The molecular chemistry and excitation of obscured luminous infrared galaxies

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and the MASTER (MOLECULES AS TOOLS FOR EXTRAGALACTIC RESEARCH) network

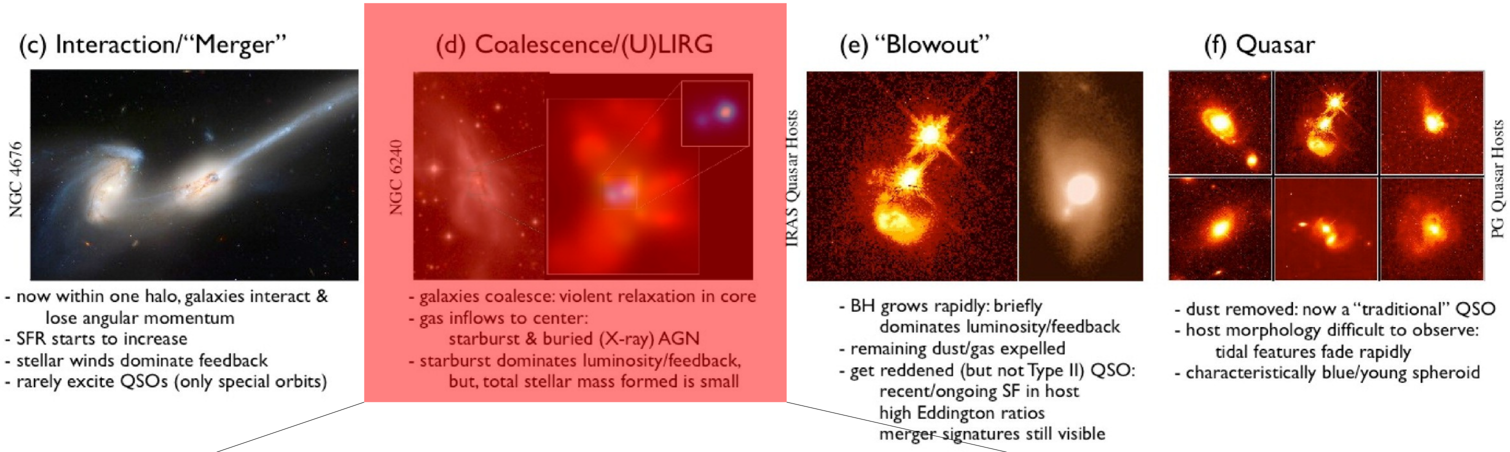
Why Extragalactic Astrochemistry ?

- A laboratory for non-standard chemistry / excitation beyond Milky-Way conditions
- Diagnostics of the ISM processing (i.e., isotopic ratios)
- Study the physical conditions of the star forming gas

  (i.e. temperature, density, heating / cooling)
- Study the impact of AGN/SF feedback on the ISM

  (i.e. , ionization, shock chemistry)
- Diagnostics of deeply obscured galactic nuclei

Compact obscured IR nuclei (CON)



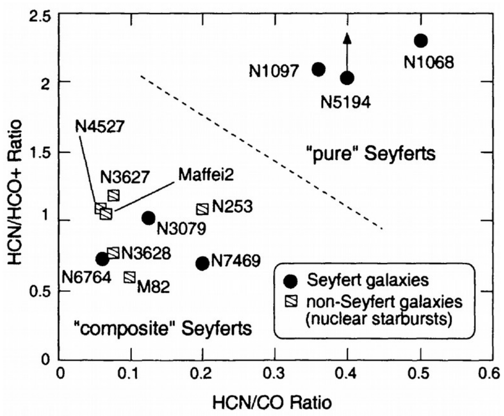
- Early stages of the AGN/Starburst co-evolution
- Bright, compact IR cores (<100 pc)
- Large molecular columns $N(H_2)>10^{24}$ cm^{-2}
- Mixed AGN/Starburst features
- Extremely rich molecular spectra

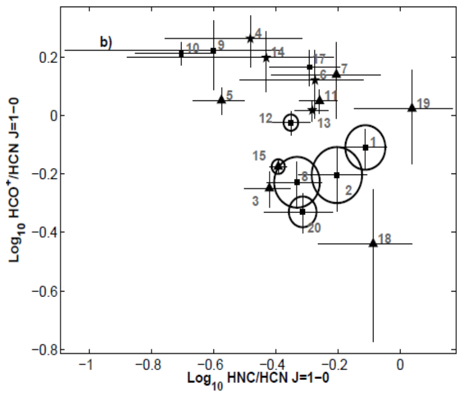
Ideal laboratories for Starburst/AGN chemistry and excitation

Extragalactic molecular diagnostics, pre-ALMA

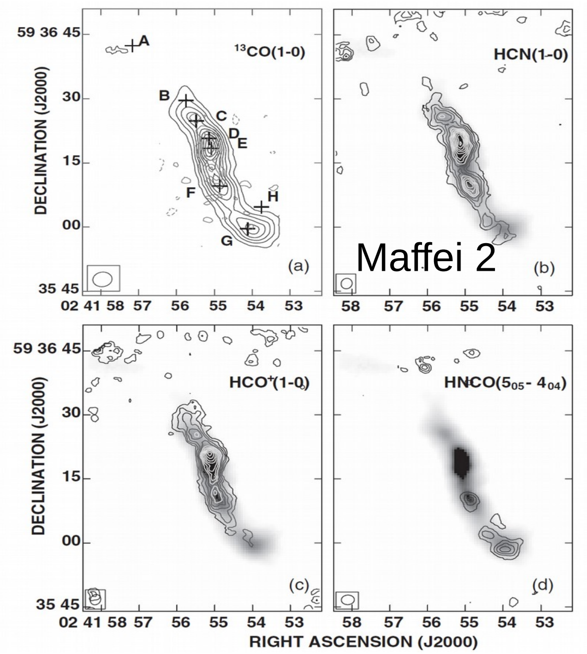
- **Line Ratios**

Kohno+2001



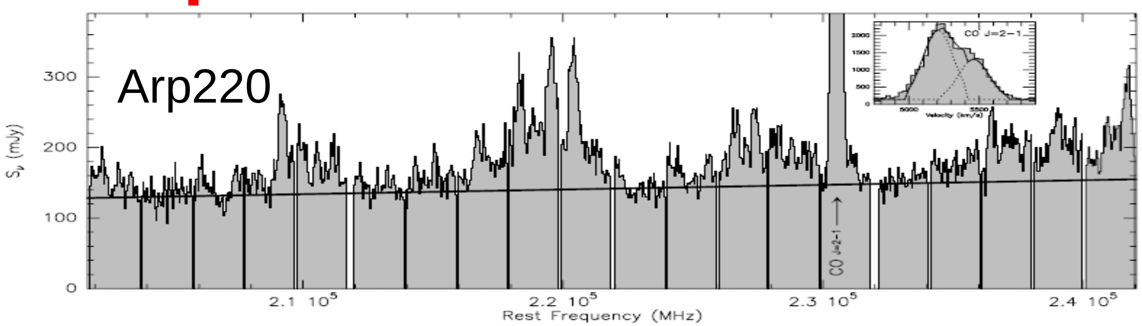


Costagliola+2011

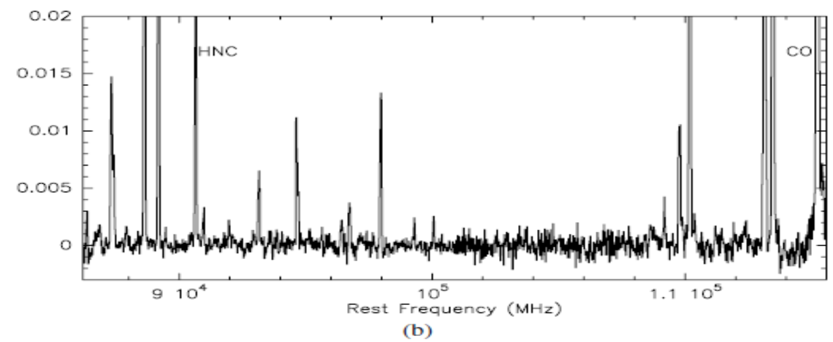


Meier & Turner 2012

- **Spectral Scans**



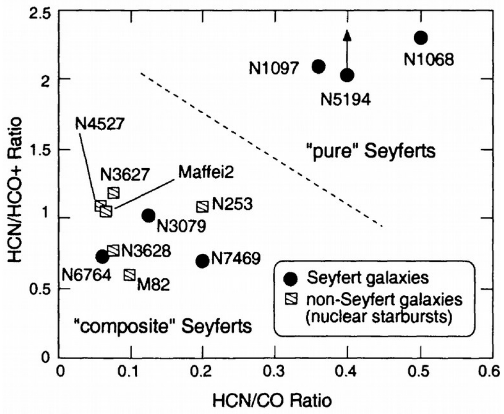
Martin+2011



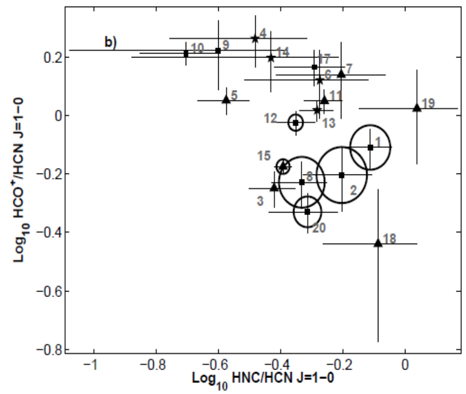
Aladro+2013

Extragalactic molecular diagnostics, pre-ALMA

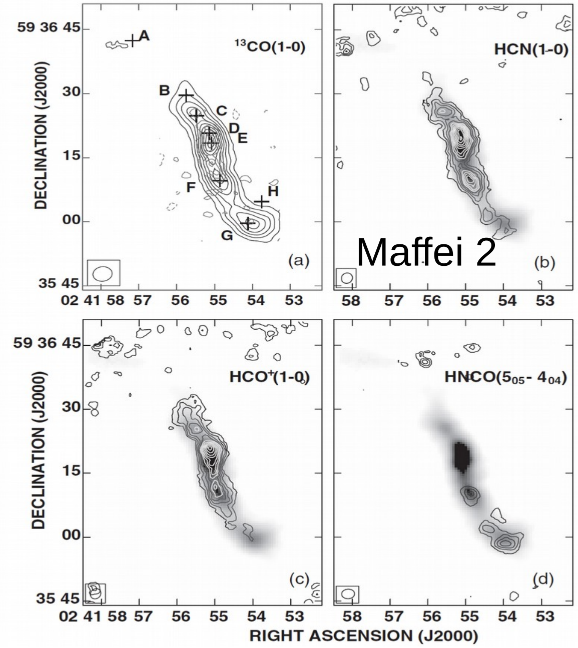
- **Line Ratios**



Kohno+2001



Costagliola+2011



Meier & Turner 2012

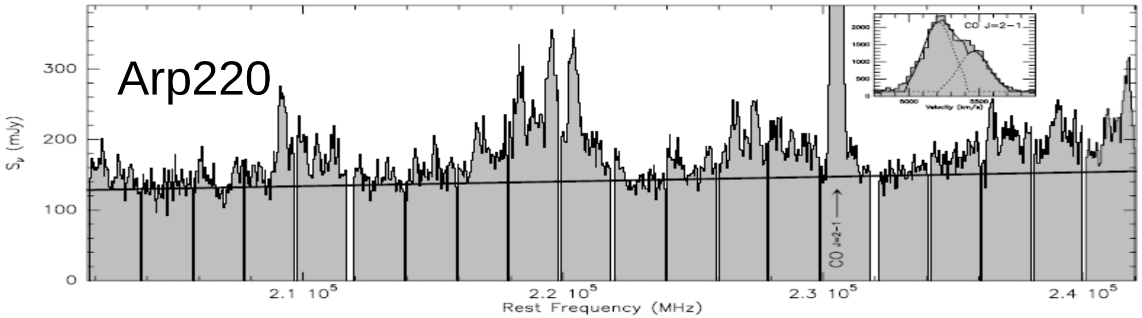
- Quick, large samples
- Only a few species studied, often optically thick
- Excitation effects difficult to account for
- Small variations, large errors
- Ambiguous interpretation with chemical models

Extragalactic molecular diagnostics, pre-ALMA

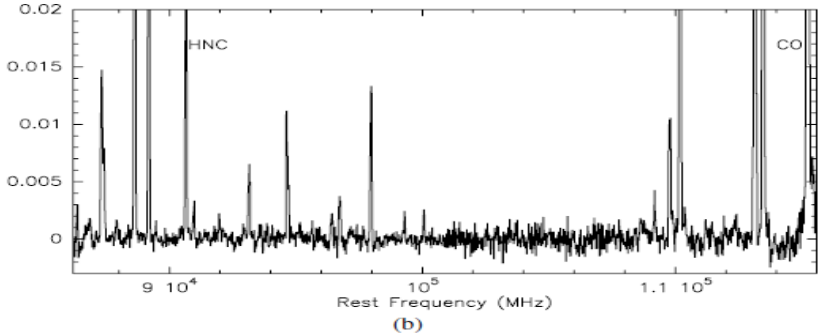
- More species, possibly more sensitive to the physics
- Time consuming
- Mostly single band
- Limited information on molecular excitation

Multi-band spectral scans needed to get the excitation!

- **Spectral Scans**



Martin+2011



Aladro+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,

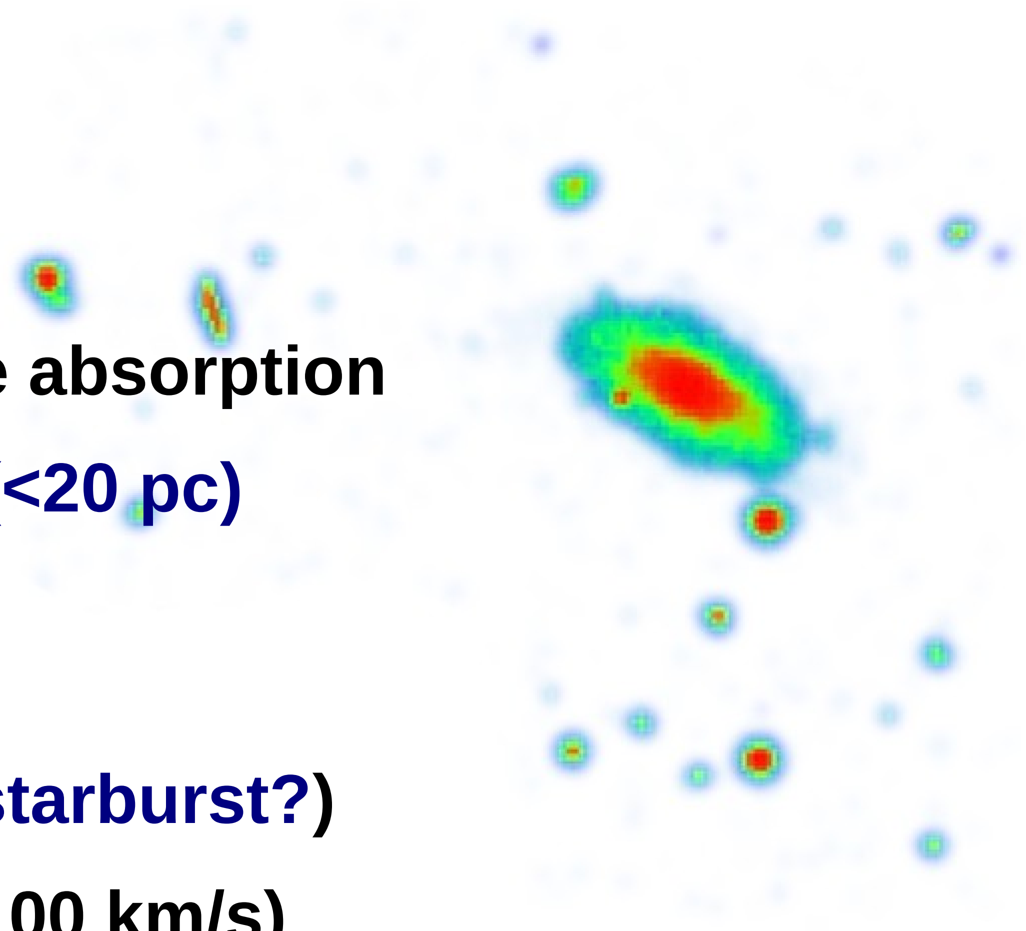
MASTER
MOLECULES AS TOOLS FOR EXTRAGALACTIC RESEARCH

- **Full coverage of atmospheric windows in Band 3, 6 and 7 : 175 GHz total**
- **First complete spectral scan of an obscured LIRG**
- **Beam – matched observations (2” resolution)**

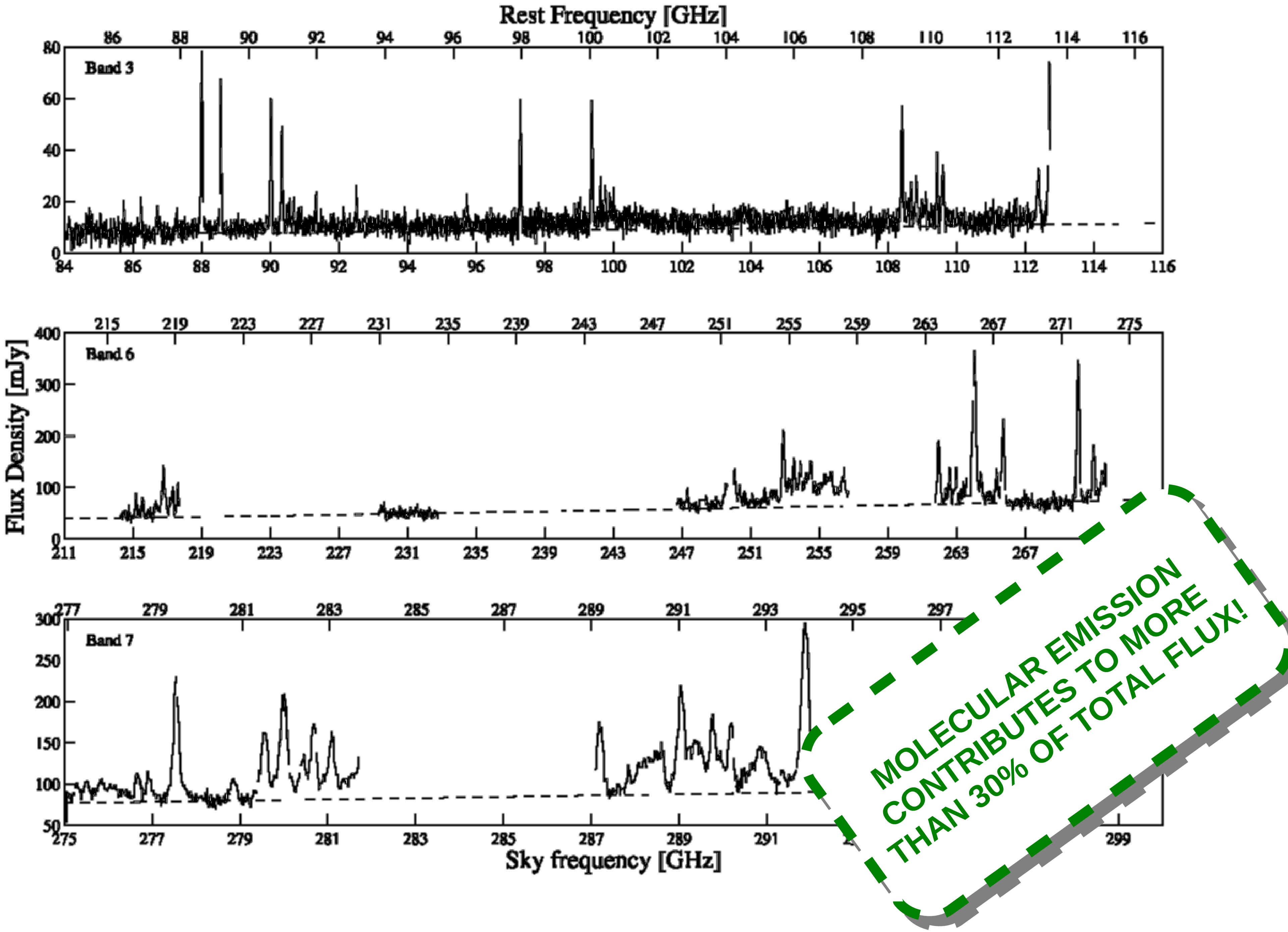
Main Goals:

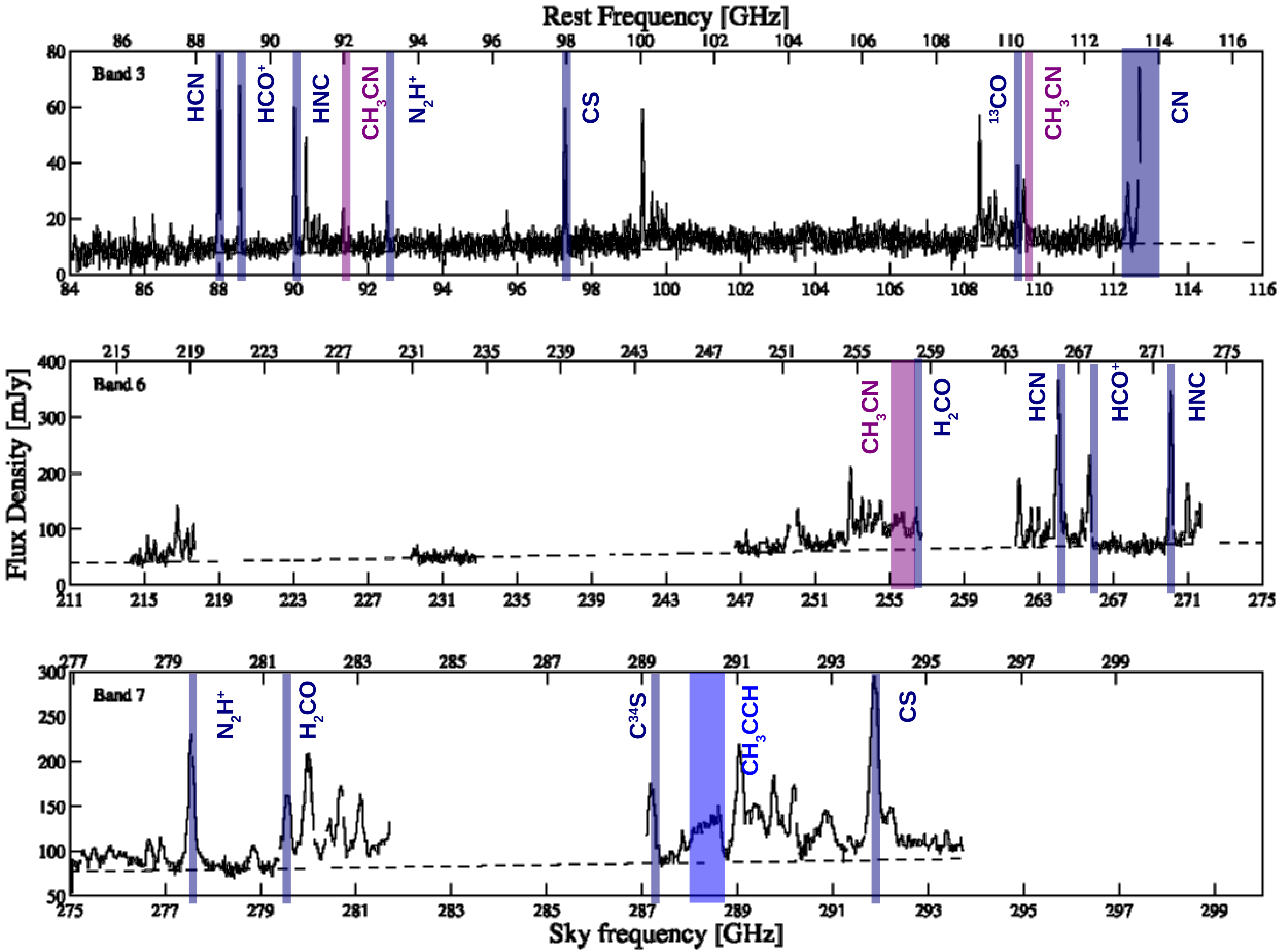
- **Obtain a template chemistry and molecular excitation for LIRGs near and far**
- **Derive accurate abundance estimates**
- **Look for more sensitive tracers of the ISM conditions**

NGC 4418:
The prototypical obscured LIRG



- $L_{IR}=10^{11}L_{\odot}$
- LIRG with **highest** silicate absorption
- Hidden **compact IR core (<20 pc)**
- SFR 10 $M_{\odot}$/yr
- 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]
MOLECULAR EMISSION
CONTRIBUTES TO MORE
THAN 30% OF TOTAL FLUX!

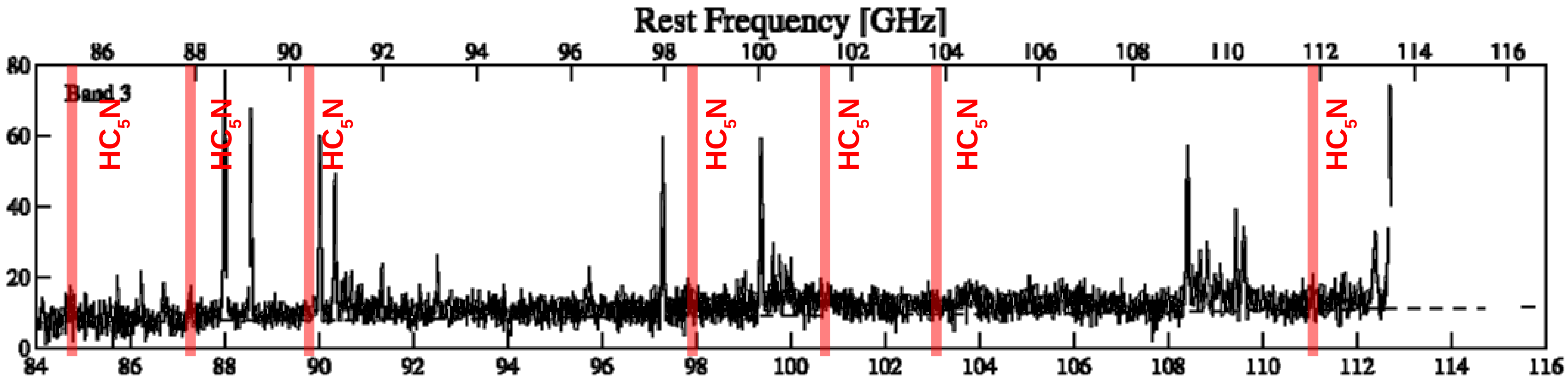

Rest Frequency [GHz]
Band 3
HCN
HCO^+
HNC
CH_3CN
N_2H^+
CS
^{13}CO
CH_3CN
CN
Band 6
CH_3CN
H_2CO
HCN
HCO^+
HNC
Band 7
N_2H^+
H_2CO
$C^{34}S$
CH_3CCH
CS
Flux Density [mJy]
Sky frequency [GHz]

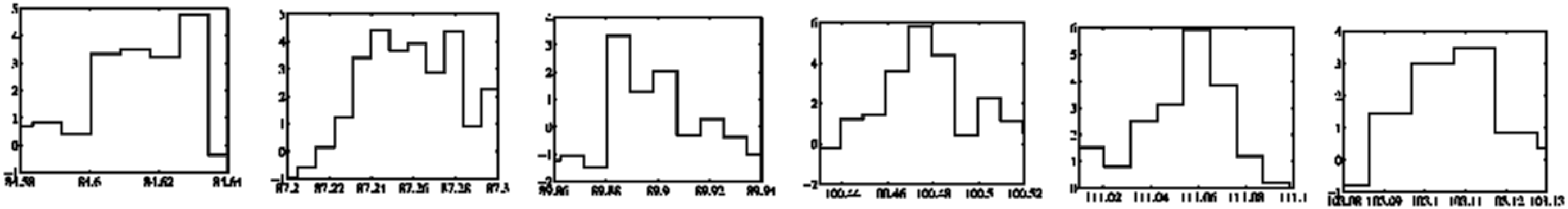
Detected Molecules

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** **317 lines > 3-sigma**
4X what we expected in the proposal



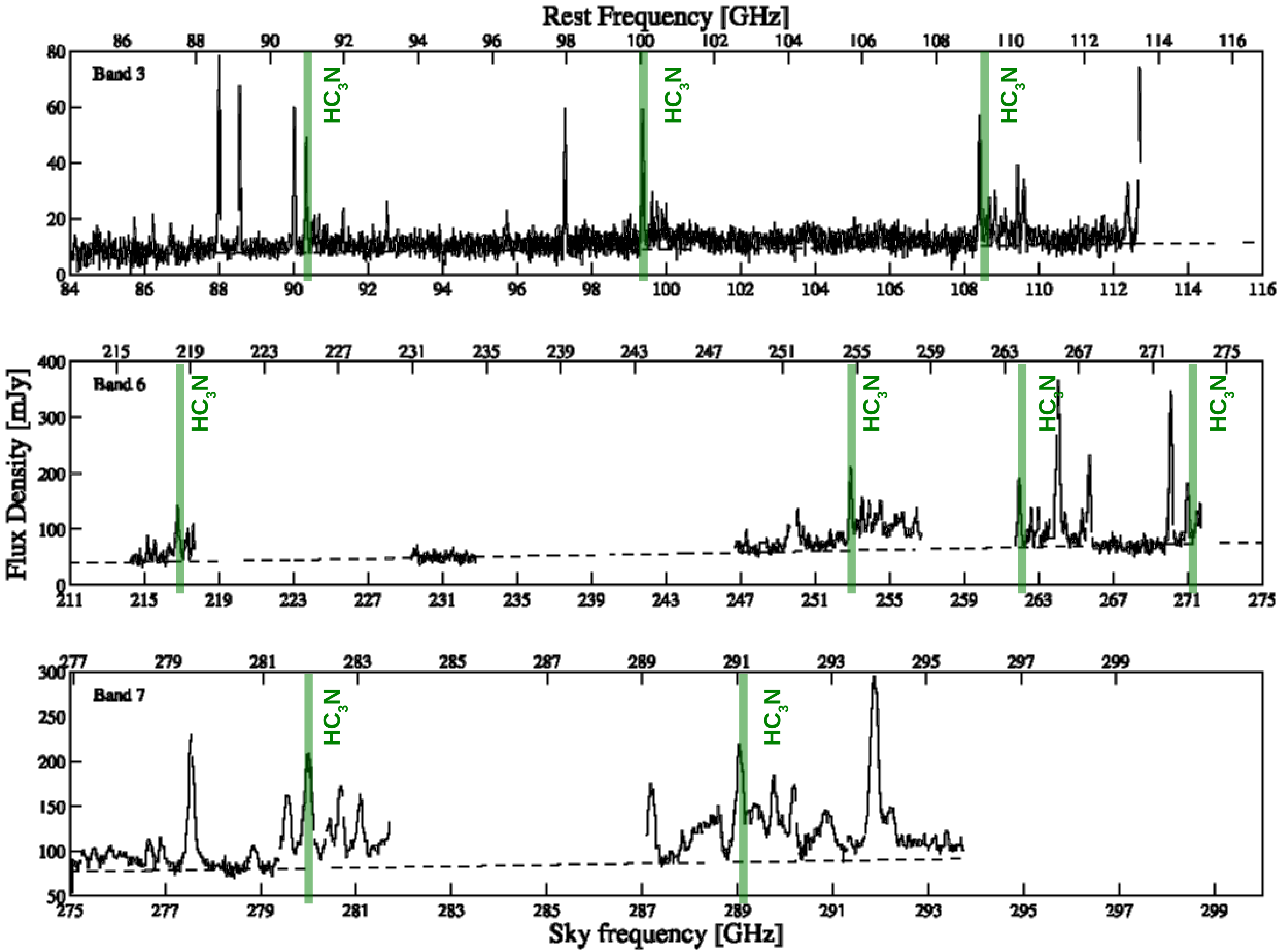


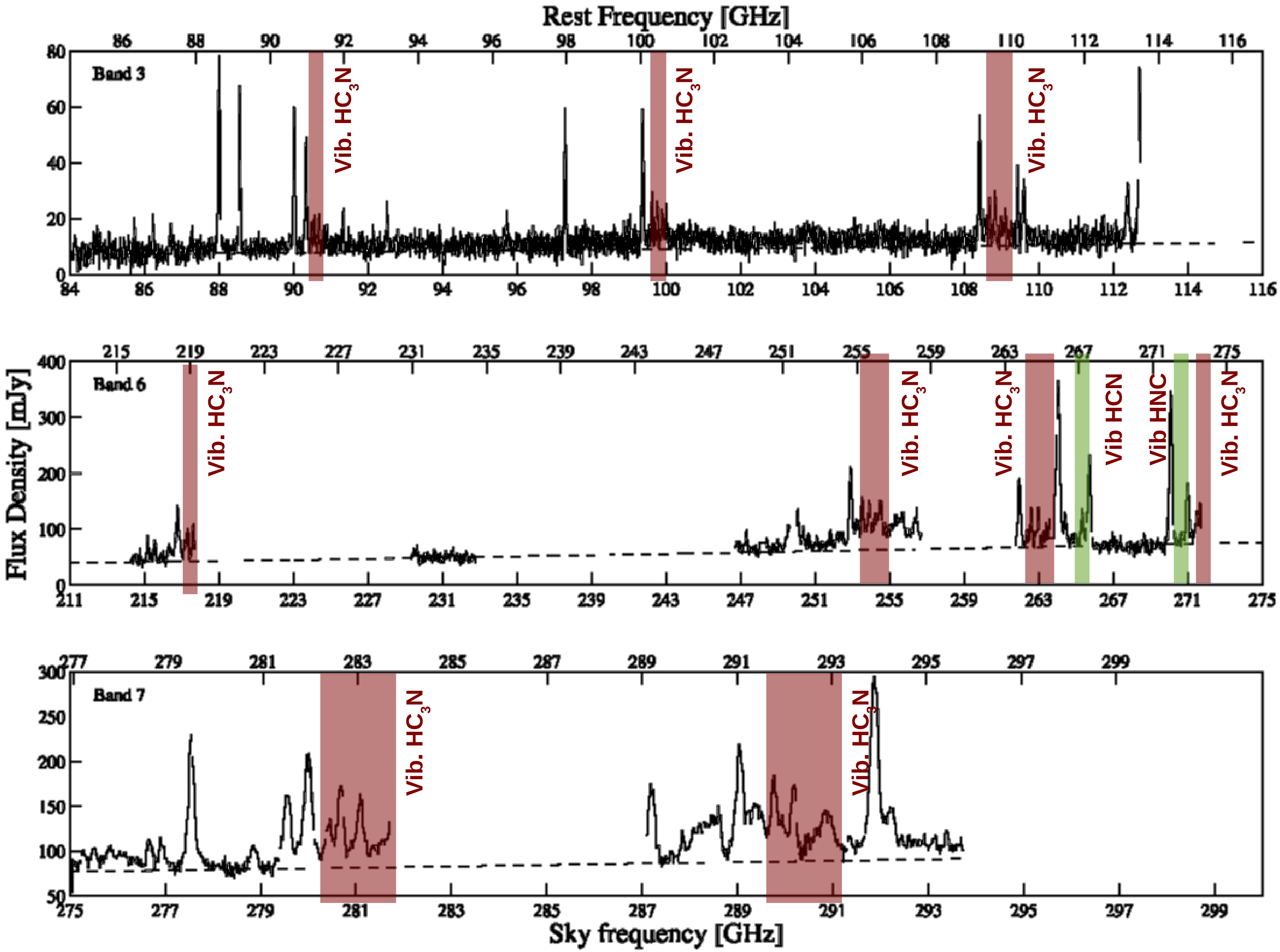
First confirmed extragalactic detection of HC5N

- 7 transitions in Band 3
- Trot = 70 K, Abundance 10^{-8}
- Gas-phase neutral-neutral formation

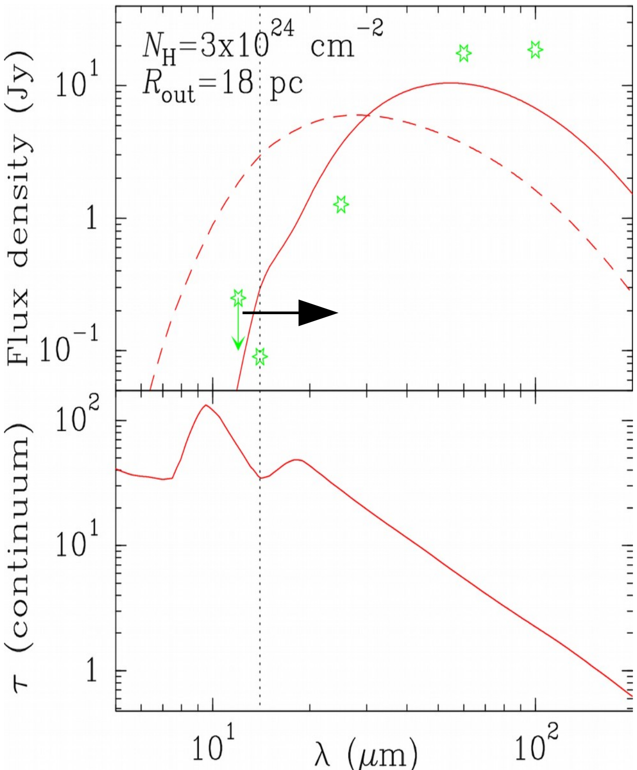
$$C_2H + C_2H_2 \rightarrow H_2CCCC + H$$
$$CN + H_2CCCC \rightarrow HC_5N + H,$$

- Short-lived Hot-core tracer / hot gas-phase chemistry

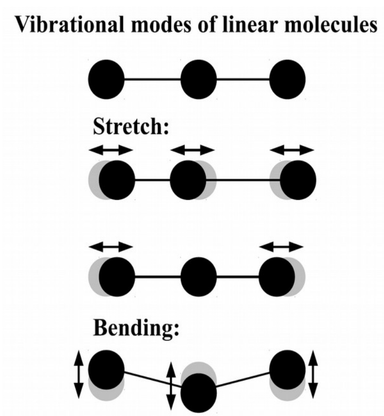

Rest Frequency [GHz]
Band 3
Band 6
Band 7
HC_3N
Flux Density [mJy]
Sky frequency [GHz]

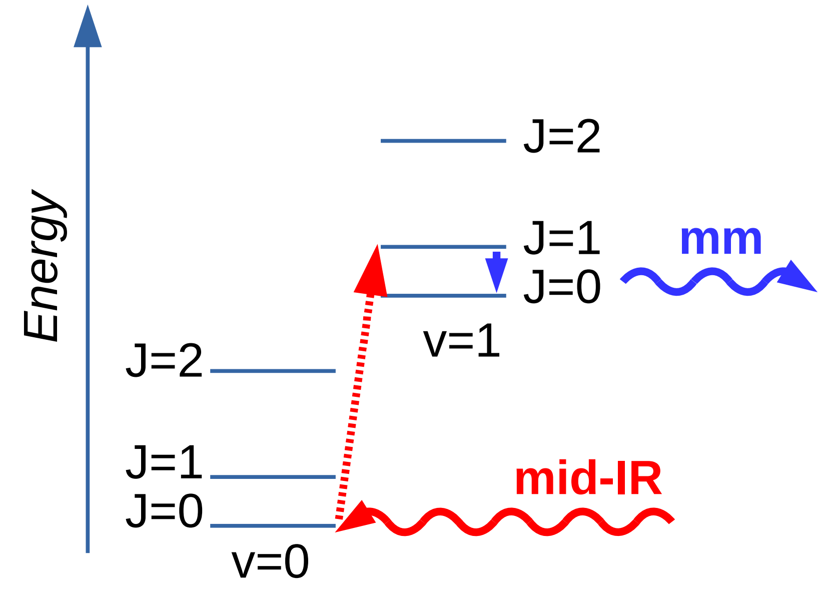

Rest Frequency [GHz]
Band 3
Vib. HC3N
Vib. HC3N
Vib. HC3N
Band 6
Vib. HC3N
Vib. HC3N
Vib. HC3N
Vib HCN
Vib HNC
Vib. HC3N
Flux Density [mJy]
Band 7
Vib. HC3N
Vib. HC3N
Sky frequency [GHz]

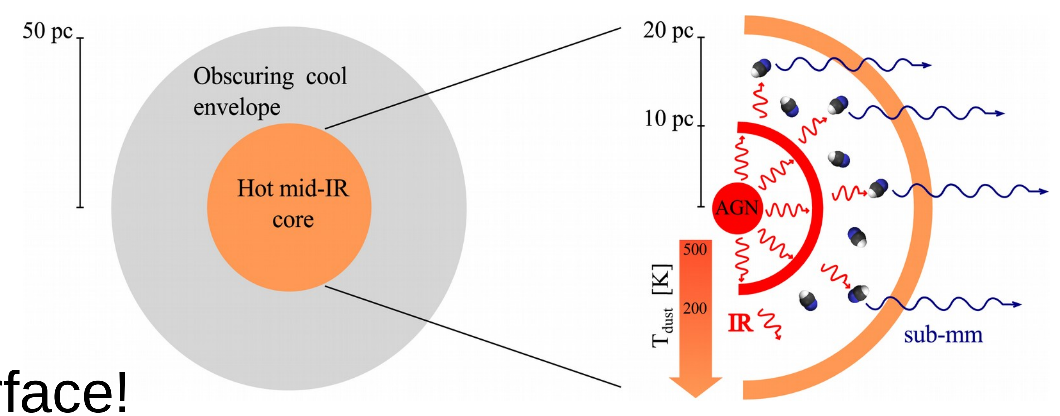
Vibrational excitation: a peek at the hidden IR core



Aalto+2015







Vibrationally excited lines probe the IR field beyond the optically thick surface!

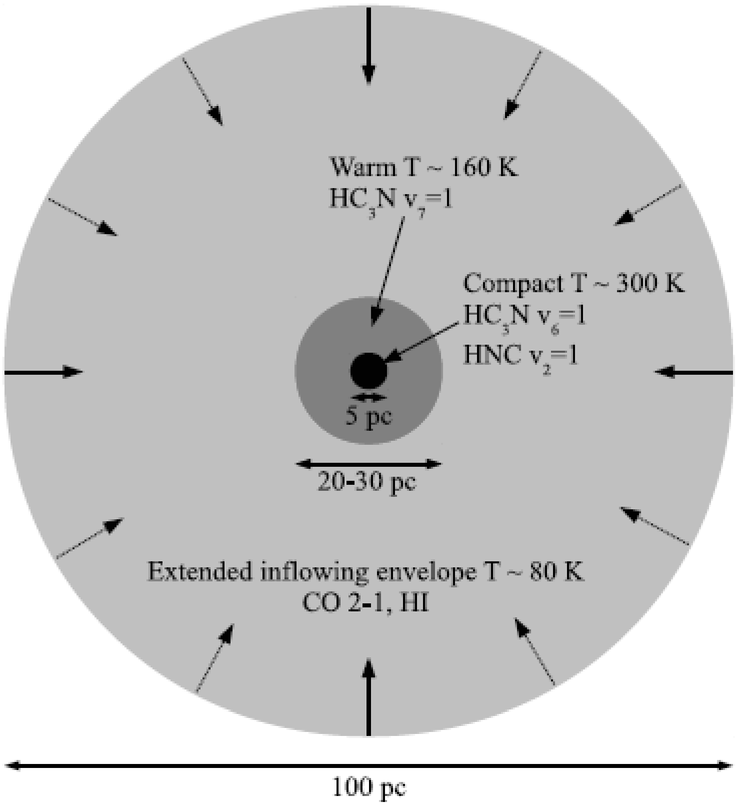
Results of the molecular excitation fit
A multi-phase ISM

- Rotational temperatures: 20-350 K
- H_2 Densities: 10^4-10^7 cm^{-3}
- CH_3CN

  T_{kin}=>500 K, $n(H_2)=10^4$ cm^{-3}
- SiO, N_2H^+

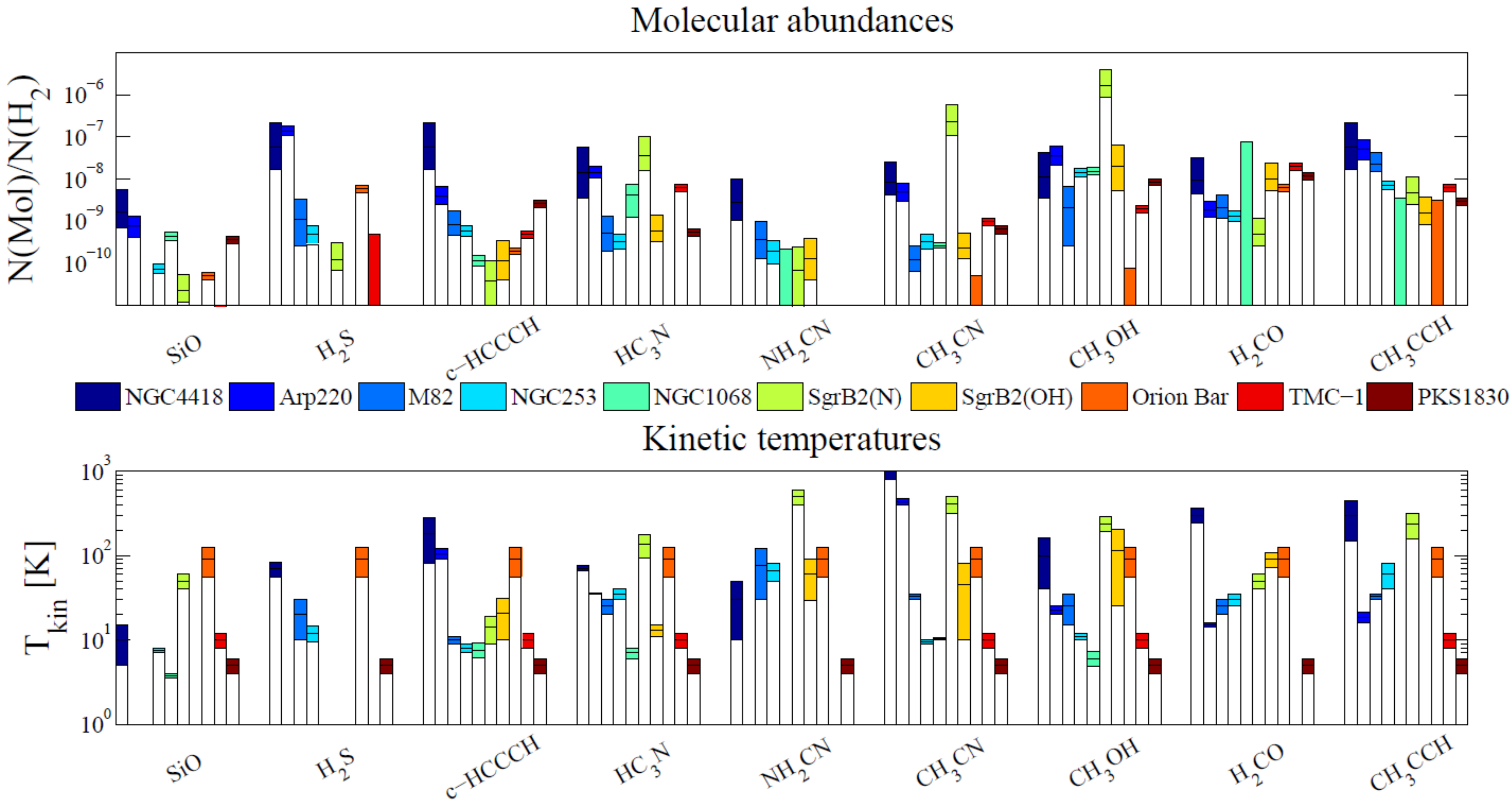
  T_{kin}=20 K, $n(H_2)>10^5$ cm^{-3}
- Vib. Excited HC_3N, HCN, HNC

  Tvib>300 K, Radiatively Excited
- Compact IR source < 5 pc



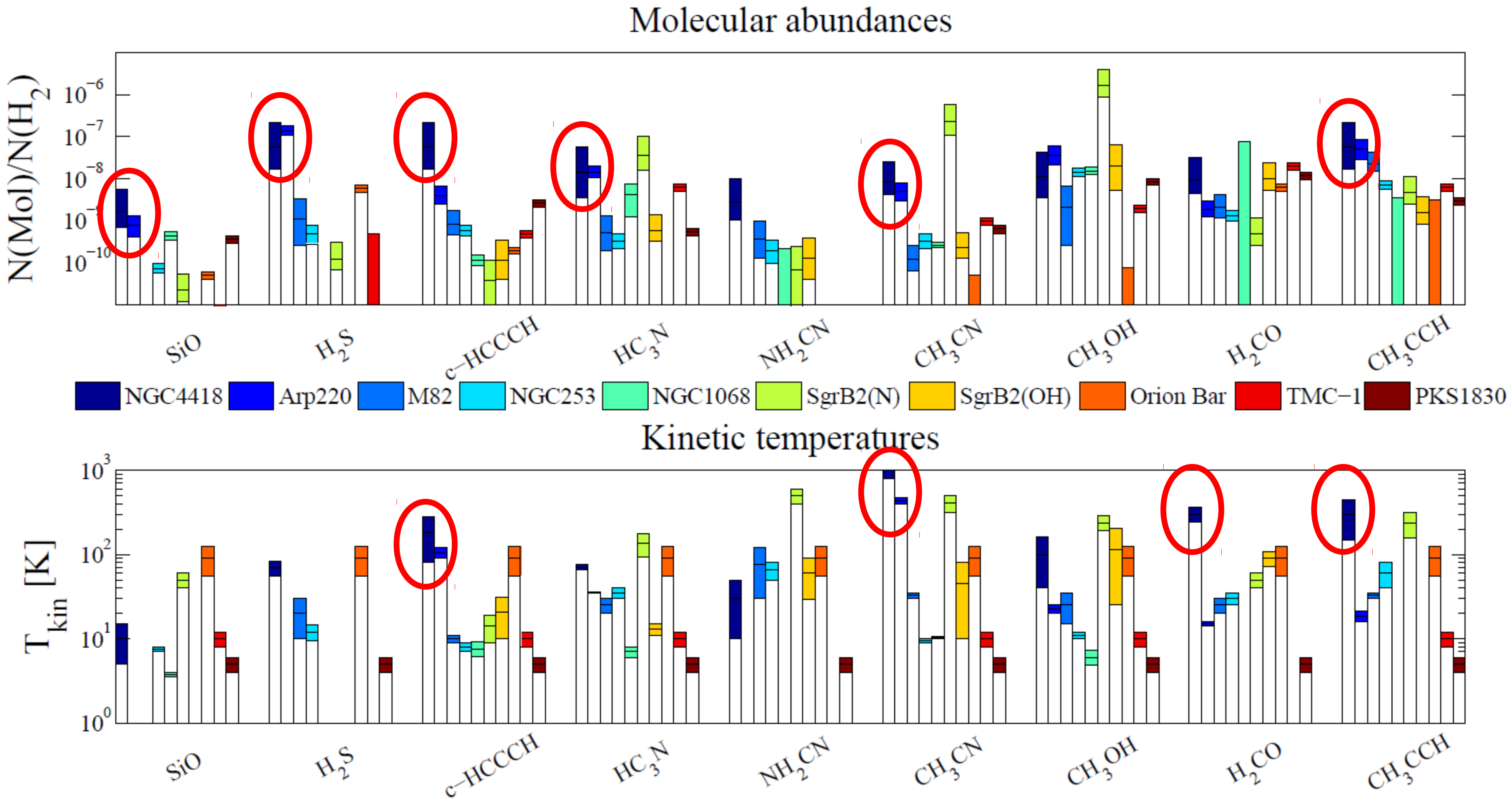
Costagliola et al., 2013,2015

Molecular Abundances



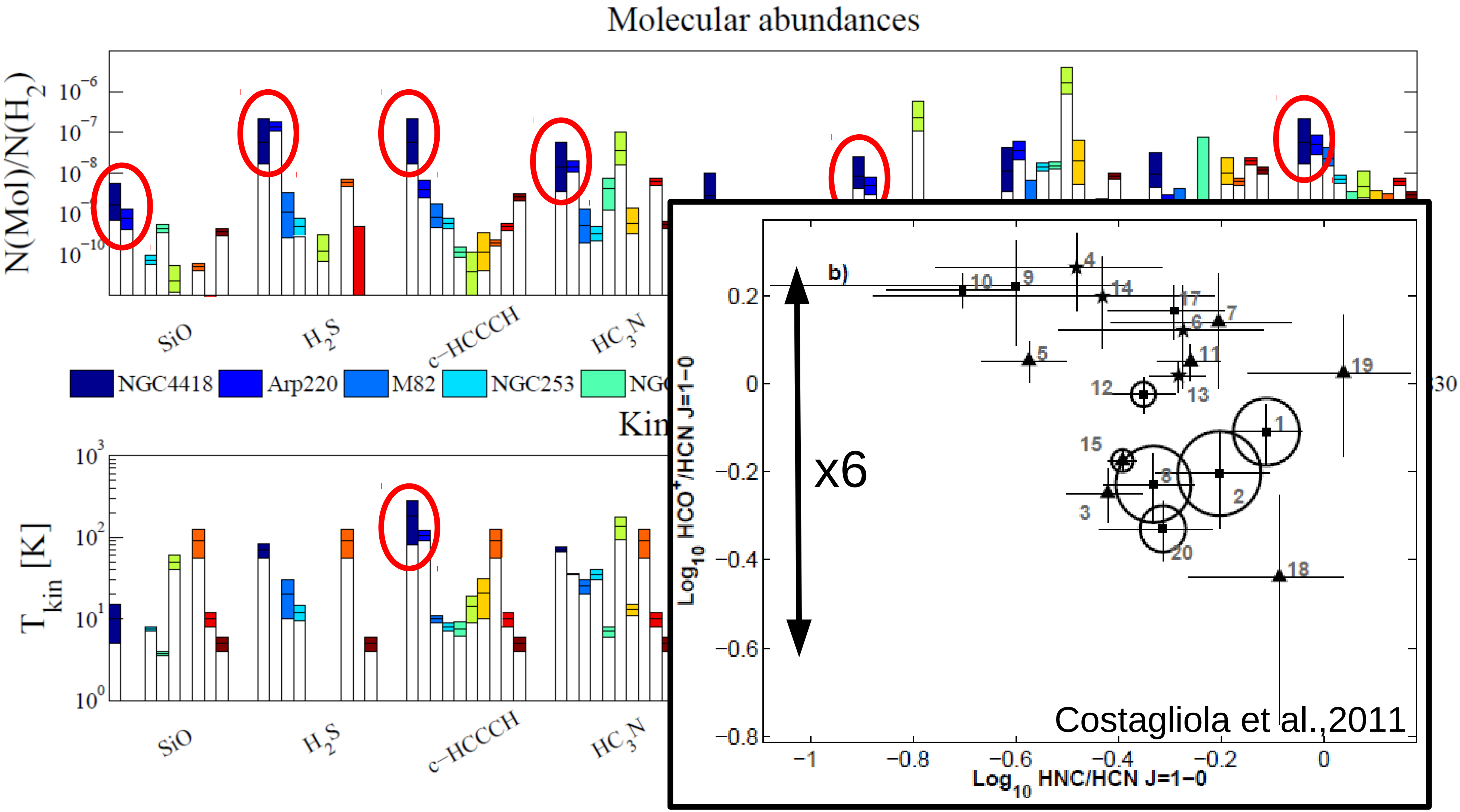
Costagliola et al.,2015

Molecular Abundances



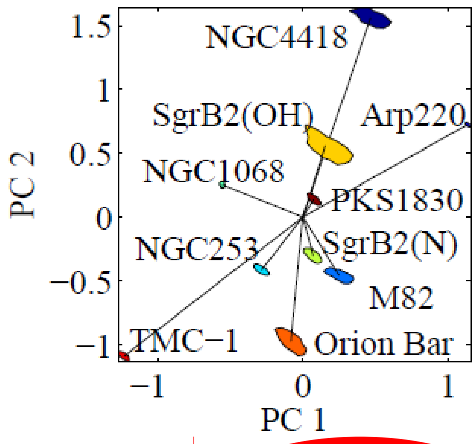
Costagliola et al.,2015

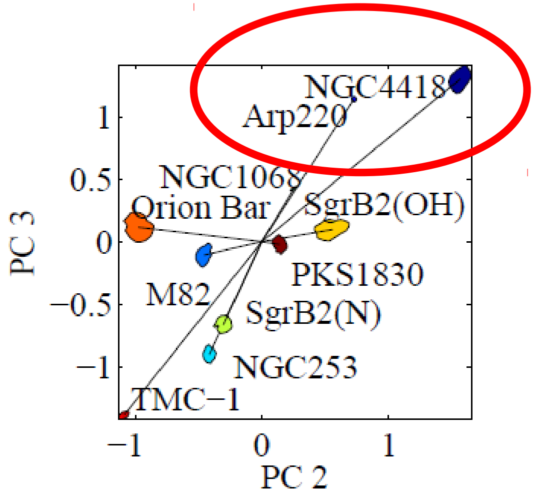
Molecular Abundances

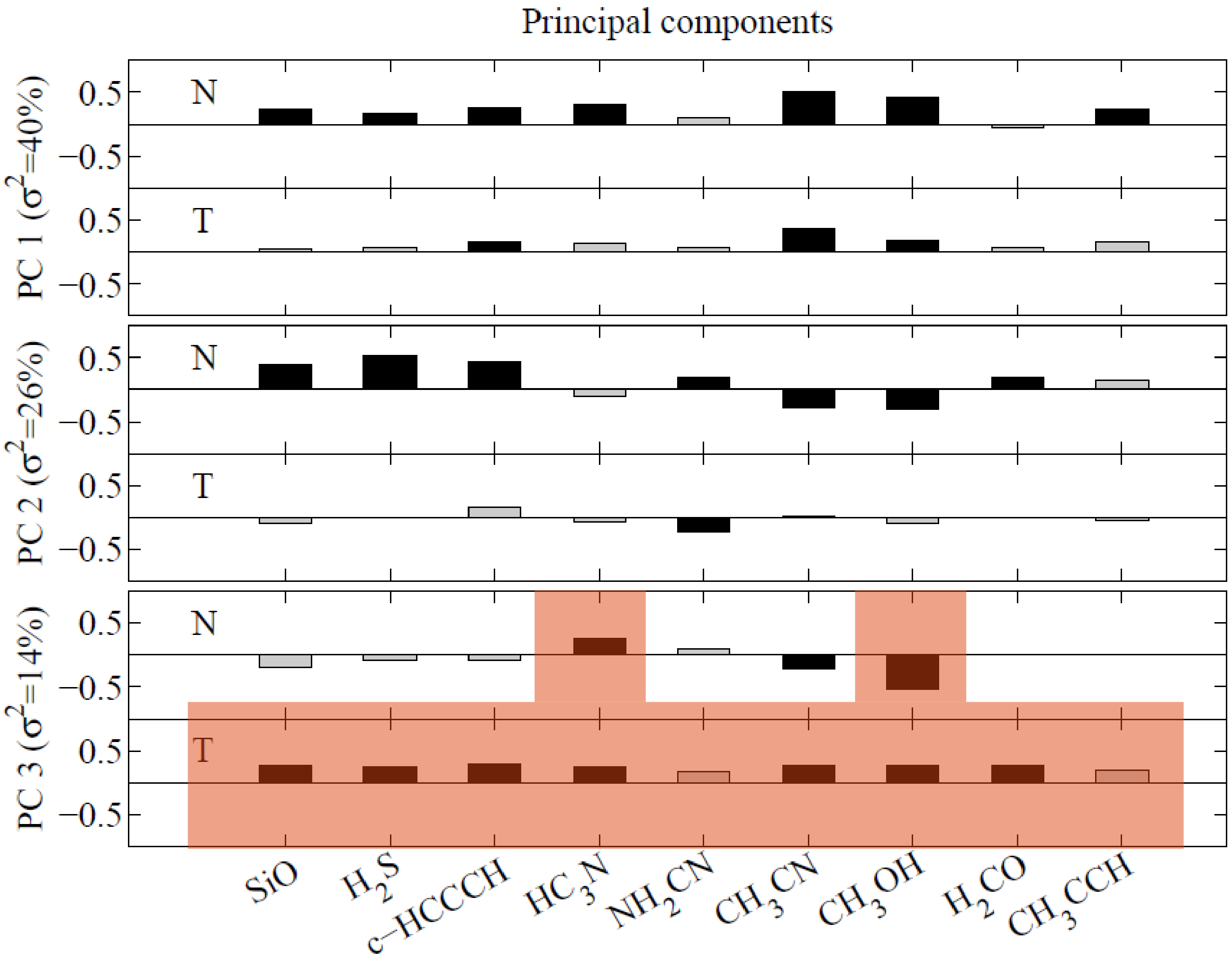


Order of magnitude differences in abundance Vs Factors of a few in line ratios !

Principal component analysis







Costagliola et al.,2015

A new CON chemistry ?

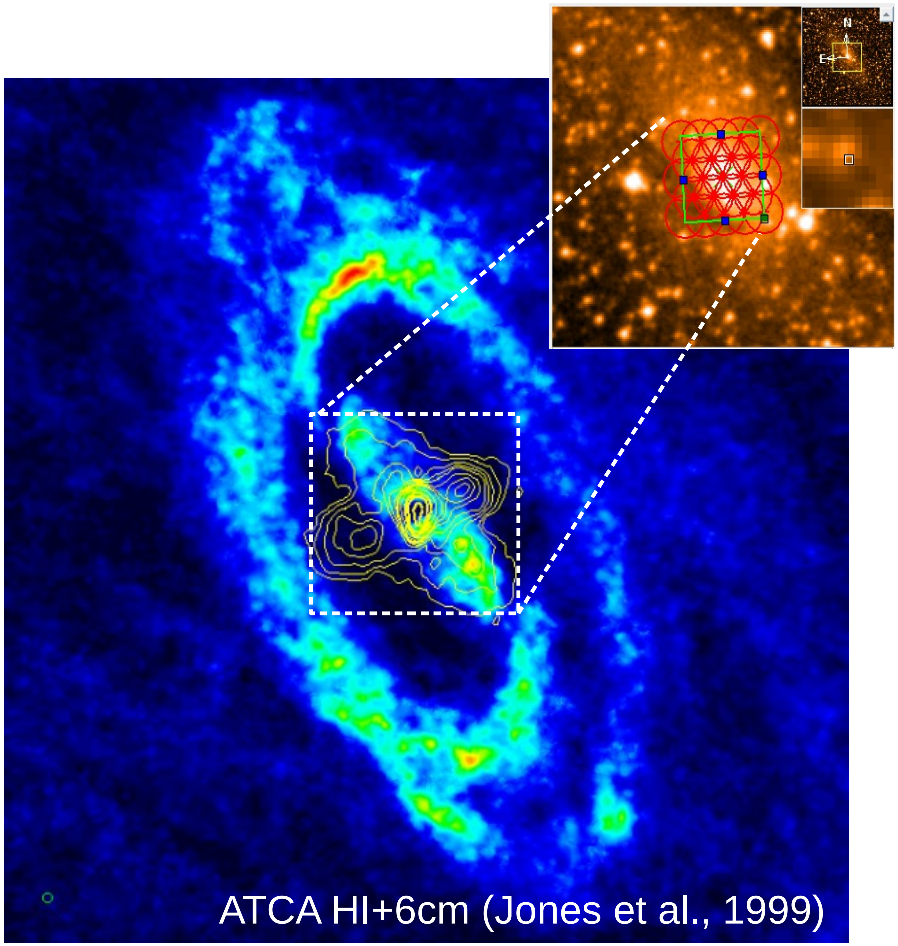
- High temperatures > 100 K
- High HC3N, CH3CN and c-HCCCH abundances
  → Hot gas-phase chemistry in the AGN thorus ?
  (Harada et al. 2010)
- High SiO, and H2S abundances
  → Sputtering of dust grains in shocks ?
- CH3OH lower than in Galactic hot-cores
  → Dissociated by X-rays or shock fine-tuning?

To take home

- Multi-band observations are crucial to derive reliable abundances and excitation
- With ALMA, multi-band spectral scans are trivial to obtain (if you get the time...)
- We see large variations of abundances and excitation, much larger than variations in line ratios
- Compact obscured IR nuclei show a rich chemistry, probably a mix of hot gas-phase chemistry and X-ray dissociation
- Vibrationally excited spectra provide a way of detecting hidden compact IR sources

The near future

Spatially resolved chemistry and excitation in the Circinus galaxy
ALMA Cycle 3 (P.I. : F. Costagliola)


ATCA HI+6cm (Jones et al., 1999)

The nearest obscured Seyfert nucleus

Combined AGN + Starburst + Outflow system

Beam-matched observations in bands 3, 6 and 7

2''.5 Resolution = 35 pc = NGC1068 (Garcia-Burillo 2014)

Sensitivity 10 times higher than in NGC1068

Target species: CO, HCN, HCO+. HC3N, vib-lines, SiO, CS, ...

Main goals:
- Derive complete excitation and reliable abundances
- Test reliability of AGN tracers (ratios, vib-lines)
- Benchmark for studies of extragalactic chemistry and excitation