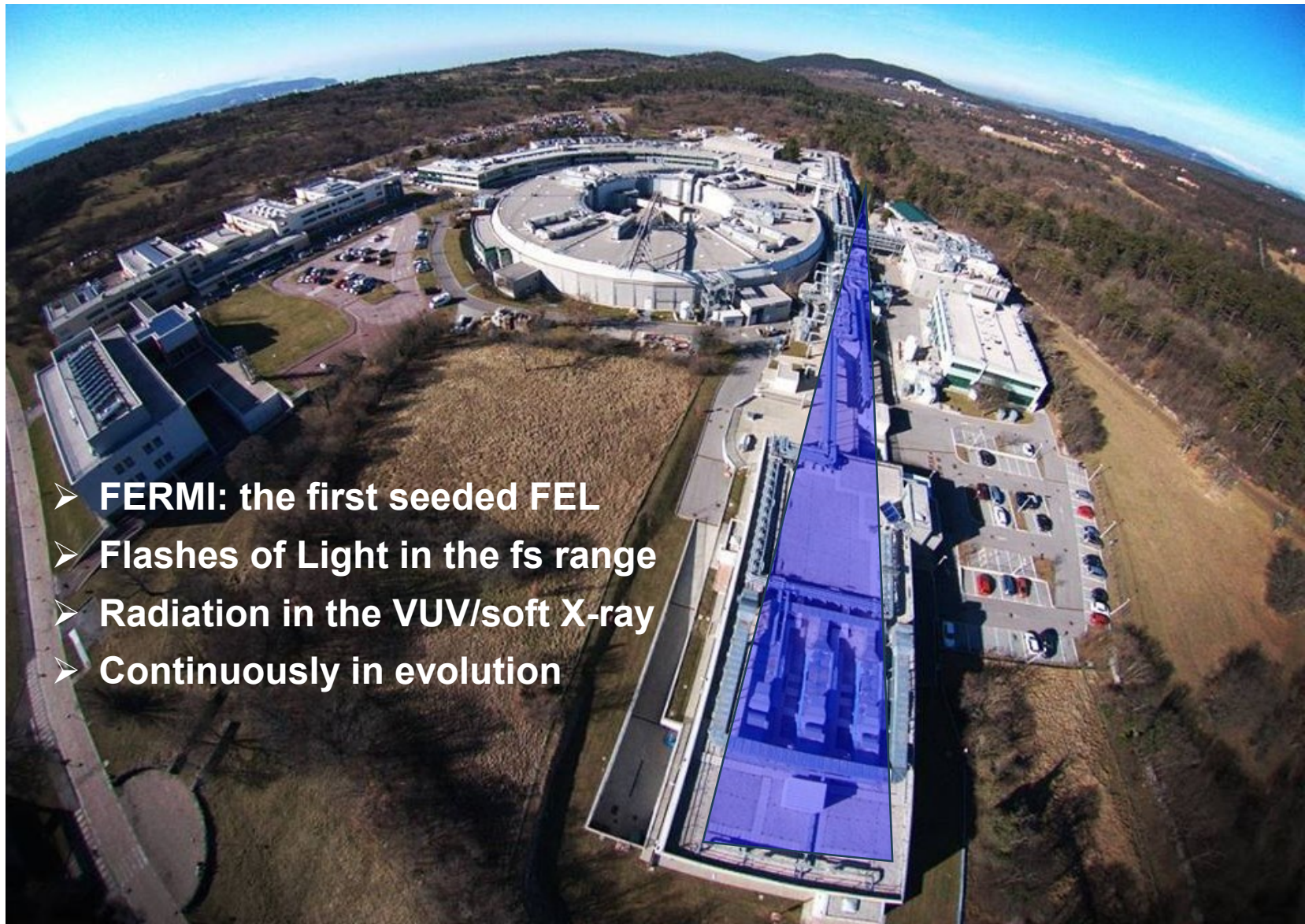


Exploring the Nanoscale with Free Electron Lasers: Current Advances and Future Prospects

Claudio Masciovecchio



- **FERMI: the first seeded FEL**
- **Flashes of Light in the fs range**
- **Radiation in the VUV/soft X-ray**
- **Continuously in evolution**



T. H. Maiman
Stanford Engineering Hero

“A solution looking for a problem”

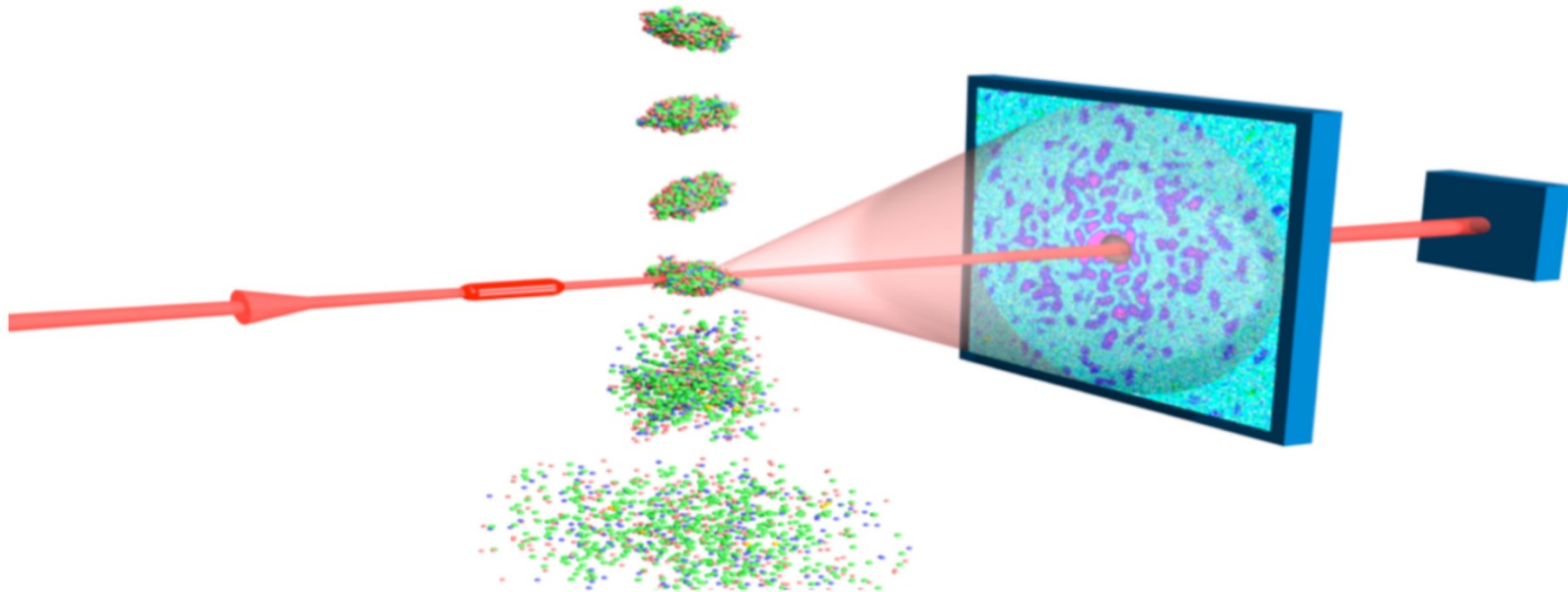
The New York Times

- 1964: A. M. Prokhorov, C. H. Townes & N. G. Basov → fundamental work in **theory**
- 1971: D. Gabor → **holography** in the late 1940's developed thanks to the laser advent
- 1981: N. Bloembergen & A L. Schawlow → laser spectroscopy and **non-linear** optical effects
- 1997: S. Chu, C. Cohen-Tannoudji & William D. Phillips → laser cooling
- 2001: E. A. Cornell, W. Ketterle & C. E. Wieman → laser cooling (Bose-Einstein condensation)
- 2005: J. L. Hall & T. W. Hänsch → optical **frequency comb** technique
- 2009: C. K. Kao → development of **fiber optics** in telecommunications
- 1999: A. Zewail → femtosecond spectroscopy (**femtochemistry**) to picture chemical reactions
- 2018: A. Ashkin, G. Mourou, D. Strickland → Optical **Tweezers** and **CPA**
- 2023: P. Agostini, A. L'Huillier, F. Kraus → **Attosecond** pulse production

Why Free Electron Lasers ?



Leonard comes home...and promptly passes out on the couch. The reason wasn't a good night on the town, however. It was the fact that he's working nights using the **free-electron laser** to conduct his **X-ray diffraction experiment**.



Many biological specimens such as whole **cells**, cellular organelles, some **viruses**, and many important **protein** molecules are difficult or impossible to crystallize and hence their **structures are not accessible** by crystallography

The Phase Problem



In the 1950s, Herbert Hauptman, a mathematician (who had taken just one chemistry class in his life) and physical chemist Jerome Karle showed that by solving a certain large set of equations, the crystal structure can be determined directly. For their (theoretical) solution they were joint recipients of the Chemistry Nobel in 1985.

In the image, combining the phases of the image of Hauptman (left) with the amplitude of Karle (right) gives the image as shown at bottom left. The image below right shows the phases of Karle with the amplitudes of Hauptman.

The phases dominate the resulting image

Nobel Prizes on Protein Structure

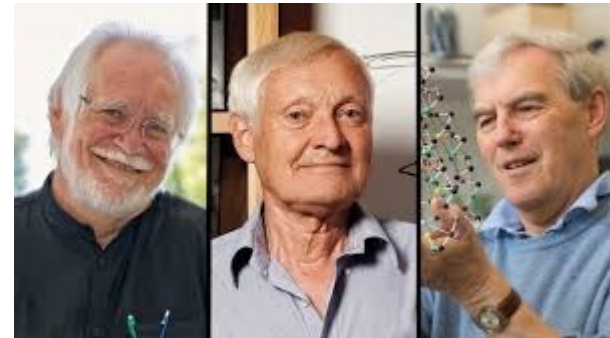
1964 - Dorothy Crowfoot Hodgkin



“....for her determinations by **X-ray** techniques of the structures of important biochemical substances.”

2017 - Jacques Dubochet, Joachim Frank, and Richard Henderson

“....for developing cryo-electron microscopy (**cryo-EM**) for the high-resolution structure determination of biomolecules.”



2024 John Jumper and Demis Hassabis



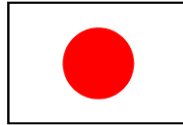
“.... for developing a game-changing AI tool for predicting protein structures called **AlphaFold**, and **David Baker**, for his work on computational protein design, which has been bolstered by AI in the past few years“

FELs worldwide



Elettra Sincrotrone Trieste

SACLA



LCLS



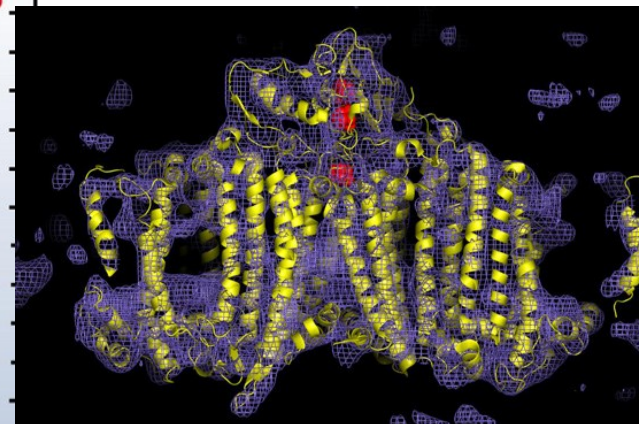
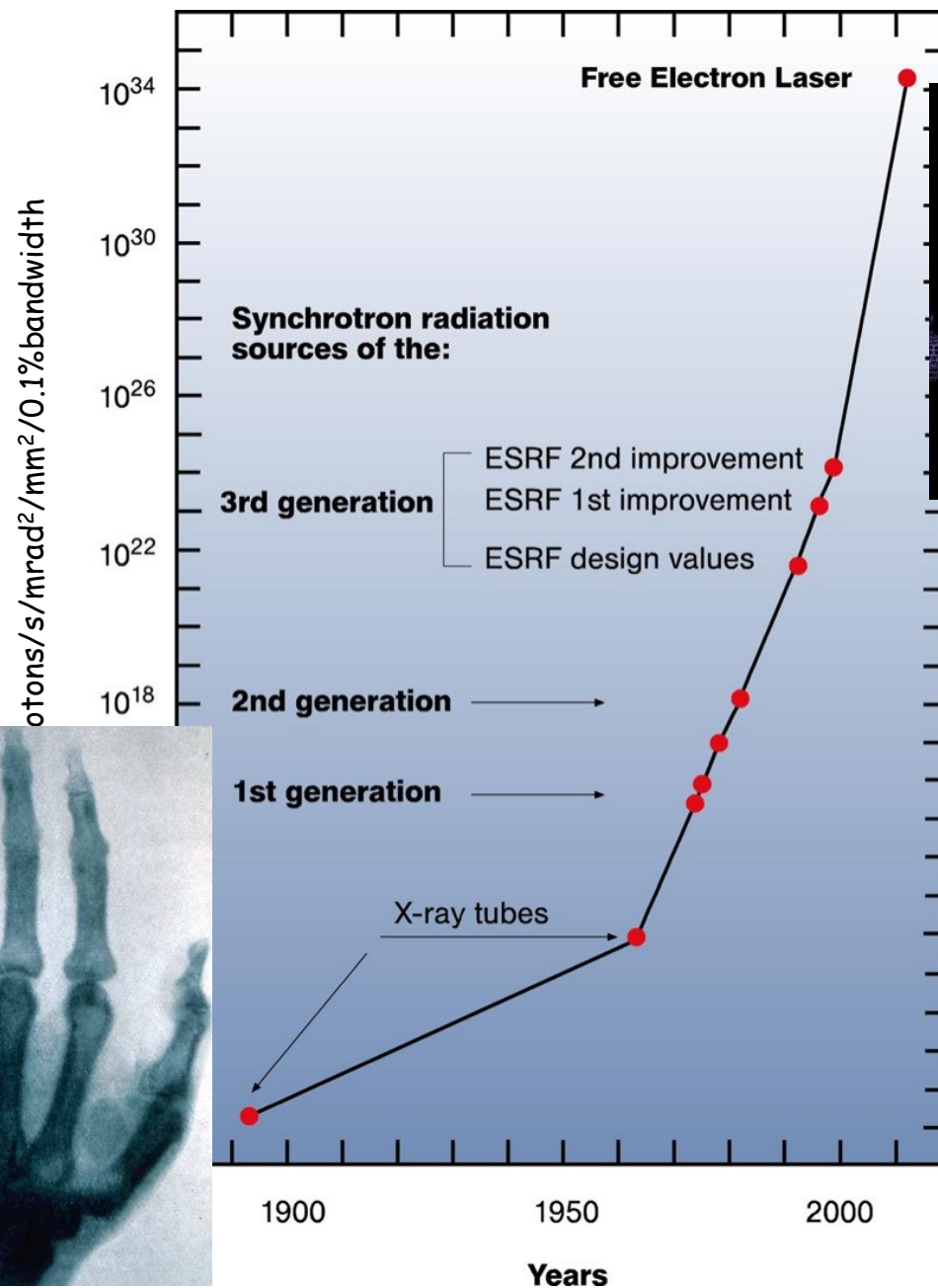
XFEL



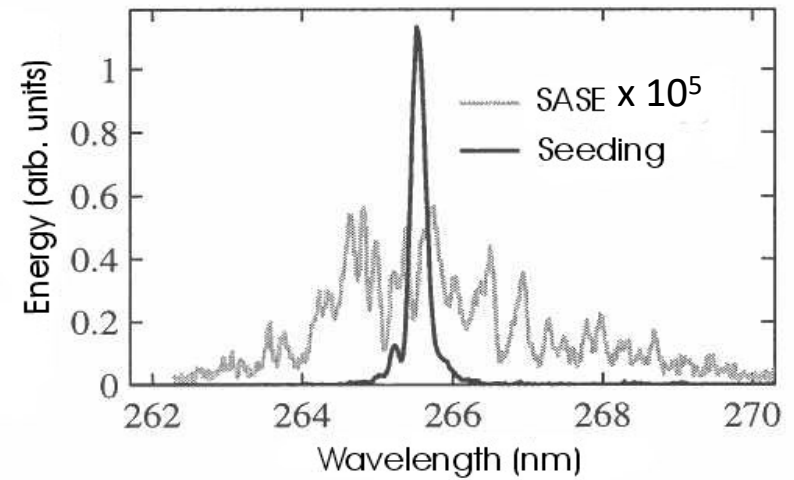
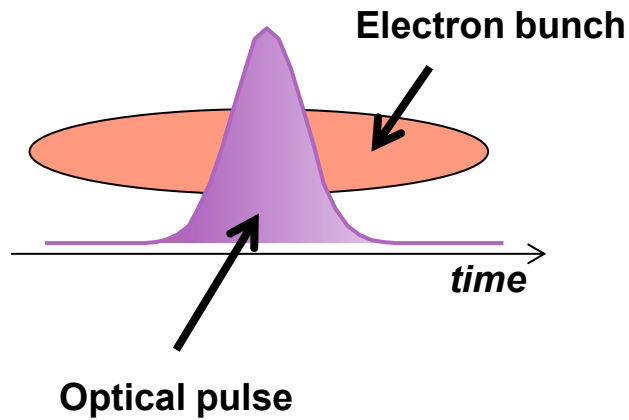
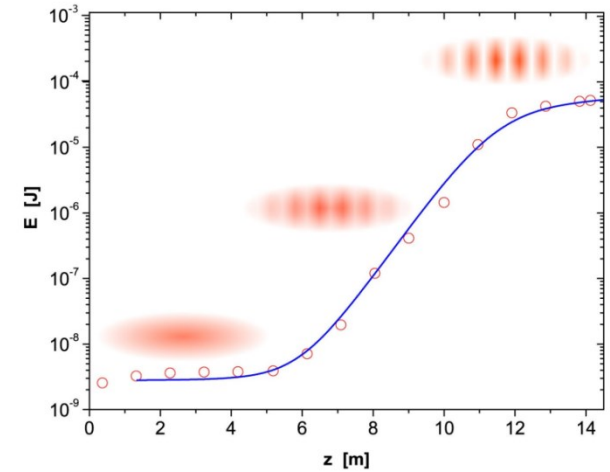
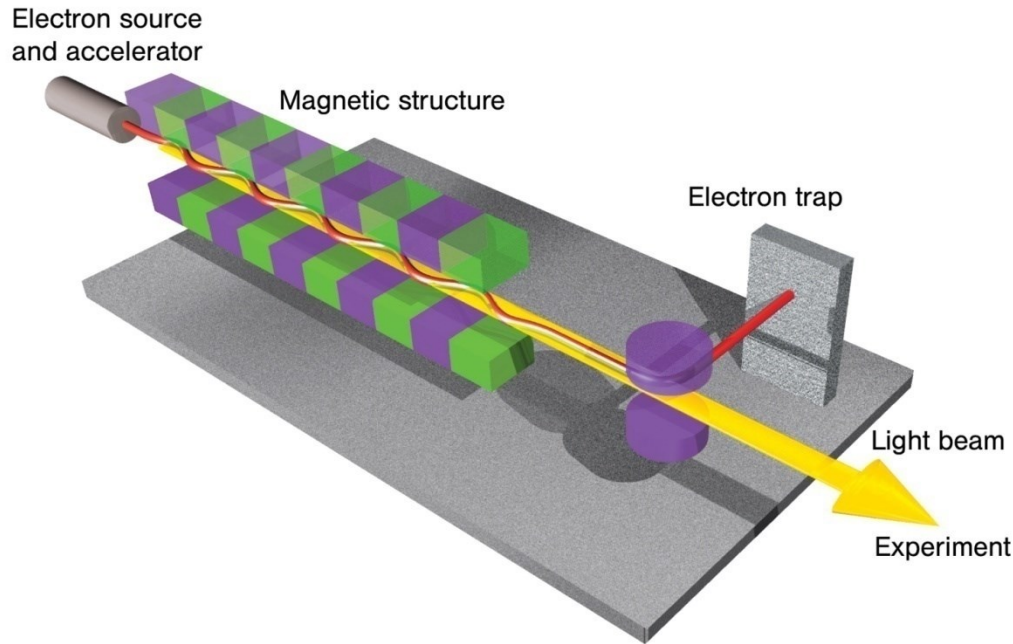
Why Free Electron Lasers ?



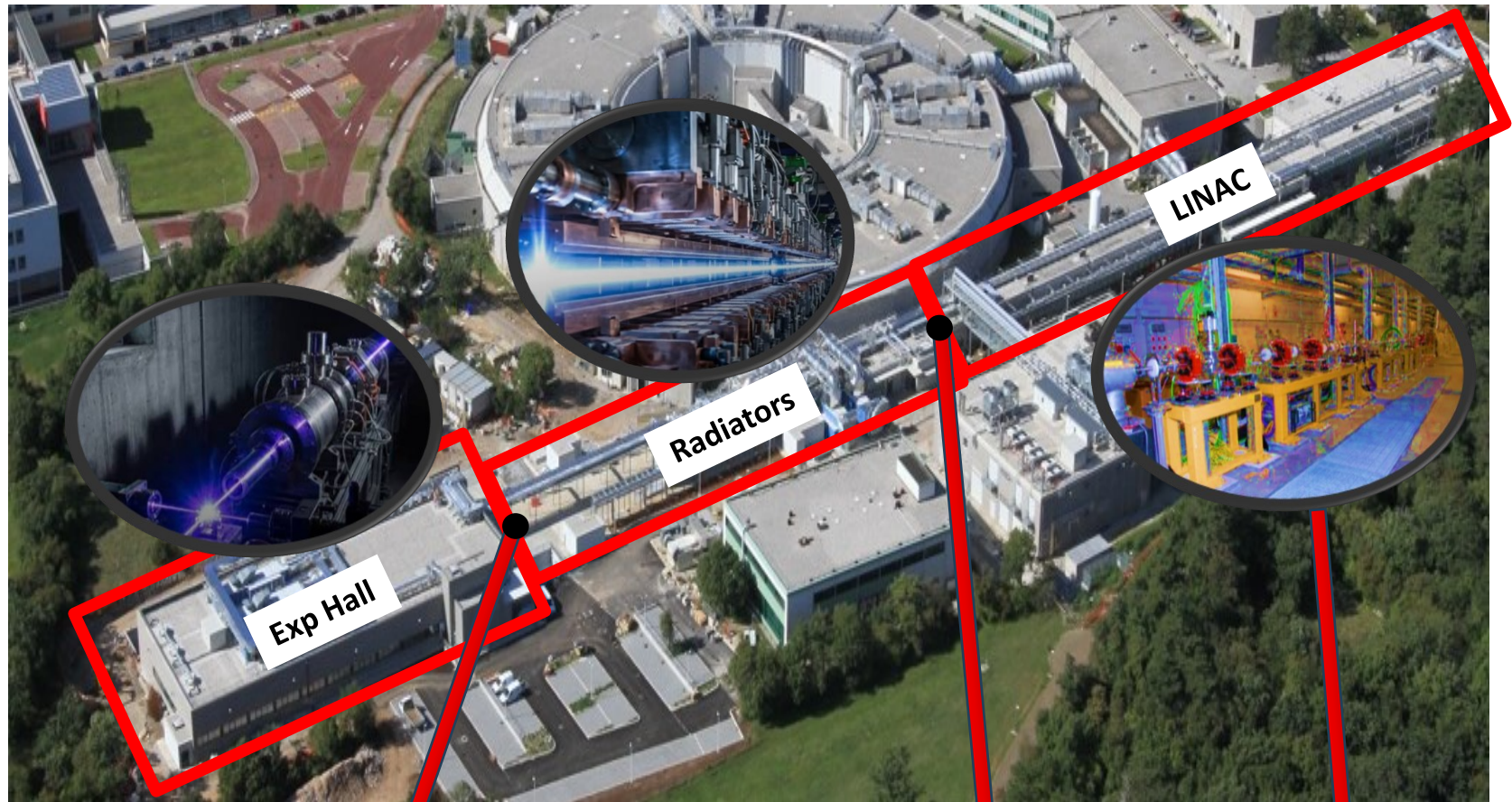
Elettra Sincrotrone Trieste



Free Electron Lasers



L. H. Yu et al., PRL (2003)



FERMI CDR (2007)

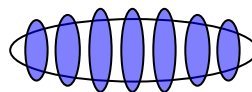
120 eV, 200 fs

Today

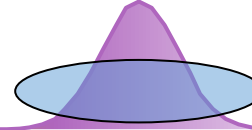
420 eV, 2 fs



FEL pulse



Microbunching



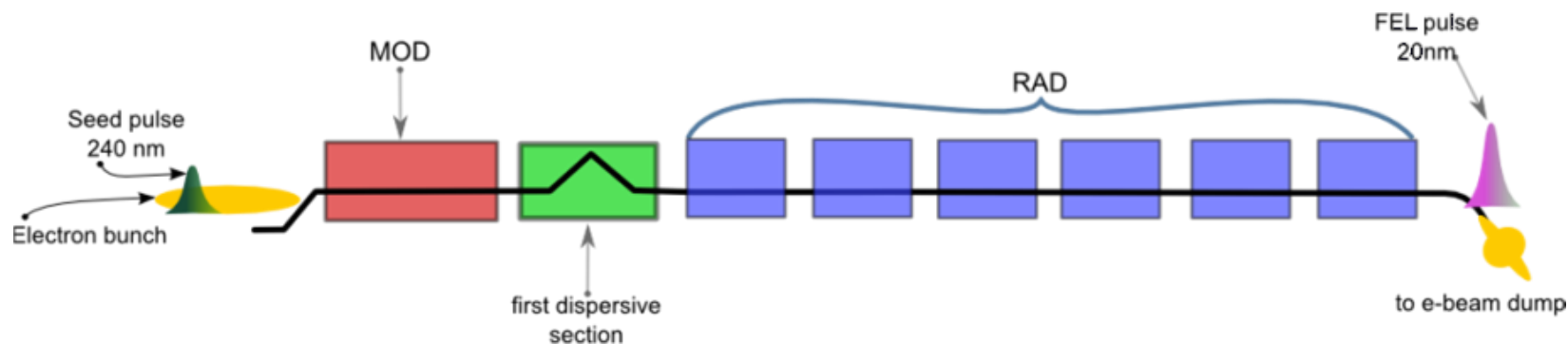
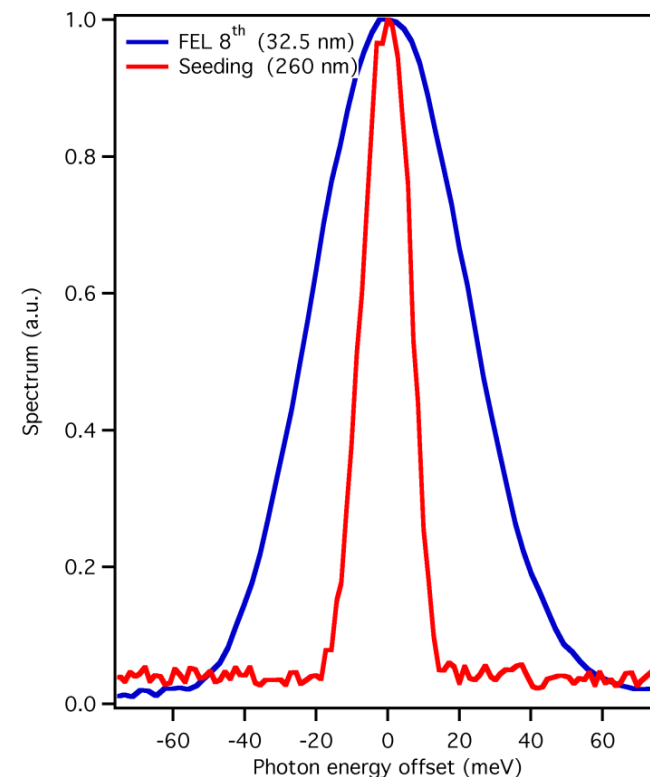
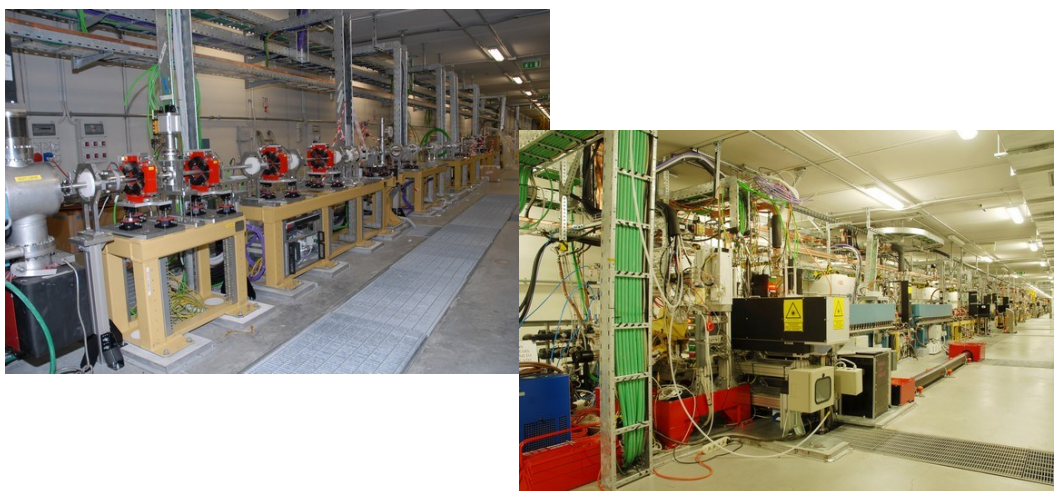
Optical pulse

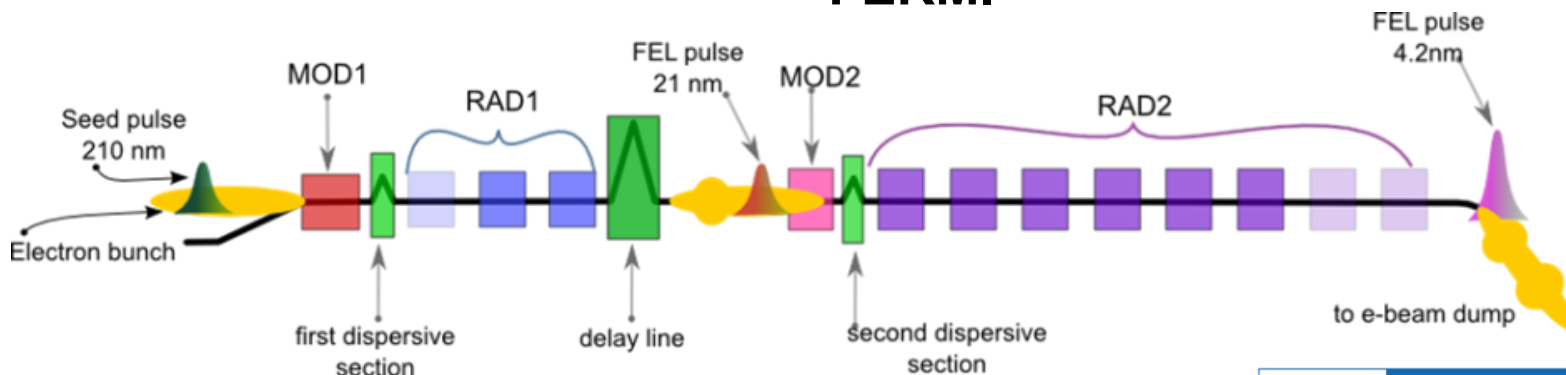


Electron bunch

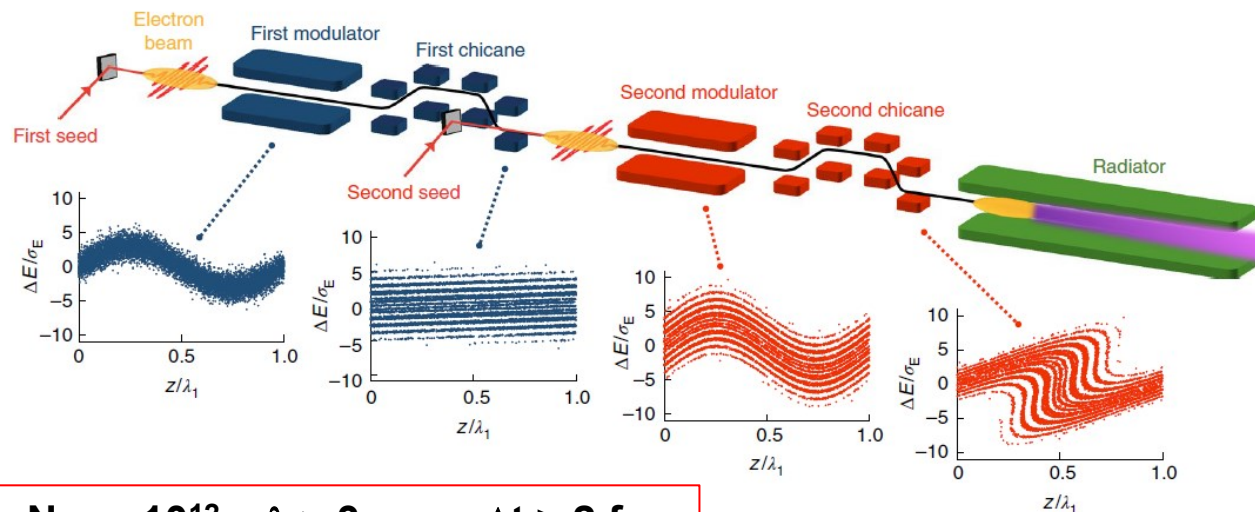
Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet

E Allaria et al., (2012)





Two-stage seeded soft-X-ray free-electron laser



Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser

$$N_{ph} \sim 10^{12} \quad \lambda > 3 \text{ nm} \quad \Delta t > 2 \text{ fs}$$

Polarization

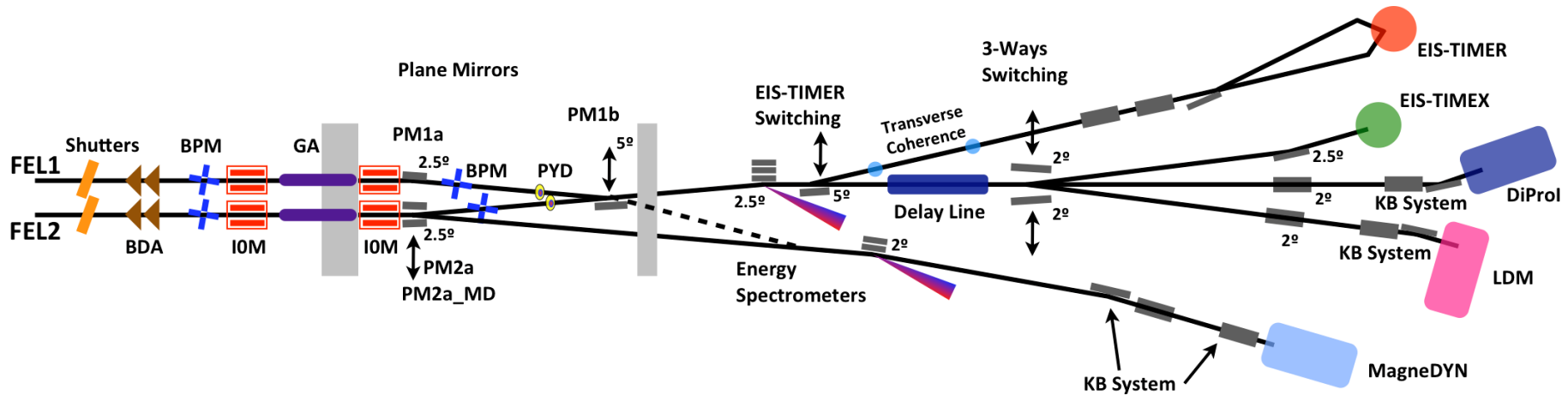
Two pulses (phase locked)

A. Wituszek et al., Nat. Comm. (2020)

Attosecond trains

P. K. Maroju et al., Nature (2020)

FERMI Beamlines



TIMER → FEL-based transient grating, wave-mixing, noncollinear pump & probe

Ref. F. Bencivenga

TIMEX → Extreme and metastable conditions, nonlinear spectroscopy

Ref. E. Principi

DiProl → Diffraction and projection Imaging, magnetic scattering, multipurpose

Ref. F. Capotondi

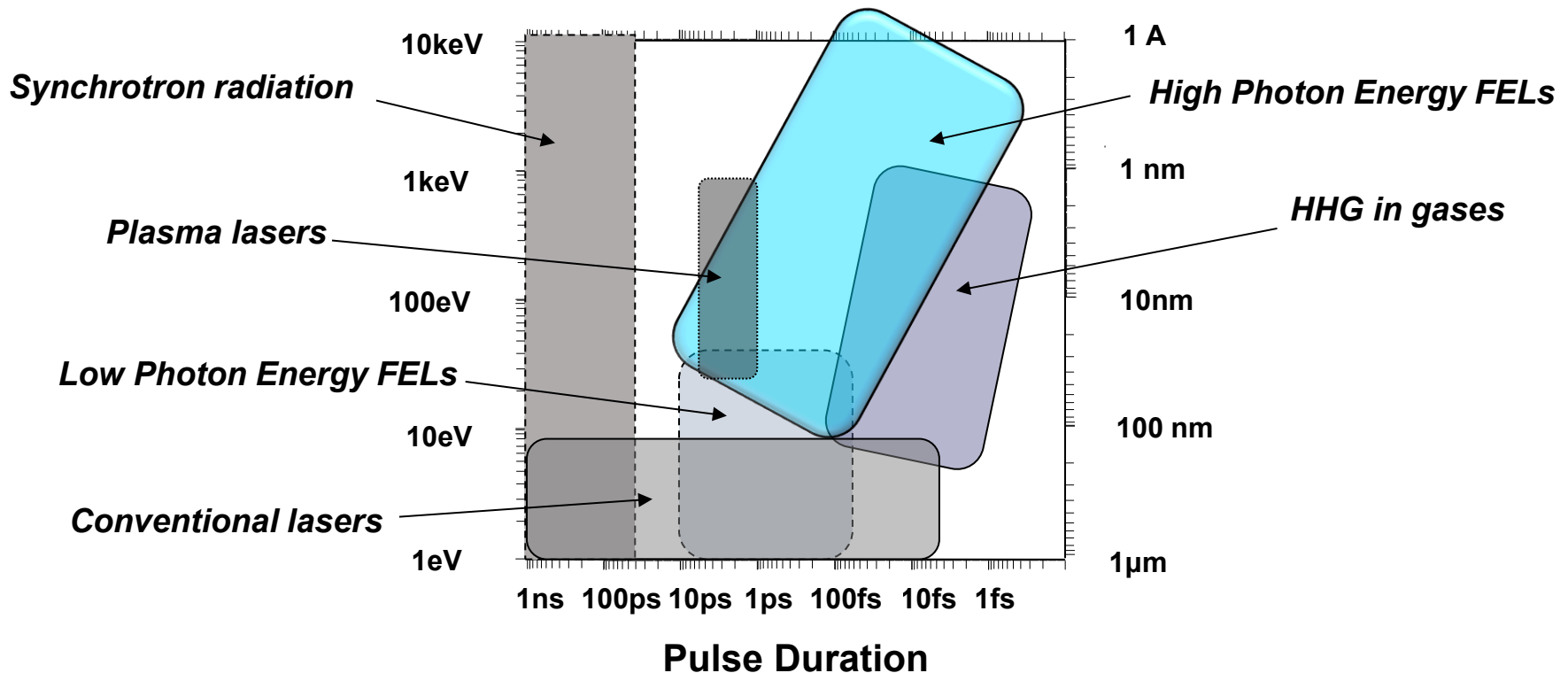
LDM → Low density matter: gas phase samples (atoms, molecules and clusters)

Ref. C. Callegari

MagneDyn → Magnetic dynamics and phase transitions in complex materials

Ref. M. Malvestuto

Why Free Electron Lasers ?

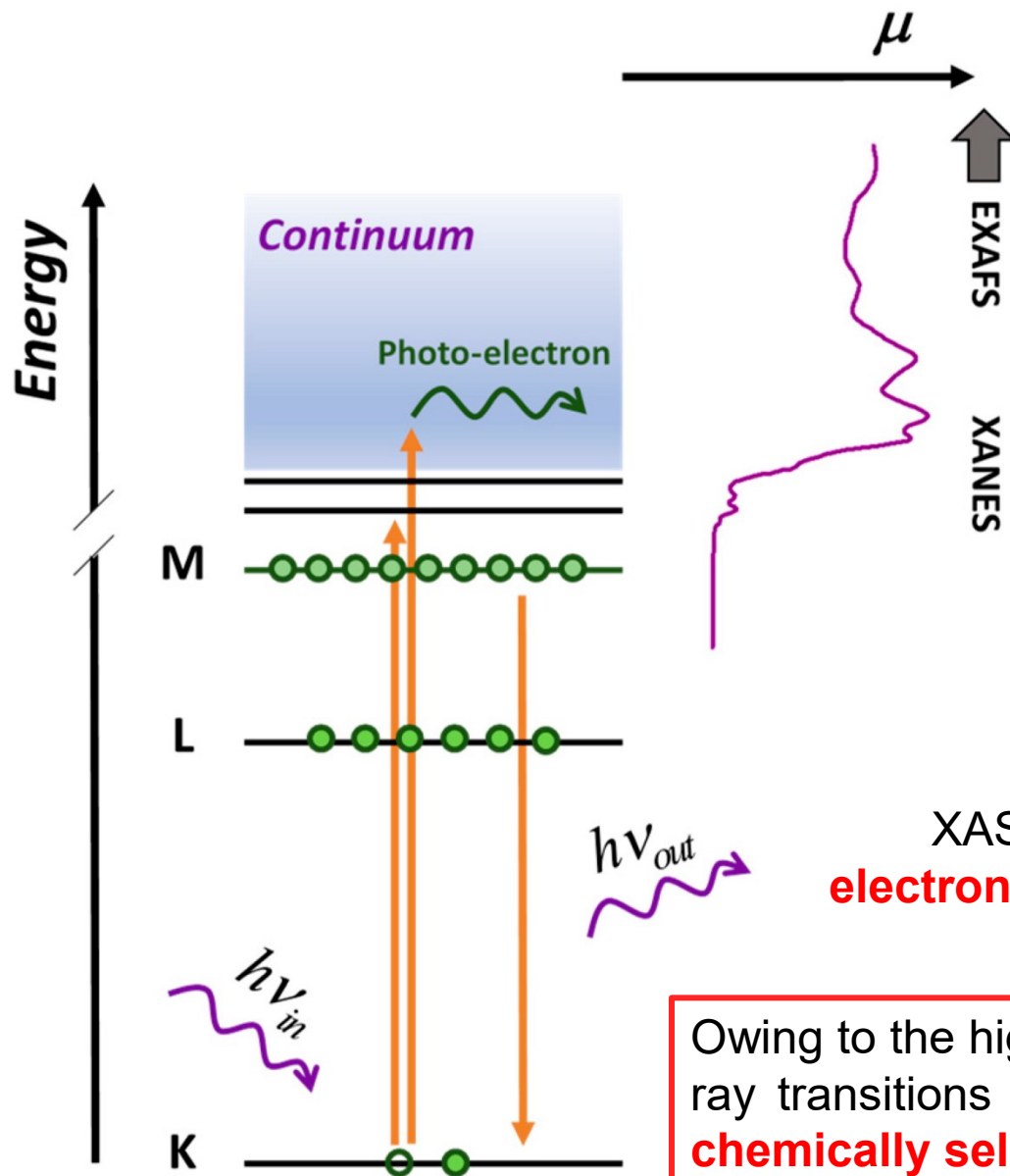


Imaging with high Spatial Resolution ($\sim \lambda$): fixed target & particle injection imaging,...

Resonant Experiments: **absorption**, circular dichroism, chemical mapping,

Dynamics: wave mixing (**nonlinear optics**), extreme condition, WDM,

X-ray Absorption



The **post-edge** part of the spectrum gives information about interatomic distances and bond angles

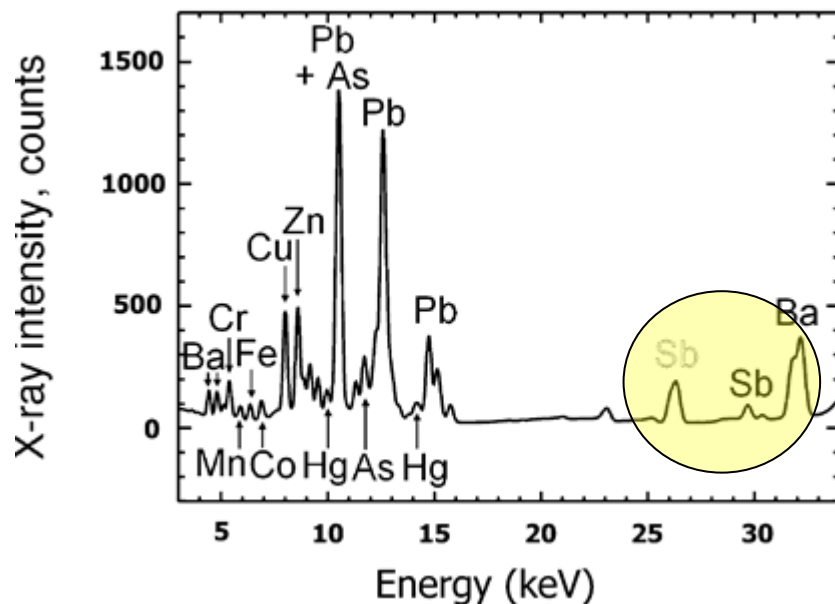
The **main edge** features are used for the determination of the local geometry around an absorbing atom (can be shifted due to bonding characteristics) and the position reveals the oxidation state

XAS provides information on the local **electronic** and **atomic structure** of a selected element

Owing to the highly localized nature of core orbitals, X-ray transitions transform individual **atomic sites** into **chemically selective probes** of electronic structure



Patch of Grass - Vincent Van Gogh



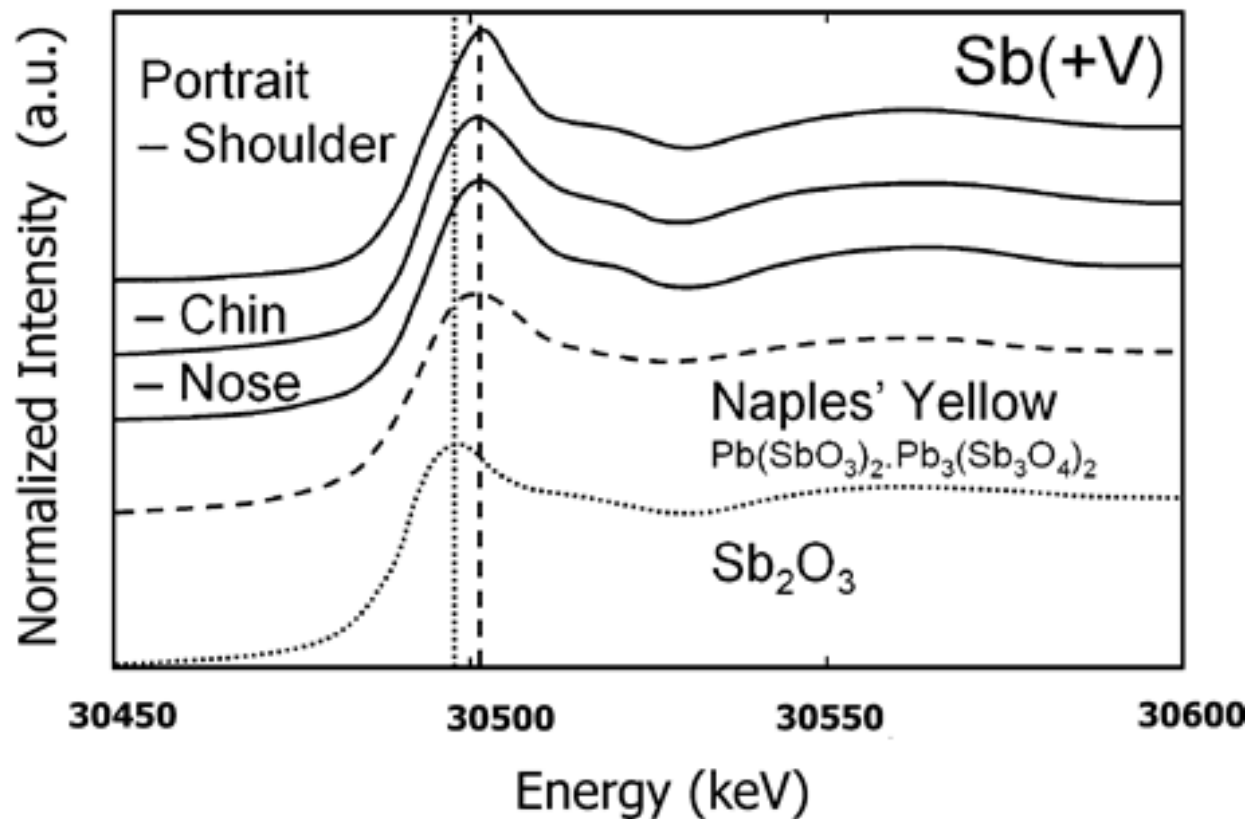
Three elements were found to overlap with the hidden face: Hg, Sb and Zn. Mercury is associated with the red pigment cinnabar and Zn with zinc white. Sb was found in the lighted parts of the face → **what pigment** was used?



Naples yellow ($\text{Pb}(\text{SbO}_3)_2$, $\text{Pb}_3(\text{Sb}_3\text{O}_4)_2$)

Antimony white (Sb_2O_3)

X-ray Absorption



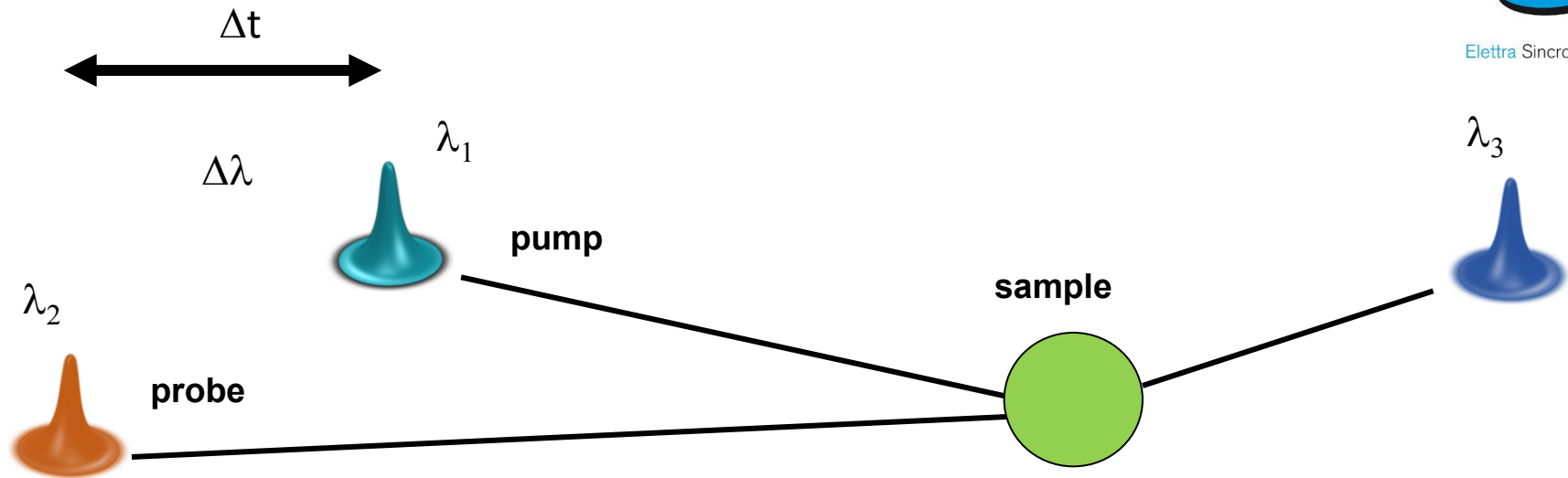
Naples yellow ($\text{Pb}(\text{SbO}_3)_2$, $\text{Pb}_3(\text{Sb}_3\text{O}_4)_2$)

Antimony white (Sb_2O_3).



Head of a woman, Nuenen, winter 1884
Vincent Van Gogh Museum, Amsterdam

Pump & Probe (Wave Mixing)



The **pump** pulse produces **a change** in the sample

- stimulate a chemical reaction
- non-equilibrium states
- extreme thermodynamic conditions
- ultrafast demagnetization
- coherent excitations
-

Pump → Table-top Laser, FEL

Probe1 → Table-top Laser (single energy or Super-continuum (CaF₂ crystal))

Probe2 → FEL (first or third harmonics (tunability))

Probe3 → Electron Diffraction (100 fs, 200 keV)

Important parameters:

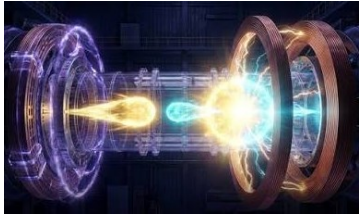
Pulse Duration, Pulse wavelength

Time Delay (100 fs ~ 30 μ m), Time Jitter

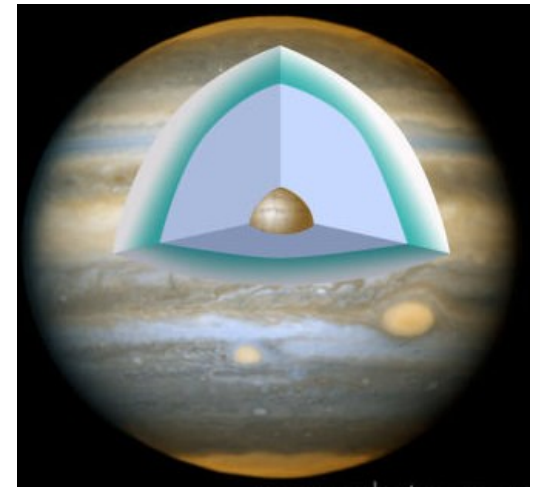
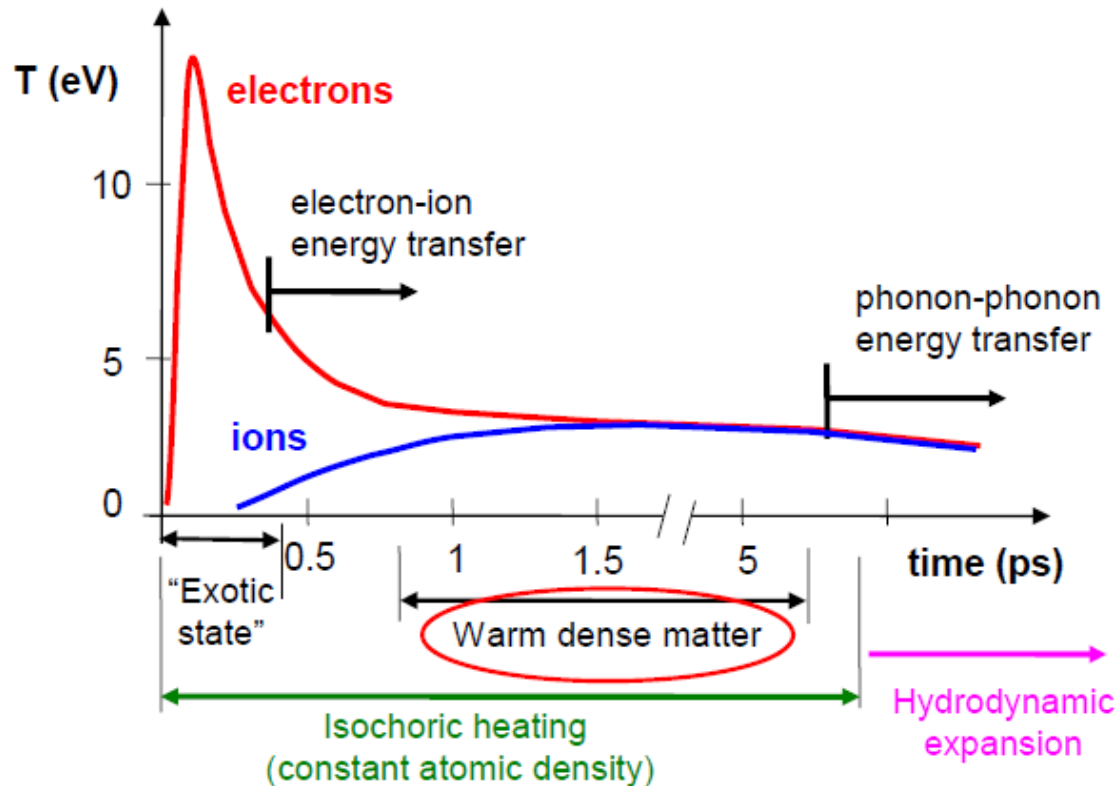
Extreme Thermodynamic Conditions



Elettra Sincrotrone Trieste



Societal challenge → Developing practical inertial confinement **Fusion** provide a virtually limitless source energy. Achieving controlled fusion requires the understanding of matter under extreme conditions



interior of **large planets** and stars

Liquid Carbon



Elettra Sincrotrone Trieste

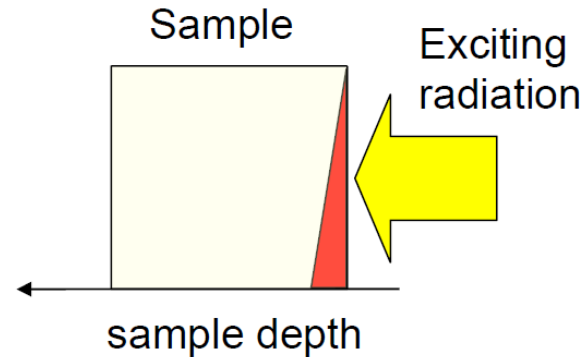
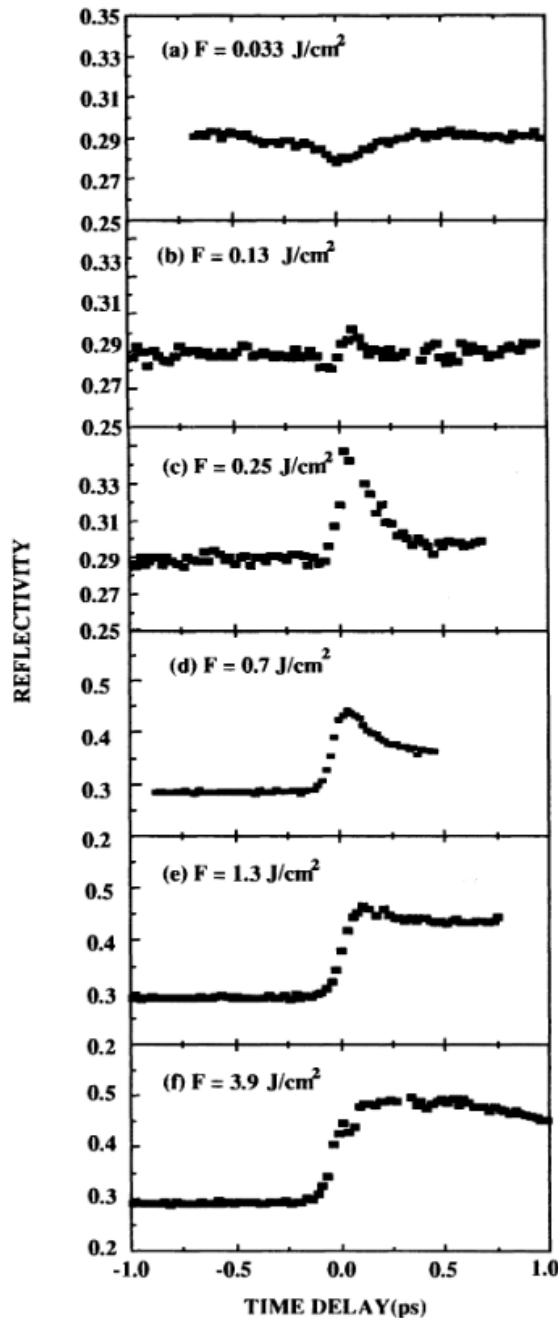


NEWS AND VIEWS
CONDENSED STATE

First light on fluid carbon

Nicolaas Bloembergen

D.H. Reitze, et al., Phys. Rev. B (1992)



For $\omega < \omega_p$ the plasma **screens** the sample from the radiation $\rightarrow$ high-reflectivity and limited ($\approx$ nm) penetration depth. Energy transfer to the bulk is reduced, the sample excitation is inhomogeneous

FEL pulses allow **uniform** heating:

300 Å Al **uniformly** heated at 1 eV (10^4 K)

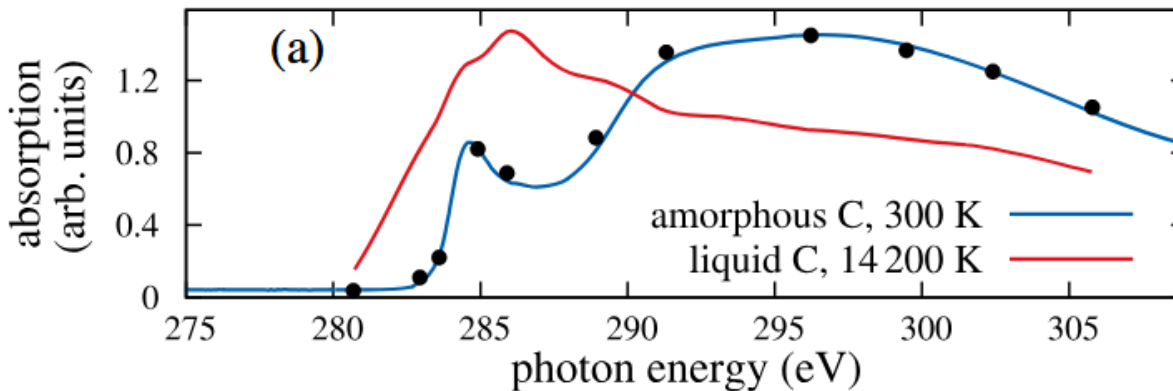
$\Delta t = 100$ fs, $\lambda = 60$ nm,

$d = 10$ mm², 10^{12} ph/pulse

Ultrafast Melting in Carbon

PHYSICAL REVIEW LETTERS **125**, 155703 (2020)

Atomic and Electronic Structure of Solid-Density Liquid Carbon



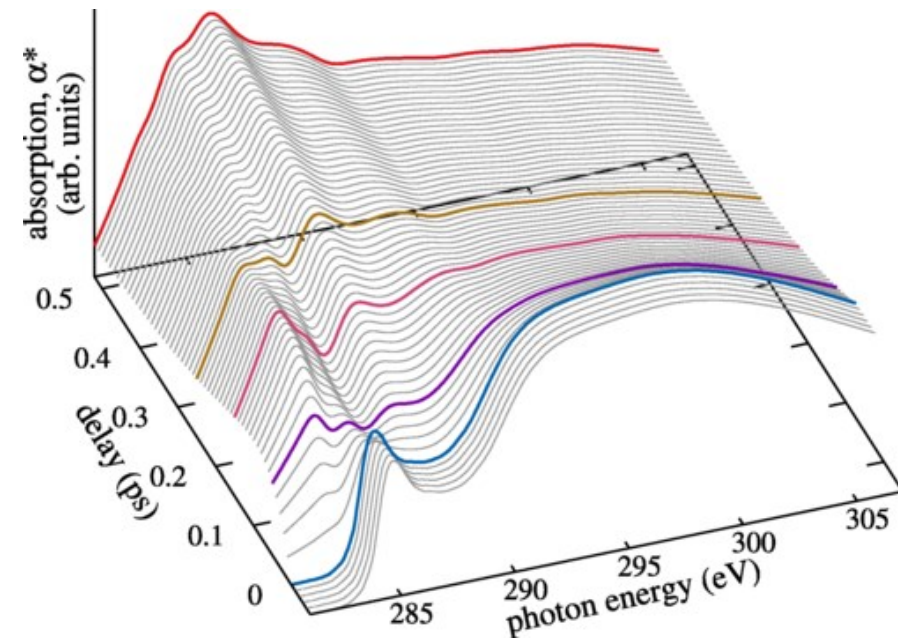
Pump → Table-top Laser (390 nm)

Probe → FEL @ Carbon K edge

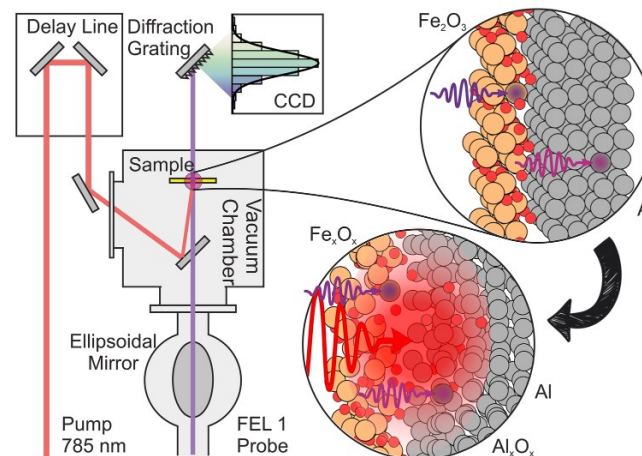
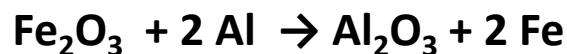
Sub-picosecond rearrangement of the electronic structure associated with a sudden change of the C bonding hybridization



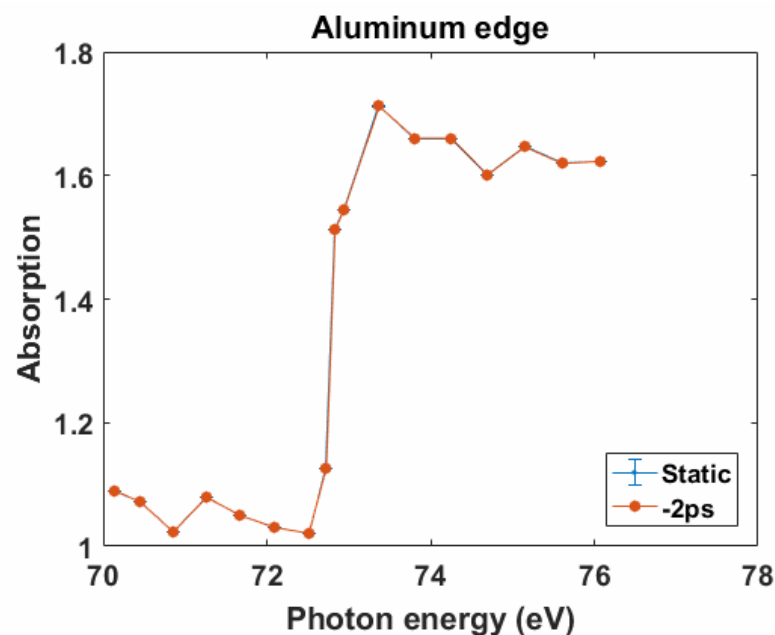
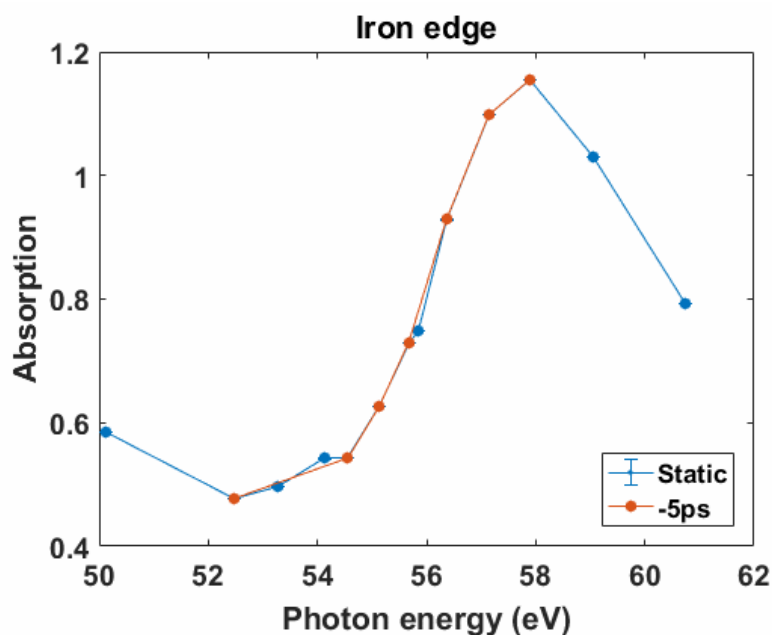
Ultrafast Melting



Time-resolved chemically-selective spectroscopic investigation of the redox reaction between hematite and aluminium



Pump → Table-top Laser (390 nm) Probe → FEL @ Al and Fe M edges





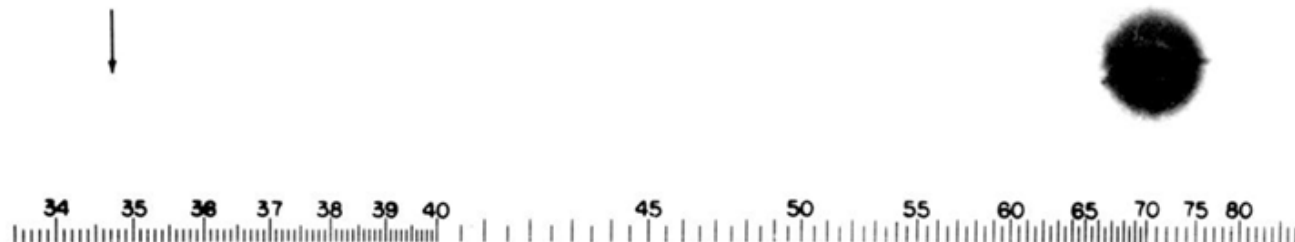
VOLUME 7, NUMBER 4

PHYSICAL REVIEW LETTERS

AUGUST 15, 1961

GENERATION OF OPTICAL HARMONICS*

P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich



Famously, when published in the journal *Physical Review Letters*, the copy editor mistook the dim spot (at 347 nm) on the photographic paper as a [speck of dirt](#) and removed it from the publication.



N. Bloembergen

$$P_i = \chi_{ij}^{(1)} E_j + \chi_{ijk}^{(2)} E_j E_k + \chi_{ijkl}^{(3)} E_j E_k E_l + \dots$$

Non linear techniques are **powerful** when one wants to measure **sample properties** that cannot be addressed by *conventional* linear spectroscopy or to obtain spectroscopic information with a higher **sensitivity** than that associated with linear spectroscopy

ω_{OUT} is a **combination** of ω_j , ω_k , and ω_l

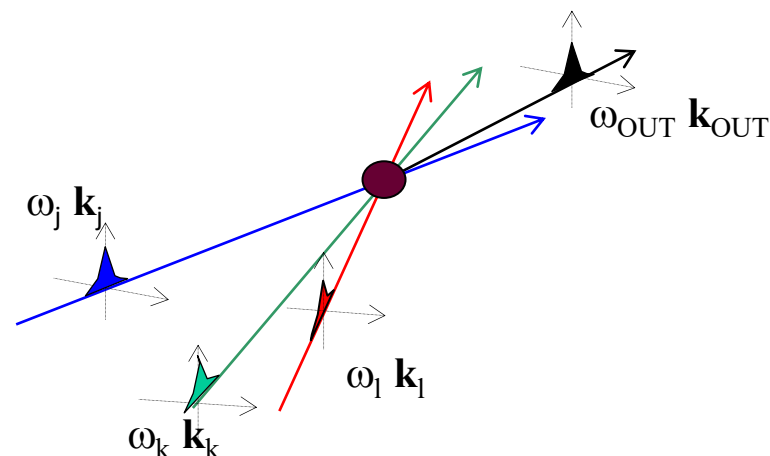
$$\omega_j + \omega_k + \omega_l$$

$$3\omega_\xi, \omega_\xi \quad \xi = j, k, l$$

$$2\omega_j \pm \omega_k, 2\omega_j \pm \omega_l, 2\omega_k \pm \omega_l$$

$$2\omega_k \pm \omega_l, 2\omega_l \pm \omega_j, 2\omega_l \pm \omega_k$$

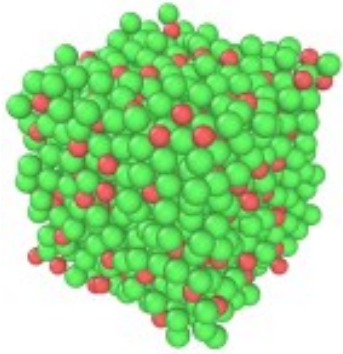
$$\omega_j + \omega_k - \omega_l, \omega_j - \omega_k + \omega_l, -\omega_j + \omega_k + \omega_l$$



$$I_{OUT} \sim I_j I_k I_l |\chi^{(3)}|^2 N^2 L^2 \text{sinc}^2(\Delta k / 2L)$$

$$\Delta k = k_{out} - \sum k_{in}$$

Transient Grating $\rightarrow \omega_j = \omega_k$

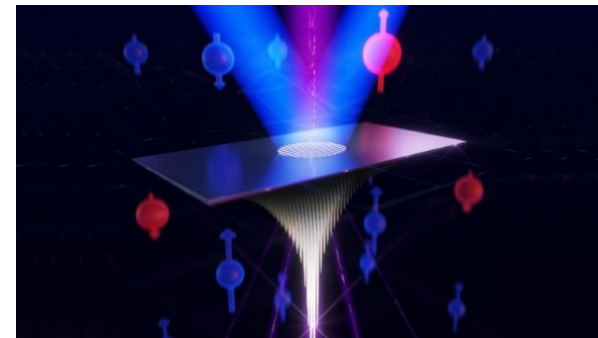


Scientific challenges → The study of collective dynamics in condensed matter at the nanoscale (**vibrational or magnetization dynamics**) is important for advancing fundamental science and modern technology

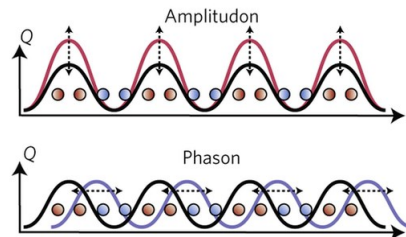
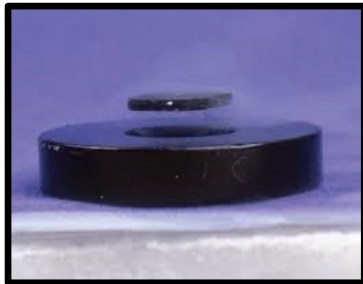
Semiconductors



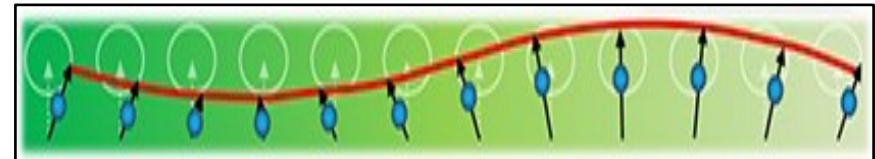
All Optical Switching



Many Body Phenomena



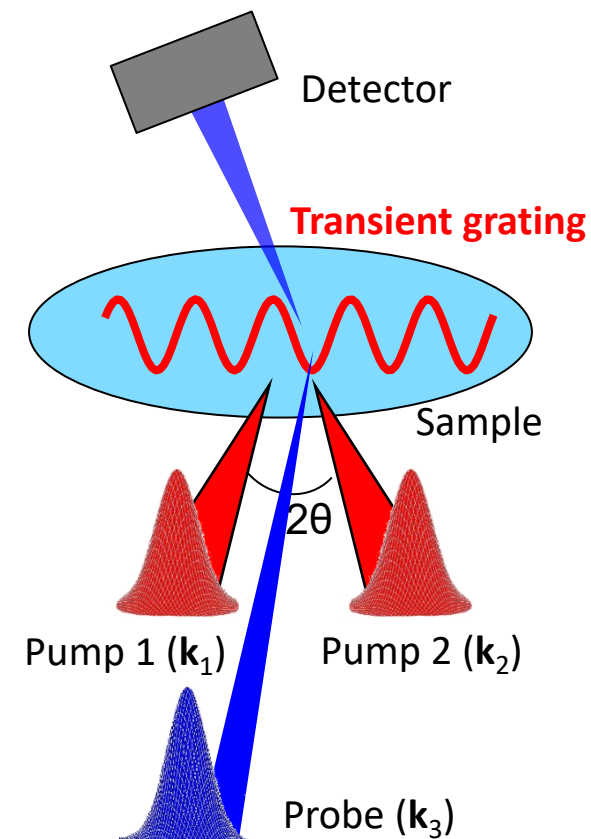
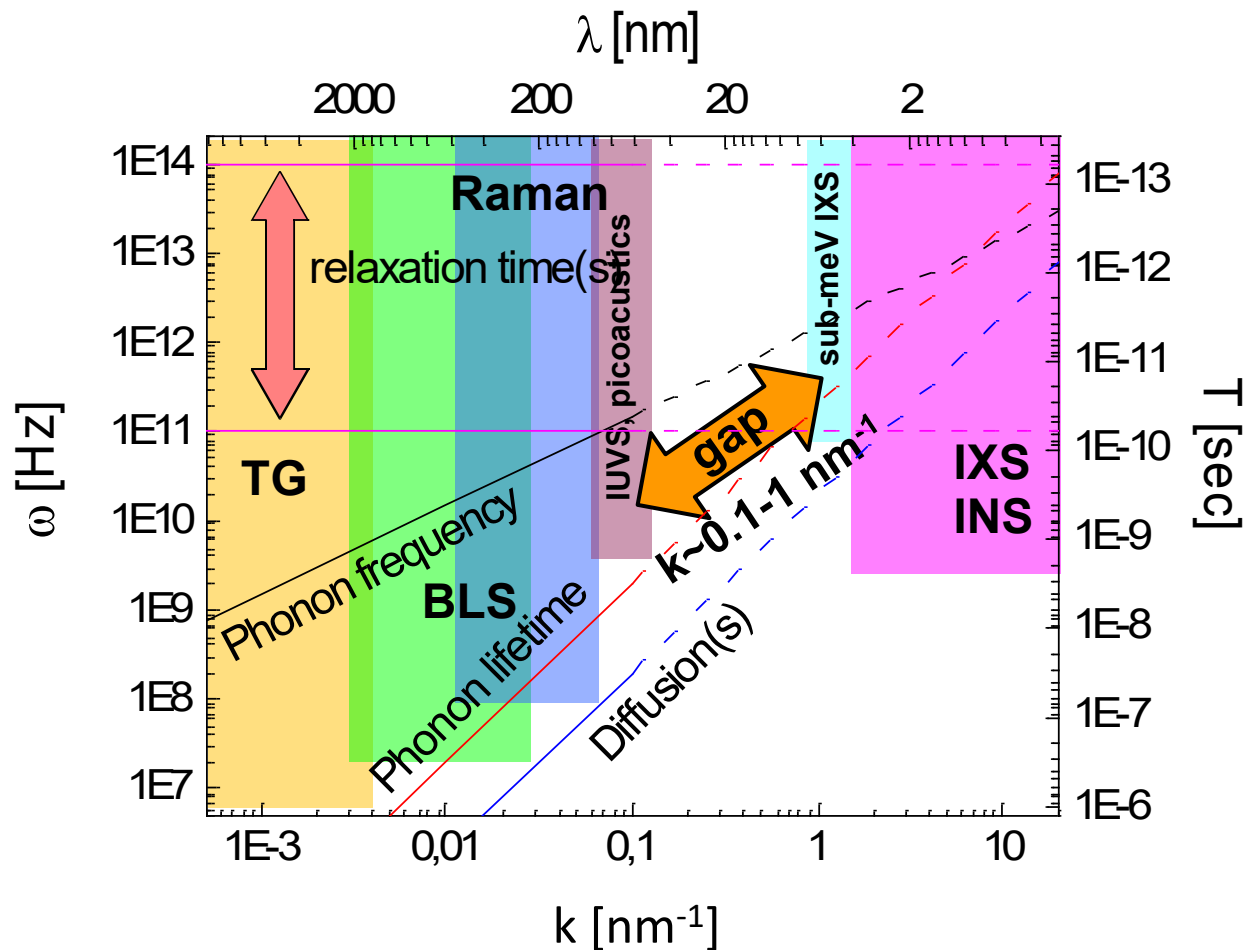
Ultrafast Magnetism



Collective Dynamics at the Nanoscale

Our initial aim was probing collective lattice dynamics ($\rightarrow$ **ps dynamics**, e.g.: phonons, transport phenomena, structural relaxations, etc.) at 'mesoscopic' scales (**10's nm**)

F. Bencivenga and C. Masciovecchio NIMA 2009



$$L_{TG} = \lambda_{\text{pump}} / 2 \sin(2\theta/2)$$

The nature of the vibrational dynamics in **glasses** at the nanoscale is still unclear (V-SiO₂)

M. Foret *et al.*, *PRL* **77**, 3831 (1996) → They are localized above $\sim 1 \text{ nm}^{-1}$

P. Benassi *et al.*, *PRL* **77**, 3835 (1996) → Existence of propagating excitations at high ω

F. Sette *et al.*, *Science* **280**, 1550 (1998) → They are acoustic-like

G. Ruocco *et al.*, *PRL* **83**, 5583 (1999) → Change of sound attenuation mechanism at 0.5 nm^{-1}

B. Rufflè *et al.*, *PRL* **90**, 095502 (2003) → Change is at 1 nm^{-1}

C. Masciovecchio *et al.*, *PRL* **97**, 035501 (2006) → Change is at 0.2 nm^{-1}

W. Schirmacher *et al.*, *PRL* **98**, 025501 (2007) → Model agrees with Masciovecchio *et al.*

B. Rufflè *et al.*, *PRL* **100**, 015501 (2008) → Schirmacher model is not correct

G. Baldi *et al.*, *PRL* **104**, 195501 (2010) → Change is at 1 nm^{-1}

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L. Foglia *et al.*, Photoacoustics 2023

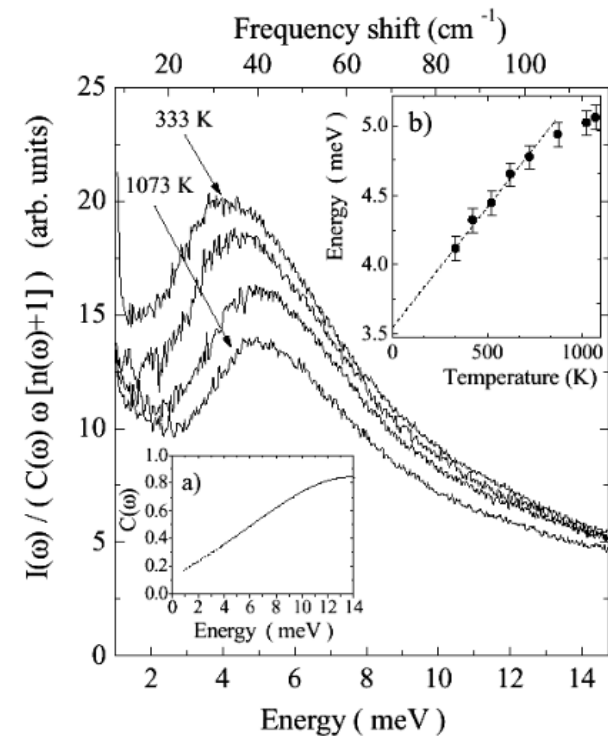
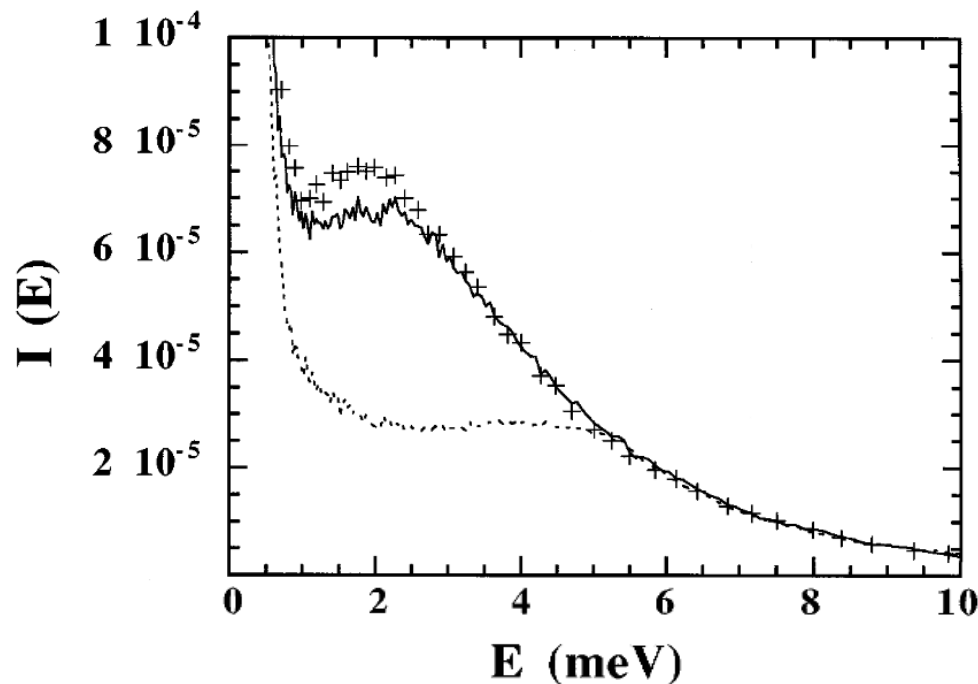
Fundamental to understand the anomalies in **glasses**



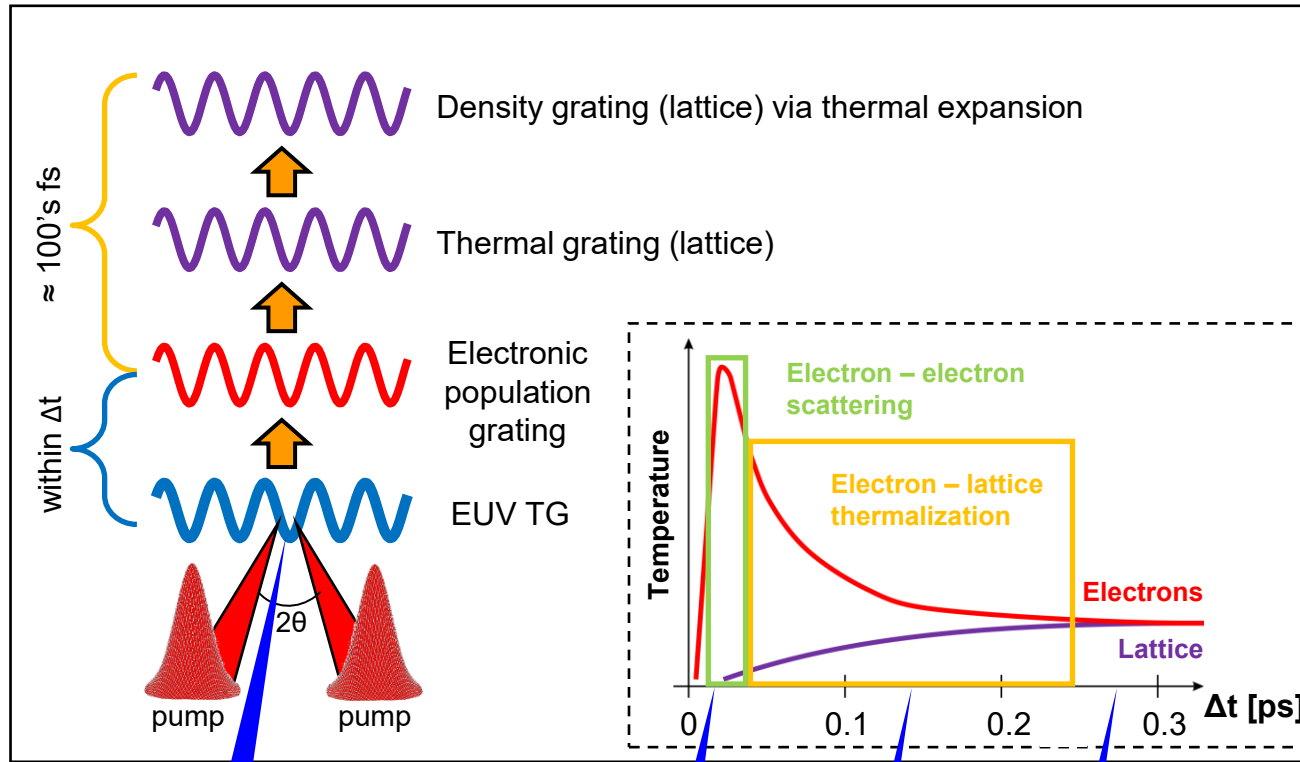
On the origin of the boson peak

Giorgio Parisi

Dipartimento di Fisica, Sezione INFN, SMC and INFM unità di Roma 1, Università di Roma La Sapienza, Piazzale Aldo Moro 2, I-00185 Rome, Italy



Transient Grating



probe

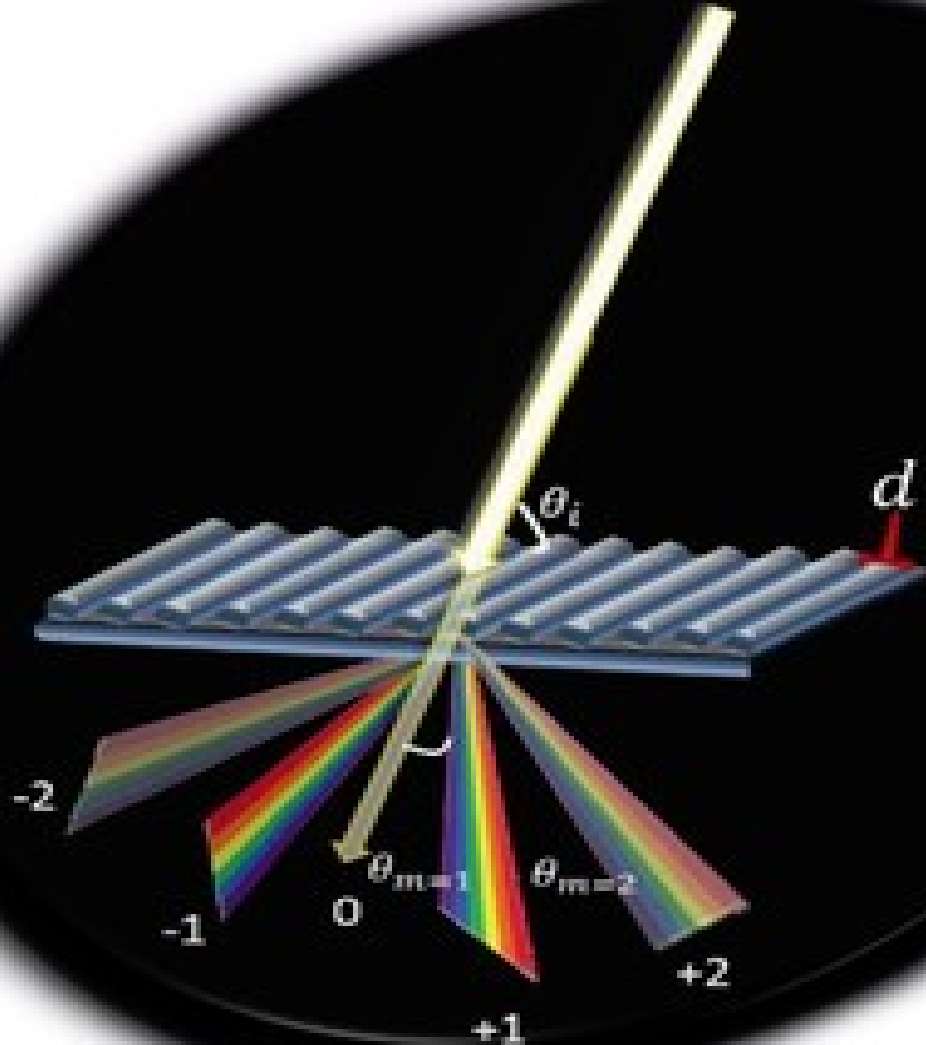
Electron/Spin
diffusion

Quasiparticle
diffusion

Phonons/Magnons and
Thermal diffusion

Δt 100's ps

Transmission Grating

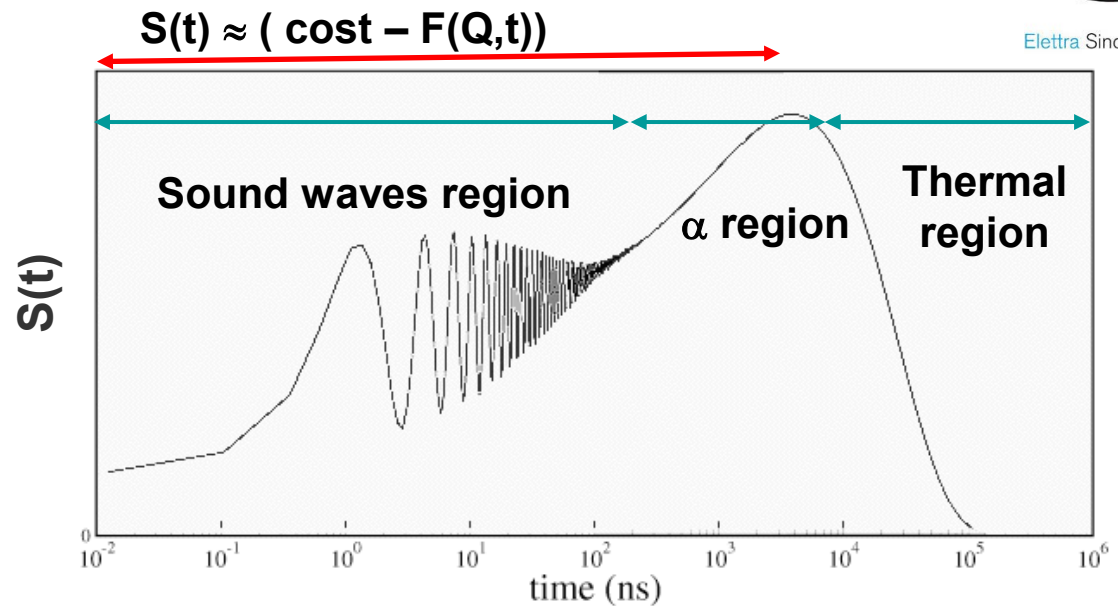


TG on disordered Systems (liquid/glasses) at the Nanoscale

Elettra Sincrotrone Trieste

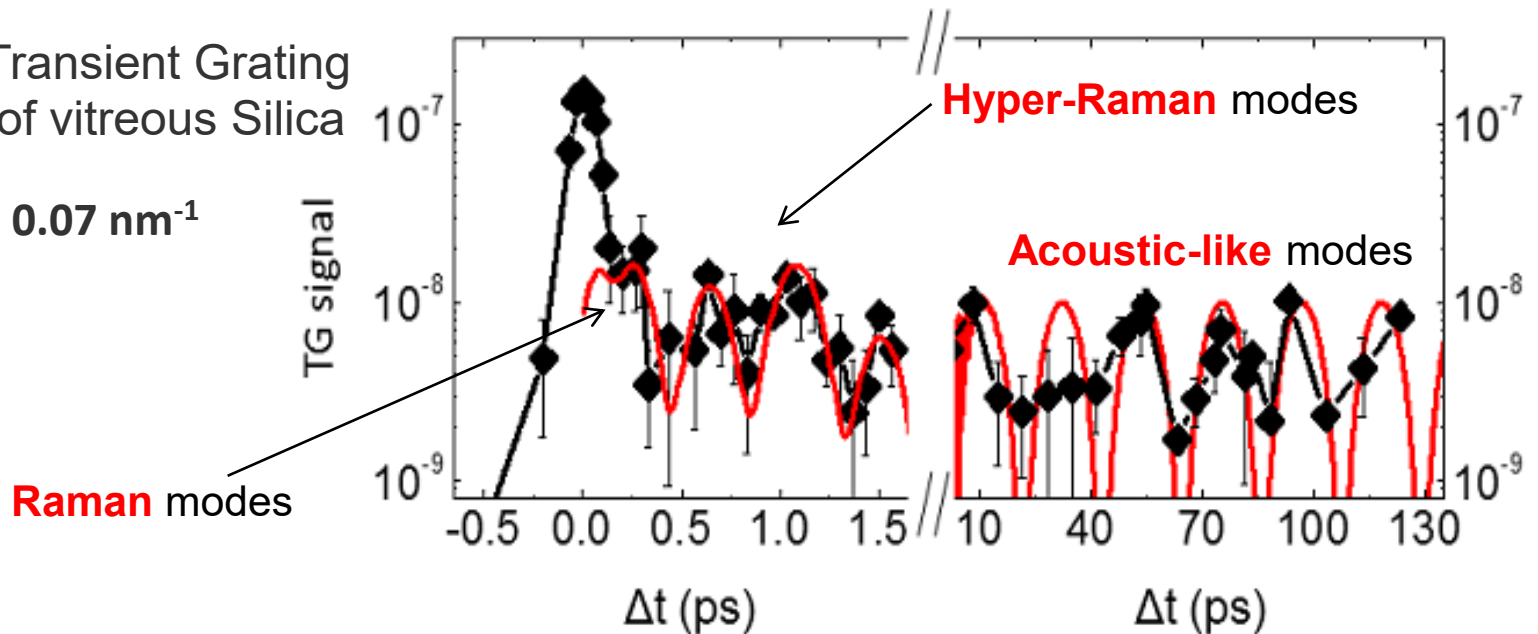
Visible Laser Transient
Grating Spectrum of Glycerol

$$Q = 0.01 \text{ nm}^{-1}$$



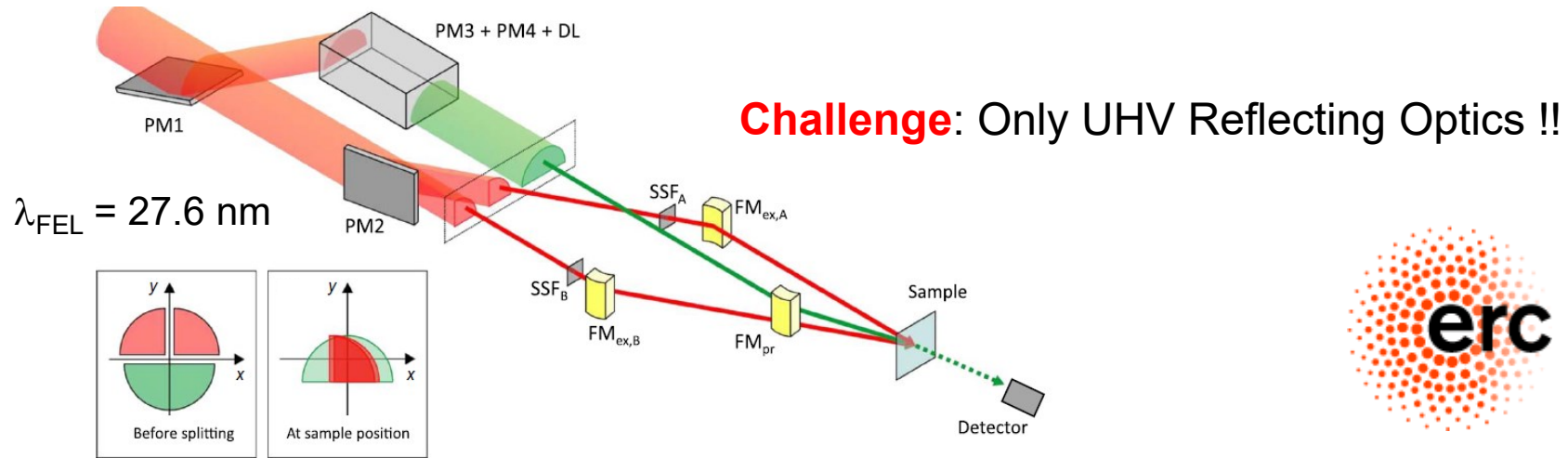
FEL VUV Transient Grating
Spectrum of vitreous Silica

$$Q = 0.07 \text{ nm}^{-1}$$



Four-wave mixing experiments with extreme ultraviolet transient gratings

F. Bencivenga et al., Nature (2015)

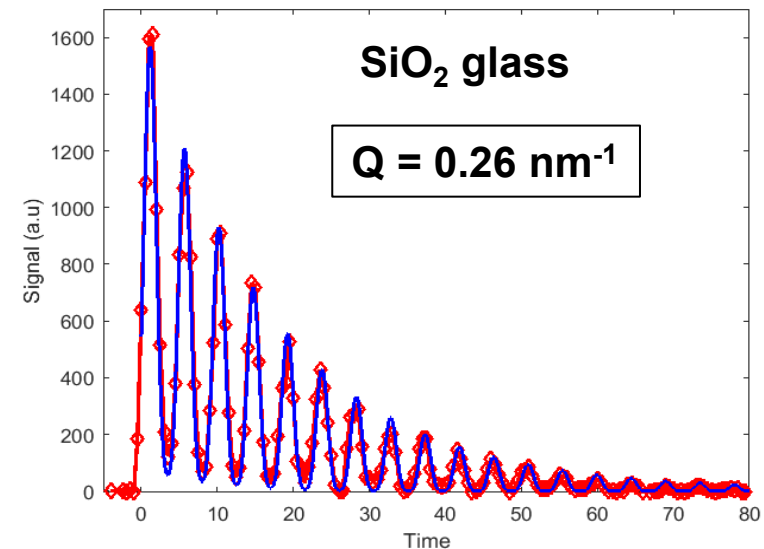


Phonon Dynamics is accessible in the mesoscopic region

Phonon decay ($\sim 30 \text{ ps}$, corresponding to $\sim \mathbf{0.1 \text{ meV energy resolution}}$)

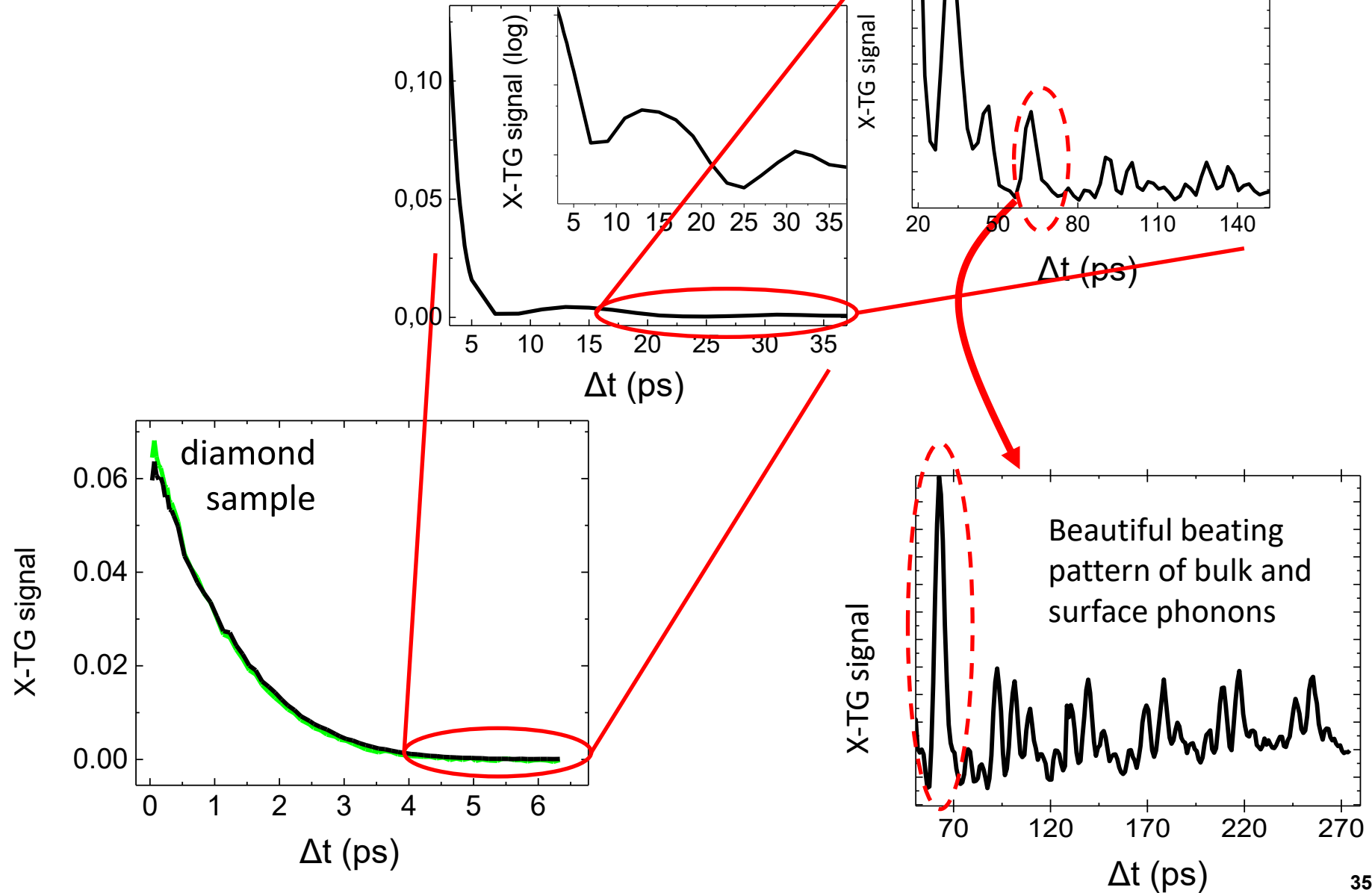
High quality data, **comparable** with optical experiments

L. Foglia et al., Photoacustics (2023)



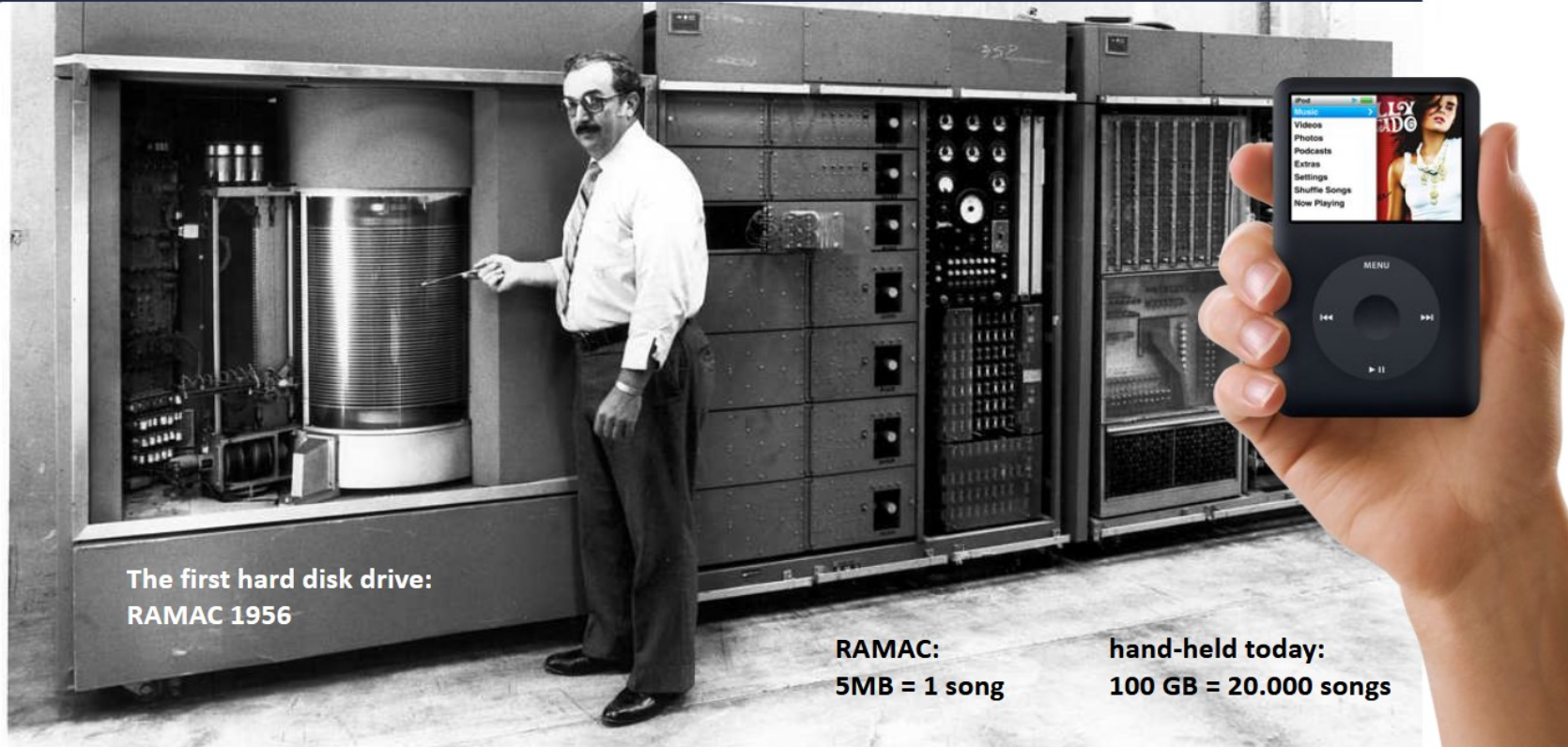
The Contrast

A. A. Maznev *et al.*, APL (2018)



Magnetic Data Storage

Cost ~ \$500,000



The first hard disk drive:
RAMAC 1956

RAMAC:
5MB = 1 song

hand-held today:
100 GB = 20.000 songs

*“We achieved something like **800 milliseconds**, and that’s where the product came out”*



Today ~ **0.1 -1 ns**

Gate Size ~ **1.3 mm**

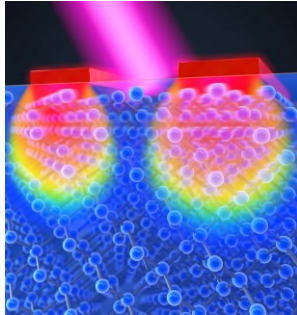


Today ~ **13 nm**

Heat Transport at the Nanoscale



Elettra Sincrotrone Trieste



Societal challenge → demand for renewable energy sources, energy-efficient information and data storage, and improved thermal management of electronics and batteries

Heat and Electron Transfer at the Nanoscale play a critical role in these applications and is a hot area of research

NEWS FEATURE | 12 September 2018 | Correction [13 September 2018](#)

How to stop data centres from gobbling up the world's electricity

The energy-efficiency drive at the information factories that serve us Facebook, Google and Bitcoin.

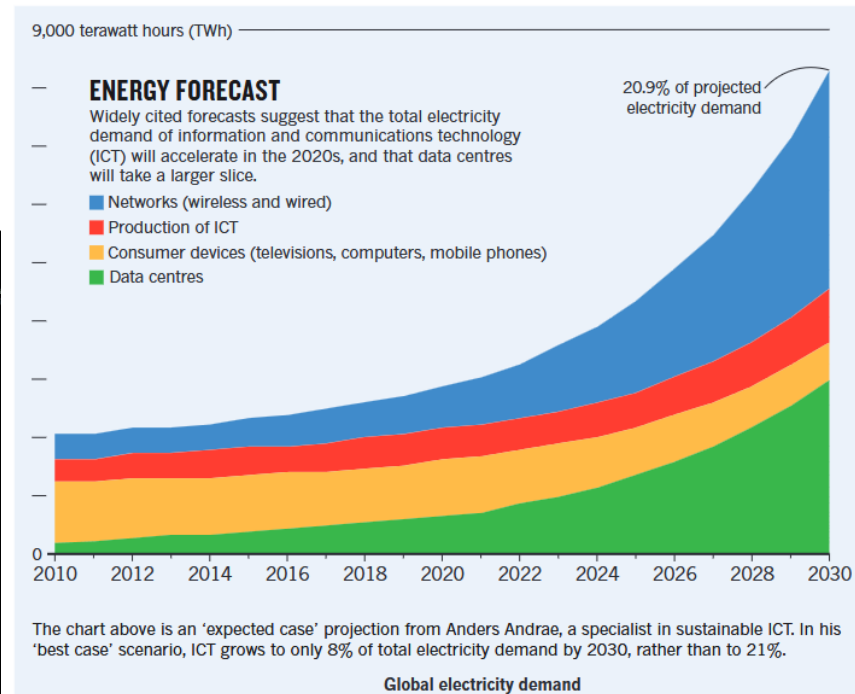
Our Cloud Data resides on Hard Disk Drives

this is the cheapest way to store large amounts of data



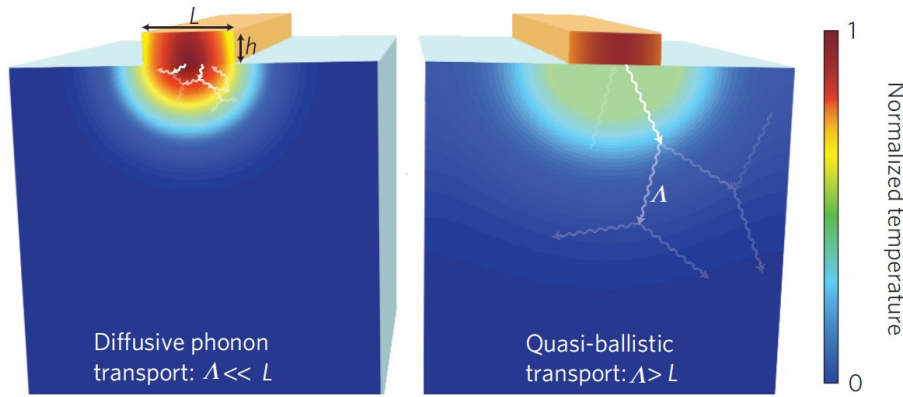
storing data in the cloud is not „for free“...

Google Data Center, Georgia
(Storage Cloud Tech.)



Water Consumption !!!

Heat Transport at the Nanoscale

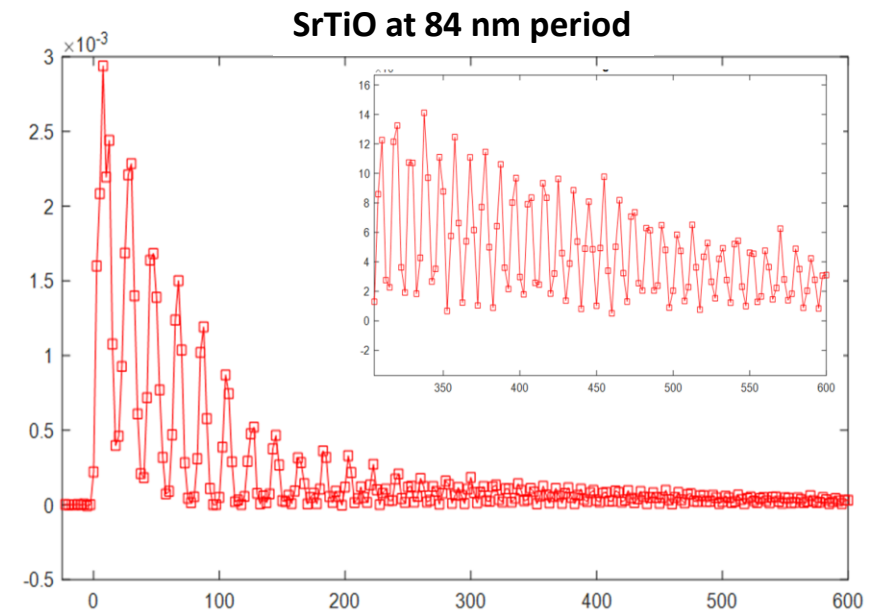
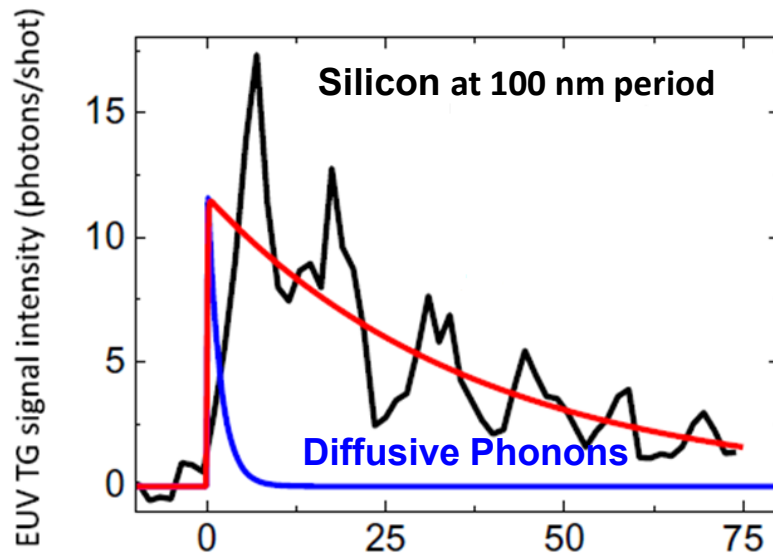


At $\lambda \approx$ to MFP of thermal phonons

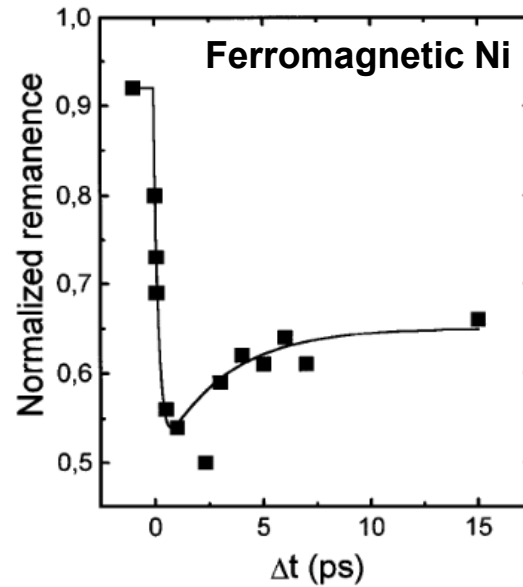


Fourier law breaks down

Deviation from diffusive thermal transport due to **ballistic phonons**

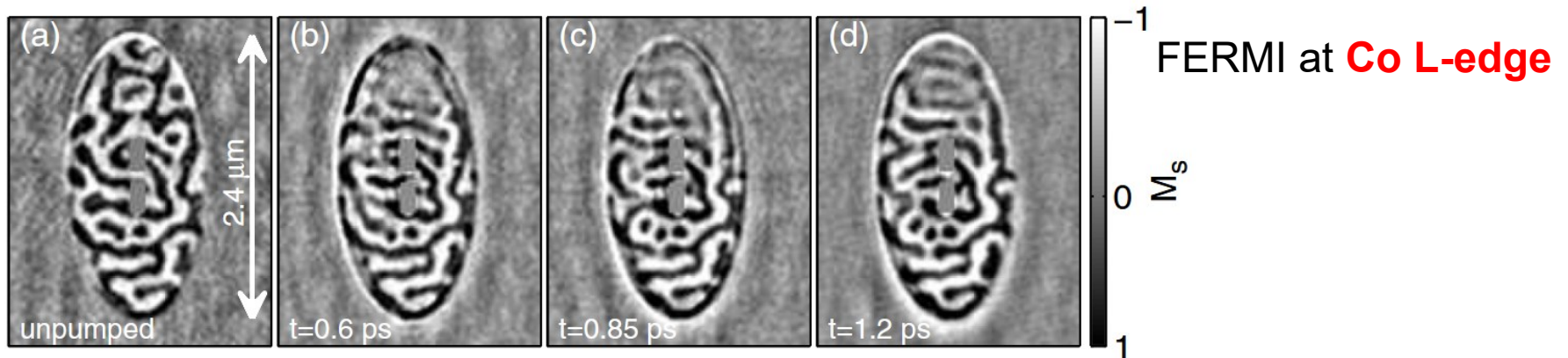


F. Bencivenga et al., Science Advances (2019)



The magnetization drops after 60 fs pulses (620 nm dye laser)

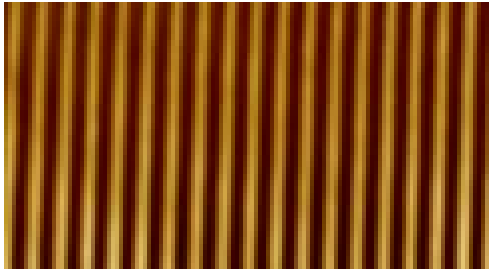
E. Beaurepaire et al., PRL 1997



C. von Korff Schmising et al., PRL (2014)

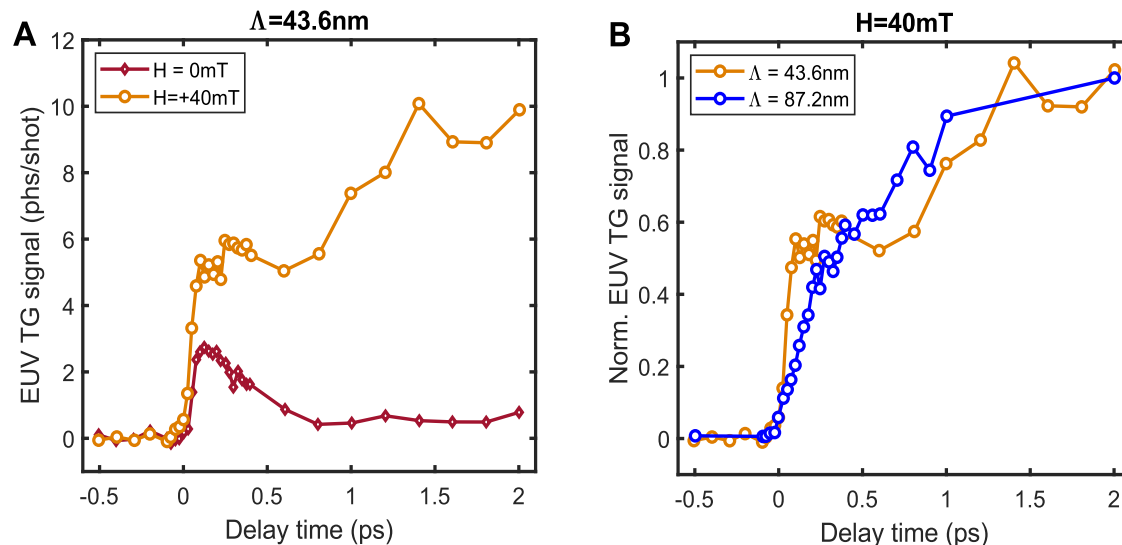
Ultrafast Demagnetization & Transient Grating

Observing the **spatio-temporal** extend of ultrafast spin diffusion with unprecedented detail



Unlike permanent magnetic structures (i.e. domain patterns or skyrmion lattices) the patterns created are transient → the magnetic sample is thermally **demagnetized** at the TG maxima

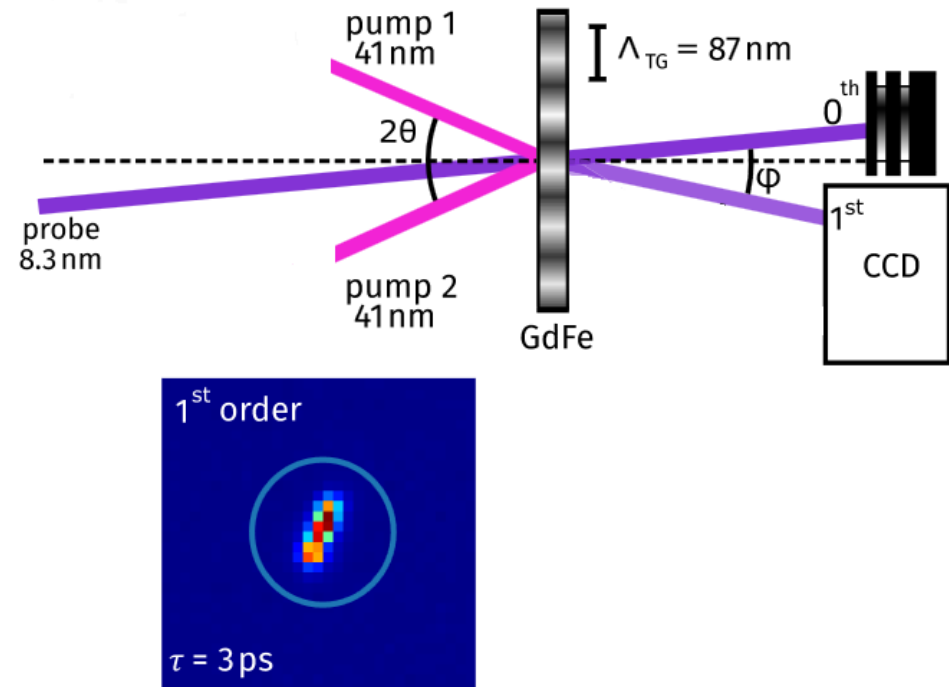
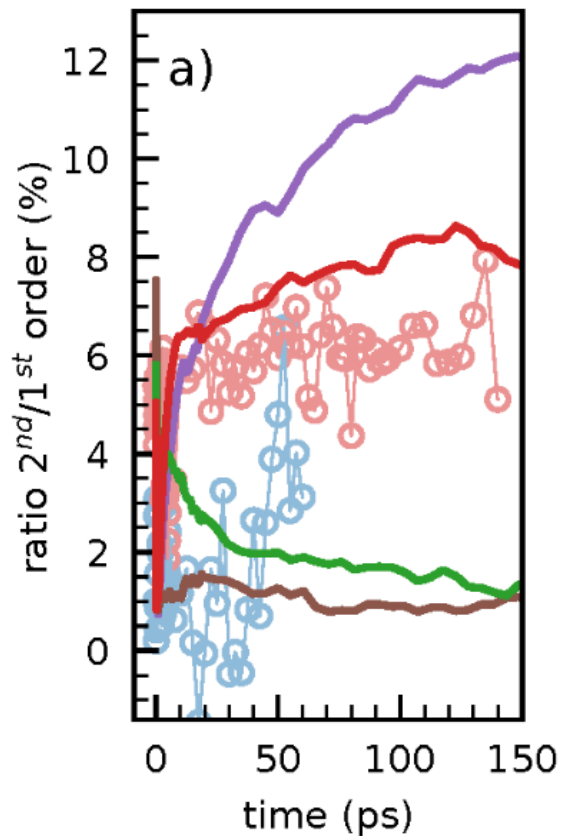
TG period down to 43.6 nm (CoGd alloy) probed on Co M-edge



The decay is ~ tens of picoseconds → thermal effects are the **leading mechanism** for washing away the magnetization grating

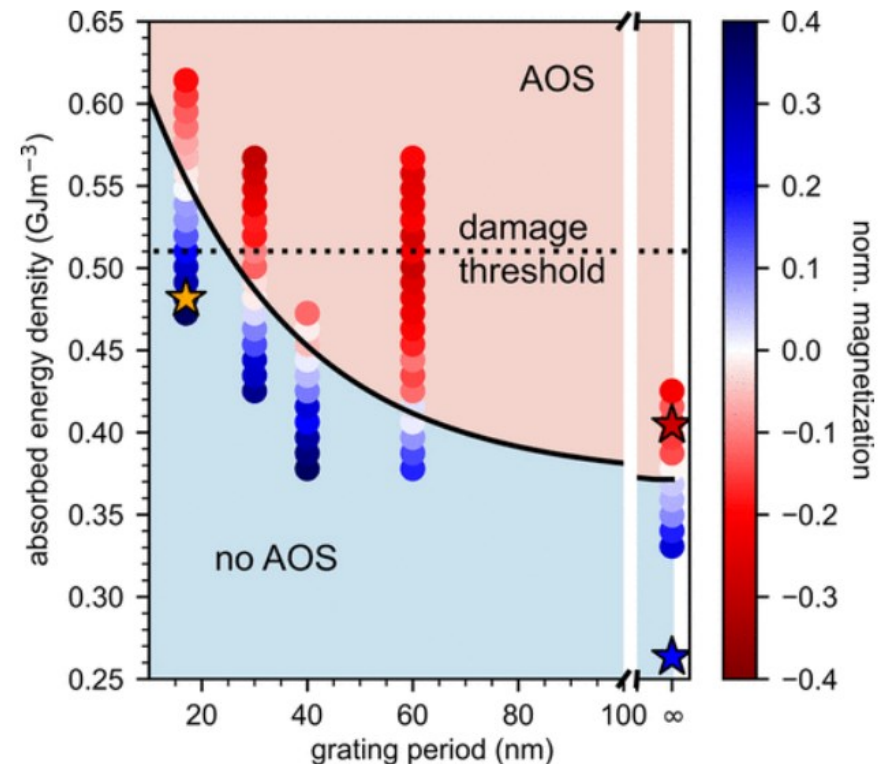
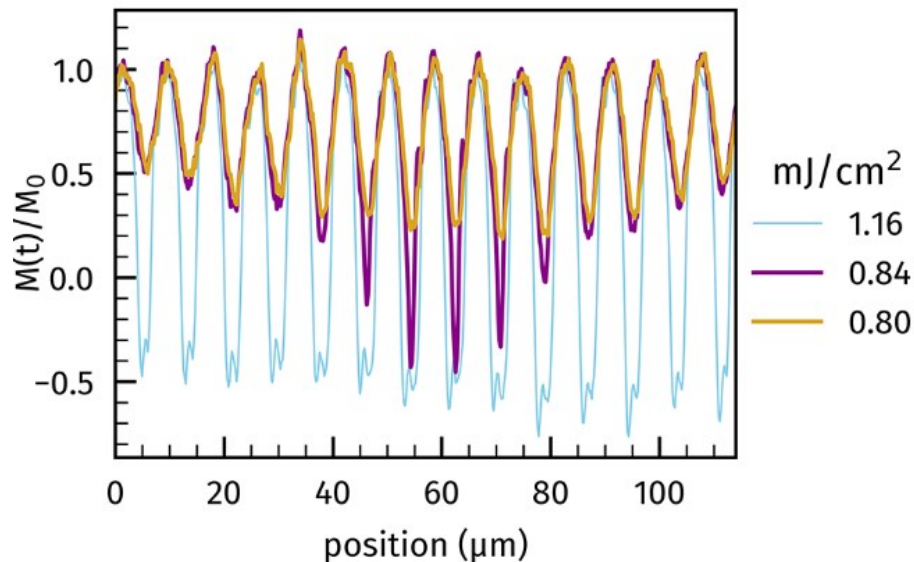
Femtosecond **All-Optical Switching** (AOS) → faster and more energy efficient data storage devices

Looking at the nonlinear demagnetization response as a function of excitation fluence → a fingerprint of **AOS**



Emergence of **AOS** on the nanometer length scale in a GdFe by XUV transient grating experiment

The understanding of the temporal control of AOS needs to be expanded into the nanometer range, where **ultrafast lateral transport processes** are expected to ultimately compete with AOS



F. Steinbac et al., Nano Letters (2024)

A high-efficiency programmable modulator for extreme ultraviolet light with nanometre feature size based on an electronic phase transition

Received: 29 March 2023

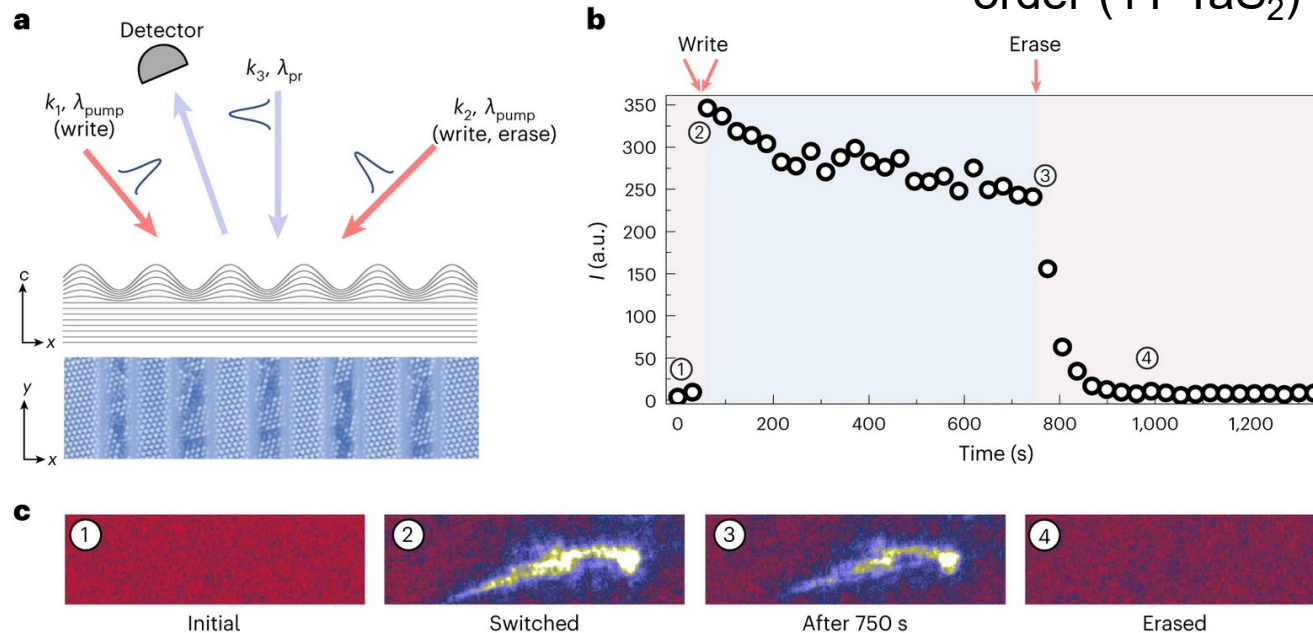
Accepted: 9 January 2024

Published online: 02 February 2024

Check for updates

Igor Vaskivskiy¹✉, Anze Mraz^{1,2}, Rok Venturini^{1,3}, Gregor Jecl^{1,3}, Yevhenii Vaskivskiy^{1,3}, Riccardo Mincigrucci⁴, Laura Foglia⁴, Dario De Angelis⁴, Jacopo-Stefano Pelli-Cresi⁴, Ettore Paltanin⁴, Danny Fainozzi⁴, Filippo Bencivenga⁴, Claudio Masciovecchio⁴ & Dragan Mihailovic^{1,5}

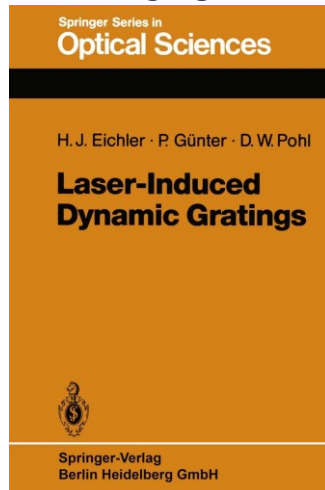
TG → phase transition to a metastable hidden electronic order (1T-TaS₂)



1975

2015

2025



LETTER

doi:10.1038/nature1434

Four-wave mixing experiments with extreme ultraviolet transient gratings

F. Bencivenga¹, R. Cucini¹, F. Capotondi¹, A. Battiston^{1,2}, R. Mincigrucci^{1,3}, E. Giangrisostomi^{1,2}, A. Gessini¹, M. Manfredda¹, I. P. Nikolov¹, E. Pedersoli¹, E. Principi¹, C. Svetina^{1,2}, P. Parisse¹, F. Casolari¹, M. B. Danailov¹, M. Kiskinova¹ & C. Masciovecchio

communications physics

Article

A Nature Portfolio journal



<https://doi.org/10.1038/s42005-025-02178-y>

All hard X-ray transient grating spectroscopy

Check for updates

Eugenio Ferrari^{1,2,3}, Hiroki Ueda^{1,2,3}, Danny Fainozzi⁴, Taito Osaka⁵, Filippo Bencivenga⁶, Max Burian⁷, Pietro Carrara^{1,8}, Joan Vila-Comamala⁹, Riccardo Cucini⁹, Christian David⁹, Alessandro Gessini⁹, Simon Gerber⁹, Andrii Goloborodko¹⁰, Ales Hrabec^{11,12}, Ichiro Inoue⁵, Yuichi Inubushi¹³, Ludmila M. Diniz Leroy¹⁴, Riccardo Mincigrucci⁹, Eugenio Paris⁹, Bill Pedrini⁹, Benedikt Roesner⁹, Jérémy R. Rouxel¹⁴, Carles Serrat¹⁵, Valerio Scagnoli^{11,12}, Kensuke Tono^{5,13}, Makina Yabashi^{5,13}, Junpei Yamada^{5,16}, Kohei Yamamoto^{17,18}, Marie Christine Zdzora¹, Martin Beye^{1,19}, Claudio Masciovecchio⁹, Majed Chergui^{9,20}, Urs Staub⁹ & Cristian Svetina^{9,21,22}

2026

2026

PHYSICAL REVIEW LETTERS 136, 176701 (2026)

nature physics

Article

<https://doi.org/10.1038/s41567-025-03161-8>

Nanoscale ultrafast lattice modulation with a free-electron laser

Received: 24 June 2025

Accepted: 17 December 2025

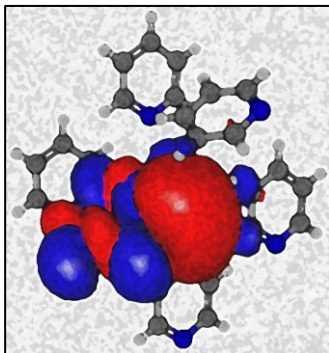
Published online: 27 January 2026

Check for updates

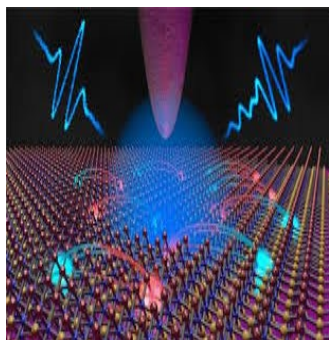
Haoyuan Li^{1,2}, Nan Wang², Leon Zhang^{4,5,6}, Sanghoon Song², Yanwen Sun², May-Ling Ng⁷, Takahiro Sato⁸, Dillon Hanlon⁷, Sajal Dahal⁹, Mario D. Balcazar⁹, Vincent Esposito², Selene She⁴, Chance Caleb Ornelas-Skarin^{5,8}, Joan Vila-Comamala⁹, Christian David⁹, Nadia Berndt¹⁰, Peter R. Miedaner¹⁰, Zhuquan Zhang¹⁰, Matthias Ihme^{11,12}, Mariano Trigo^{5,6}, Keith A. Nelson¹⁰, Jerome B. Hastings^{2,5,11}, Alexei A. Maznev¹⁰, Laura Foglia¹³, Samuel Teitelbaum⁷, David A. Reis^{4,5,11} & Diling Zhu²

Spin Waves Excited by Hard X-Ray Transient Gratings

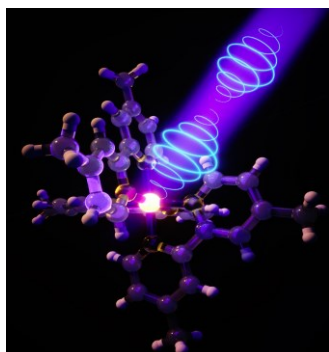
Peter R. Miedaner^{1,*}, Alexei A. Maznev^{1,†}, Mykola Biednov², Marwan Deb³, Carles Serrat⁴, Nadia Berndt⁵, Pietro Carrara⁵, Cristian Soncini⁶, Marta Brioschi^{7,8}, Daniele Ronchetti^{9,10,11}, Andrei Benediktovitch¹¹, Danny Fainozzi¹², Nupur Khata^{2,6,13}, Eugenio Ferrari¹¹, Joan Vila-Comamala¹⁴, Peter Zalden², Wojciech Gawelda^{15,16,17}, Martin Knoll², Paul Frankenberger², Ludmila Leroy¹⁴, Talgat Mamyrbayev¹⁴, Grigory Smolentsev¹⁴, Simon Gerber¹⁴, Alessandro Gessini⁶, Filippo Bencivenga⁶, Riccardo Cucini⁸, Giorgio Rossi^{7,8}, Riccardo Mincigrucci⁶, Ettore Paltanin⁶, Majed Chergui^{6,18}, Claudio Masciovecchio⁶, Stefano Bonetti¹³, Yohei Uemura², Xinchao Huang², Han Xu², Frederico Alves Lima², Fernando Ardana-Lamas², Anders Madsen², Renato Torre^{19,20}, Luis Bañares²¹, Jakub Szlachetko²², Wojciech Blachucki²³, Matias Bargheer²⁴, Thomas Feuer², Robin Y. Engel¹¹, Martin Beye^{11,25}, Christian David¹⁴, Urs Staub¹⁴, Andrea Cannizzo¹², Christopher Milne², Keith A. Nelson¹ and Cristian Svetina^{2,16,‡}



The ability to monitor **time-dependent dipole moments** and charge redistribution with atomic-site specificity addresses a fundamental challenge in understanding and controlling molecular processes underlying sustainable energy solutions, advanced functional materials, and biological function.



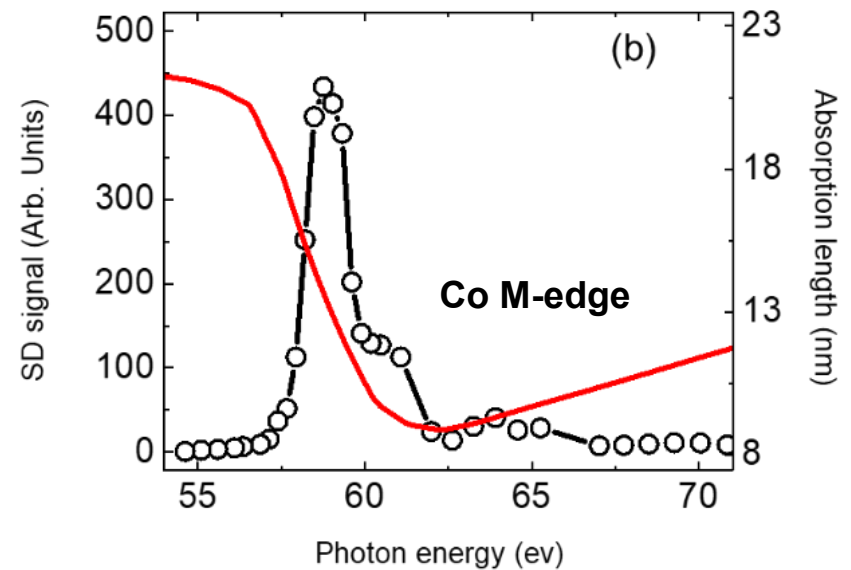
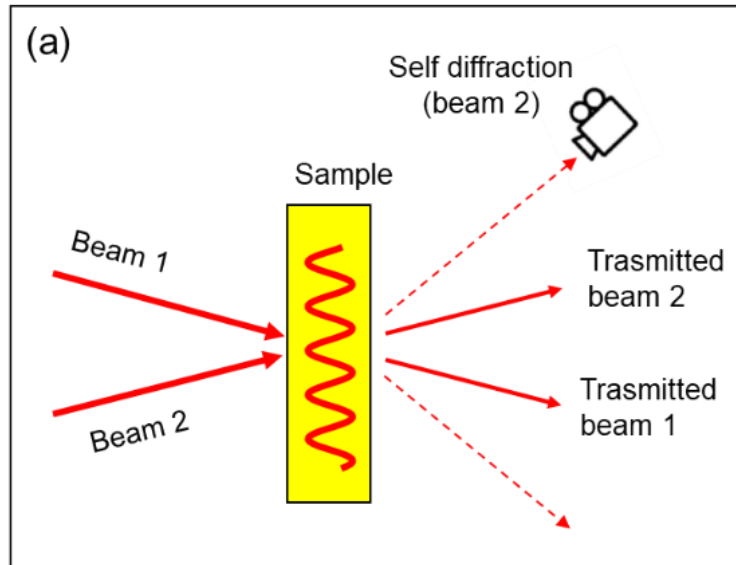
How excitons (electron-hole pairs) behave and interact in materials, is crucial for understanding processes like light emission, energy transfer, and charge separation, which are fundamental to areas like **photovoltaics**, optoelectronics, and photocatalysis.



Understanding protein-drug interaction with eventual **chiral separation** and analysis of racemic drugs. Determination of protein structure for specimens impossible to crystallize, eventually in physiological condition.

Decreasing Complexity → Self Diffraction

The diffraction efficiency of TG is linked to the modulation of the **real** and **imaginary** parts of the **refractive index**

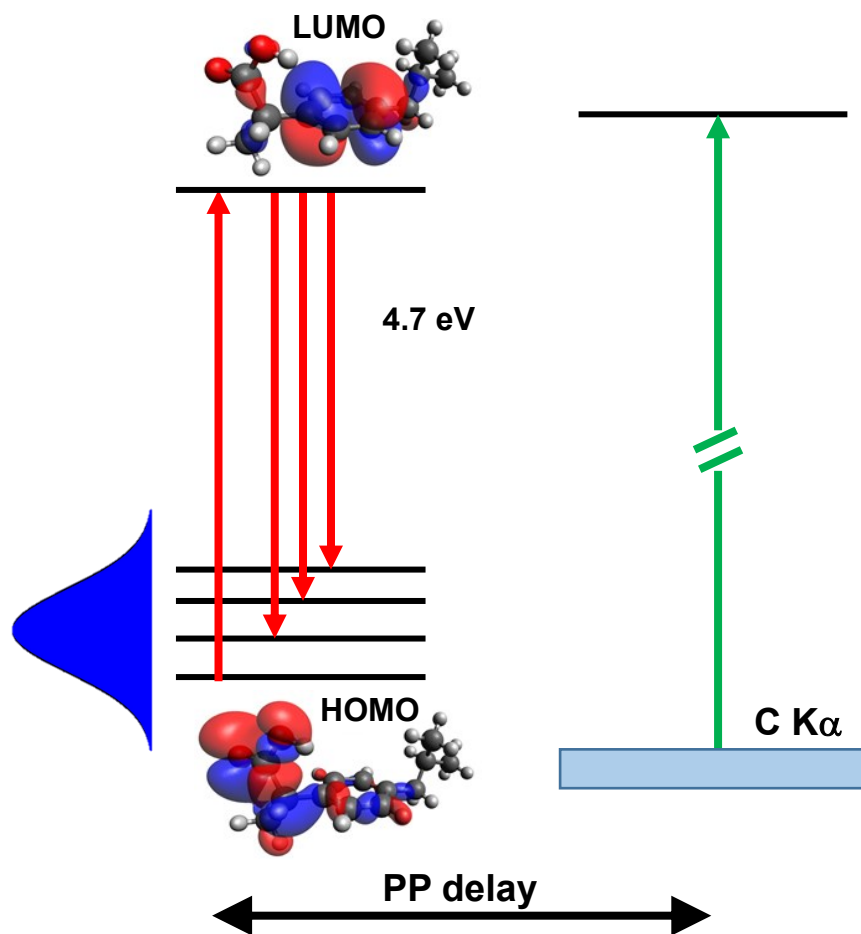


Potential of SD as a **spectroscopy tool** → We expect the fine structure of the SD spectrum to be compound-specific, potentially enabling SD-based nonlinear near-edge EUV spectroscopy technique

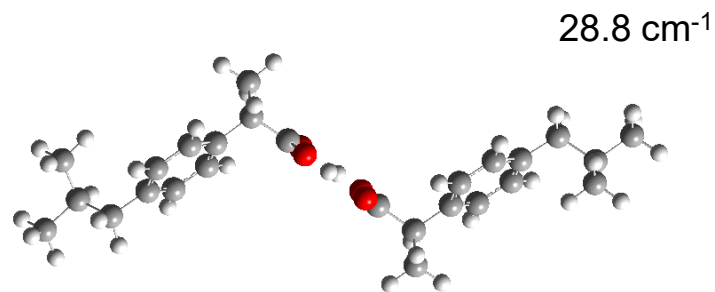
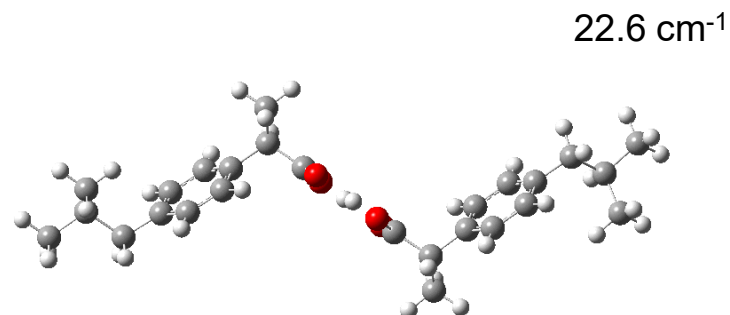
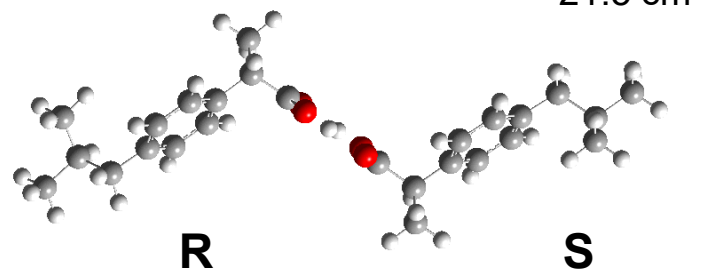
A.A.Maznev et al., arXiv:2505.07168

Super Selective Spectroscopy

Low Frequency Vibrations are very sensitive to the **conformation** of a (bio)-molecule → tool to investigate the mechanism of action of a (bio)-molecule from the viewpoint of dynamics



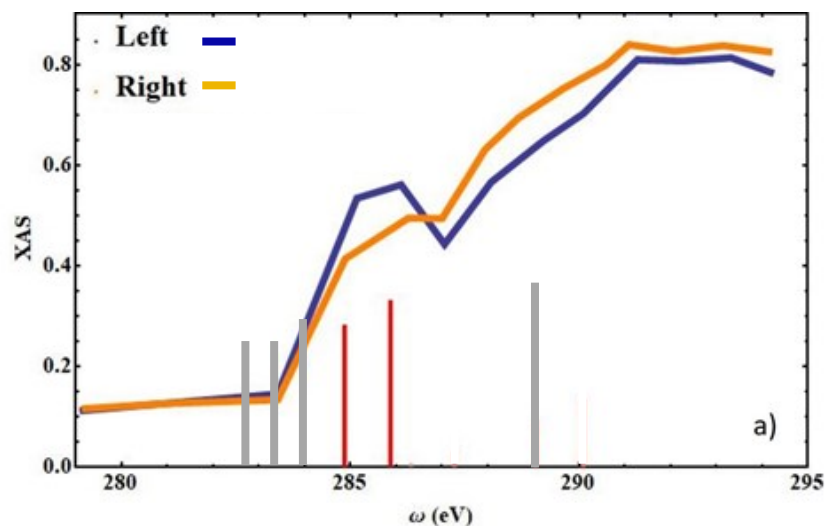
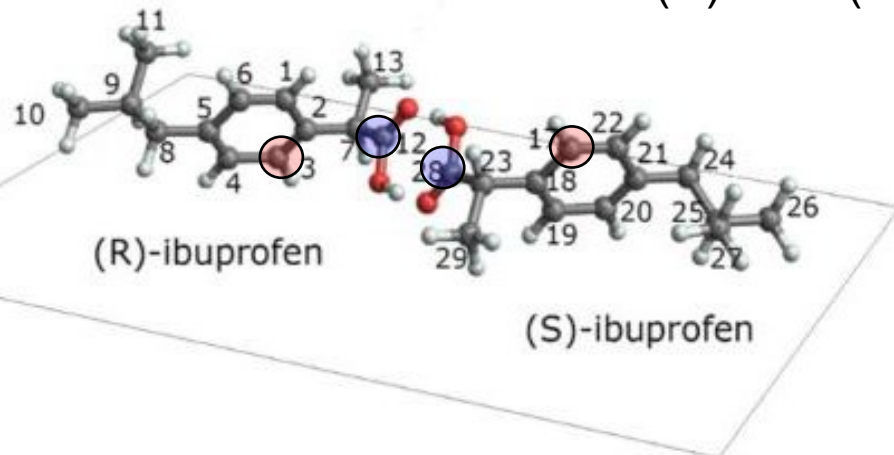
Ibuprofen



Super Selective Spectroscopy

The **strongest absorption** at

- 285 eV comes from atoms 3 (R) & 17 (S)
- 285.7 eV comes from atoms 12 (R) & 28 (S)



R. Mincigrucci et al., Nat. Comm. (2023)

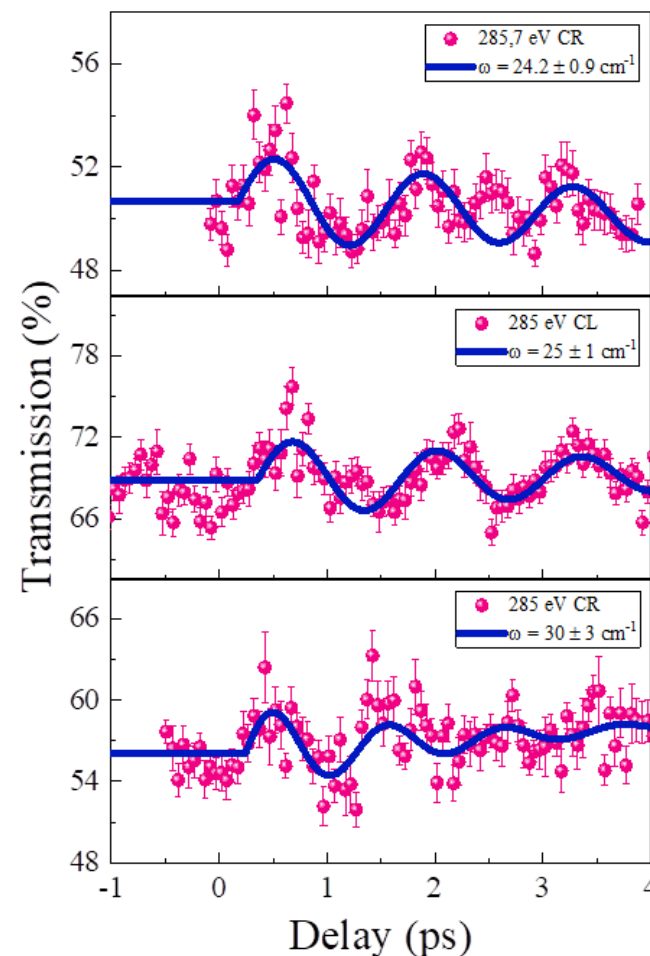
nature communications



Article

<https://doi.org/10.1038/s41467-023-36047-5>

Element- and enantiomer-selective visualization of molecular motion in real-time



Acknowledgments

FERMI Machine

L. Giannessi
G. Penco
E. Allaria
G. De Ninno
C. Spezzani
P. Rebernik Ribič
M. Trovò
G. Gaio

FERMI Laser

M. Danailov
G. Kurdi
P. Cinquegrana
A. Demidovich
I. P. Nokolov
P. Sigalotti

FERMI Exp.

F. Bencivenga
R. Mincigrucci
E. Principi
L. Foglia
F. Capotondi
O. Plekan
C. Callegari
A. Gessini

FERMI Optics

M. Zangrando
A. Simoncig
M. Manfredda
N. Mahne



M. Chergui



M. Beye



S. Bonetti
M. Pancaldi



K. Nelson
A. Maznev



C. Svetina



S. Mukamel



C. Gutt



G. Sansone
P.K. Maraju



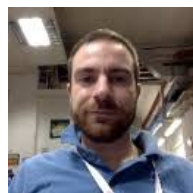
J. Rouxel



S. Eisebitt



S. Nandi



F. Segatta
M. Garavelli



I. Vaskivskiy
D. Mihailovic



N. Jauen
M. Sacchi