ELISS2023

ELI Summer School | 29 Aug – 1 Sep 2023

Dolní Břežany, Czech Republic

AMO Science at ELI Beamlines

Andreas Roos

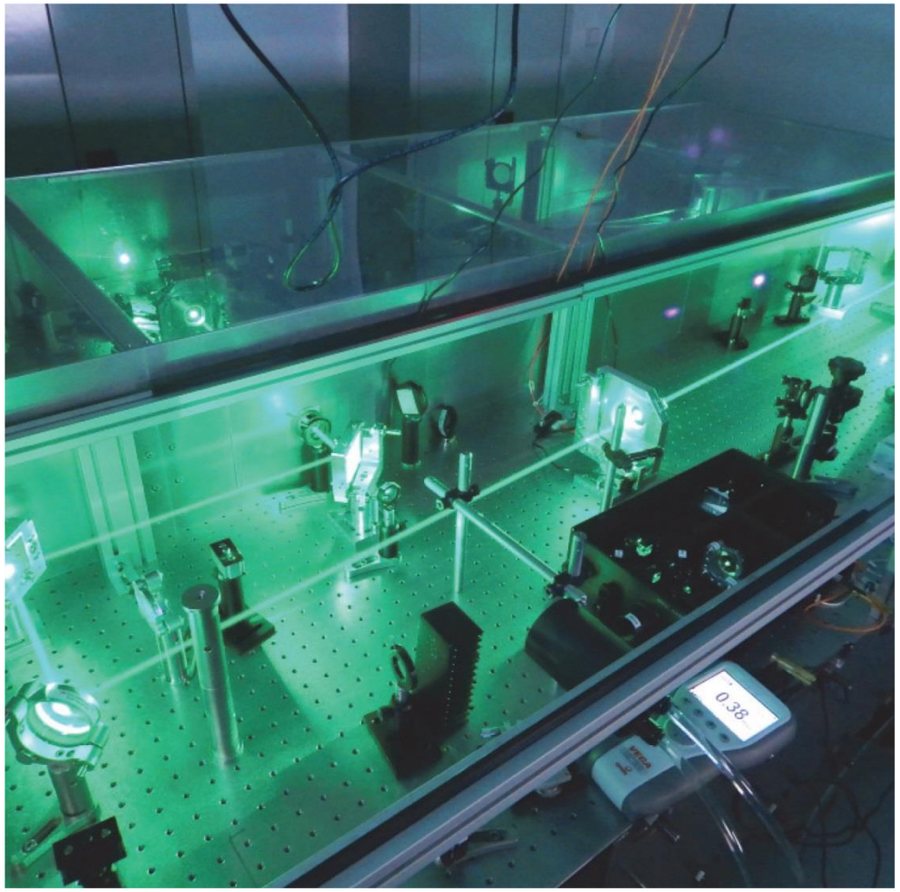
ELI Beamlines

30 August 2023

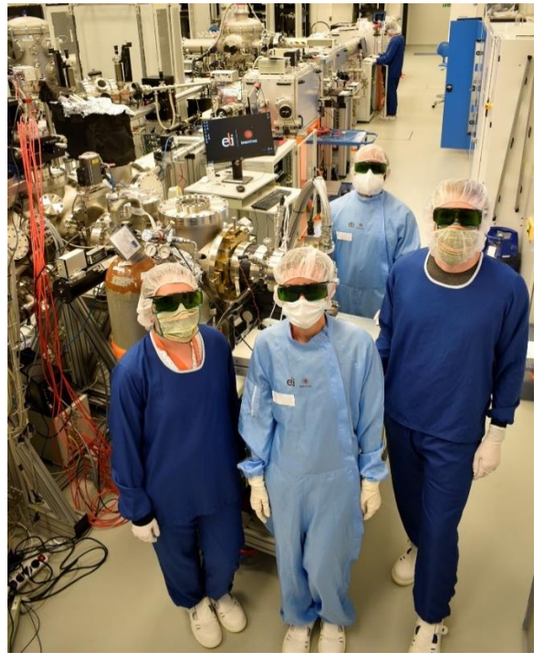
Dolní Břežany, Czech Republic

IMPULSE is funded by the European Union's Horizon 2020 programme under grant agreement No. 871161

Introduction

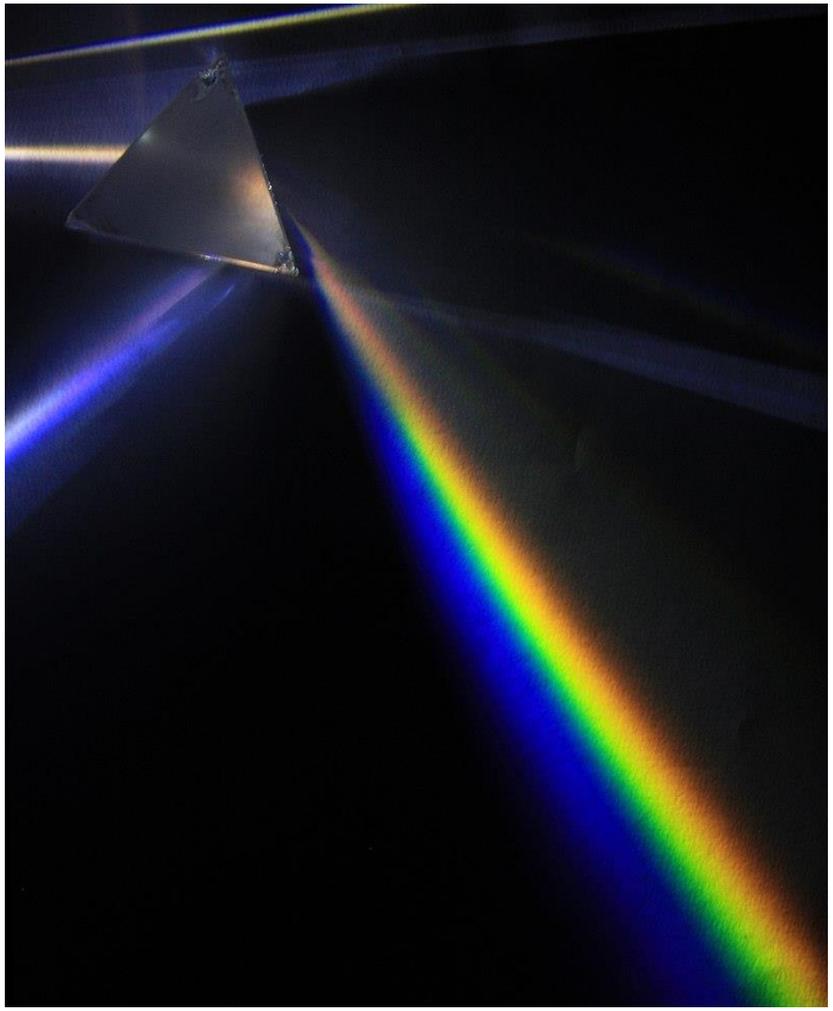


- Spectroscopy
  - What, Why, How?
- How to study the quantum world
  - Time-resolved experiment
- MAC experimental station
  - Main purpose
  - Experimental methods
- Quick example experiment
  - He-nanodroplets explosions
- More detailed experiment
  - Electron correlation dynamics in atomic Krypton



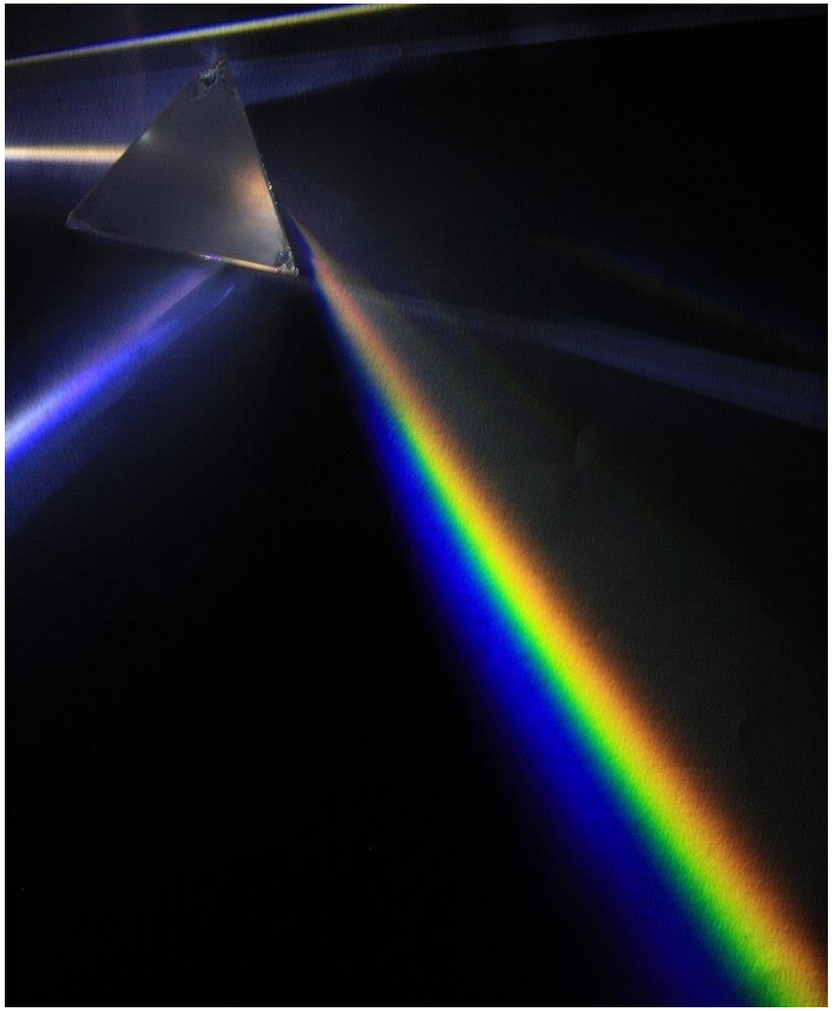
MAC team:
Maria Krikunova
Eva Klimešová
Ziaul Hoque
Andreas Roos
Smijesh Achary

Spectroscopy



What?

The field of study for the interaction of electromagnetic radiation and matter as a function of wavelength/frequency.



Why?

To explore the fundamental nature on micro/macro scales of all states of matter in...

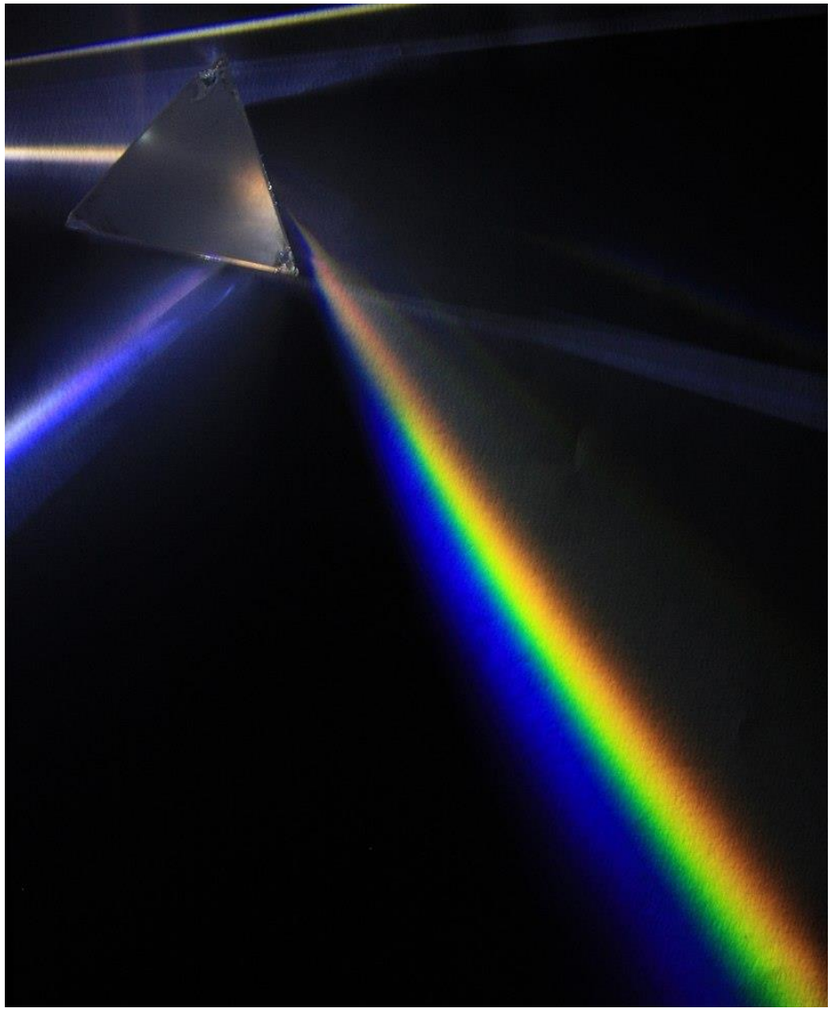
Chemistry

Biology

Astronomy

Material science

Physics



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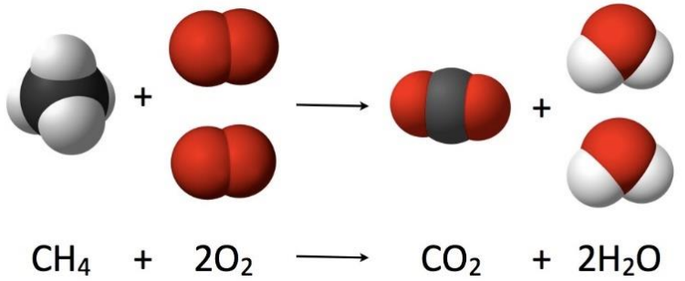
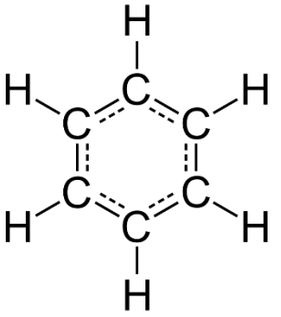


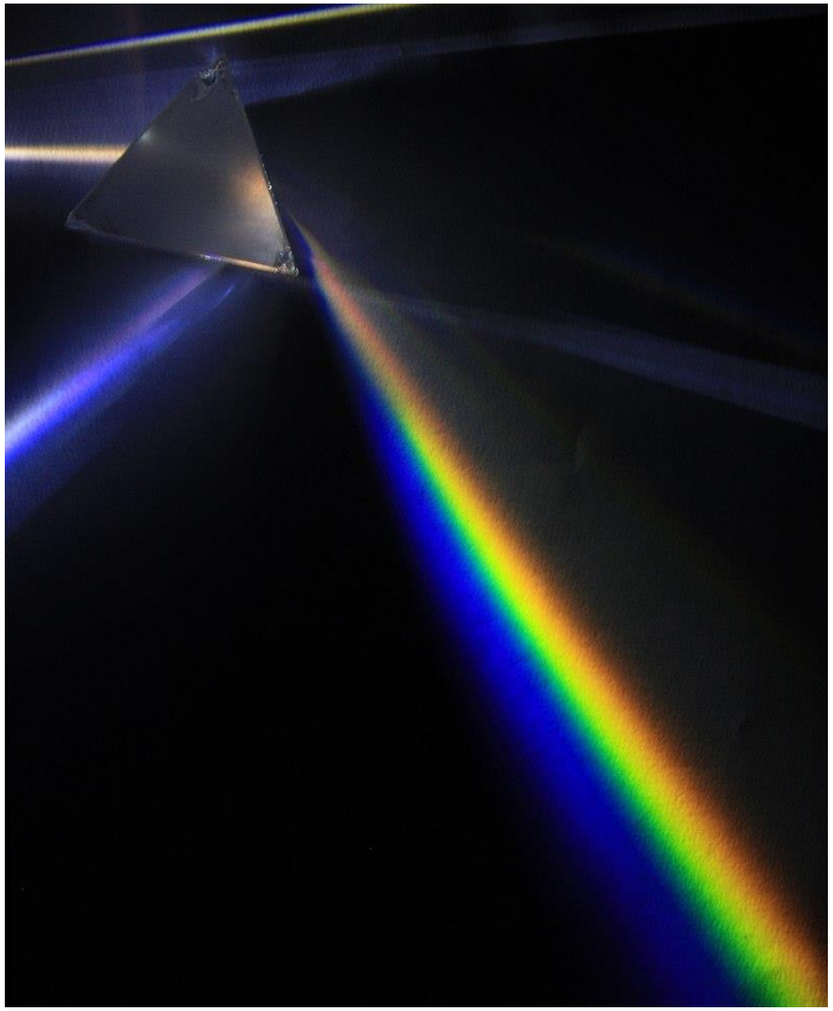
Biology

Material science



Astronomy

Physics



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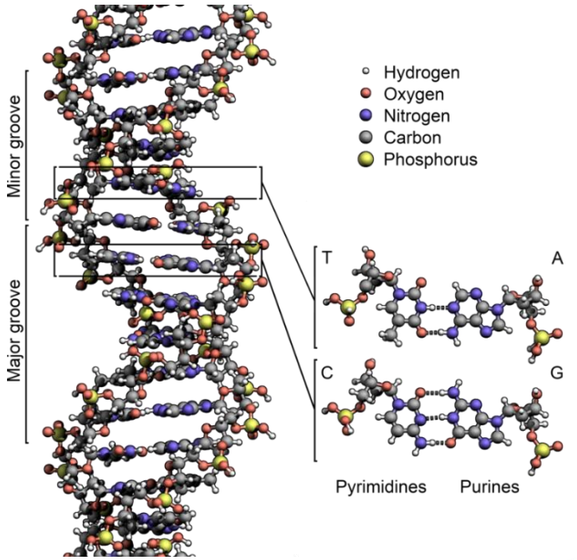

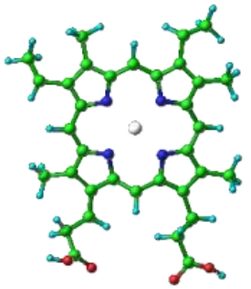

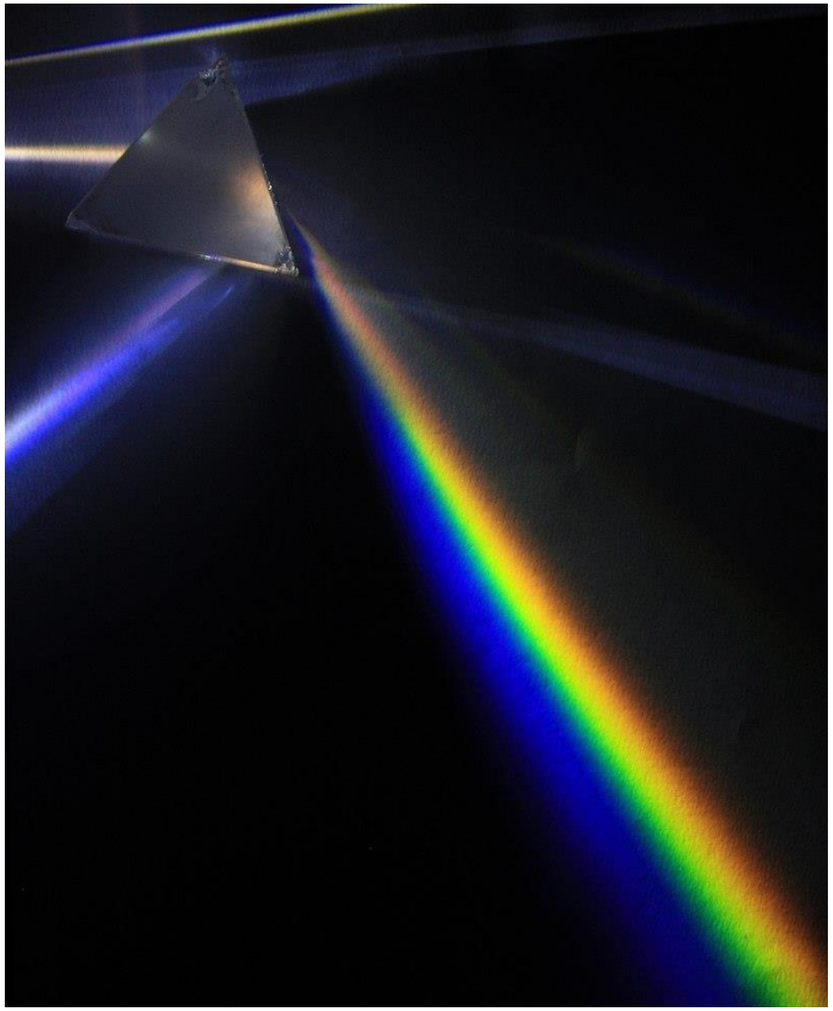

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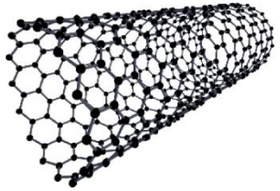
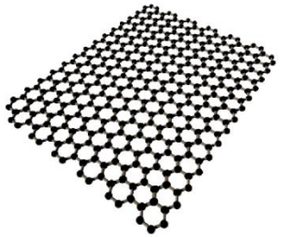
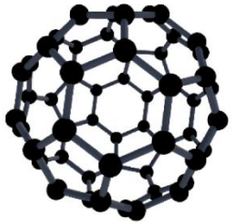
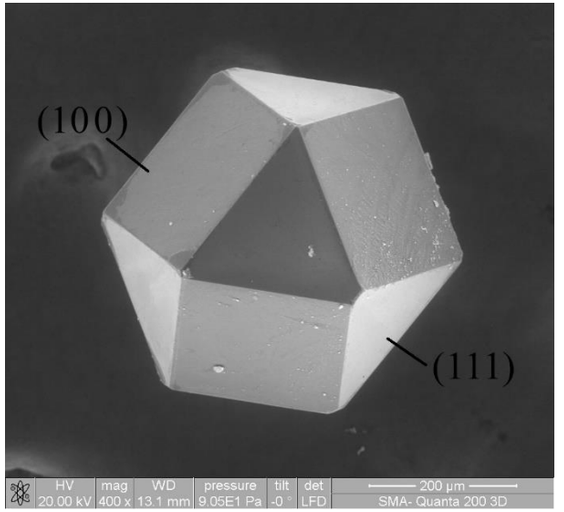
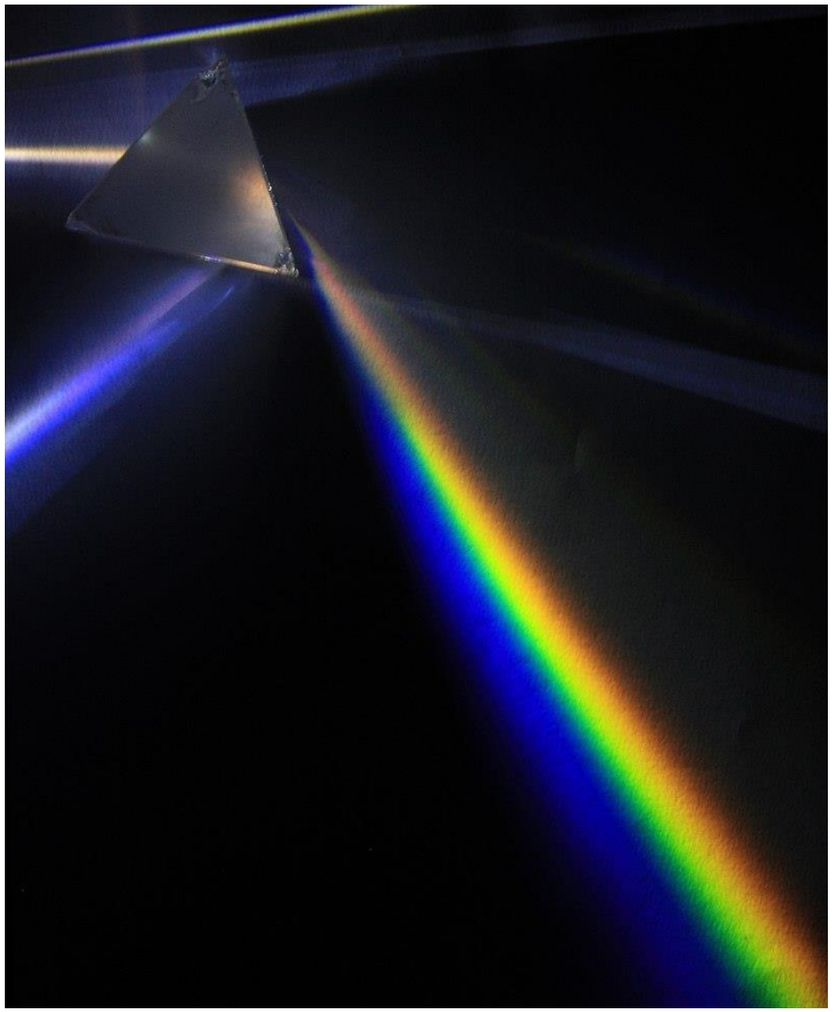






Nanomaterials **2020**, *10*(5), 838





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Material science

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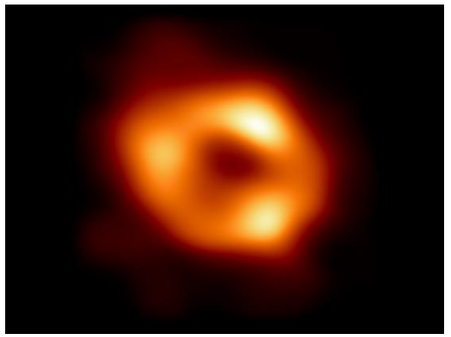
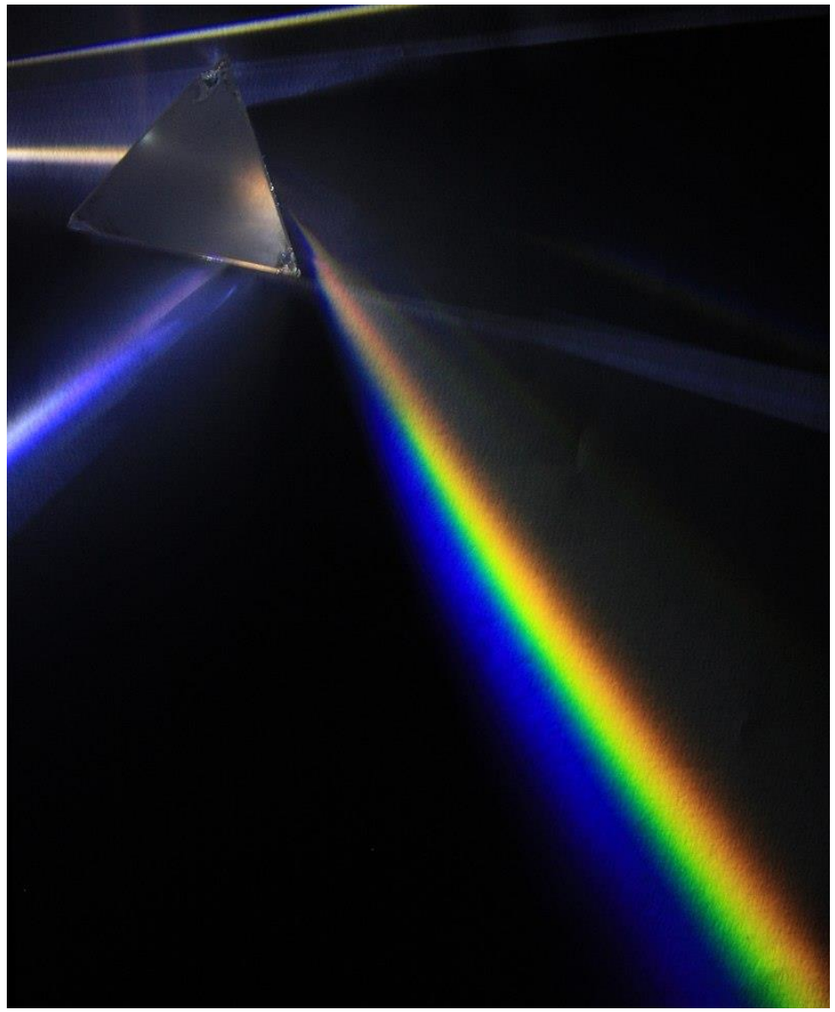
Physics

CXC/NASA, INAF, M. GUARCELLO ET AL; OPTICAL: NASA, STSCI



EHT Collaboration



Why?

To explore the fundamental nature on micro/macro scales of all states of matter in...

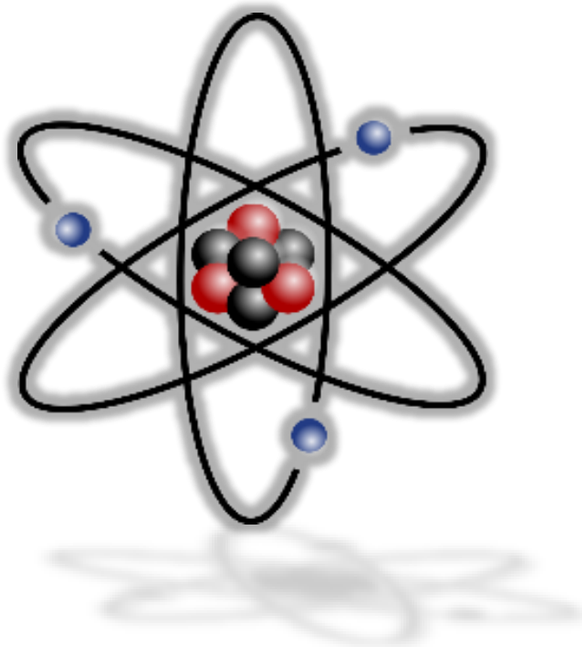
Chemistry

Biology

Astronomy

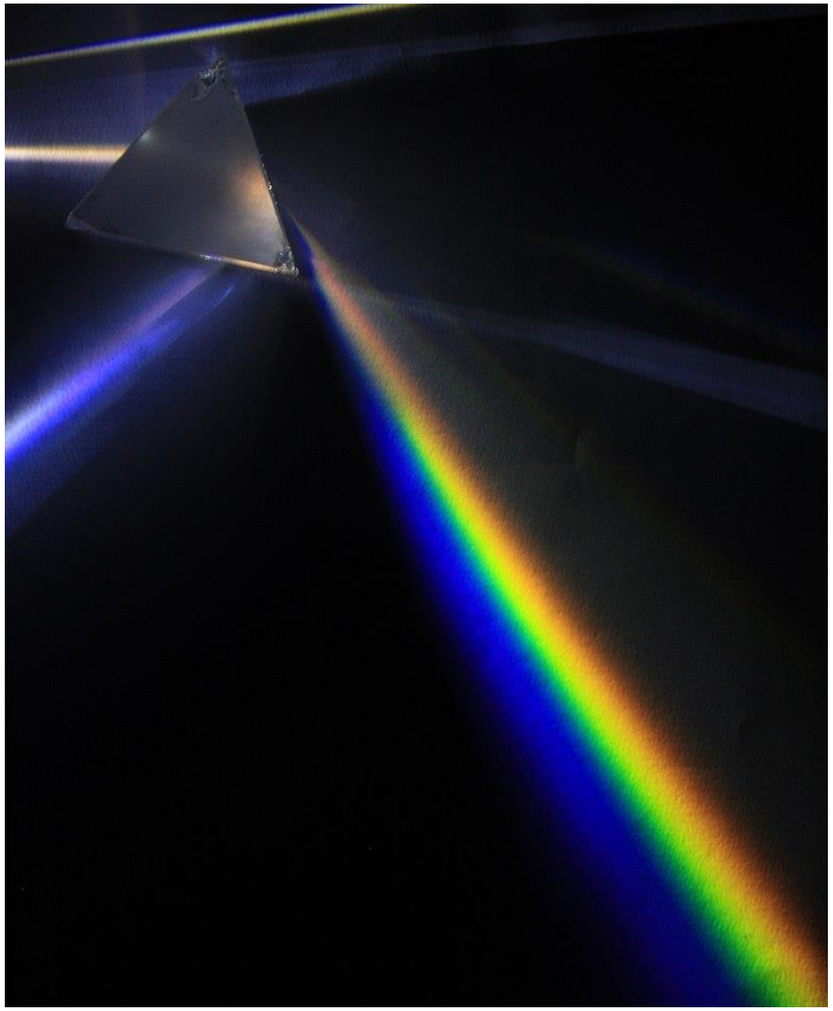
Material science

Physics – all the above...

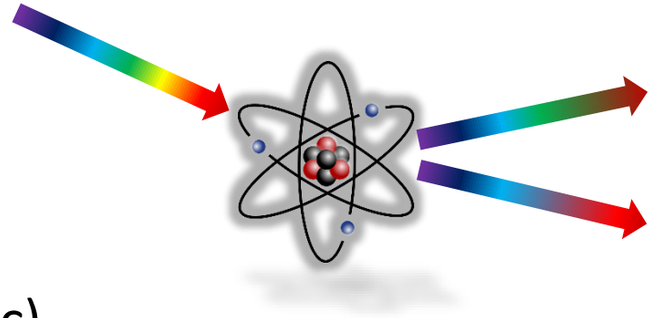


Insight into the shortest timescales (femto- & atto-seconds) that is relevant for atomic and molecular dynamics.

Spectroscopy



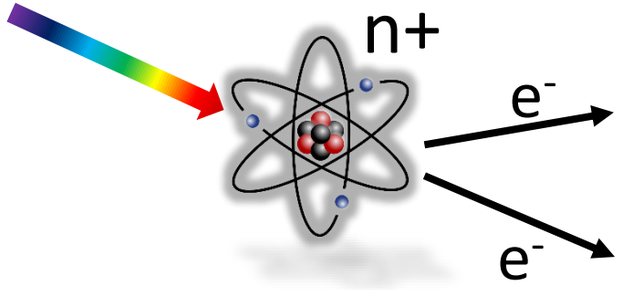
How?



- Absorption spectroscopy
- Emission spectroscopy
- Scattering (elastic/inelastic)
- Nuclear
- …

Many experimental methods... Can’t go into detail. Will present some basics in electron and ion spectroscopy.

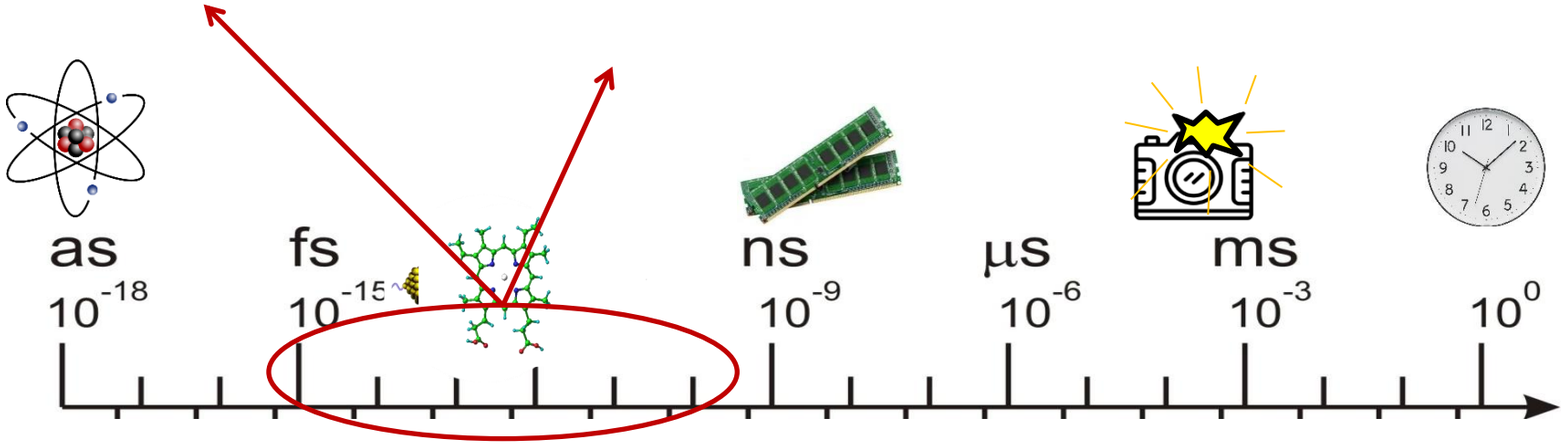
Electron/ion spectroscopy
Time-resolved spectroscopy



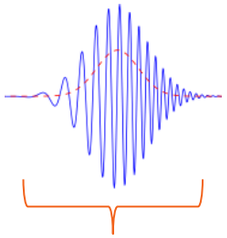
Main Purpose: Dynamics of matter at different time-scales

Interaction of light with matter

Photochemical processes



Light pulse



femtosecond scale

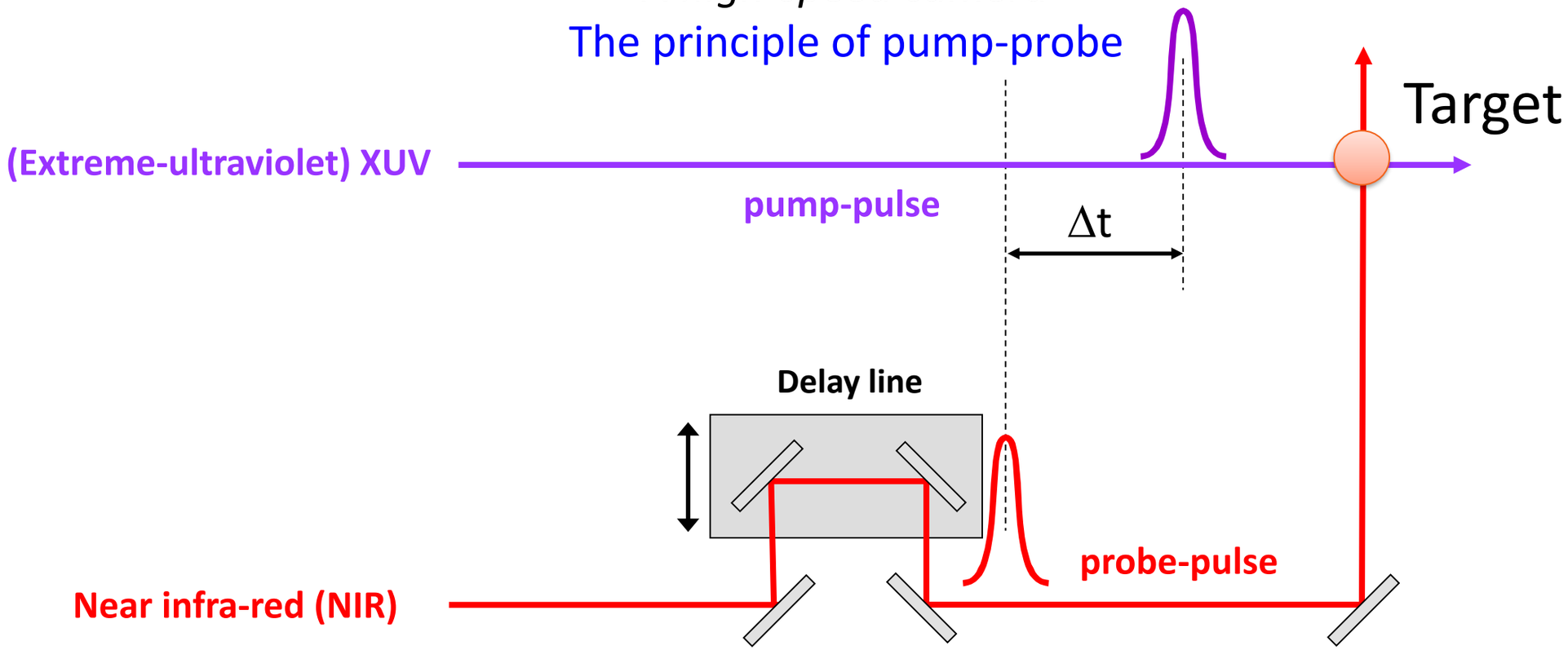
Lasers

Intense and short light pulses

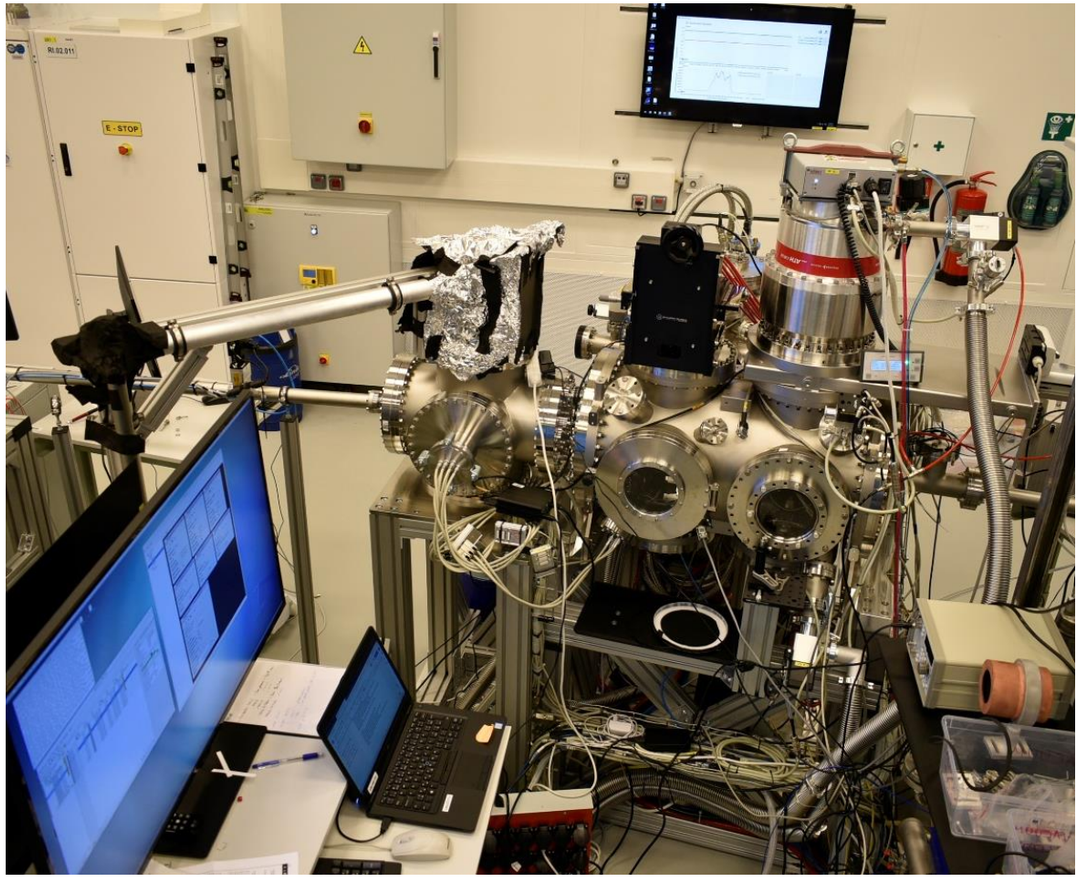
Pump-probe: The study of ultra-fast dynamics

"A high-speed camera"

The principle of pump-probe



MAC user end-station



MAC - **M**ulti-purpose user end-station for
AMO (Atomic, Molecular and Optical) sciences and
CDI (Coherent Diffractive Imaging)

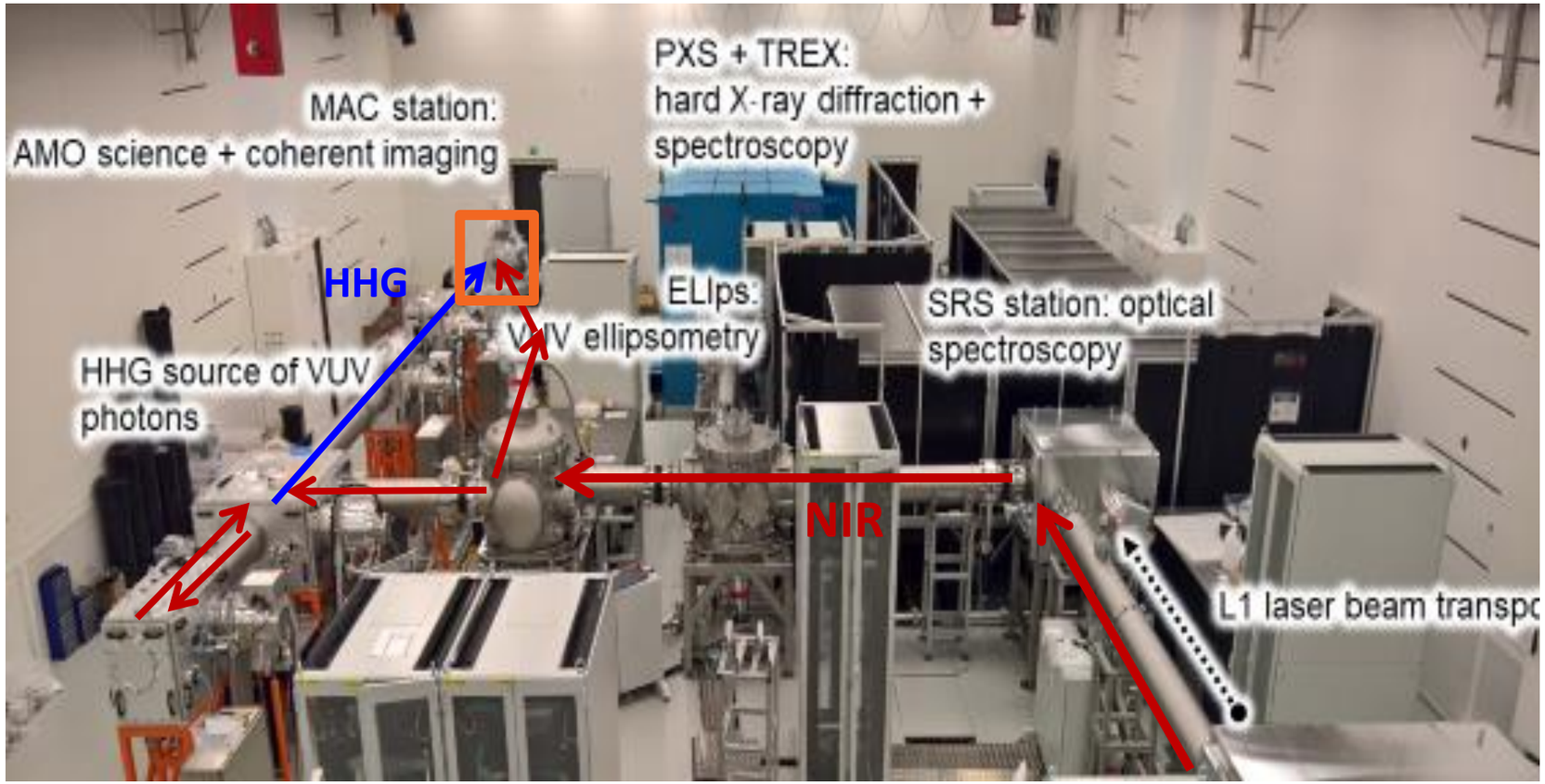
Main purpose:

Study the structure and dynamics of matter, related to Physics, Chemistry, and Biology.

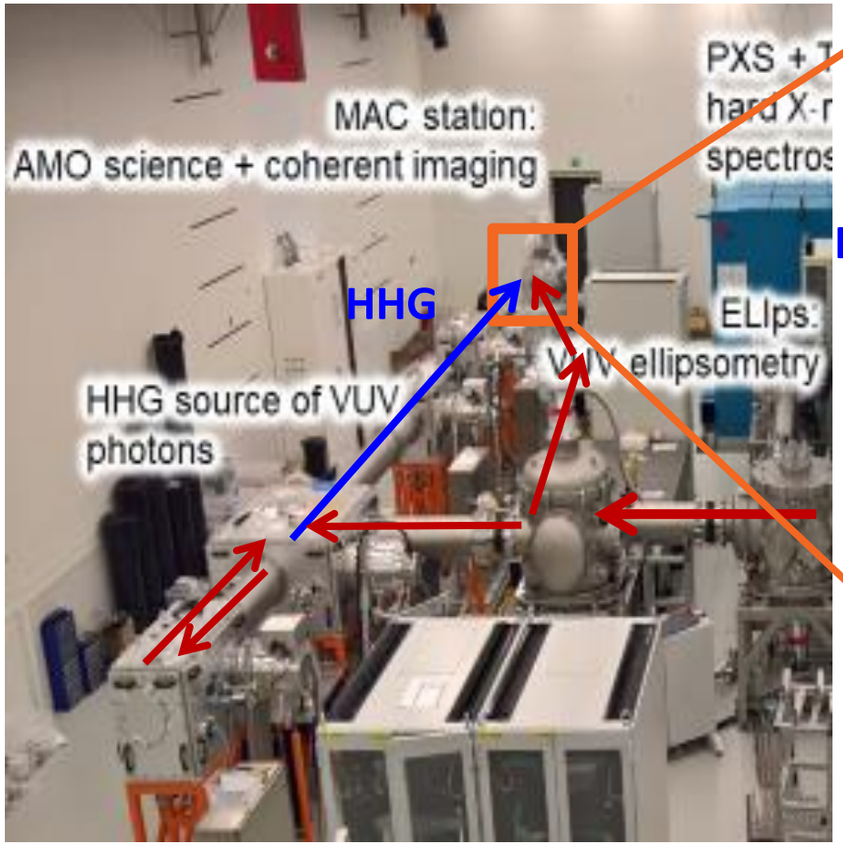
Main method:

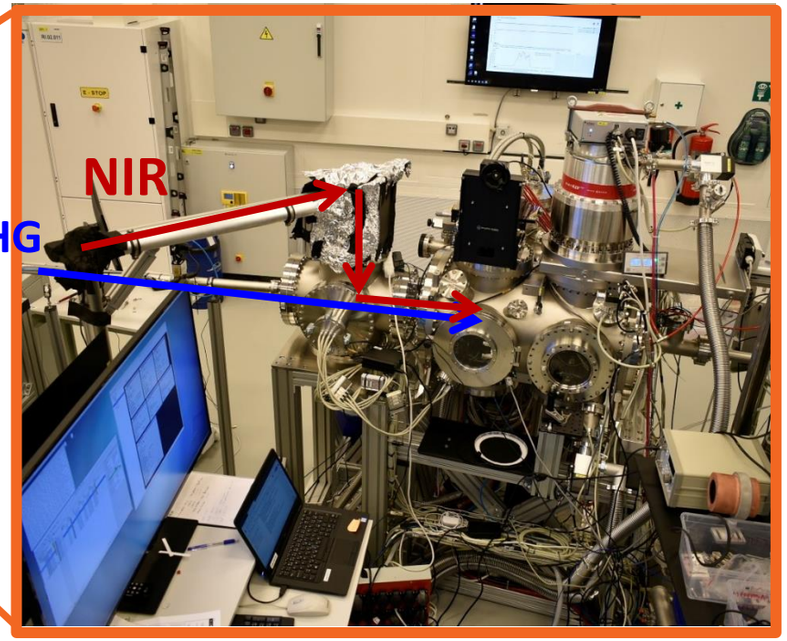
Time-resolved (femtosecond time scale) experiments using electron/ion spectroscopy (and CDI).

MAC end-station in the E1 experimental hall



MAC end-station in the E1 experimental hall



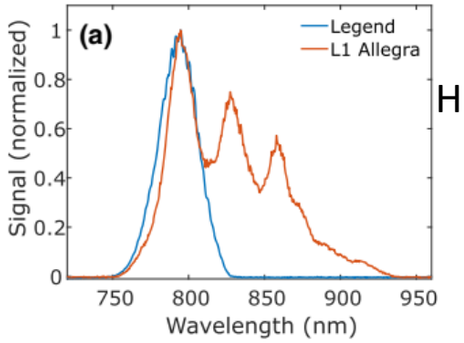


Beam overlap:
µm and **fs** (10^{-15} s) precision inside of the MAC chamber.

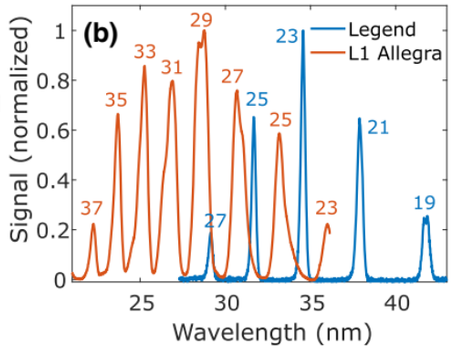
Driving laser beams:

- **L1 Allegra**: up to 100 mJ, <15 fs, ~830 nm, 1 kHz
- **Legend** Elite Duo: 12 mJ, <35 fs, 800 nm, 1 kHz
- **Hidra**-100: 100 mJ, <40 fs, 800 nm, 10 Hz

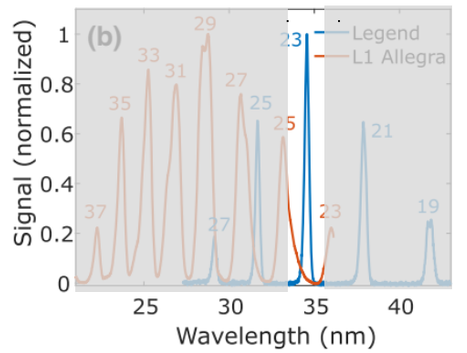
Layout of the HHG-beamline and the MAC user end-station

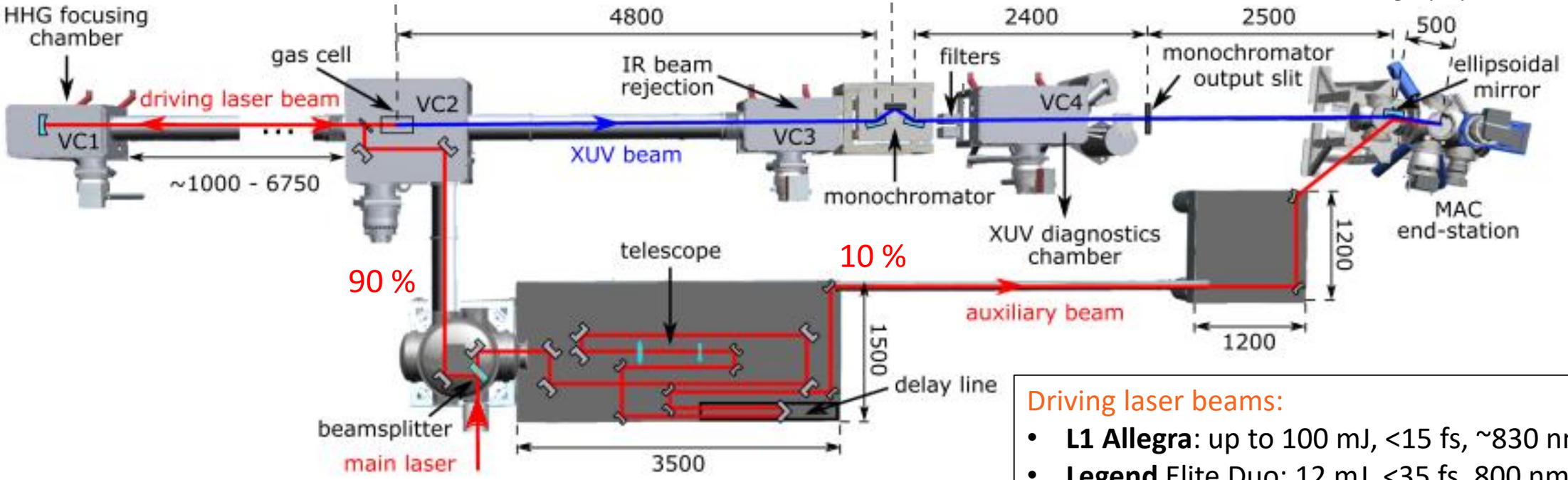


HHG team



Monochromator:
Select one harmonic





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Klimešová et al, Eur. Phys. J. Spec. Top. (2021)

How to study the quantum world?
Electron and ion spectroscopy

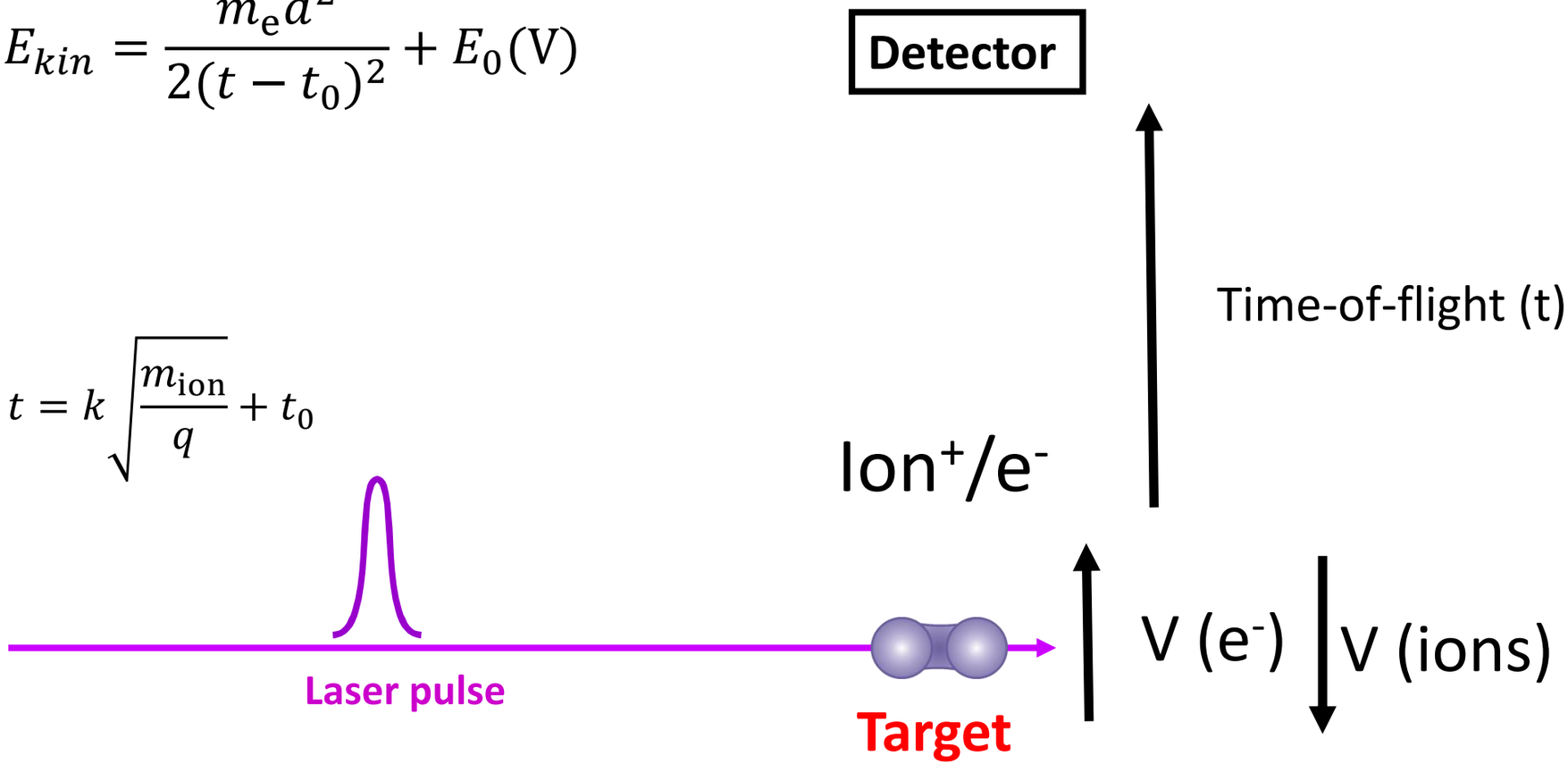
How to study the quantum world?
Electron and ion spectroscopy

Kinetic energy of electrons:

$$E_{\mathrm{kin}} = \frac{mv^2}{2}$$
$$v = \frac{d}{t}$$
$$\Rightarrow E_{kin} = \frac{m_{\mathrm{e}} d^2}{2(t - t_0)^2} + E_0(\mathrm{V})$$

Ion time-of-flight:

$$E_{\mathrm{kin}} = \frac{mv^2}{2}$$
$$E_{\mathrm{p}} = qU$$
$$(E_{\mathrm{p}} = E_{\mathrm{kin}})$$
$$\Rightarrow t = k\sqrt{\frac{m_{\mathrm{ion}}}{q}} + t_0$$

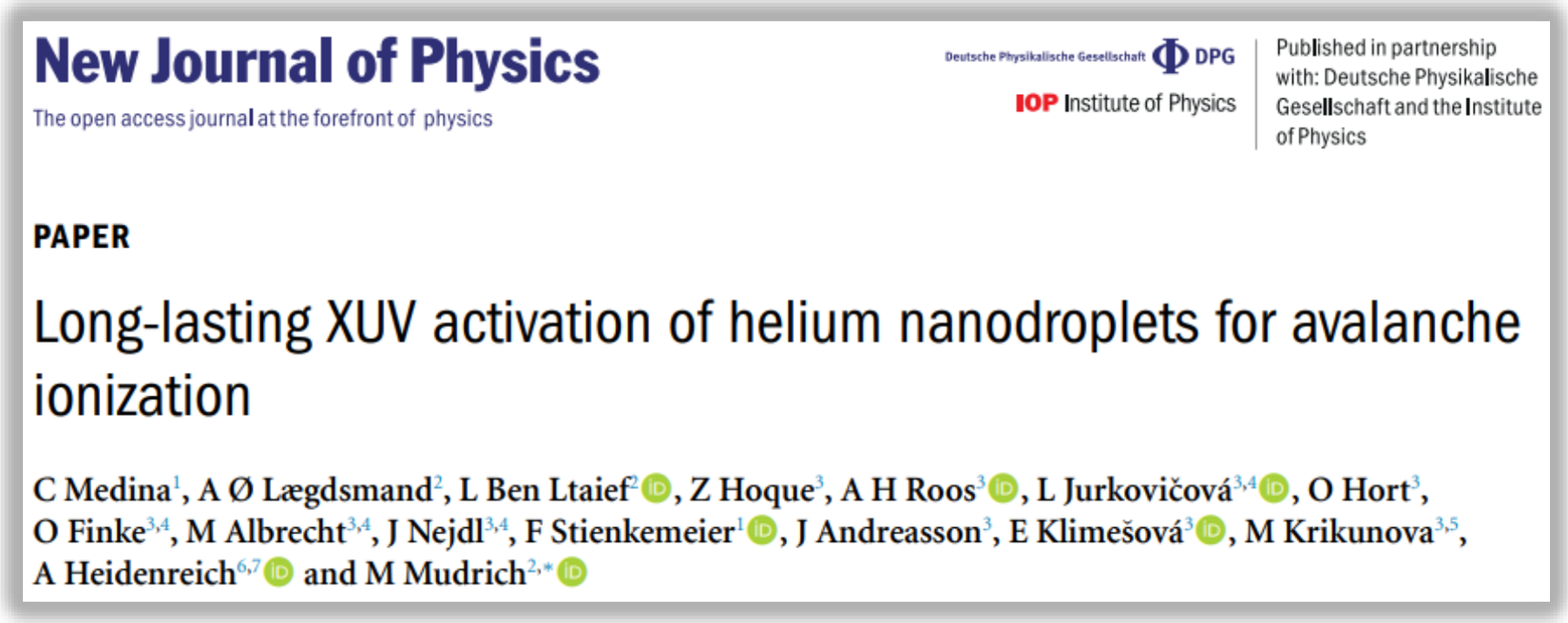


Experimental techniques at the MAC station

Example experiments:

- Helium nanodroplets explosions (Velocity Map Imaging)
- Electron dynamics in Kr satellite states (ion time-of-flight)

Recent results
Helium nanodroplets explosions



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IOP Institute of Physics

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PAPER

Long-lasting XUV activation of helium nanodroplets for avalanche ionization

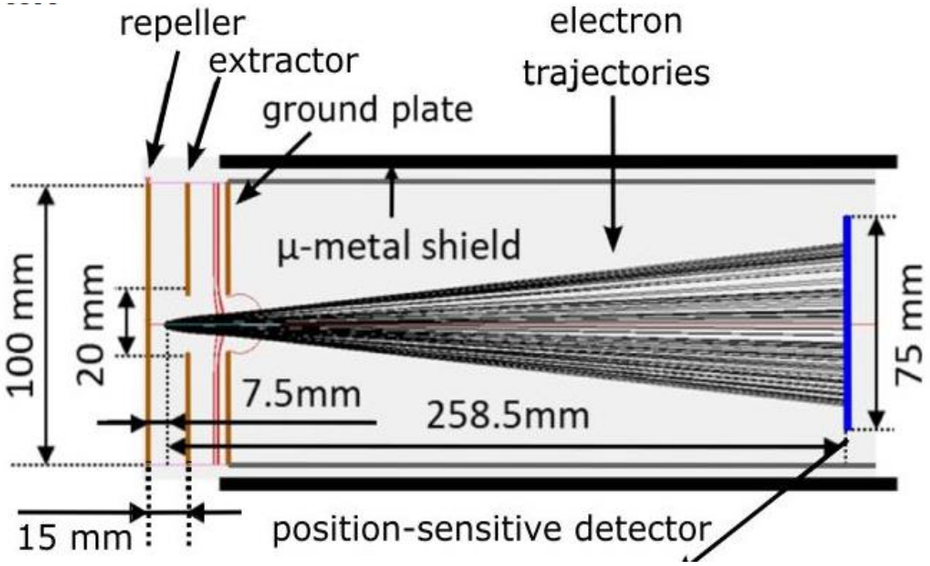
C Medina[1], A Ø Lægdsmand[2], L Ben Ltaief[2], Z Hoque[3], A H Roos[3], L Jurkovičová[3,4], O Hort[3], O Finke[3,4], M Albrecht[3,4], J Nejdl[3,4], F Stienkemeier[1], J Andreasson[3], E Klimešová[3], M Krikunova[3,5], A Heidenreich[6,7] and M Mudrich[2,*]

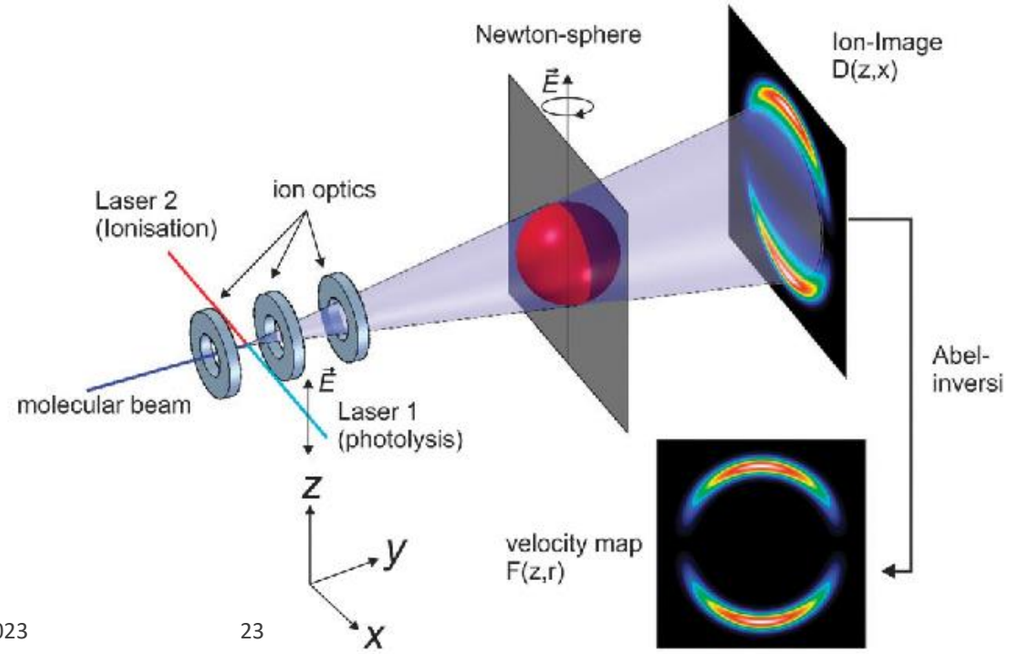
C. Medina et al., 2023 New J. Phys. **25** 053030

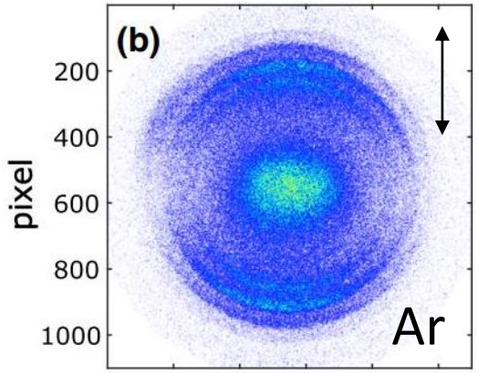
MAC user end-station – Velocity Map Imaging

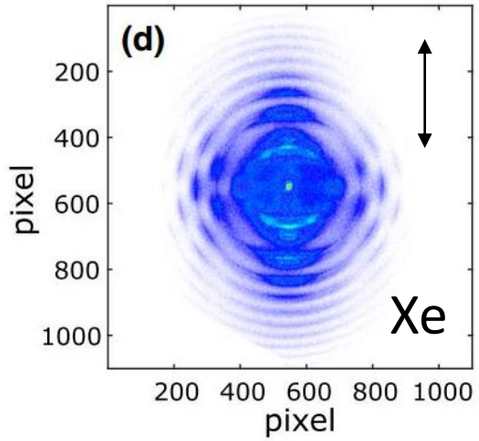
VMI detector:

- Flight Time/Energy of electrons and ions.
  - Kinetic energy
  - Ion mass/charge spec.
- Velocity imaging of electrons/ions.









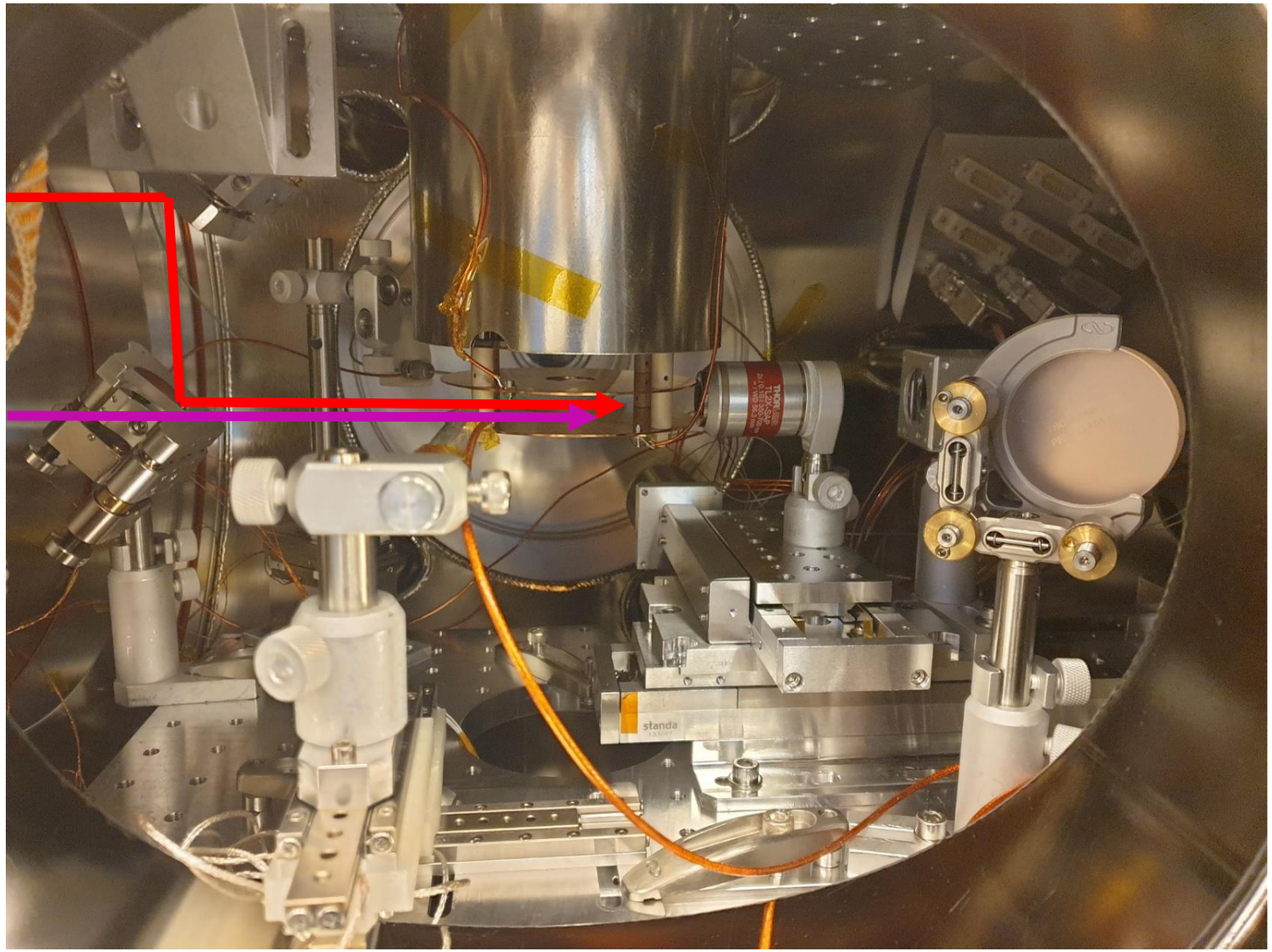
MAC user end-station – Velocity Map Imaging

Methods at the MAC station:

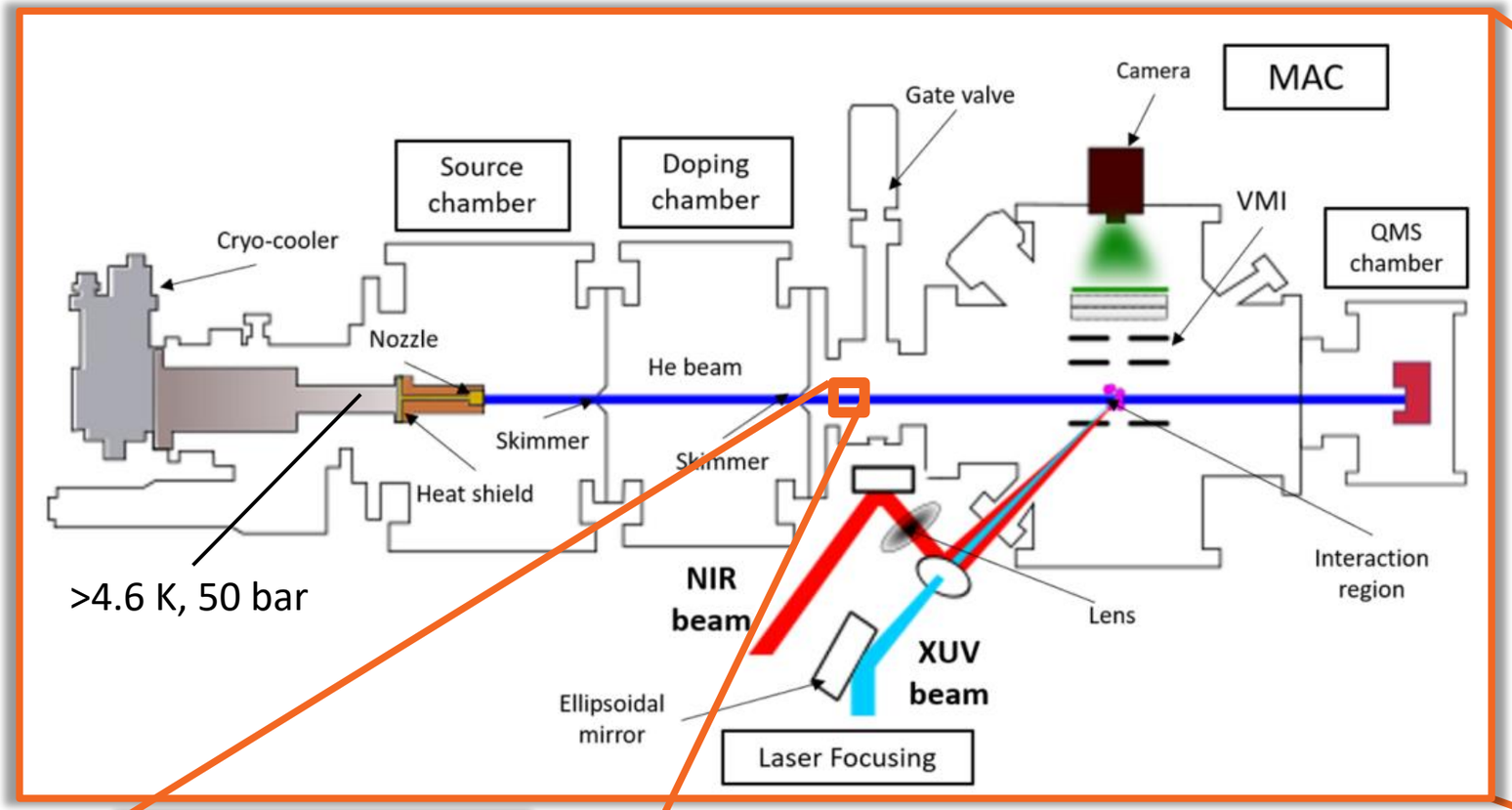
- Electron/ion time-of-flight
- Velocity map imaging (VMI)

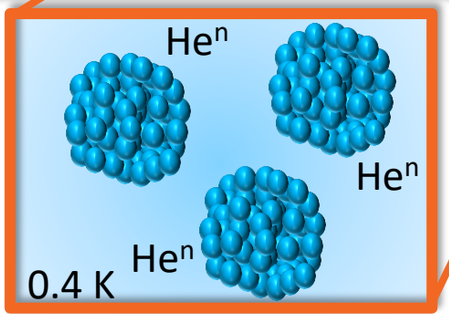
Samples:

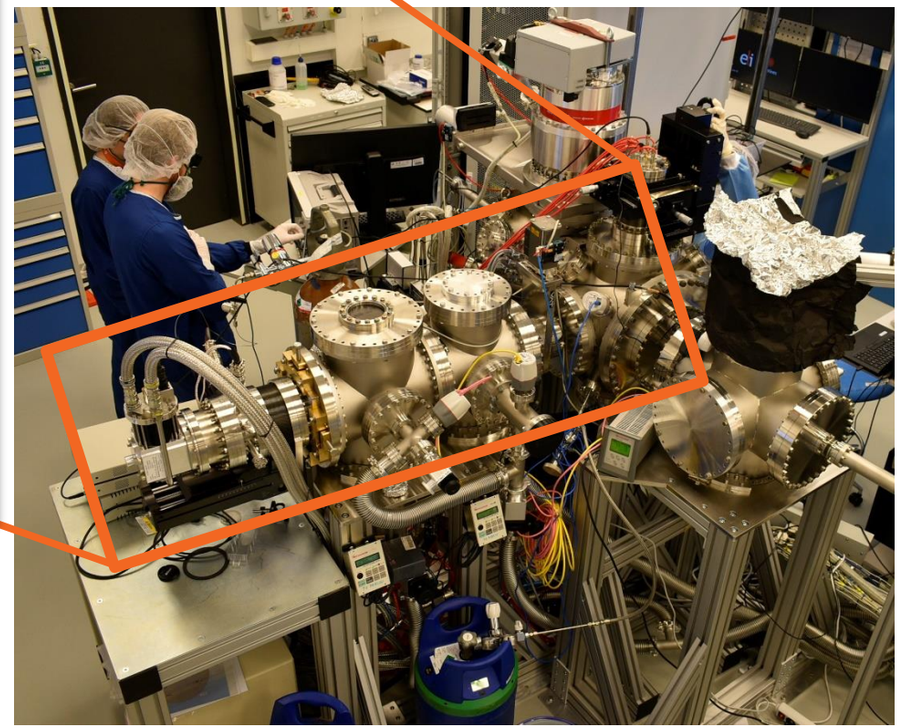
- Atoms & molecules (delivered by a gas beam or effusive needle)
- Clusters (mainly He-nanodroplets)



MAC user end-station – He nanodroplets







C. Medina et al., New J. Phys. **25** (2023) 053030

MAC user end-station – He nanodroplets

Unique spectroscopic system –

Molecules inside or at the surface of He droplets

- Possible to isolate single molecules or certain number of molecules/atoms inside a finite sized helium droplet.
- Superfluidity of cryo-cooled helium. Molecule/Atoms stays highly mobile inside the droplet.
- He is transparent from far IR to UV range (below the IP of helium, 24.58 eV).

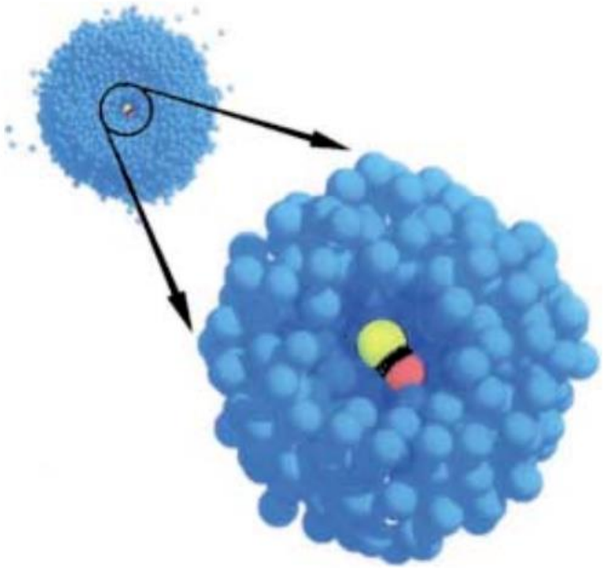
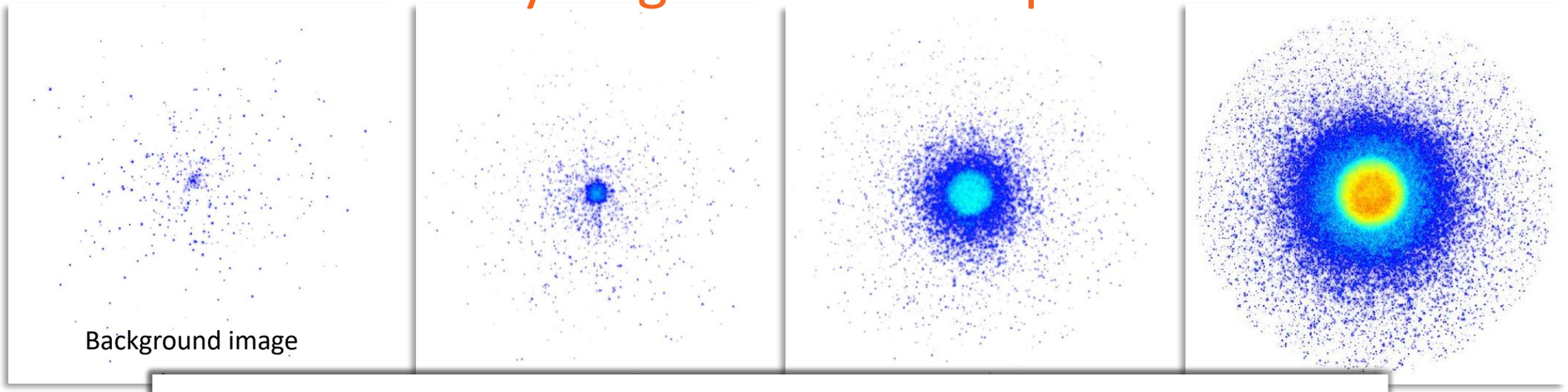


Figure 2. Computer simulation showing an OCS molecule inside a ^{4}He droplet made up of 500 atoms; ^{4}He blue, O red, S yellow, C black.[38]

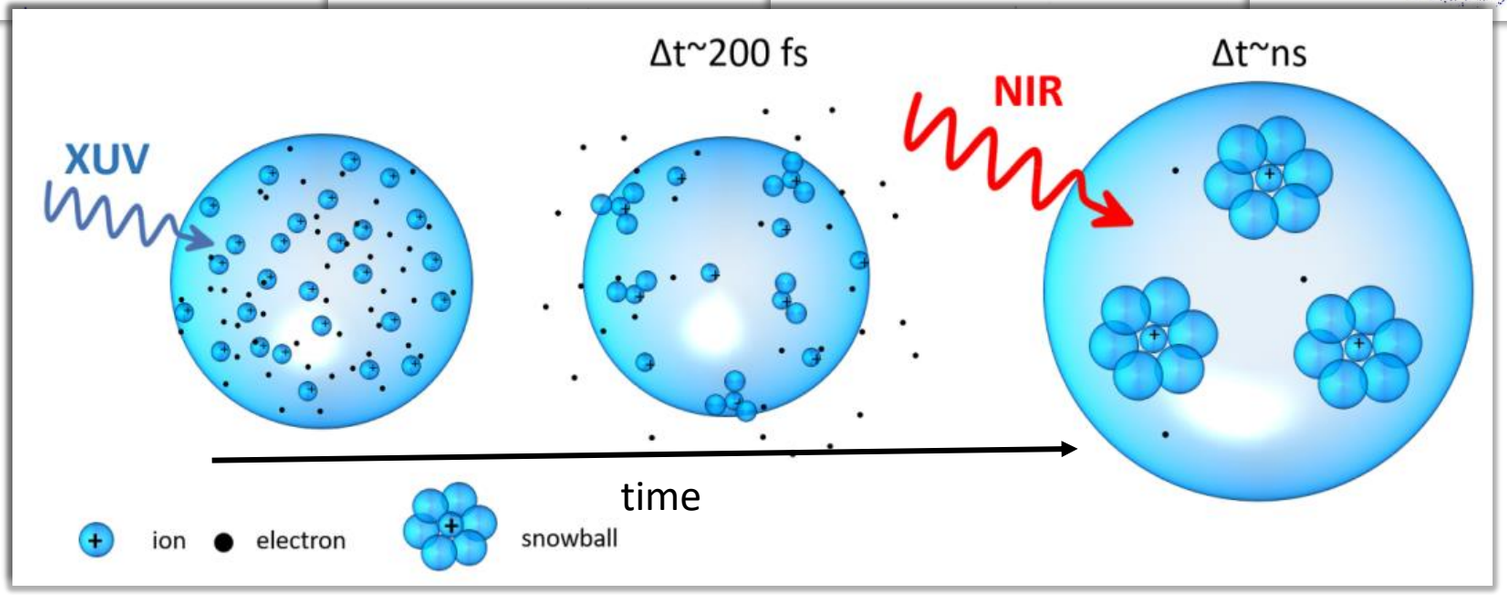
J. P. Toennies and A.F. Vilesov, Angew. Chem. Int. Ed. **43**, 2622-2648 (2004)

MAC user end-station – He nanodroplets

Every single-shot is unique



Dynamics in He-nanodroplets:
Time-resolved VMI



C. Medina et al., New J. Phys. **25** (2023) 053030

Recent results

Electron dynamics in Kr satellite states

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Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics

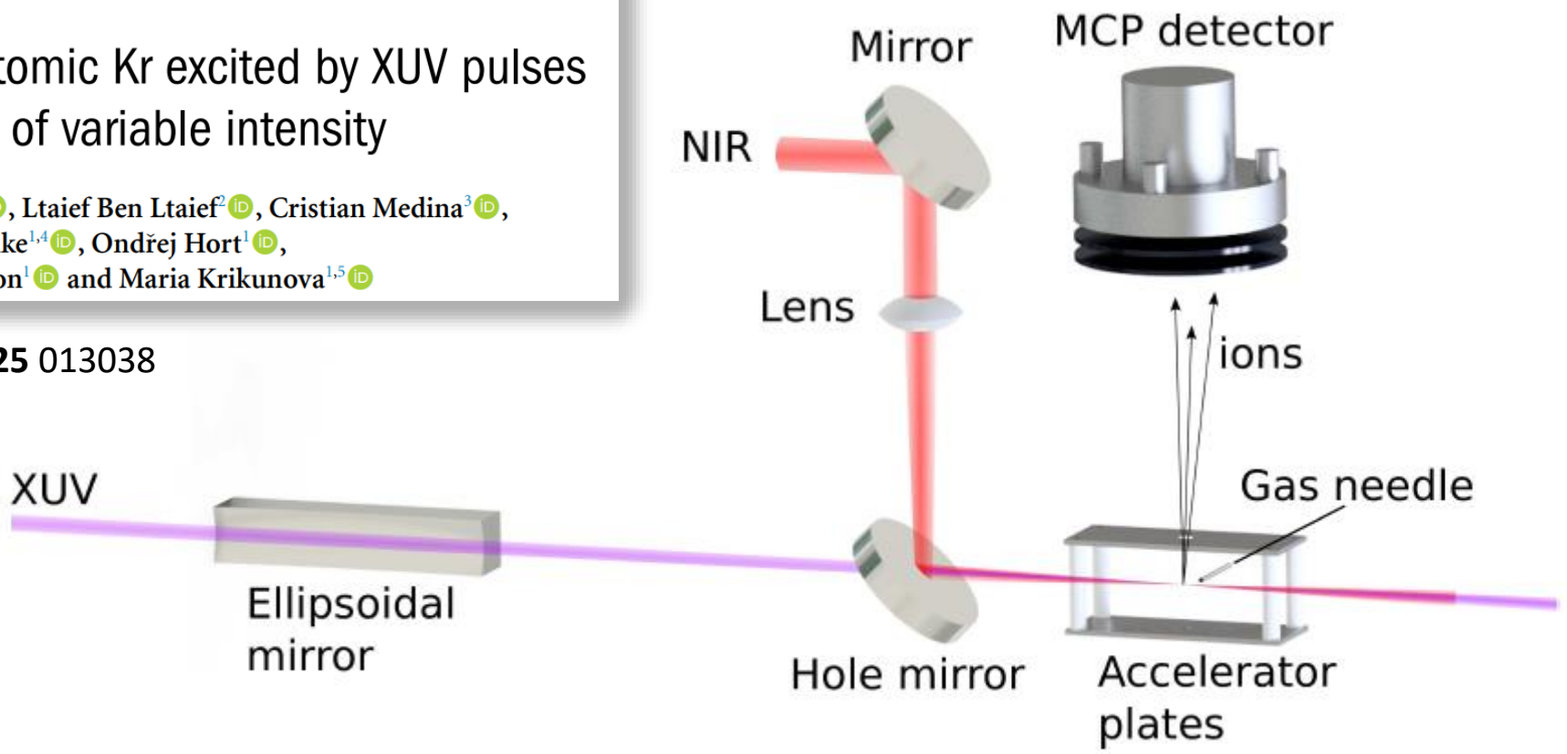
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

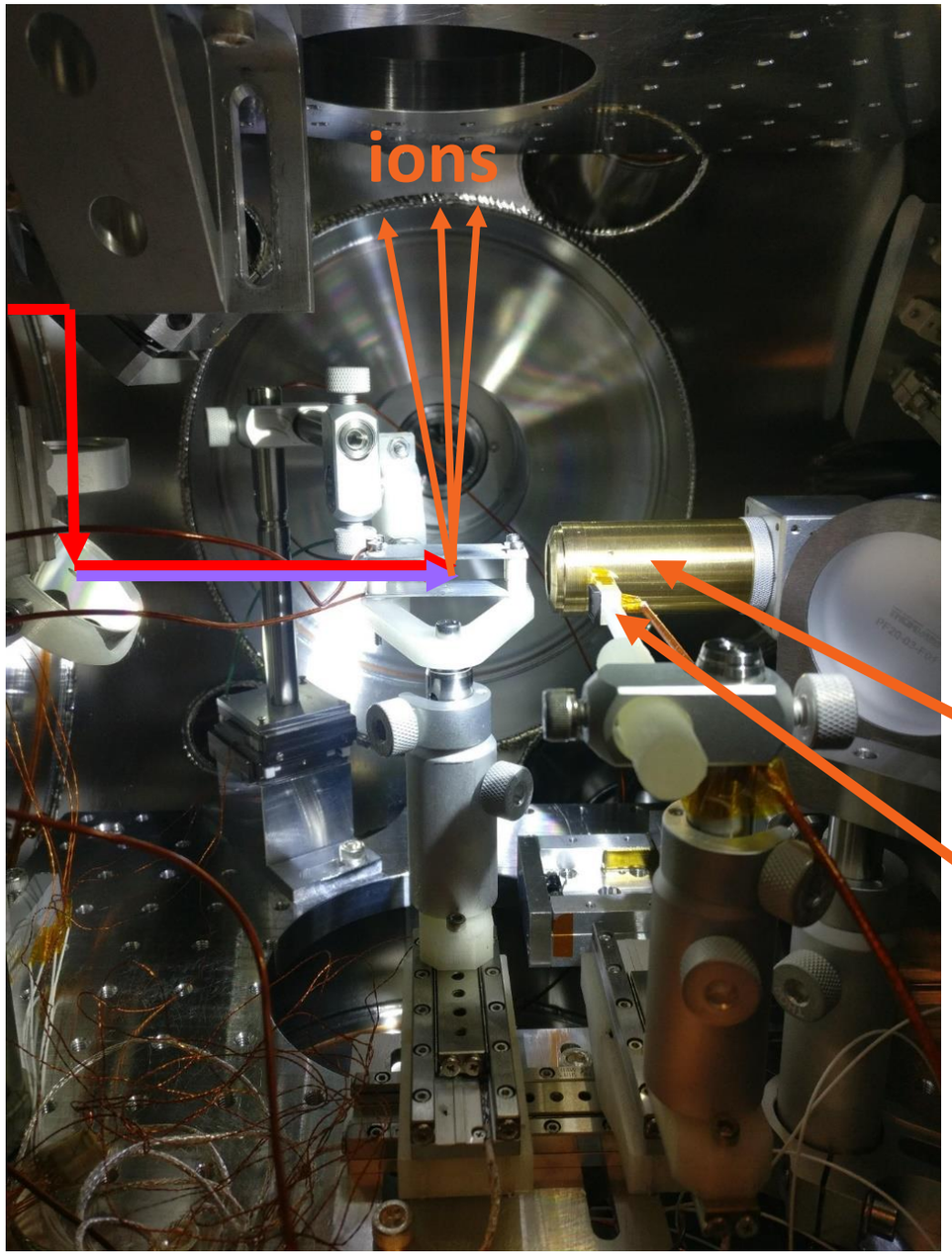
PAPER

Electron correlation dynamics in atomic Kr excited by XUV pulses and controlled by NIR laser pulses of variable intensity

Andreas H Roos[1,*], Ziaul Hoque[1], Eva Klimešová[1], Ltaief Ben Ltaief[2], Cristian Medina[3], Lucie Jurkovičová[1,4], Martin Albrecht[1,4], Ondřej Finke[1,4], Ondřej Hort[1], Jaroslav Nejdl[1,4], Marcel Mudrich[2], Jakob Andreasson[1] and Maria Krikunova[1,5]

Andreas H Roos et al., 2023 New J. Phys. **25** 013038



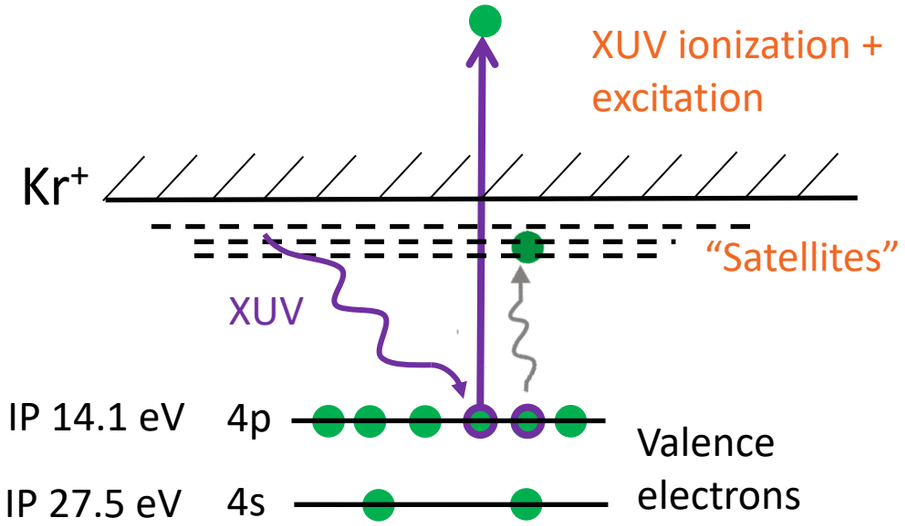


- Light propagets with ≈300 000 km/s.
  Travels about 0.3 µm in 1 fs.
- Movement of a delay stage by 1 mm corresponds to a time-delay of 6.6 ps
- We need to overlap in vacuum two beams with a precision of <10 fs in time and <10 µm in space.

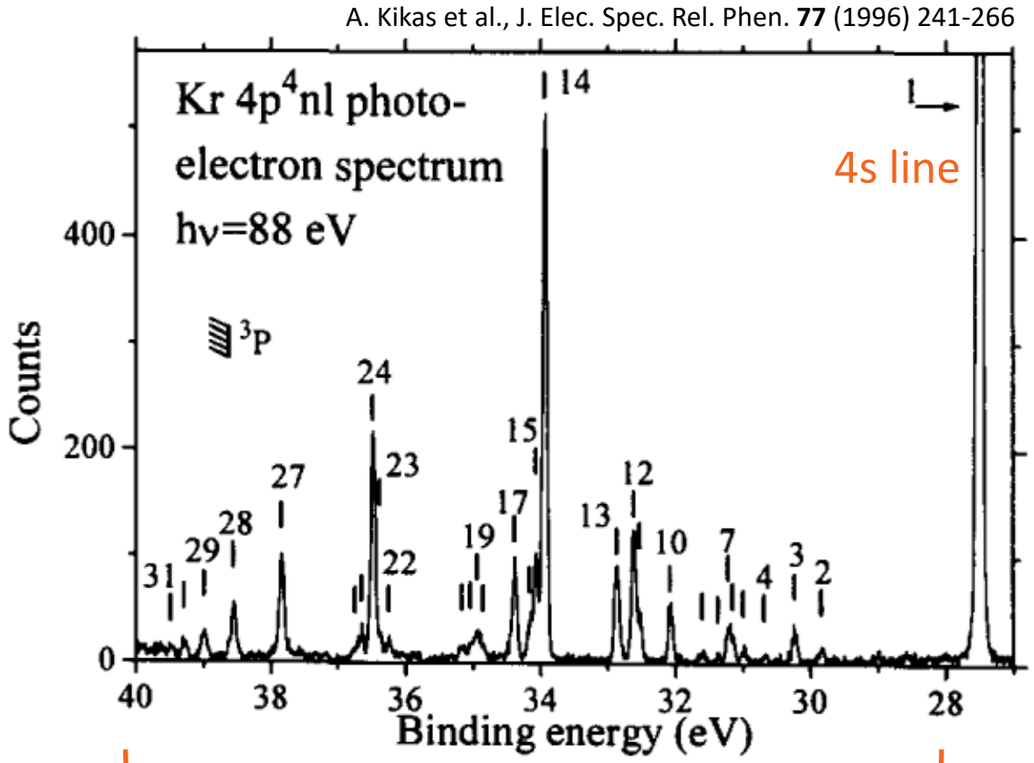
Beam diagnostics:

- In-line microscope for special overlap of IR and HH beams
- XUV photodiode and YAG:Ce scintillator for HH pulse energy diagnostic
- Fast photodiode for rough temporal overlap (50-100 ps

Dynamics of correlation satellites



A. Kikas et al., J. Elec. Spec. Rel. Phen. **77** (1996) 241-266



Satellites ($4s^2 4p^{-2} nl$)

Kr electron configuration: [Ar] $3d^{10}\ 4s^2\ 4p^6$

hv = 29.6, 32.8, 35.9 eV (HH19, HH21, HH23)

The goal of the experiment

Quantum dynamics is often not easy to observe:

- Hidden withing the signal from other dynamics.
- Or, within the noise of your experimental setup.

➢ Show the possibility to probe different quantum states by carefully varying the NIR intensity.

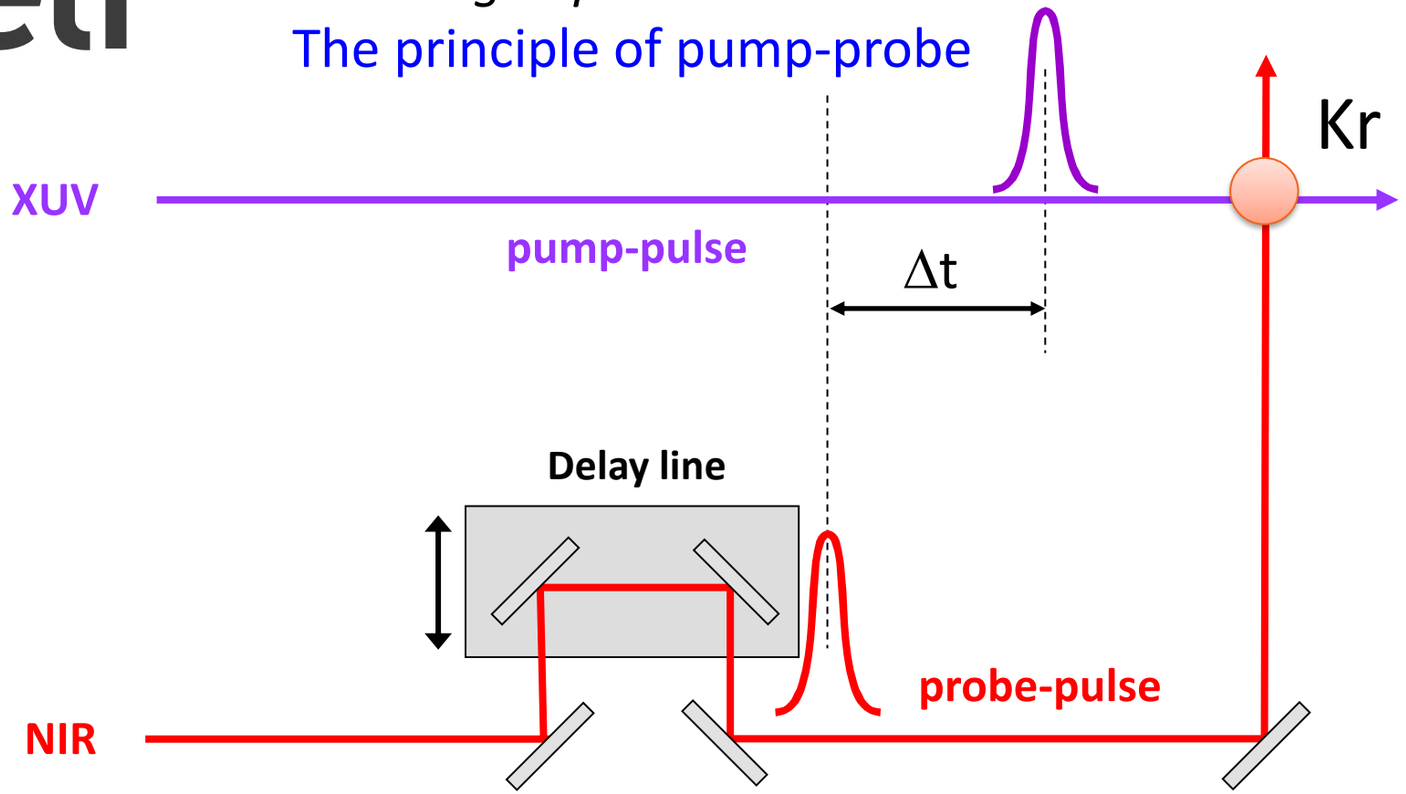
➢ And, is it possible to control which quantum states that we observe in our pump-probe signal?

To answer this, we need a very sensitive way to probe and detect these quantum states.

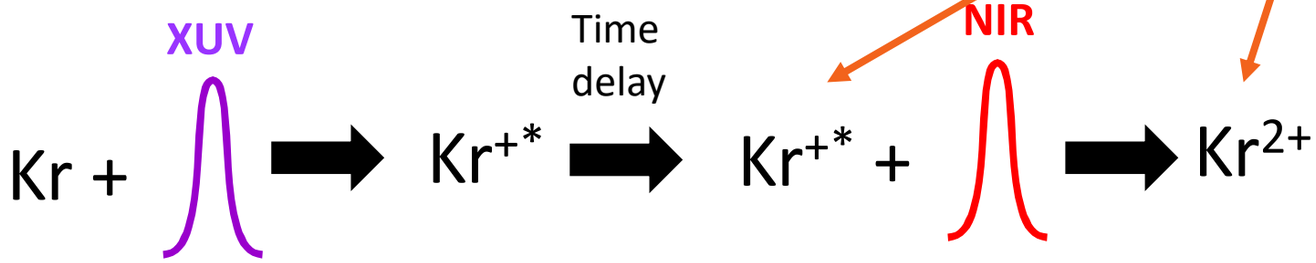
Pump-probe of Kr

"A high-speed camera"

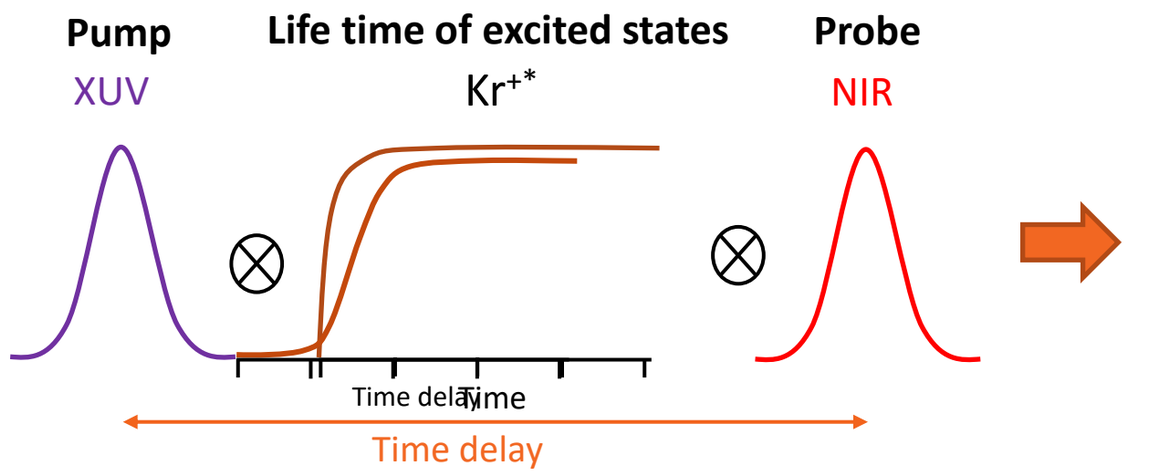
The principle of pump-probe

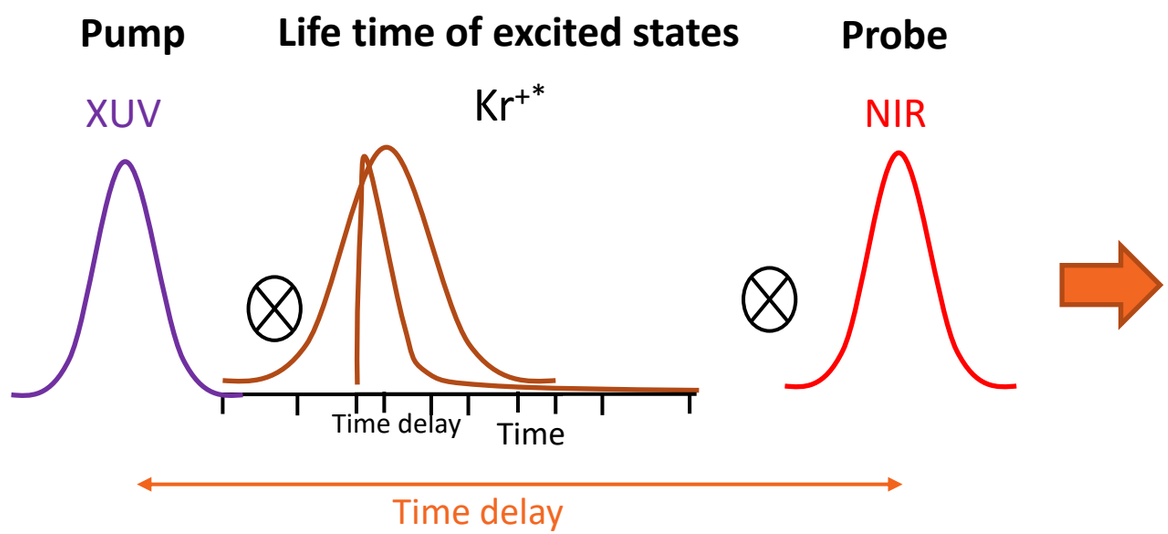


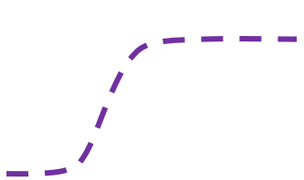
Detect the Kr ion yield of respective charge state (Kr^{+}/Kr^{2+}), at different time delays



Pump-probe of Kr



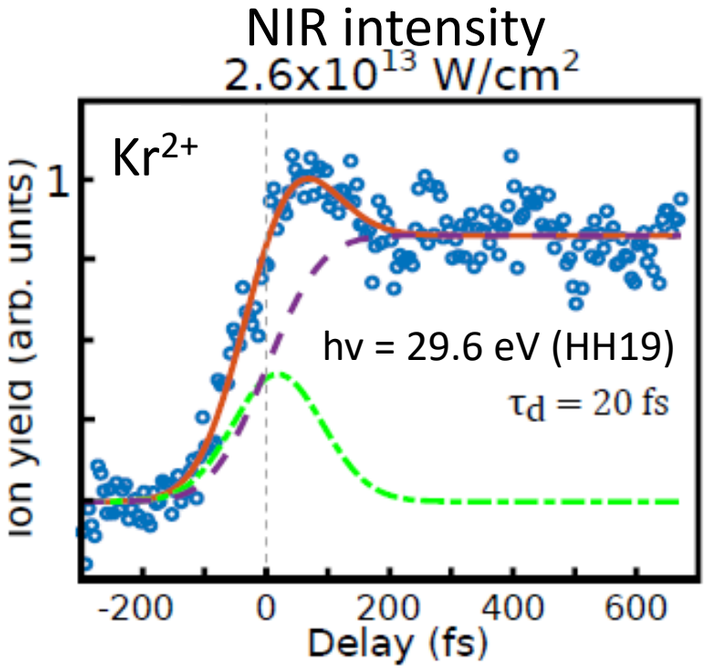


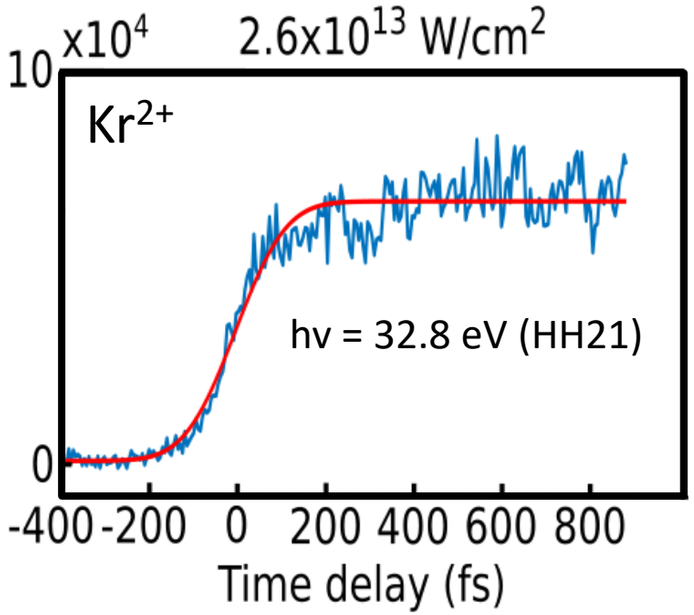


Sequential two-color double ionization

Simultaneous, non-sequential two-color double ionization: Time-delay = 0

Quantum interference between coherently excited states





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The Results

- We show that at a certain NIR intensity we can specifically probe quantum oscillations of excited electron wavepackets in a superposition of satellite states.

A quantum mechanical analogy is the so-called Schrödinger's cat.

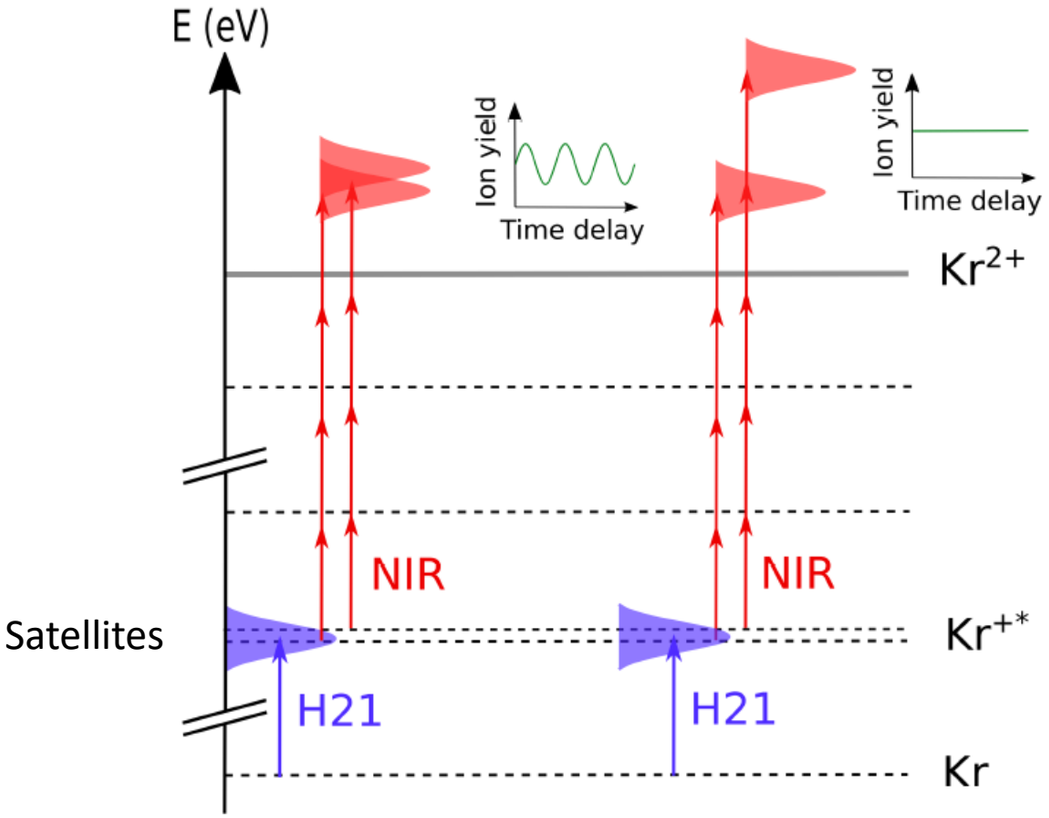
- We are able to control the ratio between different quantum pathways that are visible.

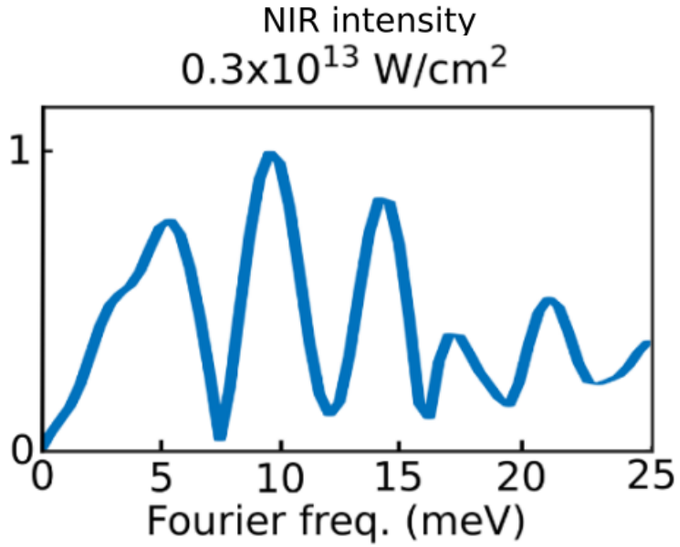
We thus domnstrate an efficeint way to control the quantum dynamics by the means of altering the NIR intensity.

Dynamics of correlation satellites

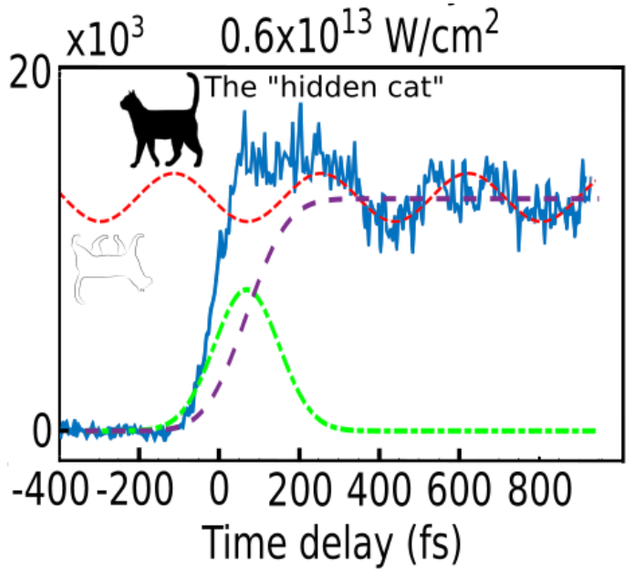
Quantum interference between coherently excited states

Quantum interference between coherently excited states – Seeing Schrödinger's cat





Fourier analysis



$$f = \frac{\Delta E}{h}$$

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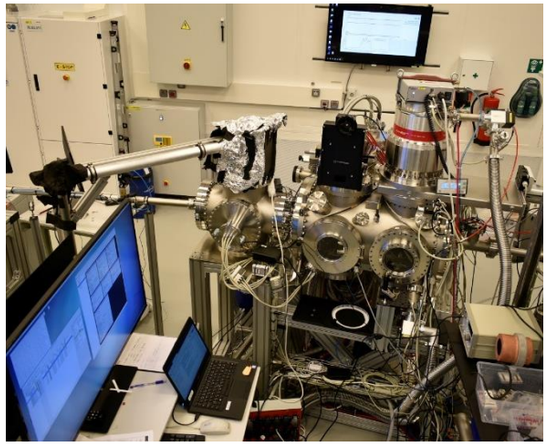
Summary

MAC

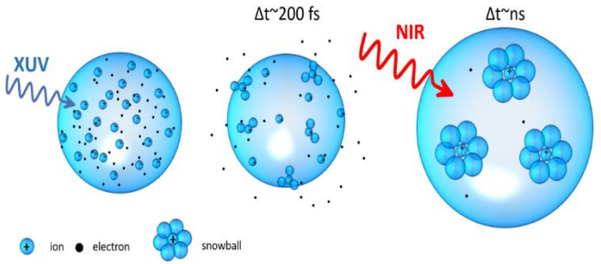
- AMO science.
- Versetile experimental station for external users.
- Time-resolved experiments (femtosecond time resolution).



Experimental methods

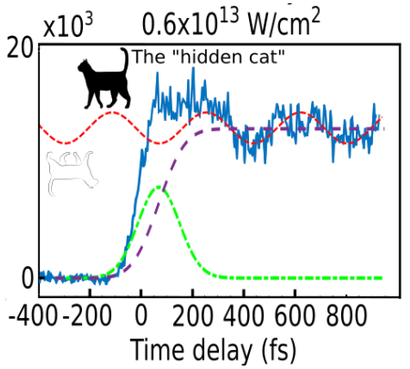
VMI:

Short example of an experiment on He nanodroplets.



Ion time-of-flight:

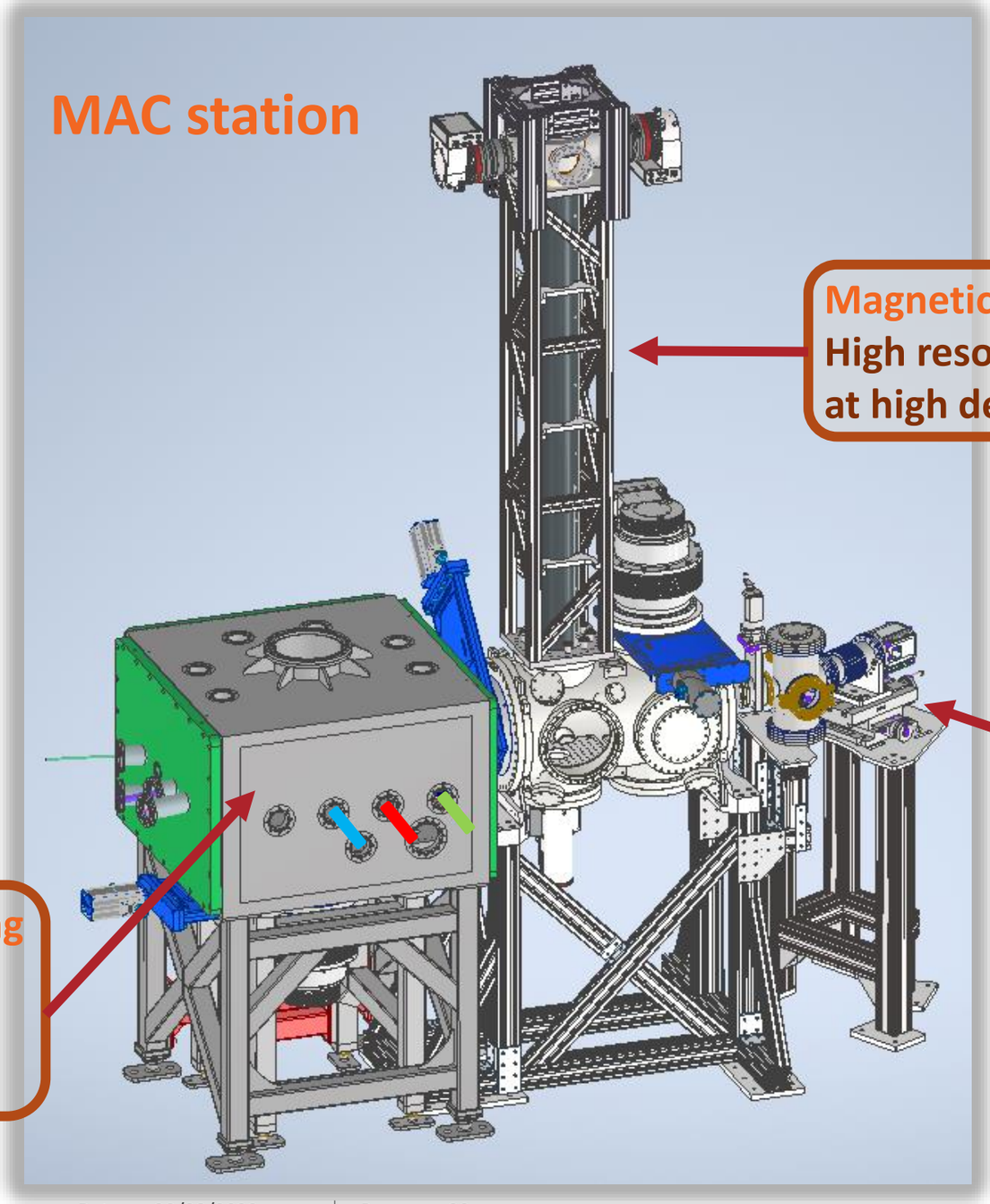
Example experiment on time-resolved dynamics of correlated satellite states.



Outlook

New detector/camera for VMI (TPX3CAM)

MAC station



Magnetic bottle electron spectrometer
High resolution electron and ion spectra at high detection efficiency

XUV spectrometer

New beam preparation/focusing vacuum chamber
Option for multi-beam pump-probe experiments

More complete overview of the MAC station

Eur. Phys. J. Spec. Top.
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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

A multipurpose end-station for atomic, molecular and optical sciences and coherent diffractive imaging at ELI beamlines

Eva Klimešová[1,a], Olena Kulyk[1], Ziaul Hoque[1], Andreas Hult Roos[1], Krishna P. Khakurel[1], Mateusz Rebarz[1], Matej Jurkovič[1], Martin Albrecht[1], Ondřej Finke[1], Roberto Lera[1], Ondřej Hort[1], Dong-Du Mai[1], Jaroslav Nejdl[1], Martin Sokol[1], Rasmus Burlund Fink[1,2], Ltaief Ben Ltaief[2], Daniel Westphal[3], Adam Wolf[1], Tomáš Laštovička[1], Fabio Frassetto[4], Luca Poletto[4], Jakob Andreasson[1], and Maria Krikunova[1,b]

[1] ELI Beamlines, Institute of Physics AS CR, v.v.i., Na Slovance 2, 182 21 Prague 8, Czech Republic
[2] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark
[3] Laboratory of Molecular Biophysics, Department of Cell and Molecular Biology, Uppsala University, Husargatan 3 (Box 596), 75124 Uppsala, Sweden
[4] Institute of Photonics and Nanotechnologies, National Research Council, Via Trasea 7, 35131 Padua, Italy

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Thank you for your attention!

Andreas Roos

ELI Beamlines

30 August 2023

Dolní Břežany, Czech Republic

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