Circularly Polarized High-Harmonics – From Symmetries to Applications

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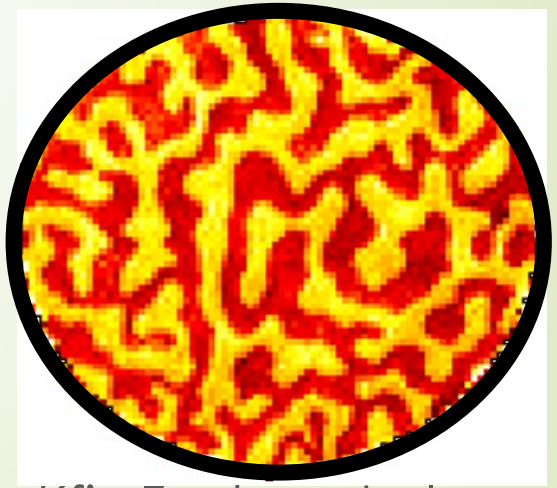
EUV sources conference, ARCNL, Amsterdam

Magnetic domains, first image with HH



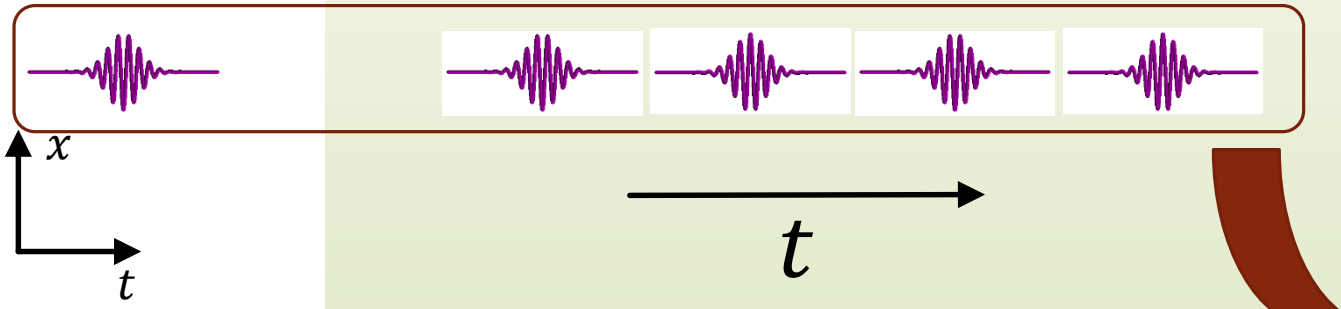
Kfir, Zayko, et al.,
Science Advances, eaao4641 (2017)

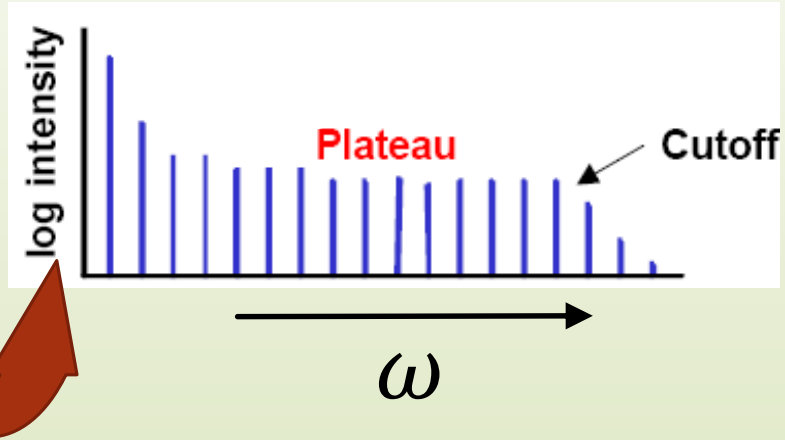
Outline

- High harmonic generation
- Circularly polarized high harmonics.
- In-line apparatus – simple!
- Imaging of magnetic domains.
- Summary

High harmonics generation - Fundamentals

A train of linearly polarized attosecond pulses

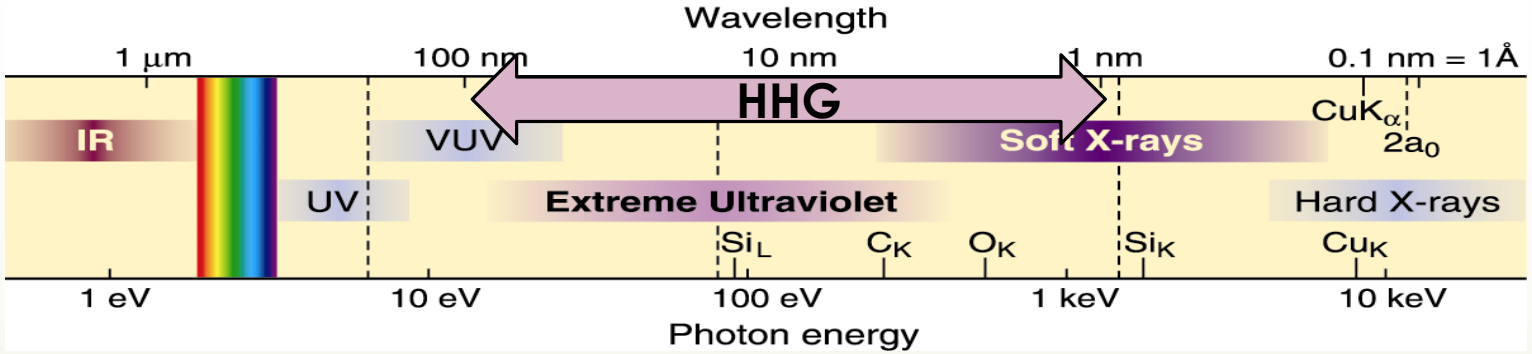




Oscillating Electric field

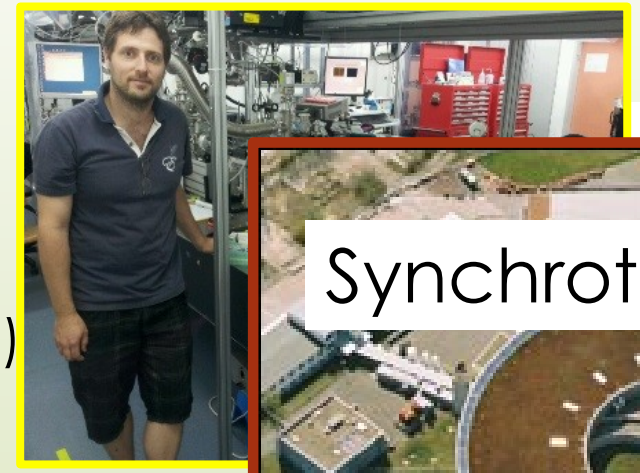
McPherson, A. *et al.* JOSA B **4** 595 (1987);
Ferray et al., J. of Phys. **21**, L31 (1988)
Corkum, P. B., PRL **71**, 1994 (1993)
Kulander, K. C., *et al.* Laser Physics **3**, 359 (1993)

HHG - a unique light source



Control

- Spectrum → Extreme-UV and soft-X-rays
- → broad / single harmonic
- Coherence (laser-like) → Lensless imaging
- Temporal → Attosecond science (*1 atto=10^{-18} sec*)
- **Polarization?** General mindset: polarization is ~ linear



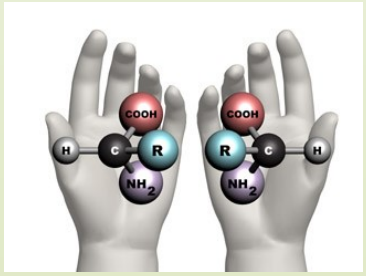
Control polarization / spin!

Fleischer, Kfir, et al., Nature Photonics Phot.
Kfir et al., Nature Photonics 9, (2015).

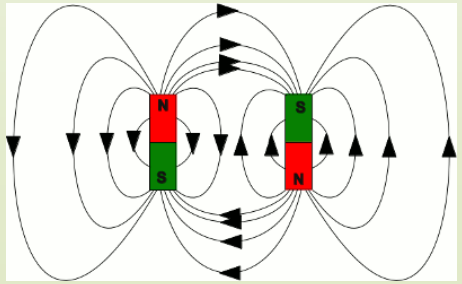
Polarization?

For chiral sensitivity the ultimate polarization is circular.

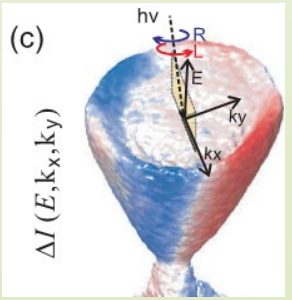
Chiral molecules



Magnetic features

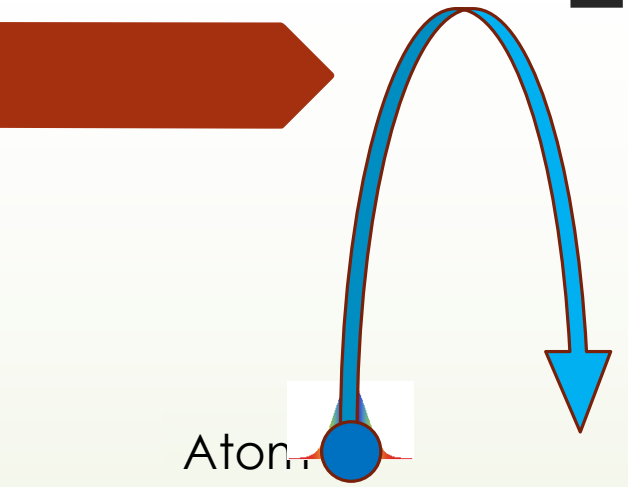


Spin textures



Wang, Hsieh, Gedik et al.,
PRL 107,207602 (2011)

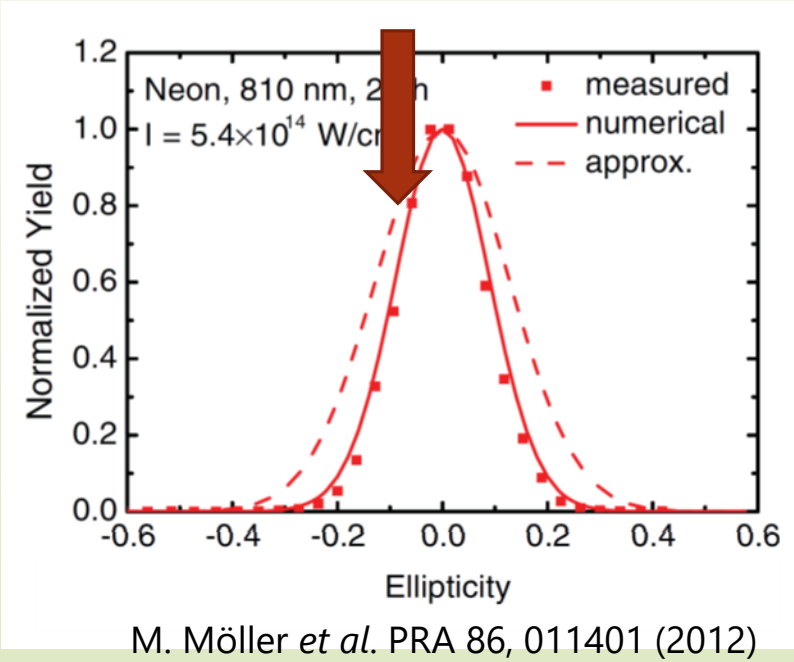
Ellipticity effects in HHG



Mindset: polarization of (bright) high harmonics is ~linear

Ellipticity diminishes HHG efficiency since the electron misses the atom

Higher orders harmonics are more sensitive to the laser ellipticity



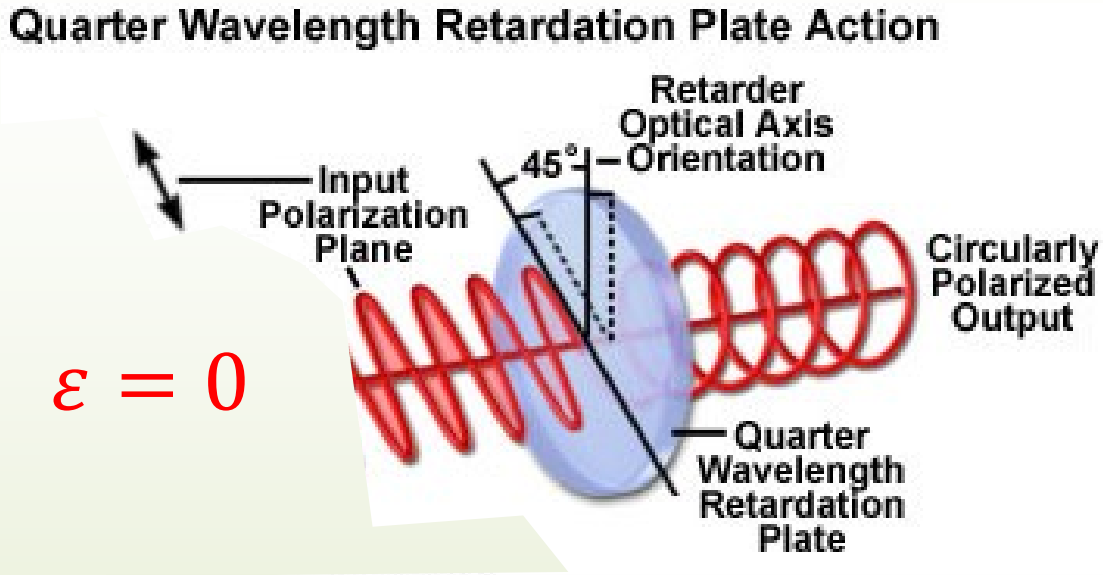
M. Möller *et al.* PRA 86, 011401 (2012)

M. Möller *et al.* PRA 86, 011401 (2012)
Weihe, F.A., *et al.*, PRA **51**, R3433 (1995)

Quarter-wave plate

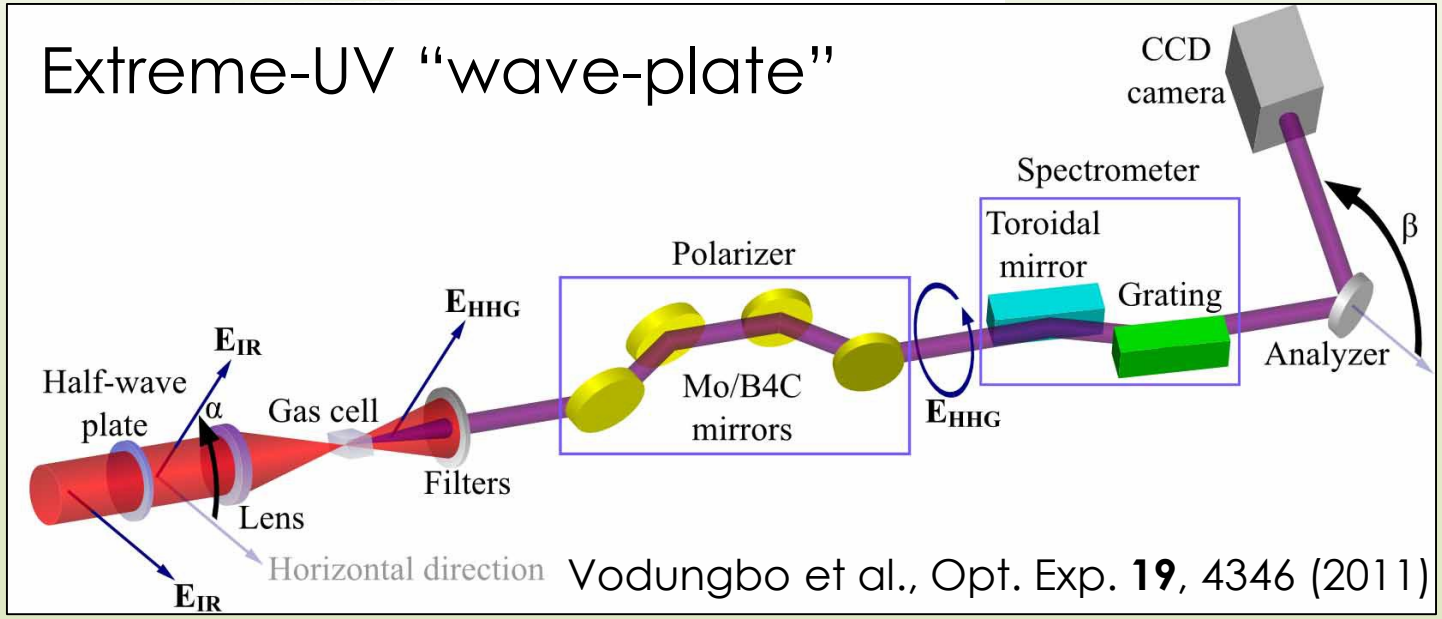
- Visible
  - Control polarization
  - Lossless

$\varepsilon = 0$



$\varepsilon = 1$

- Extreme UV
  - Lossy
  - Limited spectral regions
  - Sensitive



Outline

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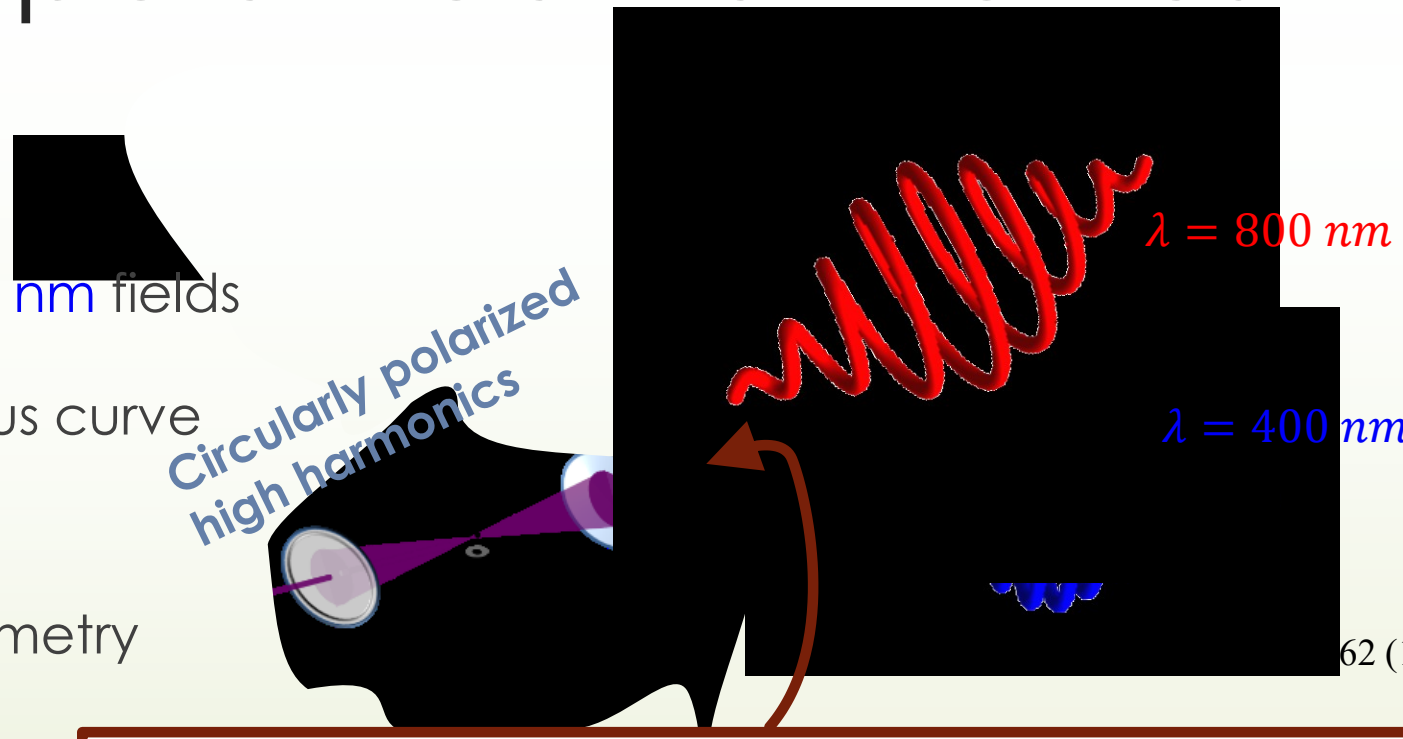
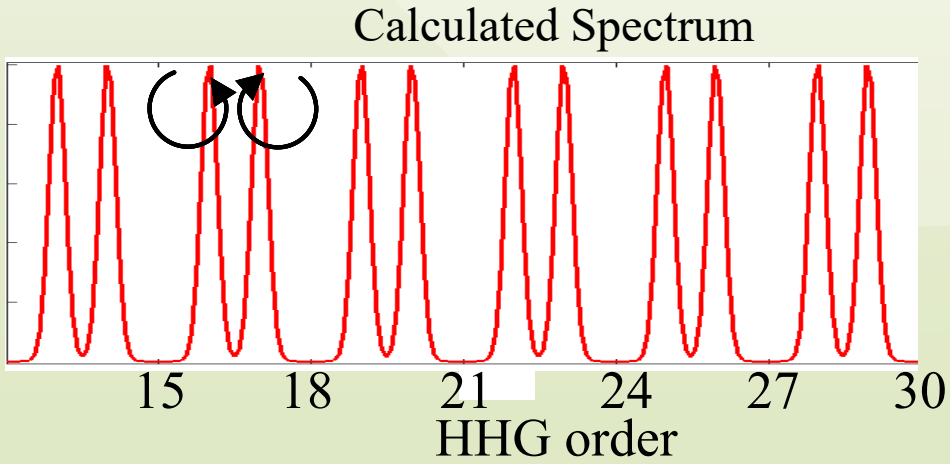
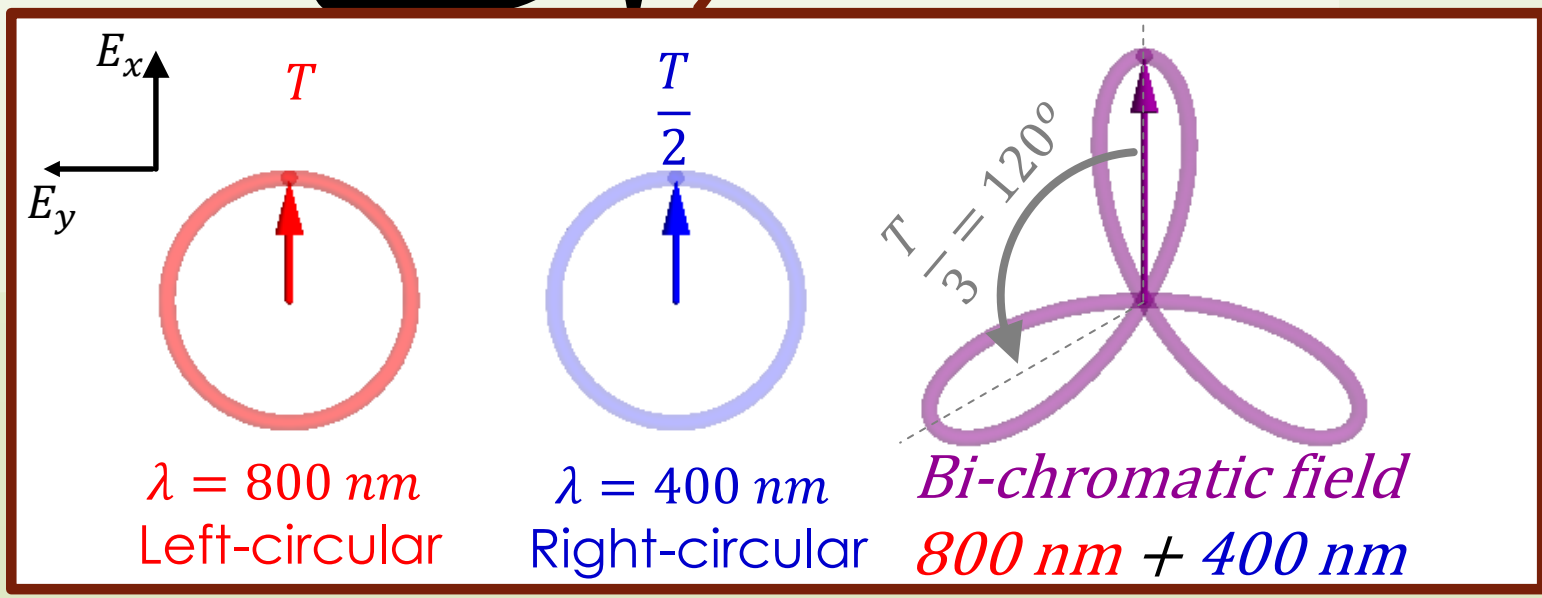
Circularly polarized harmonics

- Driven by circularly polarized counter rotating 800 nm and 400 nm fields
- The Bi-chromatic field has Lissajous curve of a 3-fold flower
- The system has a dynamical symmetry delays of $T/3 \rightarrow$ rotation of 120^o



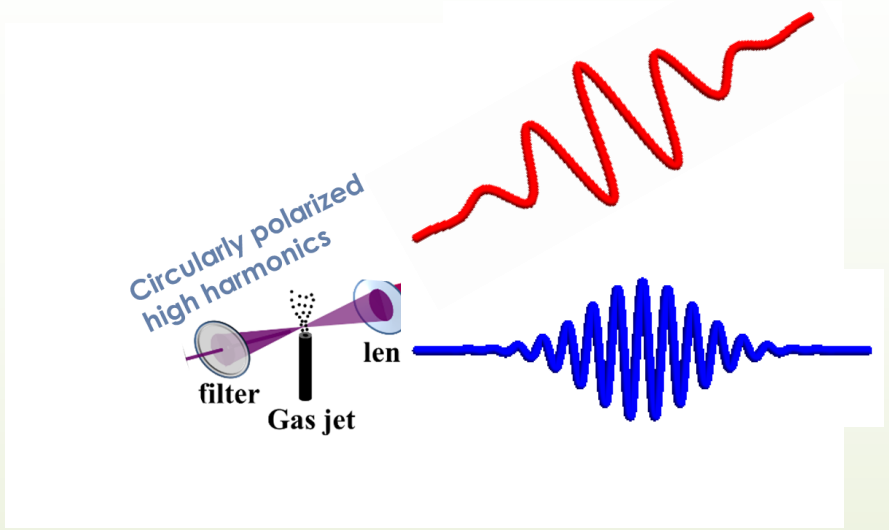
62 (1995)

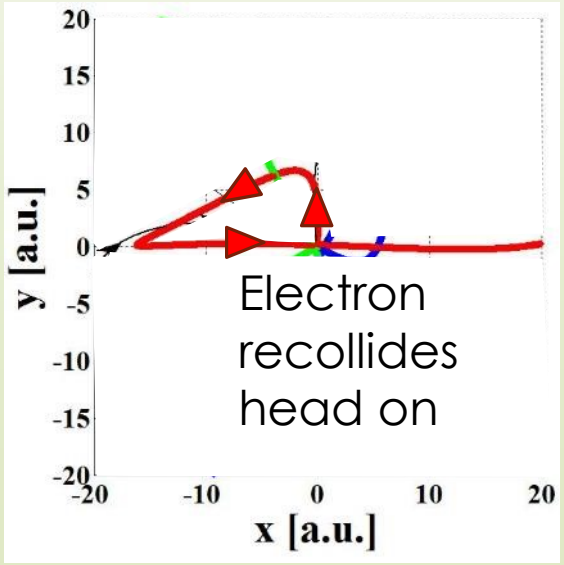




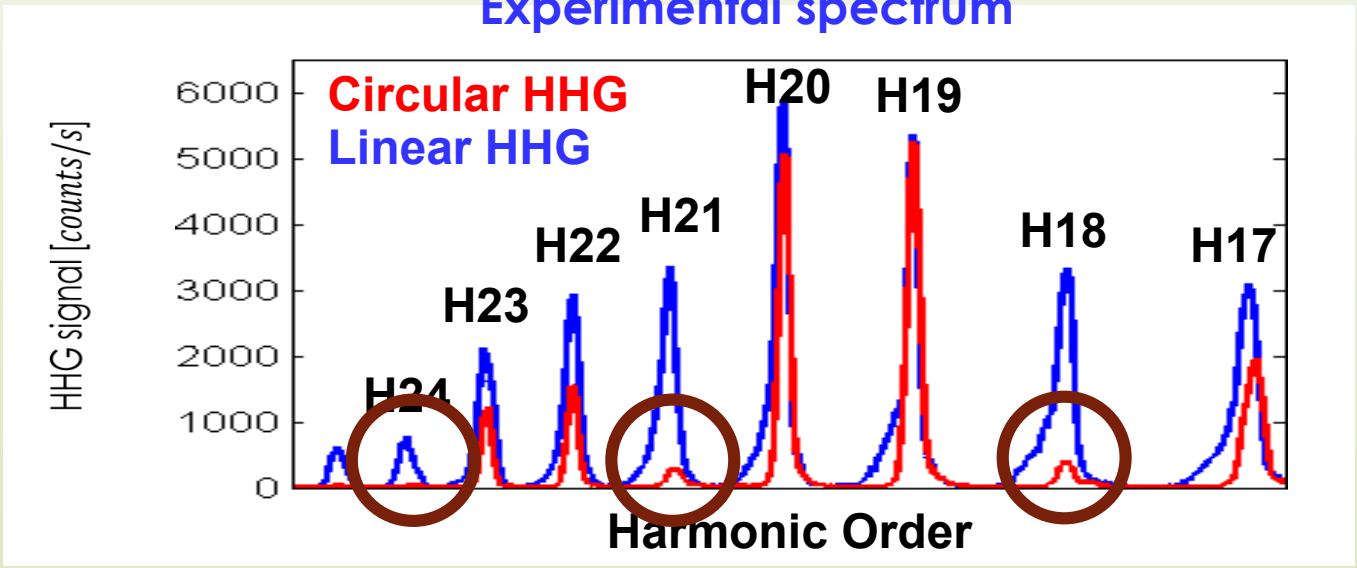
Circularly polarized harmonics

- Efficiency can be as high as for linearly polarized high harmonics.
- Electron trajectories return to origin for recollision.



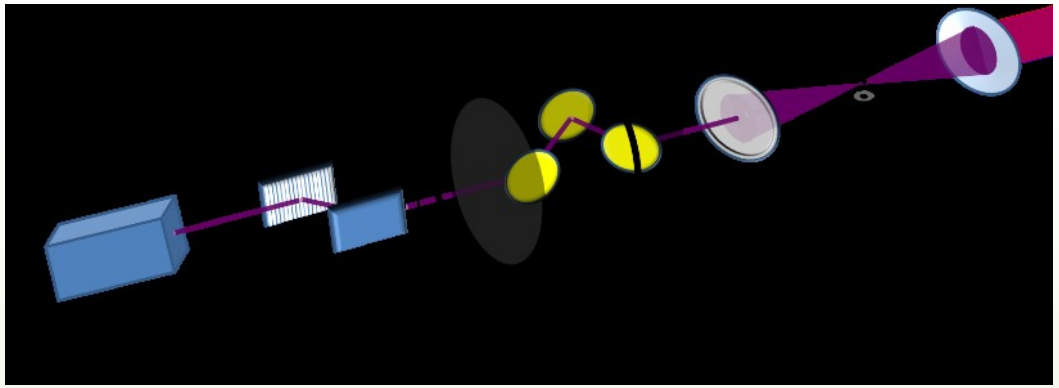


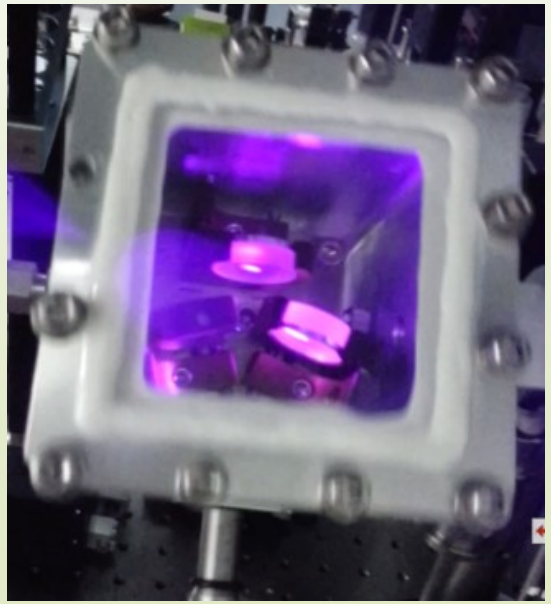
Experimental spectrum



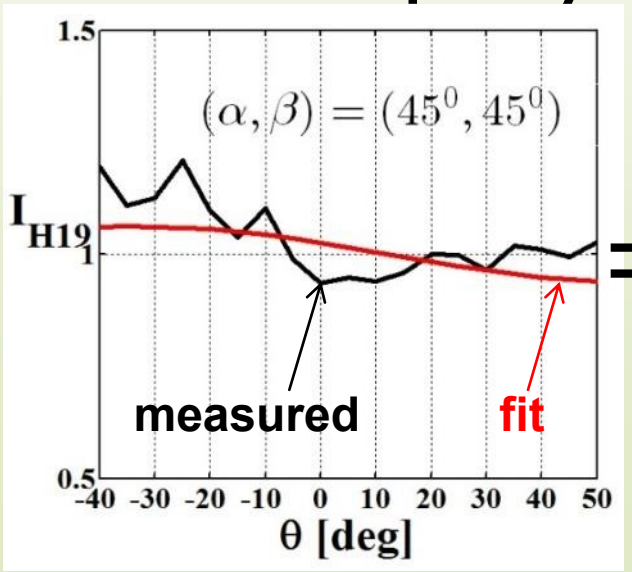
Fleischer, Kfir, et al., Nature Photonics 8, 543 (2014).

Circularly polarized harmonics





Measured ellipticity, ε



Degree of circular polarization

$$\varepsilon_{19} = 0.95 \quad \Rightarrow \frac{S_3}{S_0} = 99.87\% \quad !!!$$

$$\Rightarrow \quad \varepsilon_{19}^{theory} = 1$$

Fleischer, Kfir, et al., Nature Photonics 8, 543 (2014).

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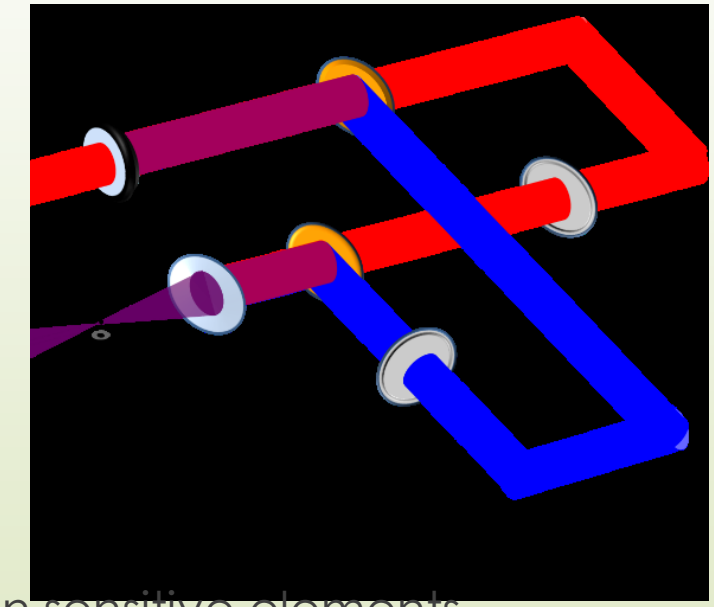
MAZEL-TOV !

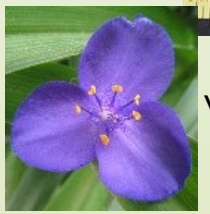
Mach-**Ze**hnder **L**ess **T**hreefold **O**ptical **V**irginia spiderwort

Mach-Zehnder apparatus
1 meter



- Large
- Unstable
- Polarization sensitive elements
- Difficult alignment and operation

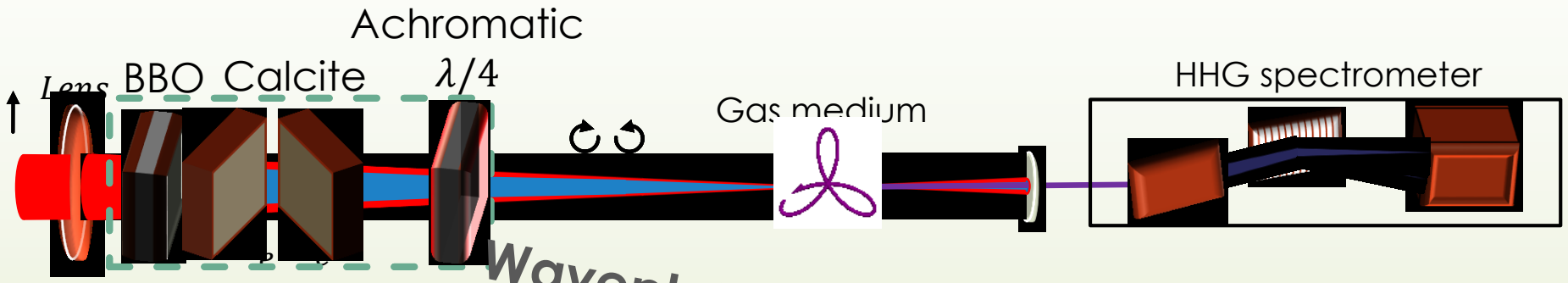
Mach-Zehnder less apparatus
0.05 meter



Virginia spiderwort

Kfir et al., App. Phys. Lett. 108, 211106 (2016)

Inline generation of circularly polarized HHG



Waveplate determines helicity L **vs.** R

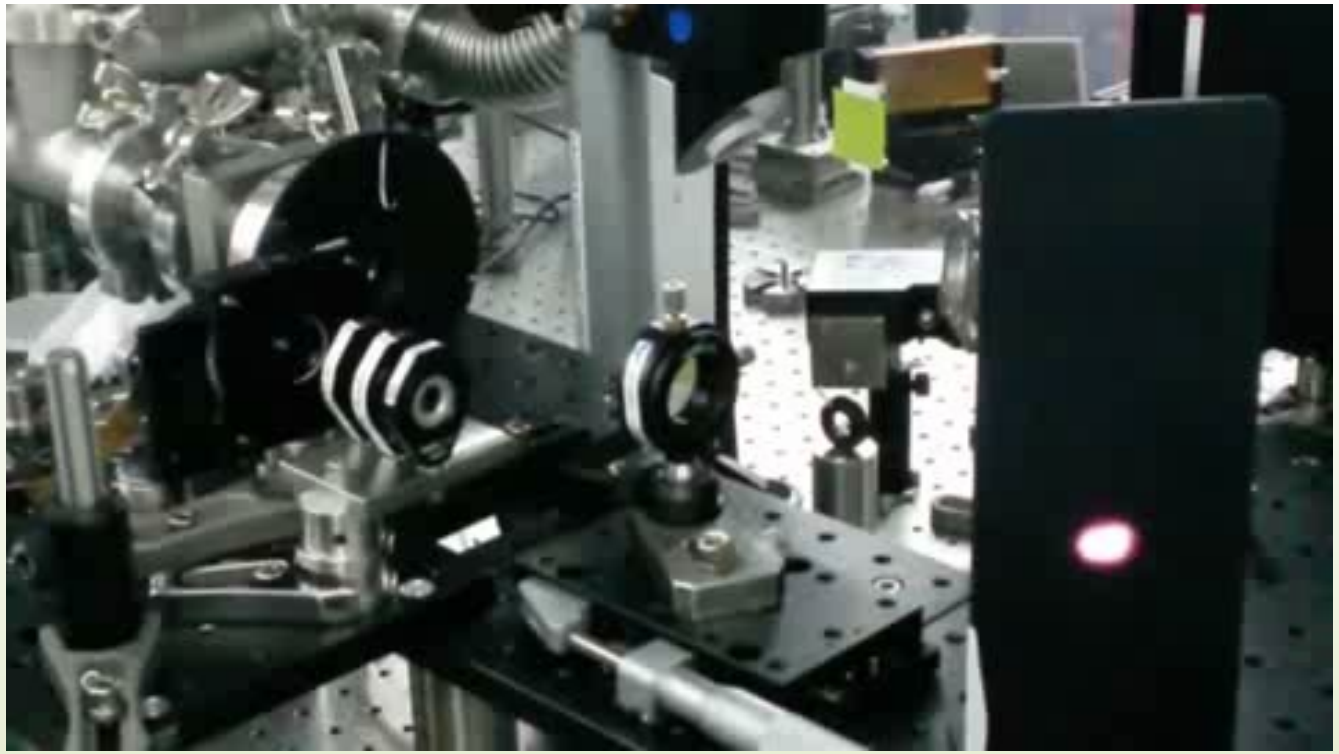
<u>Advantages:</u>

- Plug and play – no alignment
- Portable
- Stable
- Ensures <u>purely polarized</u> pump
- Controllable helicity

Kfir et al., App. Phys. Lett. 108, 211106 (2016)

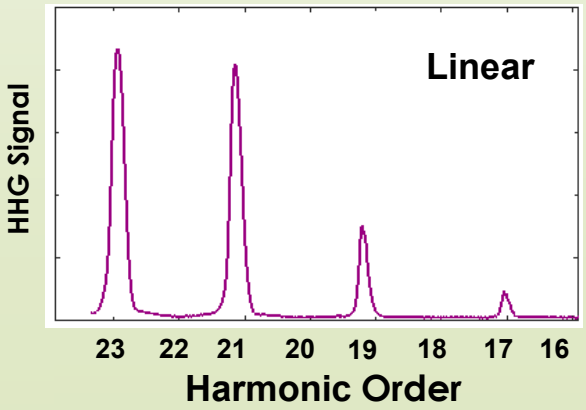
MAZEL-TOV - demonstration

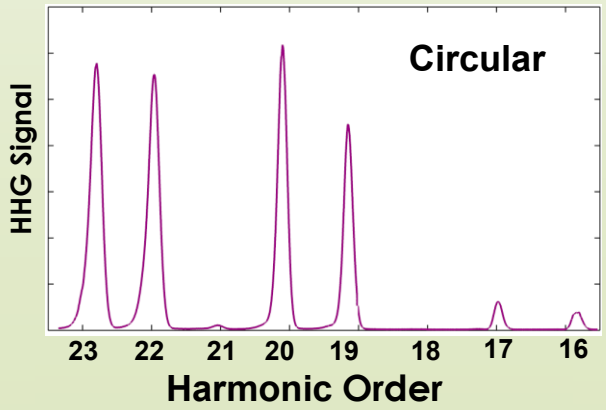
Kfir et al., App. Phys. Lett. 108, 211106 (2016)



Advantages:

- Plug and play – no alignment
- Portable
- Stable
- Ensures purely polarized pump
- No polarizing sensitive elements





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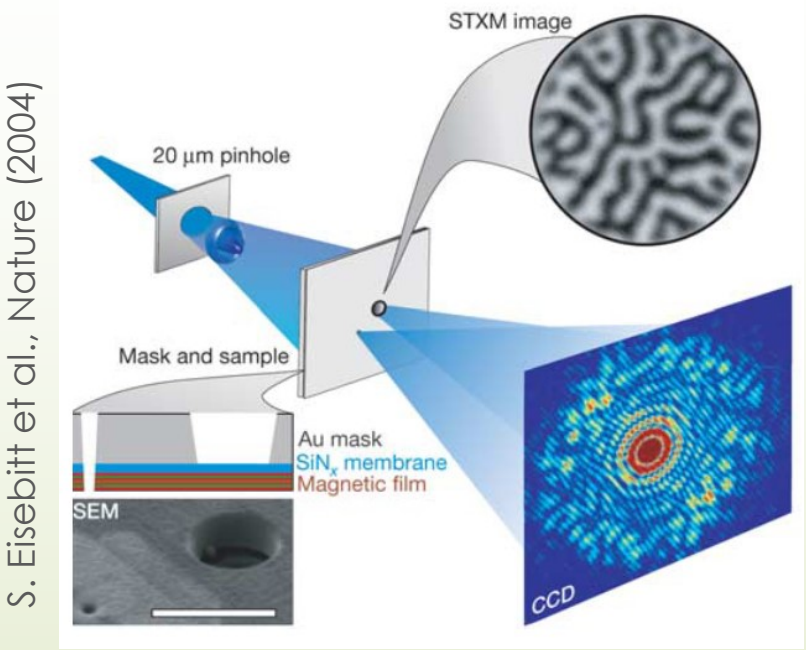
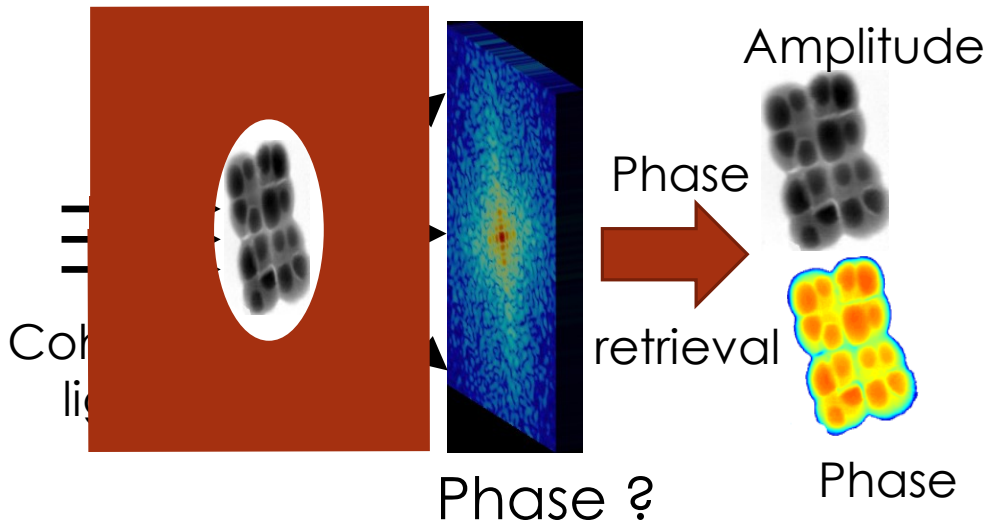
Lensless imaging with coherent radiation

Fourier Transform Holography (FTH)



S. Eisebitt et al., Nature (2004)

Coherent diffractive imaging (CDI)

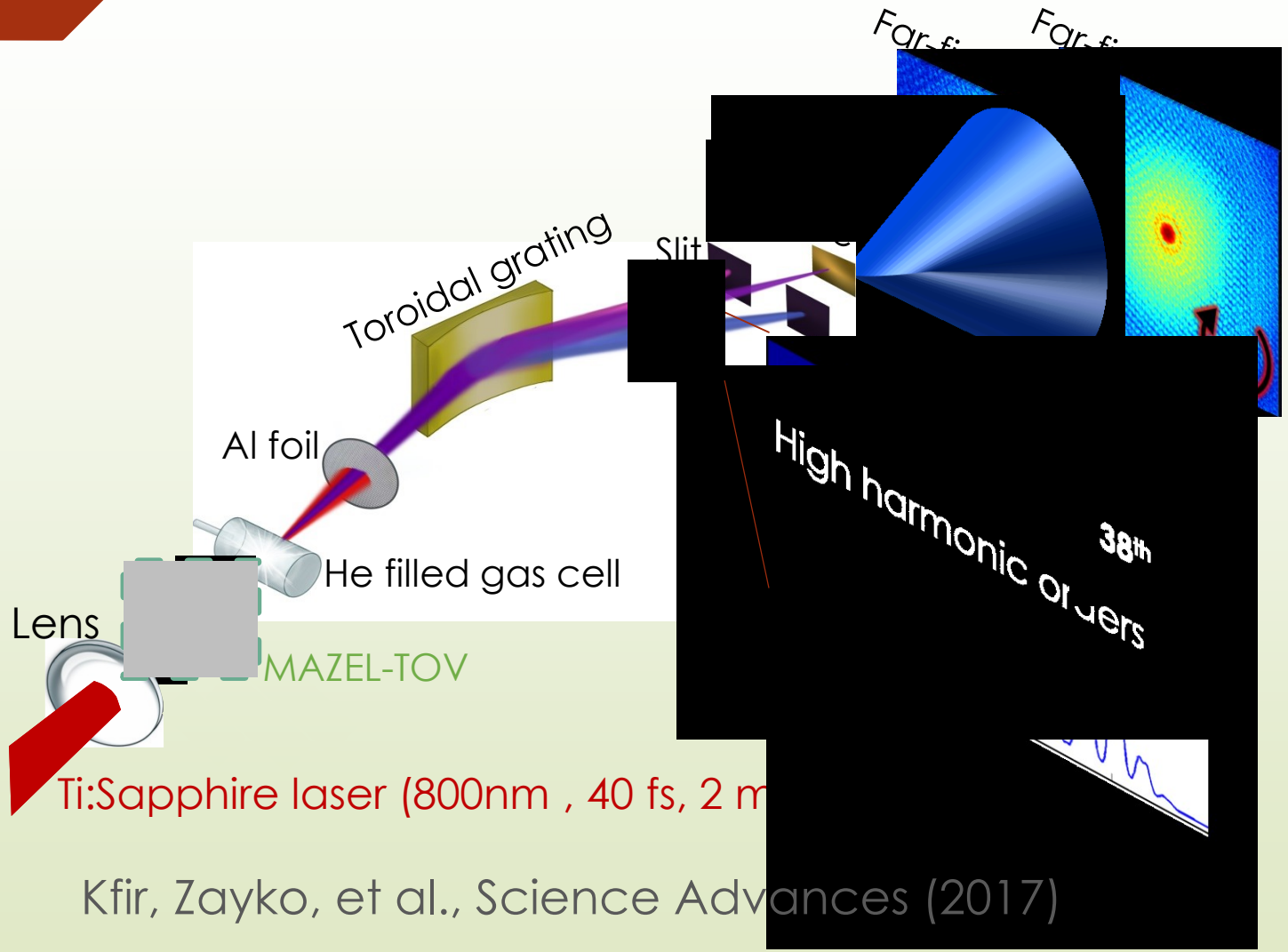


J.R. Fienup, *Opt. Lett* . 3, 27-29 (1978)
J. Miao *et al.*, *Nature* **400**, 342-344 (1999)

- **Fourier transform holography:**
  - Wave exiting a narrow hole interferes with the sample's far field
  - One-step Fourier transform reconstructs the image → Resolution is the physical size of the hole.
  - High-resolution information (smaller than the hole size) are not used.
- **Coherent diffractive imaging:**
  - Capable of full phase retrieval of the far-field → single pixel resolution of the image.
  - Requires some knowledge on the sample (i.e. finite support).

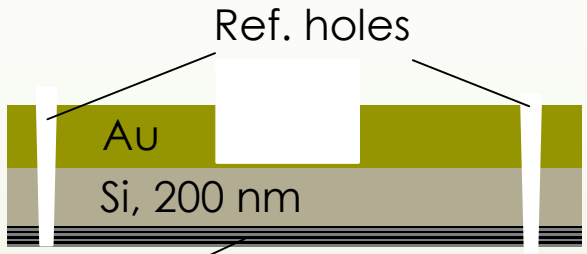
Imaging experiment

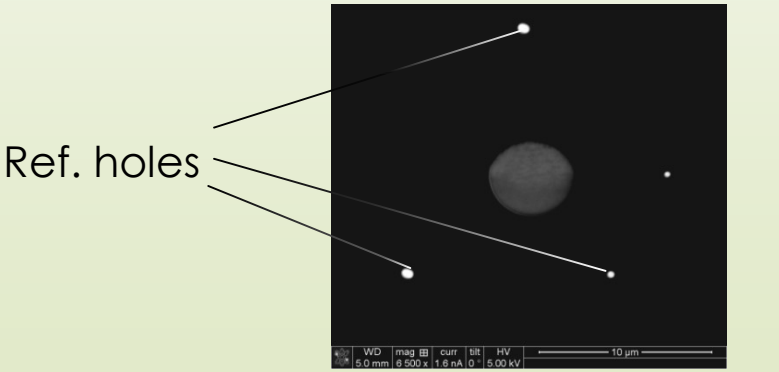
Apparatus for magnetic imaging



Kfir, Zayko, et al., Science Advances (2017)

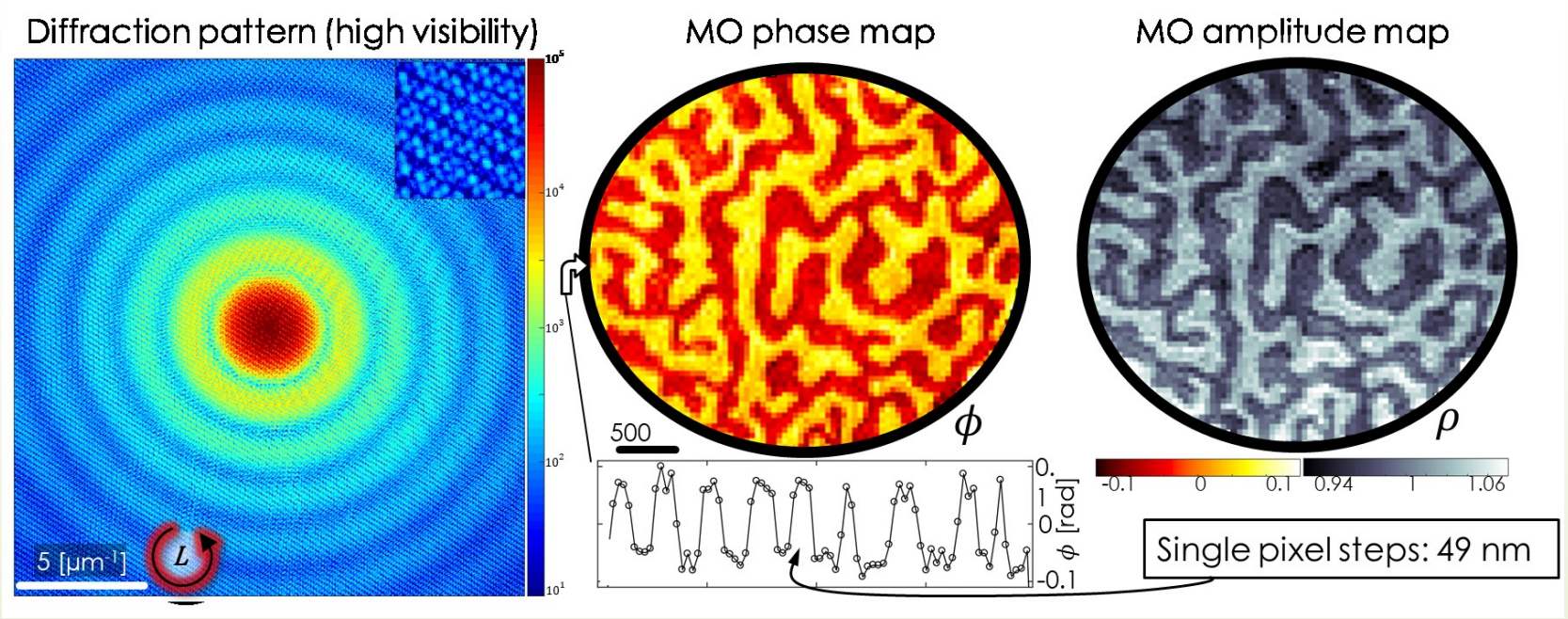
Sample





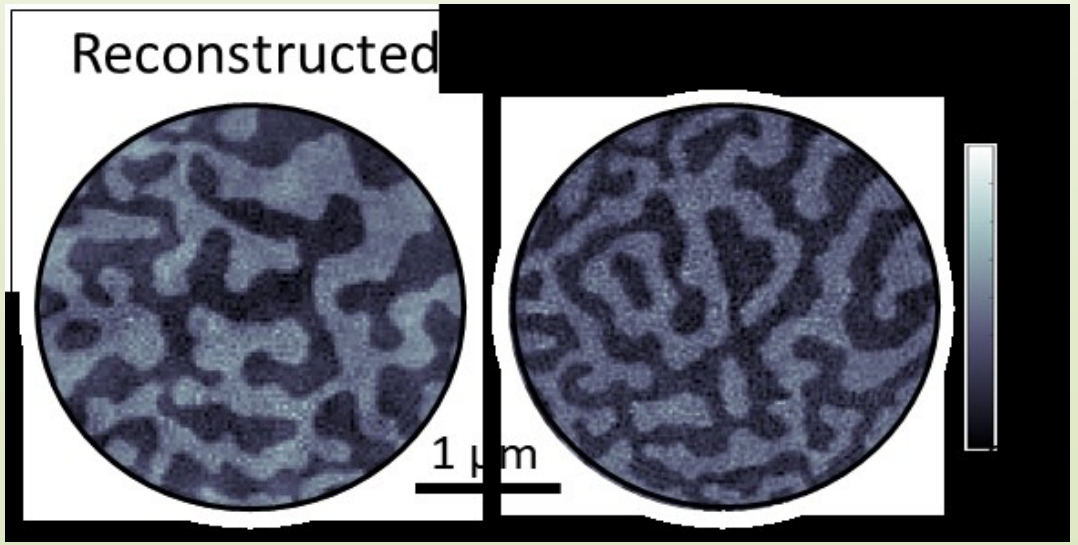
SEM image, top view

Magnetic imaging – Robust!



49 nm px size

Towards wavelength resolution (21 nm) and below

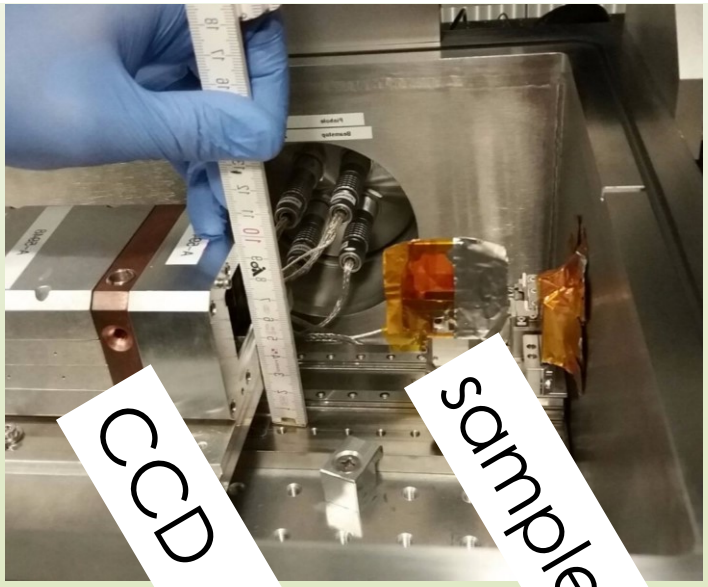


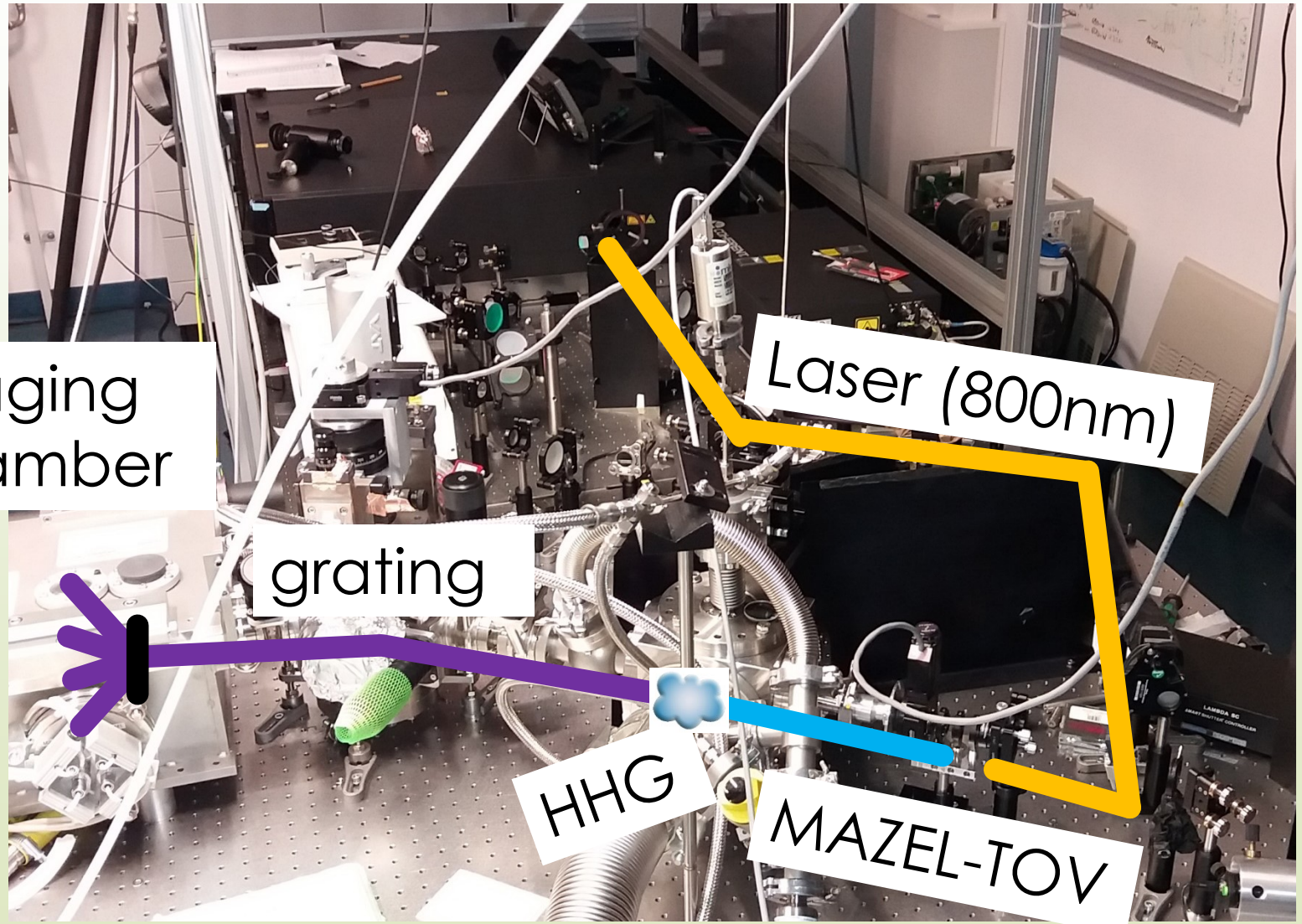
26 nm px size

19 nm px size

HHG Imaging apparatus

Imaging chamber





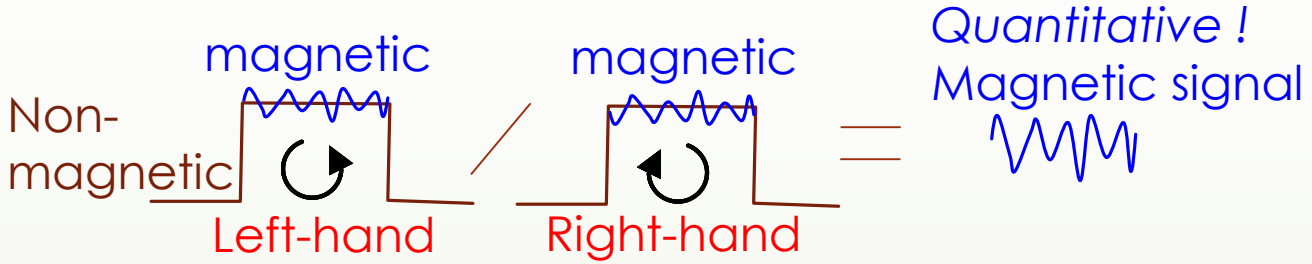
Question:

So, how come it took so long
to image magnetic texture with HHG?

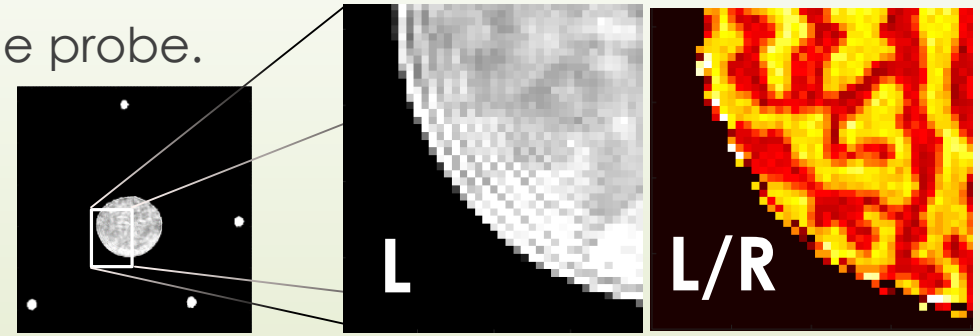
My *answer* – very challenging,
Magneto-optical scattering is very weak,
scatters 1 of 10^6 incident photons.

Contrast enhancement mechanism

- Circular dichroism isolates magnetic signal from non-magnetic background.

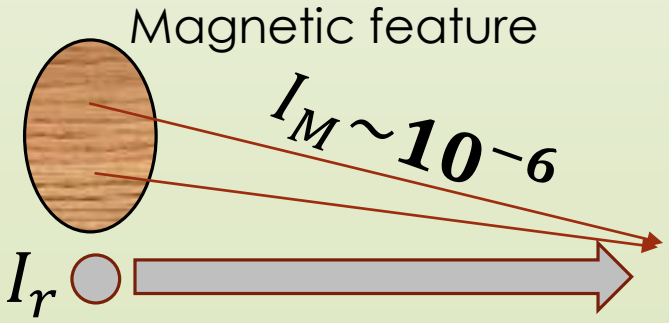


- Dichroic imaging eliminates wave effects of the probe.



Zayko et al., Opt. Express 23(15), 19911 (2015)

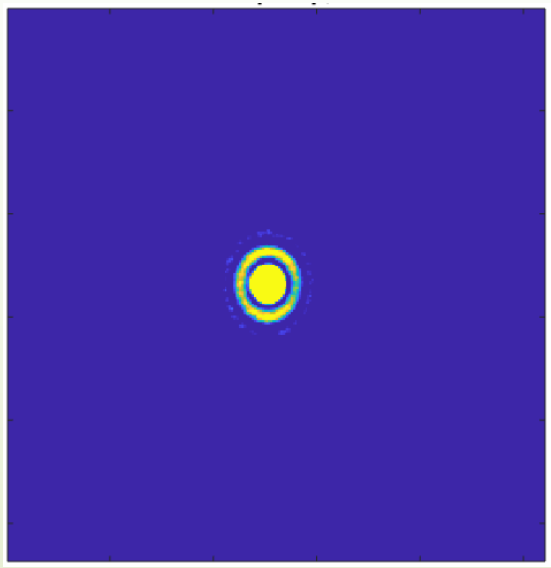
- Interference with a strong auxiliary wave enhances the weak signal (Heterodyning). (Shintake, PRE 78 041906 (2008))



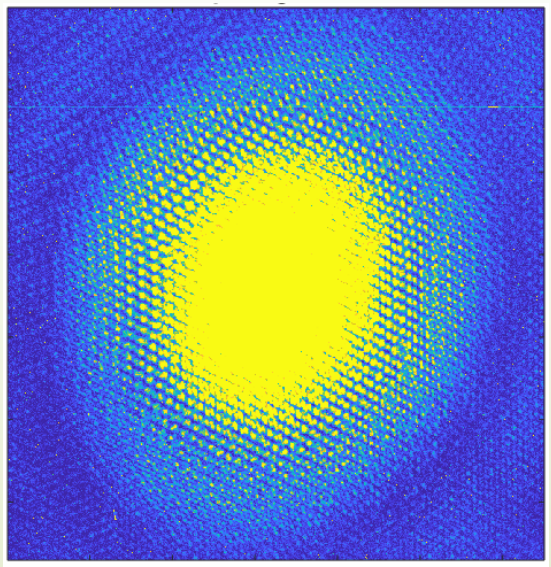
$$I = \sqrt{I_M}\sqrt{I_r} \sim 10^{-3}$$

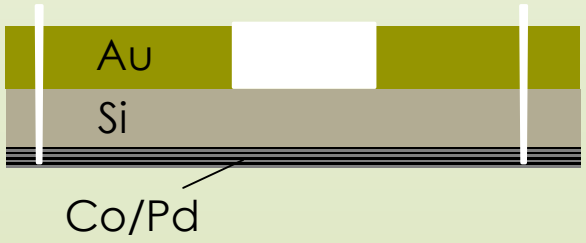
An order of magnitude enhancement

Small ref. holes

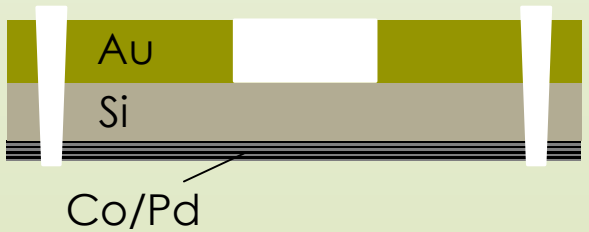


Enlarged ref. holes





Sample, side view



Sample, side view

Contibutours

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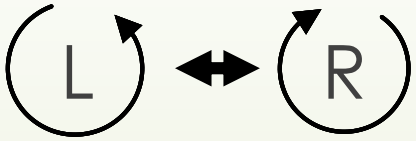
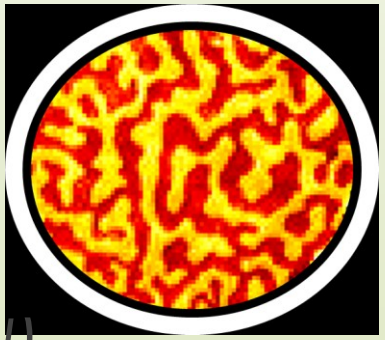
Phani Arekapudi (Chemnitz)
Birgit Hebler (Augsburg)

Summary

- High harmonics are a compact source of femtosecond pulses at the extreme-UV
- Controllable polarization (

) allows for coherent access to chiral media
- Circular polarization is protected by symmetry – putting elegant physics into practical use.
- Magnetic imaging with HHG reaches sub-wavelength resolution, at a large field-of-view.



Future: New possibilities (temporal, chiral, multi-spectral) are now open !

Technion
Israel Institute of Technology

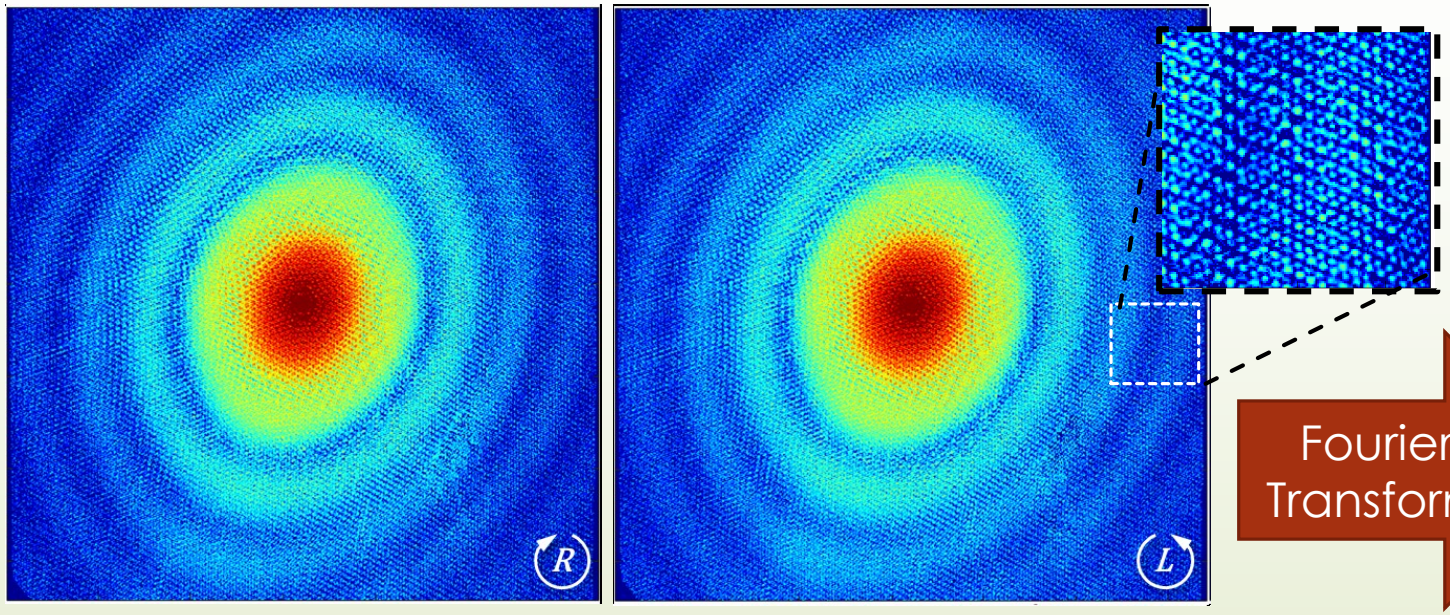
JILA
NISTCU

Georg-August Universität Göttingen

1 7 3 7

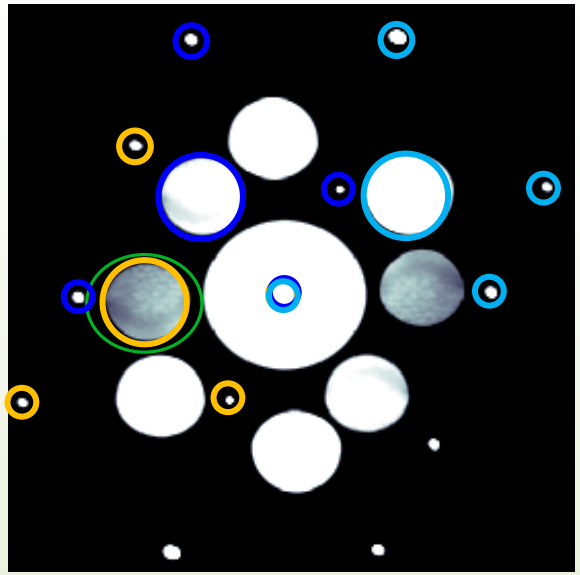
..Thanks for your attention

Holographic magnetic imaging



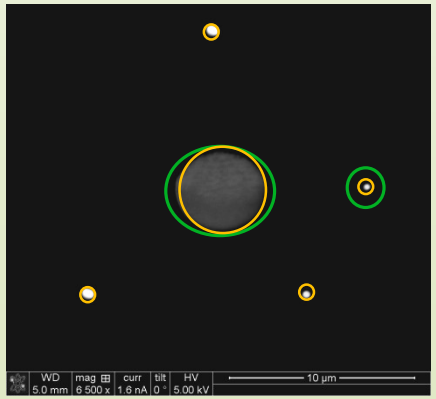
Diffraction pattern

Fourier Transform



FT of the diffraction pattern

- Each diffraction pattern (L R) results in a hologram.
- Hologram retrieves the small angle scattering.
- Includes much more information than the holographic retrieval.



SEM image

Iterative phase retrieval

We have:

- Far-field **amplitudes**
- Knowledge of the support

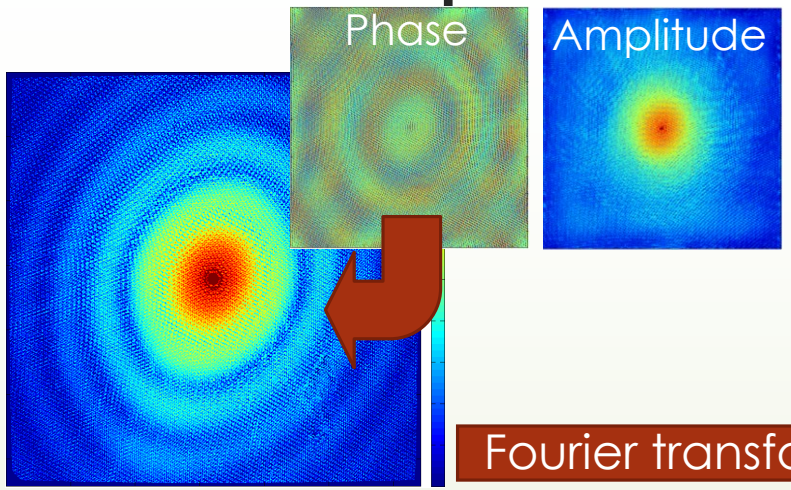
We need:

Far-field **phase** would yield the real-space complex field

→ image reconstruction

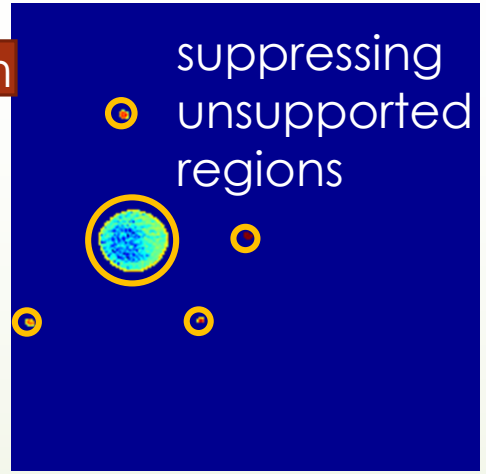
Magnetic contrast

Ratio of Left/Right images



Imposing far-field amplitudes

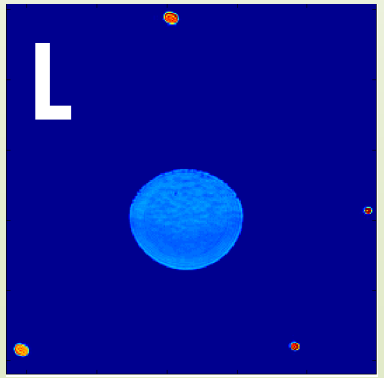
Inverse Fourier transform

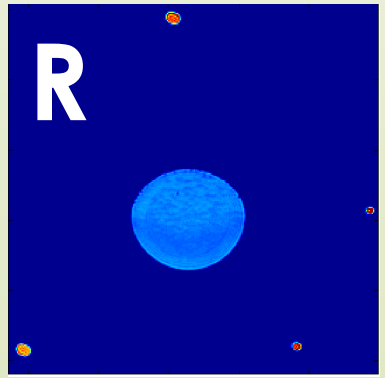


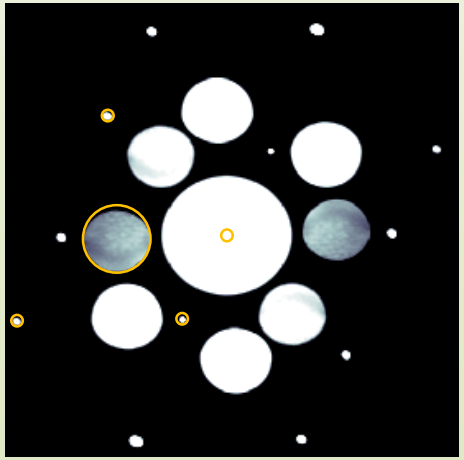
Fourier transform

RAAR phase retrieval algorithm

Final Reconstruction







The support

J. Miao, Nature **400**, 342 (1999)
D.R. Luke, Inverse Problems **21** 37 (2005)

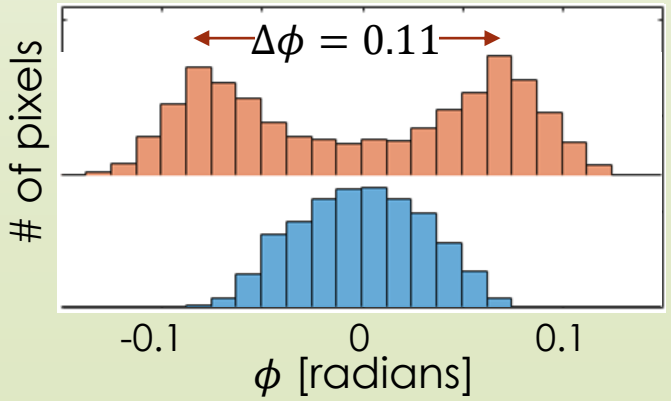
Iterative image reconstruction

- The image is refined to the level of a single pixel

  → diffraction limited resolution.

- Final image contrast is flat !

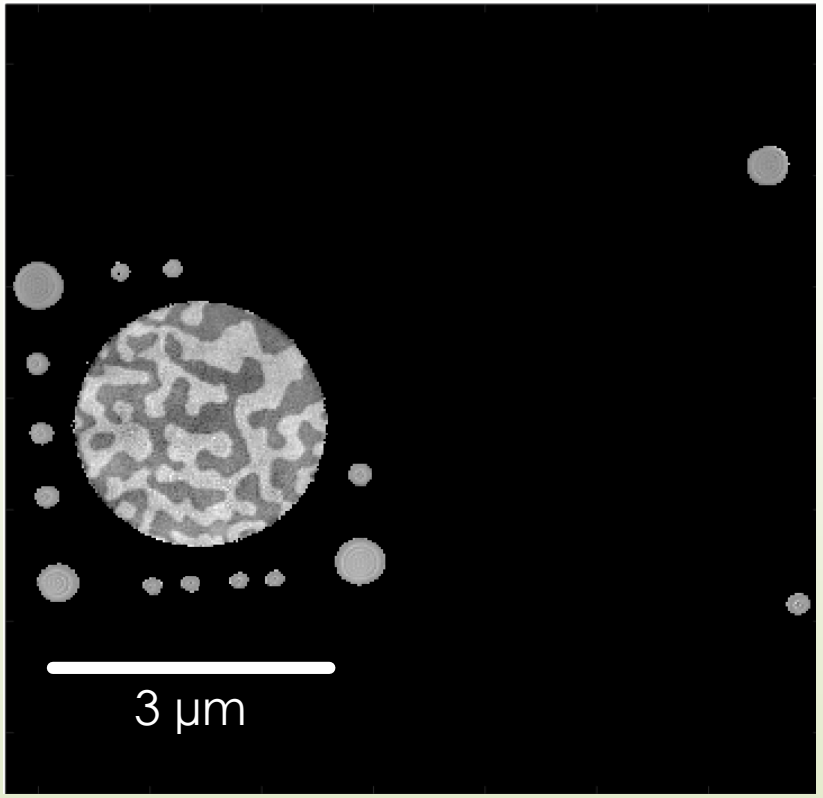
Magneto-optical phase (quantitative)

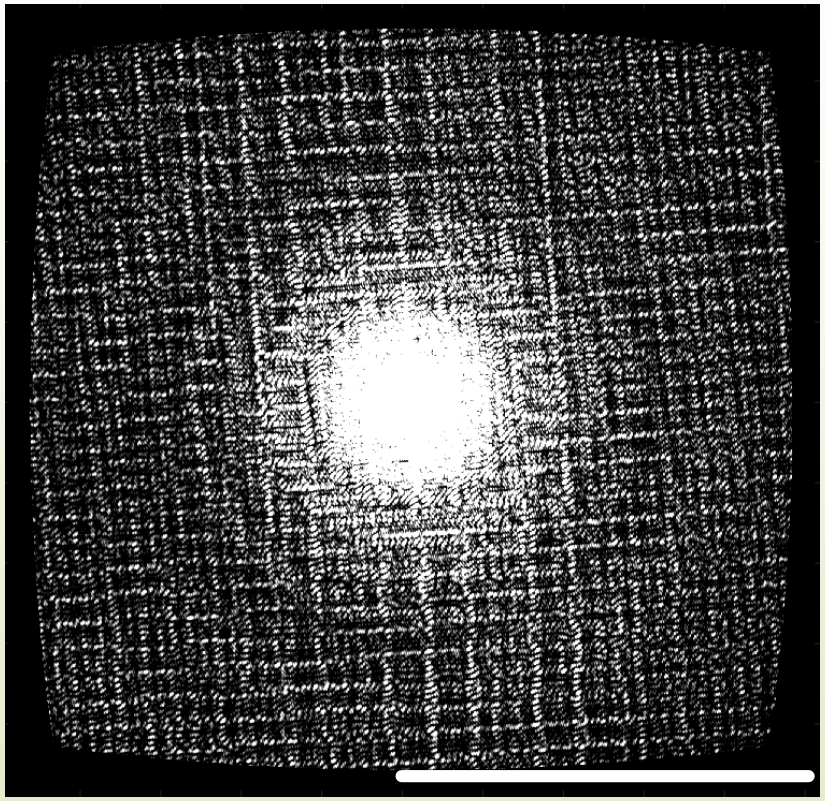


Coherent enhancement

- Example:

Near-sample holes for additional enhancement field allow to recover diffraction regions for sub-wavelength magnetic imaging.





20 μm^{-1}
(pixel size 25 nm)

Polarization cleaning by the Calcites