Laboratory Ice Astrochemistry at Large Scale Facilities

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AARHUS UNIVERSITY

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Center for Interstellar Catalysis

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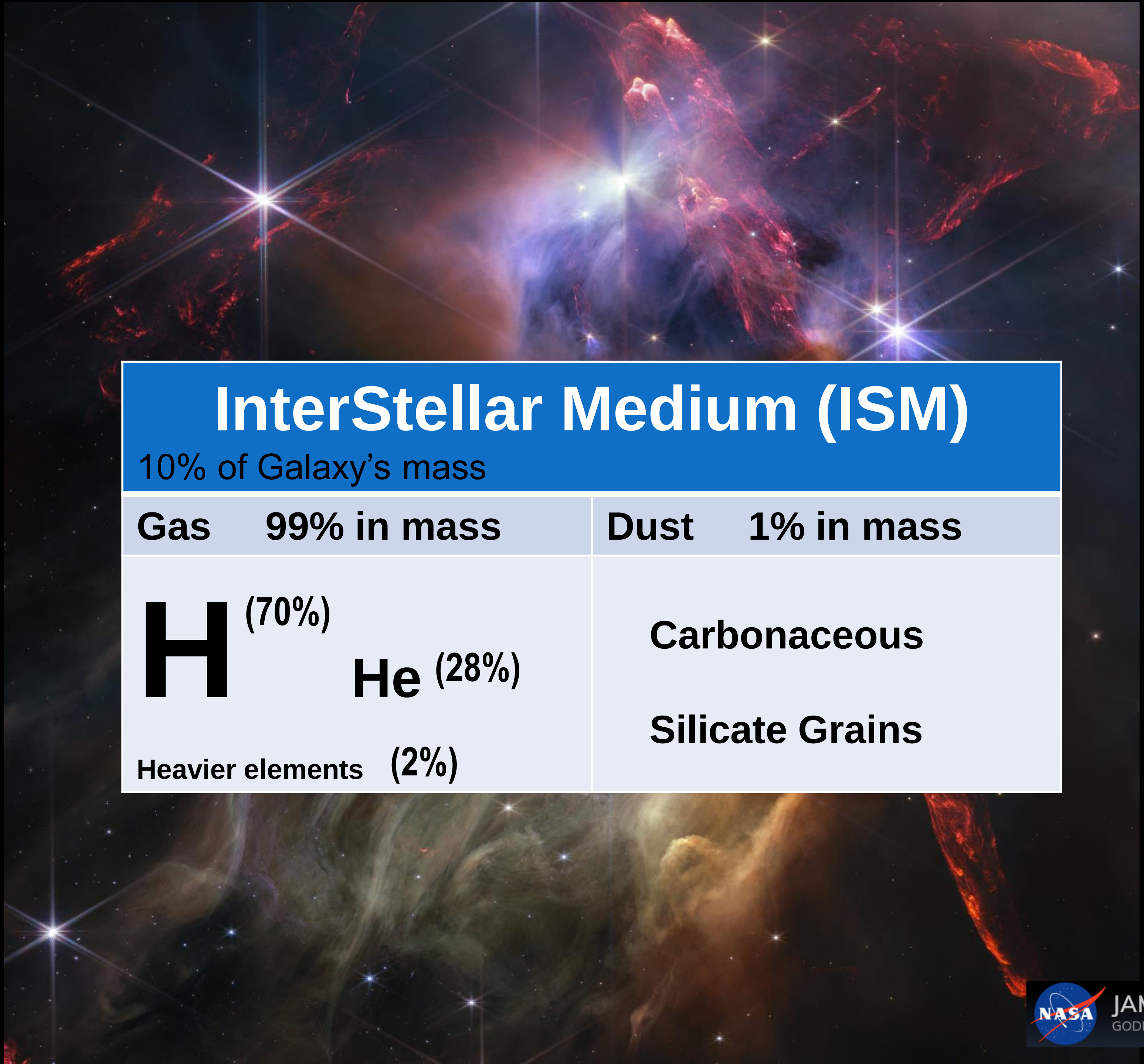


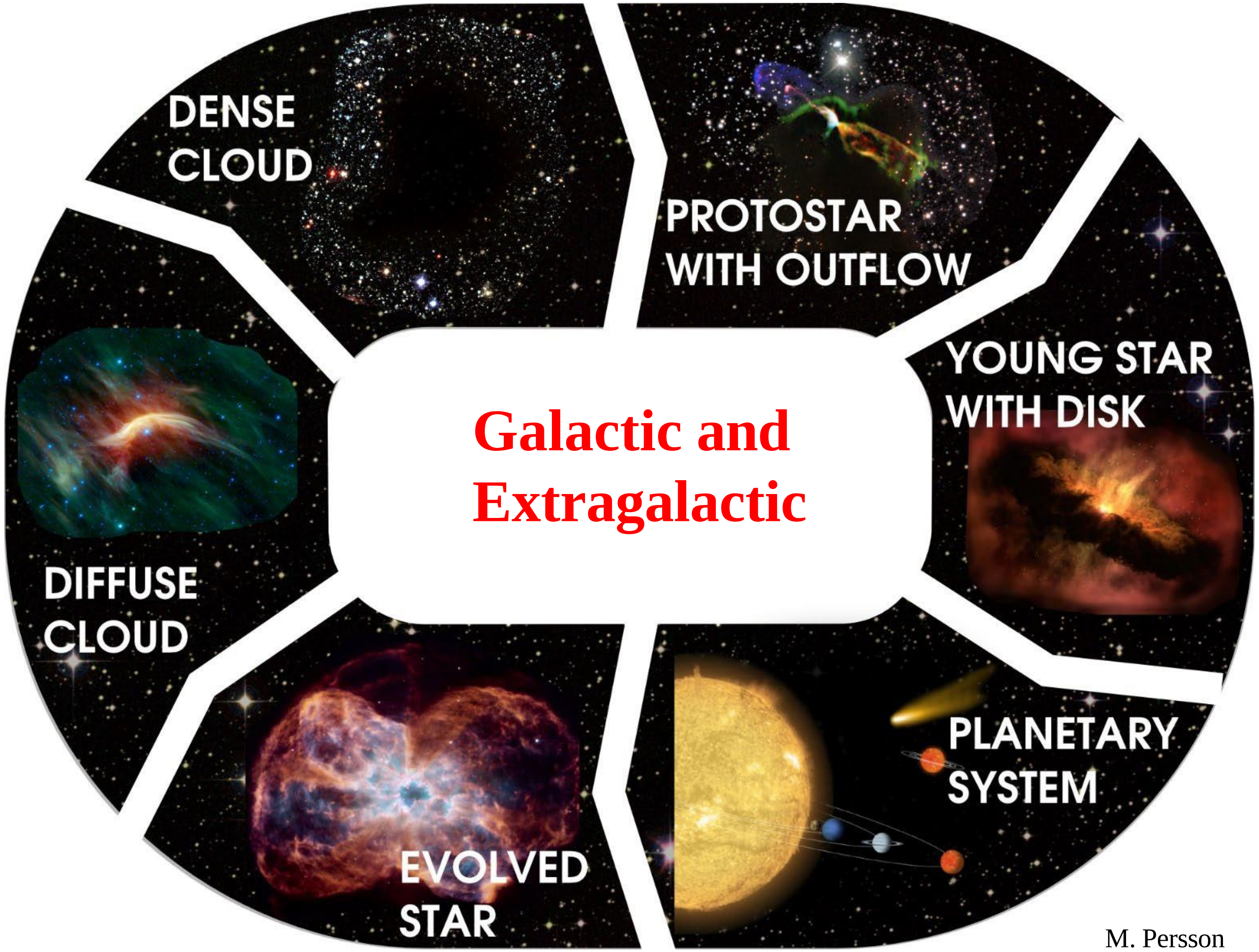
InterStellar Medium (ISM)

10% of Galaxy's mass

Gas 99% in mass	Dust 1% in mass
H (70%) He (28%) Heavier elements (2%)	Carbonaceous Silicate Grains

JAMES WEBB SPACE TELESCOPE
GODDARD SPACE FLIGHT CENTER

The Molecular Universe



M. Persson

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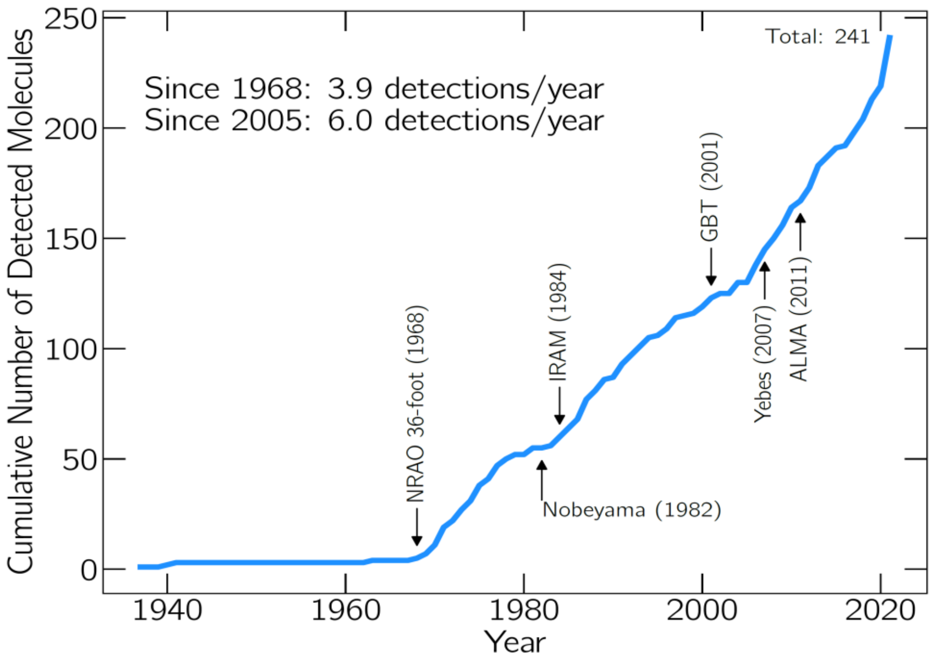
Molecules in Space

(The CDMS Catalog)
https://cdms.astro.uni-koeln.de/classic/molecules

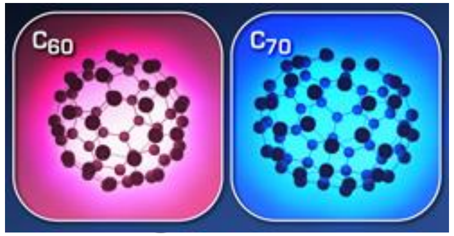
More than 300 molecules detected in space in the gas phase



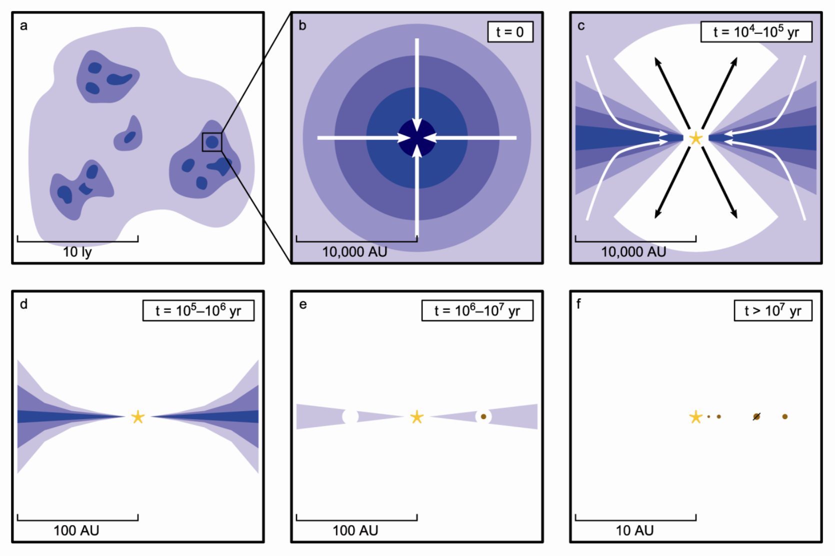
McGuire, *ApJS* (2021)

2 atoms		3 atoms		4 atoms		5 atoms		6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms
H_2	AlO	C_3 *	H_2Cl^+	c-C_3H	H_2NC	C_5 *	HC(S)CN	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *
AlF	OH^+	C_2H	KCN	l-C_3H	$HCCS^+$	C_4H	HCCCO	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN
AlCl	CN^-	C_2O	FeCN	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_2**	SH^+	C_2S	HO_2	C_3O		l-C_3H_2		CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$
CH	SH	CH_2	TiO_2	C_3S		c-C_3H_2		CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O	$CH_3C(O)CH_2OH$	1-c-C_5H_5CN
CH^+	HCl^+	HCN	C_2N	C_2H_2*		H_2CCN		CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH	c-C_5H_6	2-c-C_5H_5CN
CN	TiO	HCO	Si_2C	NH_3		CH_4 *		CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$	c-C_6H_4	$HOCH_2CH_2NH_2$	CH_3C_7N (?)
CO	ArH^+	HCO^+	HS_2	HCCN		HC_3N		HC_3NH^+	H_2CCHOH	CH_2CHCHO	C_8H^-	H_2CCCHC_3N	H_2CCCHC_4H	n-C_3H_7OH
CO^+	N_2	HCS^+	HCS	$HCNH^+$		HC_2NC		HCCCHO	C_6H^-	CH_2CCHCN	C_3H_6	C_2H_5NCO		i-C_3H_7OH
CP	NO^+ ?	HOC^+	HSC	HNCO		HCCNC		NH_2CHO	CH_3NCO	H_2NCH_2CN	CH_3CH_2SH	$C_2H_5NH_2$ (?)		
SiC	NS^+	H_2O	NCO	HNCS		HCOOH		C_5N	HC_5O	CH_3CHNH	CH_3NHCHO	HC_7NH^+		
HCl	HeH^+	H_2S	CaNC	$HOCO^+$		H_2CNH		l-HC_4H *	$HOCH_2CN$	CH_3SiH_3	HC_7O	$CH_3CHCHCN$		
KCl	PO^+	HNC	NCS	H_2CO		H_2C_2O		l-HC_4N	HCCCHNH	$H_2NC(O)NH_2$	HCCCHCHCN	$CH_3C(CN)CH_2$		
NH		HNO		H_2CN		H_2NCN		c-H_2C_3O	HC_4NC	$HCCCH_2CN$	H_2CCHC_3N	CH_2CHCH_2CN		
NO		MgCN		H_2CS		HNC_3		H_2CCNH	c-C_3HCCH	HC_5NH^+	$H_2CCCHCCH$			
NS		MgNC		H_3O^+		SiH_4 *		C_5N^-	l-H_2C_5	CH_2CHCCH	HOCHCHCHO (?)			
NaCl		N_2H^+		c-SiC_3		H_2COH^+		HNCHCN	MgC_5N	MgC_6H				
OH		N_2O		CH_3 *		C_4H^-		SiH_3CN	CH_2C_3N	$C_2H_3NH_2$				
PN		NaCN		C_3N^-		HC(O)CN		C_5S		$(CHOH)_2$				
SO		OCS		PH_3		HNCNH		MgC_4H		$HC_2(H)C_4$				
SO^+		SO_2		HCNO		CH_3O		CH_3CO^+						
SiN		c-SiC_2		HOCN		NH_4^+		C_3H_3						
SiO		CO_2 *		HSCN		H_2NCO^+		H_2C_3S						
SiS		NH_2		H_2O_2		$NCCNH^+$		HCCCHS						
CS		H_3^+ (*)		C_3H^+		CH_3Cl		C_5O						
HF		SiCN		HMgNC		MgC_3N		C_5H^+						
HD		AlNC		HCCO		NH_2OH		$HCCNCH^+$						
FeO ?		SiNC		CNCN		HC_3O^+		c-C_3C_2H						
O_2		HCP		HONO		HC_3S^+		HC_4S						
CF^+		CCP		MgC_2H		H_2C_2S								
SiH ?		AlOH		HCCS		C_4S								
PO		H_2O^+		HNCN		HC(O)SH								

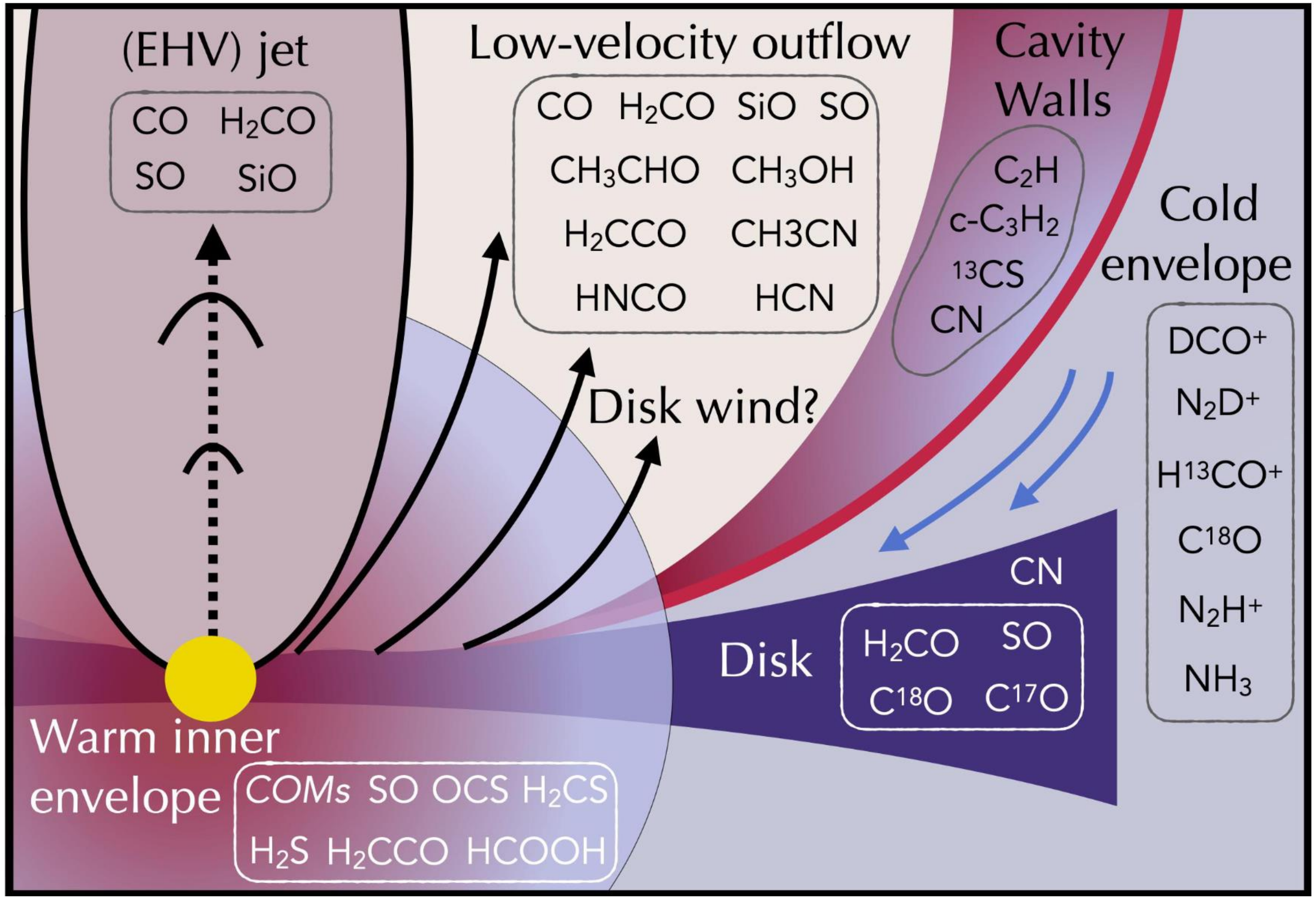
>12 atoms
C_{60} *
C_{70} *
C_{60}^+ *
c-C_6H_5CN
$HC_{11}N$
1-$C_{10}H_7CN$
2-$C_{10}H_7CN$
c-C_9H_8
1-c-C_5H_5CCH
2-c-C_5H_5CCH
c-$C_5H_4CCH_2$
2-C_9H_7CN



Star- and Planet Formation

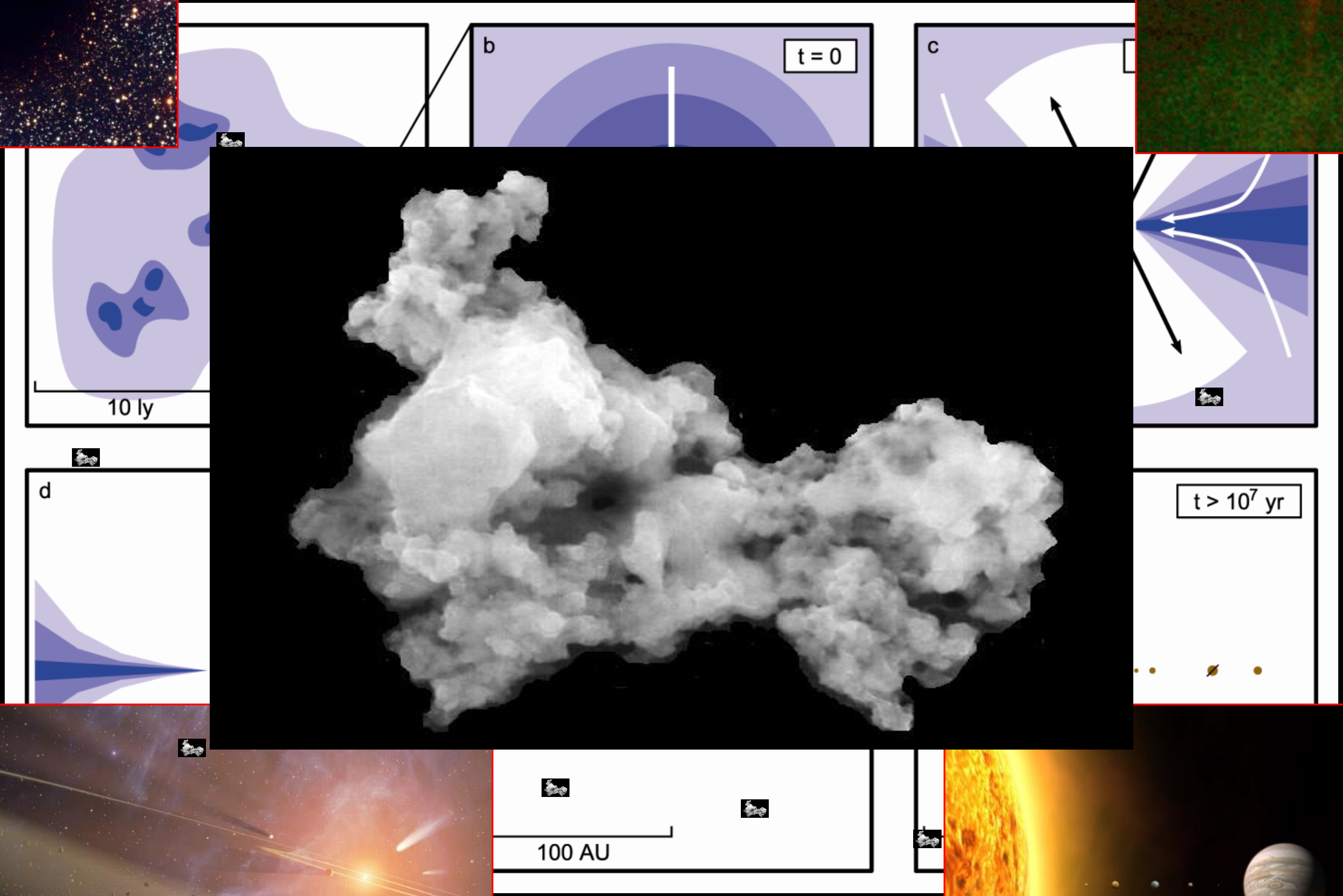


Credit: Ruud Visser



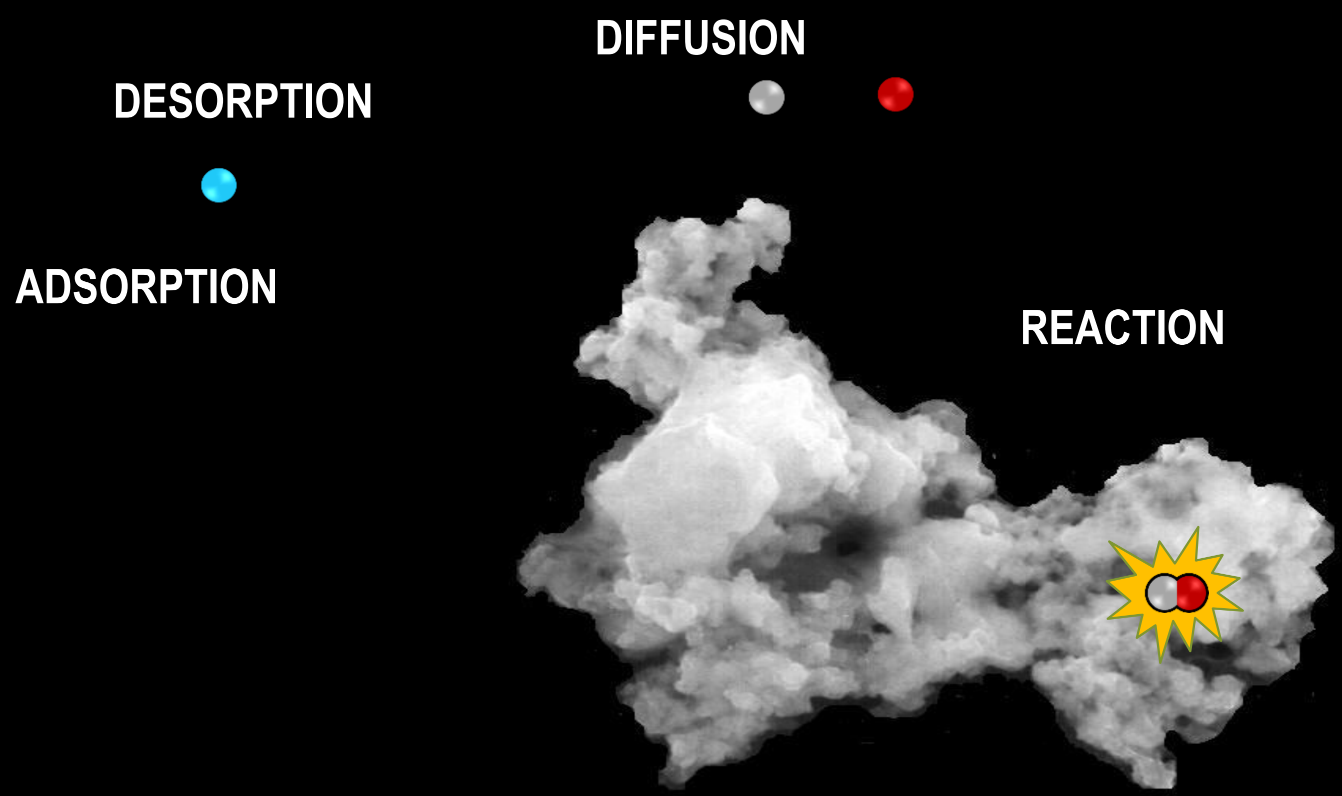
Tychoniec et al. (2021)

on and origin of a Solar-like Syste



Interstellar ice chemistry

Carbonaceous/Silicate Grains

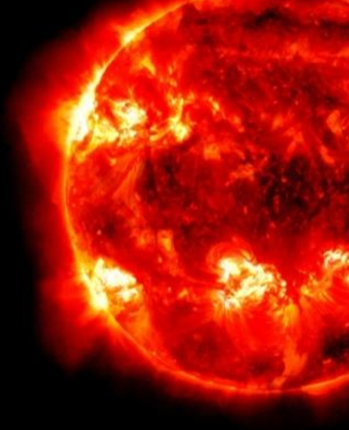


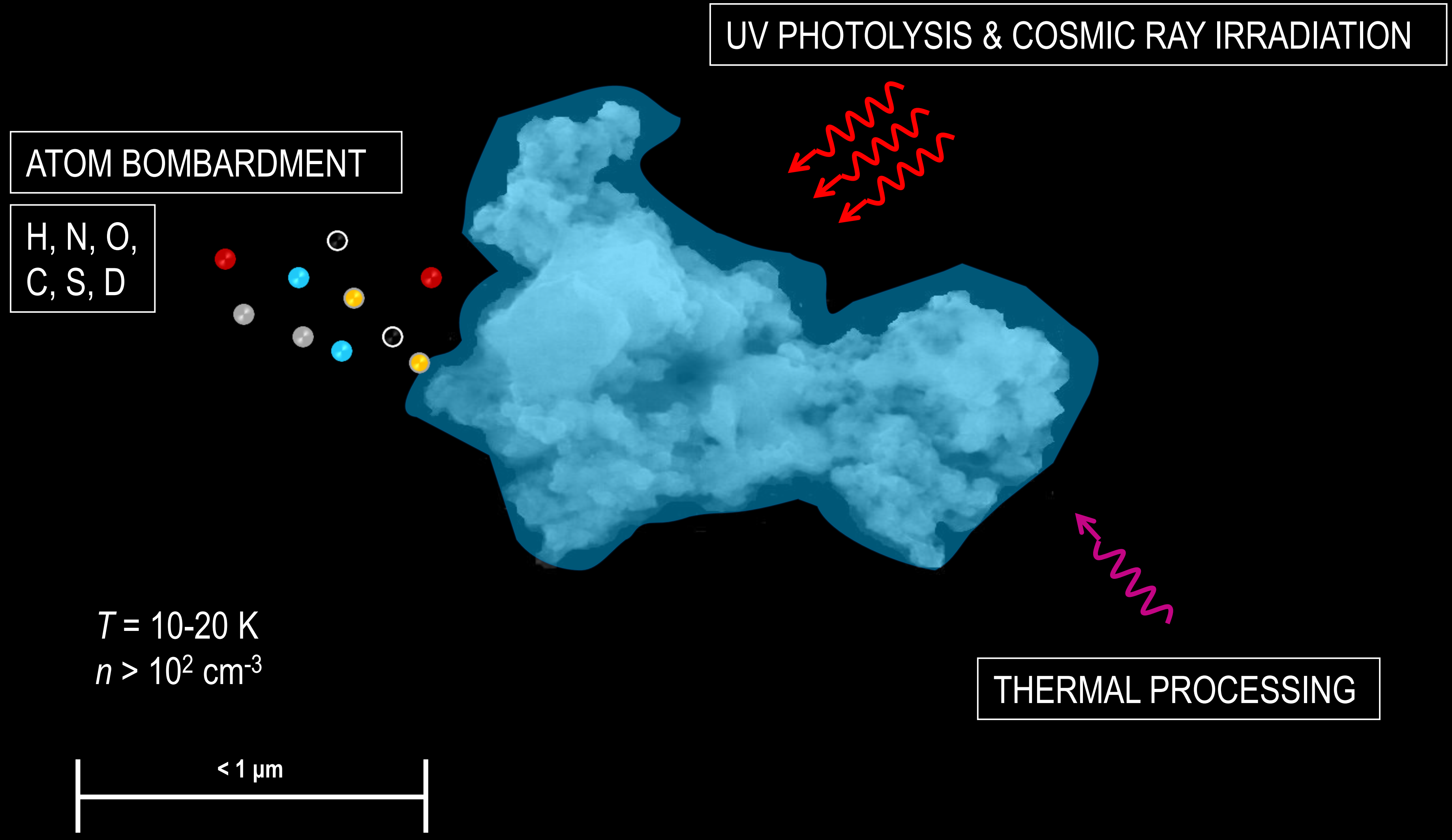
T = 10-20 K
$n > 10^2$ cm^{-3}

< 1 μm

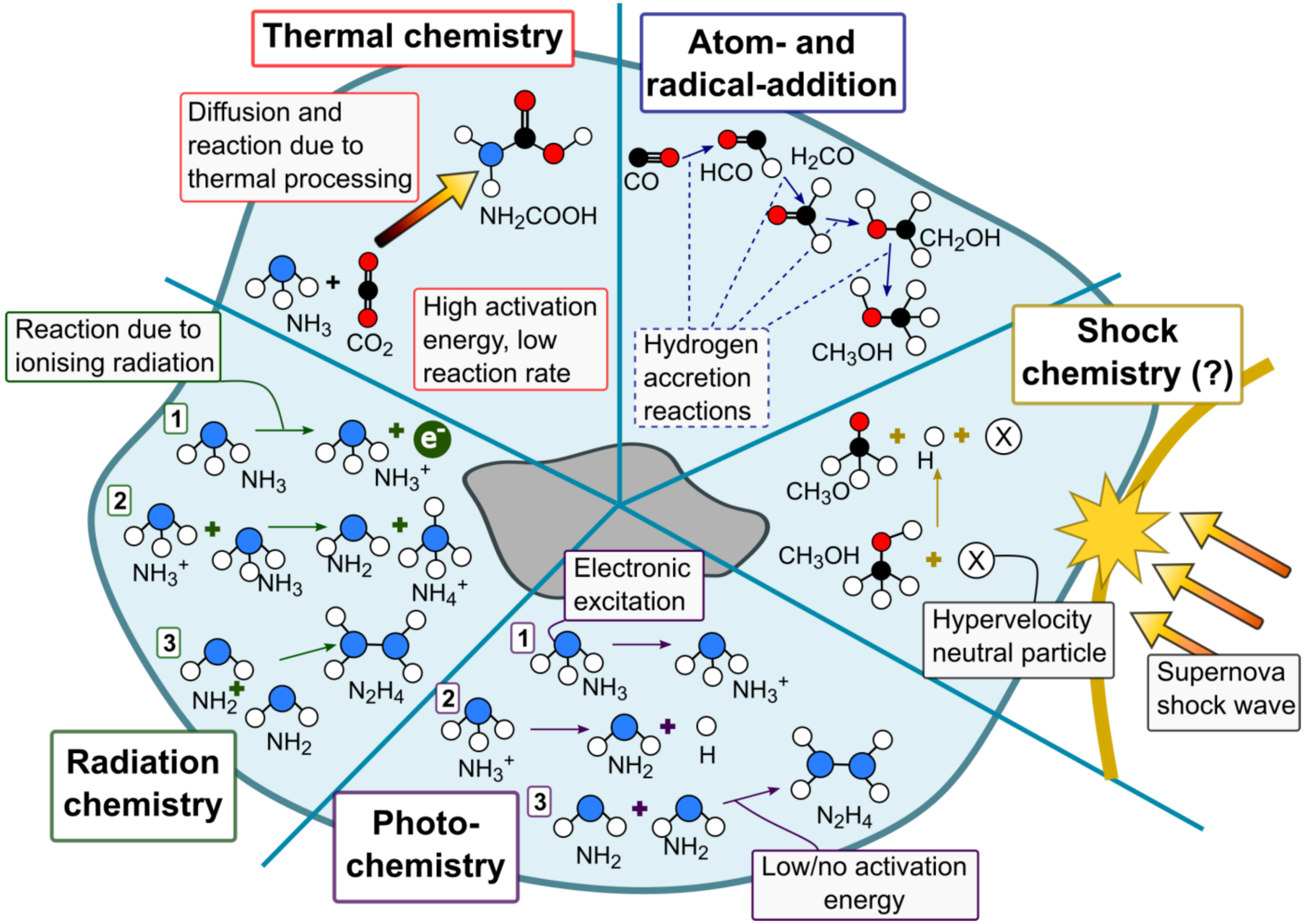
Interstellar ice chemistry

Carbonaceous/Silicate Grains



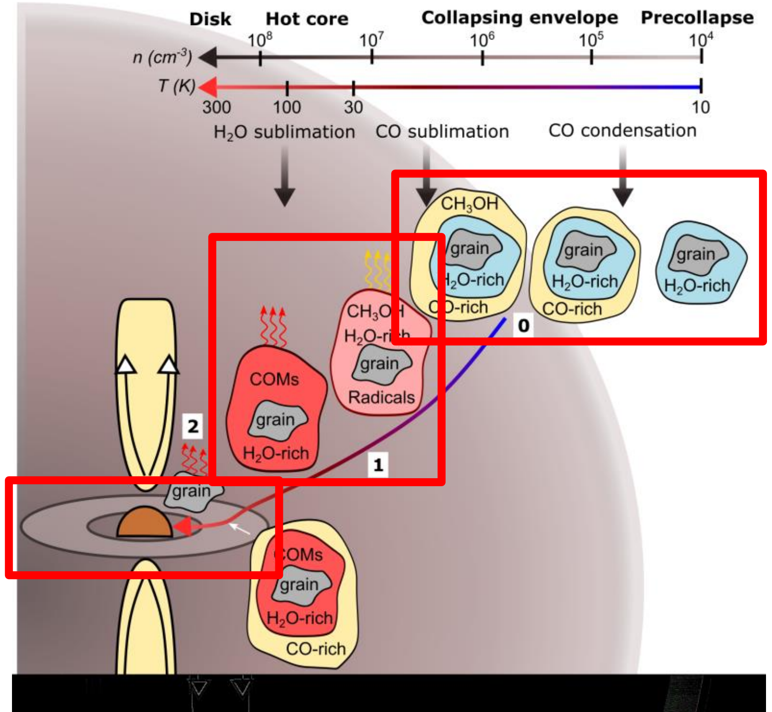


Ice Grain Chemistry

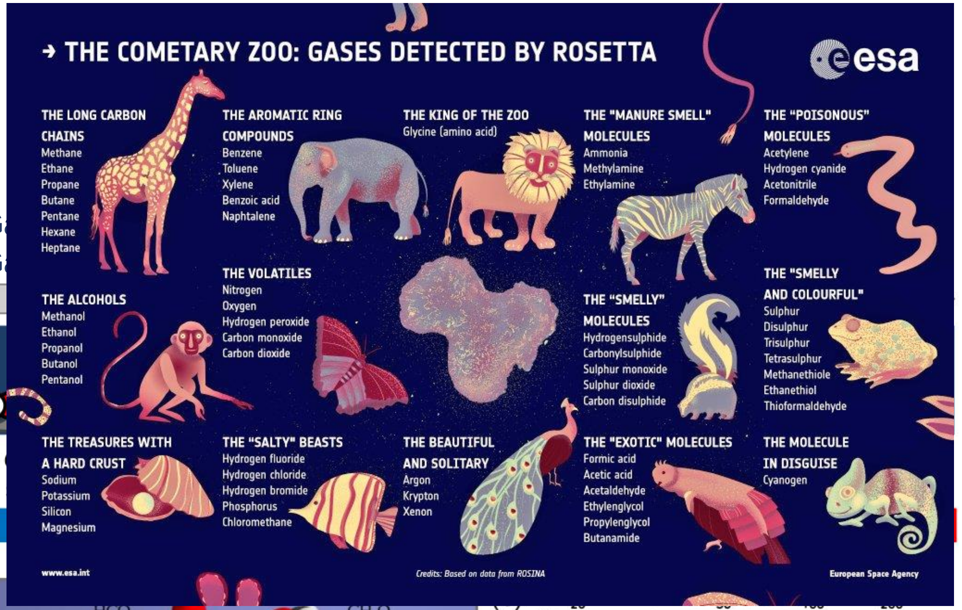


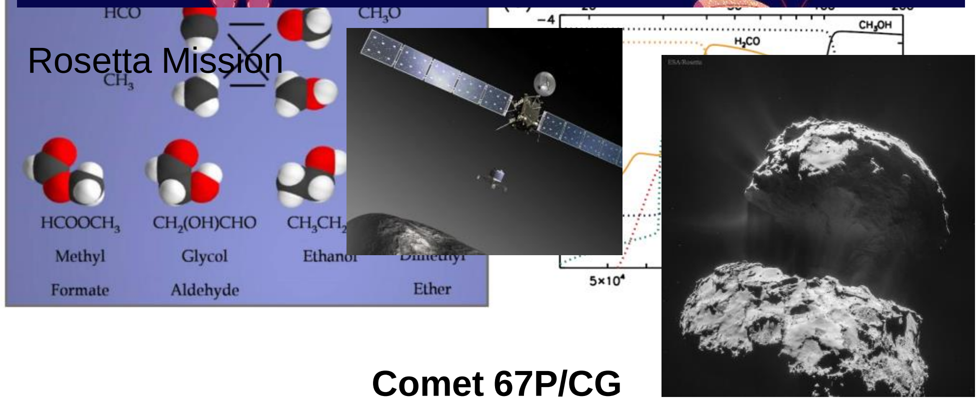
Arumainayagam et al., *Chem. Soc. Rev.* (2019)

Standard Picture



Herbst & van Dischoeck, *ARAA* (2009)





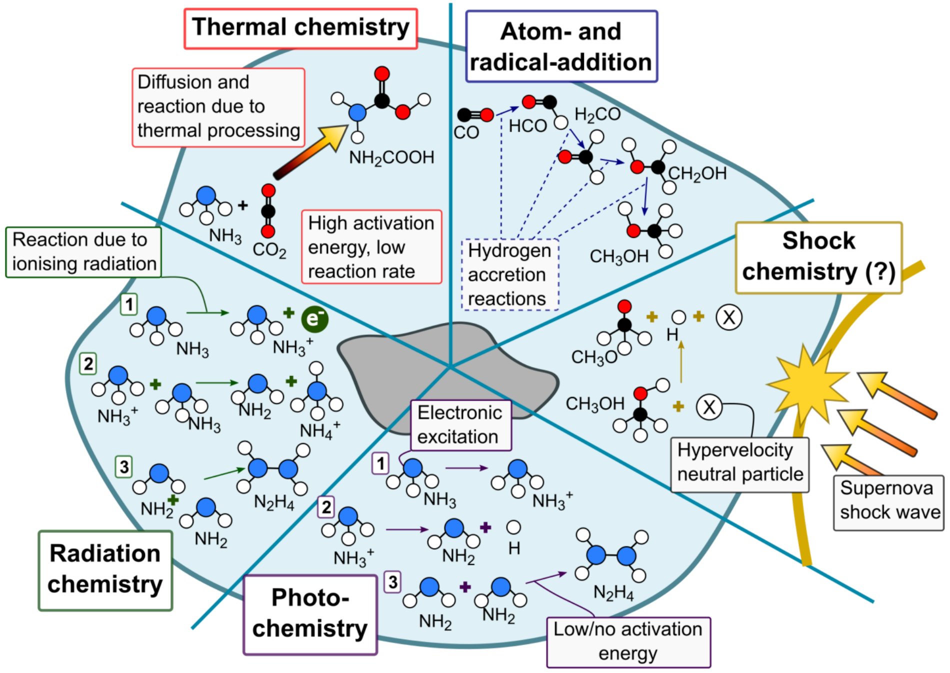
Comet 67P/CG

Challenges in Astrochemistry

Can COMs form in ices?

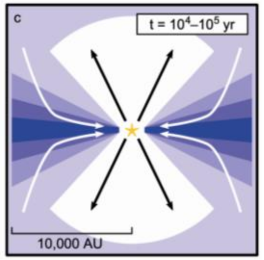
Can COMs be detected in ices?

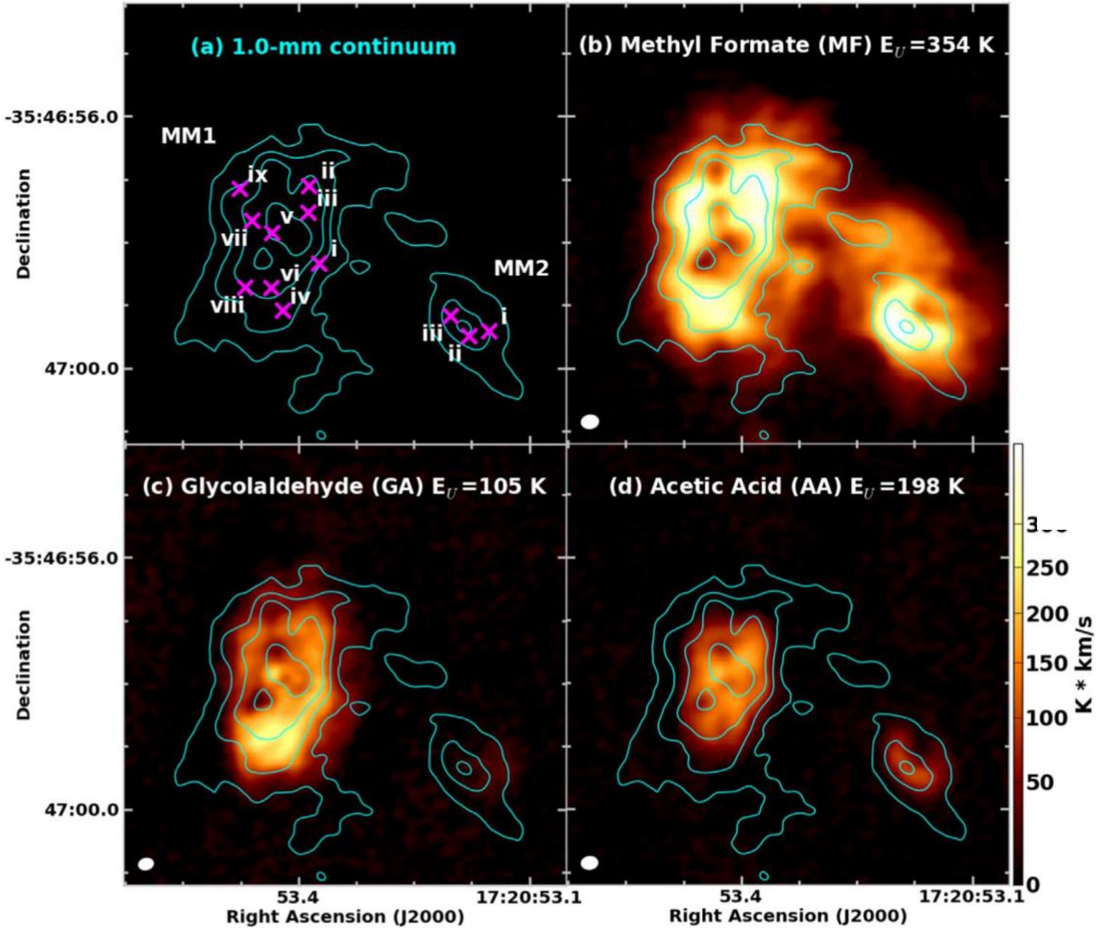
What is the physicochemical evolution of COMs in the ISM?

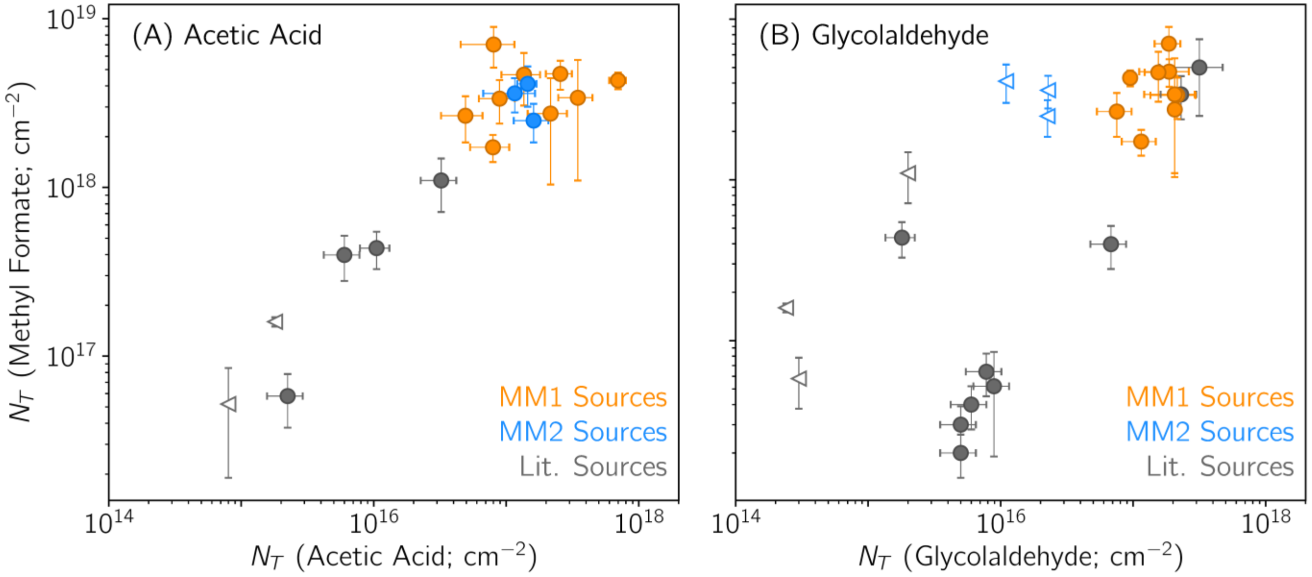


Credit: Chris R. Arumainayagam

COMs in Hot Cores

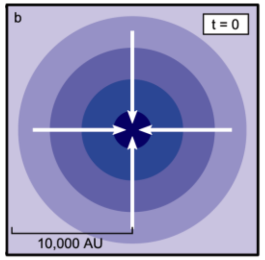




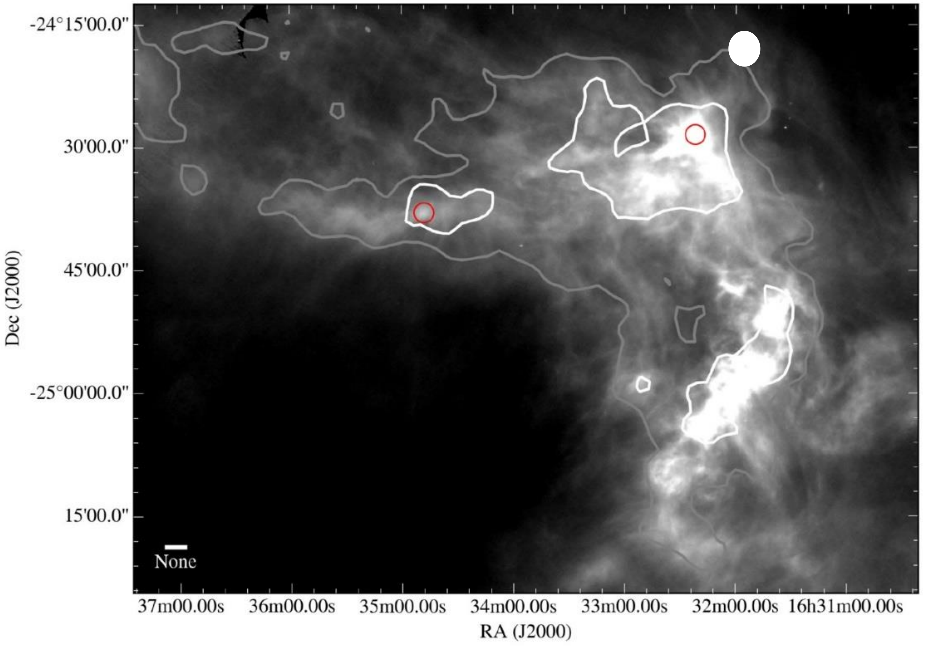


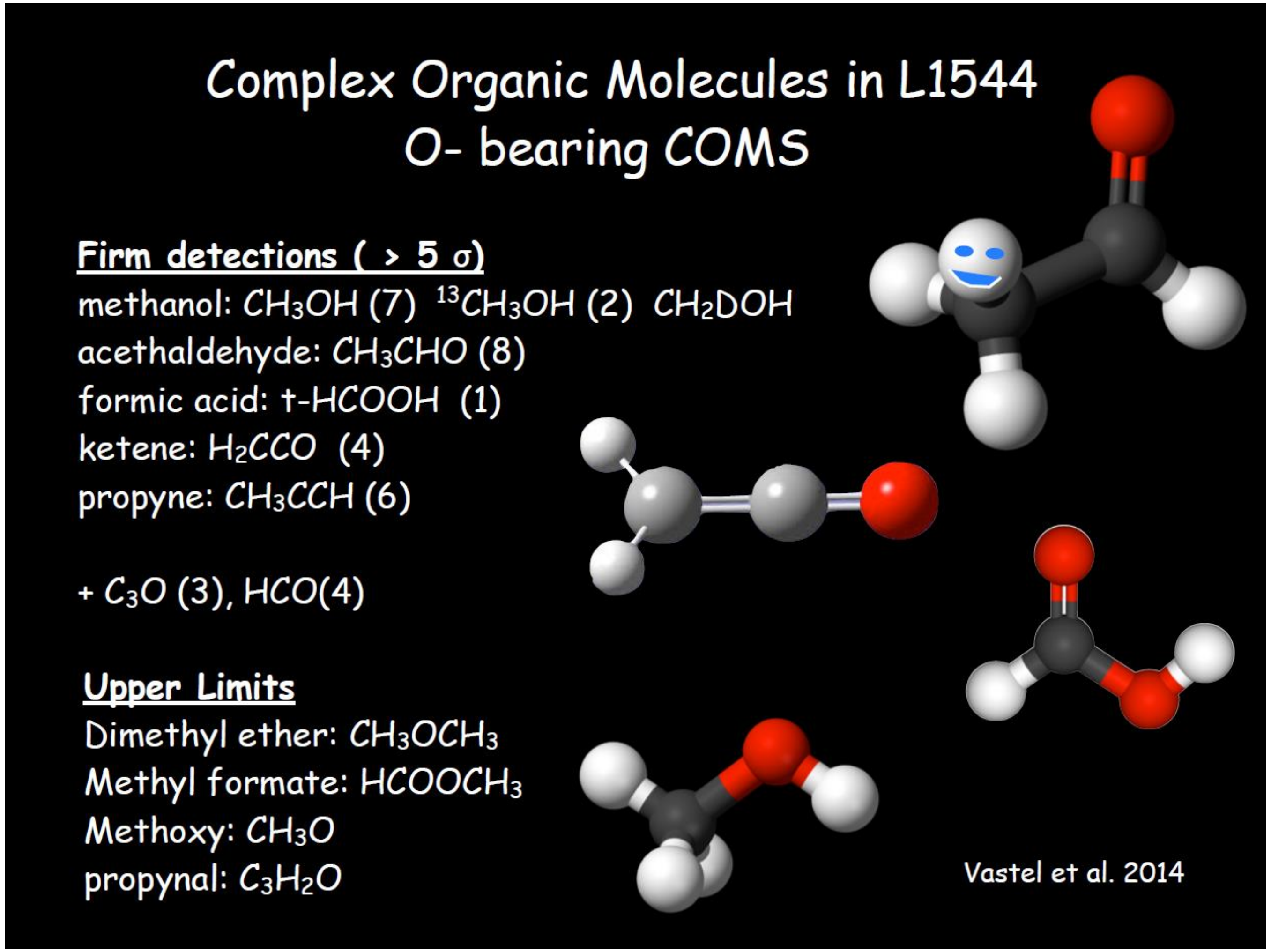
El-Abd *et al.*, ApJ (2019)

COMs in Prestellar Cores



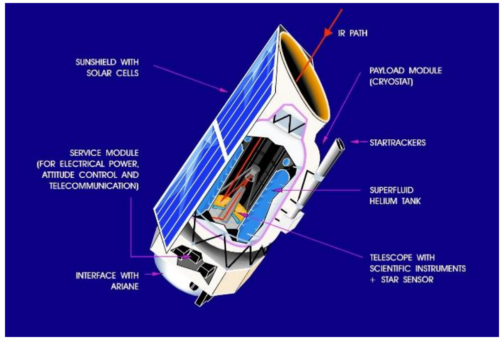
Bacmann *et al*., *A&A* (2012)
(L1689B)





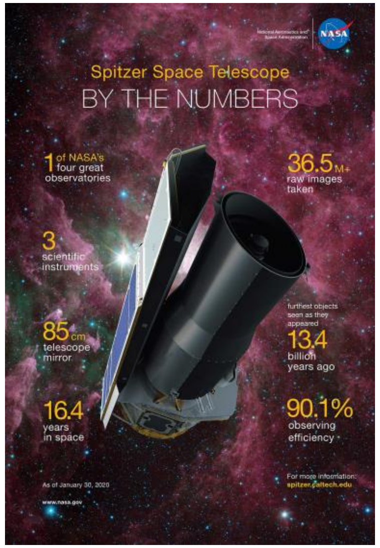
FORS Team ESO

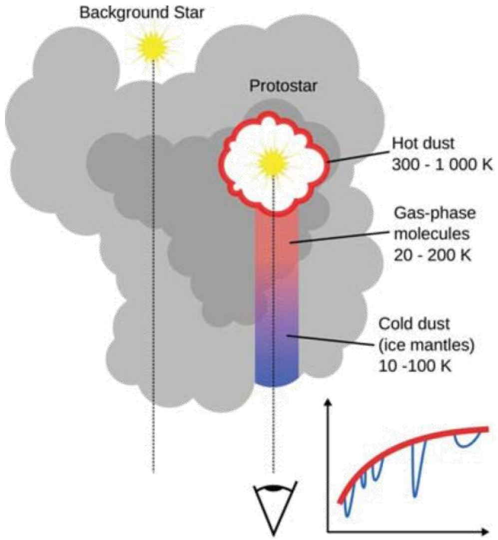
Infrared Space Observatory & Spitzer Ice Legacy

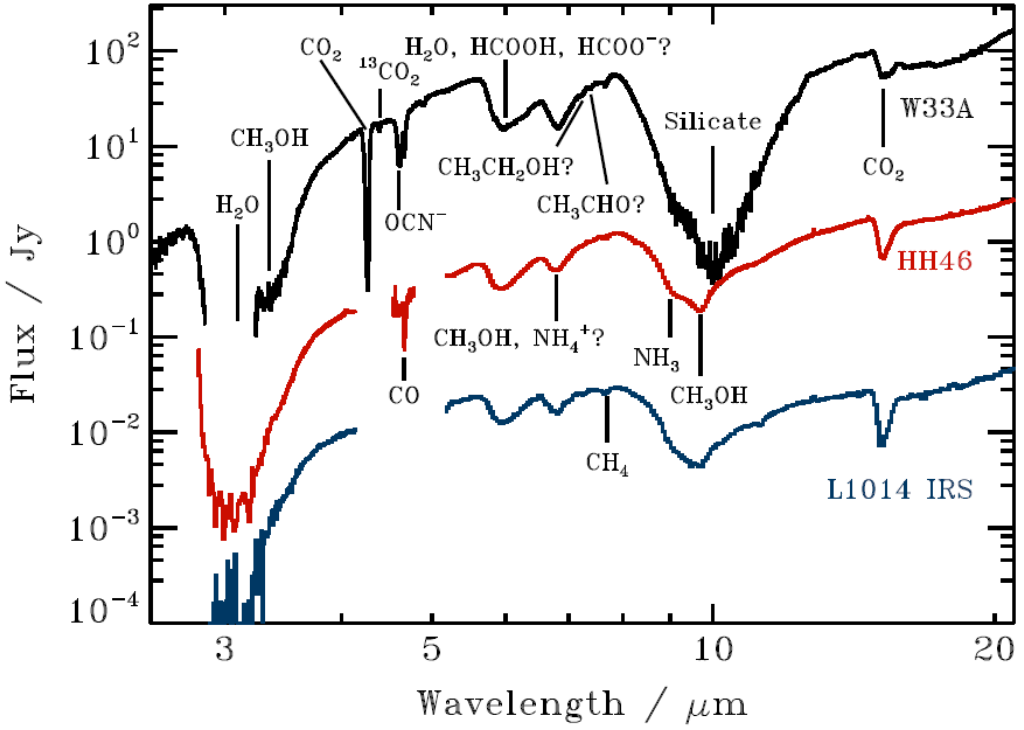


ISO

SST

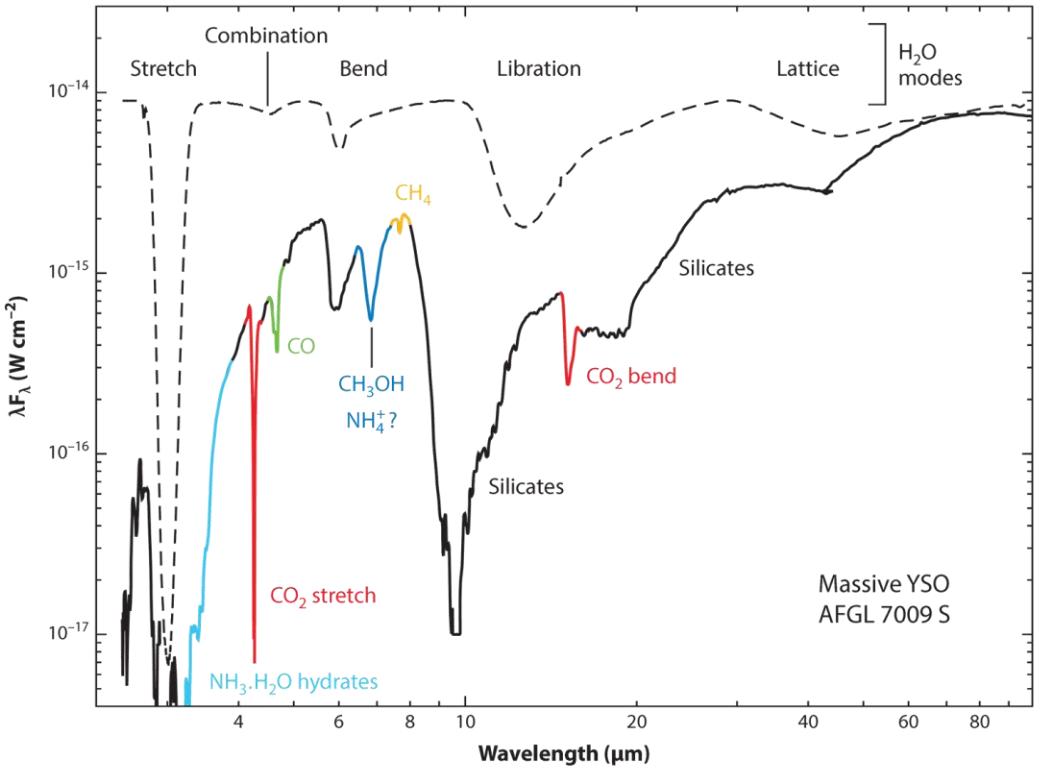




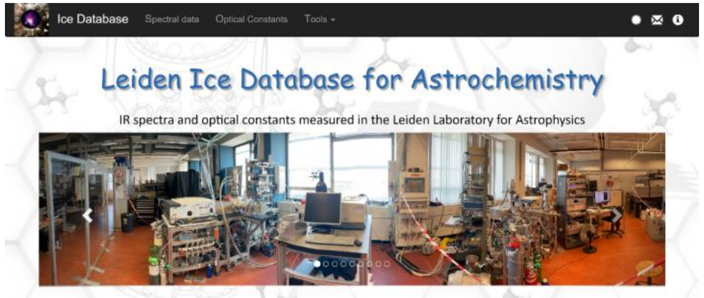


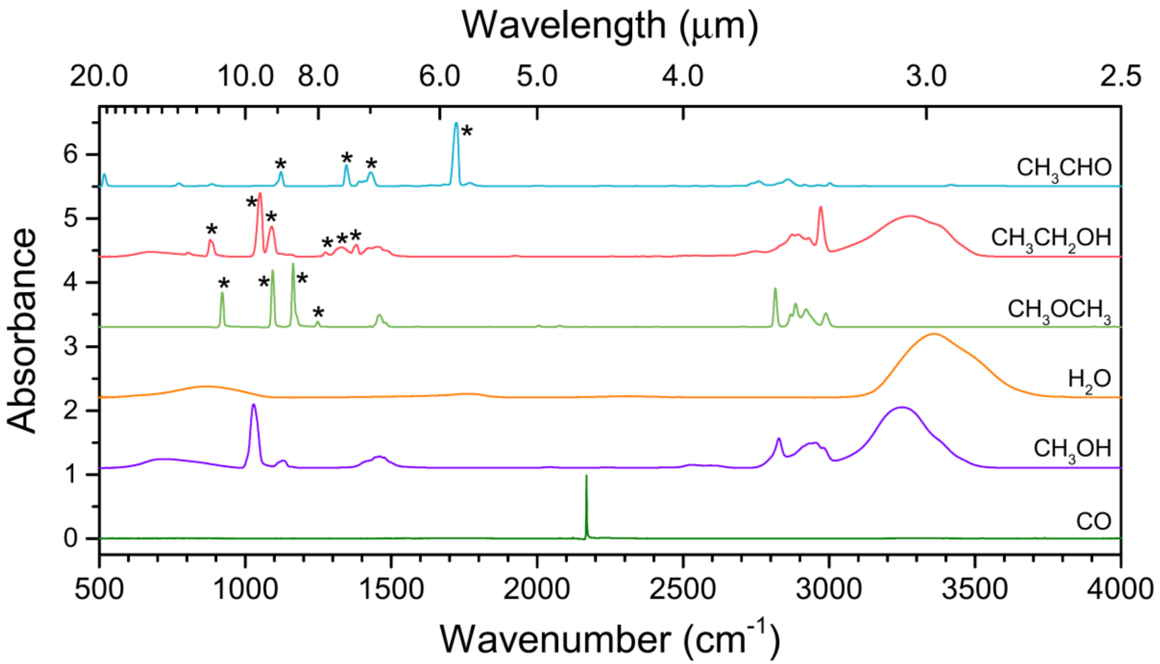
Öberg *et al.*, *ApJ* (2011)

Observations vs Laboratory



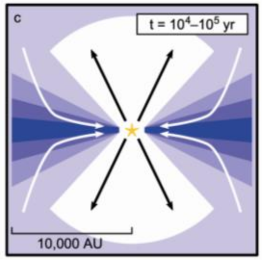
Boogert, Gerakines and Whittet, *ARAA* (2015)





Terwisscha van Scheltinga *et al.*, *A&A* (2018)

First Ice Data from JWST



Draft version August 24, 2022
Typeset using LaTeX **twocolumn** style in AASTeX62

[astro-ph.SR] 23 Aug 2022

CORINOS I: JWST/MIRI Spectroscopy and Imaging of a Class 0 protostar IRAS 15398−3359

Yao-Lun Yang,[1,2] Joel D. Green,[3] Klaus M. Pontoppidan,[3] Jennifer B. Bergner,[4] L. Ilsedore Cleeves,[2] Neal J. Evans II,[5] Robin T. Garrod,[6] Mihwa Jin,[7,8] Chul Hwan Kim,[9] Jaeyeong Kim,[10] Jeong-Eun Lee,[9] Nami Sakai,[1] Christopher N. Shingledecker,[11] Brielle Shope,[12] John J. Tobin,[13] and Ewine F. van Dishoeck[14,15]

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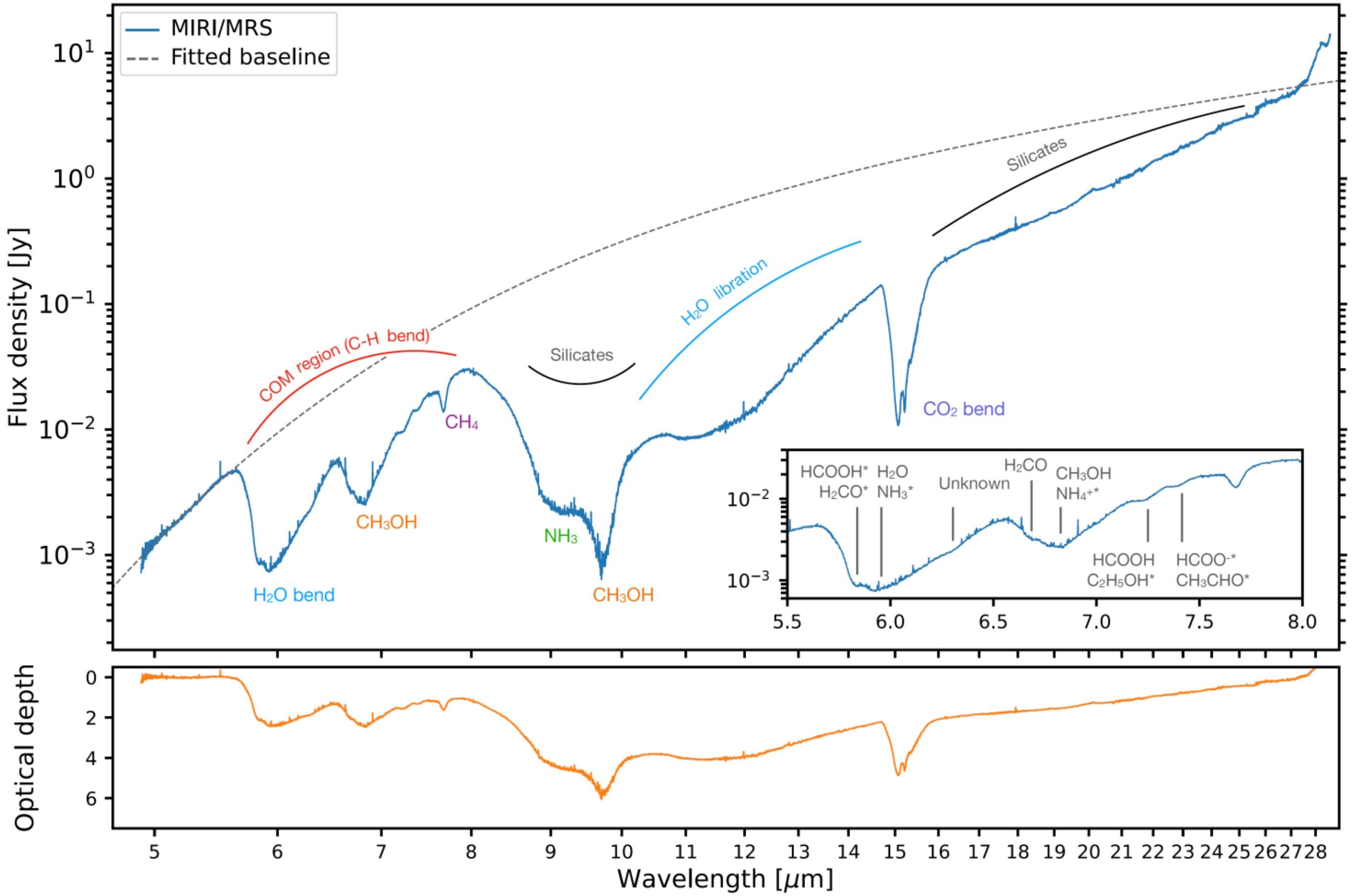
[15] *Max Planck Institute for Extraterrestrial Physics, Garching, Germany*

ABSTRACT

The origin of complex organic molecules (COMs) in young Class 0 protostars has been one of the major questions in astrochemistry and star formation. While COMs are thought to form on icy dust grains via gas-grain chemistry, observational constraints on their formation pathways have been



Extracted MIRI MRS spectrum of the IRAS 1539-3359 point source.
Yang *et al.* *ApJL* (2023)

Early Release Science program on JWST

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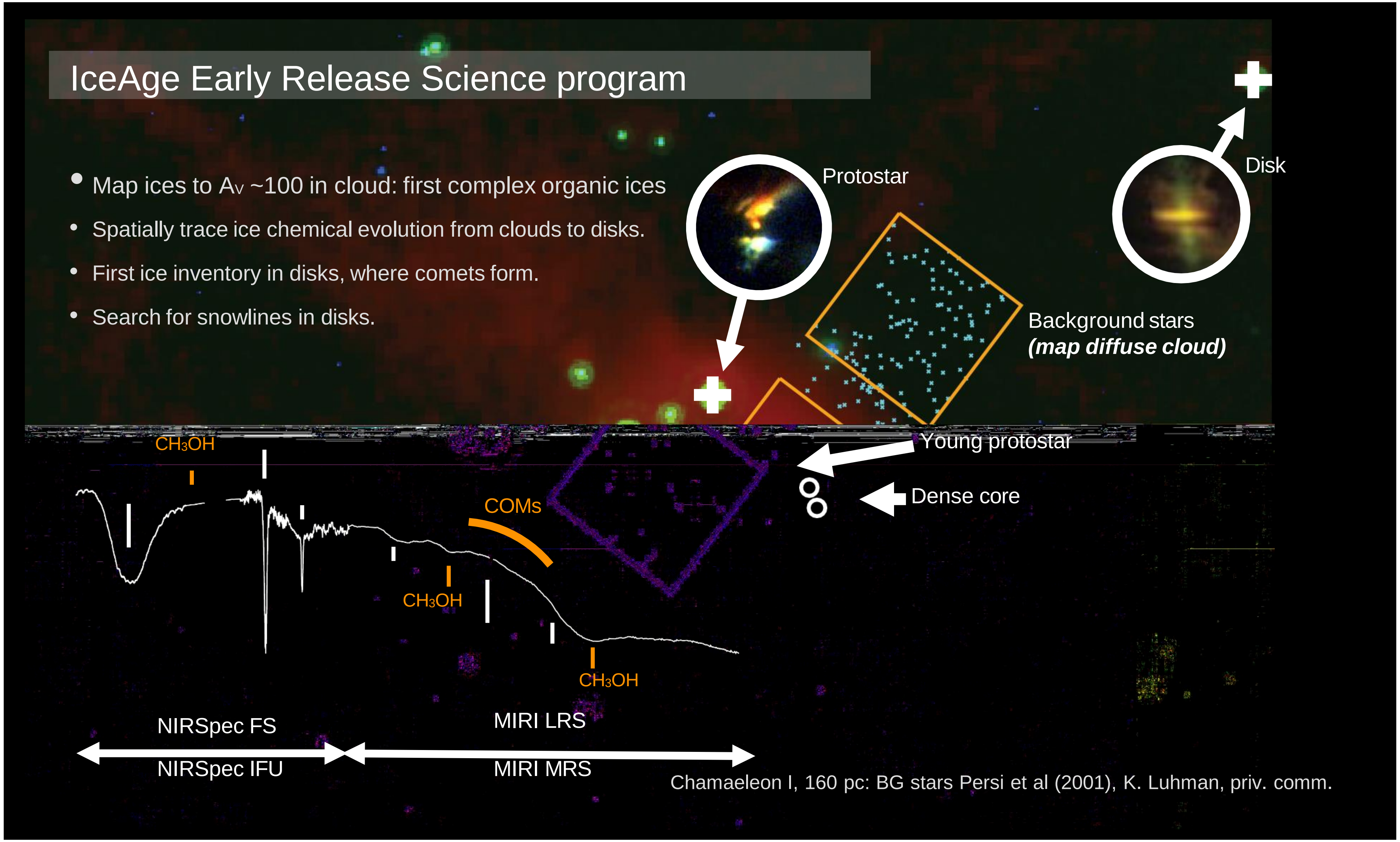
WEBB SPACE TELESCOPE

ERS: PI McClure, co-PI Boogert, co-PI Linnartz, co-I Ioppolo + 46 co-Is

Cycle 1: **PI McClure, co-**I Ioppolo + 25 co-Is

400 hours of observational time in first year to study cosmic ices



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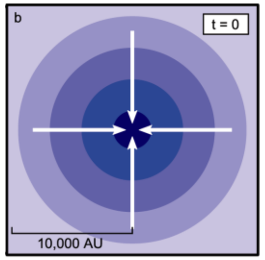
IceAge - Dense Cores



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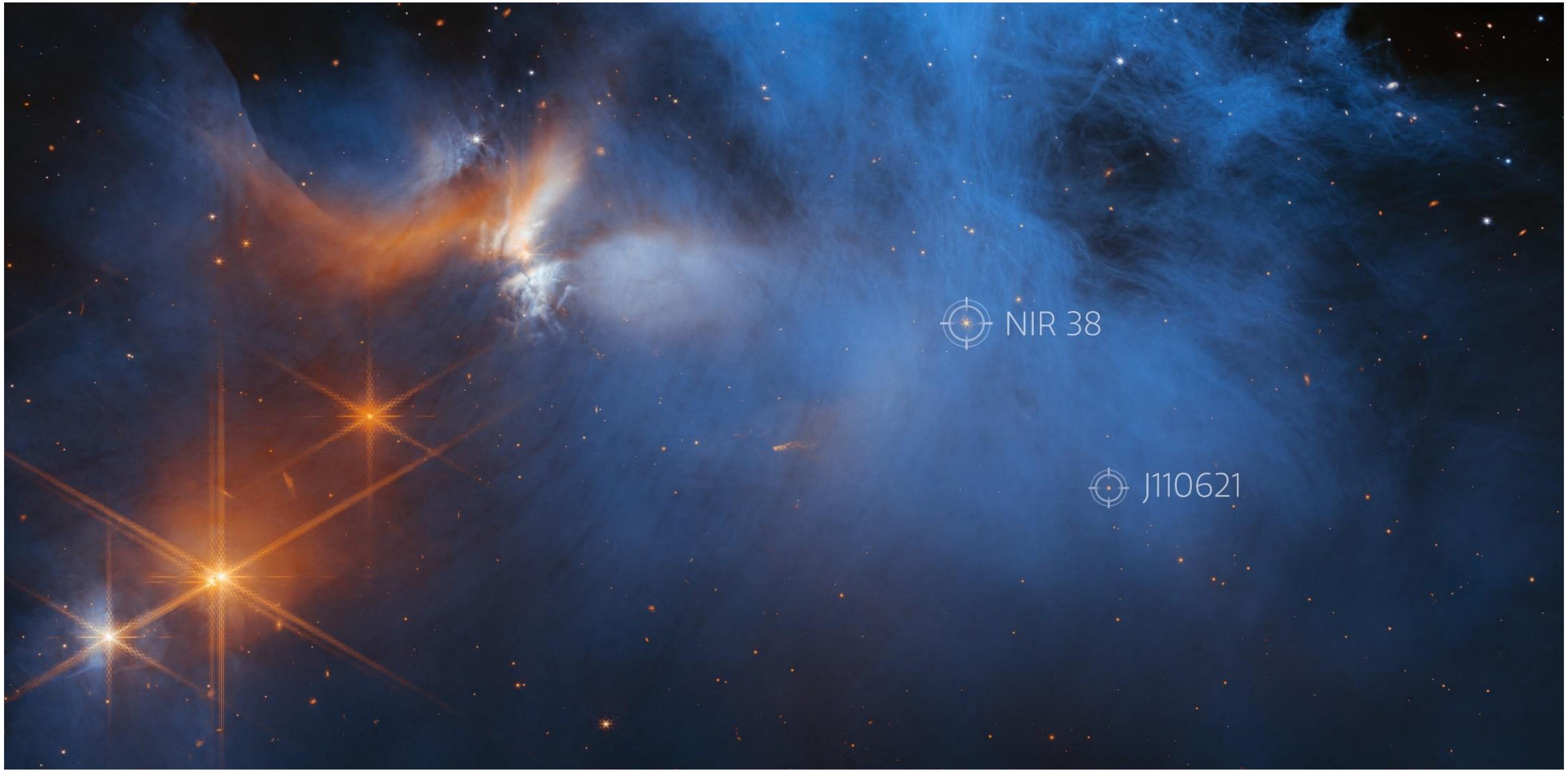

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McClure *et al.* (2023)

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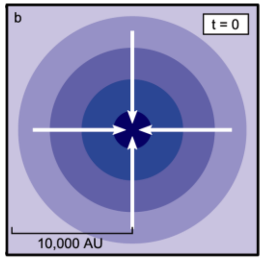
IceAge - Dense Cores



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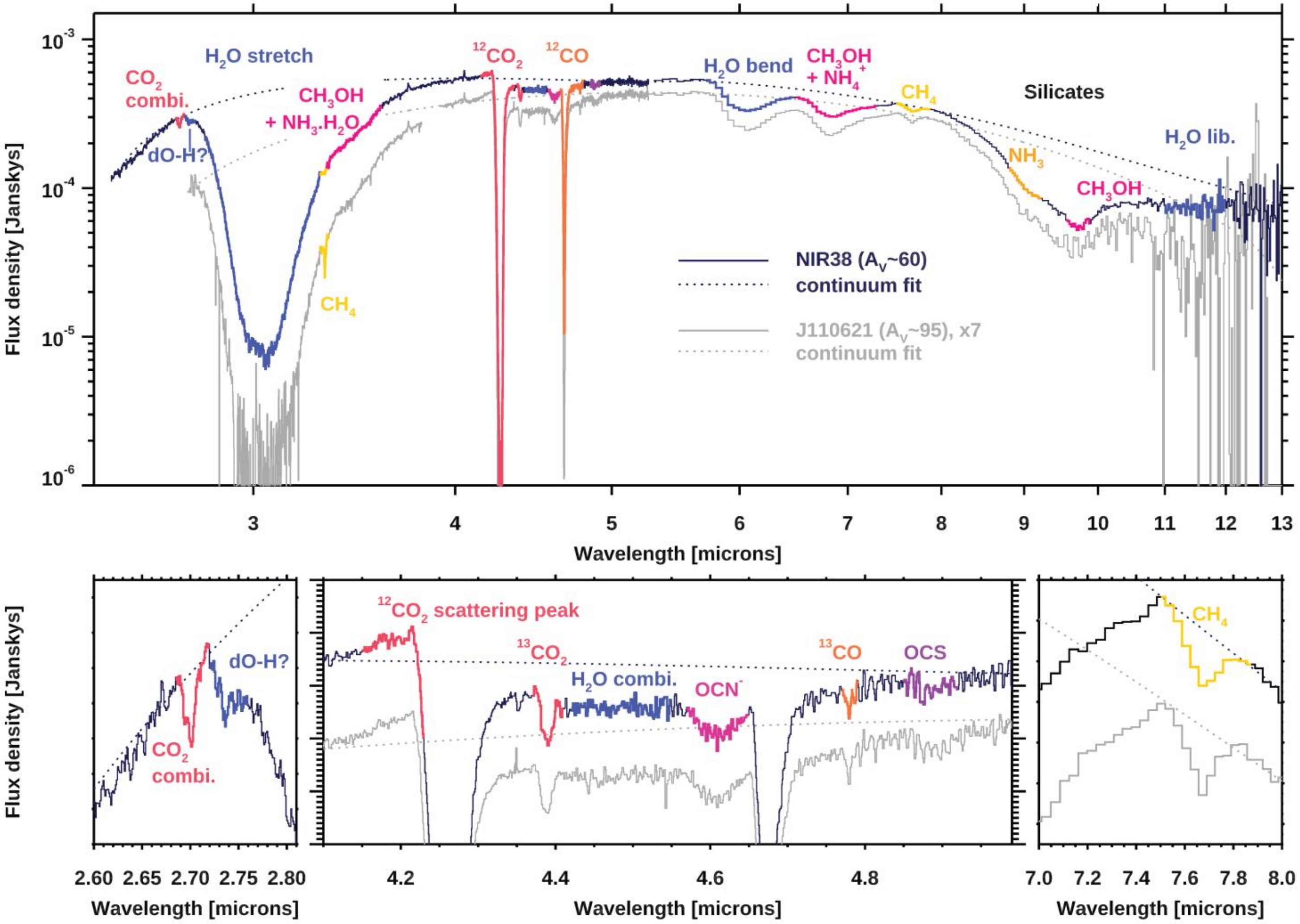
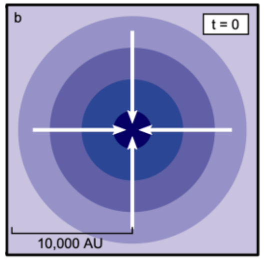


McClure *et al. Nat. Astron.* (2023)

IceAge - Dense Cores



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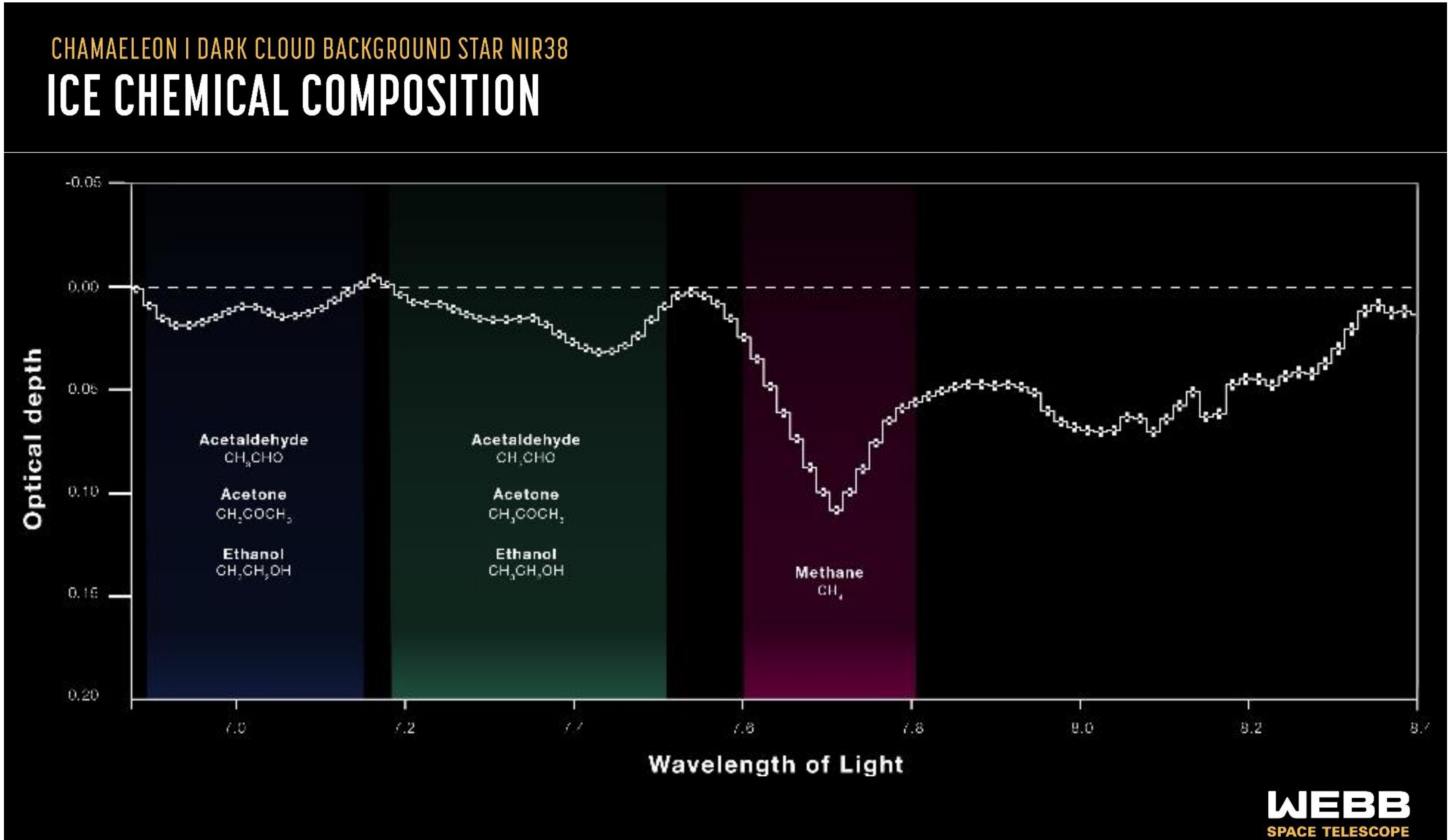

McClure *et al.* (2023)

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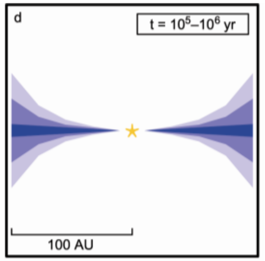
IceAge - Disk



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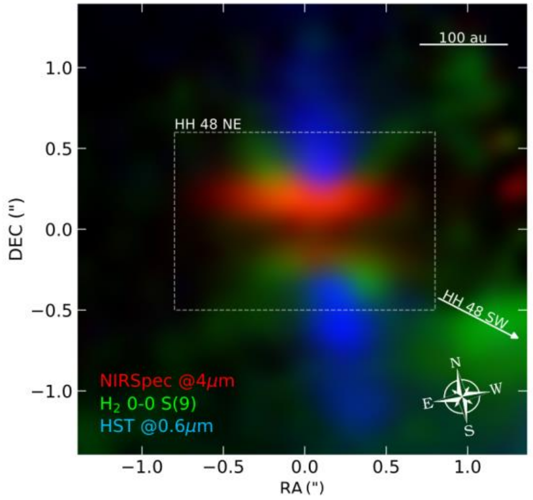

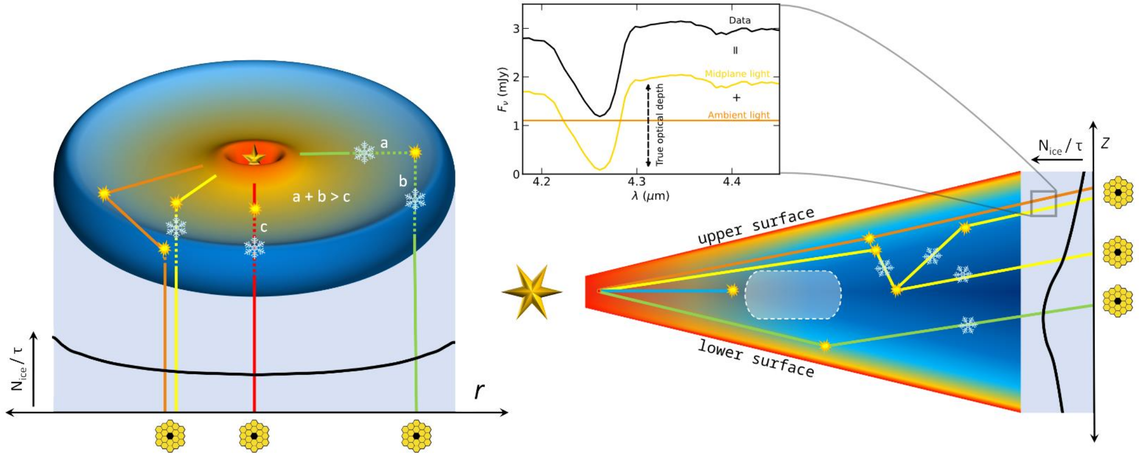

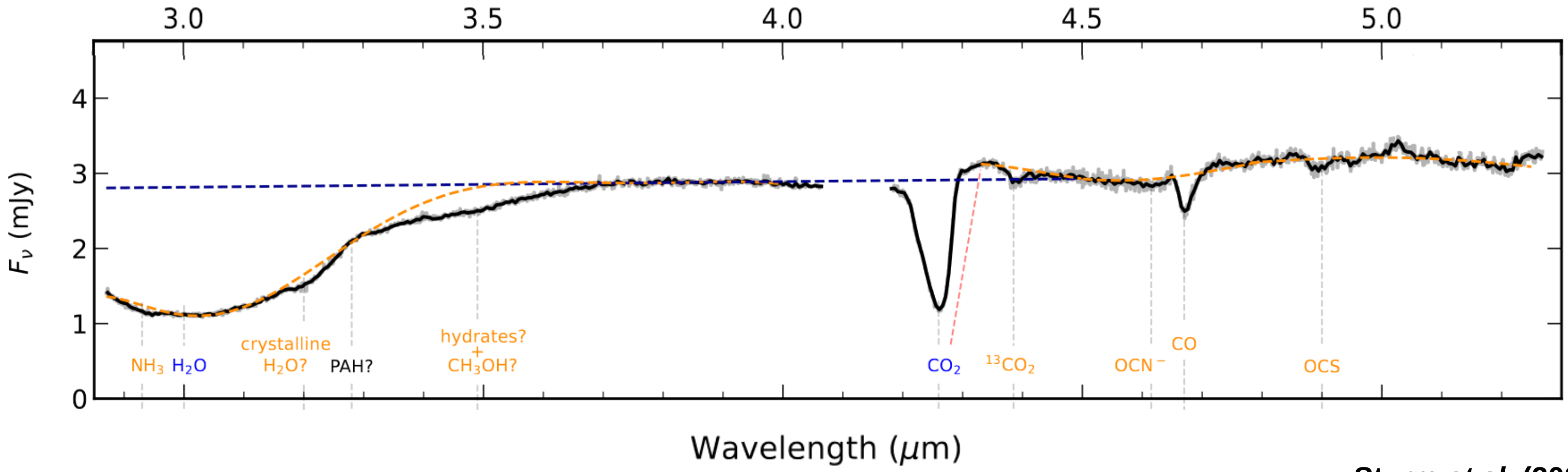

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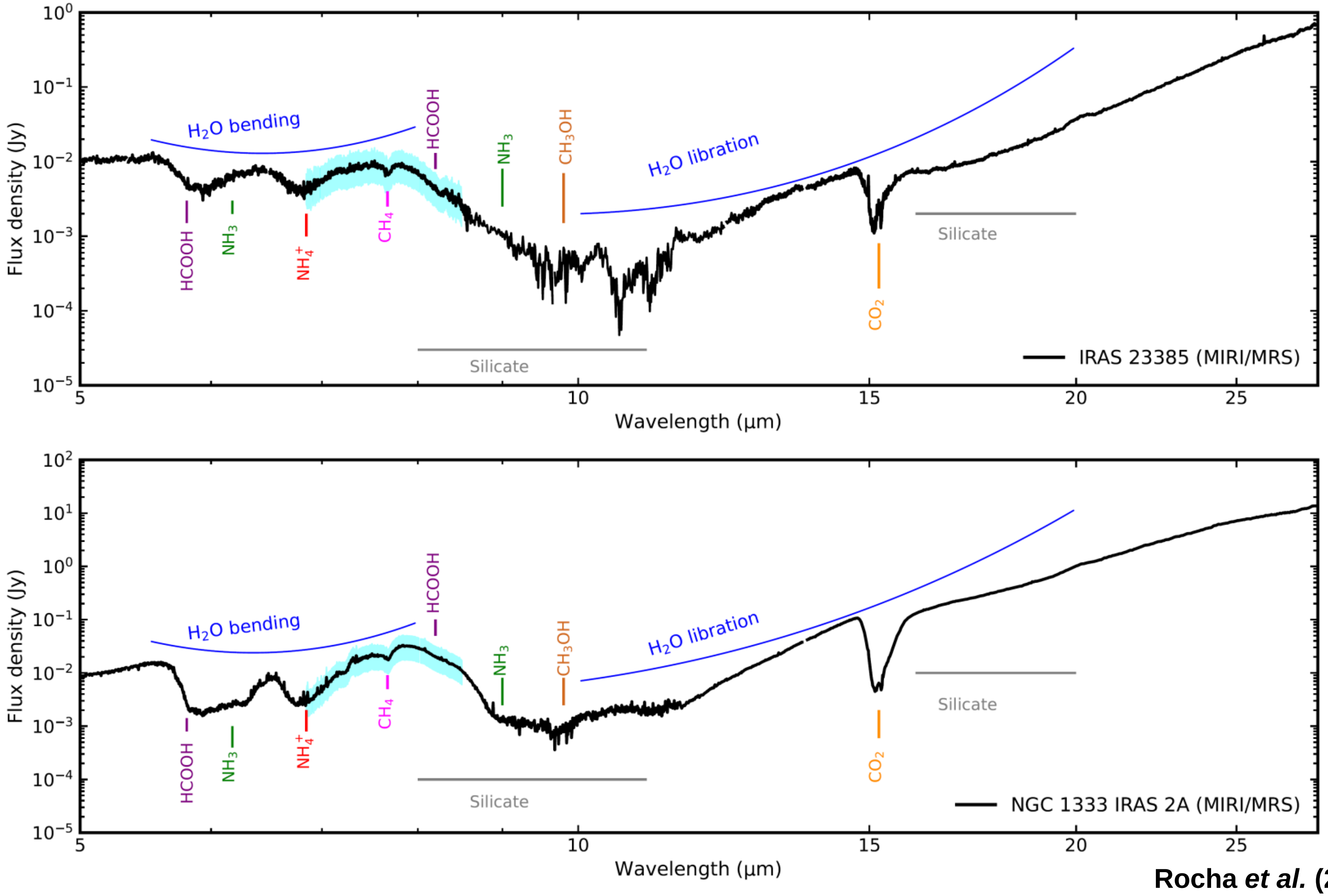
400 hours of observational time in first year to study cosmic ices

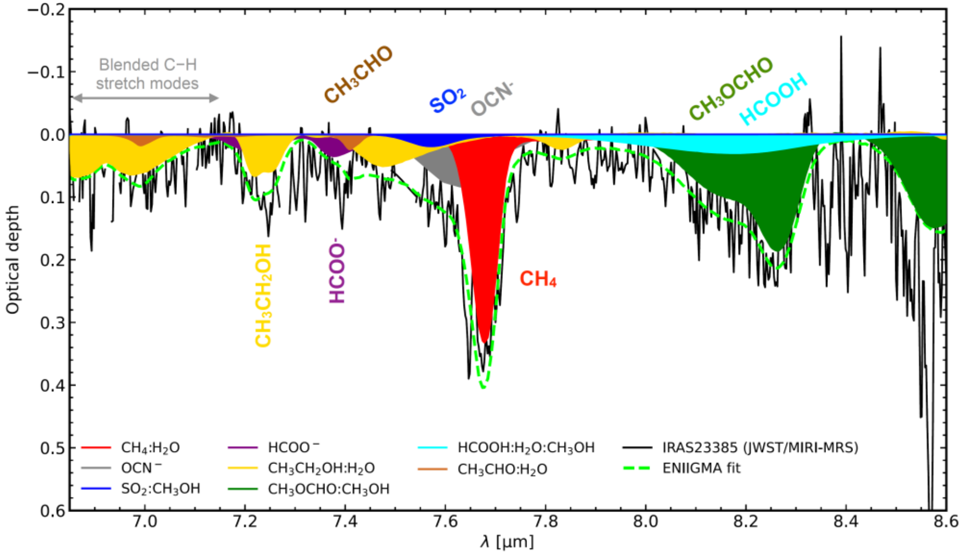
Sturm *et al.* (2023)

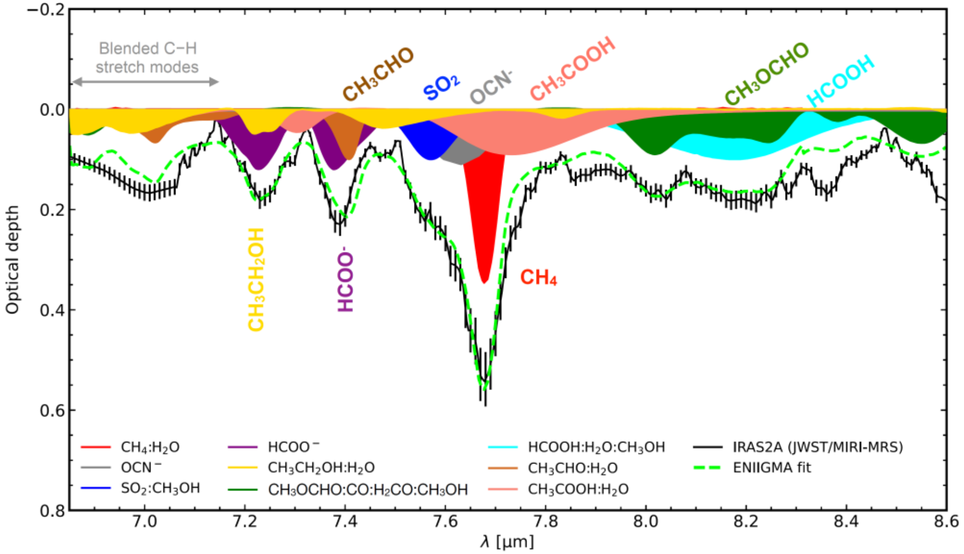
Jwst Observations of Young protoStars (JOYS)

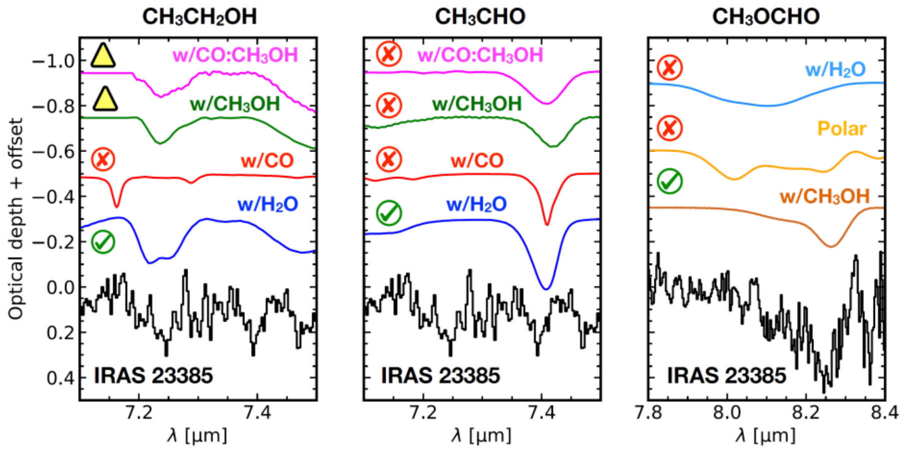


Rocha *et al.* (2024)

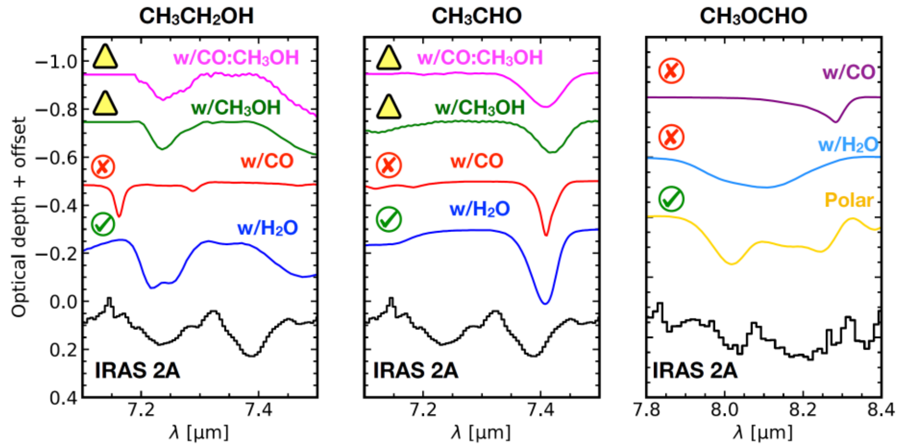
Jwst Observations of Young protoStars (JOYS)







Ethanol **Acetaldehyde** **Methyl Formate**



Rocha *et al.* (2024)

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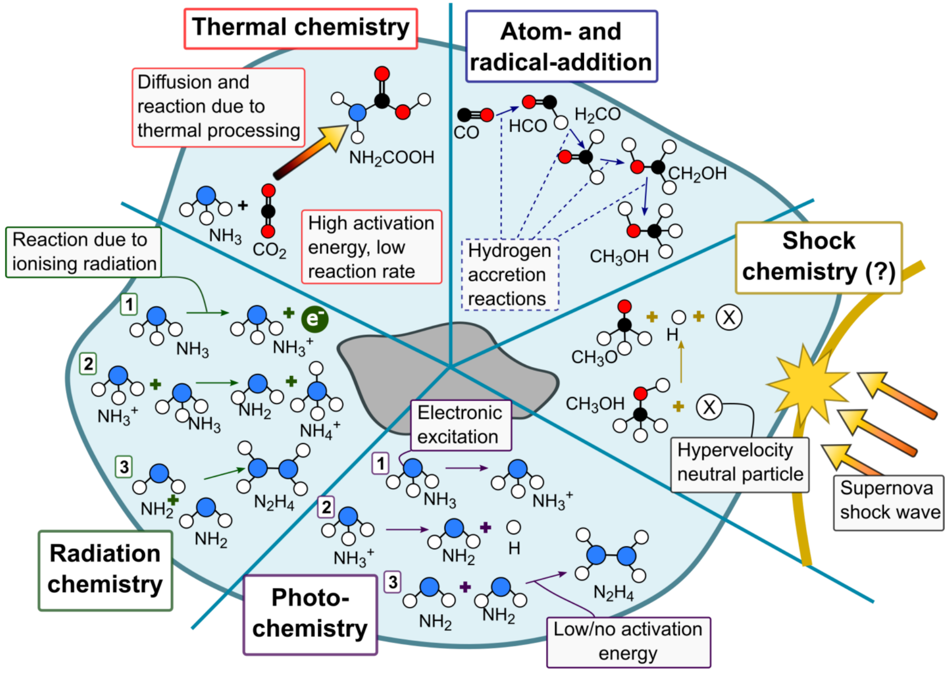
Challenges in Astrochemistry

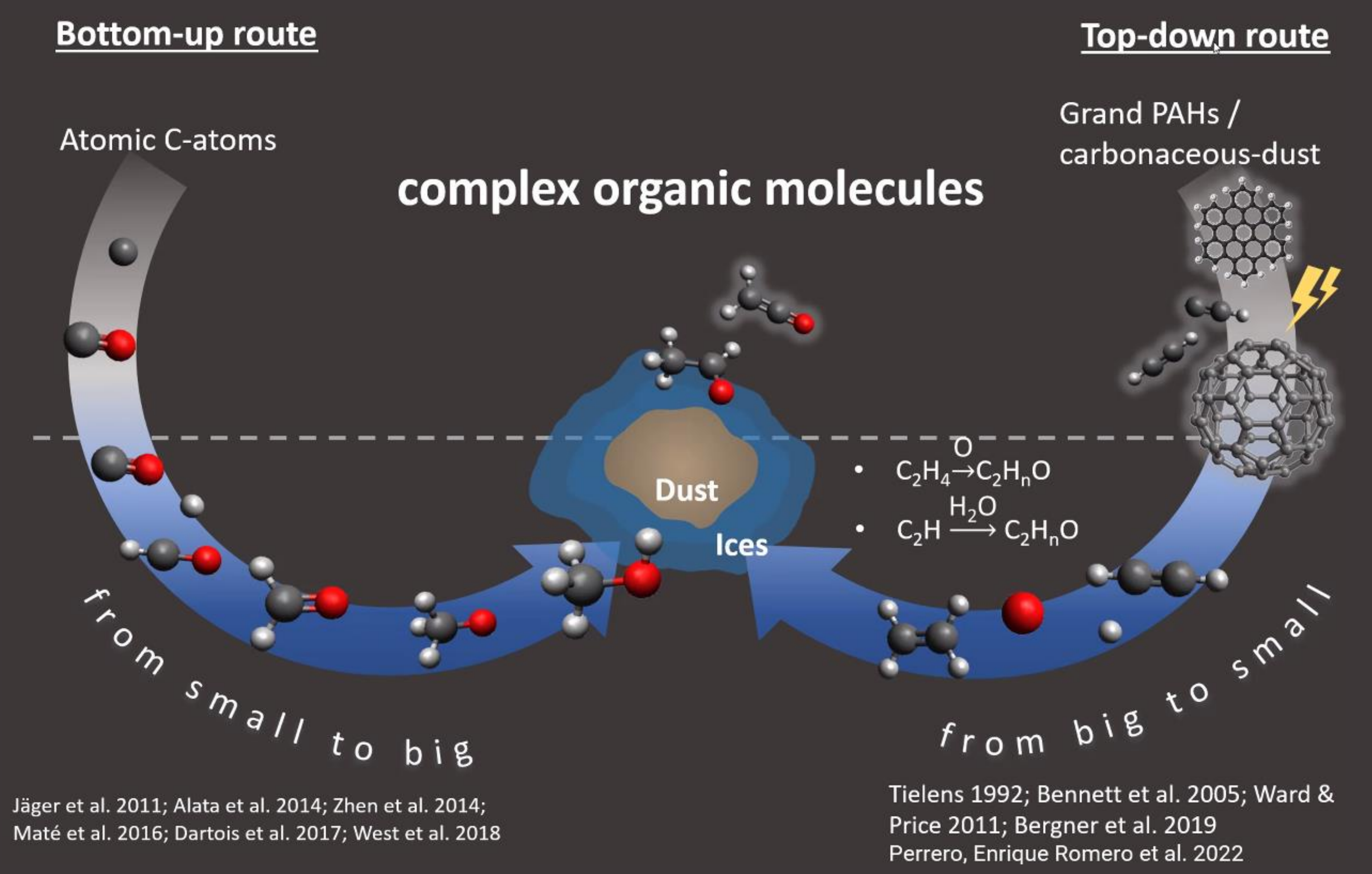
COMs form in ices

COMs are detected in ices

What is the physicochemical evolution of COMs in the ISM?



Credit: Chris R. Arumainayagam

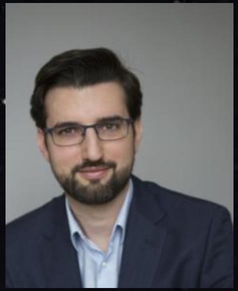


Credit: Ko-Ju Chuang

SURFRESIDE TEAM
Leiden University

Sterrewacht Leiden

Prof. Harold Linnartz
(1965 - 2023)



Dr. Ioppolo

Dr. Fedoseev

Dr. Lamberts

Dr. Chuang

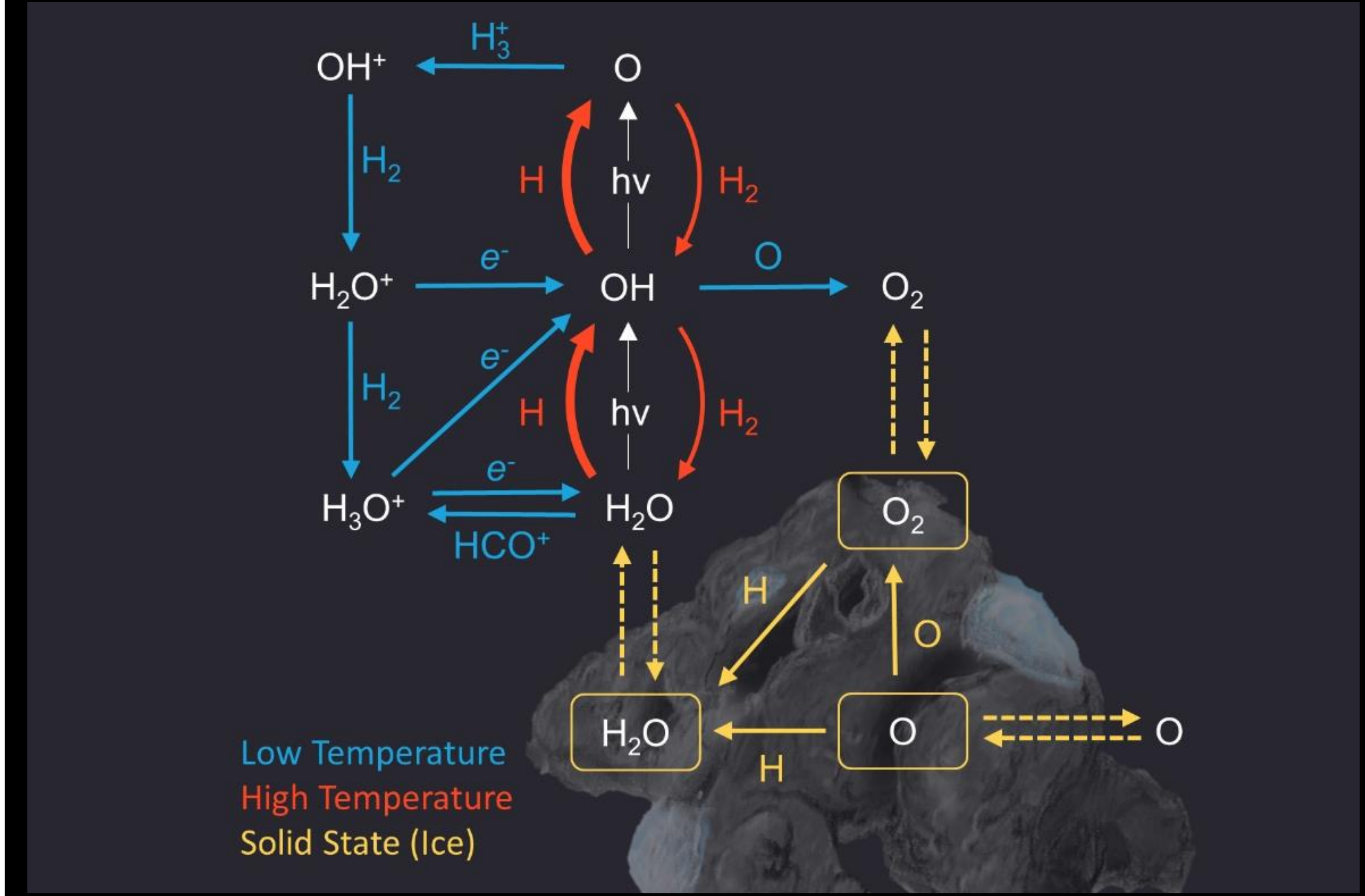
Dr. Qasim

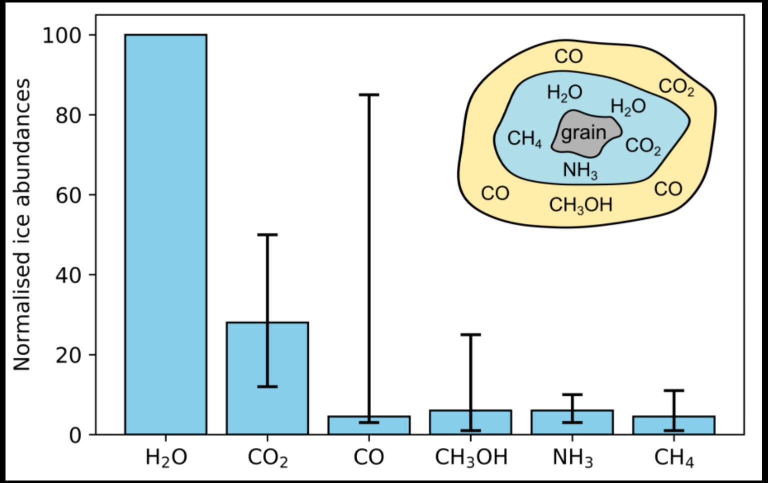
Ms. Santos

Prof. Ewine van Dishoeck

Prof. Herma Cuppen

Molecules form via Dark Chemistry





Öberg, Chem. Rev. (2016)

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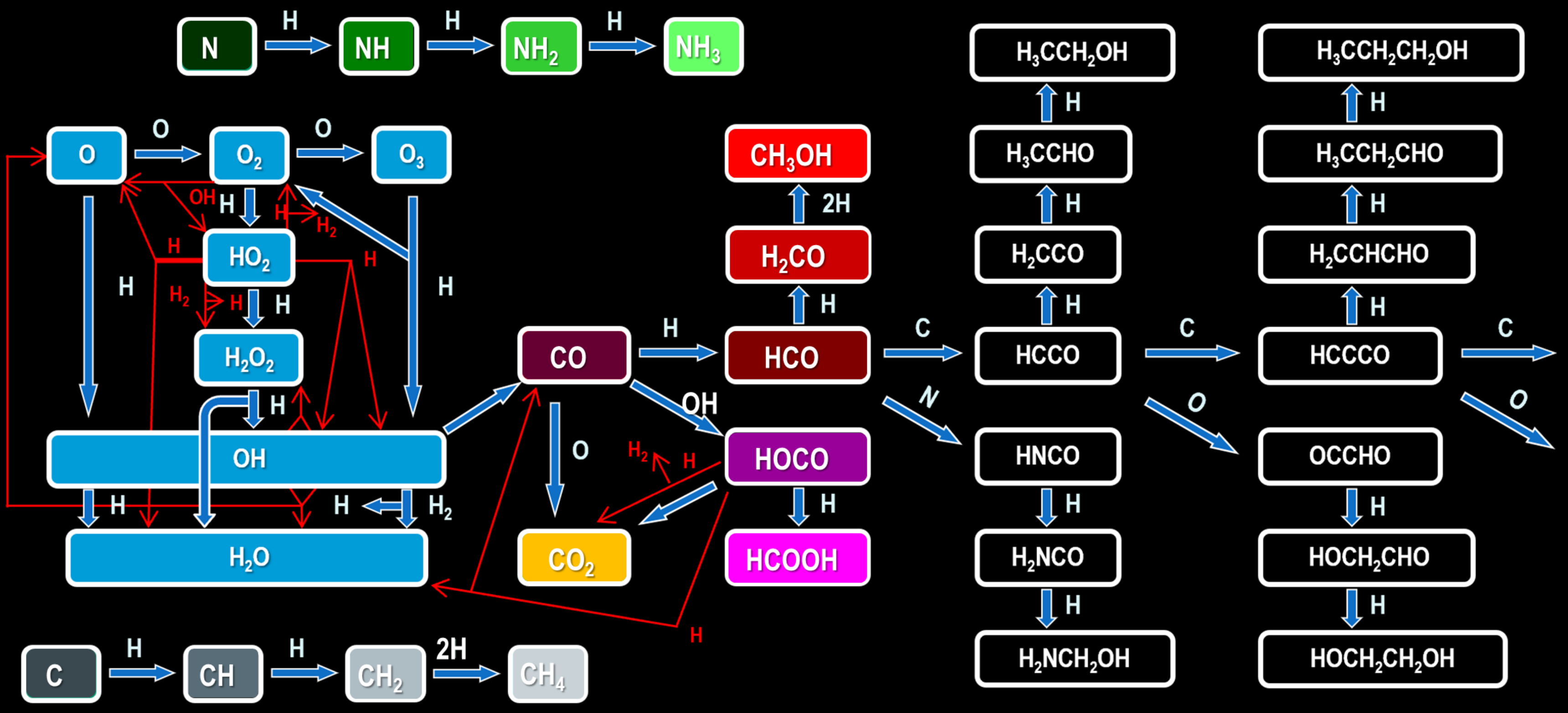
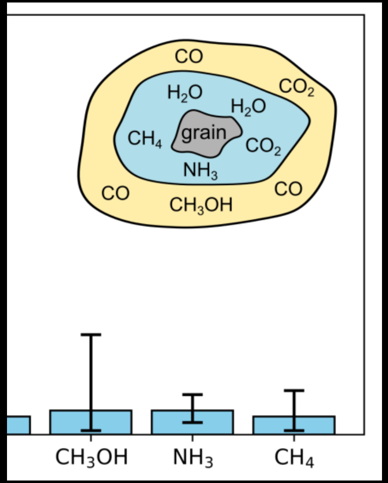
Molecules form via Dark Chemistry



Linnartz, Ioppolo & Fedoseev, *IRPC* (2015)



erg, Chem. Rev. (2016)

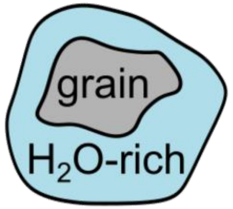
Ioppolo *et al.*, *MNRAS* (2011b)

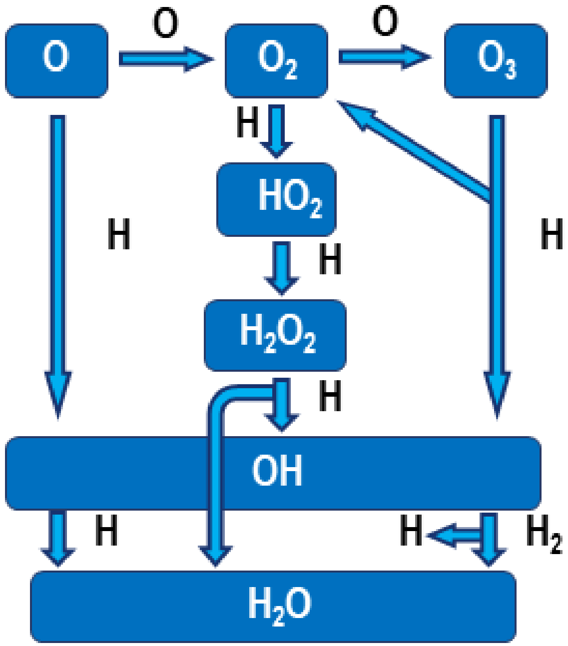
Charnley *et al.*, *A&A* (2001)

Fedoseev *et al.*, *MNRAS* (2015)

Qasim *et al.*, *Nature Astron.* (2020)

Water forms via Dark Chemistry






Astron. Astrophys. 114, 245–260 (1982)

ASTRONOMY AND ASTROPHYSICS

Model Calculations of the Molecular Composition of Interstellar Grain Mantles

A. G. G. M. Tielens* and W. Hagen**

Laboratory Astrophysics Group, Rijksuniversiteit, 2300 RA Leiden, The Netherlands

Received February 1, accepted May 19, 1982

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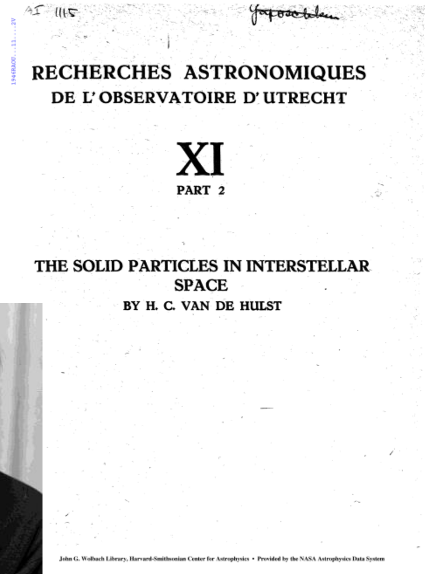
Tielens & Hagen, A&A (1982)


RECHERCHES ASTRONOMIQUES
DE L' OBSERVATOIRE D' UTRECHT

XI

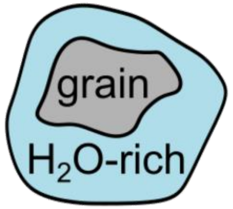
PART 2

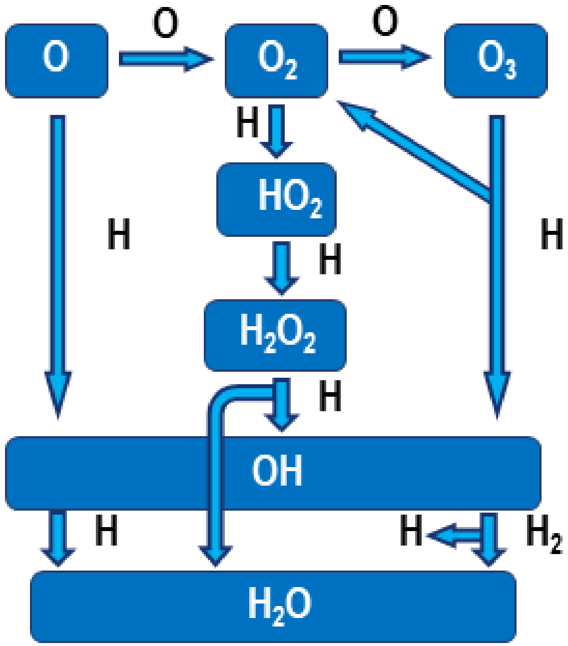
THE SOLID PARTICLES IN INTERSTELLAR SPACE

BY H. C. VAN DE HULST

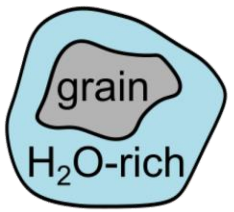
van de Hulst, RAOU (1946)

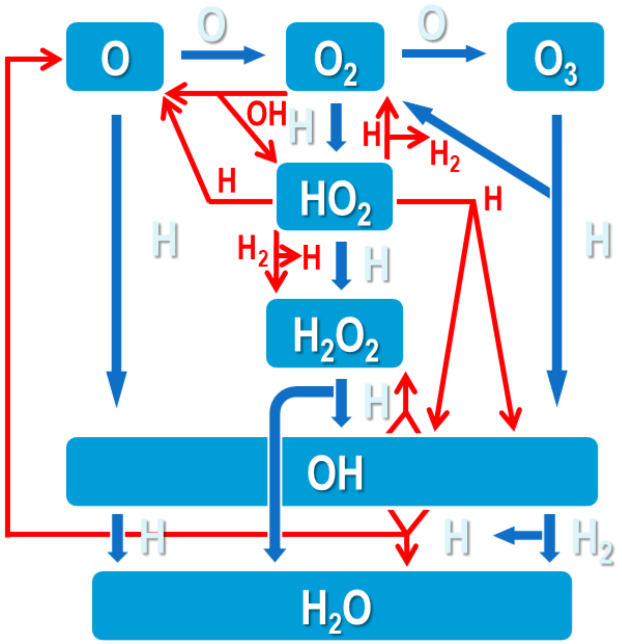
Water forms via Dark Chemistry

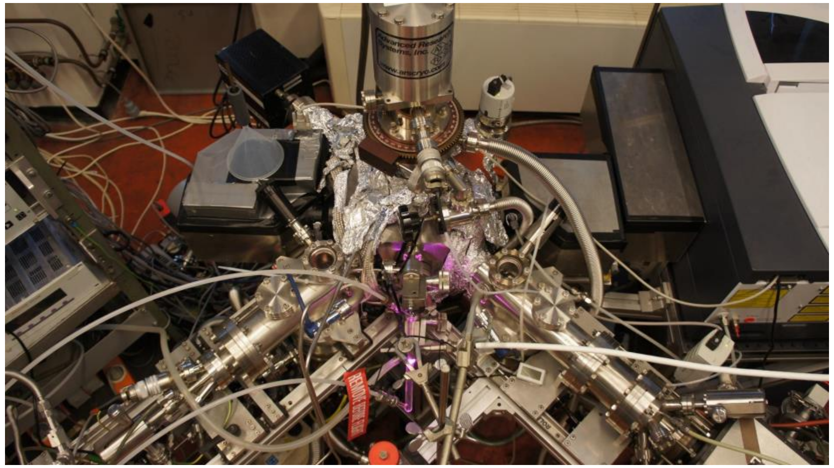




Water forms via Dark Chemistry

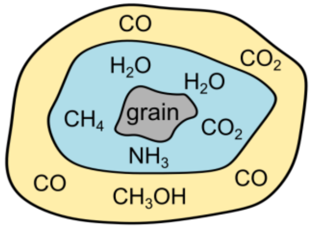




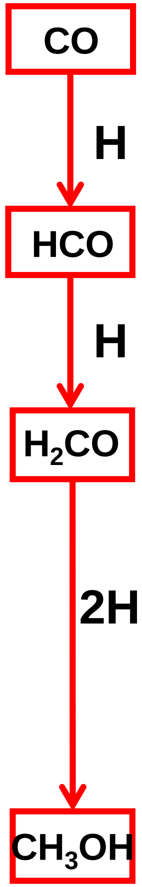


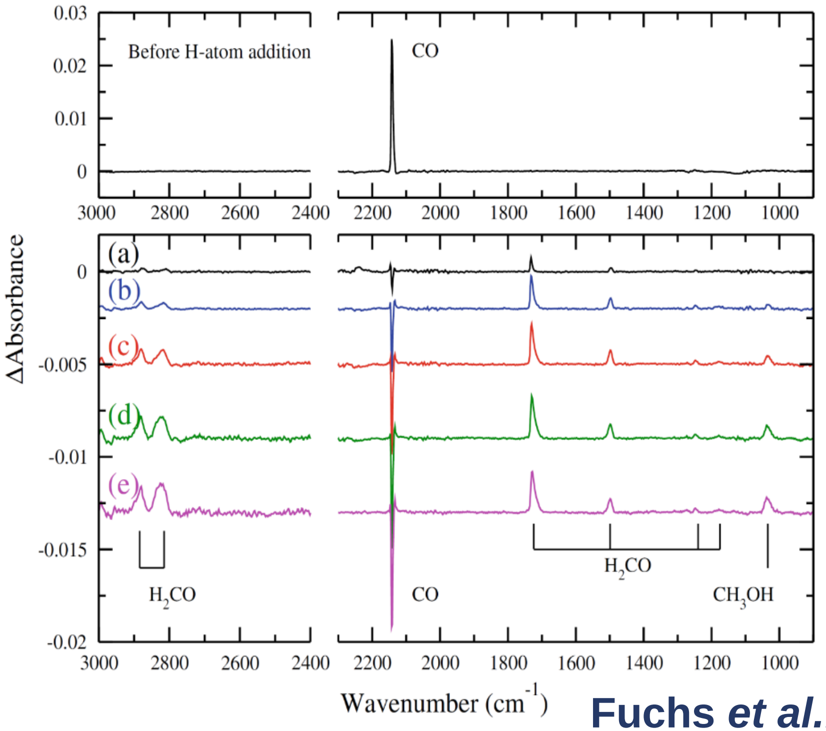
O + H	Dulieu *et al*. 2010; Jing *et al*. 2011
O_2 + H	Miyauchi *et al*. 2008; Ioppolo *et al*. 2008, 2010; Matar *et al*. 2008; Oba *et al*. 2009, 2012, 2014; Cuppen *et al*. 2010; Chaabouni *et al*. 2012; Lamberts *et al*. 2013, 2014a; 2014b; 2015; 2016
O_3 + H	Mokrane *et al*. 2009; Romanzin *et al*. 2011

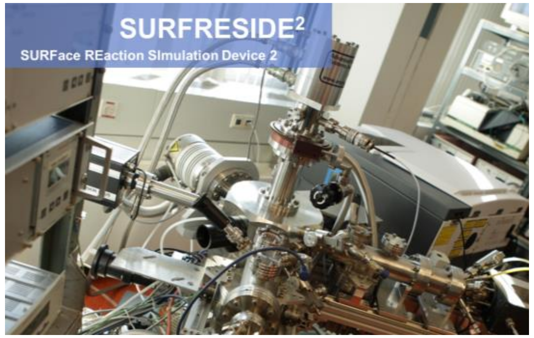
MeOH forms via Dark Chemistry



Watanabe et al., *ApJ* (2004)
Hidaka et al., *ApJ* (2004)
Hiraoka et al., *ApJ* (2002)







Fuchs *et al.*, *A&A* (2009)

COMs form via Dark Chemistry

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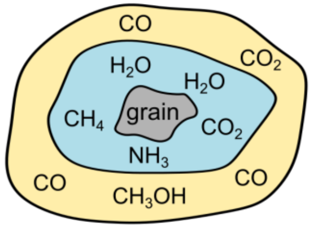
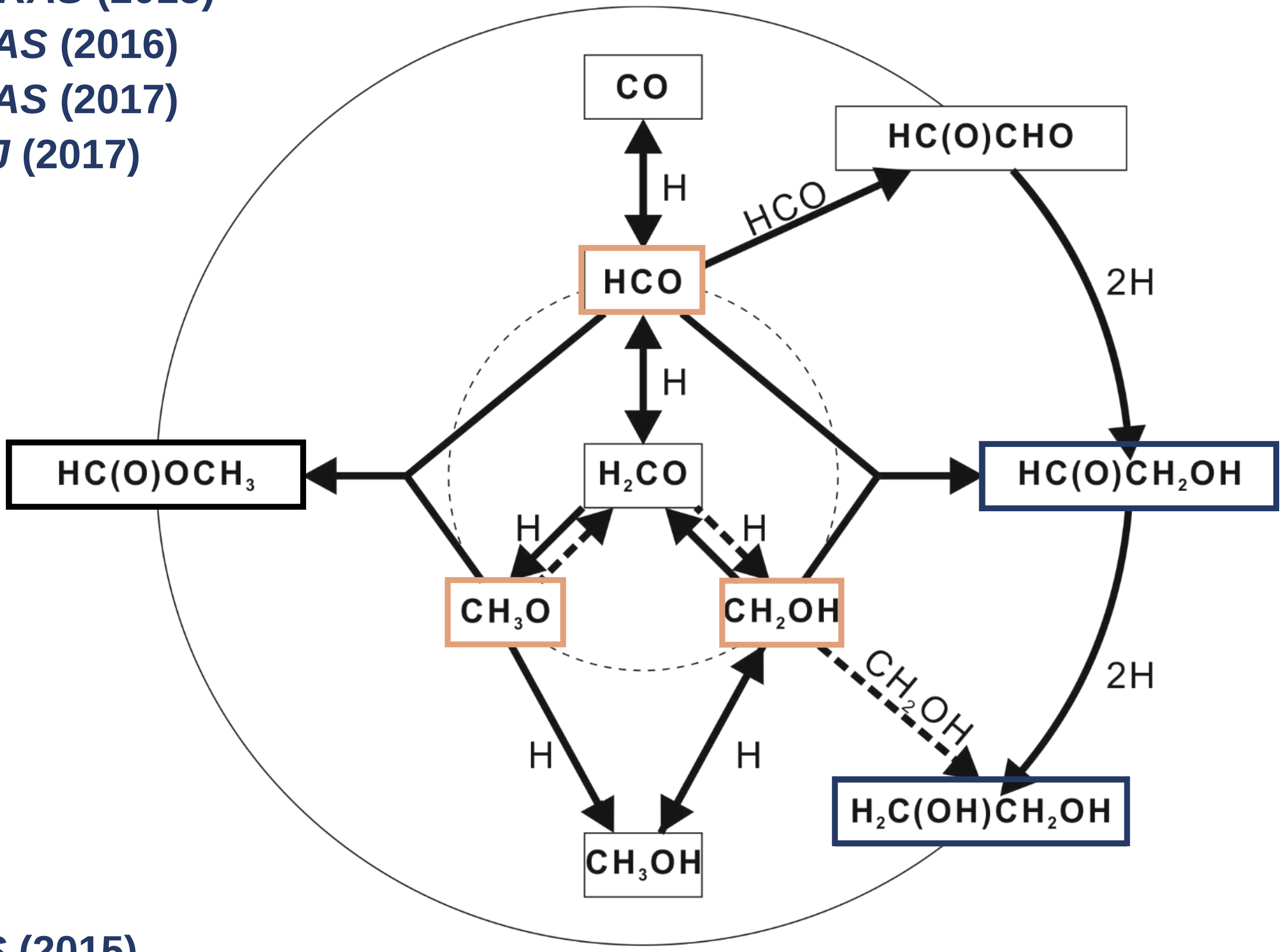
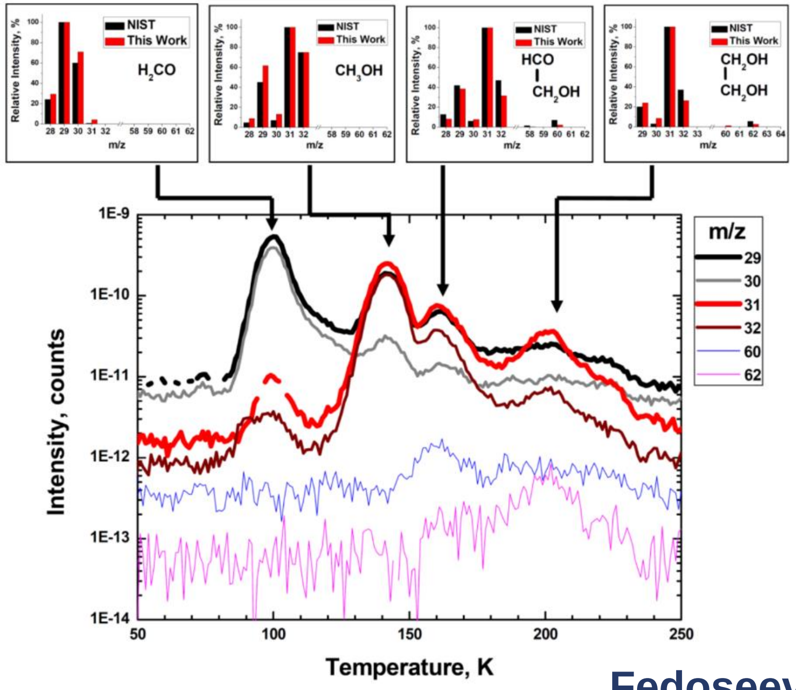


Fedoseev *et al.*, *MNRAS* (2015)
Chuang *et al.*, *MNRAS* (2016)
Chuang *et al.*, *MNRAS* (2017)
Fedoseev *et al.*, *ApJ* (2017)





Fedoseev *et al.*, *MNRAS* (2015)

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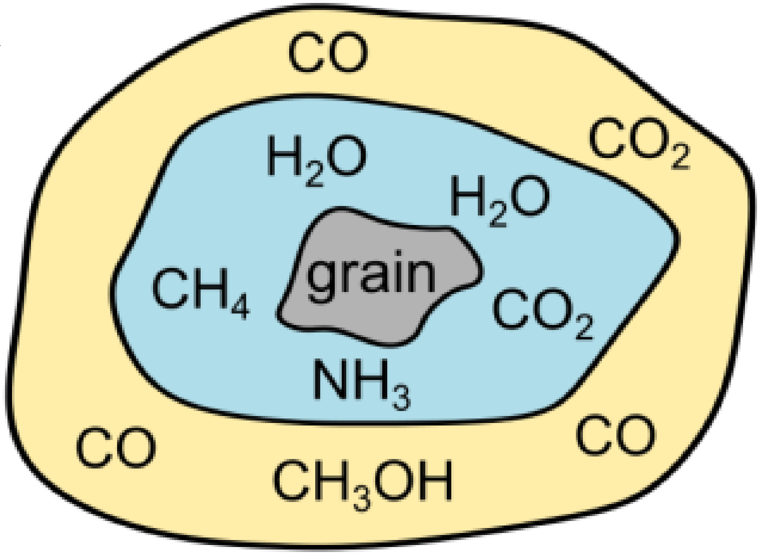
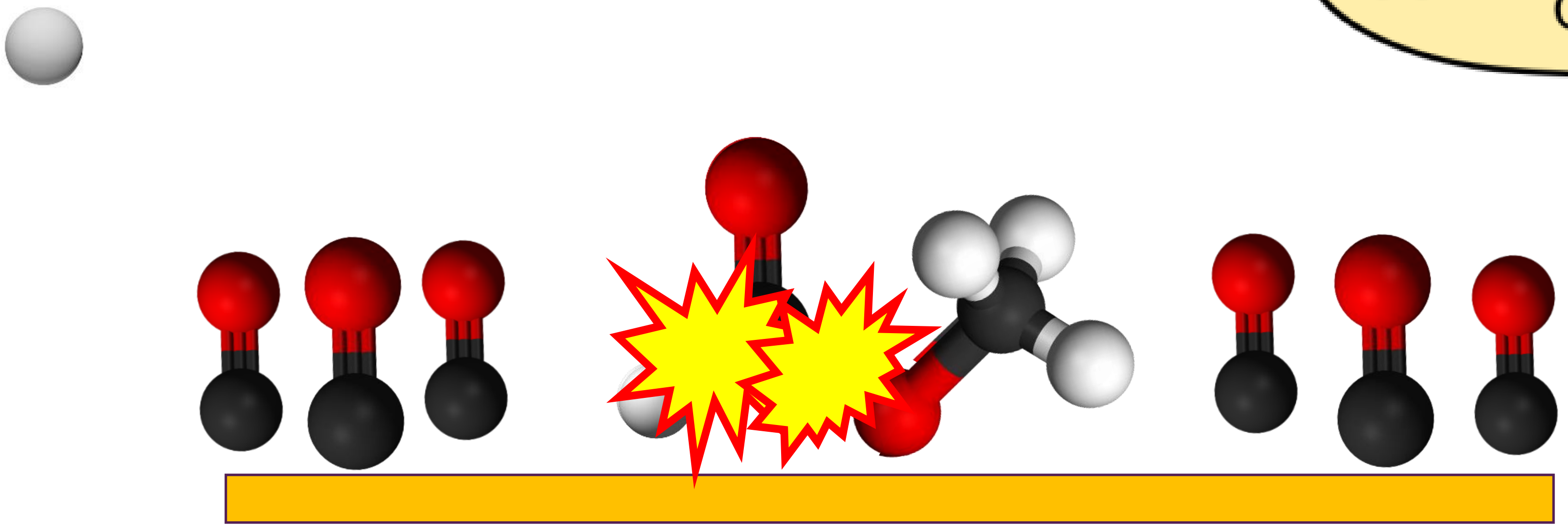
COMs form via Dark Chemistry

A non-diffusive reaction mechanism at 10 K



Fedoseev *et al.*, *MNRAS* (2015)
Chuang *et al.*, *MNRAS* (2016)
Chuang *et al.*, *MNRAS* (2017)
Fedoseev *et al.*, *ApJ* (2017)
Qasim *et al.*, *A&A* (2019)
Chuang *et al.*, *A&A* (2020)
Qasim *et al.*, *Nat. Astron.* (2020)
Ioppolo *et al.*, *Nat. Astron.* (2021)



10 K

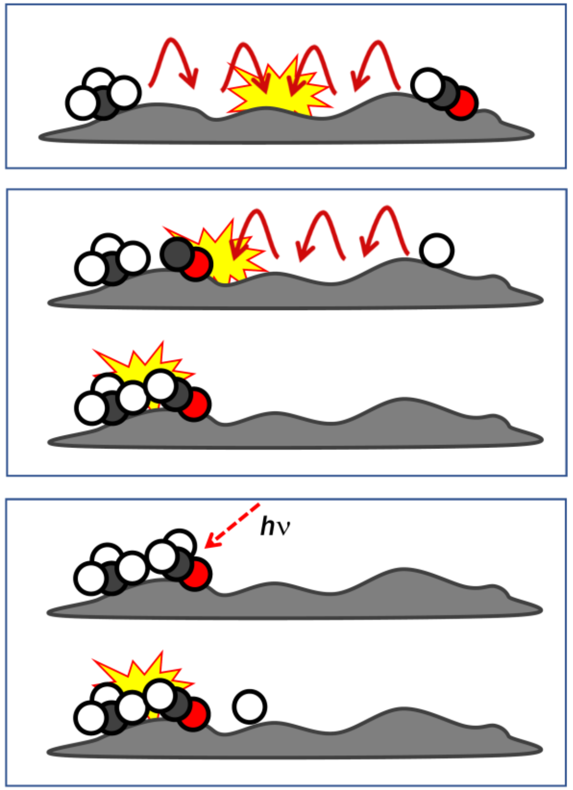
COMs form via Dark Chemistry

A non-diffusive reaction mechanism at 10 K

- *Diffusive:* CH_3 + HCO → CH_3CHO
  (very slow at low temps)

- *Non-diffusive* (***3-body reaction***, ***3B***)*:*
  [*initiating reaction*] H + CO → HCO
  [*follow-on reaction*] CH_3 + HCO → CH_3CHO
  ⇒ *only* H needs to move!

- *Non-diffusive* (***photodissociation-induced***, ***PDI***)*:*
  [*initiating process*] H_2CO + hν → HCO (+H)
  [*follow-on reaction*] CH_3 + HCO → CH_3CHO



Jin and Garrod, *ApJS* (2020)
Garrod *et al*., ApJS (2021)

First models of hot cores to use a **diffusive + non-diffusive** treatment.

COM production shifted to much earlier times / lower temperatures.

Credit R. Garrod

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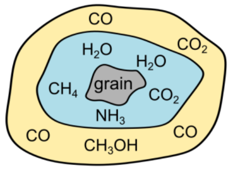
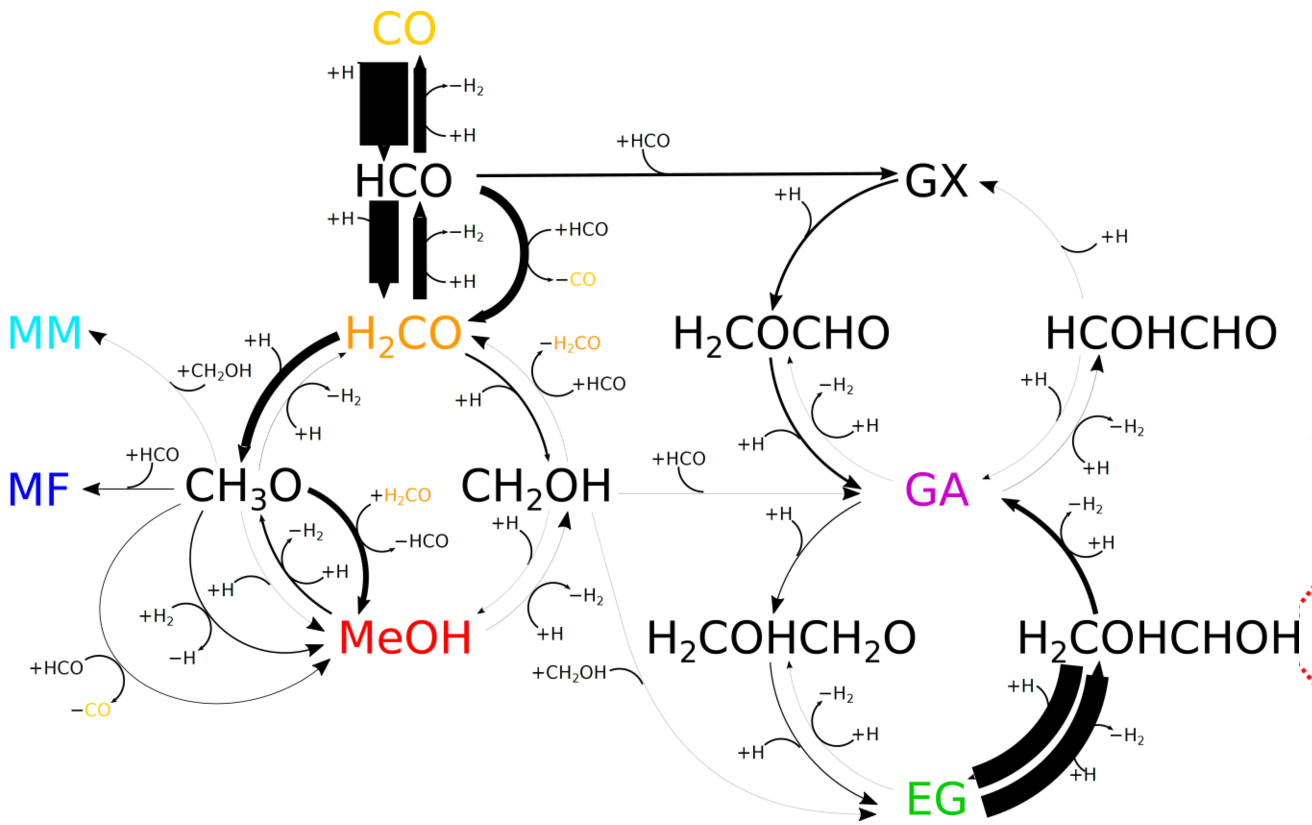
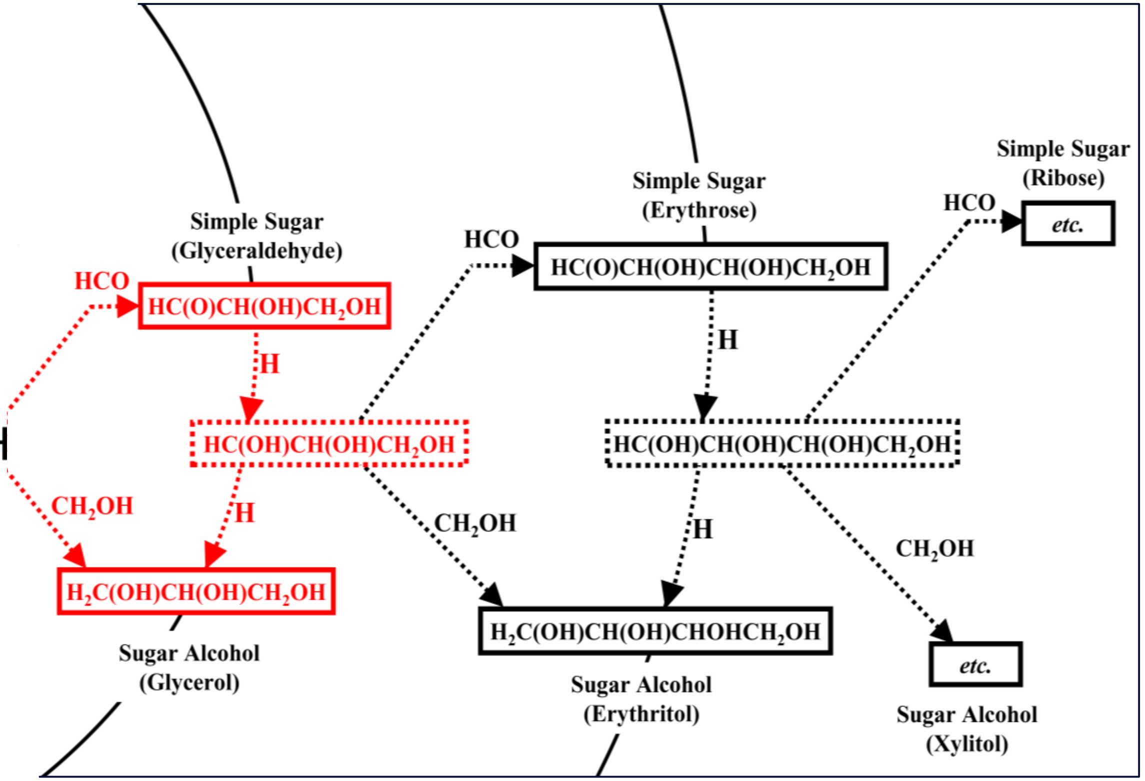
Sugars form via Dark Chemistry







Fedoseev *et al.*, *ApJ* (2017)
Simons *et al.*, *A&A* (2020)
He *et al.*, *A&A* (2021)

Glycine forms via Dark Chemistry

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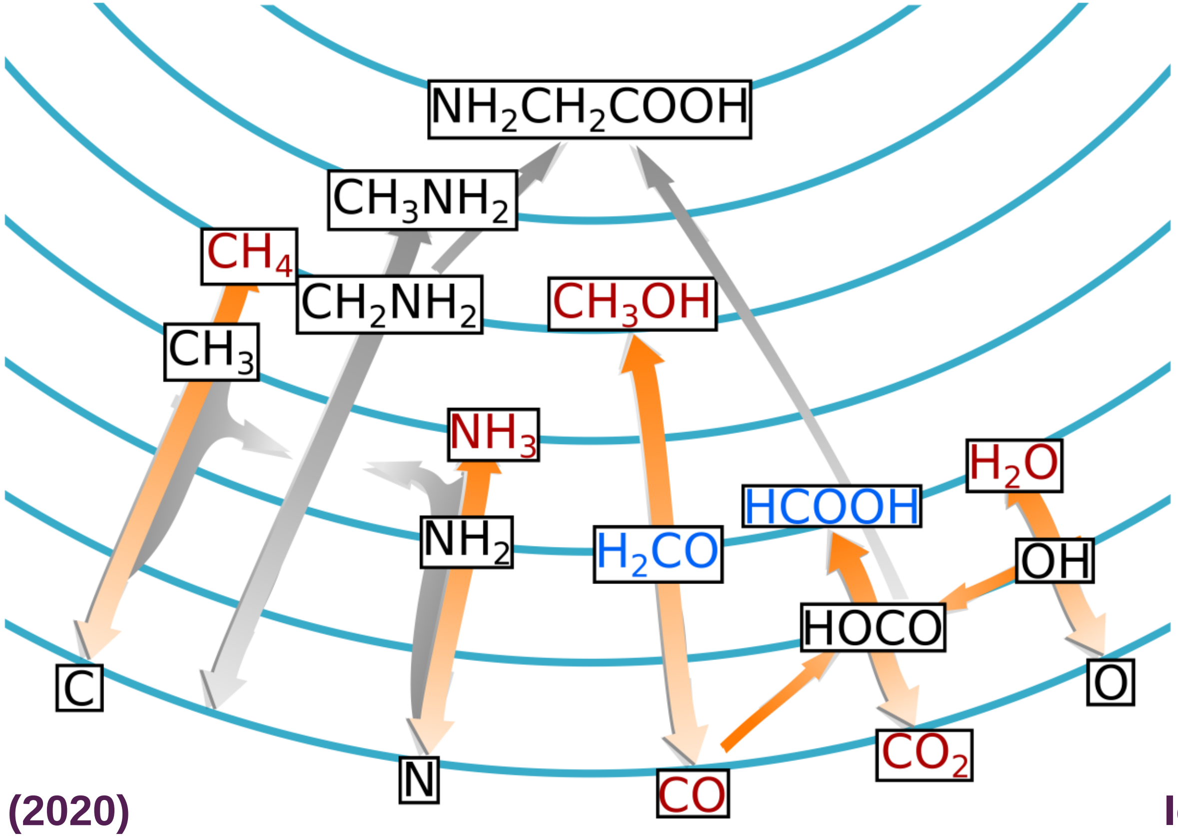

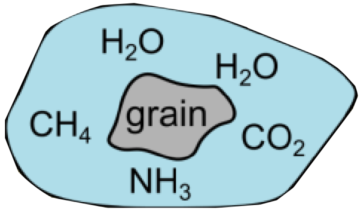

Qasim *et al., Nature Astron.* (2020)
Fedoseev *et al., MNRAS* (2015)
Fuchs *et al., A&A* (2009)

Ioppolo *et al., MNRAS* (2011a)
Ioppolo *et al., MNRAS* (2011b)
Ioppolo *et al., ApJ* (2008)

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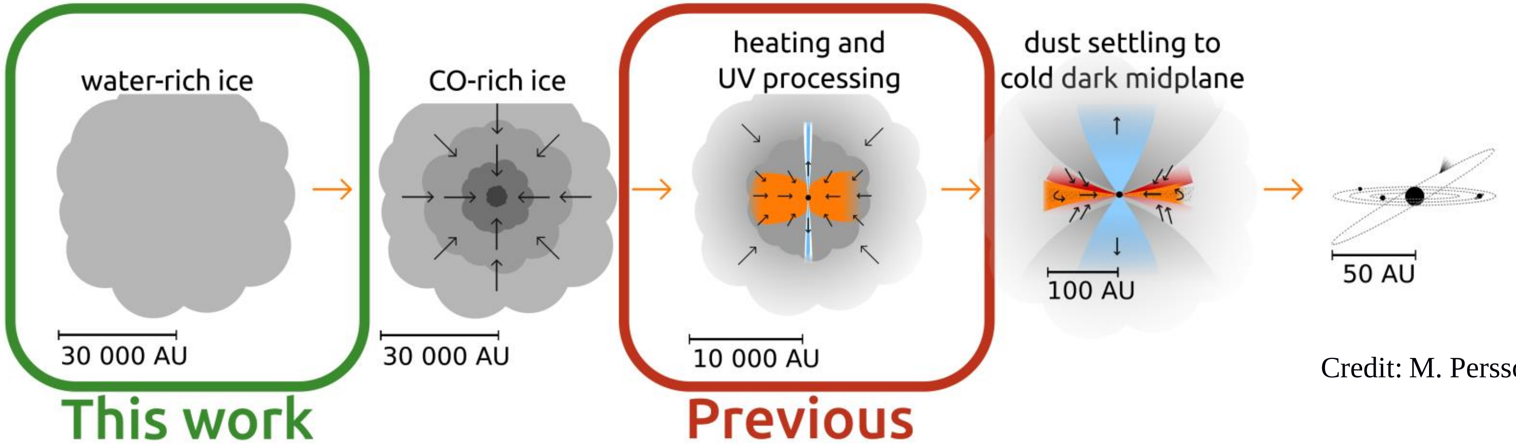
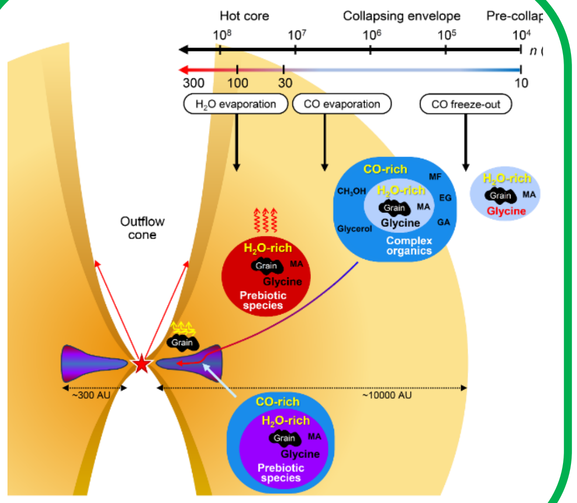
Glycine forms via Dark Chemistry



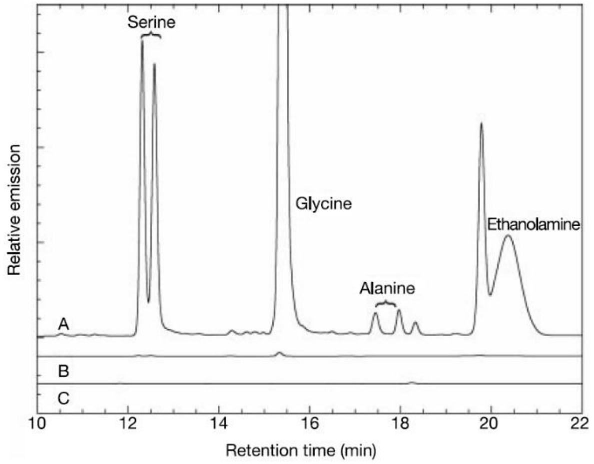
Credit: M. Persson

Ioppolo *et al.*, *Nature Astron.* (2021)

Bernstein et al., *Nature* 416, 401 (2002)



Star Formation Process



UV photolysis of interstellar ice analogues

$H_2O:CH_3OH:NH_3:HCN = 20:2:1:1$

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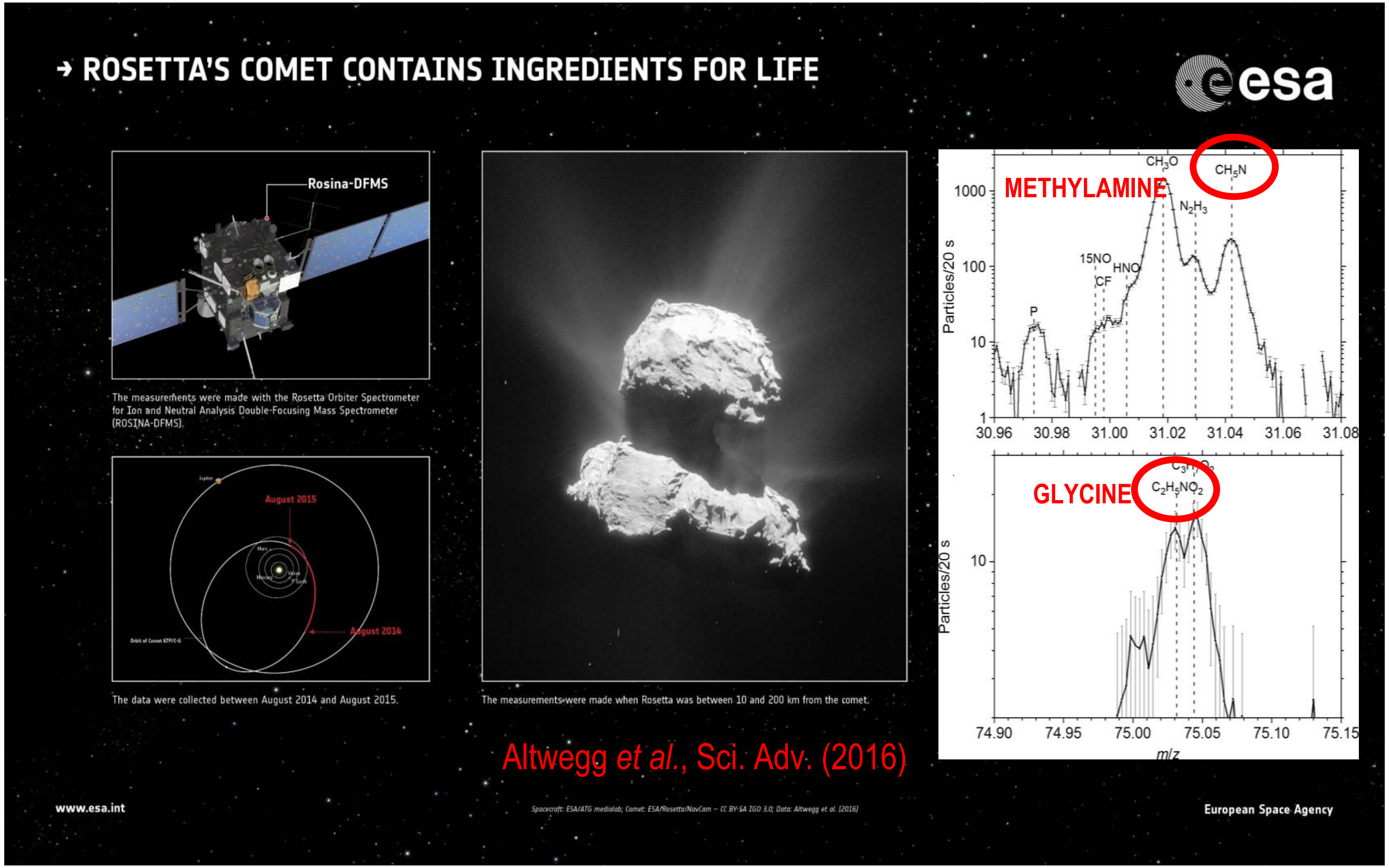
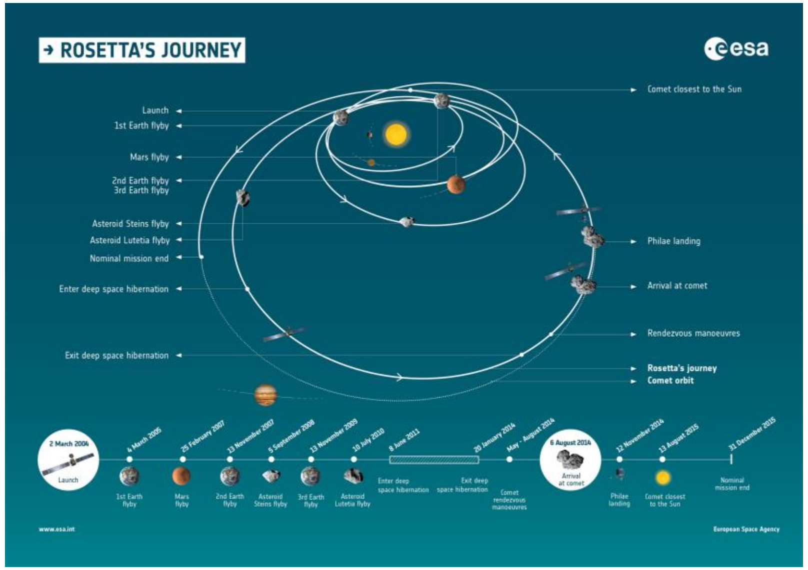
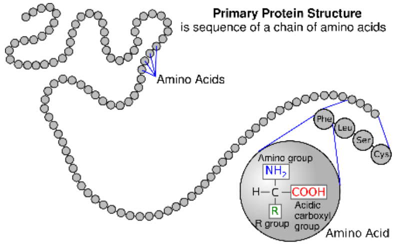
Glycine forms via Dark Chemistry



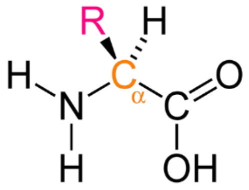


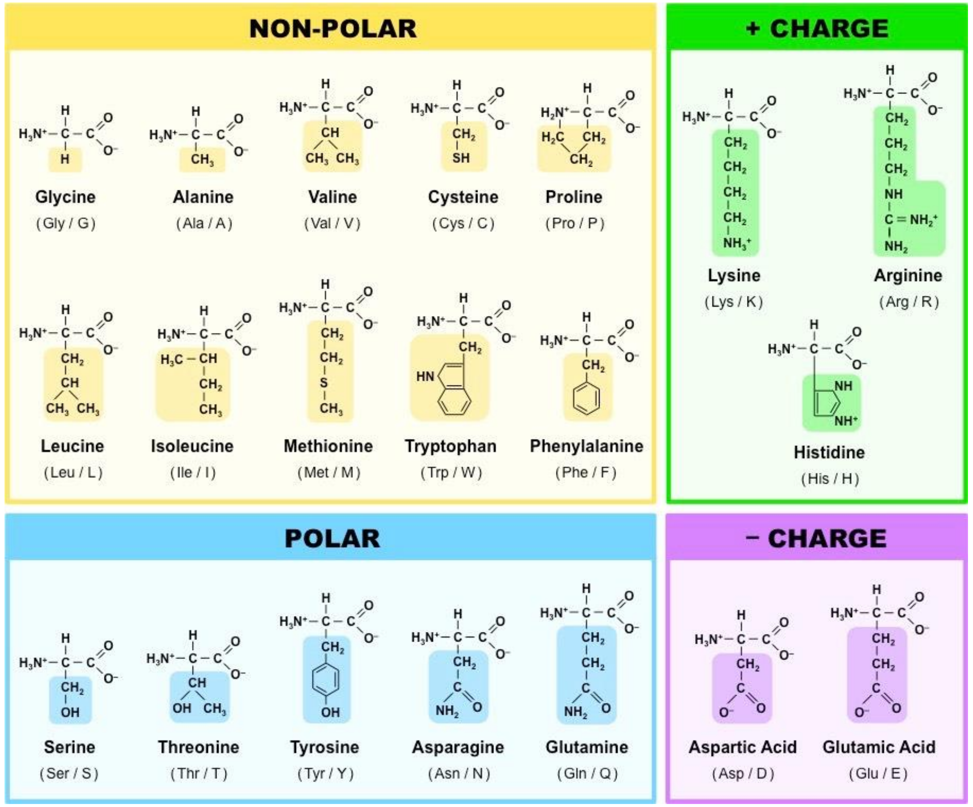
Amino acids formation via Dark Chemistry

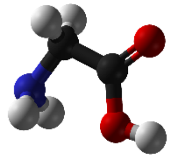


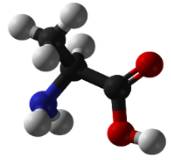
Oba *et al.*, *CPL* (2015) showed
H-abstraction on R-group

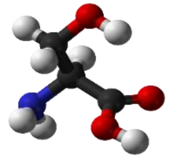
Formation of proteinogenic α-amino acids?





α-glycine 

α-alanine  ?

α-serine  ?

….

….

InterCat: Shedding Light on the Formation of the Building Blocks of Life in Space

Center for Interstellar Catalysis

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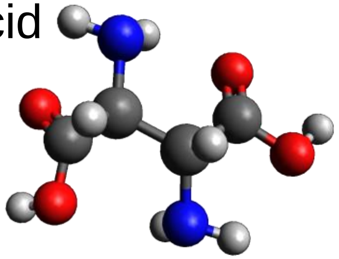
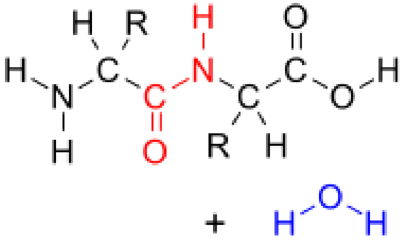
Investigation of peptide bond formation

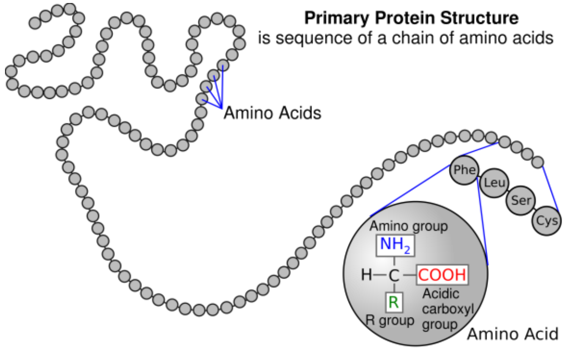
Alfred Hopkinson

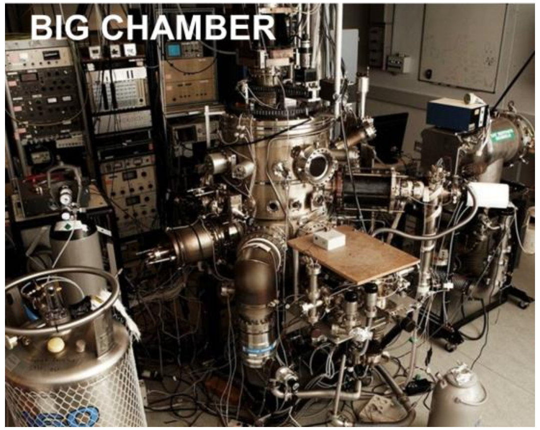
1) **Hydrogenation/Deuteration of Gly on cold grain analogs**
   Deuterium exchange observed
   Formation of **larger species**
2) **1 keV e^- irradiation of Gly**
3) **20 keV H^+ irradiation of Gly**
4) **1 MeV H^+ irradiation of Gly**
   Peptide-like bonds

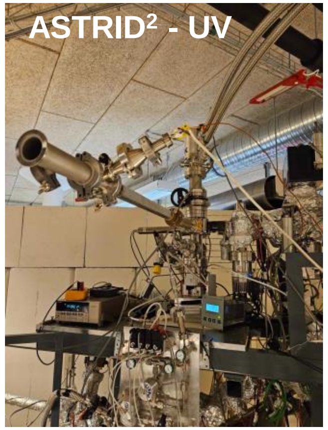


3-Aminoaspartic Acid









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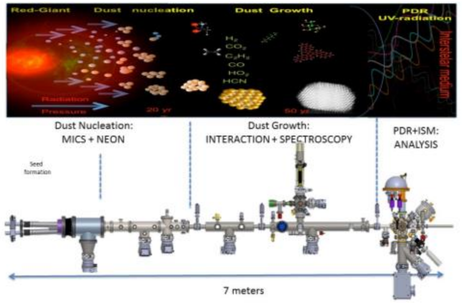
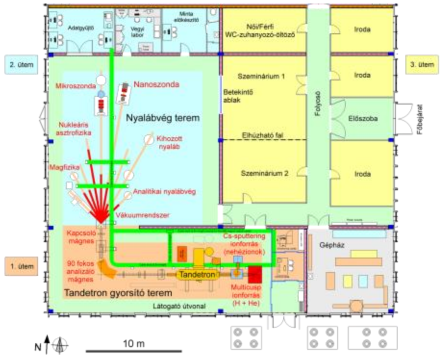
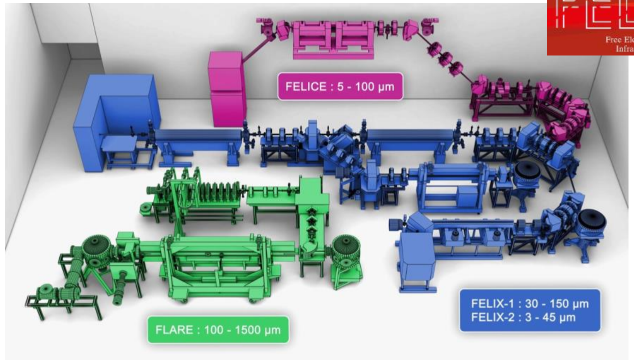
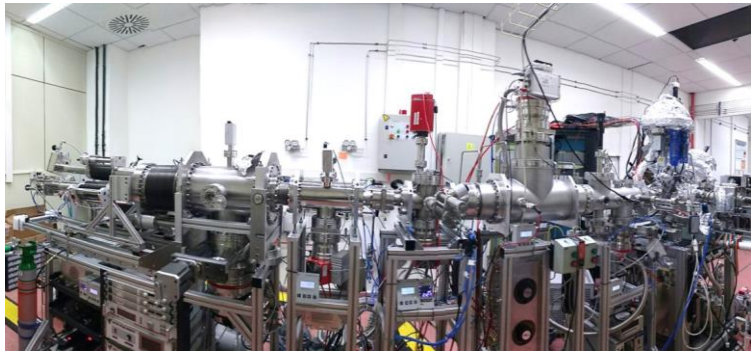
Astrochemistry at Large-Scale Facilities



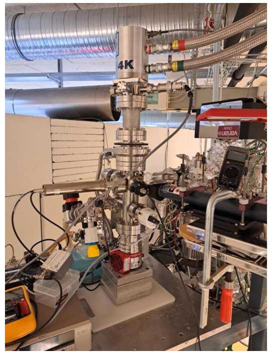




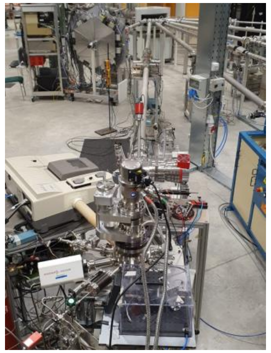
STARDUST MACHINE



ICE CHAMBER

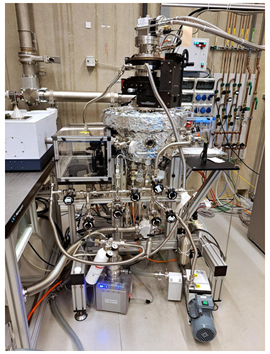


ICA



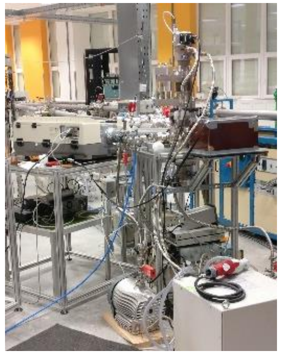
AQUILA

LISA



ATOMKI

CRs and electron irradiation of ice material relevant to ISM & Solar System



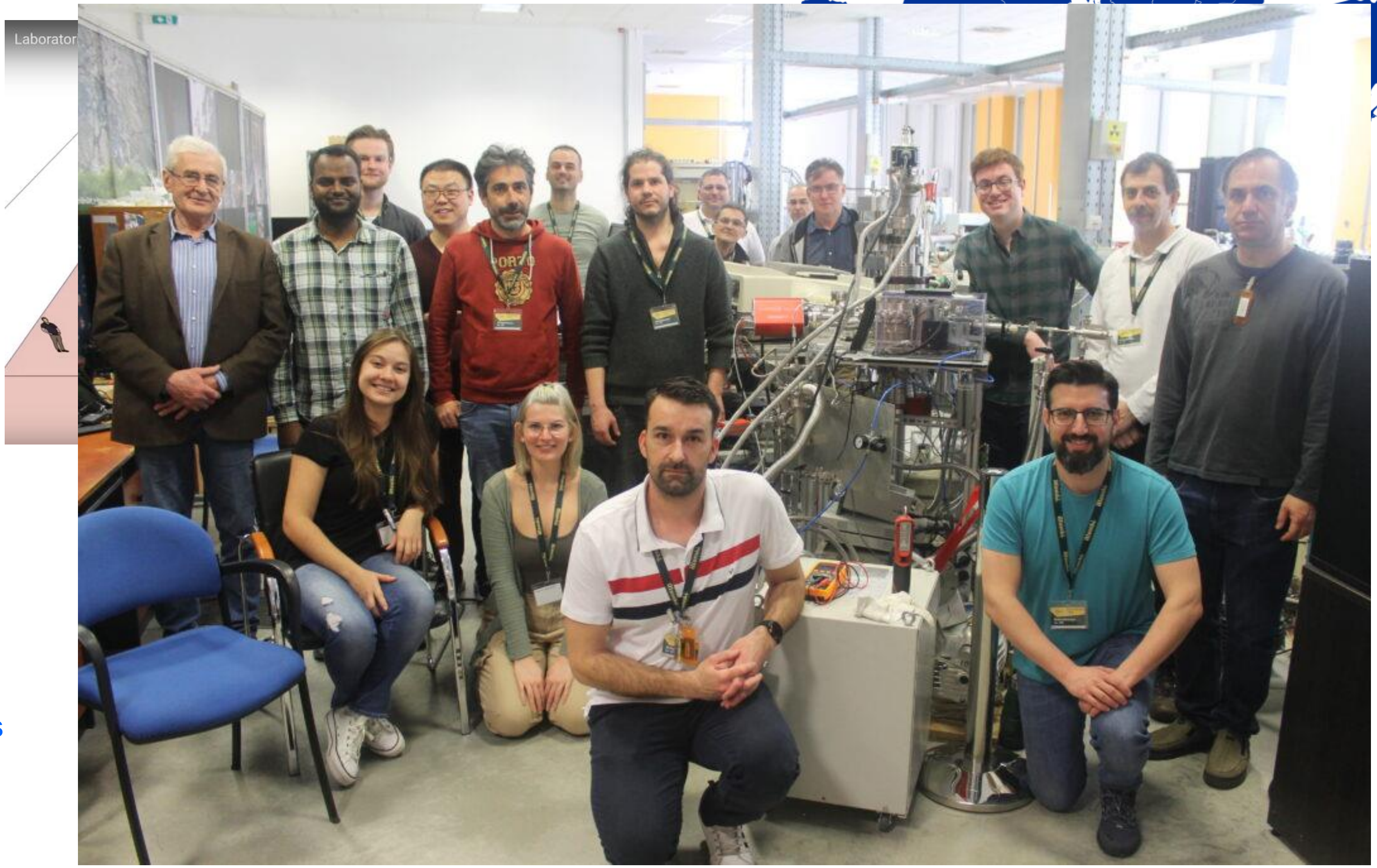
ICA

P **< 1x10^{-9} mbar**
***T*$_{surf}$ = 20 - 300 K**
E$_{ions}$ = 200 keV – 4 MeV H^{+}
H^{+}, He^{+}, He^{++}, C^{+}, C^{++}, O^{+}, O^{++}, S^{+}, S^{++}
Current = nA - µA

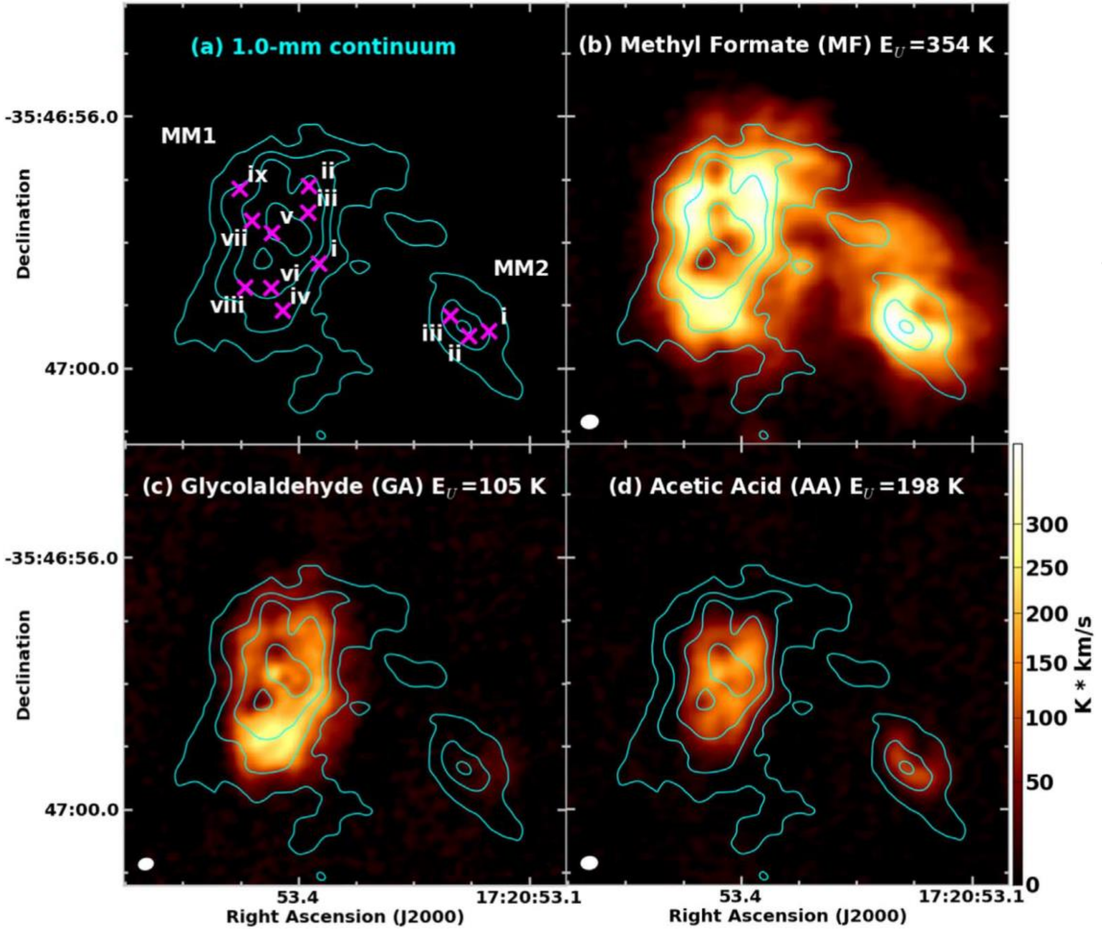
- **2 keV electron gun**
- **Effusive Cell**

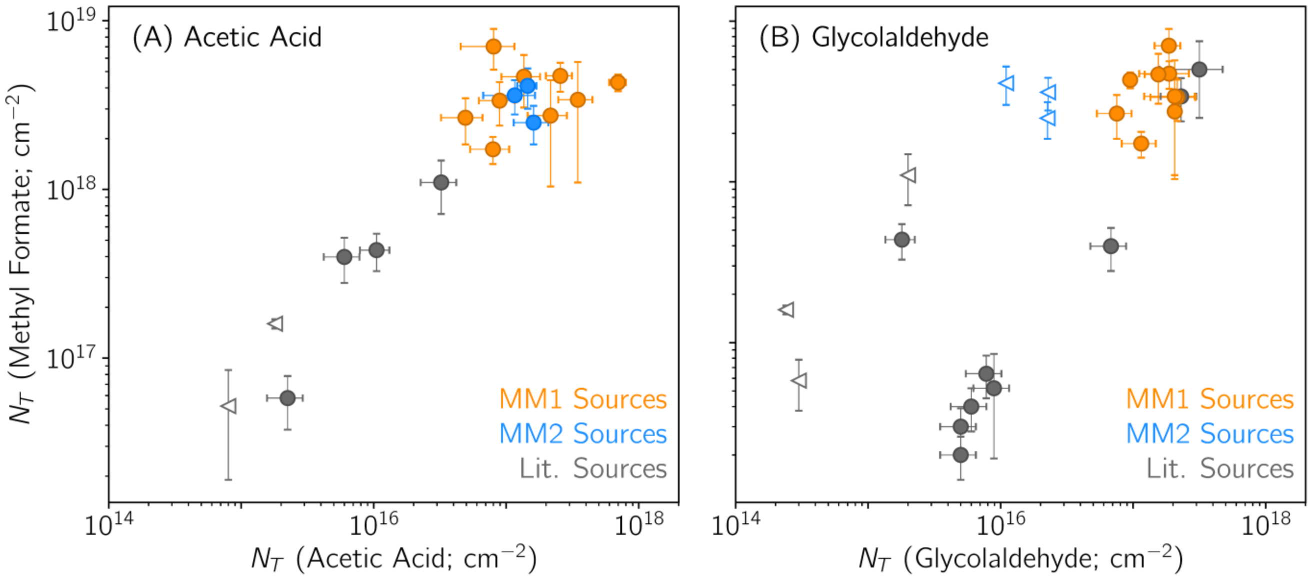
AQUILA

P **< 1x10^{-9} mbar**
***T*$_{surf}$ = 20 - 300 K**
E$_{ions}$ = 100s eV – 10s keV
Solar Wind: H, He, C, O, Si, Fe, Ni ions
High charge state of ions
Positive/negative ions or molecular ions



Detection of MF Isomers in space

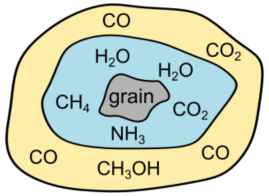




MF $$HCO + CH_3O \longrightarrow HCOOCH_3 \quad (1)$$

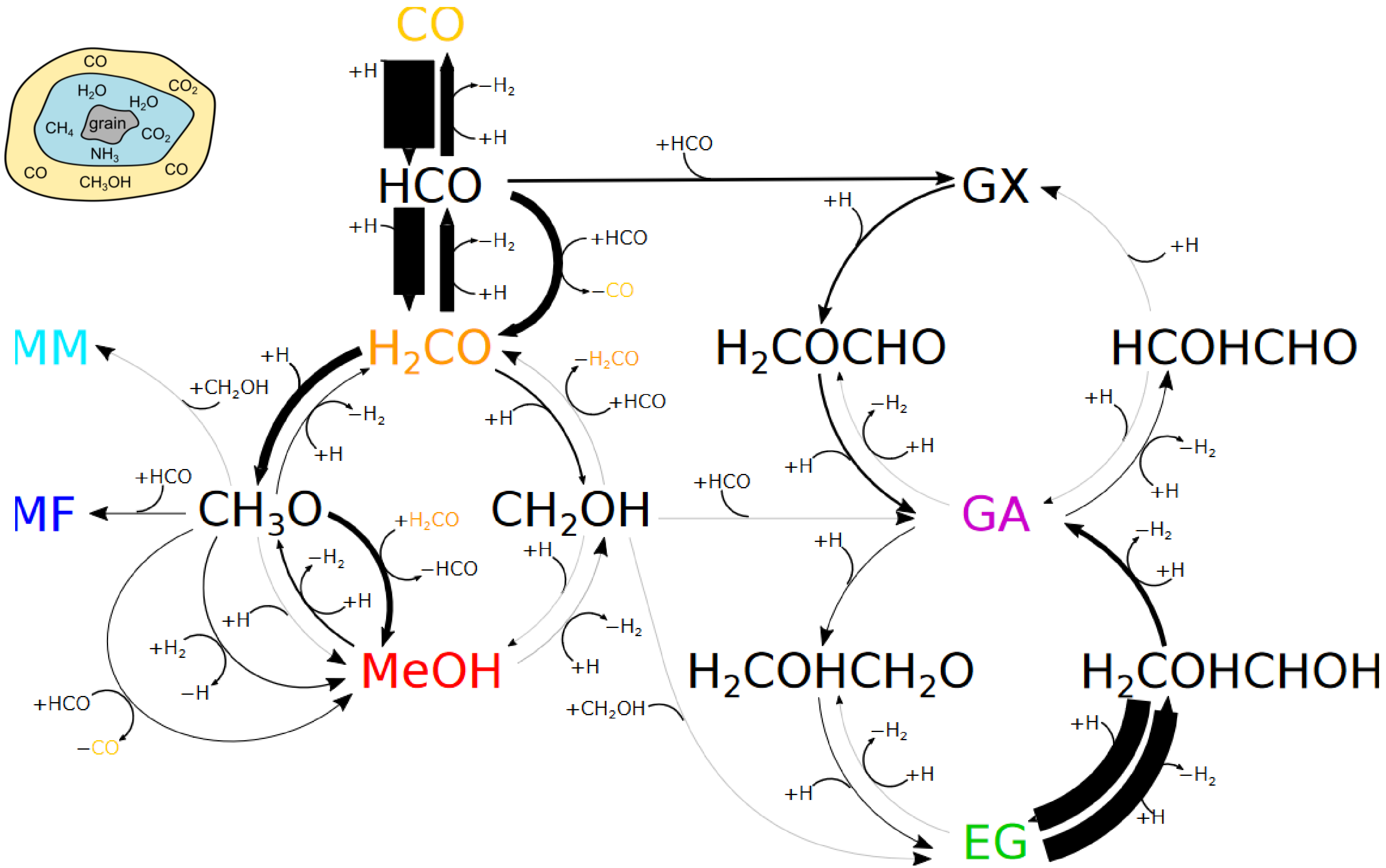
GA $$HCO + CH_2OH \longrightarrow CH(O)CH_2OH \quad (2)$$

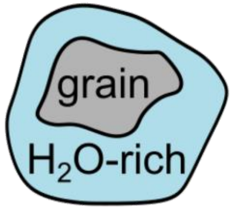
AA $$CH_3 + COOH \longrightarrow CH_3COOH \quad (3)$$



El-Abd *et al.*, ApJ (2019)

Formation of MF Isomers in space



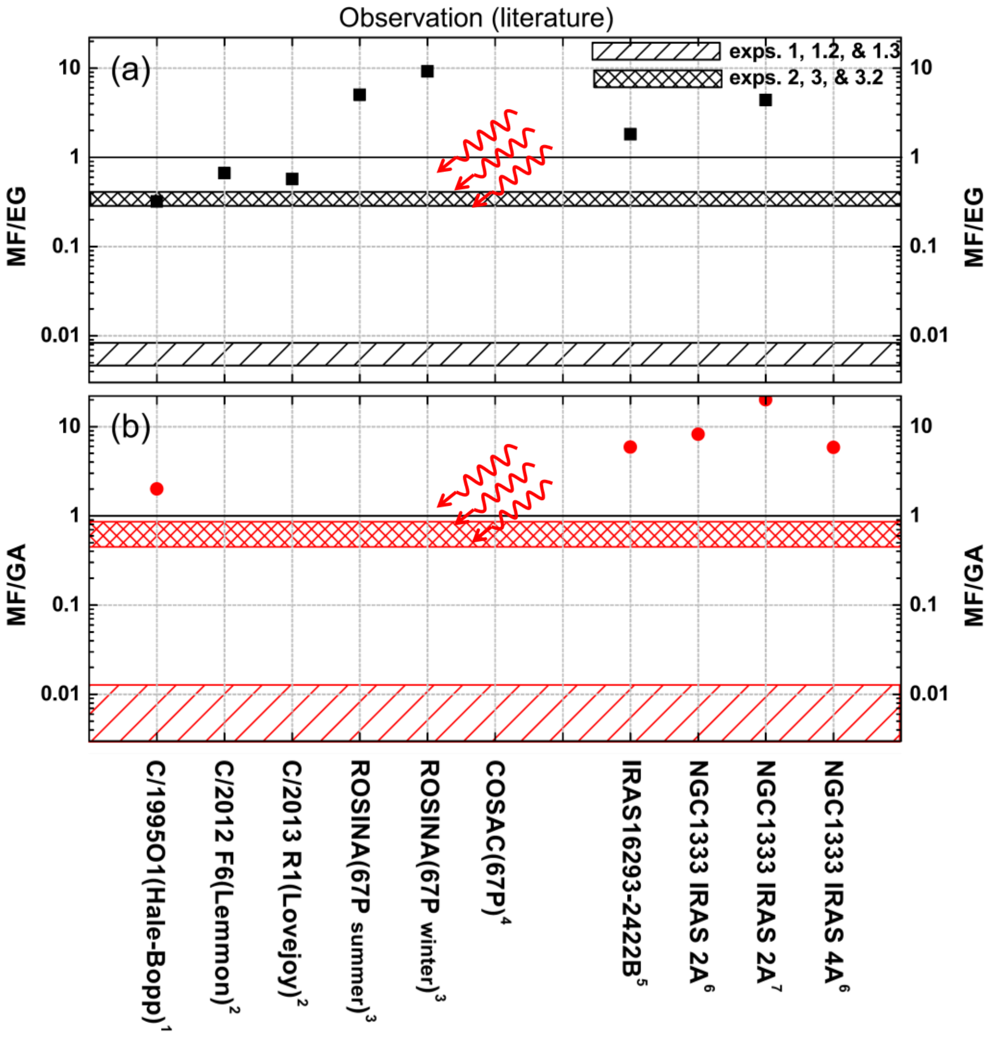


AA -> $CH_3 + COOH \longrightarrow CH_3COOH$

Simons *et al.*, A&A (2020)

He *et al.*, A&A (2022)

Formation of MF Isomers in space

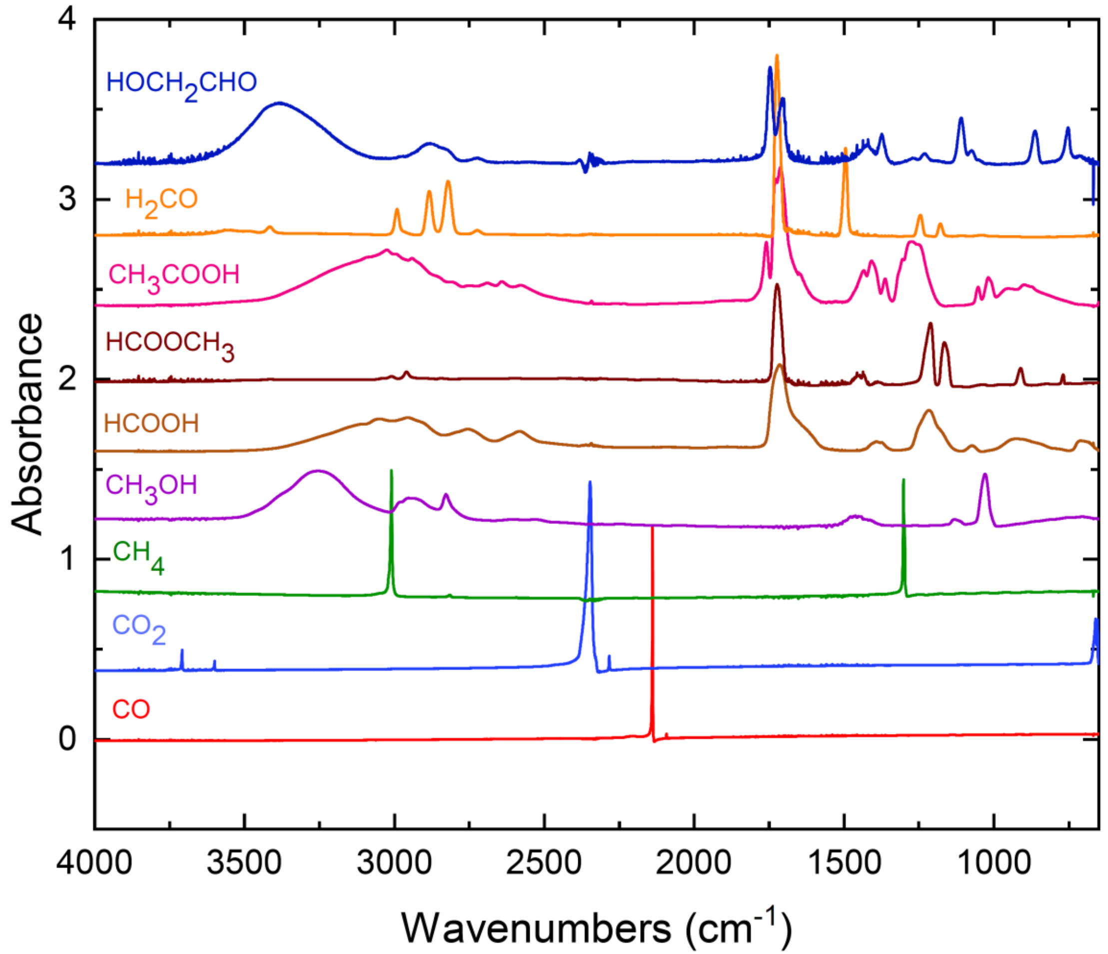


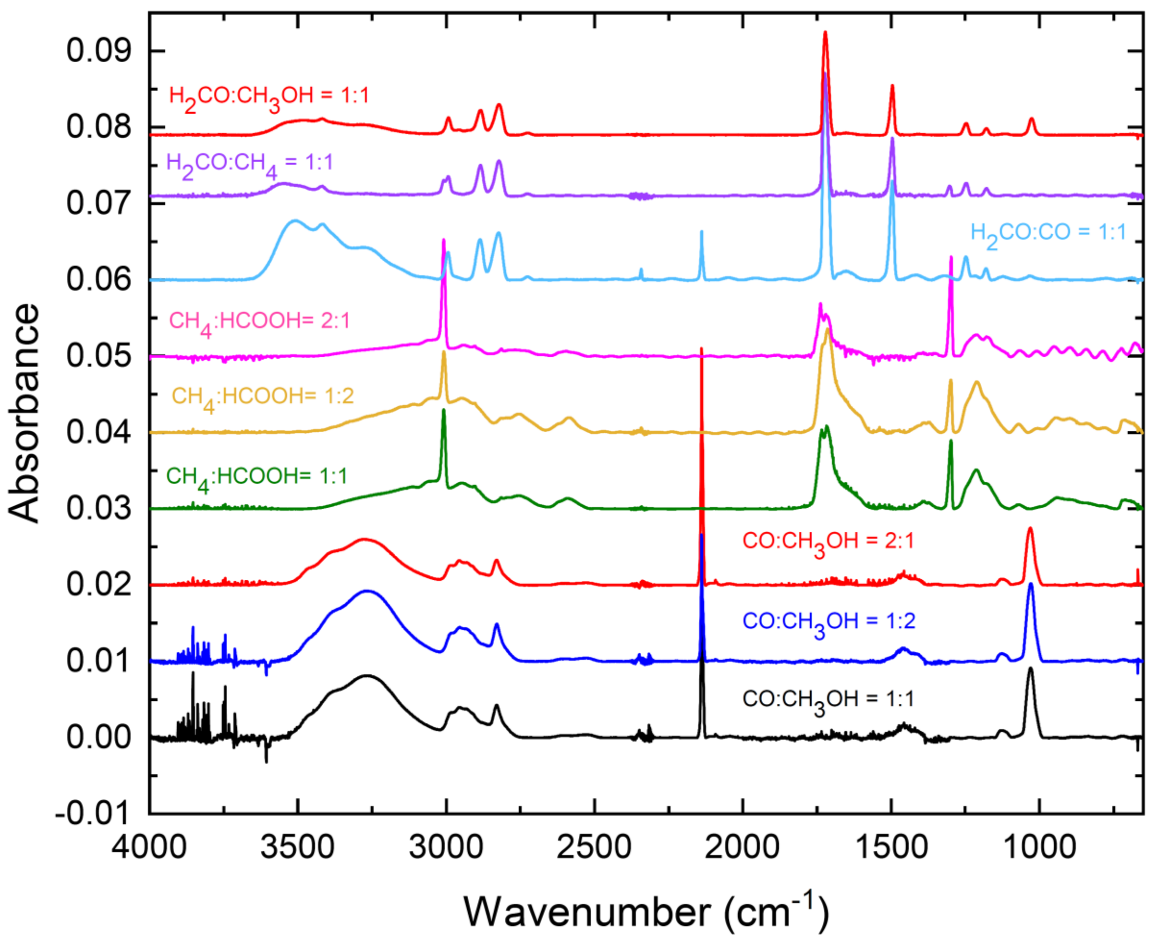
No.	Experiments	T_{sample} (K)	Ratio ($CO:CH_3OH$)	$Flux_{(CO+CH3OH)}$ ($cm^{-2}s^{-1}$)	$Flux_H$ ($cm^{-2}s^{-1}$)	$Flux_{UV}$ ($cm^{-2}s^{-1}$)	Time (s)
1	$CO + CH_3OH + H$	14	4:1	1.2E13	6.0E12	–	3600
2	$CO + CH_3OH + h\nu$	14	4:1	1.2E13	–	4.0E12	3600
3	$CO + CH_3OH + H + h\nu$	14	4:1	1.2E13	6.0E12	4.0E12	3600
No.	Control experiments	T_{sample} (K)	Ratio ($CO:CH_3OH$)	$Flux_{(CO+CH3OH)}$ ($cm^{-2}s^{-1}$)	$Flux_H$ ($cm^{-2}s^{-1}$)	$Flux_{UV}$ ($cm^{-2}s^{-1}$)	Time (s)
1.1	$CO + CH_3OH + H_2$	14	4:1	1.2E13	–	–	3600
1.2	$CO + CH_3OH + H$	14	4:1	2.0E12	1.0E12	–	21600
1.3	$CO + CH_3OH + H$	14	4:1	2.0E12	6.0E12	–	21600
3.1	$CO + CH_3OH + H_2$	14	4:1	1.2E13	–	–	3600
3.2	$CO + CH_3OH + H_2(100\%) + h\nu$	14	4:1	1.2E13	–	4.0E12	3600
3.3	$CO + CH_3OH + H_2(70\%) + h\nu$	14	4:1	1.2E13	–	4.0E12	3600
4.1	$CO + CH_3OH + Ar(100\%) + h\nu$	14	4:1	1.2E13	–	4.0E12	3600
4.2	$CO + CH_3OH + Ar(70\%) + h\nu$	14	4:1	1.2E13	–	4.0E12	3600
4.3	$CO + CH_3OH + Ar(30\%) + h\nu$	14	4:1	1.2E13	–	4.0E12	3600

Chuang *et al.*, MNRAS (2017)

Formation of MF Isomers in space

Ices + 0.2 & 1 MeV H^+ / 1 keV e^-

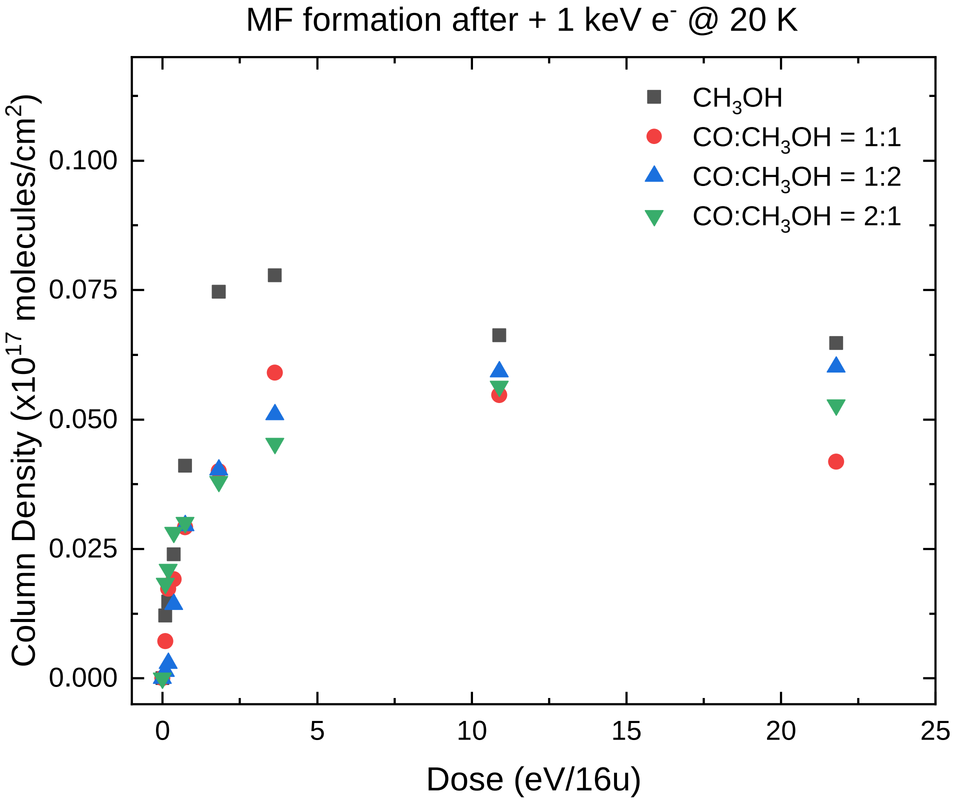


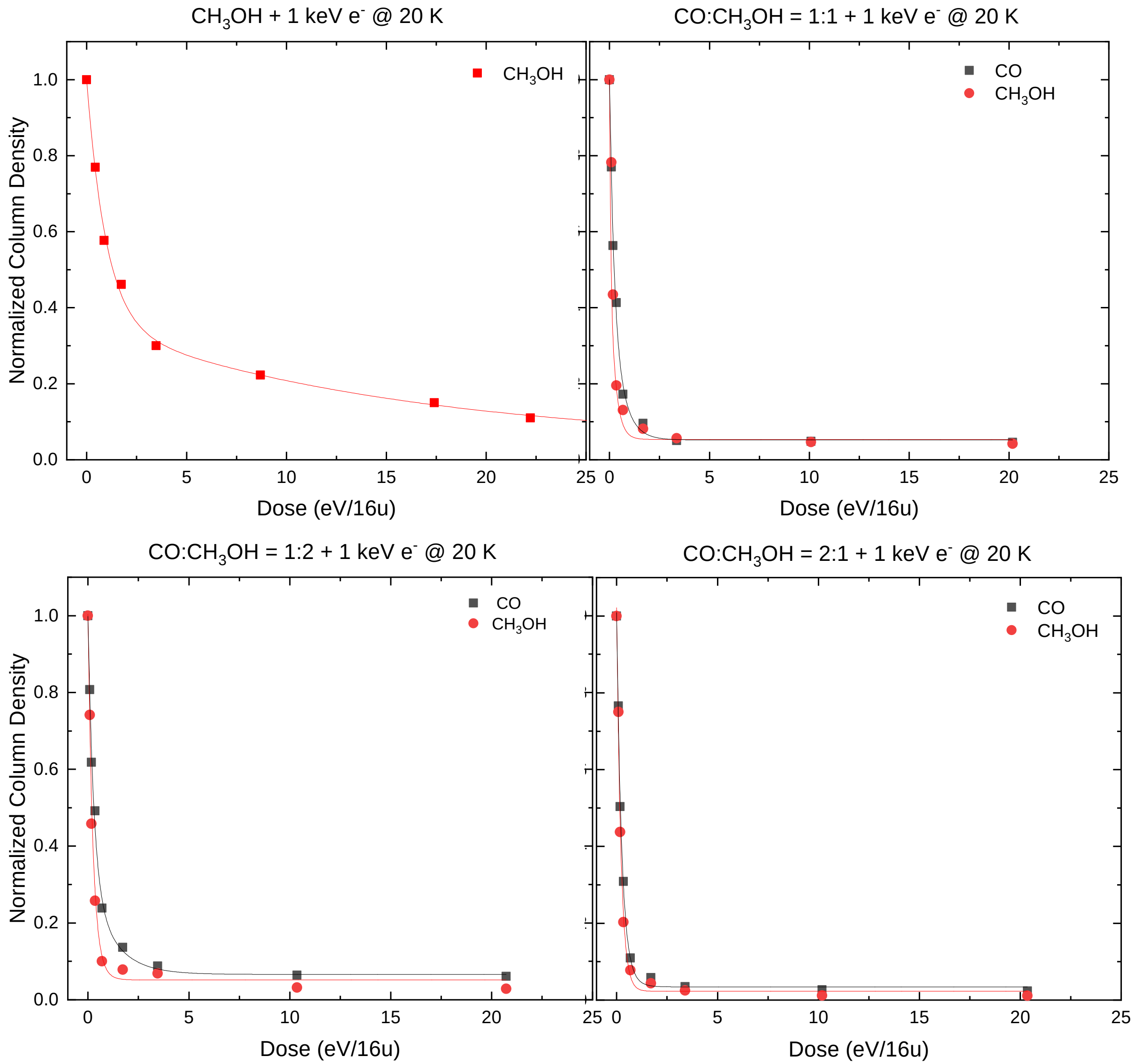


Traspas Muina et al., *in prep.*

Formation of MF Isomers in space

MeOH-rich + 1 keV e⁻

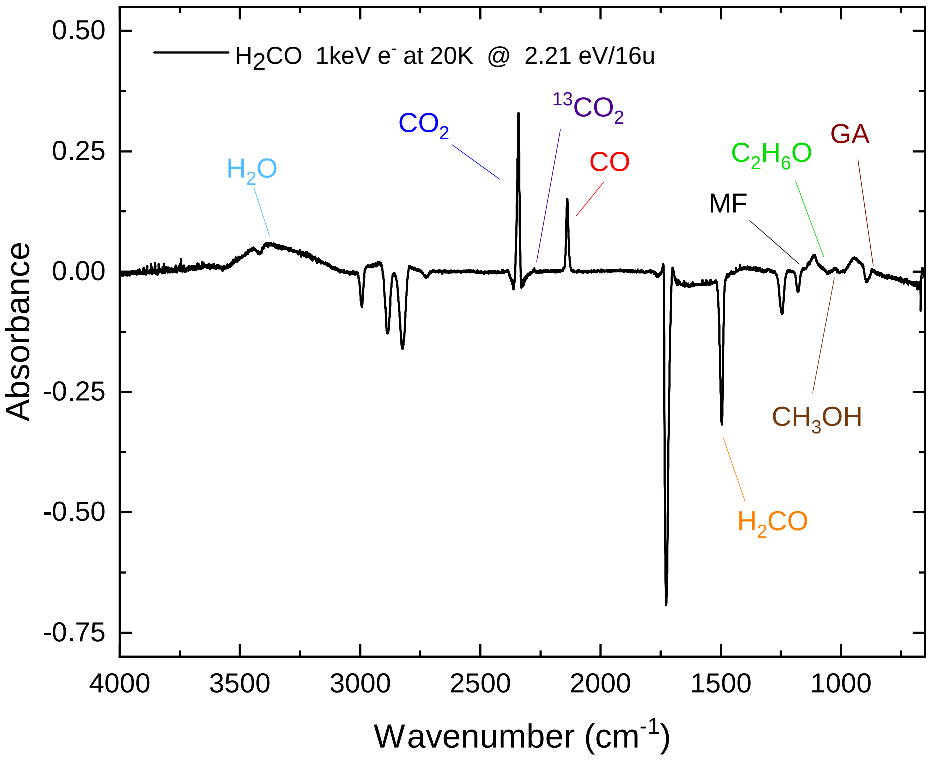


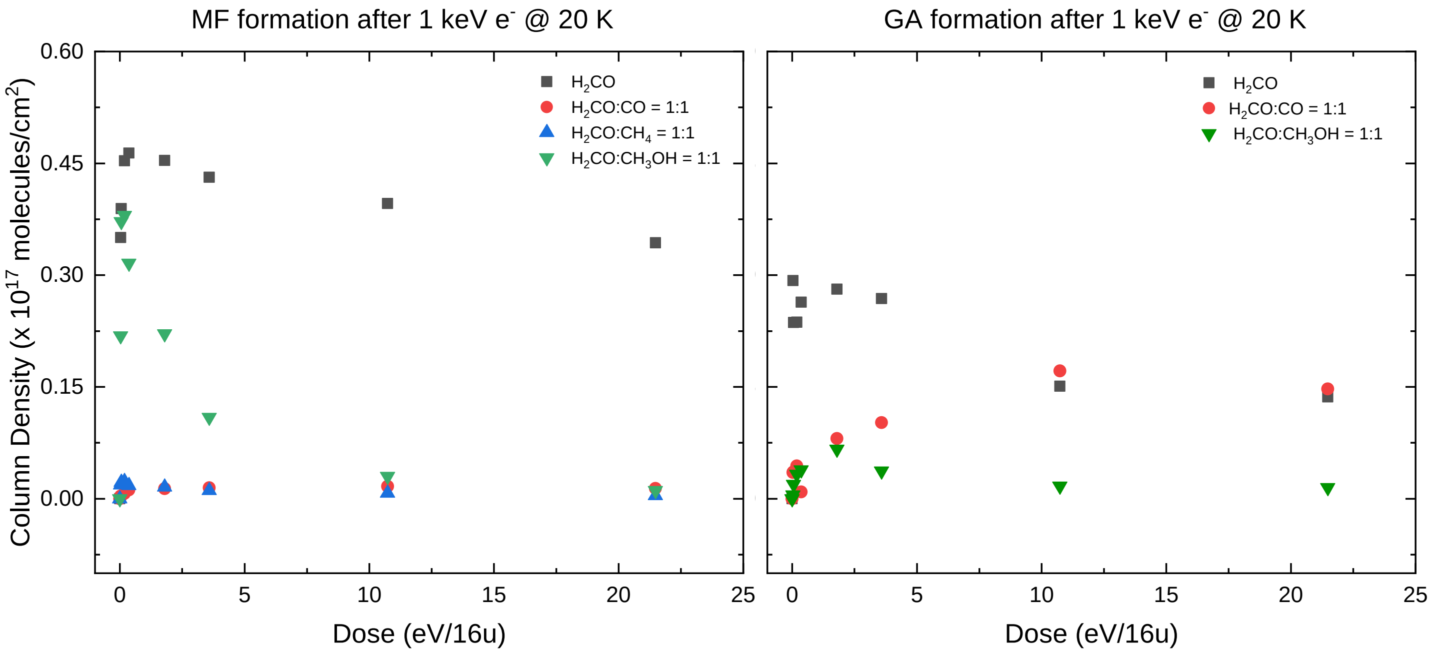


Traspas Muina et al., *in prep.*

Formation of MF Isomers in space

H_2CO-rich + 1 keV e^-

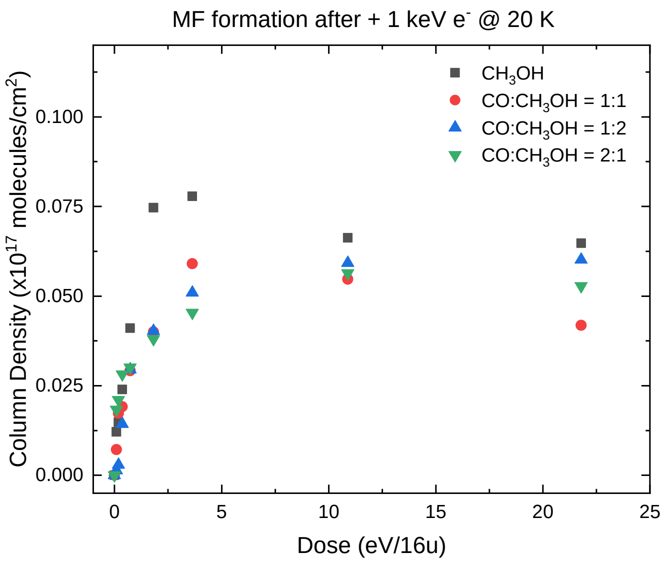


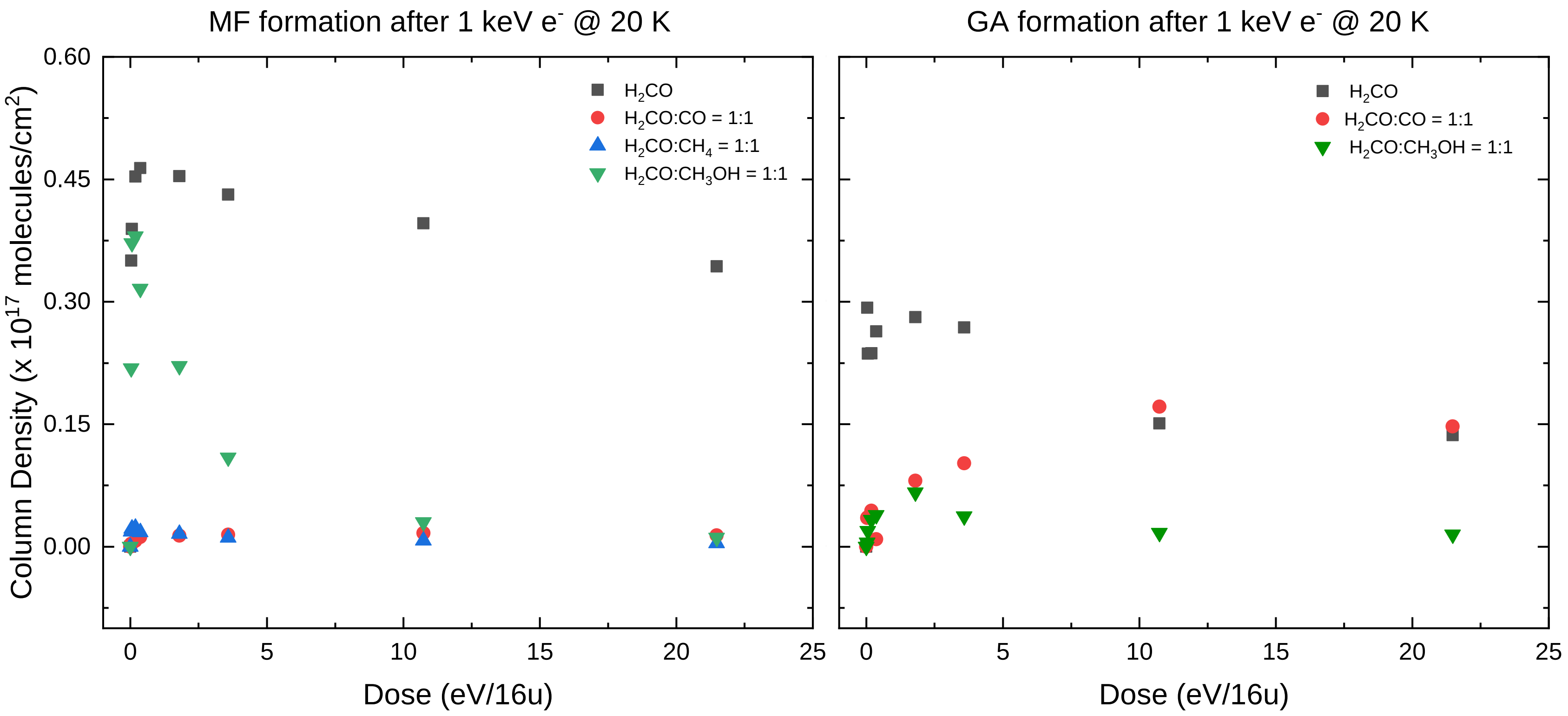


Traspas Muina et al., *in prep.*

Formation of MF Isomers in space

H_2CO-rich + 1 keV e^-

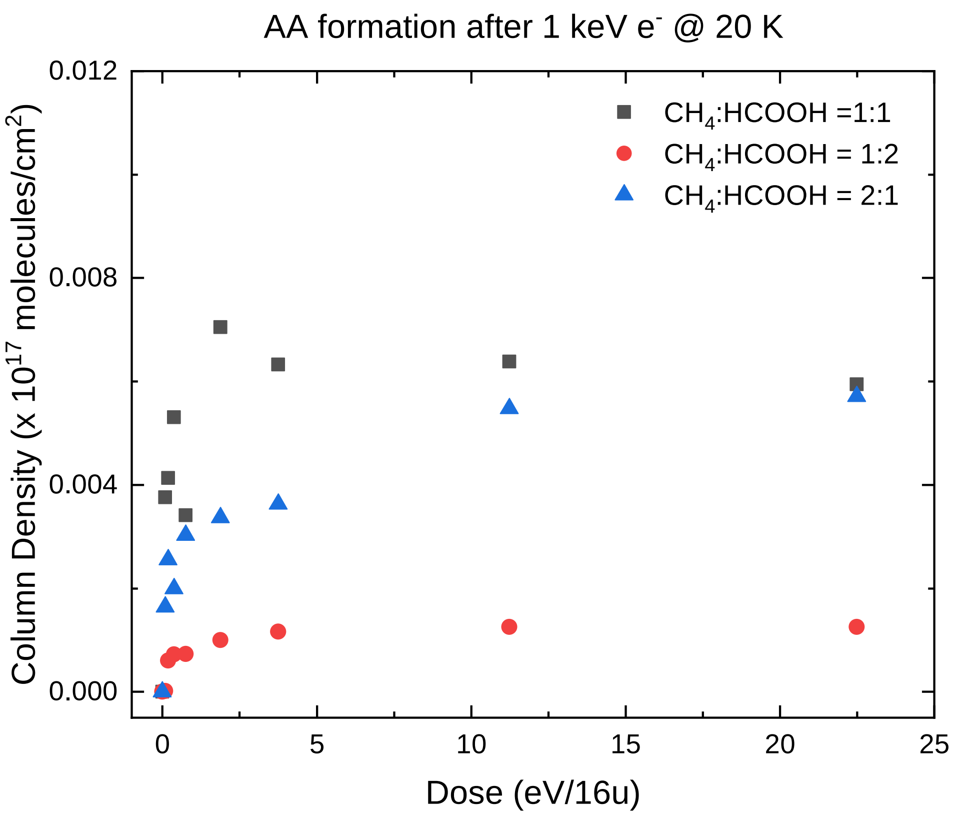


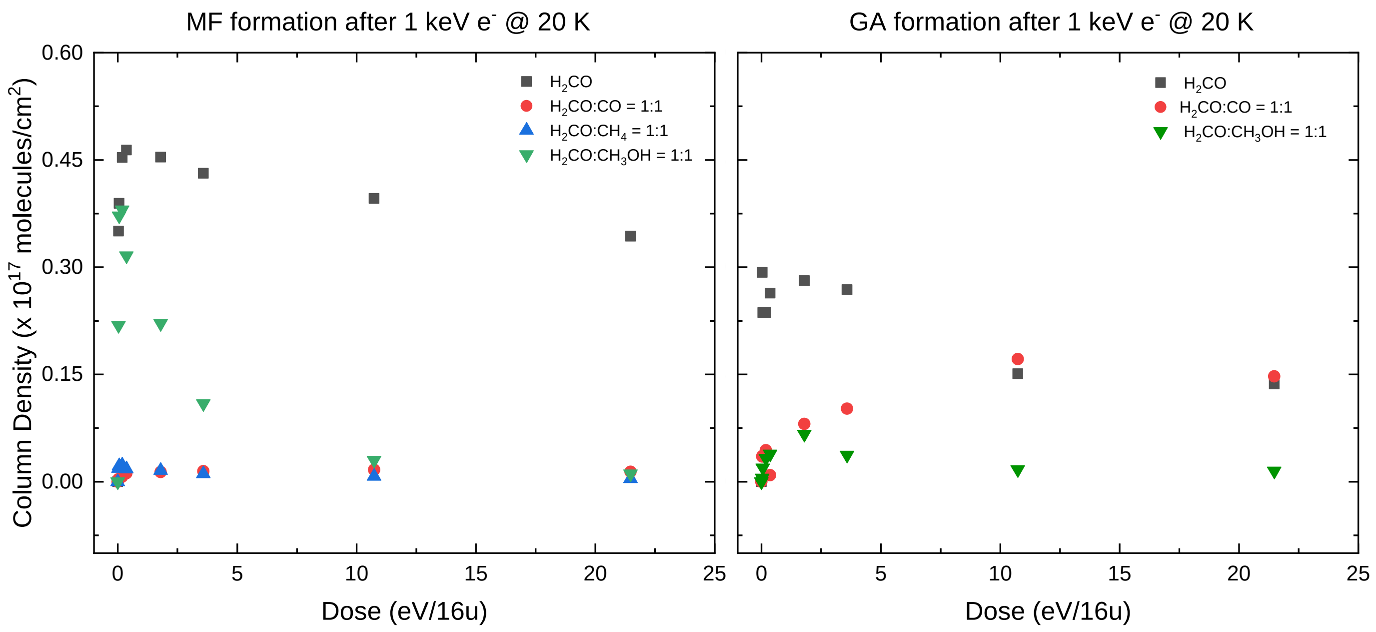


Traspas Muina et al., *in prep.*

Formation of MF Isomers in space

CH_4:HCOOH + 1 keV e^-





Observed MF-AA and MF-GA correlations probably due to warm surface and gas phase chemistry

Balucani et al. (2015); Ascenzi et al. (2019); Garrod et al. (2022)

Traspas Muina et al., *in prep.*

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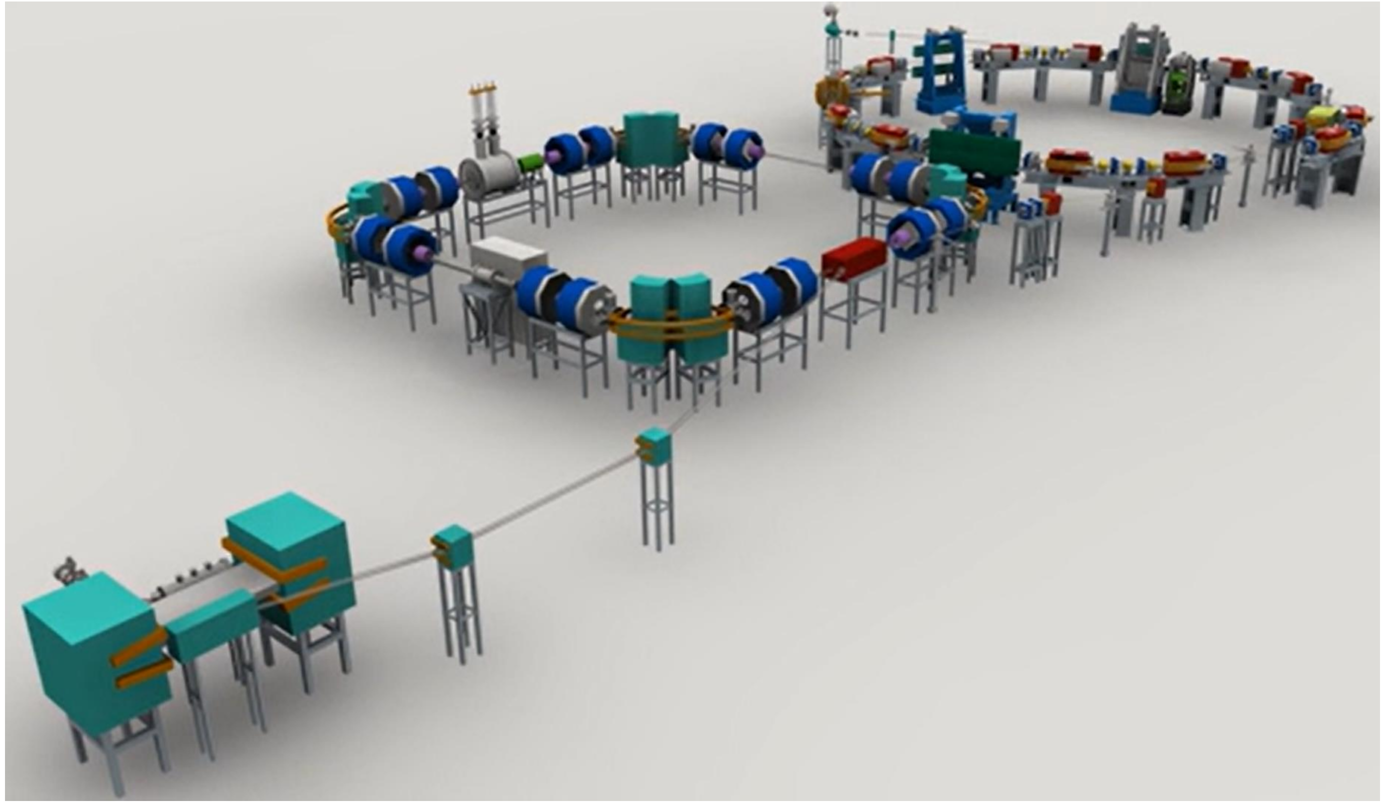
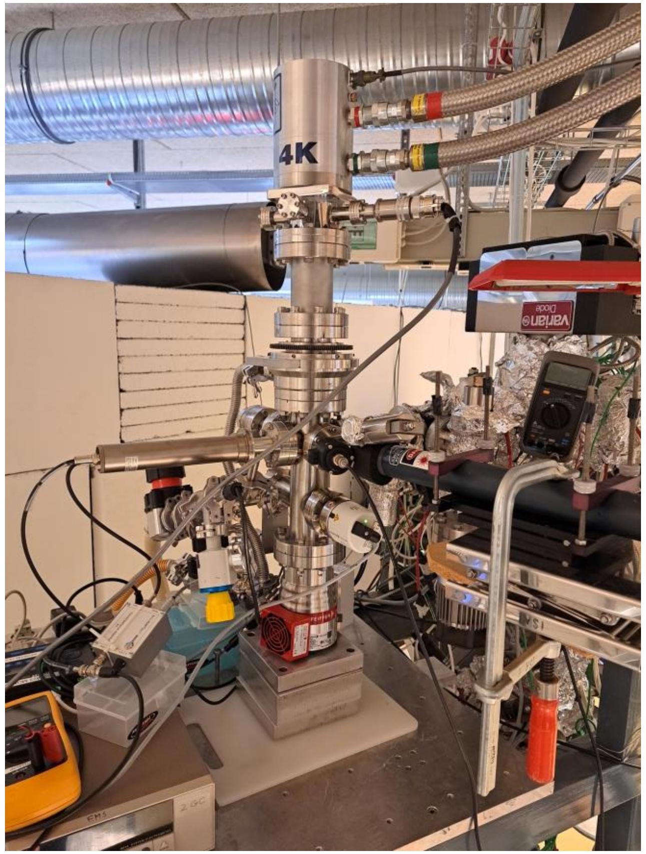
ASTRID^2



ISA

Ice Chamber (IC)

VUV and UV-vis spectroscopy of ices and electron irradiation



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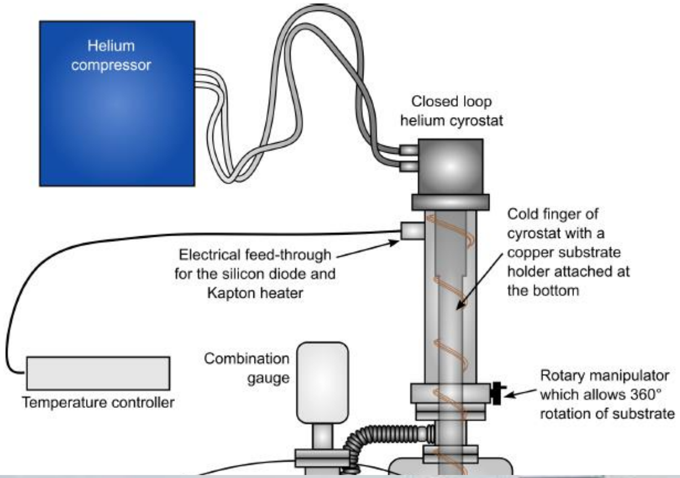
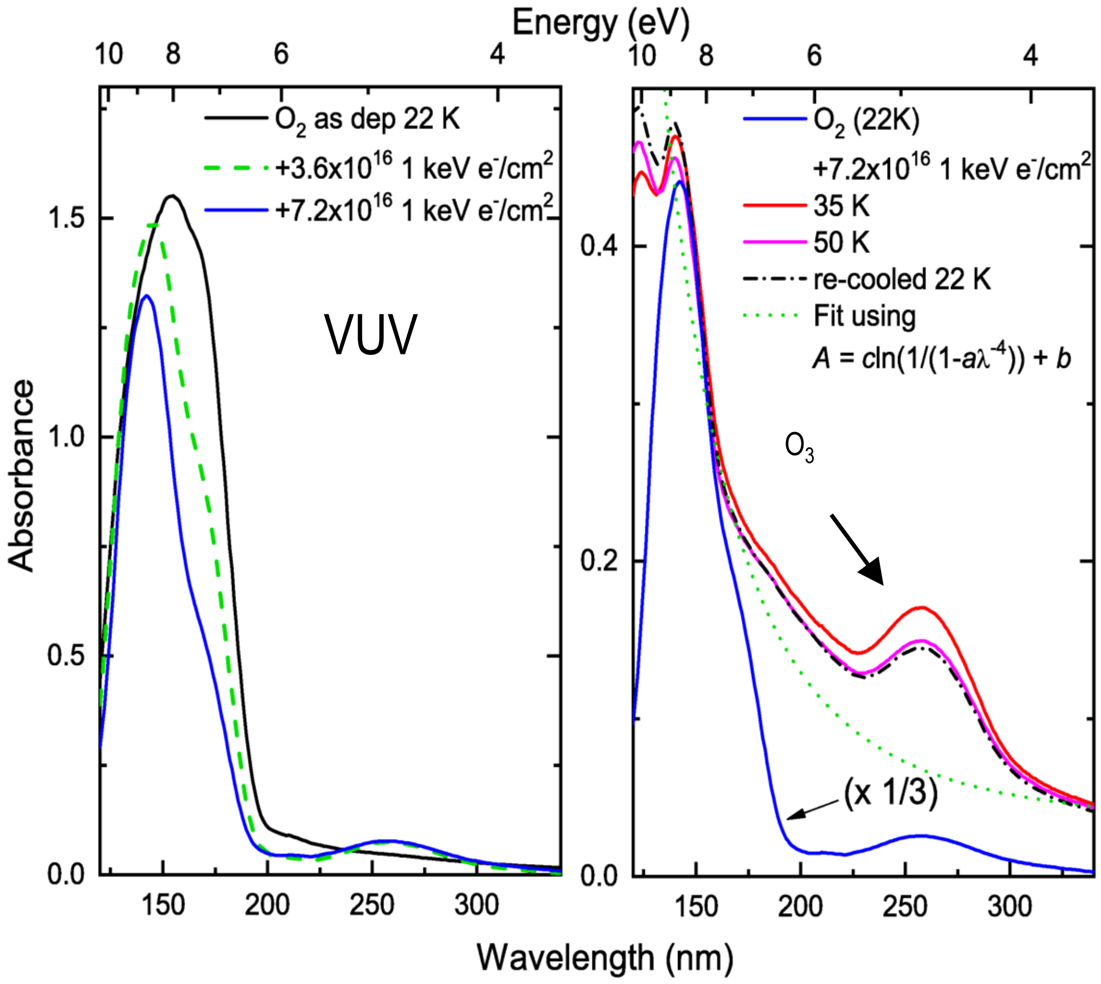
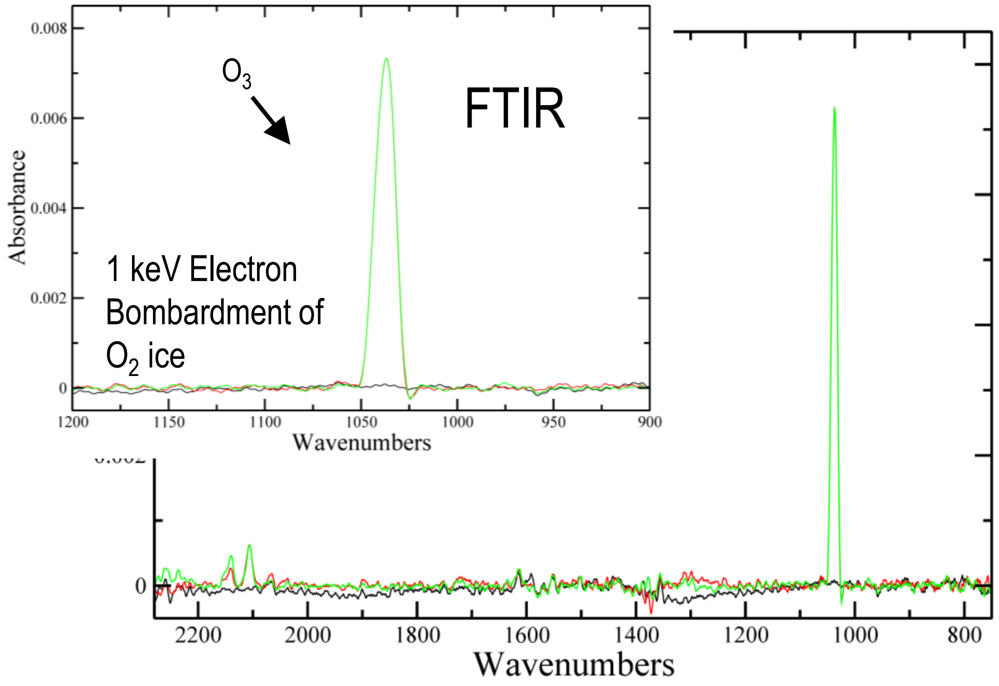


VUV vs IR Spectroscopy



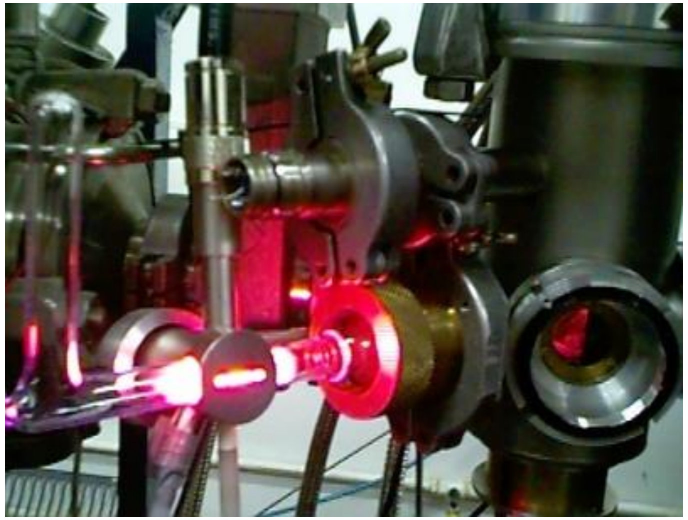


Ioppolo et al., *A&A* (2020)

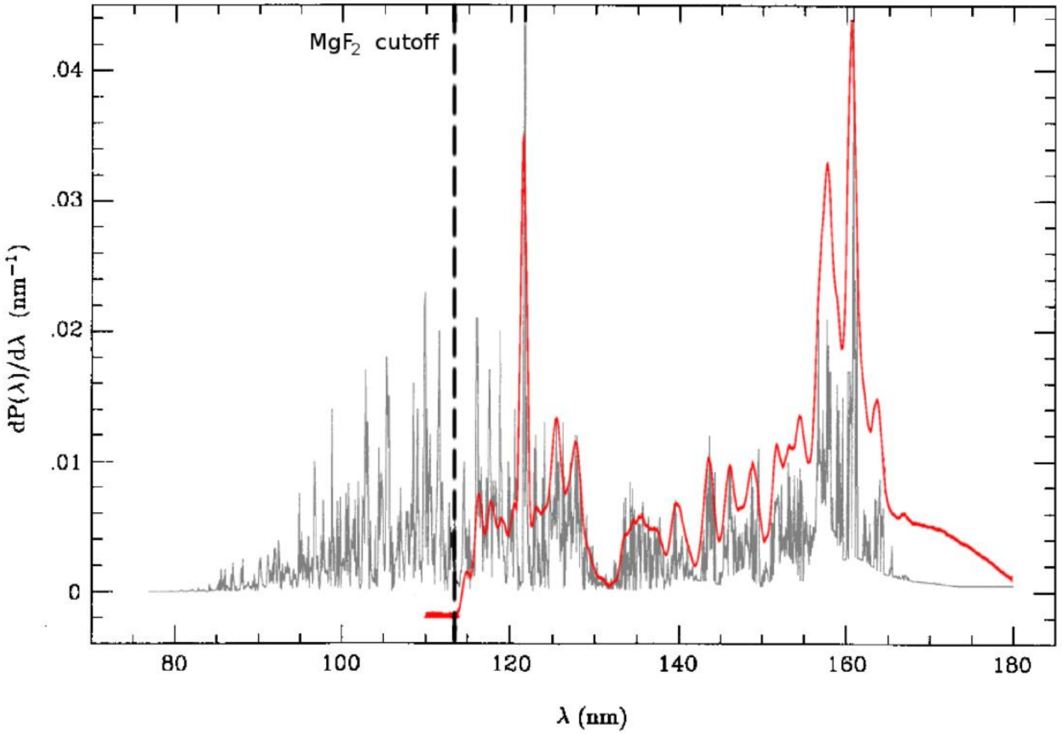
VUV ice Database

A comprehensive large VUV/UV-vis ice database to

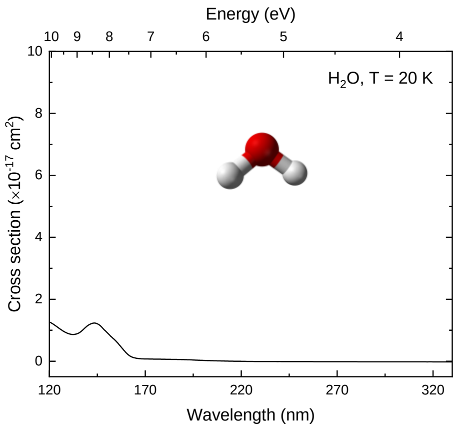
- Identify simple & complex molecules (e.g., prebiotic species) in the Solar System.
- Aid the study of UV photoprocesses.

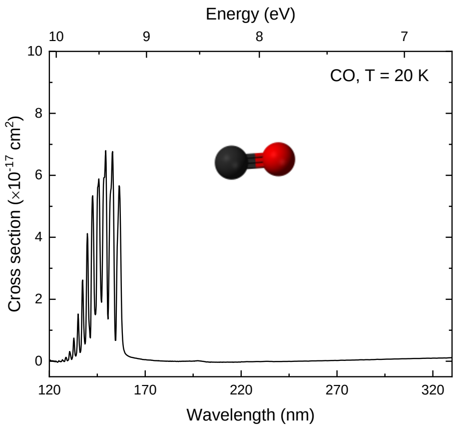


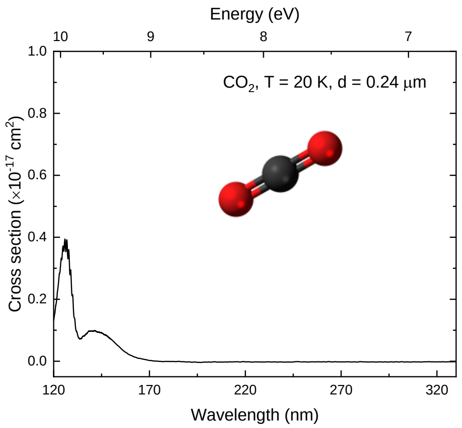
LASP INAF-Catania

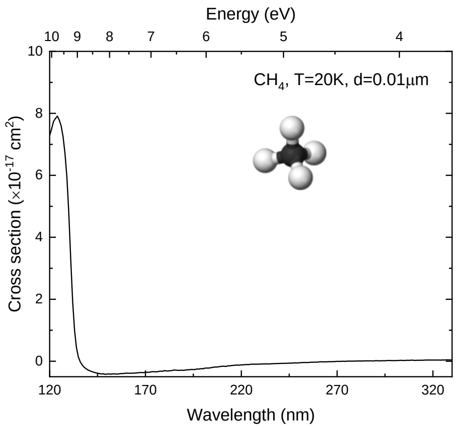


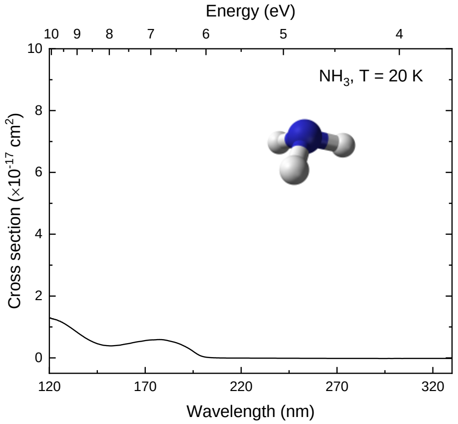
VUV ice Database

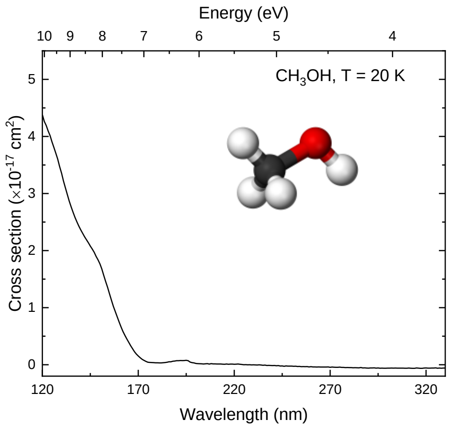


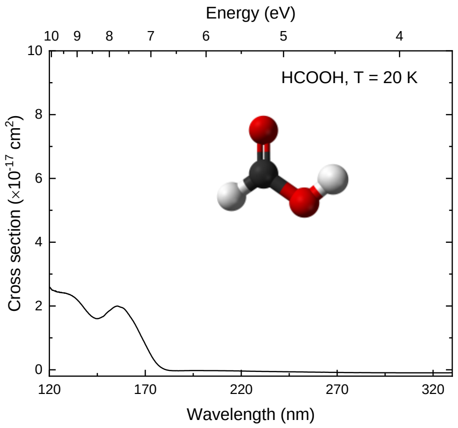


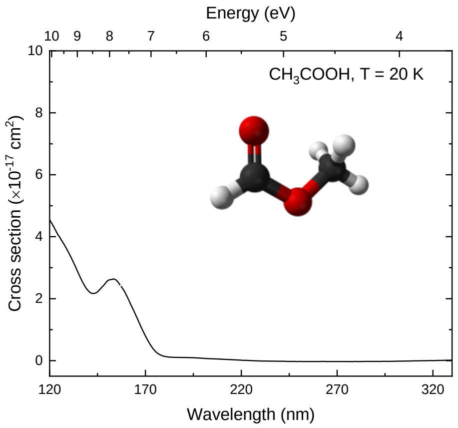






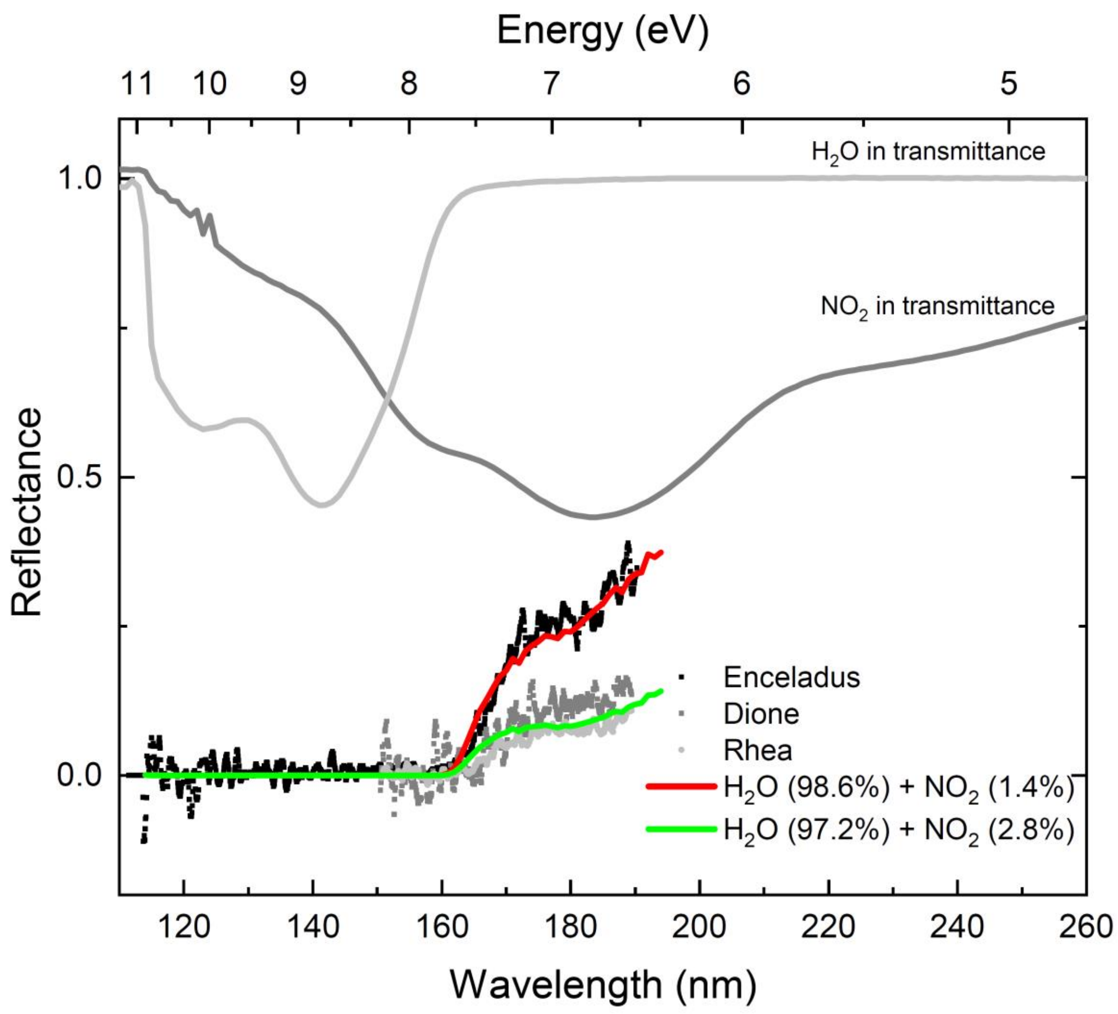


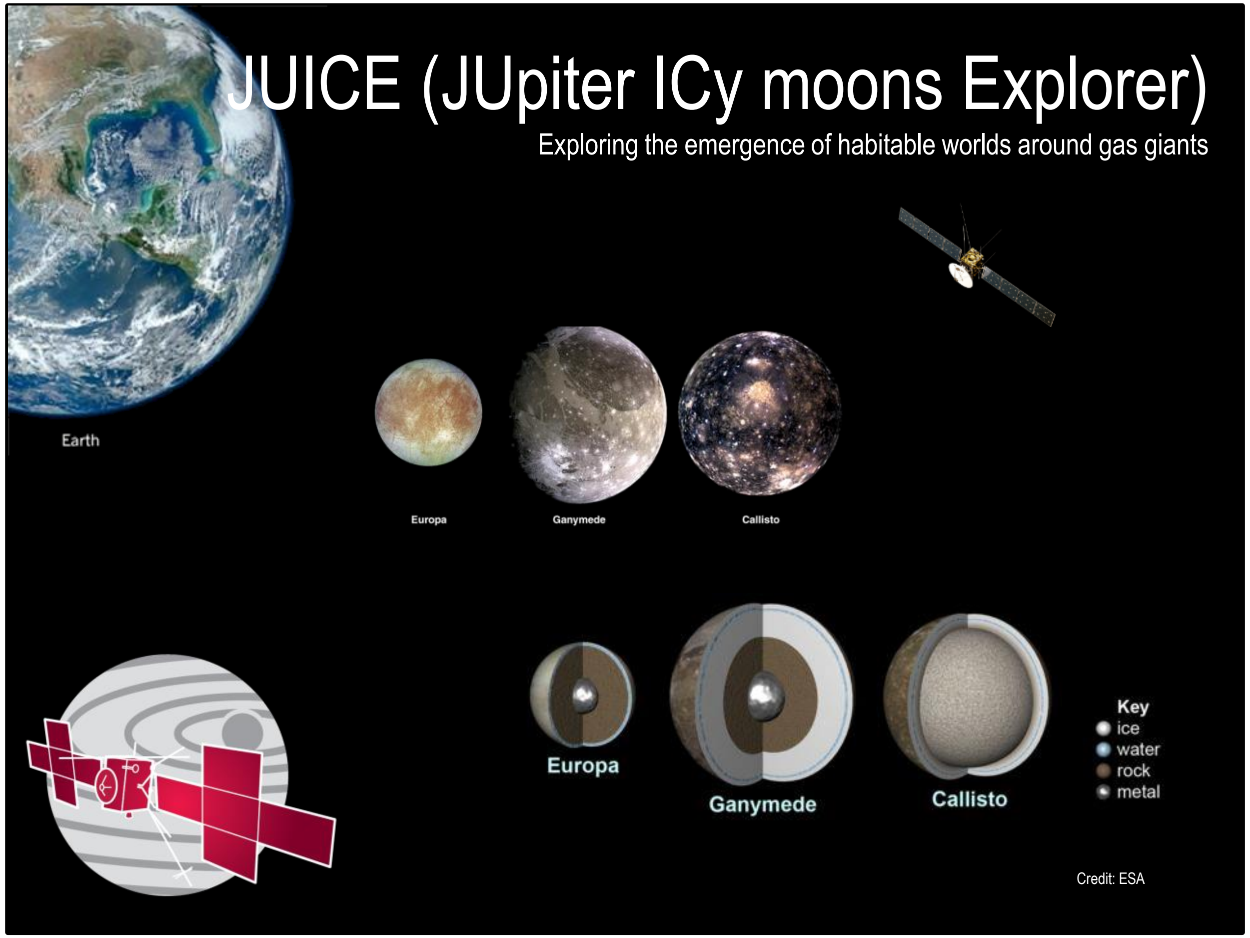




Traspas Muiña *et al.*, in prep.

Ices in the Solar System

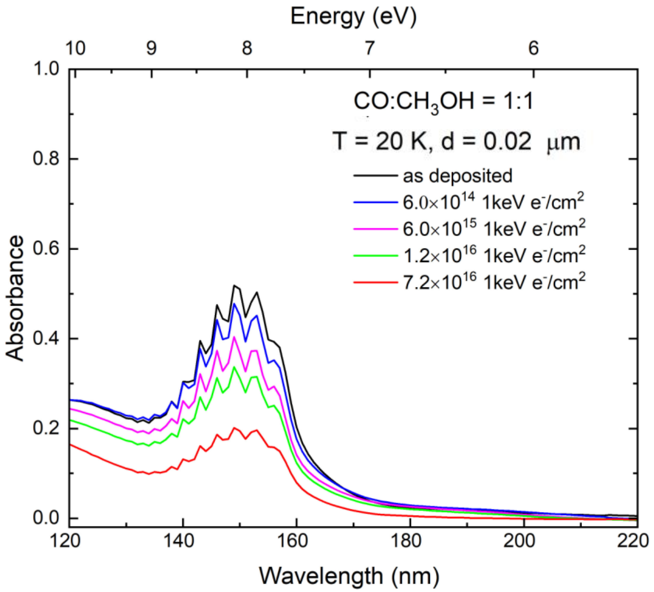


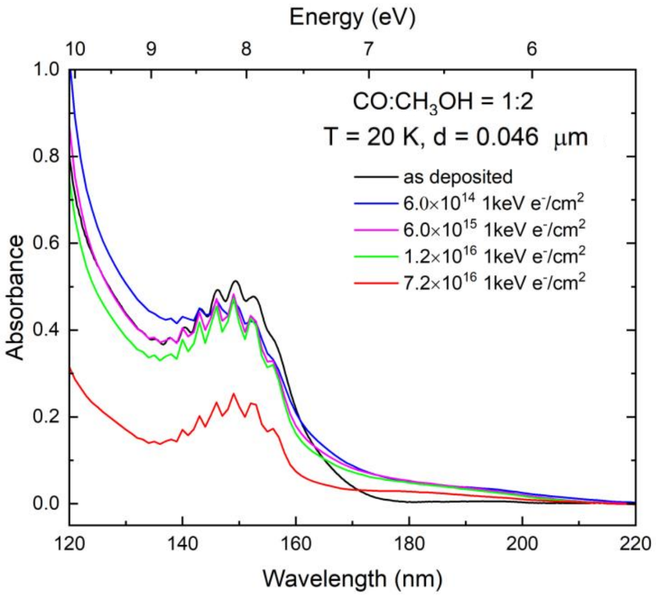


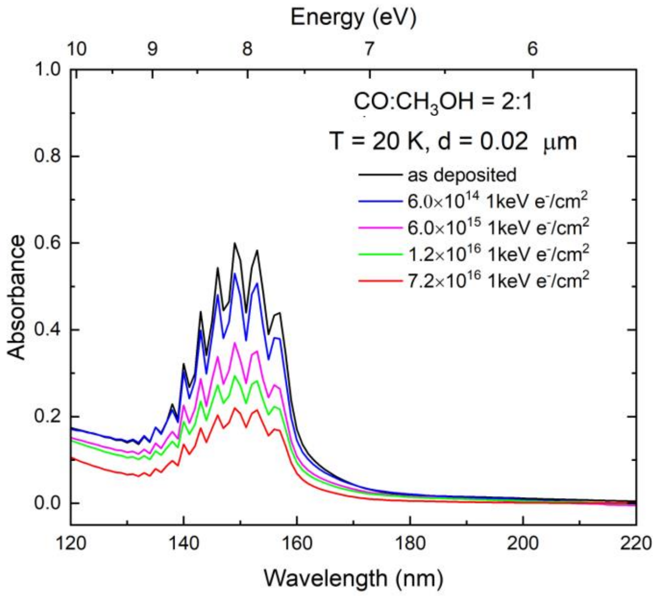
Ioppolo et al., *A&A* (2020)

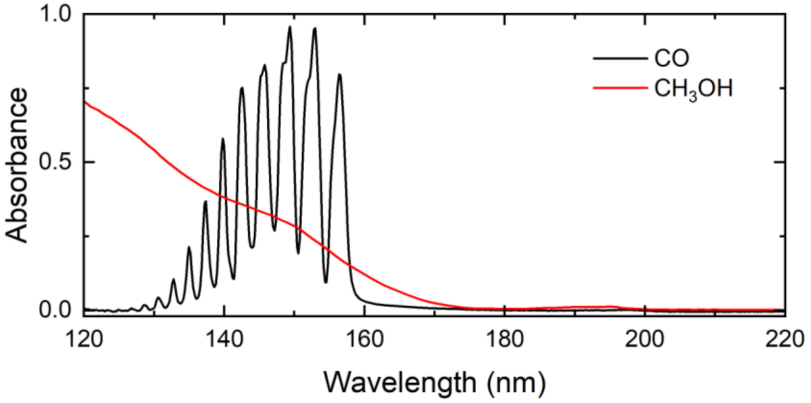
Formation of MF Isomers in space

MeOH-rich + 1 keV e^-









Traspas Muina et al., *in prep.*

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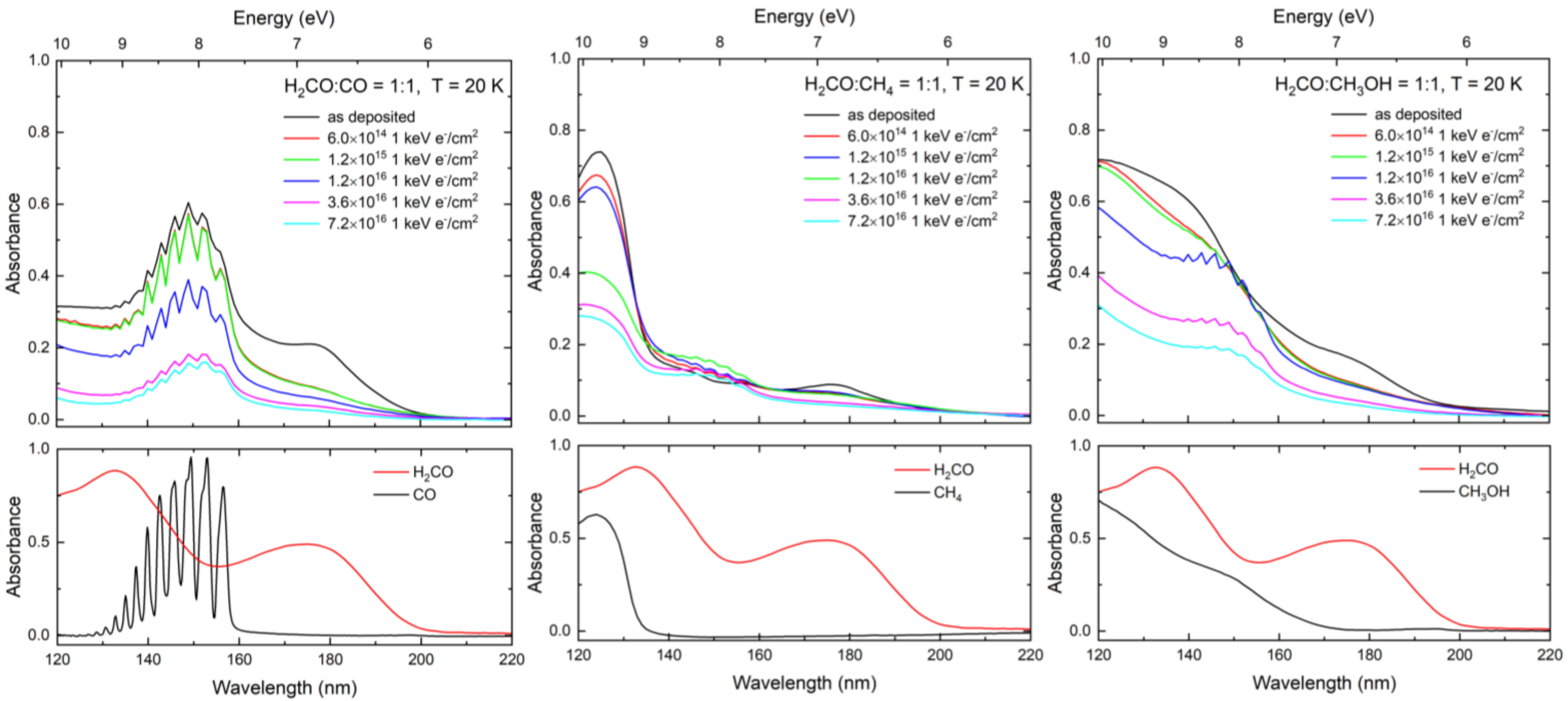

Traspas Muina et al., *in prep.*

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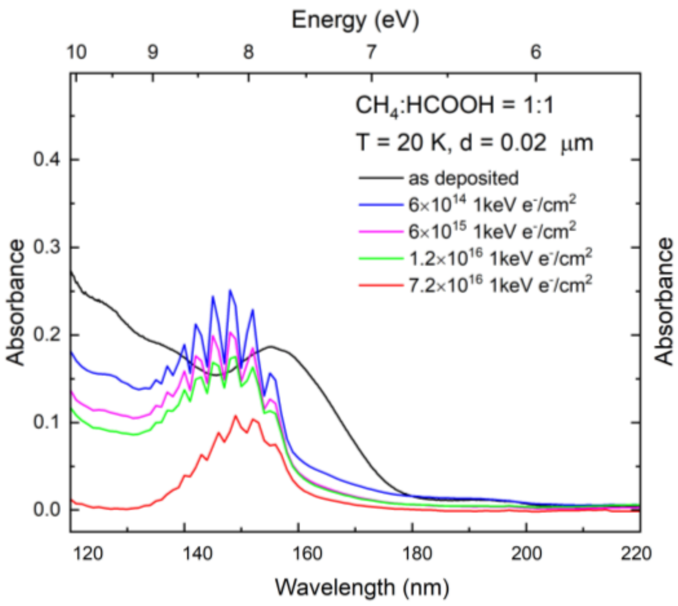
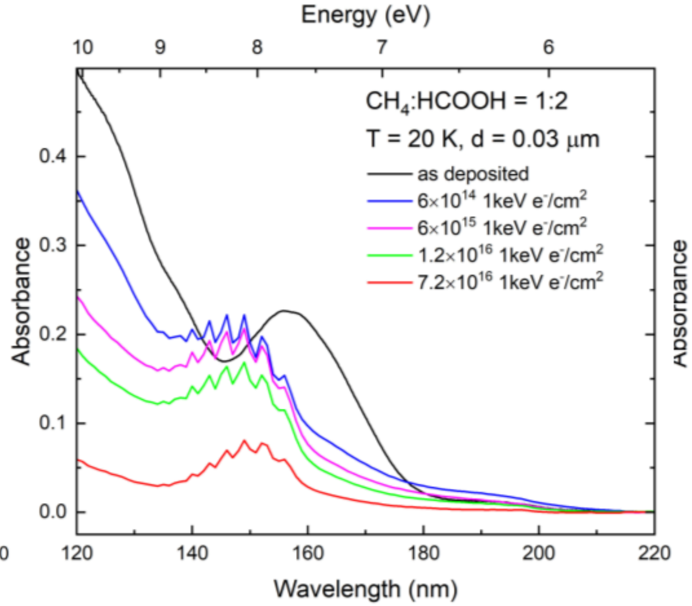
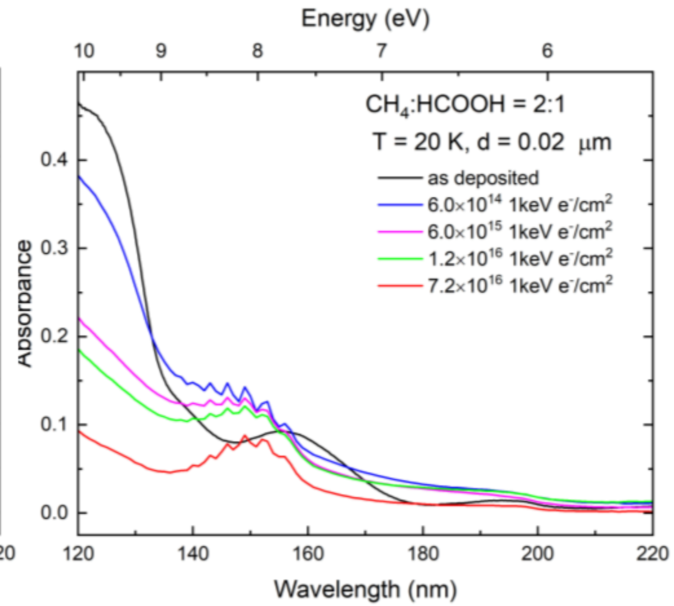
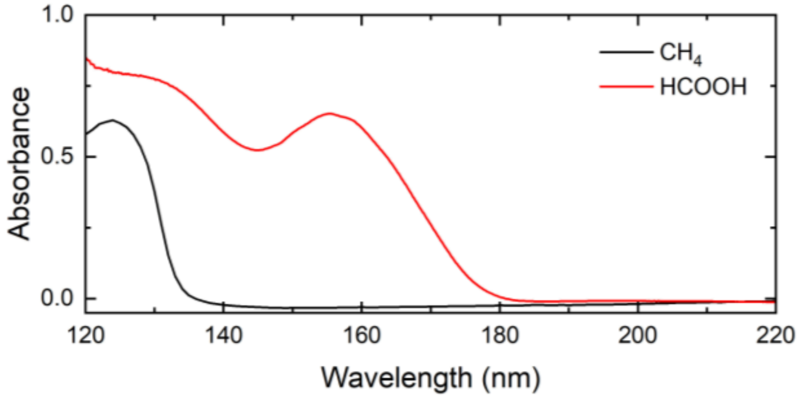
CH_4:HCOOH + 1 keV e^-









Traspas Muina et al., *in prep.*

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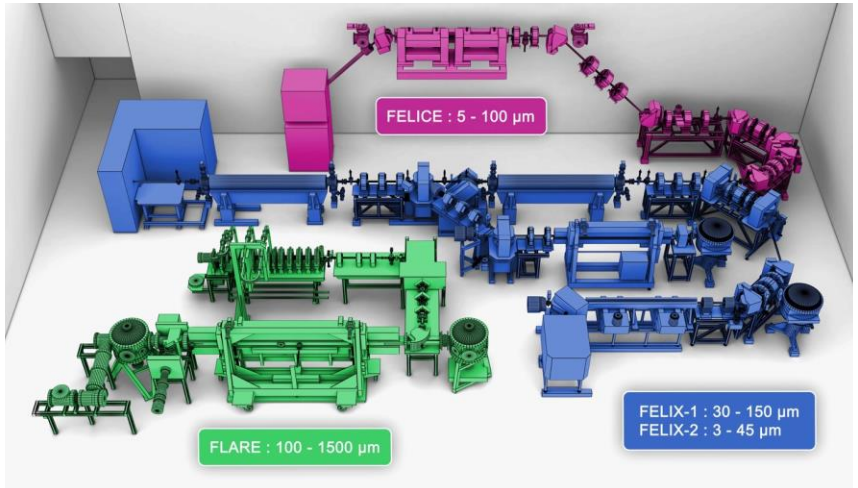
HFML-FELIX

Radboud Universiteit Nijmegen

FELIX
Free Electron Lasers for Infrared eXperiments

Radboud University
Nijmegen, The Netherlands



Lab Ice Surface Astrophysics (LISA)

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HFML
Science in High Magnetic Fields

FELIX
Free Electron Lasers for Infrared eXperiments

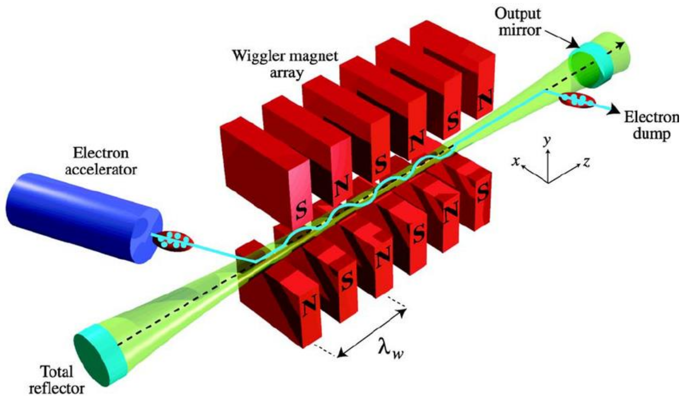
End Station at FEL-1 & FEL-2 (2.7 – 150 μm):

UHV Chamber (P = 1x10^{-10} mbar T = 8 - 450 K)

Analytical Tools (FTIR & QMS)

Sample Manipulation (Rotation + XYZ)

Source (5 keV electron gun)



Wide tunability

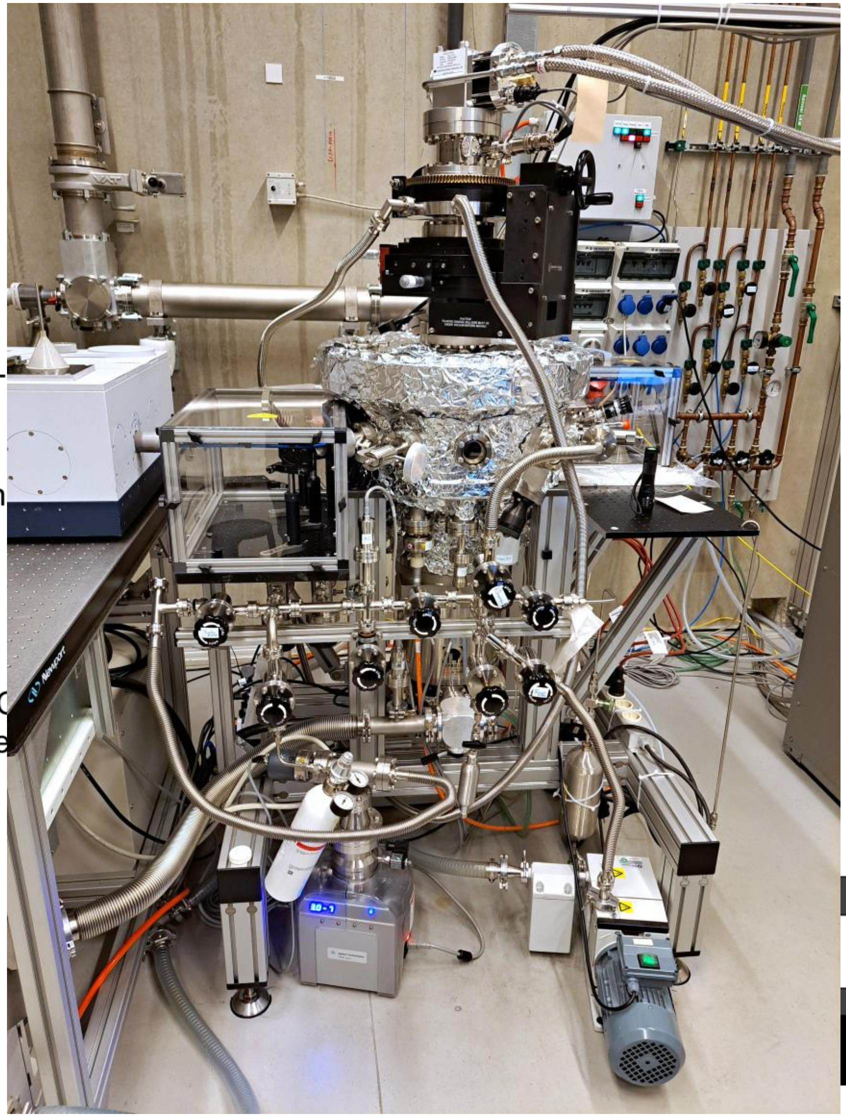
High intensity

Ultrashort pulses

Dosing L

5 keV
electron gun

MC
Dete



Lab Ice Surface Astrophysics (LISA)

LISA is open to internal and external users:

Selective IRFEL-induced Changes in Ices

Simulating: IR radiation, exothermic surface reactions, CRs heating, ice grain collisions, and shocks

Selective IR-induced Phase Changes in Ices (India)

Selective IR-induced Diffusion of Molecules (UK)

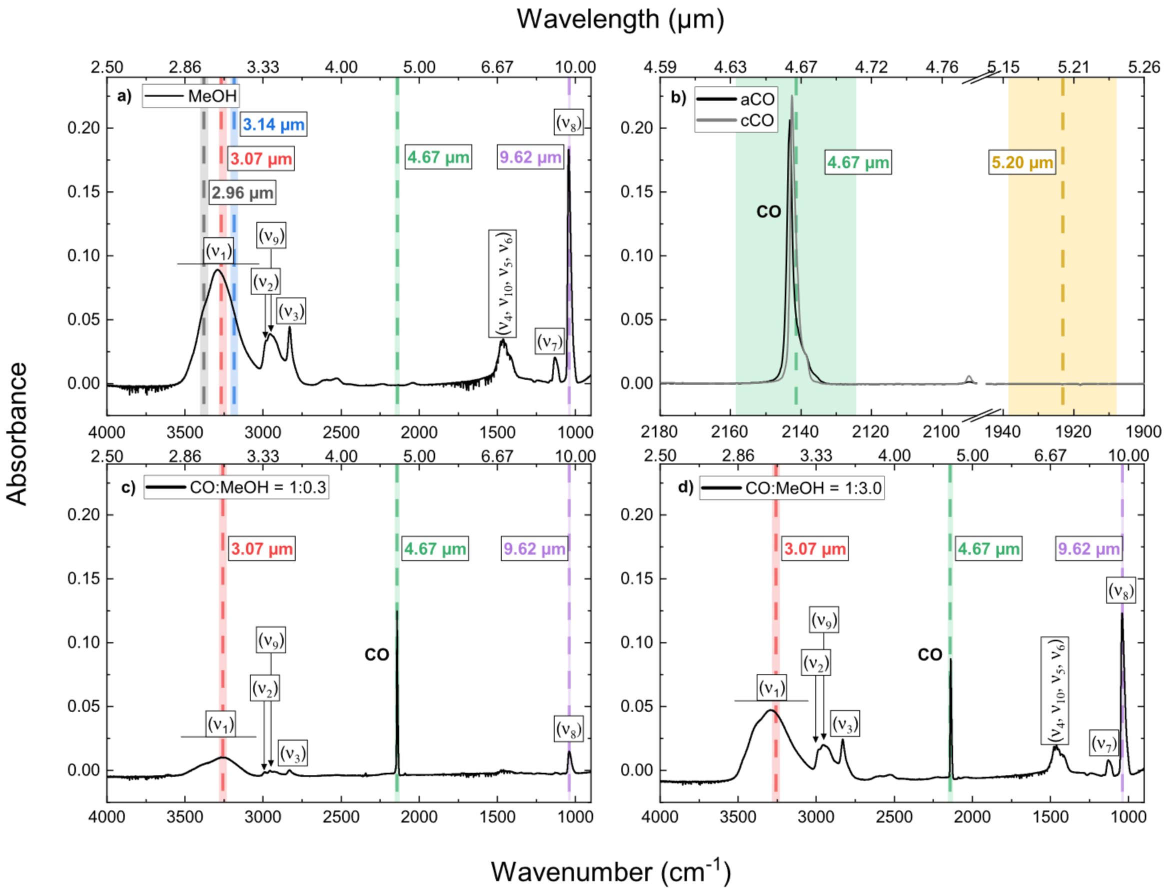
Desorption Induced upon Vibrational Excitation (NL)

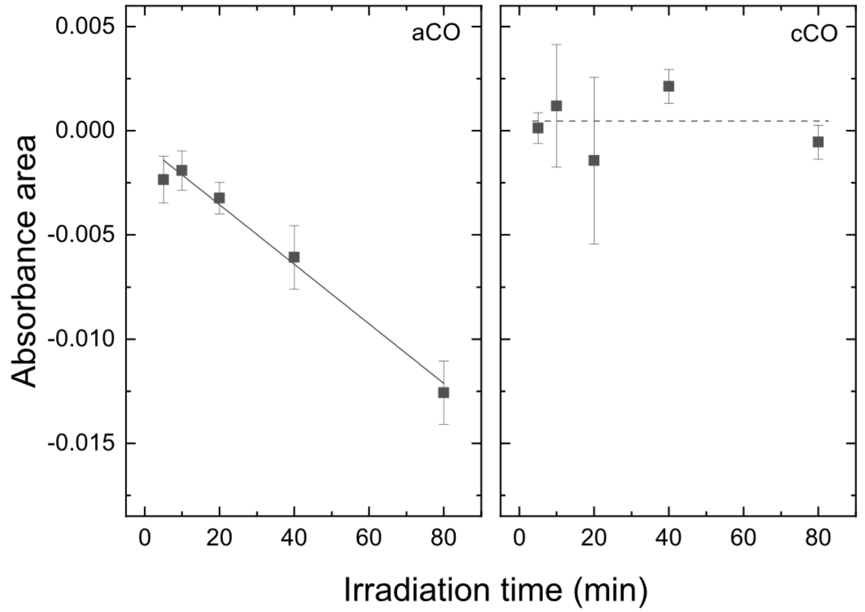
Selective IR-induced Chemistry in PAHs (DK)

INTERCAT Center for Interstellar Catalysis
Danmarks Grundforskningsfond Danish National Research Foundation
HFML Science in High Magnetic Fields
FELIX Free Electron Lasers for Infrared eXperiments
Laserlab Europe
The Royal Society
cost European Cooperation in Science & Technology
Royal Commission for the Exhibition of 1851
Queen Mary University of London
Aix Marseille université
cnrs
FLUENCE Felix Light for the Uk: Exploiting Novel Characteristics and Expertise
EPSRC Engineering and Physical Sciences Research Council

Desorption Mechanisms

IR Photodesorption





Santos et al. (2023)

Desorption Mechanisms

IR Photodesorption

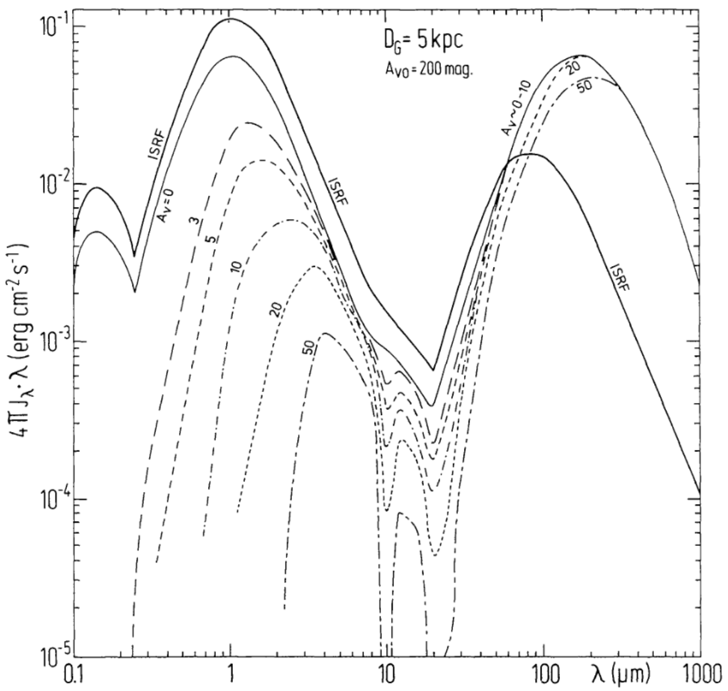


Fig. 4. The radiation field inside a giant molecular cloud, located at $D_G = 5\,\mathrm{kpc}$ and with a visual extinction to its center of $A_{V_0} = 200\,\mathrm{mag}$. ISRF refers to the radiation field at far distances from the cloud, $A_V = 0$ is the radiation field at the surface of the cloud, $A_V = 3$, 5, 10 etc. is the radiation field inside the cloud at distances $A_V = 3$, 5, 10 etc. mag from the surface of the cloud

Table 2. Comparison of the estimated fluxes, desorption rates, and desorption efficiencies of CH_3OH and CO species induced by IR and UV photons.

		Interstellar flux (photons cm^{-2} s^{-1})	Rate (molecules photon^{-1})	Estimated efficiency (molecules cm^{-2} s^{-1})
CO	IR	$>3 \times 10^9$ [a]	$\lesssim(1.1 \pm 0.3) \times 10^{-8}$ [c]	$\sim3.3 \times 10^1$
	UV	$\sim1 \times 10^4$ [b]	$\sim(0.14–8.9) \times 10^{-2}$ [d]	$\sim(1.4–89) \times 10^1$
CH_3OH	IR	$>4 \times 10^8$ [a]	$\lesssim(3 \pm 1) \times 10^{-8}$ [c]	$\sim1.2 \times 10^1$
	UV	$\sim1 \times 10^4$ [b]	$\sim1 \times 10^{-5}$ [e]	$\sim1.0 \times 10^{-1}$

References. [a]Mathis et al. (1983). [b]Cecchi-Pestellini & Aiello (1992). [c]This work. [d]Öberg et al. (2007); Muñoz Caro et al. (2010); Fayolle et al. (2011); Chen et al. (2014); Paardekooper et al. (2016). [e]Bertin et al. (2016); Cruz-Diaz et al. (2016).

Santos et al. (2023)

Conclusions

JWST is revolutionizing our understanding of star formation in the ISM

New systematic and consistent set of lab data are needed!

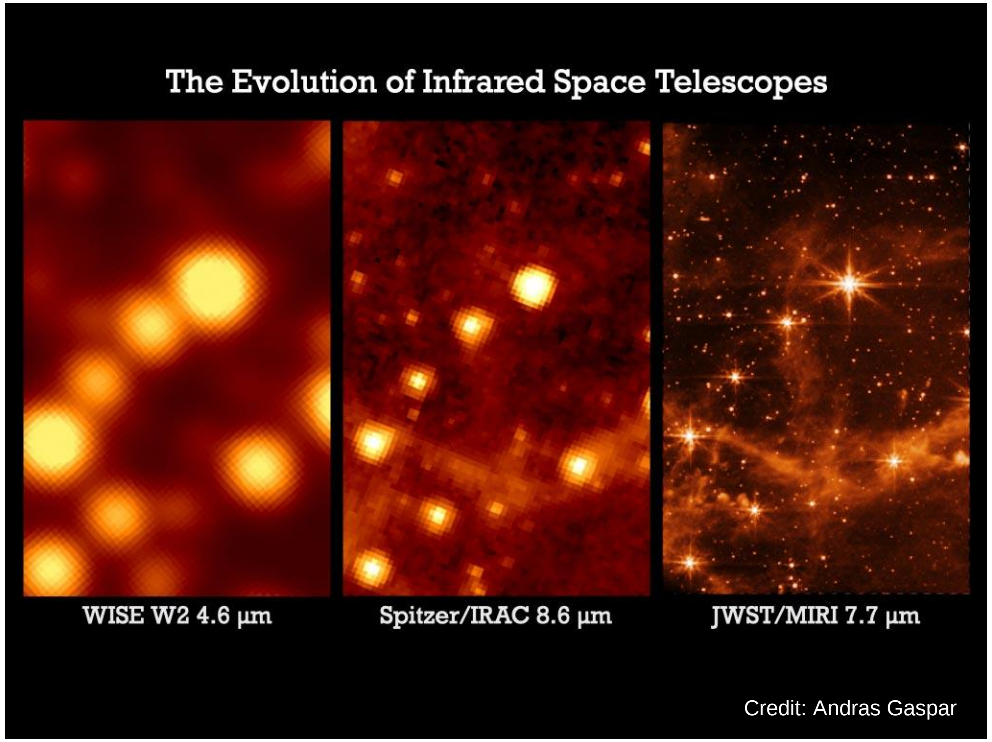
Complementary VUV/IR/THz techniques at large scale facilities can help understand the evolution of ices in space.

External users and new ideas are welcome!

HFML Science in High Magnetic Fields
FELIX Free Electron Lasers for Infrared eXperiments

atomki DEBRECEN

ISA



Acknowledgements

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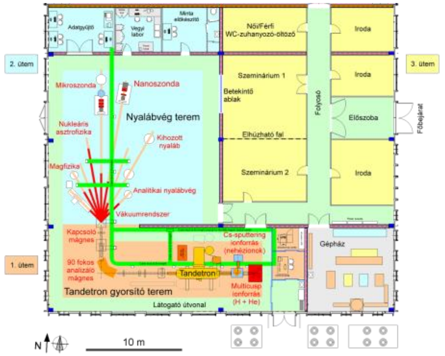
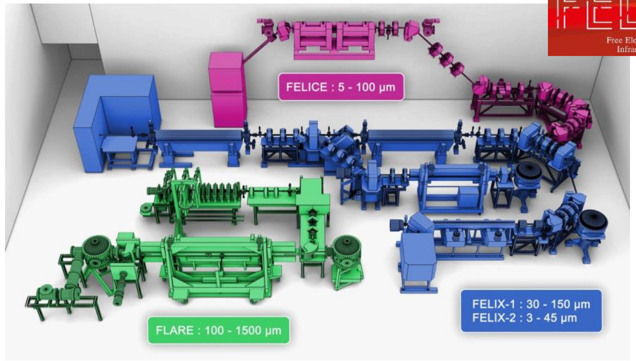
Dr Duncan Mifsud

Dian Schrauwen





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