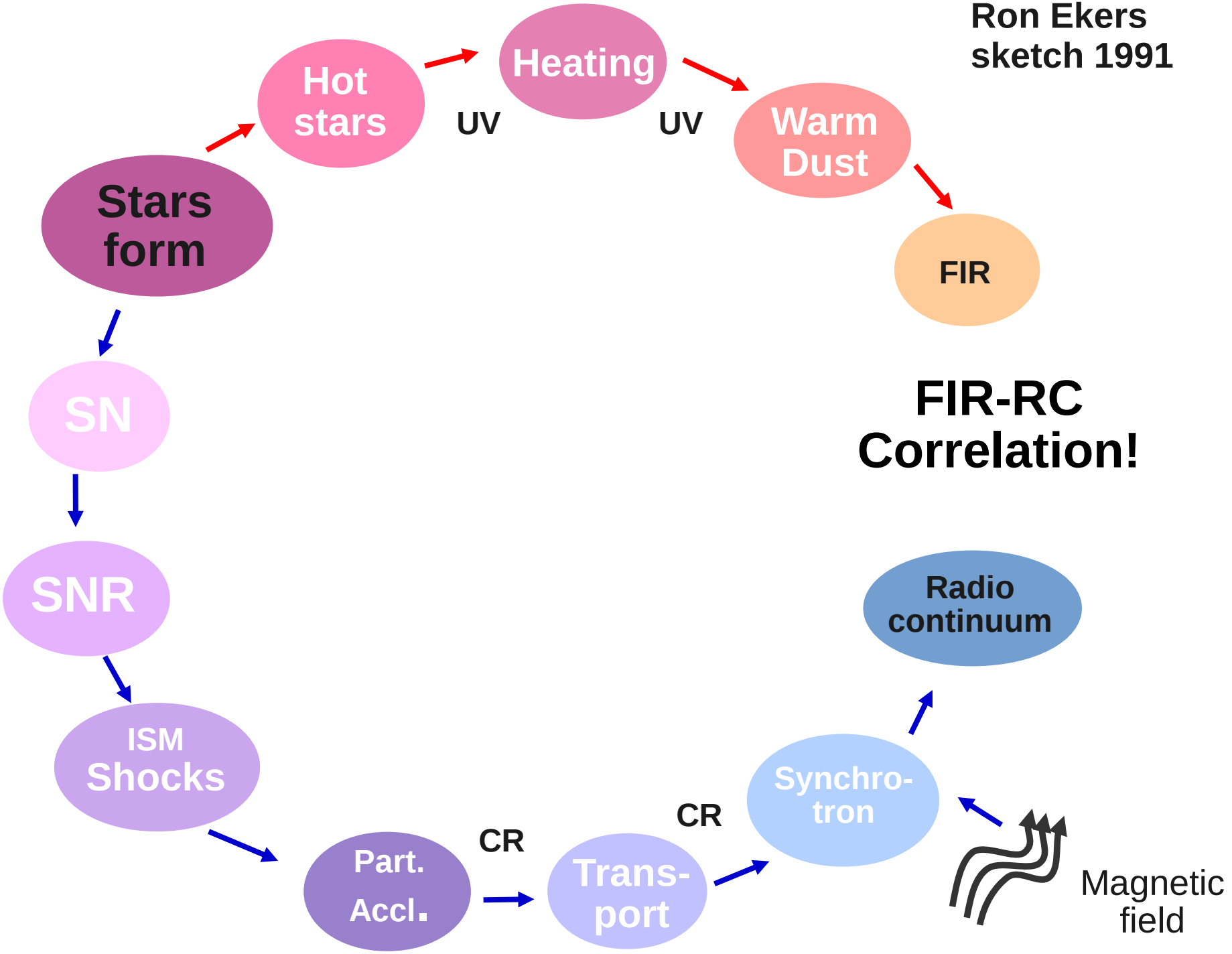
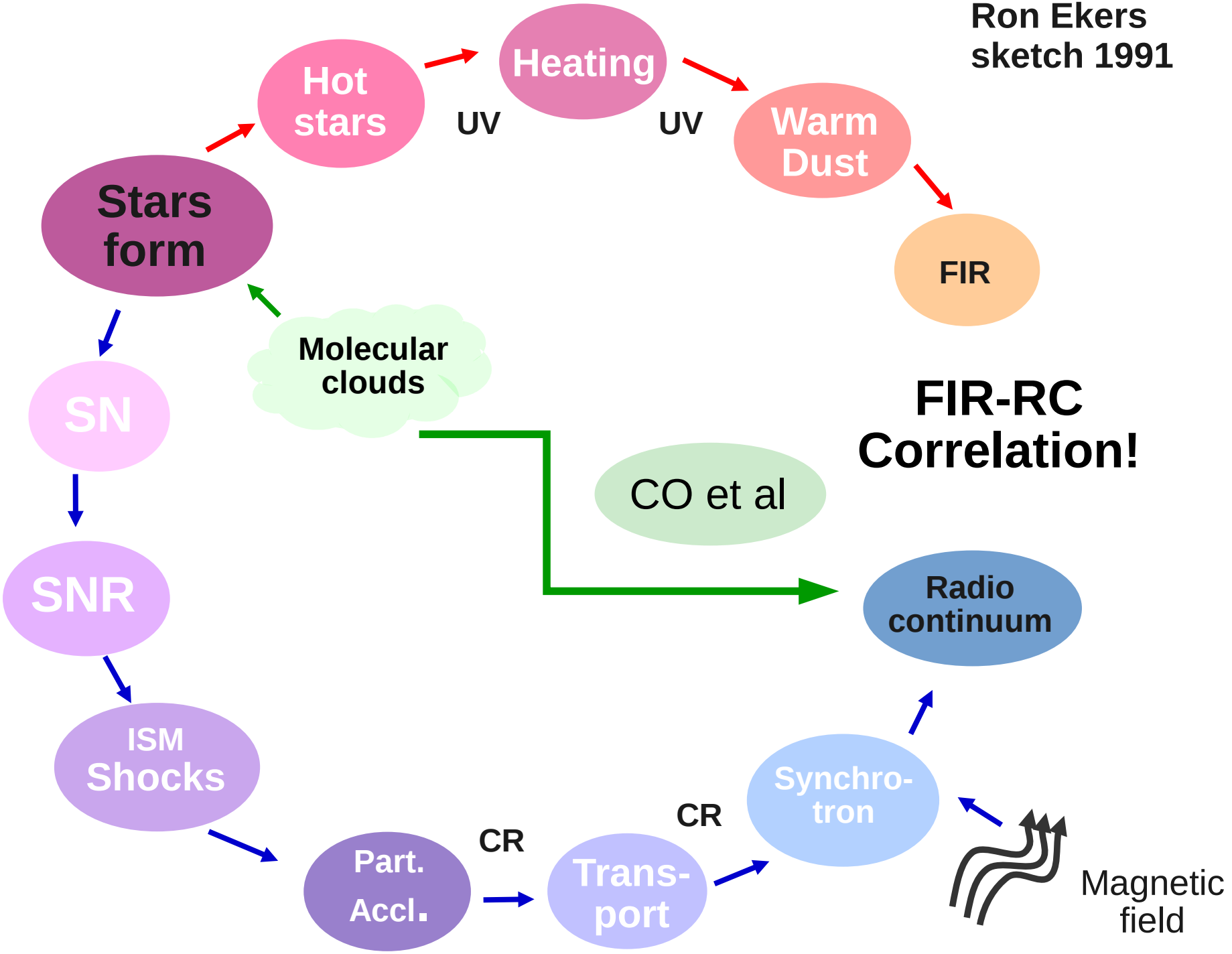
The molecular connection to the FIR-RC correlation in Nearby Galaxies

Rosita Paladino

Università di Bologna - INAF IRA


Ron Ekers
sketch 1991
Stars form
Hot stars
UV
Heating
UV
Warm Dust
FIR
SN
SNR
ISM Shocks
Part. Accl.
CR
Trans-port
CR
Synchro-tron
Radio continuum
Magnetic field
FIR-RC Correlation!

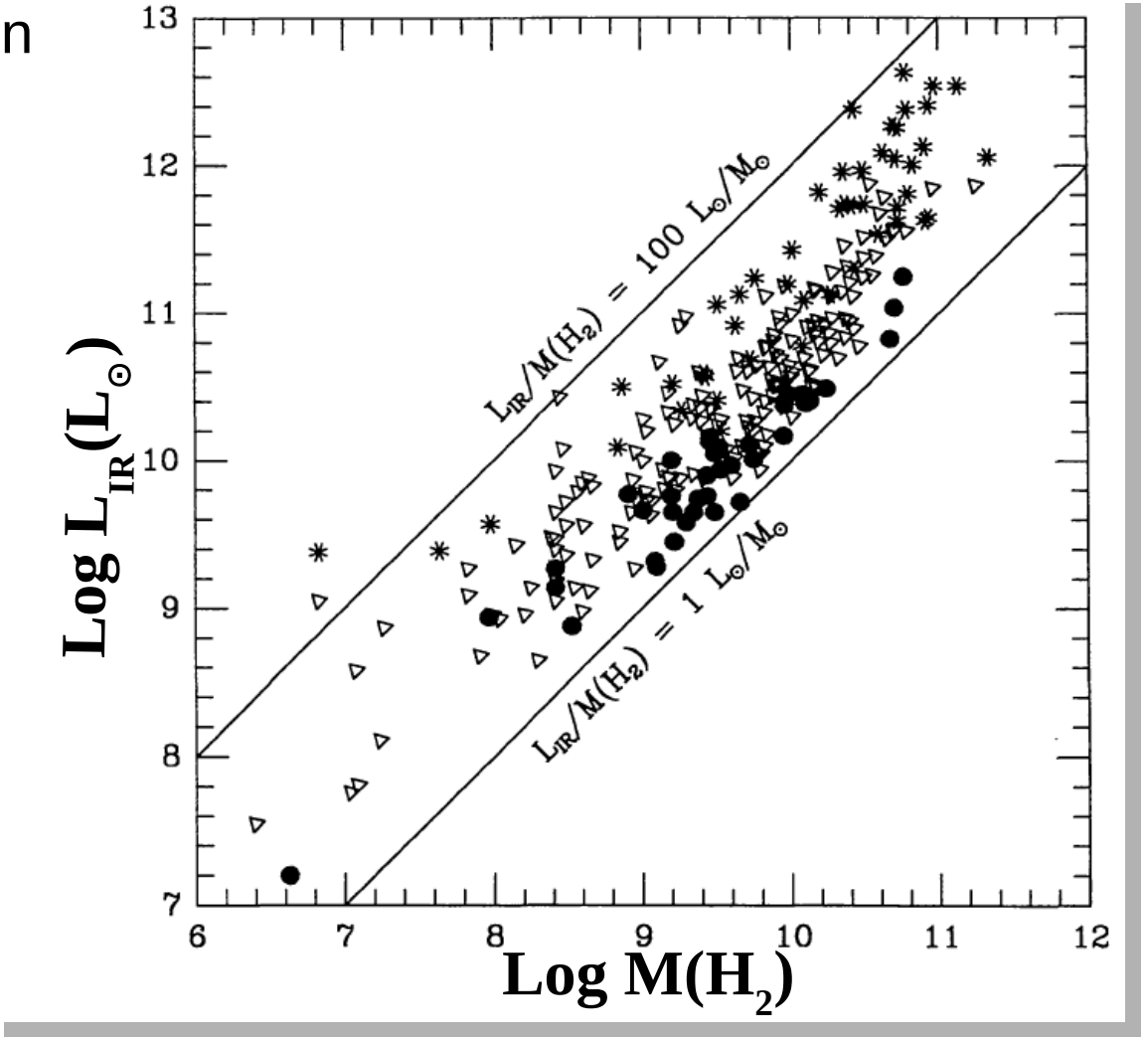

Ron Ekers
sketch 1991
Hot stars
Heating
Warm Dust
FIR
UV
UV
Stars form
Molecular clouds
SN
SNR
ISM Shocks
Part. Accl.
CR
Trans-port
CR
Synchro-tron
Magnetic field
CO et al
FIR-RC Correlation!
Radio continuum

Link between molecular and FIR

- **e.g. Young e Scoville 1991**

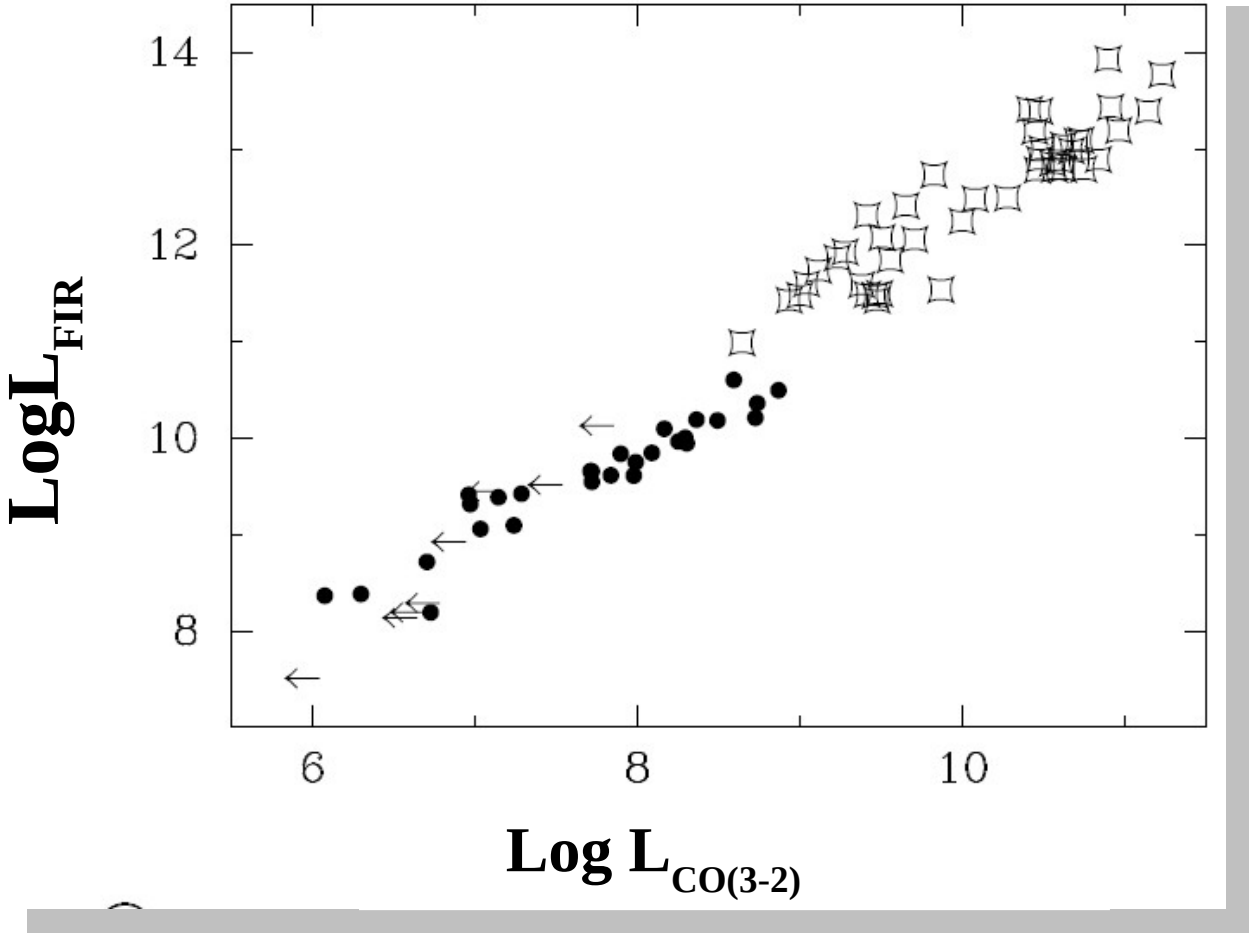
“Direct” connection between dust and molecular emission.

The ratio between IR luminosity and H2 mass is closely correlated with dust temperature



Link between molecular and FIR

- **CO(3-2) observations obtained with JCMT of a sample of SINGS galaxies (filled symbols) and luminous and ultraluminous infrared galaxies, at low and high redshift (open symbols)**



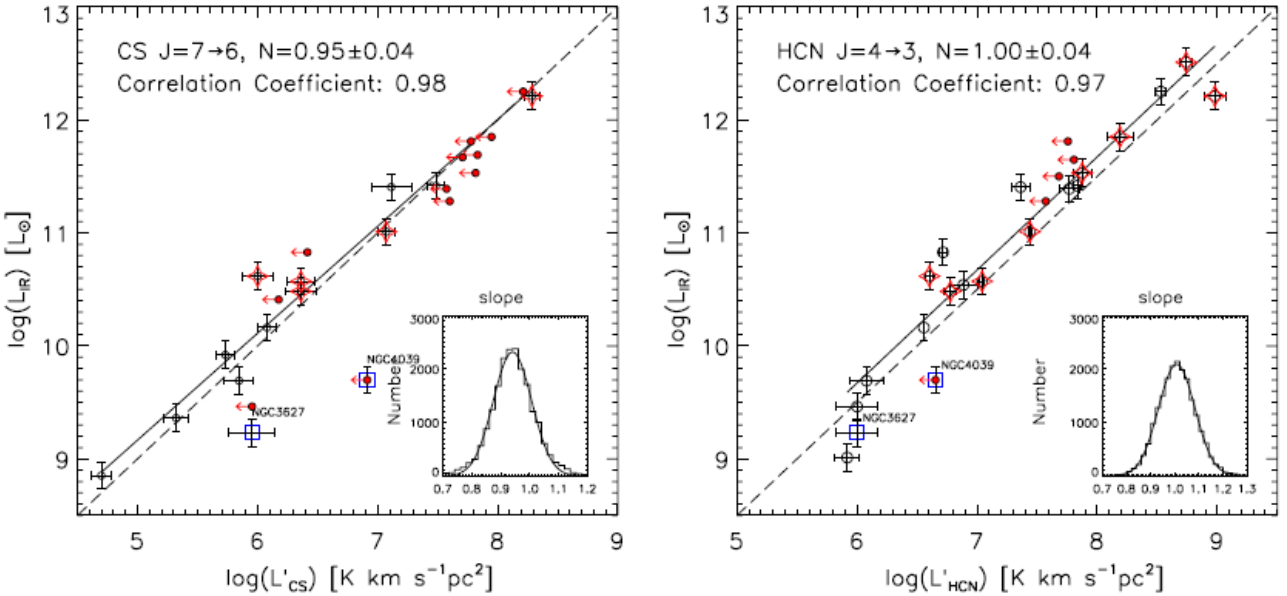
Wilson et al., 2012

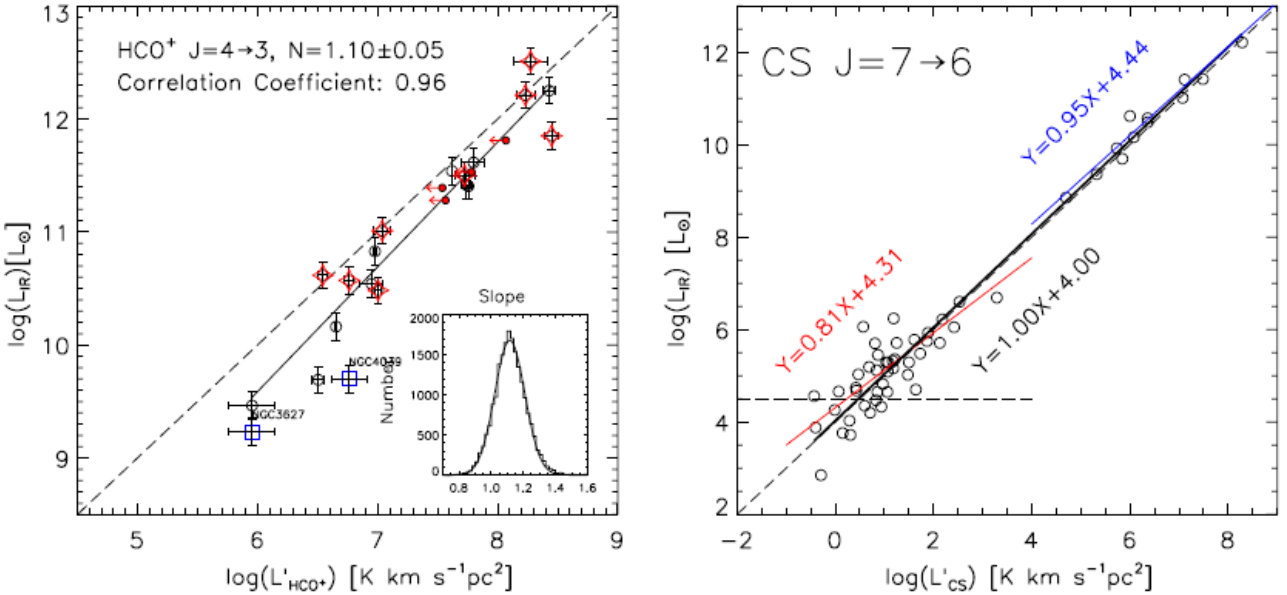
Depletion time obtained from the ratio **~ 3 Gyrs for normal disk galaxies**

50 times shorter in local and high-z ULIRGs

Link between molecular and FIR

- **Recent APEX observations of CS, HCO+ and HCN**





Linear correlations:

L_{CS}-L_{FIR}

L_{HCN} - L_{FIR}

L_{HCO+}-L_{FIR}

Zhang et al., 2014

RC – molecular correlation on global scales

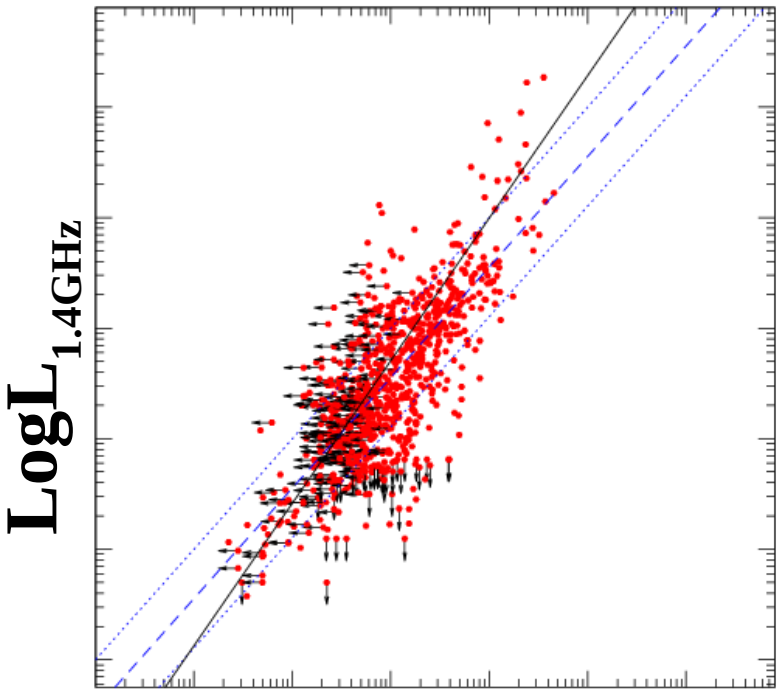
- First CO detection in external galaxies: **Rickard et al. 1975**
  Many single dish studies

- Correlation between molecular and synchrotron emission
  (e.g. **Rownd & Young, 1999; Adler et al, 1991**)

- **Murgia et al. 2002**
  Comparison of NVSS and **FCRAO CO**
  180 objects at 45 arcsec resolution.

  Spatially resolved correlation including all morphological types and starbursts.

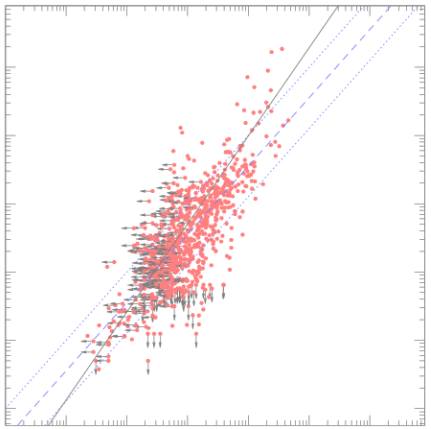
  Star formation efficiency deduced from the radio continuum, corresponds to convert 3.5% of the available molecular gas into stars on a time scale of 10^8 yrs.

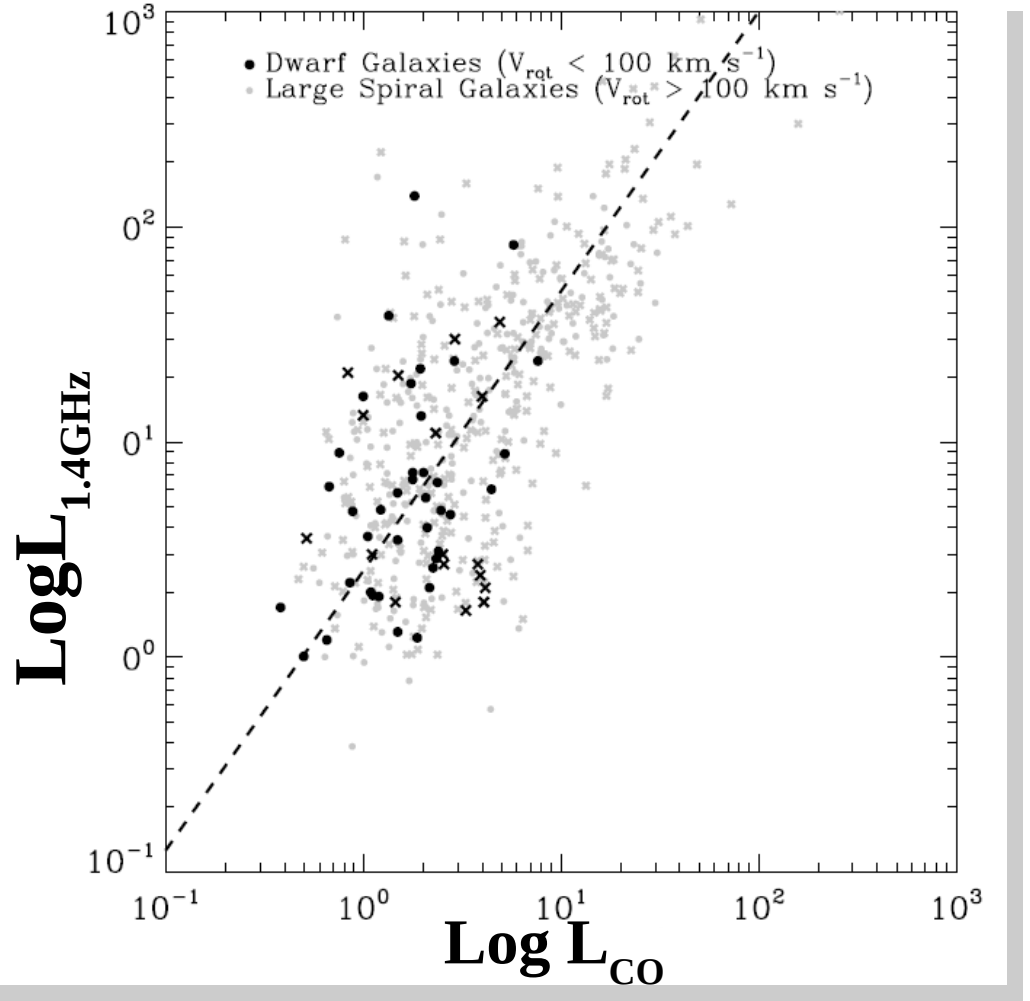


Murgia et al., 2002

RC – molecular correlation on global scales

- An analogous correlation at kpc spatial scales has been found in a sample of 28 dwarf galaxies.





Leroy et al., 2005

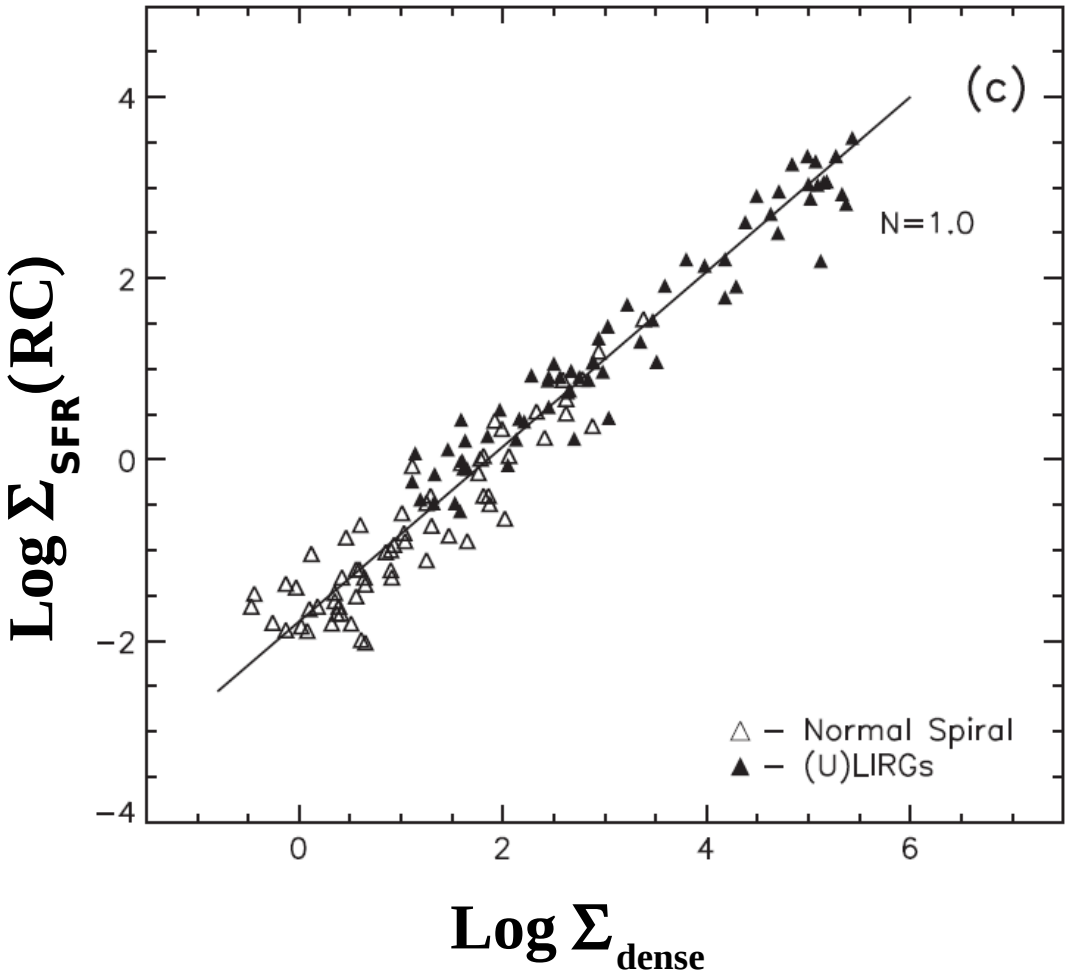
RC – molecular correlation on global scales

- A tight global correlation has been observed between HCN (dense gas tracer) and RC (e. g. **Gao & Solomon, 2004; Liu et al., 2010**)

- A study of the global star formation law in a sample of 181 galaxies (normal spirals, and ULIRGs) IR luminosity spanning five orders of magnitude

- No correlation between HI and SFR

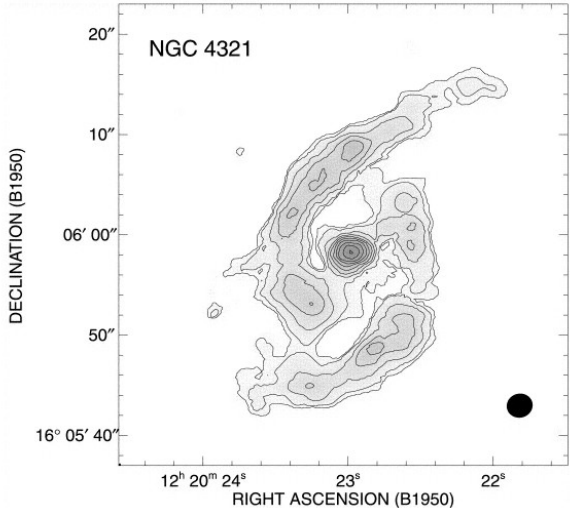
- The tightest relation in the sample is the linear relation between SFR (traced both by IR and RC) and dense gas traced by HCN emission.

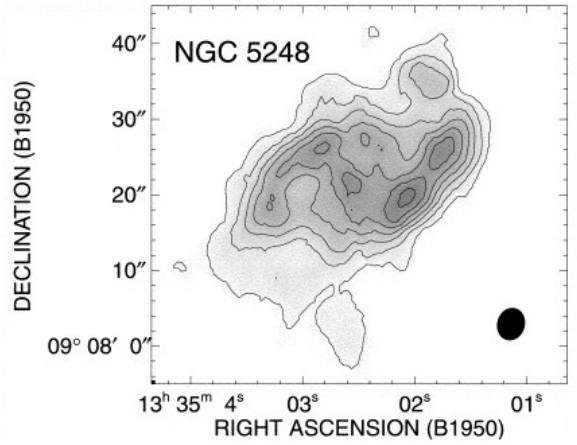


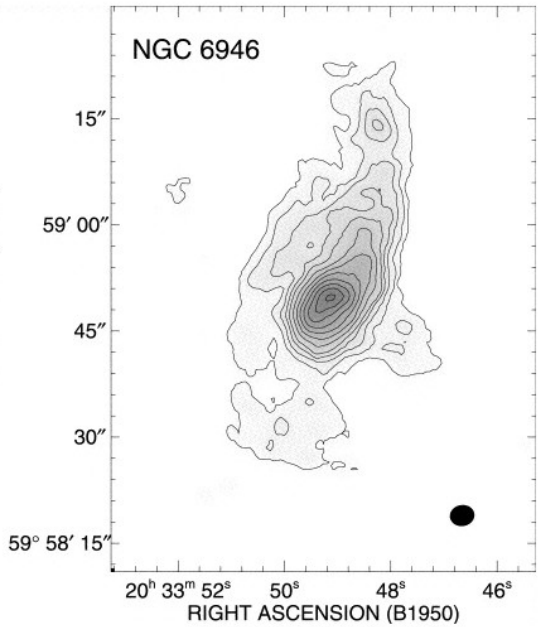
Liu et al., 2015

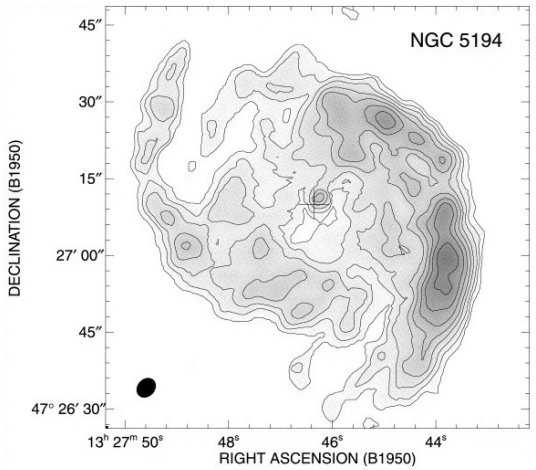
Spatially resolved observations of nearby galaxies

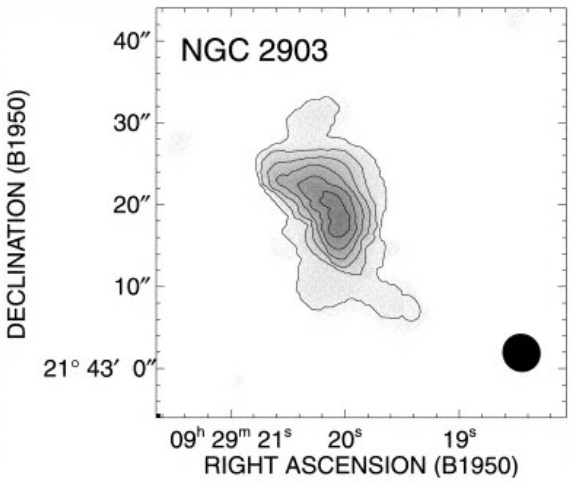
- High resolution observations:
  Nobeyama and Owens Valley Millimeter Array
  CO(1-0) bservations of the central arcmin of 20 galaxies @ 4” resolution







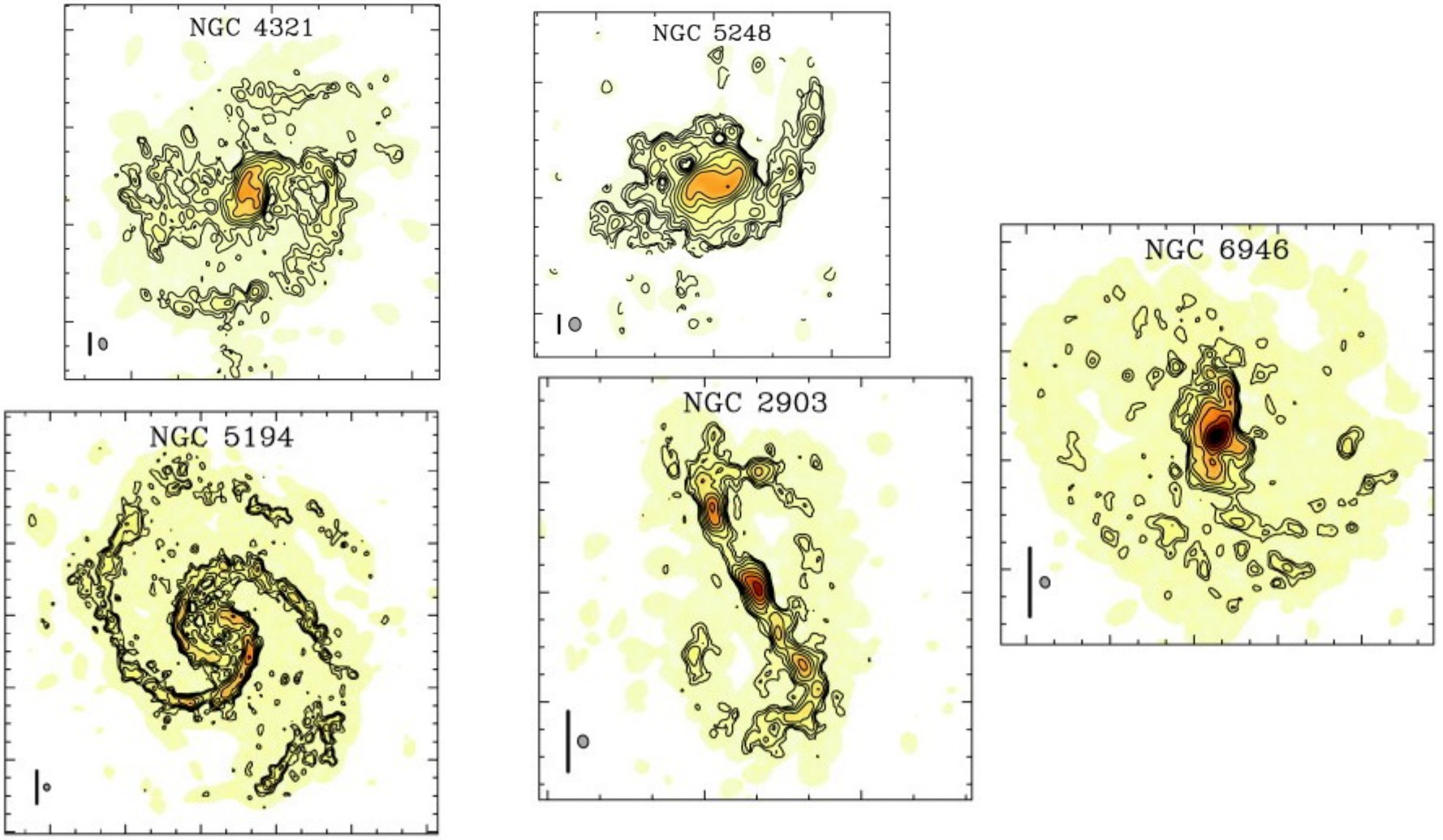




Sakamoto et al., 1999

Spatially resolved observations of nearby galaxies

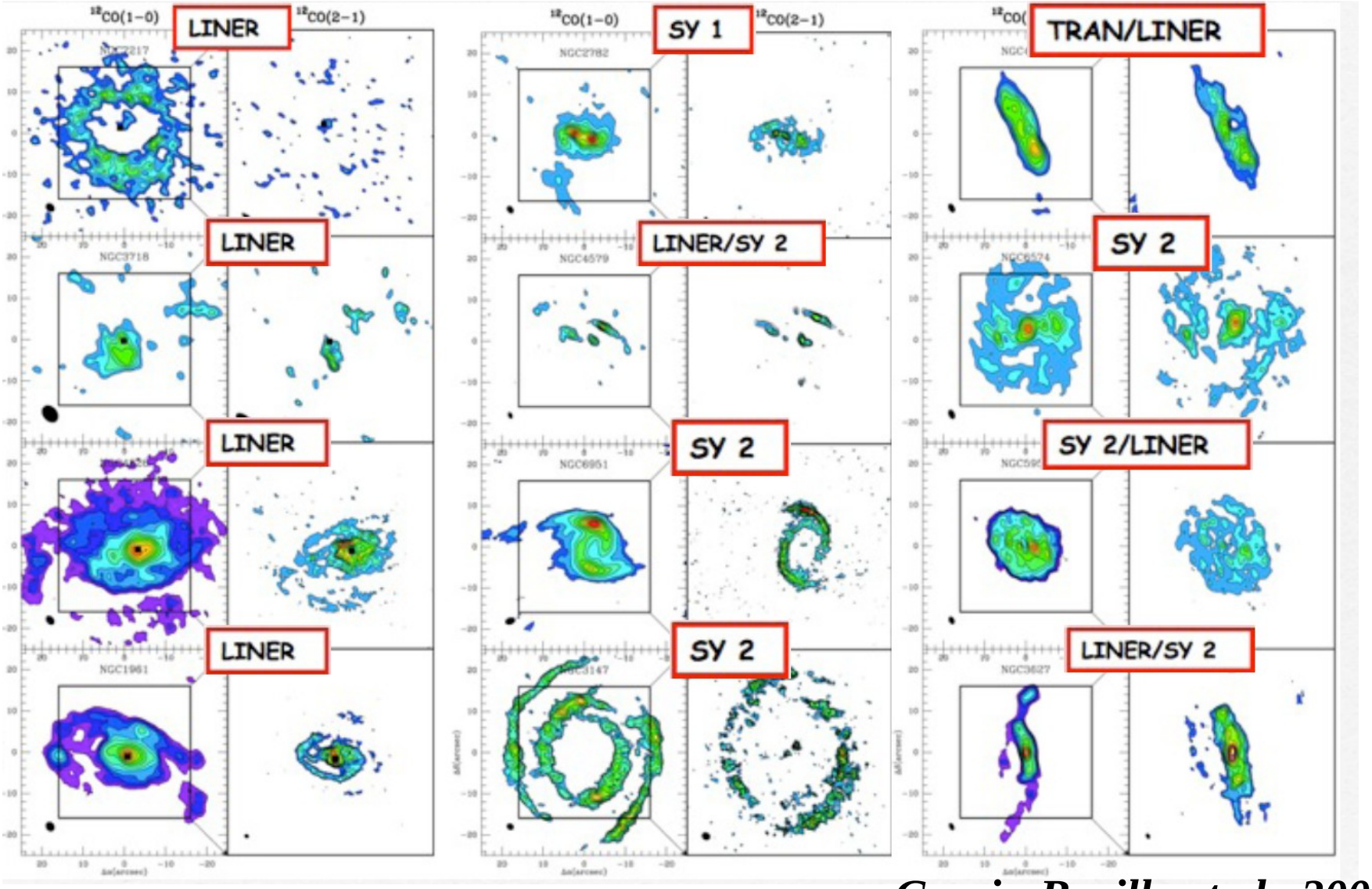
- High resolution observations:
  BIMA Survey Of Nearby Galaxies (SONG; PI: M.W.Regan and T. Helfer)
  BIMA and 12 m single dish CO(1-0) observations of 44 galaxies 6” resolution



Regan et al., 2003; Helfer et al., 2003

Spatially resolved observations of nearby galaxies

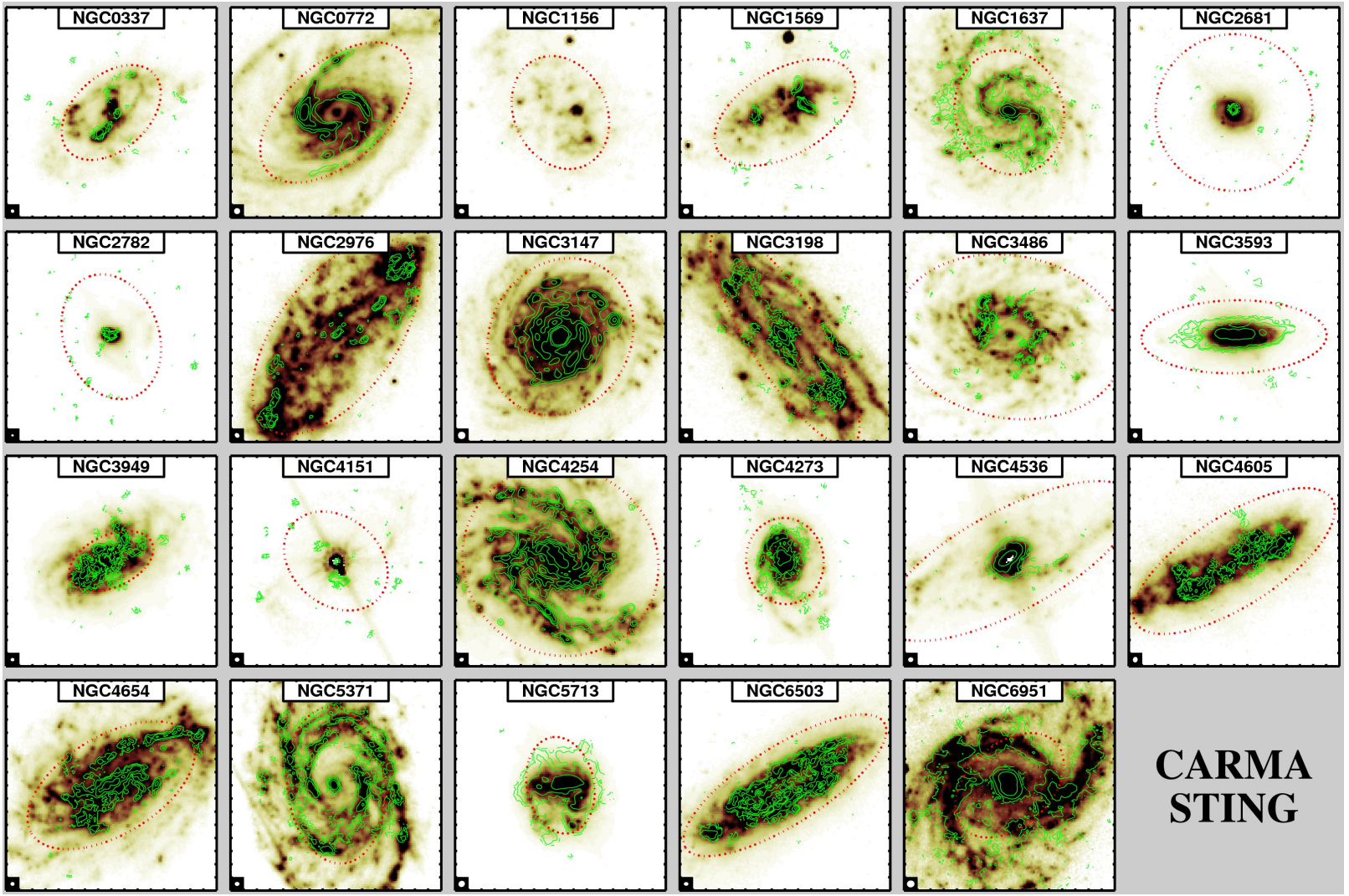
- High resolution observations:
  NUclei of GAlaxies (NUGA, PI: S. Garcia-Burillo and F. Combes)
  Plateau de Bure CO(1-0) and CO(2-1) observations of
  the central 1 kpc regions of 30 galaxies @ < 1" resolution



Garcia-Burillo et al., 2003

Spatially resolved observations of nearby galaxies

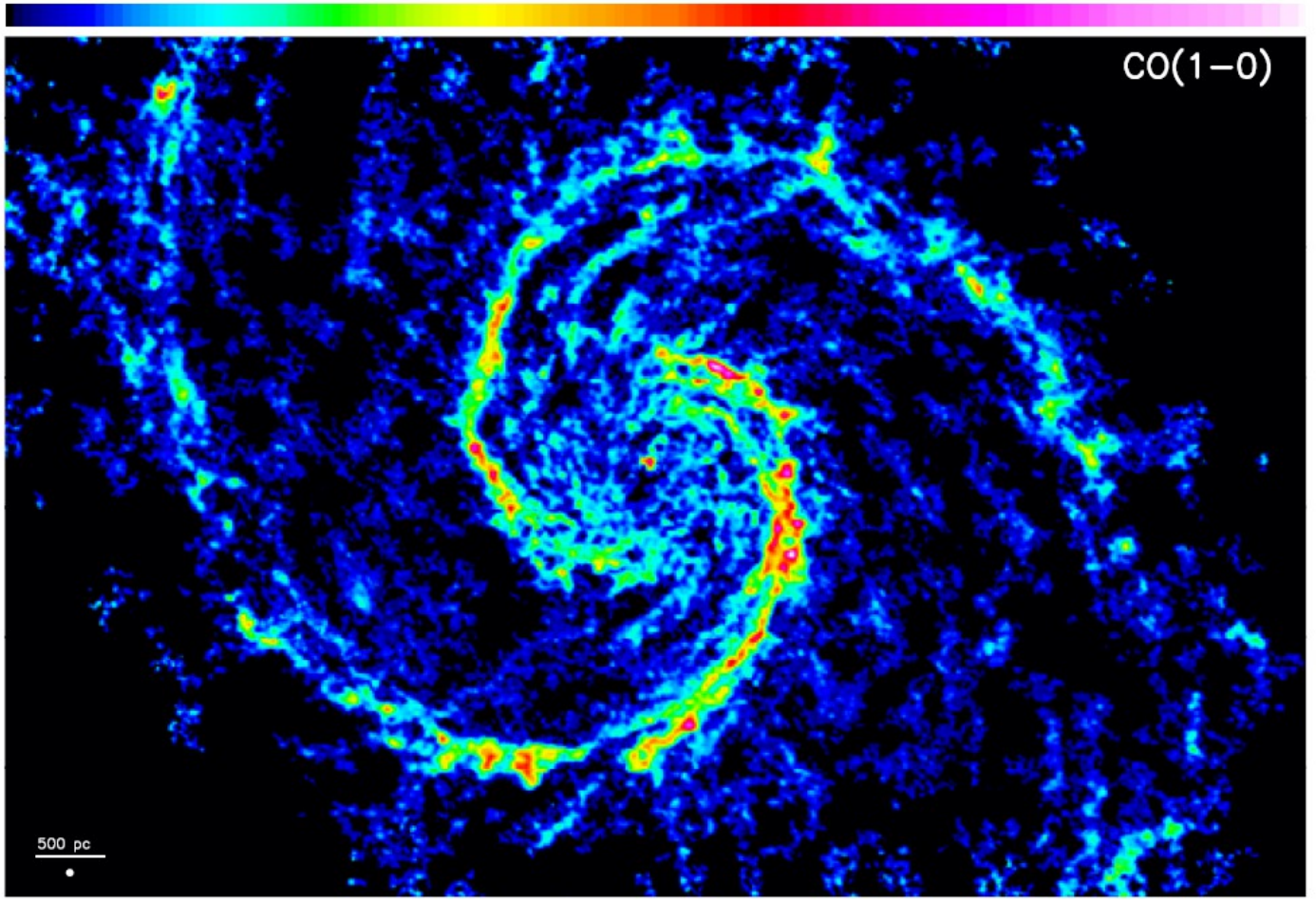
- High resolution observations:
  CARMA Survey Towards Infrared-bright Nearby Galaxies (STING; PI: A. Bolatto and T. Wong)
  CARMA CO observations of 23 galaxy disks @ 3” resolution



Nurur et al., 2011

Spatially resolved observations of nearby galaxies

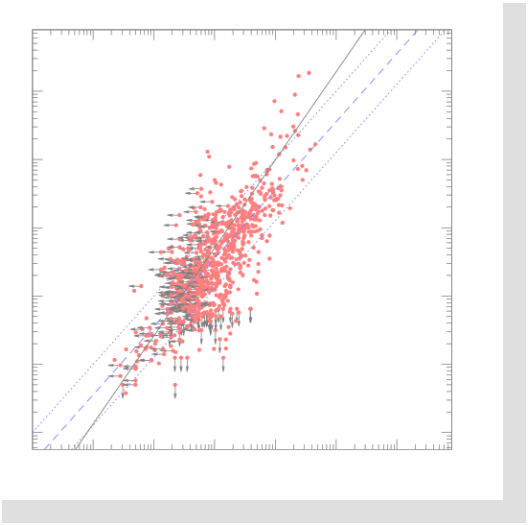
- High resolution observations:
  PdBI Arcsec Whirlpool Survey (PAWS; PI: E. Schinnerer)
  PdBI and 30 m CO(1-0) observations of the central ~9 kpc of M51 @ 1”, 3”, 6” resolution

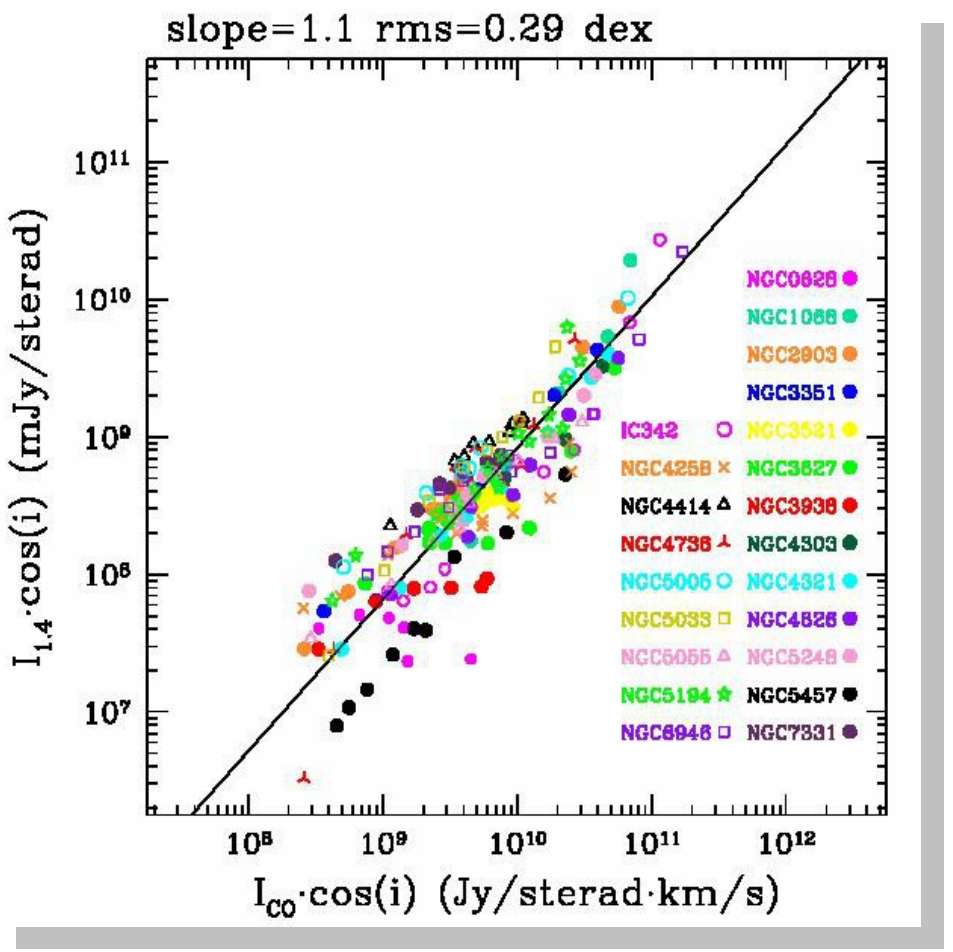


Schinnerer et al., 2013

RC-CO local correlations

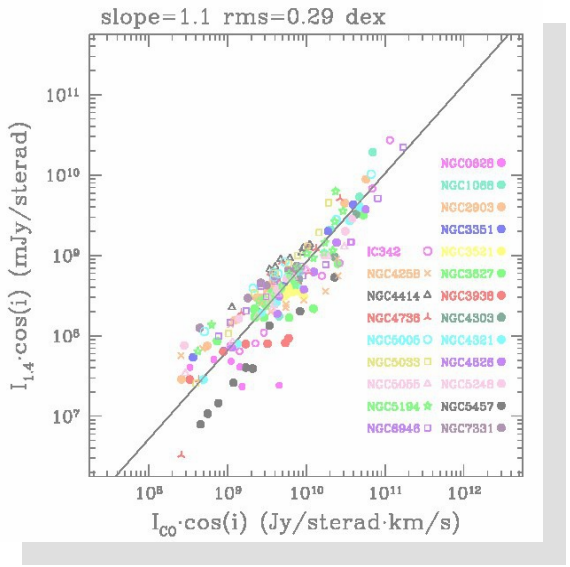
In a sample of 22 CO luminous galaxies from the BIMA SONG
Spatially resolved correlation between 1.4 GHz emission and CO(1-0)
holds down to spatial scales of hundreds of pc





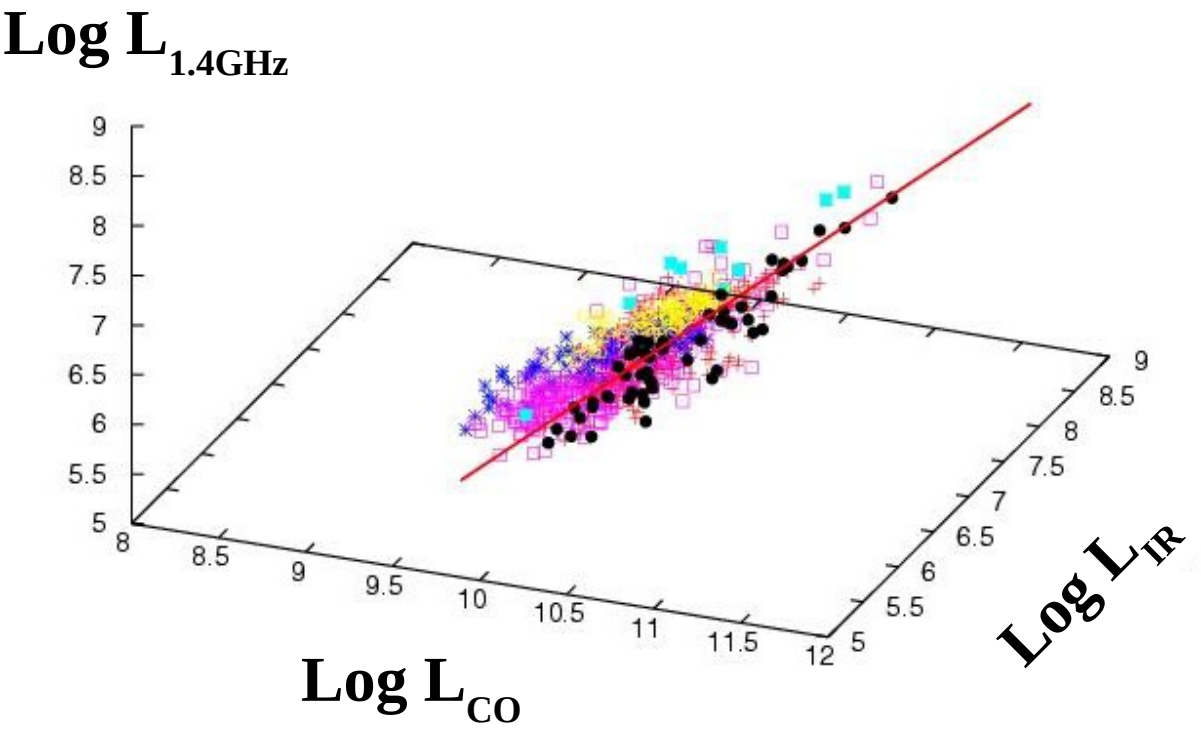
Paladino et al., 2006

RC-CO local correlations



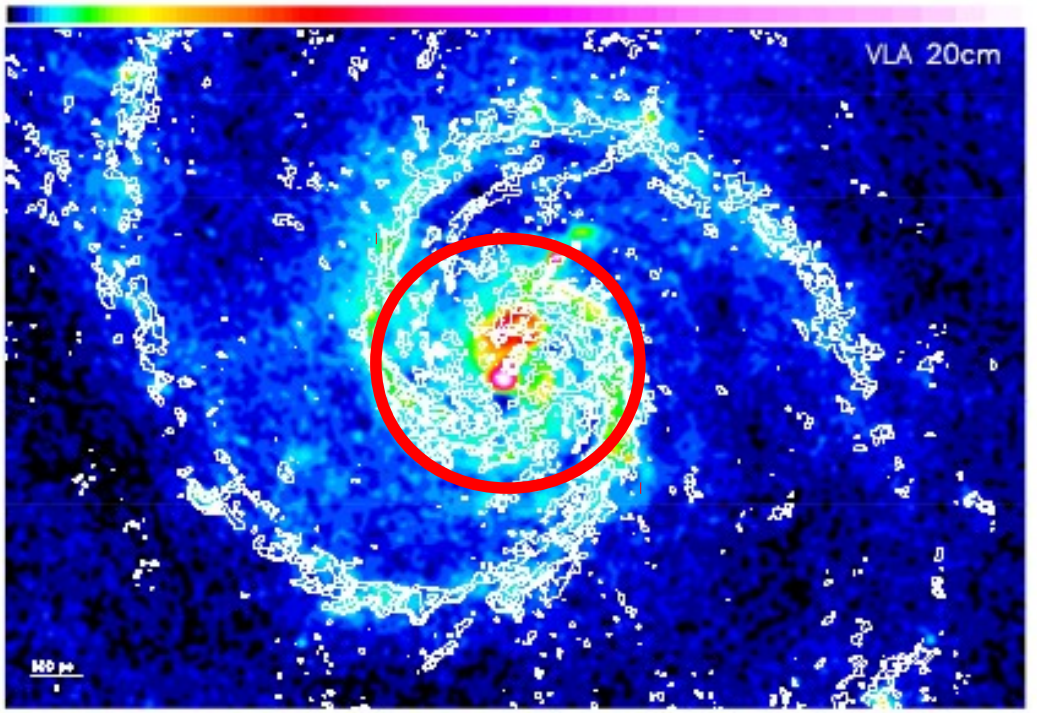
It is actually a 3D correlation between RC-FIR-CO

Example obtained for 6 galaxies @ 6” resolution



Paladino et al., 2008

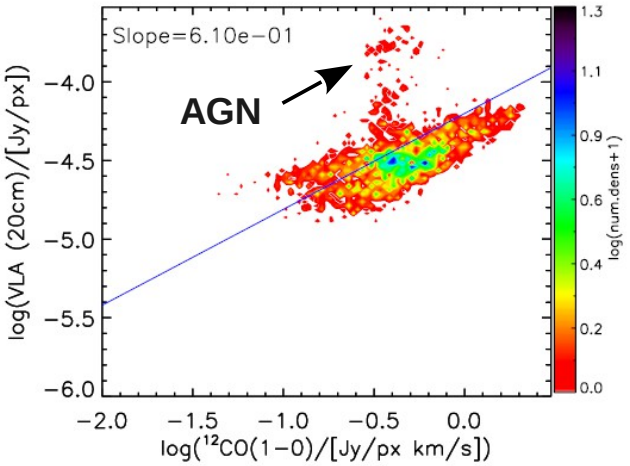
RC-CO local correlations



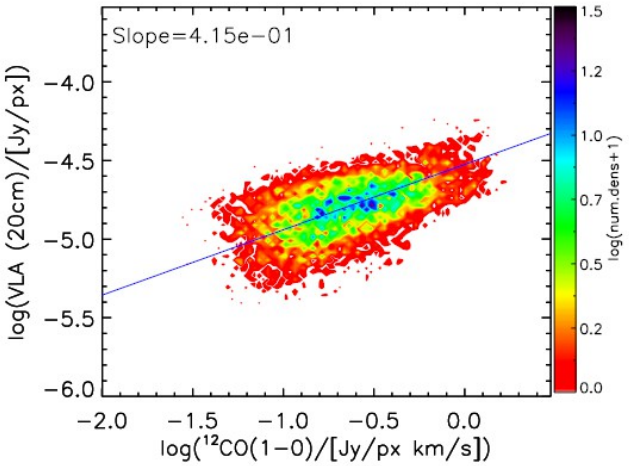
Good spatial correlation of
low-frequency RC and CO line emission.

Pixel by pixel comparison @ 3” resolution
Steeper and stronger in the central disk.
The RC emission in the central region
is brighter for a given CO flux
independenty on the AGN

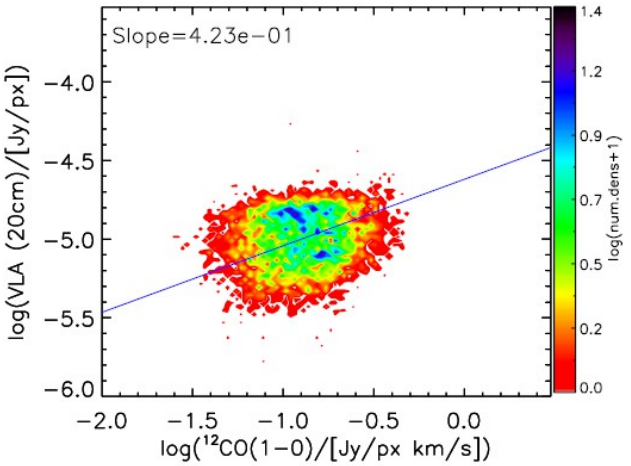
Central



Arm



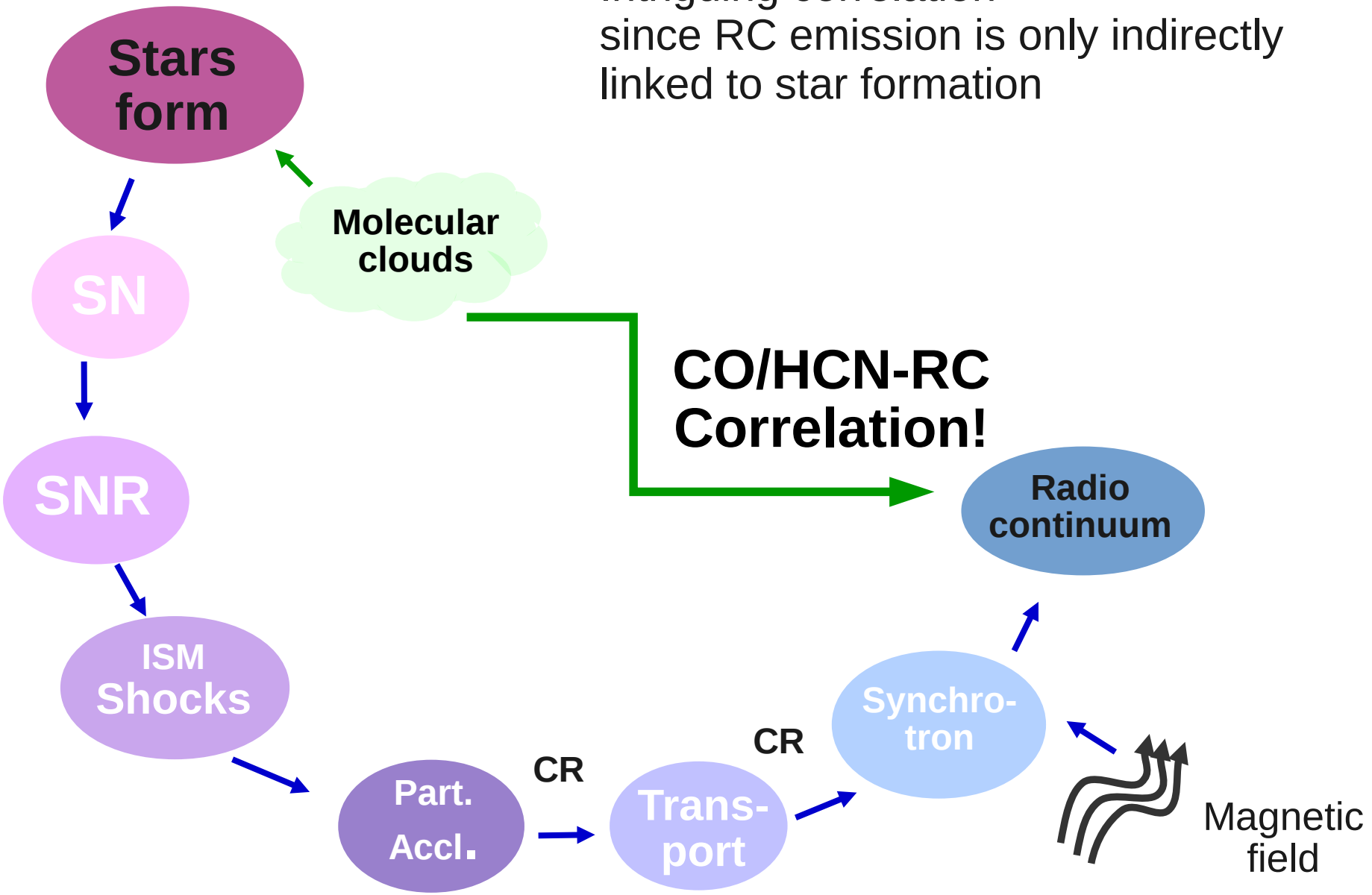
Inter-arm



Schinnerer et al., 2013

Theoretical models

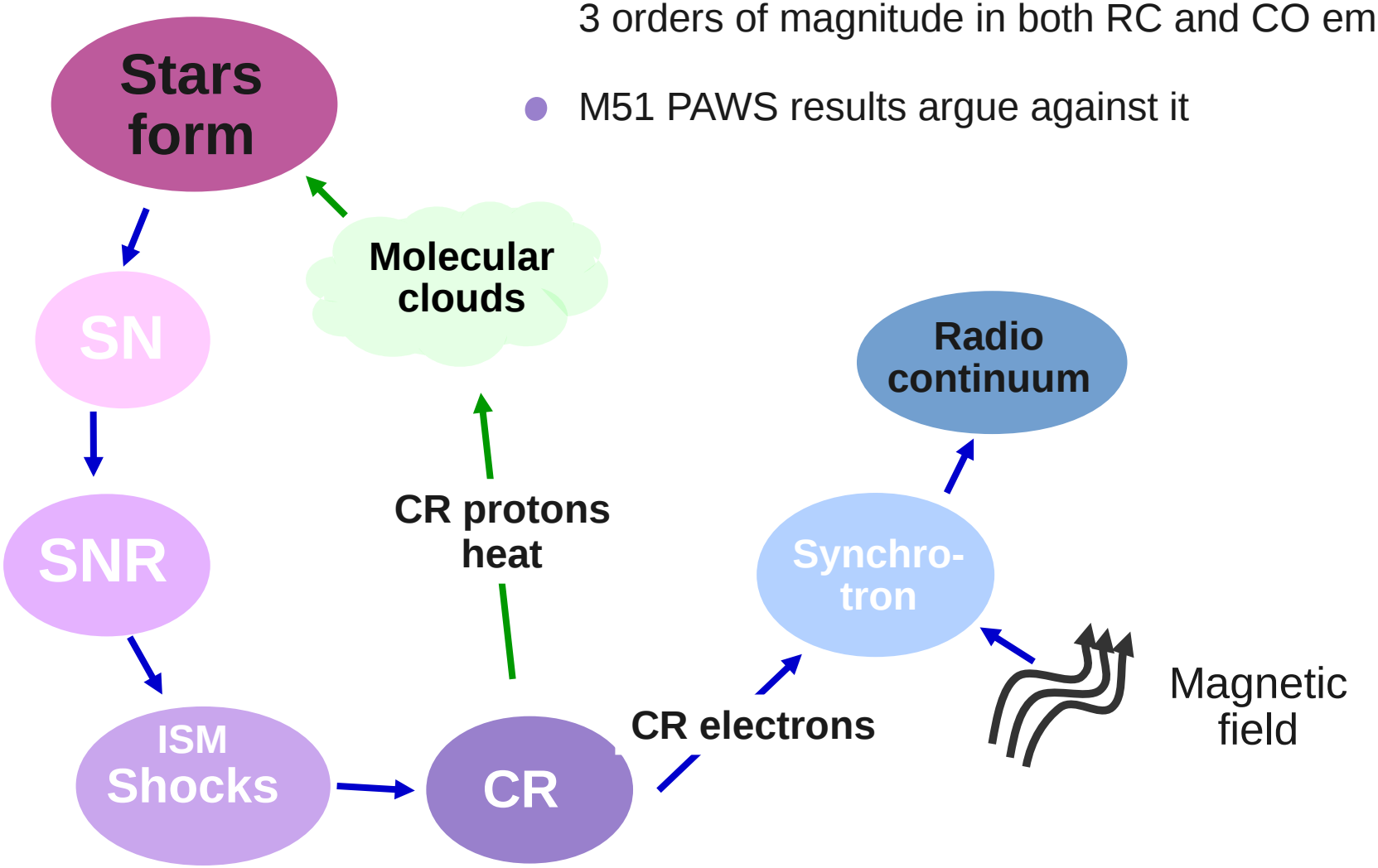
Intriguing correlation
since RC emission is only indirectly
linked to star formation



Theoretical models

Cosmic Ray heating
(Adler et al., 1991; Suchkov et al., 1993)

- **"Attractive" direct links between CR and molecular clouds**
- Does NOT justify the observed correlation spanning 3 orders of magnitude in both RC and CO emission
- M51 PAWS results argue against it

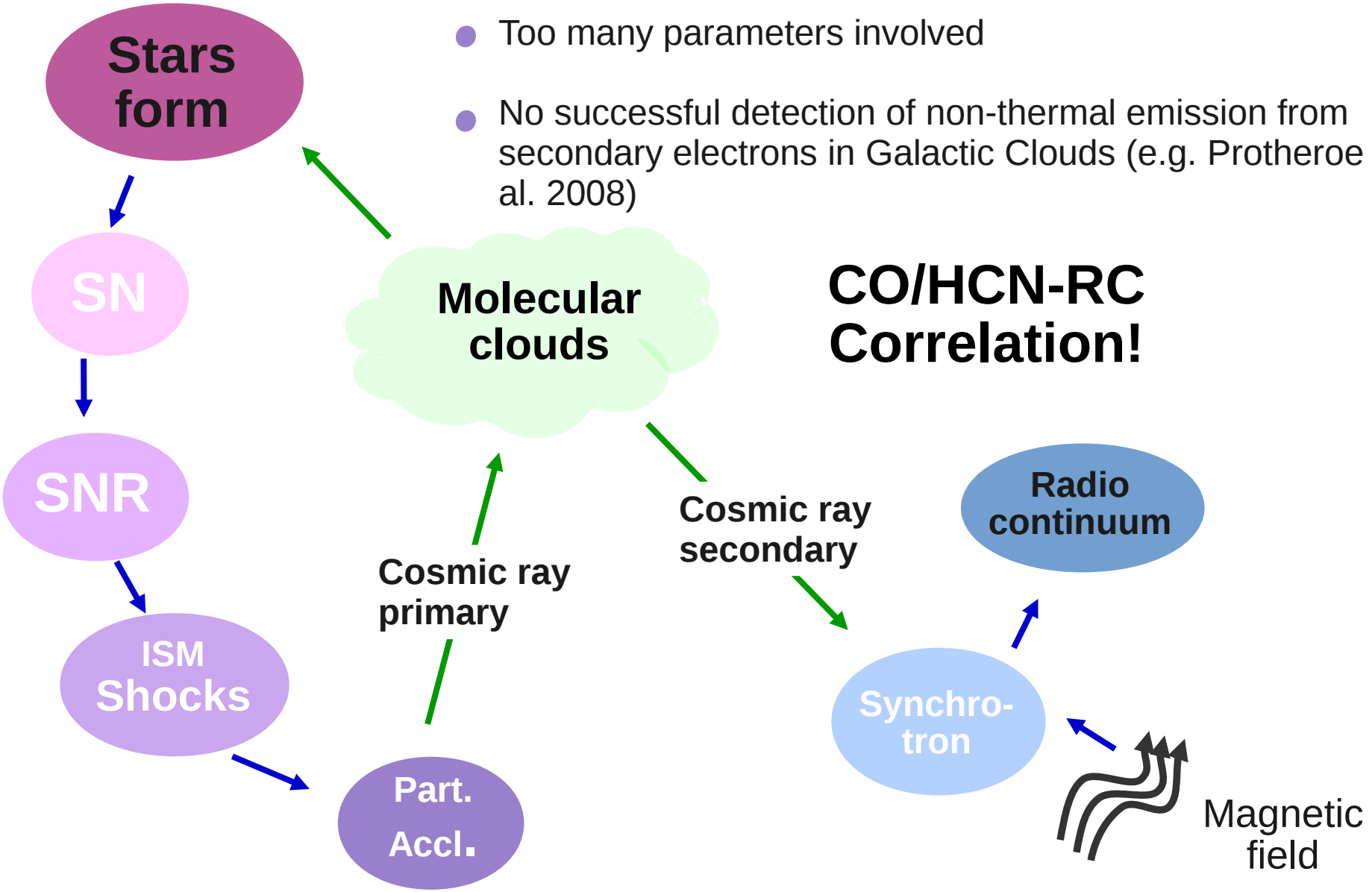


Theoretical models

Secondary electrons hypothesis

(Marsher and Brown, 1978; Murgia et al., 2005; Thompson et al., 2007)

- Non-thermal spectral index analysis...
- Too many parameters involved
- No successful detection of non-thermal emission from secondary electrons in Galactic Clouds (e.g. Protheroe et al. 2008)



CO/HCN-RC Correlation!

Theoretical models

Coupling between gas density and magnetic field

(e.g. Niklas & Beck, 1997; Murgia et al., 2005; Schinnerer et al., 2013)

CR electrons with energy spectrum $N(\epsilon) = N_0 \epsilon^{-\delta}$

produce a non-thermal radio emission with spectral index $\alpha = (\delta - 1)/2$

$$I_{RC} \propto N_{CR} B^{\alpha+1} \nu^{-\alpha}$$

The gas surface density is the projection of the volume density through the disk

$$\Sigma_{gas} \sim \rho$$

Assuming coupling between gas density ρ magnetic field strength B

$$B \propto \rho^{\beta}$$

$$\longrightarrow \quad I_{RC} \propto N_{CR} \Sigma_{gas}^{\beta(1+\alpha)}$$

What mechanism/parameter produces the coupling?
Murgia et al. (2005) proposed the **hydrostatic pressure**

Further steps

- **The state of the art**

  the highest spatial resolution correlation obtained with PAWS M51 data

- **What would be needed to go forward:**

  A statistical sample of galaxies observed at high spatial resolution

  Sensitive RC observations to further test the role of magnetic field

  Spatially resolved non-thermal spectral index maps

  Study the magnetic field at giant molecular cloud scale and its connection with the galactic magnetic field
  (e.g. M33 observations; Li et al. 2011)

Future perspectives with ALMA

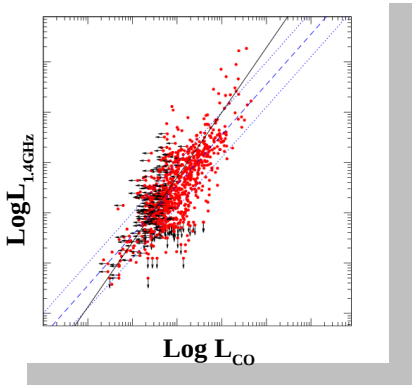
- **The state of the art M51 PAWS map has been obtained in ~200 hrs of PdBI observing time**

  mapped area 11x7 kpc
  resolution ~1”
  rms 0.4 K in 5 km/s

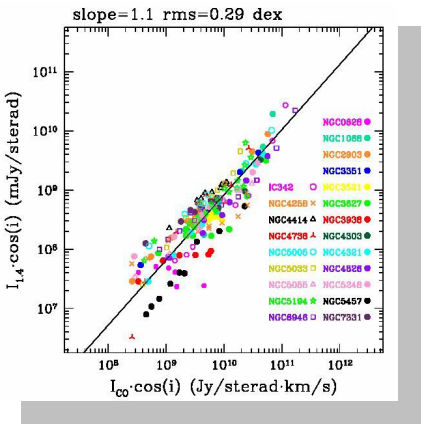
- **ALMA cycle 3 (36 antennas)** would have obtained the same sensitivity covering the same area in **a M51-like galaxy (@ LMC position)** in **~18 hrs**

Future perspectives with ALMA

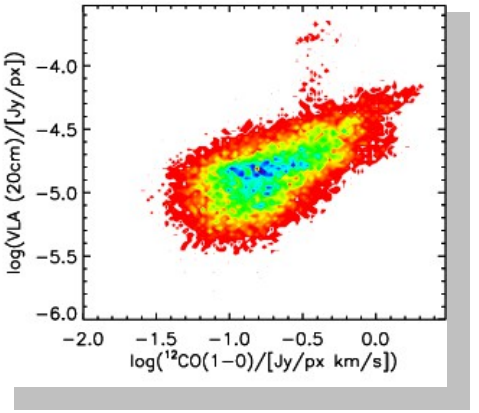
- **ALMA will allow a step forward in spatial resolution**



kpc scale
disk scale

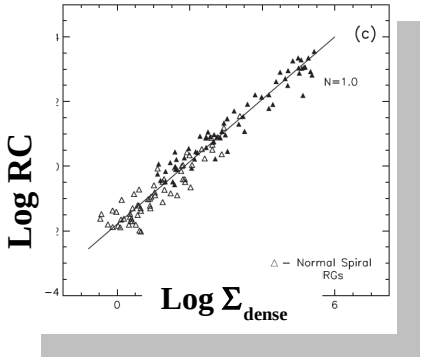


~100pc
spiral arm



10pc
GMC scale

- **and a step forward in sensitivity**



global scale

Spatially resolved correlation between dense gas tracers and RC are still missing

Link between molecular and FIR

RC – molecular correlation on global scales

Spatially resolved observations of nearby galaxies

RC-CO local correlations

Theoretical models

Further steps

Future perspectives with ALMA

Grazie