Optics and Photonics Subcommittee of the Mathematics and Physical Sciences Advisory Committee

Tony Heinz, Chair

Columbia University

New York, NY 10027

Our Charge

- The subcommittee is asked to address the *adequacy of the current MPS portfolio in optics and photonics*, and to identify a set of basic research grand challenges that would enable new technological advances.
- In addition, the subcommittee should *identify basic research opportunities* as well as the need, if any, for *investments in the development of research infrastructure* to support optics and photonics.
- The report should also address *education-related research efforts* needed to support the professional development of the next generation of the U.S. optics and photonics workforce.
- The report should identify, insofar as possible, optics and photonics *scientific priorities* within each discipline.

Online workshop and presentations

- Two days of symposia and discussion
- Conducted as four separate online meetings, each committee member gave a presentation of about 1 hour with extensive discussion
- Committee members identify key research advances driving and defining in the field and addressed explicitly
    - ✓ Current opportunities
    - ✓ Current needs
    - ✓ Timeliness of investments

OPSC Workshop Presentations 1

Quantum Information and Spintronics
David Awschalom, U. Chicago

Frontiers of Image Sensor Technologies for Astrophysics
Jim Beletic, Teledyne

Coherence and Control
Phil Bucksbaum, Stanford University/SLAC

New Optical Techniques and Their Impact on the Life Sciences: Making What's Invisible Today, Visible Tomorrow
Taekjip Ha, University of Illinois

OPSC Workshop Presentations 2

Frontiers of Mathematical Modeling in Optics and Photonics
William Kath, Northwestern University

Optics and Photonics in Molecular Materials
Seth Marder, Georgia Tech

Frontiers of Quantum Optics – Mechanical Effects of Light, Resonances and Cavities
Pierre Meystre, University of Arizona

Ultrafast X-Ray Science: Quantum Physics at an Extreme and Applications in Materials and Nano Science
Margaret Murnane, U Colorado/JILA

OPSC Workshop Presentations 3

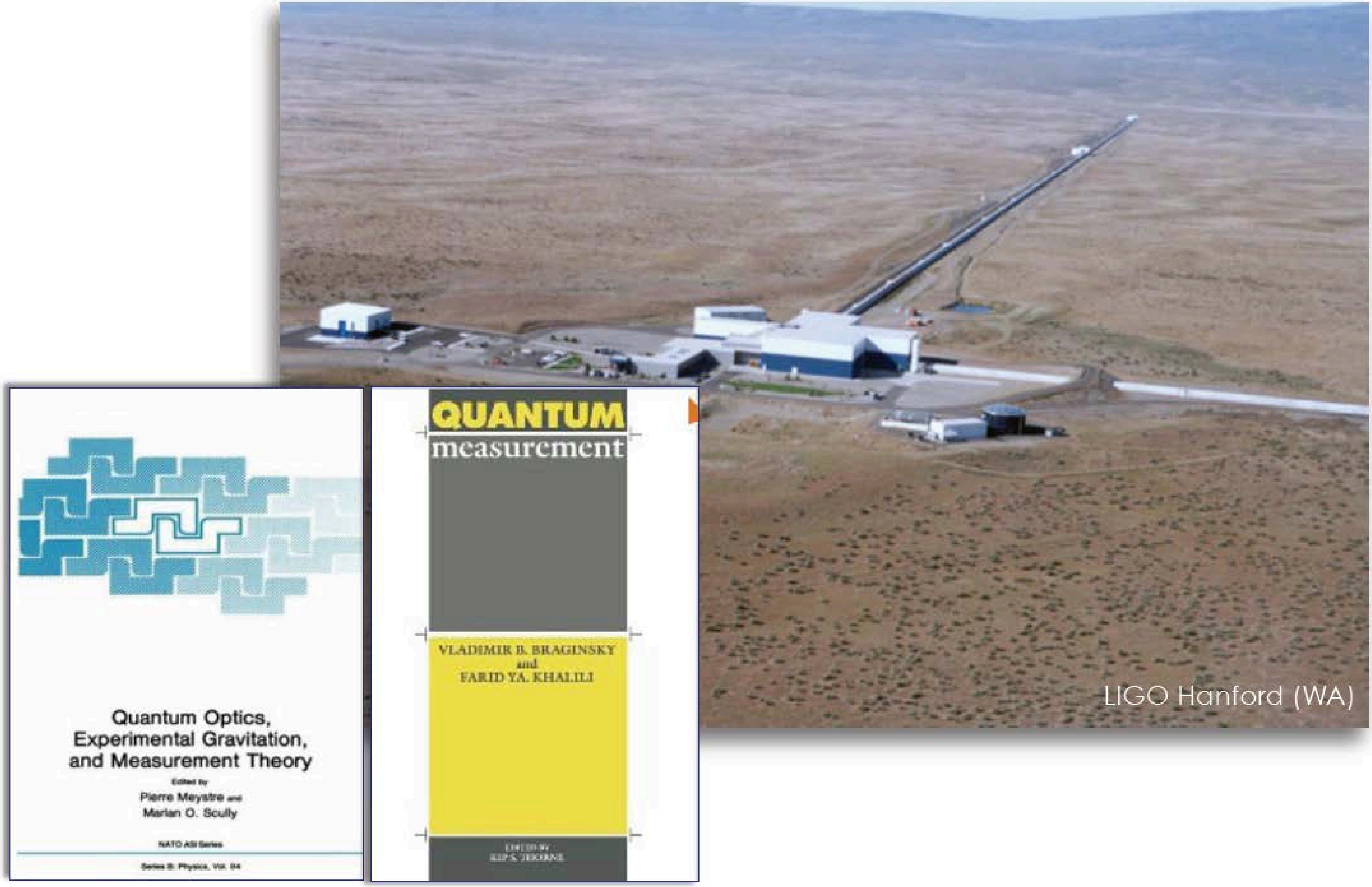
Optically Driven Molecular Motors and Switches
Roseanne Sension, U. Michigan

Nanophotonics Enabled by Plasmonics and Metamaterials: From Classical to Quantum
Vladimir Shalaev, Purdue University

Scientific Frontiers of Optics and Photonics

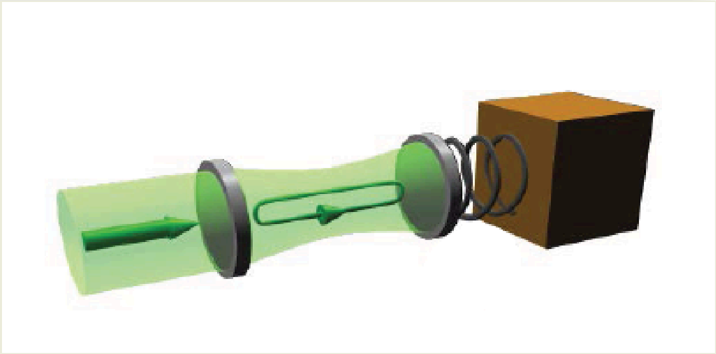
- **Plasmonics and nanophotonics –optical fields and propagation on the nanoscale**
- **Coherent electromagnetic fields – attosecond time scales and x-ray photon energies**
- **Frontiers of quantum optics and information**
- **Creating and control quantum states in gases, molecules, and solids**
- **Optical imaging - beyond the diffraction limit and beyond the scattering length**
- **Sensing the universe – optics and photonics for astrophysics**

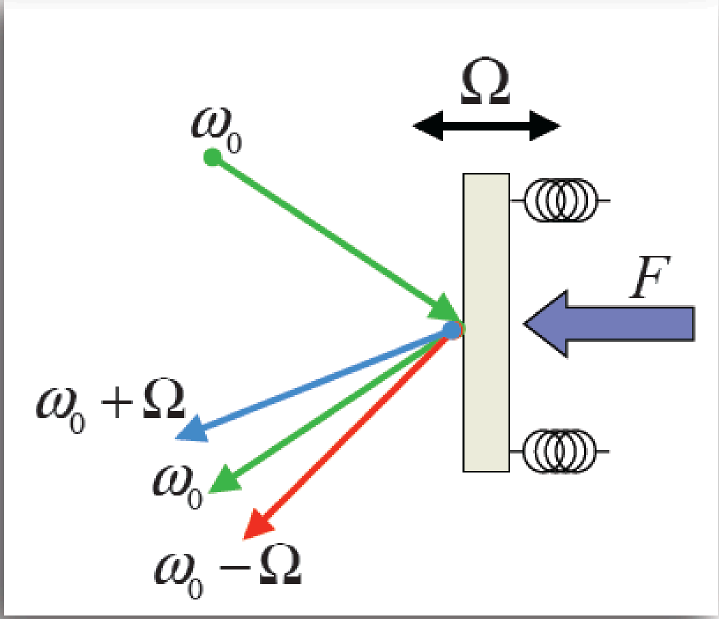
Gravitational wave detection

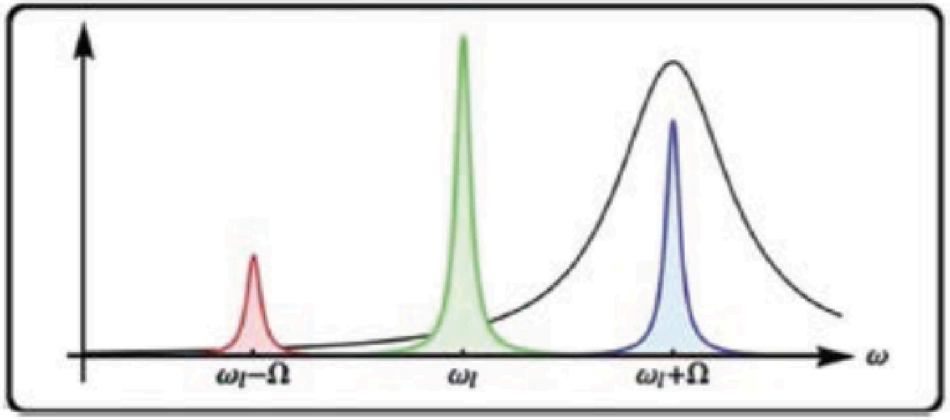


radiation pressure cooling

Basic idea:
Use radiation pressure to change frequency and damping of a mirror mounted on a spring/cantilever in an engineered resonant optical structure







Stokes

anti-Stokes

Same idea as used in sideband cooling of ions (D. Wineland)

Beating the "standard quantum limit"

✧ Low temperatures

to eliminate thermal noise

✧ Nonclassical states

to put all the noise in observables you don't care about

✧ Back-action evading techniques

(QND Measurements) to make sure that this noise doesn't feed back into the observable of interest

Reference Slides:

Scientific Highlights

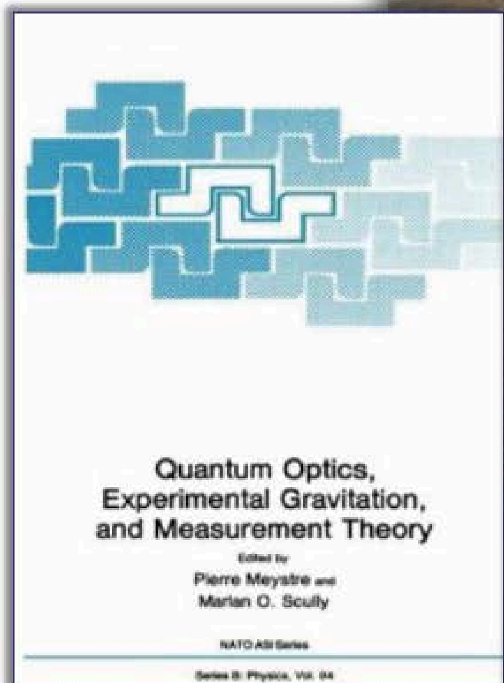
Frontiers of Quantum Optics –

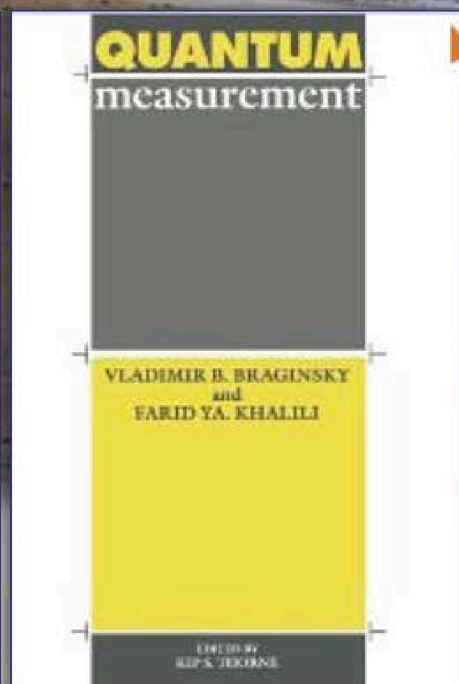
Mechanical effects of light, resonances & cavities

Pierre Meystre
The University of Arizona

- Ultracold atoms and molecules
- Cavity QED
- Quantum optomechanics

Gravitational wave detection





A powerful convergence

- **Quantum optics and atomic physics**
  - Exquisite control of light-matter interaction
  - Mechanical effects of light, laser cooling
  - Harnessing of measurement back-action, nonclassical fields
  - Quantum noise, decoherence, …

- **Nanoscience and semiconductor industries**
  - Ultrasensitive micromechanical and nanomechanical devices
  - Sensing of extremely tiny forces and fields
  - Spatial resolution at atomic scale
  - Cryogenics, nanofabrication

mechanical sensing – current state of the art

Existing technology:

Single electron spin detection via magnetic resonance
Rugar *et al.*, Nature **430**, 329 (2004)

Attometer scale displacement sensing ($10^{-18}\mathrm{m}$)
Arcizet *et al.* (PRL **97**, 133601 (2006)

Zeptonewton scale force sensing ($10^{-21}\mathrm{N}$)
Mamin & Rugar, APL **79**, 3358 (2001)

Yoctogram scale mass sensitivity ($10^{-24}\mathrm{g}$)
Jensen *et al.*, Nature Nanotech **3**, 533 (2008)
Naik *et al.*, Nature Nanotech **4**, 445 (2009)

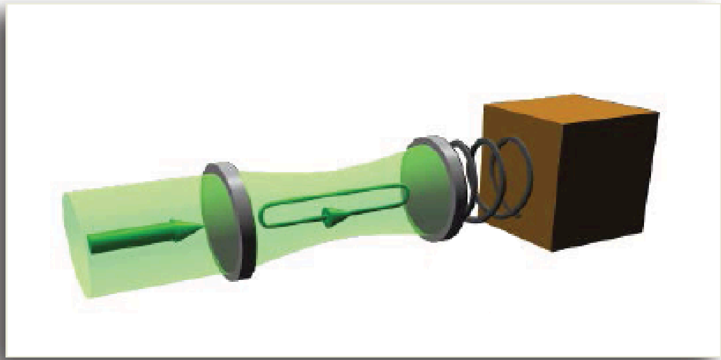
(courtesy Markus Aspelmeyer)

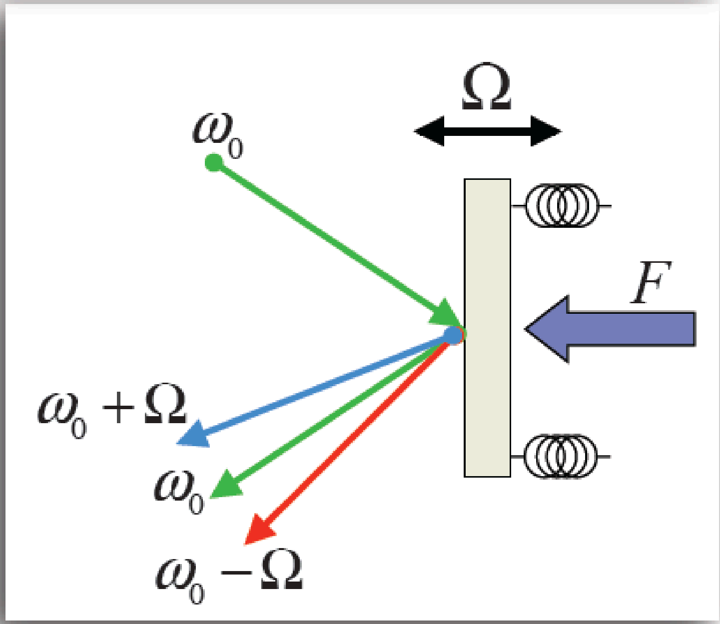
Beating the "standard quantum limit"

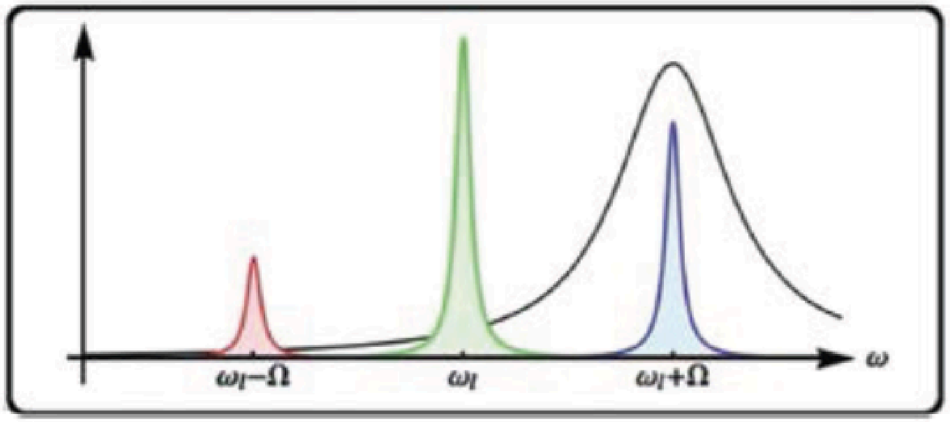
- ✧ **Low temperatures**
  to eliminate thermal noise
- ✧ **Nonclassical states**
  to put all the noise in observables you don't care about
- ✧ **Back-action evading techniques**
  (QND Measurements) to make sure that this noise doesn't feed back into the observable of interest

radiation pressure cooling

Basic idea:
Use radiation pressure to change frequency and damping of a mirror mounted on a spring/cantilever in an engineered resonant optical structure







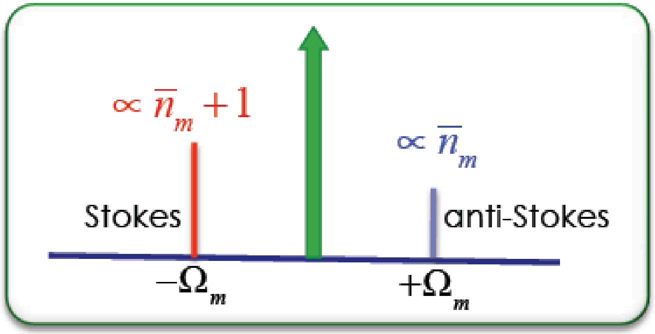
Stokes

anti-Stokes

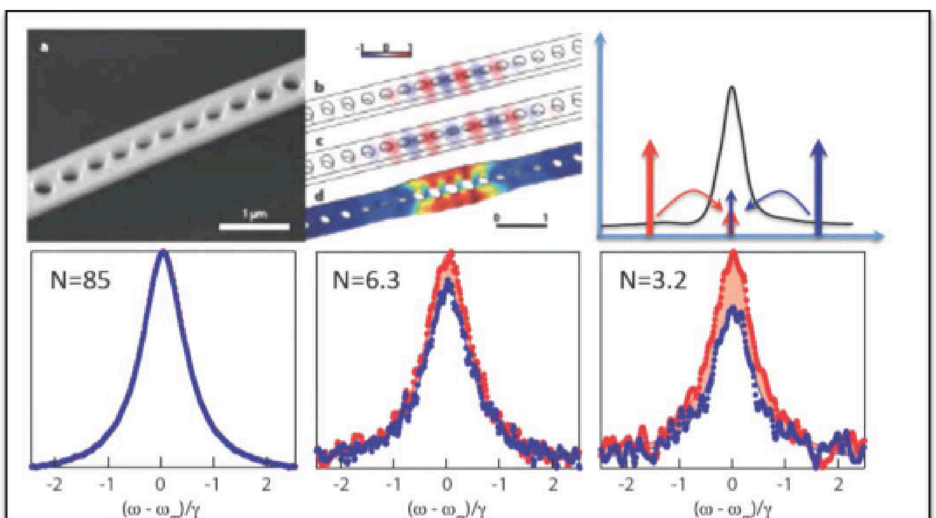
Same idea as used in sideband cooling of ions (D. Wineland)

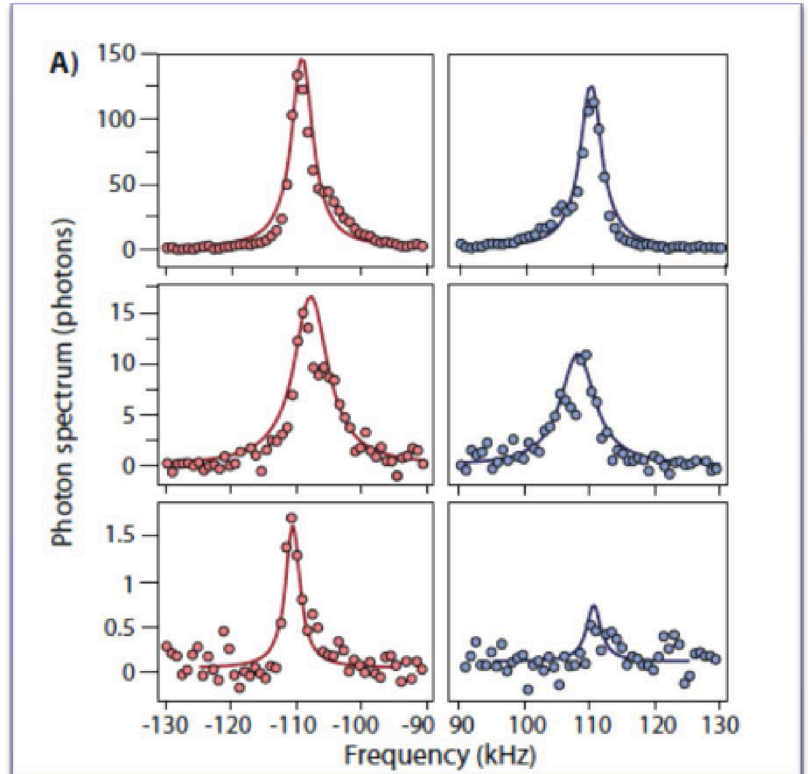
Smoking gun – asymmetric optical scattering

Scattered photon spectrum



$$n(\omega) \propto \frac{\gamma_m^2(\bar{n}_m+1)}{(\omega+\Omega_m)^2+\gamma_m^2/4} + \frac{\gamma_m^2\bar{n}_m}{(\omega-\Omega_m)^2+\gamma_m^2/4}$$





Safavi-Naeini *et al.*, Phys.. Rev. Lett. **108**, 033602 (2012)
N. Brahms *et al*, Phys. Rev. Lett. **108**, 133601 (2012)

Next...

- **"Quantum acoustics"**
  - Multimode physics
  - Nonlinear phononics
  - Phonon imaging
  - ...
- **Applications**
  - Force and field measurements
  - Beyond the Standard Quantum Limit
  - Functionalization
  - Hybrid systems (atoms, ions, molecules, artificial atoms)
  - Quantum information, quantum metrology
  - ...
- **Fundamental studies**
  - Macroscopic quantum tunneling
  - Schrödinger cats, nonclassical states, ...
  - Decoherence
  - Fundamental forces (Casimir, gravitation, ...)
  - Planck scale physics
  - ...

Gaps, opportunities, and all that…

What gaps?

- Much of the most exciting work in quantum optics is now **at the boundaries** between subfields
- The NSF (and other) funding models have **difficulties working across silos**
- Need to create/maintain/nurture a **diverse research ecosystem** that
  - Is open to game changing developments
  - Provides opportunities for research that "doesn't fit"
  - Comprises a mix of relatively conservative and high-risk components
  - Promotes interdisciplinary and cross-boundary work

What opportunities?

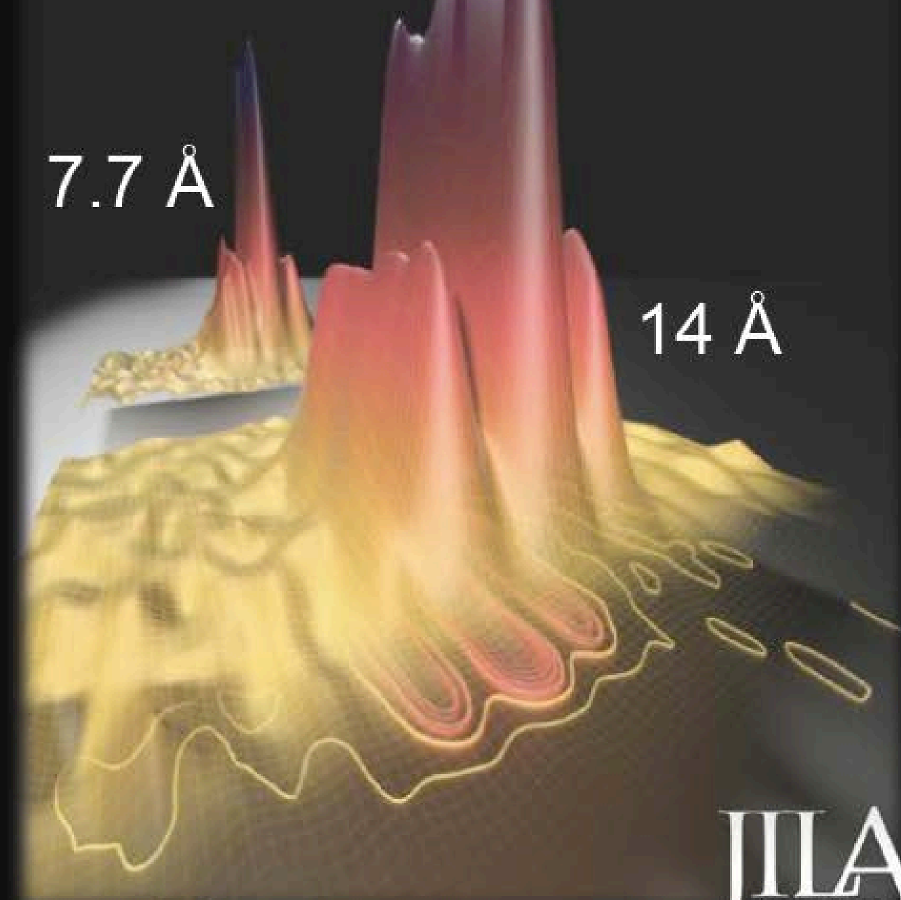
- The cross-fertilization between AMO science (e.g. ultracold science), quantum optics, low temperature physics, condensed matter physics, nanoscience, quantum information science, etc. is only beginning to bear fruit
- The potential for **applications** is considerable – e.g. sensors of feeble forces and fields, quantum metrology, quantum information science, medical applications,…
- The potential for impact on **fundamental physics** is considerable as well (tests of fundamental theories, precision measurements,…)

Why now?

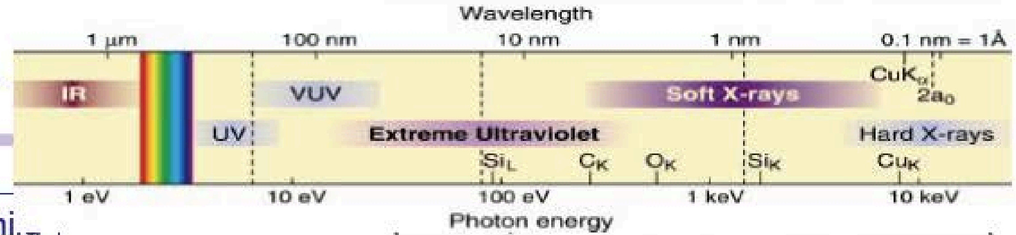
- If not now, when?

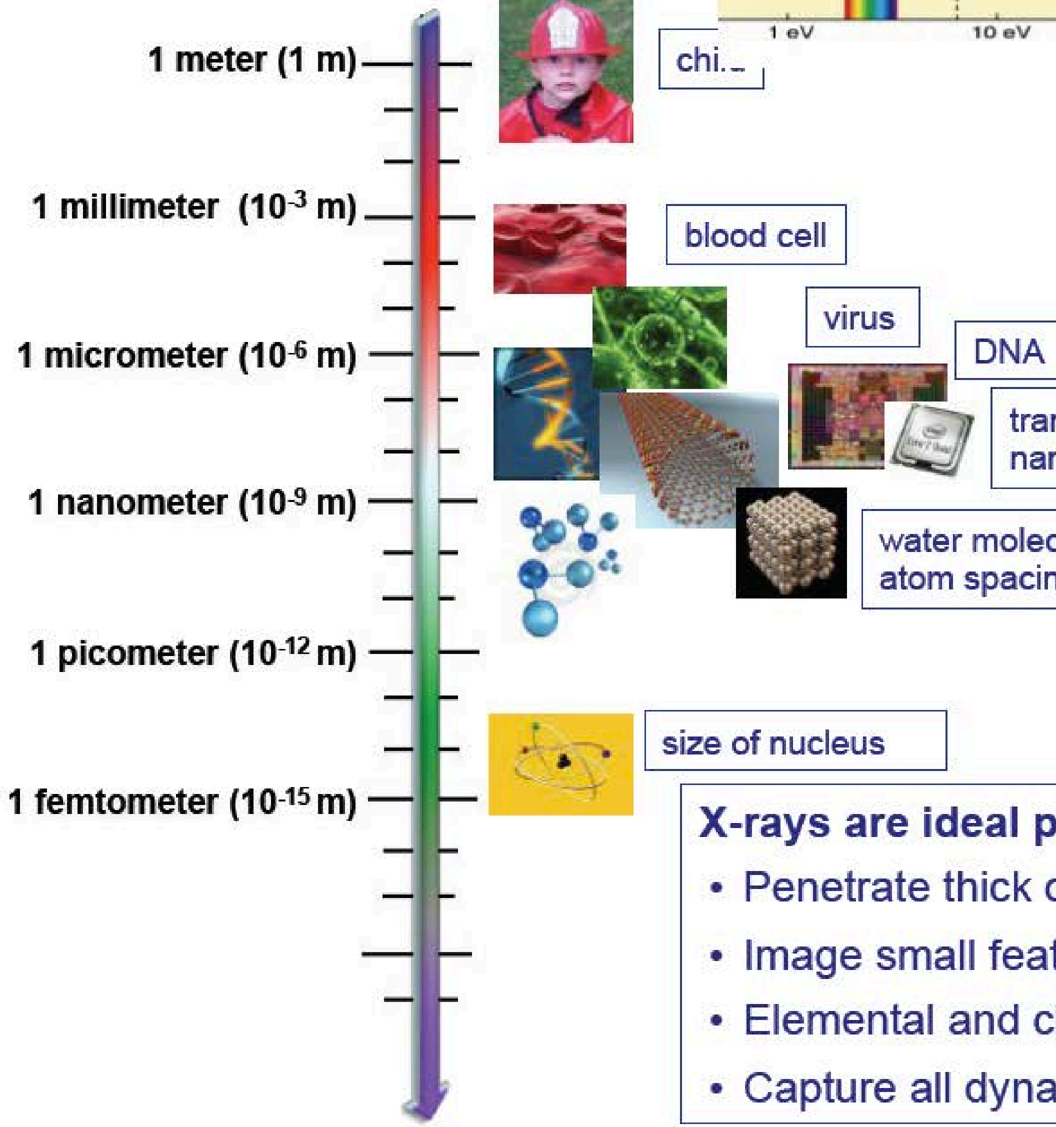
Ultrafast X-Ray Science: Quantum Physics at an Extreme and Applications in Materials and Nano Science

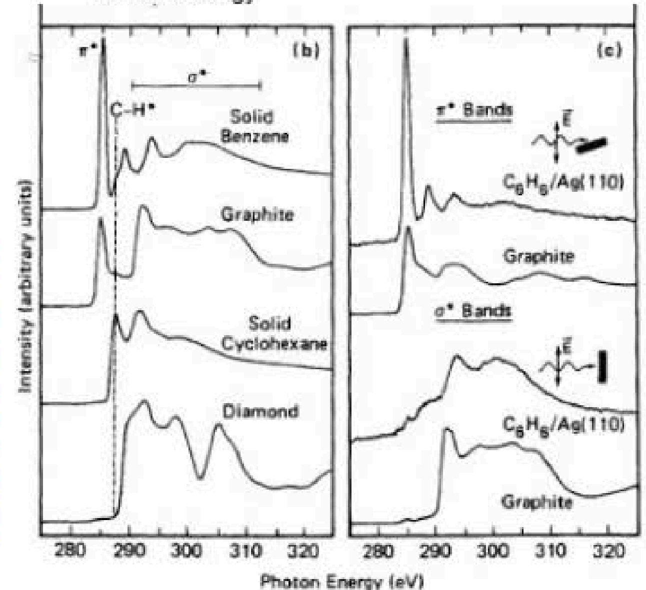
Margaret Murnane, U. Colorado/ JILA



The power of x-rays







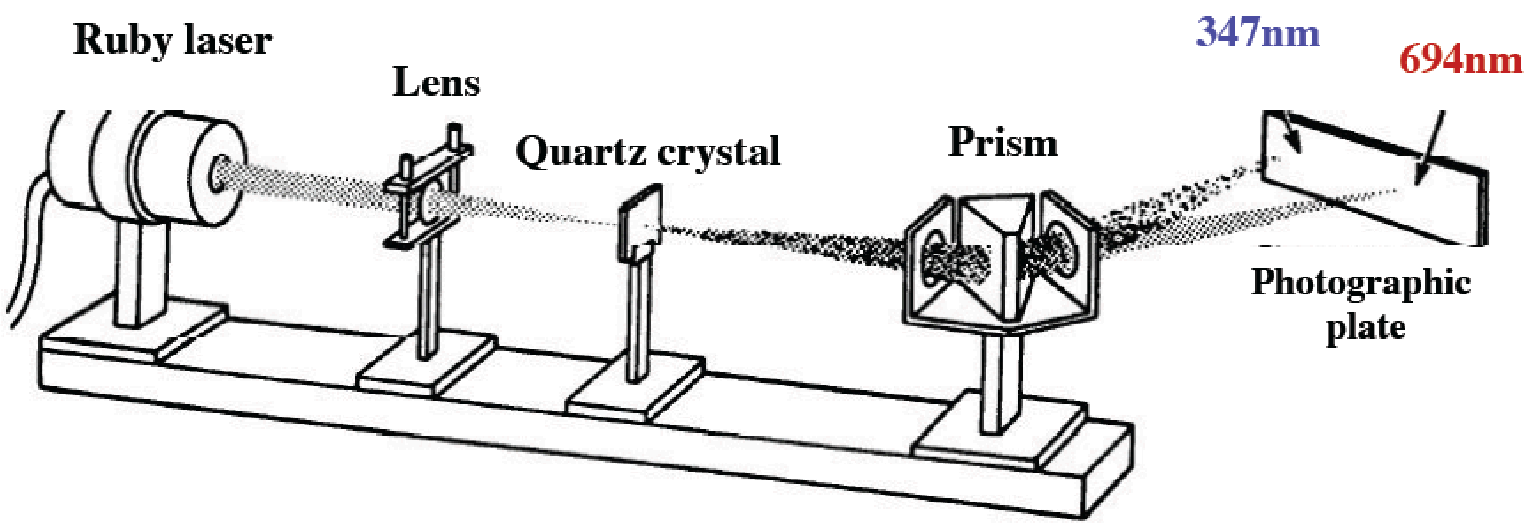
Stohr et al.

X-rays are ideal probes of the nanoworld:

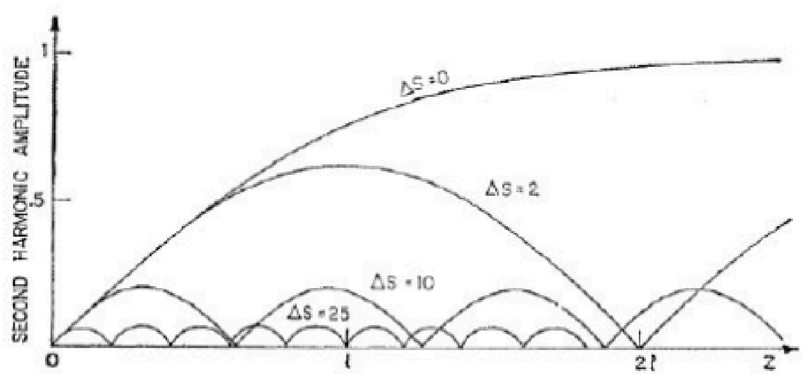
- Penetrate thick objects
- Image small features in 3D
- Elemental and chemical specificity
- Capture all dynamics relevant to function

Nonlinear Optics – phase matching

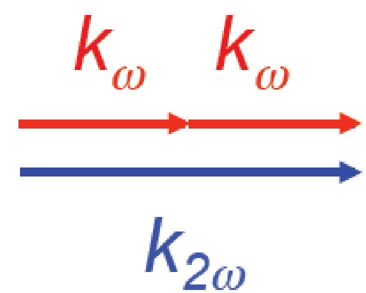
Franken et al, PRL 7, 118 (1961)



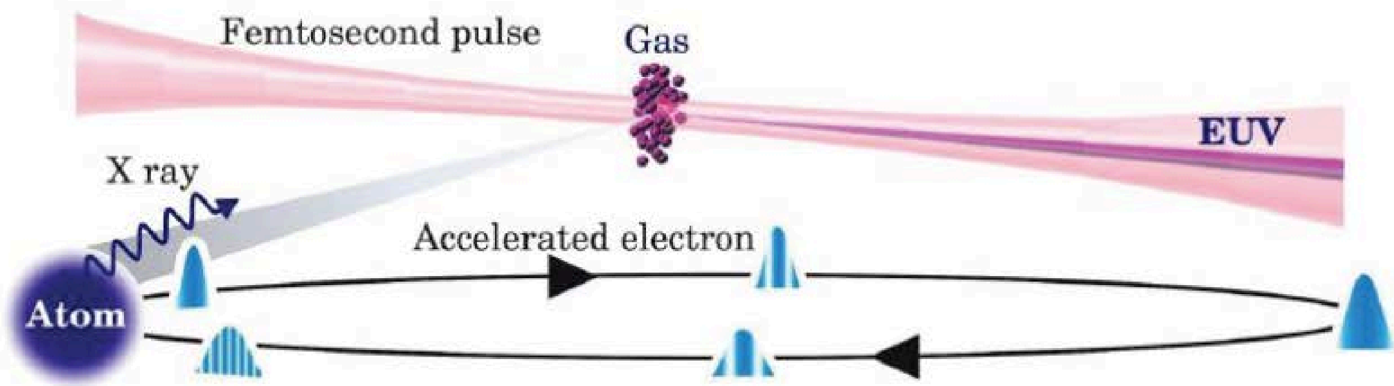
*Armstrong, Bloembergen et al., PRA **127**, 1918 (1962)*

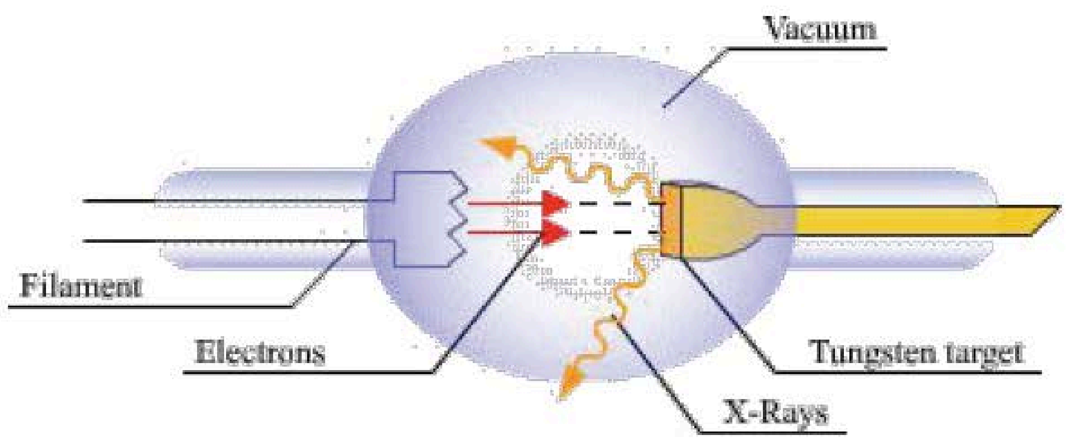


$$\boxed{V_{phase}(2\omega) = V_{phase}(\omega)}$$



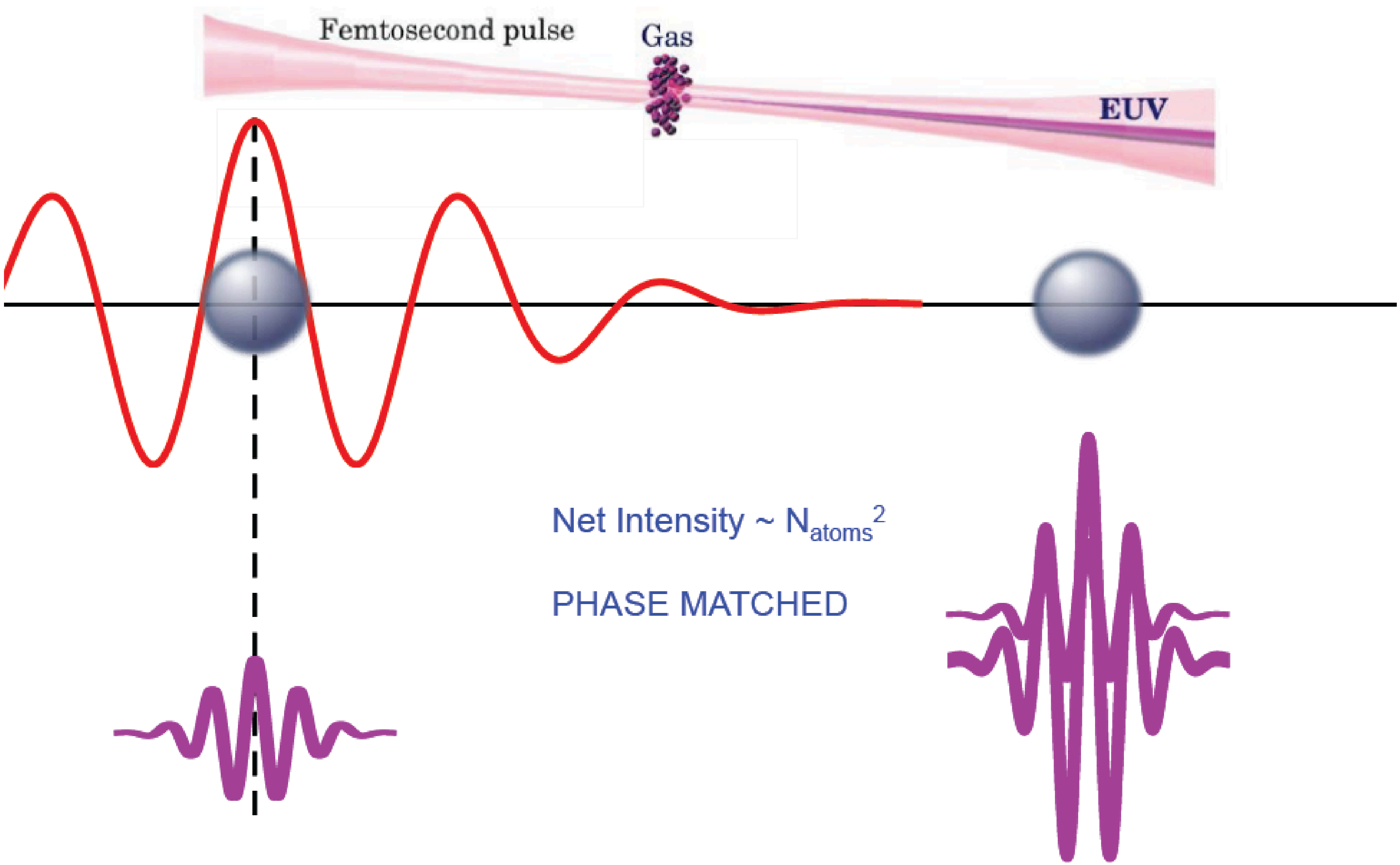
High harmonic generation – coherent version of the X-ray tube



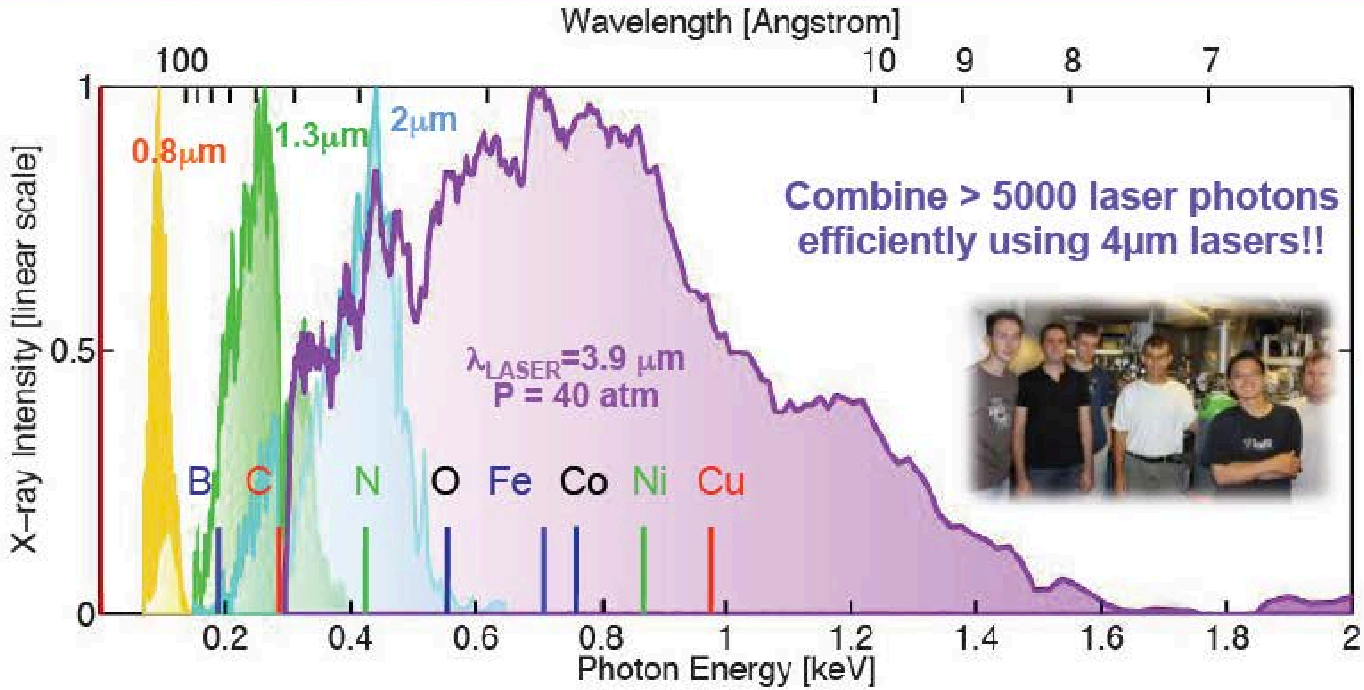


Röntgen X-ray Tube *(Roentgen, Nature (1896))*

Macroscopic phase matching challenge



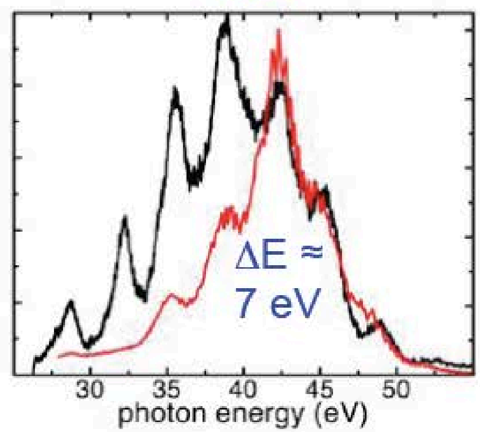
Unique X-ray source – coherent supercontinuum to 8Å

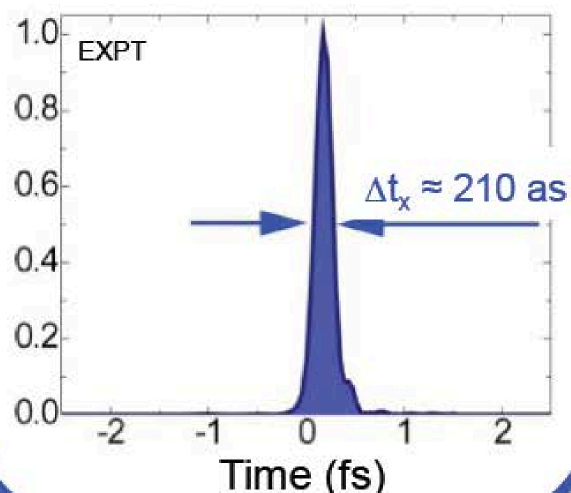


- **ONLY** bright coherent tabletop keV X-rays
- Highest nonlinear and phase matched process at > 5000 orders
- Phase matching bandwidth ultrabroad since vX-rays ≈ c
- Coherent spectrum spans many elemental x-ray edges

Femtosecond/attosecond pulses synchronized to laser

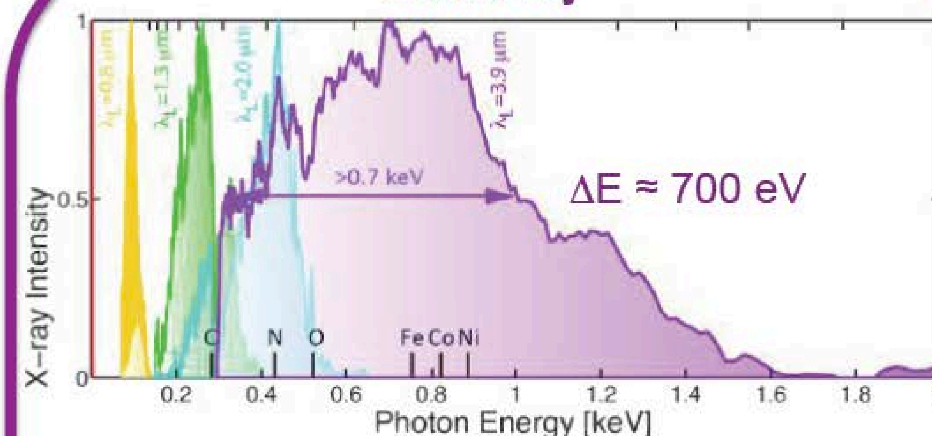
EUV



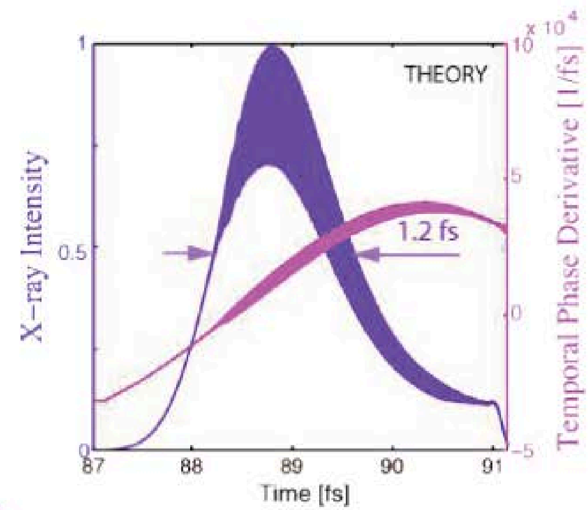


Opt. Express **17**, *4611 (2009)*

Soft x-ray



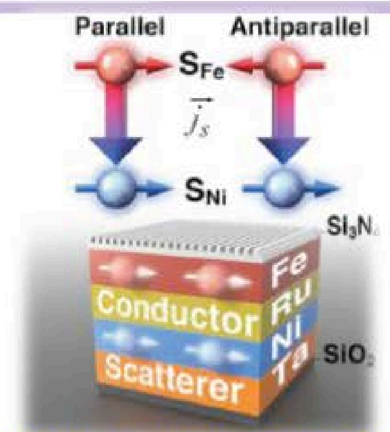
$\Delta E \approx 700$ eV

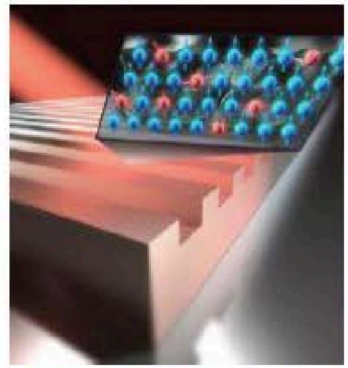


$\Delta t_x \approx 1.2$ fs
Potential 2.5 as

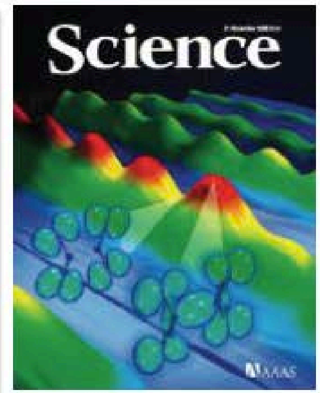
Science **336**, *1287 (2012)*

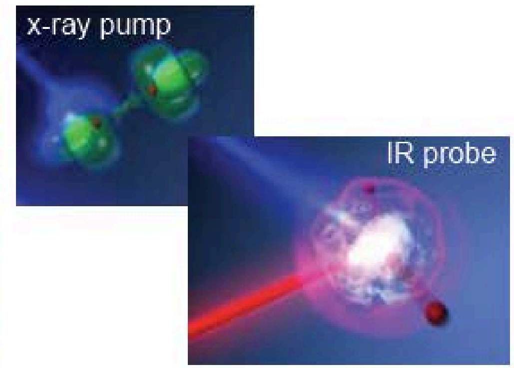
Capturing the fastest dynamics relevant to function



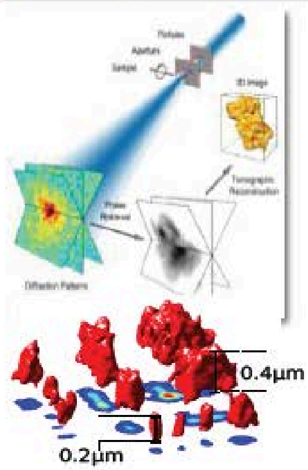


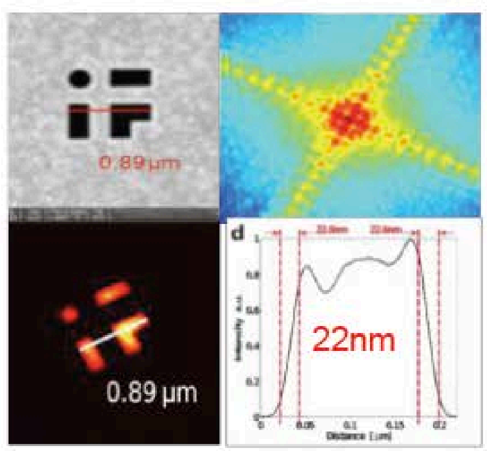
Capture charge-spin-phonon dynamics at multiple sites: *(Nature **471**, 490 (2011), PNAS **109**, 4792 (2012); Nature Comm **3**, 1037 (2012); Nature Comm **3**, 1069 (2012))*



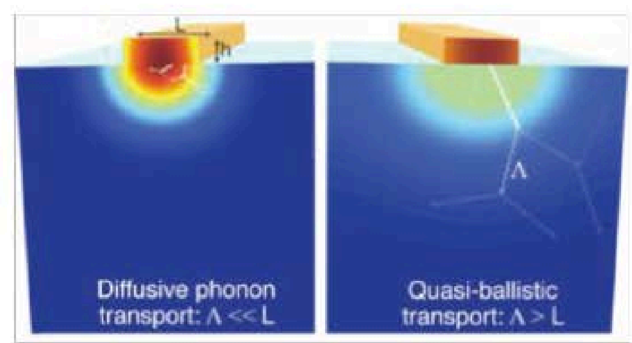


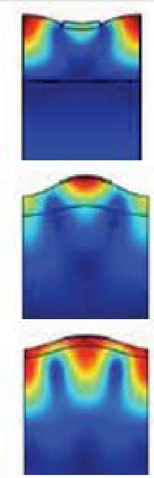
Coupled electron-nuclear dynamics in molecules: *(Science **317**, 1374 (2007), Science **322**, 1081 (2008), Nature Phys. **8**, 232 (2012), PRL **109** , 073004 (2012))*





Nanoscale imaging: Record tabletop 22nm resolution *(Op. Ex. **19**, 22470 ('11); **17**, 19050 ('12); Nature **463**, 214 (2010))*





Nanoscale energy transport: probe nanoscale energy/strain flow *(Nature Materials **9**, 26 (2010); Nano Letters **11**, 4126 (2011); PRB **85**, 195431 (2012))*

New Optical Techniques and Their Impact on the Life Sciences:

Making what's invisible today, visible tomorrow.

Taekjip Ha

Department of Physics

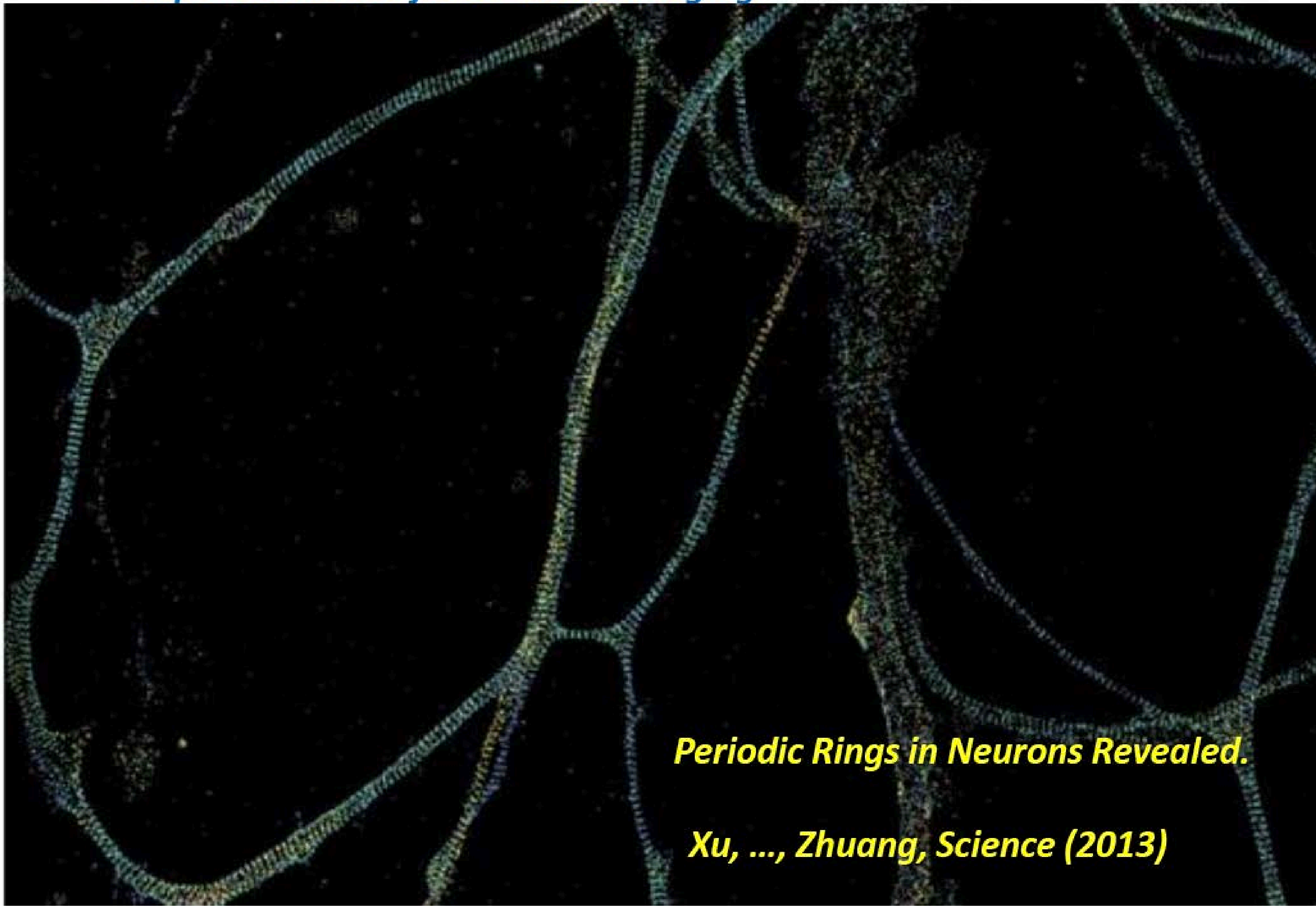
Center for the Physics of Living Cells

University of Illinois at Urbana-Champaign

Howard Hughes Medical Institute

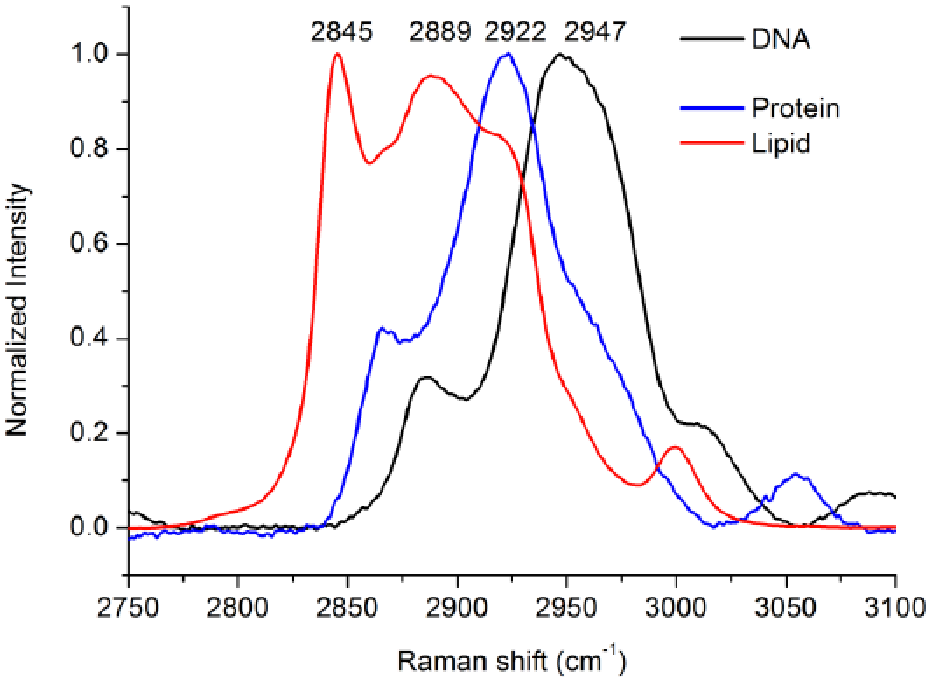
Opportunities

- ***Super-resolution fluorescence imaging***

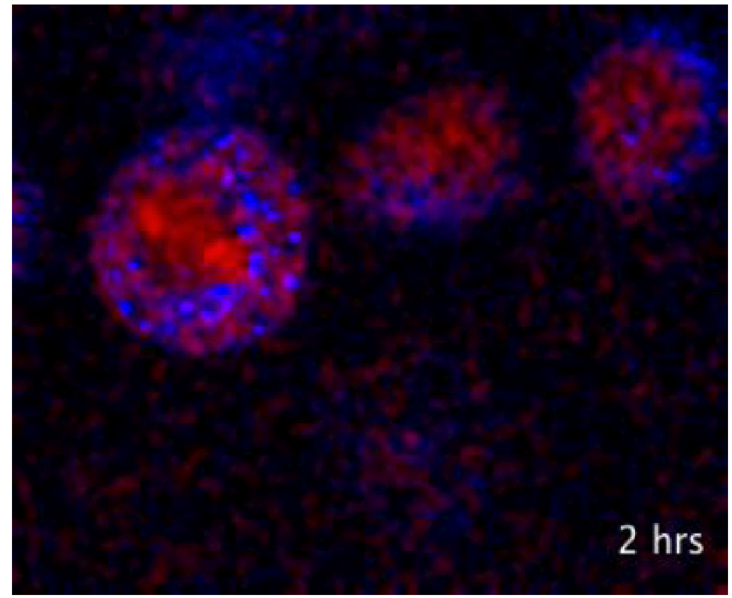


Opportunities

- ***Label-free microscopy with vibrational contrast***



Label-free imaging of live cell division



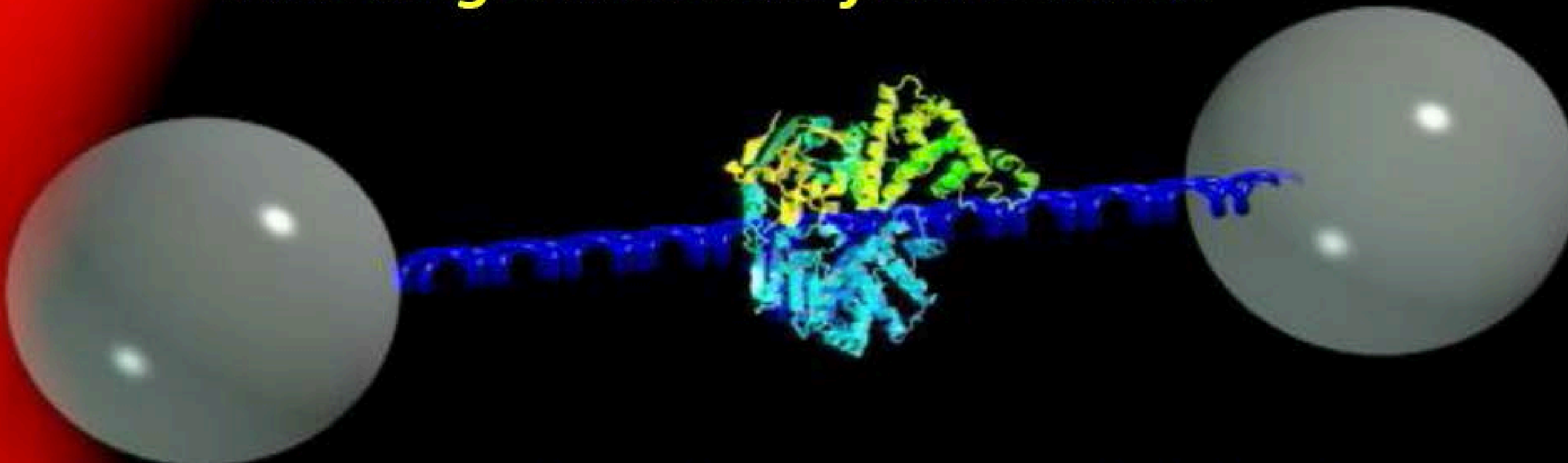
Red: DNA Blue: Lipids

Stimulated Raman Scattering Microscopy
Saar,…,Xie, Science (2010)

Opportunities

- *Fluorescence + Force*

Ultrahigh resolution optical trap with single molecule fluorescence



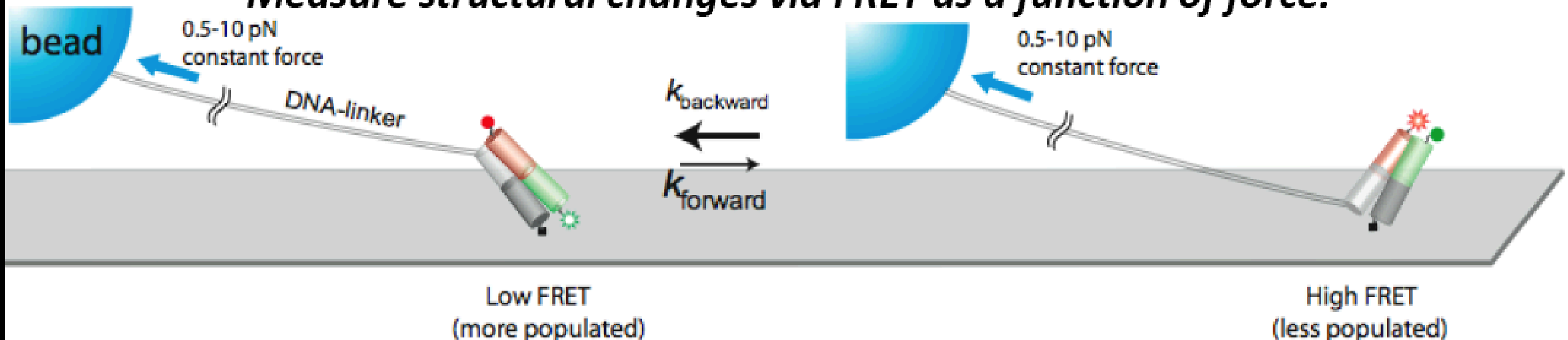
Comstock, Ha, Chemla, Nature Methods (2011)

Center for the Physics of Living Cells

Opportunities

- ***Fluorescence + Force***

Measure structural changes via FRET as a function of force.



- **Hohng, …, Ha, *Science* (2007)**
- **Grashoff, Hoffman, …, Ha, Schwartz, *Nature* (2010)**
- **Zhou, …, Ha, *Cell* (2011)**
- **Wang & Ha, *Science* (2013)**

-> single molecular force sensing in vivo

Center for the Physics of Living Cells

PULSE STANFORD

Coherence and control

Philip Bucksbaum

Stanford University and SLAC National Accelerator Laboratory

Summary: Fundamental science challenges: Coherence and Control

- **Opportunities: Quantum coherence in materials control new phenomena**
  - Quantum degeneracy and quantum coherence
  - Quantum coherence in photochemistry
  - Quantum coherence and information science
- **Gaps: Why we can’t calculate this stuff**
  - Kohn’s Law: Exponential wall prevents quantum calculations.
  - Excited state chemistry requires a new description.
  - Quantum simulators? Quantum computers? Better classical tricks? We don’t have an answer.
- **Why now? Coherence properties of novel light sources enable us to control new materials**
  - Chemical composition and chemical bond control;
  - Control of laser-driven materials properties;
  - Coherent Imaging of materials;
  - Nanoscale photonic technology has advanced.