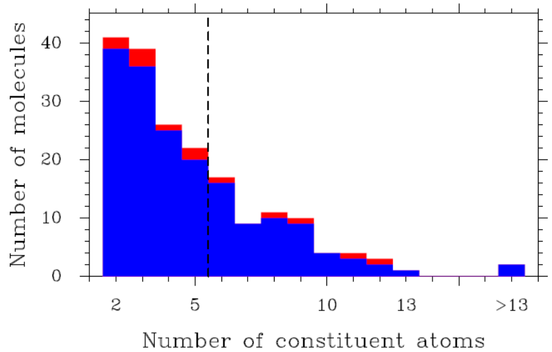
Emergence of Molecular Complexity in Solar-Type Star Forming Regions

B. Lefloch

Institute of Planetology and Astrophysics of Grenoble (France)

Molecular Complexity in the ISM

2	3	4	5	6	7	8	9	10	11	12	13
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6	c-C_6H_5CN
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$	
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH?	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	
C2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	CH_3OCOCH_3	n-C_3H_7CN	
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O			+ C_{60}, C_{70}
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH			
CN	HCO	NH_3	CH_4	CH_3SH	c-C_2H_4O	l-HC_6H	CH_3CONH_2				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	CH_2CHOH	CH_2CHCHO	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO		NH_2CH_2CN					
CSi	H_2O	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH4	H_2CCNH							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3	HCOCN								
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								
SO^+	SO_2	HCNO	NH_4^+								
SiN	c-SiC2	HOCN	H_2NCO^+								
SiO	CO_2	C_3H^+									
SiS	NH_2	HMgNC									
CS	H_3^+	HSCN									
HF	SiCN										
HD	AlNC										
FeO?	SiNC										
O_2	CCP										
CF^+	AlOH										
SiH	H_2O^+										
PO	H_2Cl^+										
AlO,	KCN										
OH^+,	FeCN										
CN^-	HO_2										



(http://www.cdms.de/)

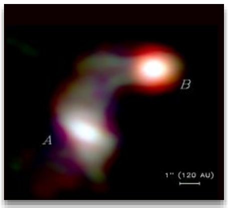
Around 200 molecules discovered mainly in massive star-forming regions (SgrB2, Orion), evolved stars, dark clouds, diffuse medium.

Complex Organic Molecules : ≥ 6 atoms + C atoms *(Herbst & van Dishoeck, 2009)*
One third of detected molecules are COMs.

The Bricks of Organic Chemistry are detected in the ISM

Pre-biotic molecules ($HCOCH_2OH$, NH_2CHO,…) but no amino acid !

Key Questions

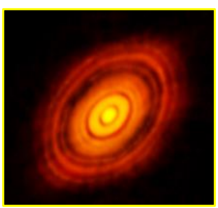


COMs and Prebiotic chemistry around Sun-like Protostars: What evidence ?

A handful of hot corino sources are known: how well ?

IRAS16293-2422: TIMASS (Caux et al. 2011), PILS (Jorgensen et al. 2016)

How and when do Complex Organic Molecules form around Sun-like systems ?



Which heritage to (exo)planetary systems ?

What is the ultimate molecular complexity that can be reached in SFRs ?

→ Origin of cometary material ? Amino-acids ?

The IRAM Large Program ASAI

(Astrochemical Surveys At IRAM)

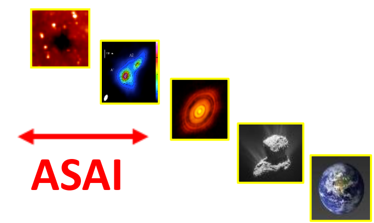
(Lefloch, Bachiller et al. 2018)

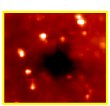
<u>Goals:</u>

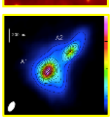
- Evolutionary view on chemistry along Solar-type Star Formation:
- Influence of environmental conditions: feedback processes

Unbiased, high sensitivity spectral line surveys from 70 to 280GHz

ASAI Source Sample: 10 templates illustrative of the different chemical stages of a sun-like protostar







Sources	Coordinates (J2000)	d (pc)	Lum. ($L_\odot$)	3 mm (mK)	2 mm (mK)	1.3 mm (mK)	$\delta\nu$ (kHz)	Comment
TMC1	$04^h41^m41.90^s$ $+25°41'27.1''$	140	–	–	4.2–4.2	–	48.8, 195.3	Early prestellar core
L1544	$05^h04^m17.21^s$ $+25°10'42.8''$	140	–	2.1–7.0	–	–	48.8	Evolved prestellar core
B1b	$03^h33^m20.80^s$ $+31°07'34.0''$	230	0.77	2.5–10.6(*)	4.4–8.0	4.2–4.6	195.3	First Hydrostatic Core
L1527	$04^h39^m53.89^s$ $+26°03'11.0''$	140	2.75	2.1–6.7(*)	4.2–7.1	4.6–4.1	195.3	Class 0 WCCC
IRAS4A	$03^h29^m10.42^s$ $+31°13'32.2''$	260	9.1	2.5–3.4	5.0–6.1	4.6–3.9	195.3	Class 0 Hot Corino
L1157mm	$20^h39^m06.30^s$ $+68°02'15.8''$	250	3	3.0–4.7	5.0–6.5	3.8–3.5	195.3	Class 0
SVS13A	$03^h29^m03.73^s$ $+31°16'03.8''$	260	34	2.0–4.8	4.2–5.1	4.6–4.3	195.3	Class I
AB Aur (†)	$04^h55^m45.84^s$ $+30°33'33.04''$	145	–	4.6–4.3	4.8–3.9	2.1–4.3	195.3	protoplanetary disk
L1157-B1	$20^h39^m10.20^s$ $+68°01'10.5''$	250	–	1.1–2.9	4.6–7.2	2.1–4.2	195.3	Outflow shock spot
L1448-R2	$03^h25^m40.14^s$ $+30°43'31.0''$	235	–	2.8–4.9	6.0–9.7	2.9–4.9	195.3	Outflow shock spot

3mm band: chemical content

After analysing the 3mm line surveys (1% U lines)

2	3	4	5	6	7	8	9	10	11	12	13
H_2	C_3	**c-C_3H**	C_5	**C_5H**	**C_6H**	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6	c-C_6H_5CN
AlF	**C_2H**	**l-C_3H**	**C_4H**	**l-H_2C_4**	**CH_2CHCN**	**$HCOOCH_3$**	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$	
AlCl	**C_2O**	**C_3N**	C_4Si	C_2H_4	**CH_3C_2H**	CH_3COOH?	**$(CH_3)_2O$**	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	
C2	**C_2S**	**C_3O**	**l-C_3H_2**	**CH_3CN**	**HC_5N**	C_7H	**CH_3CH_2OH**	CH_3CH_2CHO	CH_3OCOCH_3	n-C_3H_7CN	
CH	CH_2	**C_3S**	**c-C_3H_2**	CH_3NC	**CH_3CHO**	C_6H_2	HC_7N	CH_3CHCH_2O			
CH^+	**HCN**	C_2H_2	**CH_2CN**	**CH_3OH**	CH_3NH_2	**CH_2OHCHO**	C_8H	CH_3OCH_2OH			
CN	**HCO**	**NH_3**	CH_4	**CH_3SH**	c-C_2H_4O	l-HC_6H	CH_3CONH_2				
CO	**HCO^+**	HCCN	**HC_3N**	**HC_3NH^+**	CH_2CHOH	CH_2CHCHO	C_8H^-				
CO^+	**HCS^+**	$HCNH^+$	**HC_2NC**	**HC_2CHO**	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	**HNCO**	**HCOOH**	**NH_2CHO**	CH_3NCO	NH_2CH_2CN					
CSi	**H_2O**	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	**$HOCO^+$**	H_2C_2O	l-HC_4H							
KCl	**HNC**	**H_2CO**	H_2NCN	l-HC_4N							
NH	**HNO**	H_2CN	**HNC_3**	c-H_2C_3O							
NO	MgCN	**H_2CS**	SiH4	H_2CCNH							
NS	MgNC	H_3O^+	**H_2COH^+**	C_5N^-							
NaCl	**N_2H^+**	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3	HCOCN								
PN	NaCN	C_3N^-	HNCNH								
SO	**OCS**	PH_3	CH_3O								
SO^+	**SO_2**	**HCNO**	NH_4^+								
SiN	c-SiC2	**HOCN**	H_2NCO^+								
SiO	CO_2	C_3H^+									
SiS	NH_2	HMgNC									
CS	H_3^+	**HSCN**									
HF	SiCN										
HD	AlNC										
FeO?	SiNC										
O_2	CCP										
CF^+	AlOH										
SiH	H_2O^+										
PO	H_2Cl^+										
AlO,	KCN										
OH^+,	FeCN										
CN^-	HO_2										

Four main chemical families:

Hydrocarbons: C_xH_y

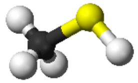
O-bearing : $C_xH_yO_z$

N-bearing : $C_xH_yO_zN_t$

S-bearing : $C_xH_yO_zN_tS_u$

also : **Si-bearing, P-bearing**

First S-bearing COM detected in low-mass SFRs: CH_3SH

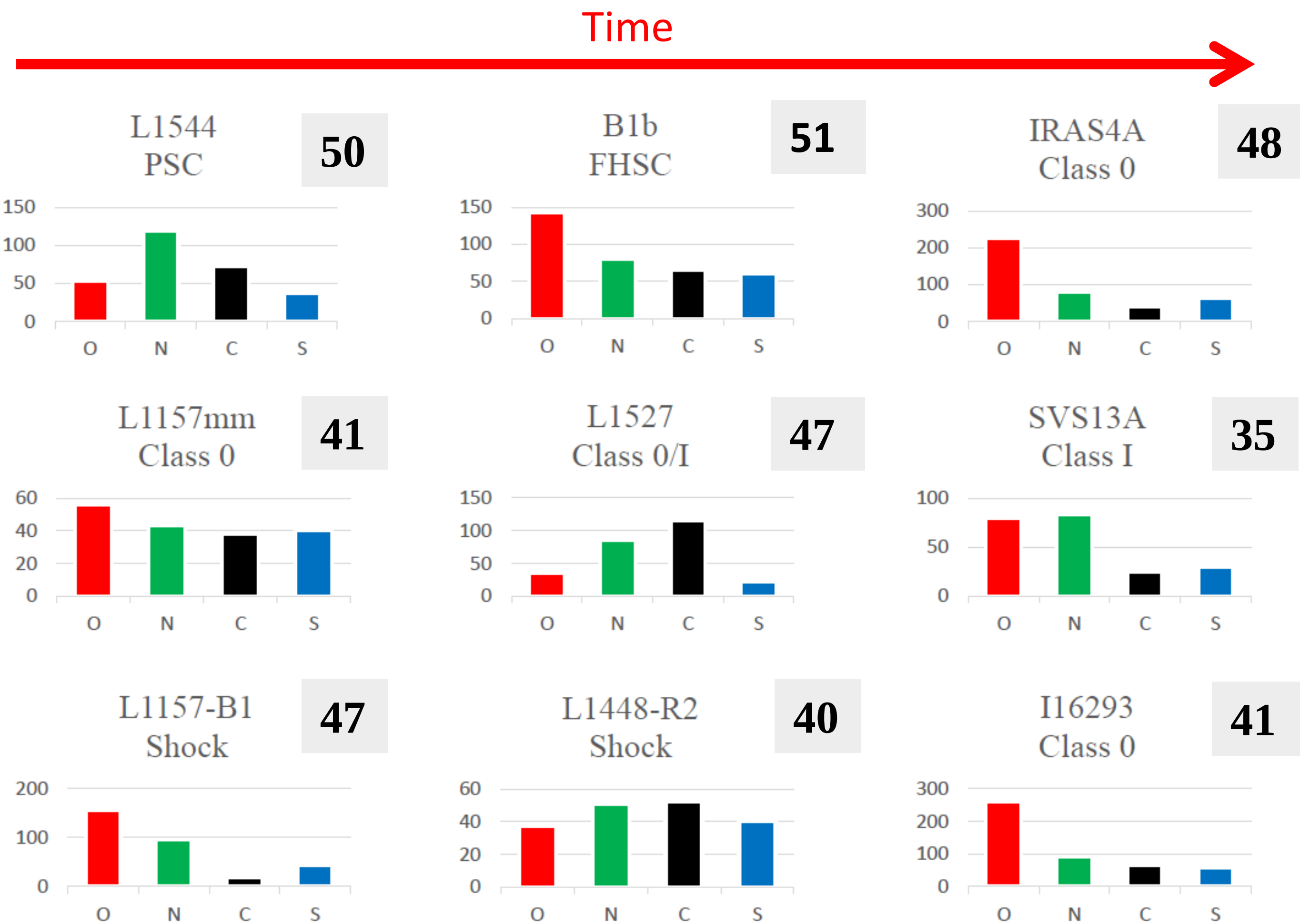


(also Majumdar et al. 2016)

No evidence for COMs larger than glycolaldehyde, dimethyl ether, ethanol

New molecular species: NO^+ , NS^+ *(Cernicharo et al. 2014, 2018),*

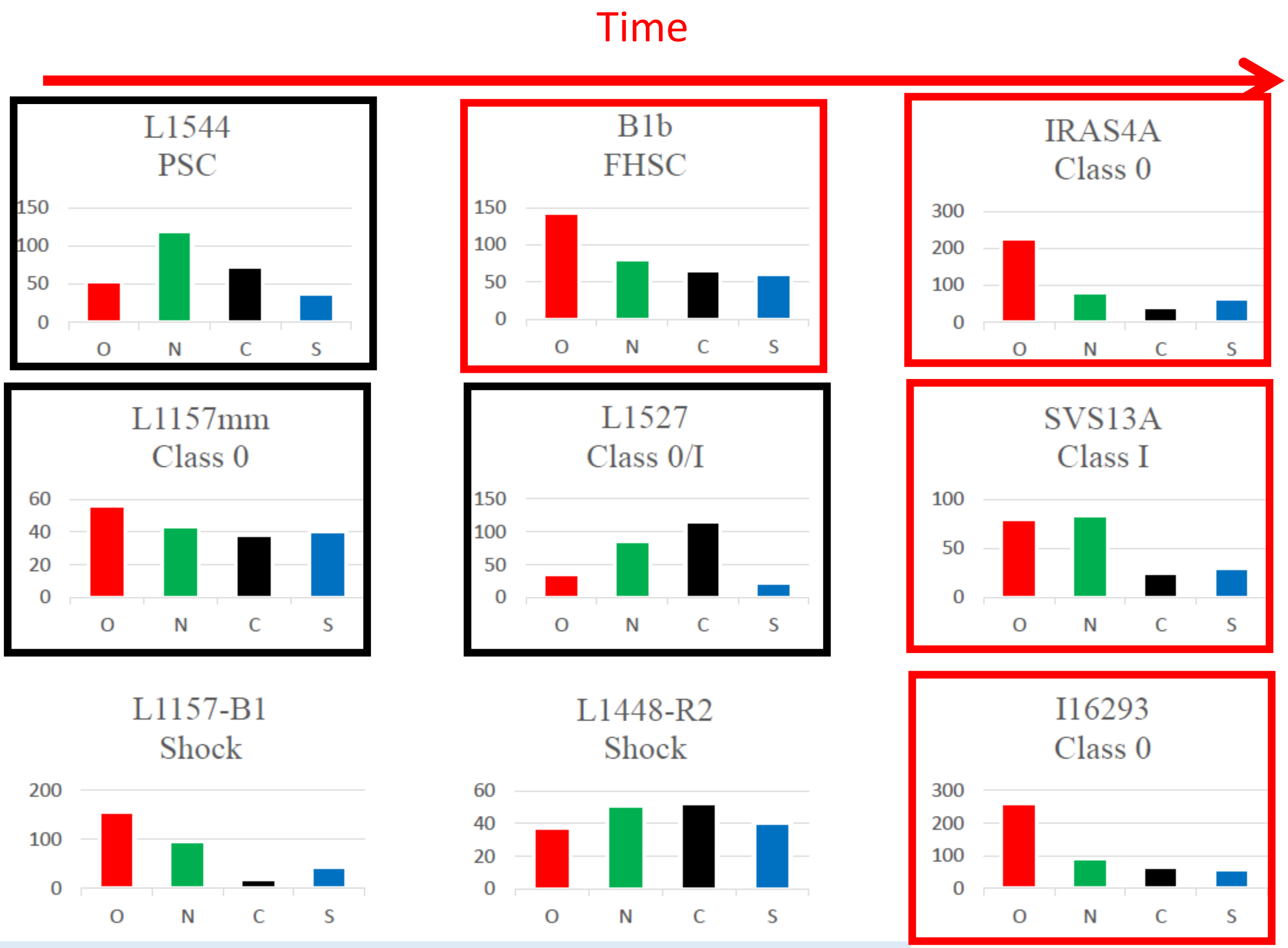
Statistics



ASAI sample
Number of *detected* molecular species : 35 – 51
Number of molecular lines : 178 – 413 (σ= 5-12 GHz^{-1})

Orion	**SgrB2**
43	56
3200	3700

Two Chemical Classes



r= N(O)/N(C) = 1 defines two chemical classes:
O-rich : hot corino sources : r= O/C > 1.5
C-rich : WCCC : r= O/C < 1.5

SVS13A : hot corino
L1157-mm : WCCC

COMs in the Prestellar Phase

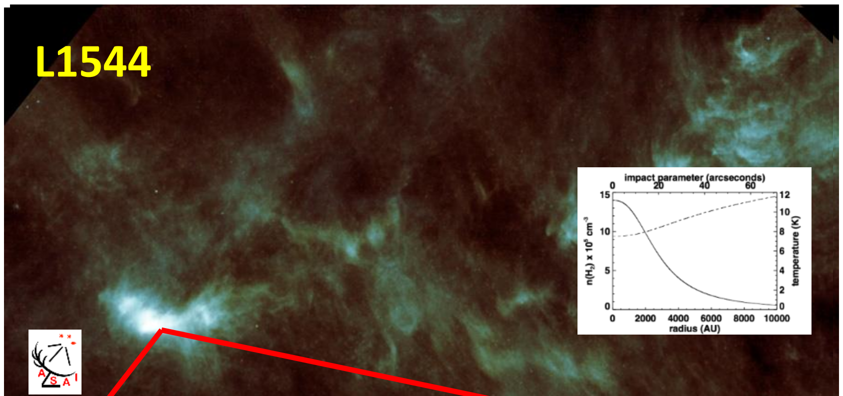
COMs are present at the prestellar stage

Bacmann et al. (2012), Cernicharo et al. (2012), Oberg et al. (2010)

TMC1: benzonitrile c-C_6H_5CN

(MacGuire et al. 2018)

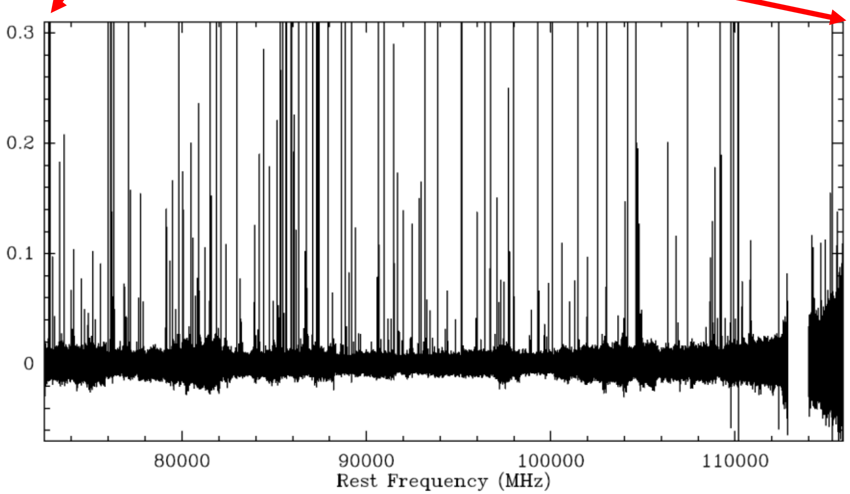
Vastel et al. (2014), Jimenez-Serra et al. (2015)

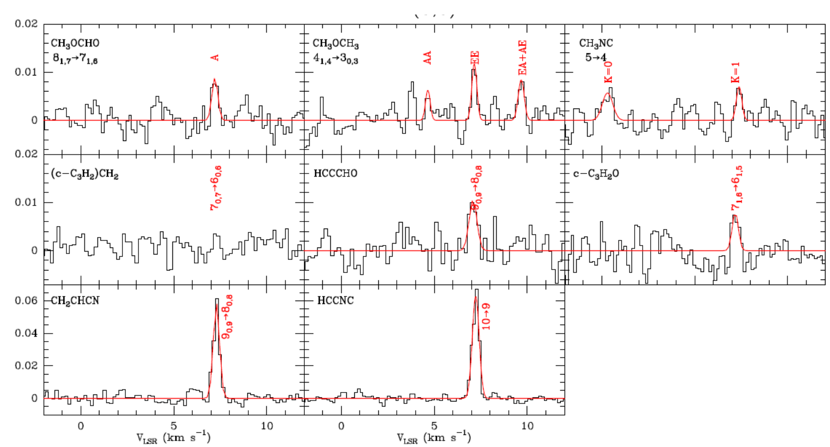


First systematic census of COMs in a PSC

CH_3OH, CH_3CHO, CH_3OCHO, CH_3OCH_3, H_2CCO, HCOOH

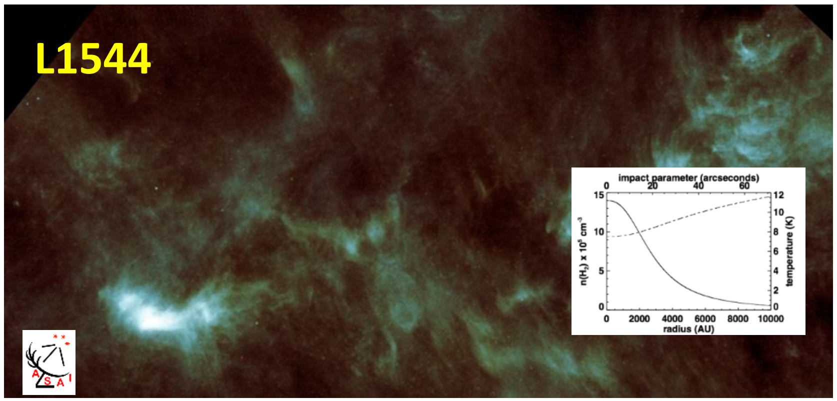
CH_3CN, CH_3NC, CH_2CHCN

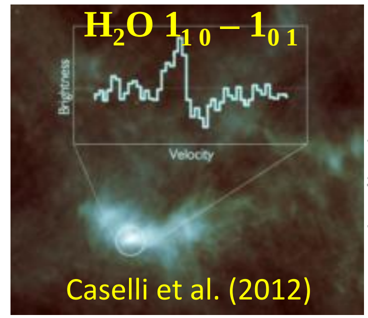


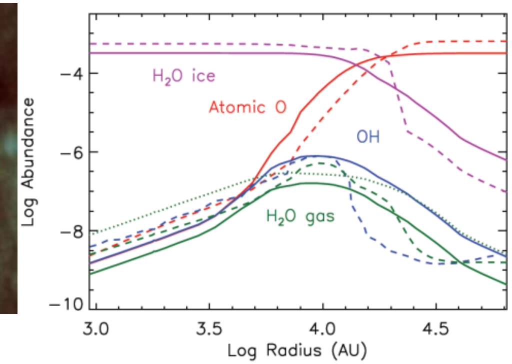


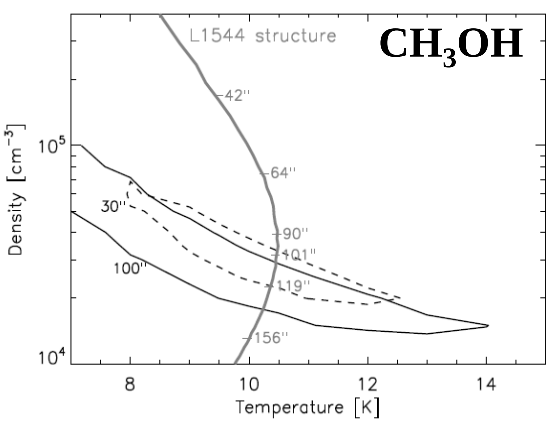
COMs in the Prestellar Phase

Vastel et al. (2014), Jimenez-Serra et al. (2015)









Emission of CH_3OH and other COMs arise from the outer layers where strong UV-photodesorption of water ice is observed

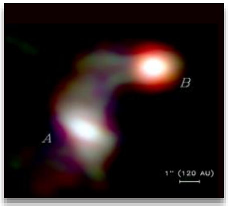
Vastel et al. (2014), Bizzochi et al. (2014)

Origin of COMs is a challenge

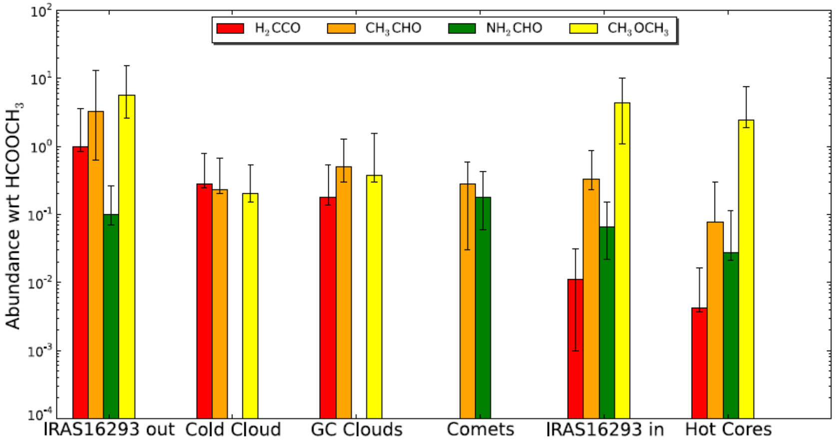
→ Non-thermal desorption of CH_3OH and C_2H_4 from grain mantles + gas phase reactions could account for the formation of some COMs *in the gas phase* : CH_3CHO, H_2CCO ?

COMs around Solar-Type Protostars

IRAS16293-2422



TIMASS (Caux et al. 2011) :
H_2CCO, CH_3CHO, NH_2CHO, $HCOOCH_3$, CH_3OCH_3, CH_3CN, $HOCH_2CHO$

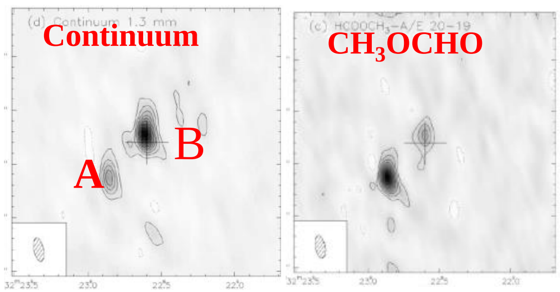


Ketene/Methyl Formate : Cold / Hot objects

(Jaber et al. 2014, Kahane et al. 2013, Jorgensen et al. 2012)

Two contributions :
Compact, Hot, dense region : **Hot corino**
Td ≥ 100K : X= 1(-9) – 1(-8)
Extended, **Cold Envelope** :
X= 3(-12) – 2(-10)

I16293 Hot Corino

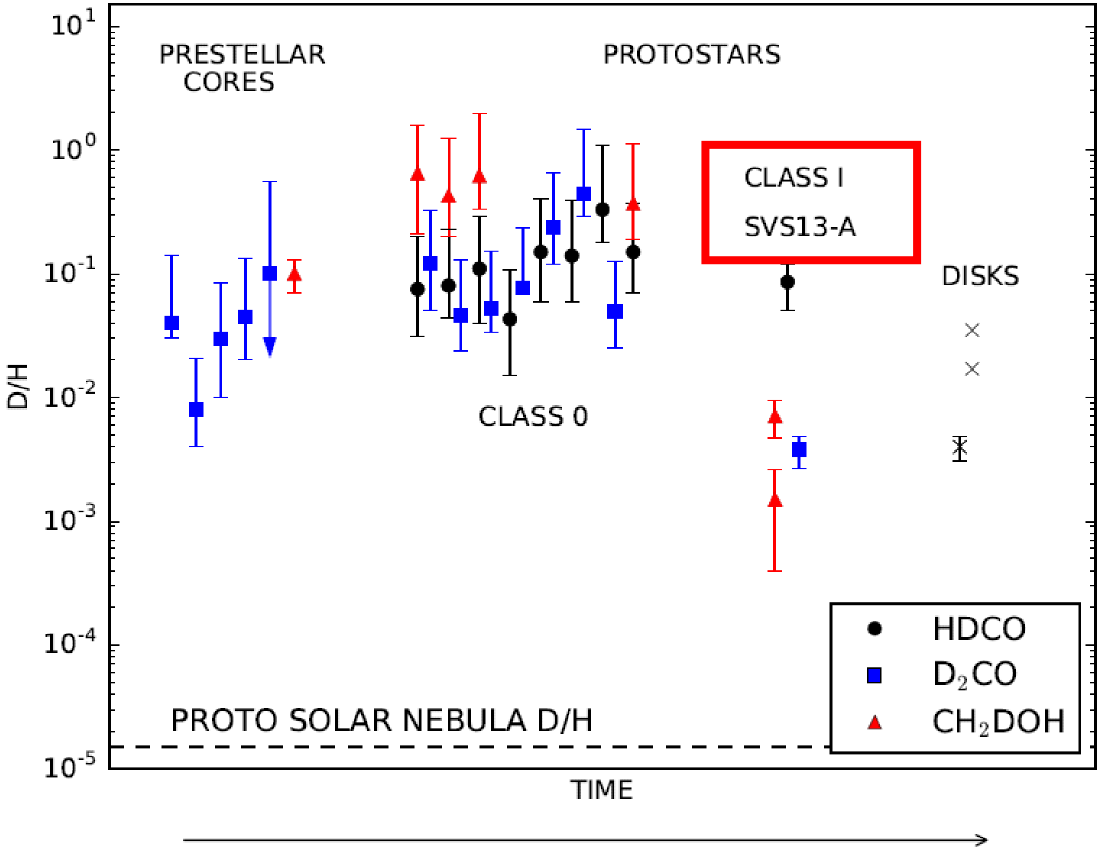


(Bottinelli et al. 2007)

Molecular Deuteration

$H_3^+ + HD \longrightarrow H_2D^+ + H_2$
($\Delta E = +230K$)

Enhanced molecular D/H in cold gas

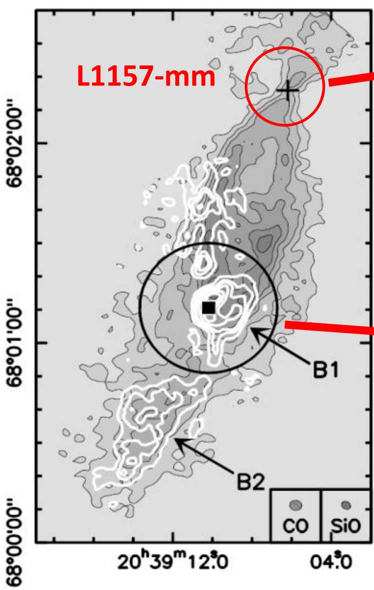


Decrease of molecular deuteration in Class I - SVS13A

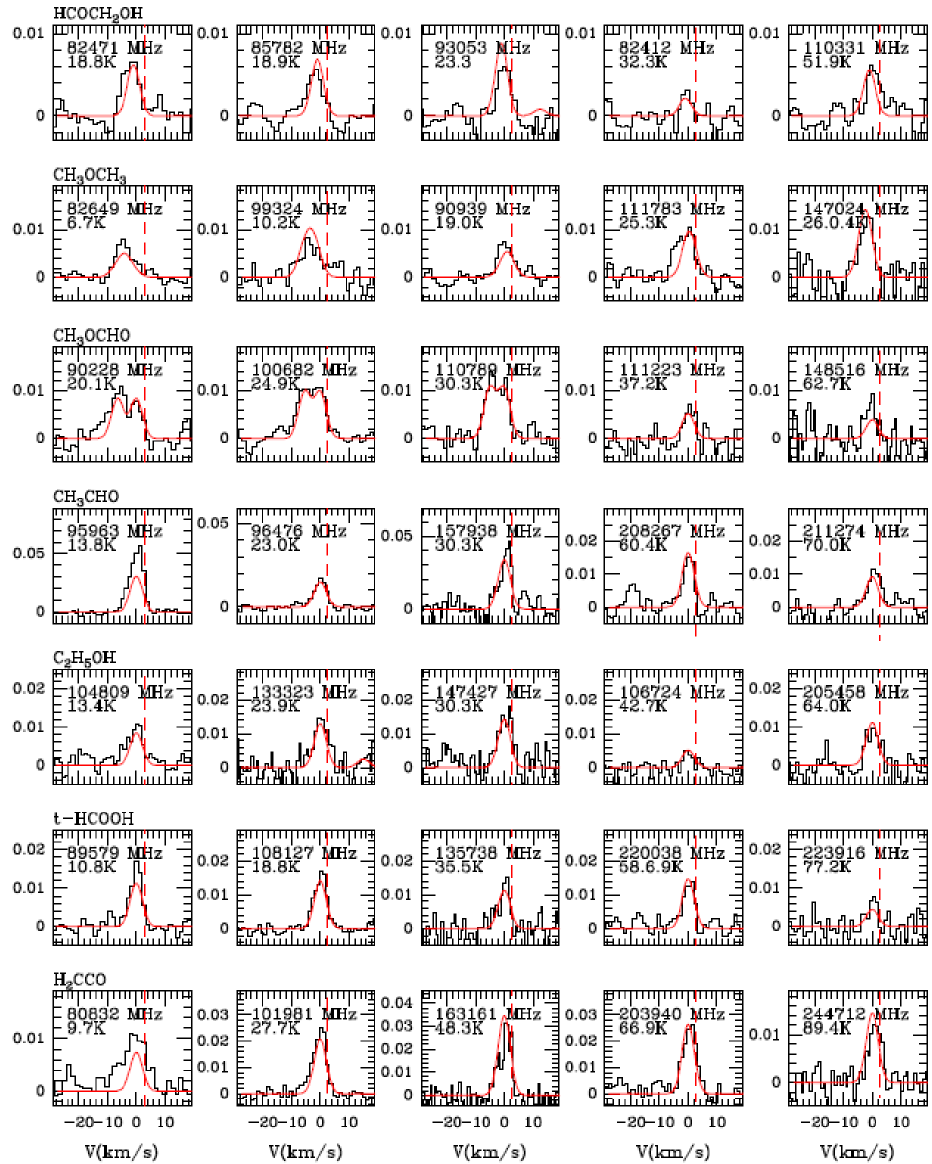
Bianchi et al. (2017)

Shocks as COM factories

Lefloch et al. (2017)



Gueth et al. (1996,98)



CH_2OHCHO

CH_3OCH_3

CH_3OCHO

CH_3CHO

C_2H_5OH

$HCOOH$

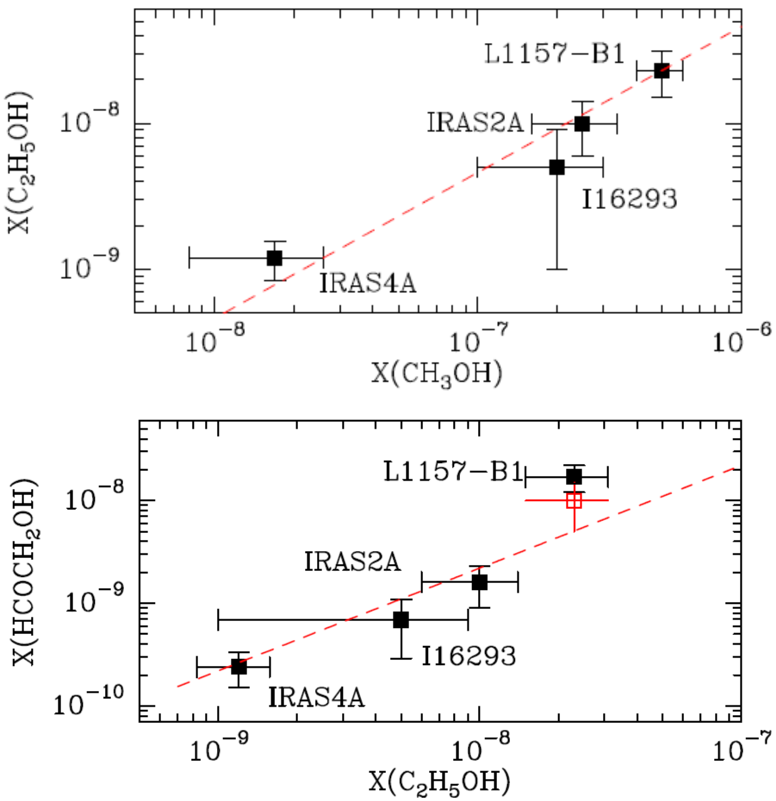
H_2CCO

N-bearing:
NH_2CHO, CH_3CN,
C_2H_3CN, HC_5N

S-bearing: CH_3SH

Shocks as COM factories

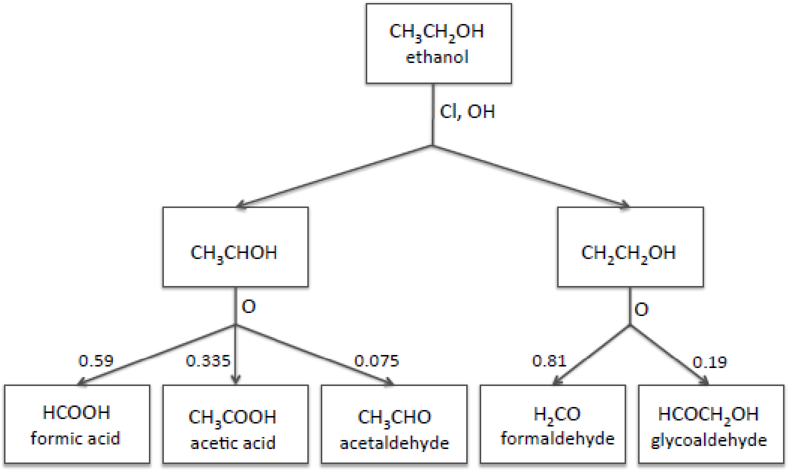
Abundances are all similar (but NH_2CHO) : 10^{-8} [H_2]
Relatively to CH_3OH: $X = 2\% - 5\ \% X[CH_3OH]$



Linear correlations: chemical families: a common origin ?

Which formation route for glycolaldehyde ?
Grain surface (CH_3OH + HCO) ?
Gas phase (H_2CO^+ + H_2CO) ?
Woods et al. (2012, 2013)

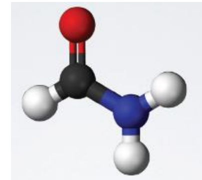
A New Scheme: The Ethanol Tree
(Skouteris et al. 2017)



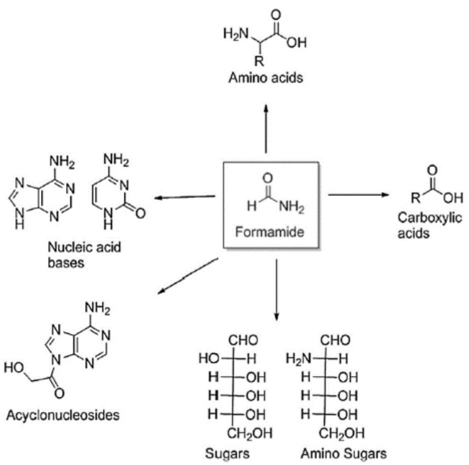
Prebiotic Molecules: NH_2CHO

Formamide NH_2CHO: an important molecule for prebiotic chemistry

- the four most abundant elements of biological systems: C,H,O,N
- the simplest molecule with a peptide bond



A precursor of prebiotic chemistry (Saladino et al. 2012)



Detected in Comets: Hale-Bopp (Bockelee-Morvan et al. 2000), **81P/Wild2** (Elsila 2009), **67P** (Altwegg 2016)

→ Exogenous delivery on Earth (Ferus et al. 2014) ?

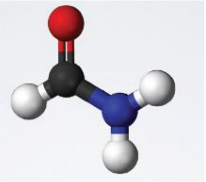
Detected in high-mass SFRs (Bisschop et al. 2007)

solar-type protostar IRAS16293-2422 (Kahane et al. 2013).

rebiotic Molecules: NH_2CHO

Formamide NH_2CHO: an important molecule for prebiotic chemistry

- the four most abundant elements of biological systems: C,H,O,N
- the simplest molecule with a peptide bond

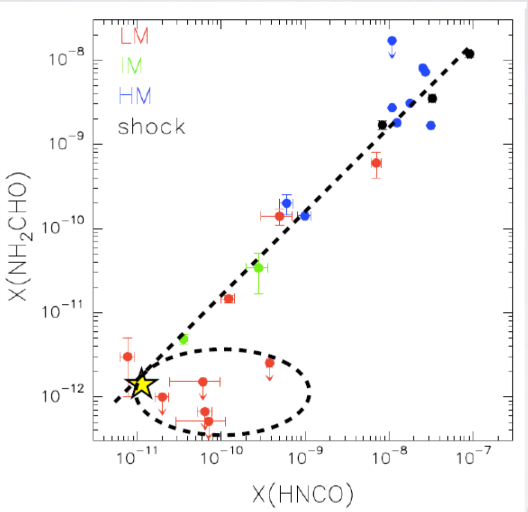


Lopez-Sepulcre et al. (2015)

ASAI: Search for NH_2CHO in solar-type environments

	Source	d (pc)	M ($M_\odot$)	L_{bol} ($L_\odot$)	Type
Not detected	TMC1	140	21	—	PSC - young
	L1544	140	2.7	1.0	PSC - evolved
	B1	200	1.9	1.9	Class 0 - early
	L1527	140	0.9	1.9	Class 0, WCCC
	L1157-mm	325	1.5	4.7	Class 0, WCCC?
Detected	IRAS 4A	235	5.6	9.1	Class 0, HC
	SVS 13A	235	0.34	21	Class 0/1
	OMC-2 FIR 4	420	30	100	IM proto-cluster
	Cep E	730	35	100	IM protostar
	L1157-B1	250	—	—	outflow shock

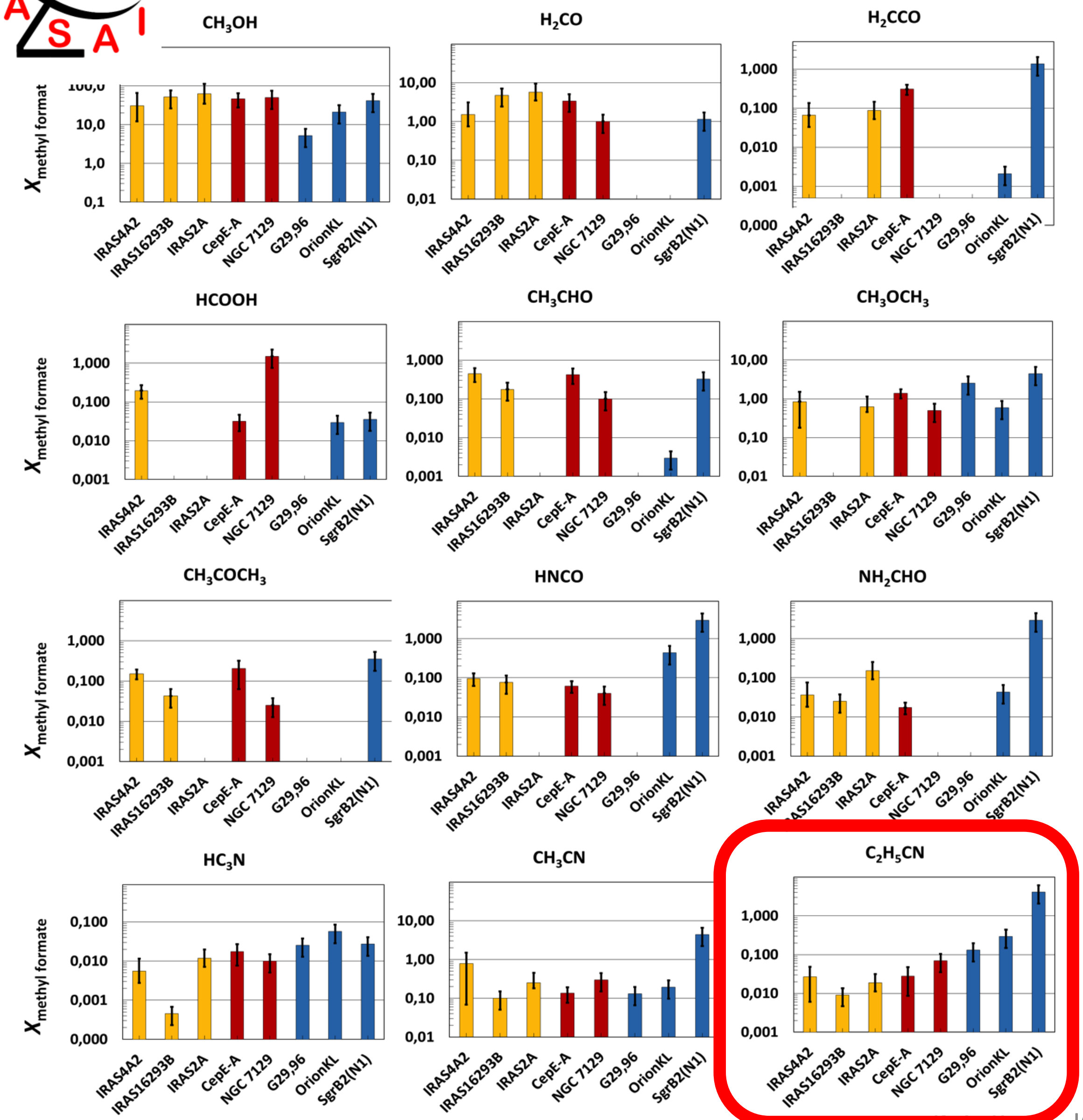
NH_2CHO/HNCO= 0.1



NH_2CHO is detected only in hot corinos and shocks
Not in PSC and WCCC sources

NH_2CHO and HNCO are chemically related
Several formation pathways for HNCO (also : Marcelino 2009)

From hot corinos to hot cores



Relative O-bearing abundances vary little with respect to luminosity
But : H_2CCO and CH_3CHO

Good correlation between CH_3OCH_3 and CH_3OCHO: a common origin ? (Balucani et al. 2016)

Relative C_2H_5N abundance increases with luminosity

(Ospina-Zamudio et al. 2018)

Conclusions and Future Prospects

Single-dish line surveys such as ASAI show that

- Molecular complexity is already present in the earliest phases of star formation, at a degree comparable to that of massive SFRs.
- No leap in molecular complexity from low- to high-mass Star Forming Regions.
- Molecules of prebiotic interest are discovered, complex and simple!

- Shocks are as chemically rich as protostellar envelopes; act a major factor of chemical feedback. They are true laboratories which help to characterize molecule formation pathways.

High-angular resolution observations with NOEMA and ALMA are opening a new window for the (astro)chemistry of Star Forming Regions.

Thanks

Thanks to all the ASAI collaborators for this fantastic and so successful journey :

C. Ceccarelli,J. Cernicharo,C. Codella,A. Fuente,A. Lopez-Sepulcre,C. Vastel, E. Caux,M. Tafalla,E. Bianchi,P. Caselli,A. Gomez-Ruiz, P. Hily-Blant, J. Holdship, I. Jimenez-Serra, C. Kahane, E. Mendoza, J. Ospina-Zamudio, S. Pacheco, L. Podio, E. Roueff, N. Sakai, B. Tercero, P. de Vicente, S. Viti, S. Yamamoto, K. Yoshida, T. Monfredini, H. Quitian