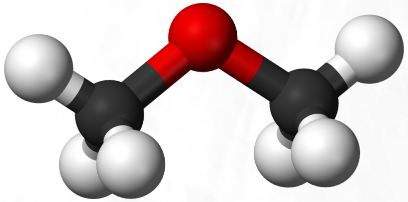
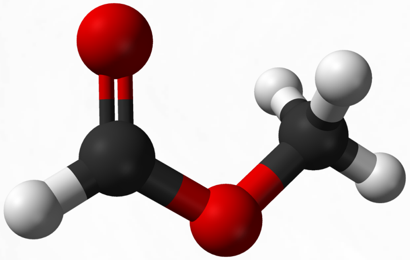
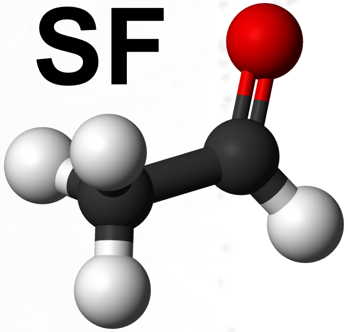
Complex organic molecules in early phases of higher-mass SF







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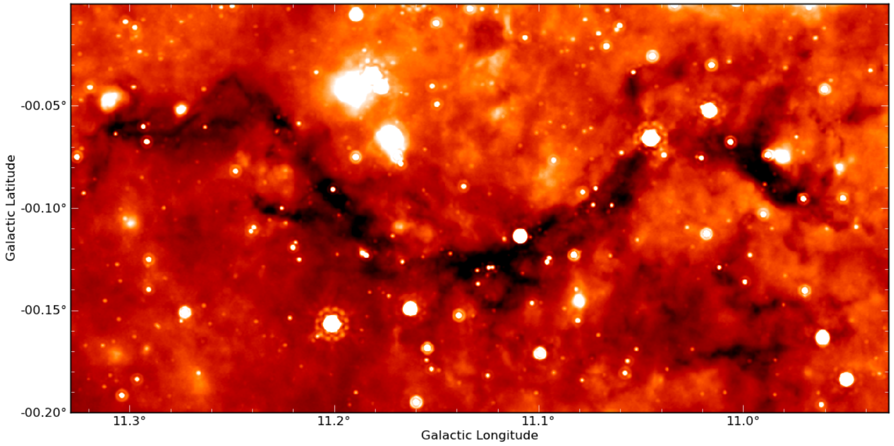

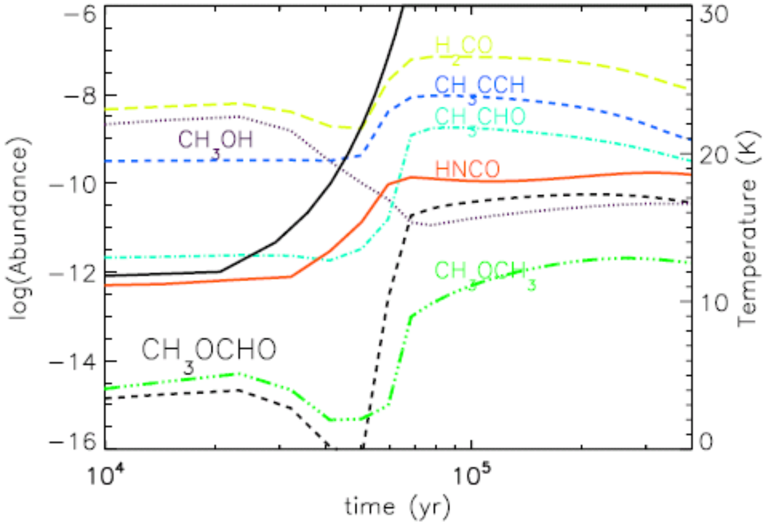

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Why studying COMs?

Complex Organic Molecules (COMs): C-bearing molecules with 6 or more atoms
→ classics like methanol (CH_3OH) or methyl cyanide (CH_3CN), but also more complex: Di-methyl ether (CH_3OCH_3), methyl formate (CH_3OCHO), or Acetaldehyde (CH_3CHO)

In our case: investigation of COMs **NOT** for reasons of establishing astro-biology
(COMs → pre-biotic molecules → pre-conditions for life)

Instead: COMs as astro-chemical tools to constrain physical conditions and evolution of higher-mass star-forming regions

Early stages of higher-mass SF

Infrared-dark clouds (IRDCs) still a good hunting ground to look for these stages

Important: IRDCs are a heterogeneous class of objects!

Besides a large variety of shapes, sizes and contrasts, also differences in properties of embedded objects

MPIA has a Herschel Key Program to investigate the FIR continuum properties of such early stages:
EPoS (PI: O. Krause)

→ many sources for our line investigation drawn from the EPoS sample

Early studies of the gas content

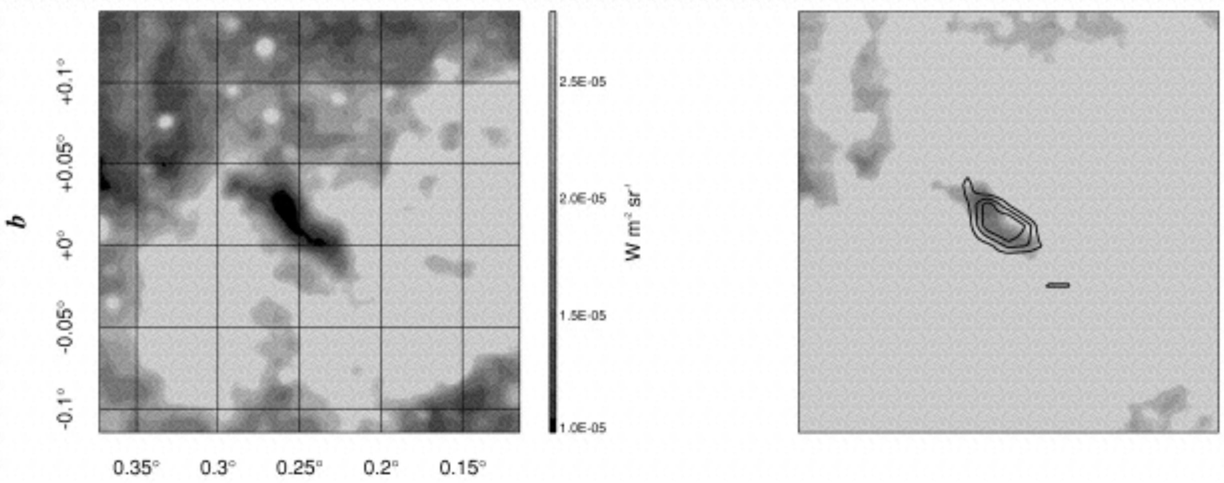
Single-dish studies to check for (dense) gas content:

Carey et al. 1998: **H_2CO**

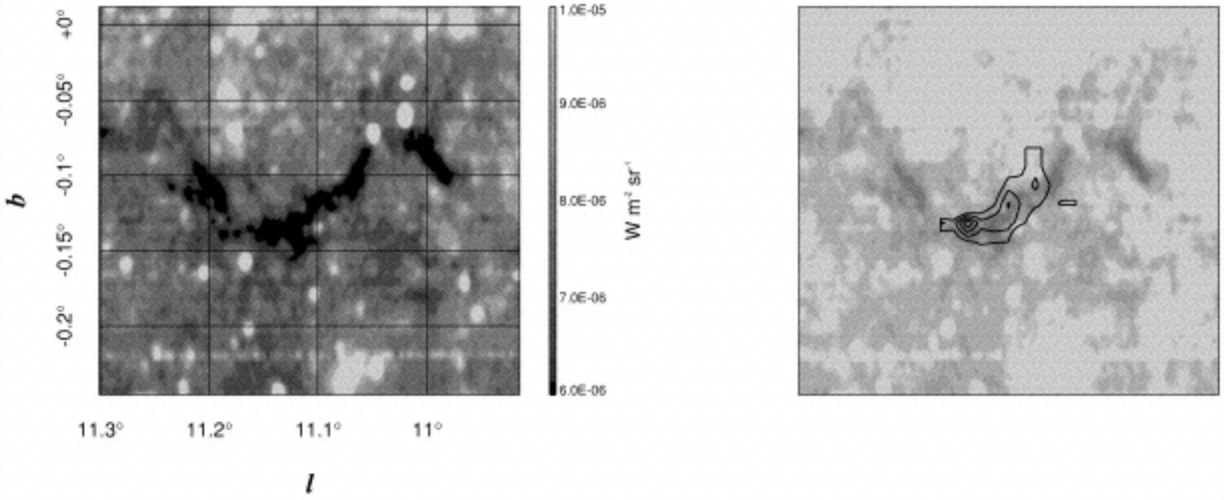
Teyssier et al. (2002): **^{13}CO + $C^{18}O$**

Pillai et al. (2006): **NH_3**

The Brick G0.253+0.016



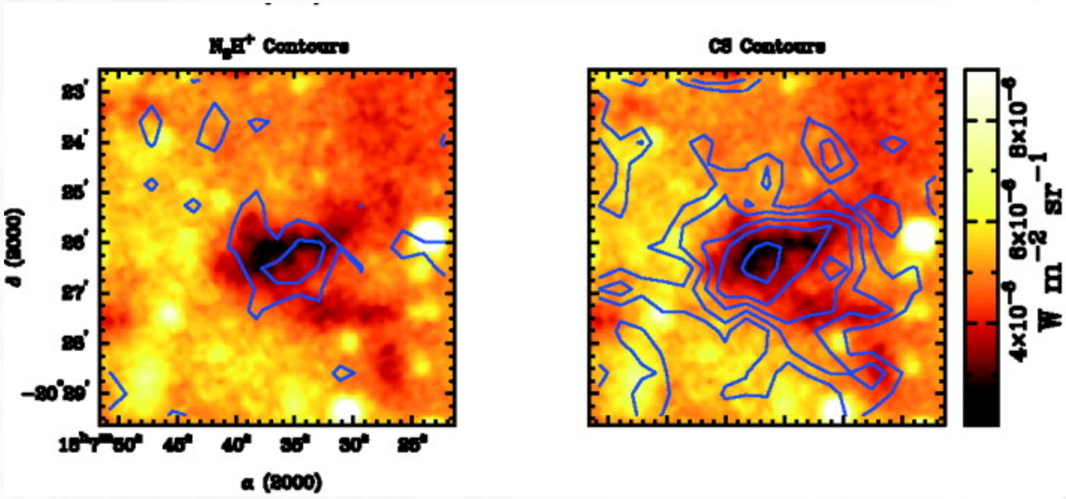
The Snake G11.11-0.12



Early studies of the gas content

Ragan et al. 2006: Observational paper with 41 IRDCs in $N_2H^+(1\text{-}0)$, CS(2-1), $C^{18}O(1\text{-}0)$

(using the 14-m FCRAO telescope → beam size of ~45")



One of Sarah Ragan's IRDCs in N_2H^+ and CS

→ Gibson et al. 2009 used this data set, enhanced by additional pointed observations in higher CS transitions
→ First application of a chemical evolution code (Calgary)
→ studied IRDCs are chemically young ($10^{4.5} – \tau – 10^{5.5}$ years)

Advent of broad-band for receivers and backends

Mopra antenna in Australia

22-m antenna for observations up to 116 GHz (3-mm band) (beam size of ~36”)

8 GHz bandwidth and up to 16 spectral zoom windows

→ used by many groups in the typical 90 GHz set up (86-94 GHz) mainly tracing the “big four”: HCO^+, HCN, HNC, N_2H^+

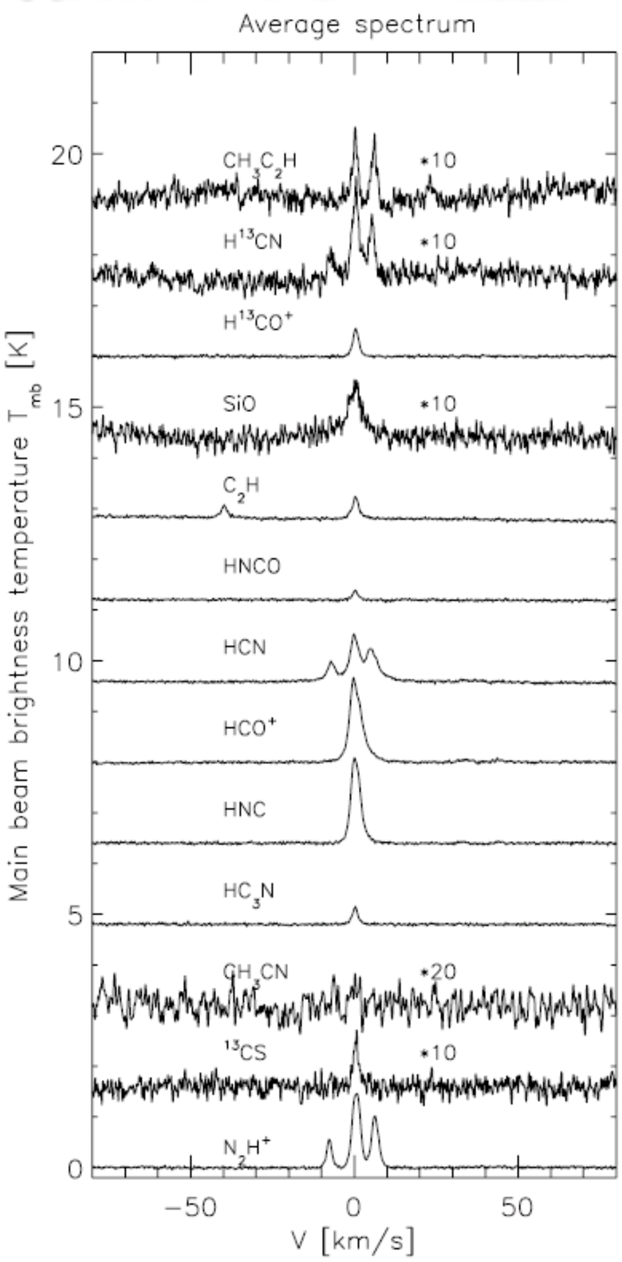
Vasyunina et al. 2011

Sanhueza et al. 2012

Hoq et al. 2013

Miettinen 2014

Advent of broad-band for receivers and backends



→ used by many groups in the typical 90 GHz set up (86-94 GHz) mainly tracing the “big four”: HCO^+, HCN, HNC, N_2H^+

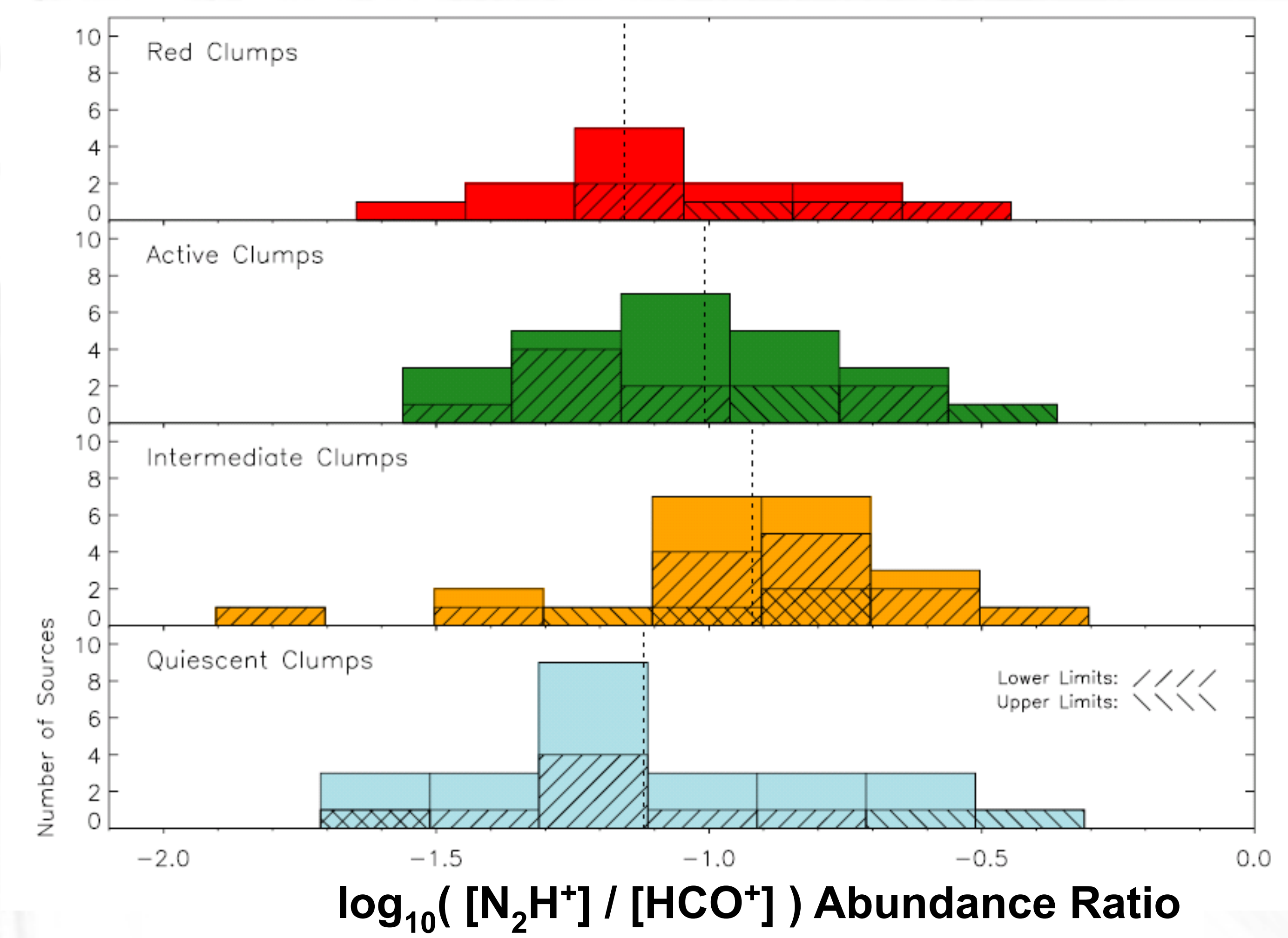
Vasyunina et al. 2011 single points

Sanhueza et al. 2012 single points

Hoq et al. 2013 MALT90 maps

Miettinen 2014 MALT90 maps

Tentative trends with evolutionary state



Evolutionary sequence (?)

from Sanhueza et al. 2012

Note: While n_{crit} is very similar for HCO^+(1-0) and N_2H^+(1-0), n_{eff} is >10 x higher for N_2H^+(1-0) than for HCO^+(1-0) (Shirley 2015).

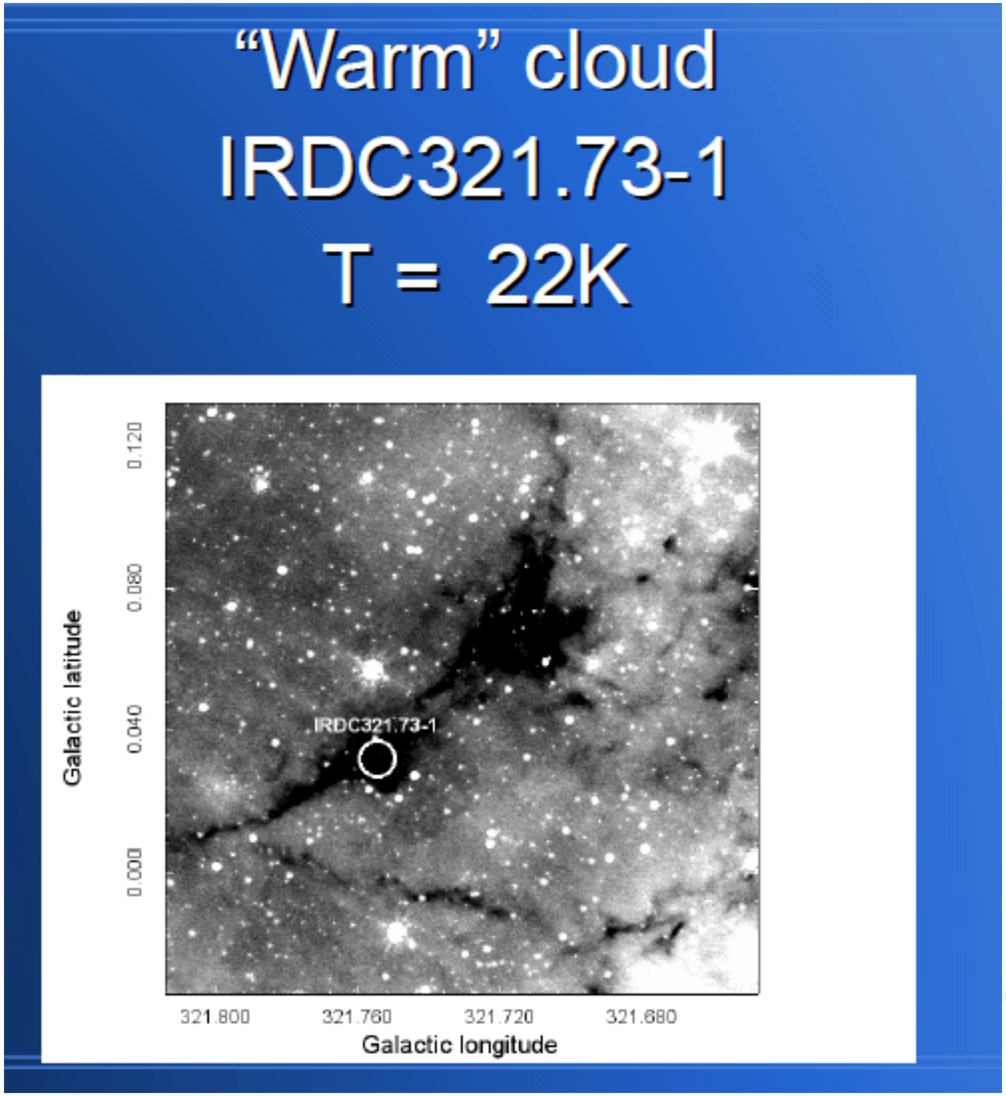
Our single-dish study of southern IRDCs

Test case for the modelling: Vasyunina et al. 2012

Model: 0-D model (constant density and temperature over time) + complete chemical network with adsorption / desorption and grain surface reactions

Results:

- **0-D model can reproduce all simple molecules**
- **Surface reactions are important at the temperatures of 20-30K, especially for N_2H^+**

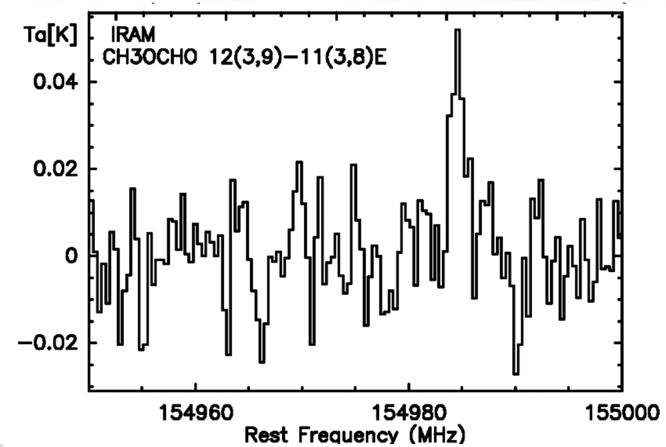


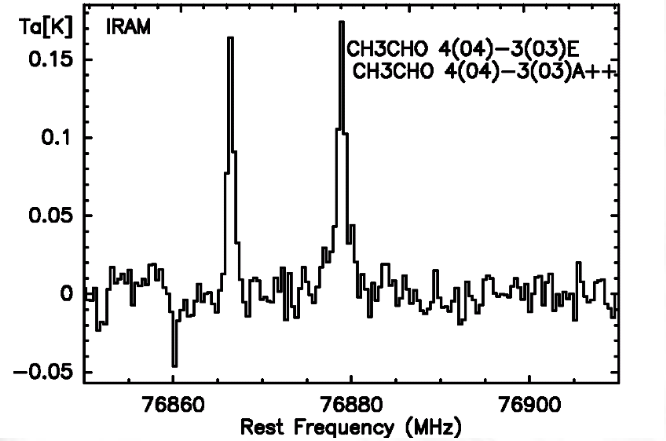
"Warm" cloud

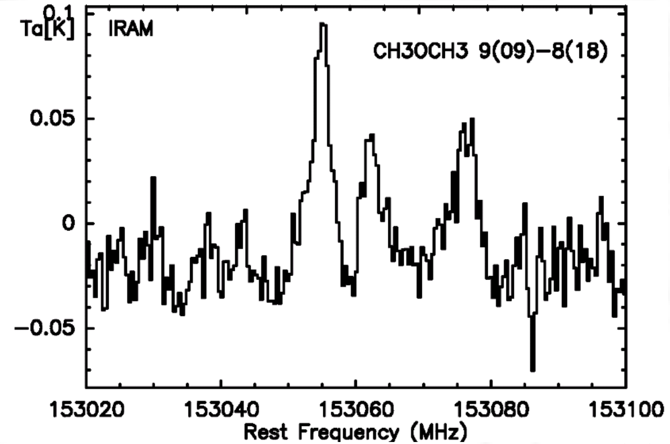
IRDC321.73-1

T = 22K

Vasyunina et al. 2014: Detection of COMs







Telescopes: Mopra, APEX, IRAM (20 – 100 mK rms)
Species: CH3OH, CH3CCH, CH3CHO, CH3OCHO, CH3OCH3

Model: 0-D model + warm-up + complete network + reactive desorption

Results:

- **One promising way to explain abundances of COMs in IRDCs is to warm-up the environment.**

- **Detailed shape of warm-up profile less important than duration of cold phase and final temperature level.**

Work in progress: high-sensitivity multi-line study

Telescope: IRAM-30m
Frequency: 99 – 107 GHz (5-6 mK); 218 – 225 GHz (14 mK)

Species: more than 25

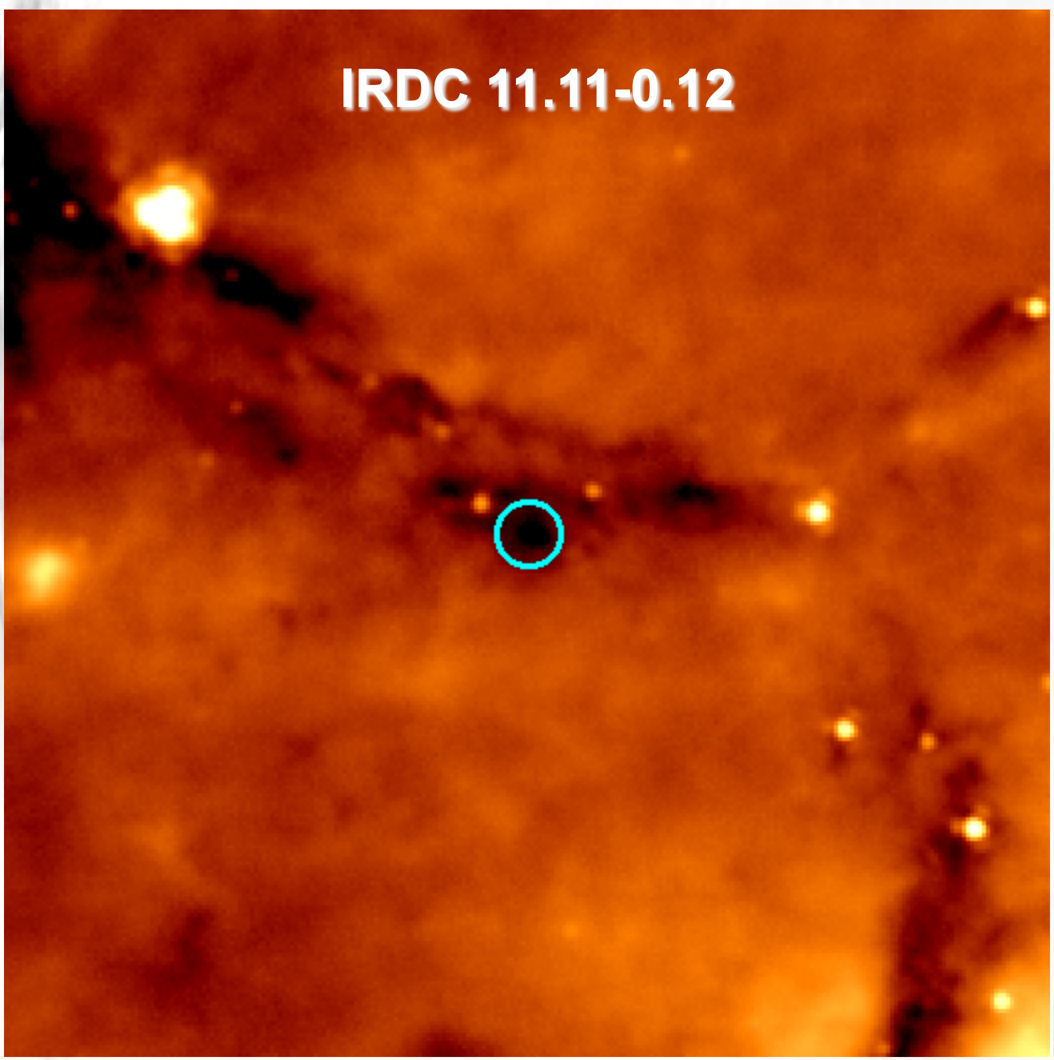
Objects: 7 quiescent and intermediate IRDC sub-regions,

2 active IRDC sub-regions,

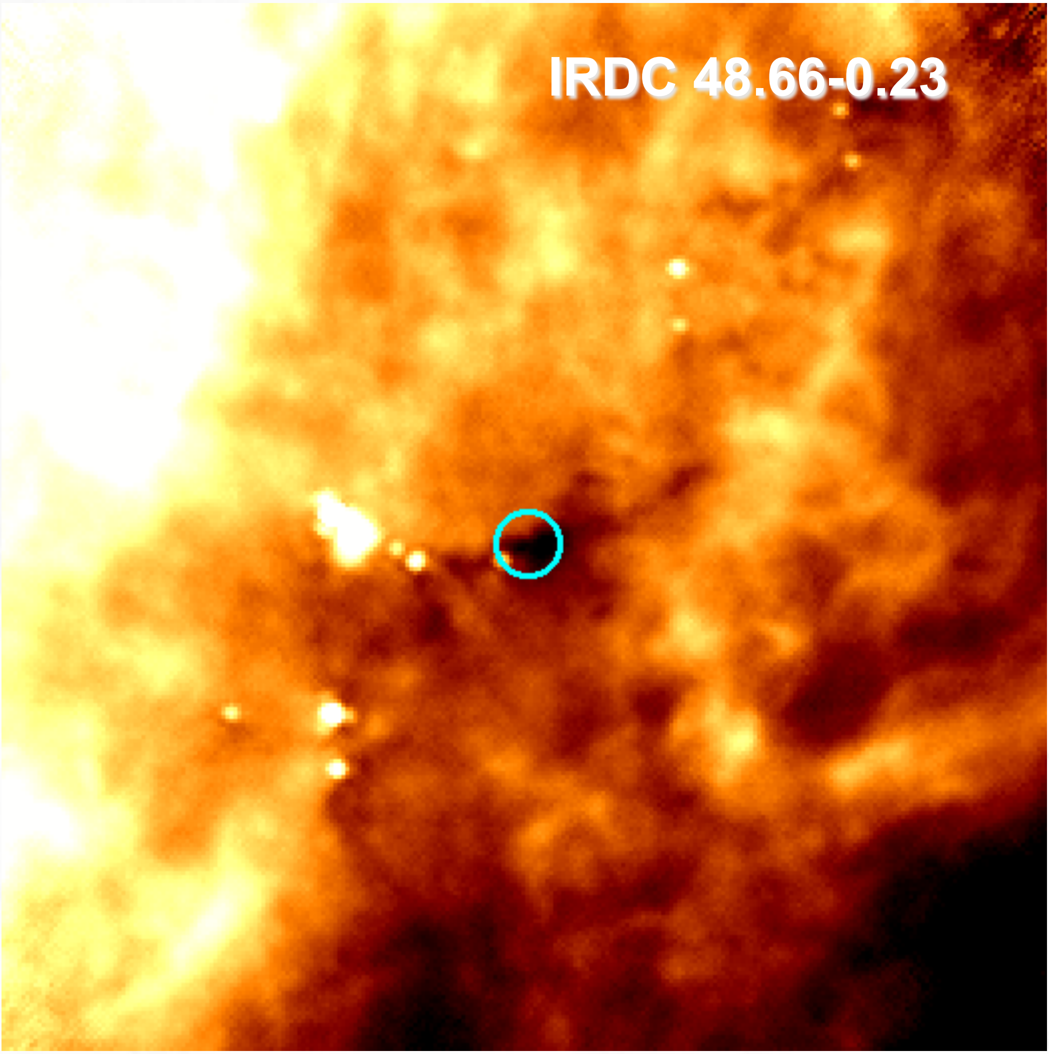
→ often, a phenomenological classification is used depending on the presence of 8-μm and/or 24-μm compact emission sources within the IRDCs, and the detection of “green fuzzies” at 4.5 μm as shock indicators (implying star-formation activity)

see, e.g., Chambers et al. 2009
→ ad-hoc evolutionary sequence from
Quiescent over Intermediate to Active IRDCs

Target Examples (I): quiescent IRDC locations

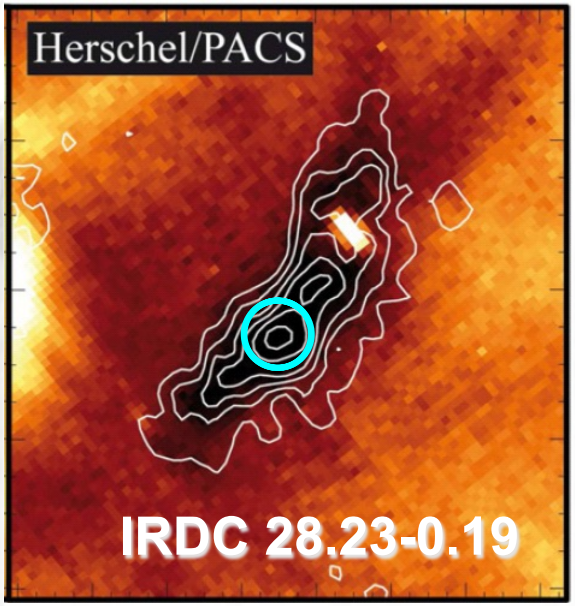


EPOS: Henning et al. 2010; Ragan et al. 2015

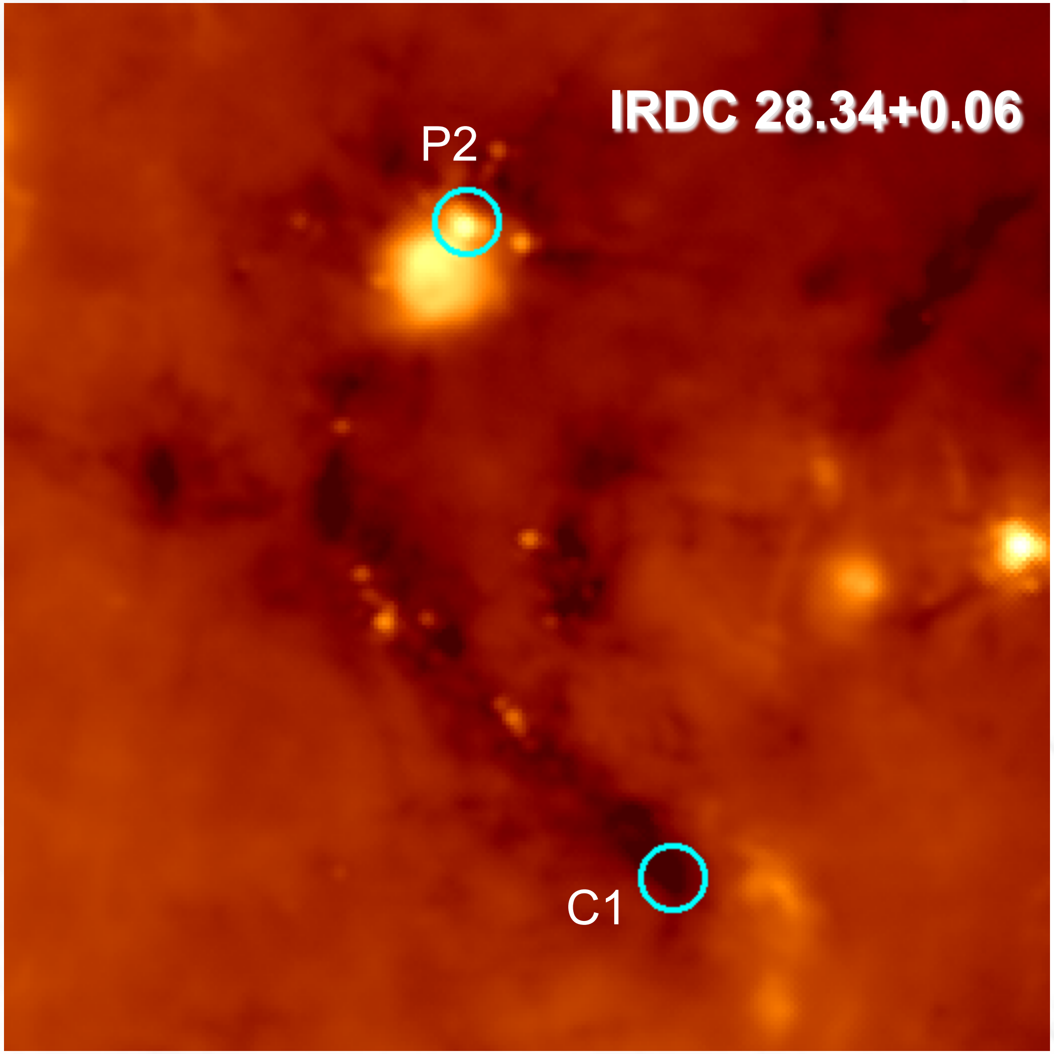


EPOS: Pitann et al. 2013

Target Examples (II): quiescent and active IRDC locations

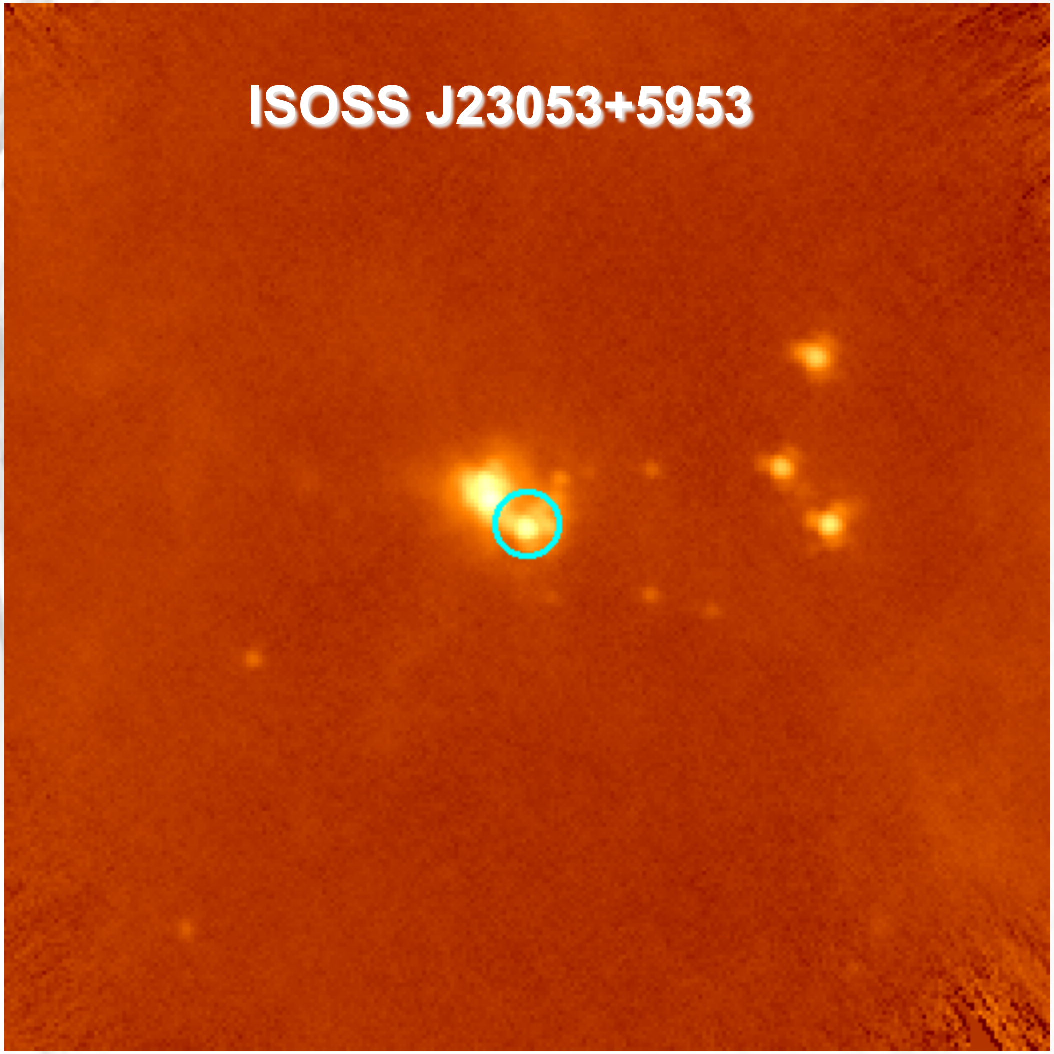


Sanhueza et al. 2013
See also their poster P38

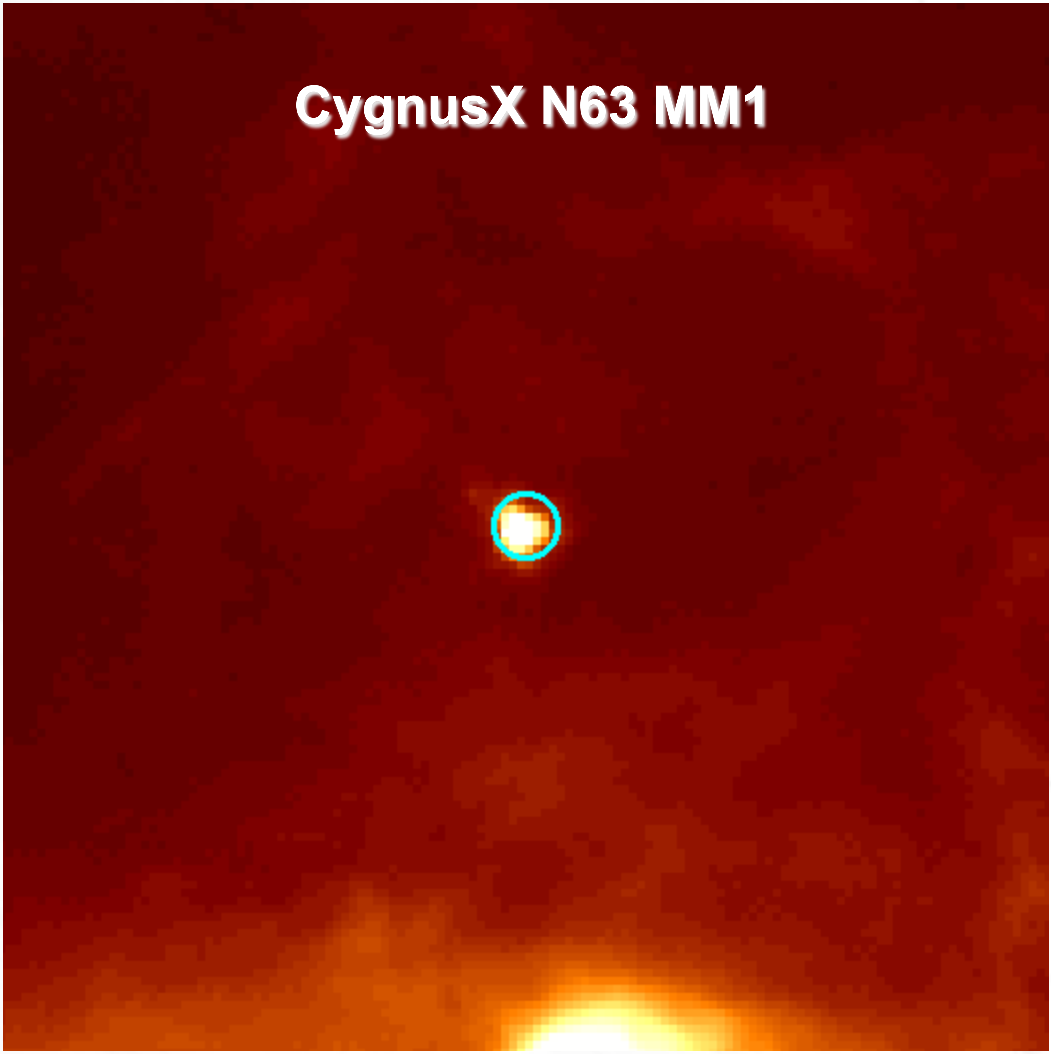


e.g., Wang+ 2006; Rathborne+ 2006; Zhang+ 2009; EPOS: Tackenberg et al. 2014

Target Examples (III): transition sources

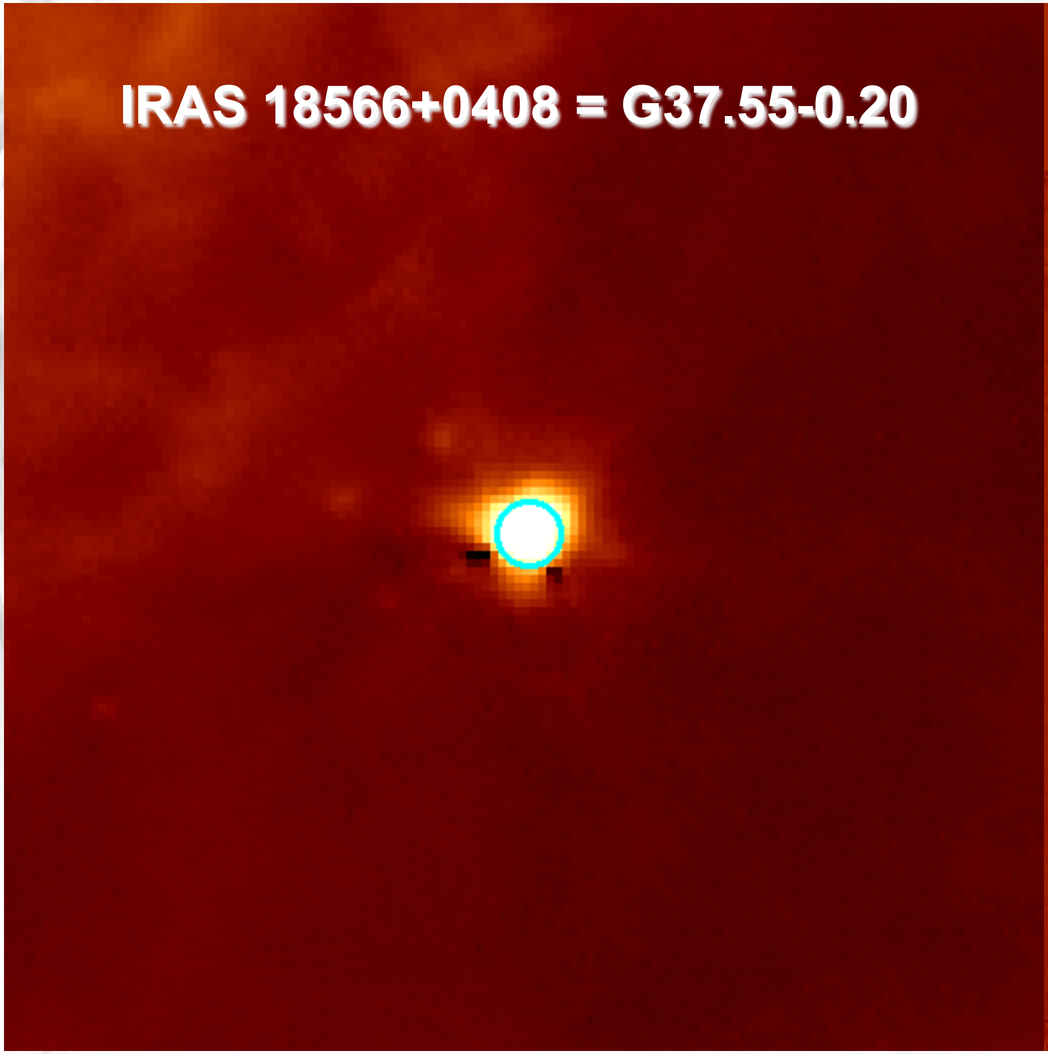


Pre-EPOS: Birkmann et al. 2007
EPOS: Ragan et al. 2012; Bihr et al. 2015a



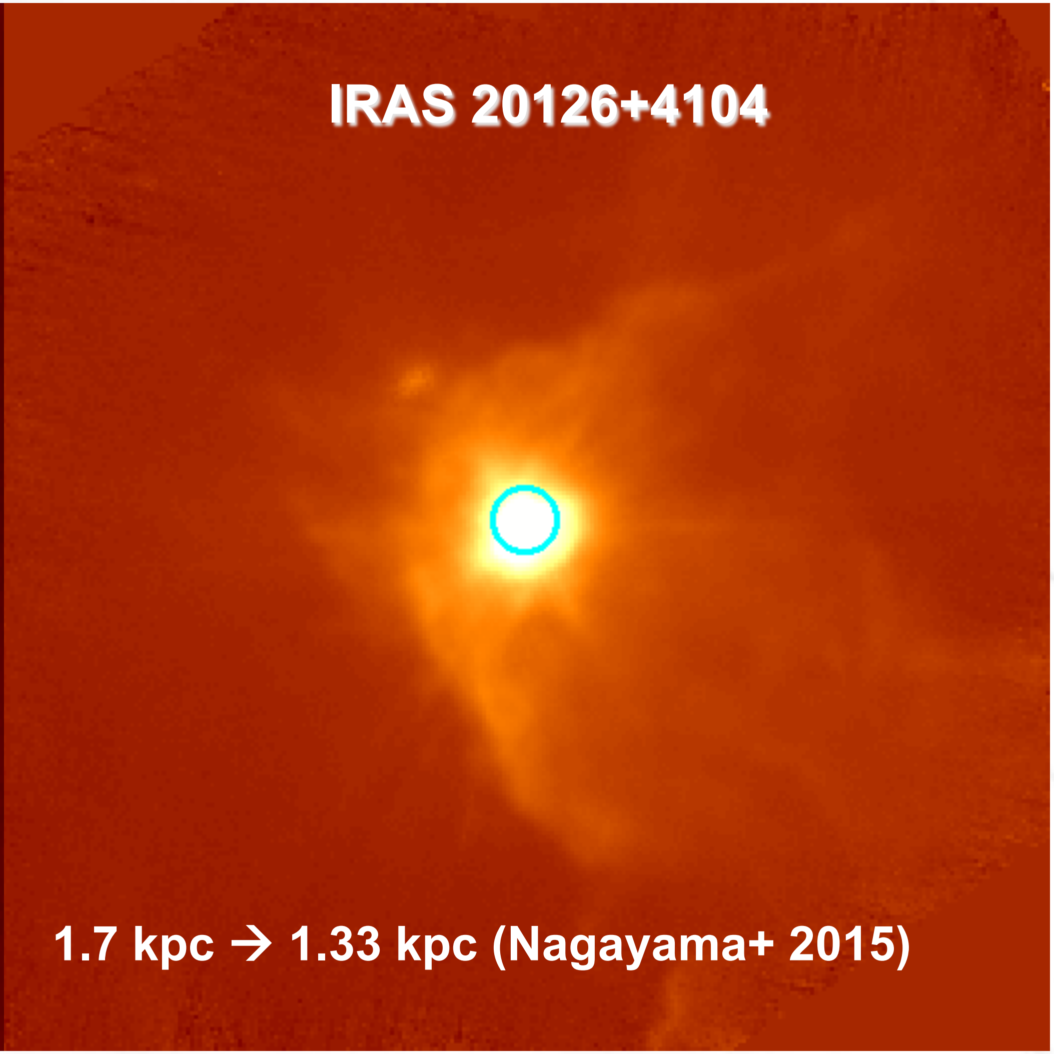
Bontemps et al. 2010, Fechtenbaum et al. 2015

Target Examples (IV): IR-bright high-mass protostellar objects (HMPOs)



IRAS 18566+0408 = G37.55-0.20

e.g., Zhang et al. 2007, Araya et al. 2007



IRAS 20126+4104

1.7 kpc → 1.33 kpc (Nagayama+ 2015)

e.g., Cesaroni et al. 2014, Johnston et al. 2011

High-sensitivity multi-line study II

Detected in quiescent IRDCs:

HCNH+, H2CS, SO, SO2(5), CCS, HC3N, CH2CO, CH3CCH, CH3OCH3(2), CH3OH(4), CF+(2), c-C3H2, C4H(2), l-C3H2(2), c-C3HD(2)

Detected in active IRDCs and HMPOs:

HCNH+, H2S, H2CS, SO, SO2, CCS, OCS, HC3N, HC5N, CH2CO, CH3OH, CH3CHO, CH3OCH3, CH3OCHO, HNCO, CH3CCH, CH3CN, c-C3H2, t-CH3CH2OH, NH2CHO, CH2CN, CH2NH, DC3N, CF+(4)

High-sensitivity multi-line study II

Detected in quiescent IRDCs:

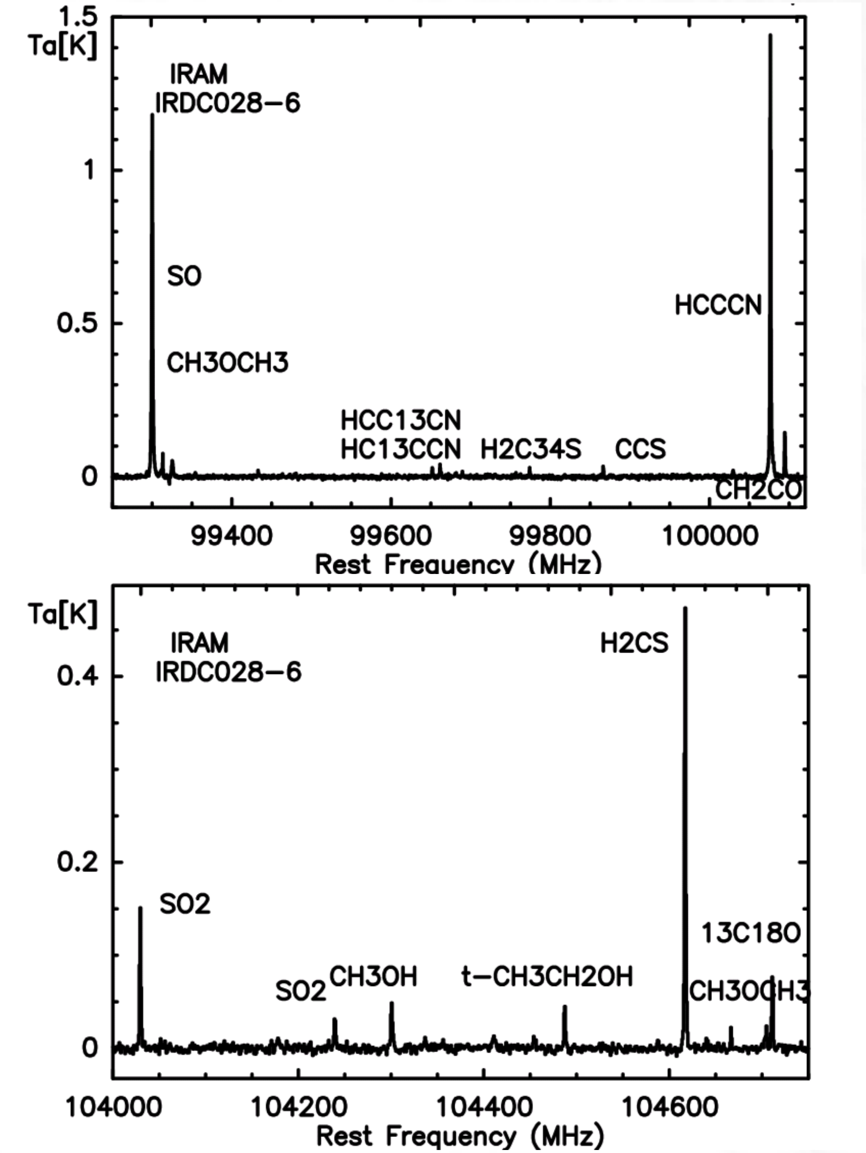
HCNH+, **H2CS**, SO, **SO2**(5), CCS, HC3N, **CH2CO**, CH3CCH, CH3OCH3(2), CH3OH(4), **CF+**(2), c-C3H2, **C4H**(2), **l-C3H2**(2), **c-C3HD**(2)

Detected in active IRDCs and HMPOs:

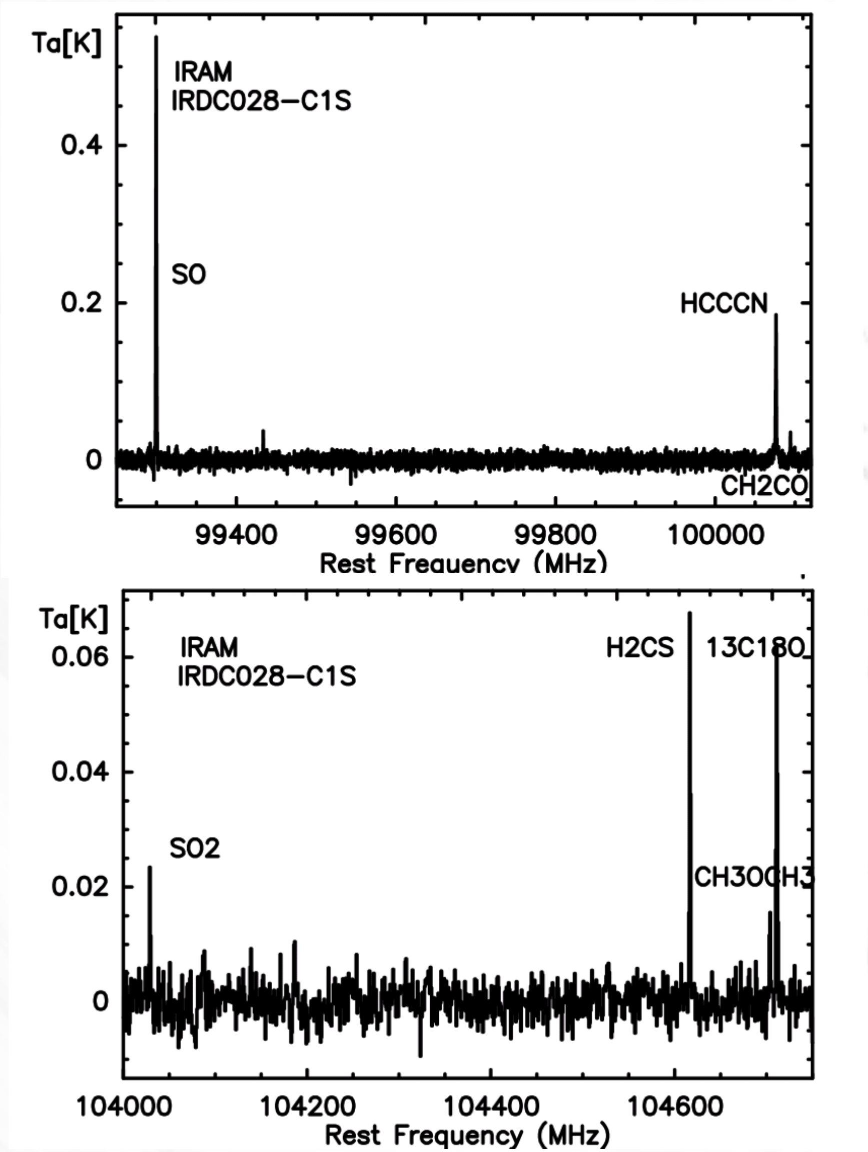
HCNH+, H2S, H2CS, SO, SO2, CCS, OCS, HC3N, HC5N, CH2CO, CH3OH, CH3CHO, CH3OCH3, CH3OCHO, HNCO, CH3CCH, CH3CN, c-C3H2, t-CH3CH2OH, NH2CHO, CH2CN, CH2NH, DC3N, CF+(4)

High-sensitivity multi-line study III

Active IRDC: G28.34 P2



Quiescent IRDC: G28.34 C1



Chemical modelling: G28.34-C1 (quiescent)

Chemical code „ALCHEMIC" (Semenov et al. 2010)
1-D model (density and temperature structure)

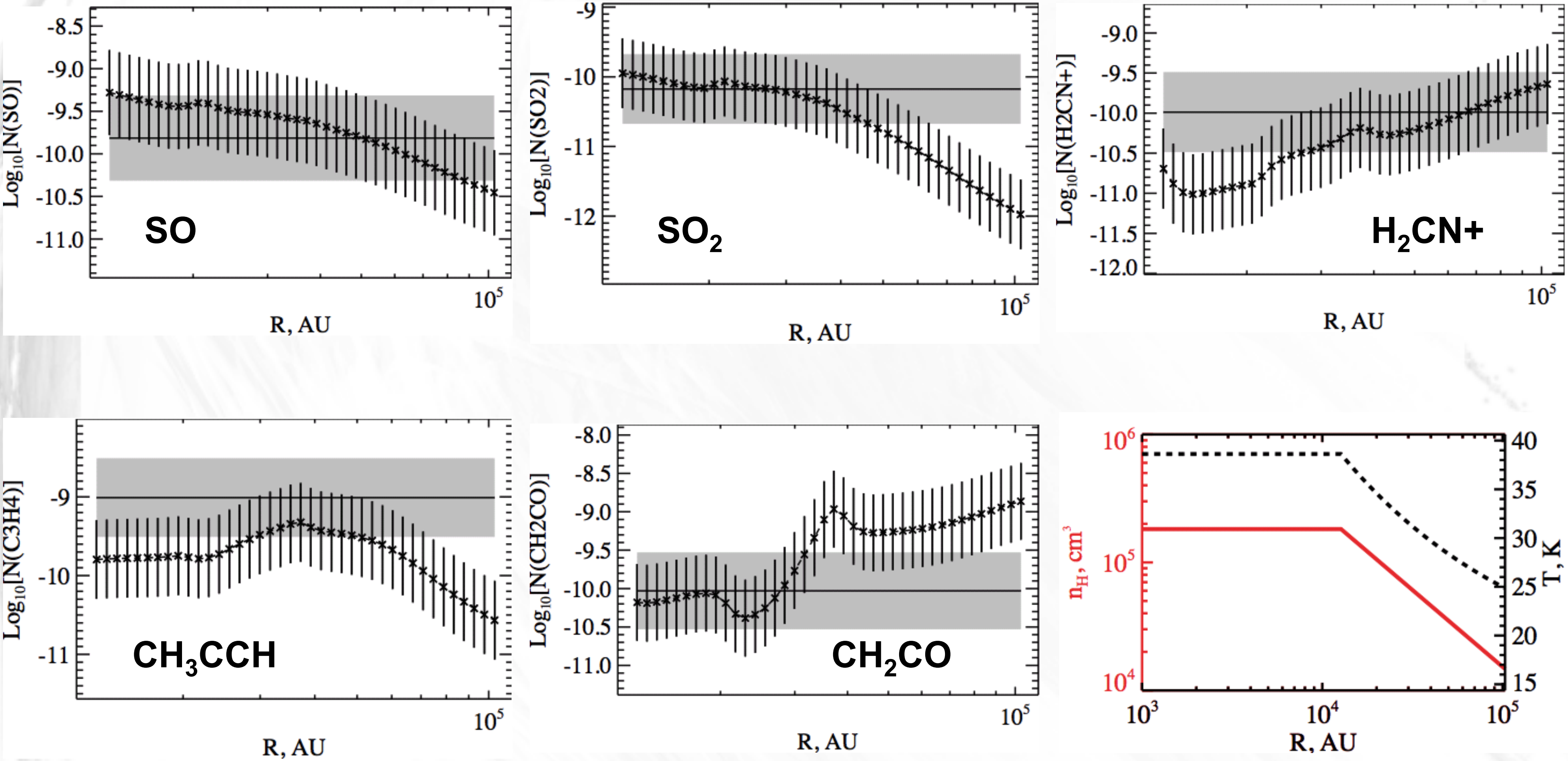
Parameters of the best fit model:

Out of 21 species, 2 are not reproduced: CCS,H2CS
Agreement: 83%   Age ~60,000 yr

Modeling results:

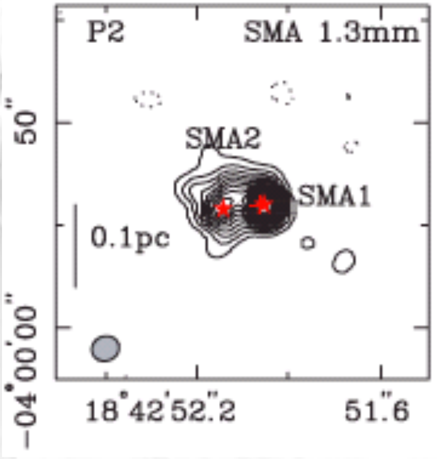
- With 21 molecules, a 0-D model is not sufficient anymore even for a quiescent IRDC.
- Elevated temperature at the inner radius might indicate beginning of star formation. Hence, IRDC028-C1S might be in a more evolved phase than a starless core.

Chemical modelling: G28.34-C1 (quiescent)

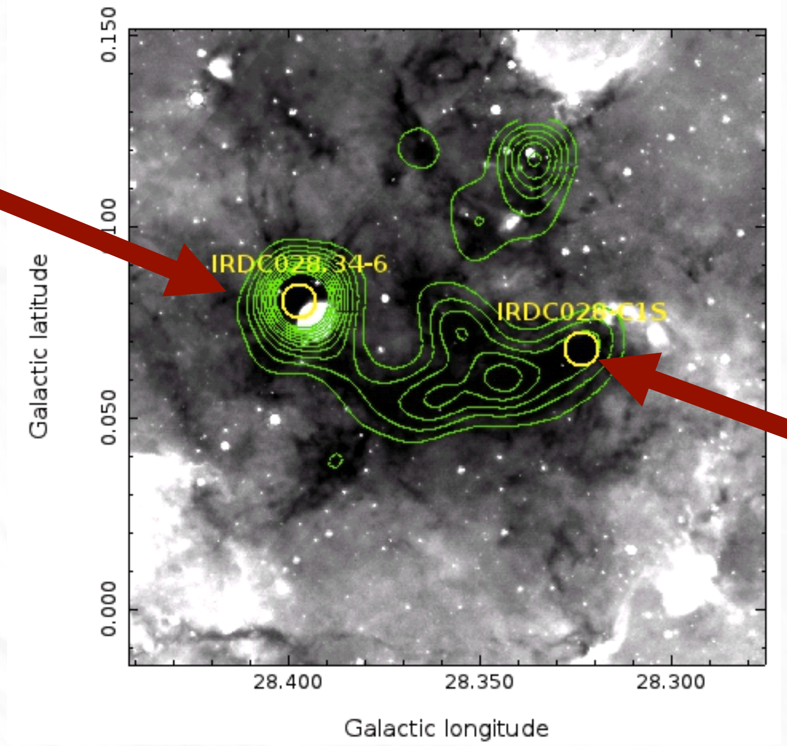


On all panels the grey area corresponds to observed value +/- error margin. Bottom right panel presents temperature and density profiles.

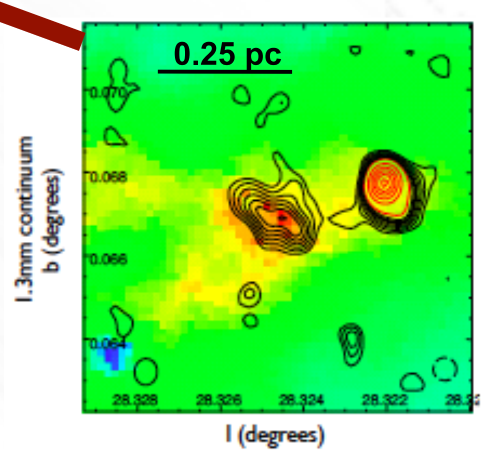
Interferometers peek into the inner spatial structure of the clumps



SMA (Zhang et al. 2009)



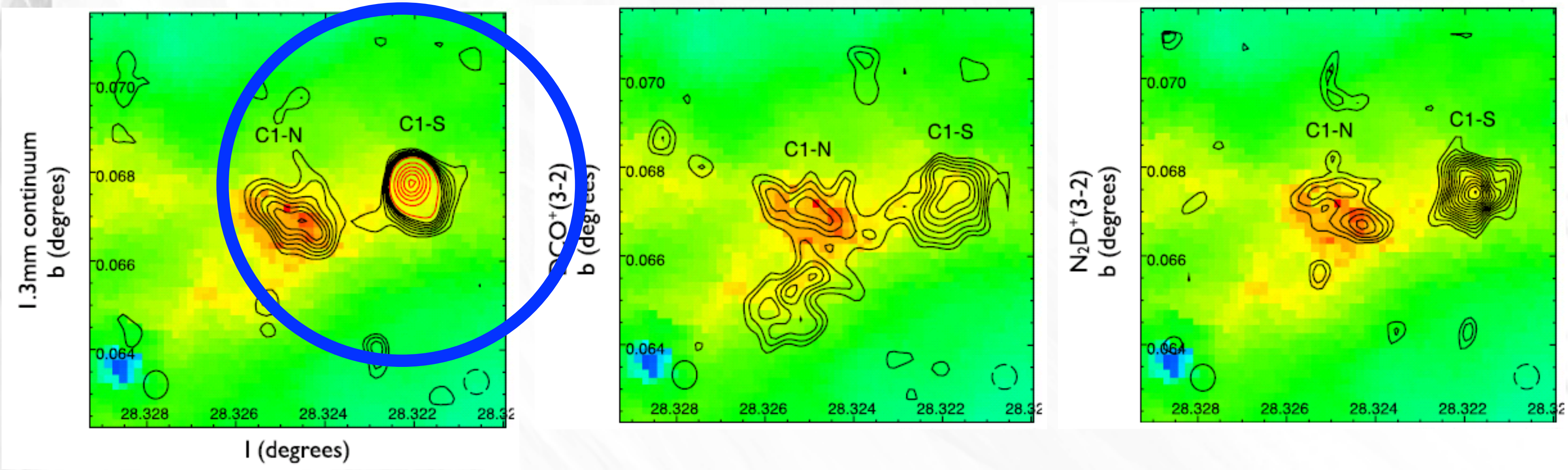
ALMA (Tan et al. 2013)



The fine structure of the G28.34 IRDC cloud complex

Tan et al. 2013

ALMA Cycle-0 study toward one of the supposedly quiescent IRDC clumps: G28.34-C1, mainly using deuterated species



FOV shown is around 34” … our IRAM high-sensitivity observations with HPBW~27” (16”) are centred on C1-S

Summary

Chemistry in IRDCs is far from boring!

→ beside the typical high-abundant dense-gas tracers, much more can be found
In particular: **complex organic molecules**

→ inclusion of such tracers in chemical evolution codes can constrain better the chemical and thermal history of the IRDCs

→ multi-line studies also important to trace different physical conditions in an IRDC and hence to constrain the chemico-spatial structure

ALMA : the perfect tool

→ ALMA gives access to low-excitation transitions of complex molecules in the bands (1+2+)3 – 6

→ ALMA is incredibly sensitive: a prerequisite to detect rarer molecules in the typical kpc distances of most IRDCs

→ ALMA brings sufficient spatial resolution to distinguish different constituents (massive pre-stellar cores, deeply embedded protostars and hot cores) on a core scale (0.1 pc) → lift the degeneracy of the observational data which limits the complexity of chemical modelling