# *Characterization of the molecular gas in local star-forming galaxies using far-IR Herschel/HIFI & sub-mm APEX data*

Enrica Bellocchi

Collaborators: Jesús Martín-Pintado
& the Max-Planck-Institut für Radioastronomie team
(R. Güsten, M. A. Requena-Torres, A. Weiß, Philipp-May, T. Klein)

CENTRO DE ASTROBIOLOGÍA
ASOCIADO AL NASA ASTROBIOLOGY INSTITUTE
CSIC INTA

24 March 2015, ESO Santiago de Chile

# Outline

- Introduction: general context
- The objectives
- The sample and observations
- Data analysis
- Results and future work

# Molecular gas emission in galaxies

Diagnostic tool to study :

- ✓ Properties of the ISM: density, temperature, kinematics..
- ✓ Conditions and processes leading to the starbursts
- ✓ Evolutionary state of starbursts
- ✓ Feeding of the nucleus
- ✓ Obscured regions (molecular emission can penetrate deeply into obscured nuclear power sources: AGN or starburst)

# Main goals:

- Derivation of the main physical parameters
  → column density, $T_{ex}$ and $V_{LRS}$ and volume gas density

- Constraining between AGN/SB activity
  → characterization of the chemical complexity in order to distinguish the powering source

- Studying the kinematics of the molecular gas & its properties using high spatial resolution data (ALMA)

# The sample

- 4 local Star-forming galaxies
- Distance: 3.4, 3.9, 14.4, 77 Mpc
- $L_{IR} = L_{[8\text{-}1000\ \mu m]} = 2 \times 10^{10}\ L_{\odot} - 1.5 \times 10^{12}\ L_{\odot}$

NGC 1068

ARP 220

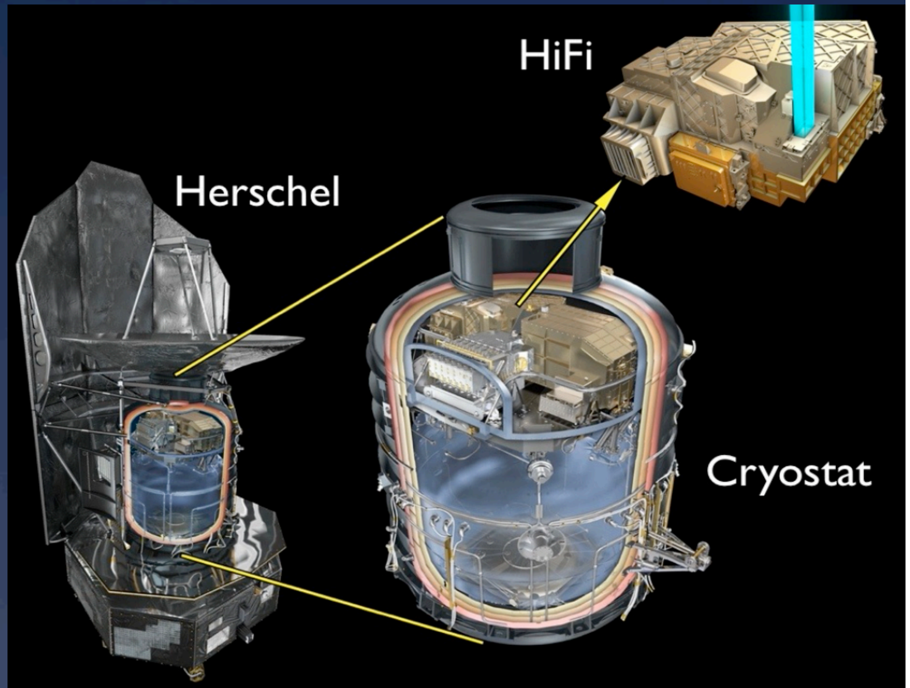
NGC 253

NGC 4945

# The observations

## Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)

- ✓ Frequency range: Far-IR 480 to 1910 GHz
- ✓ beam (HPBW): 37”-12” @ 572 – 1892 GHz
- ✓ D = 3.28 m
- ✓ level 2 (fully calibrated) spectra




## Atacama Pathfinder EXperiment (APEX)

- ✓ Frequency range: sub-mm 200 to 360 GHz
- ✓ beam (HPBW): 21”-16” @ 272-354 GHz
- ✓ D = 12 m

# The analysis of the molecular emission

## Local thermodynamic equilibrum (LTE) analysis

- MADCUBAIJ (MAdrid Data CUBe Analysis in ImageJ)
  → Gaussian line fit to derive column density $N_{mol}$, $T_{ex}$, $v_{LSR}$

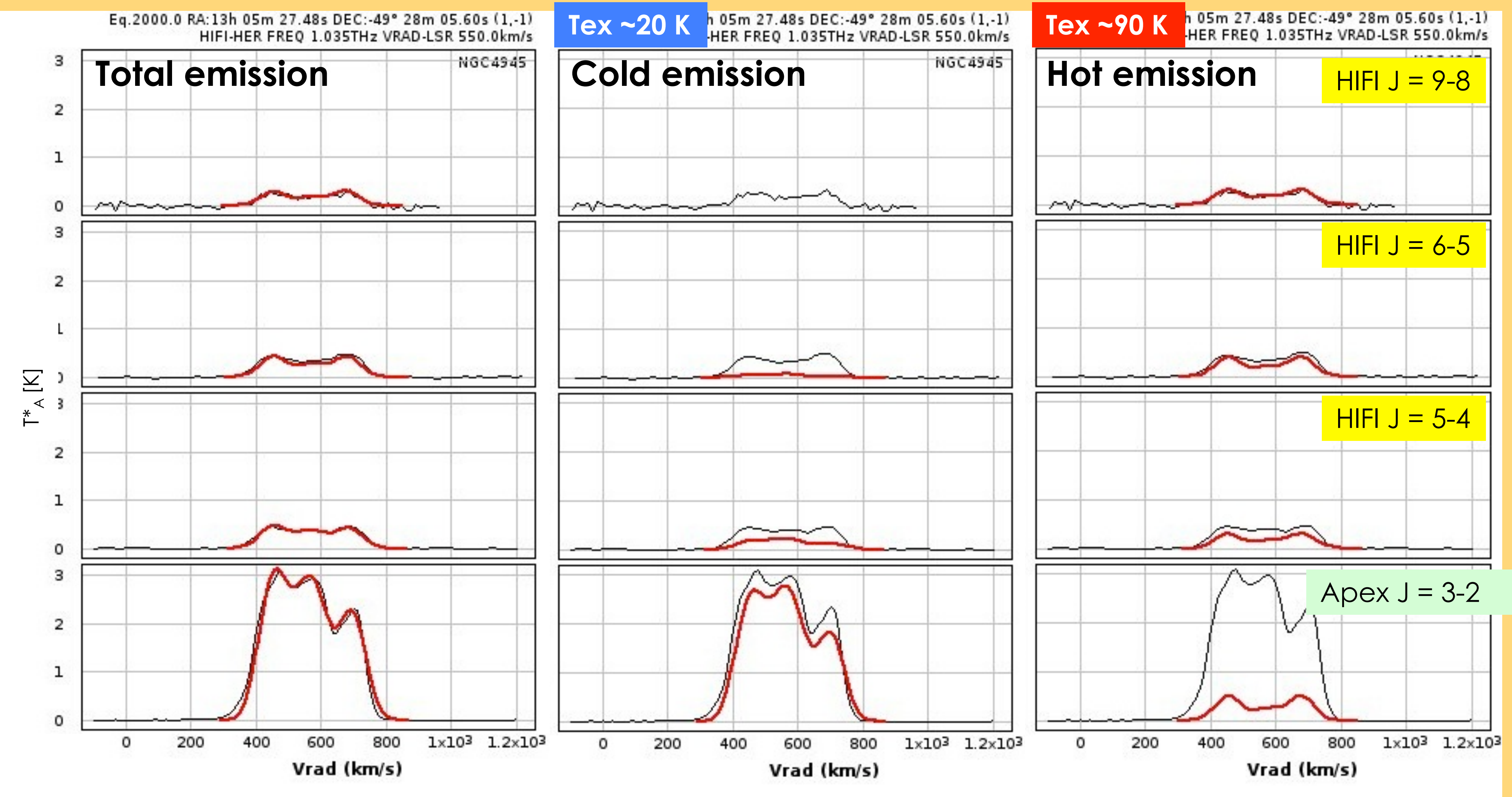
## Non-LTE analysis

- RADEX → estimate of the volume gas density (van der Tak+07)

# Results from MADCUBA

LTE conditions

## $^{12}CO$ emission in NGC 4945




→3 velocity components

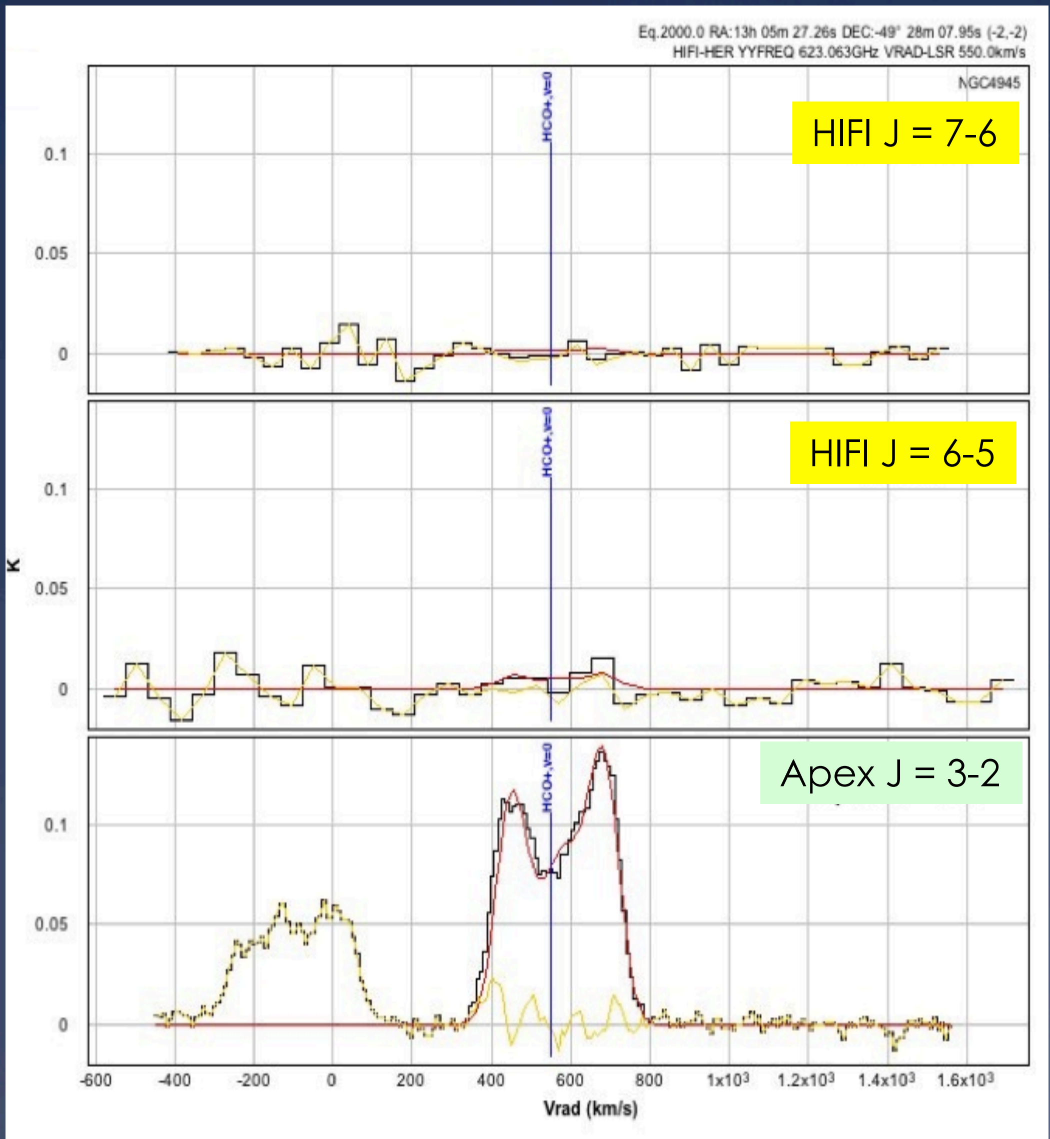
→2 components of temperature:

COLD emission (dominates at low J) & HOT emission (dominates at higher J)

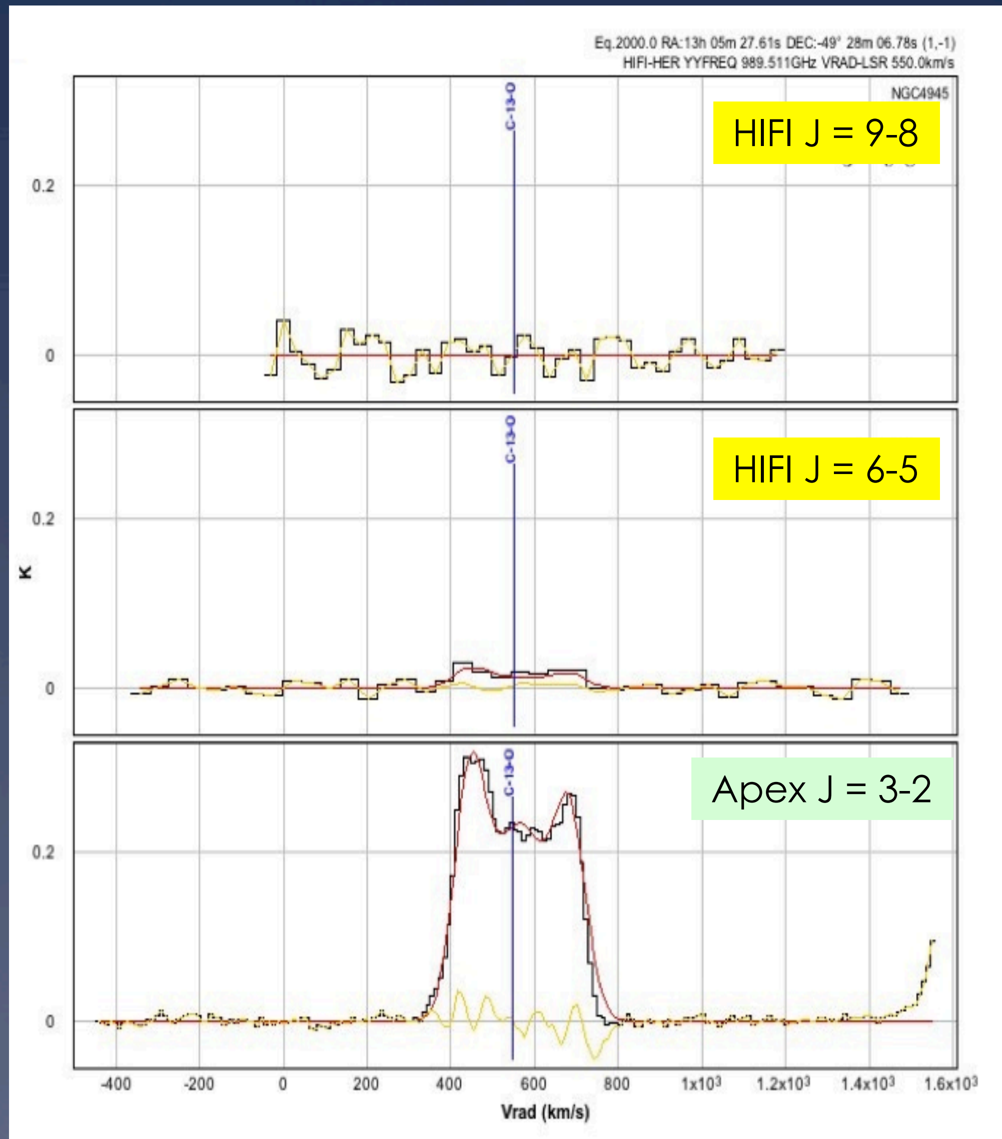
# Other molecules detected

Molecular emission lines detected: $^{13}CO$, CI, CH as well as some dense gas tracers such as HCO+, HCN, HNC, CS

HCO+ (NGC 4945)




$^{13}CO$ (NGC 4945)



# Summary of results for NGC 4945

MADCUBA
(LTE)

| Molecule | J Transition (Frequency [GHz]) | | LTE | | |
|---|---|---|---|---|---|
| | Herschel | Apex | log $N_{mol}$ [$cm^{-2}$] | $T_{ex}$ [K] | $v_{LSR}$ [km $s^{-1}$] |
| **CO** | 9-8; 6-5; 5-4 (1036.91; 691.47; 576.27) | 3-2 (345.79) | 16.5-16.7<br>17.3-17.7 | 84-92<br>17-18 | 455; 578; 683<br>451; 566; 705 |
| **$^{13}$CO** | 9-8; 6-5 (991.33; 661.067) | 3-2 (330.588) | 16.3-16.5 | 22-25 | 446; 566; 685 |
| **HCN** | 12-11; 7-6; 6-5 (1062.98; 620.30; 531.72) | 4-3 (354.50) | 13.2-13.5 | 17-21 | 446; 574; 683 |
| **HNC** | 7-6; 6-5 (634.511; 543.897) | 4-3; 3-2 (362.63; 271.981) | ∼13 | 17-18 | 448; 571; 683 |
| **$HCO^+$** | J = 7-6; 6-5 (624.208; 535.061) | 4-3 (356.734) | 13.1-13.2 | 18 | 450; 580; 685 |
| **CS** | 13-12; 12-11; 10-9 (636.53; 587.62; 538.69; 489.75) | 7-6; 6-5 (342.883; 293.912) | 13.1-13.3 | 28-33 | 444; 564; 671 |
| **CI** | $^3P_2 \rightarrow {}^3P_1$; $^3P_1 \rightarrow {}^3P_0$ (809.344; 492.16) | — | 17.5-17.7 | 103-174 | 448; 568; 688 |
| **CH** | N=2, J=$\frac{5}{2}$-$\frac{3}{2}$; N=1, J=$\frac{3}{2}$-$\frac{1}{2}$ (1661.14; 1656.97; 536.76; 532.72) | — | 14.08-14.16 | ∼13-14 | 434; 547; 684 |

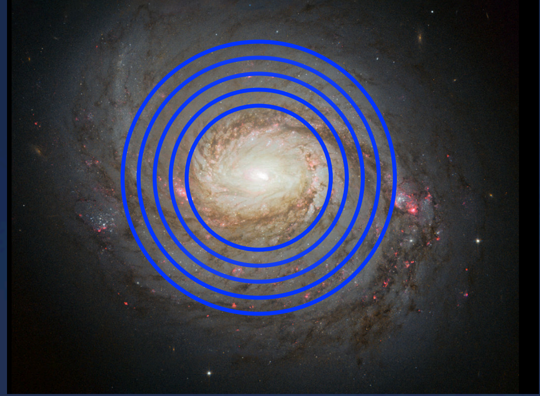
# Summary of results for NGC 4945

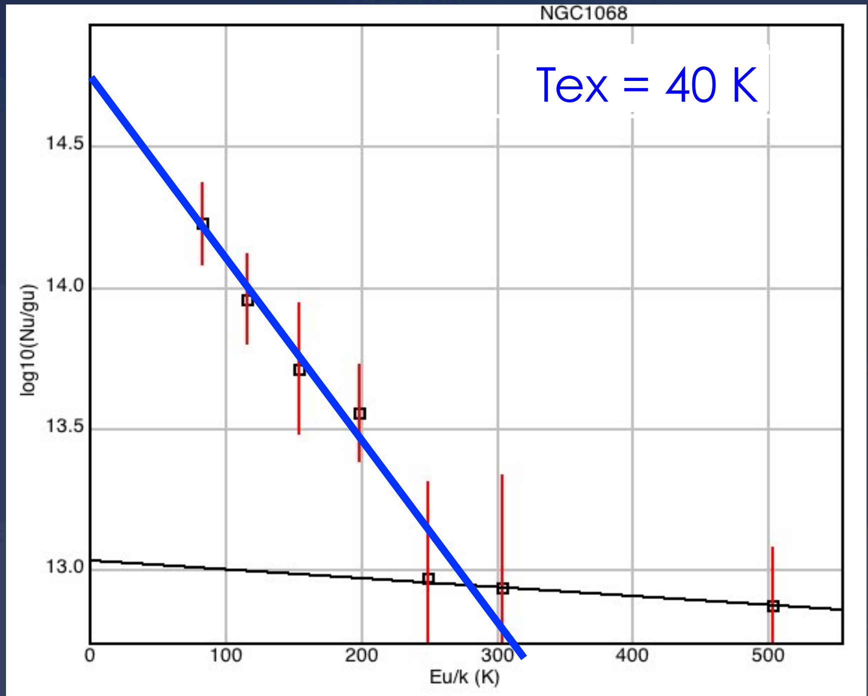
MADCUBA (LTE) | RADEX (non-LTE)

| Molecule | J Transition (Frequency [GHz]) Herschel | Apex | LTE log $N_{mol}$ [$cm^{-2}$] | $T_{ex}$ [K] | $v_{LSR}$ [km $s^{-1}$] | LVG n($H_2$) [$cm^{-3}$] | log $N_{mol}$ [$cm^{-2}$] |
|---|---|---|---|---|---|---|---|
| CO | 9-8; 6-5; 5-4 (1036.91; 691.47; 576.27) | 3-2 (345.79) | 16.5-16.7<br>17.3-17.7 | 84-92<br>17-18 | 455; 578; 683<br>451; 566; 705 | $5.5 \cdot 10^4$<br>$7.2 \cdot 10^3$ | 16.7<br>17.3 |
| $^{13}$CO | 9-8; 6-5 (991.33; 661.067) | 3-2 (330.588) | 16.3-16.5 | 22-25 | 446; 566; 685 | $3.8 \cdot 10^3$ | 16.35 |
| HCN | 12-11; 7-6; 6-5 (1062.98; 620.30; 531.72) | 4-3 (354.50) | 13.2-13.5 | 17-21 | 446; 574; 683 | $1.2 \cdot 10^6$ | 13.40 |
| HNC | 7-6; 6-5 (634.511; 543.897) | 4-3; 3-2 (362.63; 271.981) | ~13 | 17-18 | 448; 571; 683 | $1.4 \cdot 10^6$ | 13.00 |
| $HCO^+$ | J = 7-6; 6-5 (624.208; 535.061) | 4-3 (356.734) | 13.1-13.2 | 18 | 450; 580; 685 | $3.6 \cdot 10^5$ | 13.24 |
| CS | 13-12; 12-11; 10-9 (636.53; 587.62; 538.69; 489.75) | 7-6; 6-5 (342.883; 293.912) | 13.1-13.3 | 28-33 | 444; 564; 671 | $9.0 \cdot 10^5$ | 13.09 |
| CI | $^3P_2 \rightarrow {}^3P_1$; $^3P_1 \rightarrow {}^3P_0$ (809.344; 492.16) | — | 17.5-17.7 | 103-174 | 448; 568; 688 | $1.0 \cdot 10^5$ | 17.56 |
| CH | N=2, J=$\frac{5}{2}$-$\frac{3}{2}$; N=1, J=$\frac{3}{2}$-$\frac{1}{2}$ (1661.14; 1656.97; 536.76; 532.72) | — | 14.08-14.16 | ~13-14 | 434; 547; 684 | — | — |

The average volume gas density is moderate → from low gas density tracers , like CO and CI (deriving gas density of $10^3$-$10^4$ $cm^{-3}$) to high gas density tracers as HCN, HNC, HCO+ and CS (≤ $10^6$ $cm^{-3}$)

# CO emission in NGC 1068

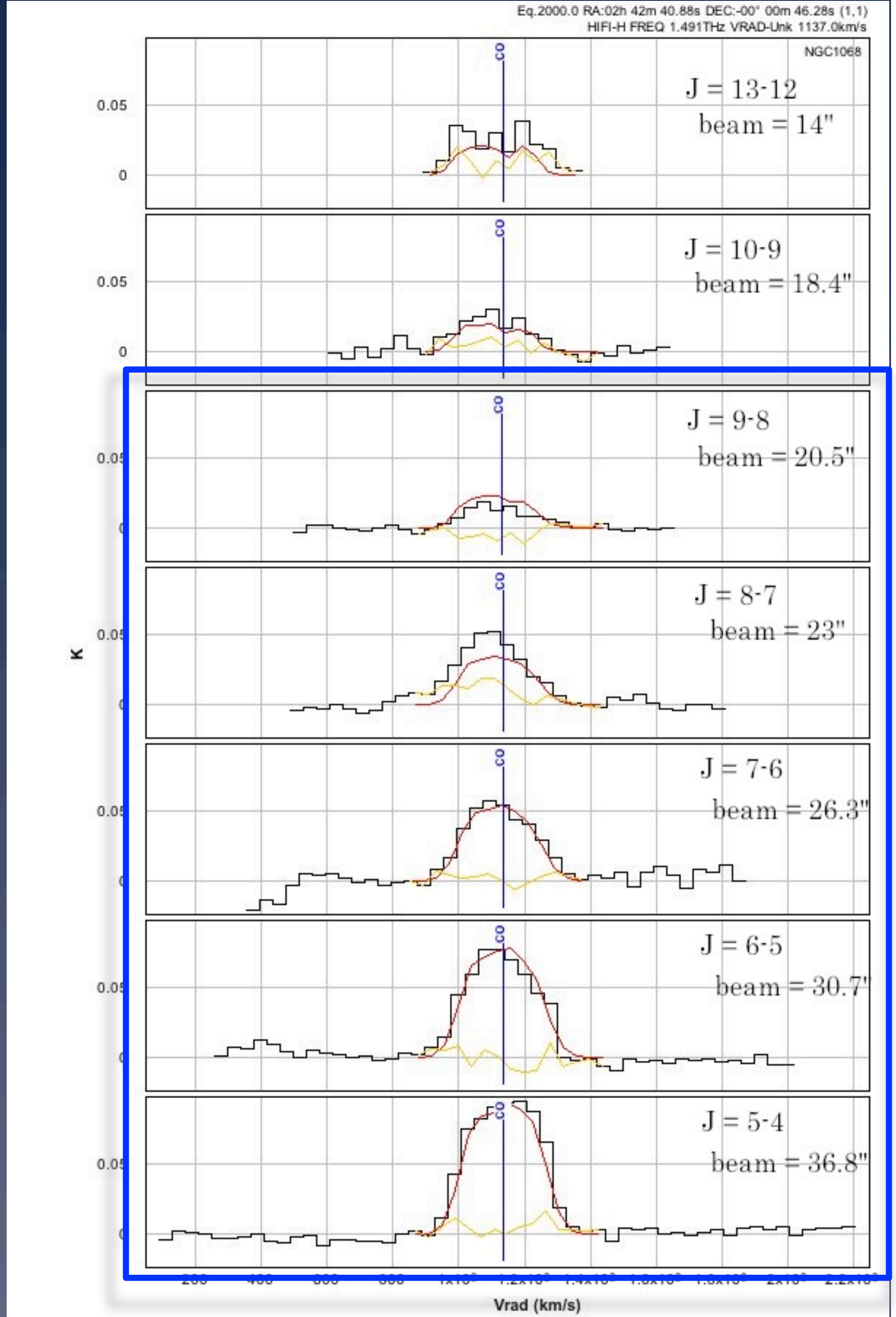




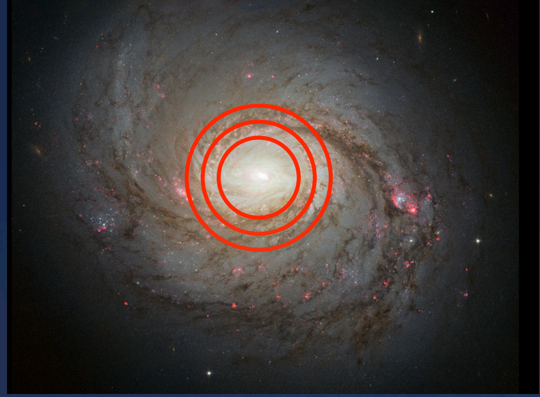

2 components with different T

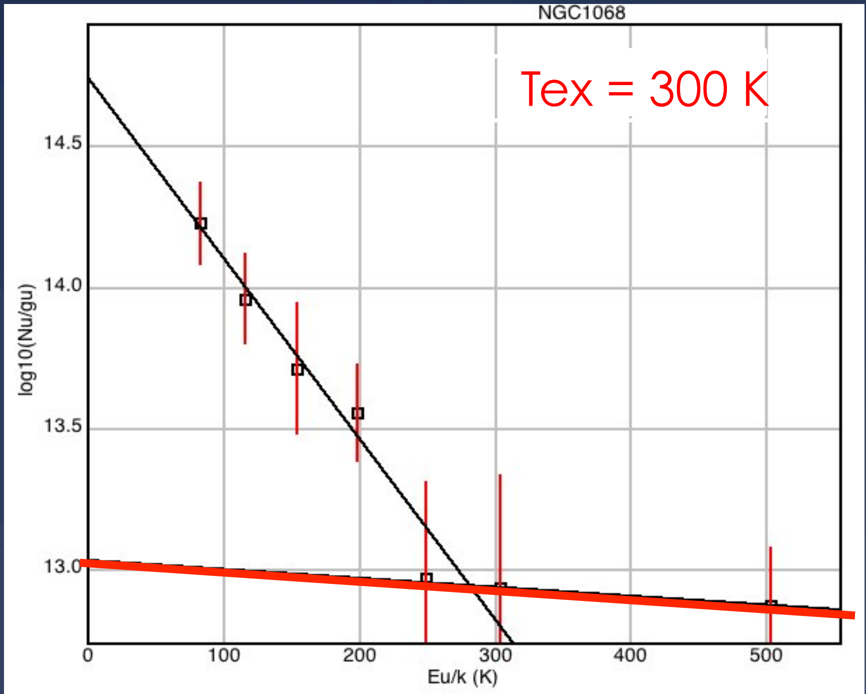
Lower J transitions: 5-4 up to 9-8
Cold component
Large beams: 21” - 37”

COLD emission dominates LARGE scales



# CO emission in NGC 1068

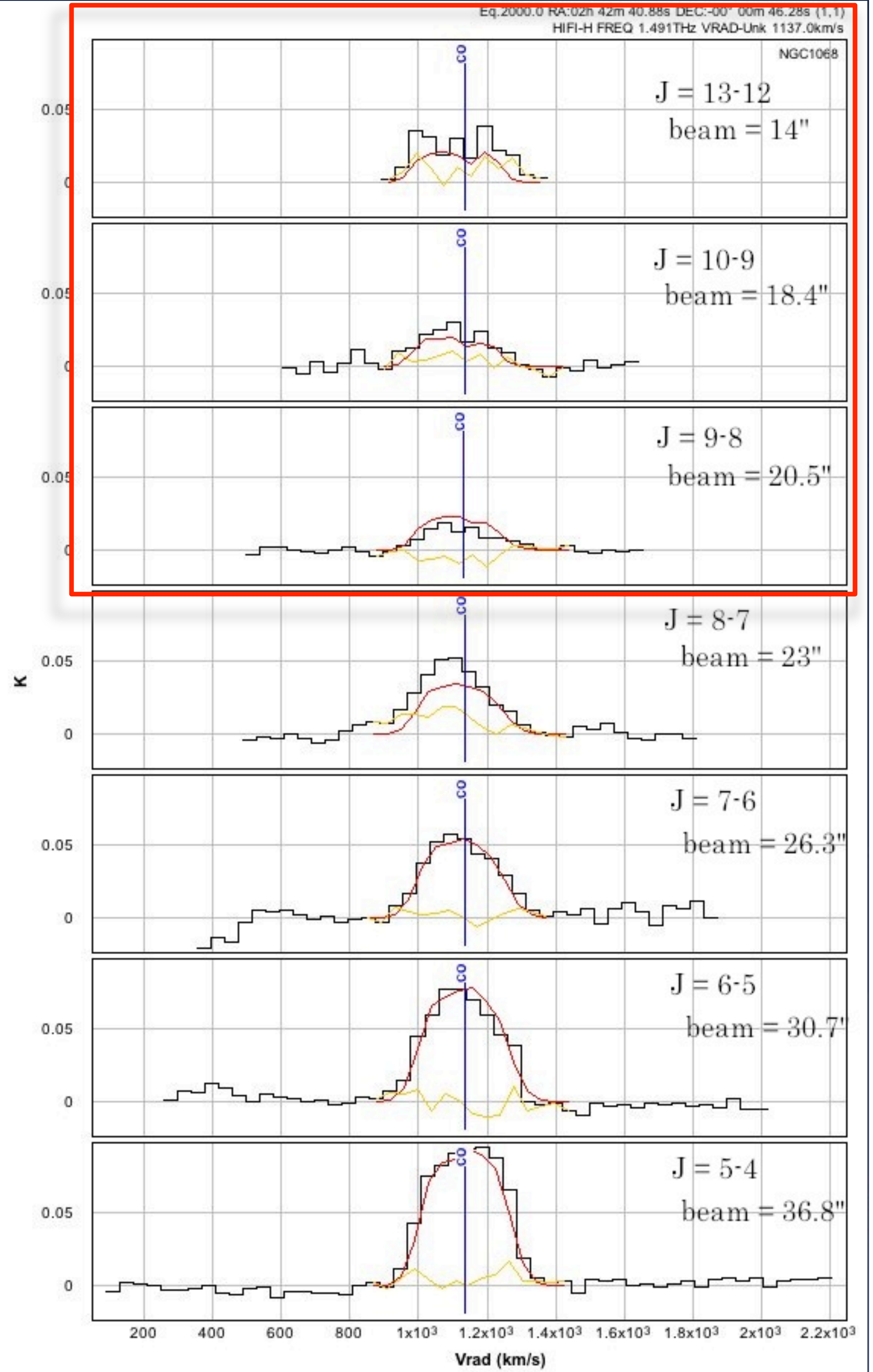




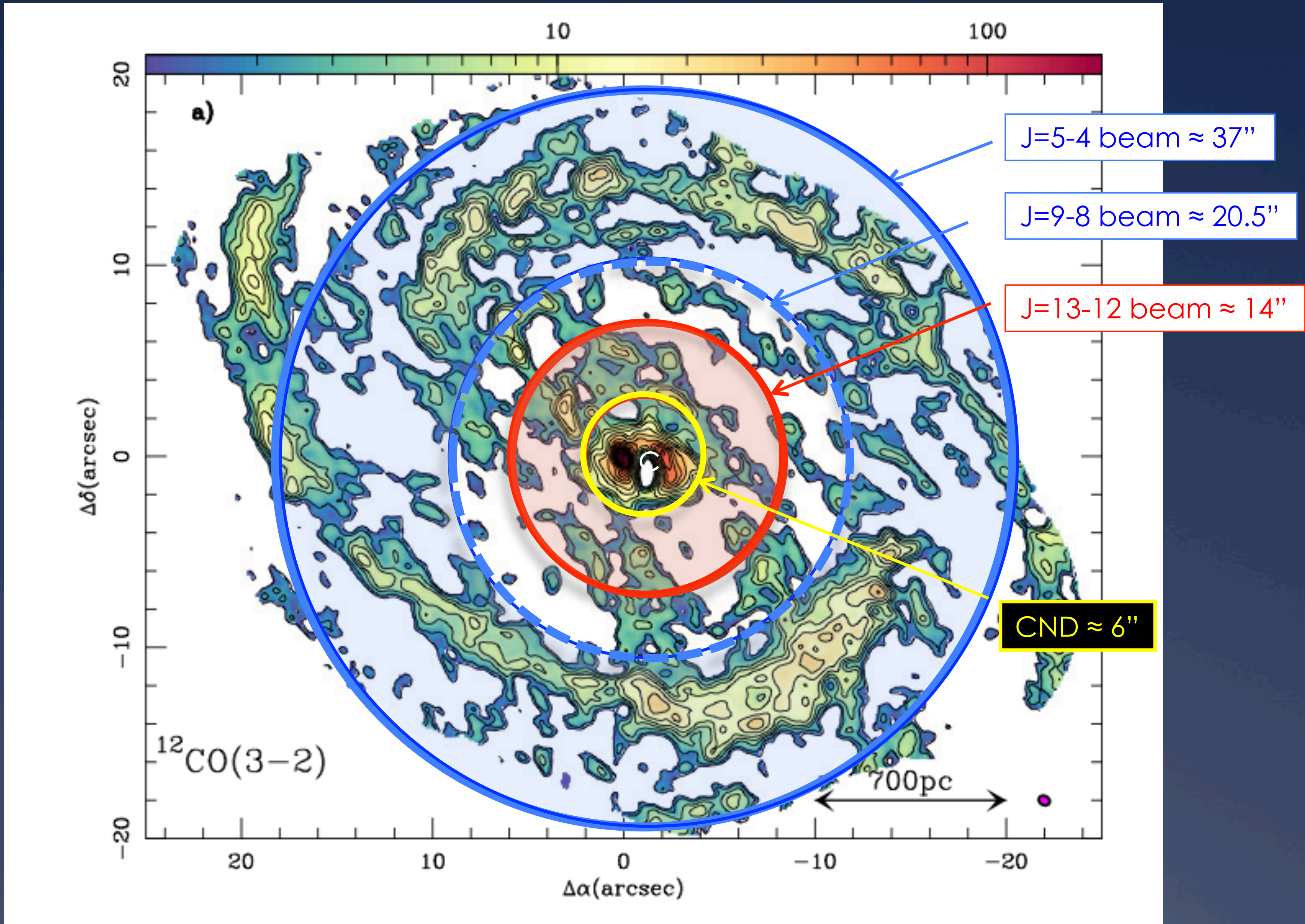

2 components with different T

Higher J transitions: 9-8 up to 13-12
Hot component
Smaller beams: 14"- 21"

HOT emission from the INNER region



# Agreement with high angular resolution ALMA results (S. García-Burillo+14)




Several transitions (different beams) constrain the region of influence of the cold and hot CO components

# Ongoing and Future works

- Analysis of the absorption molecular lines (e.g., CH+, NH, $NH_3$, OH+, $H_2O$, HF)

- Constraining between SB/AGN activities in the highly obscured galactic nuclear regions
  → different line ratios (HCO+/HCN, HCN/CO; Krips+08) using high J transitions

- From single dish to high angular resolution → **ALMA**

  ✓ Spatially resolve the gas properties (e.g., temperatures, densities, isotopic ratios)

  ✓ Study of the kinematics of the molecular gas using the "kinemetry" method …

# Kinemetry analysis

$$K(\psi, r) = A_0(r) + \Sigma\, A_i(r) \sin(i \cdot \psi) + B_i(r) \cos(i \cdot \psi)$$

where $\Psi$ is the azimuthal angle in the plane of the galaxy

→ quantify the kinematic asymmetries

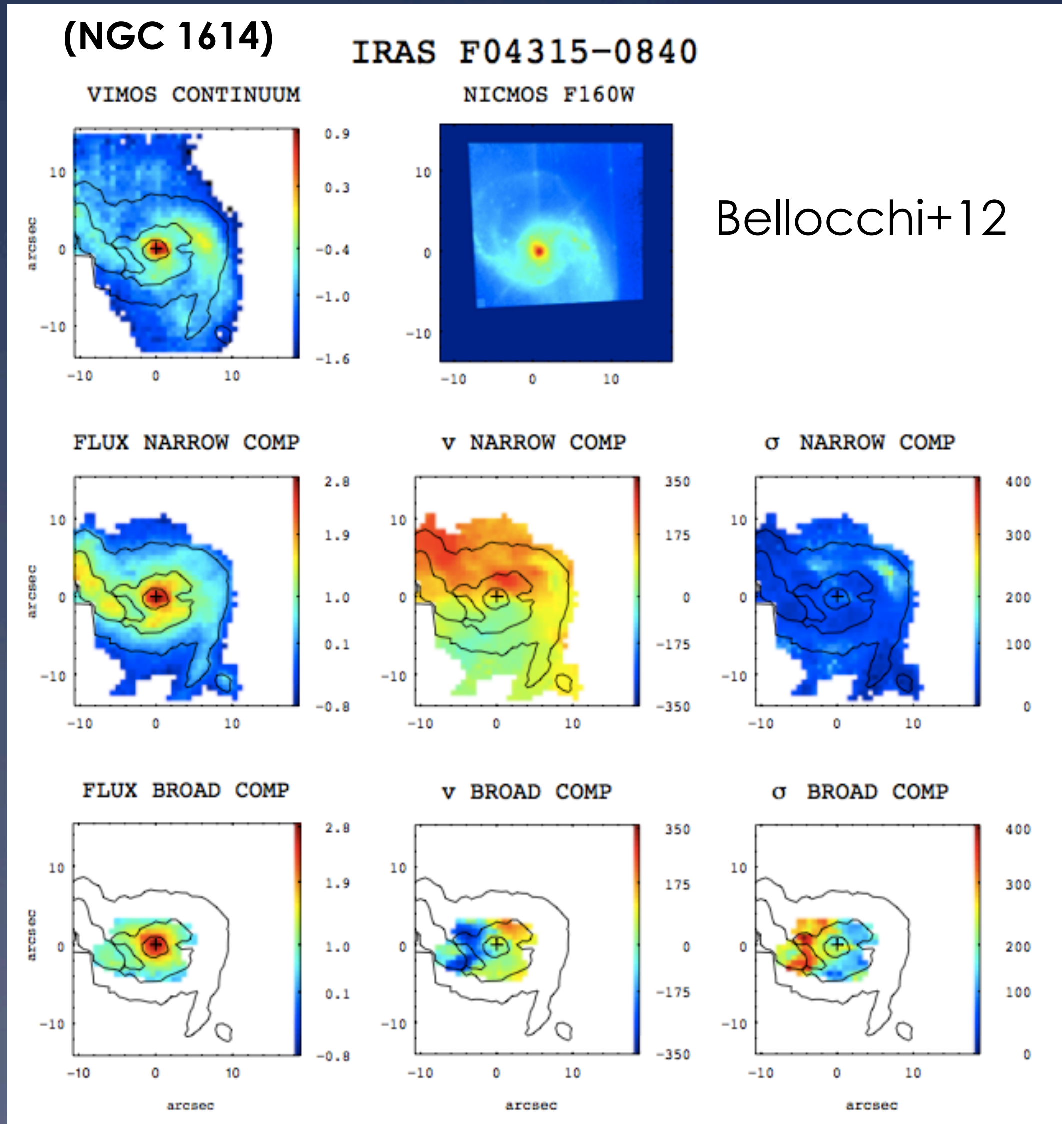
Previously applied to IFS data to study the kinematic asymmetries of the ionized gas of a large sample of local (U)LIRGs

→distinguish "disks/mergers"

(Bellocchi+12, Bellocchi in prep.)

Kinematic characterization of the molecular gas revealed by ALMA maps

(ALMA proposal preparation)




¡ Gracias !