Ion chemistry in exoplanetary atmospheres: a new probe for habitability?

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LATMOS

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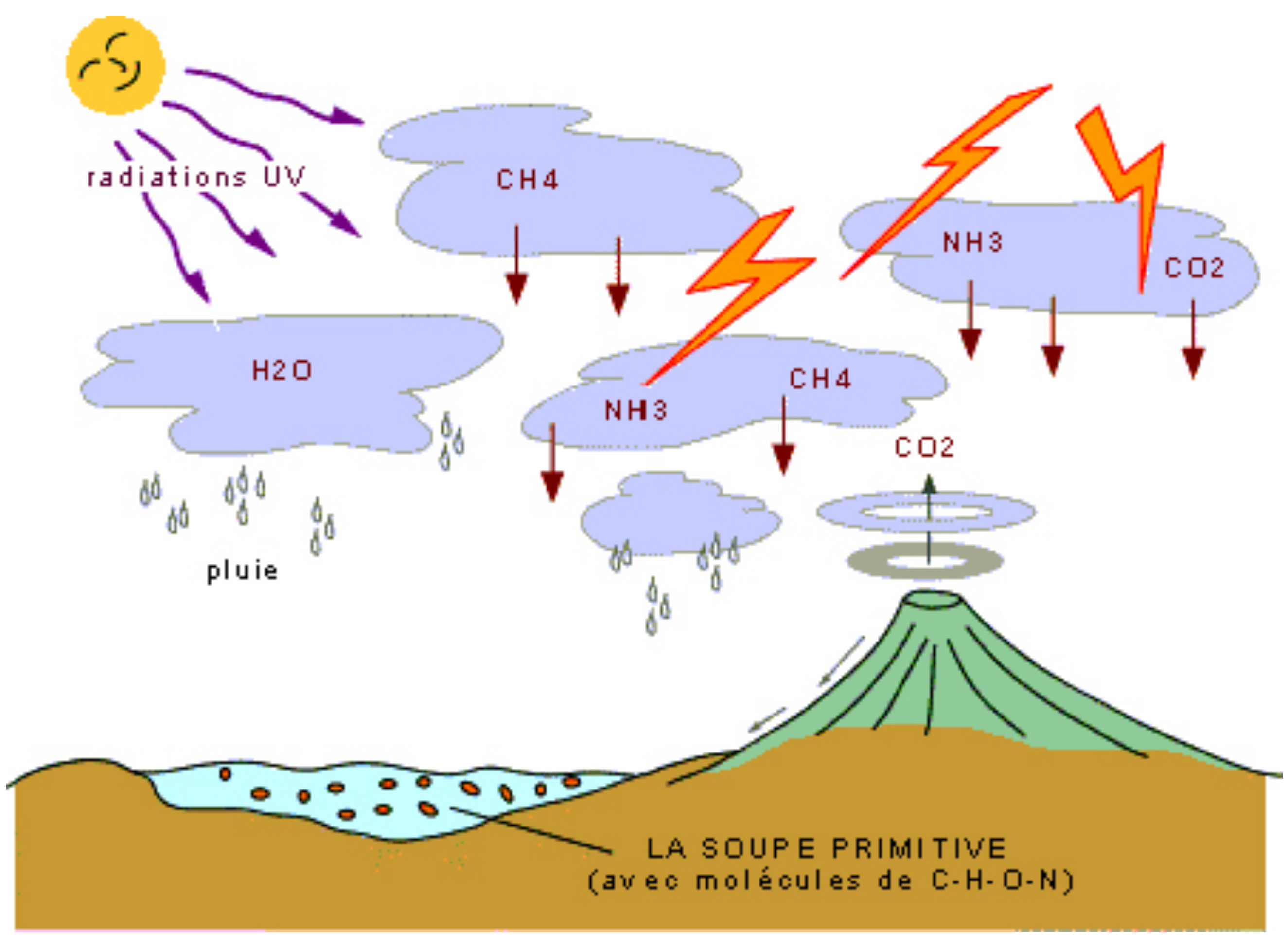
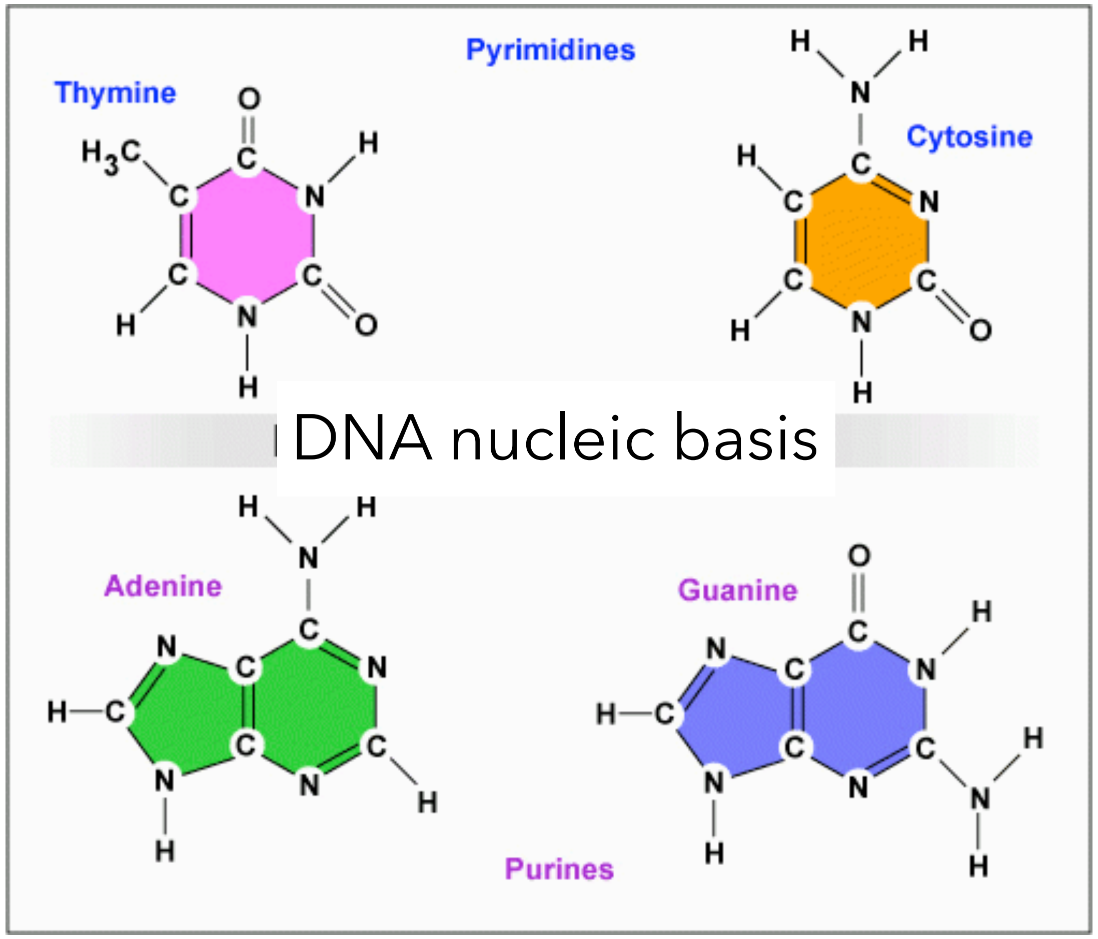
How did atmospheric chemistry support the emergence of life on Earth?

Prebiotic chemistry?

Endogenous source of N- and O-rich organic molecules





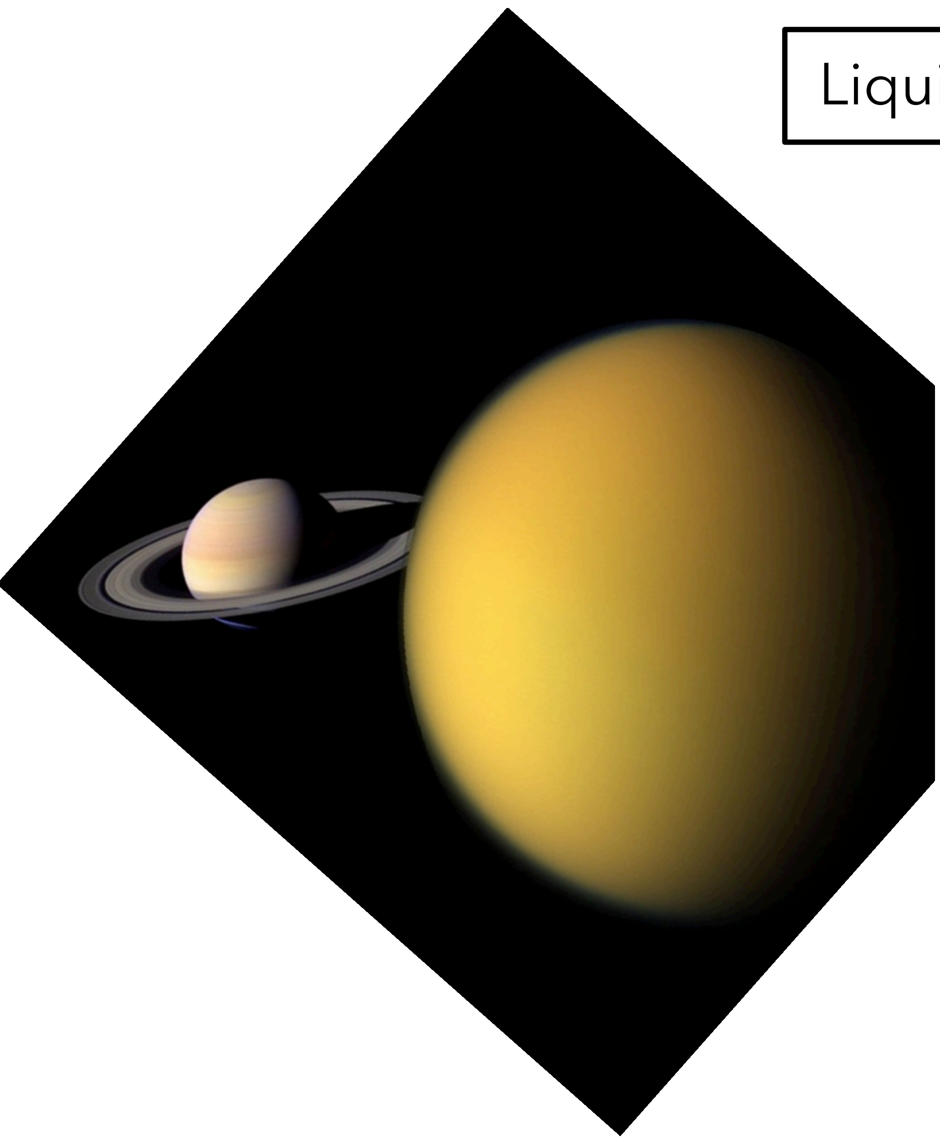
Oparin [1924], Miller [1959]

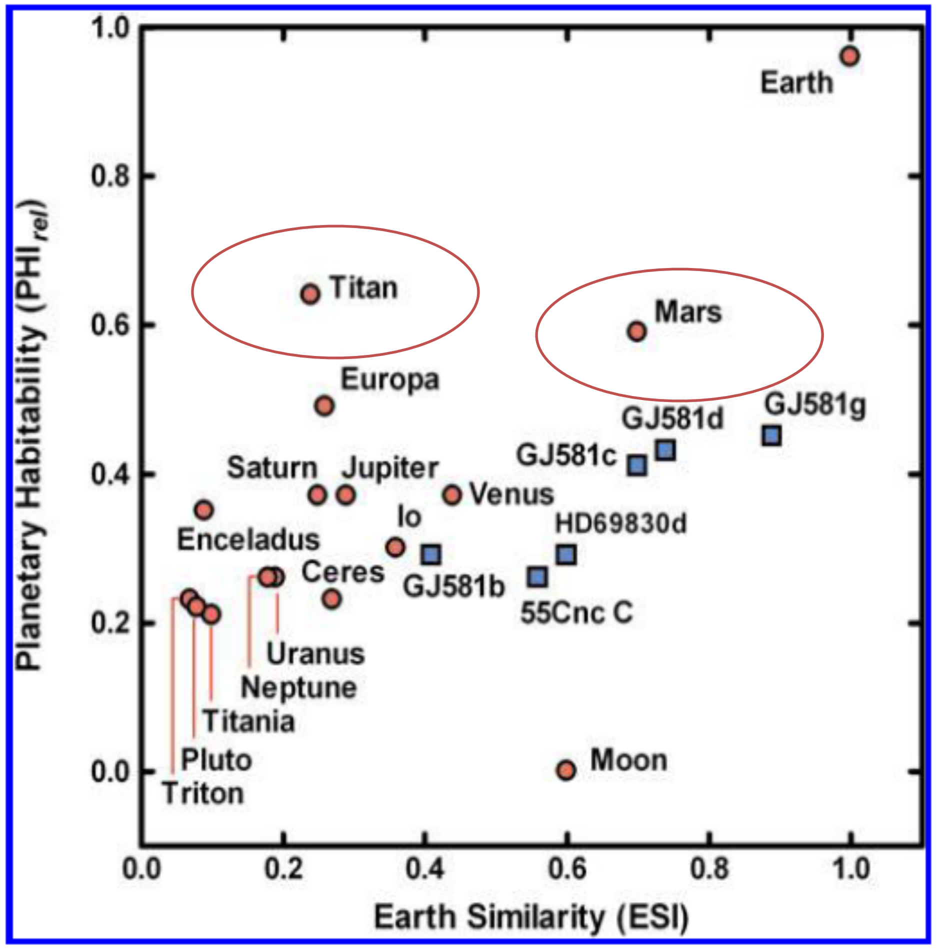
How did atmospheric chemistry support the emergence of life on Earth?

No geological archives old enough on present Earth
→ Investigation of other bodies in the solar system

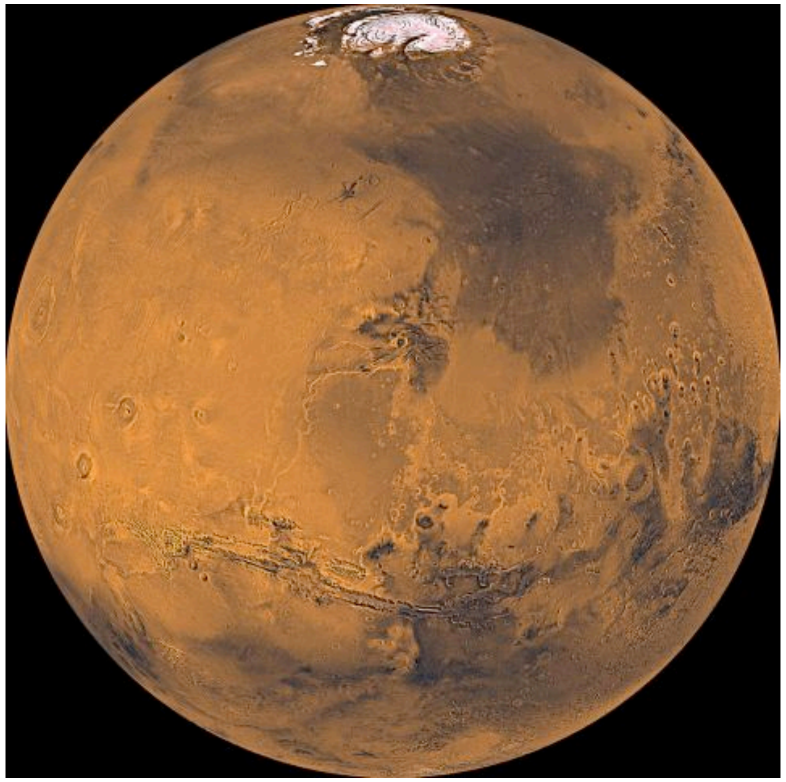
HABITABILITY

Liquid Water	Organic chemistry	Energy source



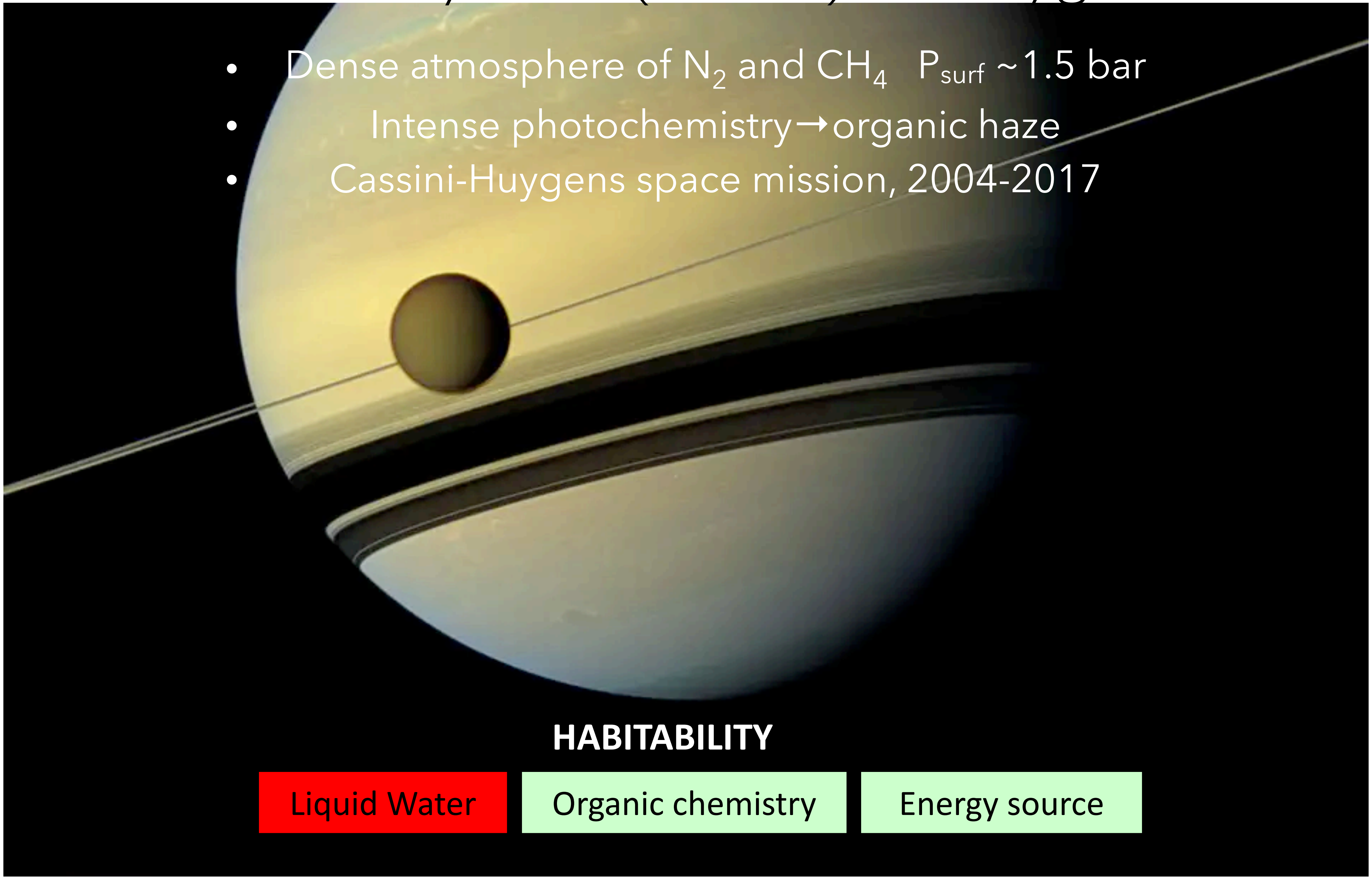


Schulze-Makuch [2011]

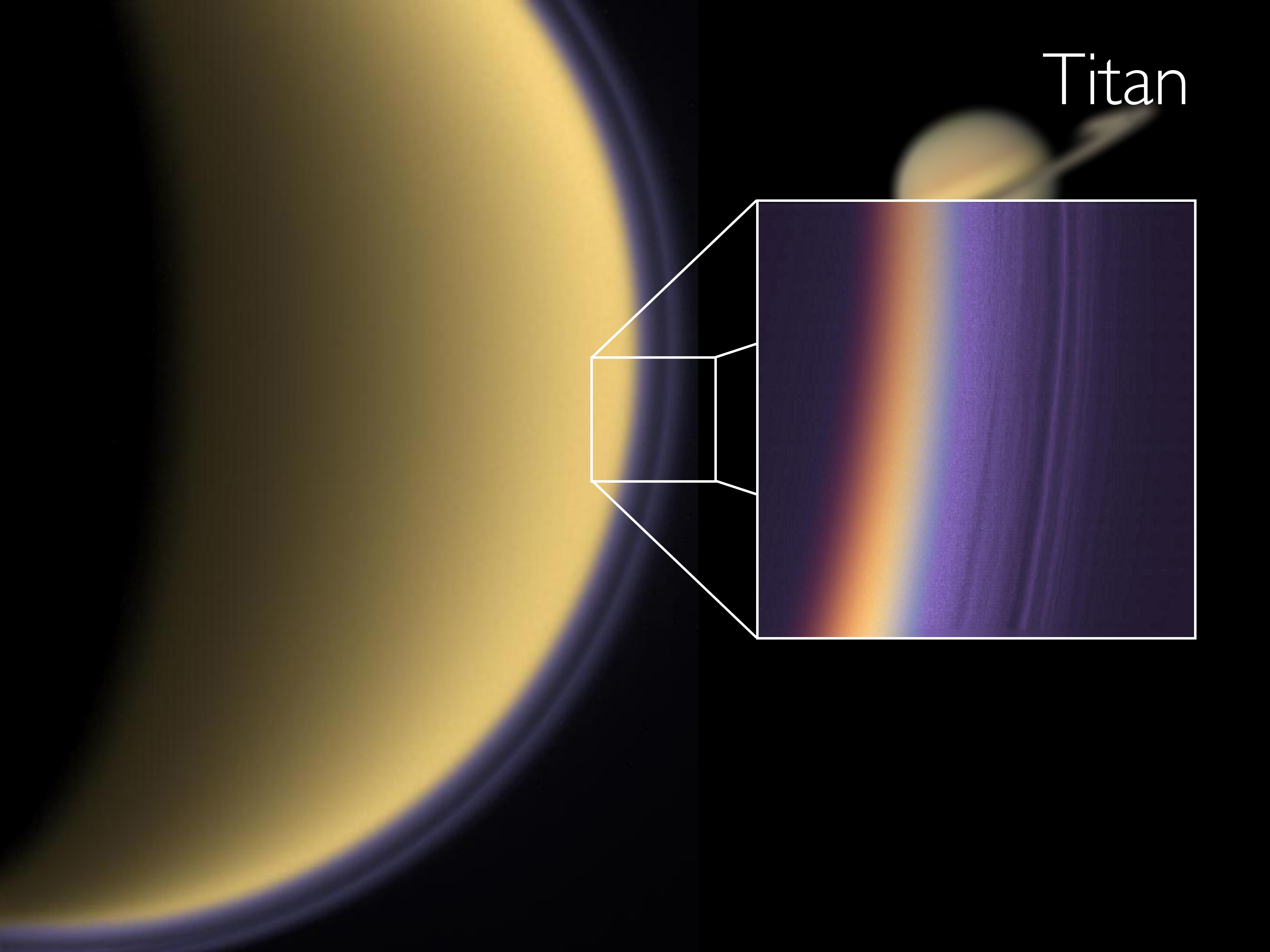


Credits: NASA-JPL

Titan: a unique place to observe prebiotic chemistry with (almost) no oxygen

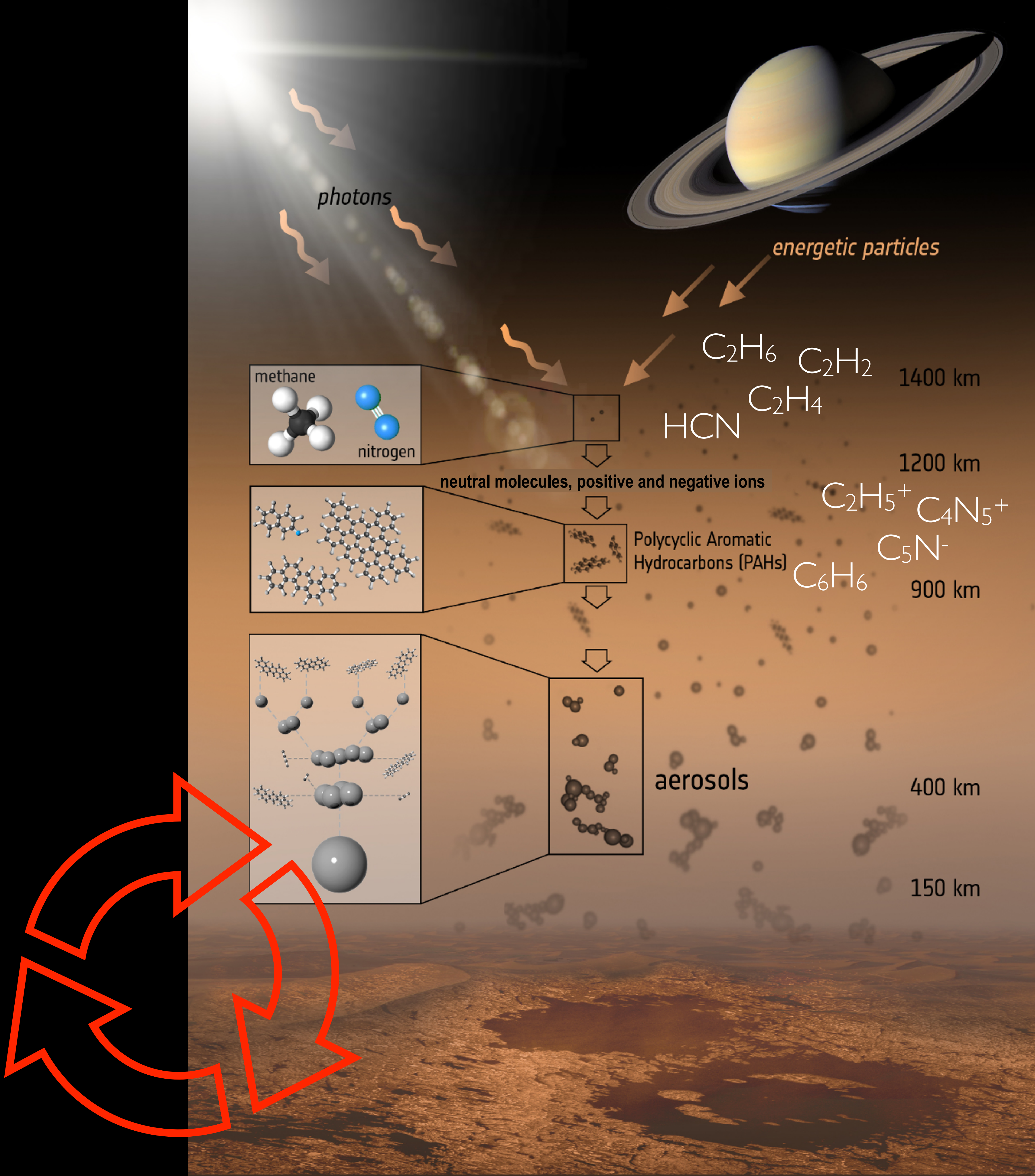


Crédit : NASA-Cassini


Titan

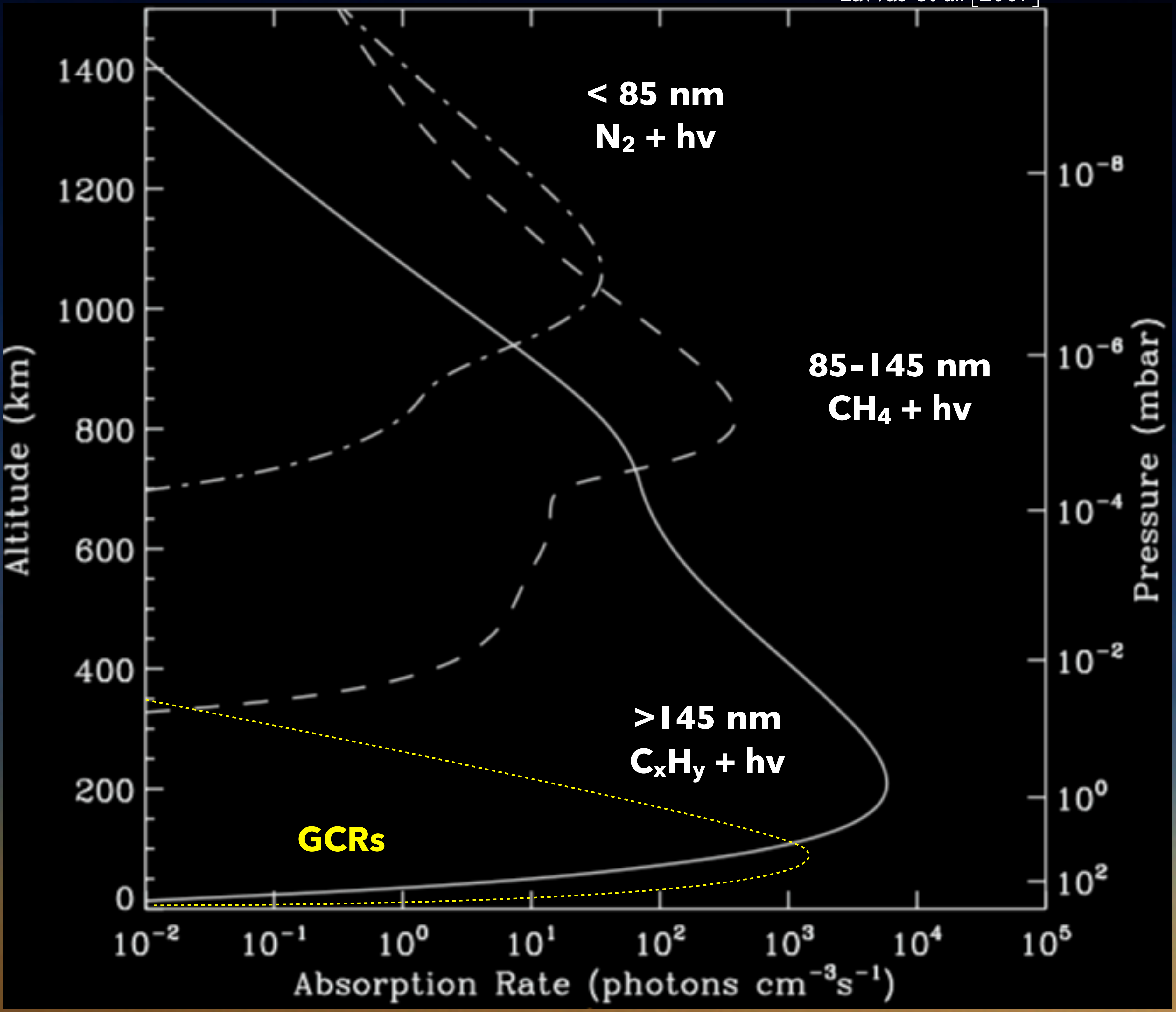
Titan

Lifetime :
τ_{CH_4} = 10-100 Myr



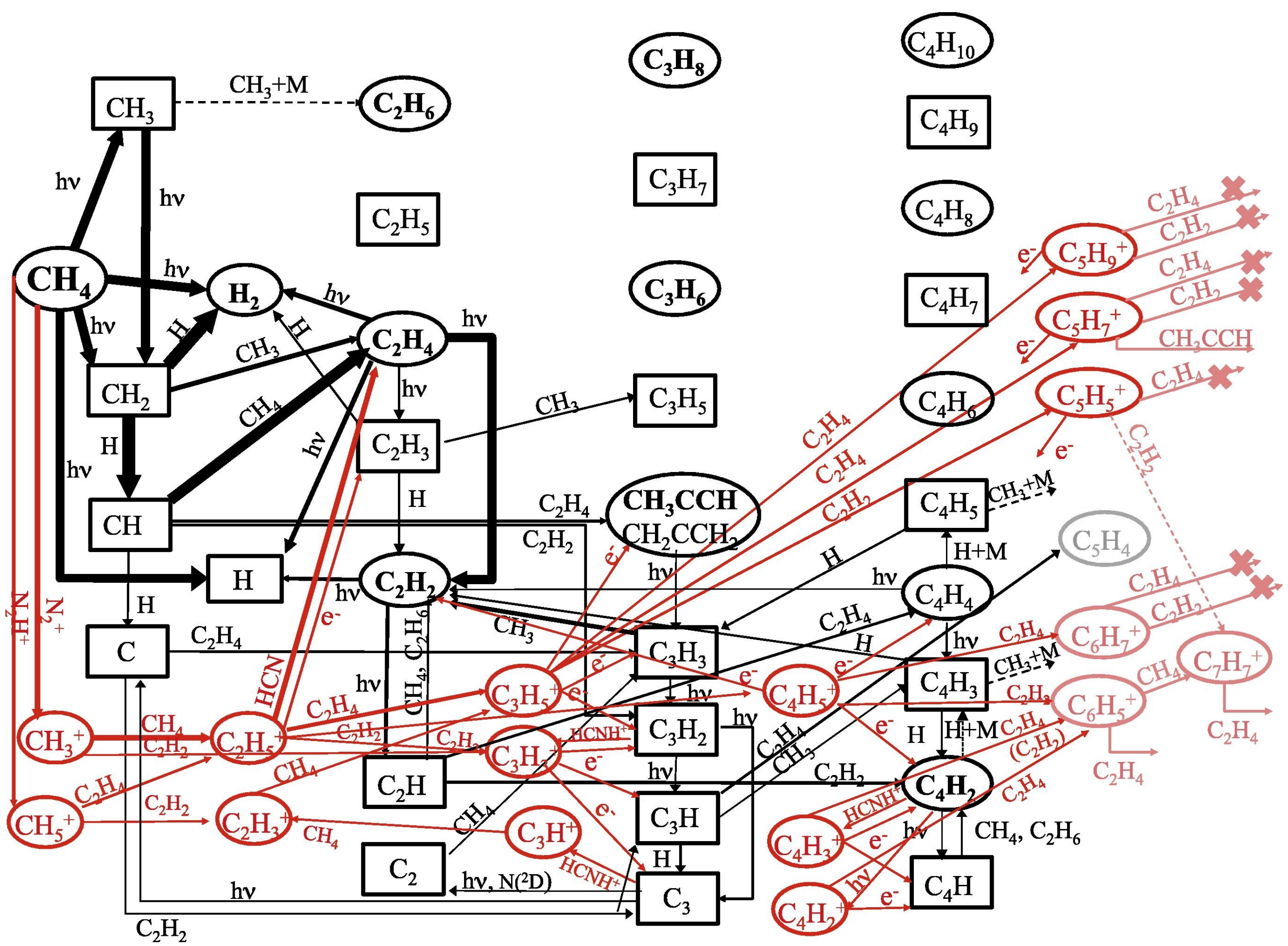
Titan

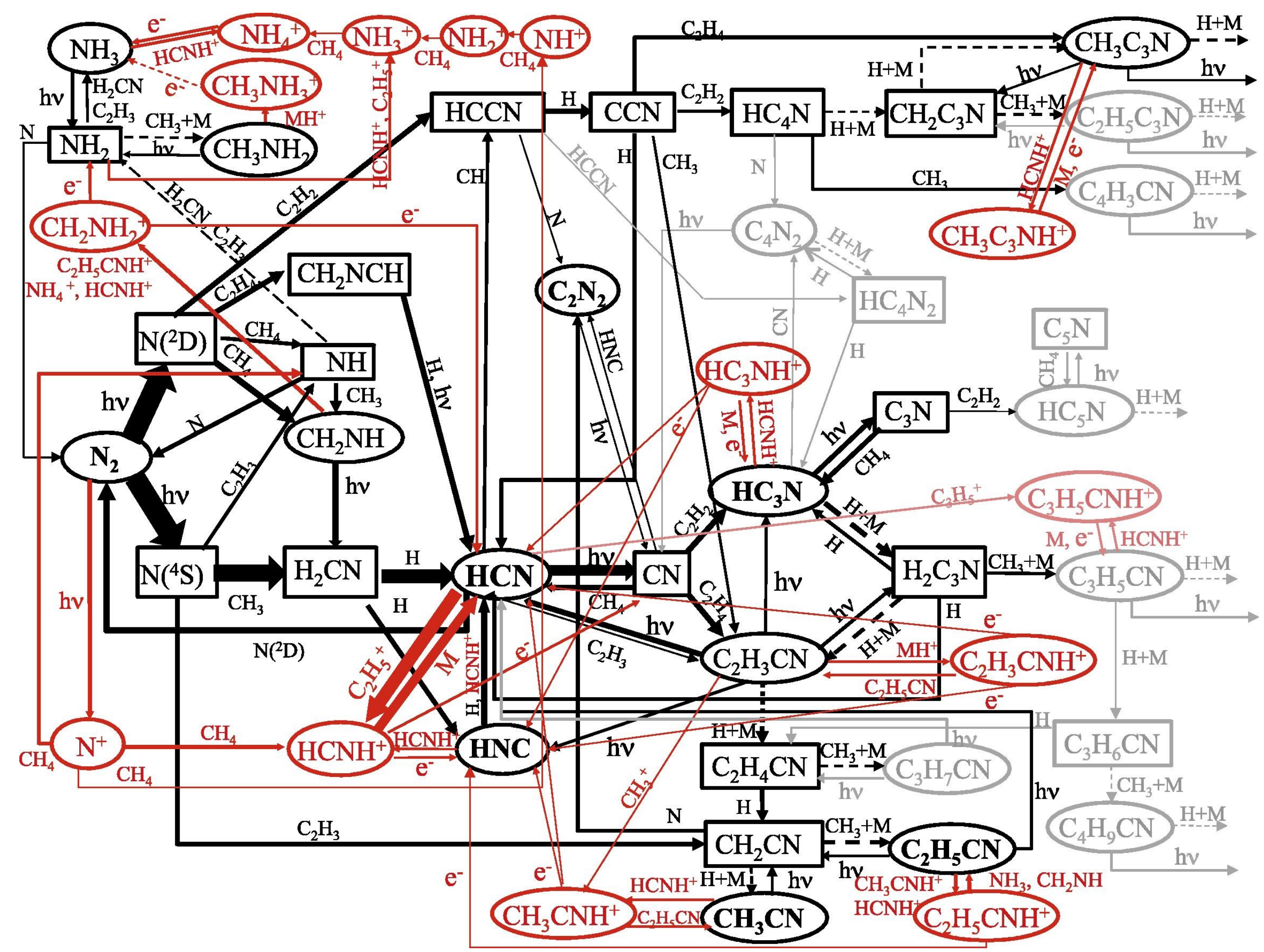
Lavvas et al. [2009]



Titan

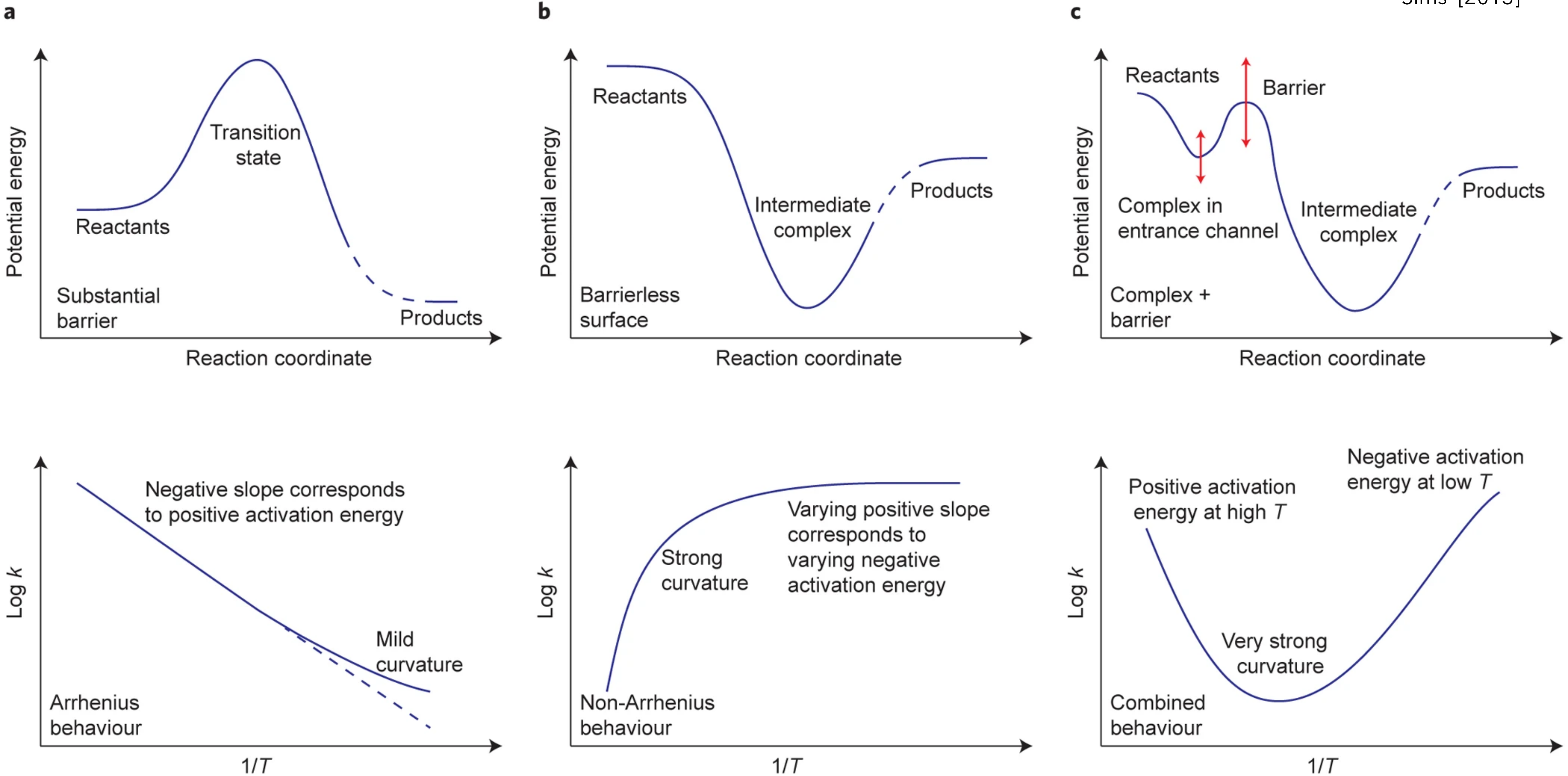
Dobrijevic et al. [2016]



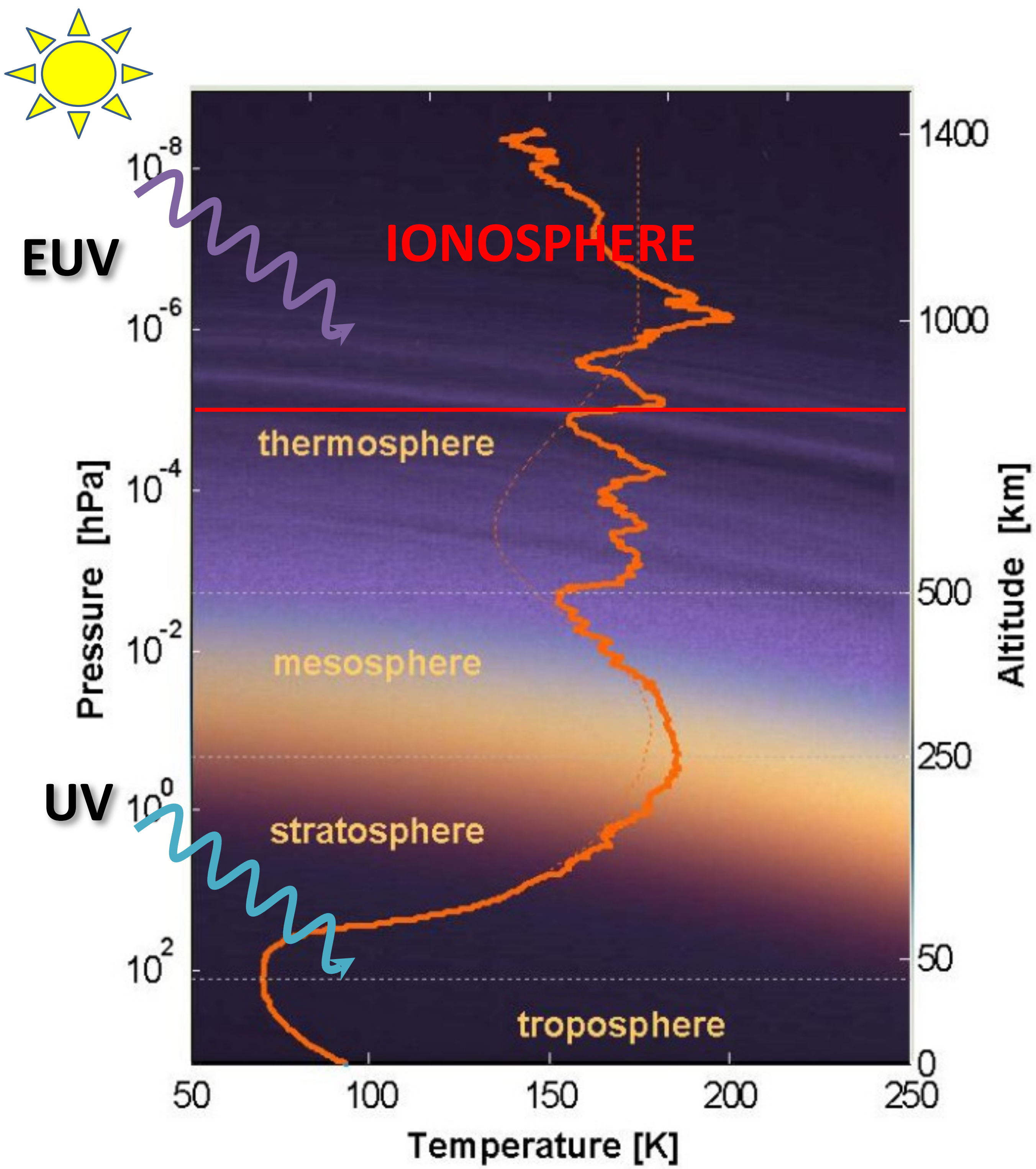


Low-temperature chemistry

Sims [2013]



Most striking result from Cassini space mission: Large N-rich ions (up to 10,000 amu)

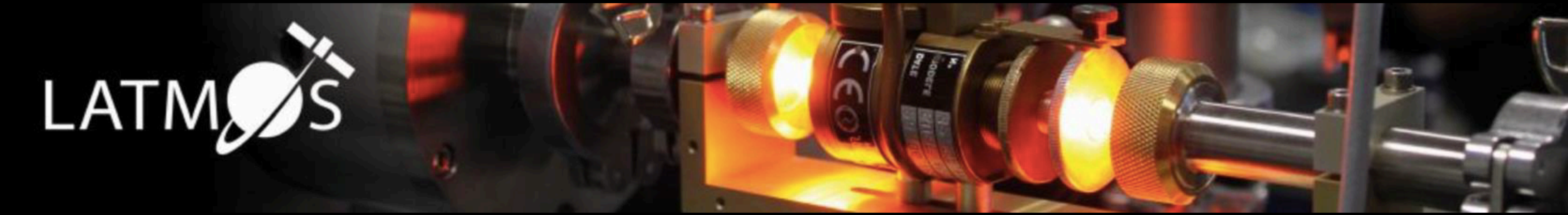


→ Solid organic aerosols
→ High prebiotic interest (amino-acids)

Ionosphere: a new source of prebiotic molecules

Specificity: Extreme-UV photons trigger N_2 reactivity

Dutuit et al. [2013]



Building extreme-UV laboratory experiments to simulate Titan's ionospheric chemistry

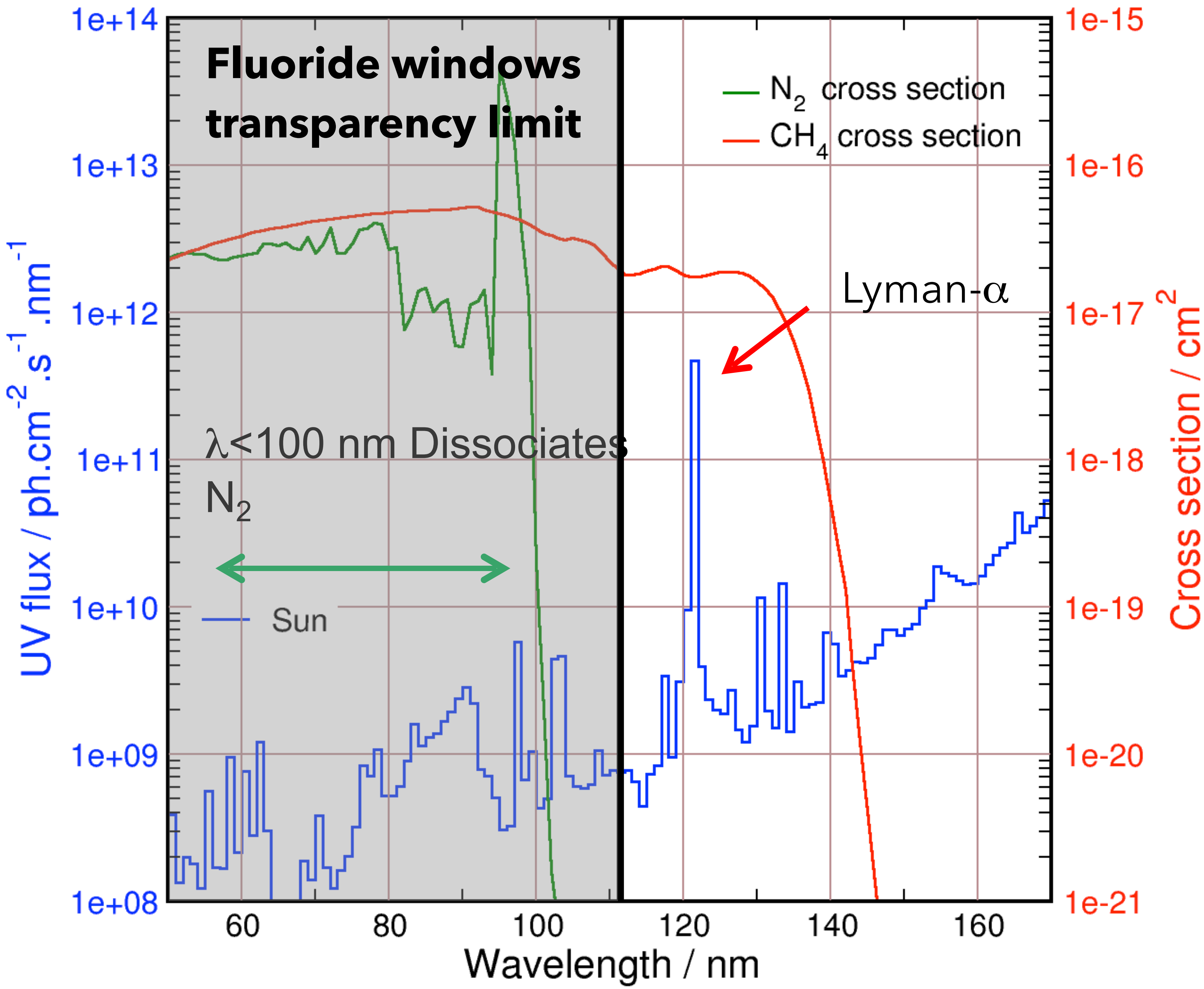
Groups:

Imanaka and Smith, University of Arizona

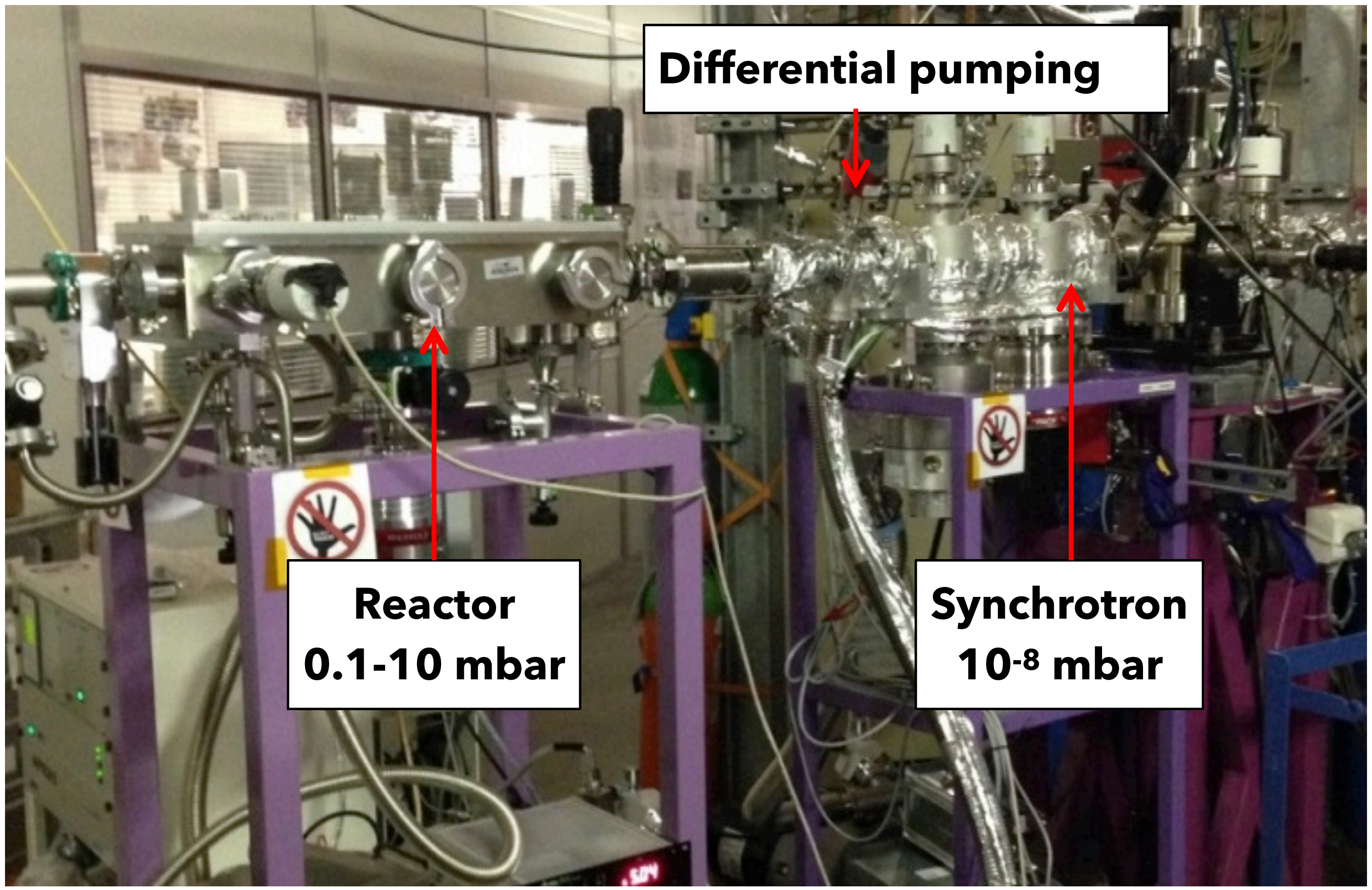
Hörst and col., John Hopkins University

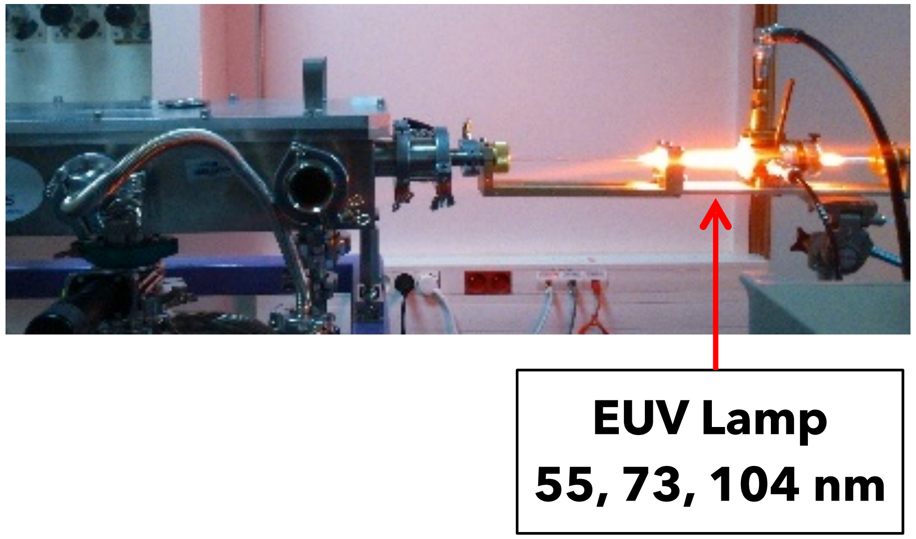
Carrasco and col., Université Versailles Saint Quentin

N_2 photochemistry in closed cells impossible in the lab



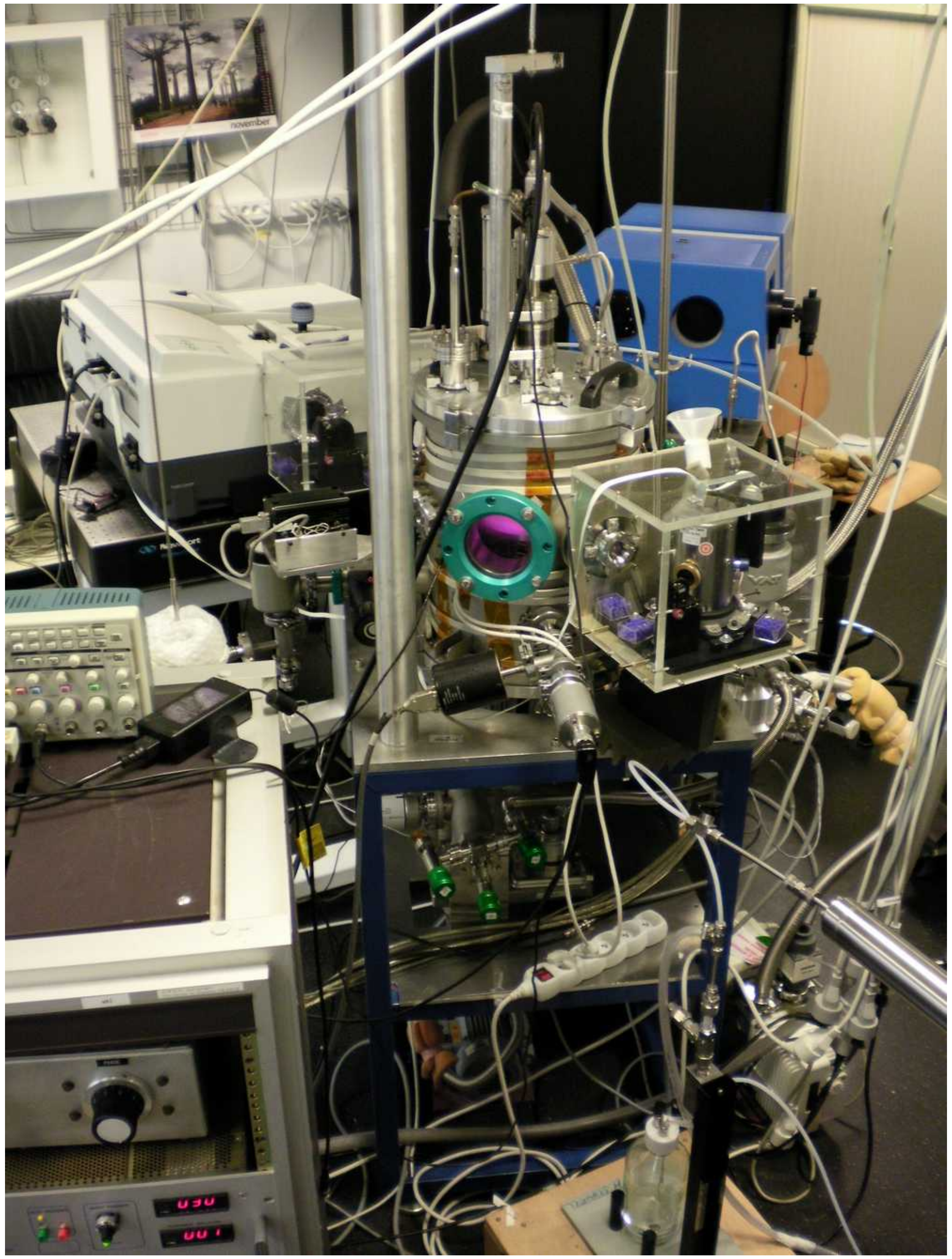
EUV photochemical reactors



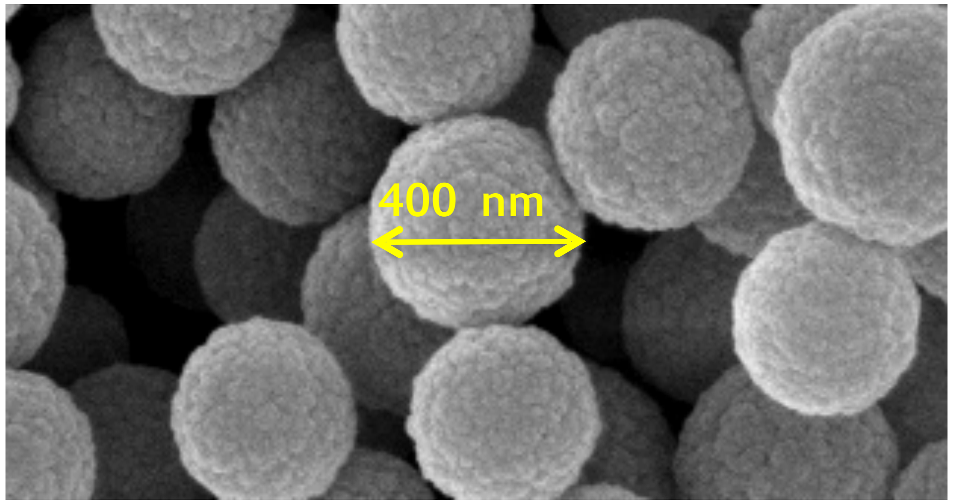


Tigrine et al. [2016]
Carrasco et al. [2011]

Dusty plasma experiment



- Optimized for haze production



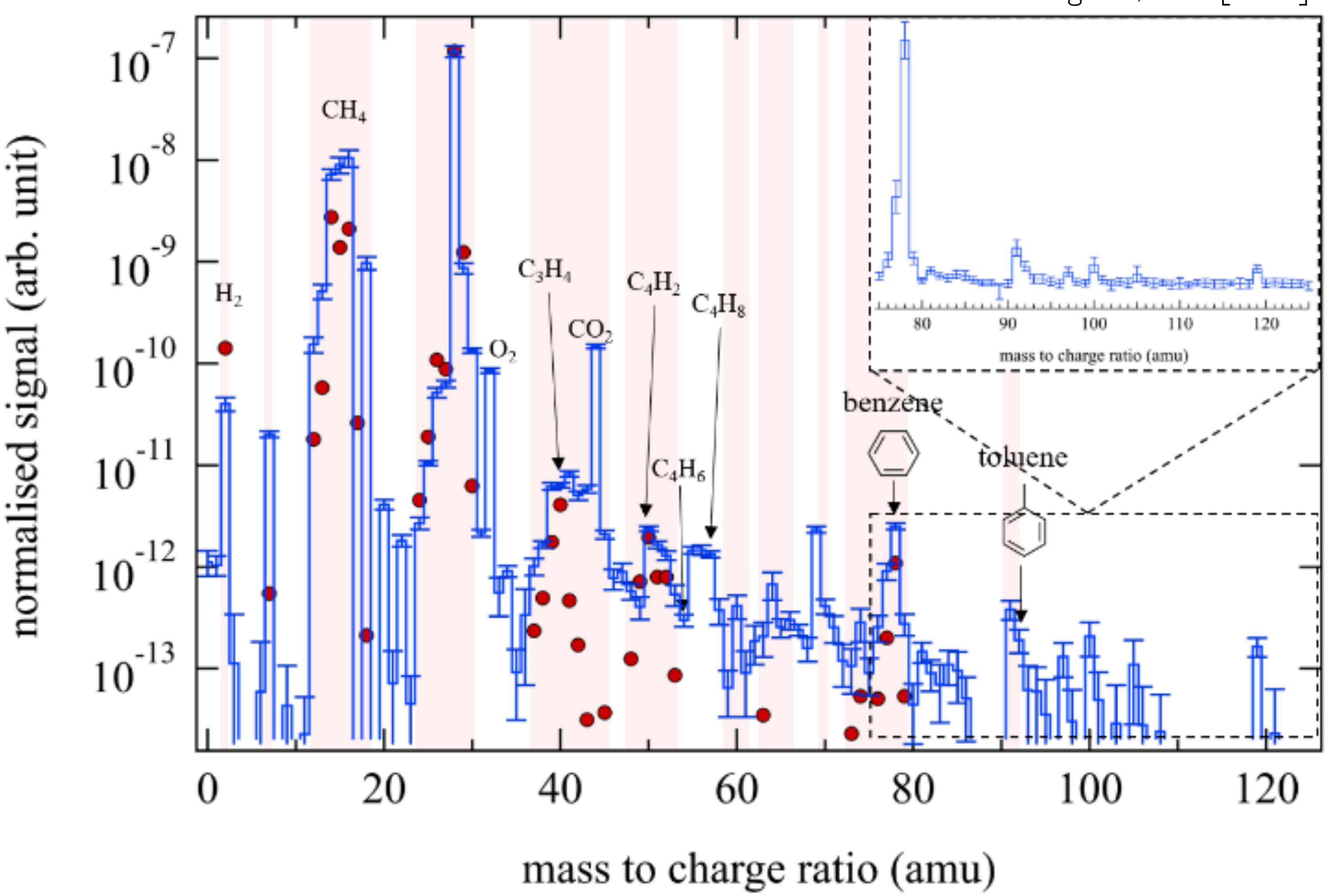
Hadamcik et al. [2009]

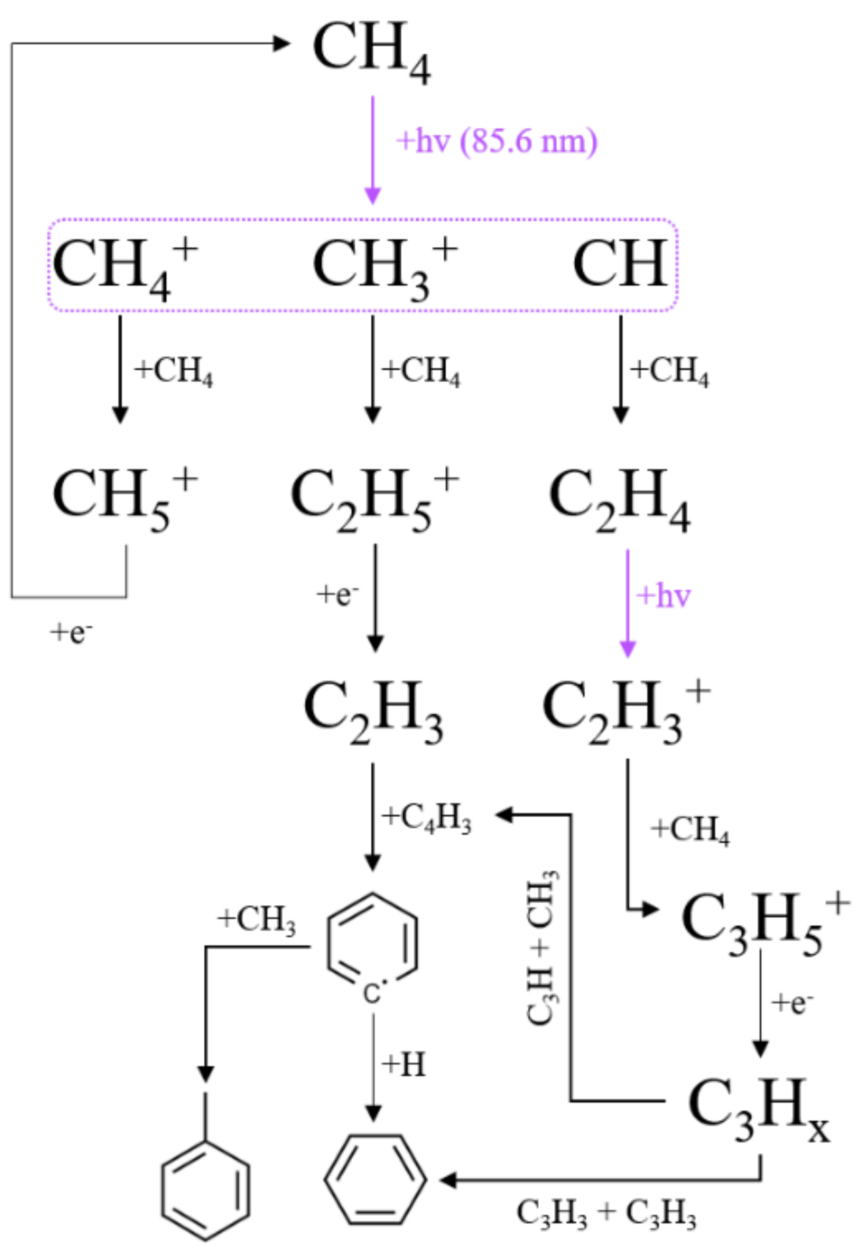
- Radicals and ions from electronic impact

Positive ions: pathways to aromatics

EUV photolysis at 85.6 nm: CH_4 ionized, N_2 dissociated

Bourgalais, et al. [2021]

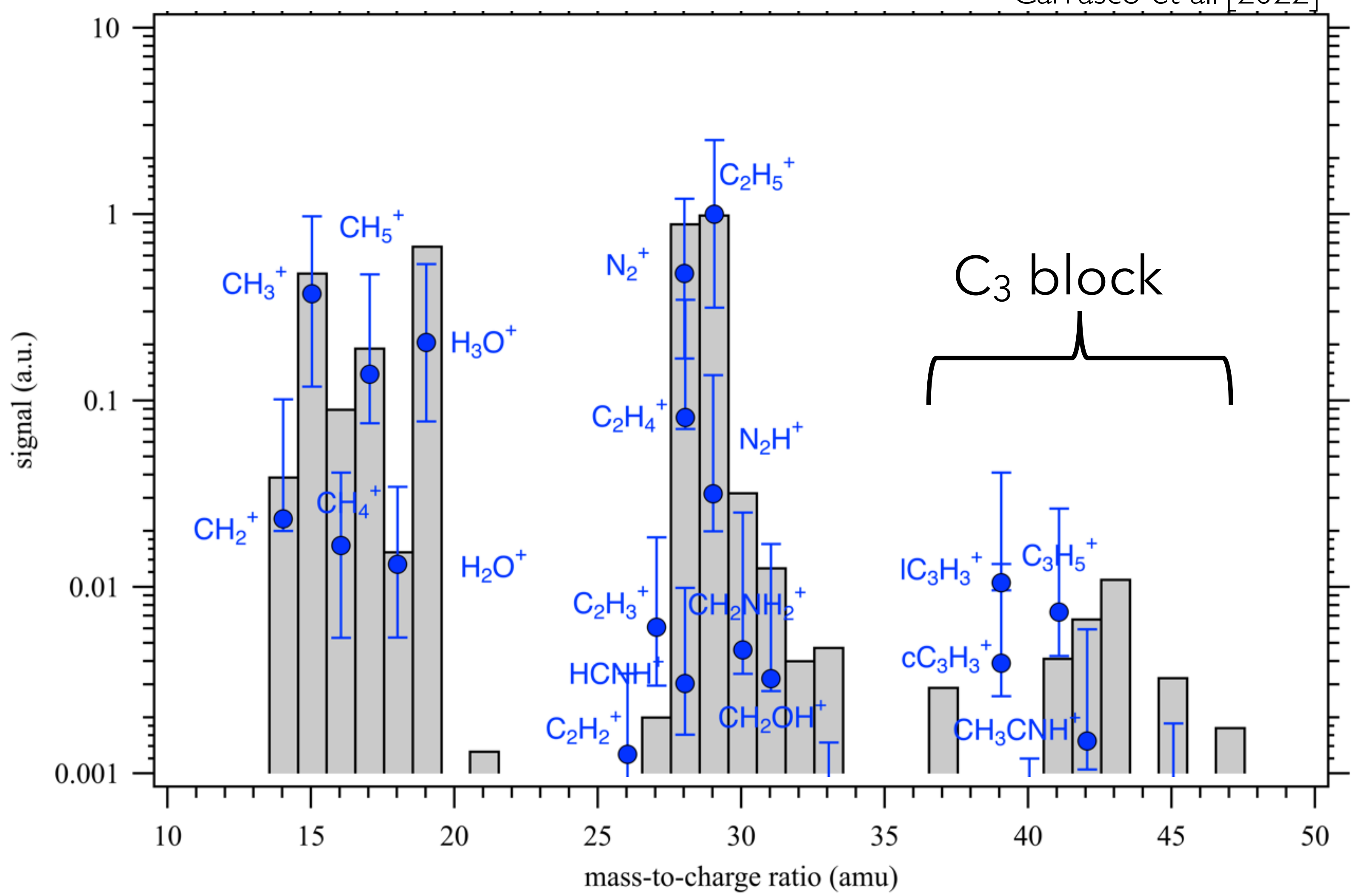




Positive ions investigation

1/ Limited predictions for ions with more than 3 heavy atoms

Carrasco et al. [2022]



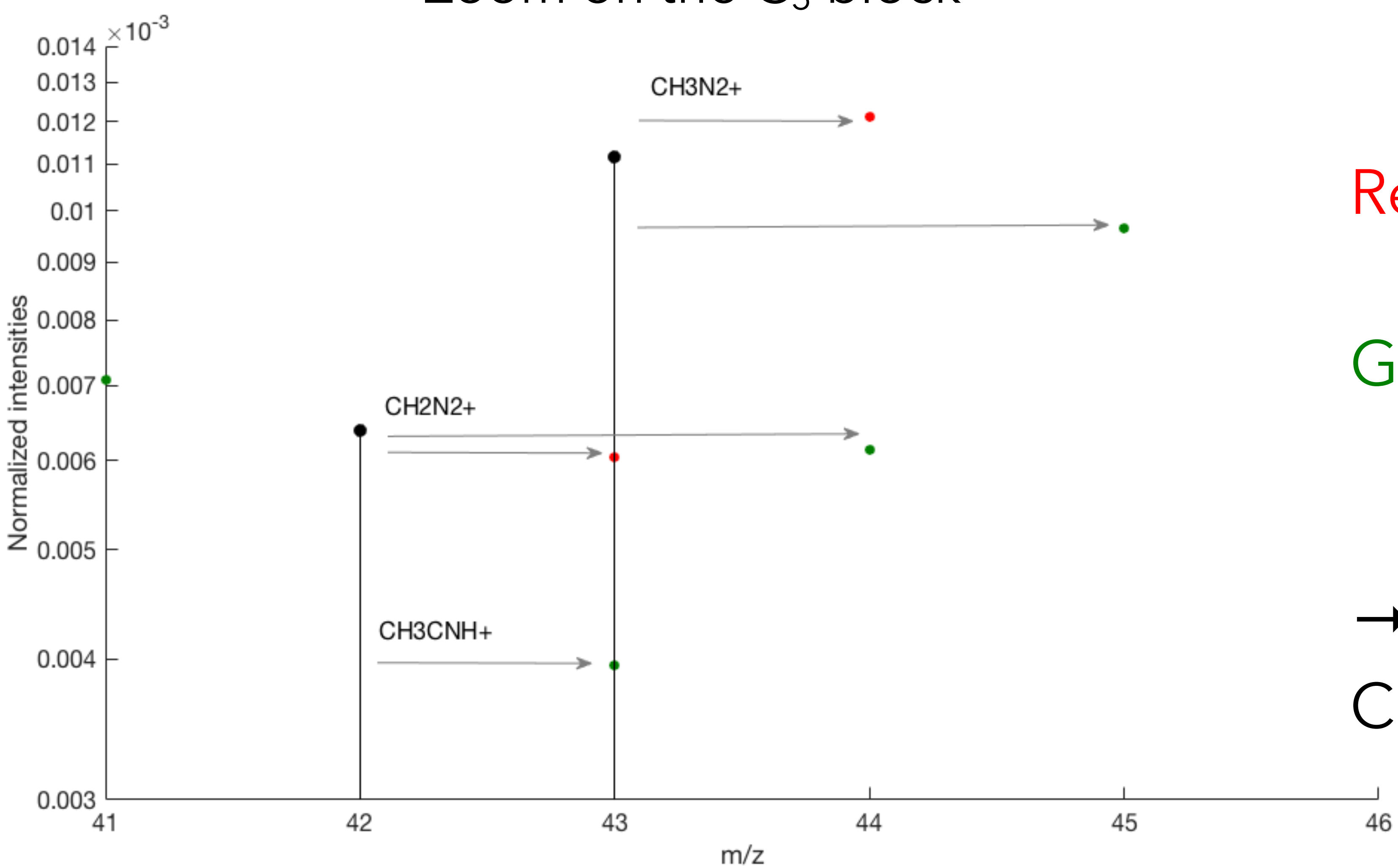
Comparison of the experimental measurements with 0D chemical model predictions

→Limitation with our current knowledge on C_3 ions

Positive ions investigation

2/ Isotopic labelling: diazo cations identification

Zoom on the C_3 block



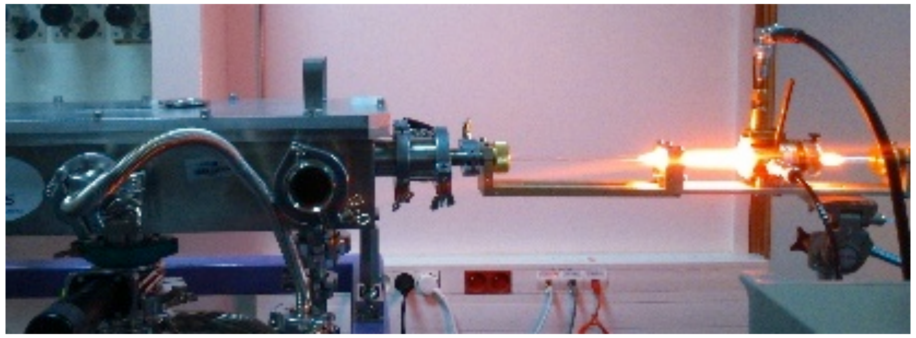
Red: ^{13}C labelling

Green: ^{15}N labelling

→Reveal the formation of $CH_2N_2^+$ and $CH_3N_2^+$

Positive ions investigation

3/ Process explaining their formation: $N_2^+ + CH_3$



EUV Lamp @73.6 nm

$N_2 \rightarrow N_2^+ + e^-$

$CH_4 \rightarrow CH_4^+ + e^-$

$CH_4 + CH_4^+ \rightarrow CH_5^+ + CH_3$

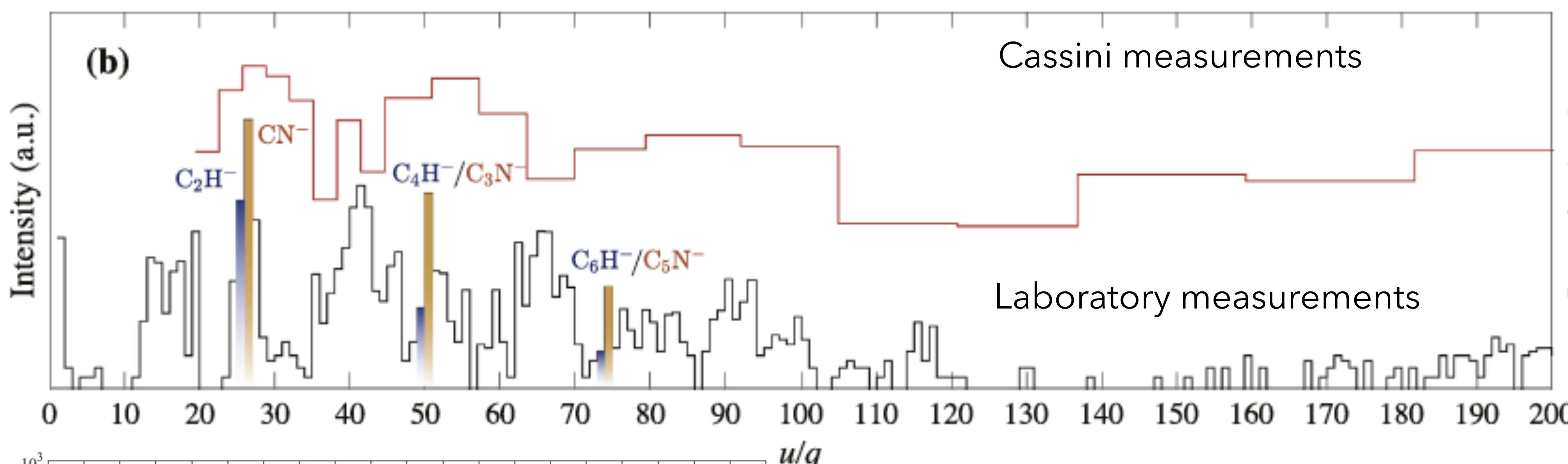
- Abundant reactive species produced by primary processes
- Not yet studied : $N_2^+ + CH_3$

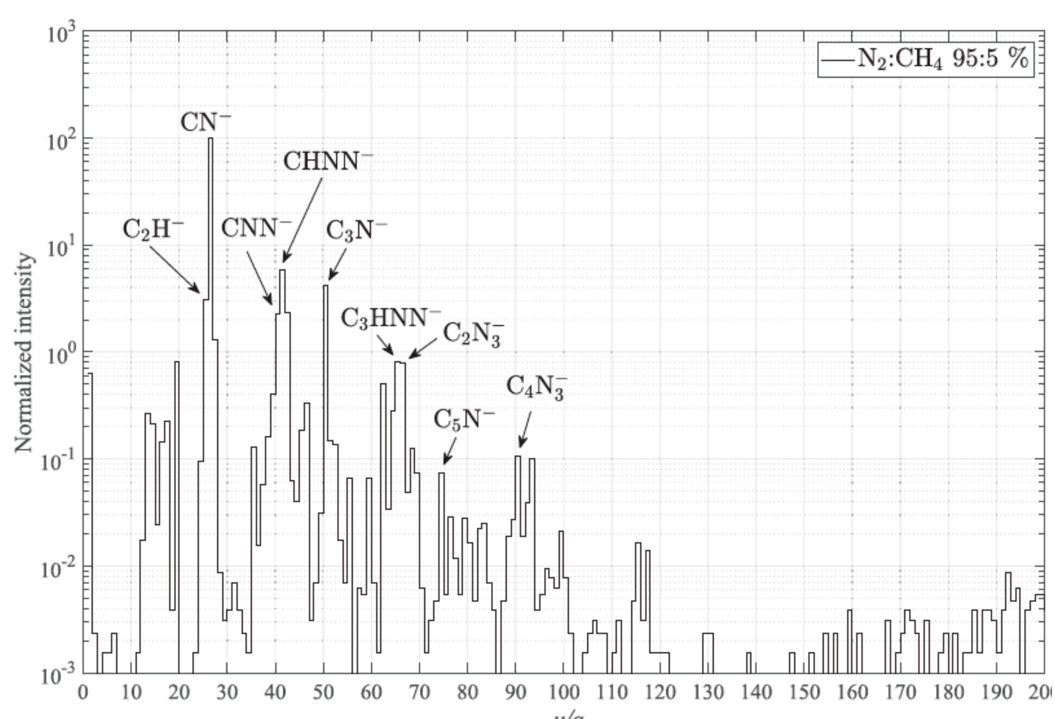
→Theoretical study calculations

Conclusion: abundant ions in Titan ionospheric conditions, between 10^{-2} and 10^{-4} × $HCNH^+$

Negative ions identification

Better performances of lab instruments, Diazo anions





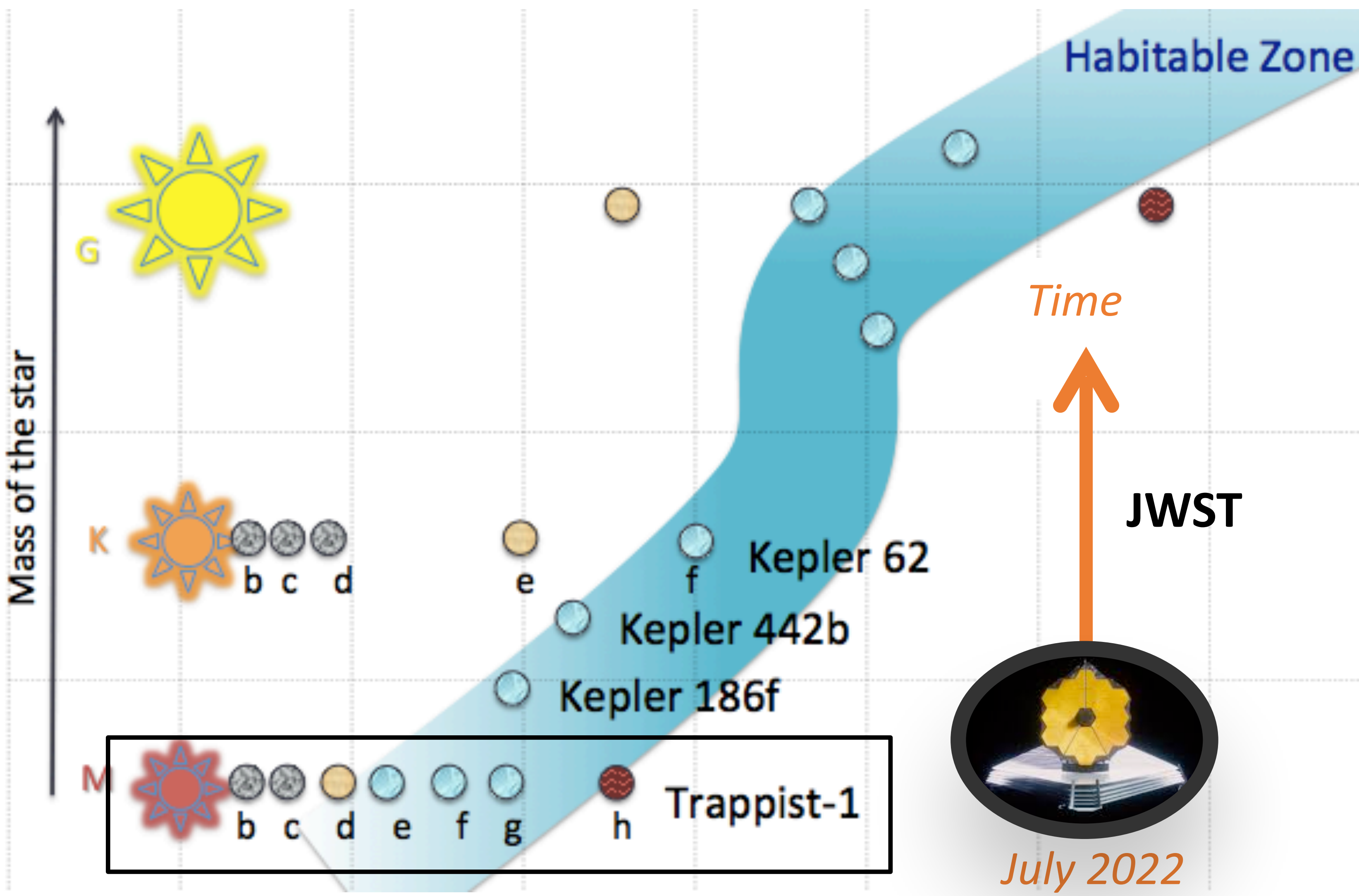
Dubois et al. [2019]

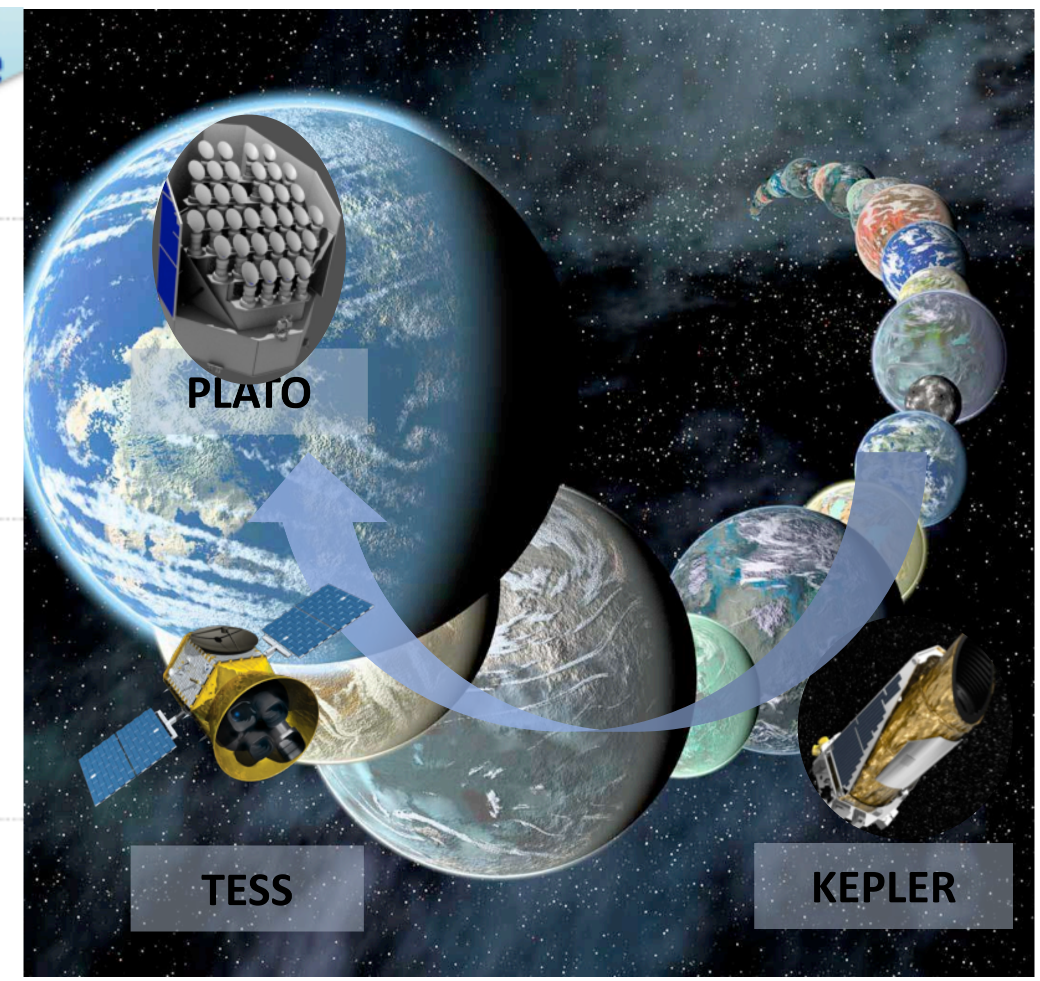
- Identification of negative ions not yet predicted by models
- Consistent with positive ions
- N incorporation in organic molecules

Search for Earth-analogs outside the solar system
Humid conditions : the Habitable Zone (HZ)

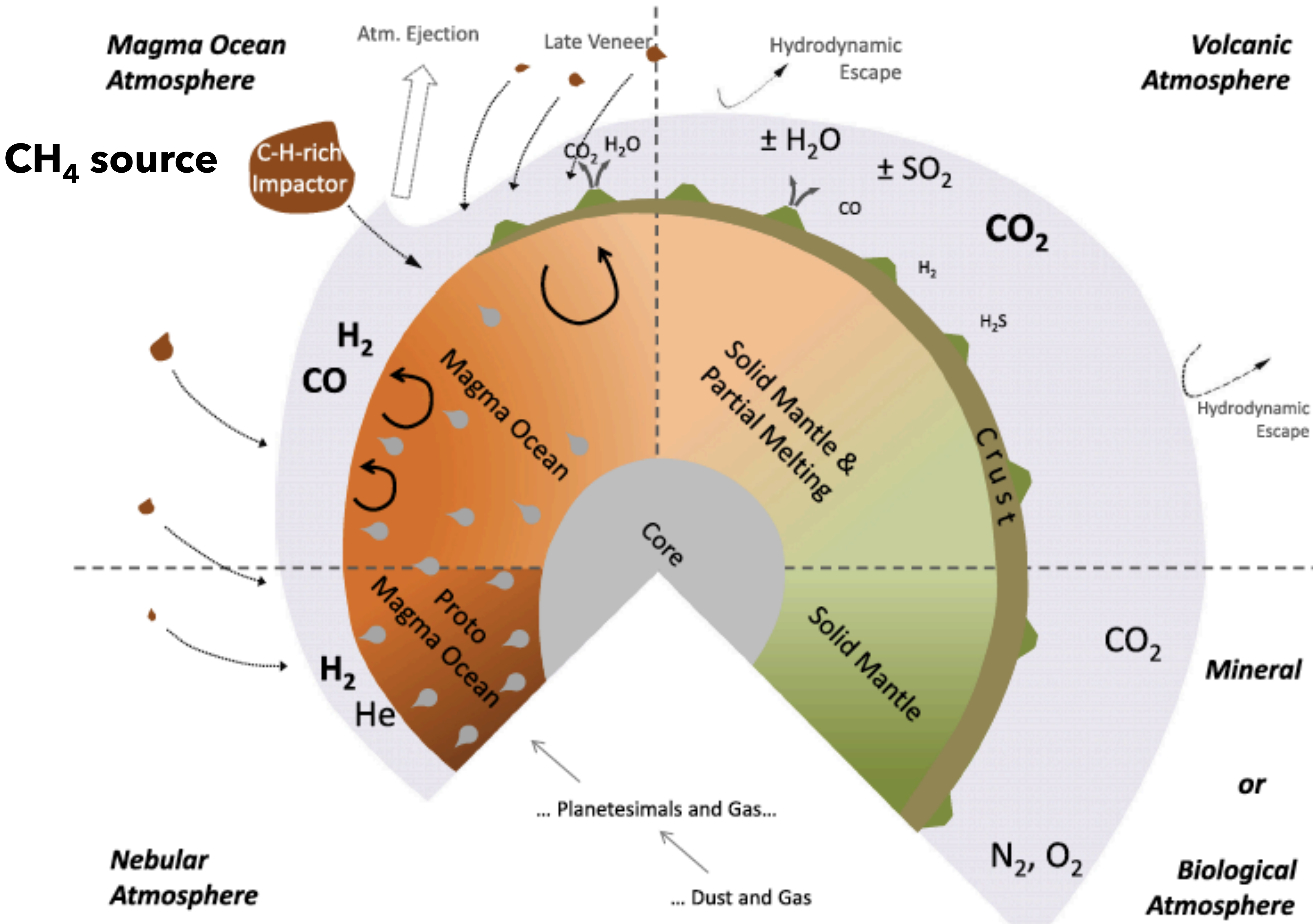
HABITABILITY

Liquid Water	Organic chemistry	Energy source





Adapted from Nasa/JPL-Caltech



Gaillard and Scaillet [2014]

Large range of possible atmospheric compositions: CO_2, CO, CH_4, N_2, H_2O, H_2, etc

Schaefer and Fegley [2010]

Table 1
Major gas compositions of impact generated atmospheres from chondritic planetesimals at 1500 K and 100 bars.

Gas (vol.%)	*CI*	*CM*	*CV*	*H*	*L*	*LL*	*EH*	*EL*
H_2	4.36	2.72	0.24	**48.49**	**42.99**	**42.97**	**43.83**	14.87
H_2O	**69.47**	**73.38**	17.72	18.61	17.43	23.59	16.82	5.71
CH_4	2×10^{-7}	2×10^{-8}	8×10^{-11}	0.74	0.66	0.39	0.71	0.17
CO_2	19.39	18.66	**70.54**	3.98	5.08	5.51	4.66	9.91
CO	3.15	1.79	2.45	26.87	32.51	26.06	31.47	**67.00**
N_2	0.82	0.57	0.01	0.37	0.33	0.29	1.31	1.85
NH_3	5×10^{-6}	2×10^{-6}	8×10^{-9}	0.01	0.01	9×10^{-5}	0.02	5×10^{-5}
H_2S	2.47	2.32	0.56	0.59	0.61	0.74	0.53	0.18
SO_2	0.08	0.35	7.41	1×10^{-8}	1×10^{-8}	3×10^{-8}	1×10^{-8}	1×10^{-8}
Other[a]	0.25	0.17	1.02	0.33	0.35	0.41	0.64	0.29
Total	99.99	99.96	99.95	99.99	99.97	99.96	99.99	99.98

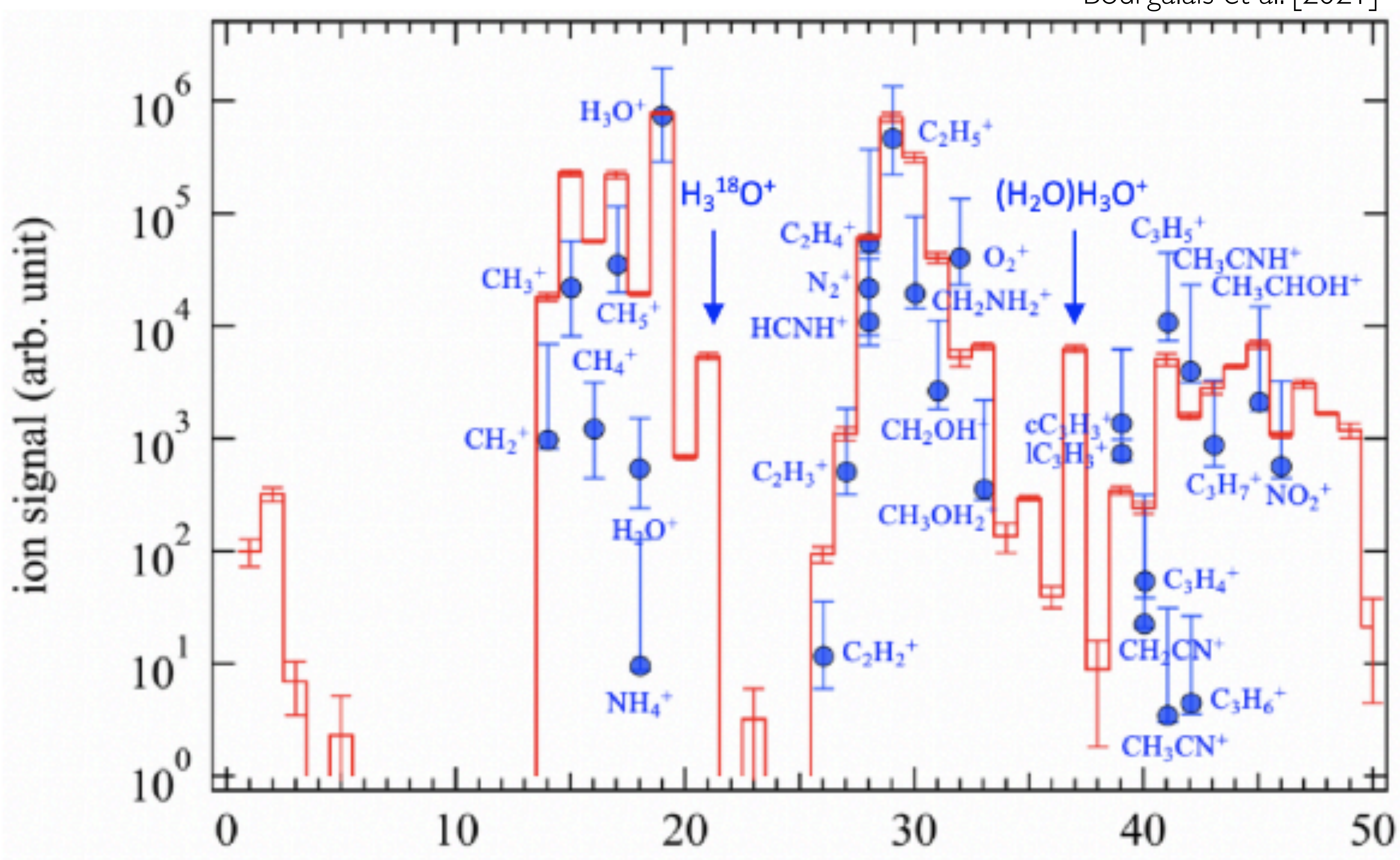
[a] Other includes gases of the rock-forming elements Cl, F, K, Na, P, and S. See text.

- Experimental method
  - Specific cases, along with JWST future detections
  - Parametric approach
    - E.g. : varying the C/O ratio, at a given N_2 concentration

Ion chemistry: Titan in the Habitable Zone

Efficient oxygen incorporation in
N_2-dominated atmospheres (N_2/CH_4 + ξ H_2O)

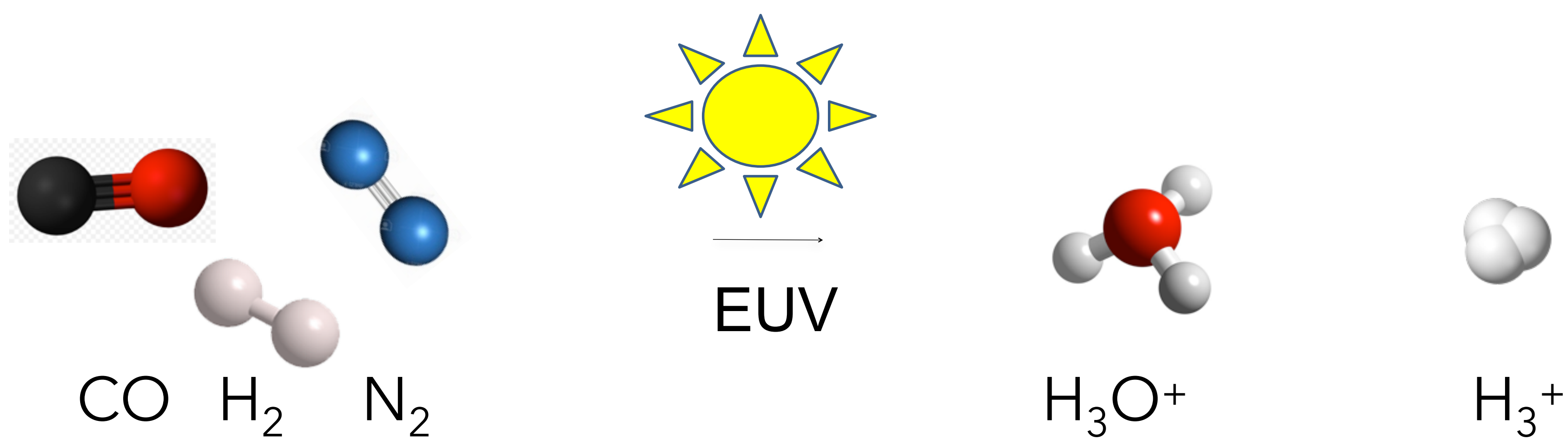
Bourgalais et al. [2021]



Detectability of ions with JWST and ARIEL?

Ionospheric signature above the cloud deck?

Bourgalais et al. [2020]

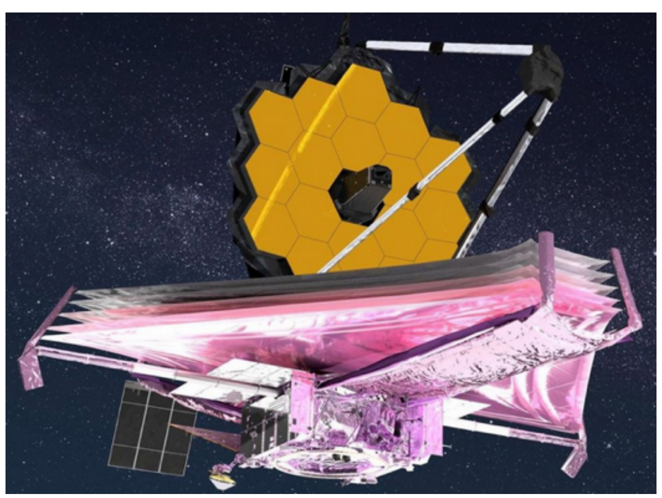


0.1 $\xrightarrow{H_2}$ 96%

Major ions

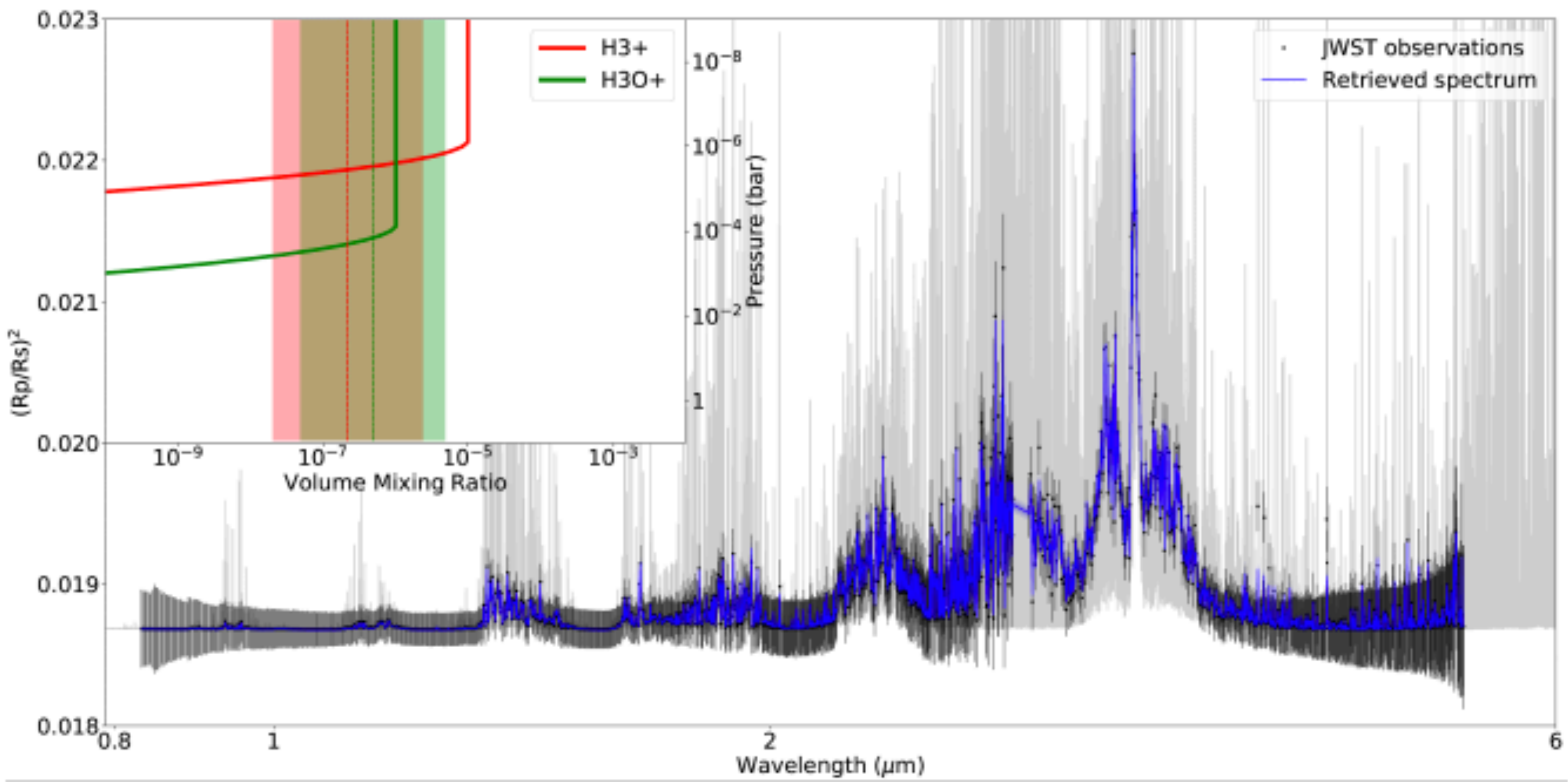
Detectability of ions with JWST and ARIEL?

Ionospheric signature above the cloud deck?



Nasa GSFC/CIL/Adriana Manrique Gutierrez

Bourgalais et al. [2020]



Retrieved spectra for simulations
of a GJ1214b-like planet with H_3O^+ and H_3^+ ions.

Detectability of ions with JWST and ARIEL?

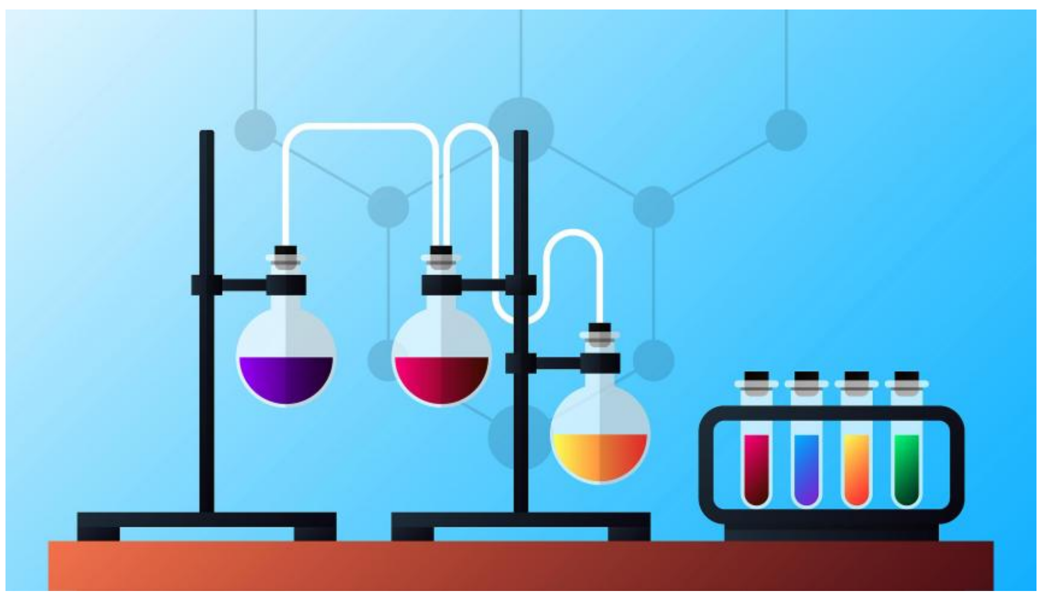
Ionospheric signature above the cloud deck?

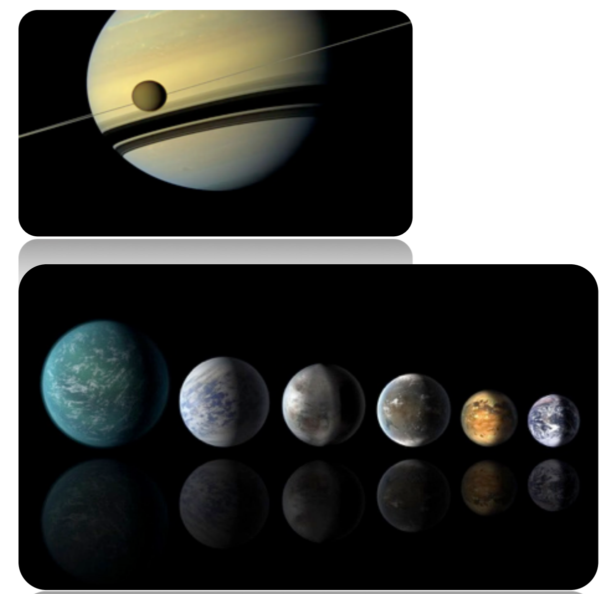
Bourgalais et al. [2020]

Detectable with ARIEL and JWST	H_3O^+	H_3^+
Volatile-Rich Super-Earths	✔	✔
Rocky Super-Earths	✔	✖

Possibility to distinguish H_2-rich and H_2-poor atmospheres from their main ions signatures

Primitive Chemistry in upper planetary atmospheres





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Activate N_2 chemistry

Chemical growth with ions

Detectable ion signatures