Compact Obscured Nuclei in the ALMA era

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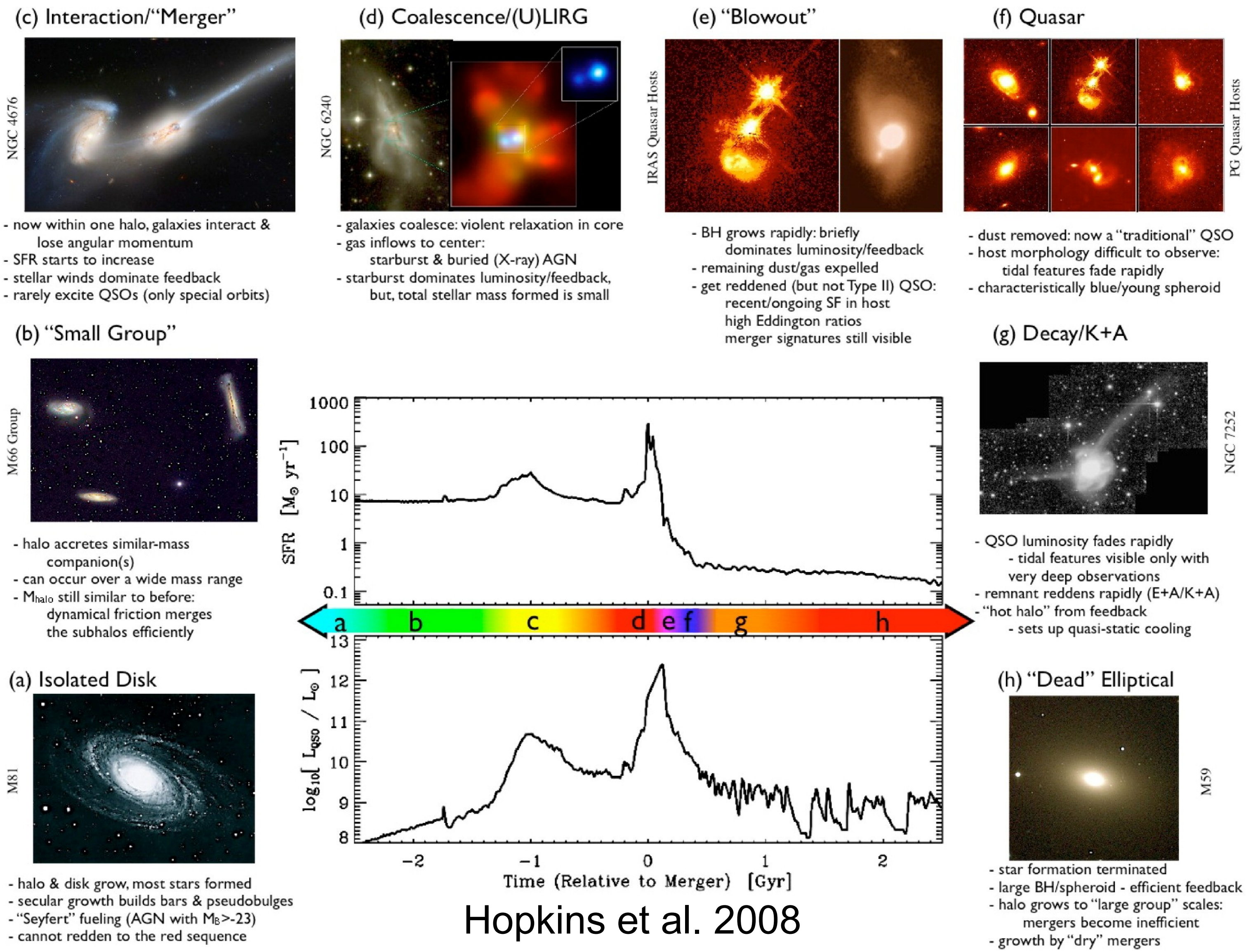
S.Aalto, S. Muller, K. Sakamoto, S. Martin, A. Evans, M. Spaans, S. Garcia-Burillo, S. Mühle, P. van der Werf,

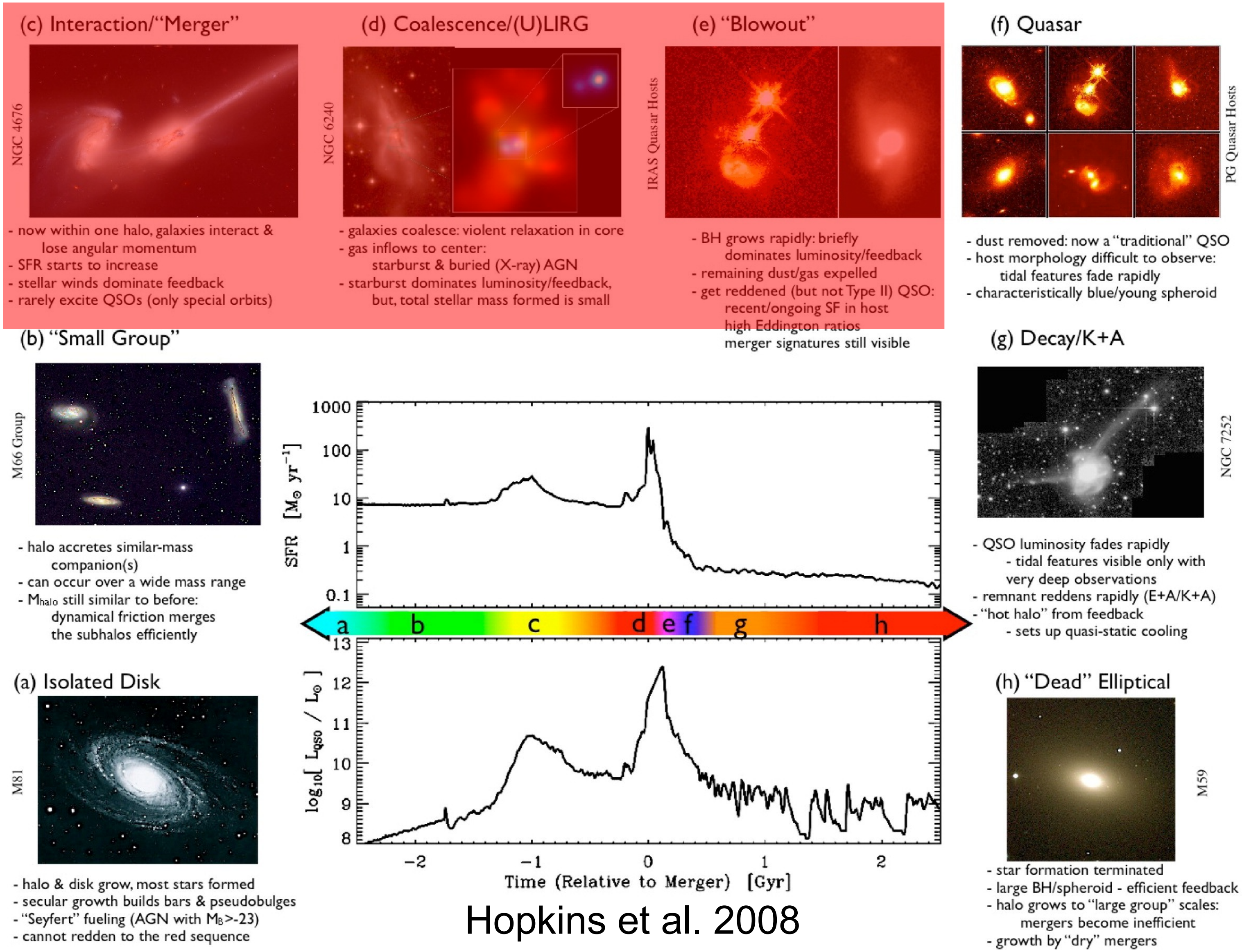
and the MASTER network

An Evolutionary Scheme for LIRGs



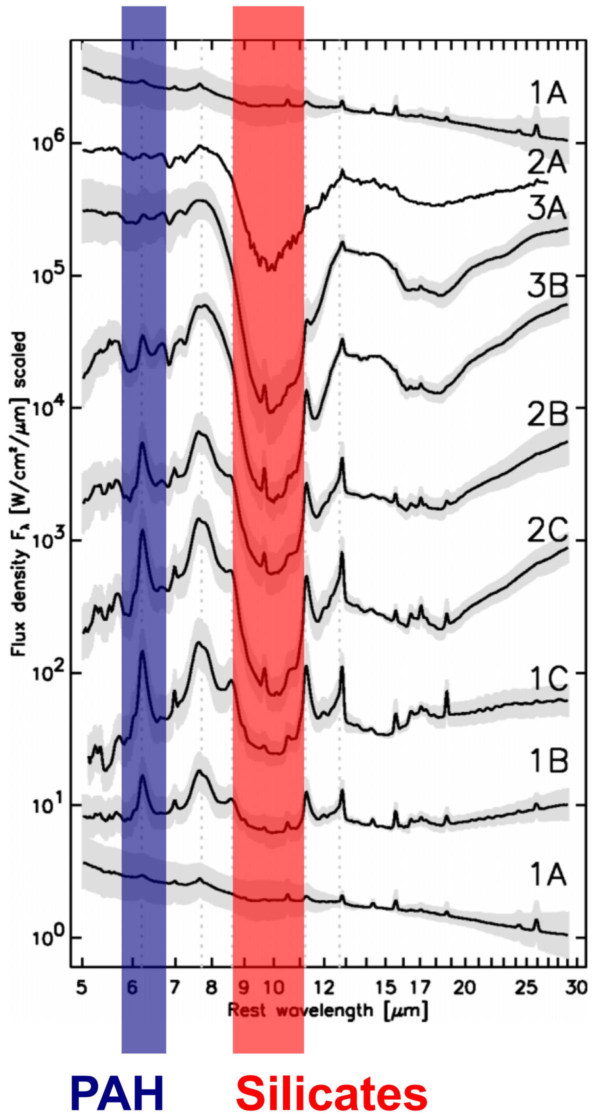
Hopkins et al. 2008

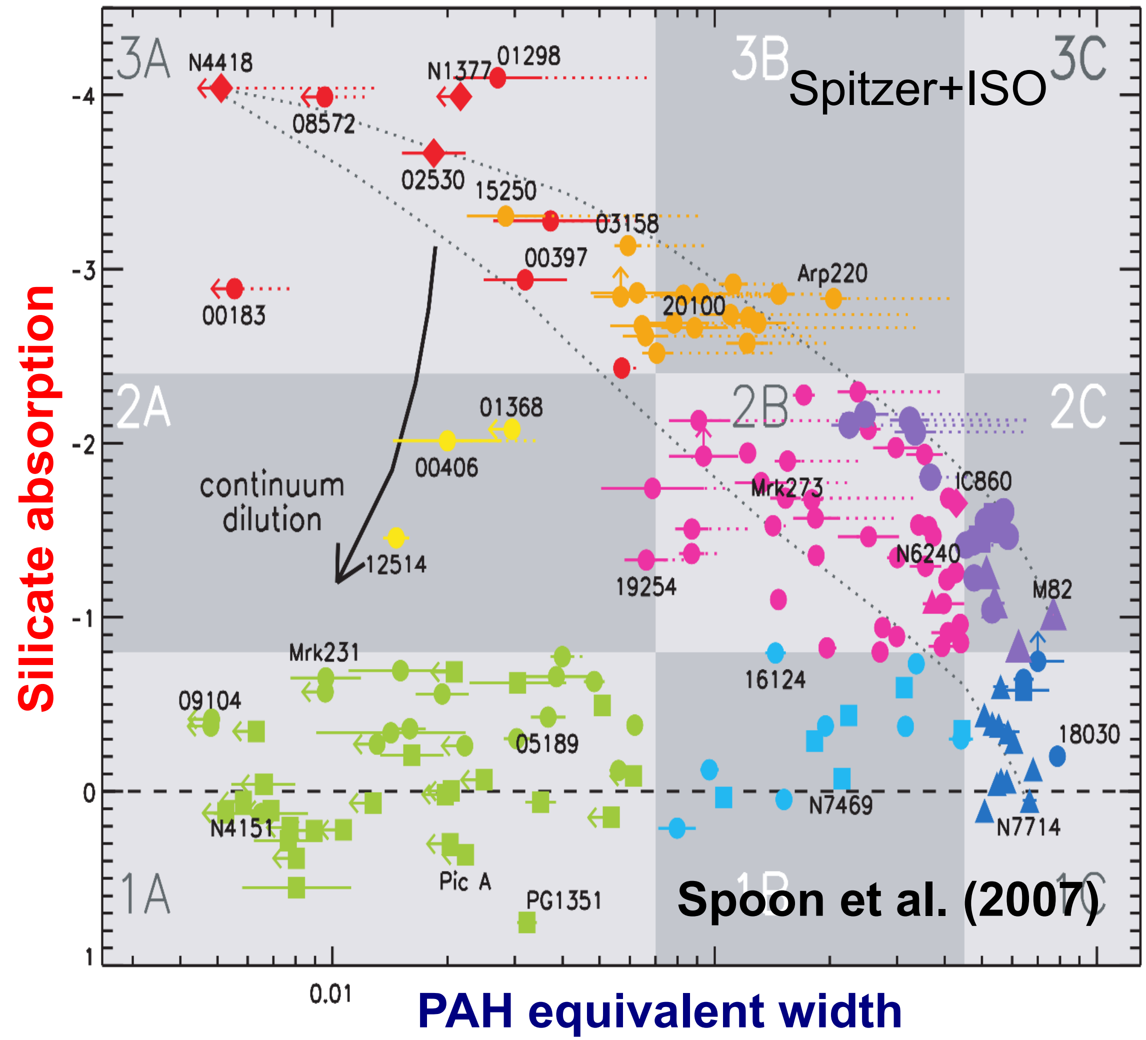
An Evolutionary Scheme for LIRGs



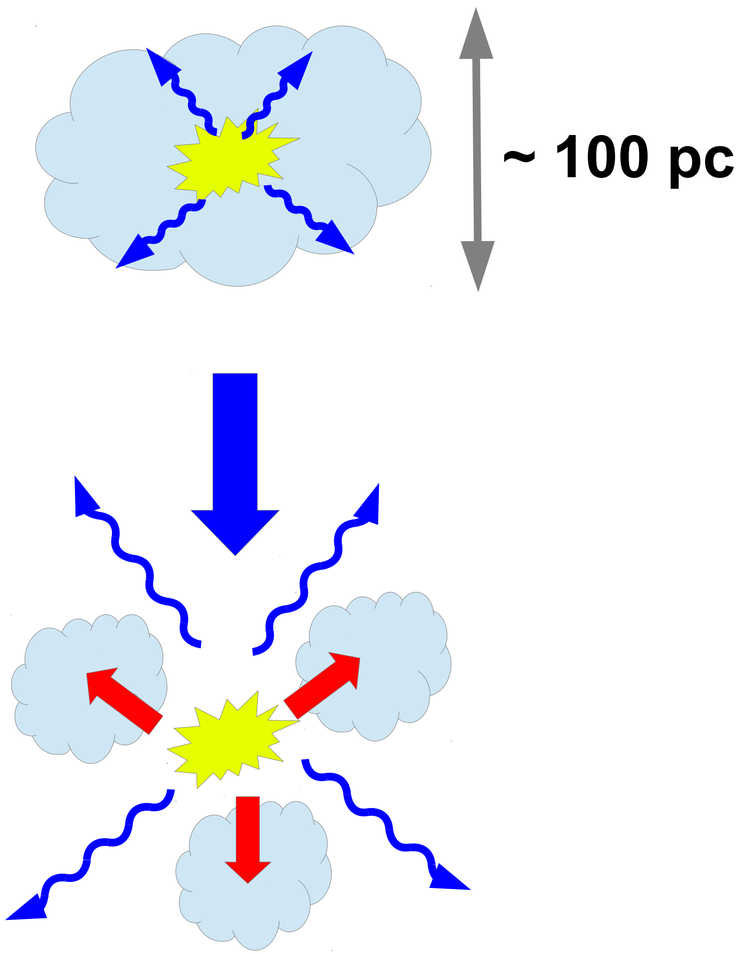
Hopkins et al. 2008

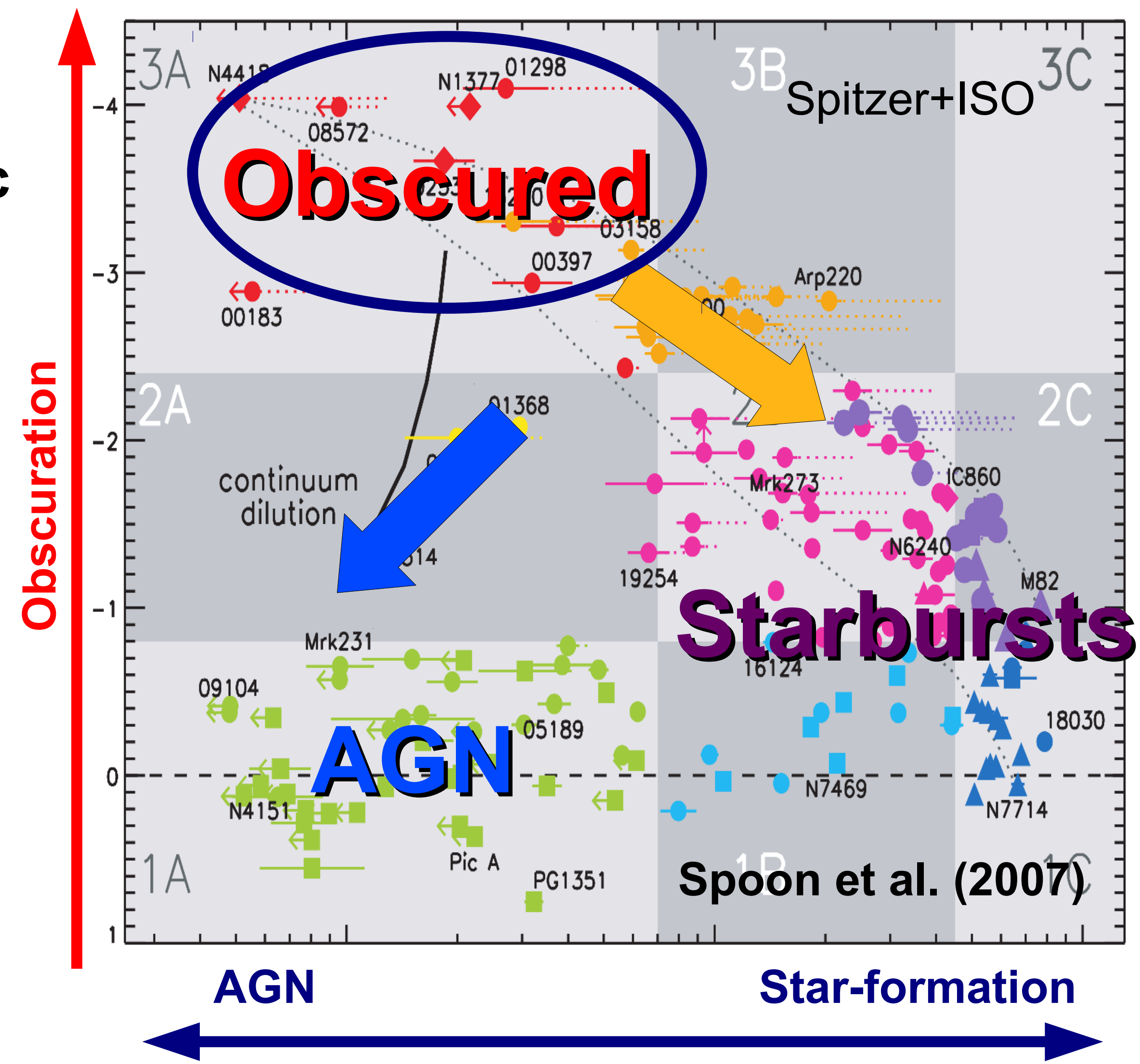
Obscured LIRGs



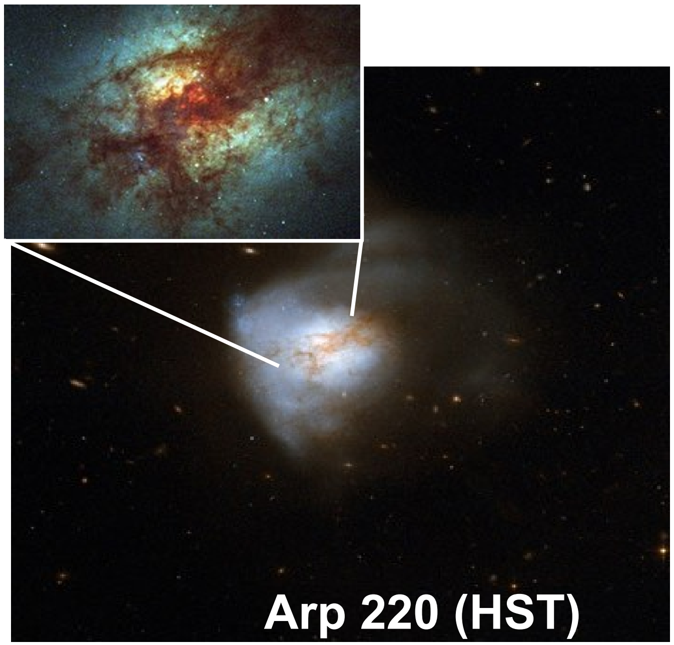


Obscured LIRGs





Obscured LIRGs


Arp 220 (HST)

- Hot (>100 K), compact (<100 pc) molecular and IR cores
- SFR > 10 M⊙/yr
- Extreme obscuration

  $N(H_2)>10^{24}\ cm^{-2}$

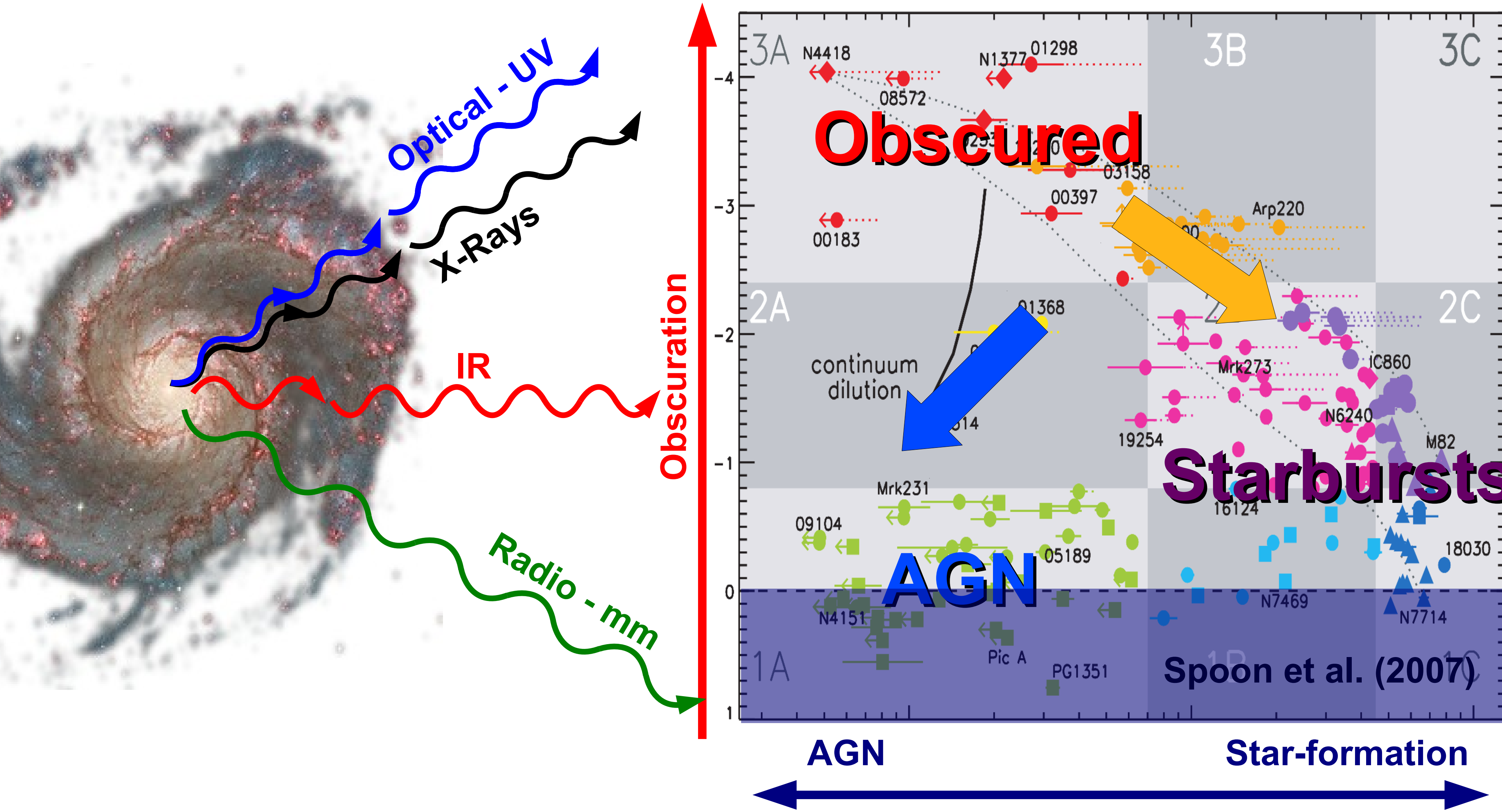
- Mixed AGN/Starburst features
- Is the IR coming from star formation ?
- AGN contamination in high-z SFR surveys ?

Why do we like obscured LIRGs?

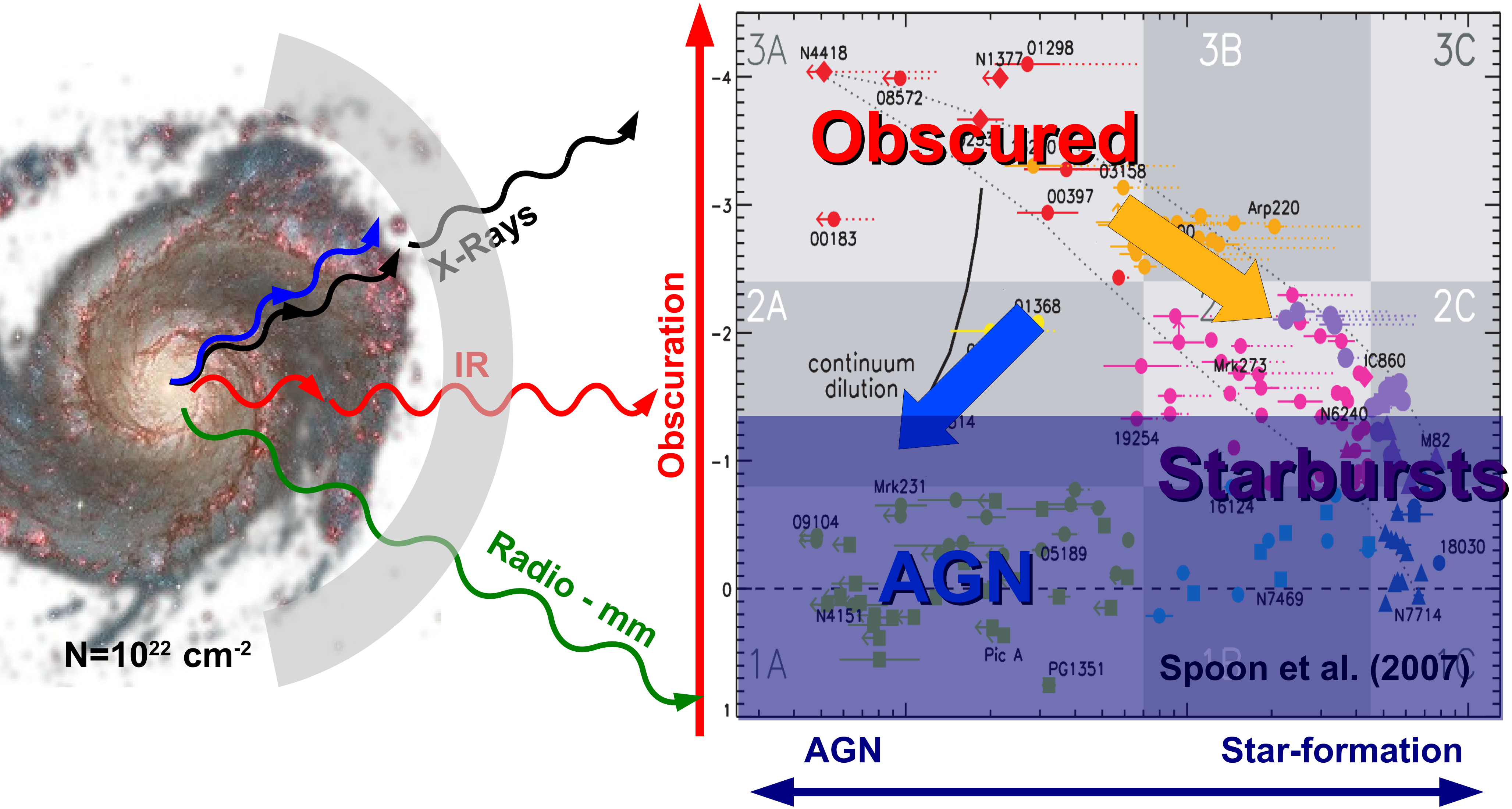
- **Young stages of Starburst/AGN?**
  - Radio-deficient → Nascent starbursts ?
  - Study onset of Starburst/AGN feedback

- **Star Formation (Near and far)**
  - SFR >10 $M_\odot$/yr → Enhanced SF efficiency ?
  - Starburst/AGN contribution → Is IR tracing SFR ?

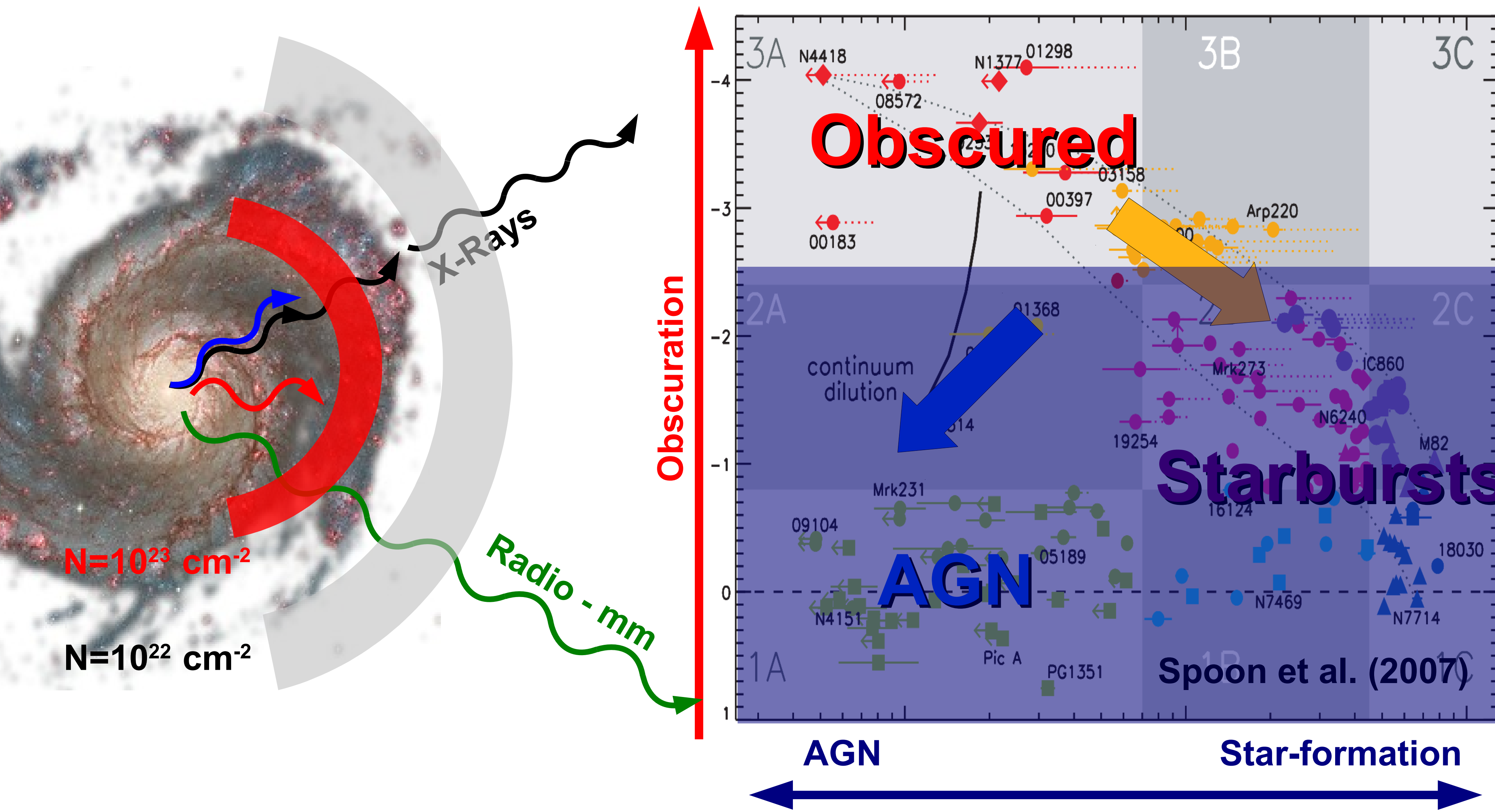
Multi-wavelength diagnostics



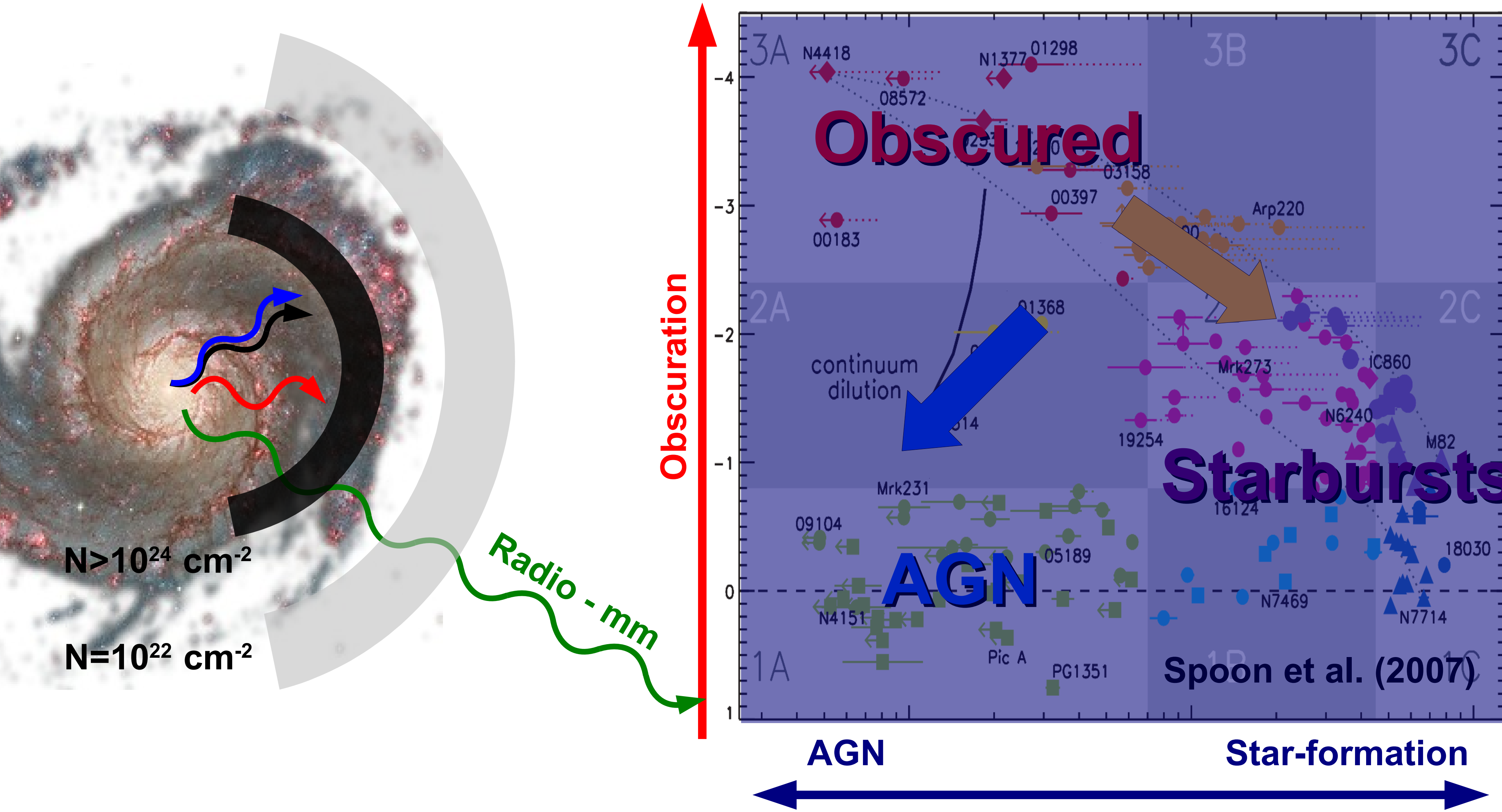
Multi-wavelength diagnostics



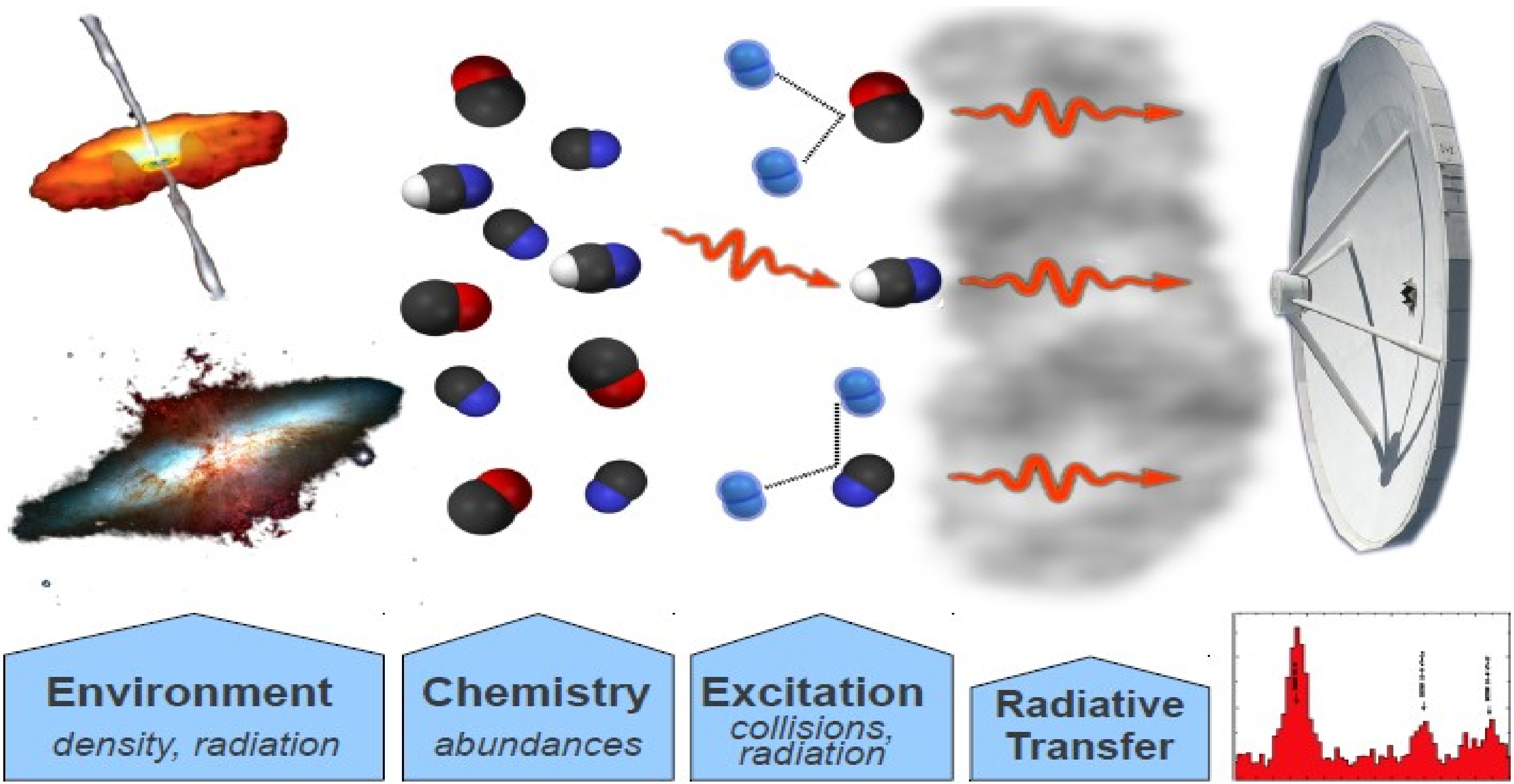
Multi-wavelength diagnostics



Multi-wavelength diagnostics

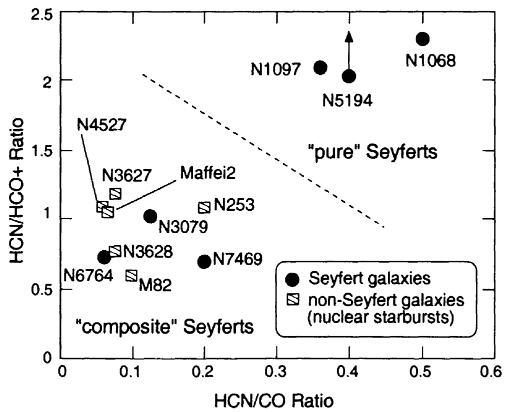


Molecular diagnostics

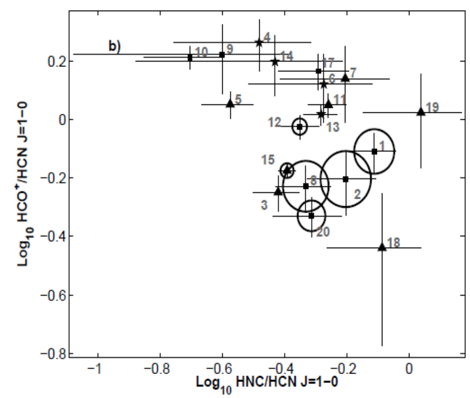


Molecular diagnostics, pre-ALMA

- **Line Ratios**

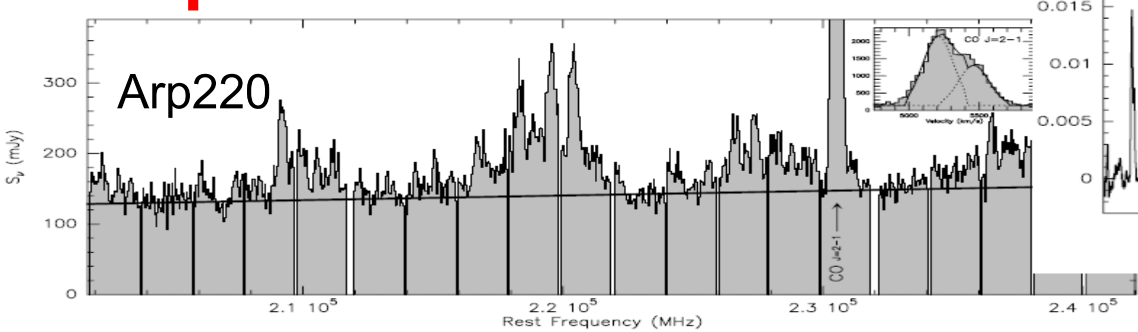


Kohno et al. 2001

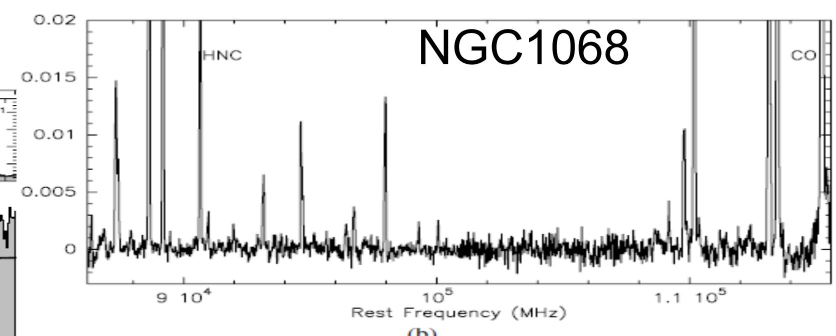


Costagliola et al.,2011

- **Spectral Scans**



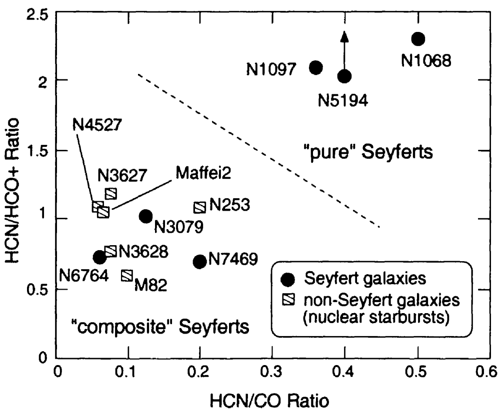
Martin et al. 2011



Aladro et al. 2013

Molecular diagnostics, pre-ALMA

- **Line Ratios**



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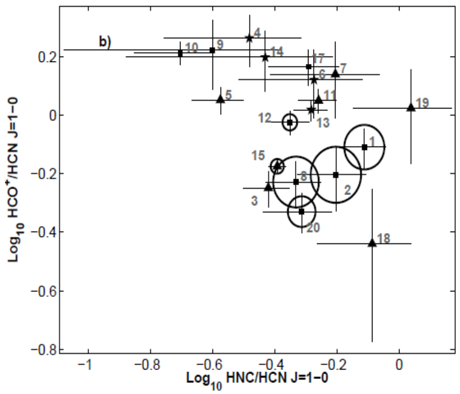


Costagliola et al.,2011

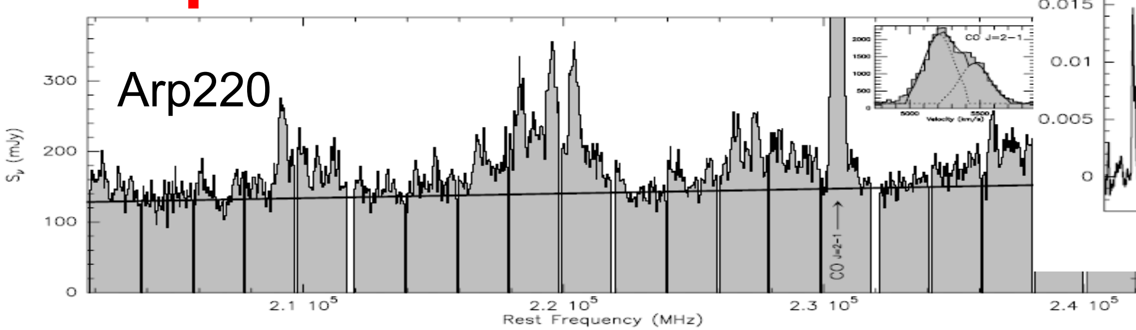
- Quick, large samples
- Only a few species studied, often optically thick
- Excitation effects
- Small variations, large errors
- Ambiguous interpretation with chemical models

Molecular diagnostics, pre-ALMA

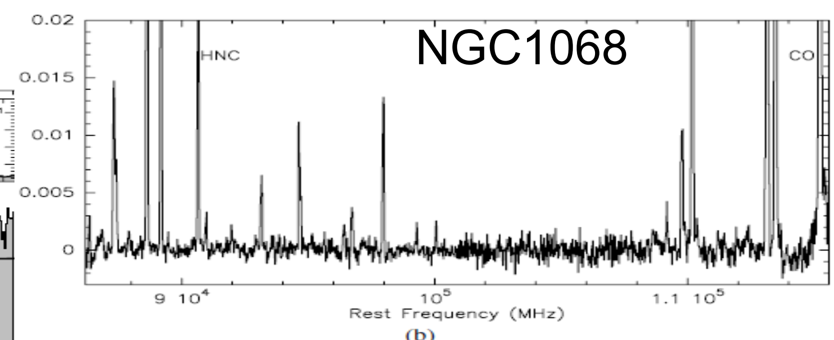
- More species
- Time consuming
- Mostly single band
- Limited information on molecular excitation

Multi-band spectral scans needed to get the excitation!

- **Spectral Scans**



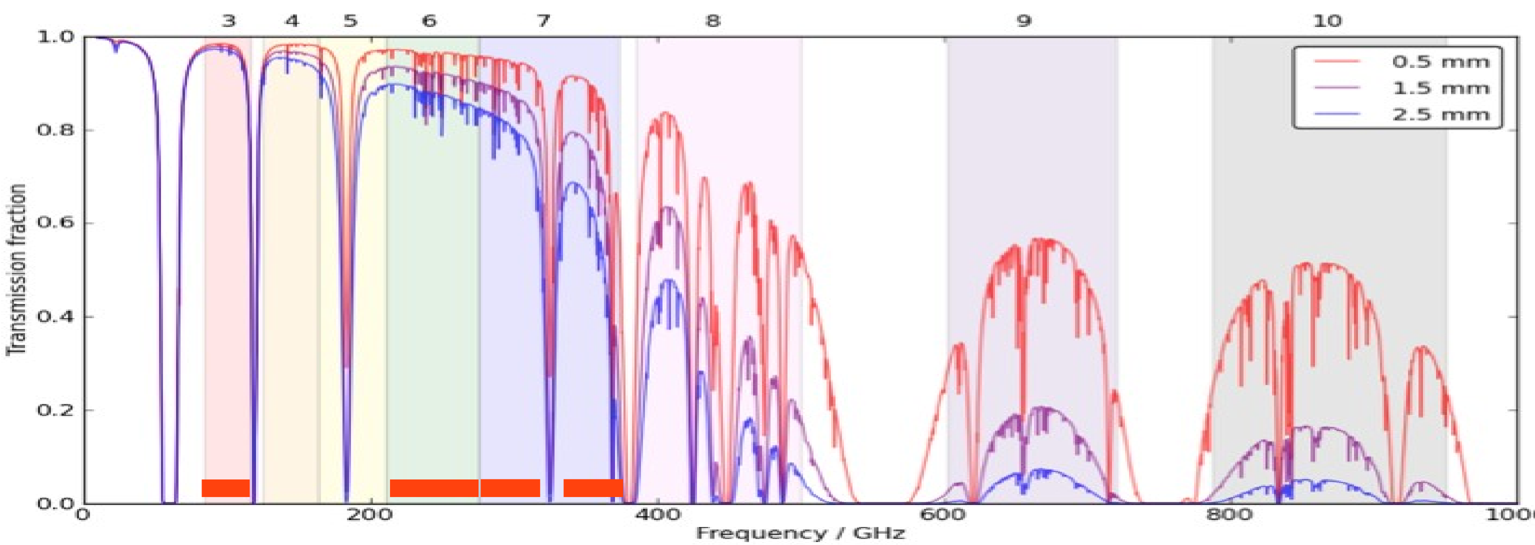
Martin et al. 2011



Aladro et al. 2013

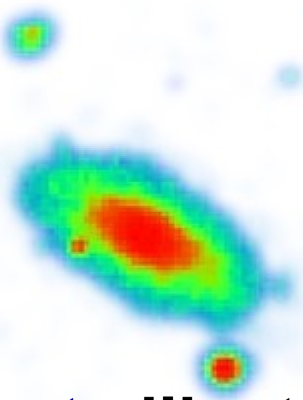
ALMA Cycle 0
A 175 GHz-wide scan of NGC 4418

F. Costagliola, K. Sakamoto, S. Aalto, S. Muller, S. Martin, A. Evans, M. Spaans, S. Garcia-Burillo, S. Mühle, P. van der Werf,

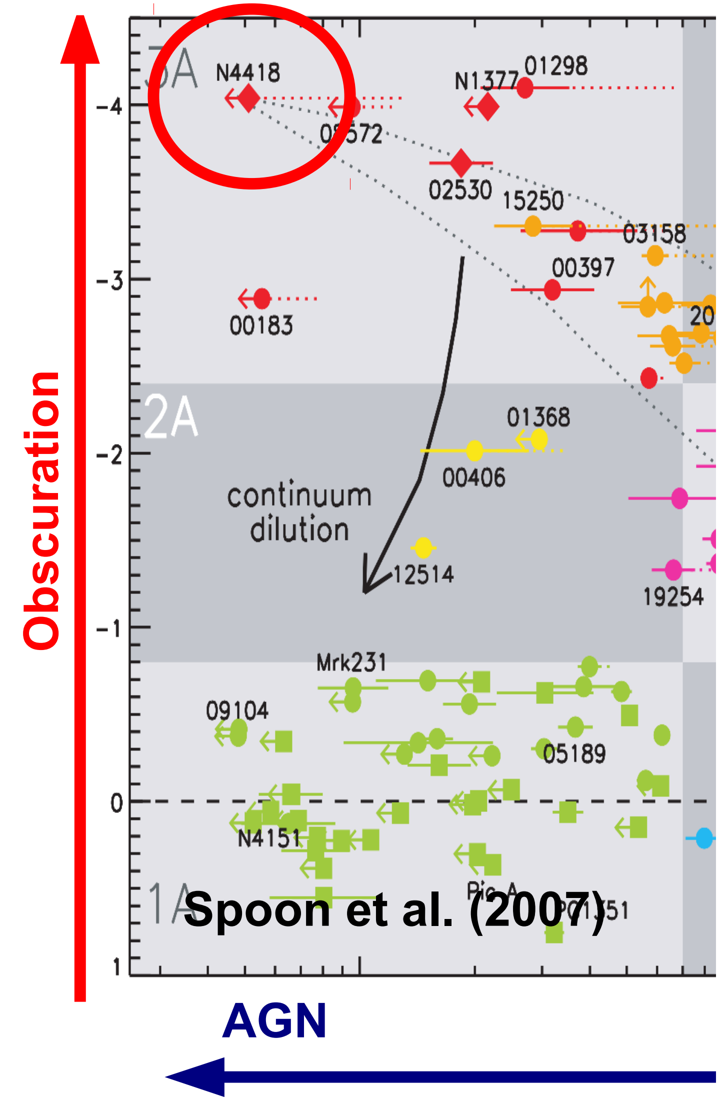


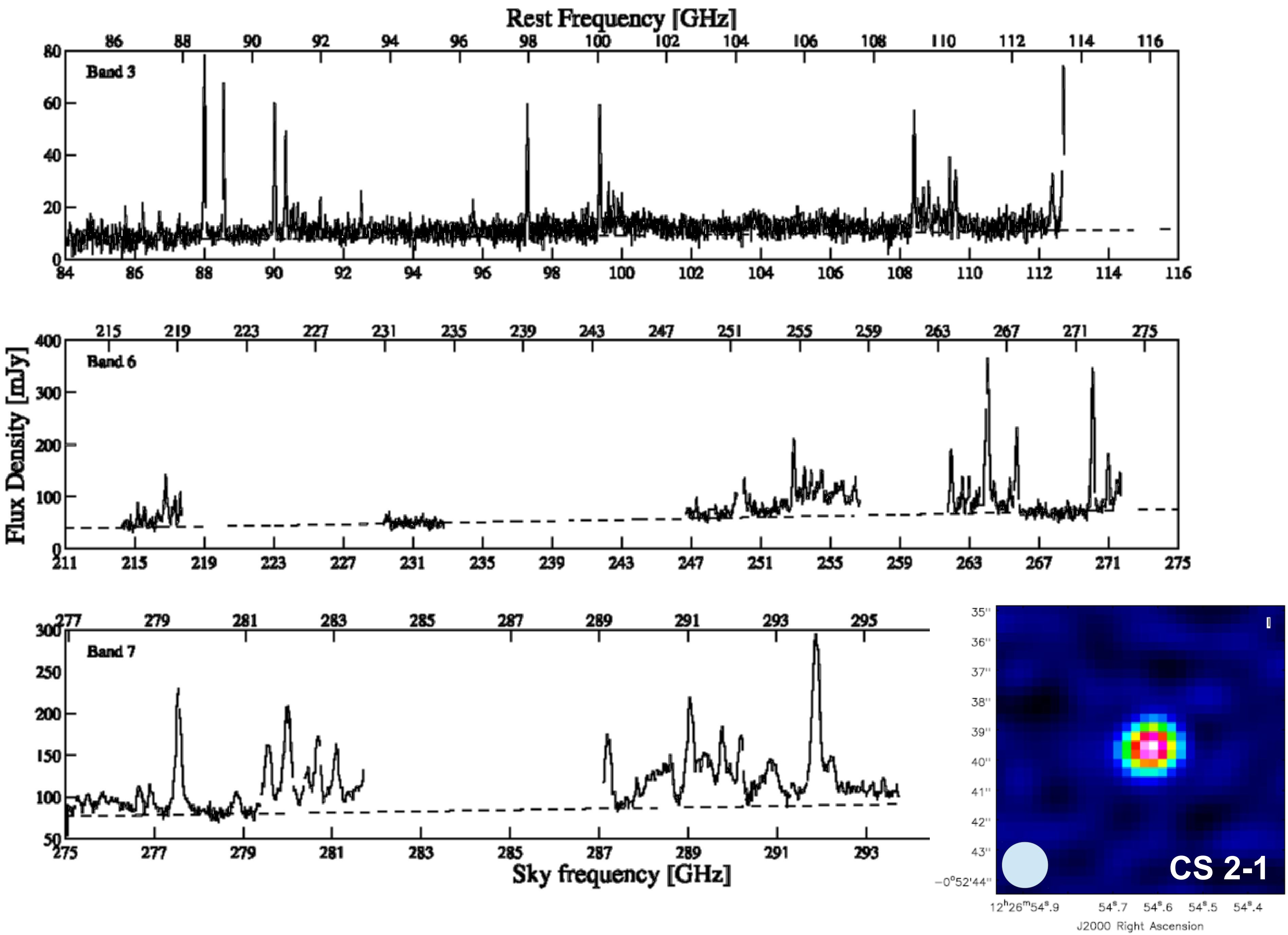
- **Obtain a template chemistry and molecular excitation for LIRGs near and far**
- **Derive accurate abundance estimates**
- **Look for more sensitive tracers of the ISM conditions**

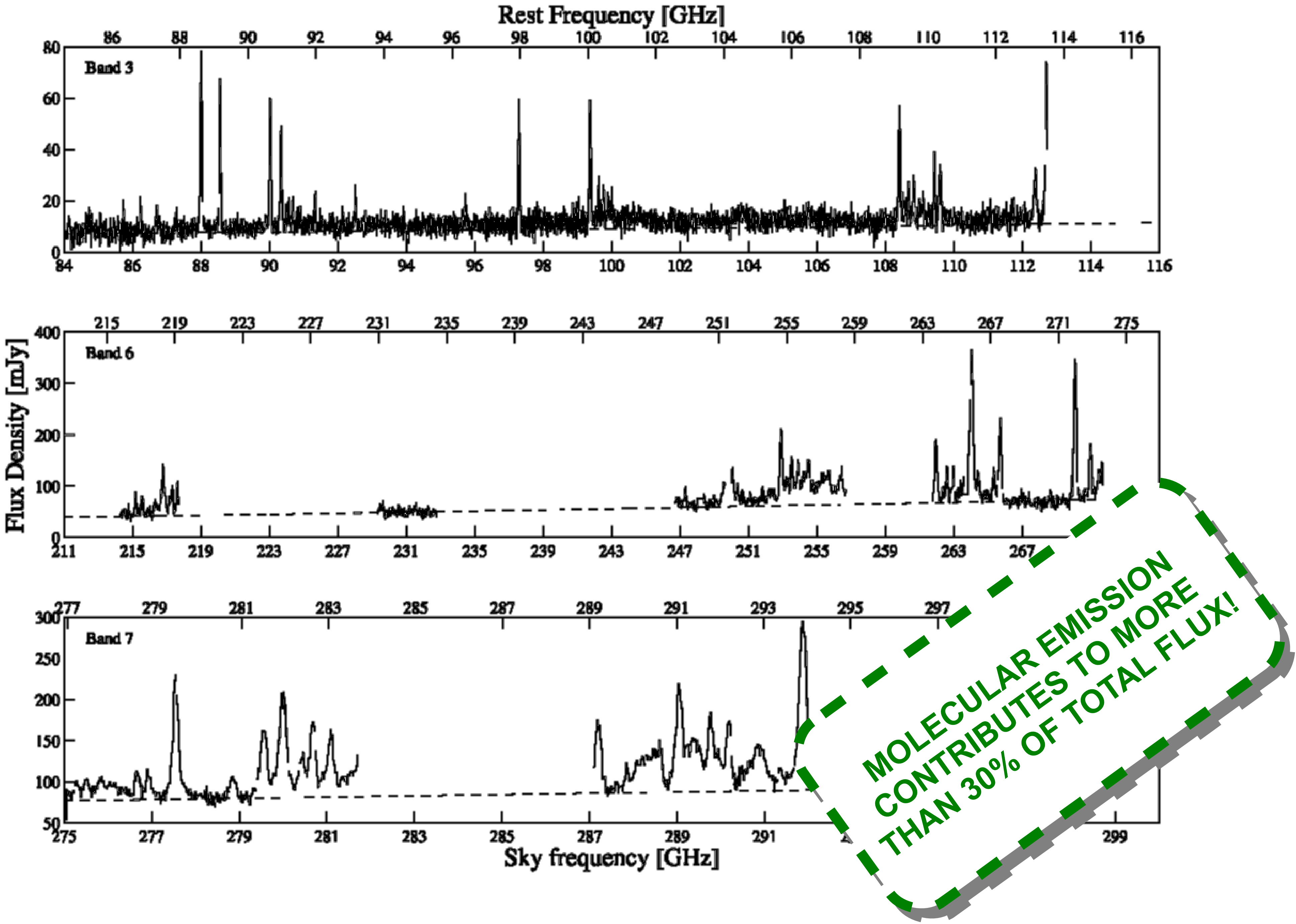
NGC 4418: The prototypical obscured LIRG



- $L_{IR}=10^{11}L_{\odot}$
- SFR 10 $M_{\odot}$/yr
- LIRG with **highest** silicate absorption
- Hidden **compact IR core (<20 pc)**
- Radio-deficient (**<5 Myr starburst?**)
- **Narrow** molecular lines (100 km/s)

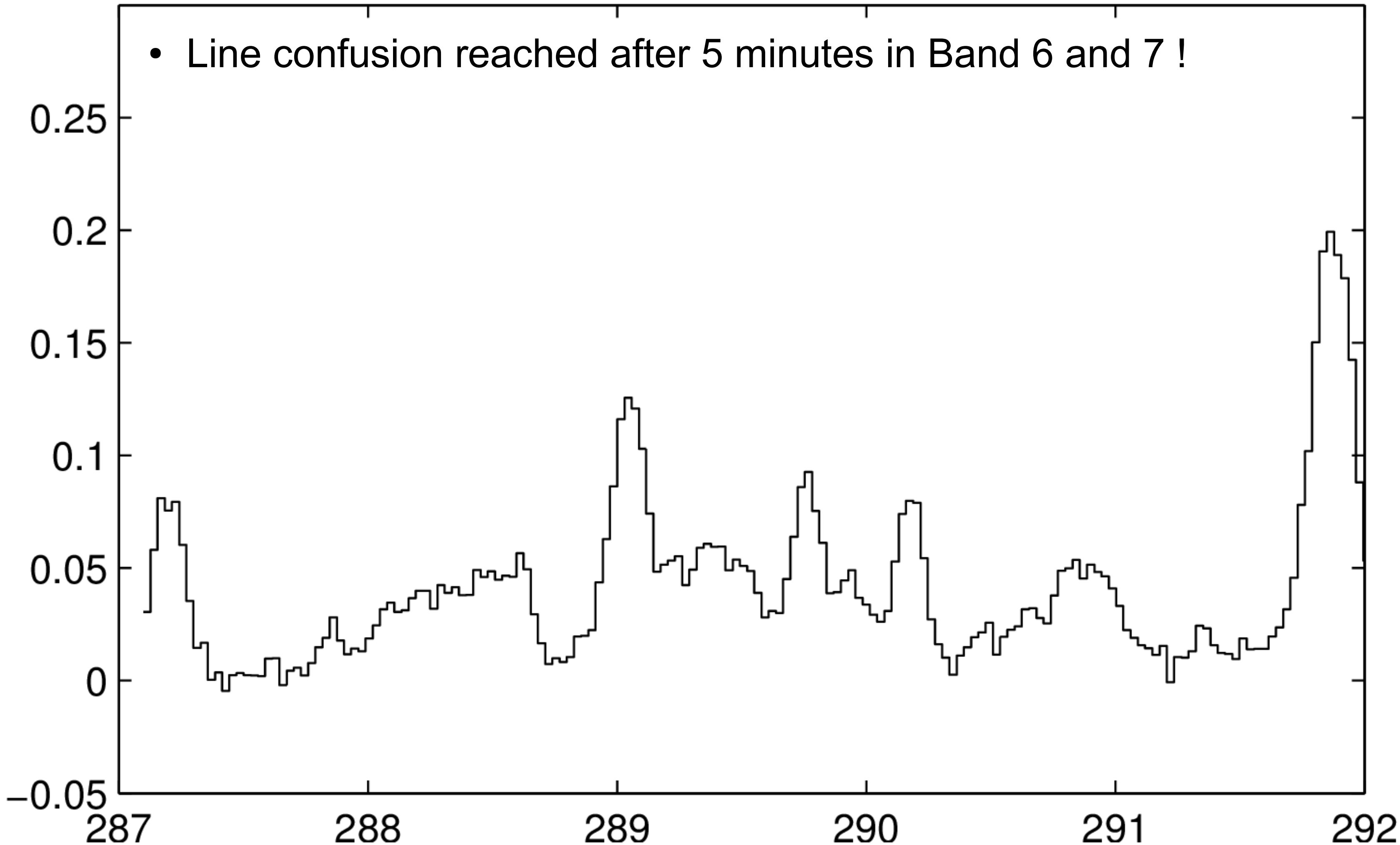



Rest Frequency [GHz]
Band 3
Band 6
Band 7
Flux Density [mJy]
Sky frequency [GHz]
CS 2-1
J2000 Right Ascension

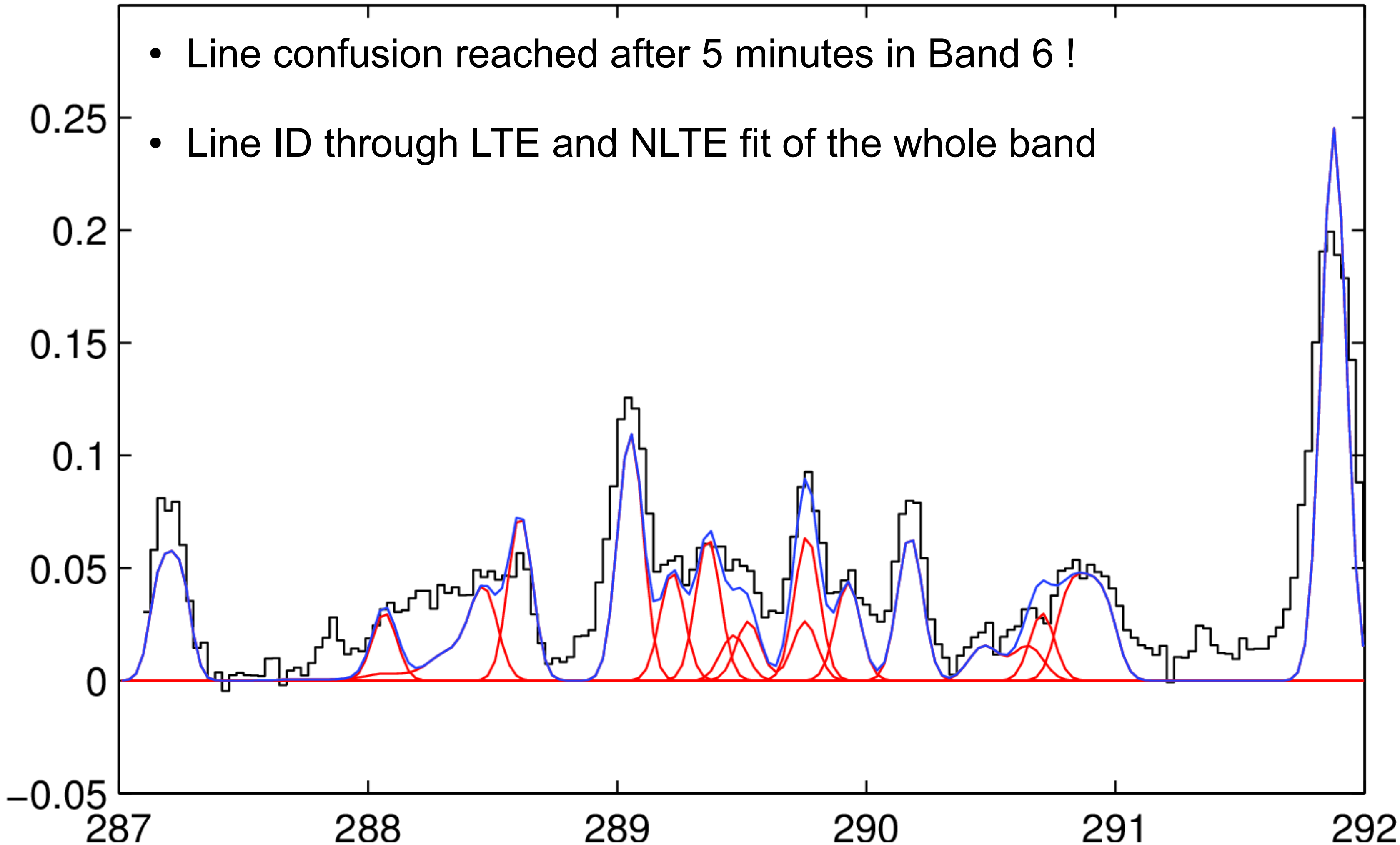

Rest Frequency [GHz]
Band 3
Band 6
Band 7
Flux Density [mJy]
Sky frequency [GHz]
MOLECULAR EMISSION
CONTRIBUTES TO MORE
THAN 30% OF TOTAL FLUX!

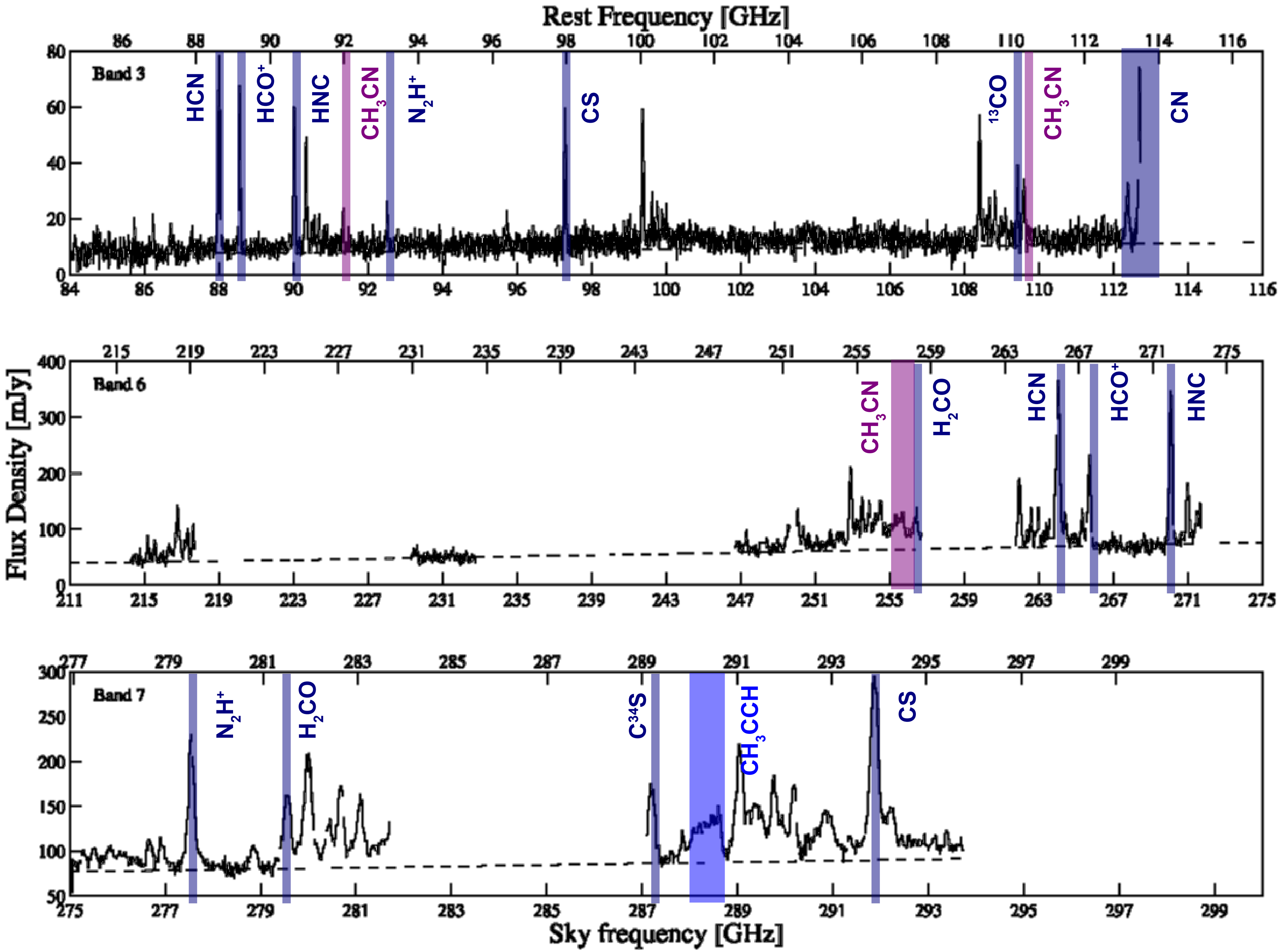
Line identification and fit

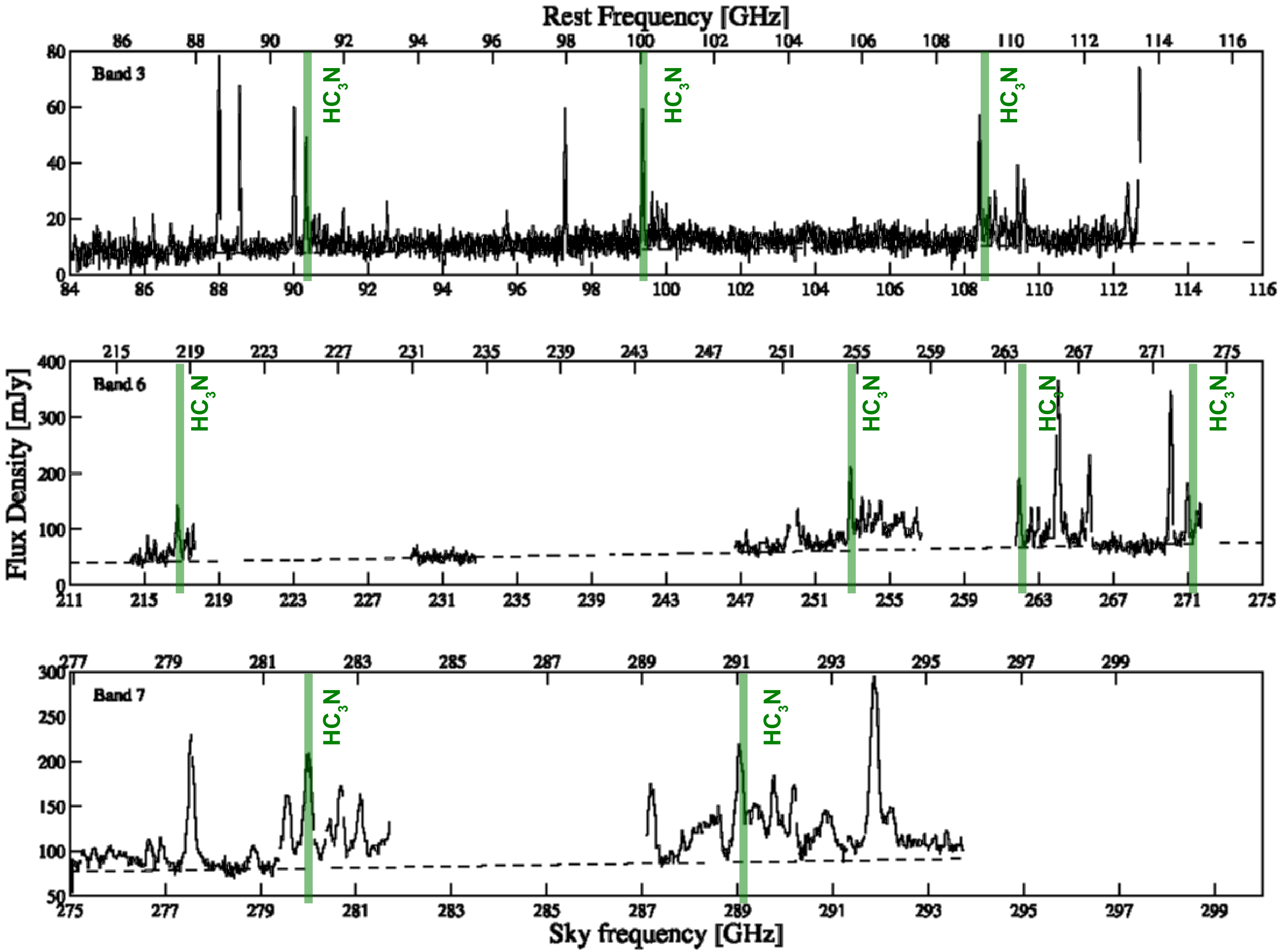
- Line confusion reached after 5 minutes in Band 6 and 7 !

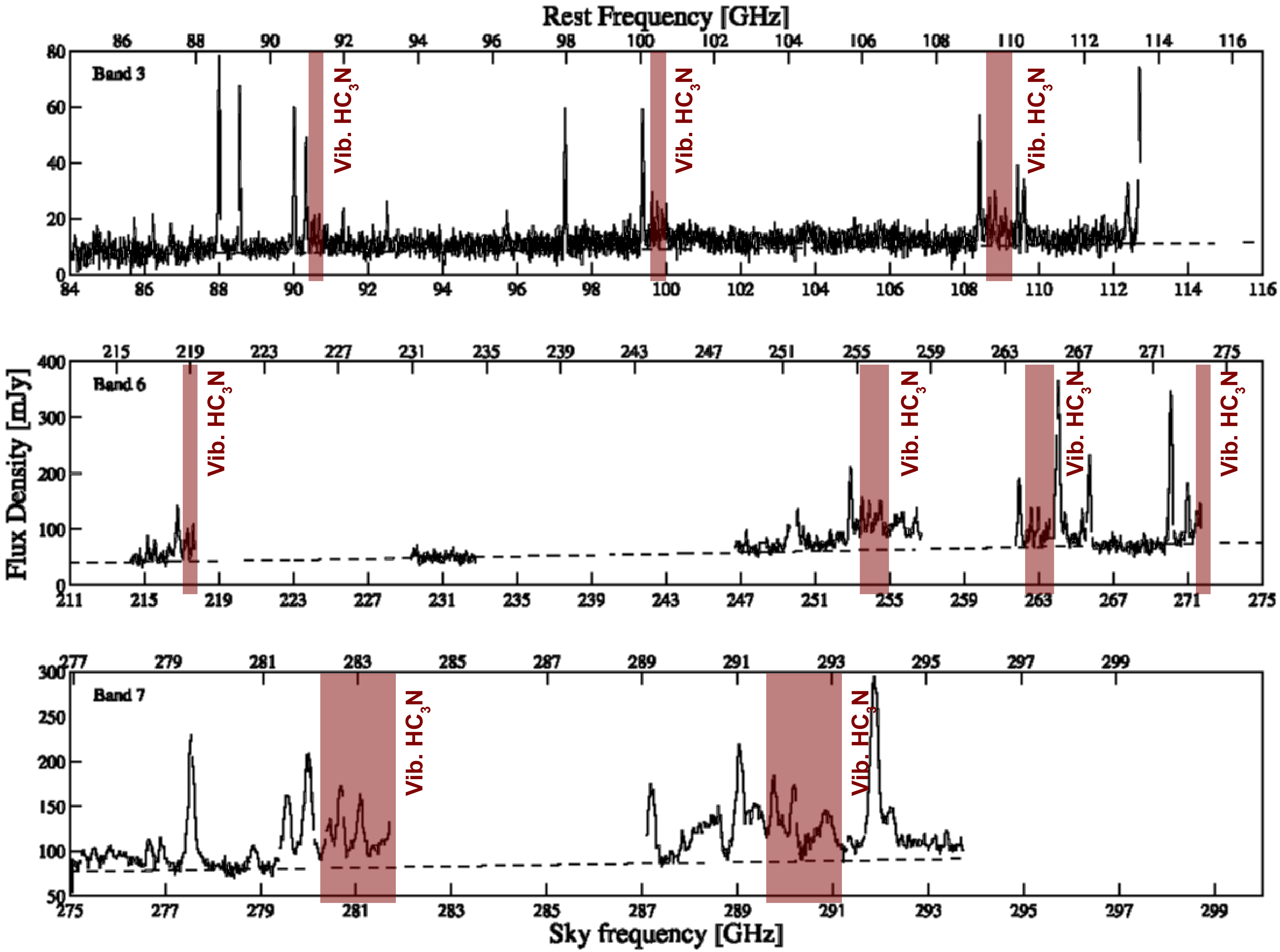


Line identification and fit




Rest Frequency [GHz]
Band 3
HCN
HCO+
HNC
CH3CN
N2H+
CS
13CO
CH3CN
CN
Band 6
CH3CN
H2CO
HCN
HCO+
HNC
Flux Density [mJy]
Band 7
N2H+
H2CO
C34S
CH3CCH
CS
Sky frequency [GHz]


Rest Frequency [GHz]
Band 3
Band 6
Band 7
HC3N
Flux Density [mJy]
Sky frequency [GHz]


Rest Frequency [GHz]
Band 3
Band 6
Band 7
Vib. HC_3N
Flux Density [mJy]
Sky frequency [GHz]

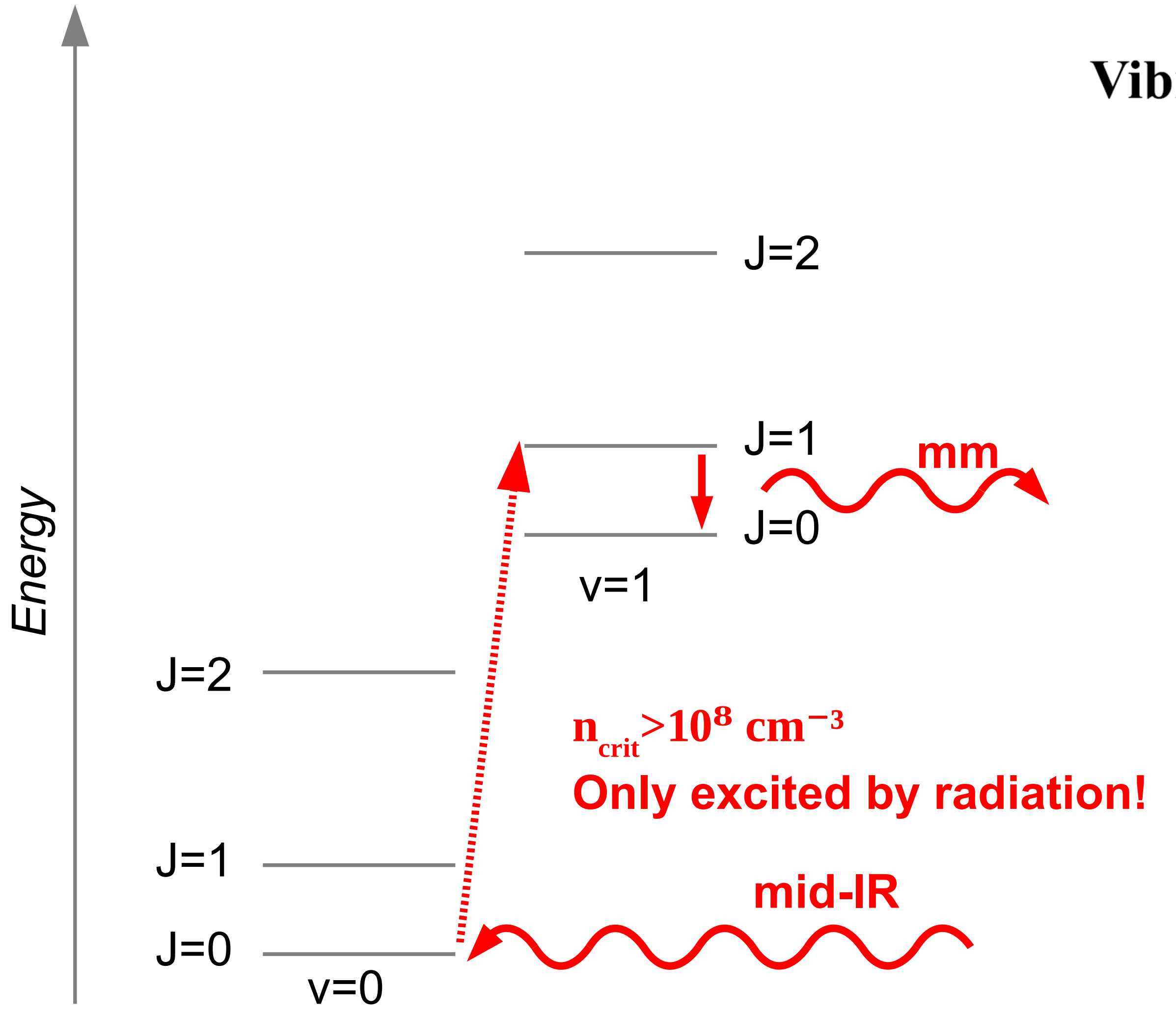
Detected Molecules

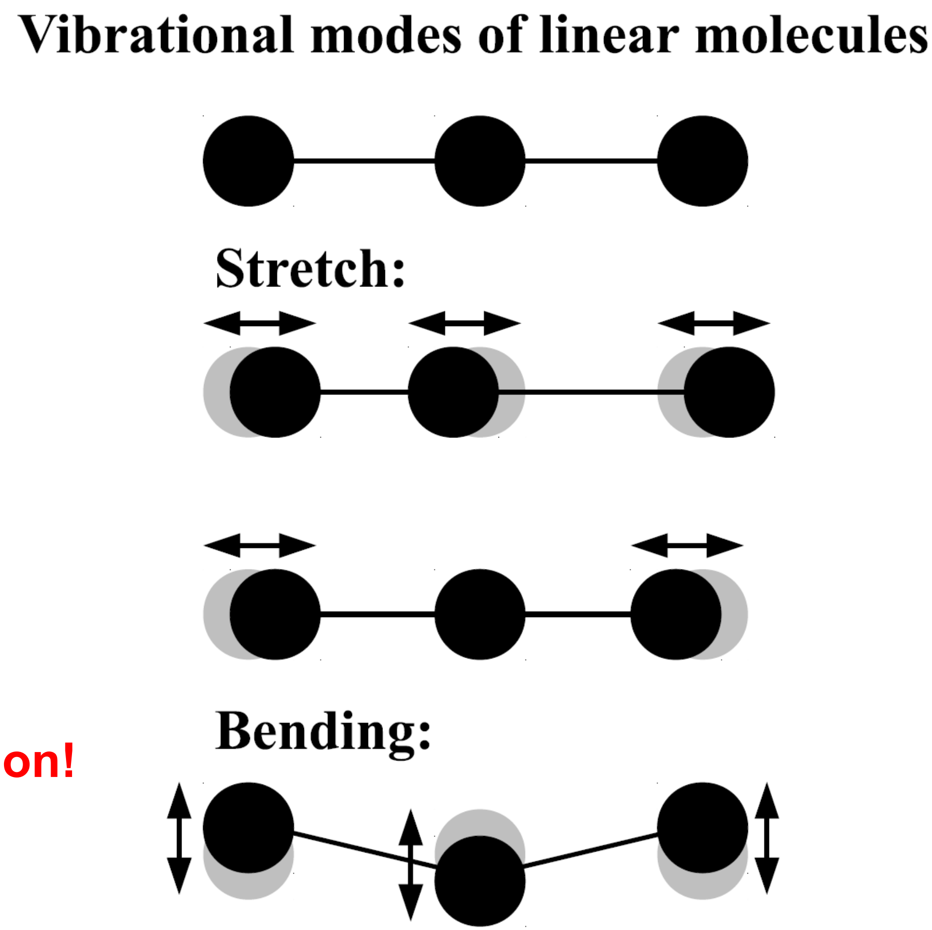
Summary of detected molecules

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms
CS	HCN	p-H_2CO	HC_3N	CH_3CN	CH_3CCH
^{13}CS	$H^{13}CN$	o-H_2CO	$HCC^{13}CN$	CH_3OH	*HC_5N*
$C^{33}S$	HCN,v2=1	c-HCCCH	HC_3N,v6=1		
$C^{34}S$	HNC	H_2CS	HC_3N,v7=1		
^{13}CO	$HN^{13}C$		HC_3N,v6=1,v7=1		
$C^{18}O$	HNC,v2=1		HC_3N,v7=2		
CN	HCO^+		CH_2NH		
NS	$H^{13}CO^+$		NH_2CN		
SO	H_2S				
SiO	CCH				
^{29}SiO	HCS^+				
^{30}SiO	CCS				
	N_2H^+				

Detected **40 Molecules** **and** **295 lines > 3-sigma**
4X what we expected in the proposal

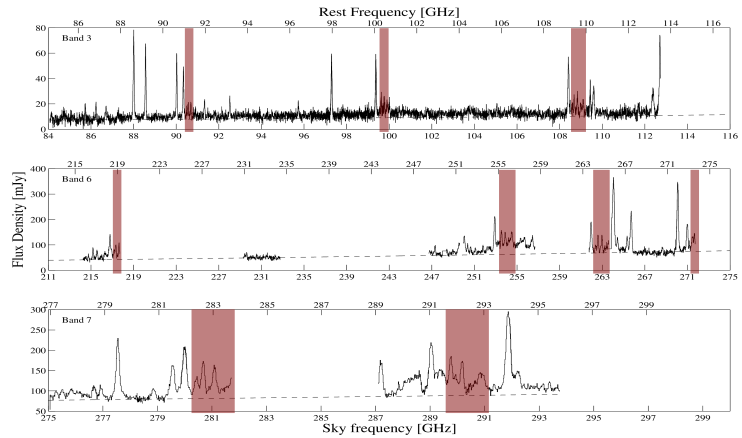
Vibrationally Excited Lines:

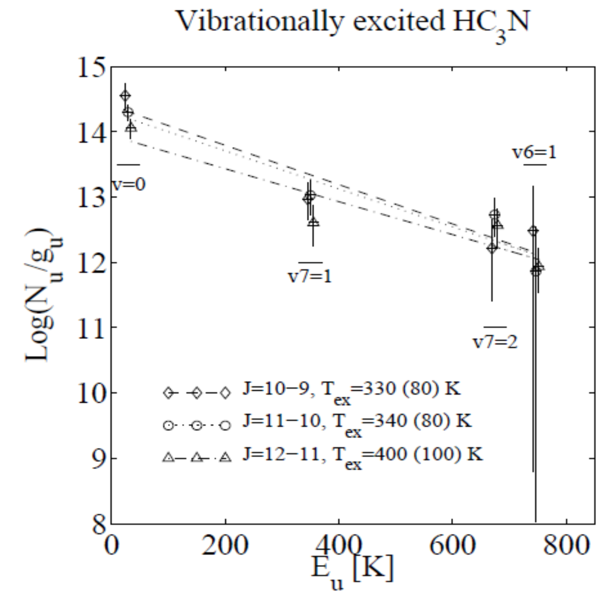


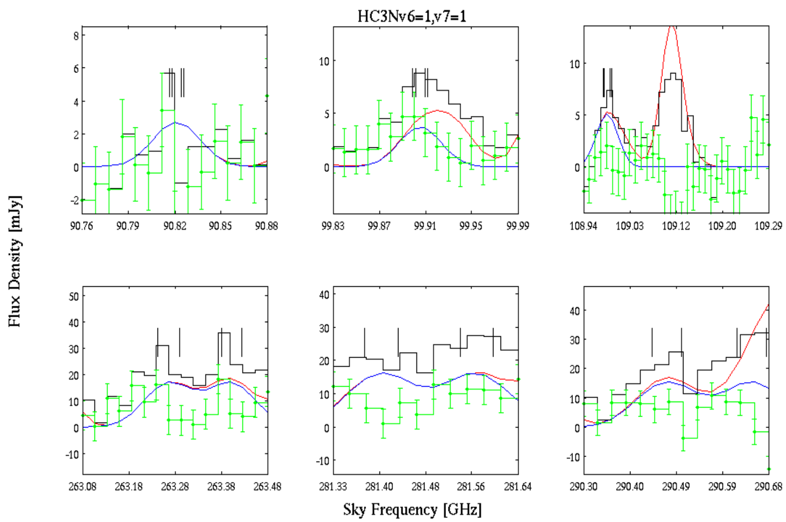


Vibrationally excited HC_3N

- HC_3N v7=1
- HC_3N v7=2
- HC_3N v6=1
- HC_3N v6=1, v7=1 (Eu>900 K!)
- Tvib=300-400 K
- Hot, compact IR

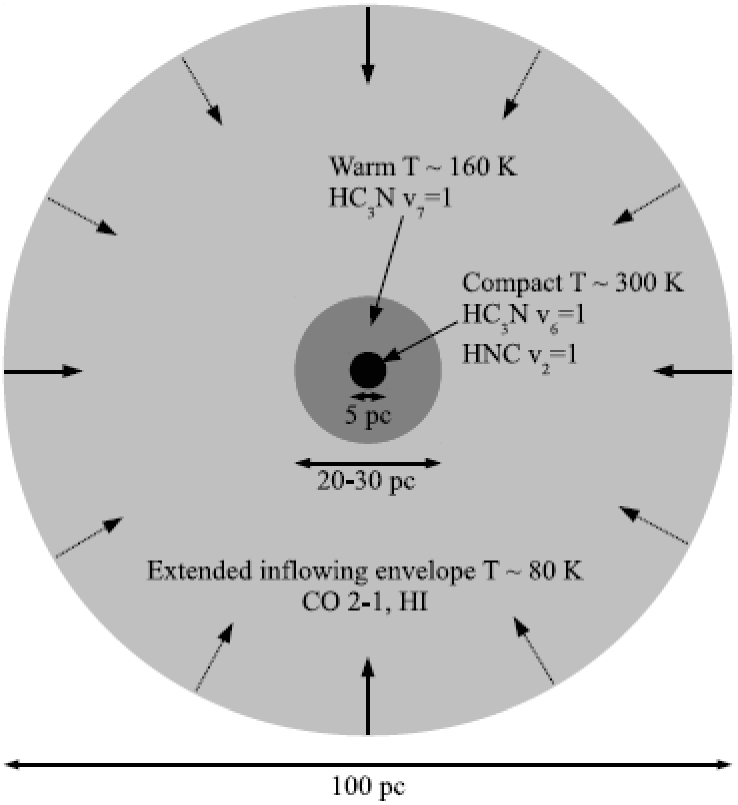






Excitation fit results

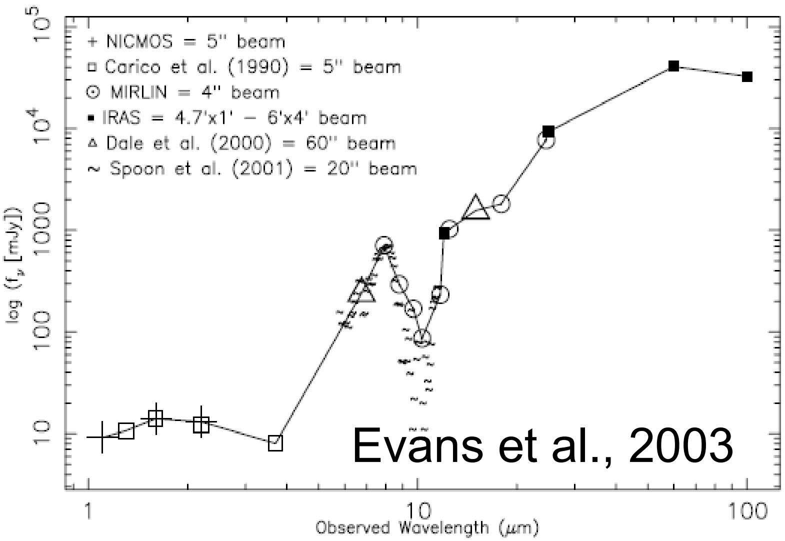
- Rotational temperatures: 20-350 K
- H_2 Densities: 10^4-10^7 cm^{-3}
- Steep density and temperature gradient
- Compact IR source, T>300 K



Costagliola et al., 2013

Vibrationally excited HC_3N, HCN, HNC

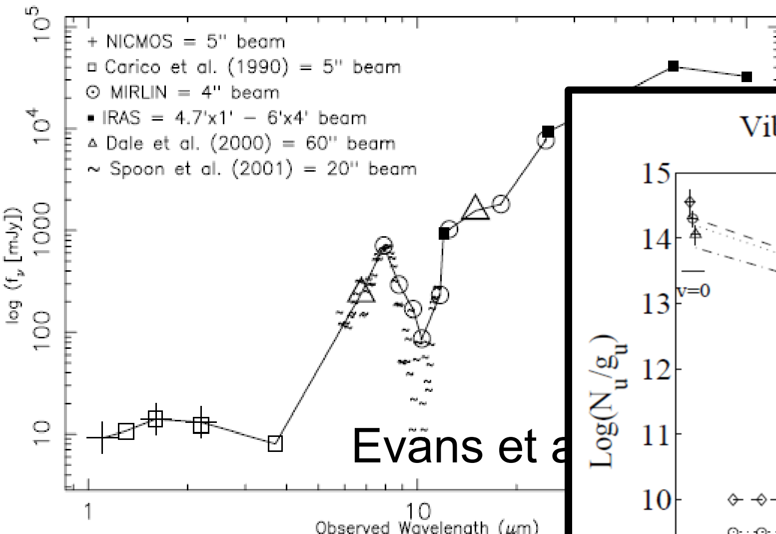
Detecting compact IR sources beyond the telescope's resolution



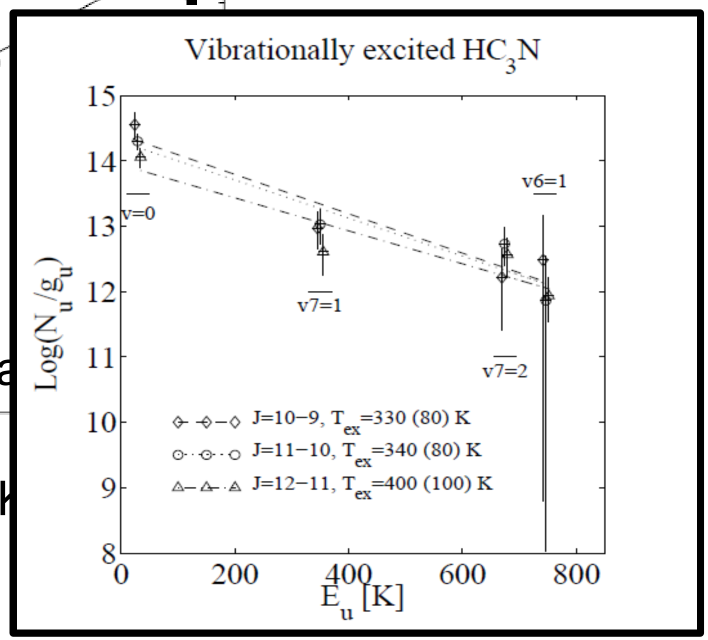
F60/F100 → Tdust=85 K → 70 pc

Vibrationally excited HC_3N, HCN, HNC

Detecting compact IR sources beyond the telescope's resolution



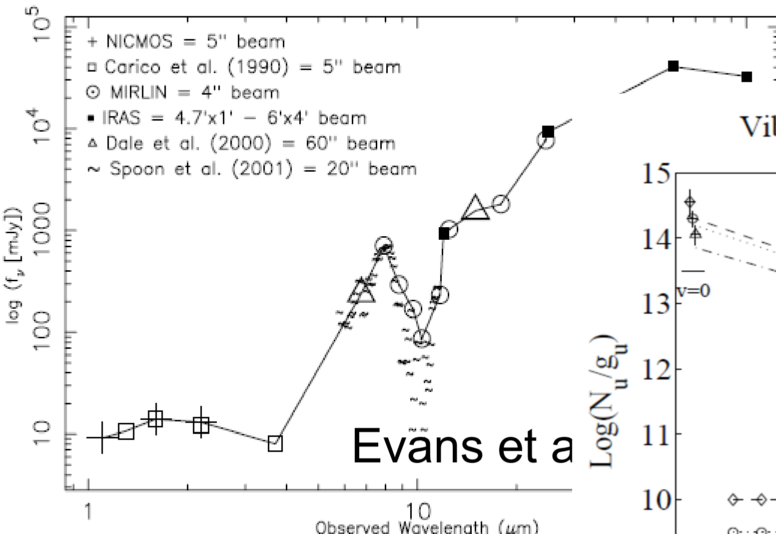
F60/F100 → Tdust=85 K



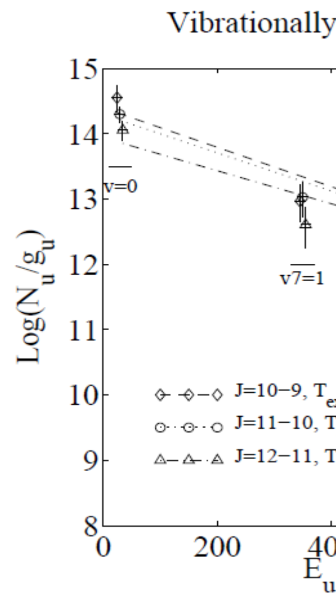
Tvib=300-400 K → IR < 5 pc !

Vibrationally excited HC_3N, HCN, HNC

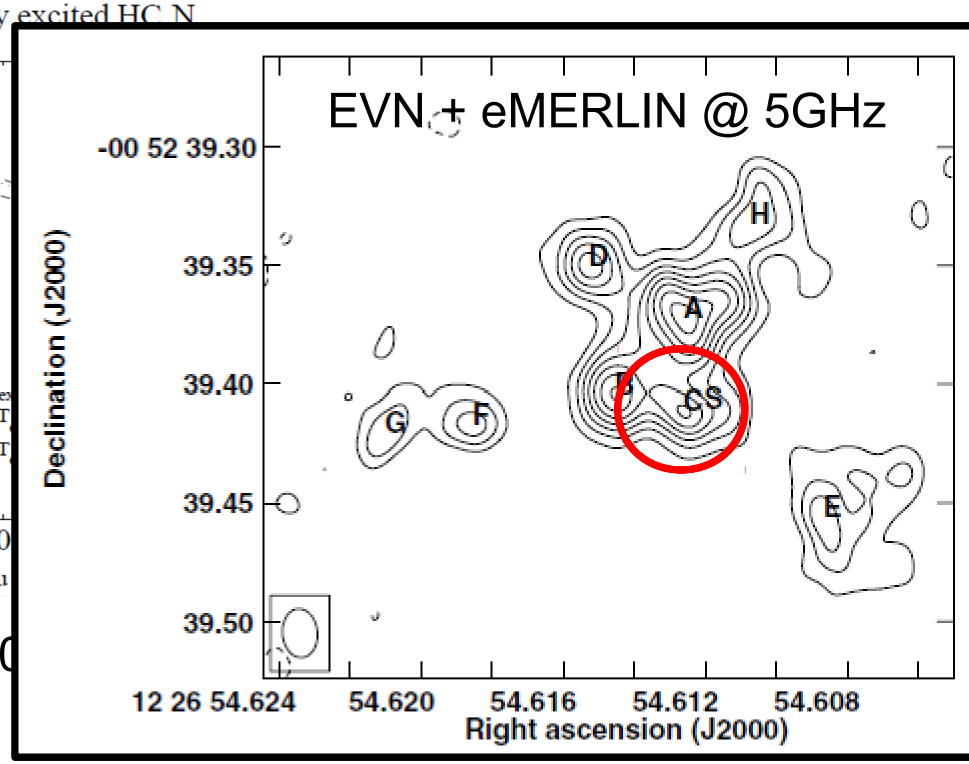
Detecting compact IR sources beyond the telescope's resolution



F60/F100 → Tdust=85 K

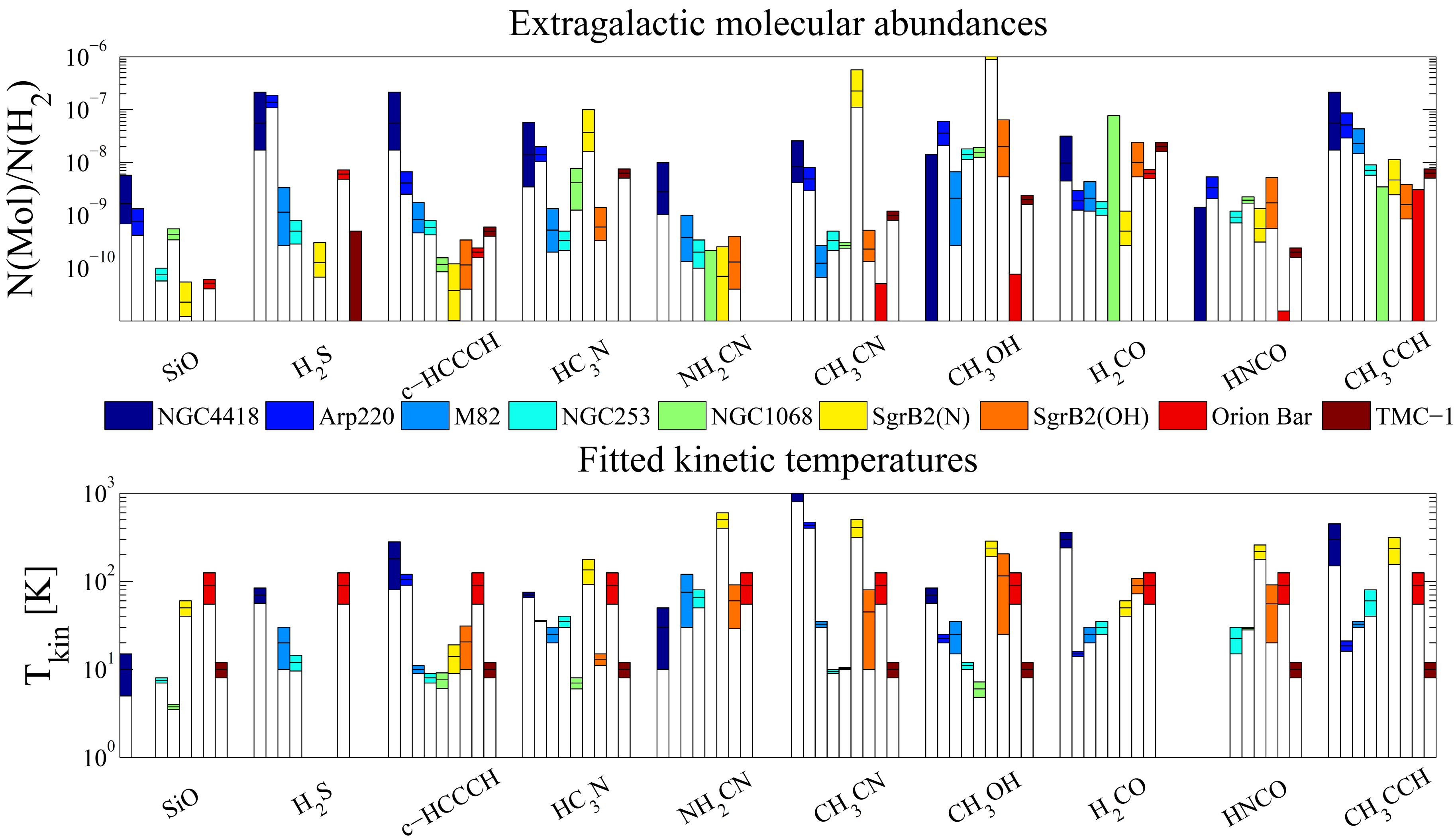


Tvib=300-400

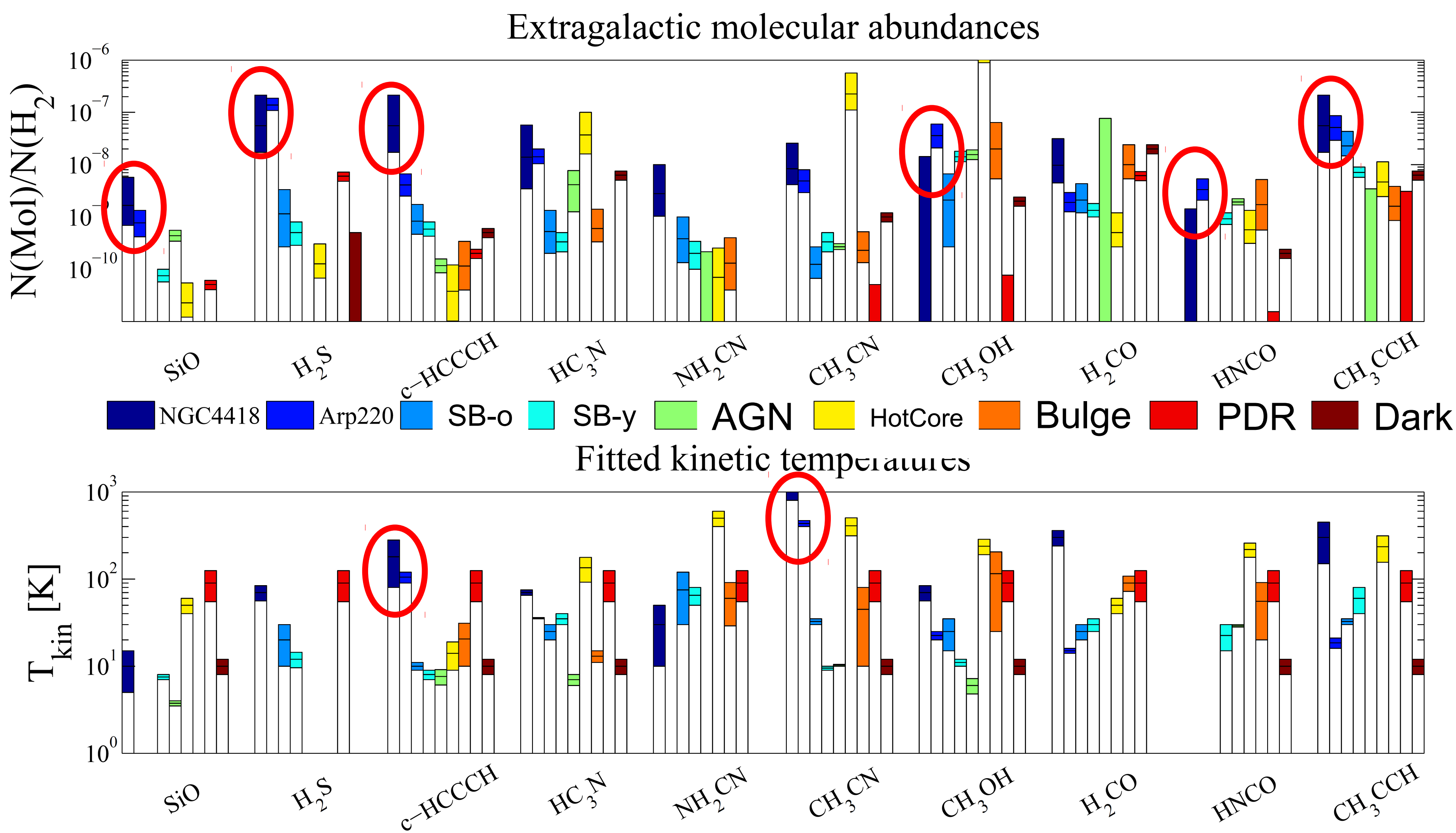


5 pc compact source detected with EVN!

Molecular Abundances

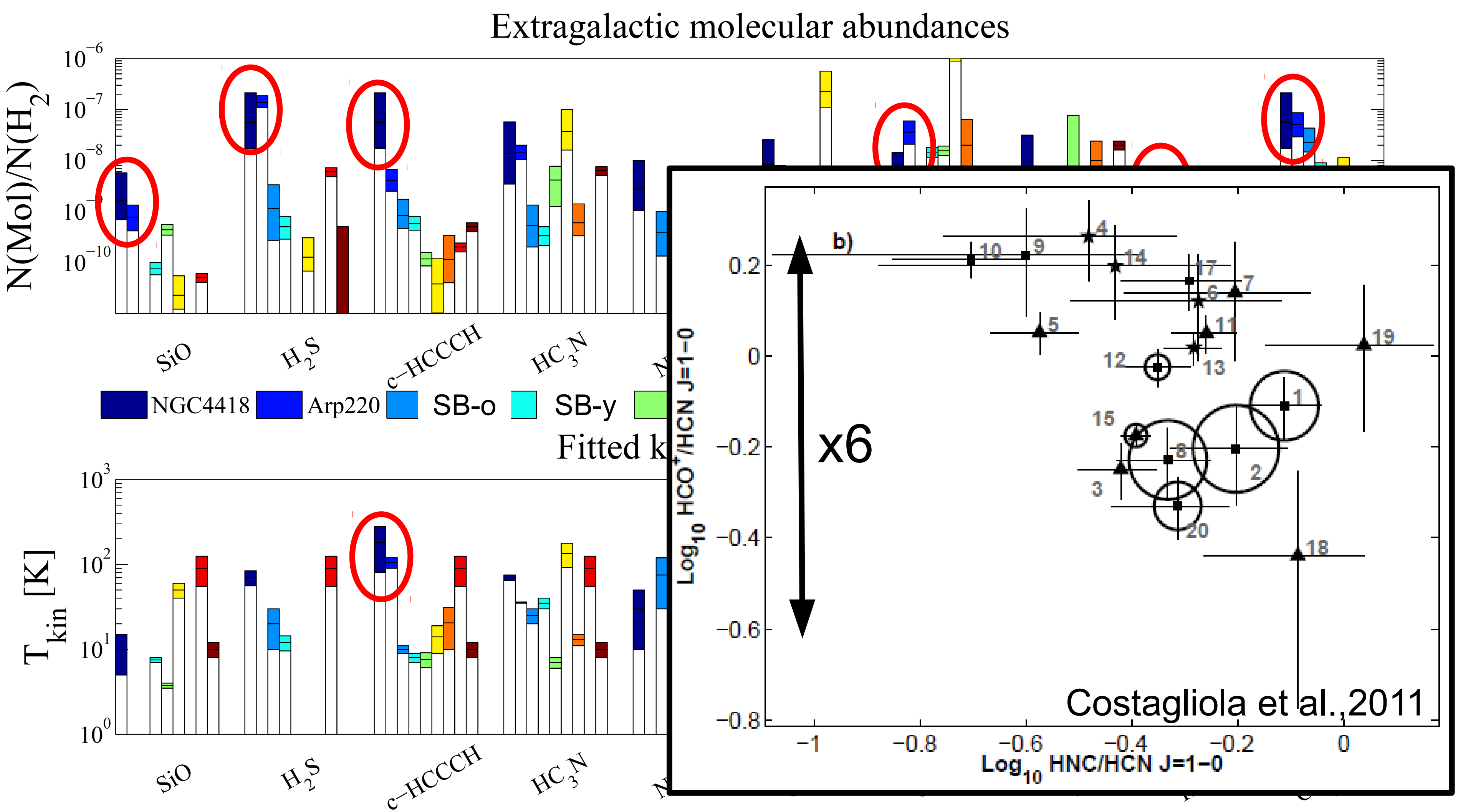


Molecular Abundances



NGC4418 (LIRG) and Arp 220 (ULIRG) show similar chemistry, a new CON chemistry ?

Molecular Abundances



Order of magnitude differences in abundance Vs Factors of a few in line ratios !

The NGC4418 scan, a summary:

- In less than 3 hours we covered 71 GHz in Bands 3, 6, 7
- We detect >200 lines from 40 molecular species
- LTE and NLTE analysis confirms the layered structure of the core
- Bright vibrationally excited HC_3N, HNC, HCN

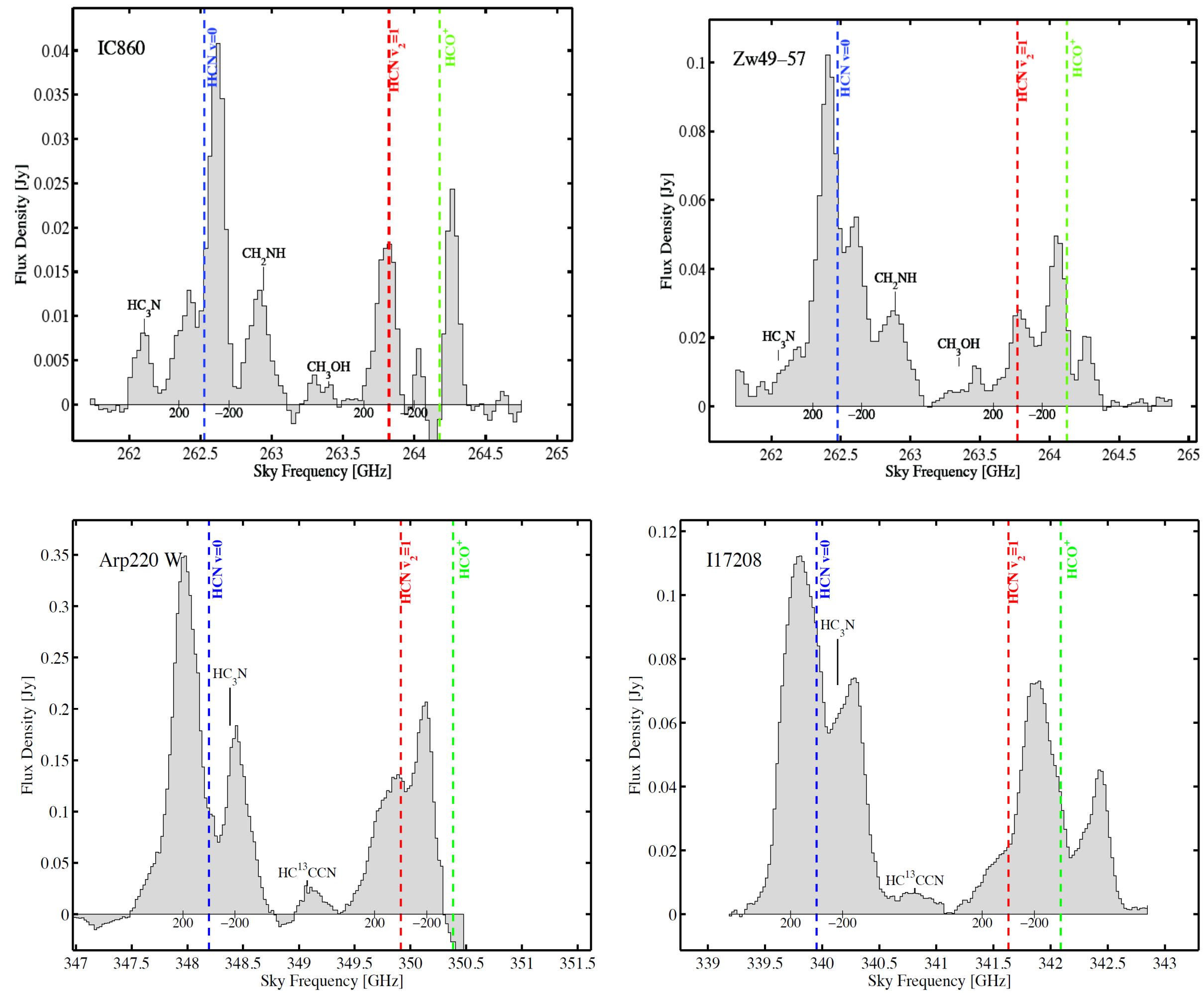
  → Compact IR
- Abundances and temperatures similar to Arp 220
- Compact LIRGs show distinctive chemical signatures

Self-absorbed line profiles in CONs

Steep temperature gradients create self-absorbed HCN and HCO+ lines and bright vibrationally-excited HCN v2=1

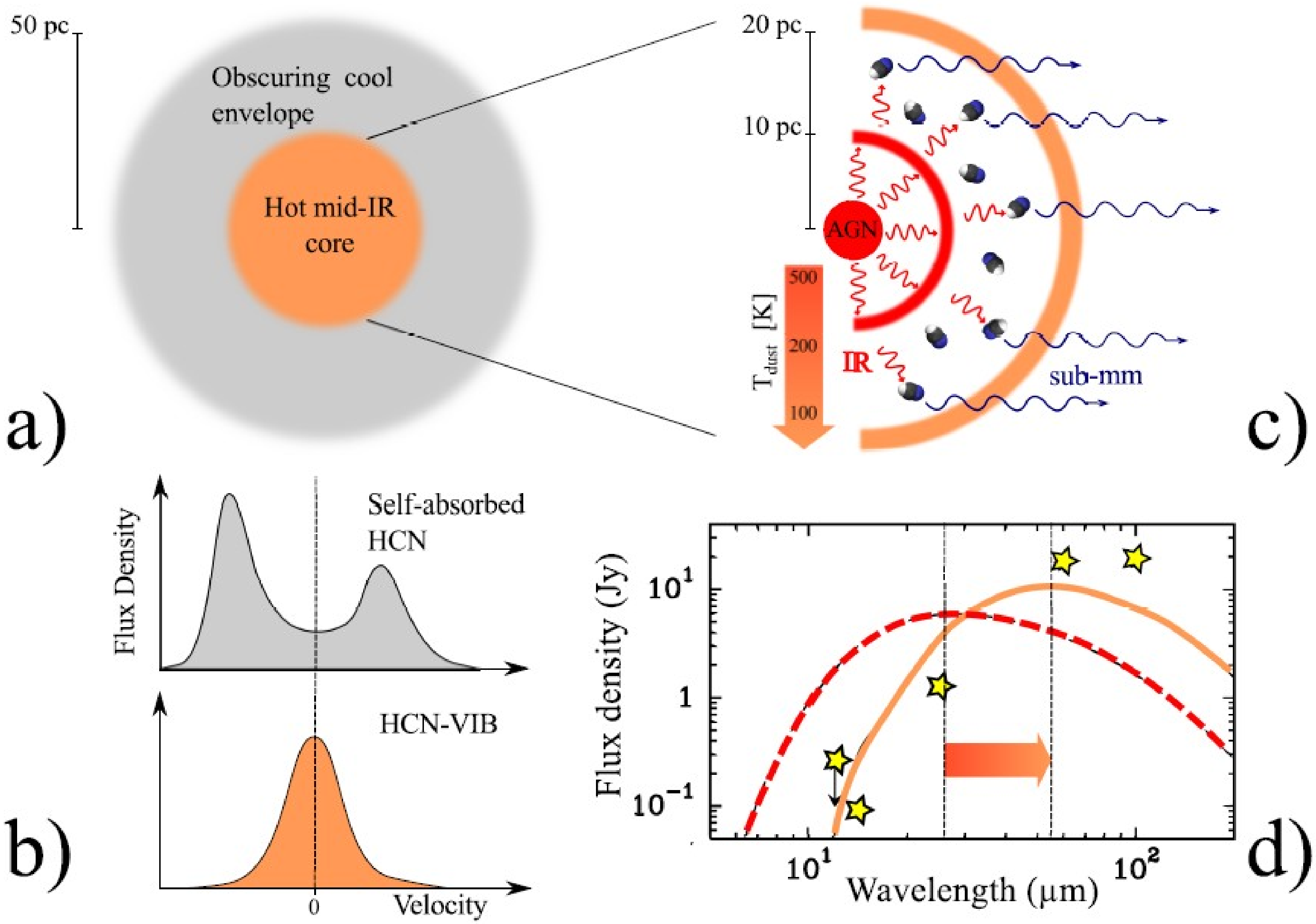
This happens both in LIRGS and ULIRGS

Observed with PdBI (top) and ALMA Cycle 1 (PI:S. Aalto, S. Martin)



Aalto et al., in prep

Peeking inside the core



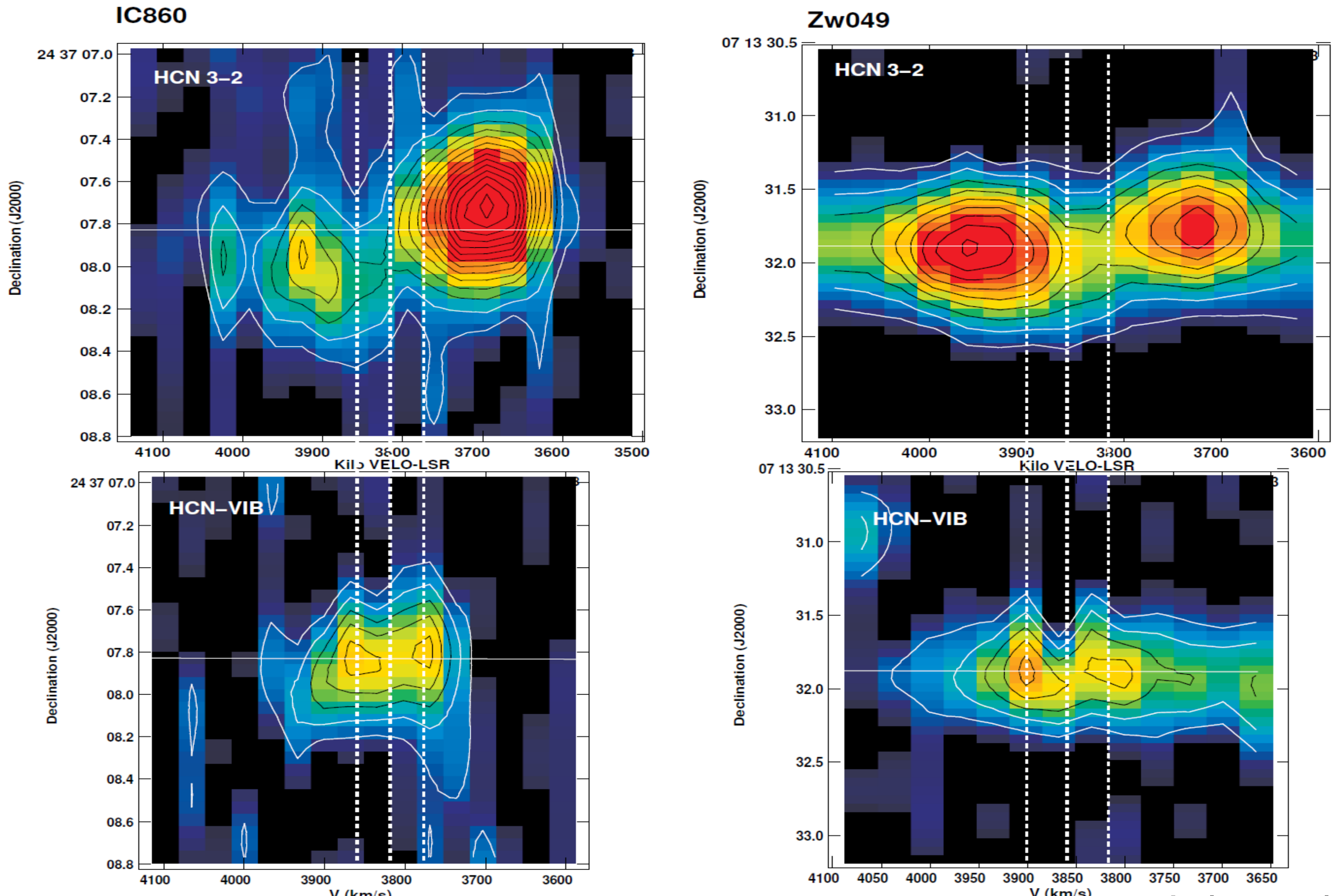
VIB-HCN emerging from buried core *inside HCN-HCO⁺ self-absoprtion.*

VIB-HCN pumped by intense 14 μm emission
Possibly also by NIR emission
VIB-HCN allows us to reconstruct SED and reveal a buried hot dust core – absorbed by cooler dust

Extreme starburst or near-Eddington SMBH ?

Aalto et al., in prep

Tracing the core with vib-lines

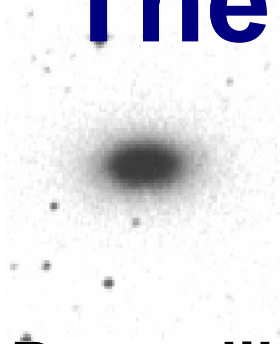


Aalto et al., in prep

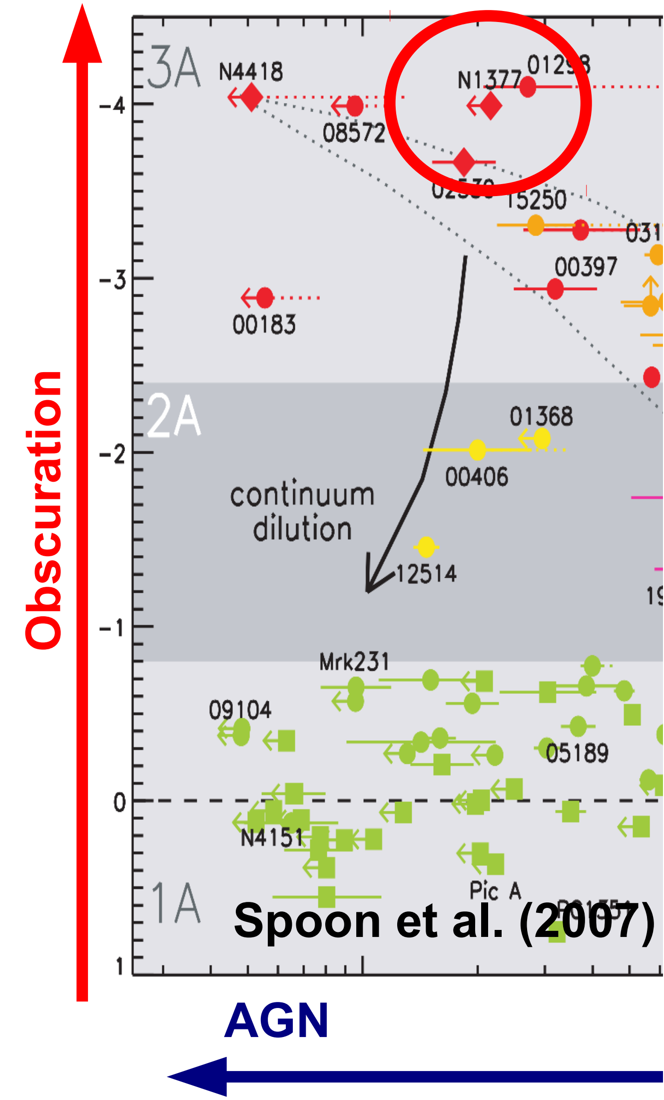
Molecular Outflows

- Molecular outflows from Starburst / AGN galaxies are being routinely detected by interferometers (even at high-z!)
- The properties of the outflow are related to the launching mechanism and to the nature of the central power source
- To derive the mass loss rate is not easy and requires resolved, sensitive observations: ALMA!

The Extreme FIR-Excess Galaxy NGC 1377



- Deep silicate obscuration
- Warm dust (80 K) in a 100 pc core (Spoon, 2001)
- No HI and Hα



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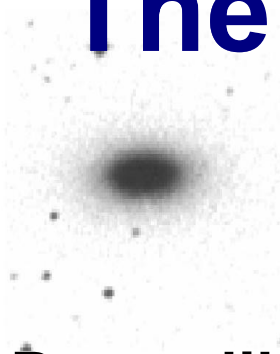
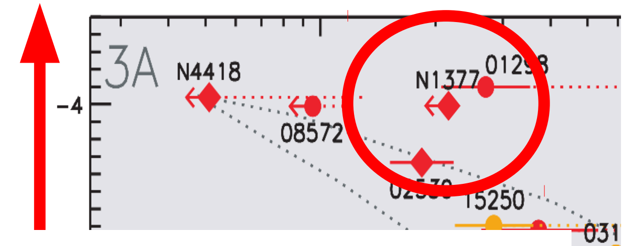
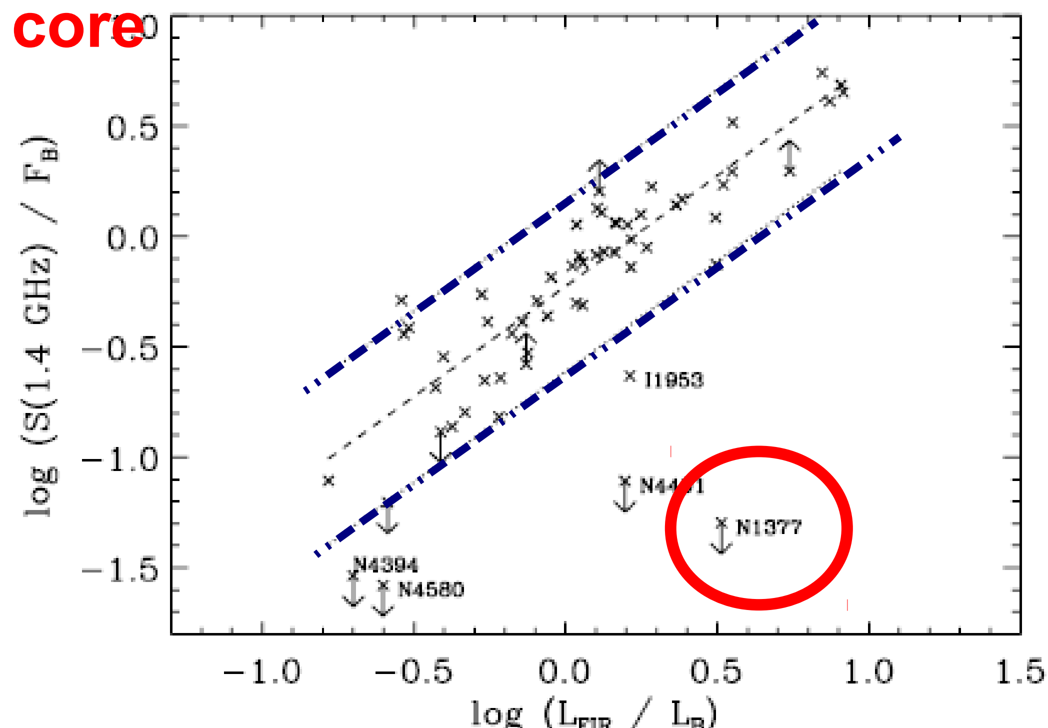


- Deep silicate obscuration
- Warm dust (80 K) in a 100 pc core (Spoon, 2001)
- No Hα
- Radio-deficient (Roussel, 2003)
- No supernovas !
- No HII regions !





Nascent (<1 Myr) starburst or obscured AGN?

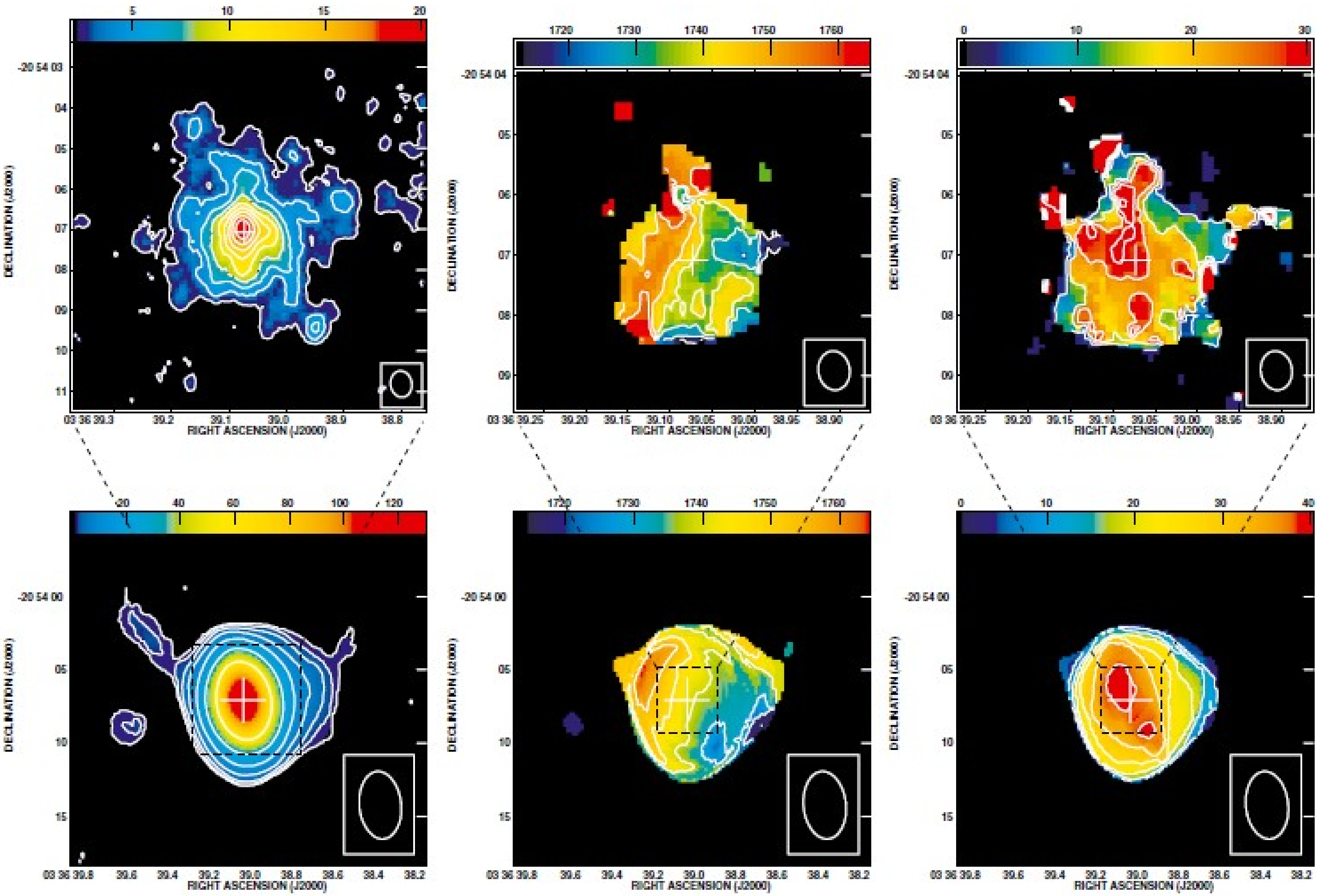
A Molecular outflow: SMA

CO 2-1 emission with the SMA in Extended and Compact configuration (Aalto et al. 2012)

Moment 0 | Moment 1 | Moment 2

Extended (0."65)

Compact (4 ")



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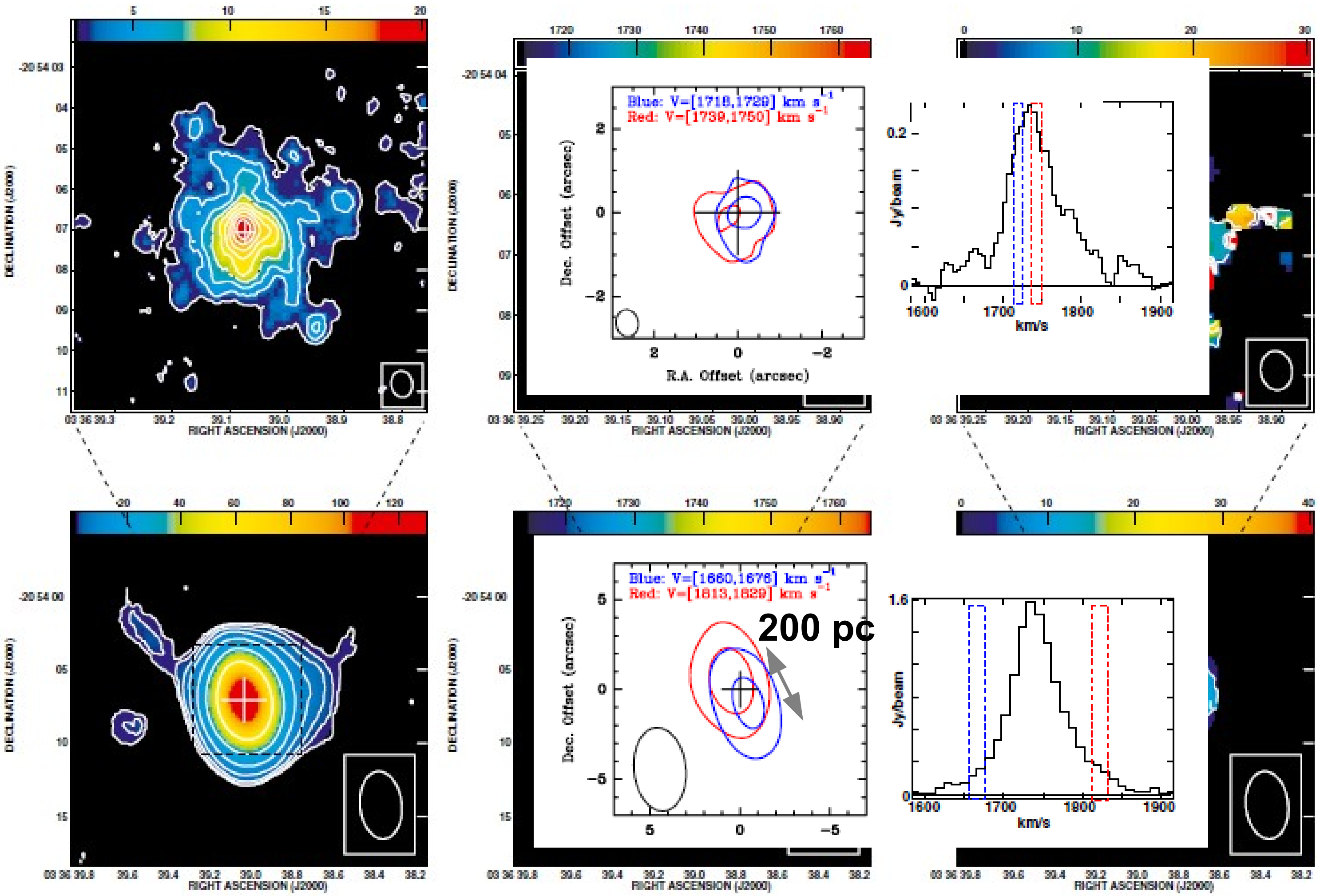
Extended (0."65)

Compact (4 ")



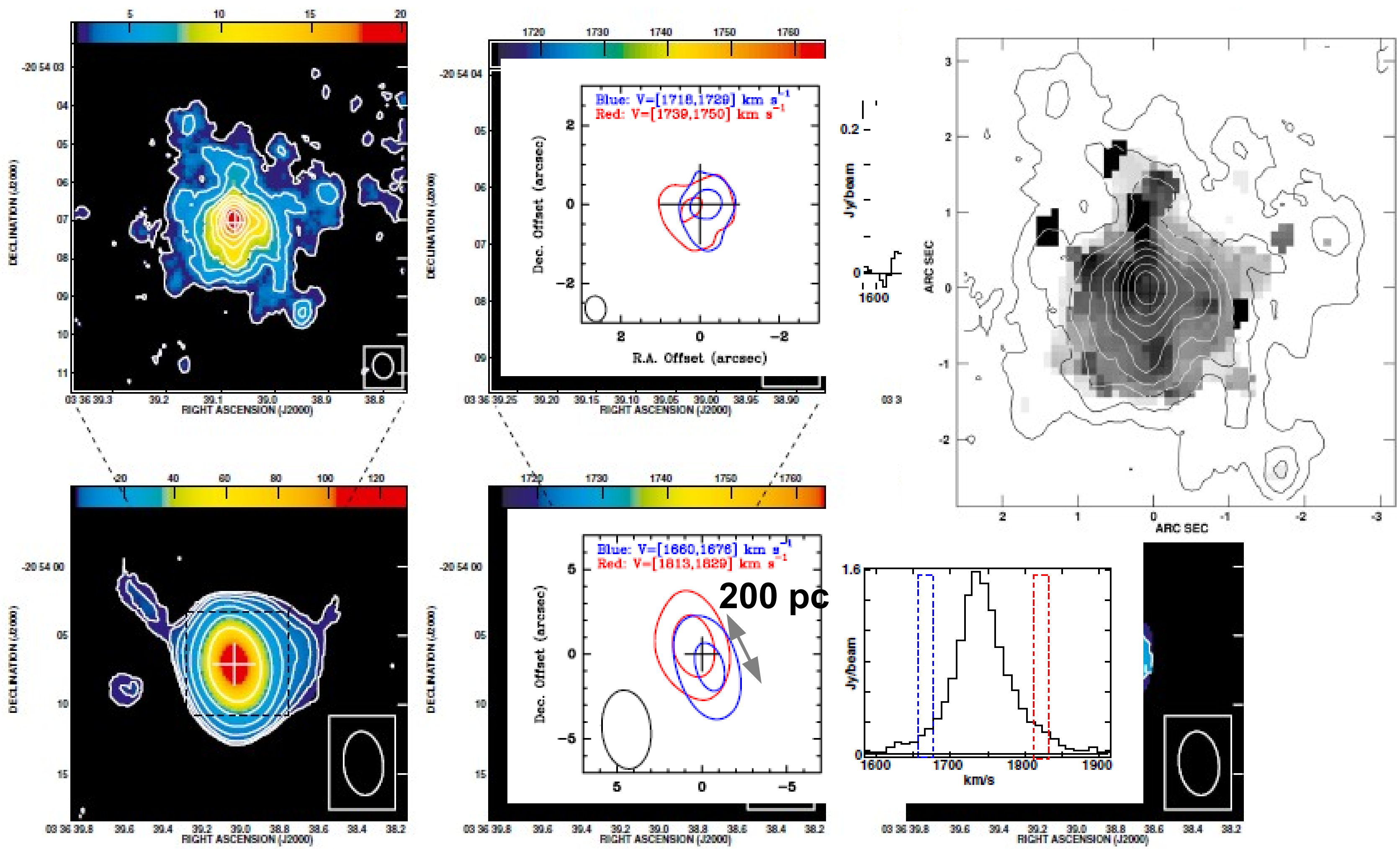
A Molecular outflow: SMA

CO 2-1 emission with the SMA in Extended and Compact configuration (Aalto et al. 2012)

Moment 0 Moment 1 Moment 2

Extended (0."65)

Compact (4 ")



A Molecular outflow: SMA

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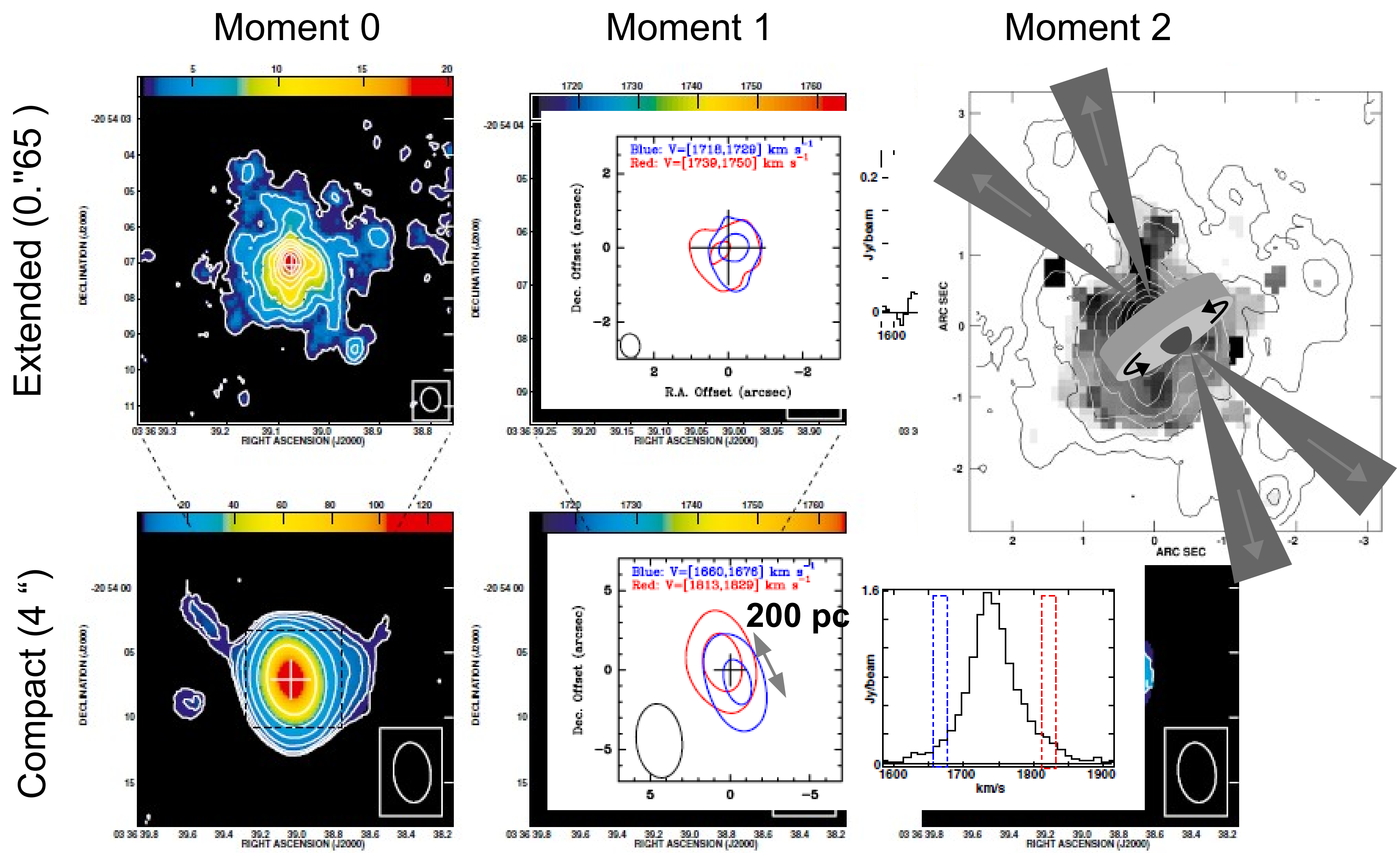
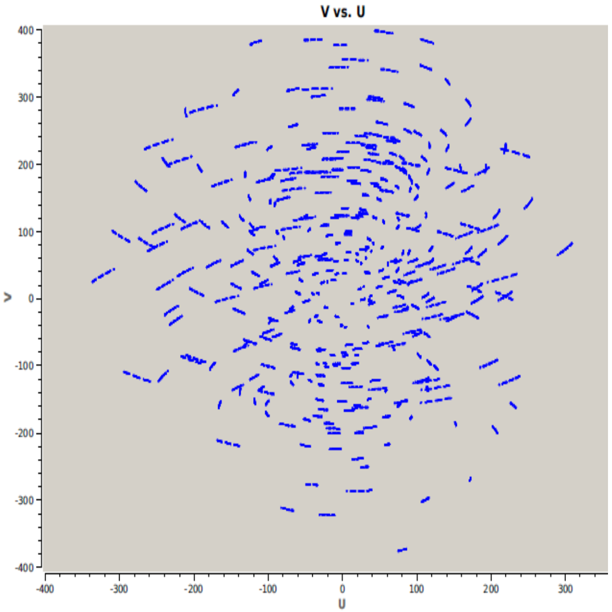
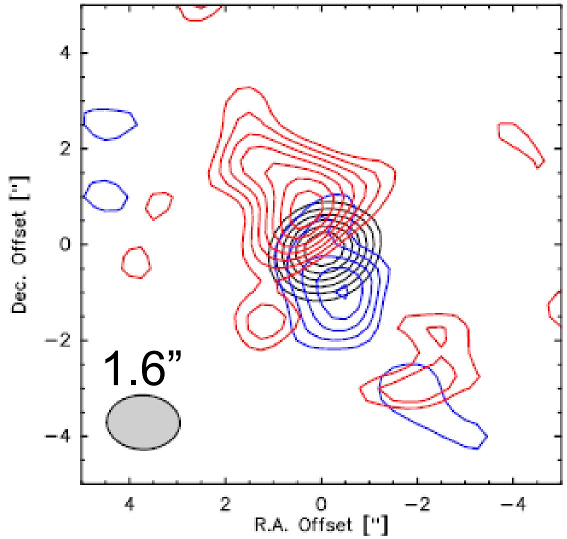


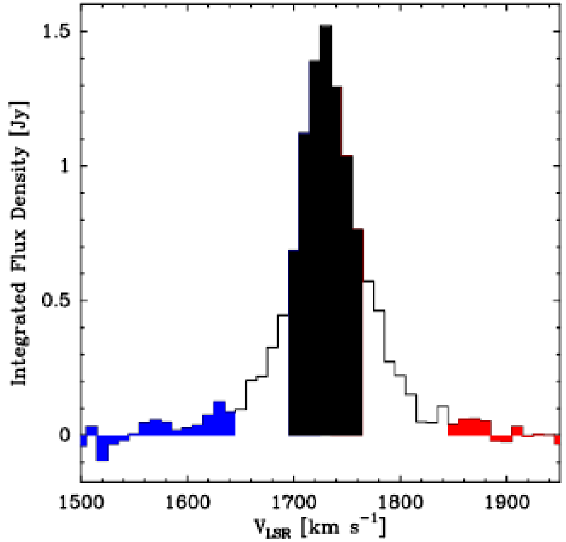
Cycle 0 CO 1-0: Outflow resolved!

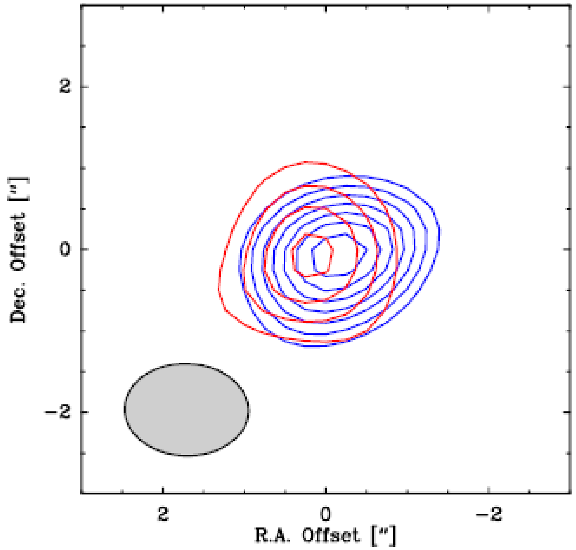
One hour track

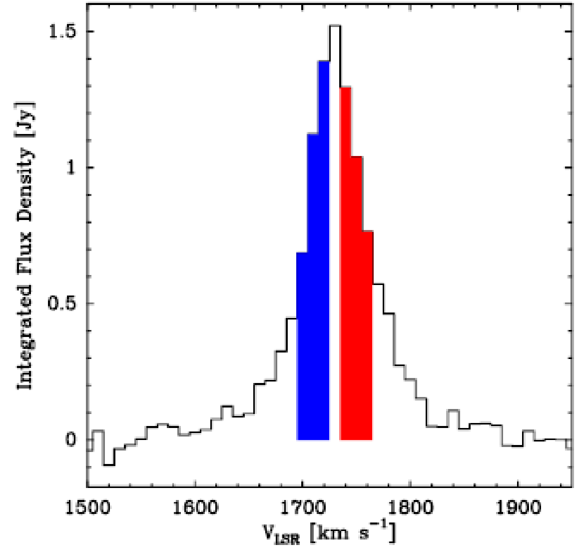
18 Antennas



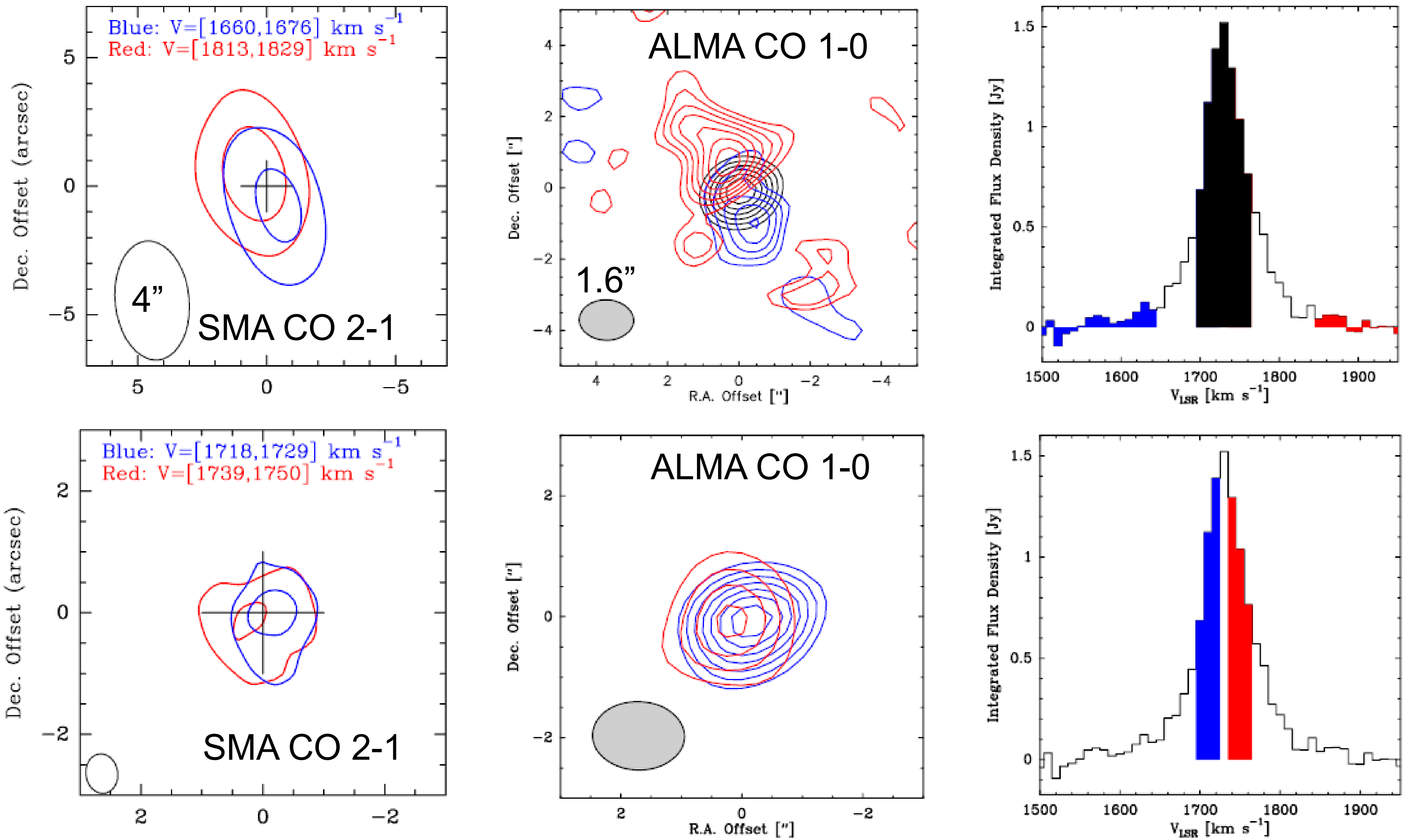




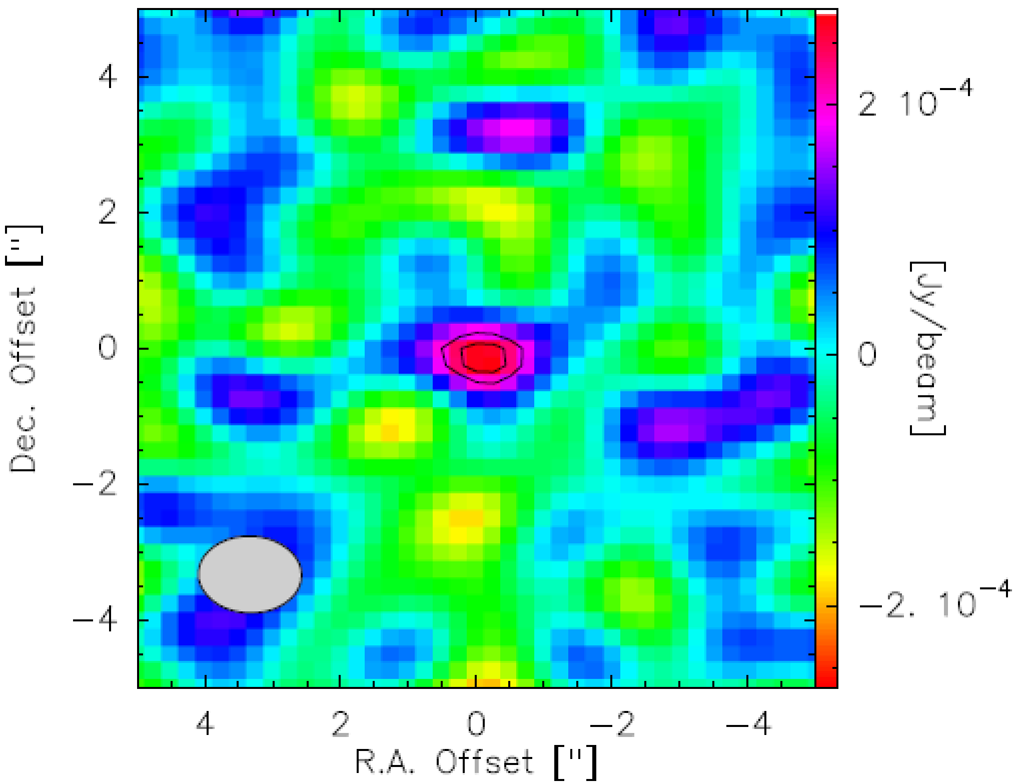




Cycle 0 CO 1-0: Outflow resolved!

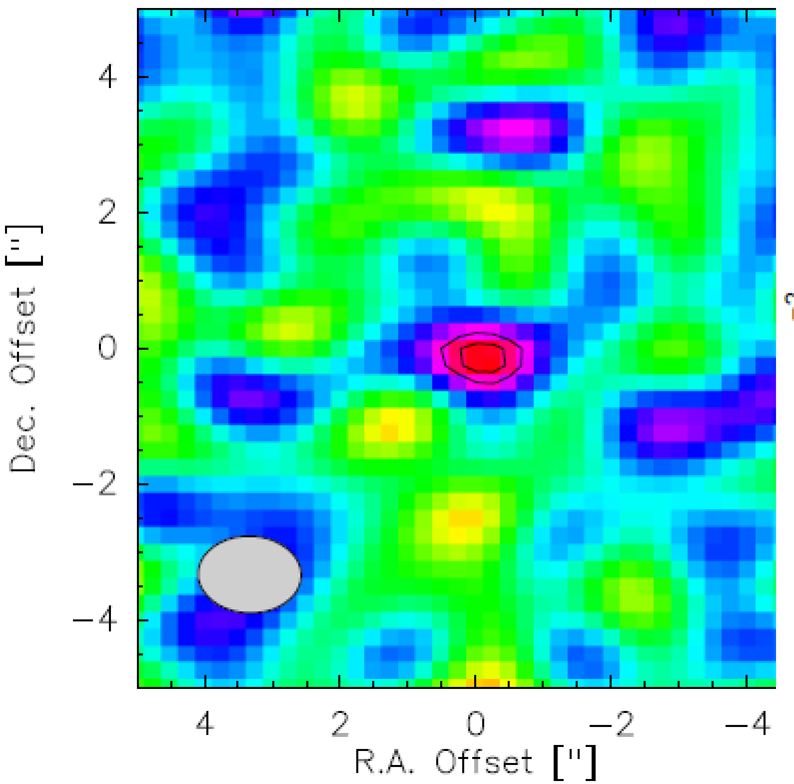


Detected radio continuum!

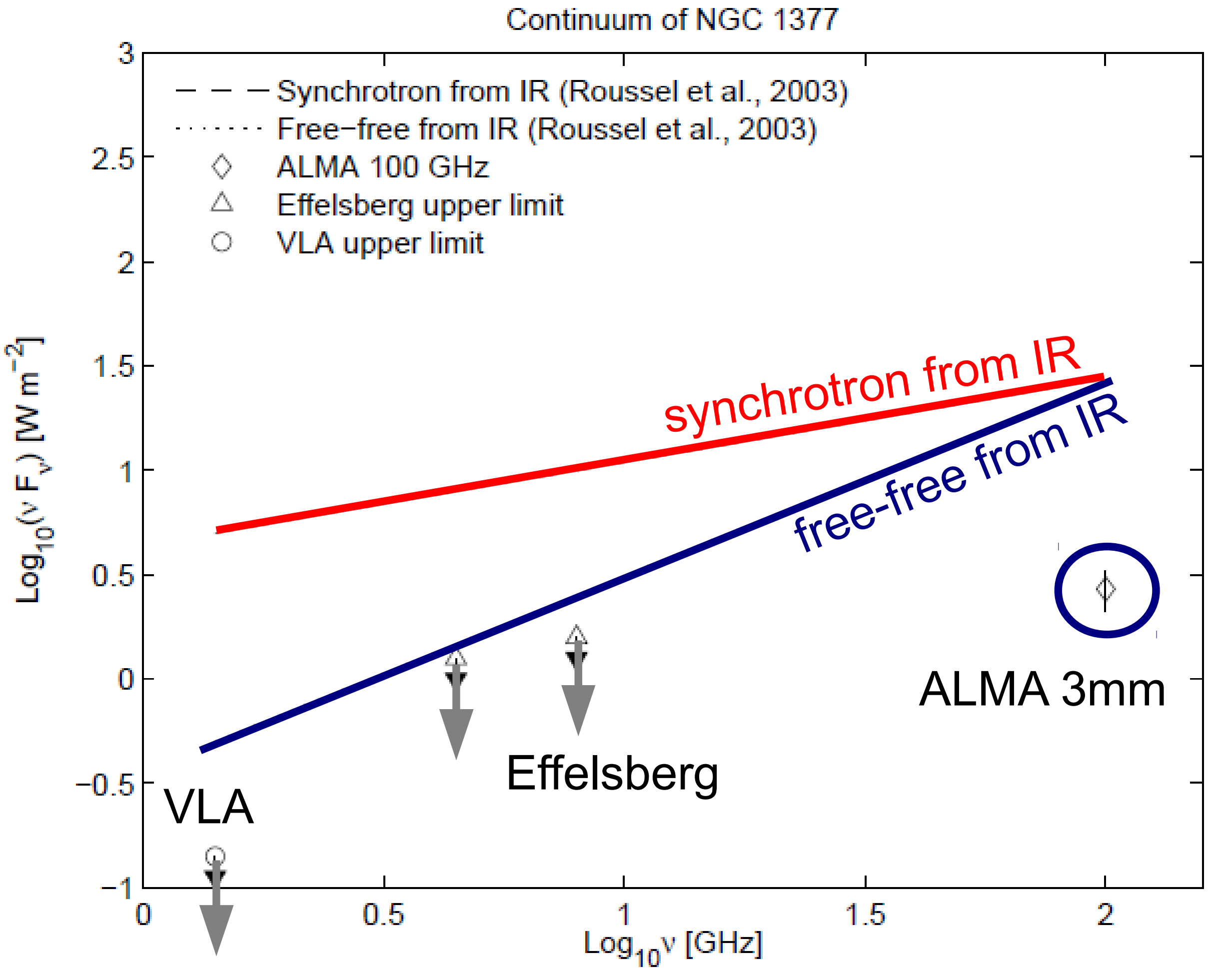


4-sigma detection

Detected radio continuum!



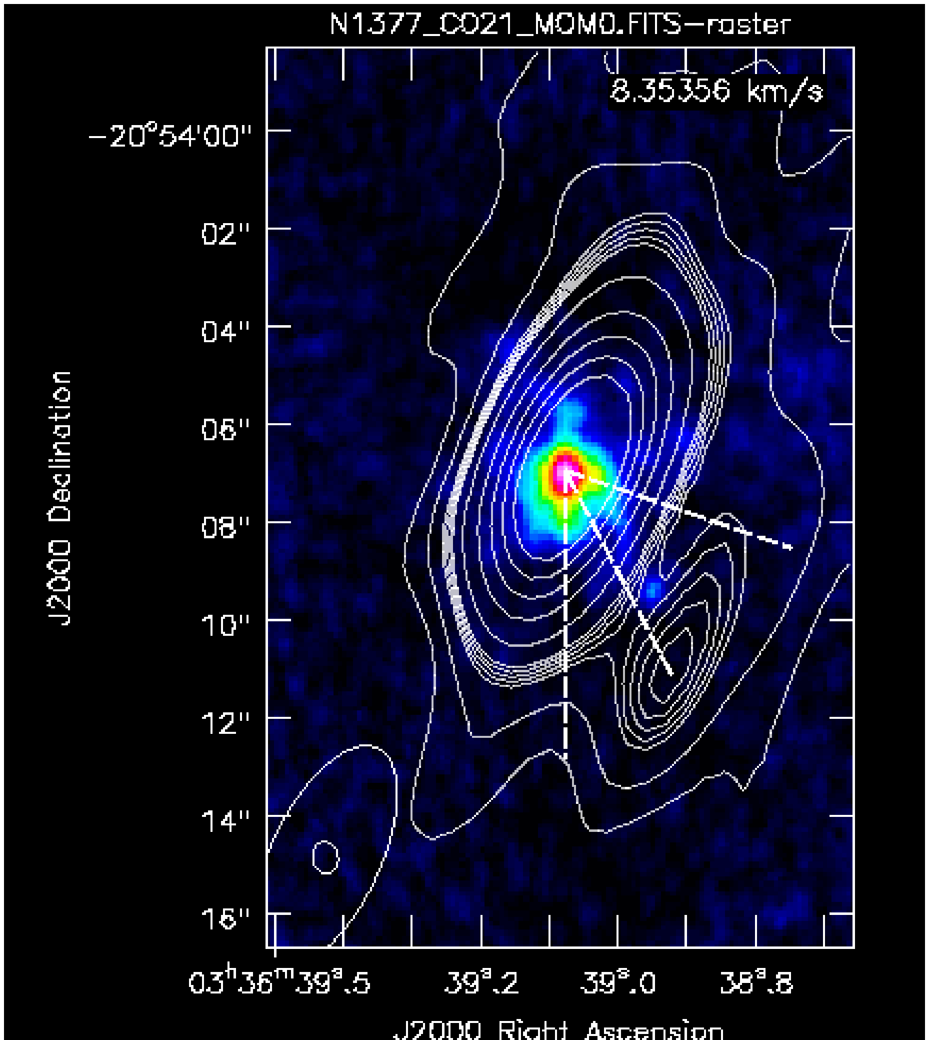
4-sigma detection



What do we learn from the outflow?

- Mass outflow rate: 8 M⊙/yr
- Age: 1Myr
- No radio = no supernovae, what is driving the wind?
  - Ram pressure ? No evidence of hot gas
  - Radiation pressure from:
    - Compact (<20 pc) starburst (50% efficiency??)
    - 10^6 M⊙ AGN at 10% Eddington, heavily obscured

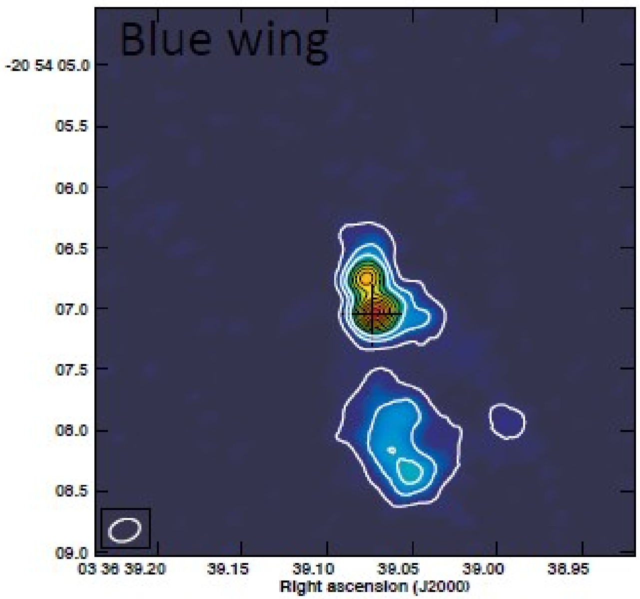
...and we got it !



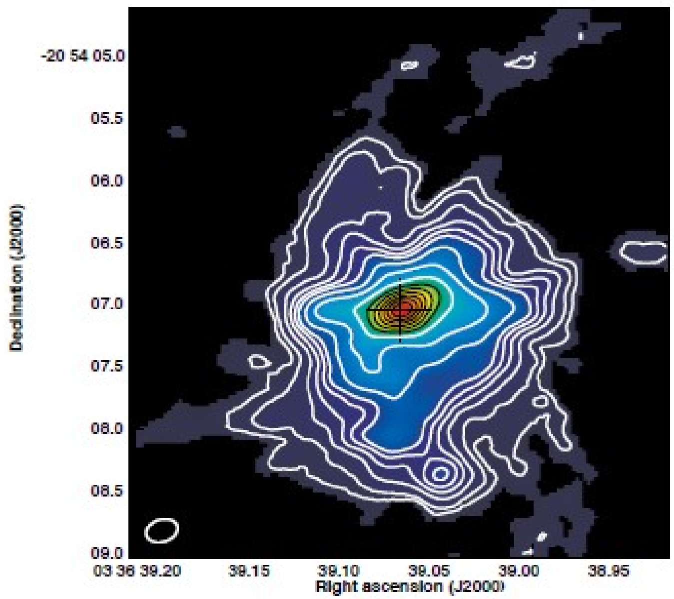
- EVLA 8GHz
- Detected radio continuum at 26-sigma
- Consistent with free-free absorbed AGN !

Costagliola et al., in prep

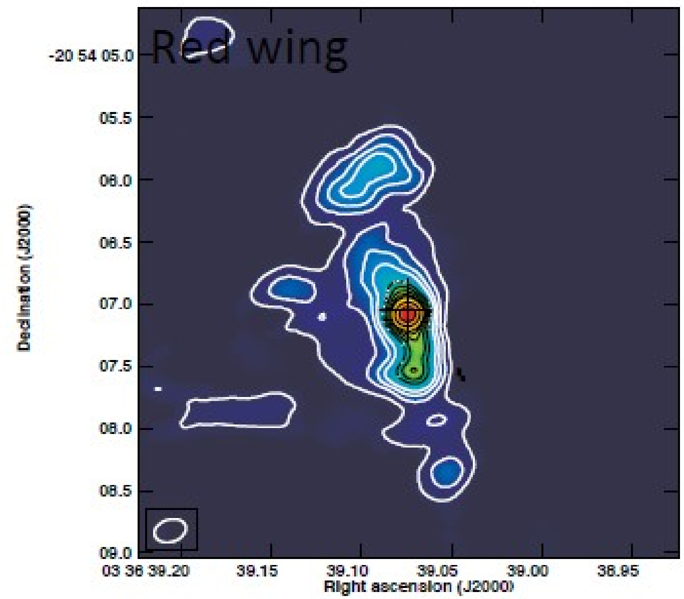
ALMA Cycle 2 CO 3-2



V=1580–1690 km/s



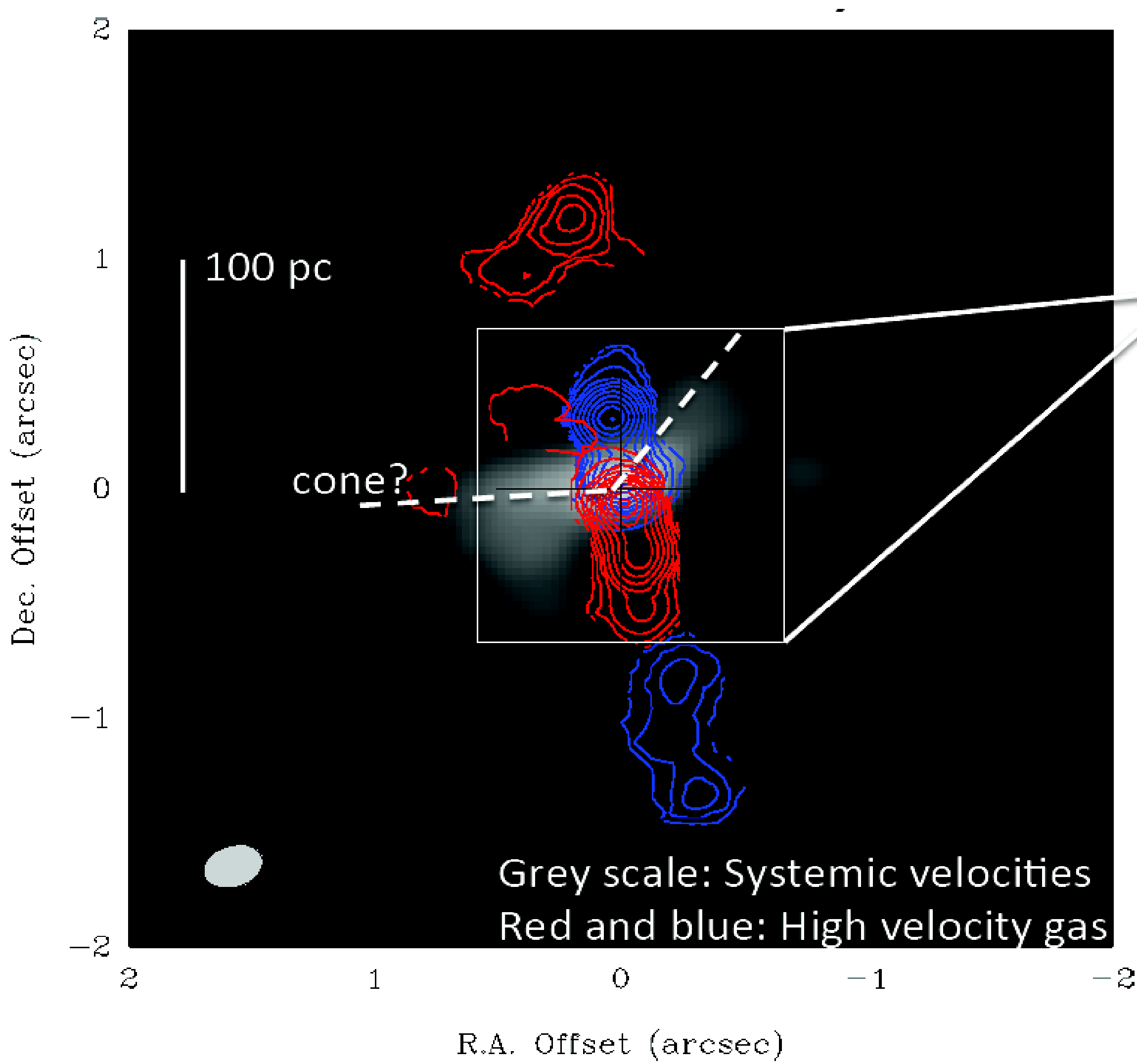
V=1700–1780 km/s



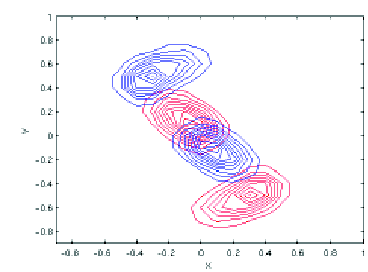
V=1790–1930 km/s

Aalto et al, in prep.

When things get really weird...



New ALMA result: Outflow appears to flip near the nucleus. Origin unclear – high velocity gas extremely well aligned along line-of-sight



A molecular jet rotating around an axis perpendicular to the line of sight could tentatively reproduce observations

To take home

- Mm and radio observations can penetrate the extremely obscured cores of LIRGs
- Multiple strategies: chemistry, dynamics, excitation
- Vibrationally excited HCN, HC3N ideal tracers of kinematics in the core
- Outflows provide crucial information on the properties of the power source
- ALMA and other upgraded radio facilities (EVLA,NOEMA) make it possible to extend these studies to large samples and to the far Universe