THE COLD INTERSTELLAR MEDIUM IN STARBURSTS

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Outline

Introduction

- Molecular emission: a powerfull tool to study obscured regions
- Why molecular studies in galactic nuclei?

Chemical complexity and the heating in the Galactic center

- Shocks: complex organic molecules & grain chemistry
- XDRs-AGN: traced by the Fe 6.4 keV and enhancement of SiO/CS
- PDRs: HNCO/CS changes by nearly 2 orders of magnitude

Chemical complexity & density structure of clouds in SB galaxies

- Shock heating versus PDRs heating. Starburst evolution
- Structure of molecular clouds (chemical and physical)
- Superwinds in M82 and AGN activity in NGC1068

Recent burst of star formation in the ULIRG Arp 220

- Very recent starburst versus AGN: Proto starclusters

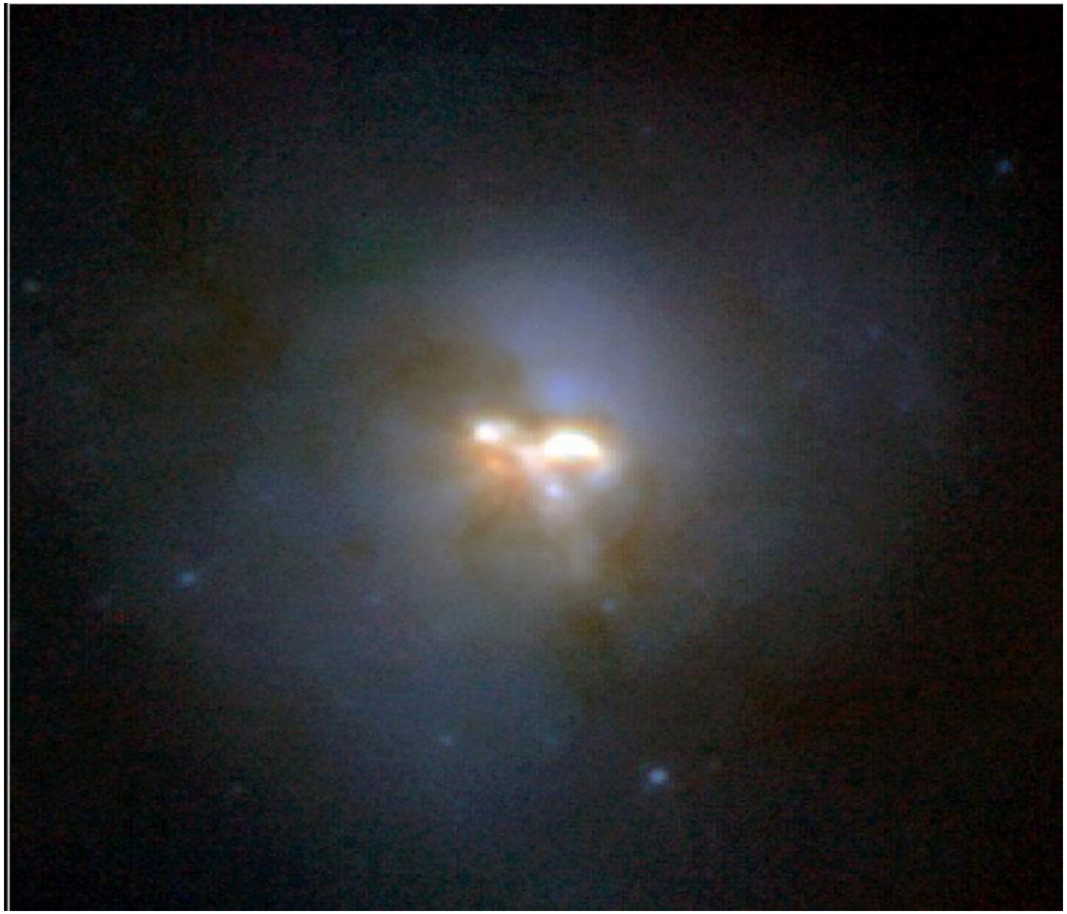
Proto starclusters in the Galactic center

ALMA and Herschel and e-VLA: Astrochemistry at high z

Extragalactic nuclei are heavily obscured regions

ULIRGS (Arp 220 Av >10000) , Sub-mm Galaxies , ..

Star formation, nuclear activity, ..



Extragalactic Molecular Emission

Molecular emission trace:

- **The total mass content of galaxies (CO emission)**
- **The high density component in galaxies (HCN) Gao et al. (2004)**

Molecular emission diagnostic tool of :

- **Properties of the ISM: density, temperature, kinematics..**
- **The deeply obscured nuclear power sources: AGN or starburst – Shocks, XDR, PDR or shock chemistry?**
- **The feeding of the nucleus**
- **The conditions and processes leading to the starbursts**
- **Starburst evolution**

The Galactic Center

The closest center of a galaxy we can study in detail

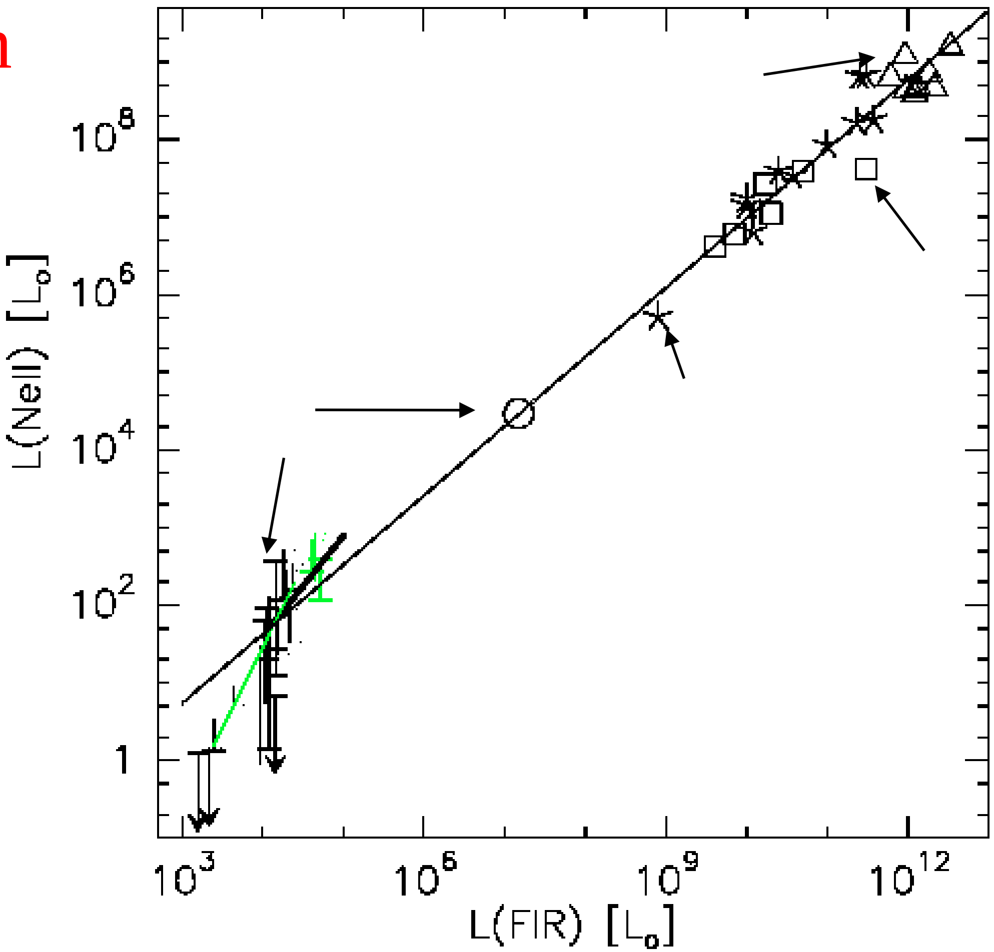
In NGC253: 0.040” (ALMA) corresponds to 17” in the GC

The GC contains all ingredients to test molecular tracers (benchmarking):

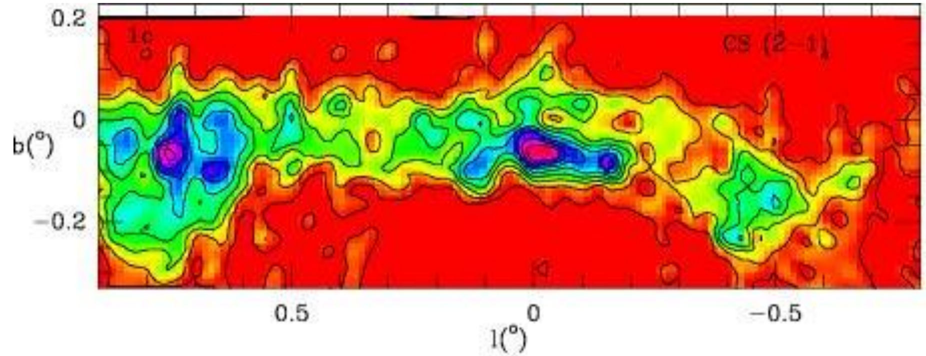
- Star formation seen throughout the region
- Hot cores like Sgr B2N, Sgr B2M .. (proto super starclusters)
- Large PDRs illuminated by clusters of massive stars
- Strong emission of X-rays (Fe 6.4 keV), gamma-rays (XDRs), CRs

Comparison with external galaxies

GC is similar to low excitation starburst galaxies



Gas and dust properties in the GC



Dust: cold component ~15 K
warm component 27- 30K

Gas temperatures: 20-500 K (NH_3 & H_2)
30% is in warm-hot gas

T_{gas} >T_{dust} in starburst galaxies

Mauersberger et al. (2003) and Ott et al (2005)

Densities: 10^4 - few 10^5 cm^{-3} >> Tex = 8-18 K

Very turbulent medium: (linewidths of 20 km/s)

Heating Mechanism: C-type shocks and PDRs

(Rodriguez-Fernandez et al. 2000, 2001,2004

Complex organic molecules

Requena-Torres et al .(2005;2008)

Atom addition

Typical Clouds

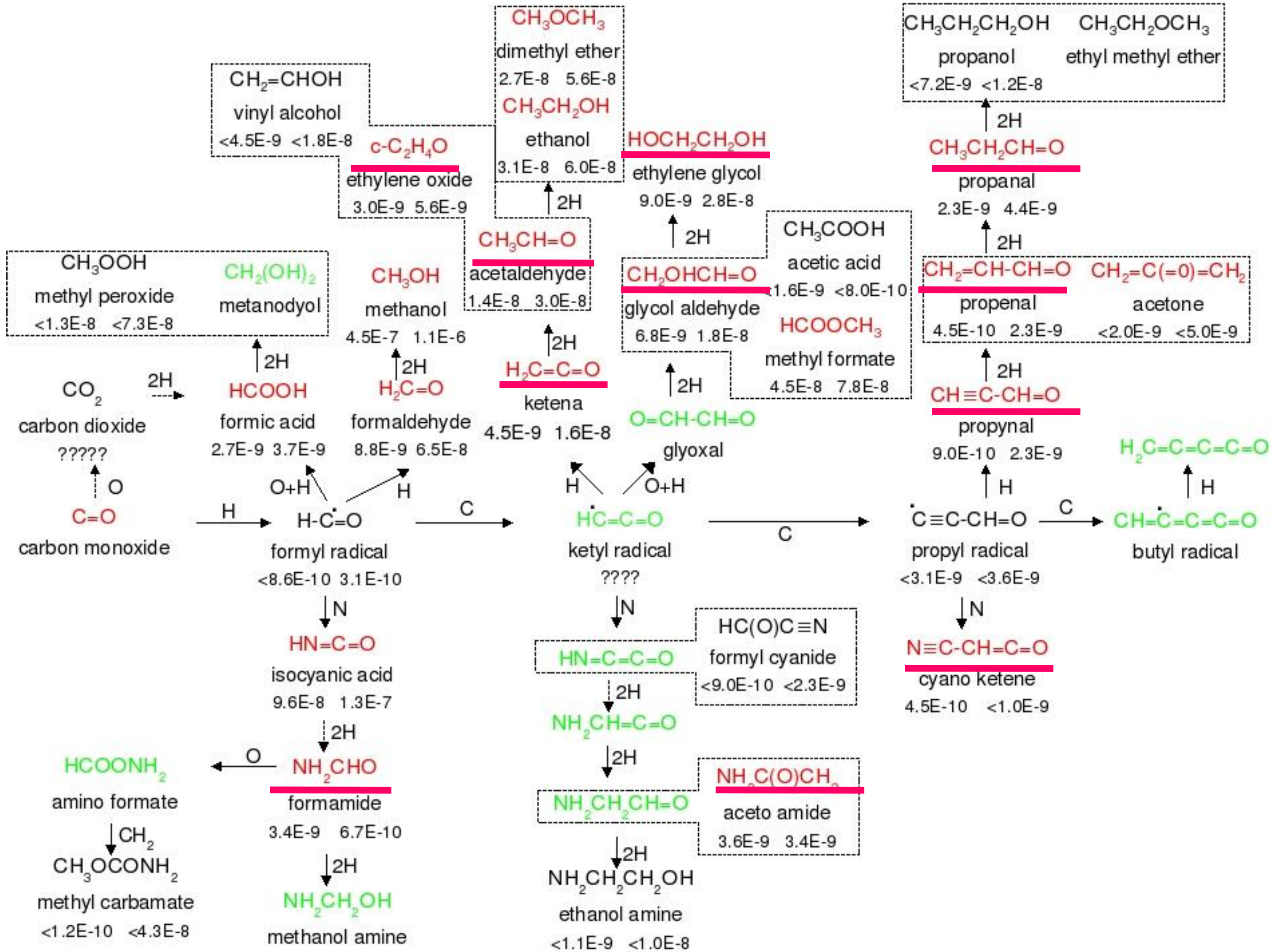
GBT, 30-m

Constant abundance < factor 3

Larger abundance than in Hot Cores

Similar ice mantles

H ↑ **Abundance** ↑



Complex organic molecules

Requena-Torres et al .(2008)

Dust properties:
Core: Silicate (SiO-) and graphite (C)
Ices: H_2O, CO, CO_2, CH_4, CH_3OH, H_2CO, OCS, NH_3, C_2H_6, HCOOH,..

Similar ice mantles

Grain chemistry

- **Hydrogenation**
- **Cosmic Rays**

FREQUENT SHOCKS

Origin?: Turbulence, ..

Complex organic molecules

Grain chemistry radical reactions:

Bennett & Kaiser (2007)

$CH_3OH + CR \rightarrow CH_3O + H$

$\rightarrow CH_2OH + H$

$CO + H \xrightarrow{5\ 10^{-8}} HCO$ 7 10^{-9} $^{<}10^{-9}$

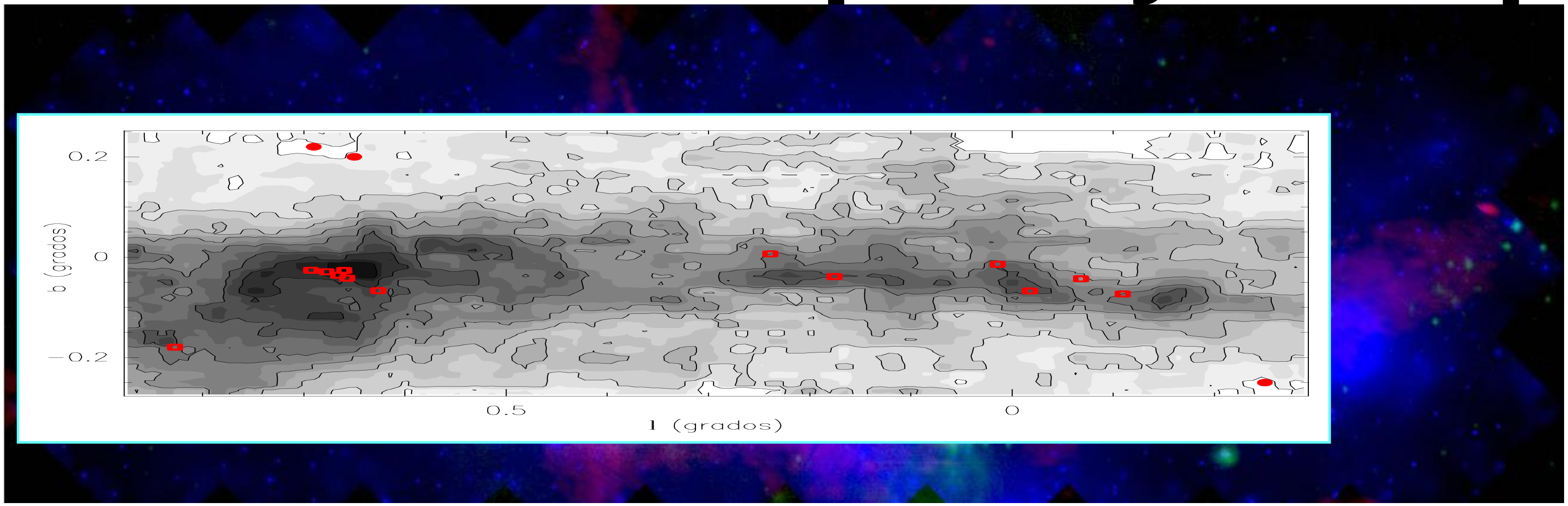
$HCO + CH_3O \rightarrow HCOOCH_3$ **10**

$HCO + CH_2OH \rightarrow CH_2OHCHO$ **1**

CH_3COOH **<<**

Methanol ~water on grain mantles

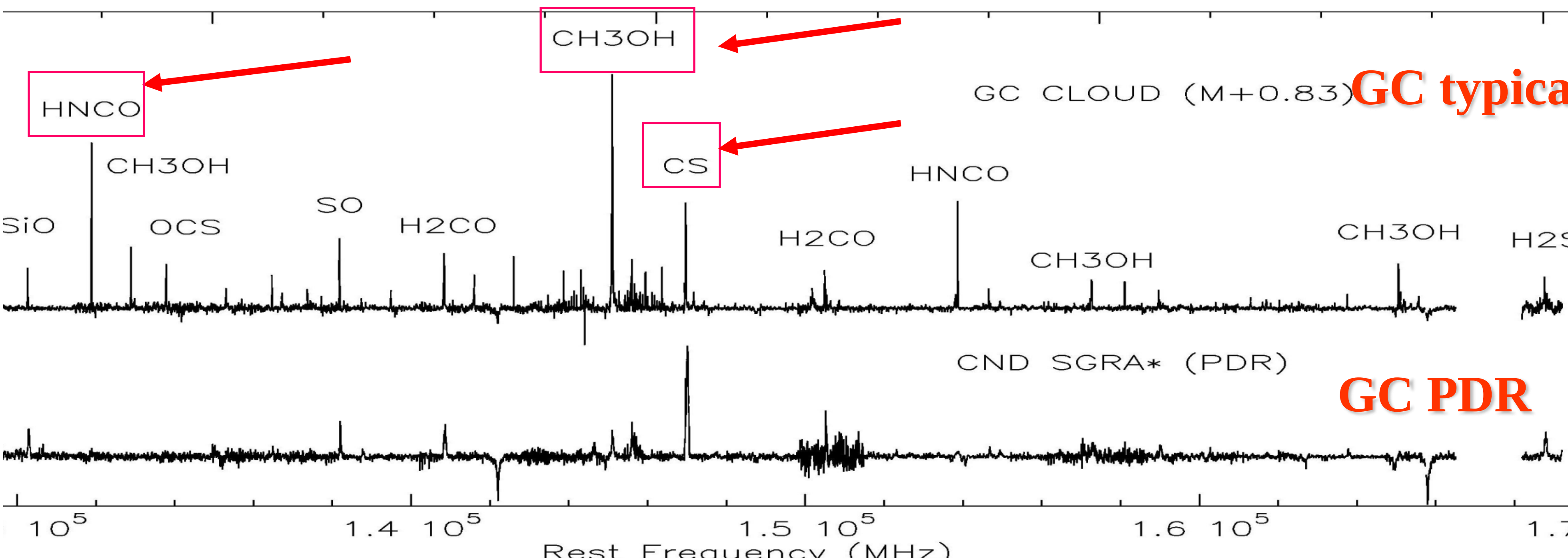
Chemical complexity: Templates



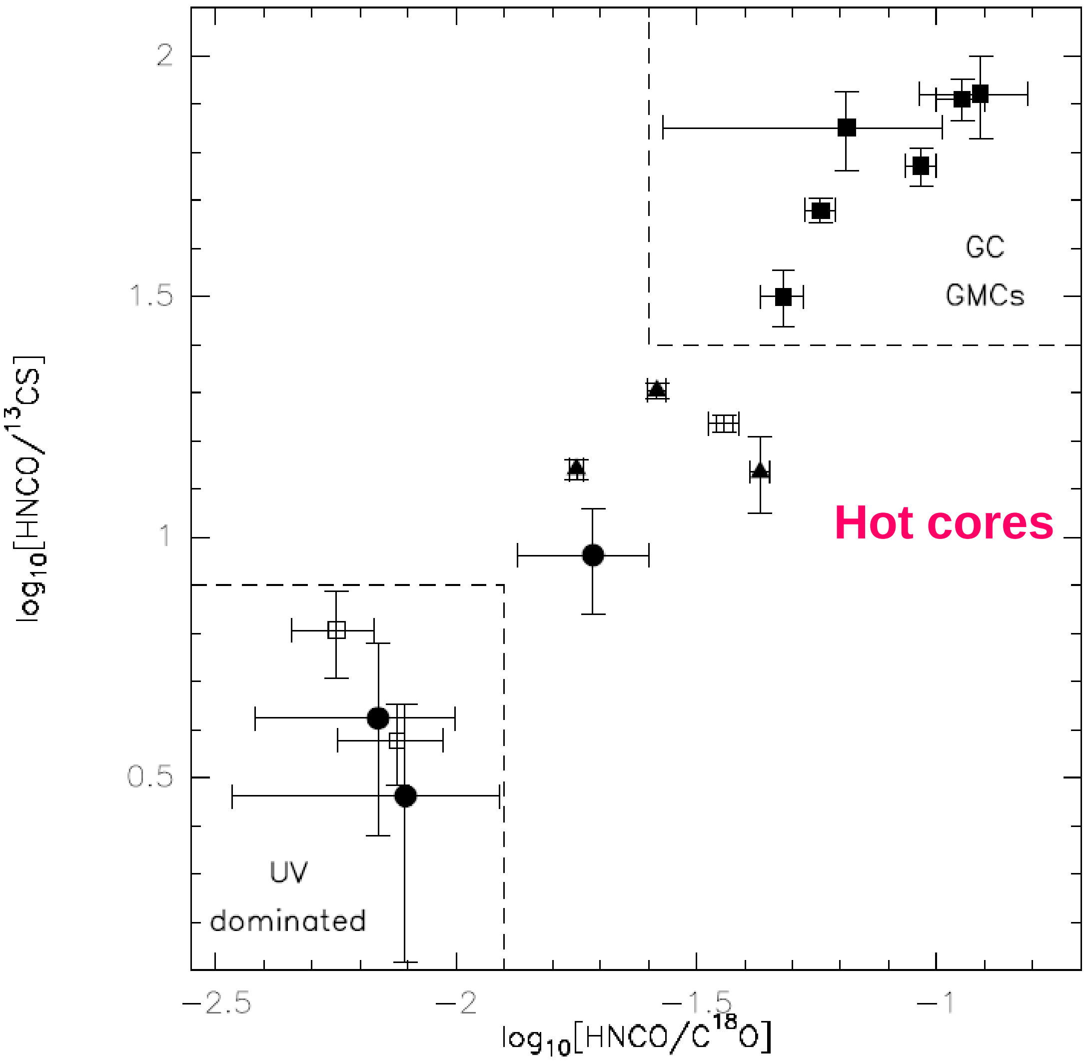
IRAM 30m

13 surveys
2 mm window
3 mm window

Martin et al, 2007
Aladro et al. 2009



Diagnostic diagram for PDRs



Martin et al. (2008)

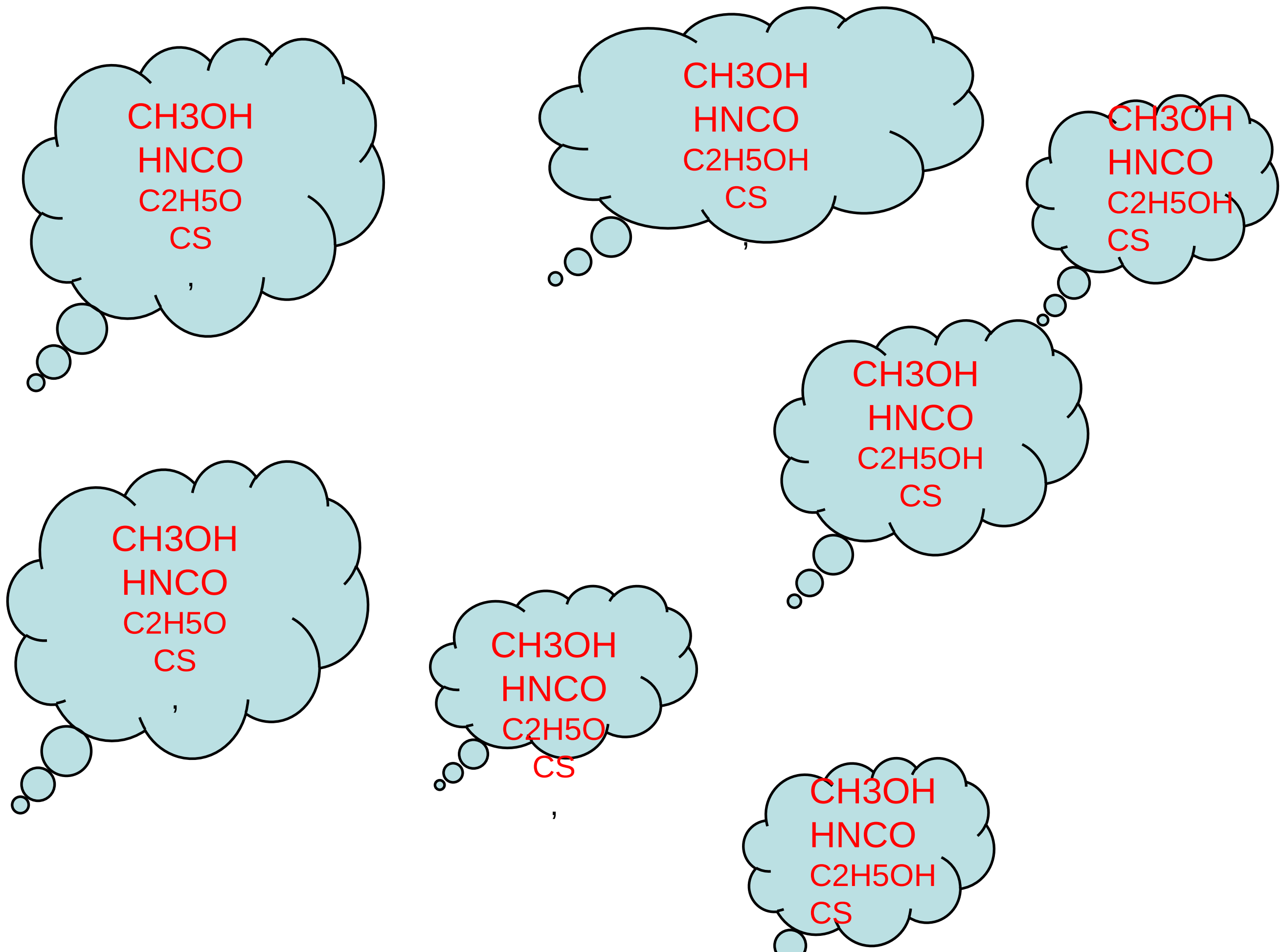
PDRs:

Large abundance changes

HNCO & CH3OH ↓↓
Not included in models
CS ↑↑

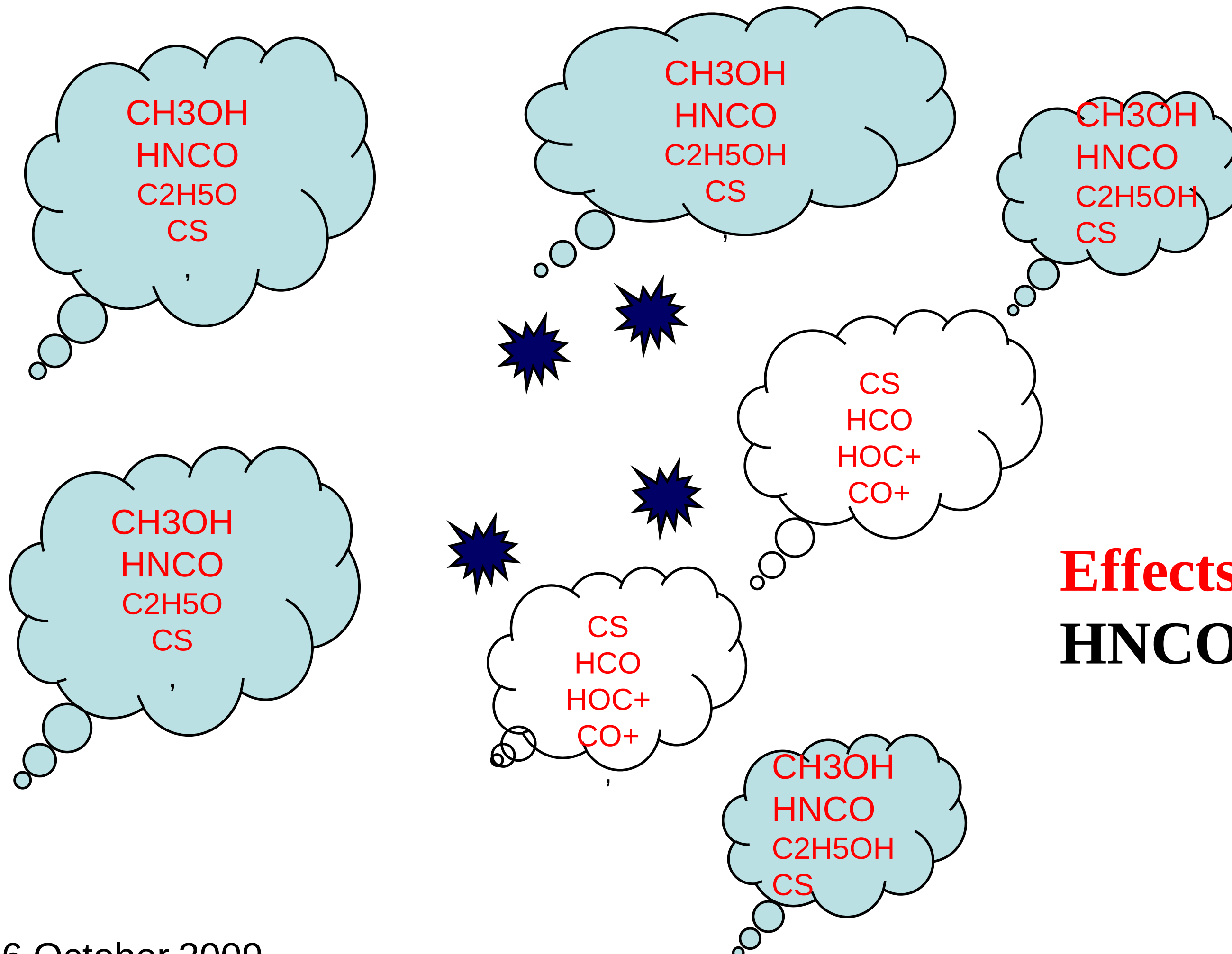
Picture for typical clouds in the CMZ

Large complexity: CH3OH, C2H5OH, (CH3)2O, HCOOCH3, HCOOH, CH3COOH



Picture for typical clouds in the CMZ

Large complexity: CH3OH, C2H5OH, (CH3)2O, HCOOCH3, HCOOH, CH3COOH
PDRs: destroy HNCO and CH3OH and produce CO+, HOC+, HCO
XDRs: produce SiO, (CO+, HOC+, HCO??)



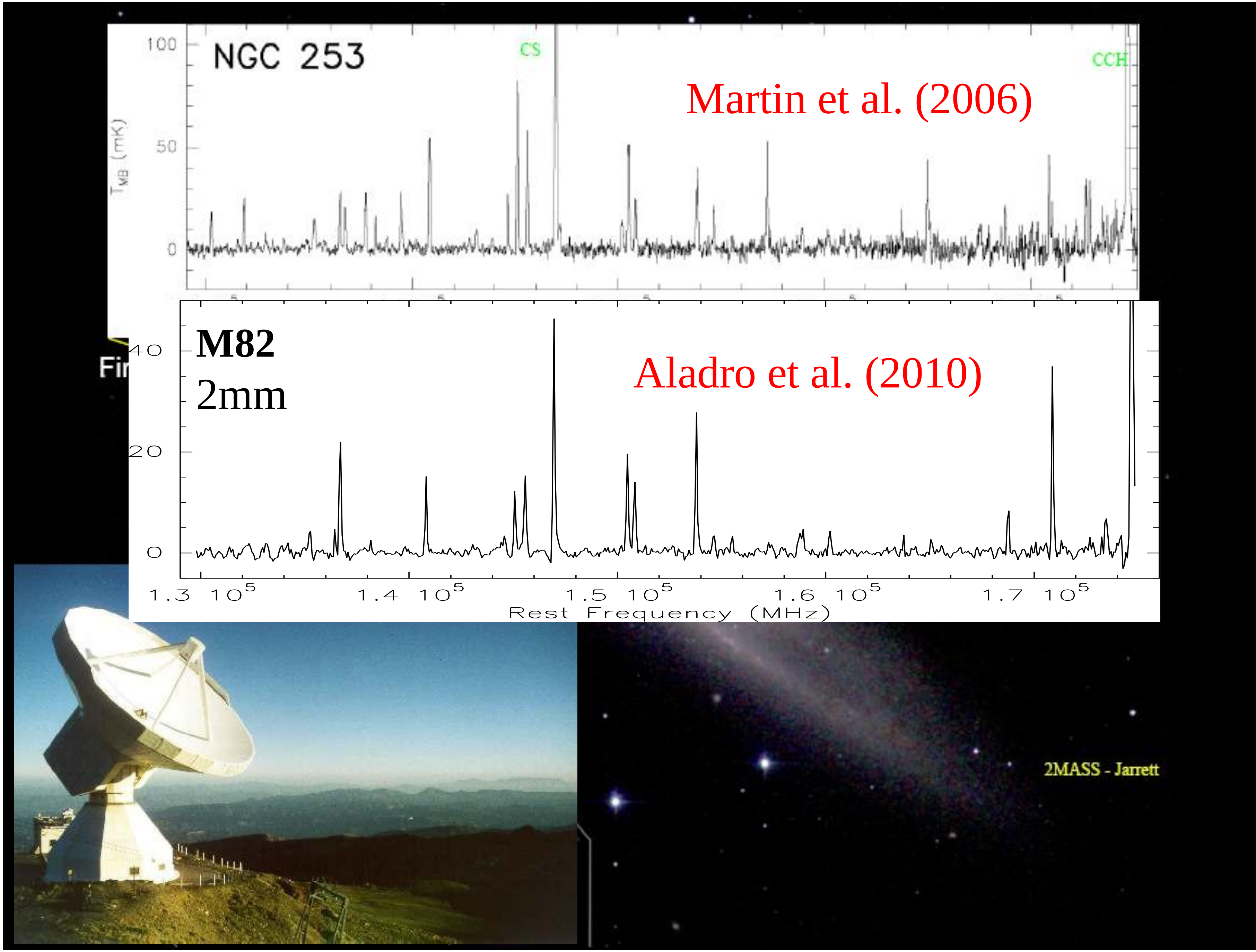
Effects of the clusters:
HNCO/CS gradient

Chemical complexity in SBs

L_{IR}=2x10^{10} $L_\odot$
SFR_{IR} = 4 $M_\odot yr^{-1}$
Galactic superwind

L_{IR}=3x10^{10} $L_\odot$
SFR=9 $M_\odot$ $year^{-1}$
Galactic superwind

Chemical complexity in SBs



DETECTED EXTRAGALACTIC MOLECULES

2 Atoms	3 Atoms	4 Atoms	5 atoms	6 Atoms	7 Atoms
H_2 (+1)	H_2O	H_2CO	c-C_3H_2	CH_3OH	CH_3CCH
OH	HCN (+2)	H_2CS	HC_3N	CH_3CN	
CO (+3)	HNC (+2)	NH_3	*CH_2NH*		
CH	HCO	HNCO	NH_2CN		
CS (+2)	HCO^+ (+3)	*C_3H*			
CH^+	H_2S	*$HOCO^+$*			
CO^+	SO_2	**HCNH+?**			
NO	C_2H				
CN	HOC^+				
NS	C_2S				
SiO	N_2H^+ (+1)				
SO (+1)	OCS				
NH	H_3^+ **NH_2**				

Italics = tentative

* NGC 253's chemistry closely resembles that of the Galactic center

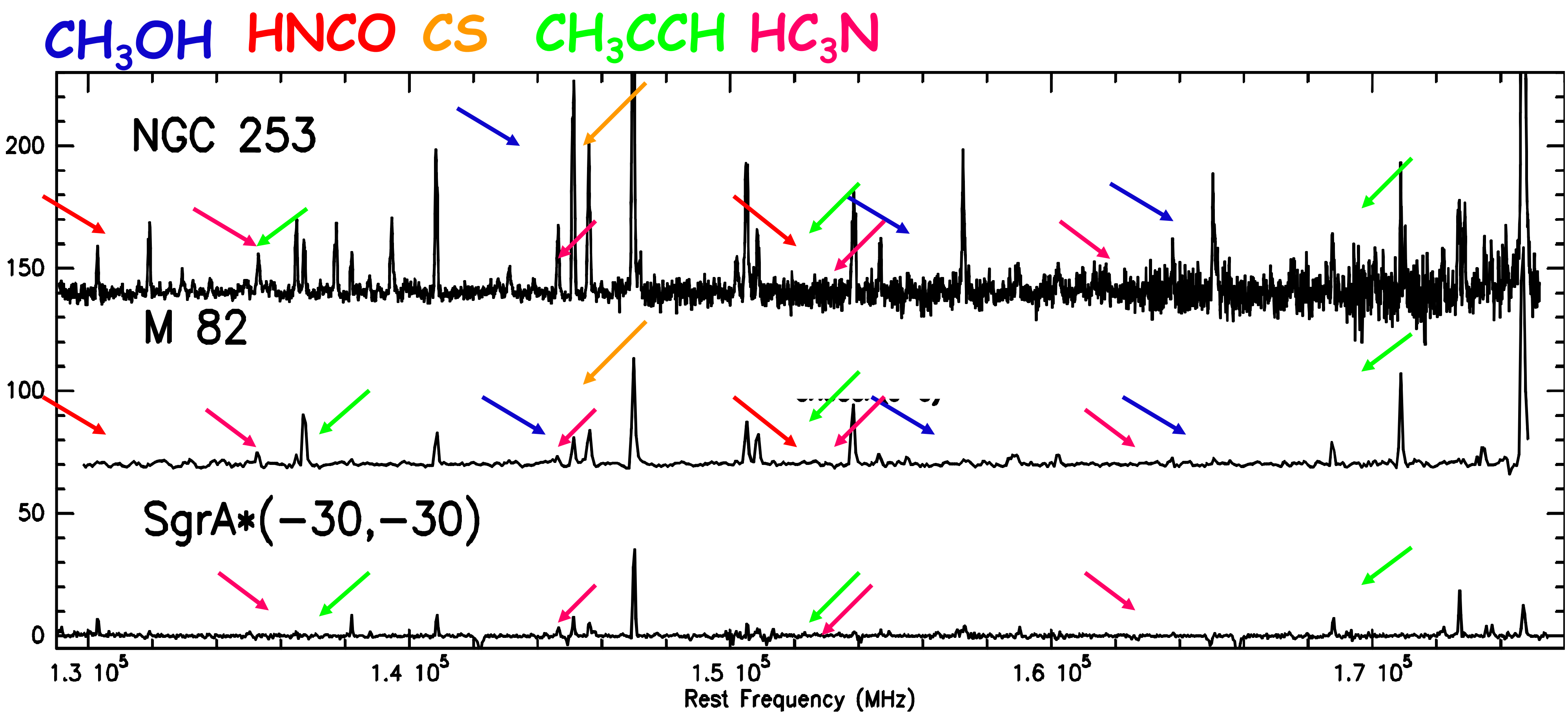
To Date:

* 38 + 4 tentatively) detected species

* 13 (+ 2 tentatively) detected rare isotopic substitutions

(Compiled: Martin et al 2006; updated by Meier)

Chemical complexity Templates



Wang et al. (2004) covered most relevant molecules in NGC 495

Chemical complexity Templates

Wang et al. (2004) covered most relevant molecules in NGC 495

Table 7. Column densities and densities[a)]

Molecule	N (cm^{-2})	n_{H_2} (cm^{-3})
CO [b)]	4.6×10^{18}	4.0×10^{3}
^{13}CO	9.2×10^{16}	4.9×10^{3}
$C^{18}O$	2.4×10^{16}	2.6×10^{3}
$C^{17}O$	3.7×10^{15}	4.0×10^{3}
CN [c)]	2.5×10^{14}	$\sim1.0\times10^{4}$
CS [d)]	3.7×10^{14}	5.0×10^{4}
$C^{34}S$	2.7×10^{13}	5.5×10^{4}
^{13}CS	$\lesssim7.4\times10^{12}$	5.5×10^{4}
SO [e)]	1.0×10^{14}	1.0×10^{5}
C_2H [f)]	6.8×10^{15}	...
HCN [b)]	1.3×10^{15}	1.5×10^{5}
$H^{13}CN$	2.6×10^{13}	1.5×10^{5}
$HC^{15}N$	9.3×10^{12}	1.5×10^{5}
HCO^+ [e,g)]	$\gtrsim1.9\times10^{13}$	...
HNC [b,h)]	1.8×10^{15}	...
$HN^{13}C$ [h)]	3.5×10^{13}	...
N_2H^+ [e,h)]	4.2×10^{12}	...
OCS [e)]	$\lesssim5.2\times10^{14}$	...
ortho-H_2CO [e)]	1.0×10^{14}	4.0×10^{5}
HNCO [e)]	2.3×10^{14}	1.6×10^{4}
C_3H_2 [e)]	3.3×10^{14}	...
HC_3N [e)]	7.0×10^{13}	1.0×10^{5}
CH_3OH [e)]	5.5×10^{14}	1.1×10^{4}
CH_3CCH [i)]	2.4×10^{14}	...

Key molecules (Abundances)

	NGC 253	M82	NG4945
N(**CS**) / N(H_2)	$4x10^{-9}$	$5x10^{-9}$	$6x10^{-9}$
N(**CH_3OH**) / N(CS)	2.4	1.1	1.5
N(**HNCO**) / N(CS)	0.3	<0.05	0.6
N(**HC_3N**) / N(CS)	0.1	0.2	0.2
N(**CH_3CCH**) / N(CS)	1.4	14	0.6

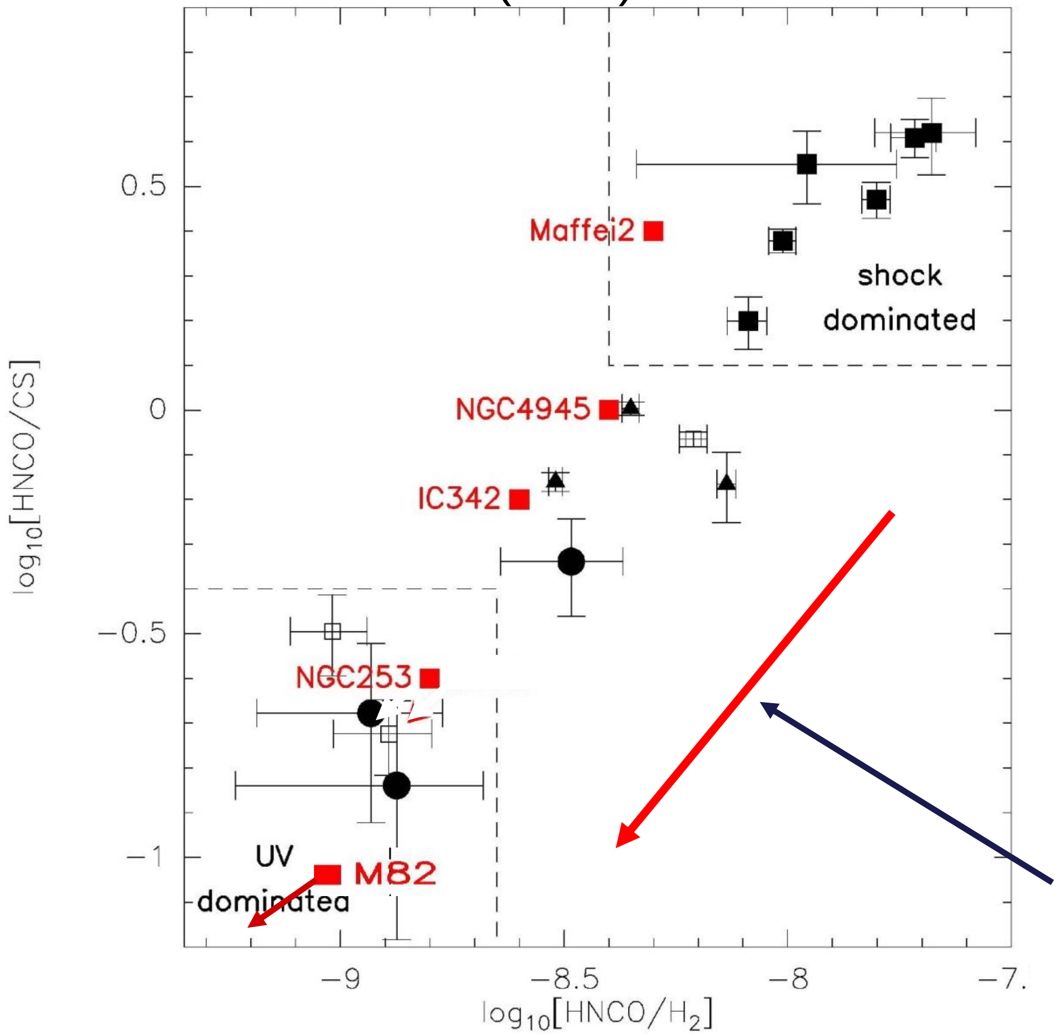
Chemical complexity in SBs

- The properties of the ISM in NGC253 and NGC4945 are similar to those found in the typical GC molecular cloud indicating **SHOCK dominated ISM**

- The ISM in M82 is completely different with low Tk from Ammonia and low HNCO and very high CH3CCH abundances. The heating and the chemistry of the ISM are dominated by UV radiation from the stellar superclusters. **PDR dominated ISM**

HNCO diagnostic diagram

Martin et al. (2009)



Maffei2 is heated by shocks

HCN/HCO+ ~2.6

NGC253 shocks +(UV?)

HCN/HCO+ ~1

NGC4945 shocks+ (UV)

HCN/HCO+ ?

HCO detected by Wang et al (2004)

M82 is dominated by UV

HCN/HCO+ ~0.5

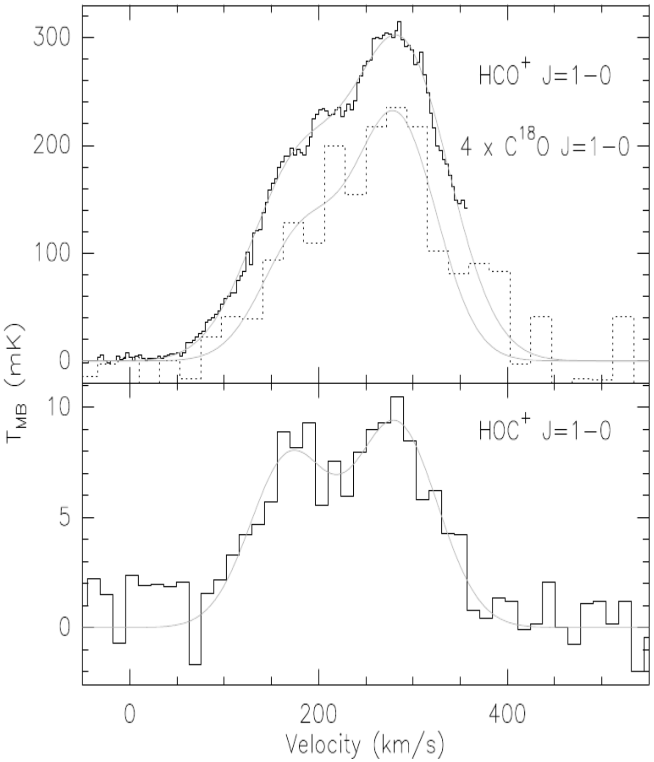
HCO Garcia-Burillo et al. (2001)

HOC+, CO+ Fuente et al. (2005, 6)

Effect of starburst evolution

PDRs in Shocked ISM: NGC253

Martin et al. (2009) detected HCO, HOC+, CO+ in NGC 253



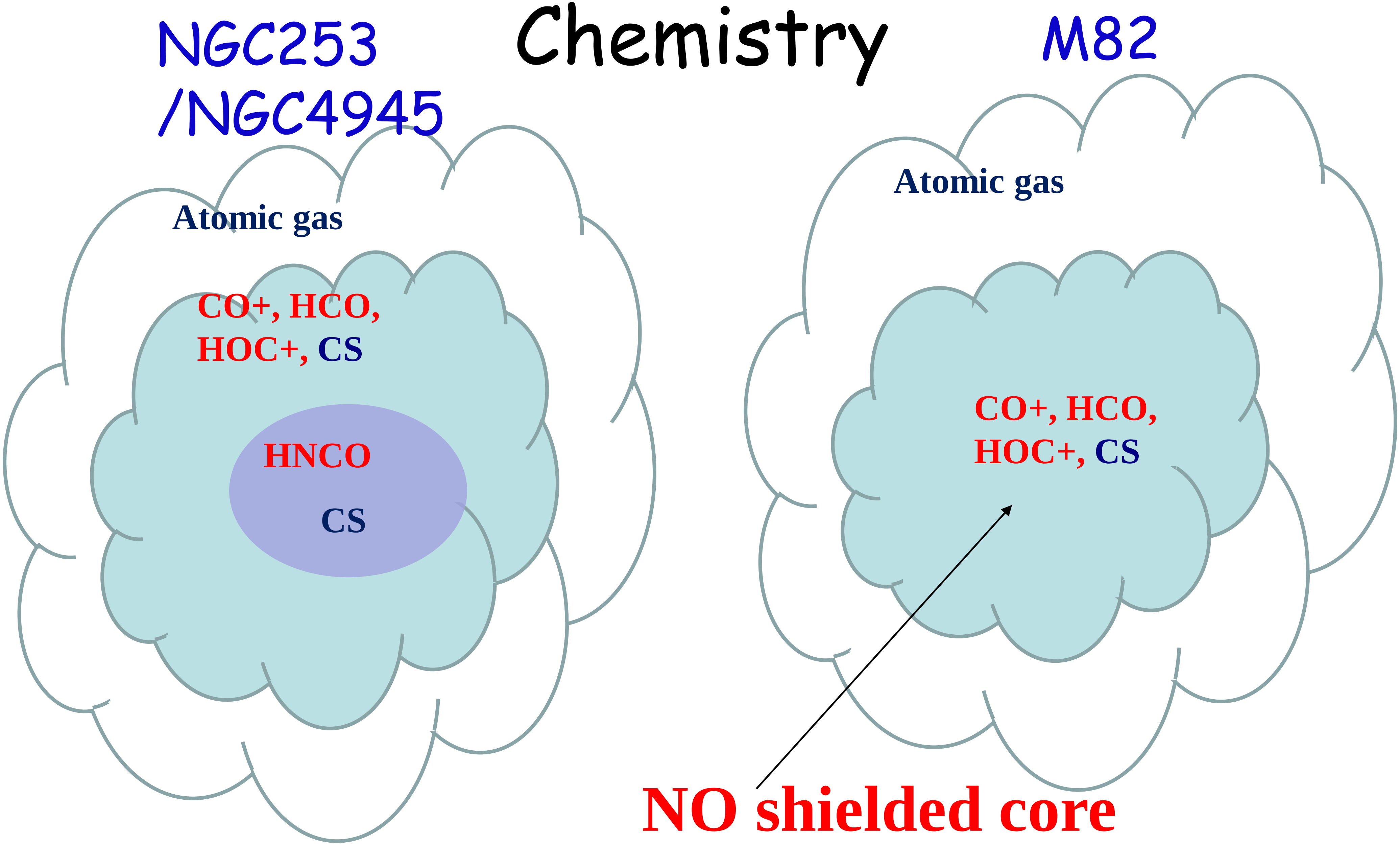
Source	$[HCO^+]/[HOC^+]$	$[HCO^+]/[HCO]$	$[HCO^+]/[CO^+]$
NGC 253	80 ± 30	5.2 ± 1.8	38 ± 15
	63 ± 17	5.4 ± 1.3	...
M 82	60 ± 28 [a]	9.6 ± 2.8 [b]	32 ± 16 [a]
NGC 1068	128 ± 28 [c]	3.2 ± 1.2 [d]	...
NGC 4945	...	2.4 ± 1.2 [e]	...

For NGC253 and M82:

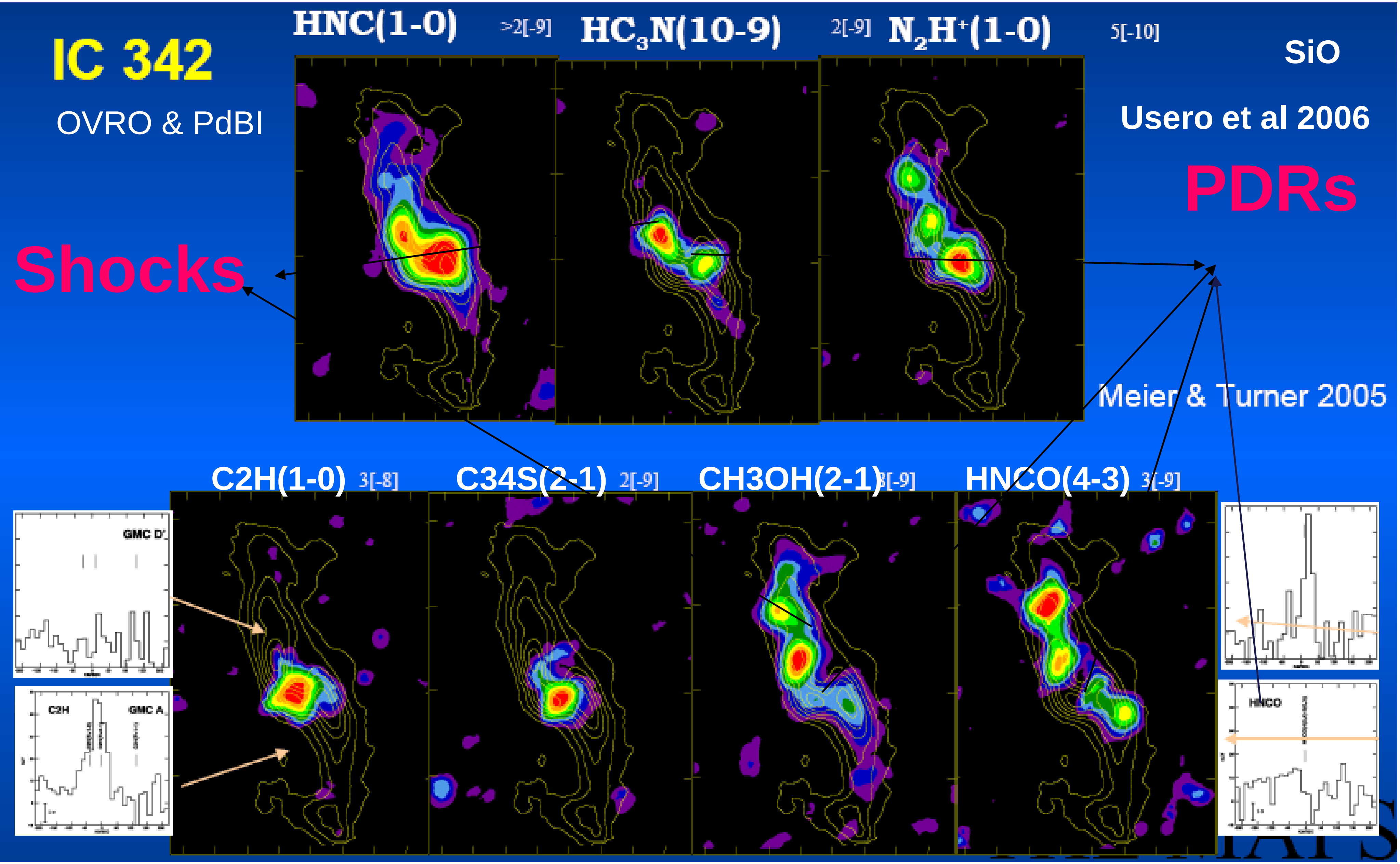
•Similar PDR components: Av~ 3-4 mag

•HNCO survive Av> 7 mag

Structure of clouds in Starburst Chemistry



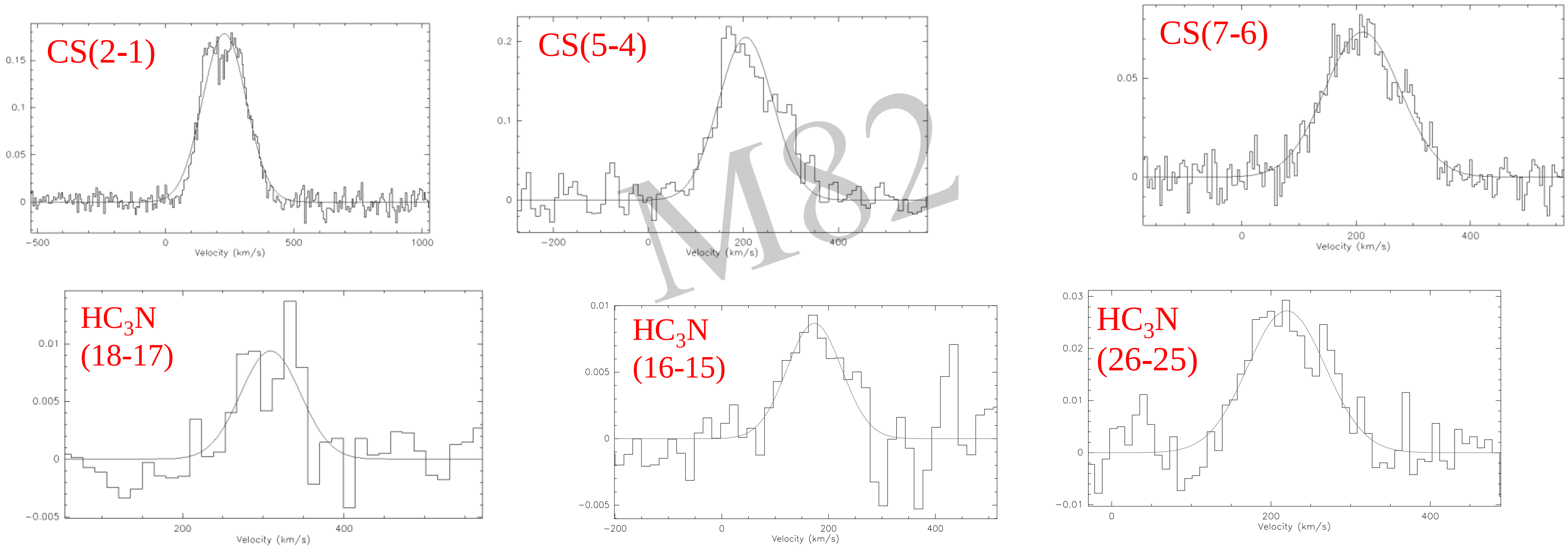
IC342: PDR+shocks



Structure of clouds in Starburst density

NGC253

- Physical properties of the clouds: T_k, N, $n(H_2)$
- Relationship chemistry-physical conditions
- Multiline analisys of CS, HC3N and CH3CCH

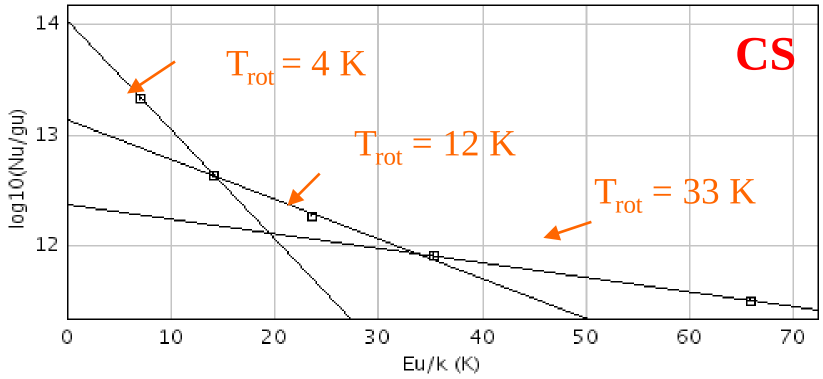


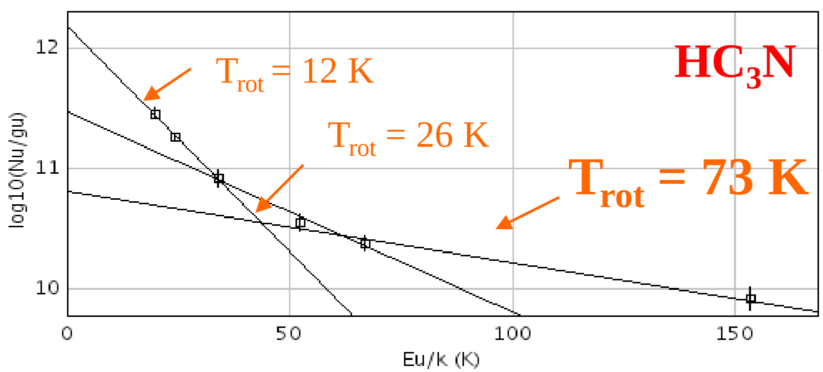
LTE Analysis

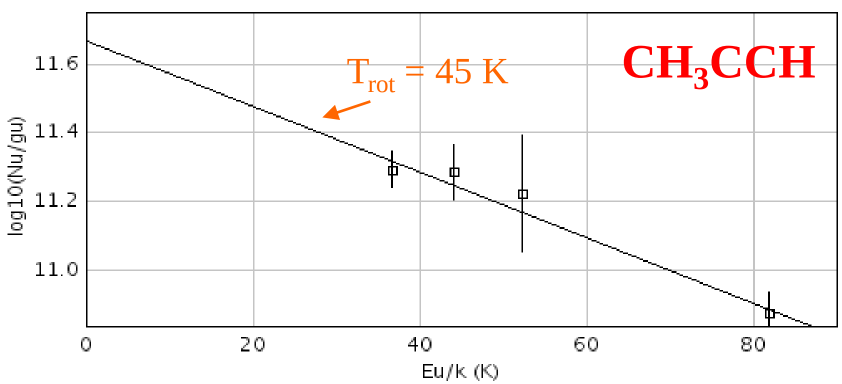
T_{kin}^{NH3} = 120 K

T_{kin}^{NH3} = 29 K

NGC253

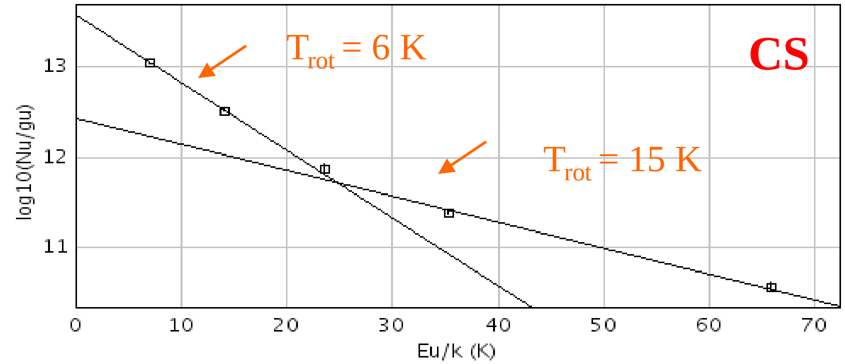


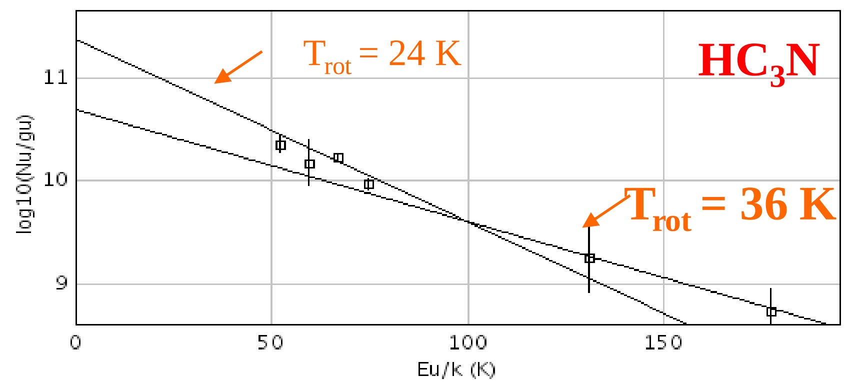


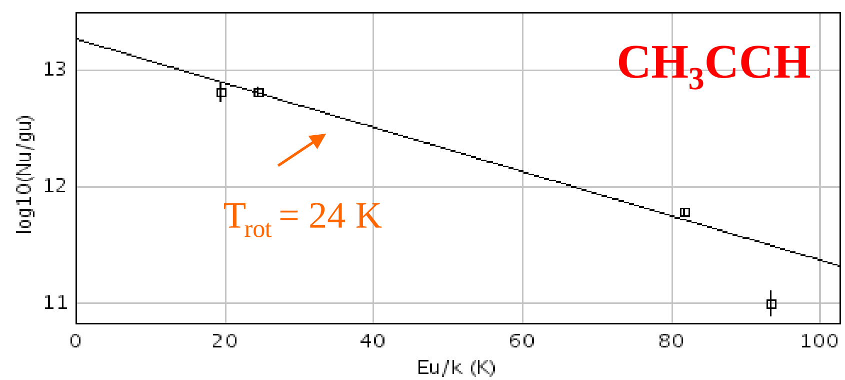


M82

60 K < T_{kin}^{CO} < 130 K

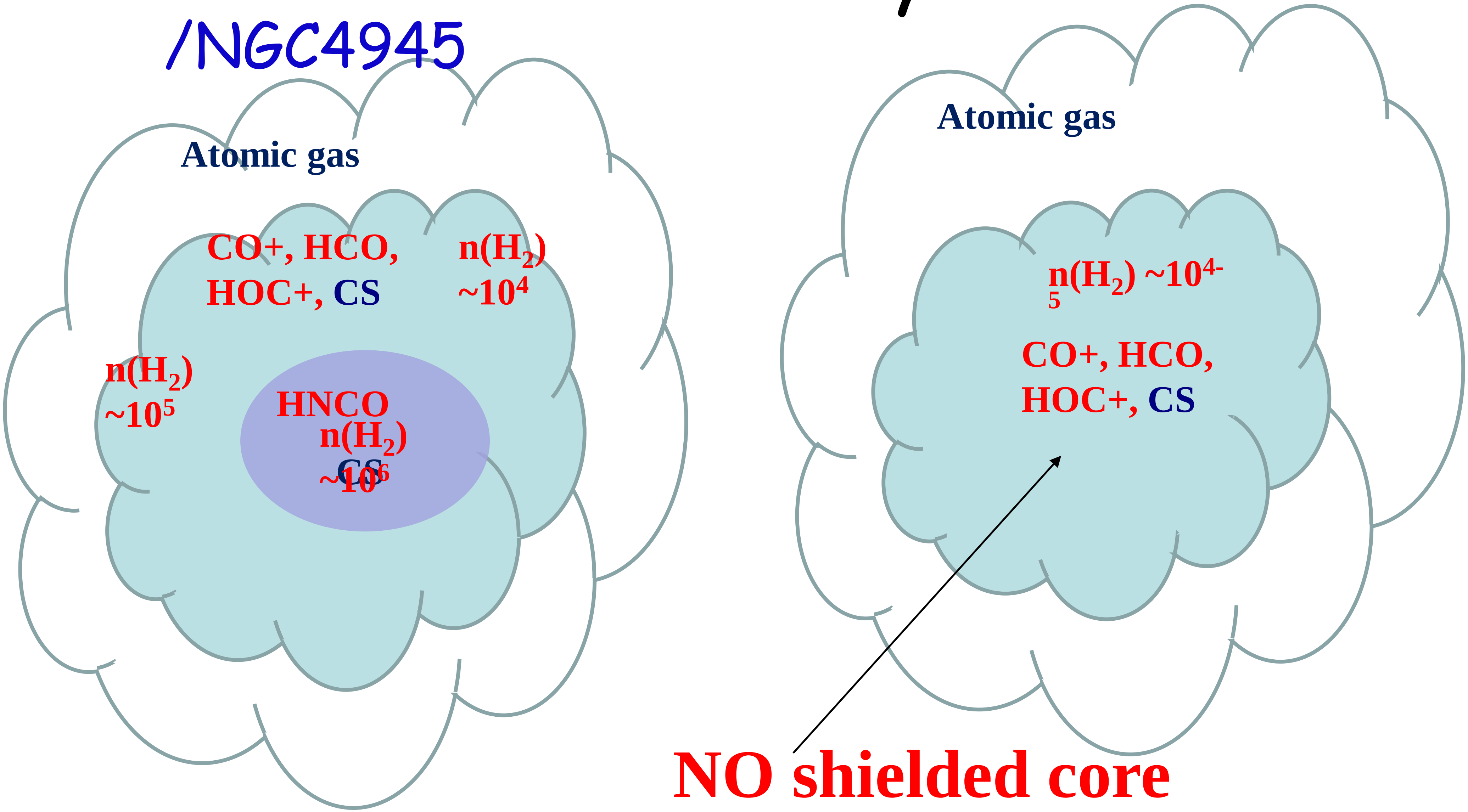






Structure of clouds in Starburst Chemistry

NGC253 /NGC4945 M82



Metalicity: Isotopic ratios

12C is primary and 13C is secondary
Usually 12CO & 13CO are used to derive 12C/13C

12C/13C ratios:
Solar: 90 GC: 22
M82 and NGC253 : 40-50
New values (C2H) for M82 and NGC253: > 140

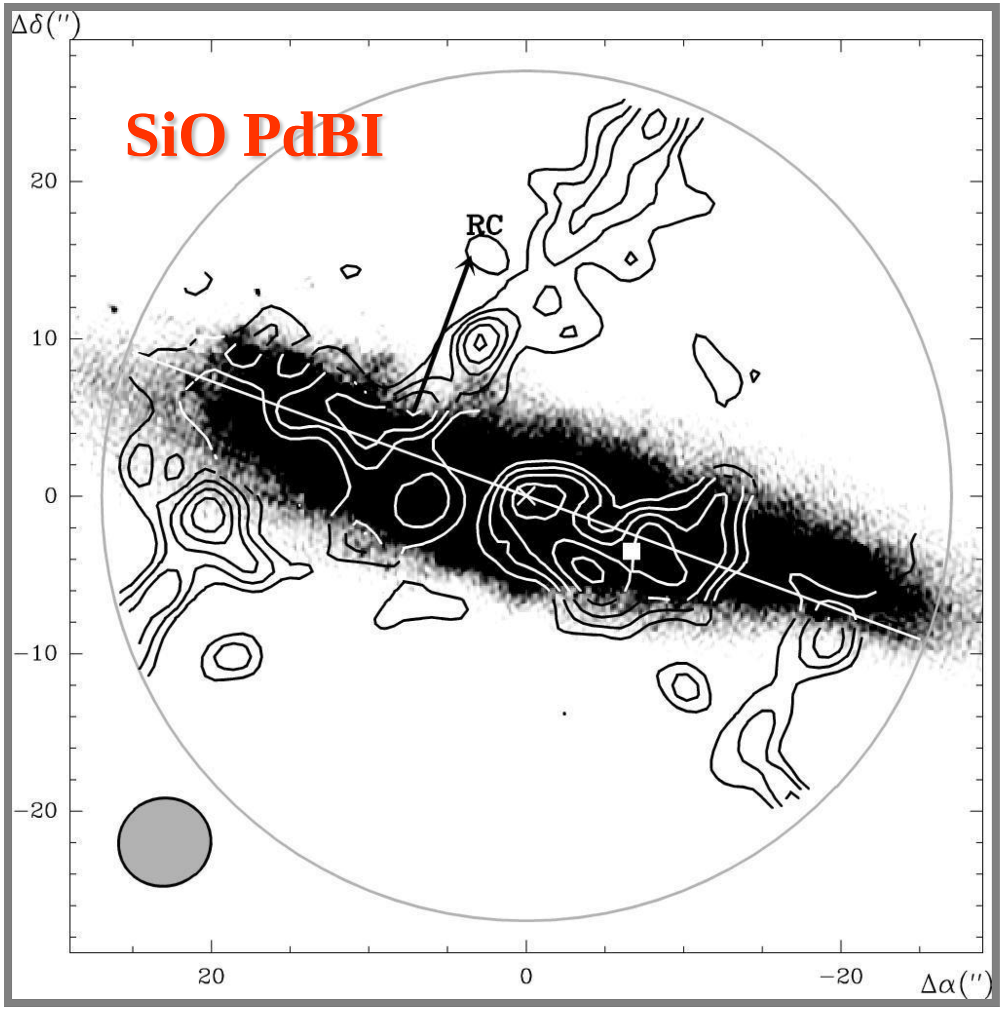
-Isotopic fractionation for C2H
-Gas has been accreted or undergoing “first” SB

Chemical complexity in M82

SiO emission (shock tracer) is out of the plane

- Traces the walls of the supershells not the star forming regions
- Vertical filament: SiO chimney

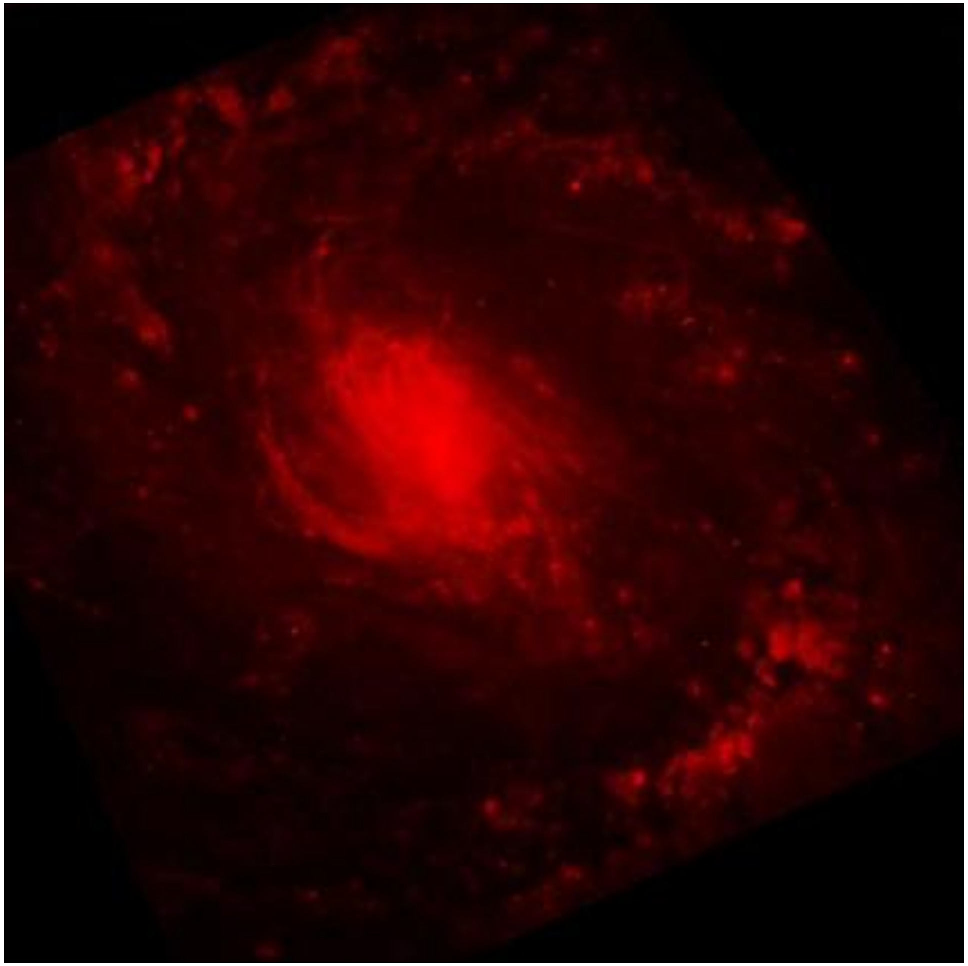
Gas ejected by the starburst: Superwinds



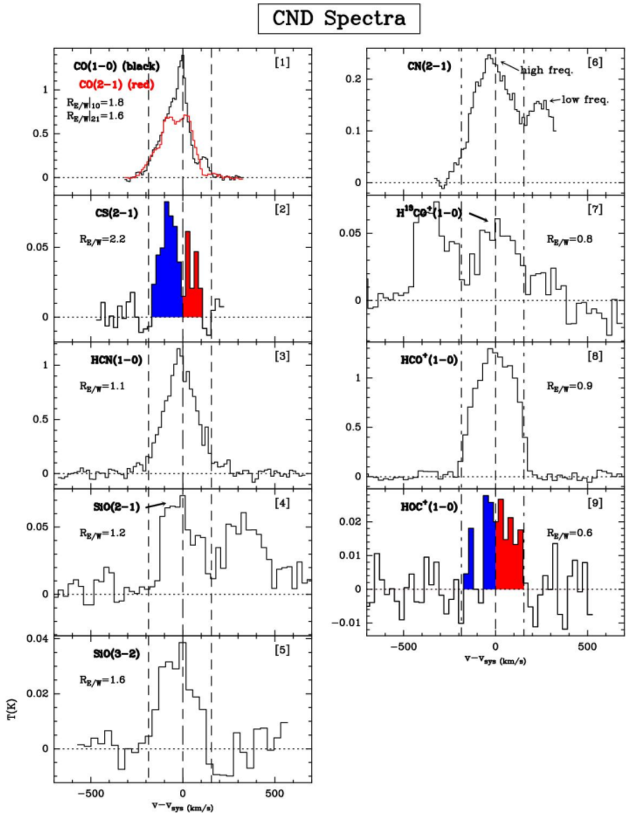
XDRs in AGNs

NGC 1068: XDR Chemistry

Usero et al. 2004, A&A, 419, 897



SiO and HOC+ and strong Fe 6.4 keV

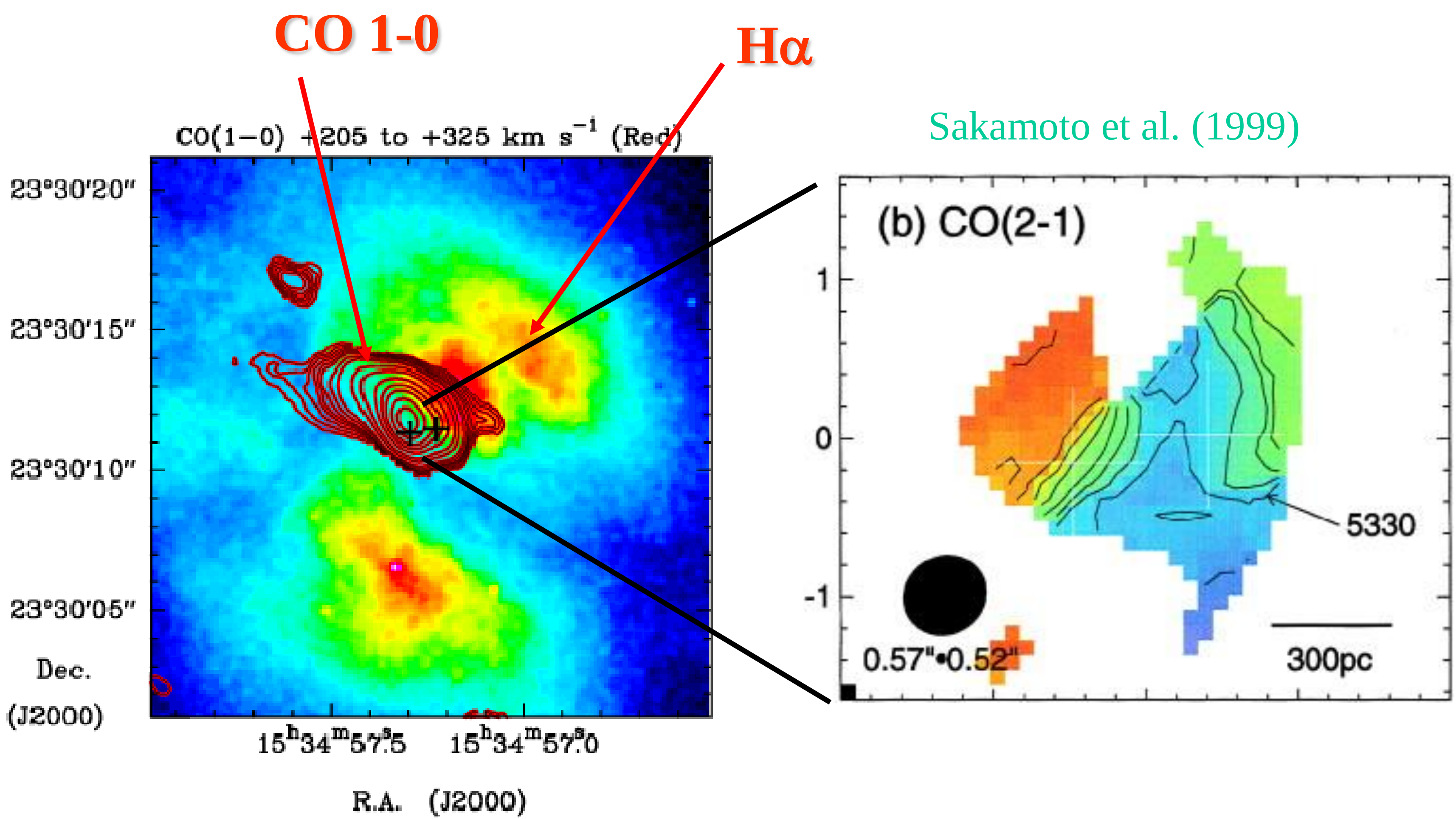


Proto super starclusters in Arp220

ULIRGs are believe to be nearby counterparts for high-z starburst galaxies

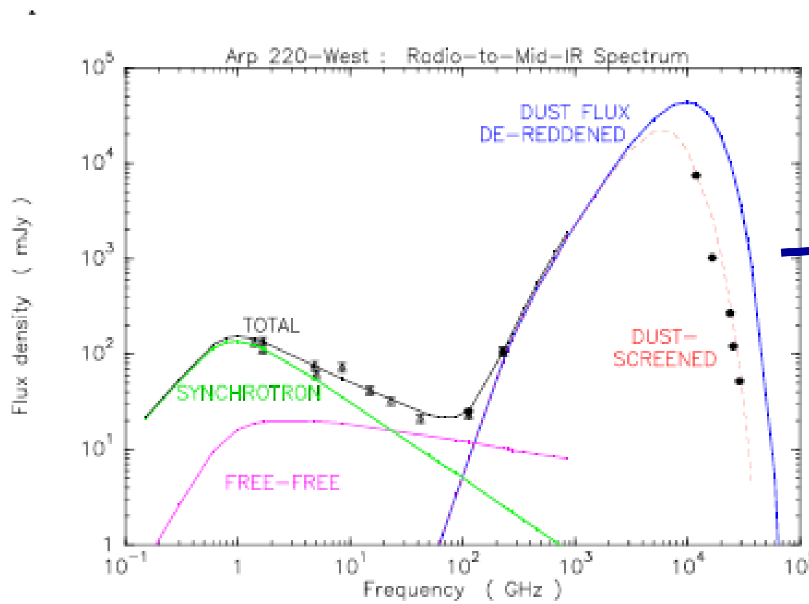
Arp220 is in the final stage of galaxy merger

Two nuclei at the center (~1” / 370 pc separation)



Proto super starclusters in Arp220

Downes et al. 2007 **: Compton thick AGN**



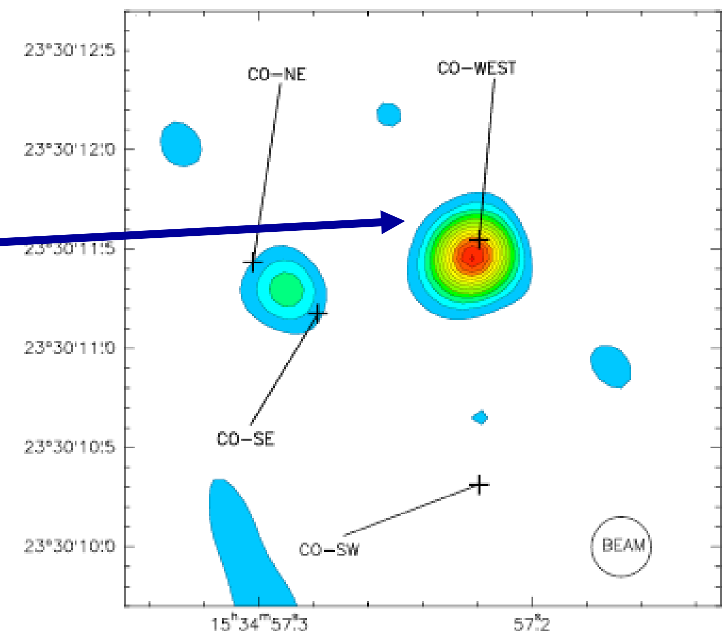


Fig. 2. Continuum map at 1.3mm (229.4 GHz). Contour steps are 6 mJy beam^{-1}. The Arp 220-West peak is 79 mJy beam^{-1}, and the East peak is 23 mJy beam^{-1}. Note that the continuum peaks do not coincide with the CO(2–1) peaks, which are marked with crosses. The beam is 0.30″ (lower right).

OPTICALLY THICK AT 1.1 MM

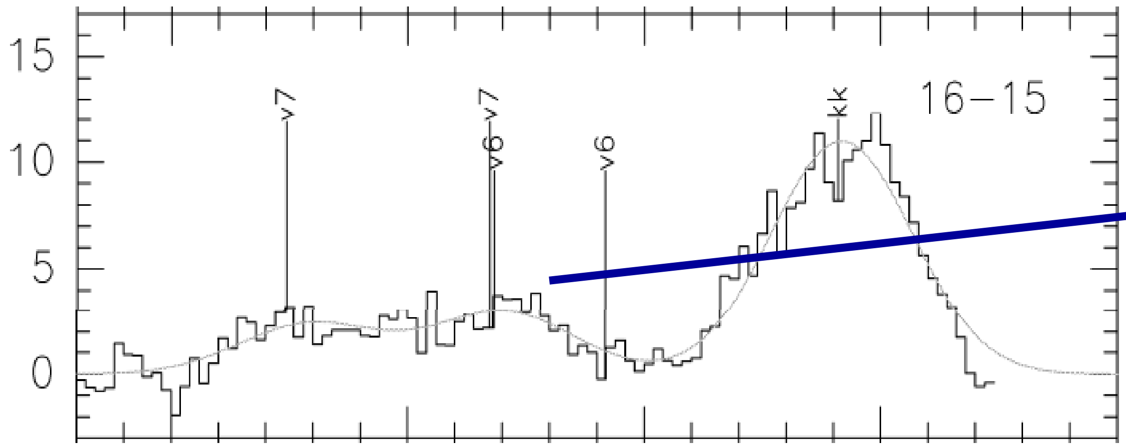
$NH_2 \sim 10^{25}$ cm^{-3}

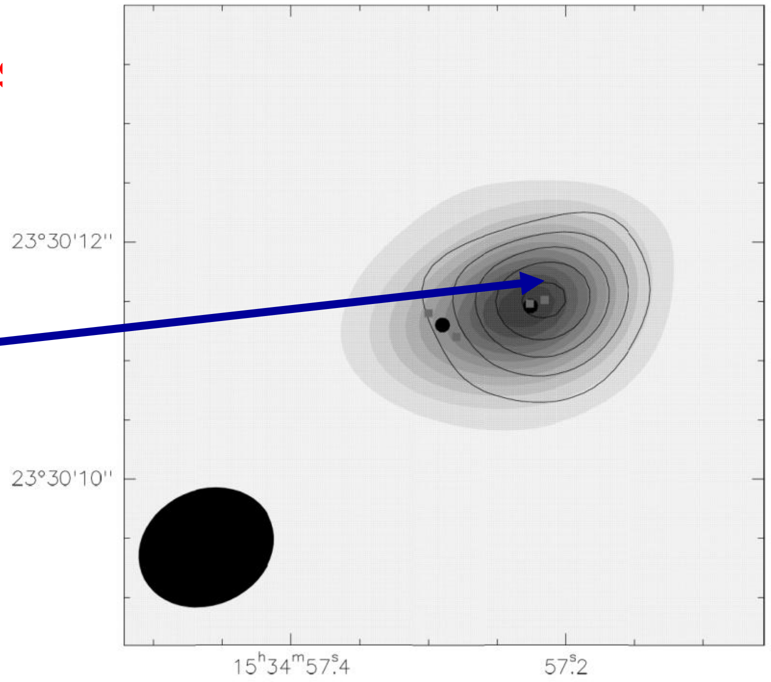
Molecular astrophysics: the solution?

Proto super starclusters in Arp220

Compton thick AGN?

DETECTION OF HC3N* = Hot cores =protostars



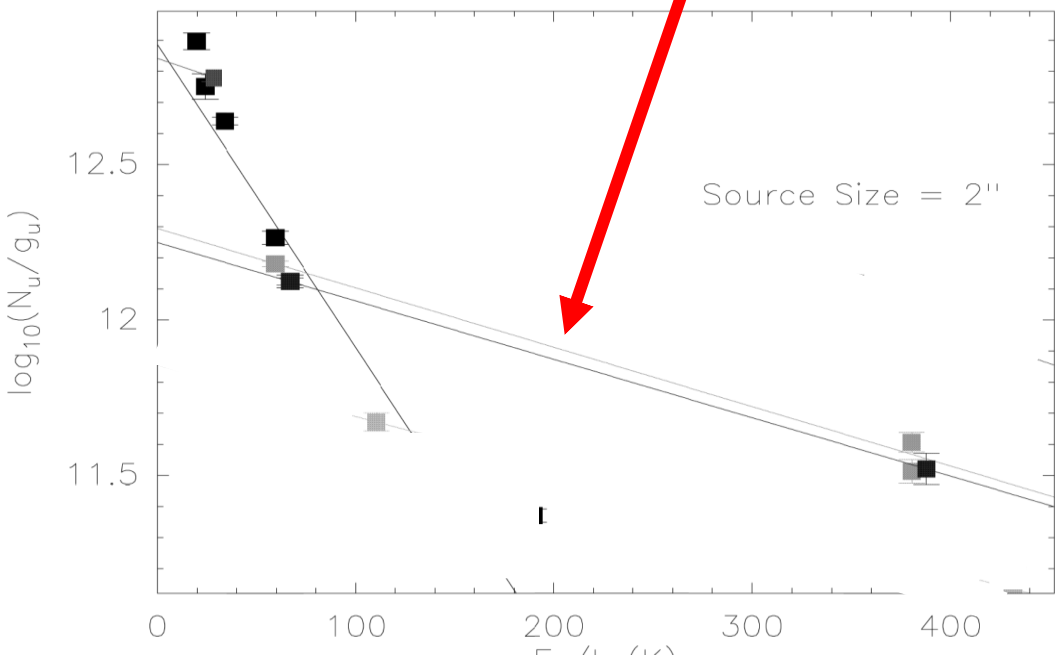


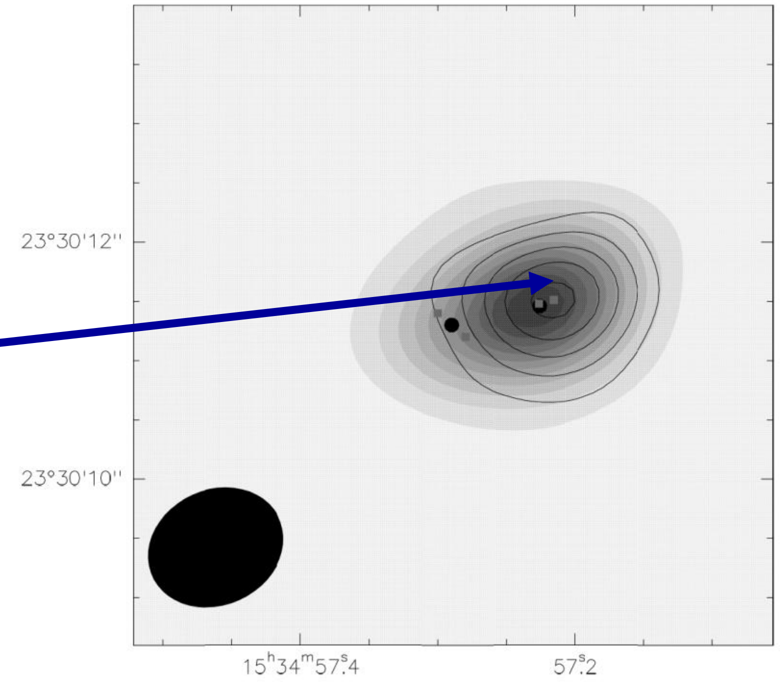
V7 IS TRACING HOT GAS & DUST VIBRATIONALLY EXCITED BY MID-IR RADIATION

DUST IS OPTICALLY THICK AT 1.1 MM RADIATES LIKE A BLACK BODY

Proto super starclusters in Arp220

Excitation temperature of ~220 K





Size from line intensity and Tex > 50 mas

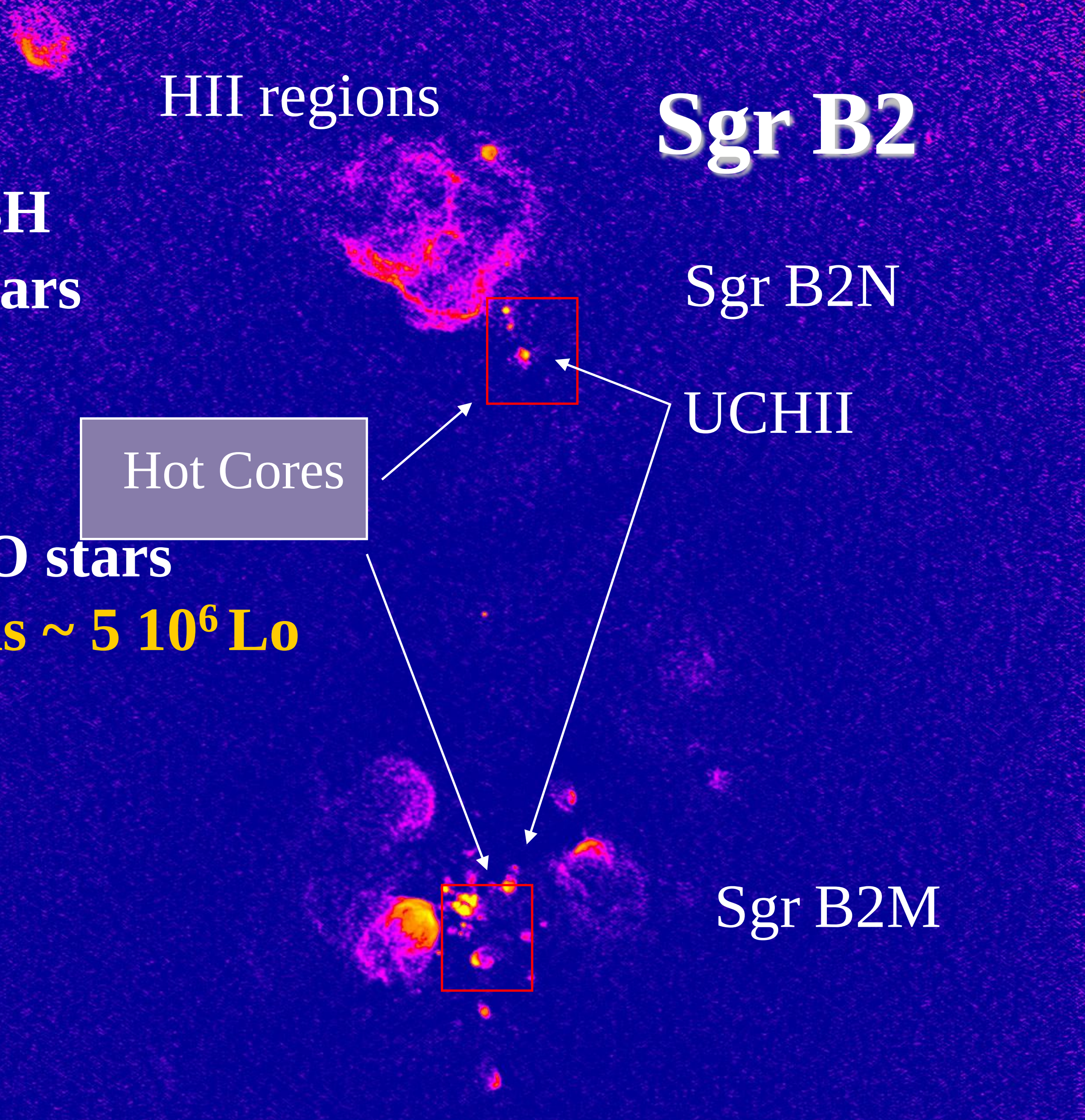
LUMINOSITY = $\pi * r^2 * \sigma * T^4 > 5\ 10^{11}$ Lo from star formation!!

Likely the powering source is Proto Stellar Clusters

Proto super starclusters in the GC

70 pc from the BH
L ~ 10^8 L_o , < 10^6 years

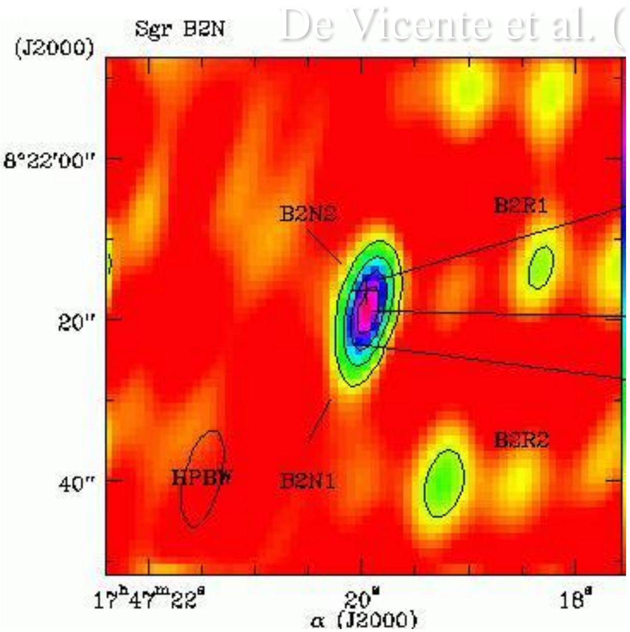
UC HII regions with O stars
Luminosity of HII regions is ~ 5 10^6 Lo



Proto starclusters in the GC

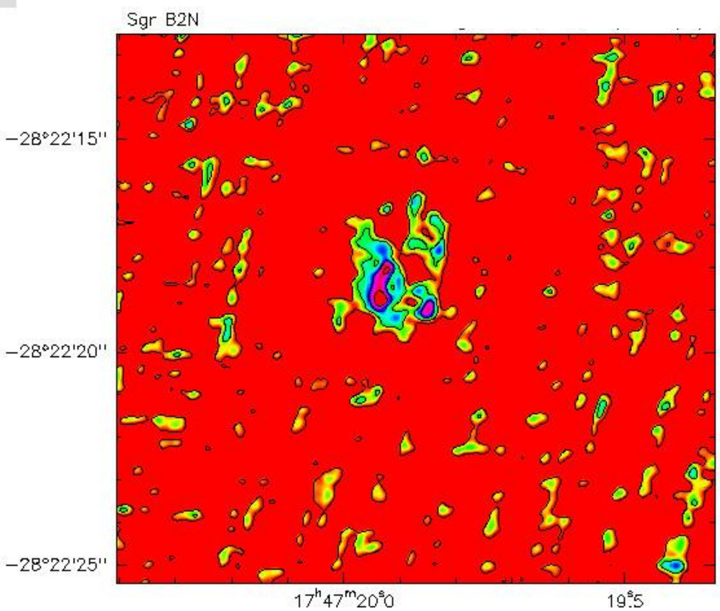
Table 1. Properties of massive clusters in the Galactic Center[a] Figer et al. (2004)

Cluster	Log(M1) $M_\odot$	Log(M2) $M_\odot$	Radius pc	Log(ρ1) $M_\odot$ pc^{-3}	Log(ρ2) $M_\odot$ pc^{-3}	Age Myr	Log(L) $L_\odot$	Log(Q) s^{-1}
Quintuplet	3.0	3.8	1.0	2.4	3.2	3–6	7.5	50.9
Arches[b]	4.1	4.1	0.19	5.6	5.6	2–3	8.0	51.0
Center[c]	3.0	4.0	0.23	4.6	5.6	3–7	7.3	50.5
Sgr B2N			**0.1**				7	



HC_3N* v7, v6, v5,
T ~ 300 K
L ~ 10^7 Lo

Condensations
with L ~ 10^5 Lo



Protocluster: IMF? Merging possible?

Chemistry as a tracer of activity

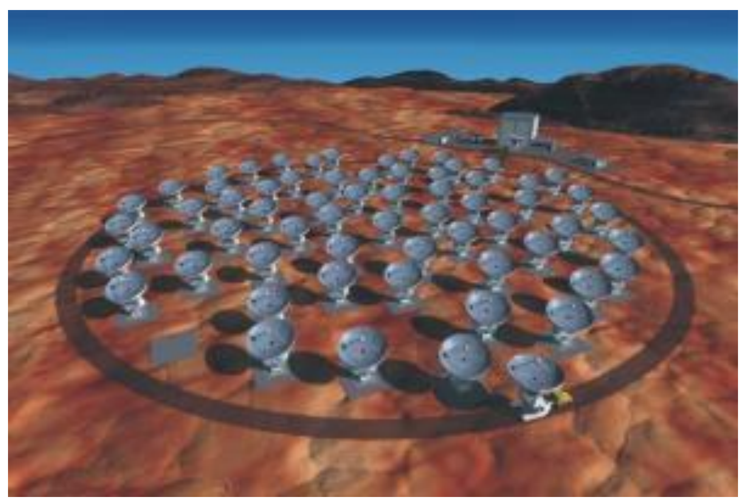
Molecular obervations provides unique information on:

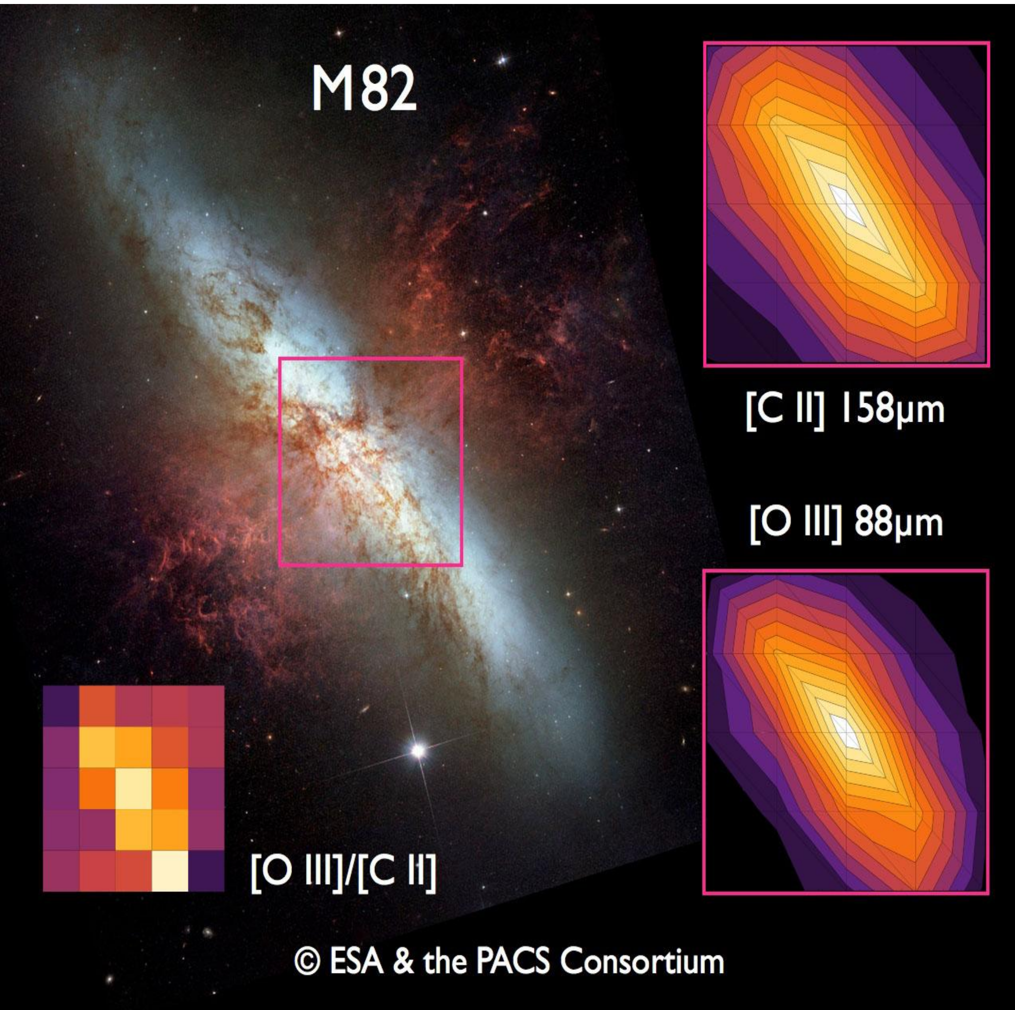
- **The large of Complex Organic Molecules in the nuclei of galaxies**
- **The powering source (shocks, UV, AGN)**
- **The structure of the molecular clouds and their evolution**
- **The evolutionary state of the nuclear starburst**
- **The starburst and AGN effects on the surrounding ISM**
- **The formation of starbursts (superclusters) at early stages**

THANK YOU

Expanded Very Large Array

ALMA




M82
[C II] 158μm
[O III] 88μm
[O III]/[C II]
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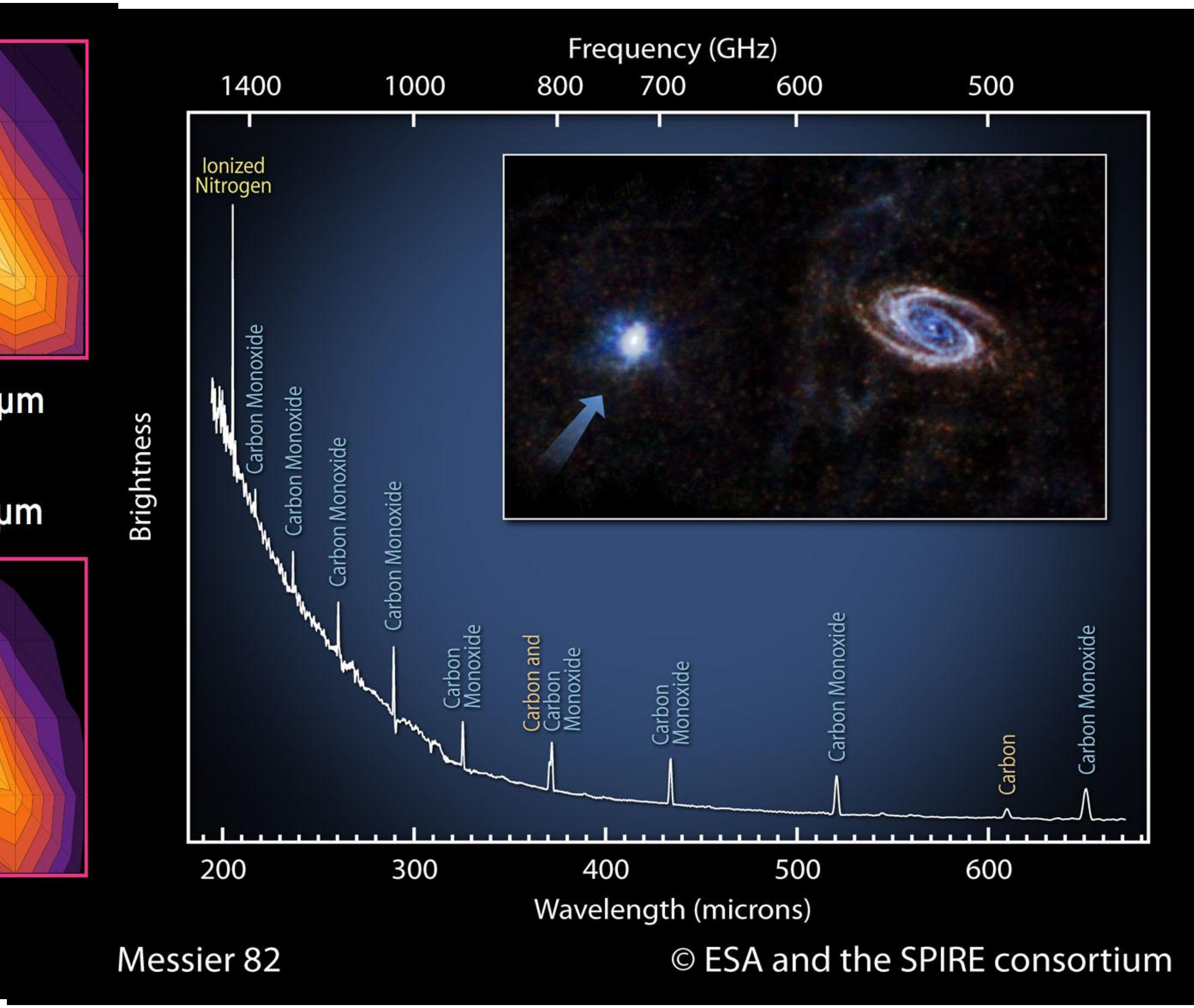
Frequency (GHz)
1400
1000
800
700
600
500
Ionized Nitrogen
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon and Carbon Monoxide
Carbon Monoxide
Carbon Monoxide
Carbon
Carbon Monoxide
Brightness
200
300
400
500
600
Wavelength (microns)
Messier 82
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