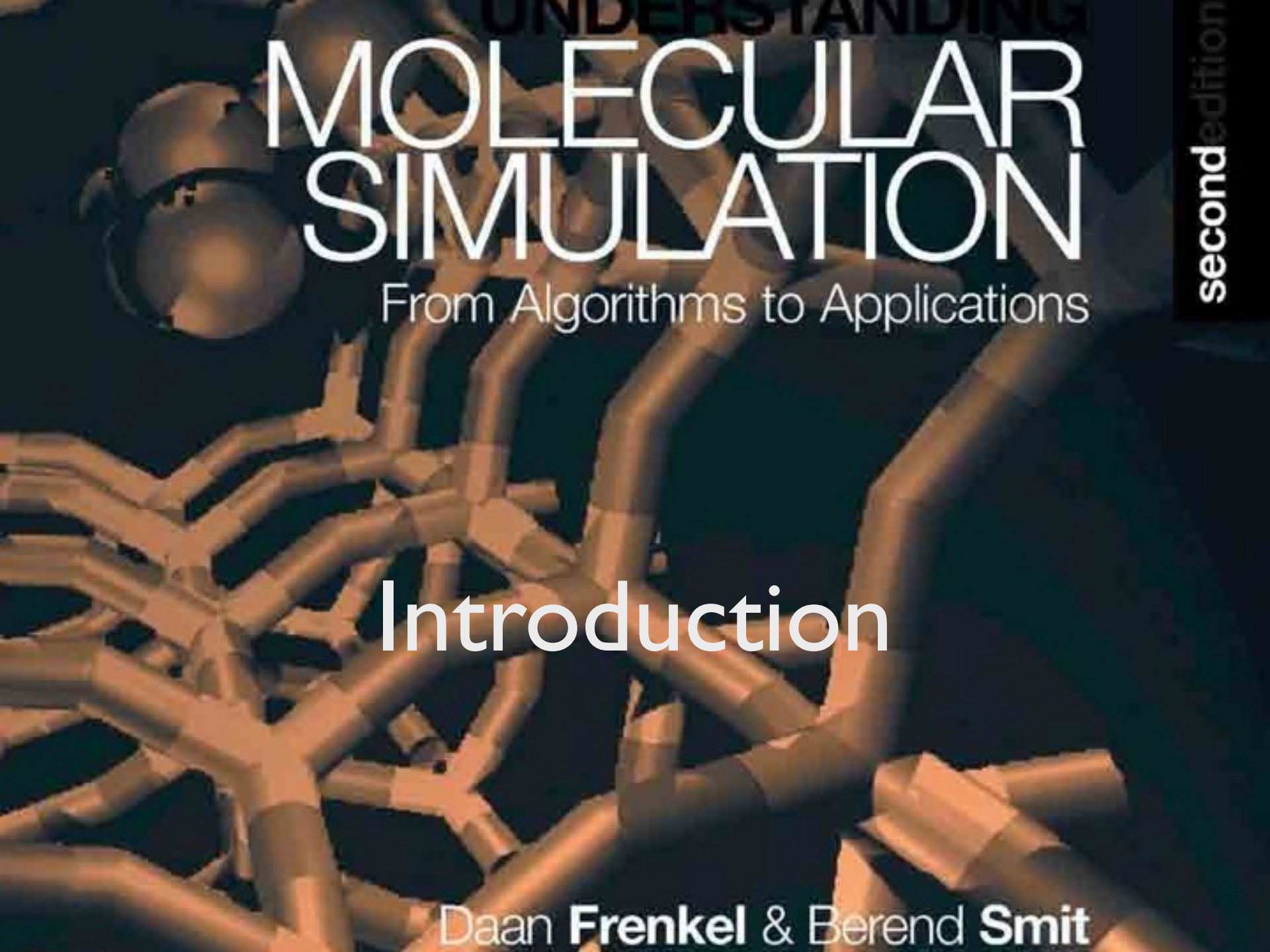
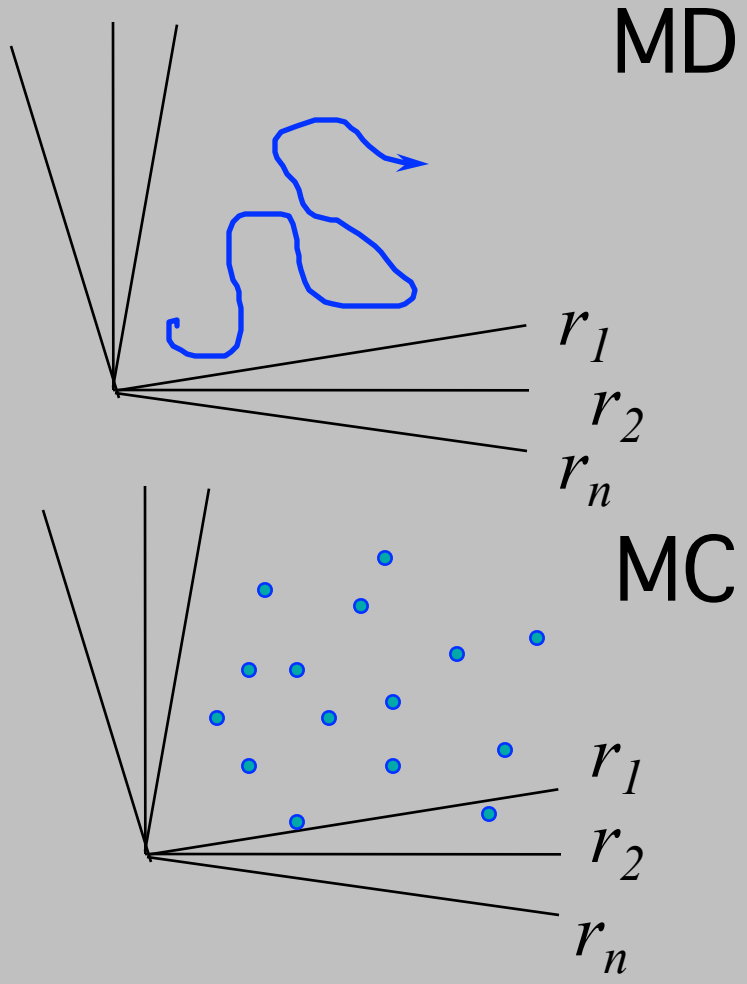

UNDERSTANDING
MOLECULAR SIMULATION
From Algorithms to Applications
second edition
Introduction
Daan Frenkel & Berend Smit

Introduction

- Why to use a simulation
- Some examples of questions we can address

Molecular Simulations

- **Molecular dynamics**: solve equations of motion
- **Monte Carlo**: importance sampling
- Calculate thermodynamic and transport properties for a given intermolecular potential



Uses of Molecular Simulations

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

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We assume the interactions between the particles are known!

Uses of Molecular Simulations

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Uses of Molecular Simulations

Exact= in the limit of *infinitely* long simulations the error bars can be made *infinitely* small

The idea is, for a given *intermolecular potential*

"*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Uses of Molecular Simulations

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Uses of Molecular Simulations

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Pressure
Heat capacity
Heat of adsorption
Structure
….

Uses of Molecular Simulations

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Uses of Molecular Simulations

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Diffusion coefficient
Viscosity
…

Uses of Molecular Simulations

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Uses of Molecular

If one could envision an experimental system of these N particles that interact with the potential.

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Uses of Molecular Simulations

The idea for a given *intermolecular potential* "*exactly*" compute the *thermodynamic* and *transport* properties of the *system*

Why Molecular Simulations

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Paul Dirac, after completing his formalism of

quantum mechanics: "*The rest is chemistry…".*

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Intermolecular potential

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The intermolecular potential can:

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The intermolecular potential can:

- Mimic the experimental system as accurate as possible:
  - Replace experiments (dangerous, impossible to measure, expensive, ...)

Intermolecular potential

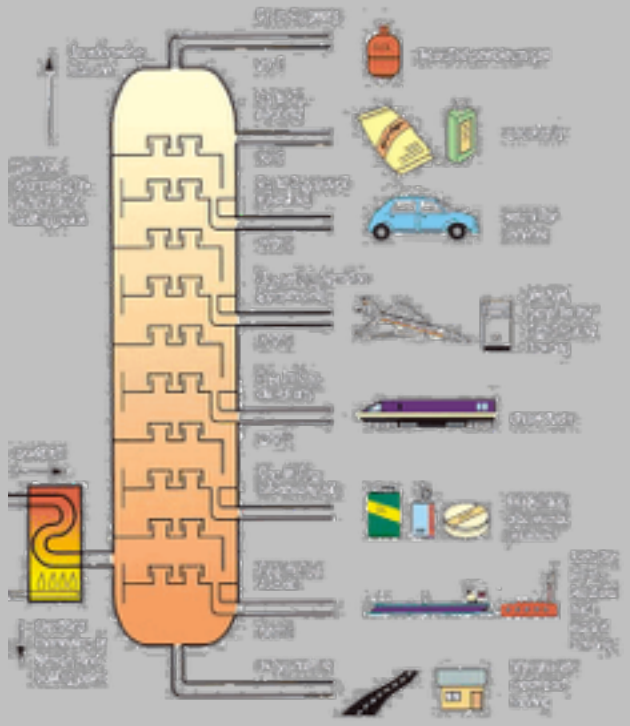
The intermolecular potential can:

- Mimic the experimental system as accurate as possible:
  - Replace experiments (dangerous, impossible to measure, expensive, ...)
- Make a model system:
  - Test theories that can not directly be tested with experiment

If we know/guess the “true” intermolecular potential

Example 1: Mimic the “real world”

Critical properties of long chain hydrocarbons



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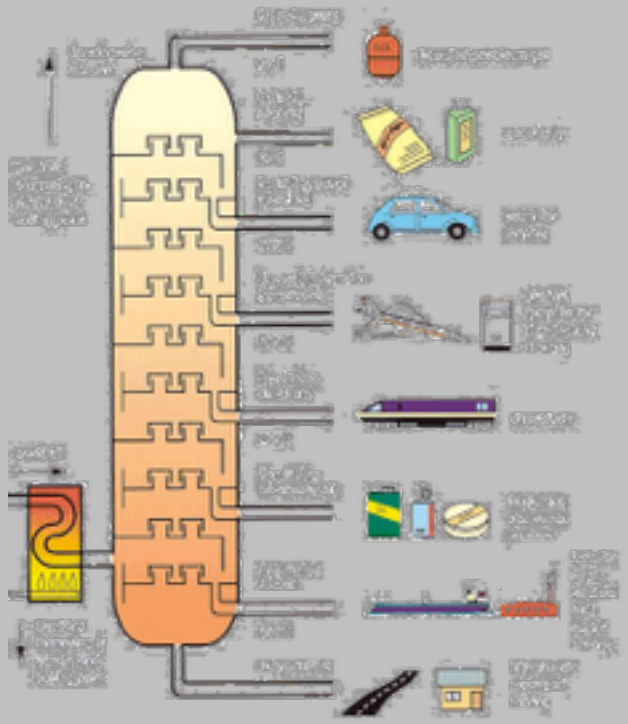
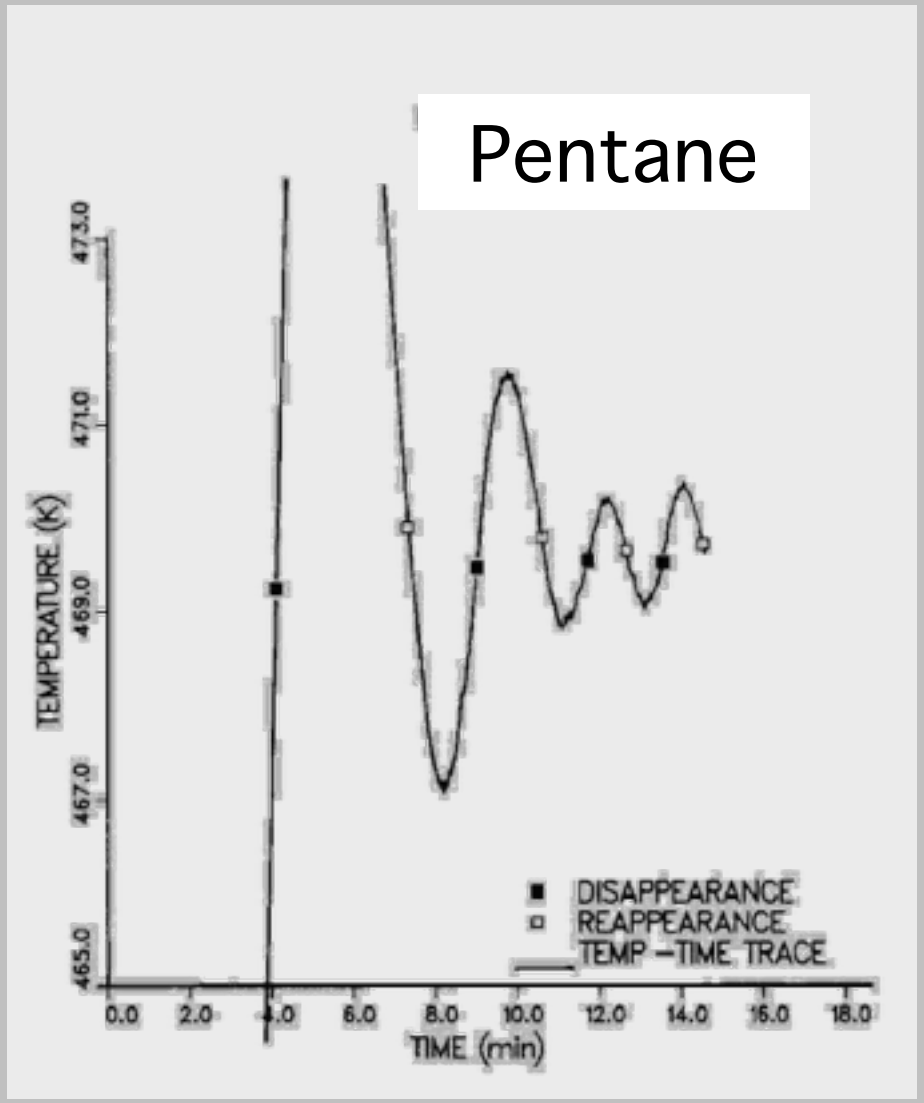


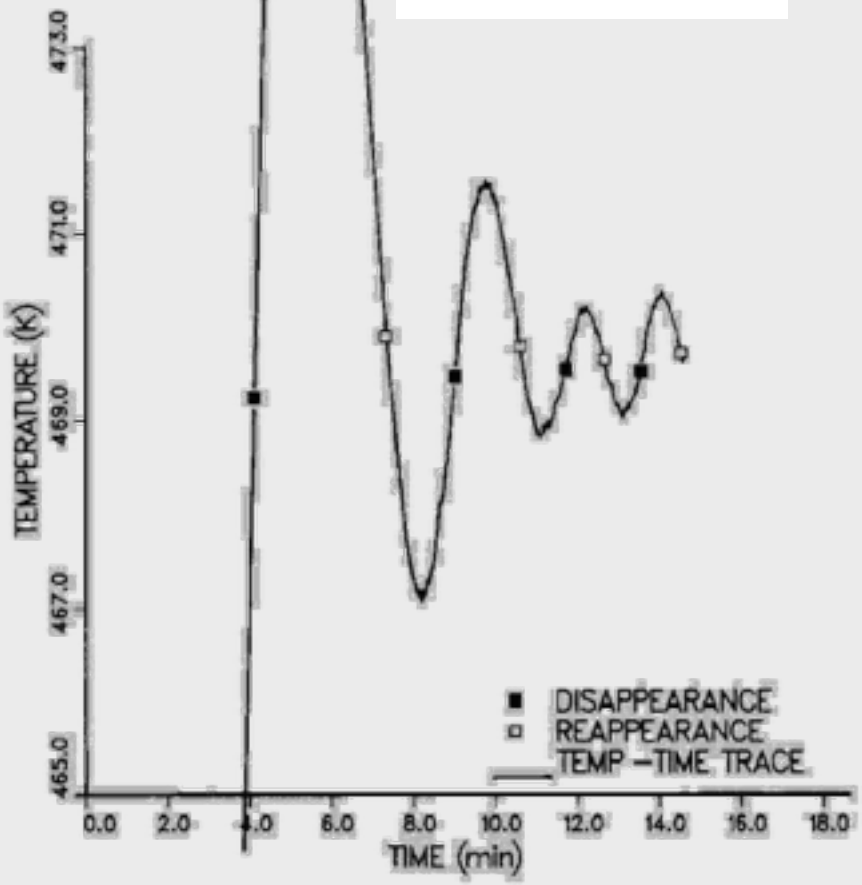
To *predict* the thermodynamic properties (boiling points) of the hydrocarbon mixtures it is convenient (=Engineering models use them) to know the critical points of the hydrocarbons.

Critical points of long chain hydrocarbons

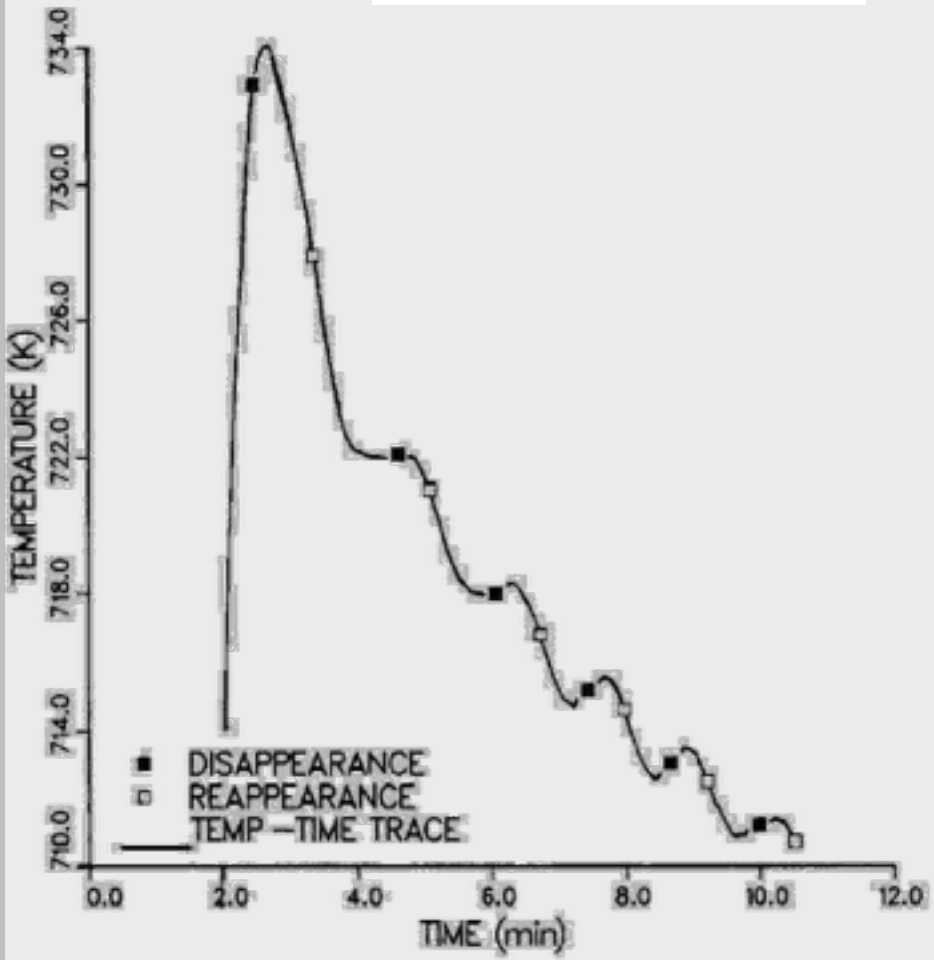


Critical points of long chain hydrocarbons

Pentane



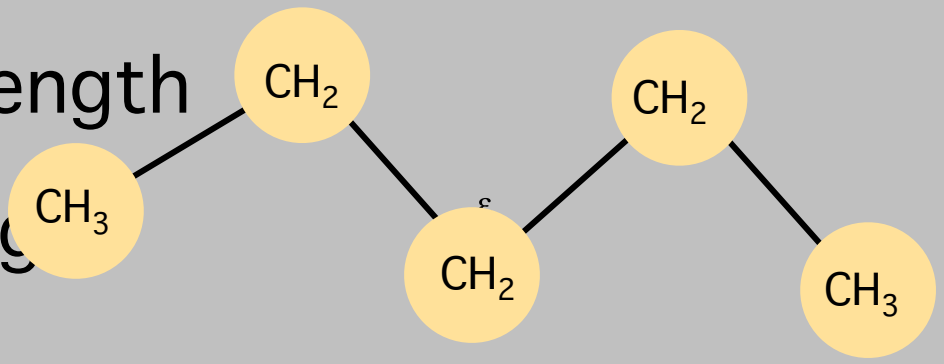
Heptadecane



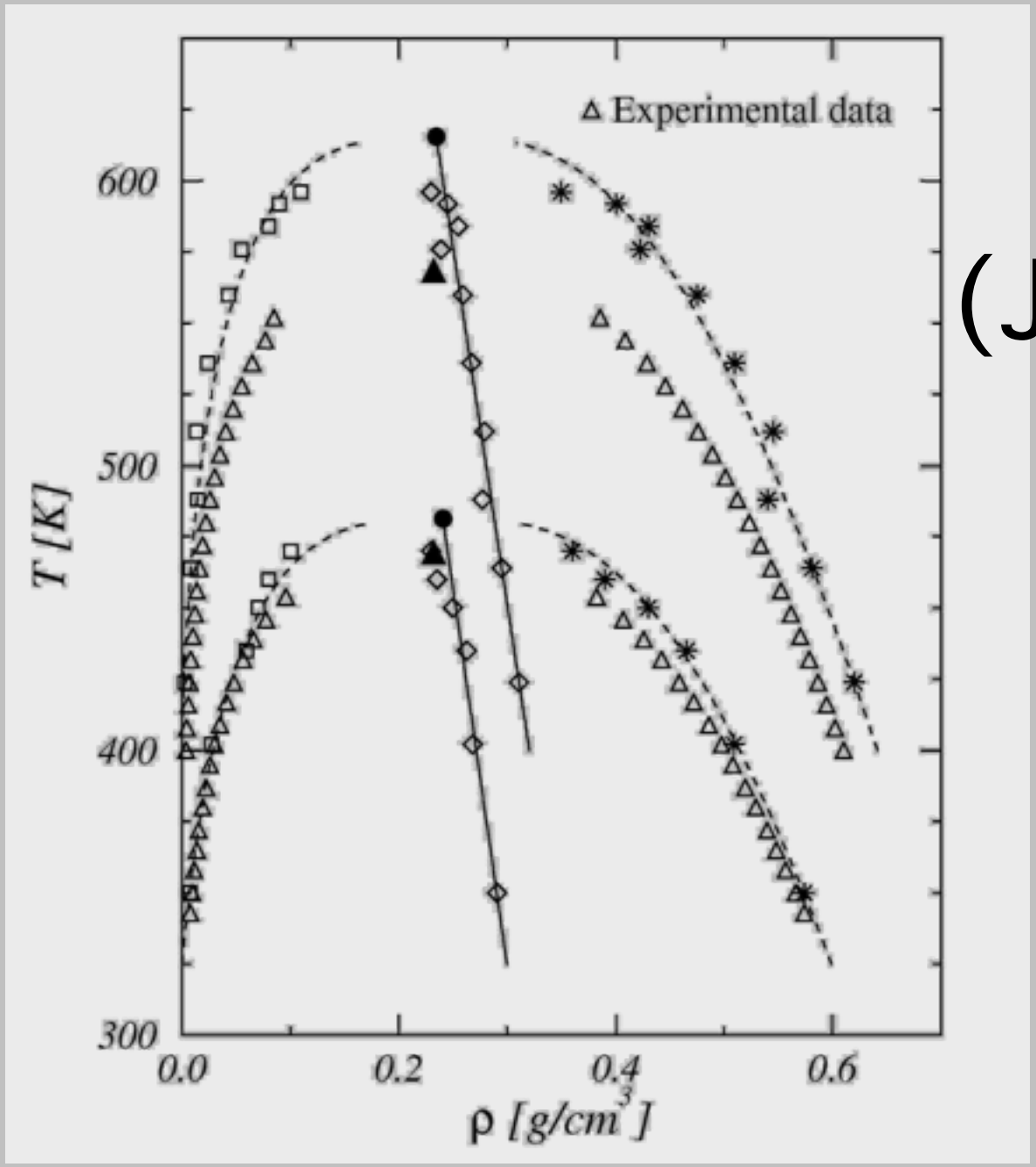
Hydrocarbons: intermolecular potential

United-atom model

- Fixed bond length
- Bond-bending
- Torsion
- Non-bonded: Lennard-Jones

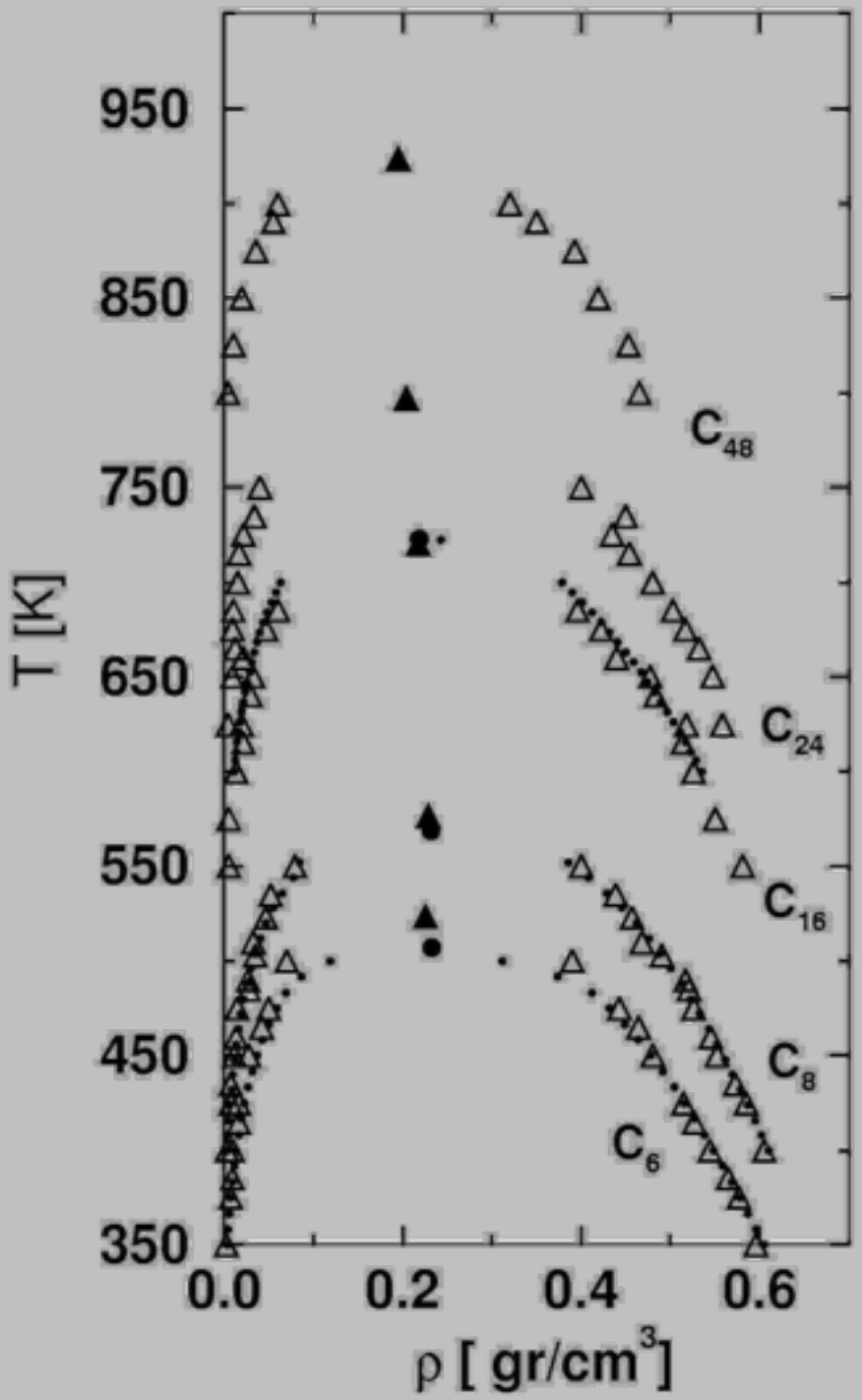


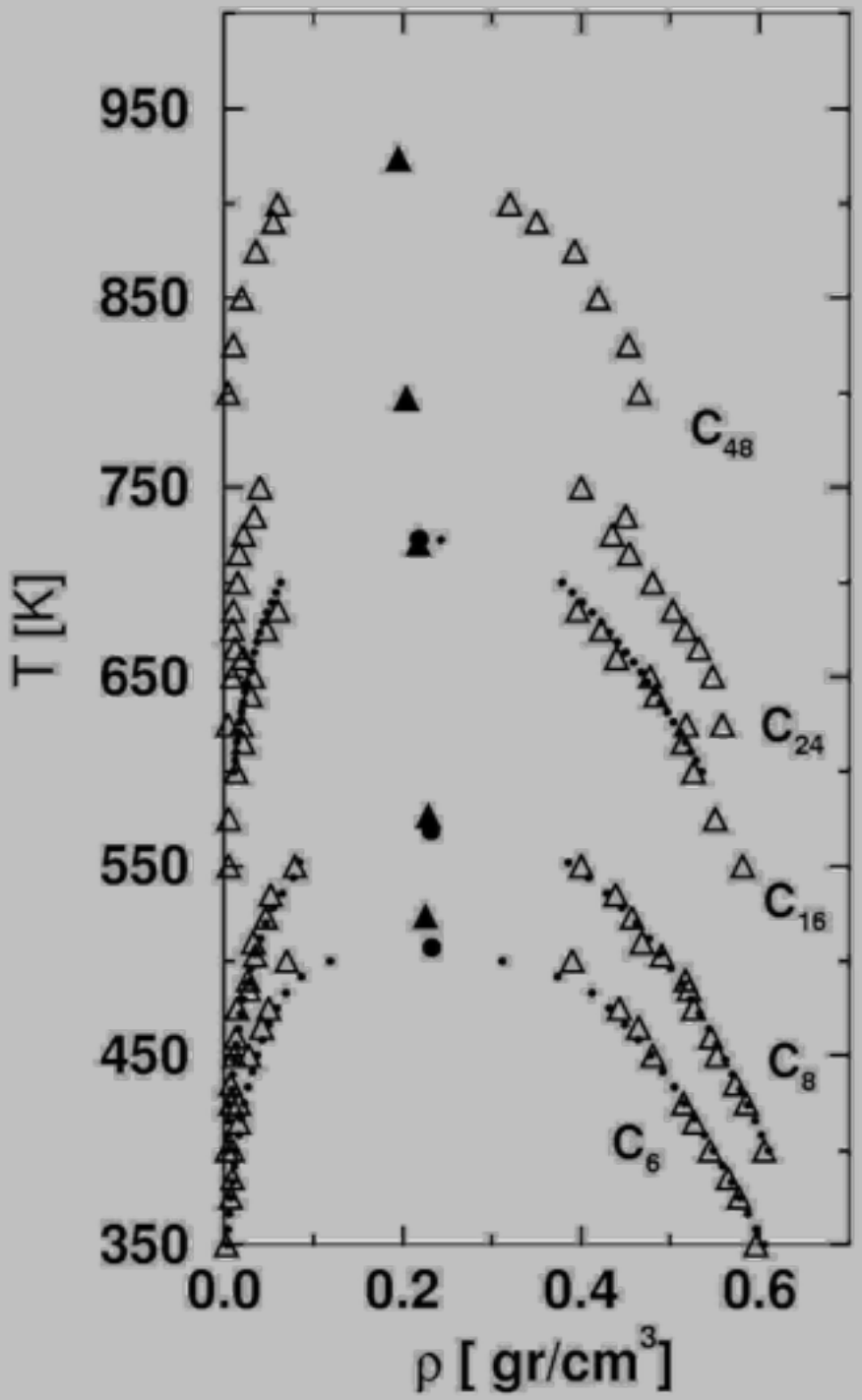
$$u(r) = 4\varepsilon_{ij}\left[\left(\frac{\sigma_{ij}}{r}\right)^{12} - \left(\frac{\sigma_{ij}}{r}\right)^{6}\right]$$



OPLS (Jorgensen) Model

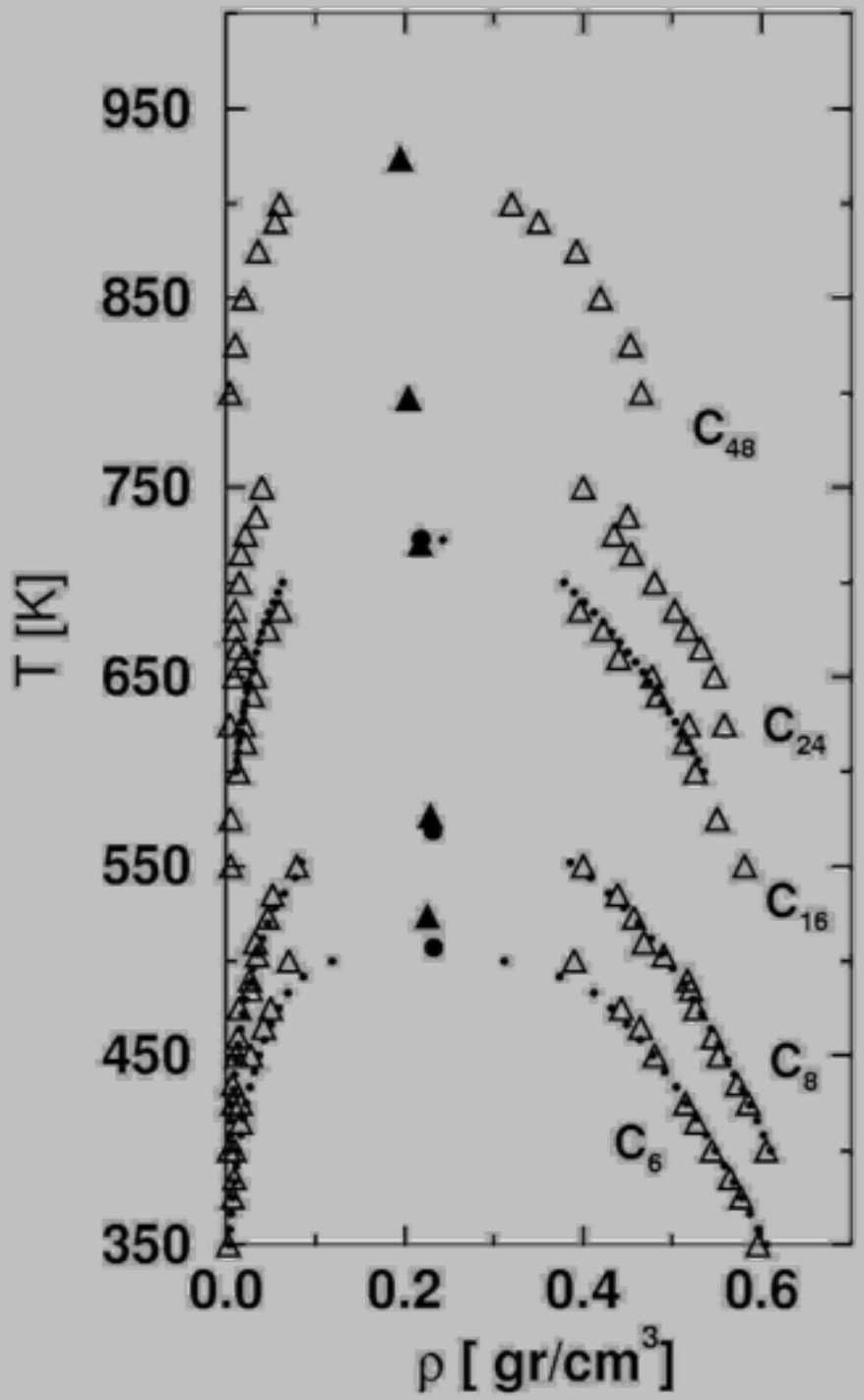
Vapour-liquid equilibria





Vapour-liquid equilibria

Computational issues:



Vapour-liquid equilibria

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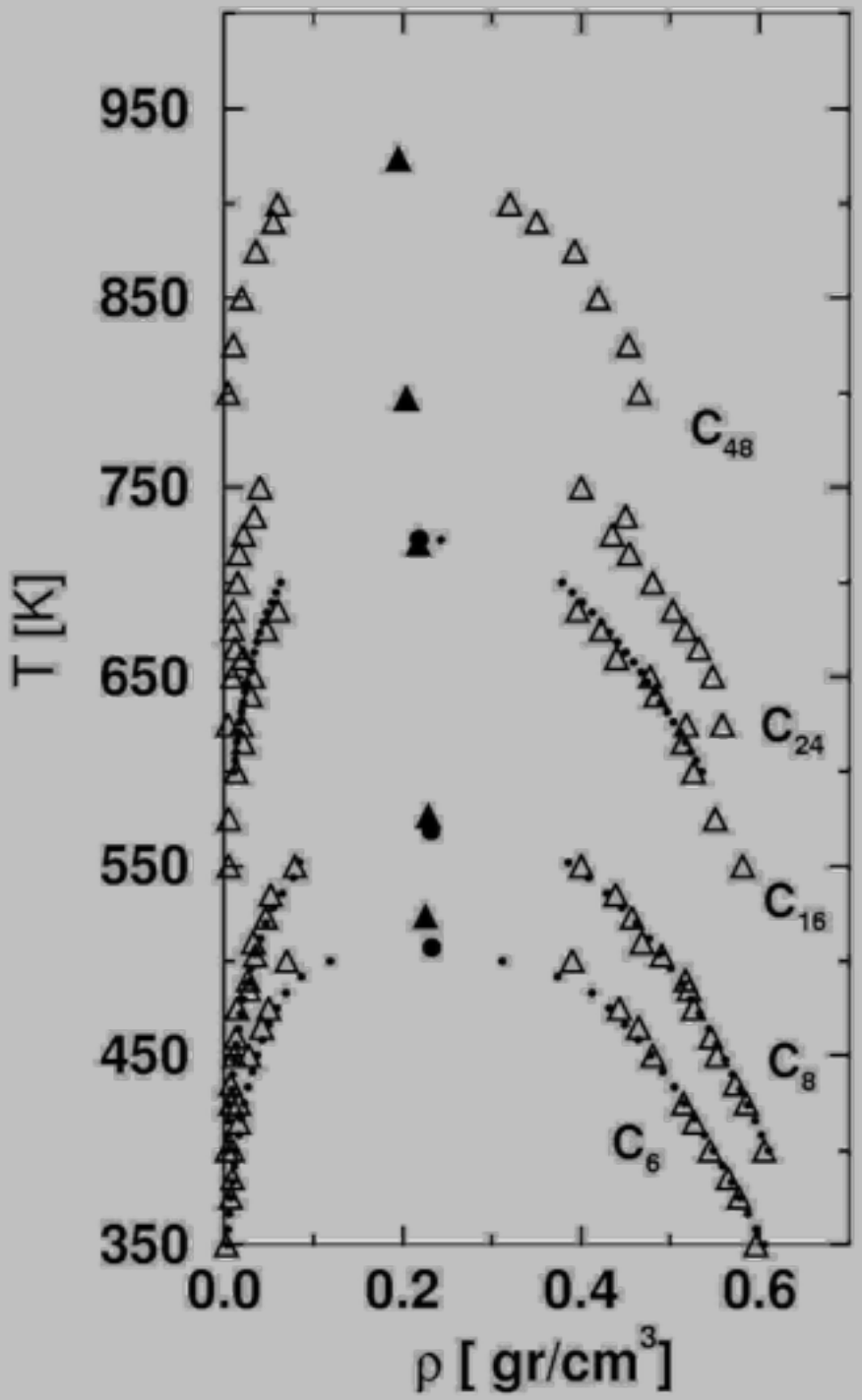

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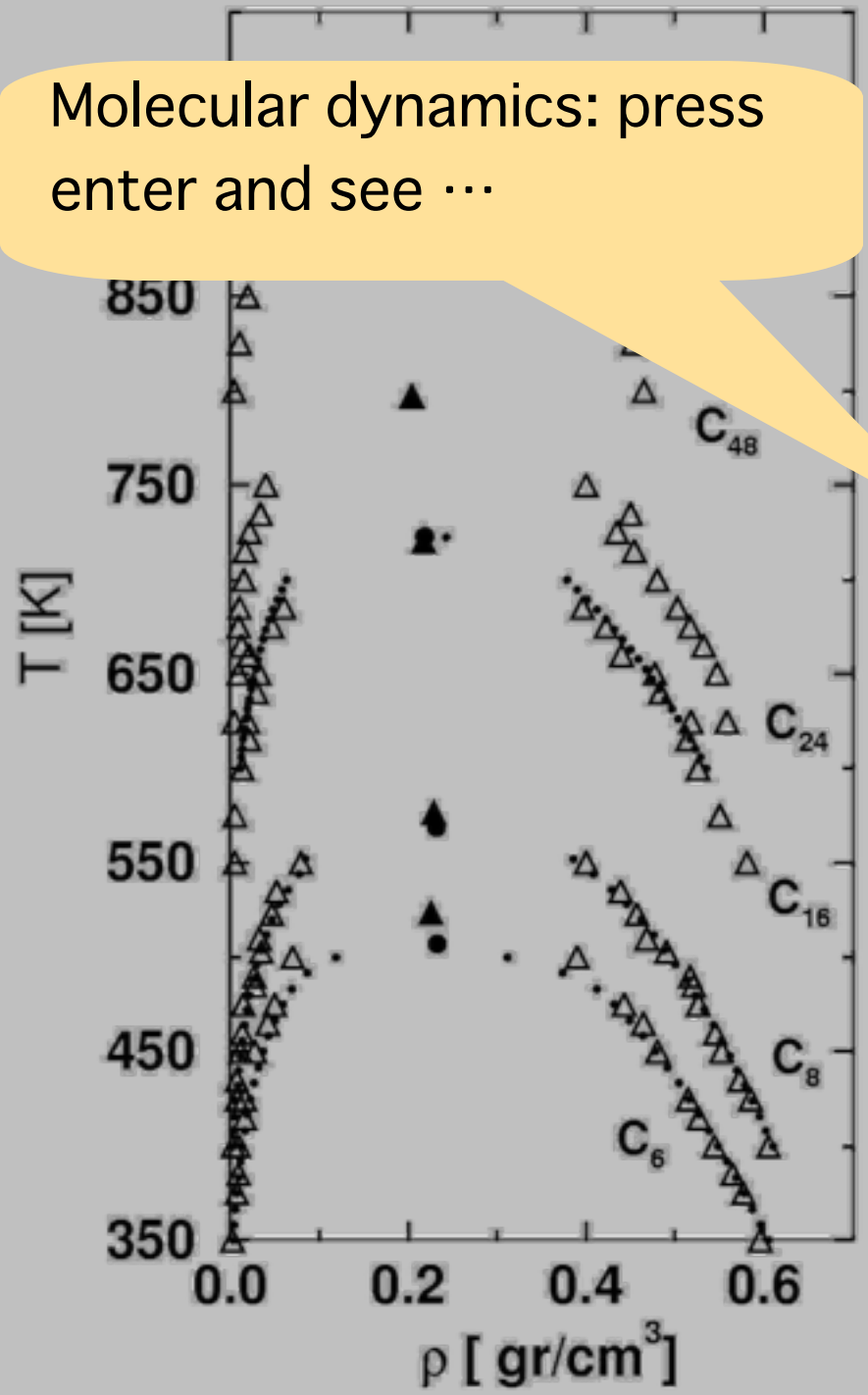
- How to deal with long chain hydrocarbons?

Molecular dynamics: press enter and see …



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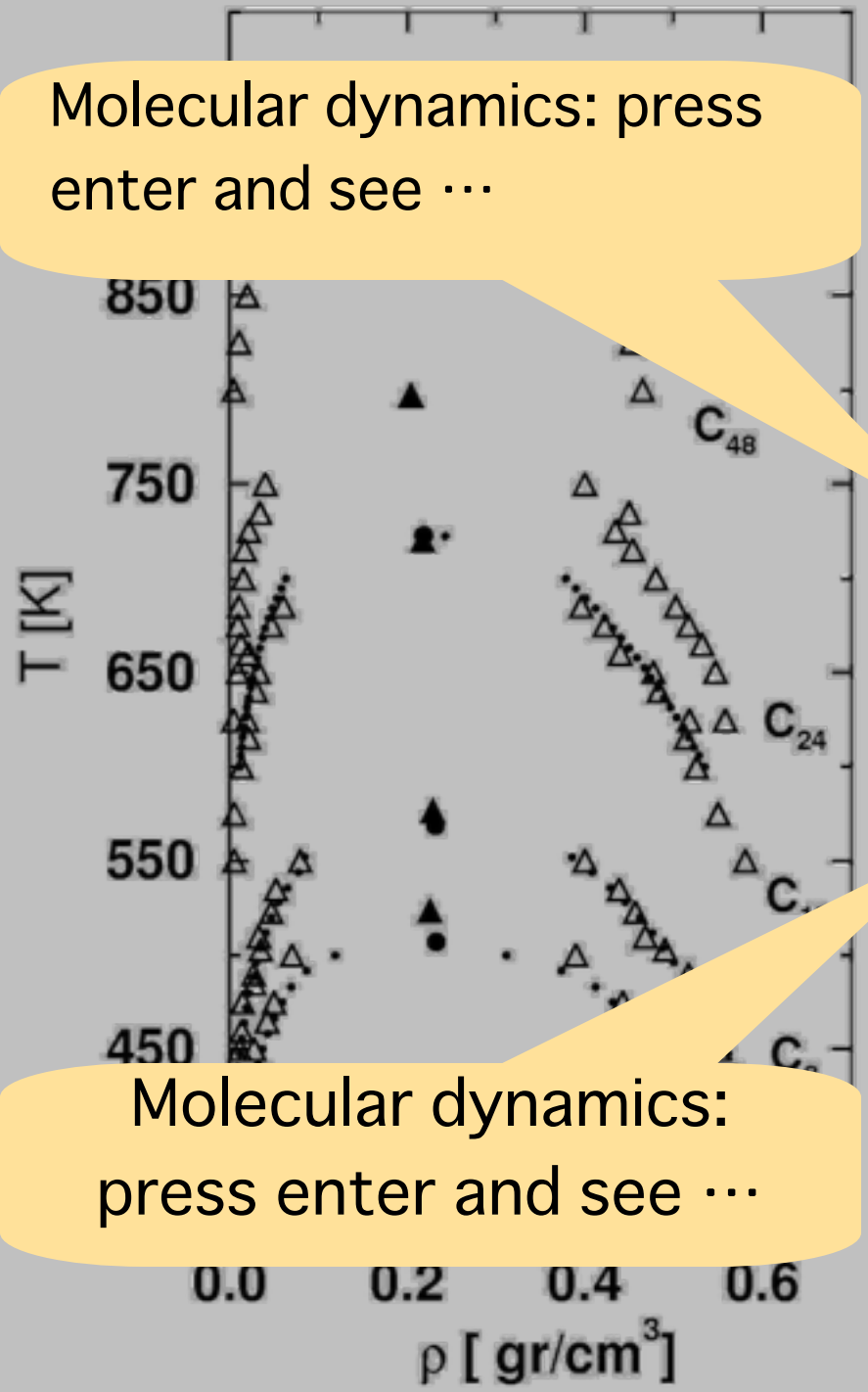

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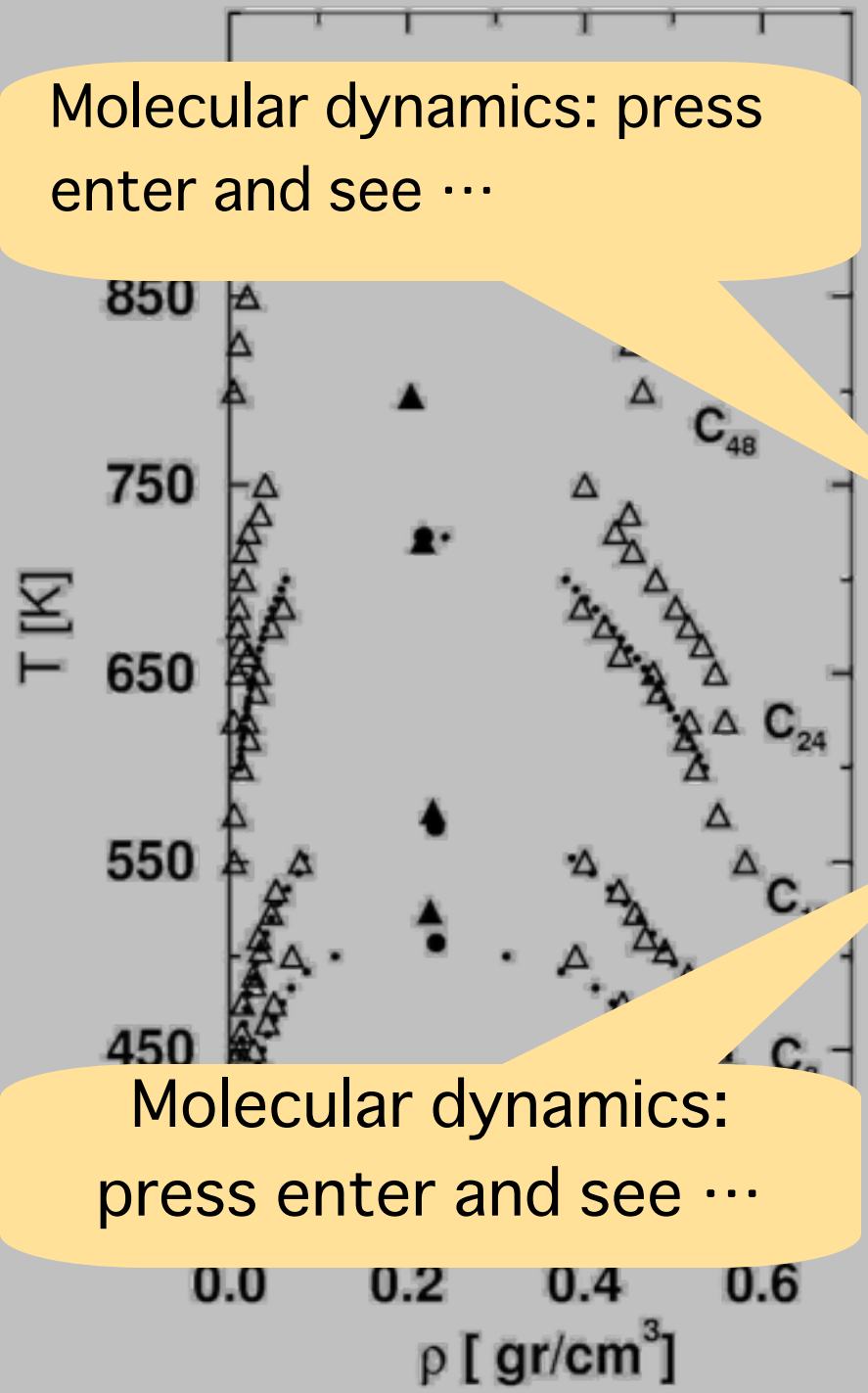

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But my system is extremely small, is the statistic reliable?

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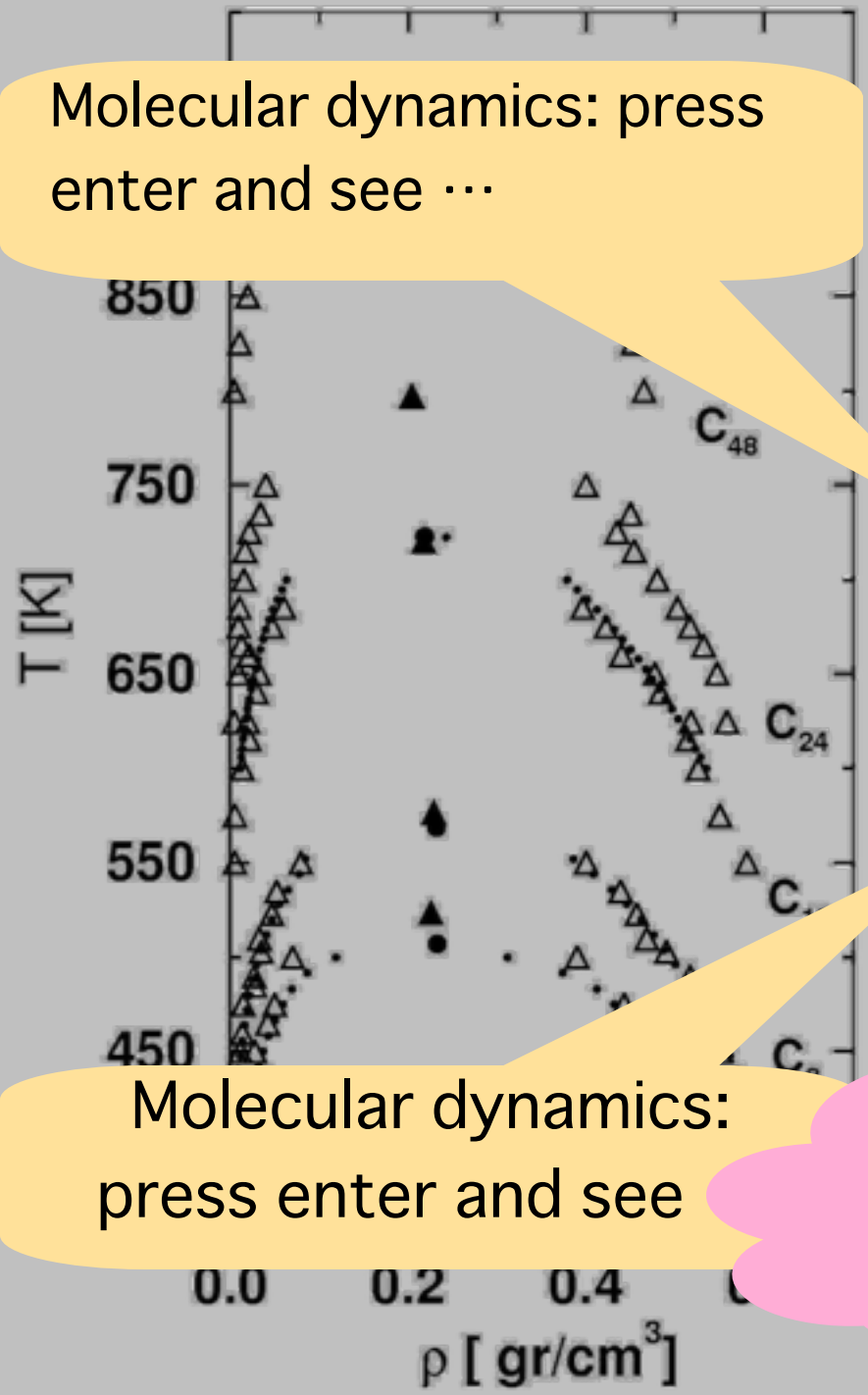

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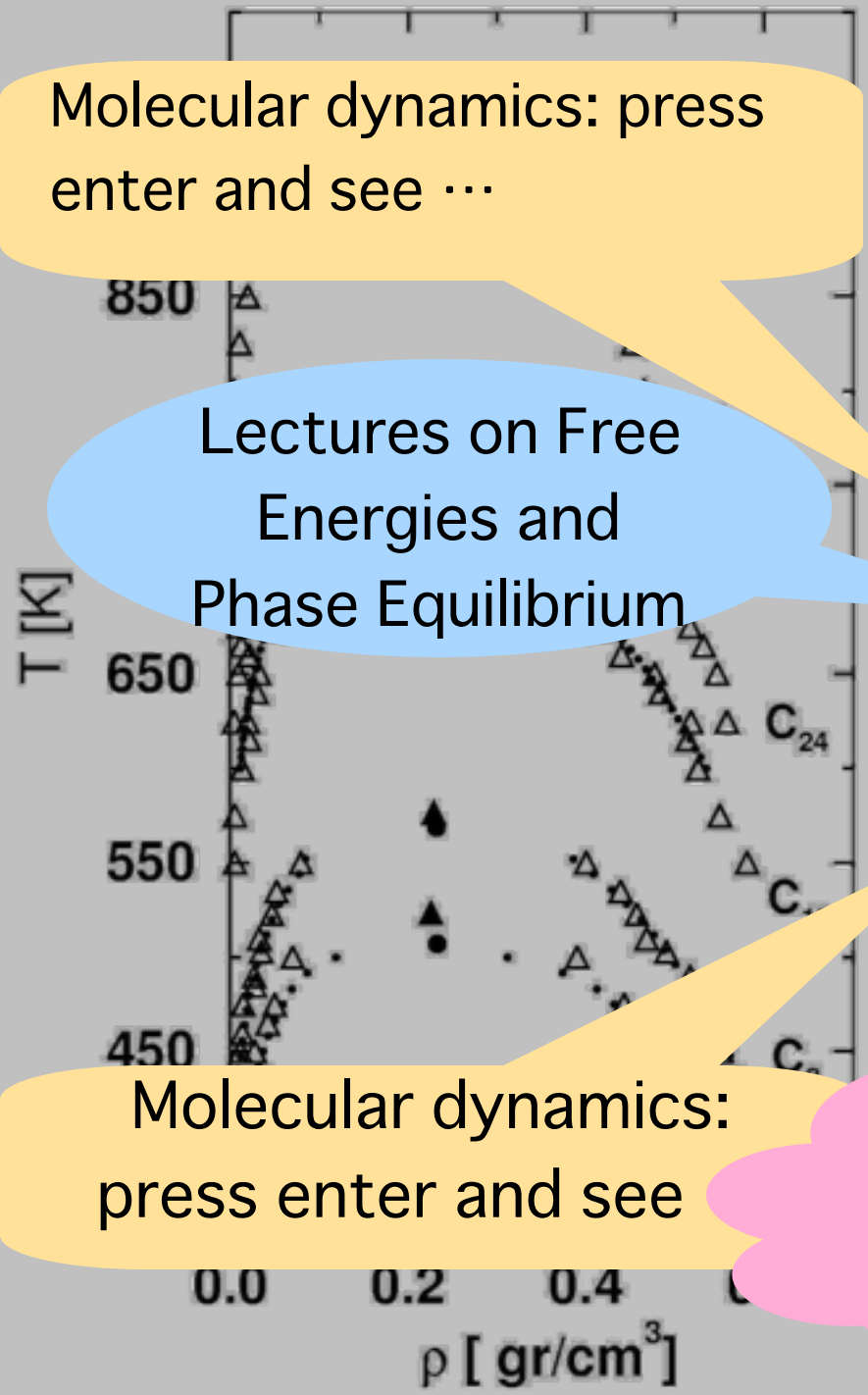
But C48 moves much slower than methane (C1). Do I have enough CPU time



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Lectures on Free Energies and Phase Equilibrium

Computational issues:

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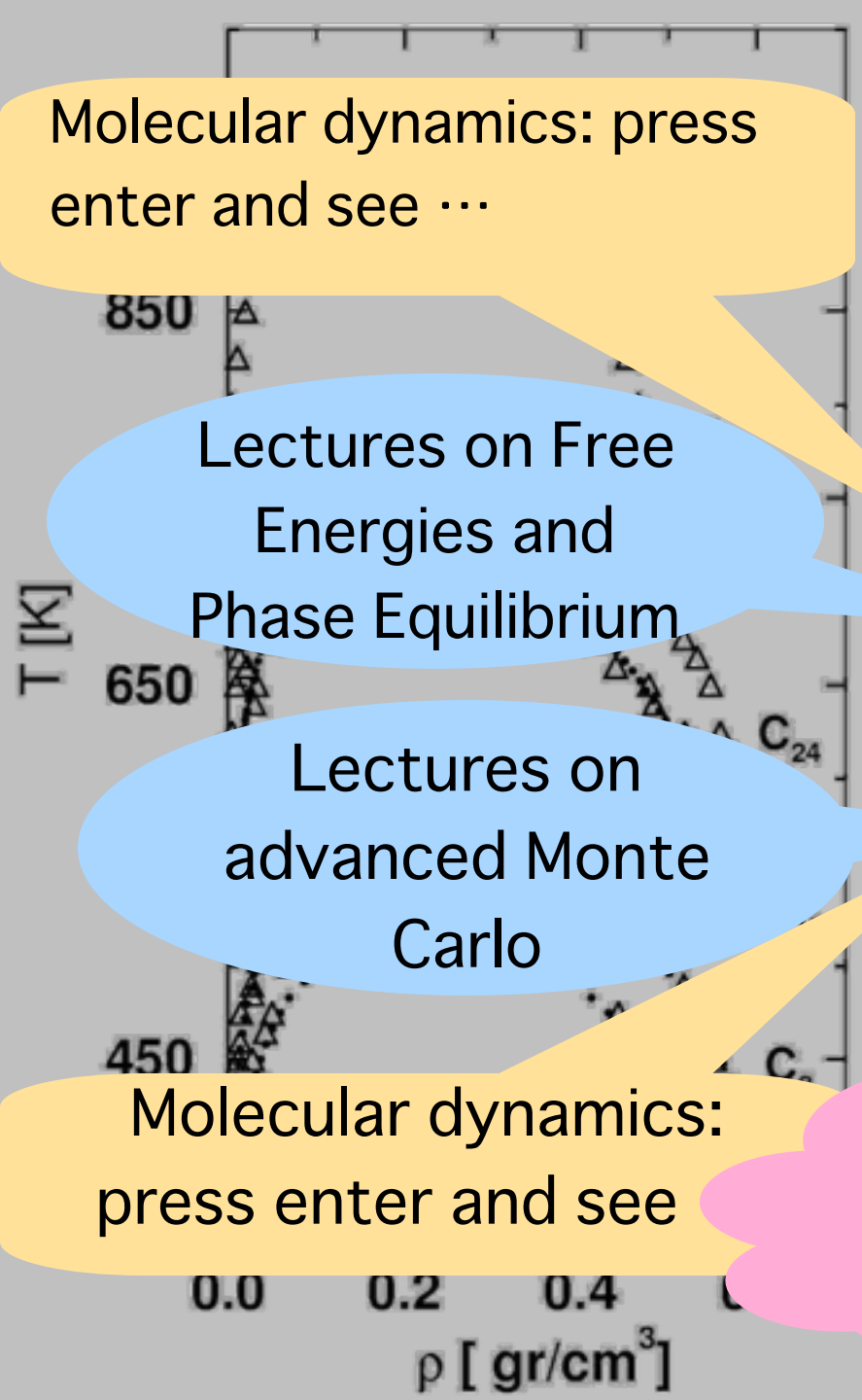

Molecular dynamics: press enter and see …

Lectures on Free Energies and Phase Equilibrium

Lectures on advanced Monte Carlo

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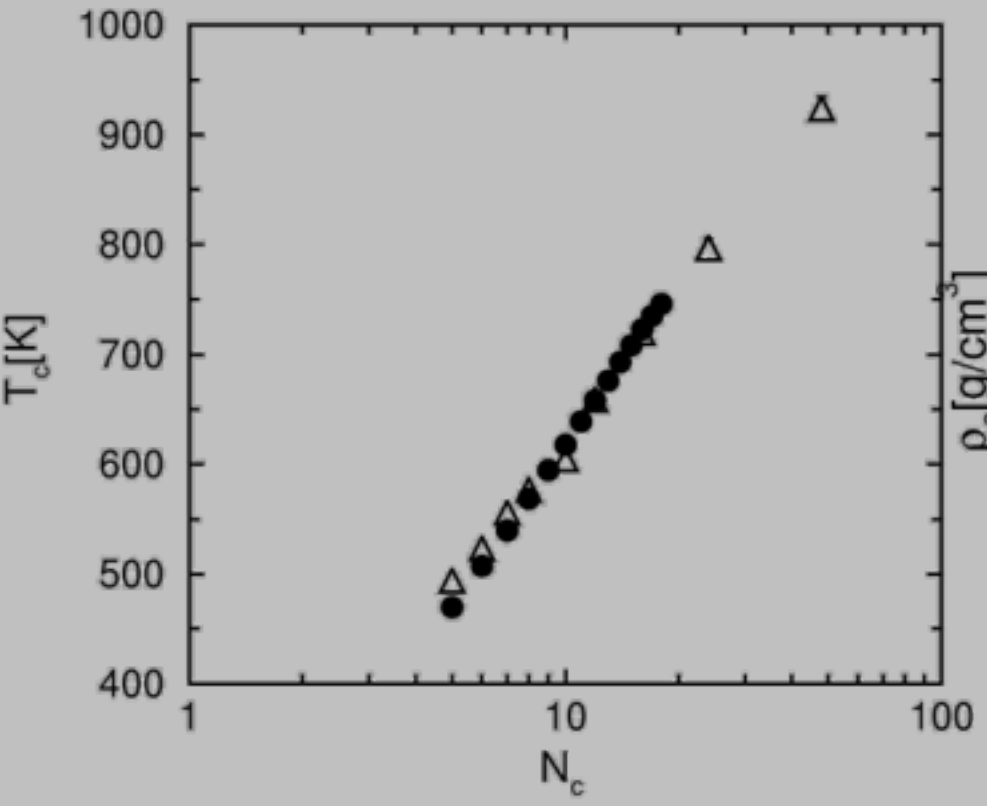
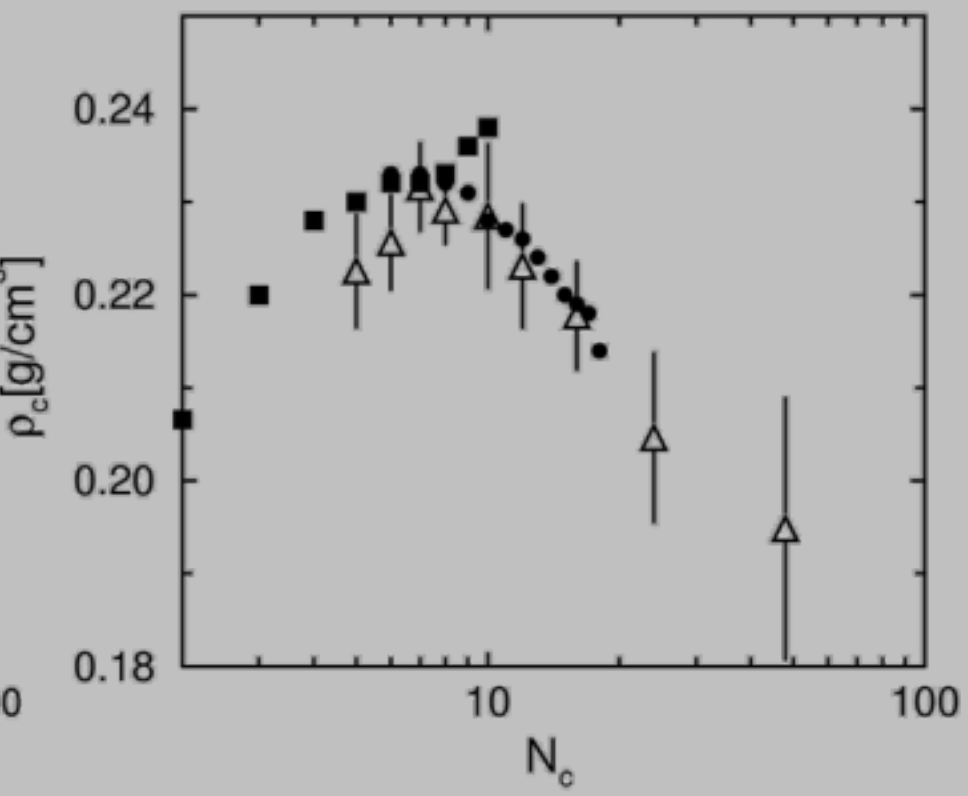
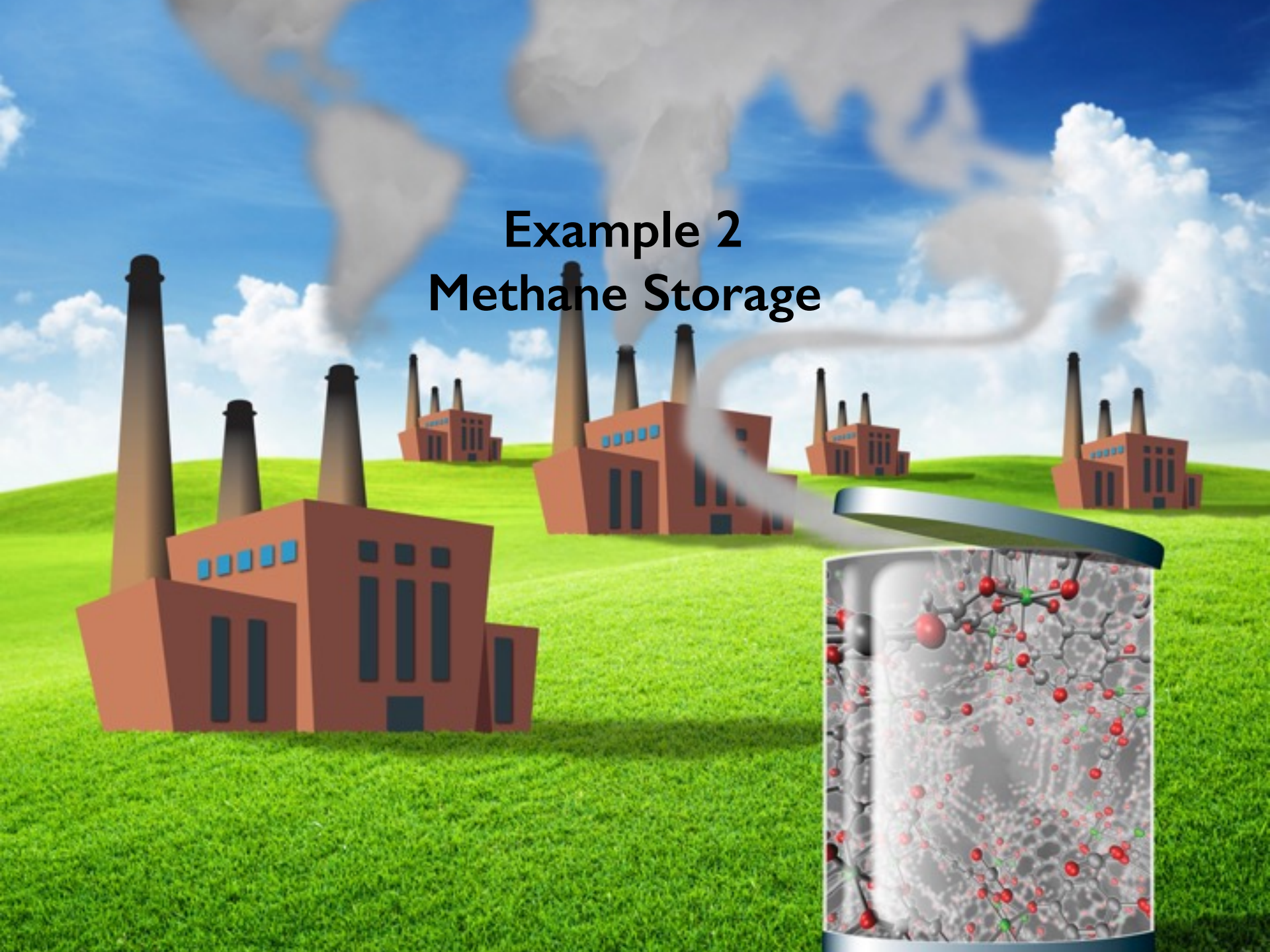
Critical Temperature and Density





Nature **365**, 330 (1993).

Example 2
Methane Storage

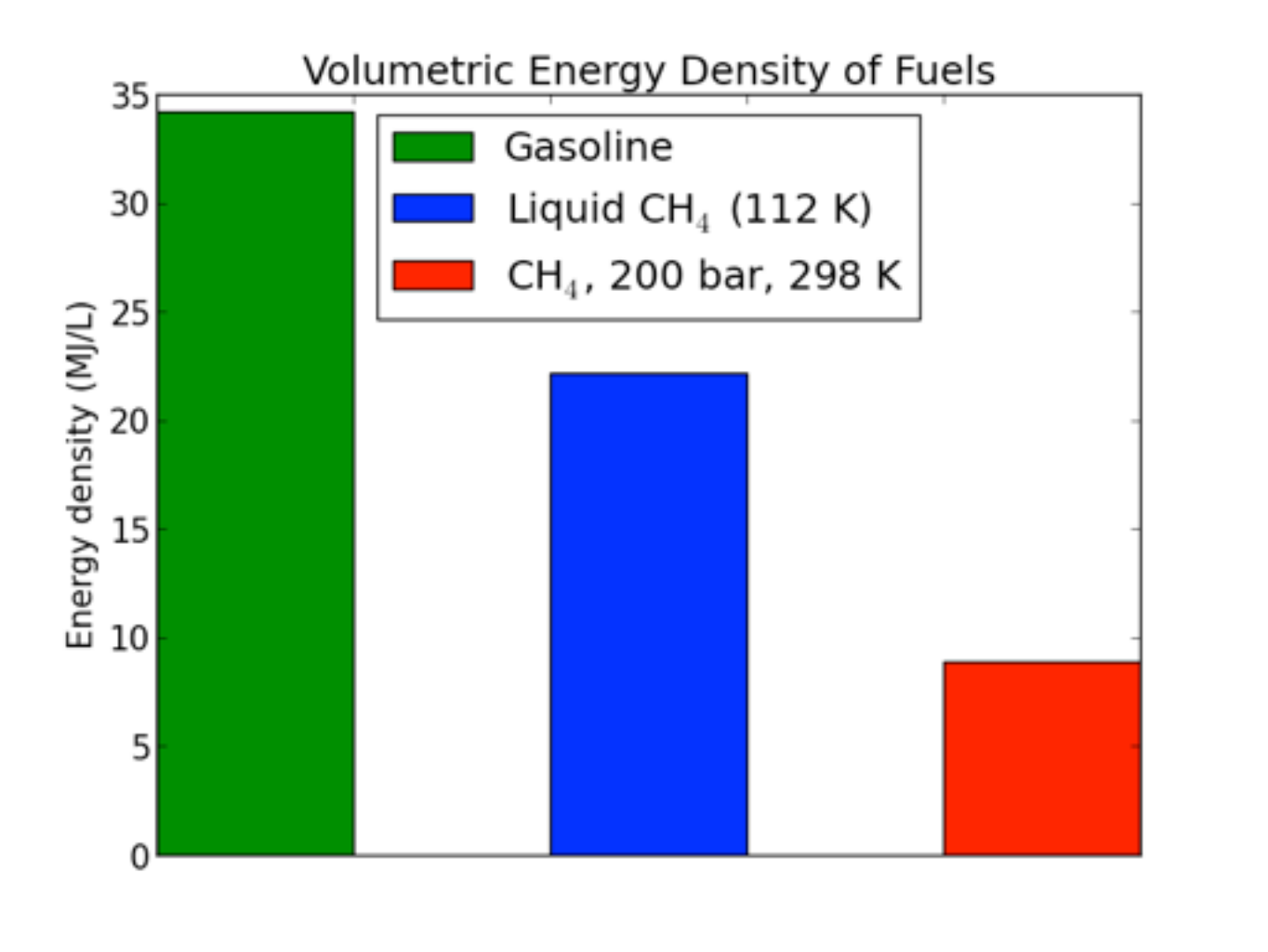


Methane cars: the technological obstacle

0.036 MJ

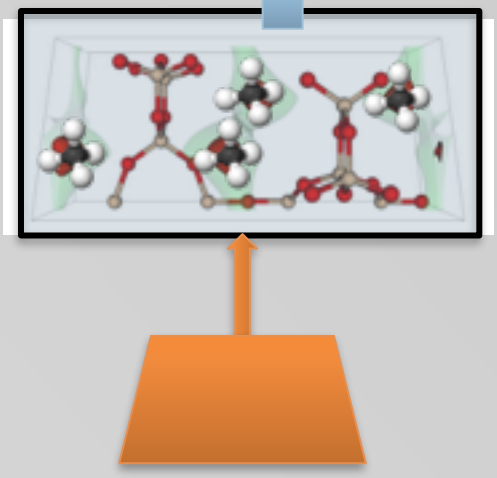
34.2 MJ

Methane versus gasoline



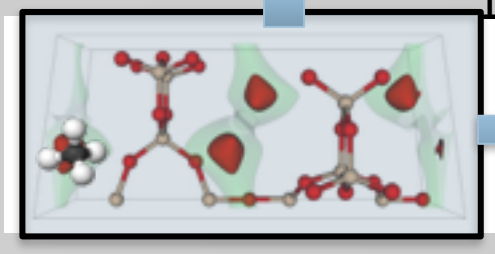
Makal *et al*. *Chem. Soc. Rev.* **2012** 41.23, 7761-7779.

65 bar



P_H = 65 bar

5.8 bar

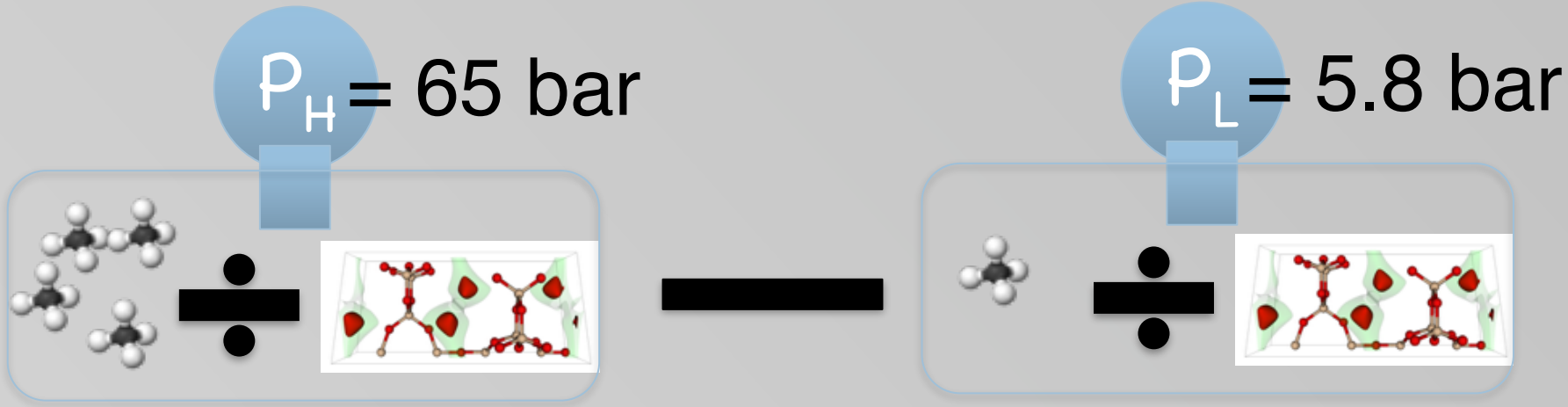


Insufficient flow

~1 bar

P_L = 5.8 bar

The deliverable capacity



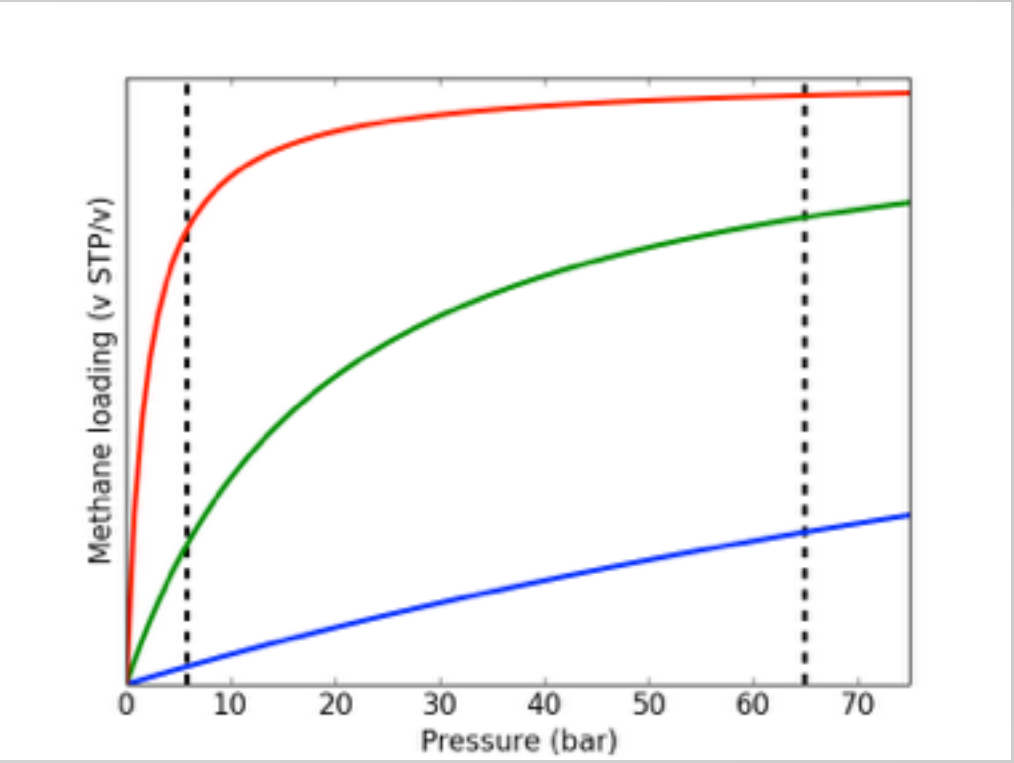
Methane adsorbed
(v STP/v)
at tank charging
pressure

Methane adsorbed
(v STP/v)
at tank discharge
pressure

ARPA-E (DOE) target: 315 m^3 STP methane/m^3 adsorbent

An optimal heat of adsorption?

Goal: maximize deliverable capacity



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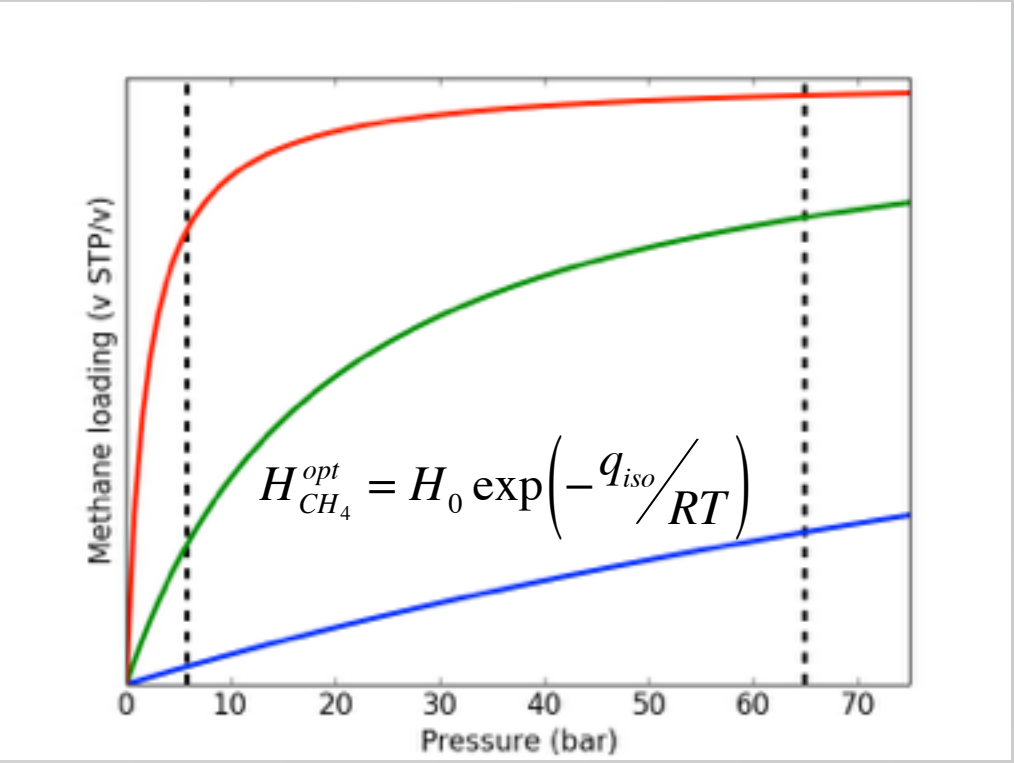

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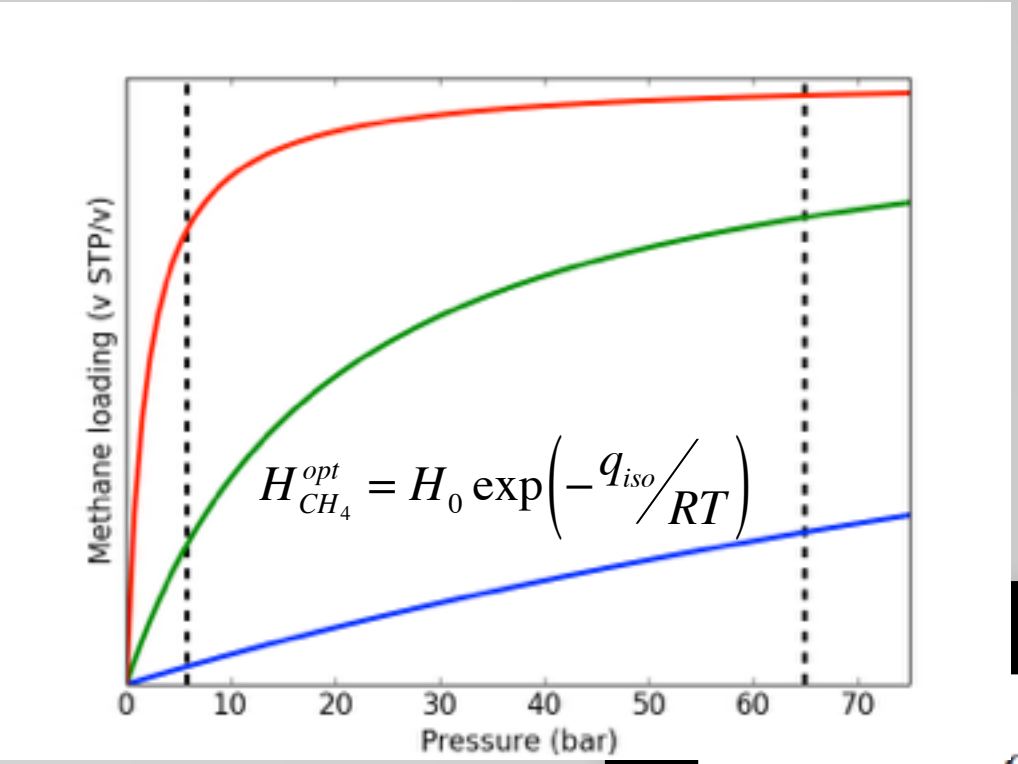

Langmuir 2006, *22*, 1688–1700

Optimum Conditions for Adsorptive Storage

Suresh K. Bhatia†

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Alan L. Myers*

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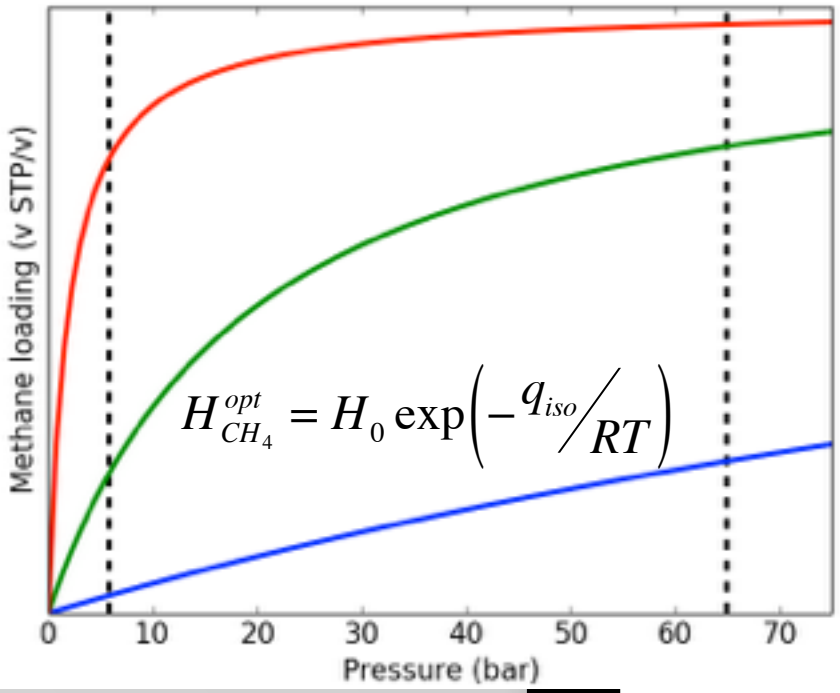

"For methane, an optimal enthalpy change of [16.2] kJ/mol is found."

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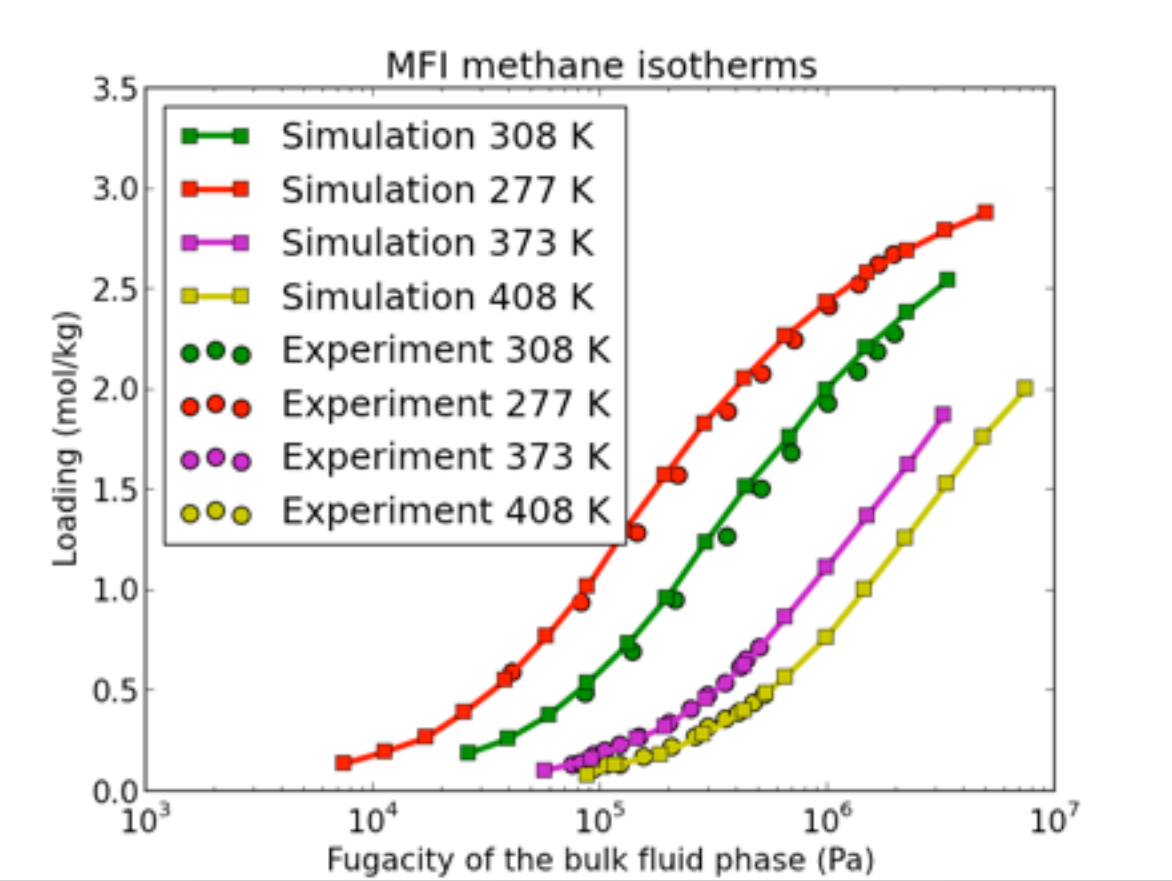
In silico screening of zeolites



MFI expt'l data: Sun *et al*. (1998) *J. Phys. Chem. B.* 102(8), 1466-1473.
Zhu *et al.* (2000) *Phys. Chem. Chem. Phys.* 2(9), 1989-1995.
Force field: Dubbeldam *et al*. (2004) *Phys. Rev.* 93(8), 088302.

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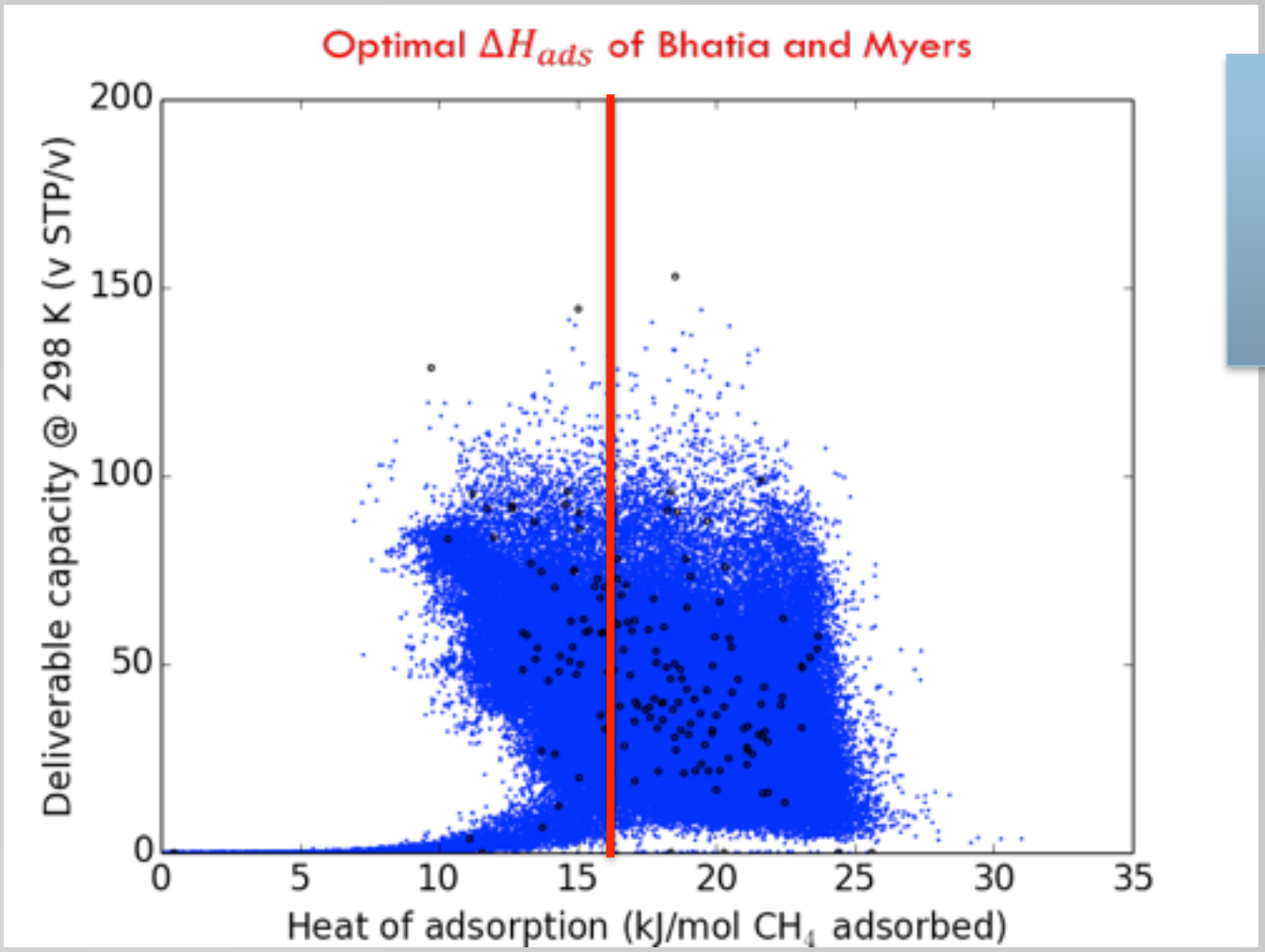
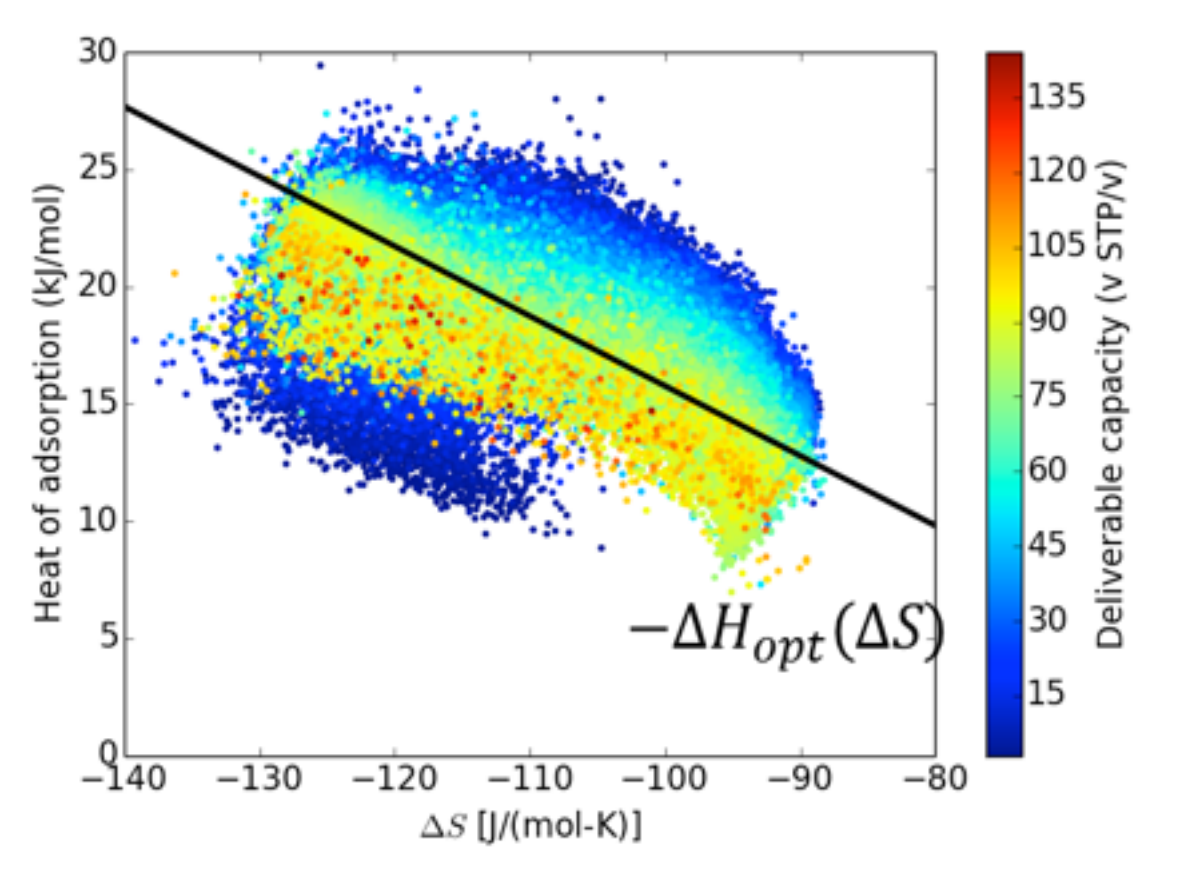


C. Simon *et al*. (2014) *Phys. Chem. Chem. Phys*. 16 (12), 5499-5513

Enthalpy vs. entropy

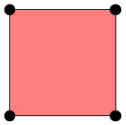
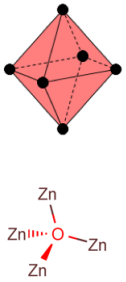
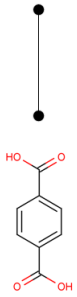
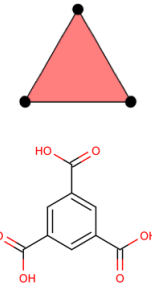
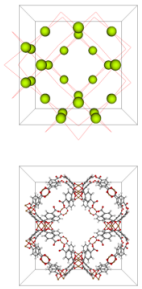
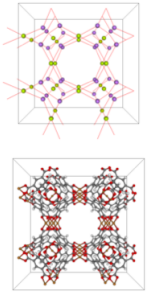
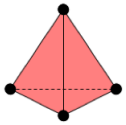
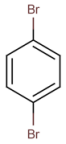
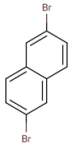
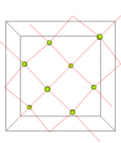
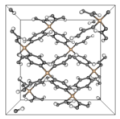
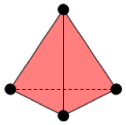
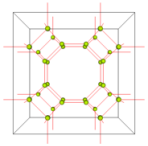
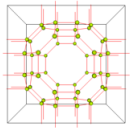
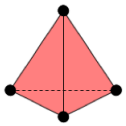
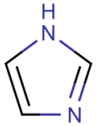
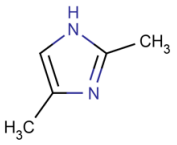
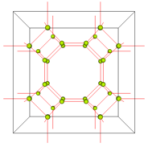
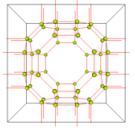
- ΔS not the same for all materials
- Wide range of ΔH that yields optimal material



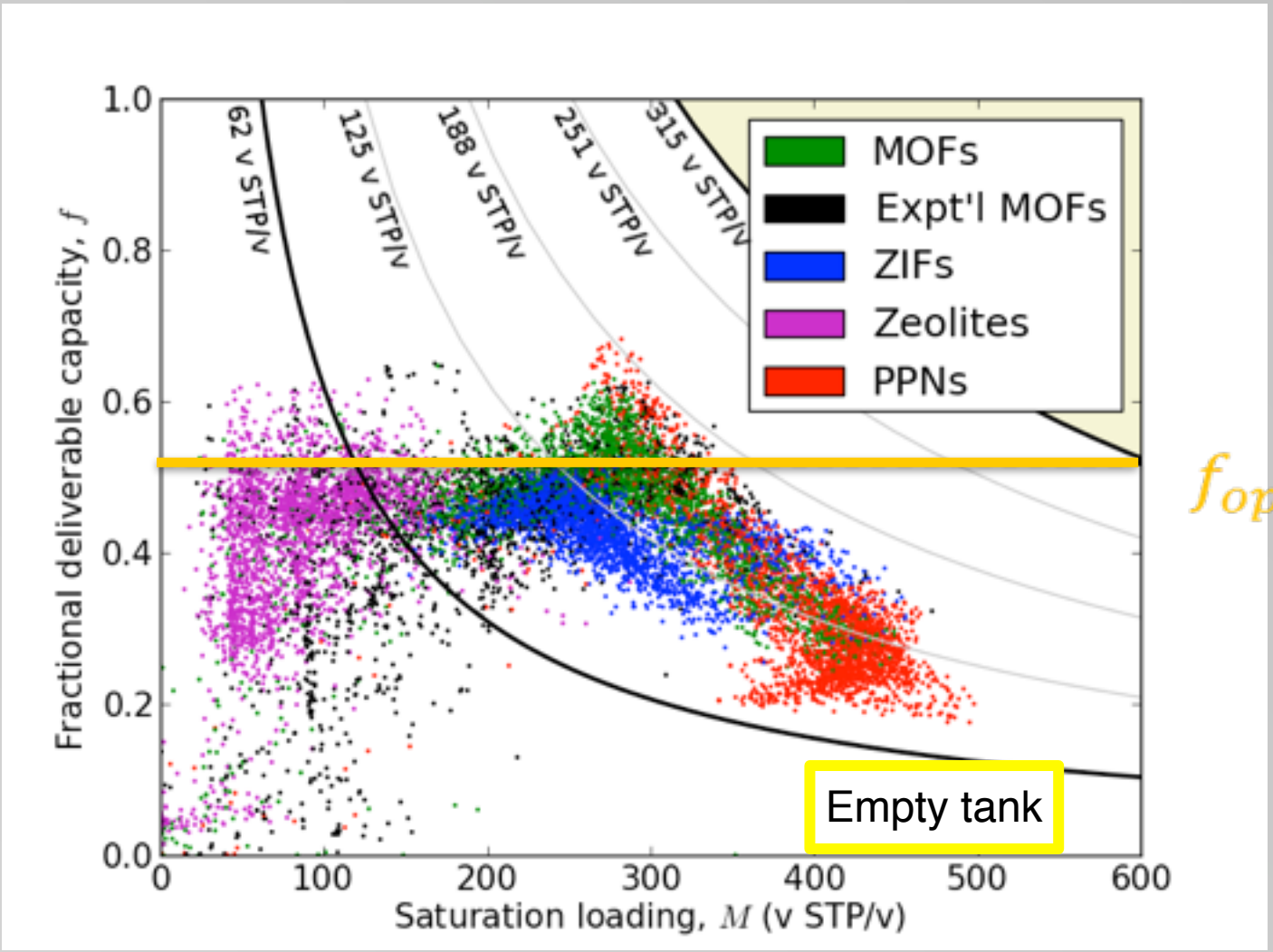
Can we find a material that meets the DOE target?

Screening > 100,000 materials

- zeolites
- Metal organic Frameworks, MOFs (Snurr and co-workers)
- zeolitic imidazolate frameworks, ZIFs, (Haranczyk)
- Polymer Porous Networks, PPNs (Haranczyk)

Material class	Building blocks				Topologies	
MOFs	 Cu—Cu					
PPNs	 Si Ge					
Zeolites	 Si		O			
ZIFs	 Zn Fe					

Insight from the model



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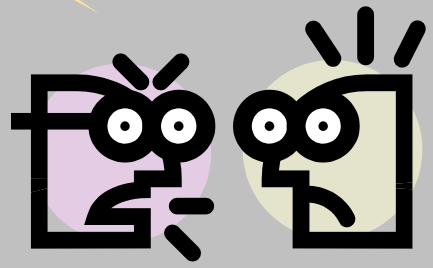

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My theory is **RIGHT**: but this experimentalist refuses to use molecules that do not have any attractive interactions

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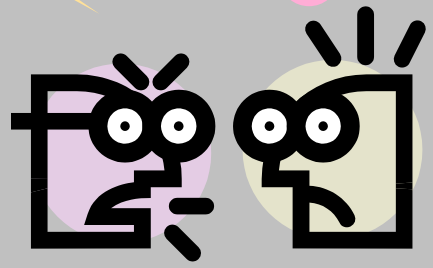

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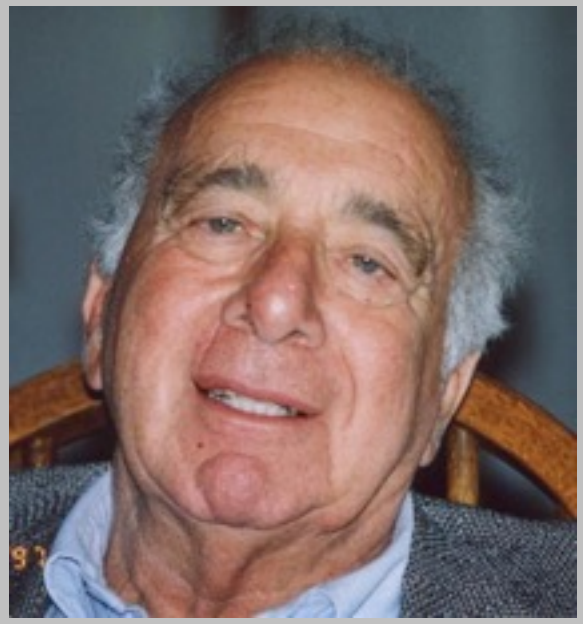

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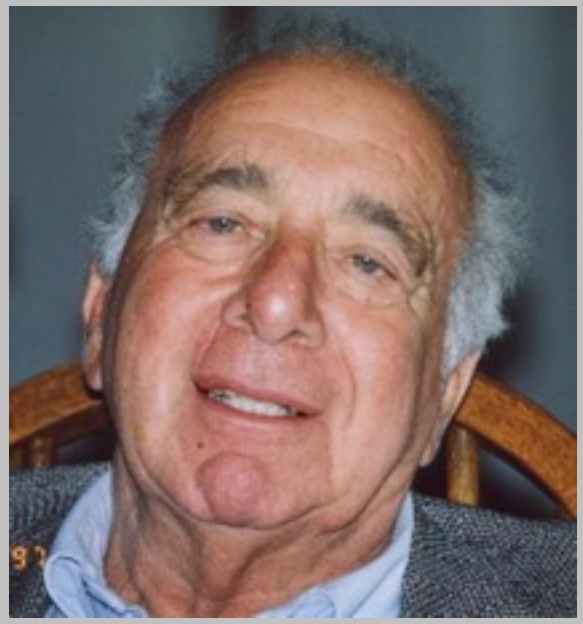

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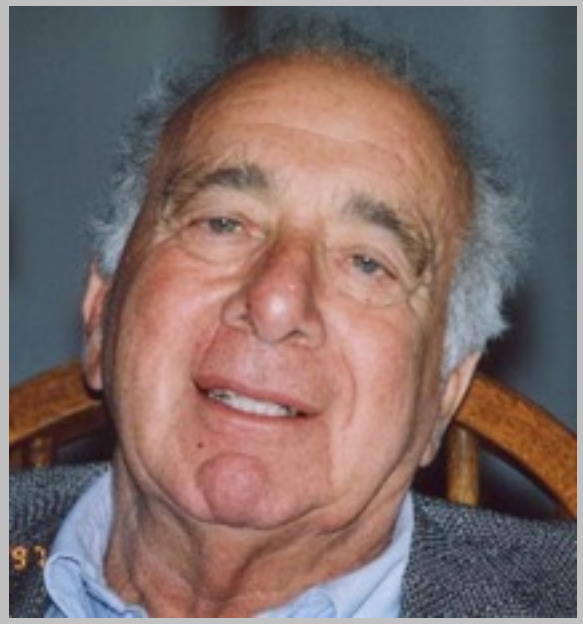

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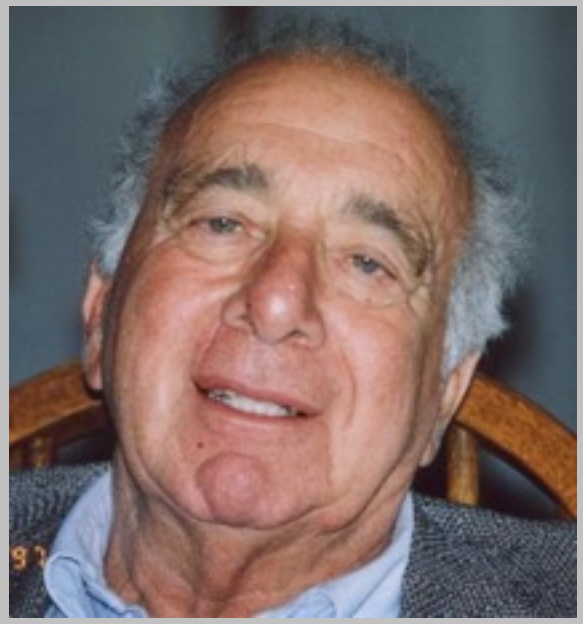

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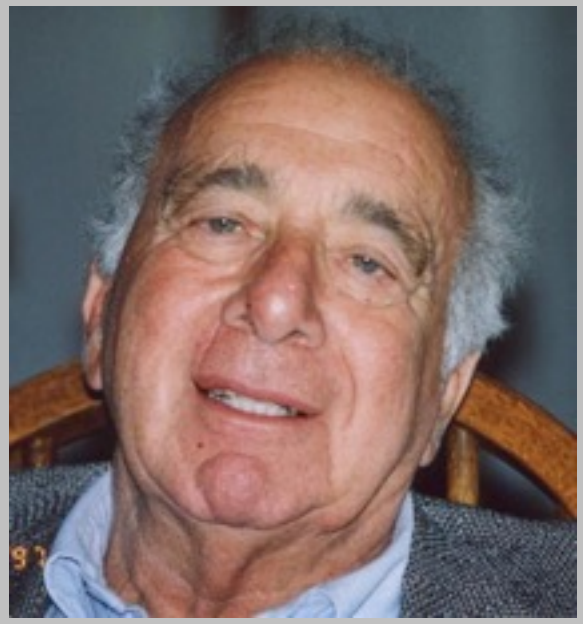

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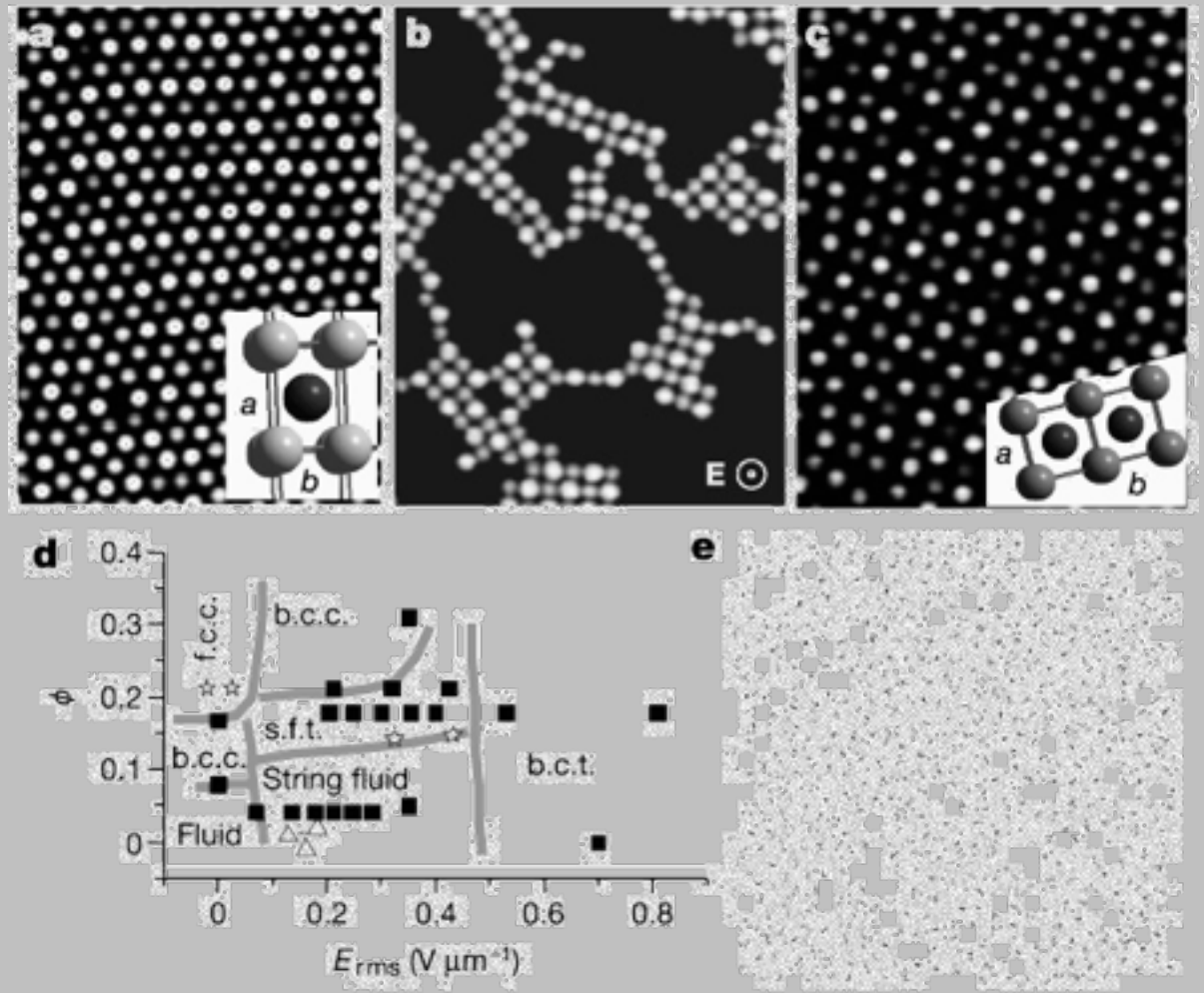

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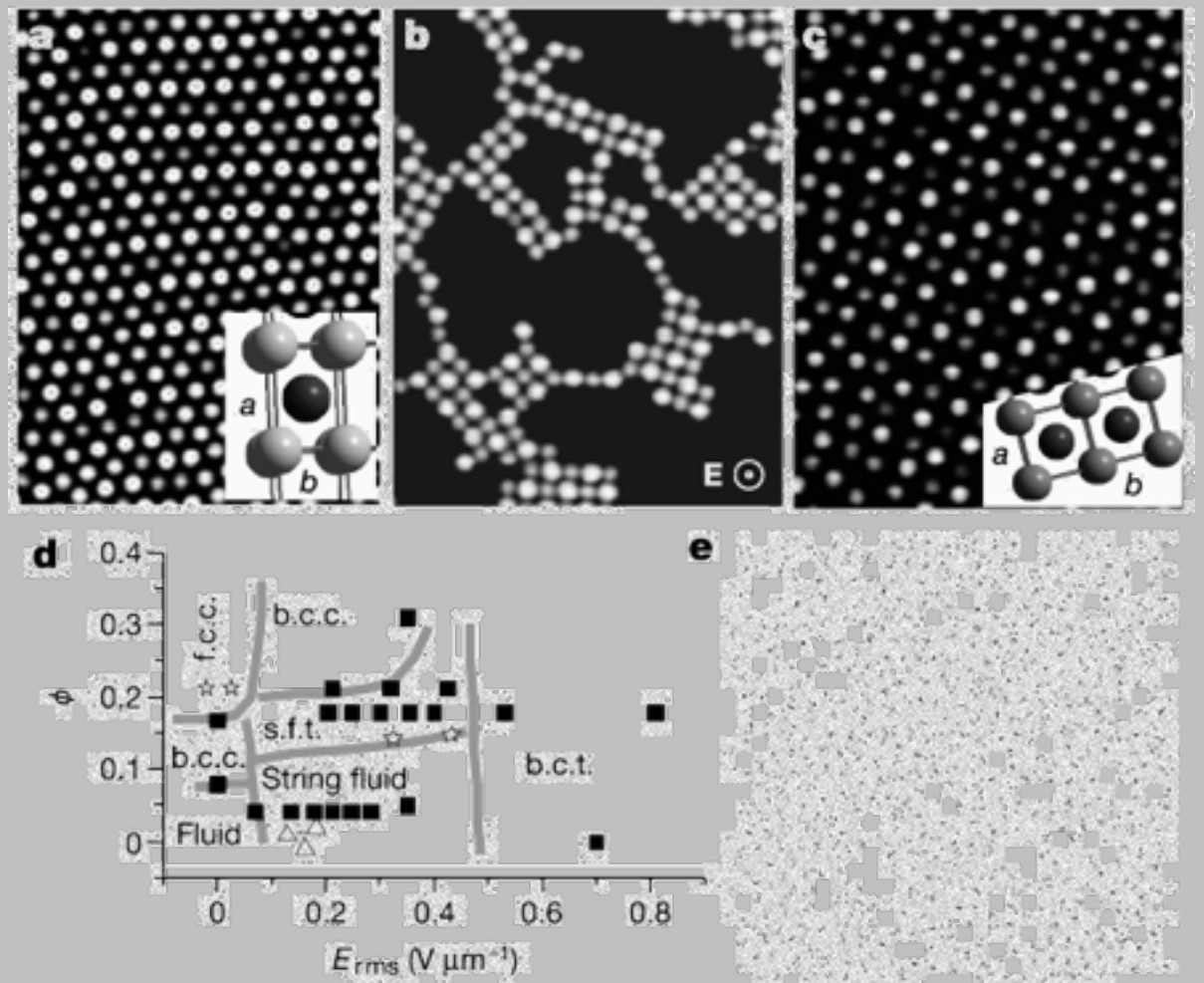


From the following article:

A colloidal model system with an interaction tunable from hard sphere to soft and dipolar

Anand Yethiraj and Alfons van Blaaderen

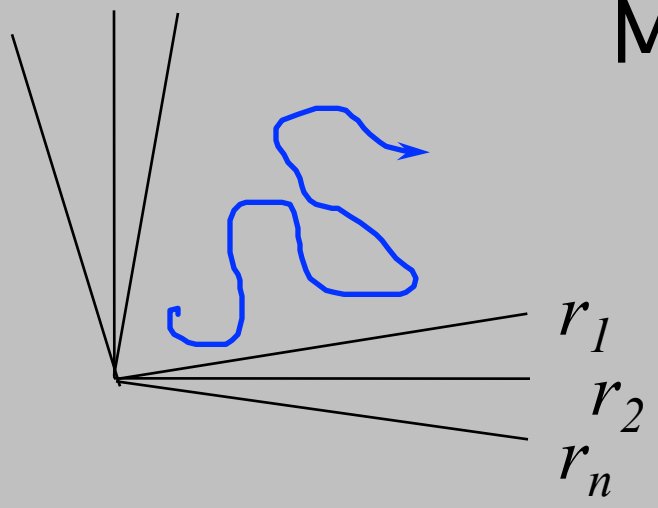
Nature 421, 513-517 (30 January 2003)

Molecular Dynamics

MD

- Theory:

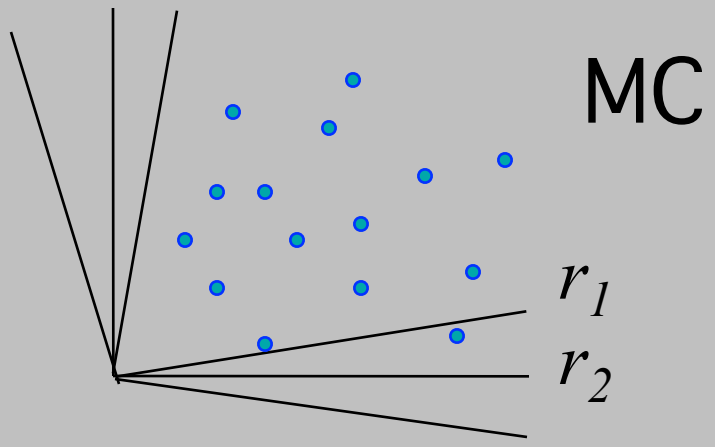
$$\mathbf{F} = m\frac{d^2\mathbf{r}}{dt^2}$$



- Compute the forces on the particles
- Solve the equations of motion
- Sample after some timesteps

Monte Carlo

- Generate a set of configurations with the *correct* probability
- Compute the thermodynamic and transport properties as averages over all configurations



Monte Carlo

What is the correct probability?
Statistical Thermodynamics

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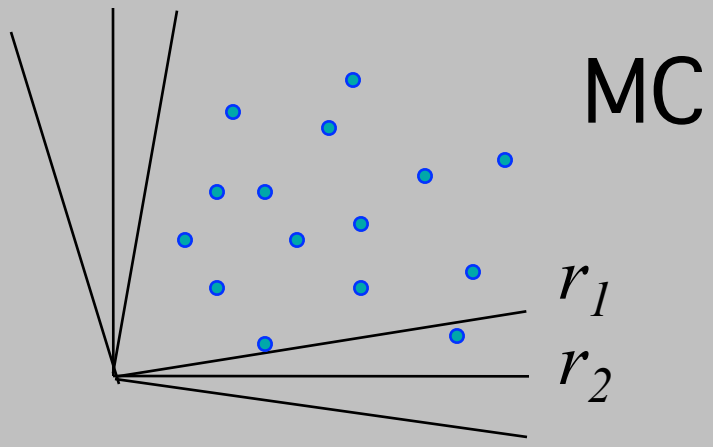

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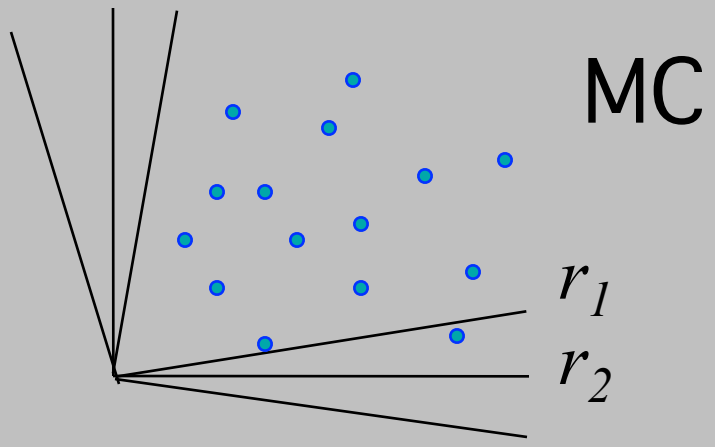

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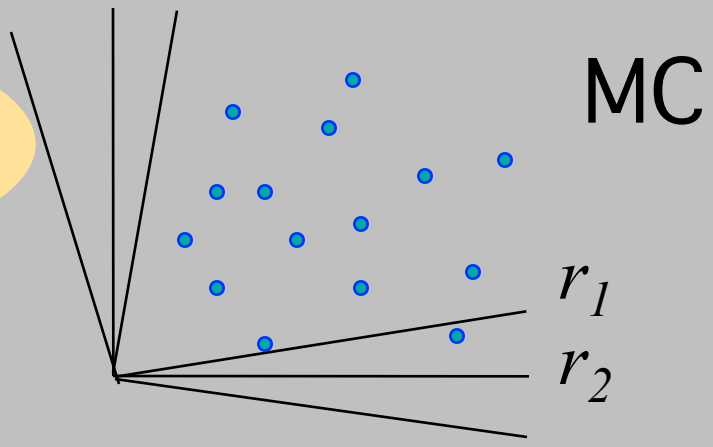
How to compute these properties from a simulation?



Classical and Statistical Thermodynamics

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- Thermodynamics: relation of the free energies to thermodynamic properties