MVSem--Masterseminar
2021-04-20

The sound of the phase: *Atoms&molecules respond to intense laser flashes*

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MPIK Heidelberg

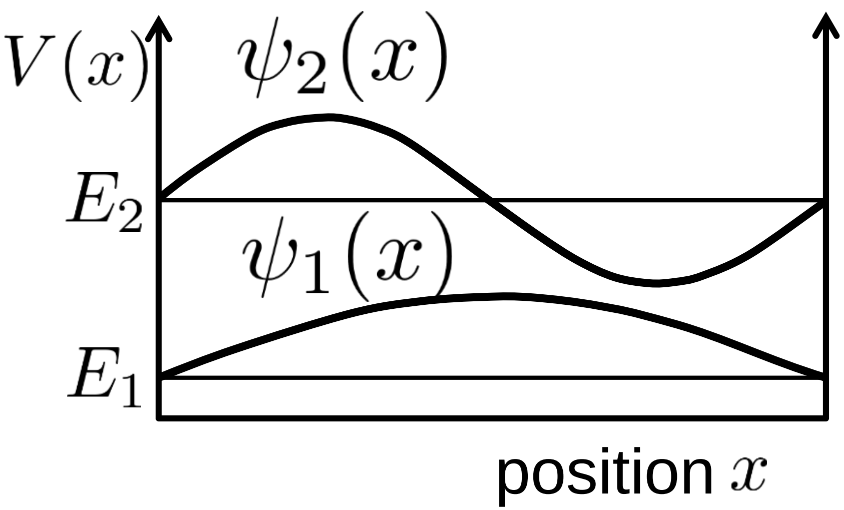
Fundamental Quantum Dynamics

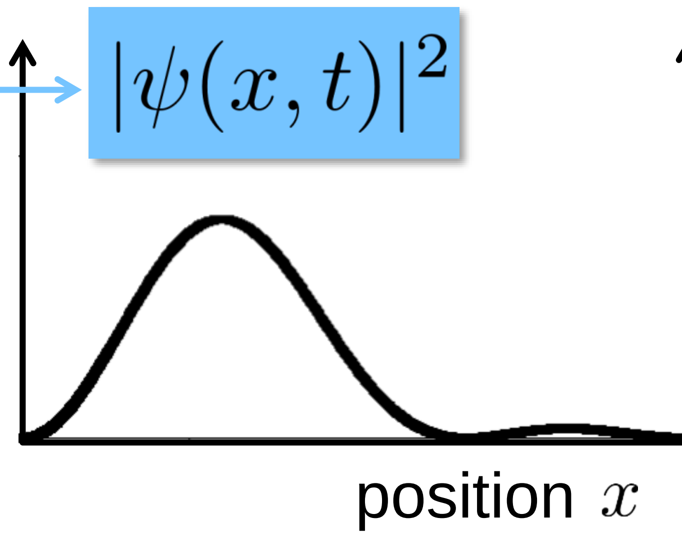
$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \mathcal{H}\psi(x,t)$$

Interference of quantum states

Feynman: "... the ***only*** mystery [at the heart of quantum mechanics]."

Potential





$$\psi(x,t) \propto a_1\psi_1(x)e^{\overbrace{-\frac{i}{\hbar}E_1 t}^{\text{Phase }\varphi_1}} + a_2\psi_2(x)e^{\overbrace{-\frac{i}{\hbar}E_2 t}^{\text{Phase }\varphi_2}}$$

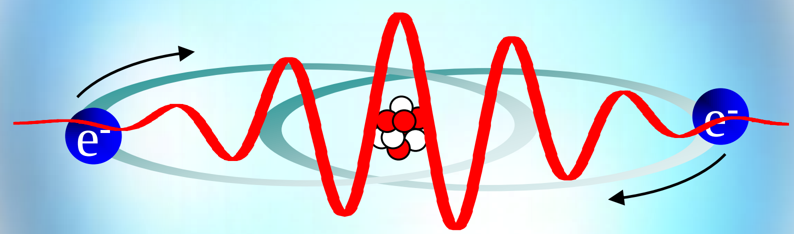
few-body quantum dynamics

a fundamental scientific question:

"how do two or more excited electrons move and interact in atoms and molecules?"

spatial scale
R ~ sub/few Å

temporal scale
T ~ sub/few fs



The "**quantum** **few-body problem**" ***in strong fields***

0 as

Science goal:

measure / understand / control
the ***quantum dynamics*** *of*
small systems
in strong fields

- (x-ray) movies of single molecules
- Laser control of chemical reactions
- Petahertz-clocked computing
- x-ray precision spectroscopy

Electron Facts

- lightest charged elementary particle
- 'chemical glue', holding molecules together
  -> making and breaking of bonds in chemical reactions
- carriers of electric current
  -> electricity generation/conversion/transport
- carriers of information
  -> electronics, computing, data storage
- mediating interactions of matter with light
  -> role in photosynthesis, photovoltaics, vision, ...

...typically more than one electron involved...

What is the problem?

(with two or more electrons)

Correlated e⁻lectron dynamics

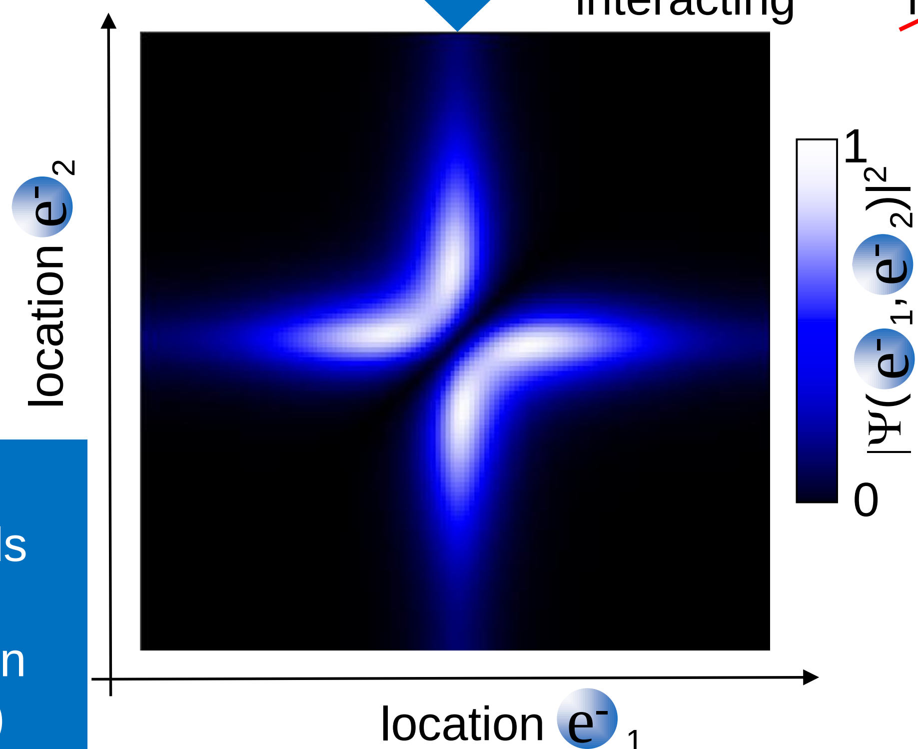
$e^- \sim e^-$

interaction (Coulomb)

symmetry (Fermions)

Correlation

$$\underbrace{\Psi(e^-_1, e^-_2)}_{\text{'interacting'}} \neq \cancel{\underbrace{\Psi(e^-_1) \times \Psi(e^-_2)}_{\text{'non-interacting'}}}$$



problem for:

- Hartree–Fock methods
- DFT
  (exchange-correlation potential not known)

Why is it important?

Time-dependent correlated e^-lectron dynamics

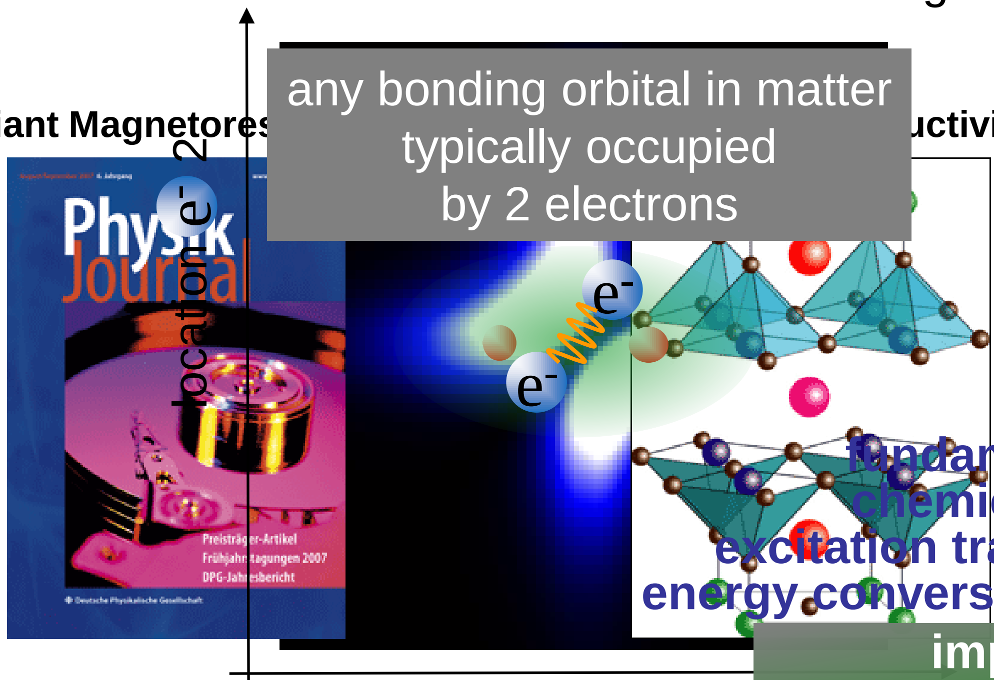
$e^- \sim e^-$

interaction (Coulomb)

symmetry (Fermions)

Correlation

$$\underbrace{\Psi(e^-_1, e^-_2)}_{\text{'interacting'}} \neq \underbrace{\Psi(e^-_1) \times \Psi(e^-_2)}_{\text{'non-interacting'}}$$

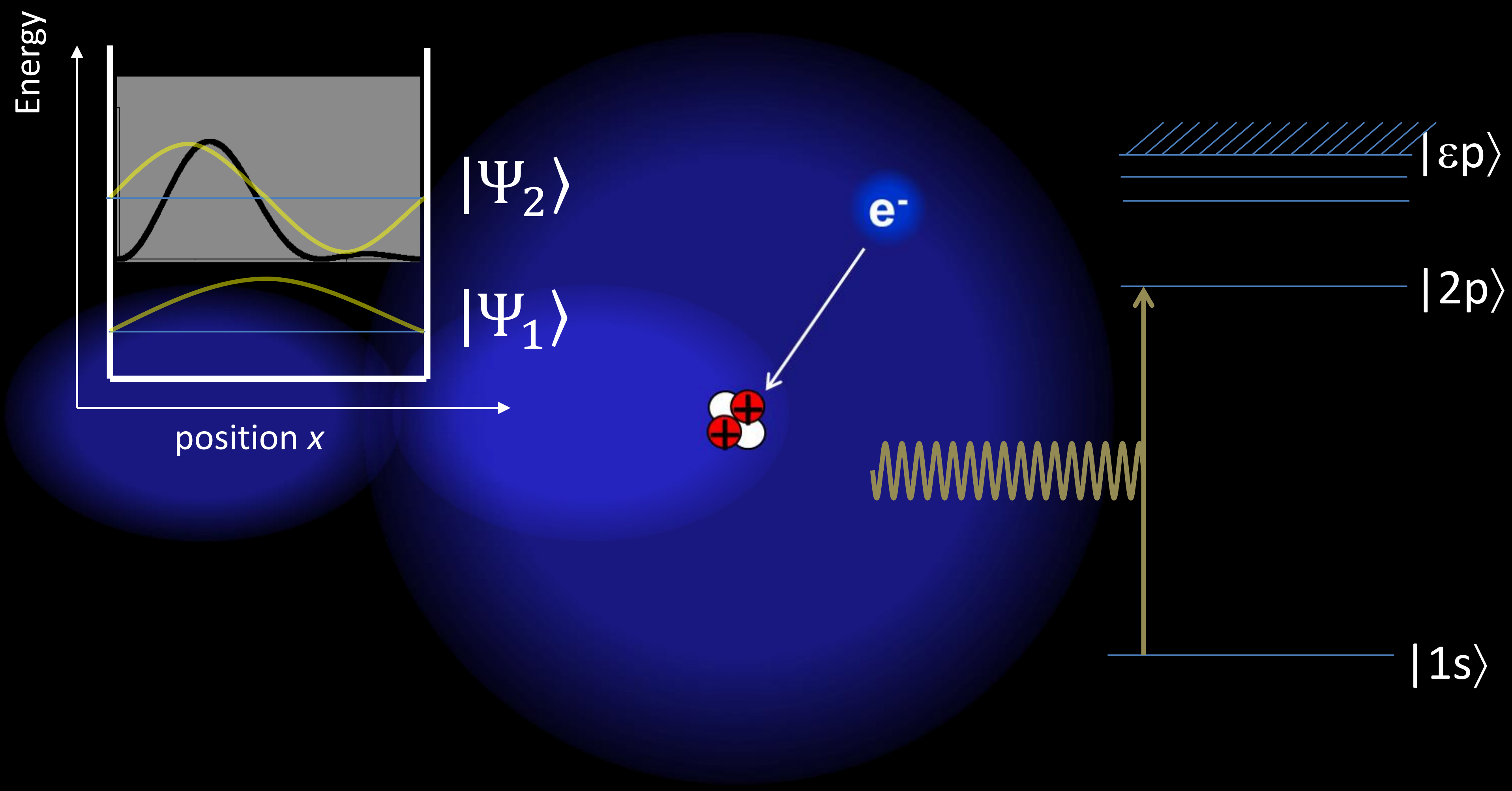


any bonding orbital in matter typically occupied by 2 electrons

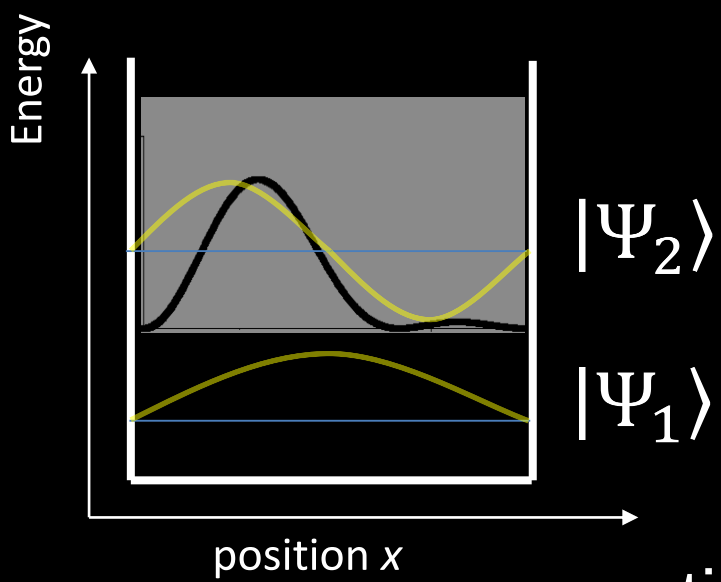
fundamental role in chemical reactions excitation transfer, e^- transport energy conversion, radiation damage

importance in many branches of science

the language electrons speak …
… and why is it so fast?



Wavepacket dynamics and observation



Quantum beat period:

$$\Delta T = \frac{\hbar}{\Delta E} \approx 4.1\ \text{fs} \,/\, \Delta E\,[\text{eV}]$$

$$\Psi(t) \sim \Psi_1 e^{\frac{-i}{\hbar}E_1 t} + \Psi_2 e^{\frac{-i}{\hbar}E_2 t}$$

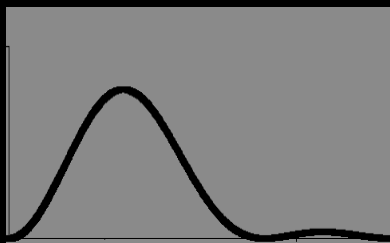
e.g. time-dependent position/dipole:

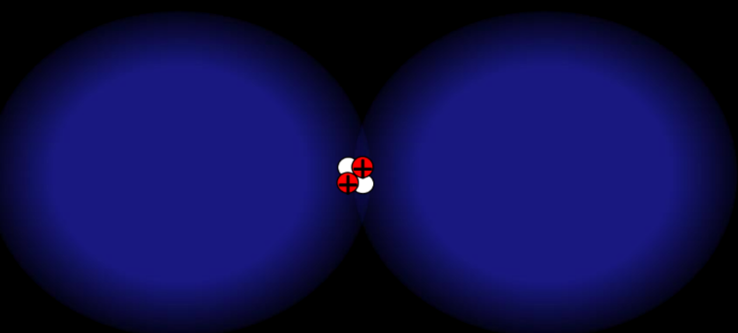
$$x(t) = \langle \Psi(t)|\hat{x}|\Psi(t)\rangle$$

$$= \tfrac{1}{2}\left\langle \Psi_1 e^{\frac{-i}{\hbar}E_1 t} + \Psi_2 e^{\frac{-i}{\hbar}E_2 t} \middle| \hat{x} \middle| \Psi_1 e^{\frac{-i}{\hbar}E_1 t} + \Psi_2 e^{\frac{-i}{\hbar}E_2 t} \right\rangle$$

$$= |\langle \Psi_1|\hat{x}|\Psi_2\rangle\rangle| \; \cos\left[\frac{(E_1 - E_2)}{\hbar} t + \varphi_0\right] \longrightarrow \varphi(t)$$

the language electrons talk ... ... and why is it so fast?





and the way we "listen"...:

Spectroscopy

Quantum beat period:

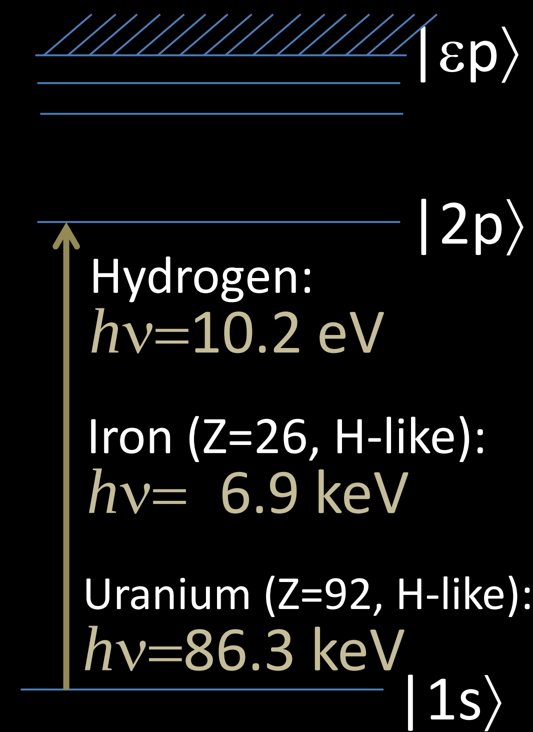
$$\Delta T = \frac{\hbar}{\Delta E} \approx 4.1 \text{ fs} / \Delta E[\text{eV}]$$

Oscillation period:

Hydrogen:
$T = 0.4$ fs (10^{-18} s)

Iron (H-like):
$T = 0.6$ as (10^{-18} s)

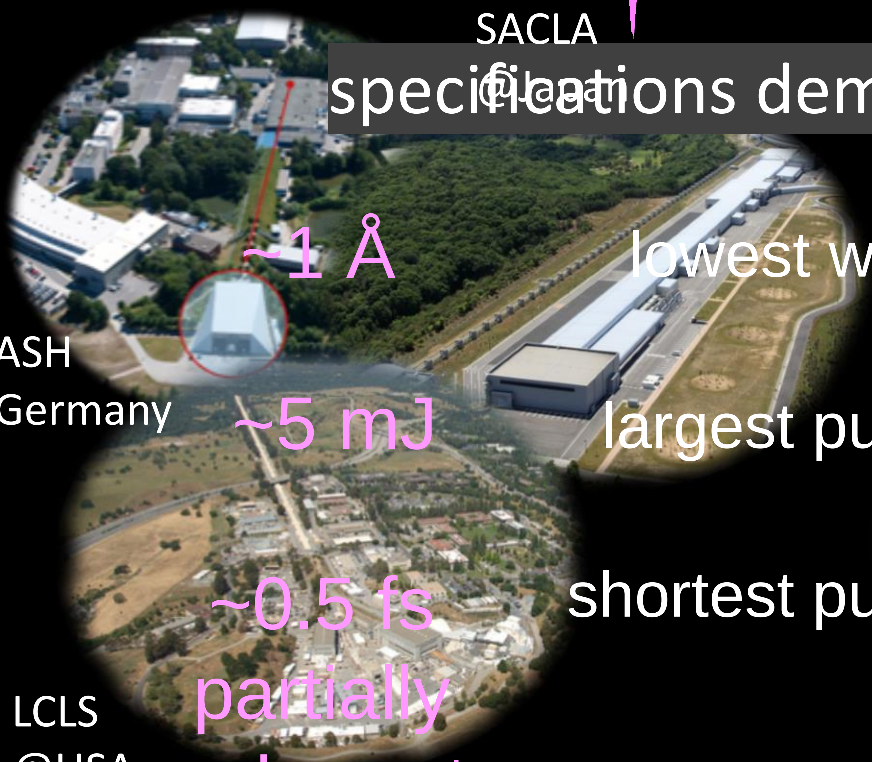
Uranium (H-like):
$T = 48.0$ zs (10^{-21} s)



The light sources: Provided by two parallel revolutions in ultrashort x-ray/XUV laser science

Free **E**lectron **L**asers

High **H**armonic **G**eneration

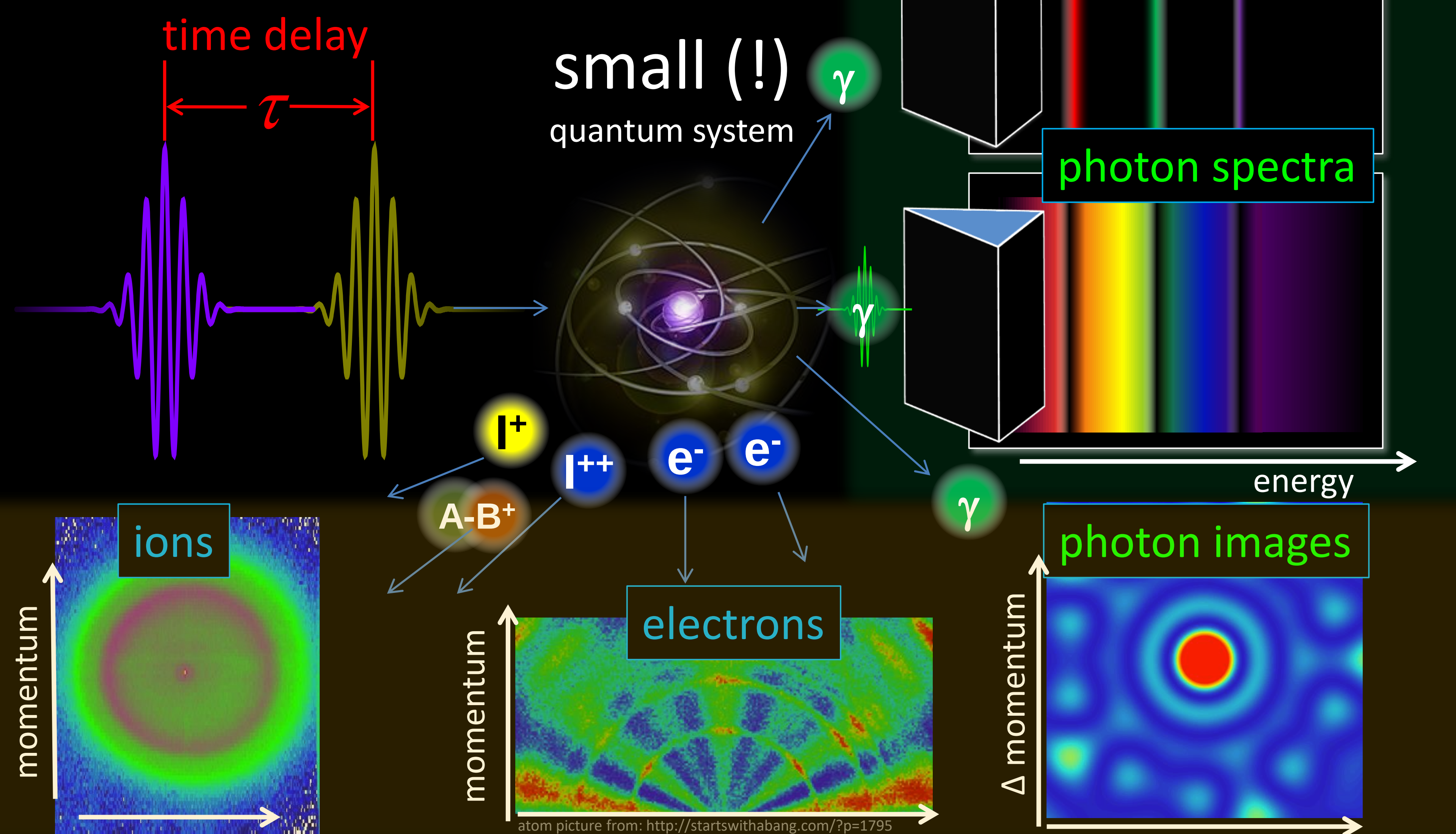


specifications demonstrated thus far:

Free Electron Lasers		High Harmonic Generation
~1 Å	lowest wavelength	~1 nm
~5 mJ	largest pulse energy	~1 µJ
~0.5 fs	shortest pulse duration	~50 as
partially coherent		fully coherent

Quantum dynamics imaging and spectroscopy

Our "Eyes" ... and "Ears" ...



Our Experimental Focus

Employing **Bright Light**

(Free Electron) Lasers

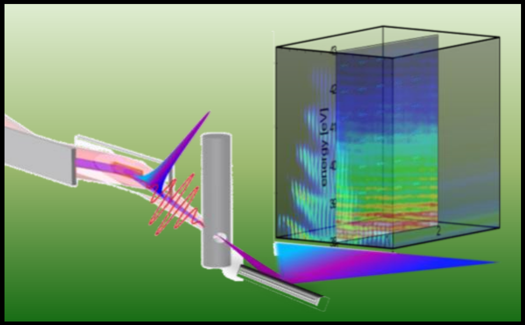
High Harmonic Generation

to understand &control

Atoms, Ions & Molecules

"listening"

Multidim. optical spectroscopy

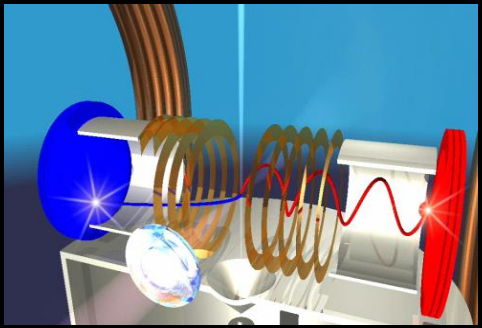


time&energy-resolved detection of photons

Goal: extract complete information

"imaging"

Reaction microscope/COLTRIMS



coincidence detection of electrons/ions

atom image from: http://startswithabang.com/?p=1795

Our Experimental Focus

(Free Electron) Lasers

Bright Light

High Harmonic Generation

to understand &control

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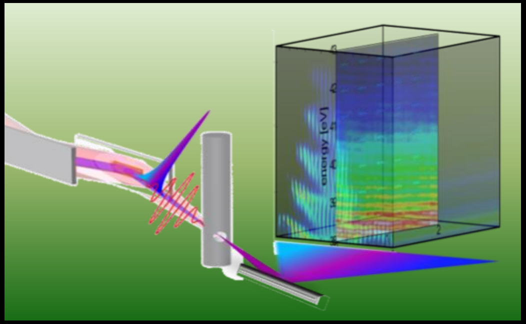
"listening"

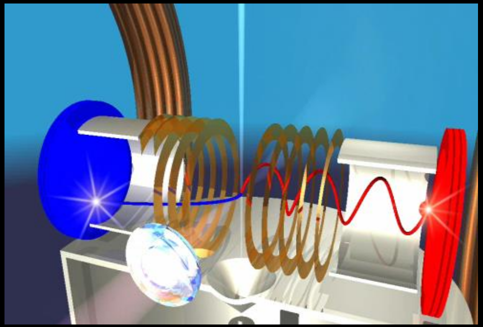
Multidim. optical spectroscopy



time&energy-resolved detection of **photons**

"imaging"

Reaction microscope/COLTRIMS



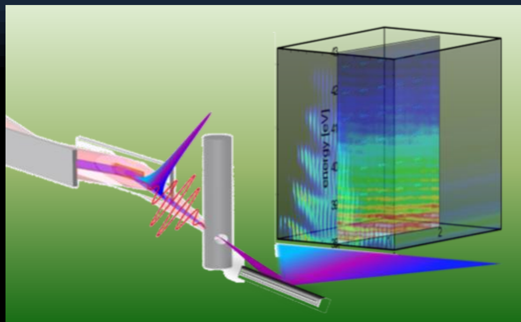
coincidence detection of **electrons/ions**

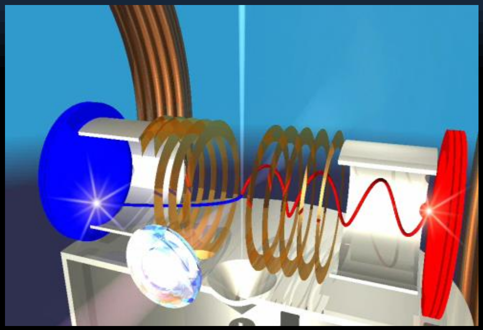
Goal: extract complete information

Experimental observation of few-body dynamics

Multidim. optical spectroscopy

Reaction microscope/COLTRIMS

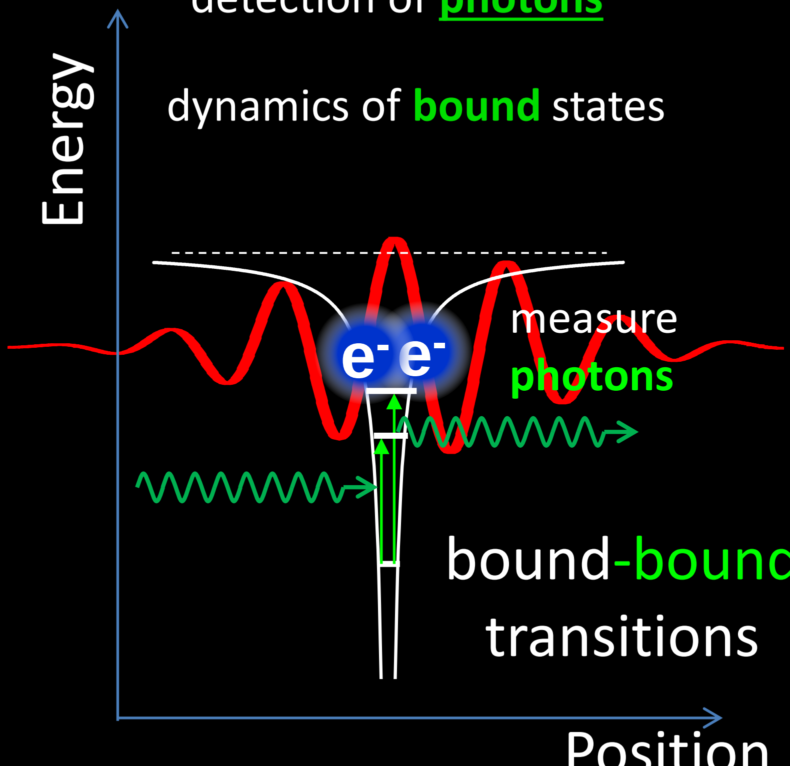


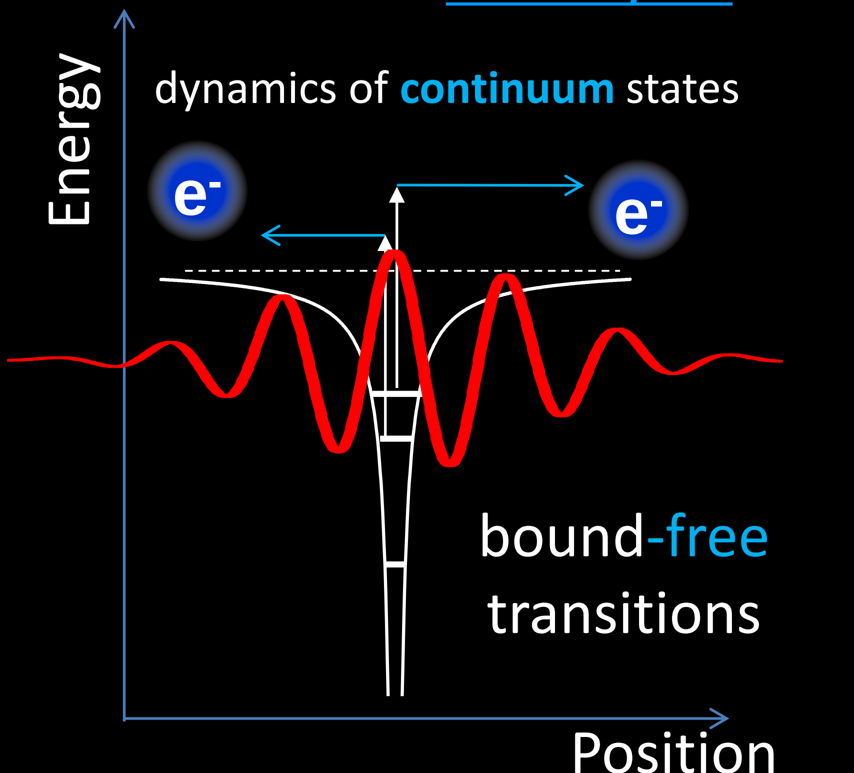


time&energy-resolved detection of **photons**

Goal: extract complete information

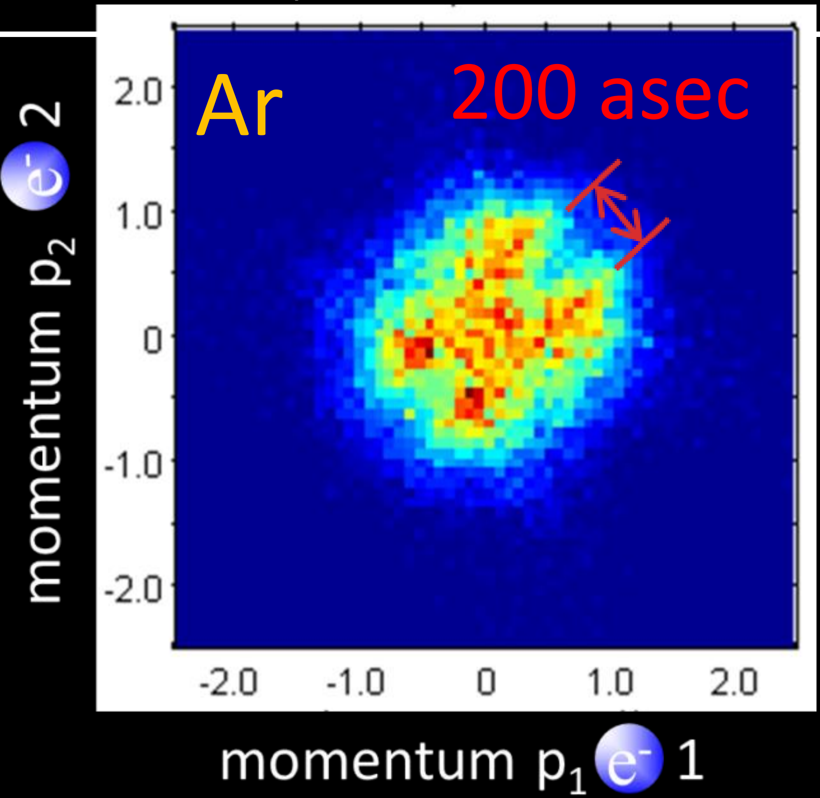
coincidence detection of **electrons/ions**





Strong-field Recollision Physics
in “nonsequential” double ionization

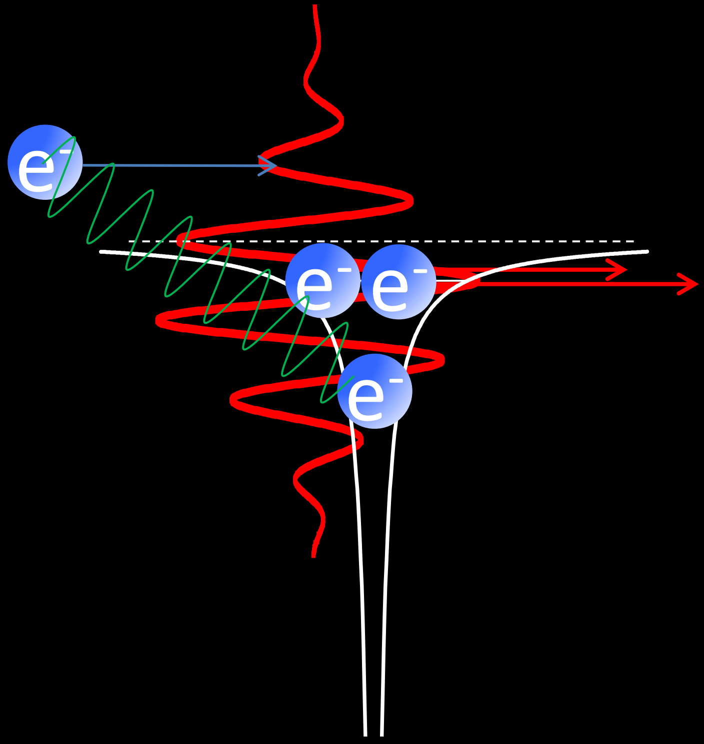
N. Camus *et al.* Phys. Rev. Lett. **108**, 073003



characteristic time delay

?

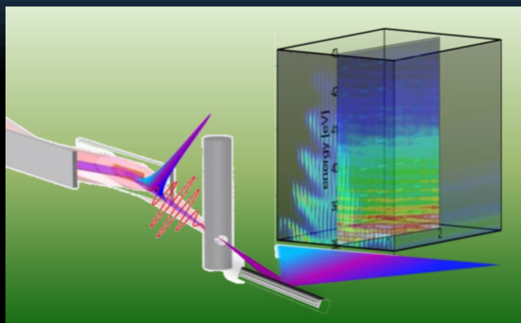
low intensity
low recollision energy

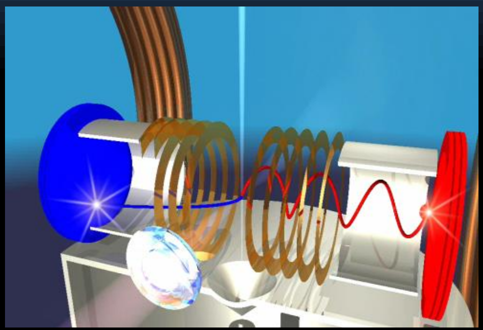


Experimental observation of few-body dynamics

Multidim. optical spectroscopy

Reaction microscope/COLTRIMS

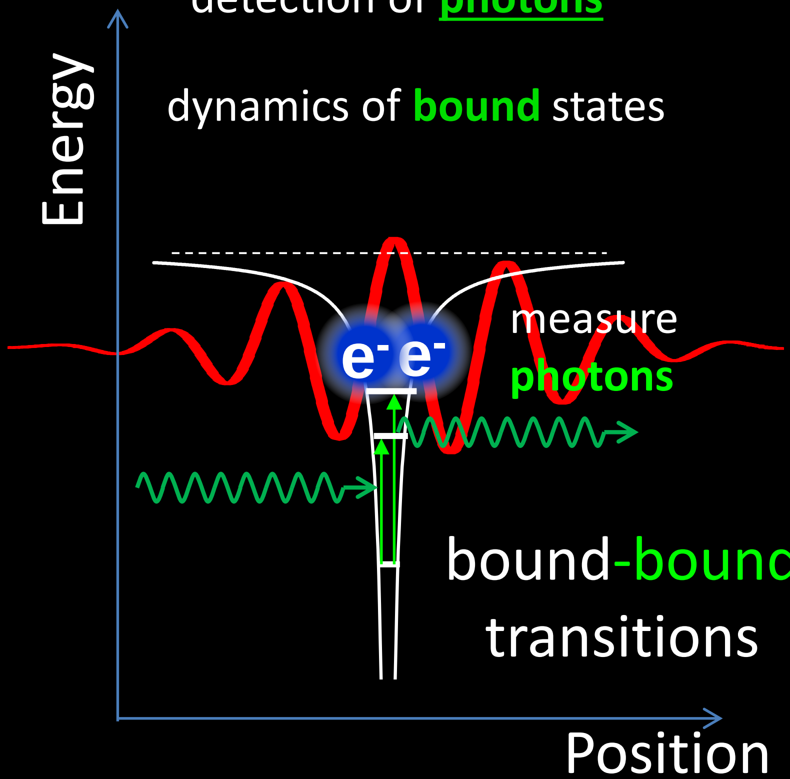


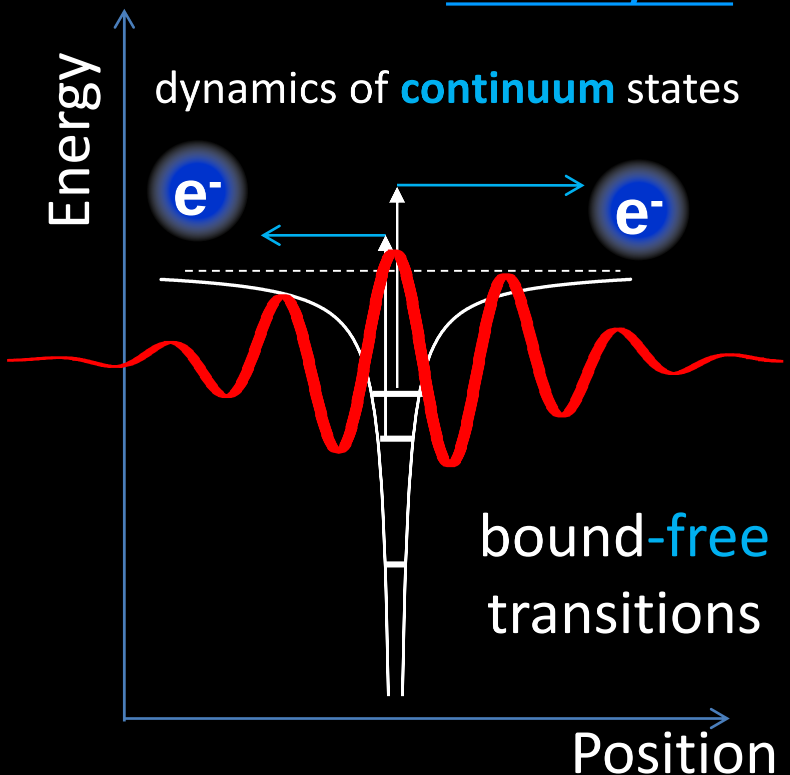


time&energy-resolved detection of **photons**

Goal: extract complete information

coincidence detection of **electrons/ions**

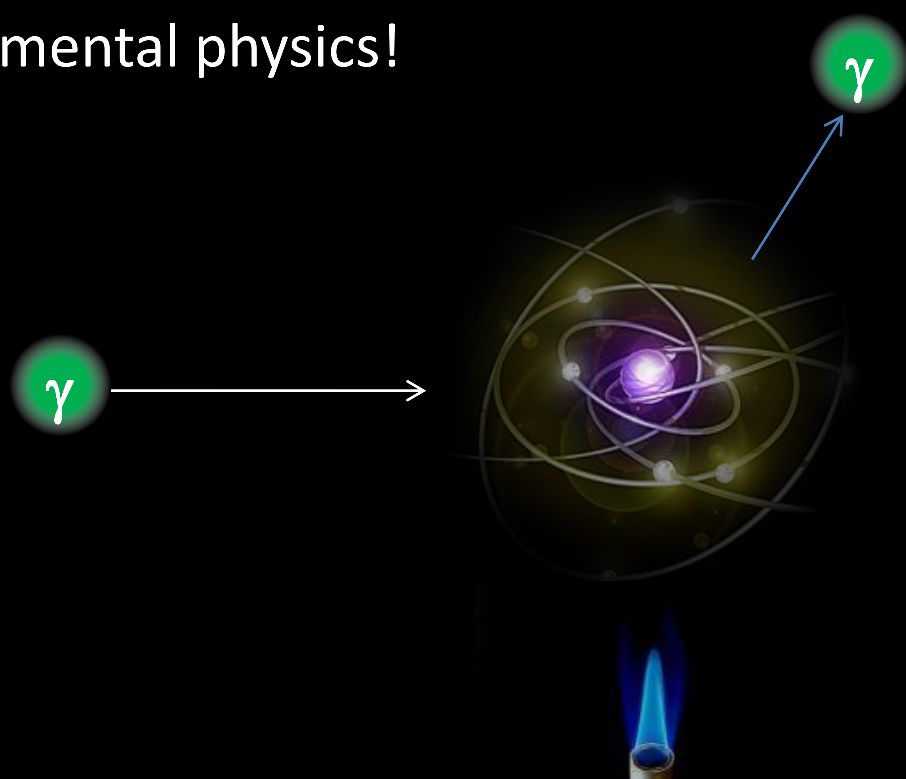


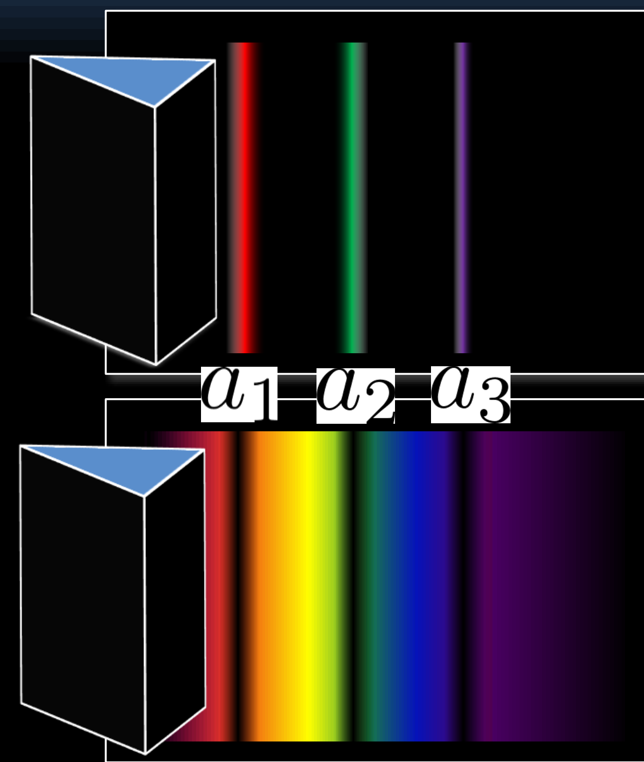


traditional spectroscopy

(Kirchhoff, Bunsen, *et al. @Heidelberg ~1860*)

Electrons in atoms already taught us a lot of fundamental physics!

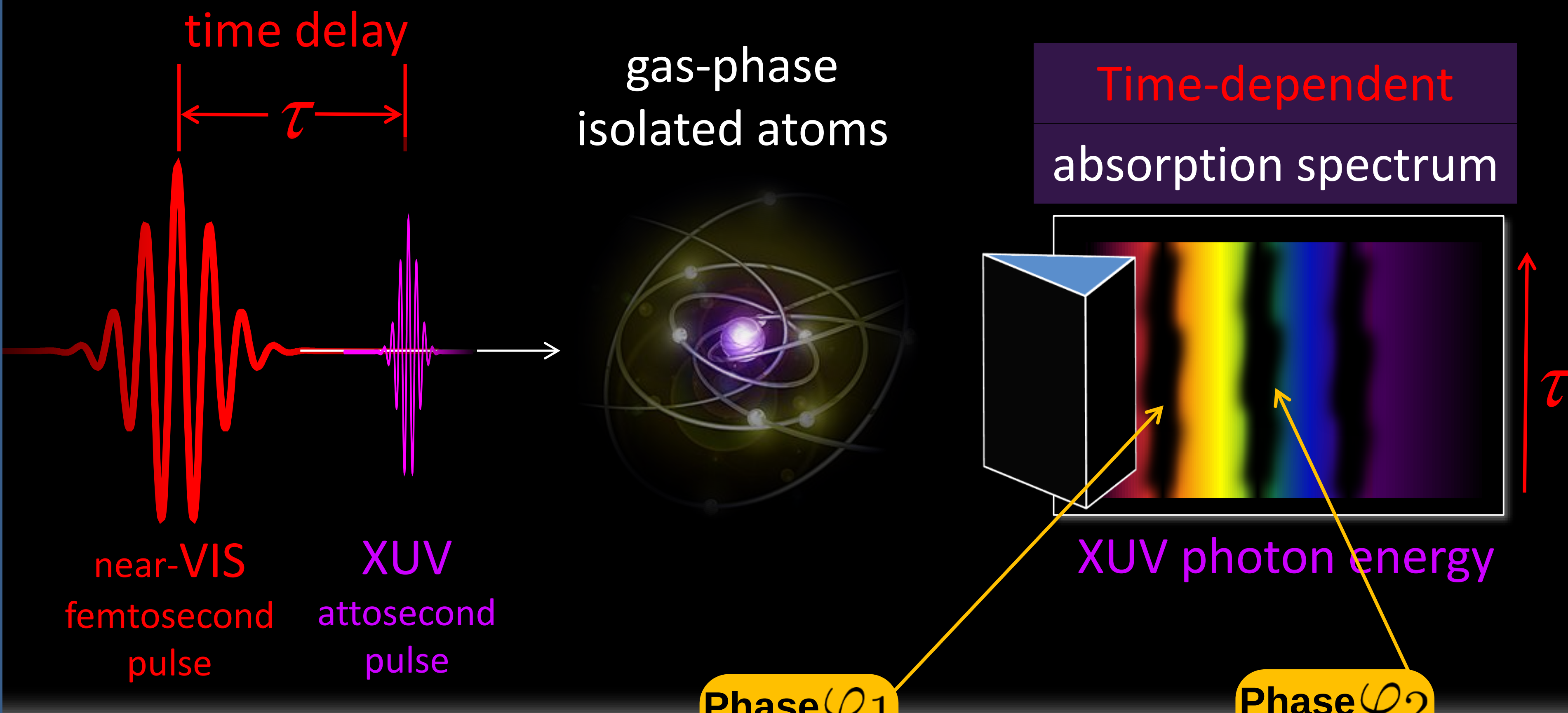




e.g. Fraunhofer *et al.*

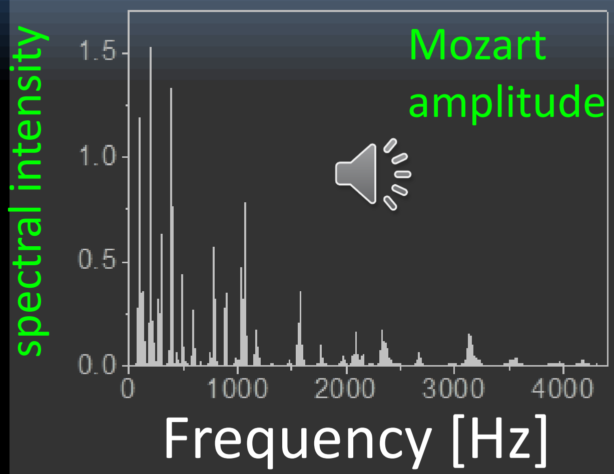
$$\psi(x,t) \propto \boxed{a_1}\psi_1(x)e^{\overbrace{-\frac{i}{\hbar}E_1 t}^{\text{Phase}\,\varphi_1}} + \boxed{a_2}\psi_2(x)e^{\overbrace{-\frac{i}{\hbar}E_2 t}^{\text{Phase}\,\varphi_2}}$$

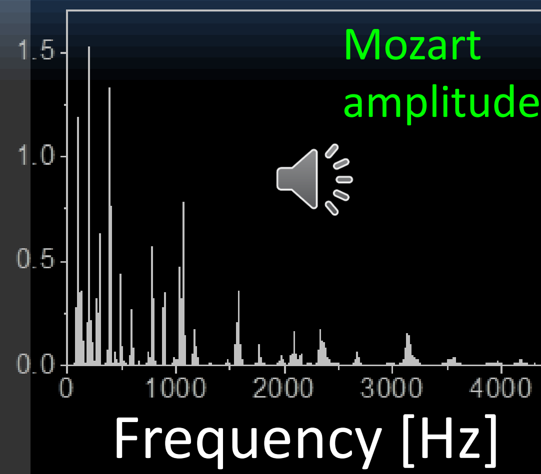
time-dependent absorption spectroscopy

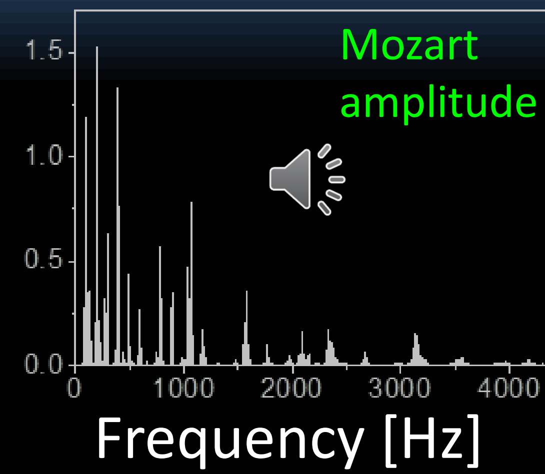


$$\boxed{\psi(x,t)} \propto a_1\psi_1(x)e^{-\frac{i}{\hbar}E_1 t} + a_2\psi_2(x)e^{-\frac{i}{\hbar}E_2 t}$$

Listening to phases



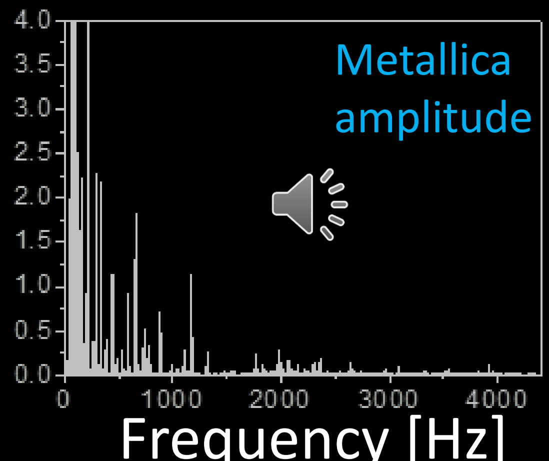


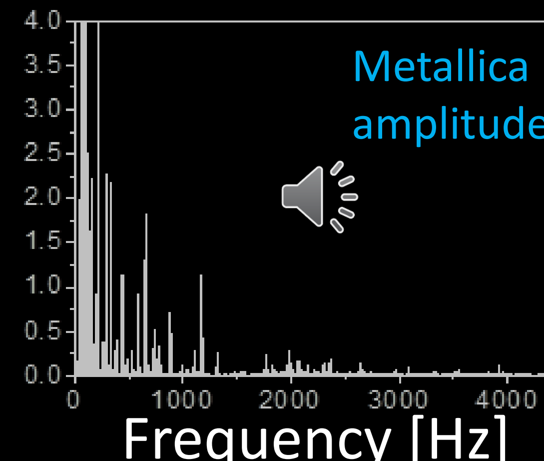


spectral phase by
by W. A. Mozart (1787)
(Eine kleine Nachtmusik)

spectral phase
by Chance
(randomized)

spectral phase
by Metallica (1992)
(Nothing else matters)





Properties of different light sources

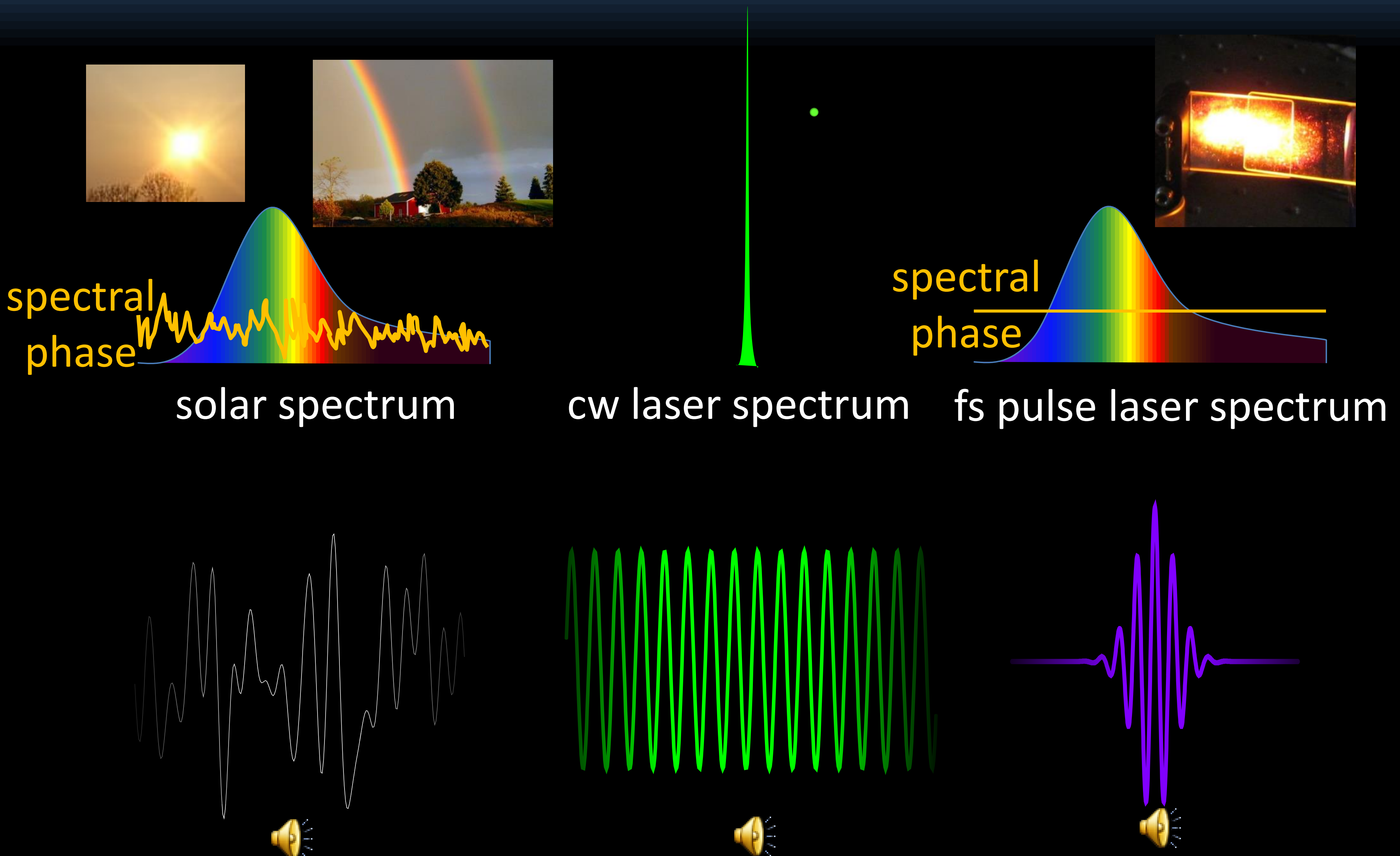
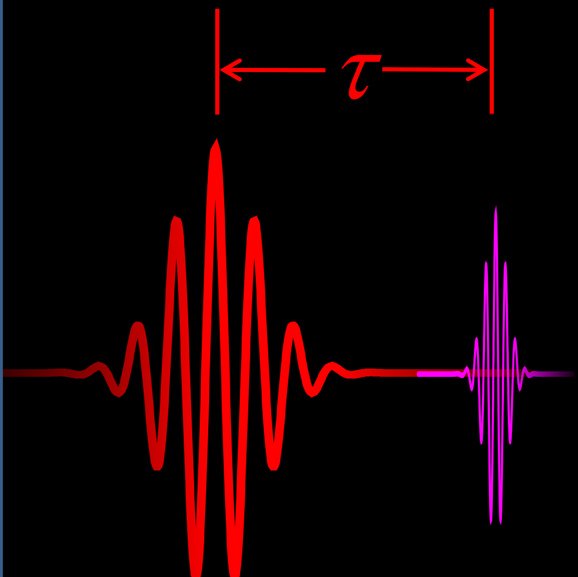


Bild-Quellen: http://www.bhakti-love.com/fotos/sonnenlicht.jpg,
http://climate.met.psu.edu/www_prod/data/frost/images/rainbow.jpg

time-dependent absorption spectroscopy

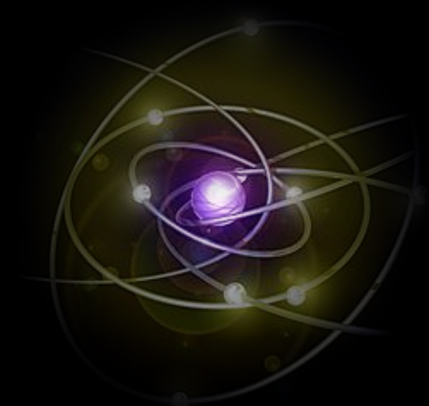
What's the dynamics of bound states and resonances in *short* and **strong** fields?

time delay

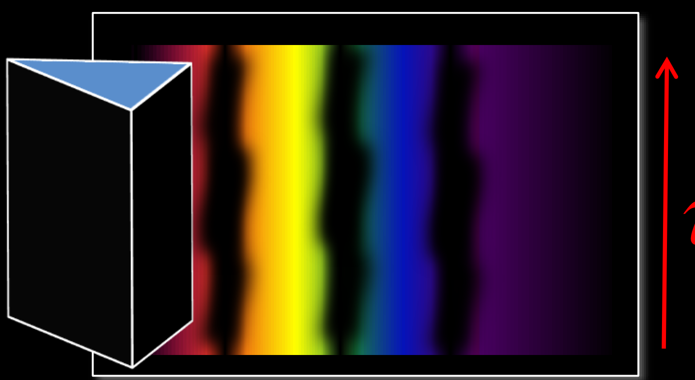


near-VIS femtosecond pulse

XUV attosecond pulse



Time-dependent absorption spectrum



XUV photon energy

Phase $\varphi 1$

Phase $\varphi 2$

$$\boxed{\psi(x,t)} \propto a_1\psi_1(x)e^{\boxed{-\frac{i}{\hbar}E_1 t}} + a_2\psi_2(x)e^{\boxed{-\frac{i}{\hbar}E_2 t}}$$

General: coupling of states

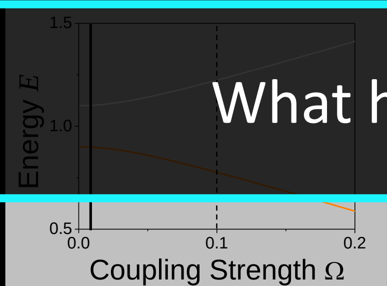
coupling of **one** to **one other** state

coupling of **one** to **multiple** states

coupling of **one** to a **continuum** of states

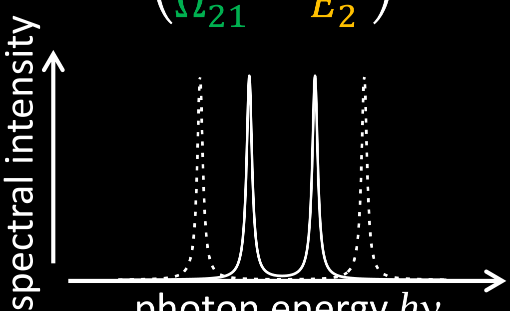
Quite well understood for cases of time-independent (or adiabatic) couplings

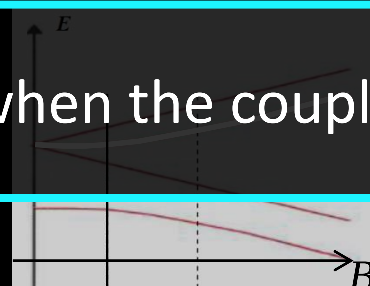
What happens when the coupling is **ultrashort** ?



Rabi oscillation
in strong coupling

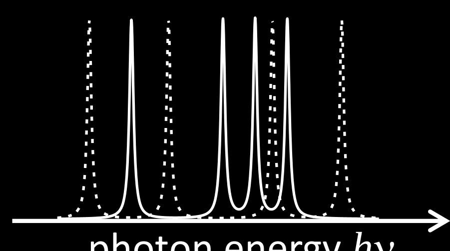
$$\begin{pmatrix} E_1 & \Omega_{12} \\ \Omega_{21} & E_2 \end{pmatrix}$$

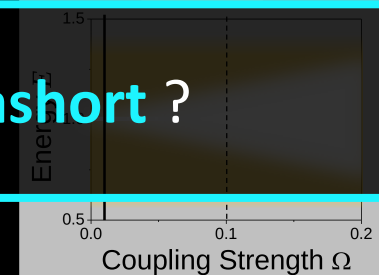




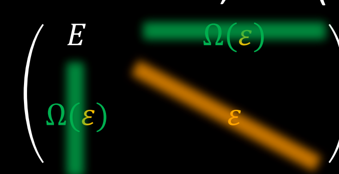
Breit-Rabi
e.g. Paschen-Back regime

$$\begin{pmatrix} E_1 & \Omega_{12} & \Omega_{13} & \Omega_{14} \\ \Omega_{21} & E_2 & \Omega_{23} & \Omega_{24} \\ \Omega_{31} & \Omega_{32} & E_3 & \Omega_{34} \\ \Omega_{41} & \Omega_{42} & \Omega_{43} & E_4 \end{pmatrix}$$

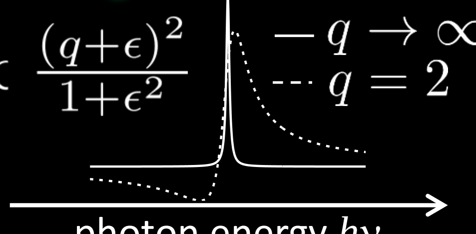




U. Fano (1935)
Phys. Rev. **124**, 1866 (1961)
Nuovo Cim. 12, 154 (1935)

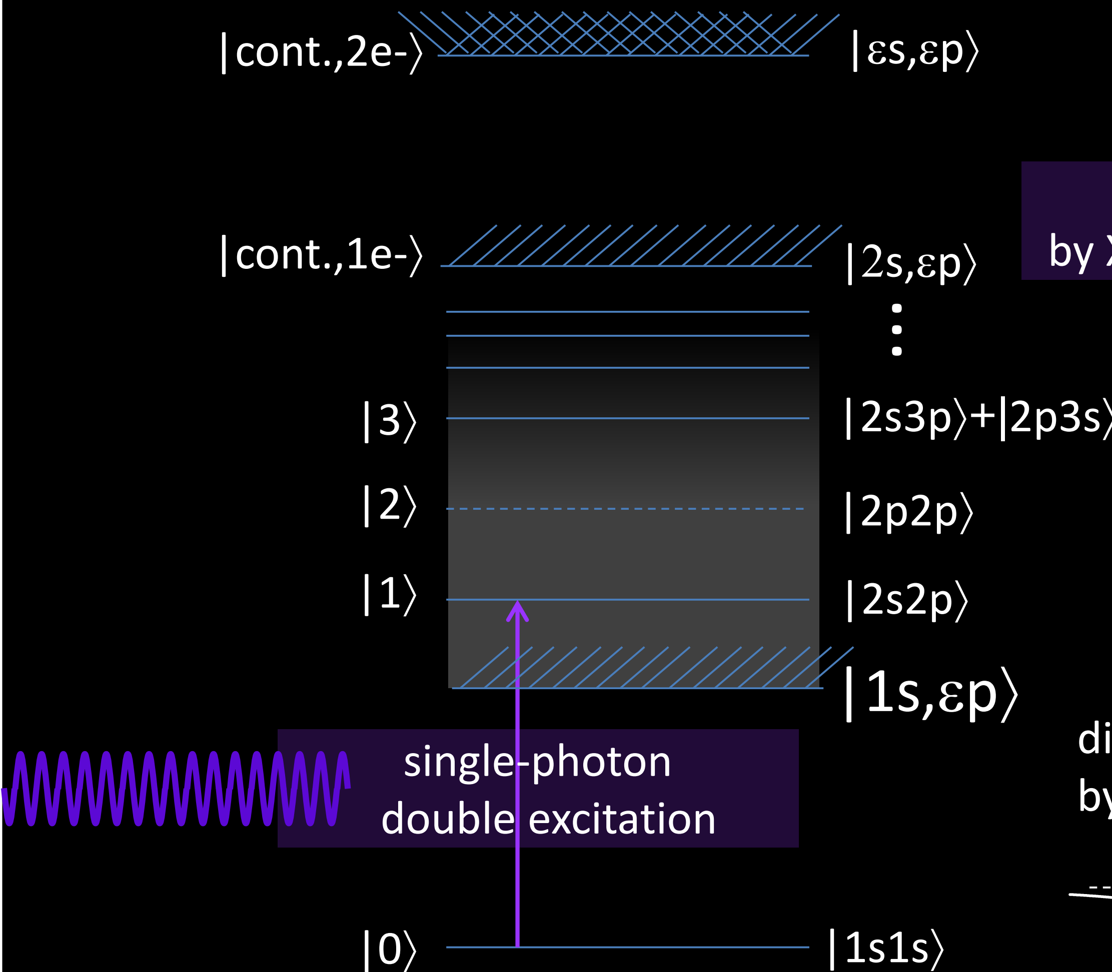


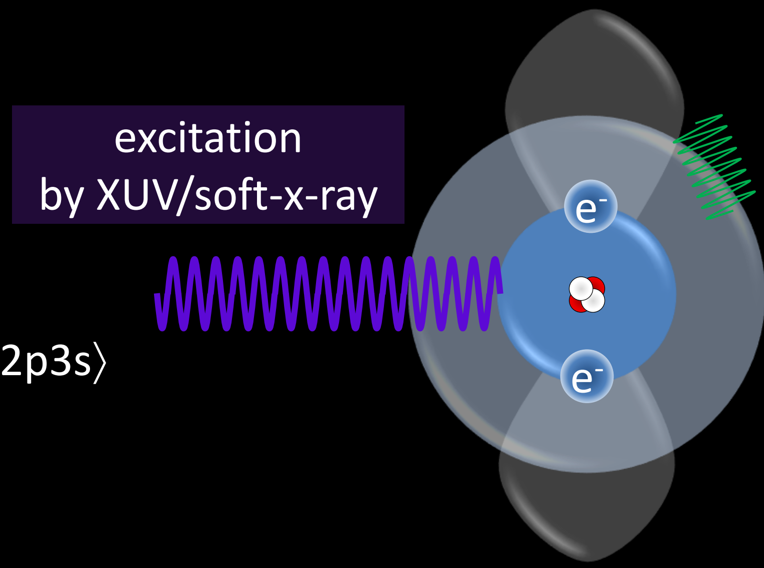
$$\sigma \propto \frac{(q+\epsilon)^2}{1+\epsilon^2}$$



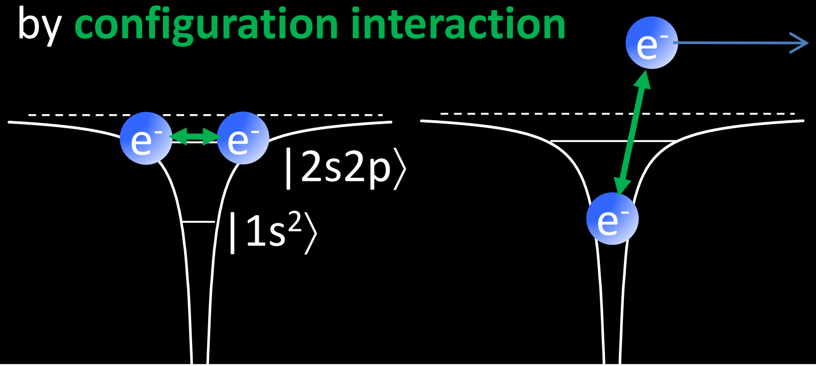
fundamental e^-–e^- correlation in atoms

prototypical target: He atom



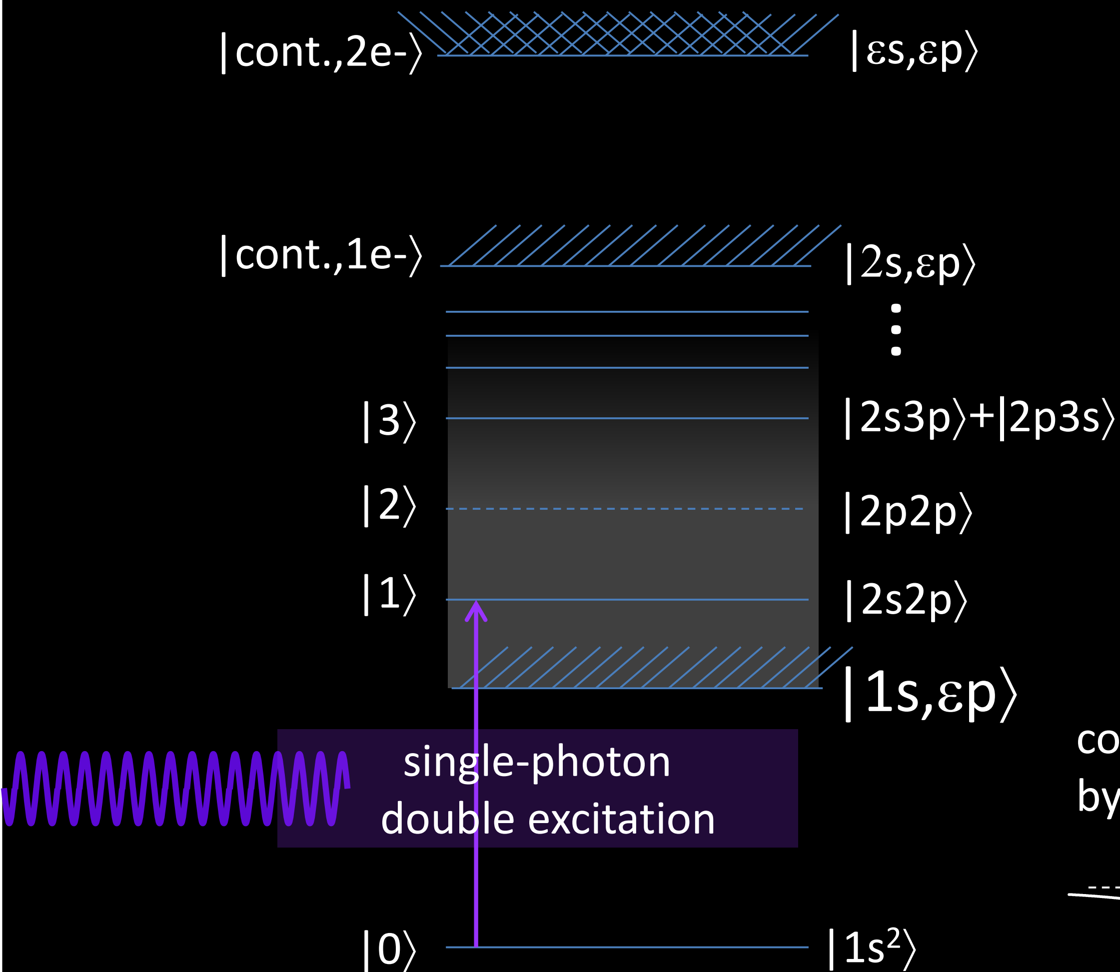


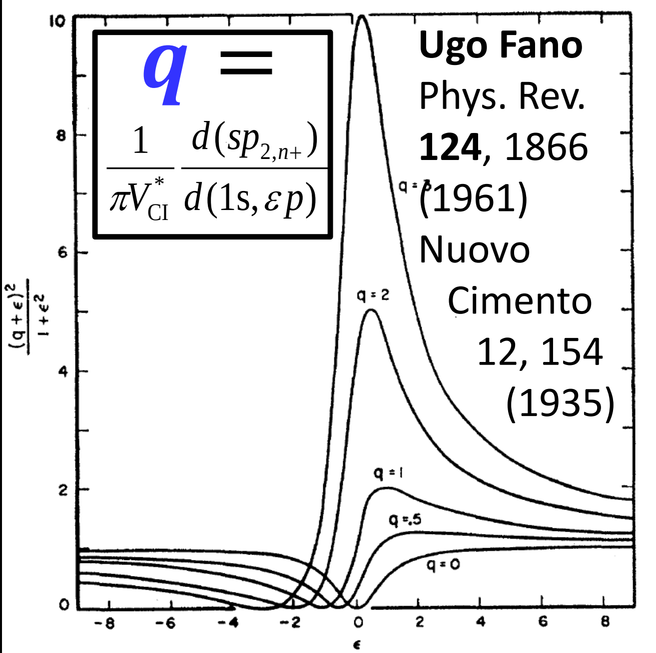
discrete states coupled to continuum
by **configuration interaction**



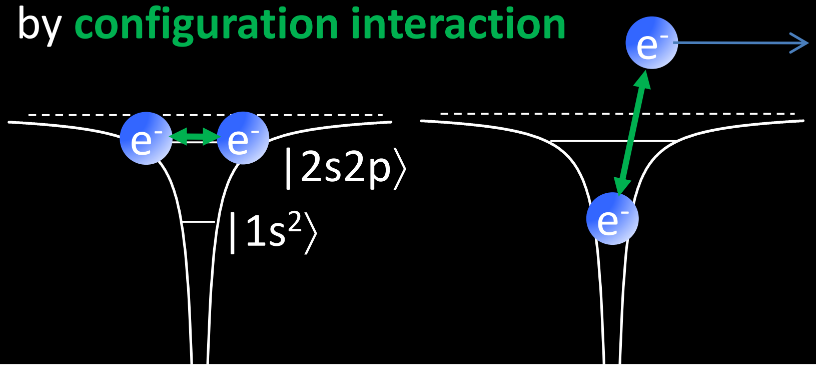
doubly excited helium: Fano resonance

$$\sigma_{Fano} \sim \frac{(q+\varepsilon)^2}{1+\varepsilon^2}$$



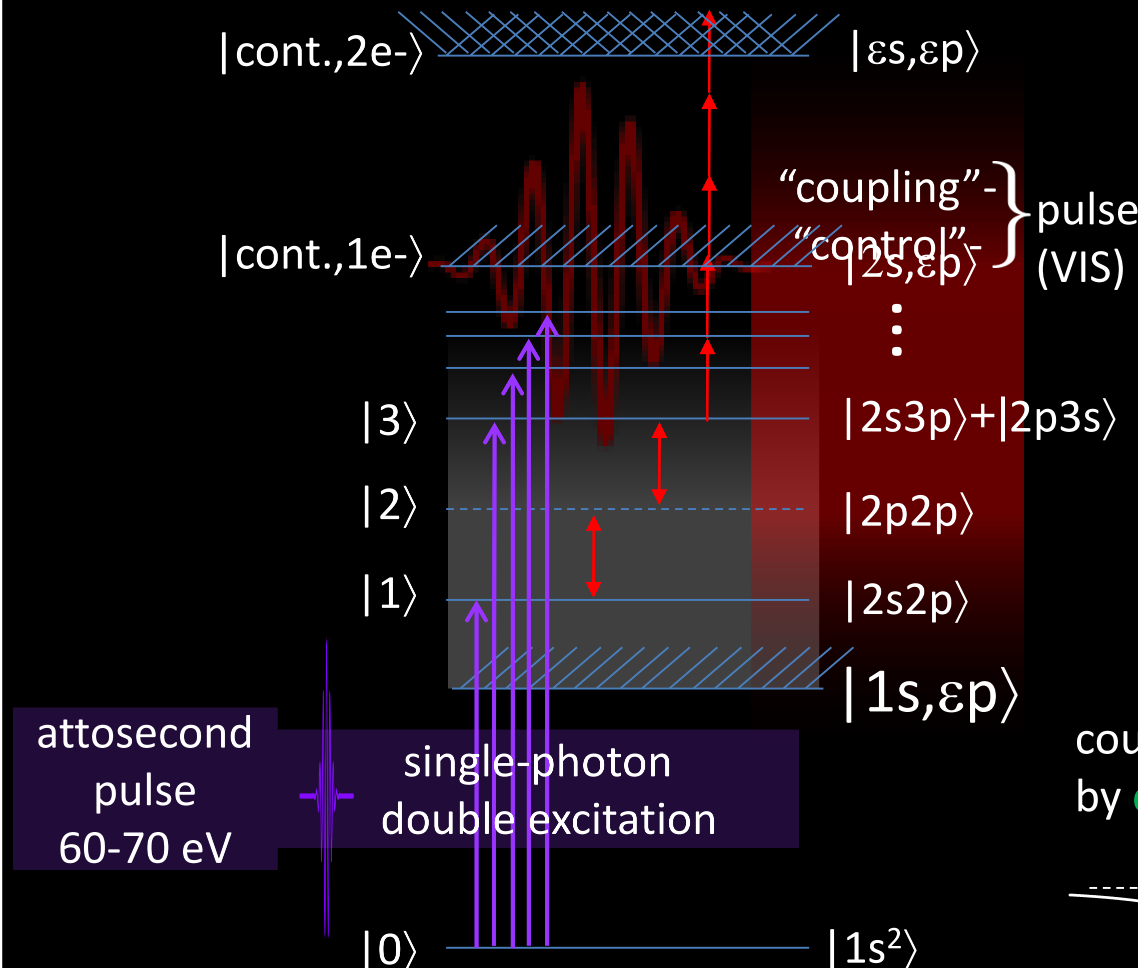


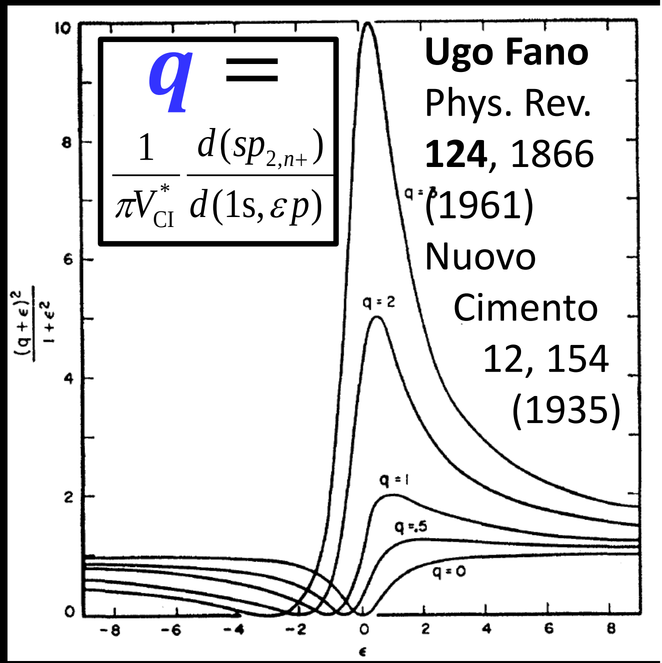
coupled
by **configuration interaction**



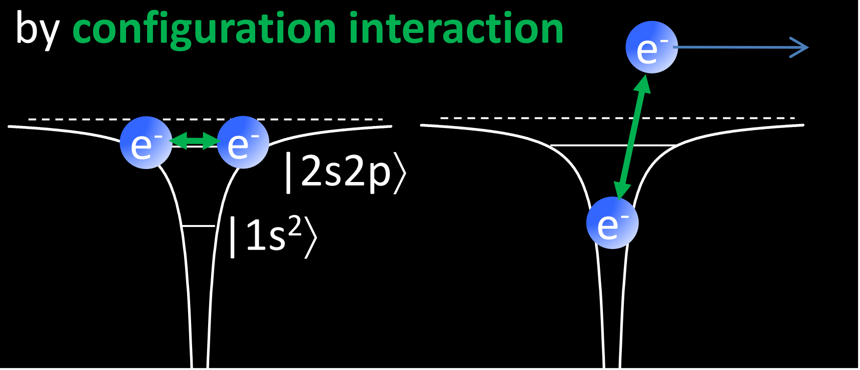
doubly-excited helium, in a strong laser field

$$\sigma_{Fano} \sim \frac{(q+\varepsilon)^2}{1+\varepsilon^2}$$

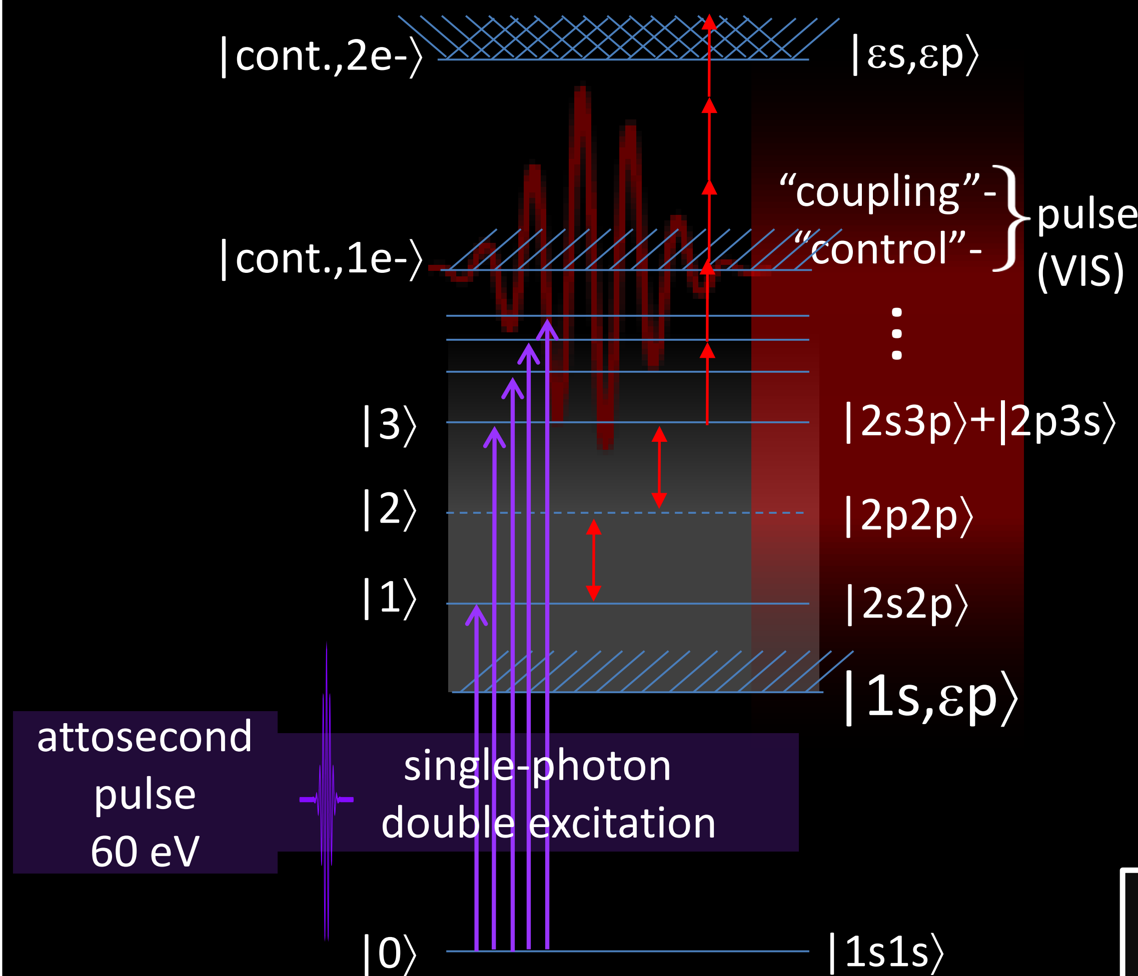




coupled
by **configuration interaction**



doubly-excited helium, in a strong laser field



<u>Previous work</u>
(on laser coupling of doubly-excited helium):

Theory:
e.g. Phys. Rev. A **24**, 379 (1981)
- Madsen, Themelis, **Lambropoulos**
- Zhao, Chu, **Lin** *et al.*

e.g. Phys. Rev. A 87, 013415 (2013)
...

Experiment:
Chem. Phys. **350,** 7 (2008)
- Loh, Greene, **Leone**, *et al.*
- Gilbertson, **Chang** *et al.*

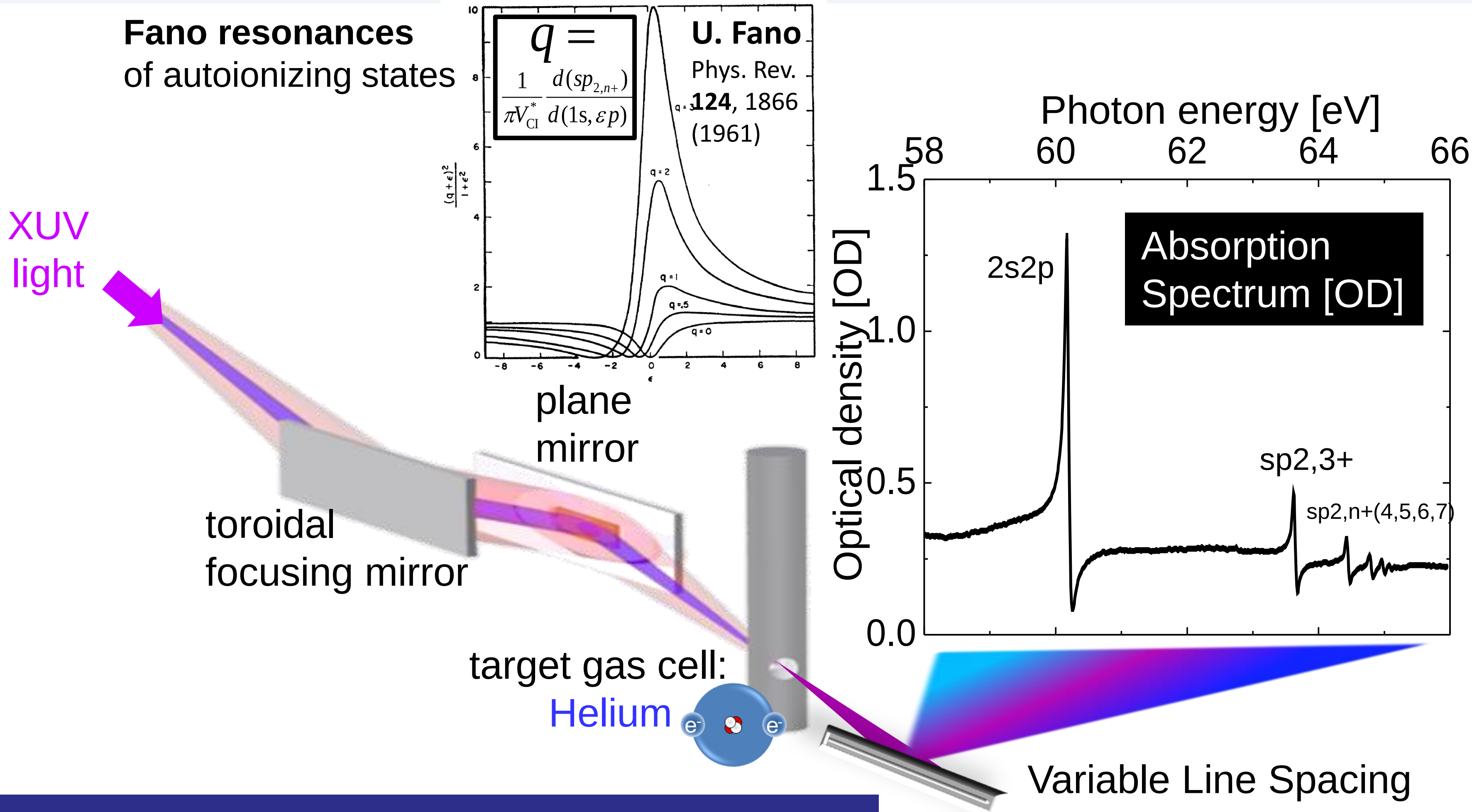
Phys. Rev. Lett. **105**, 263003 (2010
...

Experimental challenge:
- high (asec) temporal and
- high (meV) **spectral resolution**

required at the same time

Experimental setup

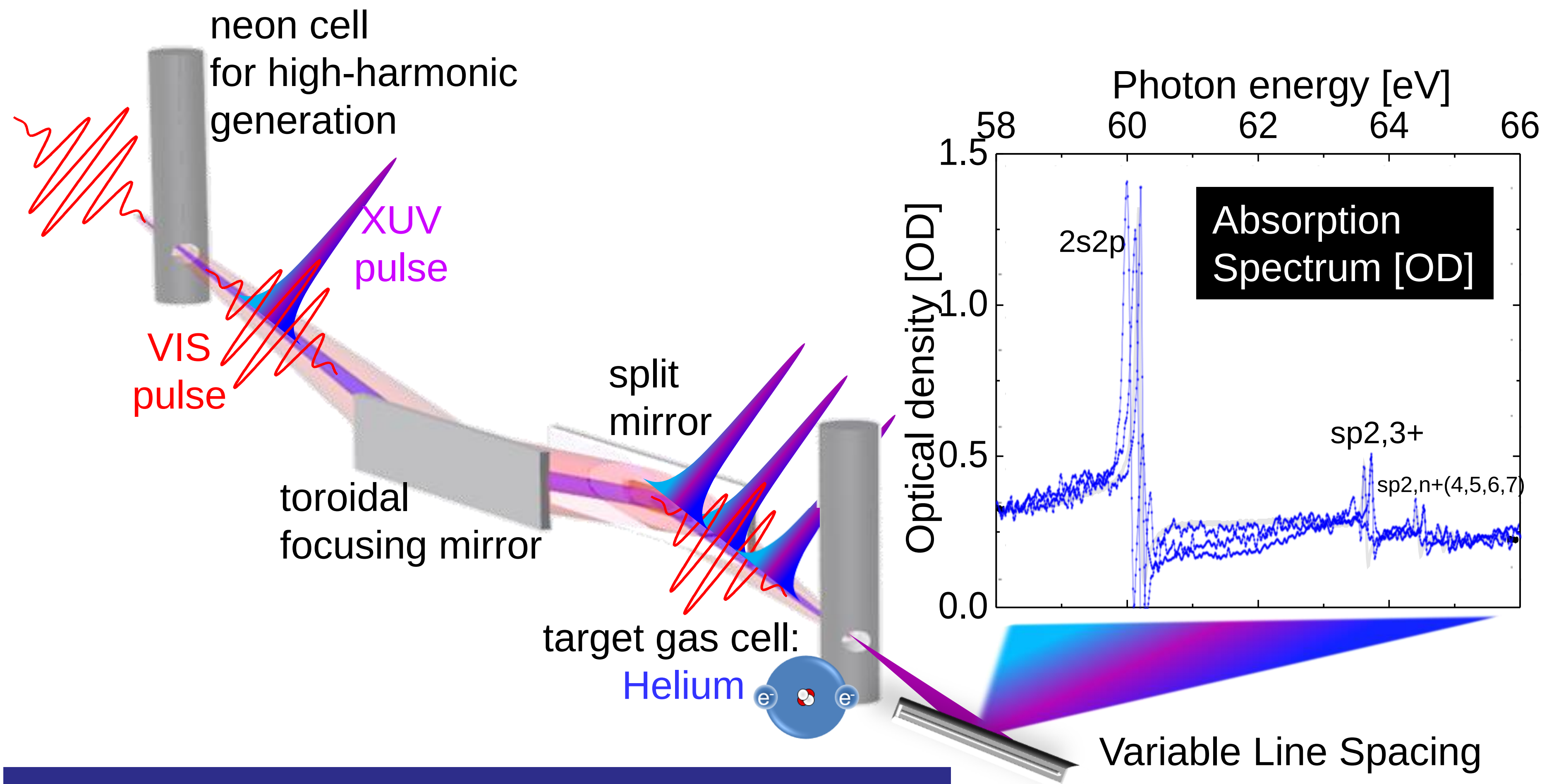
for XUV absorption spectroscopy



Experimental key challenge: **High resolution**
In photon energy ... : **ΔE = 20 meV (@60 eV)**

Experimental setup

for time-resolved XUV absorption spectroscopy

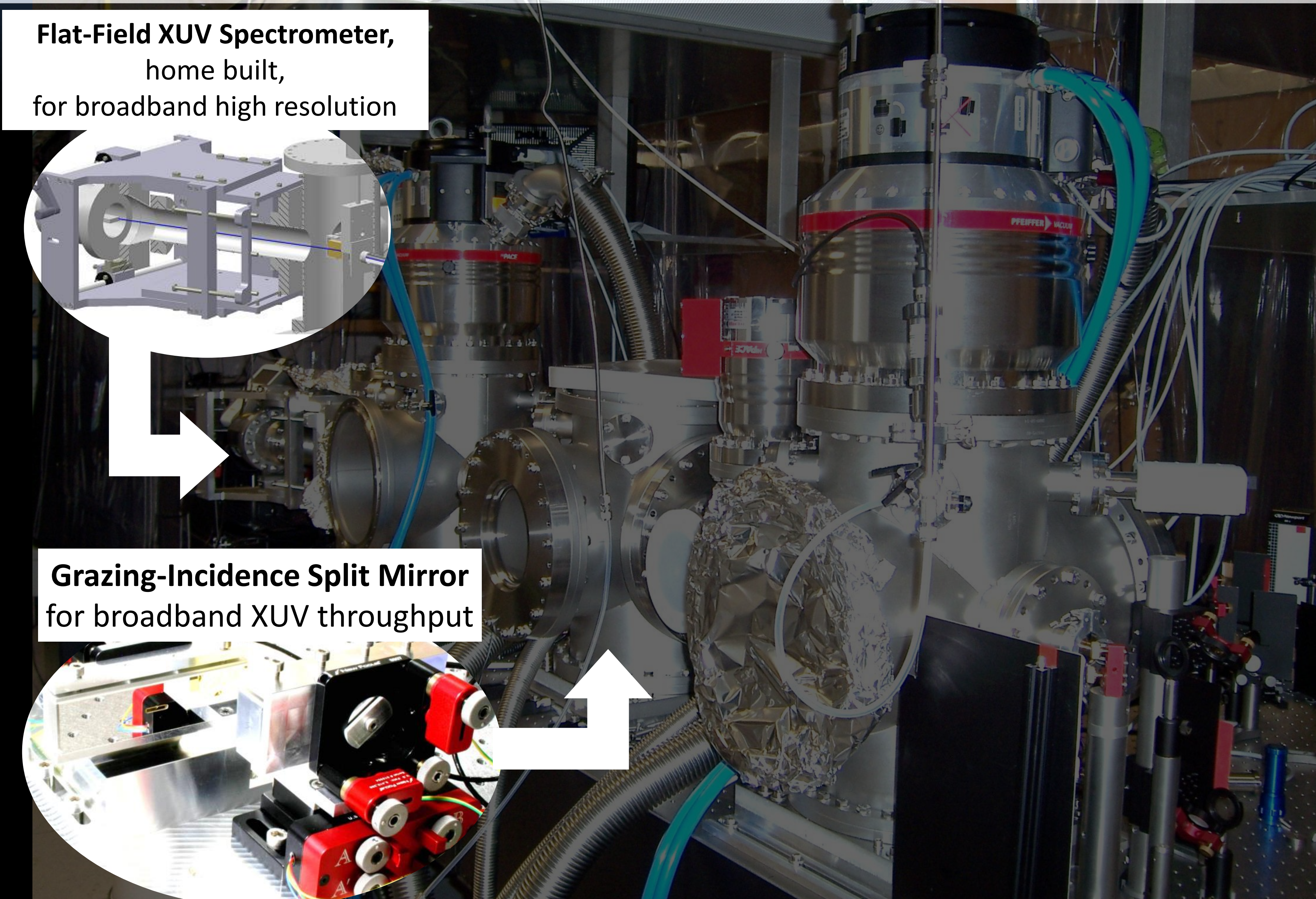


Experimental key challenge: **High resolution**

In photon energy ... : **ΔE = 20 meV (@60 eV)**

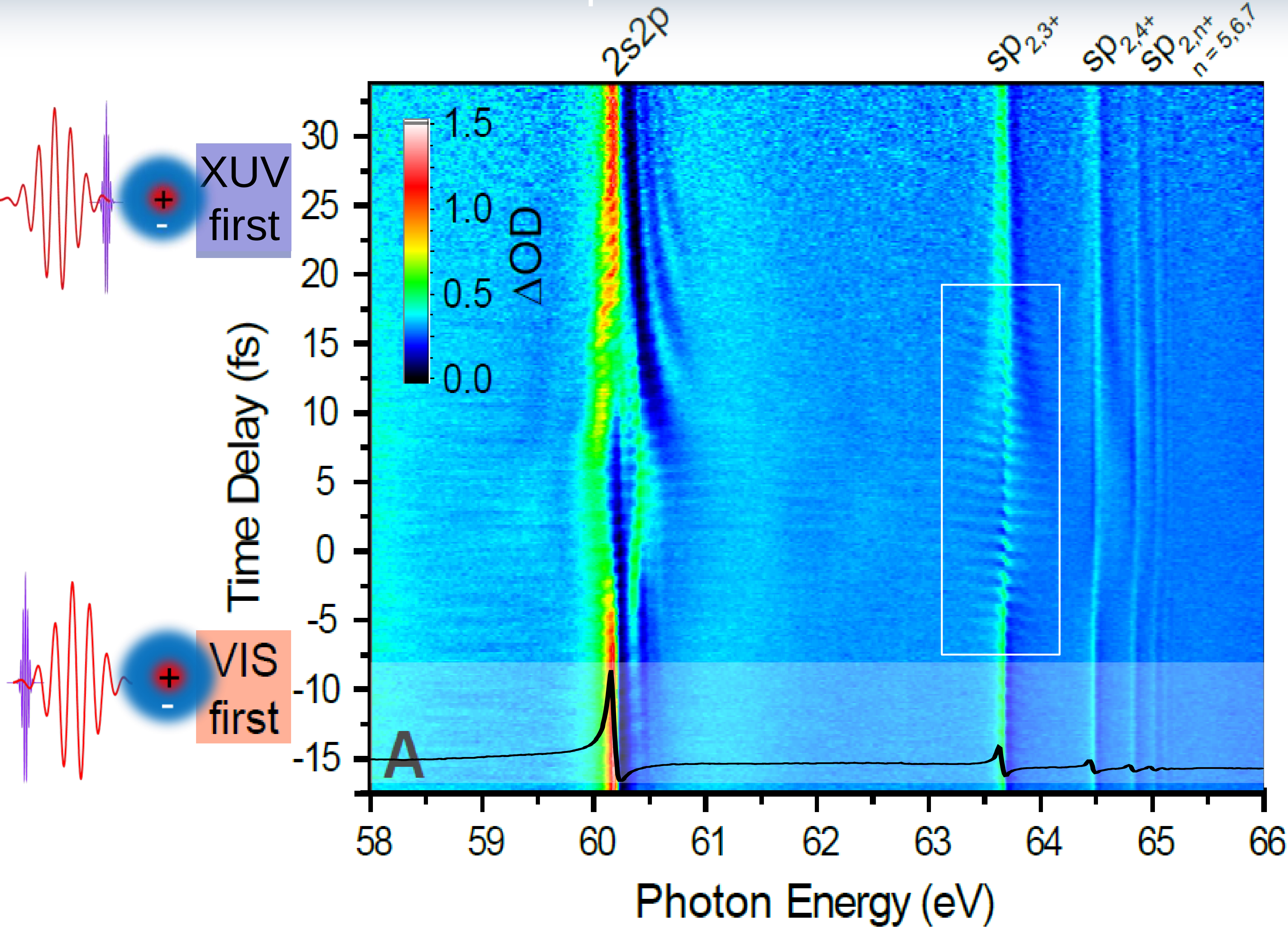
... and time delay : **Δτ = 10 as**

Experimental Setup in the Lab

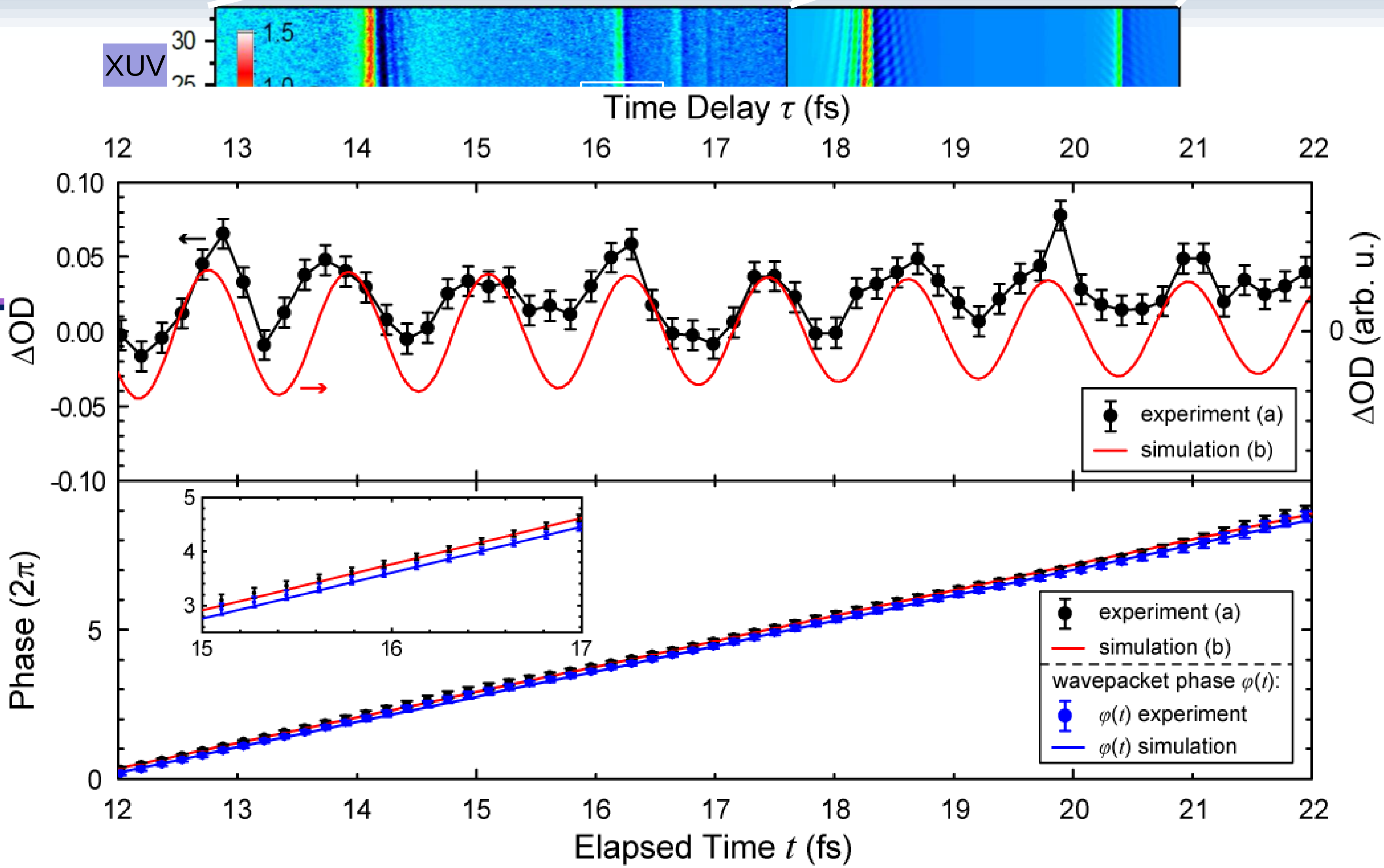


Time-resolved doubly-excited 2e⁻ dynamics in He

Experimental data



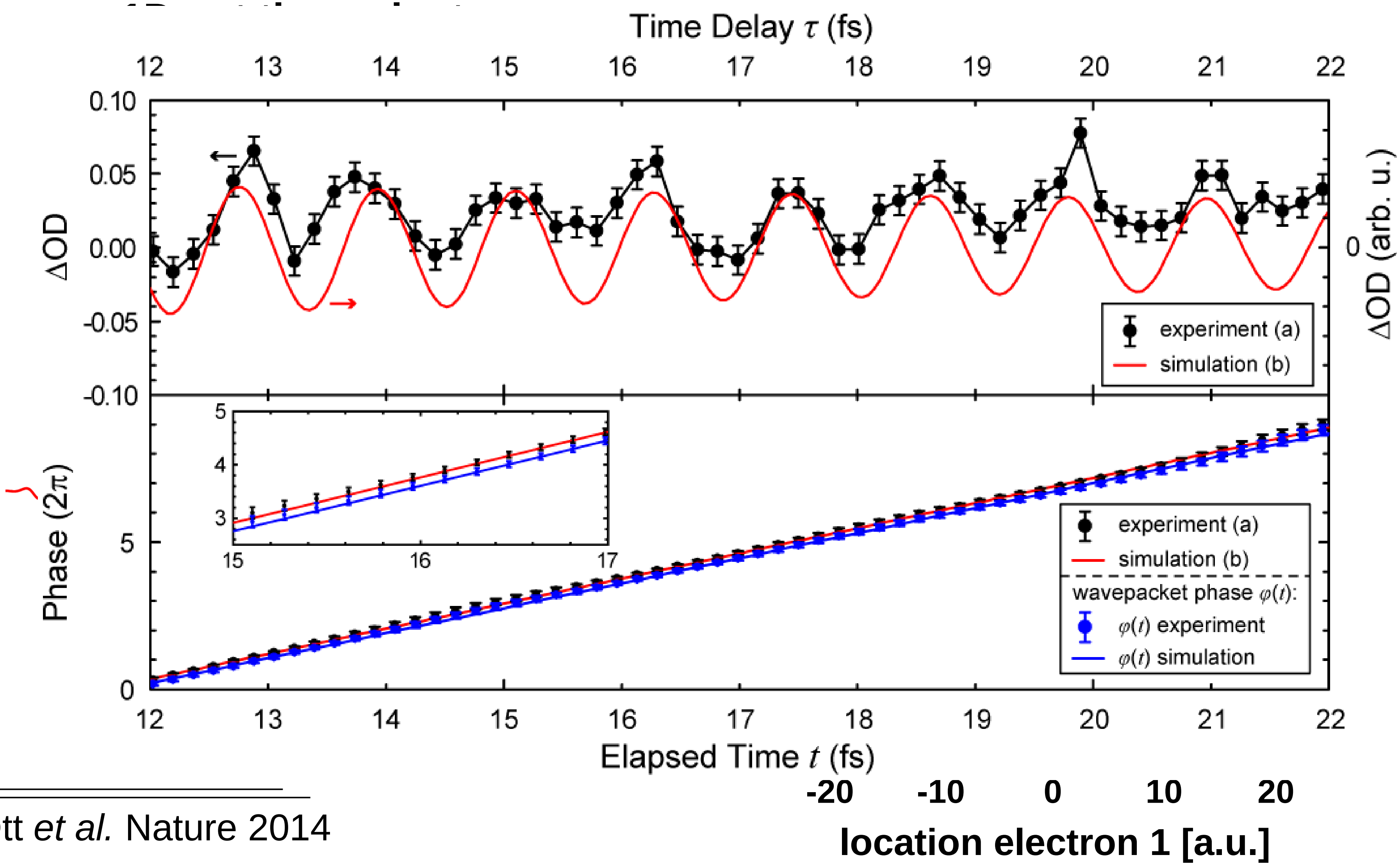
comparison experiment and theory



⇒ Wavepacket

Measuring the time-dependent phase difference of 2s2p and sp_{23+} autoionization states

cooperation with Javier Madroñero (Theory, TU München)

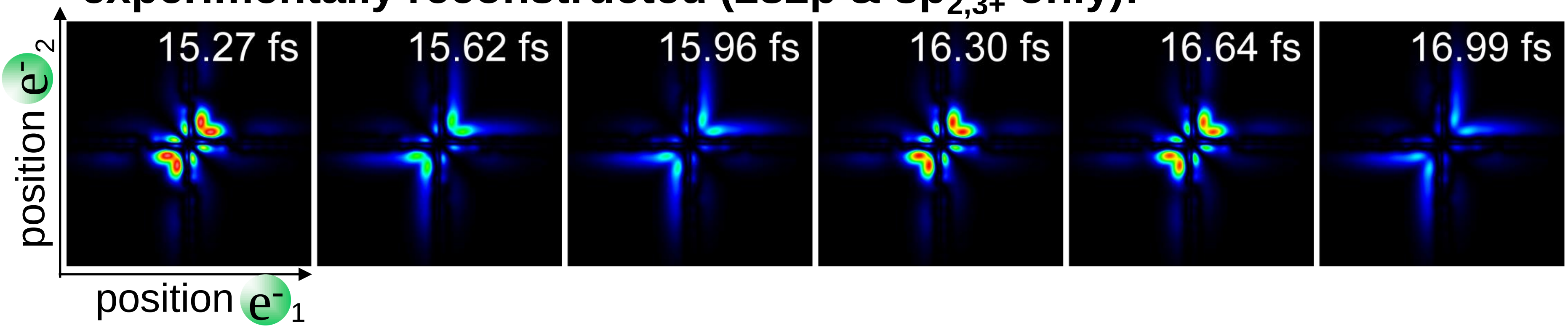


Ott *et al.* Nature 2014

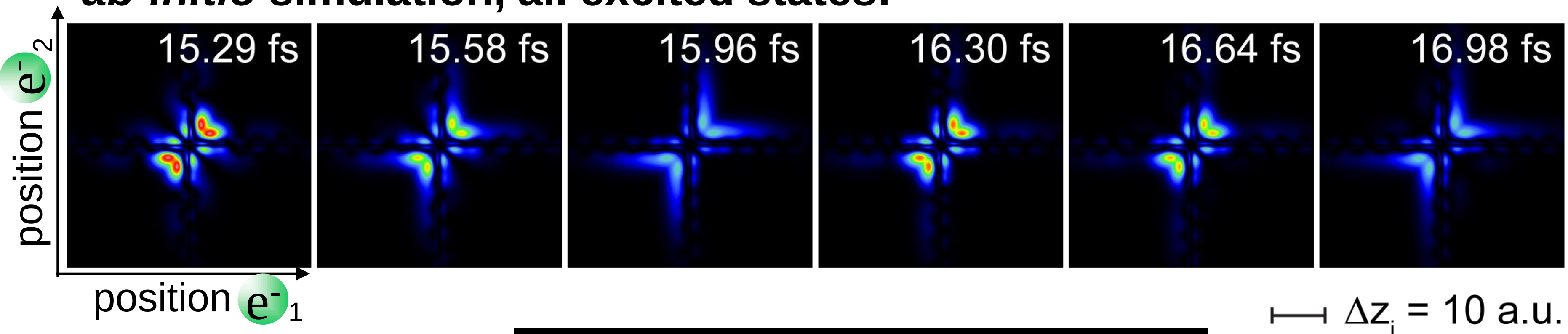
Testing *ab-initio* theory of e^- correlation dynamics

cooperation: Luca Argenti & Fernando Martín (UAM Madrid, Spain)
Javier Madroñero (TU Munich)

experimentally reconstructed (2s2p & $sp_{2,3+}$ only):



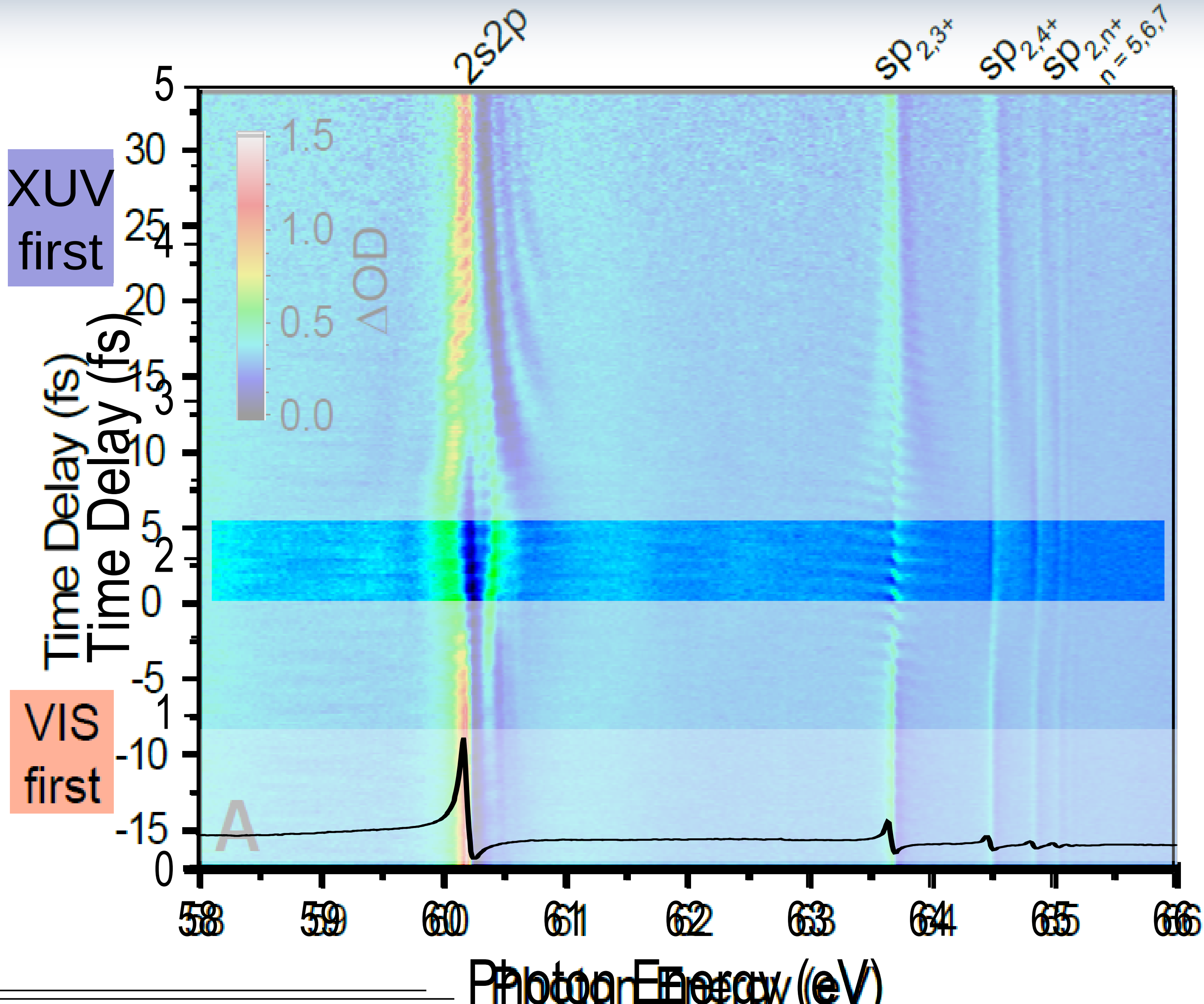
***ab-initio* simulation, all excited states:**



first experimental observation
of **two-electron wavepacket** motion

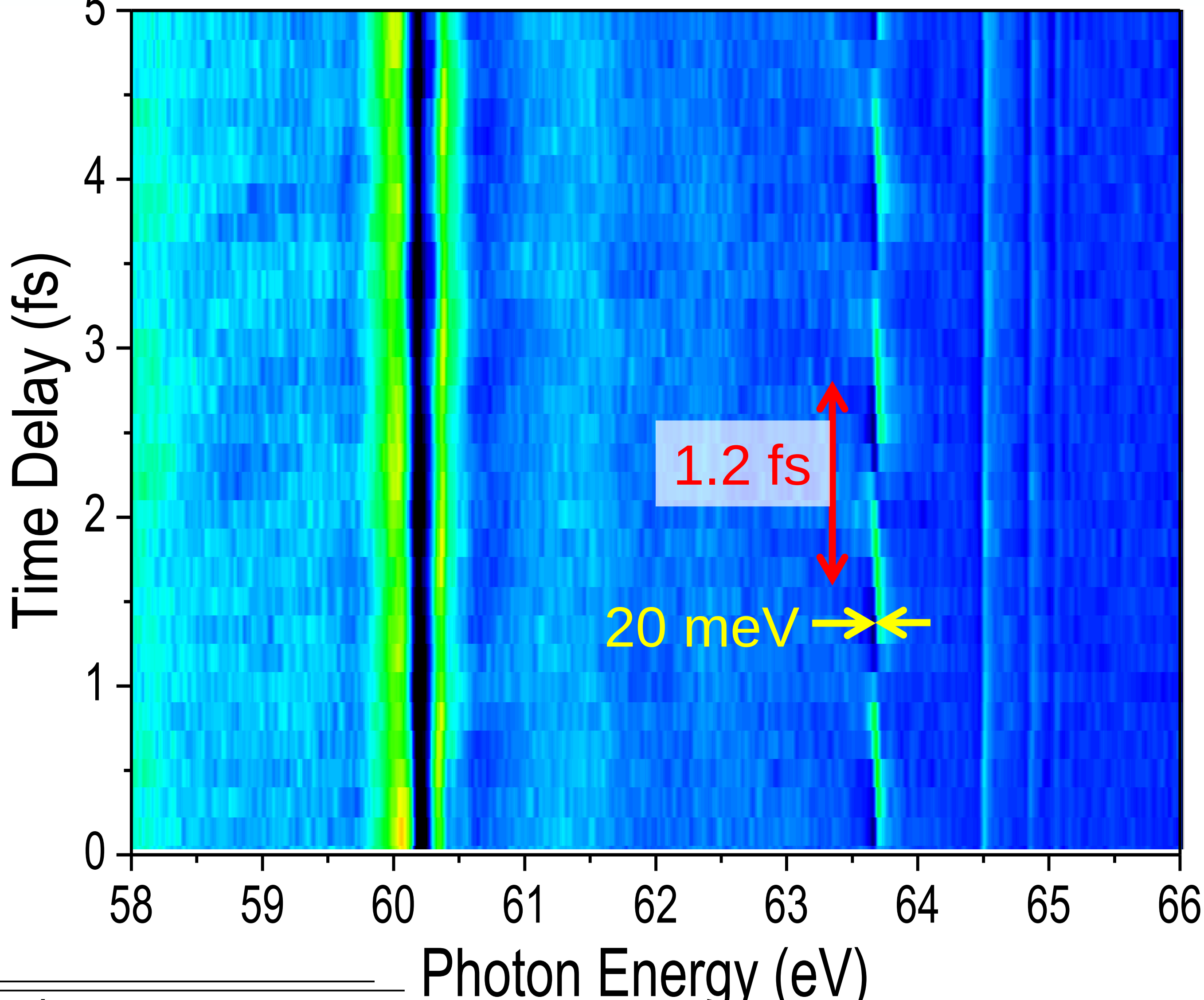
Ott *et al.*
Nature 2014

Time-resolved doubly-excited 2e⁻ dynamics in He



Ott *et al.* Nature 2014

Time-resolved doubly-excited 2e$^-$ dynamics in He



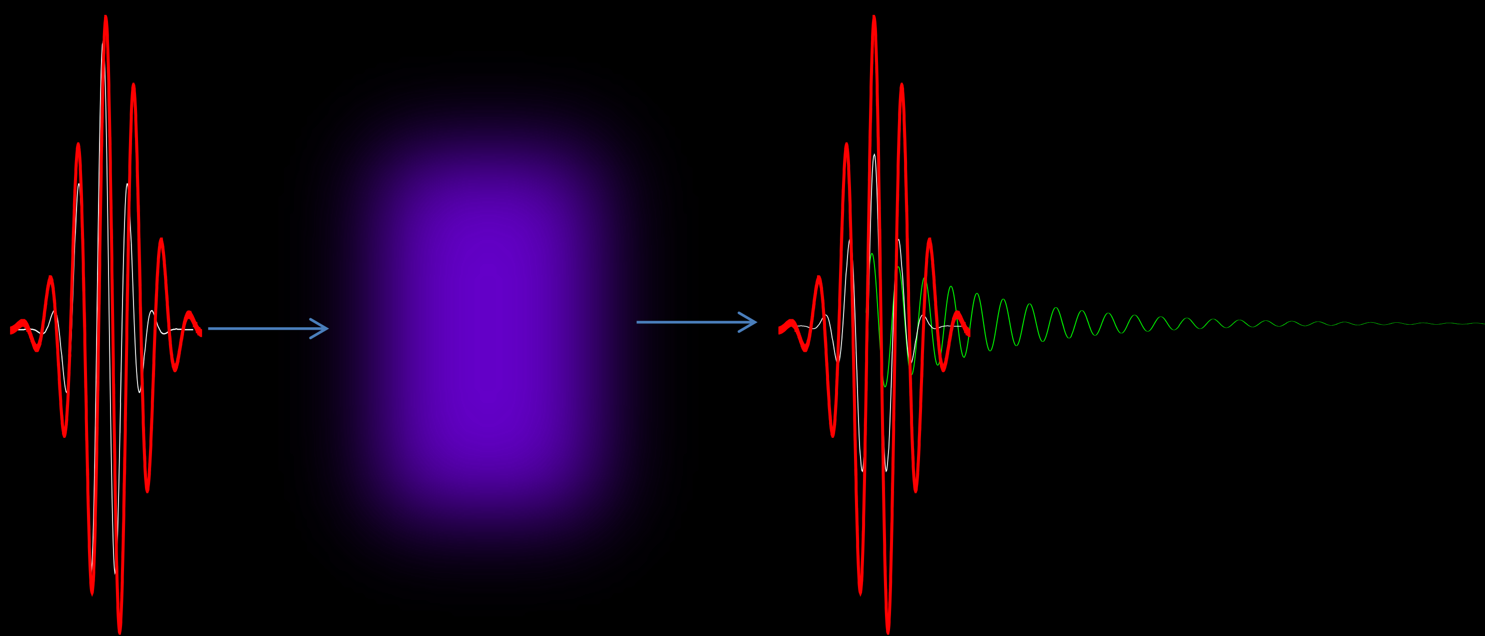
high temporal and high spectral resolution are required simultaneously

Ott *et al.* Nature 2014

Hold on, can I ask you a few questions?

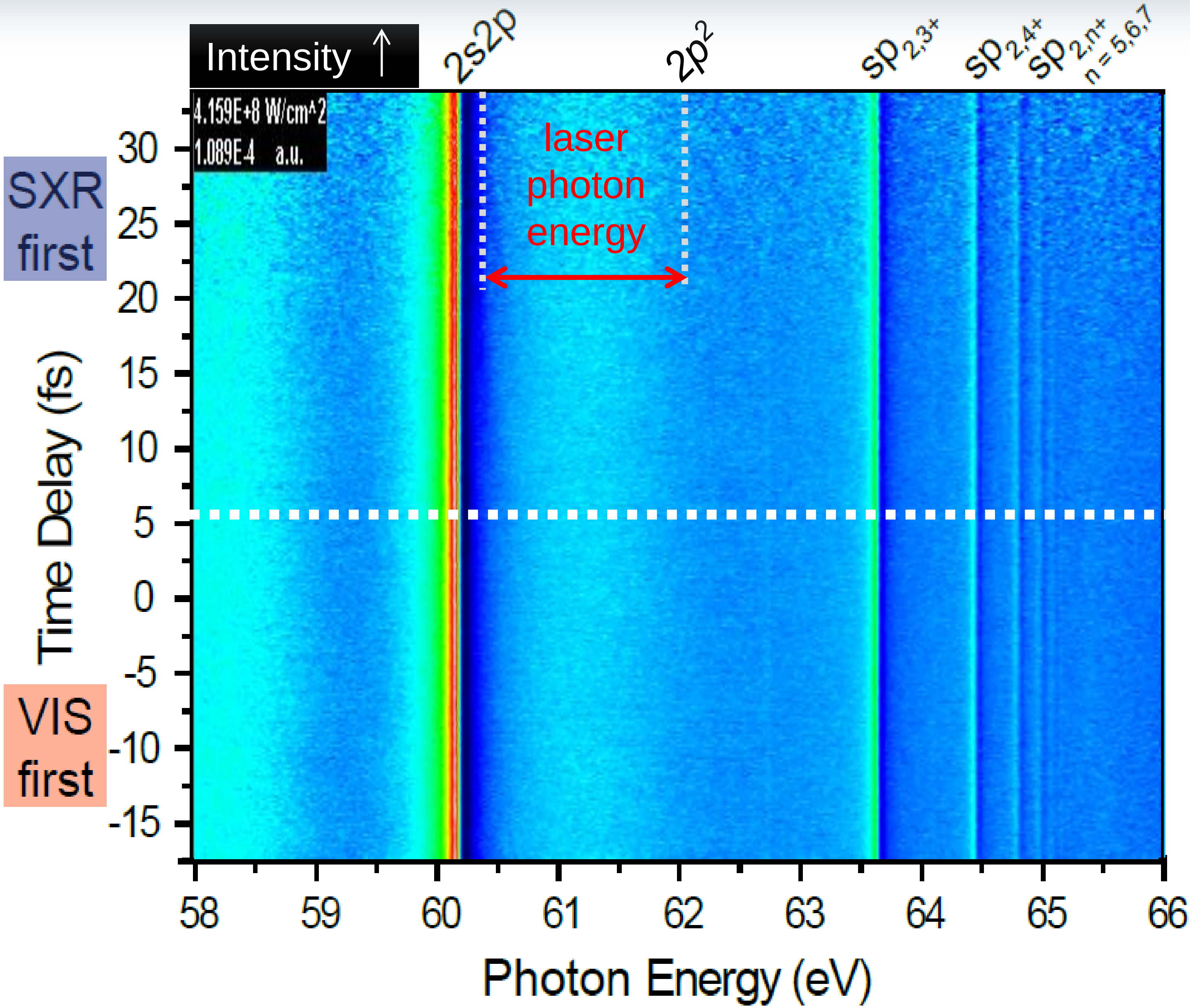
What is absorption?

And how does it respond to intense pulsed light?



Control the electrons, and measure their response

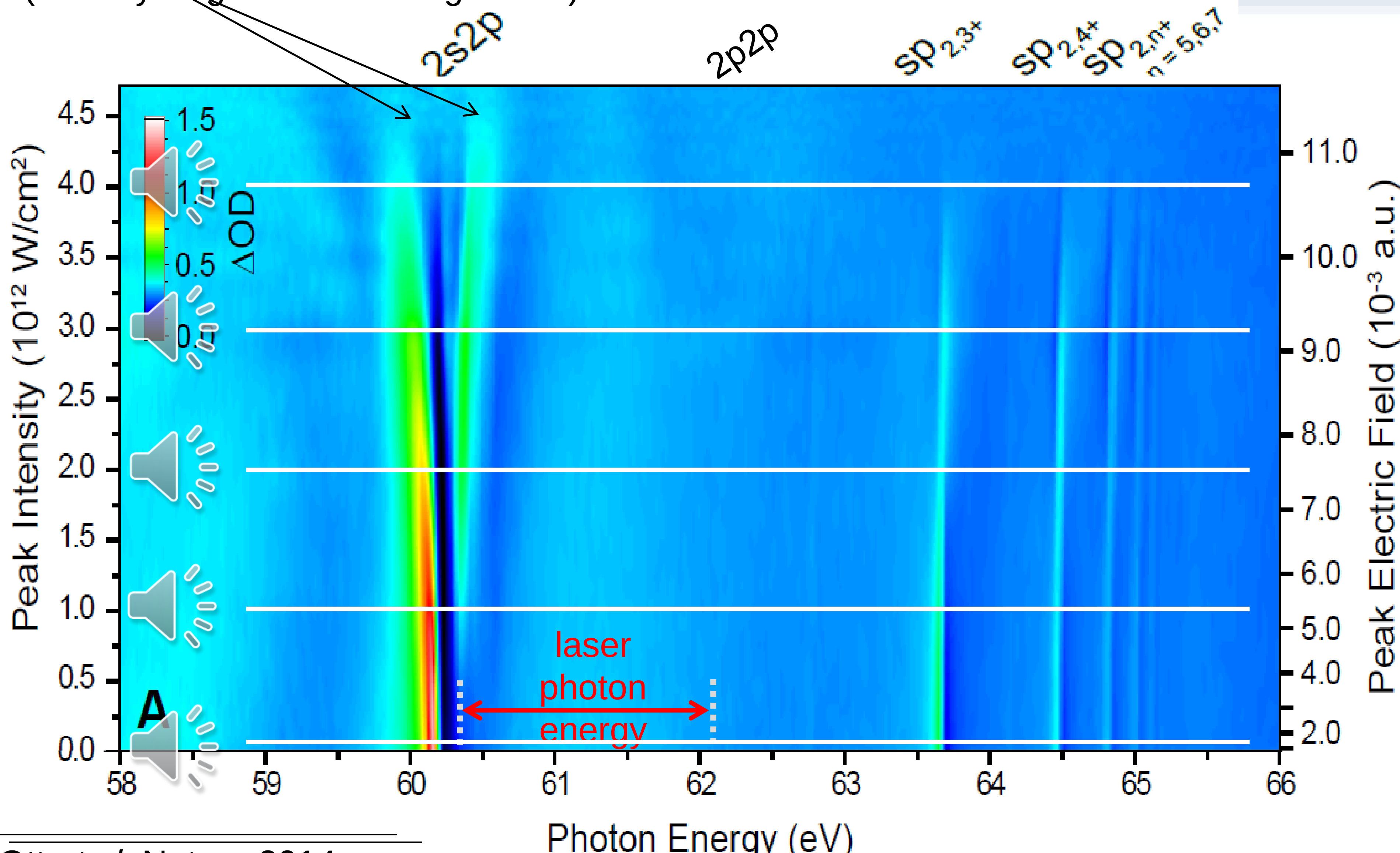
"Ask" "listen"



Intensity, the control knob

Autler-Townes doublet
(Rabi cycling of autoionizing states)

tuning from weak perturbative to strong fields



Ott *et al.* Nature 2014

Intensity, the control knob

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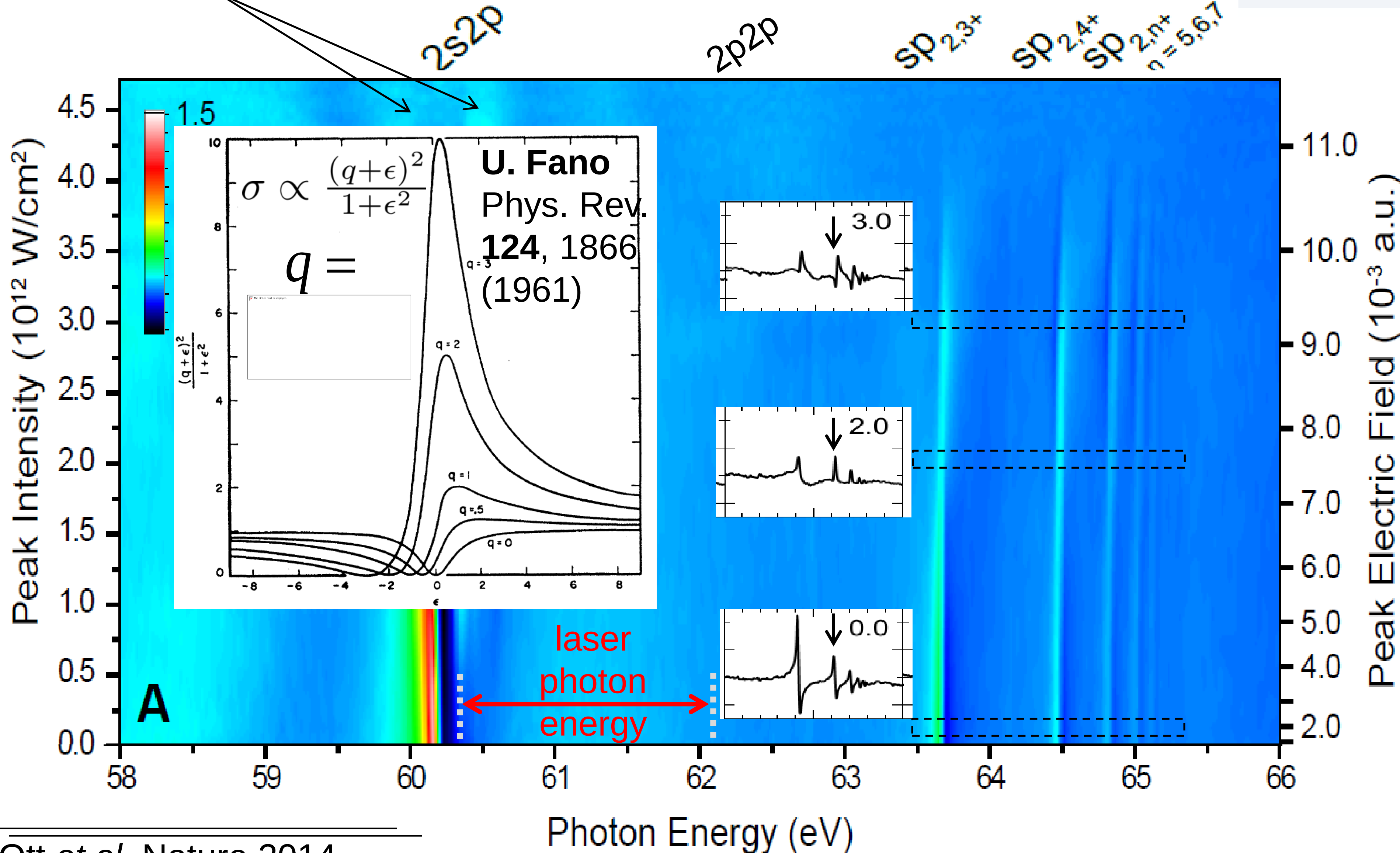


Ott *et al.* Nature 2014

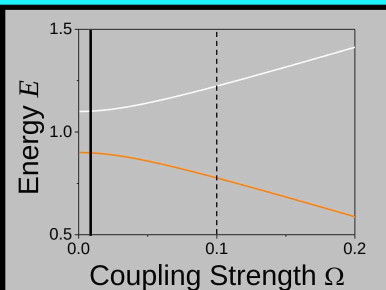
General: coupling of states

coupling of **one** to **one other** state

coupling of **one** to **multiple** states

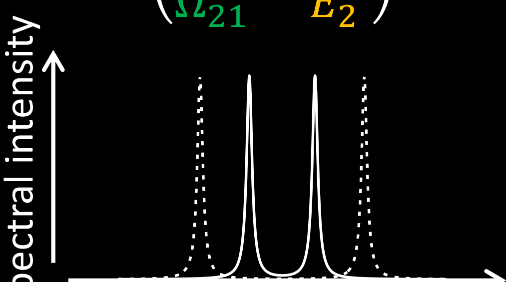
coupling of **one** to a **continuum** of states

What happens when the coupling is **ultrashort** ?

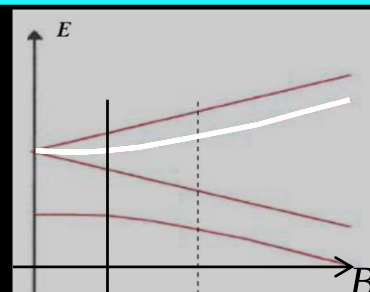


Rabi oscillation
in strong coupling

$$\begin{pmatrix} E_1 & \Omega_{12} \\ \Omega_{21} & E_2 \end{pmatrix}$$

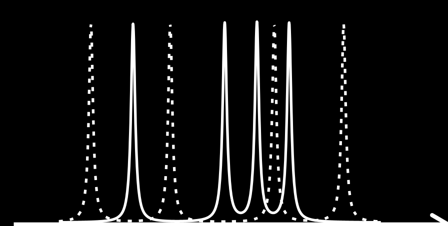


photon energy $h\nu$

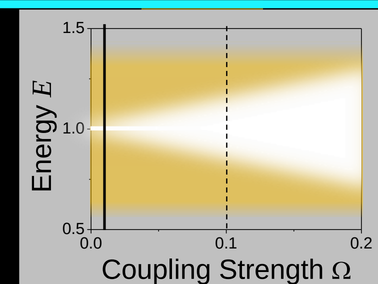


Breit-Rabi
e.g. Paschen-Back regime

$$\begin{pmatrix} E_1 & \Omega_{12} & \Omega_{13} & \Omega_{14} \\ \Omega_{21} & E_2 & \Omega_{23} & \Omega_{24} \\ \Omega_{31} & \Omega_{32} & E_3 & \Omega_{34} \\ \Omega_{41} & \Omega_{42} & \Omega_{43} & E_4 \end{pmatrix}$$



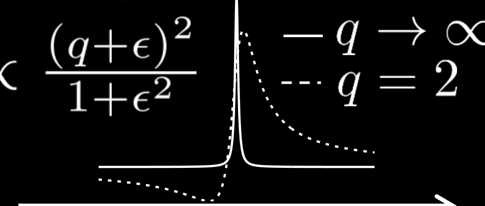
photon energy $h\nu$



U. Fano (1935)
Phys. Rev. **124**, 1866 (1961)
Nuovo Cim. 12, 154 (1935)

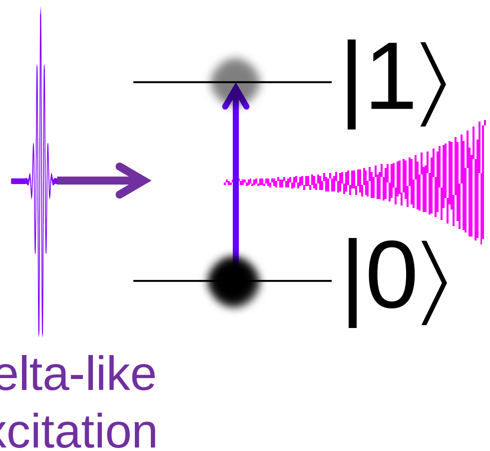
$$\begin{pmatrix} E & \Omega(\varepsilon) \\ \Omega(\varepsilon) & \varepsilon \end{pmatrix}$$

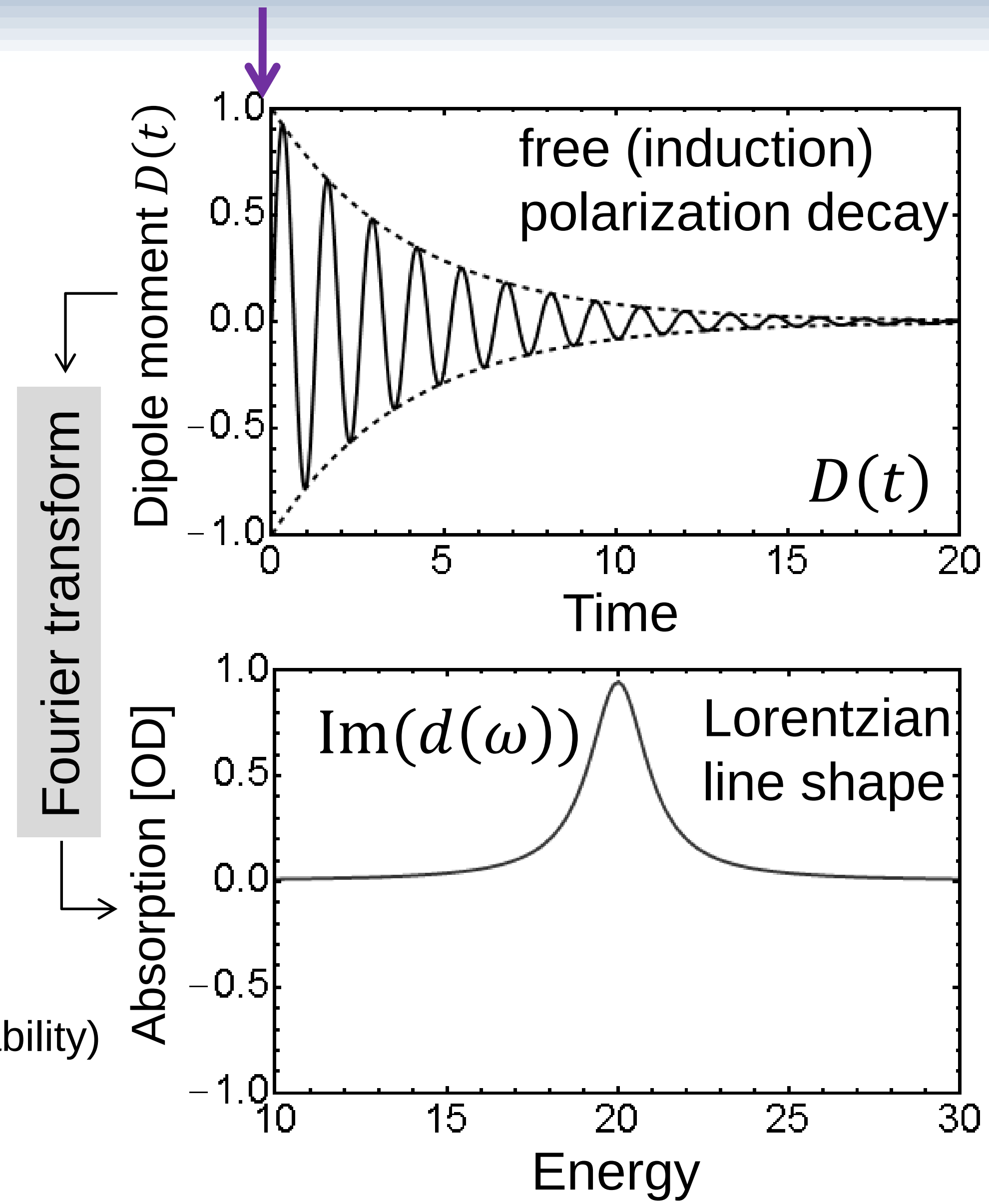
$$\sigma \propto \frac{(q+\epsilon)^2}{1+\epsilon^2}$$



photon energy $h\nu$

Resonance absorption in the Time Domain





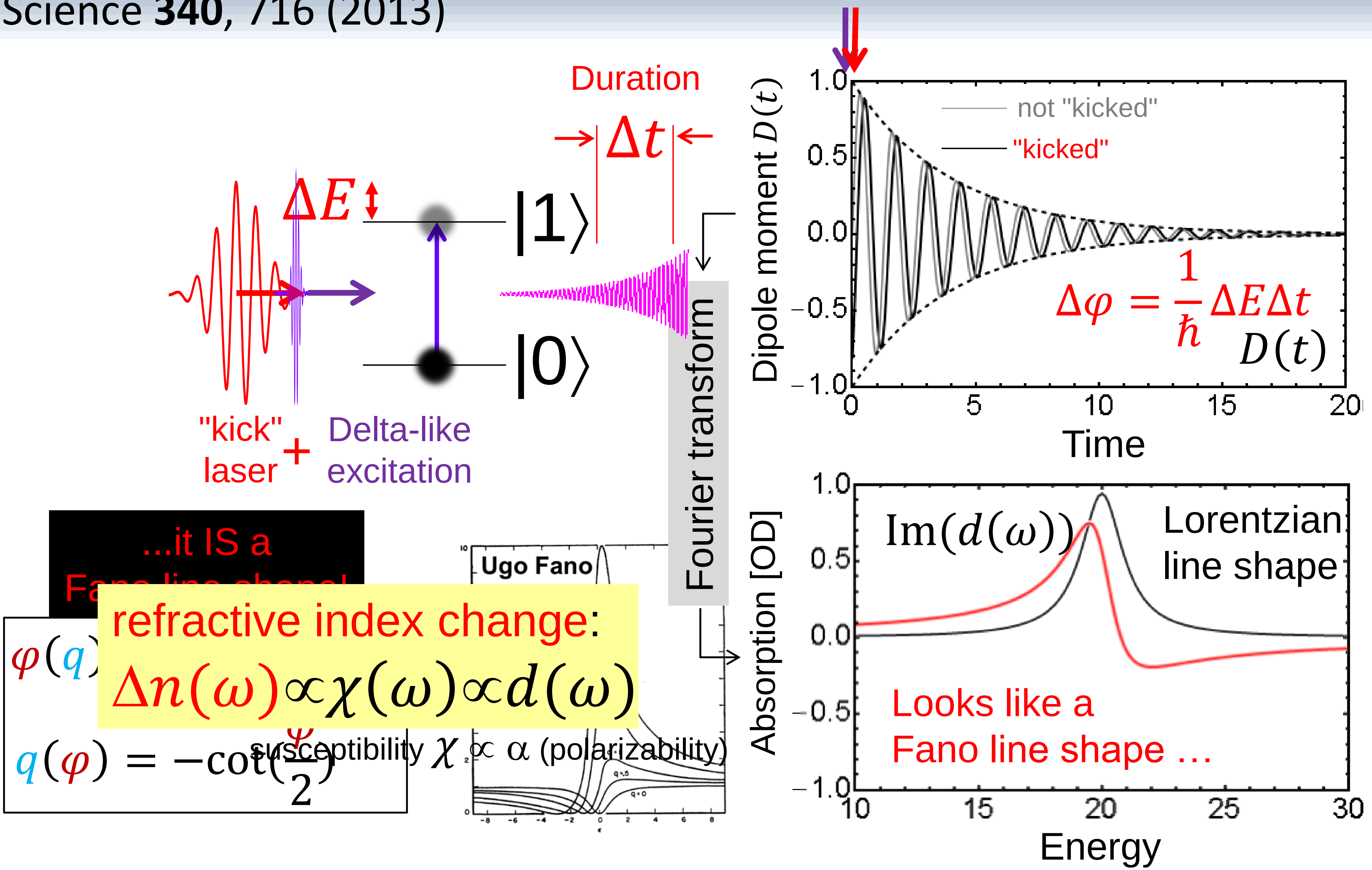
refractive index change:

$$\Delta n(\omega) \propto \chi(\omega) \propto d(\omega)$$

susceptibility $\chi \propto \alpha$ (polarizability)

Resonance absorption in the Time Domain

Science **340**, 716 (2013)



The Fano dipole phase

Exact mapping from Fano q parameter to temporal phase shift φ

cooperation with C. Greene (Purdue), J. Evers and C. Keitel (MPIK)

$$\sigma_{Fano} \sim \frac{(\varepsilon + q)^2}{\varepsilon^2 + 1}$$

$$=$$

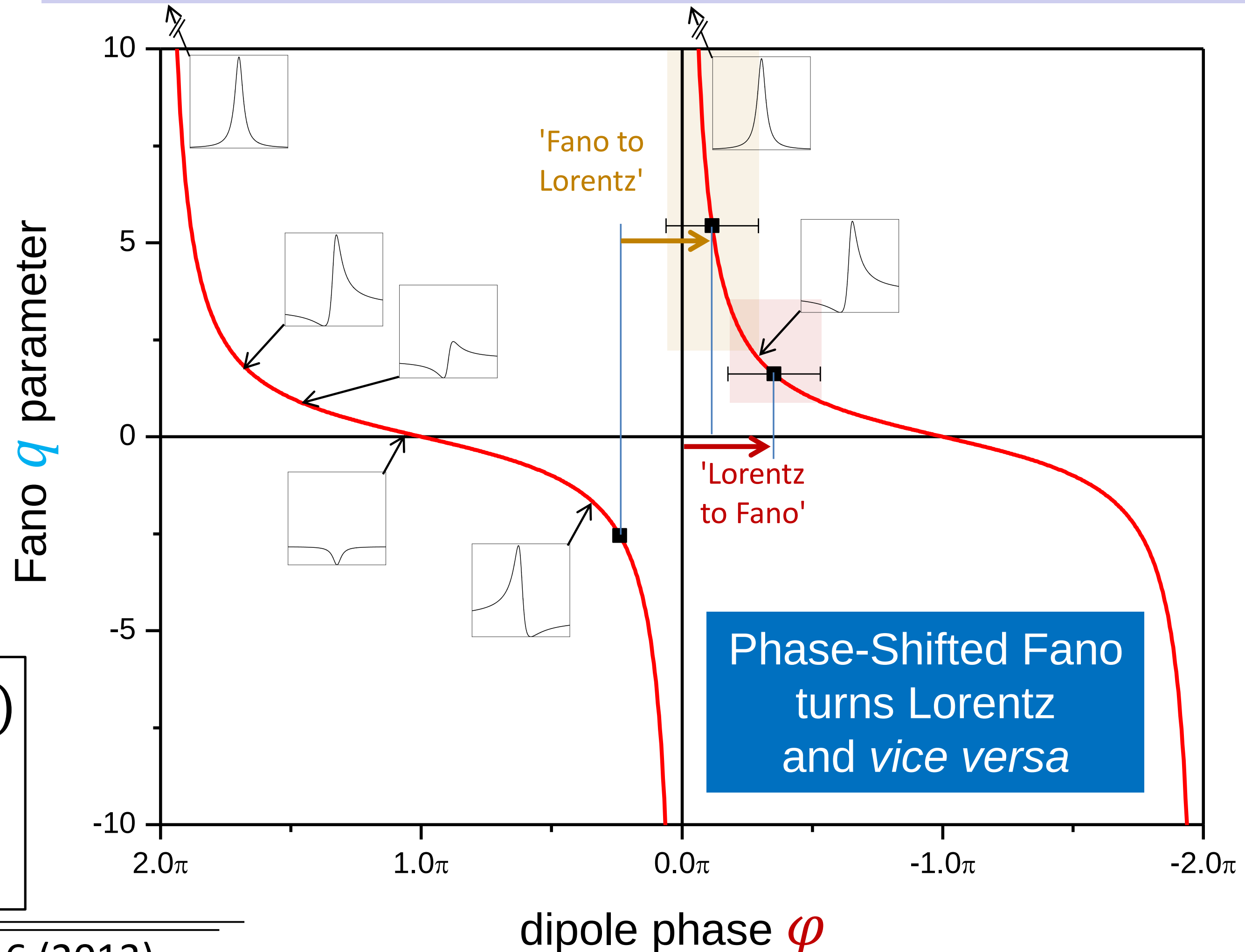
$$\mathrm{Im}\left(\frac{-1}{i+\varepsilon}\exp(i\varphi)\right) + const.$$

Phase-shifted Lorentzian

...it IS a
Fano line shape!

$$\varphi(q) = 2\arg(q - i)$$

$$q(\varphi) = -\cot\left(\frac{\varphi}{2}\right)$$

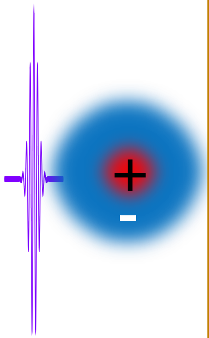


C. Ott *et al.* Science **340**, 716 (2013)

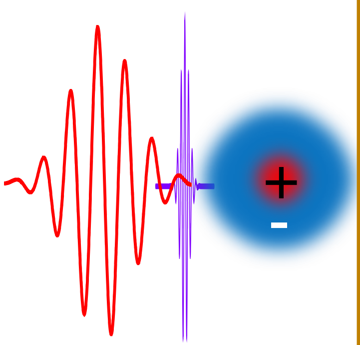
Fano to Lorentz, and Lorentz to Fano

doubly-excited Helium
originally Fano lineshape

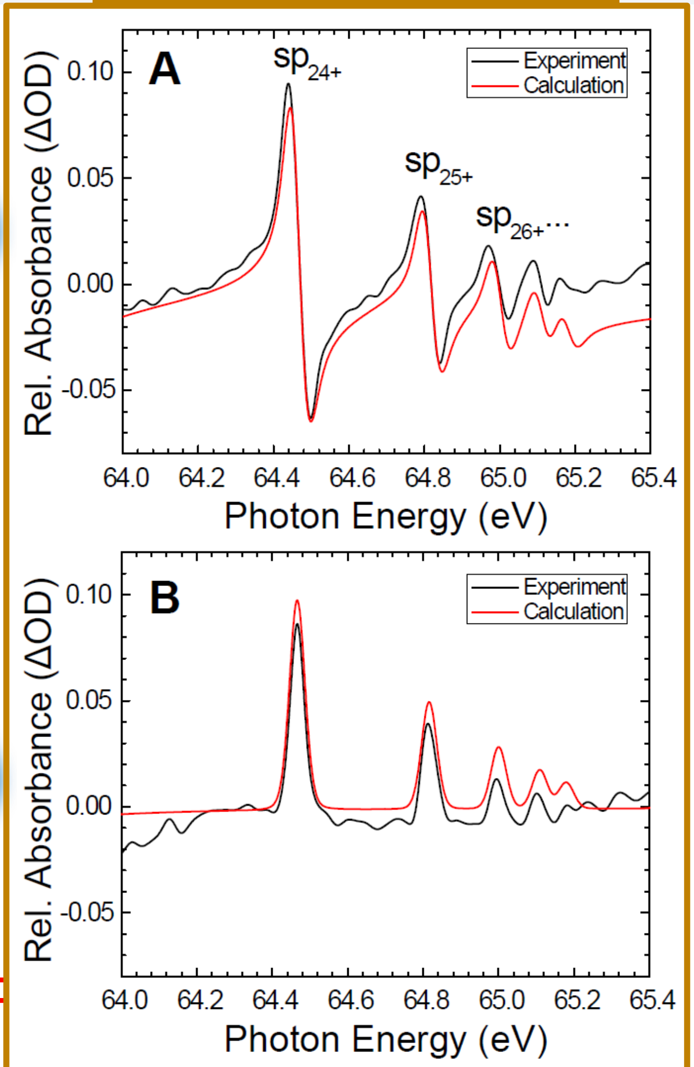
singly-excited Helium
originally Lorentzian

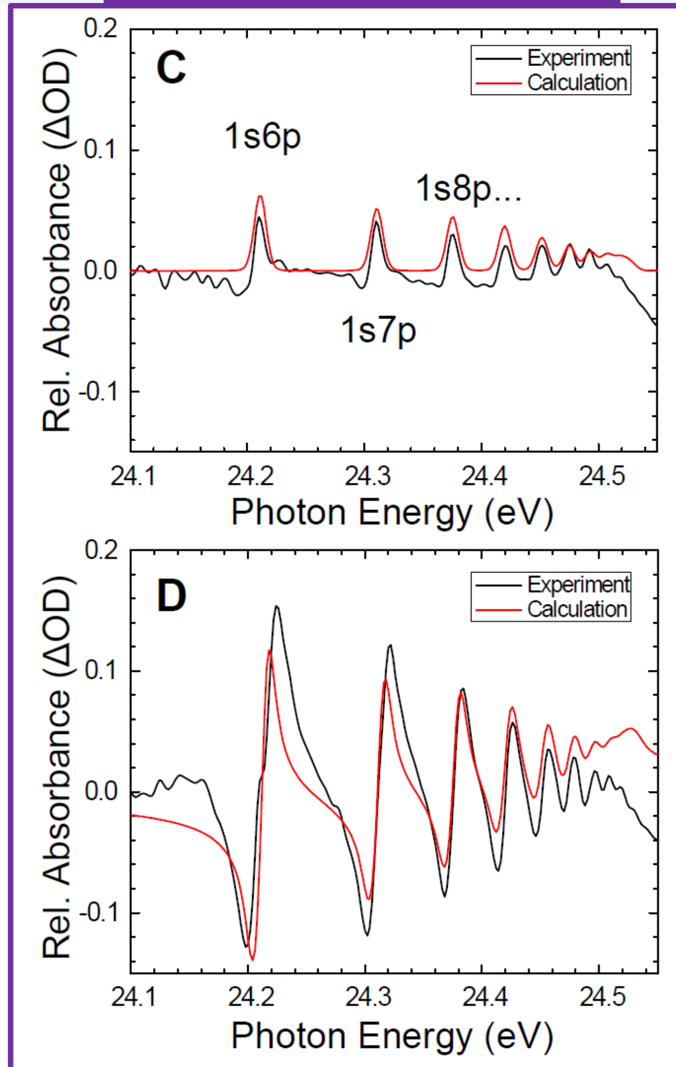


no laser



Laser Intensity:
$2 \cdot 10^{12}$ W/cm^2



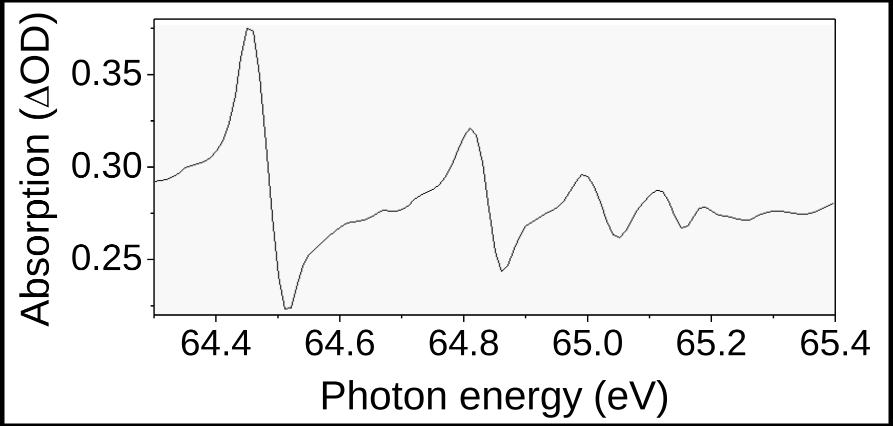


Science **340**, 716 (2013)

Laser Control of Fano and Lorentzian resonances

'2s4p' '2s5p' '2s6p' ...

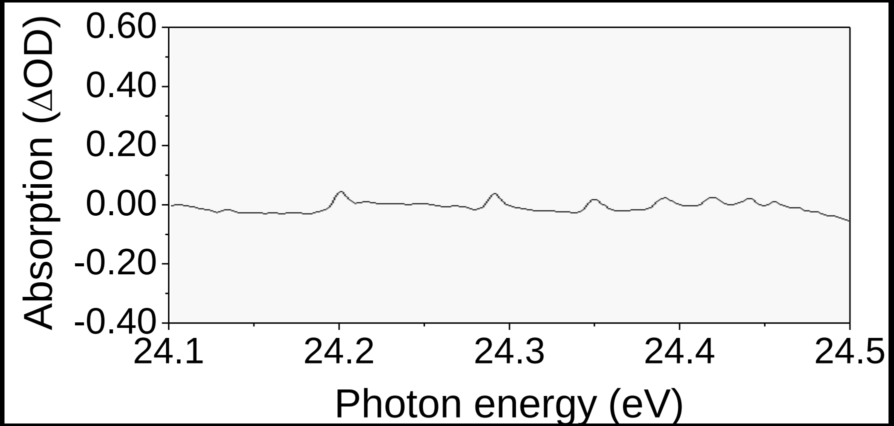
Helium **doubly** excited (**above** the continuum threshold)



turning original 'Fano' into 'Lorentz'

1s6p 1s7p 1s8p ...

Helium **singly** excited (**below** the continuum threshold)



turning original 'Lorentz' into 'Fano'

$$q = -\cot\left(\frac{\varphi}{2}\right)$$

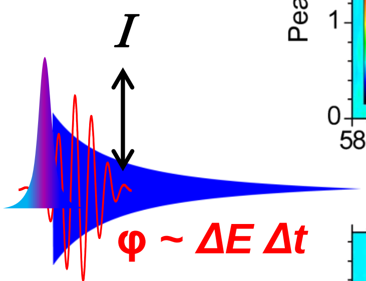
$q = -2.55 \Rightarrow \varphi = 0.24\,\pi$

Science **340**, 716 (2013)

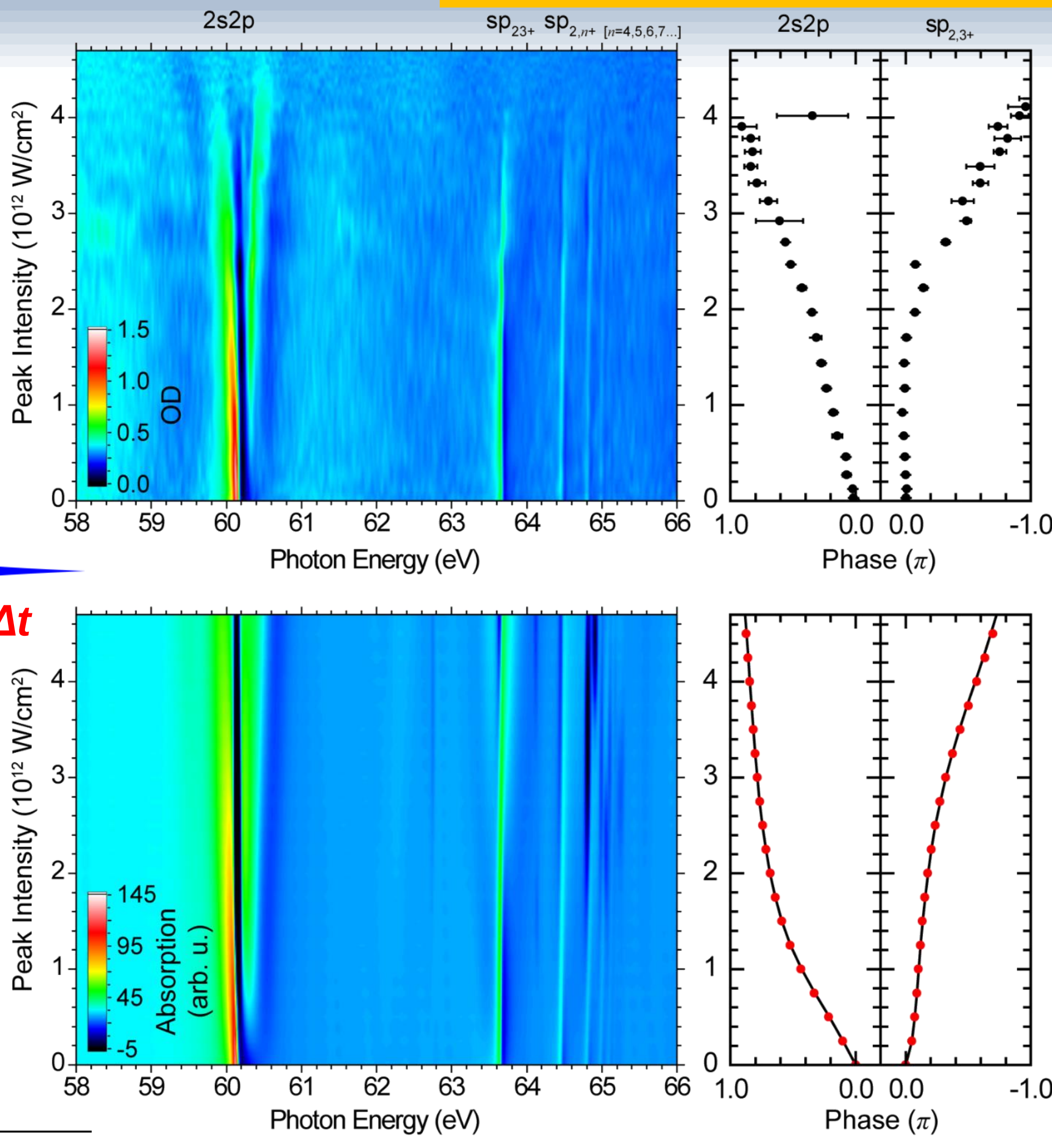
Extracting the laser-induced phase shift

Cooperation with J. Madronero, L. Argenti, F. Martín

experiment



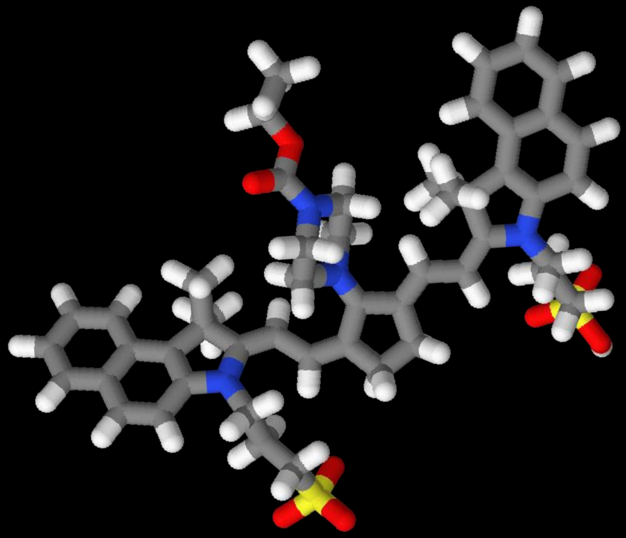
***ab-initio* theory**
(Argenti/Martin)



C. Ott *et al.* Nature 2014

Phase control of "real molecules"

Can we change the (spectral) shape of complex molecules?

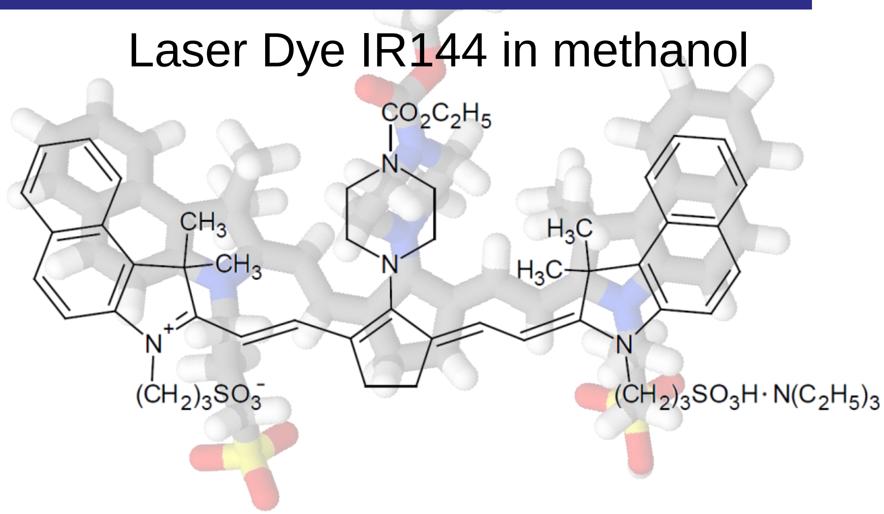


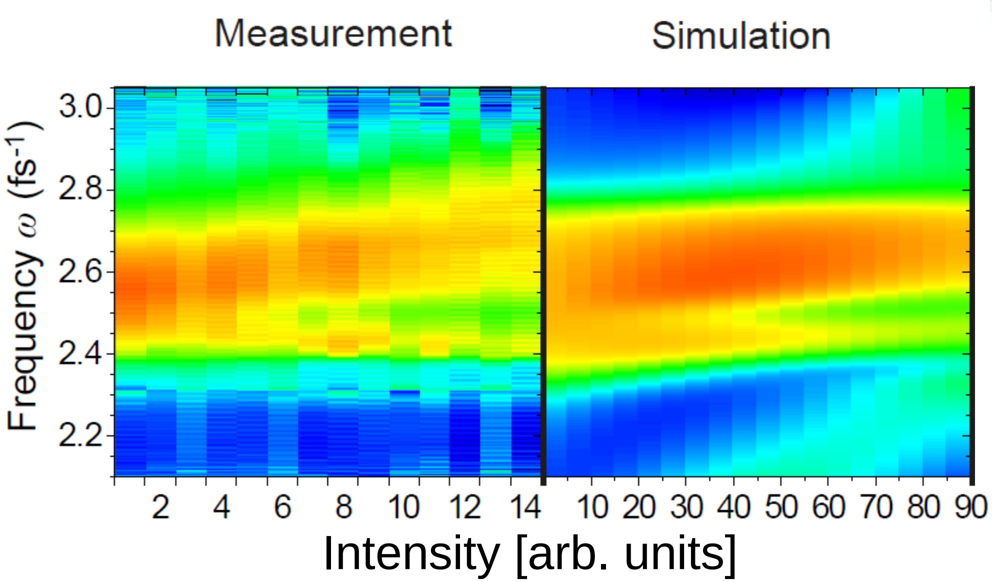
Fano control of molecules in the liquid phase

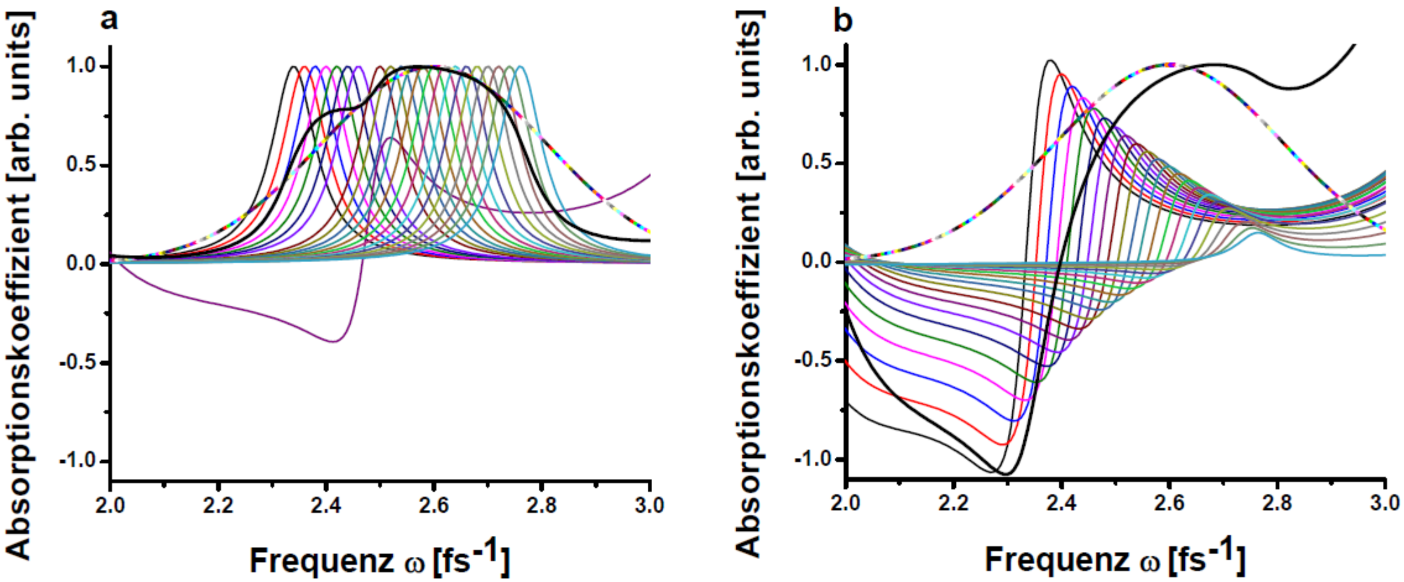
cooperation with J.-M. Mewes, A. Dreuw, T. Buckup, M. Motzkus@Univ. Heidelberg

Kristina Meyer *et al.*, PNAS (2015)

Laser Dye IR144 in methanol

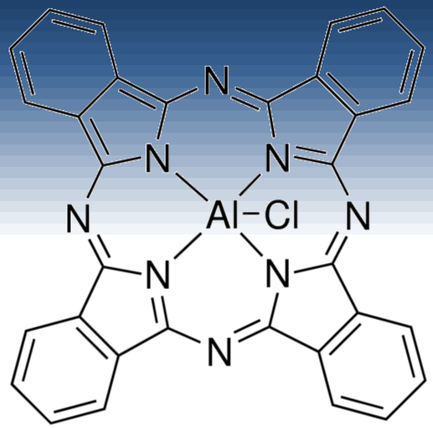


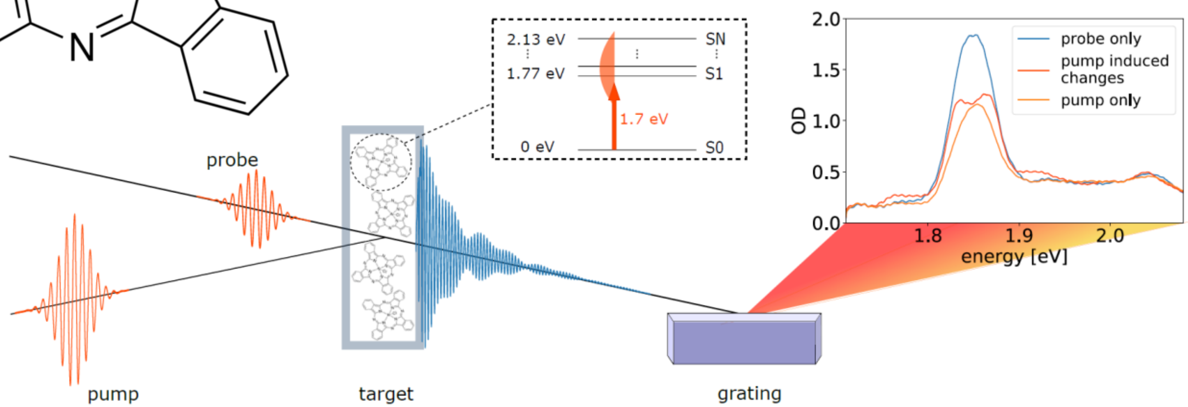


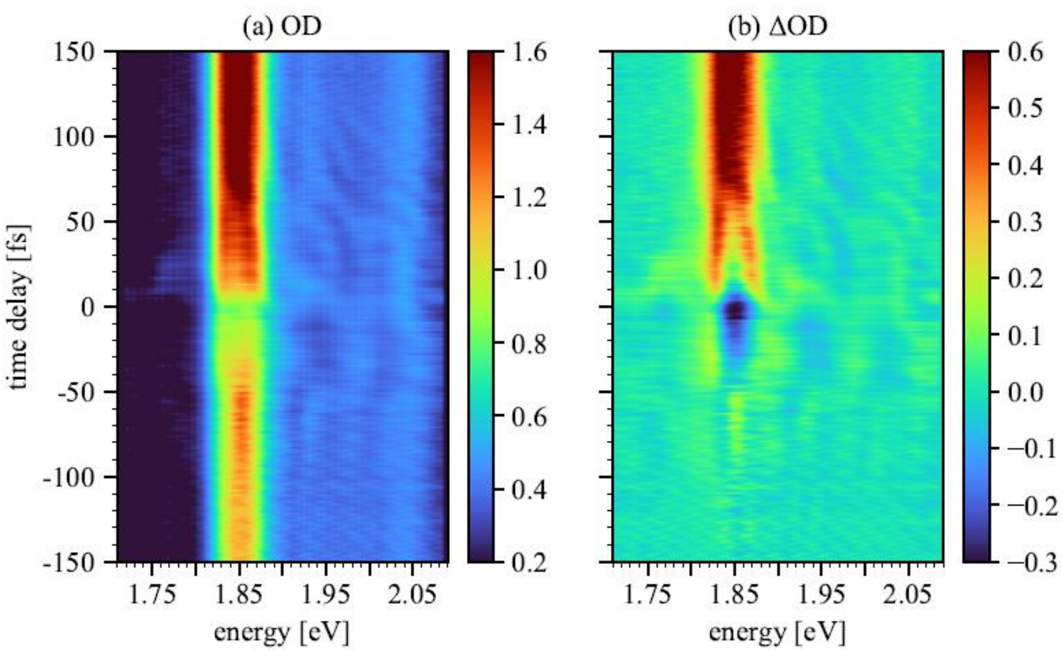


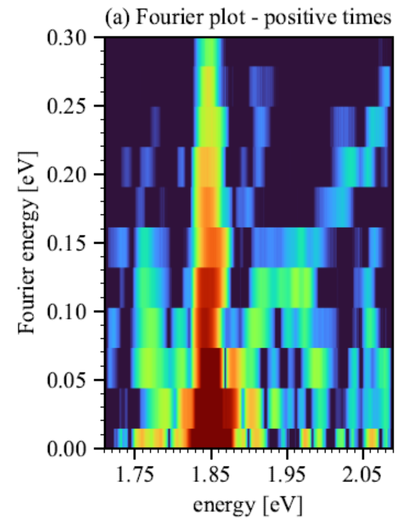
Recent measurements in Aluminum-phthalocyanine-chloride (AlPhCl)

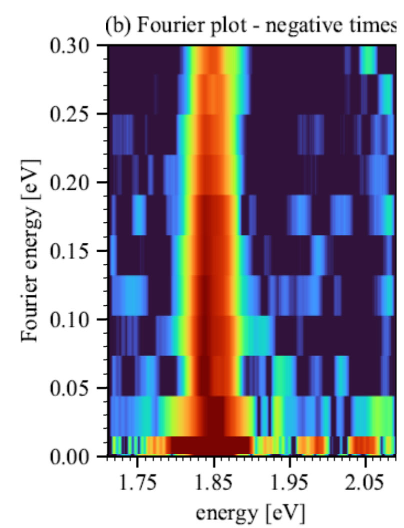
Carina da Costa Castanheira *et al.* (in preparation)







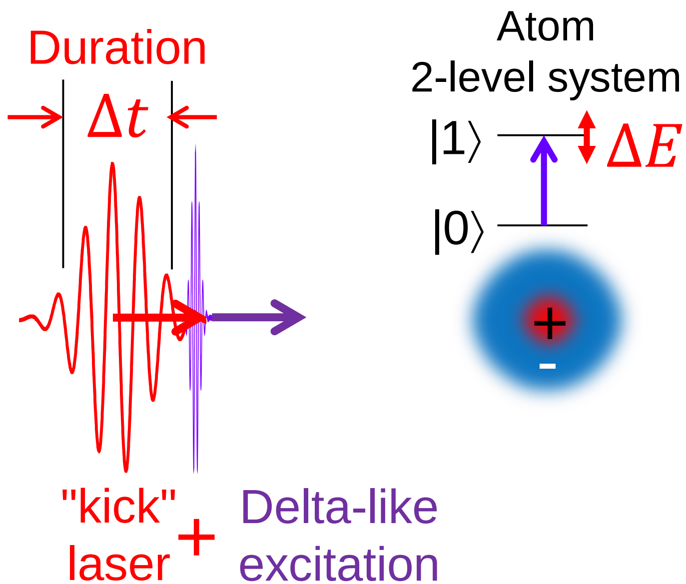


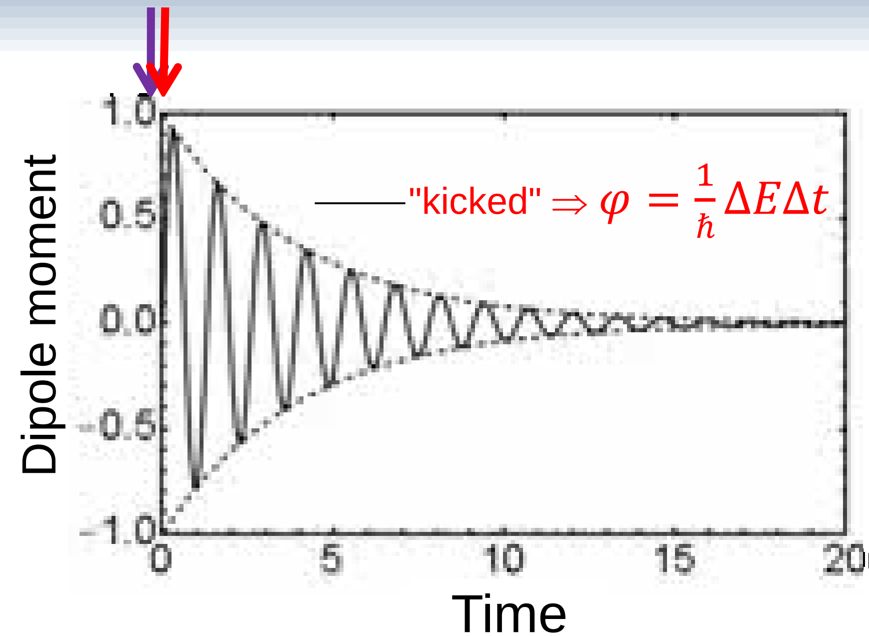


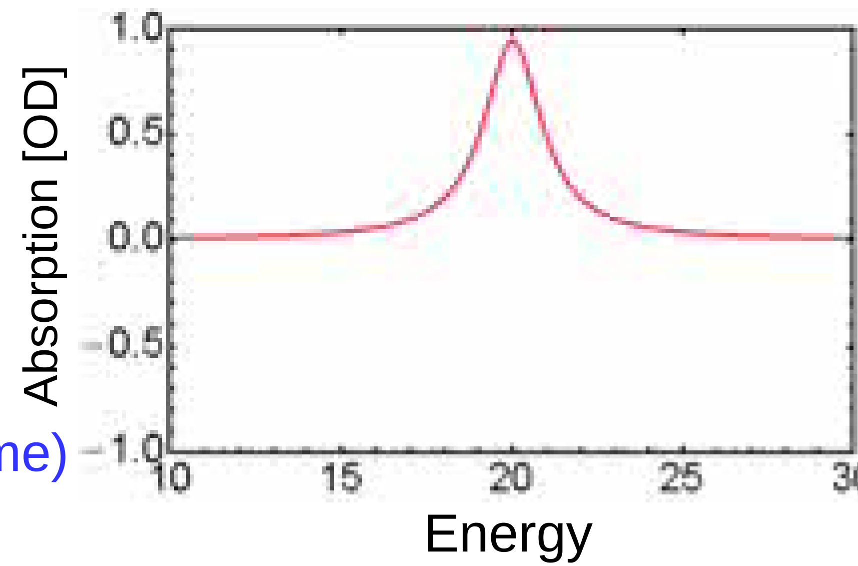
Time-domain, *impulsive*, resonance control

Variation of intensity: tuning of coupling strength, phase

Science **340**, 716 (2013)





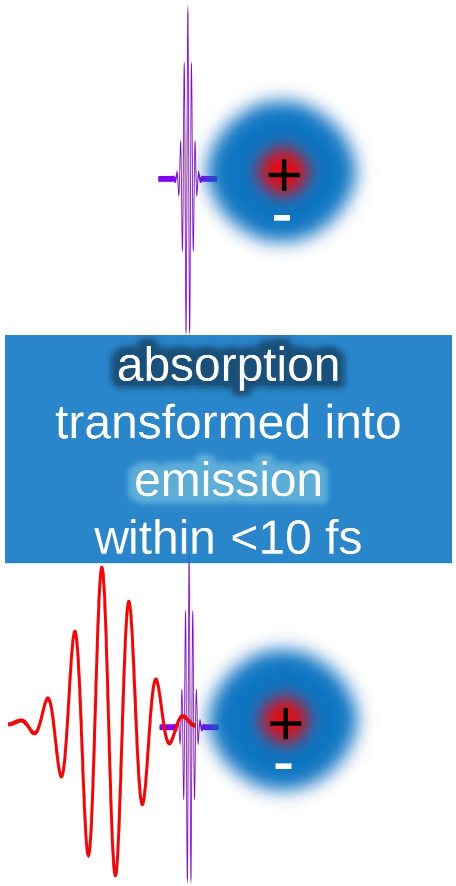


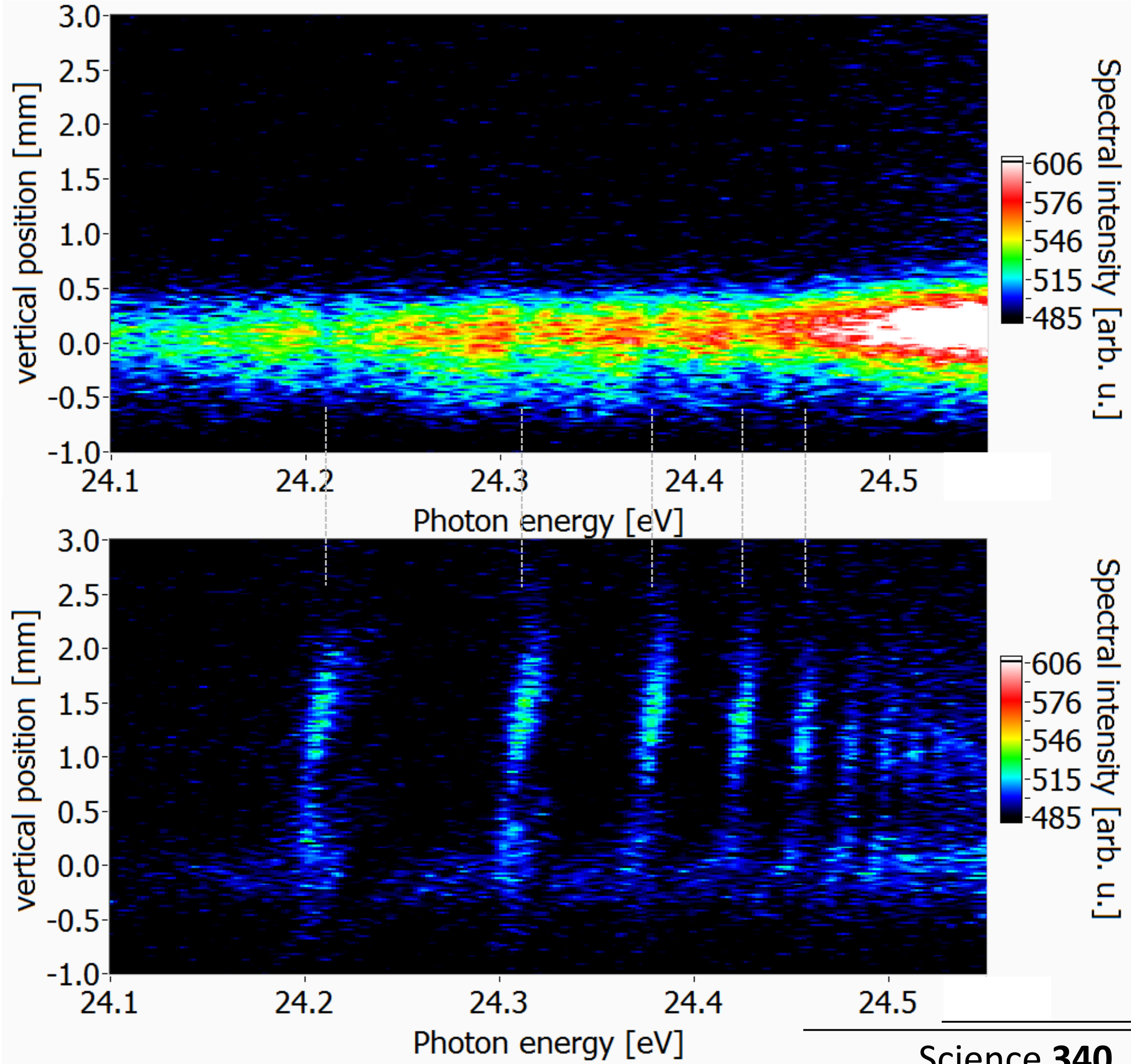
Tuning from absorption to gain!

... in the "impulsive" limit!
(much shorter than the lifetime)

Proof-of-Principle: Observation of Resonant Gain

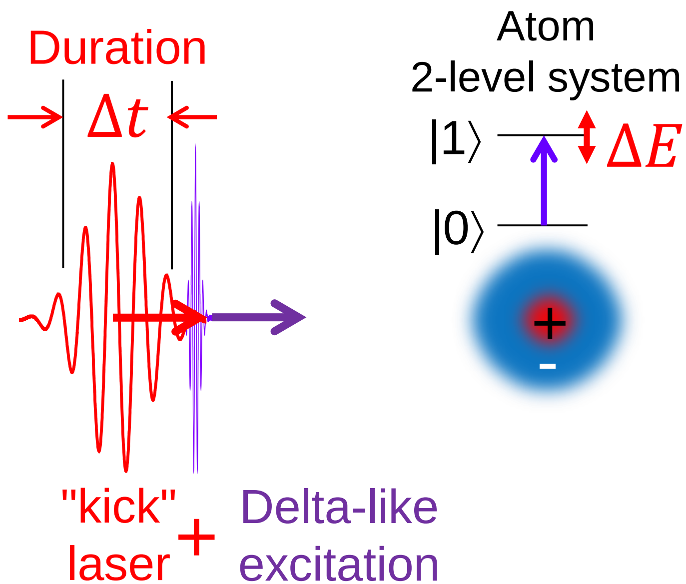
in singly-excited helium



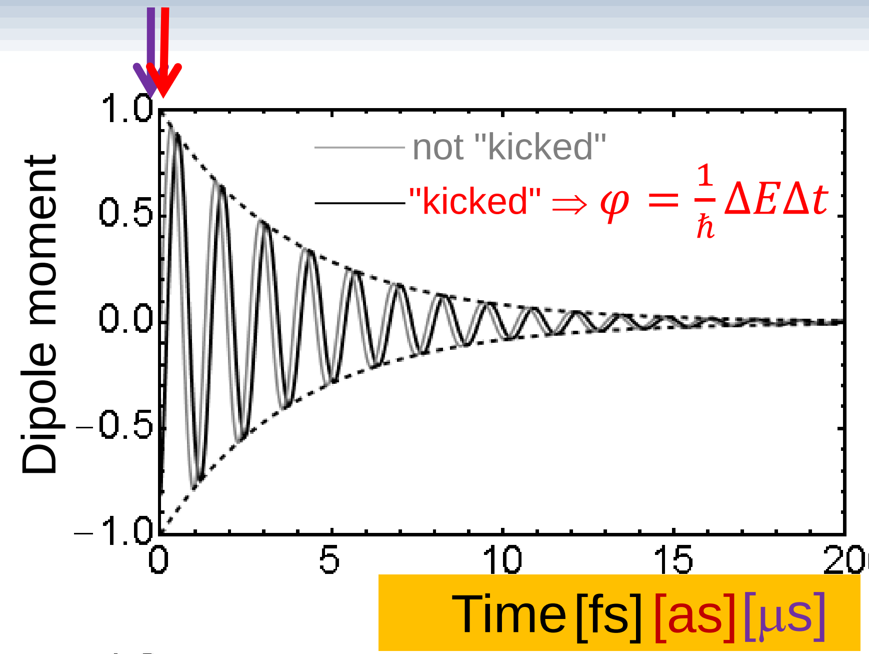


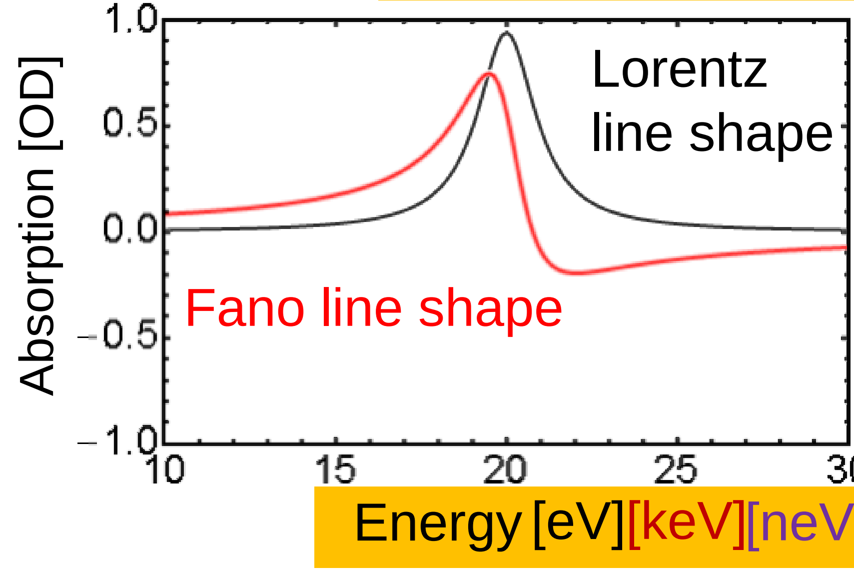
Science **340**, 716 (2013)

The Beauty of a Fundamental Mechanism



applies to all
time scales and
photon energies...

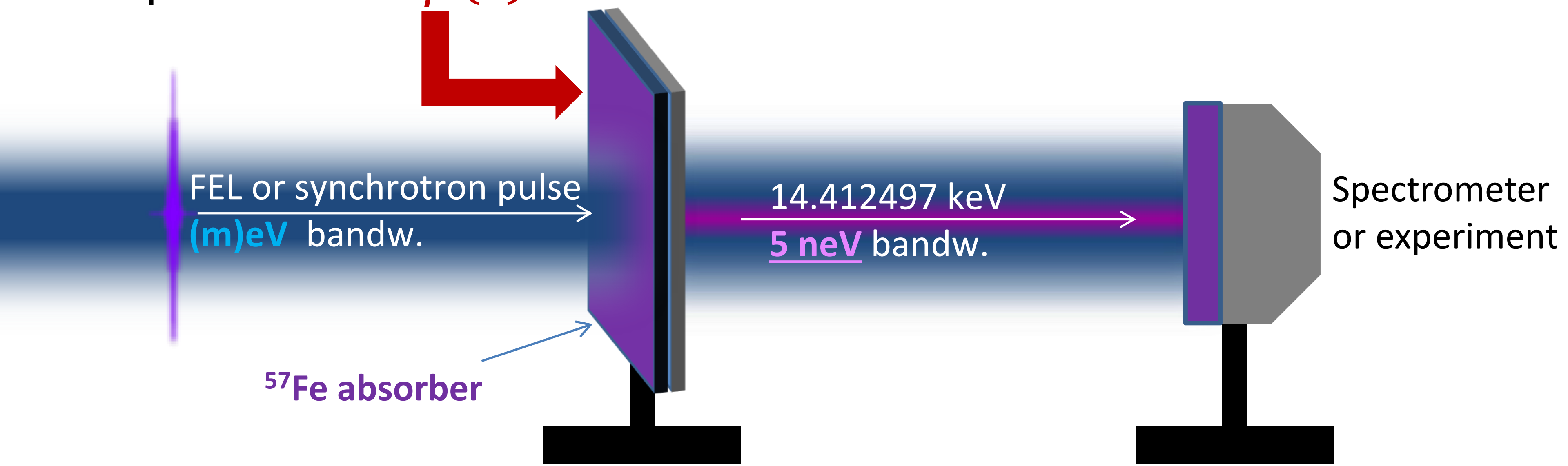




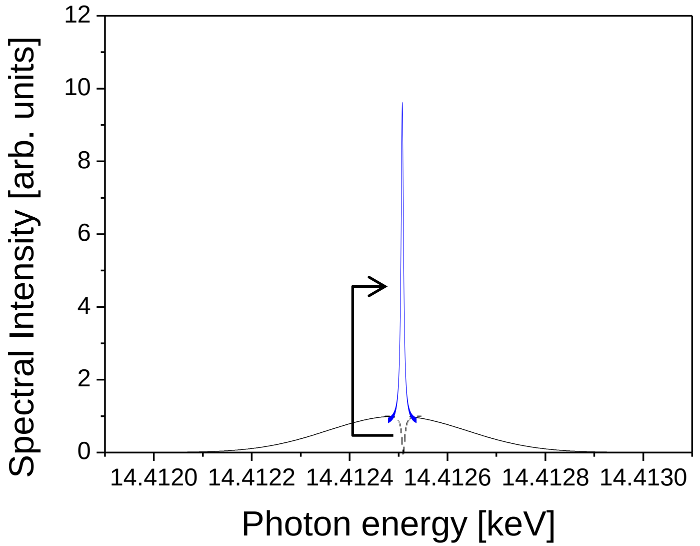
Resonant gain for hard x-rays

14.4 keV, ^{57}Fe Mössbauer

phase shift $\varphi(t)$ at $t = 0$



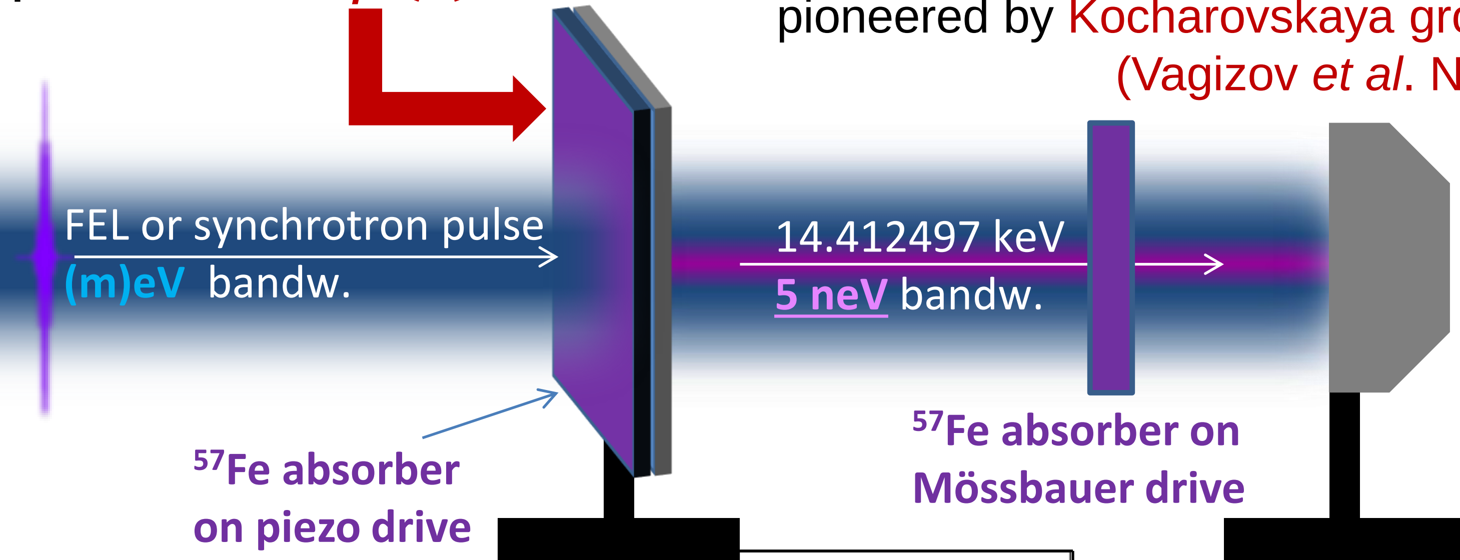
Laser-like narrowband line emission at hard x-rays



Resonant Mössbauer "gain" @ESRF,ID18

Heeg *et al.* Science (2017) cooperation with groups of J. Evers, R. Röhlsberger, R. Rüffer

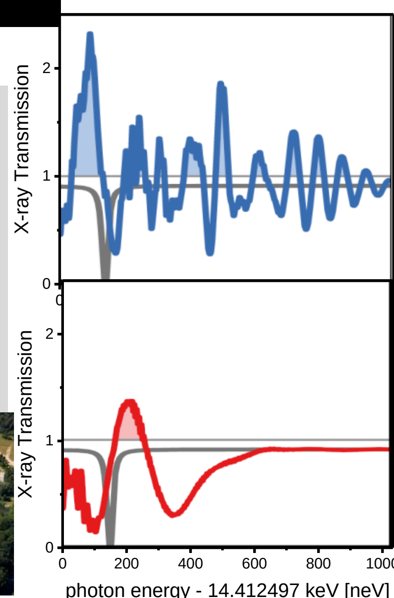
phase shift $\varphi(t)$ at $t = 0$ using a Mössbauer Coherent Control method pioneered by Kocharovskaya group (Vagizov *et al*. Nature (2014))

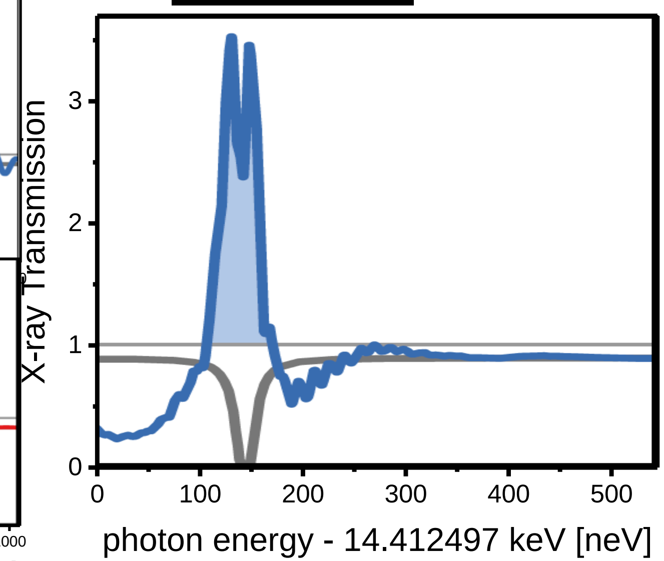


Now: Mechanical motion for phase shift
=> nanosecond response

Future: Optical control of phonons
=> femtosecond response

X-ray pulse shaping?

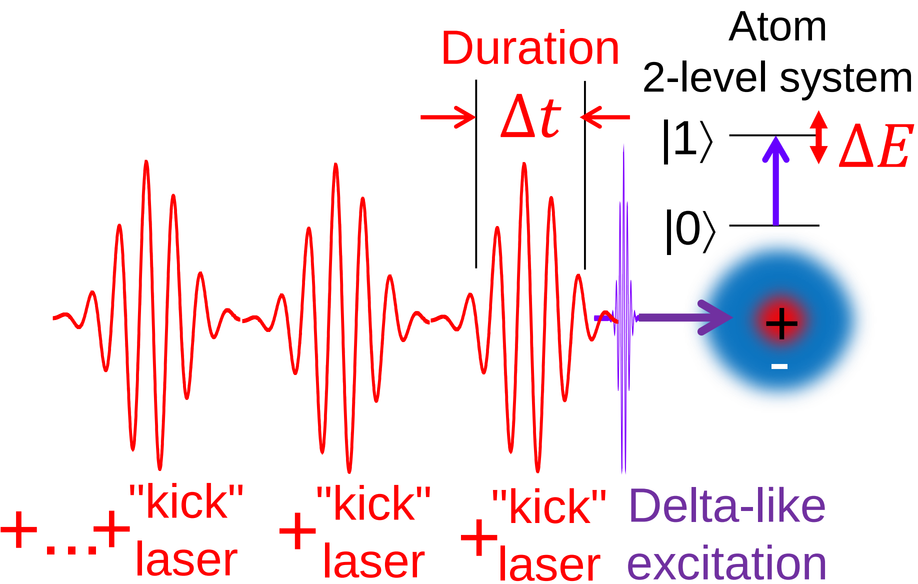


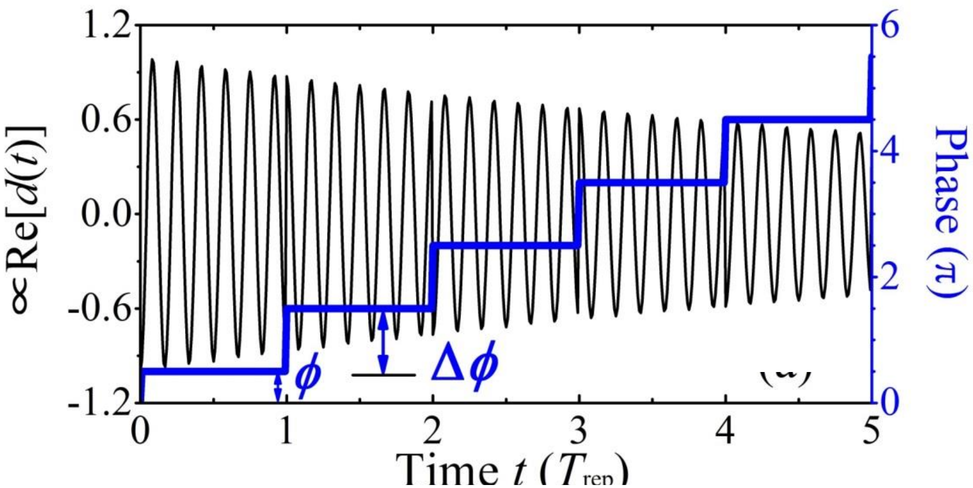


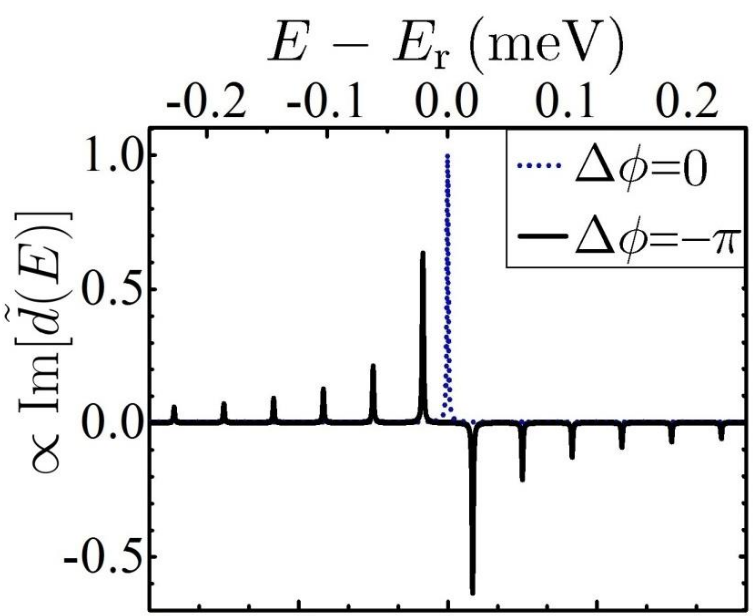
Experiment@PETRAIII

Towards x-ray frequency combs

Cooperation with group of C. H. Keitel (MPIK): Cavaletto, Harman *et al.*, Nat. Photonics (2014)
Liu, Ott, *et al.*, New. J. Phys. (2014)





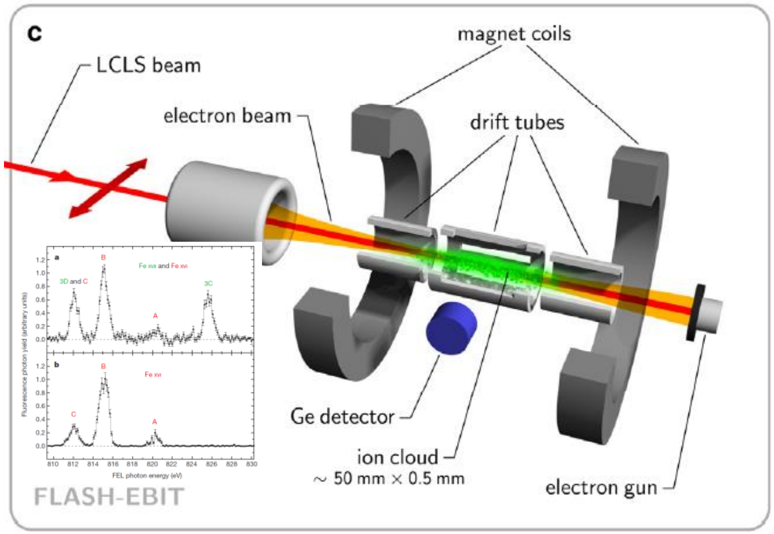


Using a **pulse train** for periodic phase shifting ...

... creates a **frequency comb** precisely locked to an atomic transition

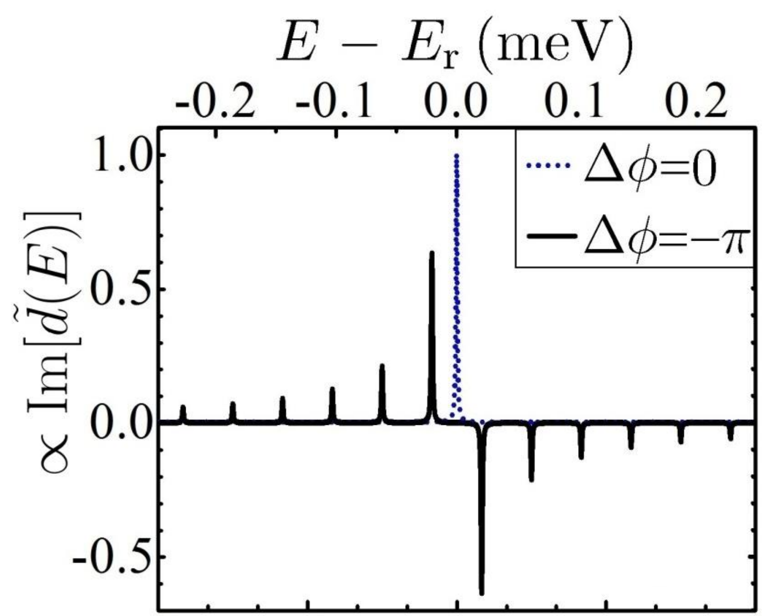
Towards x-ray precision metrology of highly-charged ions

Crespo group (MPIK)
(image modified from:
Bernitt *et al.* Nature **492**, 225 (2012))

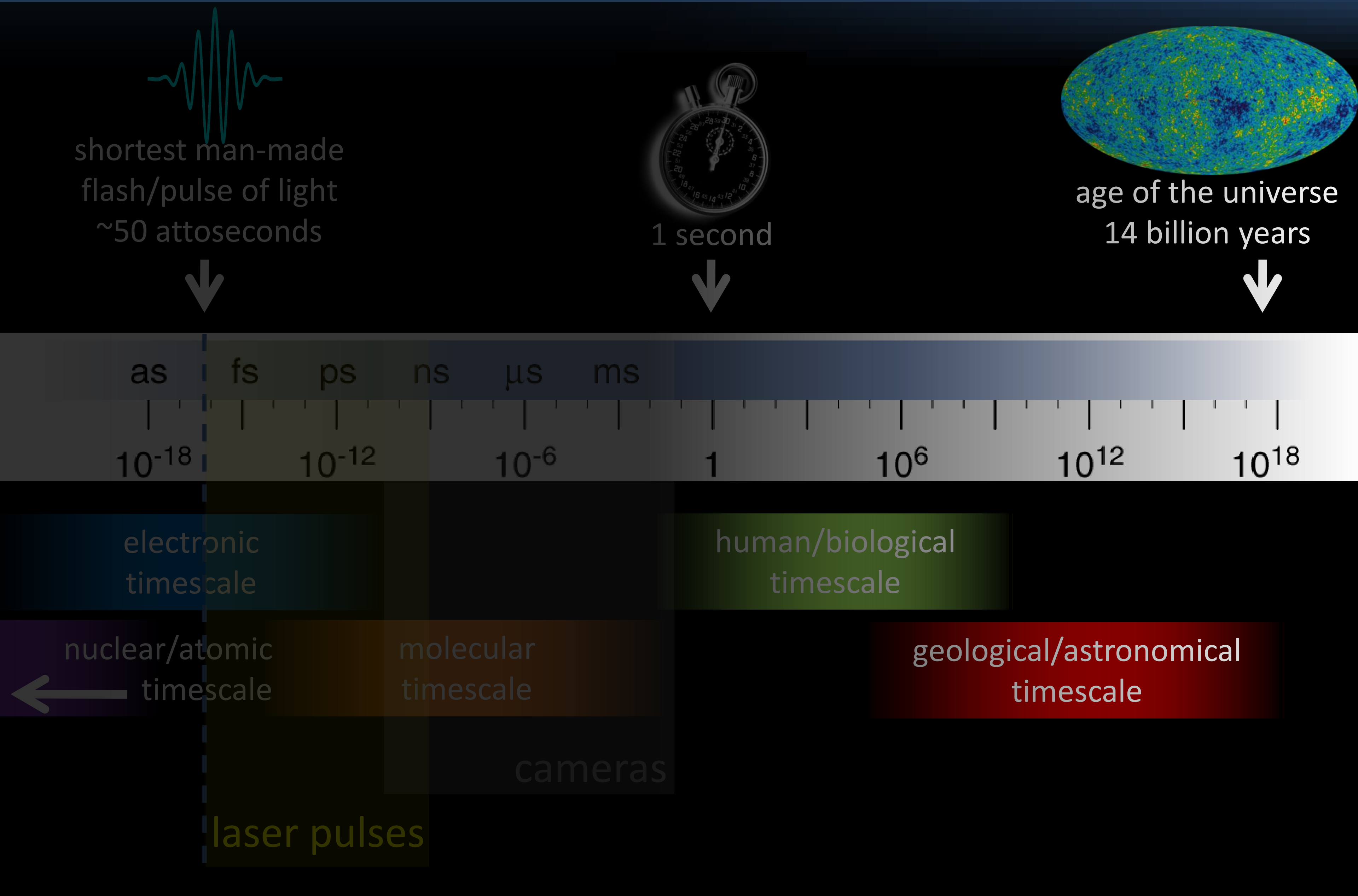


High-resolution spectroscopy of long-lived transitions in highly-charged ions:

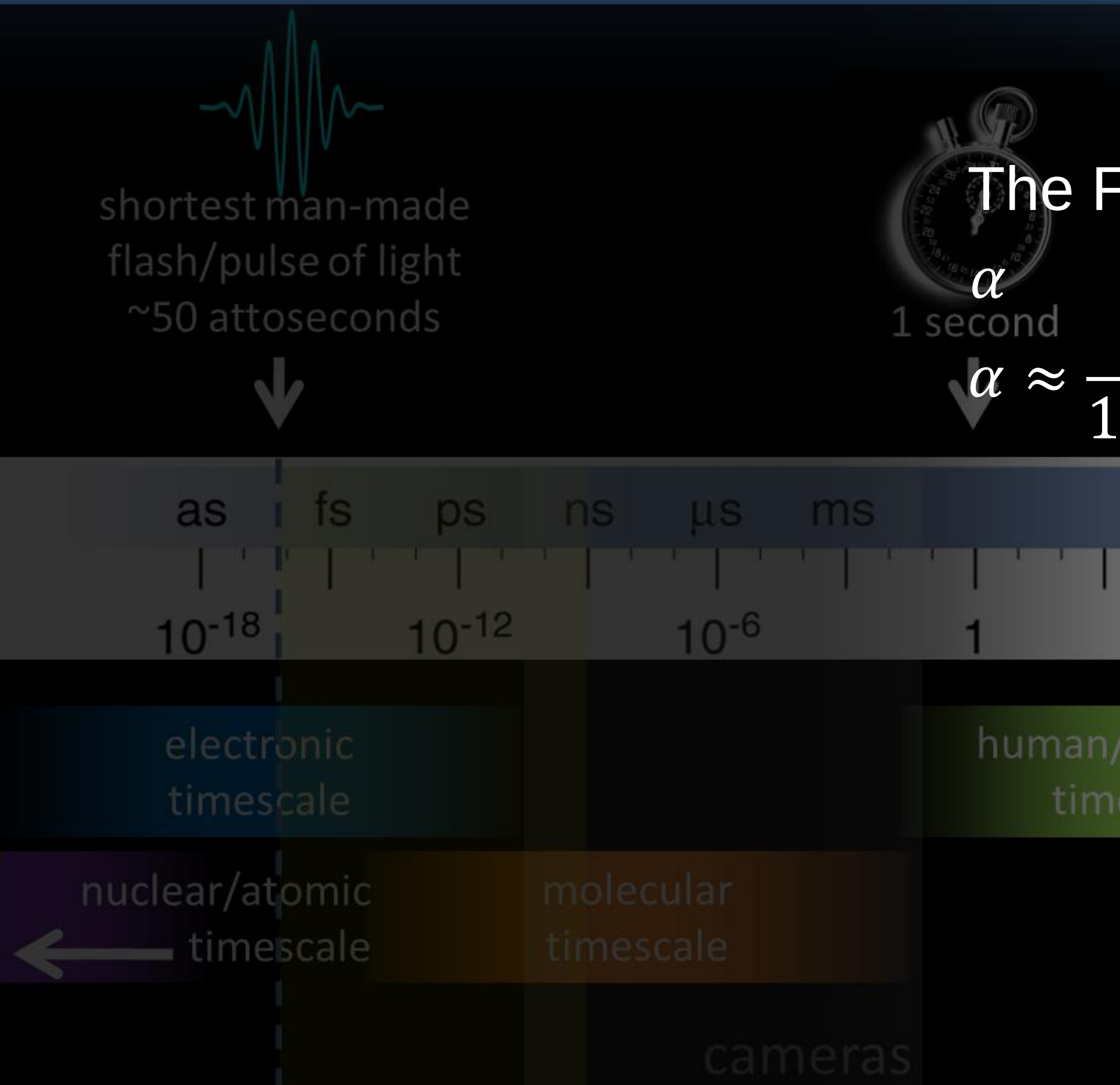
- Precision tests of theories in heavy ions (QED, nuclear&relativistic-electronic structure)
- linking nuclear/electronic x-ray transitions: variation of coupling "constants"?



time scales in science



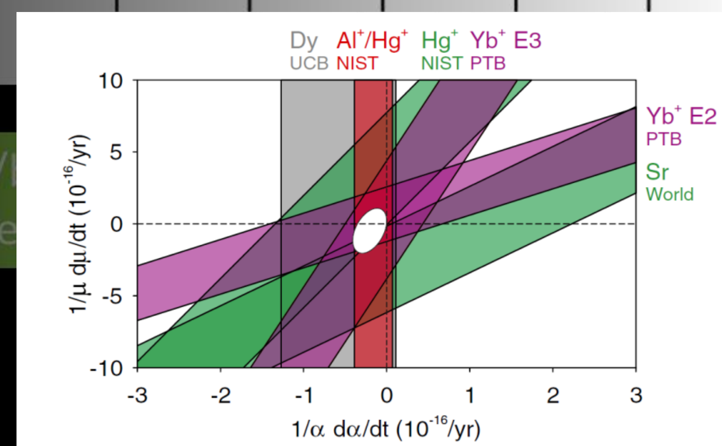
Ultra s l o w dynamics…



The Fine structure constant:

α fundamental constant?

$$\alpha \approx \frac{1}{137.035999139(31)} + \dot{\alpha} \times t$$

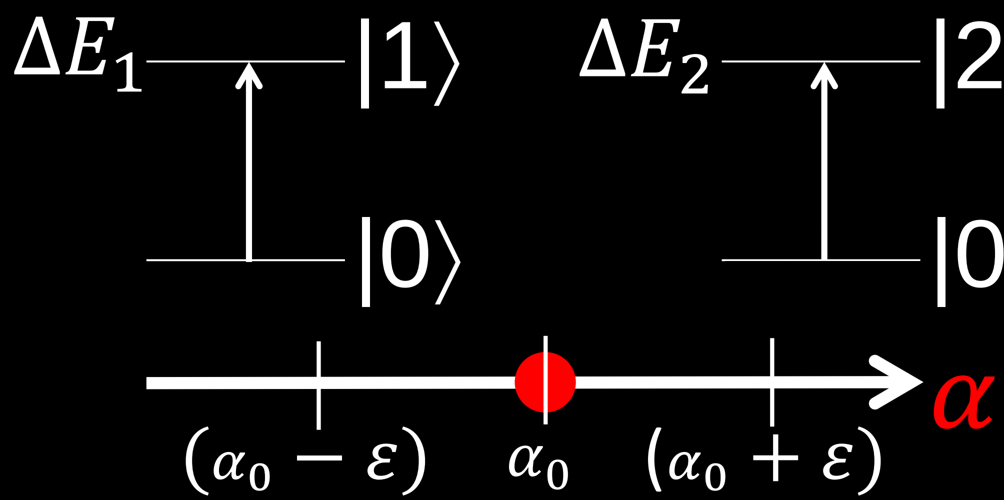


Godun *et al.* PRL **113**, 210801 (2014)
Huntemann et al. PRL **113**, 210802 (2014)

sensitivity to α variation

Dzuba, Flambaum, Webb
PRL 82, 888 (1999)

$$\Delta E_n = \frac{E_n}{\nu}(Z\alpha)^2\left[\frac{1}{j+1/2} - C(j,l)\right]$$



The highly charged ion (HCI) advantage: ***Enhanced*** sensitivity to α variation

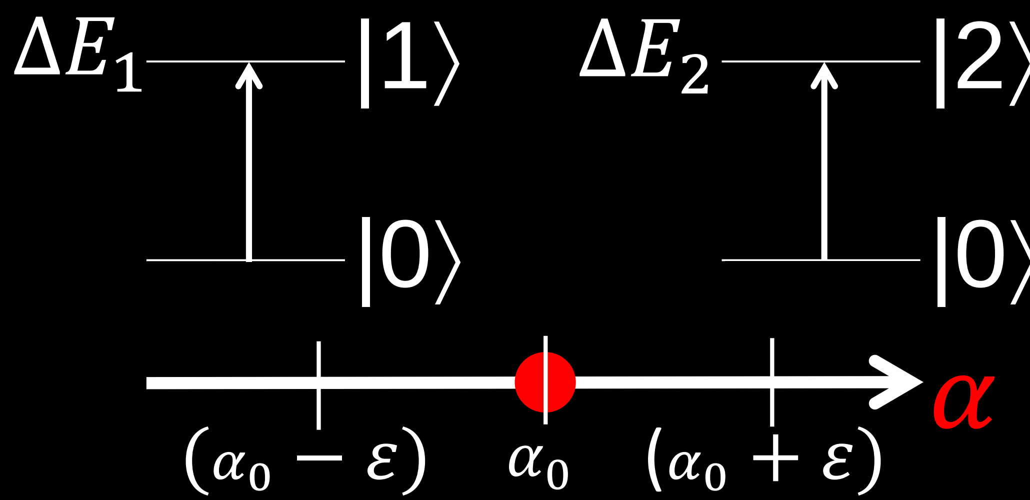
Dzuba, Flambaum, Webb
PRL 82, 888 (1999)

$$\Delta E_n = \frac{E_n}{\nu}(Z\alpha)^2\left[\frac{1}{j+1/2} - C(j,l)\right]$$

$$= 2\, q\, \Delta\alpha/\alpha + const.$$

Hg^{+} : q ~ 52 200 cm^{-1}

Ir^{17+}: ***q* ~ 740 000 cm^{-1}**



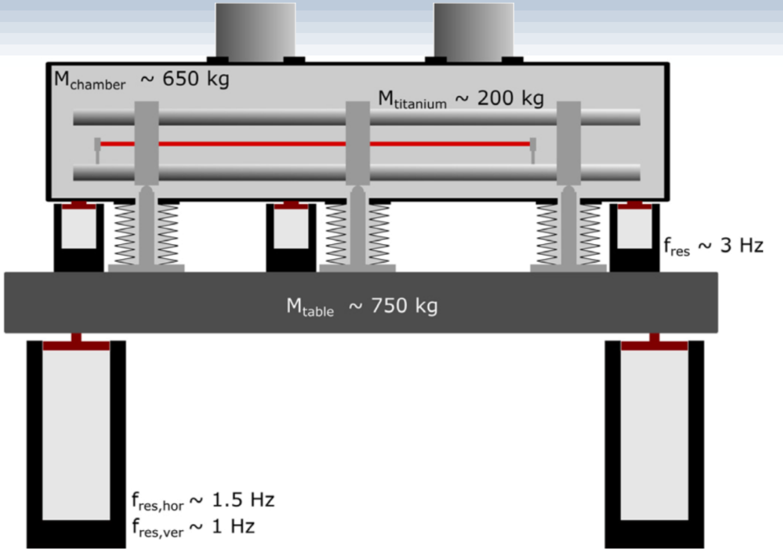
At some point,

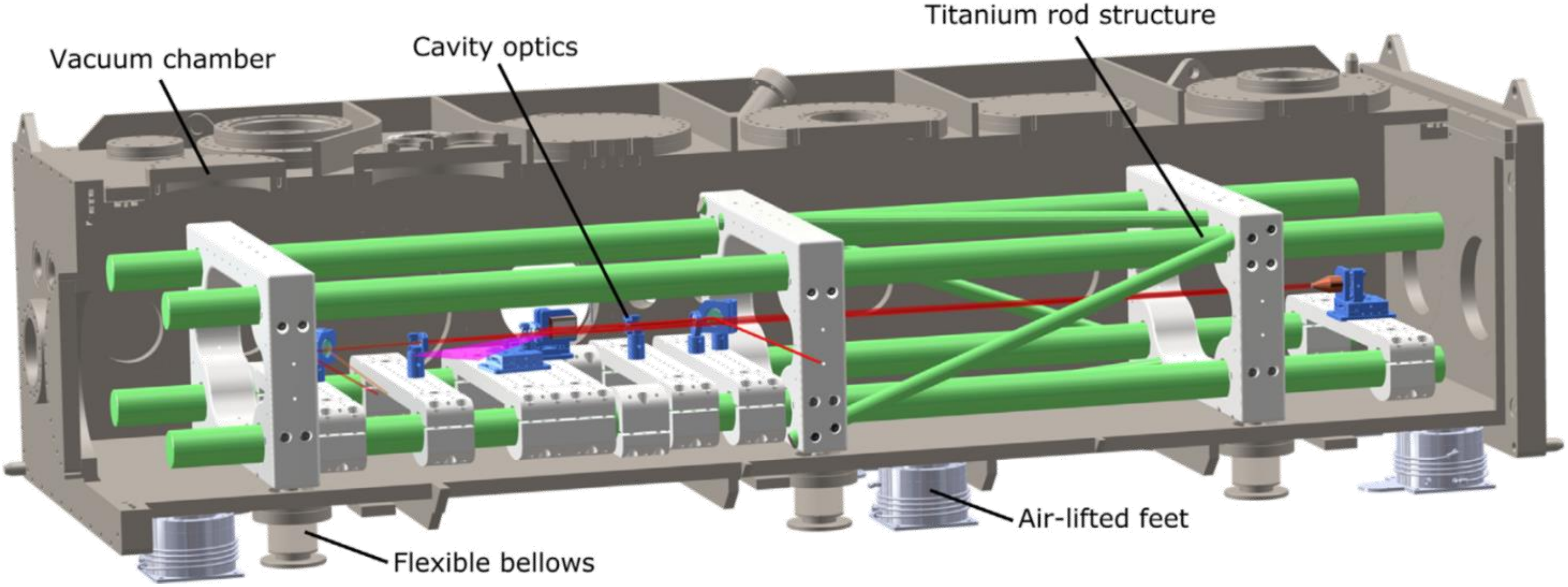
controlled/precision VUV/XUV/xray light may be helpful…

Can we generate VUV frequency combs?

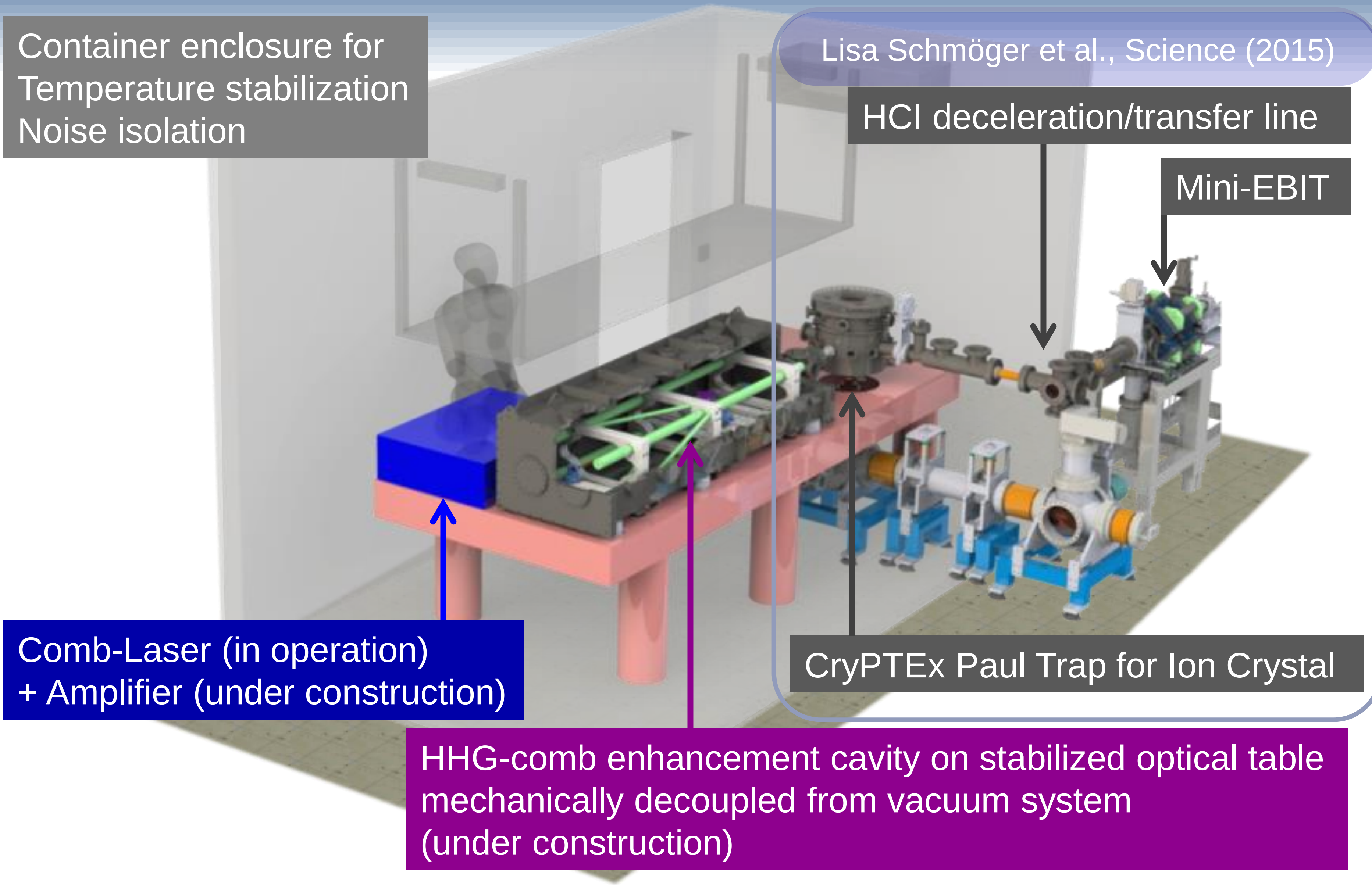
Design of enhancement/HHG cavity

- Enhancement cavity mounted on high-stiffness titanium frame on optical table
- Pump vibrations absorbed through mechanical low-pass filter, factor 10 reduction in amplitude

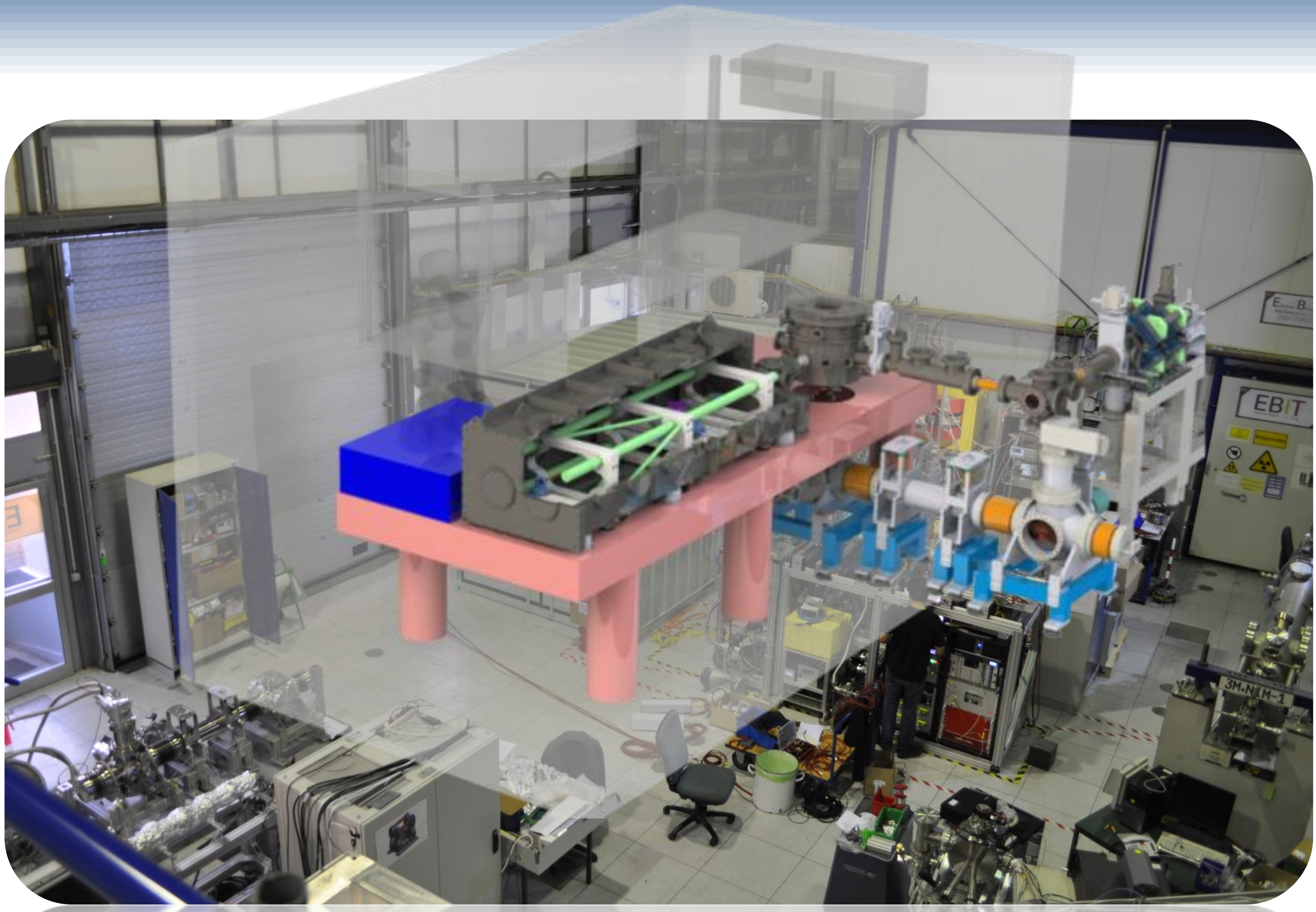




VUV-Comb-in-a-box (planning: -3 yrs)

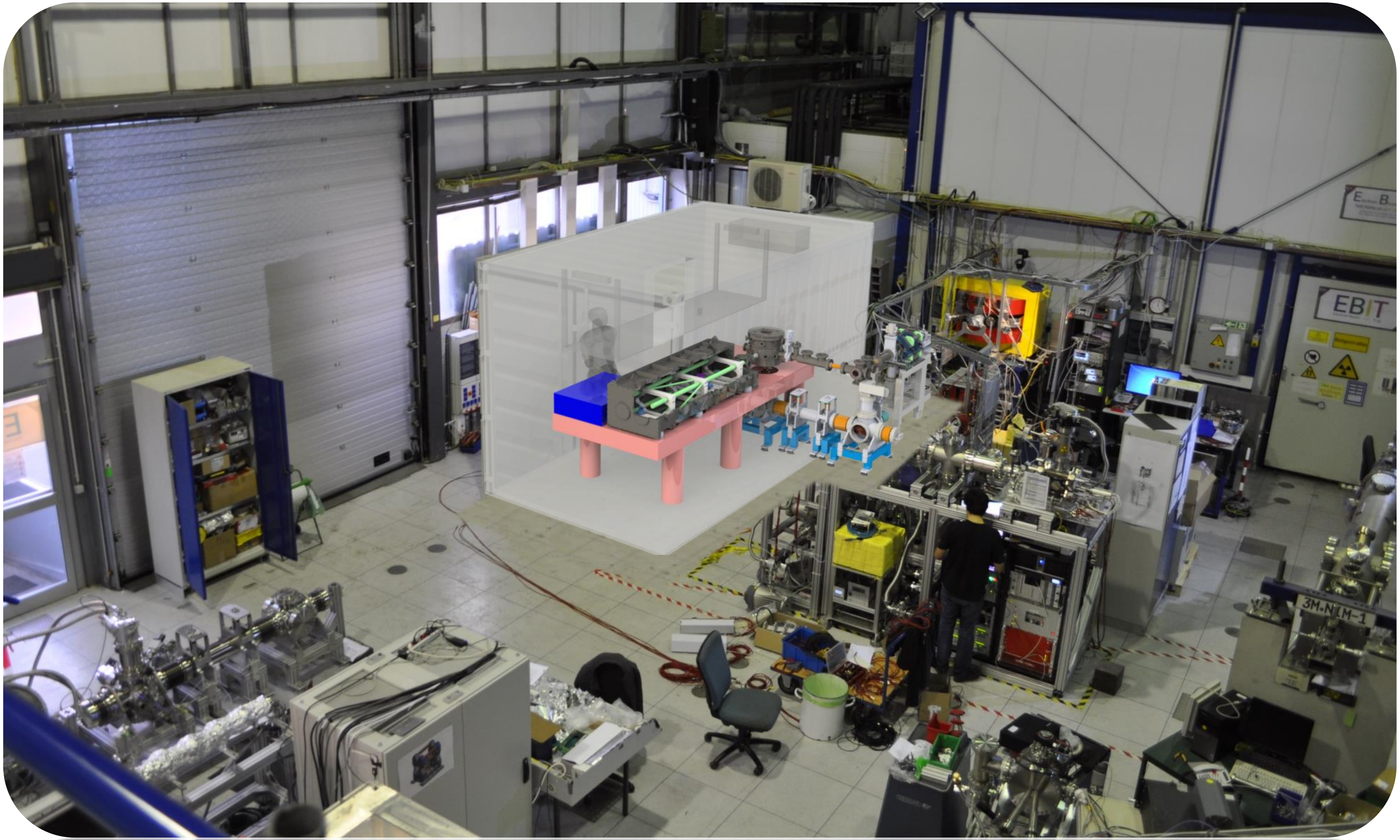


VUV-Comb-in-a-box



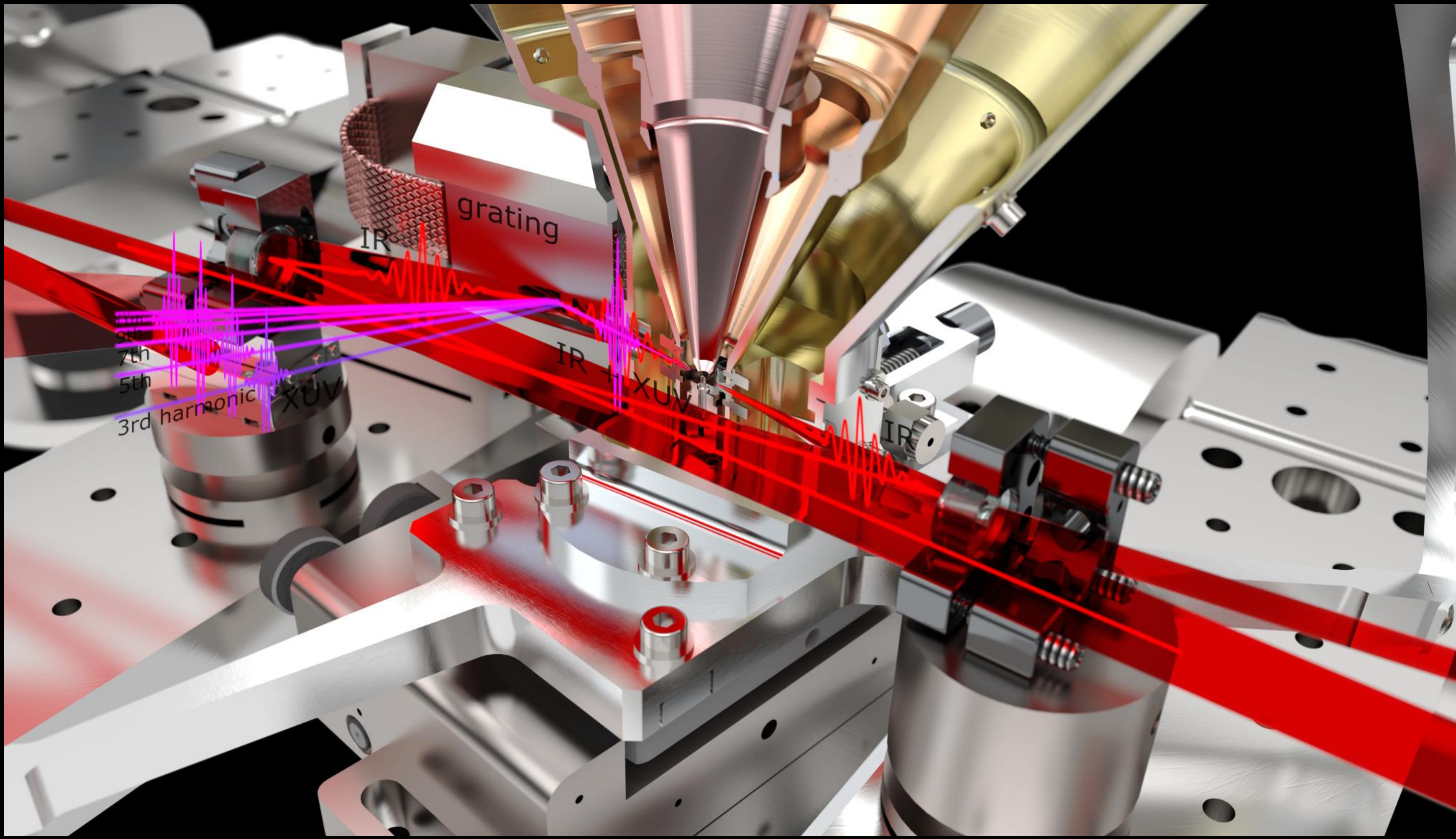
VUV-Comb-in-a-box

EBIT Hall Area

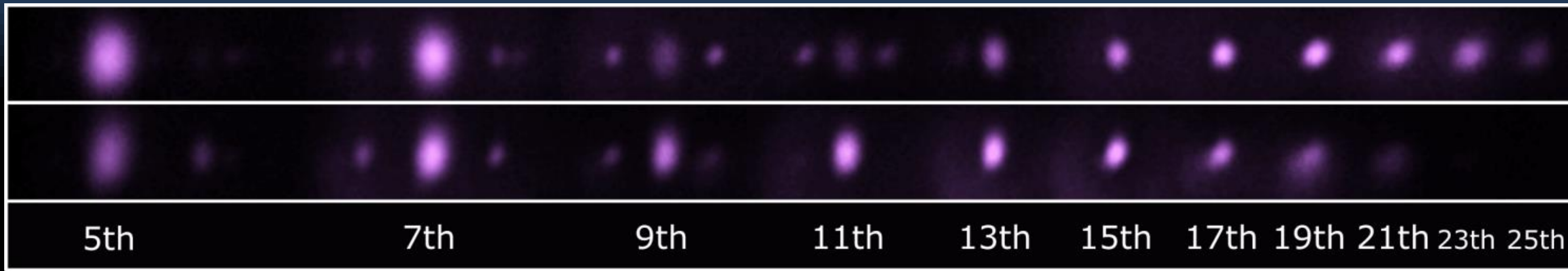


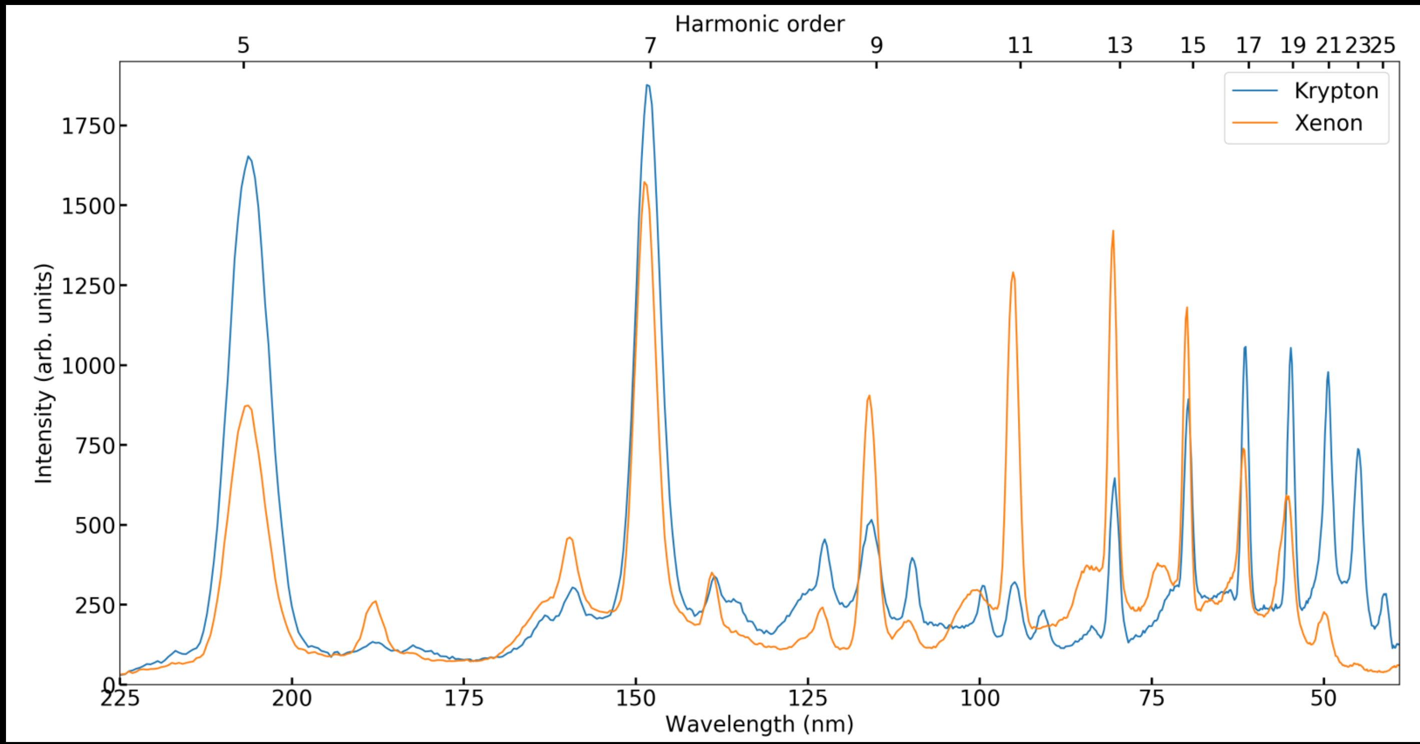
Assembling the cavity vacuum chamber

Design of the HHG interaction region



VUV-comb experimental results

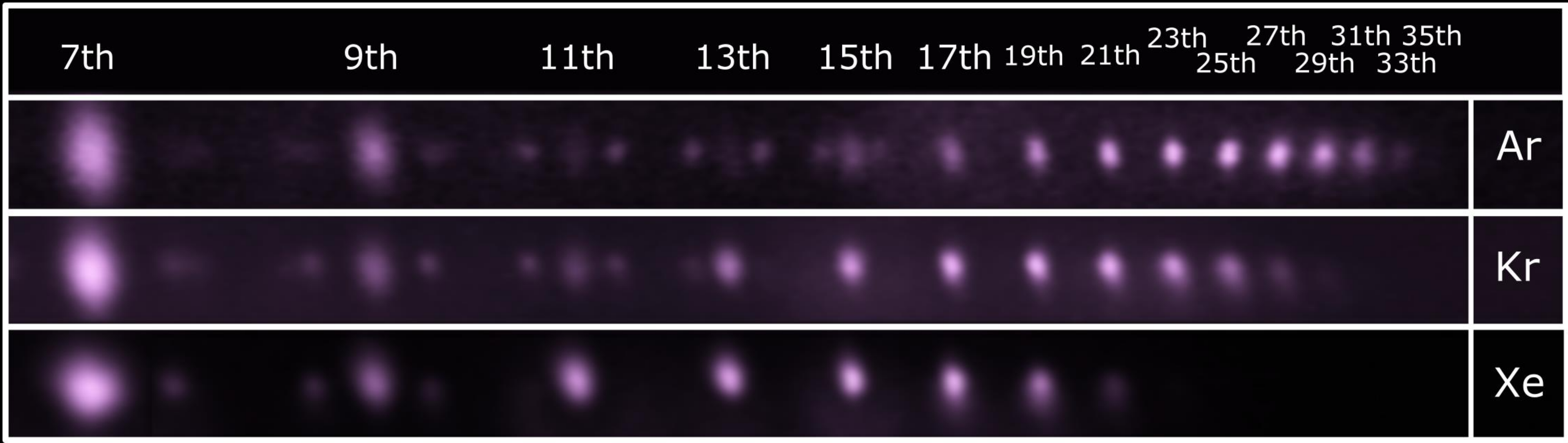




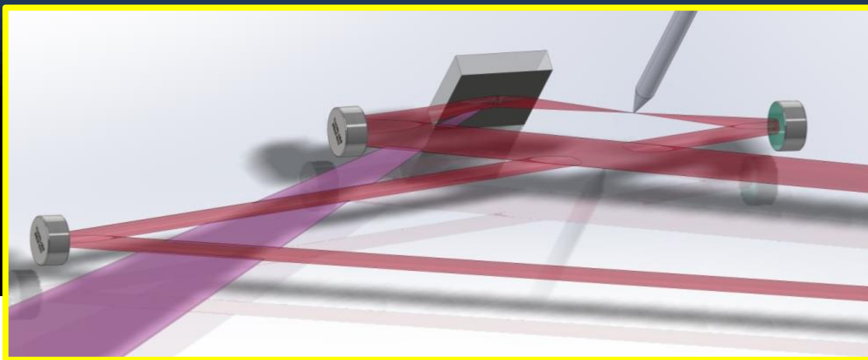
25th harmonic observed with high-density jet on fluorescent screen (Janko Nauta, Jan-Hendrik Oelmann, José Crespo *et al.*)

VUV-comb experimental results

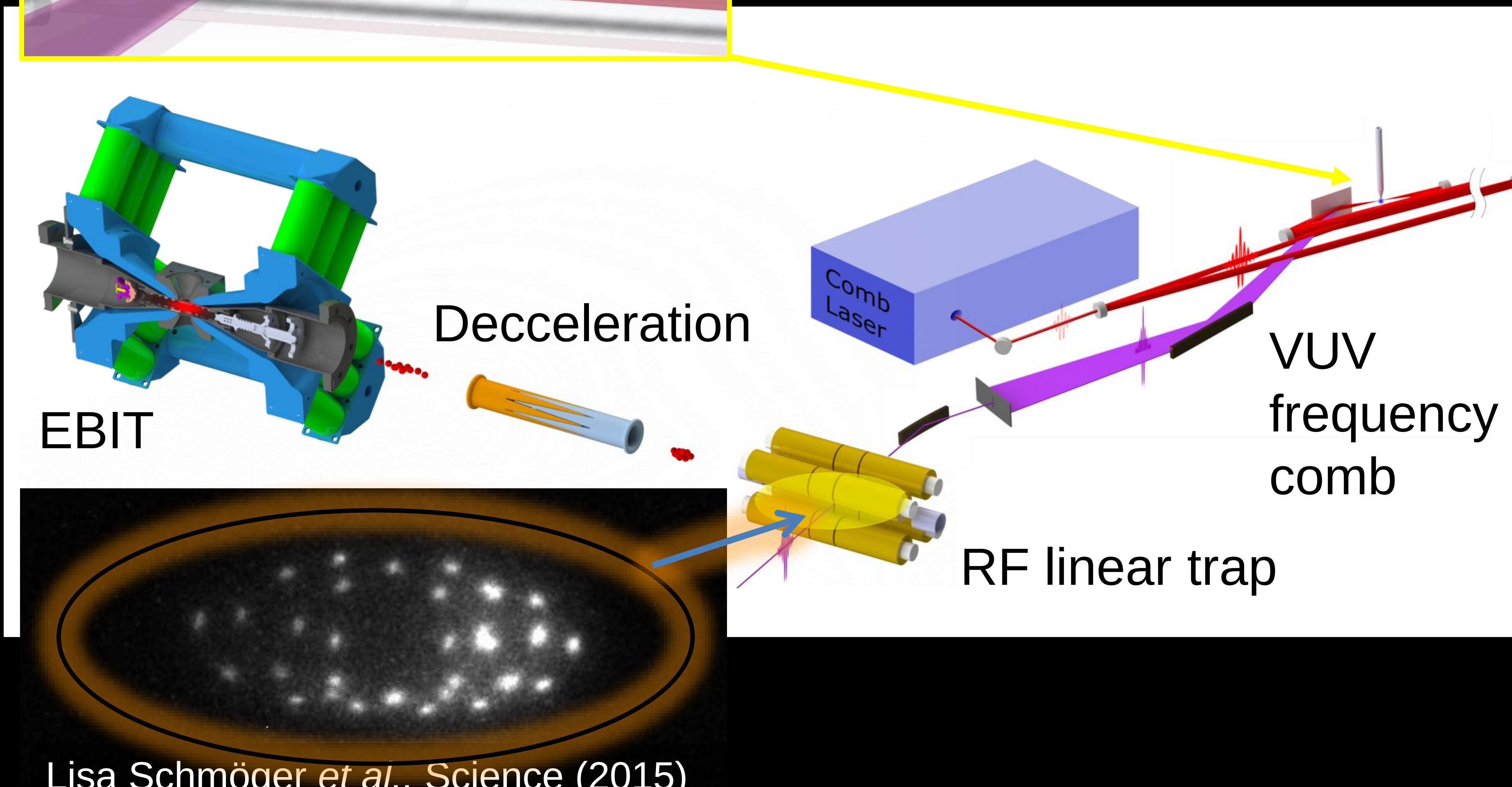
Cavity scanning, 2.5 kW, Xenon 1.6 bar



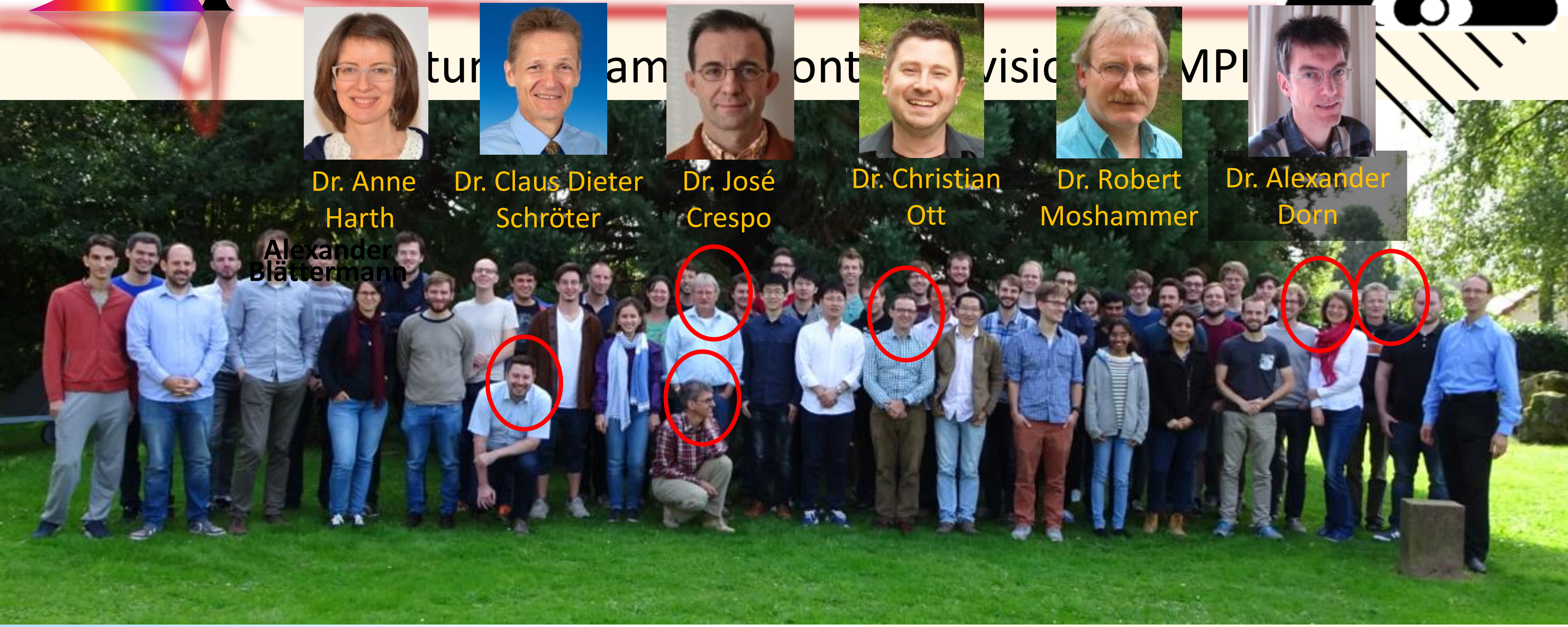
Next-step VUV-Spectroscopy of HCIs



- In-vacuo enhancement cavity
- In 15 µm focus: $\approx 10^{13}$ W/cm^2
- 100 MHz repetition rate



Acknowledgements



Main Cooperators: Thanks to … and many more !

C. Keitel, J. Evers, Z. Harman, S. Cavaletto and groups (MPIK): Fano physics
C. Greene (Purdue Univ., USA): Fano physics
L. Argenti, F. Martín (Univ. A. Madrid, Spain): $2e^-$ WP, 2D spec
J. Madroñero (TUM&Univ. del Valle, Cali, Colombia): $2e^-$ WP
A. Brown, H. Van der Hart (Queens University, Belfast): 2d spec Neon
J. M. Mewes, A . Dreuw, T. Buckup, M. Motzkus (U. Heidelberg): Liquid phase
S. Roling, H. Zacharias (Univ. Münster): FLASH FEL Split and Delay
S. Düsterer, R. Treusch, N. Stojanovich,
G. Brenner, M. Braune (DESY): FLASH FEL exp.
A. Attar (UC Berkeley, USA): FLASH exp.
Z.-H. Loh (NTU, Singapore): FLASH exp.
T. Gaumnitz (ETH Zurich, Switzerland): FLASH exp.

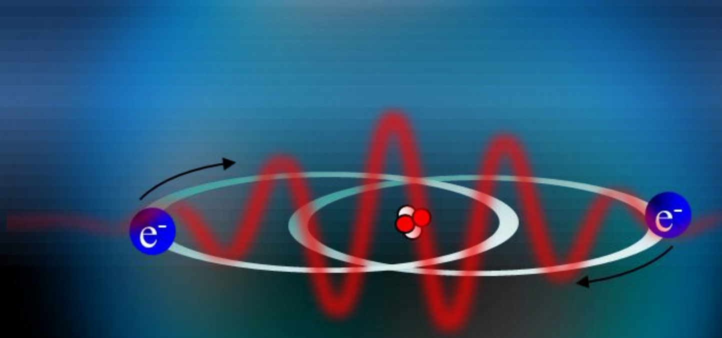
Funding:

DFG
Grant #PF790

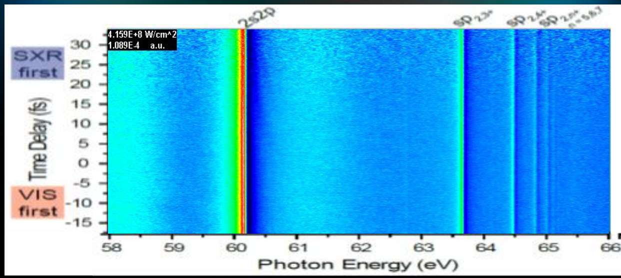
erc
X-MuSiC

Heidelberg Center for Quantum Dynamics

Summary



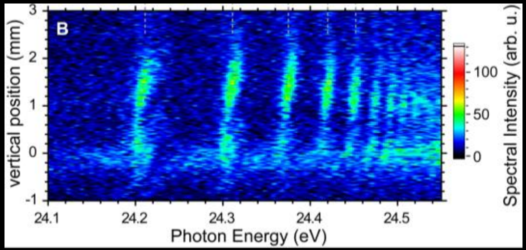
- Ultrafast Laser quantum control of
  small atomic/molecular quantum systems
  (natural, well-defined "Å-labs")
  for fundamental-physics experiments

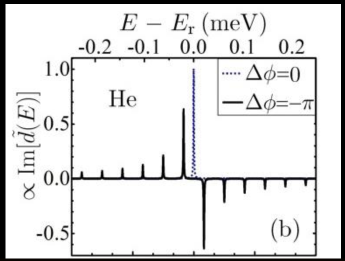


- Phase information is key to quantum dynamics
  and can be retrieved by time-"resolved" experiments

- qualitatively new insights into fundamental processes
  (e.g. Fano ↔ Lorentz, Absorption ↔ Gain)

  => New ideas…





Understand, and modify, general mechanisms of Quantum Dynamics
Unifying Ultrafast Control and Precision Physics