

# Laser-driven dynamics of CO on Ru(0001)

## A computational study using electronic friction (MDEF) and the generalized Langevin oscillator (GLO)

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## 1 Introduction

- Motivation - in general and system specific
- First impressions of fs-laser-driven dynamics

## 2 Models and methods

- Foundations: 6D potential and two-temperature model
- Electronic friction: non-adiabatic coupling approximated
- The generalized Langevin oscillator (GLO)
- “Half-time”: short summary (and maybe time for a few questions)

## 3 Results and discussion

- Laser-driven diffusion
- Laser-driven desorption
- Physisorbed precursor states?

## 4 Summary and Outlook

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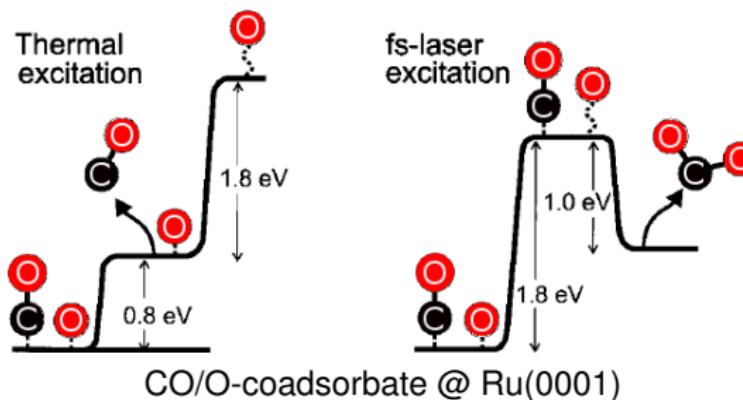
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# General motivation

## Why investigate fs-laser-driven surface dynamics?

- gain fundamental understanding of adsorbate bonding  
⇒ additional tool besides scattering experiments and STM
- possible direct application in catalysis: “femtochemistry”  
⇒ new reaction pathways opened up by fs-lasers



M. Bonn *et al.*, *Science* 1999

# Specific motivation for investigating CO/Ru(0001)

CO/Ru(0001) system important for catalysis, e.g.:

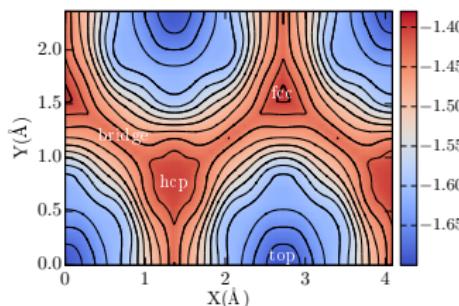
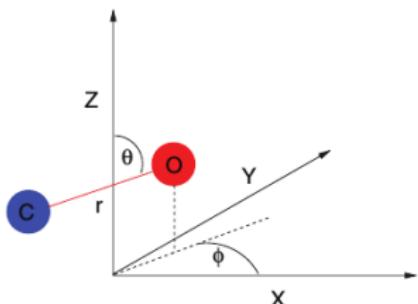
- Fischer-Tropsch synthesis
- exhaust gas converters (systems with similar metals)

Experimentally well studied system

- especially regarding fs-laser irradiation:
  - e.g. Bonn *et al.*, *Science* 1999; Funk *et al.*, *JChemPhys* 2000
  - (both Ertl group ⇒ chemistry Nobel prize 2007).
- desorption kinetics: large prefactors ⇒ still not understood
- recently, time resolved x-ray spectra (XAS and XES)  
⇒ “movie” of changes in orbital density of states
  - Dell'Angela *et al.*, *Science* 2013

# Further specific motivation for investigating CO/Ru

Füchsel *et al.*, JChemPhys 2014



Important prior theory work was done at our group

Füchsel *et al.*, JChemPhys 2014

- Development of a potential energy surface (PES)
    - from over 90 000 DFT points!
    - all 6 dimensions of the adsorbate
    - very fast because preconstructed
- ⇒ **enables large-scale dynamics!**

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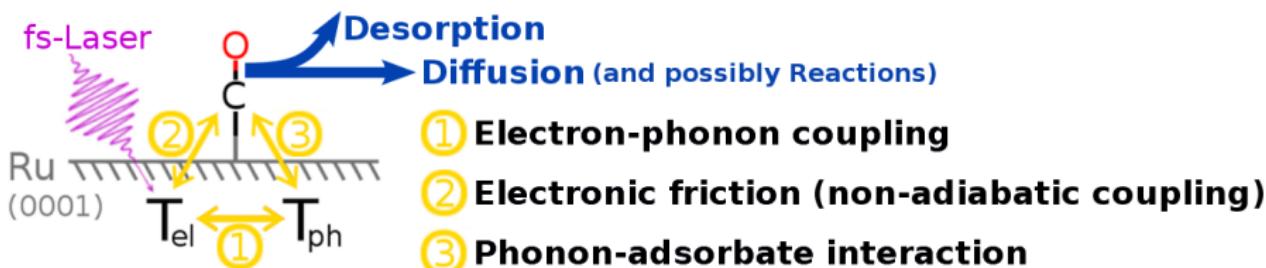
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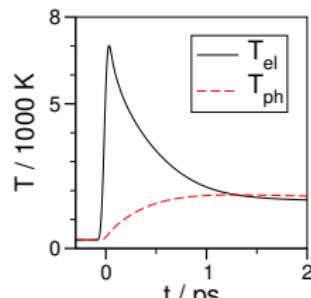
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# What happens after fs-laser excitation of the metal?



Coupling between 3 kinds of degrees of freedom:

- electron gas ( $T_{el}$ )
  - initially absorbs laser energy
  - low heat capacity  $\Rightarrow$  high  $T_{el}$  ( $\approx 5\text{-}10\text{ kK}$ )
- lattice vibrations ( $T_{ph}$ )
  - thermalization with electrons: ps time scale  
 $\Rightarrow$  fs-laser causes two distinct temperatures!
- adsorbate movement ( $T_{ads}$ )



# Details of the time-resolved x-ray experiment

Dell'Angela *et al.*, *Science* 2013 (experimental part by Nilsson group, SLAC/LCLS, Stanford)

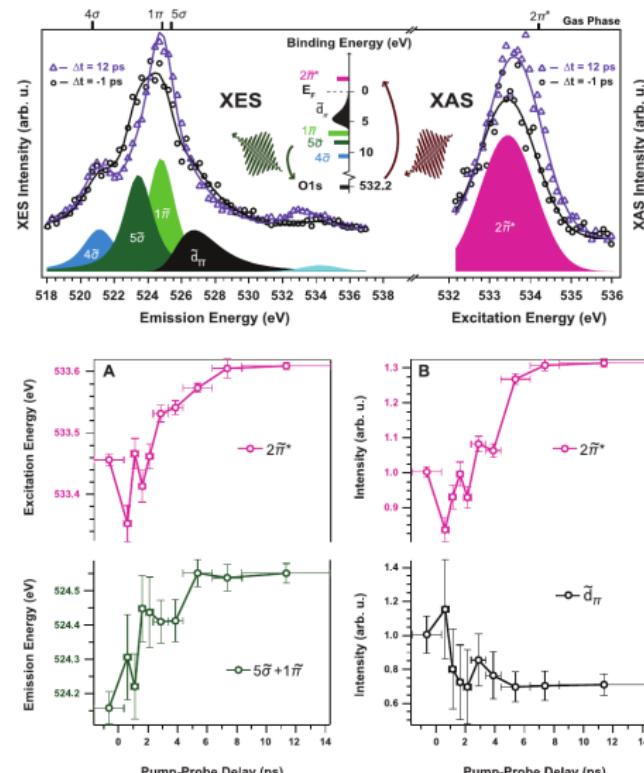
## What was done?

- pump: *vis-fs-laser*
- probe: x-ray free  $e^-$  laser
  - K-edge of O-atom

## What is observed?

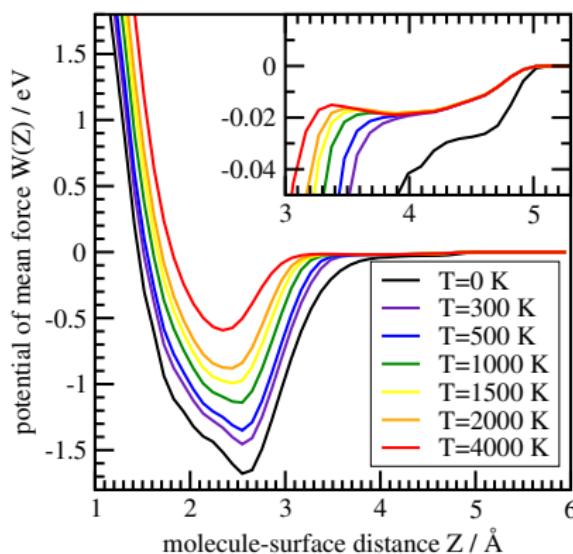
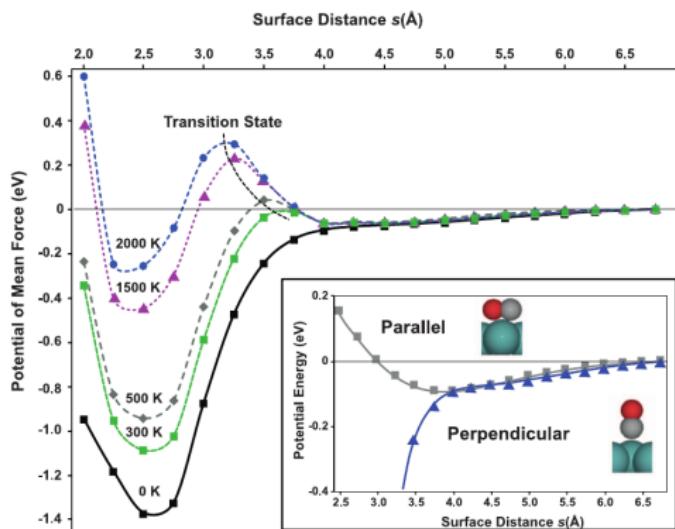
- orbital density of states at O
- energies shift towards gas-phase values of CO
- intensities change
  - $2\tilde{\pi}^*$   $\Rightarrow$  increase by  $\sim 30\%$
  - $\tilde{d}_\pi$   $\Rightarrow$  decrease by  $\sim 30\%$
  - participant peak appears

⇒ physisorbed precursor(?)



# Details of the accompanying theory

still Dell'Angela *et al.*, *Science* 2013 (theory part by Nørskov group, SUNCAT, Stanford)



Dell'Angela *et al.*, *Science* 2013

Scholz *et al.*, *PhysRevB* 2016

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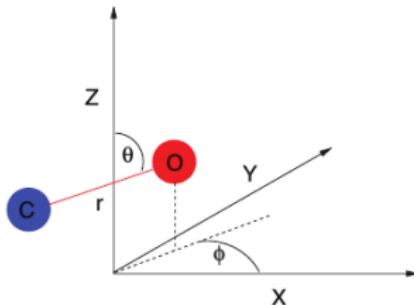
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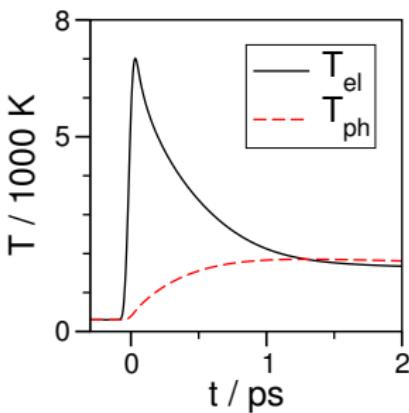
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# Ab-initio-based, full-dimensional (6D) potential energy surface (PES)



# Two-temperature model (TTM)

$$C_{\text{el}} \frac{\partial T_{\text{el}}}{\partial t} = \frac{\partial}{\partial z} \kappa \frac{\partial}{\partial z} T_{\text{el}} - g(T_{\text{el}} - T_{\text{ph}}) + S(z, t),$$
$$C_{\text{ph}} \frac{\partial T_{\text{ph}}}{\partial t} = g(T_{\text{el}} - T_{\text{ph}}).$$



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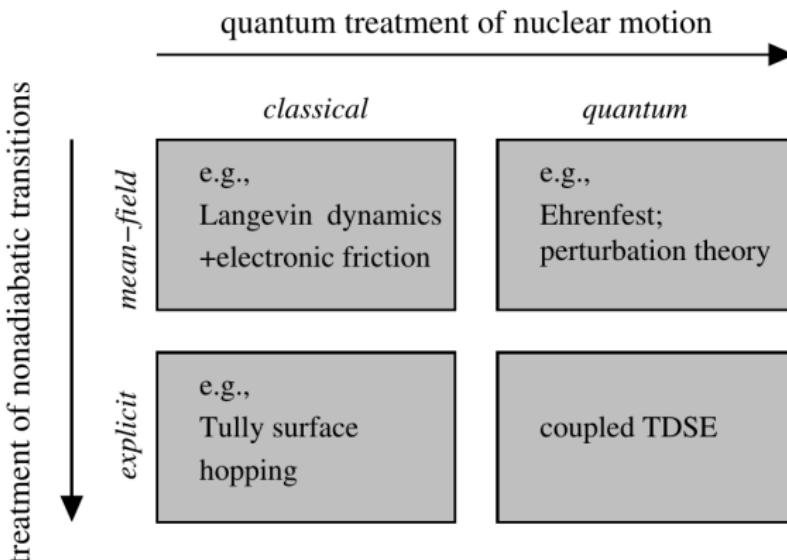
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# Different approaches to describe non-adiabatic coupling



# Langevin Dynamics

$$\underbrace{m_k \frac{d^2 \underline{r}_k}{dt^2}}_{\text{Force on Atom } k} = \underbrace{-\nabla_k V(\underline{r}_1, \underline{r}_2)}_{\text{Force due to PES}} - \underbrace{\eta_{\text{el},k}(\underline{r}_k) \frac{d\underline{r}_k}{dt}}_{\text{Friction force slows movement}} + \underbrace{R_{\text{el},k}(t)}_{\text{Random force from e-h pairs}}.$$

- $R_{\text{el},k}(t)$  = Gaussian white noise
  - describes excitation by hot electron-hole pairs
  - dependent on:  $\eta_{\text{el},k}(\underline{r}_k)$  and  $T_{\text{el}}$

# Local density friction approx. plus independent atoms

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# Generalized Langevin Oscillator

$$m_s \frac{d^2 \underline{r}_s}{dt^2} = \underbrace{-\nabla_s V(\underline{r}_1 - \underline{r}_s, \underline{r}_2 - \underline{r}_s)}_{\text{Force due to PES}} - m_s \underline{\underline{\Omega}}^2 \underline{r}_s + m_s \underline{\underline{\Lambda}}_{gs} \underline{r}_g$$

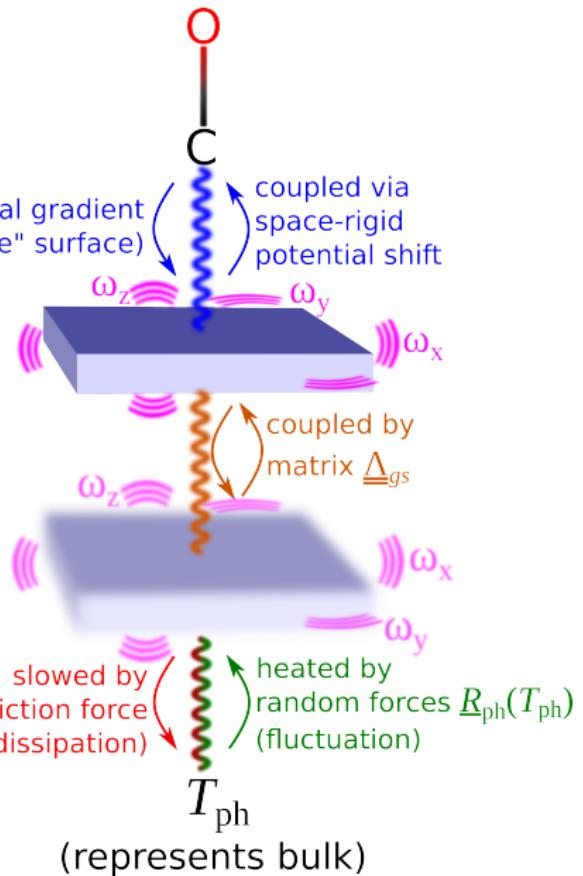
Force due to PES      Harmonic oscillator      Coupling to ghost oscillator

## Surface oscillator

both oscillate in the 3 dimensions x, y, z

## Ghost oscillator

$$m_s \frac{d^2 \underline{r}_g}{dt^2} = \underbrace{-m_s \underline{\underline{\Omega}}^2 \underline{r}_g}_{\text{Harmonic oscillator}} + \underbrace{m_s \underline{\underline{\Lambda}}_{gs} \underline{r}_s}_{\text{Coupling to surface oscillator}} - \underbrace{\eta_{ph} \frac{d \underline{r}_g}{dt}}_{\text{Friction force}} + \underbrace{\underline{R}_{ph}(T_{ph})}_{\text{Random forces}}$$



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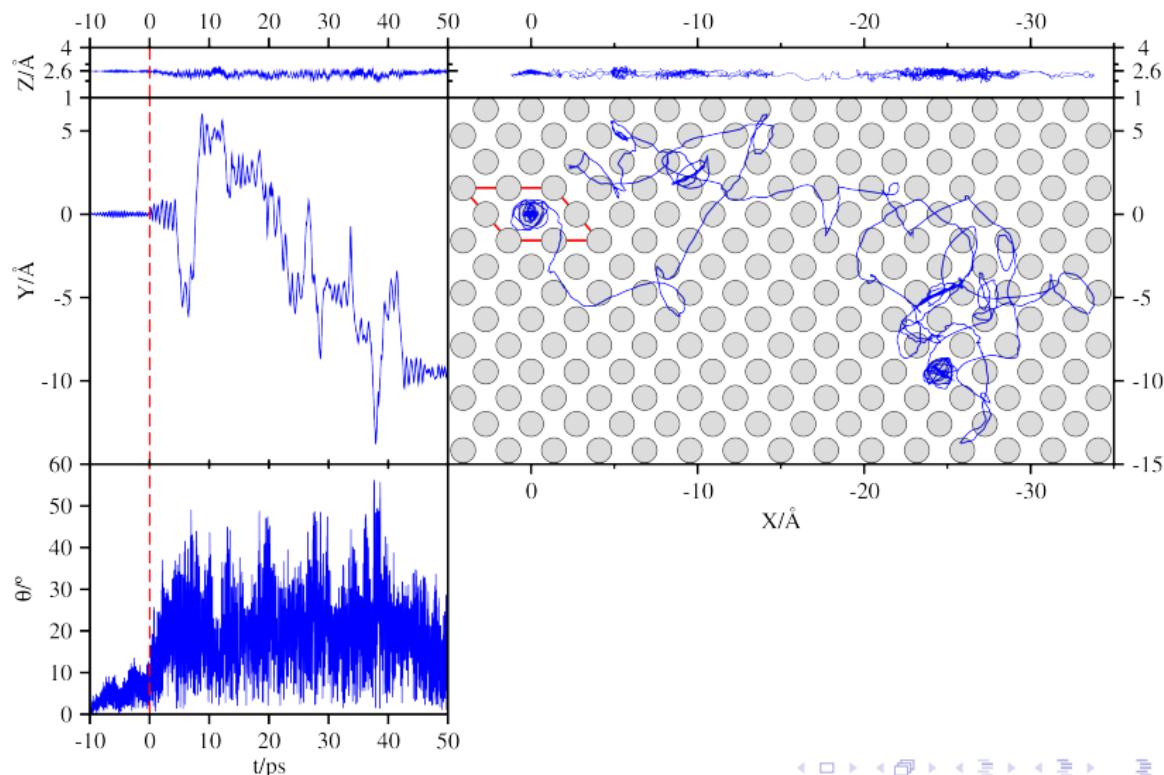
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# Example trajectory

(in this case without GLO-model)



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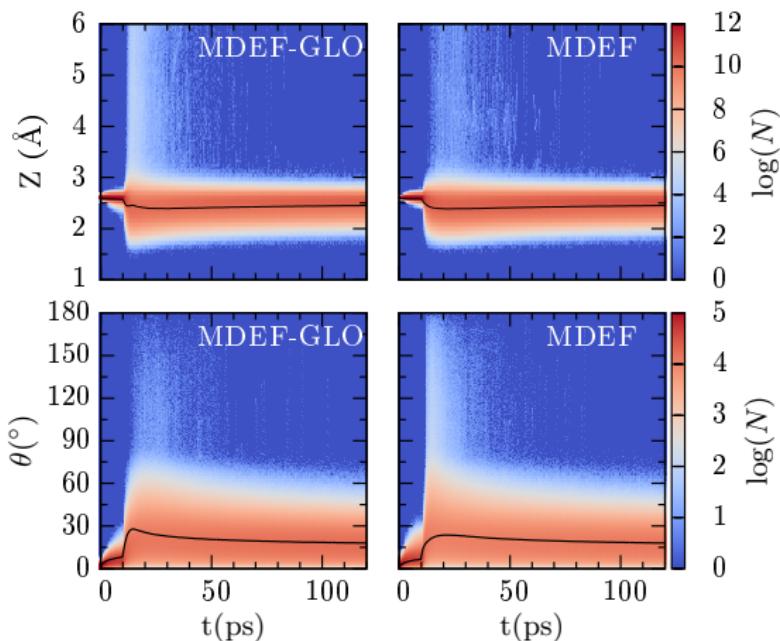
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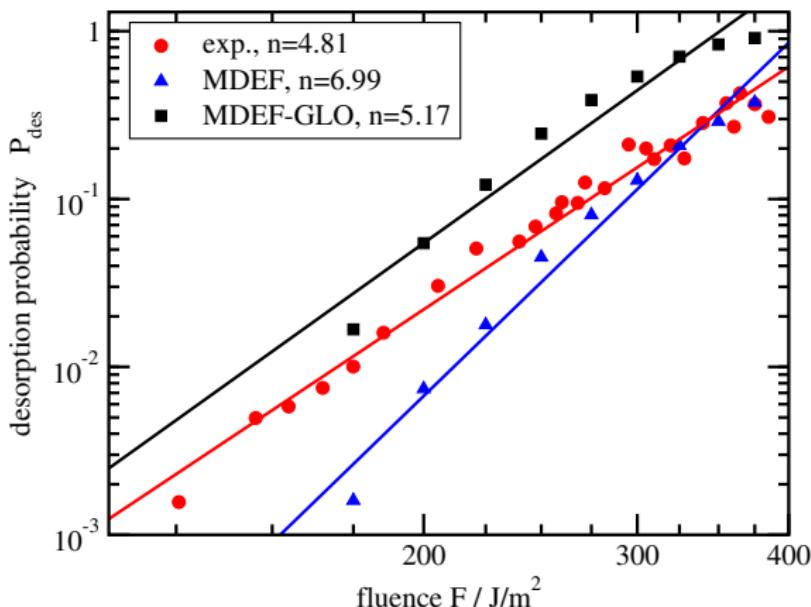
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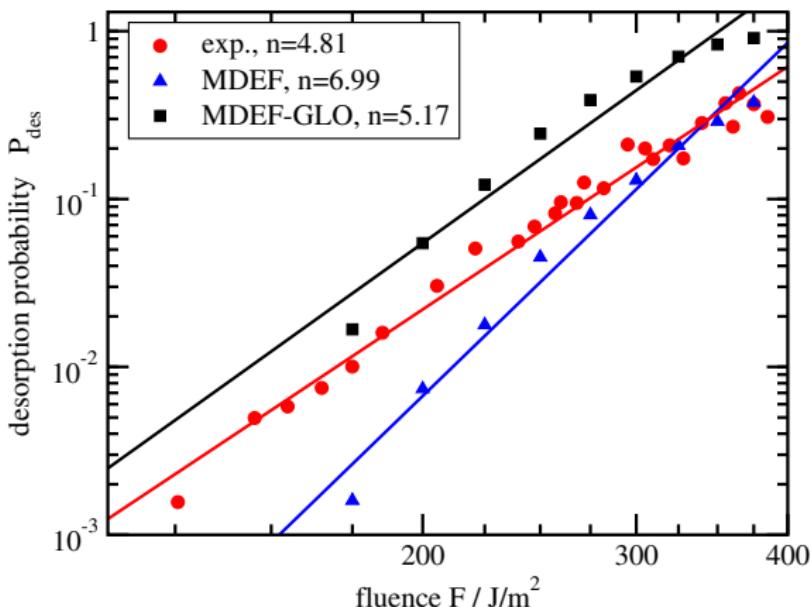
# Heating of DOFs $Z$ and $\theta$



# Fluence-dependence of desorption yield $P_{\text{des}}$



# Two-pulse correlation of desorption



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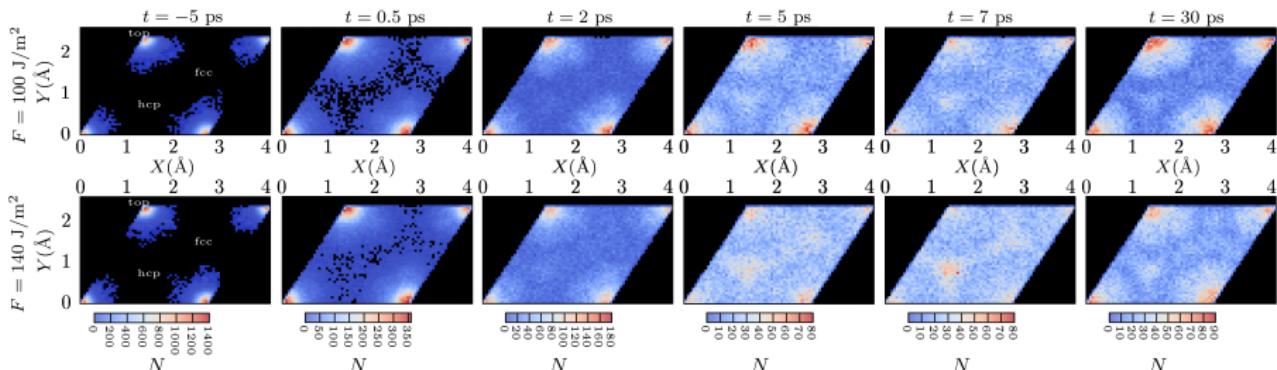
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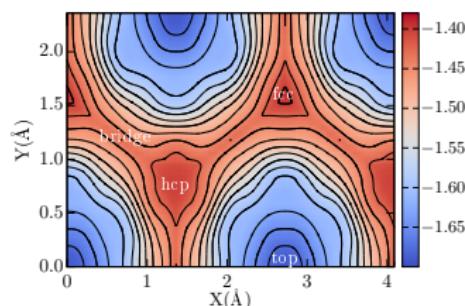
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# Anisotropic diffusion patterns + dynamical trapping



## Surprising patterns in XY-distribution

- preference of **hcp-site** after 5-7 ps, despite it being a local maximum!  
⇒ **dynamical trapping** (cf. 30 ps)
- effect dependent on fluence  
⇒ consistent with experiment  
(weaker “precursor”-signal for lower fluence)



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