# The formation of prebiotic molecules in star-forming regions

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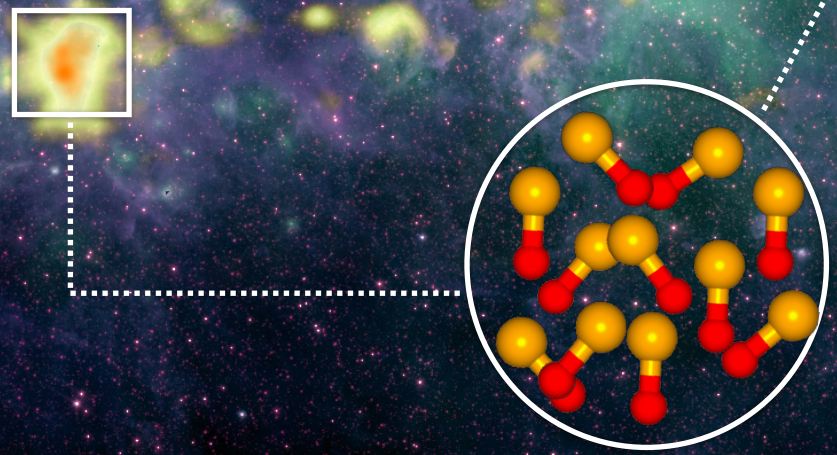


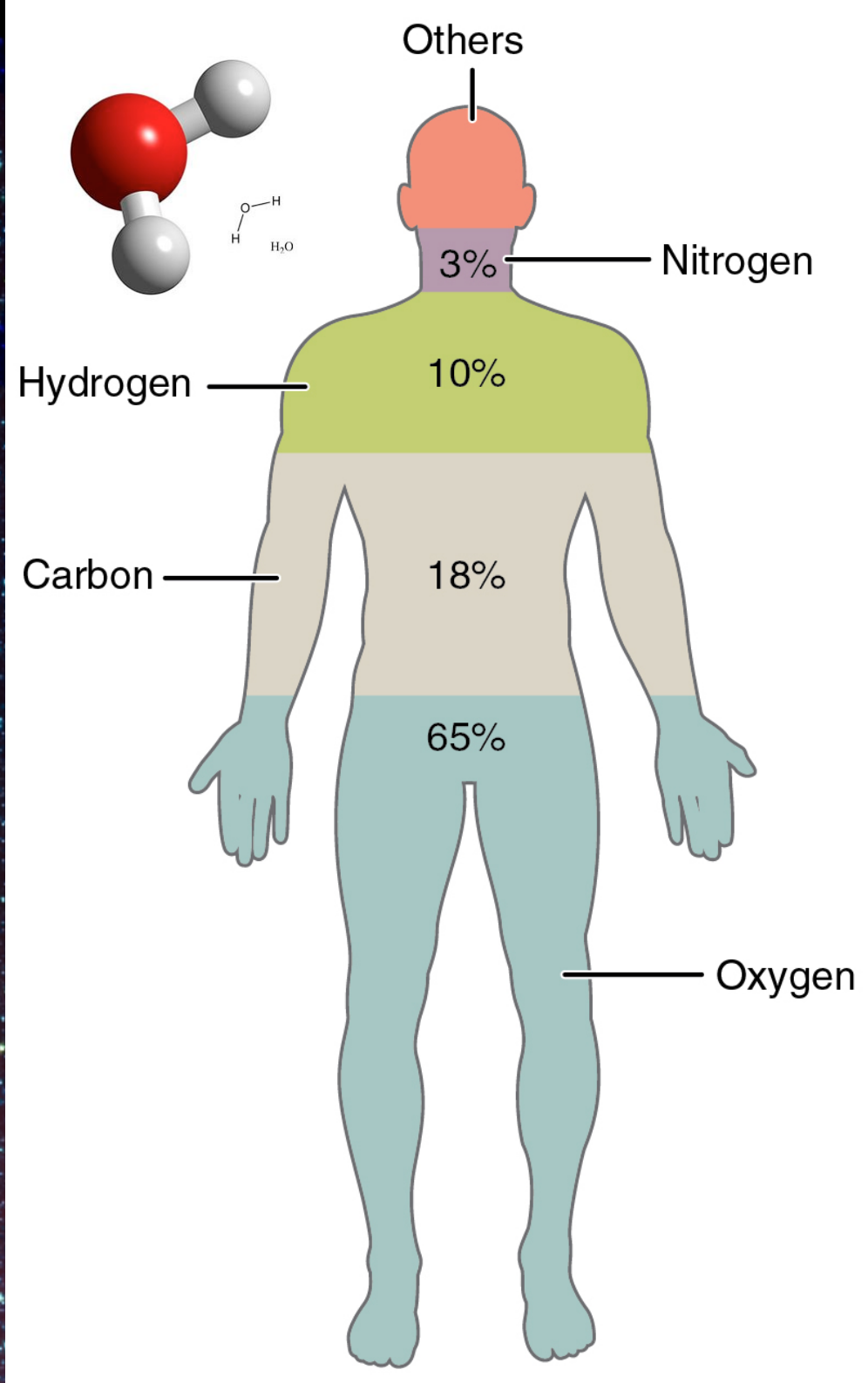
Nitrogen

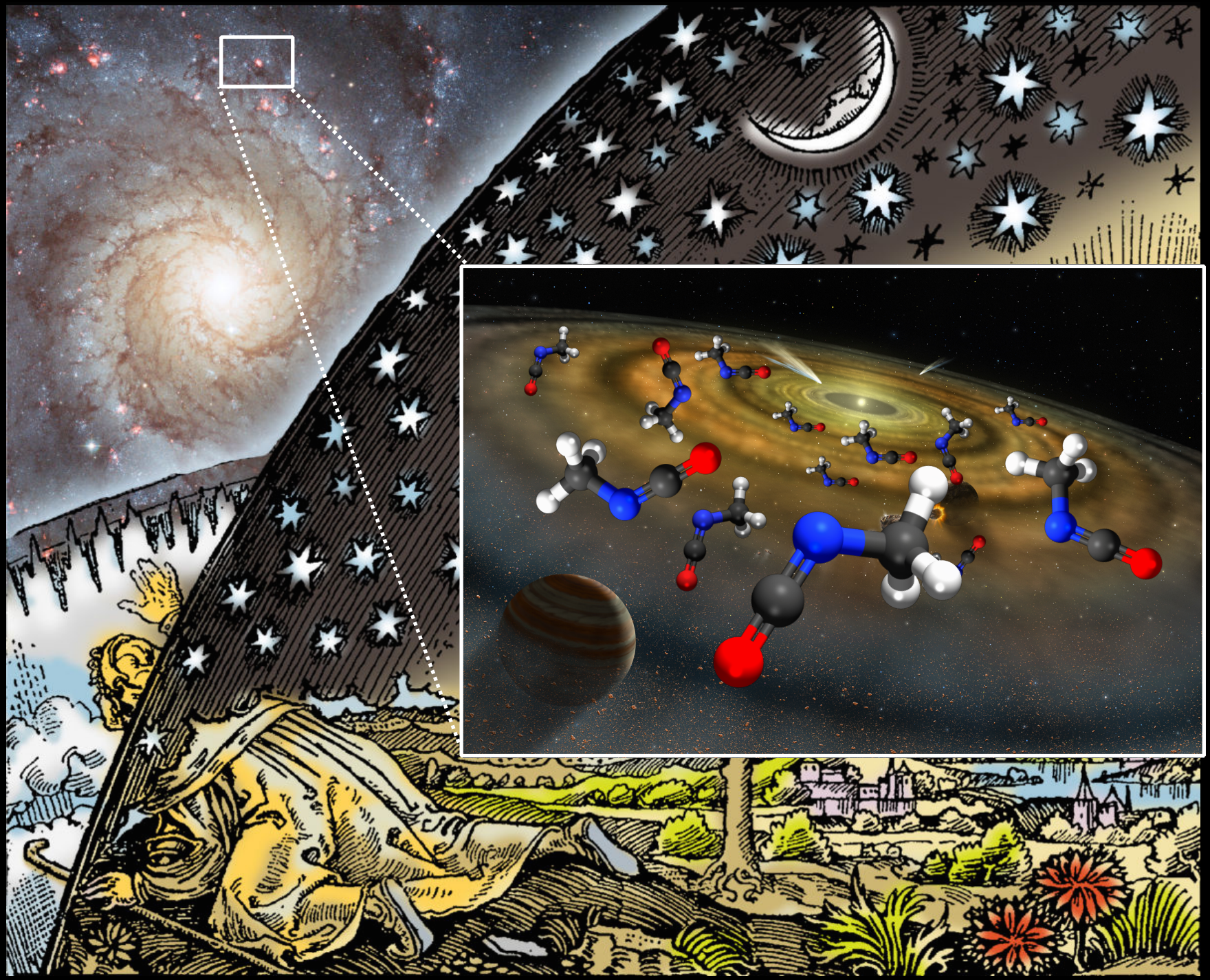
Francesco´s Legacy, Florence, June 5-9 2017

# We are chemistry !

Atoms aggregated in …

**MOLECULES**



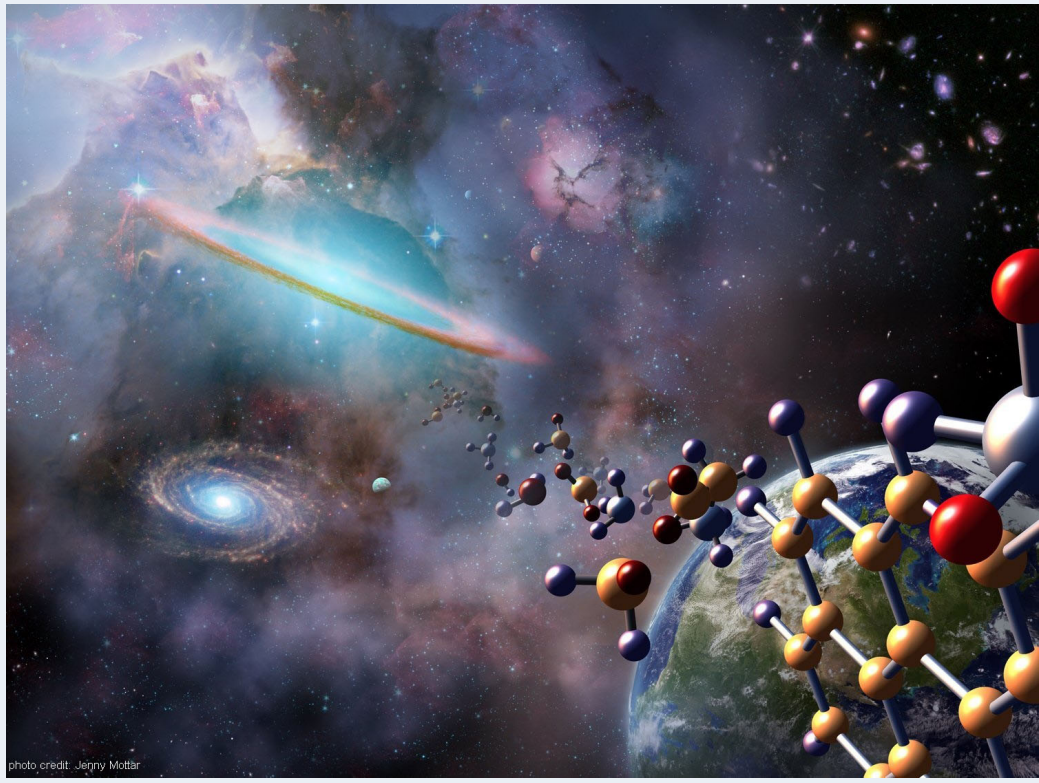


## Molecules in the Interstellar Medium or Circumstellar Shells (as of 02/2016)

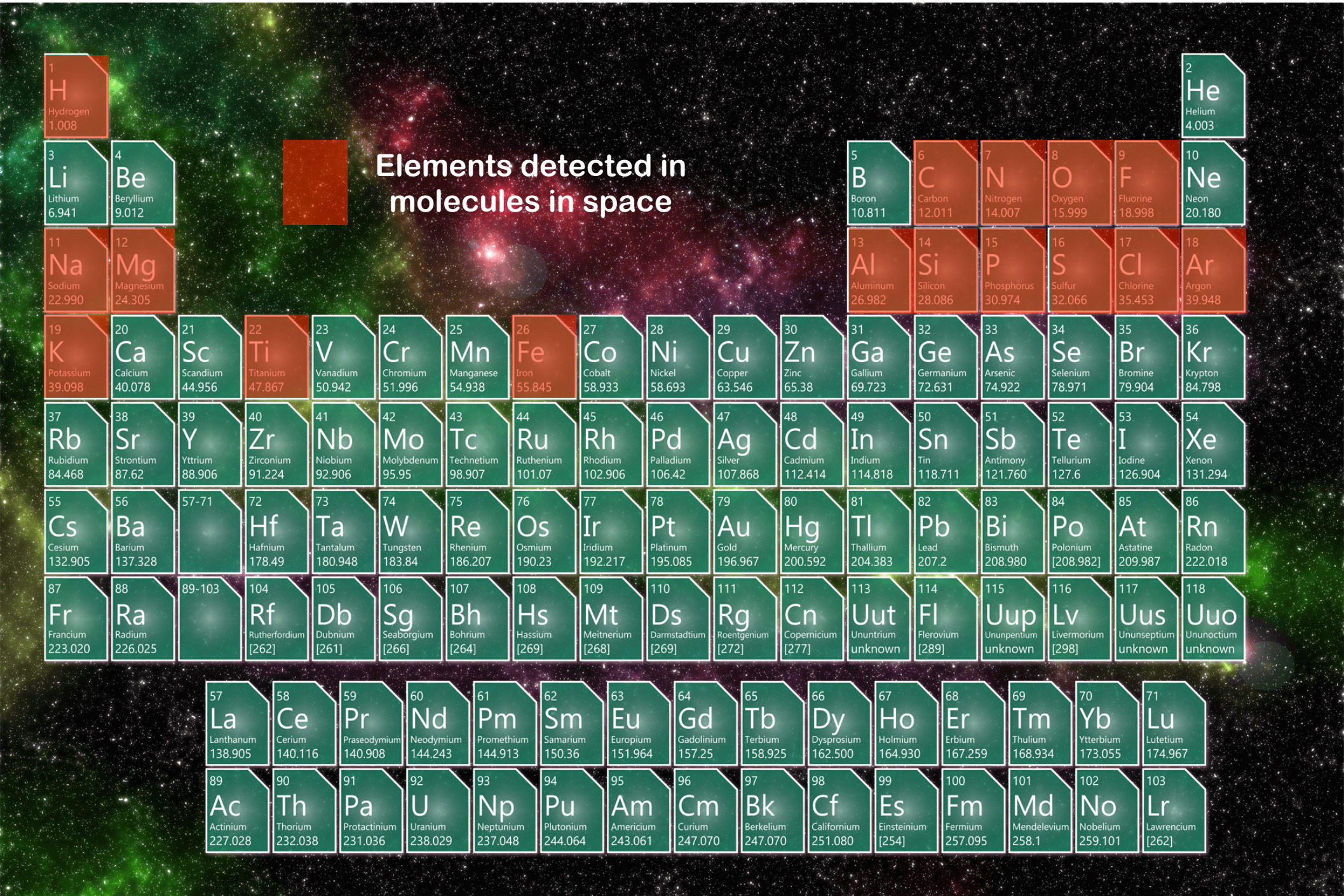
| 2 atoms | 3 atoms | 4 atoms | 5 atoms | 6 atoms | 7 atoms | 8 atoms | 9 atoms | 10 atoms | 11 atoms | 12 atoms | >12 atoms |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ | $C_3$ * | *c*-$C_3H$ | $C_5$ * | $C_5H$ | $C_6H$ | $CH_3C_3N$ | $CH_3C_4H$ | $CH_3C_5N$ | $HC_9N$ | *c*-$C_6H_6$ * | $HC_{11}N$ |
| AlF | $C_2H$ | *l*-$C_3H$ | $C_4H$ | *l*-$H_2C_4$ | $CH_2CHCN$ | $HC(O)OCH_3$ | $CH_3CH_2CN$ | $(CH_3)_2CO$ | $CH_3C_6H$ | *n*-$C_3H_7CN$ | $C_{60}$ * |
| 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*-$C_3H_7CN$ | $C_{70}$ * |
| $C_2$** | $C_2S$ | $C_3O$ | *l*-$C_3H_2$ | $CH_3CN$ | $HC_5N$ | $C_7H$ | $CH_3CH_2OH$ | $CH_3CH_2CHO$ | $CH_3OC(O)CH_3$ | $C_2H_5OCH_3$ ? | $C_{60}^+$ * |
| CH | $CH_2$ | $C_3S$ | *c*-$C_3H_2$ | $CH_3NC$ | $CH_3CHO$ | $C_6H_2$ | $HC_7N$ | | | | |
| $CH^+$ | HCN | $C_2H_2$* | $H_2CCN$ | $CH_3OH$ | $CH_3NH_2$ | $CH_2OHCHO$ | $C_8H$ | | | | |
| CN | HCO | $NH_3$ | $CH_4$ * | $CH_3SH$ | *c*-$C_2H_4O$ | *l*-$HC_6H$ * | $CH_3C(O)NH_2$ | | | | |
| CO | $HCO^+$ | HCCN | $HC_3N$ | $HC_3NH^+$ | $H_2CCHOH$ | $CH_2CHCHO$ (?) | $C_8H^-$ | | | | |
| $CO^+$ | $HCS^+$ | $HCNH^+$ | $HC_2NC$ | $HC_2CHO$ | $C_6H^-$ | $CH_2CCHCN$ | $C_3H_6$ | | | | |
| CP | $HOC^+$ | HNCO | HCOOH | $NH_2CHO$ | $CH_3NCO$ 2015 | $H_2NCH_2CN$ | $CH_3CH_2SH$ (?) | | | | |
| SiC | $H_2O$ | 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 | $H_2CS$ | $SiH_4$ * | $H_2CCNH$ (?) | | | | | | | |
| NS | MgNC | $H_3O^+$ | $H_2COH^+$ | $C_5N^-$ | | | | | | | |
| NaCl | $N_2H^+$ | *c*-$SiC_3$ | $C_4H^-$ | HNCHCN | | | | | | | |
| OH | $N_2O$ | $CH_3$ * | HC(O)CN | | | | | | | | |
| PN | NaCN | $C_3N^-$ | HNCNH | | | | | | | | |
| SO | OCS | $PH_3$ | $CH_3O$ | | | | | | | | |
| $SO^+$ | $SO_2$ | HCNO | $NH_4^+$ | | | | | | | | |
| SiN | *c*-$SiC_2$ | HOCN | $H_2NCO^+$ (?) | | | | | | | | |
| SiO | $CO_2$ * | HSCN | $NCCNH^+$ 2015 | | | | | | | | |
| SiS | $NH_2$ | $H_2O_2$ | | | | | | | | | |
| CS | $H_3^+$ (*) | $C_3H^+$ | | | | | | | | | |
| HF | SiCN | HMgNC | | | | | | | | | |
| HD | AlNC | HCCO 2015 | | | | | | | | | |
| FeO ? | SiNC | | | | | | | | | | |
| $O_2$ | HCP | | | | | | | | | | |
| $CF^+$ | CCP | | | | | | | | | | |
| SiH ? | AlOH | | | | | | | | | | |
| PO | $H_2O^+$ | | | | | | | | | | |
| AlO | $H_2Cl^+$ | | | | | | | | | | |
| $OH^+$ | KCN | | | | | | | | | | |
| $CN^-$ | FeCN | | | | | | | | | | |
| $SH^+$ | $HO_2$ | | | | | | | | | | |
| SH | $TiO_2$ | | | | | | | | | | |
| $HCl^+$ | $C_2N$ | | | | | | | | | | |
| TiO | $Si_2C$ 2015 | | | | | | | | | | |
| $ArH^+$ | | | | | | | | | | | |
| $NO^+$ ? | | | | | | | | | | | |

# Molecules detected in space

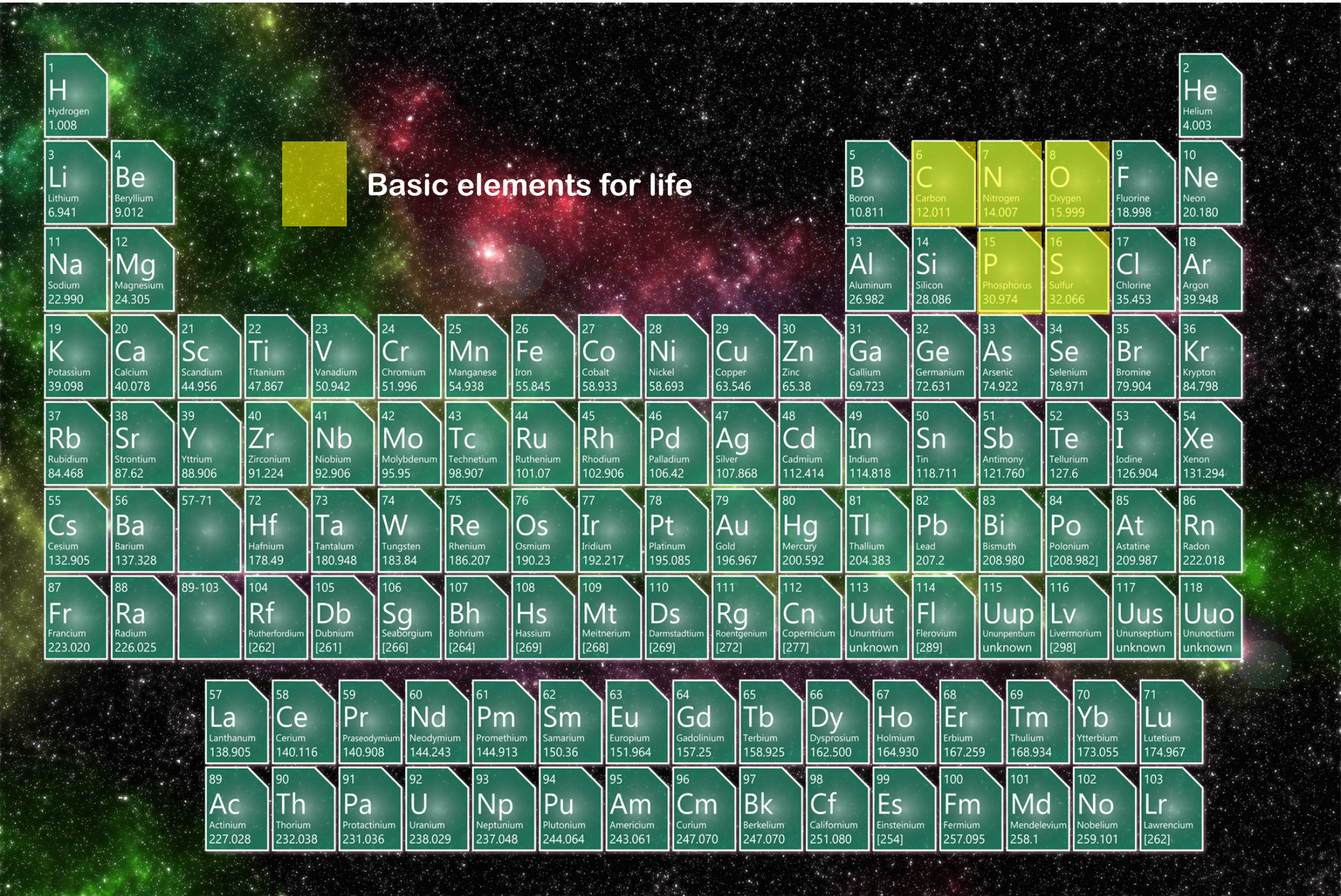
**Almost 200 molecules have been detected in space**



# ”ASTROCHEMICAL” table of elements



# ”ASTROBIOLOGICAL” table of key-elements



# Prebiotic molecules: the building blocks of life

- Molecules containing the 5 key elements for the development of LIFE (C, N, O, S, P).
- Relevant for prebiotic chemistry due to its structural and functional role in DNA, RNA, ATP…
- The detection in star-forming regions has open the possibility of understanding how LIFE could emerge on Earth.

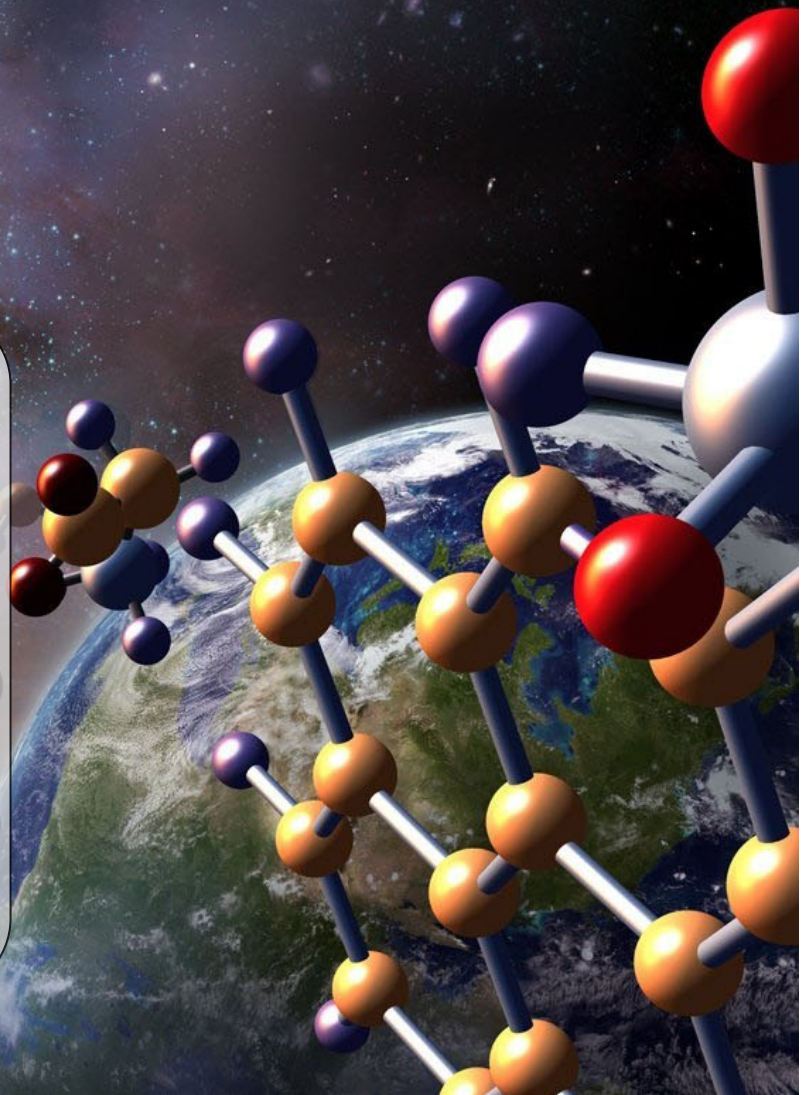
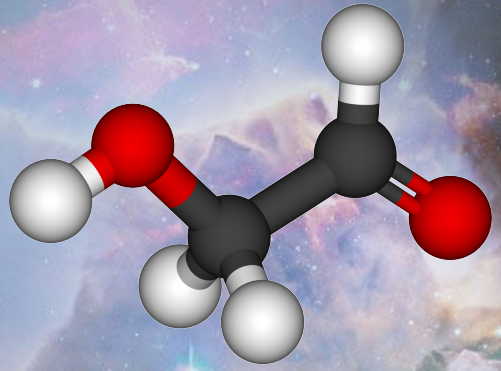


photo credit: Jenny Mottar



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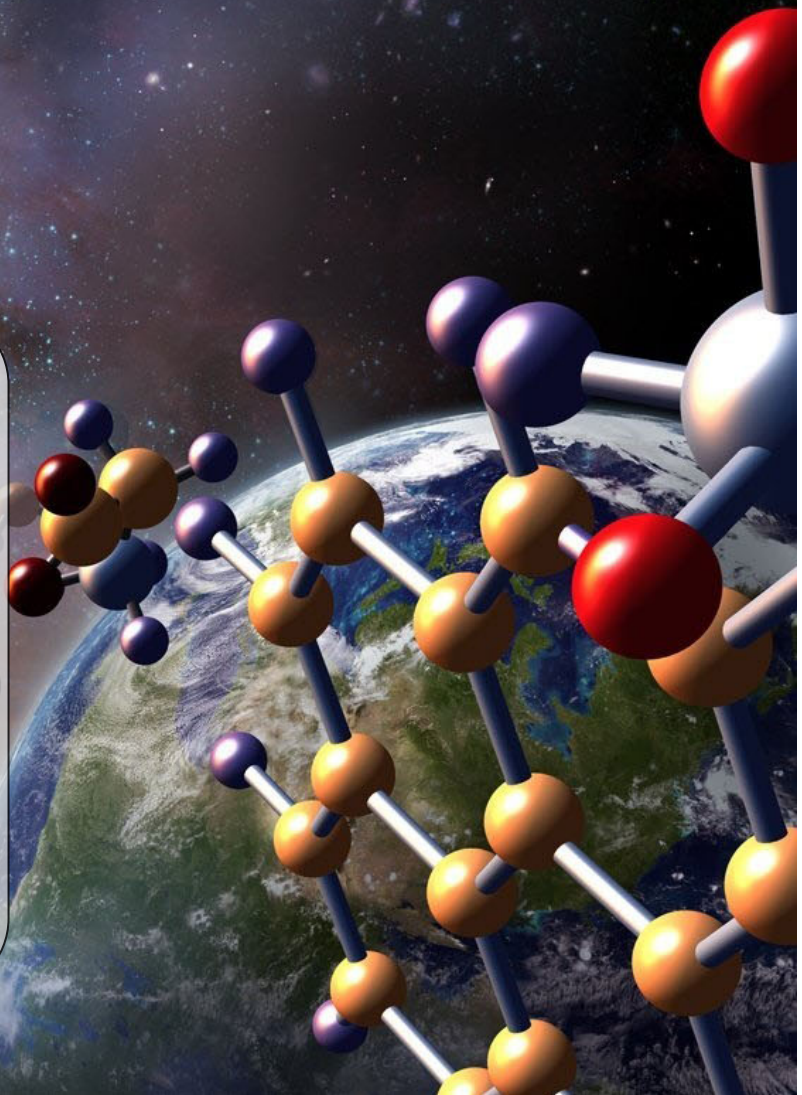

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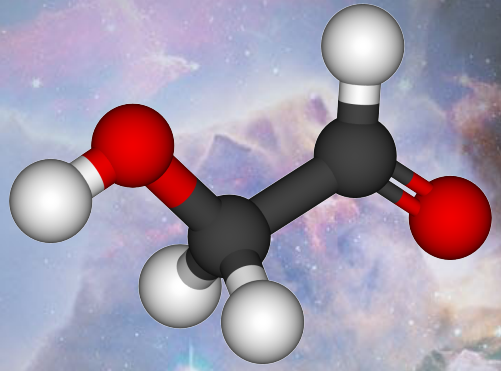

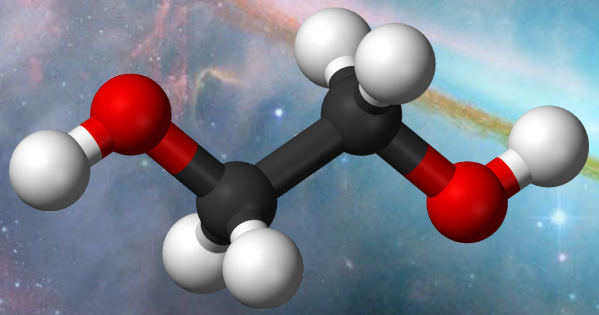

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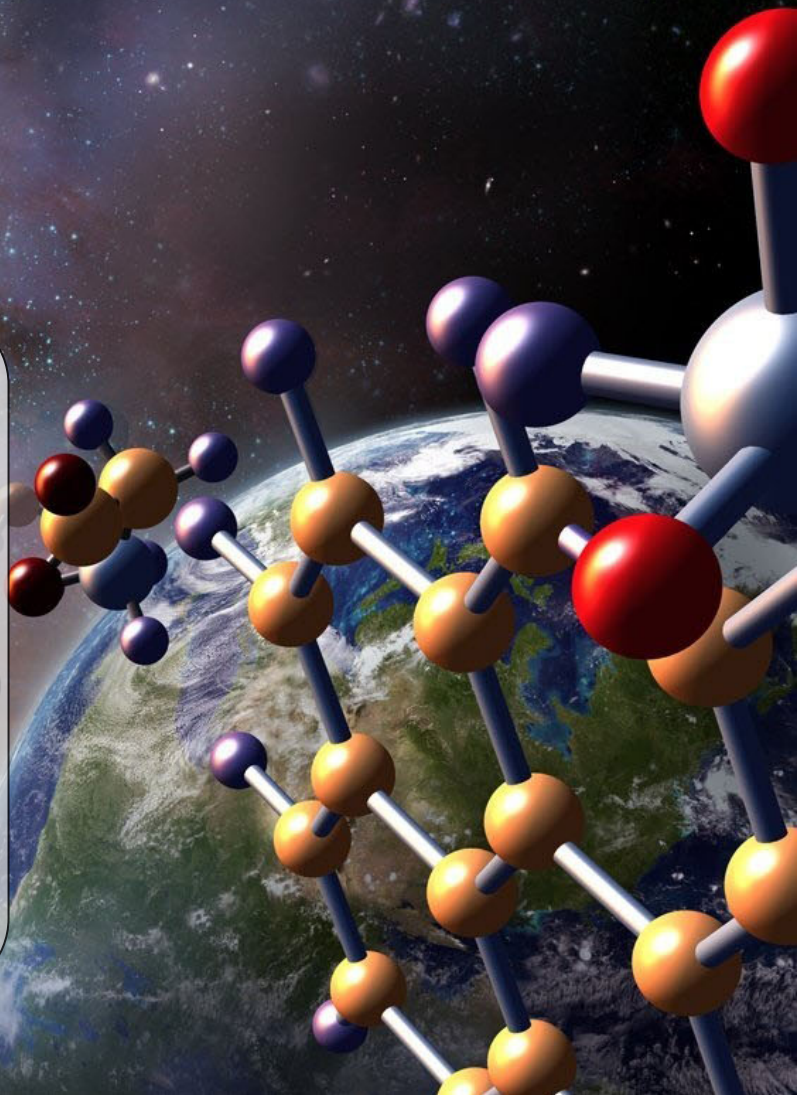

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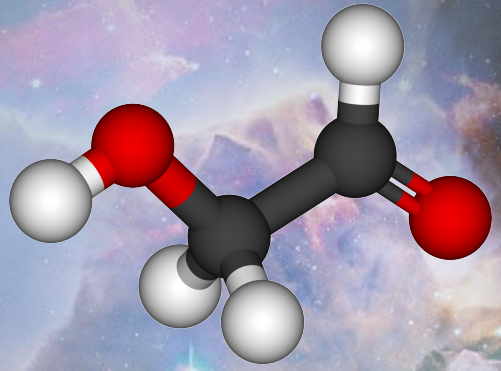

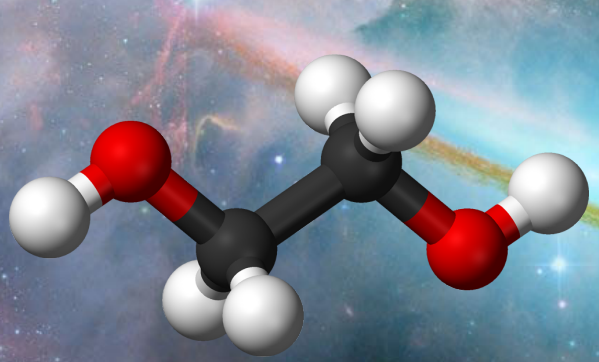

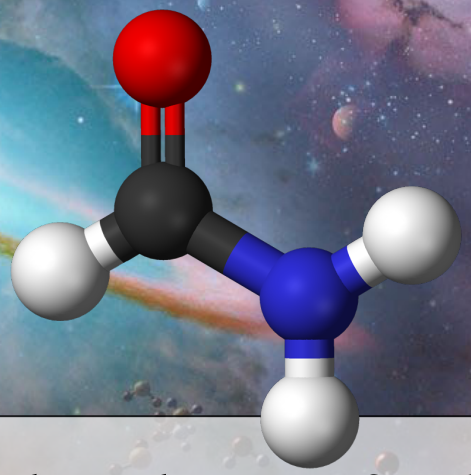

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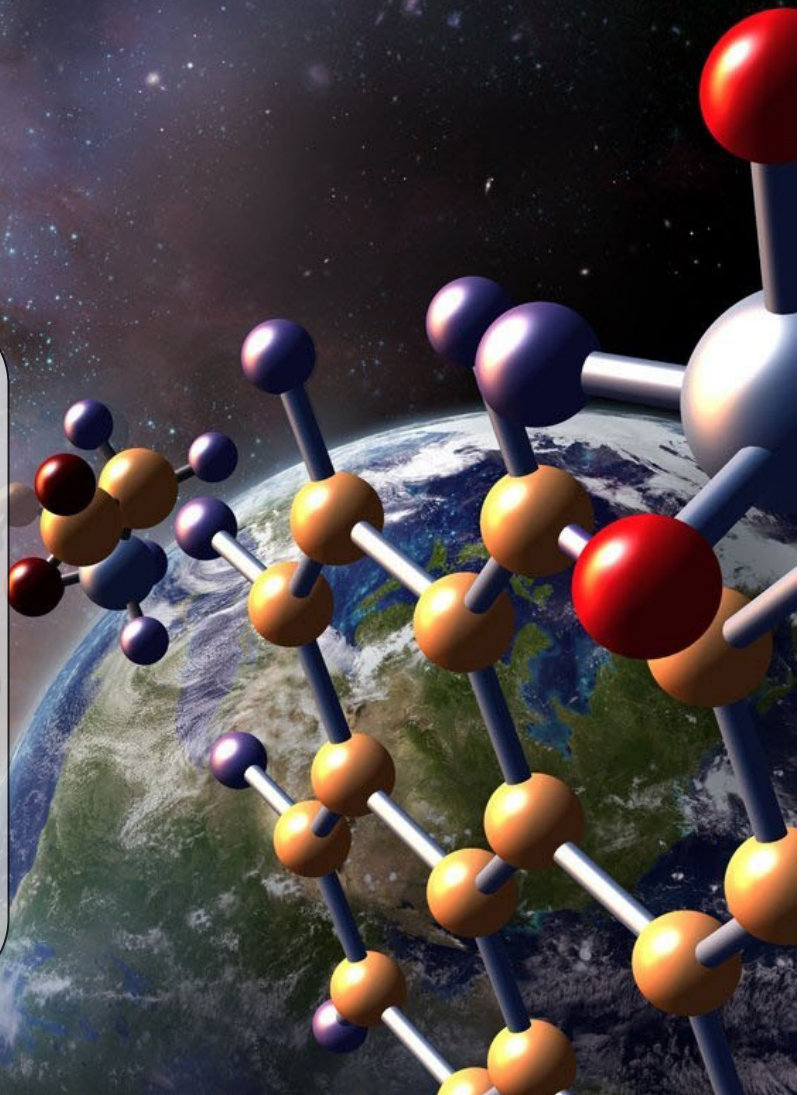

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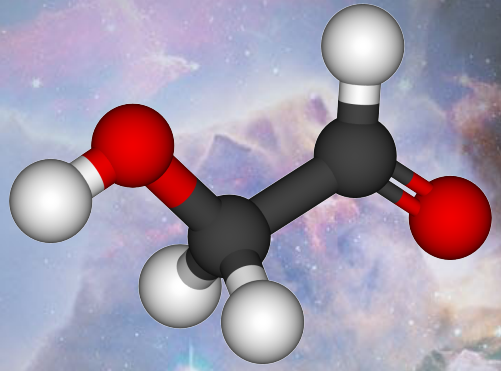

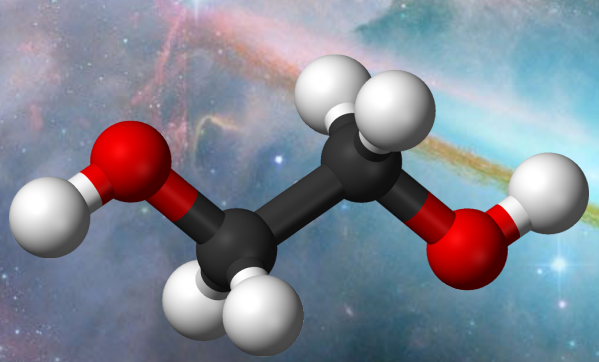

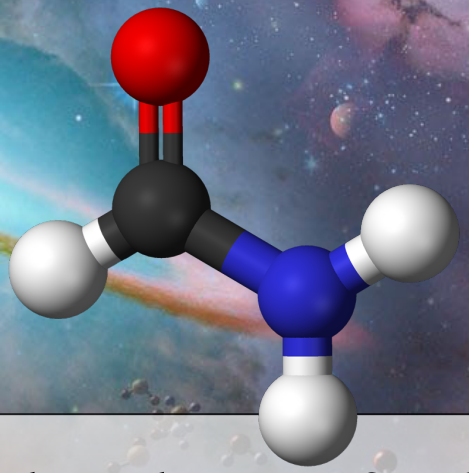

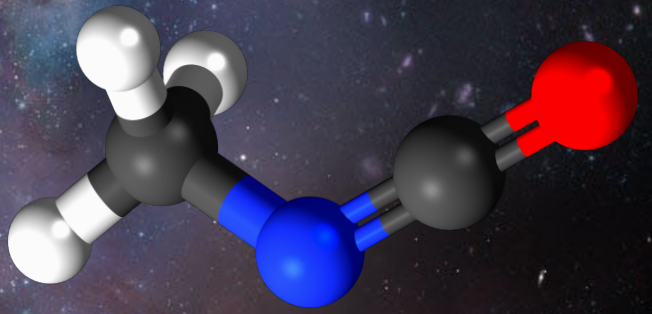

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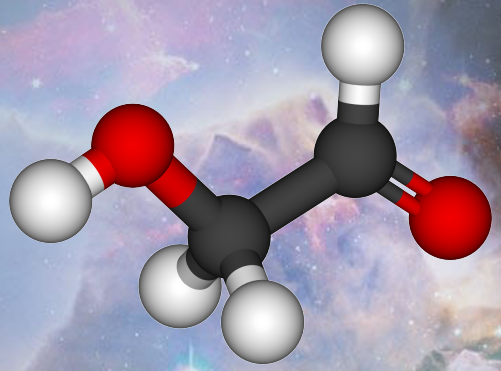

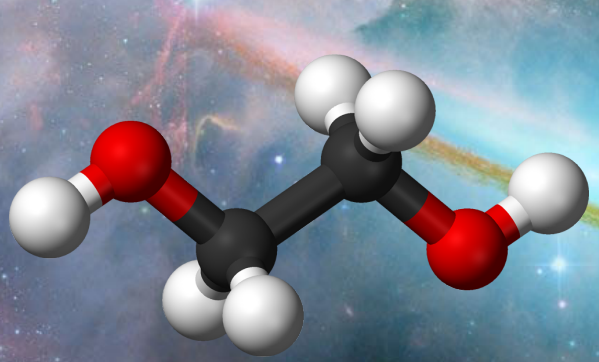

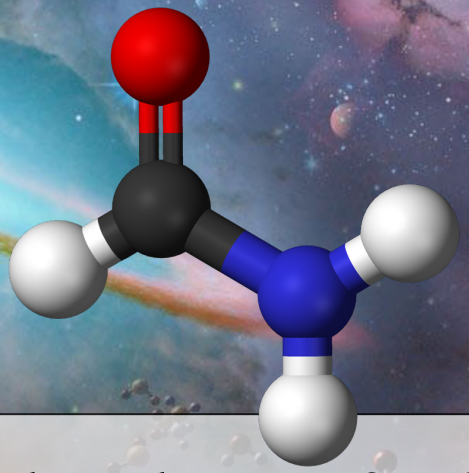

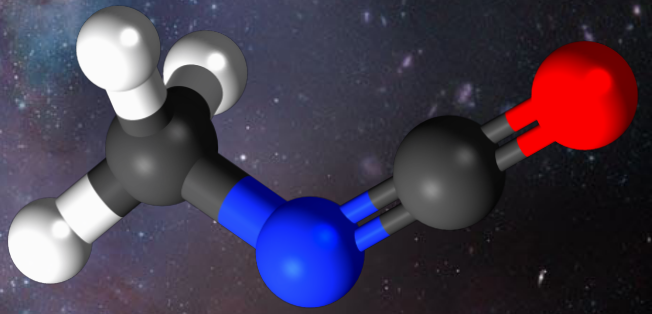

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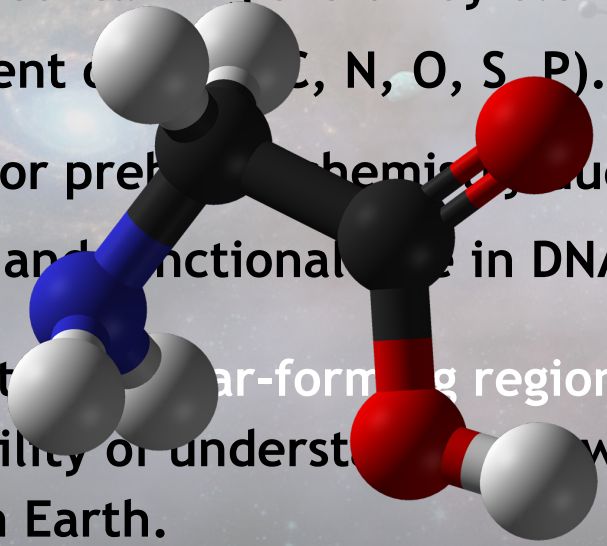



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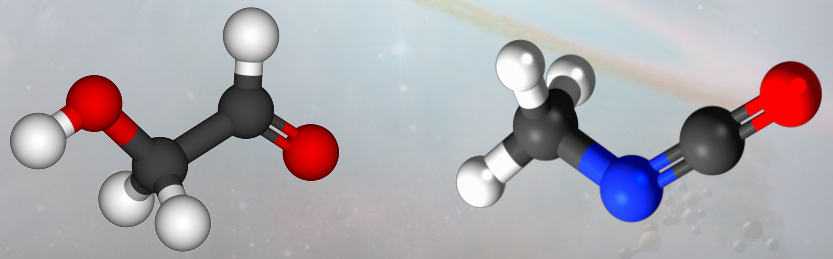
# Prebiotic molecules: the building blocks of life

## COMPLEX ORGANIC MOLECULES



## PHOSPHORUS-BEARING MOLECULES

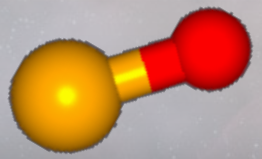


Photo credit: Jenny Mottar

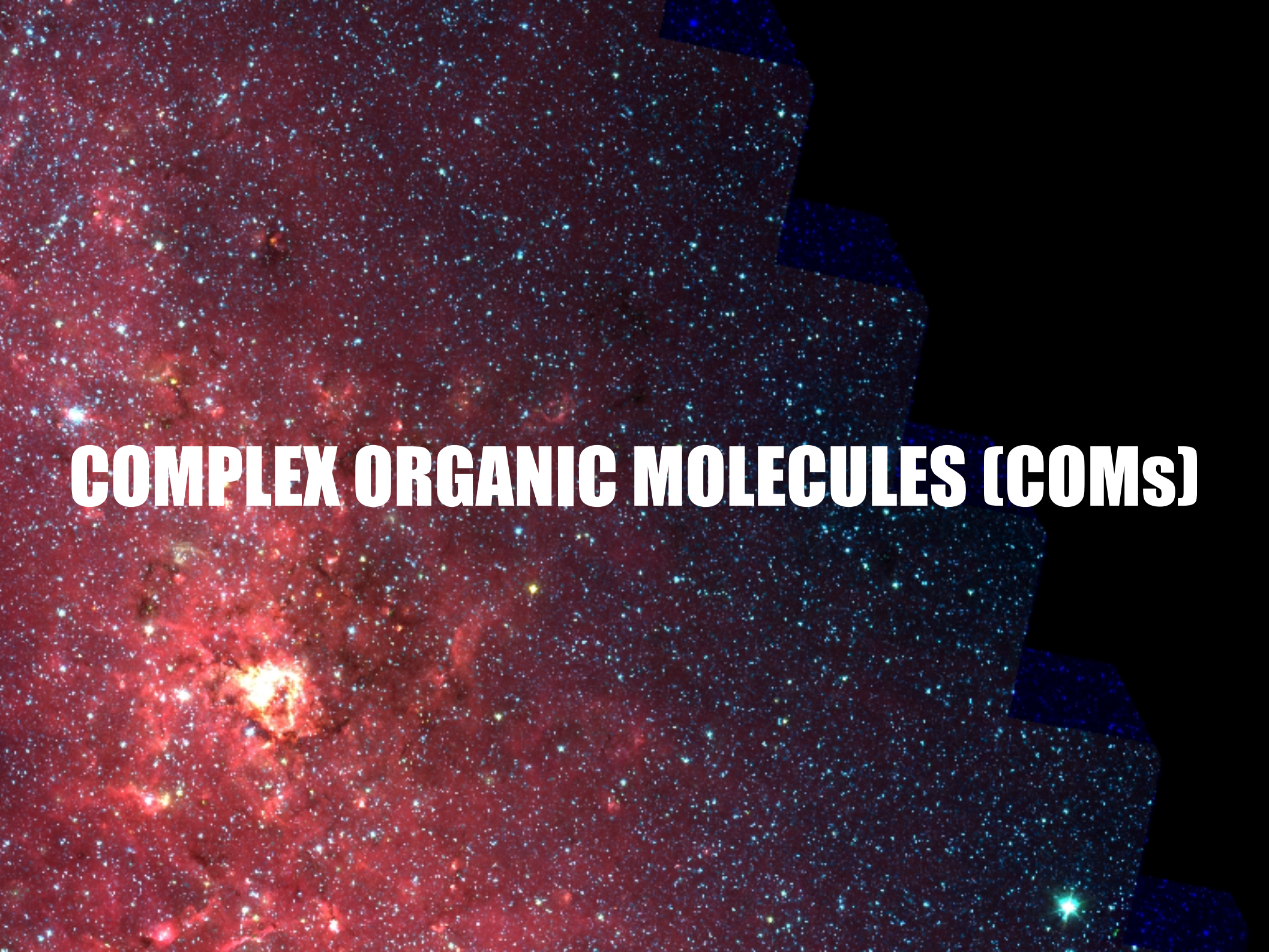
Osservatorio Astrofisico di Arcetri (Florence) - Star Formation Group:

# Understanding the formation of prebiotic molecules in star-forming regions

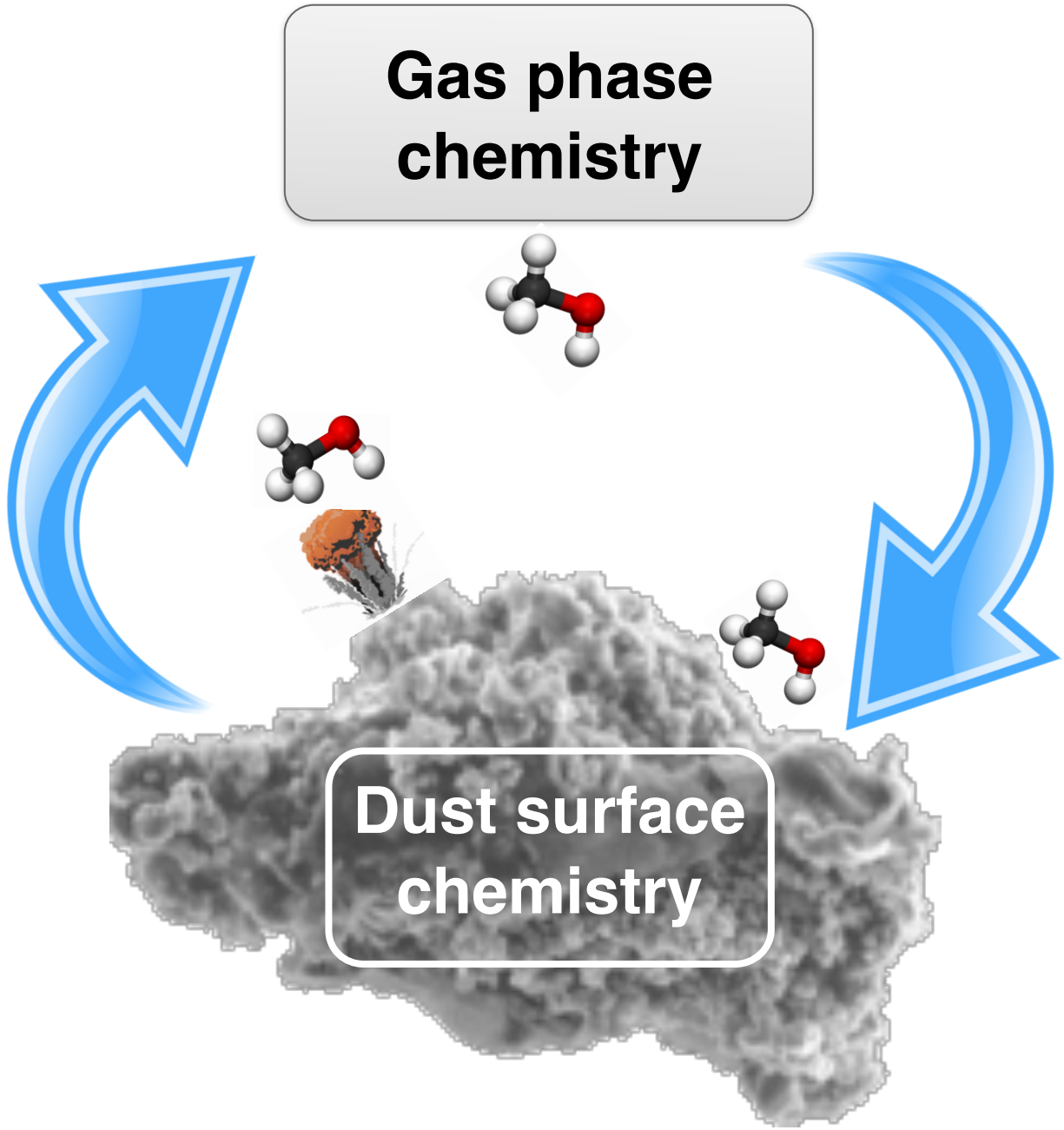
1 - **Detection** of prebiotic molecules in star-forming regions

2 - Derivation of physical parameters: **molecular abundances** and temperatures.

3 - Comparison with **chemical models** → how are they formed?


COMPLEX ORGANIC MOLECULES (COMs)

# COMs formation scenarios




G31.41+0.31

## O-bearing

- 2 atoms: CO, $C^{17}O$, $C^{18}O$, $C^{13}O$
- 3 atoms: HCO, $HC^{18}O^+$, $HC^{17}O^+$, $H^{13}CO^+$
- 4 atoms: $H_2CO$, $H_2{}^{13}CO$
- 5 atoms: $CH_2CO$, HCOOH
- 6 atoms: $CH_3OH$, $^{13}CH_3OH$
- 7 atoms: $CH_3CHO$, c-$H_2COCH_2$
- 8 atoms: $CH_3OCHO$, $CH_2OHCHO$
- 9 atoms: $CH_3OCH_3$, $C_2H_5OH$,
- 10 atoms: $CH_3COCH_3$, $(CH_2OH)_2$

## N-bearing

- 2 atoms: NH, CN, NS
- 3 atoms: HCN, $H^{13}CN$, $HC^{15}N$, $HN^{13}C$, $H^{15}NC$, $N^{15}NH^+$
- 4 atoms: HNCO, $HNC^{18}O$
- 5 atoms: $HC_3N$
- 6 atoms: $NH_2CHO$, $CH_3CN$, $CH_3{}^{13}CN$
- 7 atoms: $HC_5N$, $CH_3NCO$, $C_2H_3CN$
- 9 atoms: $C_2H_5CN$

## Only C and H

- 3 atoms: CCH
- 5 atoms: c-$C_3H_2$
- 7 atoms: $CH_3CCH$

## Si-bearing

- 2 atoms: SiO, SiS

## S-bearing

- 2 atoms: SO, $^{34}SO$, $^{13}CS$, $^{13}C^{34}S$, $C^{34}S$
- 3 atoms: $SO_2$, $^{34}SO_2$, $H_2S$, OCS, $O^{13}CS$, $^{18}OCS$, $OC^{34}S$, $HCS^+$
- 4 atoms: $H_2CS$

## P-bearing

- 2 atoms: PN

## Deuterated

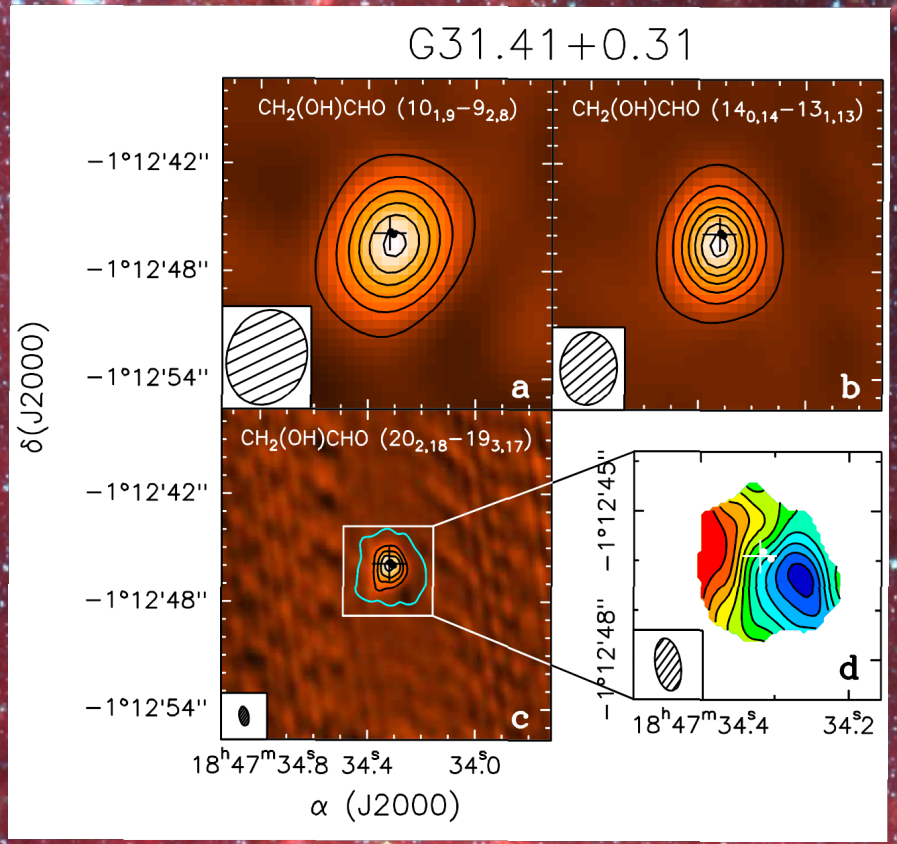
- 3 atoms: DCN, DCO+
- 4 atoms: NH2D
- 6 atoms: CH2DCN, CH2DOH, CH3OD

## H recombination lines

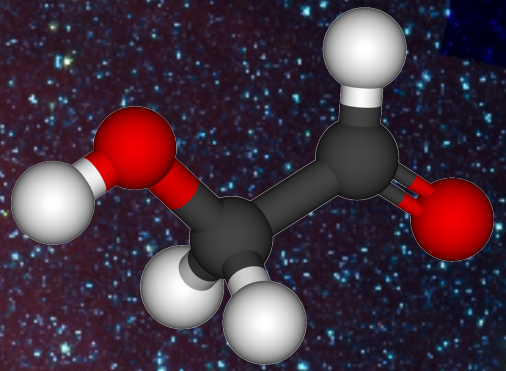
- H-alpha
- H-beta
- H-gamma,
- He-alpha

**45 molecular species, 16 COMs**, 23 isotopologs, 6 deuterated species, 2 cyclic molecules, 4 positive ions and hydrogen recombination lines

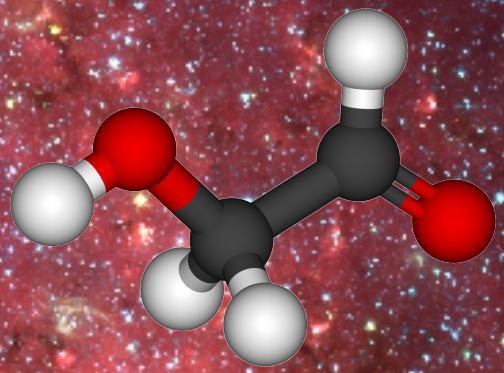
# G31.41+0.31



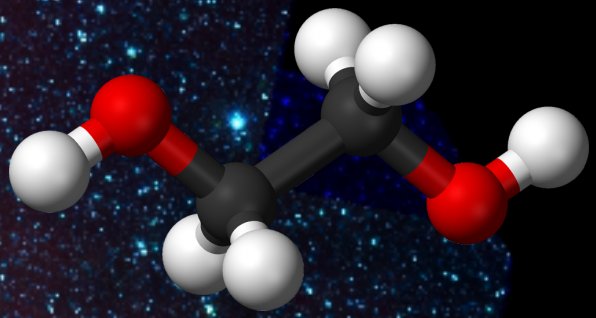

- First detection of **glycolaldehyde** outside the Galactic Center by Beltrán et al. (2009)

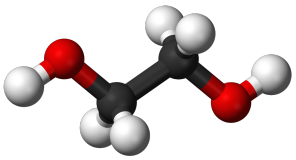


glycolaldehyde
(8 atoms)

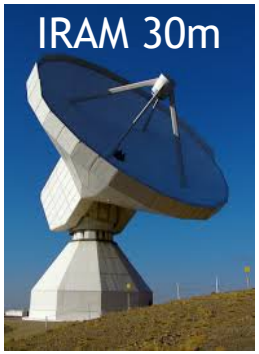


ethylene glycol
(10 atoms)





# Ethylene glycol $(CH_2OH)_2$ in G31





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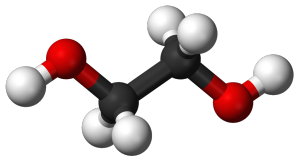
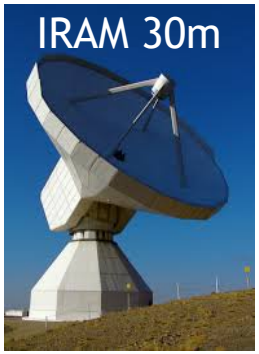
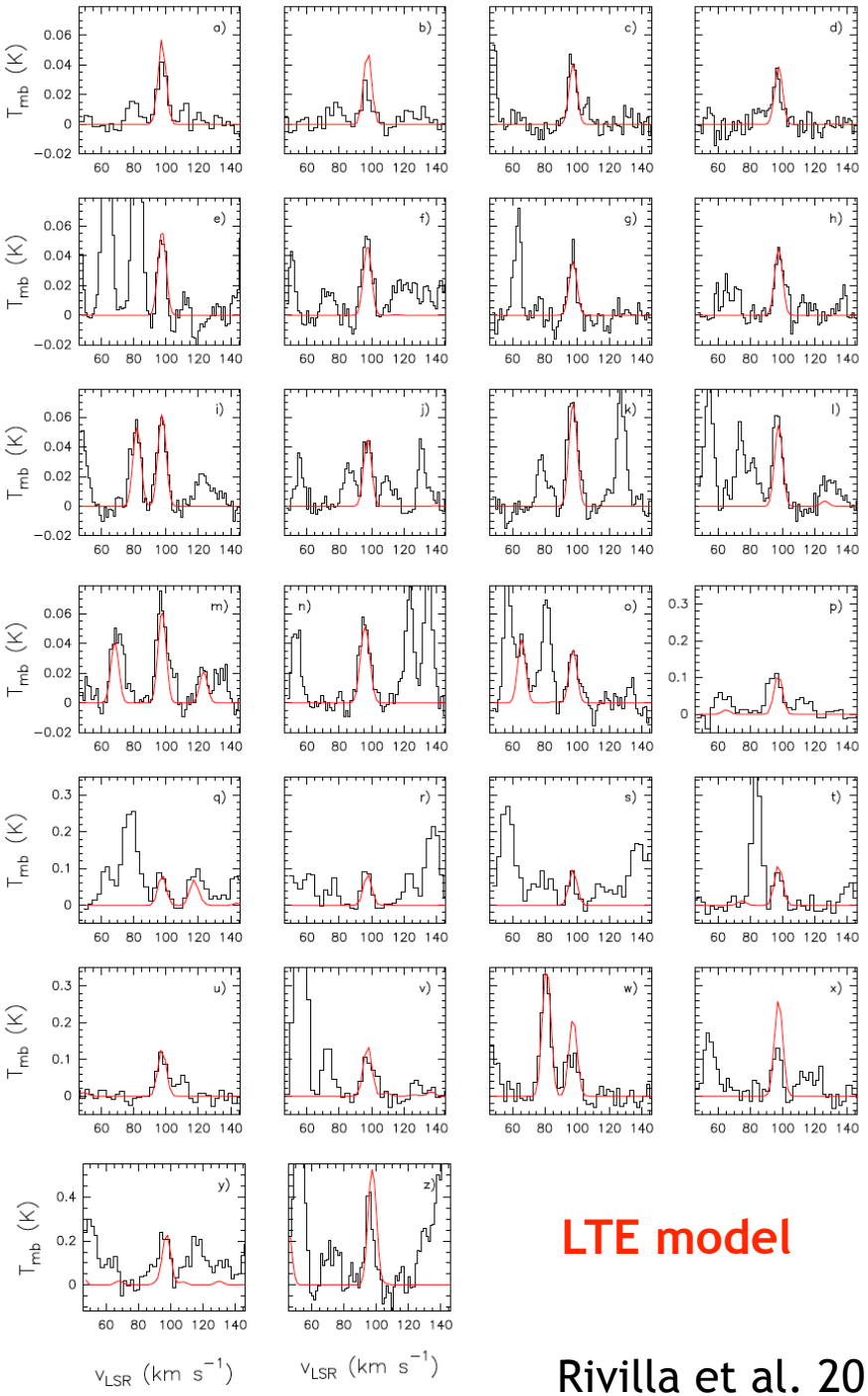


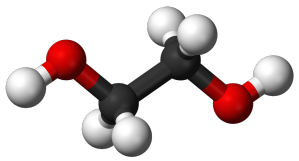





**LTE model**

Rivilla et al. 2017a



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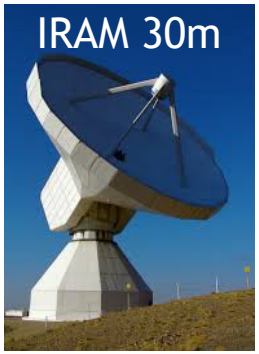




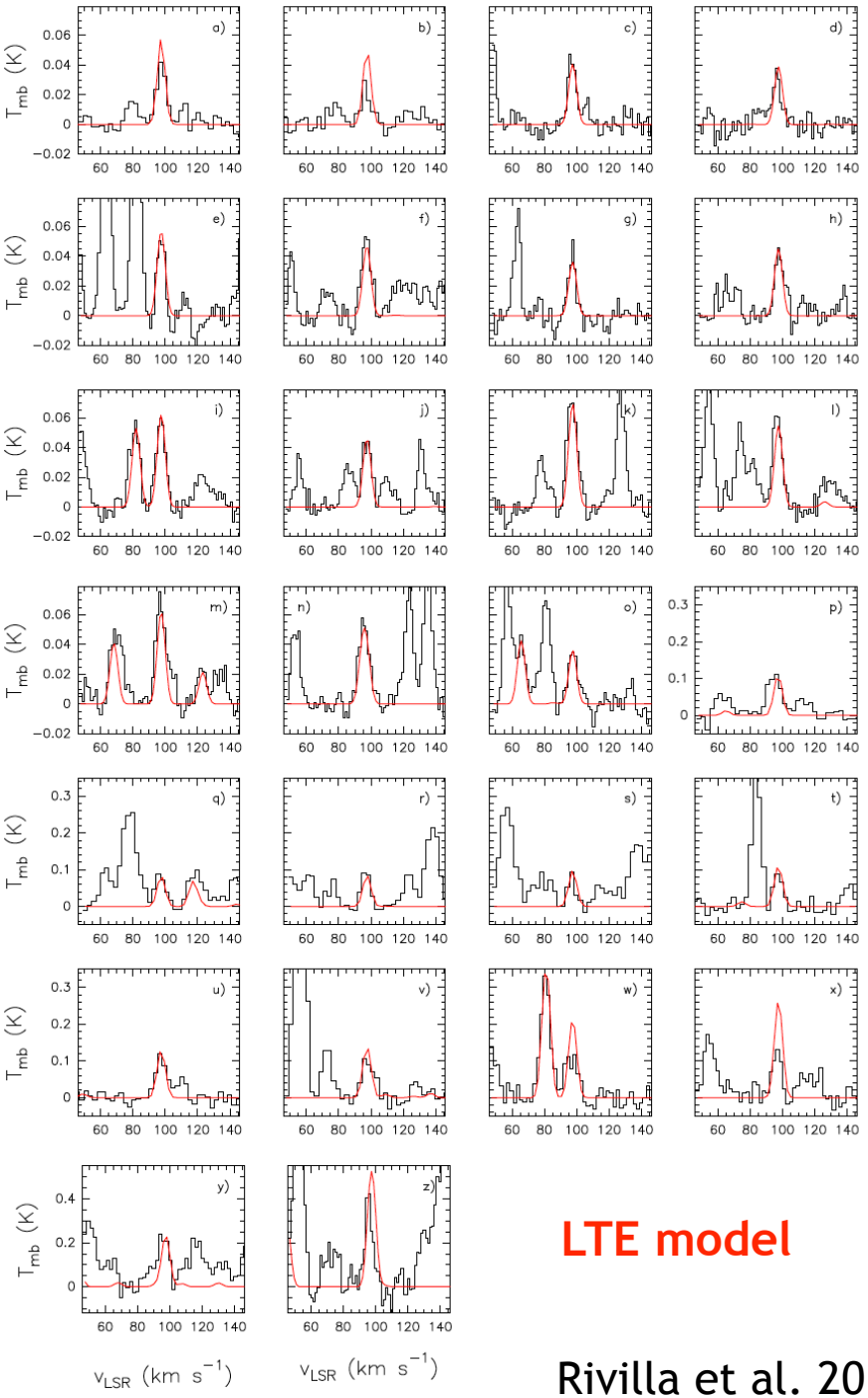


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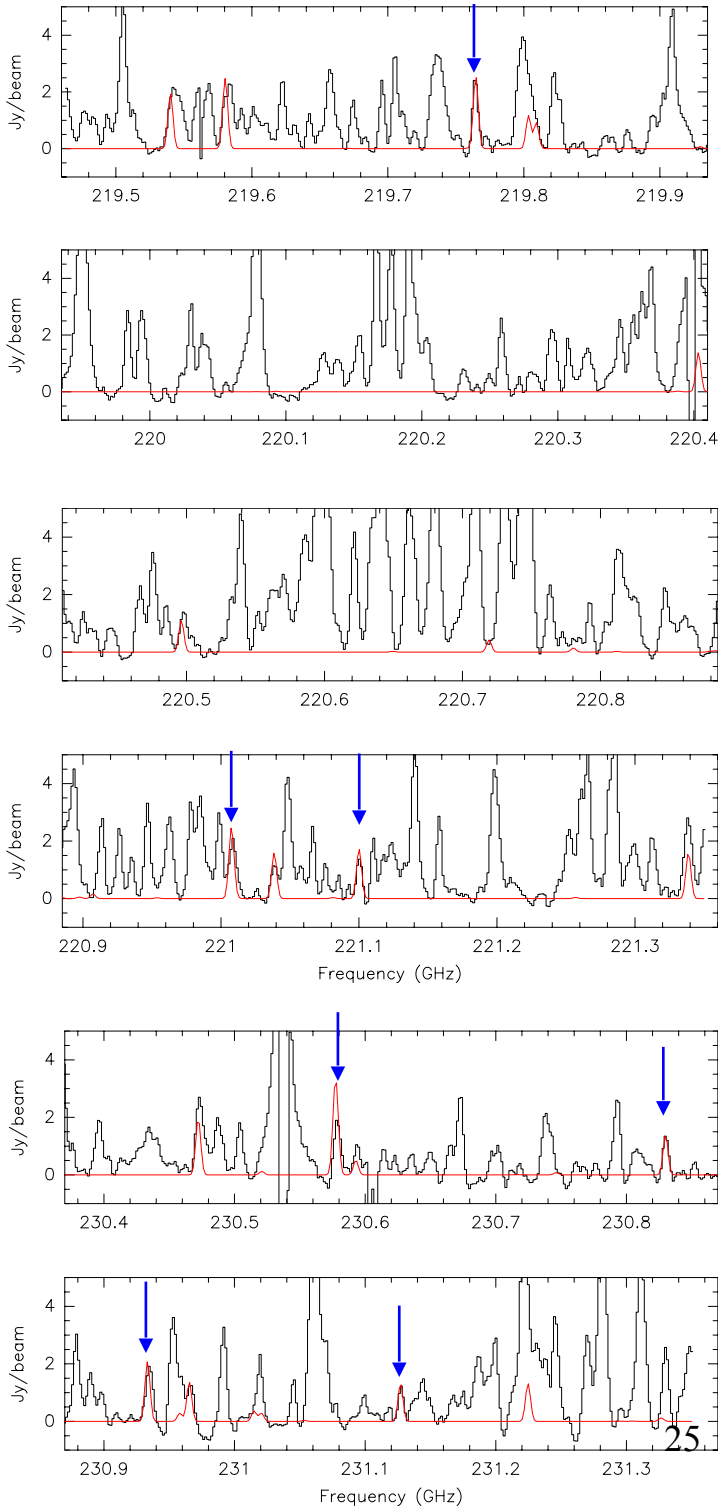
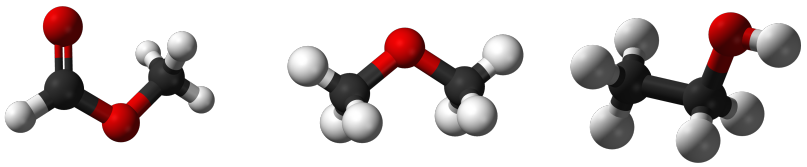
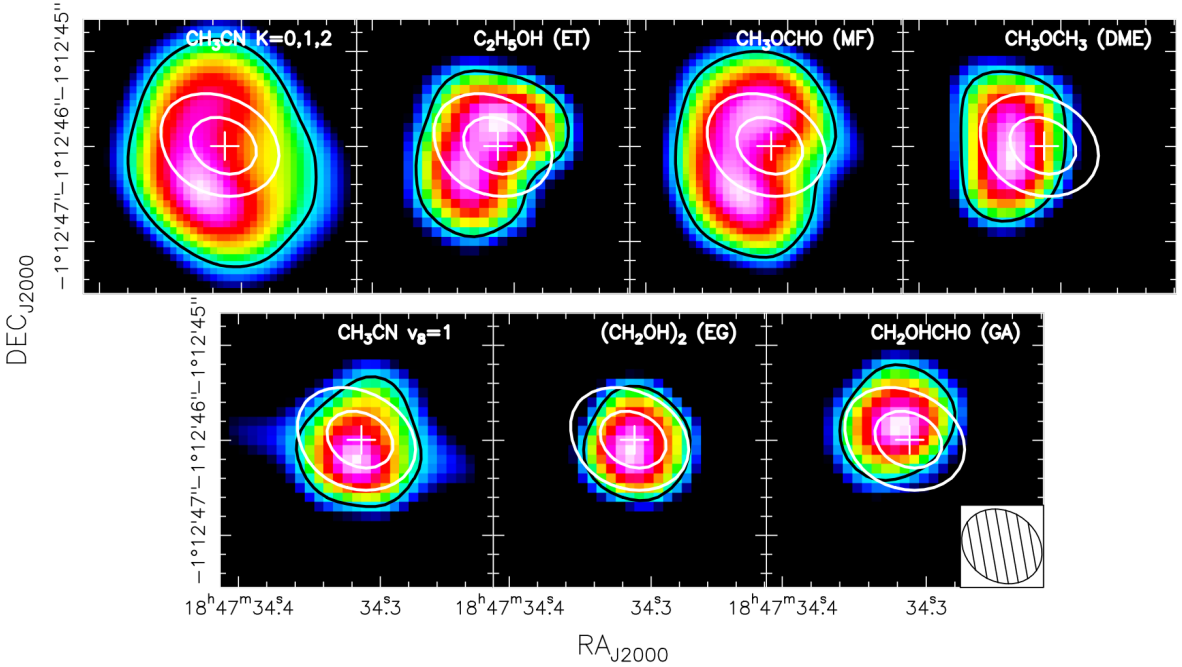


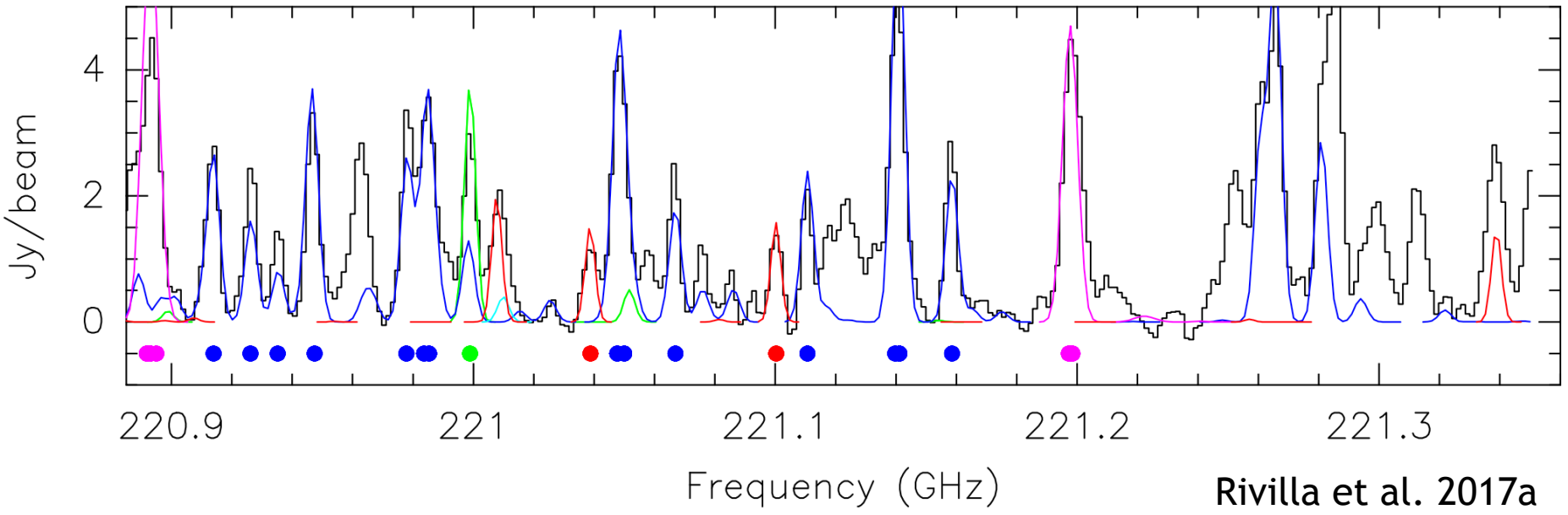

Rivilla et al. 2017a

# More COMs in G31.41



**Methyl formate** **Dimethyl ether** **Ethanol**




Rivilla et al. 2017a

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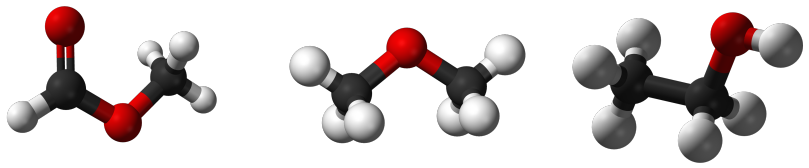
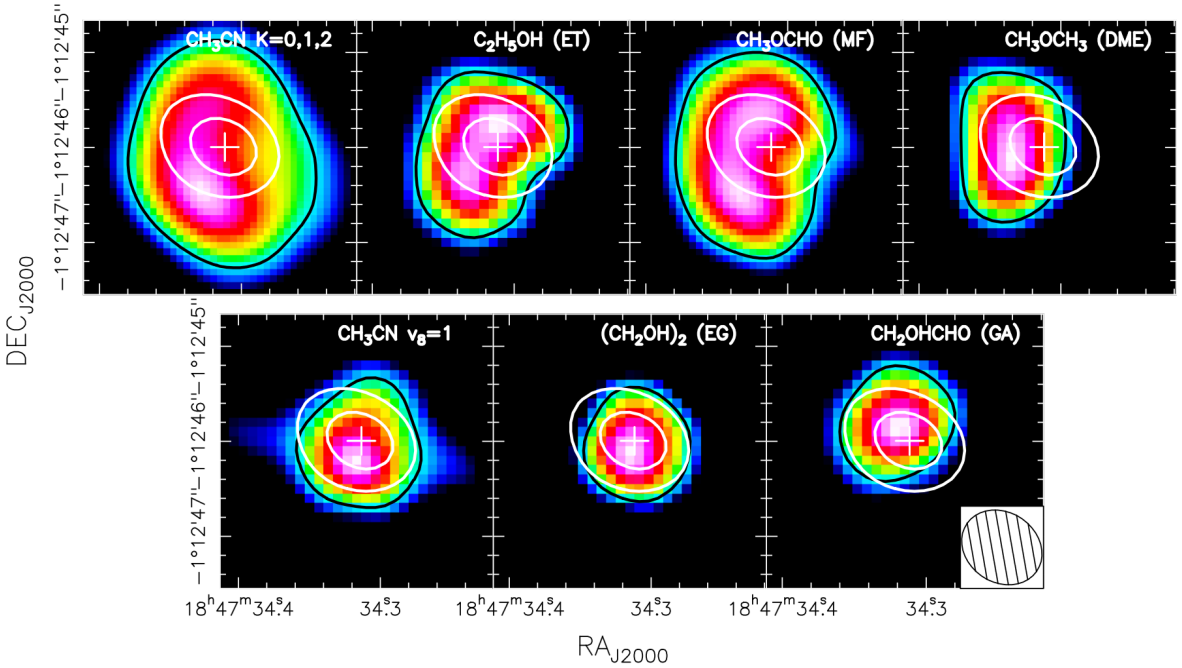
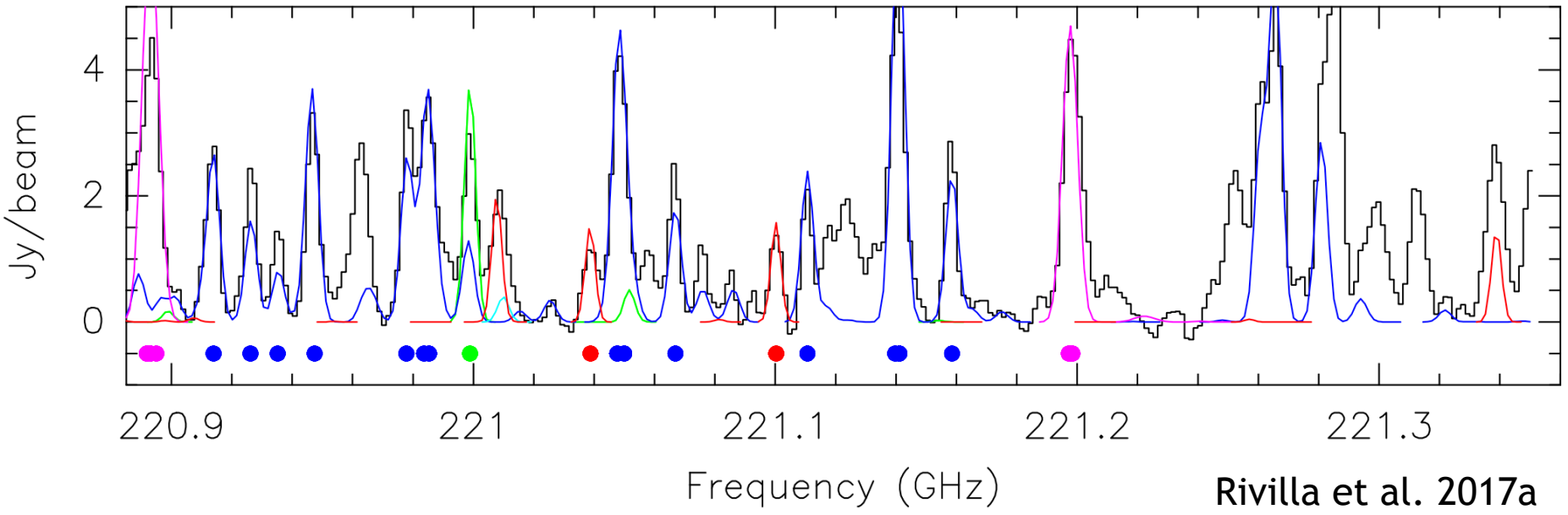


Methyl formate Dimethyl ether Ethanol

**DERIVED PHYSICAL PARAMETERS**

| | EG | ET | GA | MF | DME |
|---|---|---|---|---|---|
| $N$ ($\times 10^{17}$ cm$^{-2}$) | 6.3 | 8.5 | 0.8 | 19 | 40 |
| $X$ ($10^{-8}$)$^b$ | 2.1 | 2.8 | 0.3 | 6 | 13 |
| $T_{ex}$ (K) | 165$^a$ | 120 | 165$^a$ | 165 | 135 |
| $v_{LSR}$ (km s$^{-1}$) | 97.6 | 97.6 | 96.1 | 97.6 | 97.0 |
| $\Delta v$ (km s$^{-1}$) | 5.6 | 5.4 | 5.3 | 4.7 | 4.4 |

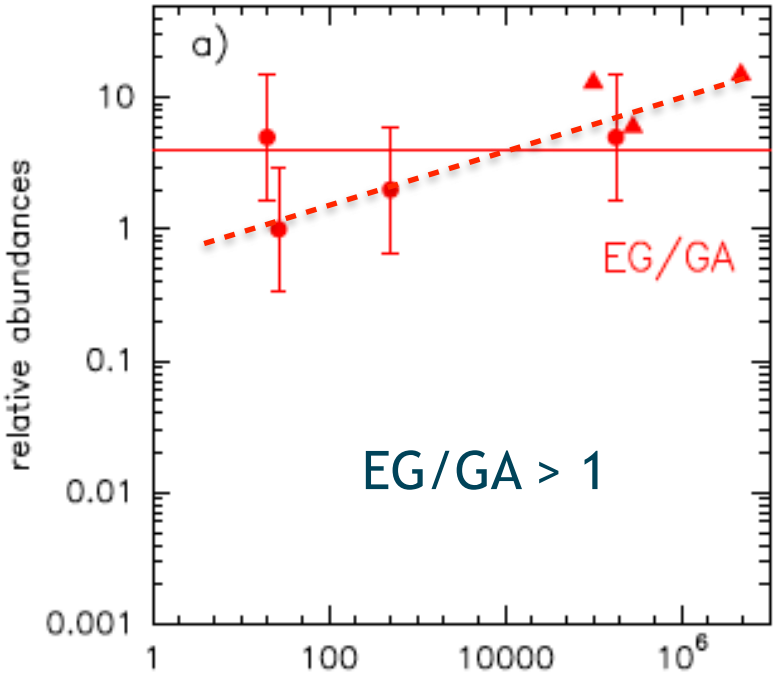



Rivilla et al. 2017a

# Observational results: EG/GA abundance ratio

| Source | [EG/GA] |
|---|---|
| *Hale-Bopp (comet)* | **>6** |
| *Lemmon (comet)* | **>3** |
| *Lovejov (comet)* | **>5** |
| IRAS 16293-2422 | **1** |
| NGC 1333 IRAS2A | **5** |
| NGC7129 FIRS2 | **2** |
| SgrB2N | **1.3** |
| **G31.41+0.31** | **5** |
| Orion hot core | **>10** |
| W51e2 | **>16** |
| G34.3+0.2 | **>6** |
| *G-0.02, G-0.11,G+0.693* | **1.2-1.6** |

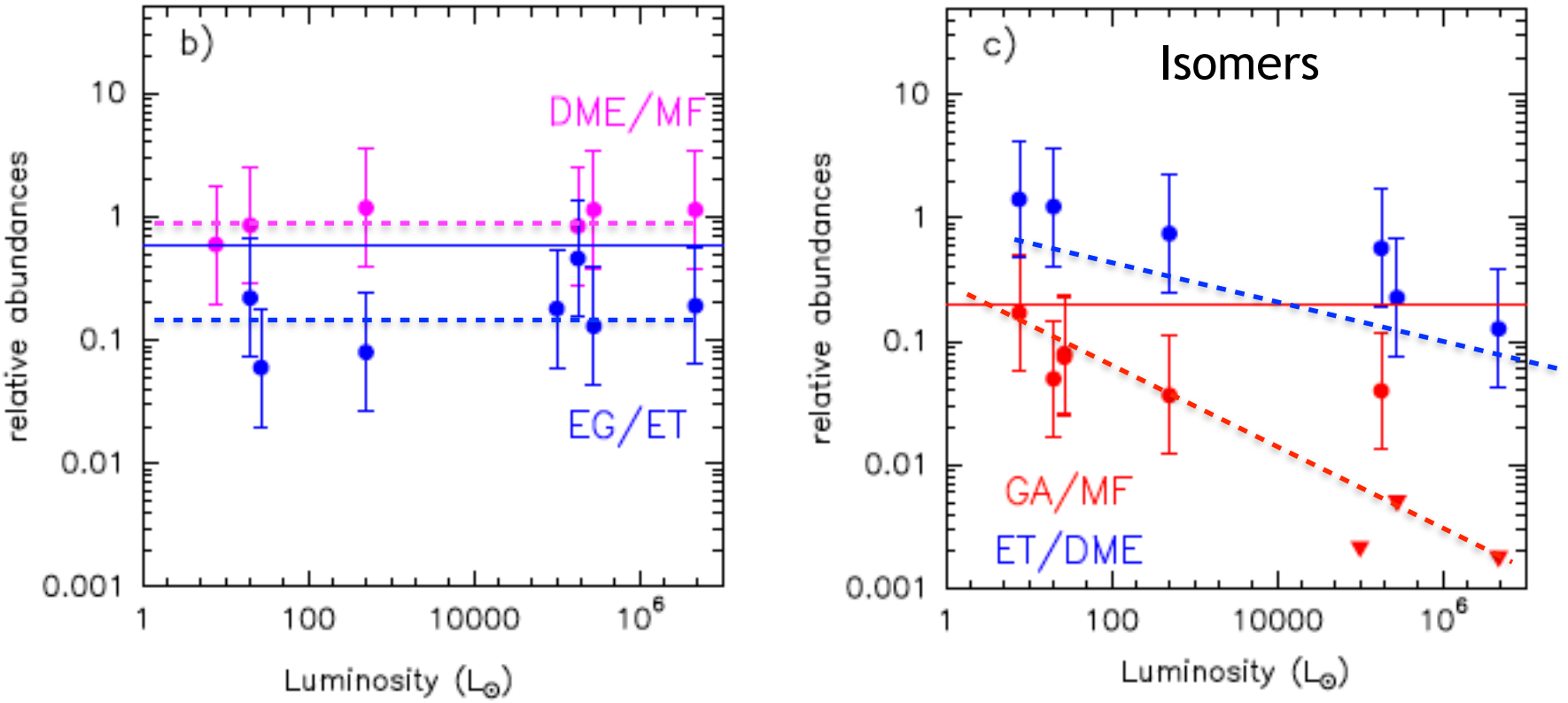



Rivilla et al. 2017a

Hollis+00,02, Crovisier04a, Fuente+04, Requena-Torres08, Beltrán+09, Jørgensen+12, Belloche+13 Maury+14, Biver+14, Coutens+15, Brouillet+15, Lykke+15, Taquet+15, Rivilla+17a.

# Observational results: abundances ratios

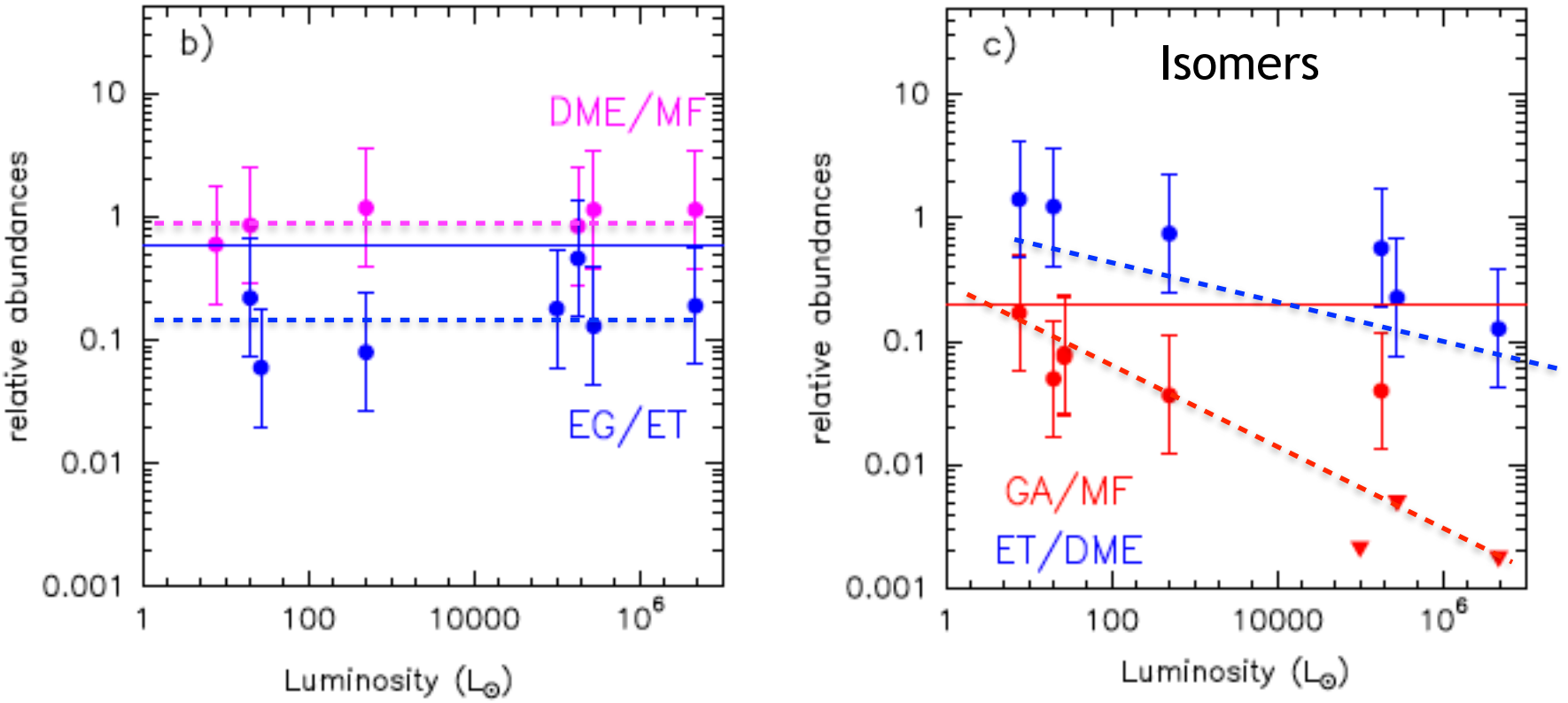
Rivilla et al. 2017a




**What can be infer about the formation of COMs from the results of the observations?**

# Observational results: abundances ratios

Rivilla et al. 2017a




**What can be infer about the formation of COMs from the results of the observations?**

If two species are chemically linked (i.e. they have a common precursor and/or one is formed from the other) their relative abundance should be nearly constant regardless the luminosity.

# Chemical pathways

| COM | | Chemical pathway |
|---|---|---|
| $(CH_2OH)_2$ (EG) | [1] | $CH_2OHCHO + 2H \longrightarrow (CH_2OH)_2$ |
| | [2] | $CH_2OH + CH_2OH \longrightarrow (CH_2OH)_2$ |
| $CH_2OHCHO$ (GA) | [3] | $2HCO \longrightarrow CO + H_2CO \longrightarrow HOCCOH;$ $HOCCOH + H \longrightarrow CH_2OCHO;$ $CH_2OCHO + H \longrightarrow CH_2OHCHO$ |
| | [4] | $HCO + CH_2OH \longrightarrow CH_2OHCHO$ |
| $CH_3OCHO$ (MF) | [5] | $CH_3O + HCO \longrightarrow CH_3OCHO$ |
| | [6] | $CH_3OCH_3 + O \longrightarrow CH_3OCHO + H$ (gas phase) |
| $CH_3OCH_3$ (DME) | [7] | $CH_3O + CH_3 \longrightarrow CH_3OCH_3$ |
| $CH_3CH_2OH$ (ET) | [8] | $CH_2OH + CH_3 \longrightarrow CH_3CH_2OH$ |

Bennett & Kaiser07

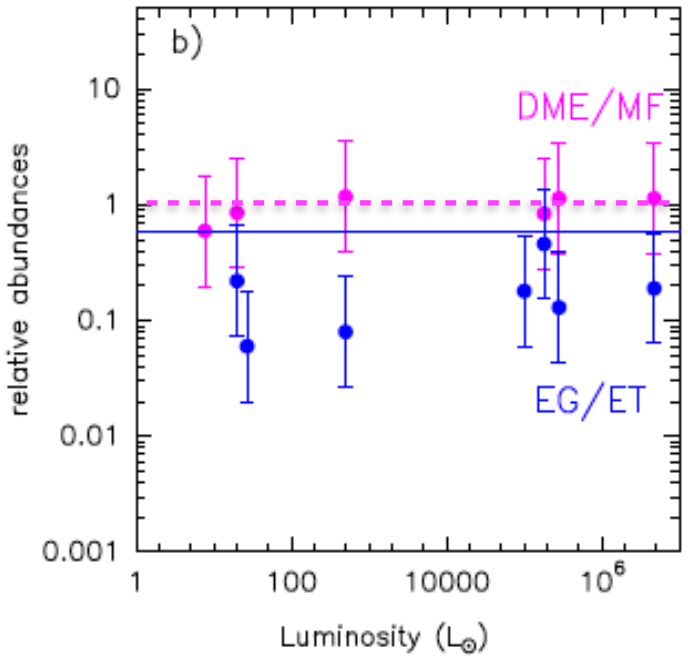
Garrod+08

Woods+13

Balucani+15

Fedoseev+14

Butscher+15




DME and MF formed from the common precursor $CH_3O$

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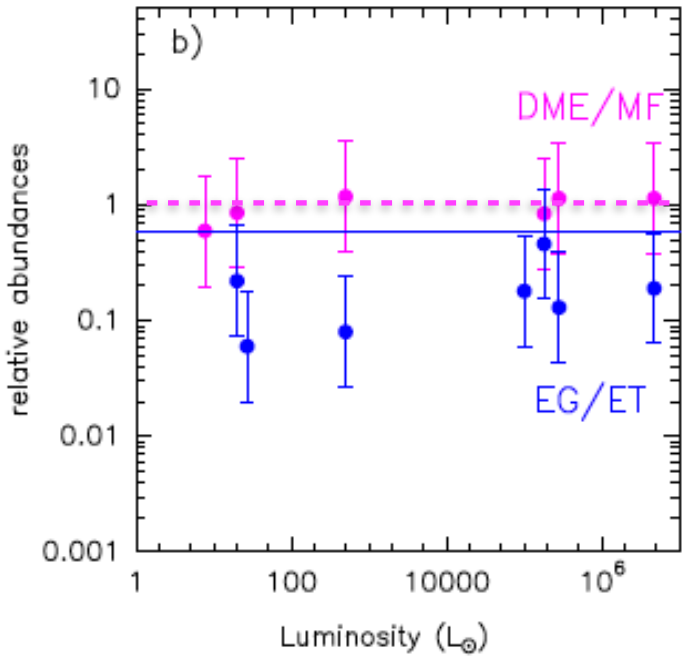
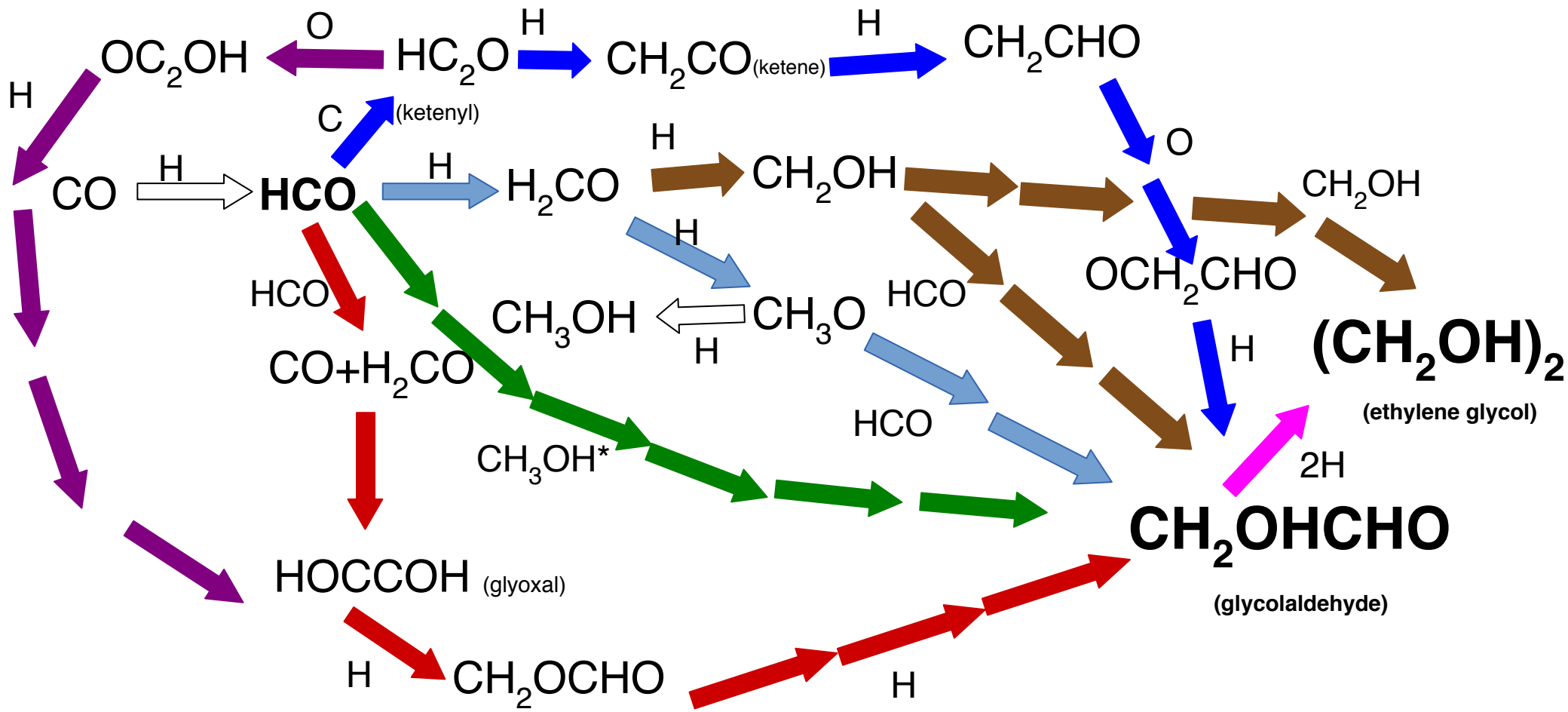



DME and MF formed from the common precursor $CH_3O$

MF formed directly from DME in gas-phase (Balucani+2015)

# Game of Reactions




(F) Woods+13, Fedoseev+15
(A) Sorrell+01, Woods+12
(E) Charnley&Rogers+05
Fedoseev+15
(D) Beltrán+09,Woods+12
Charnley&Rogers+05
(B) Bennett&Kaisser07, Garrod+08, Butscher+15

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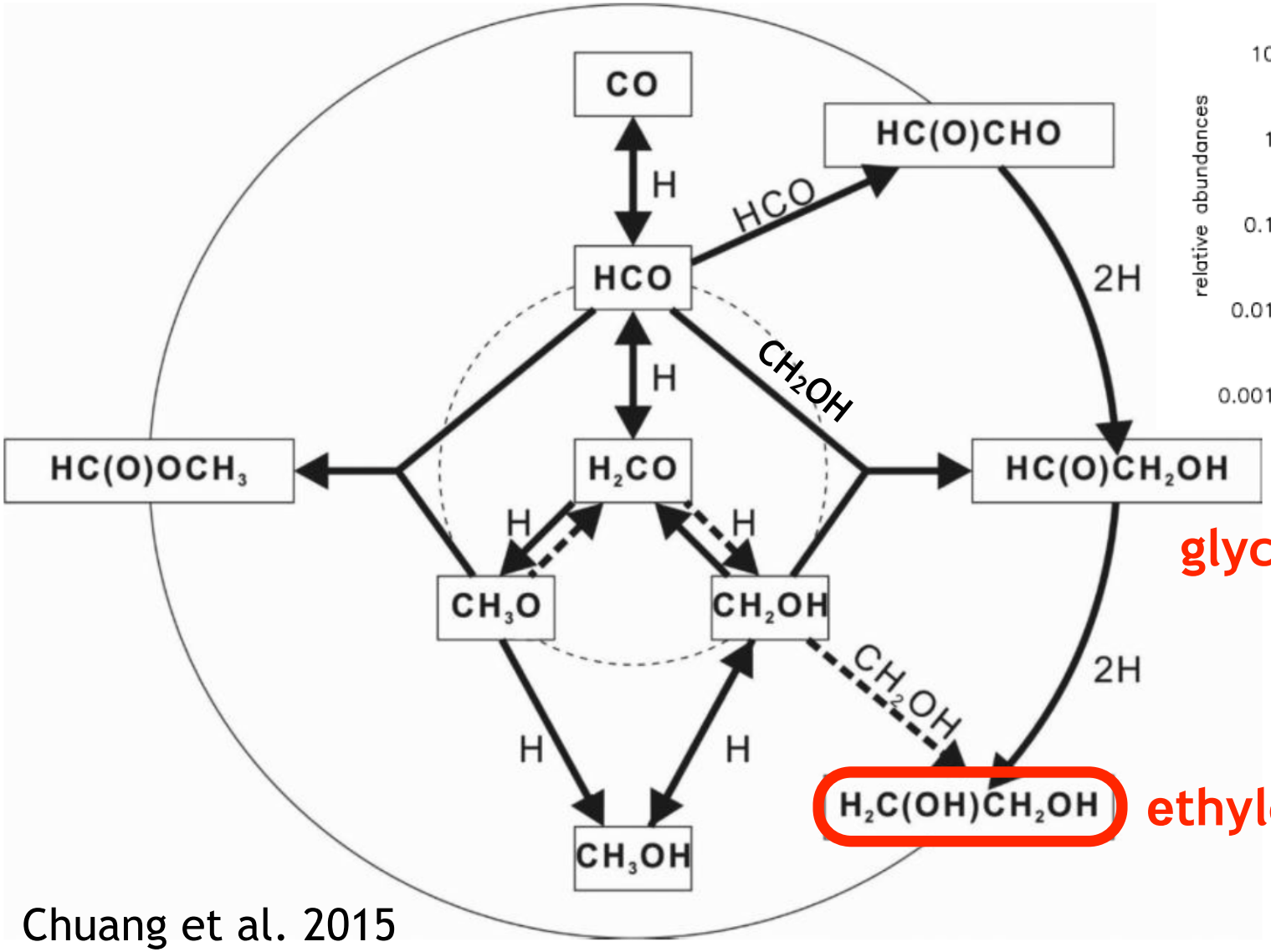
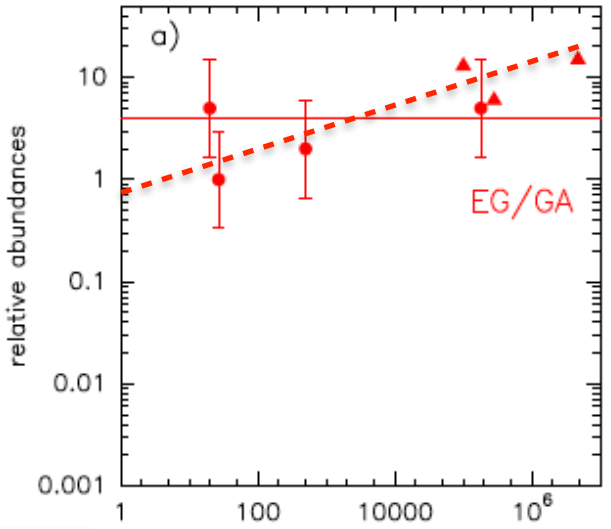
# Game of Reactions




glycolaldehyde

ethylene glycol

Chuang et al. 2015

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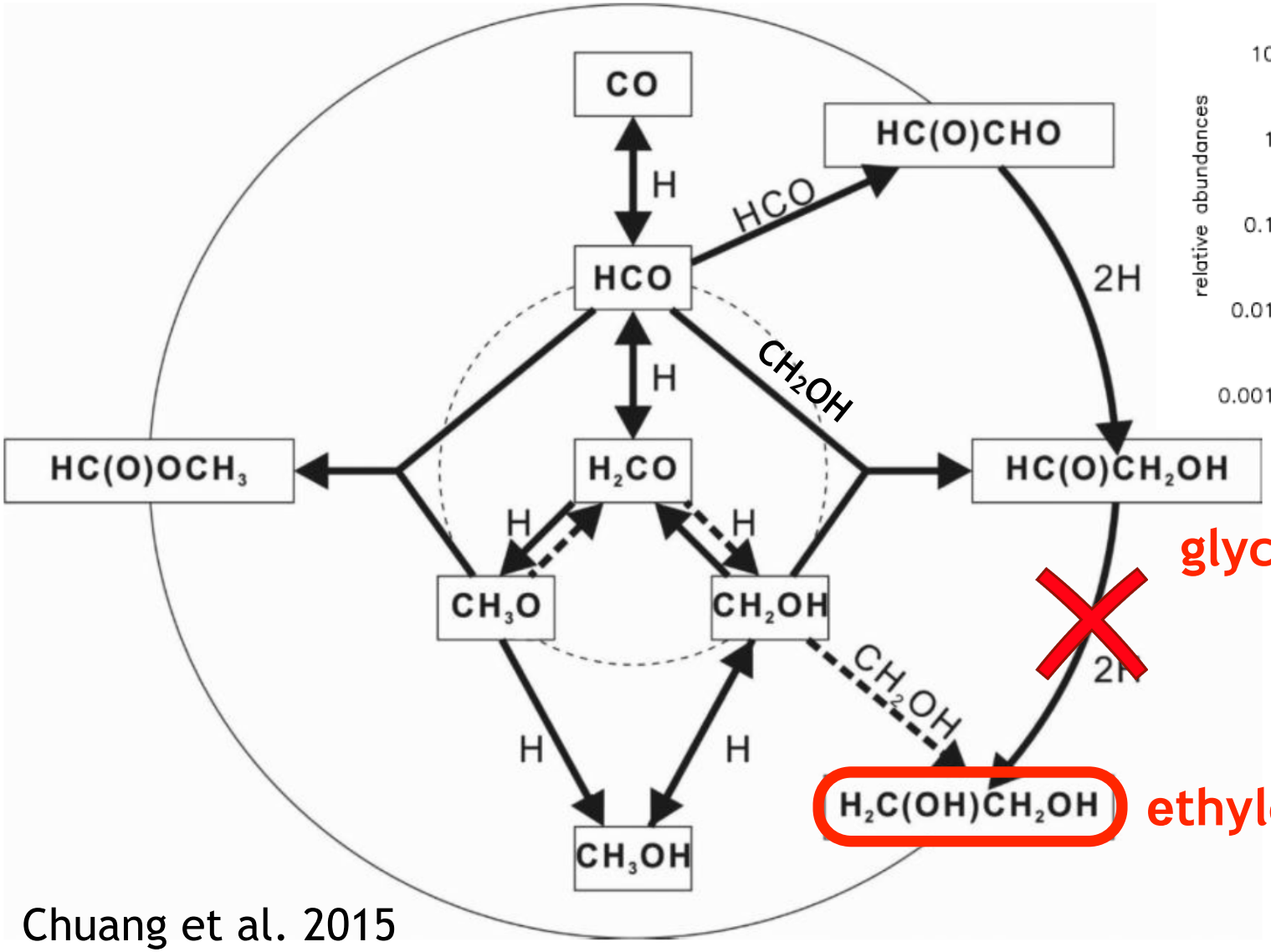


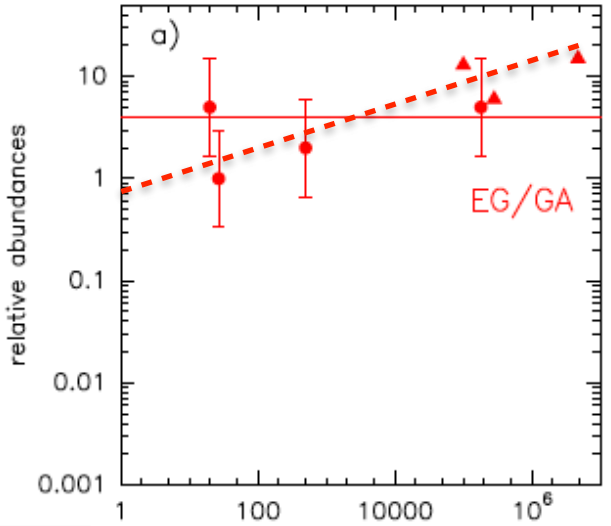


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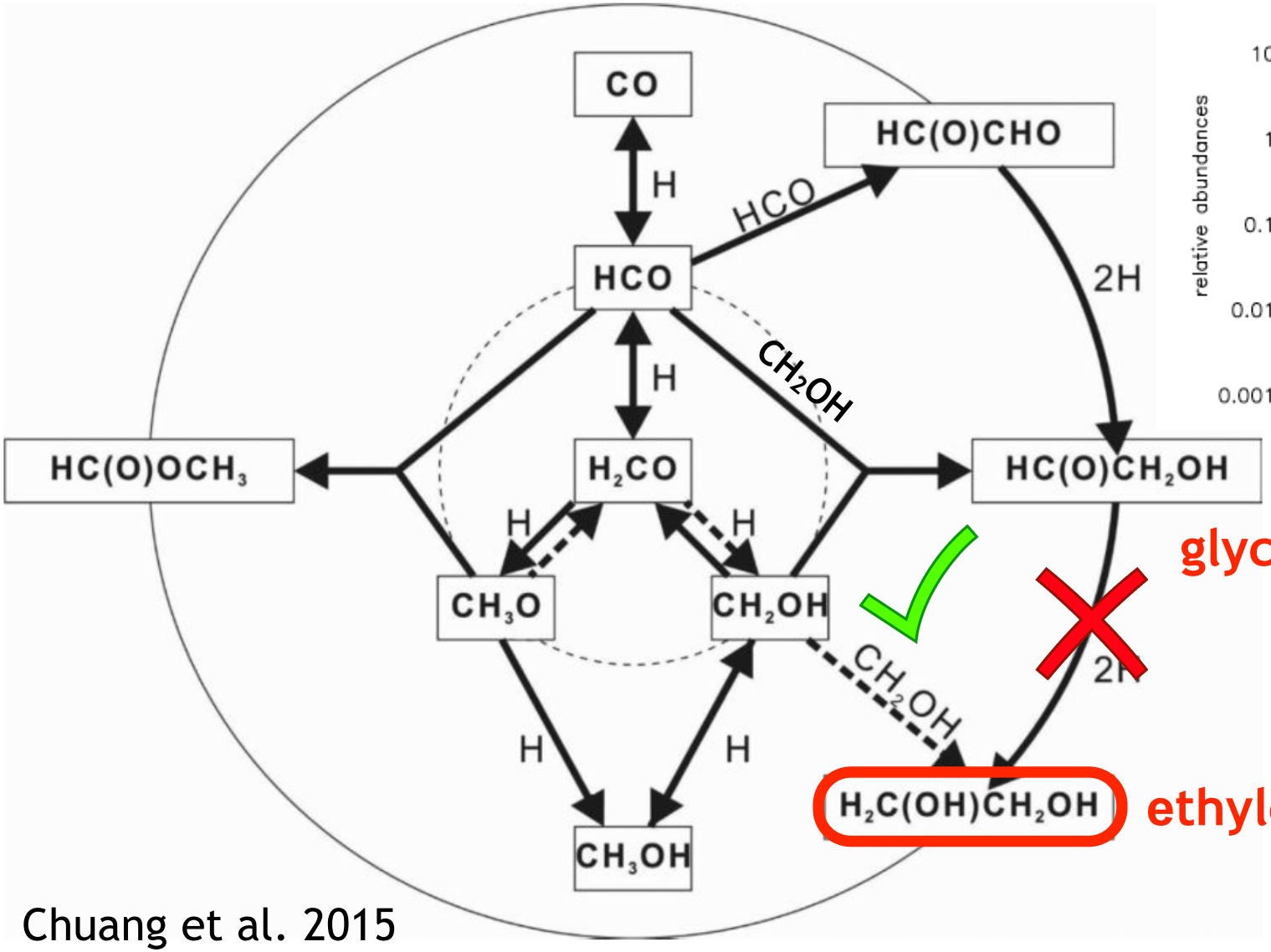


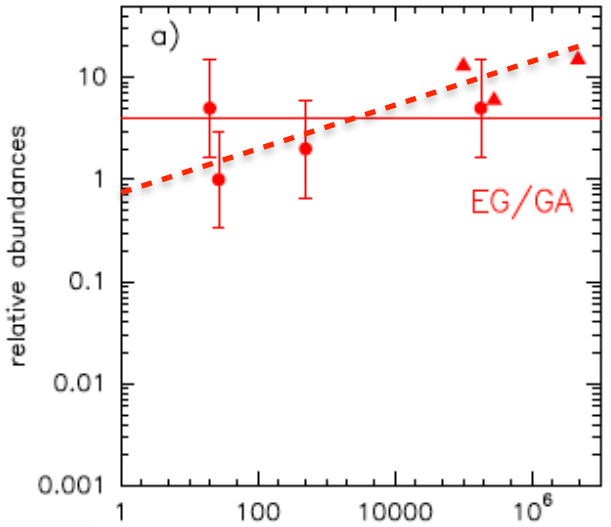


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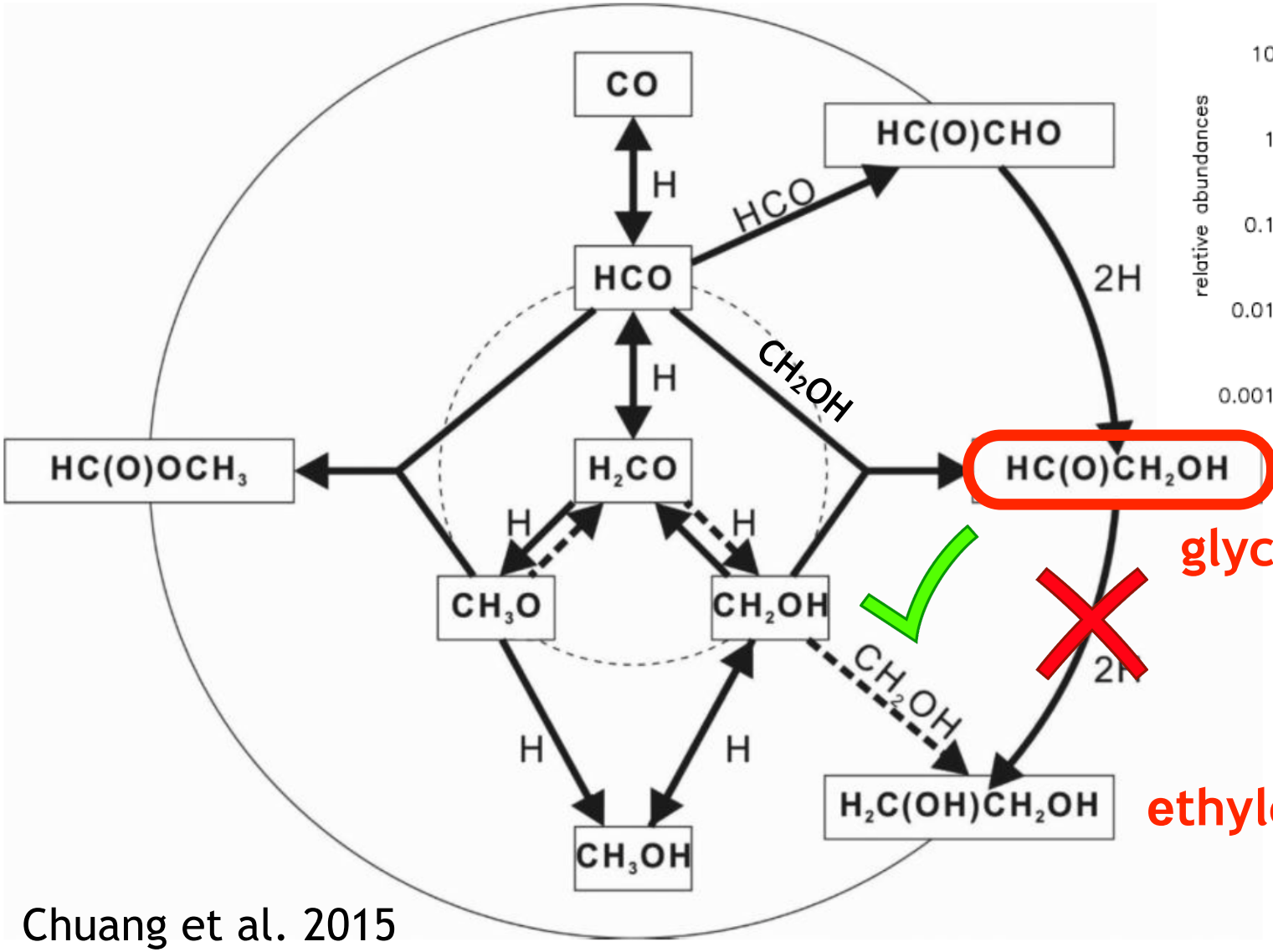


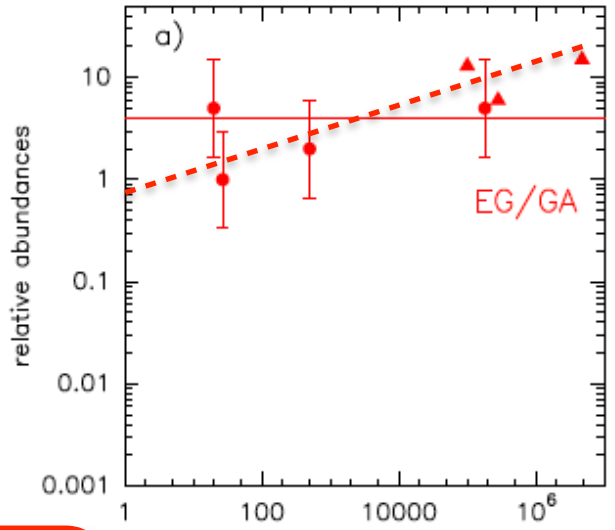


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Chuang et al. 2015

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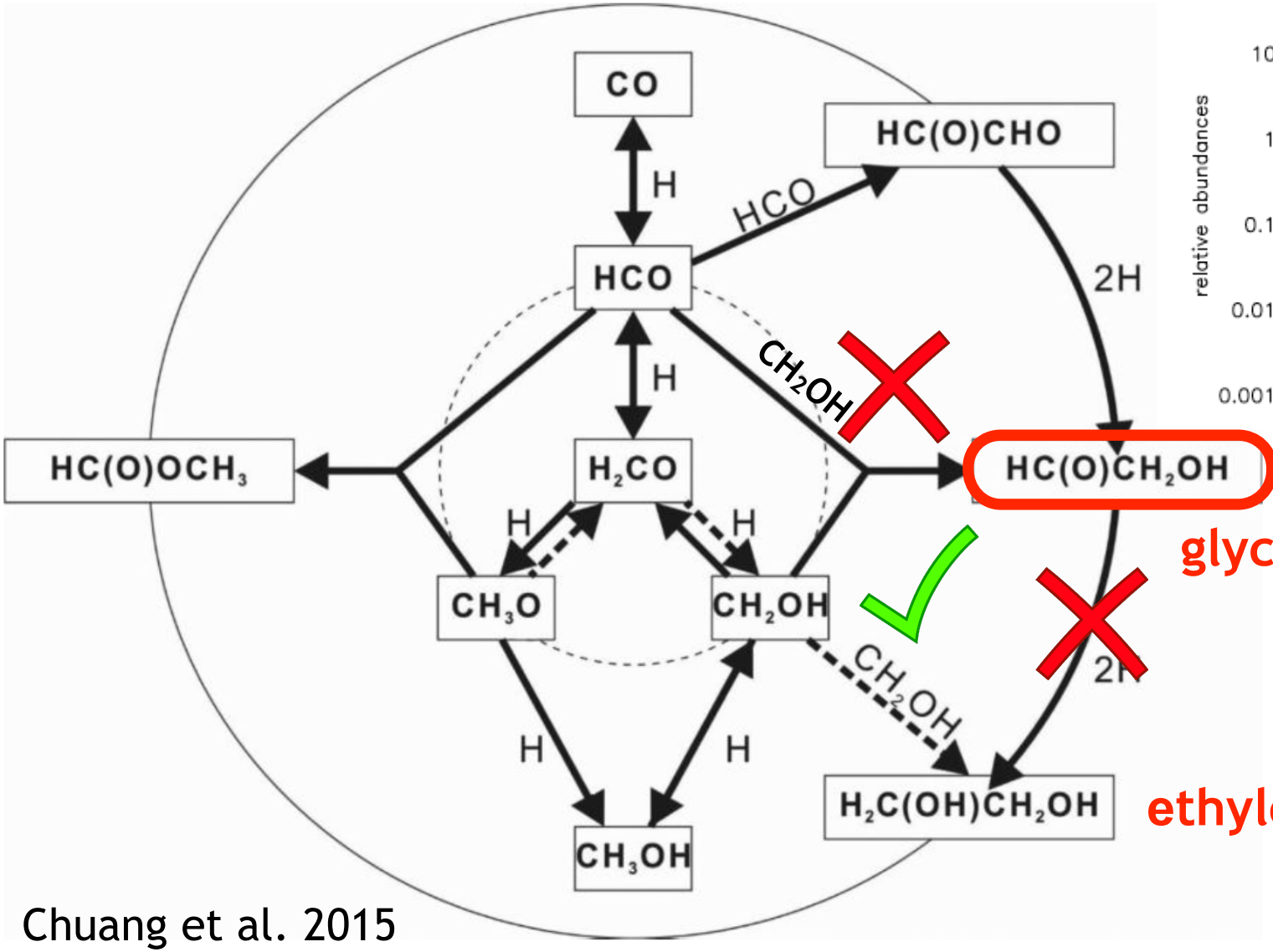


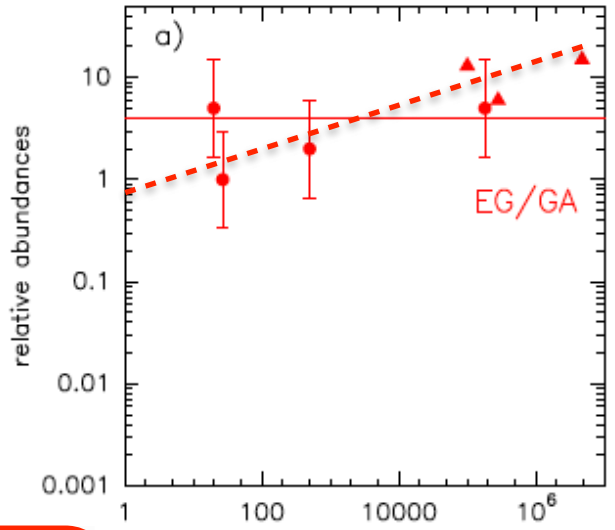


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Chuang et al. 2015

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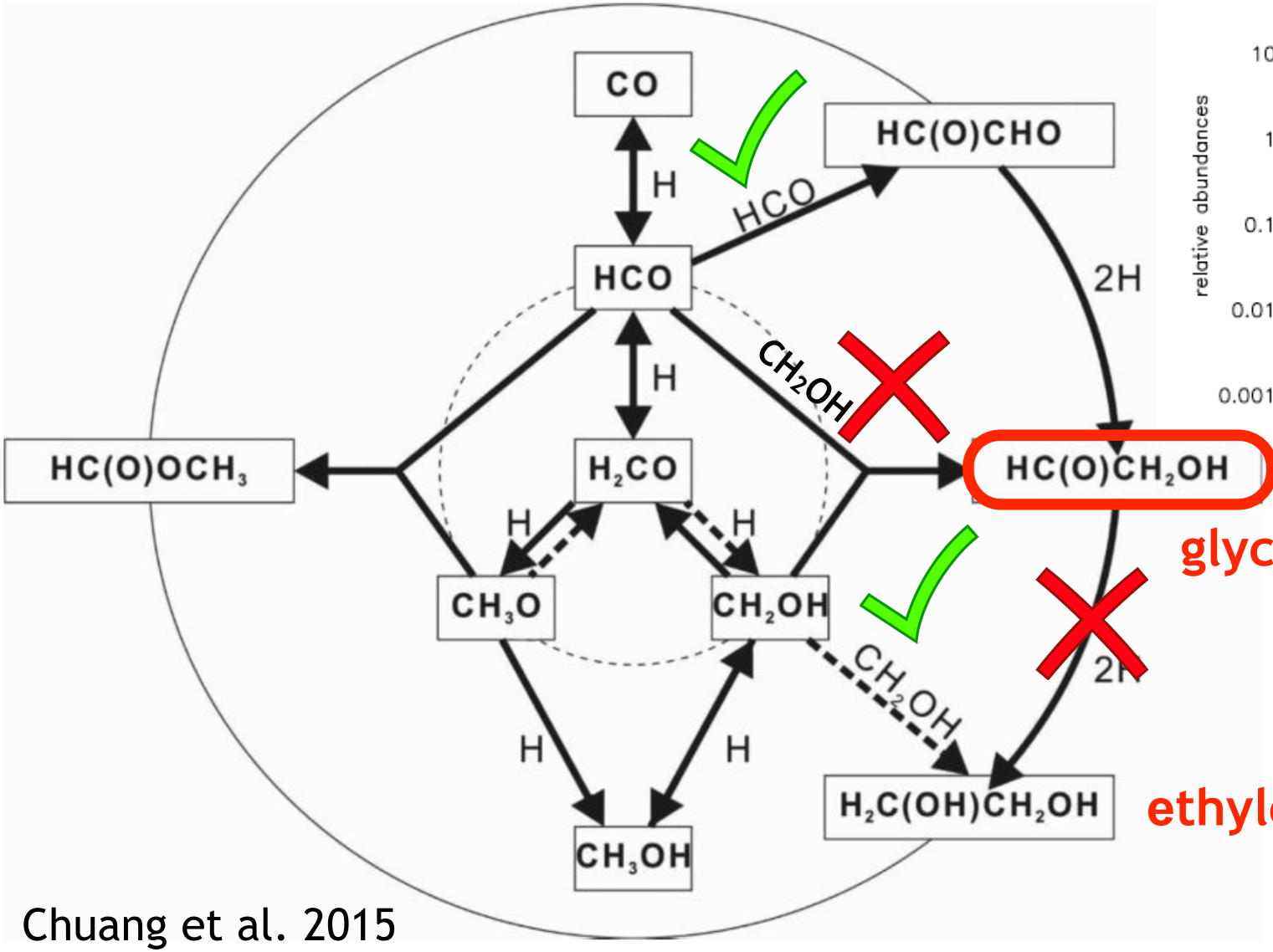


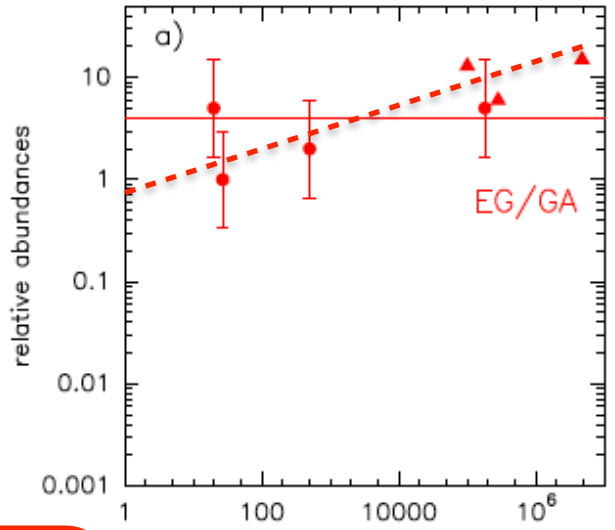


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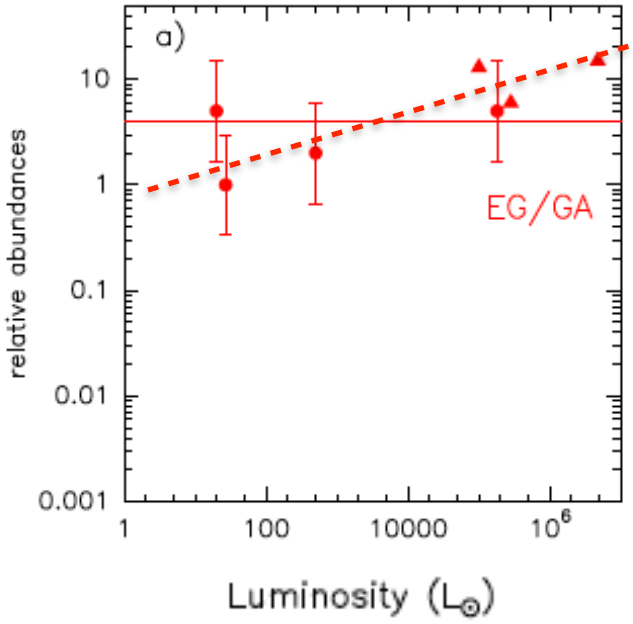
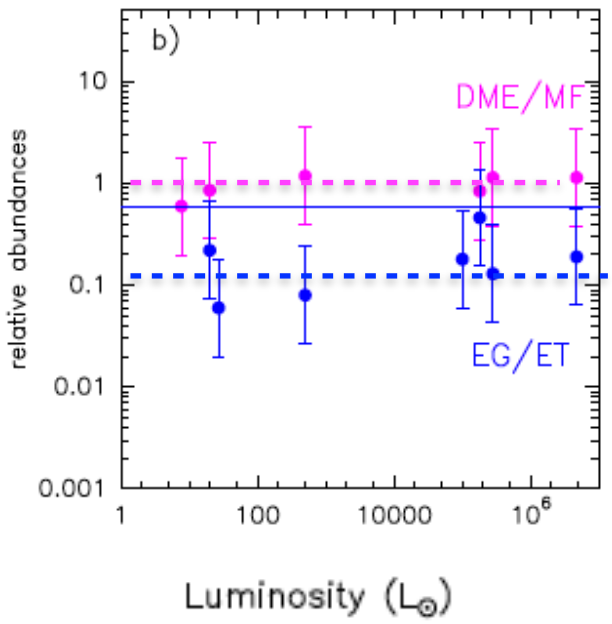
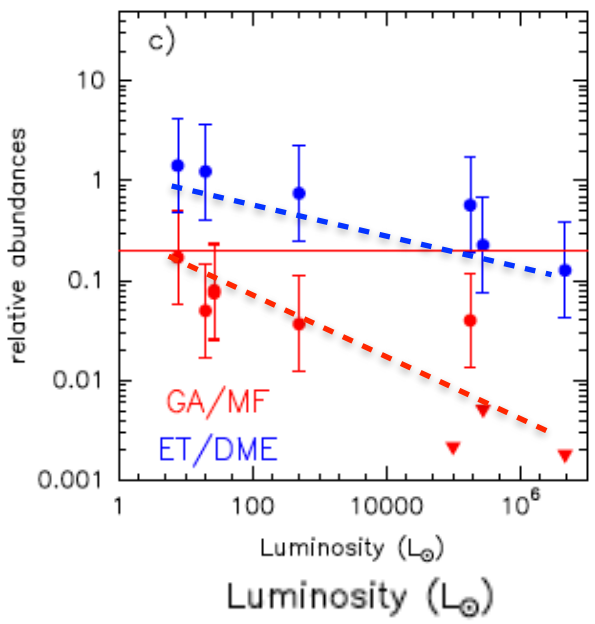
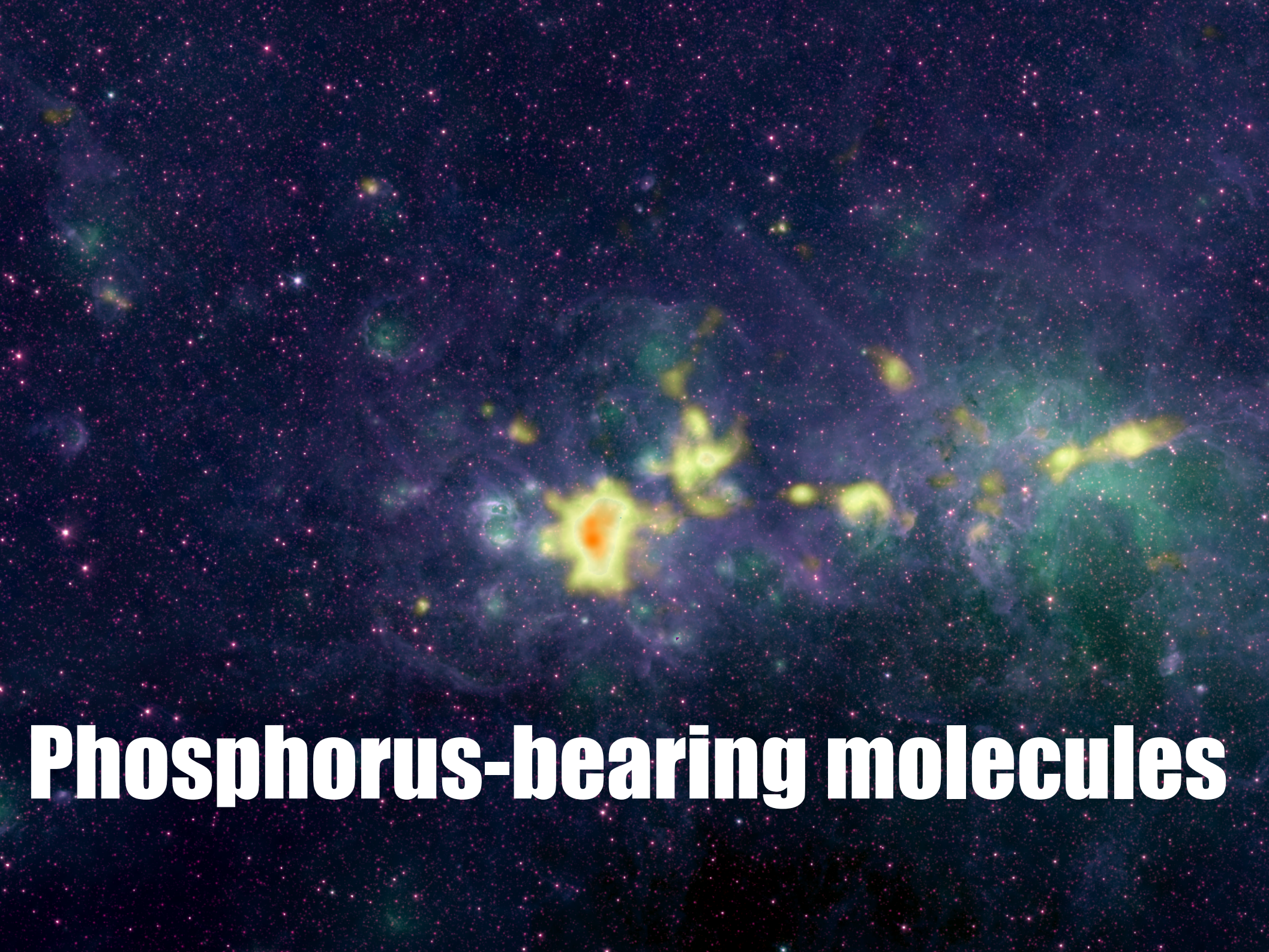


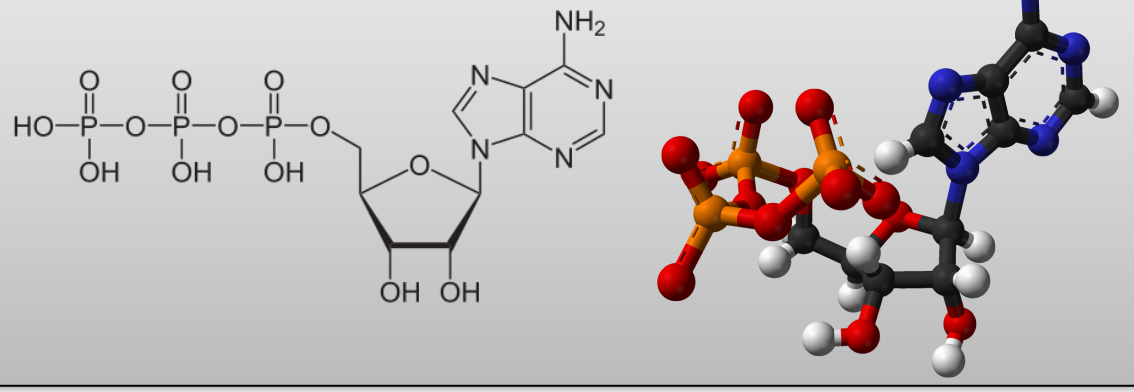

Phosphorus-bearing molecules

# Phosphorus: key to Life

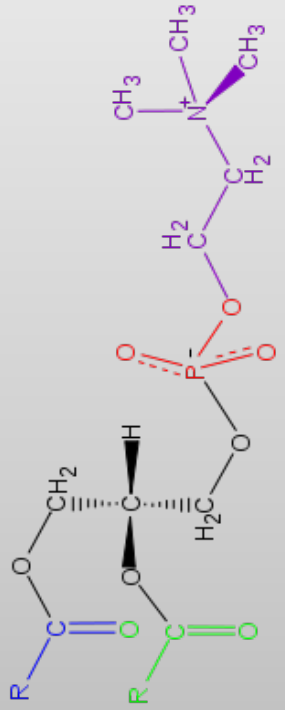
Chemical reactivity

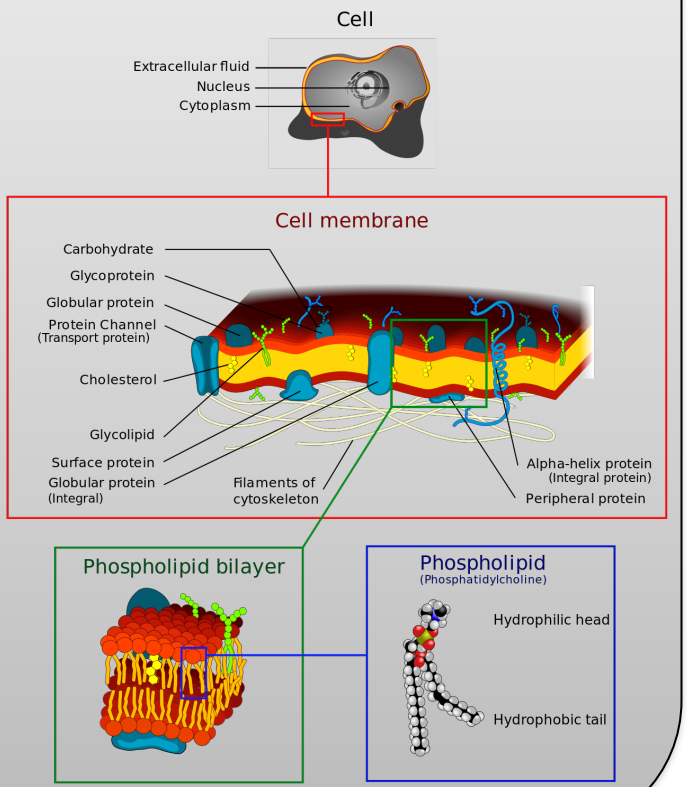
Structural stability

## ATP: Adenosine Triphosphate

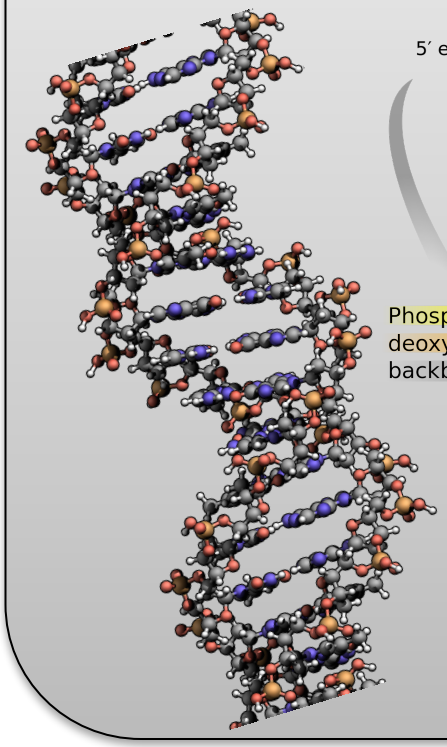


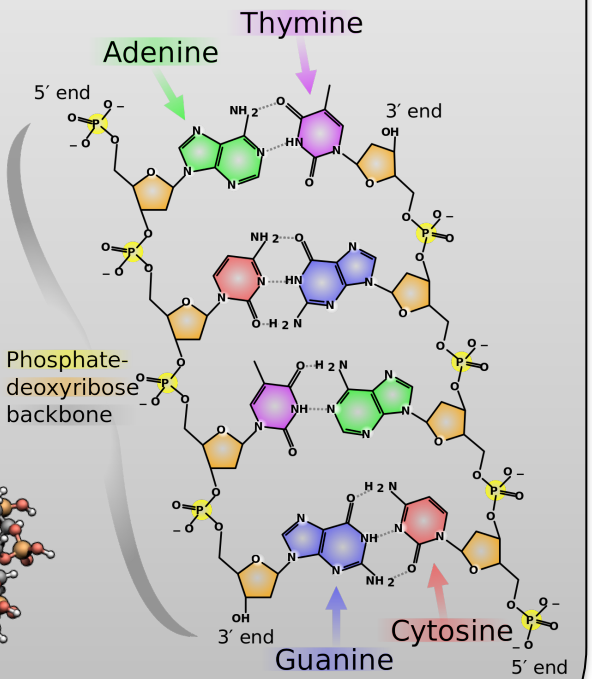

## Phospholipids

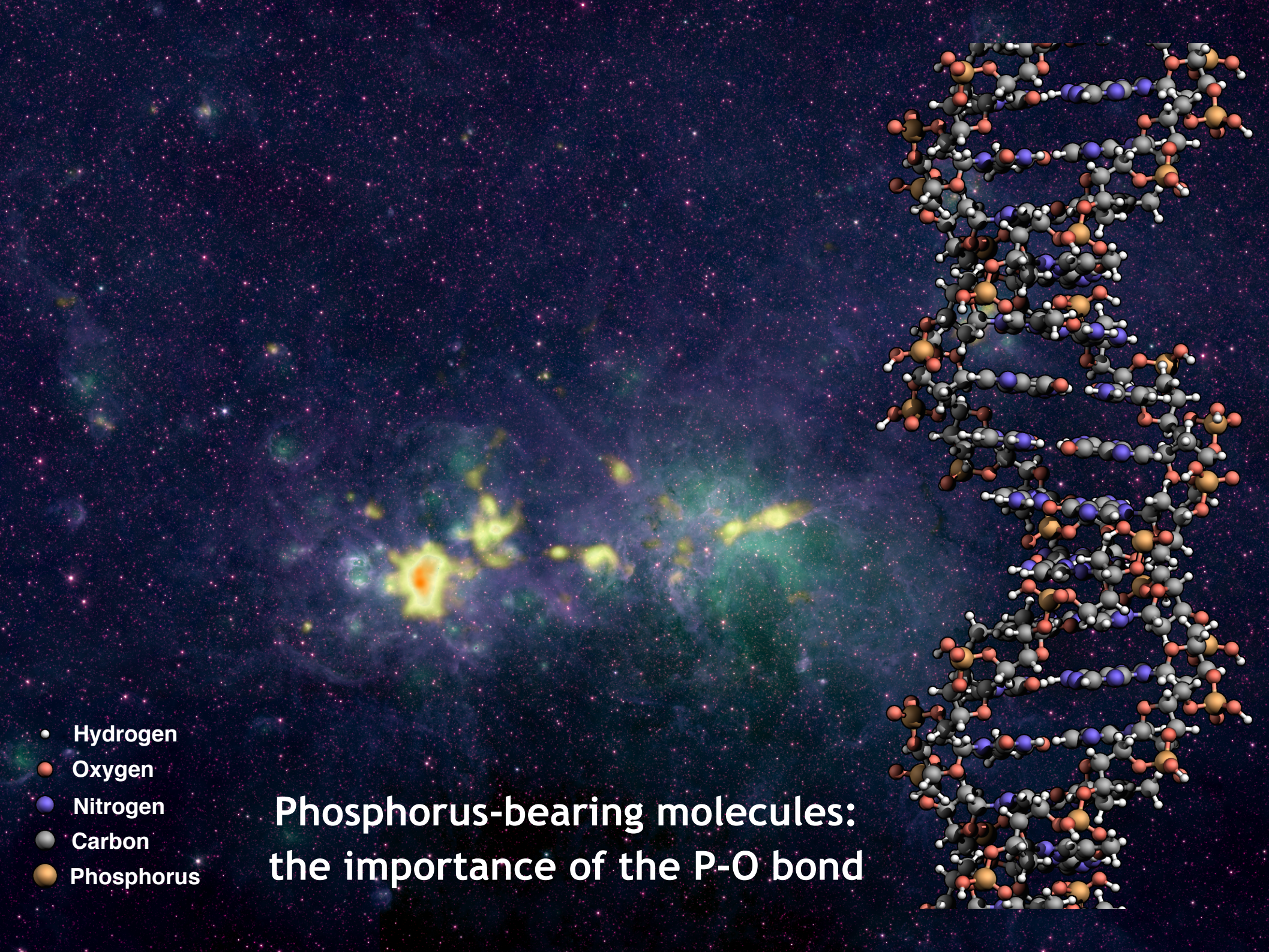


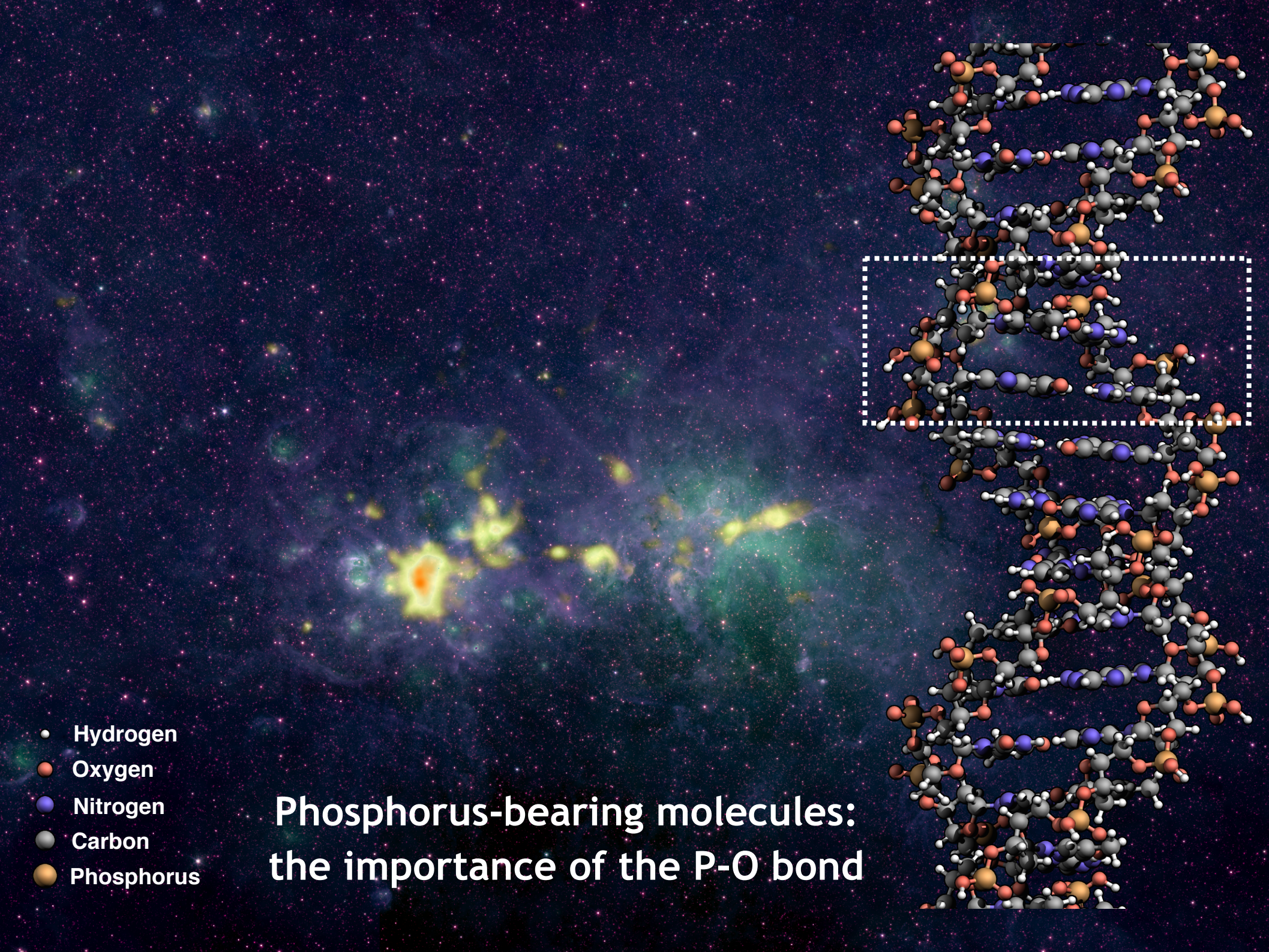



## DNA






Hydrogen
Oxygen
Nitrogen
Carbon
Phosphorus
Phosphorus-bearing molecules:
the importance of the P-O bond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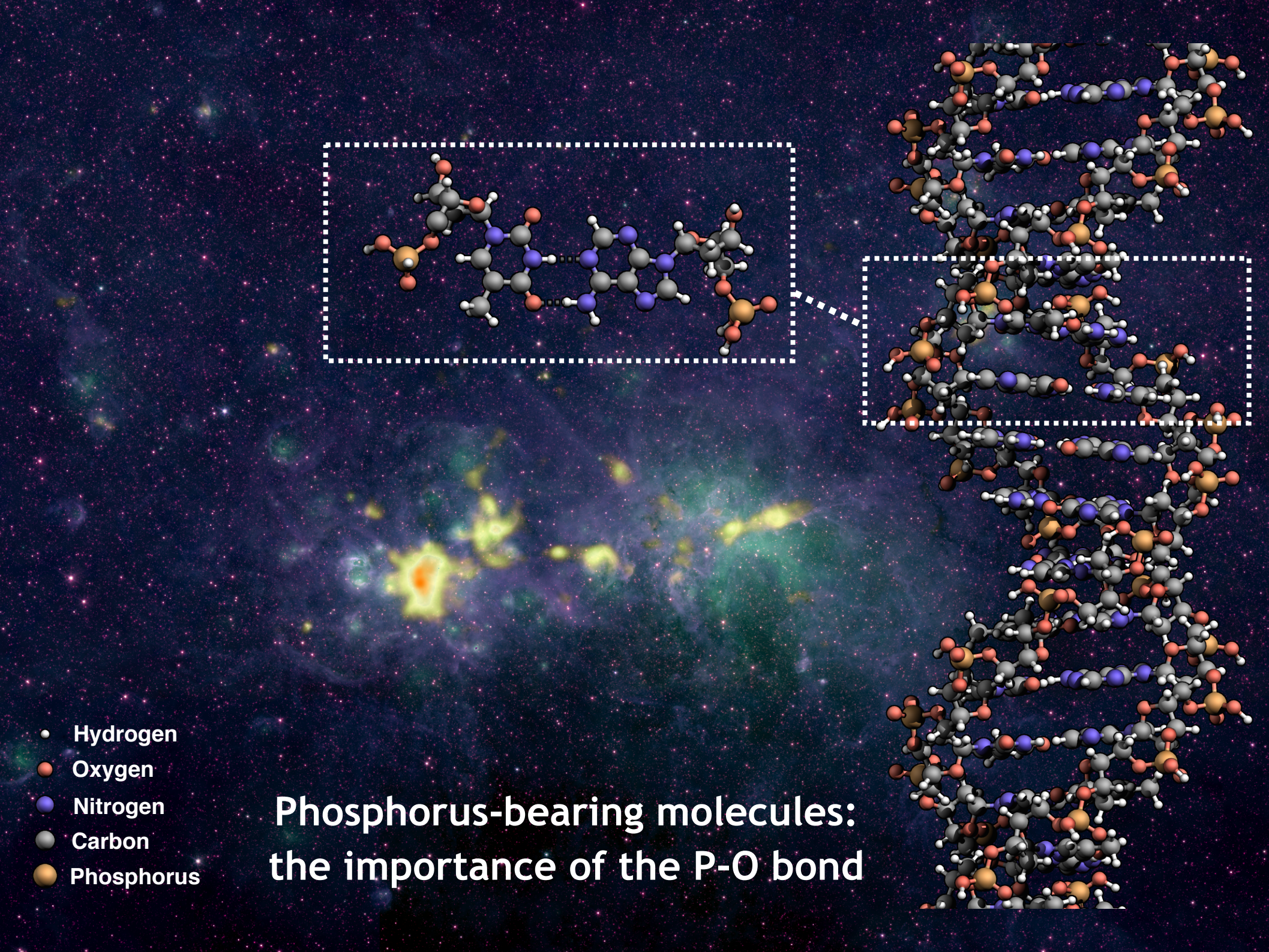
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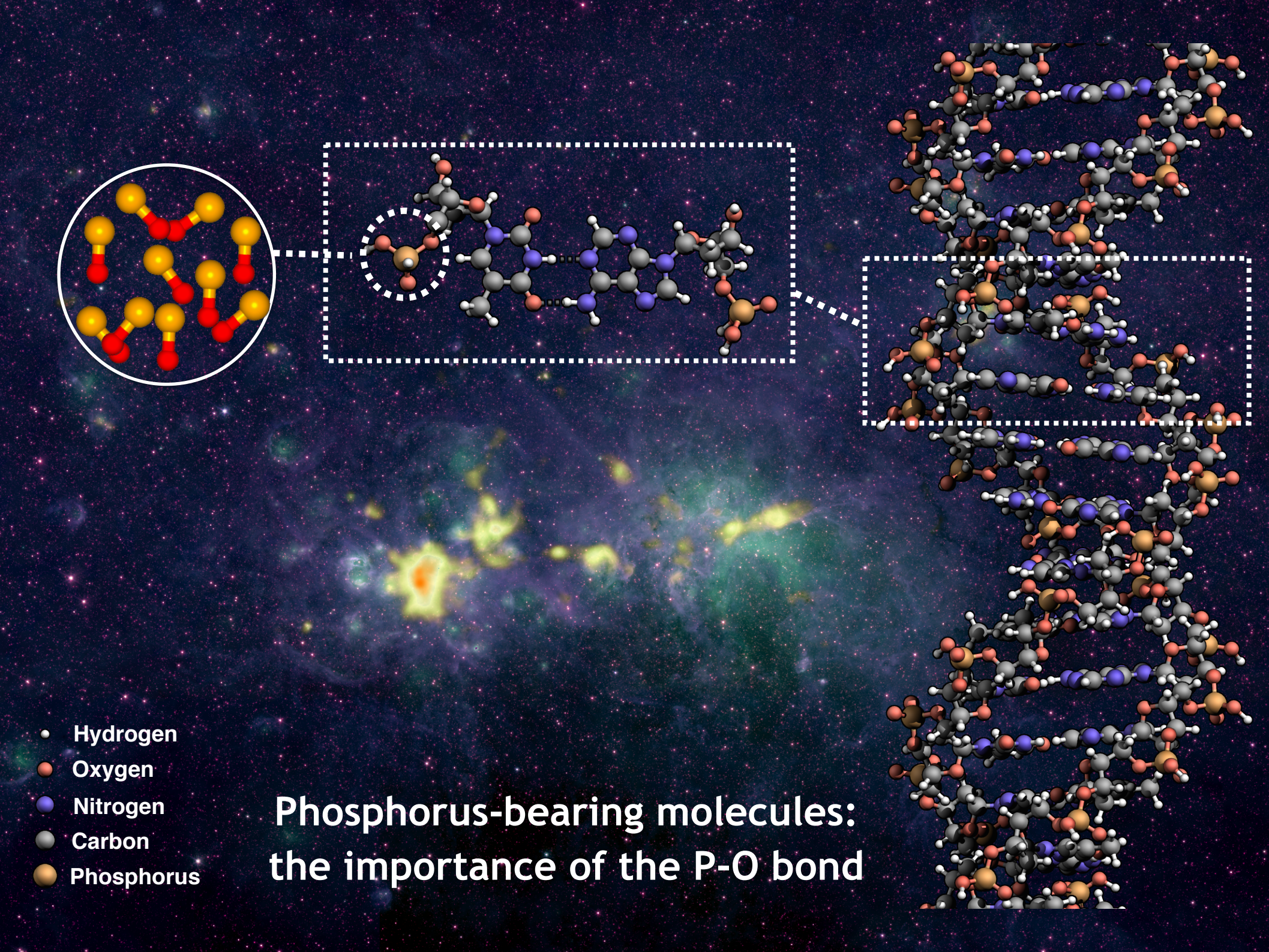
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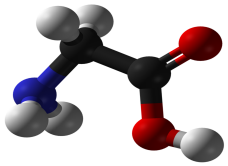
RESEARCH ARTICLE

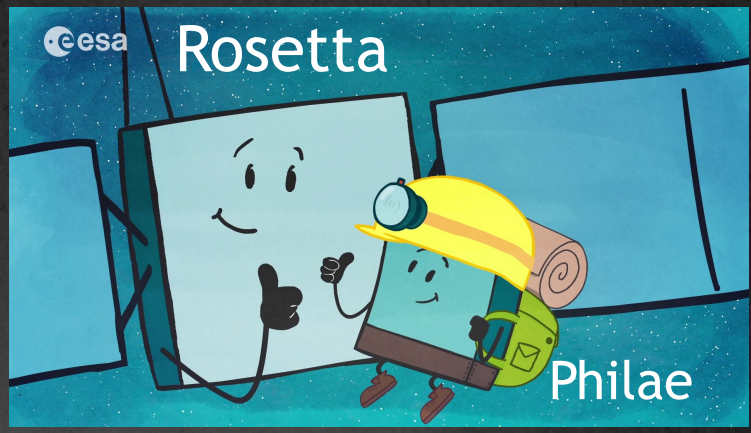
SPACE SCIENCES 2016

# Prebiotic chemicals—amino acid and phosphorus—in the coma of comet 67P/Churyumov-Gerasimenko



Kathrin Altwegg,[1,2]* Hans Balsiger,[1] Akiva Bar-Nun,[3] Jean-Jacques Berthelier,[4] Andre Bieler,[1,5] Peter Bochsler,[1] Christelle Briois,[6] Ursina Calmonte,[1] Michael R. Combi,[5] Hervé Cottin,[7] Johan De Keyser,[8] Frederik Dhooghe,[8] Bjorn Fiethe,[9] Stephen A. Fuselier,[10] Sébastien Gasc,[1] Tamas I. Gombosi,[5] Kenneth C. Hansen,[5] Myrtha Haessig,[1,10] Annette Jäckel,[1] Ernest Kopp,[1] Axel Korth,[11] Lena Le Roy,[2] Urs Mall,[11] Bernard Marty,[12] Olivier Mousis,[13] Tobias Owen,[14] Henri Rème,[15,16] Martin Rubin,[1] Thierry Sémon,[1] Chia-Yu Tzou,[1] James Hunter Waite,[10] Peter Wurz[1]

2015




Phosphorus and glycine recently detected in the 67P comet !

These prebiotic ingredients are present in the pristine material of our solar system

RESEARCH ARTICLE

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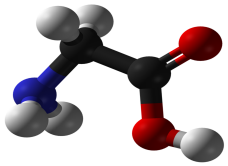

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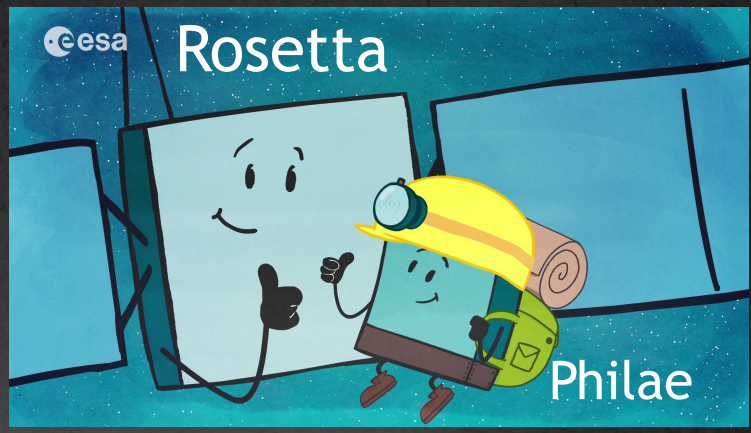


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**What about Phosphorus in the ISM?**

# P-bearing molecules in the ISM

- P is though to be synthesised in massive stars and injected to the ISM through supernova explosions (Koo et al., 2013).

- It is **barely detected in space**
  - P+ in several diffuse clouds (Jura & York 1978)
  - PN, PO, CP, HCP, $C_3P$ and $PH_3$ in circumstellar envelopes of evolved objects

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THE ASTROPHYSICAL JOURNAL, 321:L75–L79, 1987 October 1


DETECTION OF INTERSTELLAR PN: THE FIRST IDENTIFIED PHOSPHORUS COMPOUND IN THE INTERSTELLAR MEDIUM

B. E. TURNER
National Radio Astronomy Observatory,[1] Charlottesville

AND

JOHN BALLY
AT & T Bell Laboratories, Holmdel

*Received 1987 March 13; accepted 1987 April 17*

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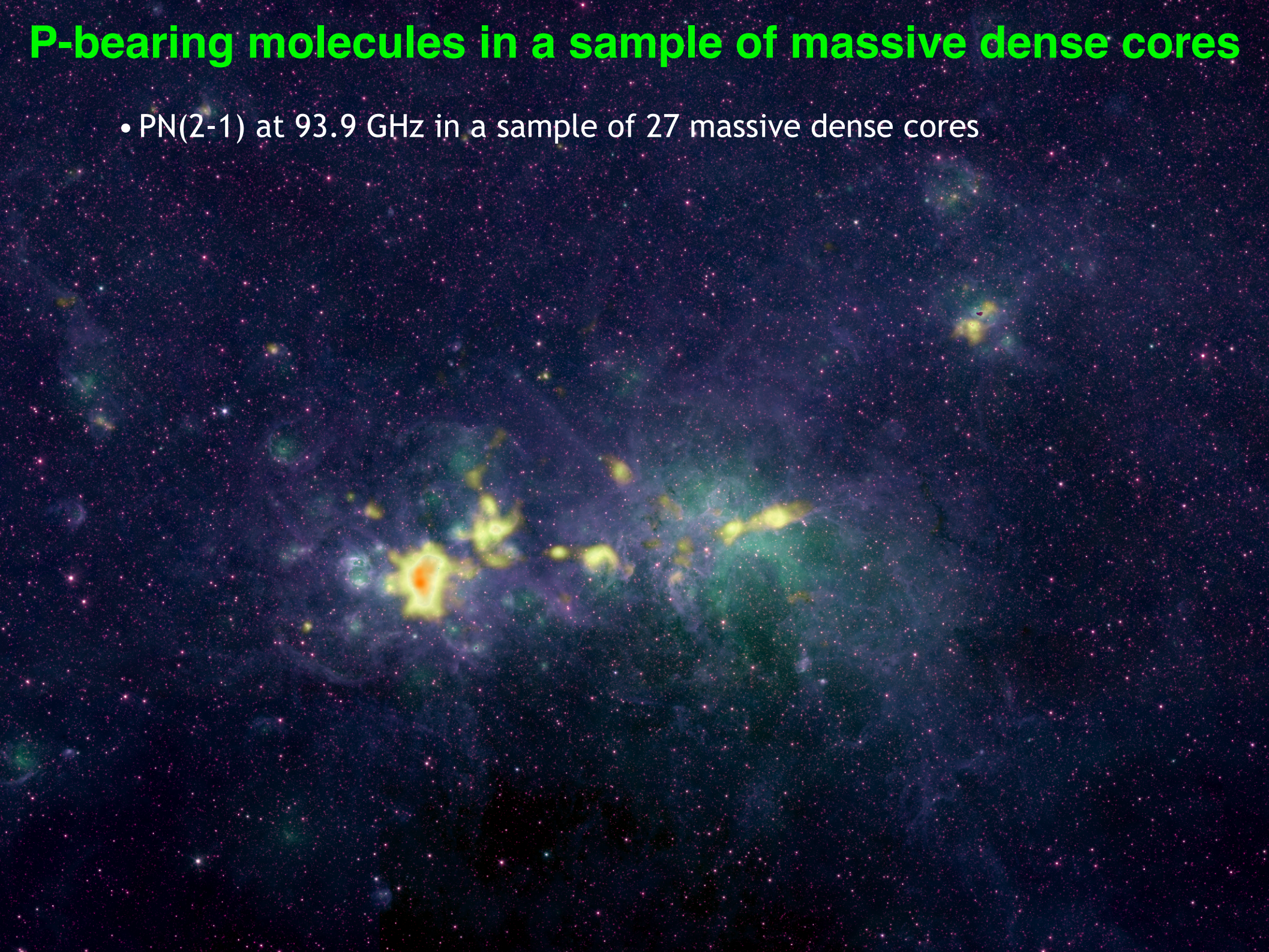
**Our group started a project to study P-bearing molecules in star-forming regions**

# P-bearing molecules in a sample of massive dense cores

- PN(2-1) at 93.9 GHz in a sample of 27 massive dense cores



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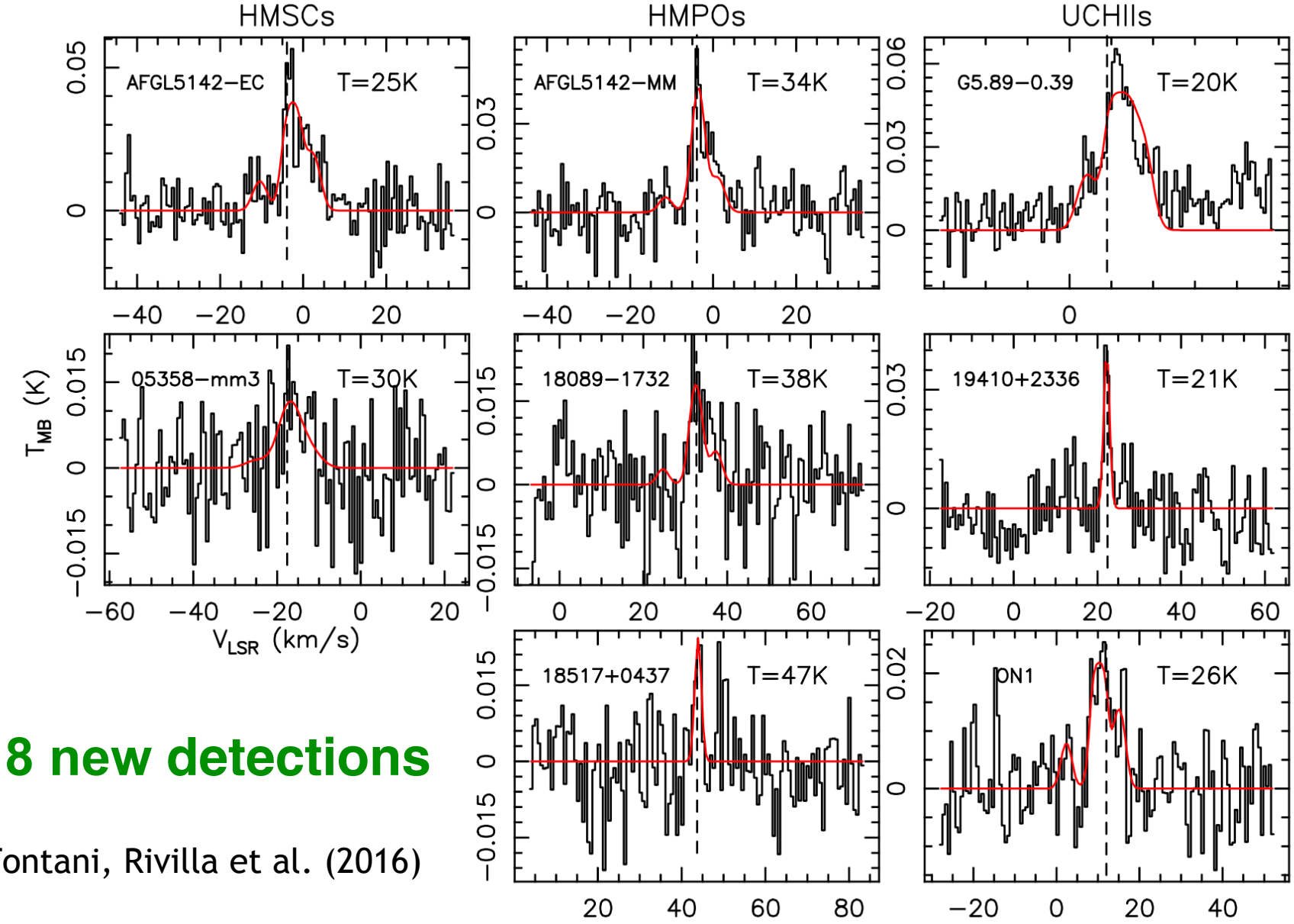


**8 new detections**

Fontani, Rivilla et al. (2016)

# What about PO ?

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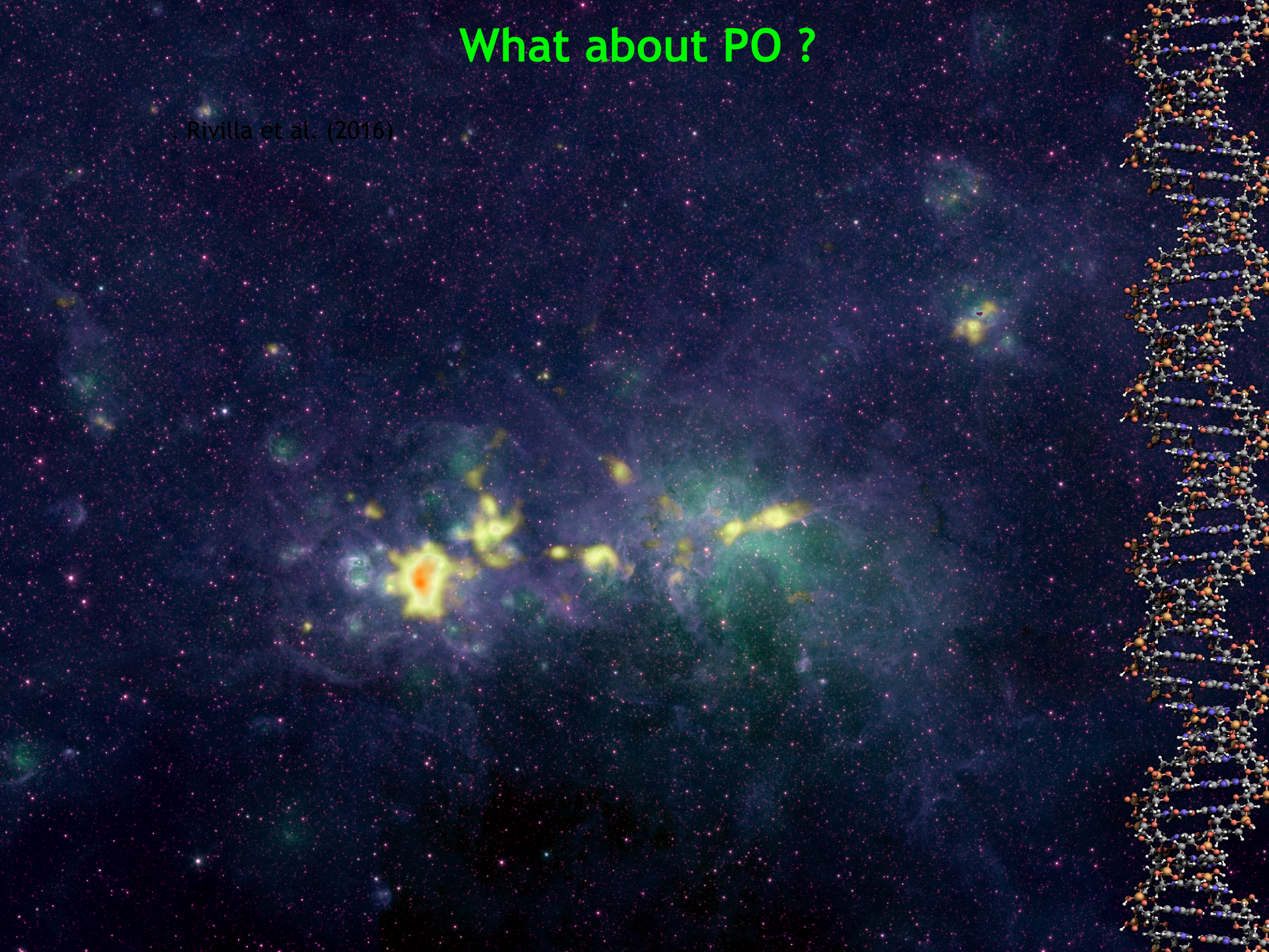

# What about PO ?

Fontani, Rivilla et al. (2016)

| source | $\Delta v$ (km s$^{-1}$) | $N(PN)^b$ $\times 10^{11}$ cm$^{-2}$ | $N(PO)^b$ $\times 10^{11}$ cm$^{-2}$ |
|---|---|---|---|
| 00117–MM2 | 1.6[a] | | |
| AFGL5142–EC | 3.8(0.6 | 5.8 | $< 20$ |
| 05358–mm3 | 6(2) | 10 | $< 13$ |
| G034–G2 | 1.6[a] | | |
| G034–F2 | 1.6[a] | | |
| G034–F1 | 1.6[a] | | |
| G028–C1 | 1.6[a] | | |
| I20293–WC | 1.6[a] | | |
| I22134–G | 1.6[a] | | |
| I22134–B | 1.6[a] | | |
| 00117–MM1 | 2.9[a] | | |
| AFGL5142–MM | 3.7(0.6 | 12 | $< 12$ |
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| 18089–1732 | 3(1) | 6.3 | $< 6.3$ |
| 18517+0437[d] | <1.8(0.7 | 4.4 | $< 4.4$ |
| G75–core | 2.9[a] | | |
| I20293–MM1 | 2.9[a] | | |
| I21307 | 2.9[a] | | |
| I23385 | 2.9[a] | | |
| G5.89–0.39 | 5.2(0.8 | 14.5 | $< 14$ |
| 19035–VLA1 | 3.5[a] | | |
| 19410+2336[d] | <1.6(0.4 | 3.3 | $< 3.3$ |
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- Good constraint on upper limits

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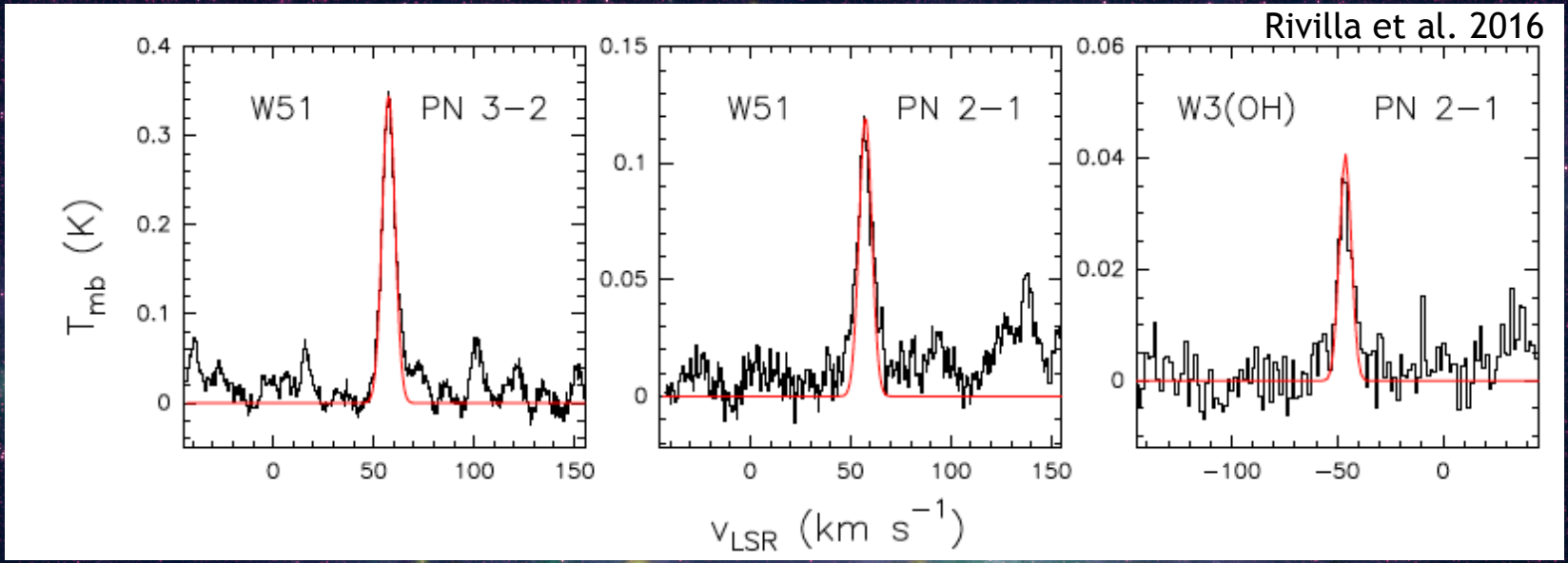
PO could be as abundant as PN

# Searching for PO

- PN brightest detections of 2 massive star-forming regions.

, Rivilla et al. (2016)



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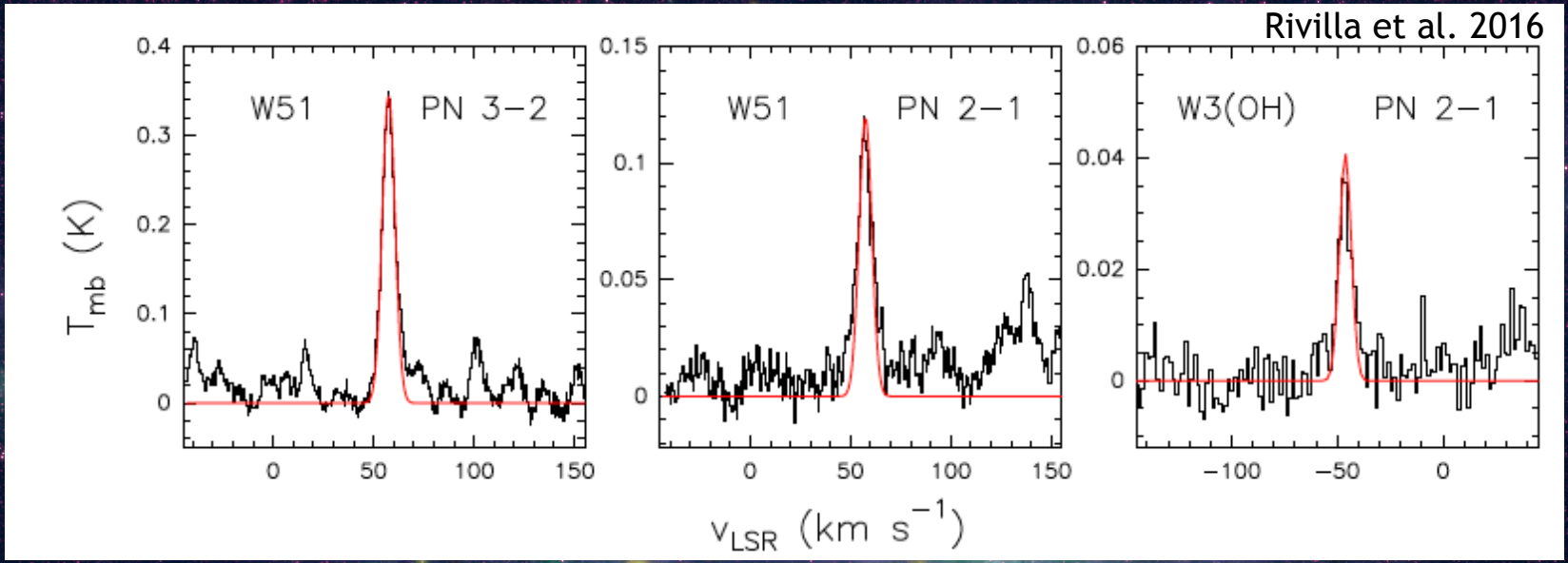



## New IRAM 30m observations

- 3 PO quadruplets at 1, 2 and 3mm.

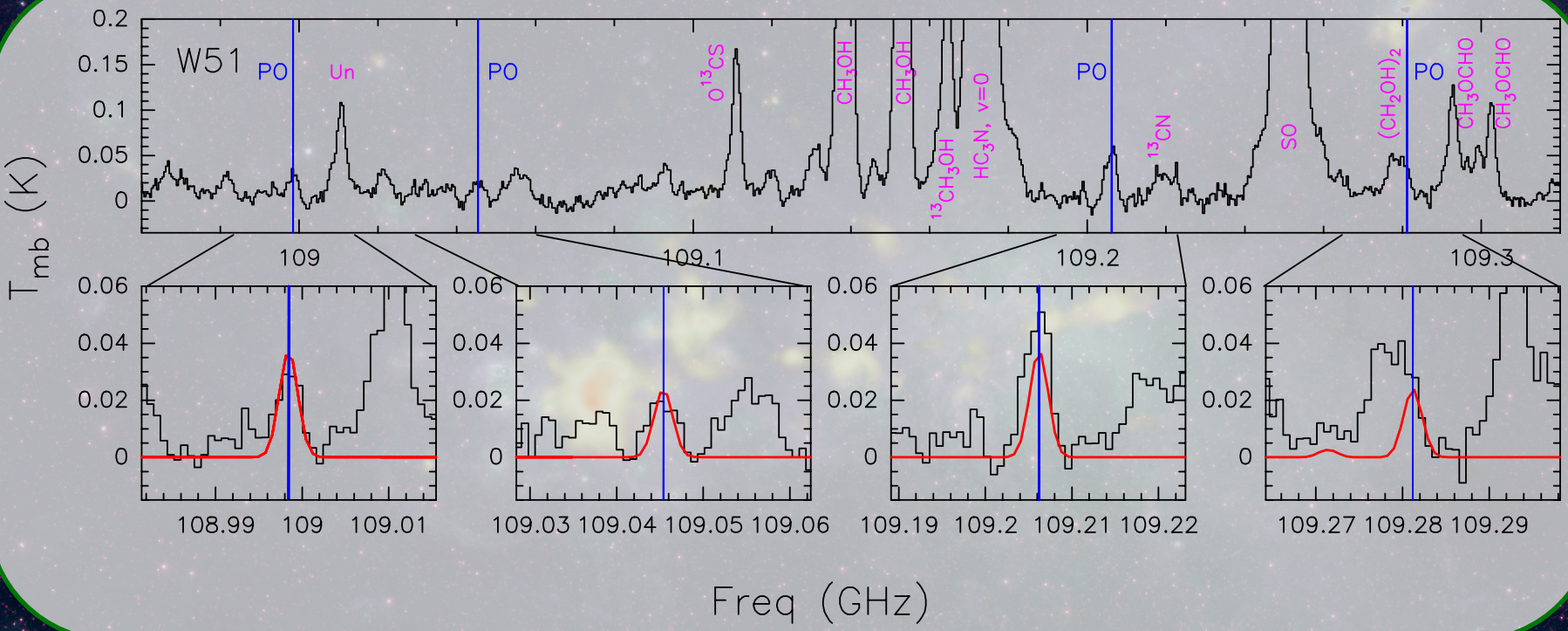
| Frequency (GHz) | Transition | $S_{ij}\mu^2$ ($D^2$) | $E_{up}$ (K) |
|---|---|---|---|
| J=5/2−3/2, Ω=1/2 | | | |
| 108.99845 | F=3−2, l=e | 9.9 | 8.4 |
| 109.04540 | F=2−1, l=e | 6.4 | 8.4 |
| 109.20620 | F=3−2, l=f | 9.9 | 8.4 |
| 109.28119 | F=2−1, l=f | 6.4 | 8.4 |
| J=7/2−5/2, Ω=1/2 | | | |
| 152.65698 | F=4−3, l=e | 13.6 | 15.7 |
| 152.68028 | F=3−2, l=e | 10.1 | 15.7 |
| 152.85545 | F=4−3, l=f | 13.6 | 15.7 |
| 152.88813 | F=3−2, l=f | 10.1 | 15.7 |
| J=11/2−9/2, Ω=1/2 | | | |
| 239.94898 | F=6−5, l=e | 20.9 | 36.7 |
| 239.95810 | F=5−4, l=e | 17.4 | 36.7 |
| 240.14106 | F=6−5, l=f | 20.9 | 36.7 |
| 240.15253 | F=5−4, l=f | 17.4 | 36.7 |

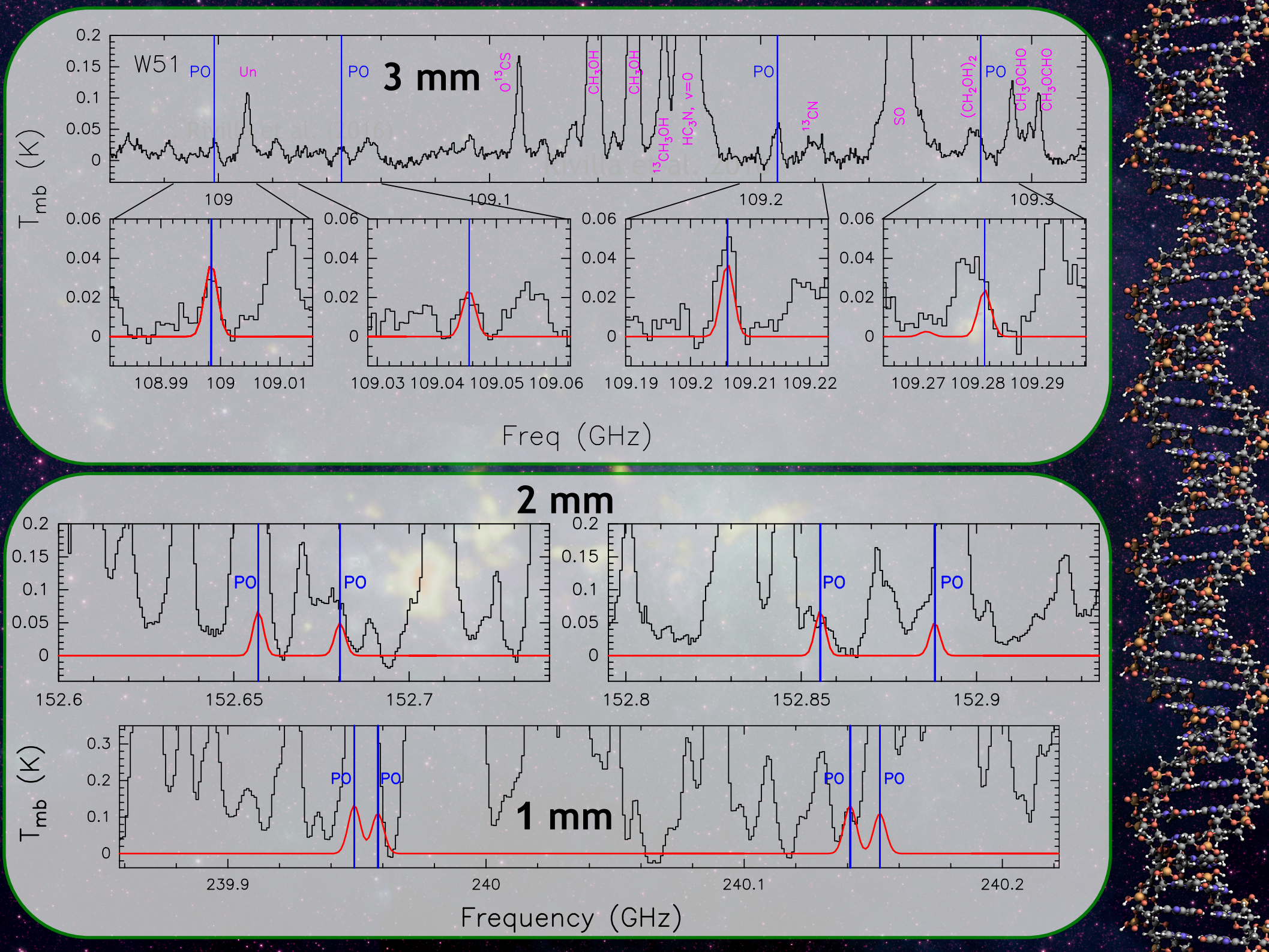
# First detections of PO in star-forming regions

, Rivilla et al. (2016)

Rivilla et al. 2016

## 3 mm

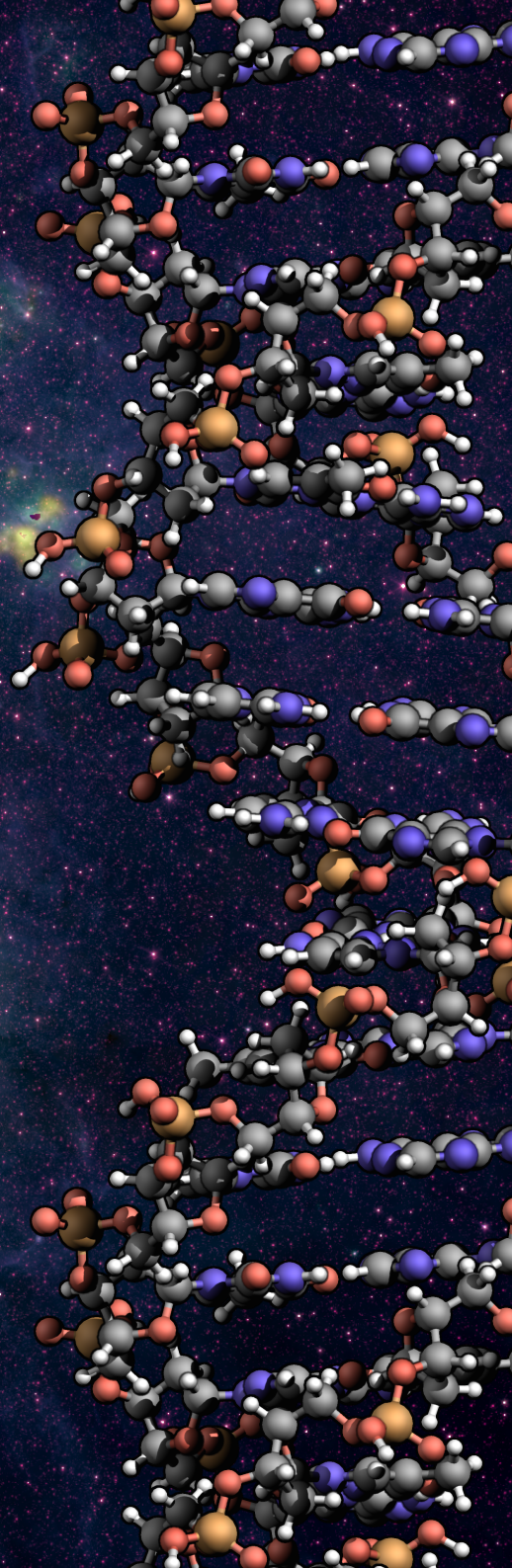



W51
PO
Un
PO
3 mm
$O^{13}CS$
$CH_3OH$
$CH_3OH$
$^{13}CH_3OH$
$HC_3N$, v=0
PO
$^{13}CN$
SO
$(CH_2OH)_2$
PO
$CH_3OCHO$
$CH_3OCHO$
$T_{mb}$ (K)
0.2
0.15
0.1
0.05
0
109
109.1
109.2
109.3
0.06
0.04
0.02
0
108.99 109 109.01
109.03 109.04 109.05 109.06
109.19 109.2 109.21 109.22
109.27 109.28 109.29
Freq (GHz)
2 mm
PO
PO
152.6
152.65
152.7
152.8
152.85
152.9
1 mm
PO
PO
PO
PO
0.3
239.9
240
240.1
240.2
Frequency (GHz)

# PO and PN physical parameters

| | N ($x10^{13}$ $cm^{-2}$) | Abundance ($10^{-10}$) |
|---|---|---|
| PN | 0.2-2.1 | 0.4-1.1 |
| PO | 0.6-4.0 | 1.2-2.0 |

PO is a factor 2-3 more abundant than PN !



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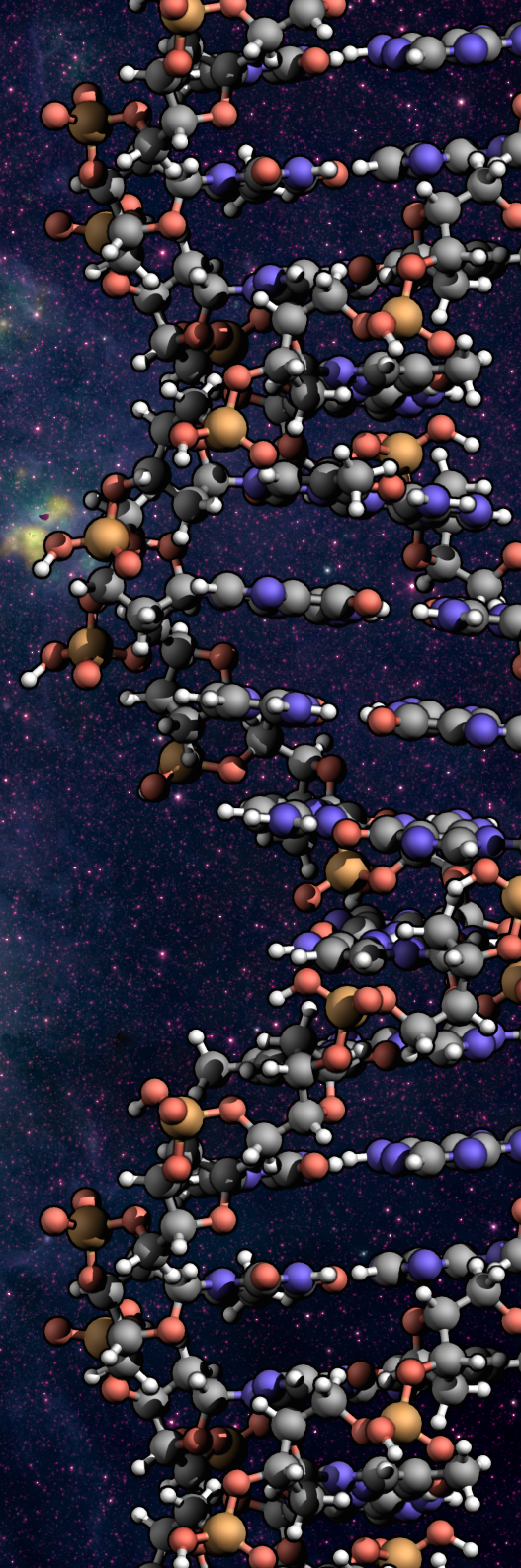
Lefloch et al. (2016) also found **PO/PN~3** in a protostellar shock



# P-bearing molecules: Chemical modelling

- Very little is known about P-chemistry.
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- The two P-bearing molecules are chemically related and form purely in a sequence of **gas-phase ion-molecule** and **neutral-neutral** reactions during the cold collapse phase.

**PO formation** | GAME OF REACTIONS | **PN formation**

$$H_3O^+ + P \longrightarrow HPO^+ + H_2$$

$$HPO^+ + e^- \longrightarrow PH + O$$

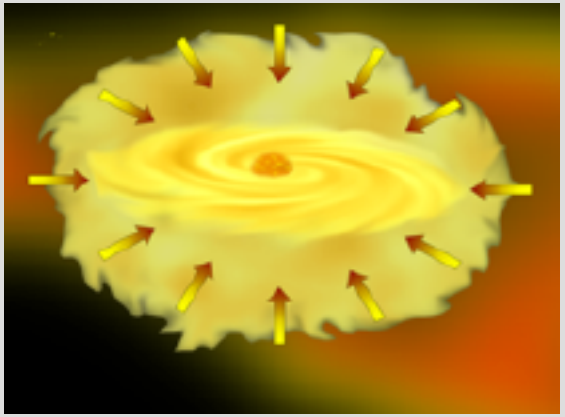
$$HPO^+ + e^- \longrightarrow \boxed{PO} + H$$

$$P^+ + H_2 \longrightarrow PH_2^+$$

$$PH_2^+ + e^- \longrightarrow PH + H$$

$$O + PH \longrightarrow \boxed{PO} + H$$

Cold starless phase



$$N + PO \longrightarrow \boxed{PN} + O$$

Rivilla et al. 2016.

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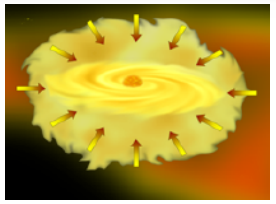

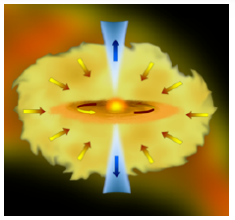

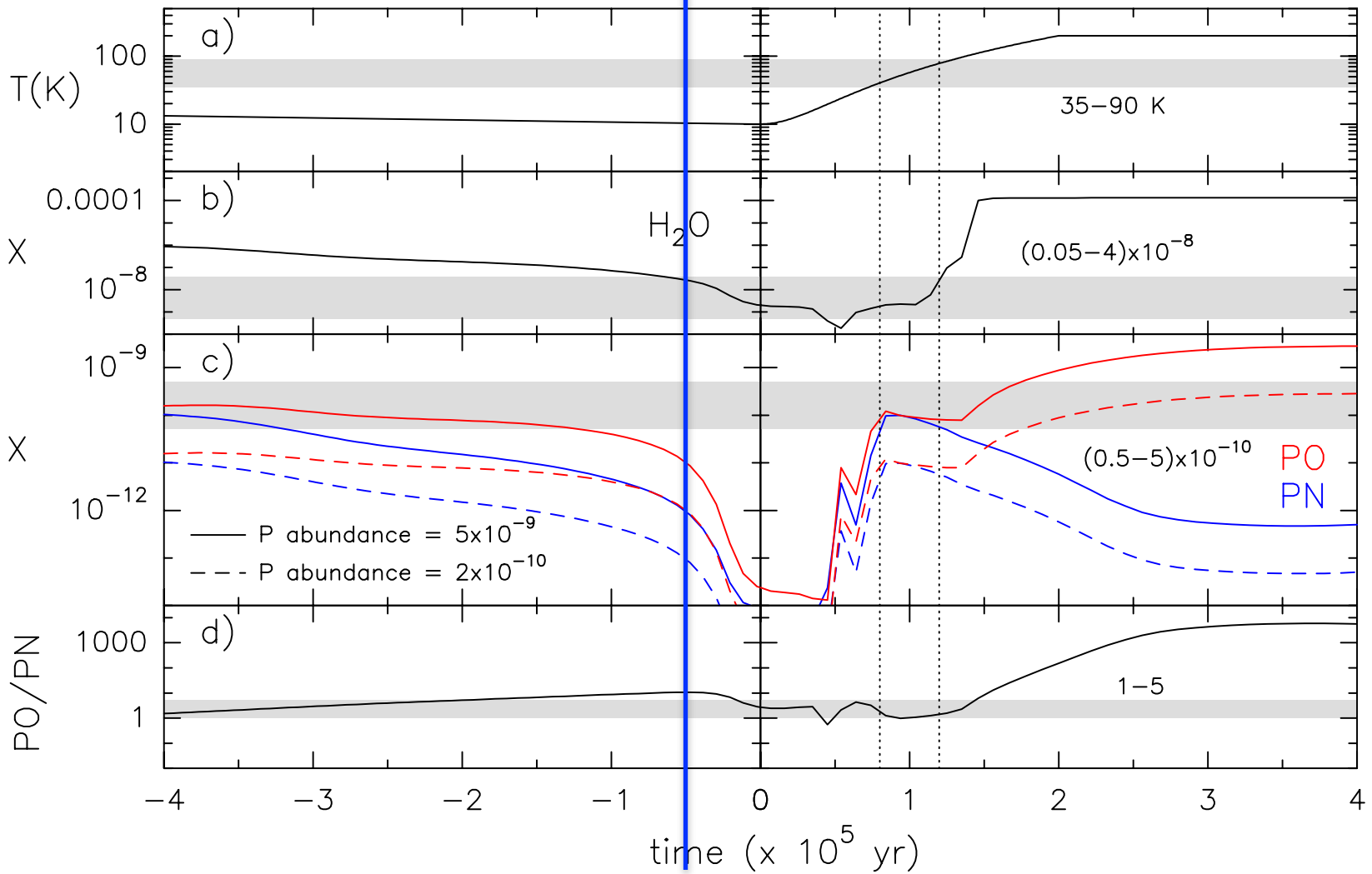


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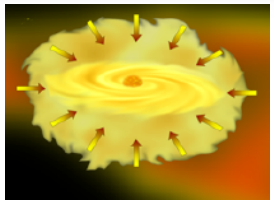

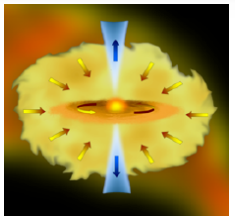

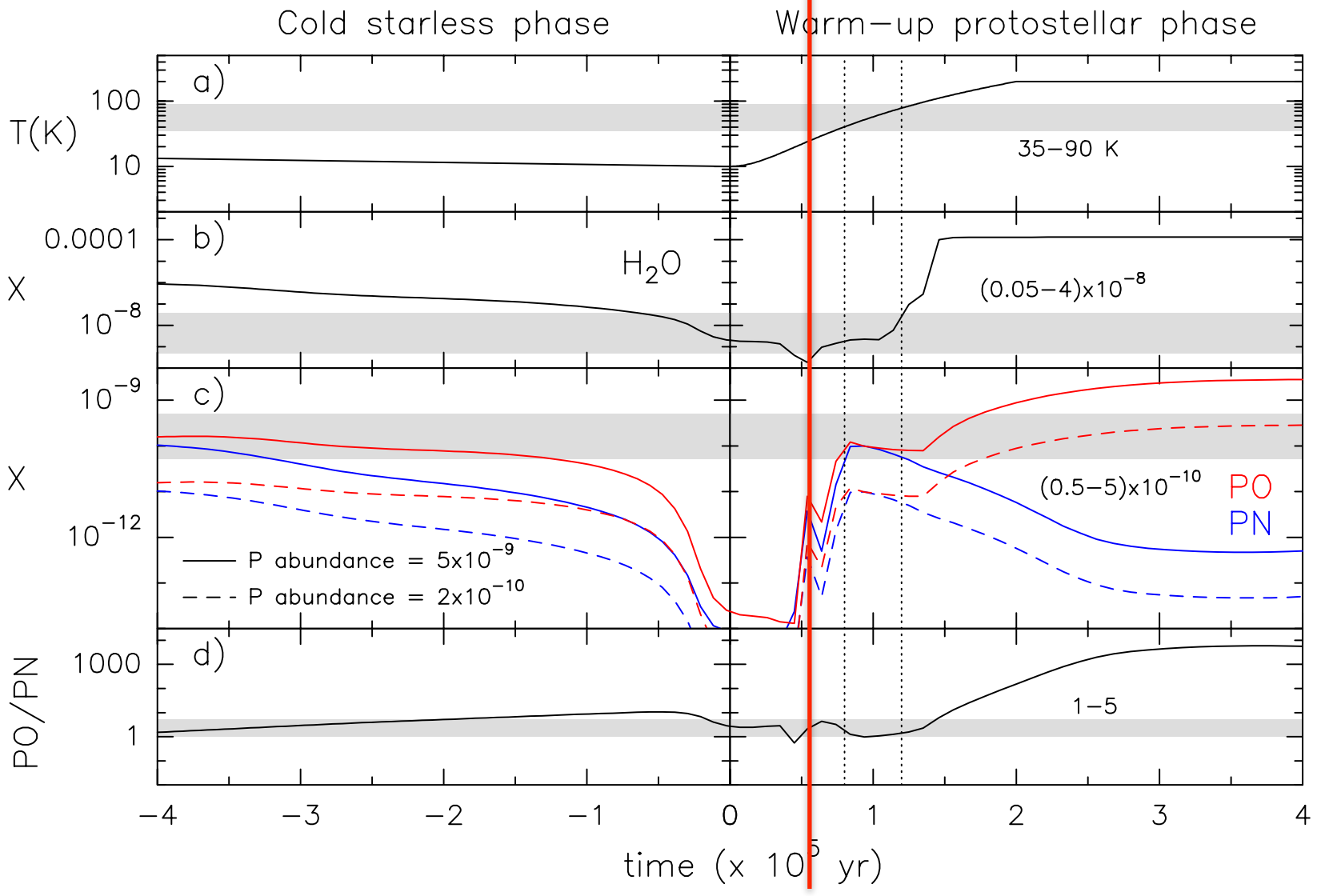


Rivilla et al. 2016.

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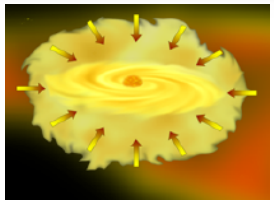
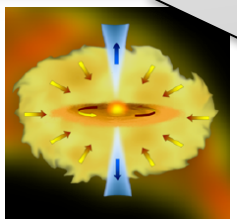
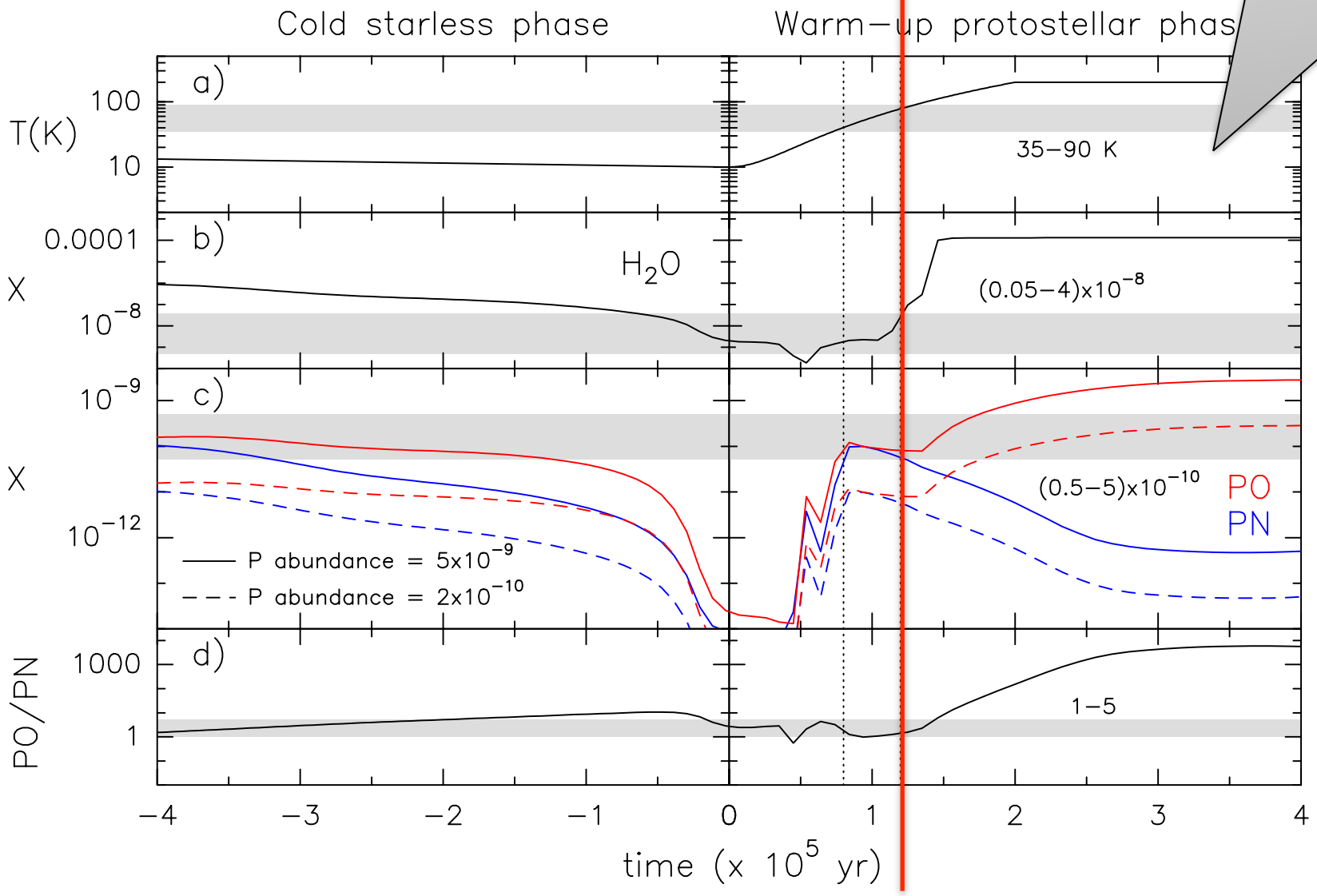




Water ices desorb ~100 K

abundance of $H_3O^+$ increases




Rivilla et al. 2016.

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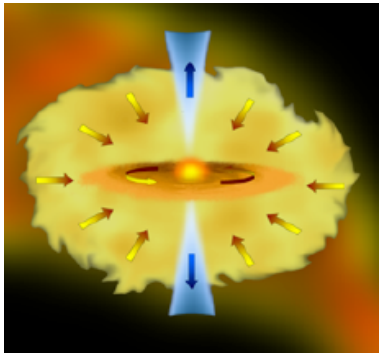

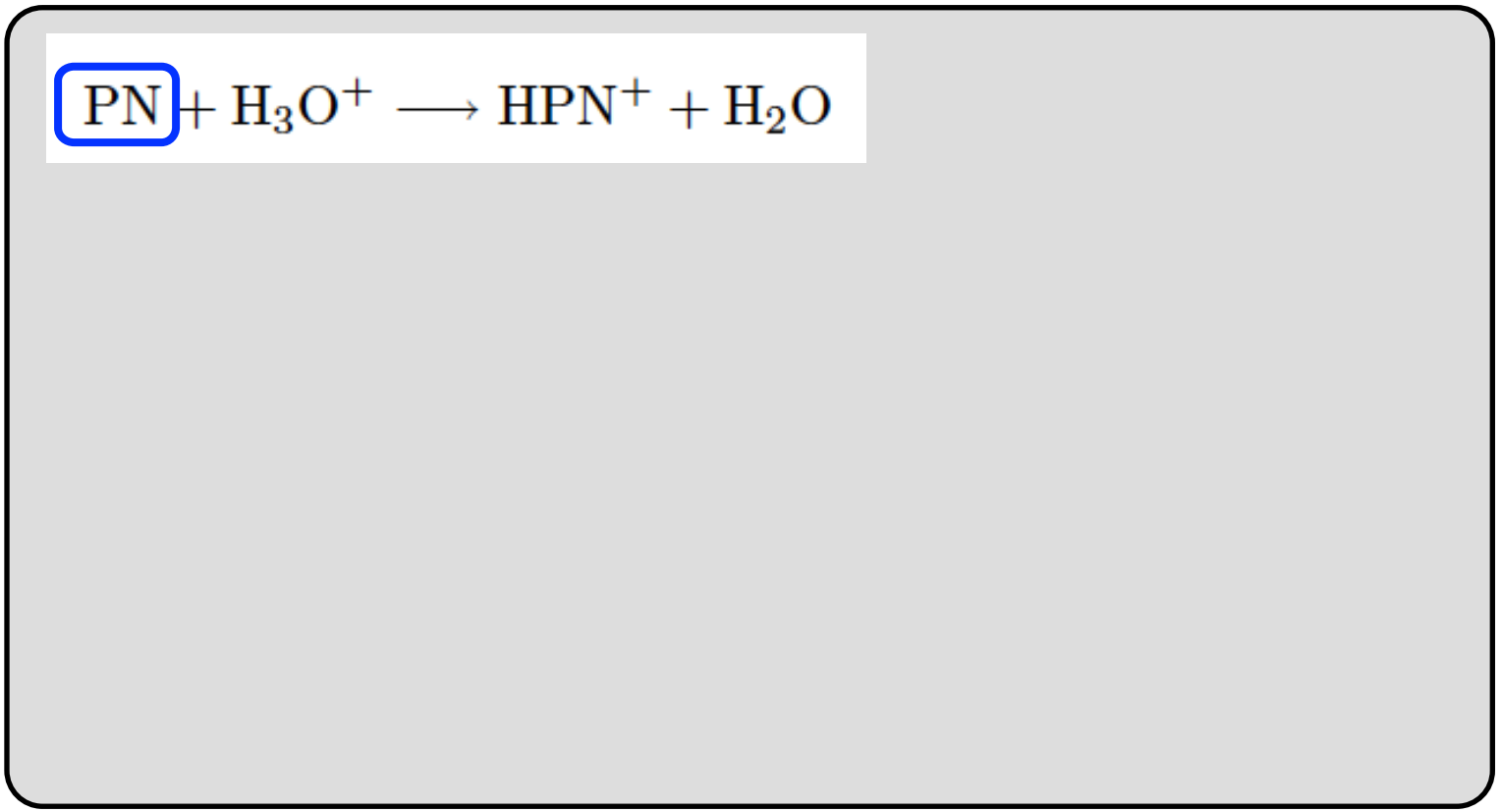


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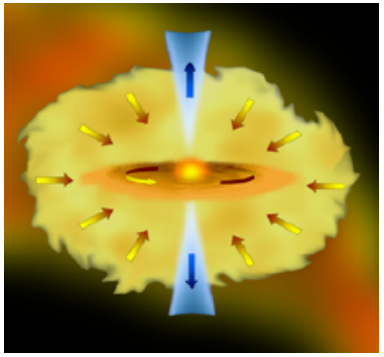

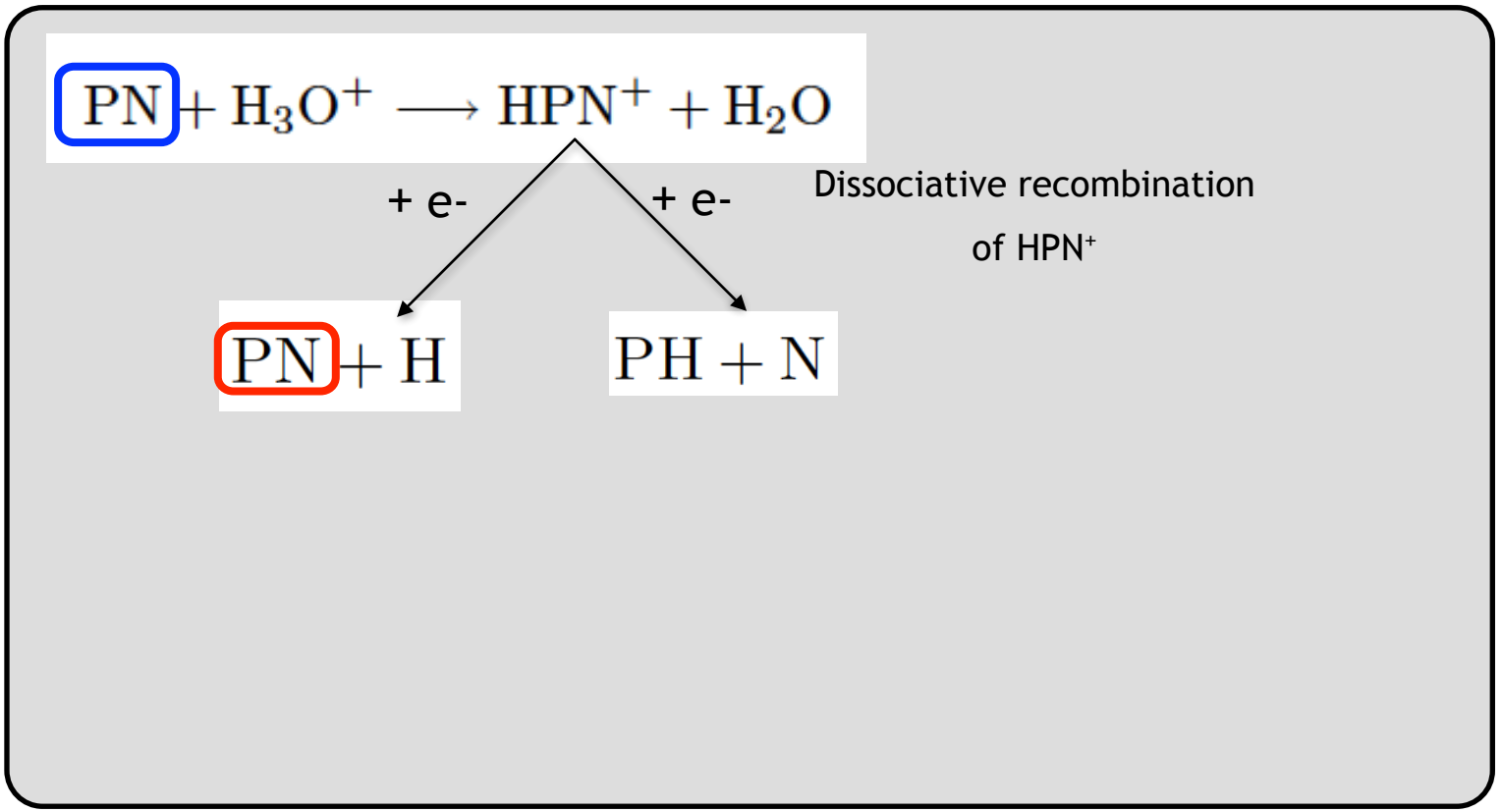


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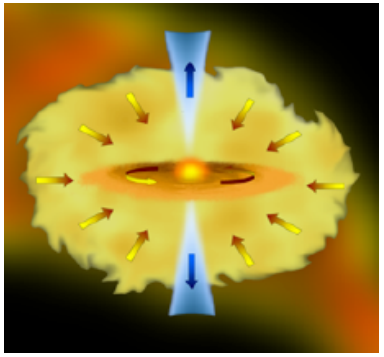
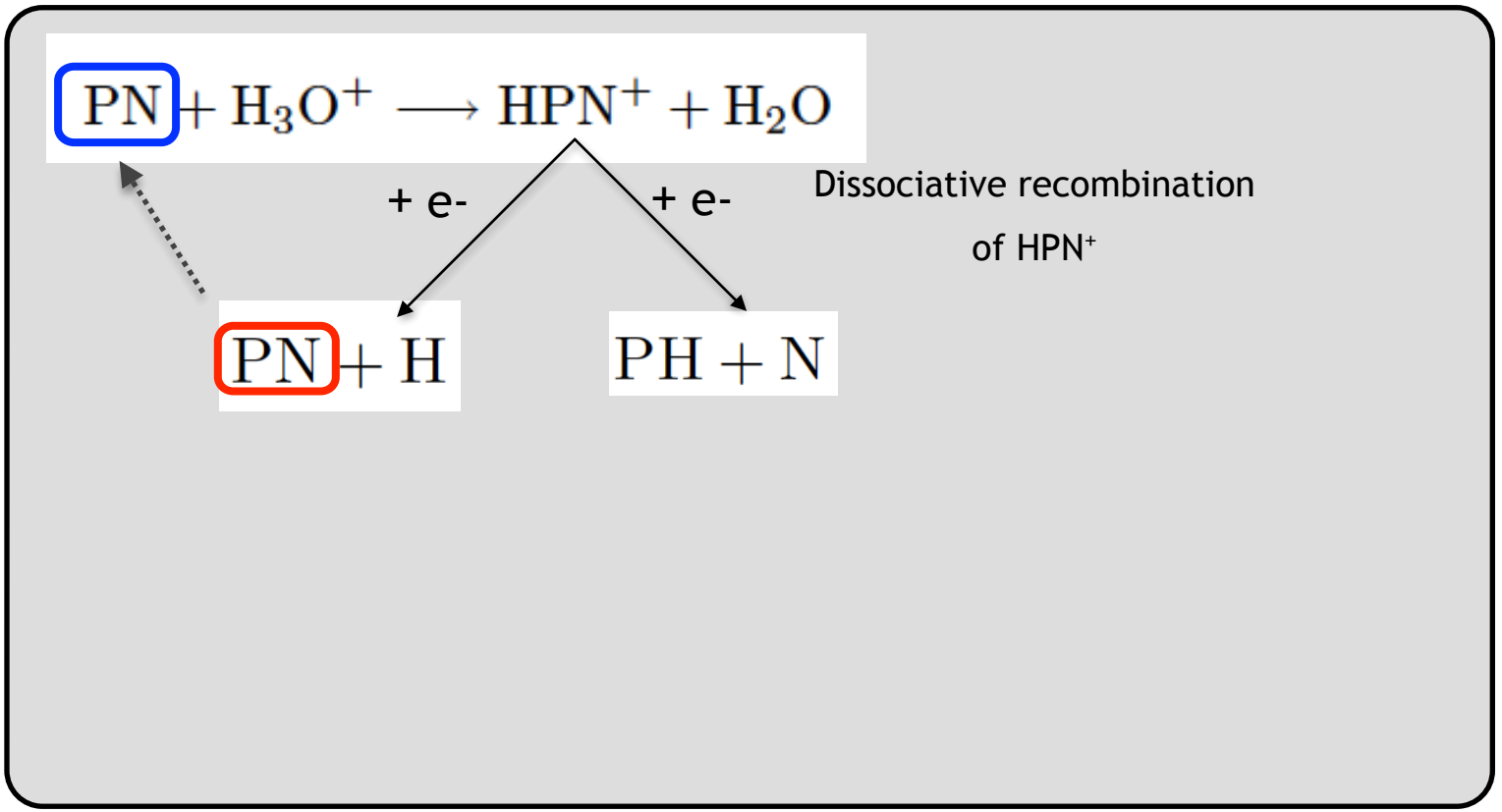


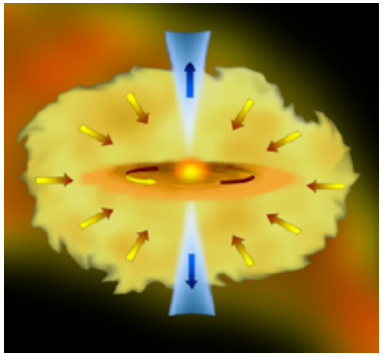


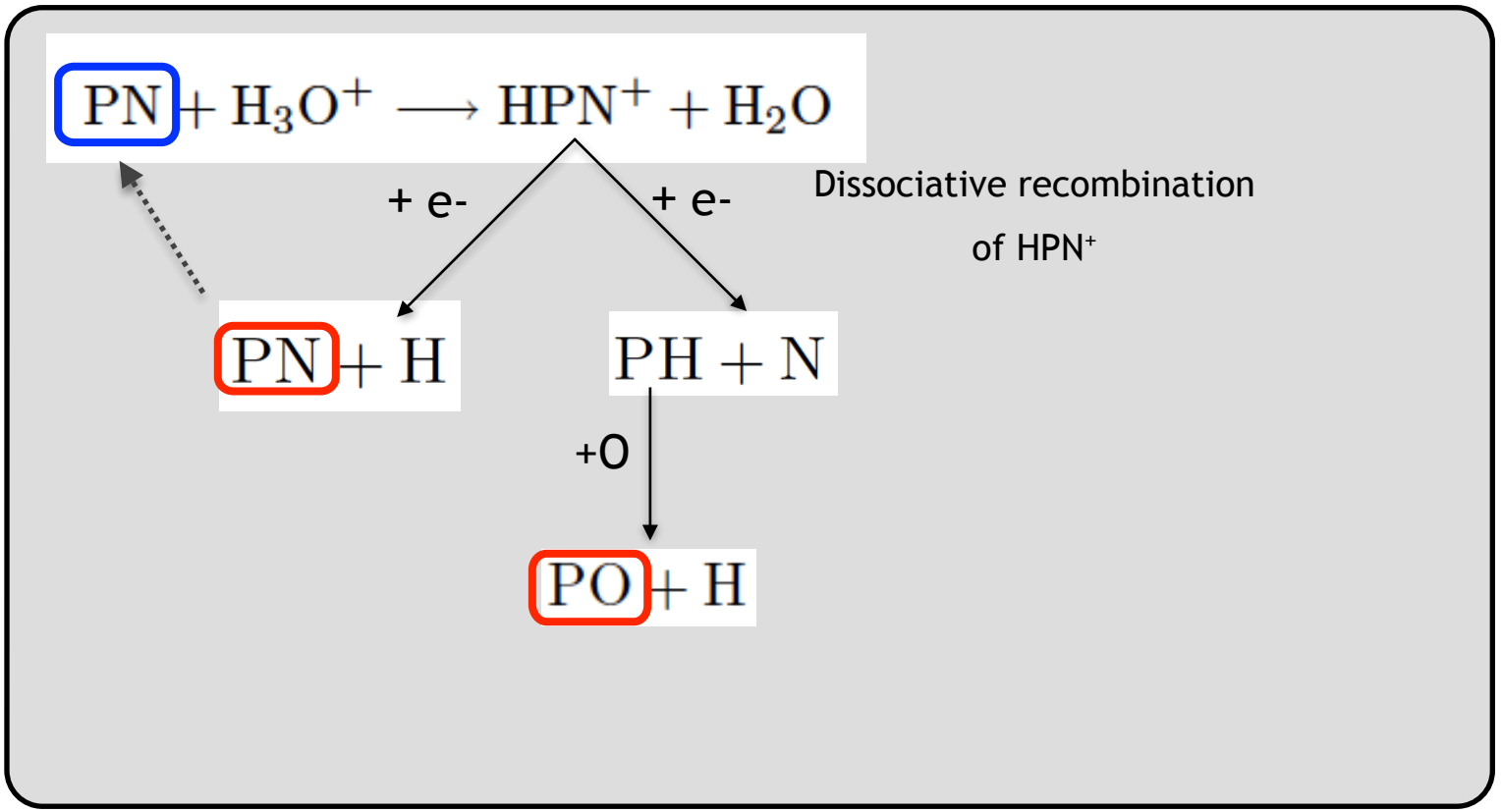

Rivilla et al. 2016.

# P-bearing molecules: Chemical modelling

- The abundance of $H_3O^+$ increases:

GAME OF REACTIONS






Rivilla et al. 2016.

# P-bearing molecules: Chemical modelling

- The abundance of $H_3O^+$ increases:

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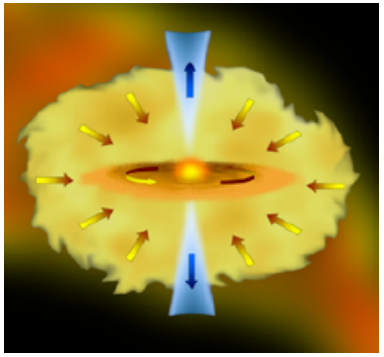
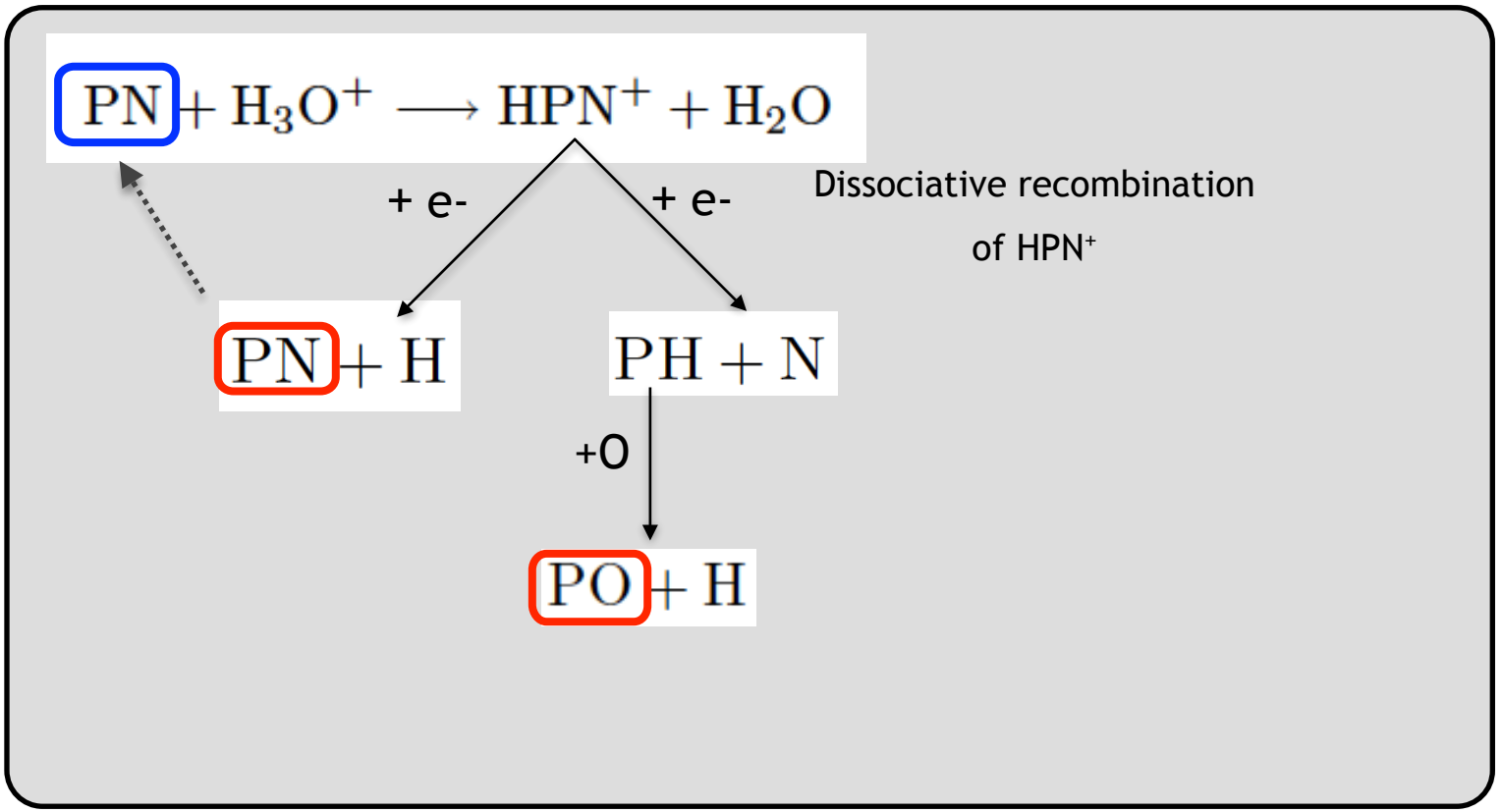
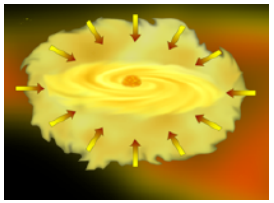
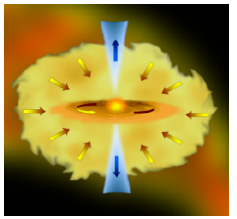





**PN is gradually destroyed and PO is additionally produced**

Rivilla et al. 2016.





Cold starless phase

Warm−up protostellar phase

a)

T(K)

100

10

35−90 K

b)

$H_2O$

X

0.0001

$10^{-8}$

$(0.05-4)\times10^{-8}$

c)

X

$10^{-9}$

$10^{-12}$

P abundance = $5\times10^{-9}$

P abundance = $2\times10^{-10}$

$(0.5-5)\times10^{-10}$

PO

PN

d)

PO/PN

1000

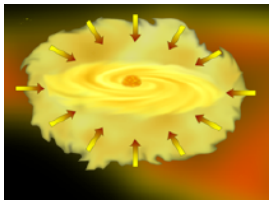
1

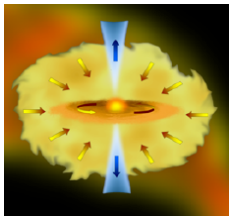
1−5

−4 −3 −2 −1 0 1 2 3 4

time (x $10^5$ yr)

Rivilla et al. 2016





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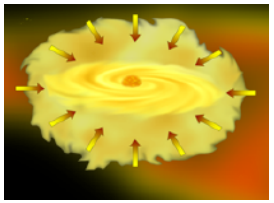
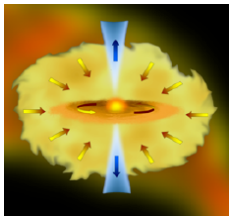
Rivilla et al. 2016





Cold starless phase

Warm−up protostellar phase

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X

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$(0.05-4)\times10^{-8}$

c)

$10^{-9}$

X

$10^{-12}$

PO

PN

P abundance = $5\times10^{-9}$

P abundance = $2\times10^{-10}$

The amount of P in the ISM is a factor x25 higher than previously thought

d)

PO/PN

1000

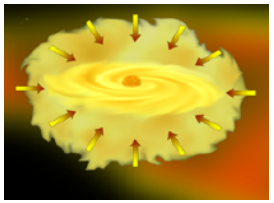
1

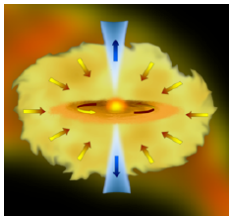
1−5

−4 −3 −2 −1 0 1 2 3 4

time (x $10^5$ yr)

Rivilla et al. 2016





Cold starless phase

Warm−up protostellar phase

a)

T(K)

100

10

35−90 K

The cosmic abundance of P is ~3x10$^{-7}$

**P DEPLETION FACTOR ~ 60** (1500 previously thought)

0.0001

X

$10^{-8}$

$10^{-9}$

c)

X

$10^{-12}$

P abundance = 5x10$^{-9}$

P abundance = 2x10$^{-10}$

The amount of P in the ISM is a factor x25 higher than previously thought

PO

PN

d)

PO/PN

1000

1

1−5

−4 −3 −2 −1 0 1 2 3 4

time (x $10^5$ yr)

Rivilla et al. 2016

# Multi-transition PN analysis: the full sample (18 sources)

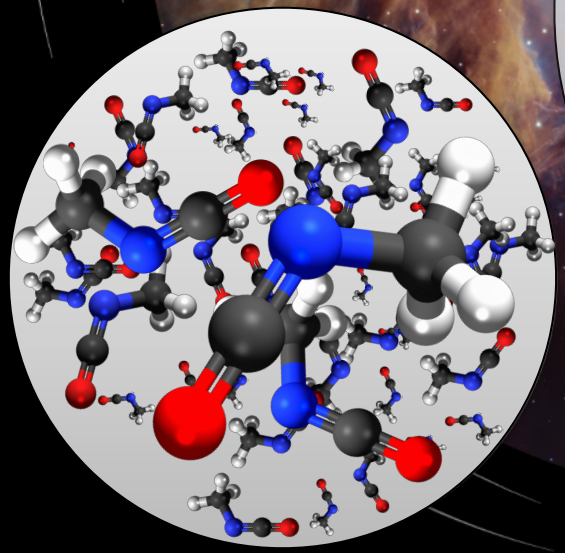
| (Mininni et al., in prep.) | PN(2-1) | PN(3-2) | PN(6-5) |
|---|---|---|---|
| 05358-mm3 | ✓ | ✓ | ✗ |
| AFGL5142-EC | ✓ | ✓ | ✗ |
| G034-G2/A | ✗ | ✗ | ✗ |
| 18517+0437 | ✓ | ✓ | ✓ |
| AFGL5142-MM | ✓ | ✓ | ✗ |
| 18089-1732 | ✓ | ✓ | ✗ |
| I20293-MM1/B | ✗ | ✗ | ✗ |
| G75-core | ✗ | ✓ | ✗ |
| G5.89-0.39 | ✓ | ✓ | ✓ |
| 19035-VLA1 | ✗ | ✗ | ✗ |
| 19410+2336 | ✓ | ✓ | ✗ |
| ON1 | ✓ | ✓ | ✓ |
| G10.47+0.03 | - | ✓ | ✗ |
| G24.78+0.08 | - | ✓ | ✗ |
| G29.96-0.02 | - | ✓ | ✗ |
| G31.41+0.31 | - | ✓ | ✓ |
| W3OH | - | ✓ | ✓ |
| W51 | - | ✓ | ✓ |

The first stars

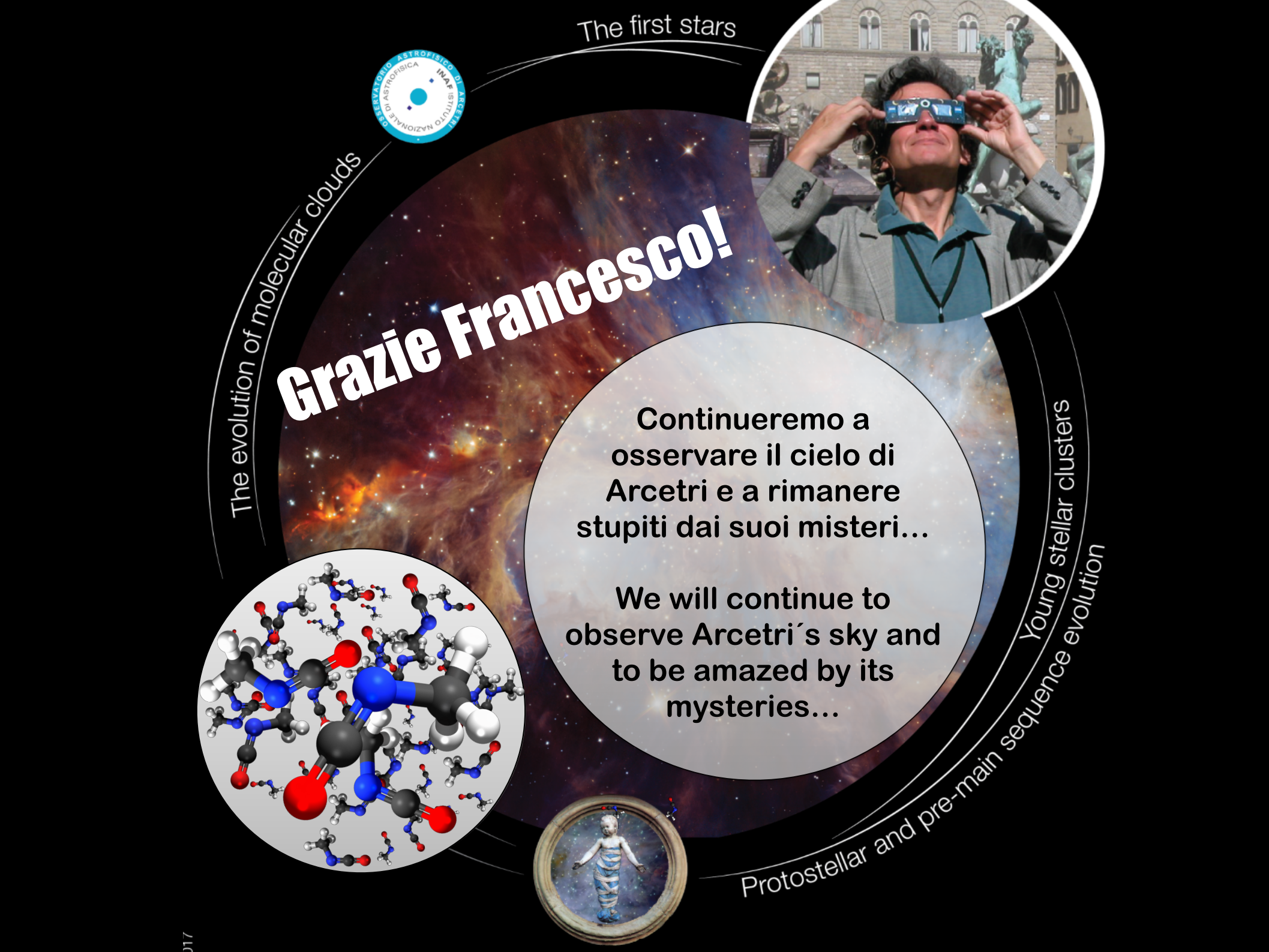
The evolution of molecular clouds

# Grazie Francesco!

Young stellar clusters



Protostellar and pre-main sequence evolution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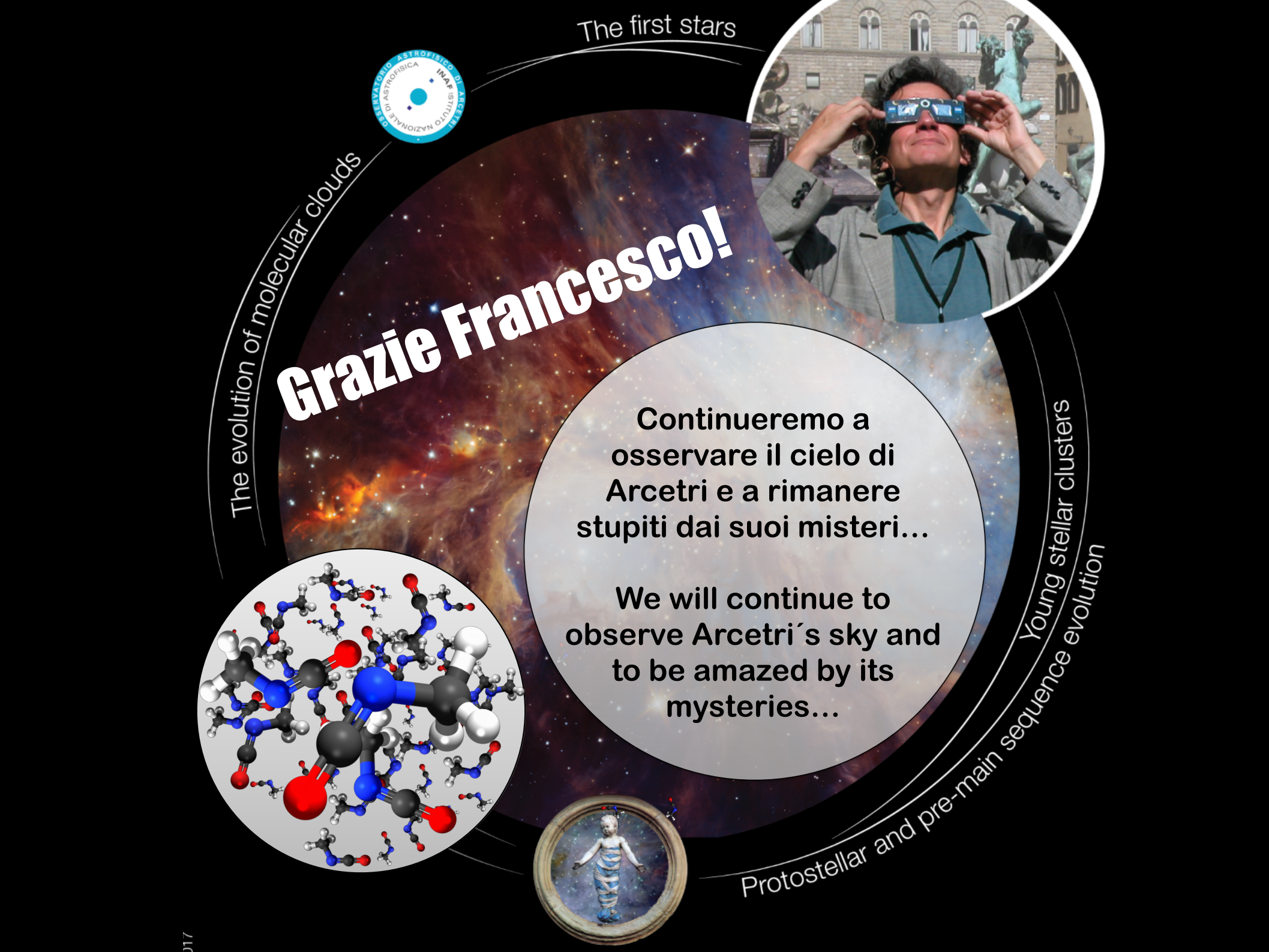
The evolution of molecular clouds
Grazie Francesco!
Continueremo a osservare il cielo di Arcetri e a rimanere stupiti dai suoi misteri...
We will continue to observe Arcetri´s sky and to be amazed by its mysteries...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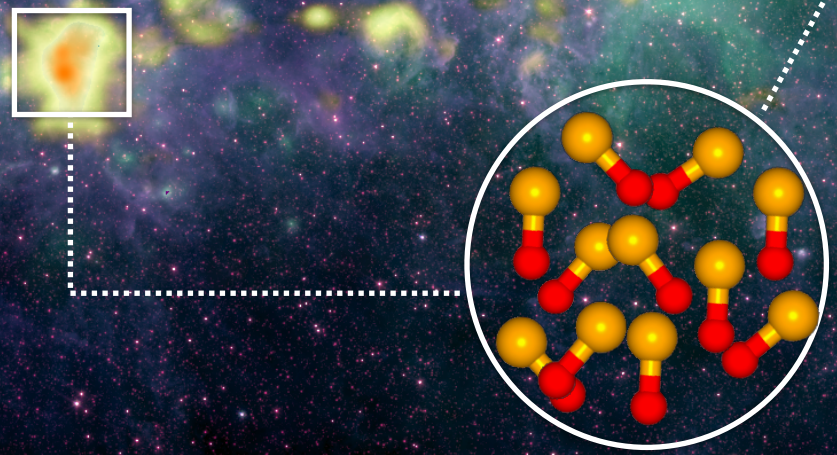
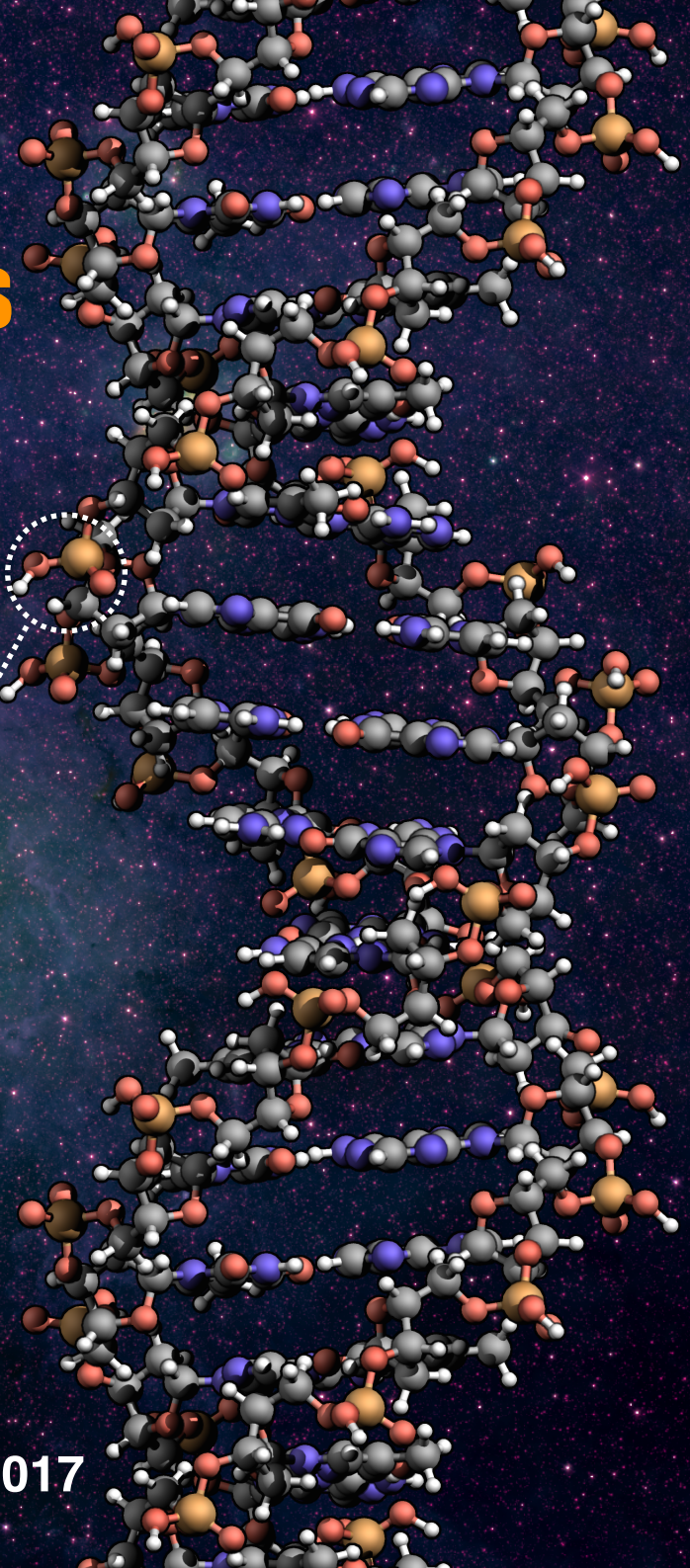
# The formation of prebiotic molecules in star-forming regions

Víctor M. Rivilla
Osservatorio Astrofisico di Arcetri, OAA-INAF





Nitrogen

INAF - Arcetri

iALMA

Francesco´s Legacy, Florence, June 5-9 2017