Observational Facilities in the Time of LLAMA

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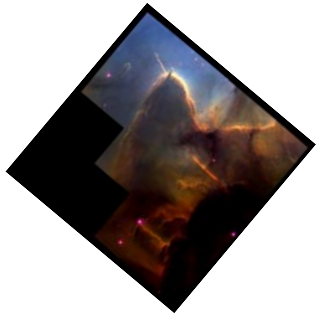
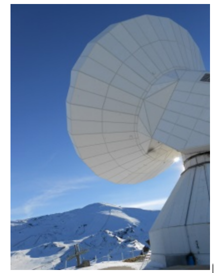
The Method of Astrochemistry

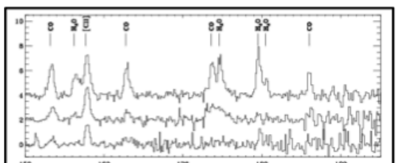




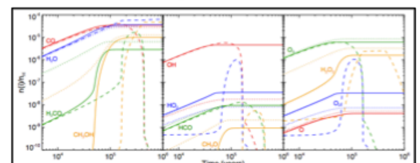
Observers should work in close contact with modellers and lab. experiments

Lab. Spectroscopy
***ab initio* Calculations**

Line catalog



1. OBSERVATIONS



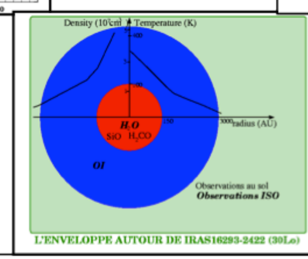
3. CHEMICAL MODEL

Reaction rates
Gas and Grain Chemistry

Theory
Lab Experiment

Molecular Collisions

COLLISIONAL COEFFICIENTS



2. DERIVED CHEMICAL COMPOSITION

Radiative Transfer

New Species | **Physical Conditions** | **Abundances** | **ϕ–χ Processes**

Current Observational Facilities

Herschel

HIFI : 490 – 1900 GHz: 10”- 40”
PACS : 200 – 58 μm: 6” – 14”

CHESS (Ceccarelli et al)

SOFIA

CO J_{up}=11 - 22   6” – 20”
C+ 158, OI 63μm

IRAM 30m

7” – 30”

70 - 360 GHz

ASAI (Lefloch, Bachiller, et al)

NOEMA

0.1” – 4”
70-360 GHz

CALYPSO (Andre et al)
SOLIS (Ceccarelli, Caselli et al.)

ALMA

EmoCA (Belloche et al.)
PILS (Jorgensen et al.)

+ APEX, ASTE,…

Preparing for LLAMA

Complementarity

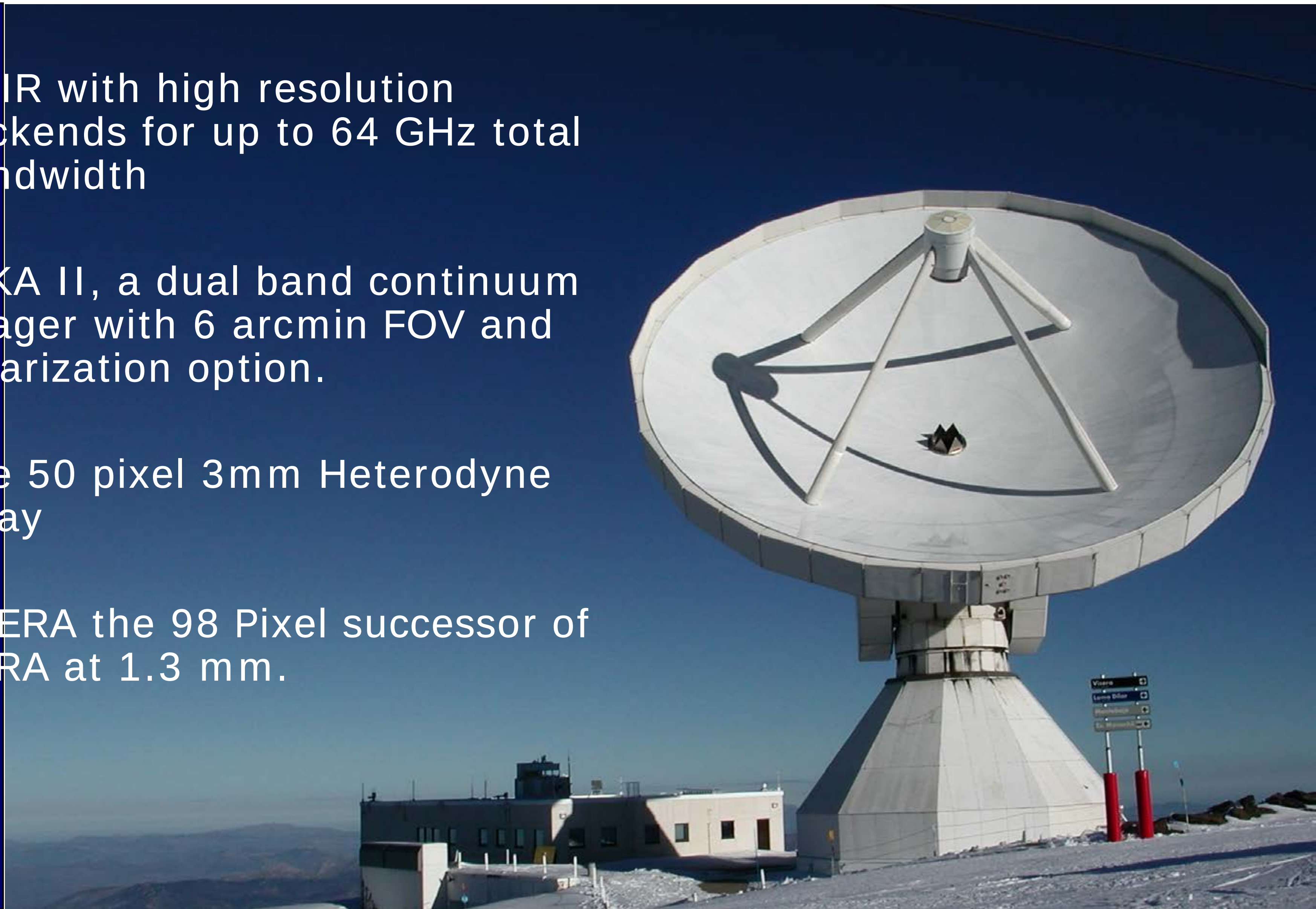
→ **Angular resolution:**
IRAM 30m : telescope beam at 3mm ≈ 1mm with LLAMA
Multi-scale approach : avoid to jump from 30" to 0.3" …

→ **Frequency: Multi-transition/Multi-wavelength approach are now very common**
LLAMA will be unique (or almost) in the submm domain
mm domain : H_2O line maser (183 GHz)

0.8mm band : Is IRAM 30m OK ?
Main-beam efficiency is low (35%); beware of the error lobe (Orion, Gal. Center)

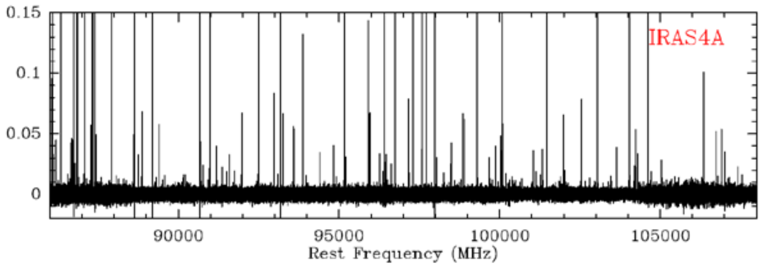
The Future Evolution of the IRAM 30m Telescope

(K. Schuster)



- EMIR with high resolution backends for up to 64 GHz total bandwidth
- NIKA II, a dual band continuum imager with 6 arcmin FOV and polarization option.
- The 50 pixel 3mm Heterodyne array
- SHERA the 98 Pixel successor of HERA at 1.3 mm.

Line Surveys



Line surveys are cheap

Unbiased Spectral Line Surveys

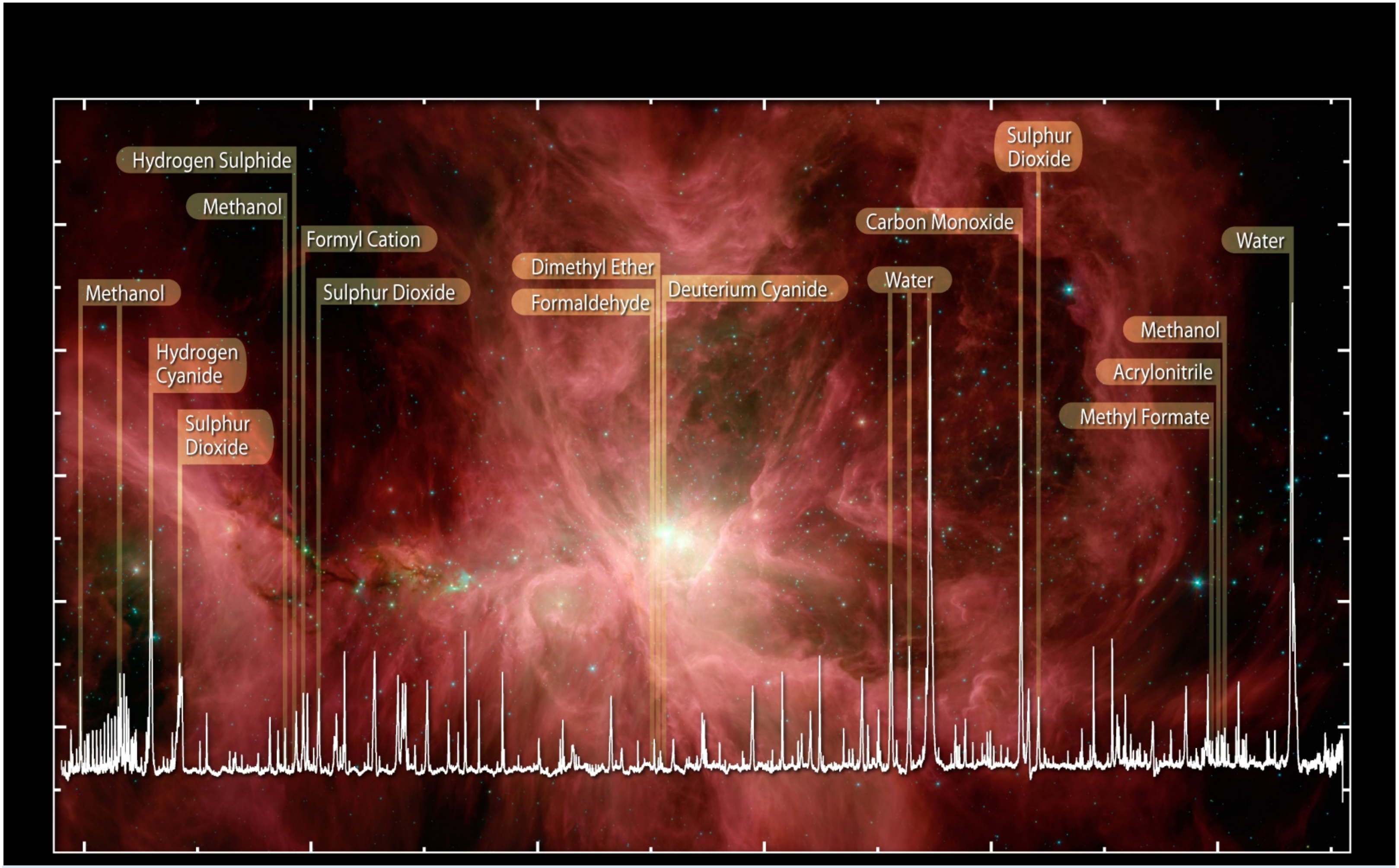
- A large number of lines: large frequency coverage to probe a wide range of A_{ij}, E_{up}
- No (important) missing line(s) : unbiased
- Full chemical census : parent, daughter molecules, radicals, etc…

Secure identification requires

- Good knowledge of the source structure (gradients (X, T, n, v) should be consistent) Emission may be extended (filtered ?)… → Mapping
- No conflict with other molecules : model emission of various molecules (consistent relative intensities and line blending)

Serendipitous discoveries: CH_3COOCH_3 (Tercero et al. 2013), CH_3CHCH_2 (Marcelino et al. 2007), …

The Ultimate Nightmare



The IRAM line survey of Orion Irc2 (Cernicharo et al., Favre et al.)

2006: 15137 lines identified : 8000 “U”nknown

2013 : Collaboration with spectroscopy groups (U. Lille, IPSL,CSIC) → 4000 U

^{13}C, ^{15}N isotopologues from CH_3CH_2CN , CH_2CHCN

Line Identification

Public Catalogs : CDMS, JPL + Spectroscopic collab.

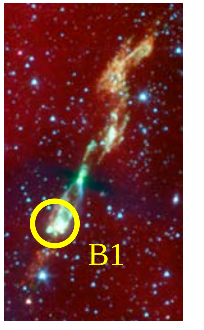
No. 1, 1997 SHOCK CHEMISTRY IN L1157 L95

TABLE 1

L1157: Column Densities, Abundances, and Enhancement Factors

Molecule (Transitions)[a]	Position (0, 0)		Position B1 (20″, −60″)			Position B2 (35″, −95″)		
	N (cm^{-2})	$X = N/N_{H_2}$	N (cm^{-2})	$X = N/N_{H_2}$	$f = X/X_{(0,0)}$	N (cm^{-2})	$X = N/N_{H_2}$	$f = X/X_{(0,0)}$
CO (1–0, 2–1)	3.0 (16)[b]	1.0 (−4)[c]	1.4 (17)	1.0 (−4)[c]	…	5.2 (16)	1.0 (−4)[c]	…
^{13}CO (1–0, 2–1)	5.2 (15)	1.1 (−6)[c]	1.4 (16)	1.1 (−6)[c]	…	1.2 (16)	1.1 (−6)[c]	…
C^{18}O (1–0)	1.3 (15)	2.8 (−7)[c]	6.7 (14)	2.8 (−7)[c]	…	∼5 (14)	2.8 (−7)[c]	…
CS (2–1, 3–2, 5–4)	1.2 (13)	2.8 (−9)	2.7 (14)	1.9 (−7)	70	1.0 (14)	1.9 (−7)	66
C^{34}S (2–1, 3–2, 5–4)	∼7 (11)	∼2 (−10)	1.8 (12)	1.3 (−8)	∼65	0.3–1.3 (13)	0.5–2.5(−8)	50–100
C_2H (1–0)	1.3 (13)	3.0 (−9)	1.7 (14)	1.2 (−7)	40	…	…	…
C_3H_2 (2–1)	1.3 (12)	2.9 (−10)	…	…	…	…	…	…
N_2H^+ (1–0)	1.7 (13)	3.8 (−9)	…	…	…	…	…	…
H_2CO (2–1, 3–2)	2–3 (13)	4–6 (−9)	3–8 (14)	2–6 (−7)	60–90	1–3(14)	2–5(−7)	60–80
CH_3OH (2–1, 3–2, 5–4) A$^+$	2.1 (14)	4.5 (−8)	0.5–2.6 (15)	0.4–1.9 (−5)	300–400	1.2 (16)	2.2 (−5)	500
HCO^+ (1–0)	6.6 (12)	1.5 (−9)	7.3 (13)	5.2 (−8)	36	1.6 (13)	3.0 (−8)	20
H^{13}CO$^+$ (1–0)	1.6 (12)	3.5 (−10)	…	…	…	…	…	…
DCO^+ (2–1)	1.3 (12)	2.8 (−10)	…	…	…	…	…	…
SiO (3–2)	…	…	8.4 (13)	6.0 (−8)	>10^5	3.9 (13)	7.4 (−8)	>10^5
CN (1–0, 2–1)	2.2 (13)	4.8 (−9)	1–4 (14)	0.6–2.6 (−7)	15–45	∼3(13)	∼5 (−8)	∼10
HCN (1–0)	1.6 (13)	3.6 (−9)	4.6 (14)	3.3 (−7)	90	2.9 (14)	5.5 (−7)	150
DCN (2–1)	2.8 (11)	6.2 (−11)	…	…	…	…	…	…
HNC (1–0)	7.2 (12)	1.6 (−9)	4.4 (13)	3.1 (−8)	20	2.5 (13)	4.8 (−8)	30
HC_3N (10–9, 15–14, 24–23)	2.1 (12)	4.6 (−10)	1.4 (13)	1.0 (−8)	25	0.6–1.2 (13)	1–2 (−8)	50
CH_3CN (6–5, 8–7, 12–11)	…	…	…	…	…	…	…	…
$HCNH^+$ (3–2)	…	…	∼8 (13)	∼6 (−8)	…	…	…	…
SO (4–3, 6–5)	∼2(13)	∼5(−9)	3–5 (14)	2–3 (−7)	50–70	1–3 (14)	2–5 (−7)	60–100

Bachiller & Perez-Gutierrez (1997)



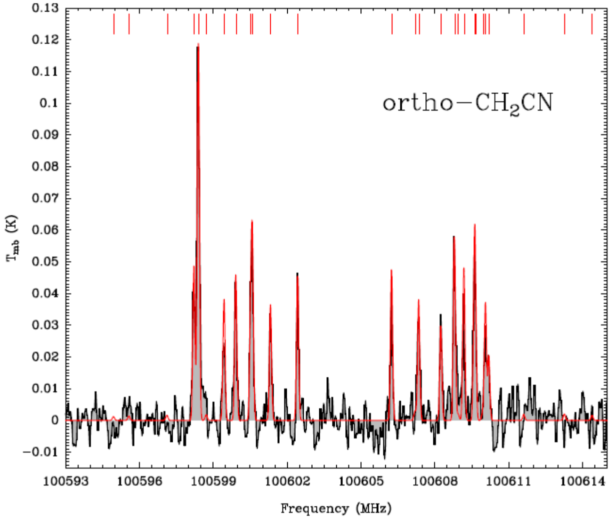
$HCNH^+$ (3-2) : 148221.46371 MHz

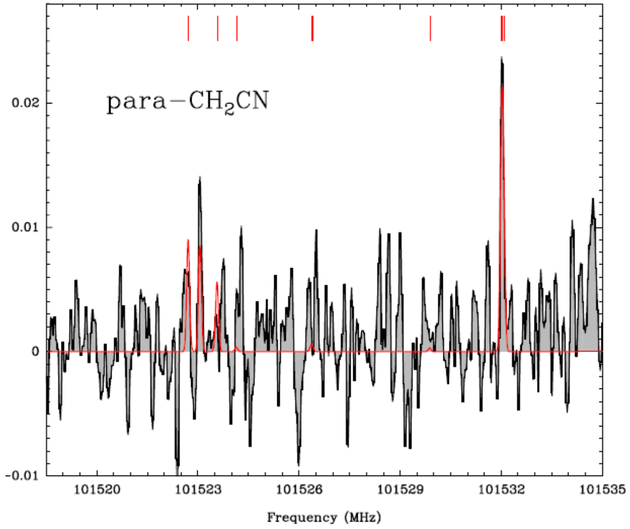
Blended with NH_2CHO $7_{2\,6} - 6_{2\,5}$ 148223.14338 MHz !

One line is not sufficient to identify a species…

Line Identification

Accurate Spectroscopic predictions are needed





Vastel , Yamamoto, Lefloch, Bachiller (2015)

Full hyperfine transition series of CH_2CN computed identified in L1544 for both o- and p- species.

LTE analysis (CASSIS):
Tex= 10 – 12K
X(CH_2CN) $\simeq$ 10^{-12} to 10^{-11}
OPR = 1

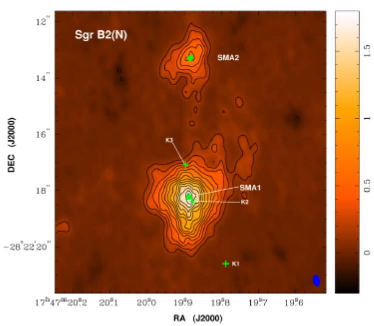
Line Identification

Accurate spectroscopic predictions are needed : NO^+ in Barnard 1 (Cernicharo 2012)

Line spectroscopy can be tricky: **Observations can help**

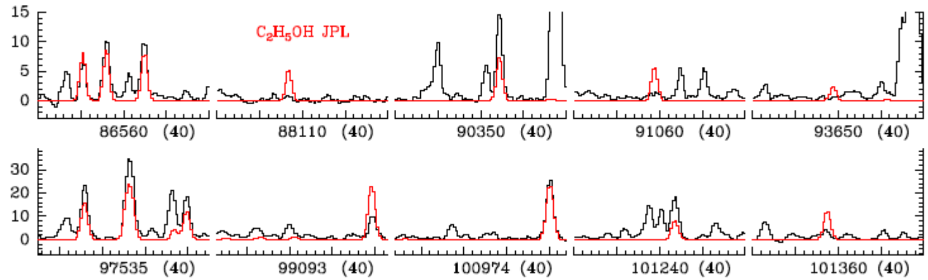
EmoCA : Survey of SgrB2(N) with ALMA (PI: Belloche et al.)

LTE Model of Ethanol with official JPL entry (Belloche, priv. comm)

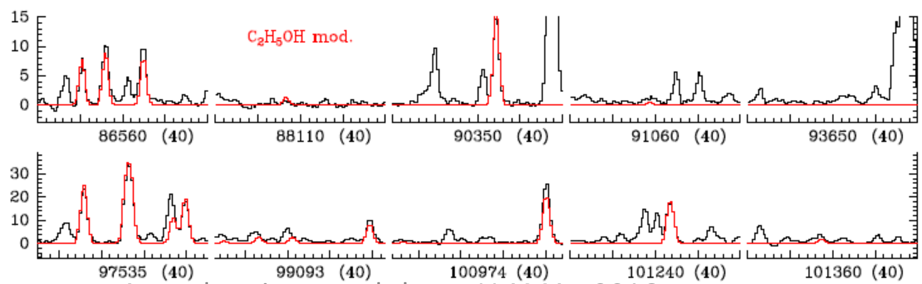


Sgr B2(N) at 850 μm

(SMA, Qin+ 2011)

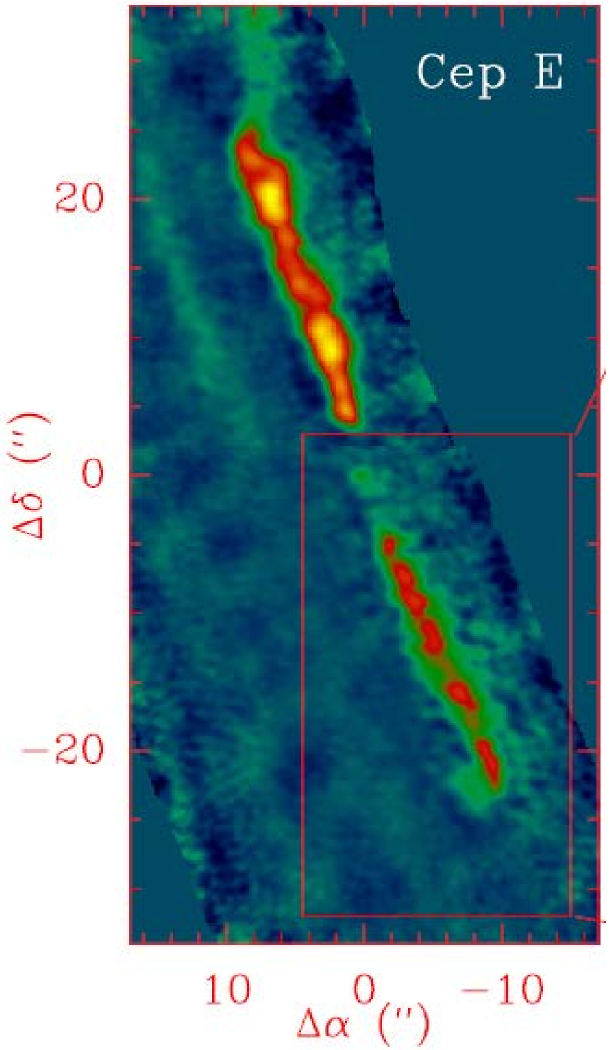


New predictions with revised parity for gauche a-dipole components (Muller, priv. comm)



Multi-transition approach

CO J=2-1 @ PdBI 1” res.



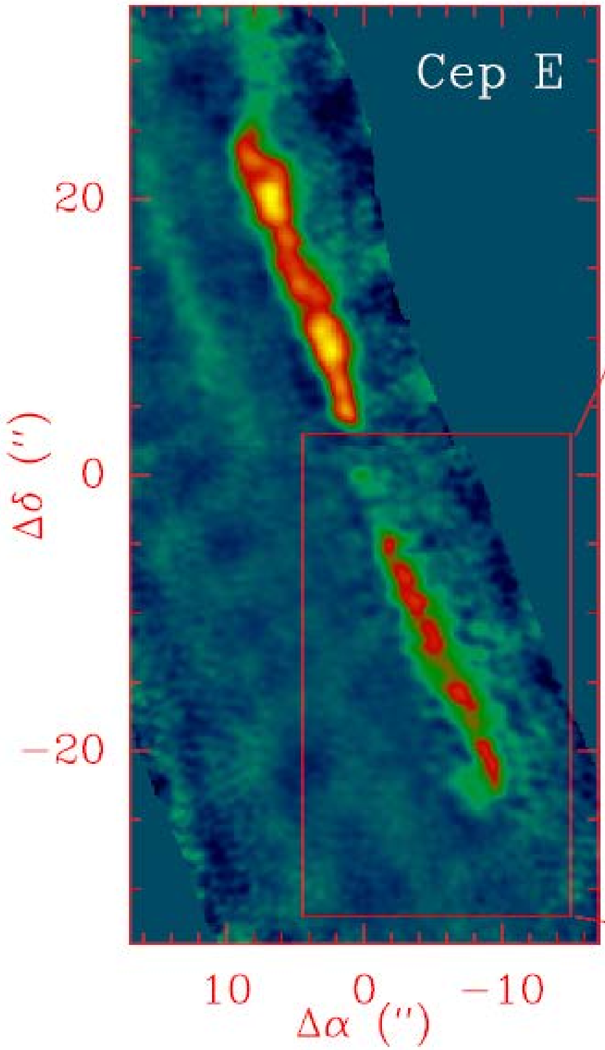
What are the physical conditions in outflows and jets ?

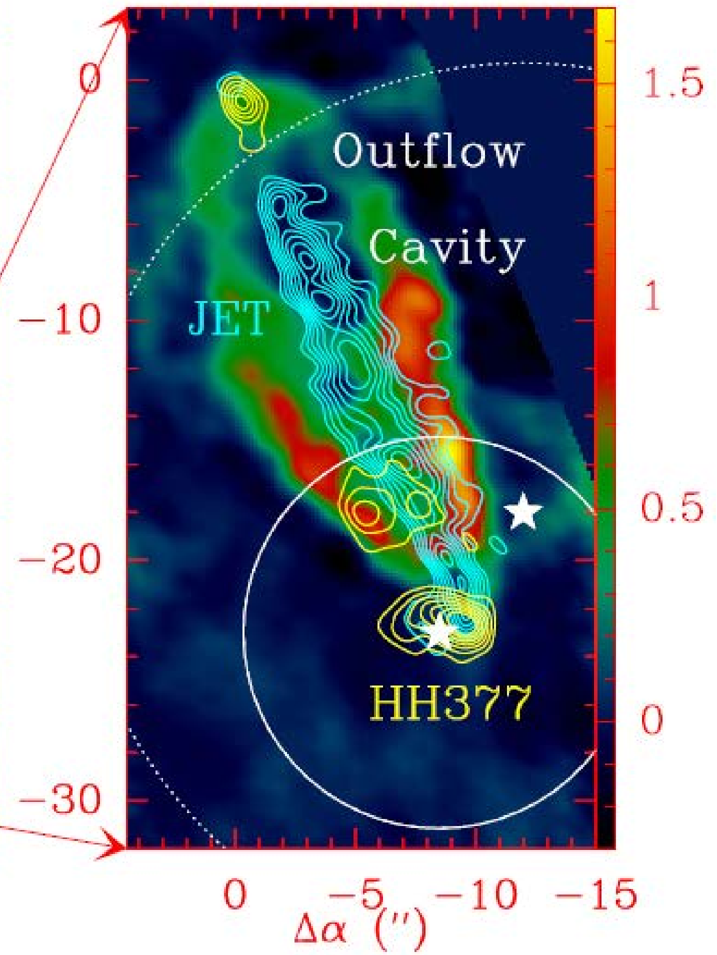
→ Feedback into the cloud
→ Probe the jet launching region at 10 AU scale

Lefloch et al. (2015)

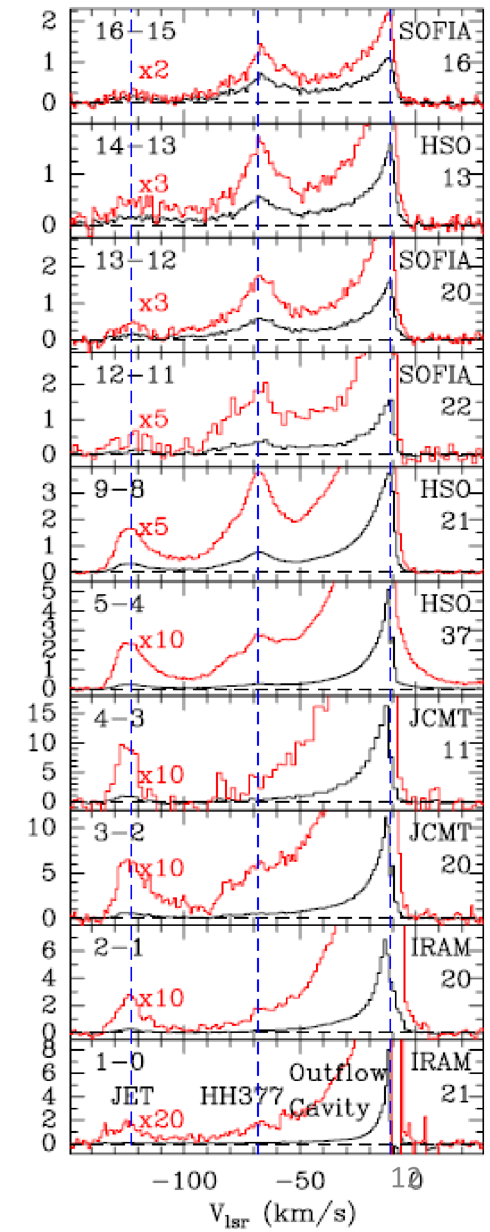
Multi-transition approach

CO J=2-1 @ PdBI 1” res.



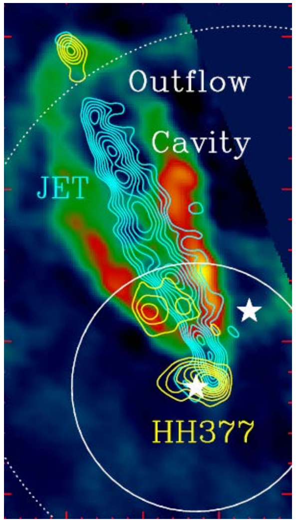


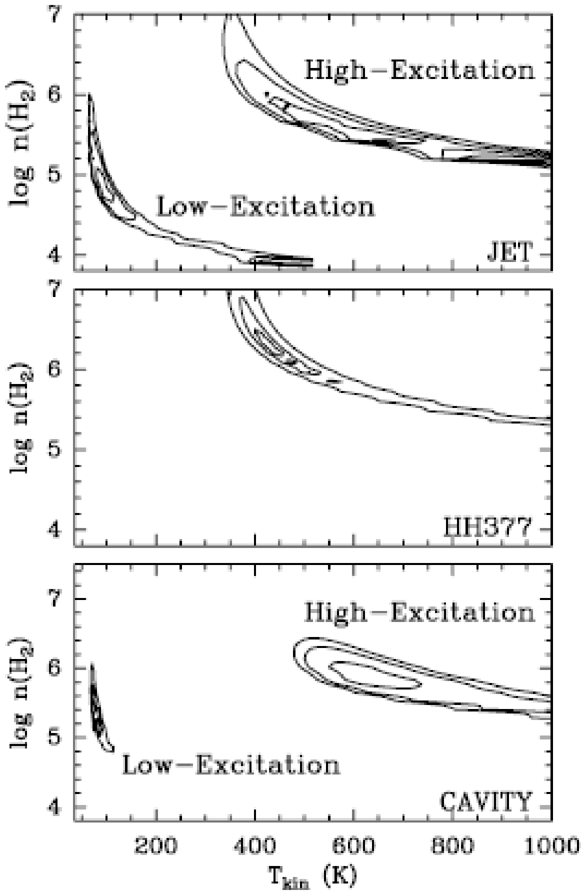
CO



IRAM 30m + JCMT + Herschel + SOFIA

Multi-transition approach

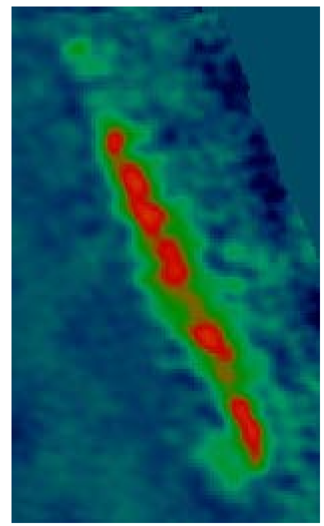


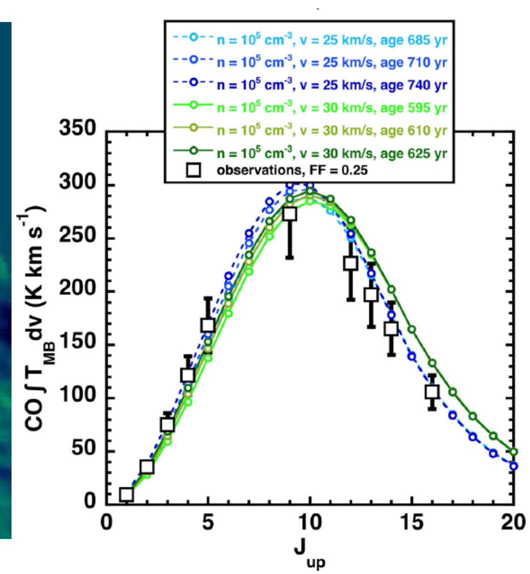


Radiative Transfer Modelling

(n,T, N) derived from J=1-16 line analysis
Spatial Information needed : maps !

Comparison with Paris-Durham shock model predictions

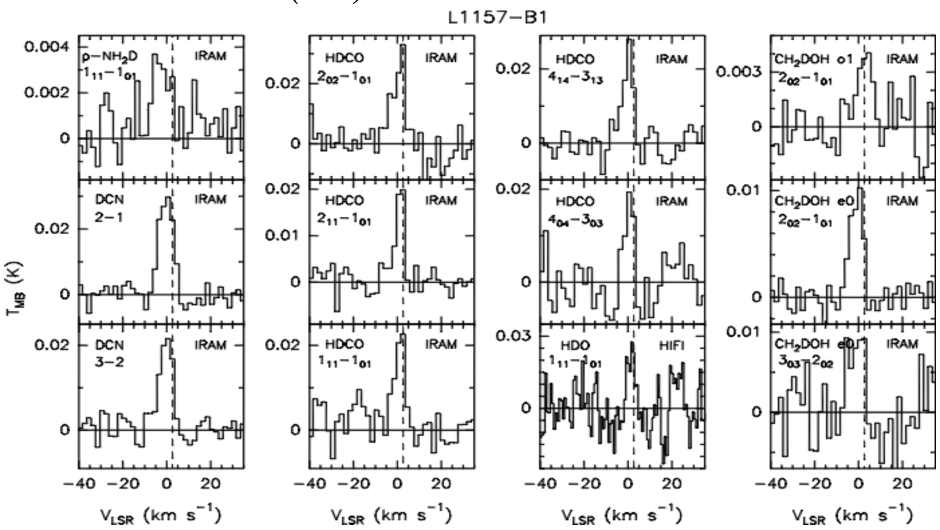


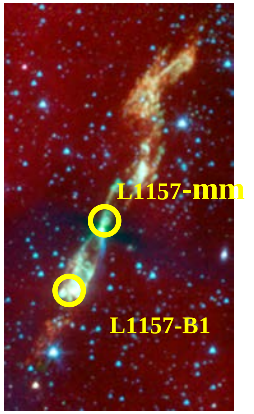


Two components in the jet :
Internal shocks revealed ?

Deuteration at 20” scale

Codella et al. (2012)



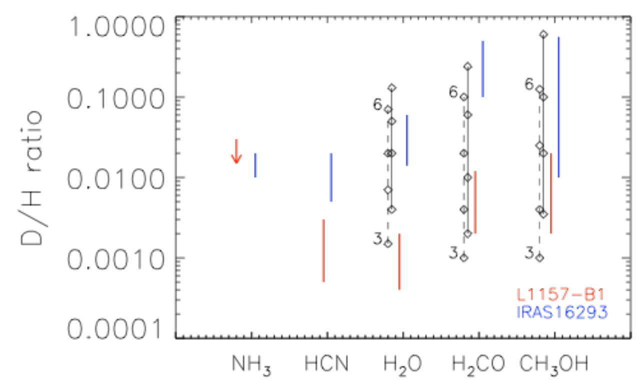


CH_2DOH, HDCO, HDCS, NH_2D, DCN, HDO

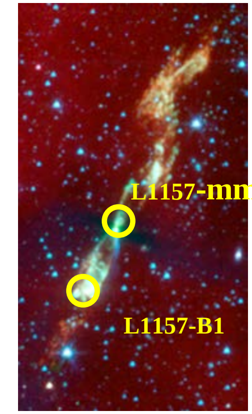
Deep Integration : rms= 1mK

Shock age : 2000-4000yr

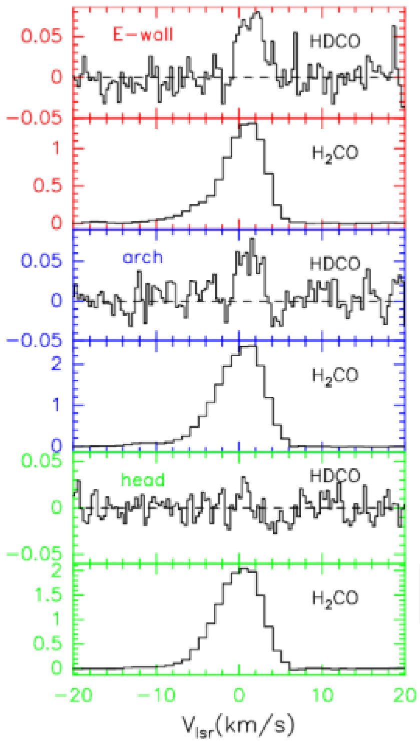
→ A record of ice mantle formation

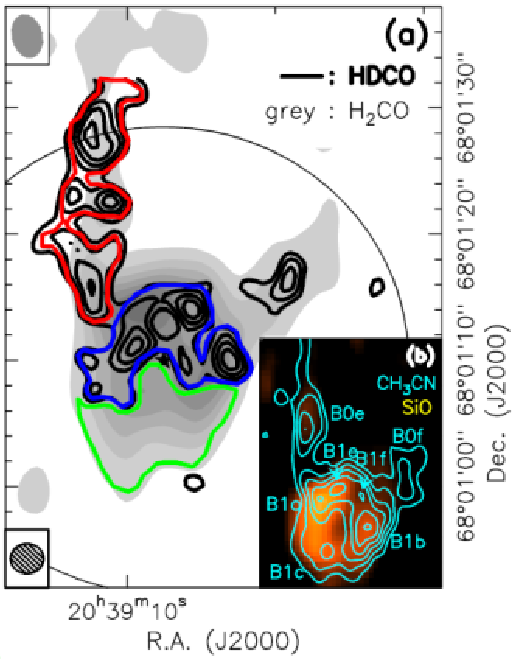


Deuteration at 3’’ scale

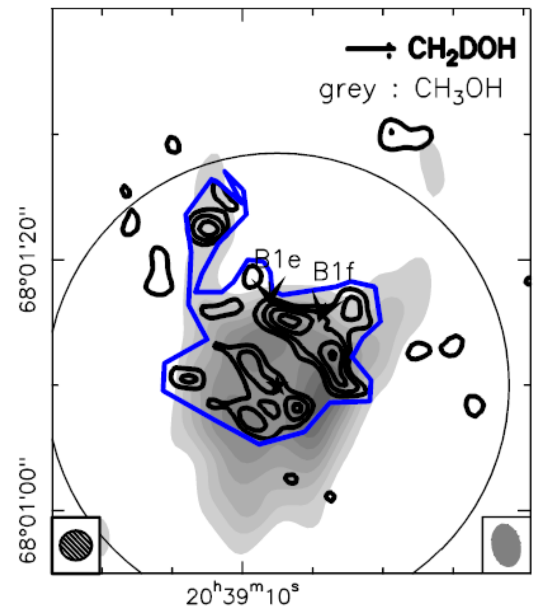


Fontani et al. (2015)





Deuteration in the L1157-B1 bowshock



HDCO is associated with shocks in the cavity walls and the arch

Extended H_2CO: gas phase formation

D-fractionation : 0.04 (arch) to 0.15 (walls)
D-fractionation on mantle grains ~ 0.11

NOEMA

NOrthern Extended Millimeter Array of IRAM

Northern Hemisphere Sources : Dec > -20

NOEMA: Currently 8 antennas – 15m diameter
70 to 373 GHz (**ALMA: 30 to 900 GHz)**
Angular resolution: 4” -- 0.2”
Currently : one band of 3.7 GHz

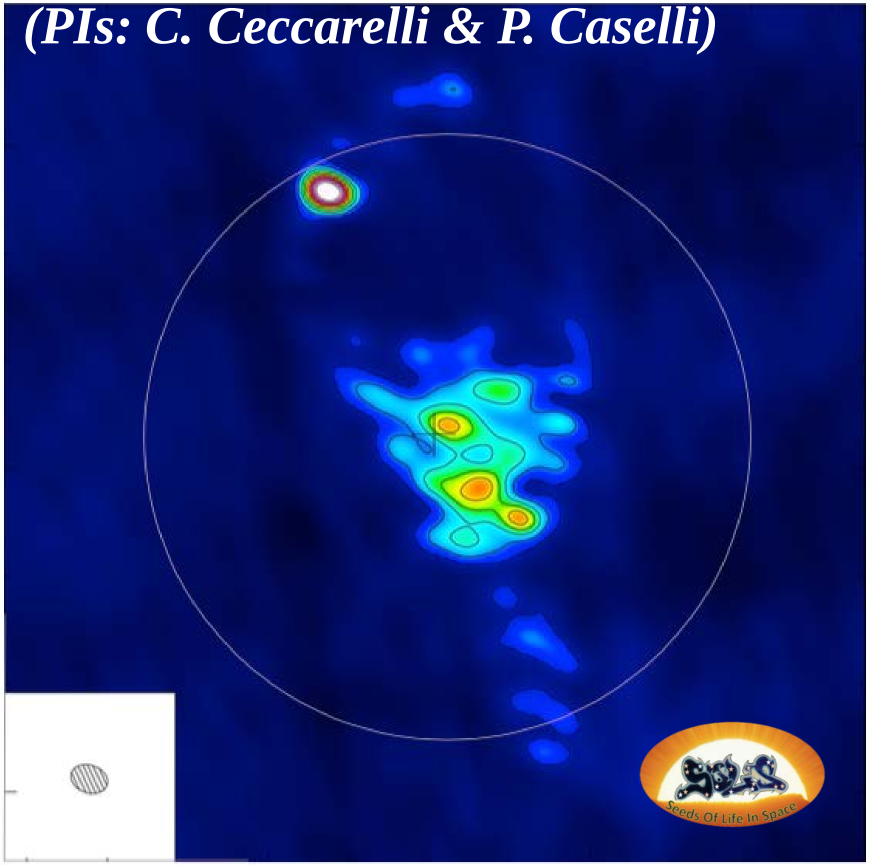
Ultimate goal : 12 antennas (15m diam) : 40% collecting area of ALMA
angular resolution down to **0.1” (ALMA : 0.01”)**

Survey mode : 2SB receivers - 16GHz bandwidth @ 256 kHz res.
→ Perfect machine for line surveys

NOEMA

NOEMA with 8 antennas

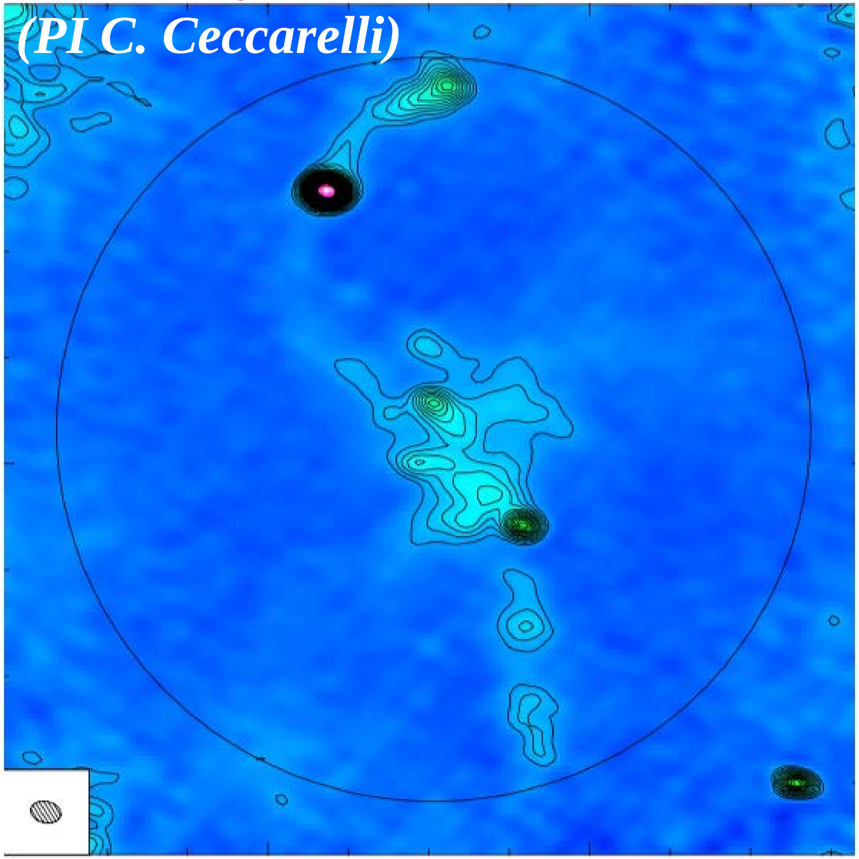
(PIs: C. Ceccarelli & P. Caselli)



SOLIS : 0.10 mJy/beam
(3.5"x2.7")

ALMA-Cycle 3

(PI C. Ceccarelli)



ALMA : 0.15 mJy/beam
(2.9"x2.0")

Seeds Of Life In Space (SOLIS)

Ongoing NOEMA Large Program
375 hrs PIs (C. Ceccarelli & P. Caselli)

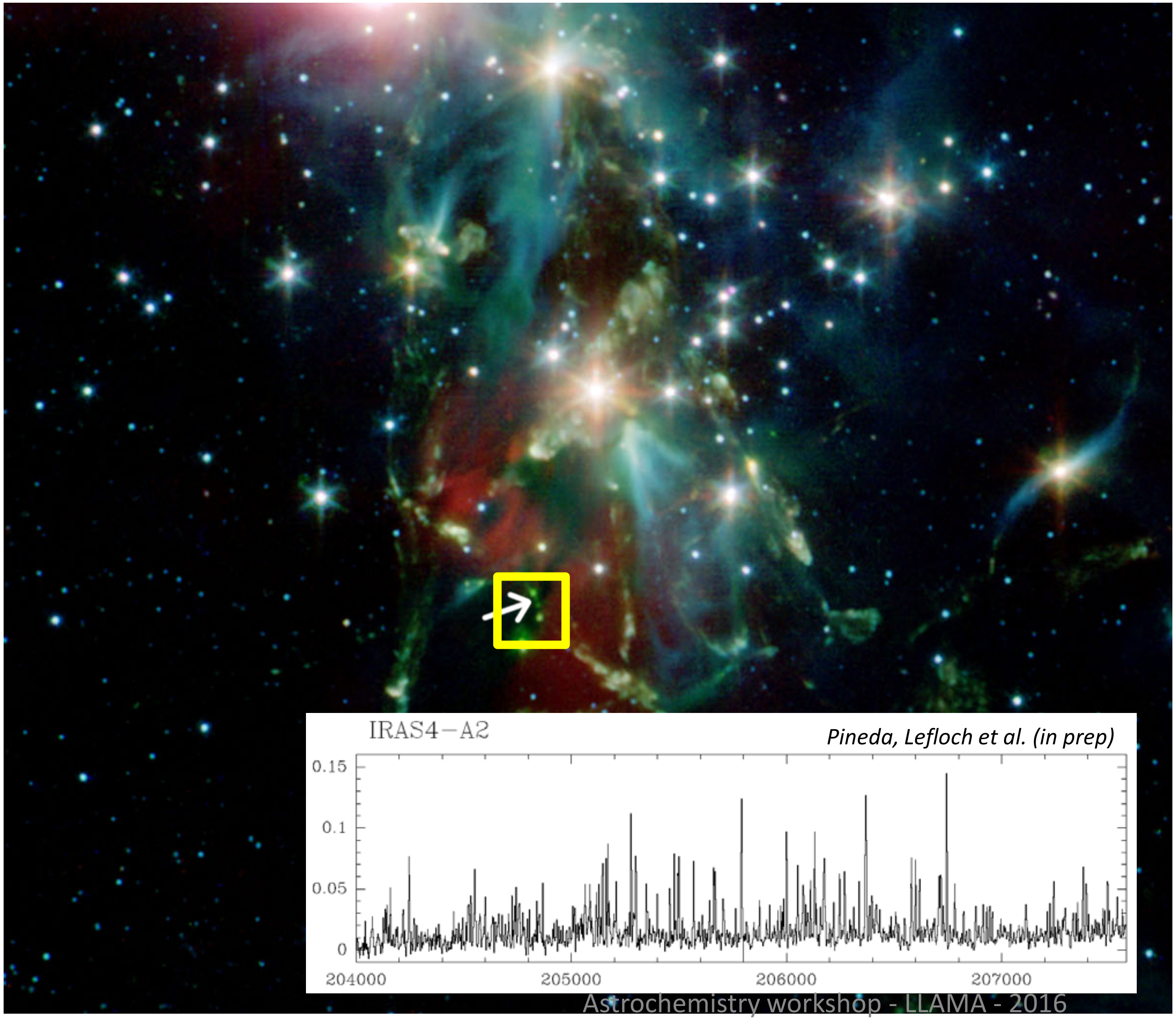
IPAG (Fr), IRAP (Fr), MPE (Ger), Arcetri (It), OAN (Sp) http://solis.osug.fr

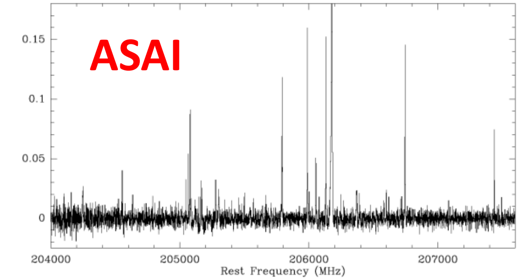
Aim: *To understand how, when and where complex organic molecules form during the early stages of solar-type stars formation.*

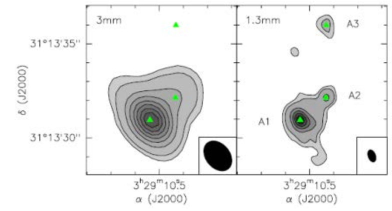
Systematic survey of a set of key COMs (and many other molecules) toward a sample of low- and intermediate mass objects

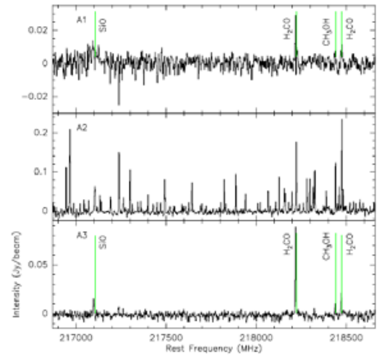
- L1544
- L1521F
- IRAS 4A
- Cep E
- SVS 13A
- OMC2-FIR4
- L1157 B1

Chemical differentiation in IRAS4A





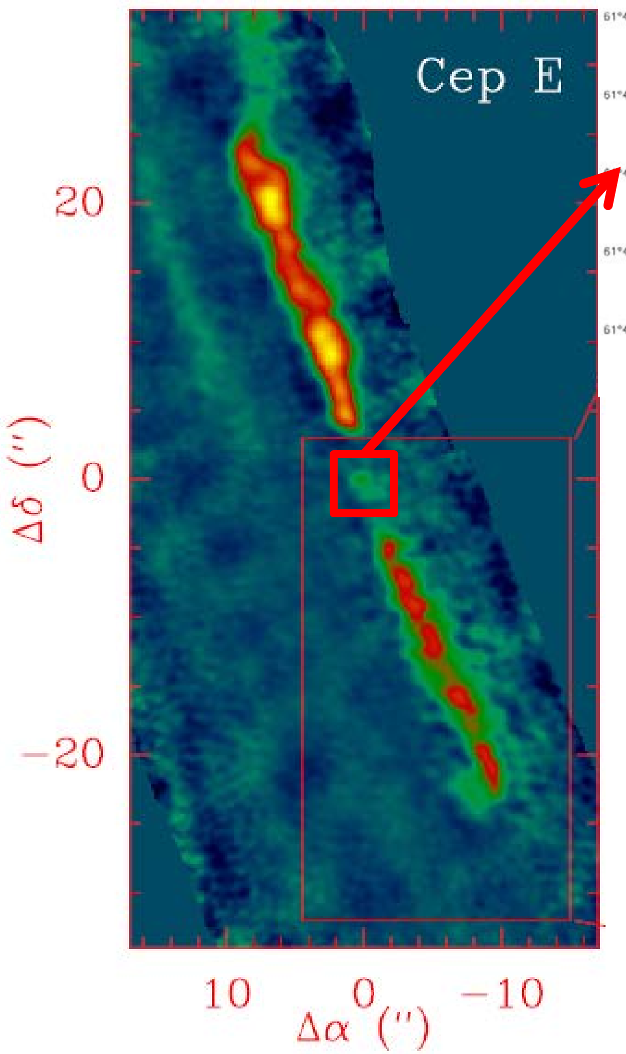


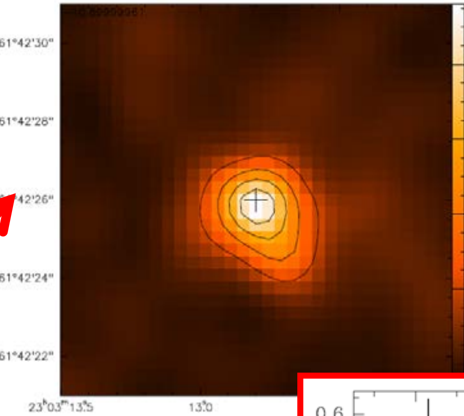


Santangelo et al. (2015)

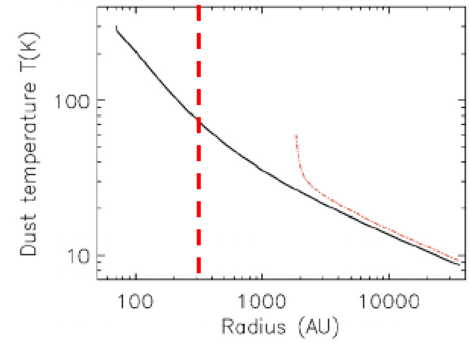
Sensitivity
6mJy / beam in 1 km/s

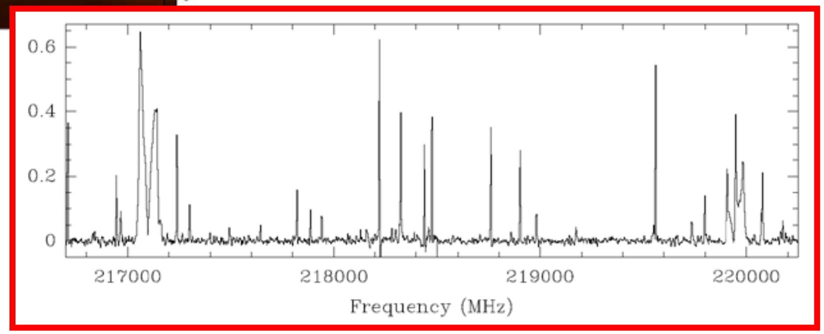
The Intermediate-Mass Protostar CepE-mm



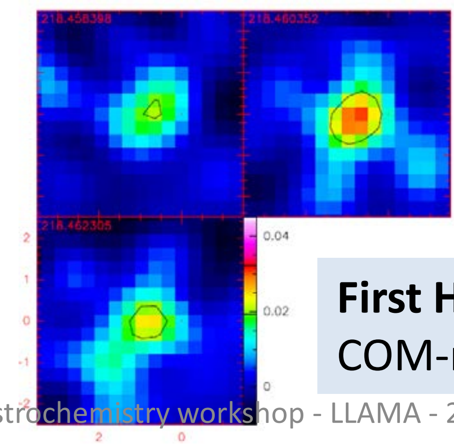


Crimier et al. (2009)





Ospina-Zamudio et al. (2016)



$NH_2CHO\ 10_{1\,9} - 9_{1\,8}$

First Hot Corino around an IM protostar

COM-rich line spectrum *resolved:* 0.8"-1"

Conclusions

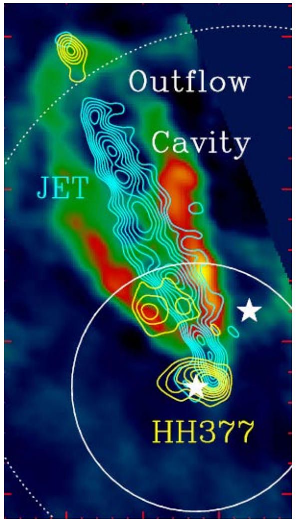
Astrochemistry is a multidisciplinary field : different expertise (and experts) are needed

Multi-wavelength, multi-transition approach : both chemical and physical conditions must be determined.
→ Spatial information (mapping) is needed
→ Several spectral bands (instruments ?) are required

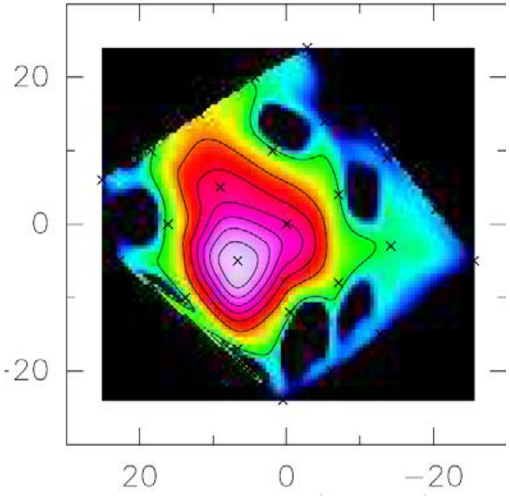
A good knowledge of the Source structure for RT and chemical modelling.

Close collaboration with spectroscopists and laboratory experiments is needed

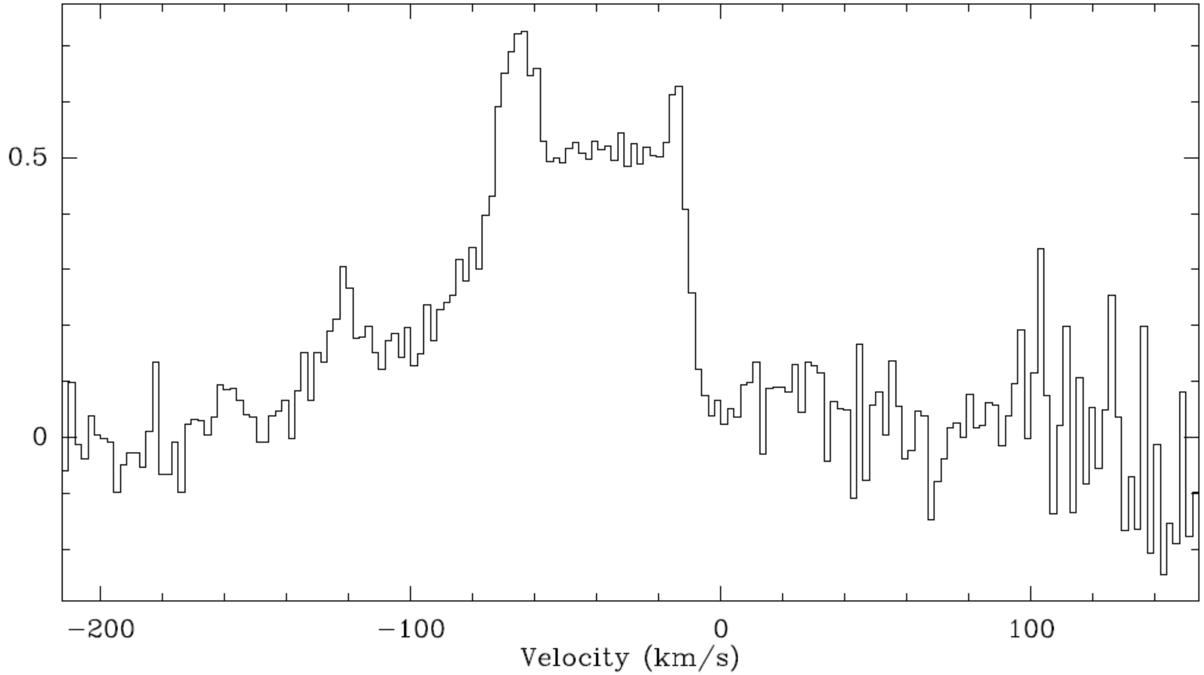
As a First Step



PACS: OI 63 μm

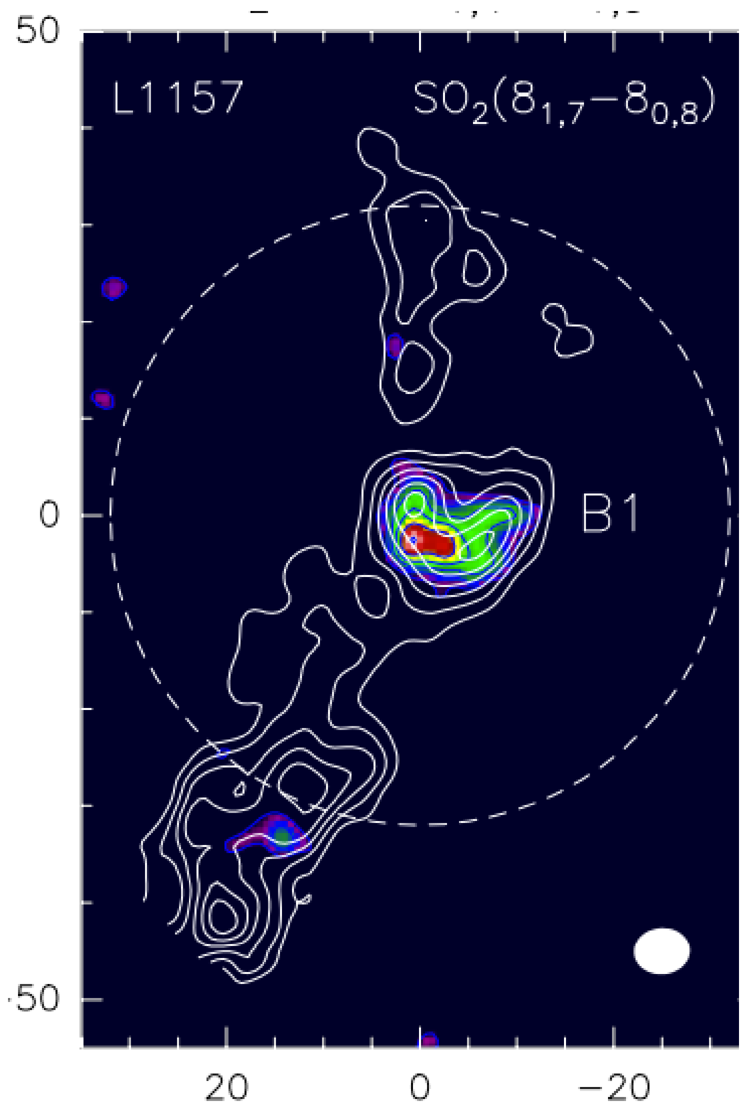


OI 63 μm towards HH377 with SOFIA

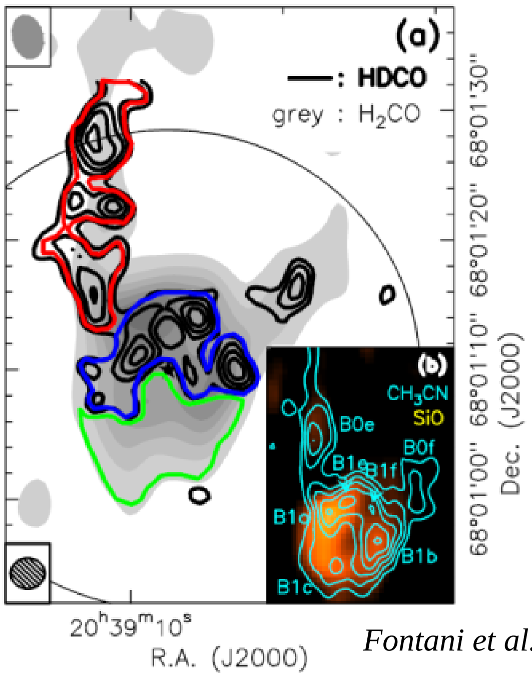


Lefloch et al. in prep

New insight from SOLIS



(Codella et al. in prep)



Fontani et al. (2015)