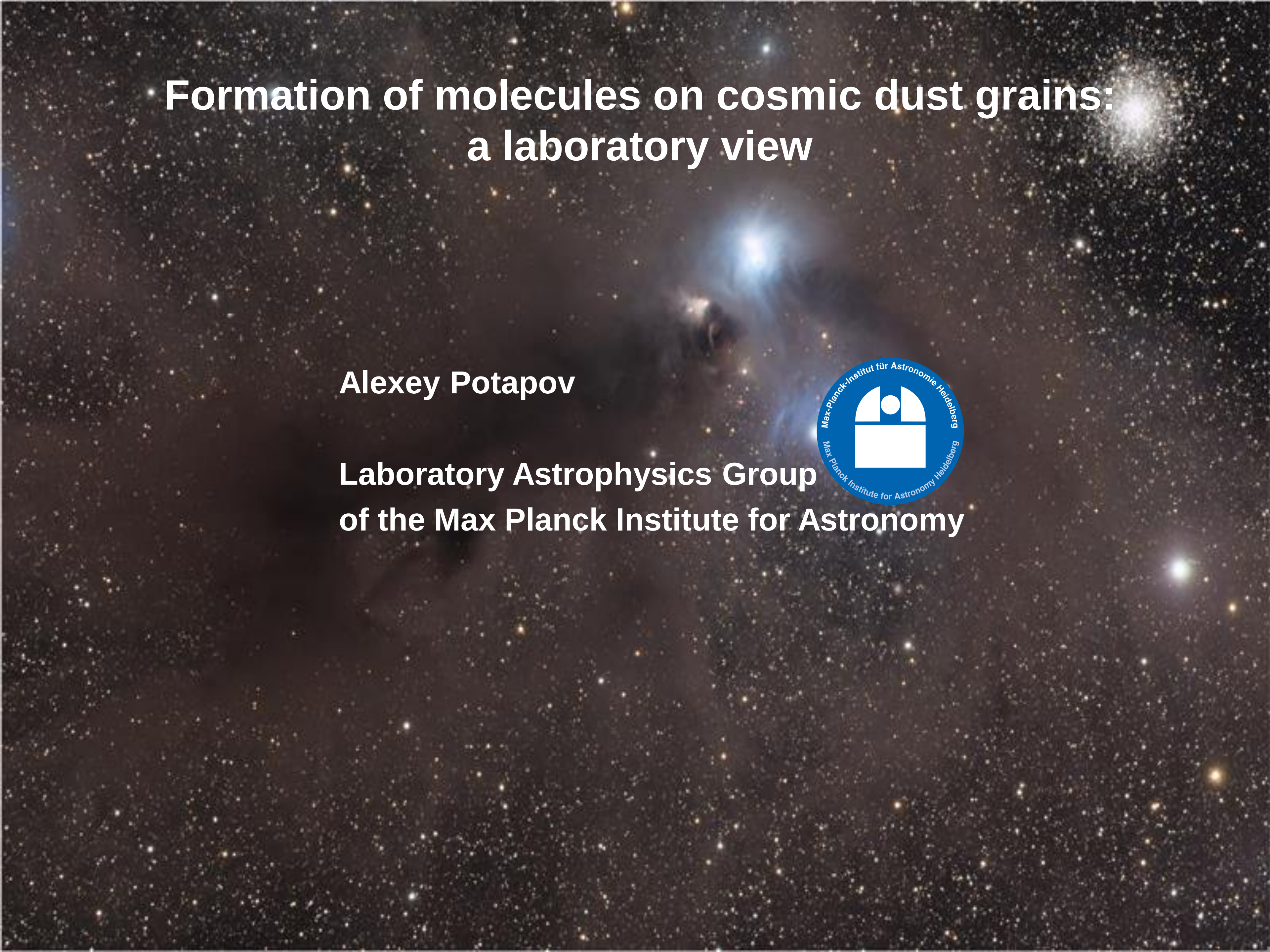


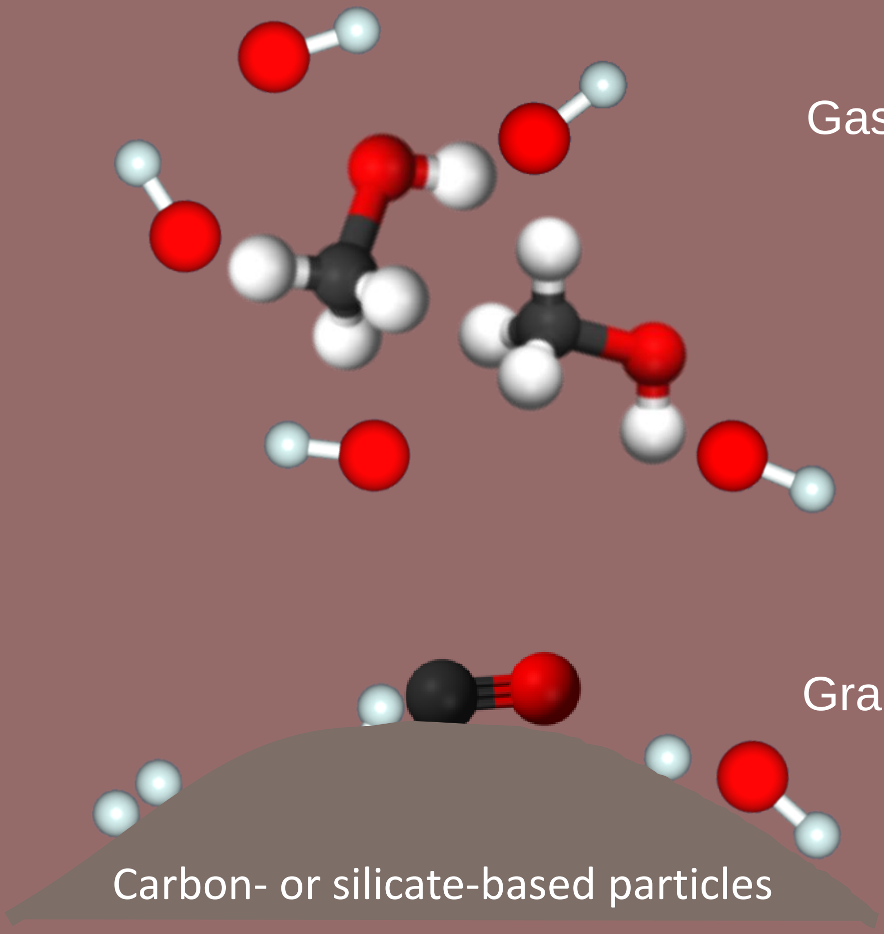
Formation of molecules on cosmic dust grains: a laboratory view

Alexey Potapov

Laboratory Astrophysics Group
of the Max Planck Institute for Astronomy

Chemistry in the ISM

Chemical processes leading to the formation of molecules in the interstellar medium (ISM)



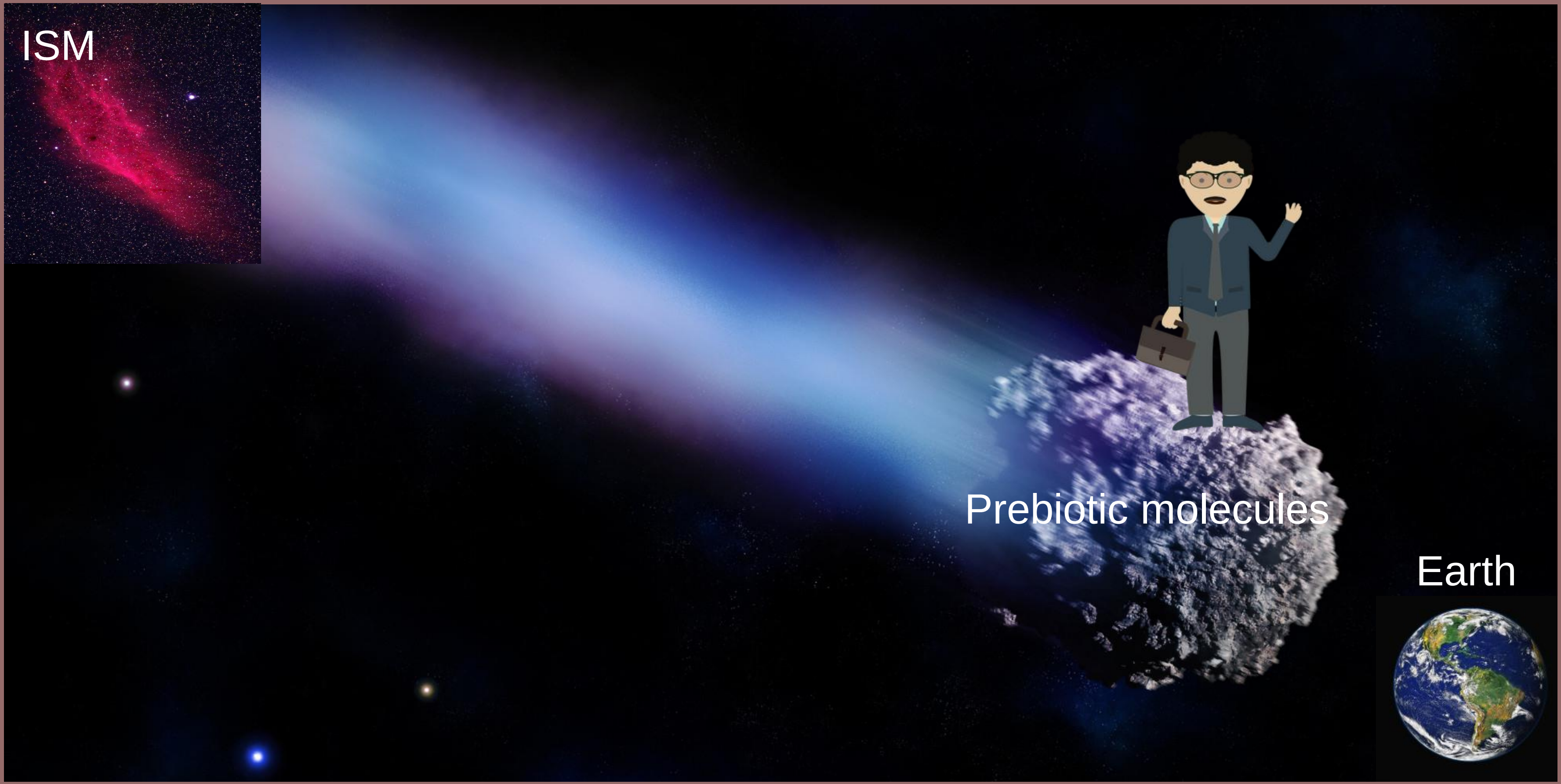
Gas phase reactions

Grain surface reactions

Carbon- or silicate-based particles

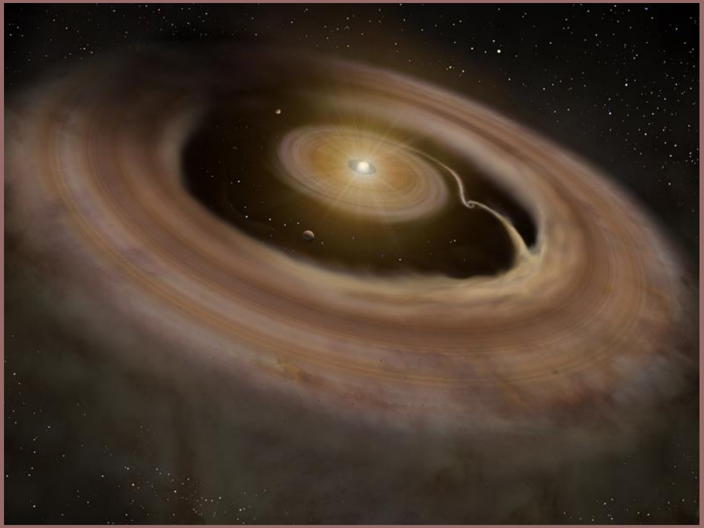
Chemistry in the ISM

Origin of Life



Cold phases of the ISM

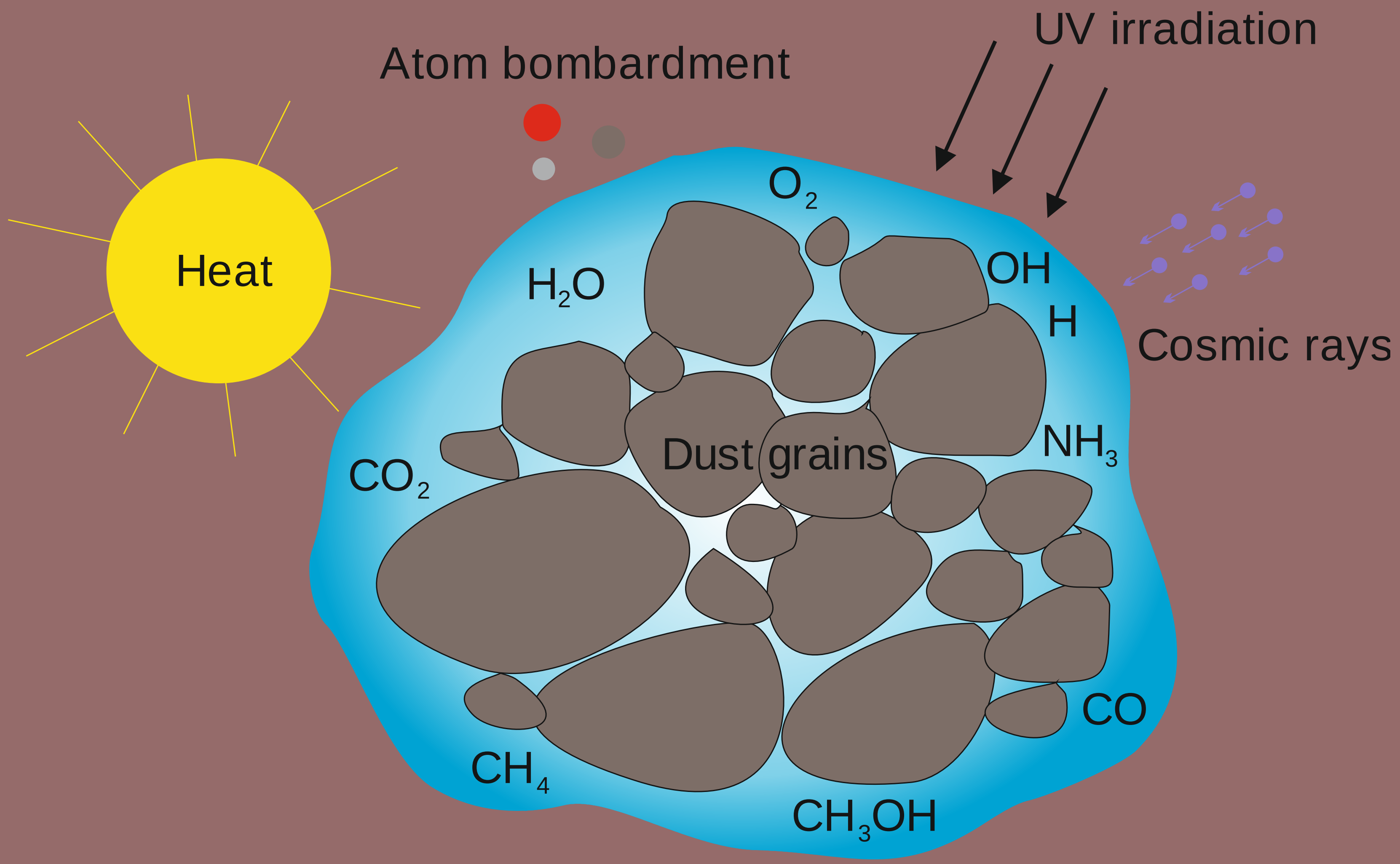
Molecular clouds



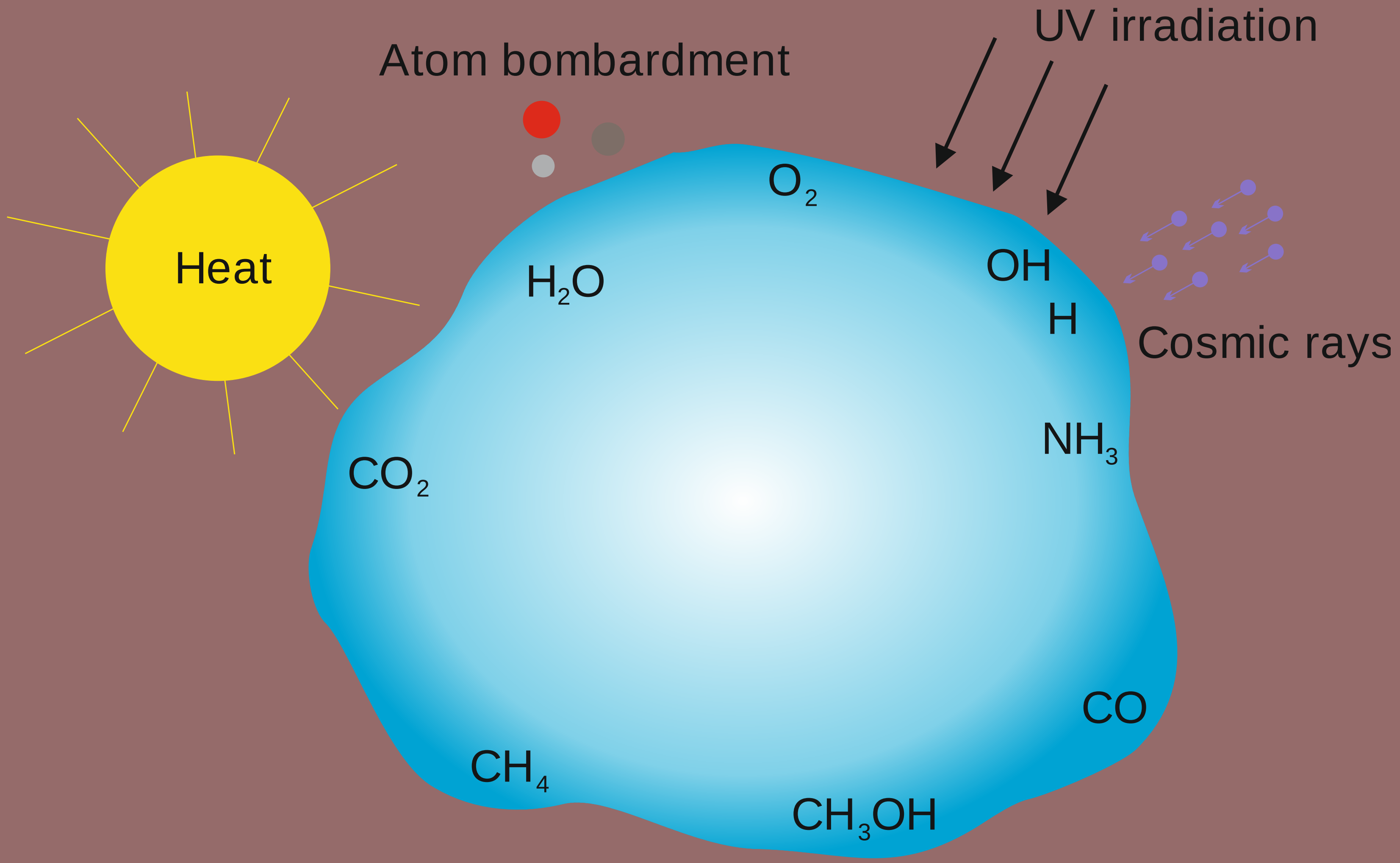
Planet-forming disks

Outer parts of envelopes of evolved stars

Cosmic dust grains



Chemistry on the surface of interstellar ice analogues



Chemistry on the surface of interstellar ice analogues

Huge number of studies

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Cite this: DOI: 10.1039/c7cp05882a

Untangling the methane chemist
and solar system ices toward ior
a combined infrared and reflectr
analysis†

Matthew J. Abplanalp,[ab] Brar

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Cite this: Phys. Chem. Chem. Phys., 2014, 16, 23604

Kinetics of the NH_3 and CO_2 solid-state reaction at low temperature

J. A. Noble,[a] P. Theule,*[a] F. Duvernay,[a] G. Danger,[a] T. Chiavassa,[a] P. Ghesquiere,[b] T. Mineva[c] and D. Talbi[b]

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CH_3OH-rich i

I. Experiment

K. I. Öberg[1], R. T. Garrod[2], E. F. van Dish

Astronomy & Astrophysi

THE ASTROPHYSICAL JOURNAL, 778:162 (11pp), 2013 December 1
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doi:10.1088/0004-637X/778/2/162

SOFT X-RAY IRRADIATION OF METHANOL ICE: FORMATION OF PRODUCTS
AS A FUNCTION OF PHOTON ENERGY

Y.-J. CHEN[1,2], A. CIARAVELLA[3], G. M. MUÑOZ CARO[4], C. CECCHI-PESTELLINI[3],
A. JIMÉNEZ-ESCOBAR[4], K.-J. HUANG[1], AND T.-S. YIH[1]

Monthly Notices of the Royal Astronomical Society

MNRAS 455, 1702–1712 (2016)

doi:10.1093/mnras/st

H-atom addition and abstraction reactions in mixed CO, H_2CO and CH_3OH ices – an extended view on complex organic molecule formation

Fedoseev,[1] S. Ioppolo,[3] E.F. van Dishoeck[2] and H. Linnartz[1]

A&A 585, A155 (2016)
DOI: 10.1051/0004-6361/201527138
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Astronomy & Astrophysics

Synthesis of formamide and isocyanic acid after ion irradiation of frozen gas mixtures

Kaňuchová[1,3], R. G. Urso[2,3], G. A. Baratta[3], J. R. Brucato[4], M. E. Palumbo[3], and G. Strazzulla[3]

A&A 506, 601–608 (2009)
DOI: 10.1051/0004-6361/200912850
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Astronomy & Astrophysics

Methylammonium methylcarbamate thermal formation in interstellar ice analogs: a glycine salt precursor in protostellar environments

J.-B. Bossa[1], F. Duvernay[1], P. Theulé[1], F. Borget[1], L. d'Hendecourt[2], and T. Chiavassa[1]

RSC Advances

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Cite this: RSC Adv., 2014, 4, 15419

Hydrogenation of CO on interstellar dust: what is the role of water molecules?

C. Pirim*[a] and L. Krim[bc]

Faraday Discussions

Cite this: Faraday Discuss., 2014, 168, 461

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THz and mid-IR spectroscopy of interstellar ice analogs: methyl and carboxylic acid groups

S. Ioppolo,*[ab] B. A. McGuire,†[c] M. A. Allodi†[c] and G. A. Blake[ac]

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Cite this: Phys. Chem. Chem. Phys., 2016, 18, 1245

Using the C–O stretch to unravel the nature of hydrogen bonding in low-temperature solid methanol–water condensates

Anita Dawes,* Nigel John Mason and Helen Jane Fraser

THE ASTROPHYSICAL JOURNAL, 738:175 (7pp), 2011 September 10
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doi:10.1088/0004-637X/738/2/175

REACTIVITY BETWEEN A CO-CONTAINING ICE AND NON-ENERGETIC OH RADICALS

EMILIE-LAURE ZINS, PRASAD R. JOSHI, AND LAHOUARI KRIM[1]

Laboratoire de Dynamique, Interactions et Réactivité, Université Pierre et Marie Curie, CNRS, UMR 7075, Case Courrier 49, Bat F 74, 4 Place Jussieu, 75252 Paris Cedex 05, France

Received 2011 February 11; accepted 2011 June 15; published 2011 August 24

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Kinetics of the NH_3 and CO_2 solid-state reaction at low temperature

J. A. Noble,[a] P. Theule,*[a] F. Duvernay,[a] G. Danger,[a] T. Chiavassa,[a] P. Ghesquiere,[b] T. Mineva[c] and D. Talbi[b]

ChemComm

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Cite this: Chem. Commun., 2016, 52, 741

Received 12th September 2015,

Synthesis of urea in cometary model ices and implications for Comet 67P/Churyumov–Gerasimenko†

M. Förstel,[a] P. Maksyutenko,[a] B. M. Jones,[a] B.-J. Sun,[b] A. H. H. R. I. Kaiser*[a]

ASTROBIOLOGY
Volume 9, Number 7, 2009
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DOI: 10.1089/ast.2008.0324

Research Article

ormation of Uracil from the Ultraviolet Photo-Irradiation of Pyrimidine in Pure H_2O Ices

Michel Nuevo,[1] Stefanie N. Milam,[1,2] Scott A. Sandford,[1] Jamie E. Elsila,[3] and Jason P

International Reviews in Physical Chemistry

ublication details, including instructions for authors and ubscription information:
ttp://www.tandfonline.com/loi/trpc20

tom addition reactions in interstellar ce analogues

. Linnartz[a], S. Ioppolo[b] & G. Fedoseev

Monthly Notices of the Royal Astronomical Society

MNRAS 448, 1288–1297 (2015)

doi:10.1093/mnras/stu2603

Experimental evidence for glycolaldehyde and ethylene glycol formation by surface hydrogenation of CO molecules under dense molecular cloud conditions

G. Fedoseev,[1]* H. M. Cuppen,[2] S. Ioppolo,[2] T. Lamberts[1,2] and H. Linnartz[1]

THE ASTROPHYSICAL JOURNAL, 586:L107–L110, 2003 March 20
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SOLID-PHASE FORMATION OF INTERSTELLAR VINYL ALC

R. L. HUDSON[1] AND M. H. MOORE[2]

Space Sci Rev (2013) 180:101–175
DOI 10.1007/s11214-013-0020-8

Complementary and Emerging Techniques for Astrophysical Ices Processed in the Laboratory

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na · E.V. Savchenko · E. Sciamma-O'Brien · G. Strazzulla

THE ASTROPHYSICAL JOURNAL, 571:L173–L176, 2002 June 1
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ICIENT FORMATION OF FORMALDEHYDE AND METHANOL BY THE ADDITION OF HYDROGEN ATOMS TO CO IN H_2O-CO ICE AT 10 K

NAOKI WATANABE AND AKIRA KOUCHI

A&A 549, A40 (2013)
DOI: 10.1051/0004-6361/201219974
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Astronomy & Astrophysics

Formaldehyde and methylamine analogues as a source of molecular

V. Vinogradoff, F. Duvernay, G. Danger, P.

Monthly Notices of the Royal Astronomical Society

Mon. Not. R. Astron. Soc. 410, 1089–1095 (2011)

doi:10.1111/j.1365-2966.2010.17515.x

Surface formation of HCOOH at low temperature

S. Ioppolo,[1]* H. M. Cuppen,[1,2] E. F. van Dishoeck[2,3] and H. Linnartz[1]

A&A 457, 741–751 (2006)
DOI: 10.1051/0004-6361:20042018
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Astronomy & Astrophysics

The effects of circularly polarized light on amino acid enantiomers produced by the UV irradiation of interstellar ice analogs

M. Nuevo[1,2], U. J. Meierhenrich[3,4], G. M. Muñoz Caro[1,5], E. Dartois[1], L. d'Hendecourt[1], D. Deboffle[1], G. Auger[6], D. Blanot[6], J.-H. Bredehöft[7], and L. Nahon[2,8,9]

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Advances in Space Research 52 (2013) 1567–1579

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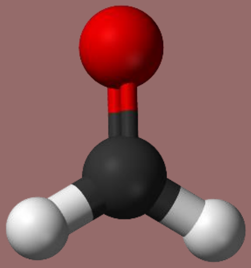
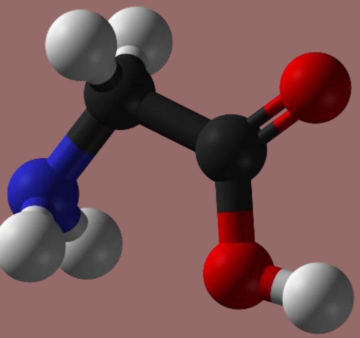
Thermal reactions in interstellar ice: A step towards molecular complexity in the interstellar medium

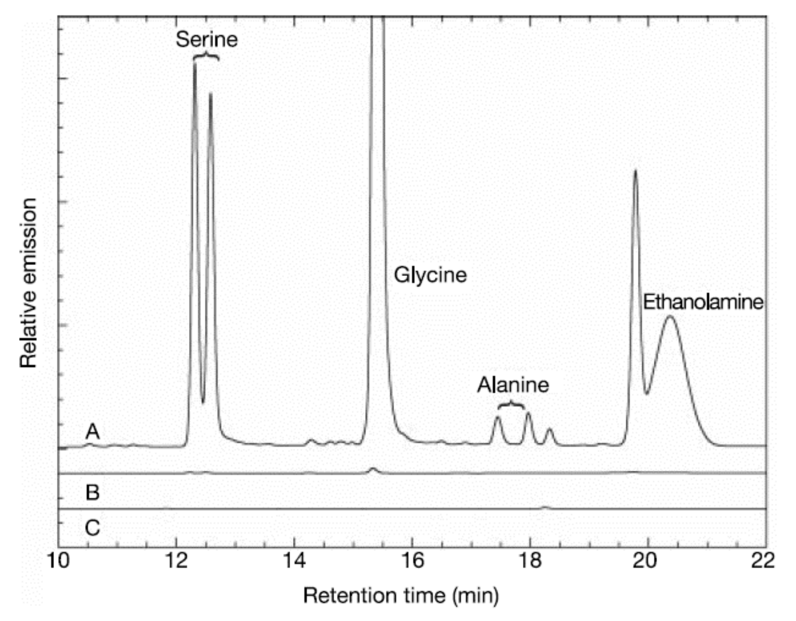
P. Theulé*, F. Duvernay, G. Danger, F. Borget, J.B. Bossa, V. Vinogradoff, F. Mispelaer, T. Chiavassa



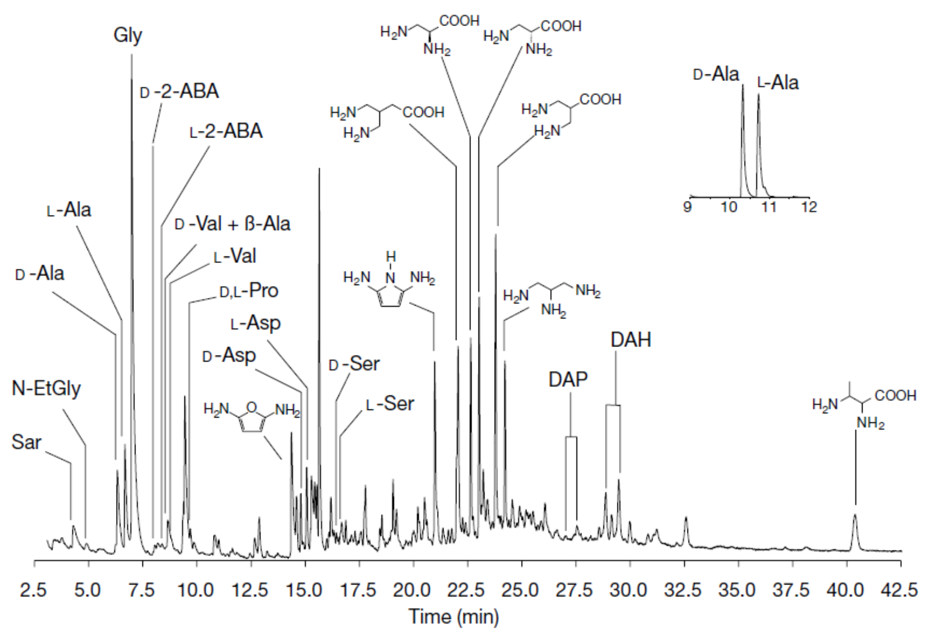
from simple molecules to amino acids



Chemistry on the surface of interstellar ice analogues

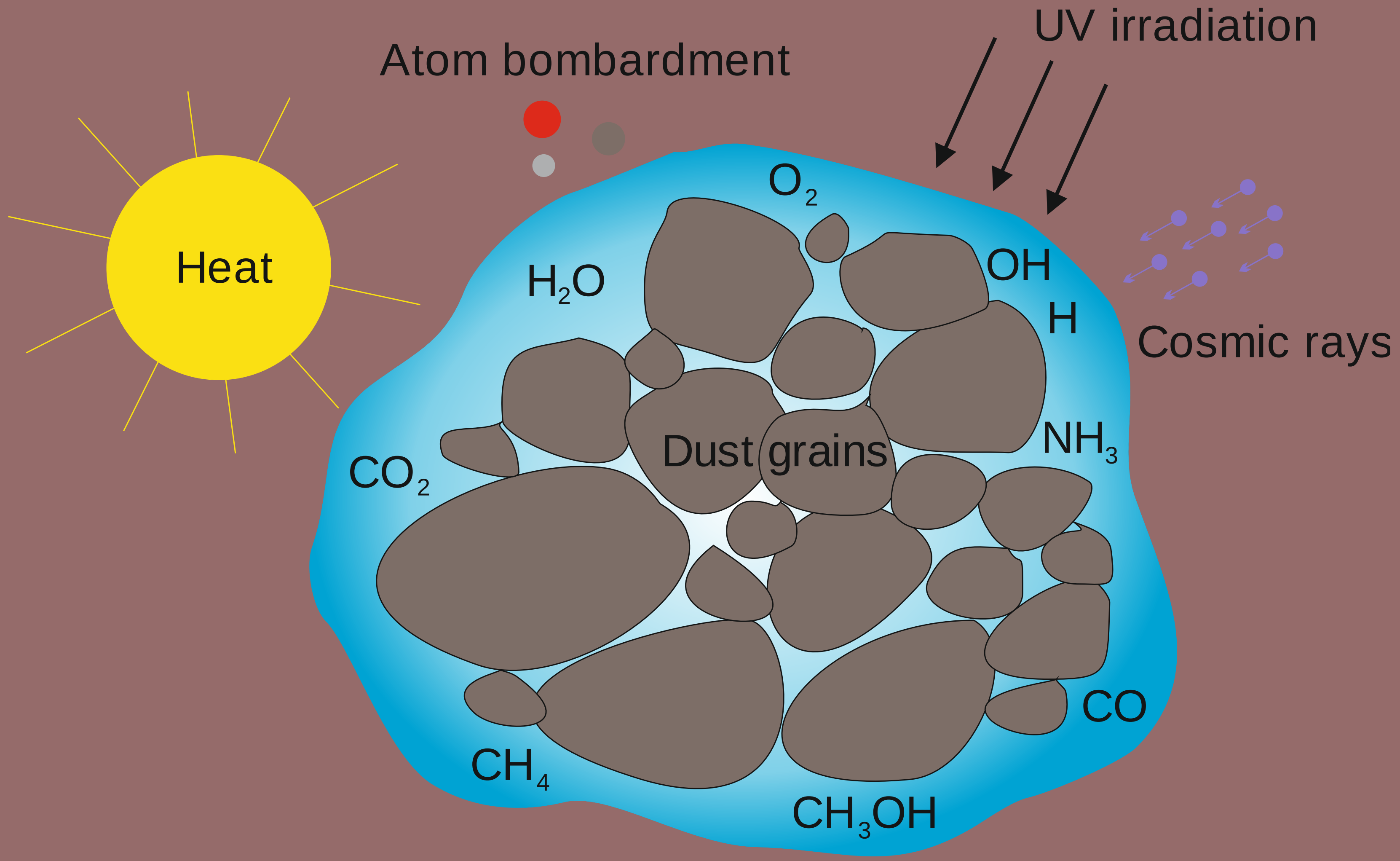


Bernstein et al., Nature 2002

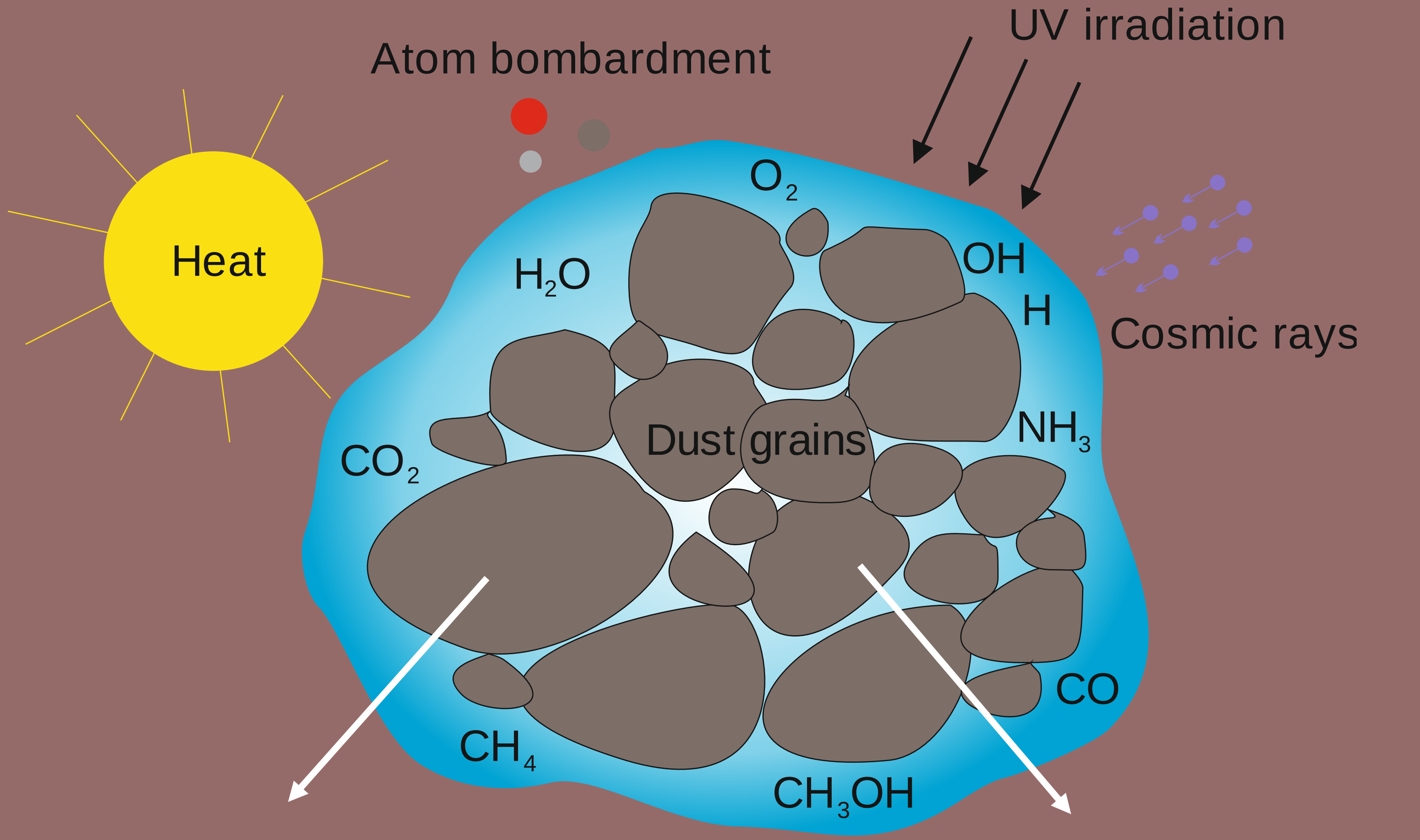


Munoz Caro et al., Nature 2002

Chemistry on the surface of interstellar grain analogues



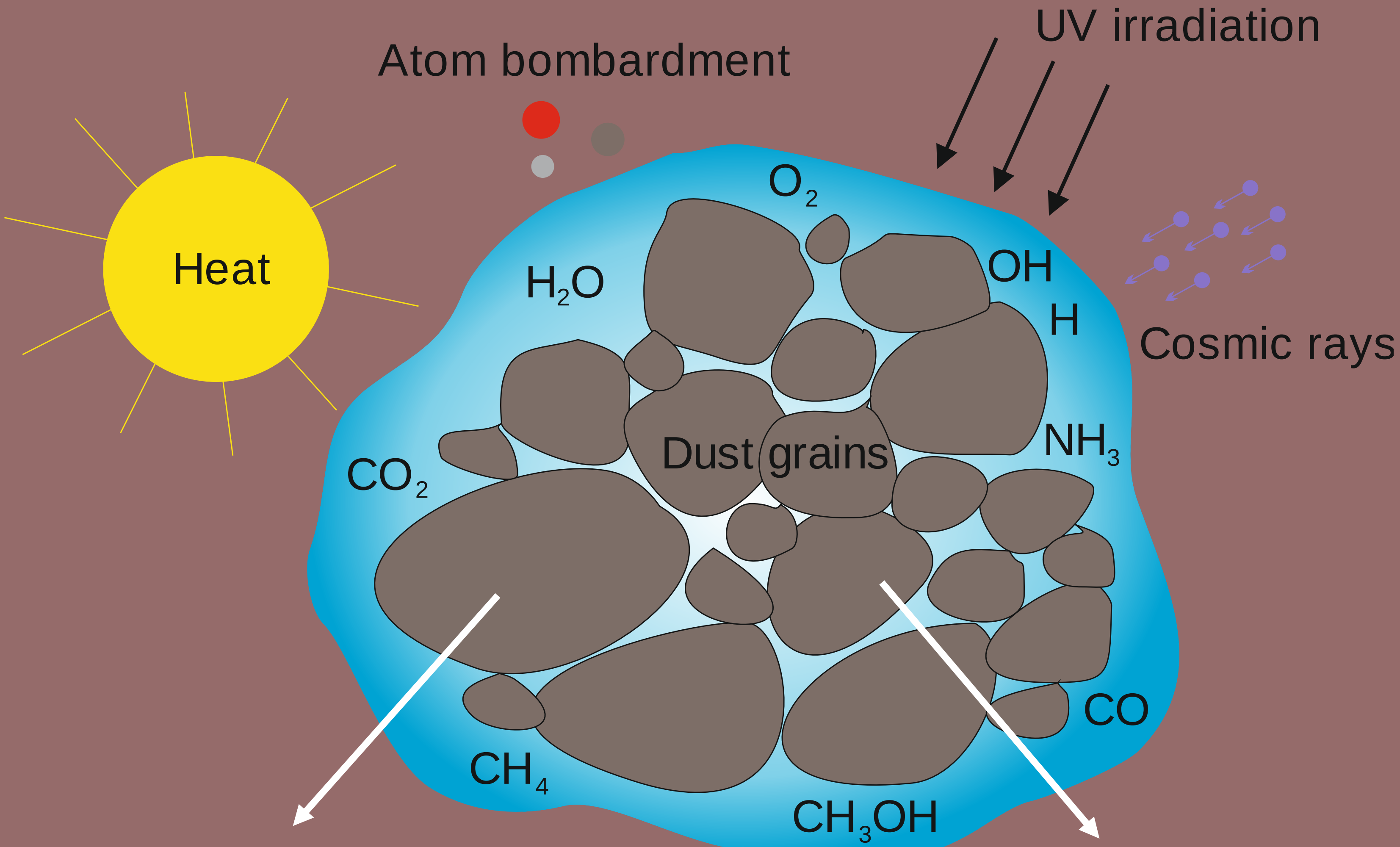
Chemistry on the surface of interstellar grain analogues



Direct participation of dust molecules

Catalytic effects of the grains surface

Chemistry on the surface of interstellar grain analogues



Atom bombardment

UV irradiation

Heat

Cosmic rays

Dust grains

O_2

H_2O

OH

H

NH_3

CO_2

CO

CH_4

CH_3OH

Direct participation of dust molecules

Catalytic effects of the grains surface

Chemistry on the surface of interstellar grain analogues

A handful of works

CO and CO_2 in H_2O ice covering hydrogenated carbon grains by ion irradiation (Mennella et al., 2004)

CO and CO_2 in H_2O ice covering hydrogenated carbon grains by UV irradiation (Mennella et al., 2006)

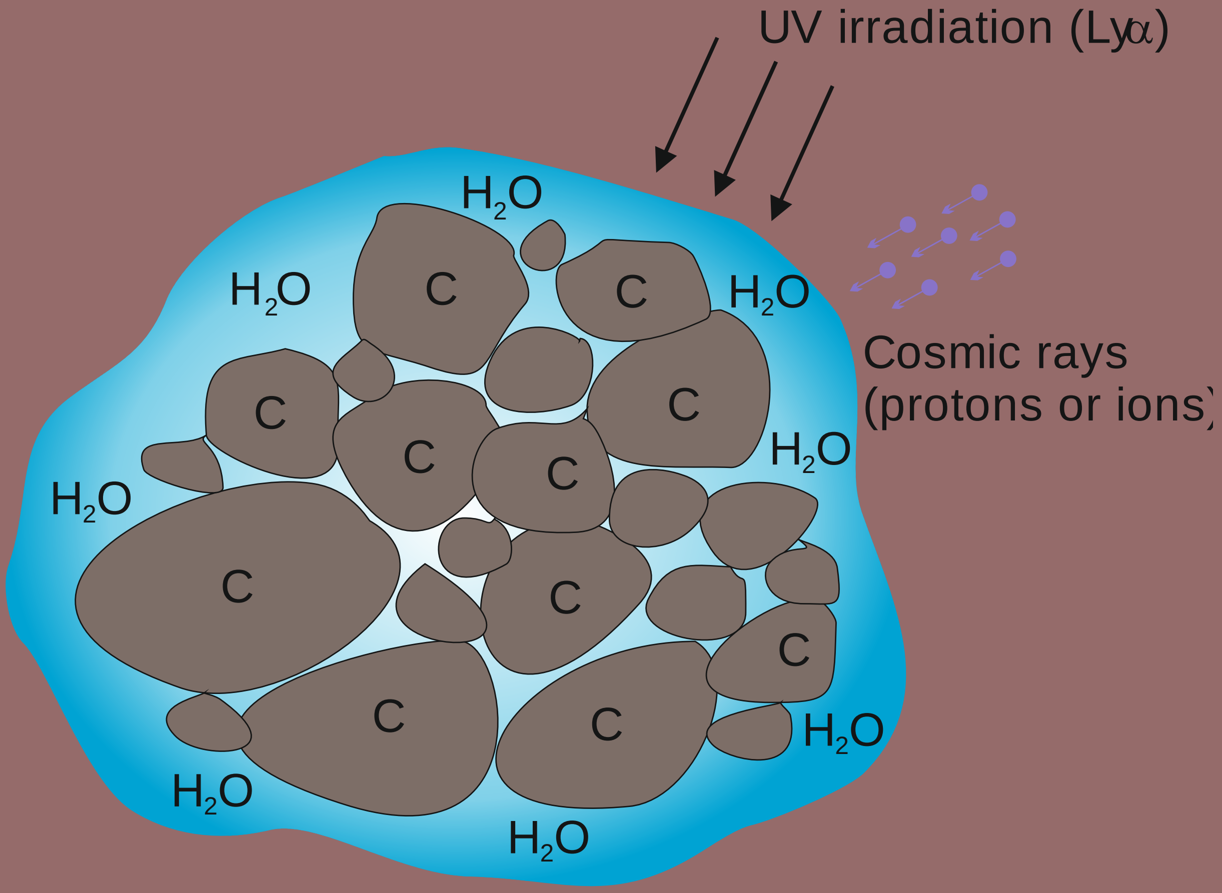
CO_2 in O_2 ice covering carbon foil by UV irradiation (Fulvio et al., 2012)

CO_2 in H_2O ice covering carbon foil by proton irradiation (Raut et al., 2012)

CO and CO_2 in H_2O ice covering hydrogenated carbon grains by proton irradiation (Sabri et al., 2015)

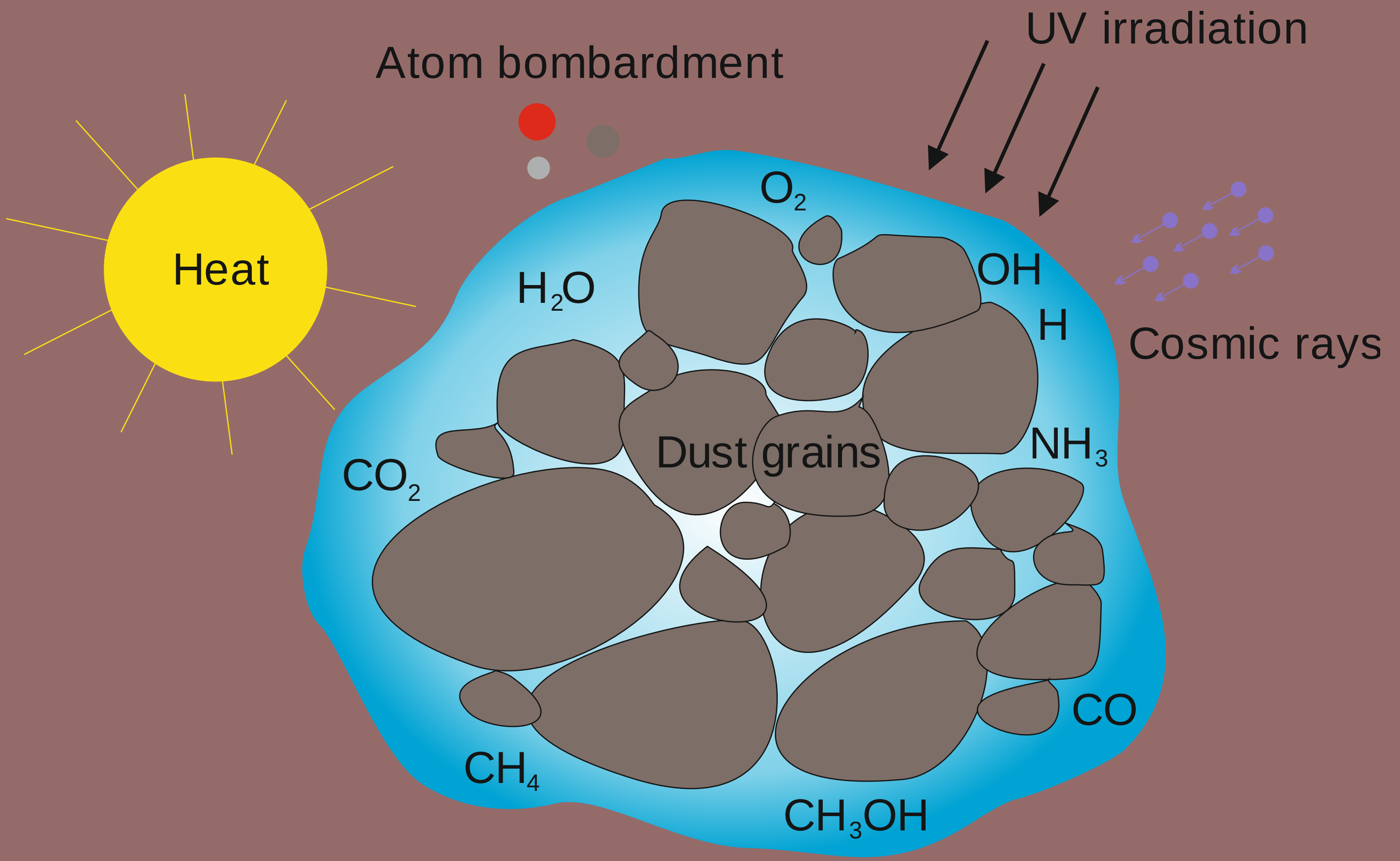
CO and CO_2 in H_2O ice covering graphite films by UV irradiation (Shi et al., 2015)

Chemistry on the surface of interstellar grain analogues

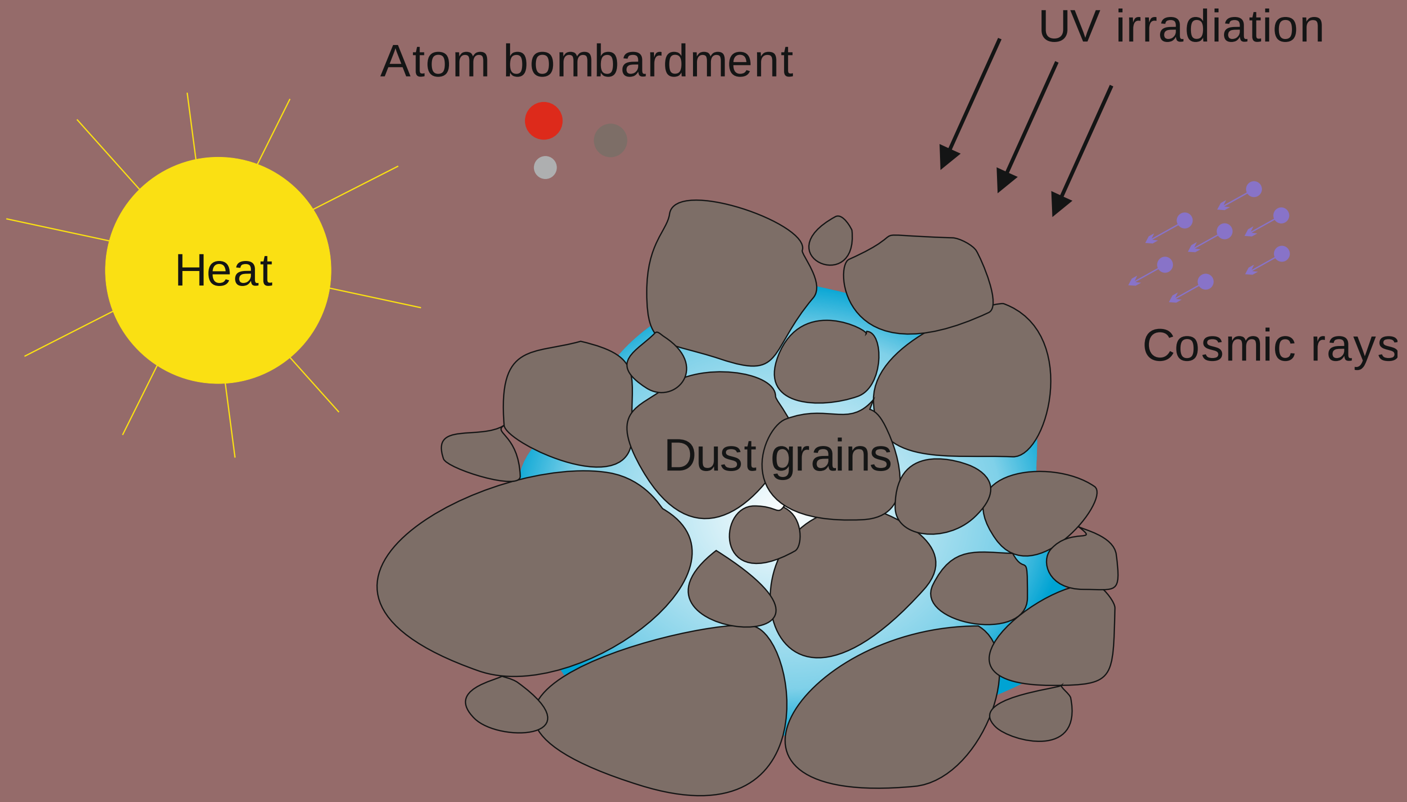


Formation of CO and CO_2

Chemistry on the surface of interstellar grain analogues



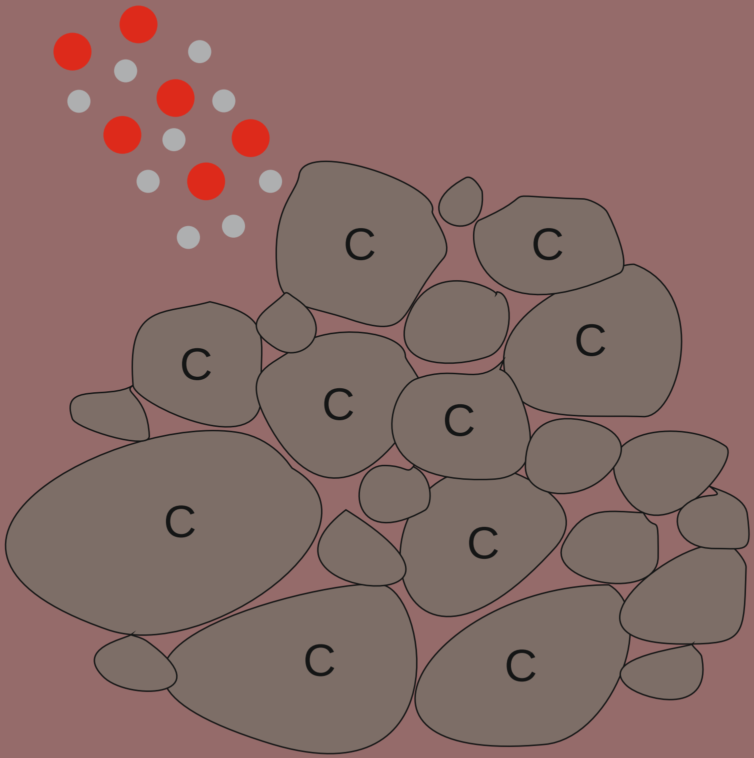
Chemistry on the surface of interstellar grain analogues



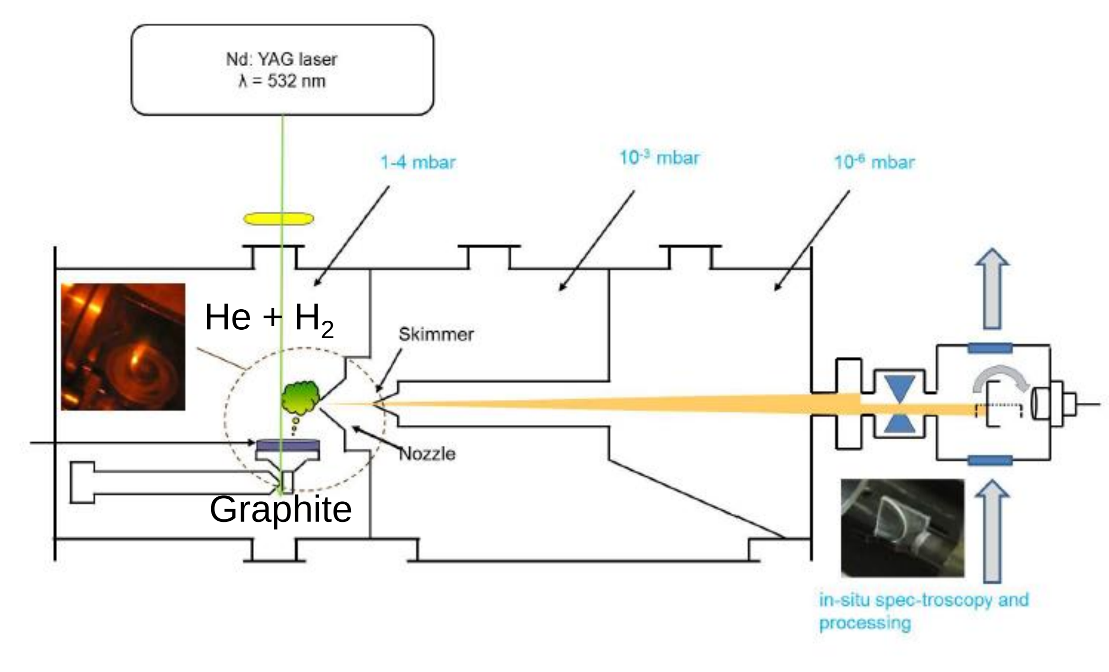
Chemistry on the surface of interstellar grain analogues

Our study

Atom bombardment (H + O)



Interstellar grain analogues in the laboratory



Ablation chamber Particle beam Deposition chamber

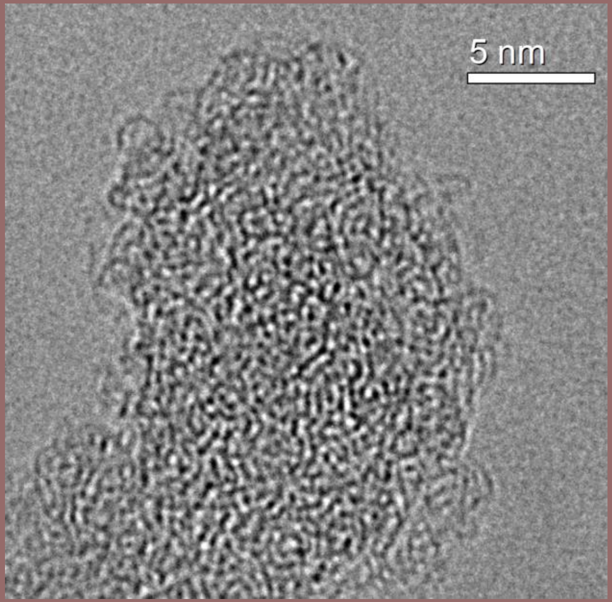
Laboratory Astrophysics Group
Jena, Germany

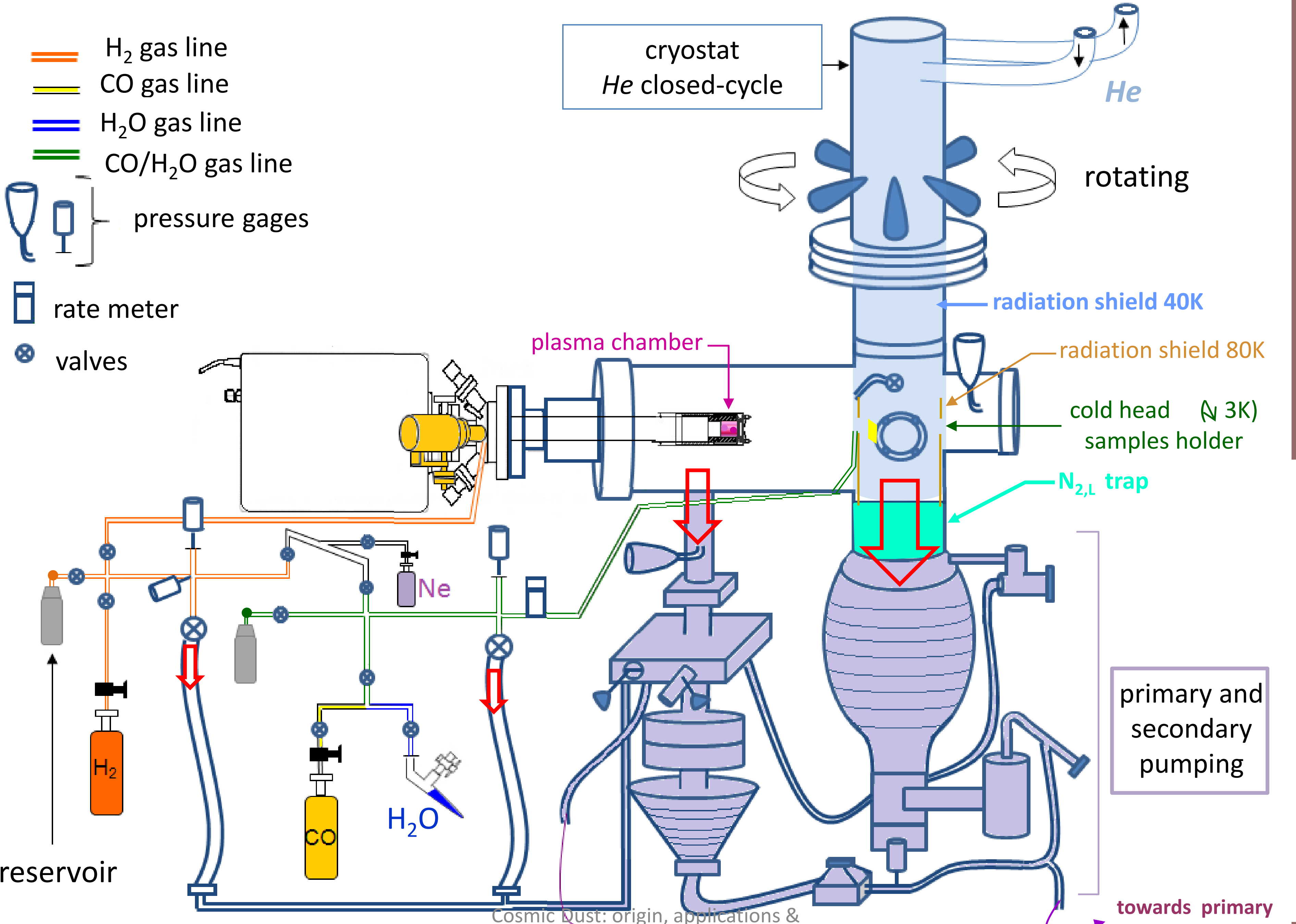
Interstellar grain analogues in the laboratory

Amorphous hydrogenated fullerene-like carbon grains

Grains on a substrate

TEM image





MONARIS laboratory, Paris, France

Experimental details

Sample - fixed on a cryogenic polished copper mirror

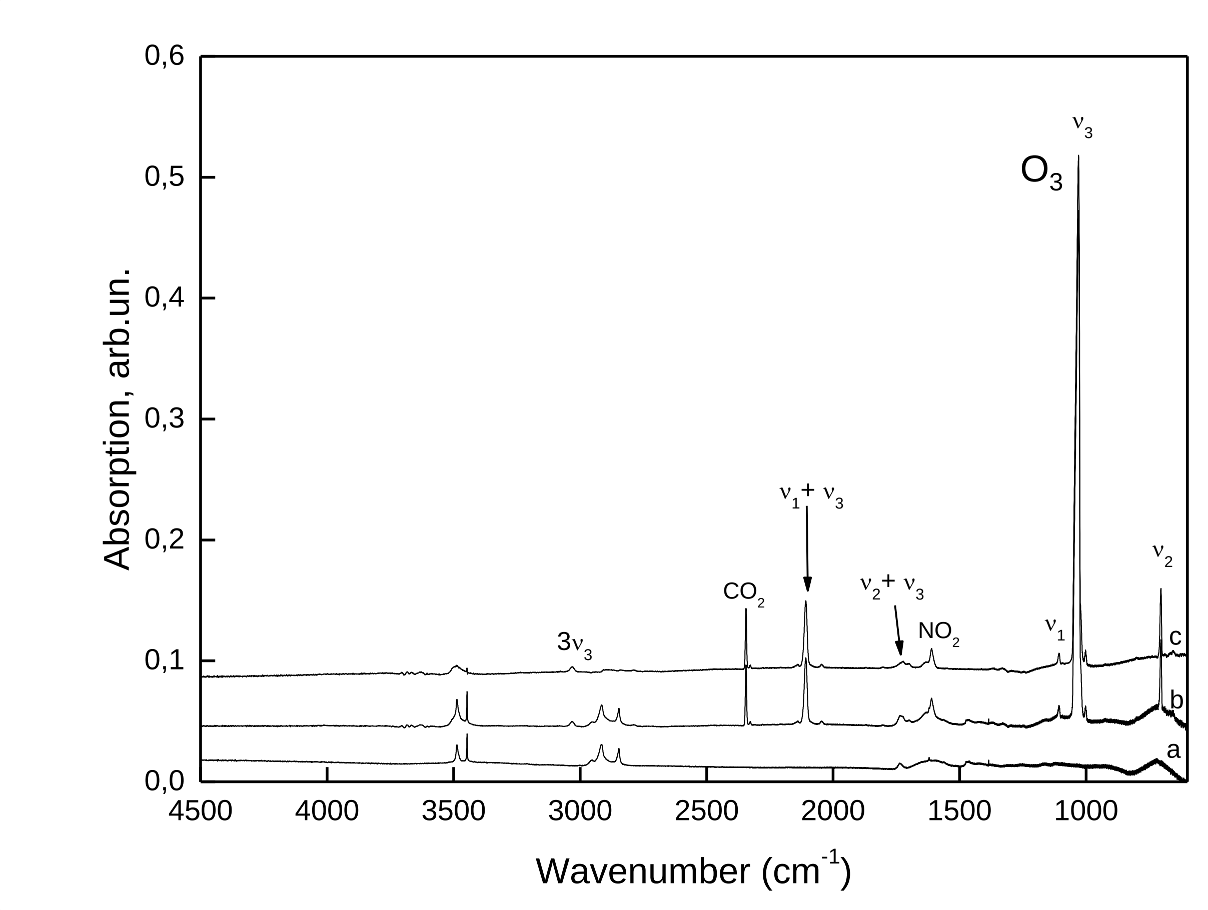
High vacuum chamber with a base pressure of 10^{-9} mbar

Temperature of the mirror - 10 K

Bombardment – 30 minutes, final atom fluence 1.8×10^{20} atoms cm^{-2}

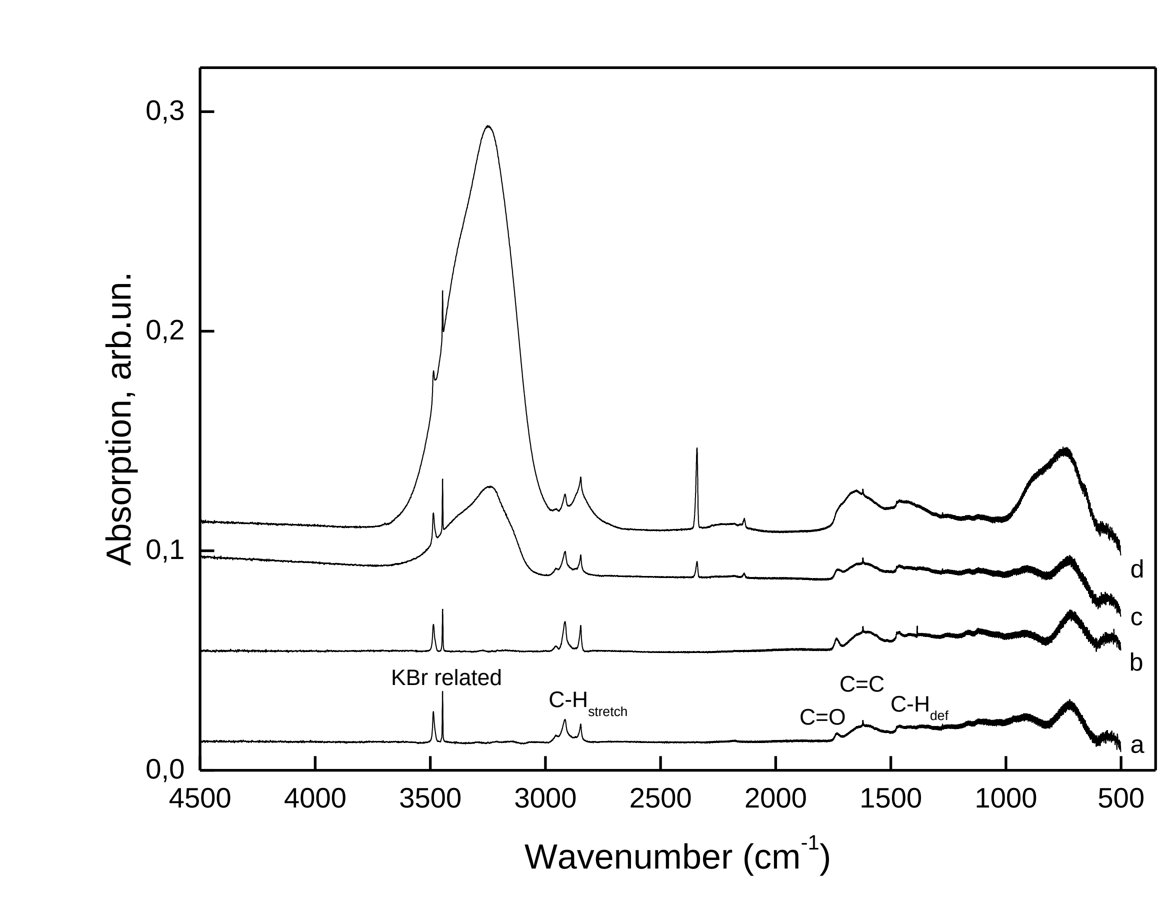
IR spectra - transmission-reflection mode between 5000 and 500 cm^{-1}
with a resolution of 0.5 cm^{-1} using a Bruker FTIR spectrometer

O addition: IR spectra at 10 K



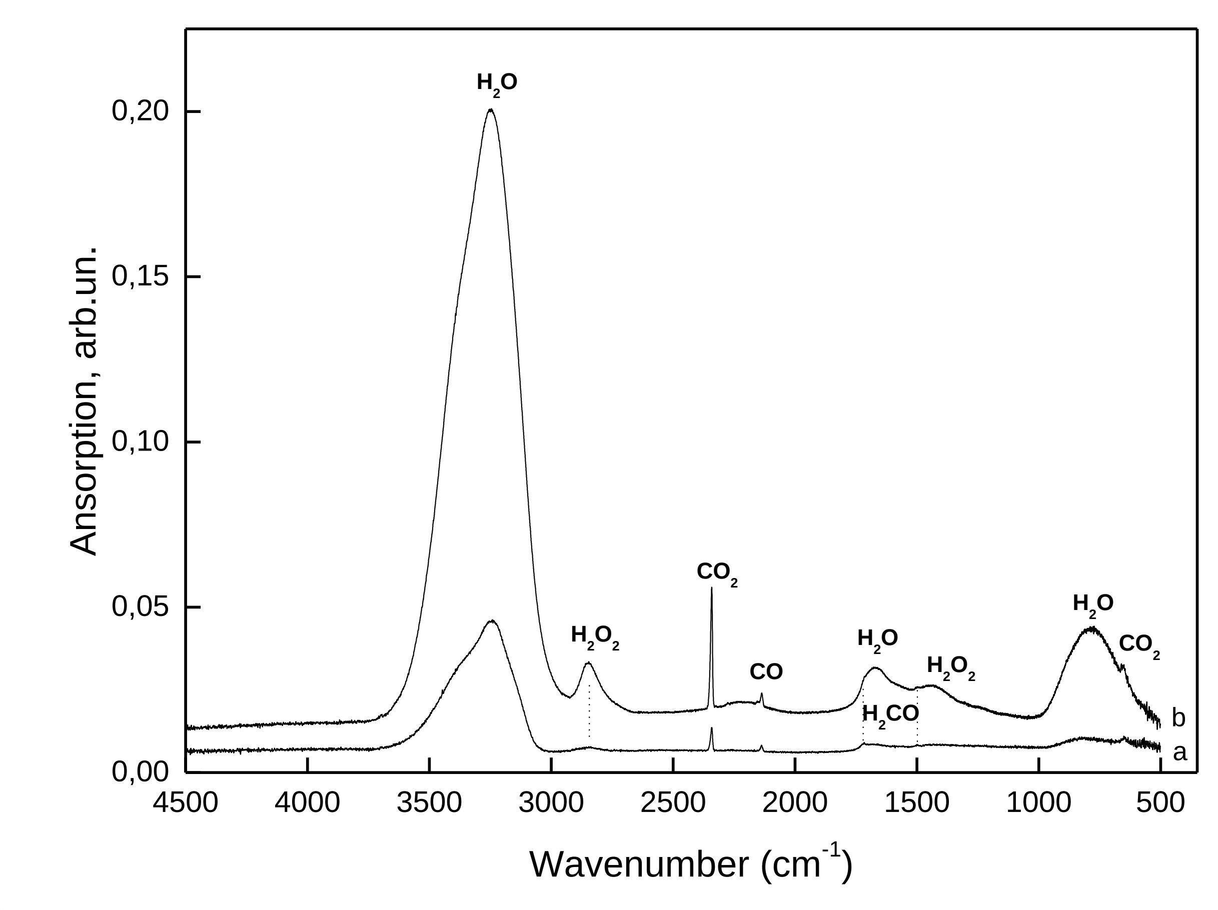
(a) carbon grains
(b) after O bombardment of carbon grains
(c) difference spectrum

O/H addition: IR spectra at 10 K



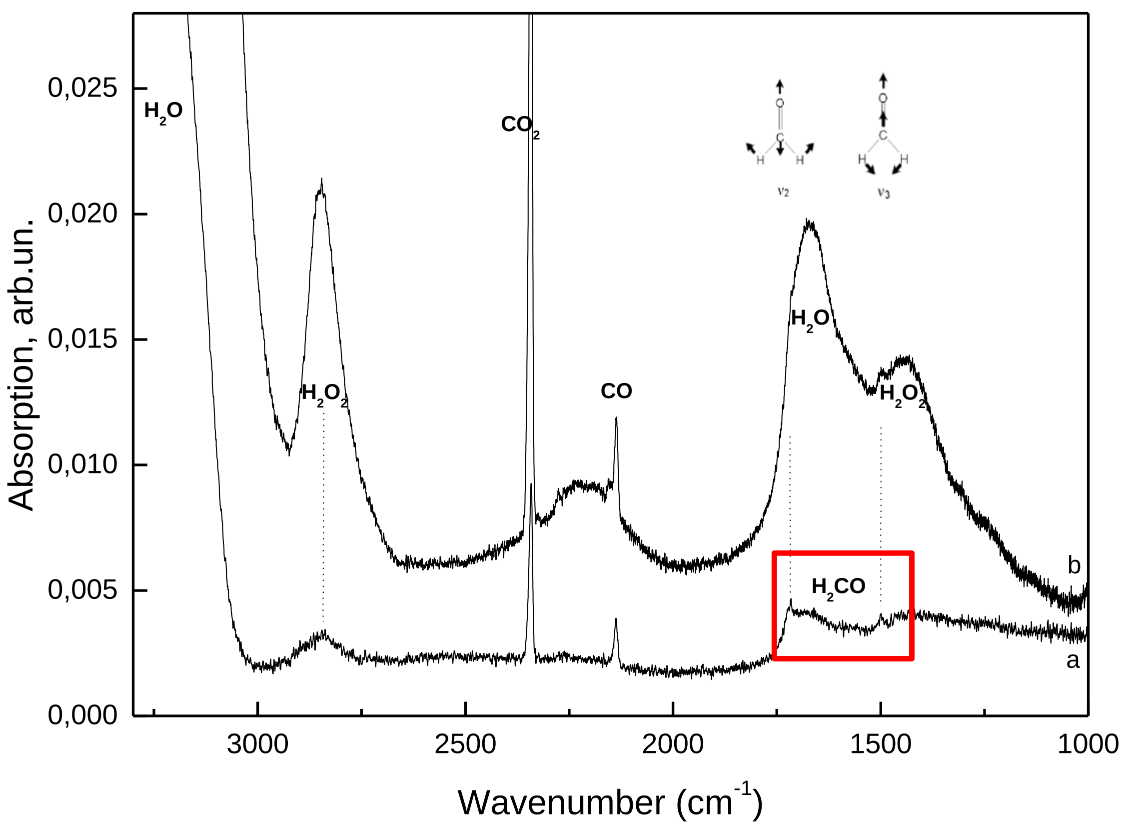
(a) carbon grains
(b) after H bombardment of carbon grains
(c) after O/H bombardment of carbon grains ($[O_2]/[H_2]$ = 1/60)
(d) after O/H bombardment of carbon grains ($[O_2]/[H_2]$ = 10/70)

O/H addition: Difference IR spectra at 10 K



(a) after O/H bombardment of carbon grains ($[O_2]/[H_2]$ = 1/60)
(b) after O/H bombardment of carbon grains ($[O_2]/[H_2]$ = 10/70)

O/H addition: Difference IR spectra at 10 K



(a) after O/H bombardment of carbon grains ($[O_2]/[H_2] = 1/60$)
(b) after O/H bombardment of carbon grains ($[O_2]/[H_2] = 10/70$)

Grain surface chemistry

$$\text{surface-C} + O \longrightarrow \text{surface-CO}$$

$$CO + O \longrightarrow CO_2$$

$$CO + H \longrightarrow HCO + H \longrightarrow H_2CO$$

$$CO + H + H \longrightarrow H_2CO$$

Grain surface chemistry

$$\text{surface-C} + O \longrightarrow \text{surface-CO}$$

$$CO + O \longrightarrow CO_2$$

Not detected

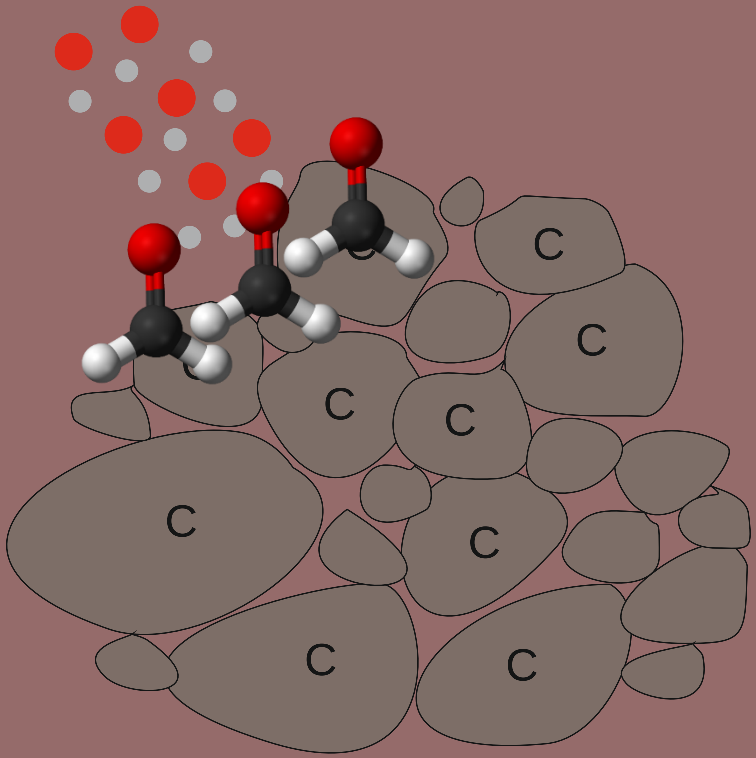
$$CO + H \longrightarrow HCO + H \longrightarrow H_2CO$$

$$CO + H + H \longrightarrow H_2CO$$

Grain surface chemistry

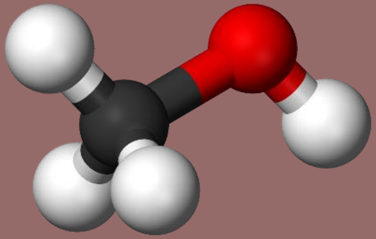
A new route of molecules formation in the ISM: grain surface processes

Atom bombardment (H + O)

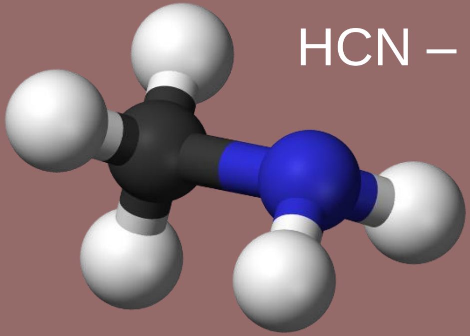


The next steps (two examples)

Methanol



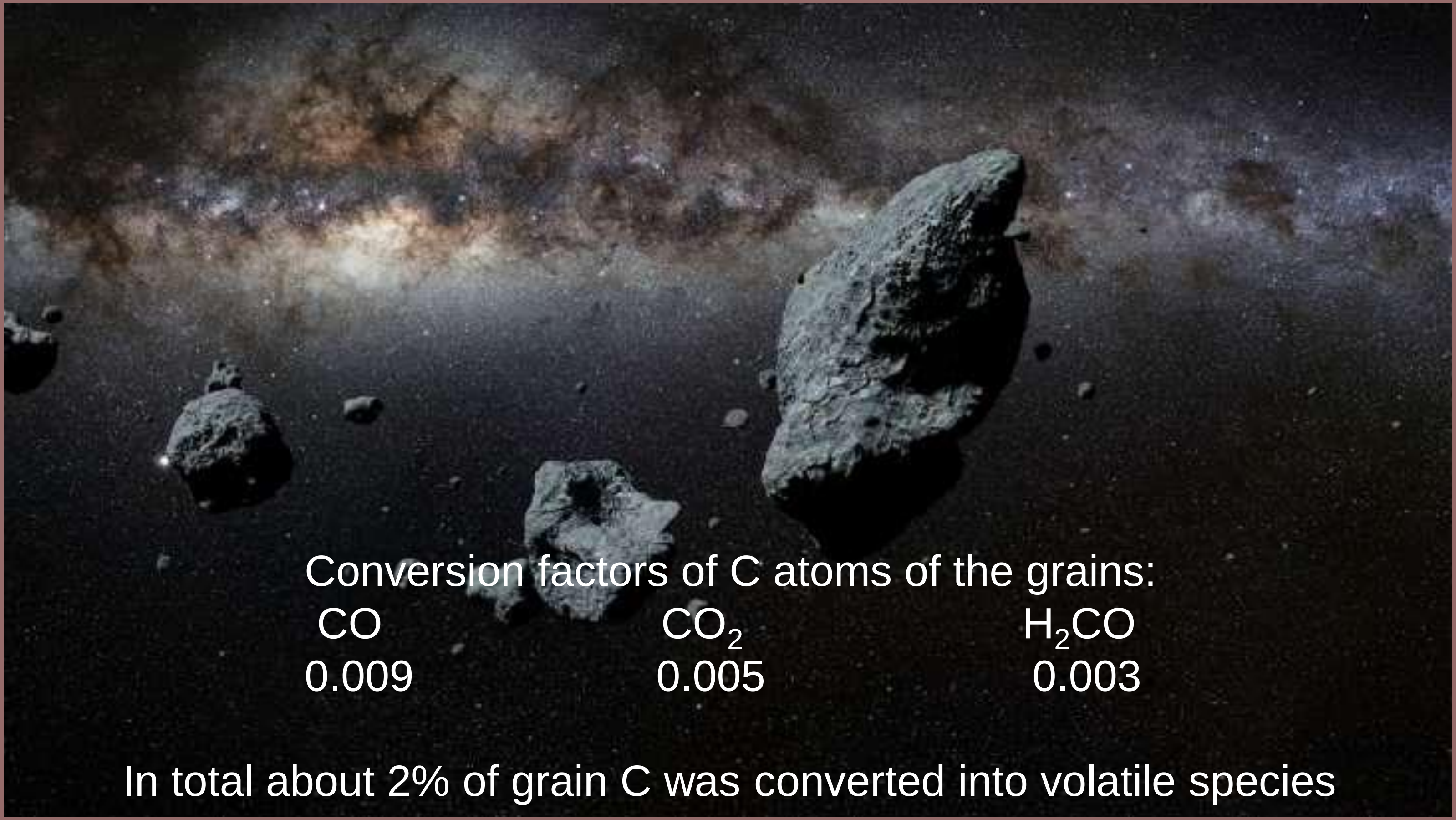
H_2CO – H_3CO – CH_3OH



HCN – CH_2N – CH_3N – CH_3NH – CH_3NH_2

Methylamine

Outlook: erosion of grains in cold environments through formation of volatile molecules



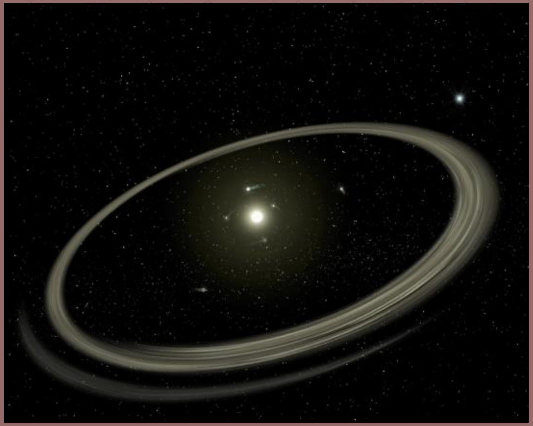
Conversion factors of C atoms of the grains:

CO	CO_2	H_2CO
0.009	0.005	0.003

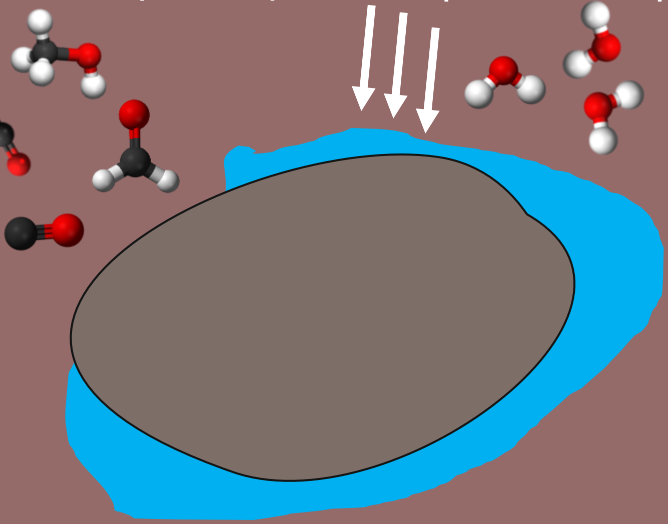
In total about 2% of grain C was converted into volatile species

Outlook: erosion of grains in cold environments

Molecular clouds

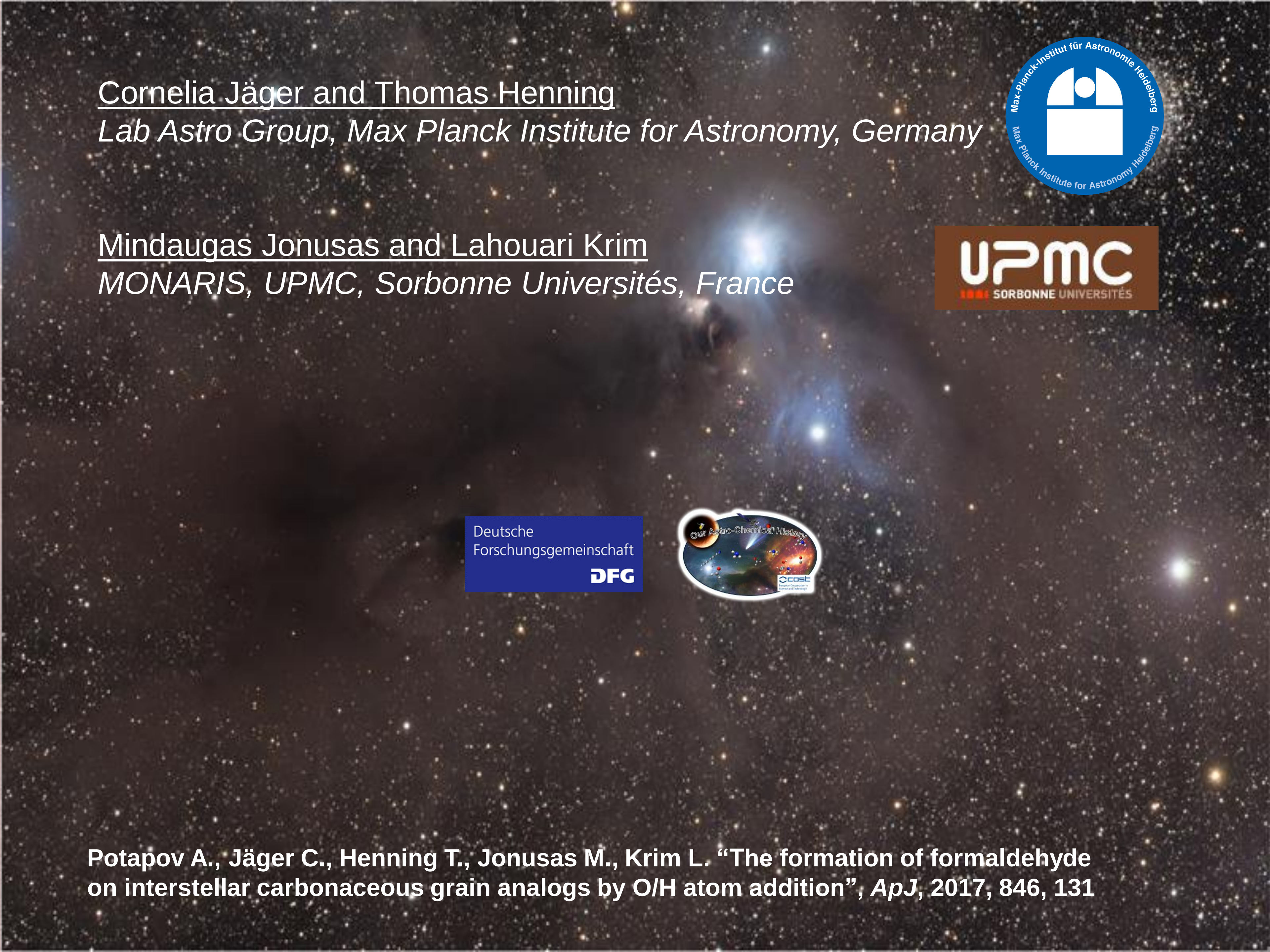


Debris disks



Surface chemistry (can be important)

UV photodesorption (typically considered)



Cornelia Jäger and Thomas Henning
Lab Astro Group, Max Planck Institute for Astronomy, Germany

Mindaugas Jonusas and Lahouari Krim
MONARIS, UPMC, Sorbonne Universités, France

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SORBONNE UNIVERSITÉS

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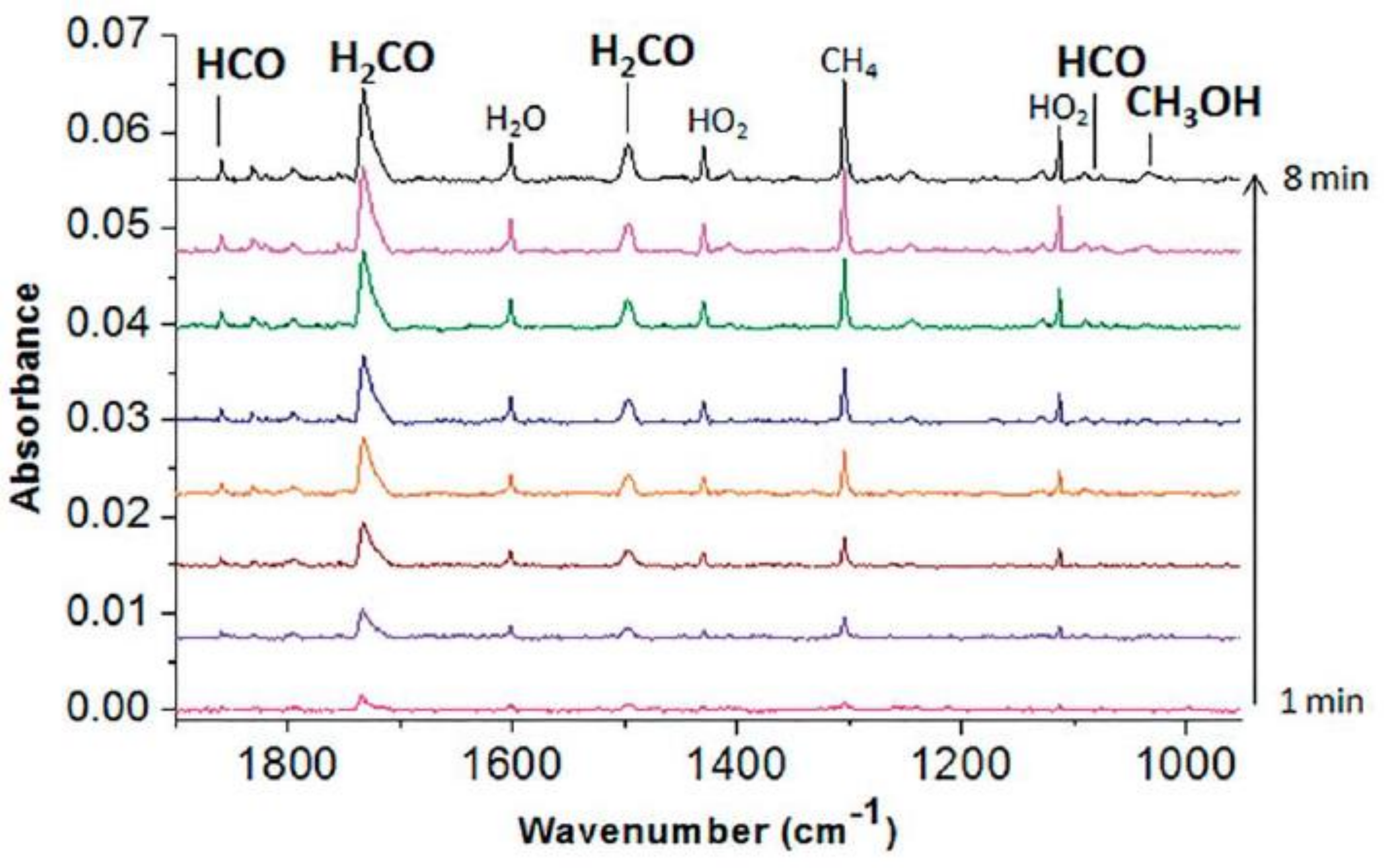
Forschungsgemeinschaft
DFG

Potapov A., Jäger C., Henning T., Jonusas M., Krim L. “The formation of formaldehyde on interstellar carbonaceous grain analogs by O/H atom addition”, *ApJ*, 2017, 846, 131

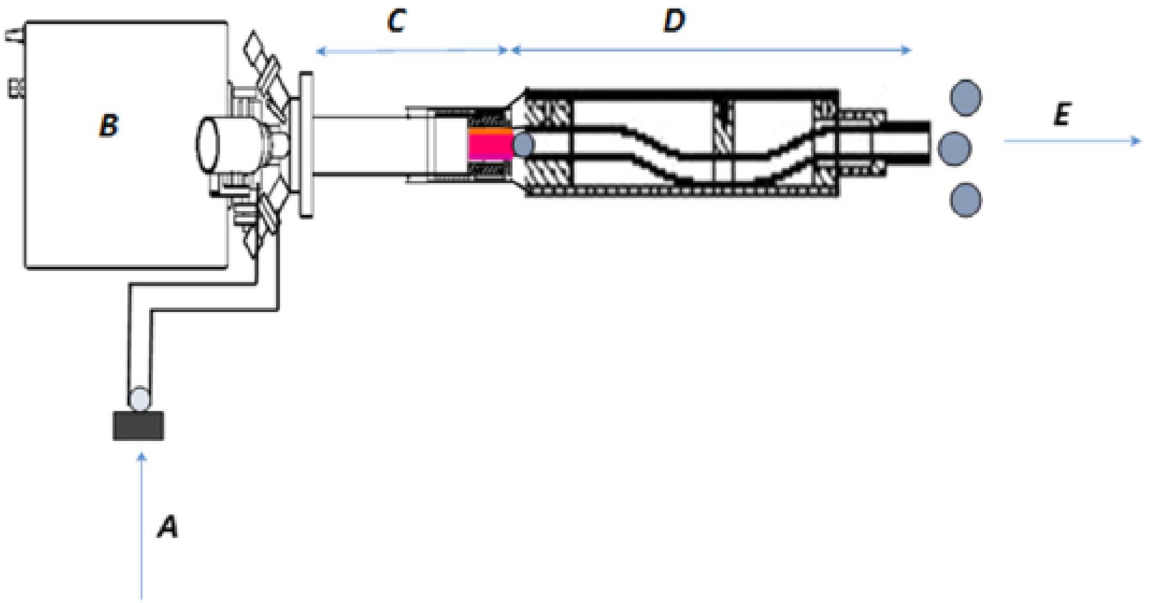
Thank you very much for your attention

Hydrogenation of CO



C. Pirim, L. Krim, *RSC Adv.* 2014, 4, 15419

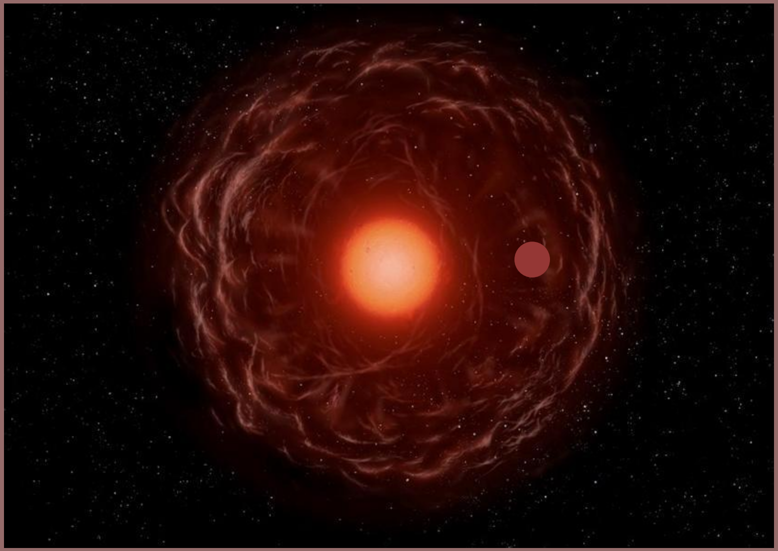
Atom bombardment (addition)

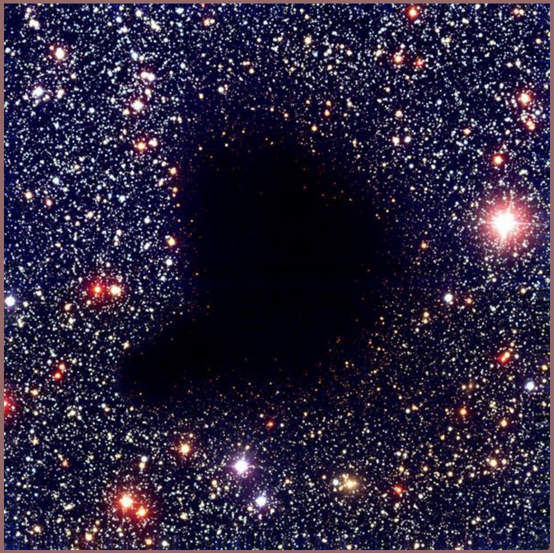


PCS-ECR atomic source with a tube added after the plasma apertures to eliminate UV photons. A—molecular gas input, B—Microwave generator, C—Plasma discharge zone, D—Teflon tube, E—Atomic beam exit.

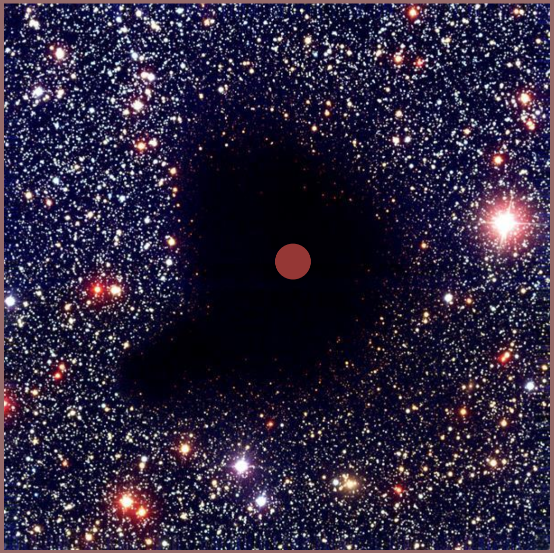
Dissociation yields - 15% and 40% for H_2 and O_2
Bombardment - 30 minutes
Final fluence - 1.8×10^{20} atoms cm^{-2}

Formation of ice/dust grains in the ISM

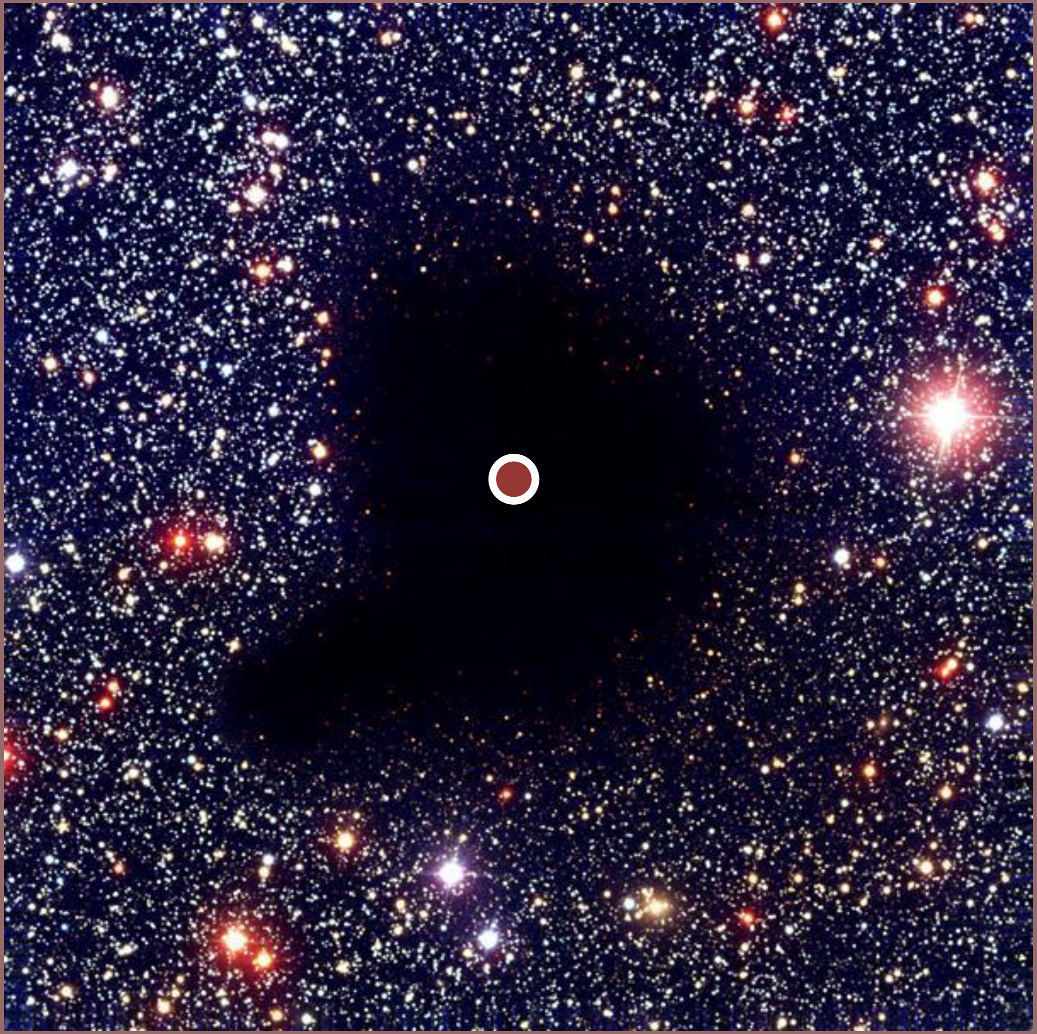




Formation of ice/dust grains in the ISM

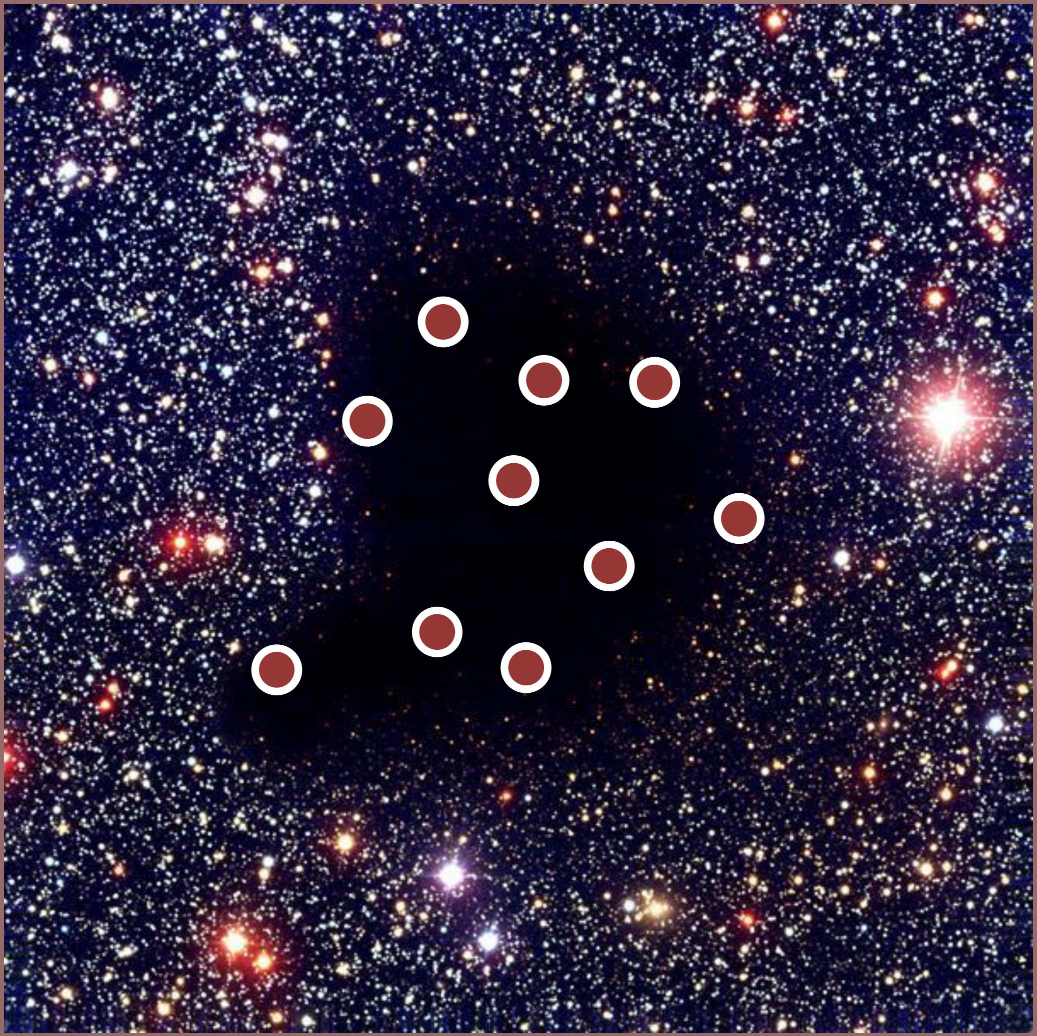


Formation of ice/dust grains in the ISM



„Cometary“ ice: H_2O, CO, CO_2, NH_3, CH_4, CH_3OH

Formation of ice/dust grains in the ISM



Formation of ice/dust grains in the ISM