Class 10: Galactic-scale star formation rates: observations

ASTR 4008 / 8008, Semester 2, 2020

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Outline

- Prelude: history of the field and the technology
- Whole-galaxy star formation rates
  - Local galaxies
  - High-redshift galaxies
  - Low surface-brightness galaxies
- Spatially-resolved star formation rates
  - Local depletion times and efficiencies
  - Phase- and metallicity-dependence
  - Pressure- and stellar mass-dependence
  - Small-scale decorrelation
- Correlations with tracers of dense gas

(Highly condensed) prelude on history

First generation (1970s - 1990s)

- Key technologies:
  - Discovery of interstellar CO 1-0 line at 2.6 mm (Wilson 1970), leading to first generation of mm telescopes (e.g., FCRAO in 1976, IRAM 30m in 1984, BIMA in 1986)
  - Space-based IR detector technology (largely borrowed from the military), leading to first IR astronomy satellites (IRAS, launched 1983)

- Combination of these two lead to first systematic exploration of relationship between gas (traced by CO and earlier 21 cm data) and star formation (traced by IR + ground-based Hα)

- Culminates in discovery of "Kennicutt-Schmidt relation"

Prelude on history

Second generation (2000s)

- Key technologies:
  - Interferometry at mm wavelengths makes it possible to map gas in nearby galaxies, and start to detect CO beyond $z = 0$ (SMA in 2003, CARMA in 2004, PdBI 1990s - 2000s)
  - *Spitzer* telescope in IR (launched 2003) — much higher resolution than IRAS, makes it possible to observe beyond $z \sim 0$ in IR for first time
  - *GALEX* telescope in UV (launched 2003) — mapping nearby galaxies in FUV
  - Efficient selection of $z > 0$ objects using HST + ground-based colours

- Main outcomes:
  - Exploration of the KS relation on sub-galactic (~1 kpc) scales in local galaxies
  - First reliable studies of star formation in dwarf galaxies
  - First studies of KS relation beyond local universe

Prelude on history

Third generation (2010s - today)

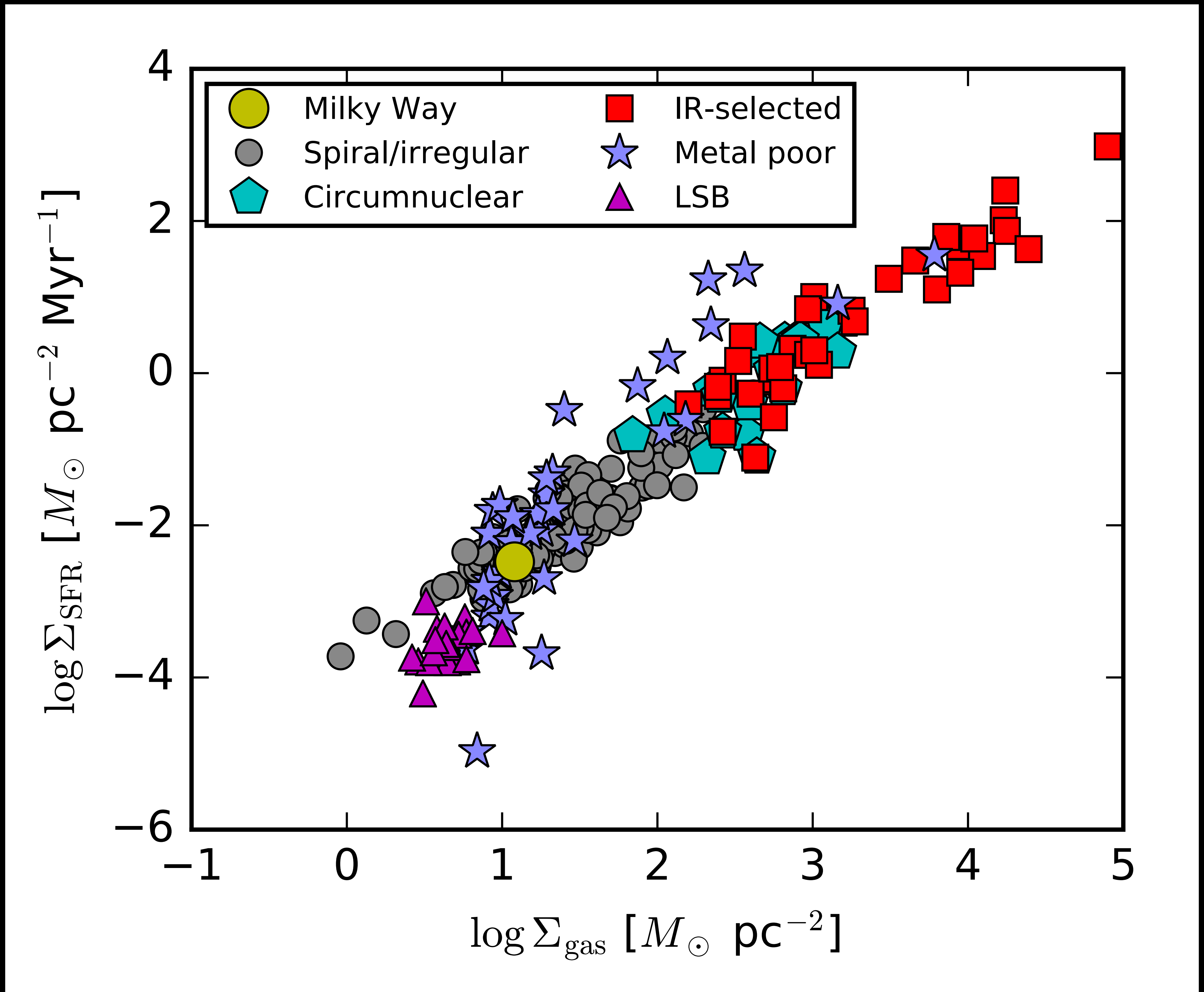
- Key technologies:
  - Atacama Large Millimeter Array (ALMA; science begins 2011) — can map nearby galaxies at $<$ 100 pc resolution, fairly easily detect CO at high z, do surveys of dense gas tracers like HCN
  - IFUs on 4m- and 8m-class ground-based telescopes (CALIFA at Calar Alto, MaNGA at Kitt Peak, SAMI at AAO, MUSE on VLT) — spectroscopic mapping of ionised gas across at $<$ 100 pc resolution in nearby galaxies

- Major discoveries:
  - KS relation for normal (non-starburst) galaxies at high-z; “main sequence” of star-forming galaxies
  - Small-scale breakdown of KS relations in local galaxies
  - “Dense gas” KS relations

Whole-galaxy star formation scalings

The Kennicutt-Schmidt relation

- Schmidt (1959) first proposed ansatz where SFR scales as density to a power
- Kennicutt (1998) showed strong scaling between SFR / area and neutral (HI + H_2) gas mass / area: $\Sigma_{SFR} \sim \Sigma_g^{1.4}$
  - One of the 20 most highly cited papers of all time in astronomy
- Exact index depends on assumed α_{CO} — 1.4 is for constant α_{CO}, but could be as low as ~1.1, or as high as ~1.7

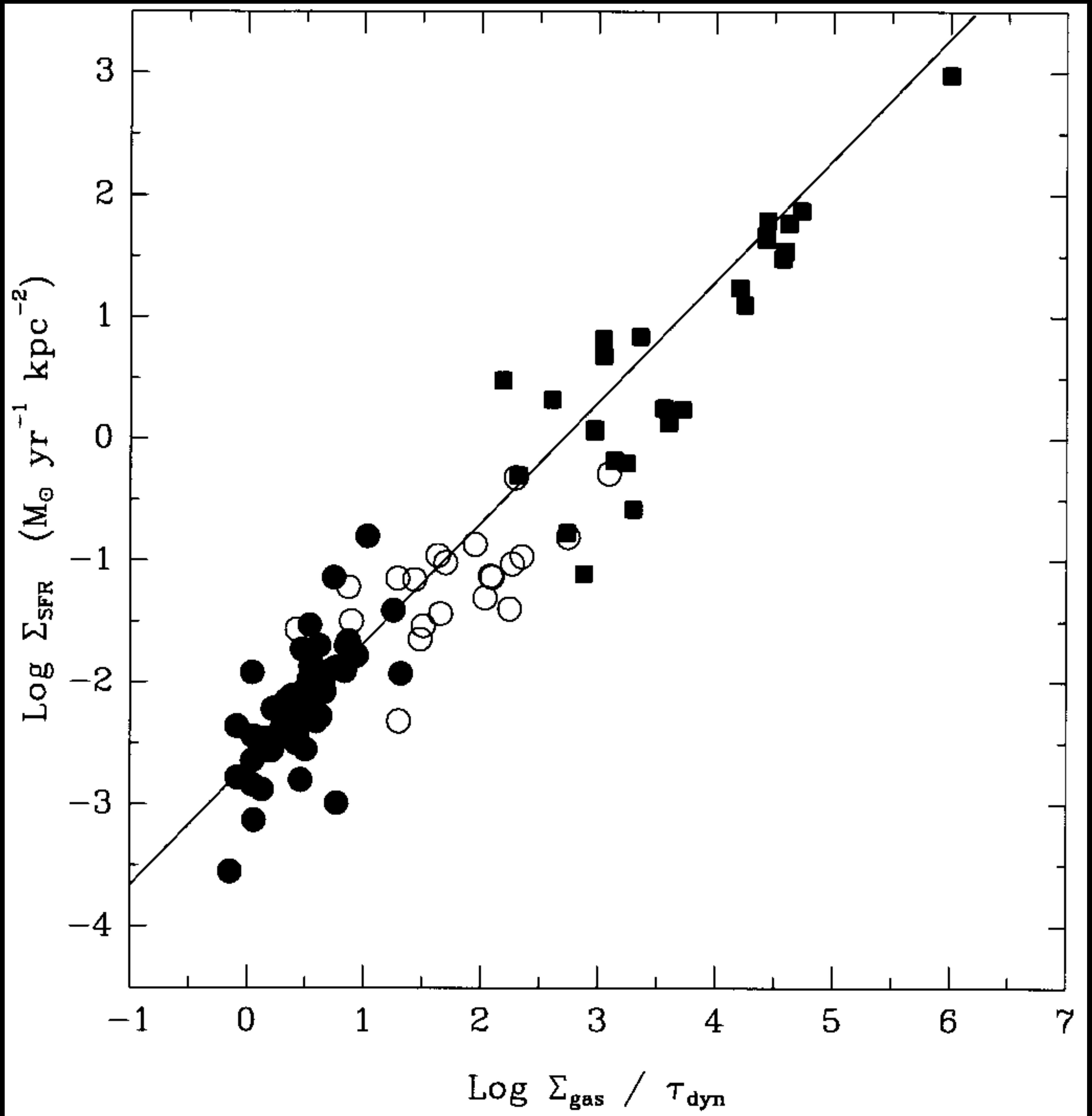


Kennicutt & Evans 2012

KS relation

Orbital period form

- Same galaxies also consistent with a relationship $\Sigma_{SFR} \sim \Sigma_g / t_{orb}$
- This relationship is linear
- Constant of proportionality is ~0.1, i.e., galaxies convert ~10% of their gas to stars per orbit
- Star formation fuelling problem: MW is ~50 orbits old, so why isn't it out of gas?

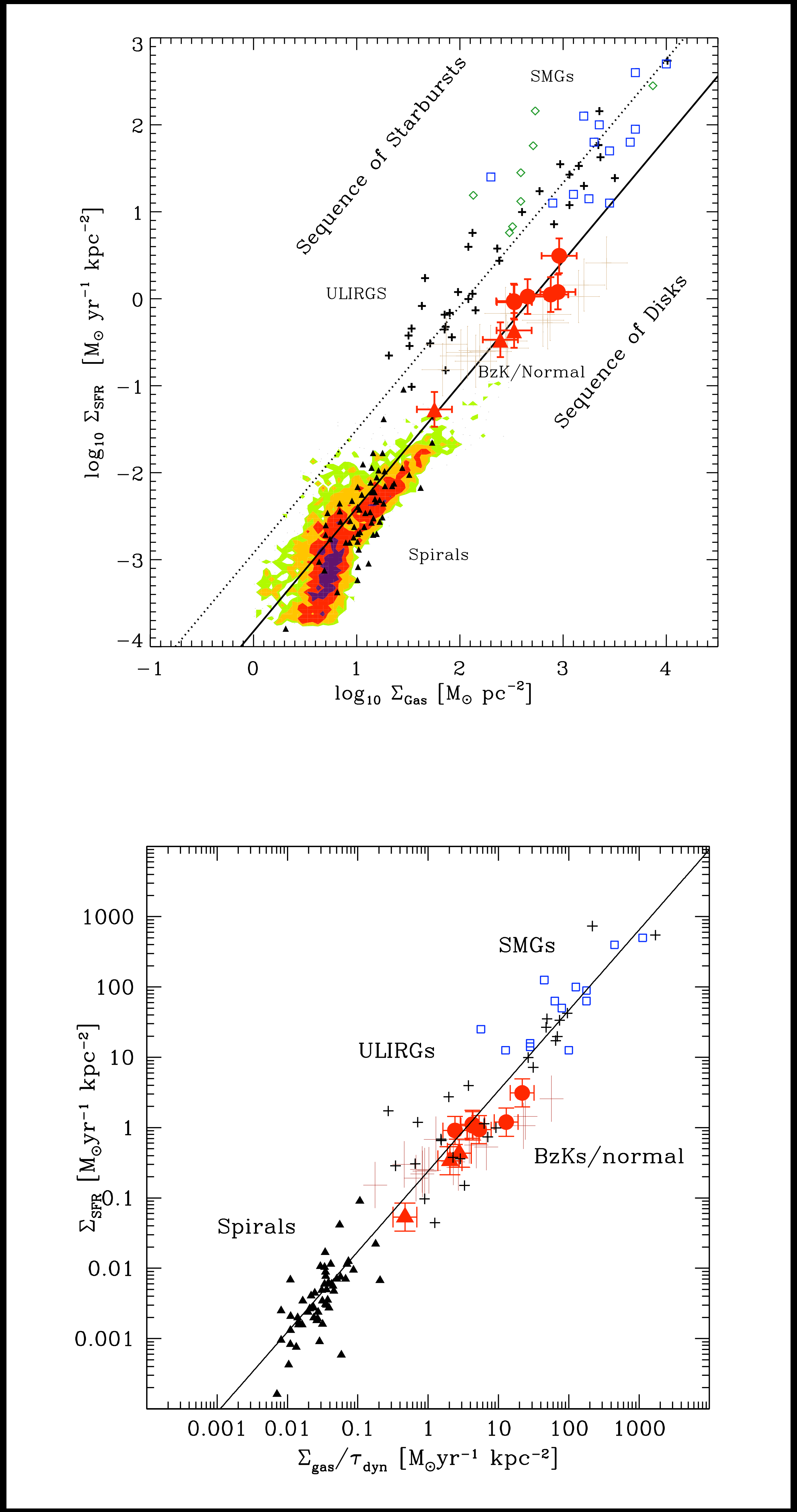


Kennicutt 1998

KS relation at high z

How the two forms hold up

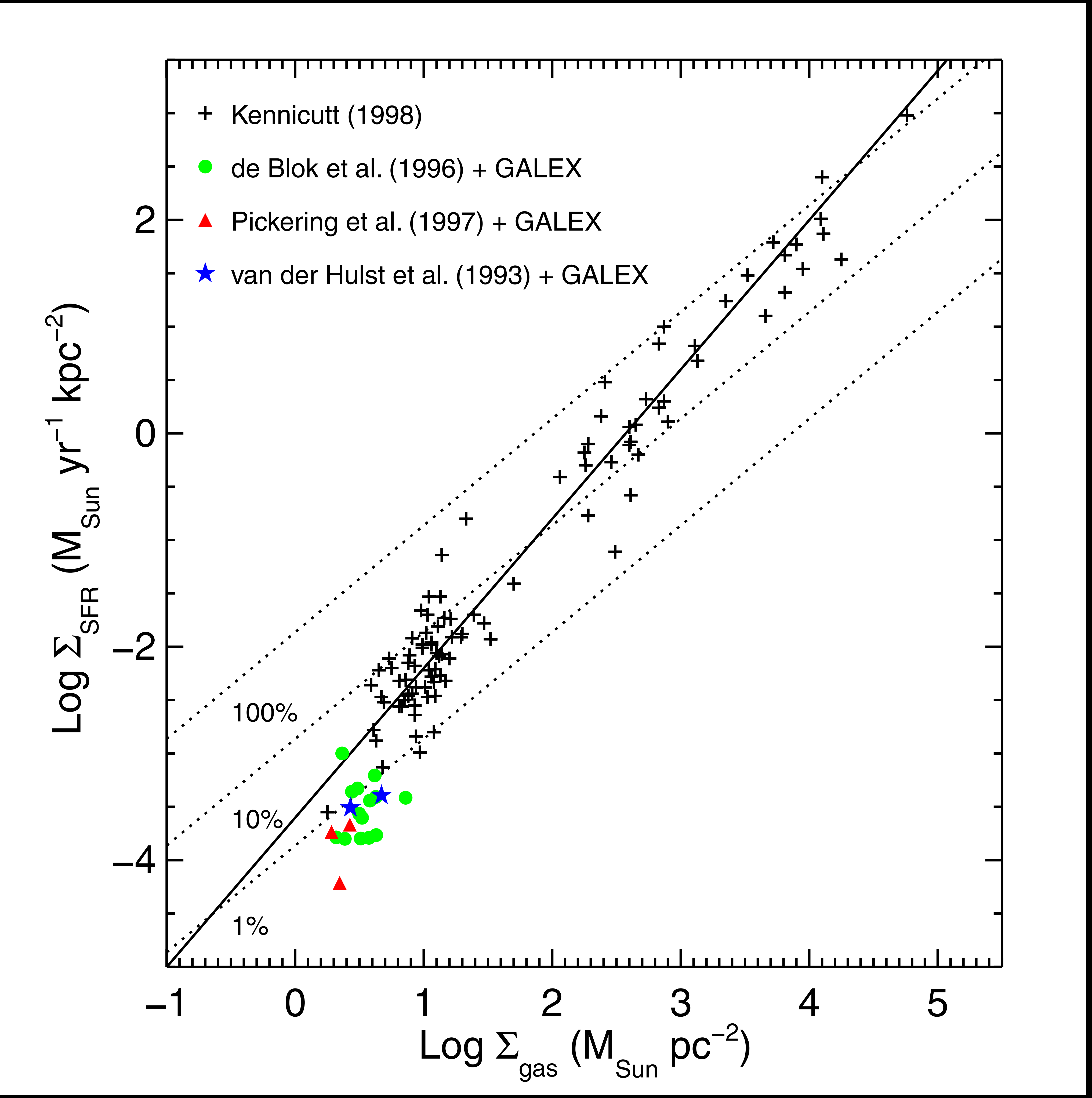
- KS relation in terms of Σ_g alone seems to break down at high-z: local merging galaxies and high-z "normal" galaxies have similar Σ_g, but starbursts have higher SFR
- Second form of KS relation seems to apply equally well at low- and high-z
- However, conclusions highly-dependent on α_{CO}; breakdown in first form of KS relation much less apparent if one assumes constant (or continuously-varying) rather than bimodal α_{CO}



Daddi 2010

KS relation in dwarfs and LSBs

- Dwarf galaxies fall substantially below the KS scaling for local spirals
- Major data issues: molecular gas very hard to observe due to low metallicity, total mass assumed dominated by HI
- If one uses only H_2, results depend entirely on choice of α_{CO}
- Hα very faint, hard to see against sky background — reliable measurement requires UV from space

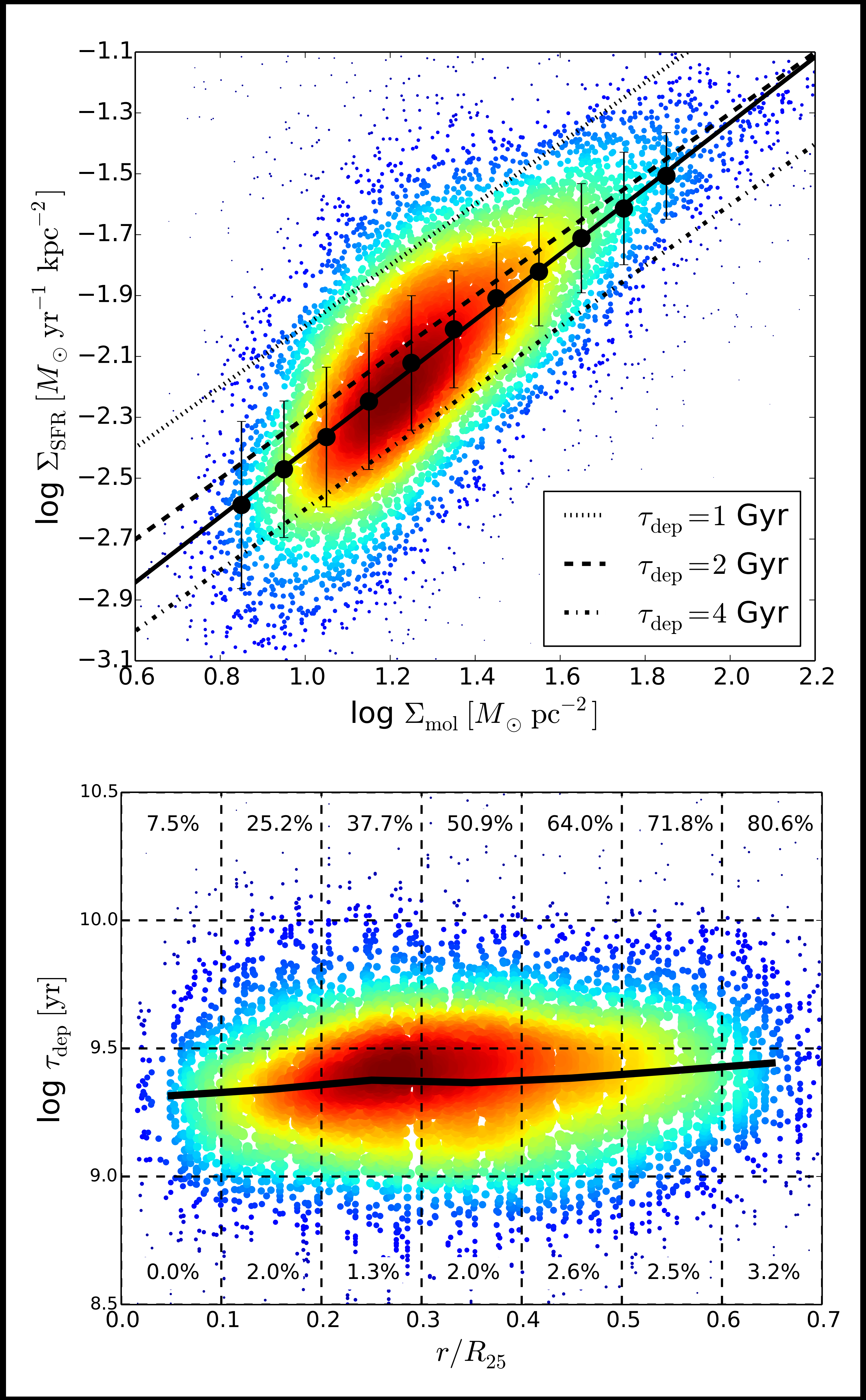


Wyder+ 2009

The spatially-resolved KS relation

Measured at ~1 kpc resolution

- Molecular gas in nearby galaxies shows a nearly universal t_{dep} ~ 1 - 4 Gyr
- No major variation with galactocentric radius, except possibly at very centre
- Conclusion only applies to nearby spirals — based on integrated measurements, t_{dep} ~ must be smaller in starburst and high-z systems
- Also holds in dwarfs, as long as one measures H_2 using something other than CO as a proxy

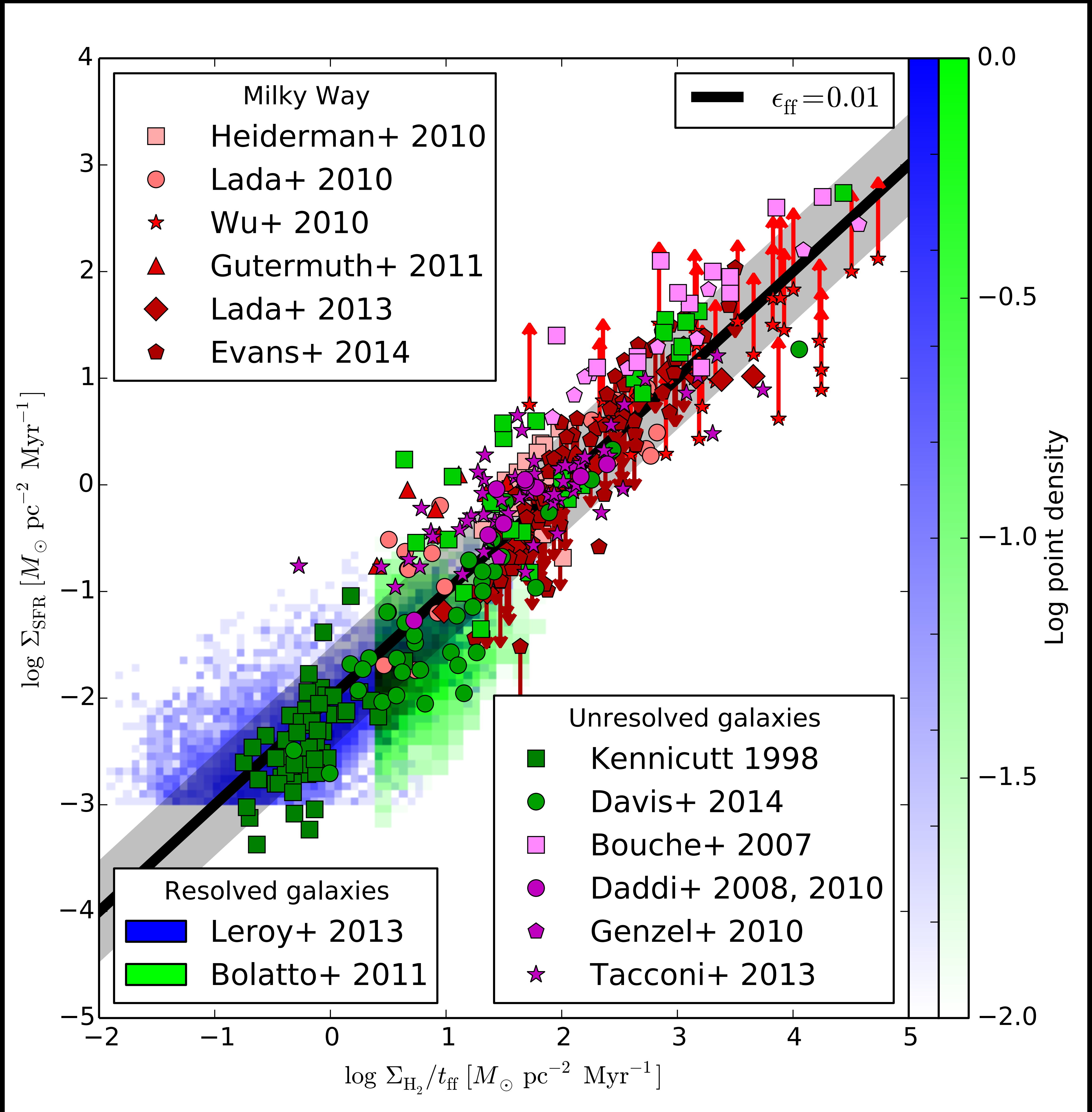


Utomo+ 2017

SF efficiency

The ε_{ff} parameter

- To include starbursts, it is helpful to normalise to free-fall time
- Estimate by assuming disc in hydrostatic equilibrium, or by using typical GMC surface densities (whichever gives higher density)
- Result: a universal efficiency $\varepsilon_{ff} \approx$ 1 - 2%, factor of ~3 scatter

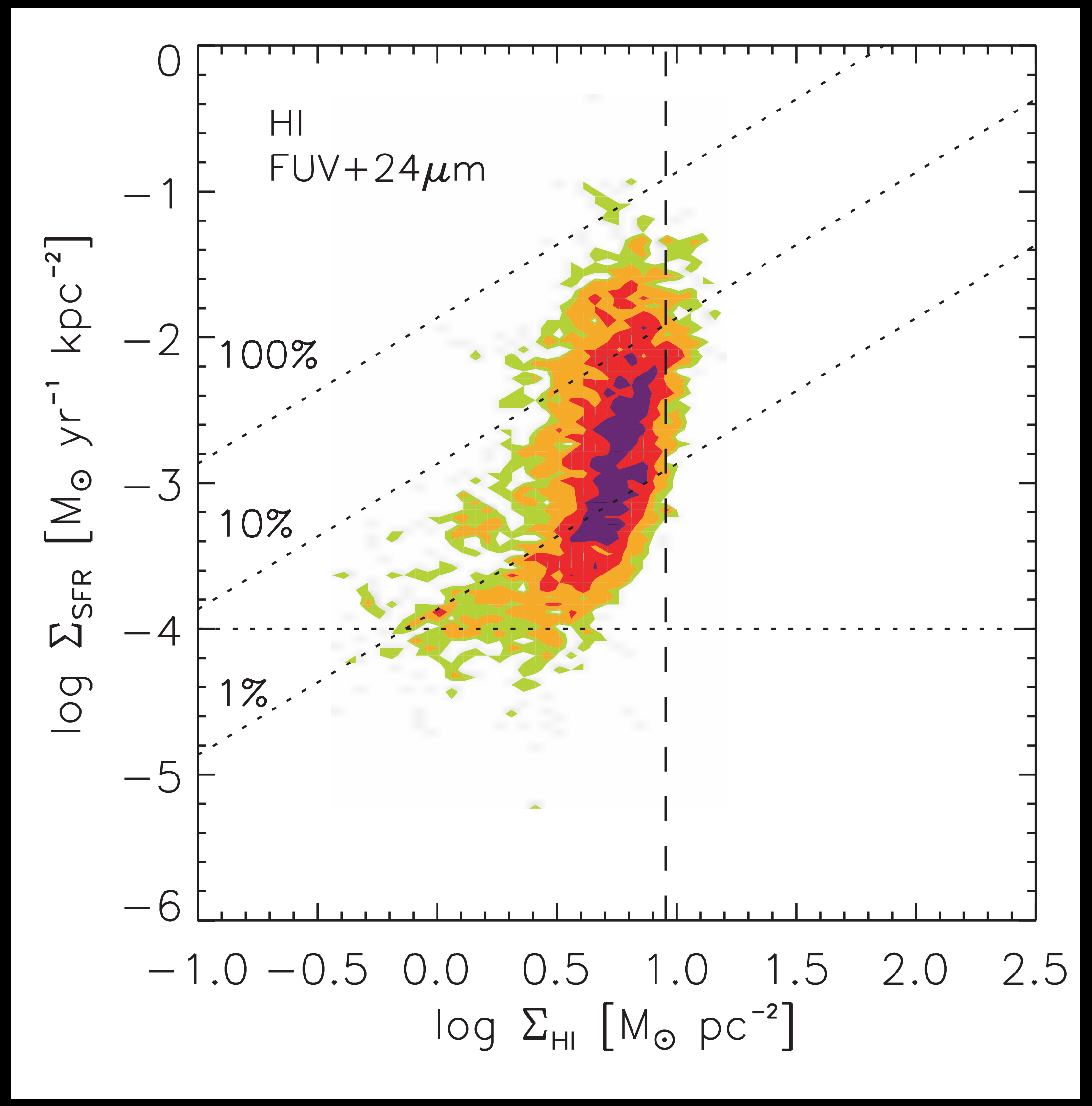


Krumholz 2014

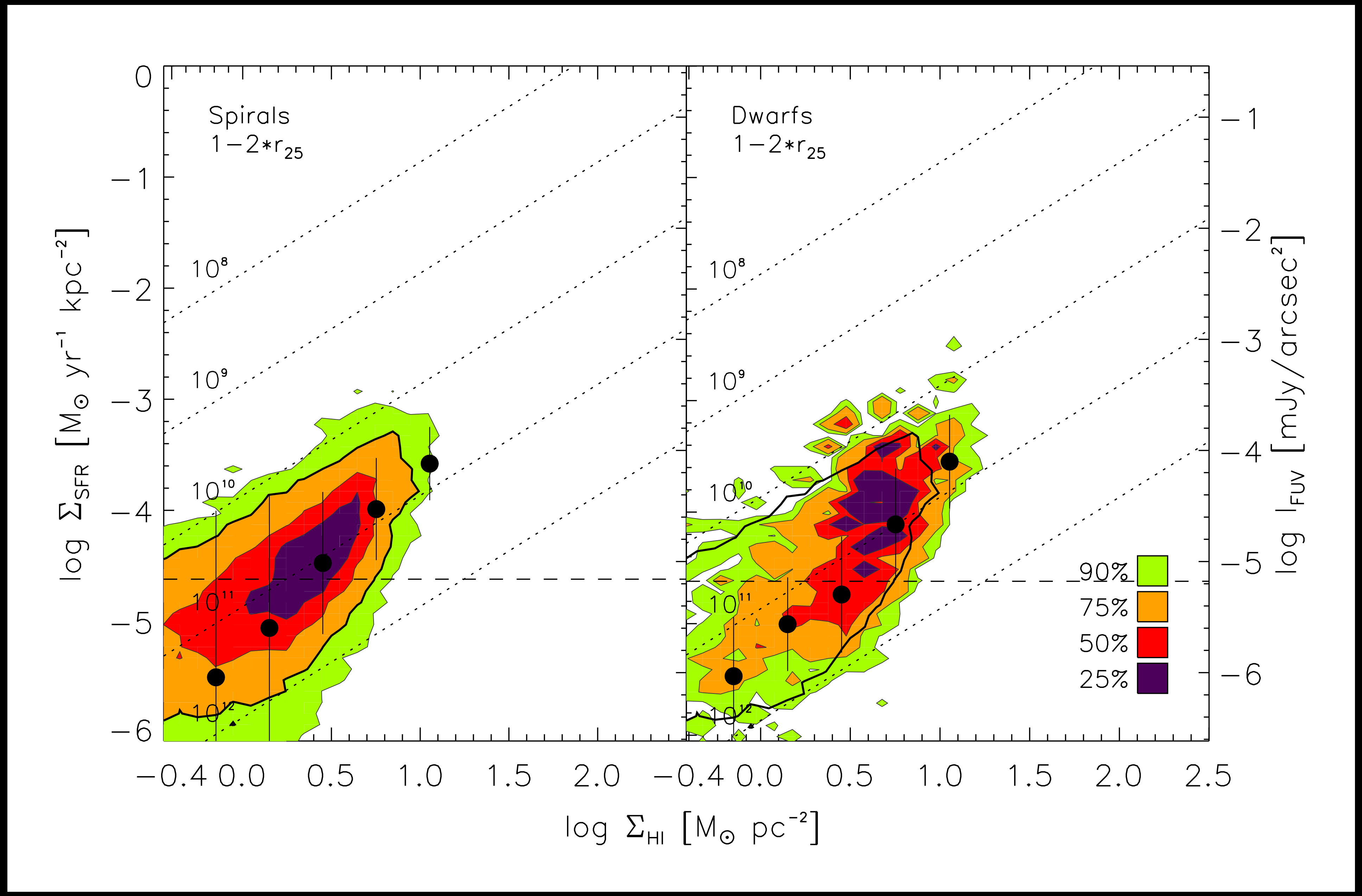
SF in atomic gas

- Outer galaxies and dwarfs dominated by HI rather than H_2
- In inner galaxies, basically no correlation between SFR and amount of HI.
- Instead HI has a maximum surface density of ~10 $M_\odot$ pc^{-2} independent of SFR
- In outer galaxies there is a correlation, but with very large scatter, and very large depletion time — t_{dep} ~ 100 Gyr
- Ratio of H_2 and HI depletion times implies a minimum H2 fraction ~2%

Bigiel+ 2008



Bigiel+ 2010



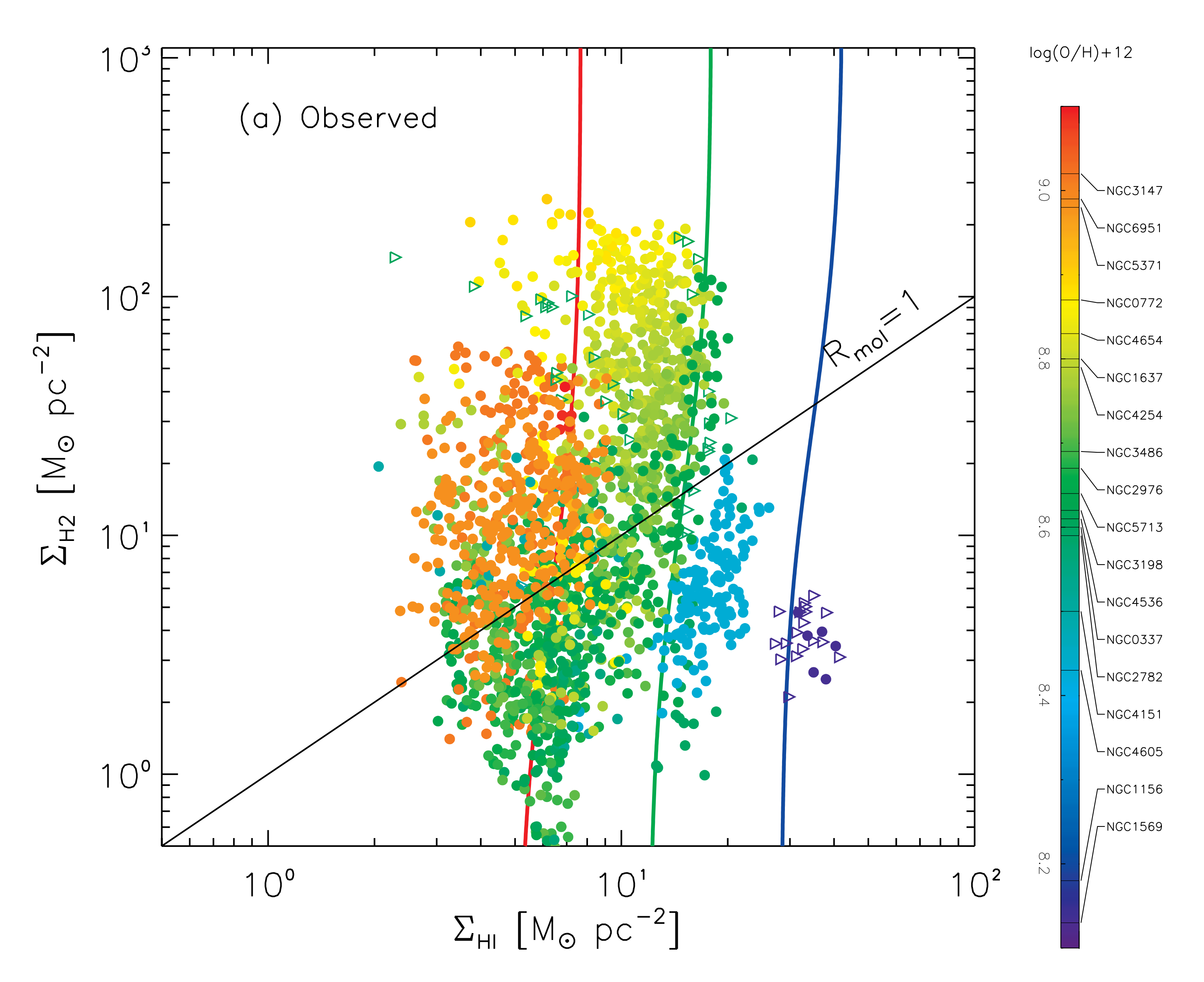
Metallicity-dependence

- HI/H_2 transition depends on metallicity — both theoretically predicted and observed

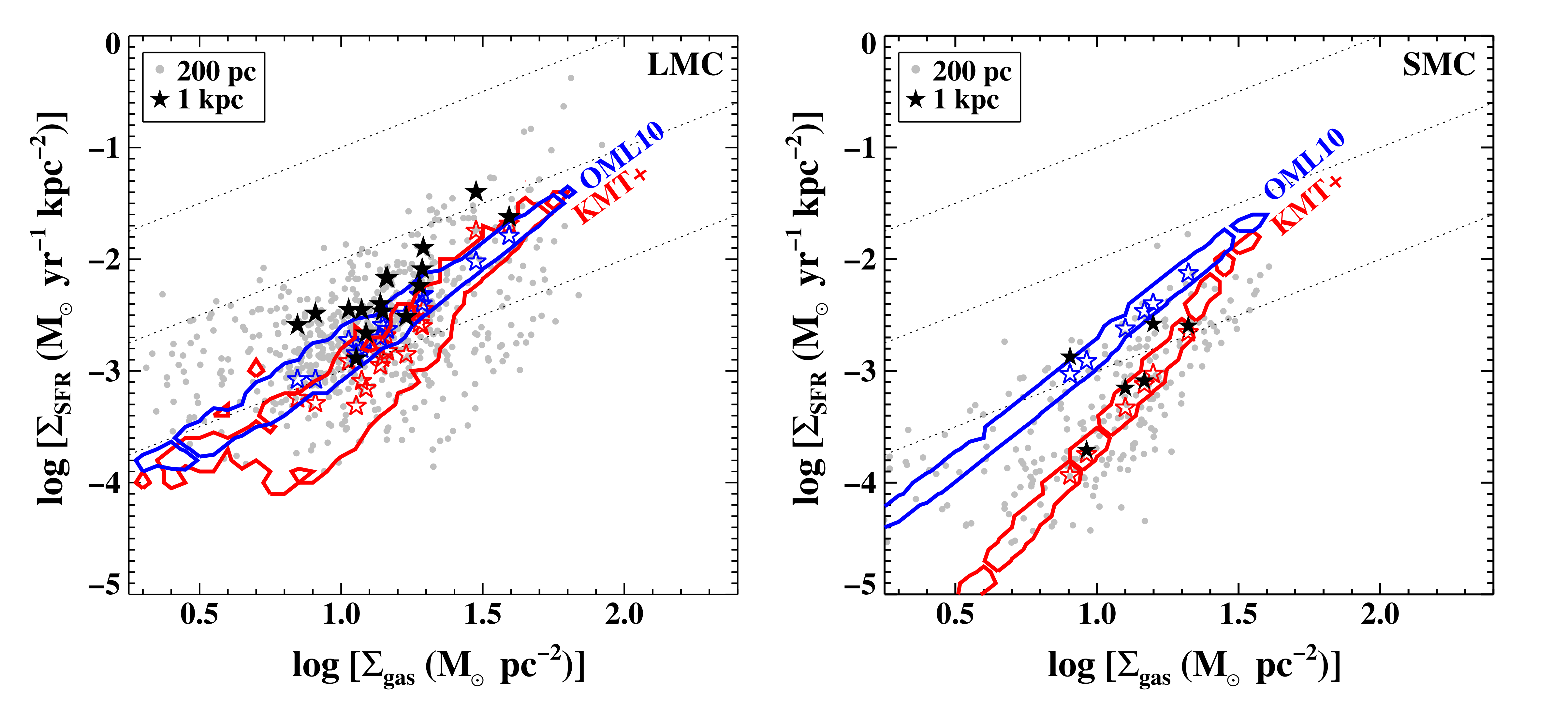
- Stars seem to form only in H_2, which suggests total gas KS relation should vary depending on metallicity

- This appears to be the case: SMC ($Z \sim 0.2\ Z_\odot$) has lower SFR at same total surface density than LMC ($Z \sim 0.5\ Z_\odot$) or spirals ($Z \sim Z_\odot$)

Wong+ 2013

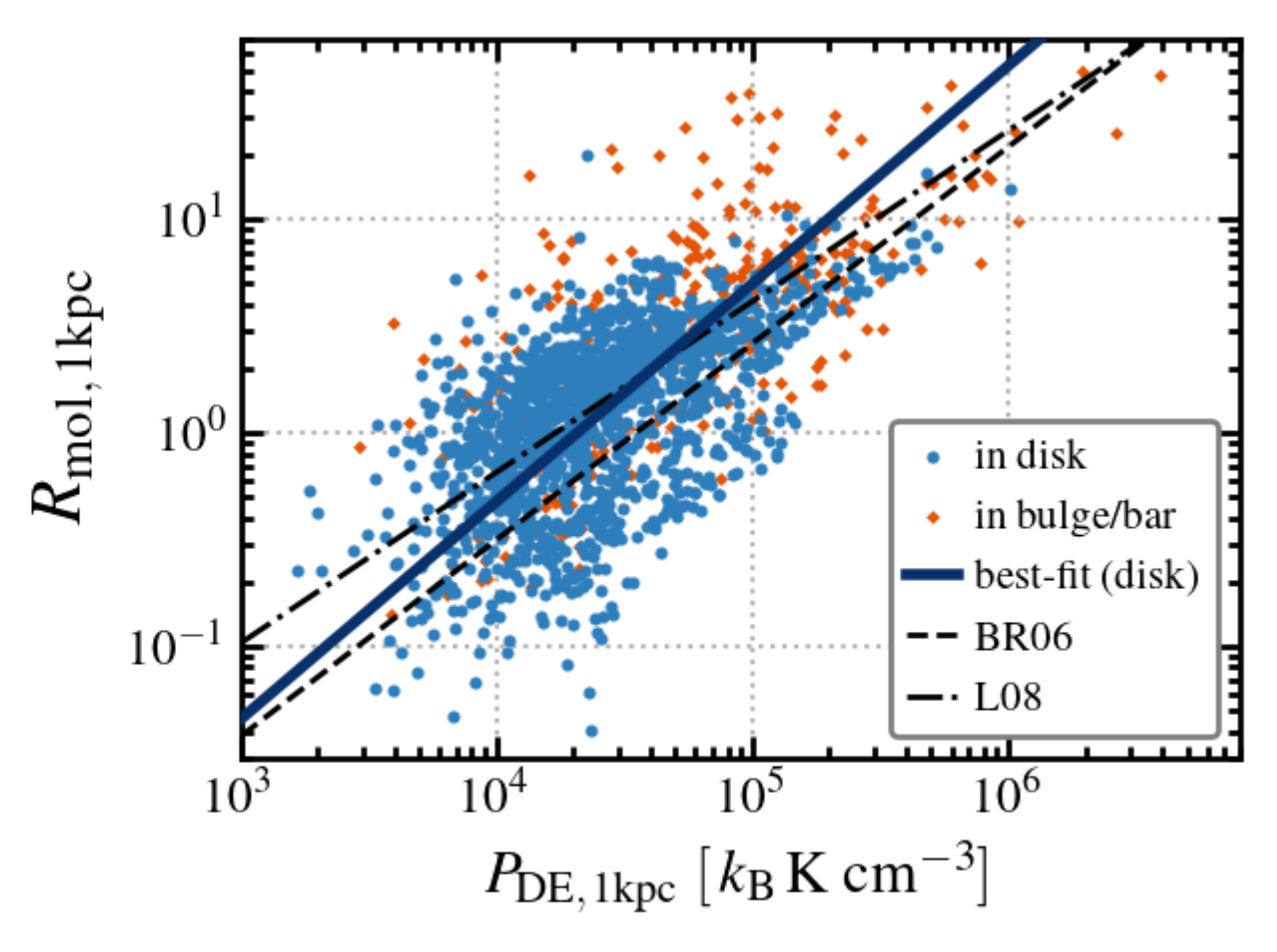


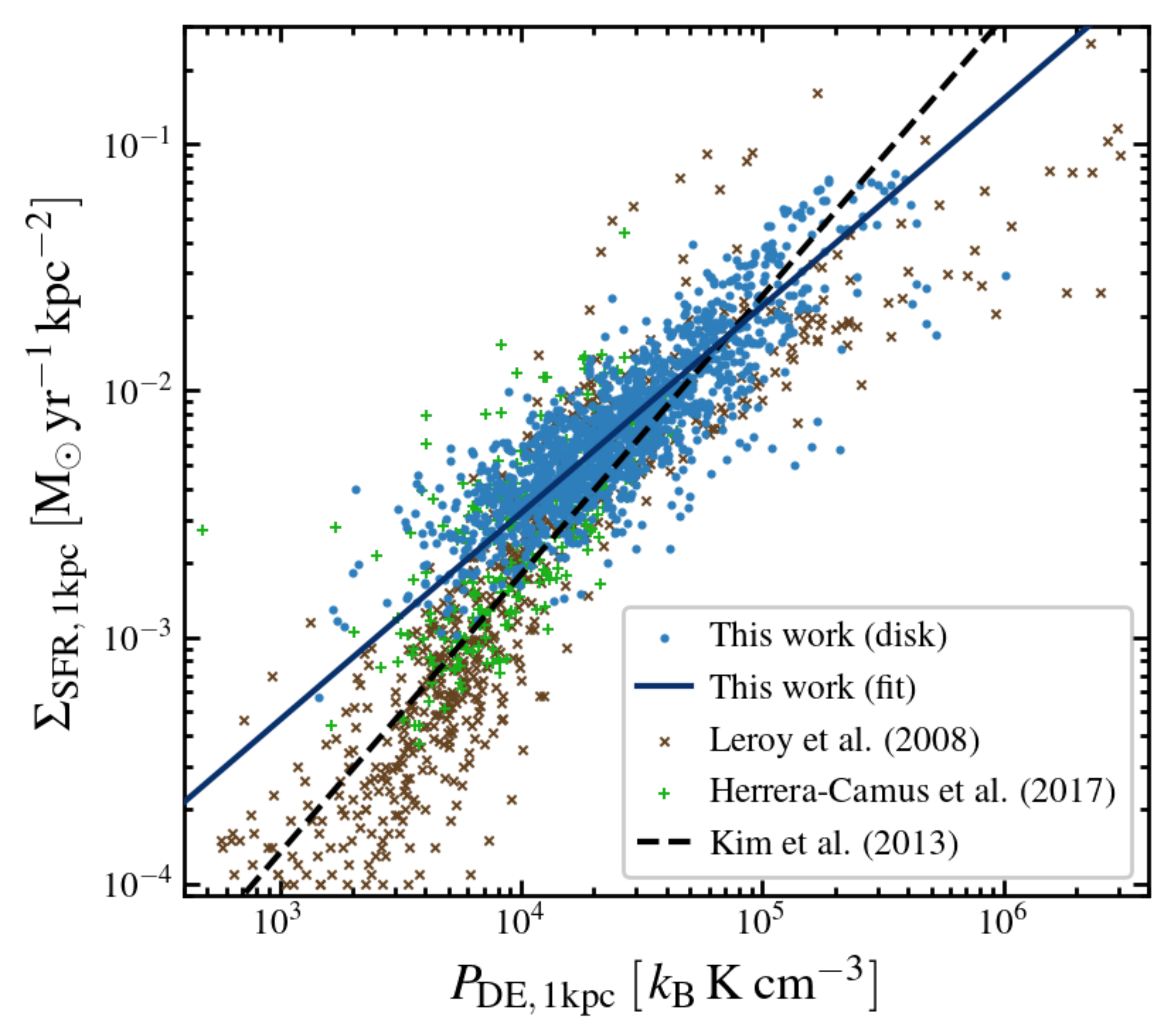
Jameson+ 2016



Pressure dependence

- In local discs, SFR and molecular fraction also correlate with ISM pressure
- Pressure depends on both gas and stellar surface density, and on ratio of stellar to gas velocity dispersion
- Degeneracy between metallicity and pressure dependence: pressure is higher in high metallicity regions (inner discs, spirals) and lower in lower metallicity regions (dwarfs, outer discs), so it is unclear which is primary variable





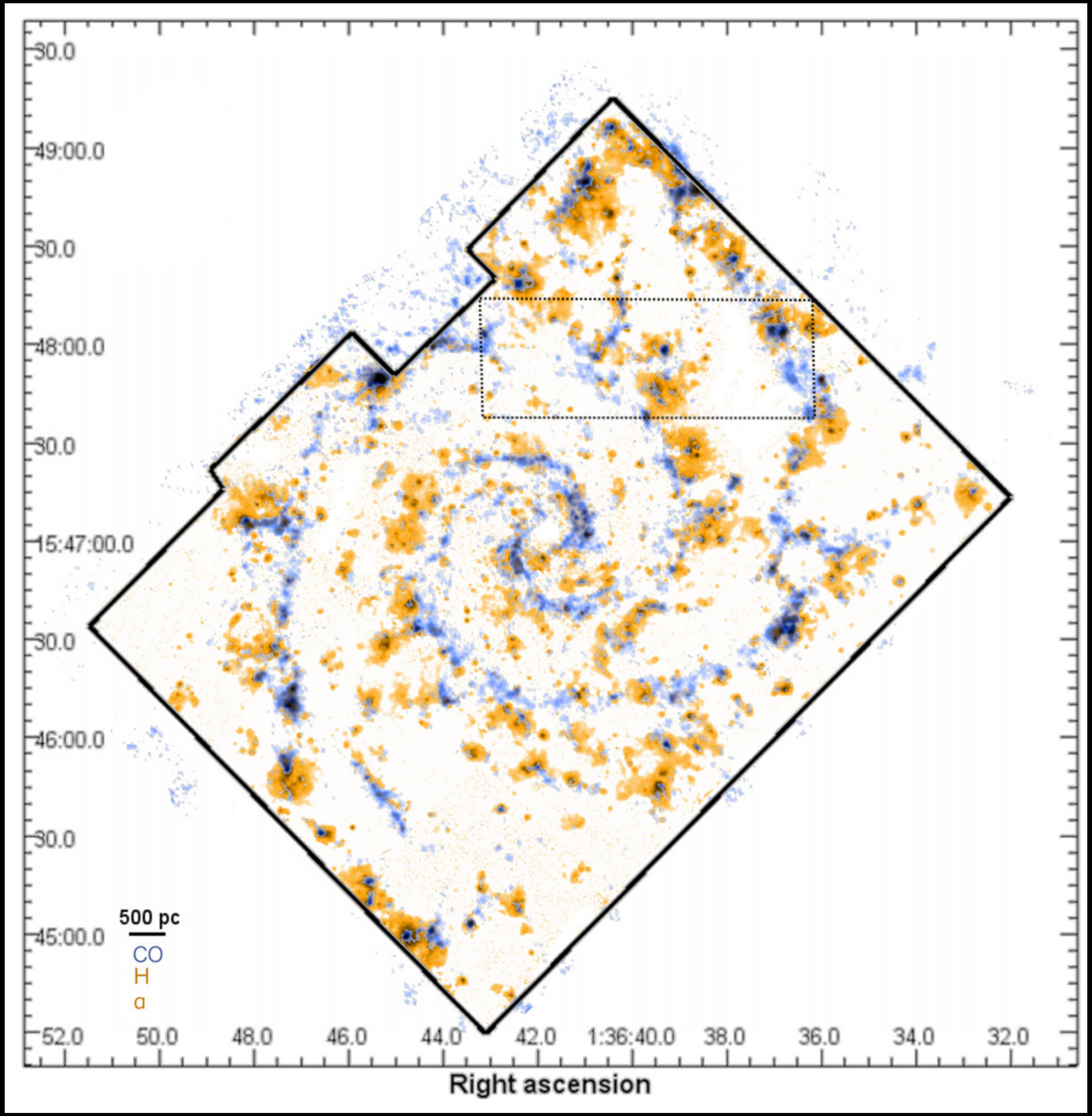
Sun+ 2020

Going to smaller scale

- Tracers of gas and star formation de-correlate on scales $\lesssim$ few hundred pc

- In grand-design spiral galaxies, CO is often on leading edge of spiral, Hα on trailing edge

- Suggested interpretation (discussed last time): result of rapid cloud destruction



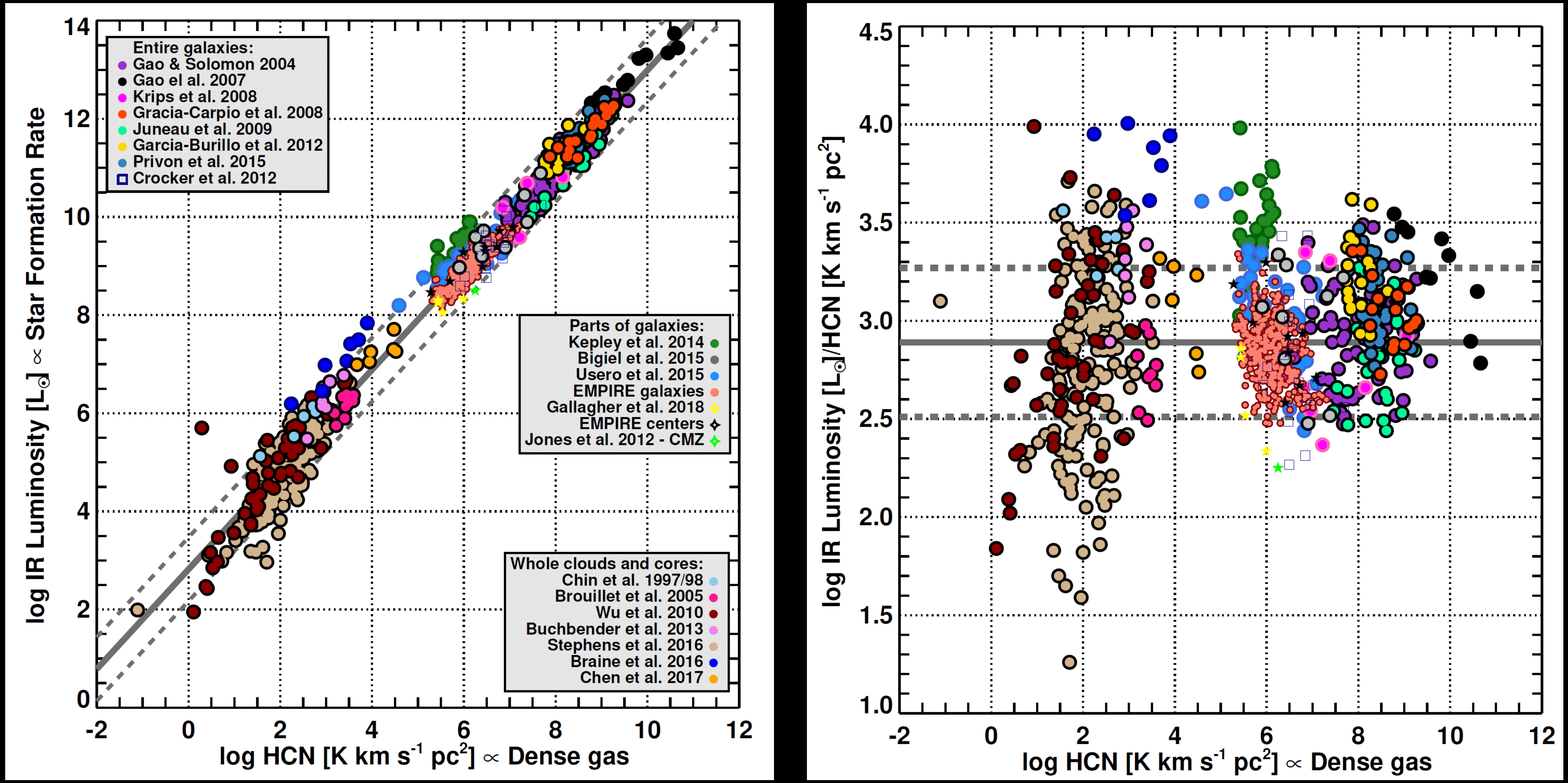
Kreckel+ 2018

Dense gas KS relations

Basic considerations

- CO has a critical density ~1000 cm^{-3}, so it traces most of the molecular gas
- It is interesting to look at denser gas, e.g., HCN traces gas at ~10^4 cm^{-3}
- This is hard due to brightness: HCN is ~10x dimmer than CO in a typical spiral galaxy, so ~100x the telescope time is needed to reach equal SNR
- Everything else even fainter, too dim to use
- Whole-galaxy HCN measurements starting appearing in 2000s, focusing mostly on bright targets (starbursts)
- First spiral galaxy HCN maps only made ~2016 - today

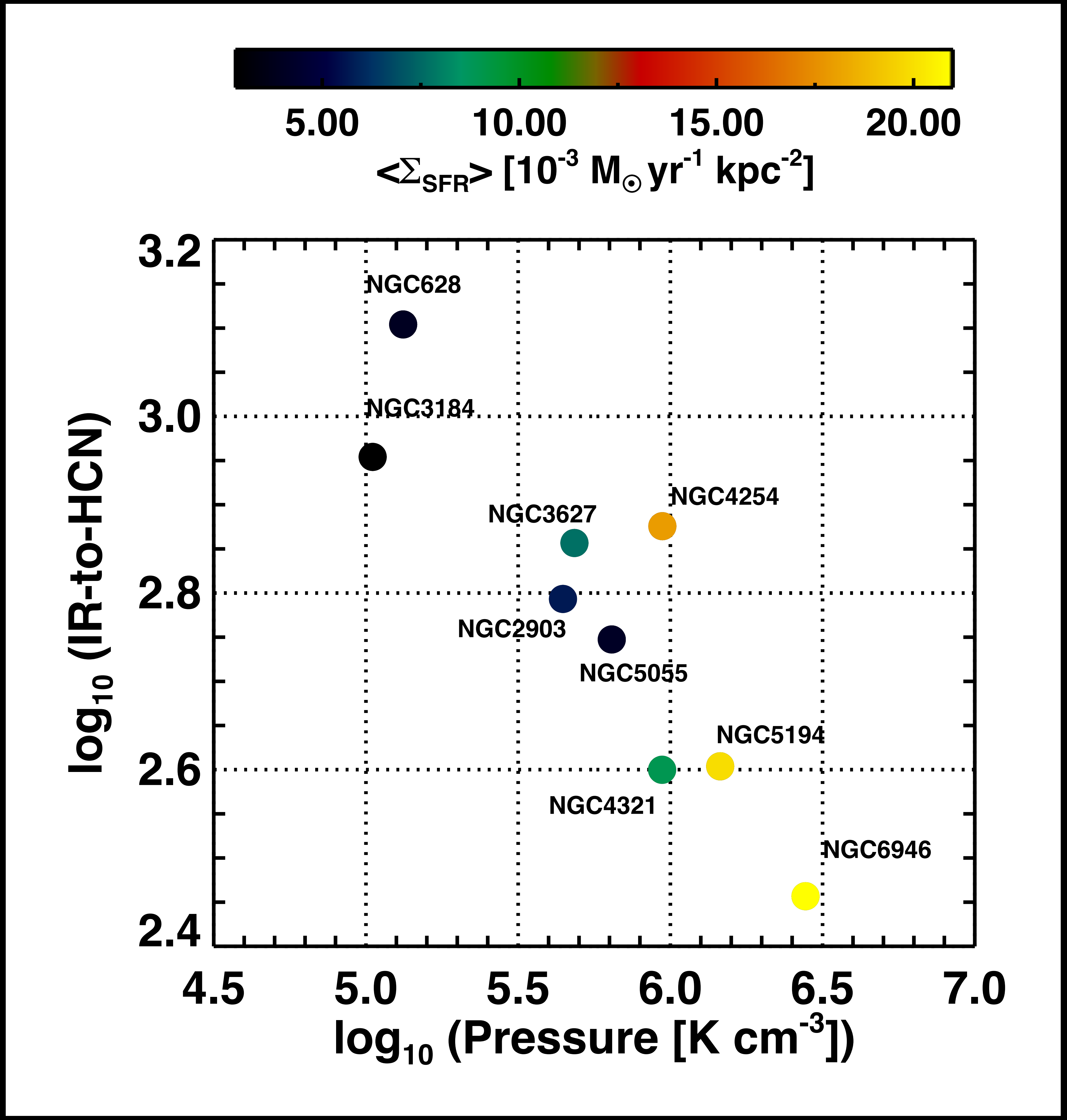
All the HCN data in one place



Jiménez-Donaire+ 2019

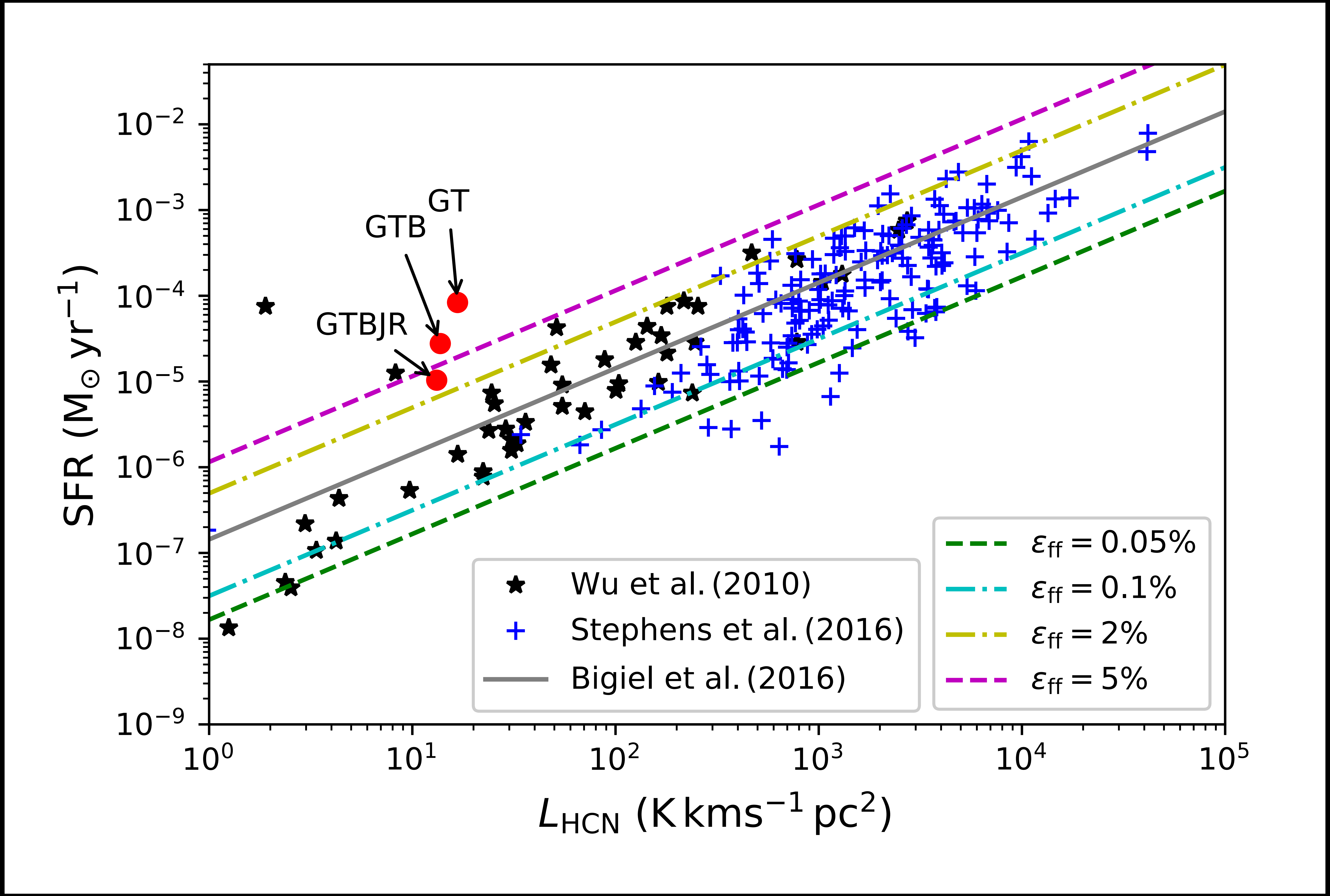
HCN-IR correlation

- To zeroth order, there is near-linear correlation between HCN (~dense gas mass) and IR luminosity (~SFR) → about constant SFR / dense gas mass
- First order: IR / HCN lower in galaxies with higher density / pressure / total SFR
- Suggested explanation:
    - Near-linear because SFR = $\varepsilon_{\mathrm{ff}}\, M / t_{\mathrm{ff}}$; $\varepsilon_{\mathrm{ff}}$ universal and t_{ff} fixed by critical density
    - Deviation from linearity because shape of PDF causes mean t_{ff} of HCN-emitting gas to go up when mean density does



Jiménez-Donaire+ 2019

HCN star formation efficiency



Onus+ 2018