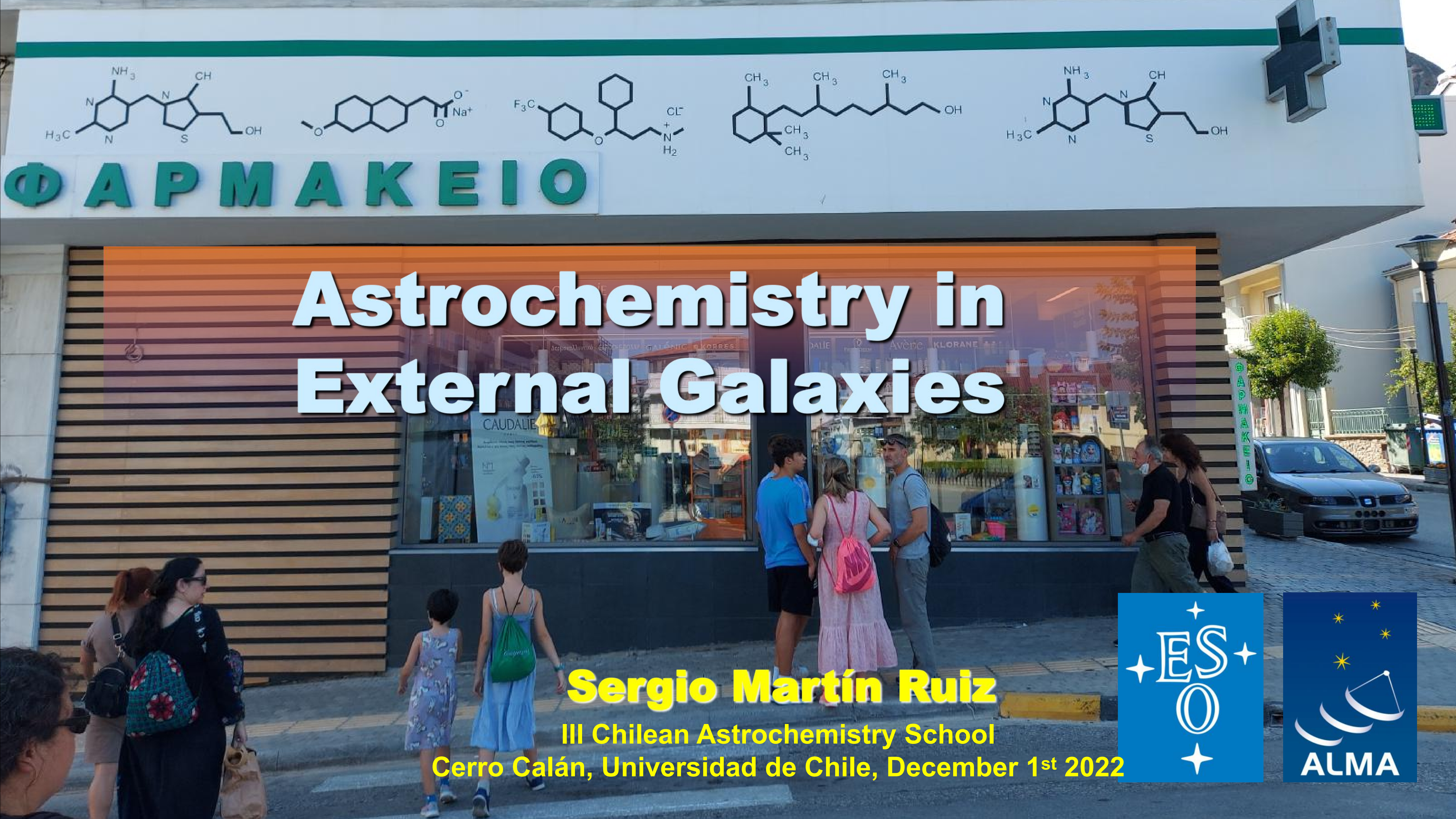


Astrochemistry in External Galaxies

Sergio Martín Ruiz

III Chilean Astrochemistry School

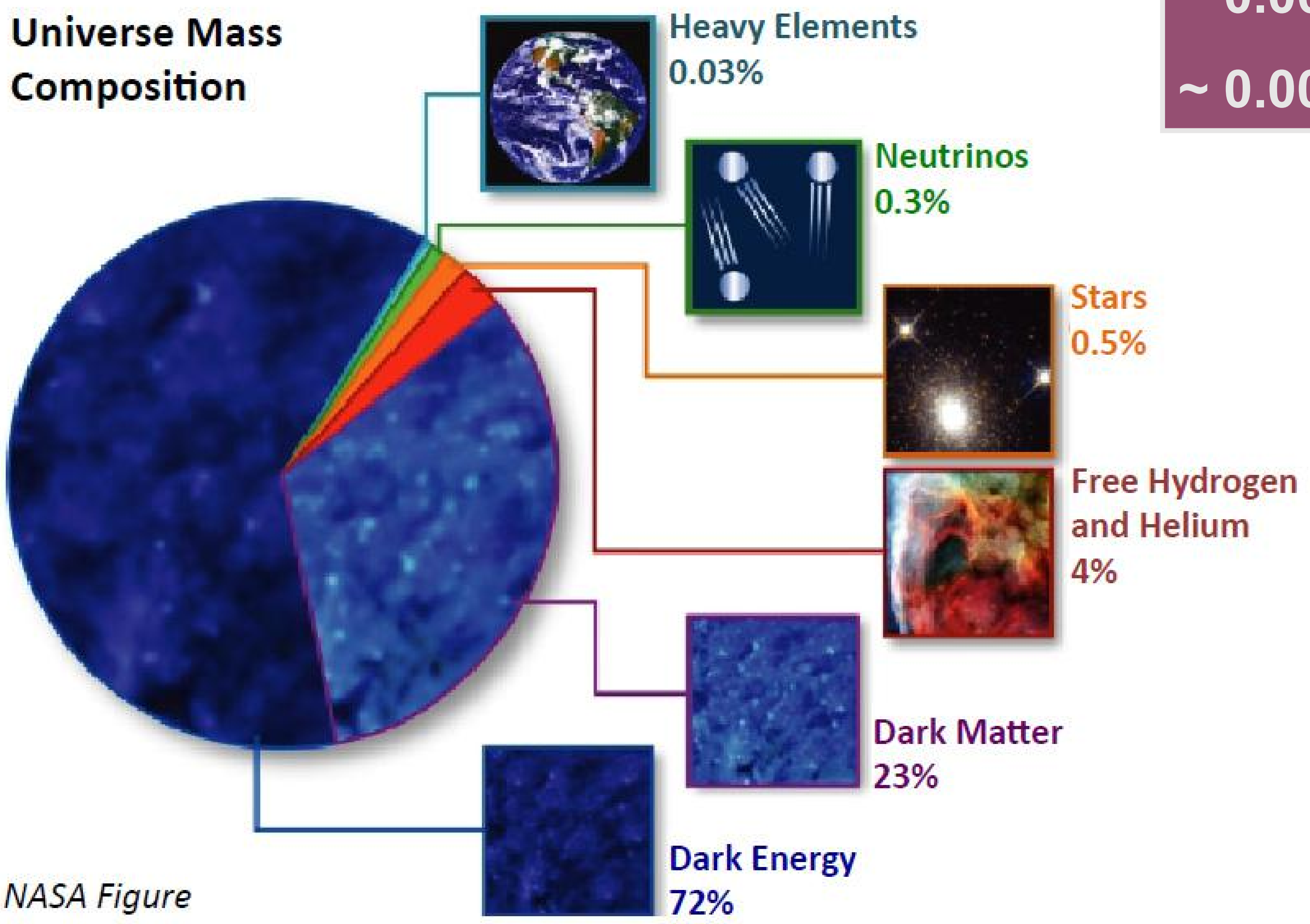
Cerro Calán, Universidad de Chile, December 1st 2022

OUTLINE

1. A brief history on e-astrochemistry
   - ALCHEMI ALMA Large Program
2. E-ASTROCHEMISTRY: Where are we now?
   - Galaxy evolution: Tracing the star formation process
   - Probing embedded AGNs: AGN vs SB in the dust obscured Universe
   - Physical conditions
   - A new environment to test astrochemistry
3. Future Challenge: Making sense of it all.

The Unbearable Lightness of Chemistry

- ~ 0.5 % Molecular (H_2)
- ~ 0.002 % CO
- ~ 0.000002 % other molecules



Main ISM Physical processes in play affecting chemistry

Starburst

- Low velocity shocks compressing the gas feeding the SB
- Photodissotiation from newly formed stars in the burst
- Shocks from SB driven outflow (mechanical heating)

Active Galactic Nucleus (AGN)

- X-ray from the central black hole
- High velocity shocks from black hole jet/outflow (mechanical heating)

A brief history on e-astrochemistry

THE ASTROPHYSICAL JOURNAL, 199:L75–L78, 1975 July 15

DETECTION OF EXTRAGALACTIC CARBON MONOXIDE AT MILLIMETER WAVELENGTHS

L. J RICKARD AND PATRICK PALMER
University of Chicago

M. MORRIS
Owens Valley Radio Observatory, California Institute of Technology

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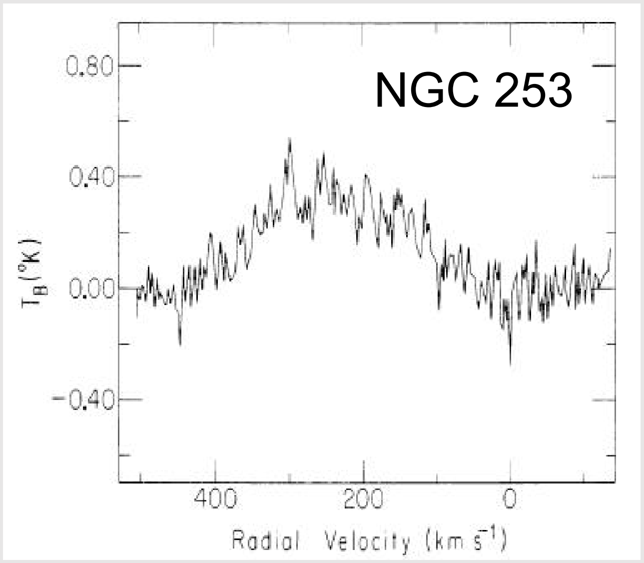
National Radio Astronomy Observatory†
Received 1975 March 6; revised 1975 March 17

ABSTRACT

We report the discovery of emission from the $J = 1 \rightarrow 0$ transition of $^{12}C^{16}O$ toward the central regions of external galaxies. In this *Letter*, we present preliminary results for two galaxies with active nuclei, M82 and NGC 253, in which the observed emission features are surprisingly strong. In the directions of the nuclear continuum peaks, the velocity range of CO emission is roughly the same as that of 21-cm absorption. For each galaxy, the CO features are spatially extended, and the velocity shift of the emission centroid along the major axis is in the sense of the galactic rotation.
Subject headings: galactic nuclei — molecules

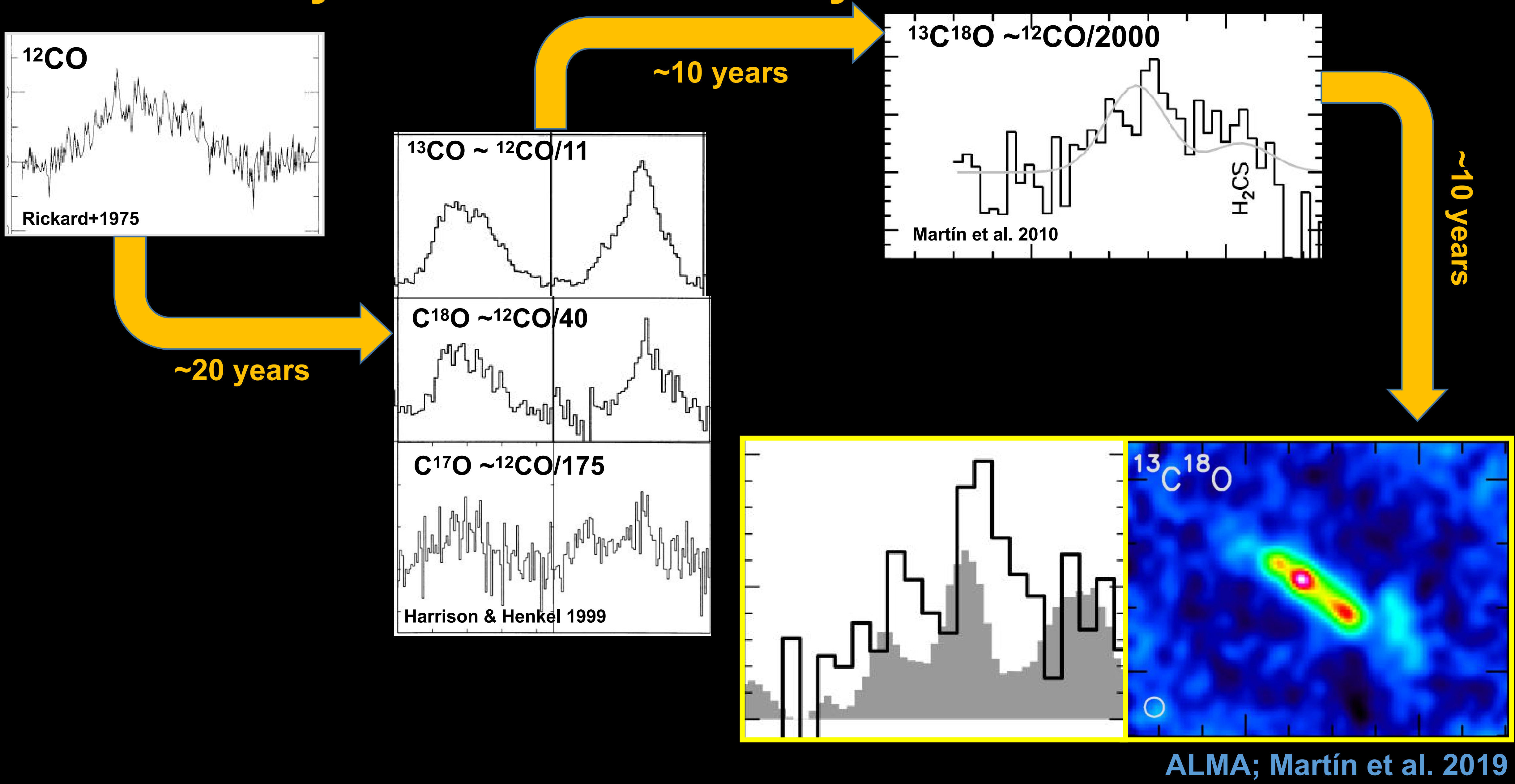


NRAO Kitt Peak 11 m

...the observed emission features are surprisingly strong.

NGC 253 SB prototype at D~3 Mpc

A brief history on e-astrochemistry



A brief history on e-astrochemistry

Dense Gas in Galactic Nuclei

1993

R. Mauersberger and C. Henkel
MPI für Radioastronomie
Auf-dem-Hügel 69, D 53121 Bonn, Germany

Abstract

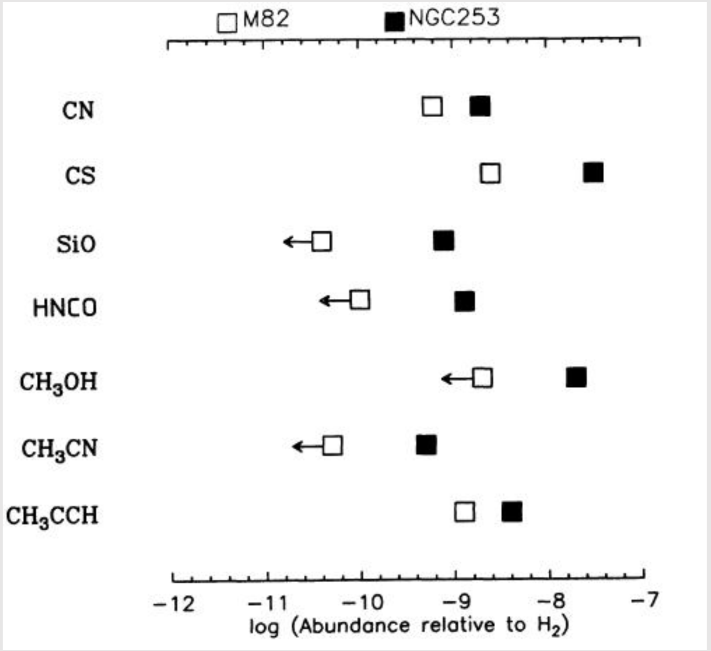
This Review contains recent results on molecular gas in the centers of galaxies and is an update to the review by Henkel, Baan & Mauersberger (1991, A&A Rev 3, 47). Following the Introduction, Sect. 2 deals with CO and HCN as tracers of the molecular mass. Included are a comparison of results from other mass tracers and a description of the detailed spatial distribution of the dense molecular gas component. The possible detection of a nearby protogalaxy and molecular observations of the distant "primeval" galaxy IRAS 10214+4724 are discussed in Sect. 3. Sects. 4 and 5 summarize results on molecular chemistry and elemental abundances in external galaxies.

Keywords: Galaxies: active, nuclei of, formation of — interstellar medium: molecules

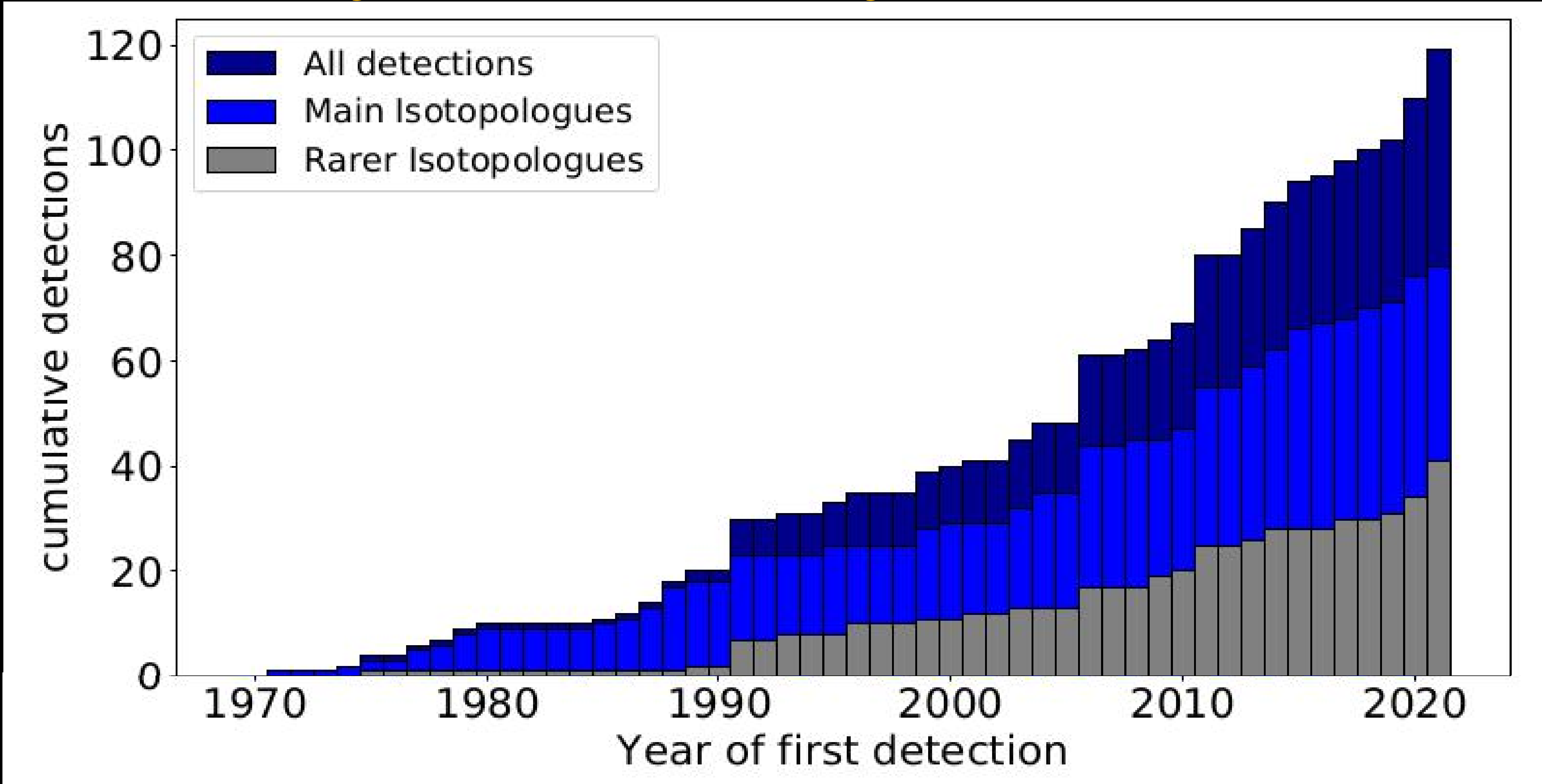
One would naively expect such variations to cancel out when one compares the chemical mixture averaged over larger volumes.

Surprisingly, the variations in chemical composition do *not* cancel out…

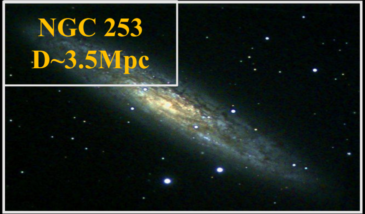
23 species + 8 isotopologues

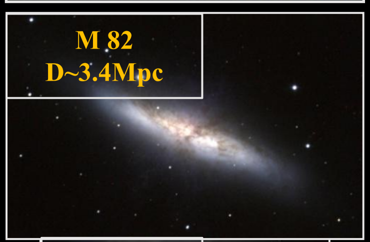


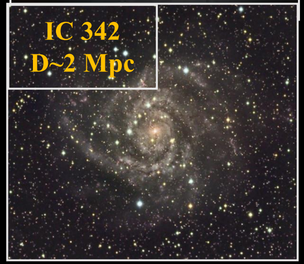
A brief history on e-astrochemistry

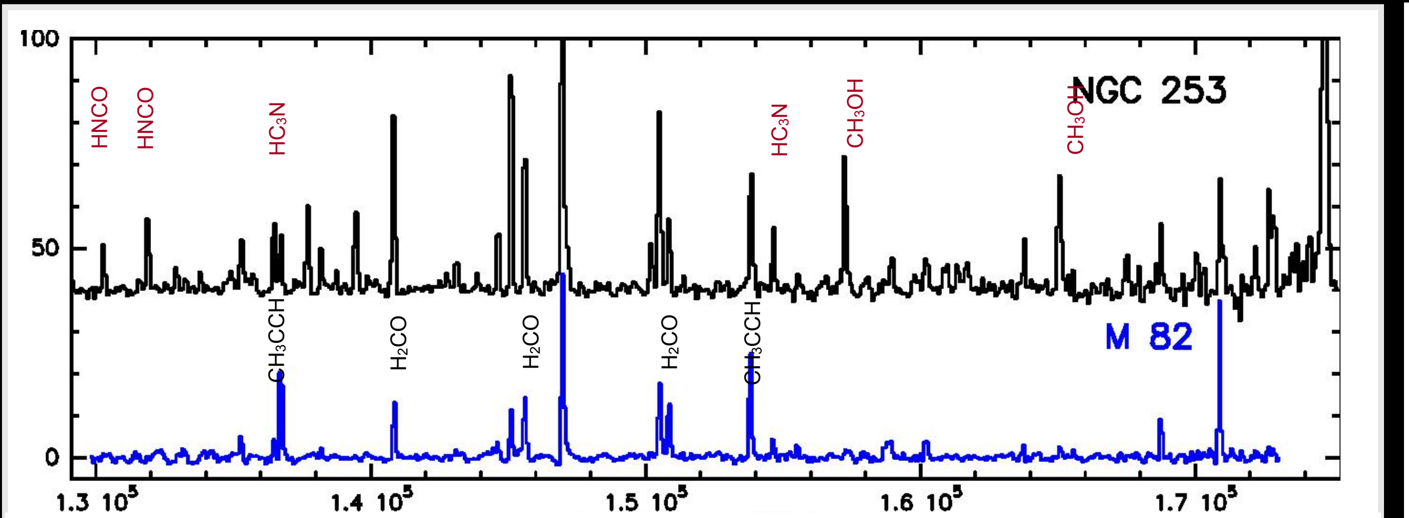


It all started here: Broadband spectral scans









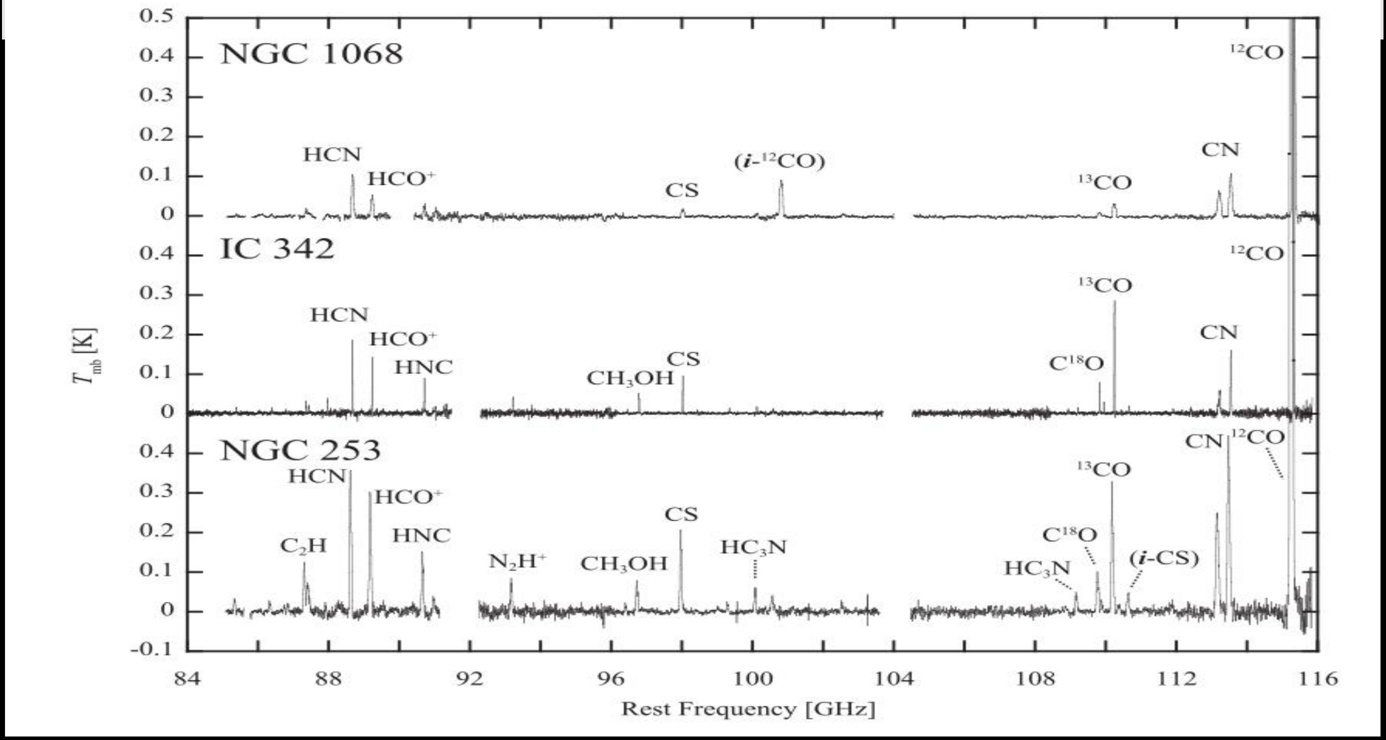


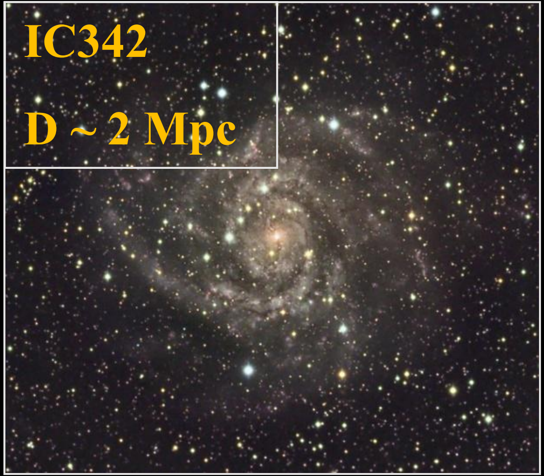
Table 1. Extragalactic spectral scans at mm and submm wavelengths.

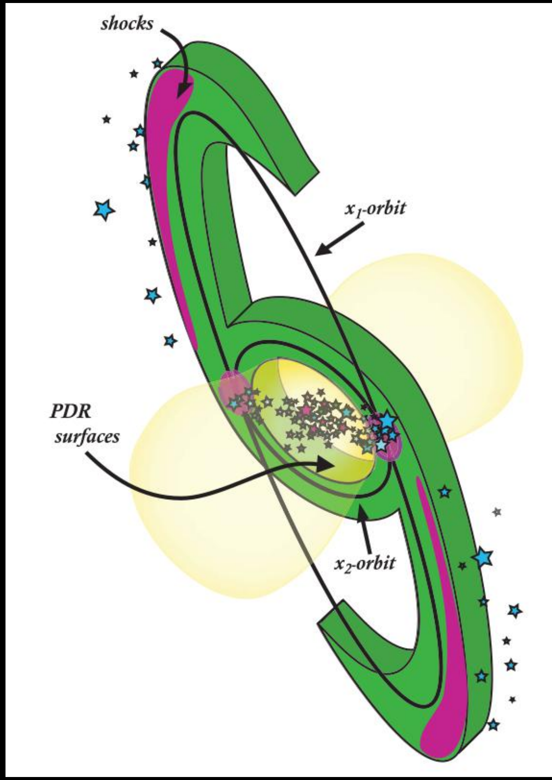
Source (#)	Frequency coverage (GHz)	Telescope	Ref.
NGC 4945	82–354 [a]	SEST 15m	1
NGC 253	86–116	IRAM 30m	2
	86–116 [b]	ALMA	3
	85–116	Nobeyama 45m	4, 5
	129–175	IRAM 30m	6
N113 (LMC)	85–357 [a]	SEST 15m	7
M 82	86–116	IRAM 30m	2
	130–175	IRAM 30m	8
	241–260	IRAM 30m	8
	190–307 [c]	CSO 10.4m	9
NGC 1068	86–116	IRAM 30m	10
	85–116	Nobeyama 45m	4, 5
	161–169 [b]	IRAM 30m	11
	176–184 [b]	IRAM 30m	11
	190–307 [c]	CSO 10.4m	12
PKS 1830-211 [d]	57–94	ATCA	13
	59–94	Yebes 40m	14
Arp 220	86–116	IRAM 30m	2
	202–242	SMA	15
M 51	86–116	IRAM 30m	2
	83–116	IRAM 30m	16
	130–148	IRAM 30m	16
M 83	86–116	IRAM 30m	2
NGC 4418	84–113	ALMA	17
	214–294 [b]	ALMA	17
IC 342	84–116	Nobeyama 45m	4, 5
IC 10	84–116	Nobeyama 45m	18
NGC 3256	85–113	ALMA	19
	214–273	ALMA	19
NGC 3627	85–116	IRAM 30m	20
	140–148	IRAM 30m	20
	85–115.5	Nobeyama 45m	20
Survey (10)	74–111 [c]	FCRAO 14m	21
Survey (23)	84–92	IRAM 30m	22
	108–116	IRAM 30m	22
Survey (4)	85–268 [b]	IRAM 30m	23
Survey (7, LMC)	85–116	MOPRA 22m	24

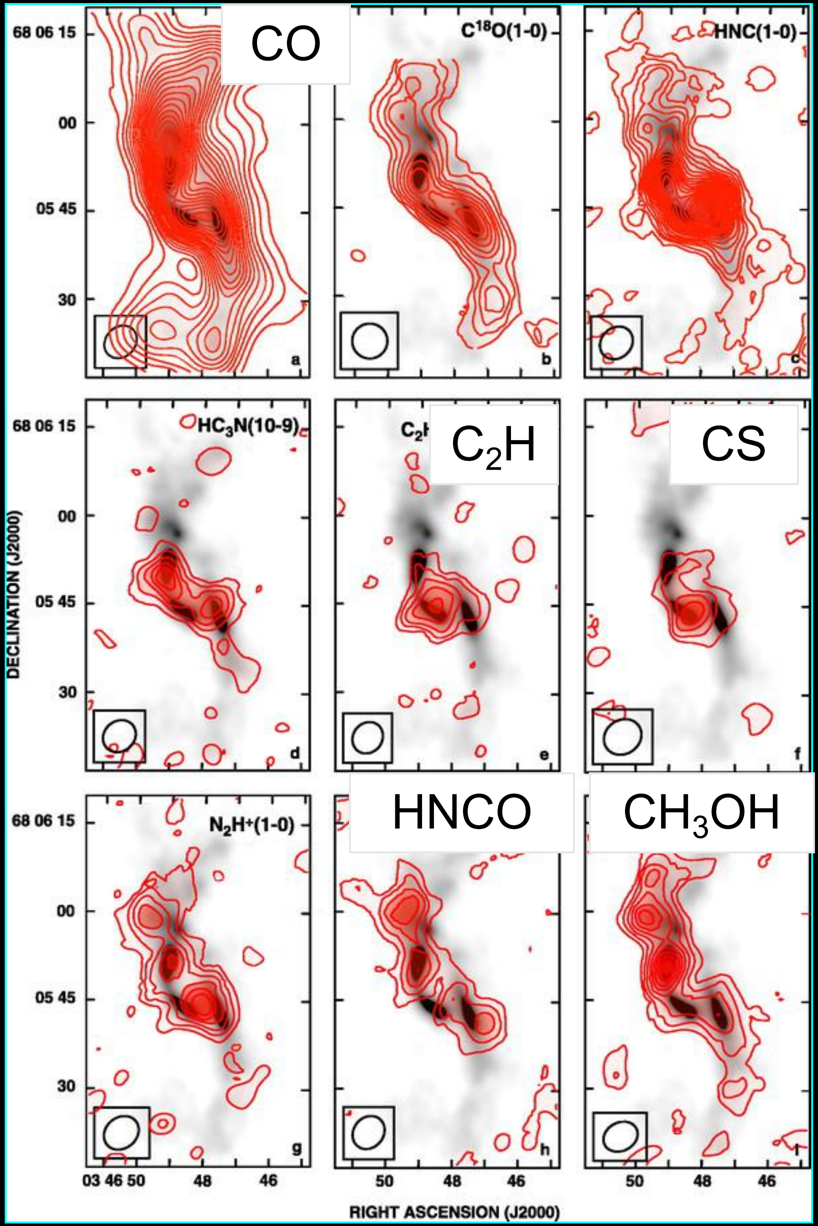
Martín+2006, Aladro+2011, Takano+2019

Martín+2021

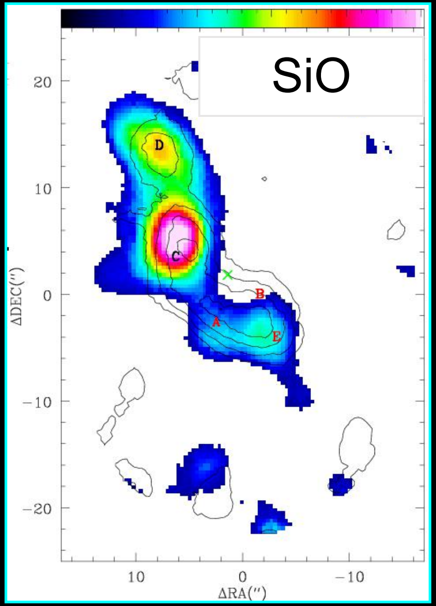
It all started here: Spatial information shows distribution of the different heating processes







OVRO; Meier & Turner (2005)



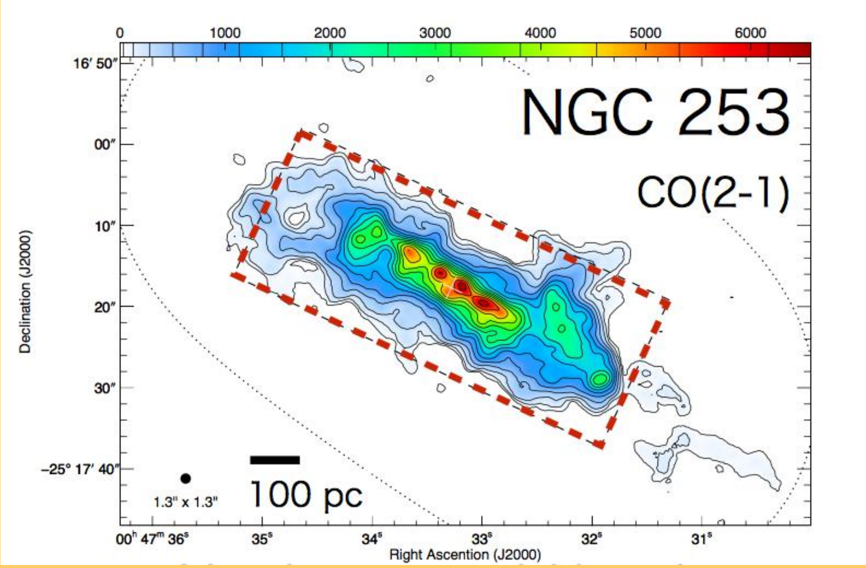
PdBI; Usero et al.(2007)

Resolving the heating mechanisms

- UV pervaded material around the central cluster
- Shocked material in the circunnuclear spiral arms

ALCHEMI ALMA Large Program

Spectral line imaging survey of the central molecular zone in the nearby prototypical starburst galaxy NGC 253 at an unprecedented combination of resolution and sensitivity.



SMA (Sakamoto+2011)

Target: NGC 253

Imaged Region: 60”x20” (800x300 pc)

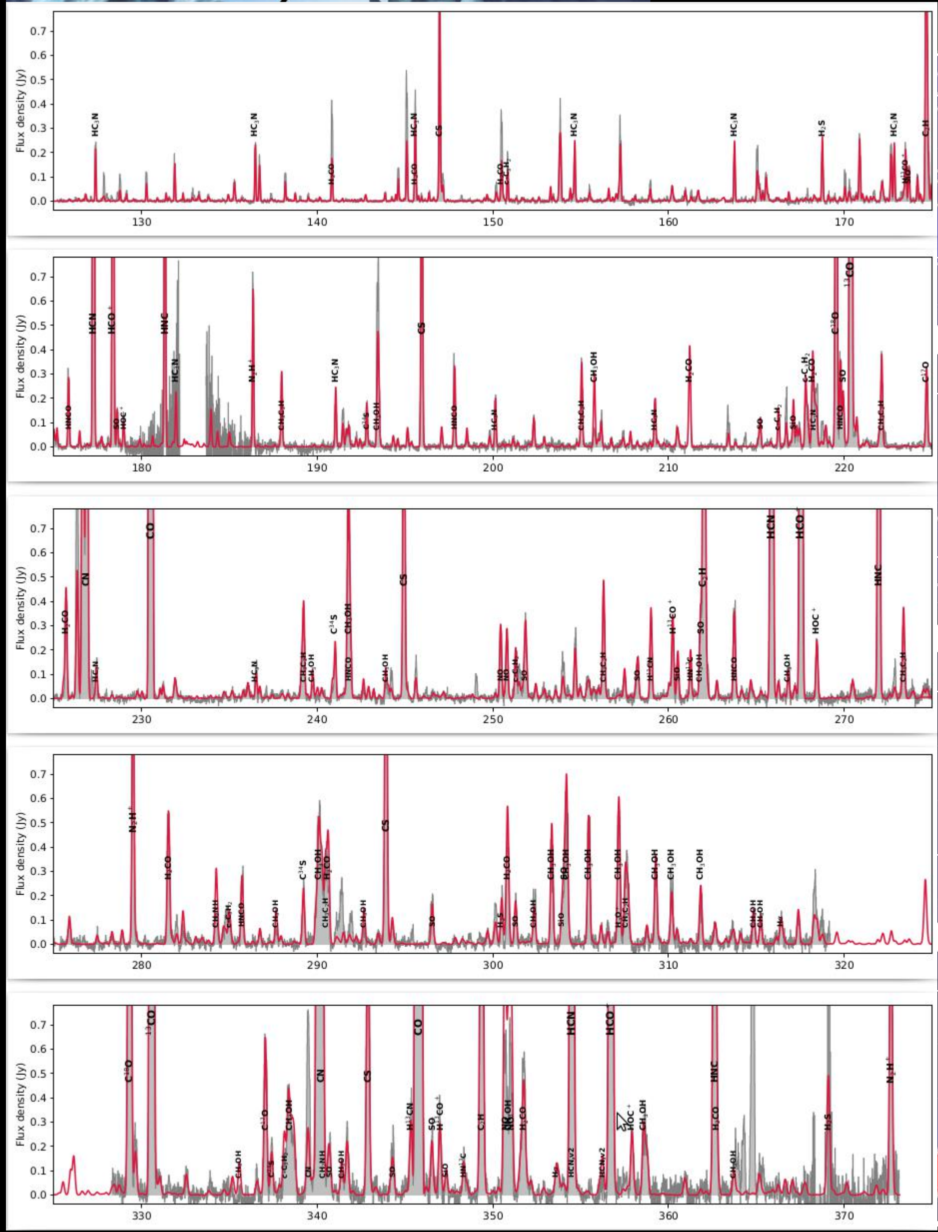
Spatial Resolution: 1.6” (28pc)

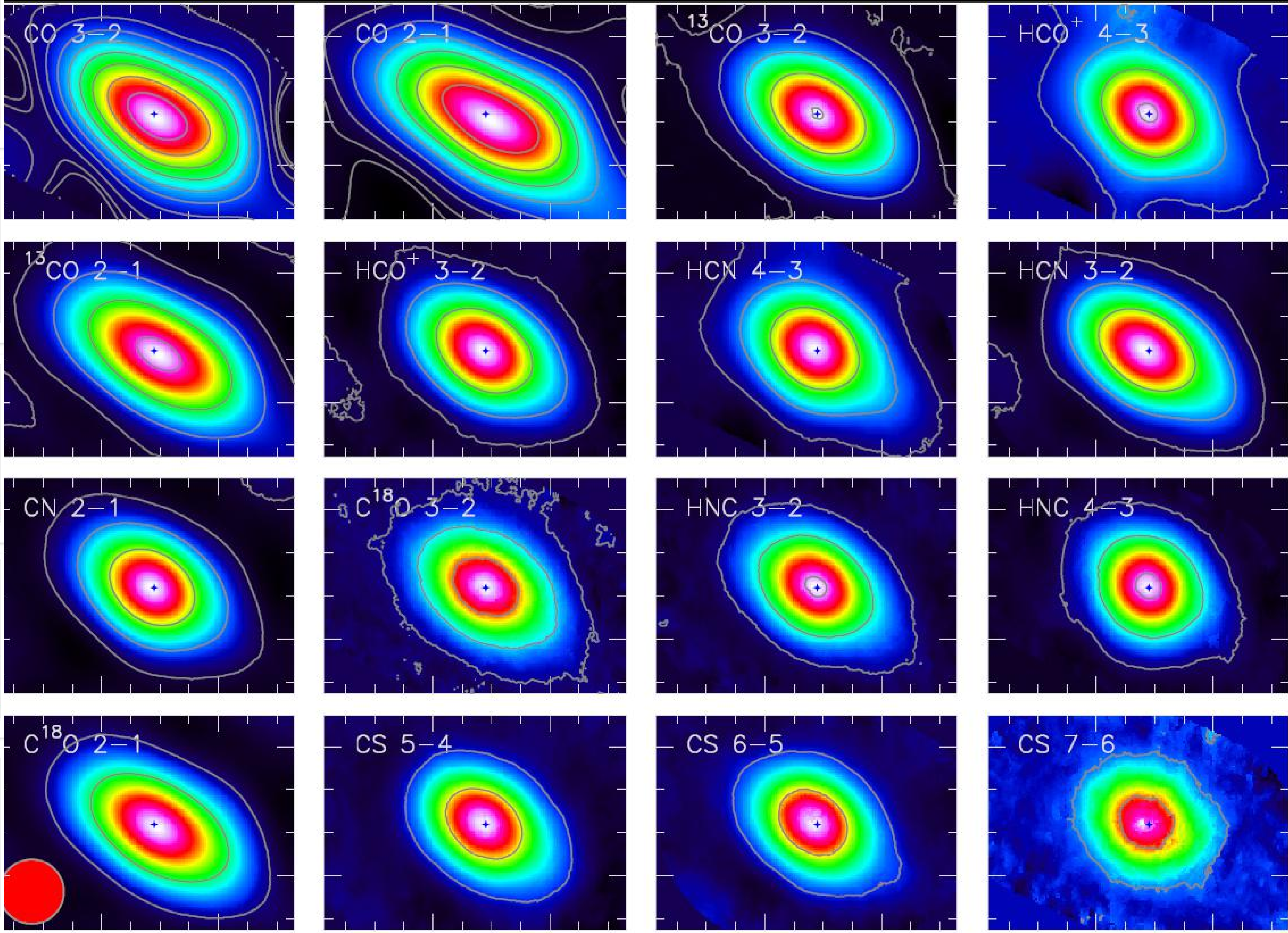
Frequency Coverage: 84 to 368 GHz (full ALMA Bands 3,4, 5, 6,and 7)

Frequency Resolution: 1 MHz (3.5-1.5 km/s)

ACA low resolution (15"=260pc): The tip of the molecular iceberg

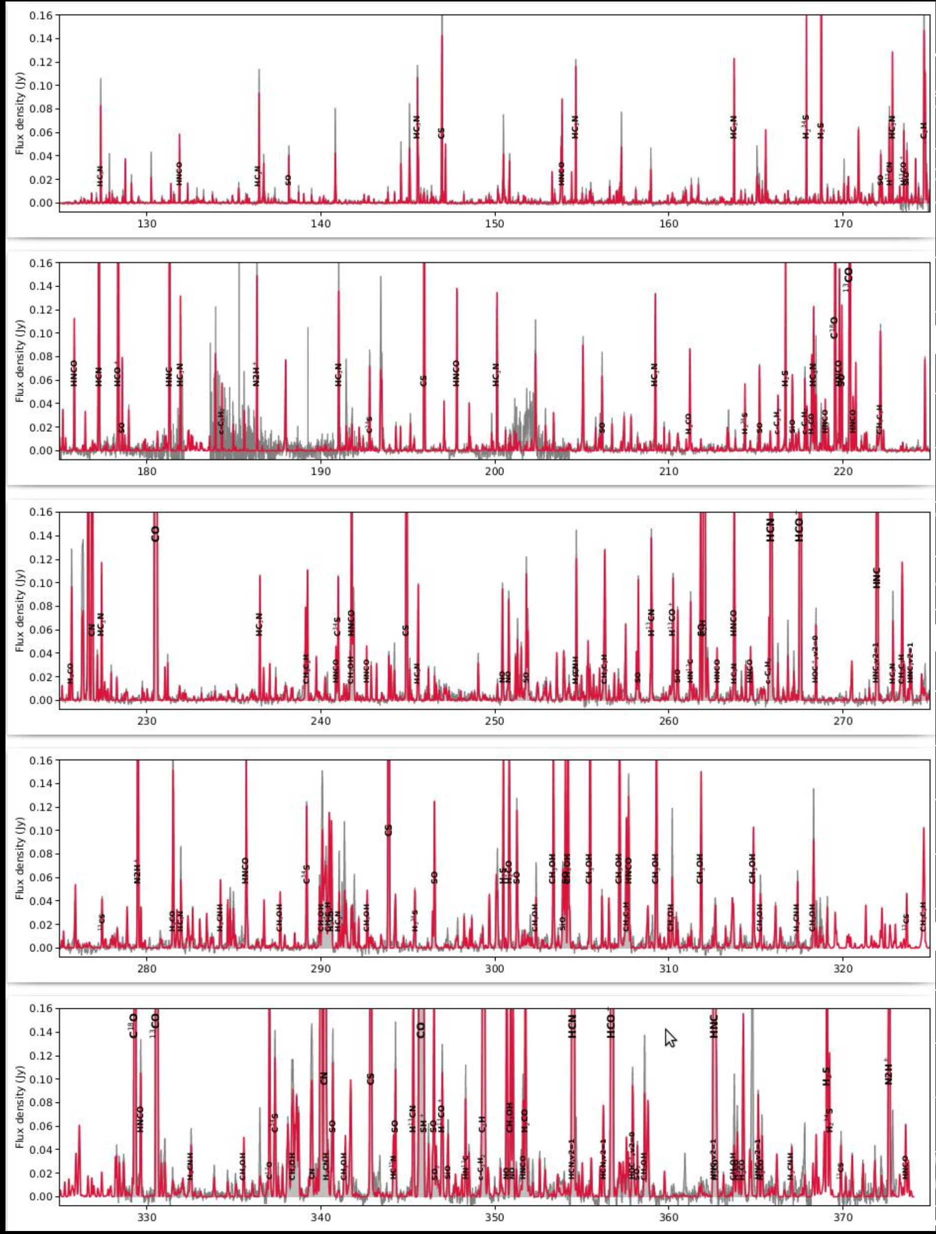
Martín+2021

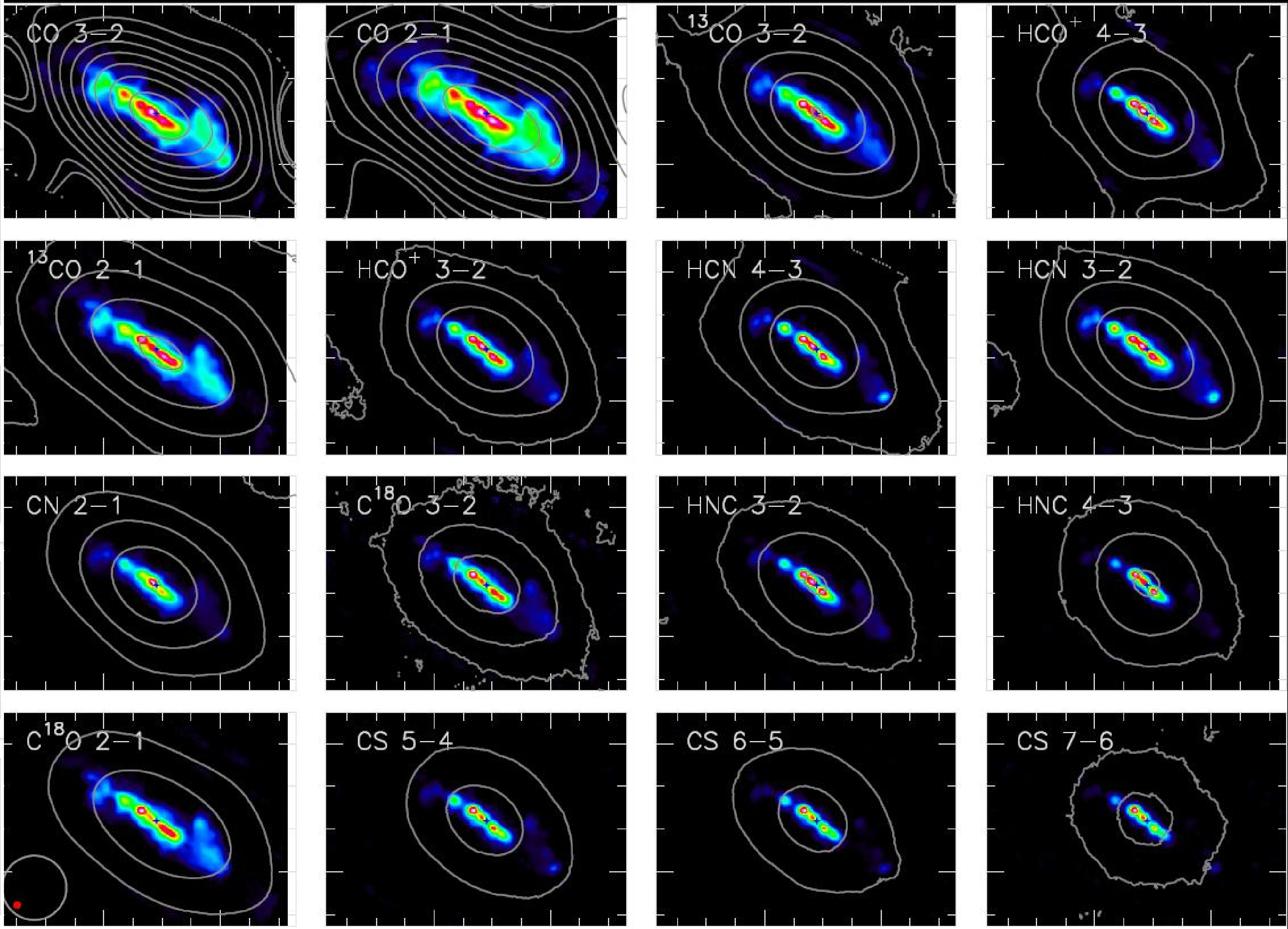




ALCHEMI full resolution (1.6”=26pc)

Martín+2021



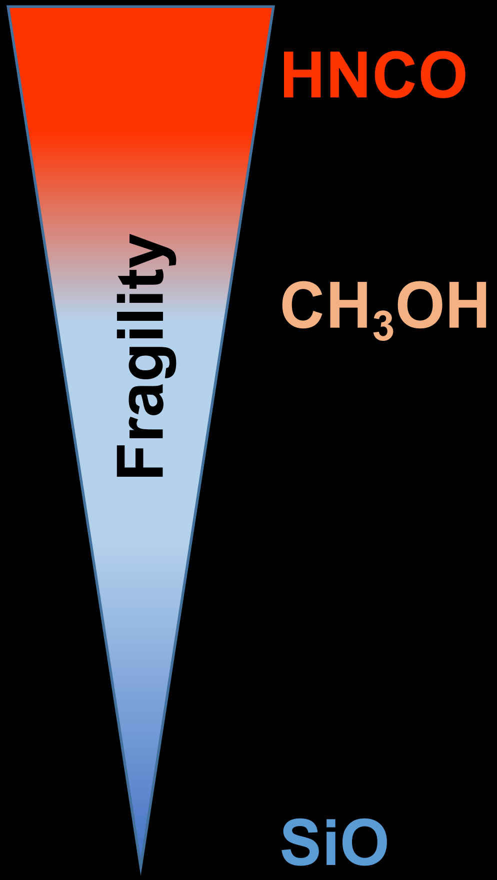


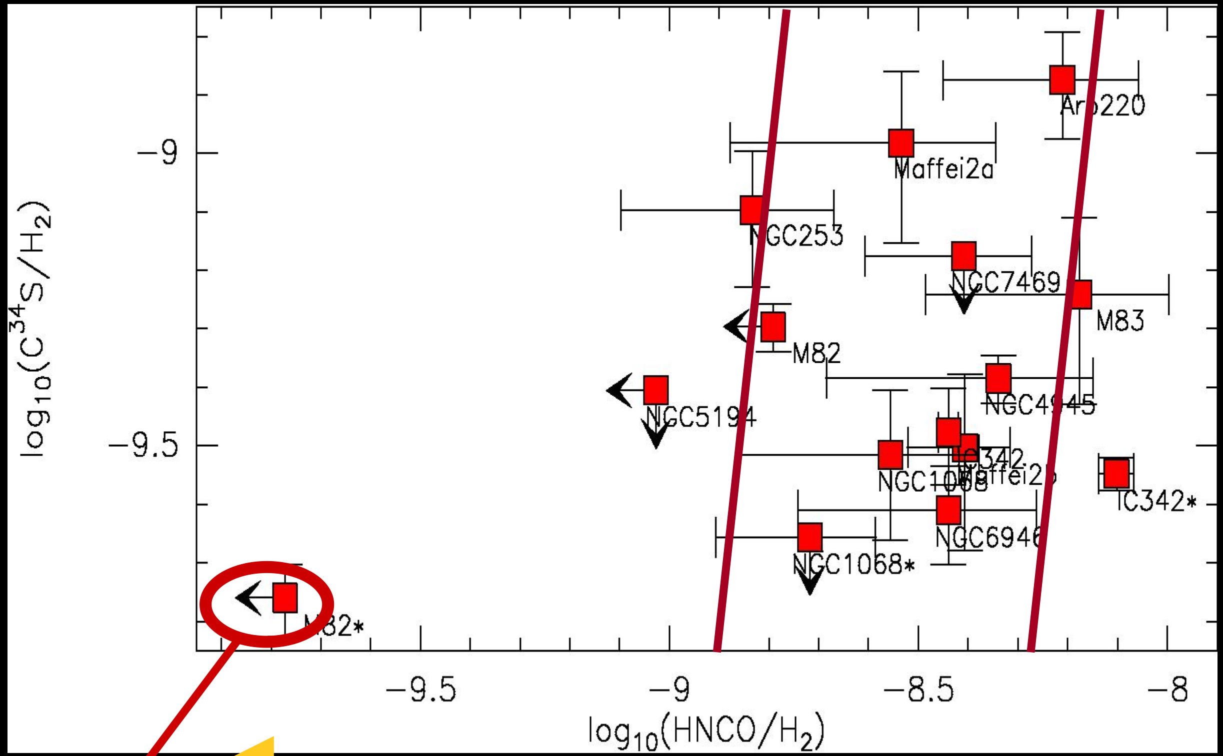
E-ASTROCHEMISTRY: Where are we now?

Galaxy evolution: Tracing the star formation process
(a.k.a putting tracers to work)

Galaxy evolution: Tracing the star formation process

Shock enhanced species





Fuel exhaustion

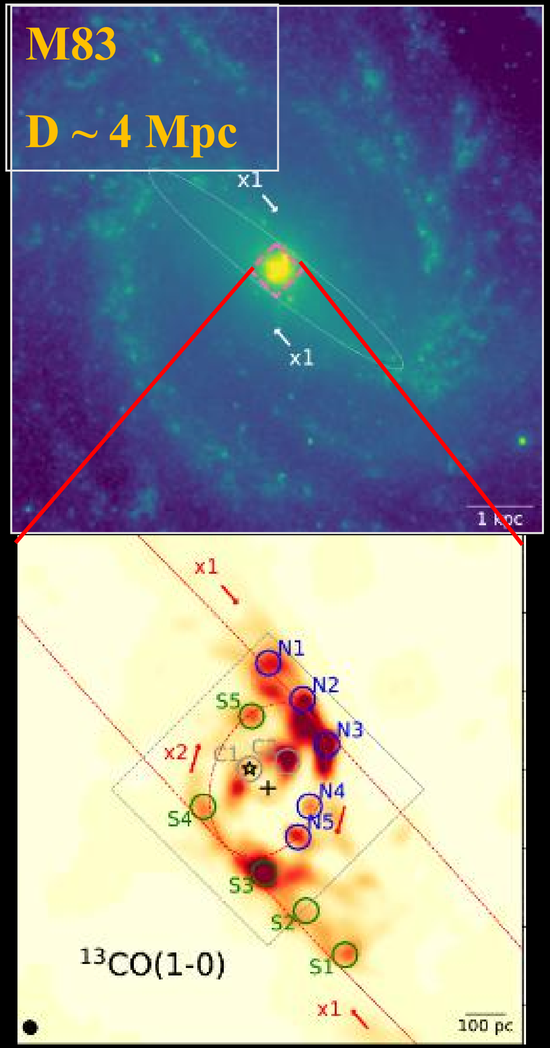
Detected in PDR molecular tracers:
HCO, HOC^+, CO^+, H_3O^+
(Garcia-Burillo et al.02, Fuente et al.05;07, Van der Tak et al. 08)

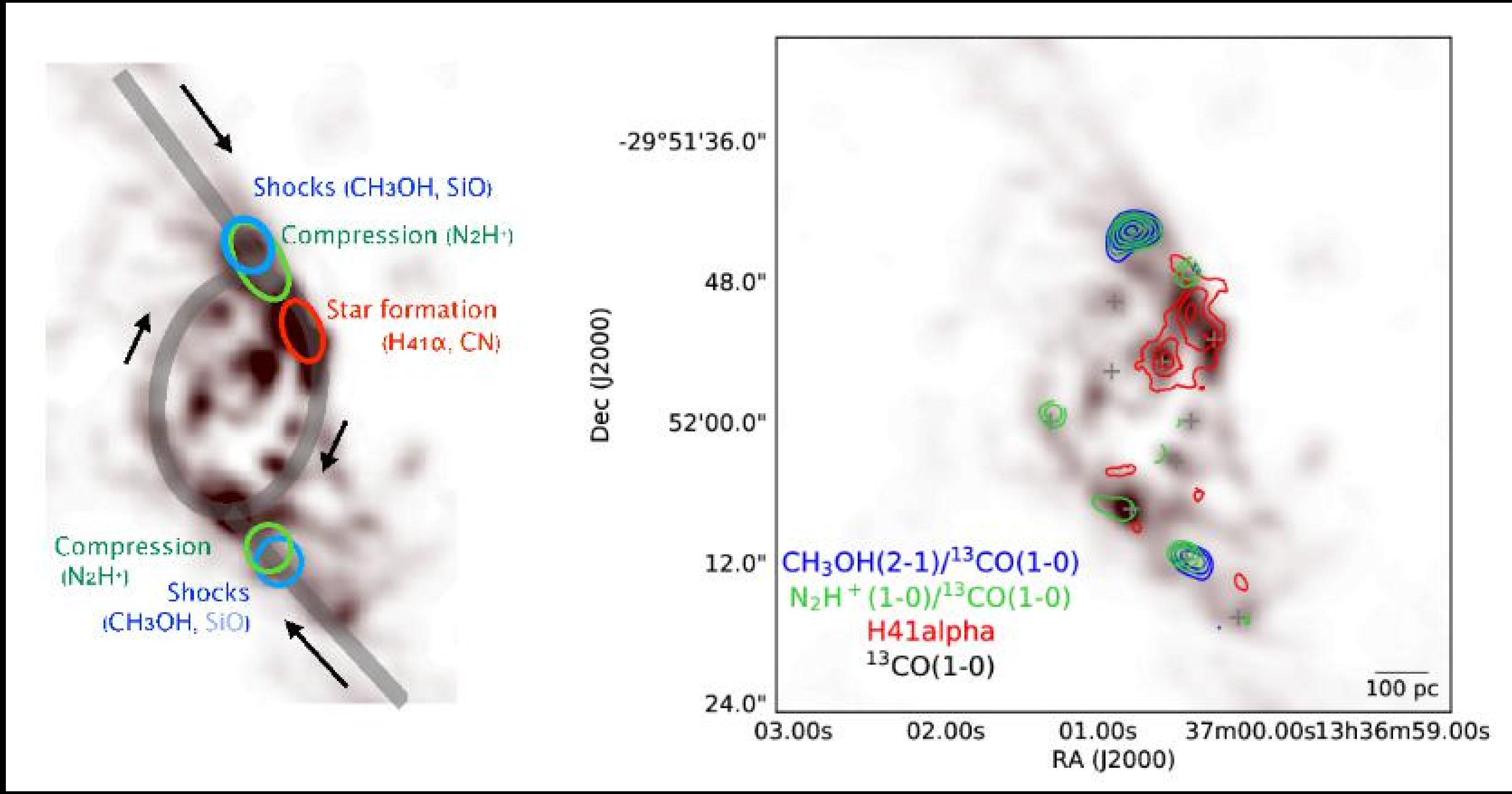
Martín+2009

Galaxy evolution: Tracing the star formation process

Chemical evolution along the circumnuclear ring of M83

- Triggered star formation along the X1-X2 orbit intersections as the gas is funneled towards the galactic center.
- Qualitative star formation driven chemical evolution

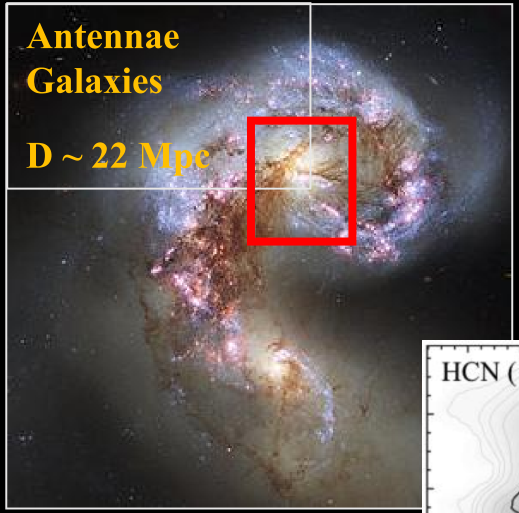


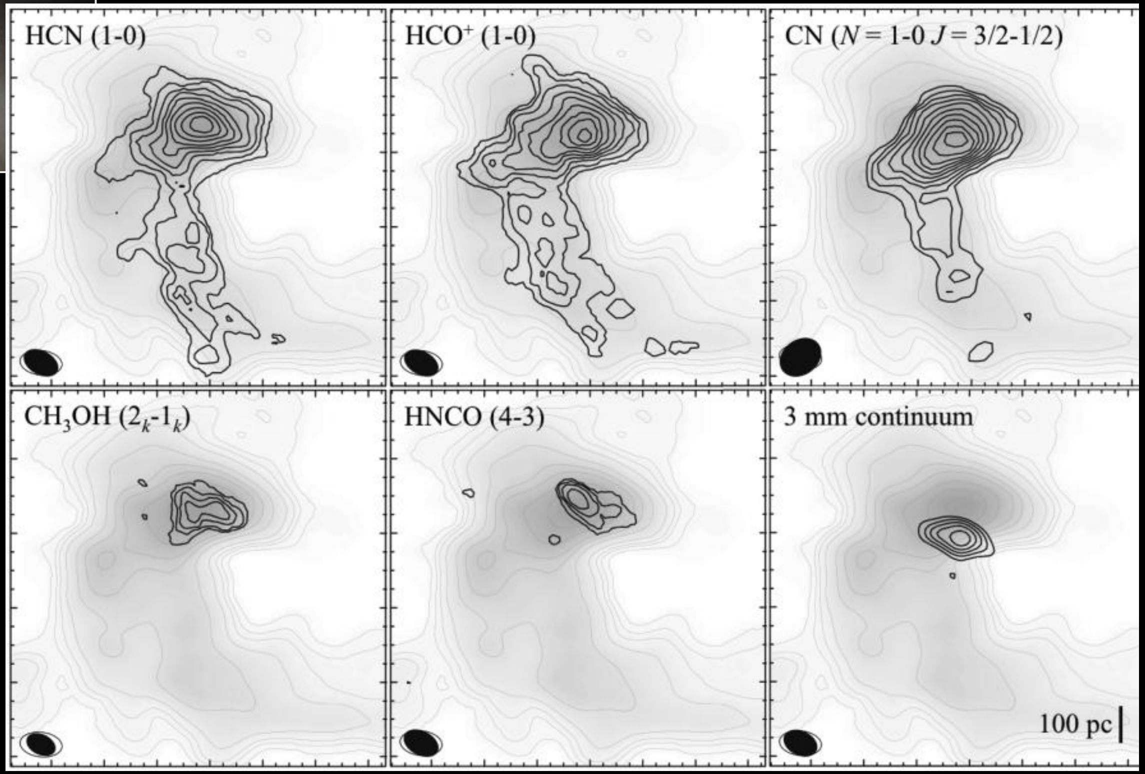


Harada+2019

Galaxy evolution: Tracing the star formation process

Interaction triggered star formation



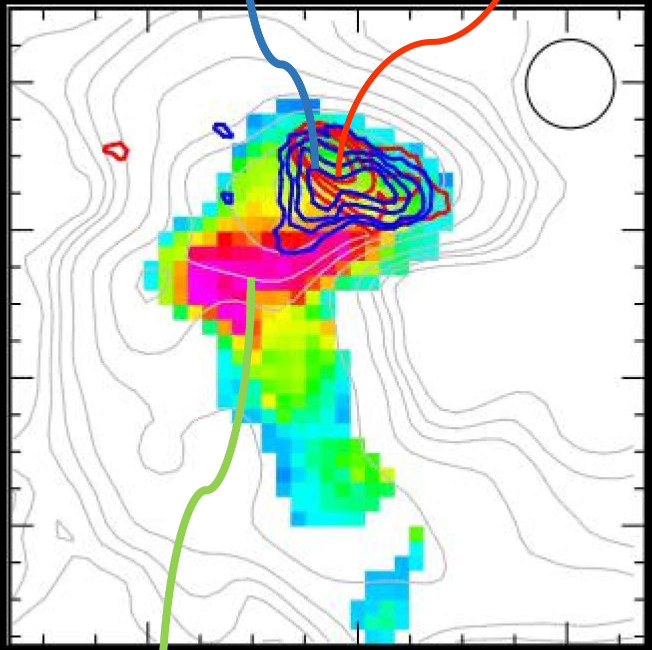


Ueda+2017

Gas shock compression

HNCO

CH_3OH



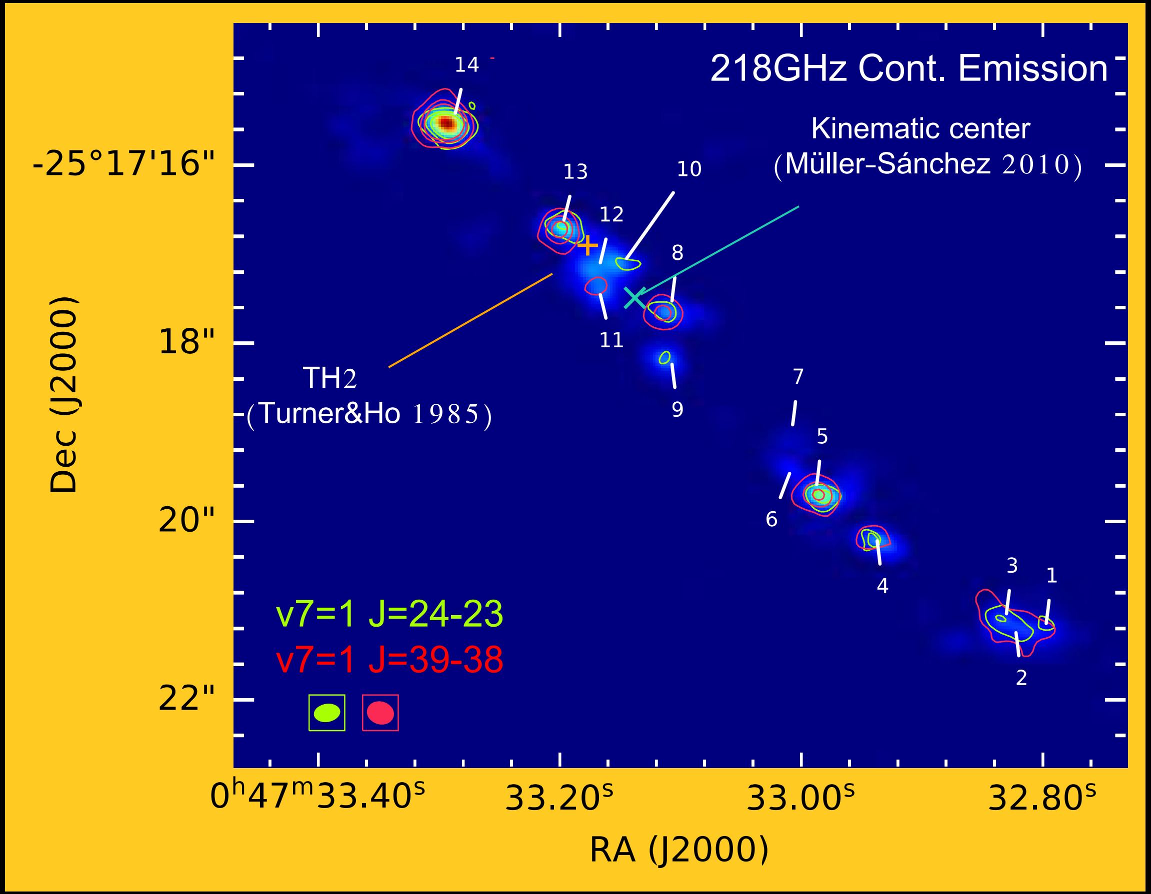
CN/HCN ~ PDR

Stellar UV illuminated gas

Galaxy evolution: Tracing the star formation process

Witnessing the early stages of the new generation of SSC through vib. excited HC3N

- HC_3N-vib rot. trans. excited by mIR so Tvib ~ Tdust
- HC_3N v7=1 rotational transitions found in 8/14 clumps (>3σ)
- $\boldsymbol{L_{p*}}\ 0.2-2\ \times 10^8 L_\odot$, that is 10x than MW HCs - Super Hot Cores
- Total Luminosity in SHC is $L_{p*}\sim\mathbf{6.5}\ \times 10^8 L_\odot$, i.e. 5% L_{bol}



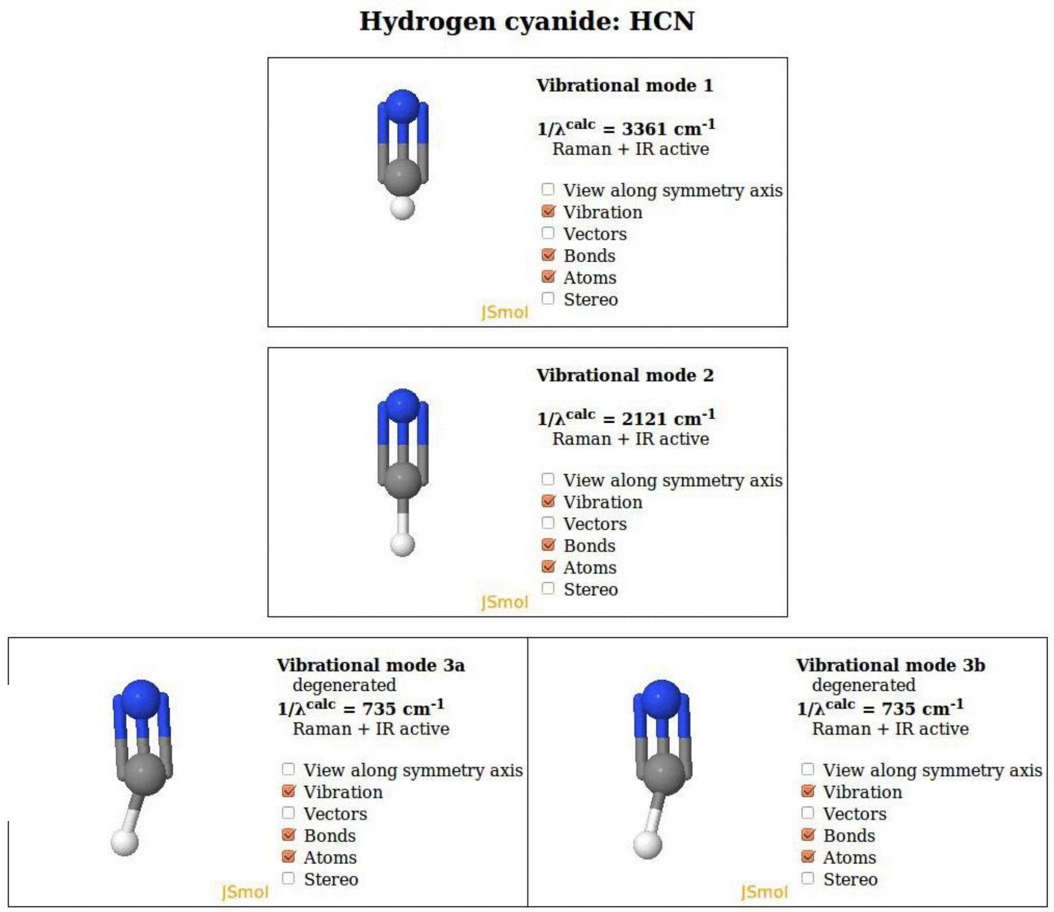
Rico-Villas+2020

Just a break to understand vibrationally excited emission

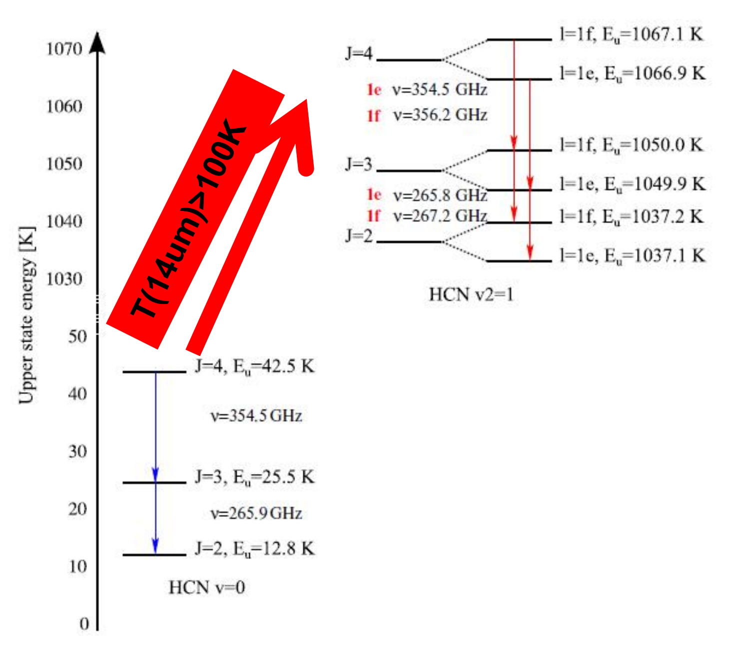
v_1
$E_u > 4500$ K

v_3
$E_u > 3000$K

v_2
$E_u > 1000$ K



http://wchem.cup.uni-muenchen.de/wvib/hcn.html



Aalto+2015

~~Collisionally excited?~~

$n_{crit} > 10^{11}$ cm^{-3}

Radiatively excited?

T_{dust}>100 K

E–ASTROCHEMISTRY: Where are we now？

Probing embedded AGNs: AGN vs SB in the dust obscured Universe
（a.k.a Nuclear activity diagnostics）

Multi-molecular observations revealing the structure of CND around AGNs

NGC 1097 Sy 1 Low luminosithy AGN

Martín+2015

NGC 1097
D~19 Mpc

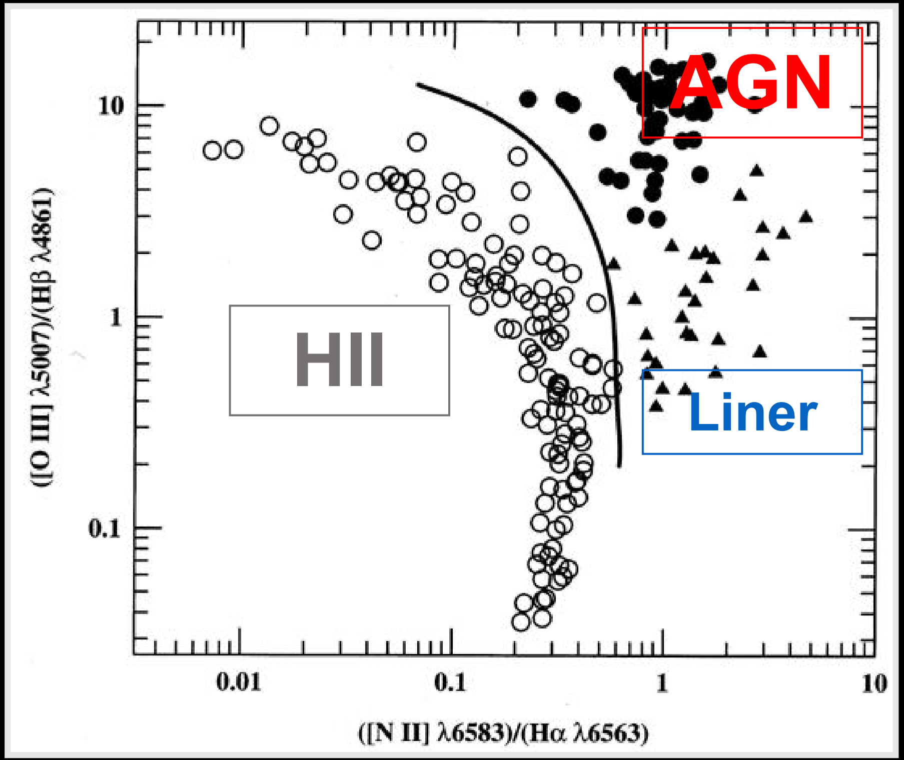
~100-200 pc resolution

NGC 1068 Sy 2 luminous AGN

Takano+2015, Nakajima+2015

Nuclear activity diagnostics: WHY ?

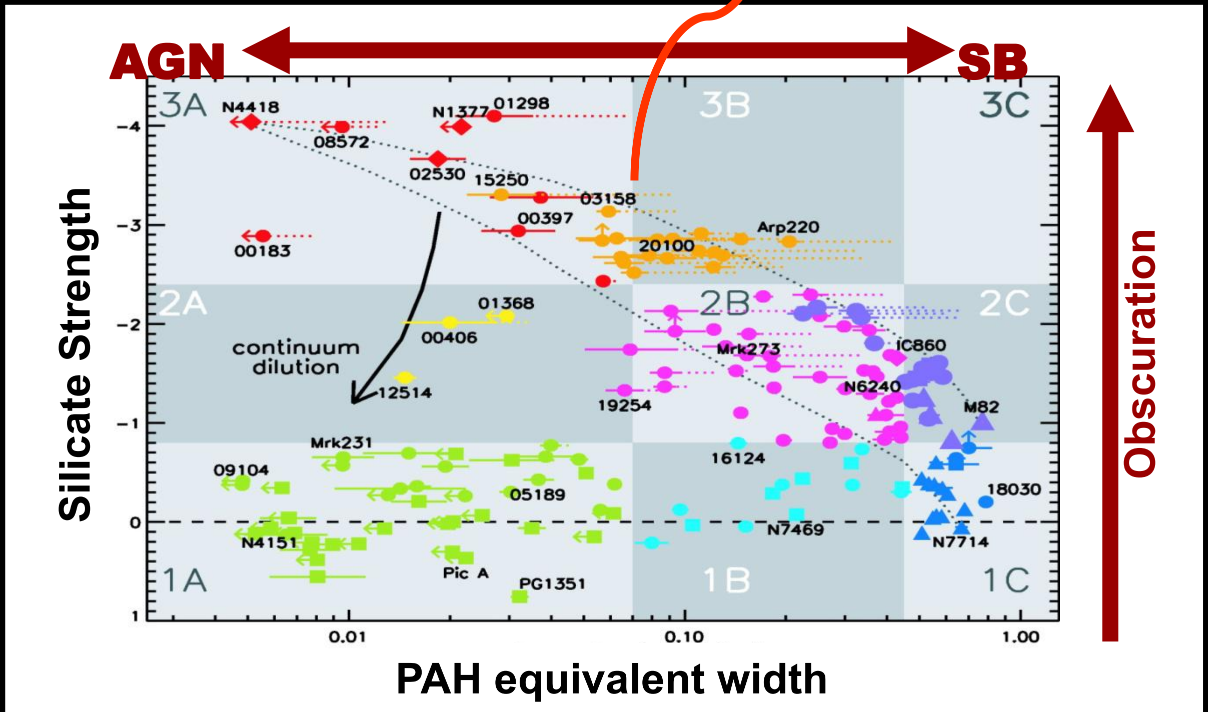
OPTICAL



``Baldwin, Phillips & Terlevich'' (BPT) diagrams

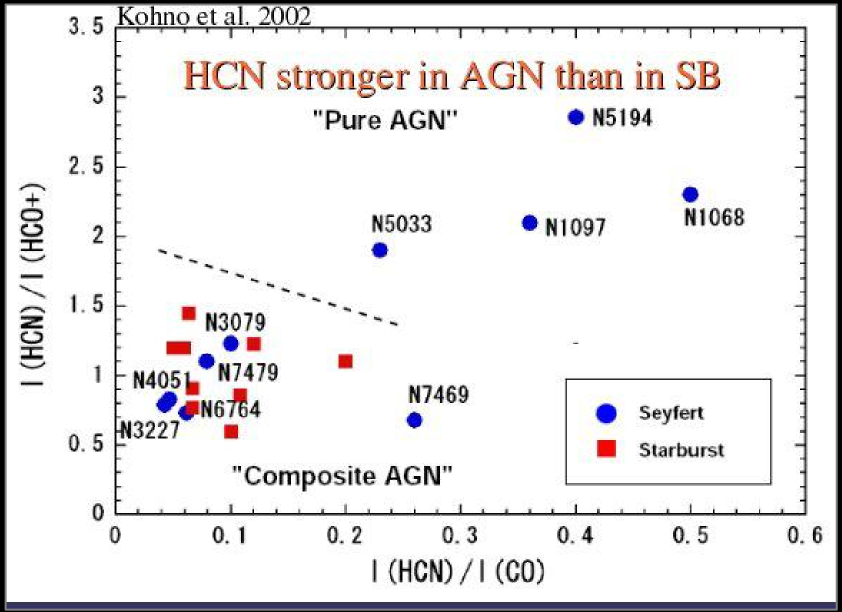
- Powering source hidden to almost every wavelength
- >1000 Av of extinction
- Direct implication on total number count of AGN in the Universe

IR

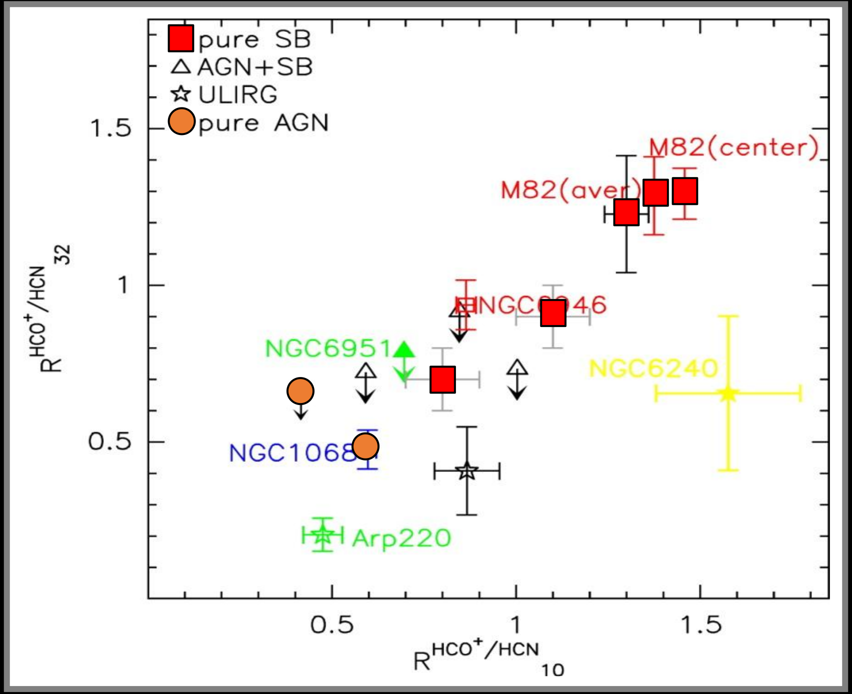


(Spoon+2007)

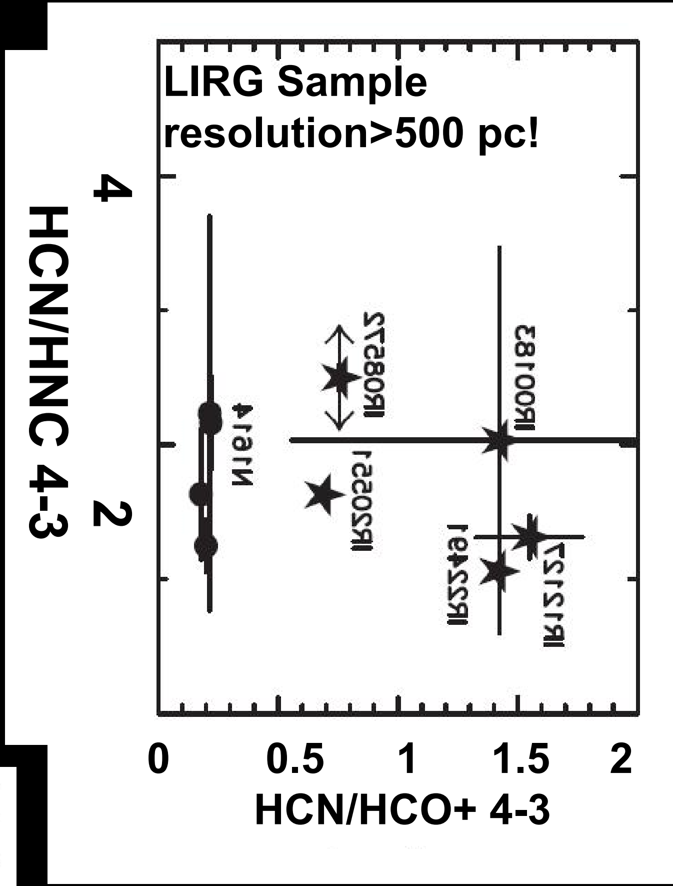
Nuclear activity diagnostics: HCN and HCO^+, the usual suspects



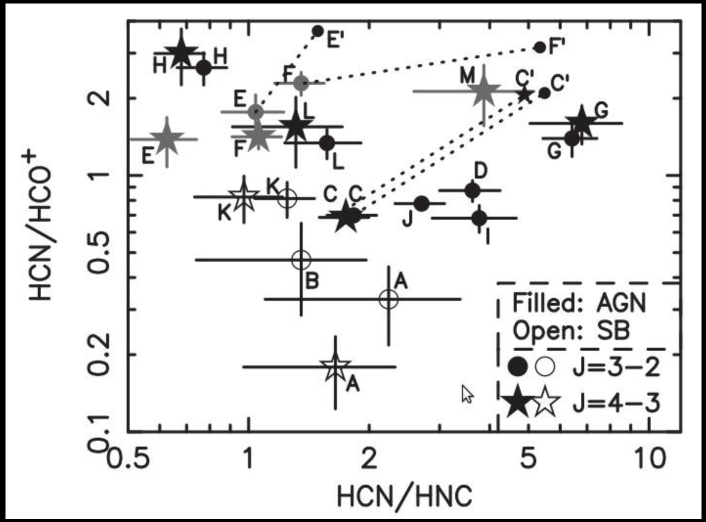
Kohno+2002



Krips+2008

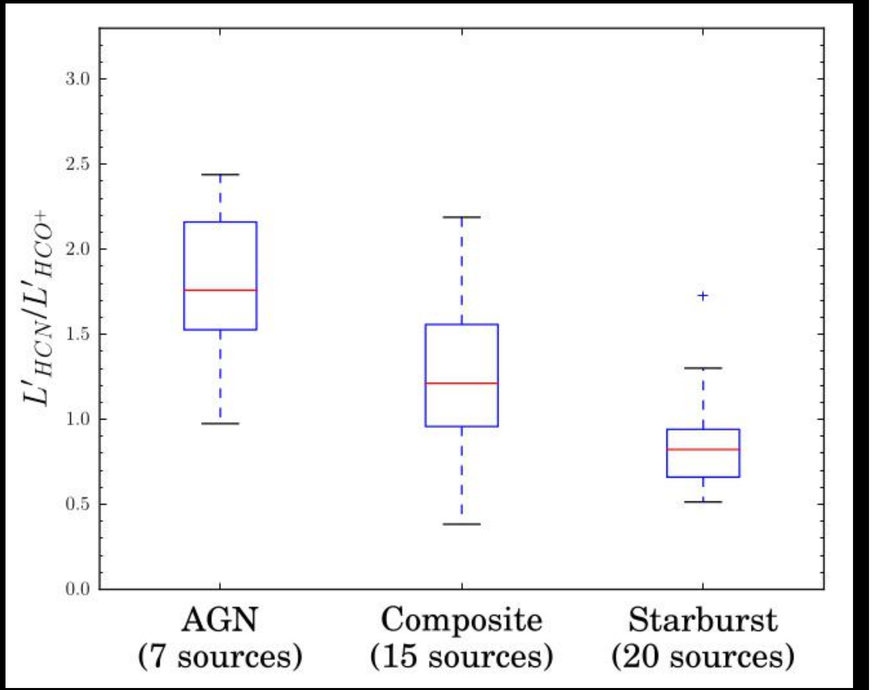


Imanishi+2014



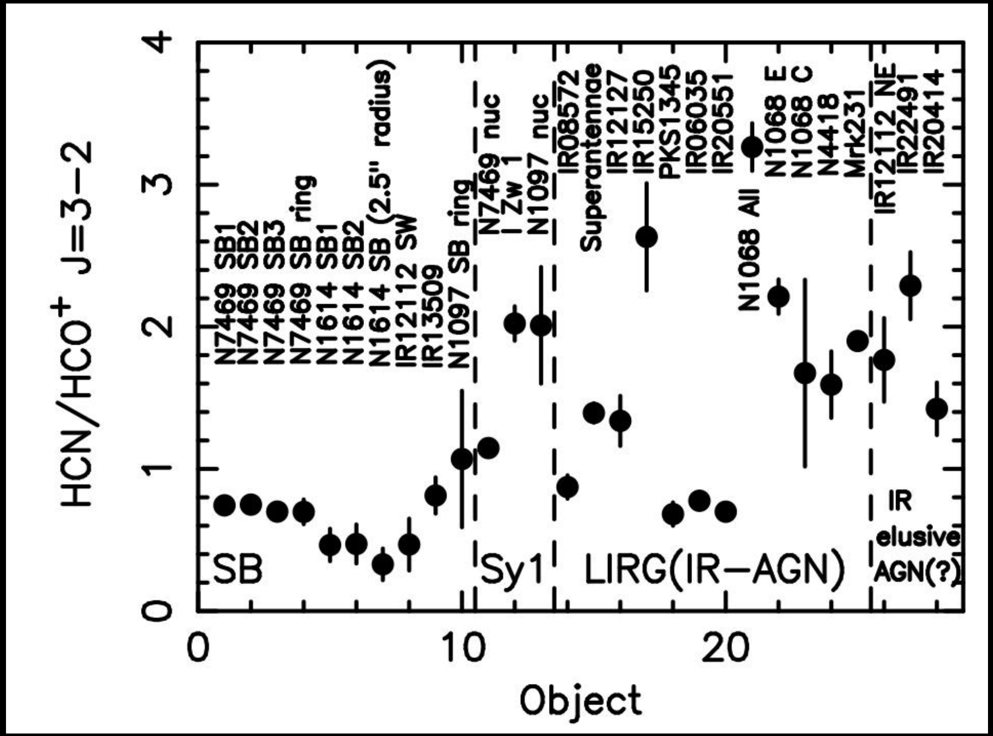
Imanishi+2018

Nuclear activity diagnostics: HCN and HCO^+, the usual suspects



58 local ULIRGs

(Privon+2015)

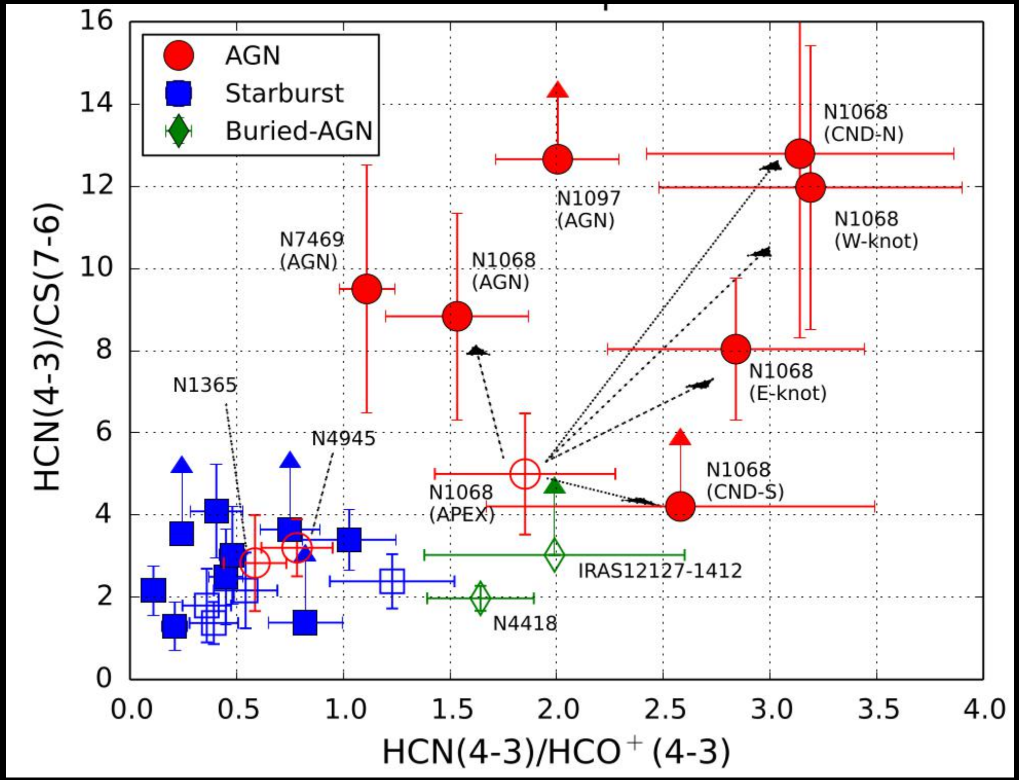


3 Sy 1 + 11 LIRGs

(Imanishi+2016)

Statisticaly, enhanced HCN/HCO^+ observed only in AGN hosting galaxies

Nuclear activity diagnostics: HCN and HCO+... and CS

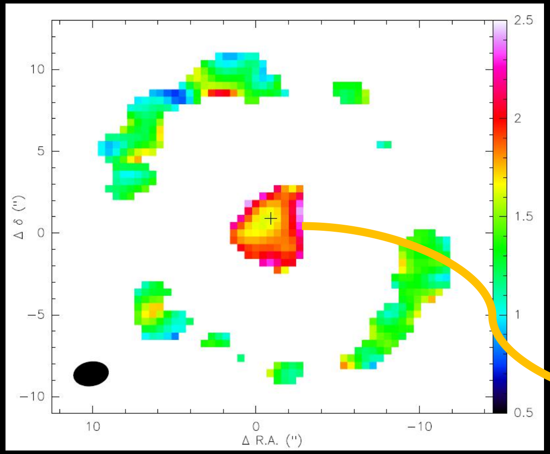


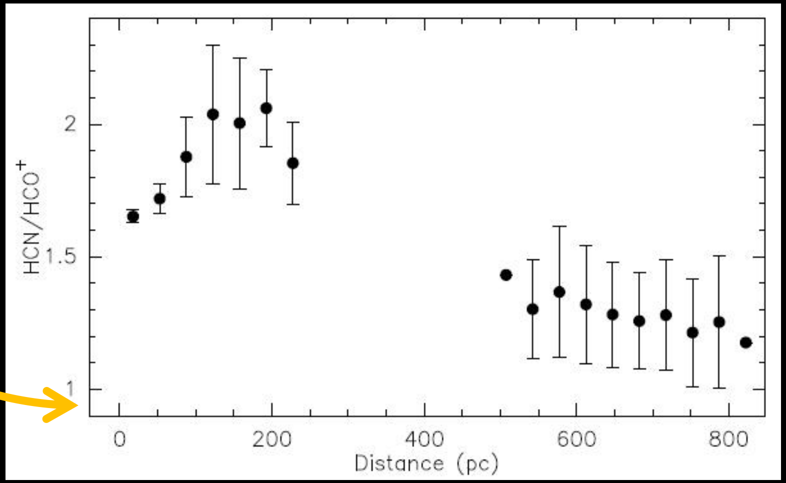
Izumi+2016, 2015, 2013

- **High temperature chemistry (Izumi+2013) or shochs (Aalto+2012) HCN enhancement, i.e. X-ray flux independent**
- **High temperature chemical models (Harada+2010, 2013)**

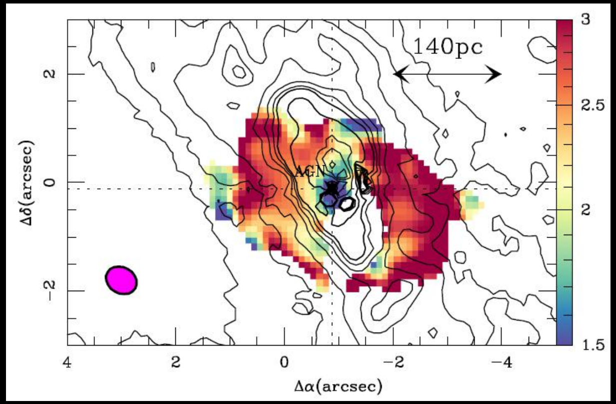
HCN/HCO+ = Mechanical Heating???

Nuclear activity diagnostics: HCN and HCO+ at high resolution

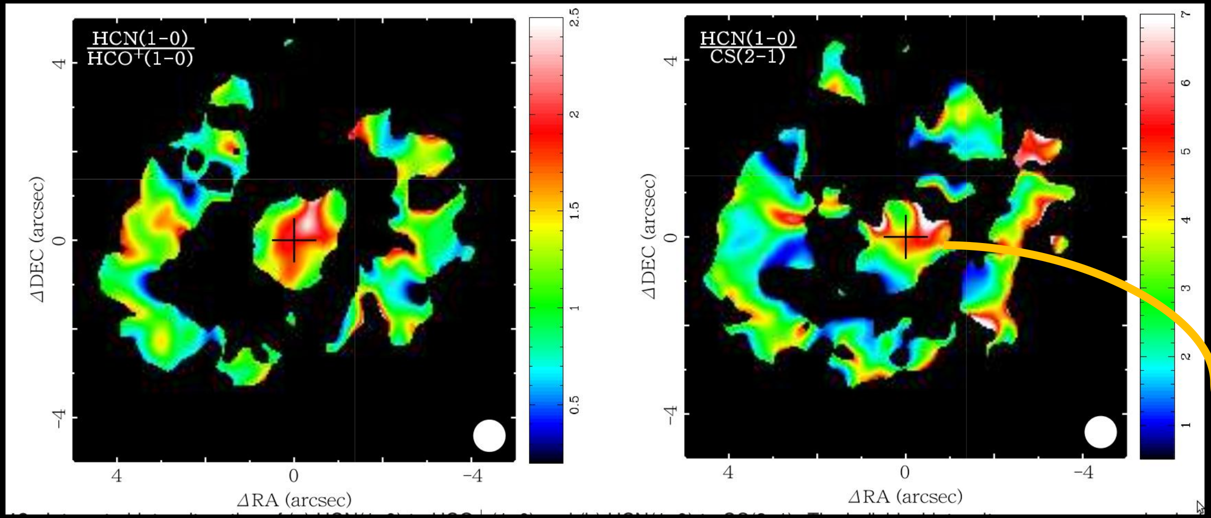




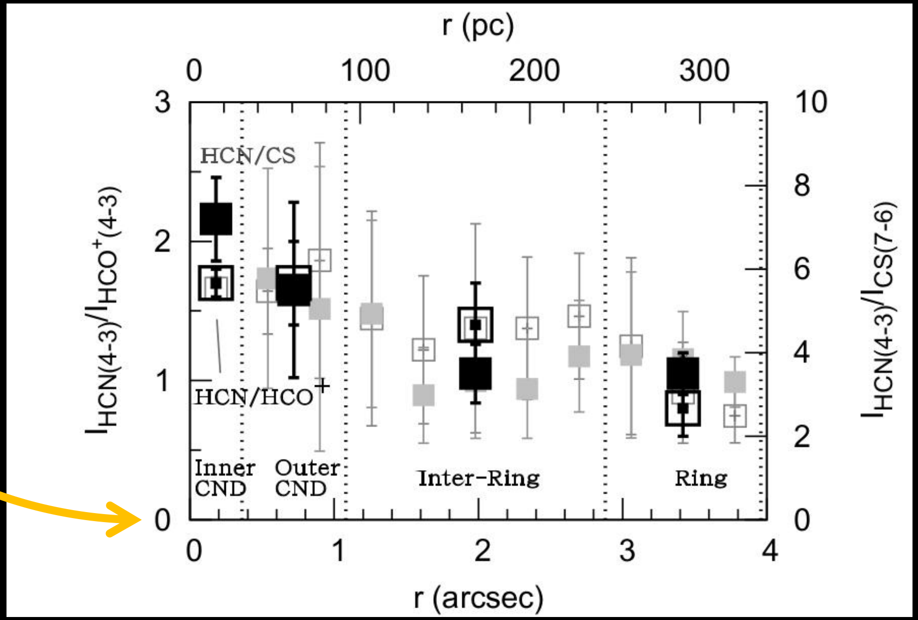
NGC 1097, res=100pc
Martín+2015



NGC 1068, res=35 pc
García-Burillo+2014,Viti+2014

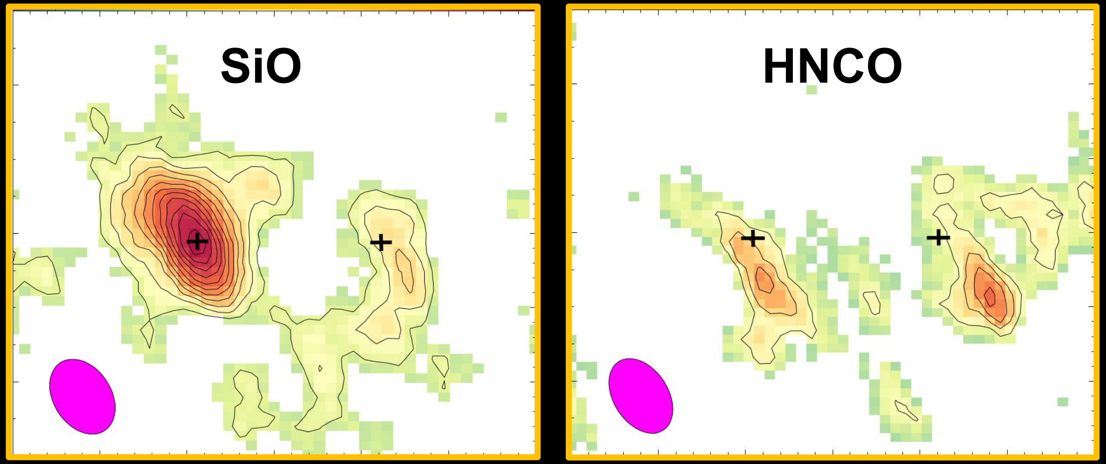


NGC 613,
Miyamoto+2014

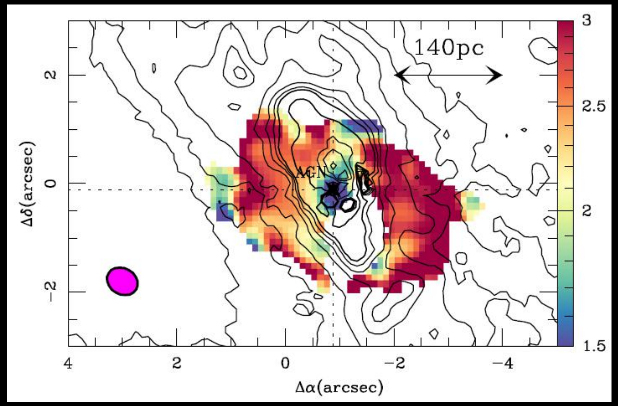


~500 K T_{kin} ~ 100 K

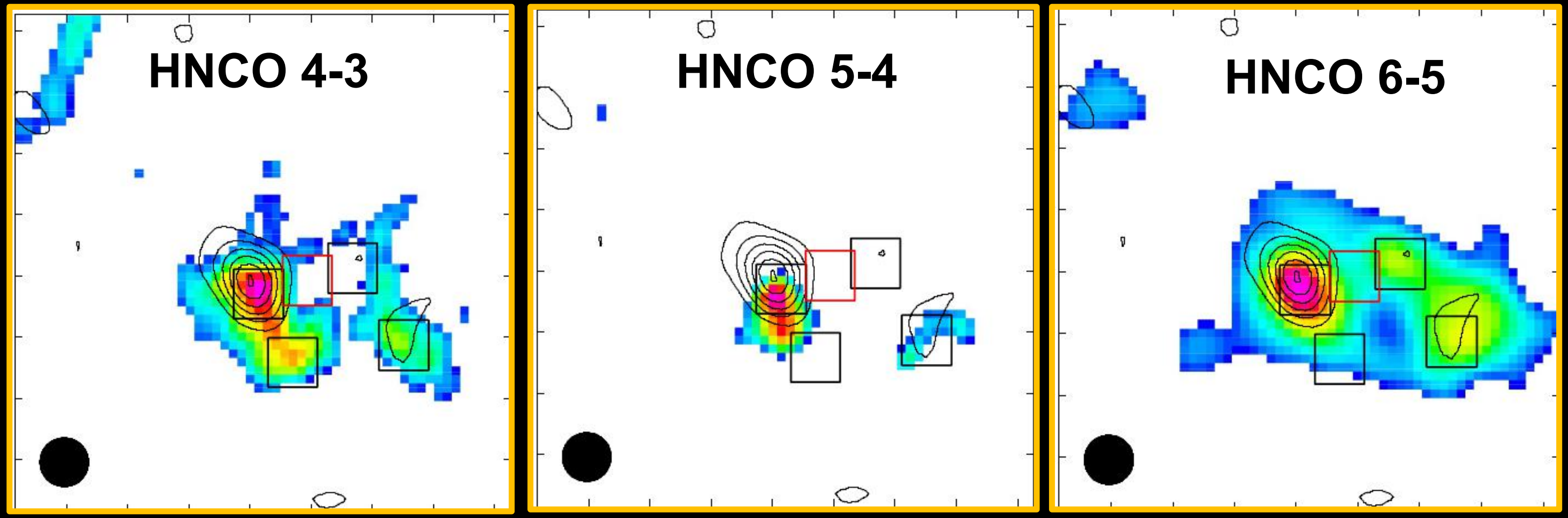
Nuclear activity diagnostics: Shocked evidences in CND



PdBI, Kelly+2017



NGC 1068, res=35 pc
García-Burillo+2014,Viti+2014



ALMA, Huang+2022

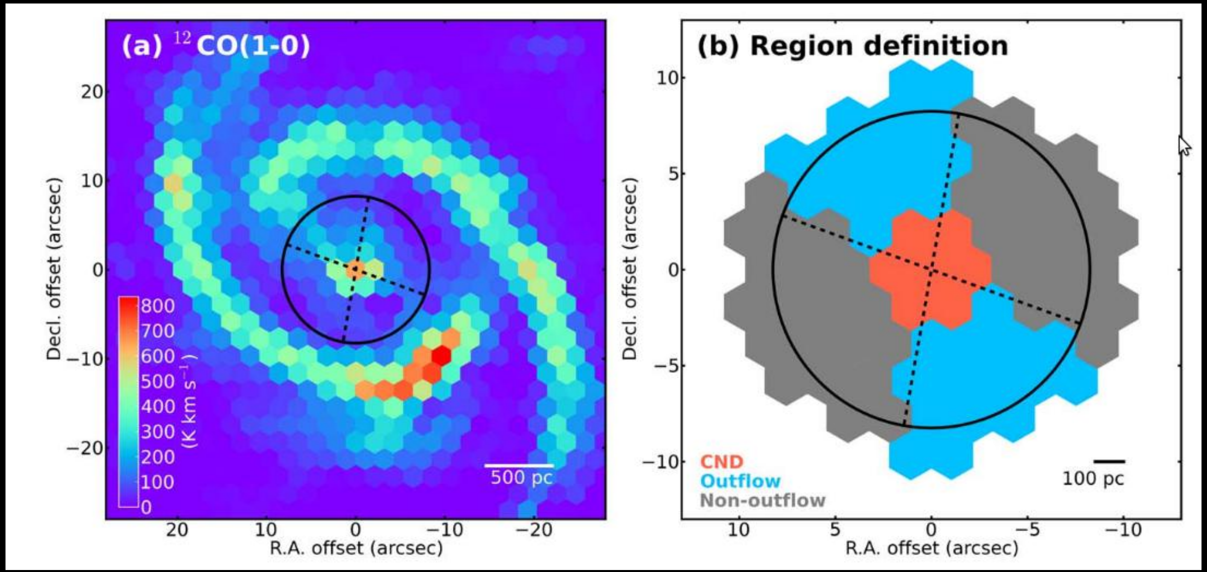
Multi-transition study

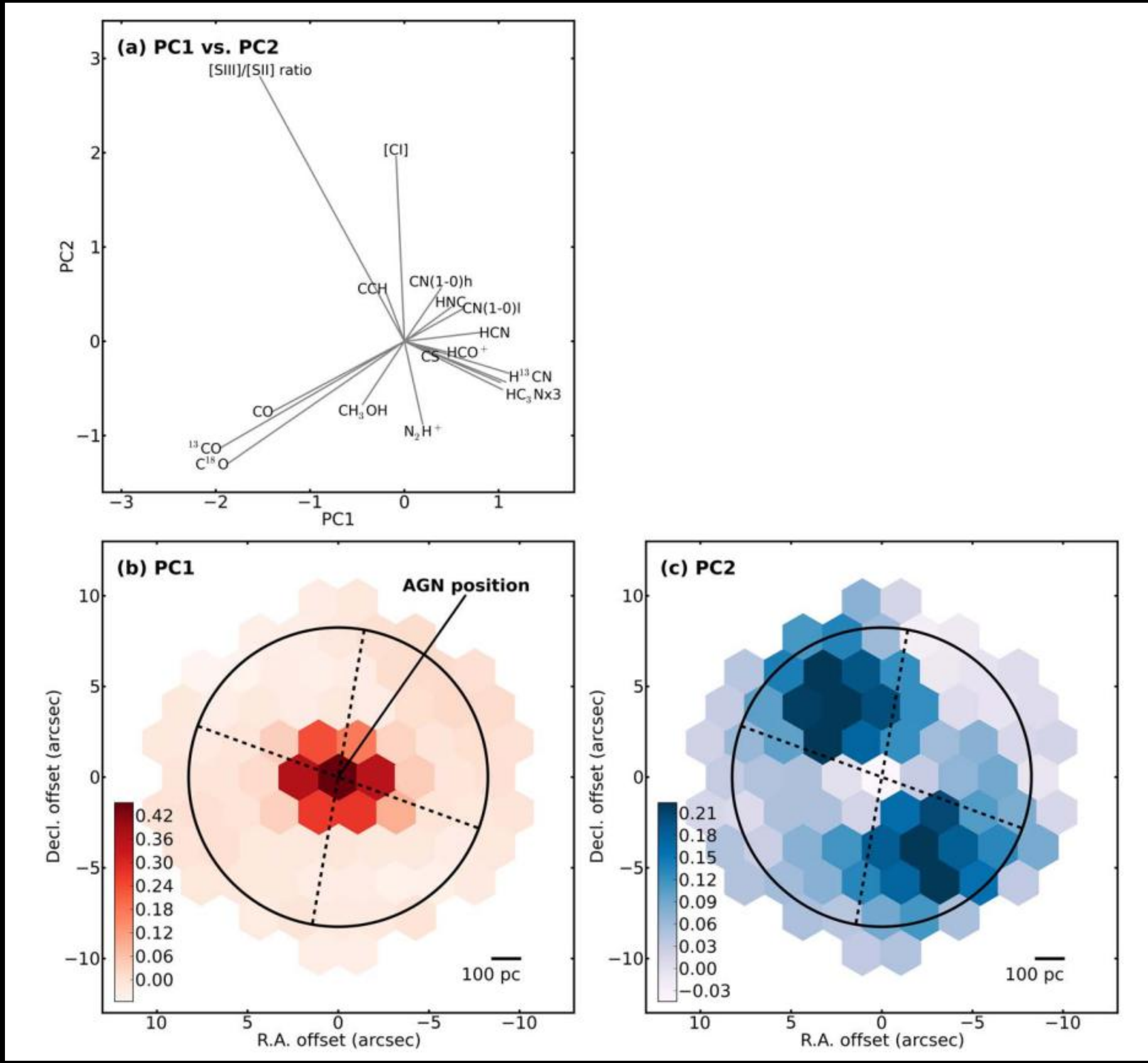
- SiO :
  - strong shocks
  - $n(H_2)$~5 x 10^4 cm^3
- HNCO
  - low-v shocks or no shocks
  - $n(H_2)$> 10^4 cm^3

Nuclear activity diagnostics: Outflow Chemistry

Saito+2022

3mm ALMA archival data

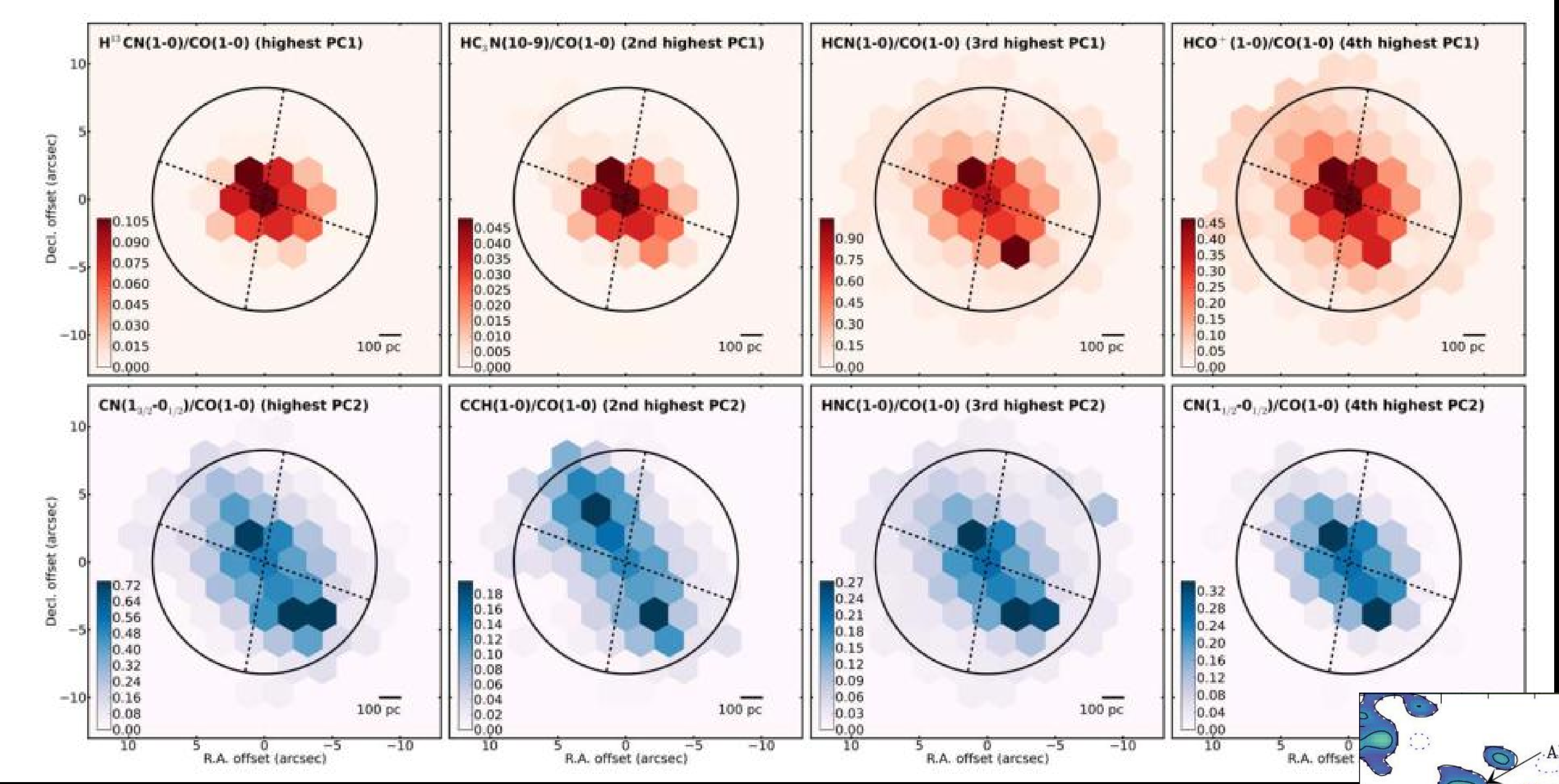




Nuclear activity diagnostics: Outflow Chemistry

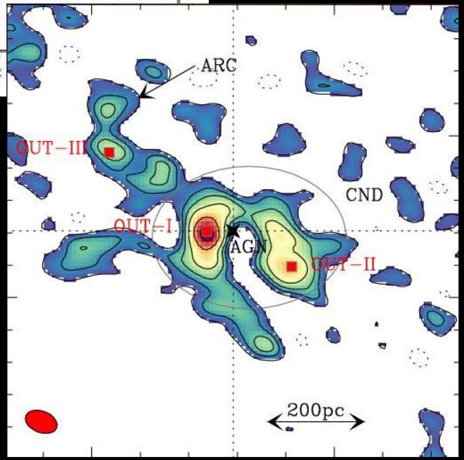
Saito+2022

Outflow suppressed: CO, N_2H^+, CH_3OH



Outflow tracers: CN, C_2H, HNC

Consistent with high resolution C_2H



Garcia-Burillo+2017

E-ASTROCHEMISTRY：Where are we now？

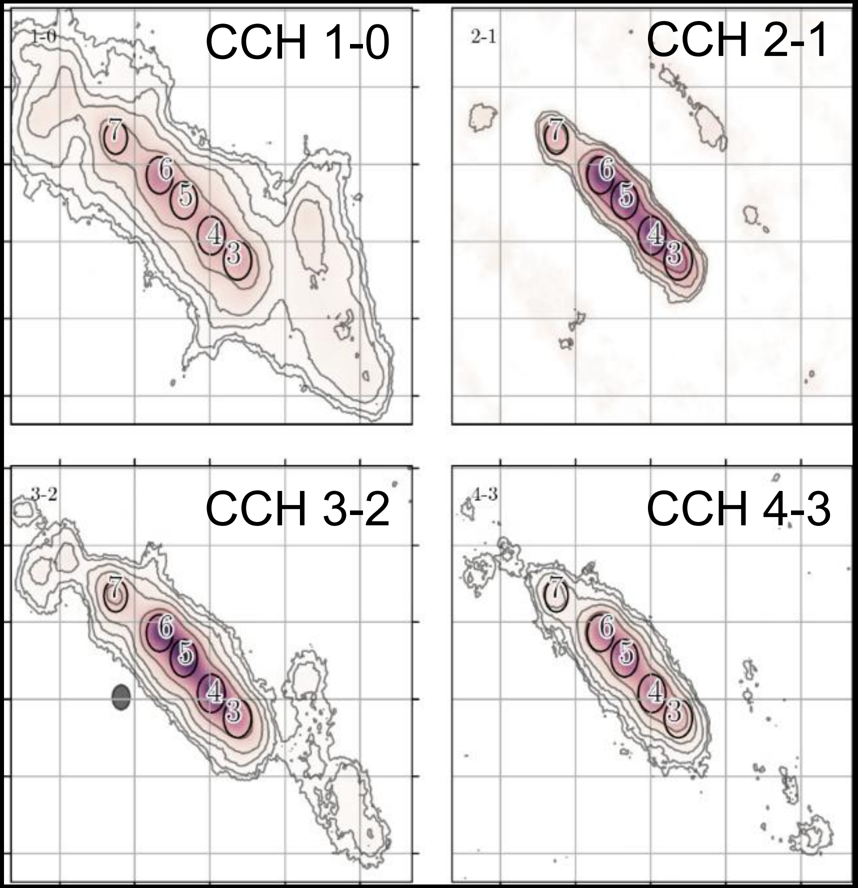
Physical conditions
（a.k.a Understanding the environment driving the chemistry in NGC ２５３）

ALCHEMI

Constraining the elevated Cosmic Ray ionization rate in NGC 253 with molecular probes and chemical models

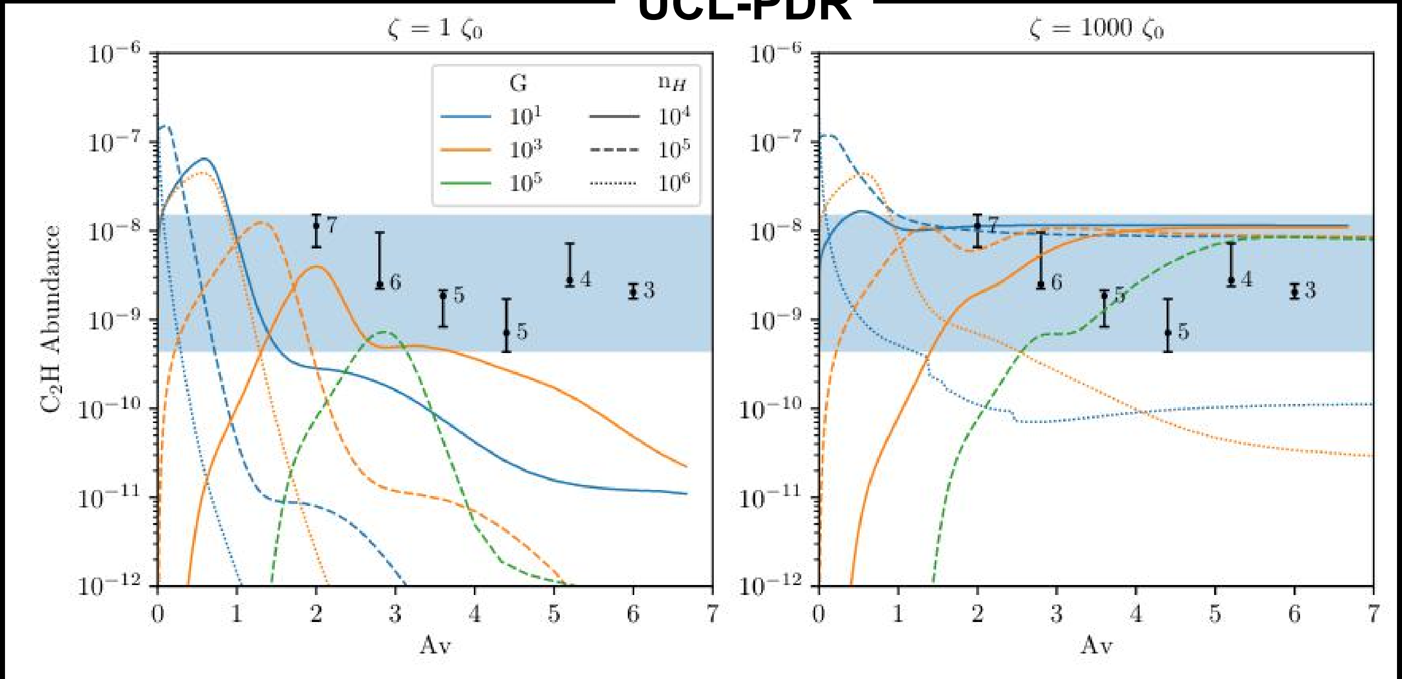
C_2H

Holdship+2021



- High observed abundance in all clouds $X(C_2H) \sim 10^{-8}$-10^{-9}
- **C_2H** abundances cannot be reproduced by
  - PDR modelling using photochemistry in low Av regions (UCL-PDR model)
  - Dense gas chemistry (UCLCHEM model)
  - Shock chemistry might increase abundances in a short 10^5 yr period
- **High cosmic ray ionization rates maintain C_2H abundance well into the cloud at observed levels.**

UCL-PDR

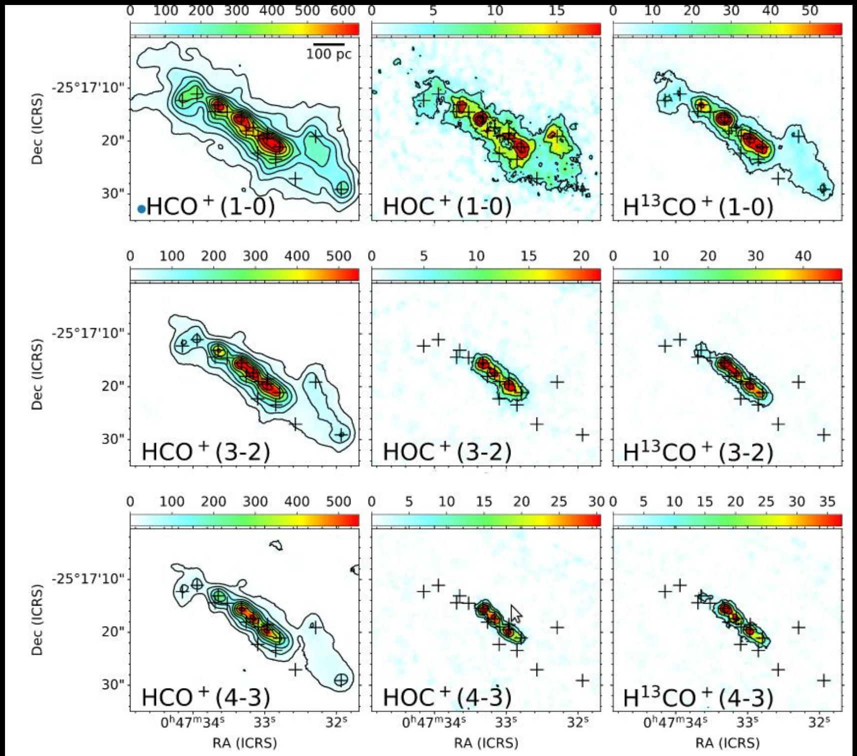


CRIR > 10^3 -10^6 MW Canonical
(Canonical 10^{-17} s^{-1})

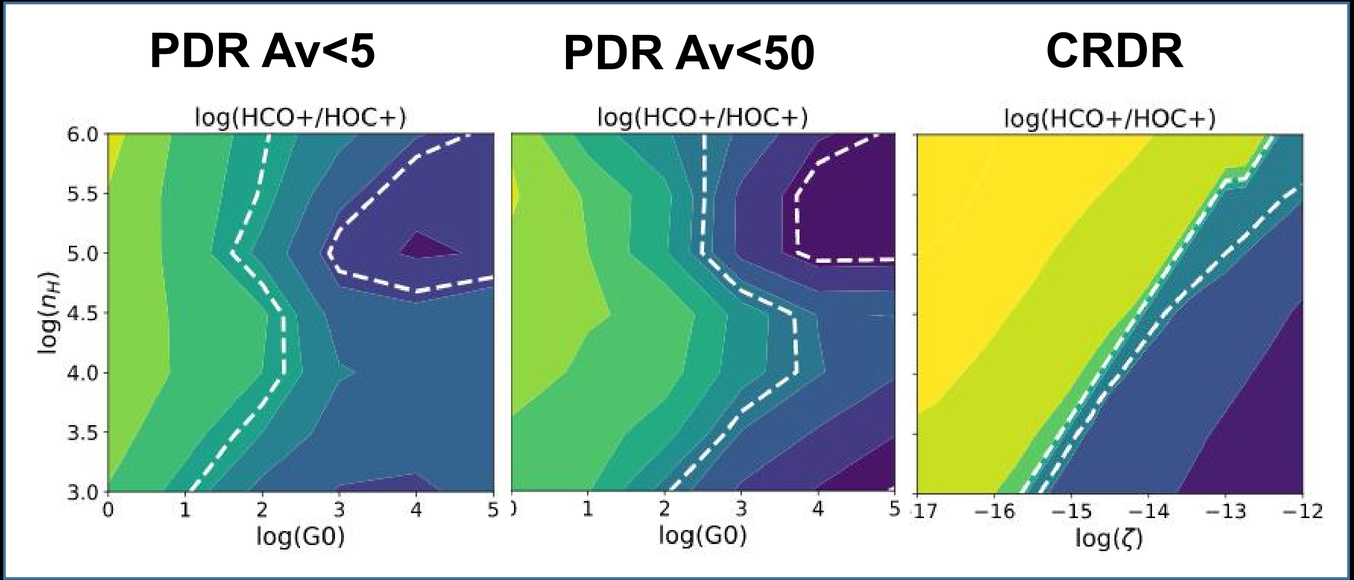
Constraining the elevated Cosmic Ray ionization rate in NGC 253 with molecular probes and chemical models

HOC^+/HOC^+

Harada+2021



- HOC^+ associated to "superbubbles" cavities
- High observed abundance of metastable isomer HOC+
- Low ratios of HCO^+/HOC^+=10-150, i.e 10-100 lower than in GC or quiescent spiral dark clouds
- **PDR and CRDR models (using modified NAUTILUS gas-grain code) reproduce ratios:**
  - **PDR for high density $n_H > 10^5$ cm^{-3} and radiation field $G_o \sim 10^3$ for $A_v < 5$ (clumpy medium). Higher A_v require even higher radiation fields**
  - **CRDR reproduce the ratio for CRIR>10^{-14} s^{-1}**
  - **A mixture of both as a consequence of intense Star Formation**

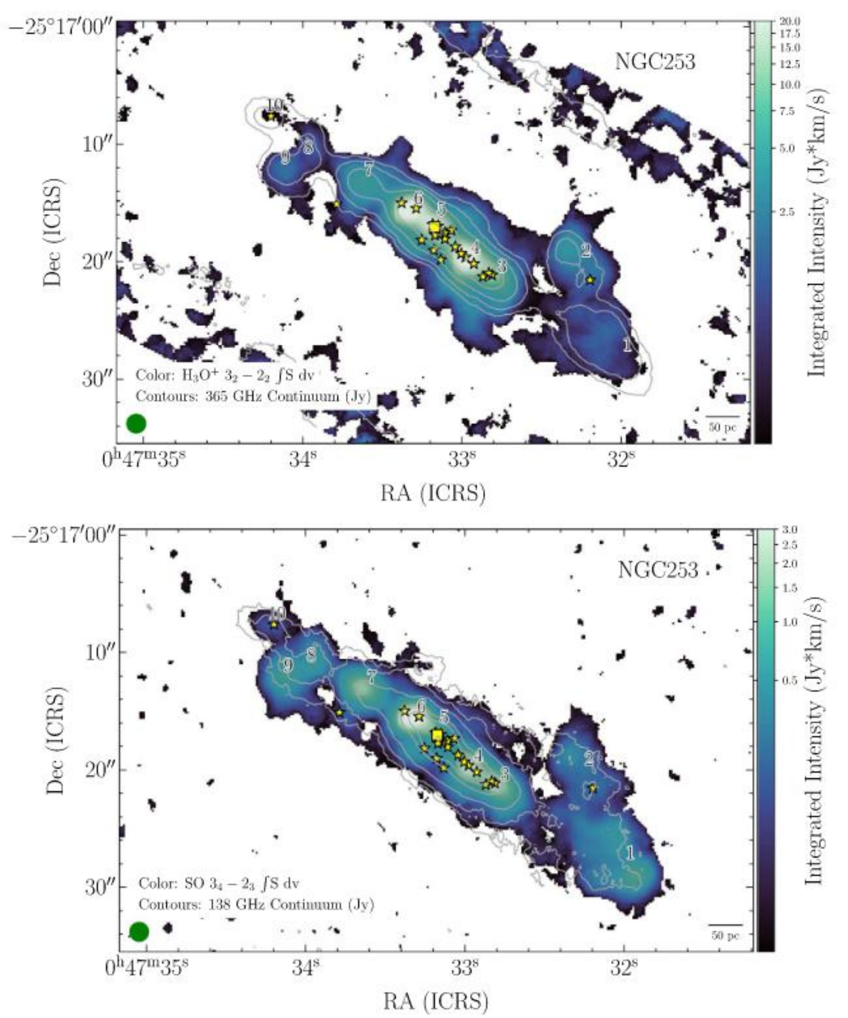


CRIR > 10^3 -10^4 MW Canonical

Constraining the elevated Cosmic Ray ionization rate in NGC 253 with molecular probes and chemical models

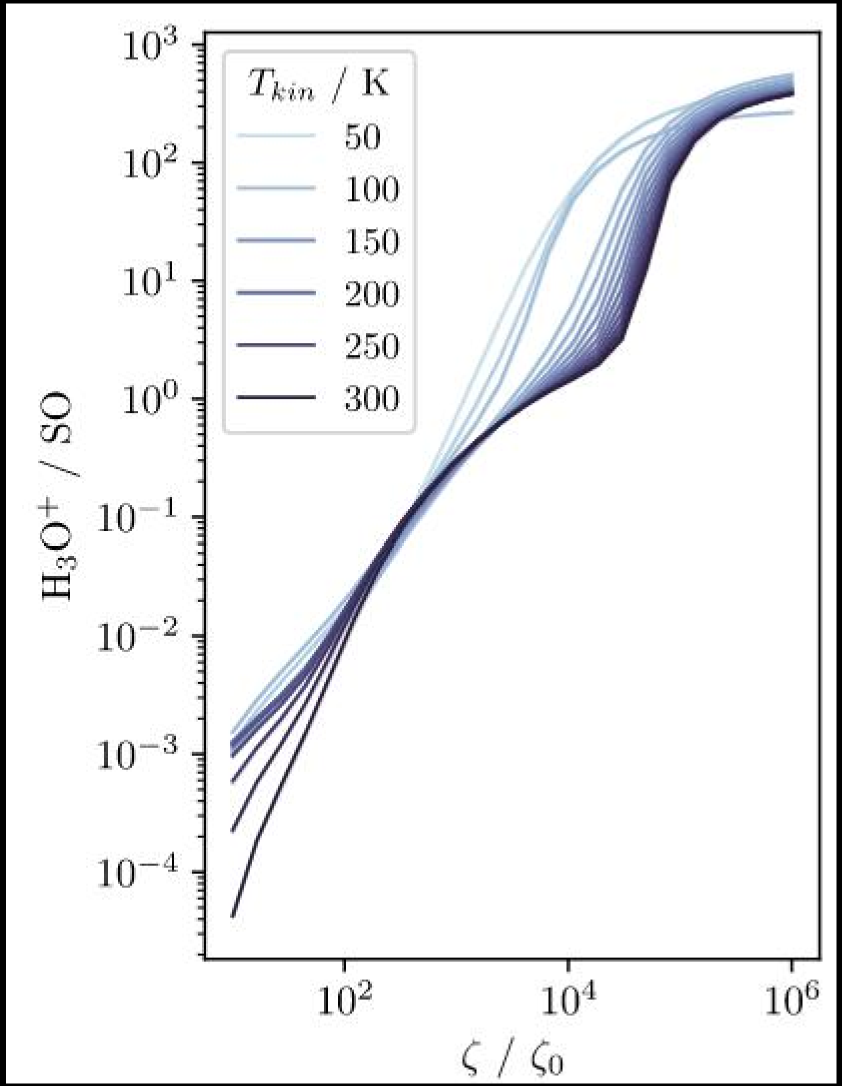
H_3O^+/SO

Holdship+2022



- Making use of strong correlation between H_3O+/SO and CRIR
- SO efficiently destroyed by CR
- H^3O^+ enhanced by the extra O^+ to form OH^+

$$H_2 + OH^+ \longrightarrow H_2O^+ + H$$
$$H_2 + H_2O^+ \longrightarrow H_3O^+ + H$$



CRIR constrained to 10^4 MW Canonical (very unlikely outside [10^3-10^5])

E-ASTROCHEMISTRY： Where are we now？

A new environment to test astrochemistry

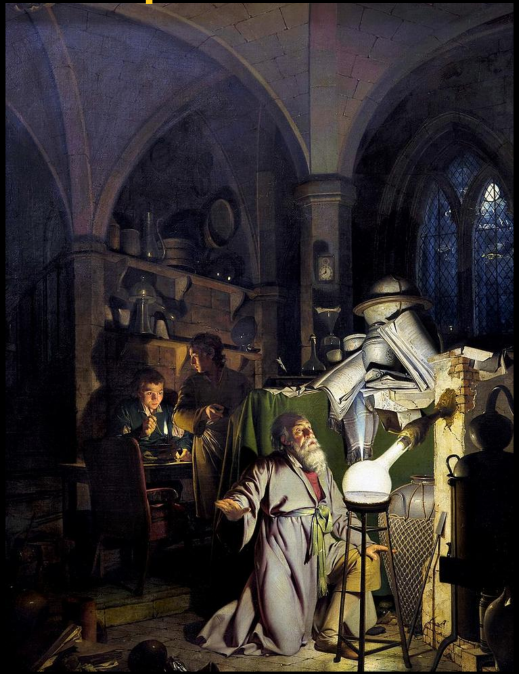
ALCHEMI

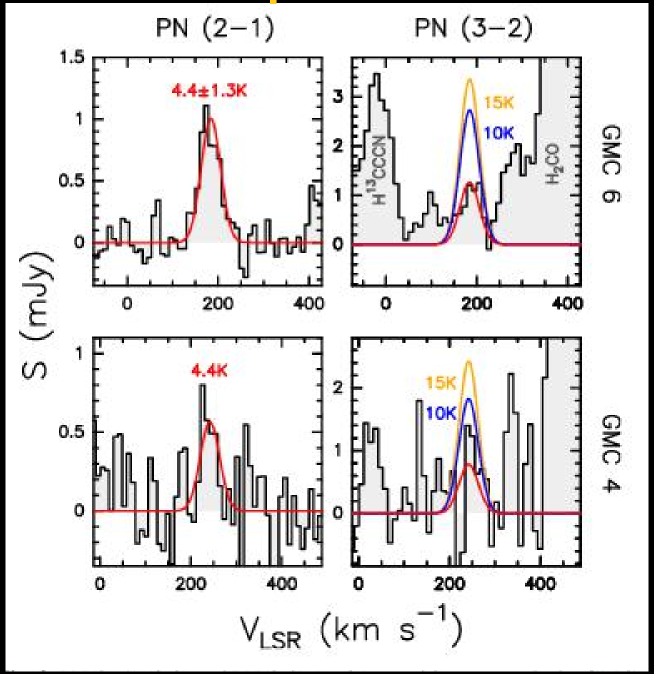
PHOSPHOROUS SPECIES: PN clear detection but no other P-species at this sensitivity

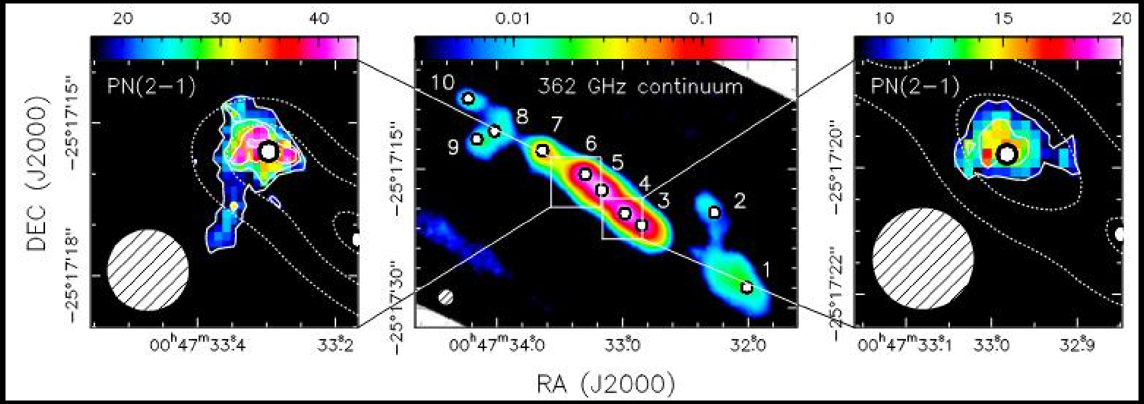
PN

Haasler+2022

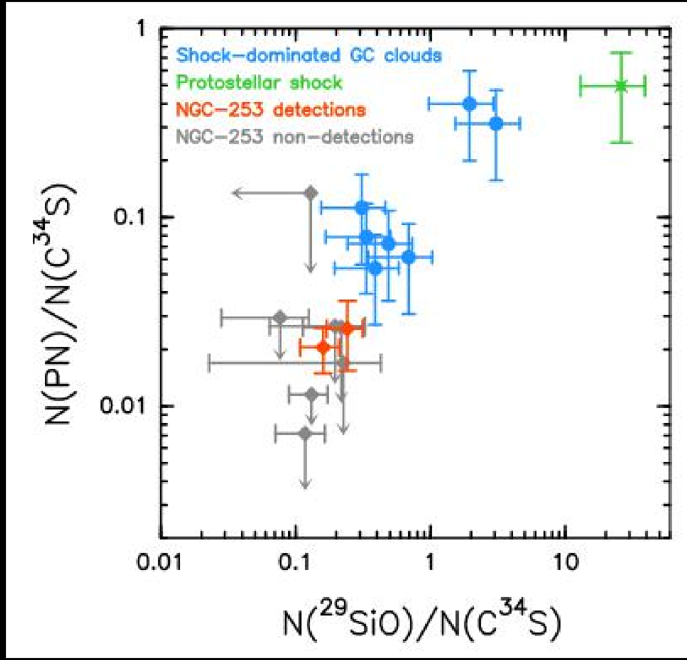
Phosphorous in the Lab...and at 3 Mpc distance!







- Detected in two GMCs
- Observed correlation between PN and SiO also holds at large scales

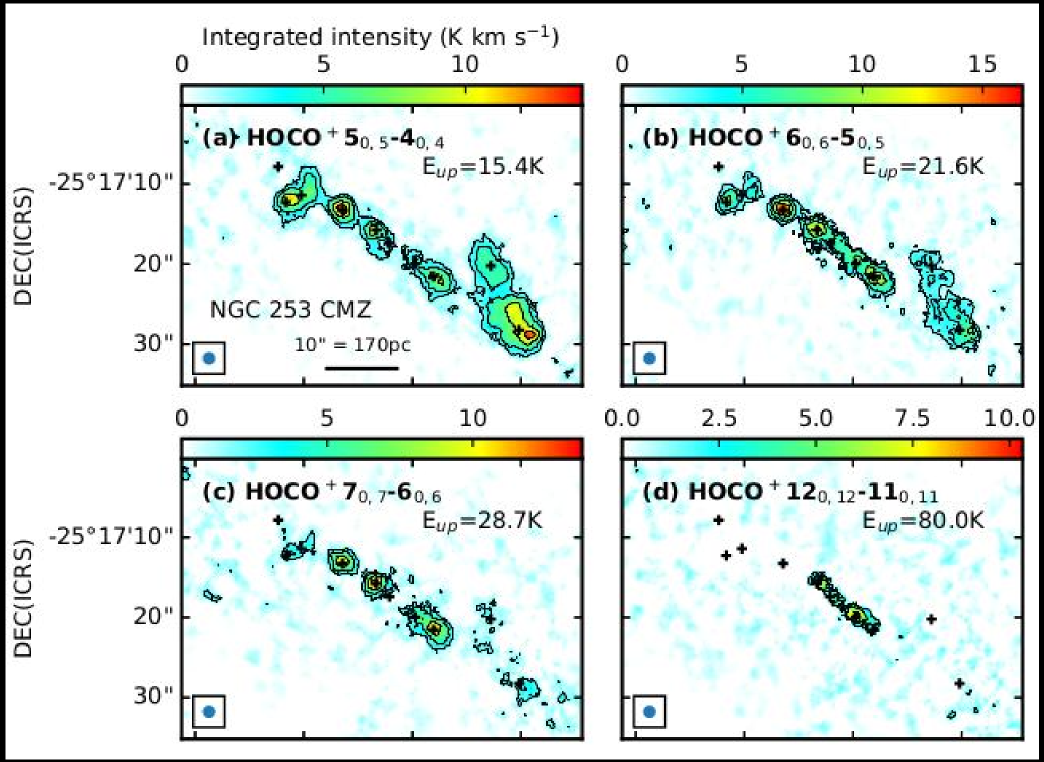


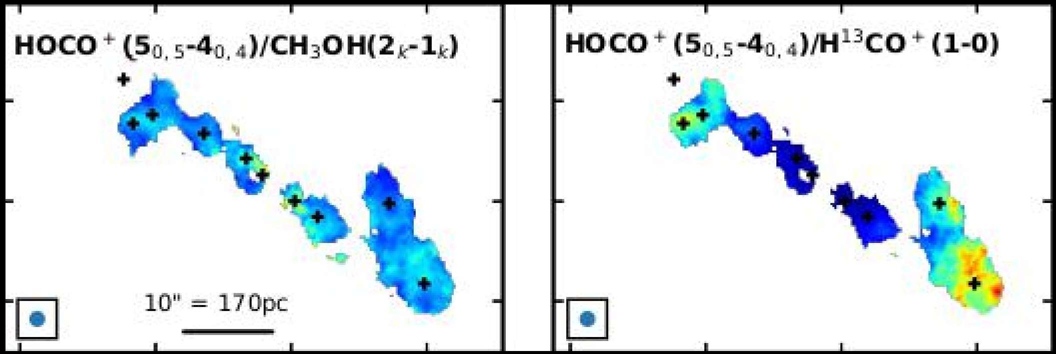
- The observations confirm the evidence of P-species being sputtered from dust grains via shocks
- The PO/PN could be regulated by photochemistry due to efficient PO photo-destruction. The PO/PN<1.3 in NCG 253 linked to the high CR ionization rate.

GAS PHASE CO2, one of the most dominan forms of ice on interstellar dust, probed by its protonated form HOCO+

HOCO+

Harada+2022





$$CO_2 + H_3^+ \longrightarrow HOCO^+ + H_2,$$

$$HCO^+ + OH \longrightarrow HOCO^+ + H$$

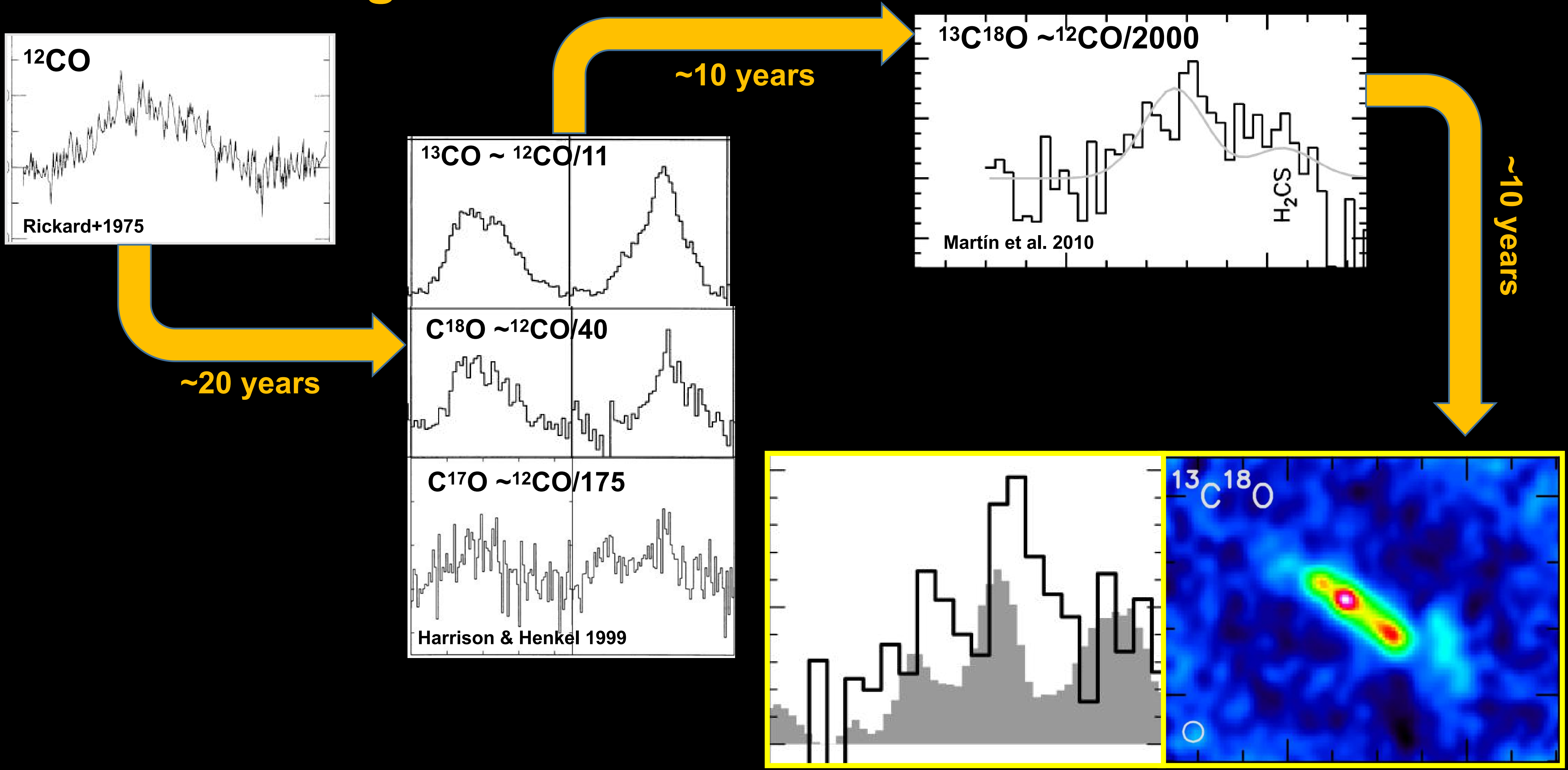
Formation of HOCO+

- **Ion-neutral reaction appears to be dominant in high-mass SFR based on correlation with H^{13}CO$^+$ (Fontani+2018)**
- **In NGC 253 the correlation with CH_3OH appears to favor the protonation of CO_2**

- **High fractional gas-phase abundance of HOCO$^+$ of ~2x10^{-9}, similar to that in the Galactic Center**
- **HOCO$^+$/CO_2 ratio of 0.001-0.01 from models yield gas-phase CO_2 abundance of (1-20)x10^{-7}**
- **The ice-phase CO_2 abundance of ~2x10^{-6} from AKARI at the peak of HOCO$^+$ indicates effective sublimation via shocks in those regions**

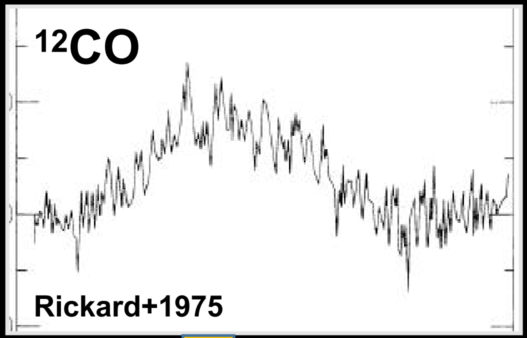
Future Challenge: Making sense of it all

Future Challenge

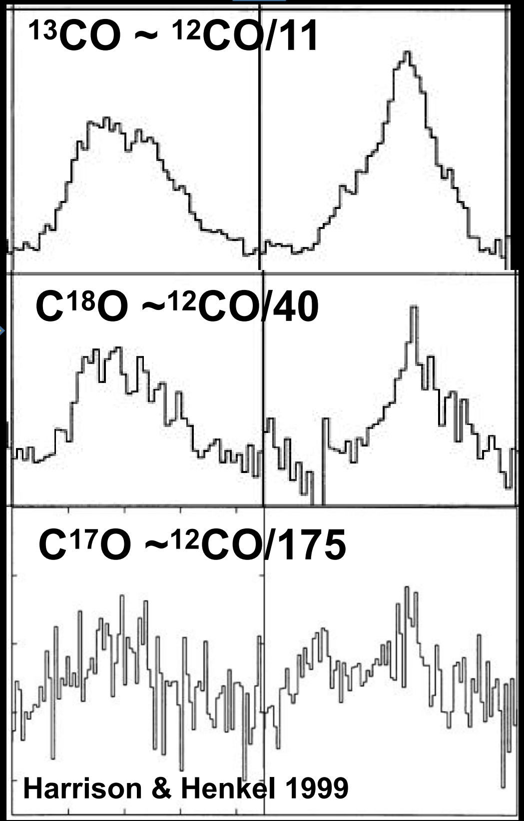


ALMA; Martín et al. 2019

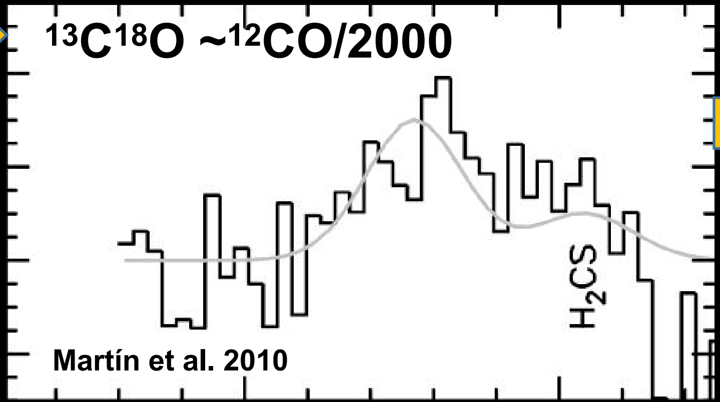
Future Challenge



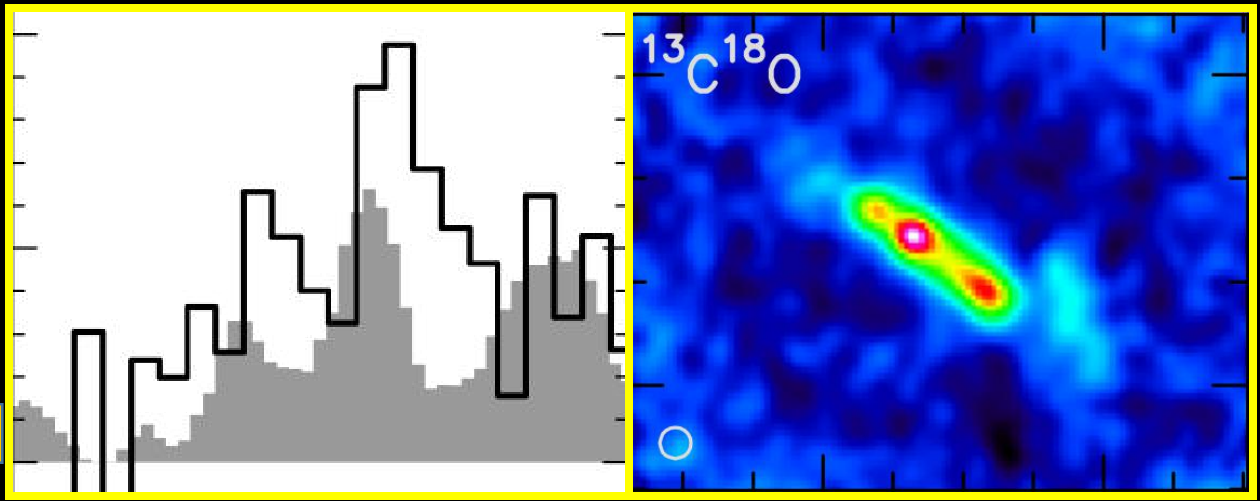
~20 years



~10 years



~10 years



ALMA; Martín et al. 2019

ALMA 2030

~10 years

Future Challenge: Making sense of it all.

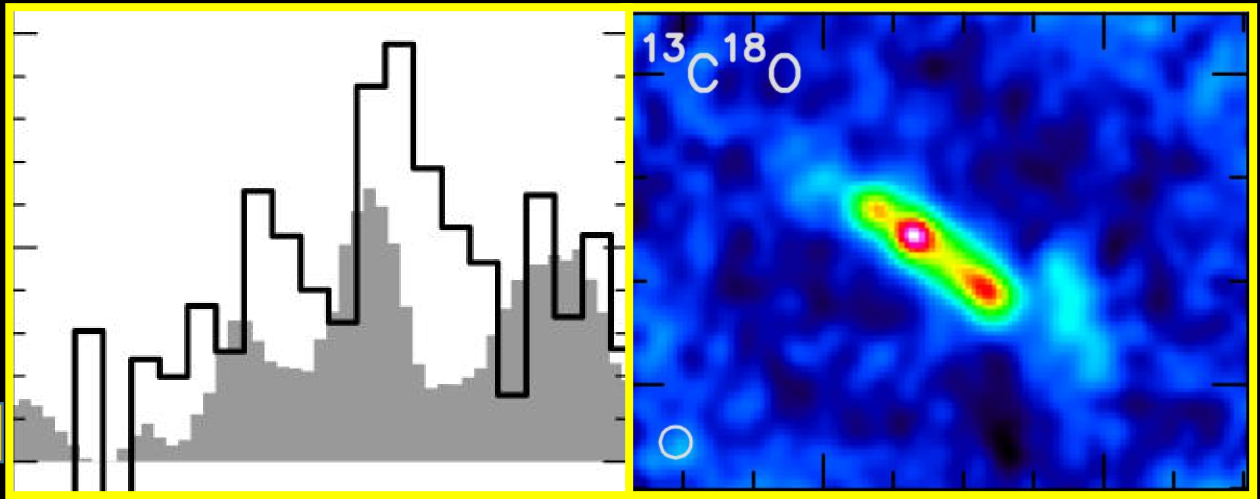
- At least x3 faster observing speed with ALMA
  - Not to forget nJVLA, SKA, and NOEMA.

- ALCHEMI-like multi-transition/molecule observations ~ excitation/chemistry

- Are available tools/methods sufficient to reduce the multi-dimensionality of the problem?

ALMA 2030

~10 years



ALMA; Martín et al. 2019