Améliorer la solubilité dans le CO2 supercritique : l'apport de la simulation

Francesca Ingrosso

SRSMC UMR 7565 CNRS-Université de Lorraine

J3P 2017 : Approches de modélisation à différentes échelles : de leur développement à leurs applications

Physique et Chimie Théoriques en Lorraine

Direction :
Xavier Assfeld (DU)
Dragi Karevski (DA)

Axes de recherche

Axe Dynamique et Symétrie : Resp. Jérôme Dubail
Axe Interaction Rayonnement-Matière : Resp. Antonio Monari
Axe Etat liquide, Interfaces, Solvatation : Resp. Francesca Ingrosso
Axe Biophysique et Biochimie : Resp. François Dehez
Axe Etat solide, Structure et Propriétés : Resp. Sébastien Lebègue

Physique et Chimie Théoriques en Lorraine

Direction :
Xavier Assfeld (DU)
Dragi Karevski (DA)

Axes transversaux
Axe Développements Théoriques et Numériques : Resp. Gérald Monard
Axe Didactique, Epistémologie et Interdisciplinarité : Resp. Bertrand Berche

Molecular Sciences in Lorraine

Director: Jean-Luc Blin
Five Laboratories (LCP2ME, CRM2, LPCT, L2CM, LCP-A2MC)
Scientific Platforms (X-ray, NMR, Mass, Interfaces)

Thematic Axes

- Molecular and Hybrid Materials (M2H). Coord. Cédric Carteret.
- Microorganisms, Macromolecules and Molecules for Life Sciences (M3V). Coord. Christophe Gantzer.
- Electron density and electronic structure, Intermolecular Interactions (R12). Coord. F. Ingrosso and Benôit Guillot.

The CECAM Node MOSER@UL

Presentation of the CECAM-FR-MOSER Node in Nancy on May 23, 2016.

cecam
Centre Européen de Calcul Atomique et Moléculaire

UNIVERSITÉ DE LORRAINE cnrs SRSMC UMR 7565 jLB

CECAM

The *Centre Européen de Calcul Atomique et Moléculaire* was founded in 1969 by Dr Carl Moser and was located at CIRCE in Orsay until 1993.

It is devoted to the **promotion of fundamental research on advanced computational methods and to their application to important problems in frontier areas of physics, chemistry, biology, and engineering**.

It include the organization of:

- **Scientific workshops** in emerging areas;
- Specialist tutorials to train at the graduate and postdoctoral level;
- Workshops on software developments;
- Brain-storming and problem solving events;
- The development of collaborative research projects in Europe

Recent evolution towards code development and consultancy for industry through the Center of Excellence E-CAM.

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E CAM

Presentation outline

- CO_2-phicility: about the nature of CO_2-carbonyl interactions.
- Solubilizers and supercritical CO_2 ($scCO_2$).
- News and perspectives.

Acknowledgments

SRSMC Lab

CNRS-University of Lorraine

Institut Jean Barriol

Nancy, France

M.F. Ruiz-López

M. Altarsha

A. Lambert

M. Martins-Costa

A. Marsura

F. Dumarçay-Charbonnier

D. Barth (ENSIC)

G. Kevern

A. Muñoz, *University of Extremadura*

E. San Fabián, *University of Alicante*

L.M. Azofra, *University of Madrid*

V. Yeguas, *University of Oviedo*

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B.M. Ladanyi

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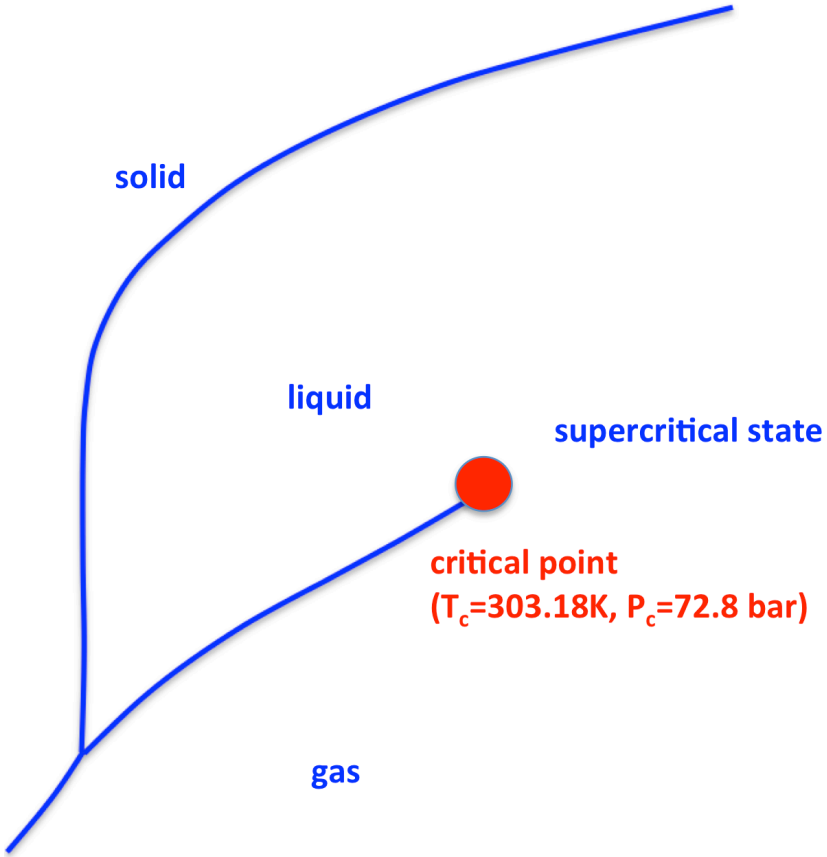
Green Solvents: $scCO_2$

Abundant, cheap

Easy to recycle

Nontoxic, easy to remove

Easy to obtain sc conditions



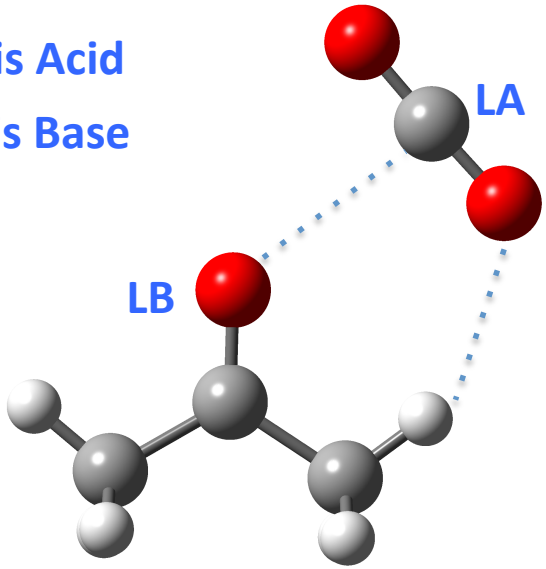
Problem: solubility!

- Use of cosolvents/mixtures.
- CO_2-philic compounds.
- More?...

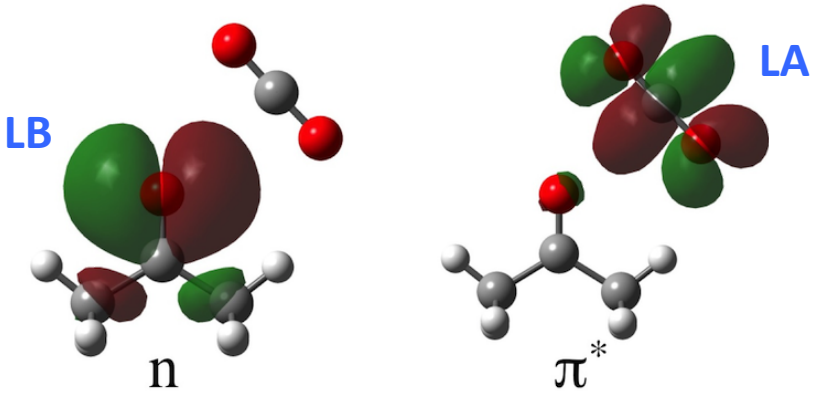
Investigating carbonyl-CO_2 intermolecular interactions

LA: Lewis Acid

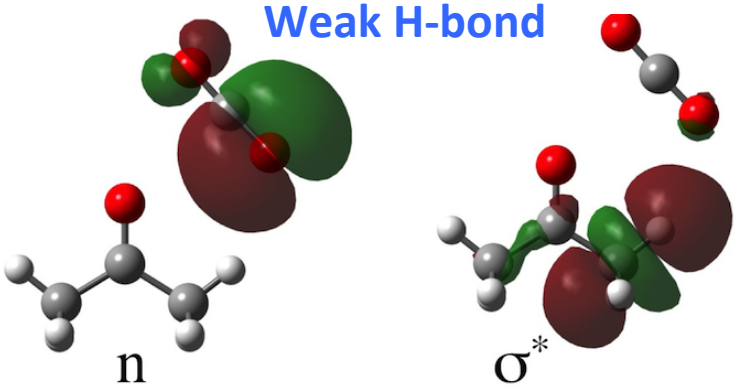
LB: Lewis Base



Ib Complex



Weak H-bond



Altarsha, Ingrosso, Ruiz-López, JPCB 2012.
Altarsha, Ingrosso, Ruiz-López, ChemPhysChem, 2012.

Investigating carbonyl-CO_2 intermolecular interactions

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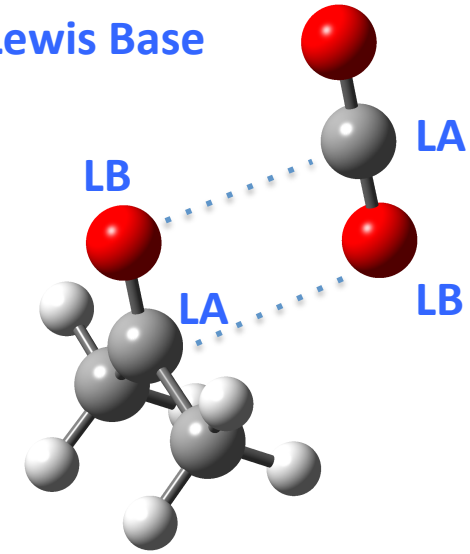
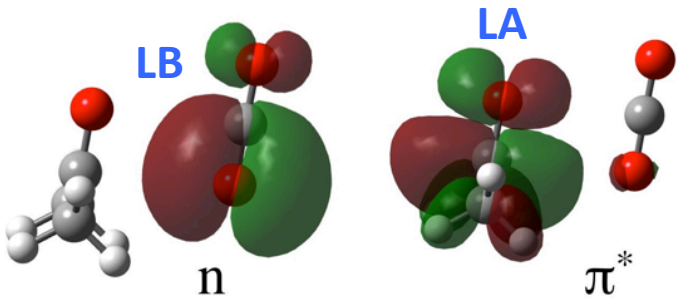
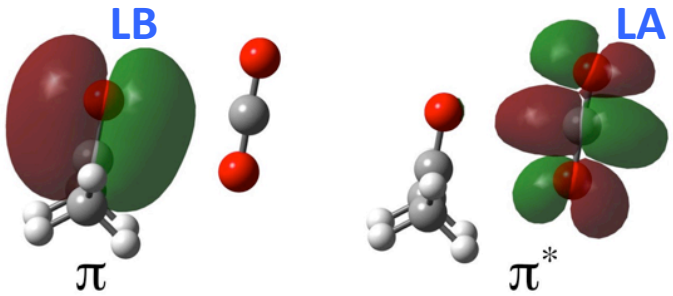


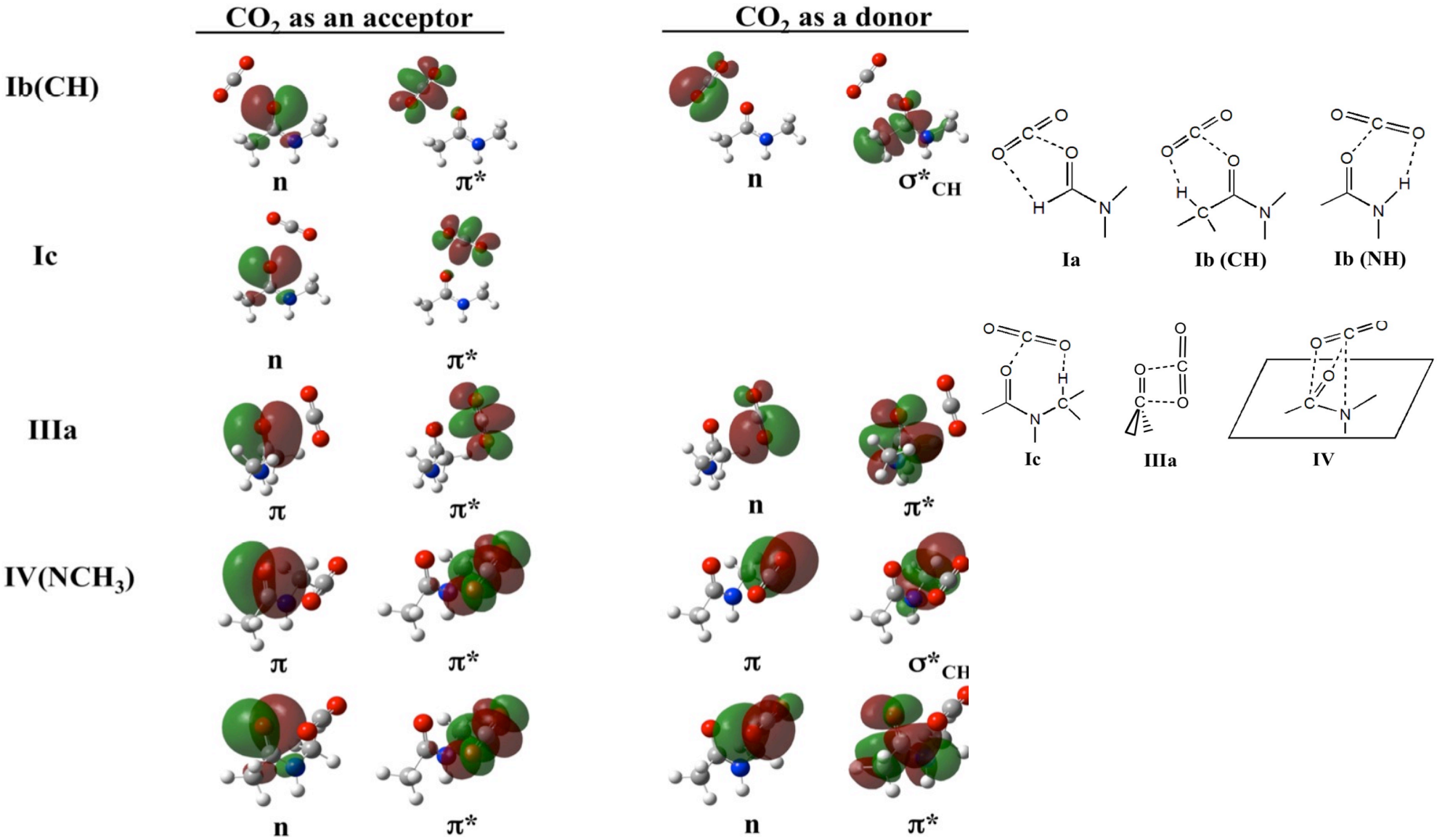
IIIa Complex





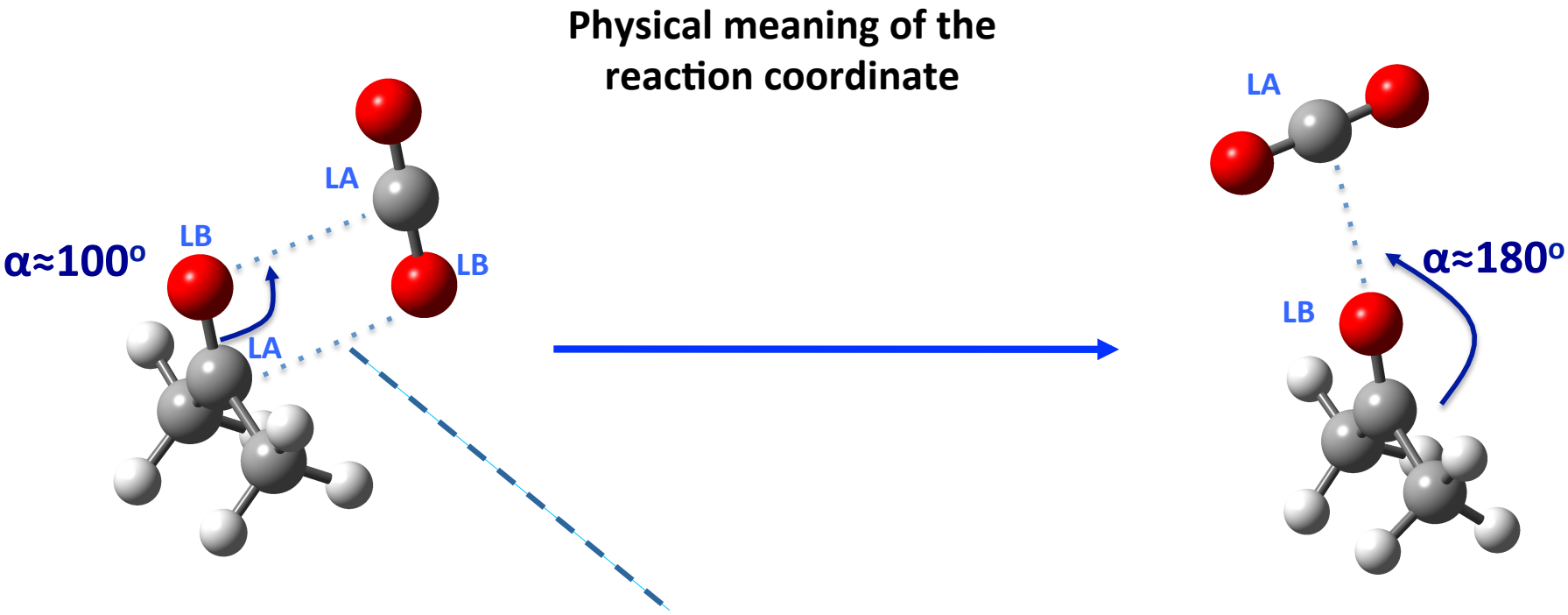
Altarsha, Ingrosso, Ruiz-López, JPCB 2012.
Altarsha, Ingrosso, Ruiz-López, ChemPhysChem, 2012.

More CO_2-philic systems

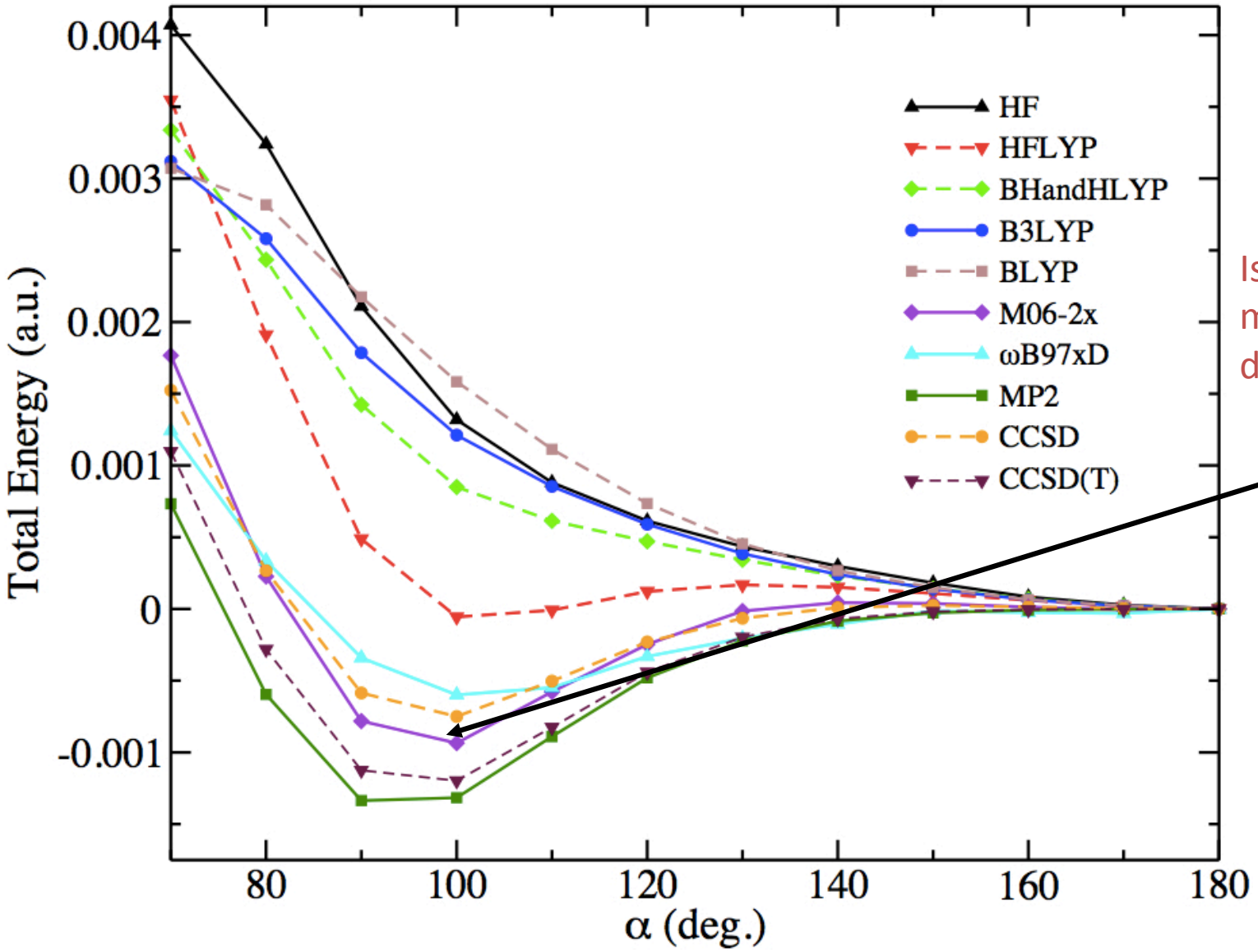


Azofra, Altarsha, Ruiz-López, Ingrosso, Theor. Chem. Acc. 2013.

Defining an *ad hoc* coordinate for a PES study



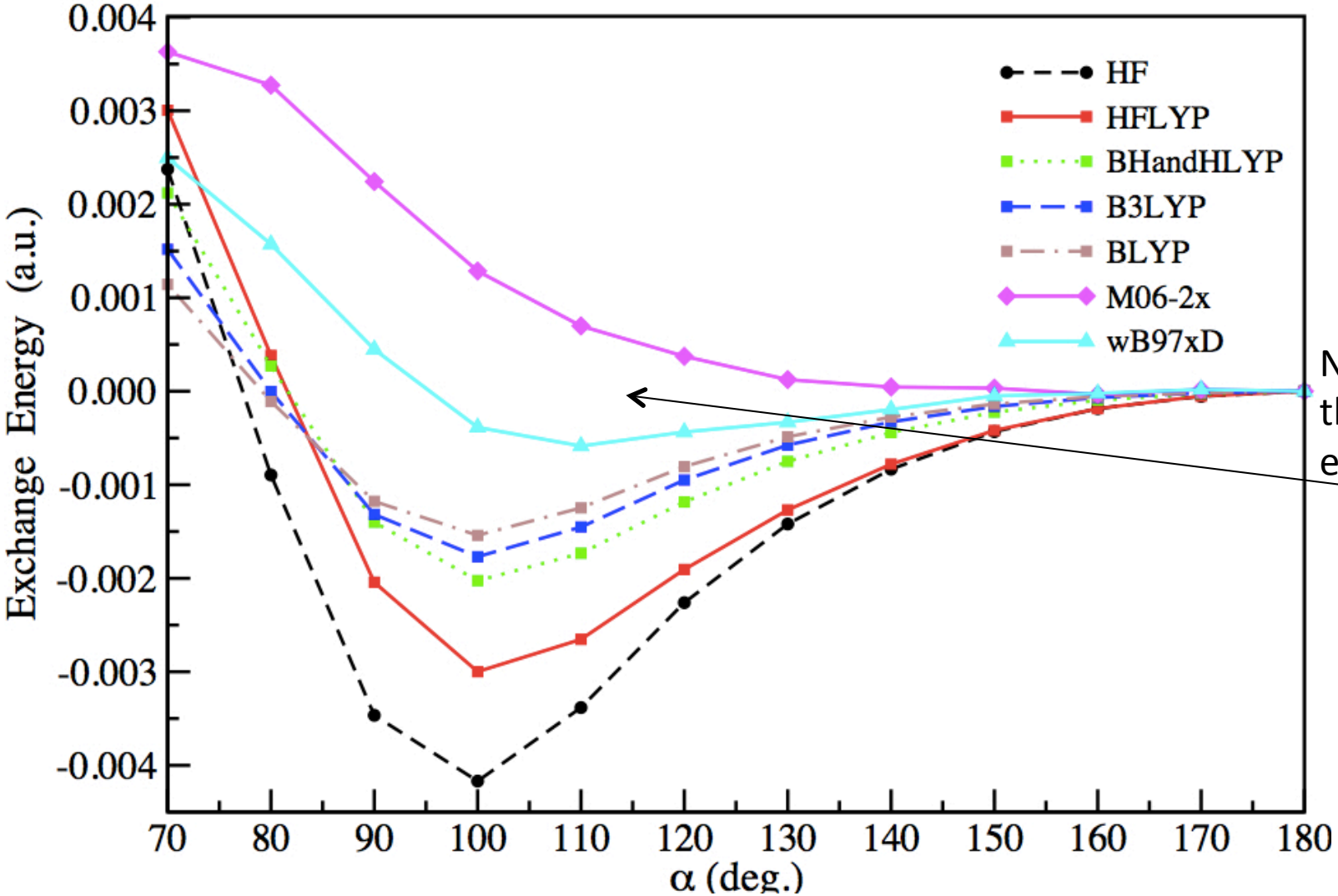
PES: the effect of the level of theory



Is this energy minimum correctly described?

San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.

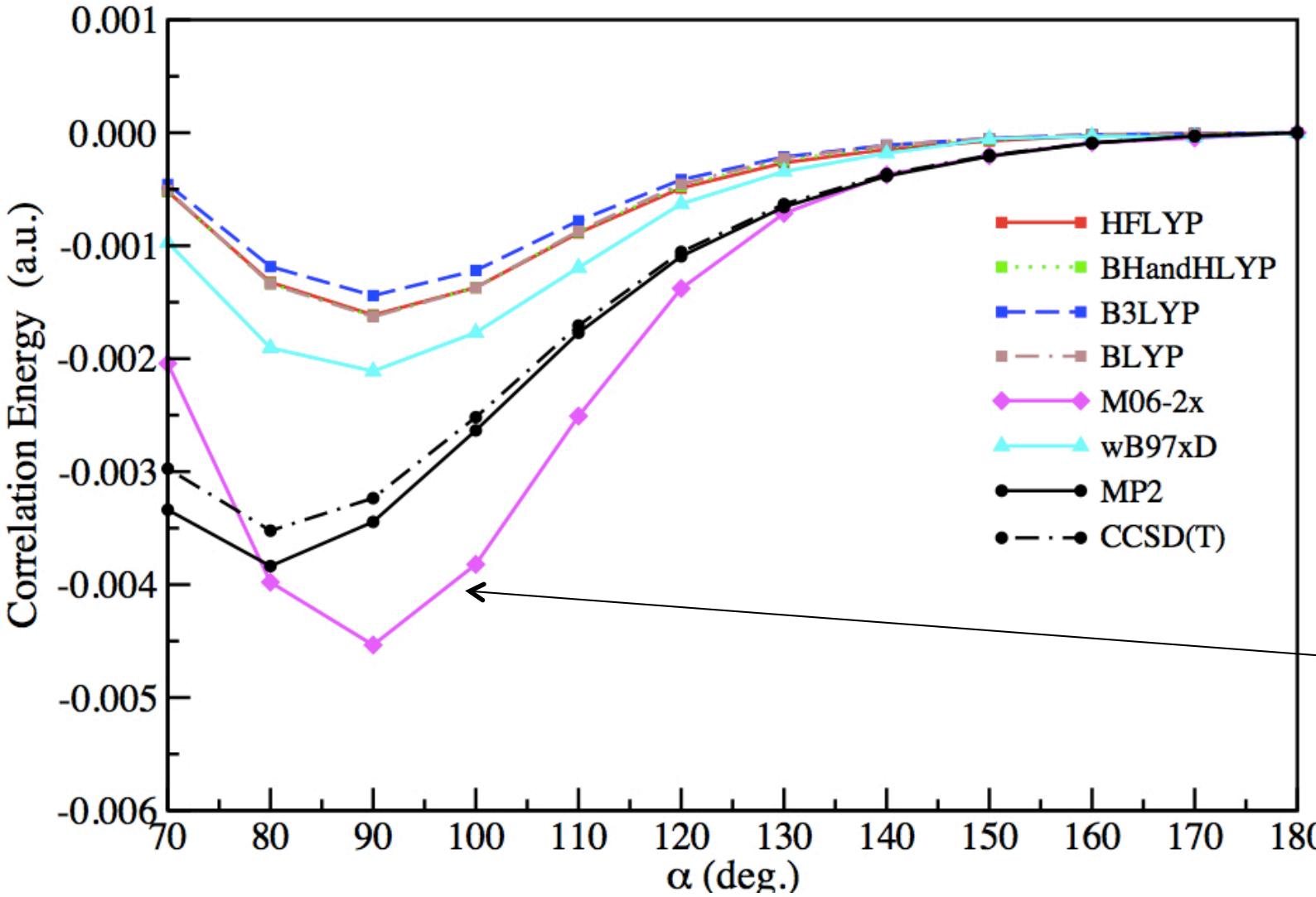
Exchange contribution



Not a minimum in the exchange energy!

San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.

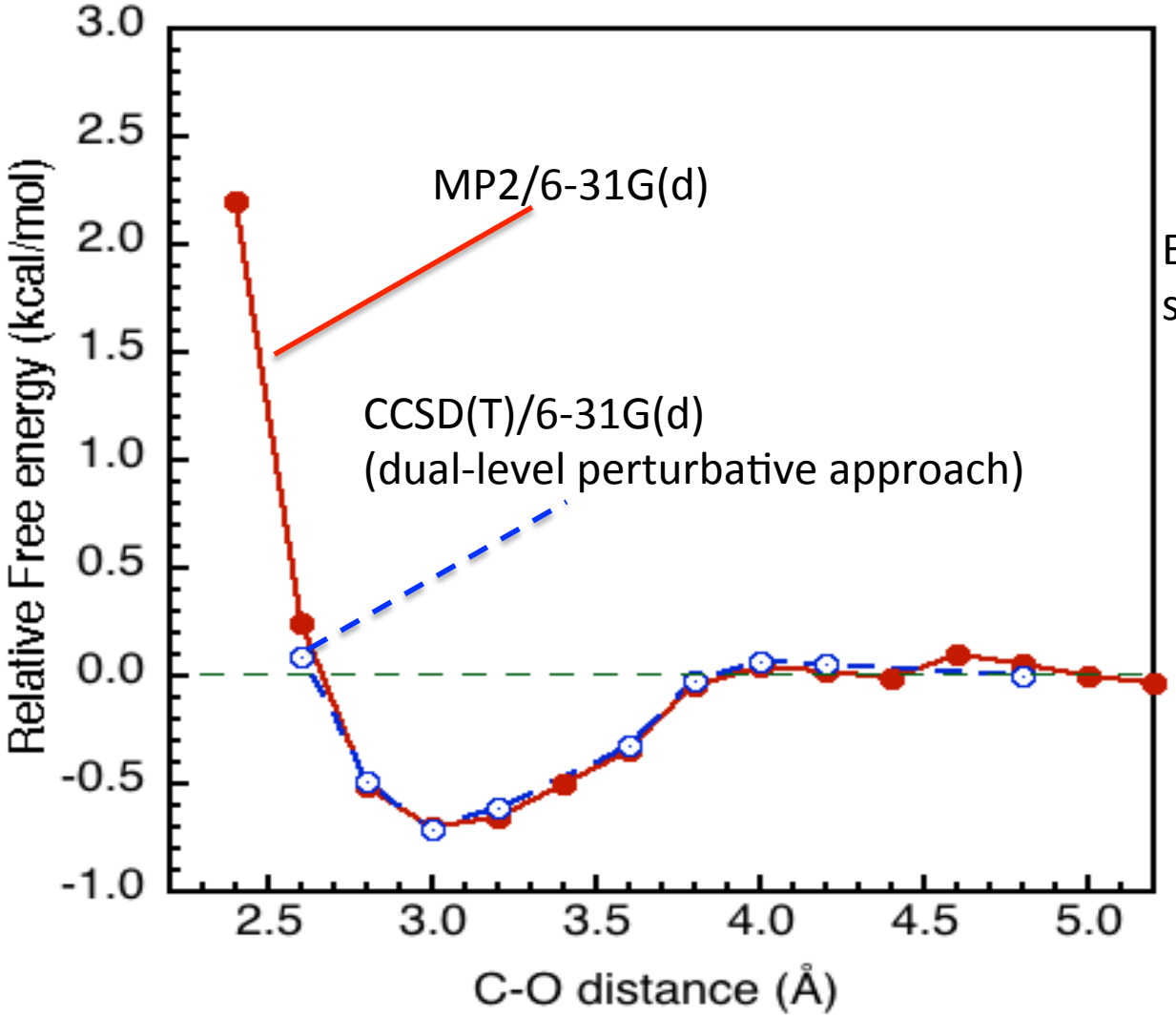
Correlation contribution



Correlation contribution is overestimated!

San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.

From interaction energies to free energies



Estimated free energy of stabilization at 304K: -0.7 kcal/mol.

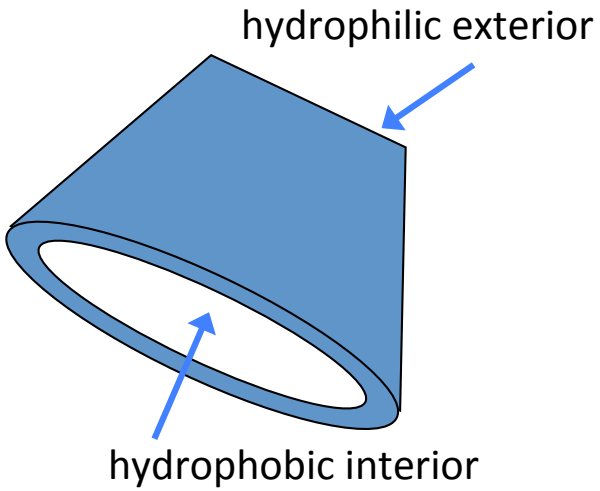
Ab initio MD umbrella sampling. PMF for the formation of the CO_2-acetone complex.

San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.
Munoz, Martins-Costa, Ingrosso, Ruiz-López, Mol. Sim. 2014.

Presentation outline

- CO_2-phicility: about the nature of CO_2-carbonyl interactions.
- Solubilizers and supercritical CO_2 ($scCO_2$).
- News and perspectives.

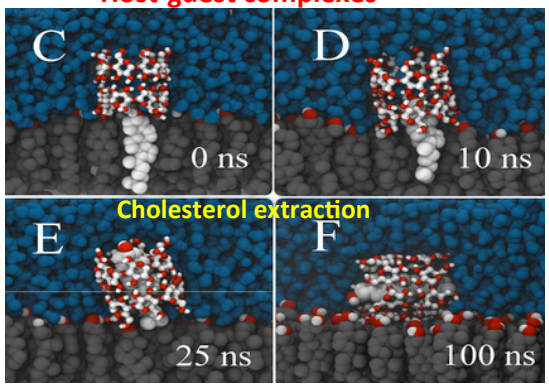
The idea behind '*solubilizers*'

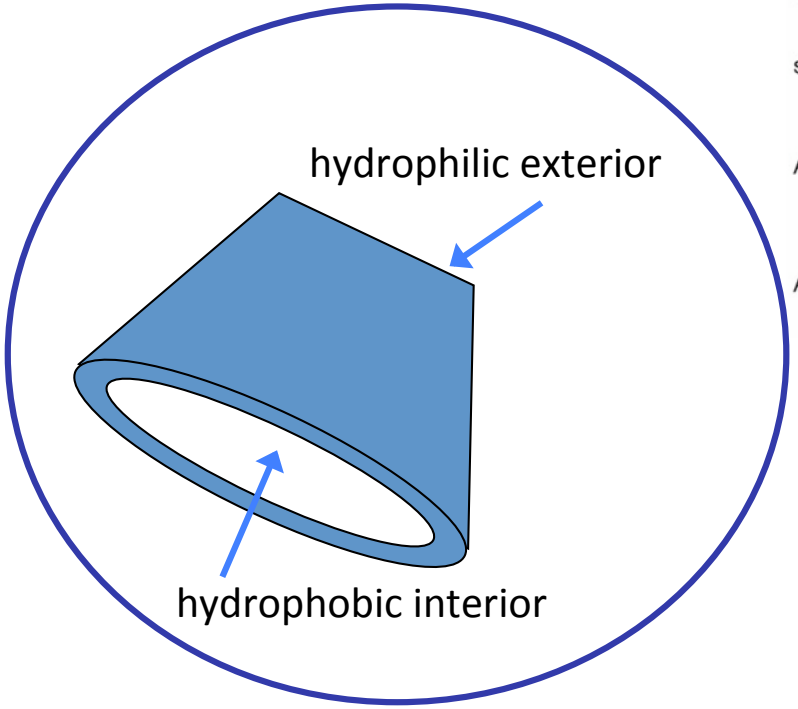


Cyclodextrines and their uses in water/organic solvents

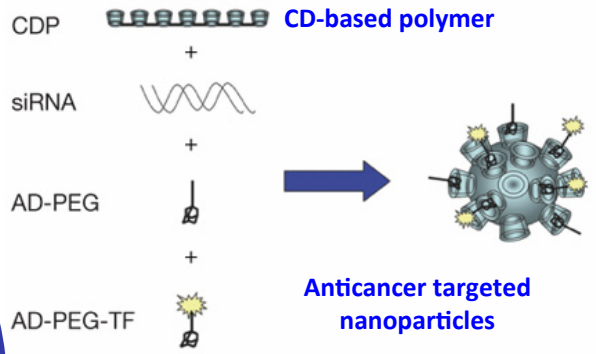
Native CDs: natural products originating from bacterial digestion of cellulose.

Host-guest complexes





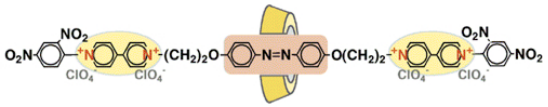
Drug delivery

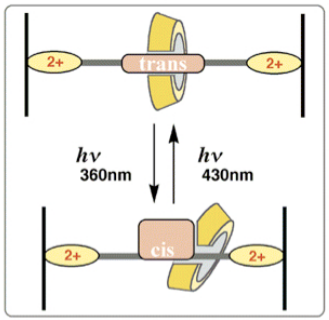


Anticancer targeted nanoparticles

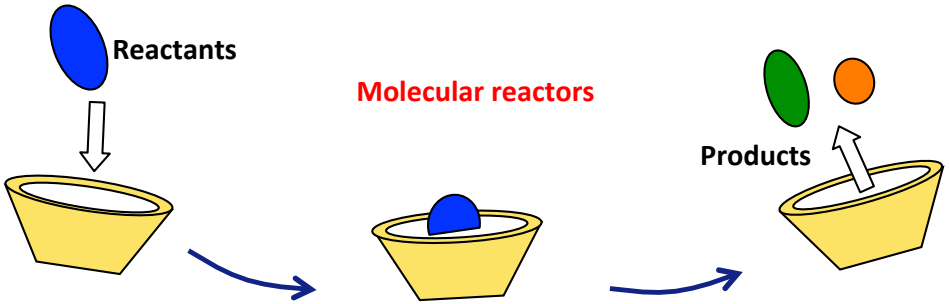
Separation of optical isomers

Supermolecular chemistry



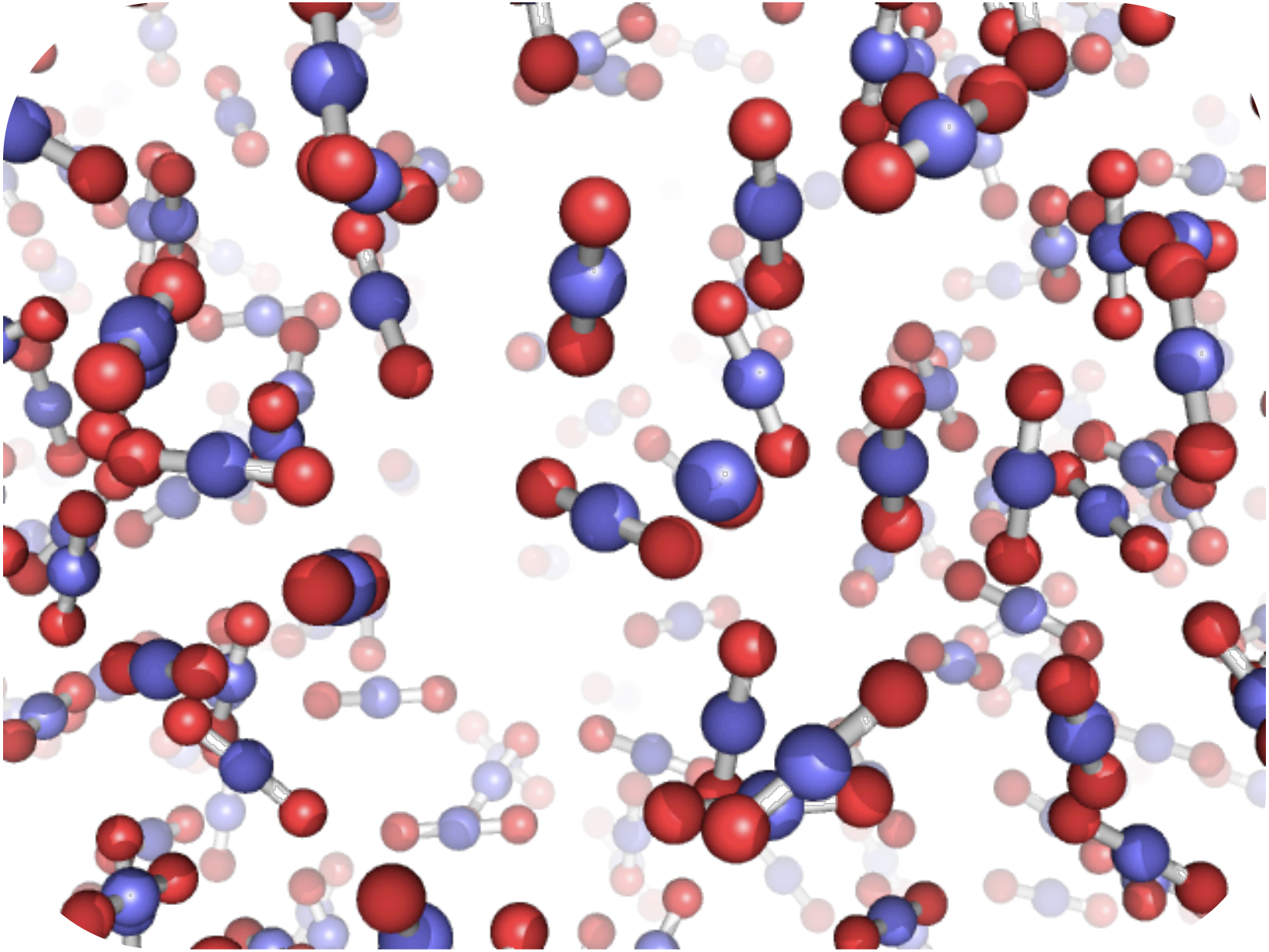


Molecular shuttles



López, de Vries, Marrink, PLOS Comput.Biol. 2011.
Harada, Acc.Chem.Res. 2001. Davis et al., Nature 2010.
Yeguas, López, Lambert, Monard, Ruiz-López Org. Biomol. Chem. 2010.

… and what about $scCO_2$?



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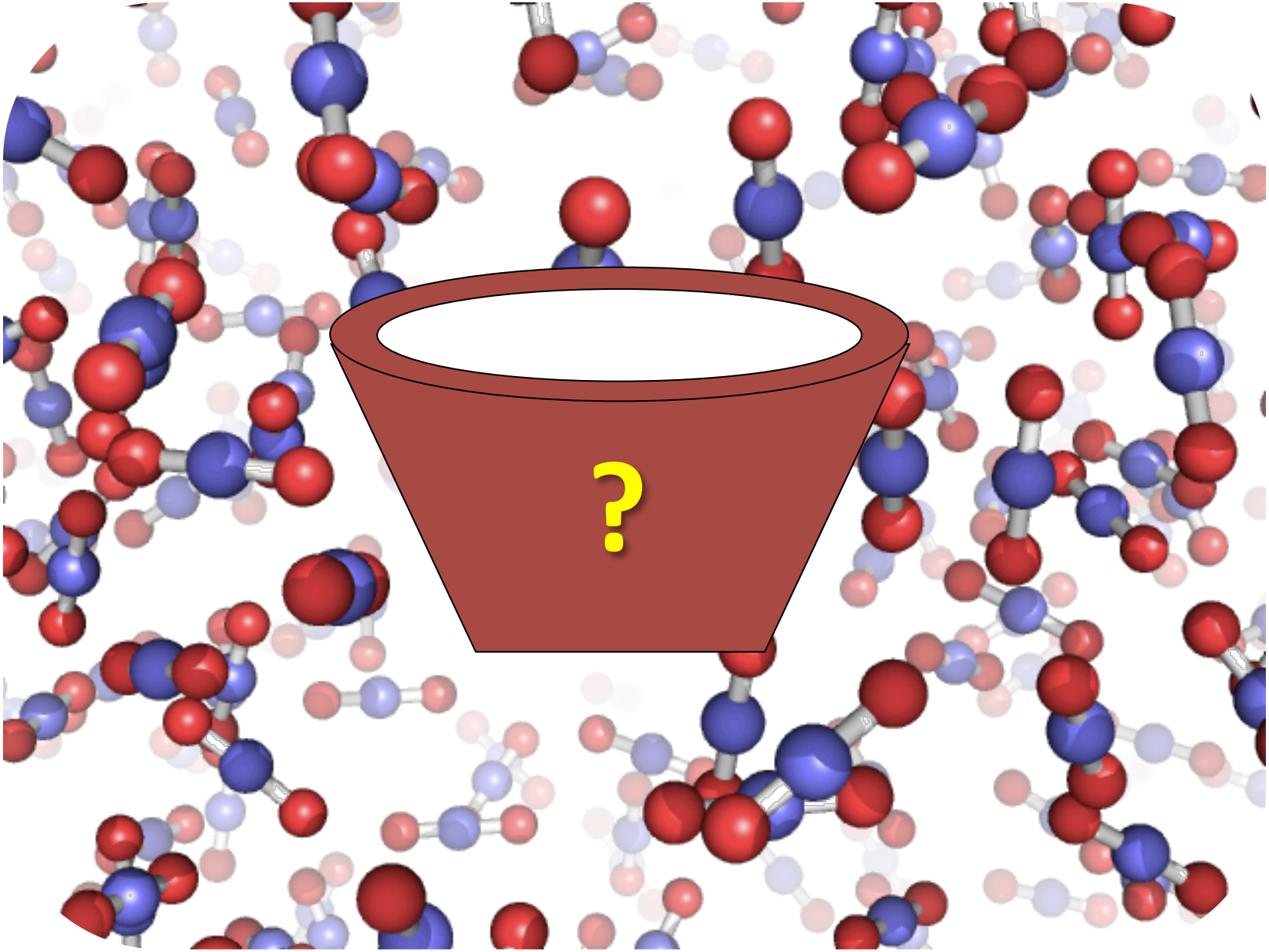
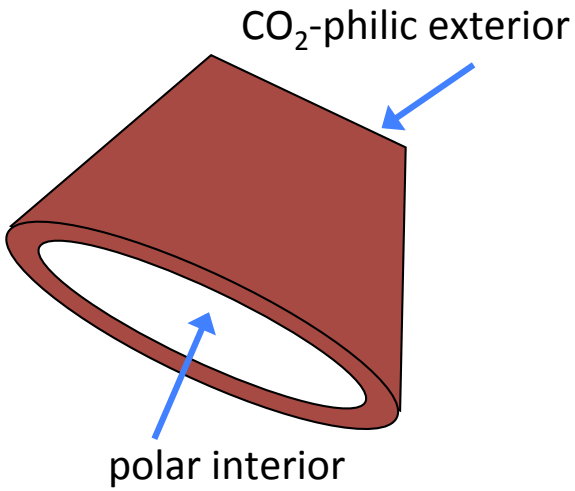


Possible '*solubilizers*' in $scCO_2$



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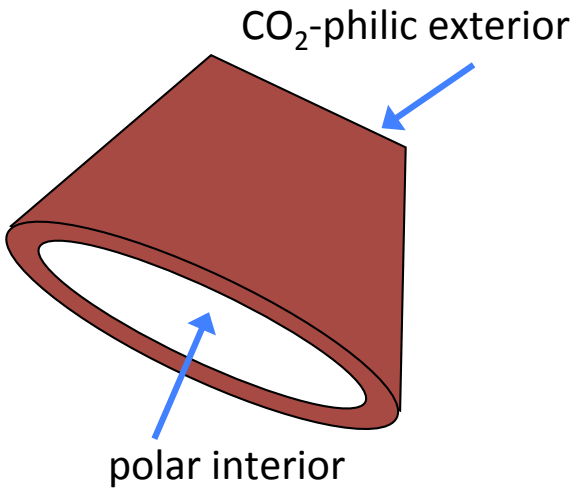
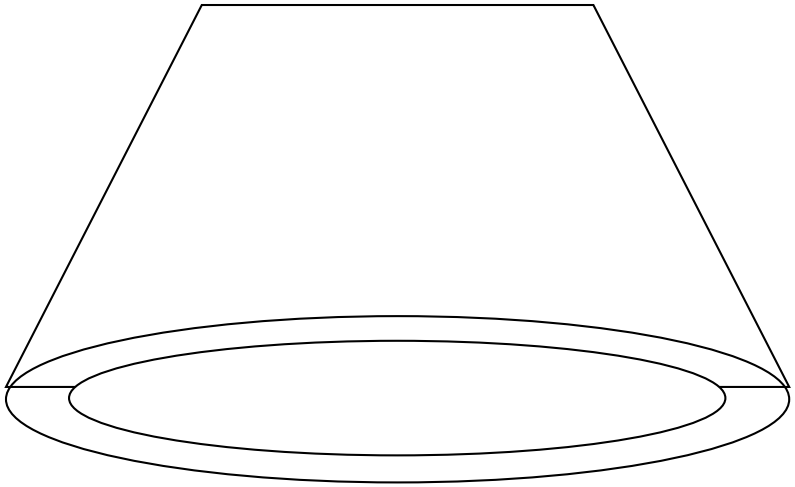
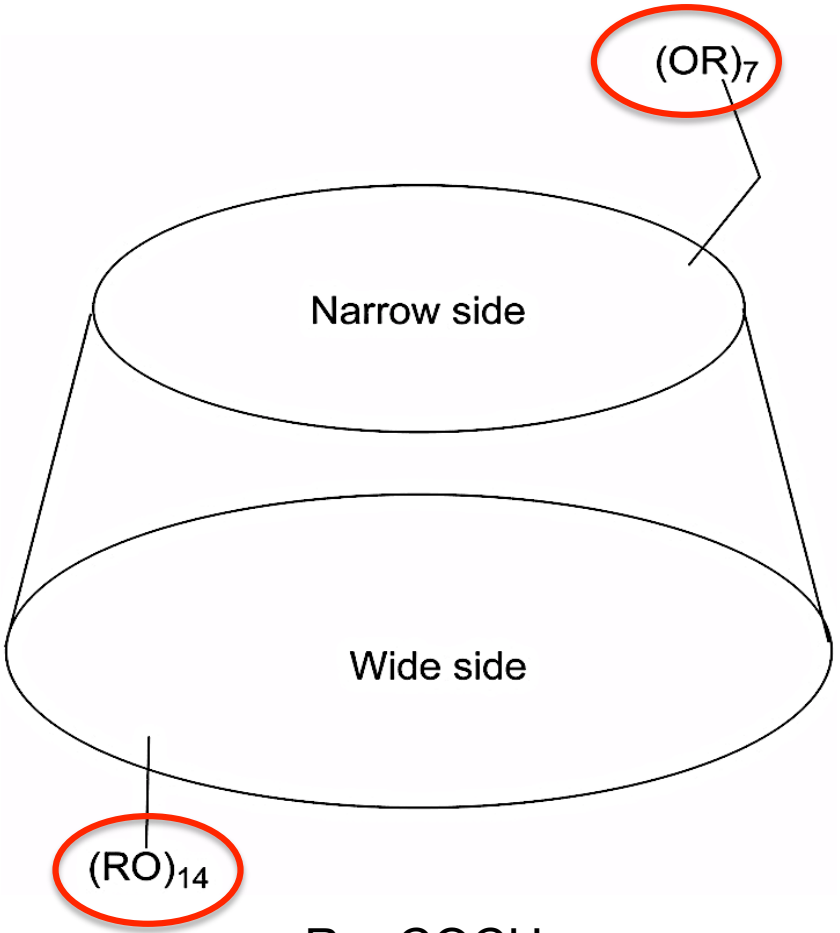


There exists one type of CO_2-philic cyclodextrins!

Peracetylated CD is soluble in $scCO_2$



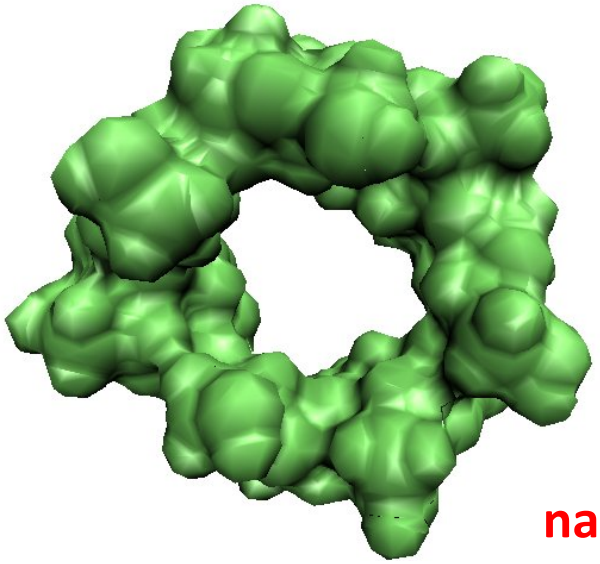


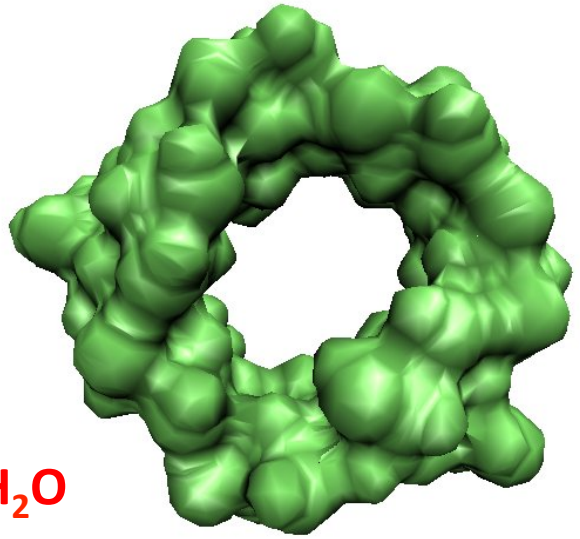
R = $COCH_3$

Potluri et al. Org. Lett. 2002.

Changes in the cavity shape

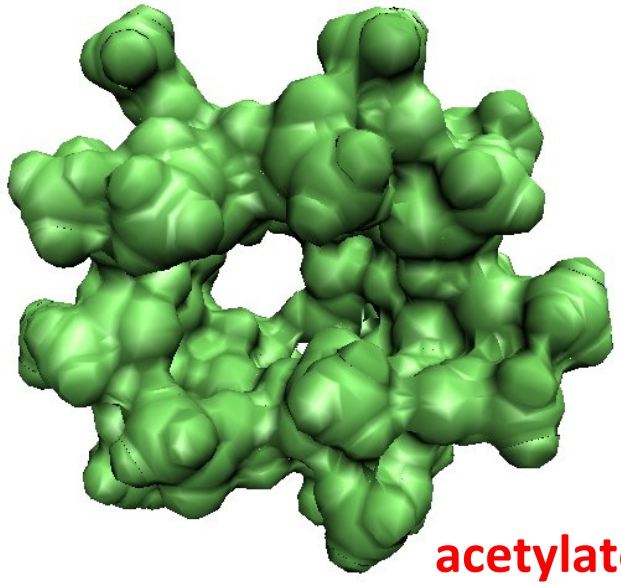
Top view

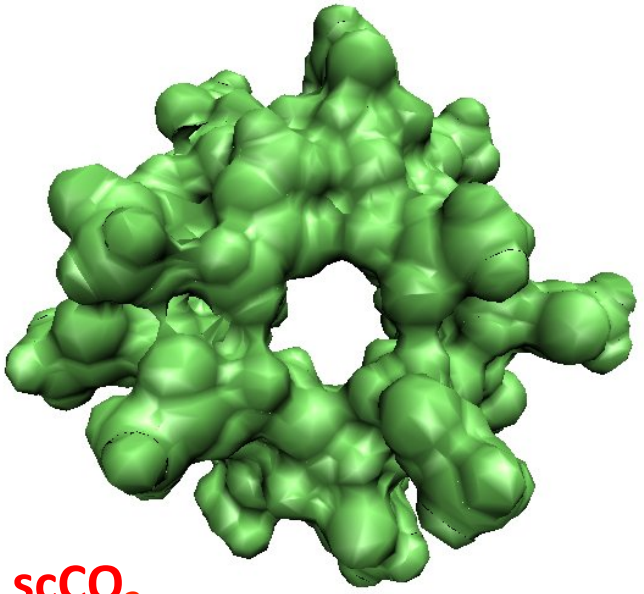




Bottom view

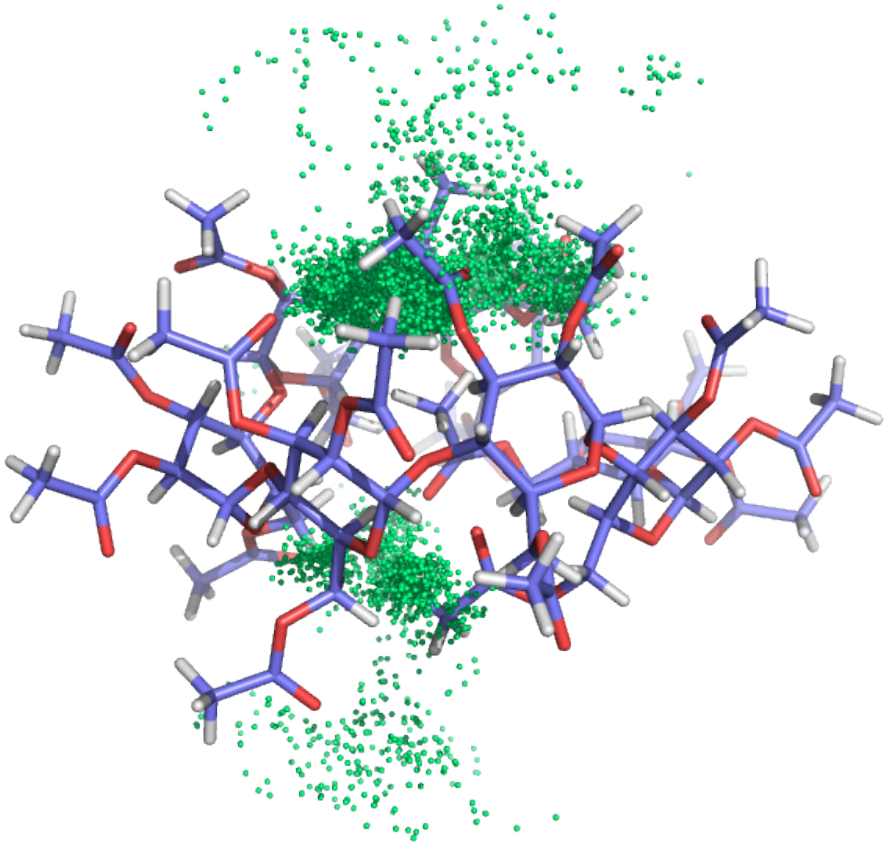
native CD in H_2O



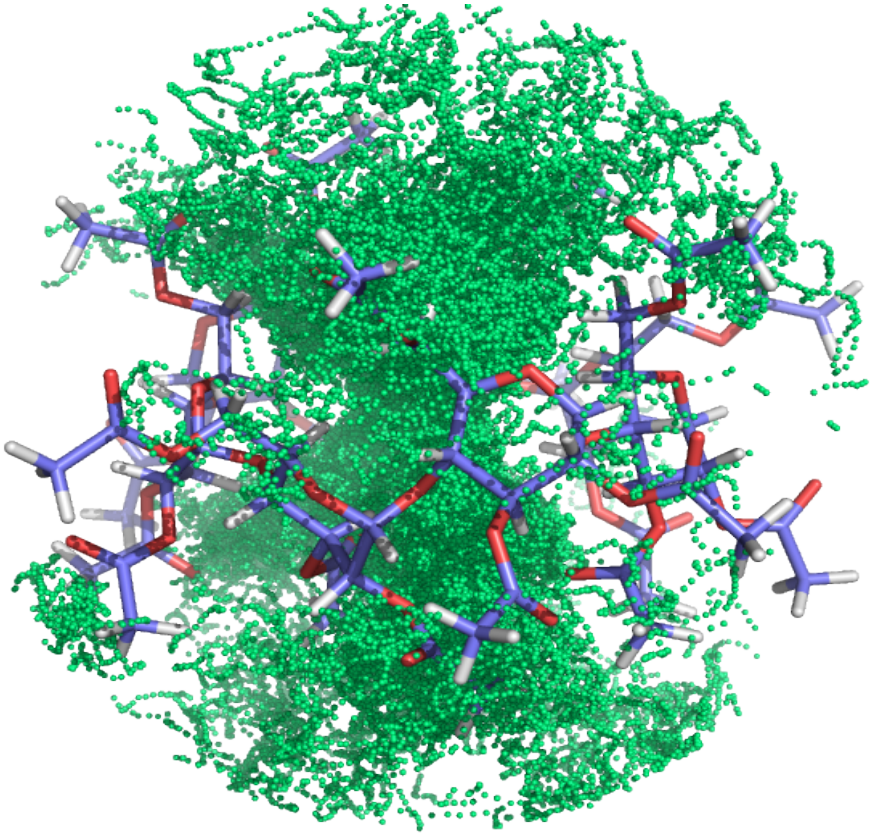


acetylated CD in $scCO_2$

Problem: solvent accessibility



Closed Cyclodextrin Cavity

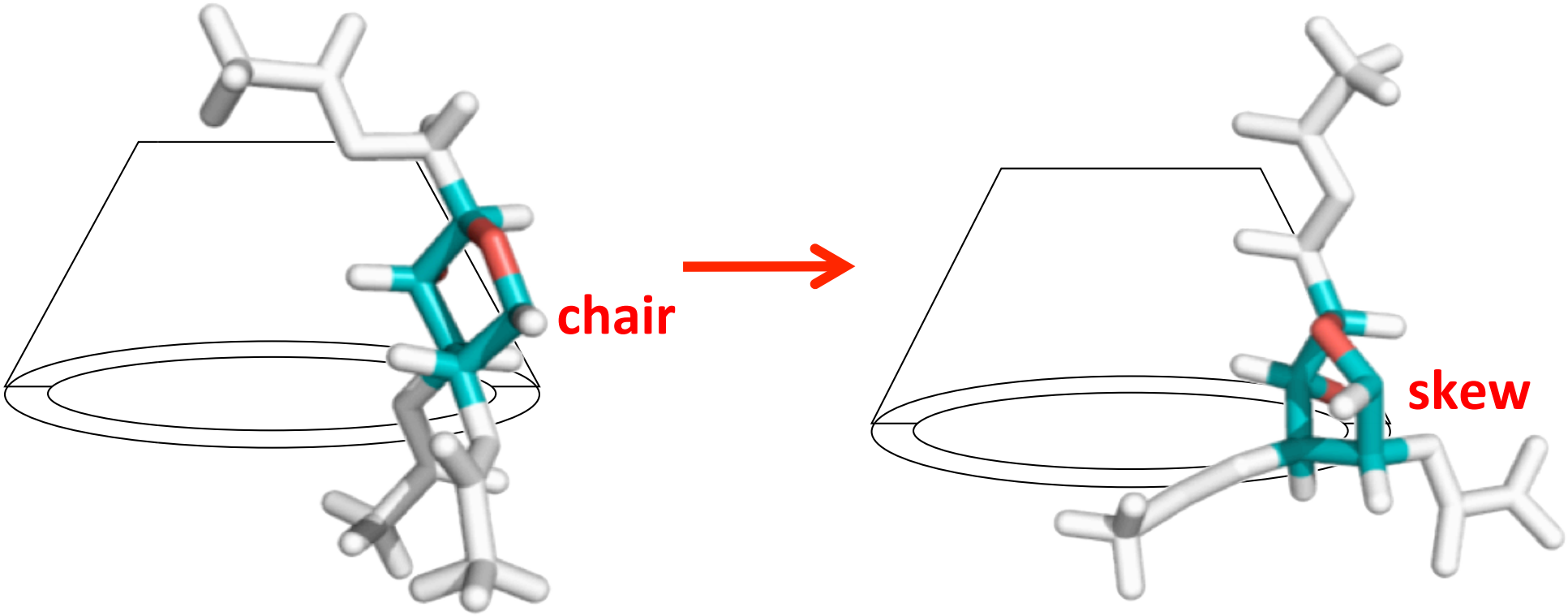


Open Cyclodextrin Cavity

Altarsha, Ingrosso, Ruiz-López, JPCB 2012.

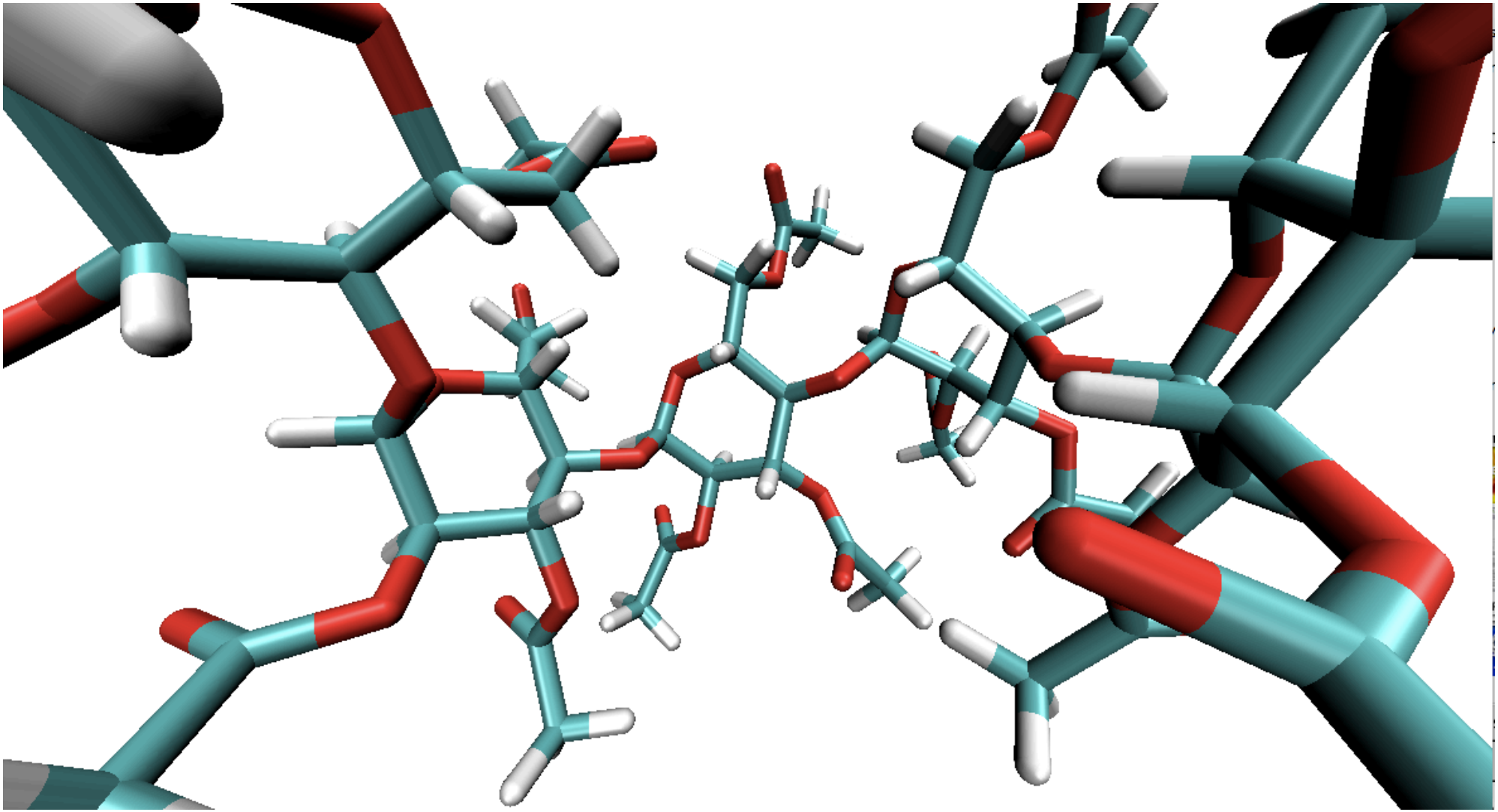
Insights into cavity distortion

Conformational changes observed in one glucopyranose unit



Altarsha, Ingrosso, Ruiz-López, JPCB 2012.

Solution: finding the right guest for our host



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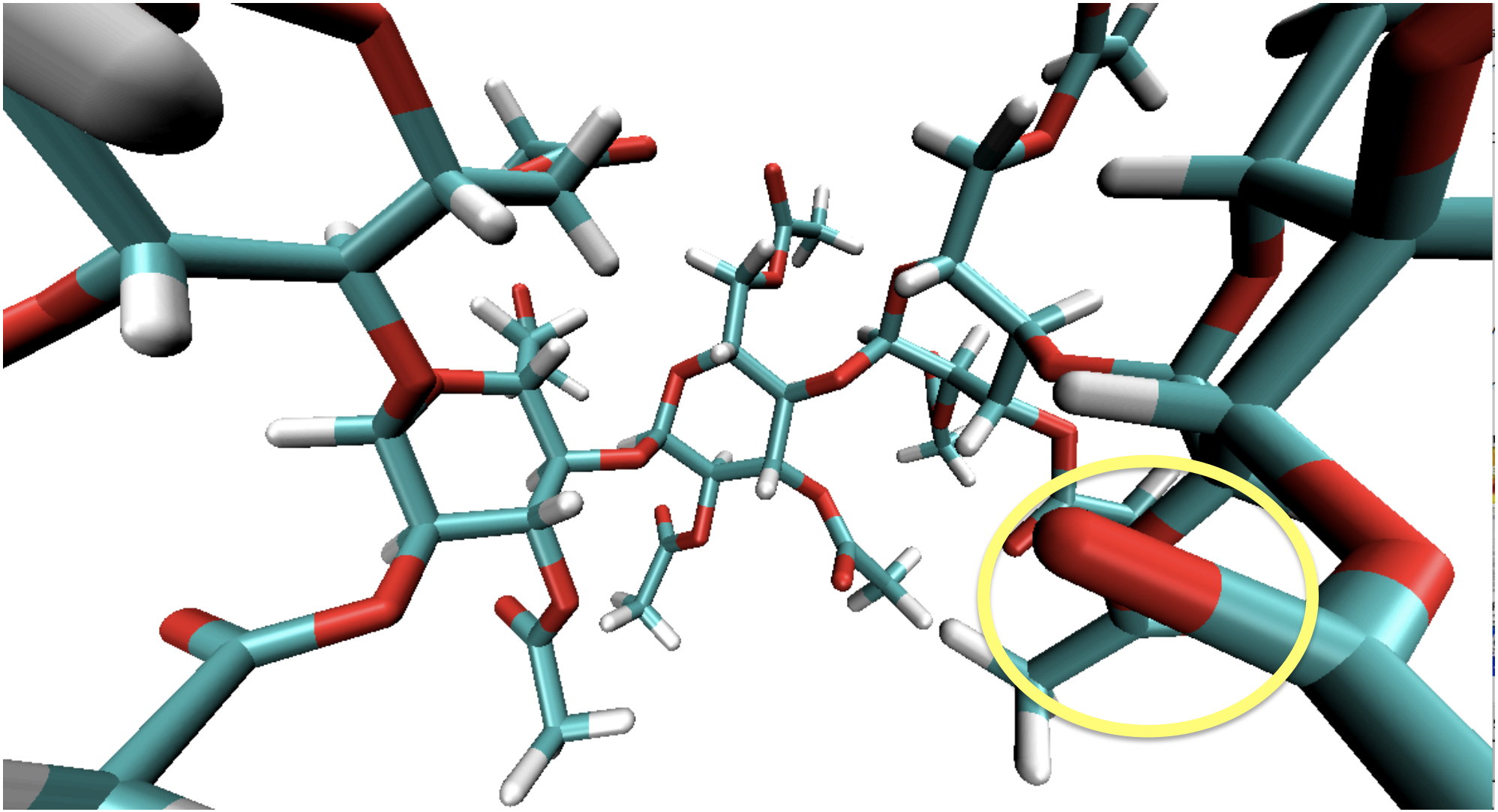

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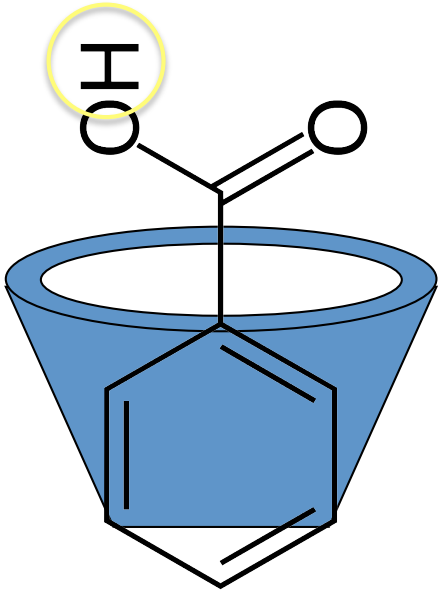
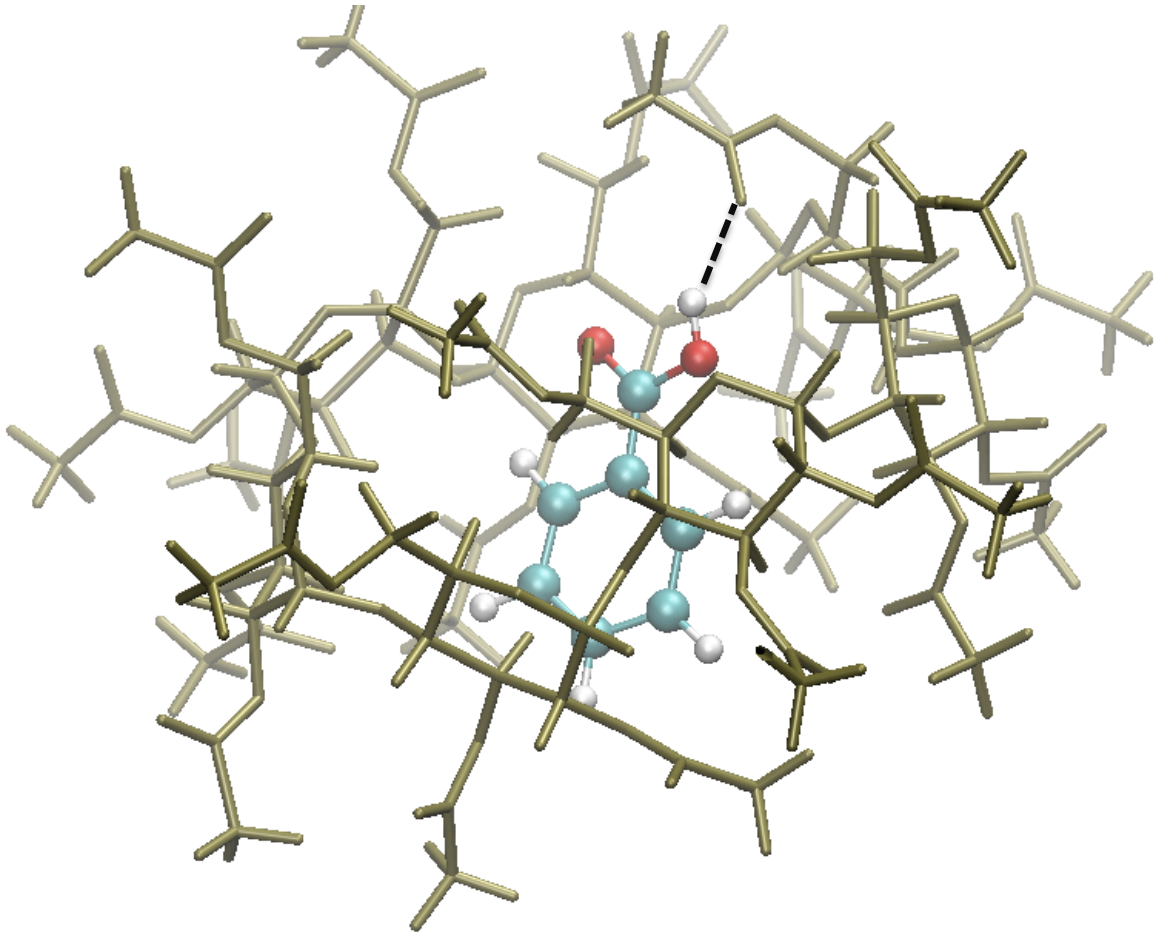
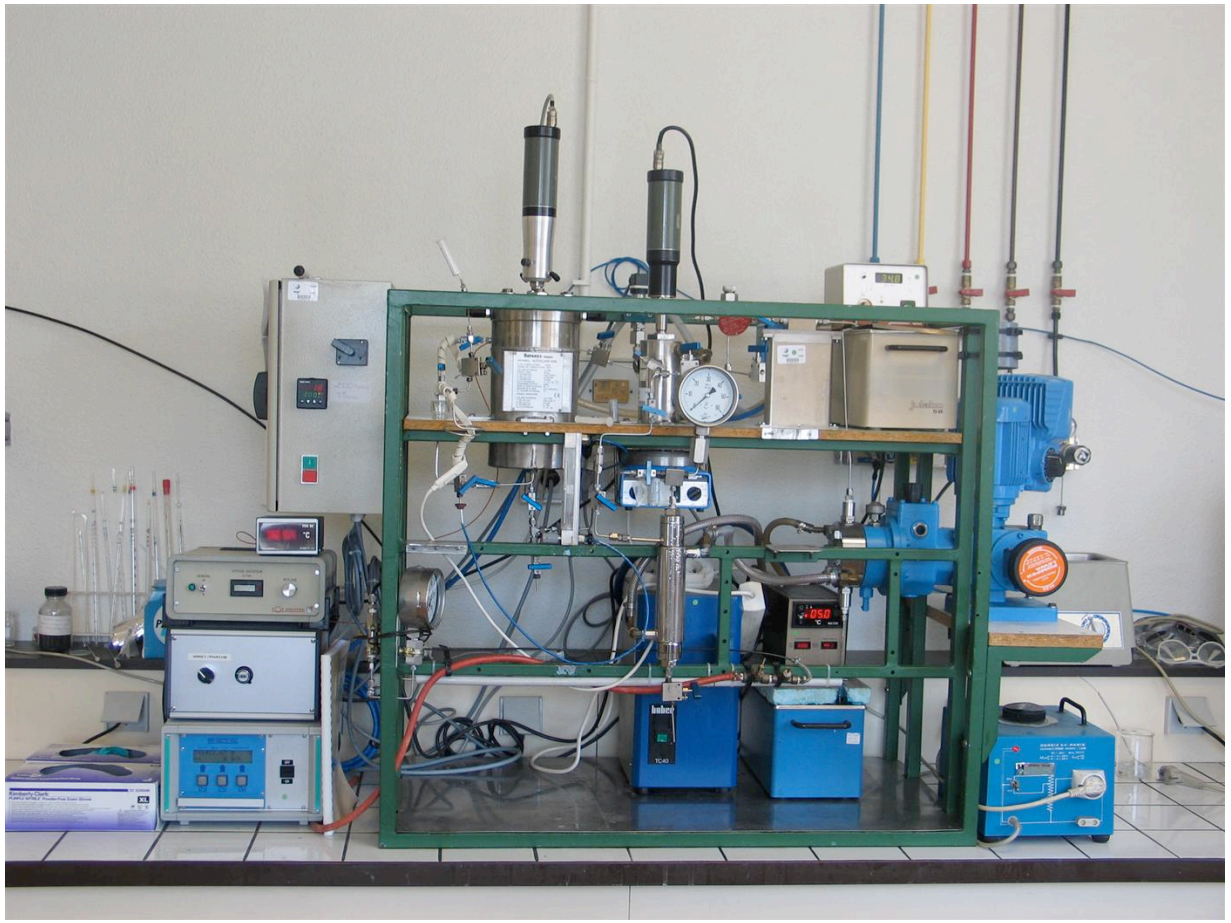


benzoic acid



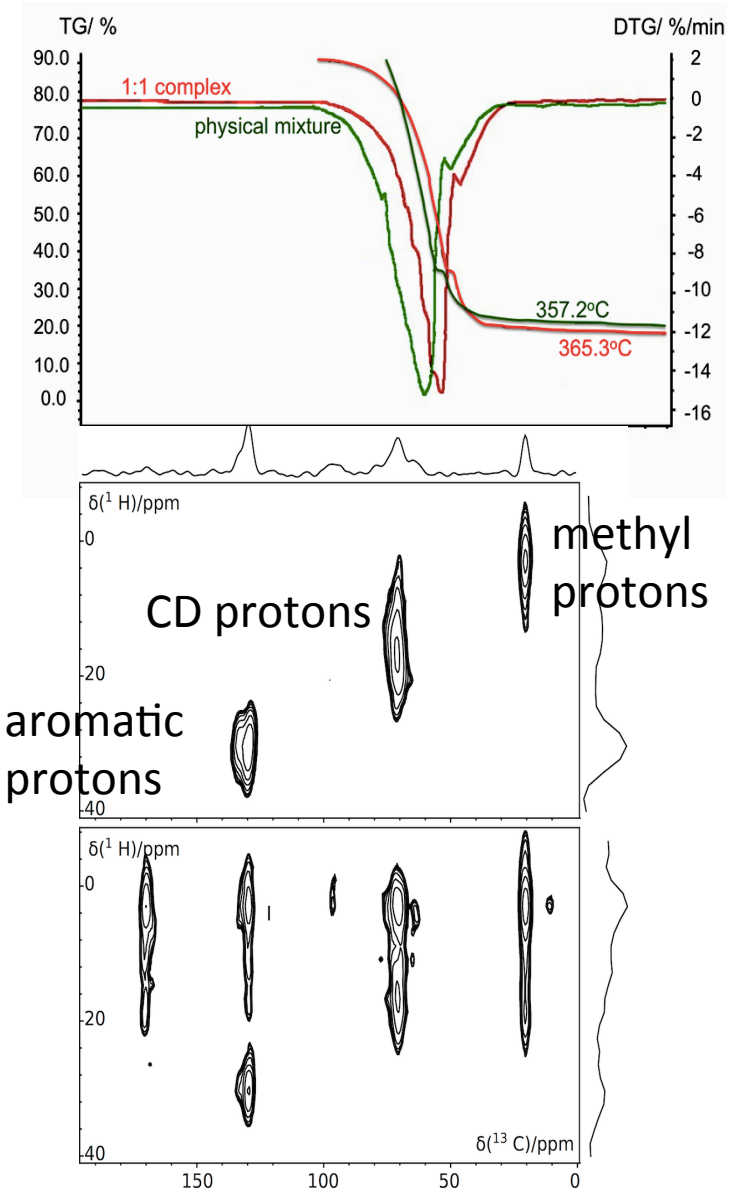
Host-(polar)guest interactions stabilized by a stable hydrogen bond formation.

Synthesis of the first host-guest complex in $scCO_2$

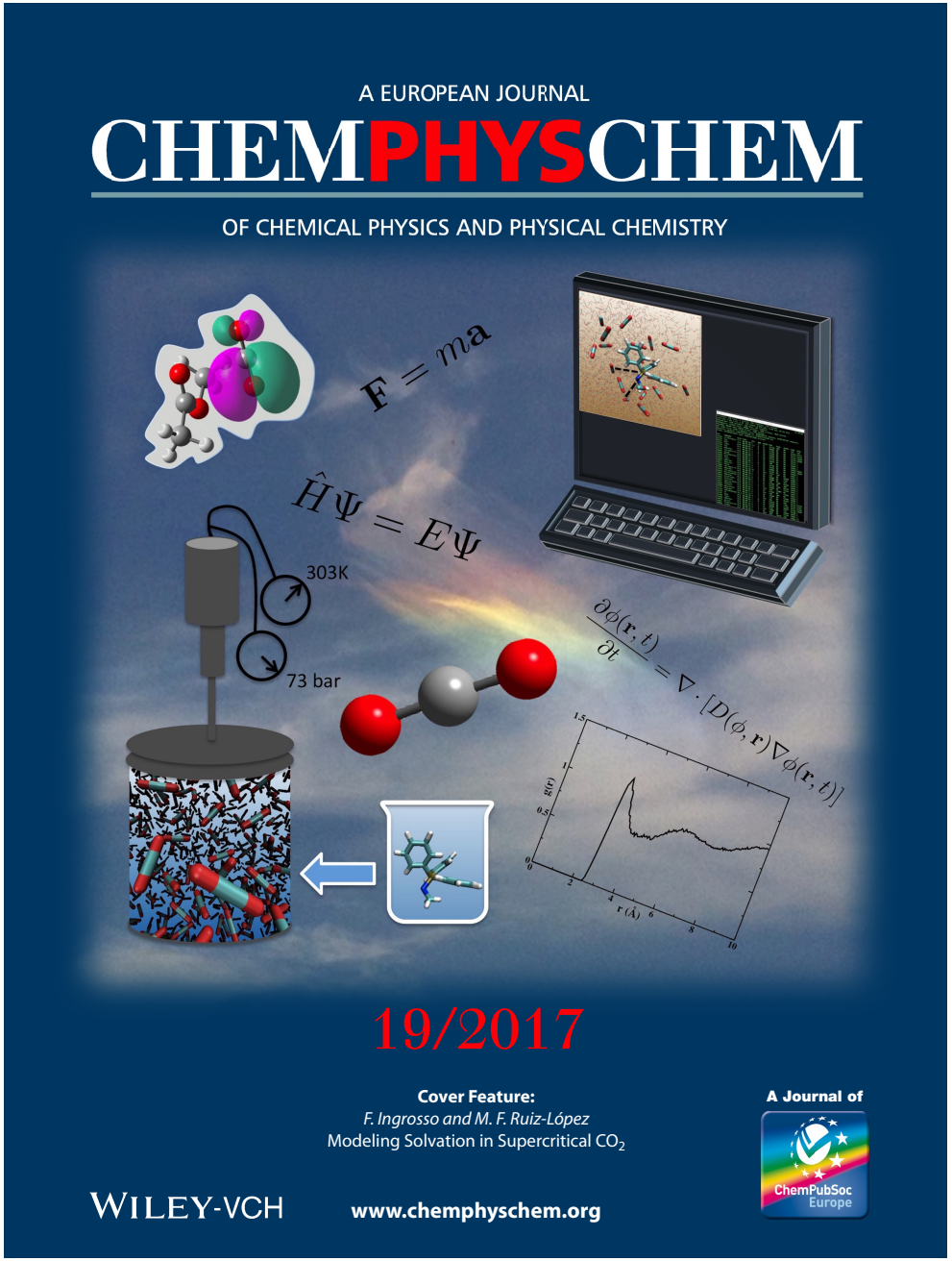


ENSIC $scCO_2$ reactor, Nancy
Courtesy of Dr. D. Barth

Synthesis of the first host-guest complex in $scCO_2$



Some review work



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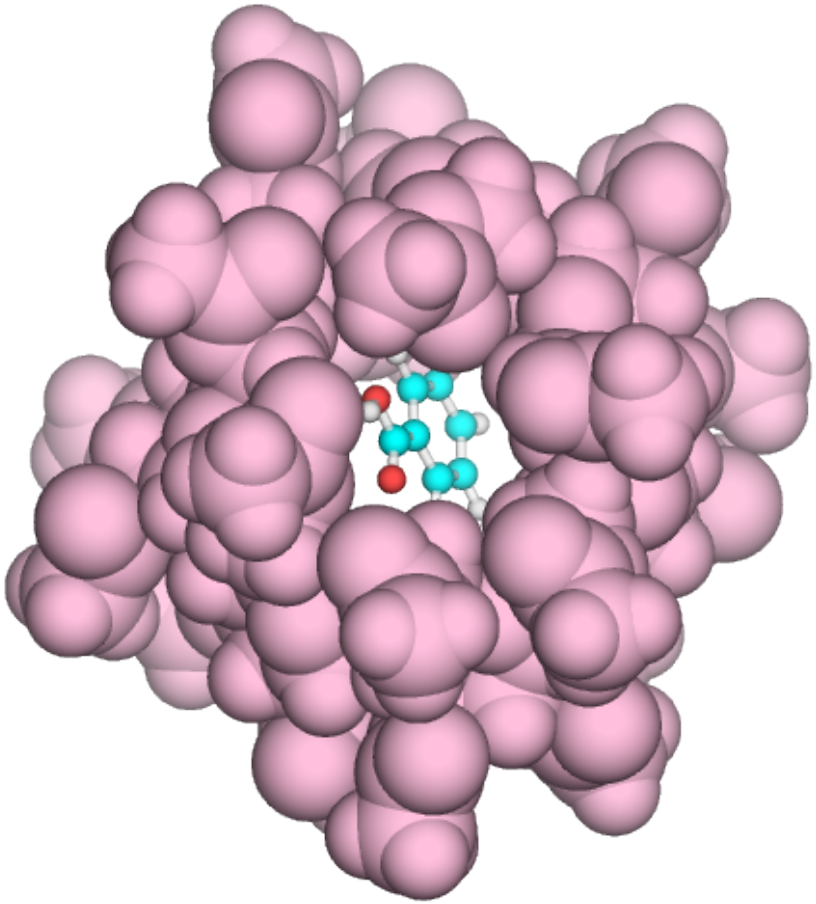
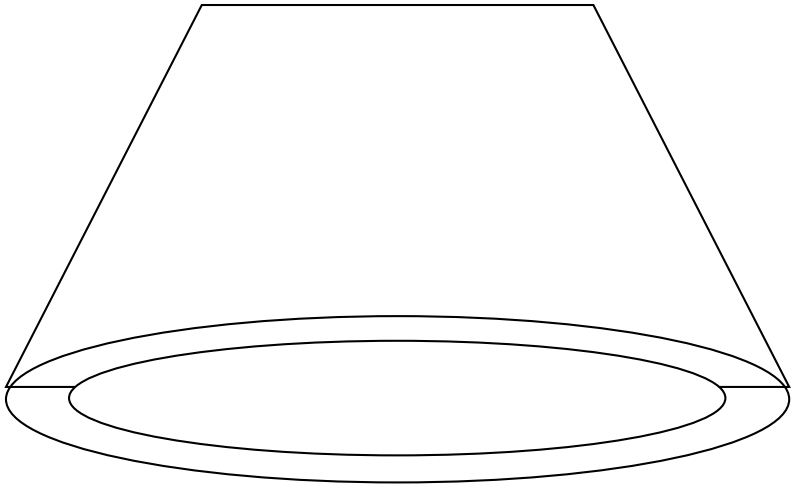
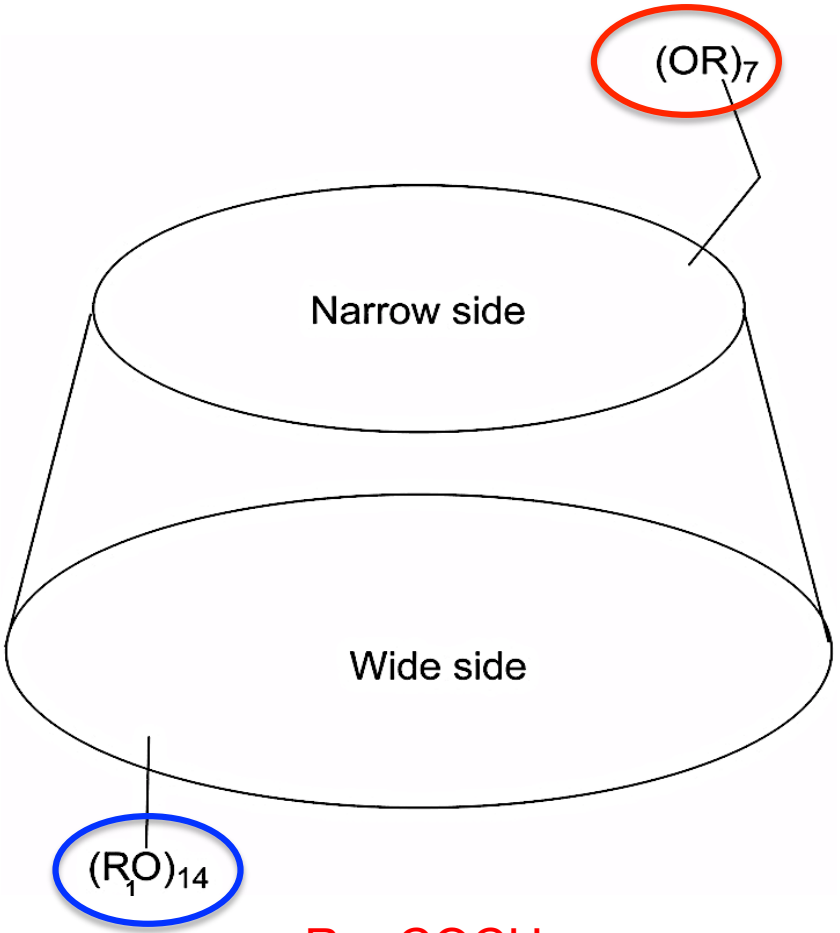


CD news…

Narrow side acetylated CD





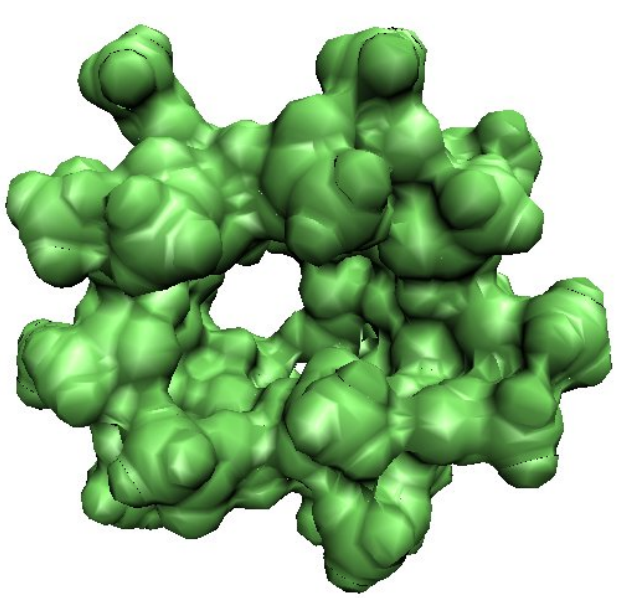
R = $COCH_3$

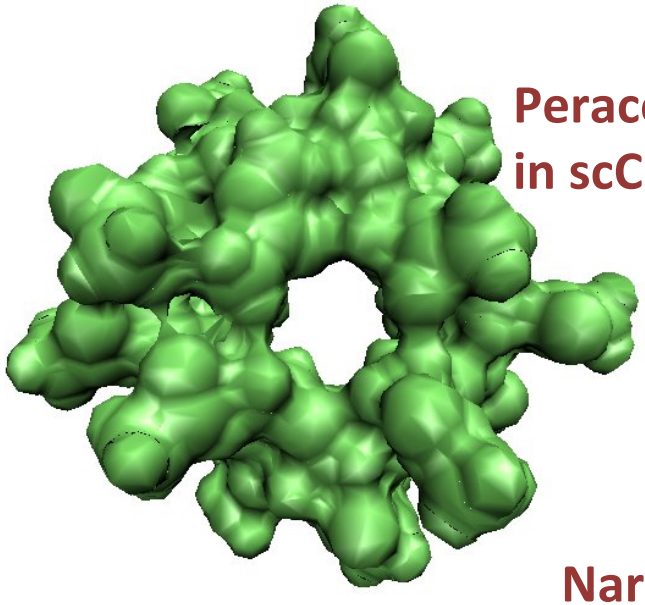
R_1 = OH

Narrow side acetylated CD in $scCO_2$

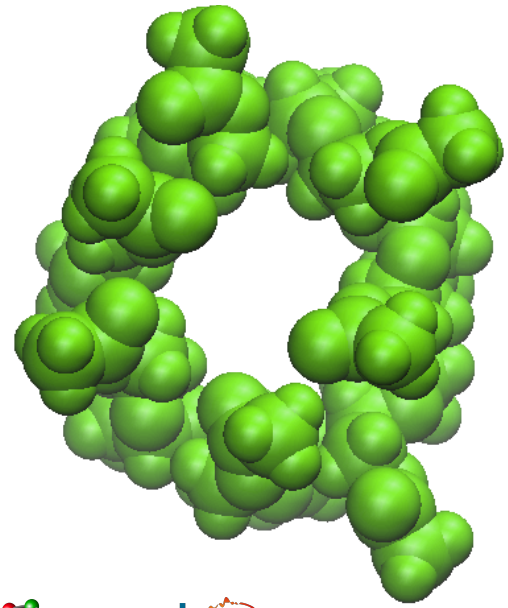
Top view

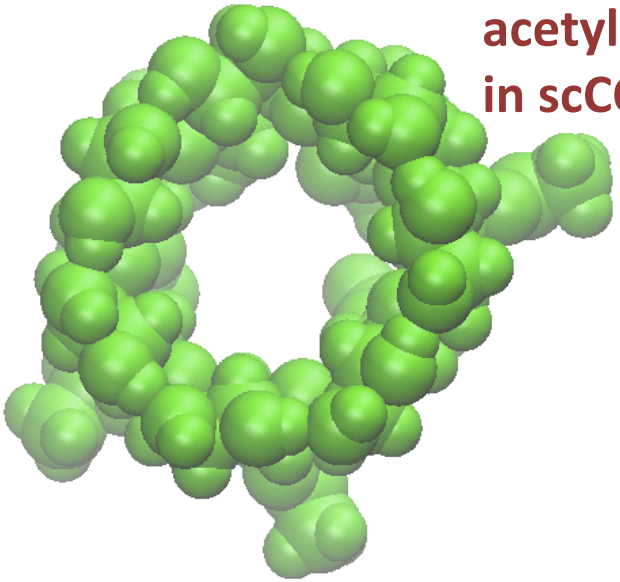
Bottom view





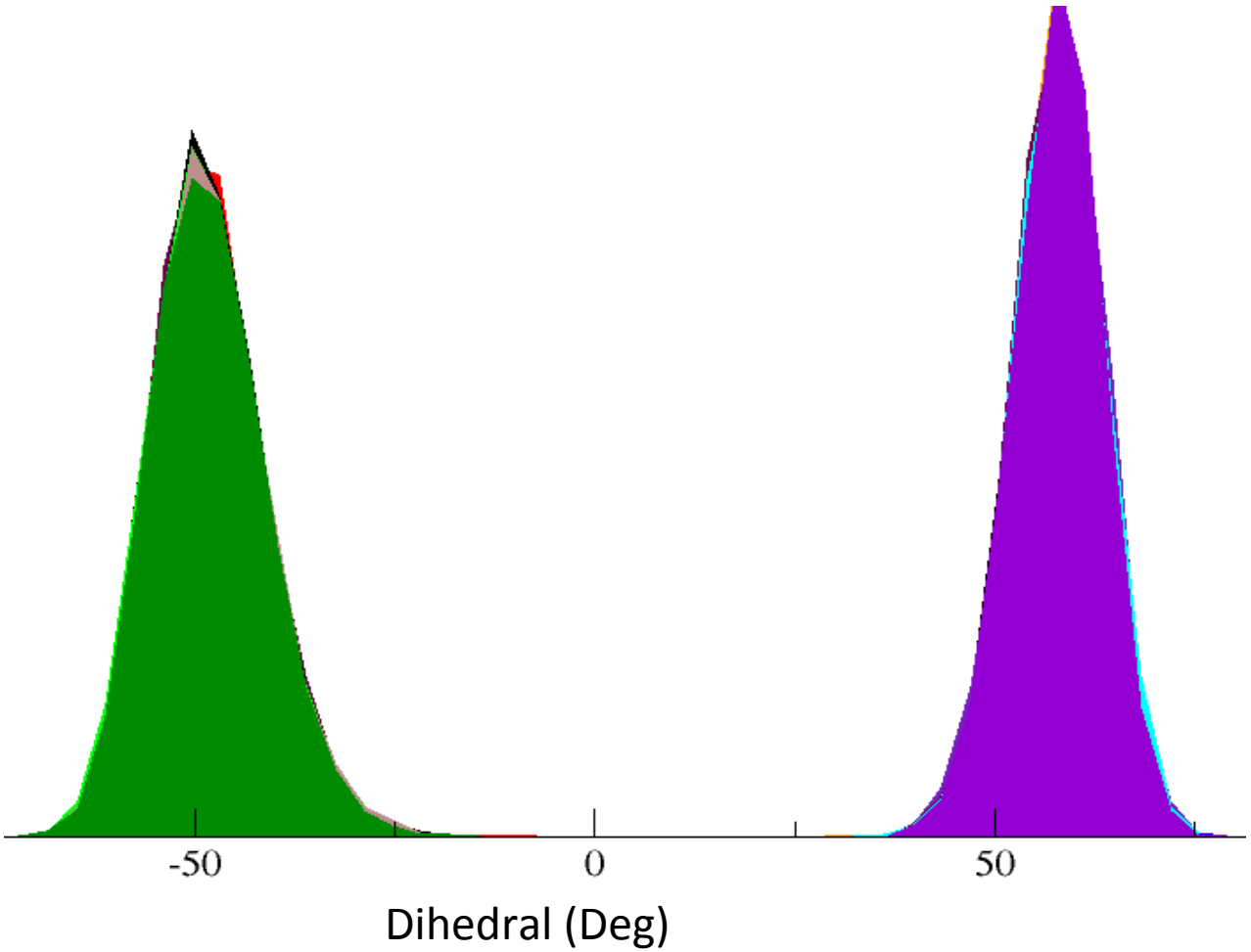
Peracetylated CD in $scCO_2$

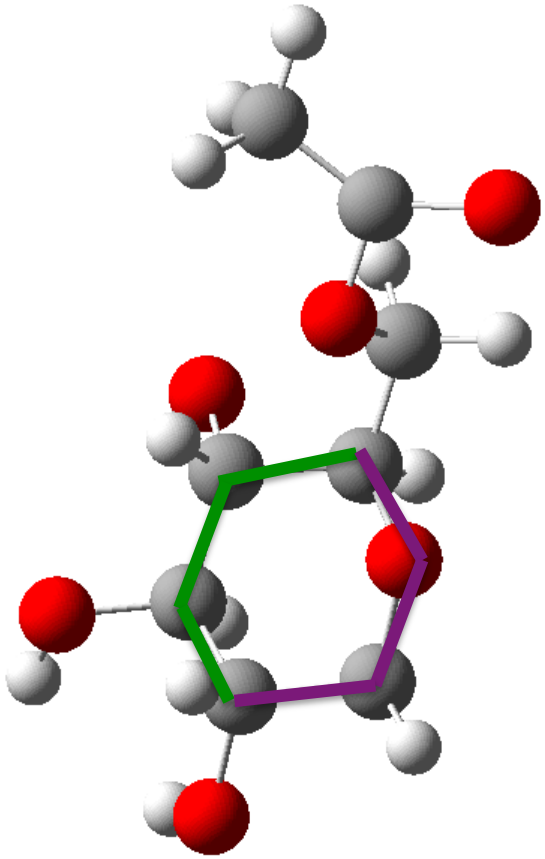




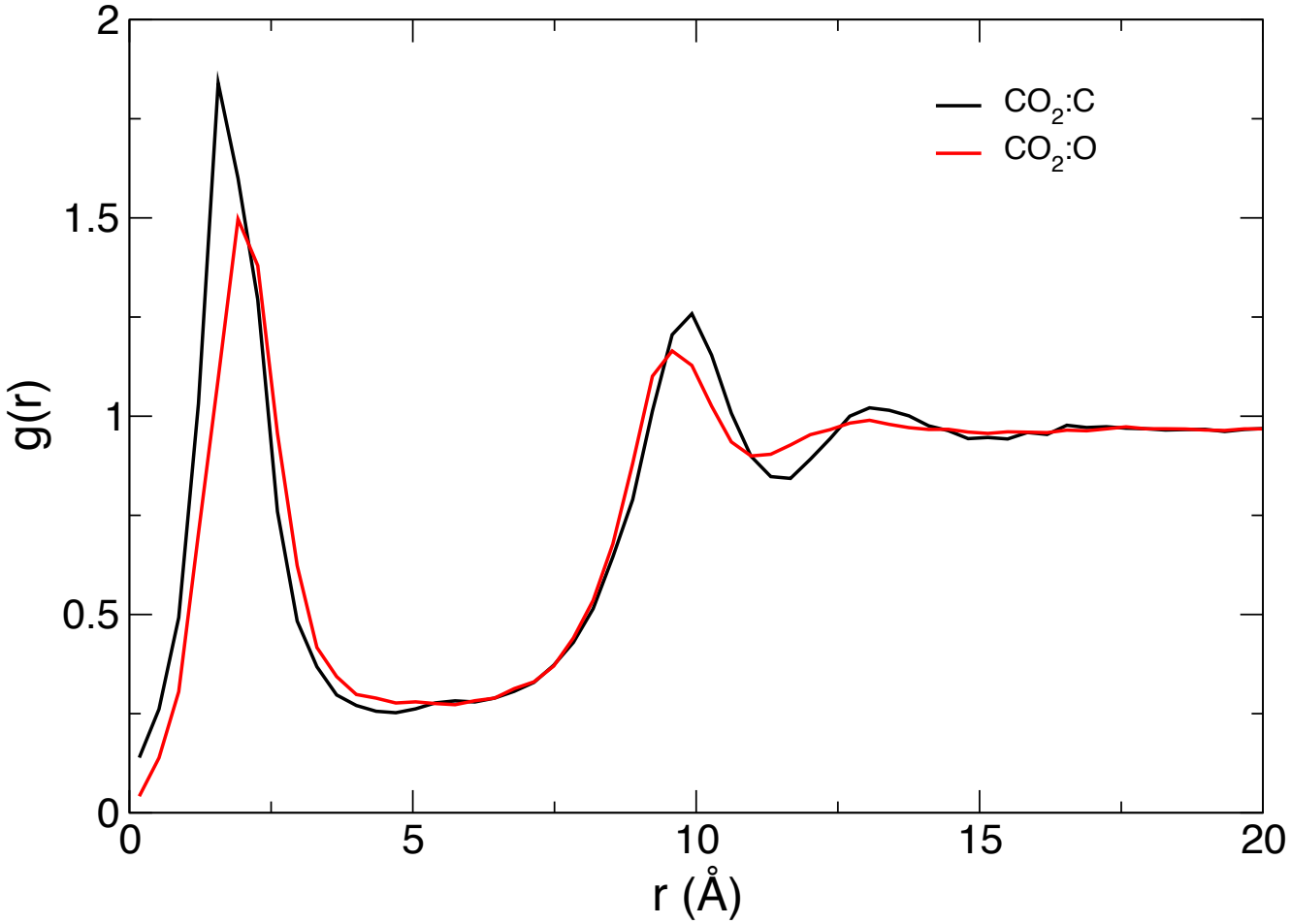
Narrow side acetylated CD in $scCO_2$

No conformational changes observed



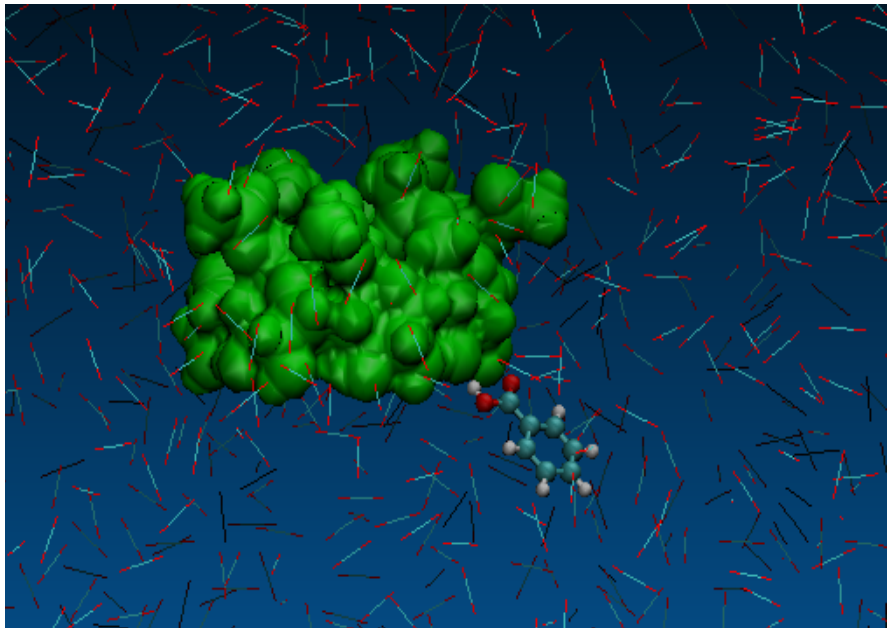


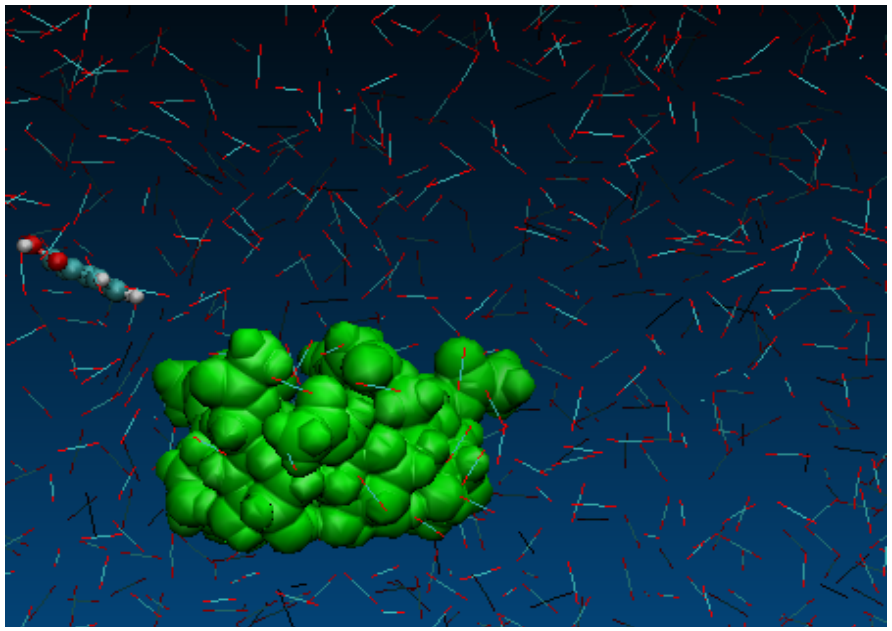
Further proofs of better solvent accessibility



Distribution of CO_2 molecules with respect to the CD center of mass

Interestingly, BEA does not stay in



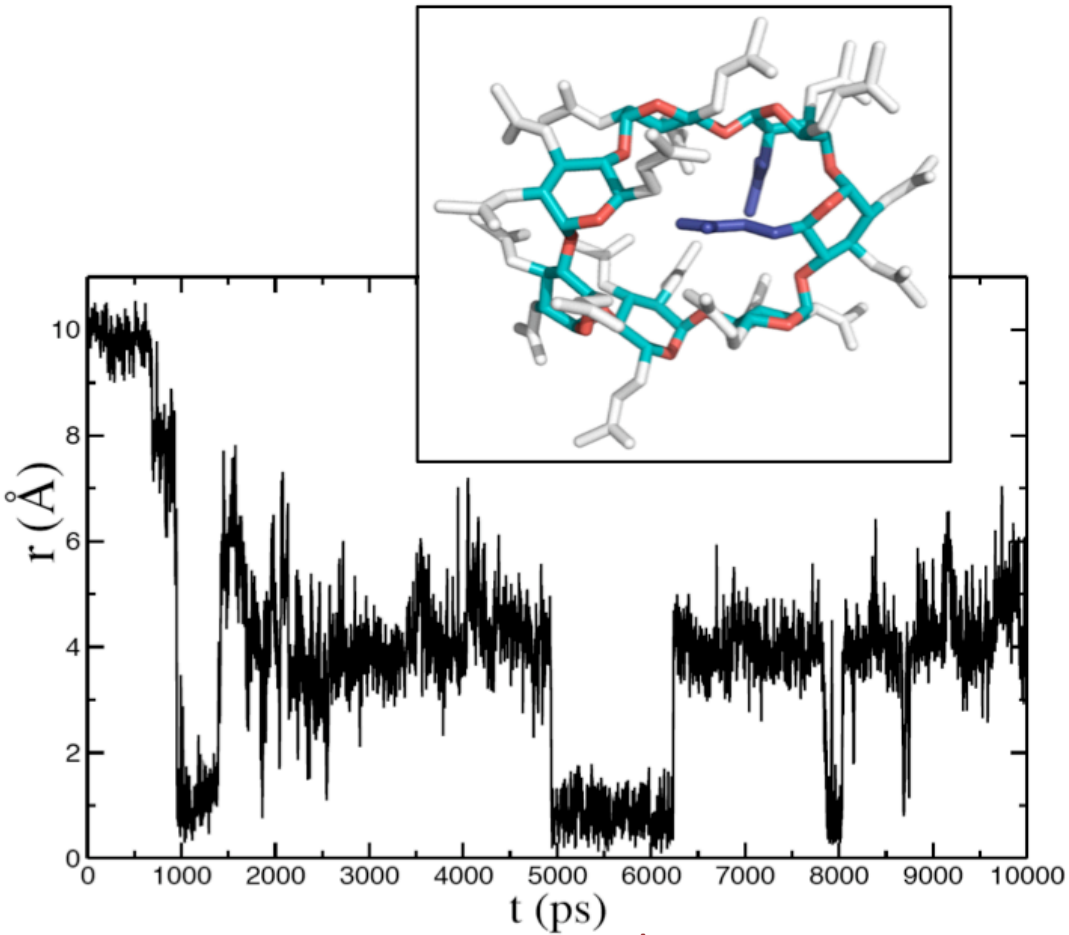


No matter the original orientation of benzoic acid within the cavity, the guest leaves after 2.3 ns (overall simulation time).

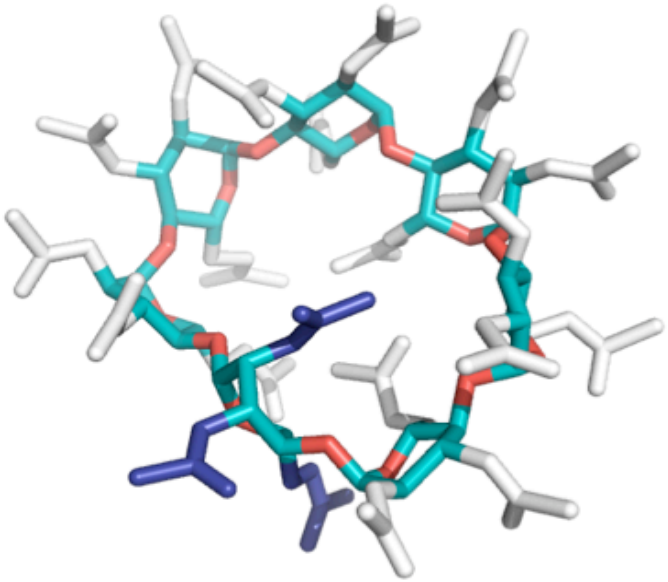
A preliminary interpretation: comparison

Peracetylated CD

Cavity deformation brings some acetyl groups toward the interior.



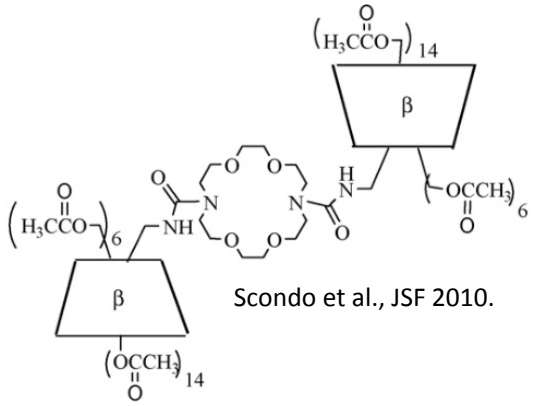
Narrow side



Wide side

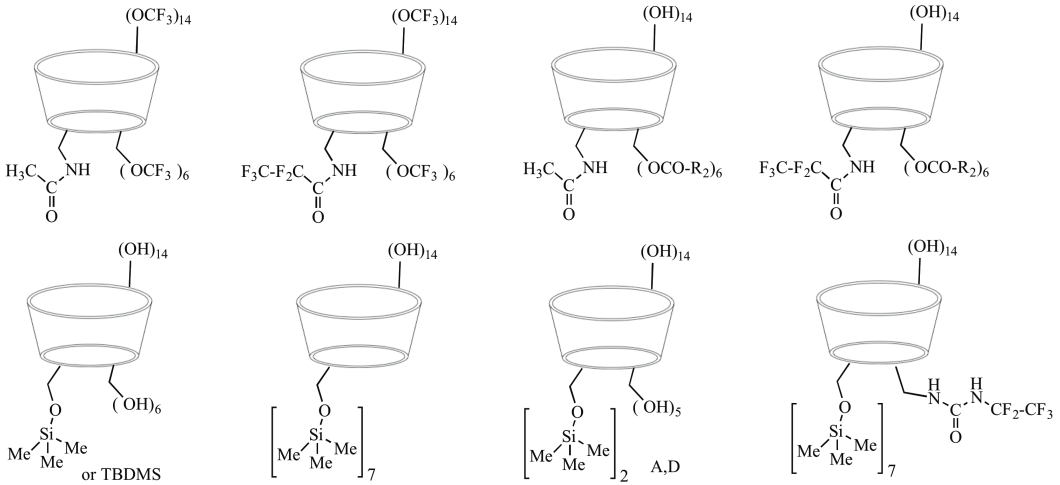
Perspectives

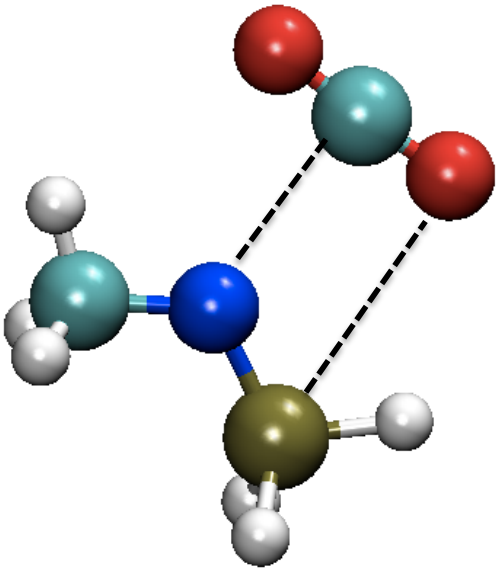
- Rationalize the influence of CD substituents on host-guest complexation.
- Reactivity: toward supramolecular Chemistry using CD in $scCO_2$.



Scondo et al., JSF 2010.

Tandem Staudinger-Aza-Wittig reaction in $scCO_2$:
$scCO_2$ is the reaction medium AND a reactant.
Key reaction step: 4 membered ring.



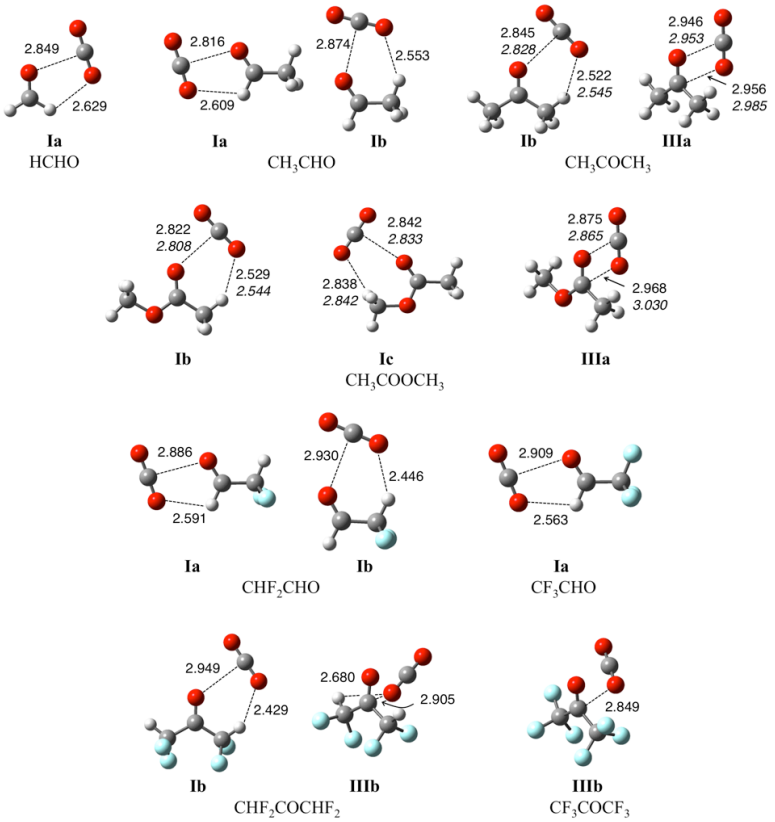


Thank you!

Supporting information

About the nature of the intermolecular interactions

Carbonyl groups -- CO_2 interactions:
***ab initio* calculations on model complexes** (ketones, aldehydes, esters)



About calculations

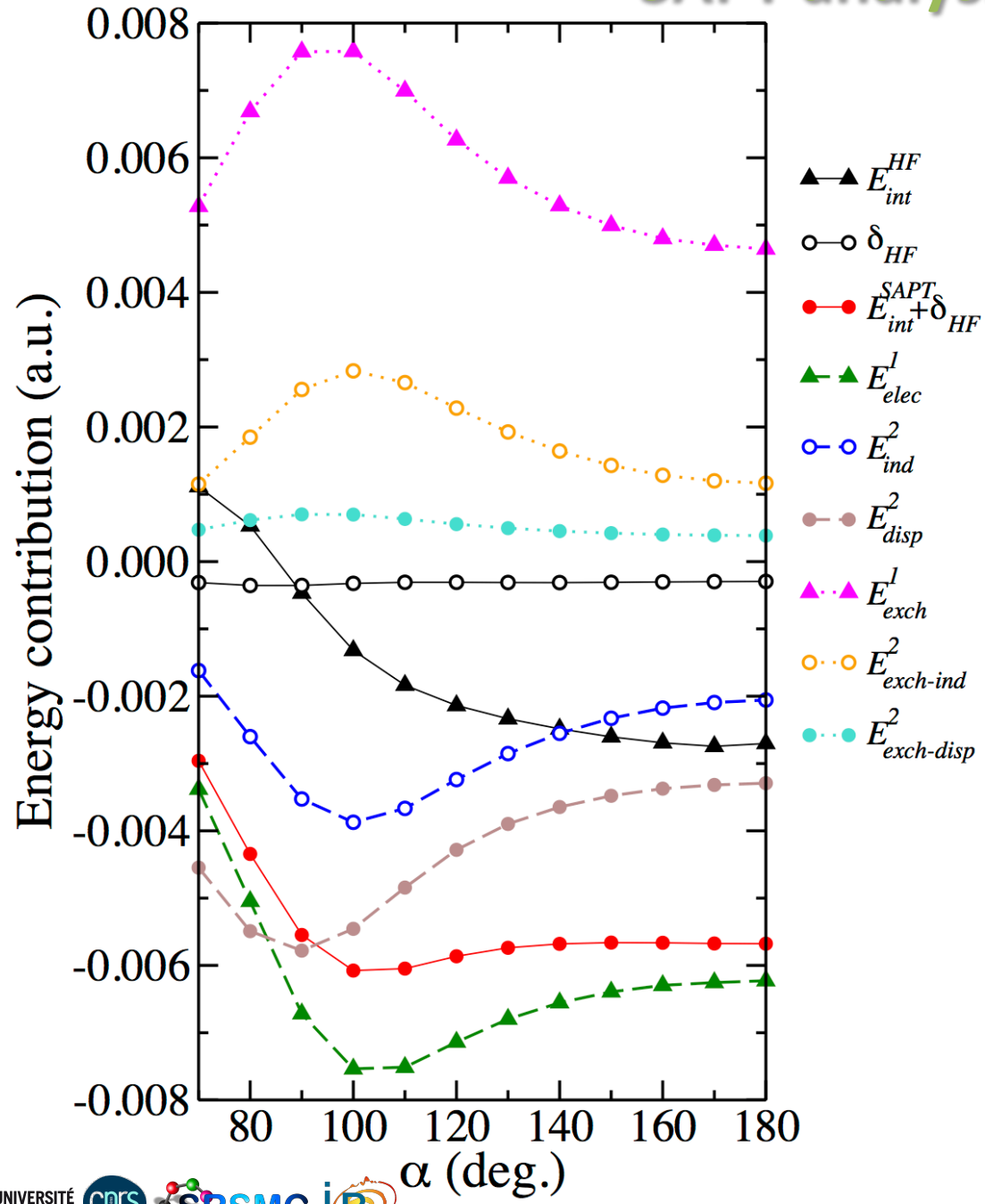
MP2/aug-cc-pVDZ : optimization.

MP2/aug-cc-pVTZ, CCSD(T)/aug-cc-pVDZ : electronic properties.

Validation on the CO_2-Acetone complex at the CCSD(T)/aug-cc-pVDZ level.

Altarsha, Ingrosso, Ruiz-López, ChemPhysChem, 2012.

SAPT analysis

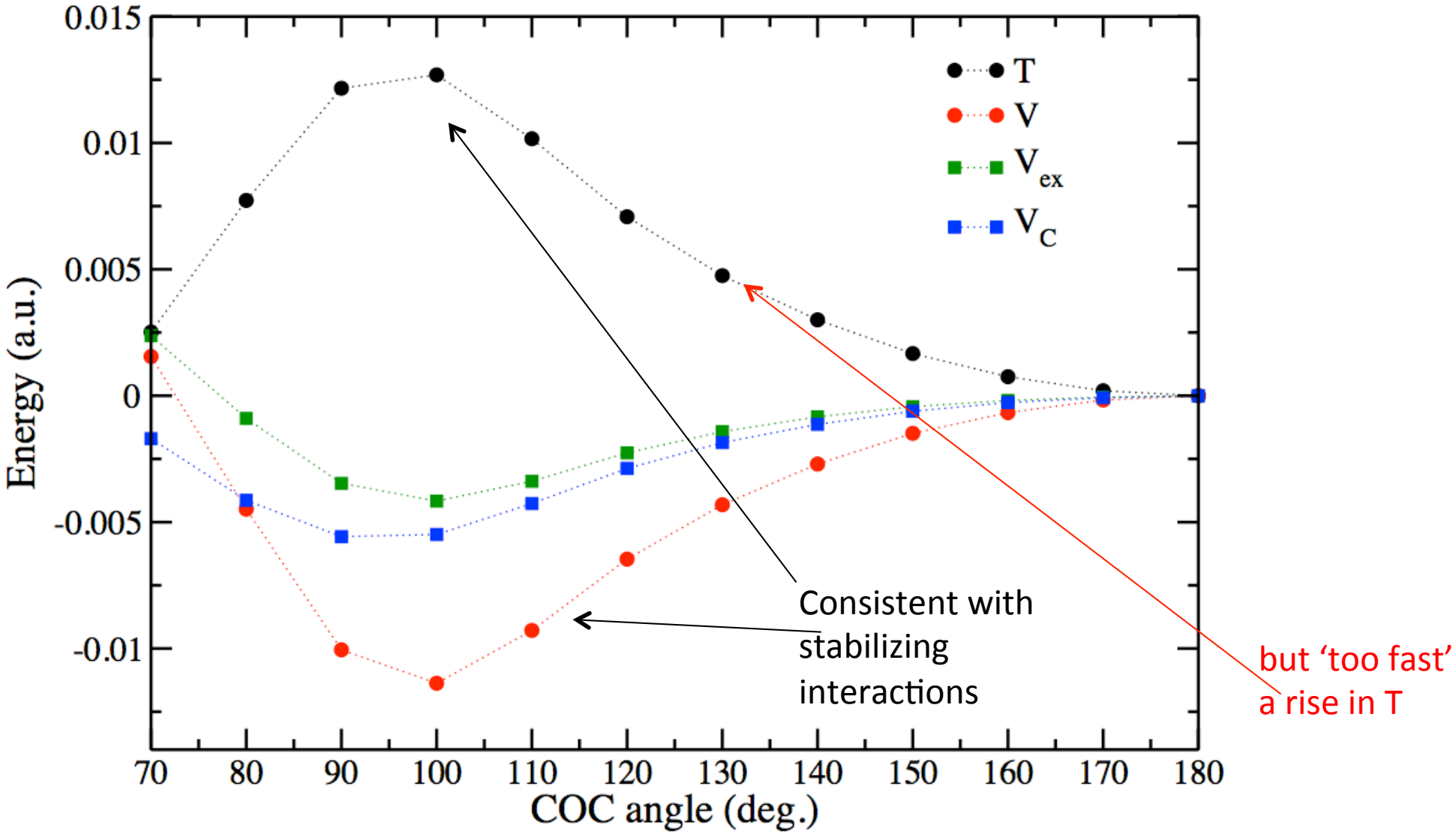


Perturbation analysis confirms our interpretation

- SAPT interaction energy: similar shape as MP2 and CCSD(T).
- Electrostatic, induction and dispersion favor complex IIIa.
- The dispersion contribution is extremely important (see E_{disp} and E_{total}).

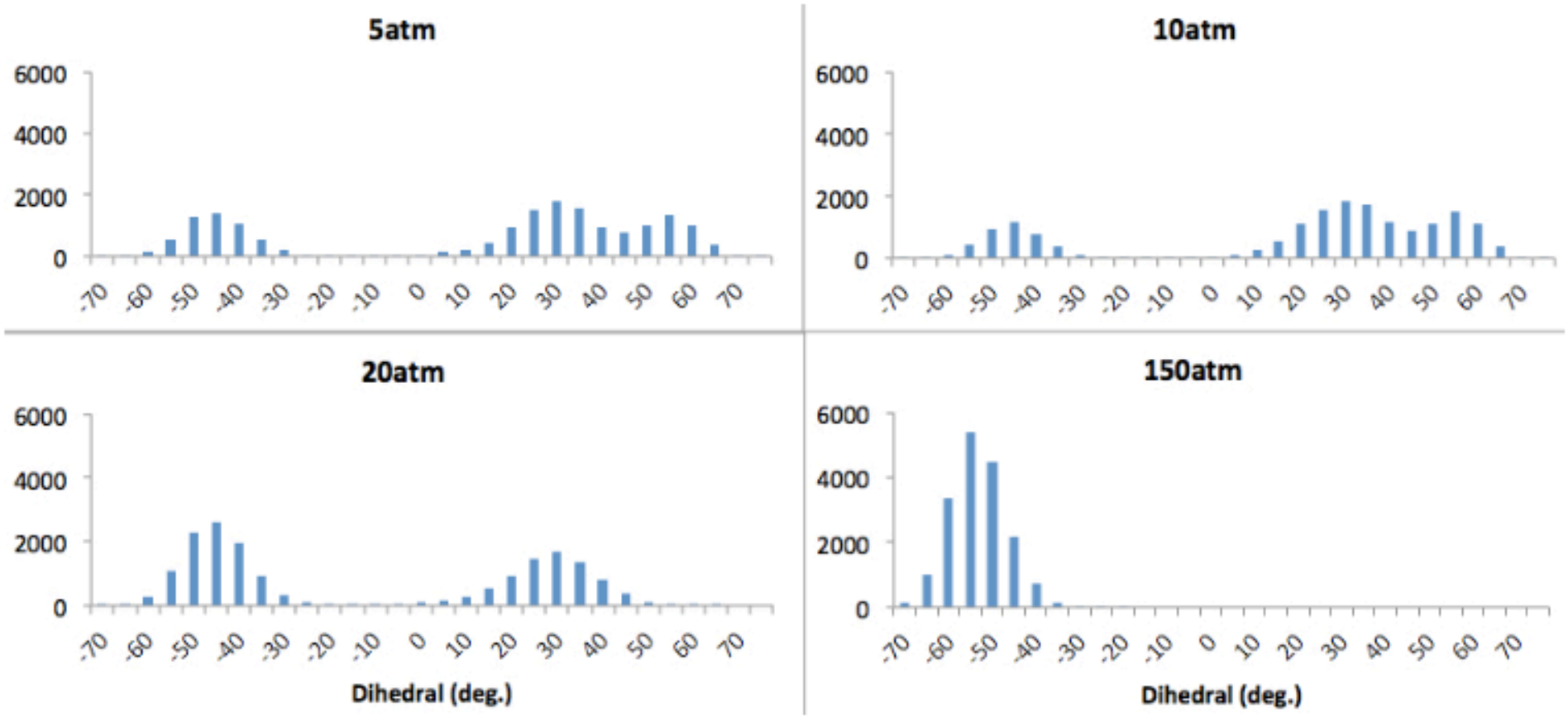
San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.

Decomposition of HF interaction energy



San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.

Pressure dependence of conformational changes



San Fabián, Ingrosso, Lambert, Ruiz-López, CPL 2014.