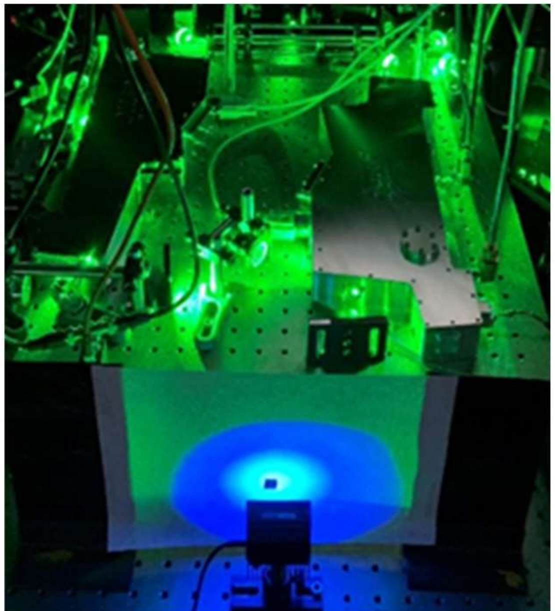
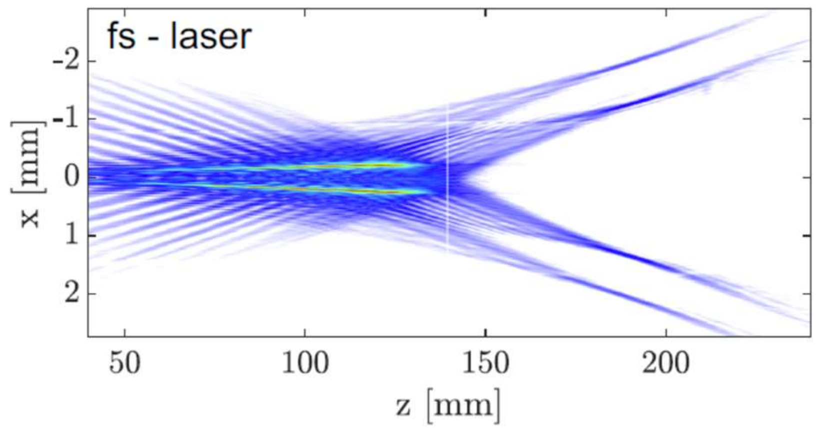
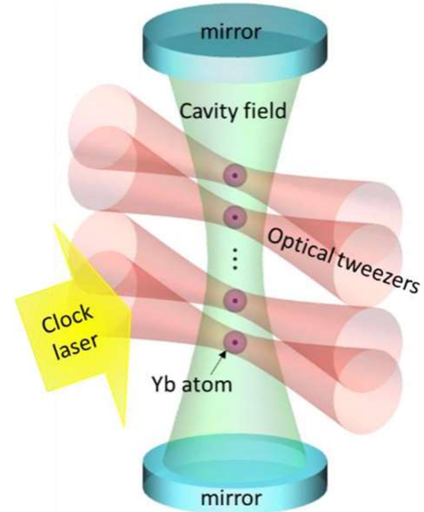
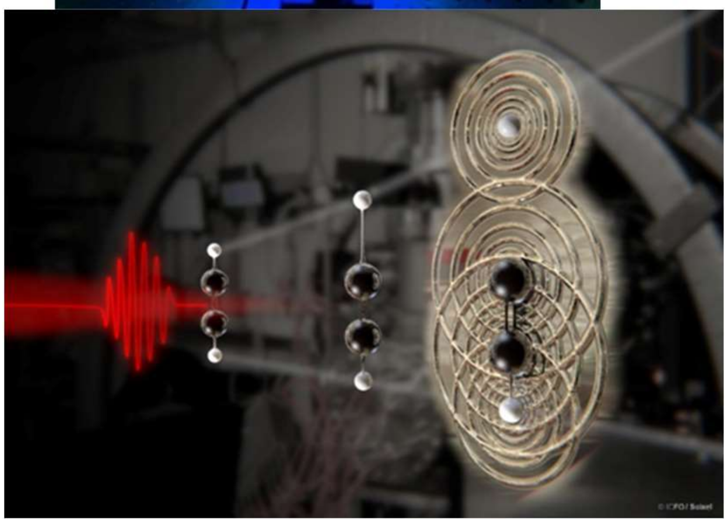
AMO @ UConn: Ultra-Cold and Ultra-Fast Experiment and Theory

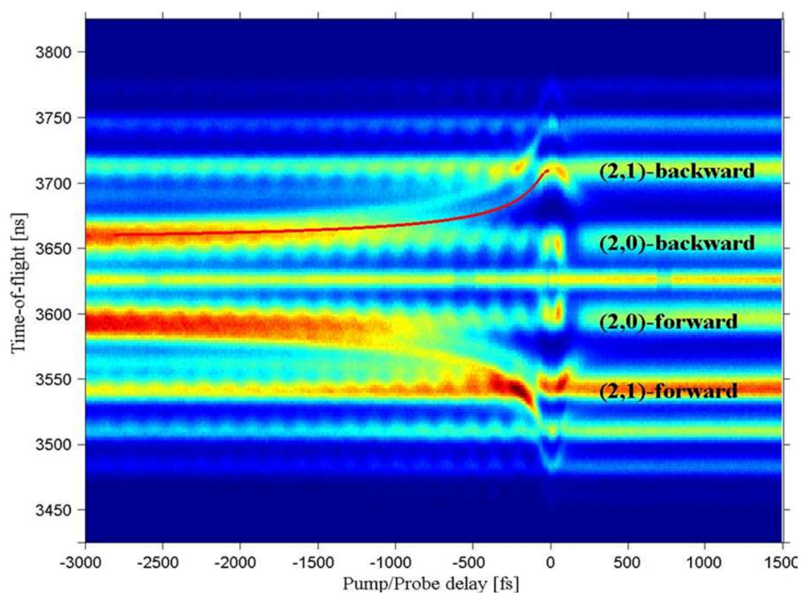
Investigate and manipulate interaction of Light with Atoms, Molecules, Clusters, Nano-particles and Solids.

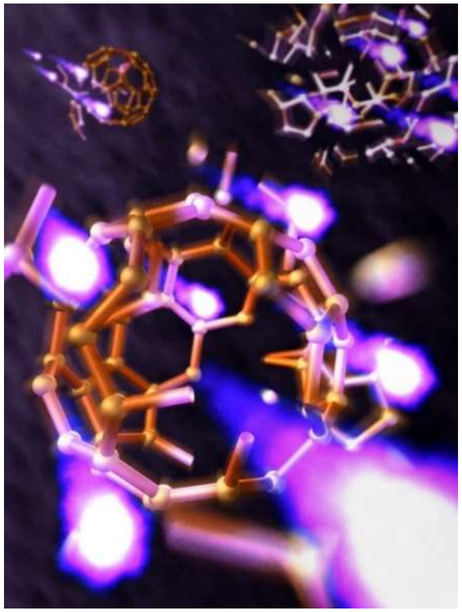












Ultracold = Controlled

Temperatures ~ 1 nK to 1μK

de Broglie wavelength:

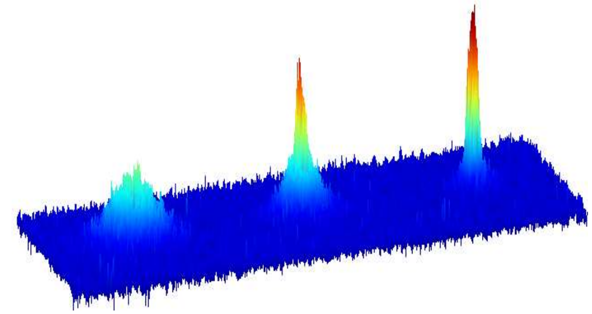
$$\lambda = \frac{h}{p} = \frac{h}{m\upsilon}$$

Figure of merit:

Phase-space density

$$\rho = n_0 \lambda^3$$

Quantum regime: $\rho \sim 1$



S. Bose, *Z. Phys* **26**, 178 (1924)

$$i\hbar \frac{\partial}{\partial t} \Psi(\mathbf{r}, t) = \hat{H} \Psi(\mathbf{r}, t)$$

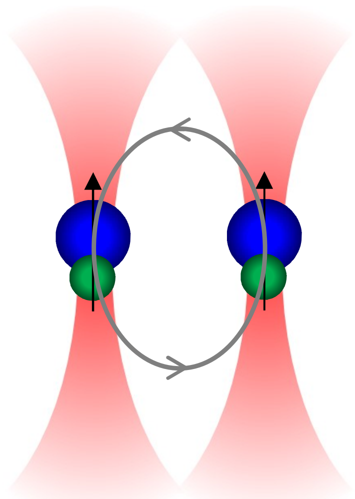
We can control *everything*

$$\hat{H} =$$

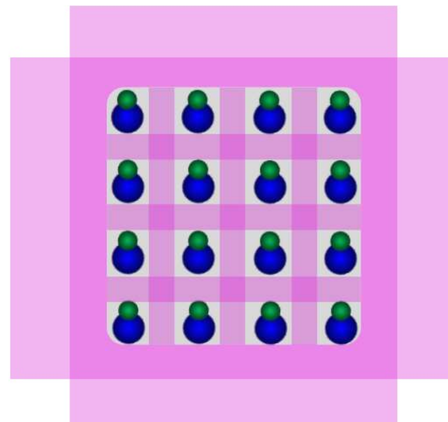
Quantum science with polar molecules

We use cryogenics and laser-cooling to advance the science of complex quantum systems and underpin new quantum technologies.

Two complementary directions:

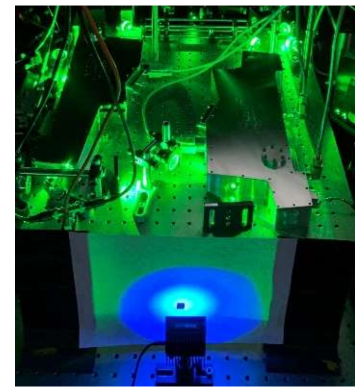


1. Small arrays of molecules:
quantum gates and computation



2. Large arrays of molecules:
quantum simulations

Lots of hands-on work…



E.g. World-record
2 W deep-UV laser

Ultracold Experiment

McCarron Group

themccarrongroup.com

Contact us to learn more:
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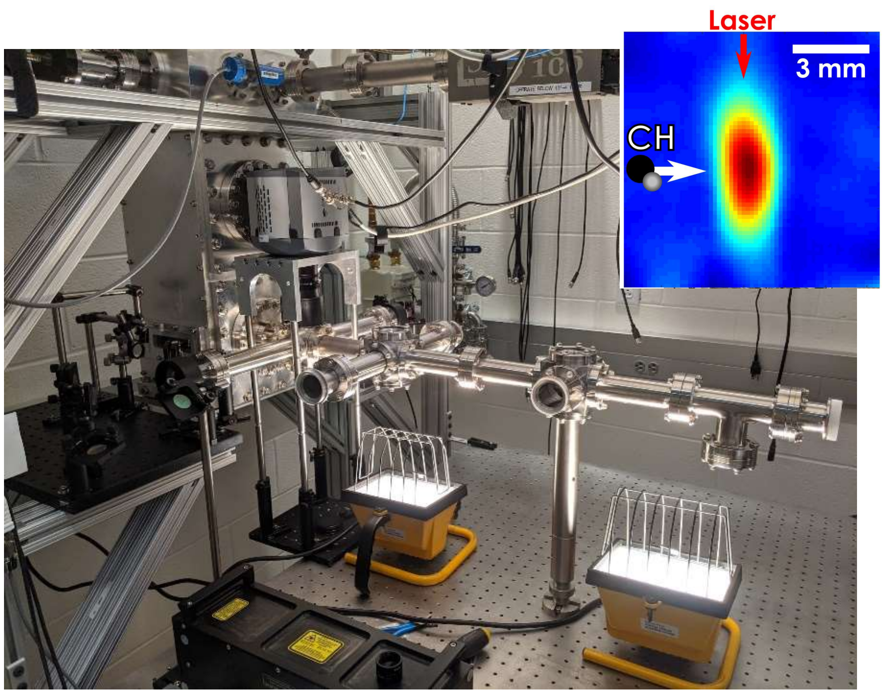
@mccarrongroup

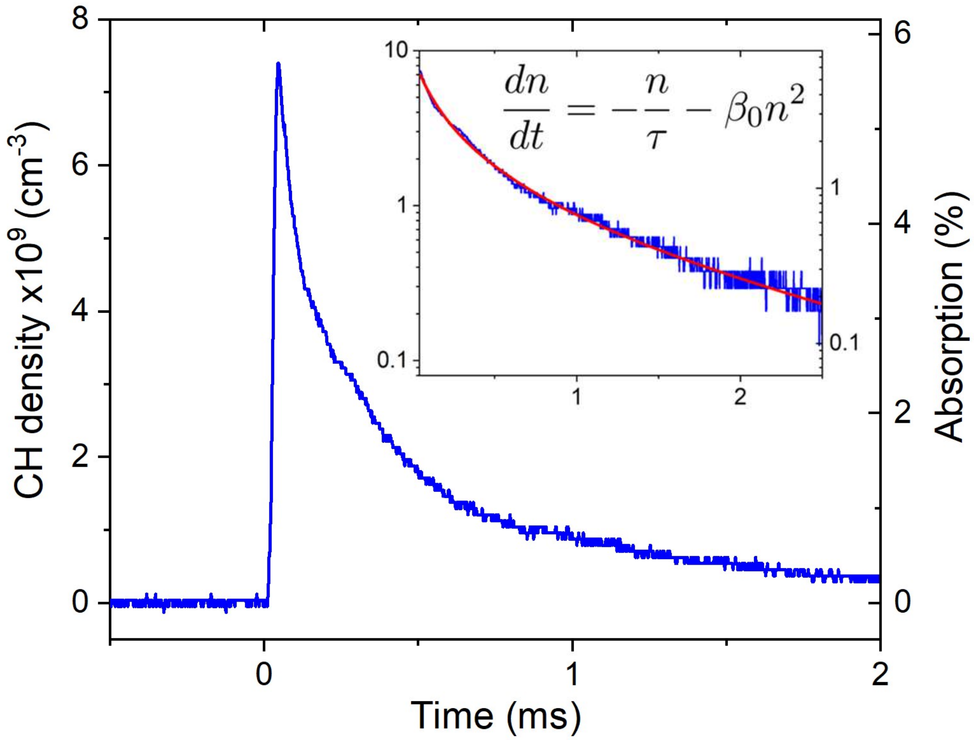
Ultracold organic chemistry

Ultracold Experiment

We cool highly-reactive CH radicals for the first tests of quantum state controlled organic chemistry.



Our CH beam machine



We already see cold organic chemistry via two-body loss!

themccarrongroup.com

Contact us to learn more:

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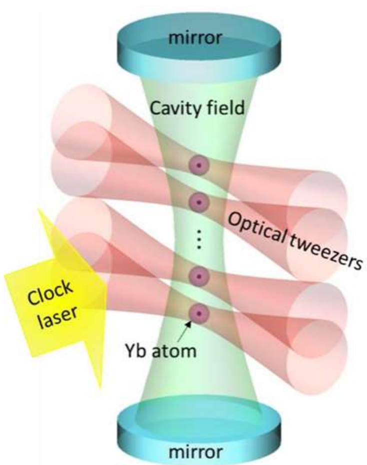
@mccarrongroup

Quantum-enhanced World at UConn

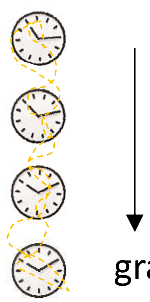
The Colombo Lab

Scientific Reason: Understanding how our universe works
How: By sensing it with the highest precision
What: Ultracold atoms -> Quantum-Enhanced Atomic Sensors

Quantum science with cavity Quantum ElectroDynamics (cQED)



$\Rightarrow$ single atom control
$\Rightarrow$ programmable atom – atom interaction



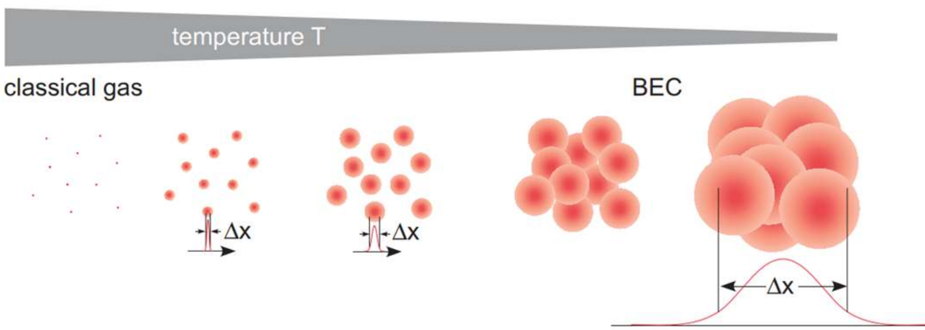
gravity

Gravitational red-shift $\approx \frac{10^{-19}}{\text{mm}}$

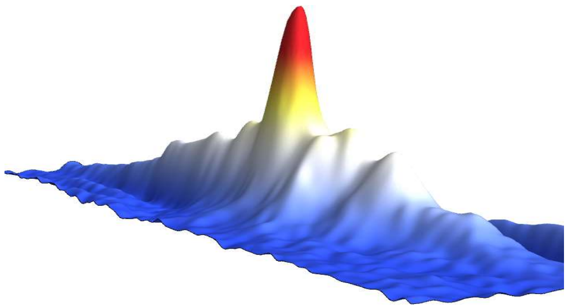
1s in 300b yrs

A system where **entanglement** and **gravitational redshift** are significant and simultaneous effects.

Studying quantum degenerate gases



At ultra-low temperatures, the delocalization of atoms becomes larger than their average distance.



Ultracold Experiment

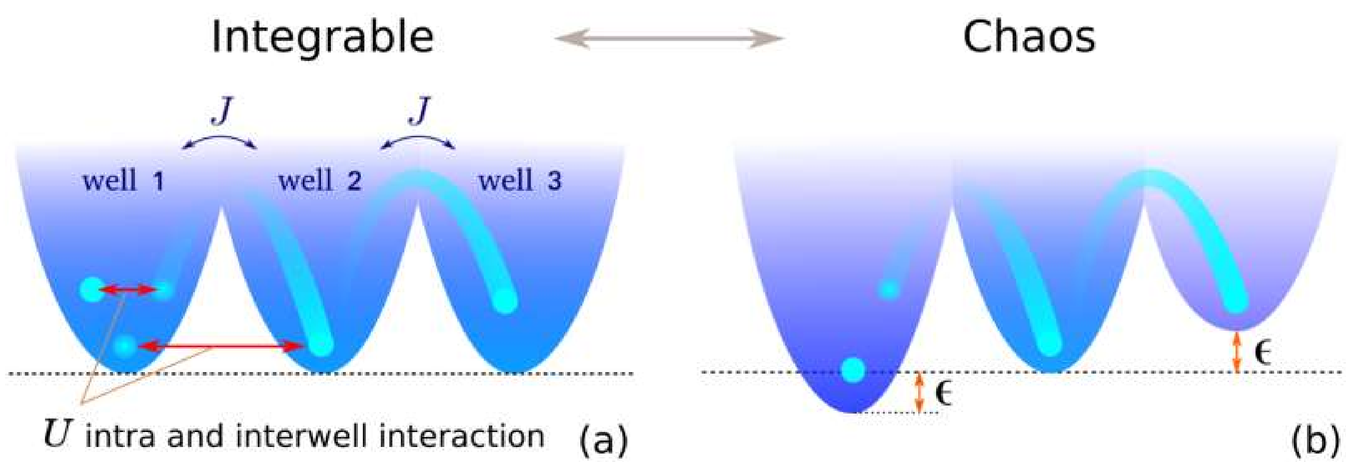
Contact us to learn more at:
simone.colombo@uconn.edu

Characterize & control many-body quantum dynamics

Timescales for relaxation, chaos and thermalization

Ultracold/CMP Theory

E.g. Three-well Bose-Hubbard model



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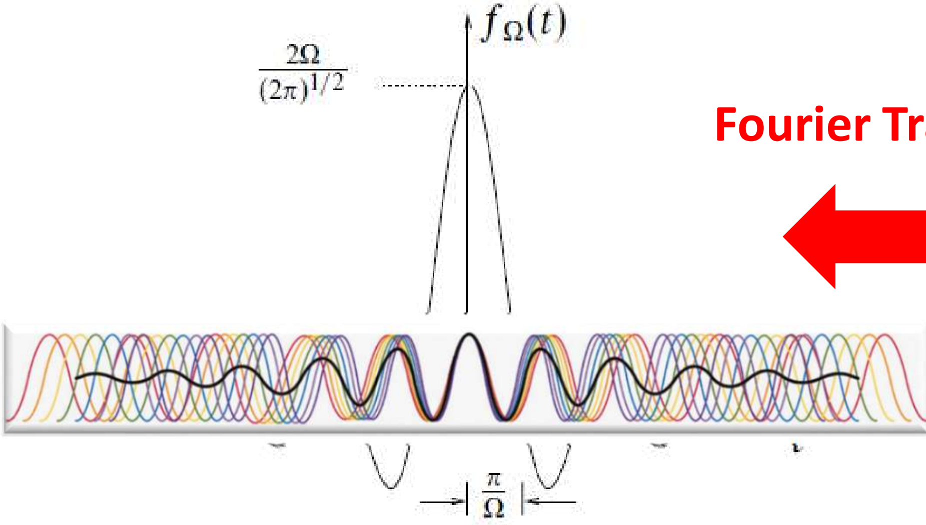
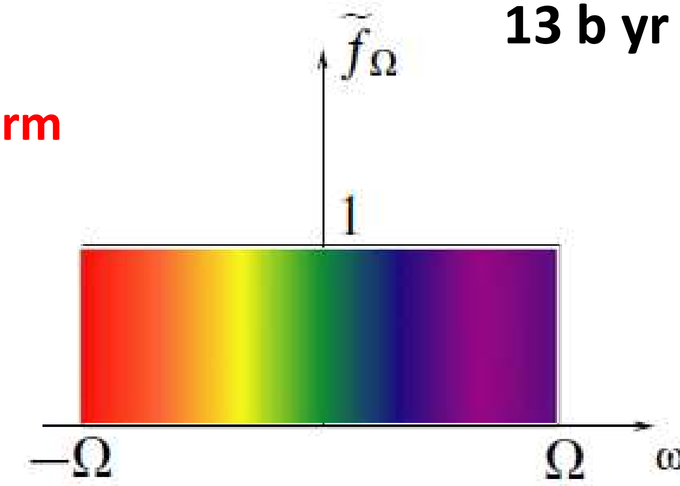
Phys. Rev. E **105**, 034204 (2022)

Ultrafast = Ultrashort & Ultrabroad

13 b yr = 4.10^{17} s



Fourier Transform



Time Domain

Frequency Domain

Femto-second = 10^{-15} s — **Routine**

Atto-second = 10^{-18} s — **State-of-the-art**

Zepto-second = 10^{-21} s — **Projected…**

Exquisite temporal control: $\Delta t_{probe} \sim 0$s for most processes – frozen dynamics

Huge peak powers & intensities:

Energy = 1 mJ

Time = 30 fs

Area ~ λ^2 ~ (100 μm)^2

Power ~ 10^{10} W

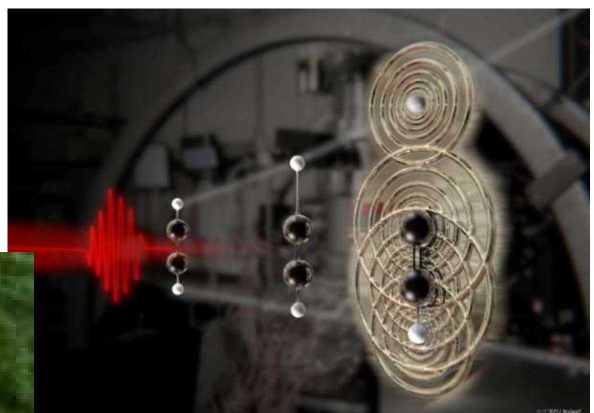
Int. ~ 10^{16} W/cm^2

An-Thu Le's Group

Ultrafast Theory

- **Research direction**: Intense laser-atom/molecule interaction and attosecond physics

- **Research goals:**
  1. Understand inner workings of atoms/molecules in very short timescales (**femtoseconds** and **attoseconds**)
  2. **Image** electronic & nuclear motions inside molecules in these ultrafast timescales: **molecular movies**
  3. **Control** chemical reactions in these ultrafast timescales



Imaging dissociating C_2H_2:
An artistic illustration - Courtesy of ICFO, Barcelona and Scixel

See our paper:
B Wolter *et al*, Science **354**, 308 (2016)

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thu.le@uconn.edu

Carlos Trallero's Group

Ultrafast Experiment

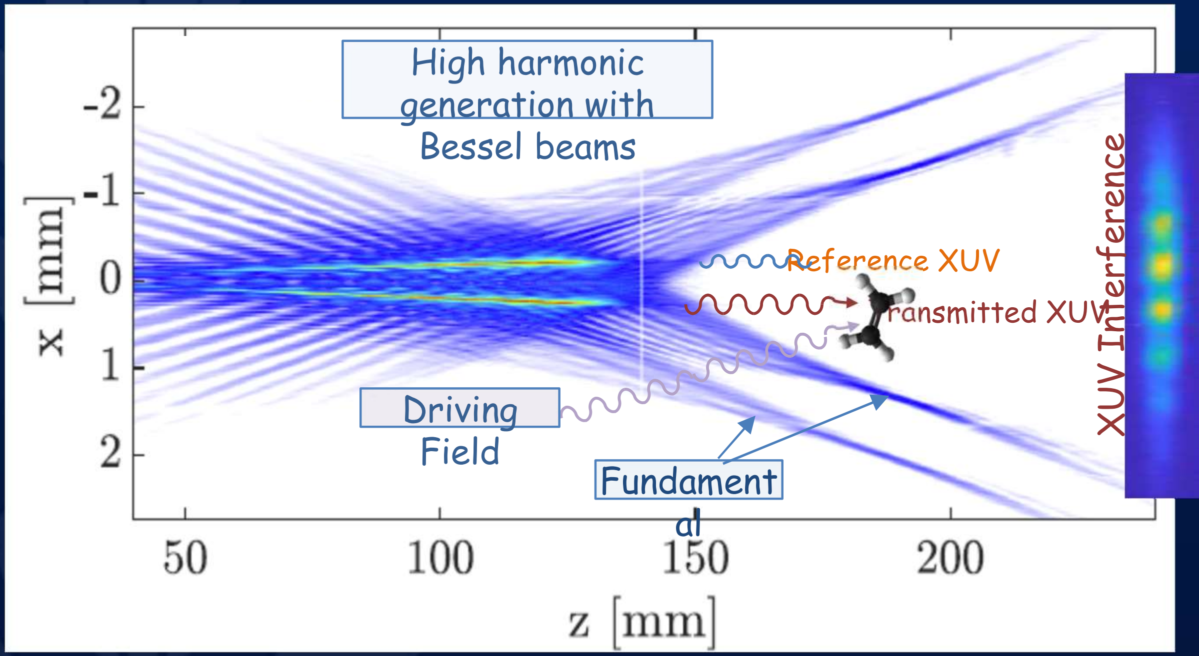
Control at "quantum" time scales

From atoms to nano particles to solids

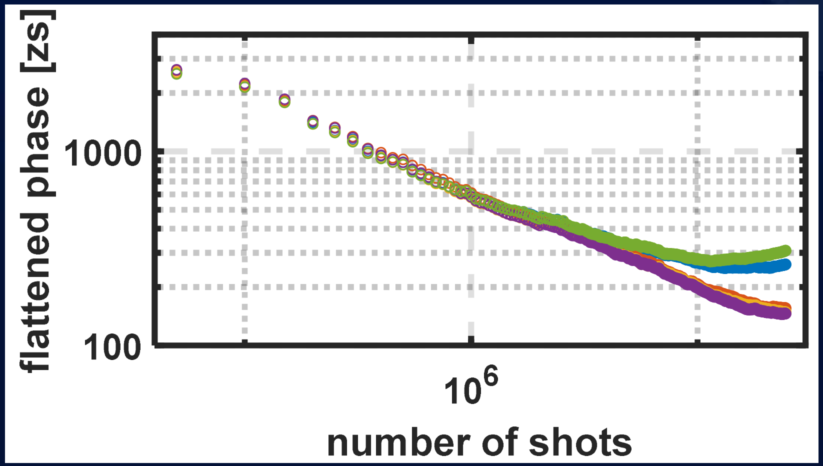
Optics and laser development

State of the art lasers

Zeptosecond Young's double slit



Temporal noise of the measurement



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Exploring *EXTREME* Non-Linear Physics with High-Intensity Lasers

Ultrafast Experiment

Contact us to know more:
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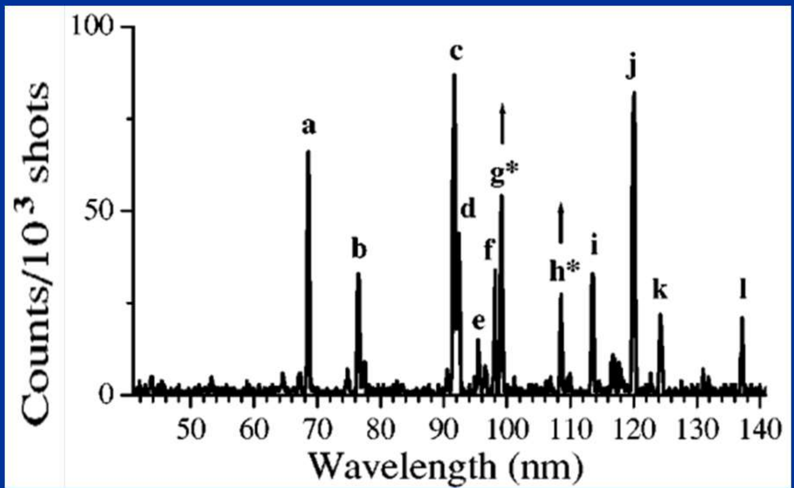
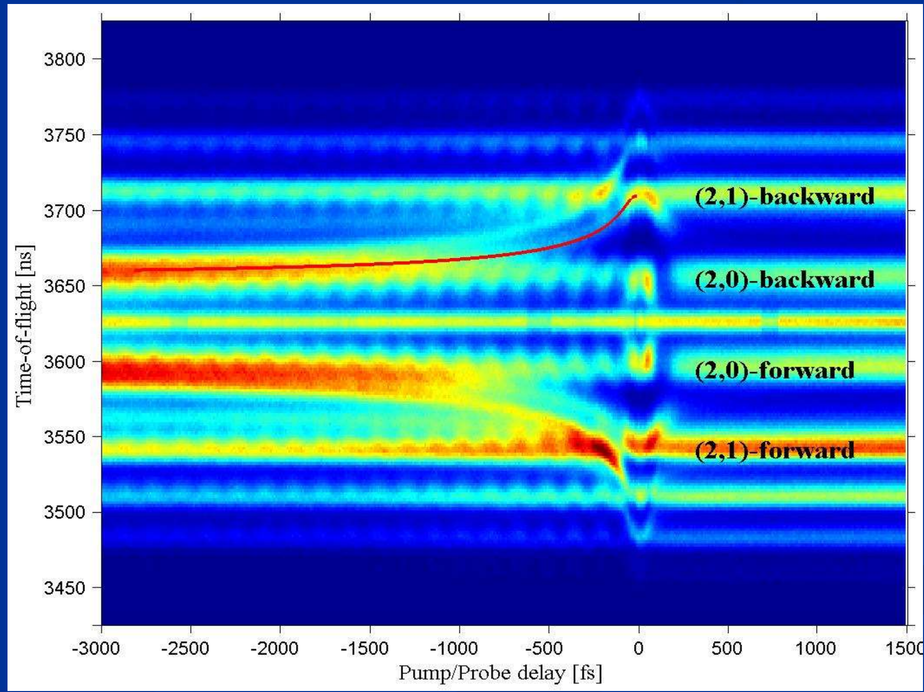


Probe molecular vibrations via pump-probe experiments.

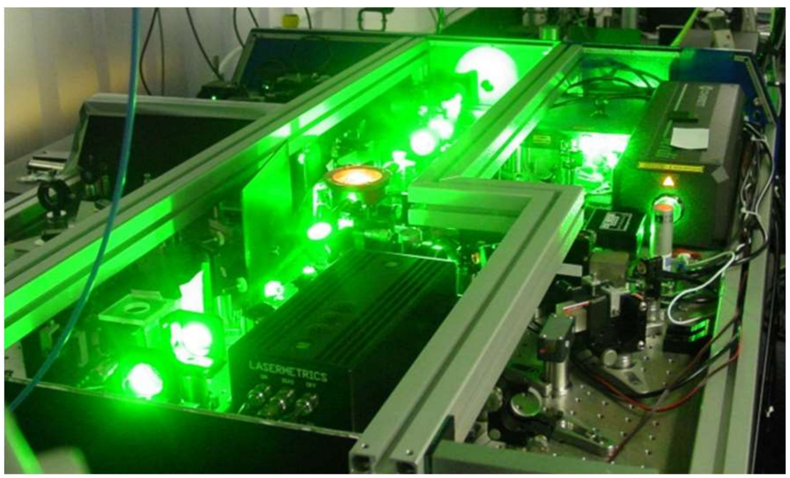


Applications in trace molecule ID in bio or environmental samples.

Bright and Fast: Lasers to Capture the Dance Between Electrons and Nuclei in Molecules

Nora Berrah's Group

Goal: Track Photo-Induced Molecular Dynamics Reactions to Make Molecular Movies w/ table-top lasers and XUV or X-Ray Free Electron Lasers (FELs) at femto & attosecond timescales



Ultrafast Experiment

E. Wang, et alJ. Phys. Chem. Lett. 14, (18), 4372 (2023).
N. Berrah, Atoms, **10**, 75 (2022)
D. Mishra et al., J Phys. Chem. Chem. Phys. **24**, 433 (2022)
A. C. LaForge et al., Phys. Rev. Lett. **127,** 213202 (2021)

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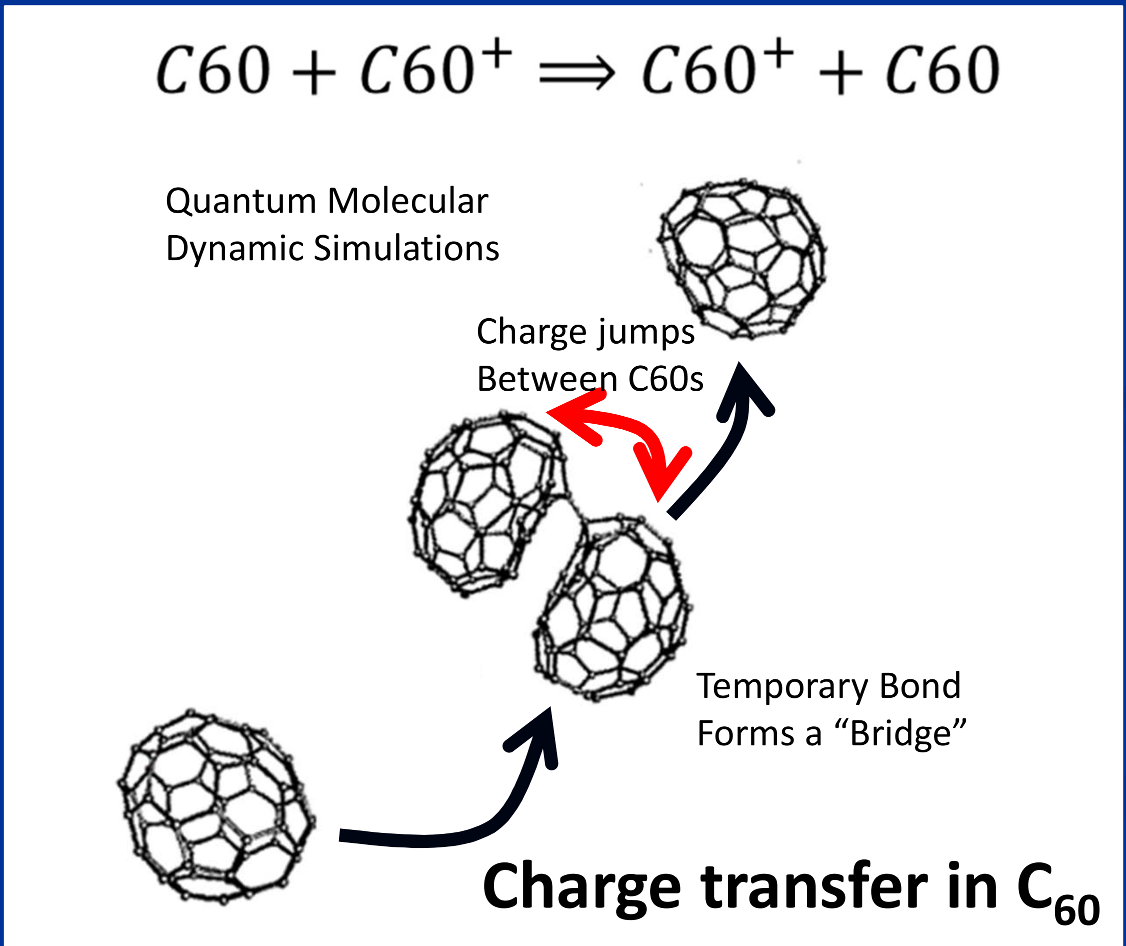
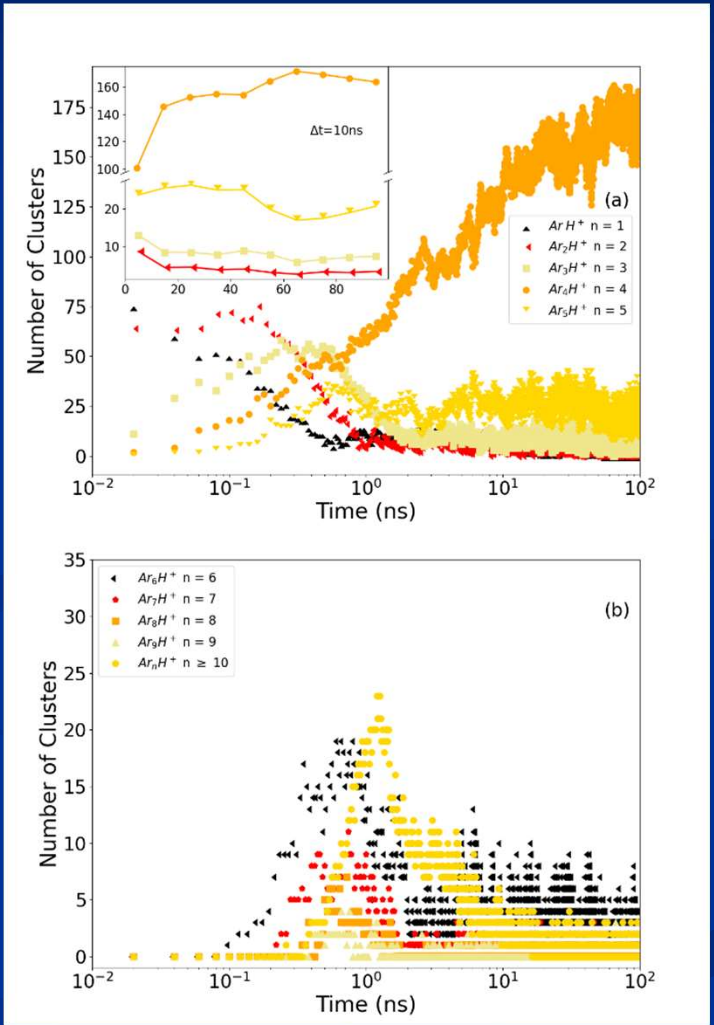
nora.berrah@uconn.edu

Kinetics and Nucleation Dynamics of Nano-Particles

- Simulate nucleation and growth dynamics of Ar_nH^+ clusters w/ classical molecular dynamics and accurate quantum potentials.

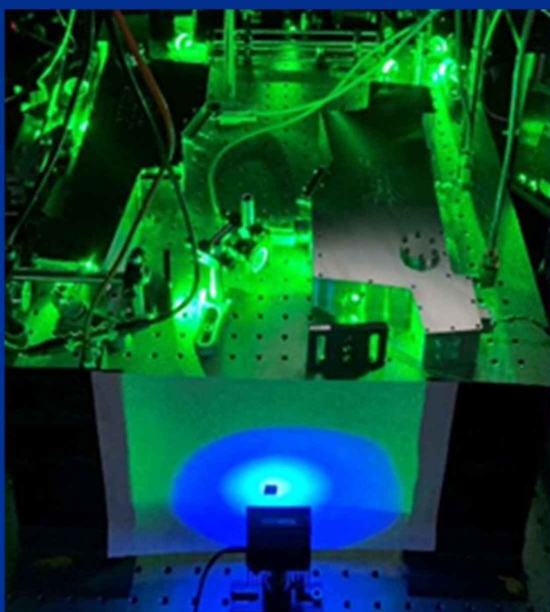


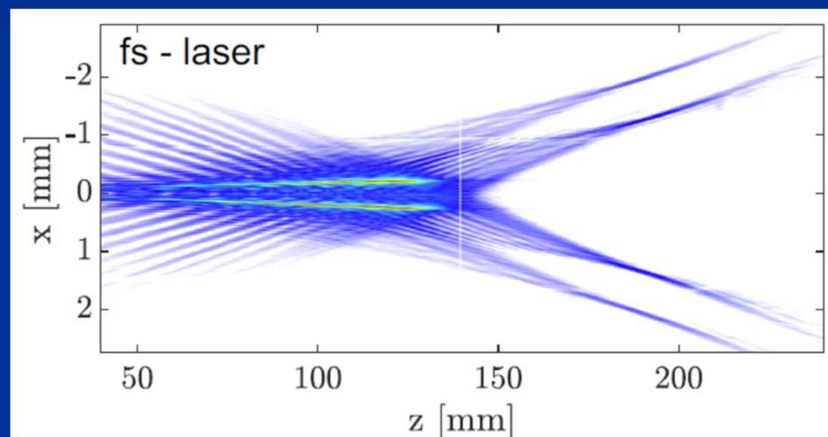


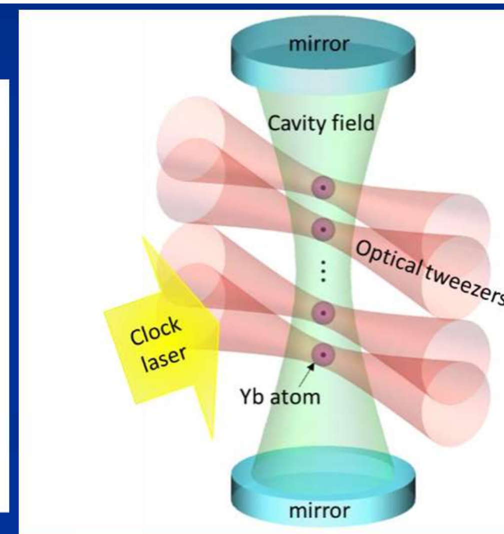
M. G. Rozman, M. Bredice et al. Phys. Rev. A 105, 022807 (2022).

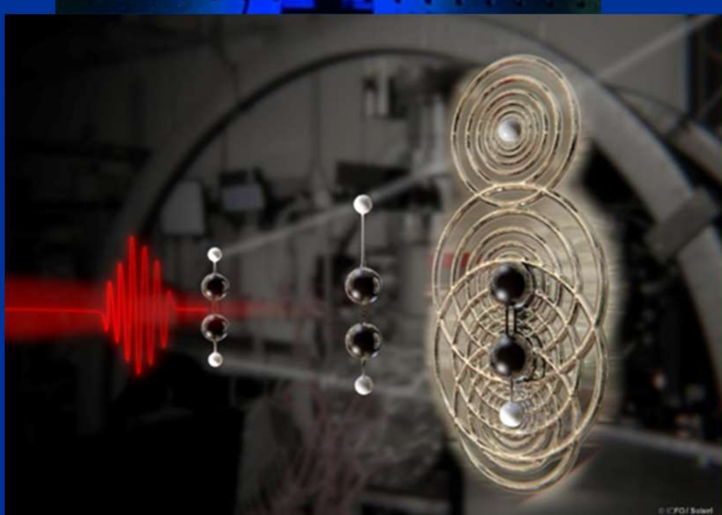
Bredice, Mitchell
Vasili Kharchenko

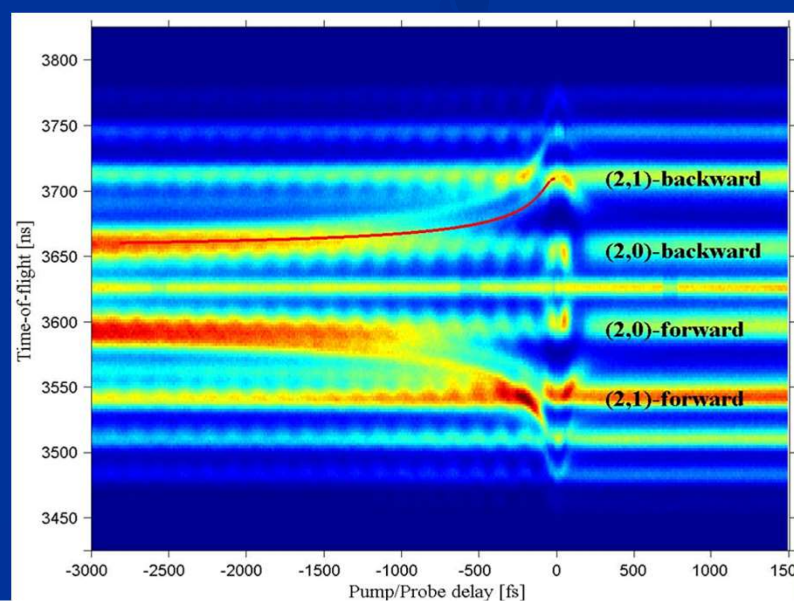
End




fs - laser
x [mm]
z [mm]
-2
-1
0
1
2
50
100
150
200


mirror
Cavity field
Optical tweezers
Clock laser
Yb atom
mirror




Time-of-flight [ns]
3800
3750
3700
3650
3600
3550
3500
3450
(2,1)-backward
(2,0)-backward
(2,0)-forward
(2,1)-forward
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
Pump/Probe delay [fs]