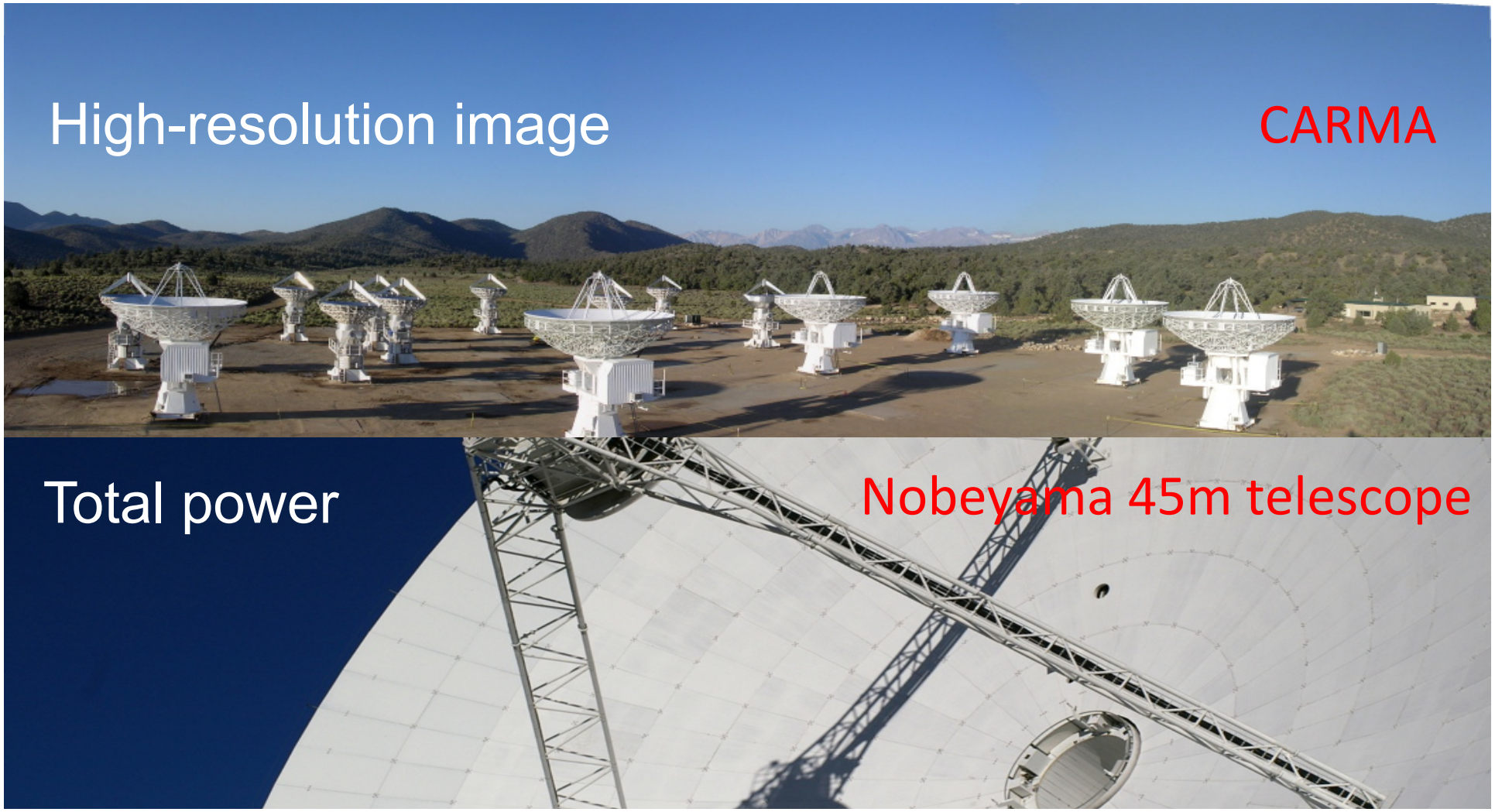
CANON –the CARMA-NOBEYAMA Nearby-galaxies CO(1-0) survey

Jin Koda (Stony Brook Univ)



Members

- Jin Koda (Project, PI) – Stony Brook Univ.
- Tony Wong (CARMA, co-PI) – Univ. Illinois
- Nario Kuno(Nobeyama, PI) -- Nobeyama Radio Observatory
- Kazuo Sorai (Nobeyama, co-PI) -- Hokkaido Univ.

- Daniela Calzetti -- UMASS
- Jennifer Donovan Meyer -- Stony Brook Univ.
- Fumi Egusa – JAXA
- Rob Kennicutt -- Cambridge Univ.
- Melissa Louie -- Stony Brook Univ
- Rieko Momose -- Tokyo Univ.
- David Rebolledo – Univ. Illinois
- Nick Scoville – Caltech
- Michiko Umei -- Hokkaido Univ.

Students and postdocs highlighted

Outline

- The CANON CO(1-0) Survey (ongoing)
- Resolved GMC analysis and constant Xco
  - Jennifer Donovan Meyer
- Power-law Schmidt law with CO(1-0): N=1.3-1.8
  - Rieko Momose et al. (see poster)
- CO(2-1)/(1-0) variation
  - Jin Koda
- Geometric offsets btw gas compression to SF across arms
  - Melissa Louie (see poster)

The CANON CO(1-0) Survey

CANON Sample & Observations

- Sample Selection
  - Select from Spitzer SINGS galaxies
    - Northern hemisphere (Declination > 0 deg)
    - $\mu_{24micron}$ in 2' aperture > 0.5MJy/str
  - Final sample = 29 northern SINGS spiral galaxies
- Observations
  - Nobeyama 45m telescope (Observatory project)
    - On-the-Fly (OTF) mapping with BEARS and FOREST Rx
    - Cover extent of 24micron disk
  - CARMA (Key project)
    - Central 2.3' (19-pointing) ~ 6kpc@10Mpc
    - 4 tracks per galaxy (2C & 2D-configuration)

2-3 times higher sensitivity and resolution (2-3") than BIMA-SONG. Detect typical GMCs in nearby spirals.

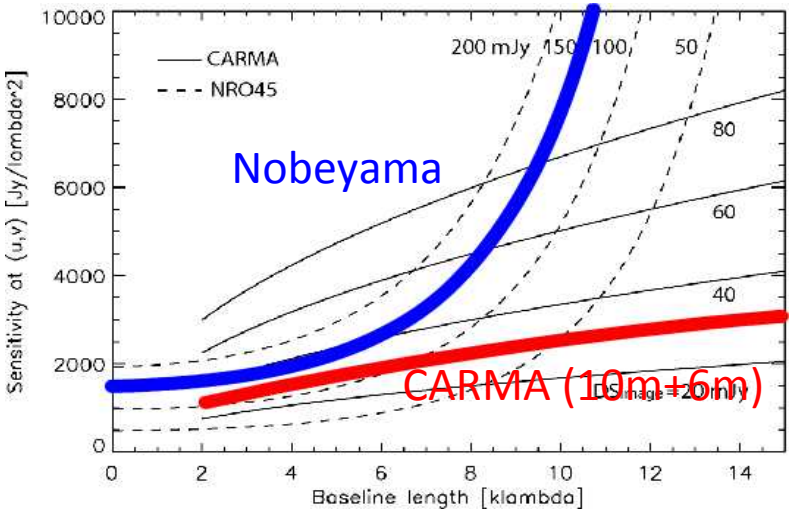
(1) Name
NGC3034
NGC6946
NGC5194
NGC3627
NGC4631
NGC4736
NGC3521
NGC5055
NGC4254
NGC7331
NGC4536
NGC2403
NGC4321
NGC2798
NGC4826
NGC3351
NGC5195
NGC0628
NGC5033
NGC4569
NGC2976
NGC3031
NGC3184
NGC3938
NGC3198
NGC4559
Mrk33
NGC2841
NGC4579

CARMA + Nobeyama 45m CO(1-0)

CARMA: 151-pointing mosaic
Nobeyama: OTF mapping
1 sigma ~ 1x10^5 M_{sun}; typical GMC ~ 4sigma

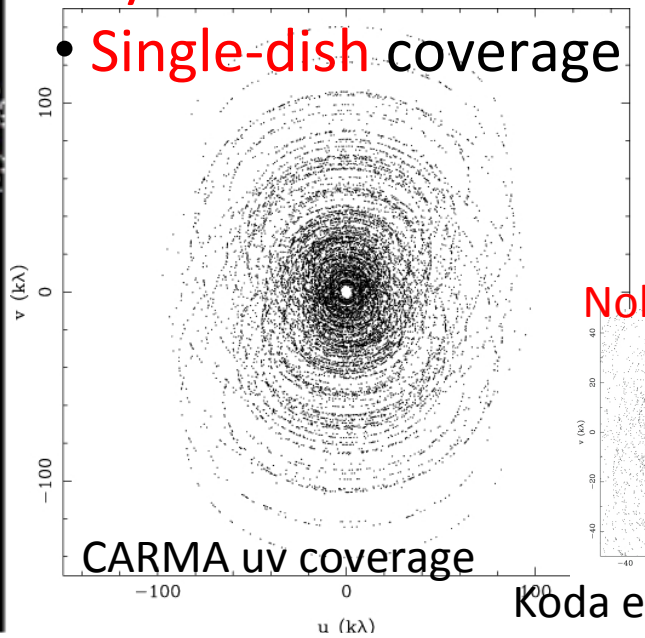
Koda et al. 2009

Sensitivity match



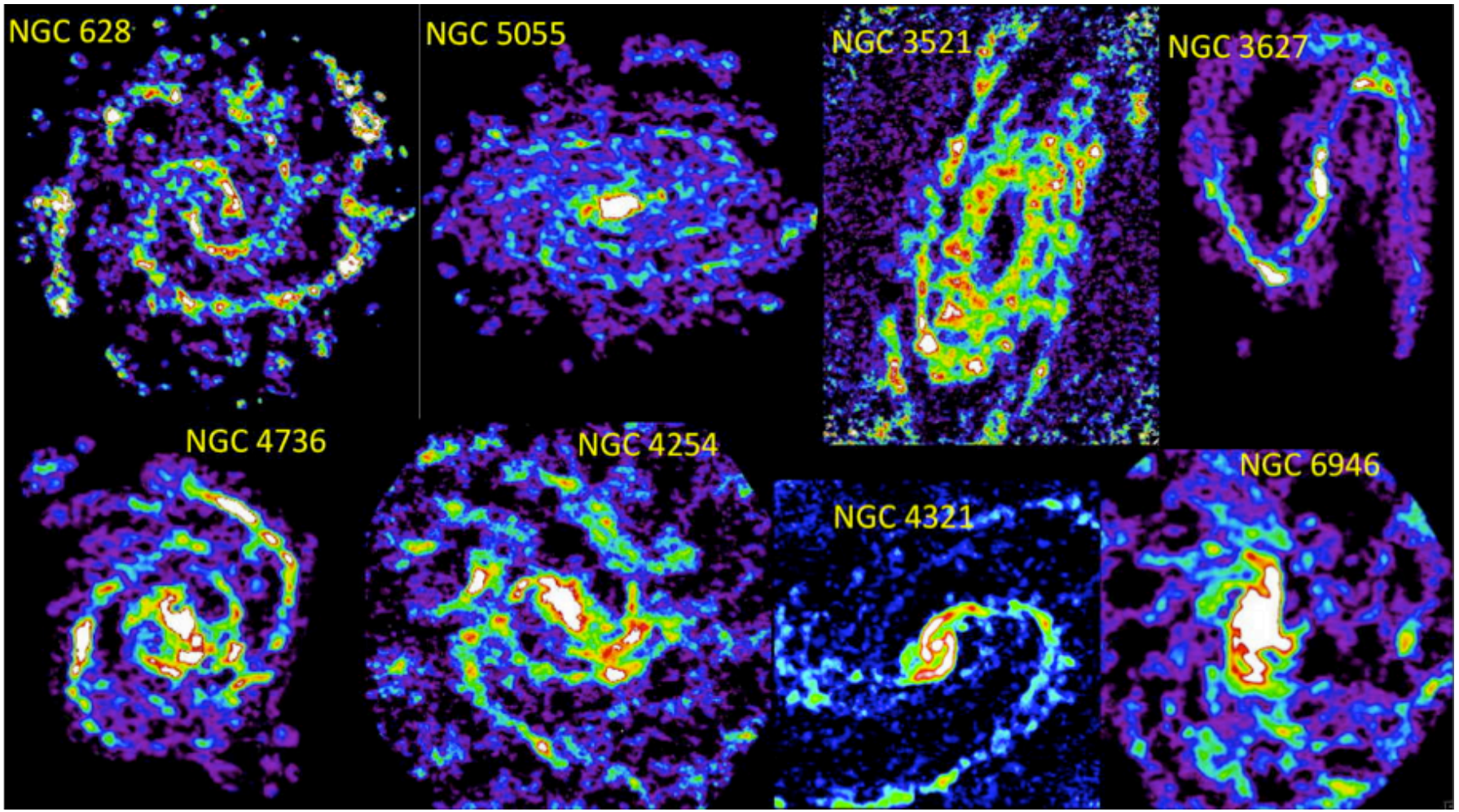
Excellent UV coverage

- CARMA: 15 antennas
- Synthesis observations
- Single-dish coverage



Koda et al. 2011

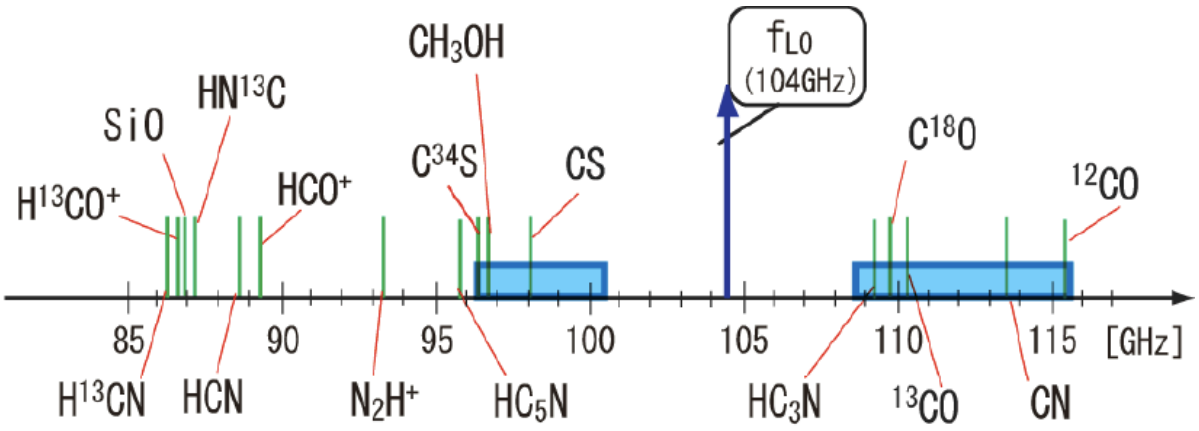
Example CO(1-0) Images from CANON

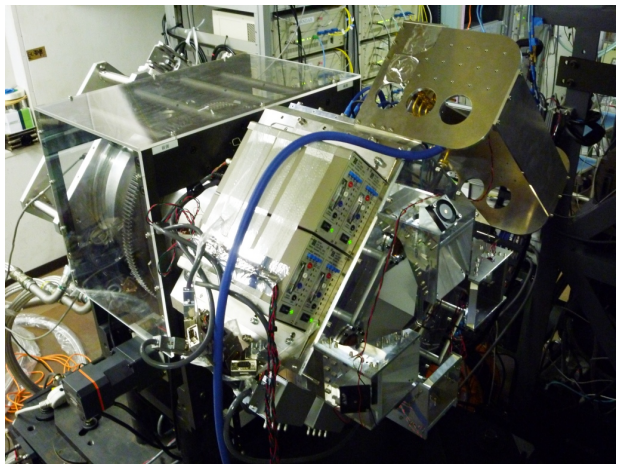


Observations and data reduction on-going.

FOREST – New Receiver on NRO 45m

- 4 Beams (=2x2, 50” sep.) + dual polarization + 2SB
- RF: 80-116GHz, IF: 4-11GHz (USB), 4-8GHz (LSB)
- Digital spectrometer (x16): 2GHz, 4096 channels





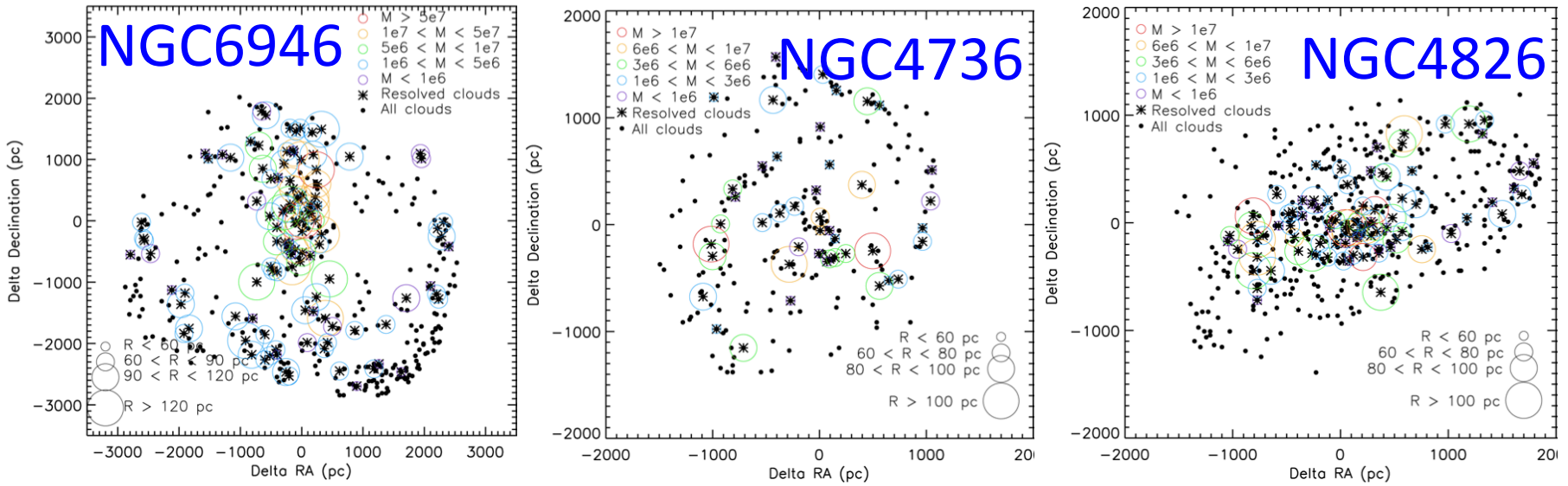
E.g. Simultaneous 12CO, 13CO, C18O (USB) [in future; & CS, CH3OH (LSB)]

Resolved Properties of GMCs

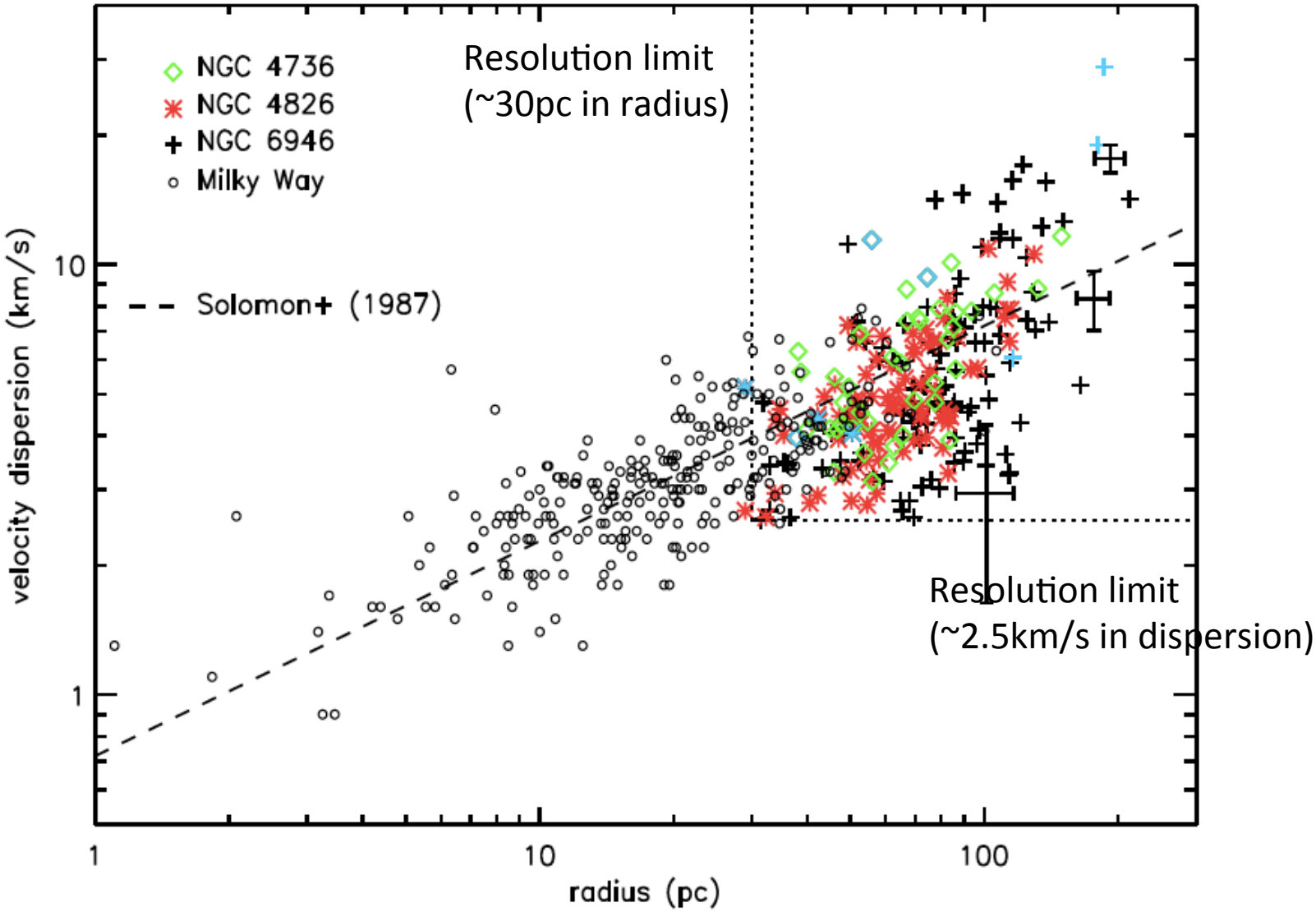
Internal properties of GMCs

- Three nearest galaxies in sample
  - NGC 4736 (5.2Mpc), NGC 4826(7.5Mpc), NGC 6946(6.8Mpc)
  - Resolution ~50-65 pc (spatial), 5km/s (velocity)
- Resolving massive GMCs
  - Identification with CLUMPFIND (Williams et al. 1993)
  - Corrections for resolution
  - Resolved GMCs: 44 in NGC 4736; 87 in NGC 4826, 113 in NGC 6946

Paper I: Donovan Meyer et al. 2012, Paper II: Donovan Meyer et al. in prep.



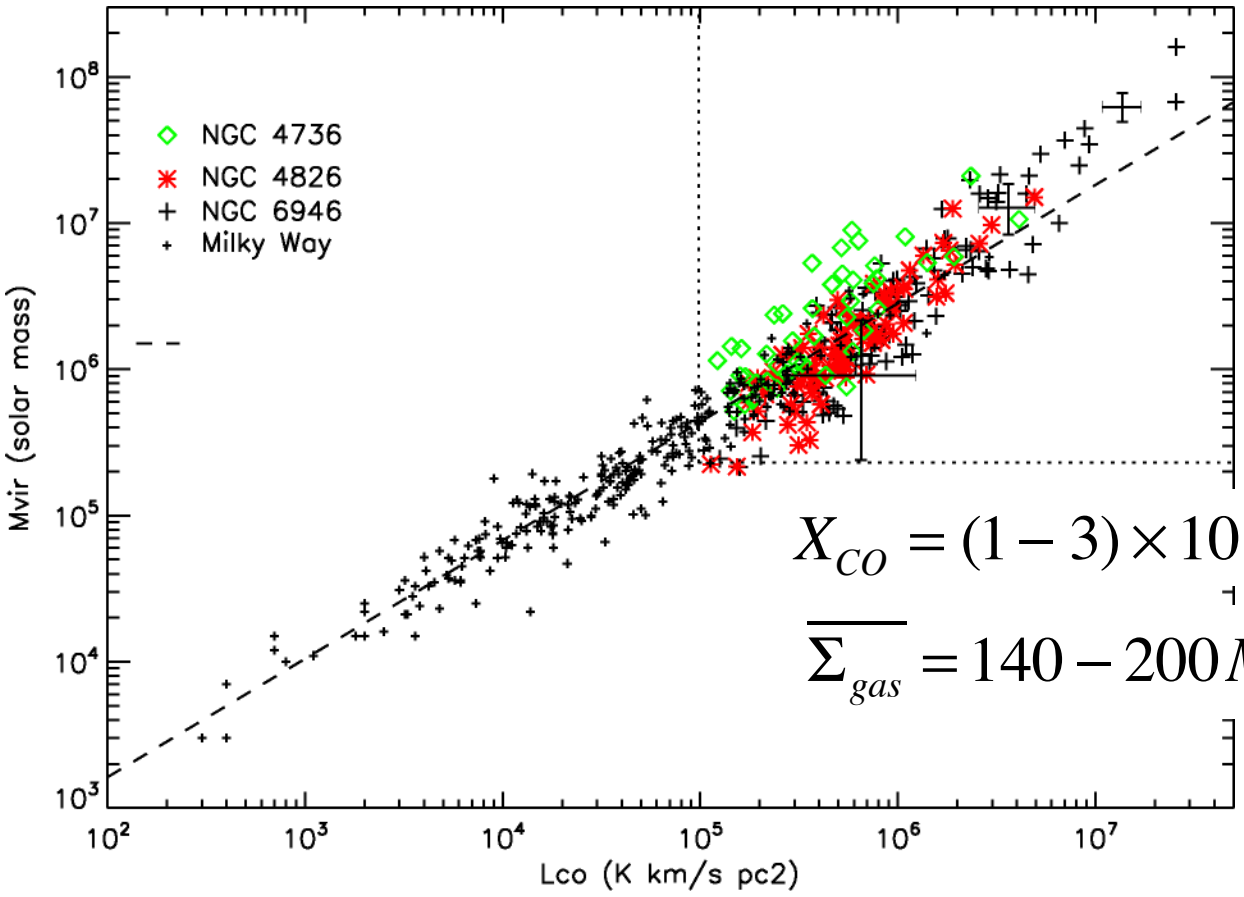
Size-Line Width Relation



GMCs in three spiral galaxies lie on the Galactic scaling relation.

Donovan Meyer et al. 2012 & in prep.

Xco - H_2-to-CO Conversion factor



$$X_{CO} = (1-3)\times 10^{20}\, cm^2\,[K * km/s]^{-1}$$

$$\overline{\Sigma_{gas}} = 140 - 200\, M_{sun} / pc^2$$

Ex. Galactic values

$$X_{CO} = 2\times 10^{20}$$

$$\overline{\Sigma_{gas}} = 170$$

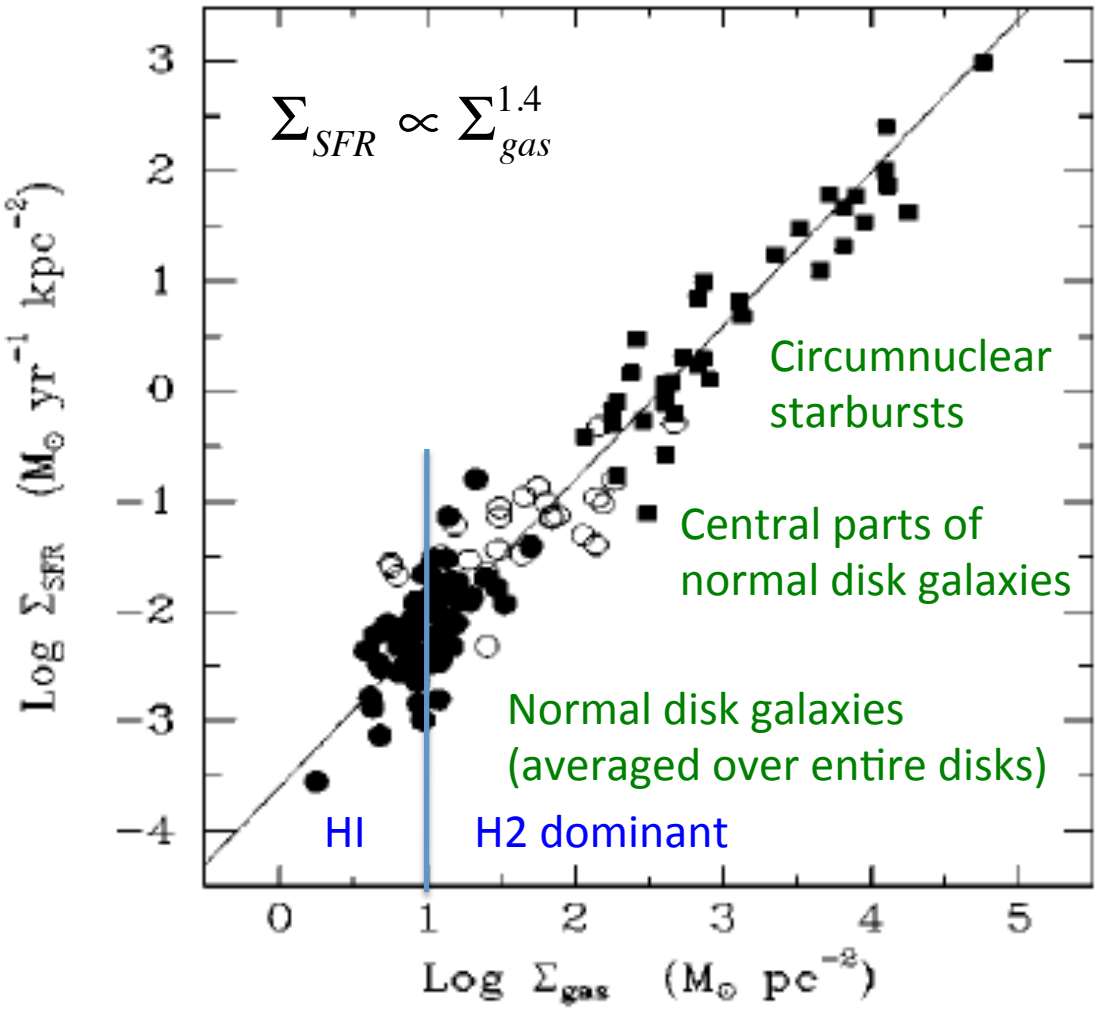
Solomon et al. 1987
Scoville & Sanders 1987

Extragalactic GMCs similar to their Galactic counterparts.

Donovan Meyer et al. 2012 & in prep.

The Schmidt Law (Spatially-Resolved)

The Schmidt Law and Index (Simplistic) Interpretations



Kennicutt 1998; 2007

$$\Sigma_{SFR} \propto \frac{\Sigma_{gas}}{t_{SF}} \propto \Sigma_{gas}^{N}$$

- **Constant SF**

  $t_{SF} = const.$

  → **N=1.0**

- **Gravitational collapse**

  $t_{SF} \propto t_{freefall} \propto \Sigma_{gas}^{-0.5}$

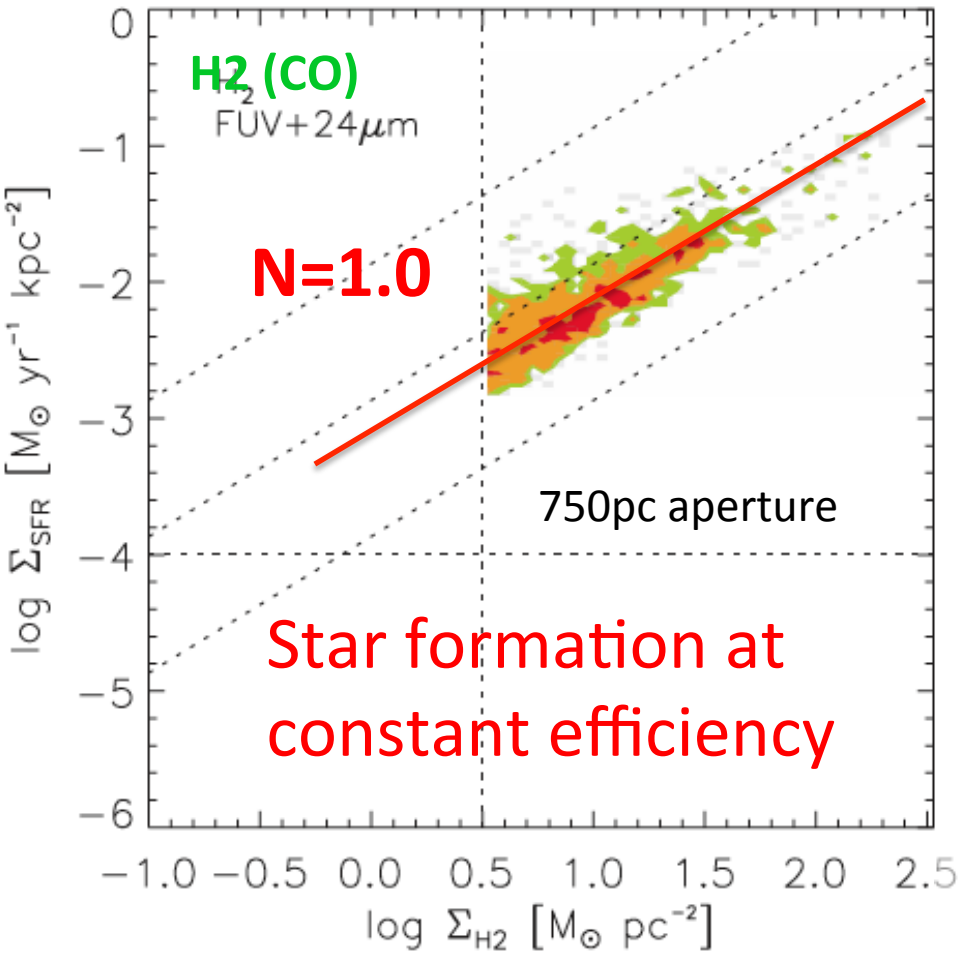
  → **N=1.5**

- **Cloud-cloud collision**

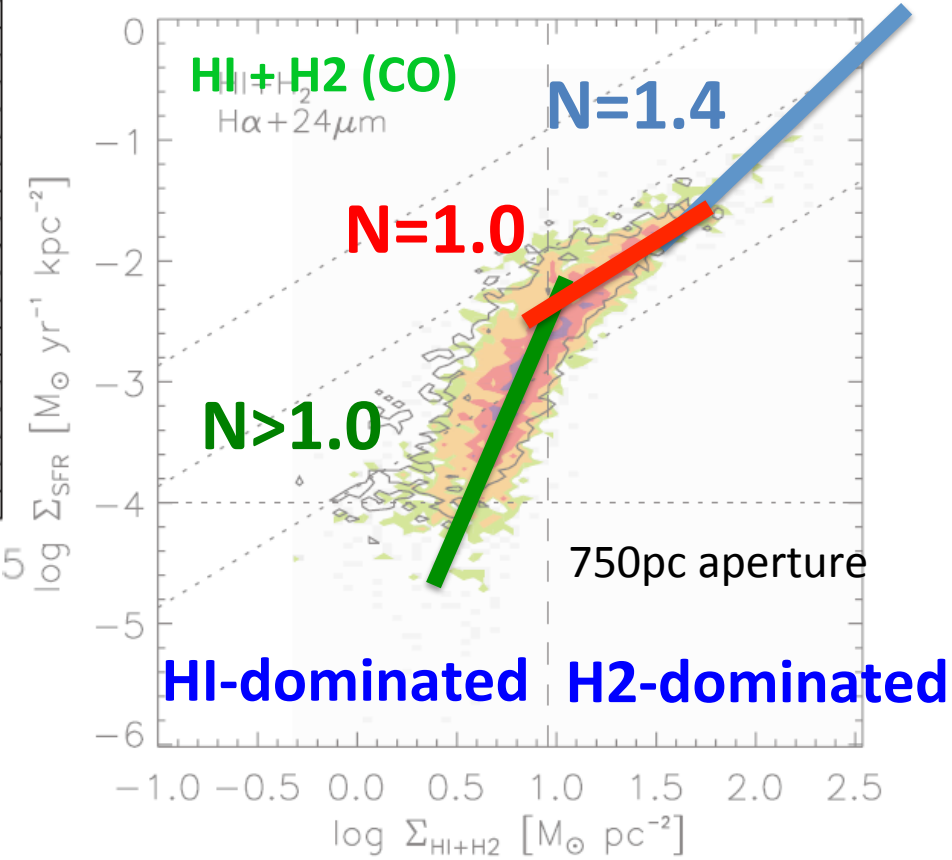
  $t_{SF} \propto t_{collision} \propto \Sigma_{gas}^{-1}$

  → **N=2.0**

The Spatially-Resolved Schmidt Law: CO(2-1)



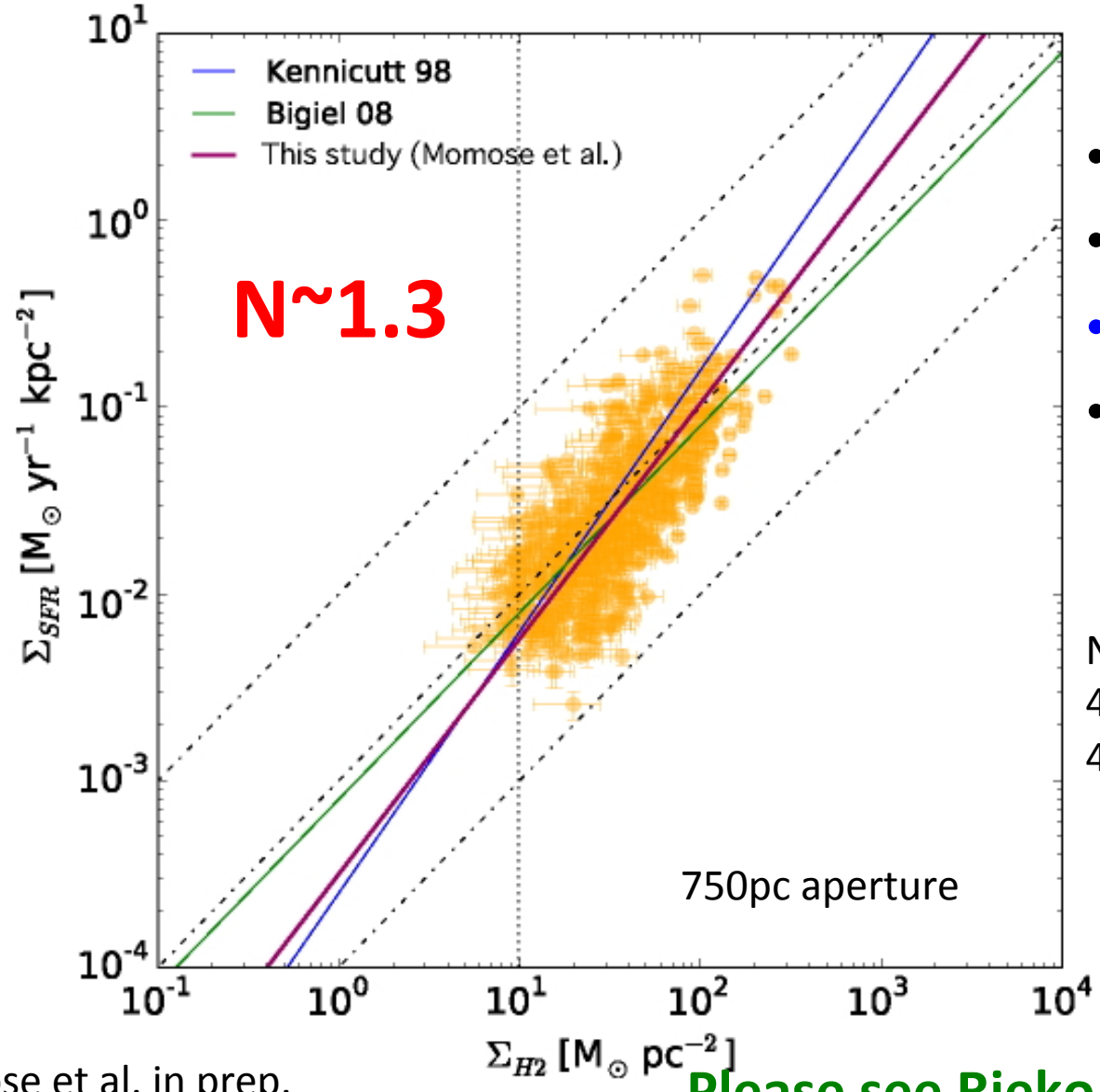
- HERACLES Survey
- 11 galaxies
- **CO(2-1)/CO(1-0) = const~0.8**
- Xco(1-0)=2e20



Bigiel et al. 2008

The Spatially-Resolved Schmidt Law: CO(1-0)

Halpha+24micron
Diffuse Background Not Subtracted



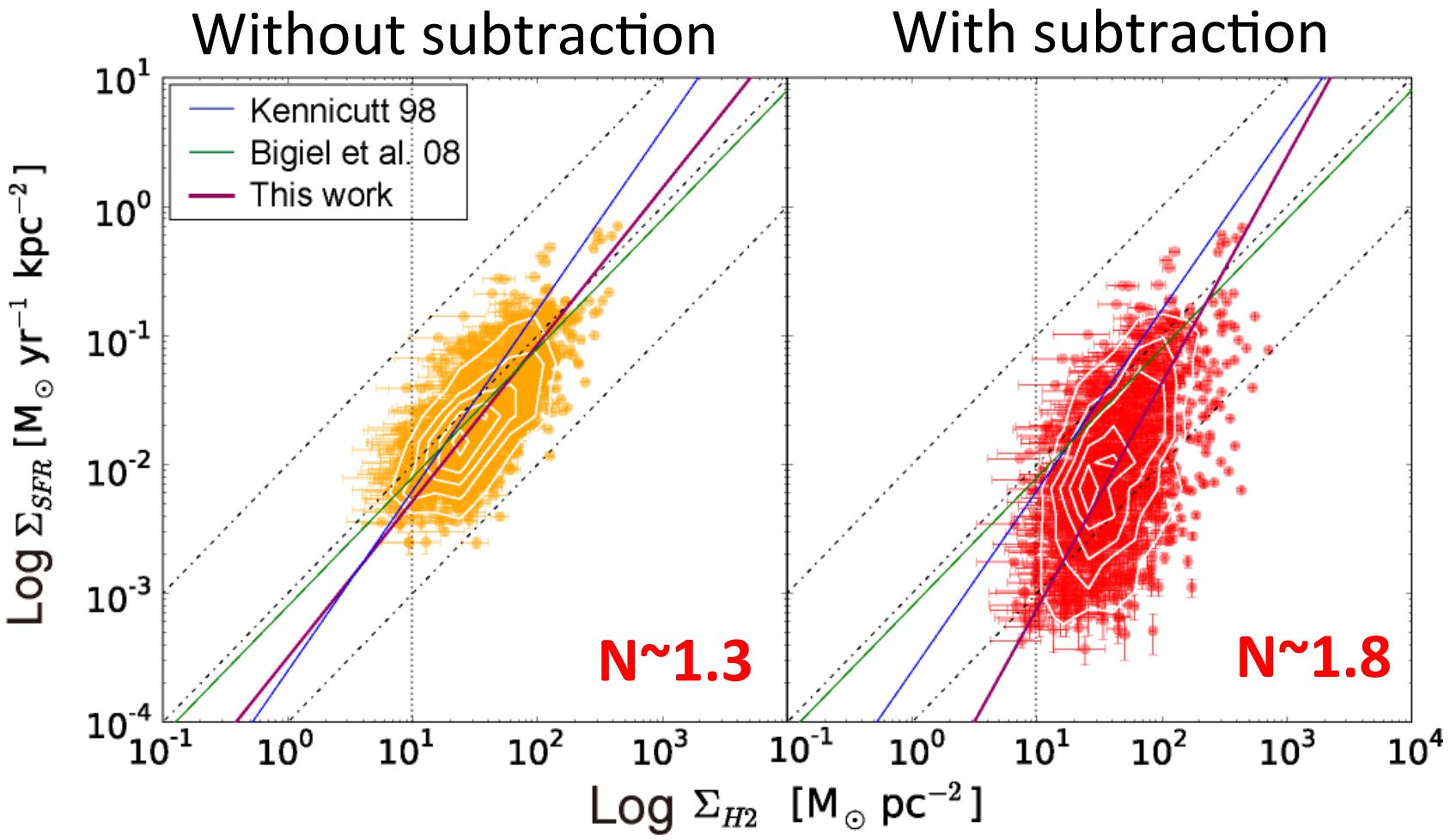
- CANON Survey
- 10 galaxies
- **CO(1-0)**
- Xco=2e20

NGC 3521, 3627, 4254, 4303, 4321, 4736, 4826, 5055, 5194, 6946

Momose et al. in prep.

Please see Rieko Momose's poster

Measurements of SFR
Diffuse 24micron Background Subtraction



500 pc aperture

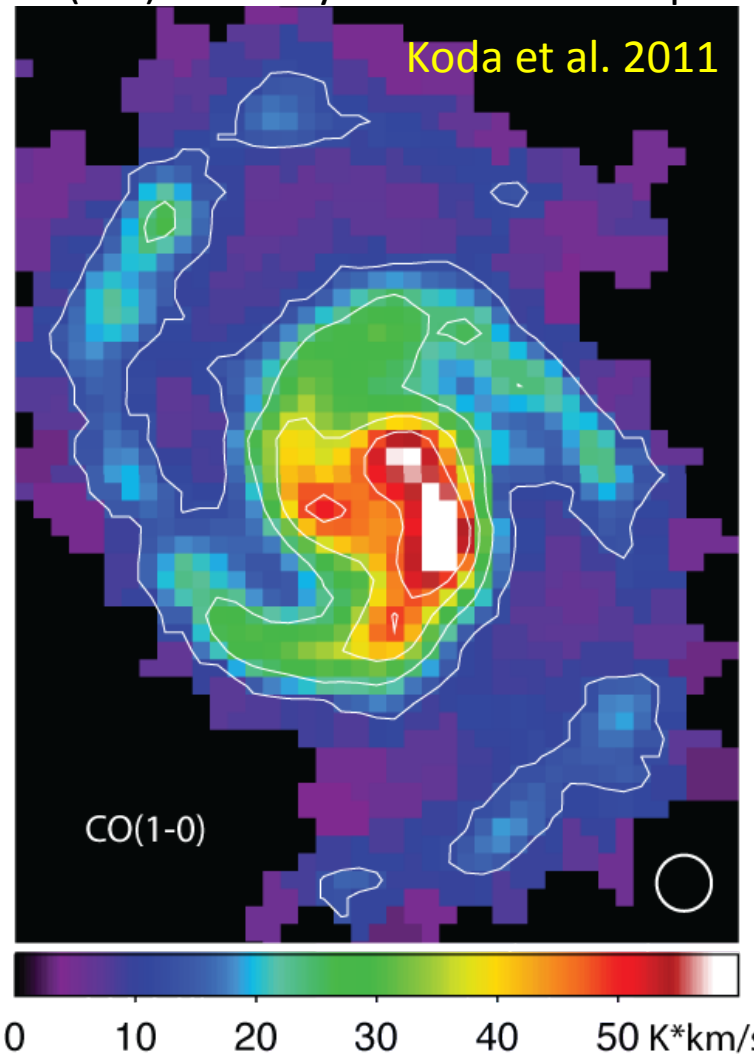
See also Liu et al. 2011

Please see Rieko Momose's poster

Spatial Variation of CO 2-1/1-0

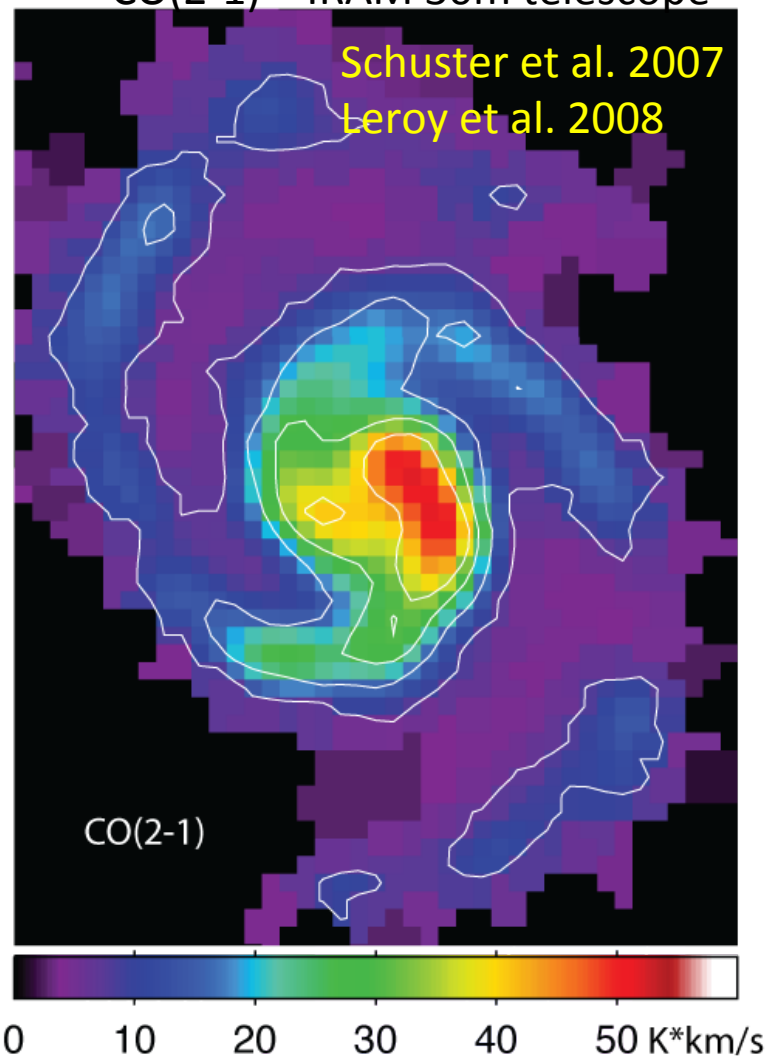
CO(1-0) and CO(2-1) Maps of M51

CO(1-0) -- Nobeyama 45m telescope



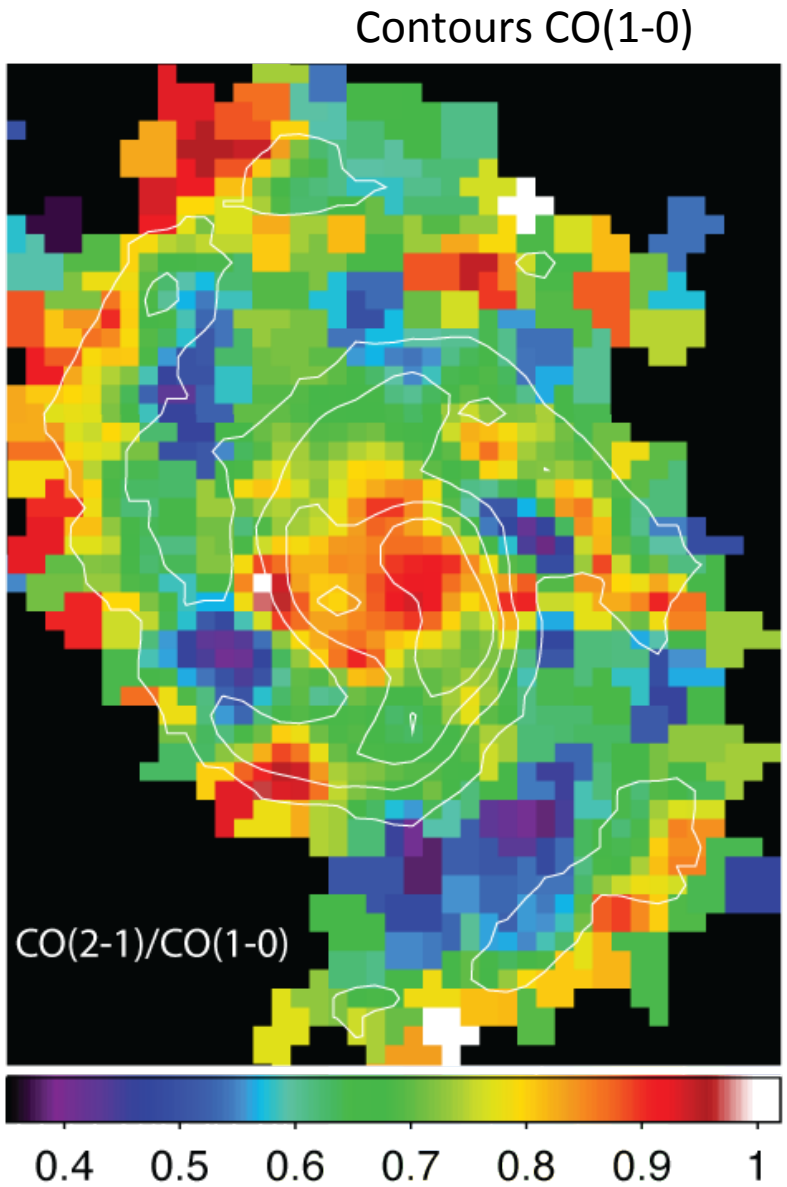
Region at ~>10 sigma significance
in both CO(1-0) and CO(2-0)

CO(2-1) – IRAM 30m telescope



Smoothed to 20”~780pc

R2-1/1-0=CO(2-1)/CO(1-0)



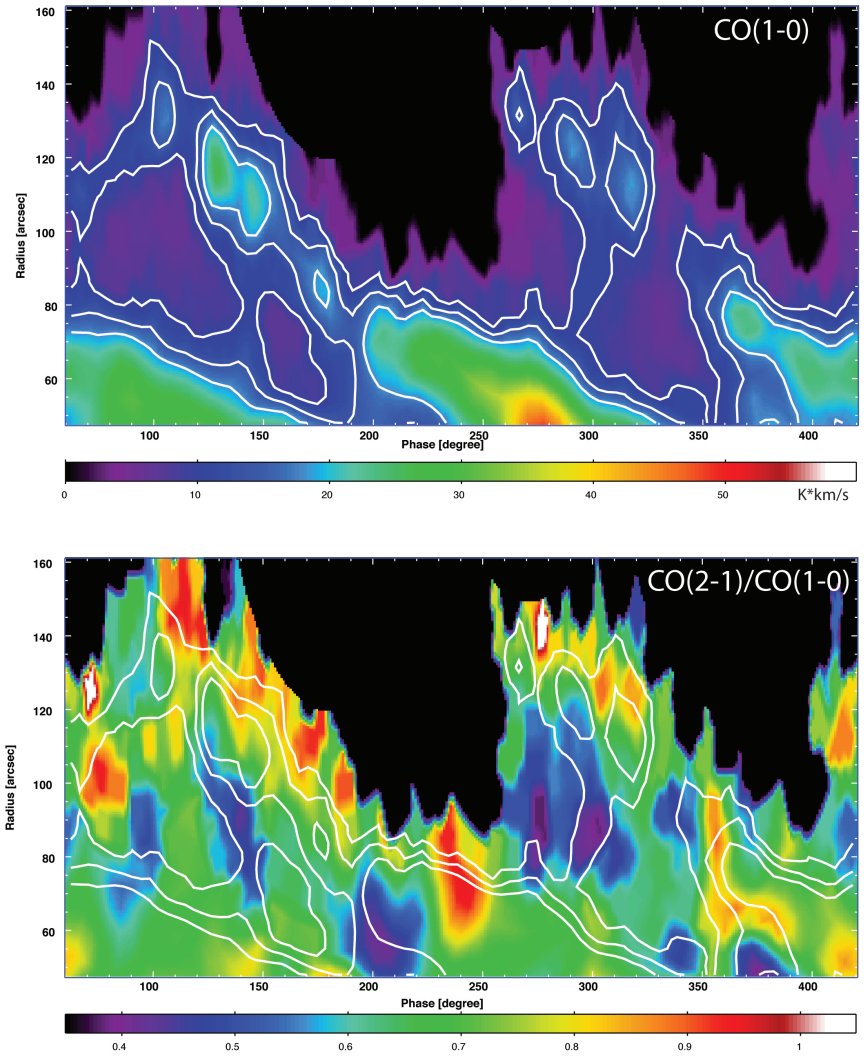
- Spiral arms (esp. downstream)
  - High ratio >0.7
  - Often ~ 0.8-1.0
- Interarm regions
  - Low ratio <0.7
  - Often ~ 0.4-0.6
- Central 2.5kpc
  - High ratio ~ 0.8-1.0

Systematic change from interarm regions to spiral arms

Koda et al. submitted

R2-1/1-0: Phase Diagram

Contours CO(1-0)



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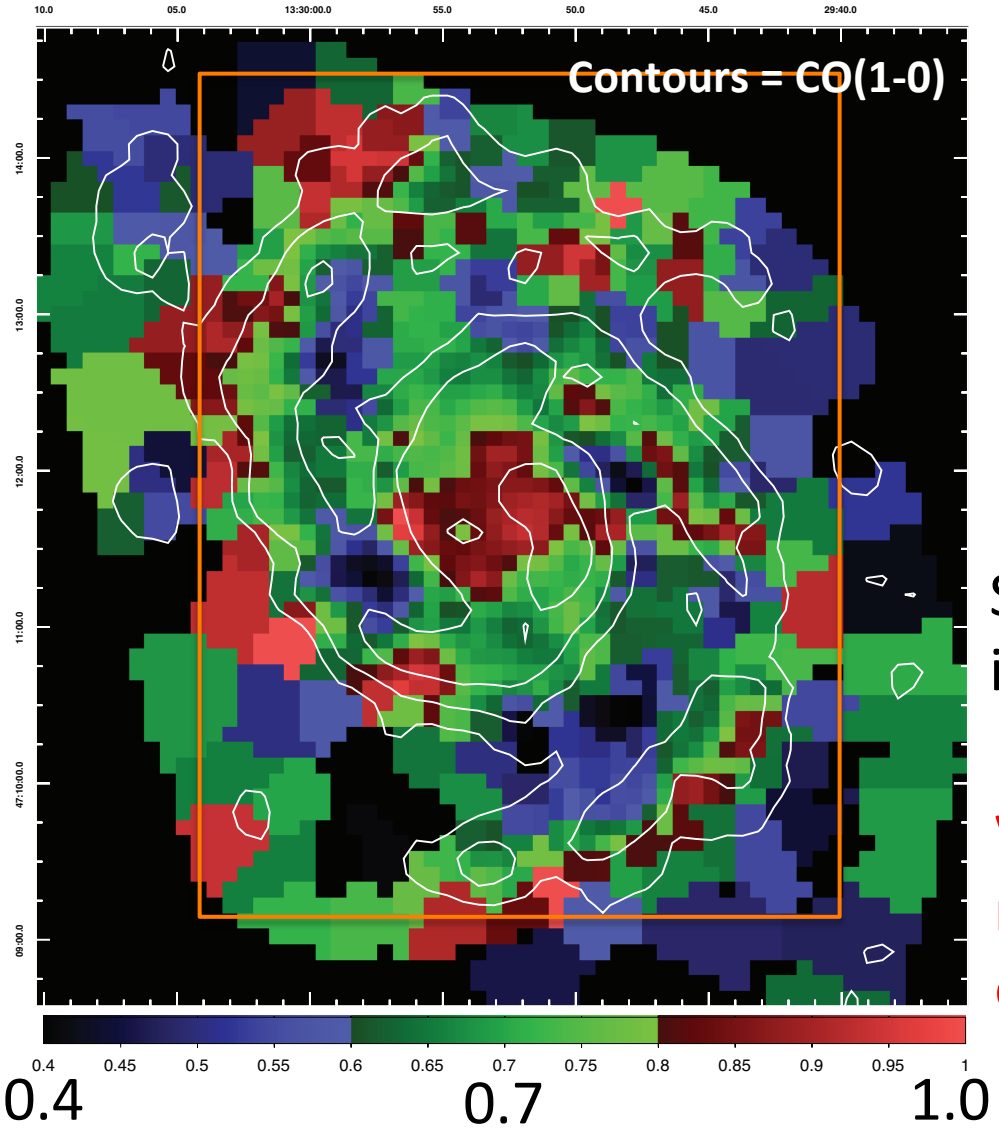
Systematic change from interarm regions to spiral arms

Koda et al. submitted

Systematic Change of $R_{2\text{-}1/1\text{-}0}$



High: 0.8-1.0

Medium: 0.6-0.8

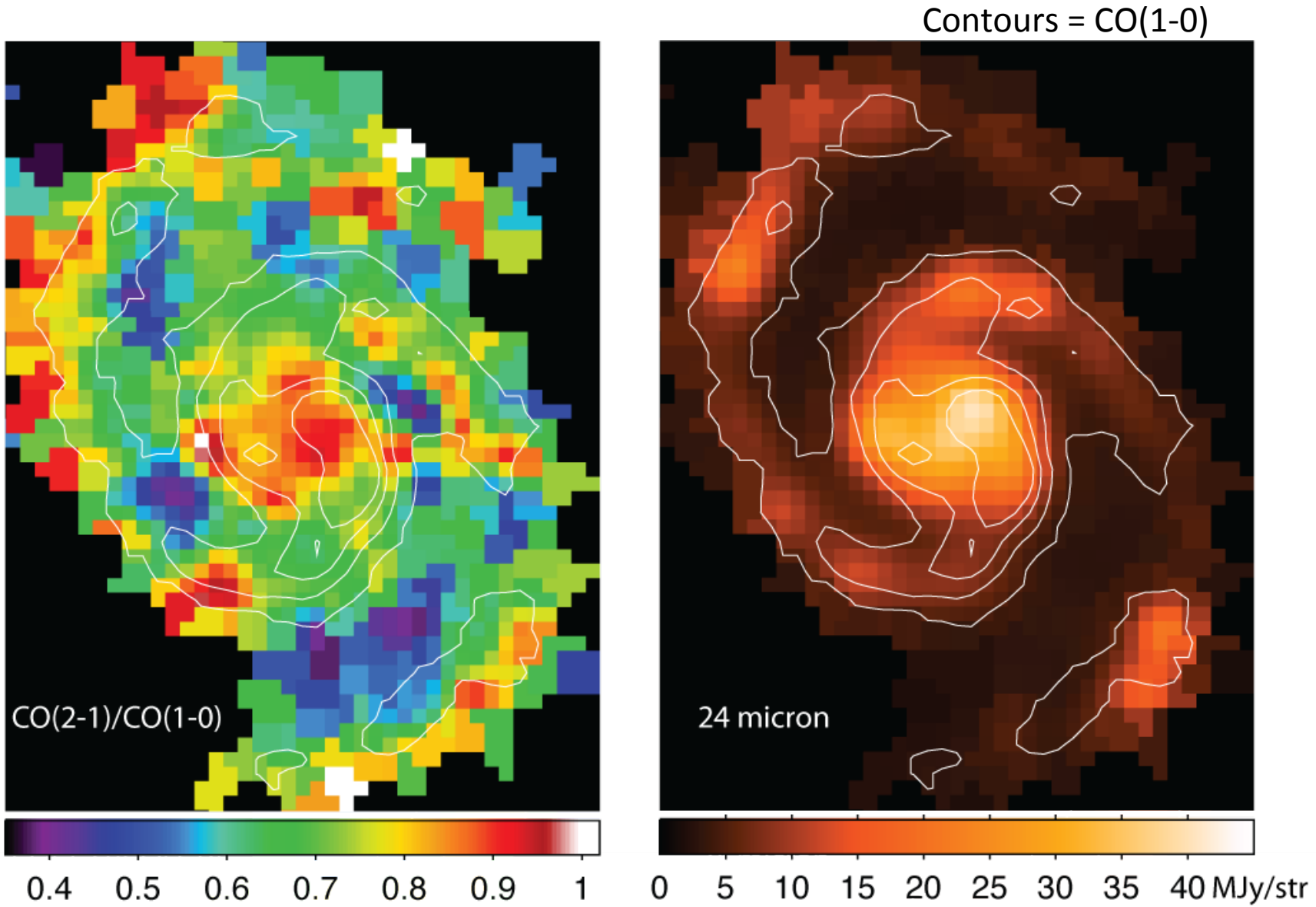
Low: 0.4-0.6

Systematic change from interarm regions to spiral arms

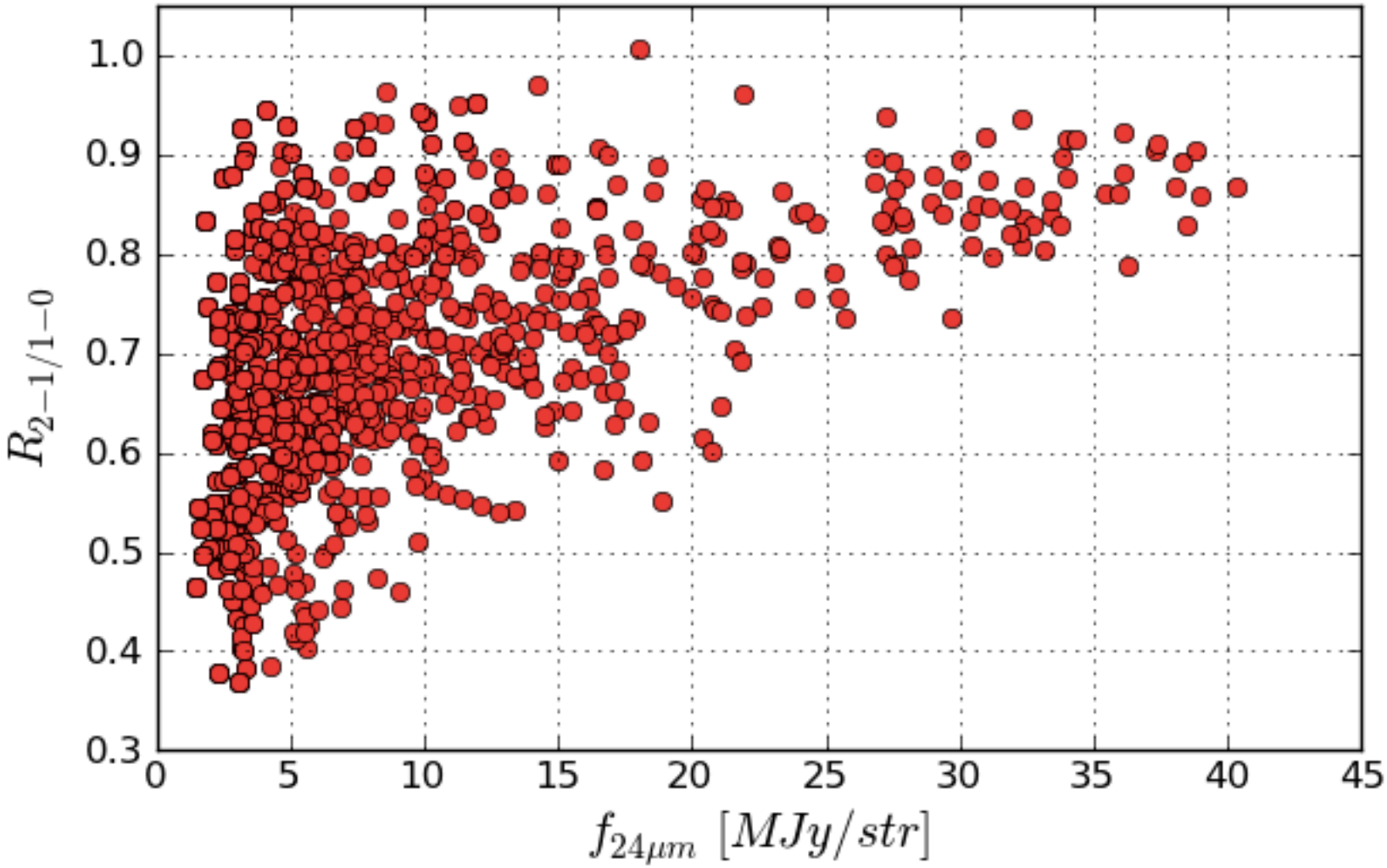
Very high ratio appears mostly at downstream side of arms.

Voronoi Adoptive Smoothing (Cappellari & Copin 2003)

$R_{2\text{-}1/1\text{-}0}$ vs 24micron



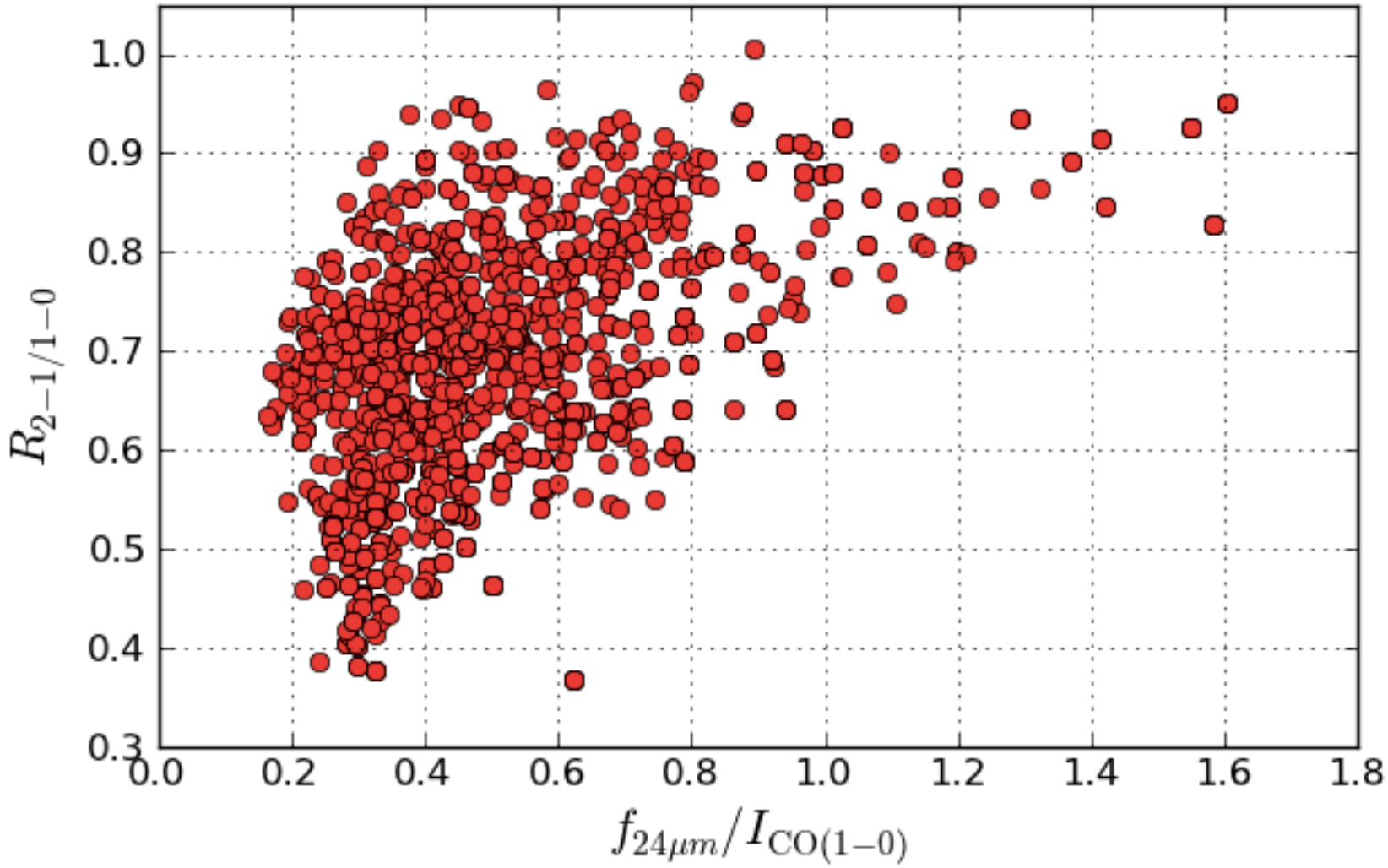
$R_{2\text{-}1/1\text{-}0}$ vs SF Rate



~ SF rate

Koda et al. submitted

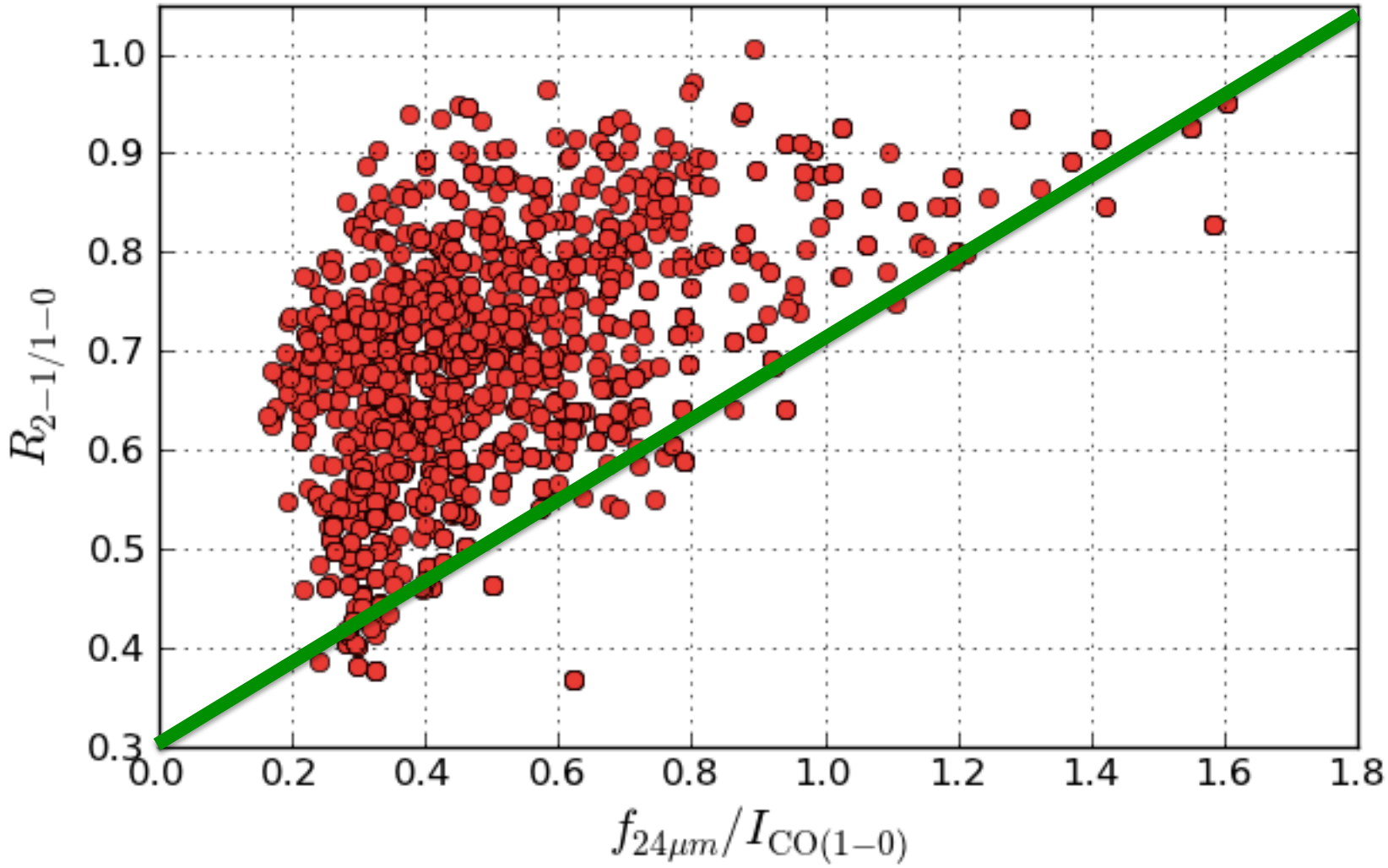
$R_{2\text{-}1/1\text{-}0}$ vs SF Efficiency



~ SF efficiency

Koda et al. submitted

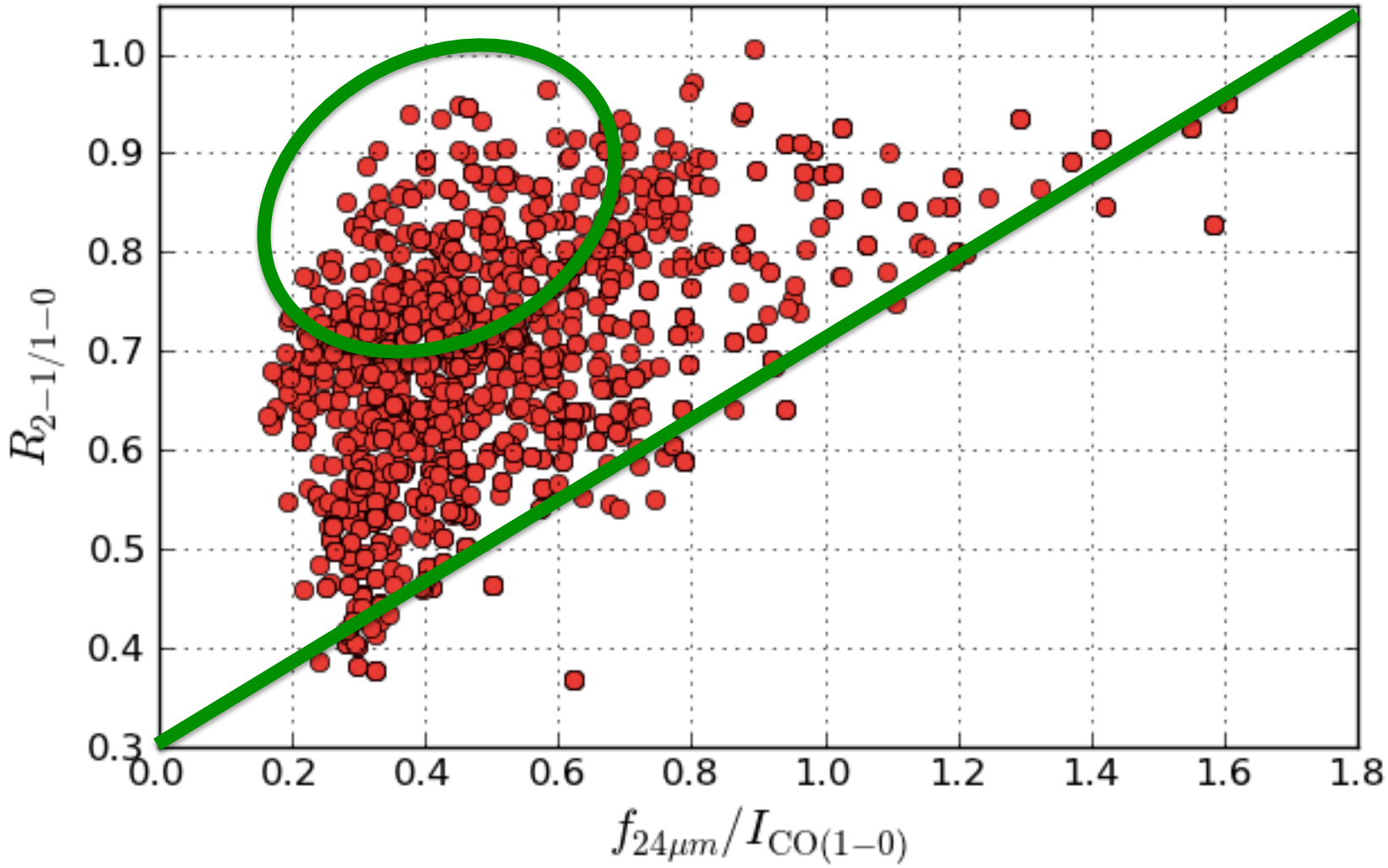
$R_{2\text{-}1/1\text{-}0}$ vs SF Efficiency



~ SF efficiency

Koda et al. submitted

$R_{2\text{-}1/1\text{-}0}$ vs SF Efficiency



~ SF efficiency

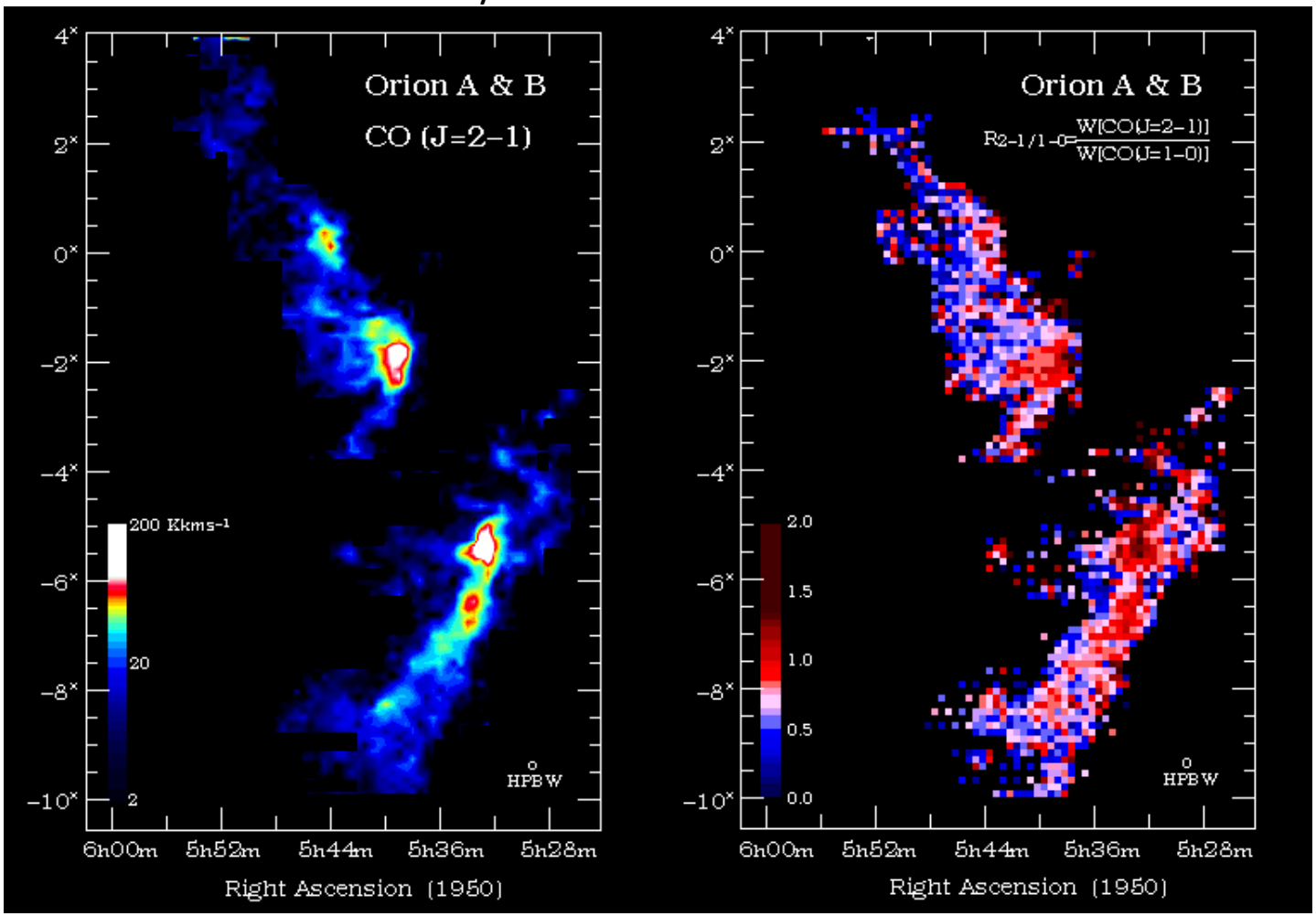
Koda et al. submitted

Galactic Counterparts

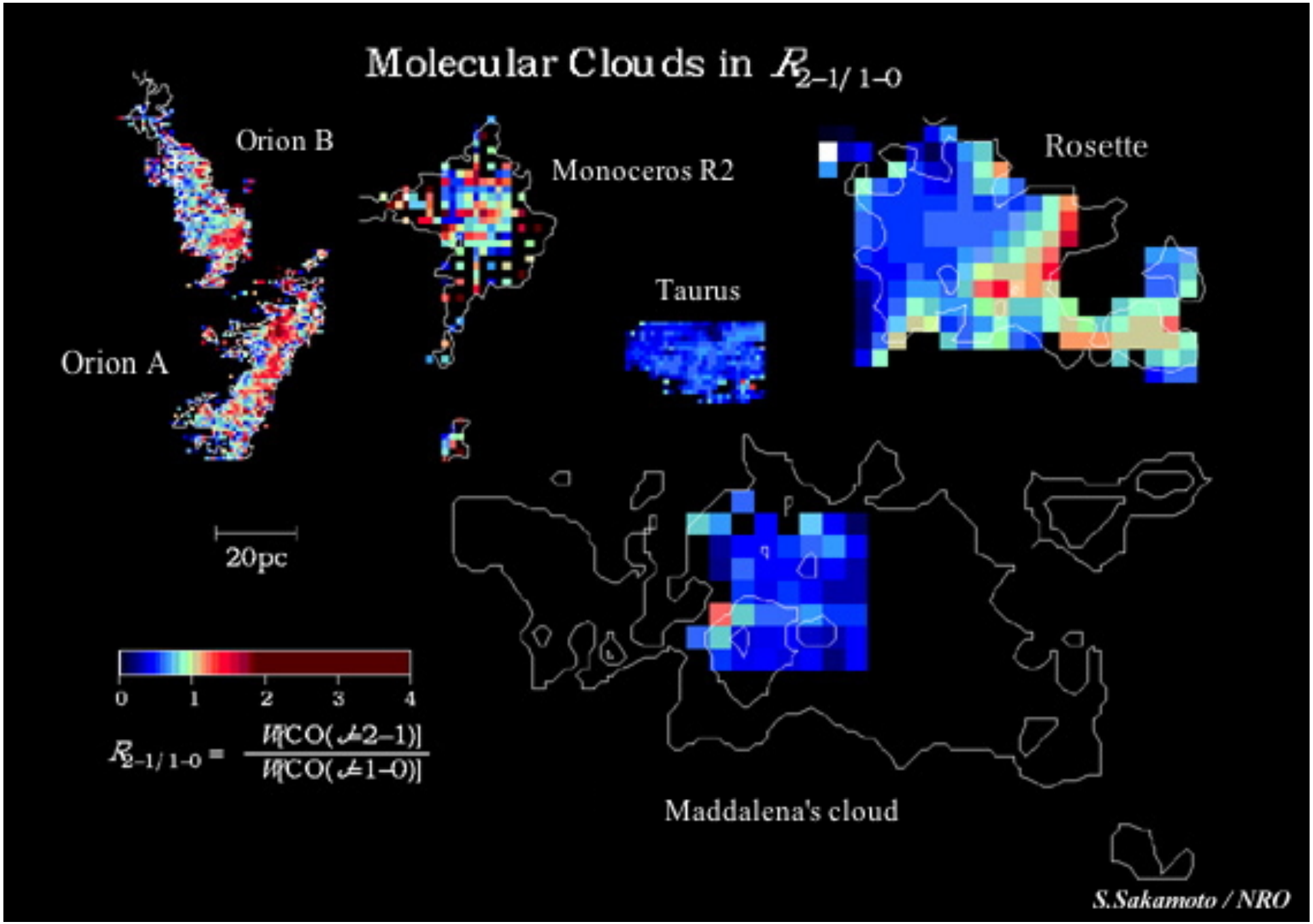
Columbia & Harvard 1.2m
CO(1-0) survey
Thaddeus, Dame, etc.

U. Tokyo 0.6m
CO(2-1) survey
Hasegawa et al.

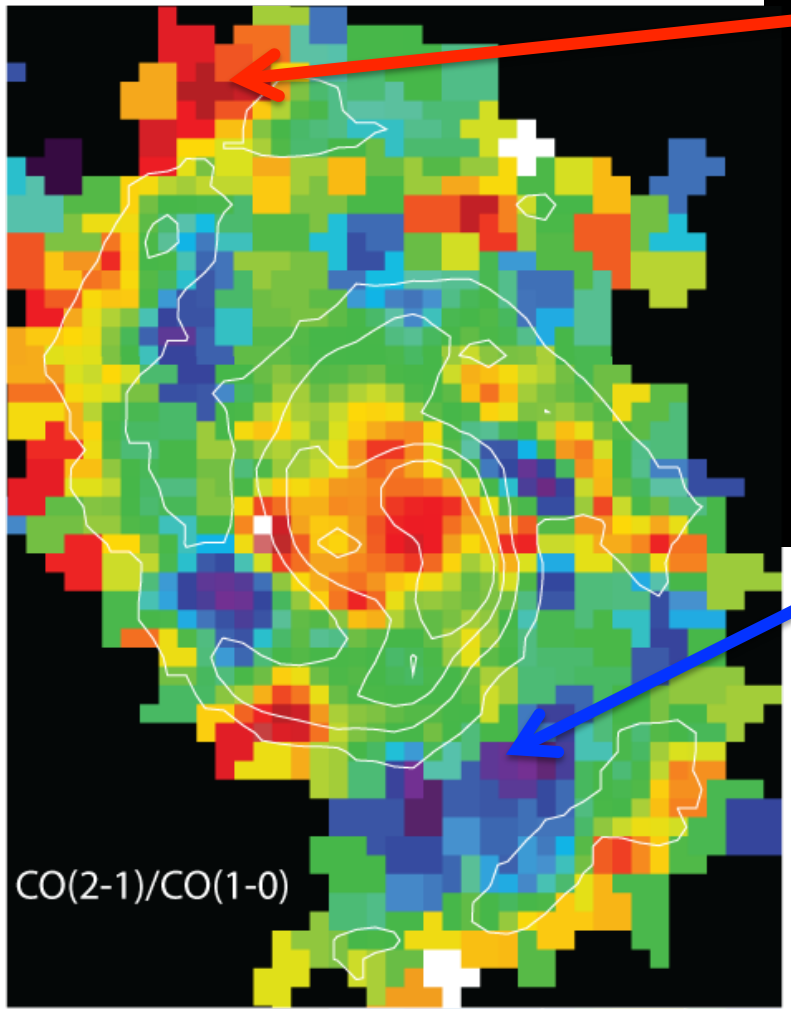
$R_{2\text{-}1/1\text{-}0}$ in Orion GMC

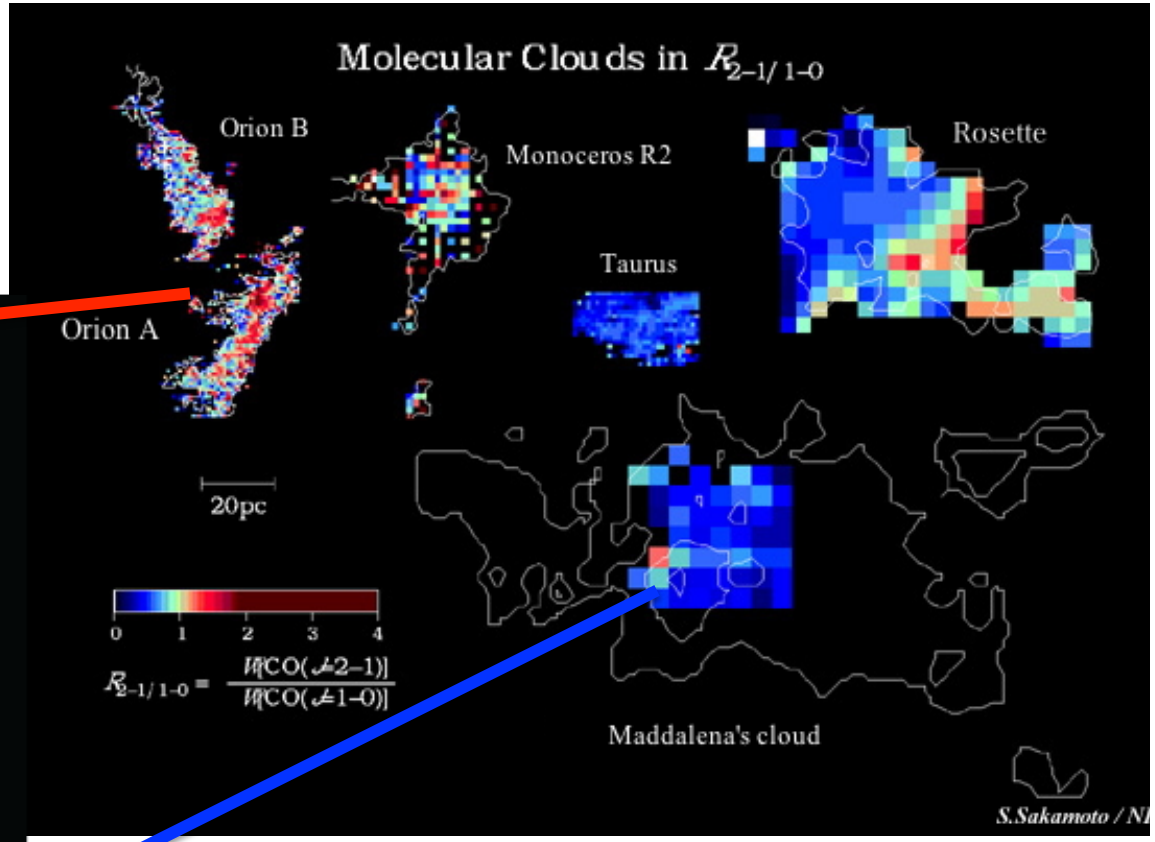


Sakamoto et al. 1994, 1997
Hasegawa 1997; Sorai 2001; Sawada 2001


Molecular Clouds in $R_{2-1/1-0}$
Orion B
Monoceros R2
Rosette
Taurus
Orion A
20pc
0
1
2
3
4
$R_{2-1/1-0} = \frac{I(CO(J=2-1))}{I(CO(J=1-0))}$
Maddalena's cloud
S.Sakamoto / NRO

R2-1/1-0

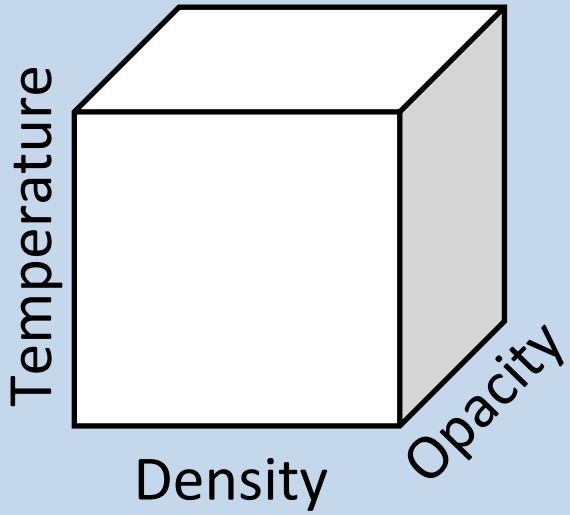




- Interarm -- dormant, less star forming GMCs
- Spiral arms – actively star forming GMCs.

Koda et al. submitted

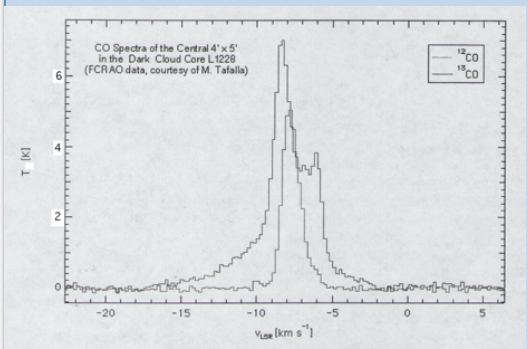
LVG Analysis: $R_{2\text{-}1/1\text{-}0}$



- Excitation Condition
  - Density & Temperature
- Radiative Transfer
  - Opacity/Column density

$$\Delta V_{obs} \gg \Delta V_{thermal}$$

Photons escape unless foreground gas block them both in space and velocity.



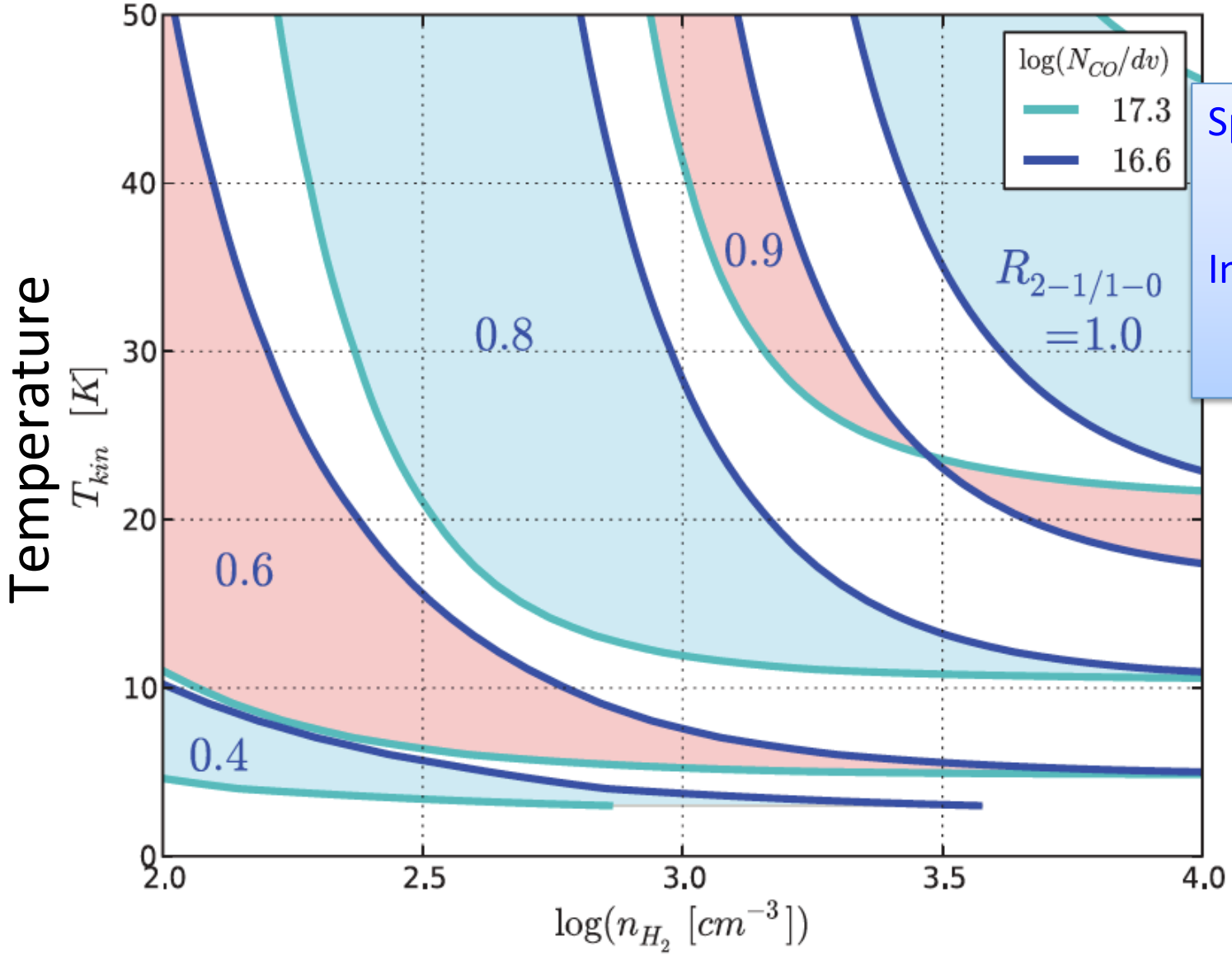
Opacity per velocity

- GMC: ~170Msun/pc2, ~4-18km/s
- M51 spiral arms: ~1000Msun/pc2, ~50-100km/s

$$\log N_{CO} / dv[cm^{-2}(km/s)^{-1}] = 16.6 - 17.3$$

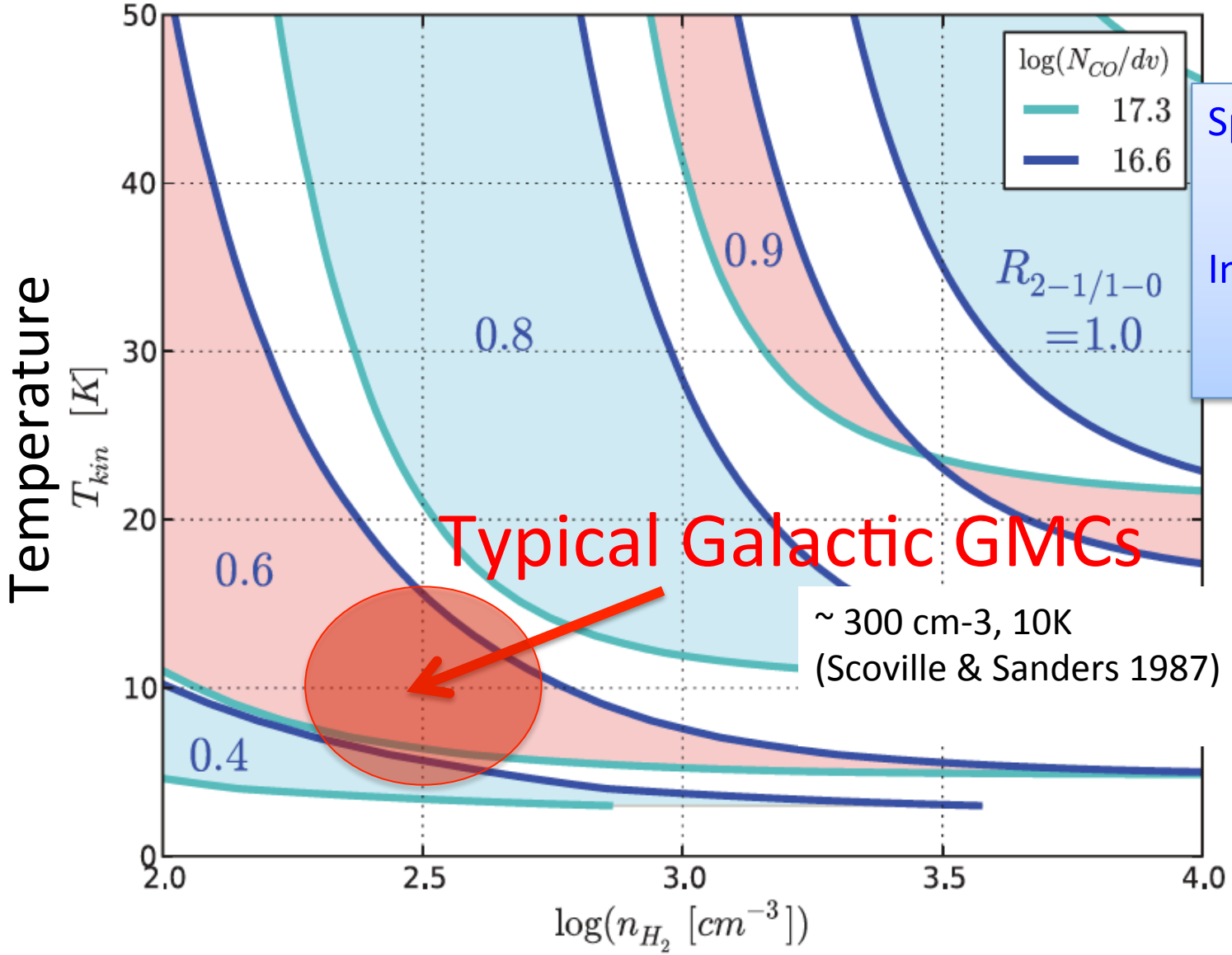
[CO/H2]~8×10^{-3}

$R_{2\text{-}1/1\text{-}0}$ from LVG Analysis



Spiral arms
>0.7
Often ~ 0.8-1.0
Interarm regions
<0.7
Often ~ 0.4-0.6

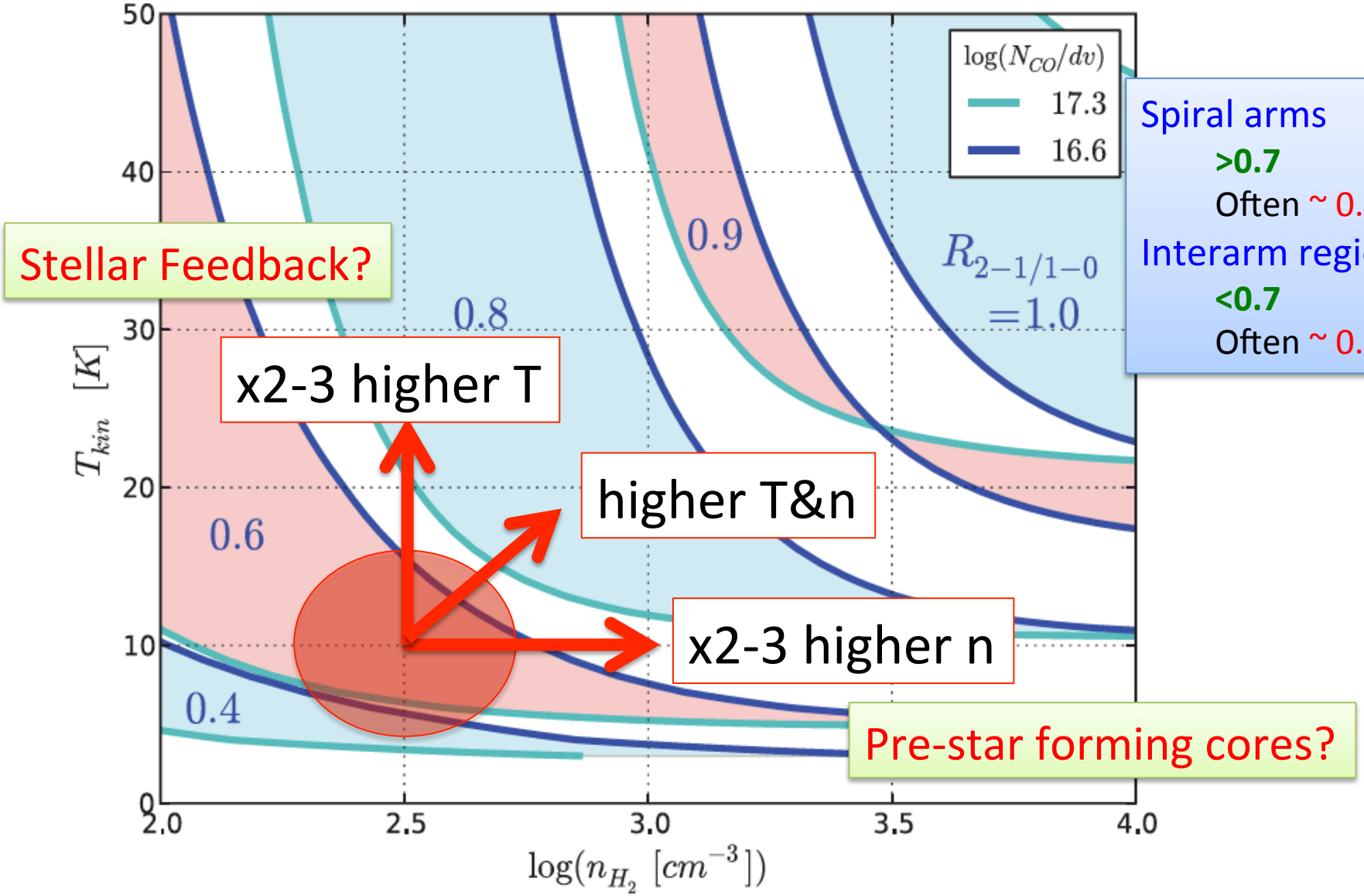
$R_{2\text{-}1/1\text{-}0}$ from LVG Analysis



Spiral arms
>0.7
Often ~ 0.8-1.0

Interarm regions
<0.7
Often ~ 0.4-0.6

$R_{2\text{-}1/1\text{-}0}$: Low → High



Stellar Feedback?

x2-3 higher T

higher T&n

x2-3 higher n

Pre-star forming cores?

Spiral arms
>0.7
Often ~ 0.8-1.0

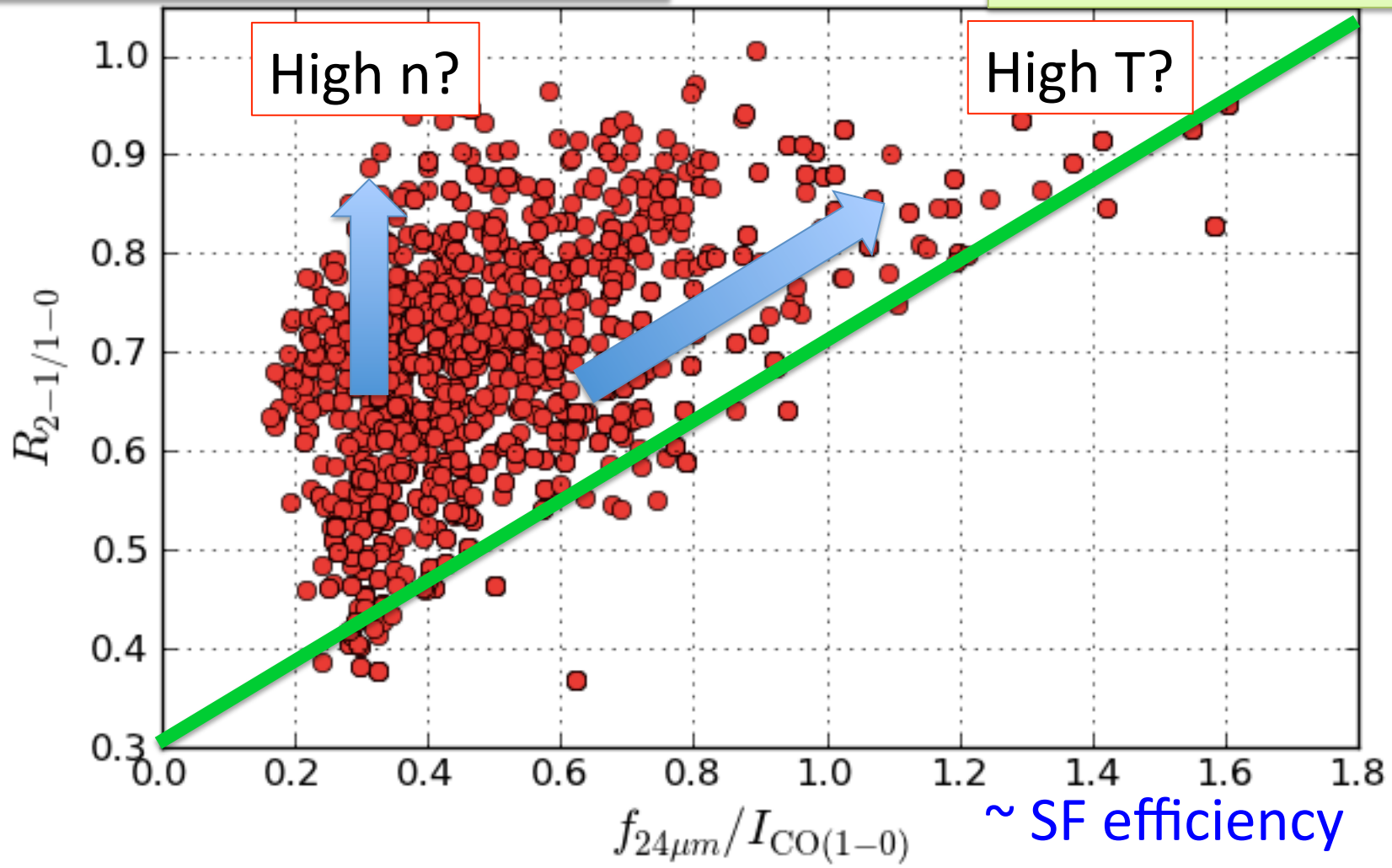
Interarm regions
<0.7
Often ~ 0.4-0.6

Mild increases in temperature OR/AND density; but note for ~780pc region.

$R_{2\text{-}1/1\text{-}0}$: Low → High

Pre-star forming cores?

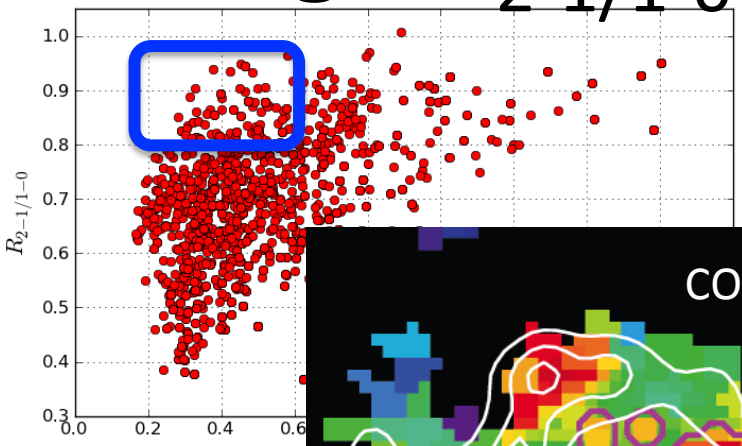
Stellar heating?

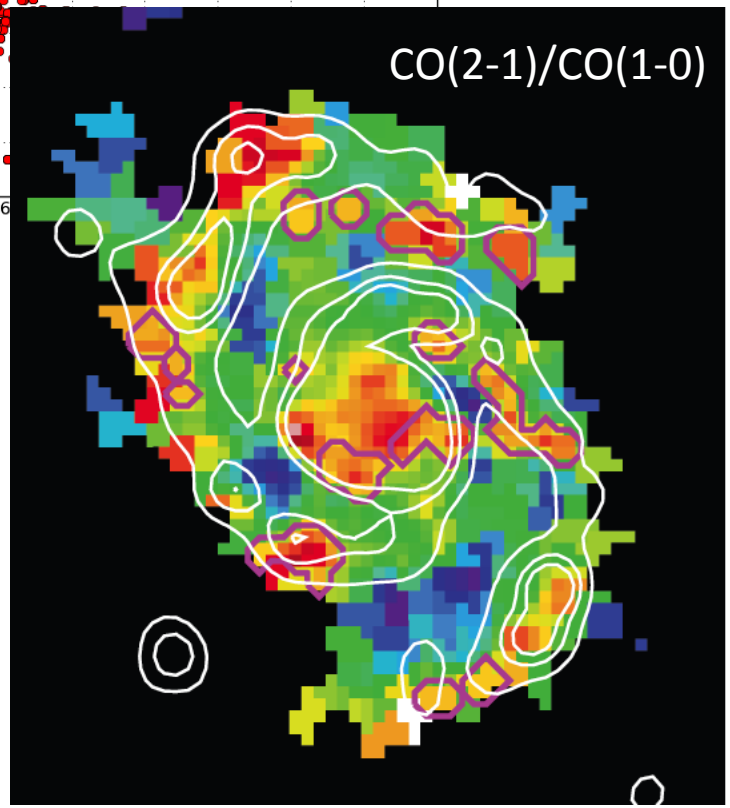


~ SF efficiency

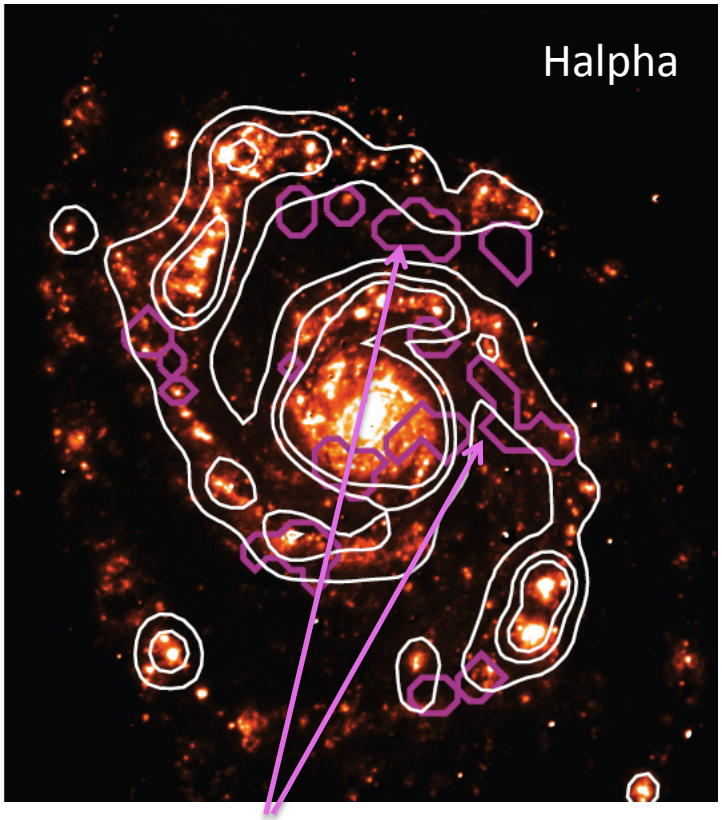
Koda et al. submitted

High $R_{2\text{-}1/1\text{-}0}$ & Low SF Efficiency





Contours
White -24micron
Purple – high R & low SFE



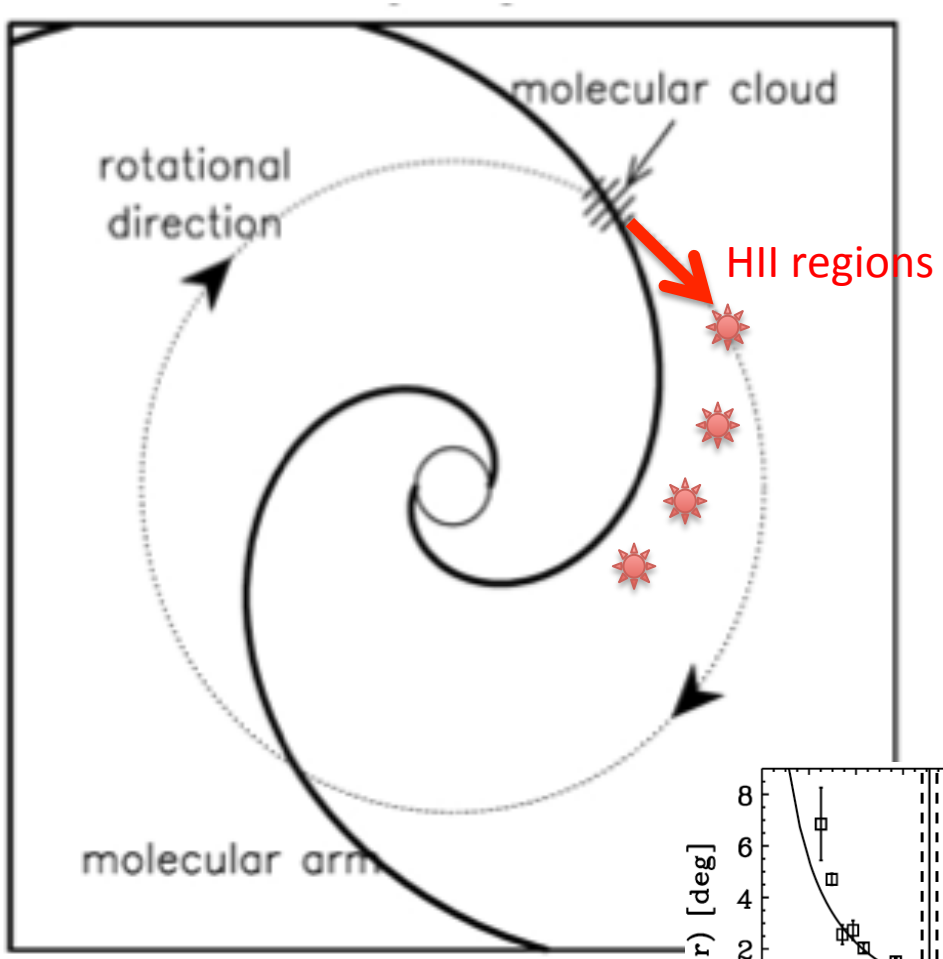
Complicated, but tend to appear at upstream side

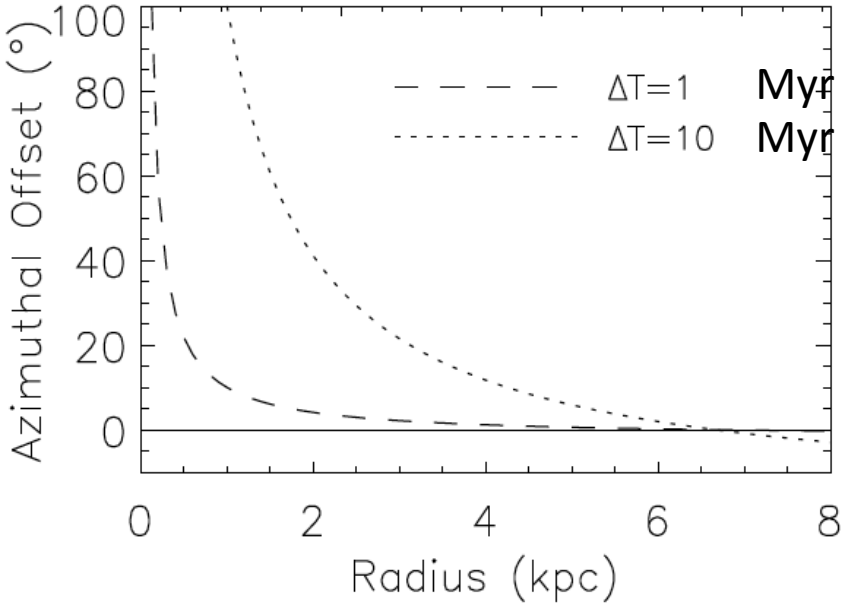
→ Pre-star forming dense cores?

Offset Measurements

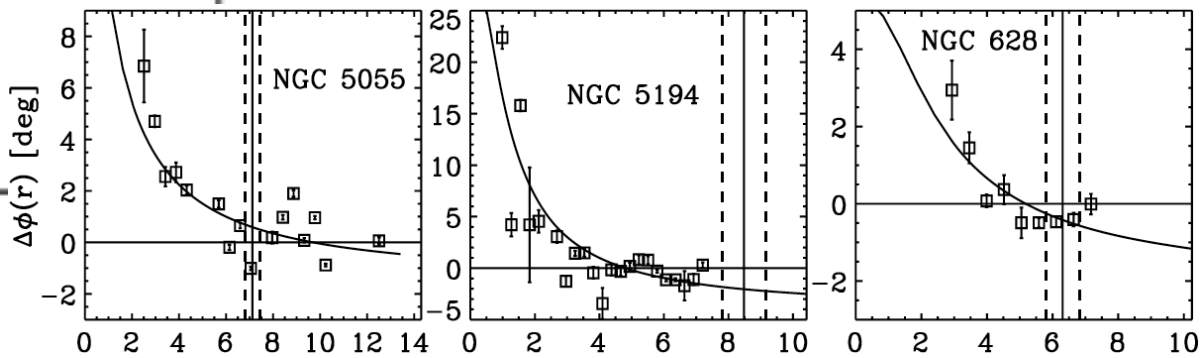
The Offset Method

$$\Delta\Theta_{offset} = \left(\Omega(r) - \Omega_p\right)\Delta t_{SF}$$





Method Developed by Egusa et al. 2004



Tamburro et al. 2008

Please see Melissa Louie's poster

Discrepancy in Previous Measurements

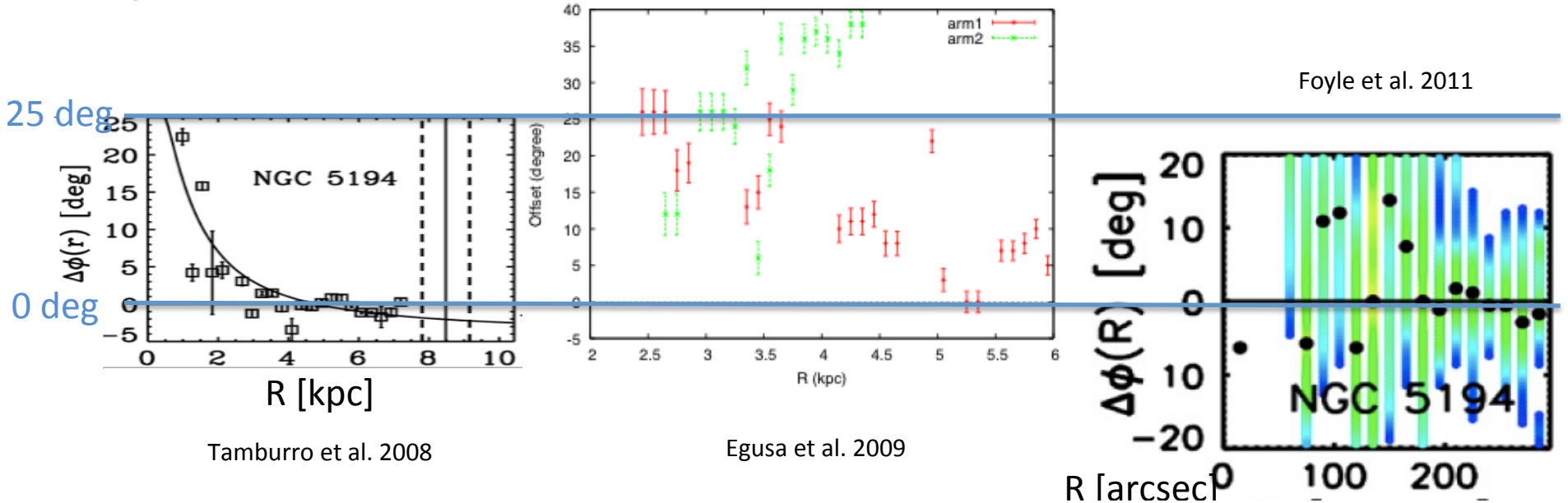
Analyzed an order of ~10 galaxies.

	Tamburro+ 2008	Egusa+ 2009	Foyle+ 2011
Gas Tracer	HI 21cm	CO	HI 21cm
SF Tracer	24micron	Halpha	24micron
Method	Cross Correlation	Peak Tracing	Cross Correlation
SF Timescale	1-4 Myr	~10 Myr	No systematic offsets

Very short GMC lifetime?

Against conventional density wave?

Why measured offsets so different?



Tamburro et al. 2008

Egusa et al. 2009

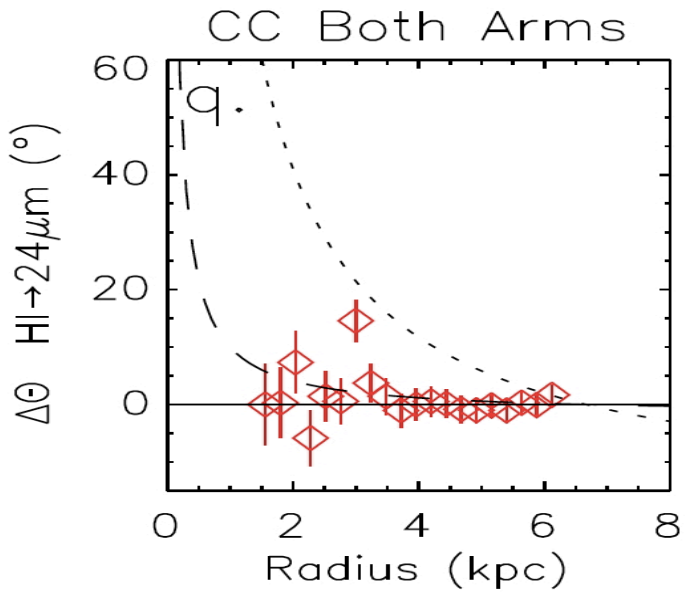
Revisit M51

- Data
  - HI: Walter et al. 2008
  - CO: Koda et al. 2009
  - 24micron & Ha: Kennicutt et al. 2003
- Measurements
  - Peak tracing (by eye)
  - Cross correlation (automated)
- Offset amounts **consistent** with previous measurement
  - Small offsets between HI and 24micron
  - Large offsets between CO and Halpha

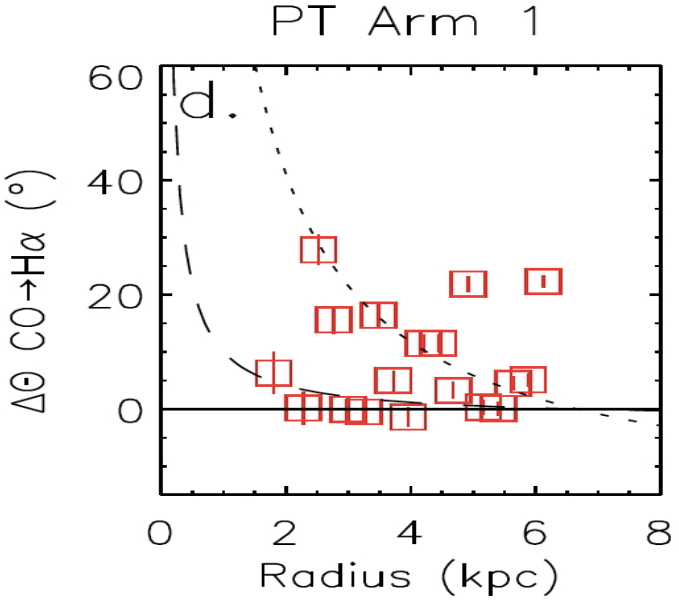
Louie, Koda & Egusa 2012, submitted

Please see Melissa Louie's poster

HI → 24micron



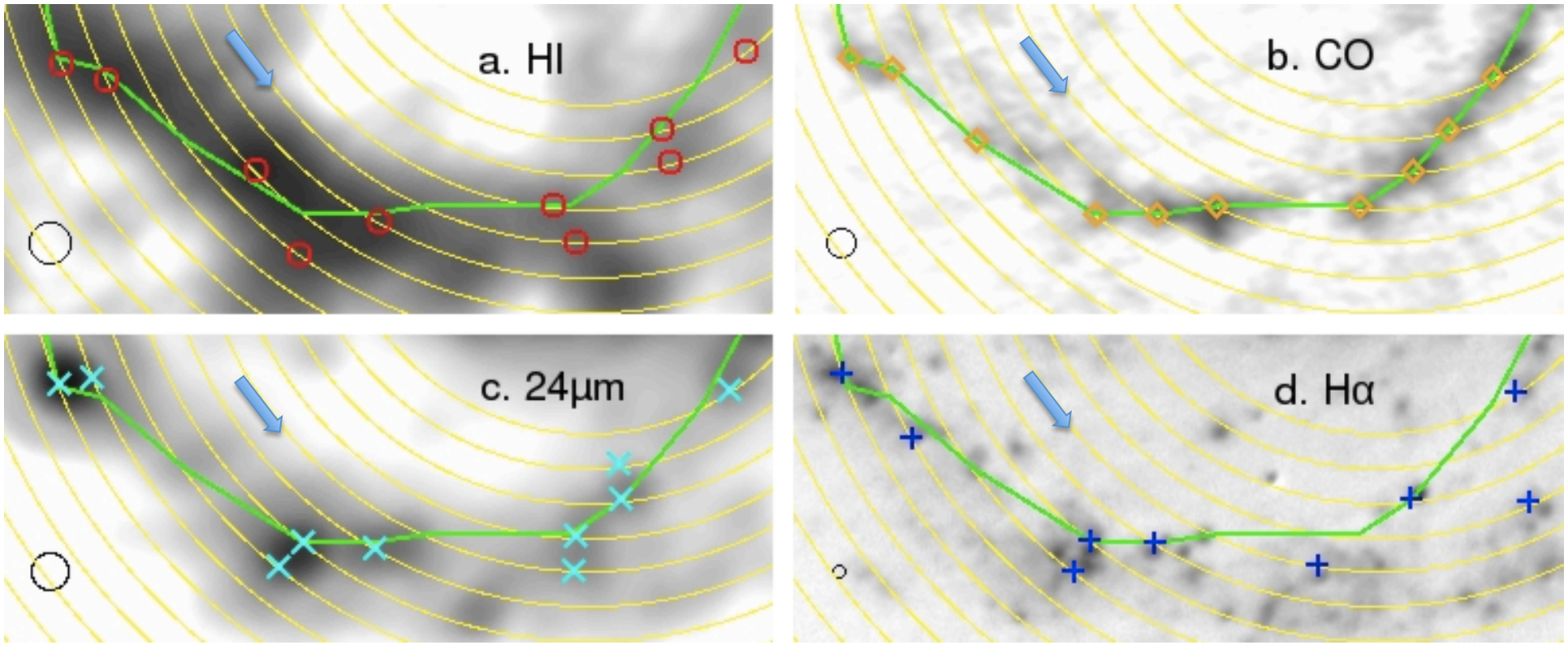
CO → Halpha



Positions of HI, CO, 24micron, and Halpha

Green line: CO peaks

Louie, Koda & Egusa 2012, submitted



HI, 24micron, and Halpha often appear downstream of CO.

→ HI emission traces the gas photo-dissociated by recent star formation (as well as the compressed gas).

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Summary

- **The CANON CO(1-0) Survey**
  - CARMA (interferometer) + Nobeyama (single-dish)
  - 29 spiral galaxies from SINGS
  - 2-3 times higher res. and sen. than BIMA-SONG
- **Resolved GMC analysis**
  - Properties similar to Galactic counterparts
  - Constant Xco among 3 spiral galaxies + MW
- **Power-law Schmidt law with CO(1-0)**
  - Non-linear when CO(1-0) is used.
- **CO(2-1)/(1-0) variation**
  - Between interarm regions and spiral arms
  - Correlate with star formation activities.
- **Offsets between gas compression to SF across spiral arms**
  - CO traces dense molecular gas for SF, but HI does not.