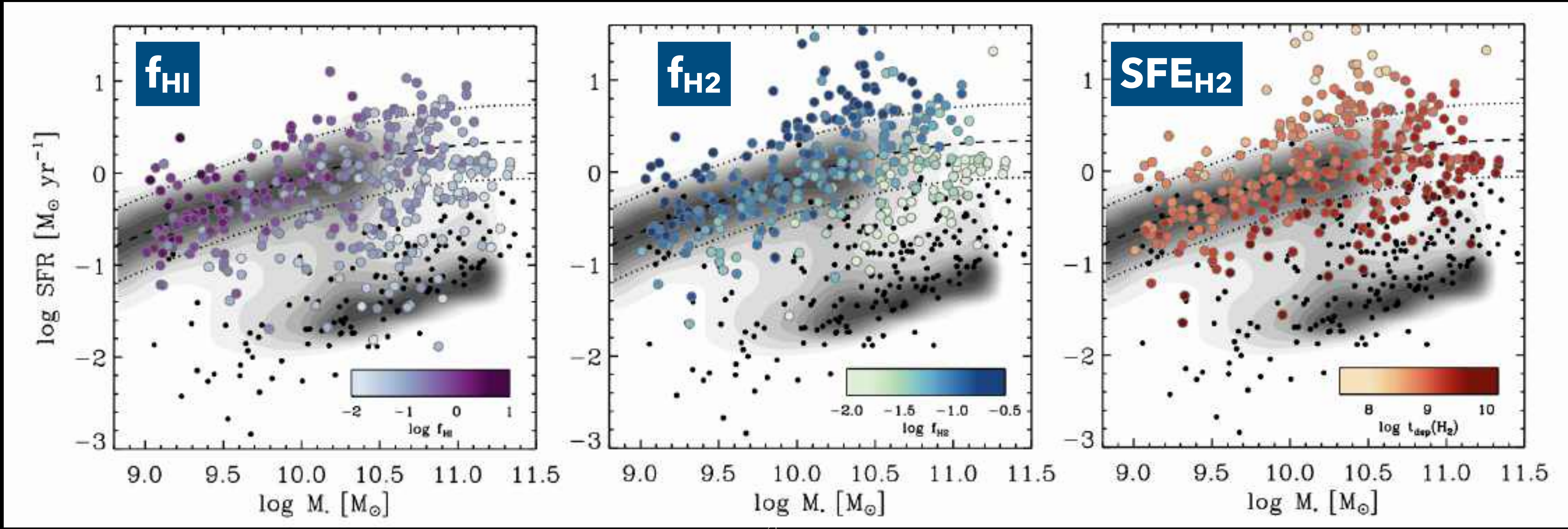
Walter+20

Star formation efficiency (SFE) vs. gas fraction (f_{H2})

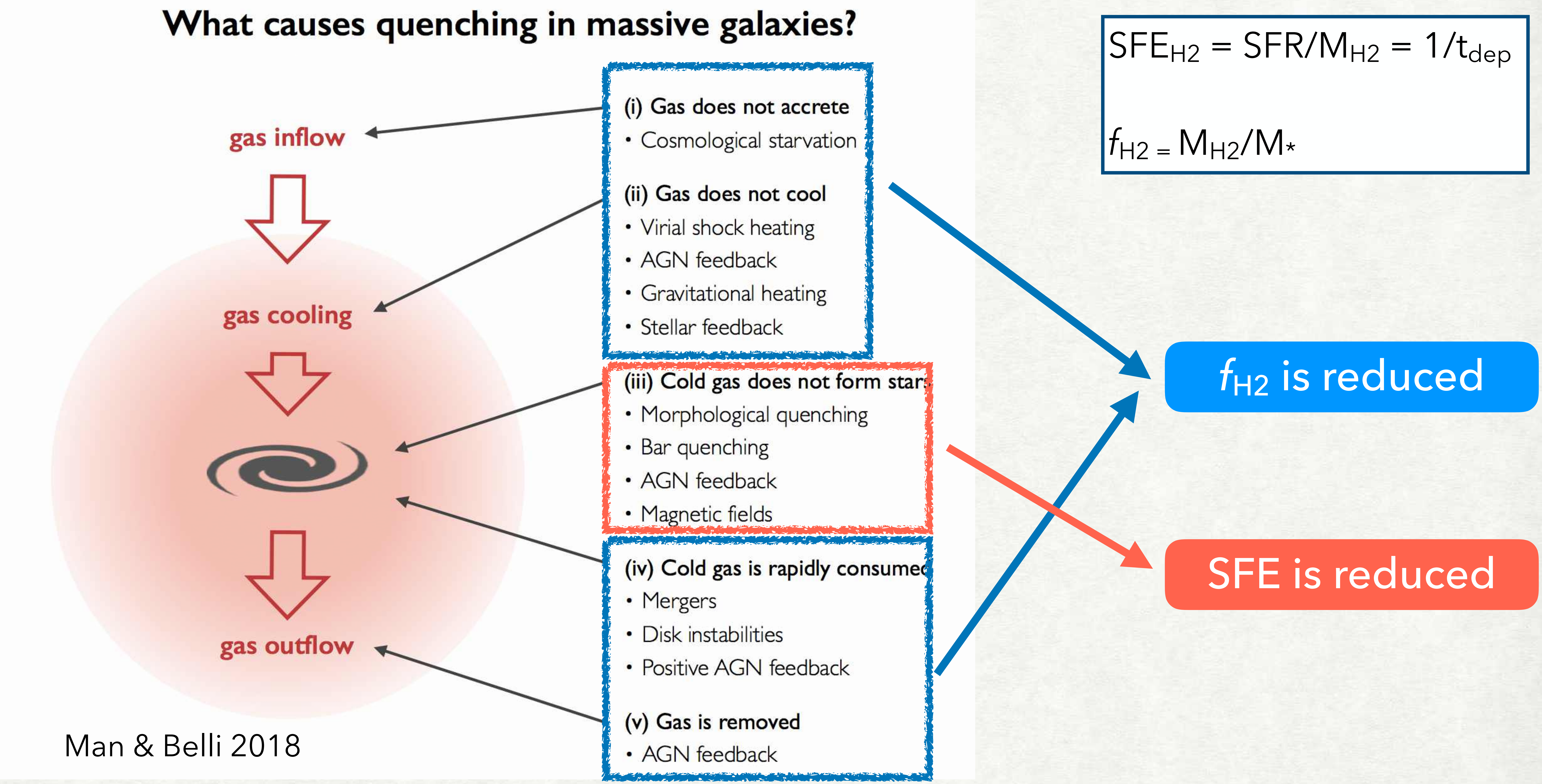
$SFE_{H2} = SFR/M_{H2} = 1/t_{dep}$

$f_{H2} = M_{H2}/M_*$

Saintonge+17



Star formation efficiency (SFE) vs. gas fraction (f_{H2})

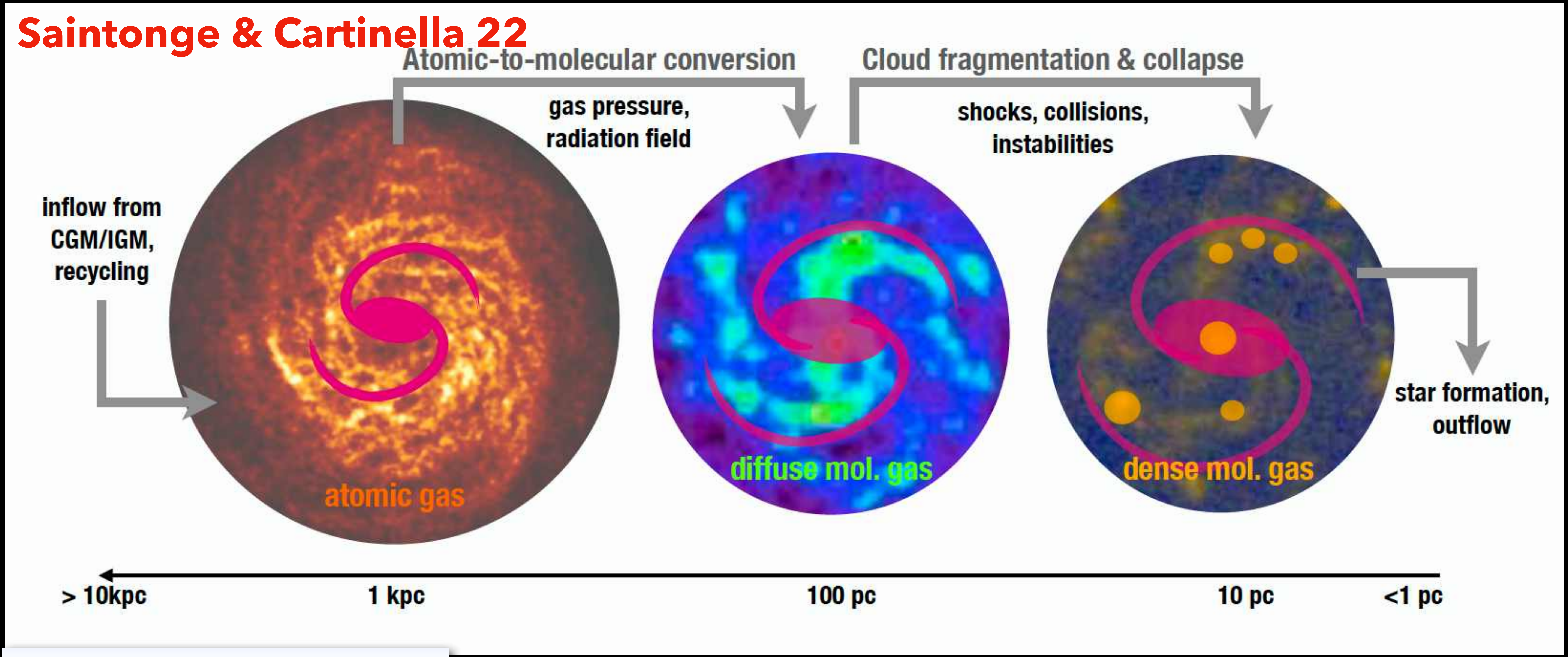


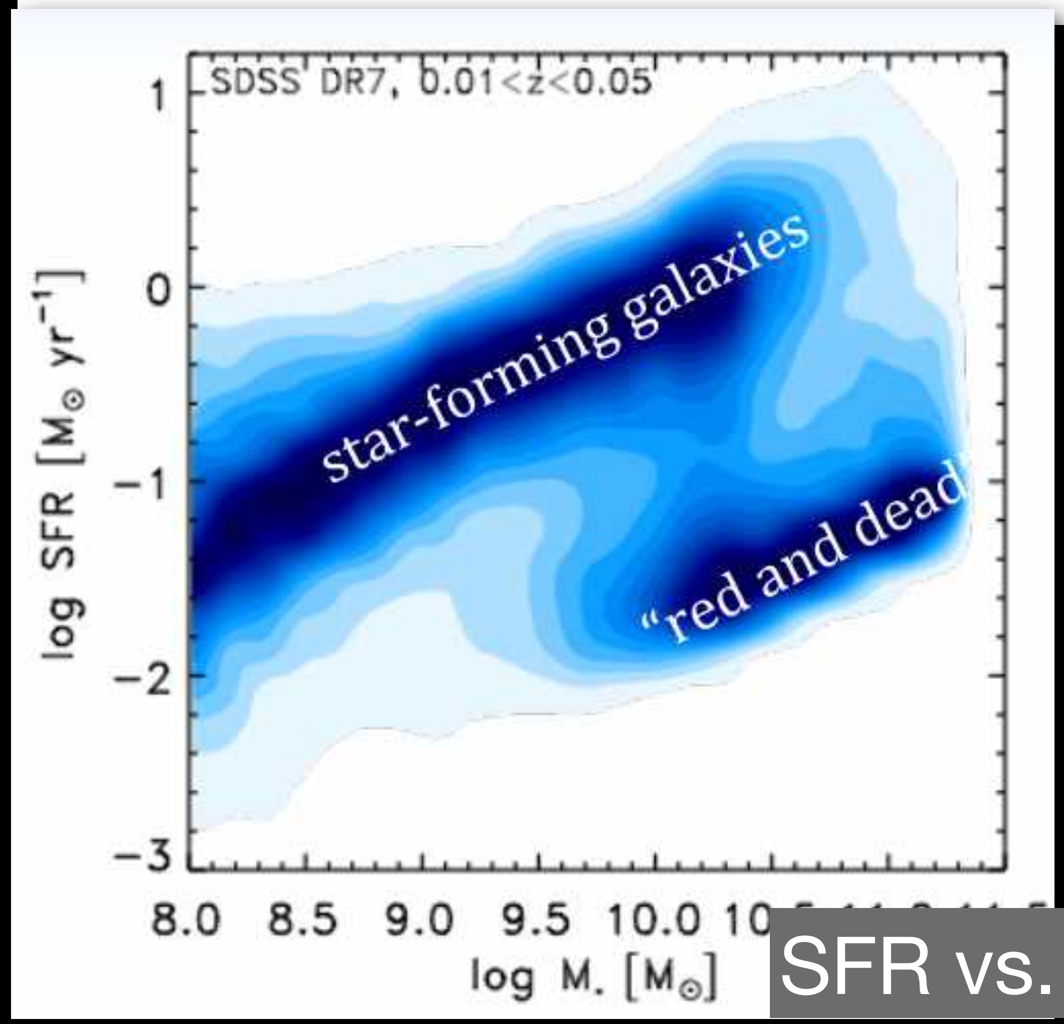
Man & Belli 2018

$SFE_{H2} = SFR/M_{H2} = 1/t_{dep}$

$f_{H2} = M_{H2}/M_*$

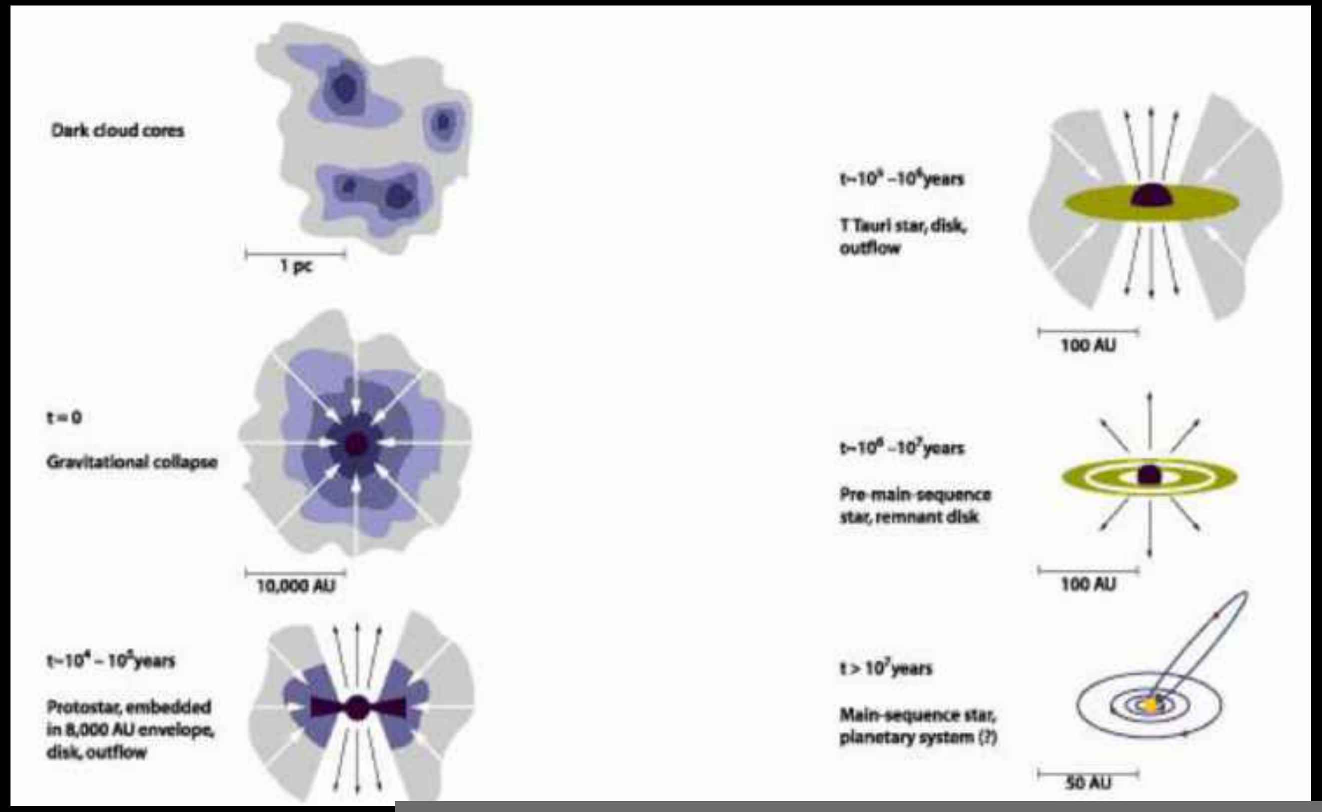
MULTI-SCALE PROBLEM





SFR vs. M*: Saintonge

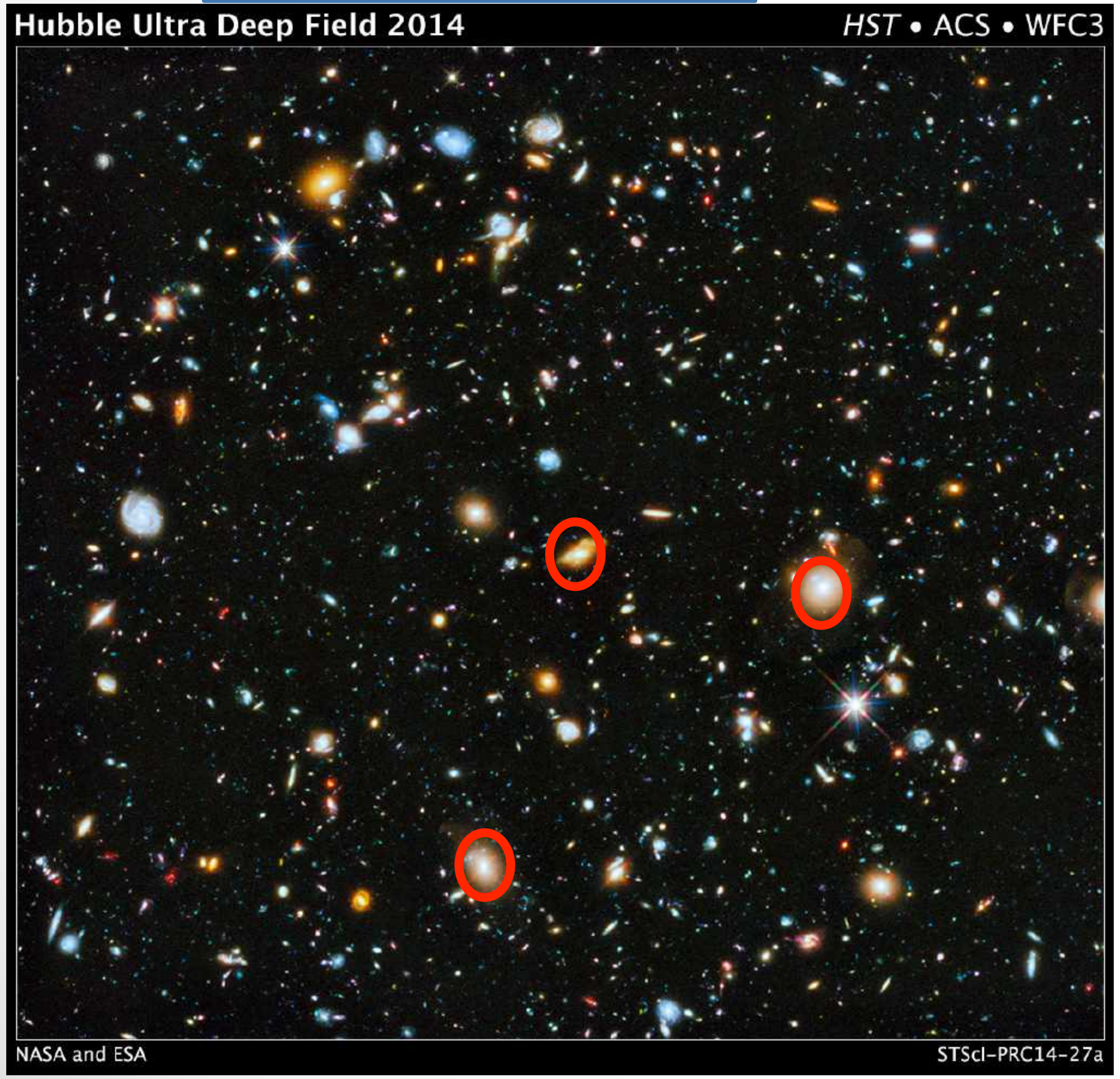
?



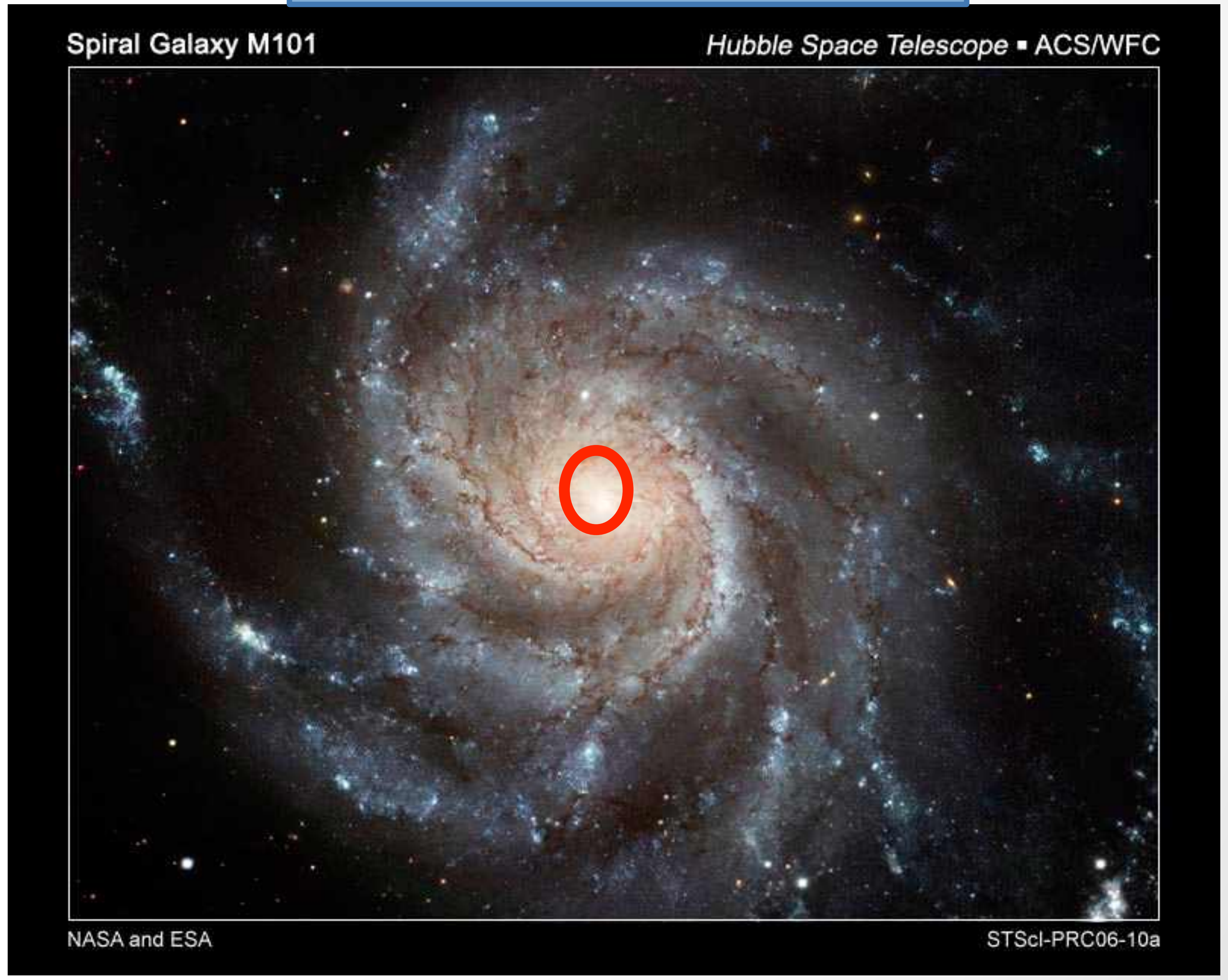
Credit:NASA/JPL-Caltech

Why need spatially resolved observations?

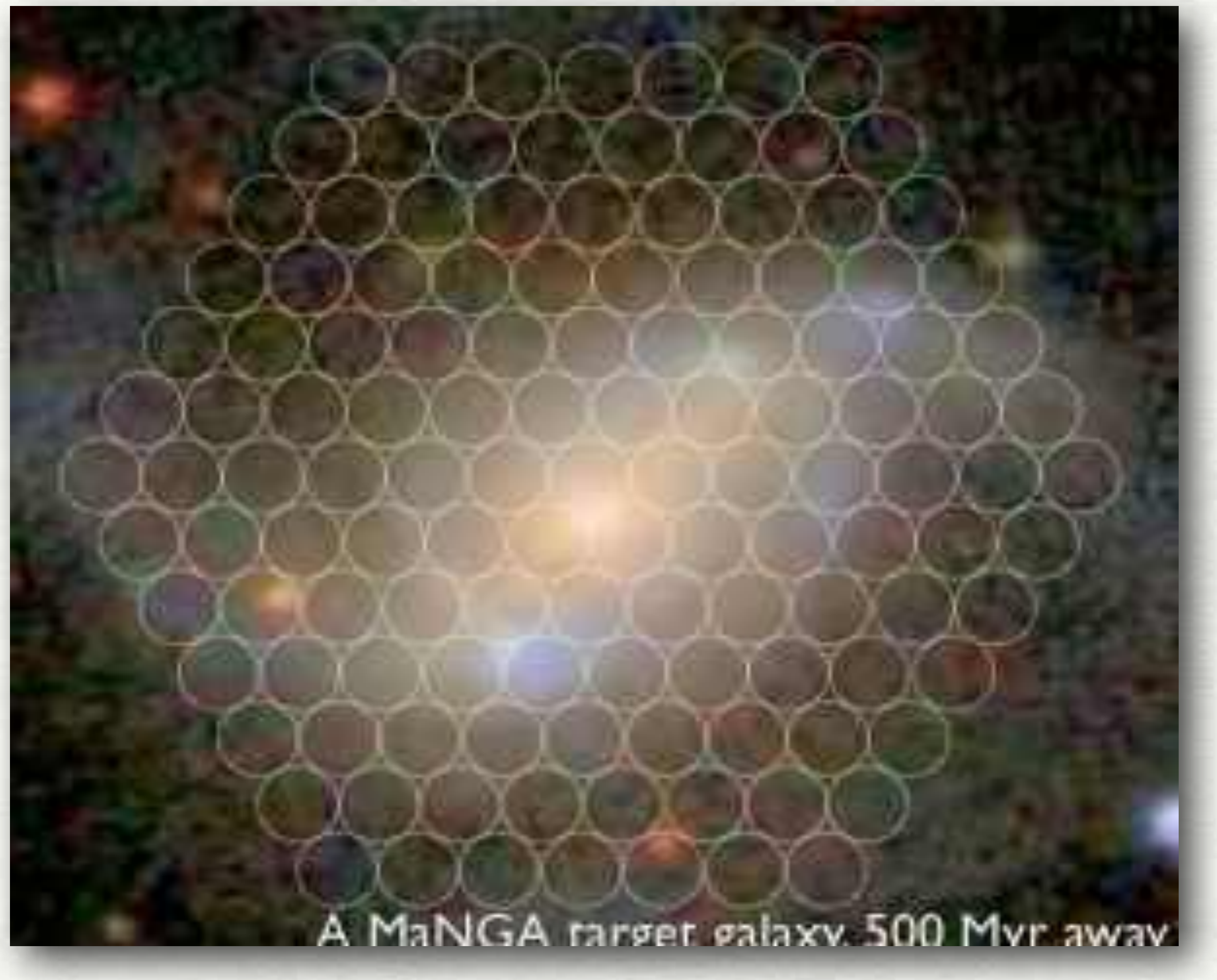
distant galaxies

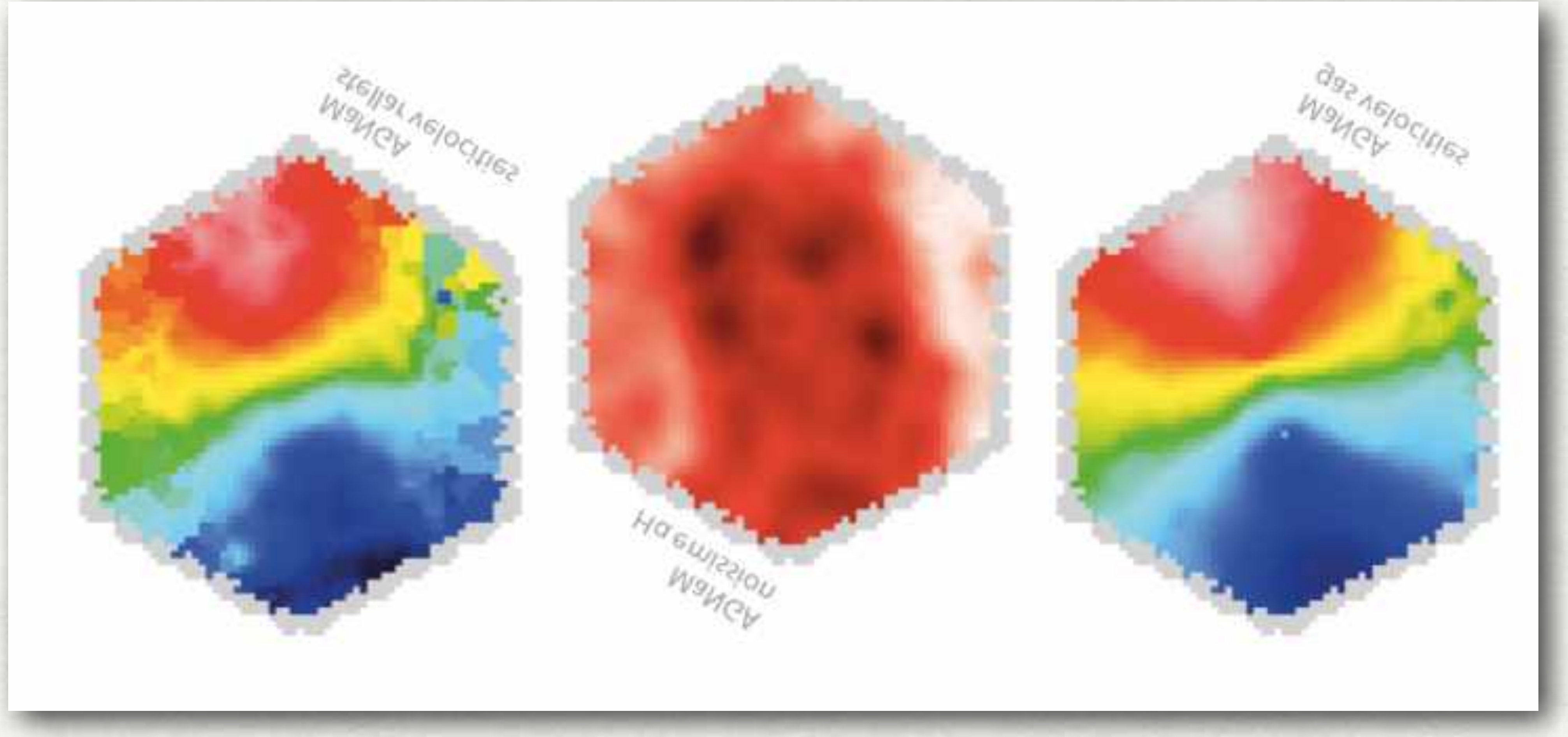


nearby galaxies



SDSS-IV/MaNGA (Mapping Nearby Galaxies at APO)
(Bundy et al.2015)





- Fall 2014-Spring 2020
- 10,000 galaxies across ~4000 deg^2, z~0.03
- 17 IFUs per 7 deg^2 plate
- 360-1000 nm with R~2000 (50-70 km/s)
- 3-hr exposures with 3 dithered positions
- Spatial sampling of 1-2 kpc
- Per-fiber S/N = 5-10 at 1.5Re
- Stellar mass selected sample ($M_{star} > 10^9\ M_\odot$) in all environments at 0.05<z<0.15

Drory+15

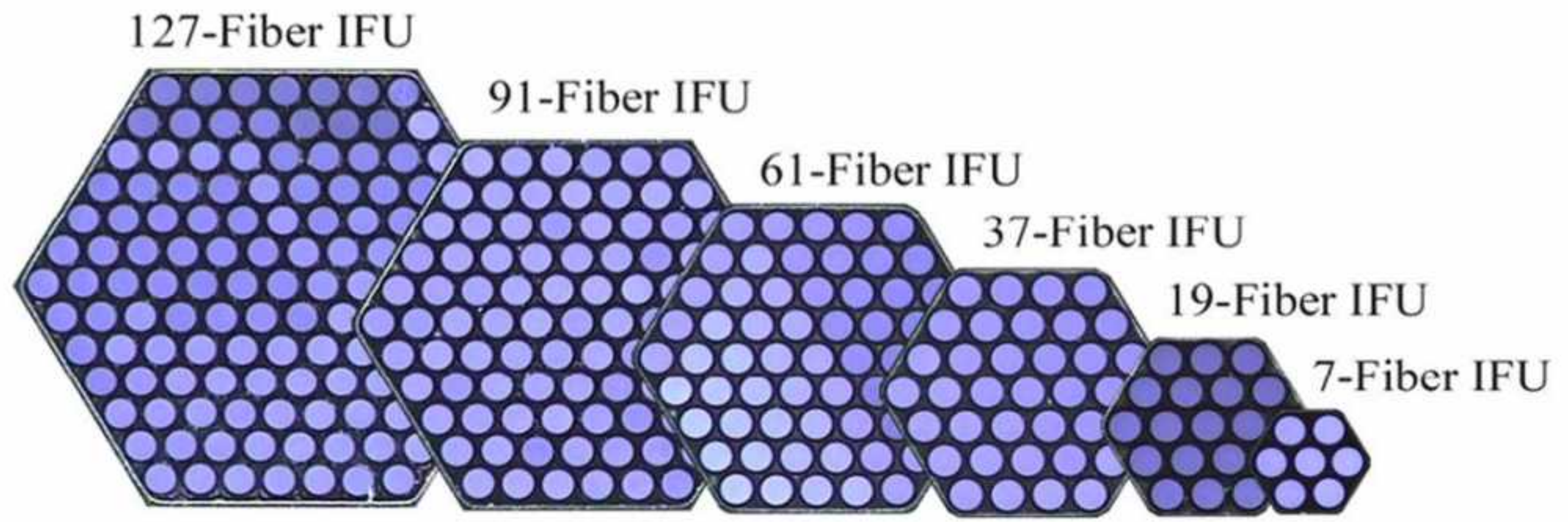
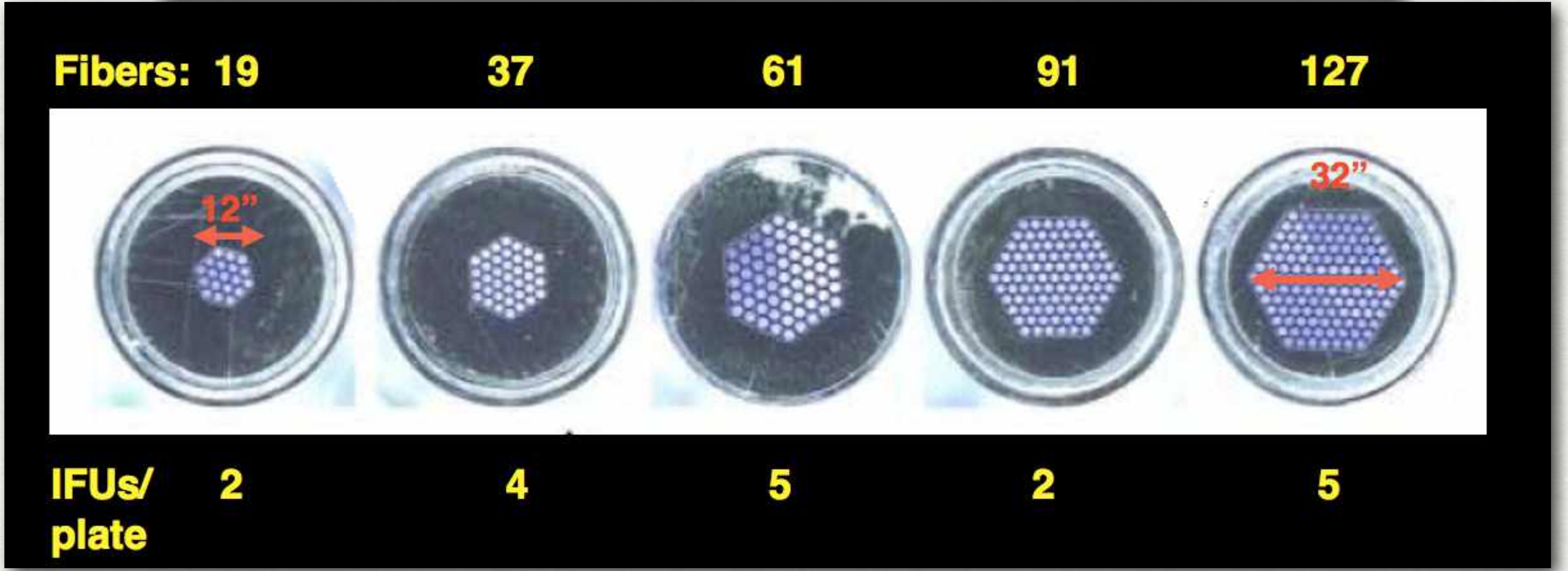
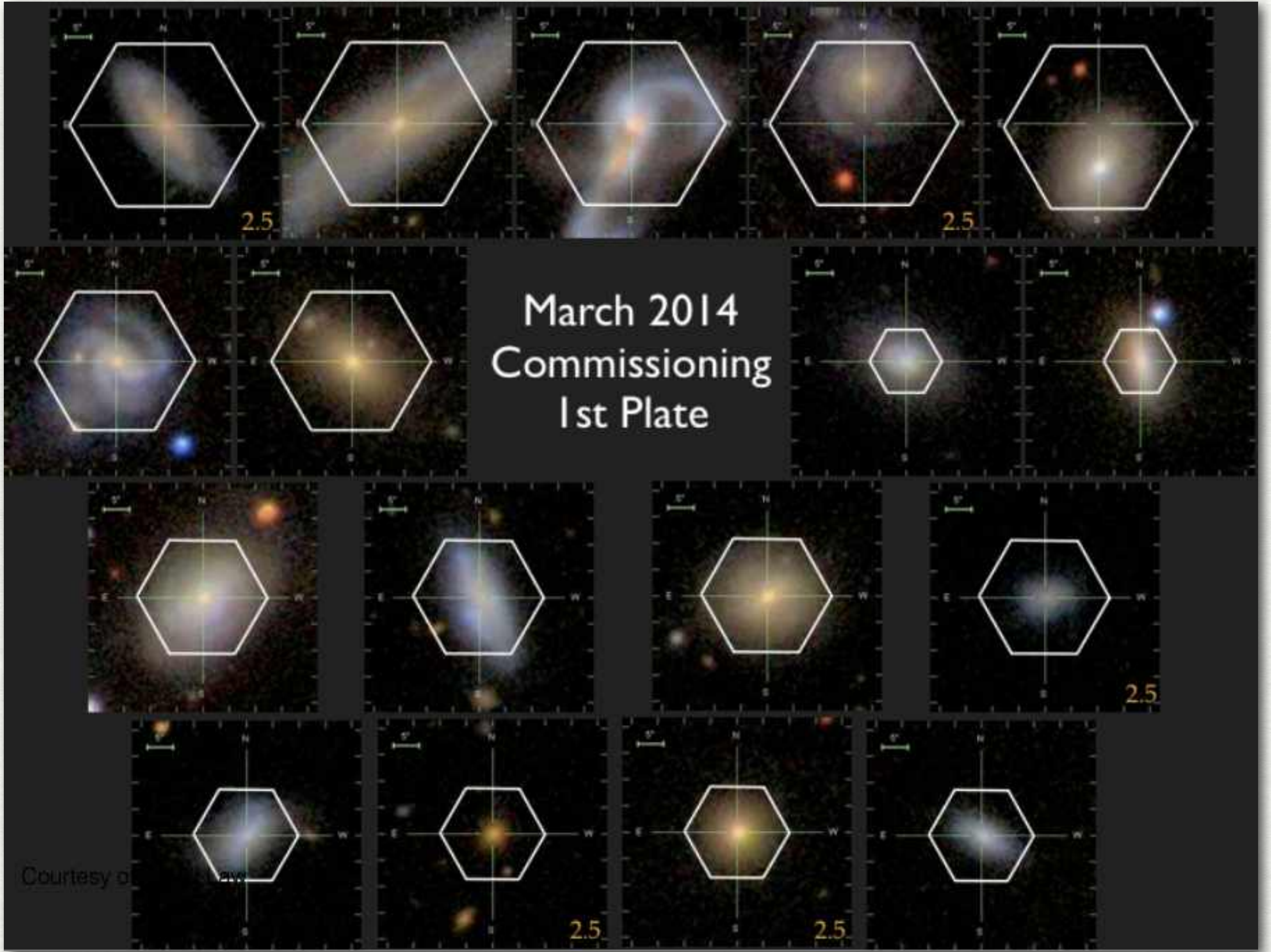


Figure 7. Images of the fibers in MaNGA IFUs ranging from 7 to 127 fibers (right to left).

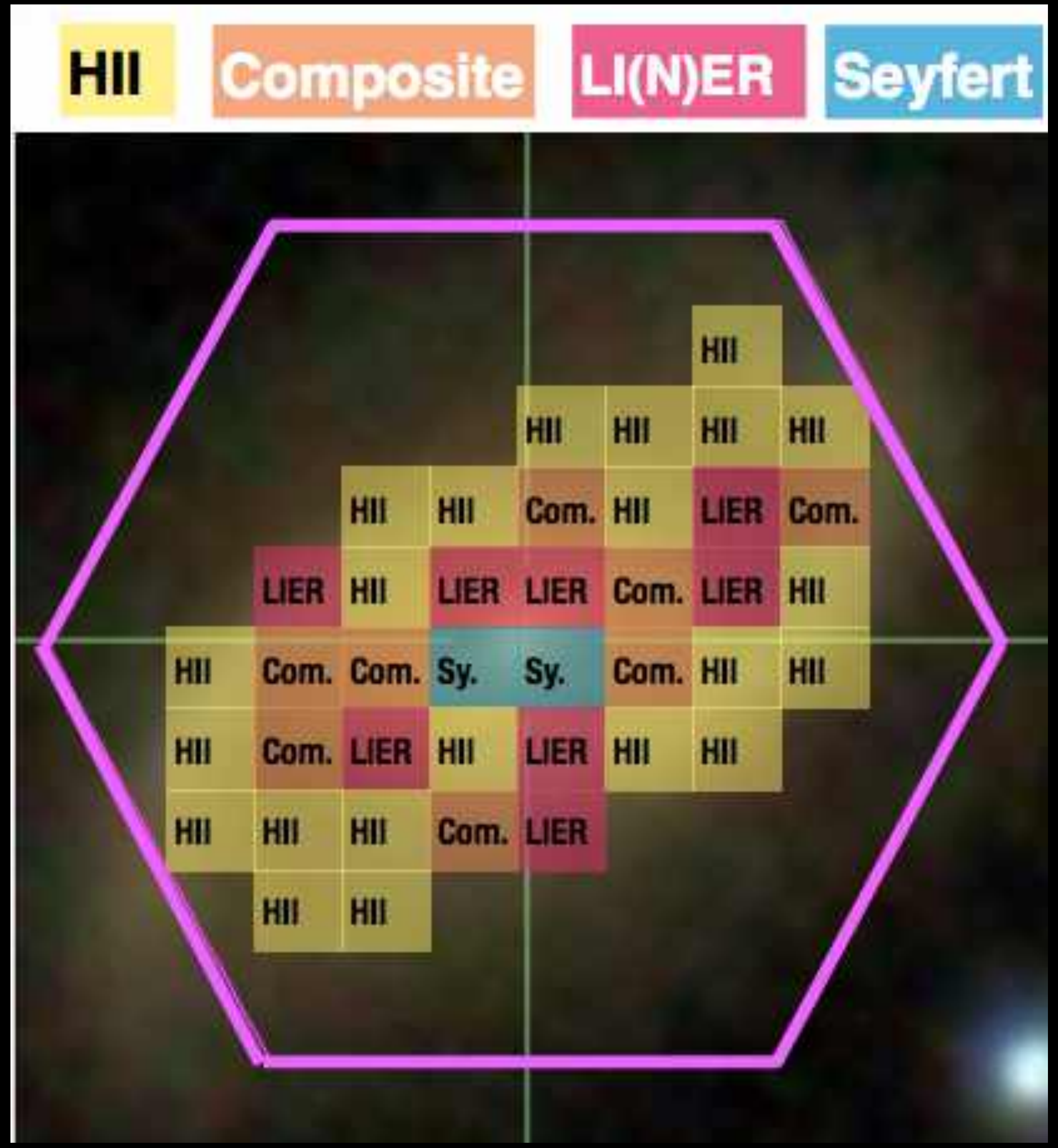


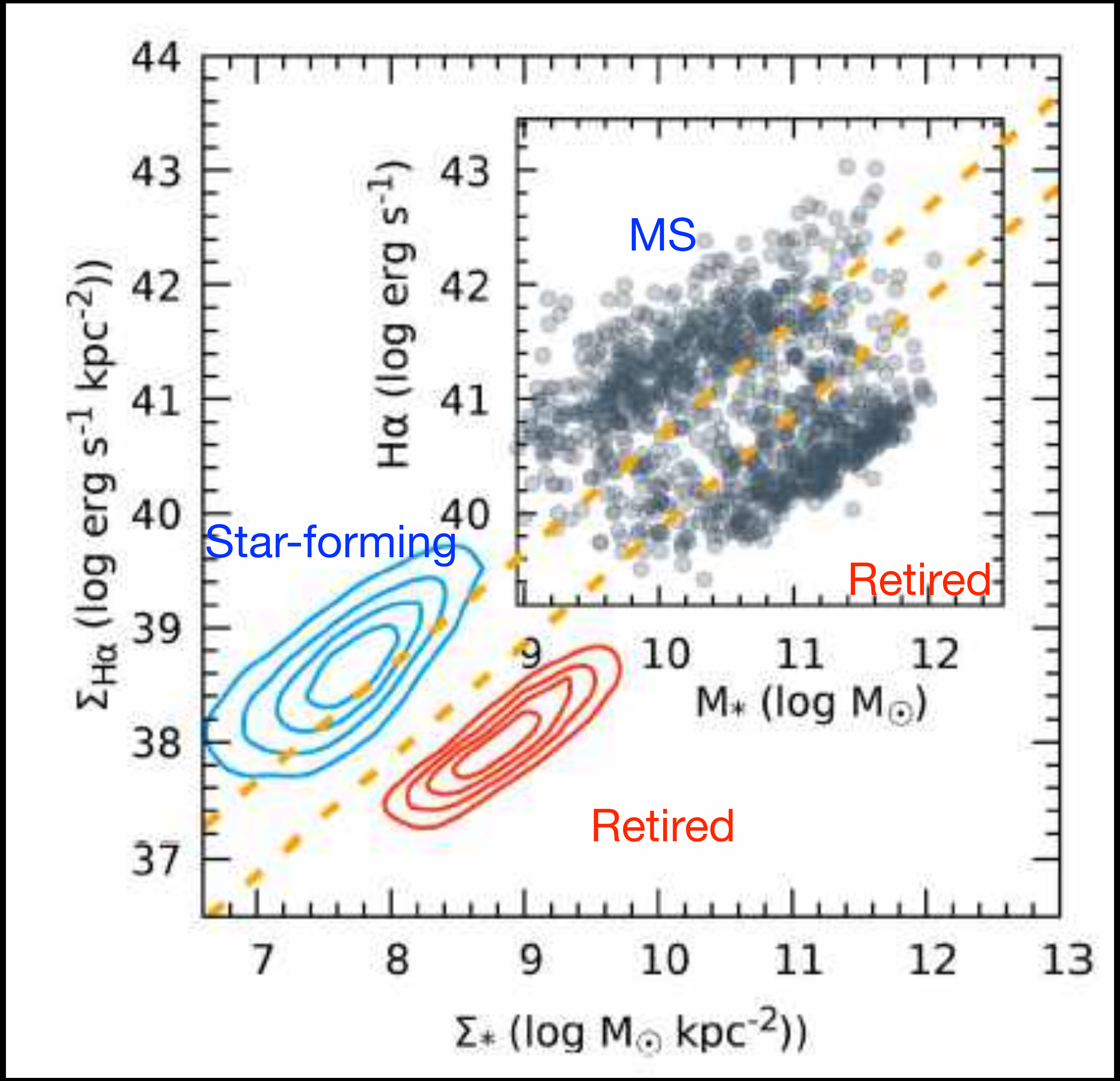

March 2014
Commissioning
1st Plate

Reflecting global properties on kpc scales

(e.g., Cano-Diaz+16; Abdurrouf & Akiyama 17; Ellison+18; Pan+18; Medling+18; Cano-Diaz+19; Vulcani+19)

Hsieh, Lin+2017 (MaNGA)

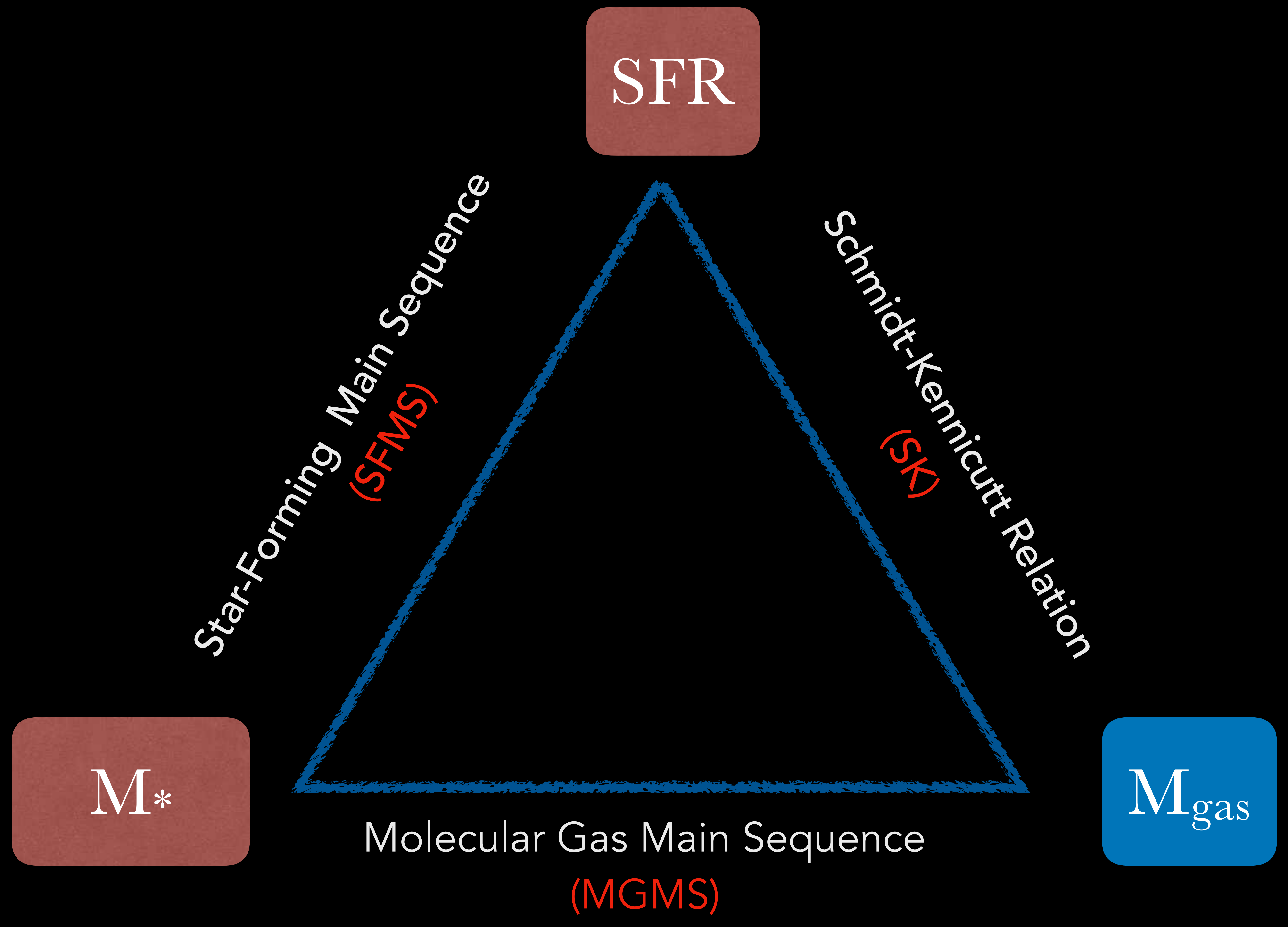




credit: Hsi-An Pan

Molecular gas is important

(e.g., Wong & Blitz 2002; Bigiel et al. 2008; Leroy et al. 2008)



SK (SFR vs. M_{gas}; Schmidt59 ; Kennicutt98; Gao & Solomon04; Bigiel+08 ; Leroy+13 ; Utomo+17; Shi+18):

- *Physically driven*

SFMS (SFR vs. M_*; e.g., Brinchmann+04; Daddi+07;; Noeske+07; Salim+07; Whitaker+12):

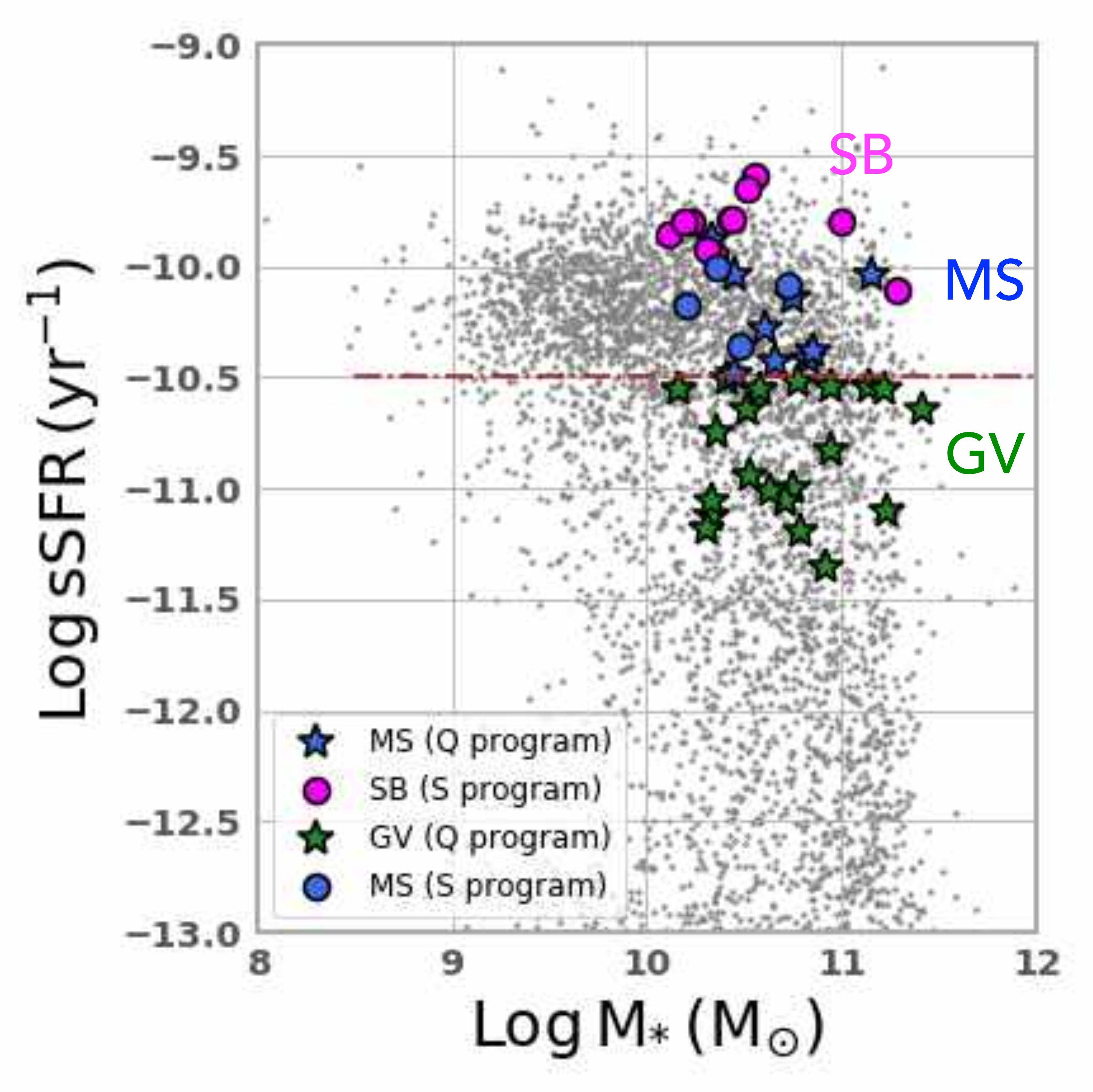
- *Empirical relation*

MGMS (M_{gas} vs. M_*; e.g., Leroy+05; Wong+13; Cicone+17; Lin+19; Morselli+20; Ellison+21a; Pessa+21; Sanchez+21; Lin+22):

- *Physically driven*

ALMaQUEST:
ALMA-MaNGA QUEnching and STar formation
(PIs: L. Lin & S. Ellison)

- ALMA CO(1-0) followups for 46 MaNGA selected sample
- z ~ 0.03; $10<\log(M_*/M_\odot)<11.5$
- ALMA Resolution:
  - ~2.5″ (spatial)
  - 11 km/s (spectral)
- Target classes:
  - 12 Main-sequence galaxies
  - 22 Green valley galaxies
  - 12 Central starburst galaxies



EDGE-CALIFA & COMING:
Larger sample size (~2-3x larger)

PHANGS-MUSE:
better spatial resolution (~10x finer)

ALMaQUEST:
Sampling a wider range of sSFR and types (SB, MS, and GV)

Extended sample: AGN (Ellison), Mergers (Pan), and AGN host mergers (Thorp) , PSBs (Rowlands)

Lin+2020; Ellison+2024

http://arc.phys.uvic.ca/~almaquest/

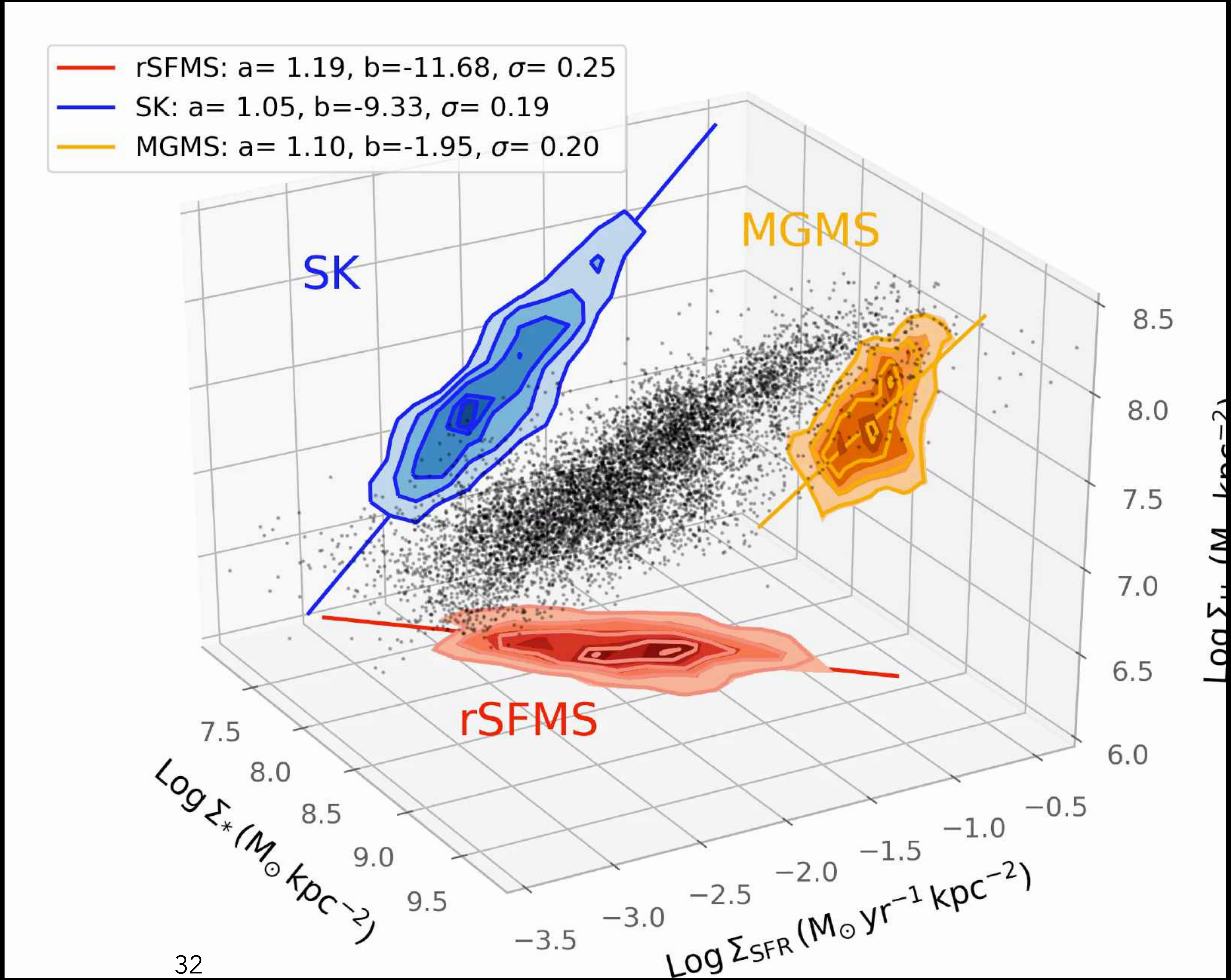
Scaling relations

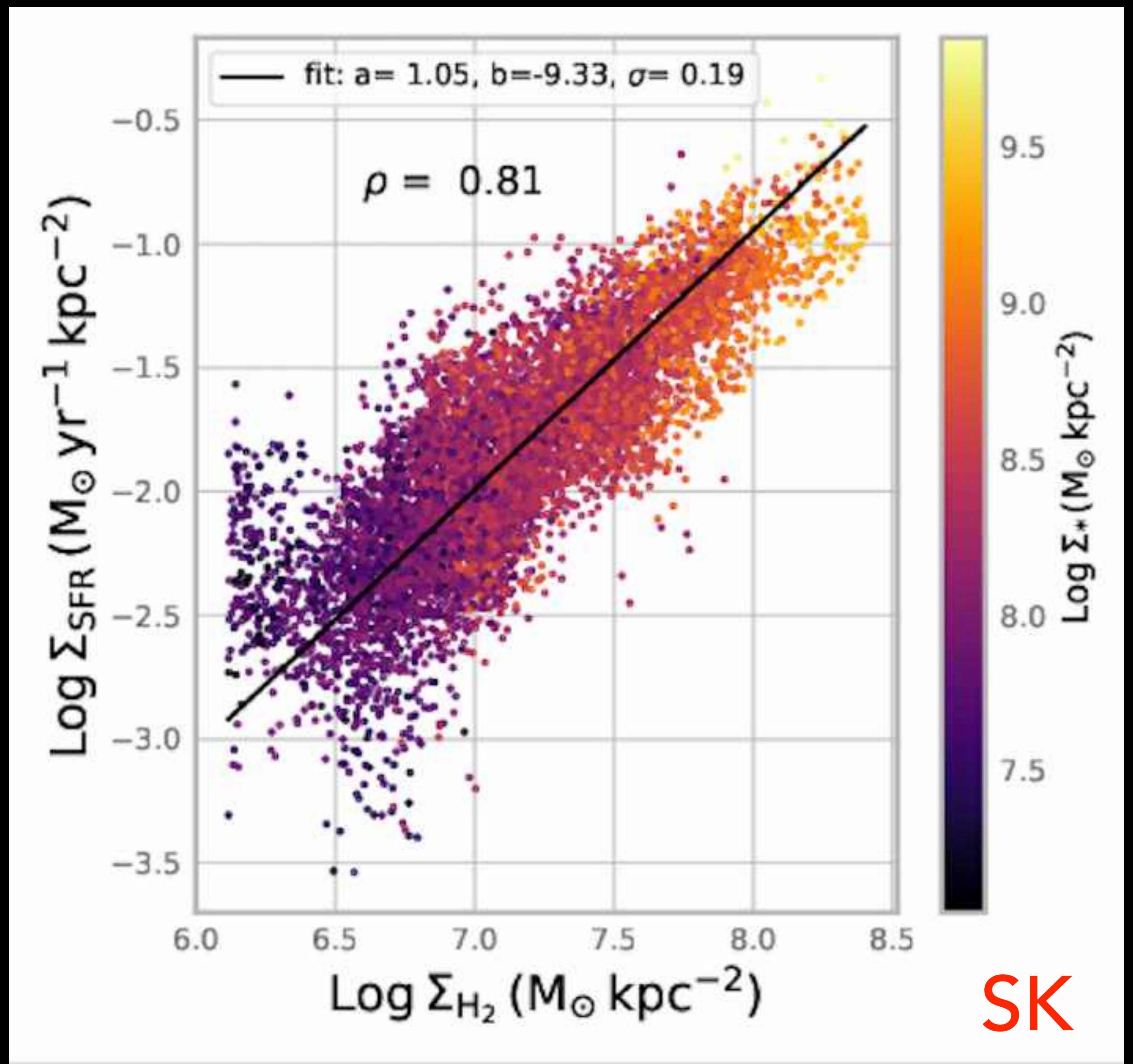
Scaling Relation of Main-Sequence (MS) Galaxies

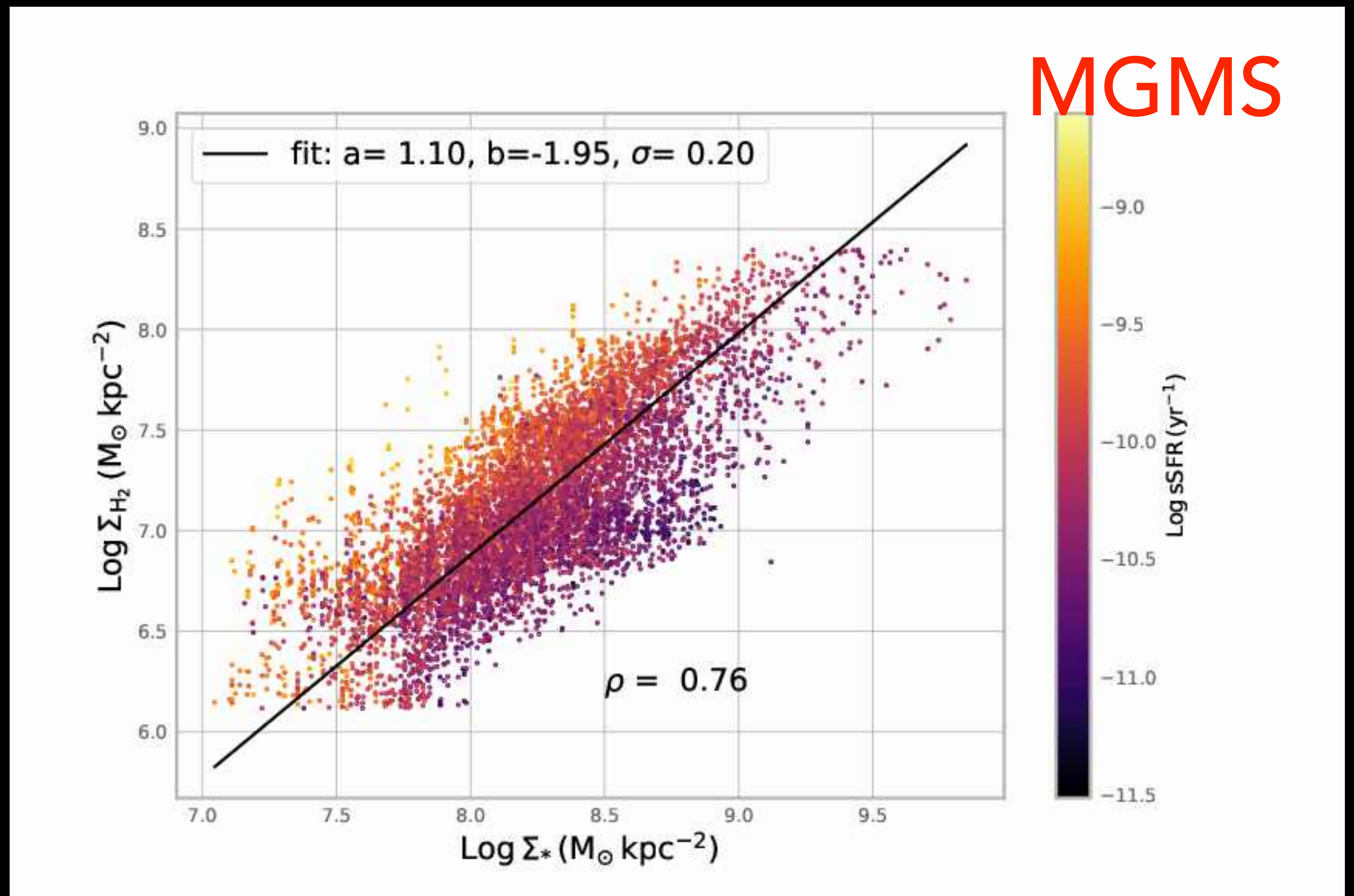
Lin et al. 2019, ApJ

- **Star-forming spaxels, particularly in MS galaxies, form tight sequence in the rSFMS, rSK, and rMGMS relations.**

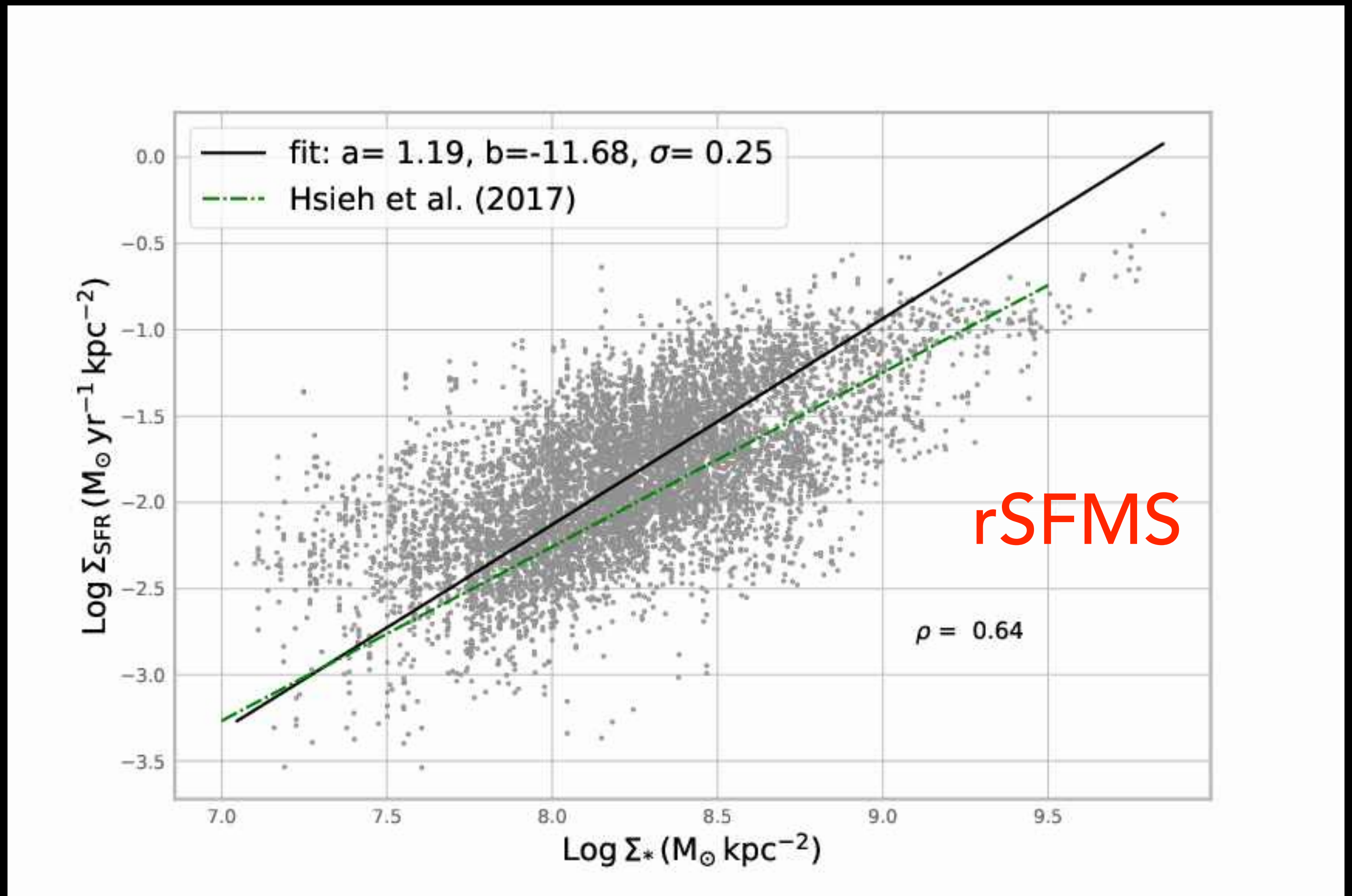
  (e.g., Lin+19; Morselli+20; Barrera-Ballesteris+20; Sanchez+20, 21; Ellison+21a; Pessa+21; Baker+22; Abdurro'uf+22)





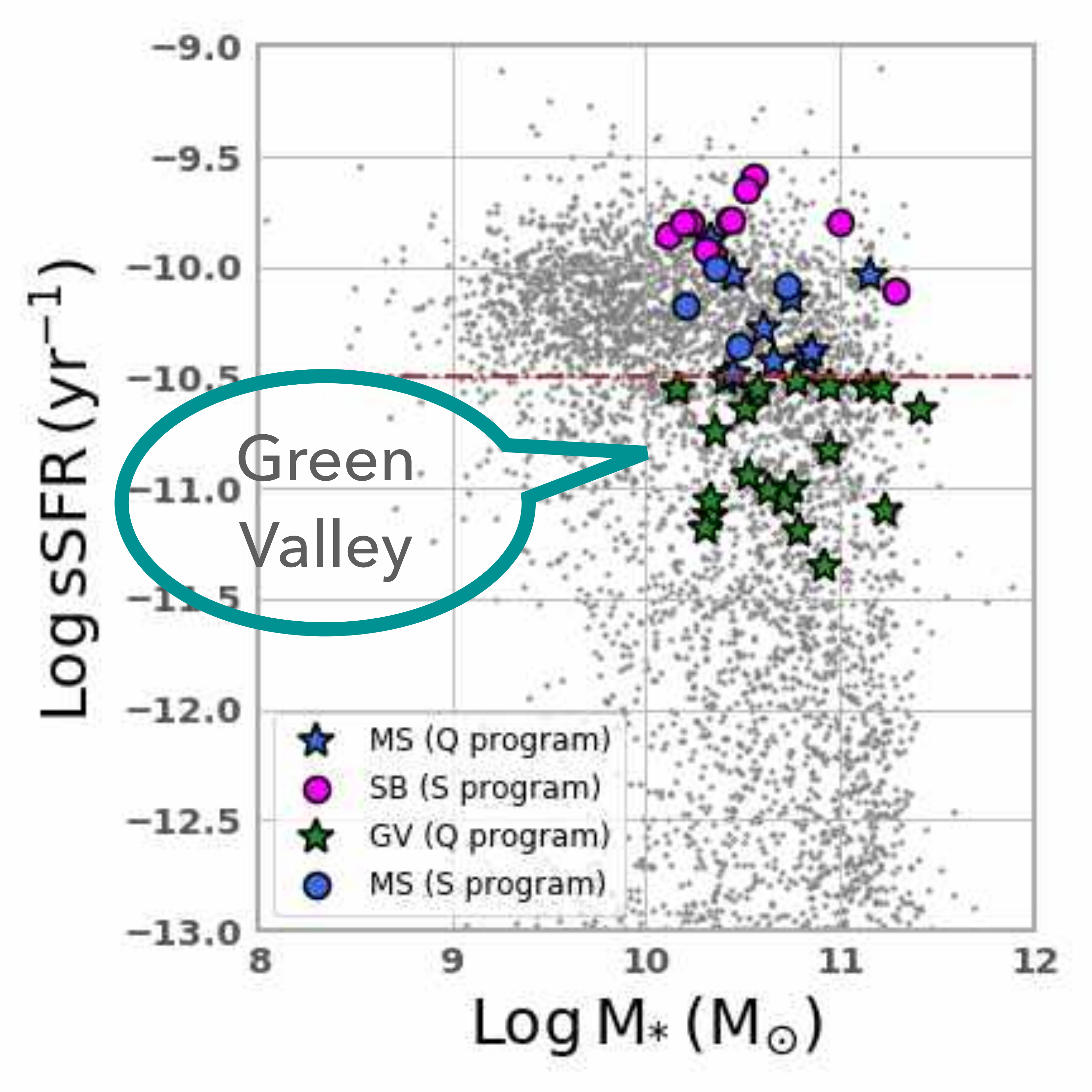


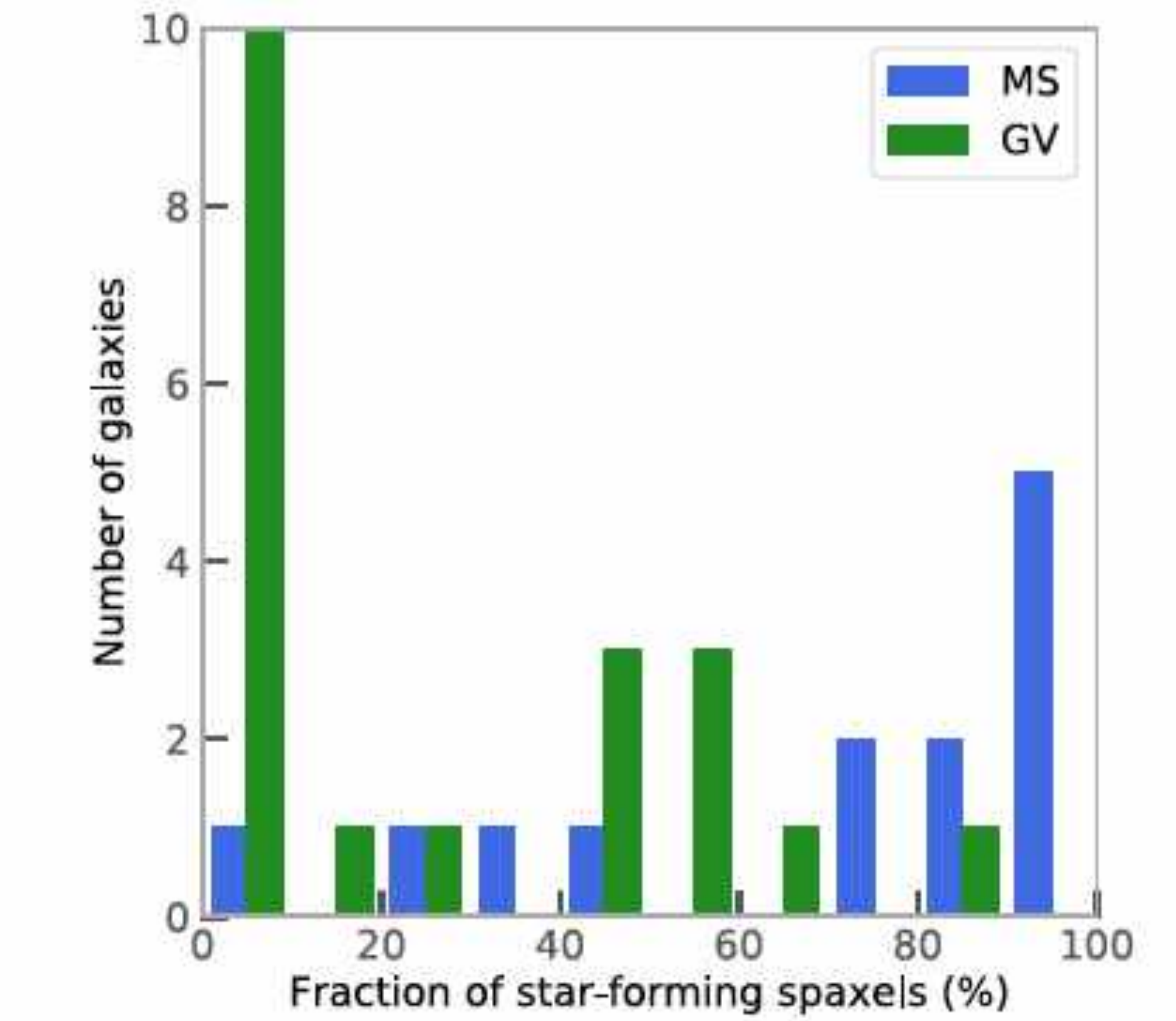
Lin et al. 2019, ApJ

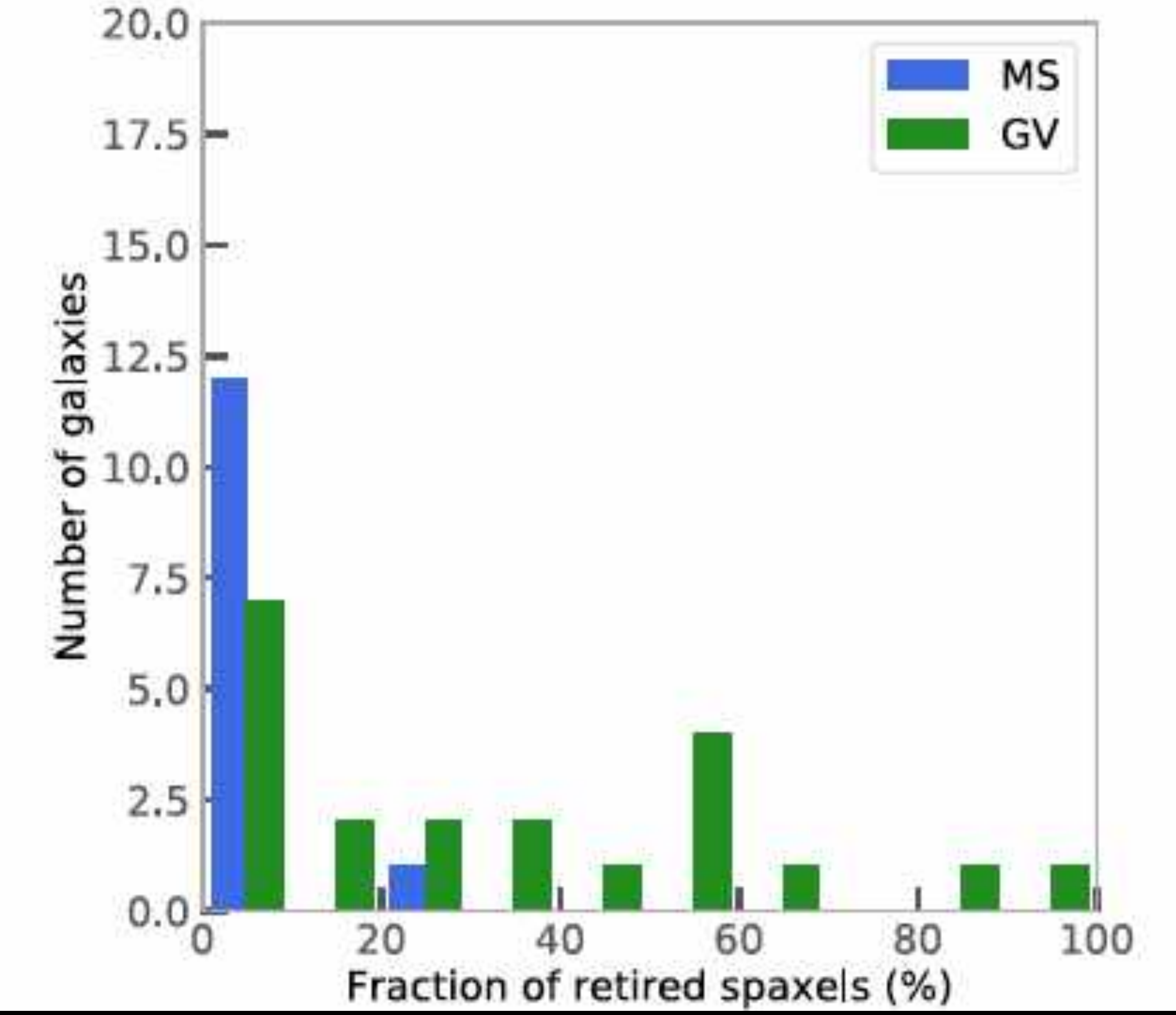


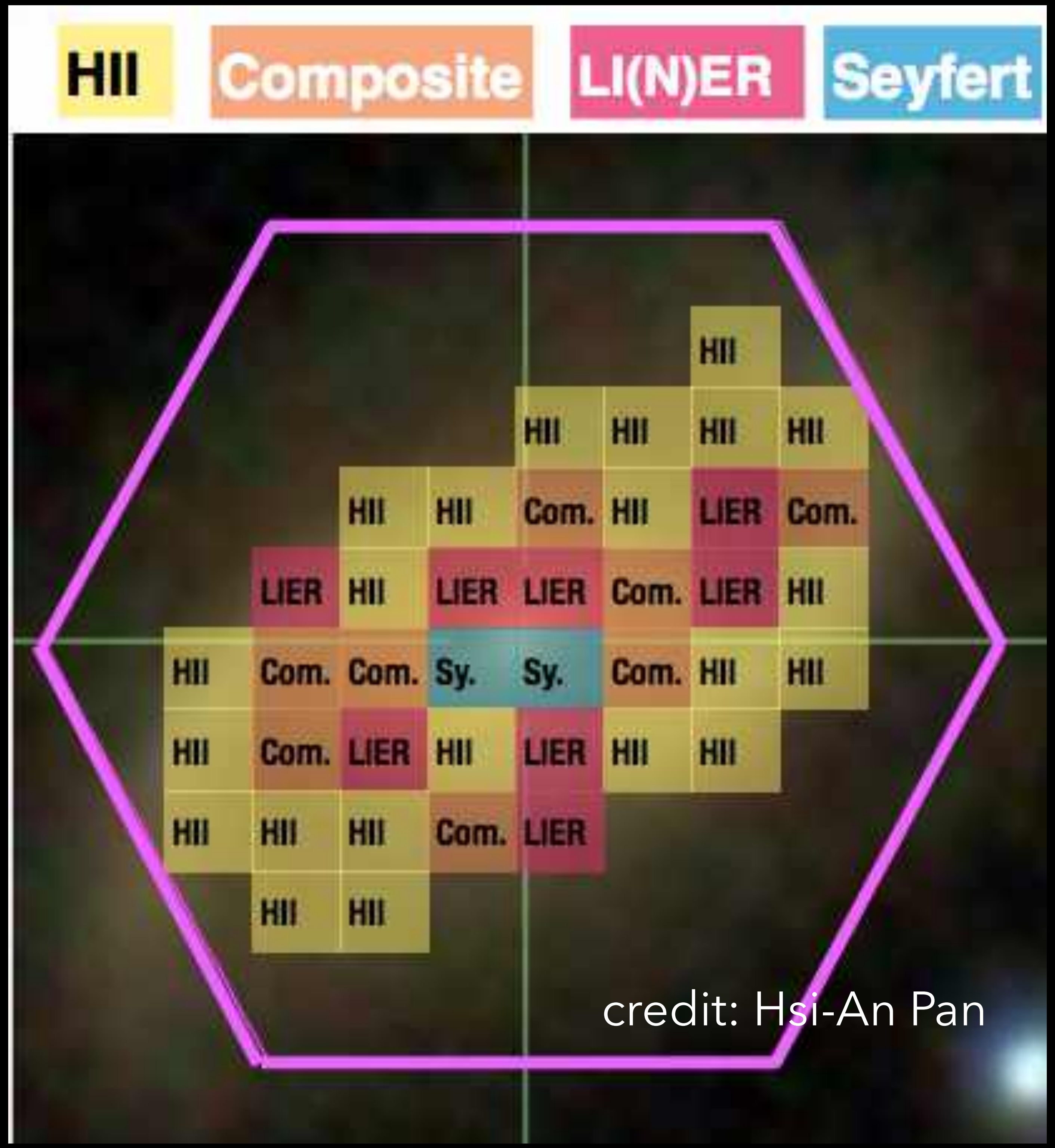
- rSFMS is the least fundamental and a natural consequence of the combination of SK and MGMS relations, supported by:
  - Scatter: rSFMS > MGMS > SK (Lin+19; Morselli+20; Ellison+21a)
  - Correlation analysis: rSFMS < MGMS ~ SK (Lin+19; Ellison+21a)
  - Partial correlation (Baker+22)
  - Neural Network (Ellison+20); Random forest regression (Baker+22)

What about galaxies undergoing quenching?



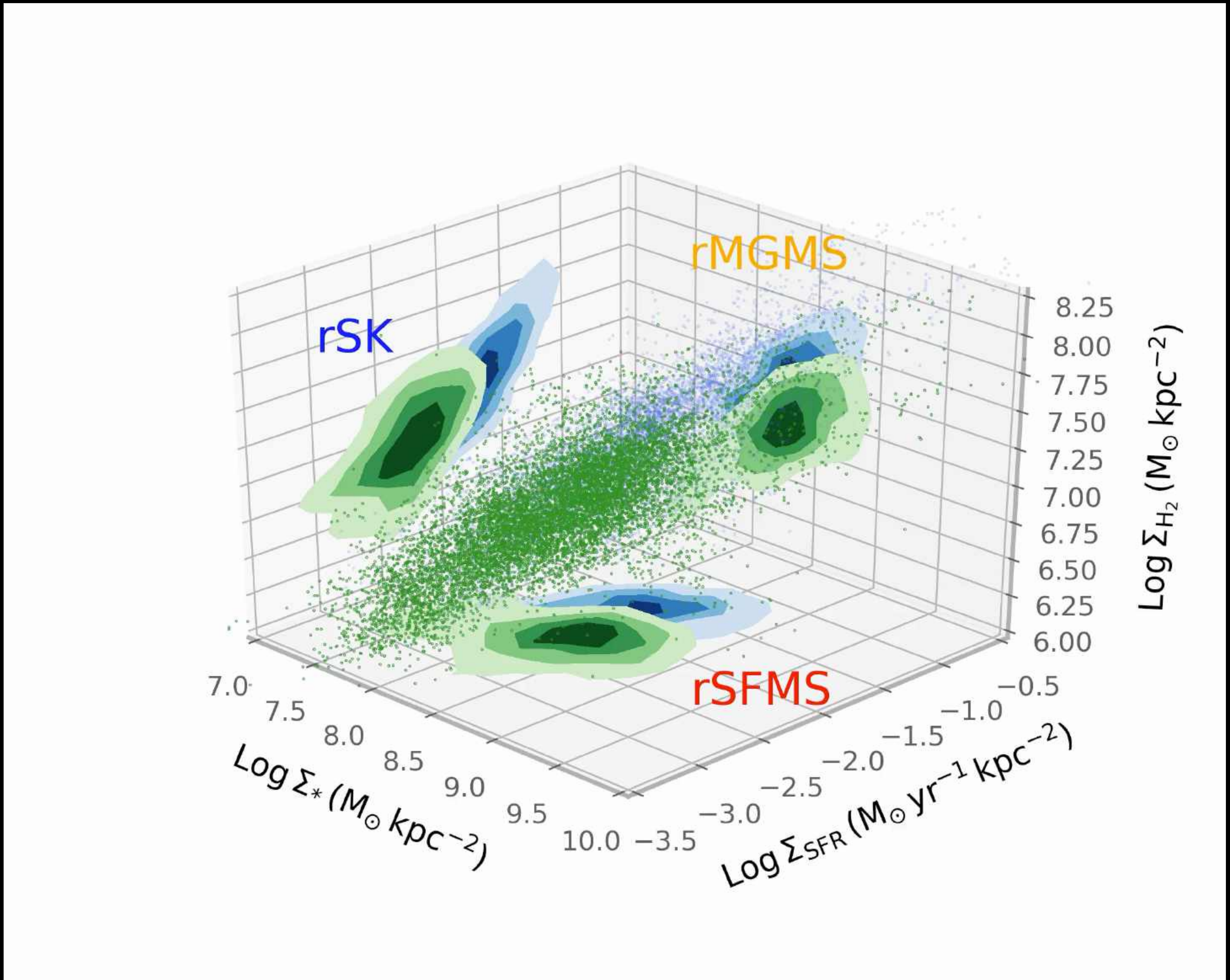






- Star-forming spaxels (blue colors):
  BPT-classified SF regions + Ha EW > 6 A
- Retired spaxels (red colors):
  0 < Ha EW < 3 A

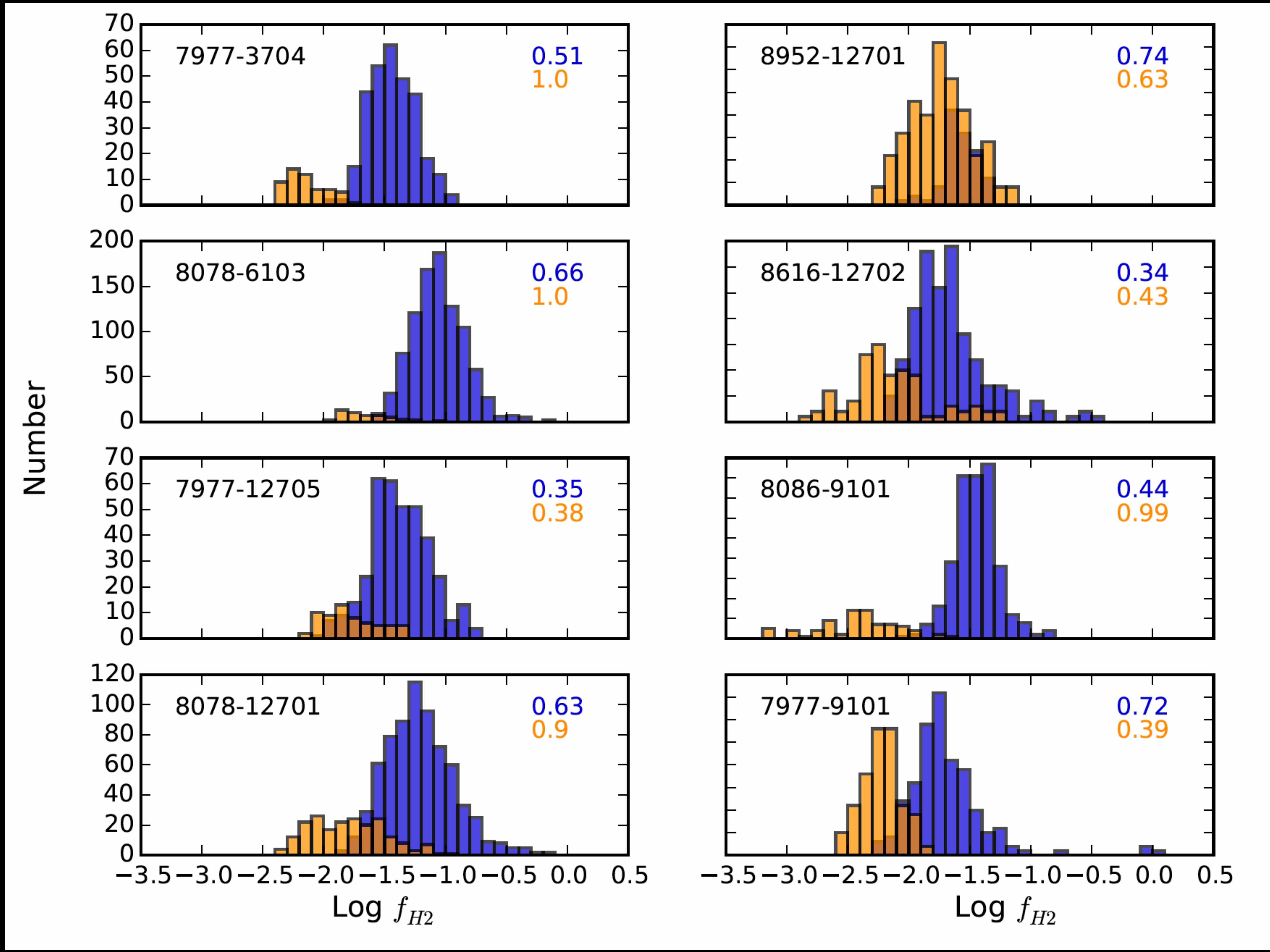
rSFMS, rSK, and rMGMS in green valley galaxies



GV galaxies deviate from the scaling relations formed by MS galaxies in all cases

Lin et al. 2022

The H2-to-M* ratio in retired regions



- Star-forming spaxels (blue colors):
  BPT-classified SF regions + Ha EW > 6 A
- Retired spaxels (red colors):
  0 < Ha EW < 3 A

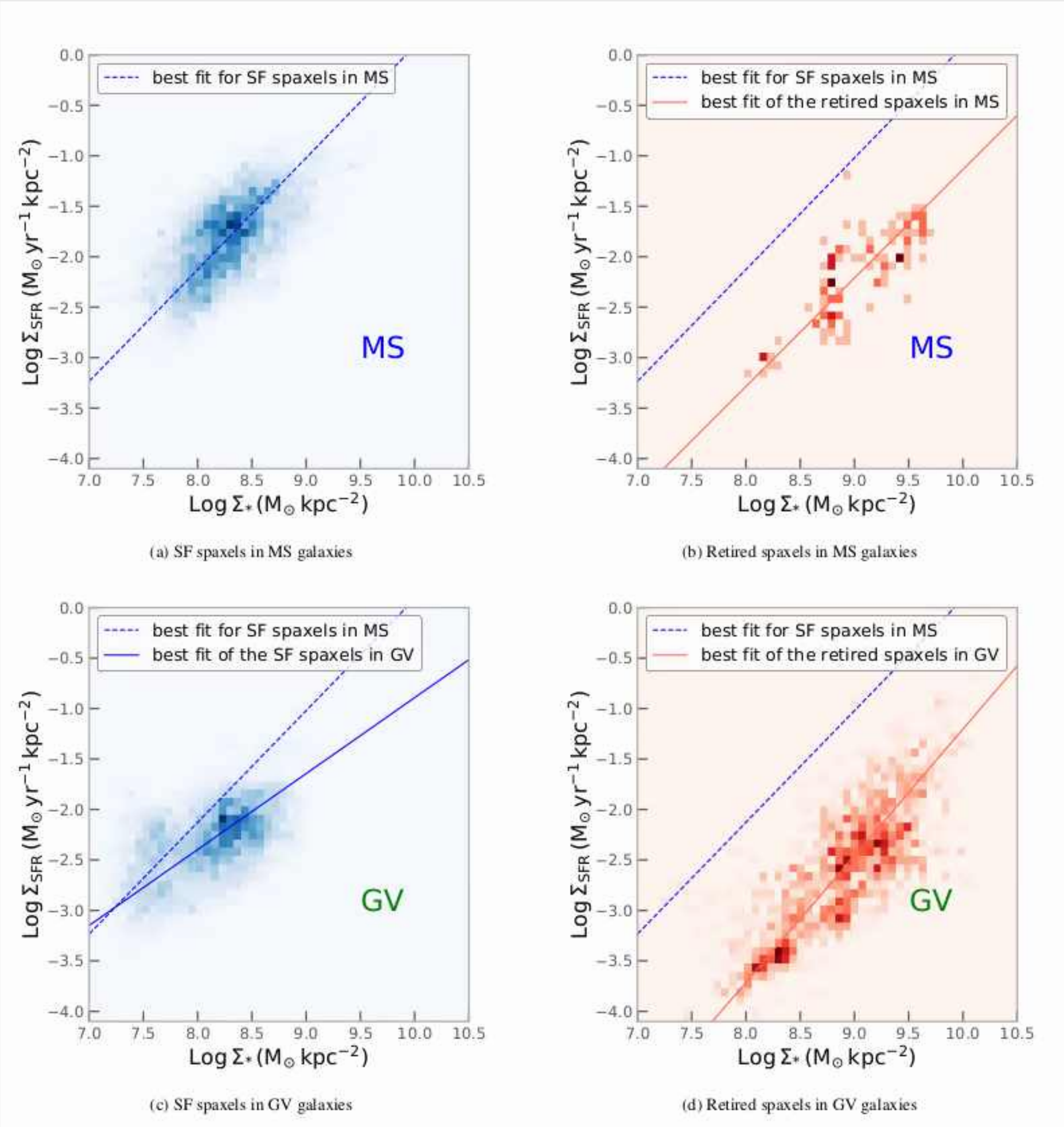
Retired regions possess gas fraction (f_{H2}) lower by an order of magnitude than star-forming regions

Ellison+21b

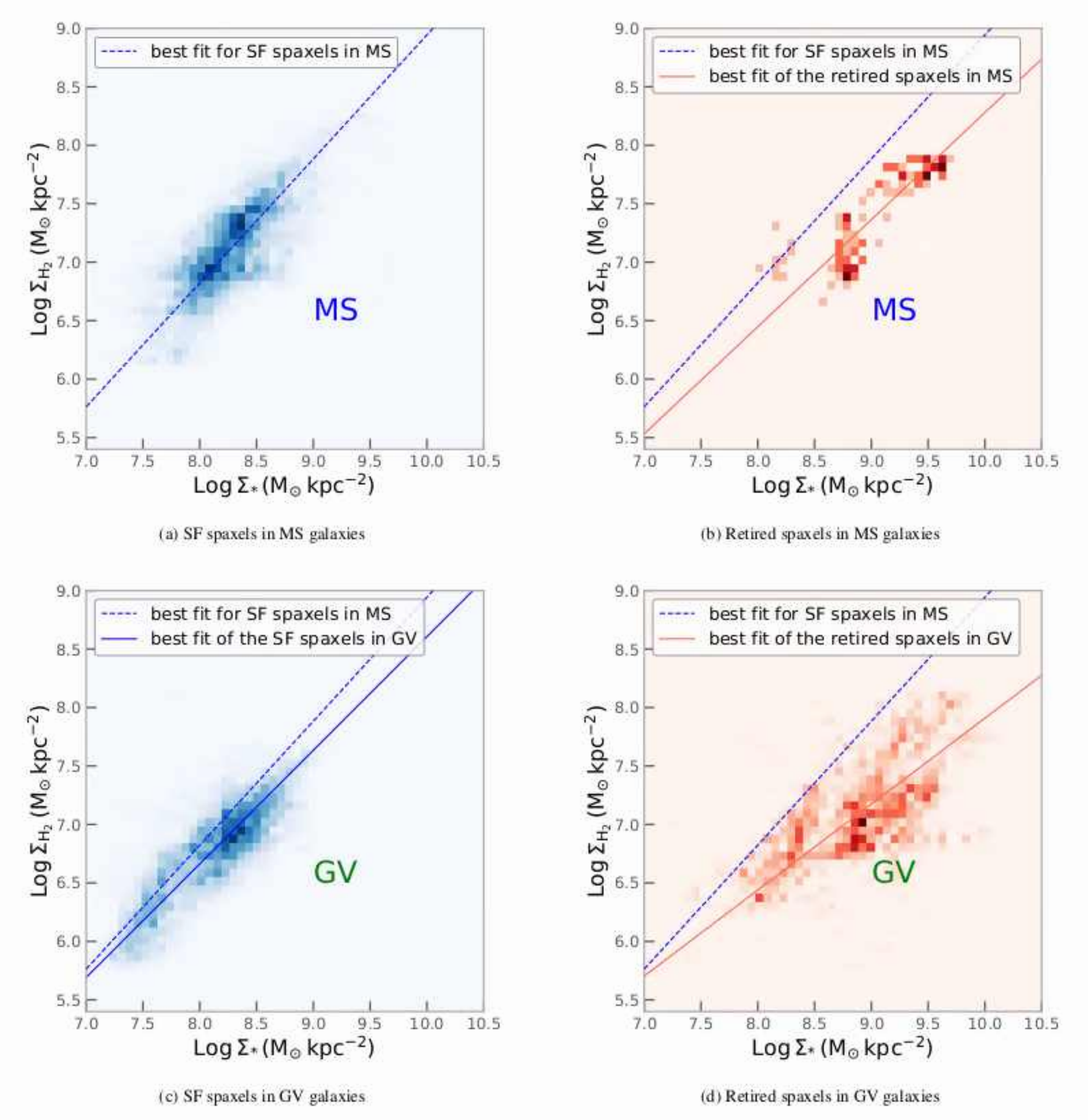
Scaling Relation in GV galaxies

- Star-forming spaxels (blue colors):
- Retired spaxels (red colors):

SK: Σ_{SFR} vs. Σ_{H2}



MGMS: Σ_{H2} vs. Σ_*

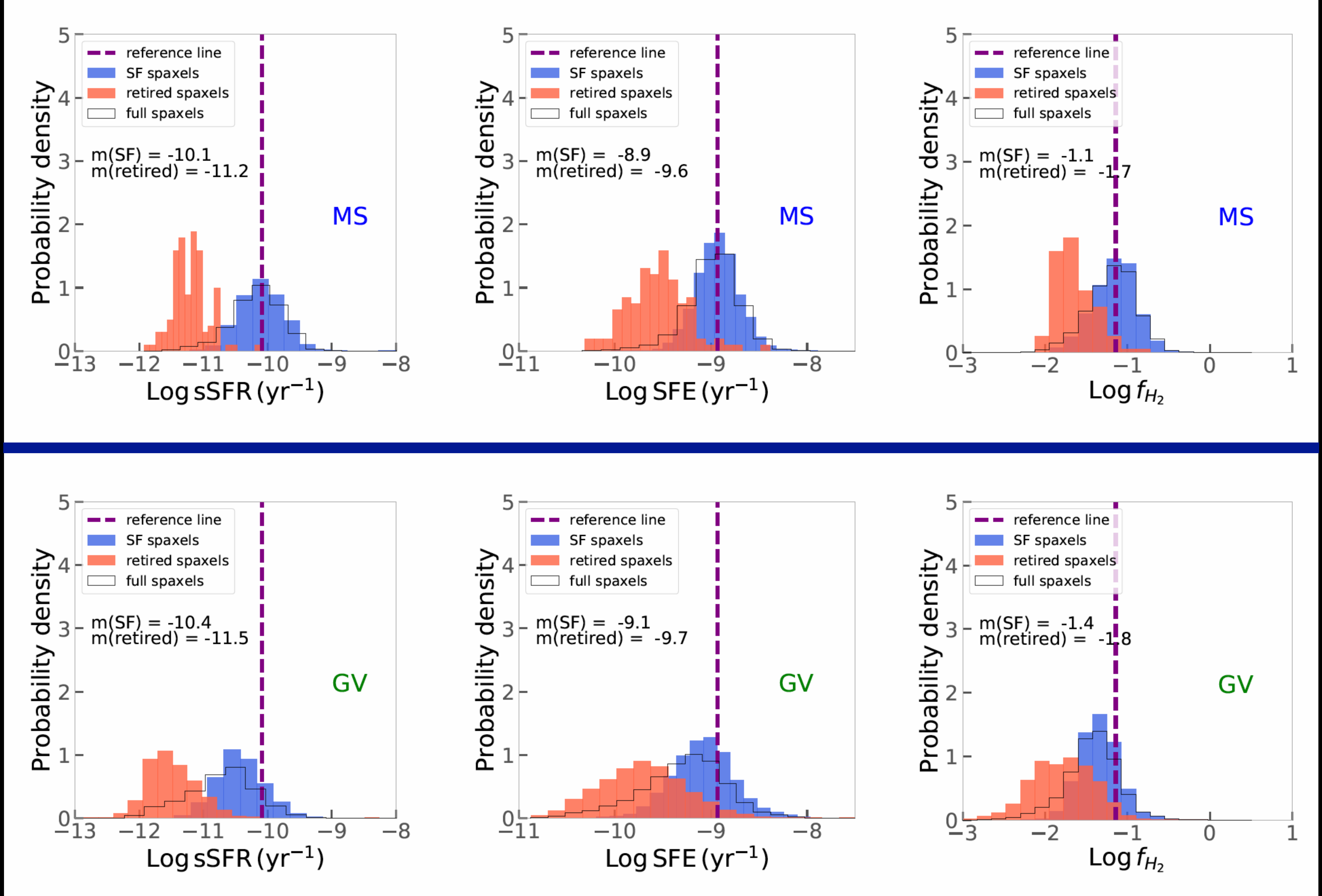


The spaxels in GV galaxies are systematically lower than those in MS galaxies, even in star-forming spaxels

Lin+22; also see Brownson+20

Comparison between main-sequence (MS) and green valley (GV) galaxies

Lin et al. 2022



$SFE_{H2} = SFR/M_{H2} = 1/t_{dep}$

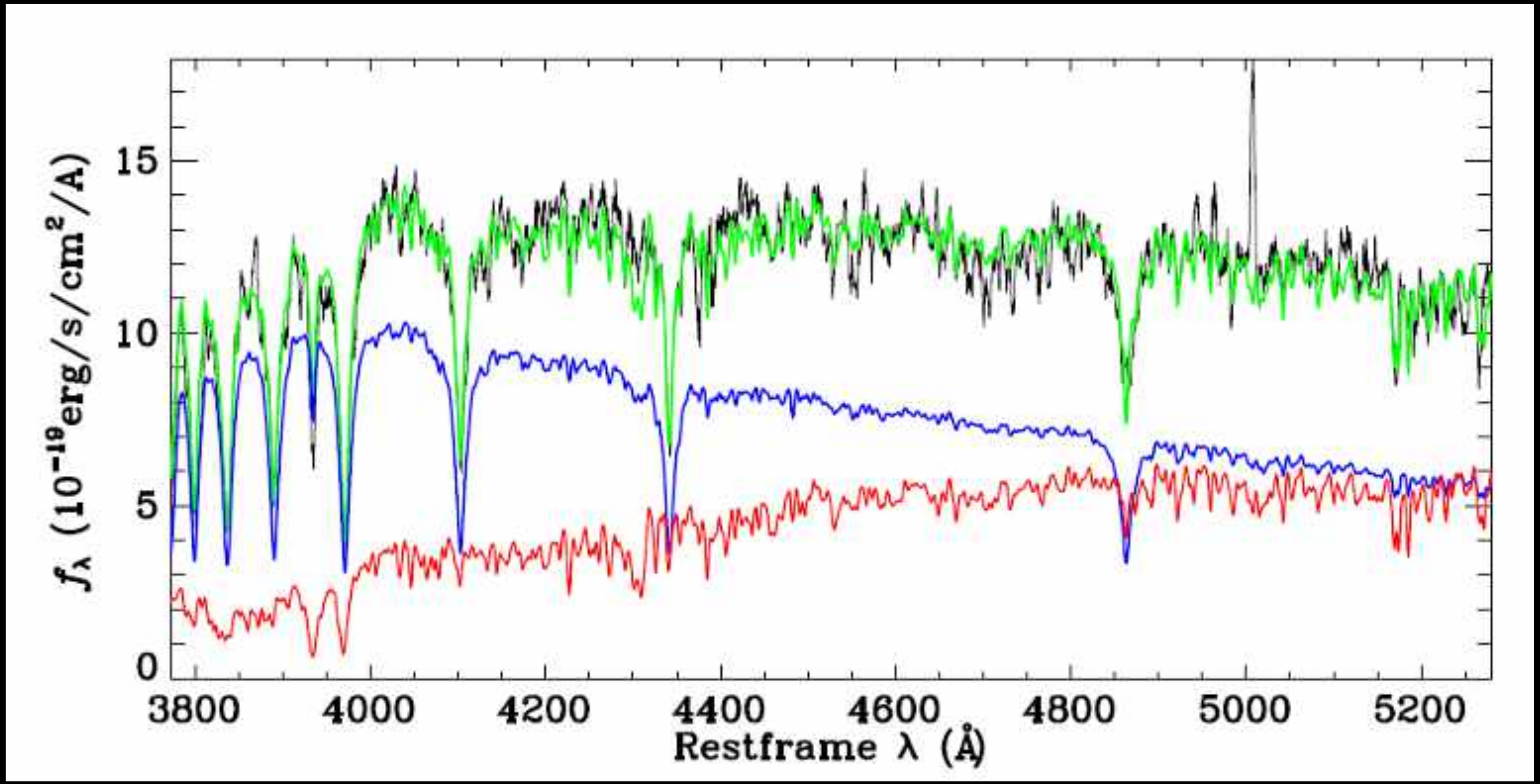
$f_{H2} = M_{H2}/M_*$

Green valley galaxies statistically have lower SFE_{H2} and lower f_{H2} compared to main-sequence galaxies.

Dense gas in transitional galaxies:

1. Post-starburst galaxies
2. green valley galaxies

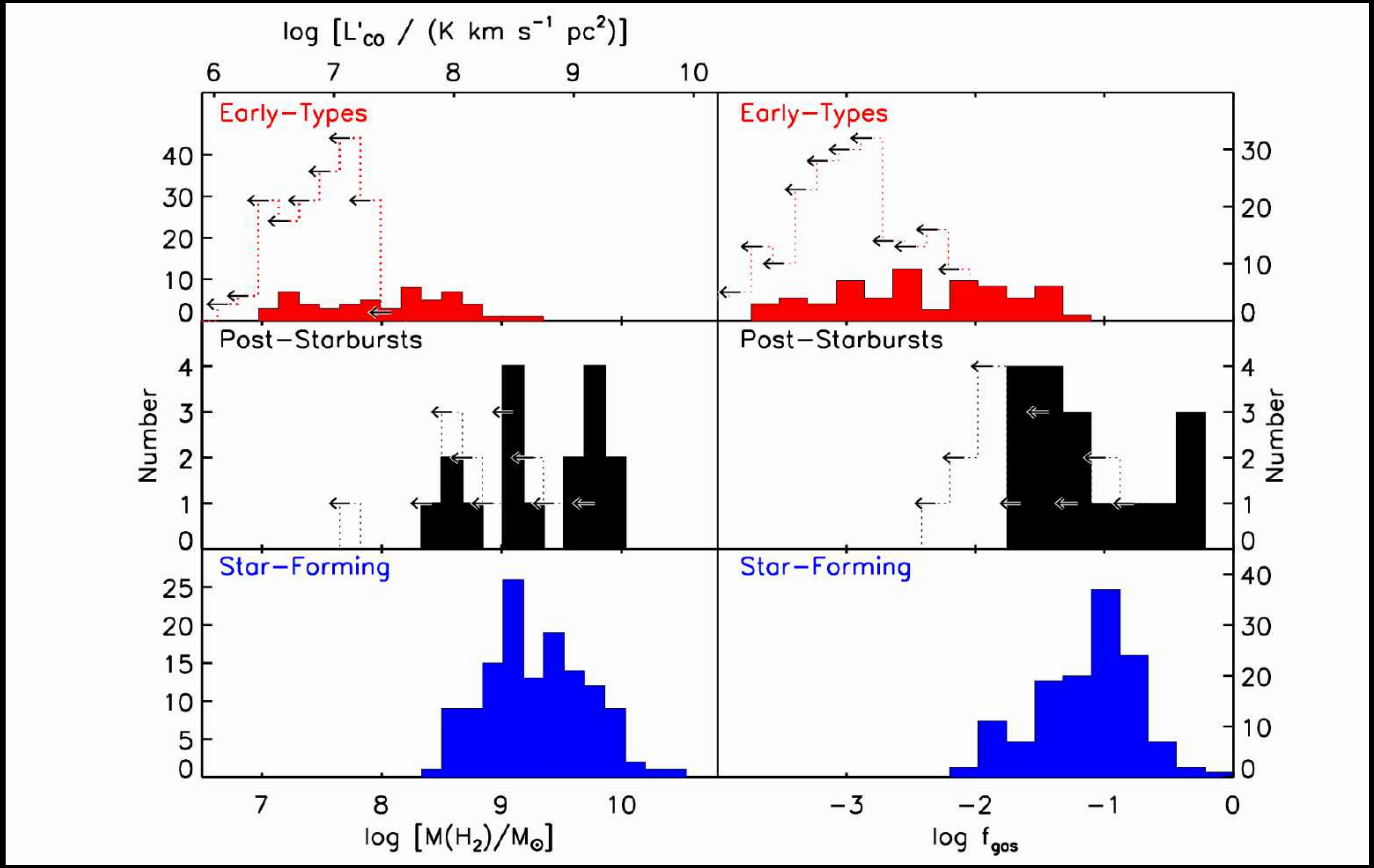
Post-starburst Galaxies



e.g., Yan+08

- E+A galaxies are galaxies that have recent star formation activities but without on-going star formation in < a few Myr
- They are thought to be undergoing transition phase between star-forming and quiescent populations
- Post-starburst galaxies make up ~1% in the local universe

Molecular gas in Post-starburst Galaxies



Recent studies have revealed high molecular gas fractions traced by CO(1-0) in local post -starburst ghalaxies.

e.g., French+15; Rowlands+15; Alatalo+16

What drives low SFE_{mol} ?

$SFE_{mol} = SFR/M_{mol}$

$SFE_{dense} = SFR/M_{dense}$

Therefore,

$SFE_{mol} = (M_{dense}/M_{mol})* SFE_{dense}$

$n_{critical}$ (CO(1-0)) = 10^3 cm^{-3}

$n_{critical}$ (HCN(1-0)) = 10^{5-6} cm^{-3}

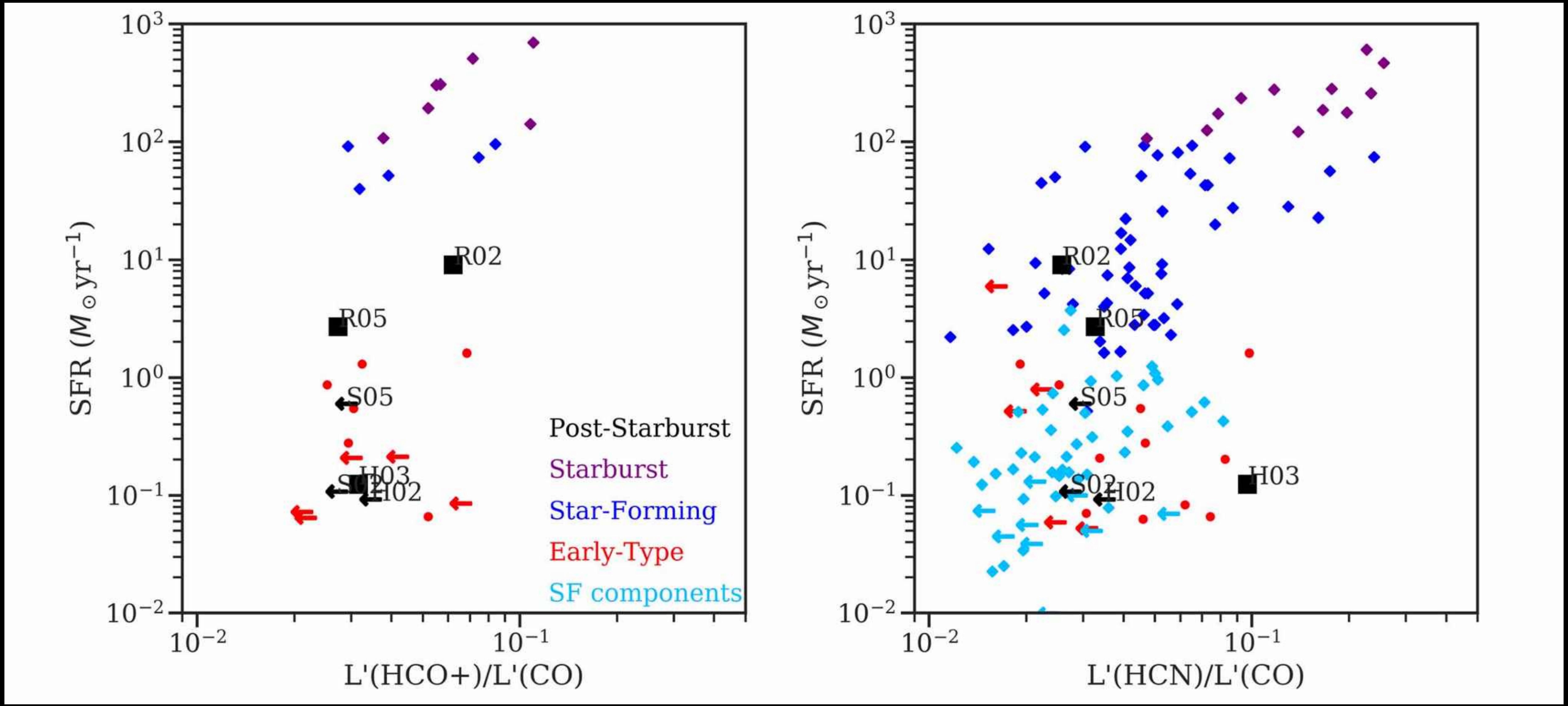
$n_{critical}$ (HCO+(1-0)) = 10^{4-5} cm^{-3}

Lower SFE_{mol} could be due to:

1. lower dense gas fraction (M_{dense}/M_{mol}) but normal SFE_{dense} (Scenario I)
2. normal dense gas fraction, but lower SFE_{dense} (Scenario II)

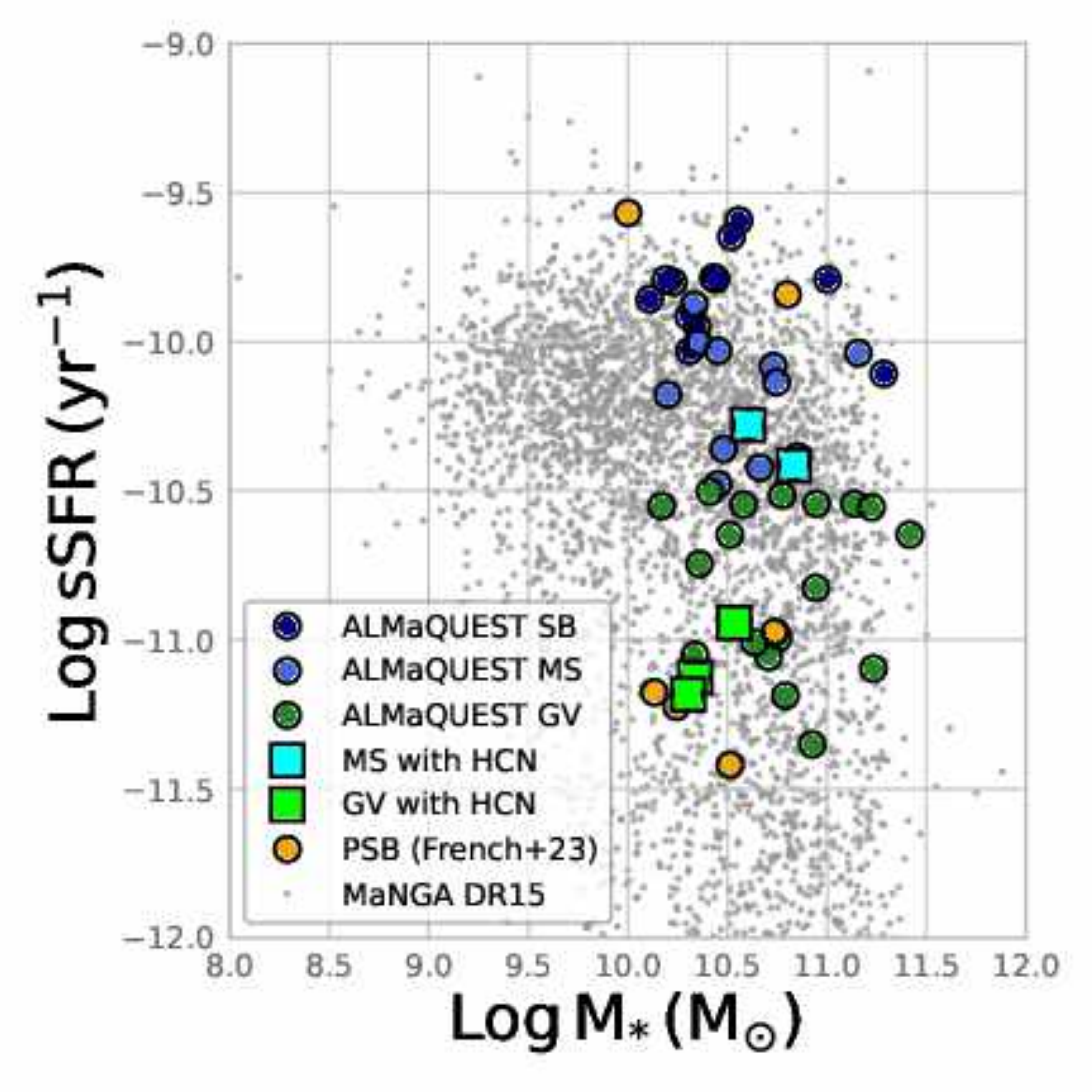
Dense Gas in Post -Starburst Galaxies

French+23



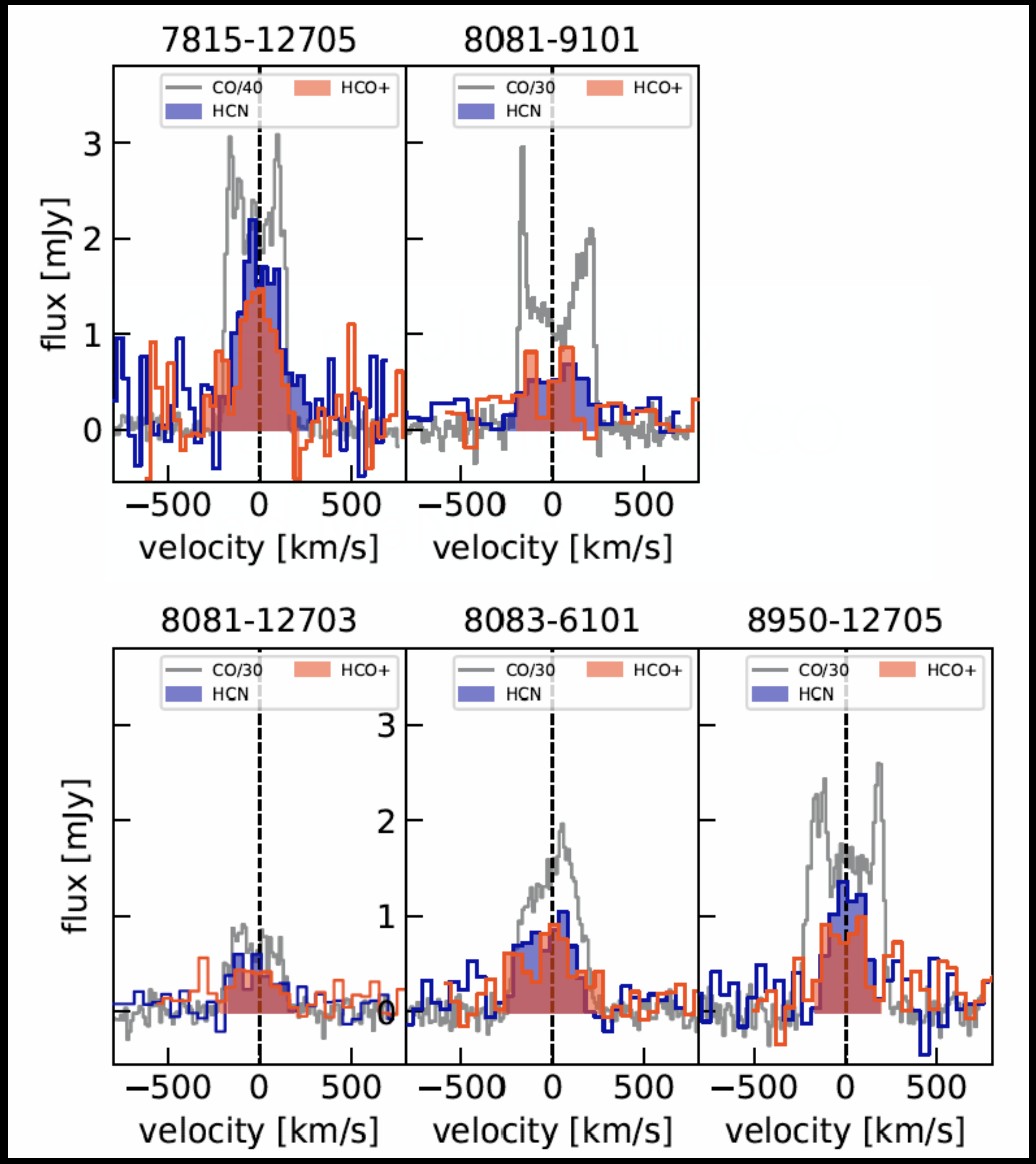
Post starbursts tend to have lower dense gas fraction (HCN/CO or HCO+/CO) than star-forming galaxies

PSB vs. GV

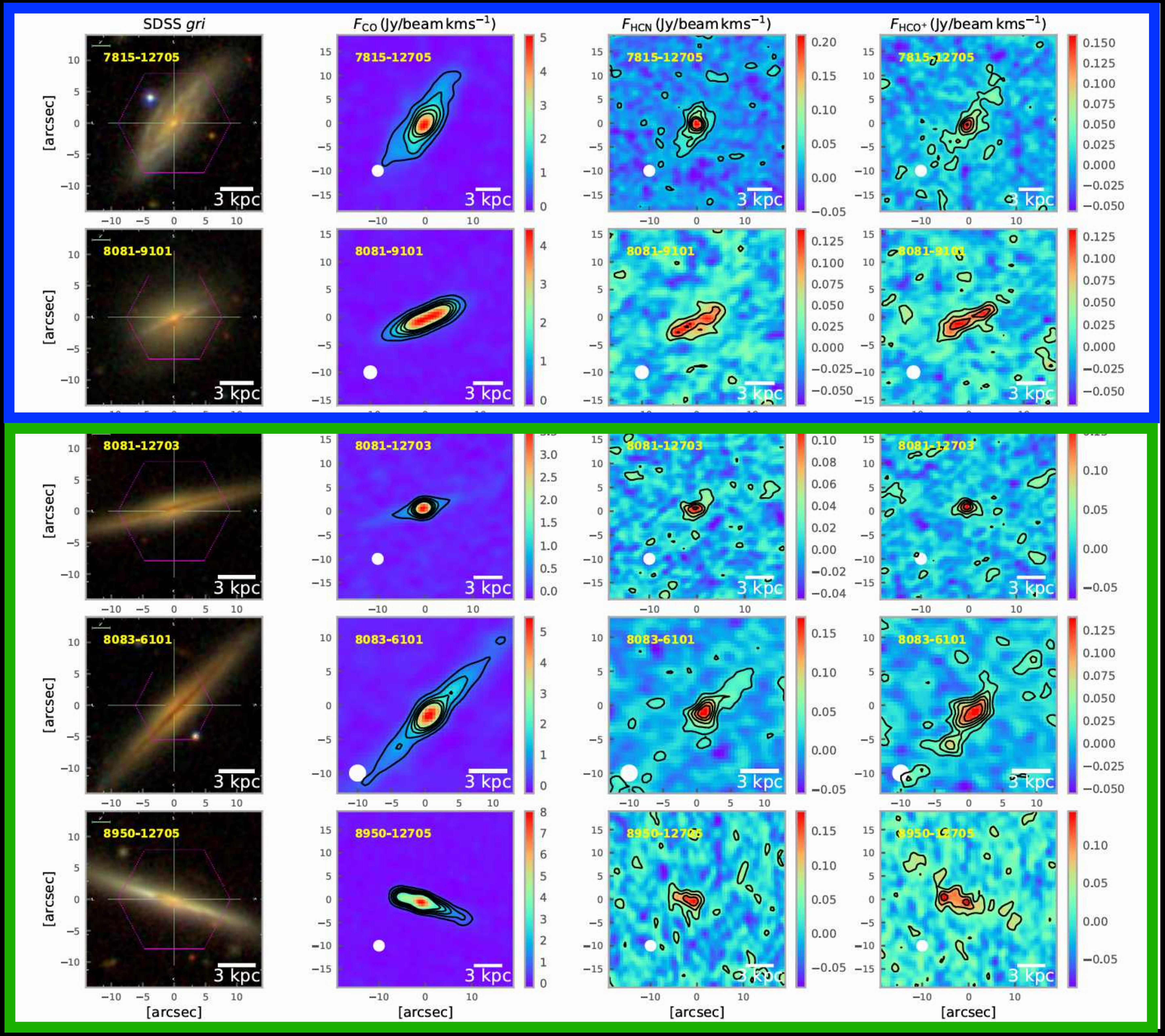


Are they different populations (paths) or at different transitional phases?

Getting (dense) molecular gas data for more galaxies in the transitional phases will be crucial!



CO HCN HCO^+



MS

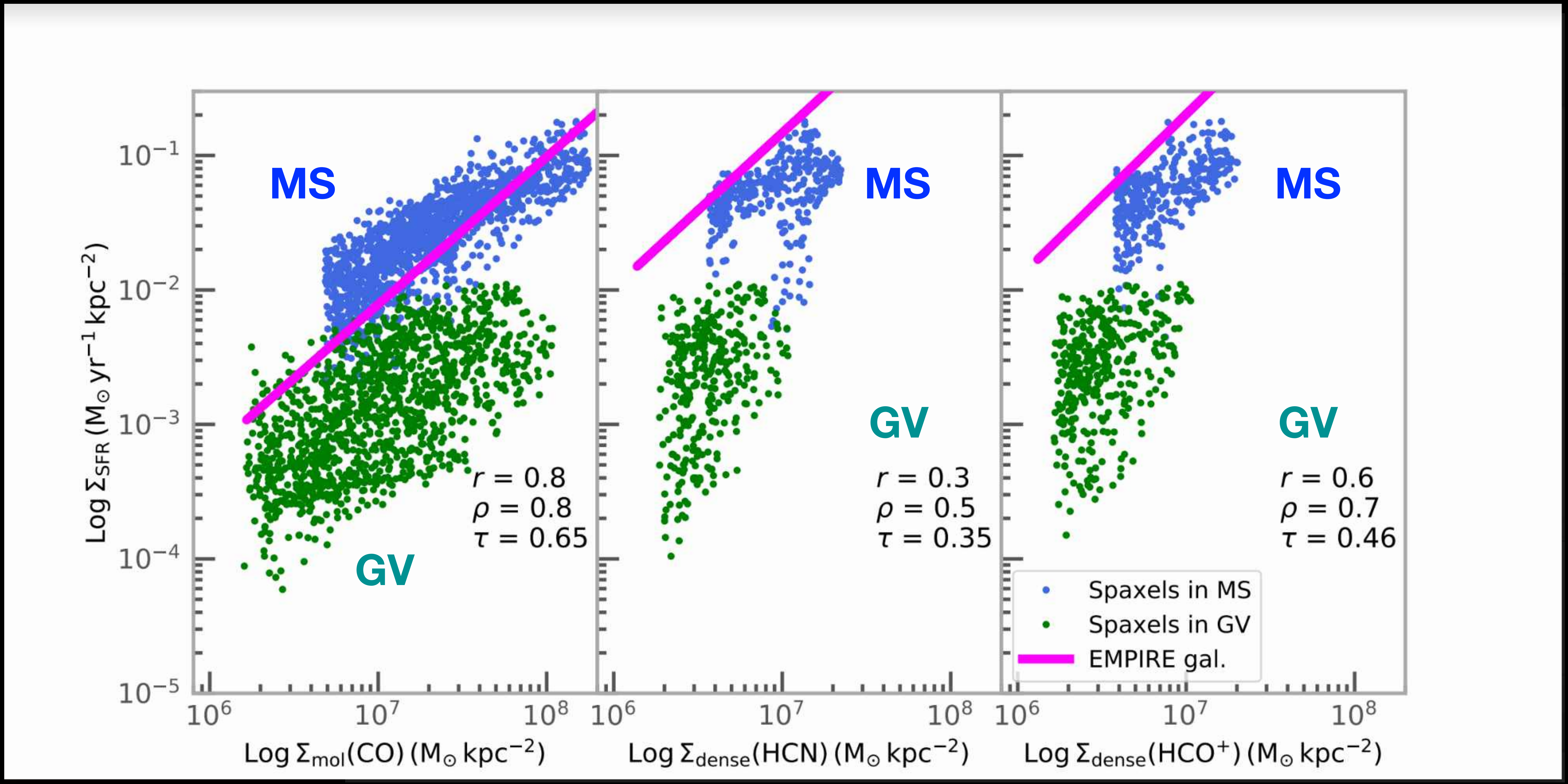
GV

HCN and HCO+ are detected in all all 5 galaxies (2 MS and 3 GV)

Lin+2024, ApJ

Resolved Dense Gas Schmidt-Kennicutt Relation

Lin+2024, ApJ

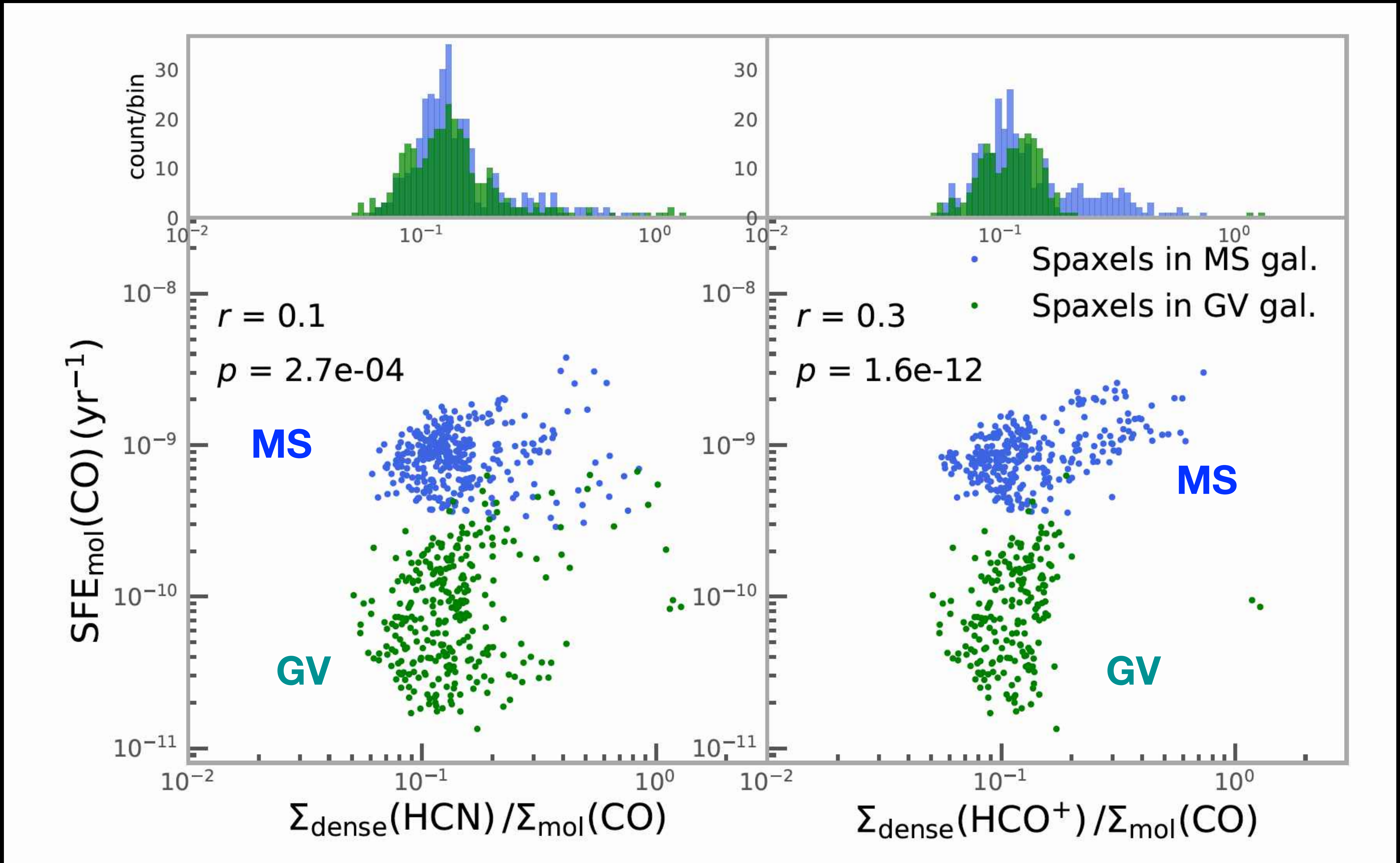


GVs do not follow the same Schmidt-Kennicutt relations of MS galaxies, i.e., GVs have lower SFE_{dense}.

Scenario I : Does SFE_{mol} (CO) depends on the dense gas fraction (M_{dense}/M_{mol}) ?

=> Not really

$SFE_{mol} = (M_{dense}/M_{mol}) * SFE_{dense}$

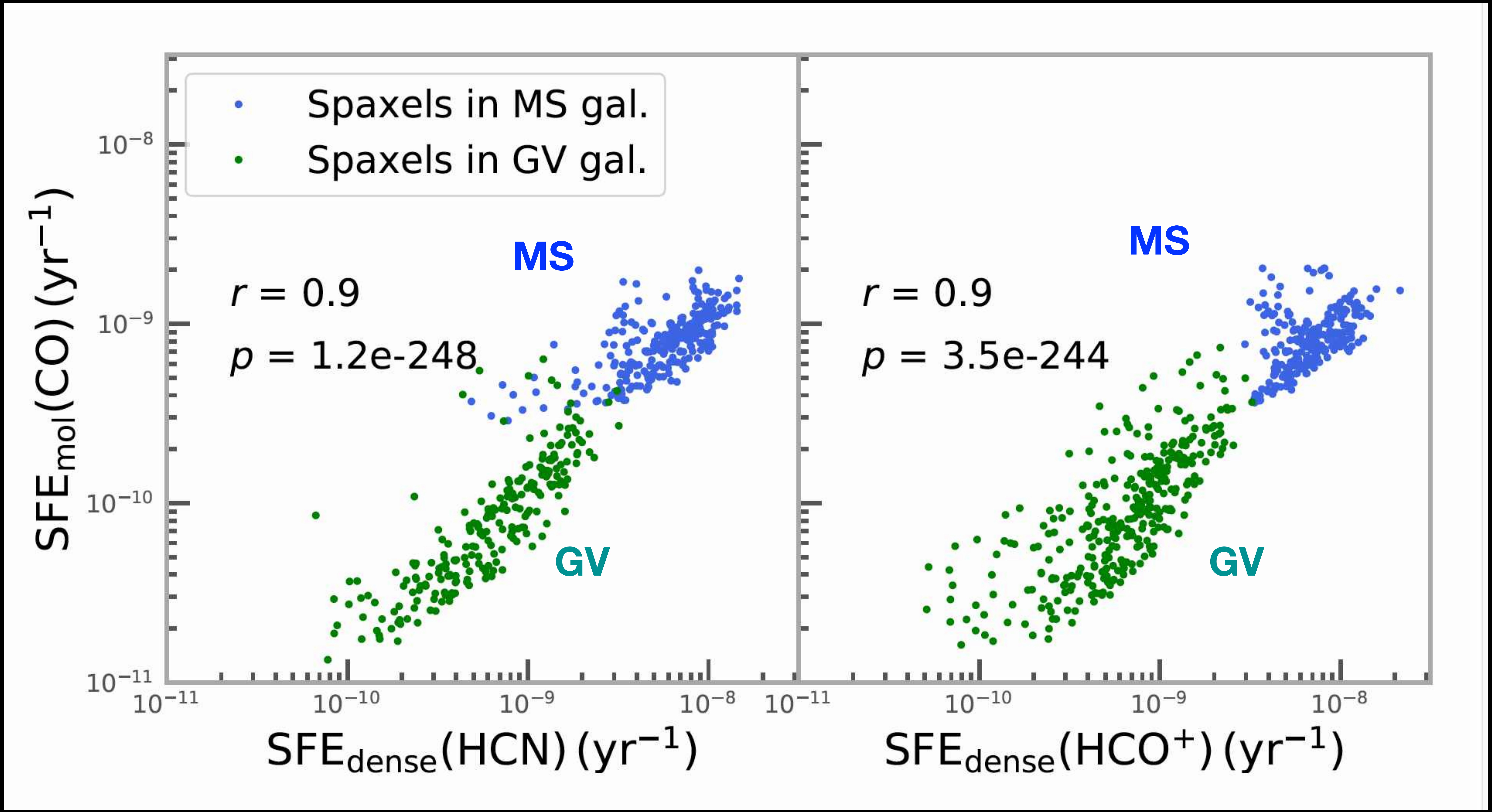


Lin+2024, ApJ

Scenario II: Does SFE_{mol} (CO) depend on SFE_{dense} (HCN or HCO+)?

=>Yes

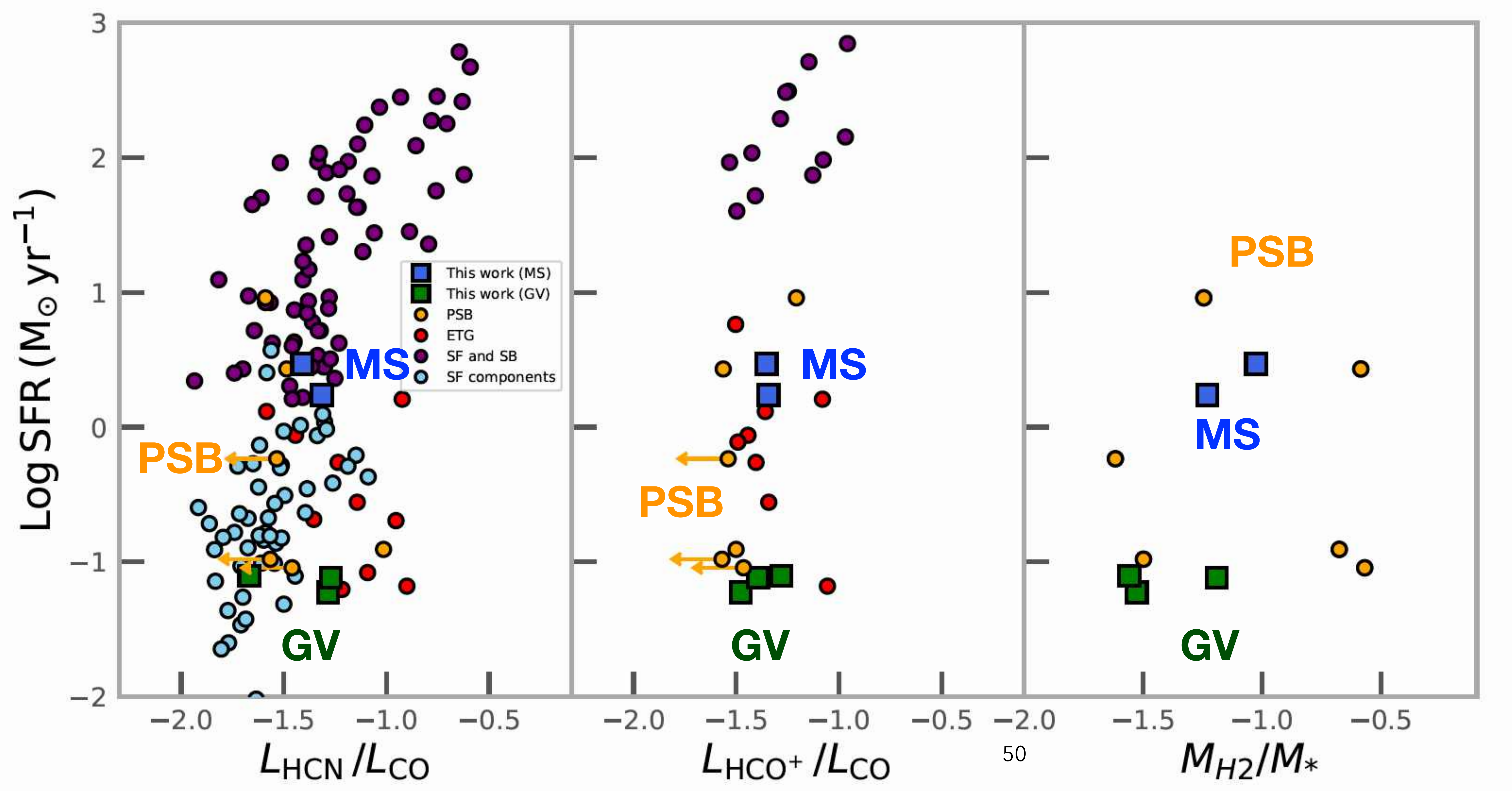
$SFE_{mol} = (M_{dense}/M_{mol}) * SFE_{dense}$



Lin+2024, ApJ

Green valley galaxies in a broader context

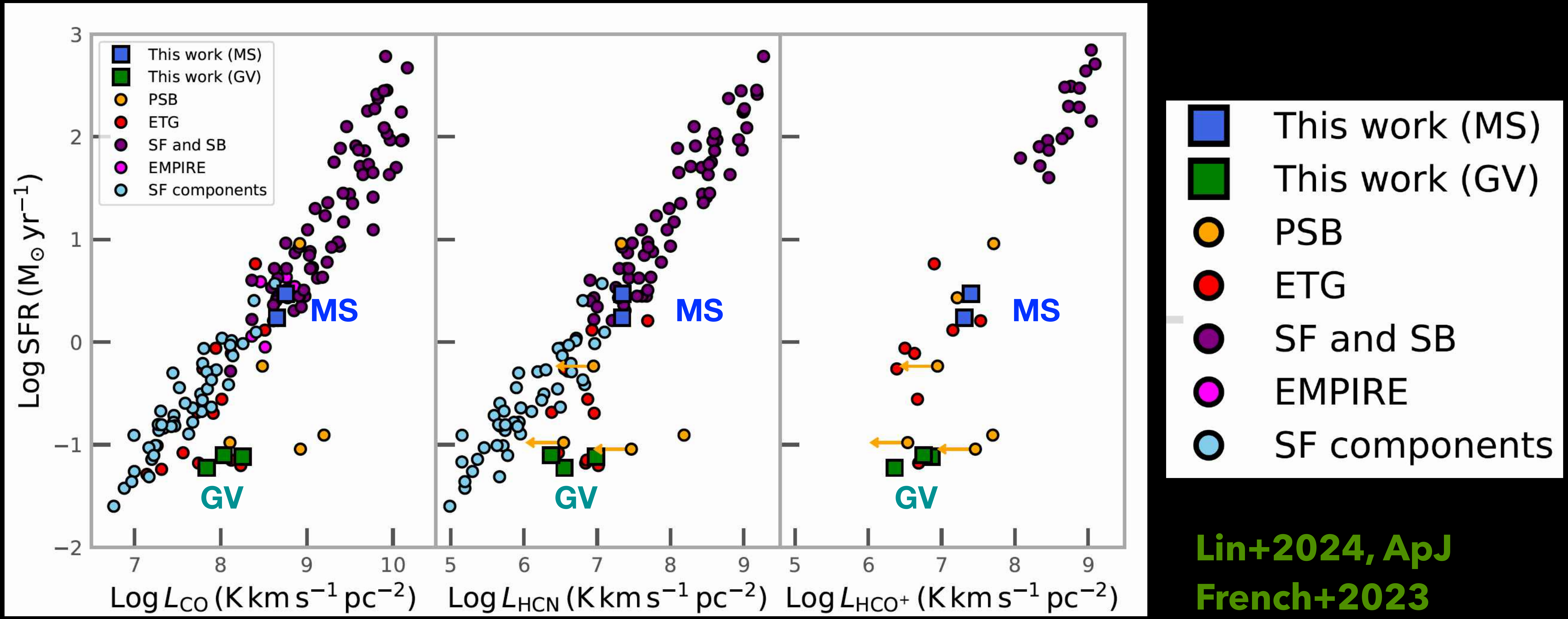
Global SFR vs. f_{dense}



This work (MS)
This work (GV)
PSB
ETG
SF and SB
EMPIRE
SF components

Lin+2024, ApJ
French+2023

Global Dense Gas Schmidt-Kennicutt Relation



Lin+2024, ApJ
French+2023

Summary

- Star-forming main sequence (SFMS)
  - The galaxy morphologies, kinematics, and gas contents vary across the star-forming main sequence
  - The amplitude of SFMS depends on redshift and environment
- The role of molecular gas
  - Green valley galaxies show reduced molecular gas fraction and star formation efficiency
  - Post-starburst galaxies have normal molecular gas fraction but reduced SFE (traced by CO)
  - The green valley galaxies and post-starburst galaxies show different behaviors in the dense gas fraction and dense gas star formation efficiency.
- The resolved star formation scaling relations
  - The resolved properties provide a powerful probe in understanding galaxy evolutions and star formation quenching.