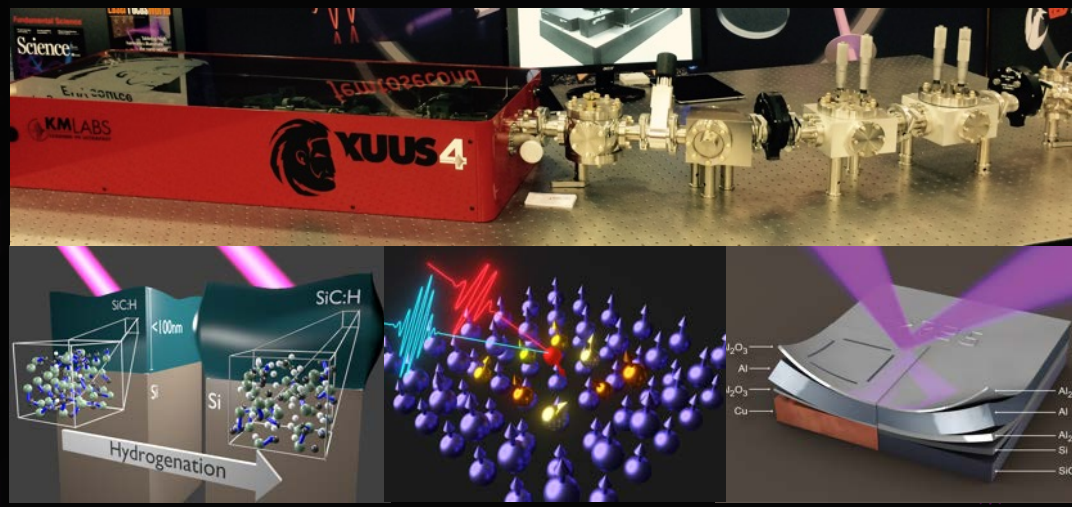
Tabletop-scale x-ray laser light sources– a new technology for defense and science

Henry Kapteyn
KMLabs Inc.
JILA, University of Colorado at Boulder

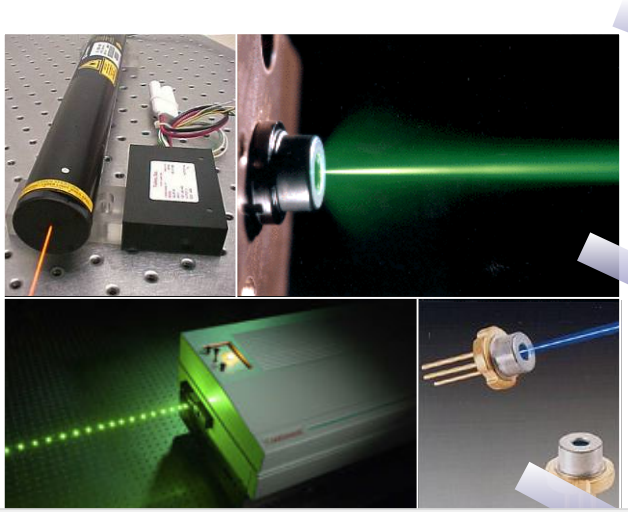


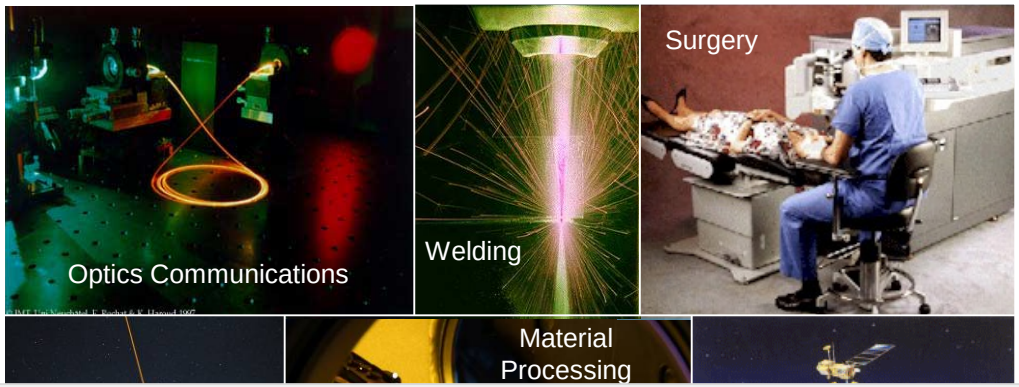
VUV/EUV/SXR **Metrology** **ARPES** **Imaging**

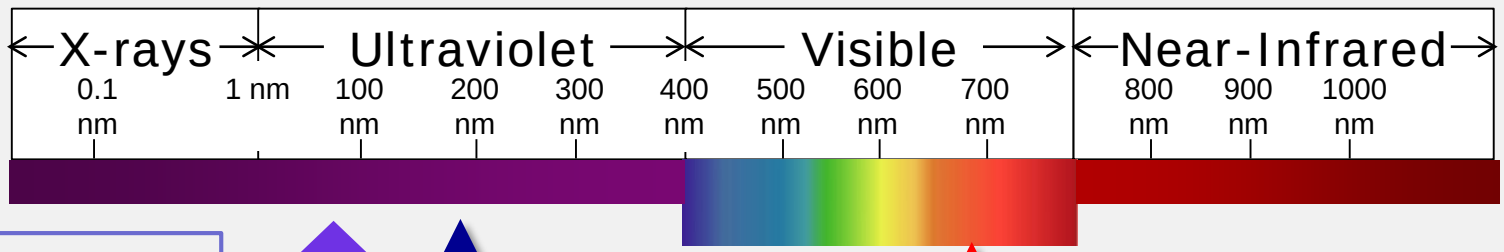
KMLABS™ inc. LEADING IN ULTRAFAST

JILA NIST CU

Lasers: progress to shorter wavelengths







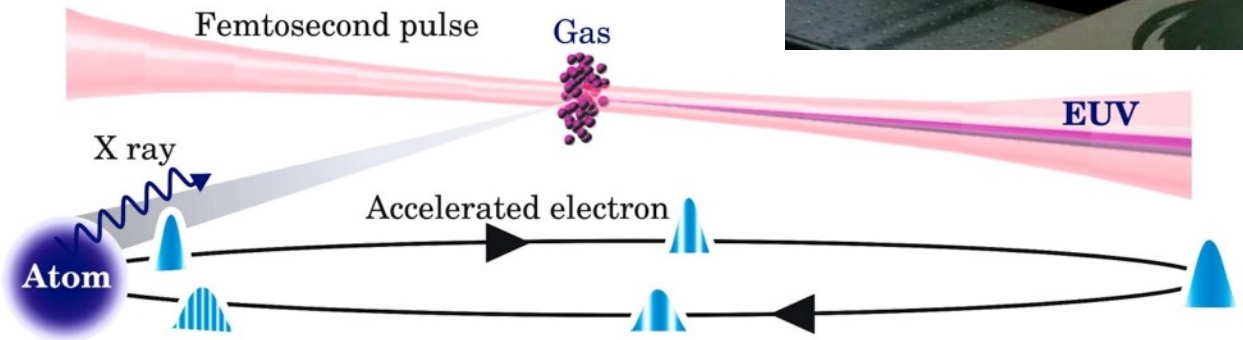
High harmonics: **first viable tabletop EUV/SXR technology**

Excimer lasers

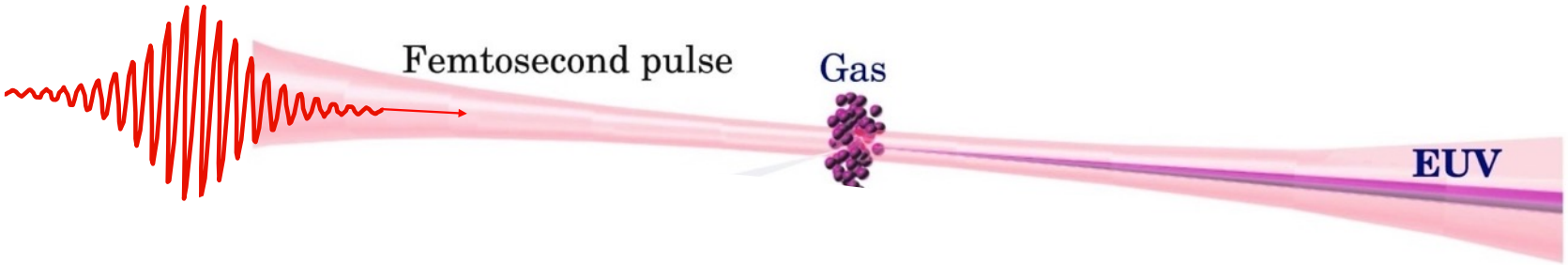
Ruby laser, 1960

Tabletop x-ray "lasers" now possible using advanced intense-pulse laser technologies

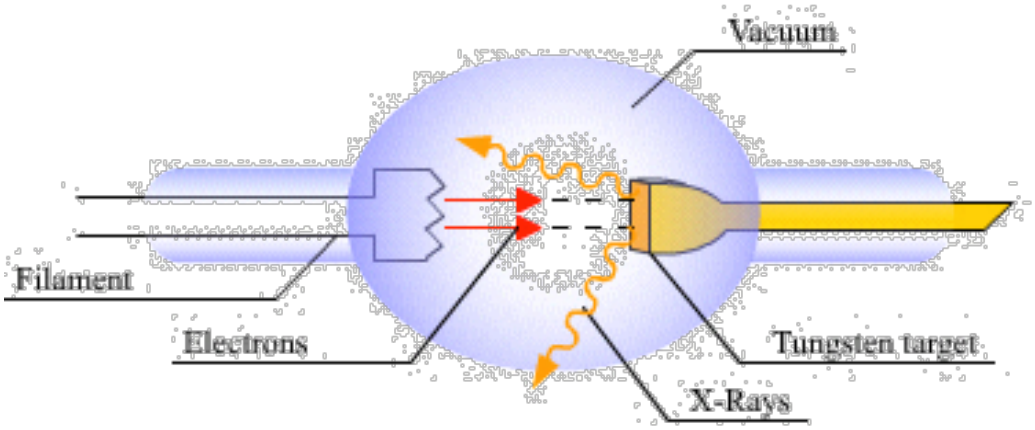
1. **Femtosecond pulses → GW peak power in a briefcase**
2. **Terawatt-level (10^{12} W) peak power on a tabletop**
3. **"Strong field" interaction of light with atoms and molecules**
   - *Coherently* upconvert light to much shorter, ultraviolet and x-ray wavelengths



HHG as a coherent, laser-driven x-ray tube



High harmonic generation *(JOSA B 4, 595 ('87); J Phys B 21, L31 ('88))*

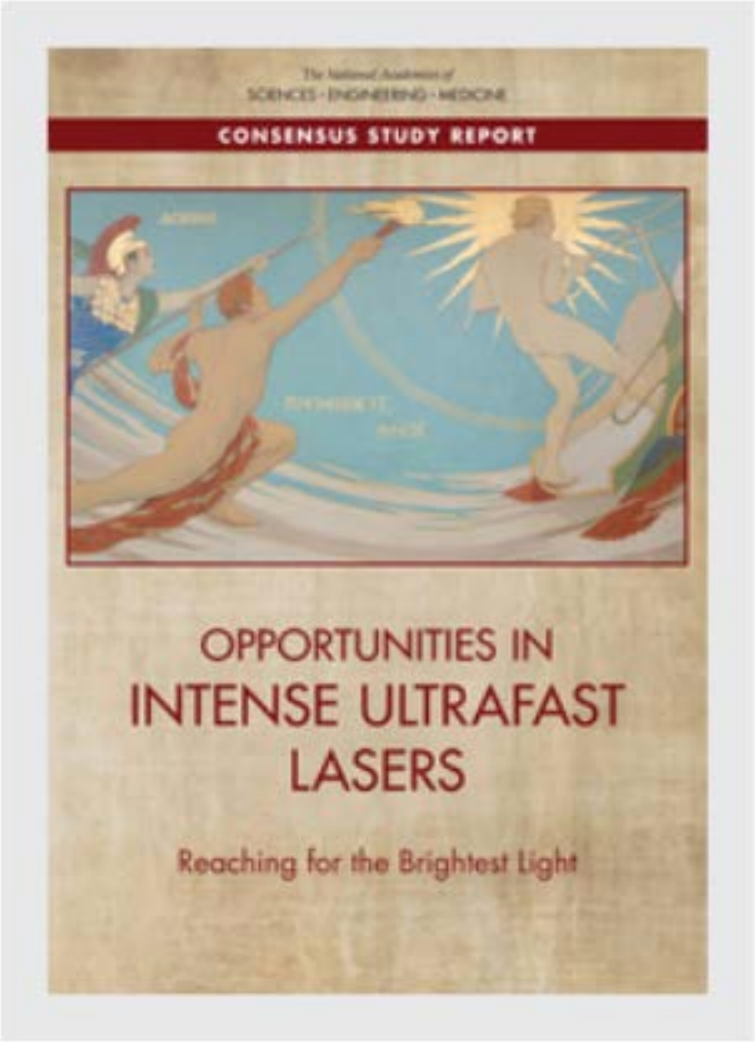


Röntgen X-ray Tube


1895

2017 NAS Report:
A new generation of lasers promises disruptive capabilities

- **"Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light," DOI 10.17226/24939**



Present-day applications in science:

Tabletop X-rays "see" new materials/nano science

Spin scattering, transport, interactions

*PNAS **109**, 4792 (2012)*
*Nat. Comm. **3,** 1037 (2012)*
*PRL **110**, 197201 (2013)*
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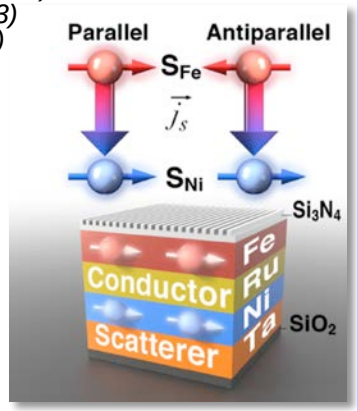
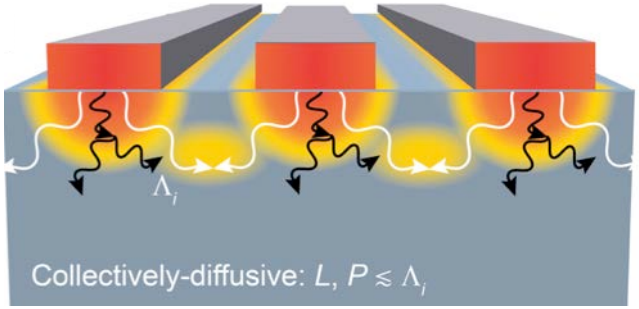
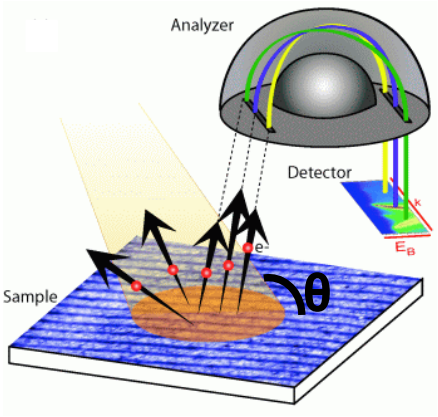


Nanoscale energy transport

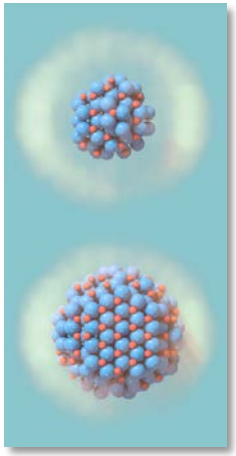


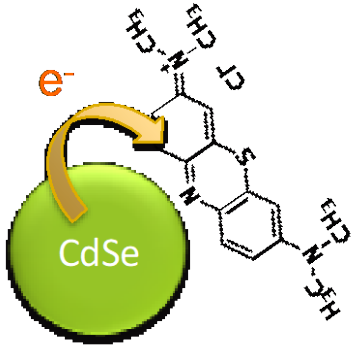
*Nature Mat. **9**, 26 (2010); PNAS **112**, 4846 (2015)*

Phase changes - full band structure in real time via ARPES



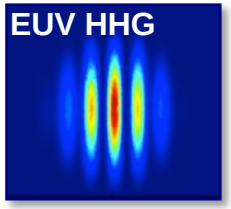
Charge transport in nano, energy science

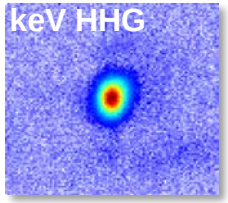


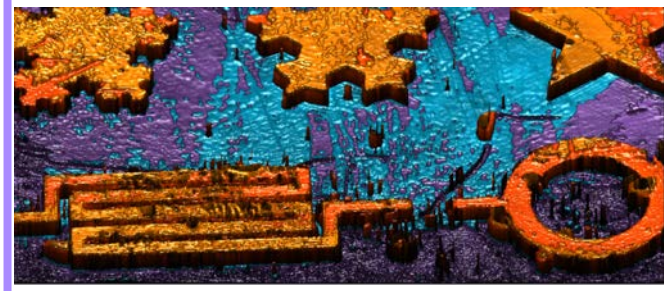


*Nano Lett. **13**, 2924 (2013)*
*JACS **137**, 3759 (2015)*

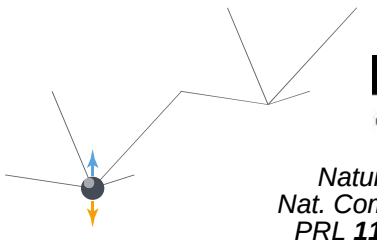
Imaging at the λ limit





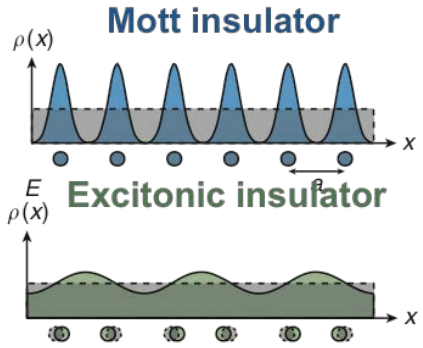


*Optica **1**, 39 (2014); Science **348**, 530 (2015)*
*Ultramicroscopy **158**, 98 (2015)*



Christian-Albrechts-Universität zu Kiel

*Nature **471**, 490 (2011)*
*Nat. Comm **3**, 1069 (2012)*
*PRL **112** , 207001 (2014)*
*PRB **92**, 041407(R) (2015)*



Future materials: promise and challenges

- **Fast, energy efficient nanoelectronics**
- **Ultrahigh performance sensors for monitoring health, manufacturing**
- **Smart windows/clothes/buildings, super-smart personal electronics**
- **Materials that change their states and properties "on demand"**
  - 2D transition metal dichalcogenides, topological materials, nano-structured quantum materials, skyrmions, magnons etc

Challenge: to capture otherwise-invisible function in systems with nanostructure, interfaces, correlated dynamics, heterogeneity, etc

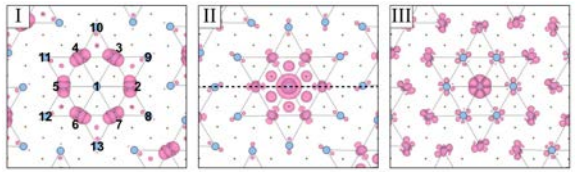
BASIC RESEARCH NEEDS WORKSHOP ON

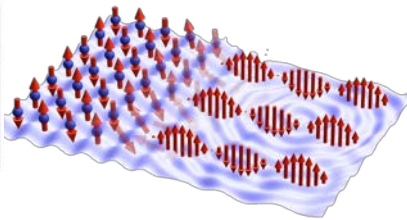
Quantum Materials for Energy Relevant Technology

REPORT OF THE OFFICE OF BASIC ENERGY SCIENCES WORKSHOP ON QUANTUM MATERIALS

CHAIR:
Collin Broholm, Johns Hopkins University

CO-CHAIRS:
Ian Fisher, Stanford University
Joel Moore, LBNL/University of California, Berkeley
Margaret Murnane, University of Colorado, Boulder





If You Can't Measure It, You Can't Make It….

- **Quantum, Neuromorphic, and Spintronic Computers will require very different device characterization compared to conventional IC's**

- **Unique performance-defining characteristics:**
  - Quantum State
  - Spin-dependent transport
  - Characterization of Interfaces (roughness, thicknesses and compositions of interdiffused layers, high resolution of surface morphology)

- **Critical Key Modalities are needed:**
  - In situ (active devices, not sacrificed to be put in TEM)
  - Sub-surface (interface transport and interfacial character cannot be measured from the top (AFM/SEM))
  - Correlation to other techniques (esp. destructive techniques like TEM)

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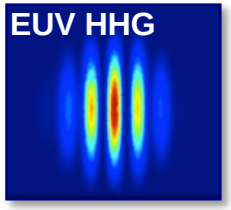

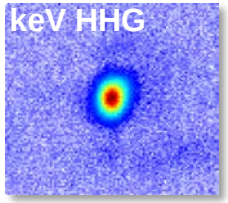

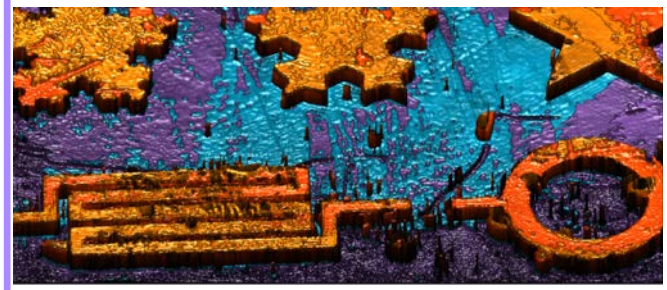

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Nature **471**, 490 (2011)
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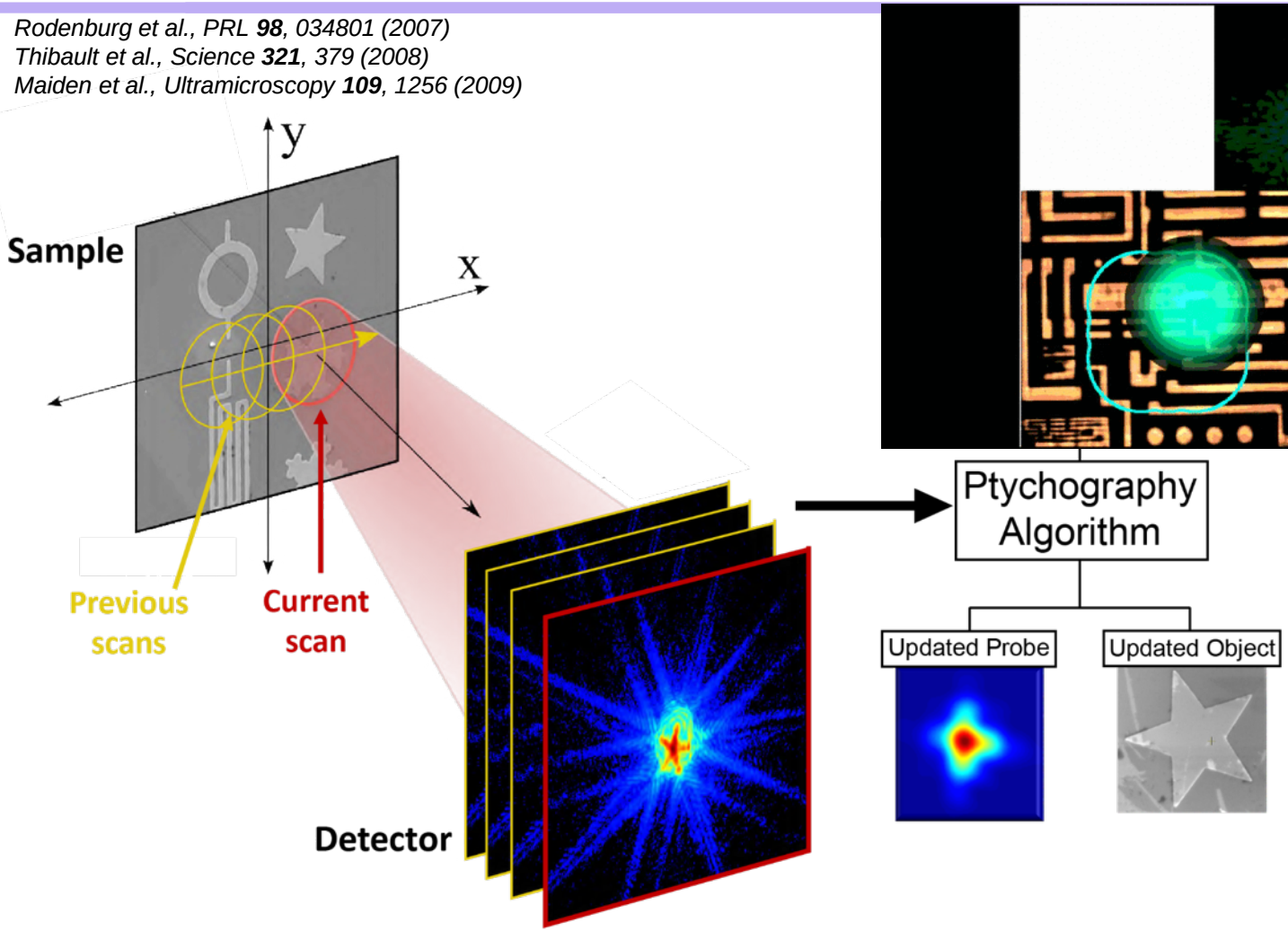
PRL **112** , 207001 (2014)
PRB **92**, 041407(R) (2015)

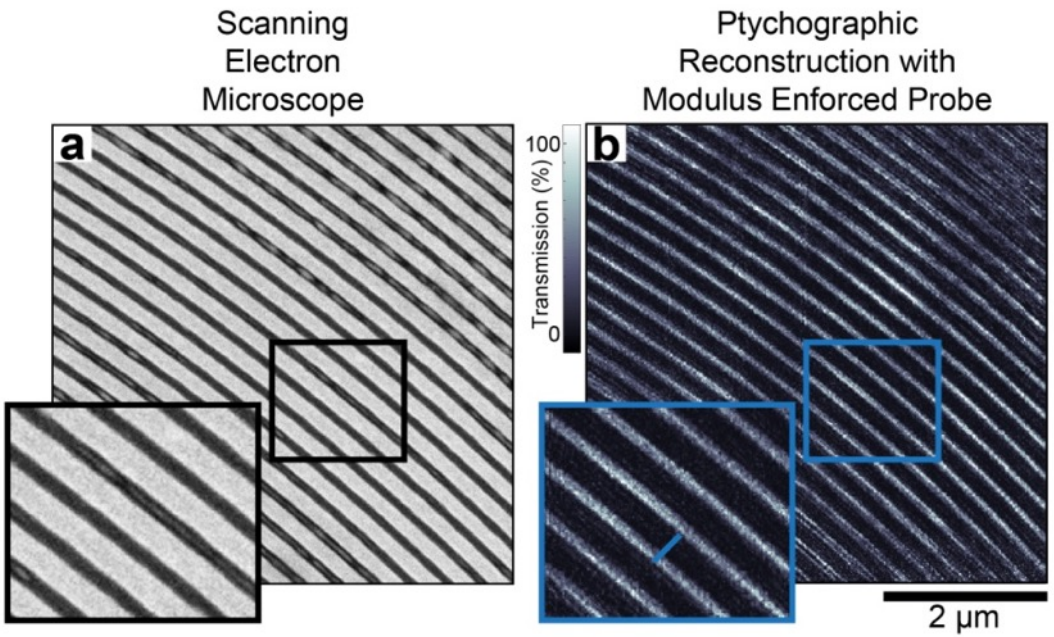
“Ptychographic” coherent imaging

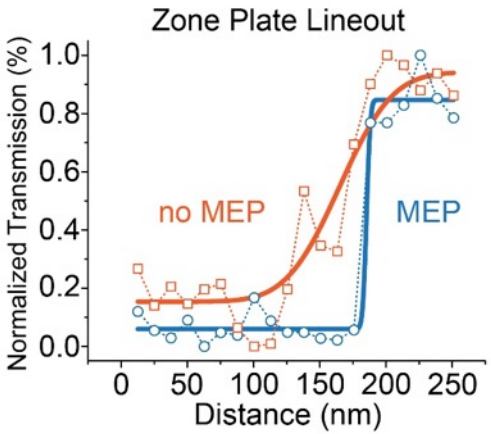
*Rodenburg et al., PRL **98**, 034801 (2007)*
*Thibault et al., Science **321**, 379 (2008)*
*Maiden et al., Ultramicroscopy **109**, 1256 (2009)*

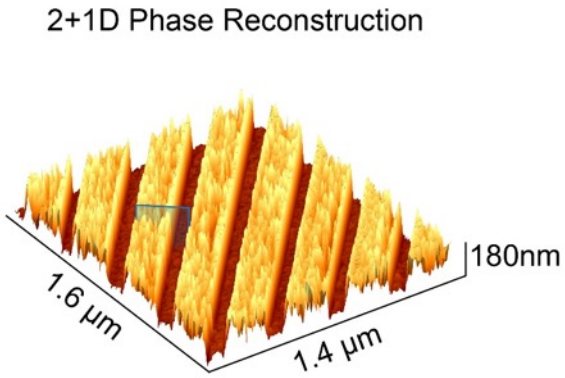


- CDI from overlapping areas to enhance redundancy
- Needs bright stable HHG beams
- Sub-wavelength resolution for high numerical aperture (NA≤1)

Unprecedented <13 nm image resolution– on a tabletop





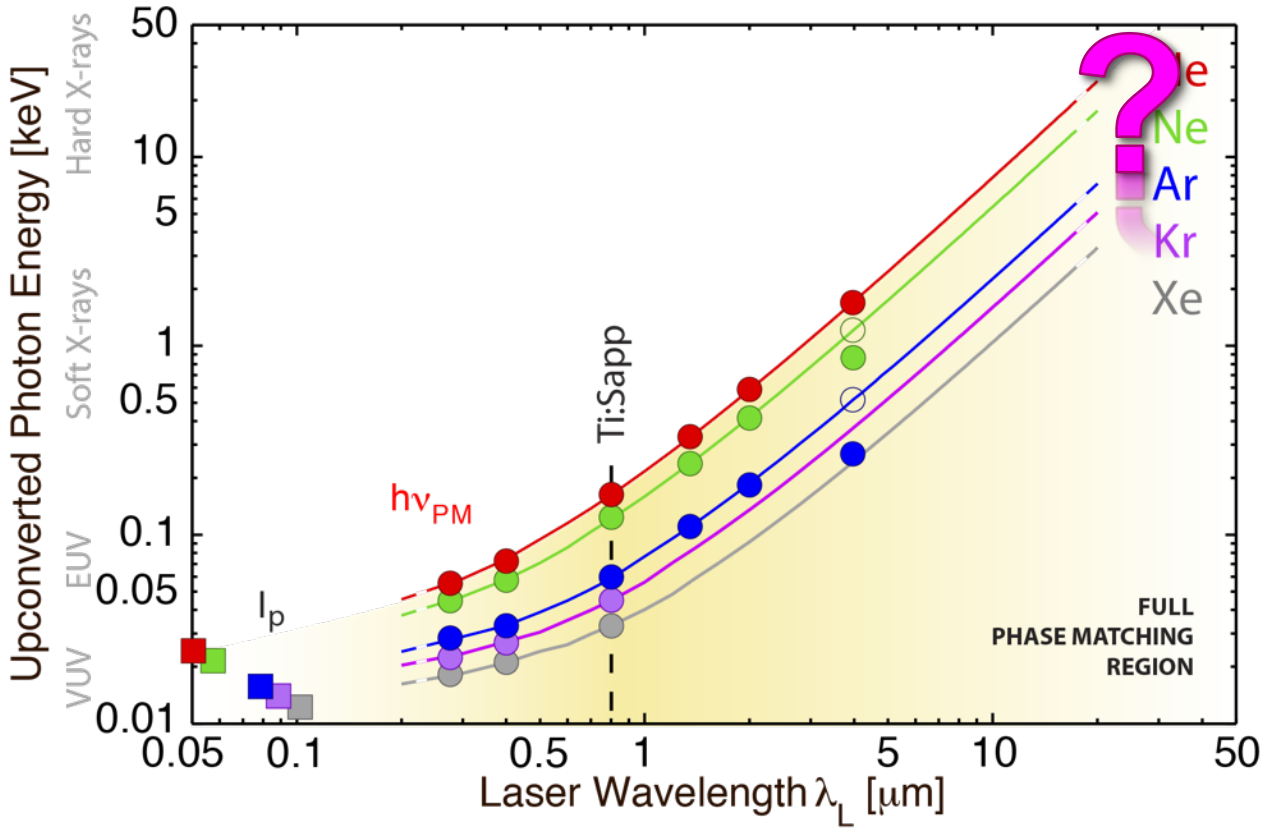


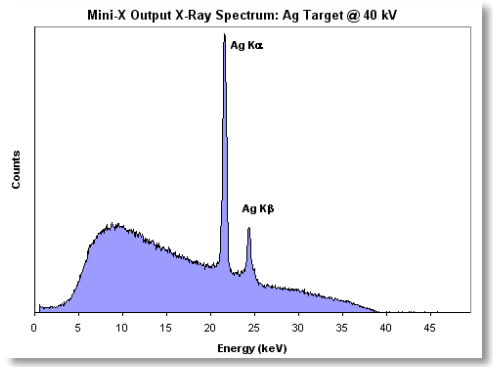
- **Record resolution for a tabletop scale optical microscope: 12 nm**
- **Immediate relevance to EUV lithography for next-generation nanoelectronics**

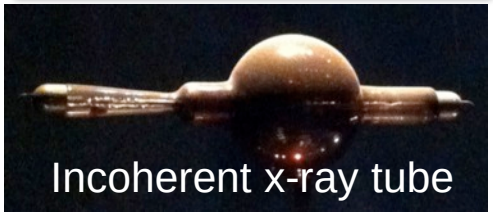
Nature Photonics ***11****, 259 (2017)*

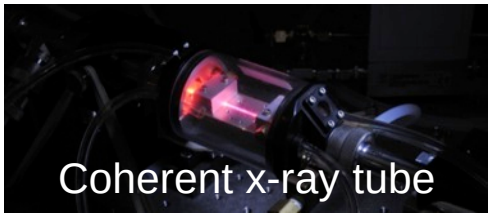
Future: Wavelength limits of HHG not yet known!

- **Scaling of basic physics:**
  - Intense 10-30 μm mid-IR lasers may generate bright **10-50 keV** hard x-rays
- **Efficiency may increase orders of magnitude**
- **Potential as a disruptive technology**







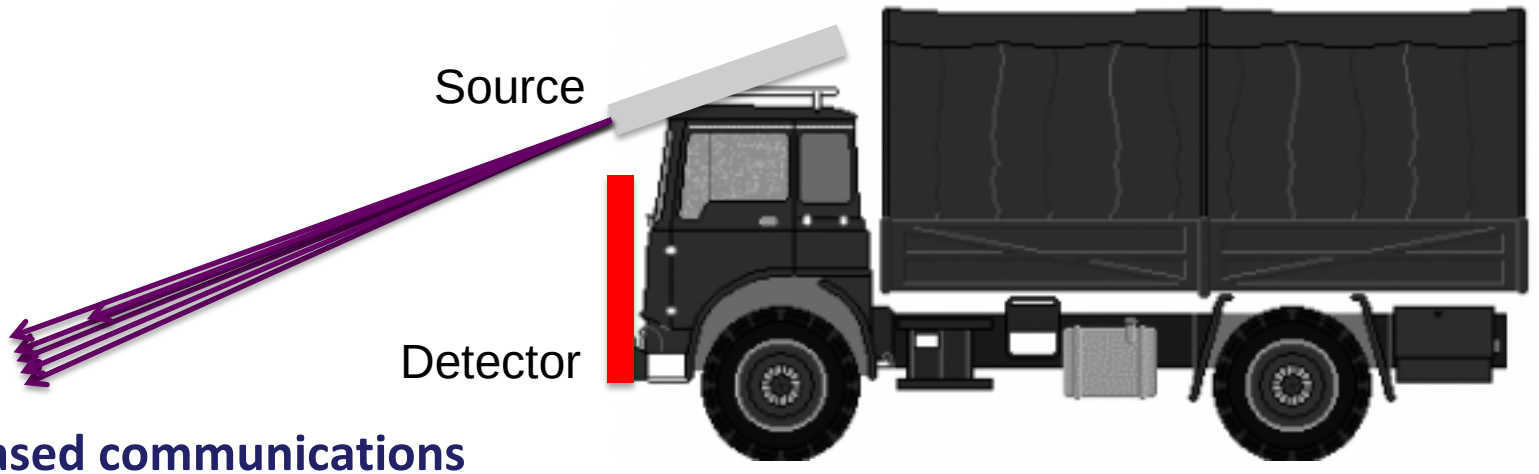


Security app: x-ray backscatter screening

1. **Embassies, military FOBs, etc.**

2. Mine/IED detection

- Ability to image buried structures allows discrimination between natural & buried objects
- Possible penetration to several absorption depths using timing discrimination



3. Space-based communications

- Dramatically reduced source divergence

4. Materials Defect Inspection

- Armor, Aircraft engines & components
- XRF nanoprobe imaging

Summary

- **New laser technologies are advancing rapidly**
- **Ultrashort-pulse, high intensity lasers provide unique capabilities for small-scale x-ray laser sources**
- **Highly competitive internationally**
  - Europe – has seized the lead on commercial applications
  - China – heavy investment
- **Opportunity to leverage current DoD investment in high-energy laser technology, advance industry and manufacturing technology**