# Molecular Gas and Dust in ULIRGs: SMA View



credit: ALMA(ESO/NAOJ/NRAO)

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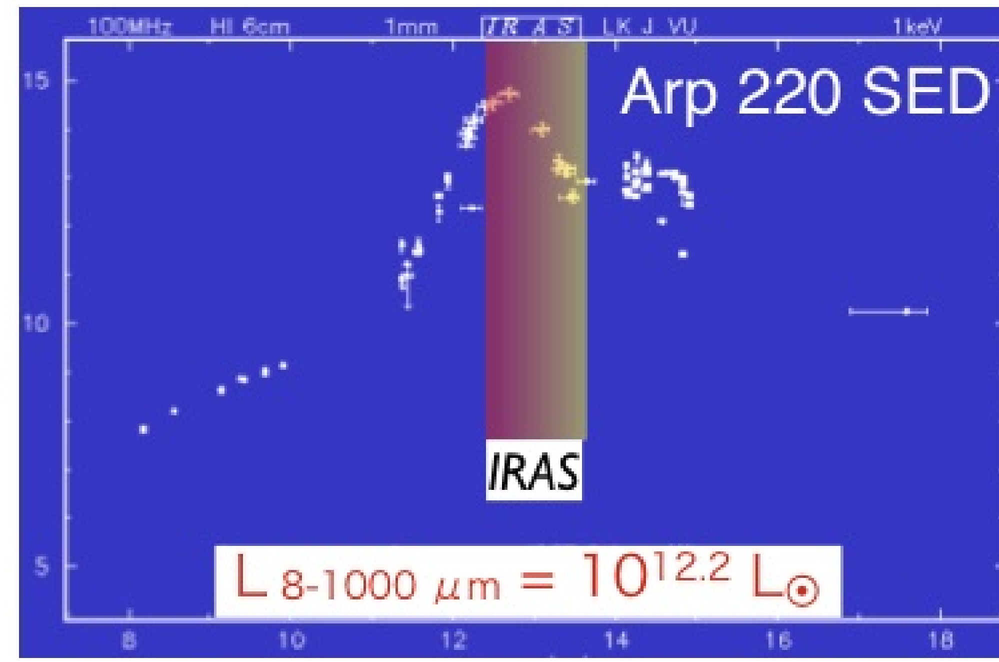
"Assembly, Gas Content and
Star Formation History of Galaxies"

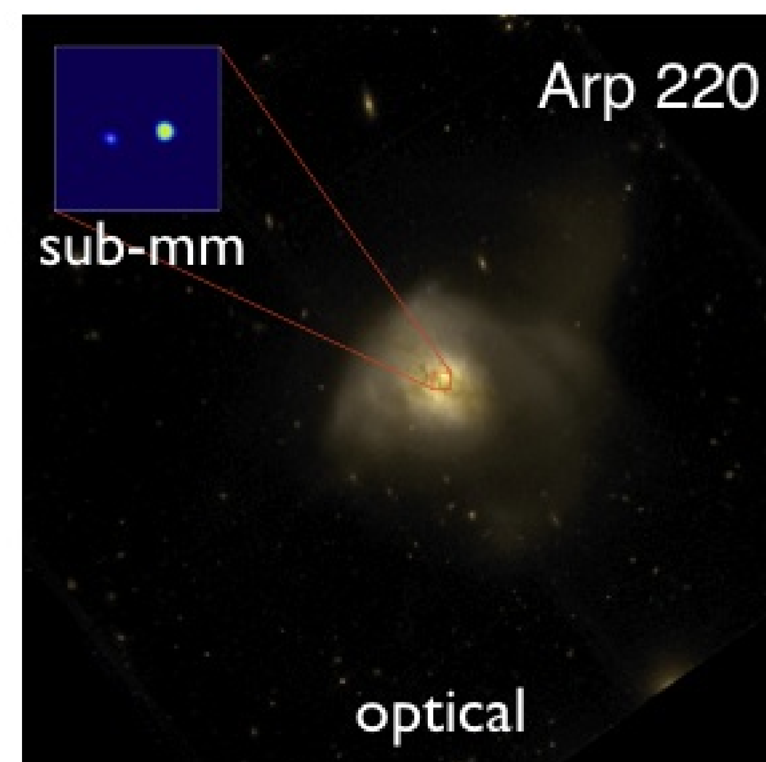
# Recent work on Molecular Gas and Dust in ULIRGs made with the Submillimeter Array (SMA)

U/LIRG : $L_{bol} > 10^{12}, 10^{11}\ L_\odot$, in mid/far-IR, mergers, S.B./AGN




Case study on Arp 220 (=nearest ULIRG)

Sakamoto et al. (2008, 2009)
Matsushita et al. (2009)
Aalto et al. (2009) → Aalto's talk
(CARMA Poster by Ashley Zauderer)



(credit: A. Evans)

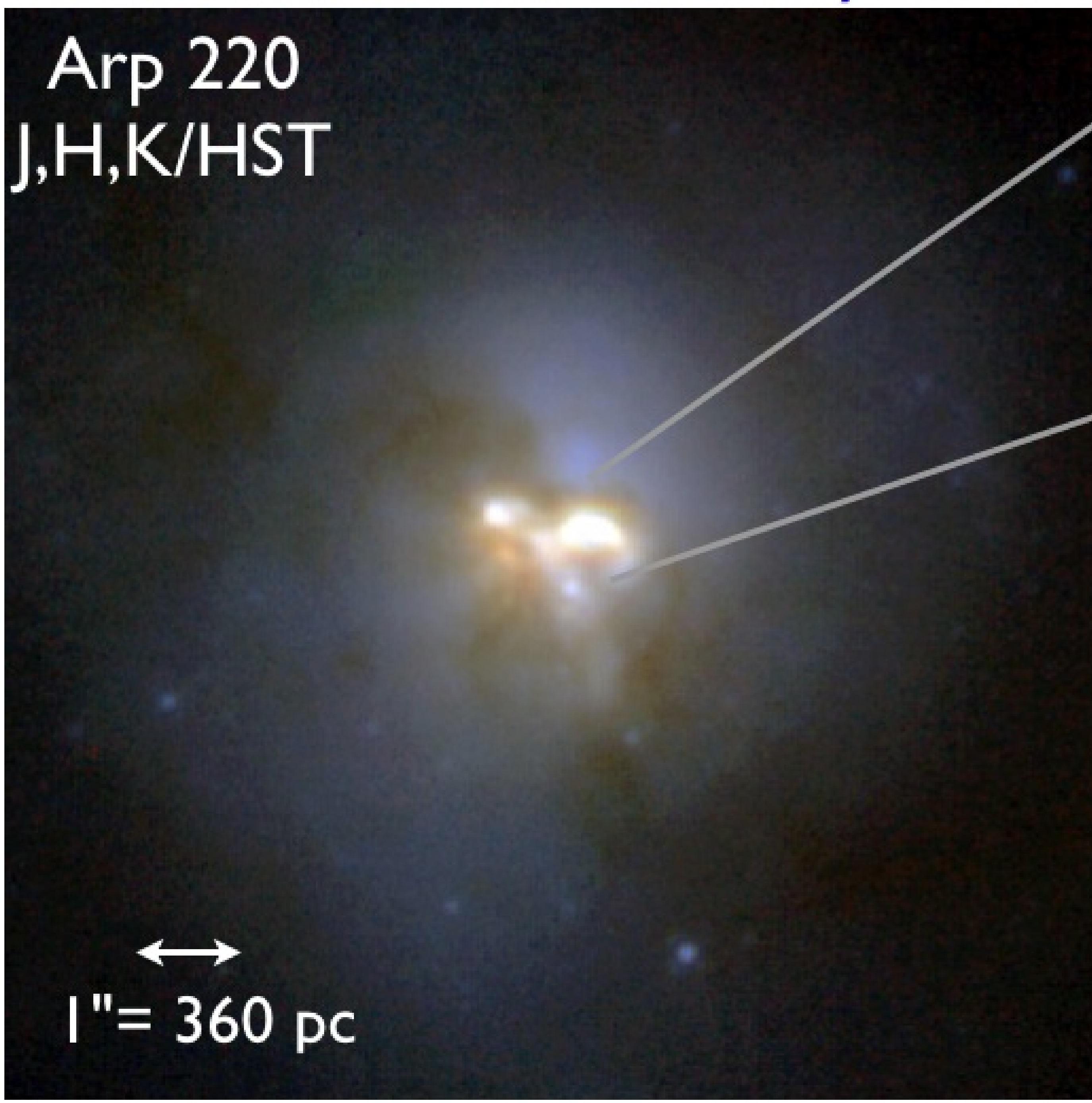
SMA Survey of U/LIRGs

Wilson et al. (2008)
Iono et al. (2009)

give you idea what ALMA will do

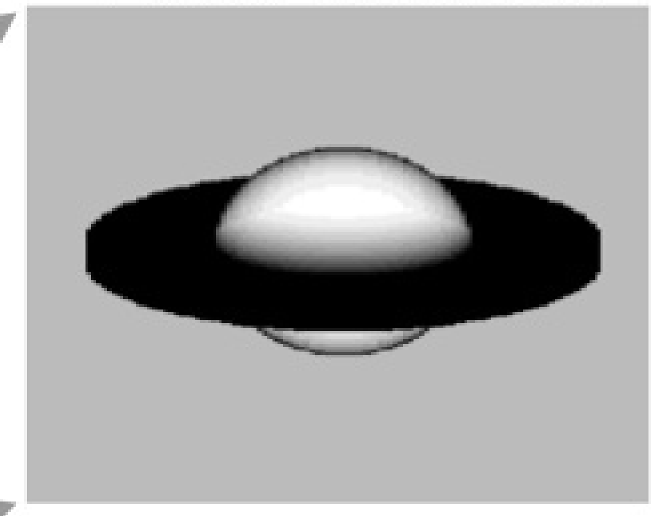
# Arp 220: Nearest ULIRG (75 Mpc), Merger

In the central kpc :
two nuclei + multi-disk system

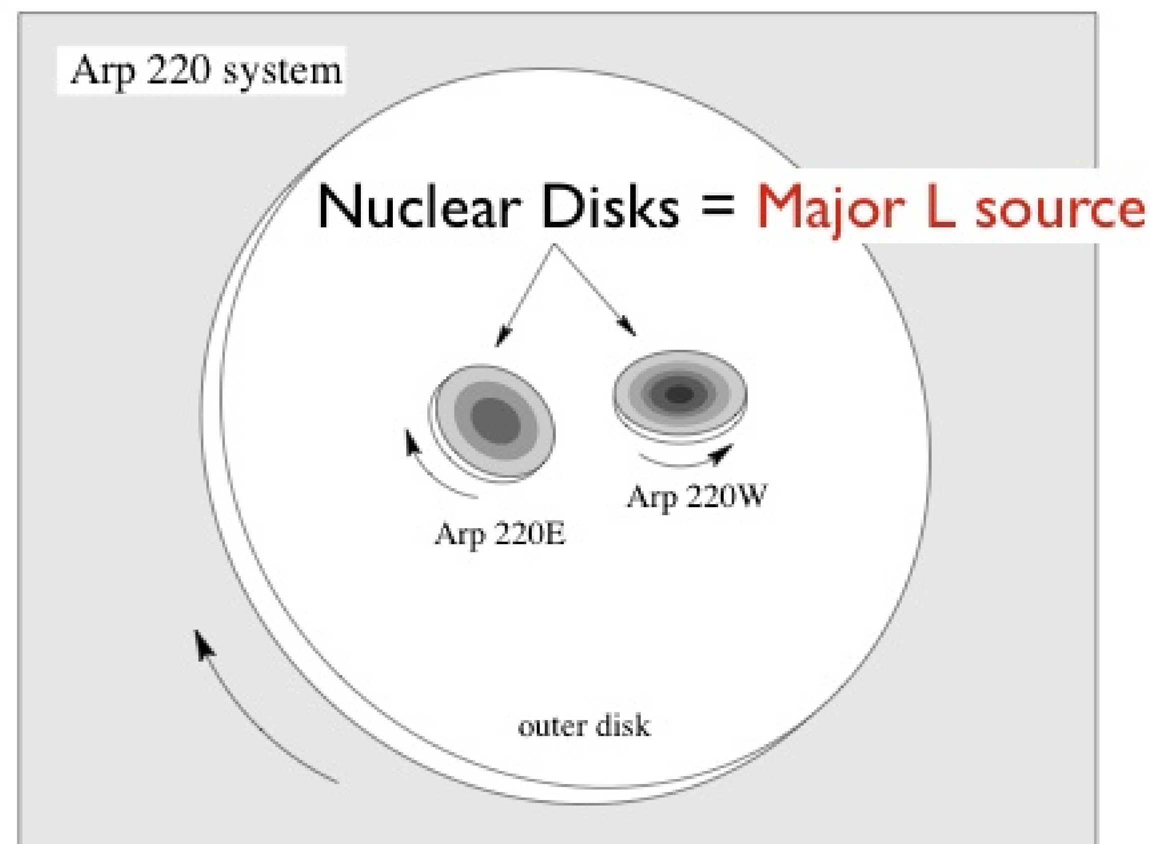



HST/NICMOS. (Scoville et al. 1998)

West nucleus

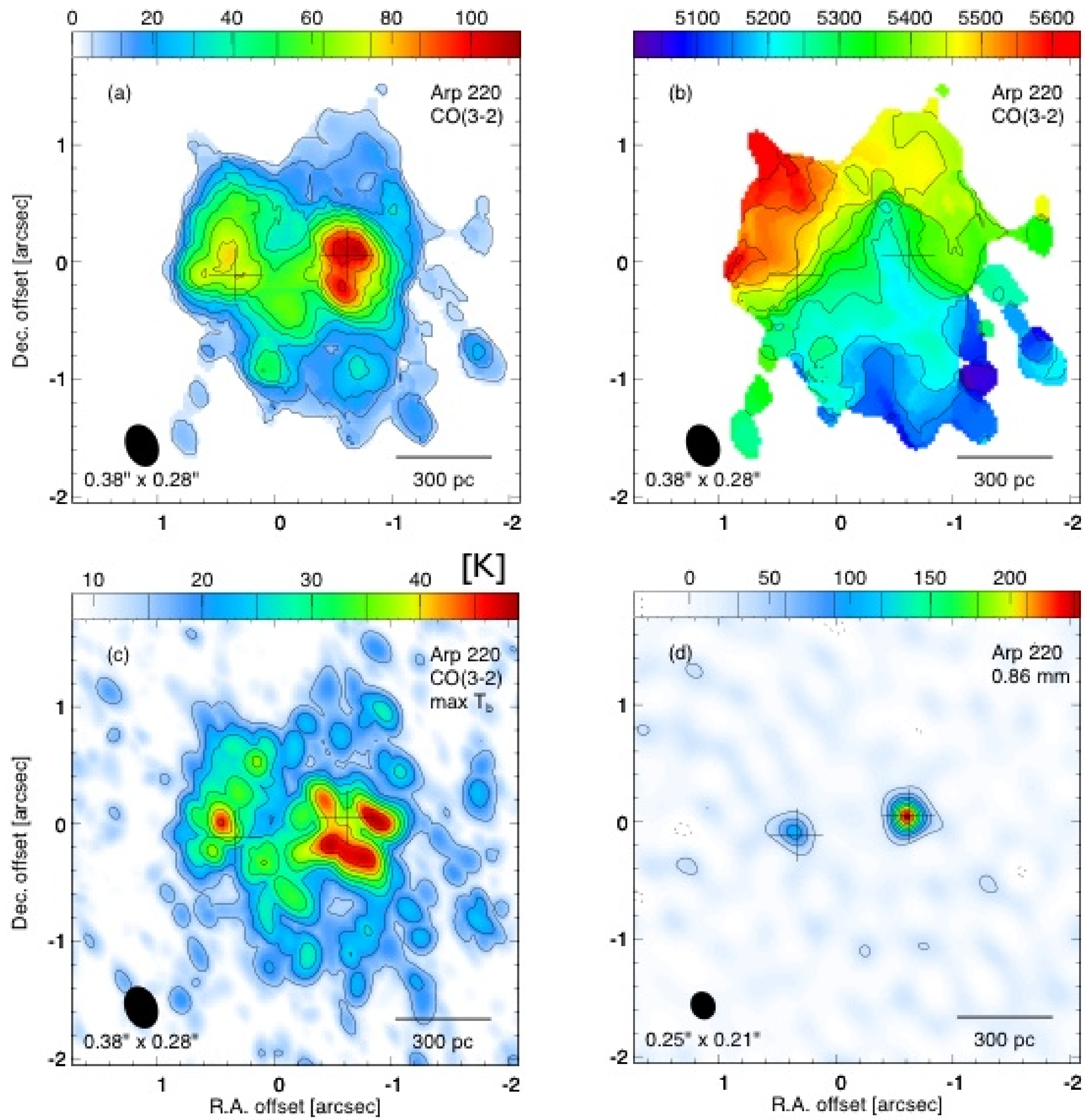


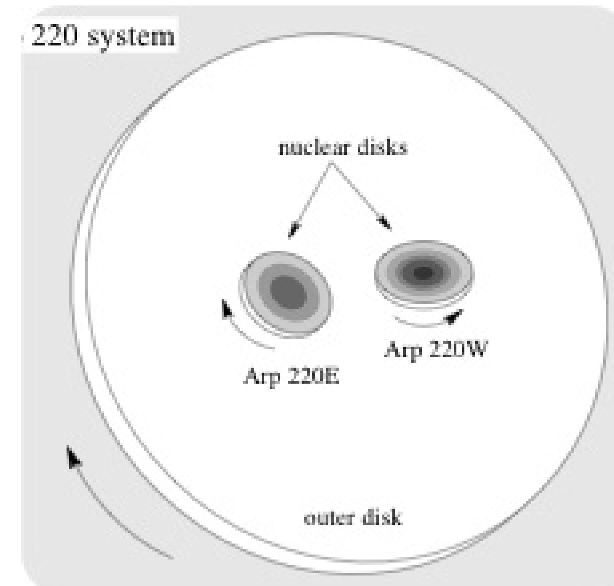
(Scoville et al. 1998)




based on OVRO CO(2-1), 0.5" res.
(Sakamoto et al. 1999)

# Arp 220 : SMA 860 μm obs.




with the max SMA resolution at 850 μm, 0.2"-0.3".

## Rotating disks & warm gas, confirmed

(Sakamoto et al. '08)

# Arp 220 : $L_{bol}$ of West Nucleus

Arp 220 W:

deconvolved size

Gaussian FWHM ~ 0.15"

uniform disk diameter ~ 0.22"

i.e., d ~ 50-80 pc

deconvolved (peak) $T_b$

$T_b$ = 90-160 K $\leq T_{dust}$

($\leq$ is due to $\tau_{dust}$)

Luminosity

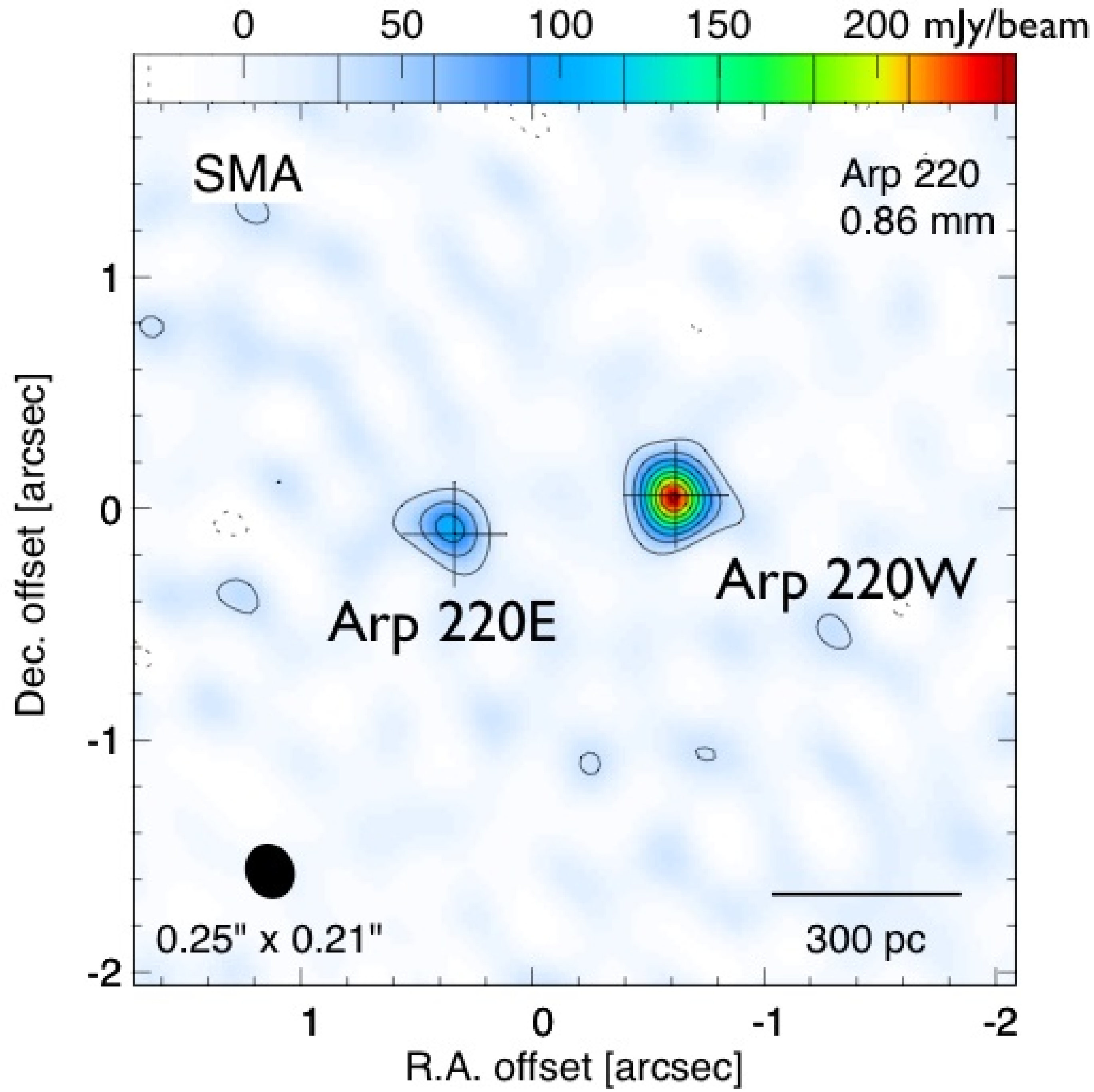
$$L_{bol} \approx \sigma T_d^4 \times \pi d^2$$

$$\geq (2\text{-}3)\times 10^{11} L_\odot$$

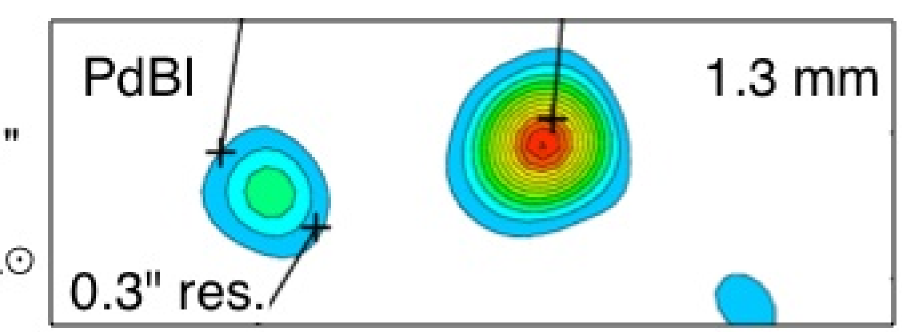
Luminosity surface density

$$\Sigma (L_{bol}) \geq 10^{7.6} L_\odot \, pc^{-2}$$

(Sakamoto et al. '08)




@ 1.3 mm
W=0.19"x0.13"
(FWHM)
$L_{bol} \geqq 3\times10^{10} L_\odot$




(Downes & Eckart '07)

# Arp 220 : $M_{dyn}$ of West Nucleus

From CO(3-2) PV diagram

Dynamical mass

$M_{dyn}$ ($r \leqq 40$pc) ~ $6\times10^8\ M_\odot$

(W's disk is nearly edge-on)

Luminosity-to-Mass ratio

$L/M \gtrsim 4\times10^2\ L_\odot/M_\odot$

(for $r \leqq 40$pc)

c.p.

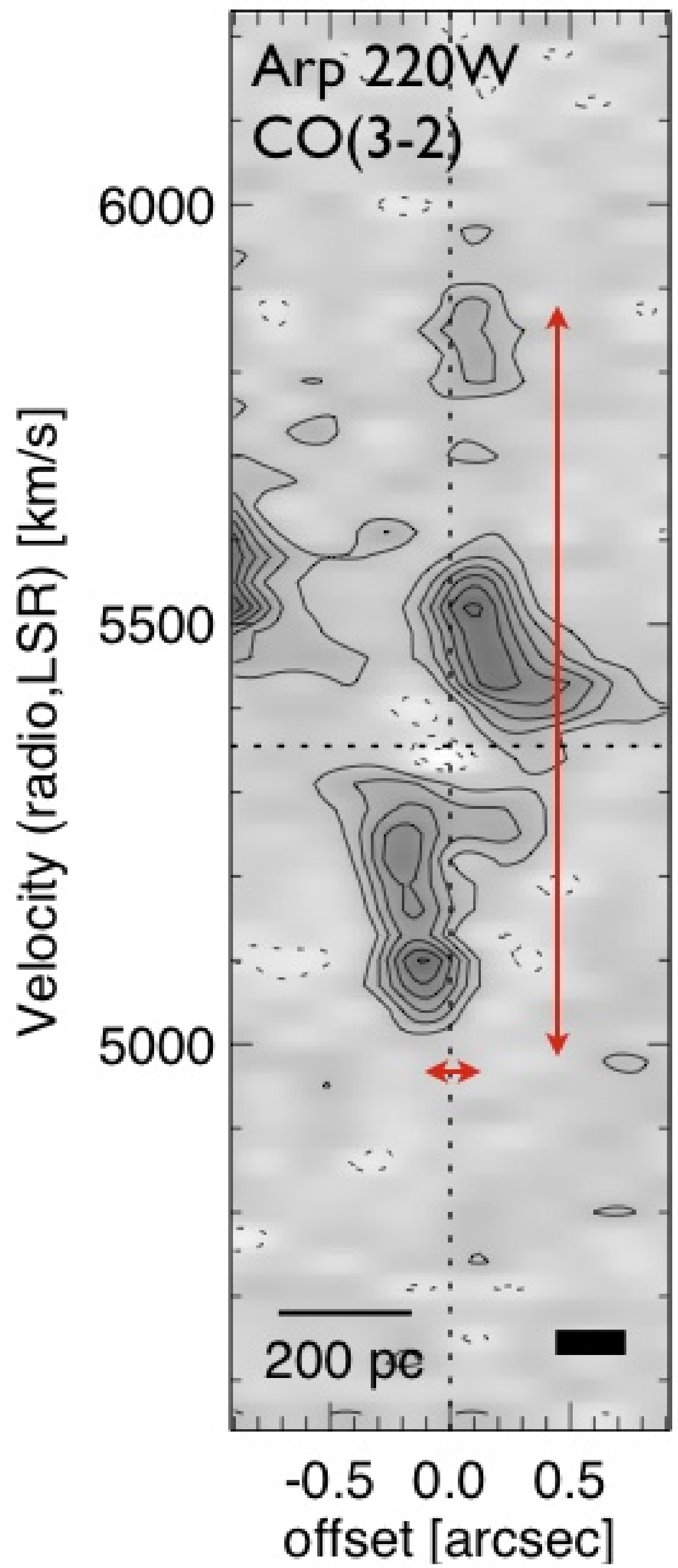
Young, < 10 Myr, starburst can have

$L/M$ ~ $1\times10^3\ L_\odot/M_\odot$ (Starburst99).

AGN can have up to

$L_{Edd}/M_{bh}$ ~ $4\times10^4\ L_\odot/M_\odot$

Thus, both can explain the min L/M.




(Sakamoto et al. '08)

# Arp 220 : New Constraints on the Power Source

- Central 80 pc of Arp 220 W has

  $L_{bol} \geqq 2 \times 10^{11}\ L_{\odot}$,

  $\Sigma_{bol} \geqq 10^{7.6}\ L_{\odot}\ pc^{-2}$,

  $M_{dyn} \sim 6 \times 10^{8}\ M_{\odot}$,

  and

  $L/M \geqq 4 \times 10^{2}\ L_{\odot}/M_{\odot}$

⇐ Robust estimates based on Stefan-Boltzmann and Newton's laws.

- The power sources consistent with these constraints are

  100s of $10^{9} L_{\odot}$ super clusters or an equivalent starburst,

  and

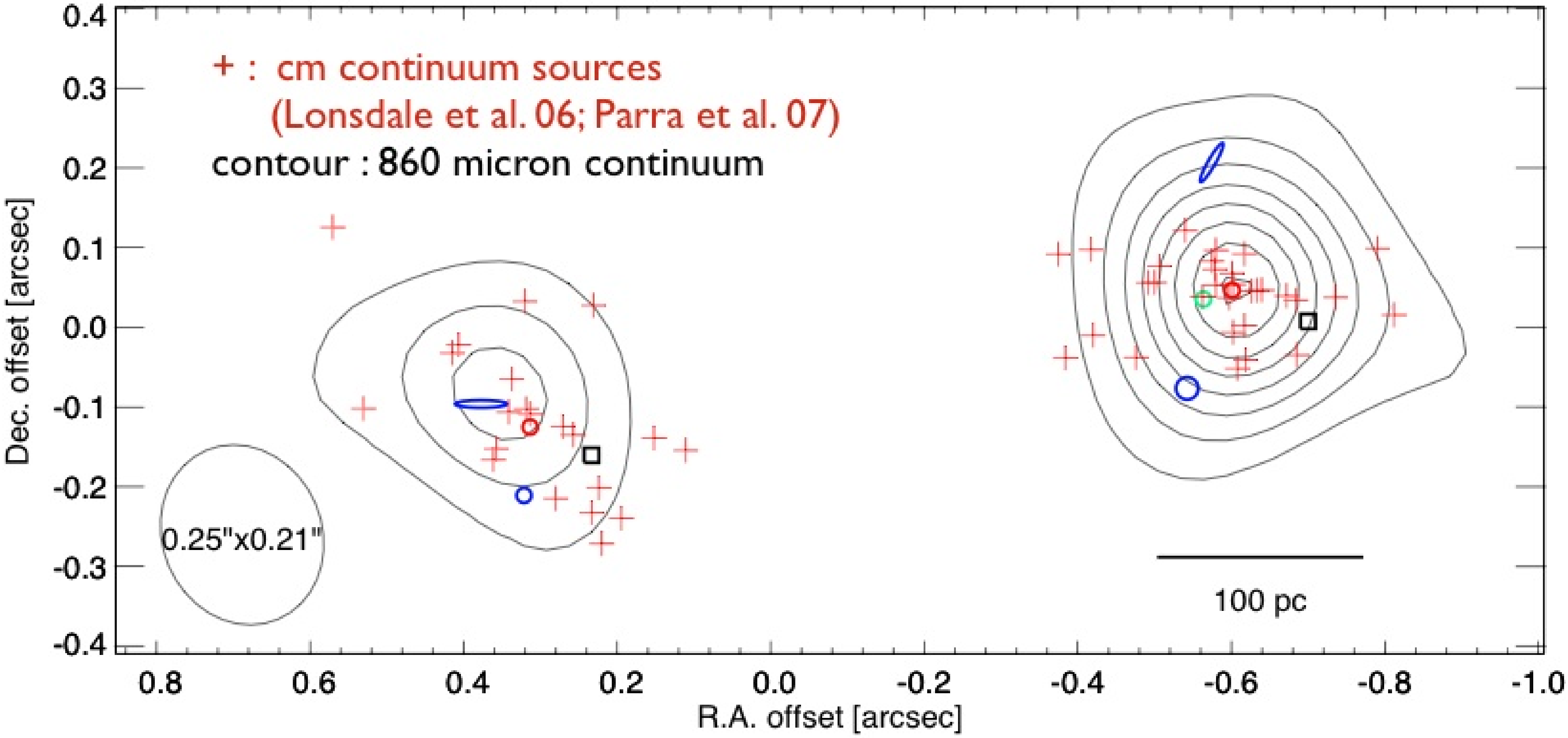
  an energetically-dominant AGN(s).

  (Sakamoto et al. '08)

- Higher-res., higher-freq. obs. ⇒ tighter constraints.

**High-resolution sub-mm obs.**
**⇒ $L_{bol}$ distribution, L/M**
**of deeply buried nuclei of ULIRGs**

# Arp 220 : Comparison of $I_{dust}$ and $\Sigma_{SNR}$




If starburst-powered,

$$I_{dust\ emission} \propto \Sigma_{SNR}^{0.75\text{-}1.25}, \quad \text{for Schmidt law's } n=1\text{-}2$$

under a few simple assumptions (S08).

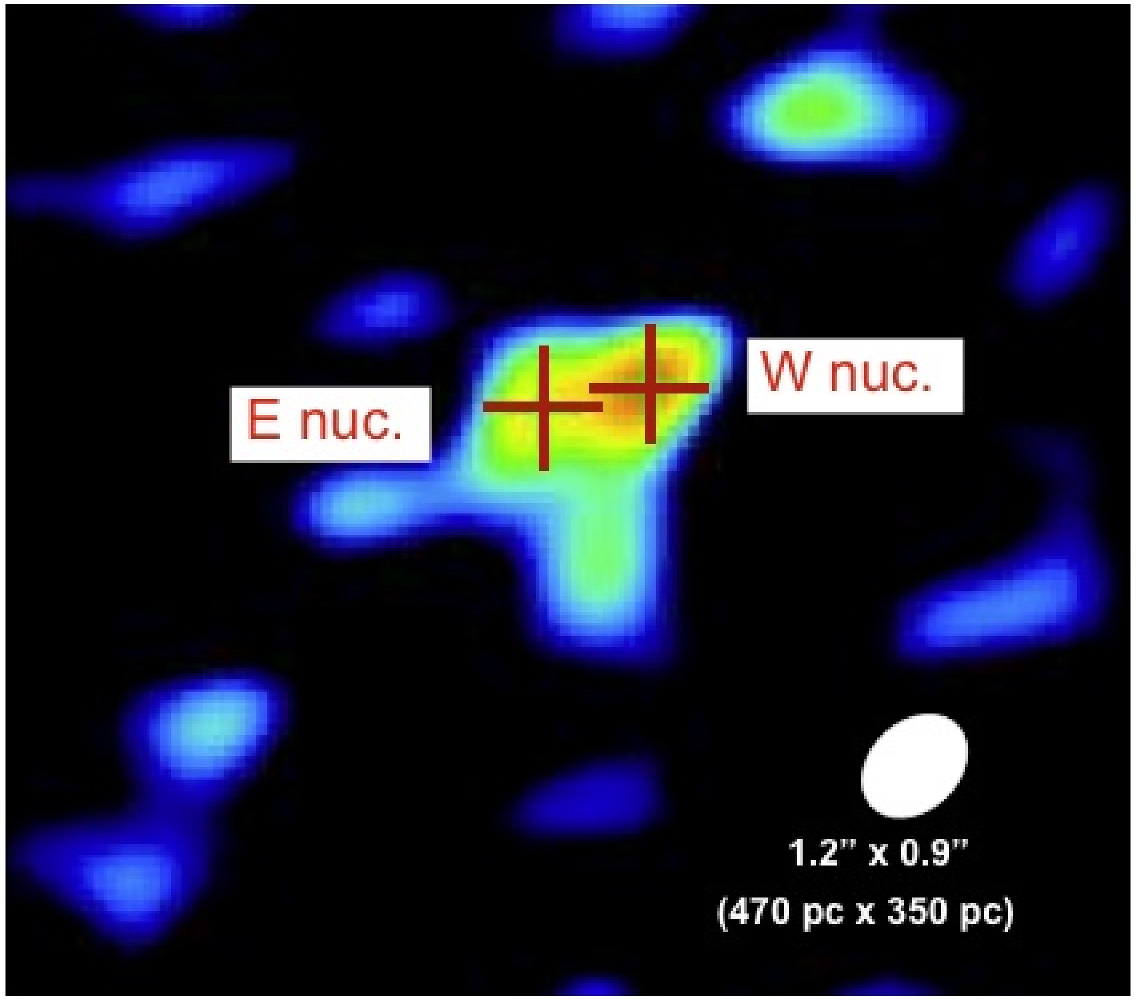
Arp 220E : PA~45° elongation in both $\Sigma_{SNR}$ and $I_{dust}$.

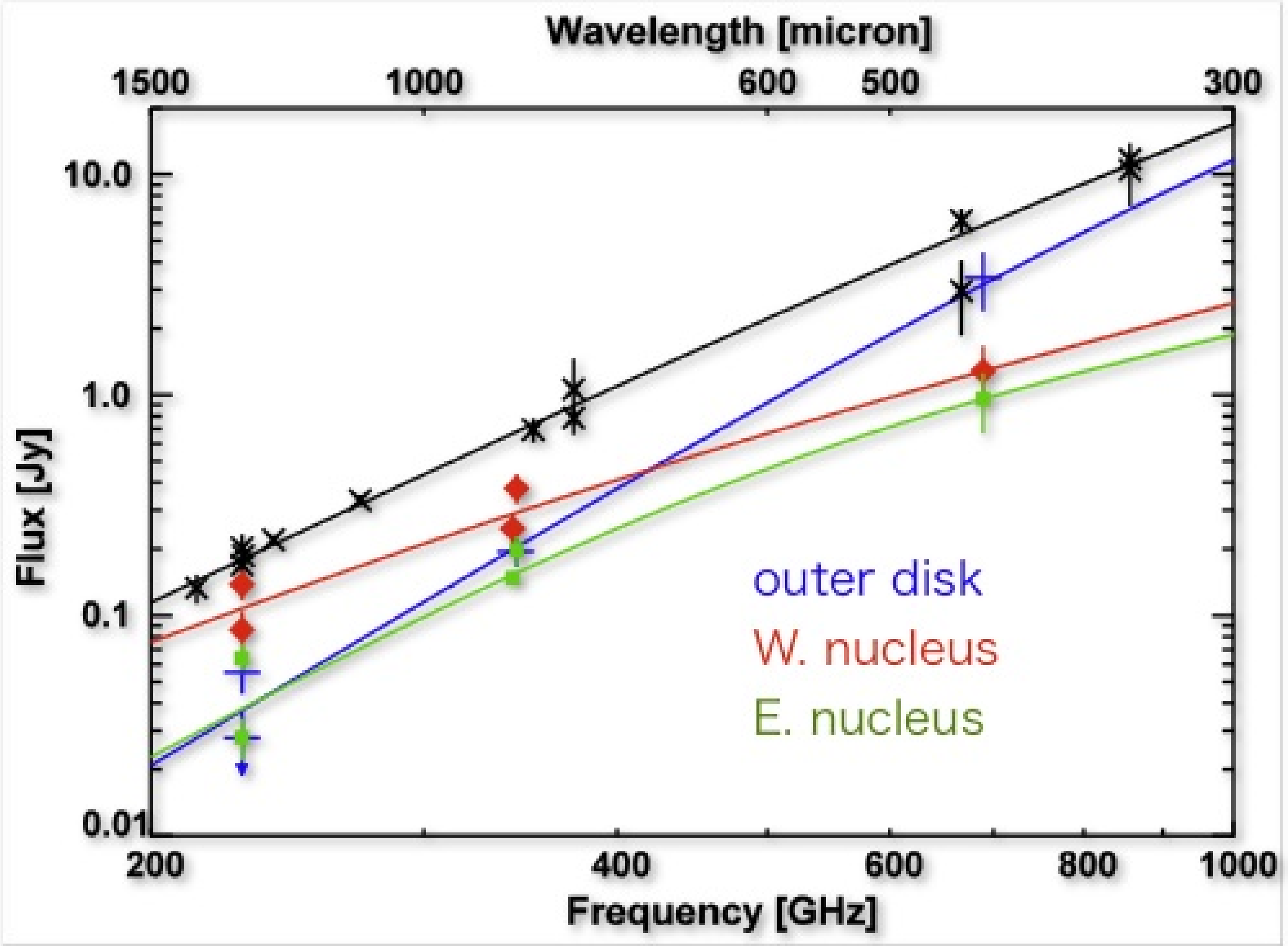
Arp 220W : different distributions

(Sakamoto et al. '08)

# Arp 220 : 435 μm (690 GHz)

Matsushita et al. (2009)




1" resolution

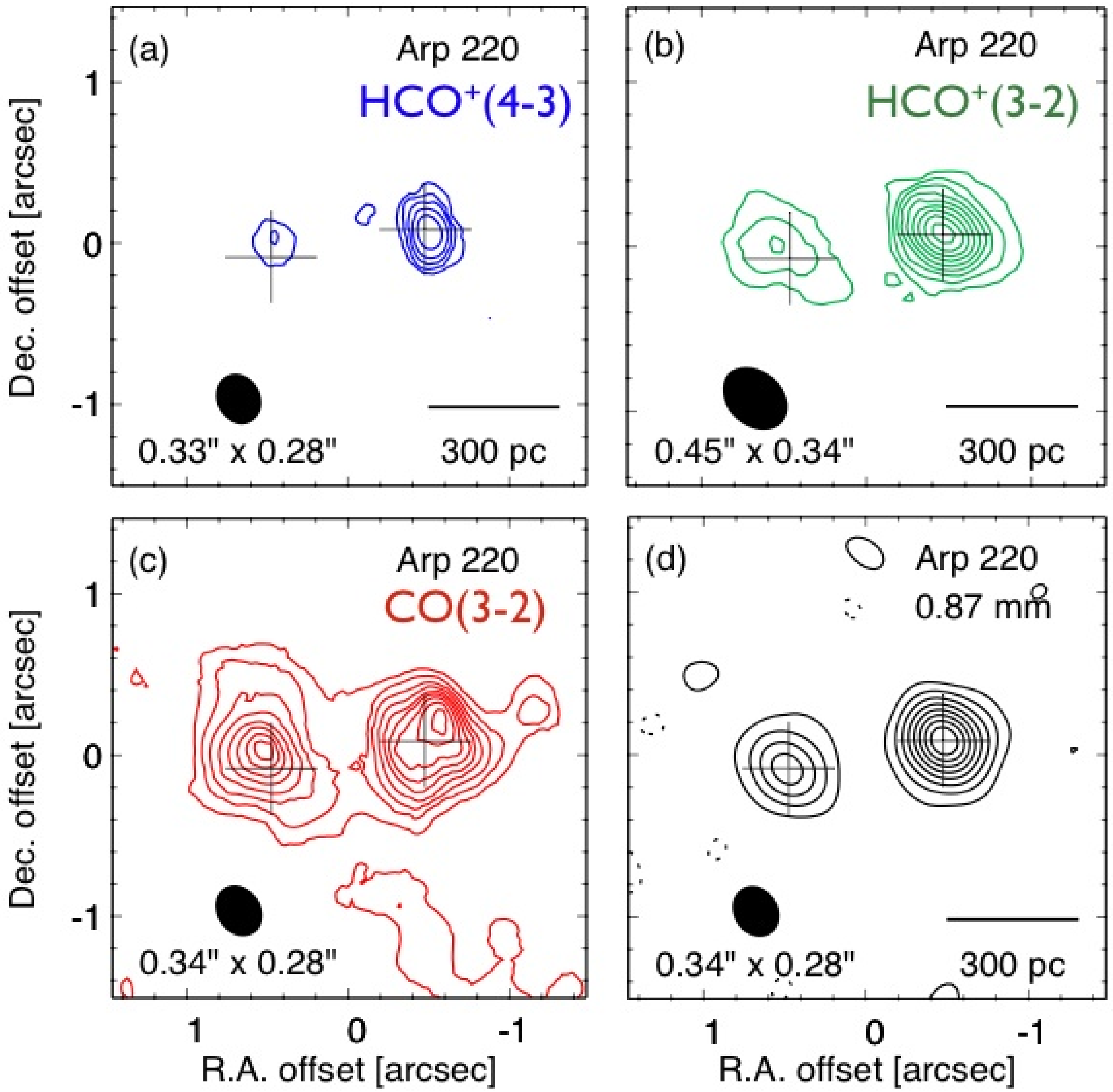
sub-mm SED for individual components of Arp 220

→ $\tau_{860}$: W, E ~1; outer disk ≪1; W > E.

not enough resolution for $L_{bol}$

(Matsushita et al. '09)

# Arp 220: High Critical-density Lines




$f_{tot}$ = F(SMA)/F(total)

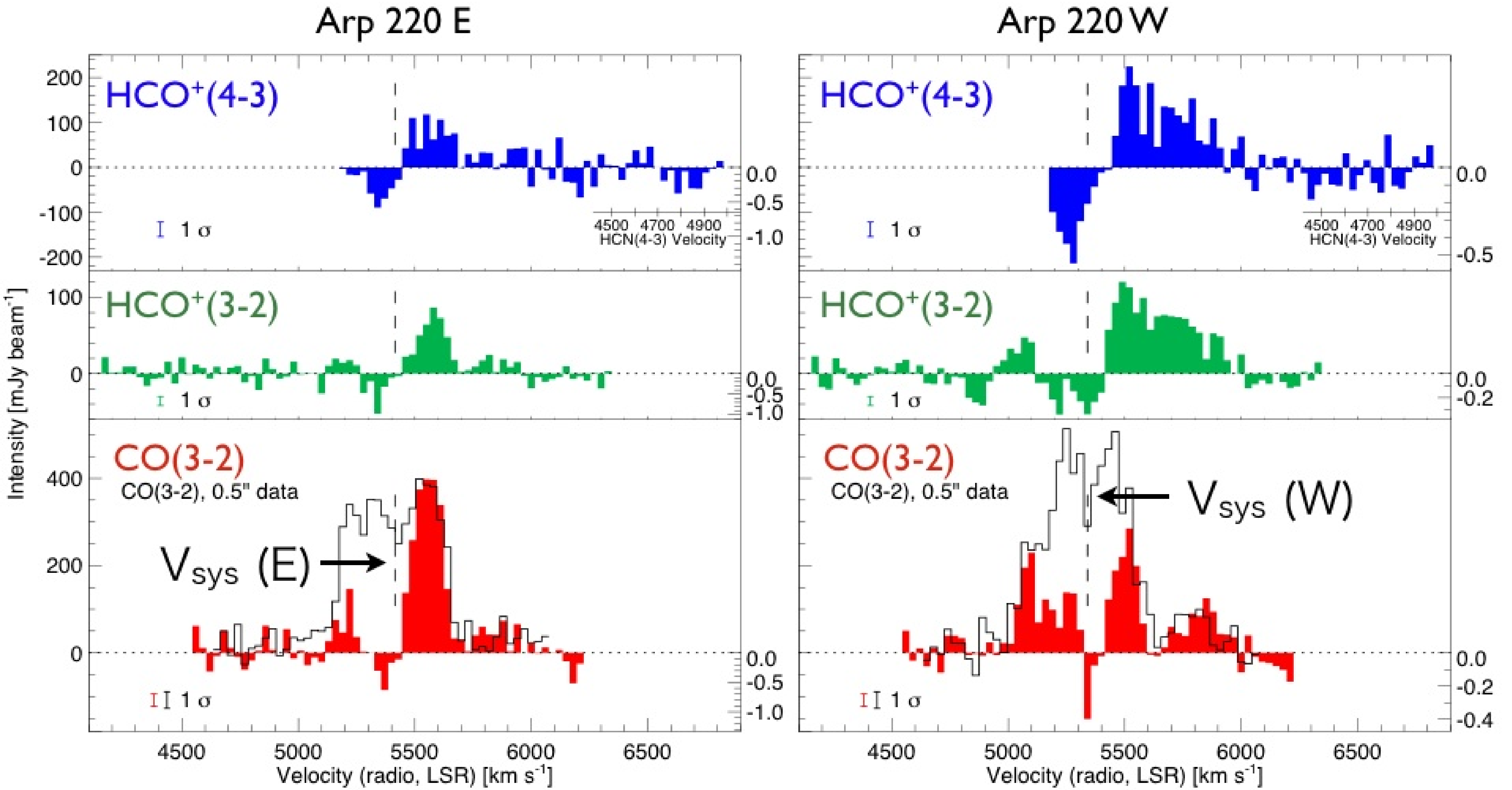
| | |
|---|---|
| 100±30% | $HCO^+$(4-3) |
| 64±13% | $HCO^+$(3-2) |
| 23± 6% | CO(3-2) |
| 100±20% | 345GHz cont. |

Compact $HCO^+$ , extended CO(3-2).

Excitation condition limits extent of $HCO^+$.

(Sakamoto, Aalto, Wilner et al. 2009)

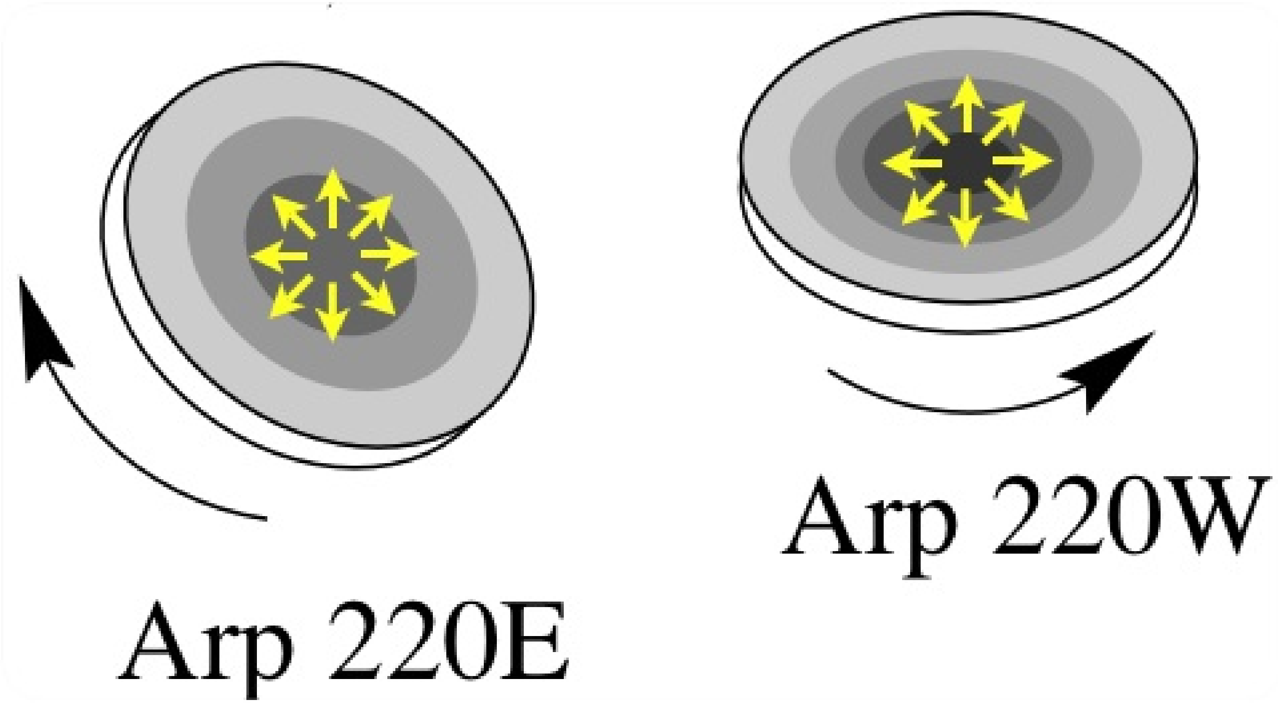
# Arp 220 : P-Cyg profiles toward nuclei

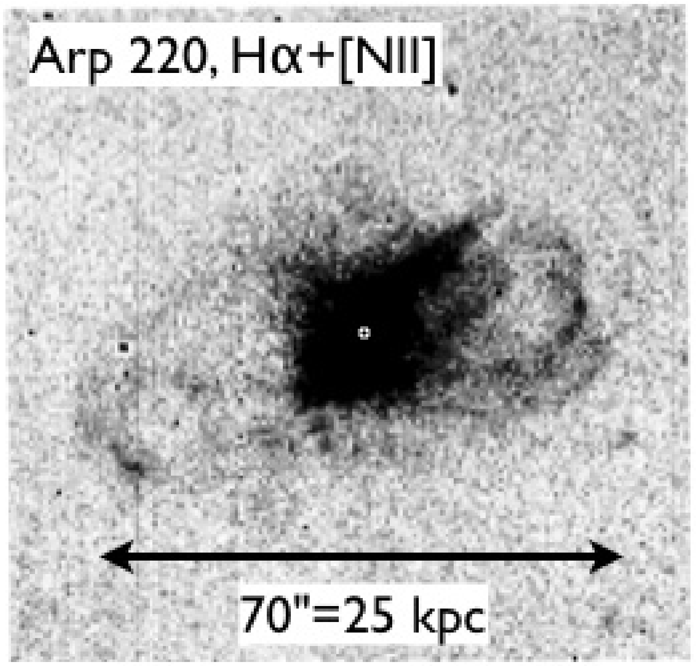



Blueshifted Absorption + Redshifted Emission
= P Cygni profile

(Sakamoto, Aalto, Wilner et al. 2009)

# Arp 220 : Nuclear Winds




Heckman et al. '87, '96

- Wind from each nucleus
  $V_{rad}$ ~ 100 km/s,    (up to 500 km/s)
  outflowing inner region +  rotation-dominated outer region

see also Poster by Spoon

- Energetically plausible
  SNR ~ 3/yr (W), 1/yr (E)    (Lonsdale et al. 2006)
  $L_{mech}$=3e50 J/Myr → ΔV=500 km/s for 1e8 $M_\odot$, at 10% eff.
  $P_{rad}$ on dust may be another driver → Thompson's talk in this session

- Outflow rate ~100 $M_\odot$/yr (w/ assumptions)

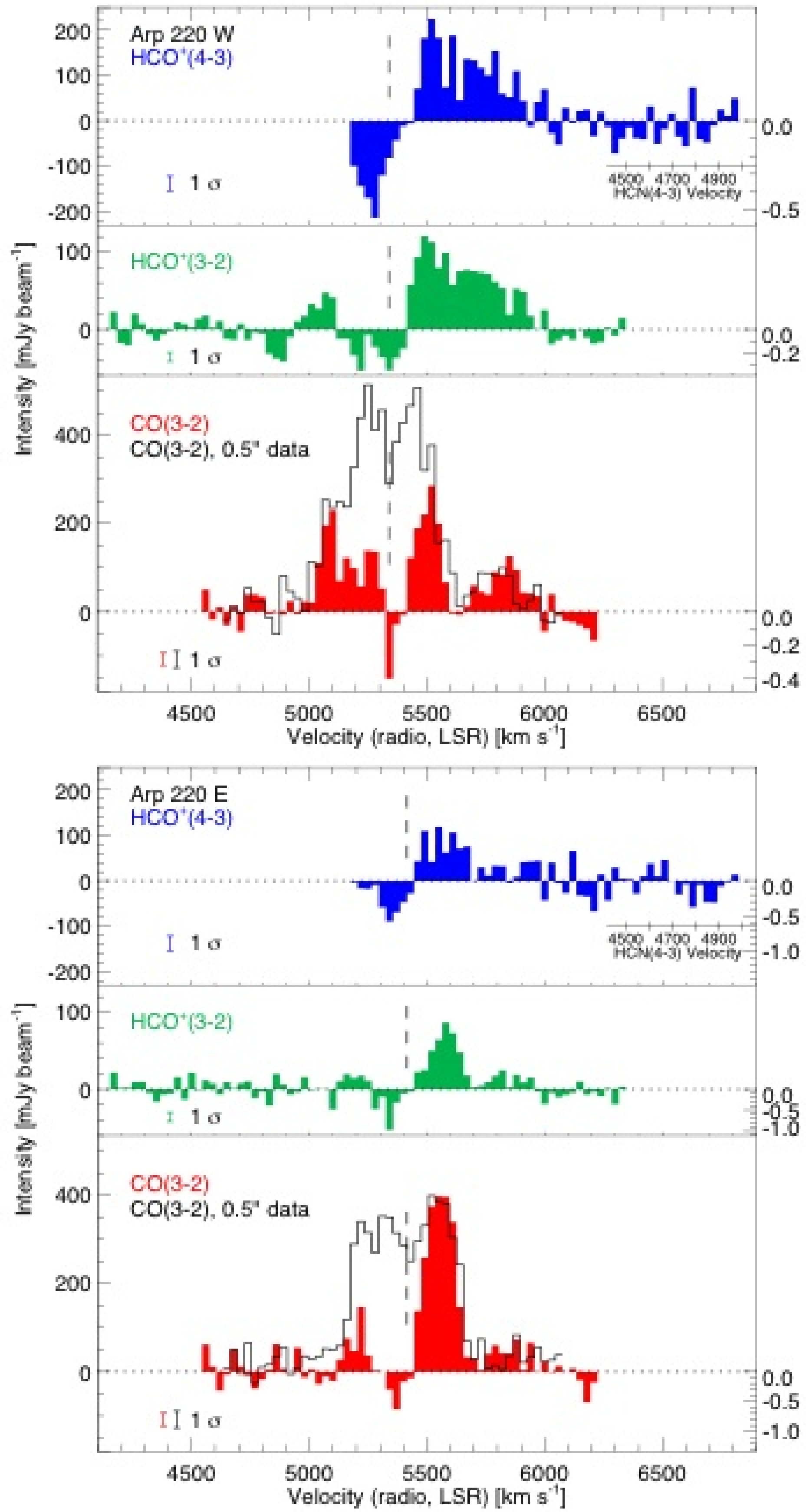
(Sakamoto, Aalto, Wilner et al. 2009)

# Arp 220 : High-res. sub-mm obs.

High-resolution sub-mm obs.

⇓

radial gas motion in ULIRG nuclei




Sub-mm :

high $T_{b,\,dust}$, low $T_{ex,\,molecule}$ ⇒ line absorption

high-J HCO+, localized around the nucleus
⇒ traces kinematics near the center

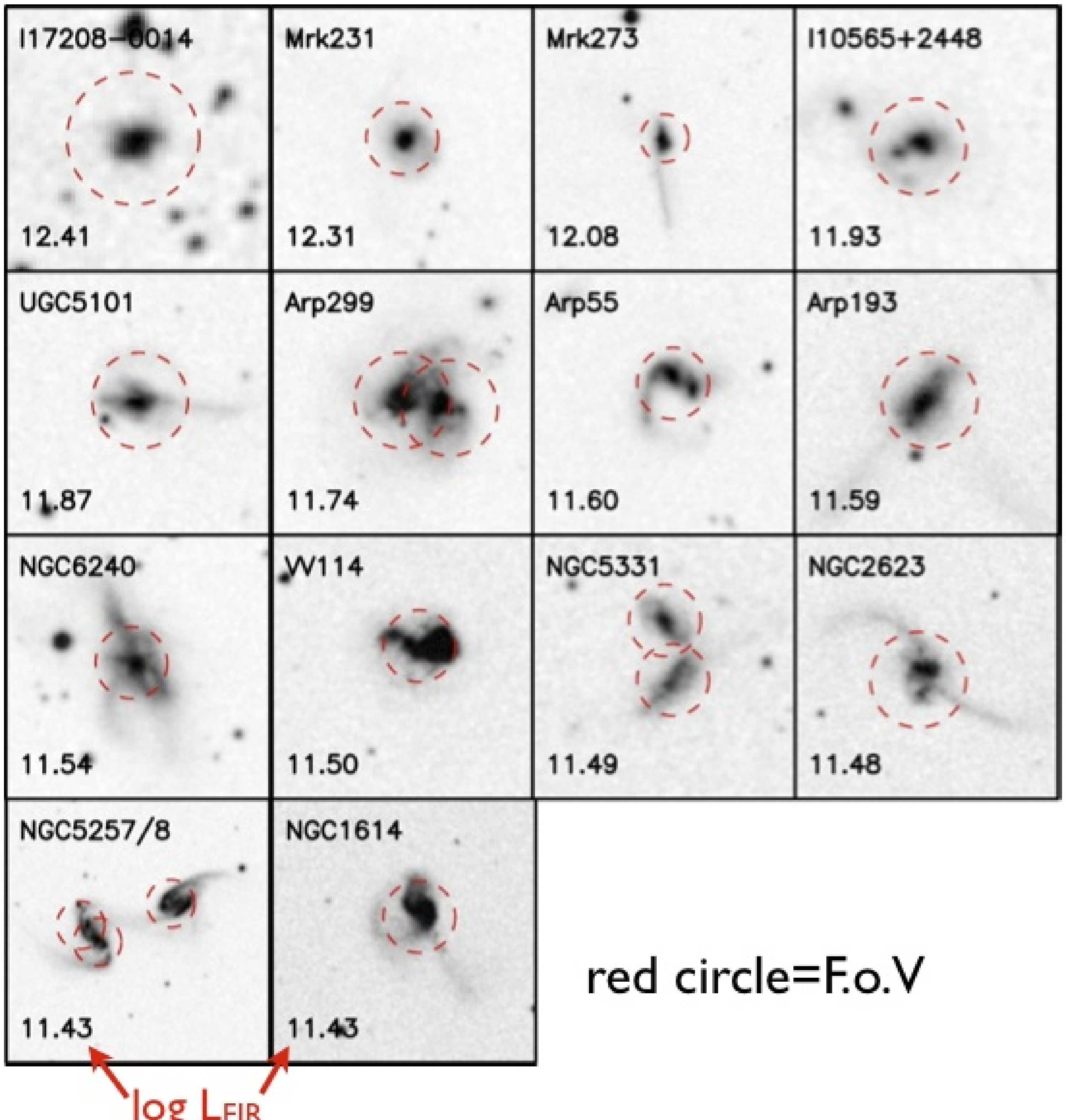
High-res. :

less contamination from non-absorbing gas.

possible with ALMA toward many ULIRGs
→ quenching of starburst / removal of quasar shroud through outflows

# SMA Survey of U/LIRGs

## Wilson et al. (2008), Iono et al. (2009), ...




red circle=F.o.V

$D_L$ < 200 Mpc
log $L_{FIR}$ > 11.4
dec. > -20°

Observed 14 (out of 39).

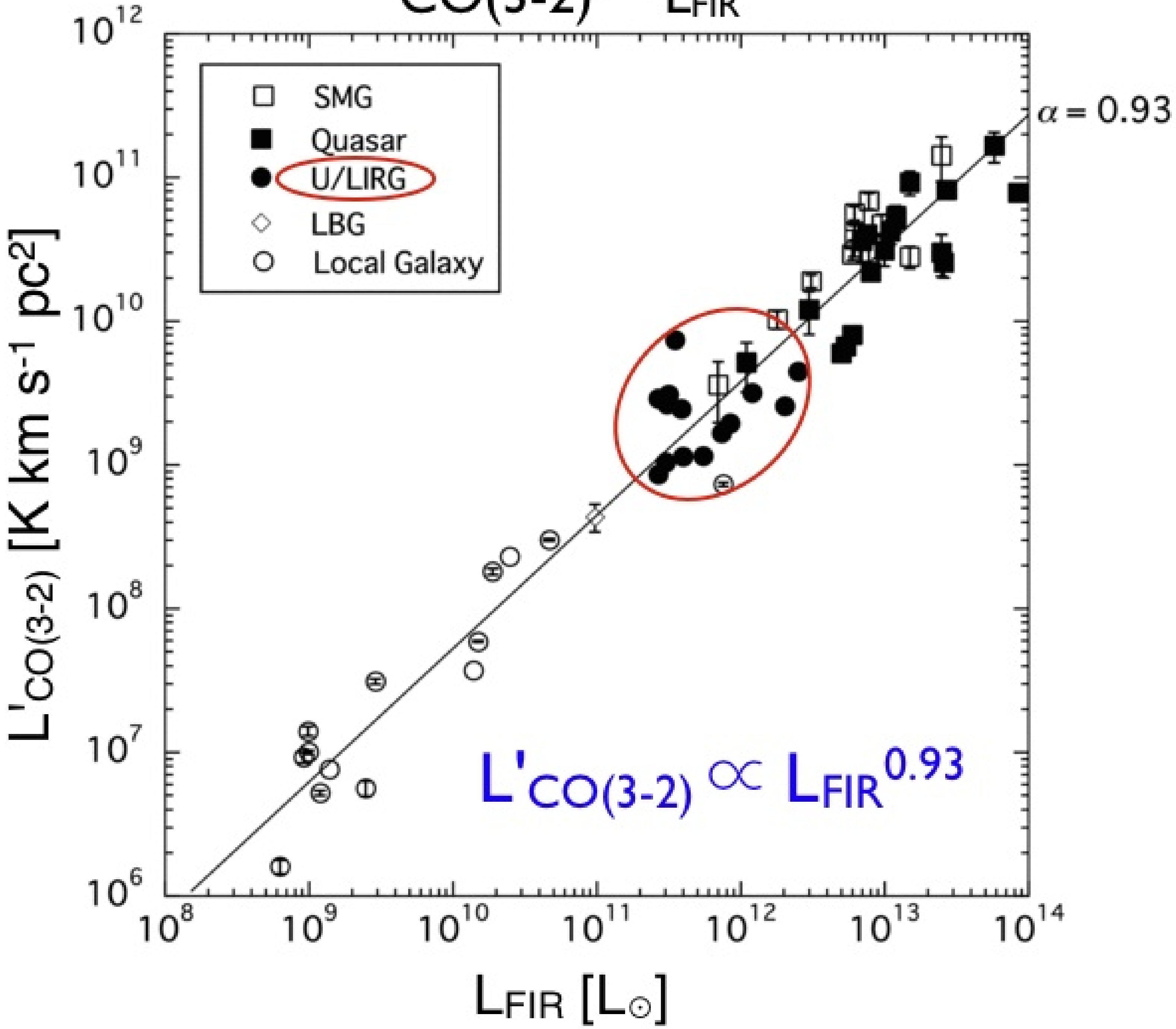
CO(3-2), (2-1), $HCO^+$ (4-3), and continuum

~1kpc (1") resolution

(Wilson et al. 2008)

# Survey: CO(3-2) and $L_{FIR}$

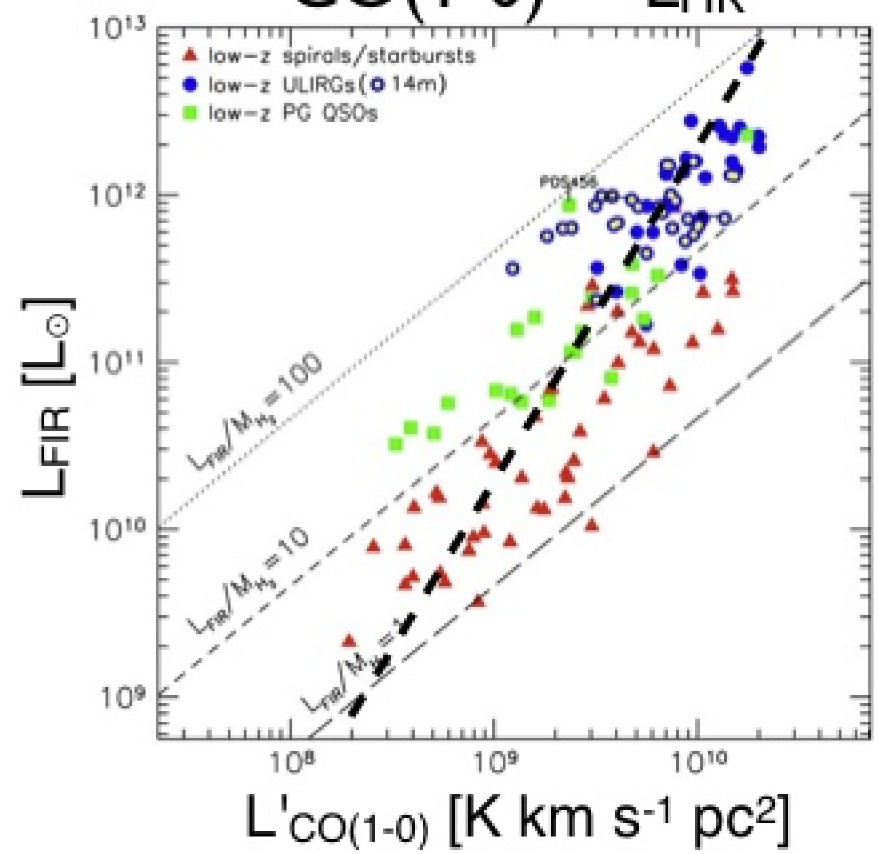
CO(3-2) — $L_{FIR}$




(Iono et al. 2009)

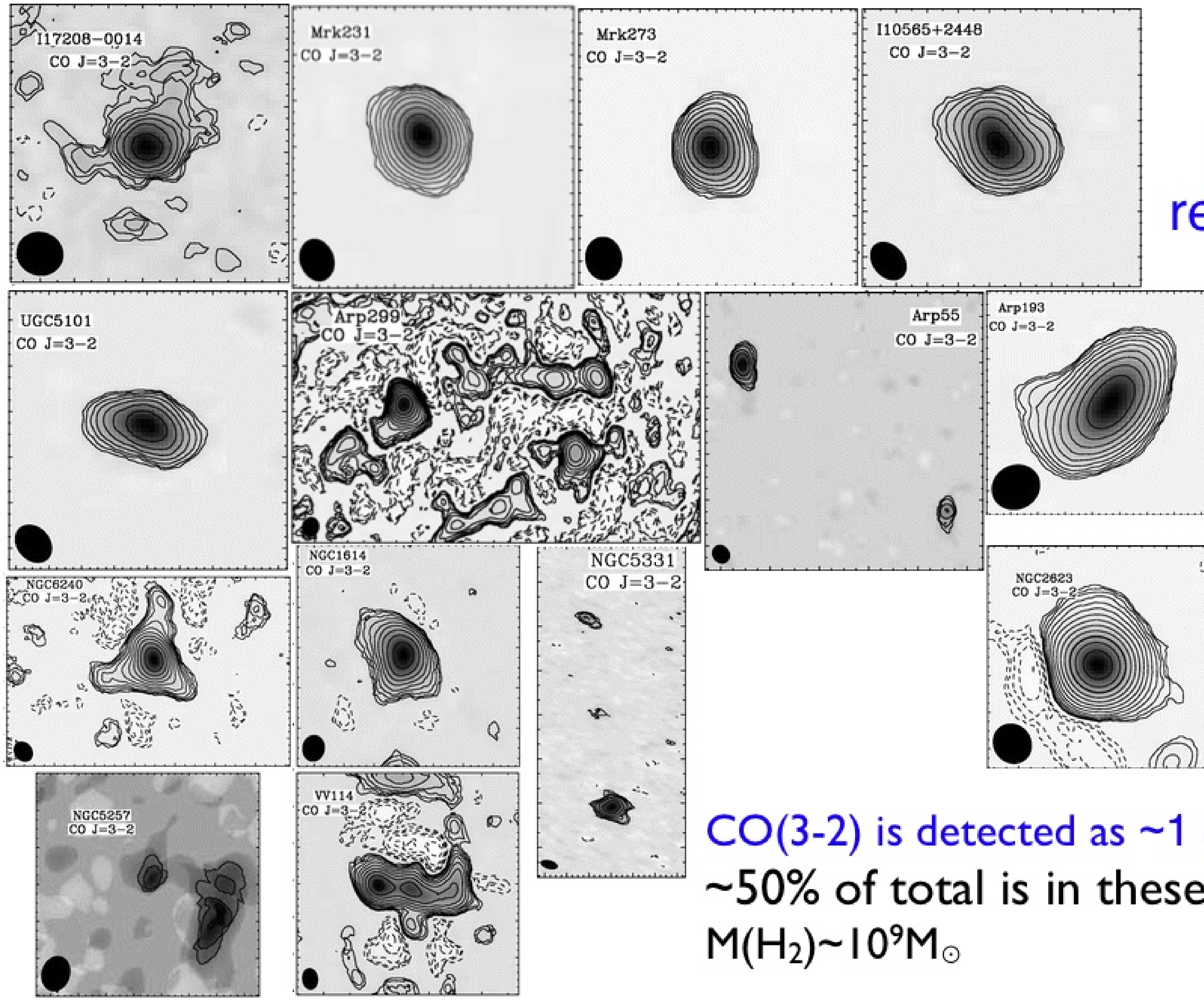
From this linear correlation one can hope that CO(3-2) is closely related to the IR-generating activities, and is a good line to study them.

CO(1-0) — $L_{FIR}$




(Chung et al. 2009)

# Survey: CO(3-2) in U/LIRGs




CO(3-2)
res. ≈ 1kpc

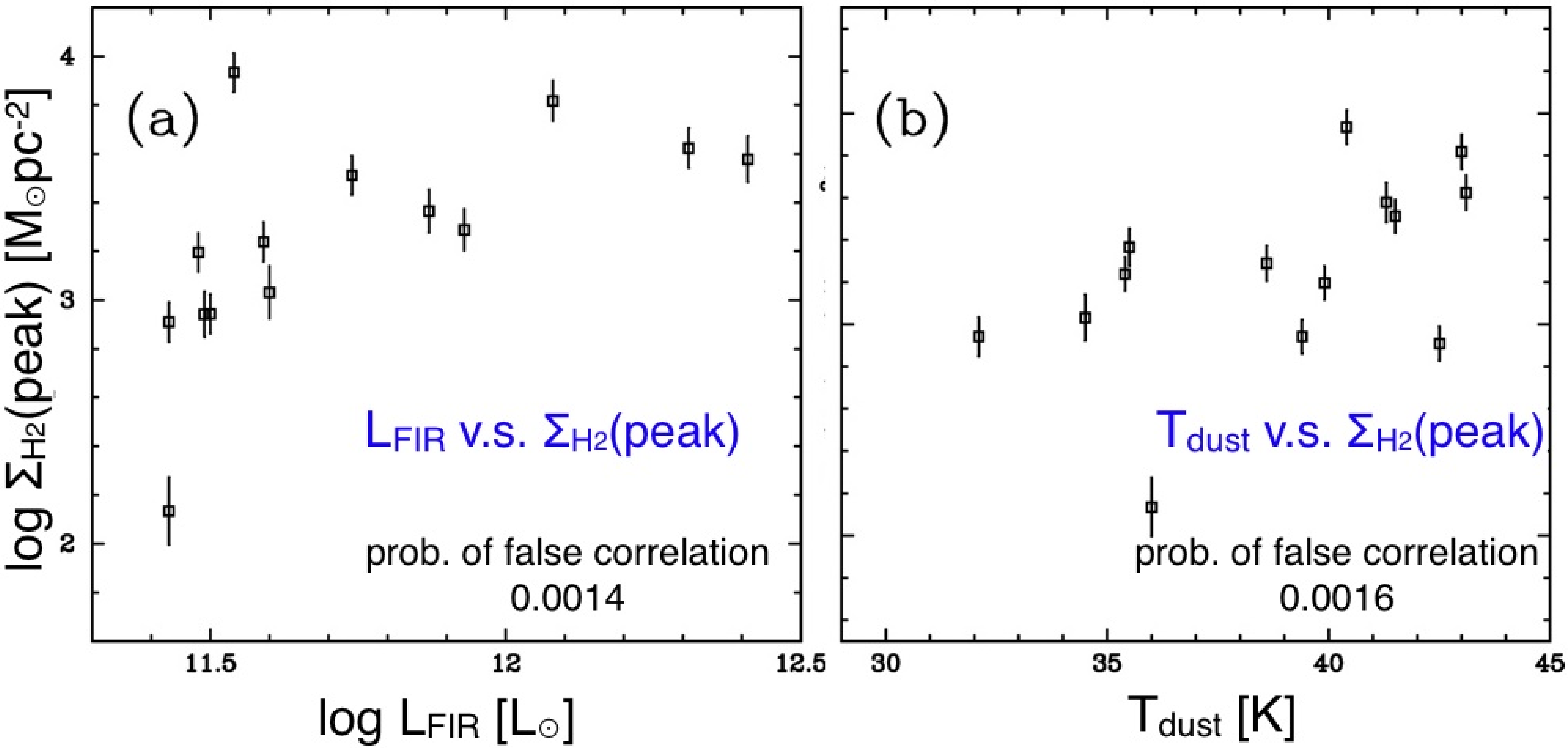
CO(3-2) is detected as ~1 kpc peaks.

~50% of total is in these peaks.

$M(H_2) \sim 10^9 M_\odot$

(Wilson et al. 2008)

# Survey: Two Tightest Correlations

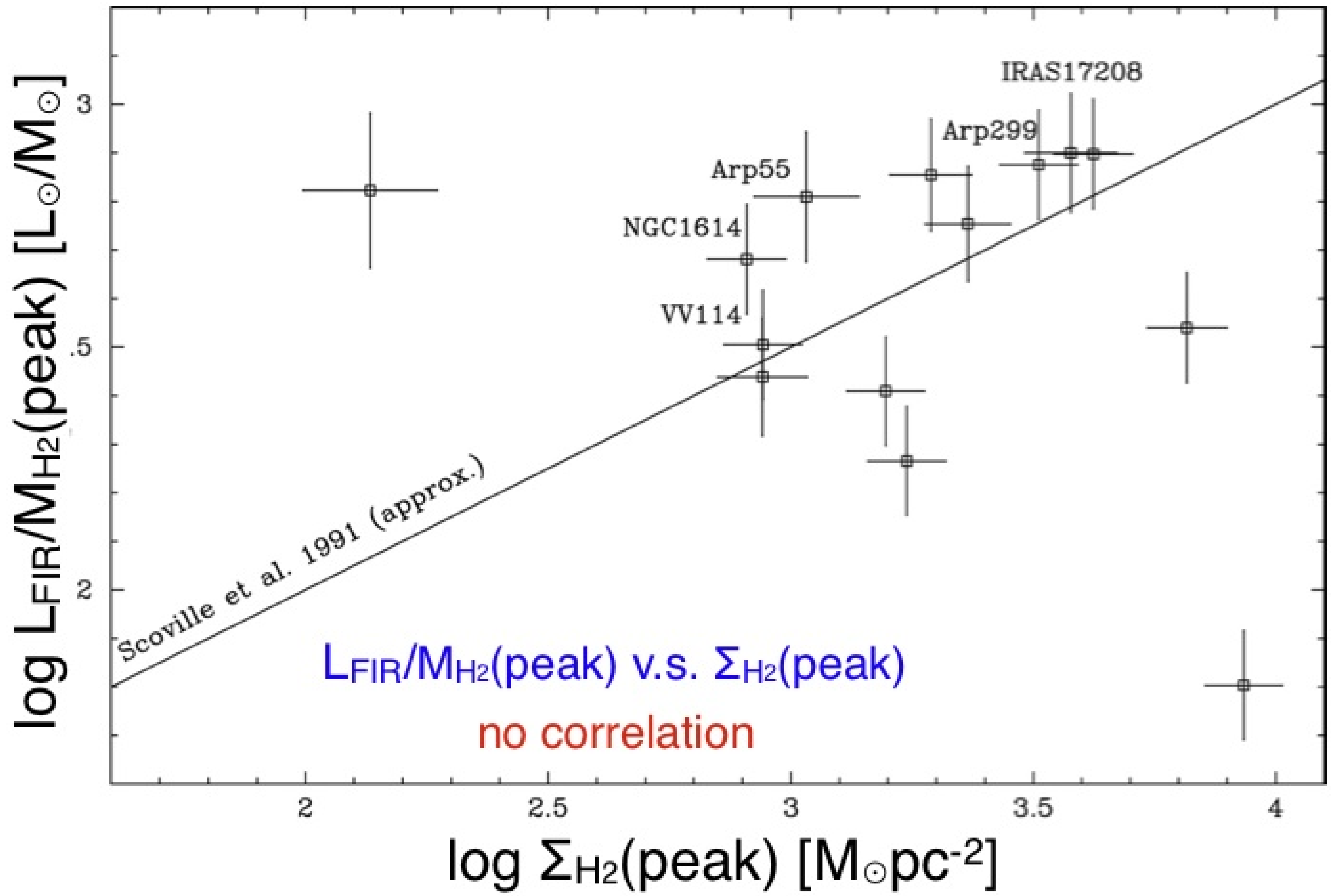



Gas concentration to the center (~kpc) ⇒ More Luminosity

⇒ Warmer ISM

(Wilson et al. 2008)

# Survey: Different from prev. studies




Gas concentration to the center (~kpc) ⇒ More Luminosity

w/o increasing efficiency (=$L_{IR}/M_{gas}$)

*More in Wilson et al. (2008), Iono et al. (2009), ...*

(Wilson et al. 2008)

# Summary

## Mol. Gas and Dust in ULIRGs : SMA

### Case study with new tricks (possible w/ high-res, high-freq.)

- sub-mm continuum image, SED → distribution of $L_{bol}$, $\Sigma_{bol}$, $L_{bol}/M_{dyn}$.
- Gas outflows through absorption (may quench starburst and/or remove quasar shroud)
- Chemistry (e.g., line-survey, anomalous chemistry and/or excitation around AGNs)
- ...

### Survey

- CO(3-2), sub-mm cont. Statistical analysis of $M_{gas}$, $\Sigma_{gas}$, $T_{gas}$, $n_{gas}$, $M_{dust}$, $T_{dust}$, $L_{FIR}$, $\Sigma_{FIR}$, etc. for star-formation law etc.
- Comparison with high-z galaxies

We can do both and more with ALMA