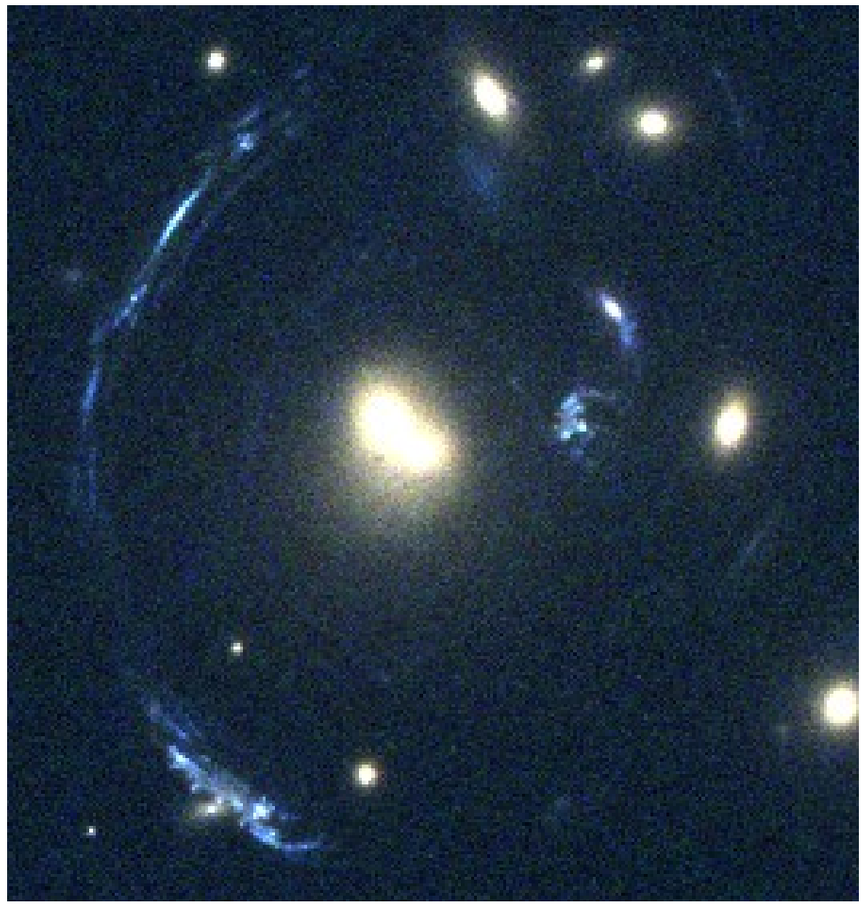
The Effects of Star Formation and Gas Tracers on the Spatially Resolved Schmidt-Kennicutt Relation at High Redshift



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Schmidt-Kennicutt Relation Reminder

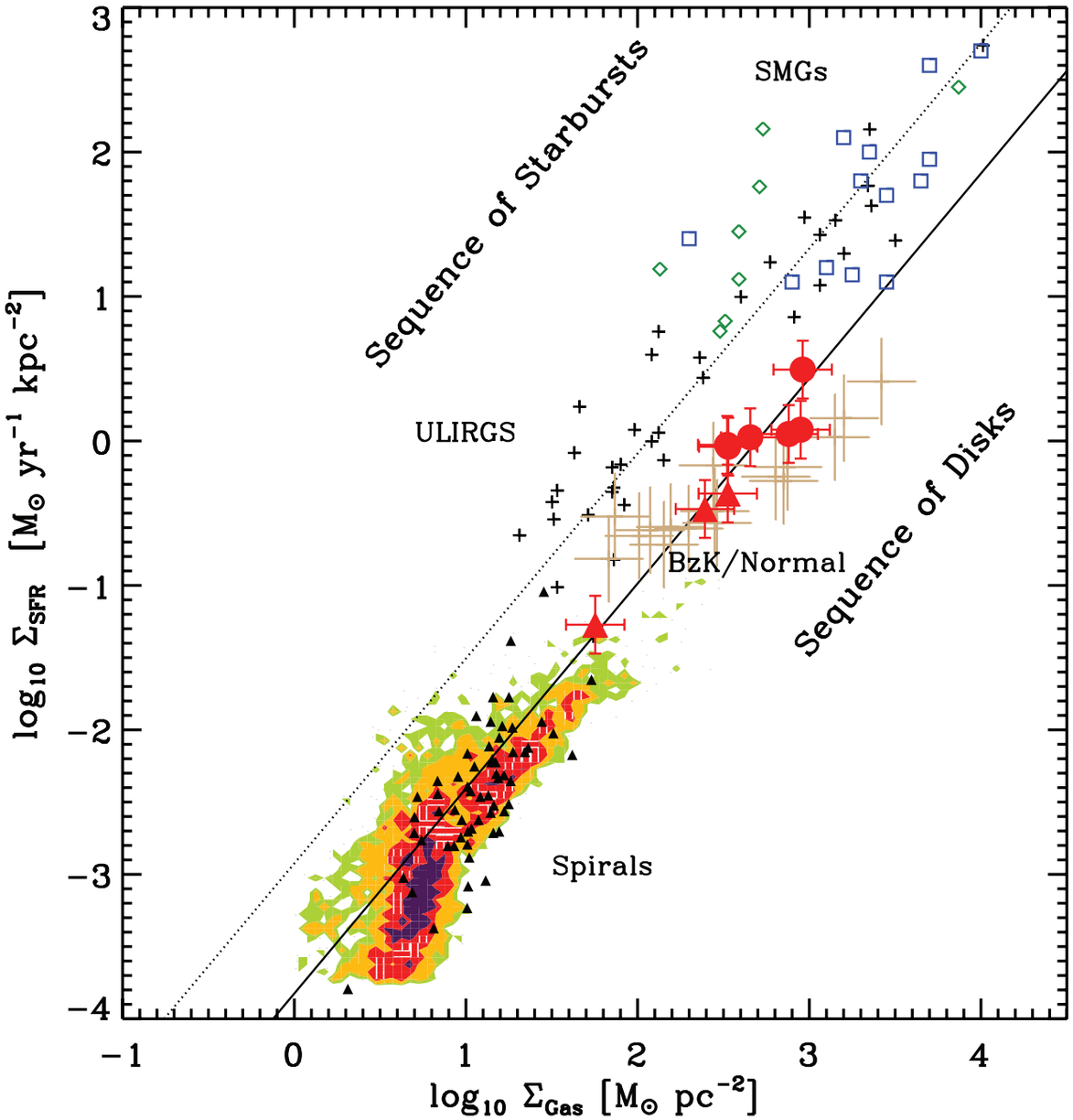
- Schmidt-Kennicutt relation is a correlation between the SFR and gas in galaxies

Want: $SFR \propto \rho_{gas}^{n}$

Observe: $\Sigma_{SFR} \propto \Sigma_{gas}^{N}$

or $L_{SFR} \propto L_{gas}^{N}$

- n and N should be the same, but subject to differential excitation effects (e.g., Narayanan et al. 2010)

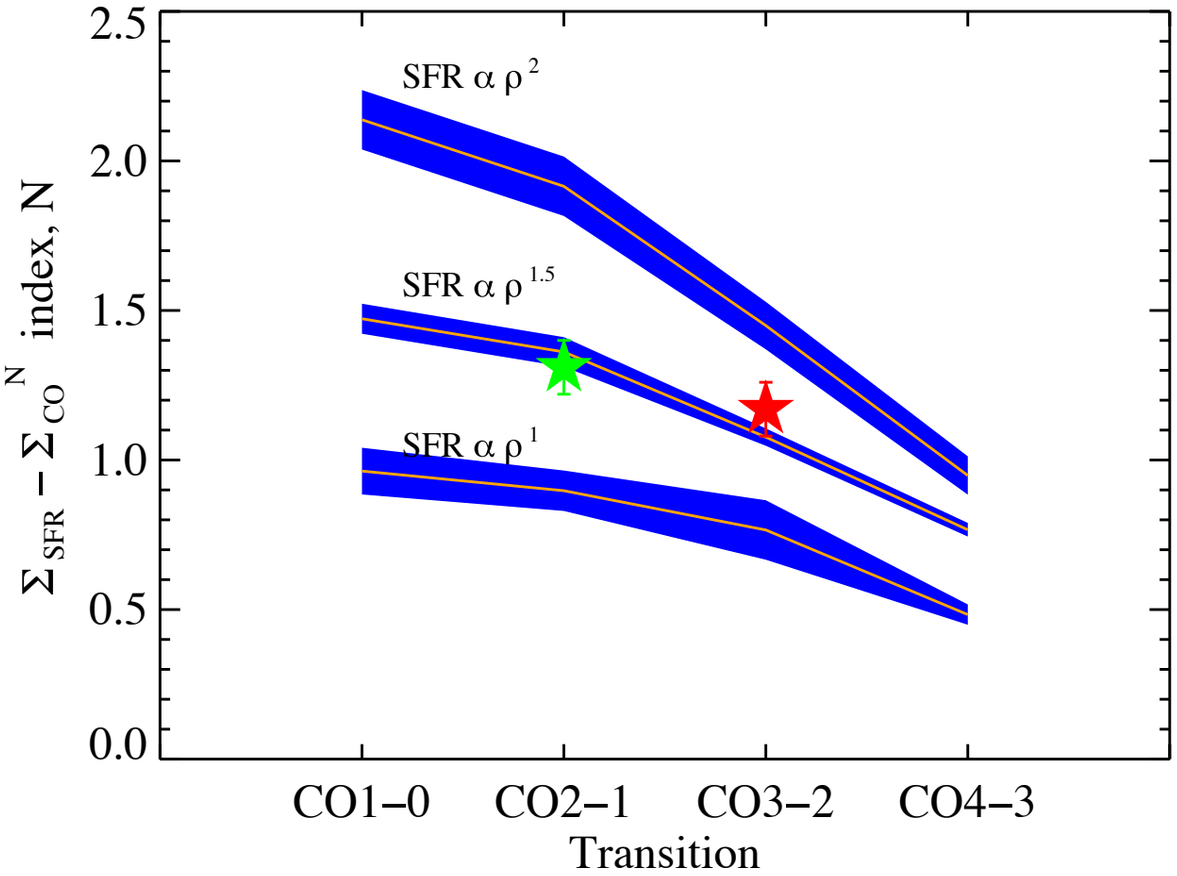


Daddi et al. 2010

→ Observed N depends on critical density of gas tracer

Schmidt-Kennicutt Relation Reminder

- Reproducing the SK relation is an important test of star formation theories
  - n=1: all gas has the same star formation efficiency (supply limited)
  - n>1: higher density gas is more efficient at turning into stars than lower density gas (n~2: collisional processes; n~1.5 *total* gas free-fall collapse time)
- Many galaxy simulations assume a star formation efficiency or enforce a SK relation

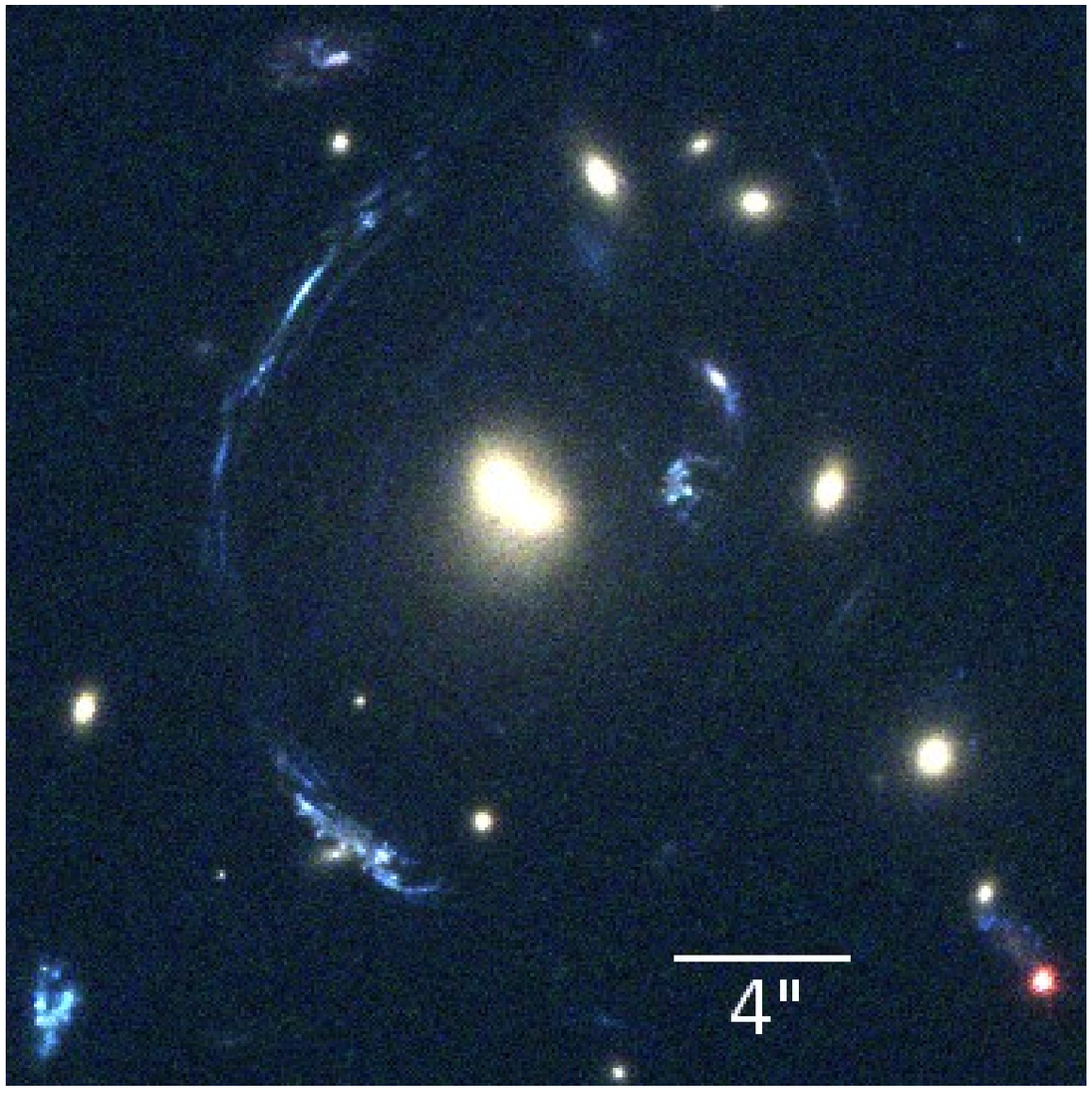


Narayanan et al. 2011

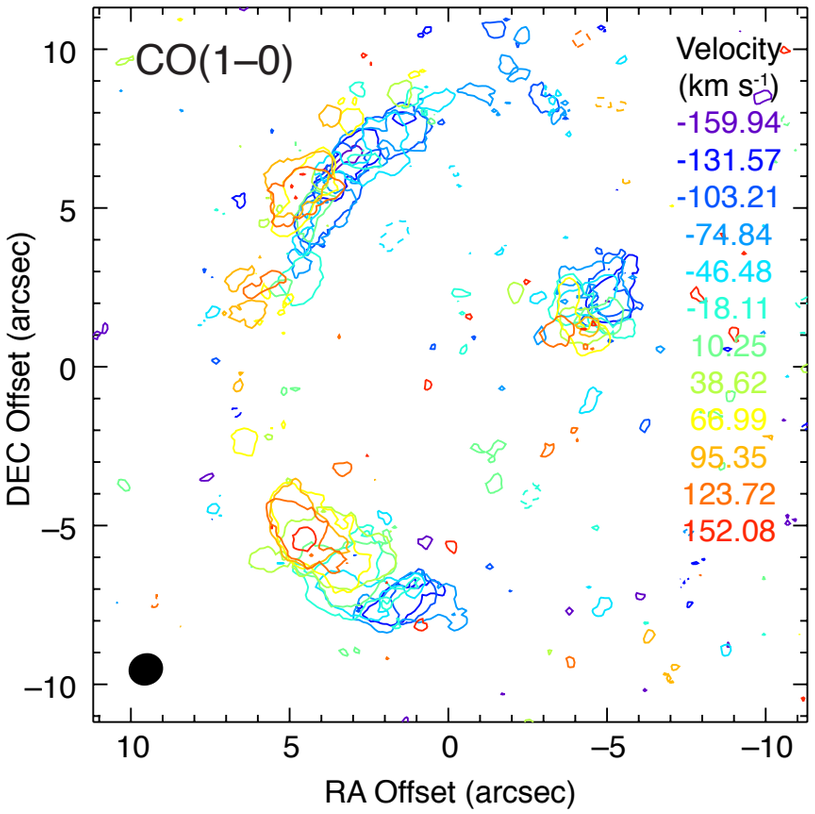
SK = Schmidt-Kennicutt

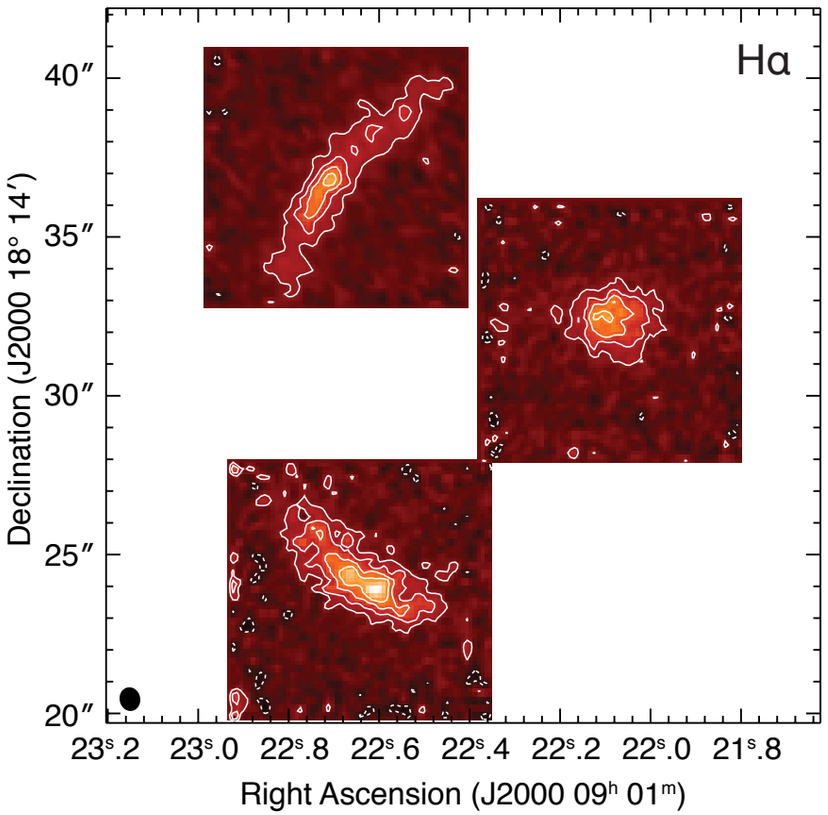
SDSS J0901+1814

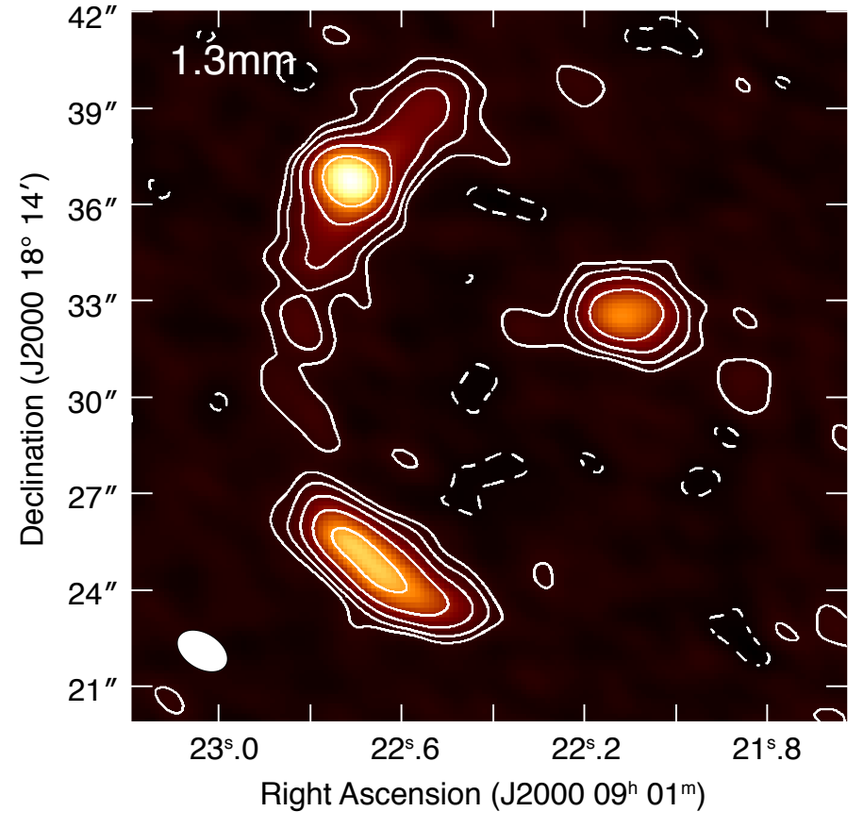
- Discovered in a systematic search for strongly-lensed star-forming galaxies in SDSS (Diehl et al. 2009)
- Bright in both rest-UV and dust emission
- Magnification ~25–30
- $SFR_{H\alpha+IR}$=580 $M_\odot$/yr
- z=2.26 face-on disk galaxy, above galaxy Main Sequence
- 12 + O/H = 8.9
- Contains an AGN, but it is not significant at long wavelengths (Fadely et al. 2010)



Observations

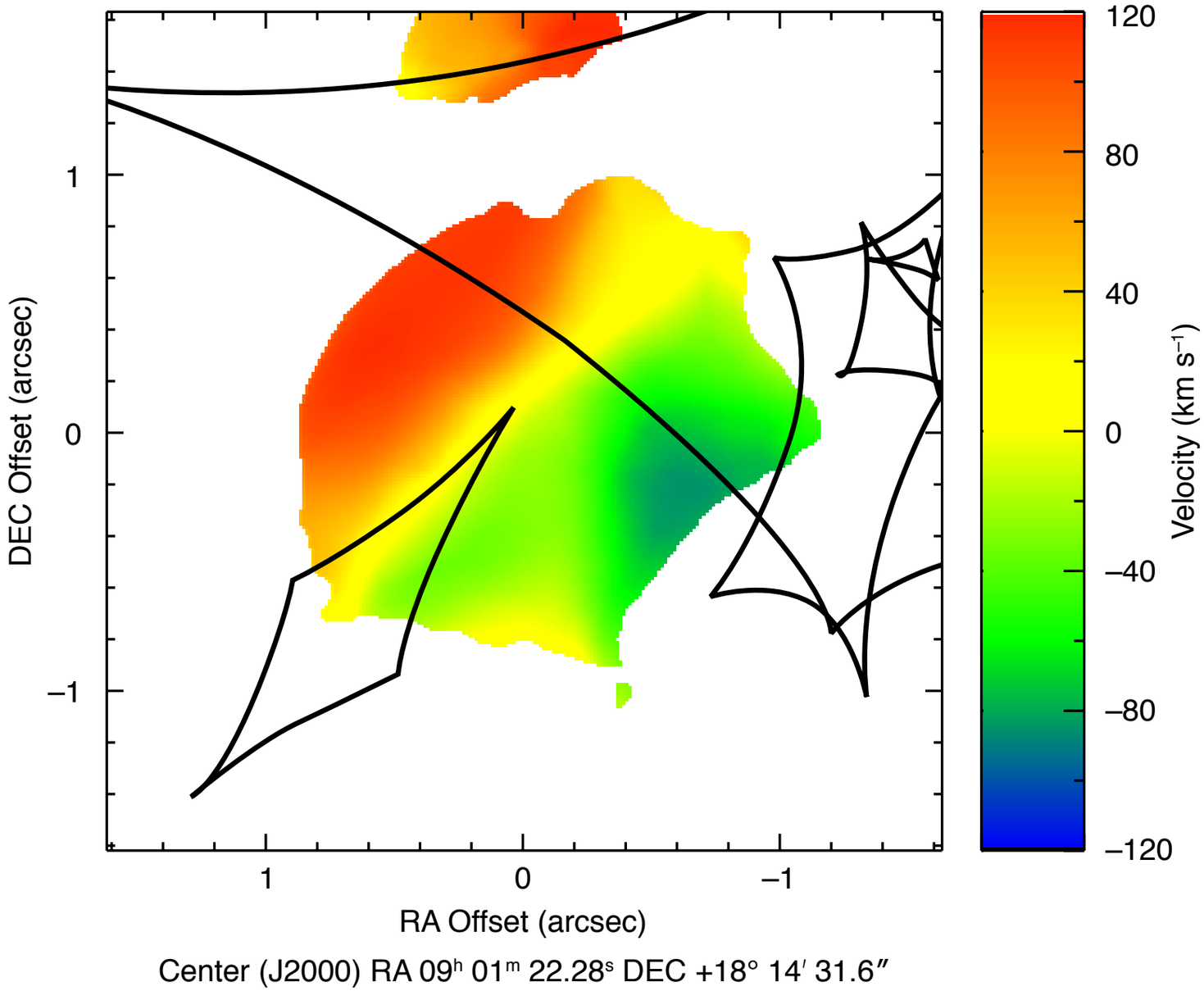






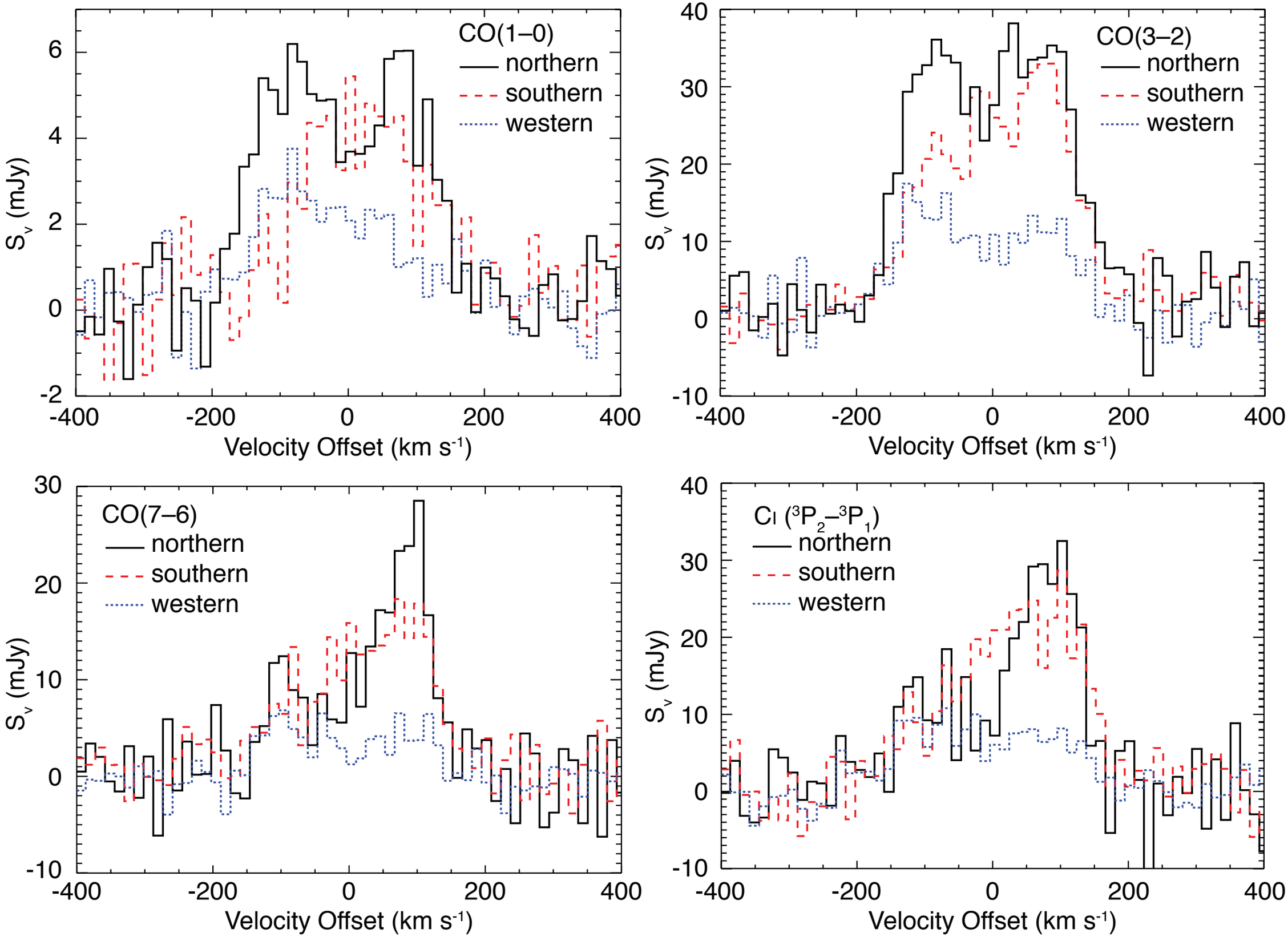
- VLA observations of CO(1–0)
- PdBI observations of CO(3–2)
- ALMA observations of CO(7–6), CI($^3P_2$–$^3P_1$), and 1.3mm continuum
- VLT/SINFONI observations including Hα and NII
- Photometry from optical through infrared

Lensing in J0901

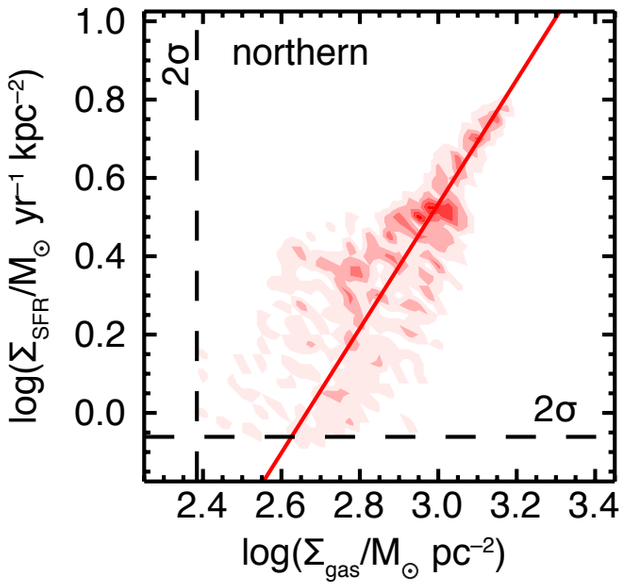


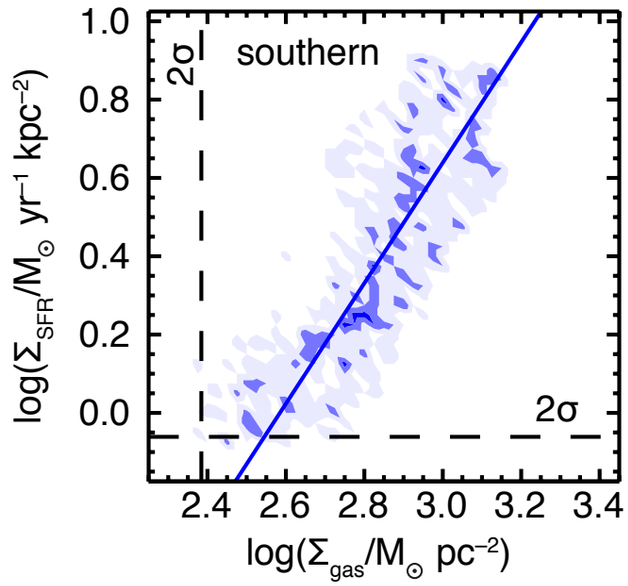
- J0901 crosses caustic → all of J0901 is doubly imaged (southern and western images), part of J0901 is quadruply imaged (northern image)
- Southern image has additional perturber → Western image/spectra likely most representative of true line profile

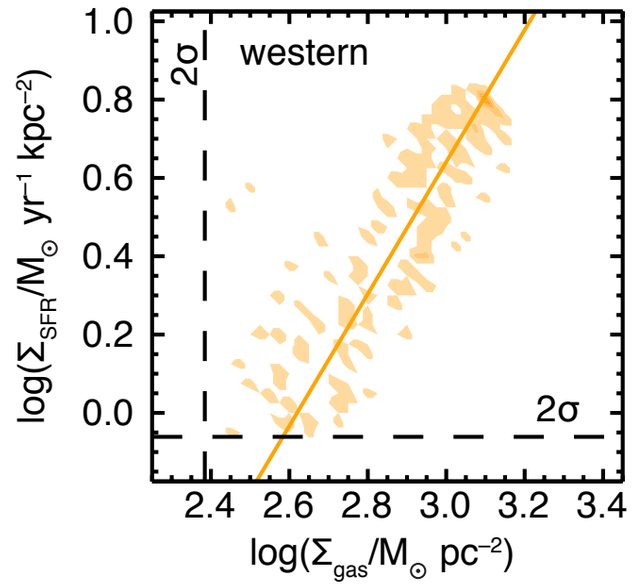
Differences in the relative line profiles of the four transitions for each image imply differential lensing

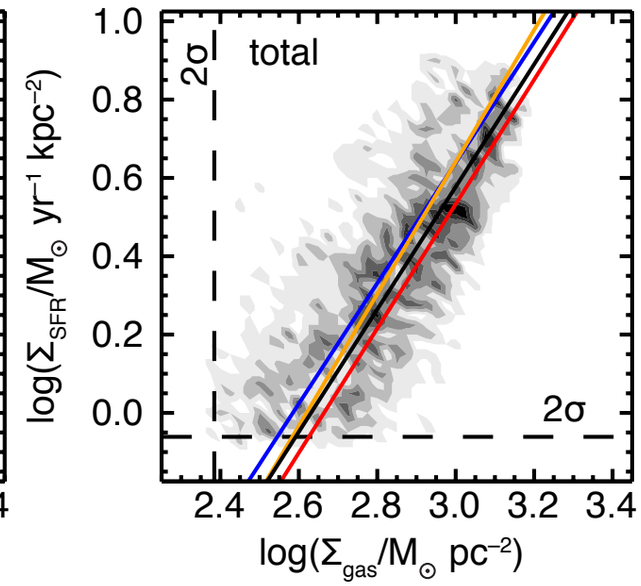


Is the SK Relation affected by lensing?









Current plots:

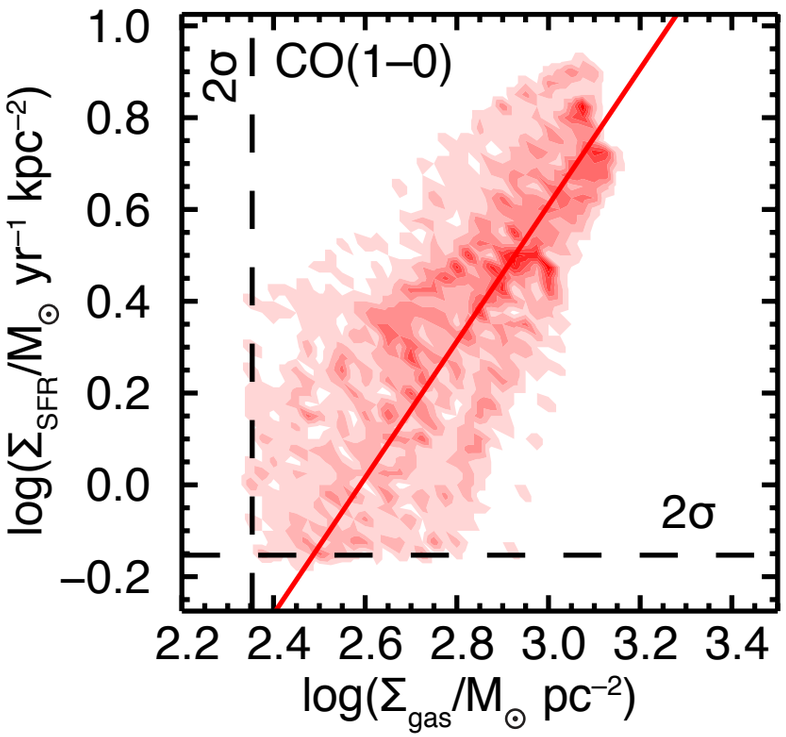
- Gas: CO(1–0), natural resolution
- SFR: Hα, but no extinction correction

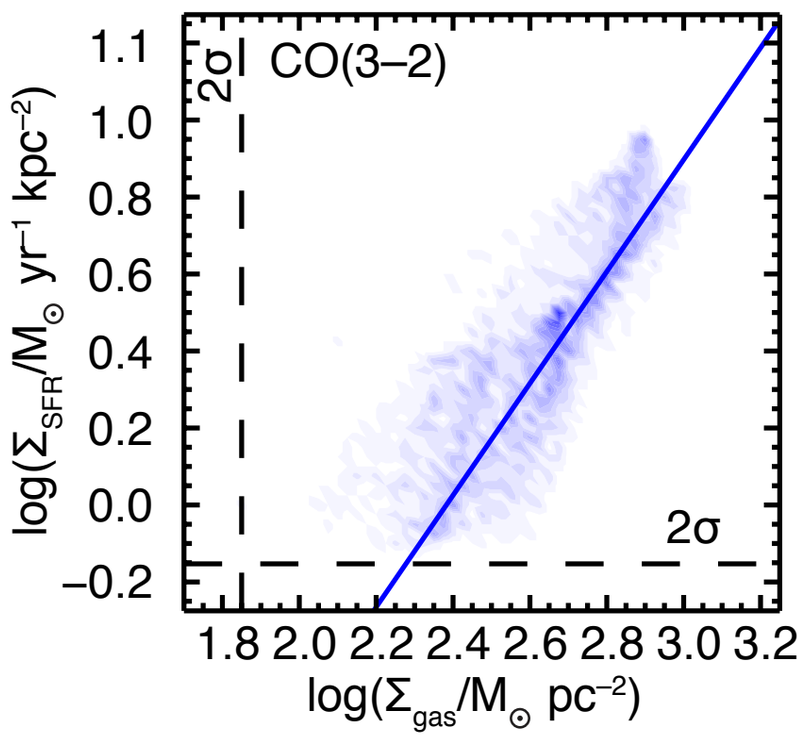
SK Indices:

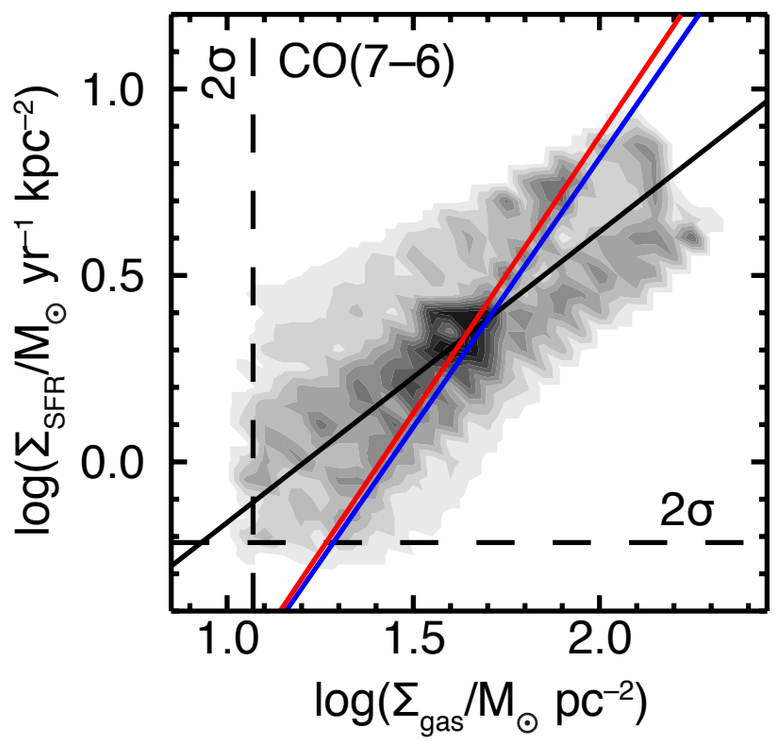
- North: 1.59±0.28
- South: 1.54±0.19
- West: 1.69±0.82
- Total: 1.56±0.26

No significant difference in SK index between images! (True for all CO lines.)

Is the SK Relation affected by CO excitation?







Current plots:

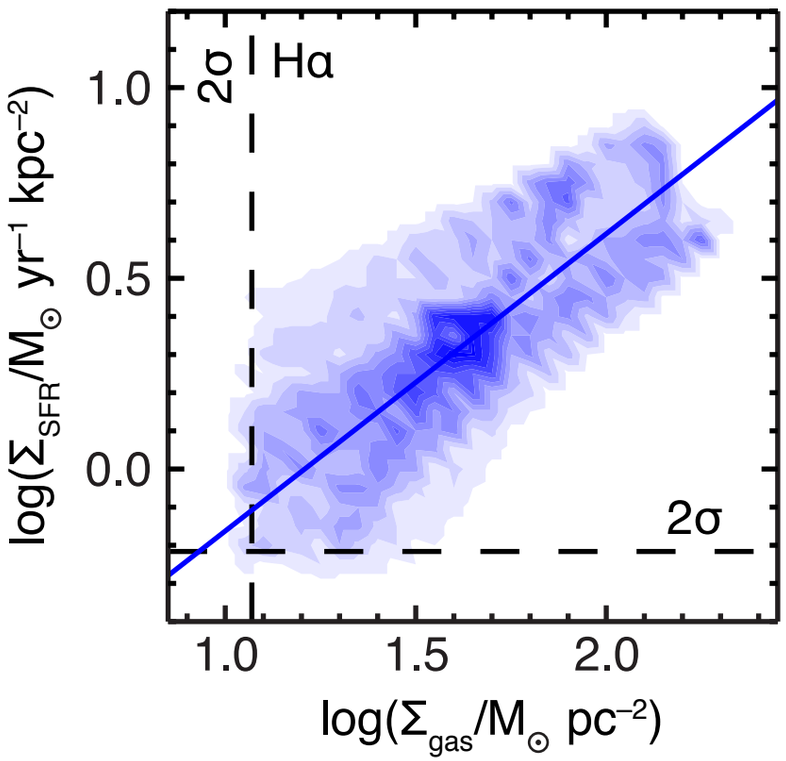
- Image: total
- Gas: matched resolution
- SFR: Hα, but no extinction correction

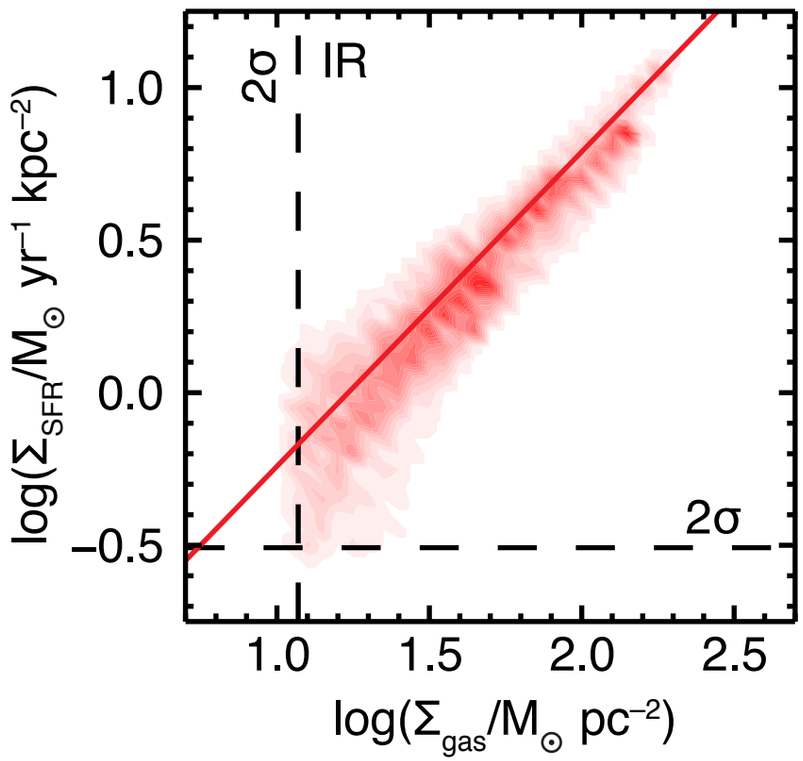
SK Indices:

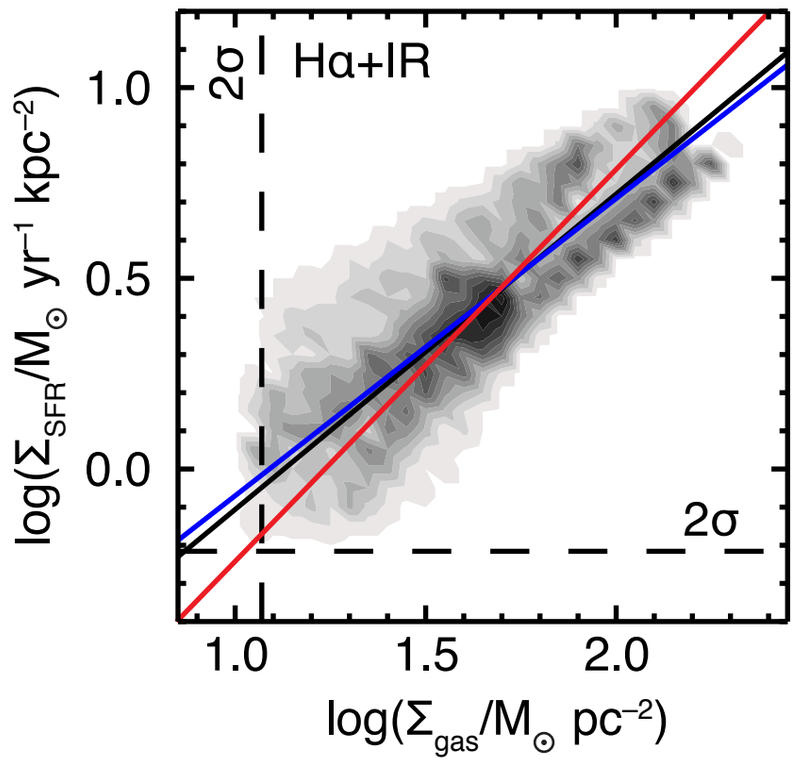
- CO(1–0): 1.48±0.21
- CO(3–2): 1.40±0.27
- CO(7–6): 0.78±0.08

Yes! The SK index decreases with CO line excitation. (True for all SFR tracers.)

Is the SK Relation affected by the SFR tracer?







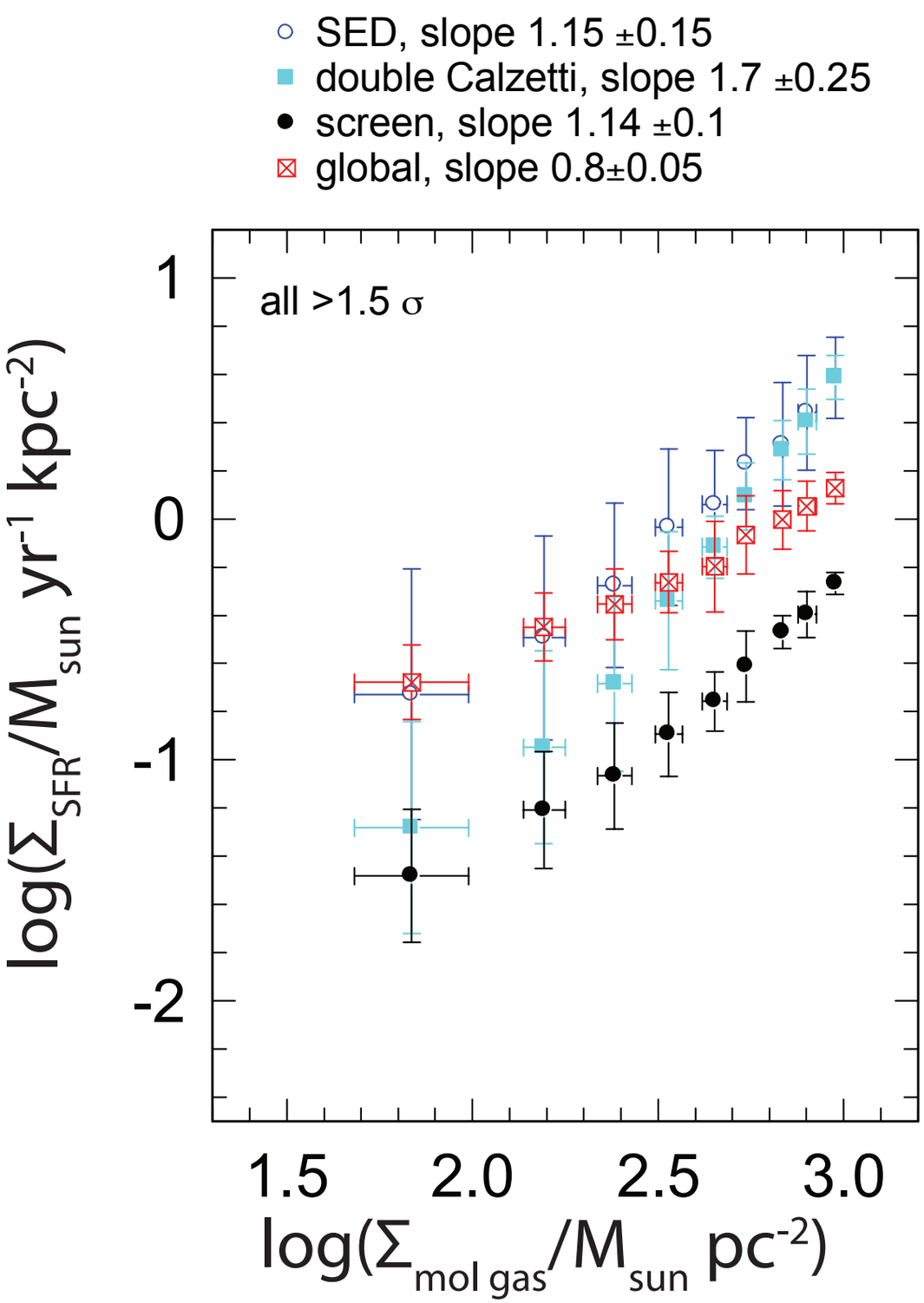
Current plots:

- Image: total
- Gas: CO(7–6), matched resolution

SK Indices:

- Hα: 0.78±0.08
- IR: 1.03±0.15
- Hα+IR: 0.83±0.09

Yes! The SK changes with SFR tracer. (True for all CO lines.)

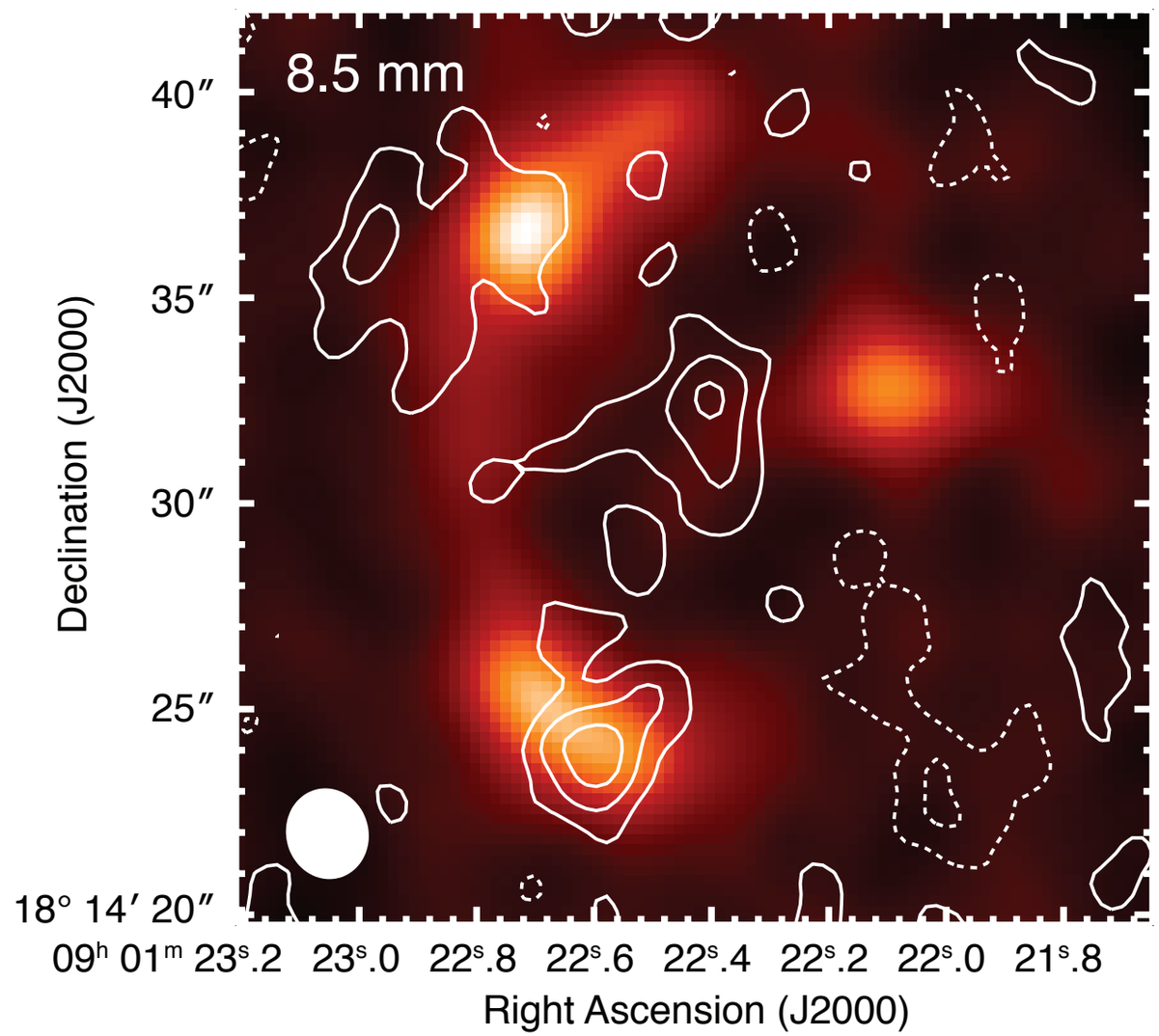


- Accounting for both obscured and unobscured star formation is critical! (see also Genzel et al. 2013)

Aside: Tracing Star Formation with Radio

- Do detect 115 GHz (rest frame) continuum emission at VLA, but only with large taper
- Does **not** appear to trace other emission as well, but low S/N…
- Excess radio emission compared to Magnelli et al. (2015) radio-IR correlation
- ≲20% of 115 GHz emission can be accounted for based on $SFR_{H\alpha+IR}$ (mostly free-free using Condon et al. 1992)
- Possibly AGN emission? And/or differential lensing?

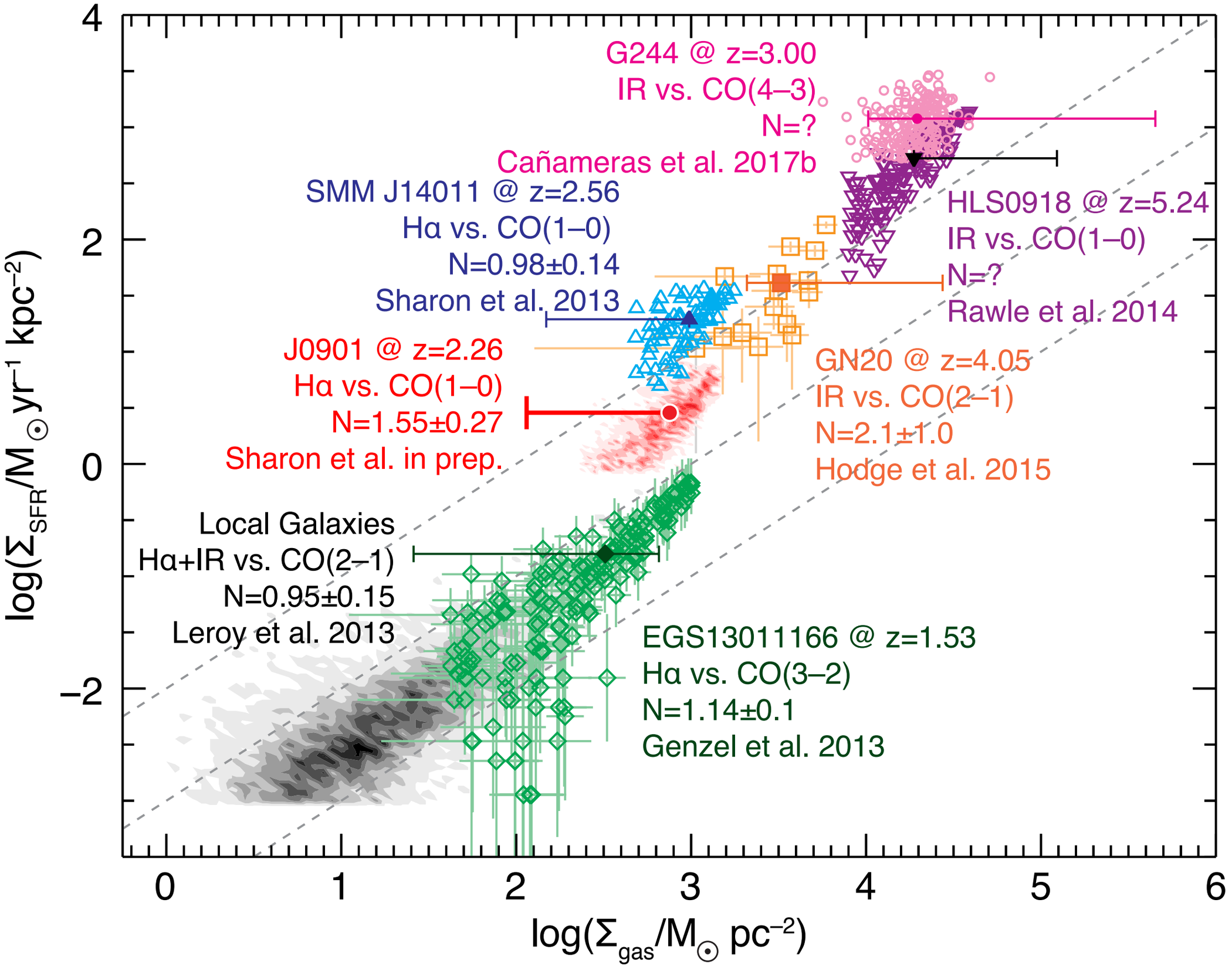
Background:
CO(3–2), same resolution



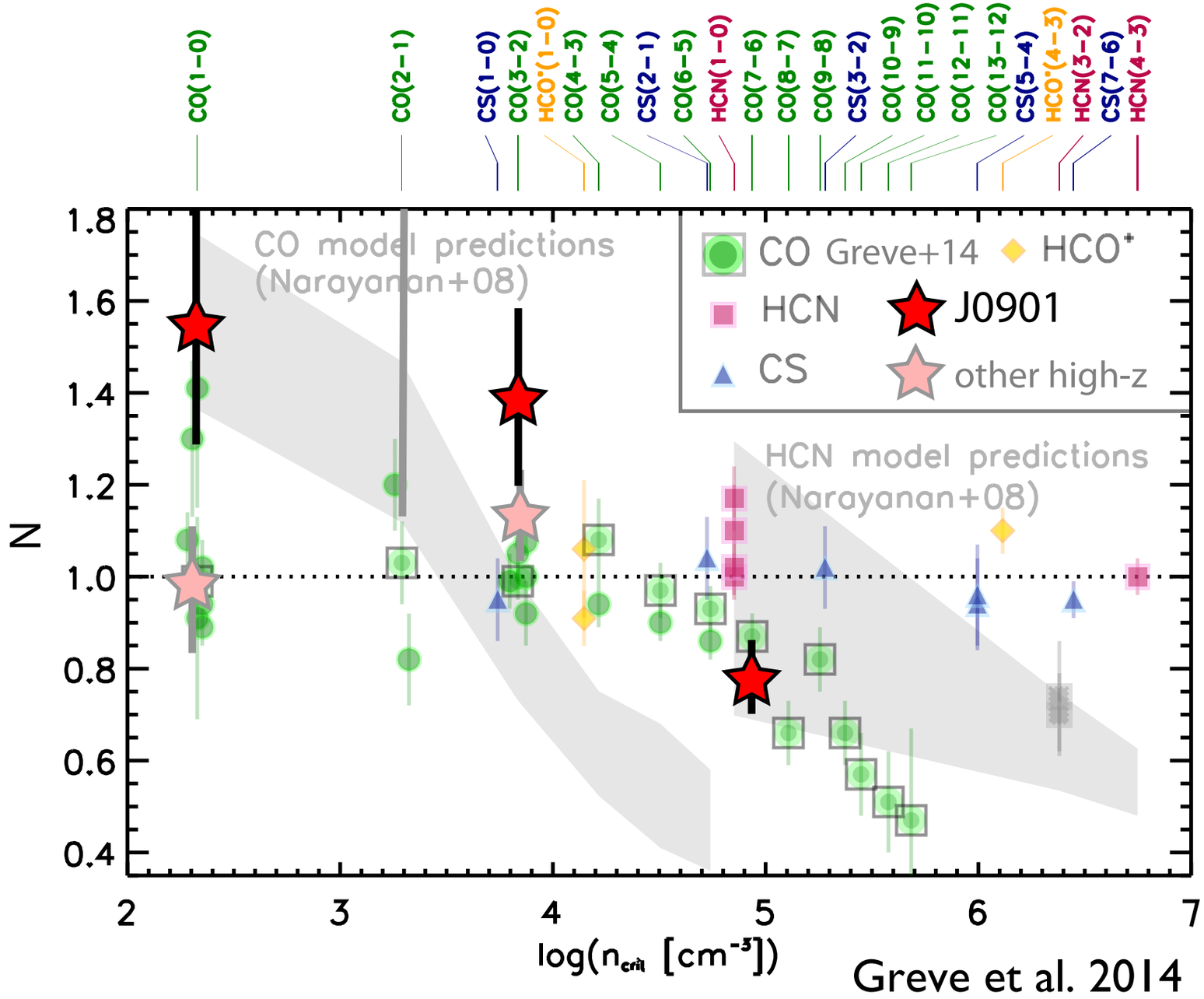
SK Index Summary for J0901

- Indices do **not** vary between images
- Indices are **not** affected by lensing (TBD for CO(7–6))
- Indices **do** change with CO line
- Indices **do** change with SF tracer

Comparisons to Other Galaxies

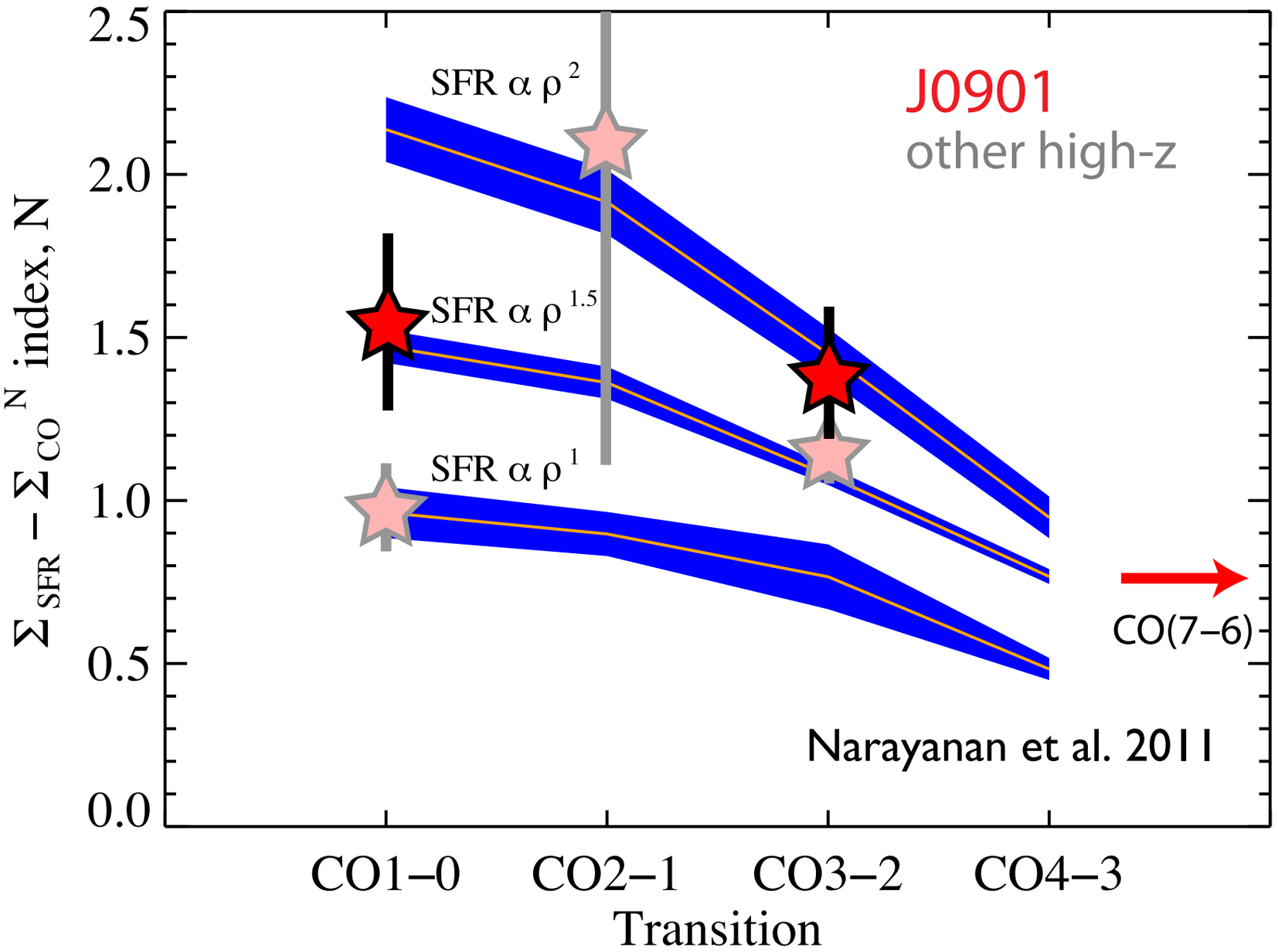


SK Index with Excitation: Comparison to Local Galaxies



- Index as function of critical density not entirely in line with integrated correlations

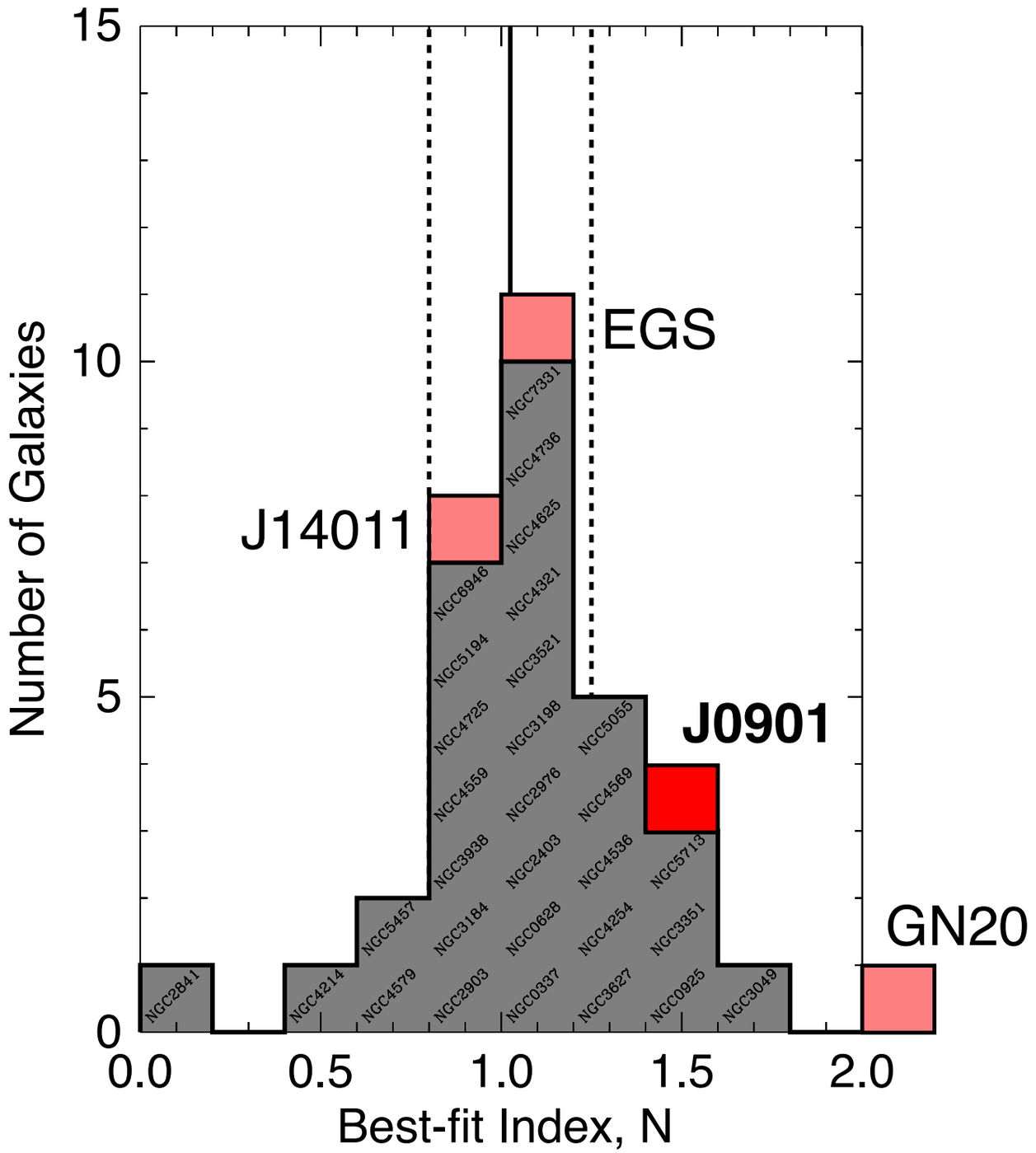
Comparison to Predictions



- Not consistent with any particular model or predicted scatter

Comparison to Low-z Galaxies

- Indices are in line with the distribution seen for local star-forming galaxies (neglecting differential excitation)
- If indices vary with other galaxy parameters, need to build larger high-z/ multi-J samples with accurate SFR measurements to find true population indices

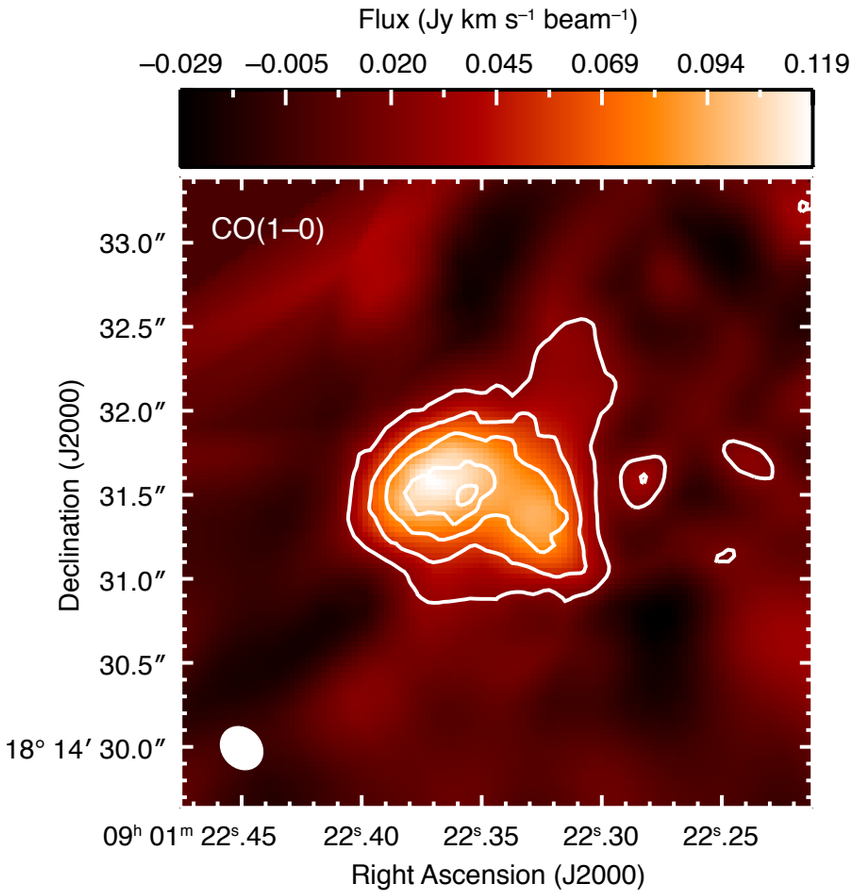


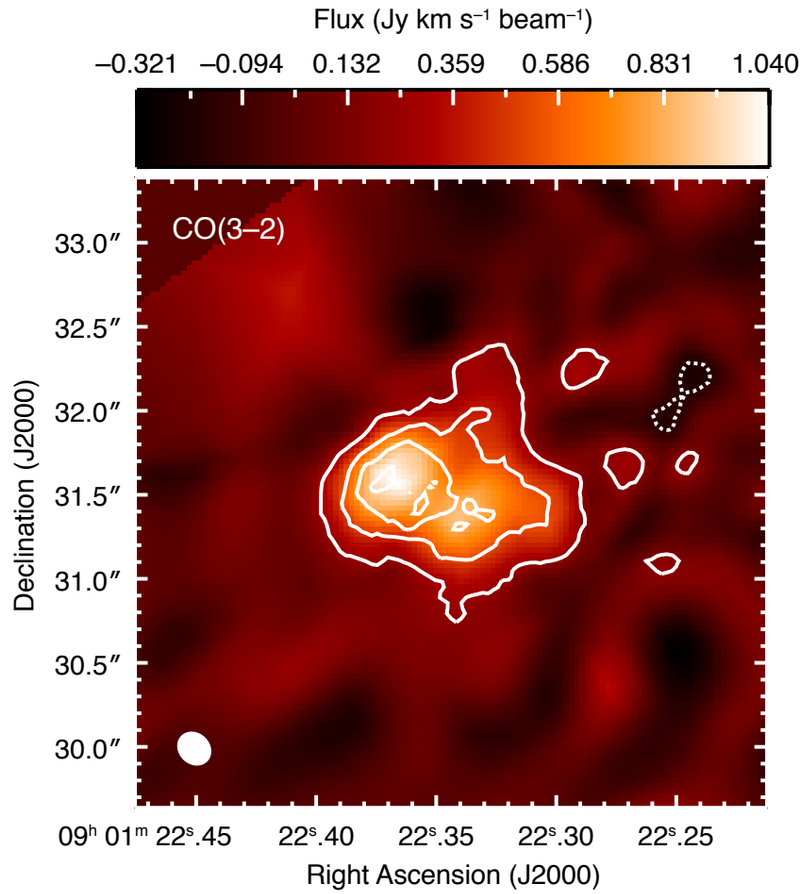
Leroy et al. 2013

Summary

- For J0901, we see a clear change in SK index for higher excitation CO lines (J>3)
- For J0901, gravitational lensing does not seem to affect the SK index (at least for low-J lines)
- Using the correct star formation tracer is critical for capturing the SK relation accurately
- A wide range of SK indices have been observed for a handful of high-z galaxies, but likely intrinsic variations require larger samples to uncover fundamental SF law and compare populations

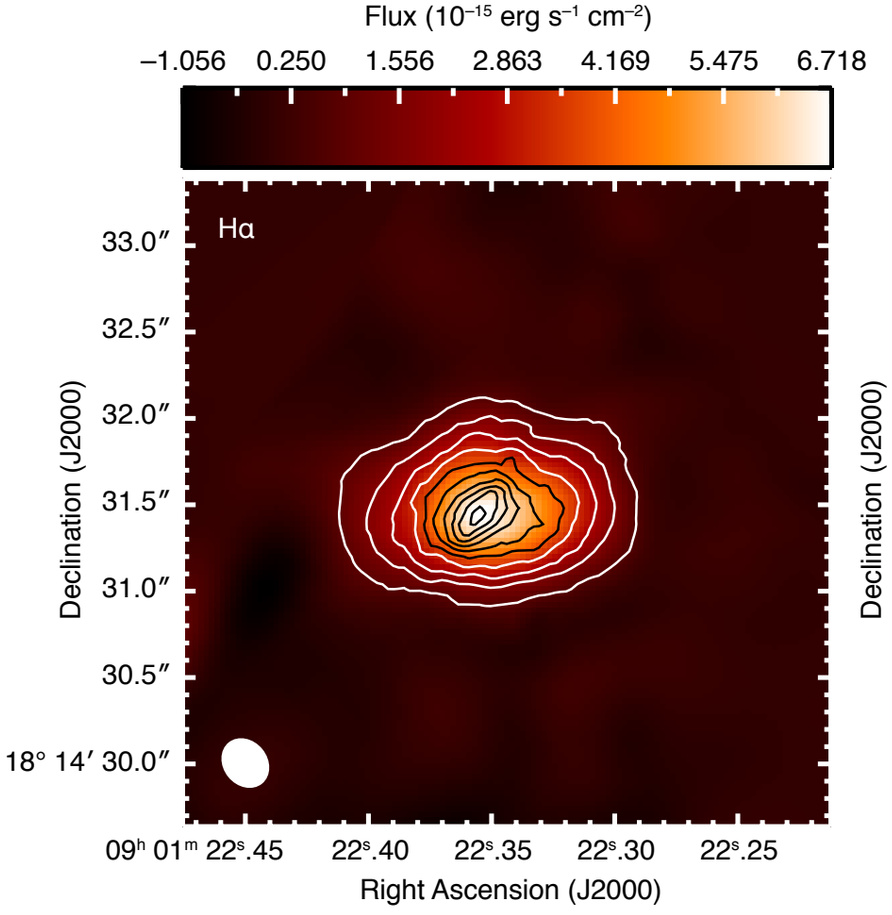
Bonus material!

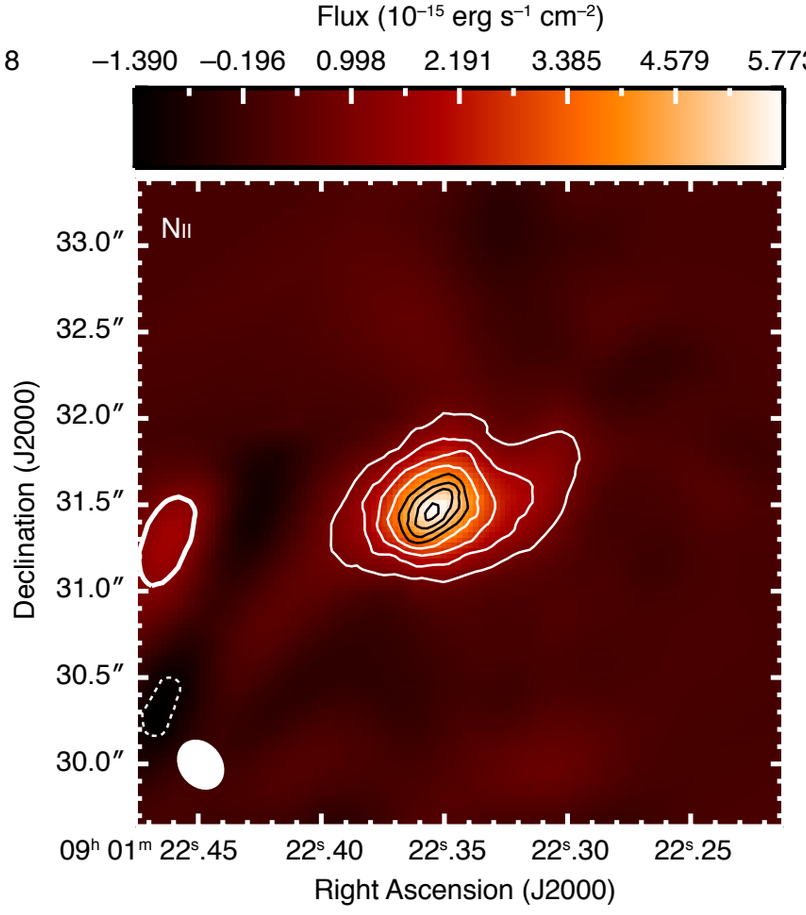


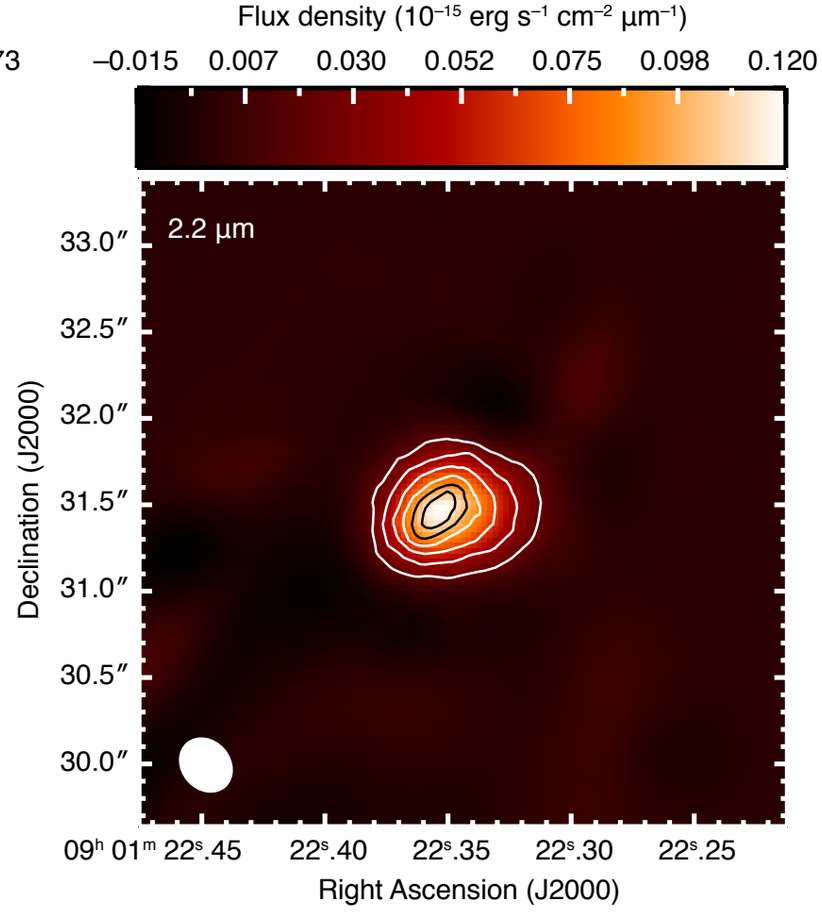


Reconstructed Images

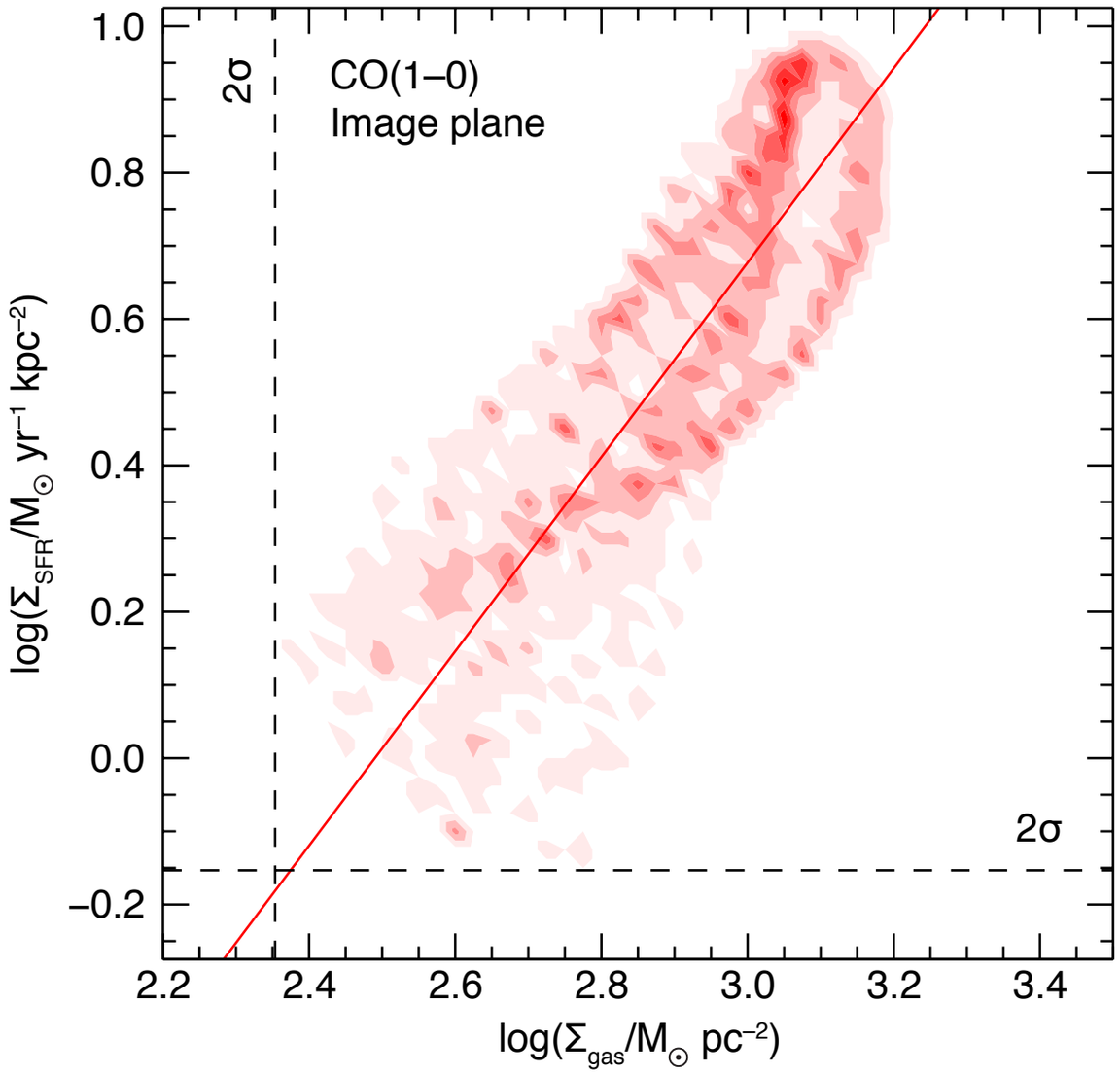
TBD for ALMA data



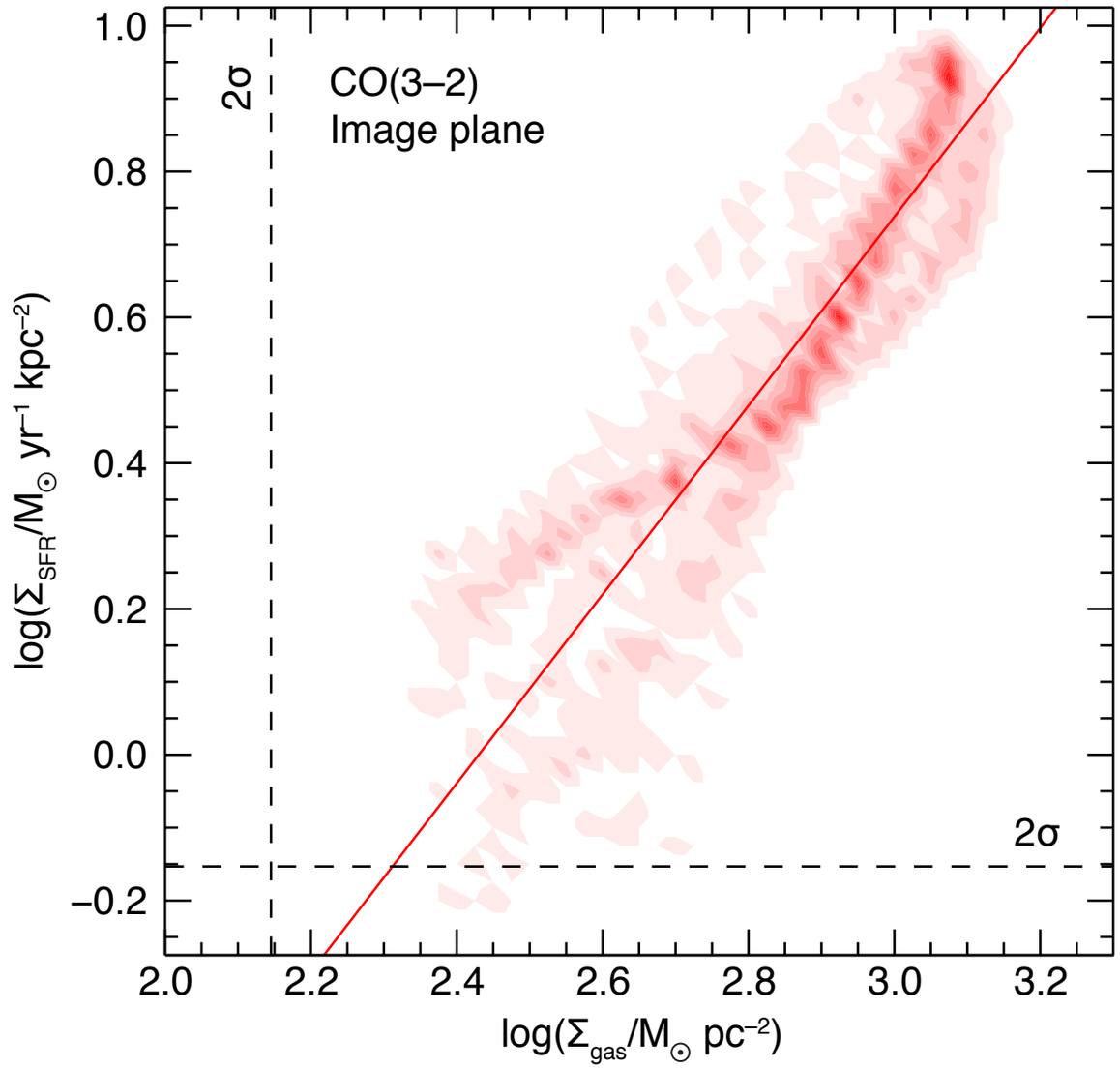




Reconstructed Images

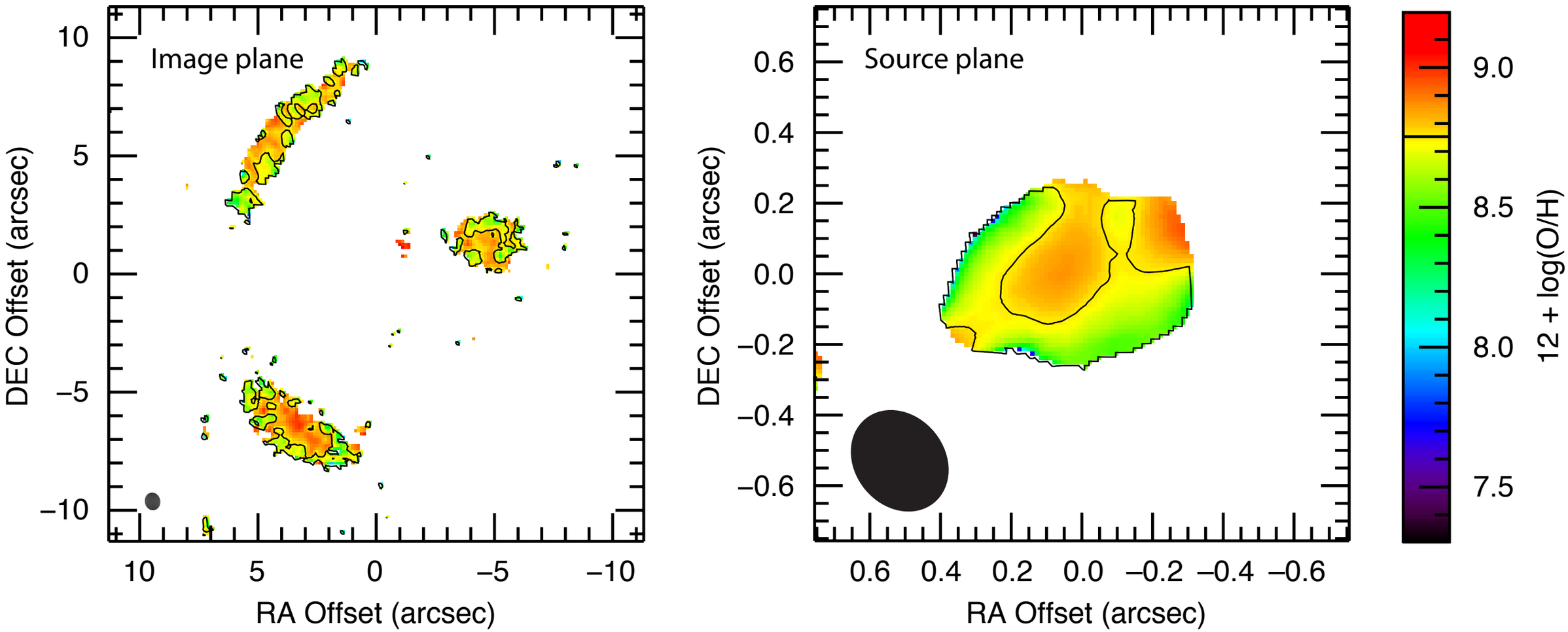


N=1.33±0.16

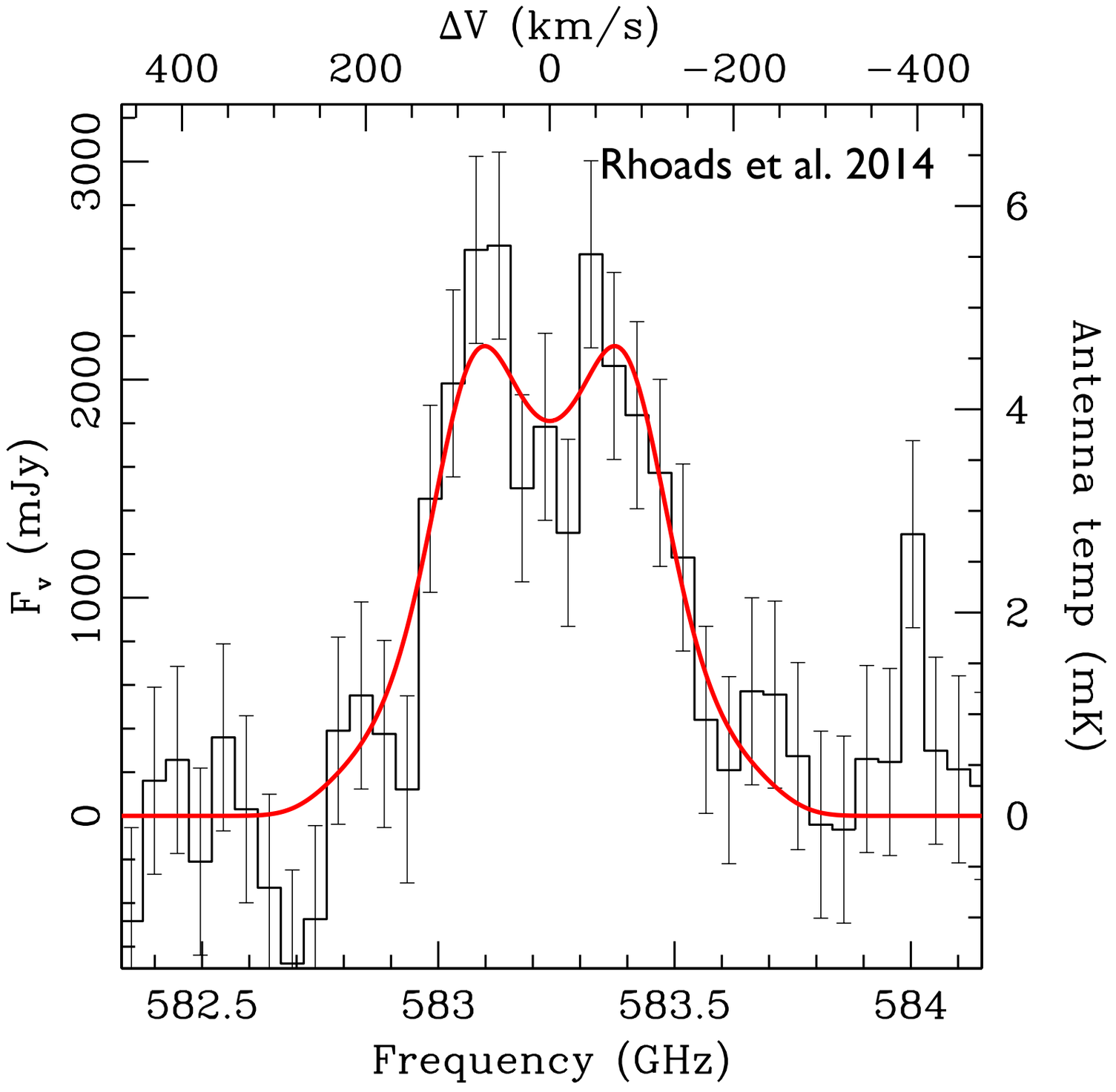


N=1.29±0.14

Metallicity Maps



Strong Lensing and Line Profiles



Herschel/HIFI spectra of CII for all images combined.