# Star Formation Scaling Relations of Nearby Galaxies in the ALMaQUEST Survey

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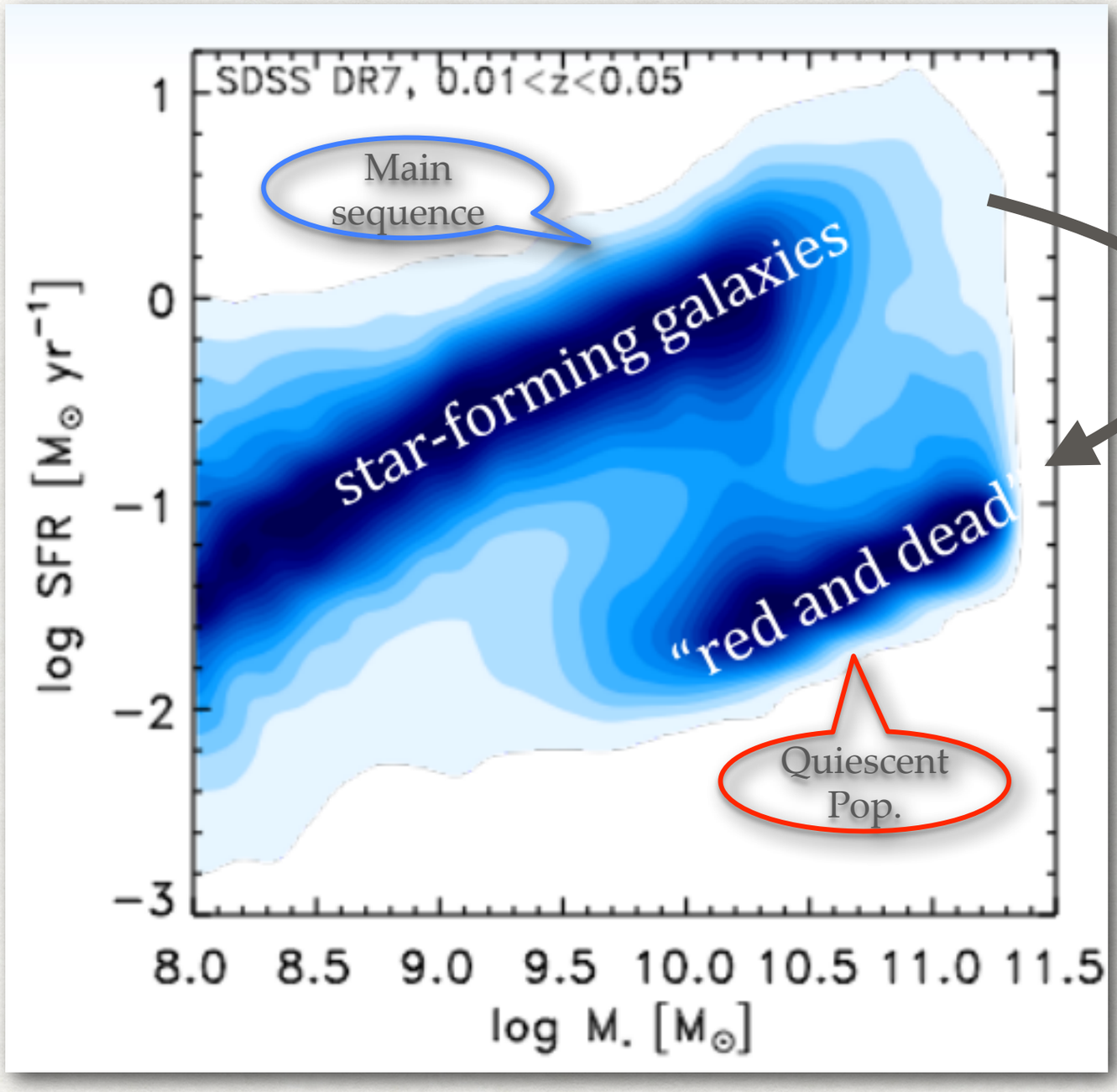
SDSS


- Part I: Background introduction
- Part II:  ALMaQUEST survey
- Part III: Results:
  - Scaling relations in the main-sequence (MS) galaxies
  - The scatters in the MS scaling relations
  - Scaling relations in the green valley (GV) galaxies
- Part IV: Summary

# Star Formation vs. Quenching

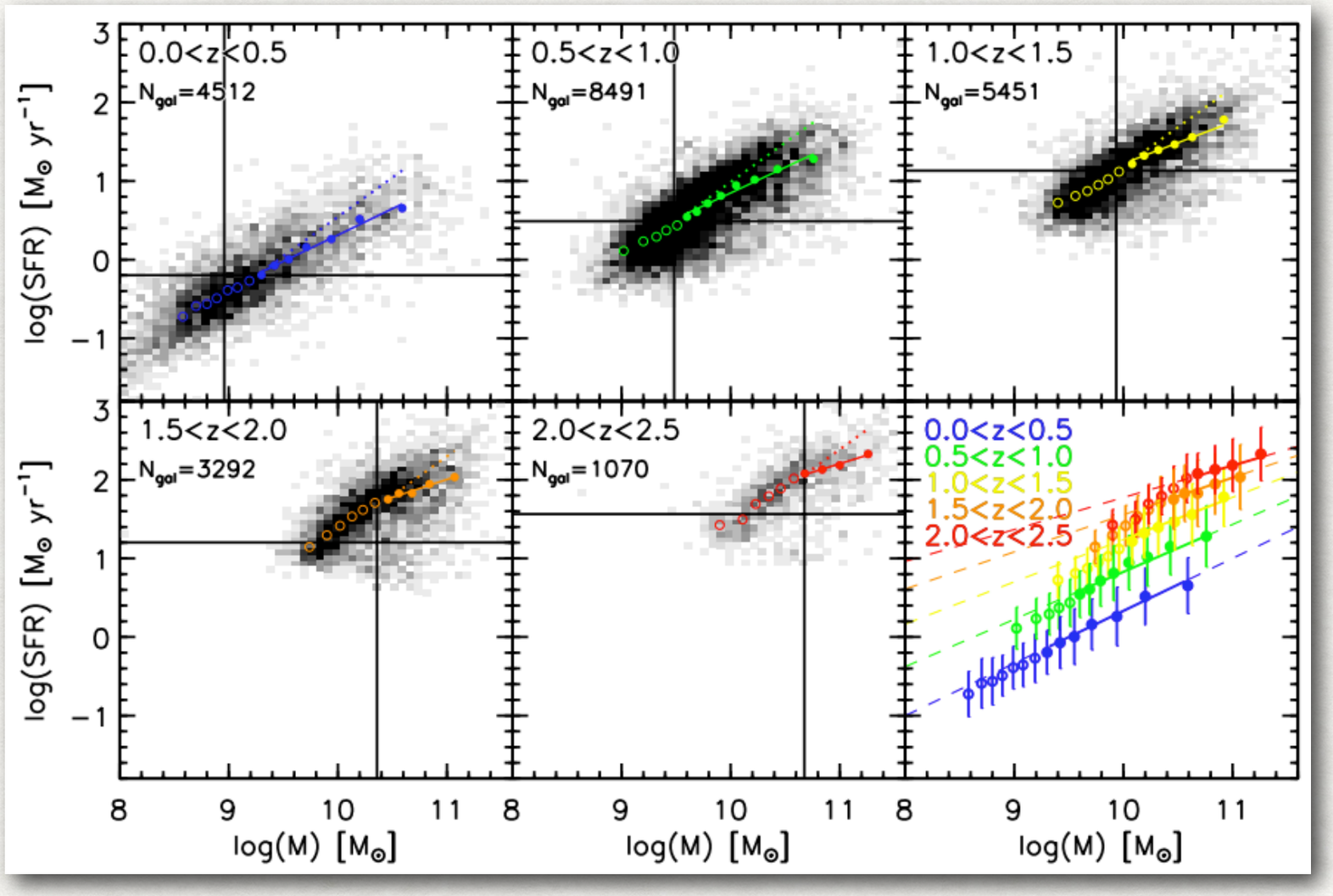



How does the star formation get quenched?

(figure credit: Amelie Saintonge)

# Relation I: Star-Forming Main Sequence (SFMS)

- A tight correlation between the total star formation rate and stellar mass for star-forming galaxies (e.g., Brinchmann+04; Noeske+07; Lin+12; Whitaker+12)

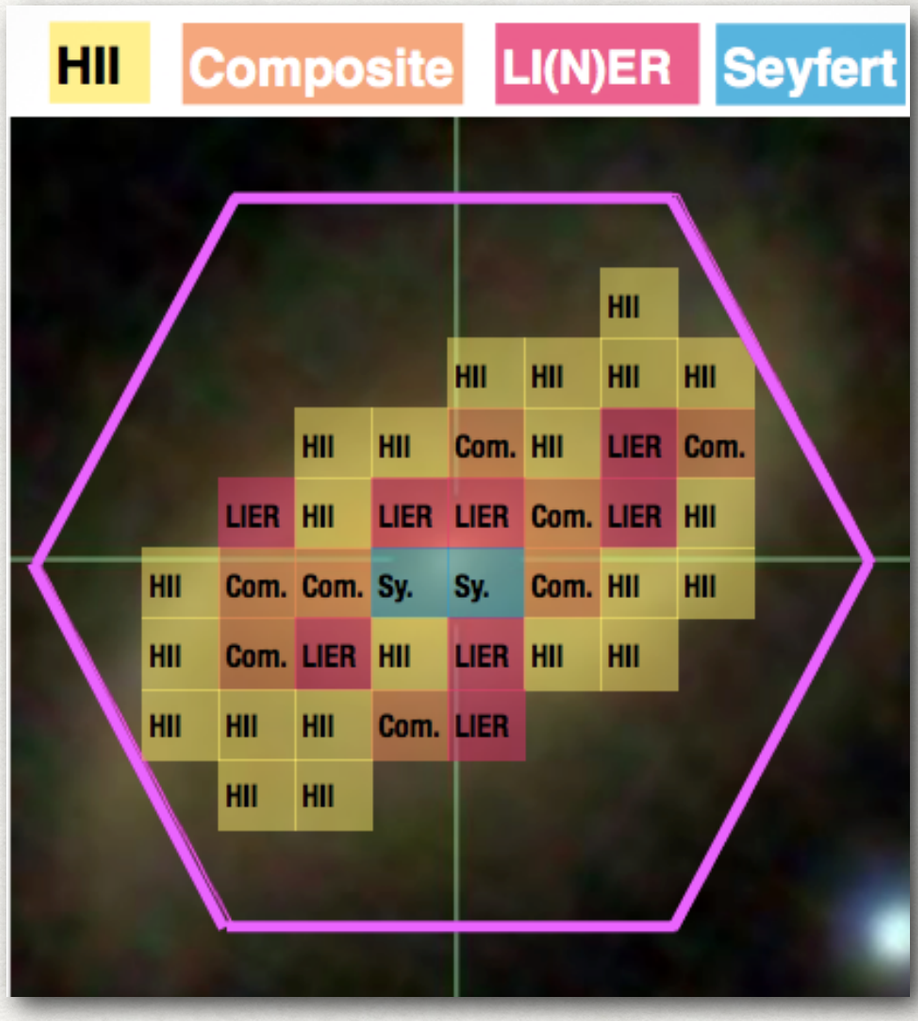



$$M_* = \int SFR\ dt$$

Whitaker+12

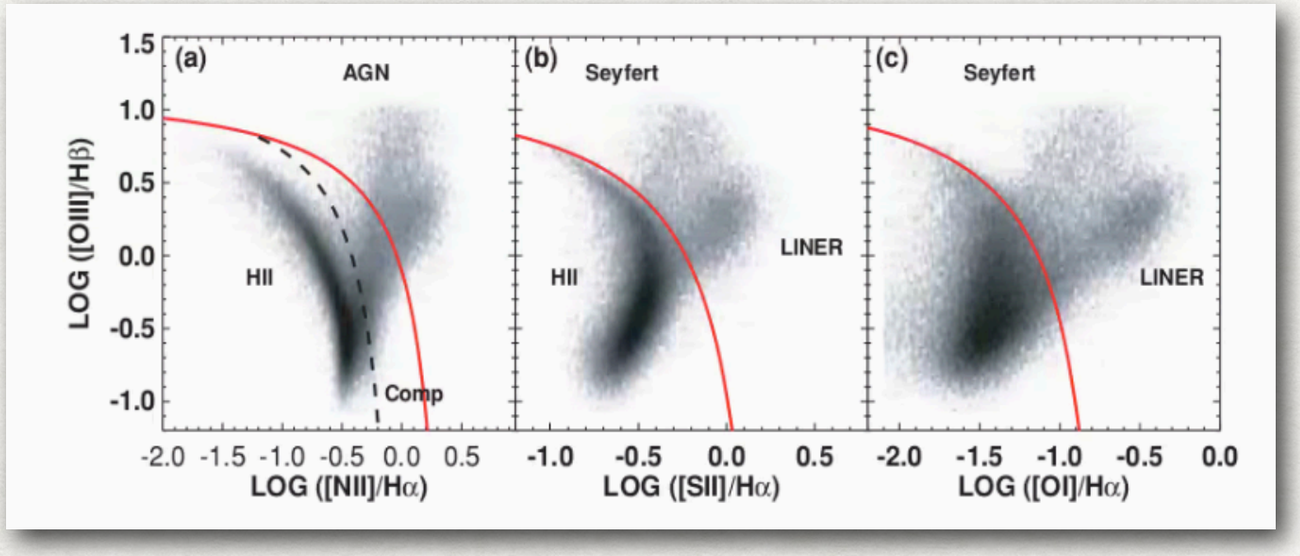
# From Global to Resolved Properties
## — "resolved main sequence" on kpc scales


- Fall 2014-Fall 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



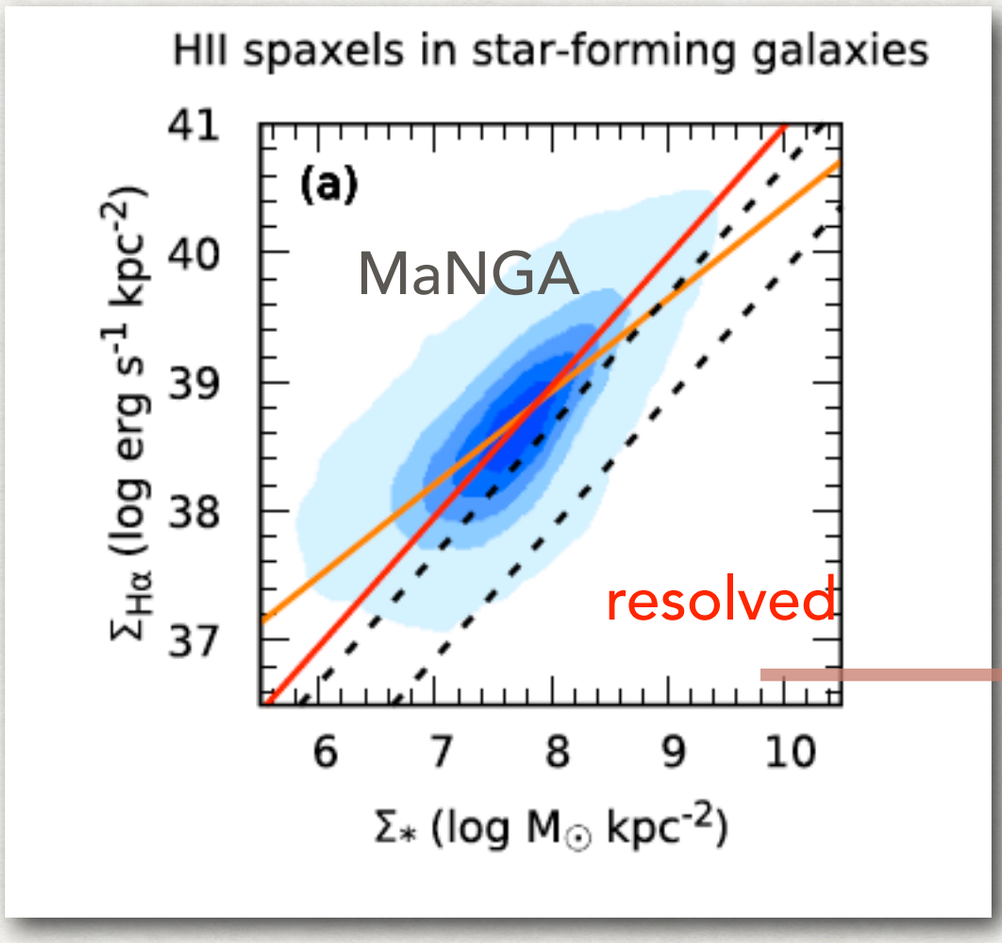

credit: H.-A Pan

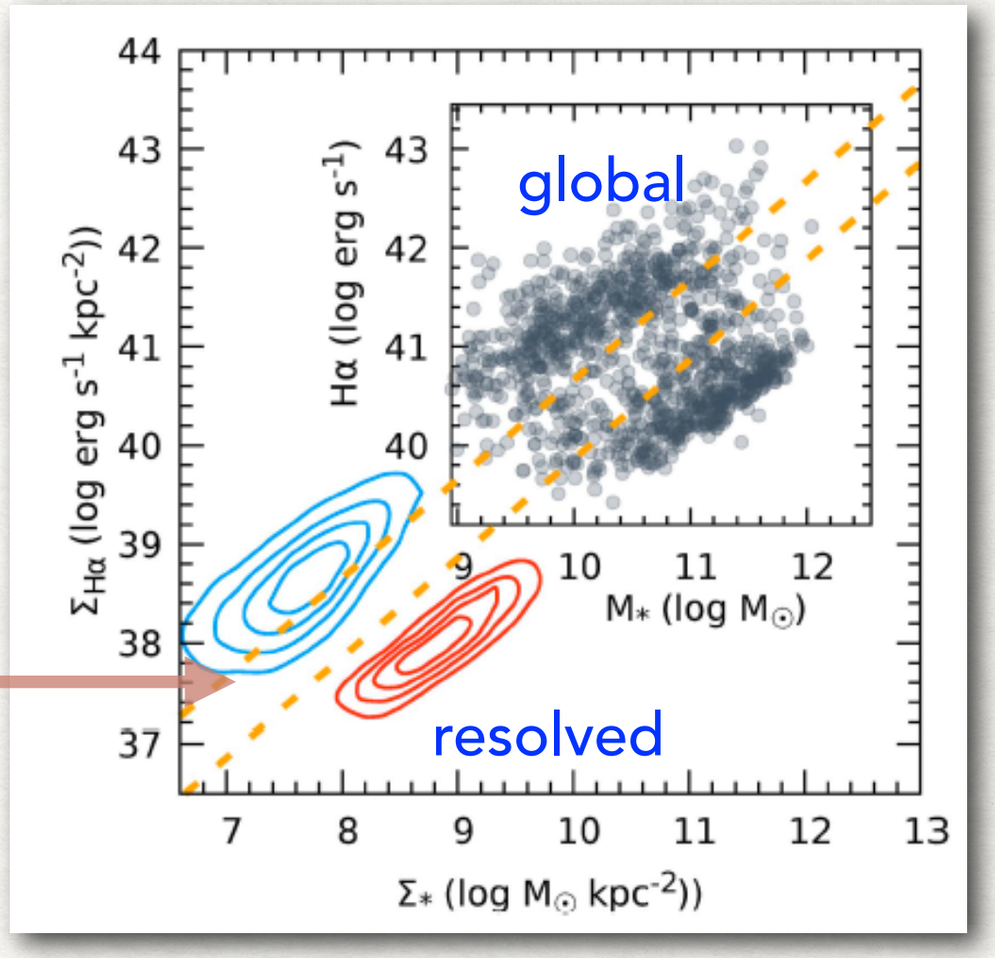
## BPT Diagram



# From Global to Resolved Properties
## — "resolved star-forming main sequence" (rSFMS) on kpc scales

Hsieh, Lin+2017

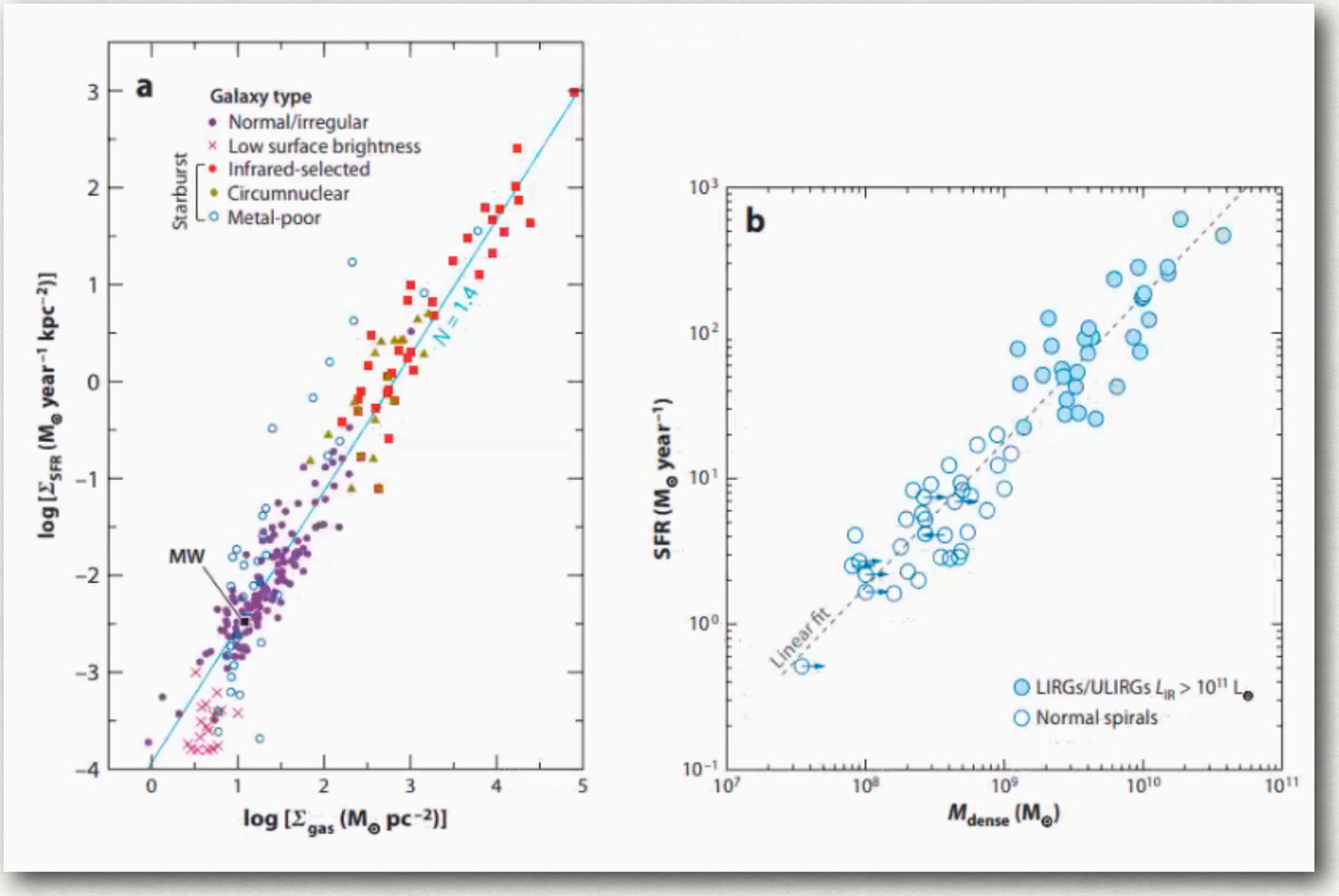



(Also see Cano-Diaz+16; Abdurrouf & Akiyama 17; Ellison+18; Pan+18; Medling+18; Cano-Diaz+19)

# Relation II: Schmidt-Kennicutt (SK) Relation

## -A tight relation between star formation rate and gas (surface density)

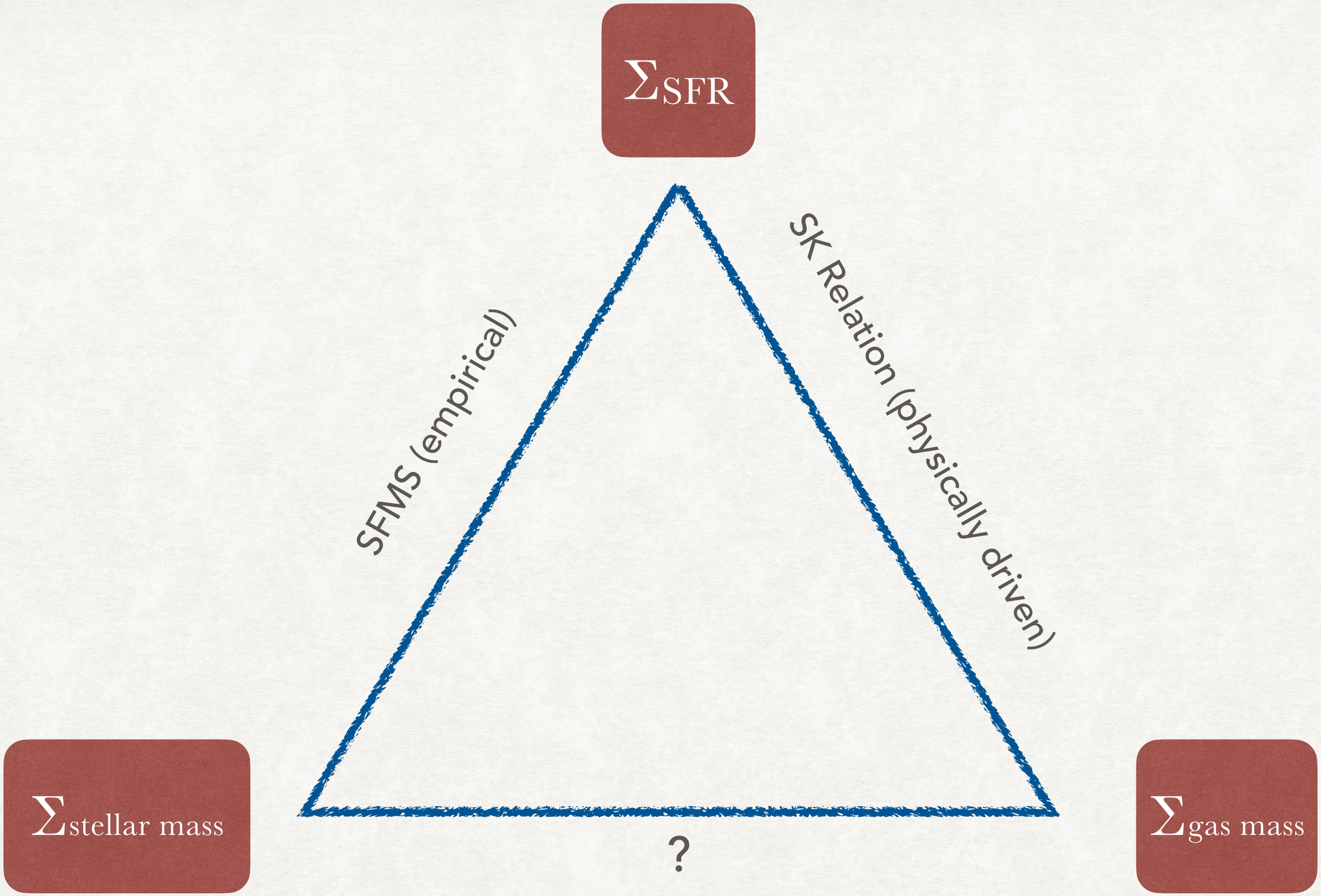



Kennicutt & Evans 12

Gao&Solomon 04

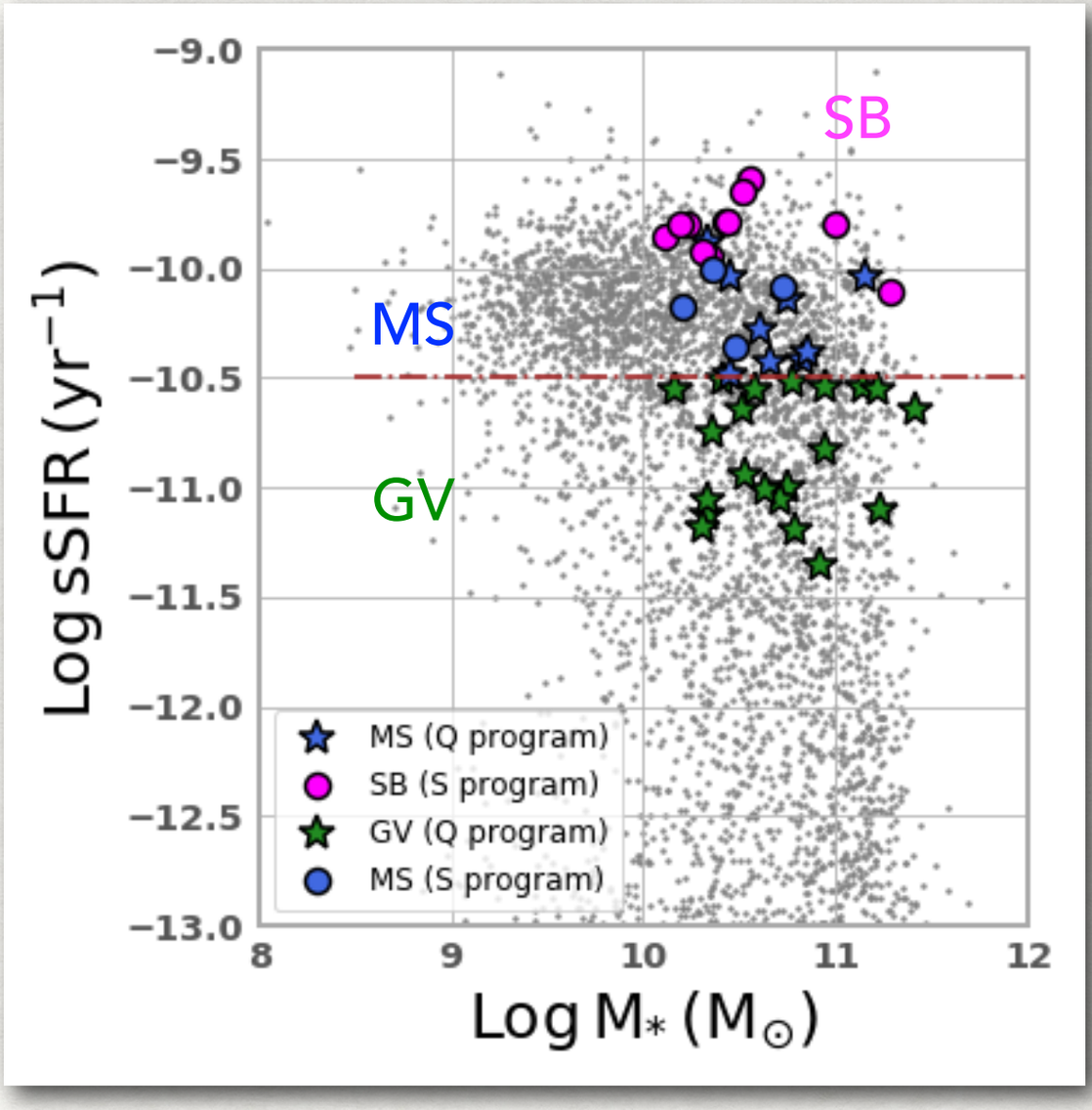
The SK relation has been explored over a wide range in physical scales: from sub-kpc, kpc, to galactic scales

(e.g. Wong & Blitz 2002; Bigiel et al. 2008; Schruba et al. 2011; Leroy et al. 2013)


$\Sigma_{SFR}$
SFMS (empirical)
SK Relation (physically driven)
?
$\Sigma_{stellar\ mass}$
$\Sigma_{gas\ mass}$

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

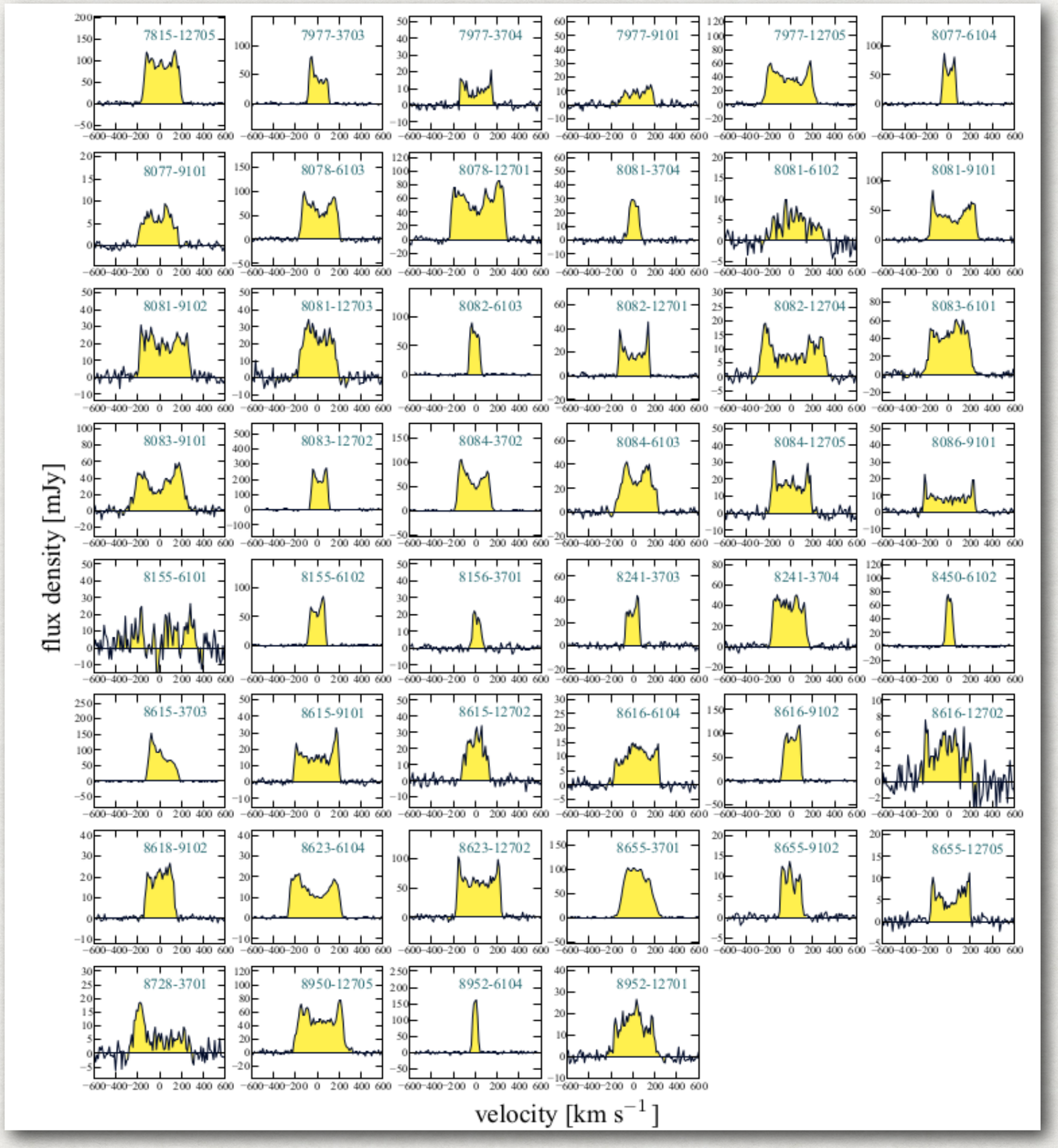
- ALMA CO(1-0) followups for 46 MaNGA selected sample
- z ~ 0.03; 10<log($M_*/M_\odot$)<11.5
- ALMA Resolution:
  - ~2.5" (spatial)
  - 11 km/s (spectral)
- Target classes:
  - 14 Main-sequence galaxies
  - 20 Green valley galaxies
  - 12 Central starburst galaxies




*Lin et al. 2020*

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

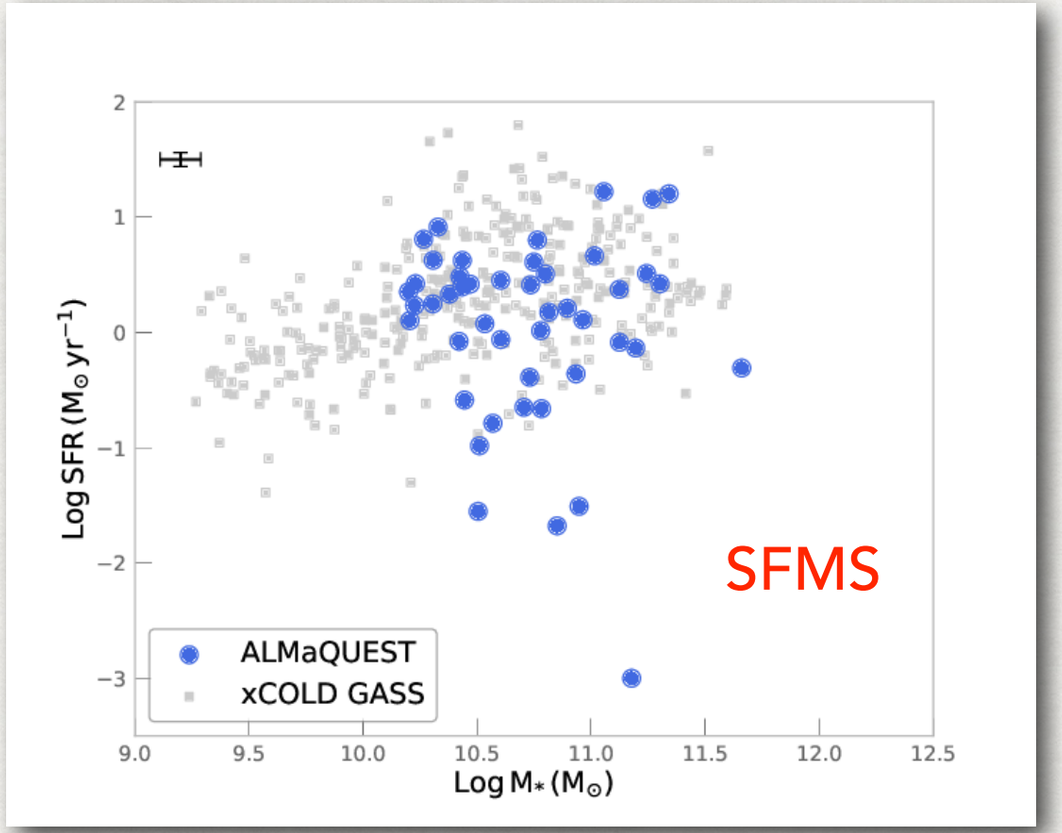
# INTEGRATED CO(1-0) SPECTRA

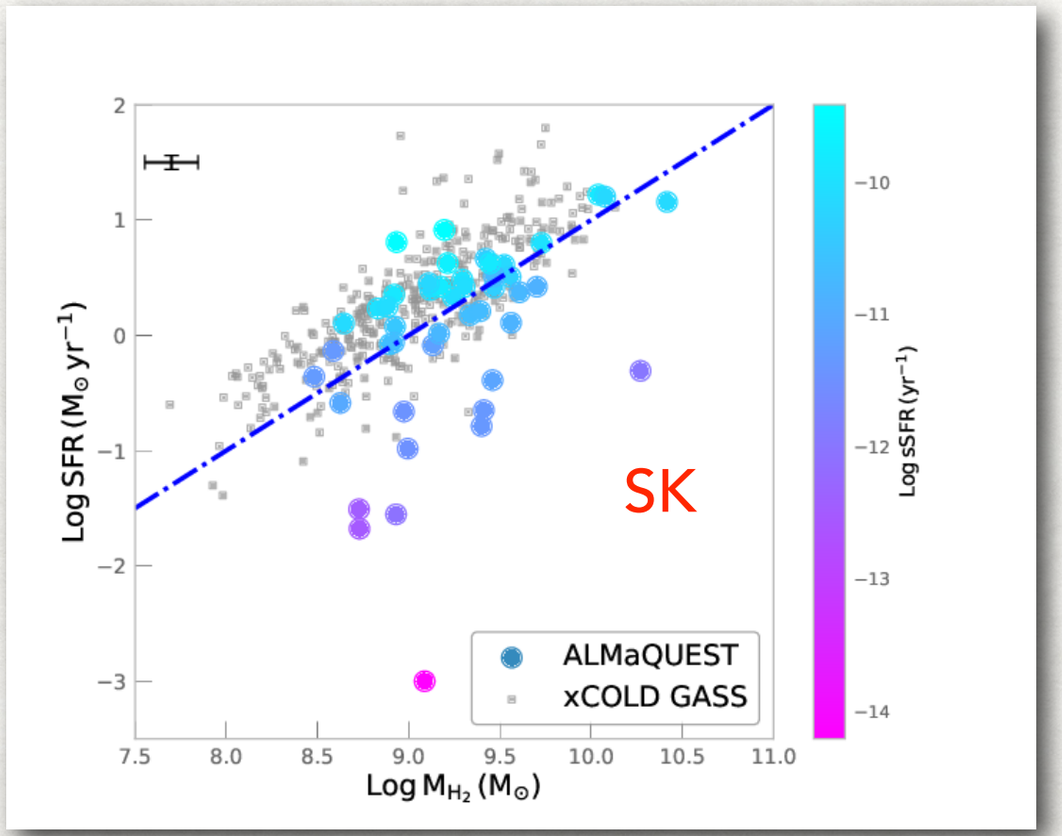


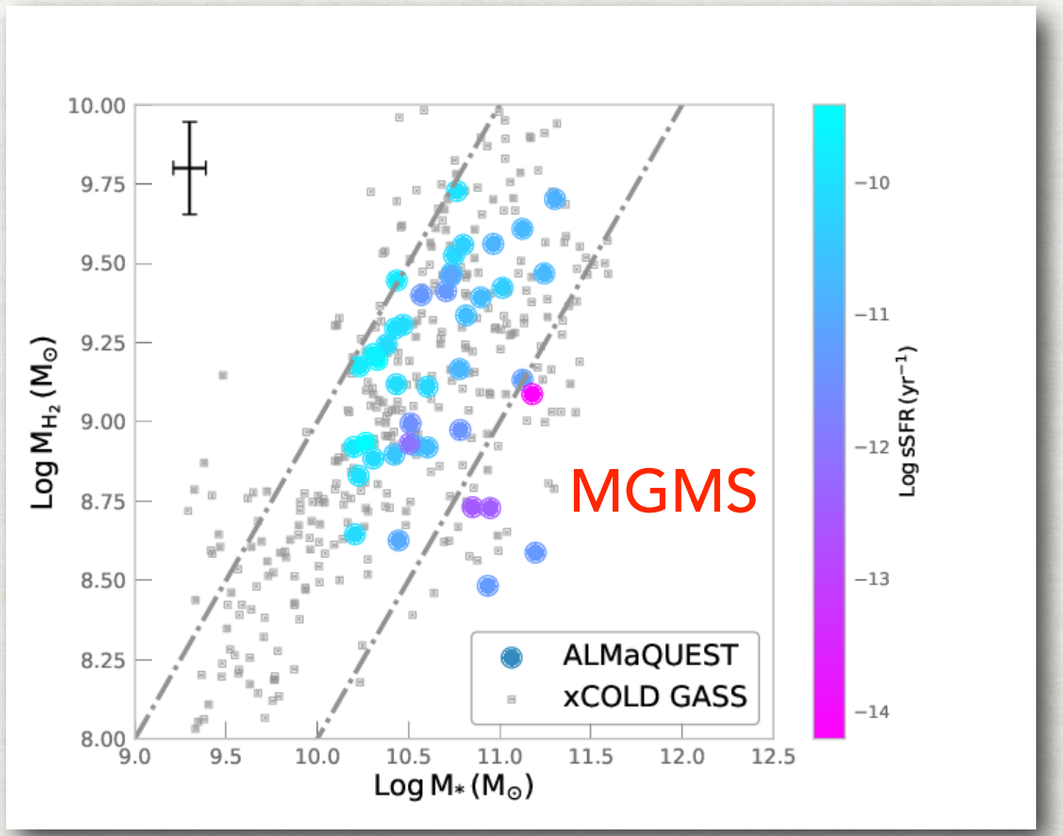

*Lin et al. 2020*

# Global Properties of ALMaQUEST galaxies

*Lin et al. 2020*



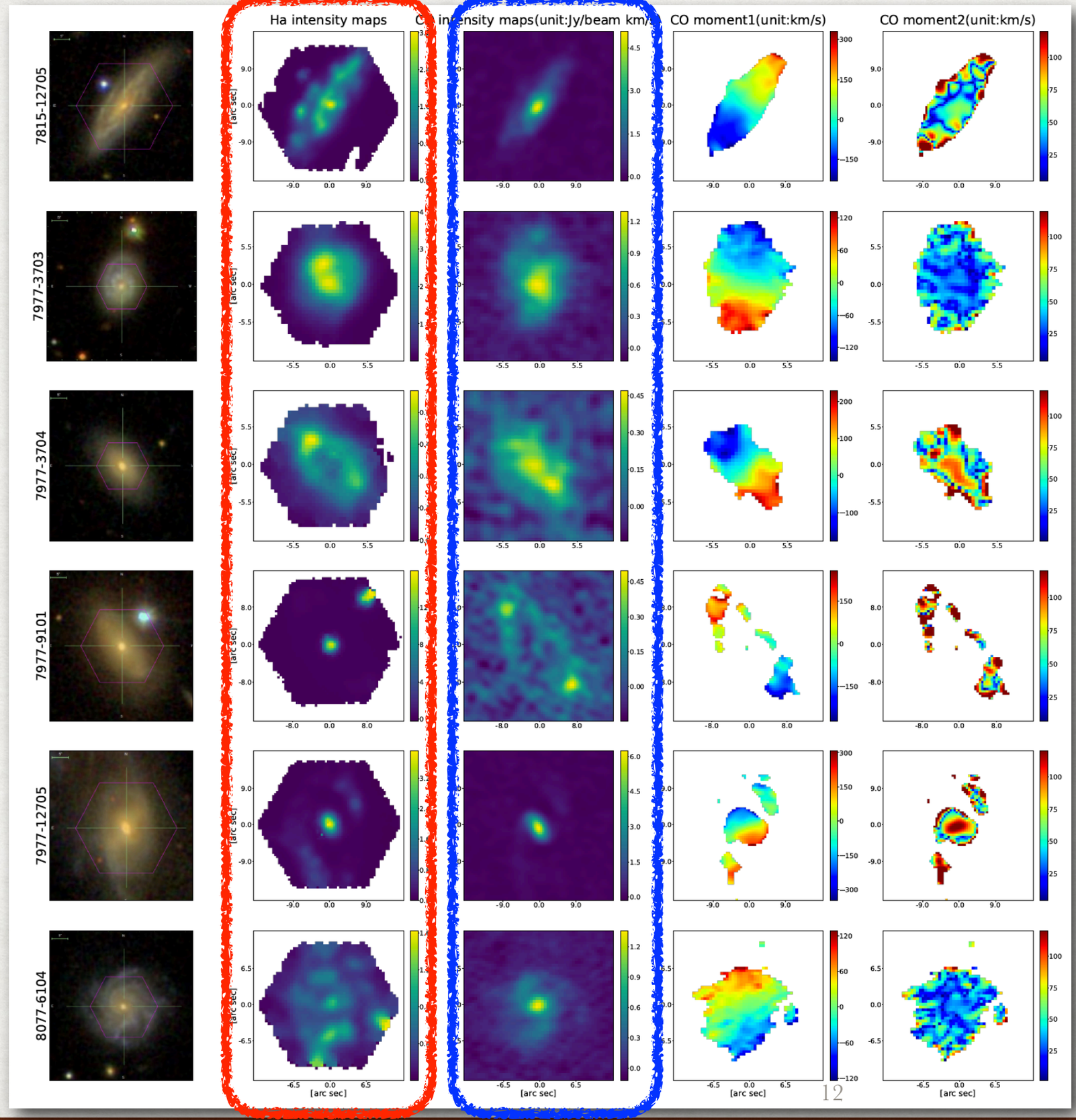



Hα intensity

CO intensity

CO velocity

CO velocity dispersion

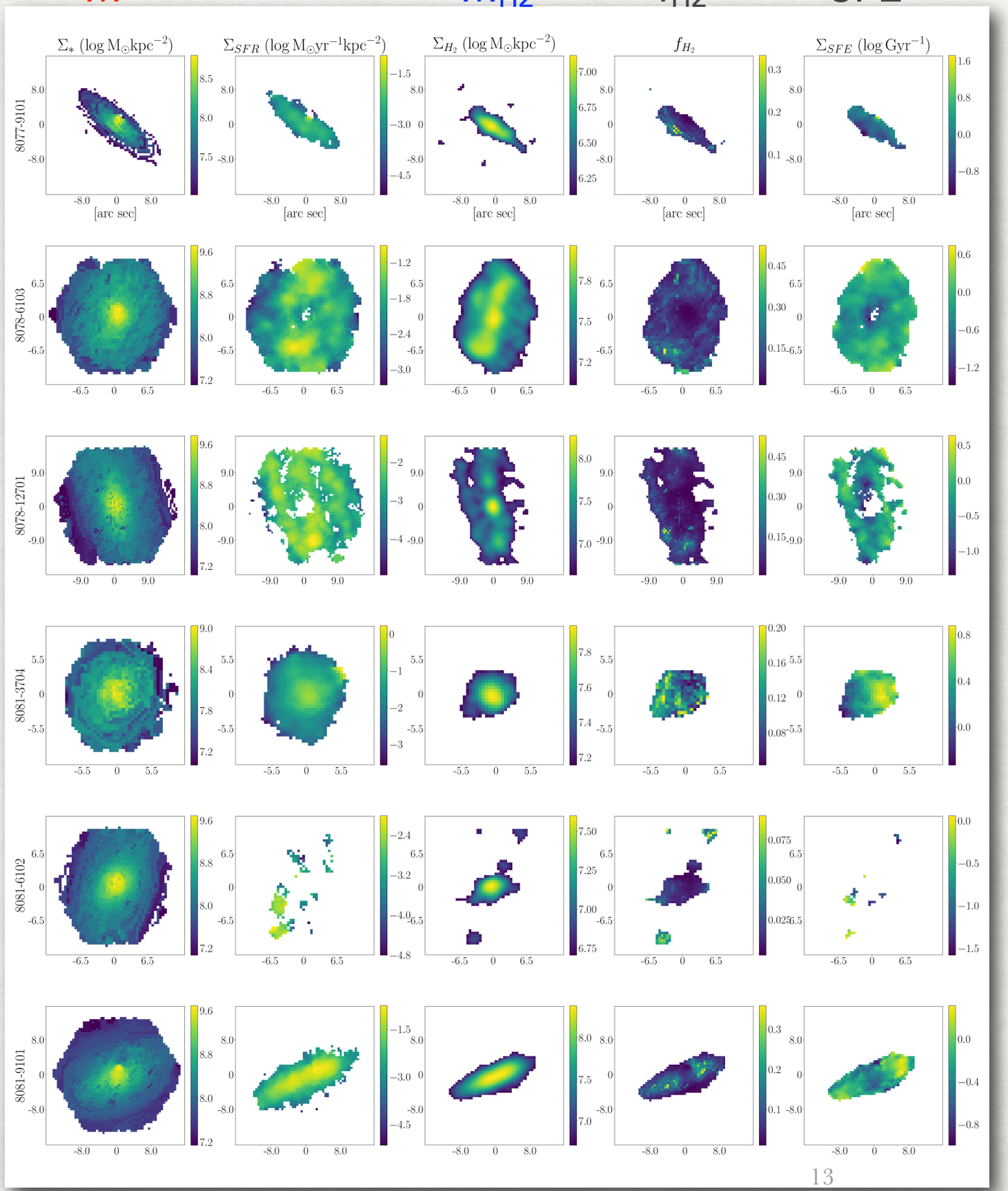



*ALMaQUEST*
*(Lin+2020)*

A diversity in the contrast between Hα and CO emissions

The SFR does not always trace the molecular gas mass

M* SFR $M_{H2}$ $f_{H2}$ SFE

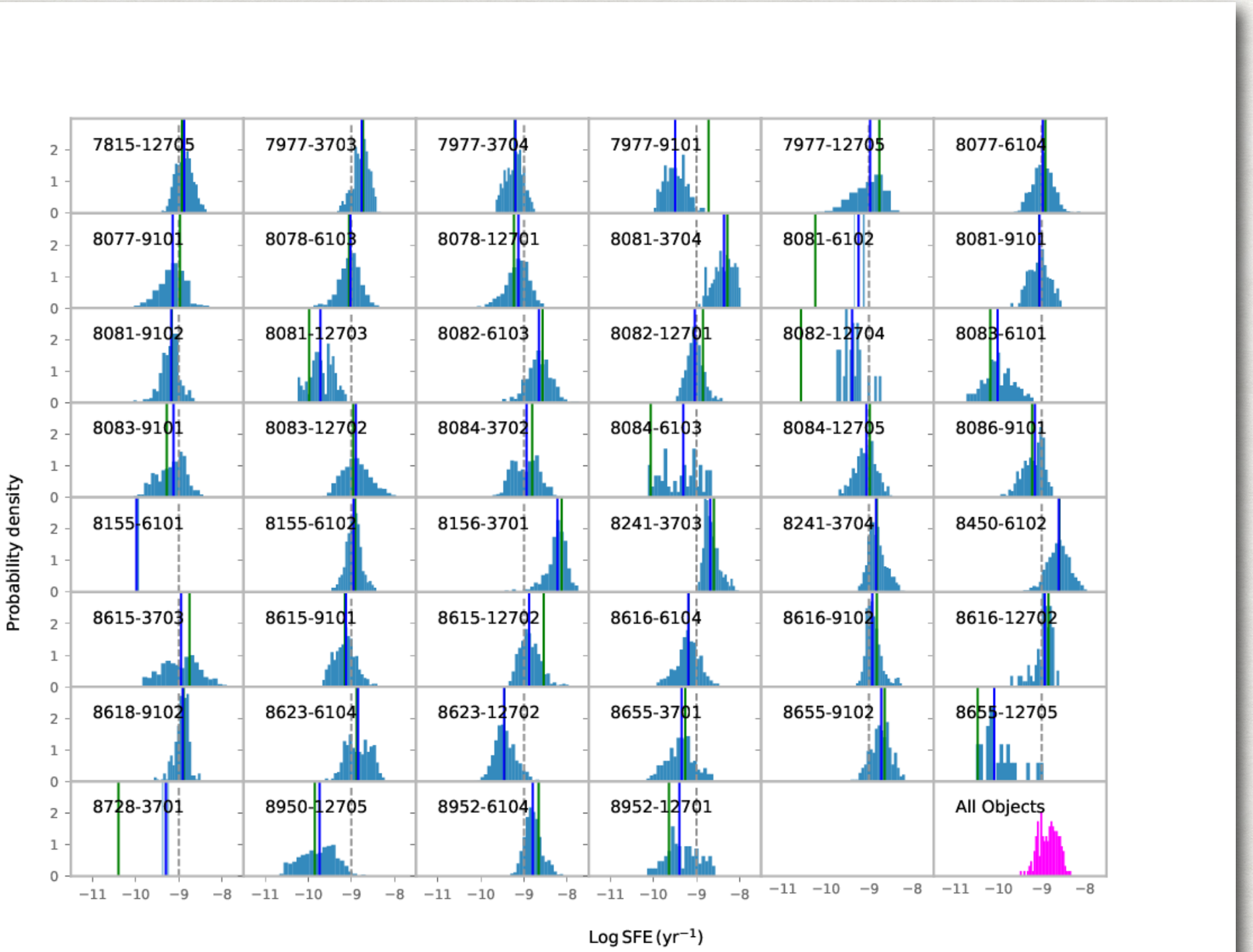



- Star-formation efficiency: SFE = SFR/M*
- Gas fraction: $f_{H2} = M_{H2}/M_*$

- spatial variation of the star formation efficiency (SFE)
- Likewise, there is variation in the molecular gas fraction ($f_{H2}$), too.

# Spaxel-by-spaxel SFE Distributions

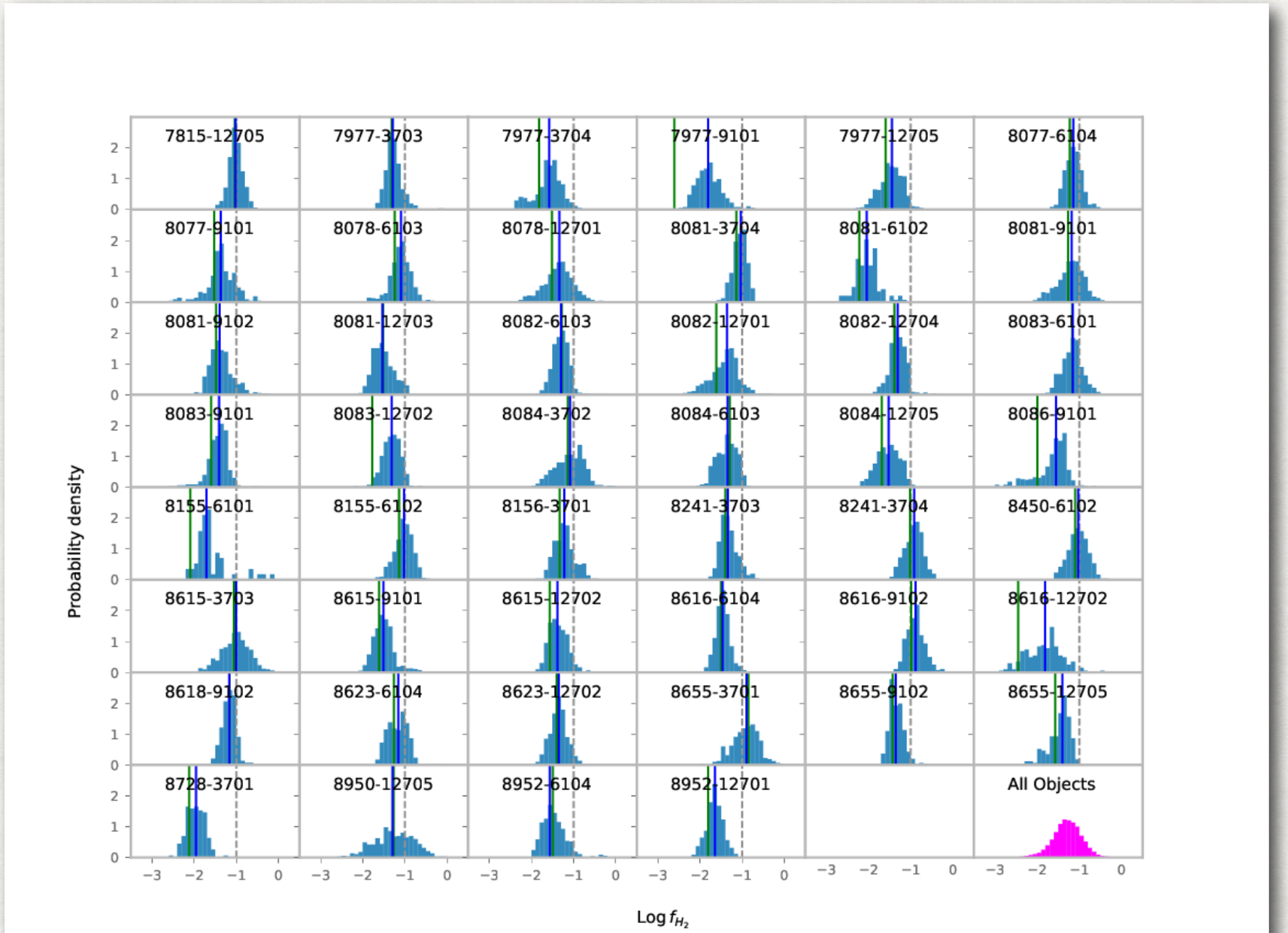
-A wide spread (over 1 dex) in SFE within a given galaxy




Lin et al. 20; Ellison et al., submitted

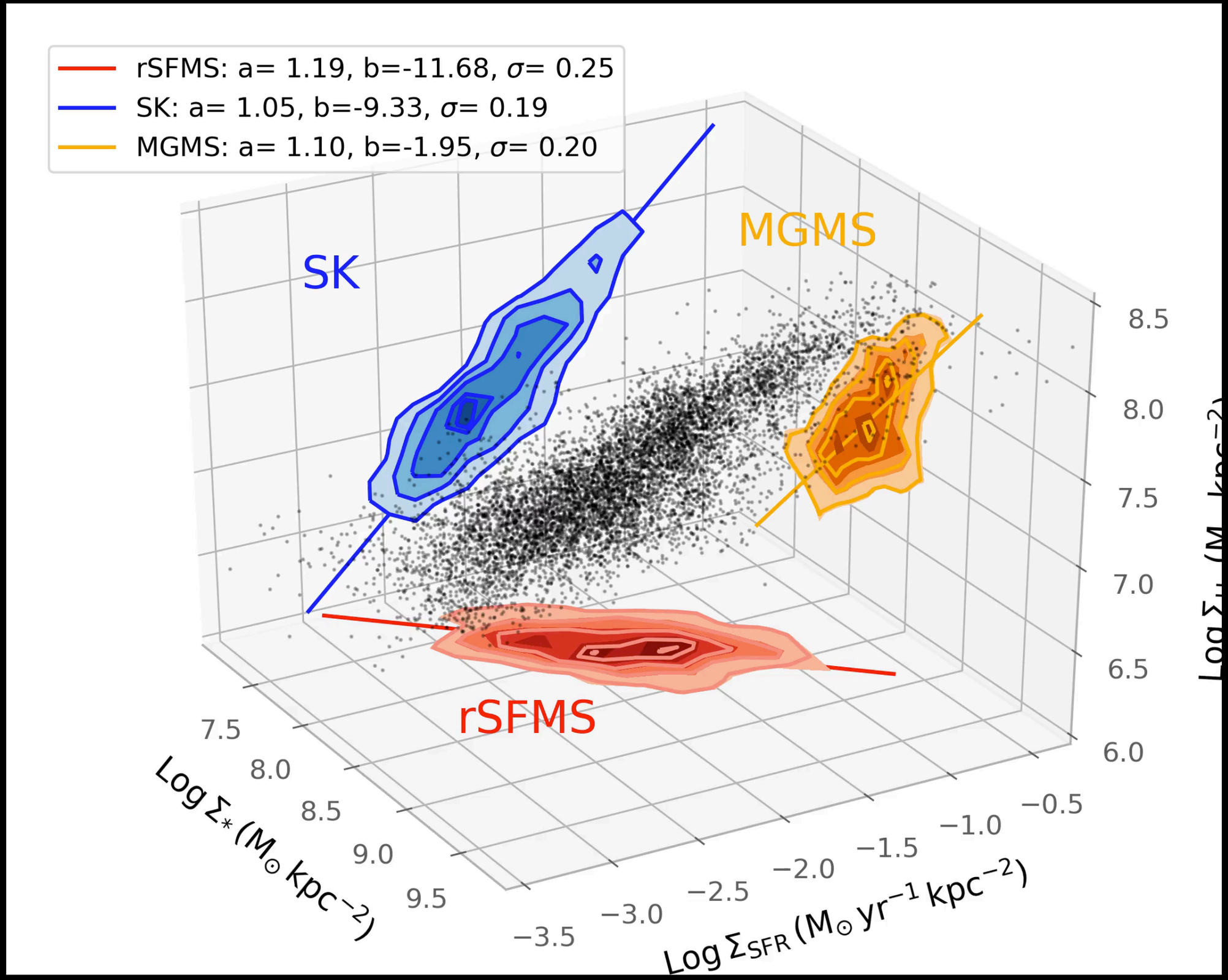
# Spaxel-by-spaxel $f_{H2}$ Distributions

-a wide spread (over 1 dex) in $f_{H2}$ within a given galaxy

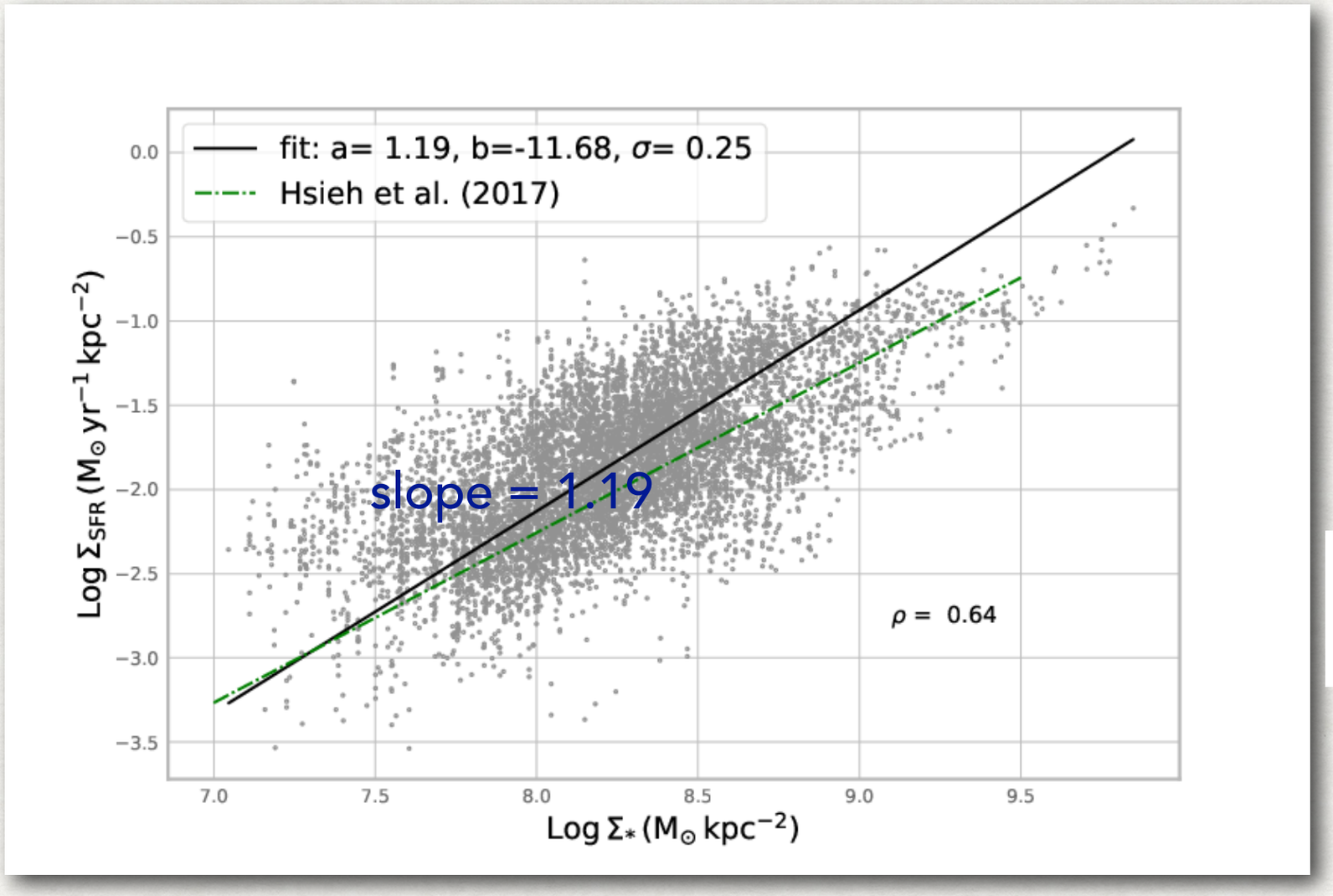



Lin et al. 20; Ellison et al., submitted

- Part 3.1: scaling relations in MS galaxies


rSFMS: a= 1.19, b=-11.68, σ= 0.25
SK: a= 1.05, b=-9.33, σ= 0.19
MGMS: a= 1.10, b=-1.95, σ= 0.20
SK
MGMS
rSFMS
7.5
8.0
8.5
9.0
9.5
Log Σ* (M⊙ kpc−2)
−3.5
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
Log ΣSFR (M⊙ yr−1 kpc−2)
6.0
6.5
7.0
7.5
8.0
8.5
Log Σ... (M⊙ kpc−2)

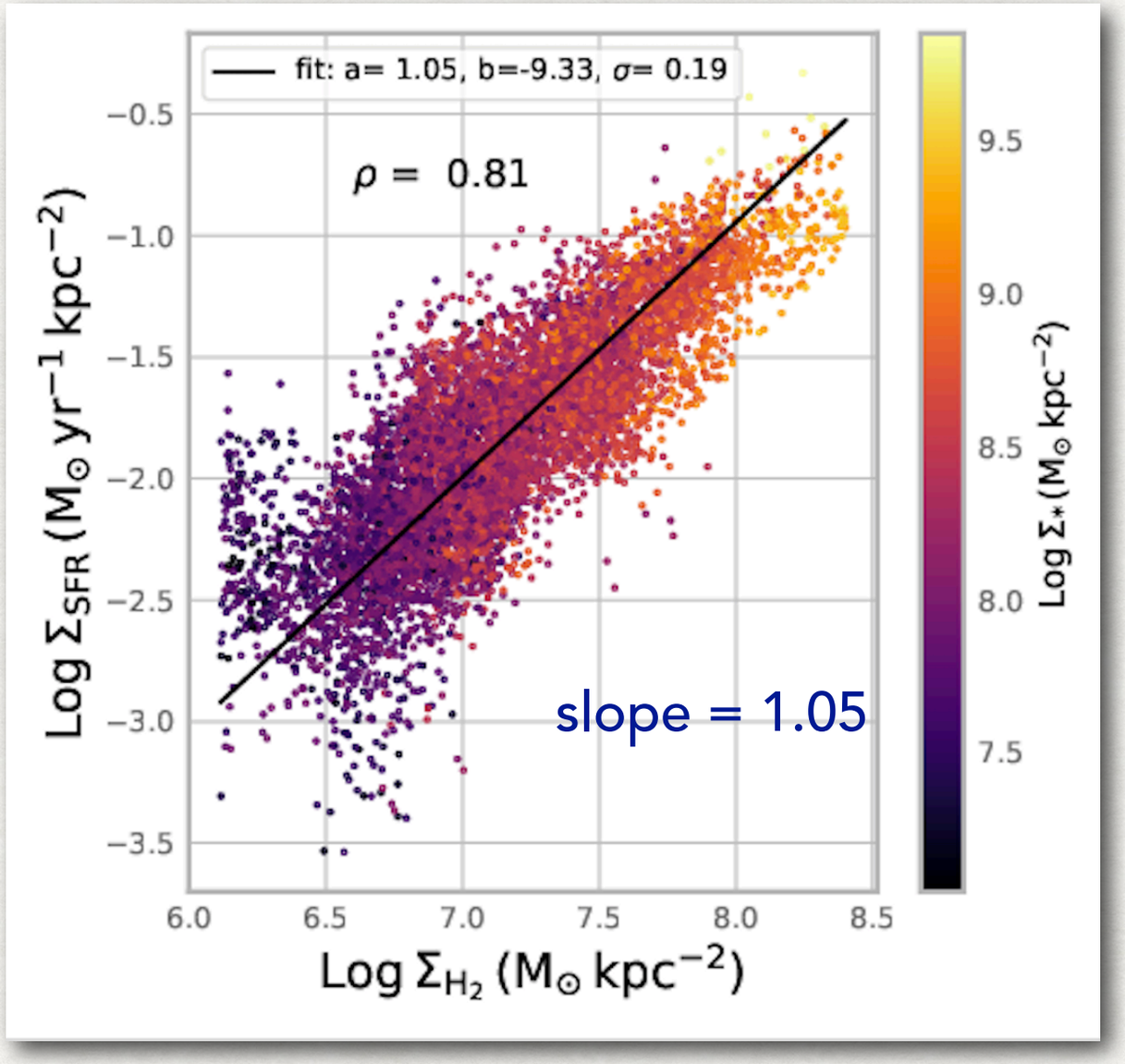
# I. Resolved Star-Forming Main Sequence (rSFMS)




Lin+19b
Ellison+, submitted

- The best fit using the HII spaxel of 14 MS galaxies is in good agreement with the full MaNGA SF sample.

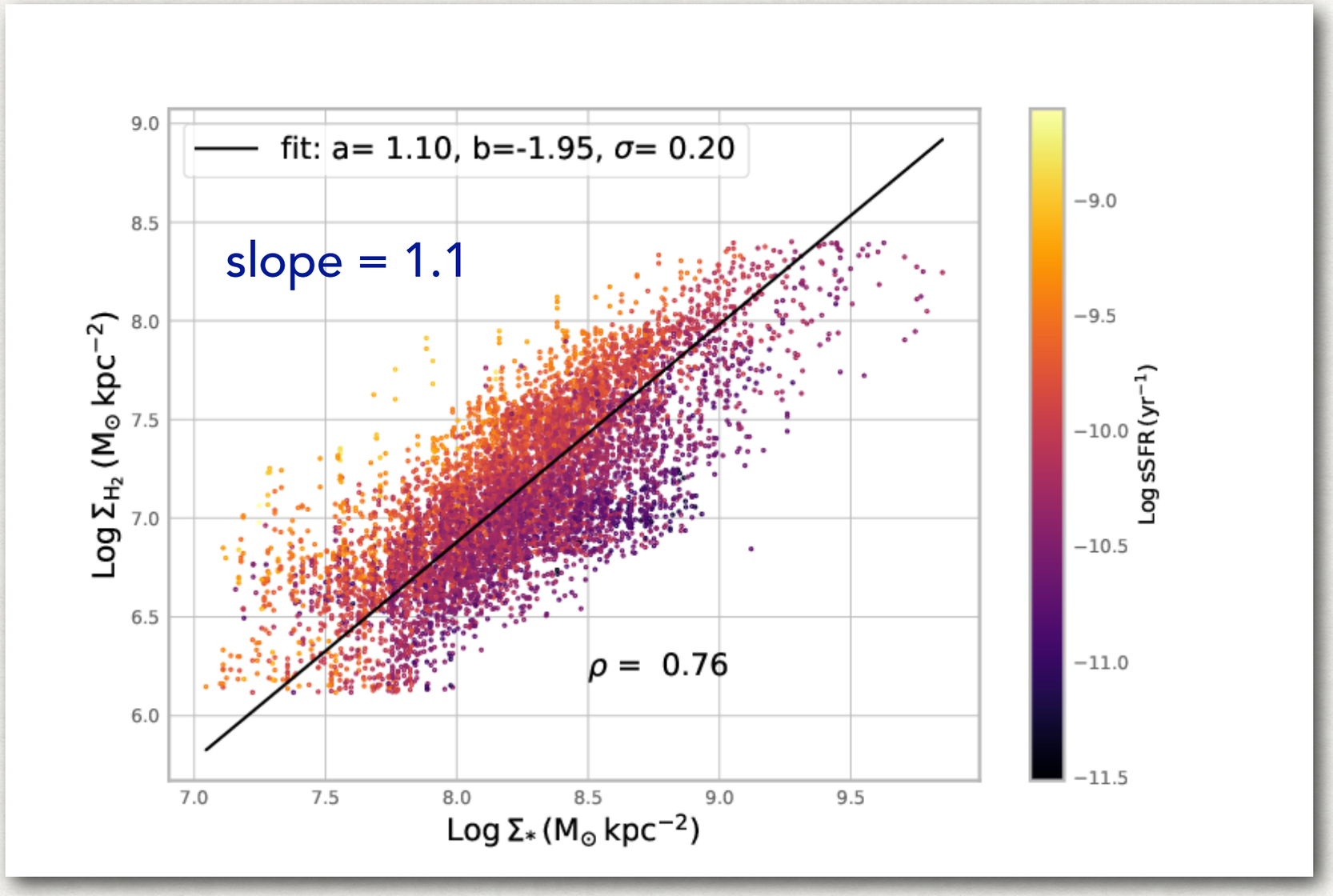
# II. Schmidt-Kennicutt (SK) Relation




Lin+19b
Ellison+, submitted

- A linear slope is found in the resolved SK relation

# III. Molecular Gas Main Sequence (MGMS)




Lin+19b
Ellison+, submitted

- The surface density of the molecular gas mass traces the stellar mass surface density with slope ~ 1.

# Which One is More Fundamental?

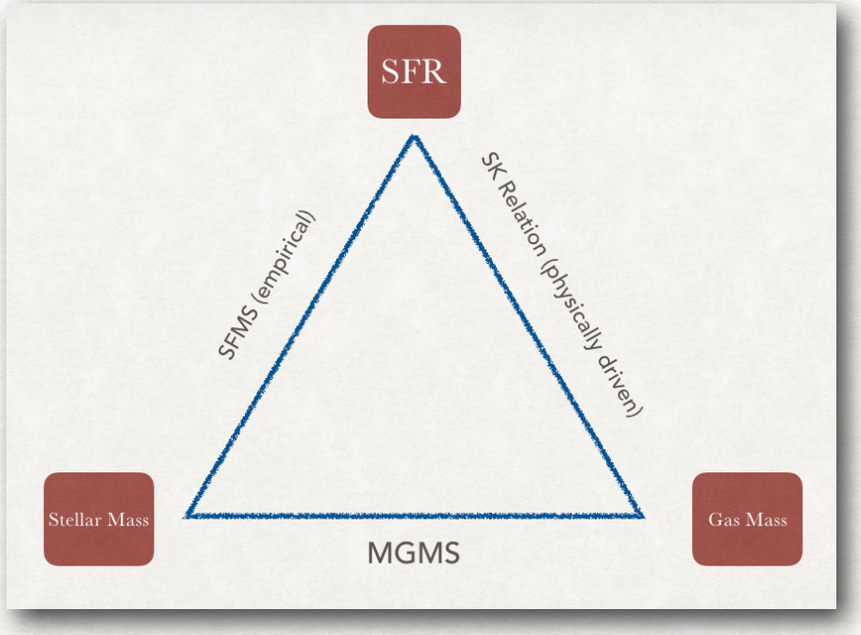
$$\Sigma_{SFR} \propto \Sigma_{H_2}{}^{a}$$ (SK)

$$\Sigma_{H_2} \propto \Sigma_{*}{}^{b}$$ (MGMS)

$$\Sigma_{SFR} \propto \Sigma_{*}{}^{a*b} = \Sigma_{*}{}^{c}$$ (rSFMS)

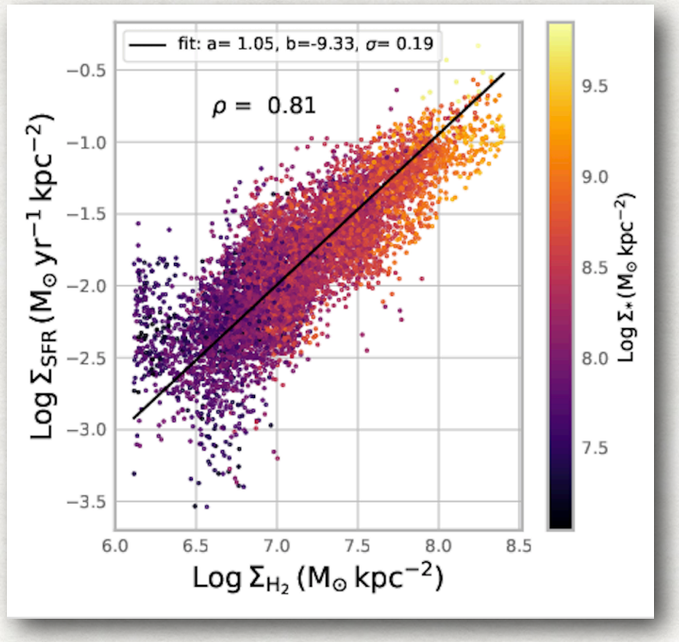
a = 1.05, b = 1.1 => c = 1.16

c (measured) = 1.19




- Scatter: rSFMS > MGMS > SK
- Pearson's correlation:

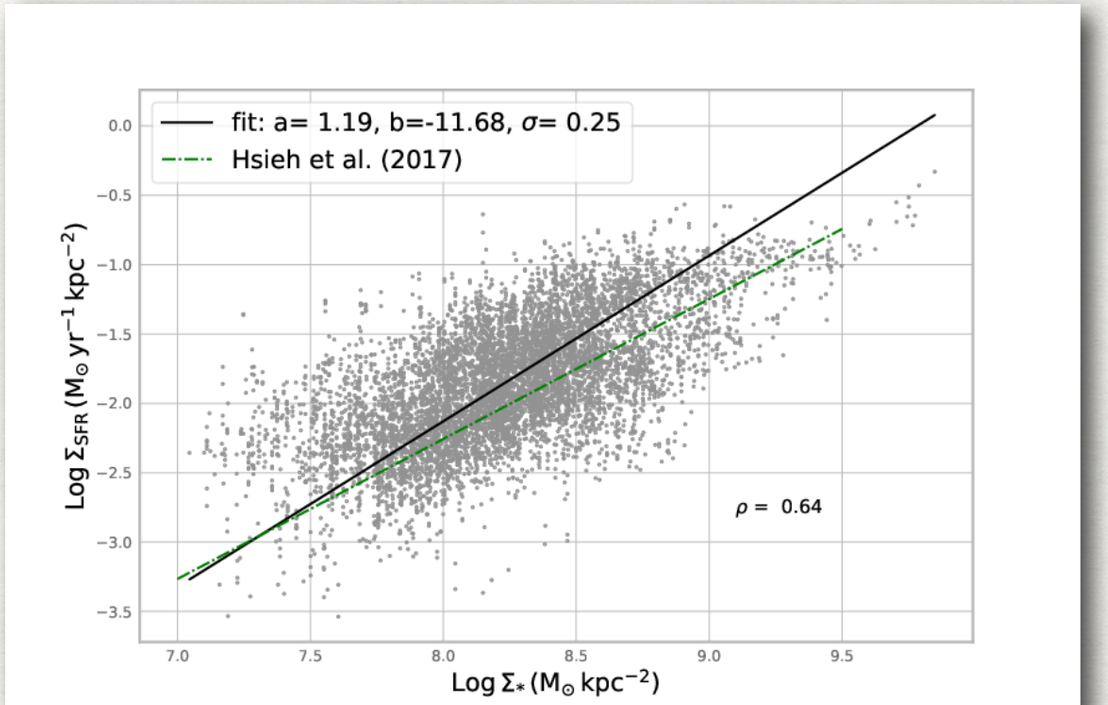
  rSFMS < MGMS < SK
- rSFMS is the least fundamental and a natural consequence of the combination of SK and MGMS relations

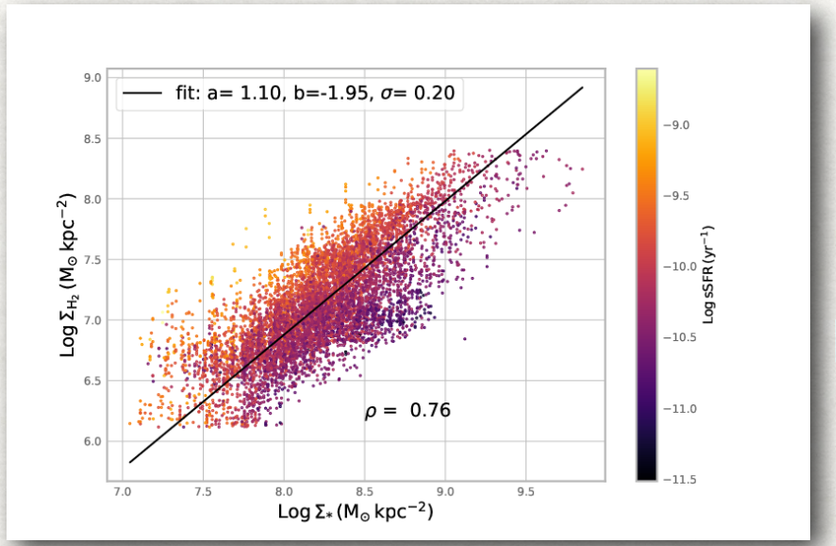



SK relation

=

rSFMS



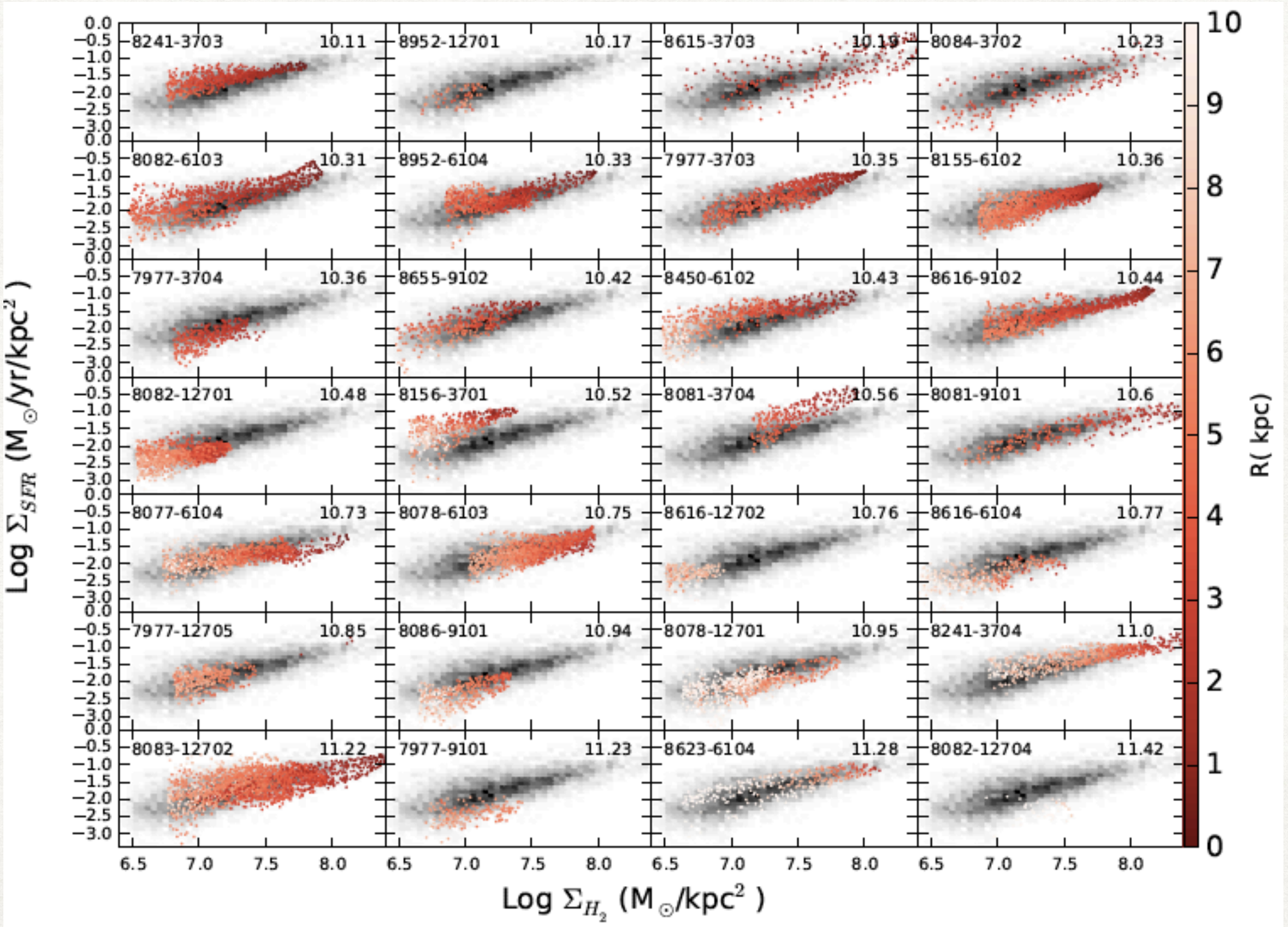




MGMS

# Part 3.2: What Controls the Scatters in These Scaling Relations?

# Galaxy-by-galaxy (kpc) scaling relations

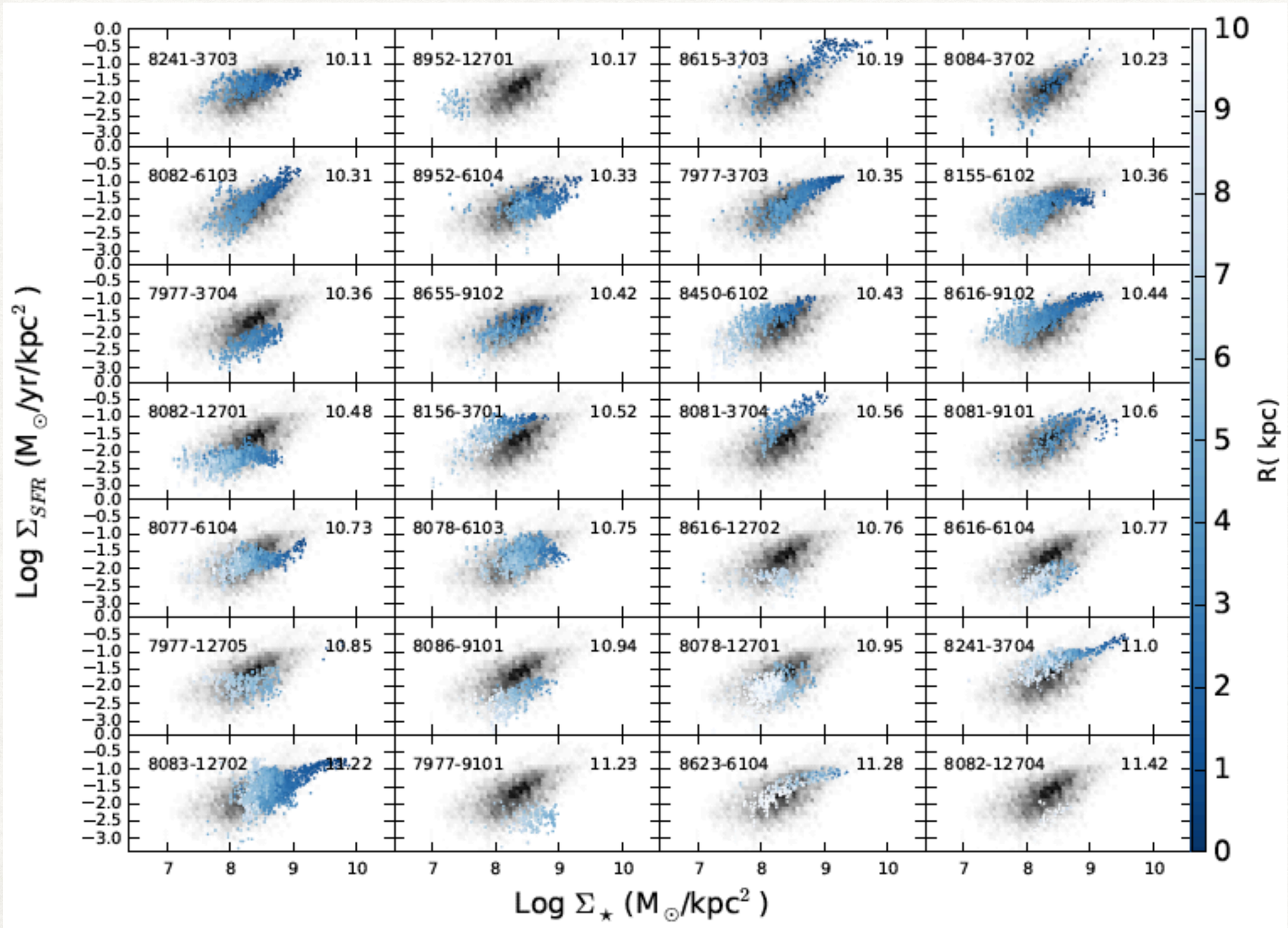
## The resolved Schmidt-Kennicutt relation (rSK)




Ellison et al. (submitted)

# Galaxy-by-galaxy (kpc) scaling relations

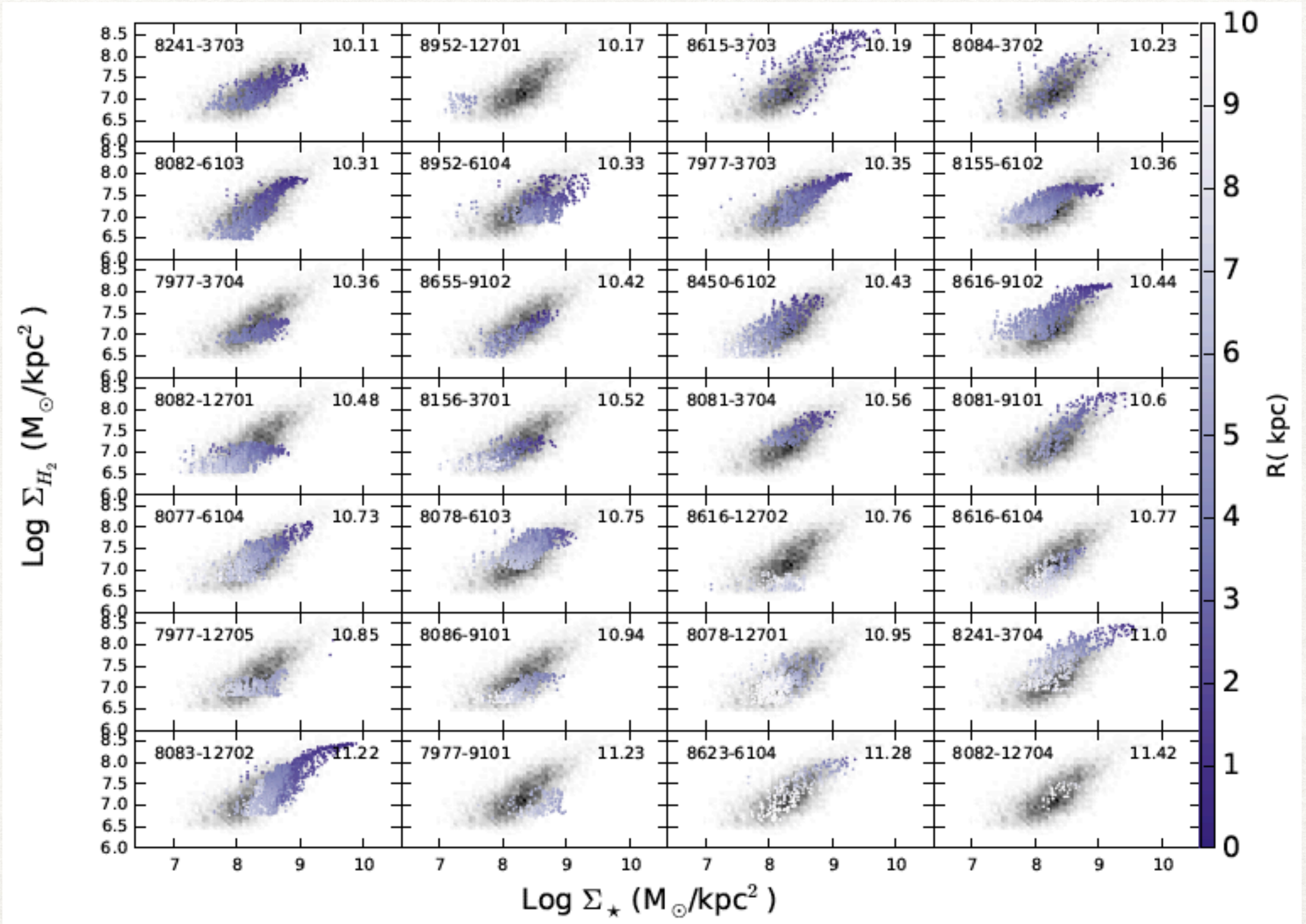
## The resolved star forming main sequence (rSFMS)



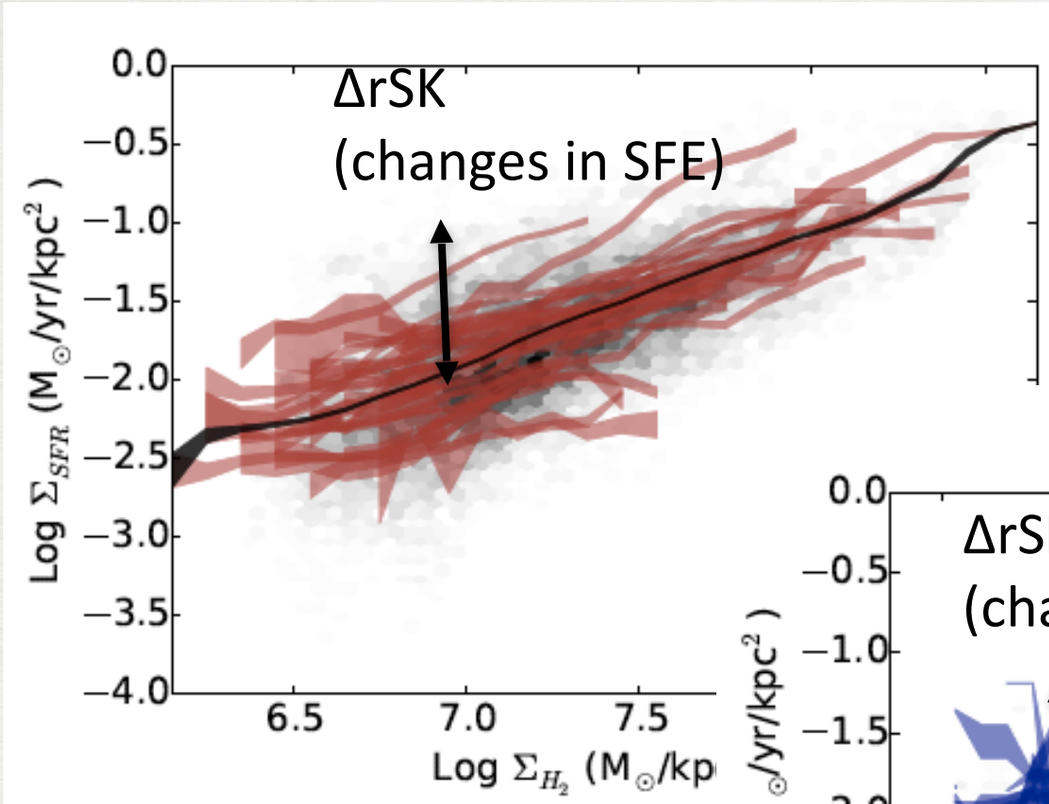

Ellison et al. (submitted)

# Galaxy-by-galaxy (kpc) scaling relations

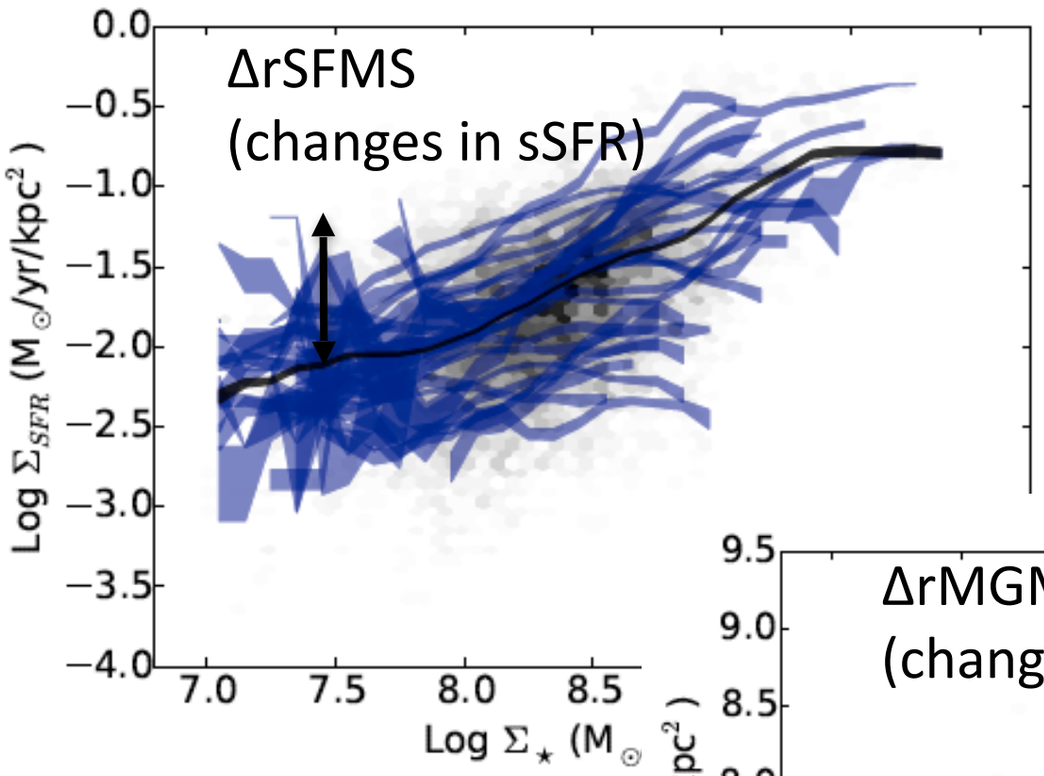
## The resolved molecular gas main sequence (rMGMS)



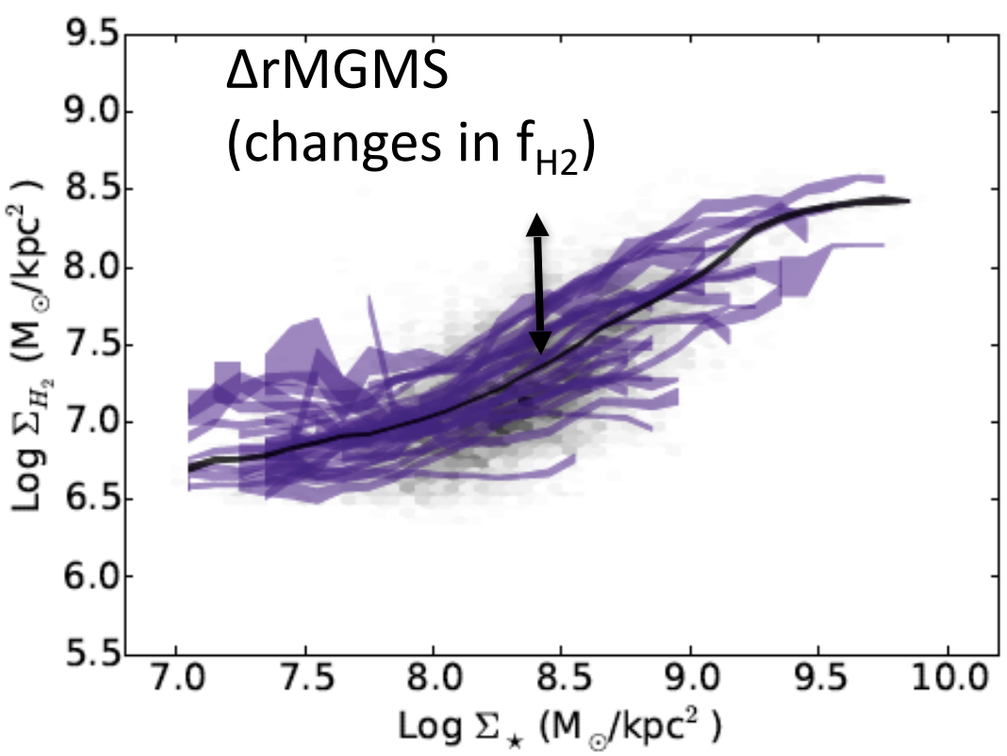

Ellison et al. (submitted)




The resolved Schmidt-Kennicutt relation (rSK)

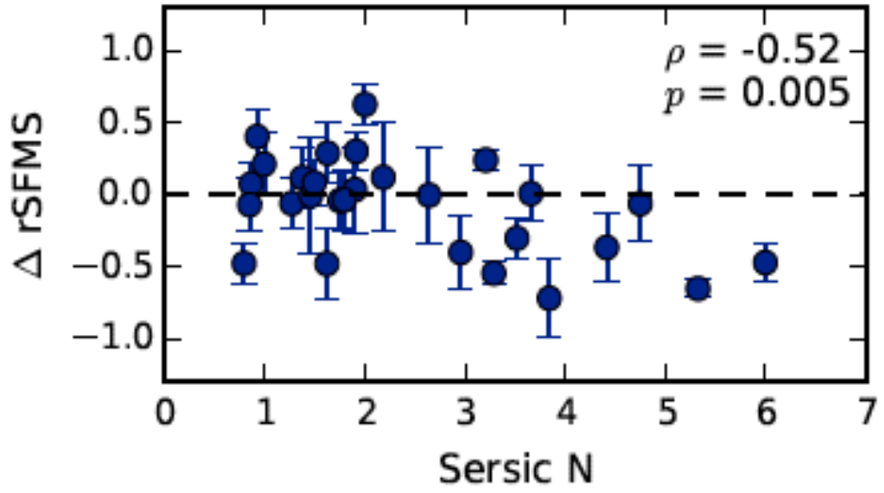


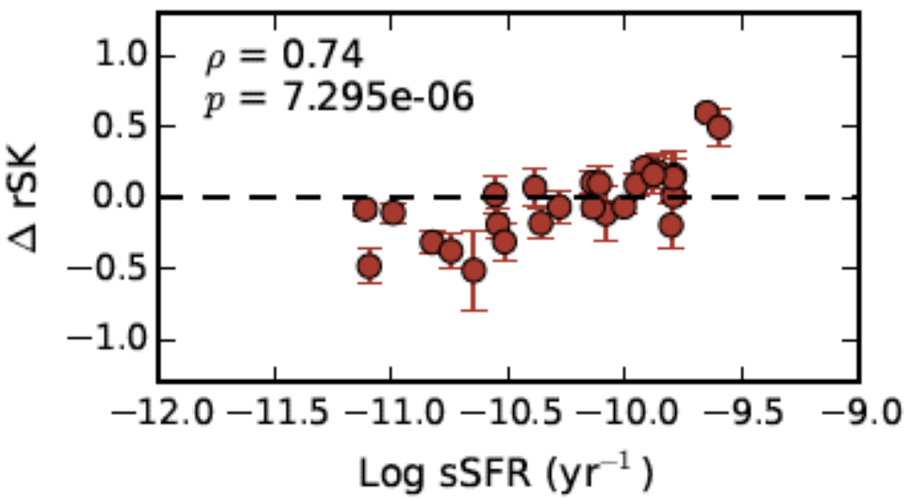

The resolved star forming main sequence (rSFMS)

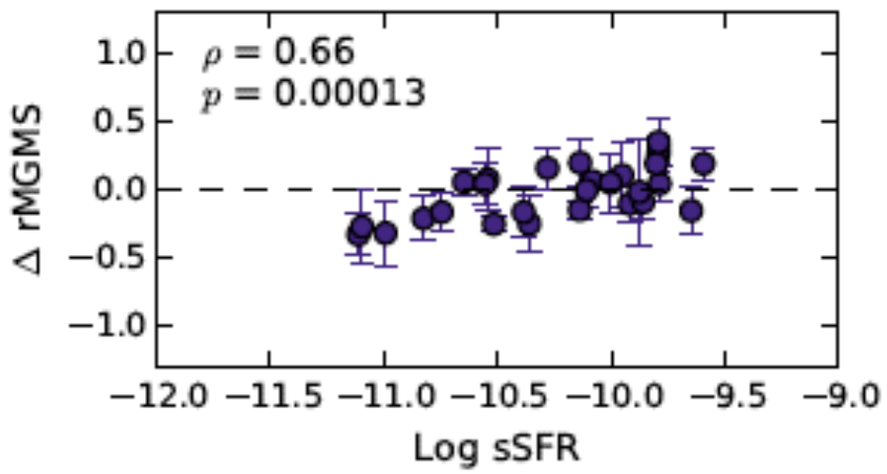



The resolved molecular gas main sequence (rMGMS)

# Galaxies show considerable variation in the scaling relations




The offset of a given galaxy from the average relation, particularly offset in rSK and rSFMS, correlates with global properties, such as morphology.

Star formation scaling relations are not universal. There is considerable galaxy-to-galaxy variation in the three resolved star formation scaling laws and correlations with global galaxy quantities.

Ellison et al. (submitted)

# Part 3.3: What about GV galaxies?

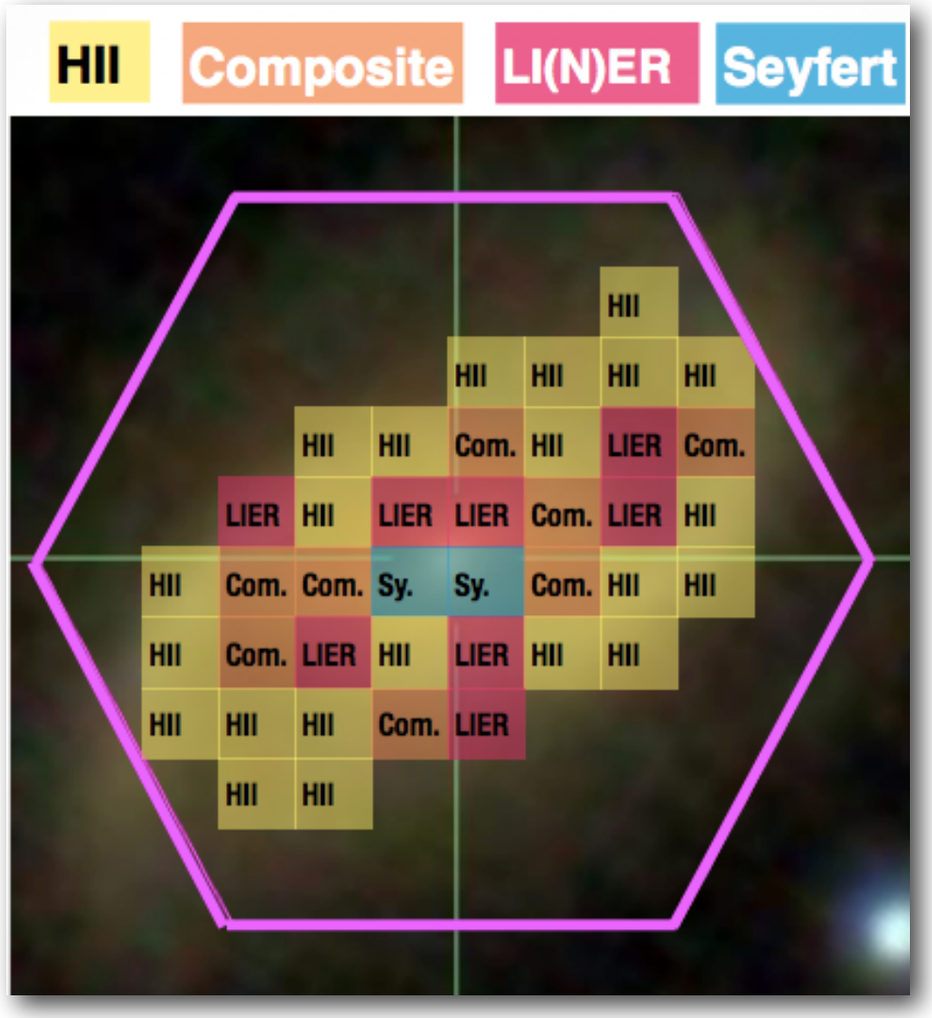
GV contains non-negligible fraction of non-SF spaxels

=> need to consider those regions, too

- Galaxy type: MS vs. GV
- Spaxel type: SF vs. retired

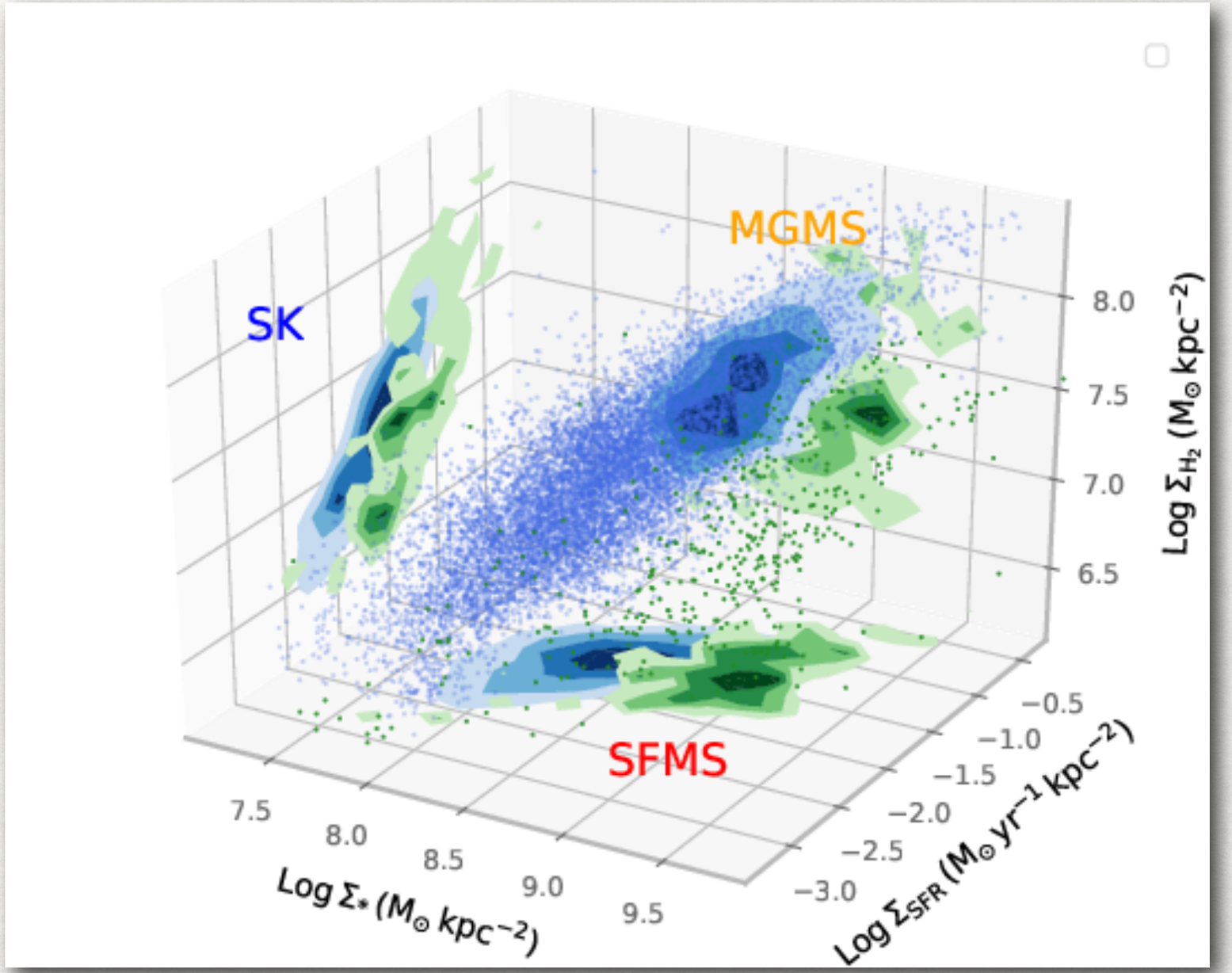
Retired spaxels:

BPT-classified LINERs & EW(Ha) < 3A



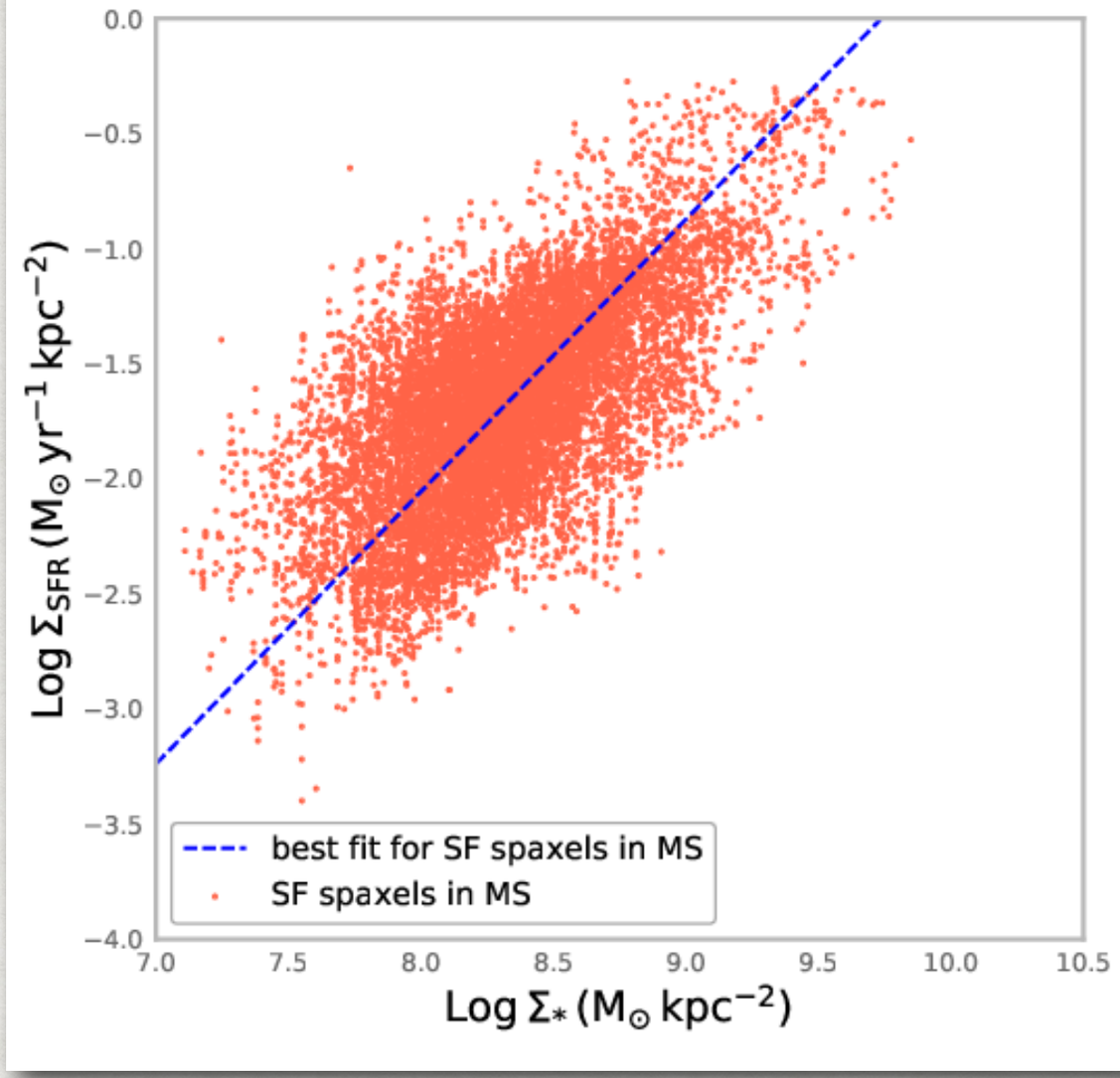
# 3D RELATIONS

- GV has flatter slopes in 3 relations
- GV has larger scatters in rSK and rSFMS but not rMGMS

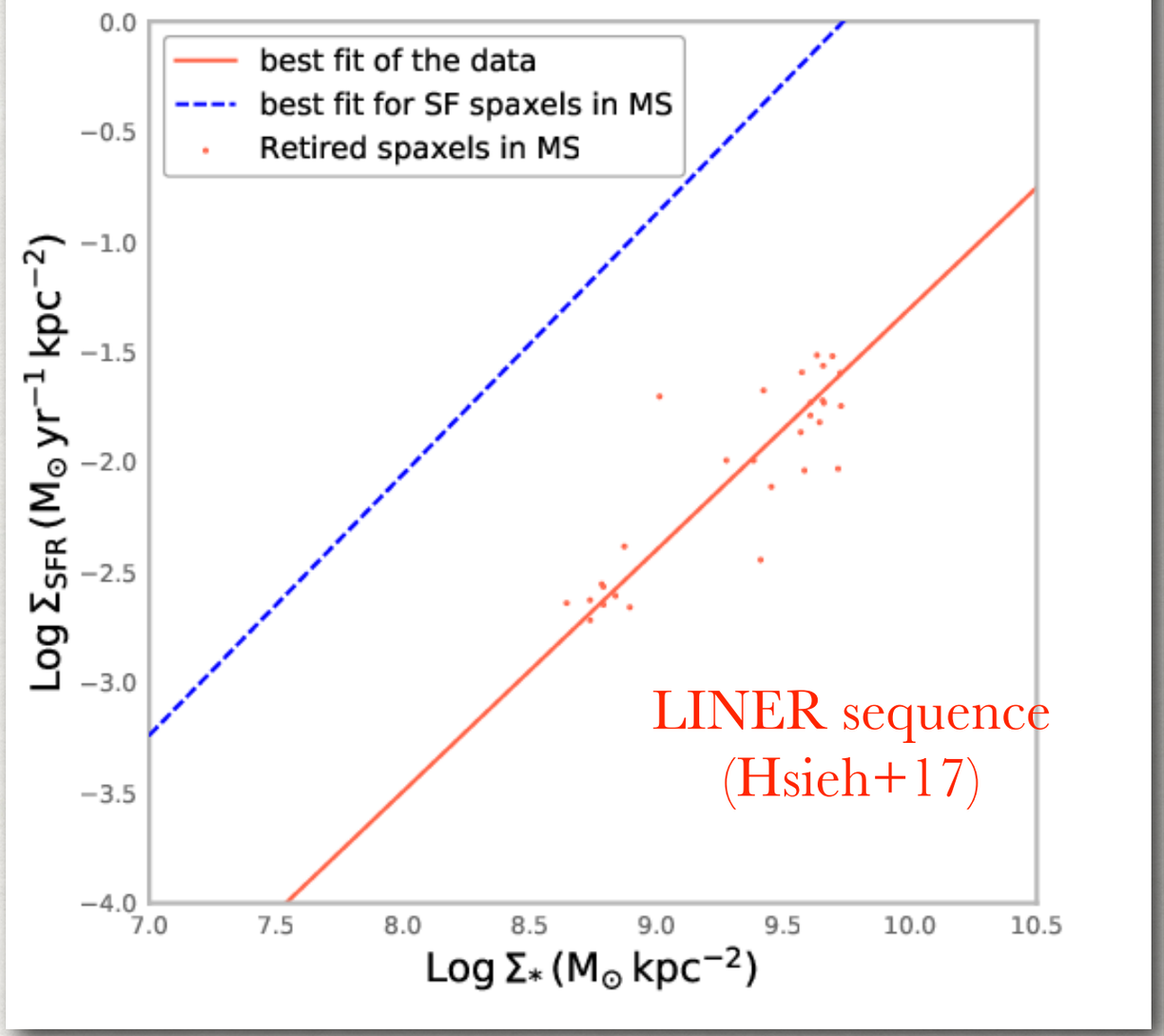


# rSFMS in MS galaxies

star-forming spaxels



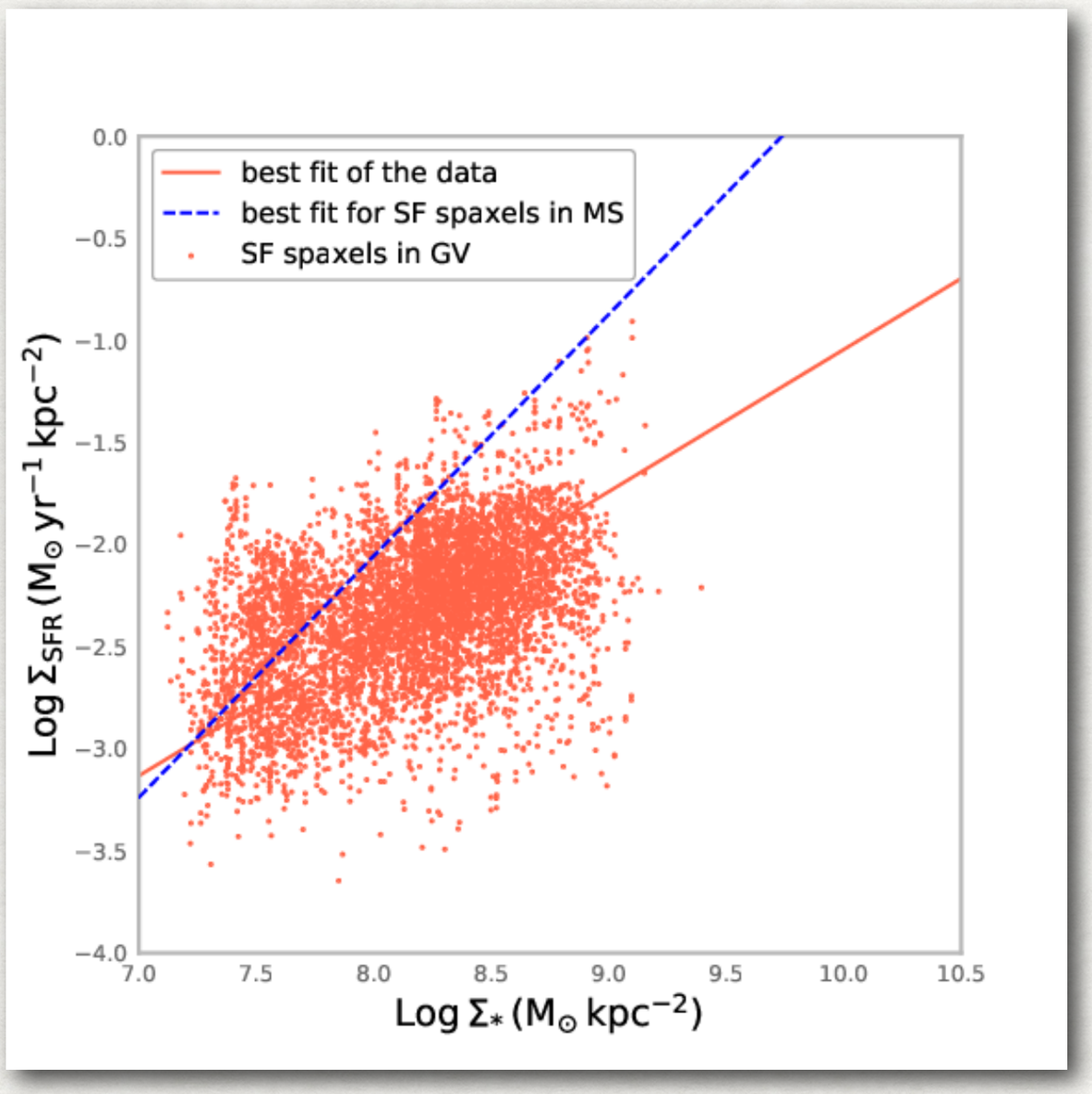

retired spaxels



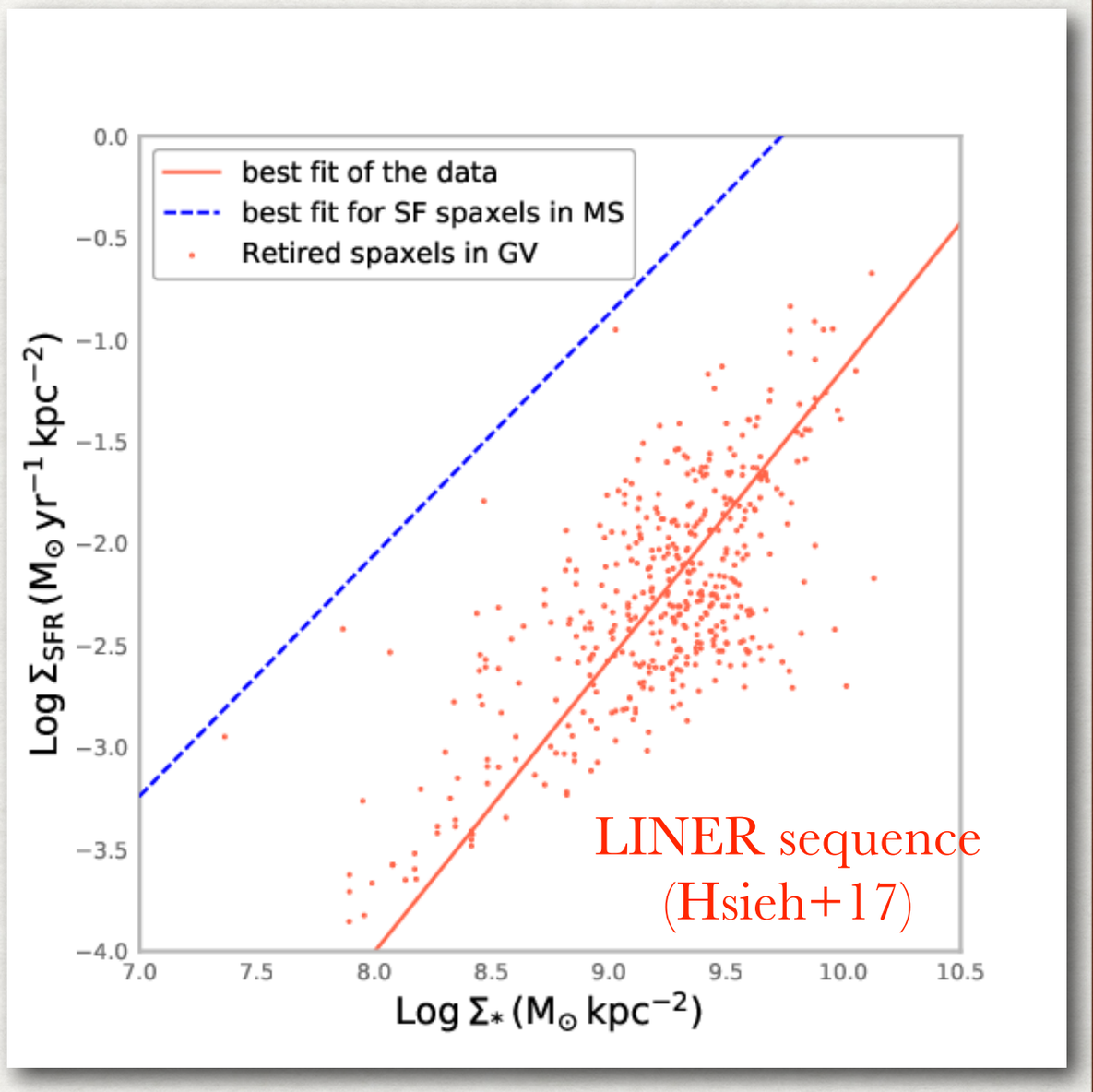

Lin+, in prep.

# rSMFS in GV galaxies

star-forming spaxels



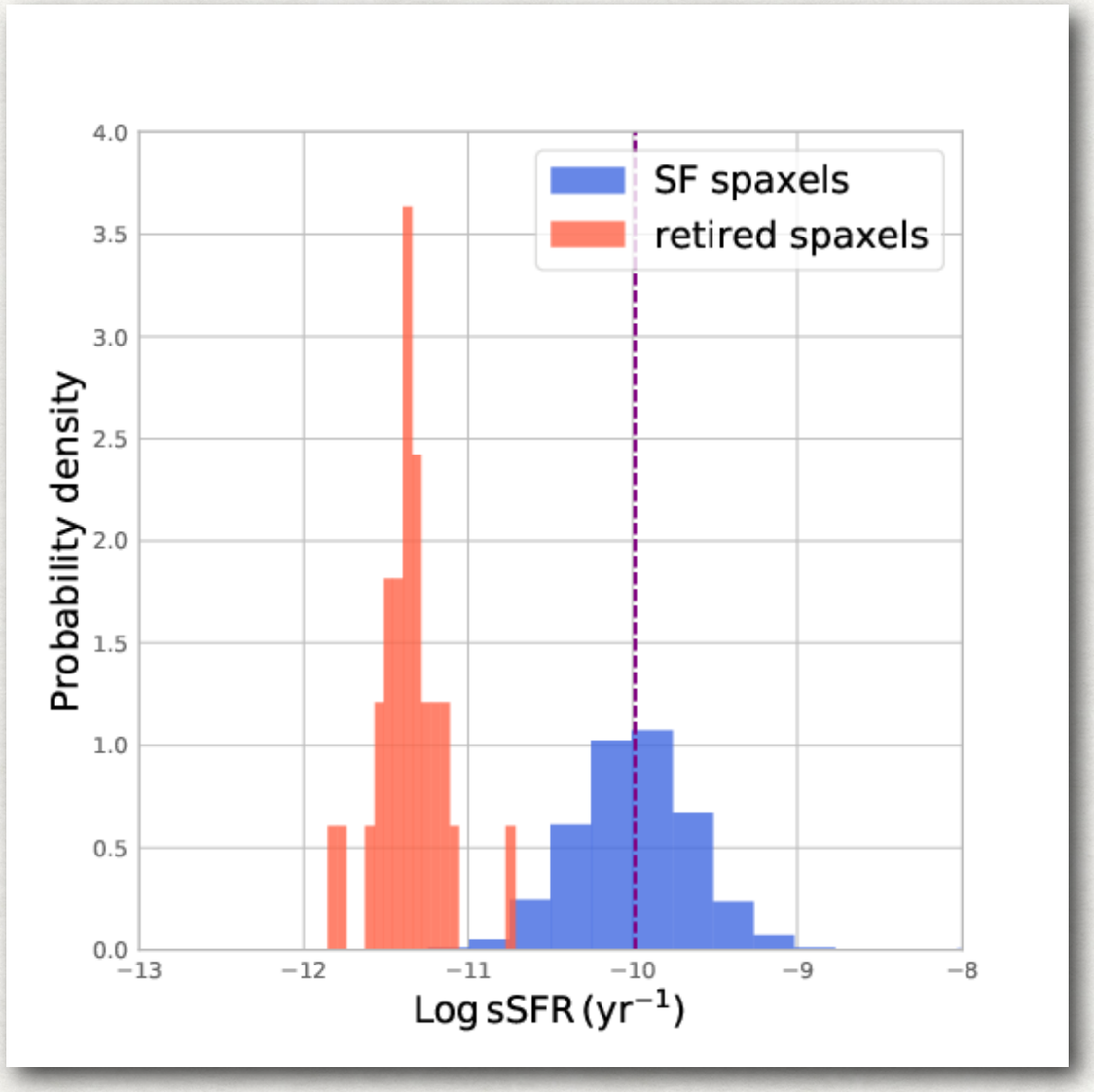

retired spaxels



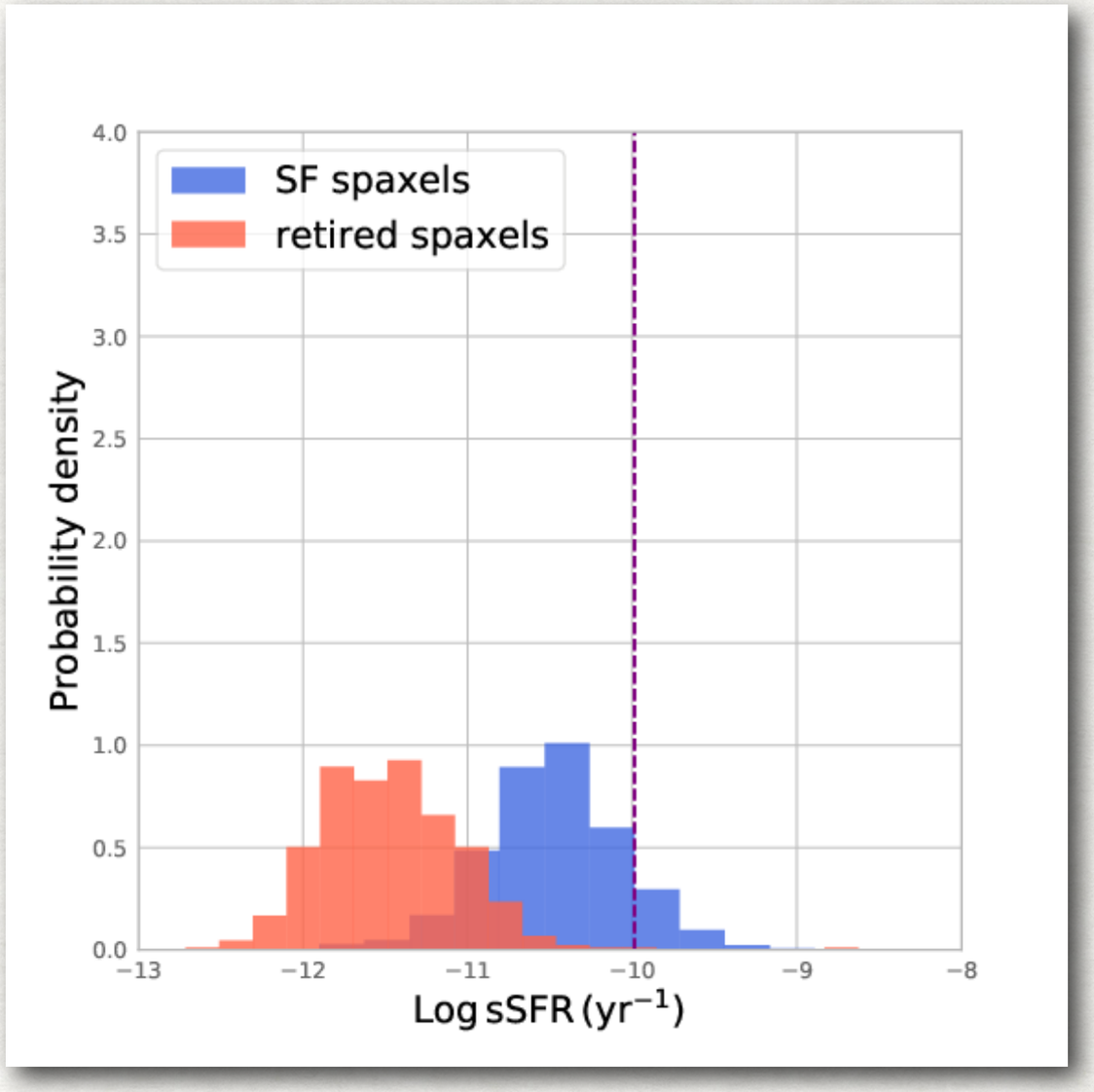

Lin+, in prep.

# SSFR

## MS galaxies




## GV galaxies



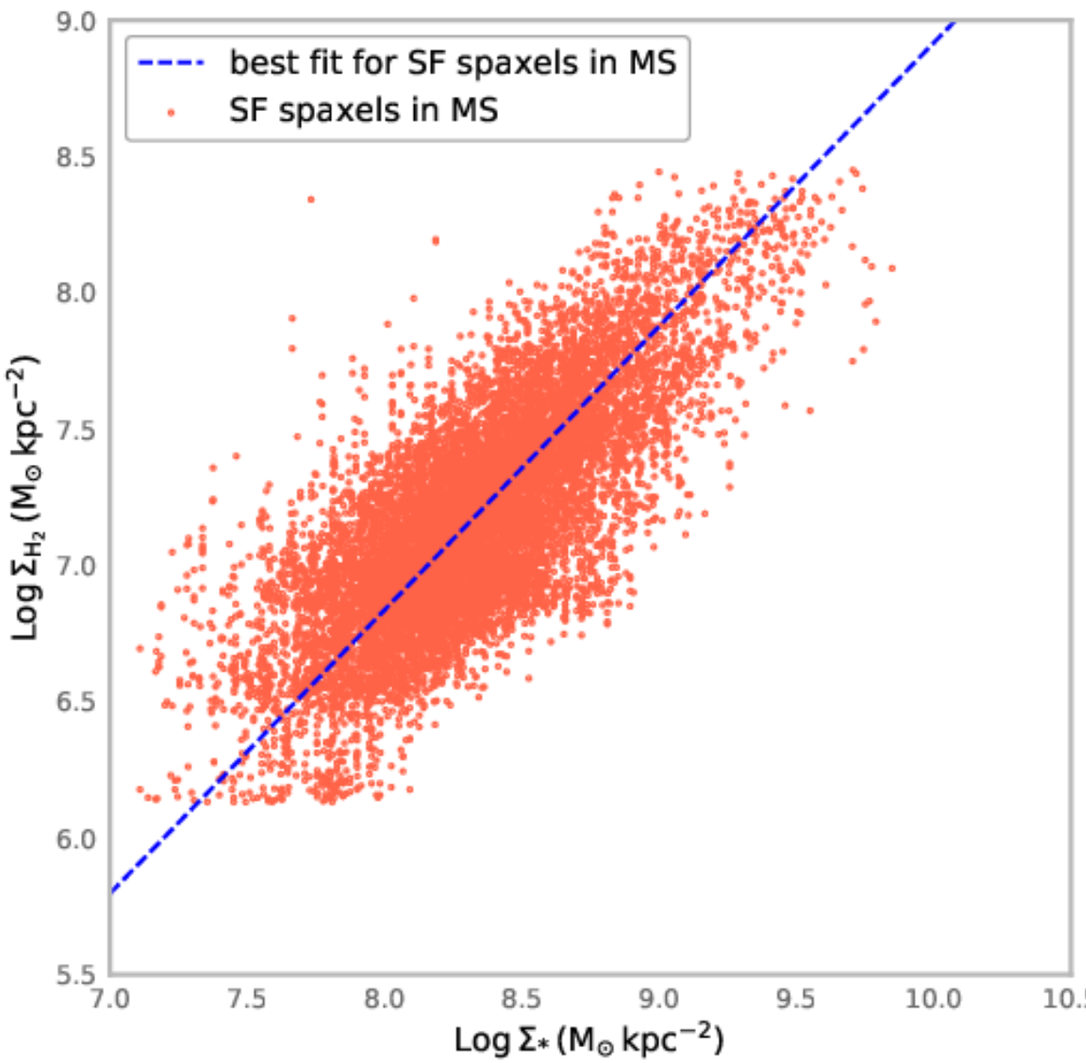

By definition, GV has lower sSFR.
sSFR of GV is lower than that of MS for both SF or retired spaxels



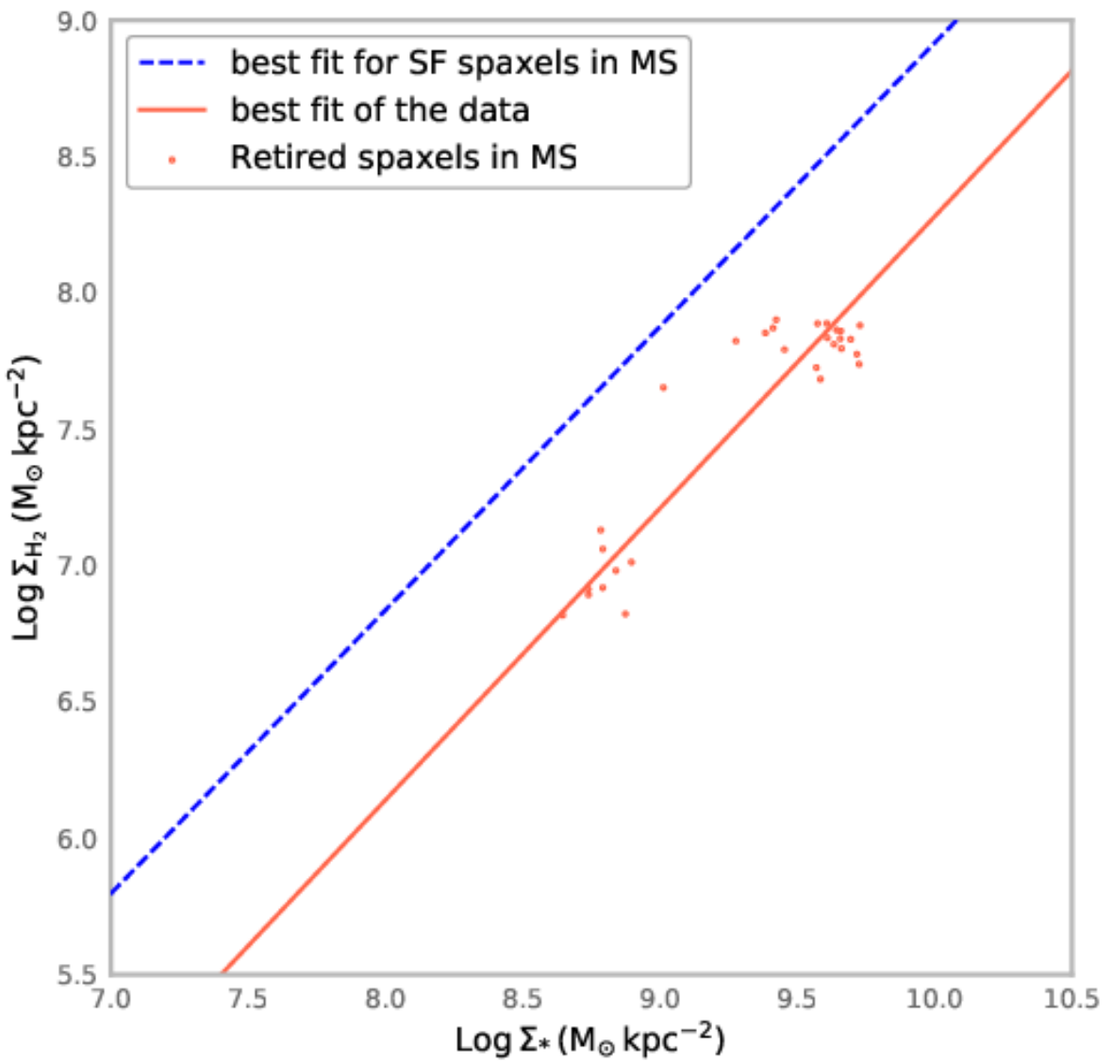
Lin+, in prep.

# rMGMS in MS galaxies

star-forming spaxels



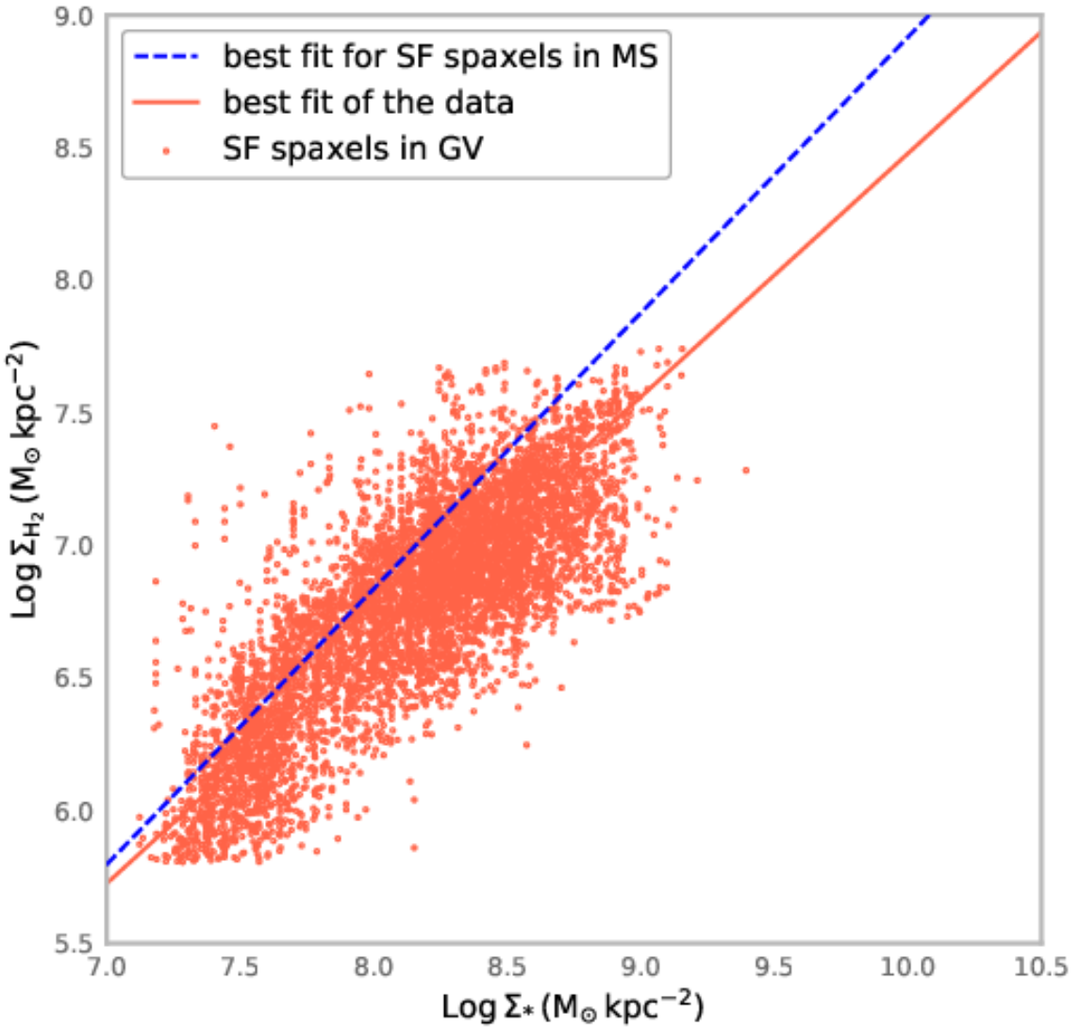

retired spaxels



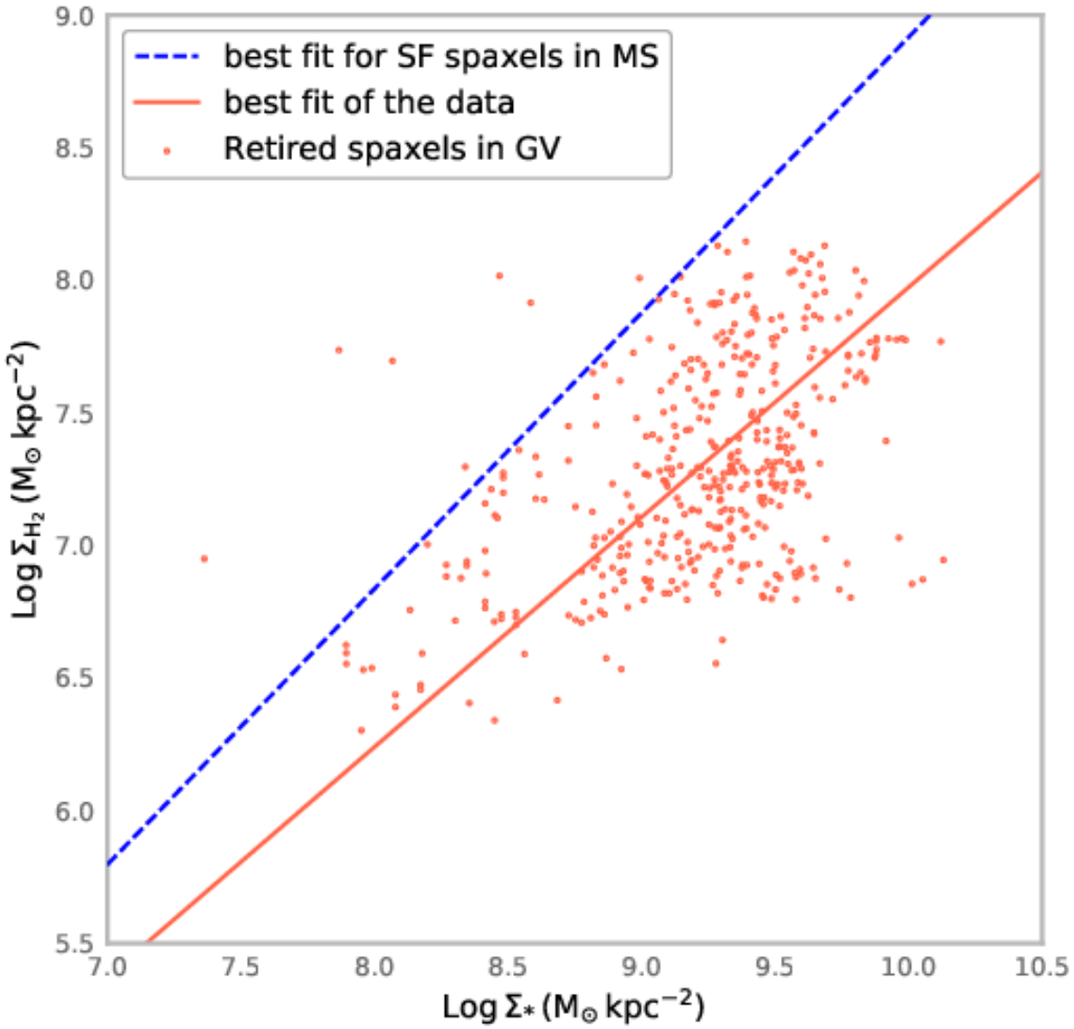

Lin+, in prep.

# rMGMS in GV galaxies

star-forming spaxels



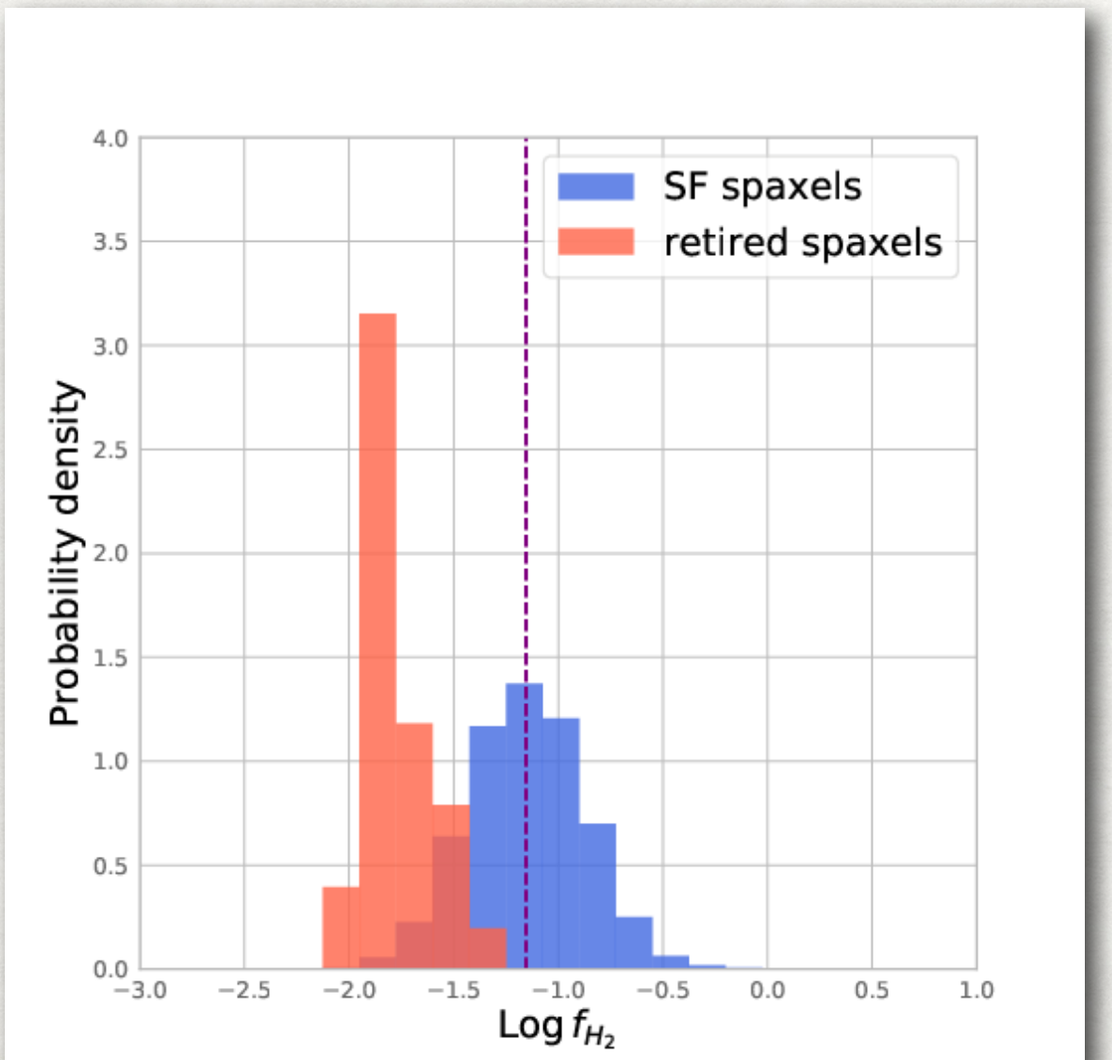

retired spaxels



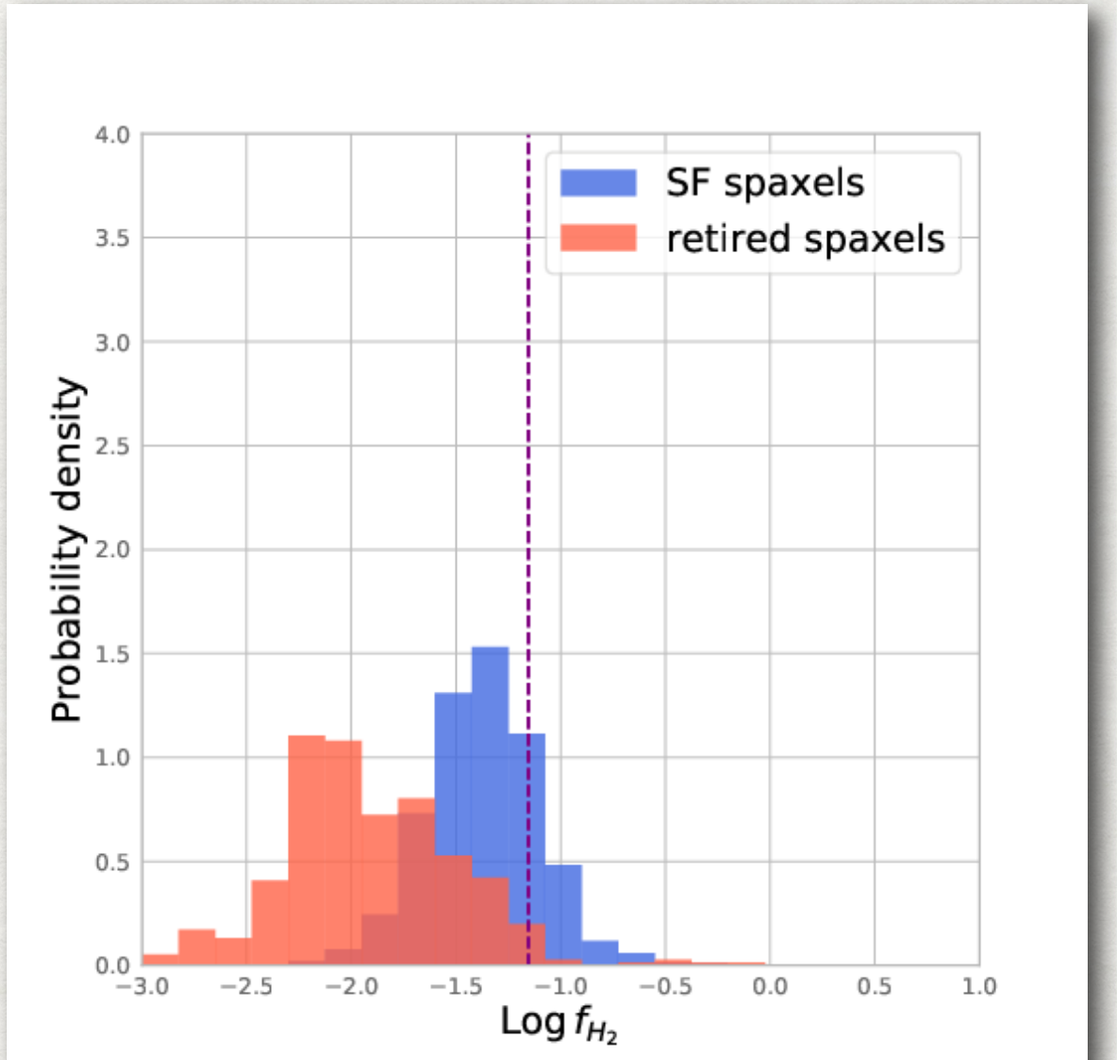

Lin+, in prep.

# $F_{H2}$

## MS galaxies




## GV galaxies

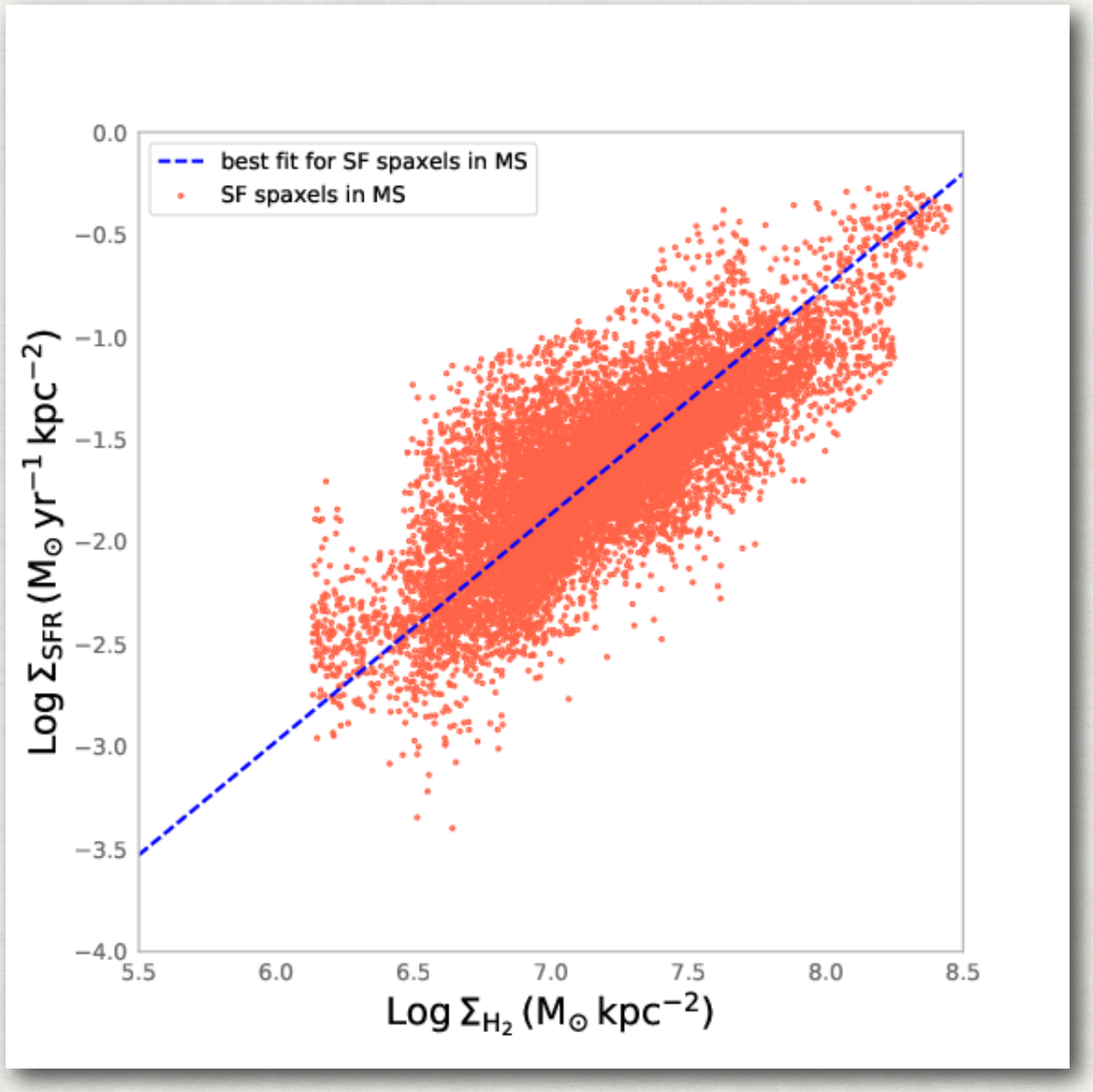



$f_{H2}$ of GV is lower in both SF and retired spaxels than that of MS

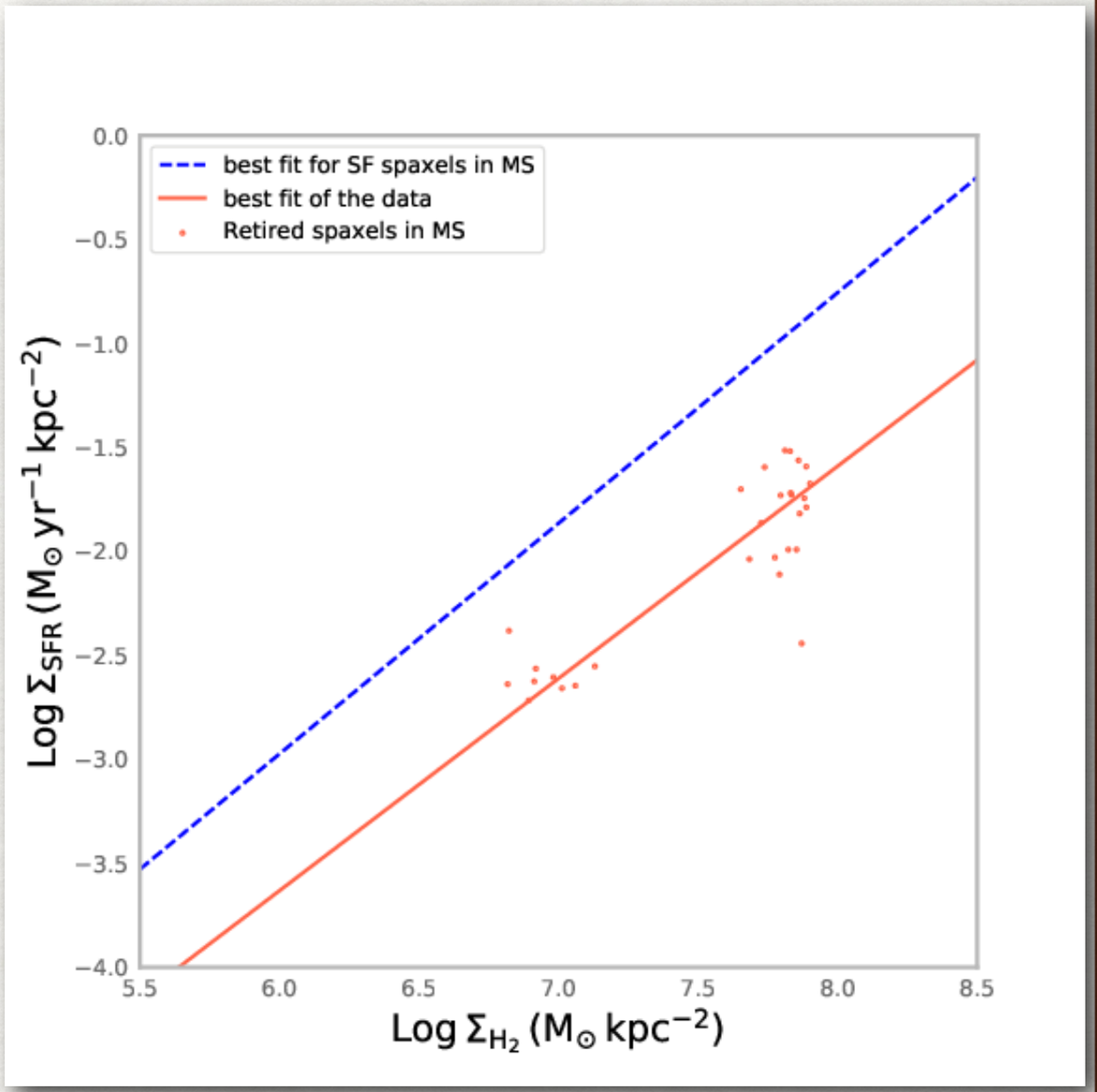
Lin+, in prep.

# rSK in MS galaxies

star-forming spaxels



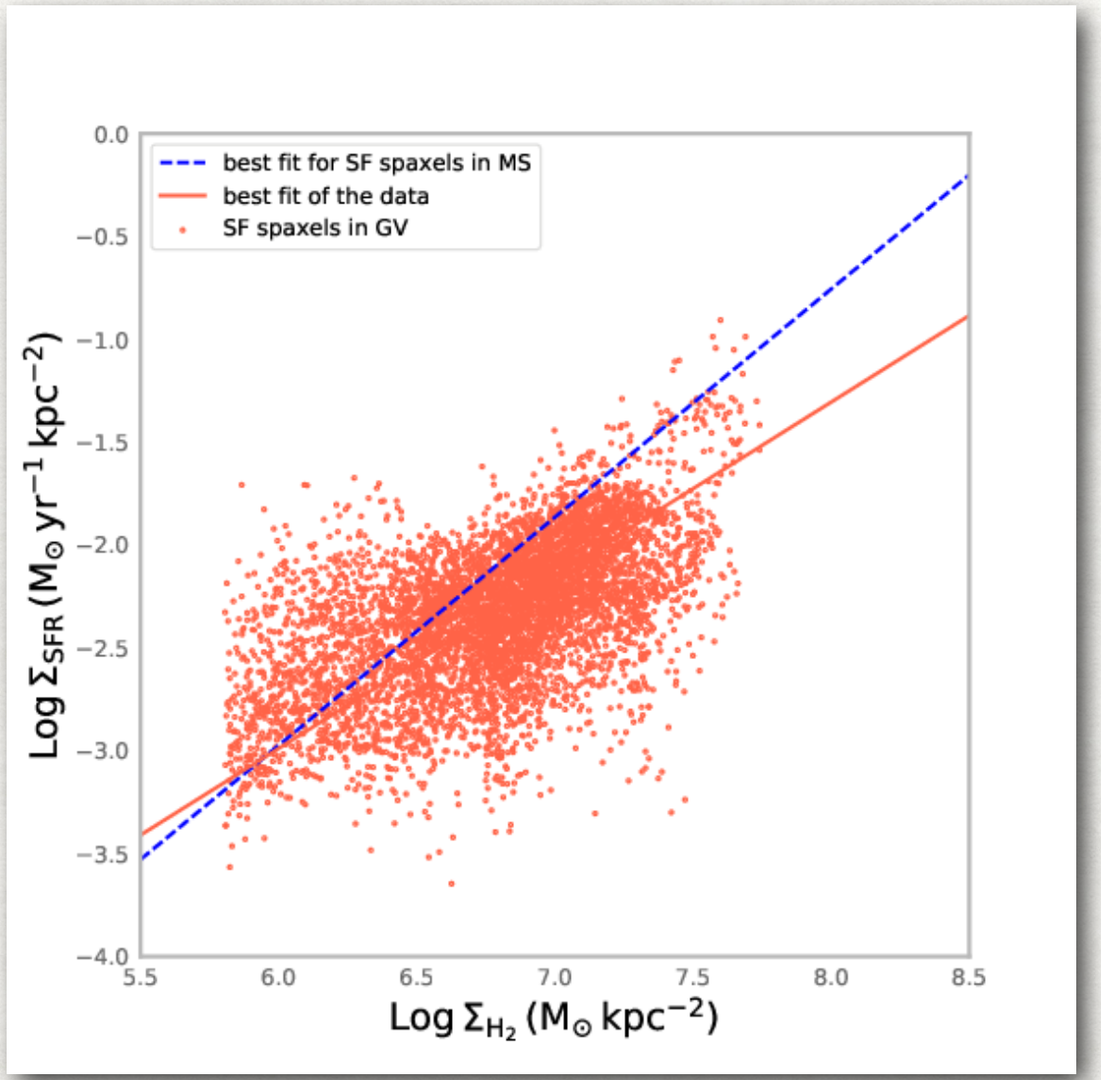

retired spaxels



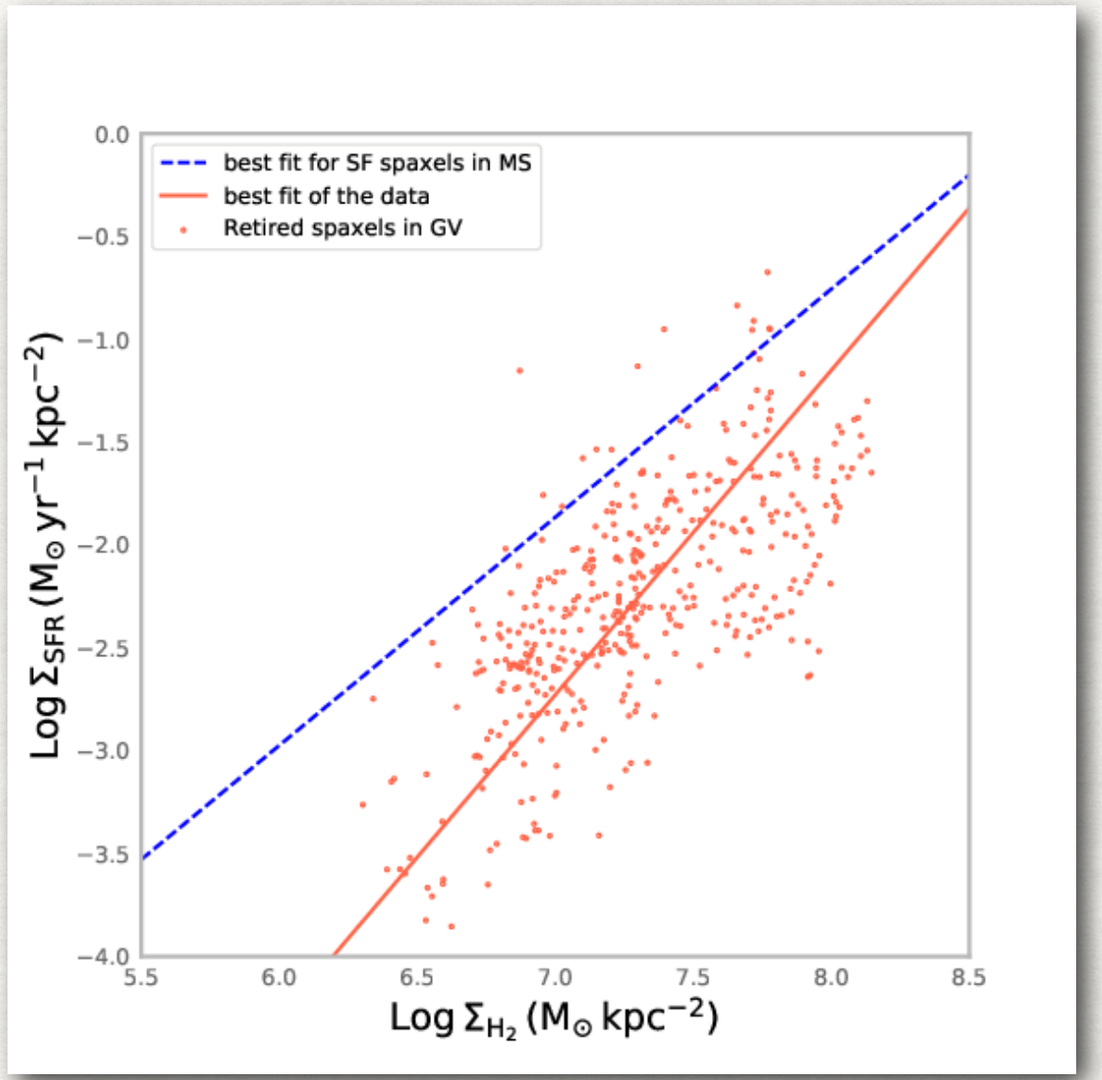

Lin+, in prep.

# rSK in GV galaxies

star-forming spaxels



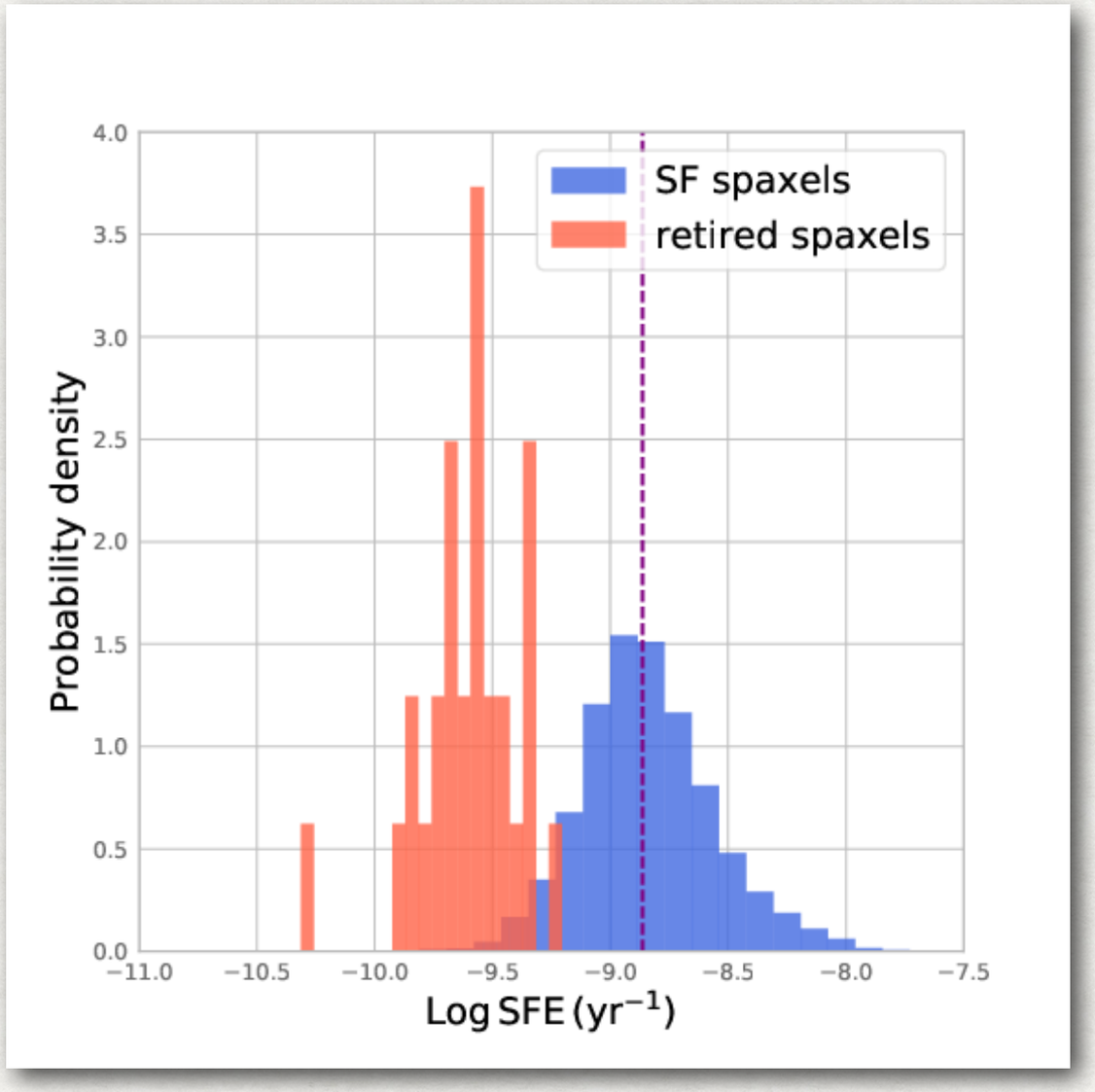

retired spaxels



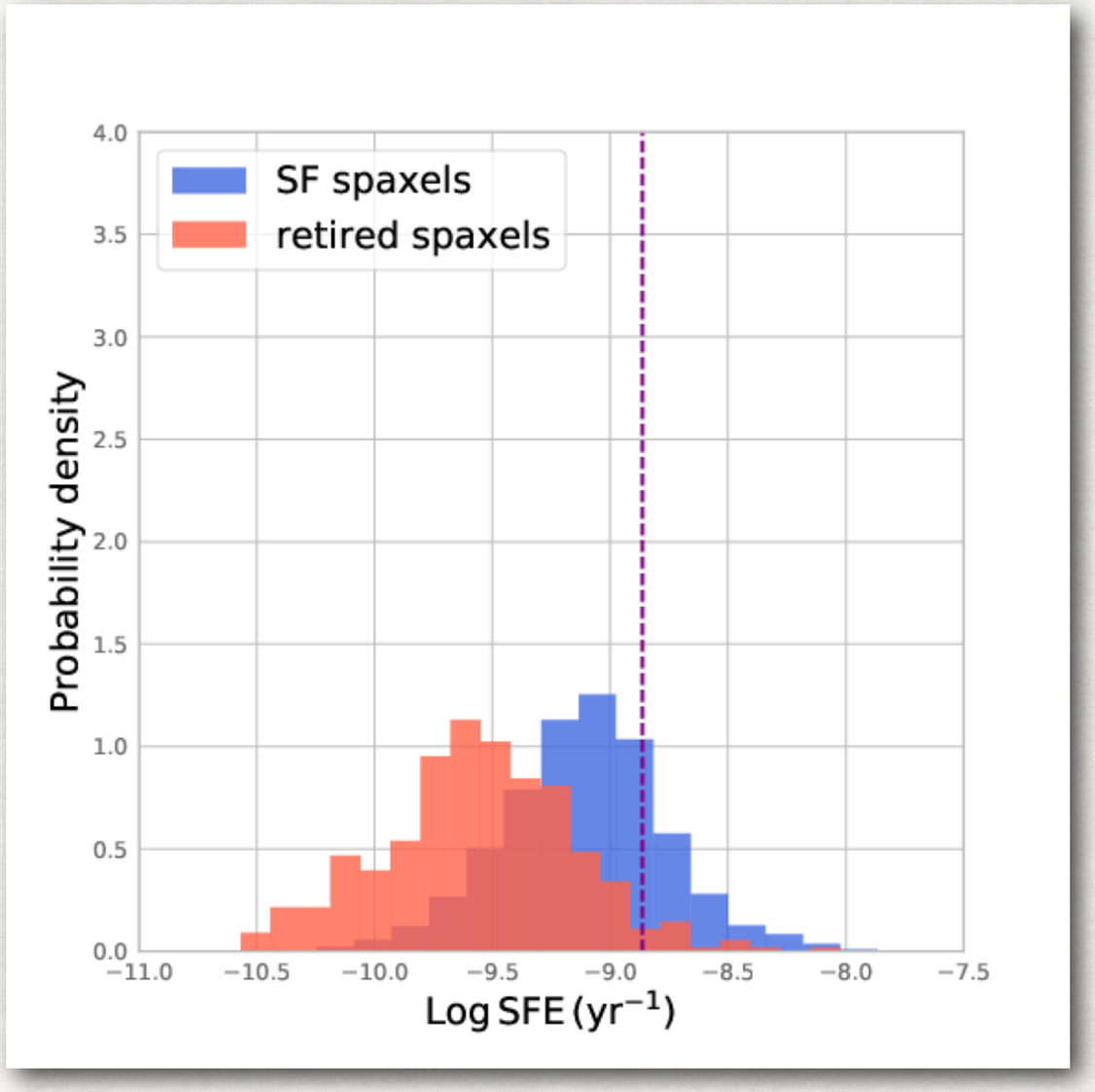

Lin+, in prep.

# SFE

## MS galaxies



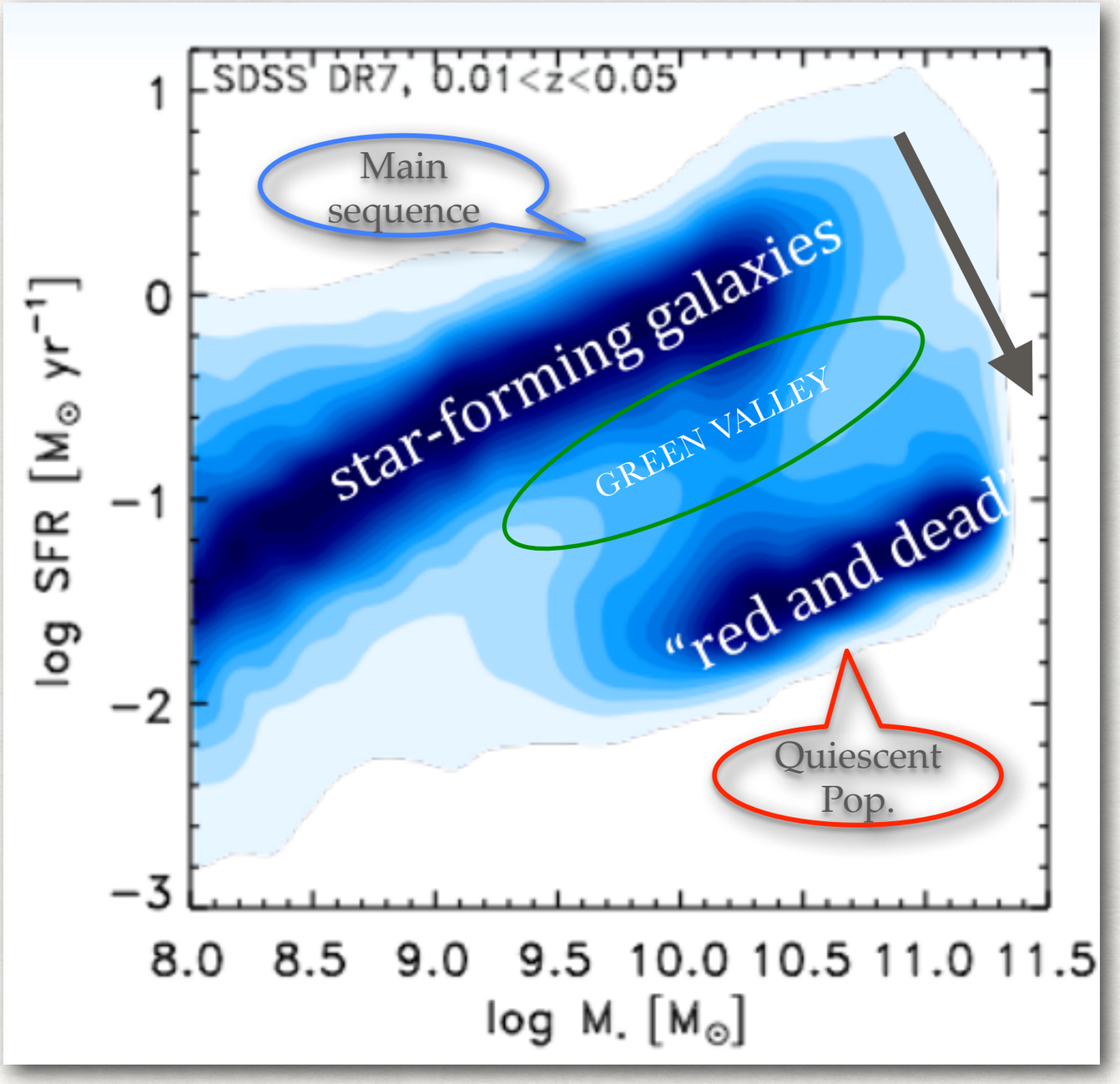

## GV galaxies




SFE of GV is lower in both SF and retired spaxels than that of MS

Lin+, in prep.

# Star Formation vs. Quenching




From SFMS to green valley: SFE and $f_{H2}$ decline globally (in both SF and retired regions)

(figure credit: Amelie Saintonge)

# SUMMARY

- ALMaQUEST (Lin et al. 2020).
  - ALMaQUEST provides dataset to simultaneously study the relationships between SFE, $M_*$, and $M_{gas}$ at kpc scales for starburst, main sequence, and green valley galaxies.
- Scaling relations of MS galaxies (Lin et al. 2019)
  - At kpc scales, the surface densities of SFR, $M_*$, and $M_{gas}$ are tightly correlated with each other. In addition to the known rSFMS and SK relations, there also exists a 3rd relation: molecular gas main sequence (MGMS).
  - rSFMS is a natural consequence of the combination of SK and MGMS.
- Galaxy-to-galaxy variations in the 3 scaling relations (Ellison et al., submitted)
  - There is significant galaxy-to-galaxy variation in all 3 scaling relations, which drives the shape and scatter of the ensemble relations. Scaling relations correlate with global galaxy parameters
- Scaling relations of GV and retired regions (Lin et al. in prep.; Ellison et al. submitted):
  - GV galaxies not only have lower sSFR (by definition), but also lower gas fraction ($f_{H2}$) and star formation efficiency (SFE), in either star-forming or retired spaxels.