

ALMA

High-Resolution Spectroscopy of Luminous Galaxies

nearby

Sergio Martín Ruiz

Zakopane, May 15th 2015



We can still check everything ALMA did so far



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More ALMA Publications

Publications

For a detailed listing of key ALMA-related publications, see [The Atacama Large Millimeter/submillimeter Array](#) Wootten, A. & Thompson, A. R. 2009 IEEE 97, 1463.

- [ALMA-Related Papers in ADS](#)
- [Conferences & Presentations](#)
- [Documentation & Memos](#)

More News

ALMA in April 2015 eNews
(April 2, 2015)

ALMA Cycle 3 Call for Proposals Released (March 24, 2015)

A New Call for ALMA Development Studies & Webinar (March 19, 2015)

[View Archived News](#)

ALMA Events

ALMA Data Reduction Party
May 06 - 08, 2015
Charlottesville, VA

NRAO NAASC Interferometry School
Jul 12 - 14, 2015
Green Bank, WV

[View Archived Events](#)

Extragalactic community is still bright-line biased

PAPER COUNTING: ~33 (no high-z)

- **CO** 15
- **HCN / HCO⁺ / CS** 7
- **MULTI-MOLECULE** 7
- **Other** 1 (H α) + 3 (cont.)

CO

**Ground breaking new
e-galactic environments**

Exploring new e-galactic environments with CO



The antennae Galaxies

- Major gas-rich merger
- Interaction vs ISM and SF ⁶
- Most stars forming in SSCs (10 Mo) ⁸
- Super GMCs (10 Mo, 500 pc)

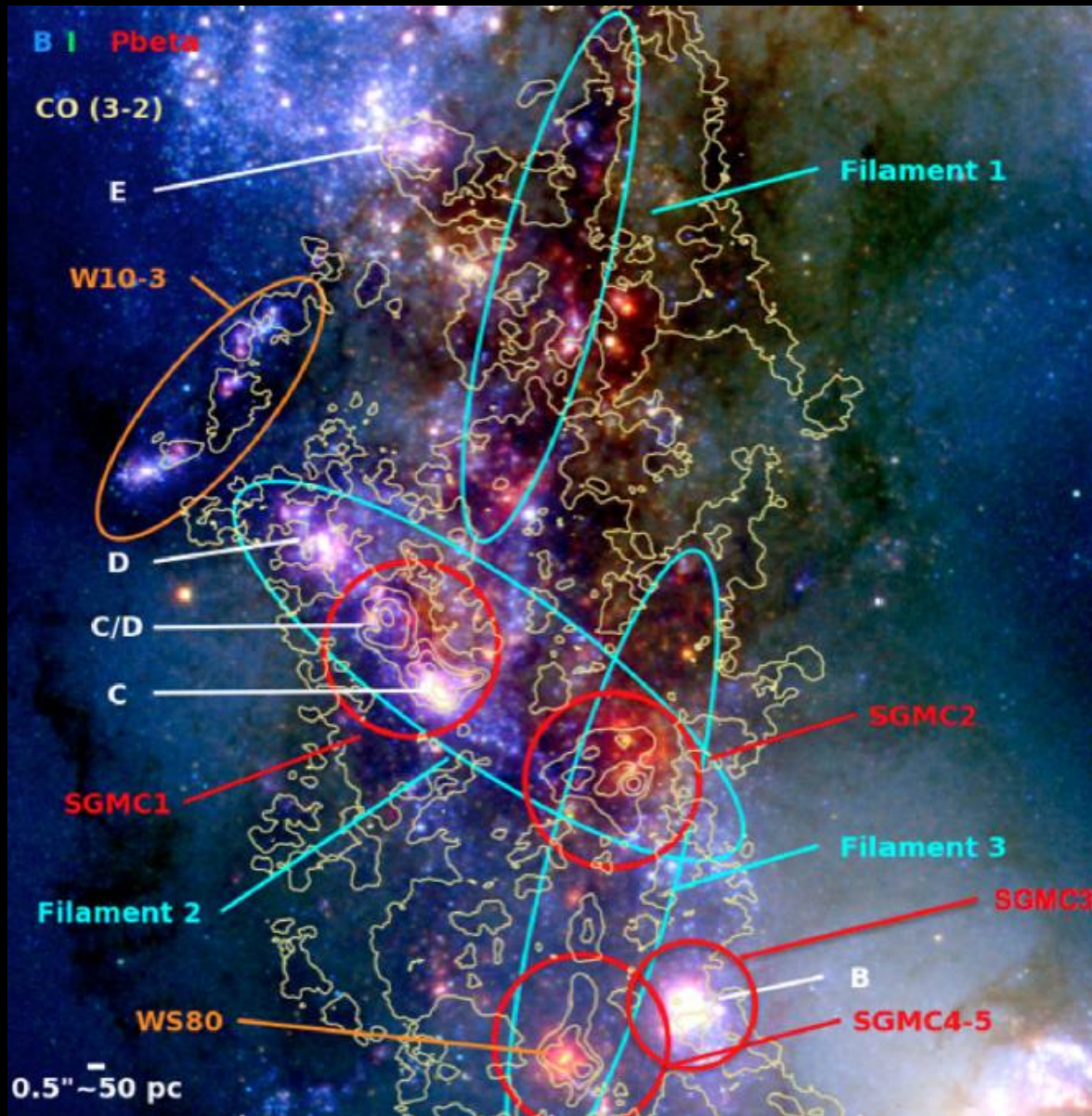


Science Verification Data:

Herrera +2012,

Espada+2012

Exploring new e-galactic environments with CO

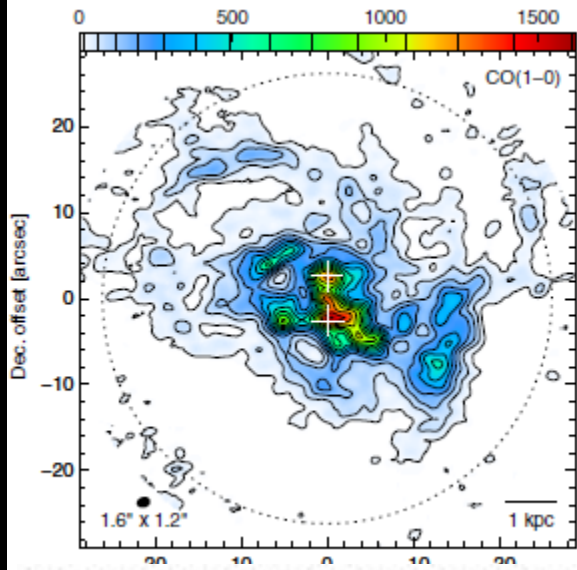


Whitmore +2014

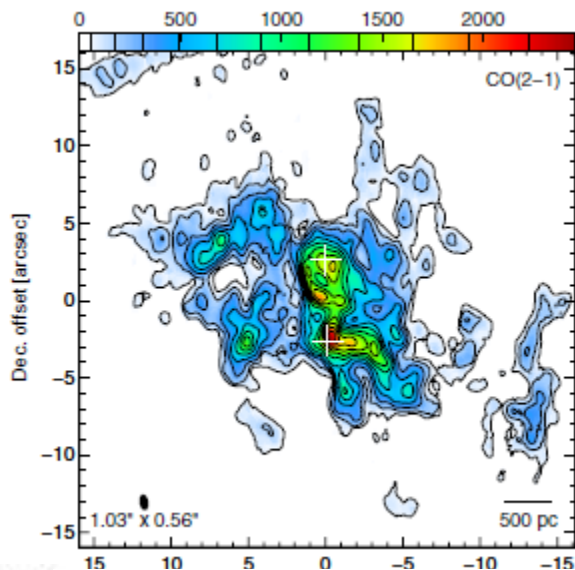
Cycle 0 dataset: Johnson+2015, Paper II, III, V (in prep.) + Cabrera Zibri+2015

Exploring new e-galactic environments with CO

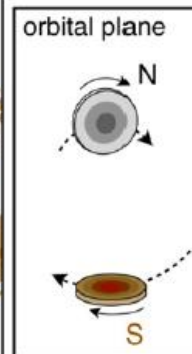
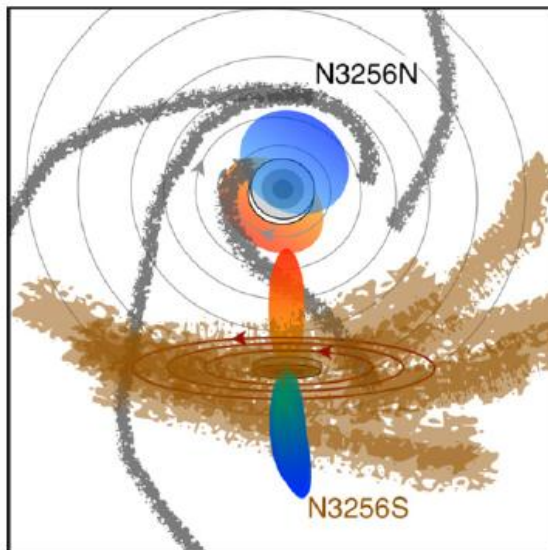
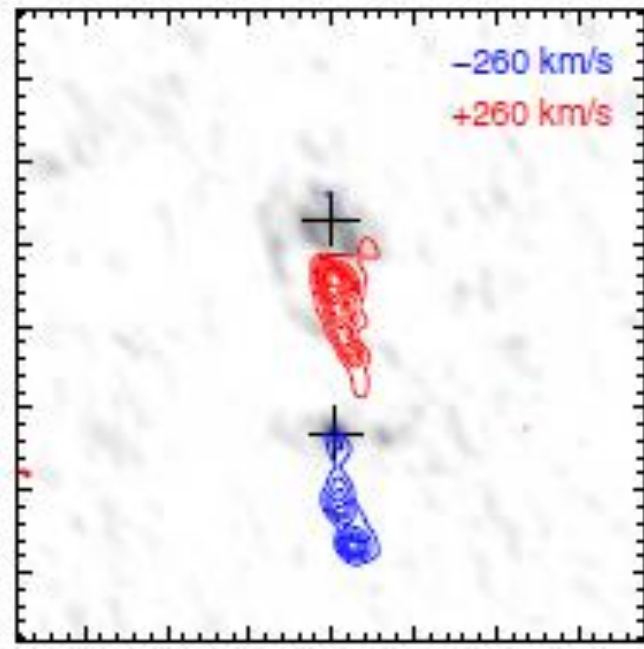
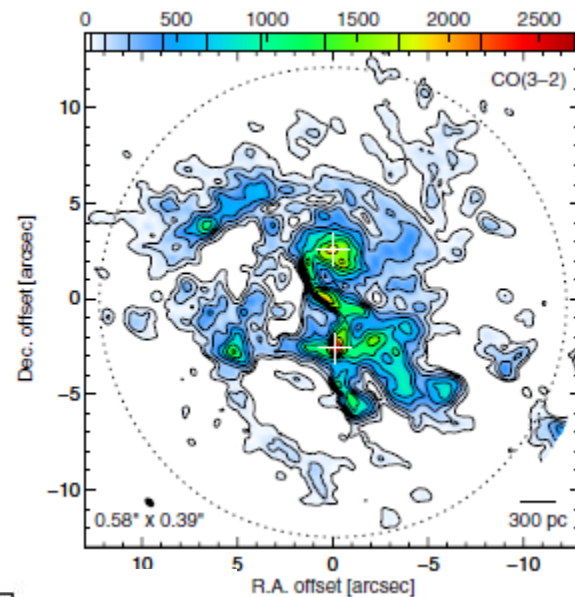
ALMA CO 1-0



SMA CO 2-1



ALMA CO 3-2

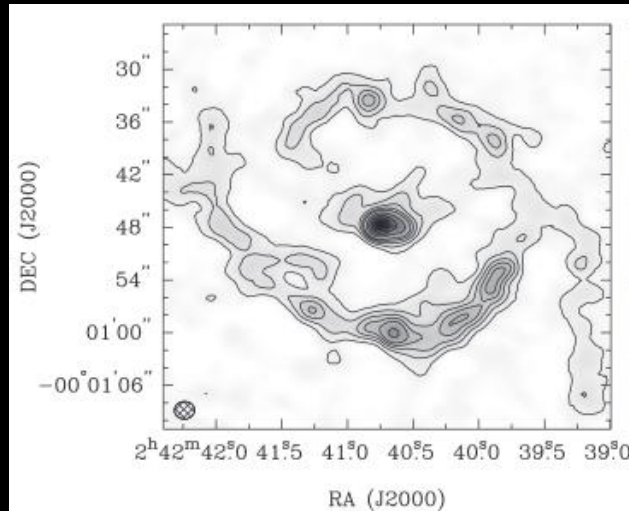


(Sakamoto+2015)

Cycle 0

NGC 3256 :
Most luminous
galaxy within
 $z=0.01$

Exploring new e-galactic environments with CO

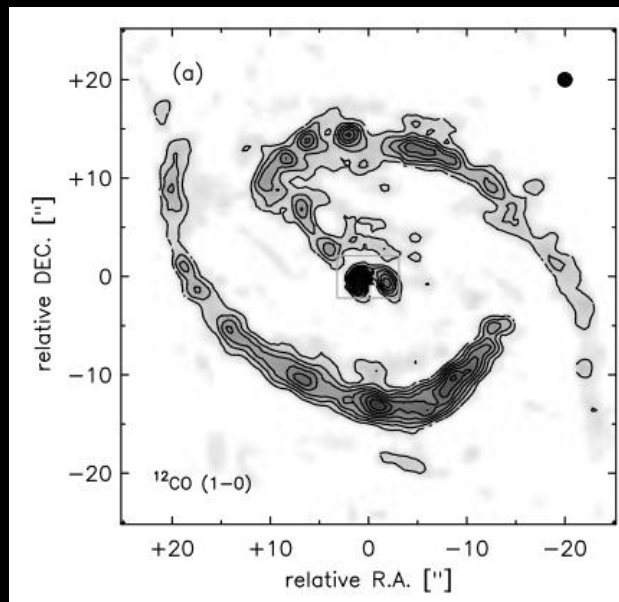


NGC 1068

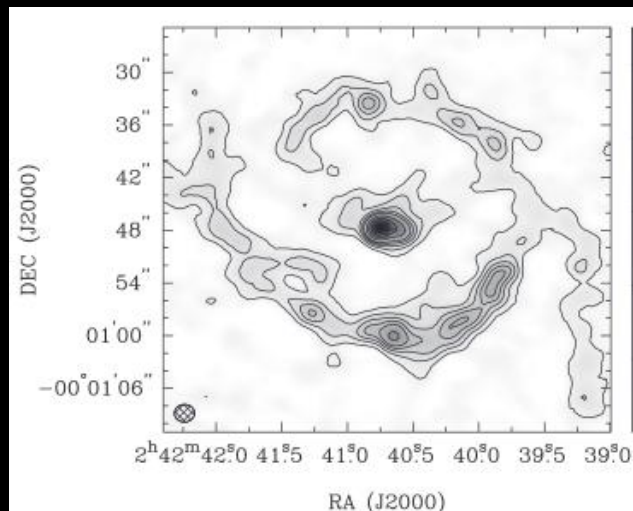
The prototypical Sy 2 nearby galaxy

CO 3-2 SMA Tsai+2012

CO 1-0 PdBI Schinnerer+2012

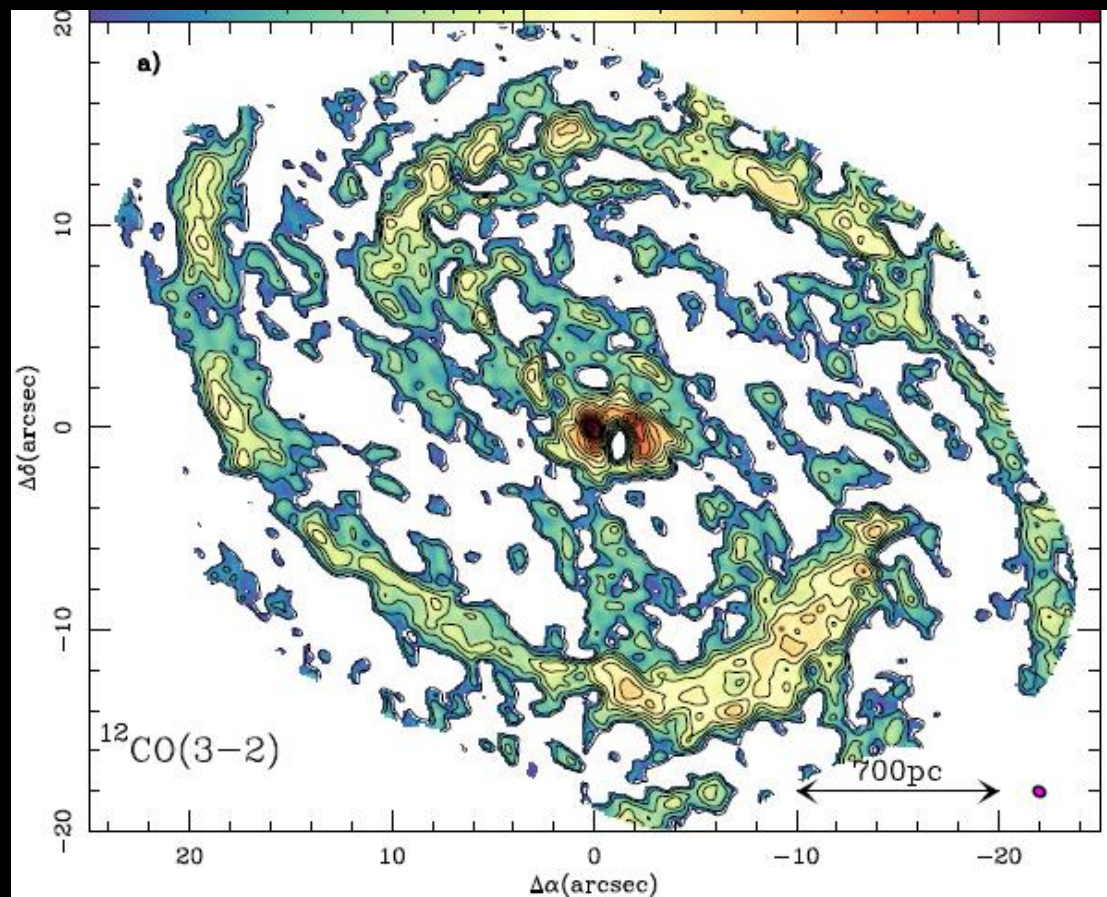
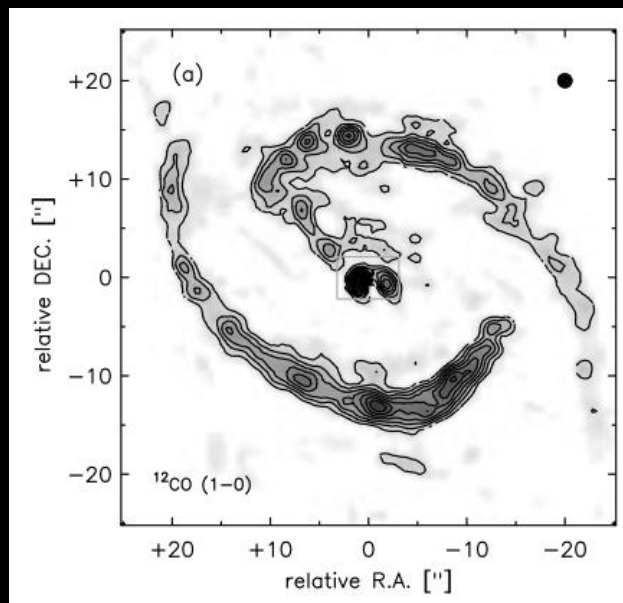


Exploring new e-galactic environments with CO



CO 3-2 SMA Tsai+2012

CO 1-0 PdBI Schinnerer+2012

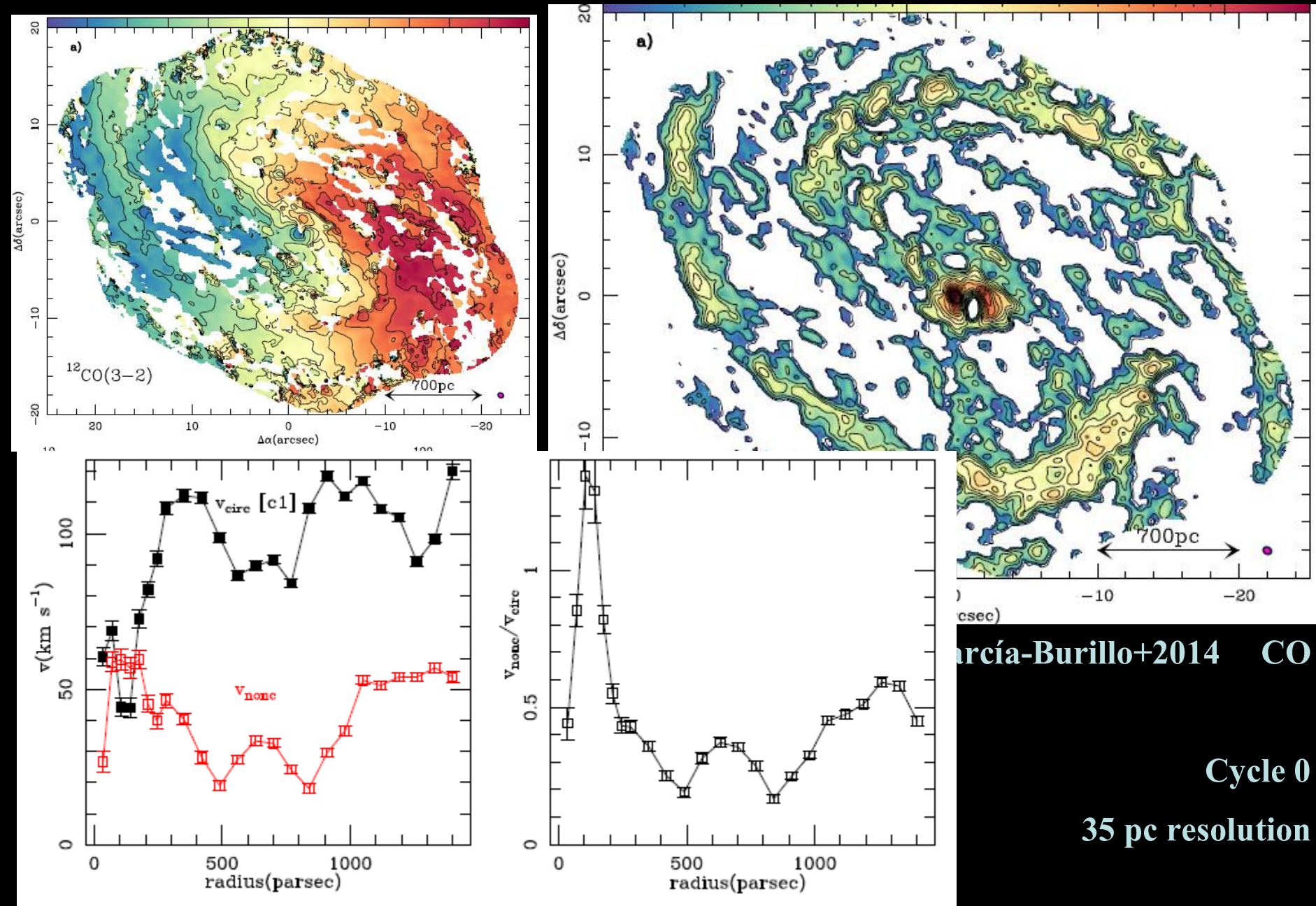


García-Burillo+2014 CO

Cycle 0

35 pc resolution

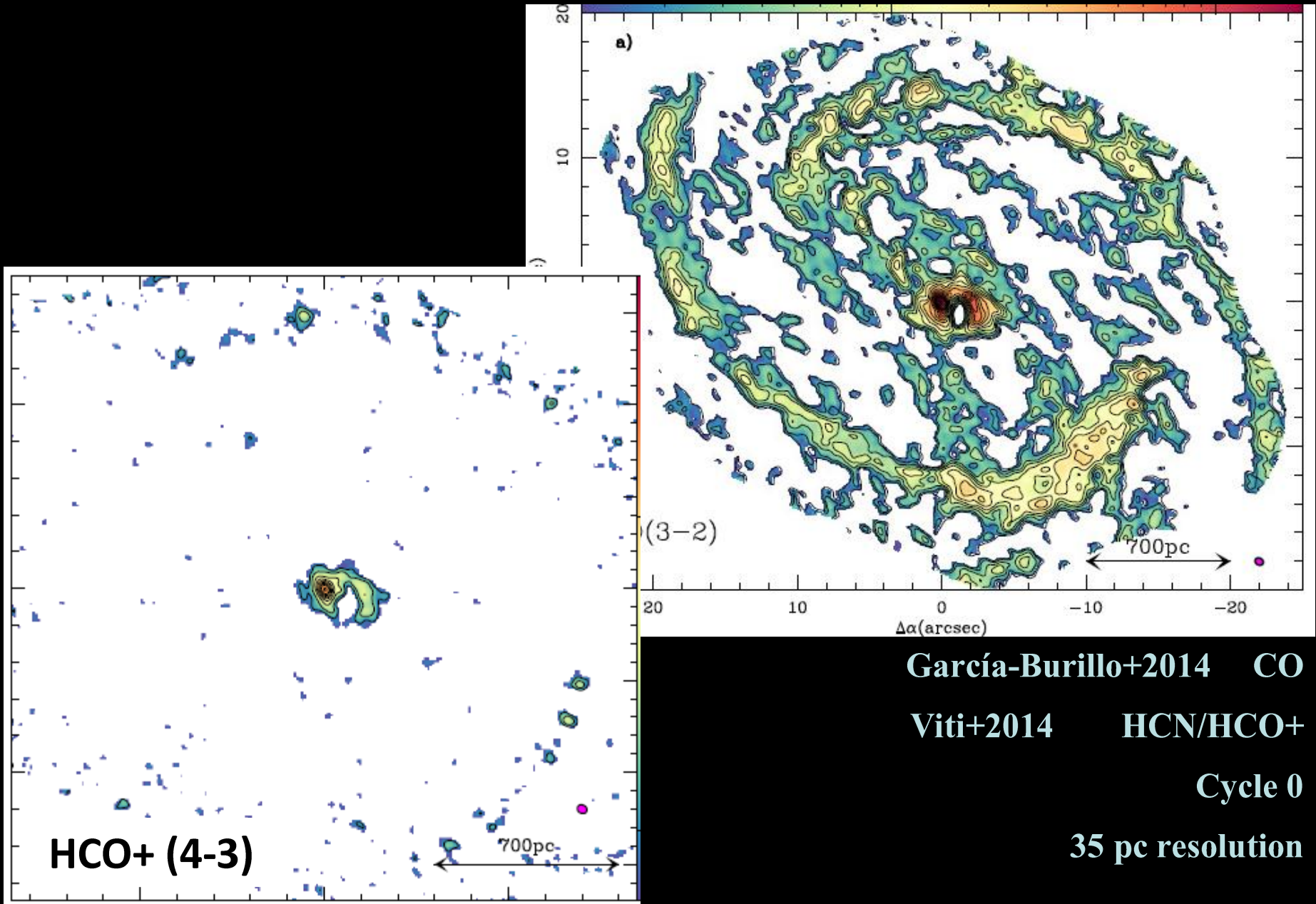
Exploring new e-galactic environments with CO



arcía-Burillo+2014 CO

Cycle 0

35 pc resolution

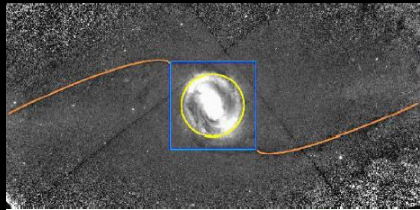


García-Burillo+2014 CO

Viti+2014 HCN/HCO+

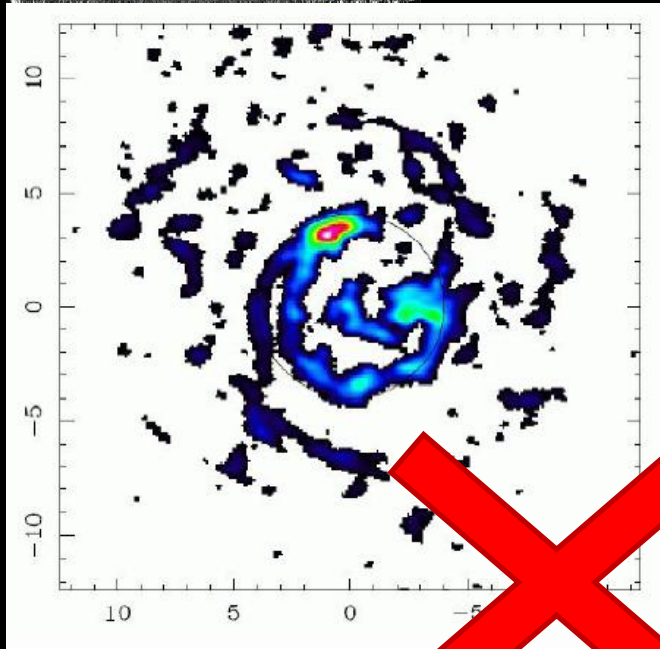
Cycle 0

35 pc resolution



NGC1433

Sy 2



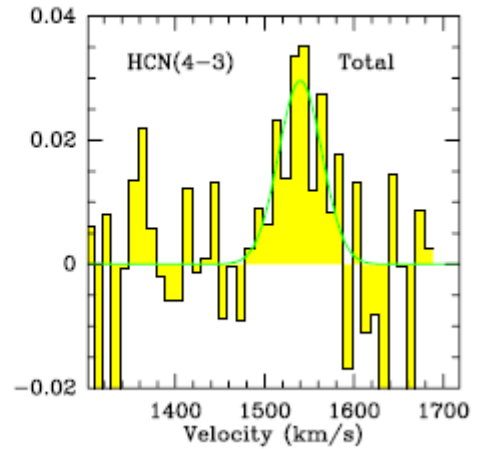
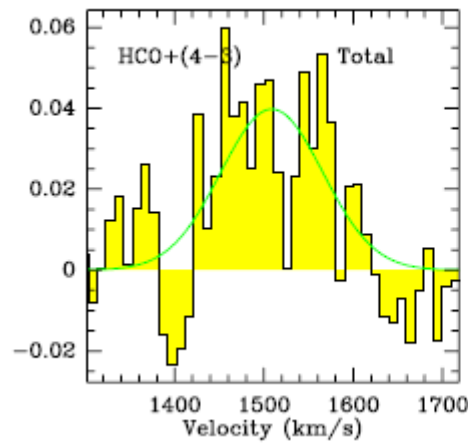
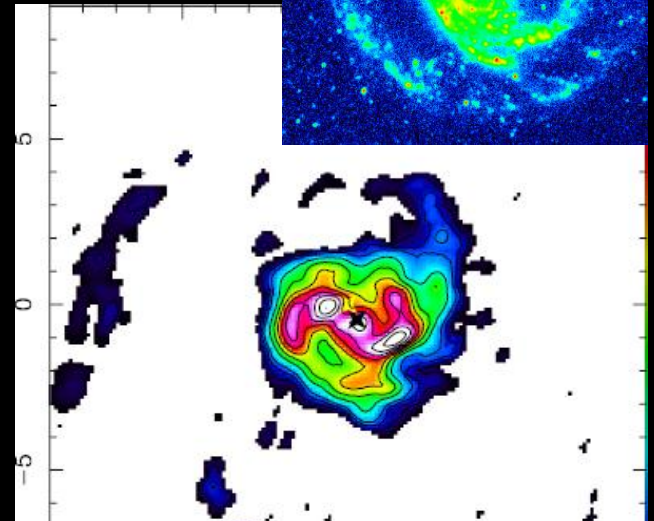
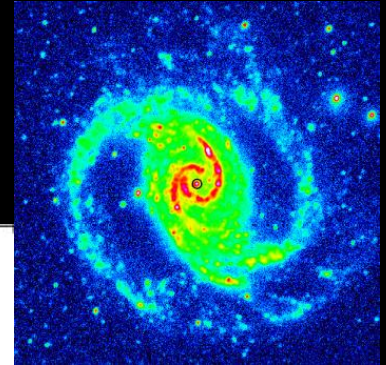
(Combes +2013)



Cycle 0
0.5''-25 pc
resolution

NGC1566

Sy 1



HCN / HCO⁺ / CS

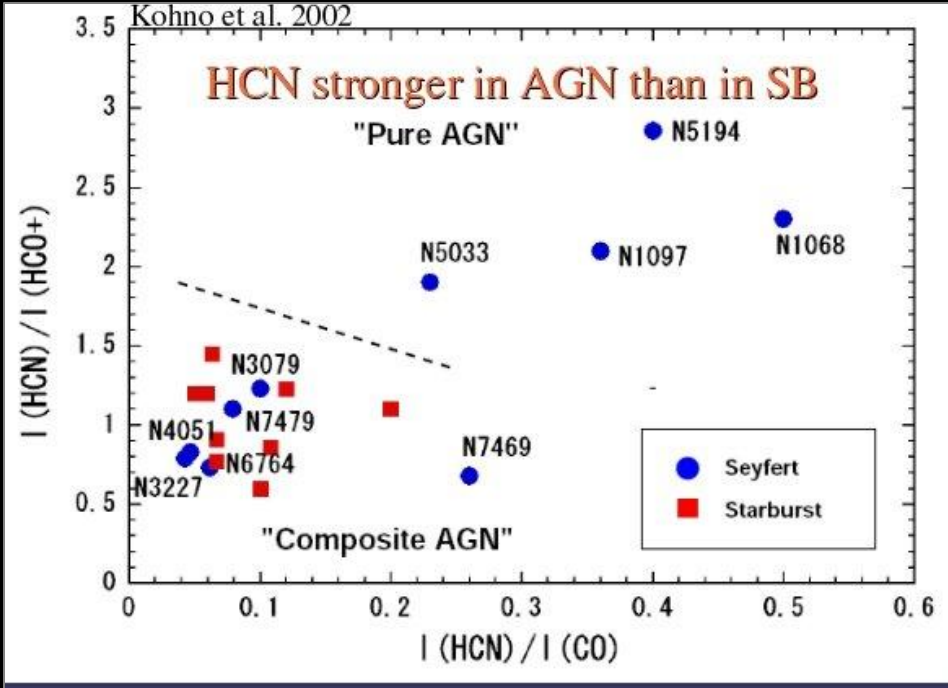
The truth is out there

HCN/HCO⁺/CS as diagnostic tools...some truth in them

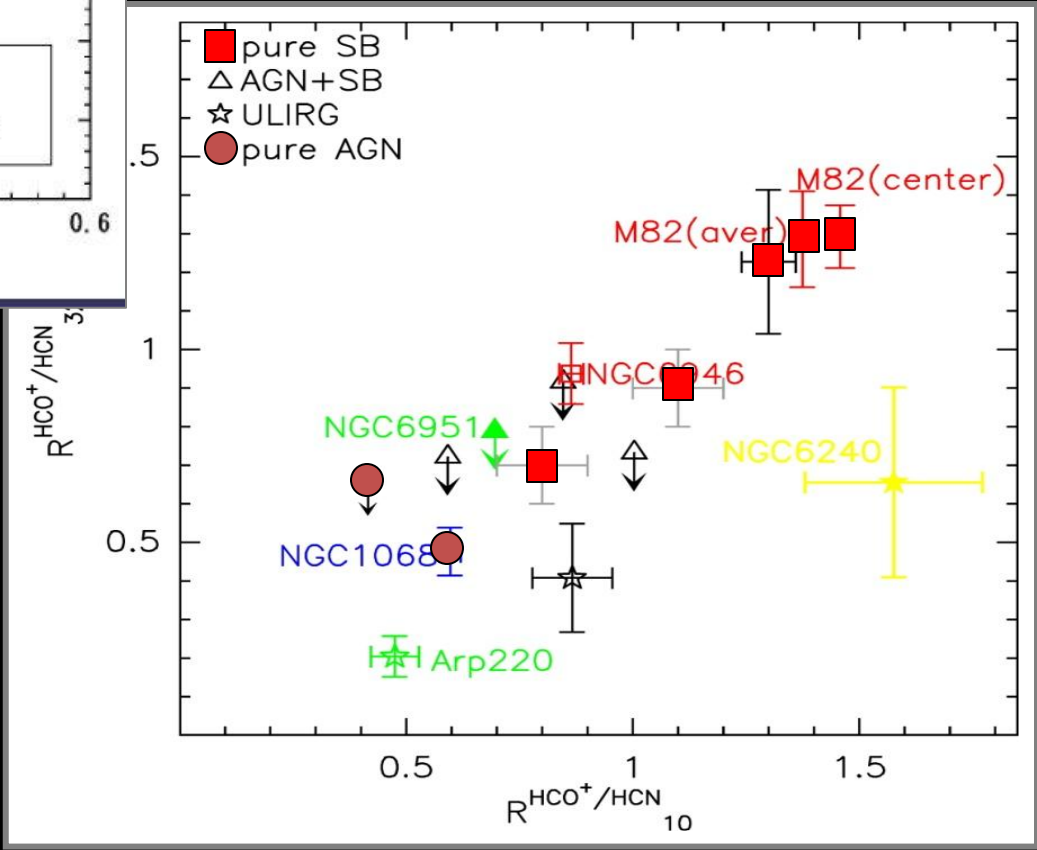
AGN vs SB

HCN/HCO⁺

(Krips et al. 2008)



(Kohno et al. 2002)



HCN/HCO⁺/CS as diagnostic tools...some truth in them

**Models predict higher HCN/HCO⁺ as a consequence of XDR chemistry
(Meijerink 2007, Imanishi et al. 2007)**

**Systematically denser in AGNs? Excitation effects? Or Real Molecular
Abundances?**

**S-D data: Starbursts systematically denser than in AGNs
(Krips+2008)**

**ALMA data: CND around the AGN denser and hotter than the clouds in the
starburst ring
(Viti+2014)**

HCN/HCO⁺/CS as diagnostic tools...some truth in them

ALMA Cycle 0:

PI K. Kohno

NGC 1097

D ~ 14 Mpc (1'' ~ 70 pc)

Seyfert 1 Nucleus

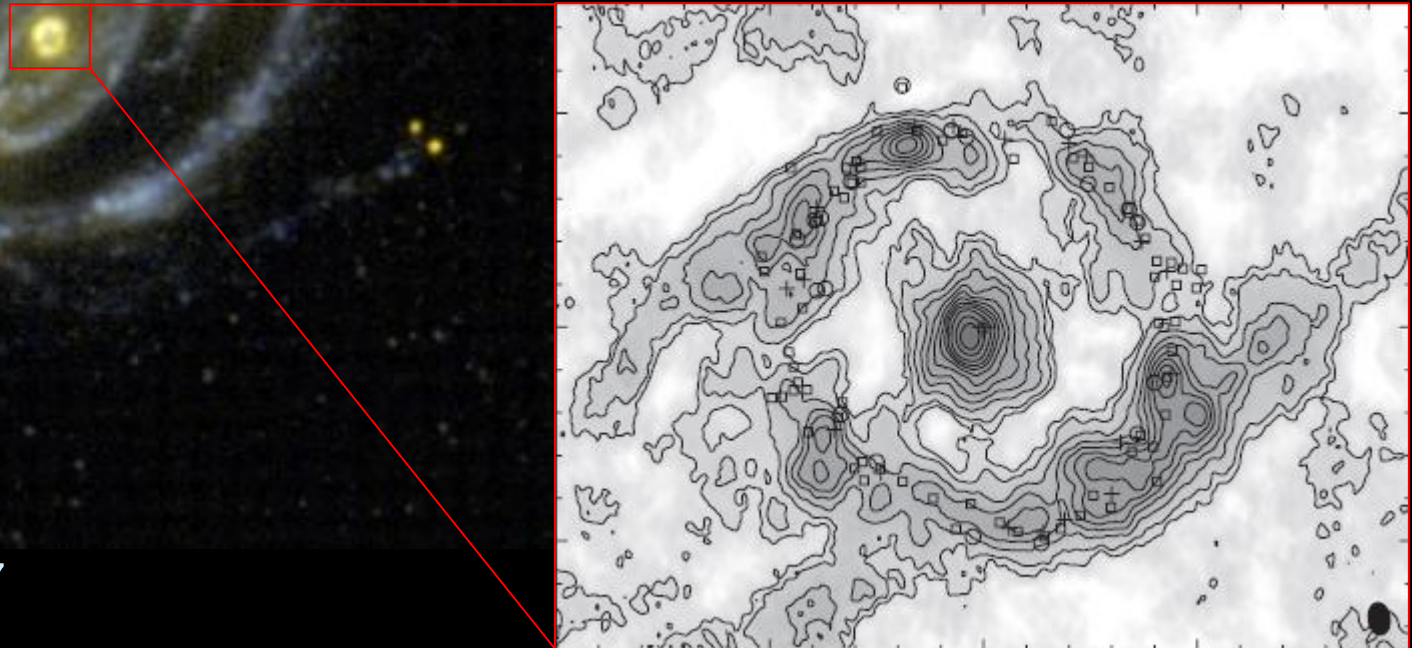
$L_{2-10 \text{ keV}} \sim 4 \cdot 10^{40} \text{ erg s}^{-1}$

$L_{\text{IR}}, L_{\text{HCN}} \sim 1/10 \text{ NGC 1068}$

Fathi+2013 - kinematics

Izumi+2013 - HCN/HCO⁺/CS

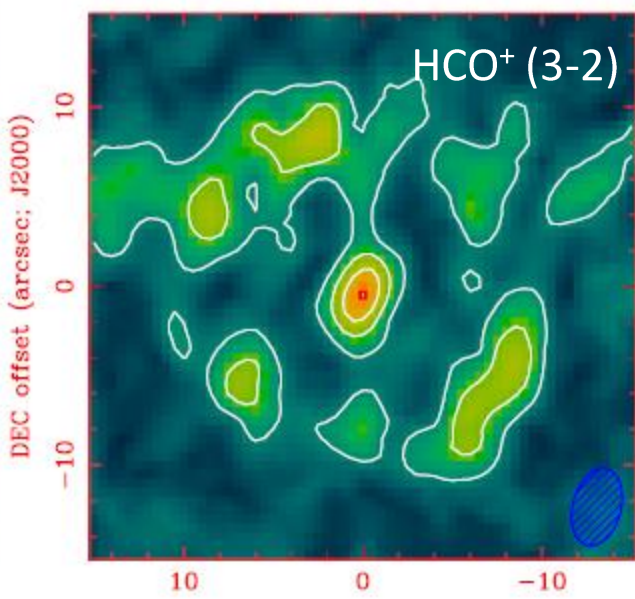
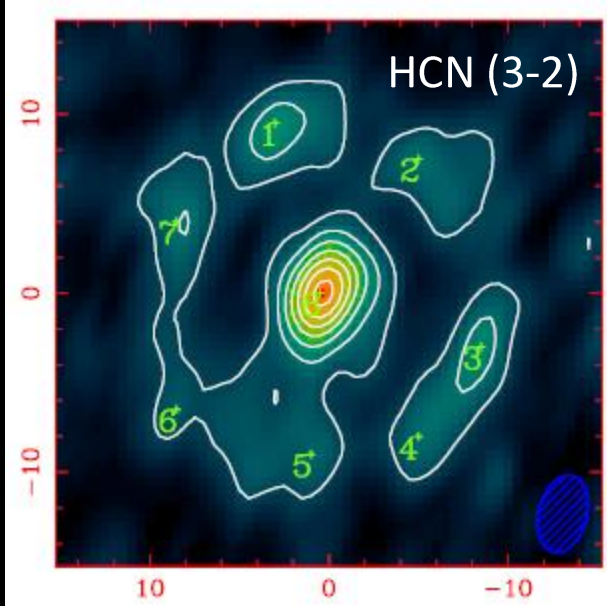
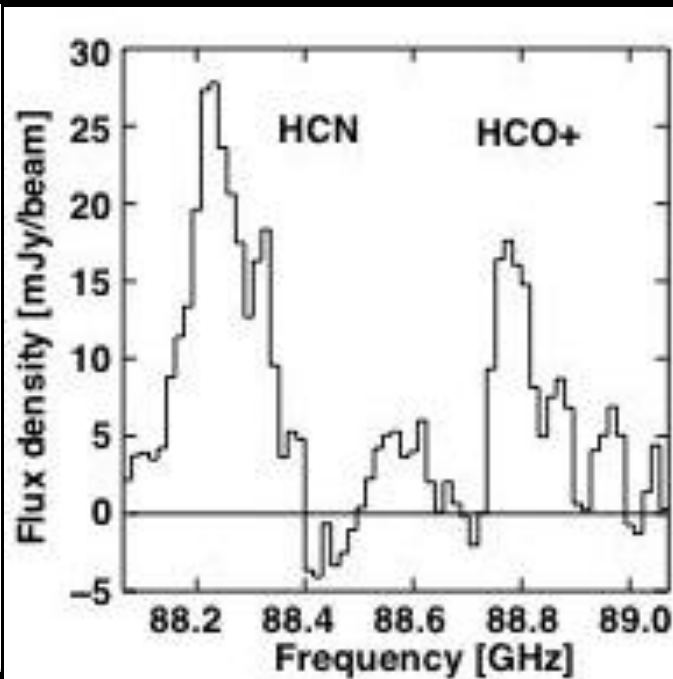
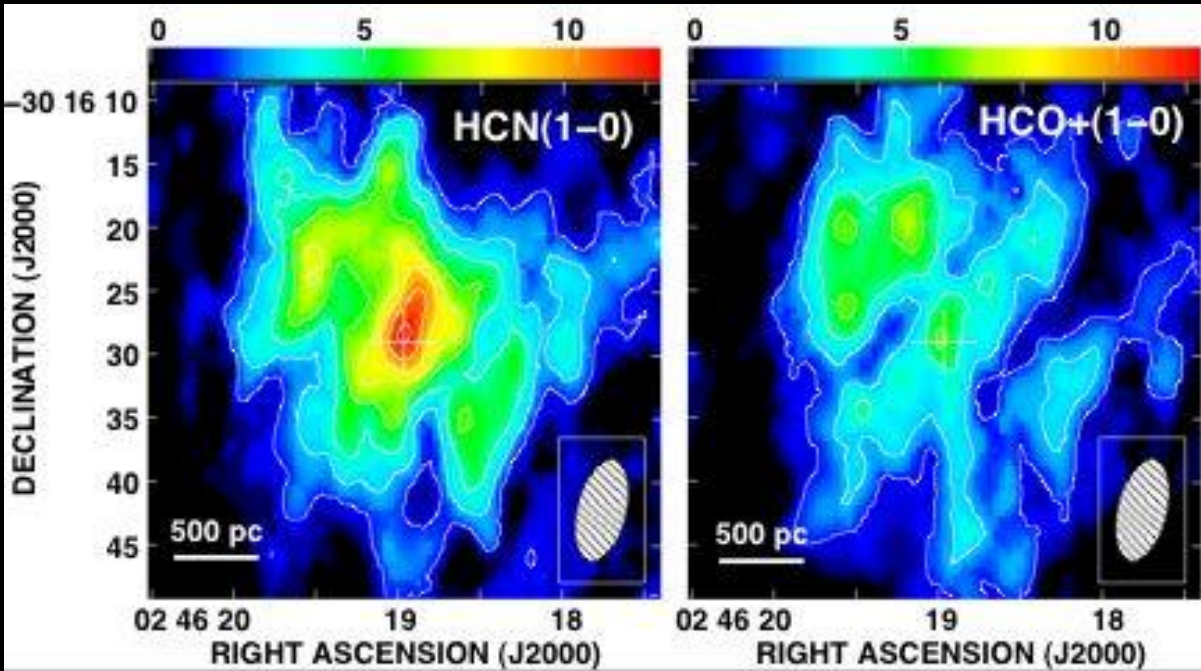
Martín+2015 - Multi-molecule
+ 2 in prep.



GALEX, Gil de Paz et al. 2007

SMA CO (2-1), Hsieh et al. 2011

HCN/HCO⁺/CS as diagnostic tools...some truth in them



NMA

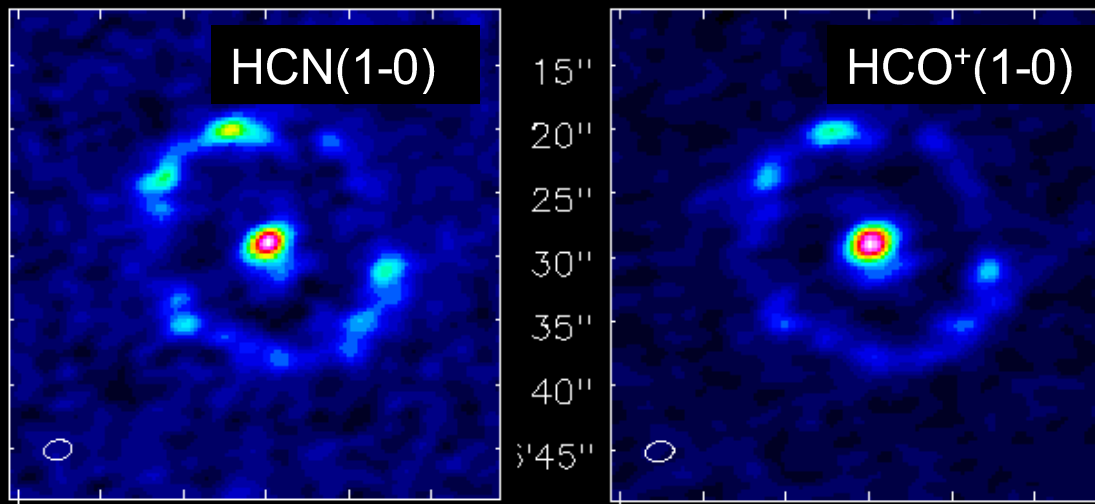
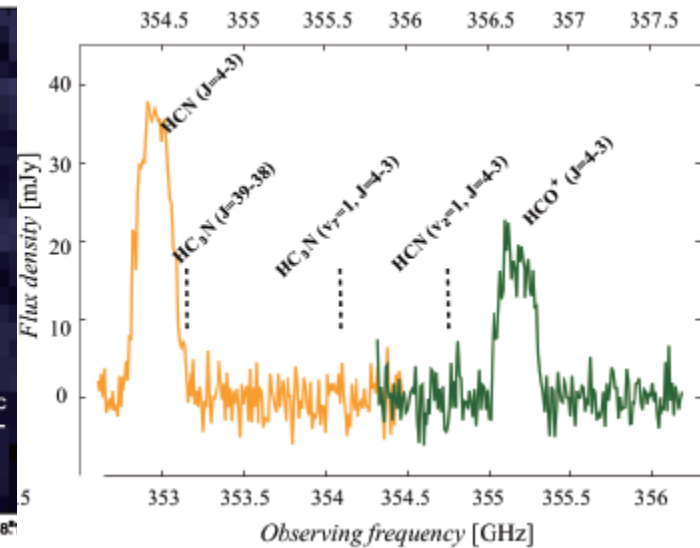
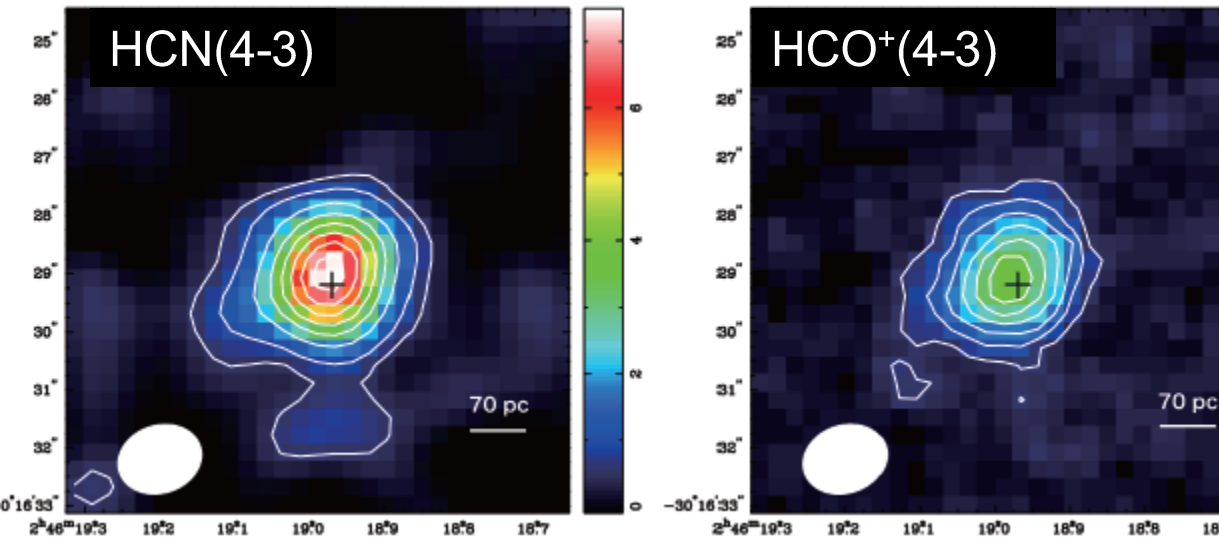
Kohno et al. 2007

SMA

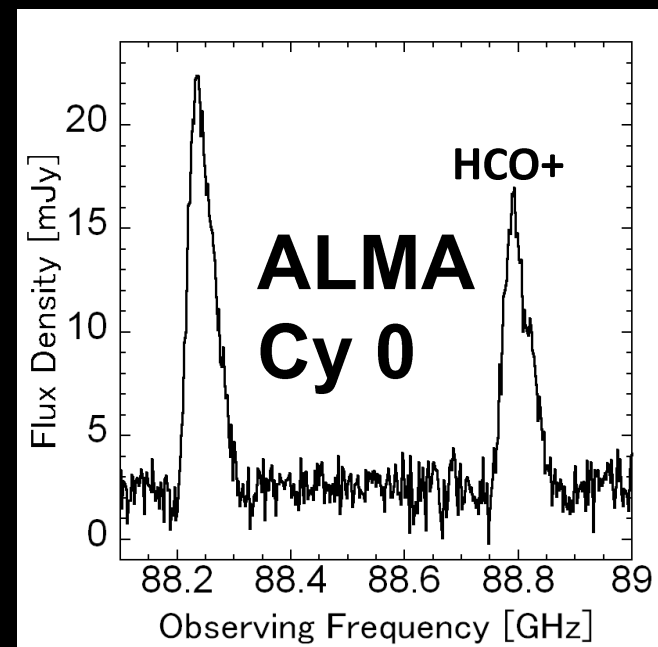
Hsieh et al. 2012

HCN/HCO⁺/CS as diagnostic tools...some truth in them

Izumi+2013



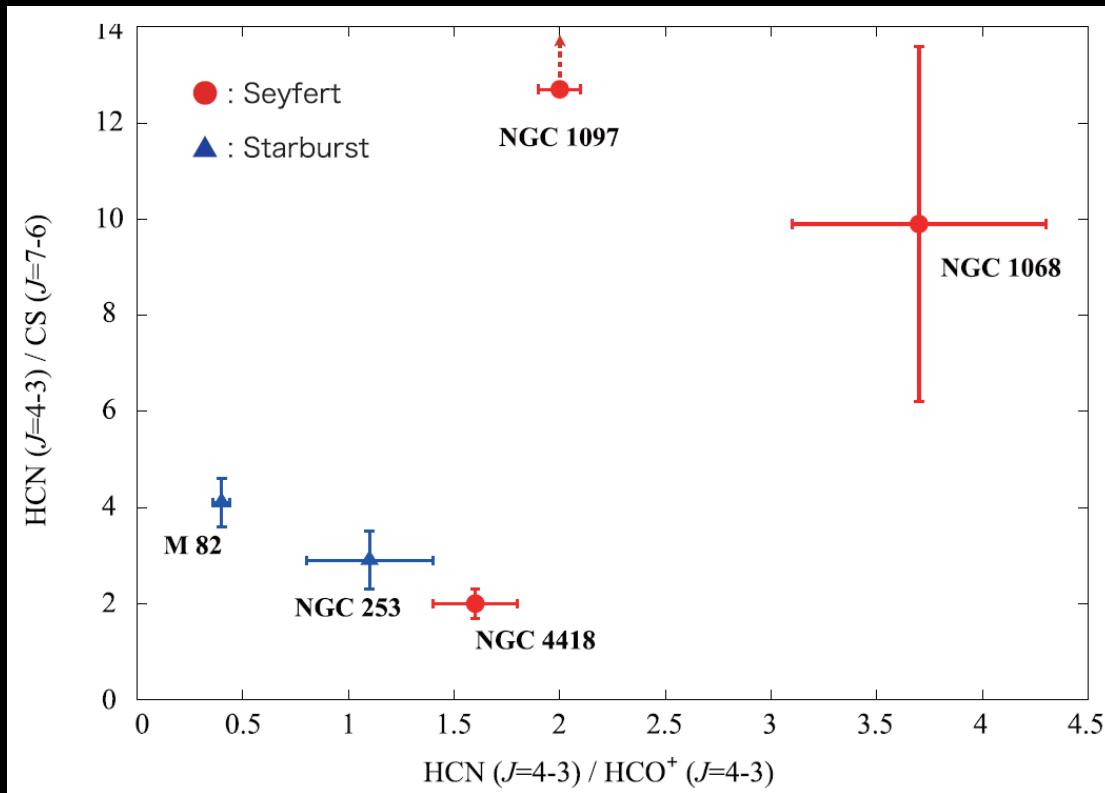
Martín+2015



HCN/HCO⁺/CS as diagnostic tools...some truth in them

AGN vs SB

HCN/CS vs HCN/HCO⁺

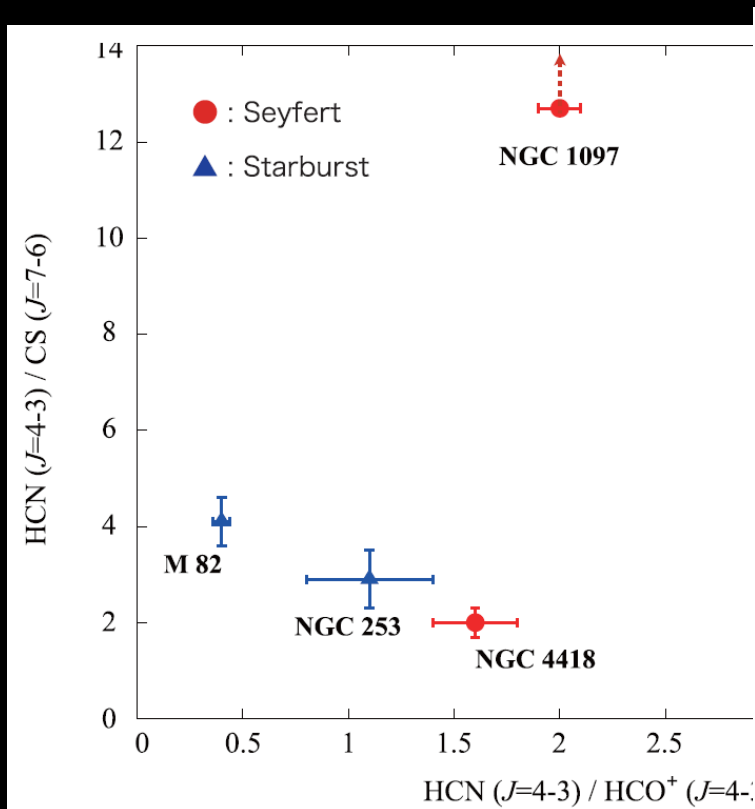


Cycle 0, Izumi +2013

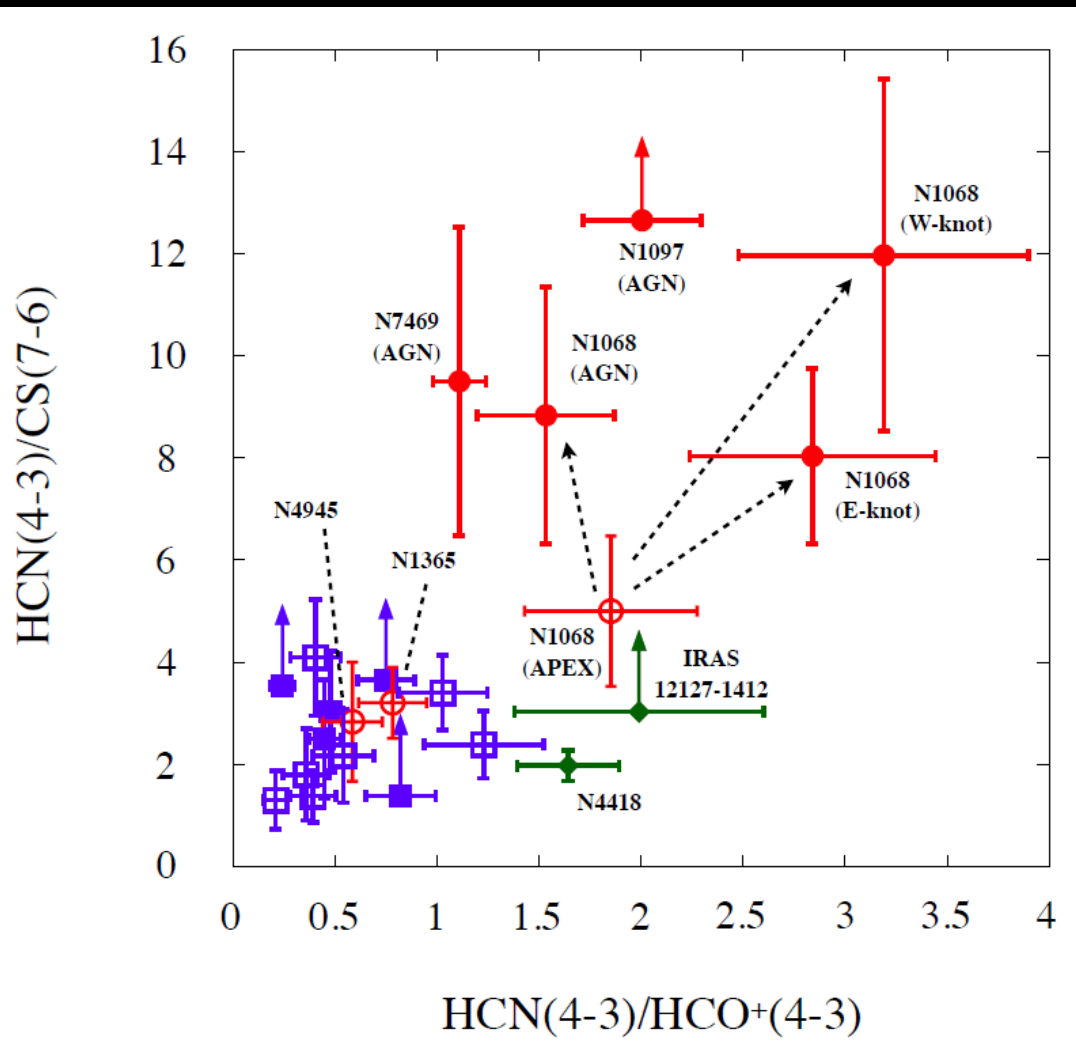
HCN/HCO⁺/CS as diagnostic tools...some truth in them

AGN vs SB

HCN/CS vs HCN/HCO⁺



Cycle 0, Izumi +2013

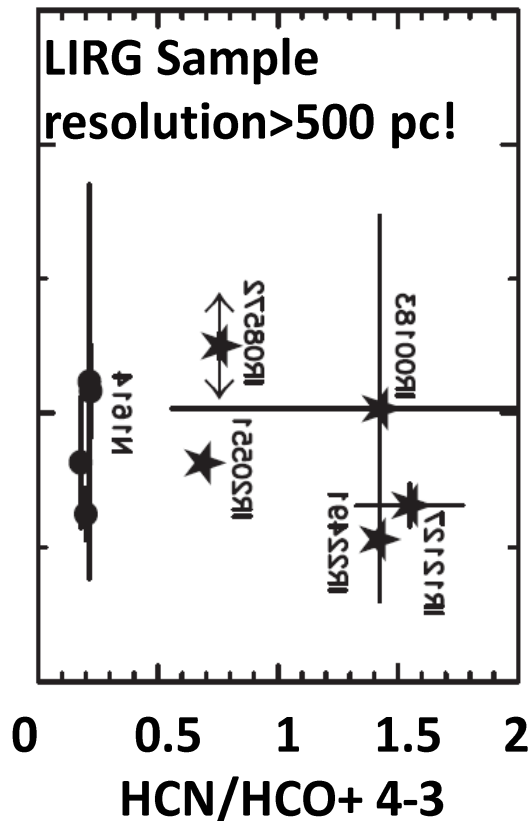


Cycle 0, Izumi submitted

HCN/HCO⁺/CS as diagnostic tools...some truth in them

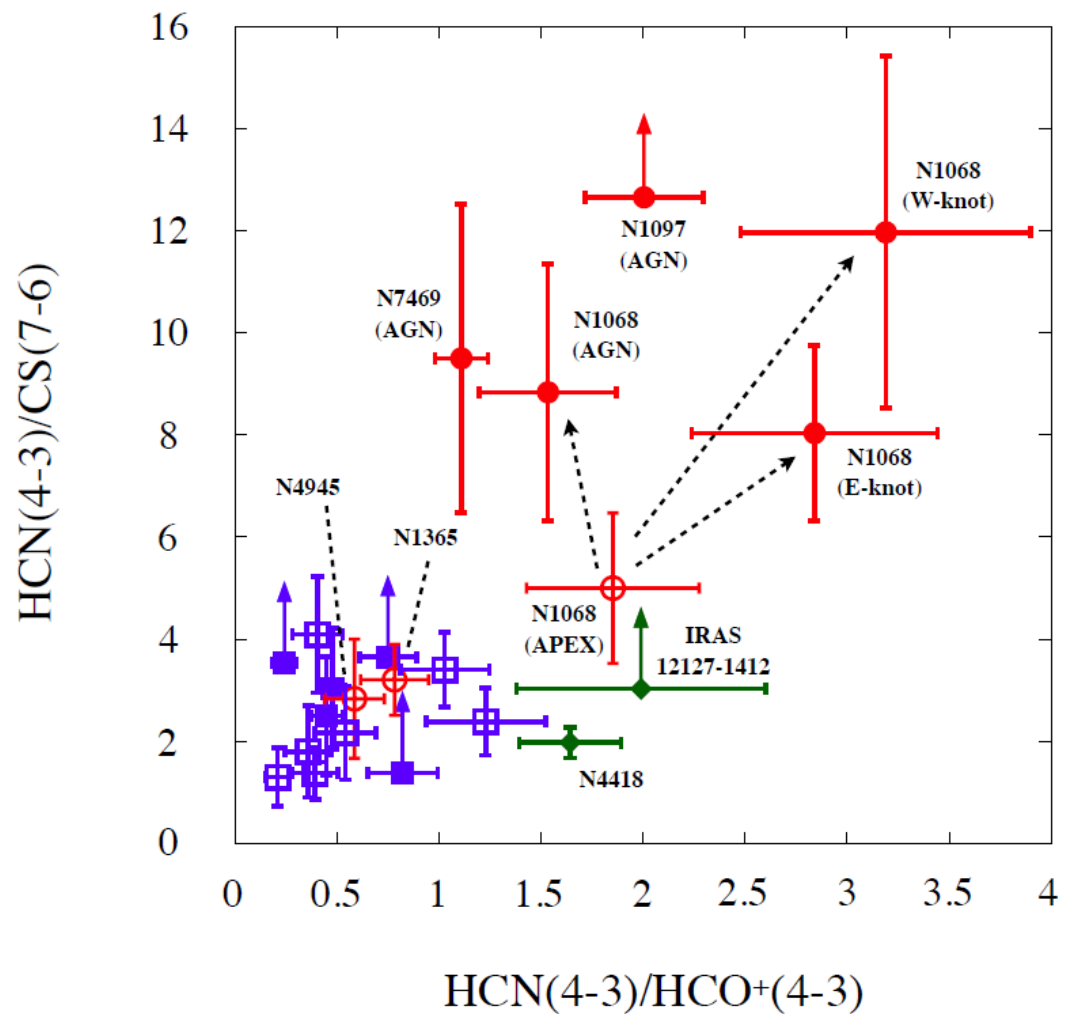
AGN vs SB

HCN/CS vs HCN/HCO⁺

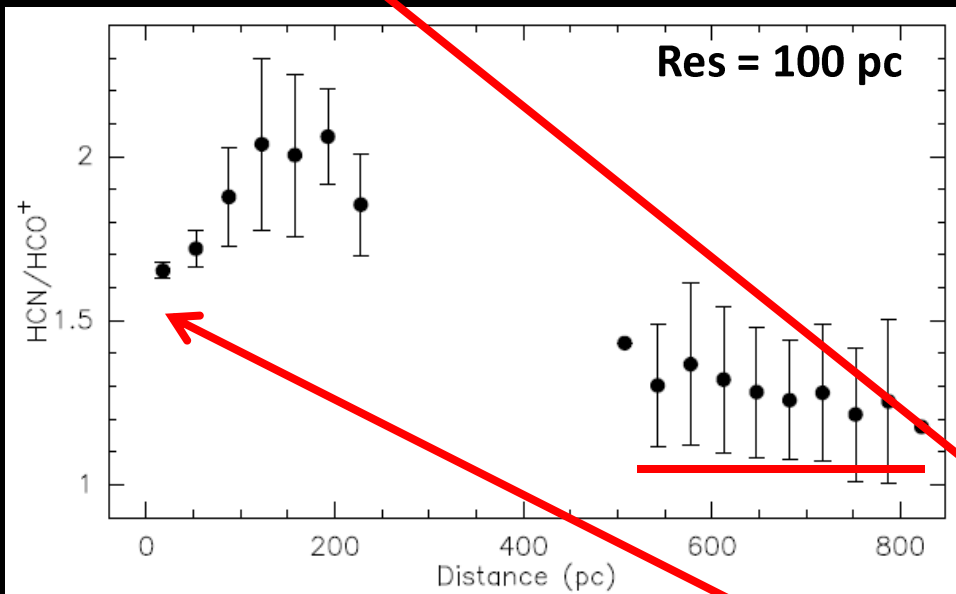


Cycle 0, Imanishi+2014

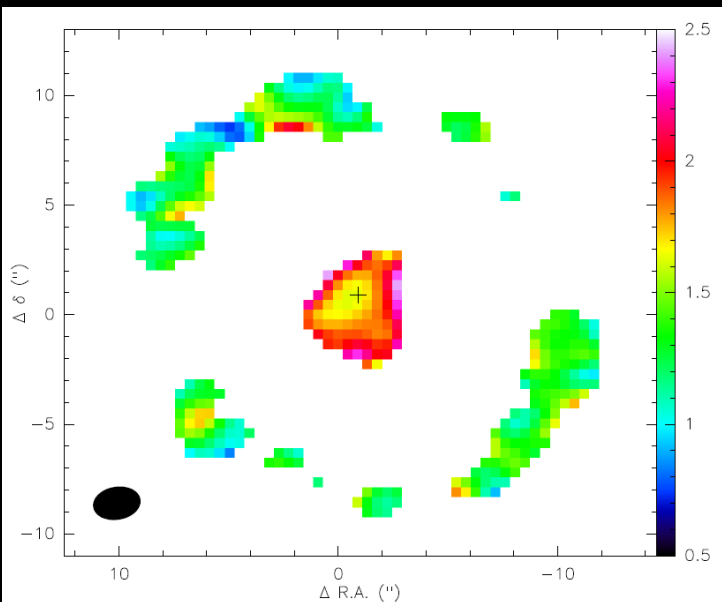
Cycle 0, Izumi submitted



HCN/HCO⁺/CS as diagnostic tools...some truth in them



NGC 1097



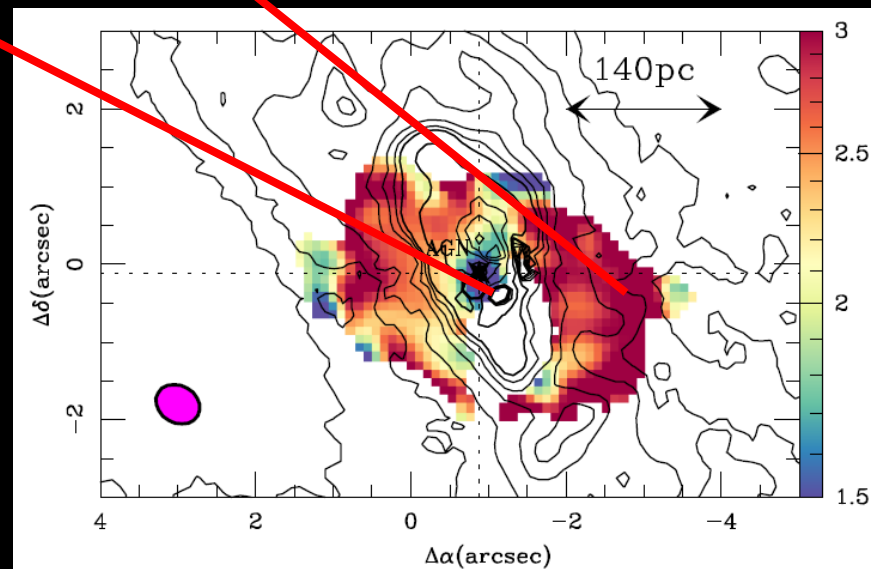
Martín+2015

Resolved HCN/HCO⁺

HCN mechanical heating enhancement:

- High temperature (Izumi et al. 2013 for NGC 1097)
- Shocks (Aalto et al. 2012 for Mrk231 outflow)

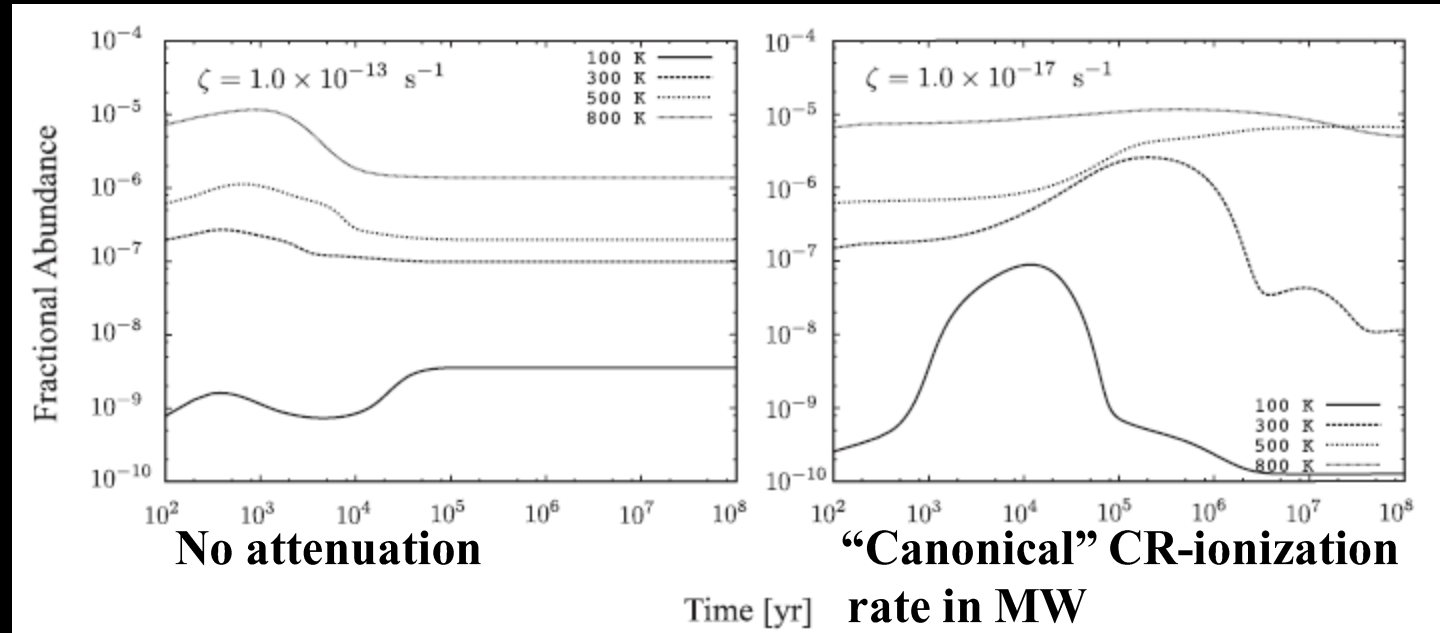
NGC 1068



García-Burillo+2014

HCN/HCO⁺/CS as diagnostic tools...some truth in them

High temperature HCN enhancement X-ray flux independent



Izumi+2013

Harada+2010

Harada+2013

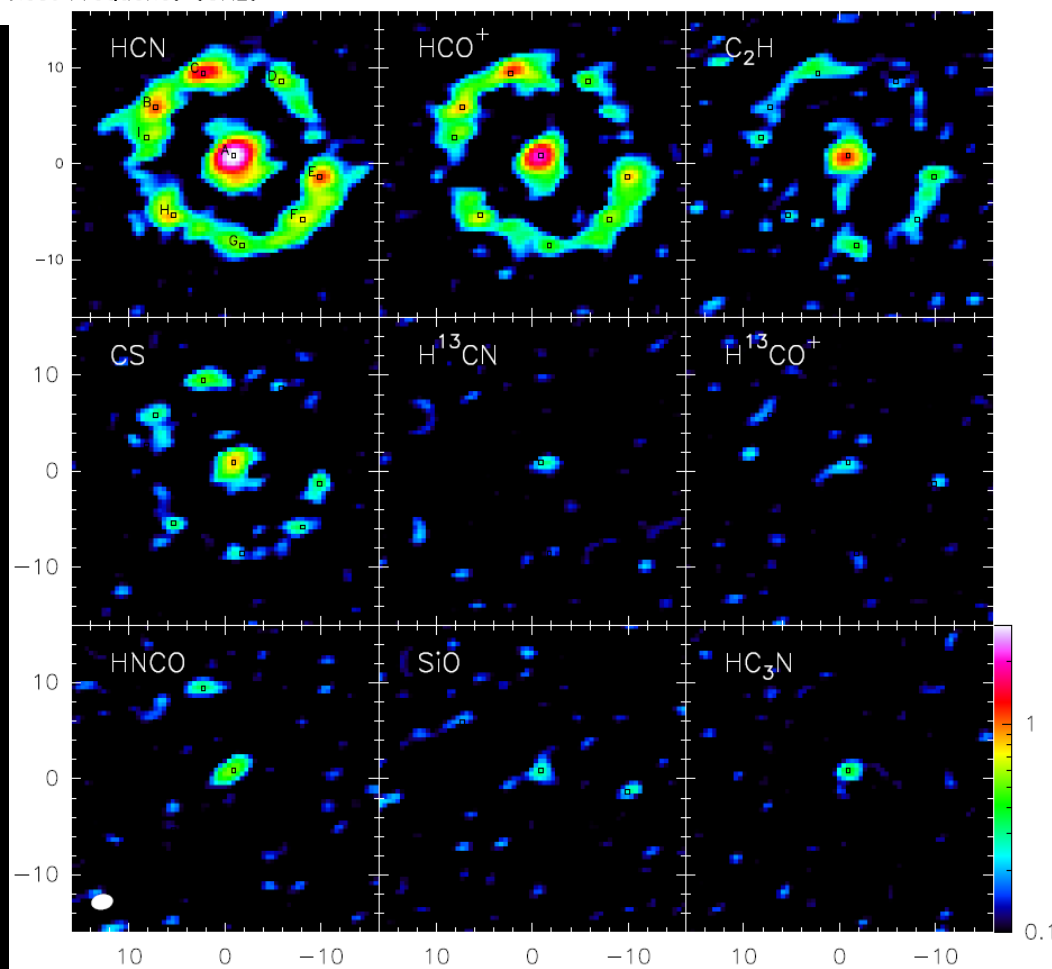
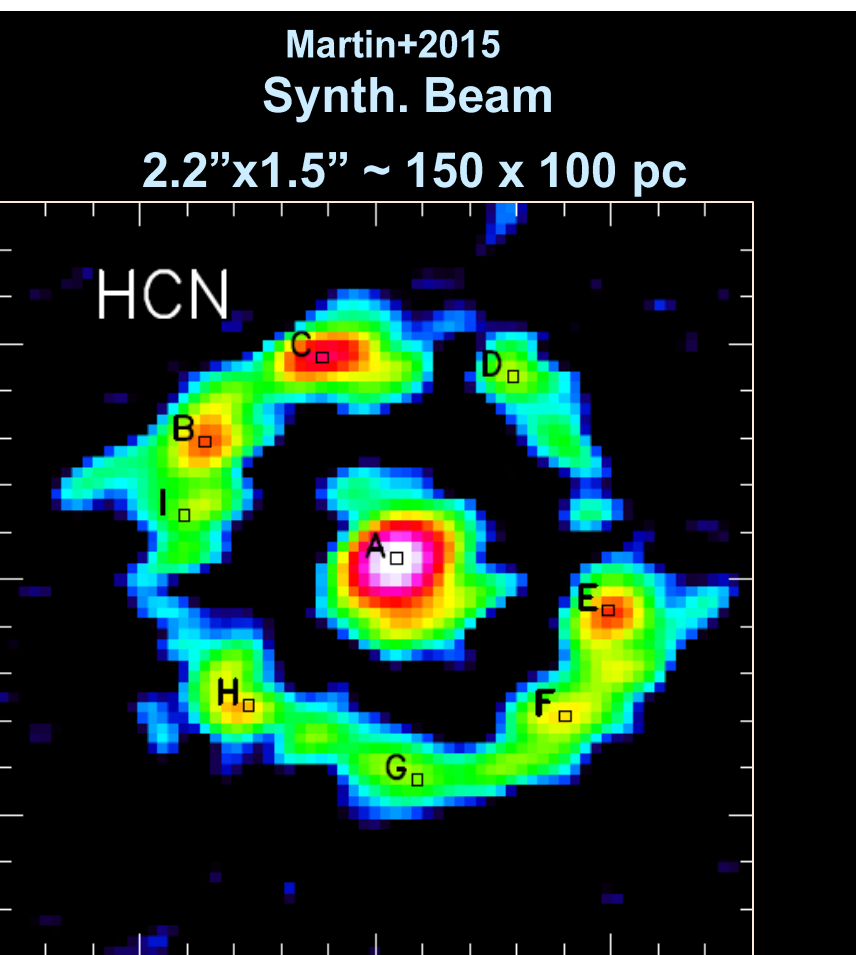
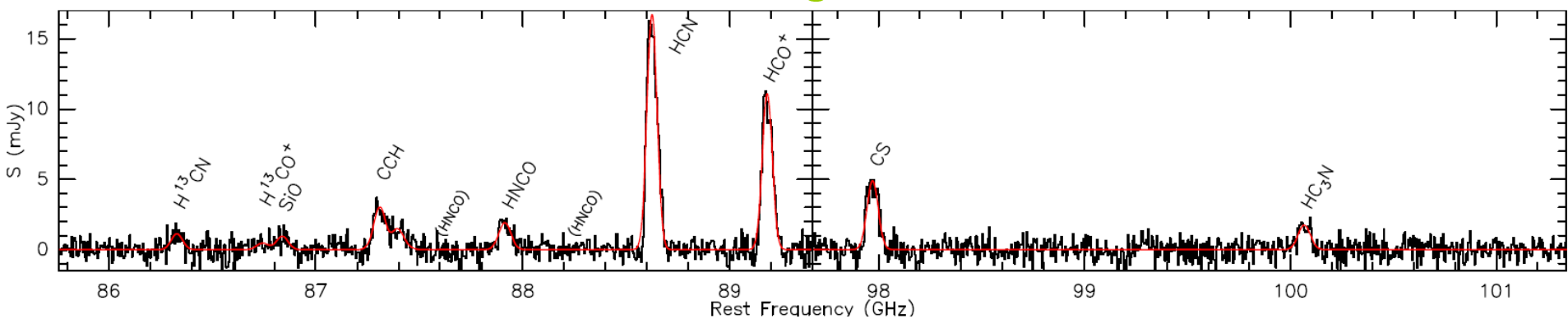


$$\gamma = 820 \text{ K}$$

Multi-molecule

The high resolution revolution

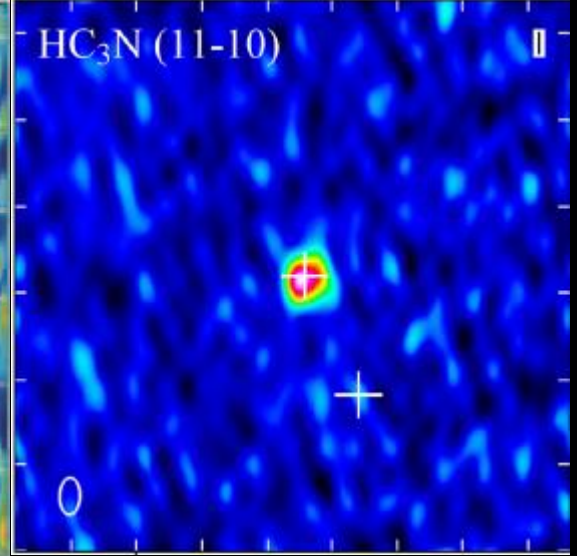
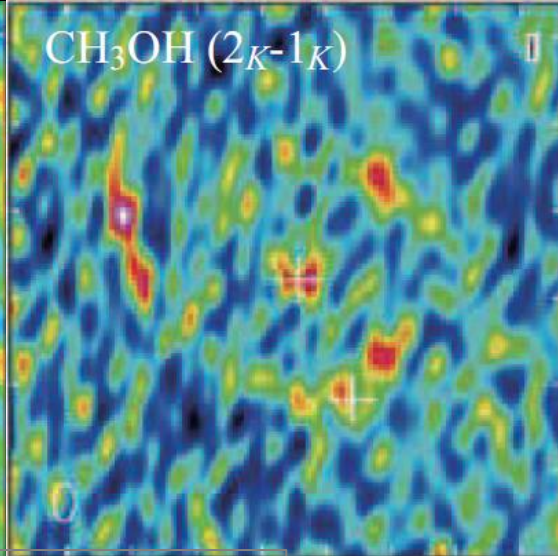
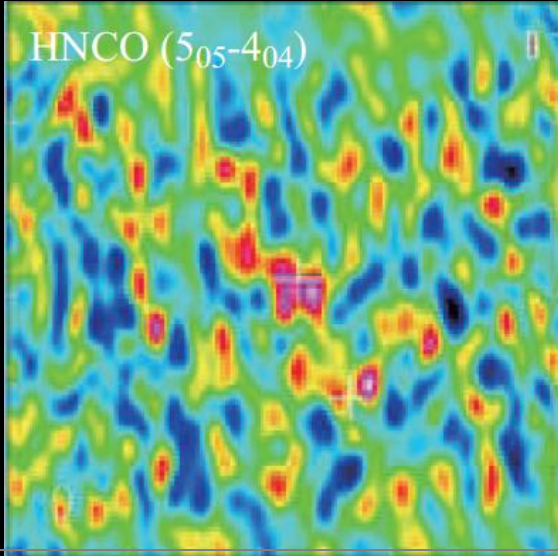
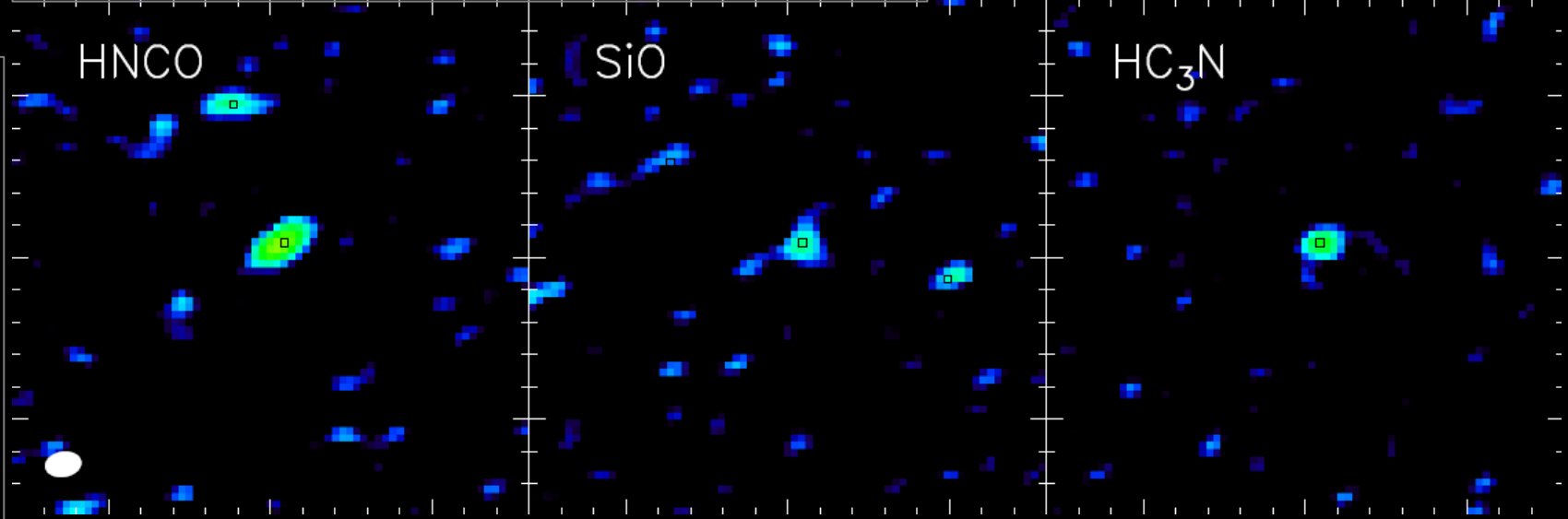
Multi-molecular observations revealing the structure of CND around AGNs



Multi-molecular observations revealing the structure of CND around AGNs

NGC 1097 Sy 1 Low luminosity AGN

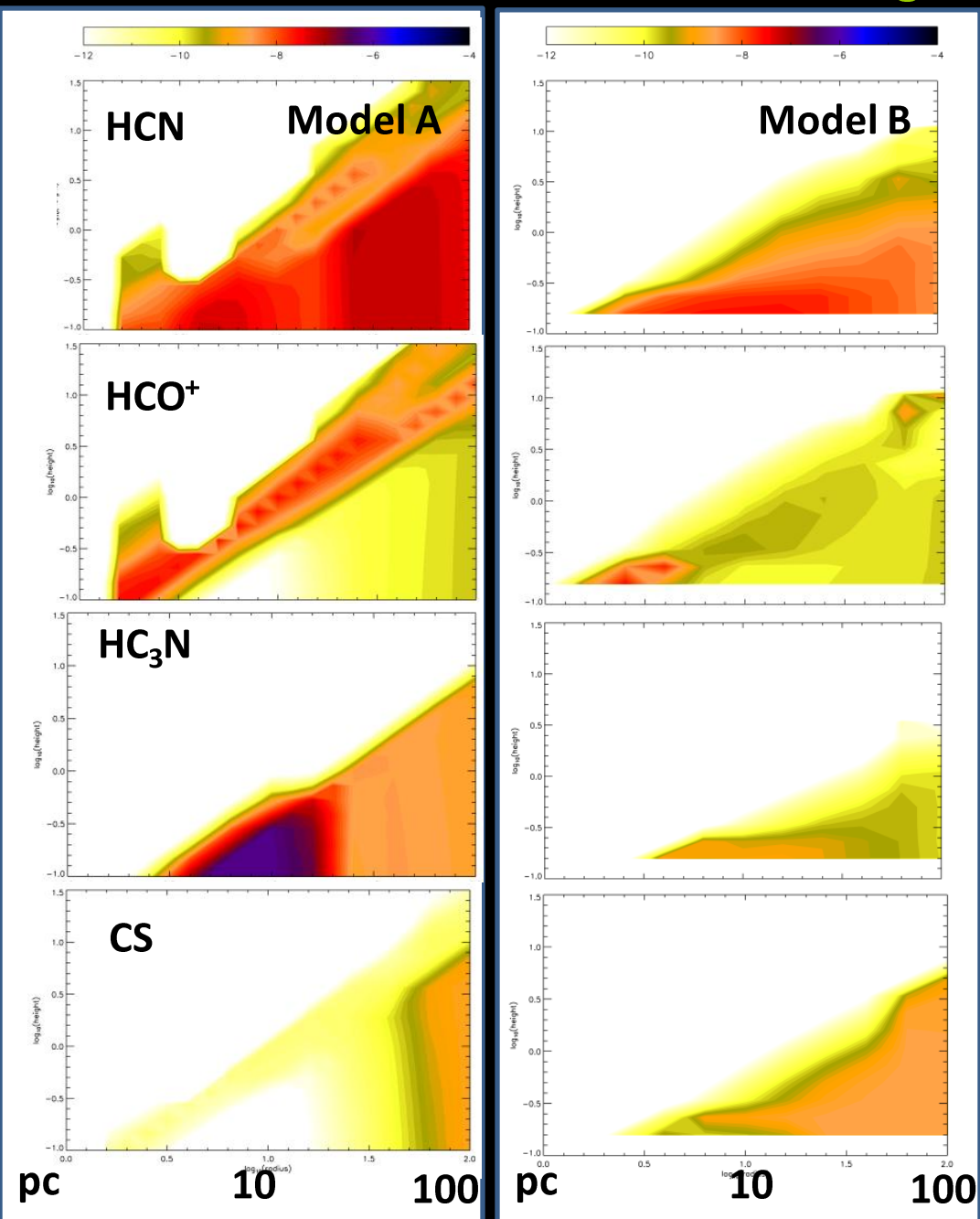
Martín+2015



NGC 1068 Sy 2 luminous AGN

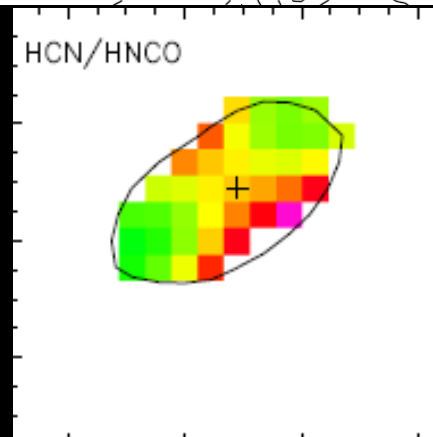
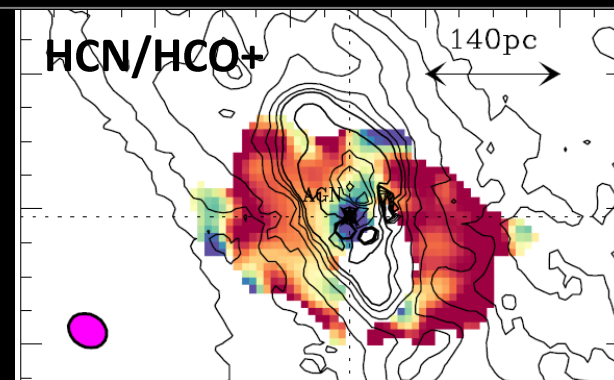
Takano+2015, Nakajima+2015

Multi-molecular observations revealing the structure of CNM around AGNs



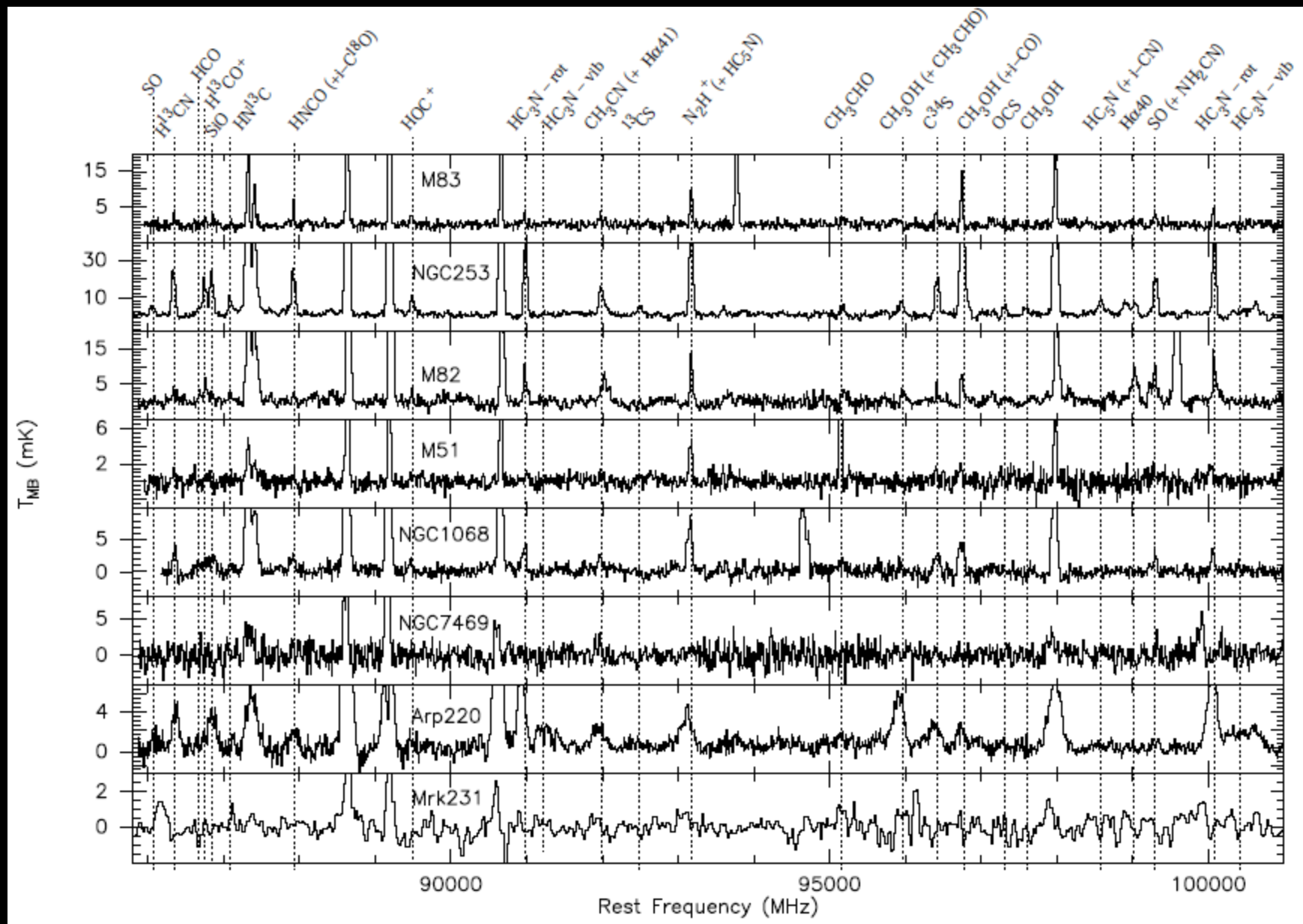
MODELING THE MOLECULAR COMPOSITION IN AN ACTIVE GALACTIC NUCLEUS DISK

NGC 1068 @ 35 pc resolution



NGC 1097 @ 100 pc resolution

Multi-molecular observations revealing the structure of SB galaxies

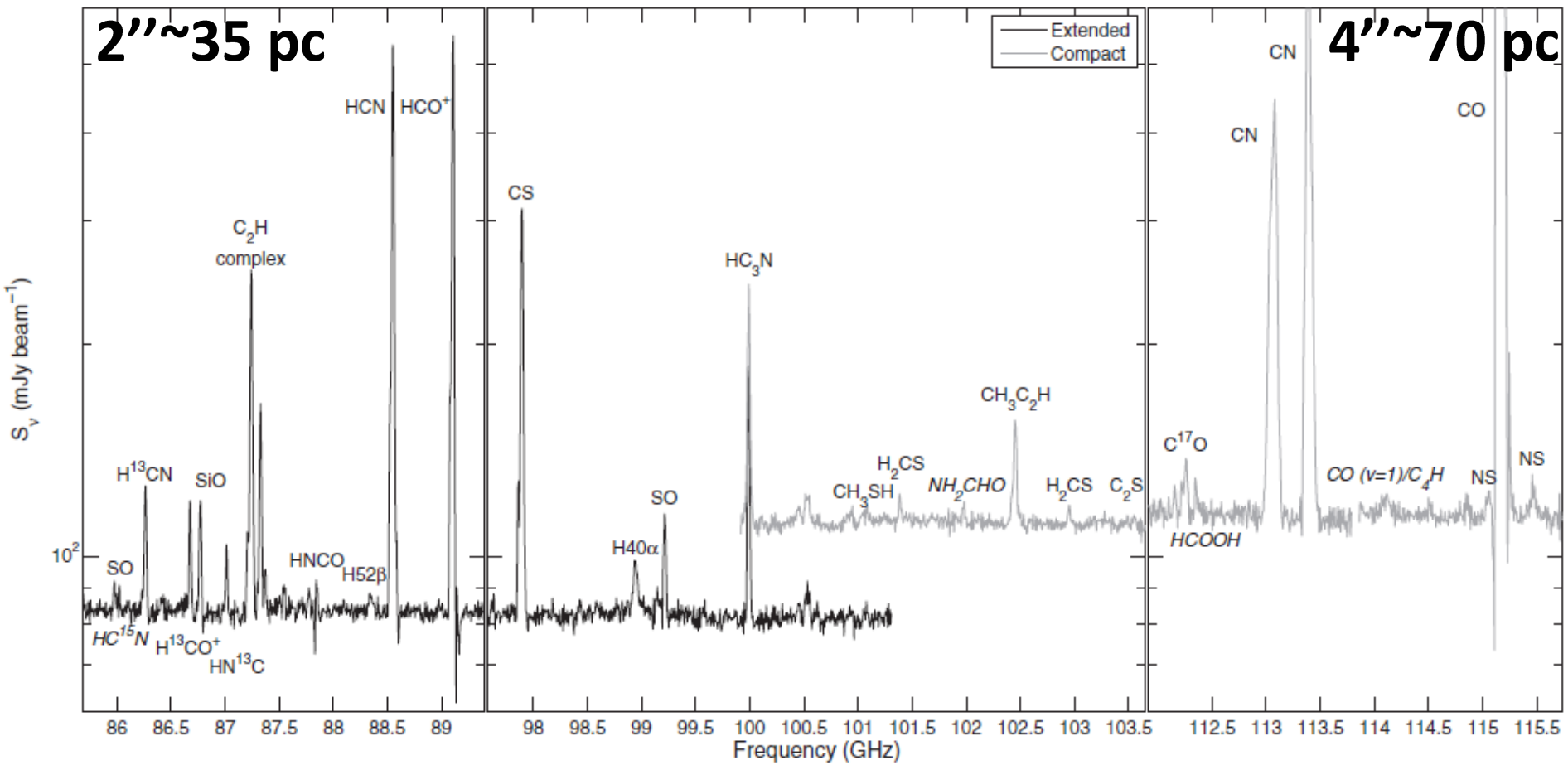


Tentative detection of HC5N in NGC 253 IRAM 30 m Aladro+2015

Multi-molecular observations revealing the structure of SB galaxies

NGC 253 SB prototype

Meier+2015



Cycle 0

Bendo+2015 (H recomb line. ALMA archive)

Meier+2015

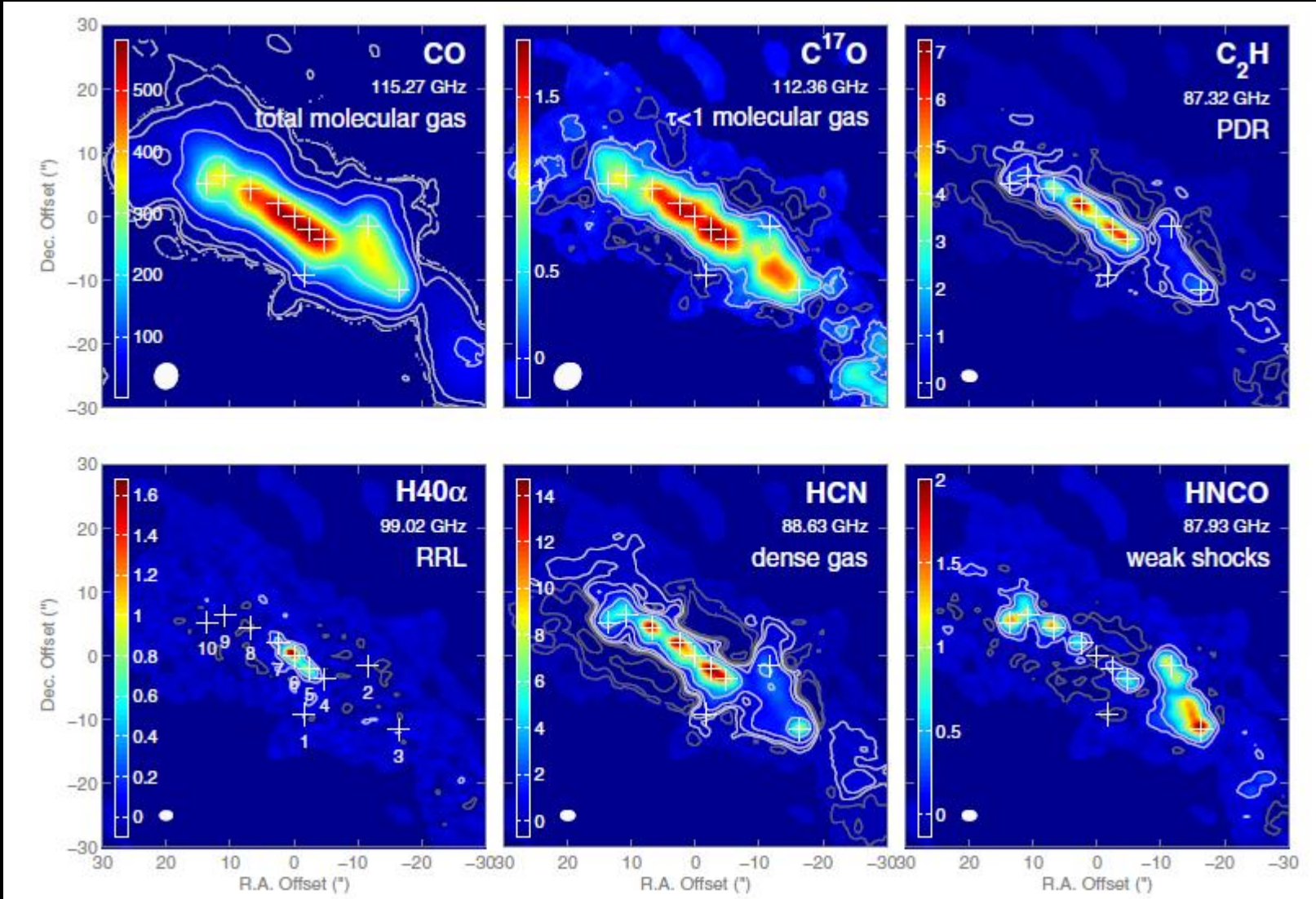
Leroy+2015 + Cycle 1 (CO, HCO $^+$, HCN, CS, isotopologues)

Bolatto+2013 CO

Multi-molecular observations revealing the structure of SB galaxies

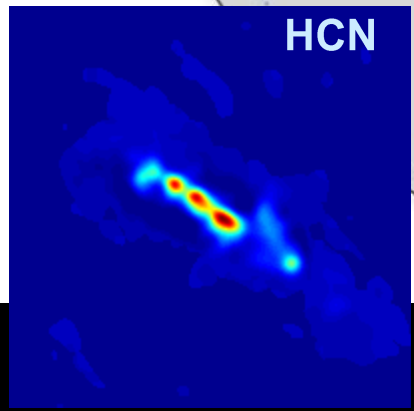
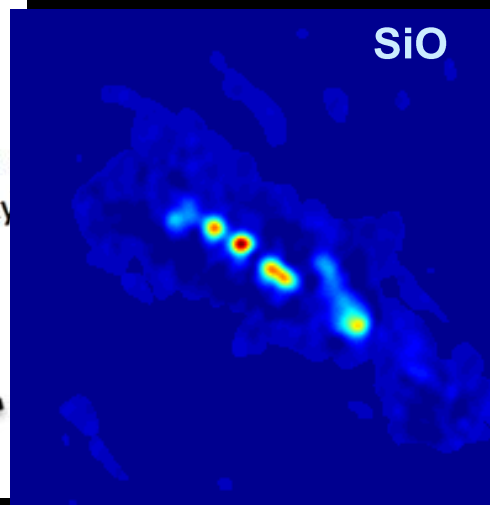
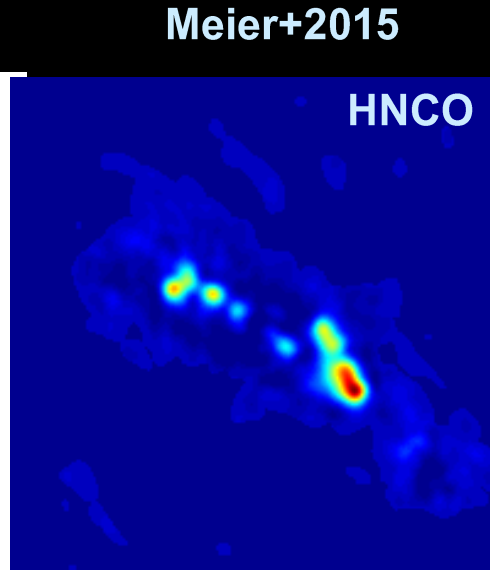
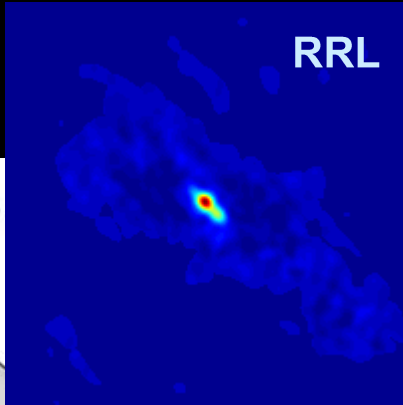
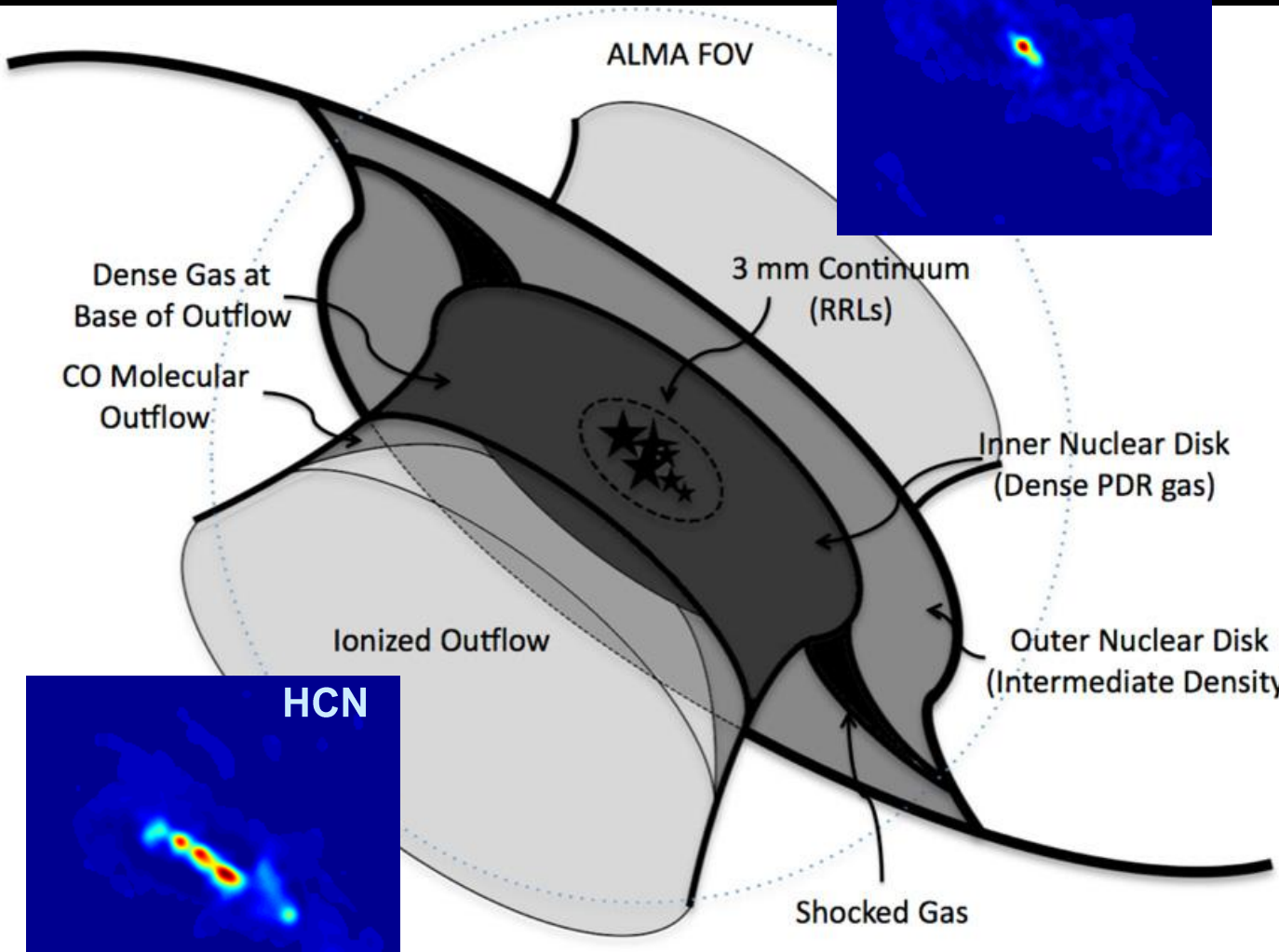
NGC 253 SB prototype

Meier+2015



Multi-molecular observations revealing the structure of SB galaxies

NGC 253 SB prototype



Compact Obscured Nuclei (CONs)

WordReference

Collins

WordReference English-French Dictionary © 2015:

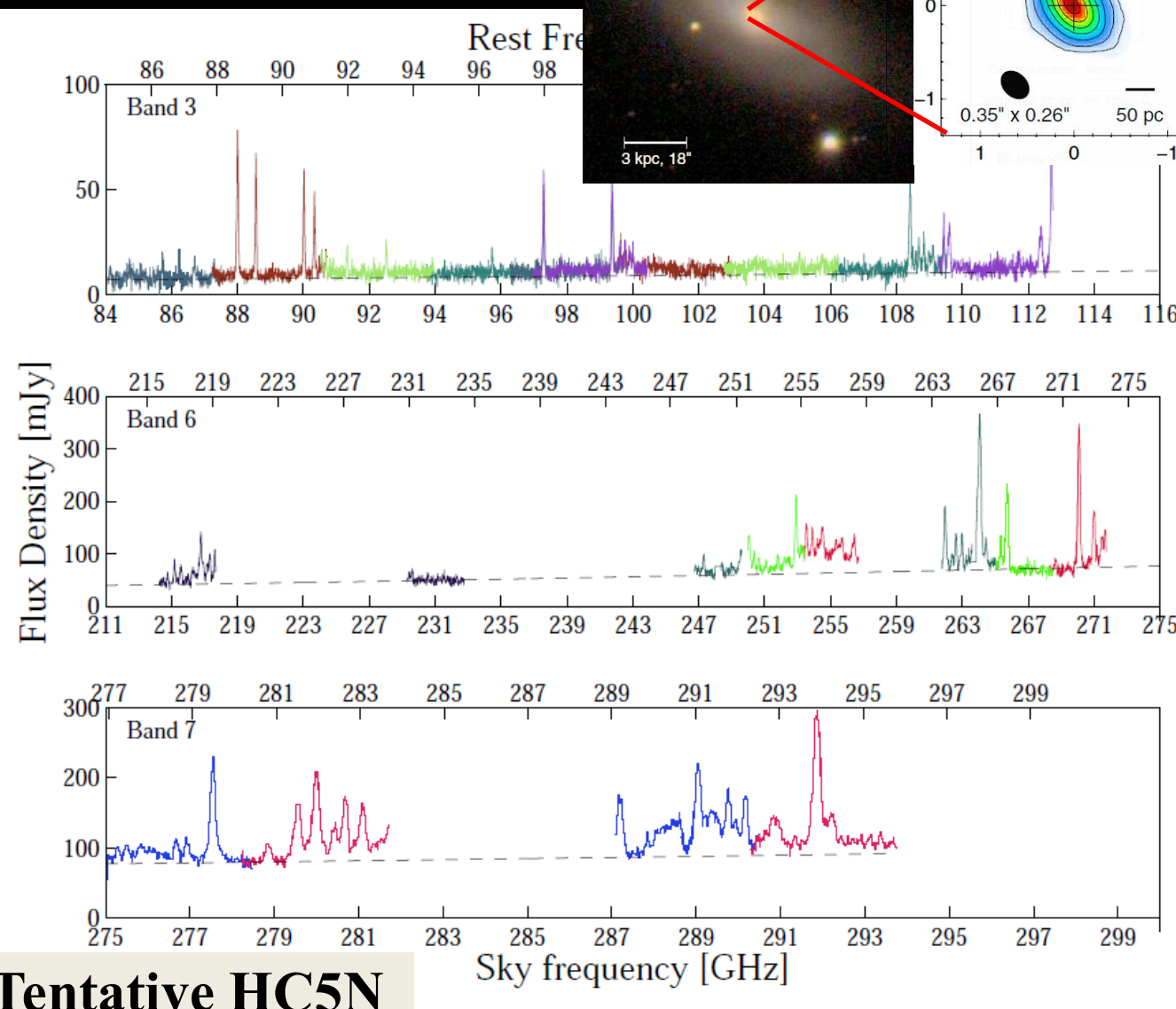
Principal Translations/Principales traductions

con *adj* *très familier, insultant* (stupide) *stupid* *adj*
(UK, informal) *thick* *adj*
(US, informal) *dumb* *adj*

- LIRGs and ULIRGs
- Radiating most of their energy as thermal dust emission in the IR
- Very compact (~few 10 pc)
- Dominant population among the most luminous extragalactic objects
- Power source: Early obscured stages of SBs and AGNs?

Multi-molecular observations the obscured most objects

NGC 4418 : LIRG



Tentative HC5N

SMA+MERLIN
Existence of
~20pc dusty core
with $L_{bol} \sim 10^{11} M_{\odot}$
(Sakamoto+2013,
Costagliola+2013)

- Compton-thick AGN
- Young (<5 Myr) compact starburst

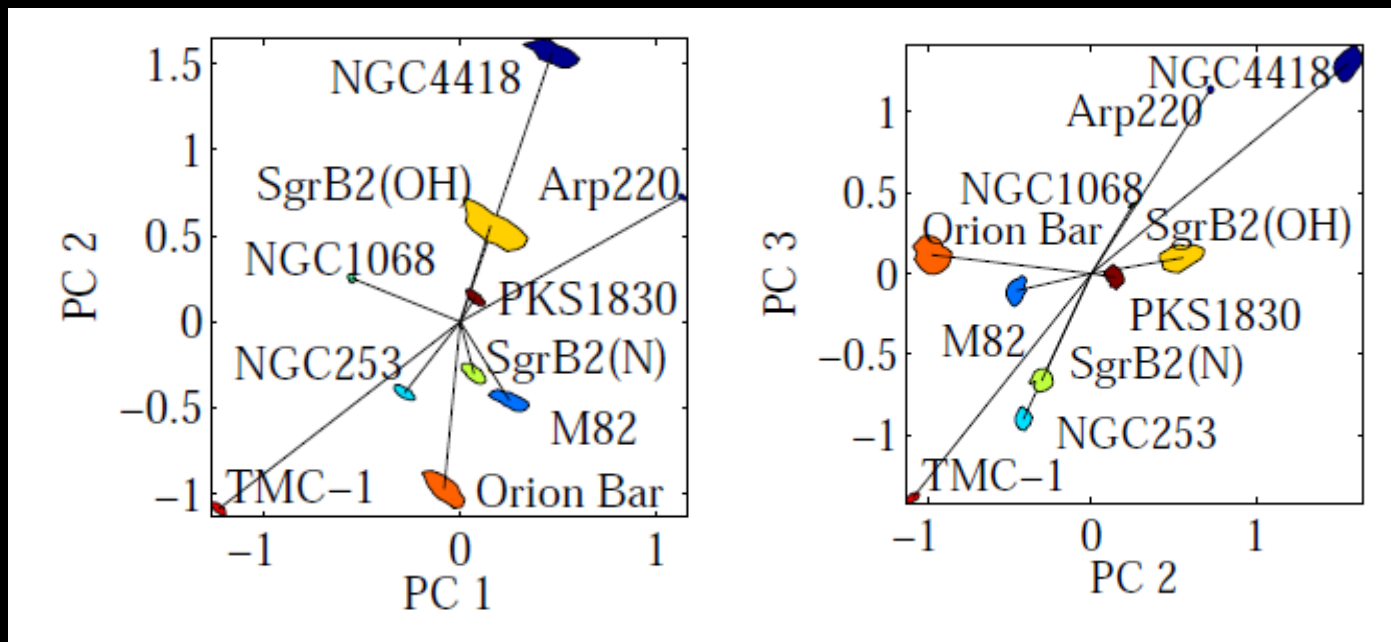
ALMA Cycle 0
71 GHz coverage
Bands 3, 6 and 7
>300 lines, 45 species

Costagliola+Submitted

Multi-molecular observations the obscured most objects

NGC 4418 : LIRG

Principal component analysis



HCN/HNC/HCO⁺ consistent with PDR models

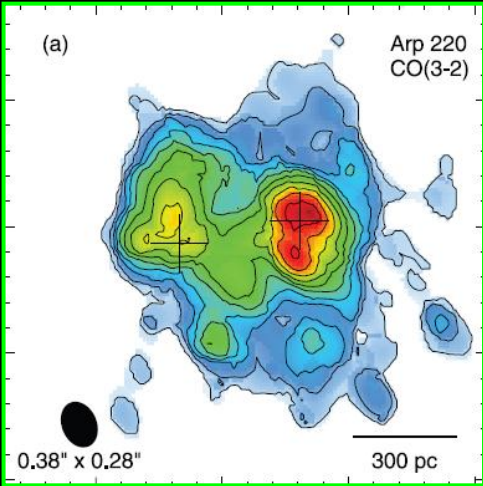
More complex species (HC₃N, c-C₃H₂) require hot core chemistry

SiO seem to require strong shocks and/or dissociation by X-ray or cosmic rays

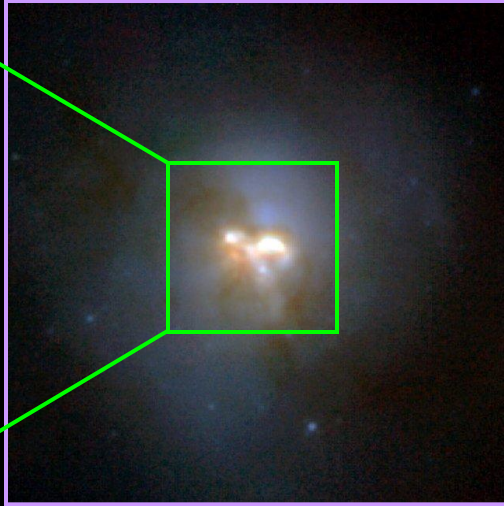
Chemical abundances + vibrational emission + compactness is consistent with AGN + SB composite

Multi-molecular observations the obscured most objects

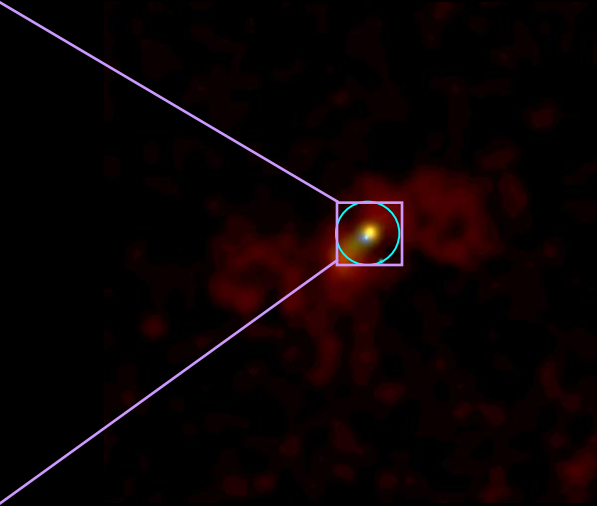
ARP 220: The ULIRG



850um – SMA
Sakamoto et al. 2008



NIR – HST
Scoville et al. 1998



X Rays – CHANDRA
Mc Dowell et al. 2002

- Arp 220 is the nearest Ultraluminous Infrared Galaxy (ULIRG)
- Advanced merger with $L_{8-1000\text{um}} > 10^{12} L_0$
- Most luminosity radiated as thermal dust emission in the IR and mm wavelengths.

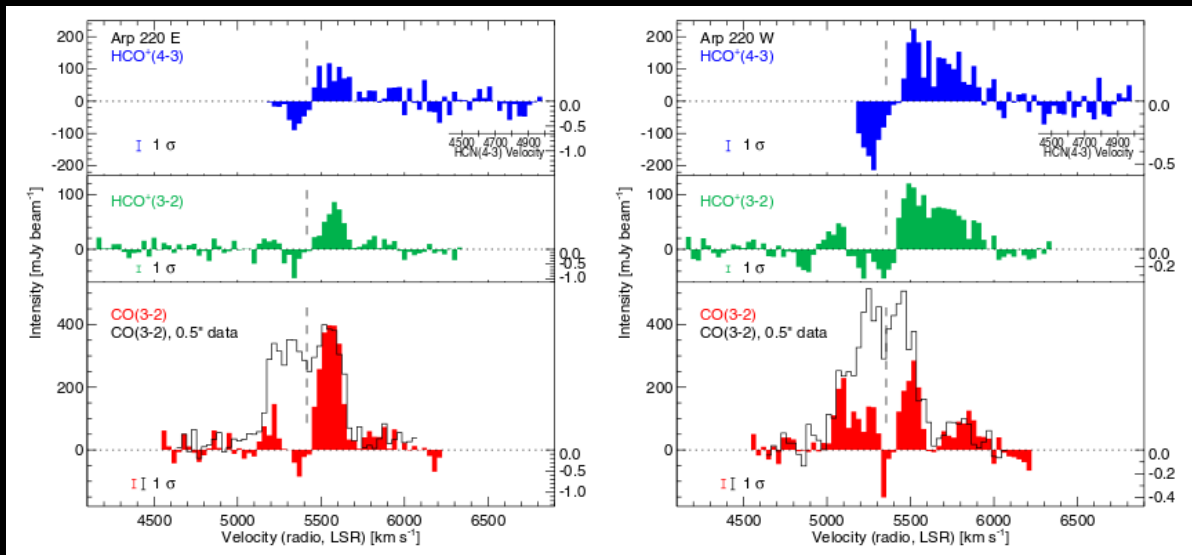
What is the leading power source driving such luminosity?

- Chandra X-ray compact sources might be a hint of the AGNs in the nuclei but the superwind could be generated by intense starformation.

Deeply buried AGN and/or extreme Starburst???
 $N_{\text{H}_2} = 10^{25} \text{ cm}^{-2}$ and/or hundreds of superclusters

Multi-molecular observations the obscured most objects

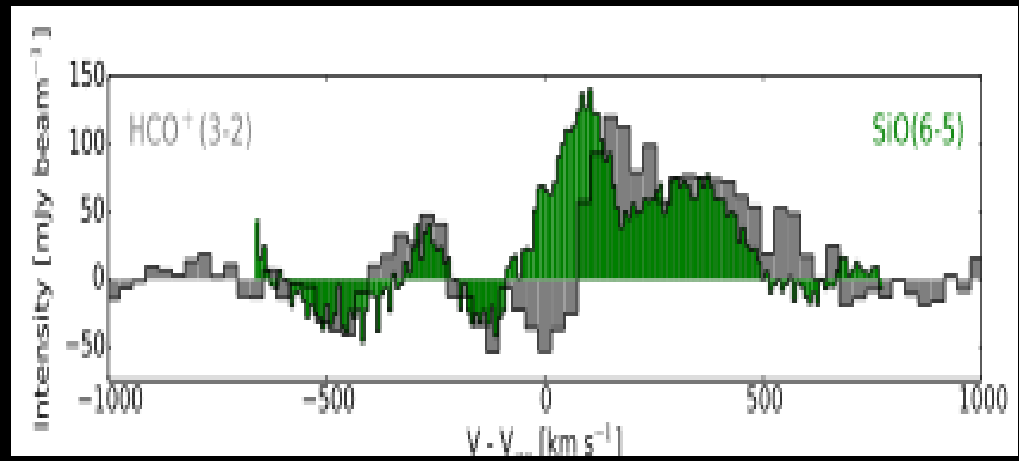
ARP 220: Surprises at high resolution



Sakamoto+2009 HCO+ P-cygni profiles, SMA

~100 km/s outward motions from the nuclei

Bipolar Outflows

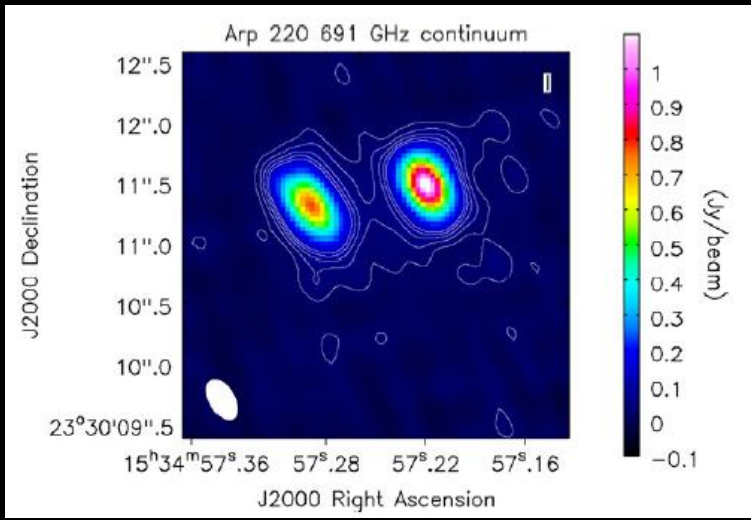


Tunnard+2015 SiO P-cygni profiles, PdBI

0.1" offset between emission/absorption

Multi-molecular observations the obscured most objects

ARP 220: The ULIRG in the ALMA spotlight



T_{dust} = 200 K (Western) and 80 K (eastern)

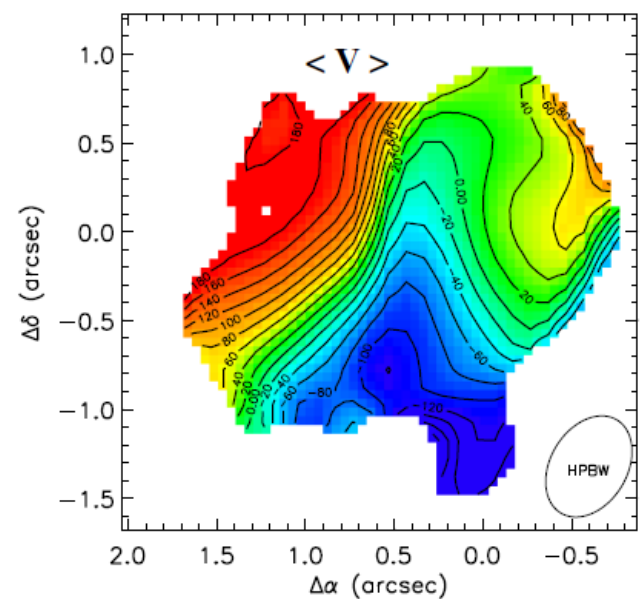
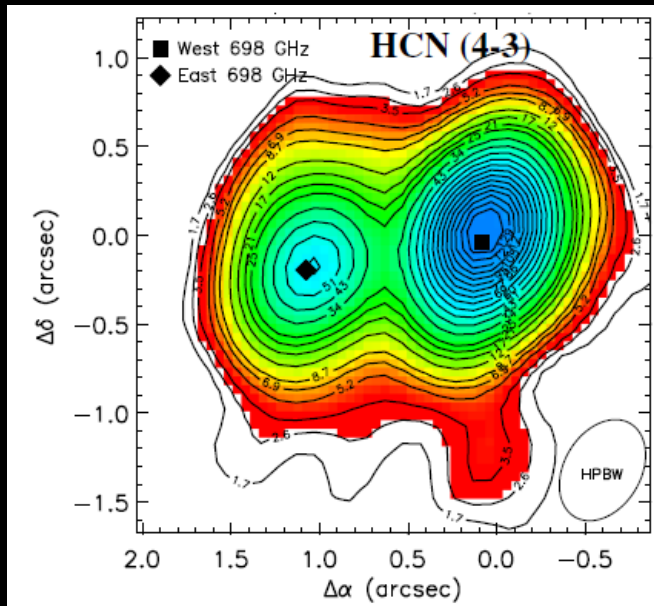
Sizes of 70 pc and 100 pc

Wilson+2014

Kinematic deconvolution of HCN

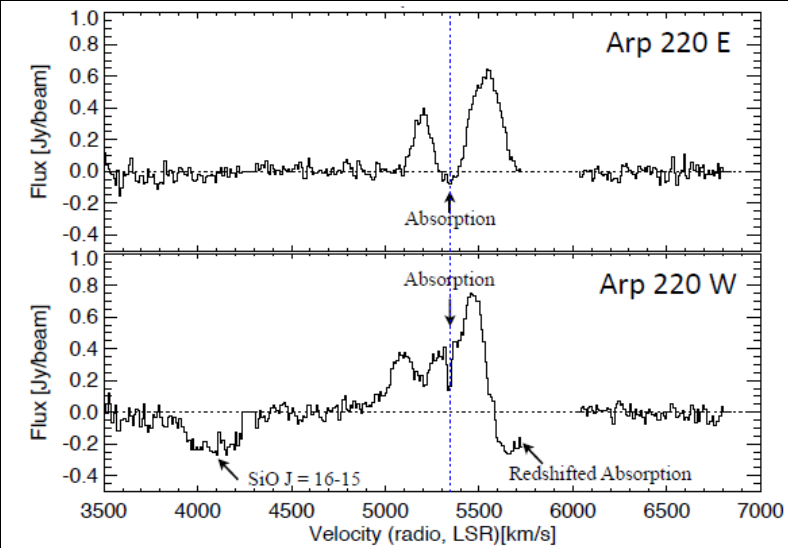
Fit to simple disk model

Scoville+2015

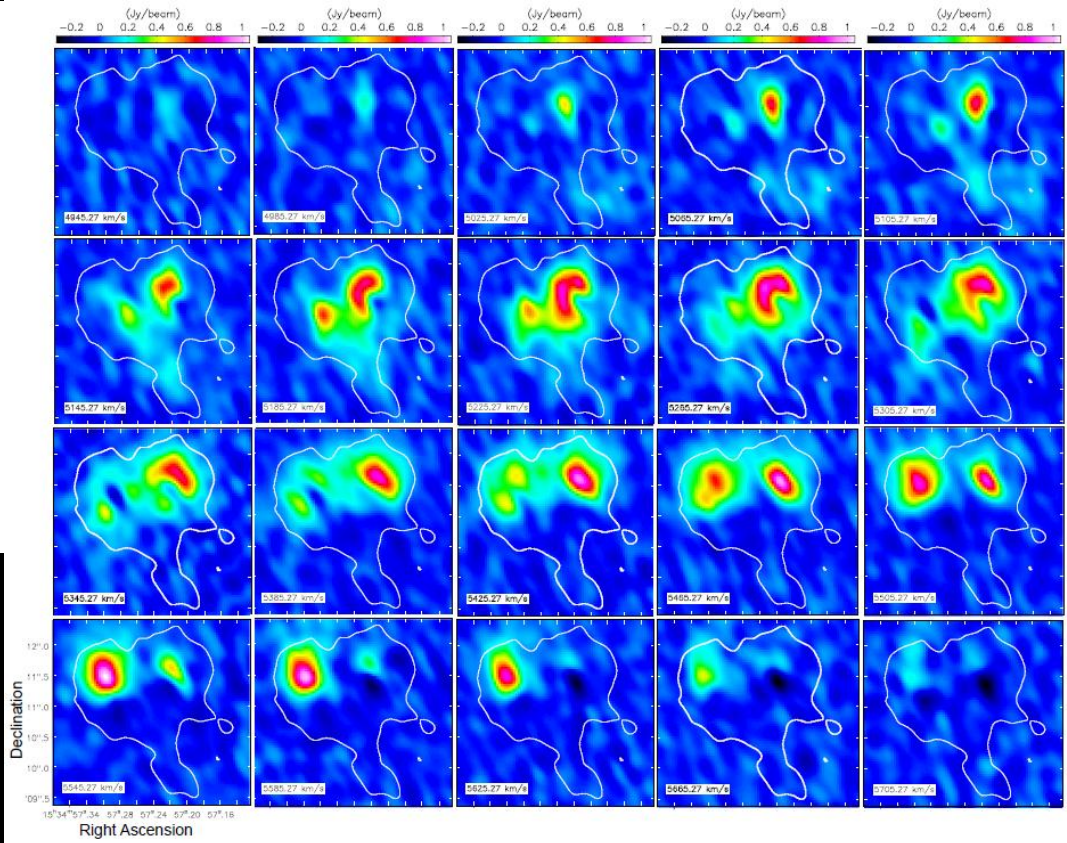


Multi-molecular observations the obscured most objects

ARP 220: The ULIRG in the ALMA spotlight

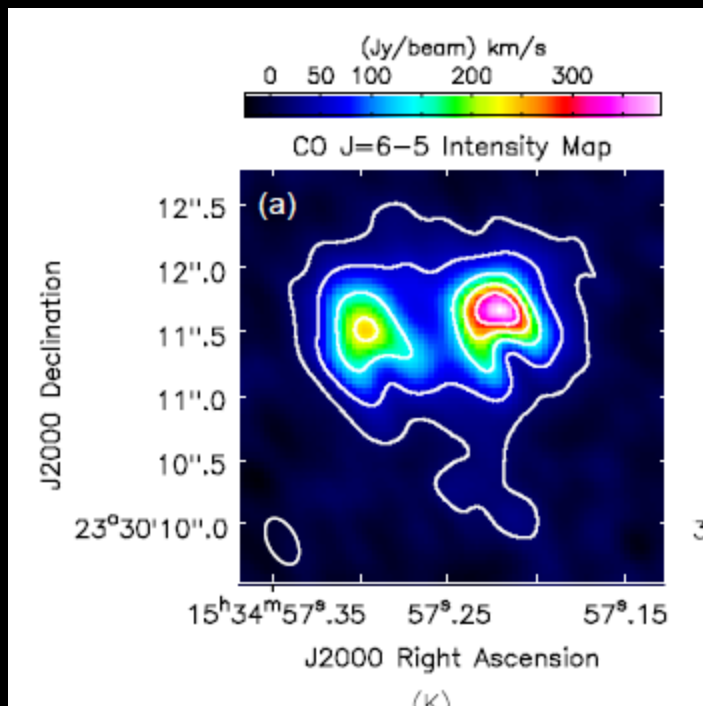


Rangwala+2015



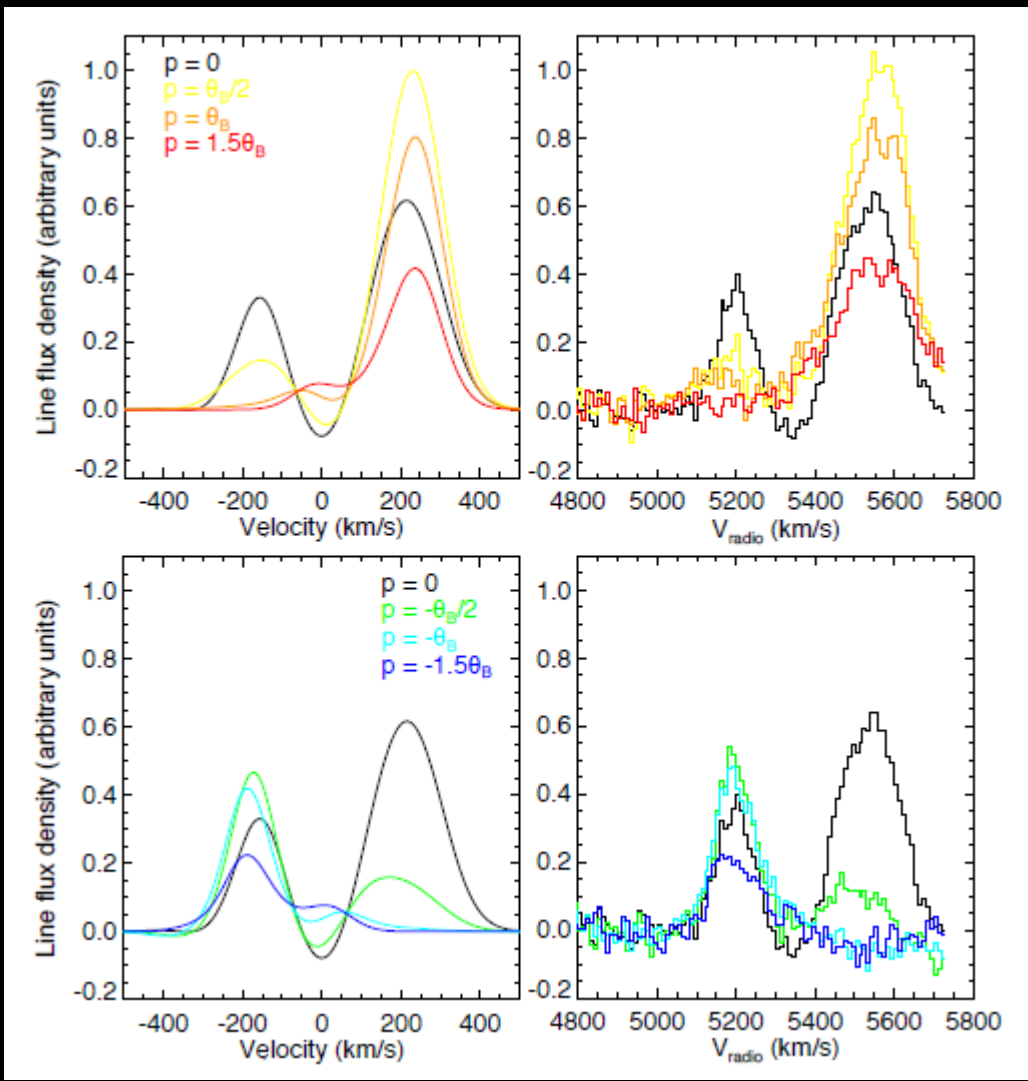
Multi-molecular observations the obscured most objects

ARP 220: The ULIRG in the ALMA spotlight



Rangwala+2015

Model: Highly turbulent rotating disk with high line center opacity and large T gradient



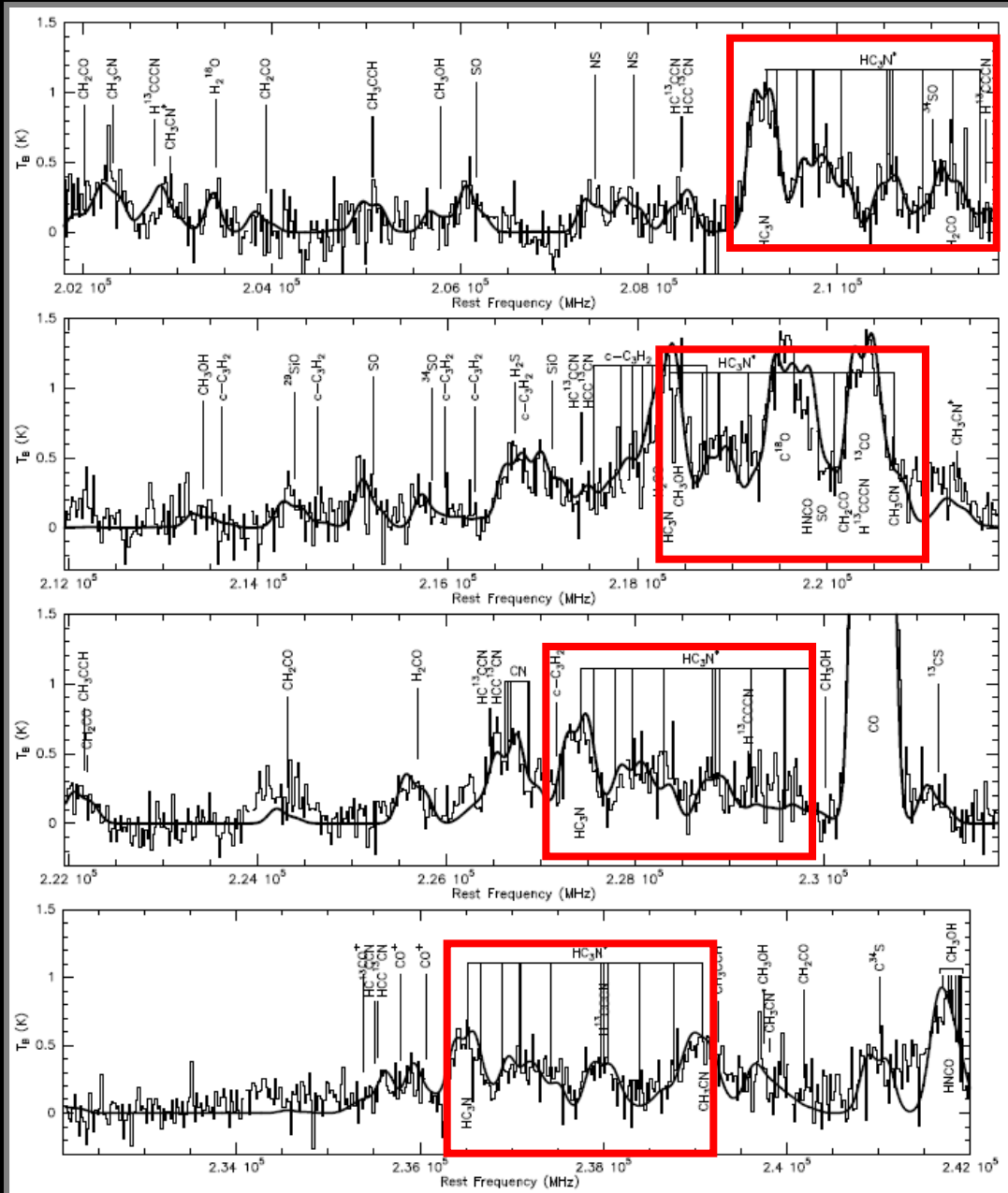
Multi-molecular observations the obscured most objects

ARP 220

Vibrationally excited emission of:



T_{vib} ~ 300-500 K



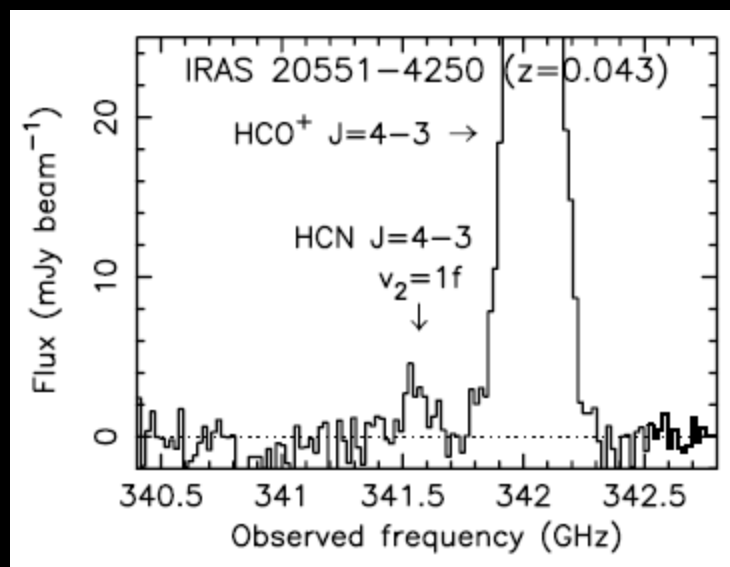
Vibrationally excited emission might be the key to unlock obscured nuclei

LIRG

- NGC4418 in HCN (SMA, Sakamoto+2010) and HC3N (IRAM 30m/JCMT, Costagliola & Aalto 2010, SMA, Costagliola+2013, ALMA, Costagliola+2015,)

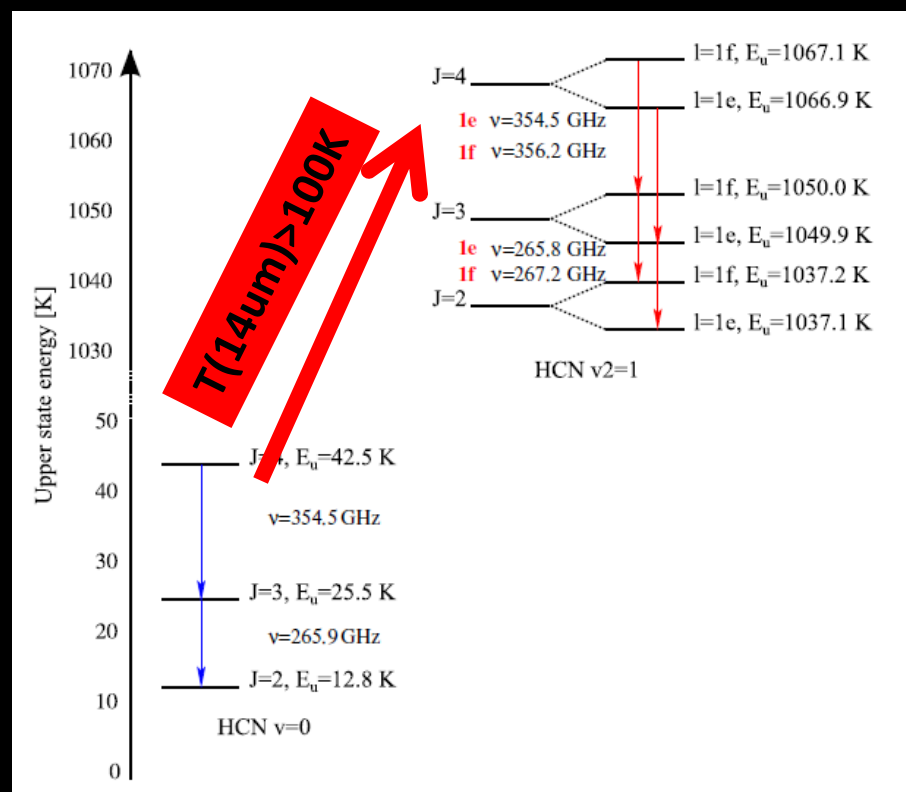
ULIRGs

- Arp220 in HCN (Arecibo, Salter+2008) and HC3N (SMA, Martin+2011)
- IRAS20551-4250 in HCN (ALMA, Imanishi & Nakanishi 2013)



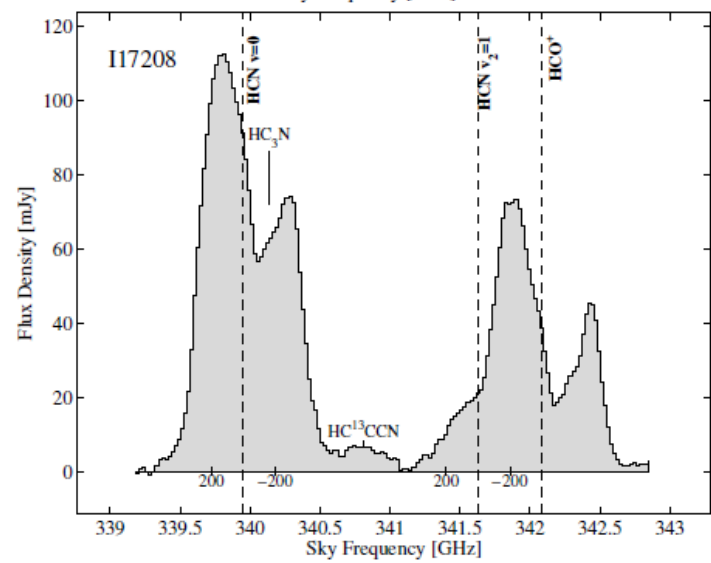
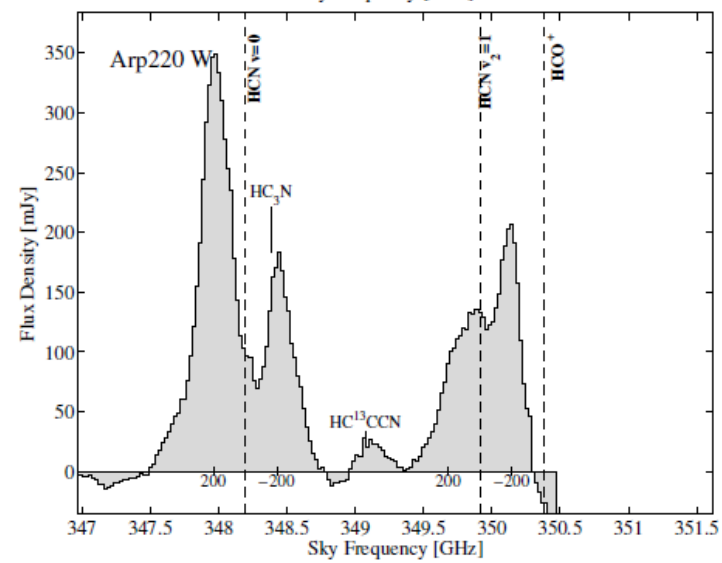
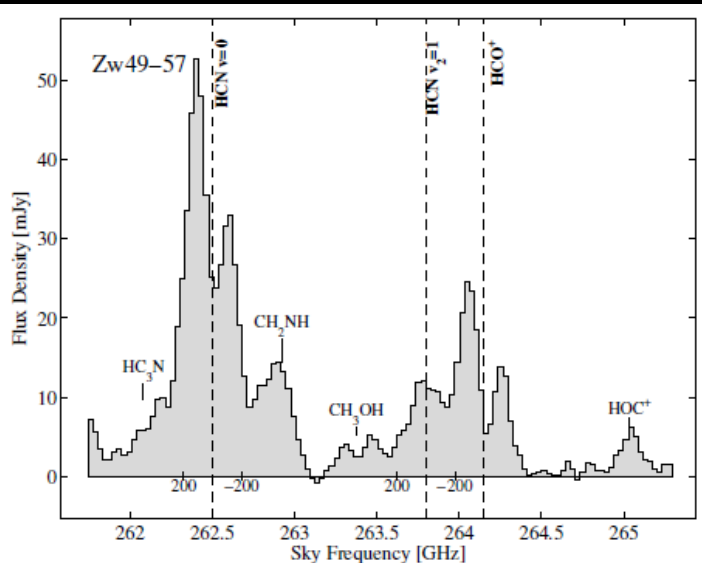
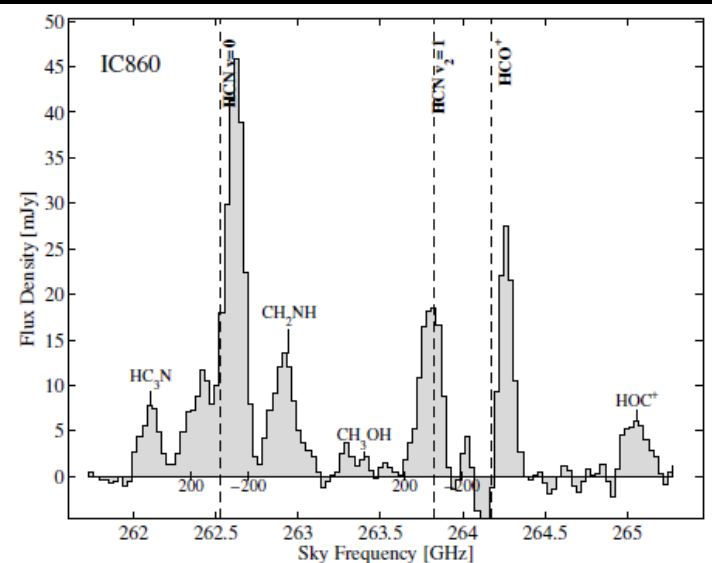
Cycle 0 Imanishi & Nakanishi 2013

Aalto+2015



Vibrationally excited emission might be the key to unlock obscured nuclei

Vibrational Emission

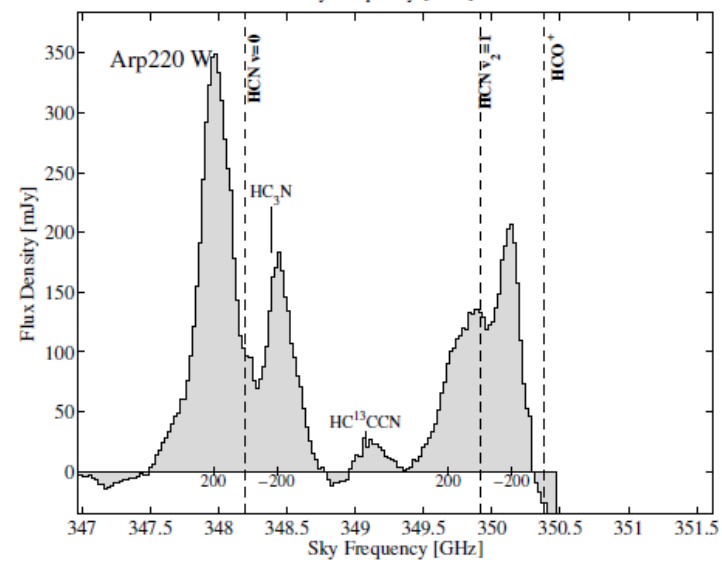
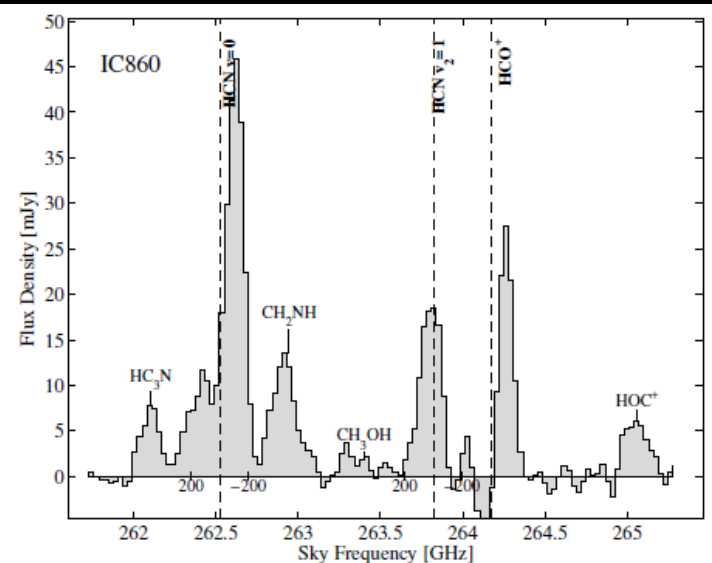


Total of 8 sources

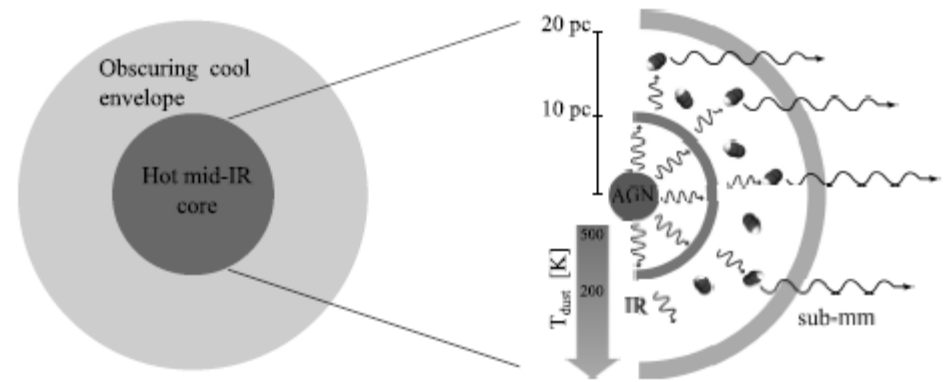
Lower L(HCN)/L_{fir}
when
V > V_{escape}

Vibrationally excited emission might be the key to unlock obscured nuclei

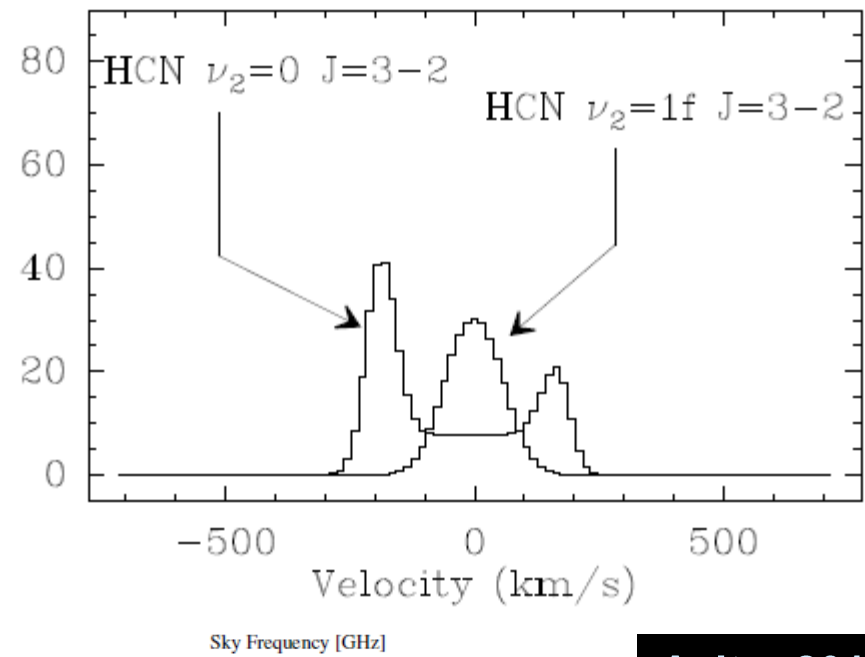
Vibrational Emission



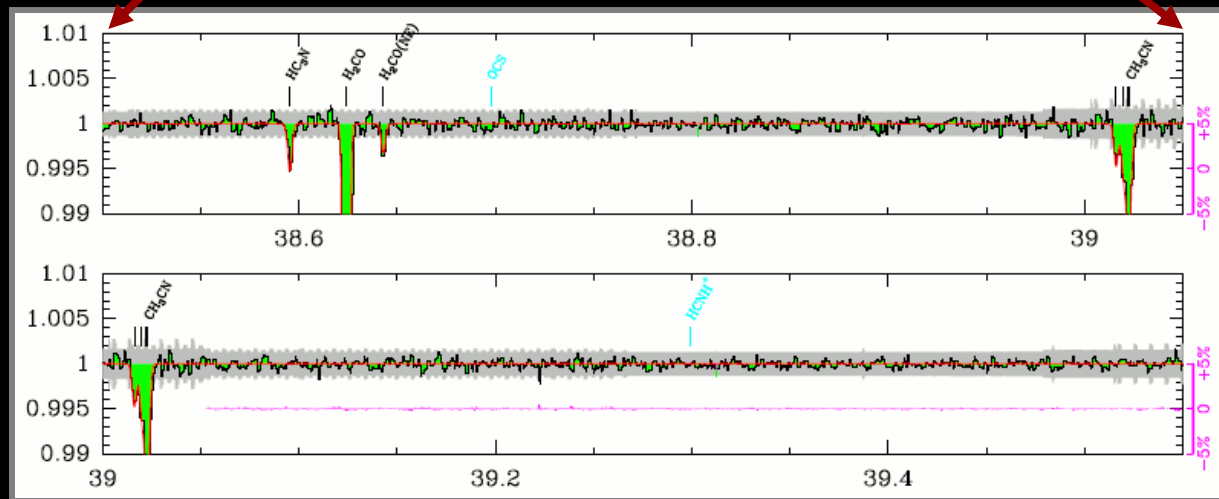
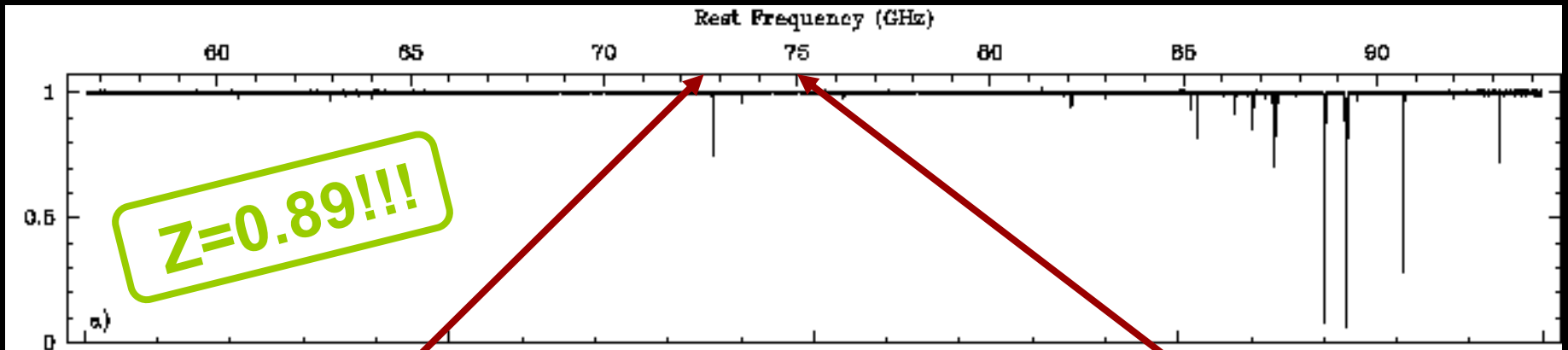
50 pc



Flux density (mJy)



Absorption systems...spectroscopy across cosmic times

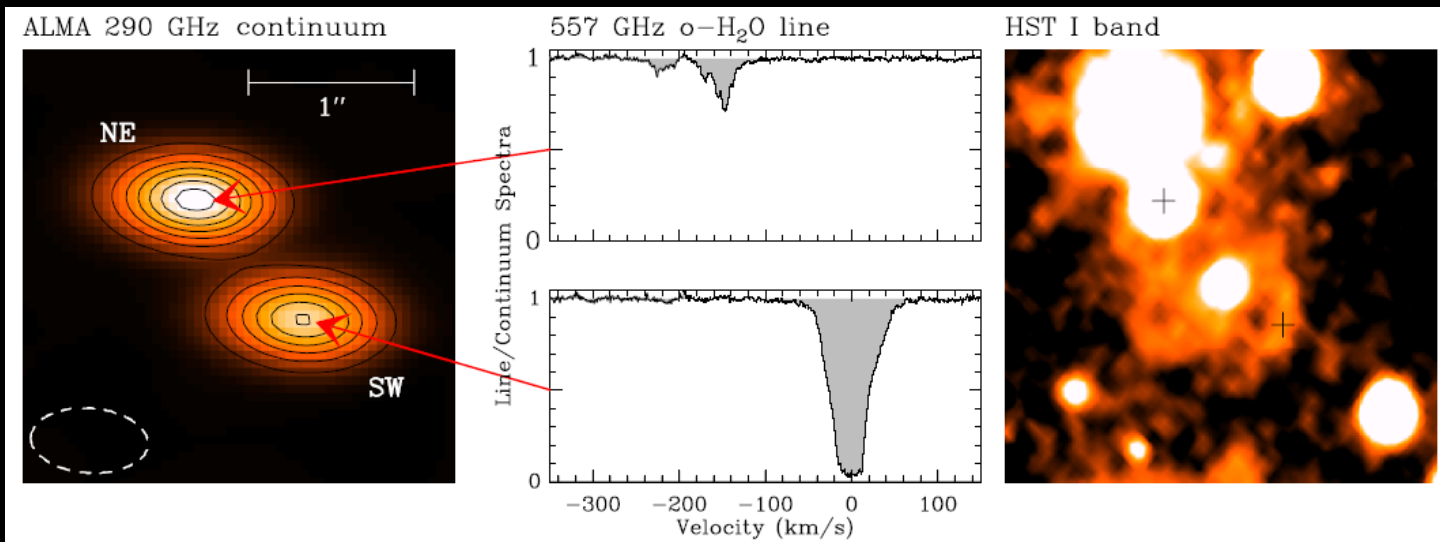


PKS 1830-211 z=0.89

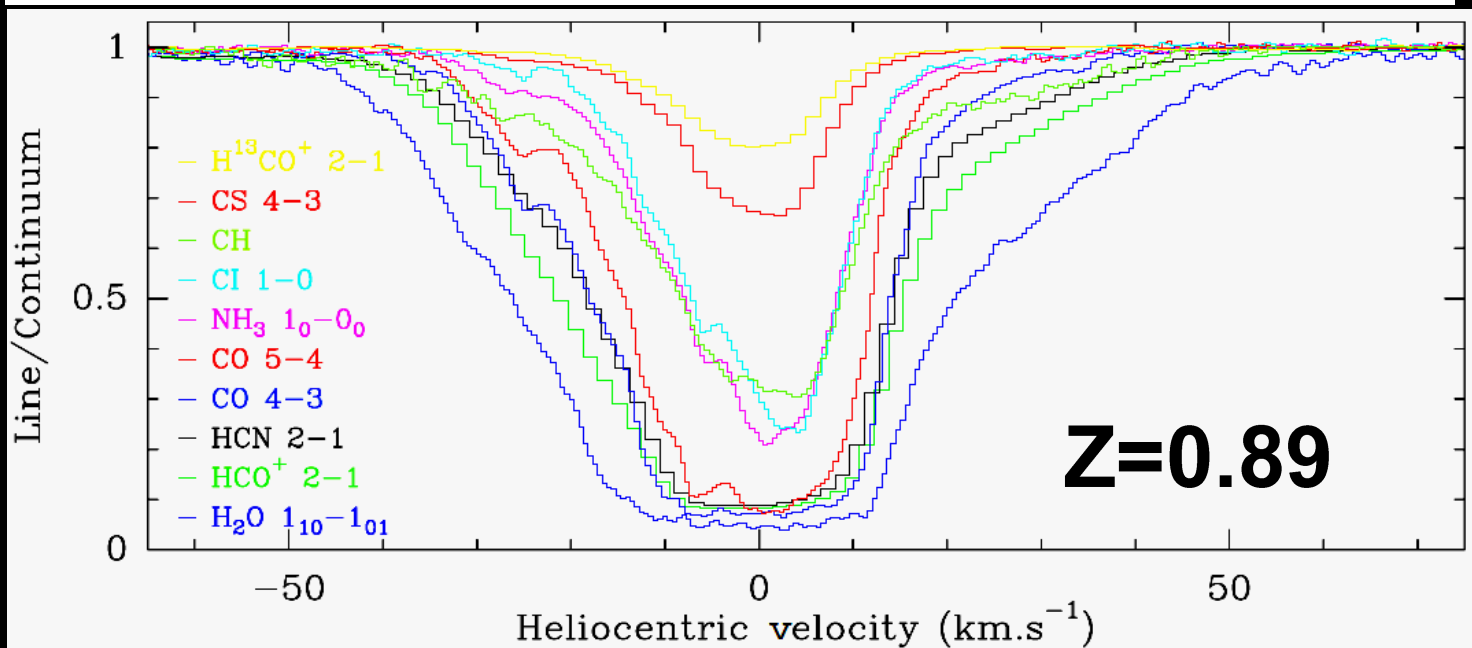
Muller+2011

ATCA

Absorption systems...spectroscopy across cosmic times



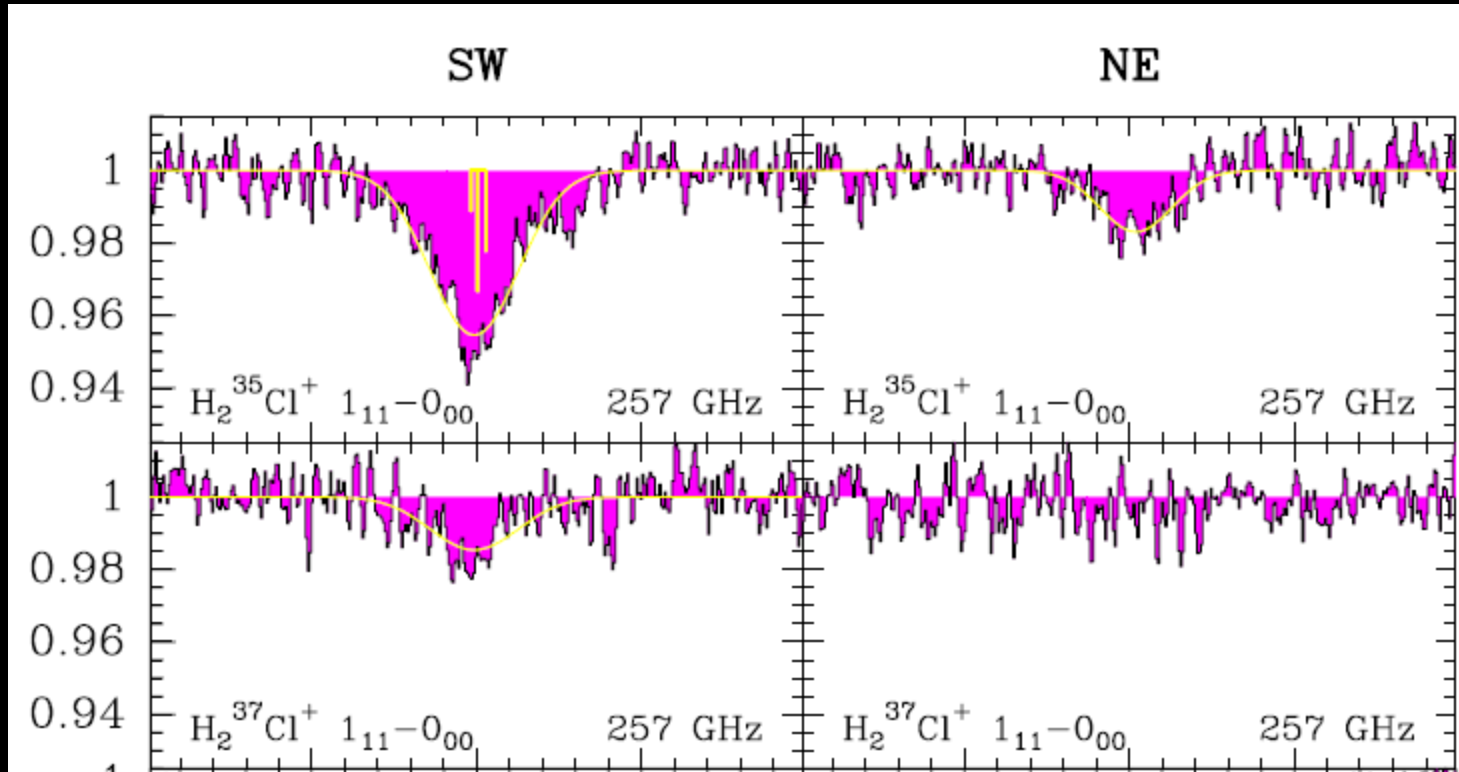
Cycle 0
Muller+2014a,
Muller+2014b



Spectroscopy
unrelated
Martí-Vidal+2013
Martí-Vidal+2015

Water has the deepest absorption. Best probe at high-z?

Absorption systems...spectroscopy across cosmic times



Cycle 0
Muller+2014b

- Chloronium detection tracing diffuse gas.
- Isotopic evolution through cosmic time

**More soon with
ALMA and NOEMA**

NOEMA...already here



Target Sensitivity >35% ALMA

7 antennas already there

8 antennas 2016 Q2

**New correlator processing 32 GHz = 2x16 GHz
2017 Q1**

Baseline 800 m-1600 m 2018 Q3 (0.4'' @ 3mm)

12 antennas 2019 Q3 (with dual frequency!)

Extragalactic CONCLUSIONS

So far mostly Cycle 0 is getting published (clearly not enough proprietary time for such rich datasets)

Community is still familiar/biased towards bright molecular transitions. But that is changing quickly (see list of Cycle 2 accepted proposals)

High resolution CO studies can be the path for interesting spectroscopic follow-ups

HCN/HCO⁺/CS diagnostic diagrams...there is some truth in them but we still do not fully understand it. High-resolution + modeling will soon provide an answer

Multi-molecular studies can dissect galaxies into their different ISM heating mechanisms at unprecedented resolution (SB structure, AGN vs SB, AGN structure)

Vibrationally excited emission is here to stay as the probe of the most deeply buried nuclei.