Active control in Nanophotonics for Super-resolution Imaging

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MARIE CURIE ACTIONS

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Outline

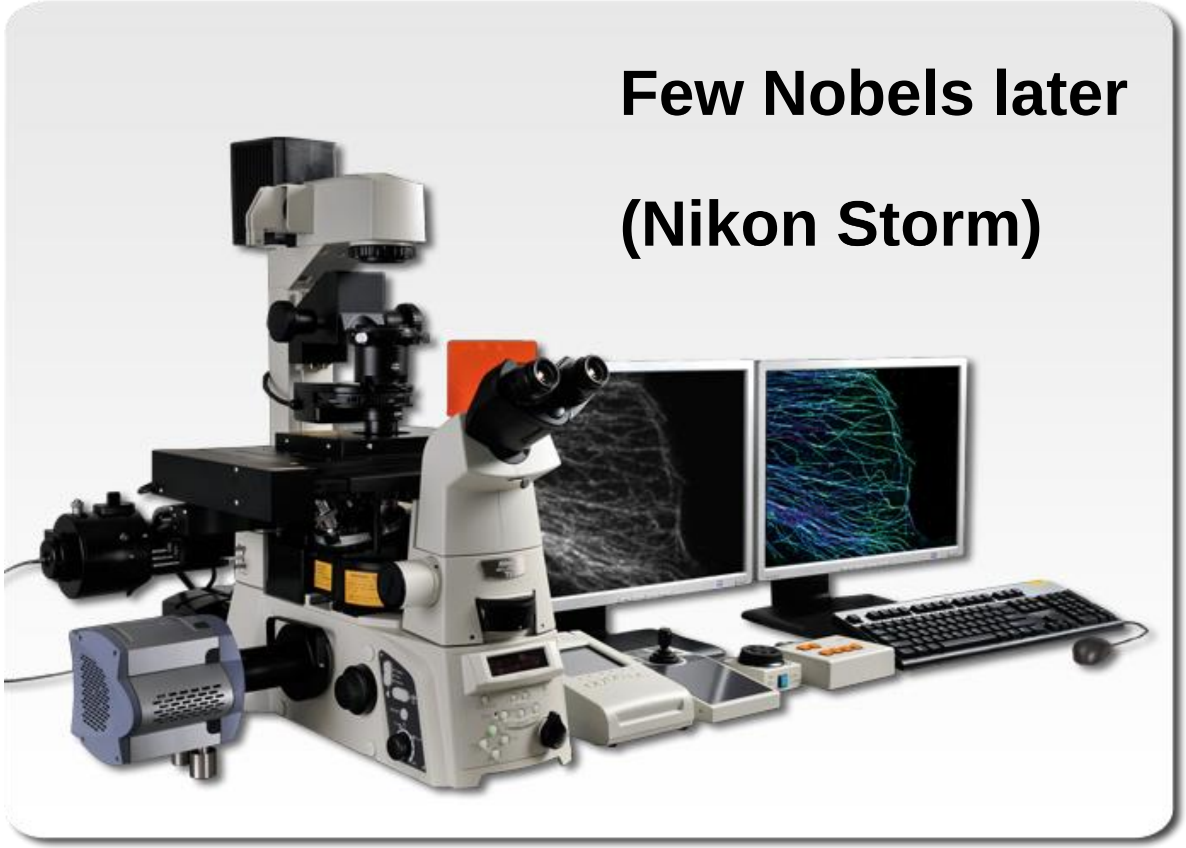
- **Background**
  - Microscopy over time
  - Nanophotonics promises for microscopy
  - Control - shaping optical wavefronts
- **Proof of concept for new microscopy**
  - Controlling nanophotonic/plasmonic wavefronts
  - Focusing and scanning microscopy
- **Super-resolution**
  - Platforms for super-resolution
  - Silicon Plasmonics

Microscopy

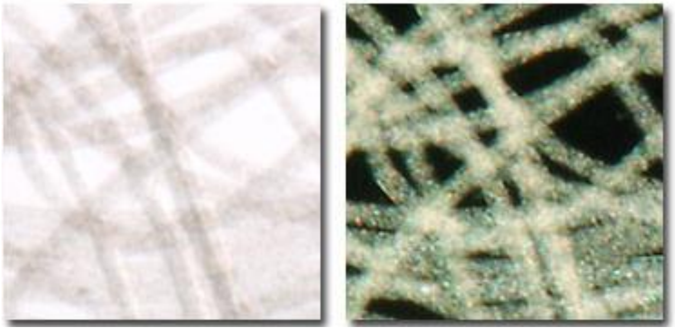
We started like this

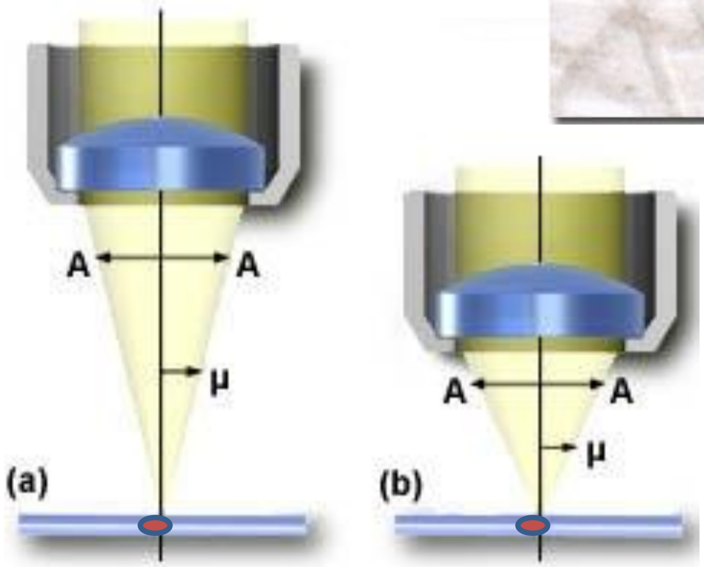
Few Nobels later

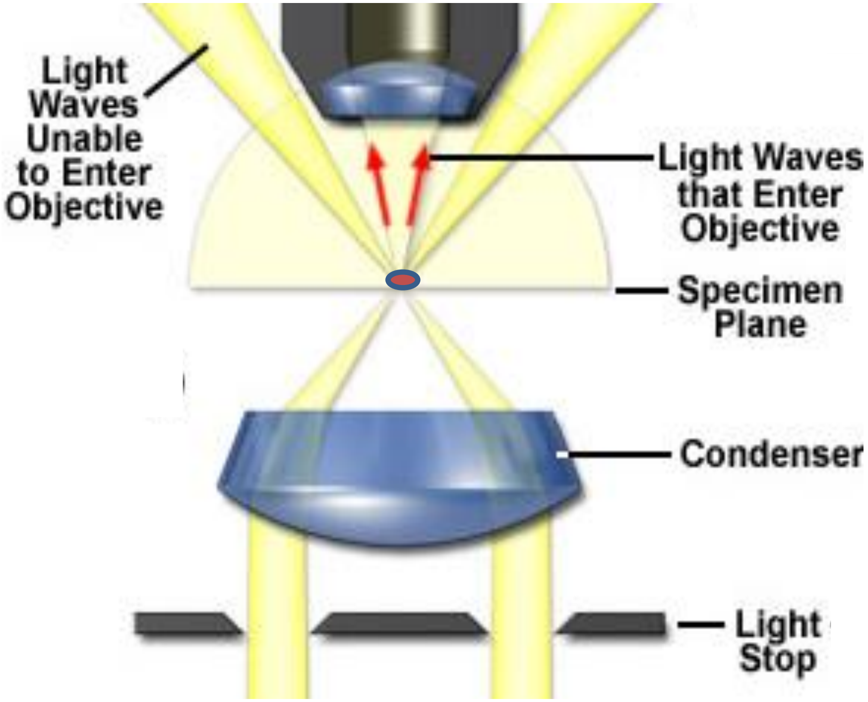
(Nikon Storm)



Bright field – Dark field

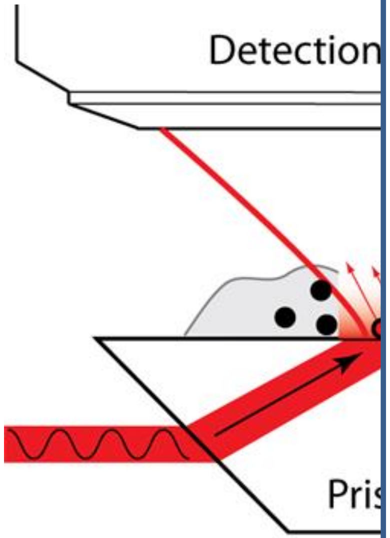


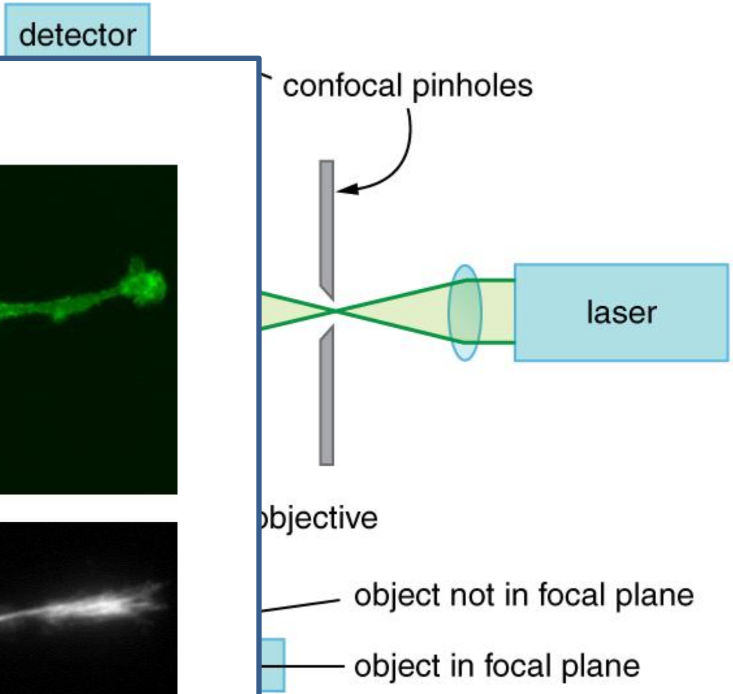


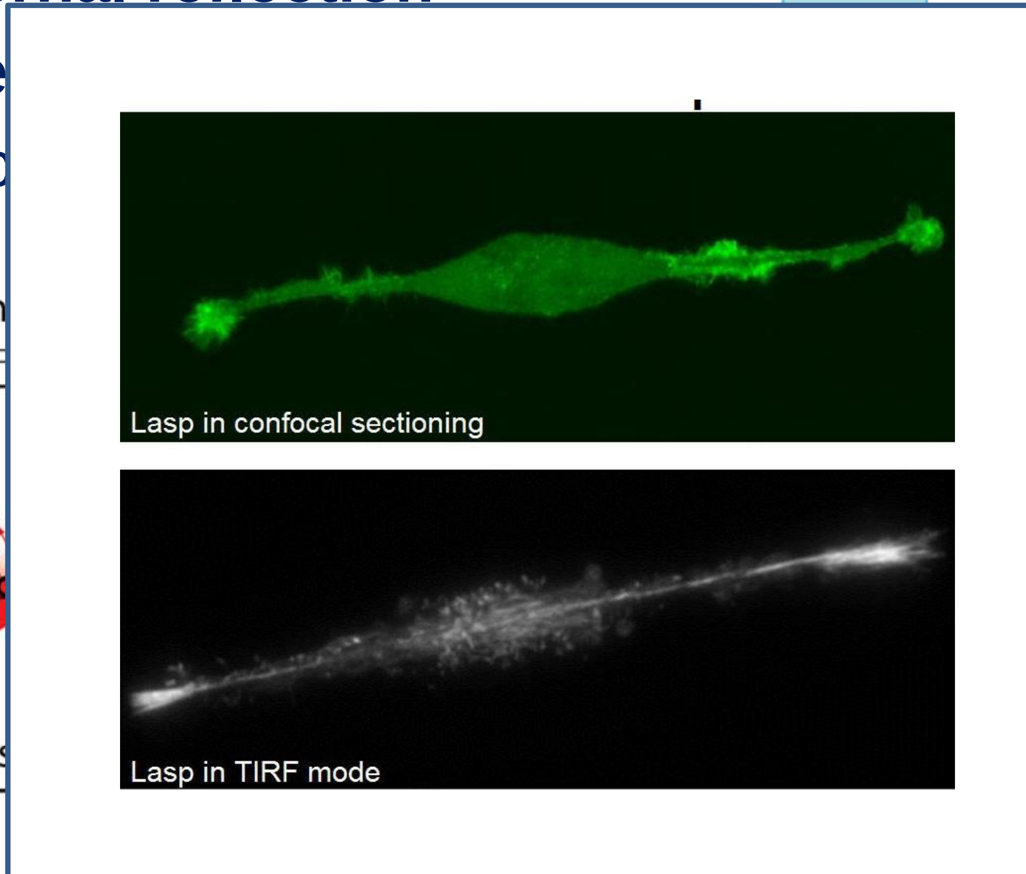


TIRF & Confocal

- **Total internal reflection**
  - Evane
  - Surfac



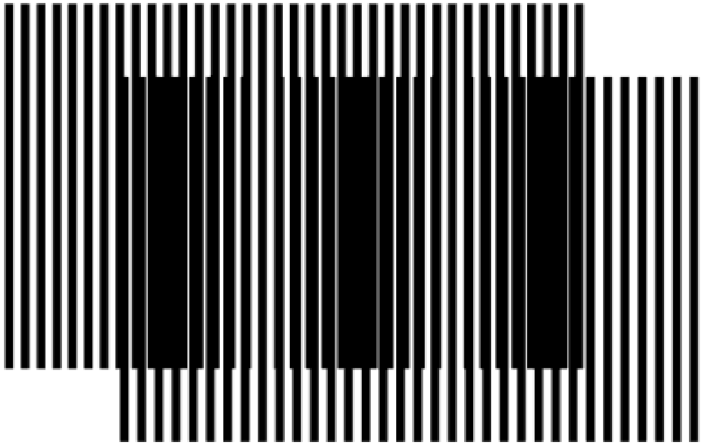




echnique
  - Focused excitation
  - Focused detection

Structured illumination

- Two different gratings generate a third one

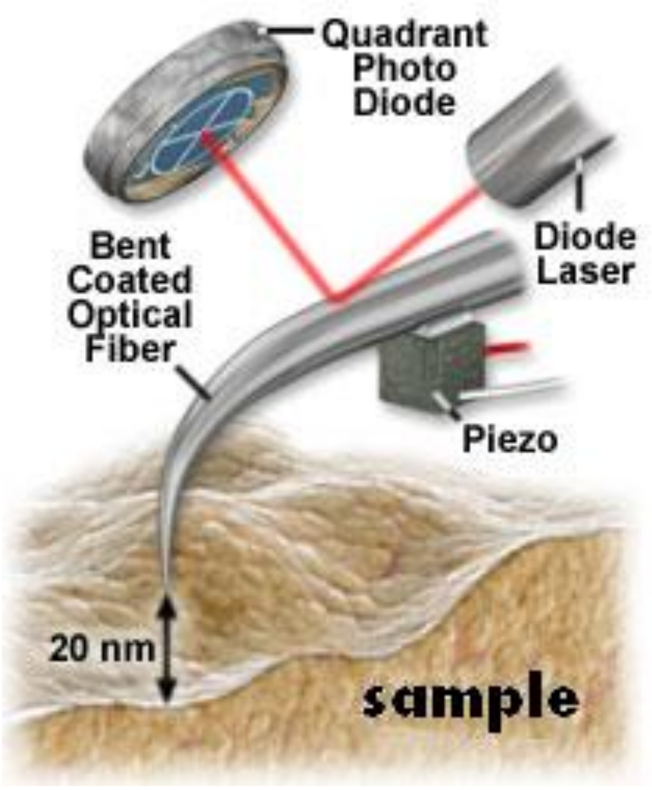


If resolution does not allow to resolve one of the gratings,

You can still deduce it from the other two.

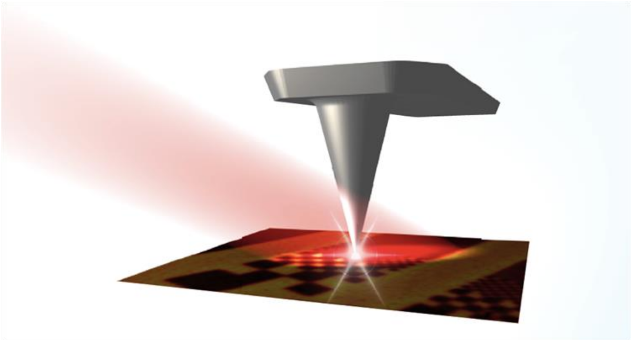
Near field Probes

- **No more lenses**
  - Detect with a scanning probe
  - Resolution is given by the probe size



Near – field techniques

Scattering NSOM
Light collected by lens/parabolic mirror



Advantages:

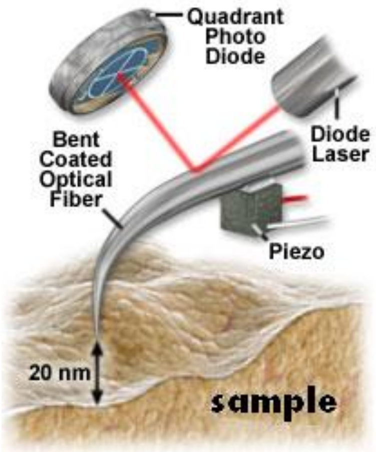
Resolution (~2-20 nm)

Disadvantages:

Far field |Bacground

Scanning Sample

Aperture NSOM
Light coupled into optical fiber



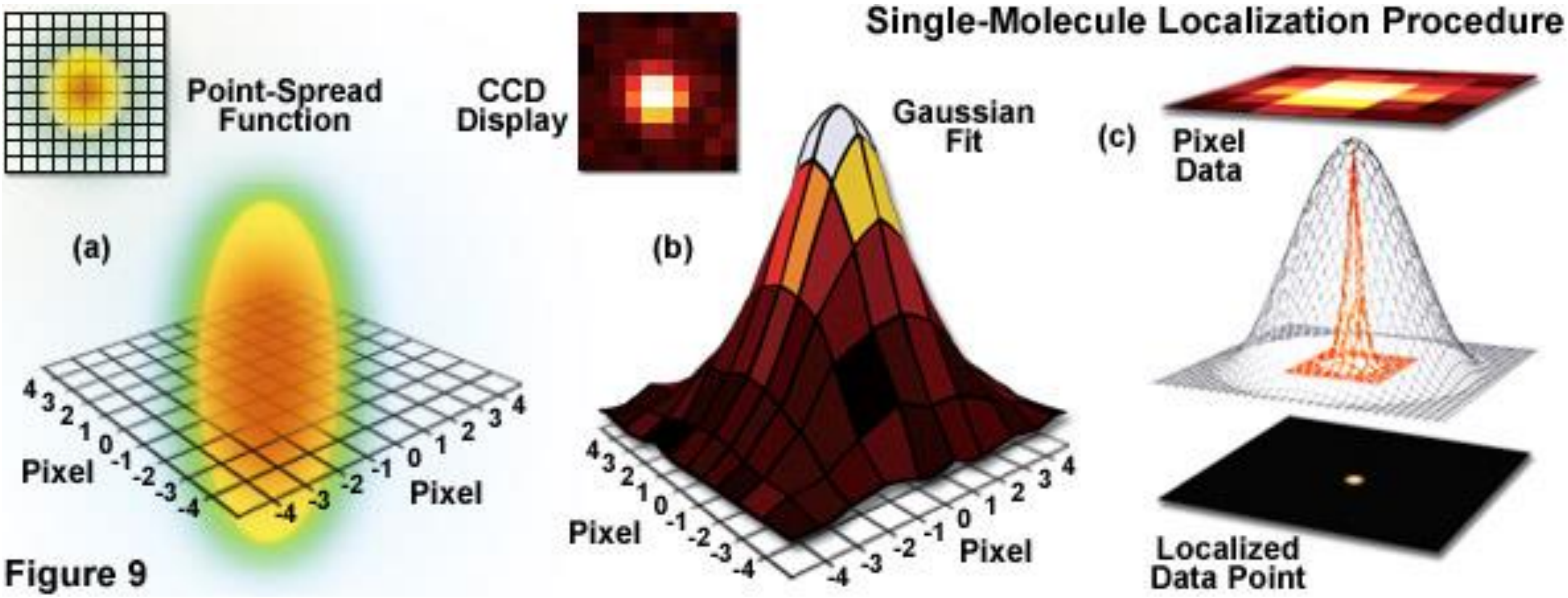
Advantages:

No Background

Disadvantages:

Limited resolution ($\sim 100nm$)

Single molecule localization

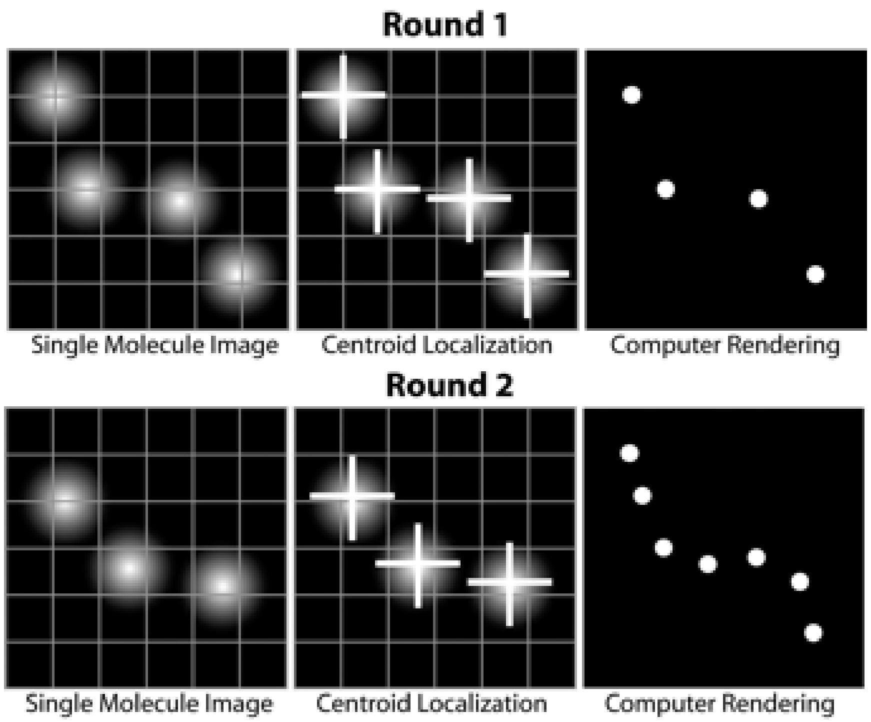


- **If two single molecules are well separated in *space***
  - You can localize them by their center of mass

PALM, STORM | STED

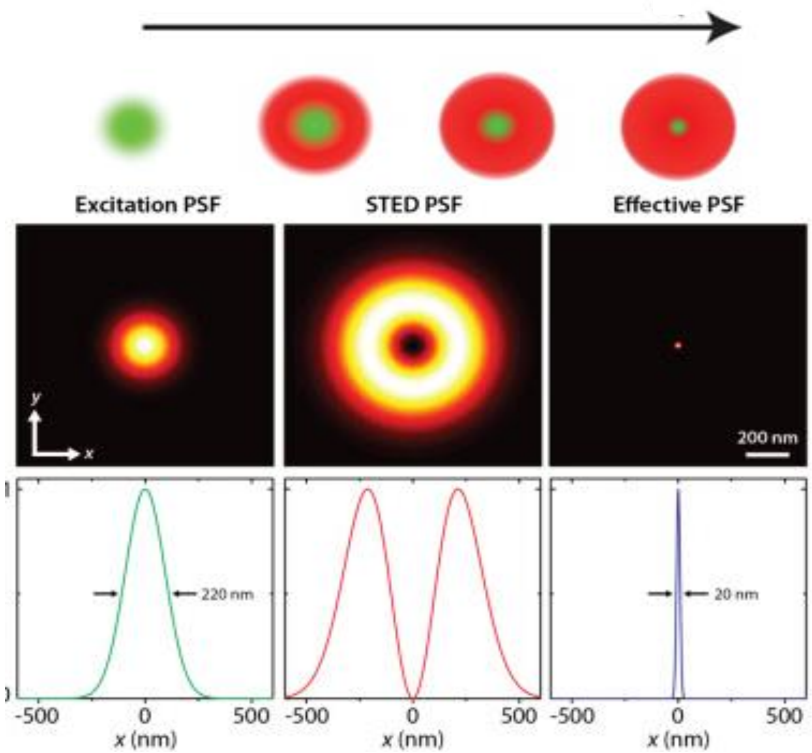
If molecules are separated in *time or space*

You can sum up an image (switching, activating)



If molecules are separated in *energy*

You can scan an image (saturation, depletion)



Outline

- **Wavefront shaping in Nanophotonics (spatial resolution)**
  - Controlling waves in nanophotonic systems
  - Focusing and scanning microscopy / Super-resolution
  - Goal: towards nanolocalized Raman excitation

- **Wavefront shaping in scattering media (spatio-temporal)**
  - Controlling speckle in time
  - Spatio-temporal focusing at targets
  - Goal: towards burning/imaging targets inside tissue

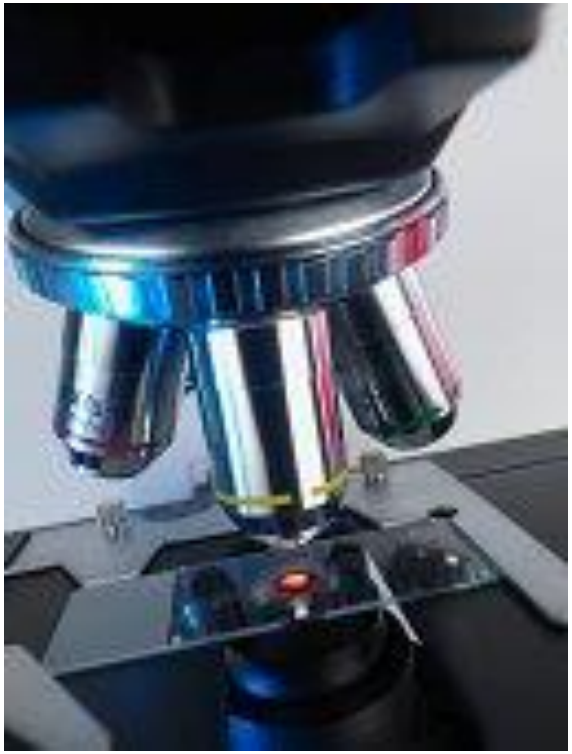
Optical microscopy: optimizations

- **Optics**
  Oil/water immersion objectives

- **Illumination**
  Dark Field, Phase Contrast (DIC)
  Total Internal Reflection (TIRF)
  Optical Coherence Tomography (OCT)
  Structured Illumination (SIM)

- **Detection**
  Fluorescence,
  Confocal, Near-Field

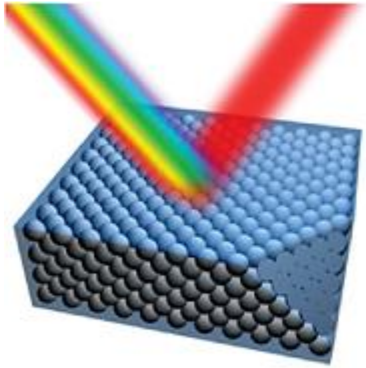
- **Light-matter interaction**
  STED, PALM, STORM
  Nonlinear, Photo-acoustic



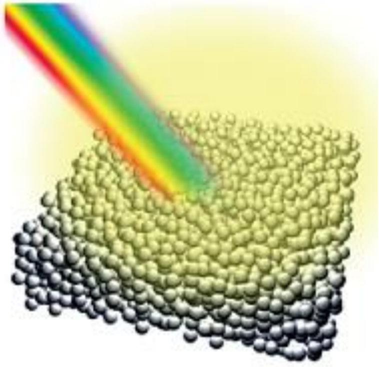
The microscope slide

The generalized microscope slide

- **Conventional**
  - Passive, compensated
  - Cheap and standard

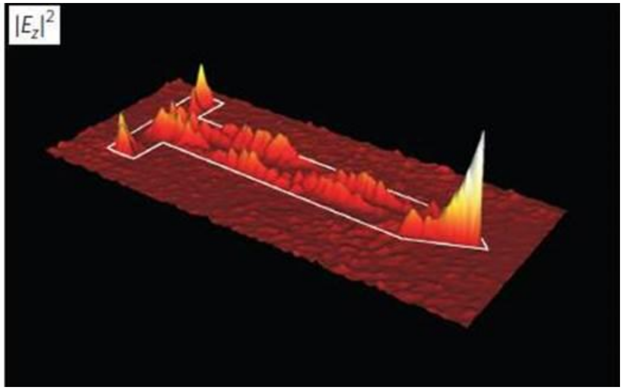


- **Nanophotonic** ***More Control!***
  - Active, focusing, filtering
  - Super, hyper, meta lens



- **Natural** ***More Control!***
  - Omnipresent, random, light scattering
  - Thin slicing *ex-vivo,* other waves

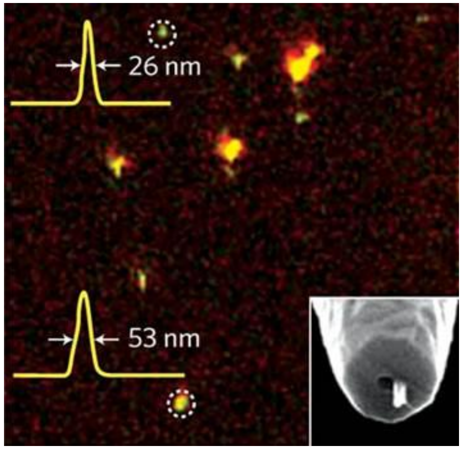
More control in Nanophotonics



Hillenbrand group (Nat Photon, **2012**)

- **Resolution**
  - Hot spots 10 – 100 nm
  - Fixed, No imaging
- **Required control**
  - Image formation

Choo, Yablonovitch (Nat Photon, **2012**)



Novotny & Van-Hulst (Nat Photon, **2011**)

Motivation

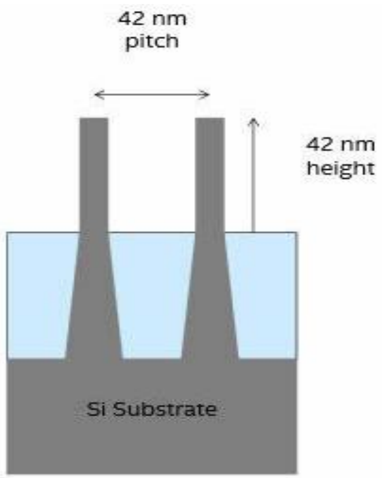
- **Why do you need new microcopies?**
  - Applied - latest transistors at 20nm

    Cannot be fluorescently labeled

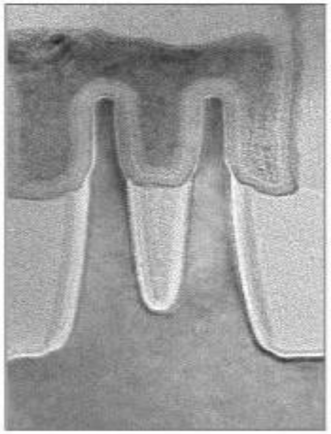
  - Fundamental – spectroscopy

    The spatial distribution provides the WHAT

    You need spectroscopy to provide the HOW

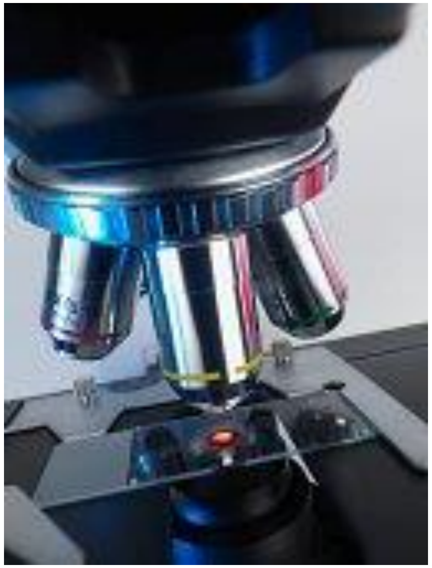


14 nm Process



14 nm 2nd Generation
Tri-gate Transistor

The slide is the lens



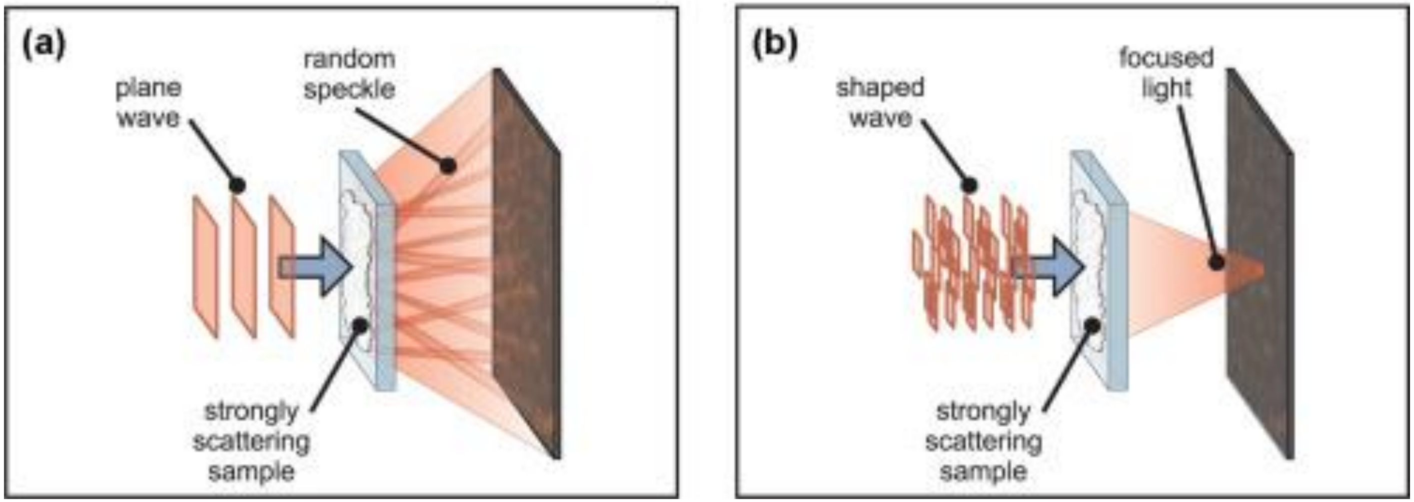
- **Metamaterial slide**
  - Negative refraction materials
  - Perfect lens

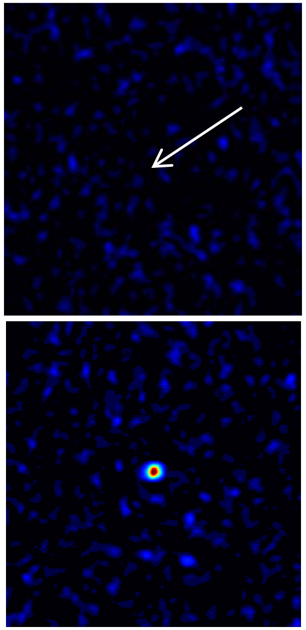
  - Hyperbolic material
  - Hyper lens

- **Plasmonics**
  - Short wavelengths
  - Plasmonic lens

Little success in bio imaging – We need more control!

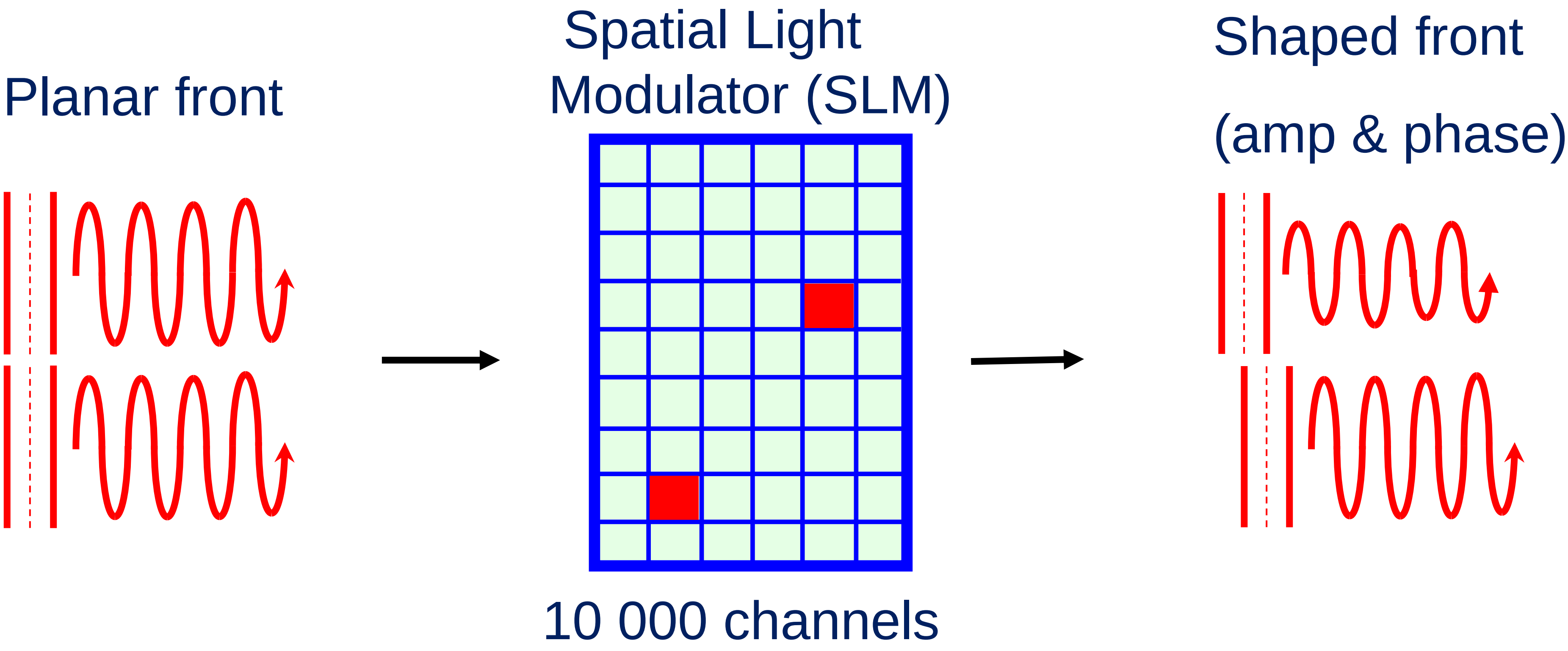
Wavefront Shaping – new control





- **Control the incident wavefront**
  - Use a spatial light modulator to shape the front
  - Use feedback to find the right wavefront
  - Achieve focusing from scattering media (paper)
  - Achieve focusing to a different spot

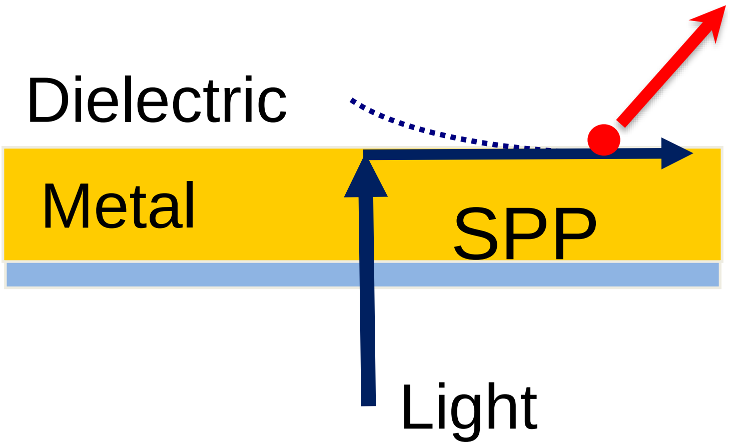
The wavefront control



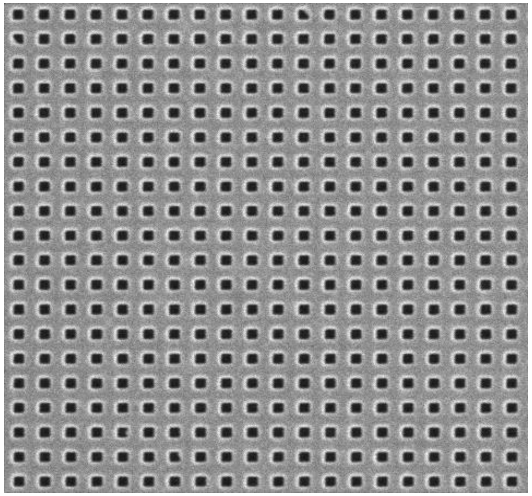
Nanophotonics wavefront control

Is wavefront control in nanophotonics applicable for microscopy?

Surface Plasmon Polaritons (SPP)



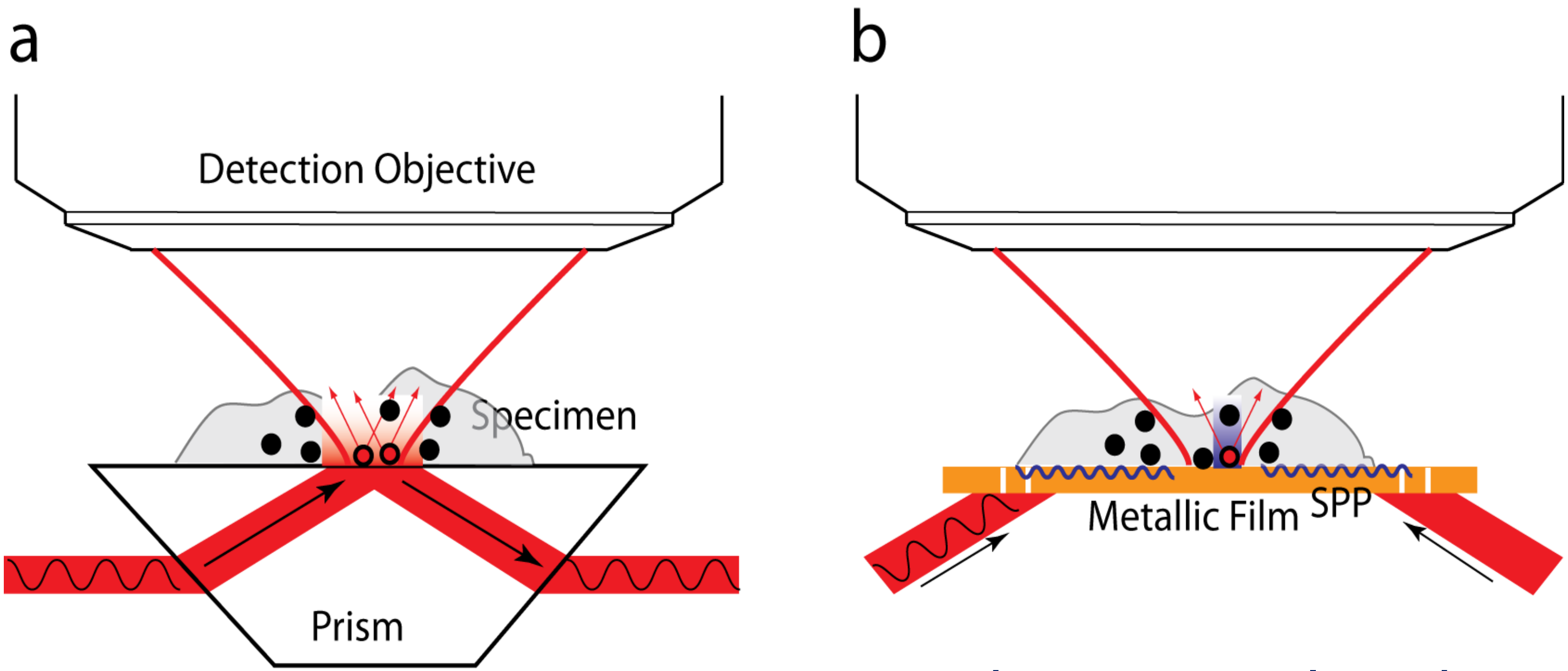
- Surface waves
- Evanescent waves
- Metal-dielectric interface
- Sensing, SERS, Q. optics



❑ Compared to photons:

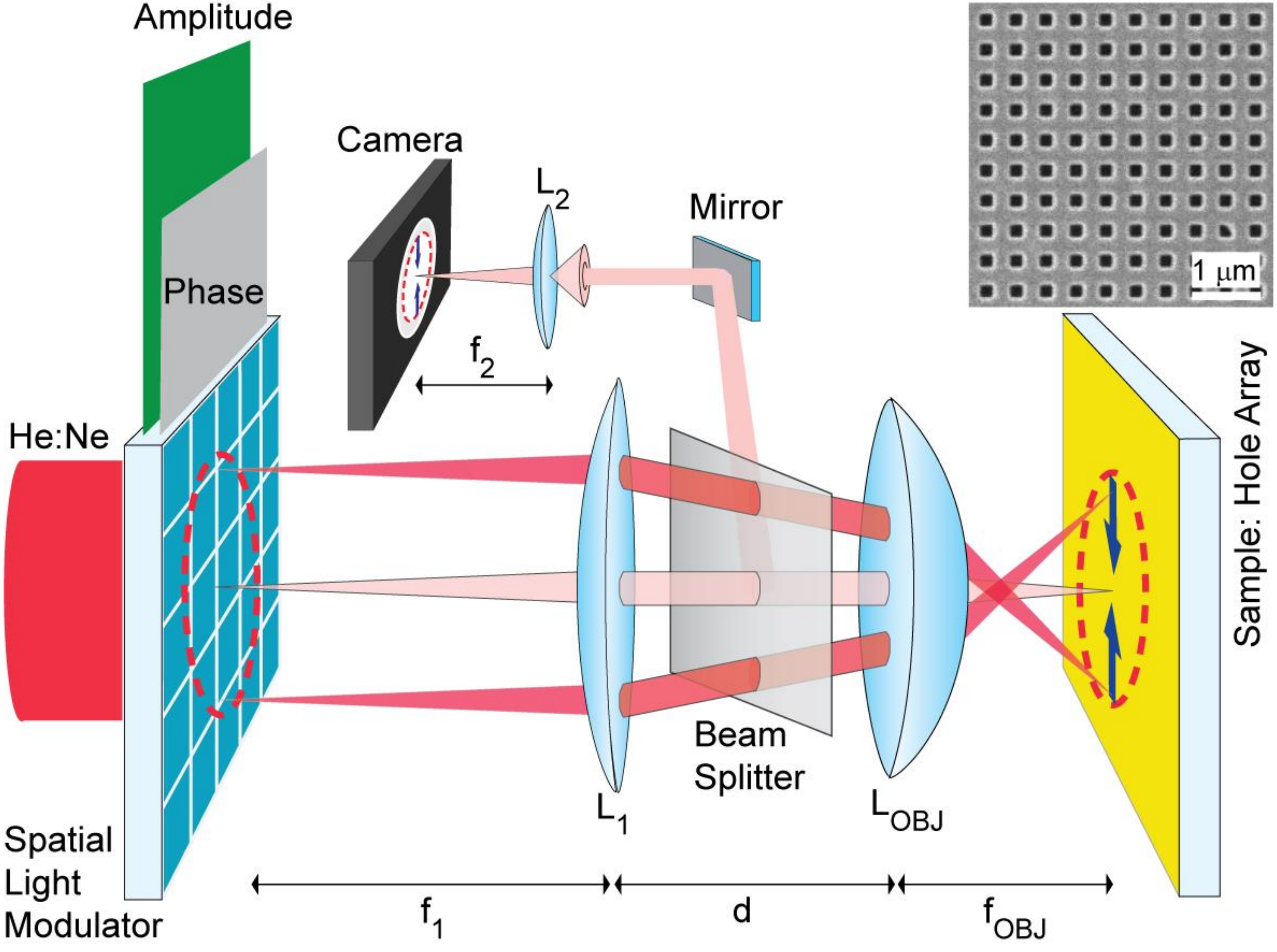
- Same energy (color)
- Shorter wavelength
- Momentum mismatch

Plasmonics for microscopy



- Shorter wavelength
- Better focusing
- Improved resolution

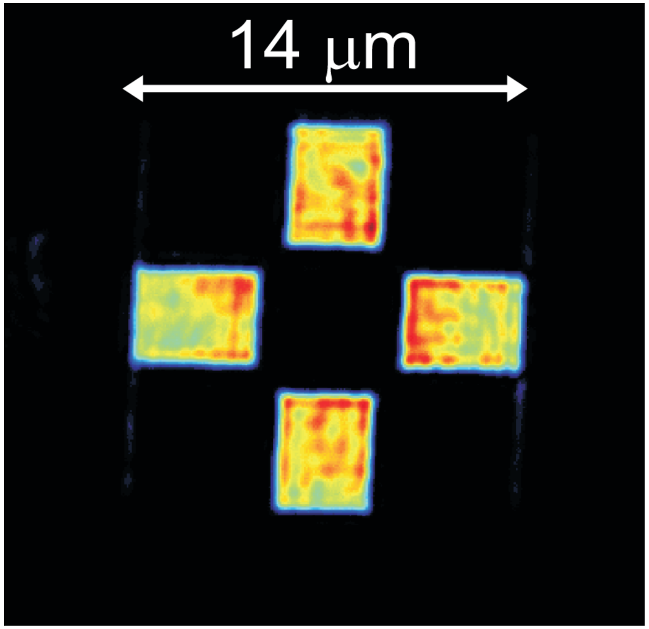
Plasmonic wavefront shaping



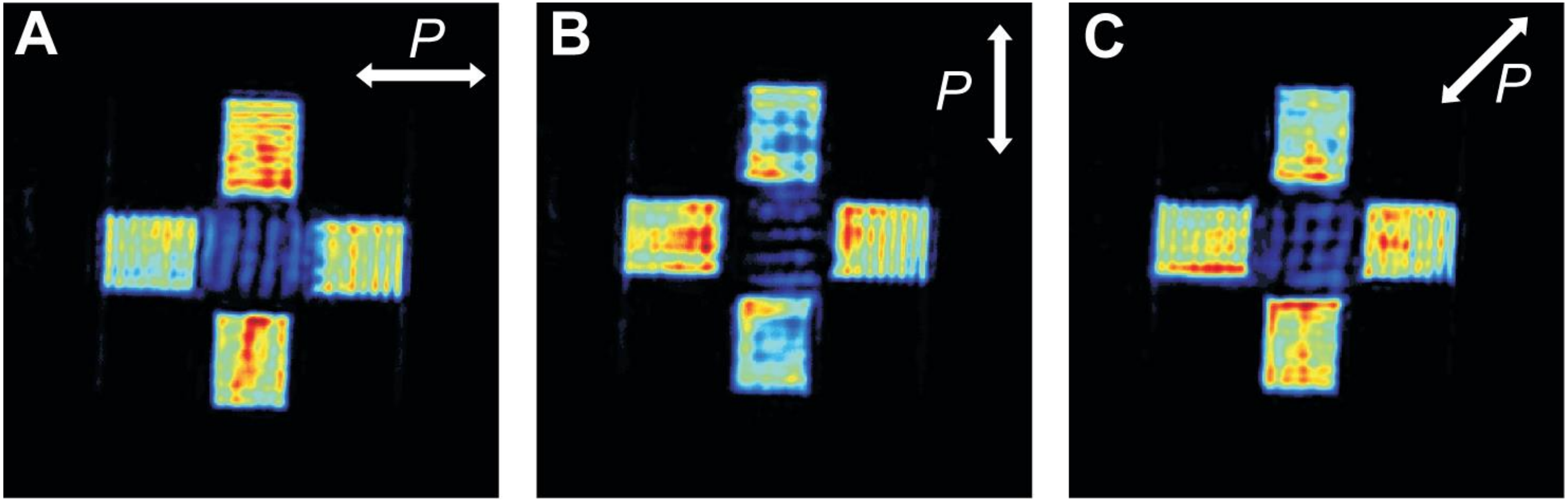
Gjonaj, Nature Photonics (2011)

Amplitude design: bare gold

Resolution: 450 nm

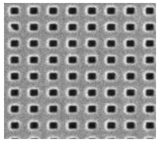


Launching SPPs: hole array

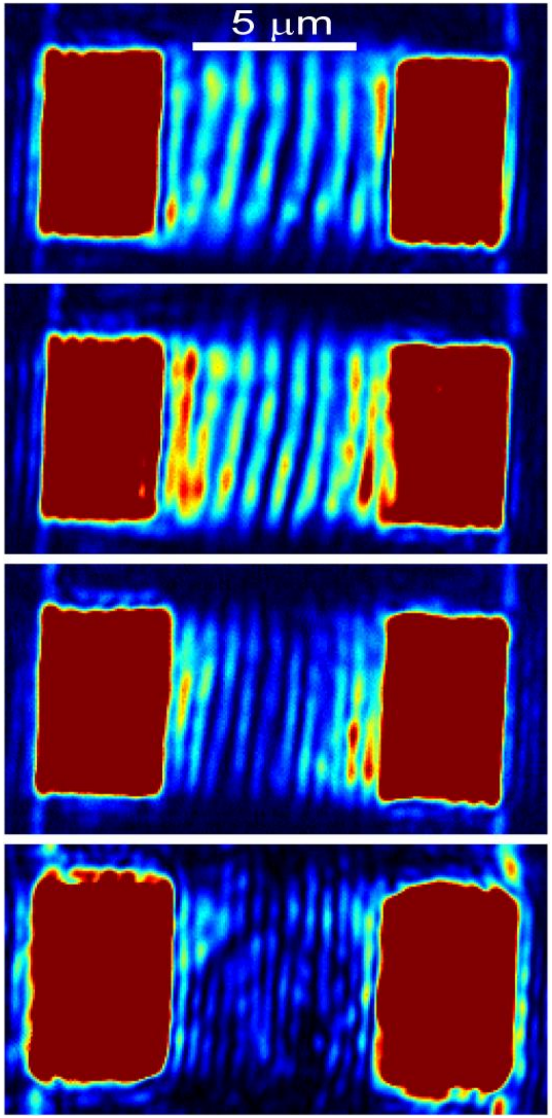


- SPP plane waves propagate into the SPP arena
- Polarization dependency
- Formation of a standing SPP wave

Fringes and gratings



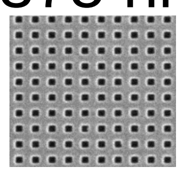
450 nm



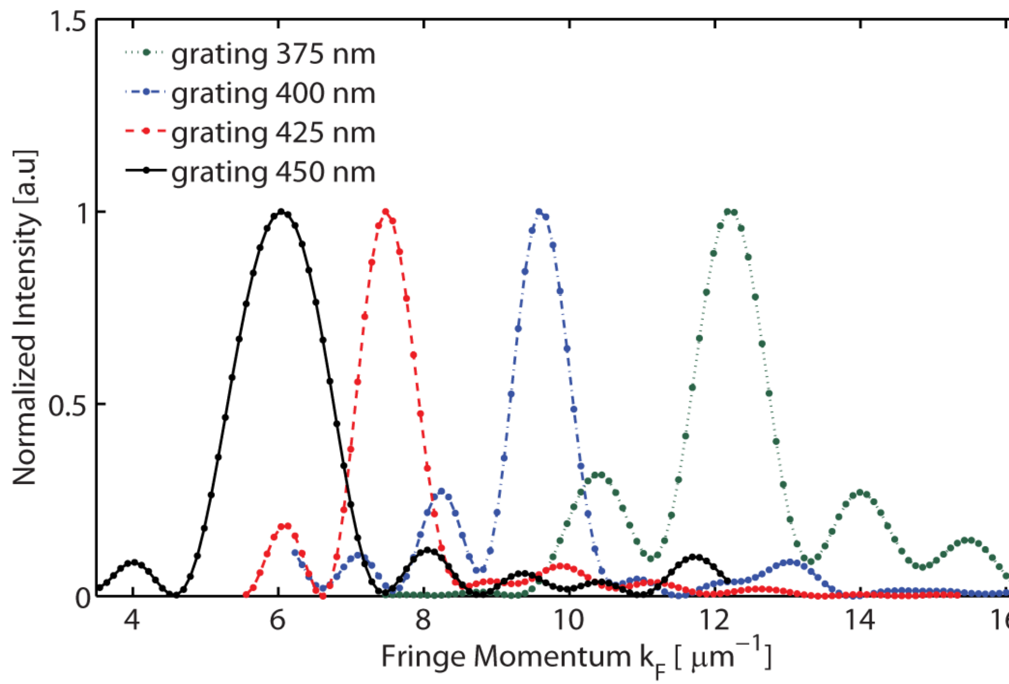
425 nm

400 nm

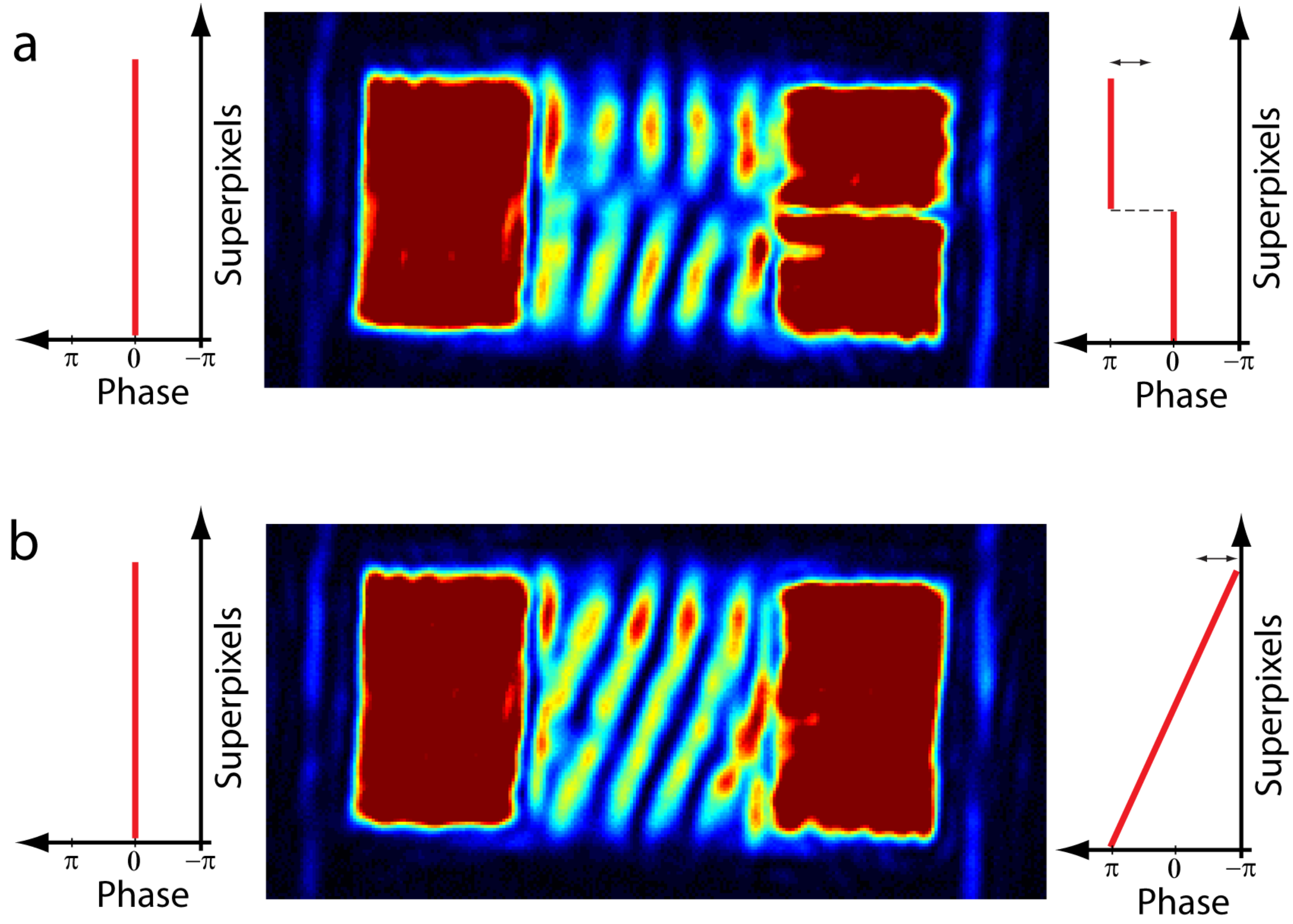
375 nm



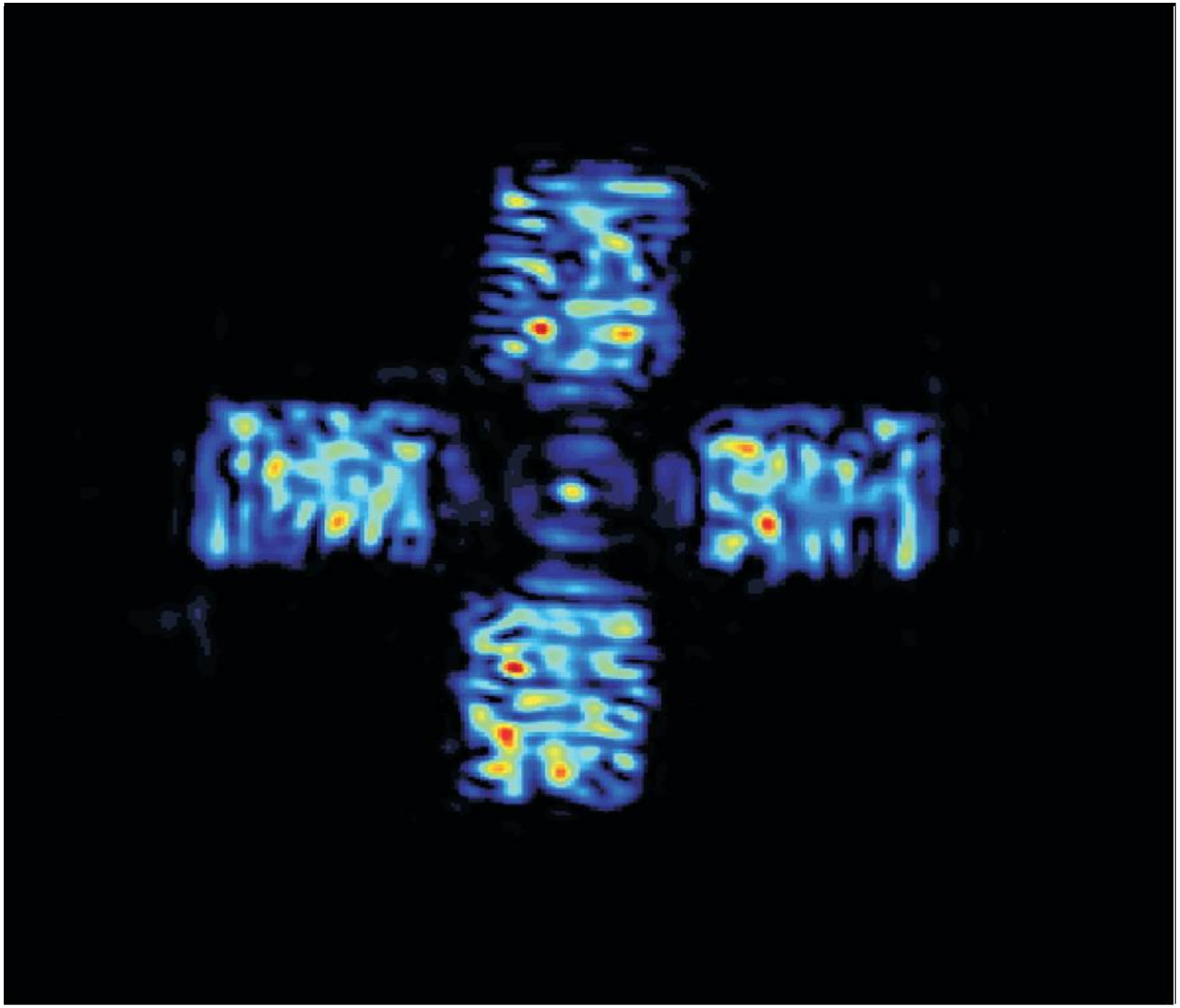
Fringe periodicity = 0.5*λ_{SPP} = 300 nm



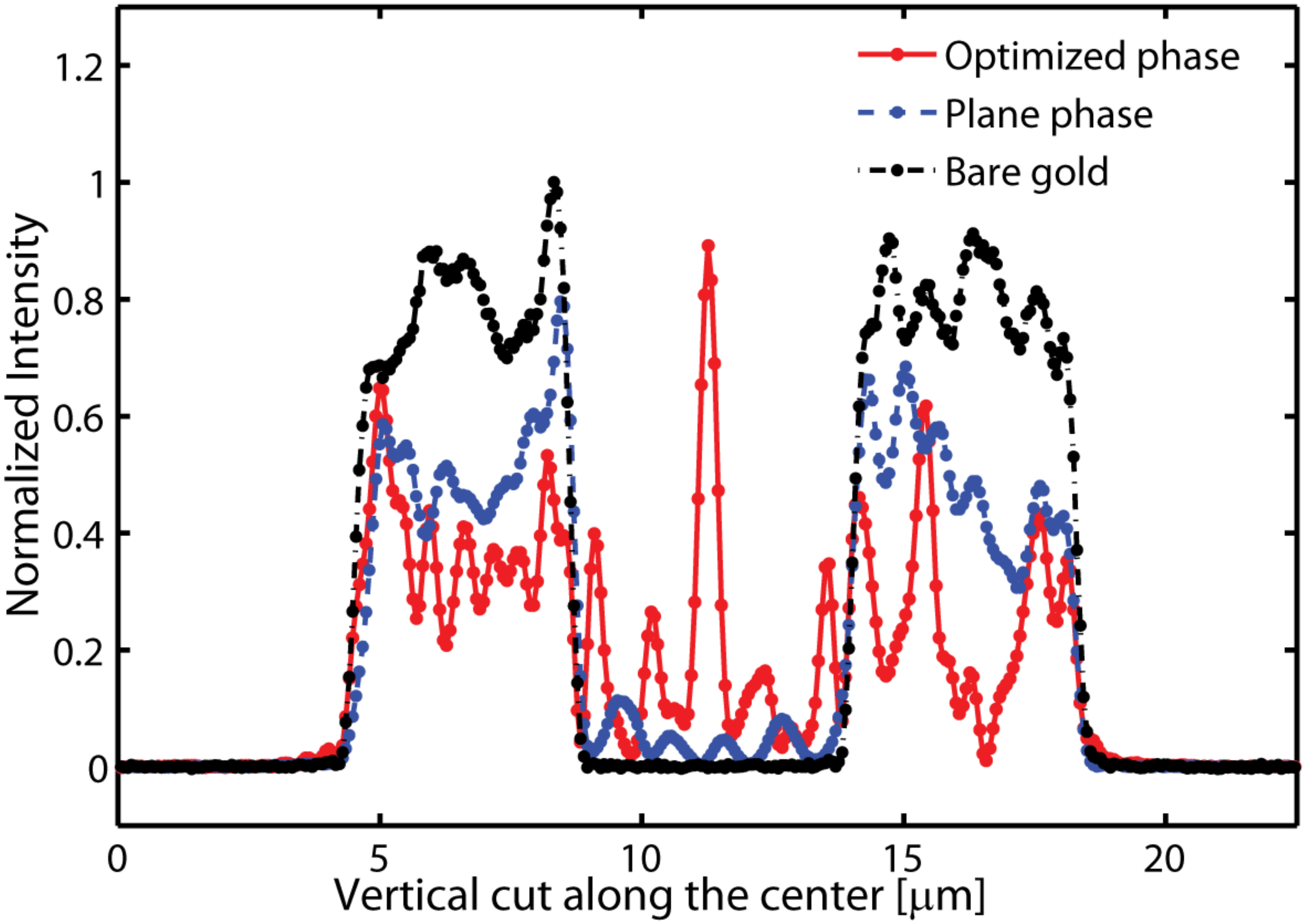
Shift & tilt of the fringes (SSIM)



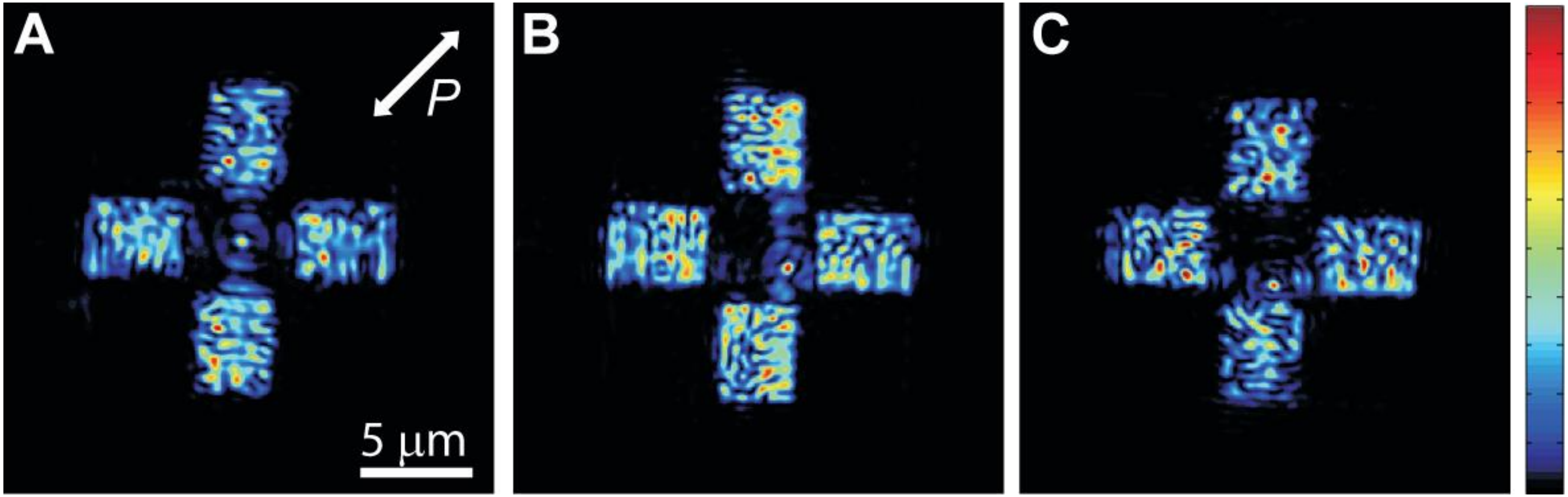
SPP focusing



The SPP focus (with feedback)

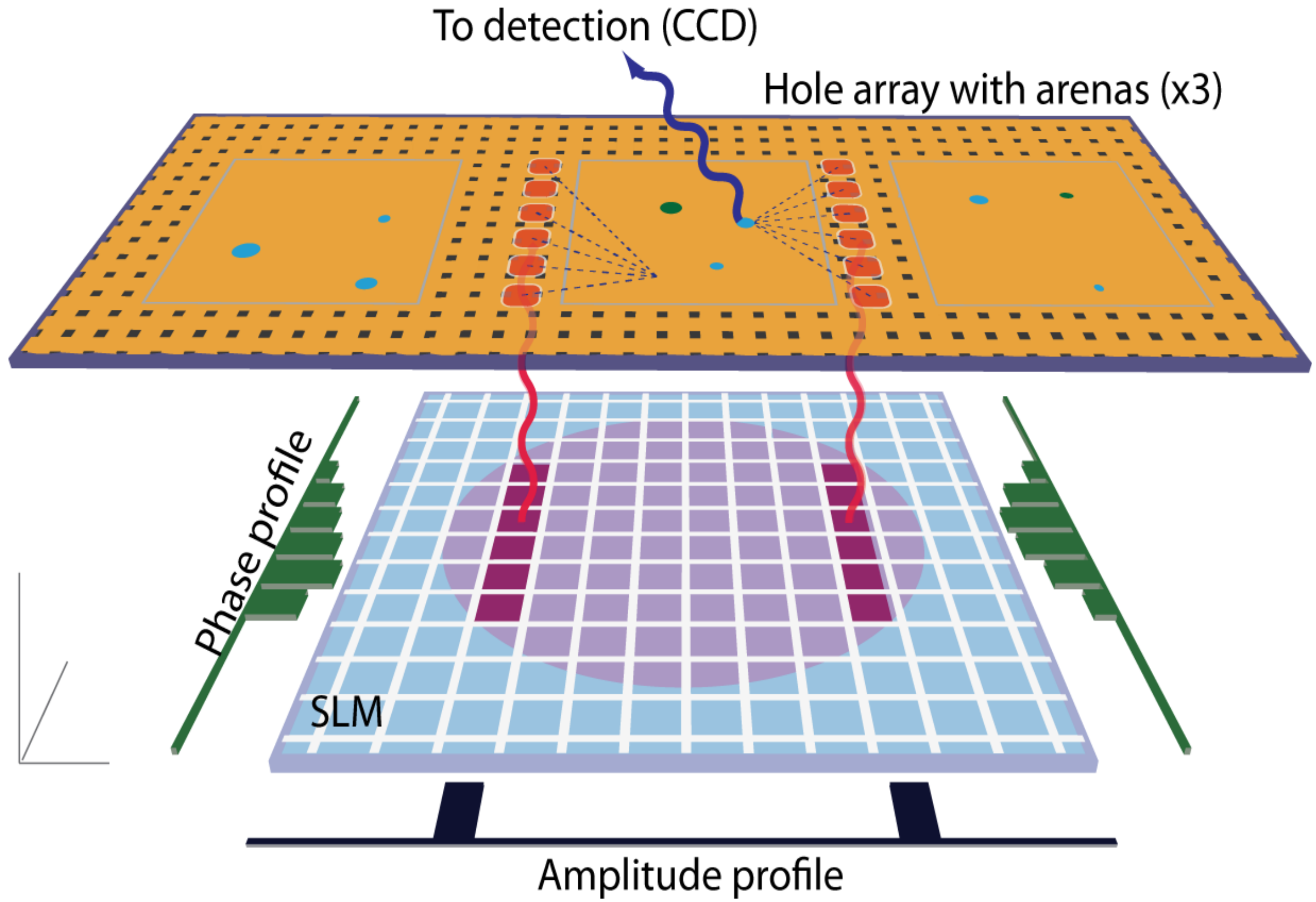


Relocating the focus

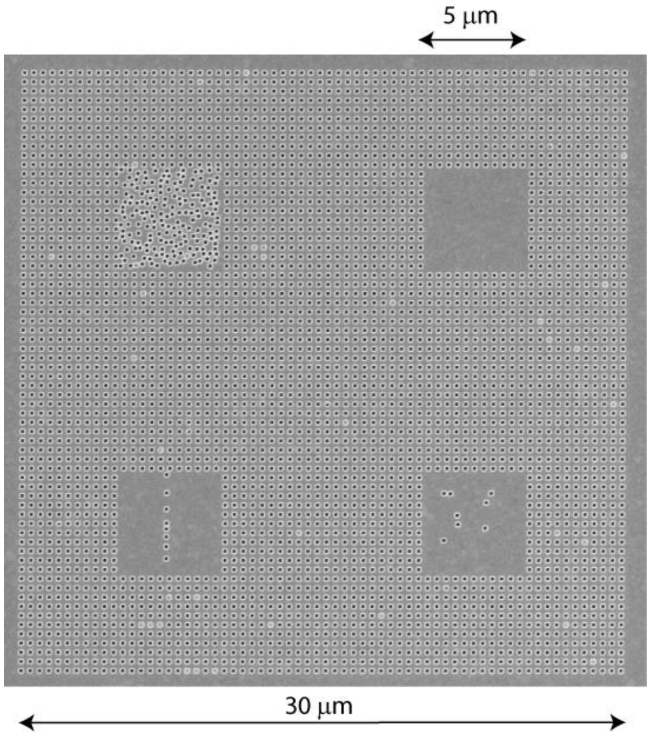


- Everywhere inside the SPP arena

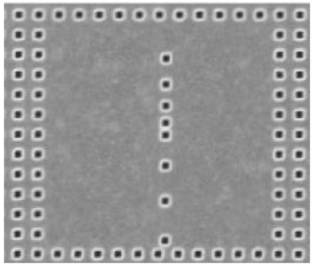
Implementation: microscopy

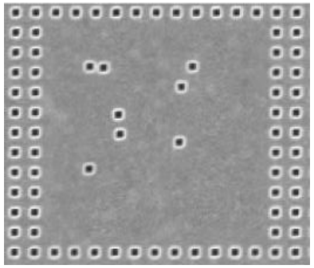


Nanostructered microscope slide

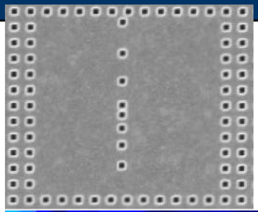


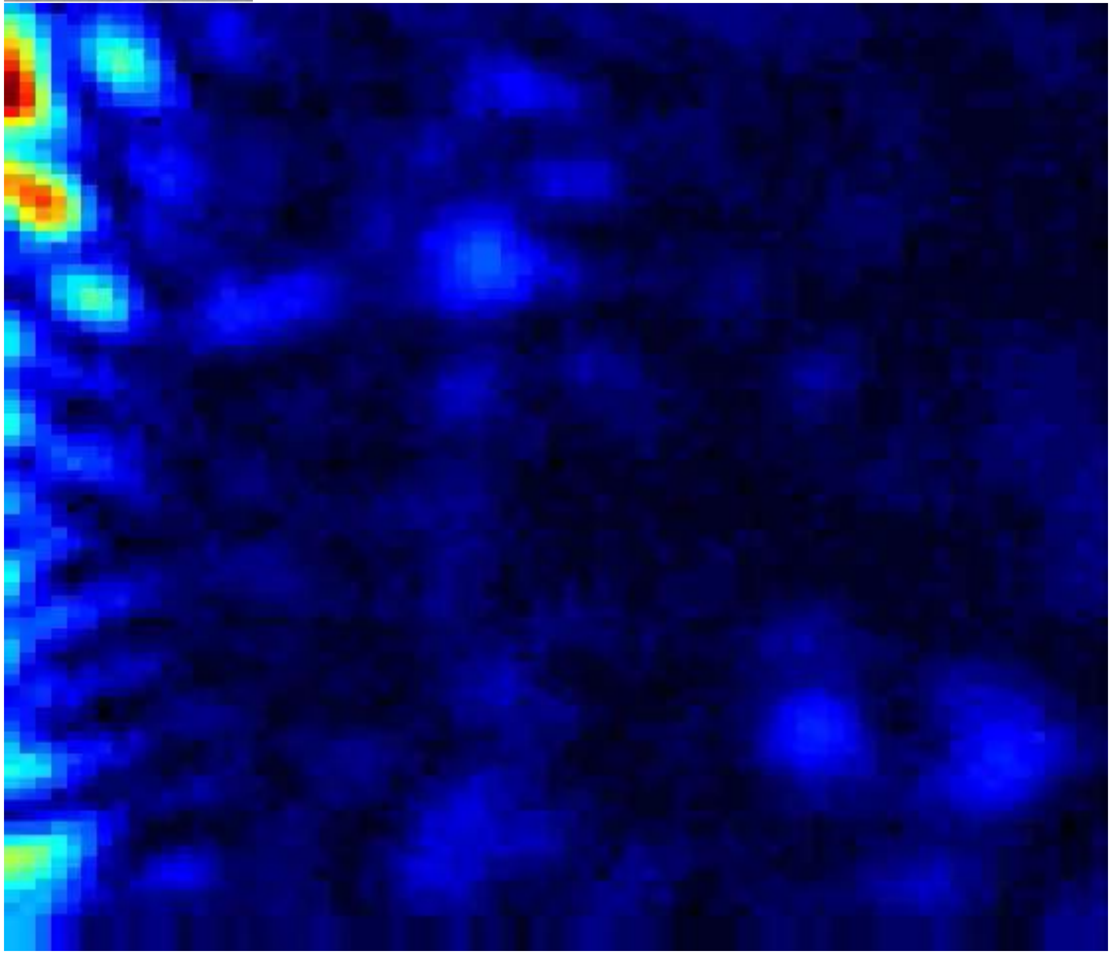
- **Hole grating : SPP launching**
- **Bare gold arenas : no feedback**
- **Free space GF : calculation**
- **Scatterers : to be imaged**
- **Metal : functionalize**

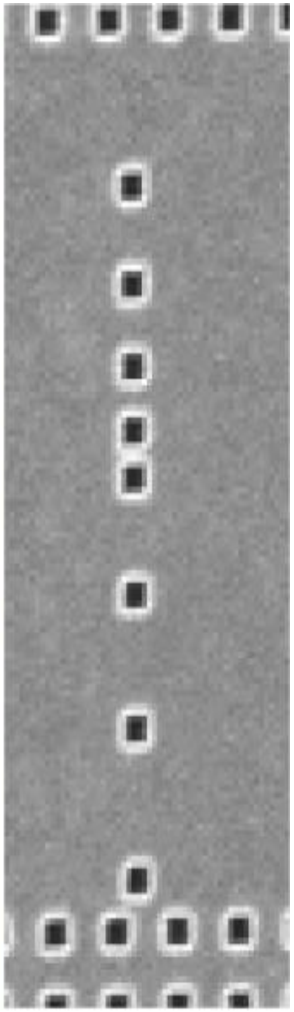


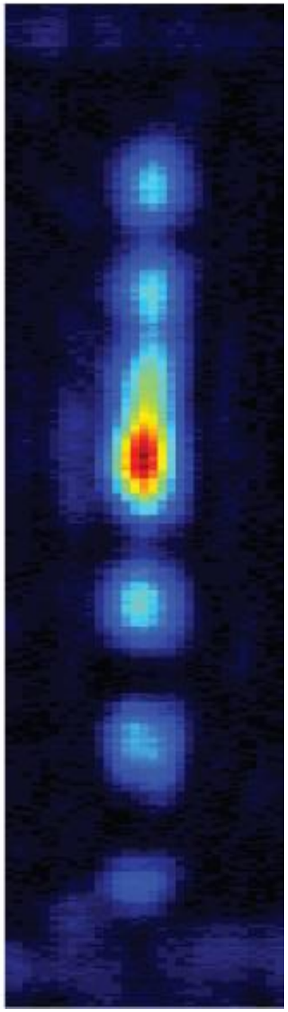


Concept – Scanning the focus



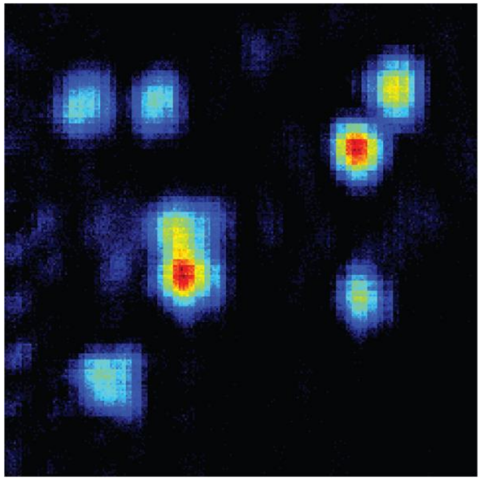


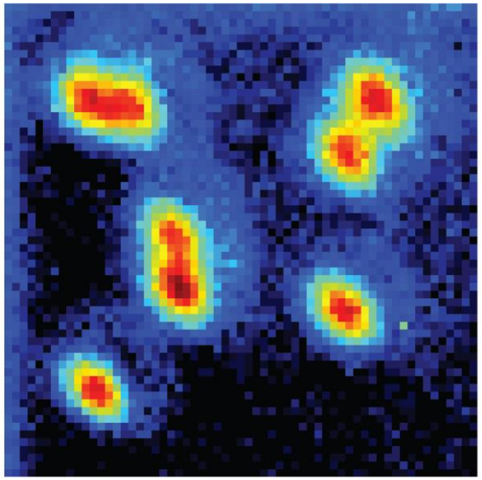




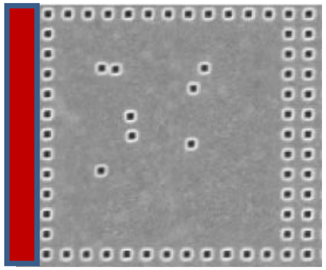
Plasmonic 2D imaging

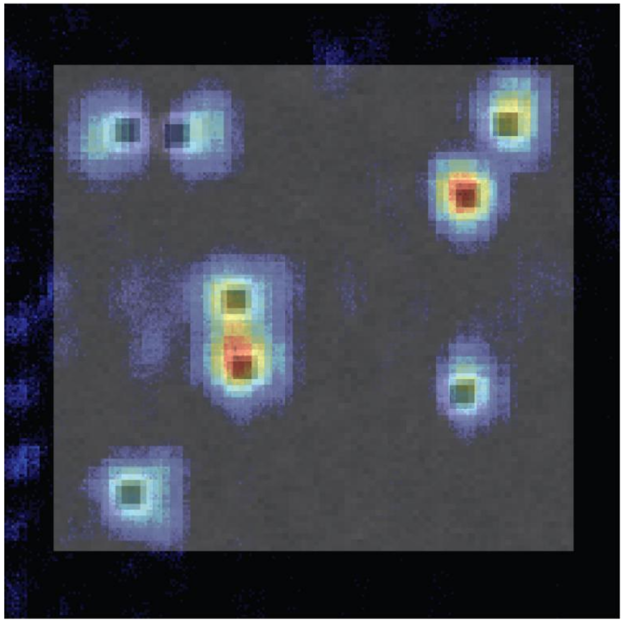
Focusing and scanning





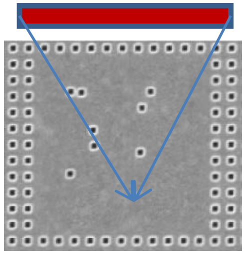
White light illumination

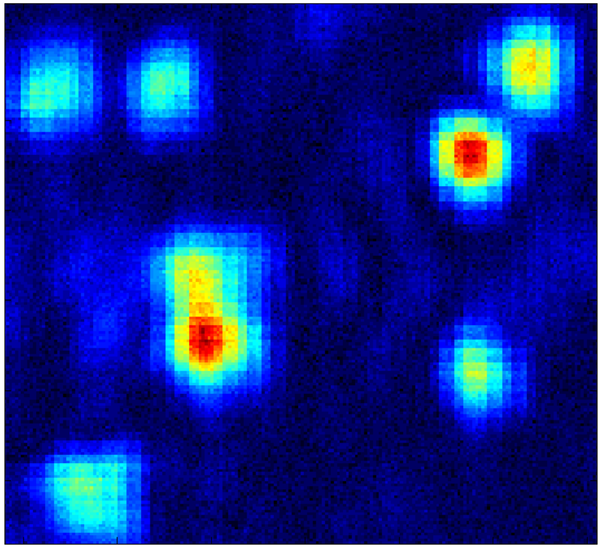


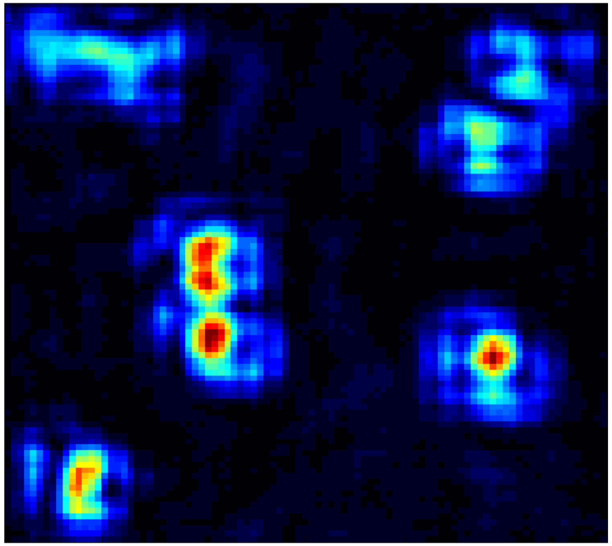


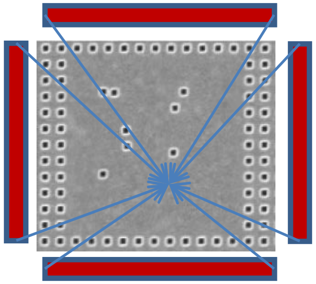
Overlap with SEM image

Enhancing the focusing/resolution



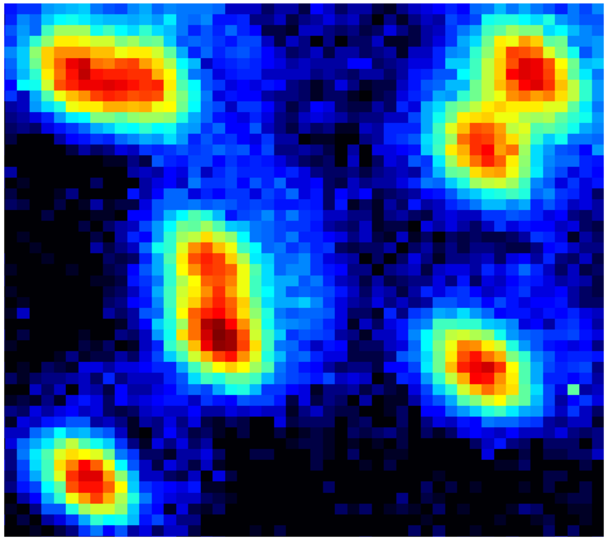


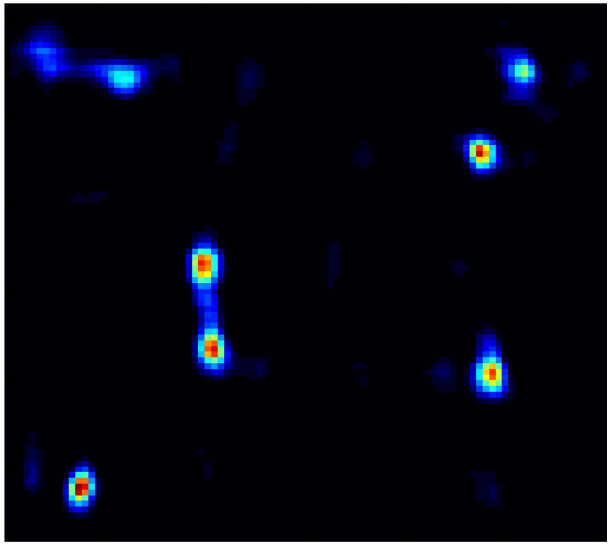




Deconvolution

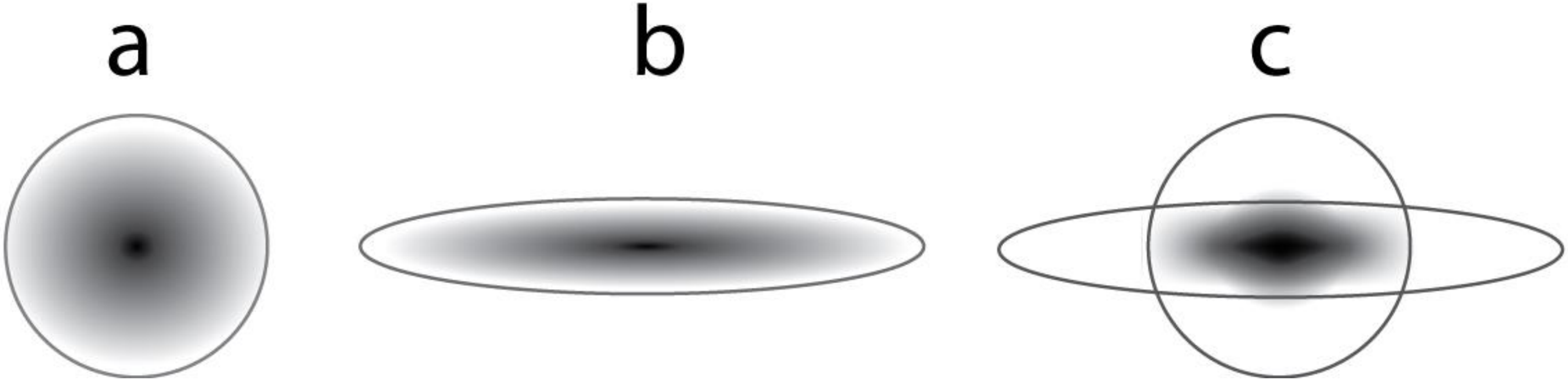
White light illumination



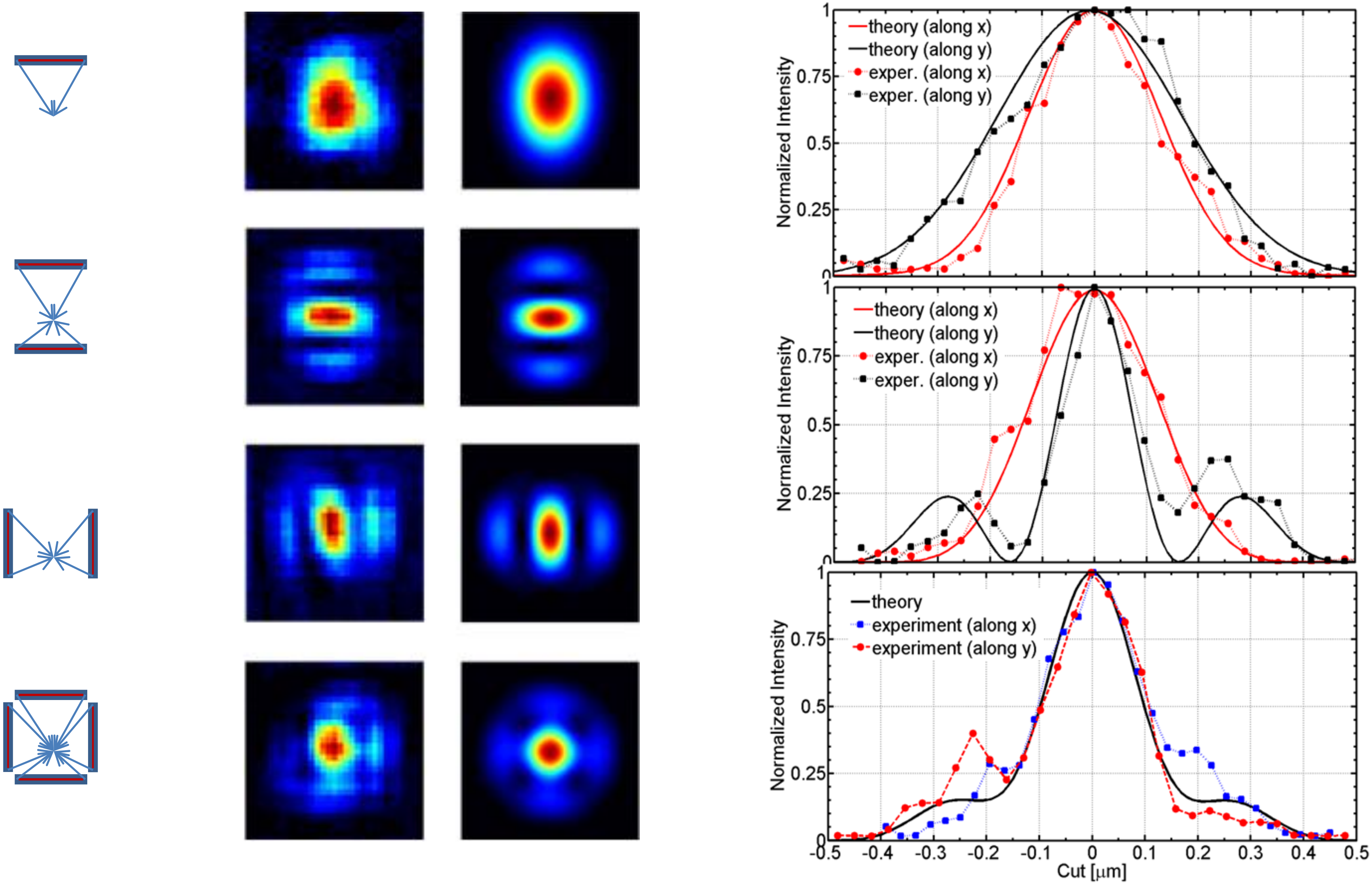


Possible read-outs

- **Single shot : detection psf**
- **Integrated intensity : excitation psf**
- **Pixel in the focus : confocal psf**



Imaging point spread functions



Gjonaj, PRL (2013)

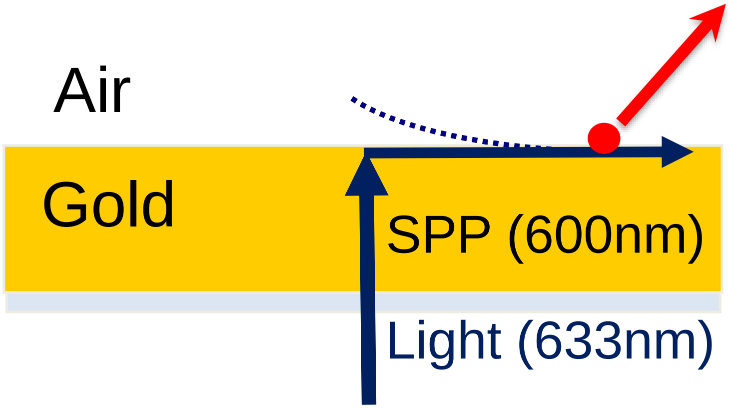
Reorganizing our thoughts

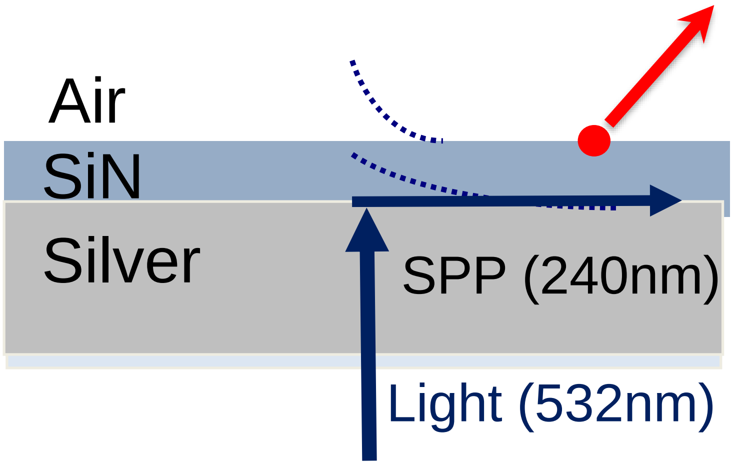
- **Concept**
  - Simple – scanning a focus to achieve imaging
  - Nice – does not require labeling
  - Competitive – delivers energy locally (nano-spectroscopy)

- **Resolution**
  - Lensing – From 450nm objective to ~ 200nm. Great
  - Wavelength – From 633nm to ~ 600nm plasmonic. (**n=1.1**)
  - Maturity – STED, PALM, STORM ~ 20nm. Unfit

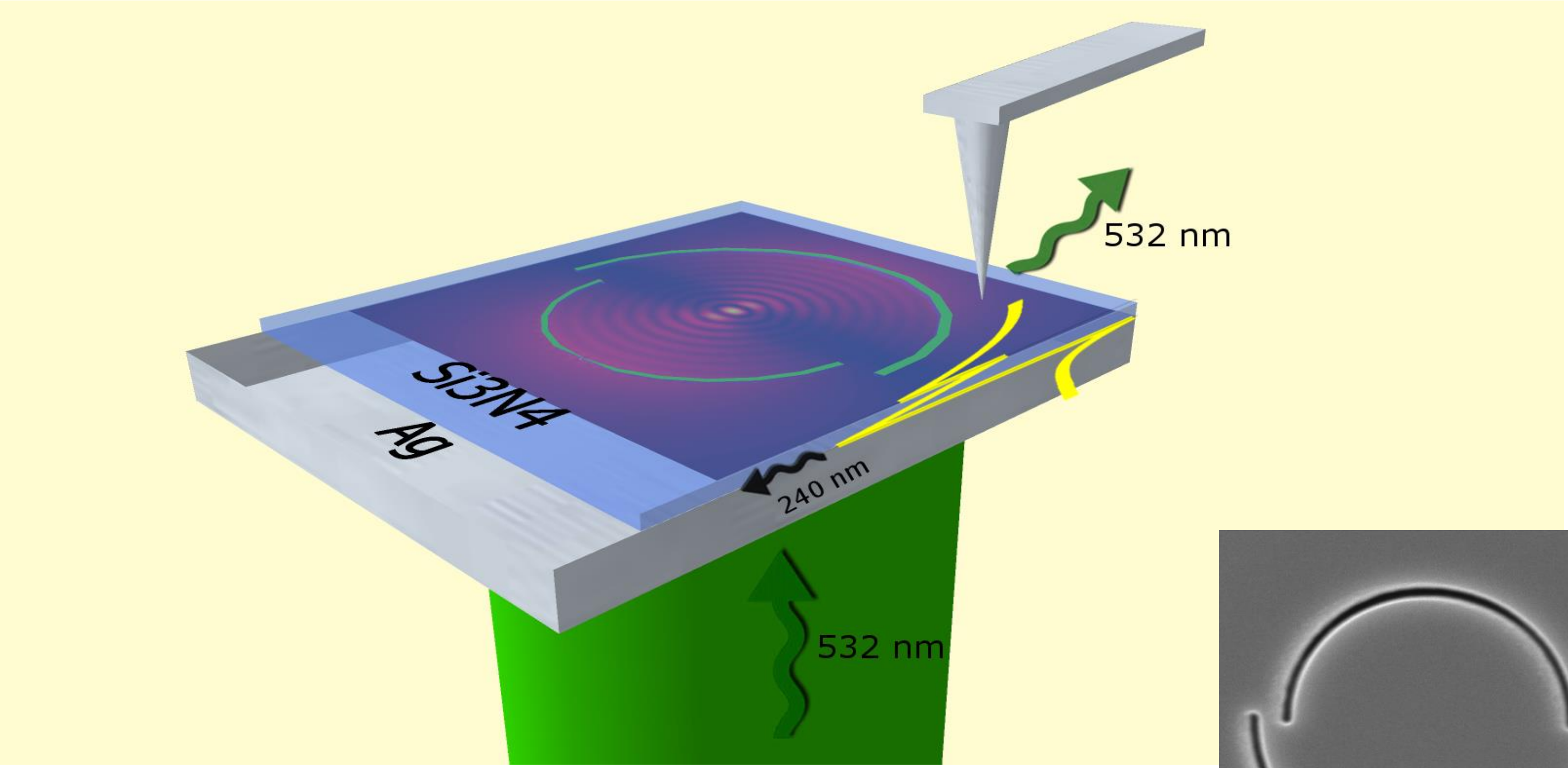
Improved waveguides – Si Nitrite

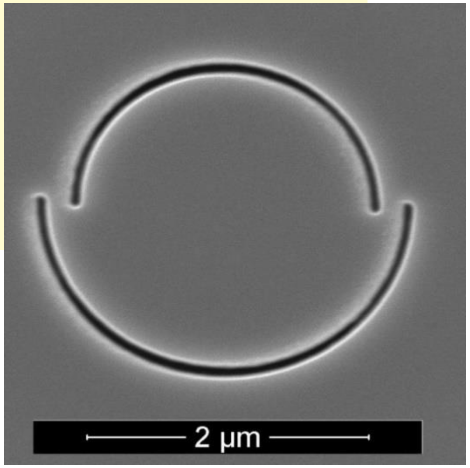
- **Next: New nanophotonics platforms**
  1. Wavelength – From 633nm to ~ 180nm. (**n=3.5**)
  2. Losses – Propagation length > 1 micrometer.
  3. Interaction – Should excite a probe or a bio molecule





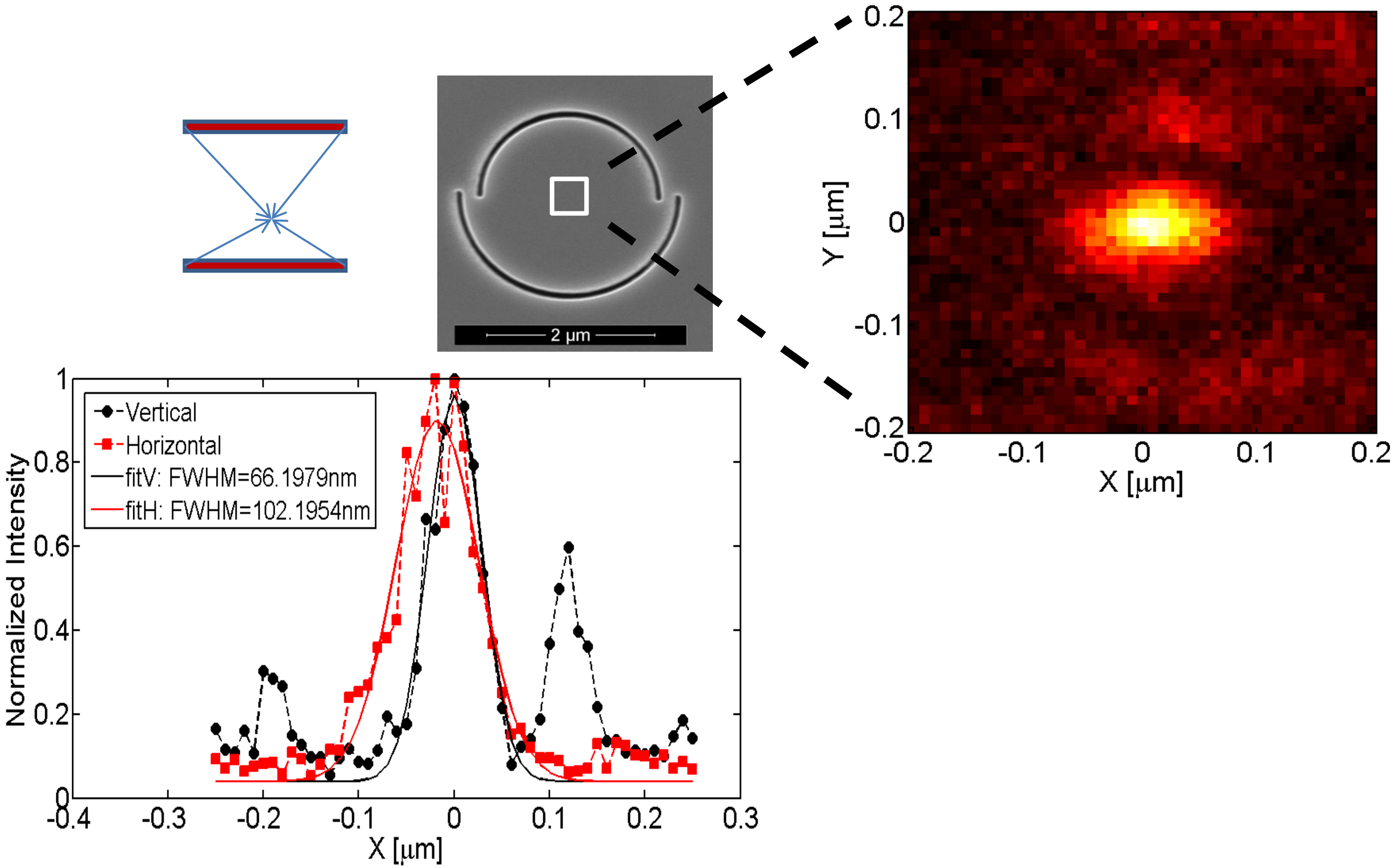
Near field measurements



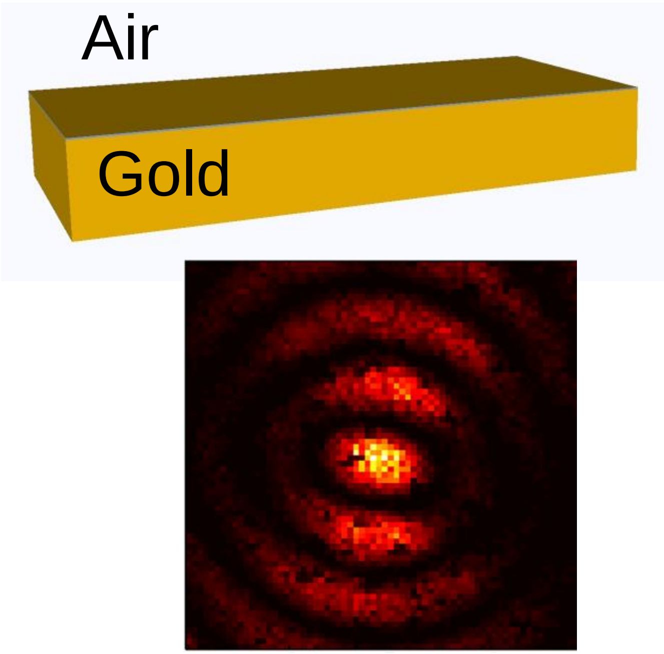


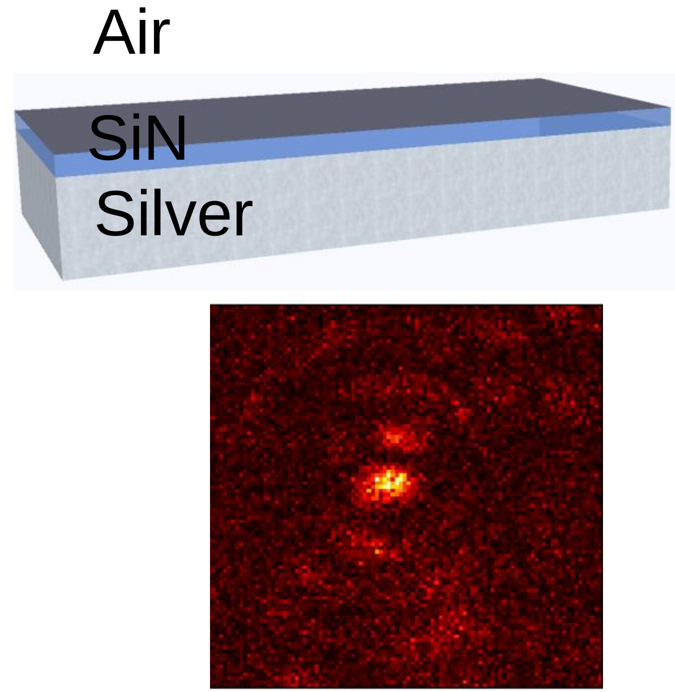
Static focus due to the shape of the slits

Wavelength 240nm; focus 66 nm



Improved waveguides – Si Nitrite



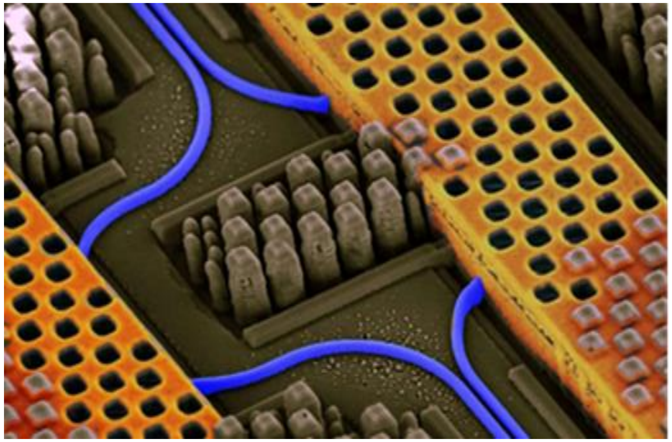


1. Wavelength – From 600nm to ~ 240nm.   Almost there
2. Losses   – Propagation length < 1 micrometer.
3. Interaction   – Should excite a probe or a bio molecule

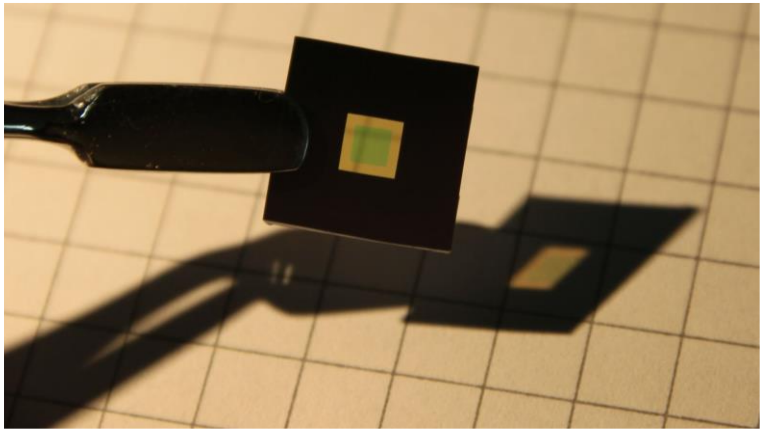
Super-resolution in Silicon domain

- **Bulk Silicon**
  - Refractive index ~ 3.5
  - Connection to Si Photonics
  - Connection to lithography
  - Absoption in the visible
  - Hard to harvest light

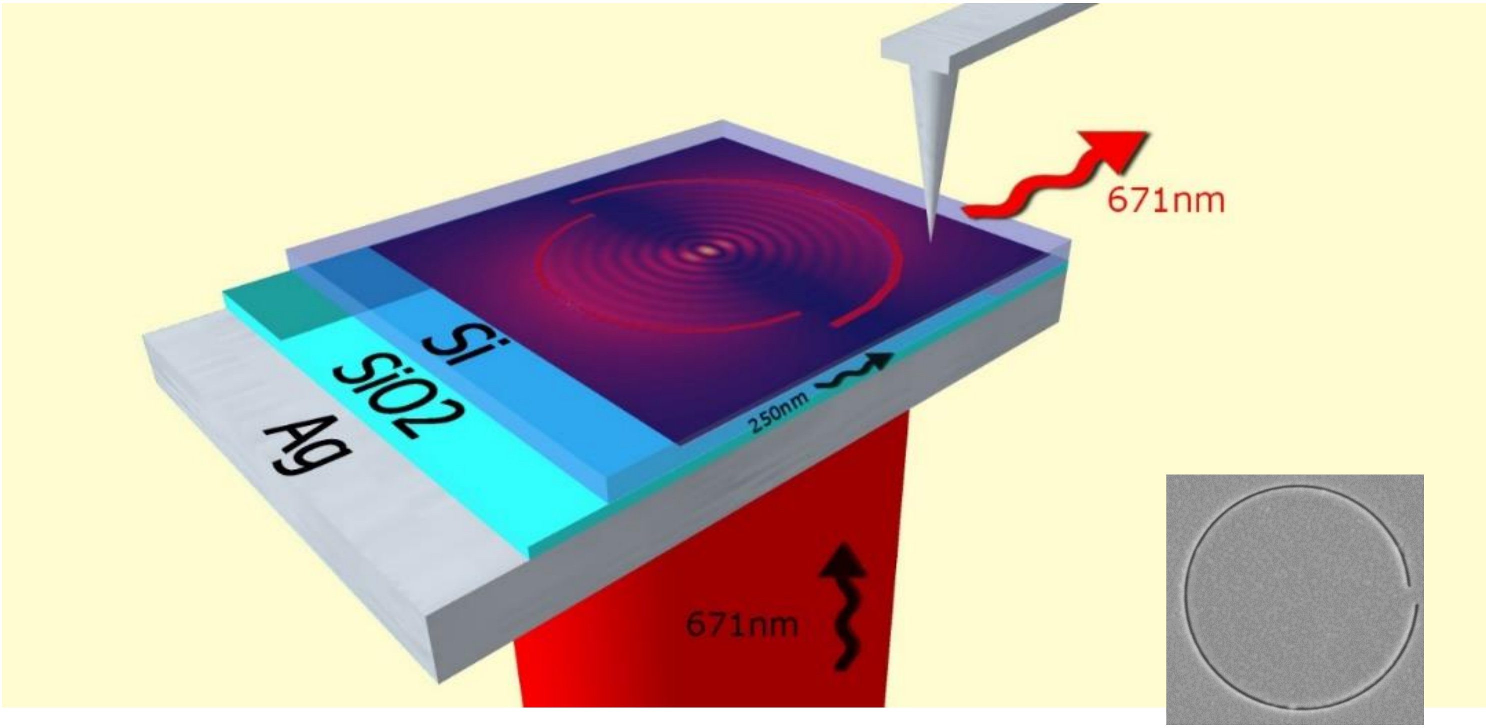
IBM Research

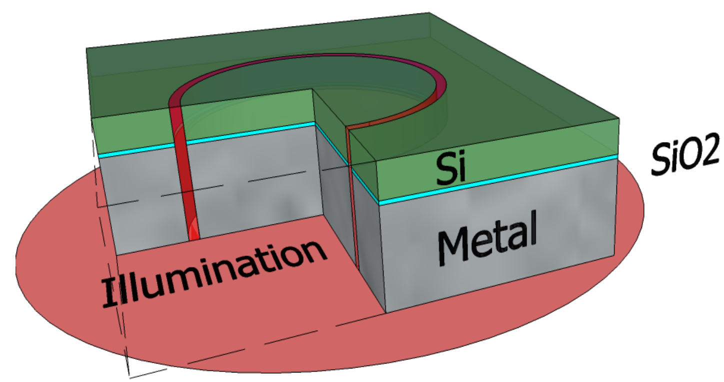


- **Thin Si waveguide**
  - Transparent
  - Guided modes in 2D
  - Propagation up to 10 um



Focusing with Silicon

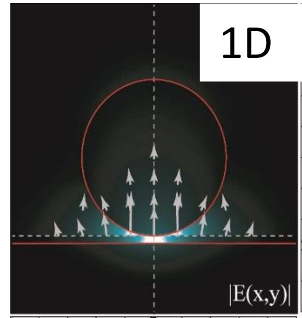




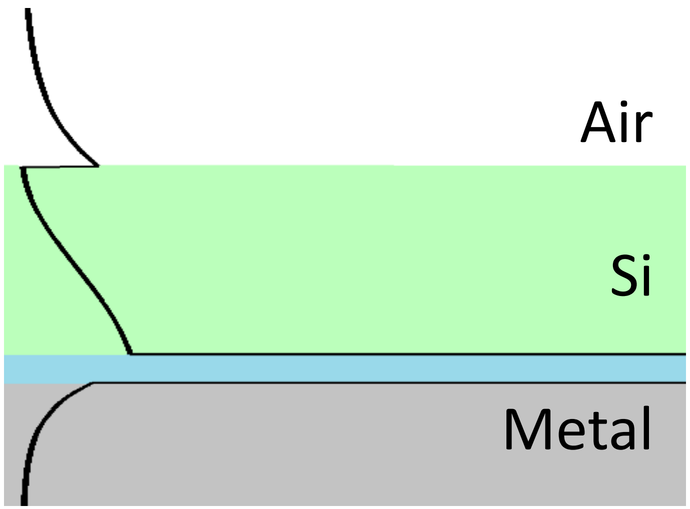
David, **Gjonaj** et al **Optica (2015)**

Hybrid photonic plasmonic modes

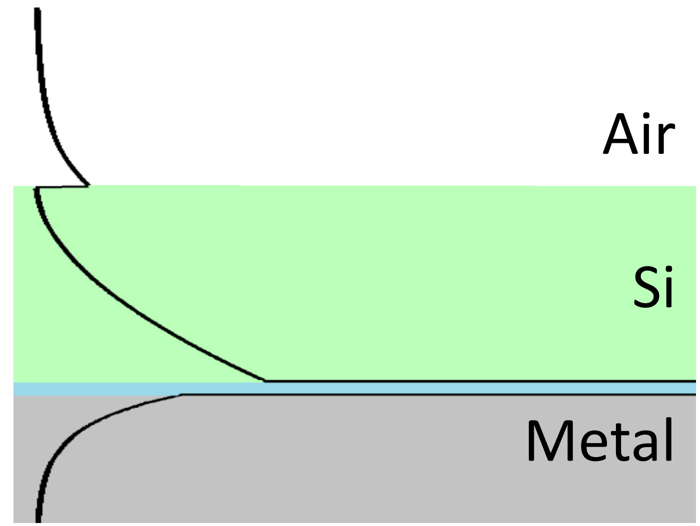
Si - SiO_2 - Ag
60 - **8** - **300** nm



Si - SiO_2 - Ag
60 - **4** - **300** nm



- SiO_2 -



- **Single hybrid mode**
  - More photonic
  - Wavelength 220 nm
  - Propagation 5.3 um

- **Single hybrid mode**
  - More plasmonic
  - Wavelength 184 nm
  - Propagation 3.3 um

Resolution: contrast or size?

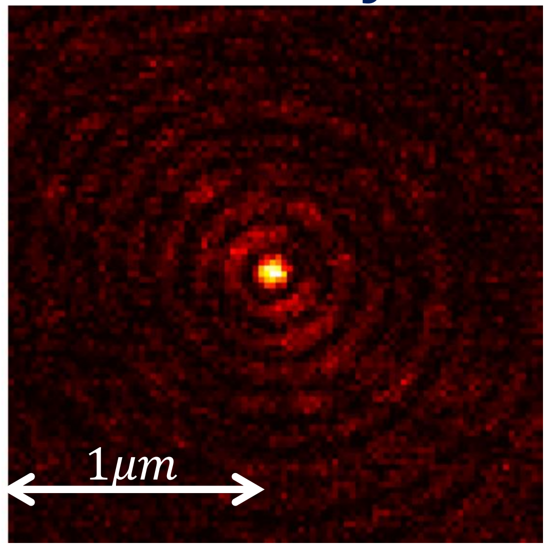
Intensity | **Phase**

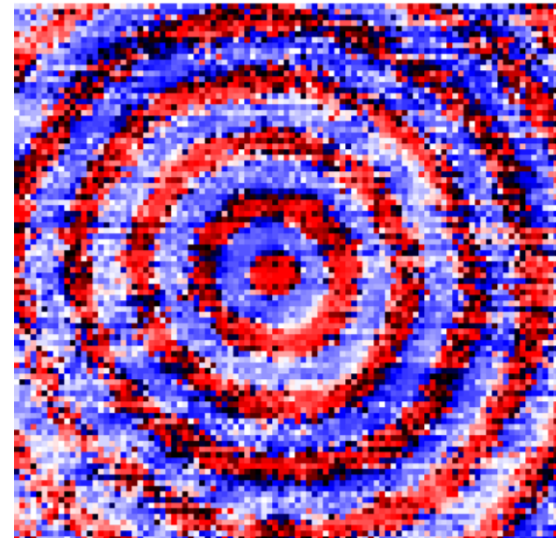
Si - SiO_2 - Ag
60 - **8** - **300** nm

Wavelength 220 nm

Propagation 5.3 um

Size (FWHM) 78 nm



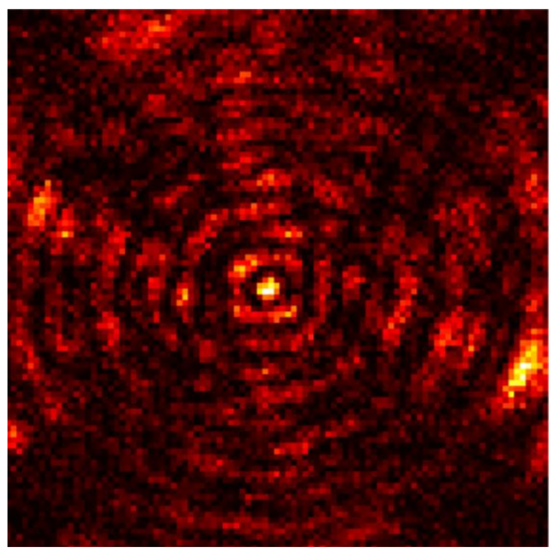


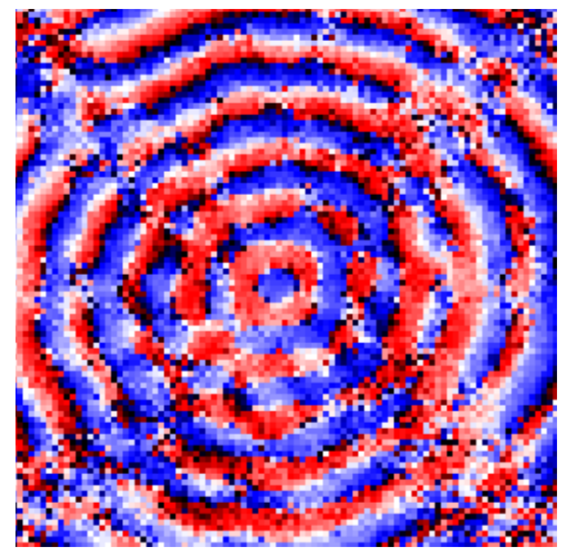
Si - SiO_2 - Ag
60 - **4** - **300** nm

Wavelength 184 nm

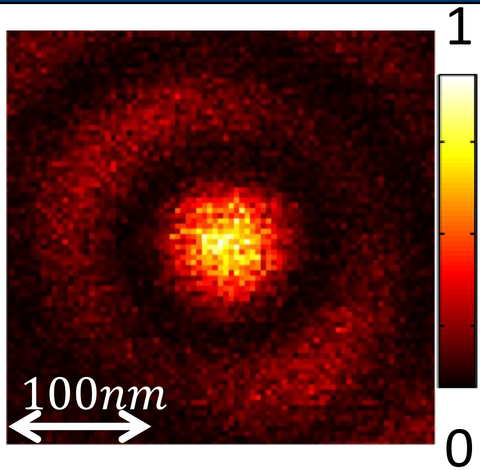
Propagation 3.3 um

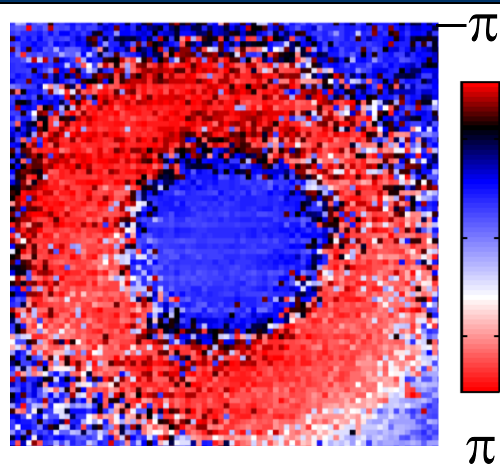
Size (FWHM) 66 nm





Tunability: better contrast focusing

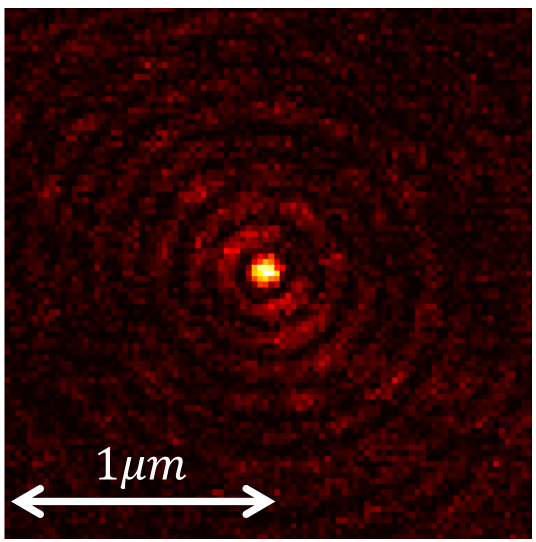


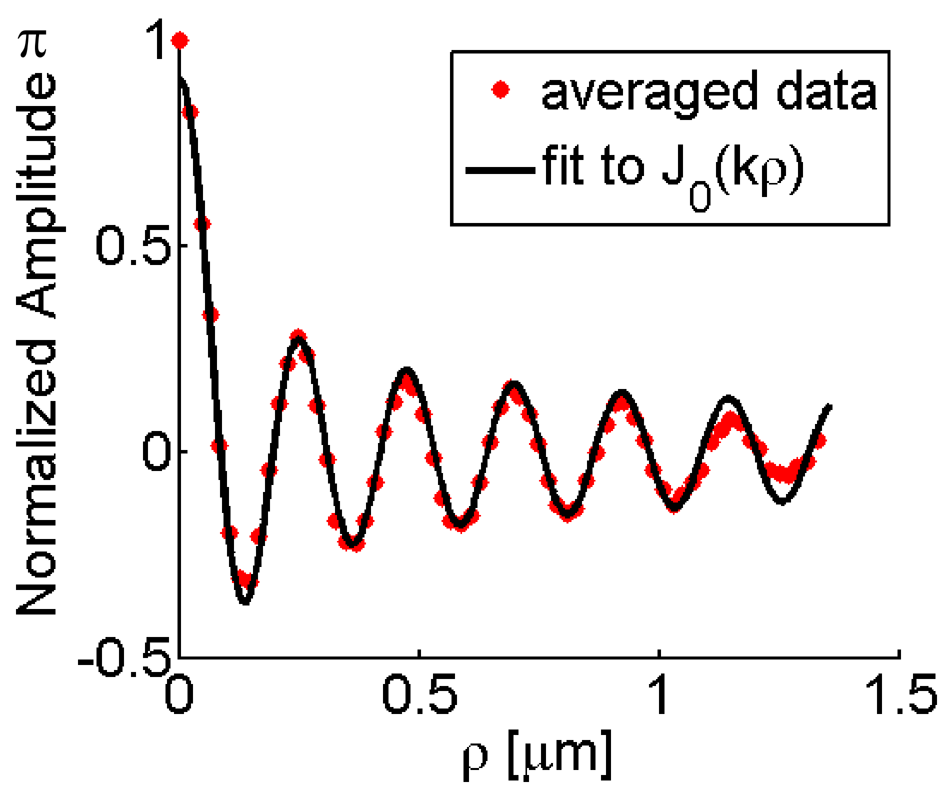


Wavelength 220 nm

Propagation 5.3 um

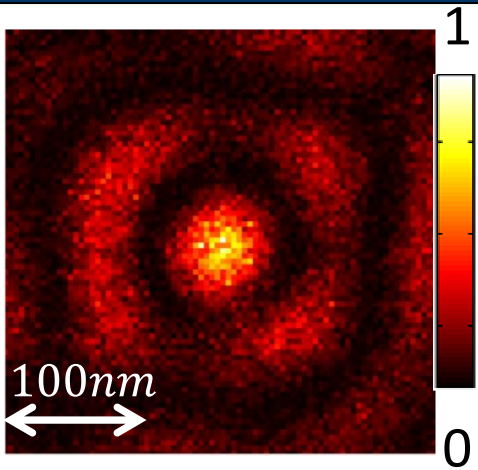
Size (FWHM) 78 nm

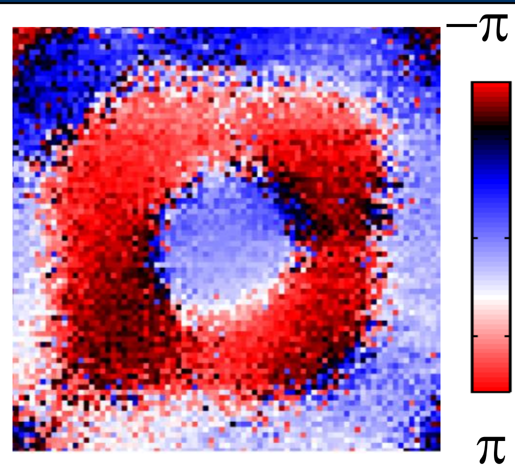




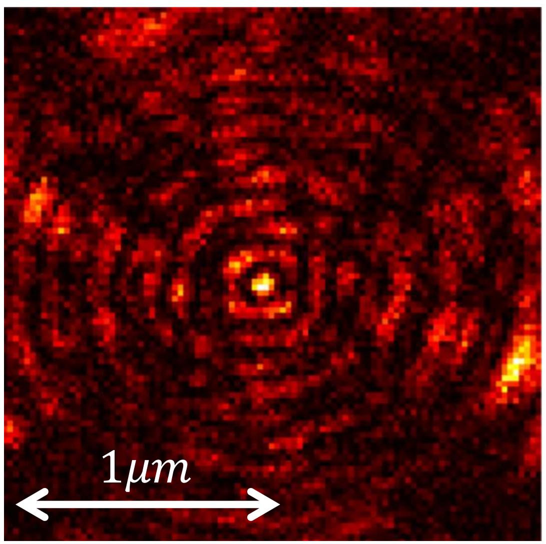
Si	-	SiO_2	-	Ag
60	-	**8**	-	**300** nm

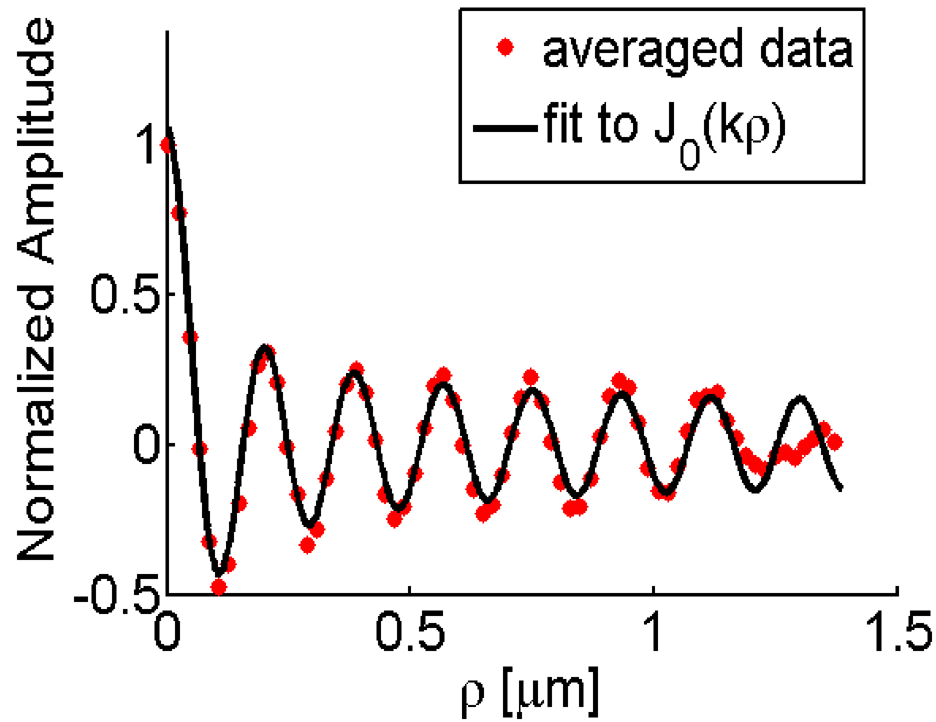
Tunability: better size focusing





Wavelength 184 nm
Propagation 3.3 um
Size (FWHM) 66 nm

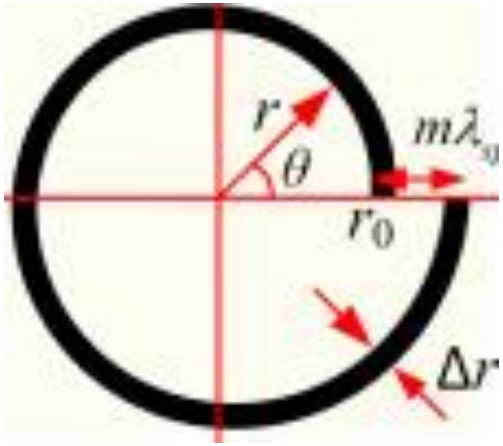




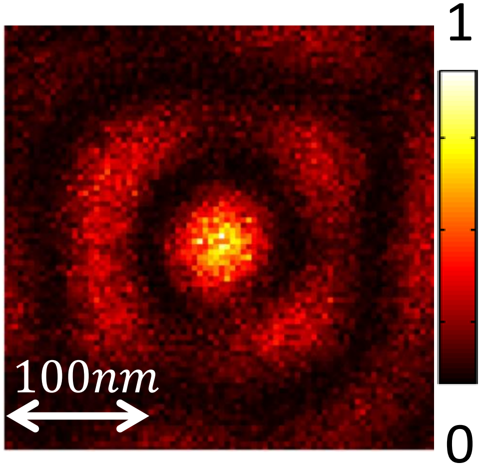
Si	-	SiO_2	-	Ag
60	-	**4**	-	**300** nm

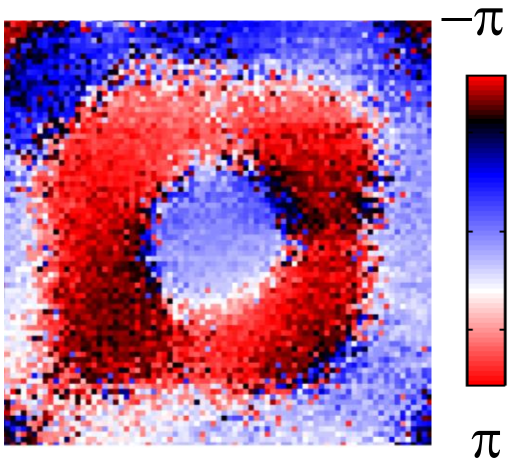
Orbital angular momentum (spiral)

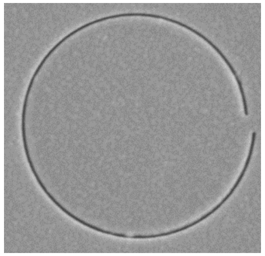
- **Spiral lens & circular polarization**
  - Angular momentum spiral = -1
  - Angular momentum polarization = 1
  - Net angular momentum L = 0



$$E(\rho,\theta) = J_0(k\rho)$$

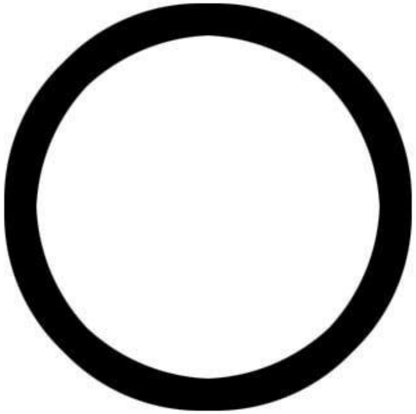




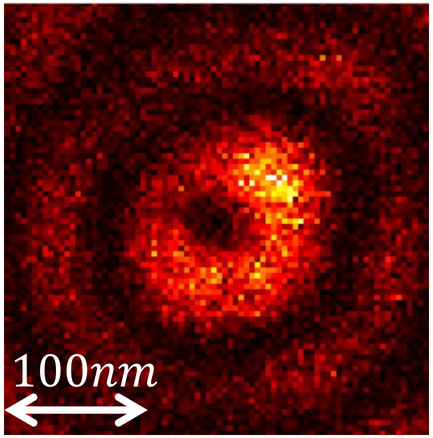


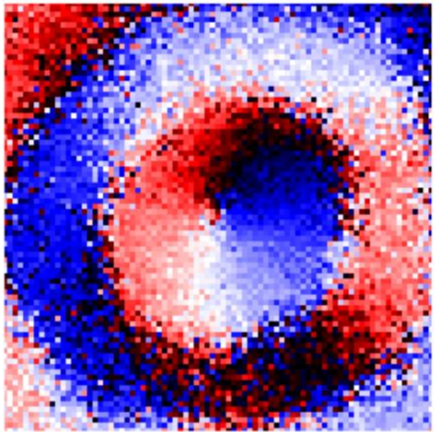
Orbital angular momentum (circle)

- **Circular lens & circular polarization**
  - Angular momentum circle = 0
  - Angular momentum polarization = 1
  - Net angular momentum L = 1



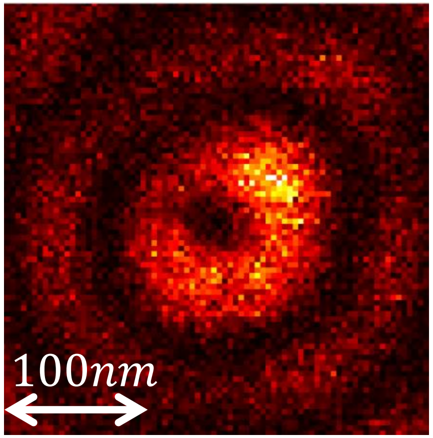
$$E(\rho,\theta) = J_1(k\rho) * e^{i\theta}$$

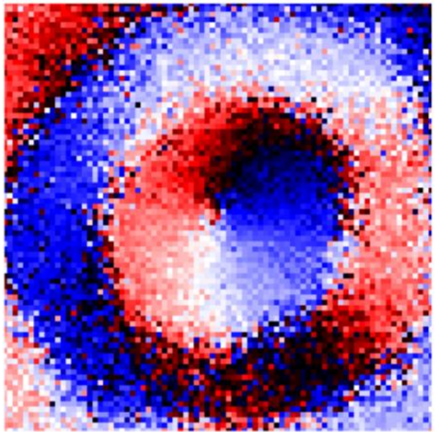




Nano vortex relevance

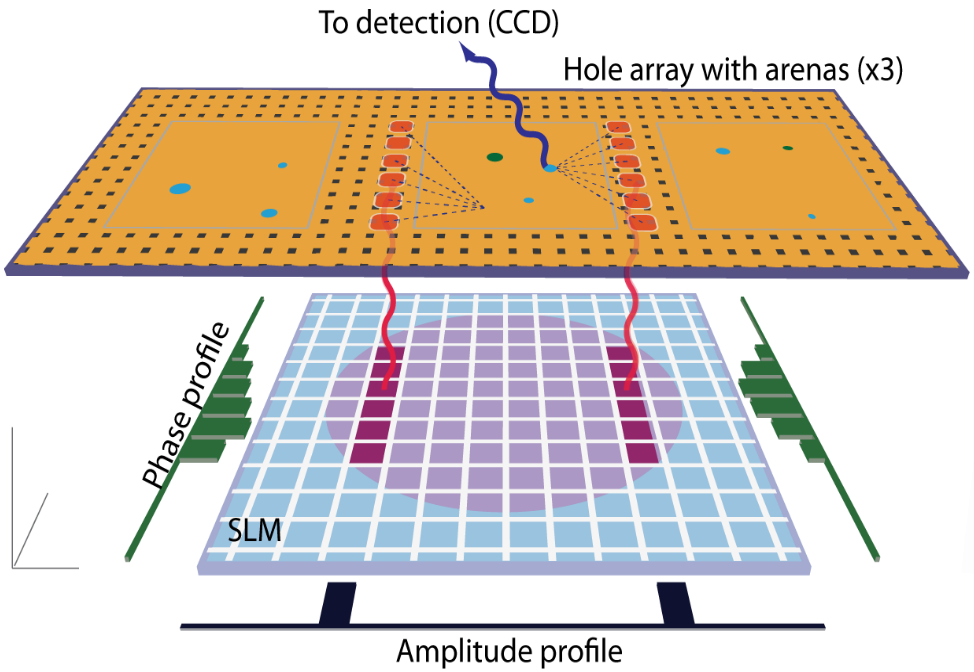
- **Optical vortices are well known and used**
  - Hasman, et al Nano Letters (2011)
- **Nano vortices are new**

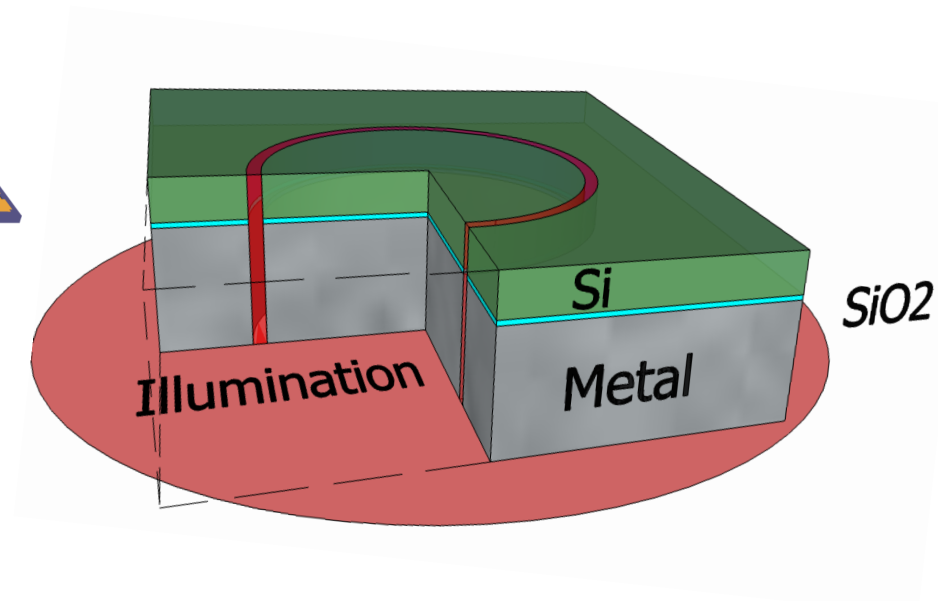




  - The size (60 nm) is comparable with quantum systems
  - For example Quantum Dots
  - Beyond the dipole transition
  - Accessing new transitions (dipole prohibited)

Joining efforts





- ❑ **Active wavefront control**
  - Raster scanning (focus or vortex)
  - Far field microscopy
  - Flexibility

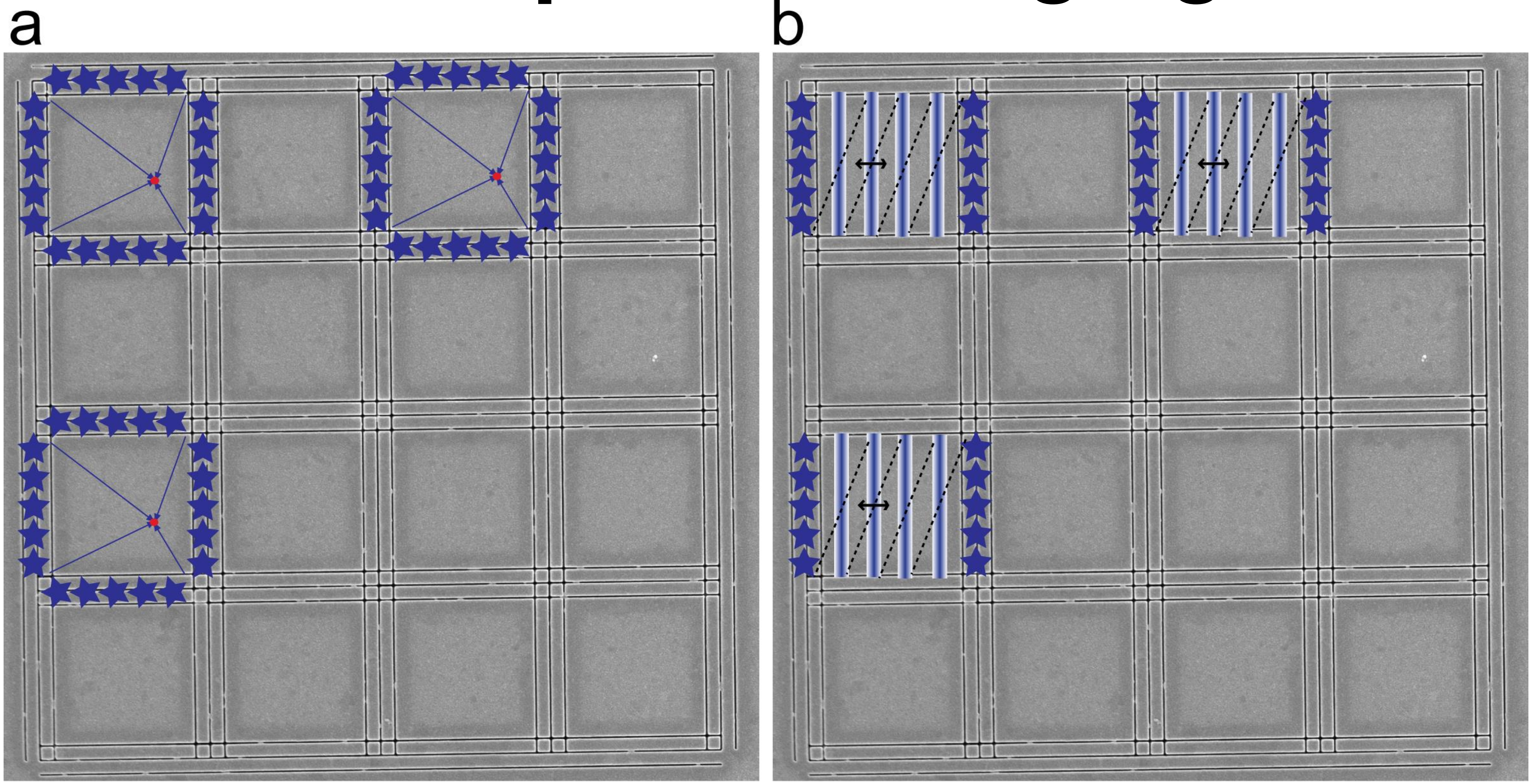
- ❑ **Silicon waveguides**
  - Wavelength 184 nm
  - Propagation 3.3 um
  - Resolution 66 nm
  - CMOS compatibility Al

Take home messages

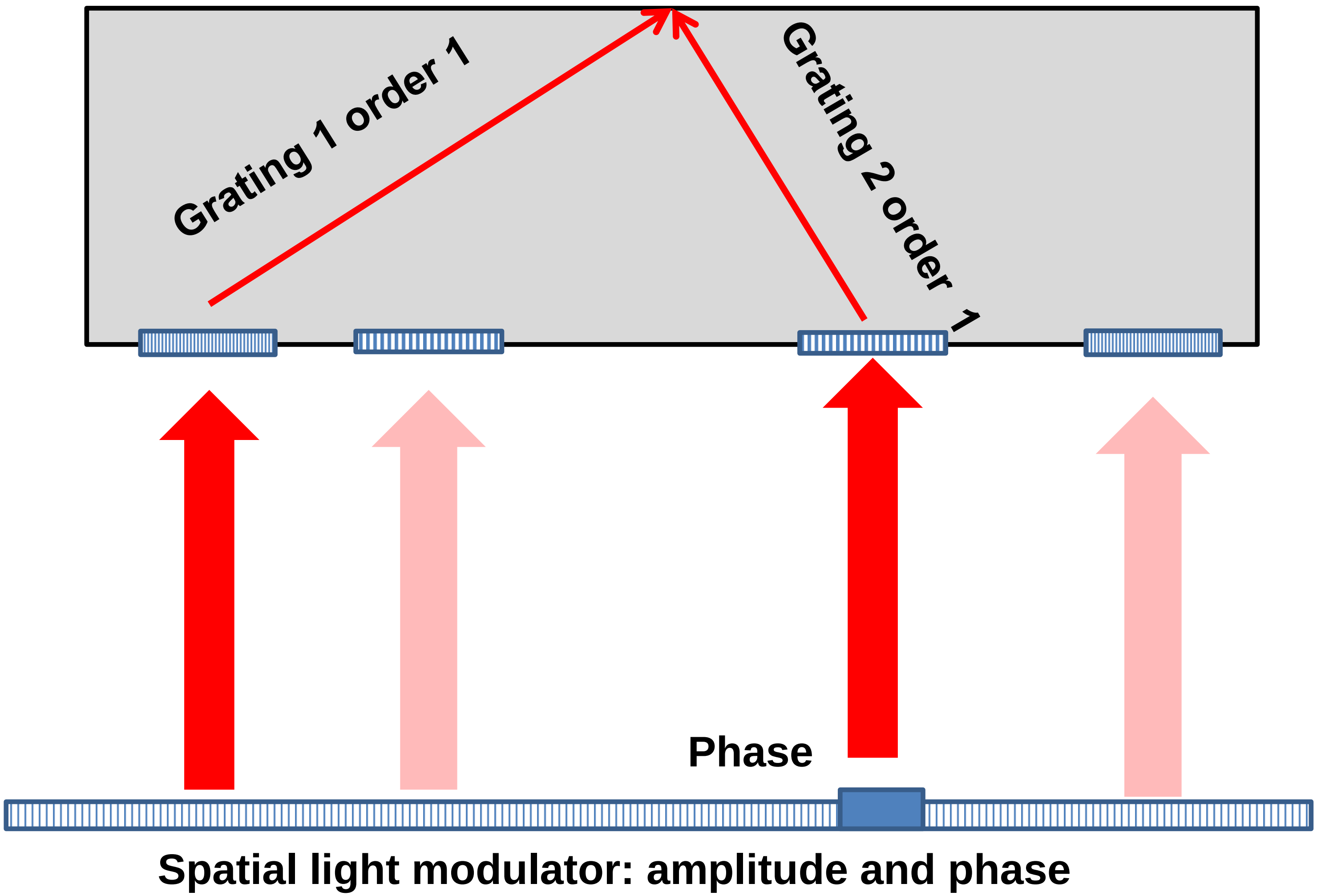
- **Microscopy is continuously growing**
- **Nanoscopy is an actuality**
  - Limitations: Fluorecent labelling, invasiveness
  - Open questions : Chips, nanospectroscopy (i.e. Raman)

- **Wavefront shaping is flexible control**
  - Microscopy by focusing and scanning (label free)
  - Deliver energy suitably for spectroscopy
- **Resolution is enhanced in Photonic 2D waveguides**
  - Static focusing to ~60 nm with reasonable contrast
  - Tunable by material properties (resolution, losses, CMOS)

Multiplexed imaging

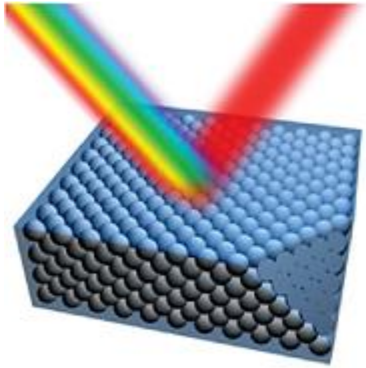


How to achieve it

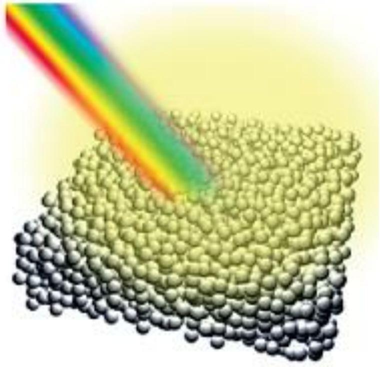


The generalized microscope slide

- **Conventional**
  - Passive, compensated
  - Cheap and standard

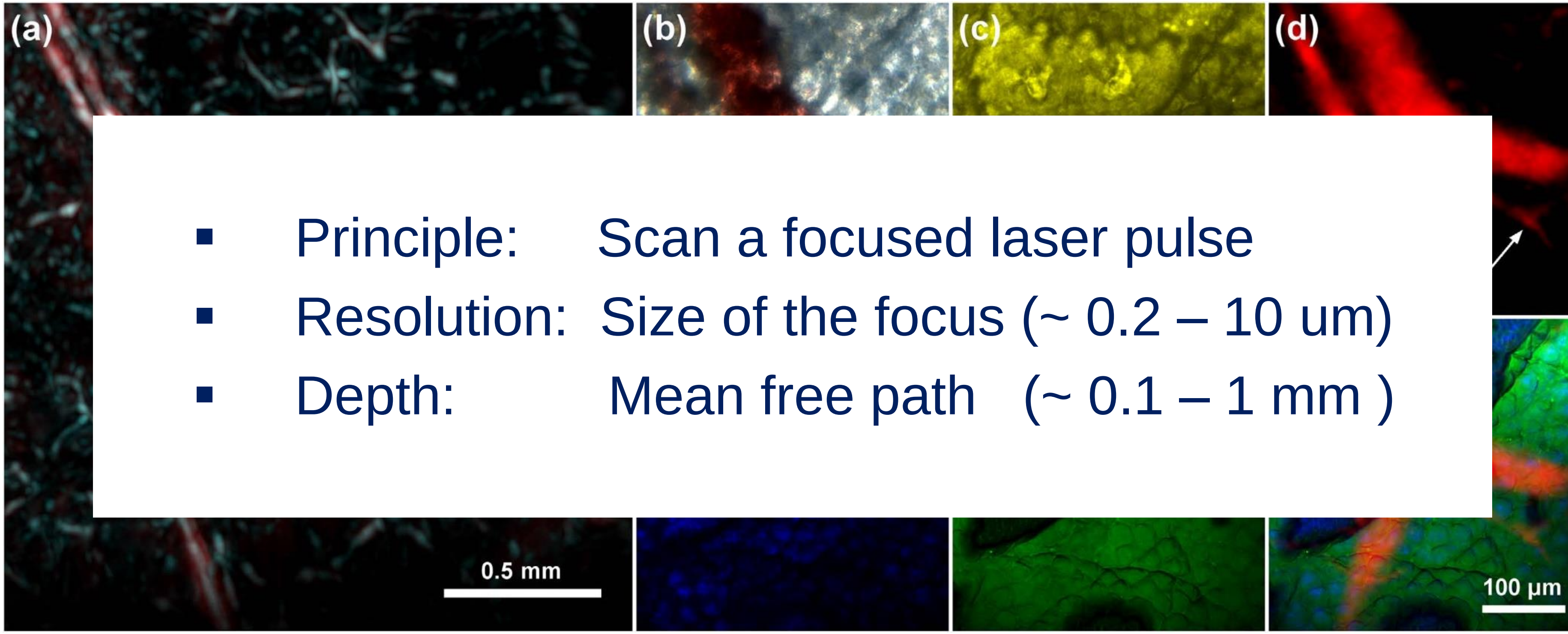


- **Nanophotonic** ***More Control!***
  - Active, focusing, filtering
  - Super, hyper, meta lens



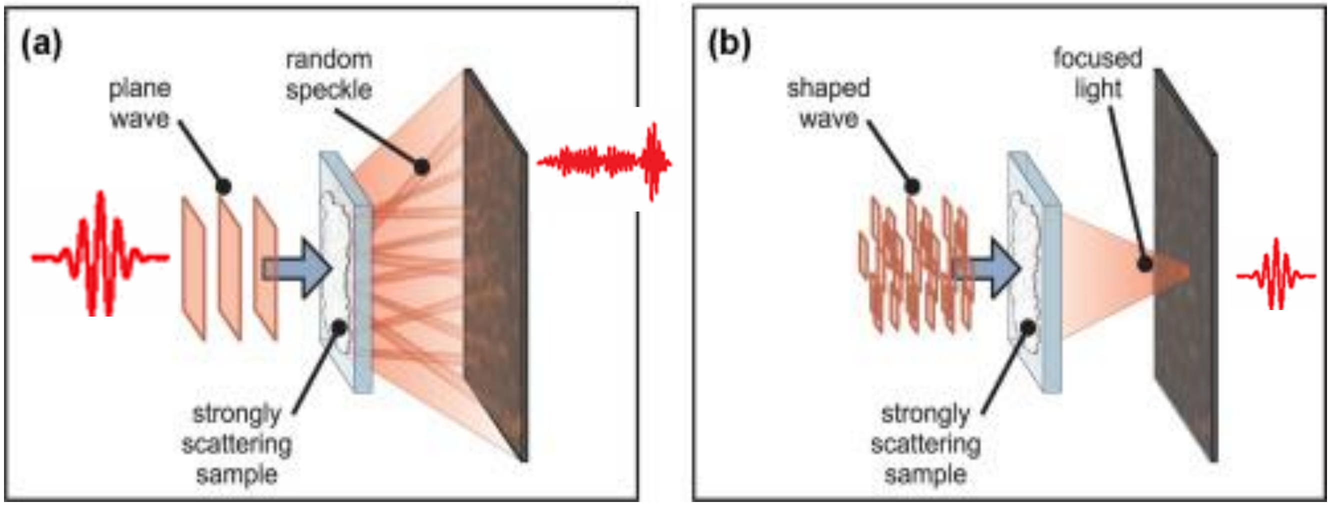
- **Natural** ***More Control!***
  - Omnipresent, random, light scattering
  - Thin slicing *ex-vivo,* other waves

Optical bioimaging – label free



- Principle: Scan a focused laser pulse
- Resolution: Size of the focus (~ 0.2 – 10 um)
- Depth: Mean free path (~ 0.1 – 1 mm)

Bypassing diffusion (space – time)



- **Acoustics**

  M. Fink, IEEE (1992)

  A. Derode, et al, PRL (1995)

- **Microwave**

  G. Lerosey, et al, PRL (2004)

  G. Lerosey, et al, Science (2007)

- **Optics** (monochromatic)

  S. M. Popoff, et al, PRL 2010

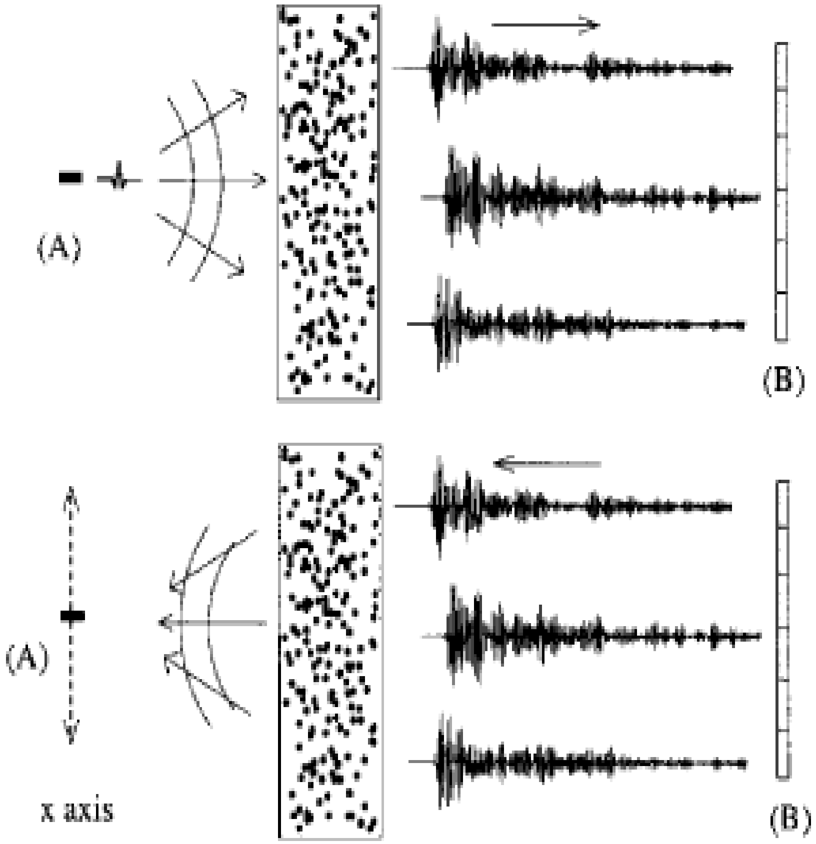
- **Optics** (pulsed)

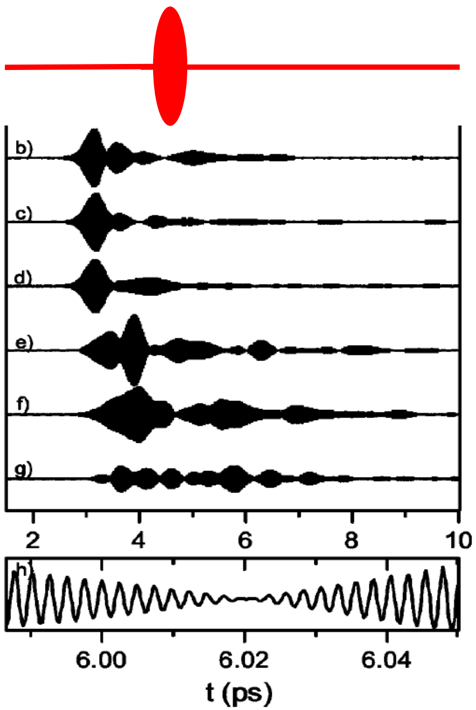
  D. J. McCabe, et al, Nat Com (2011)

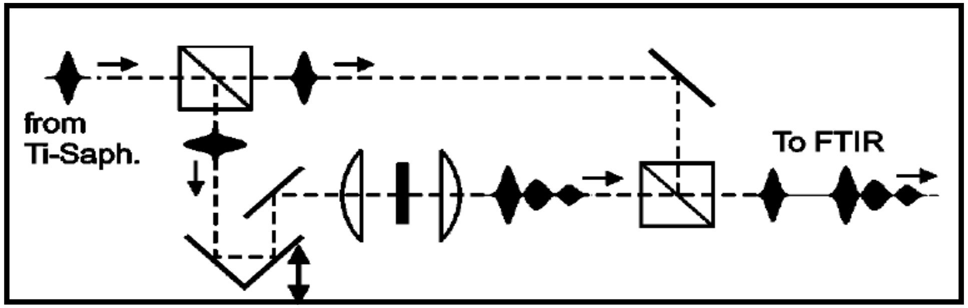
  J. Aulbach, et al, PRL (2011)

  O. Katz, et al, Nat Photon (2011)

Acoustics to optics



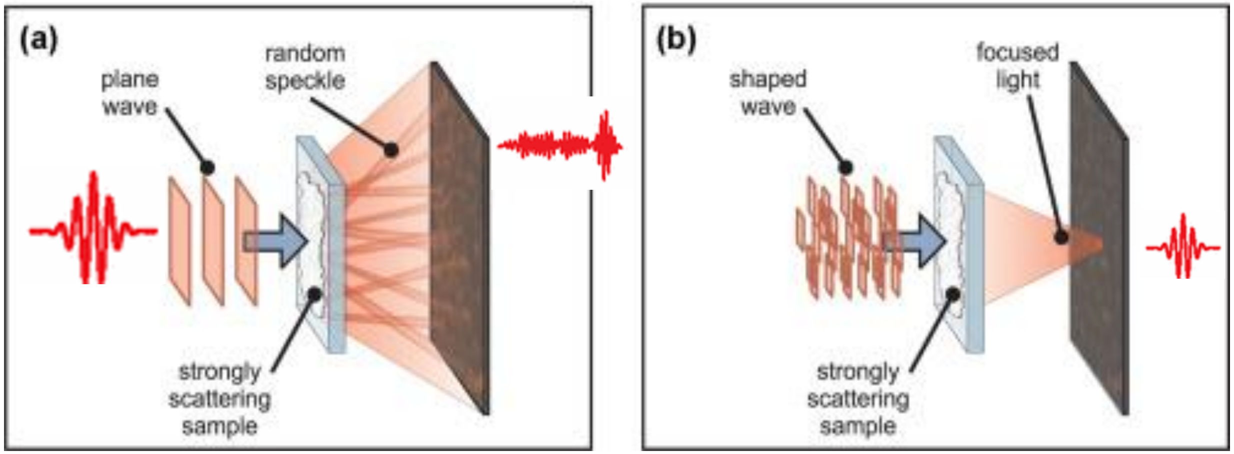


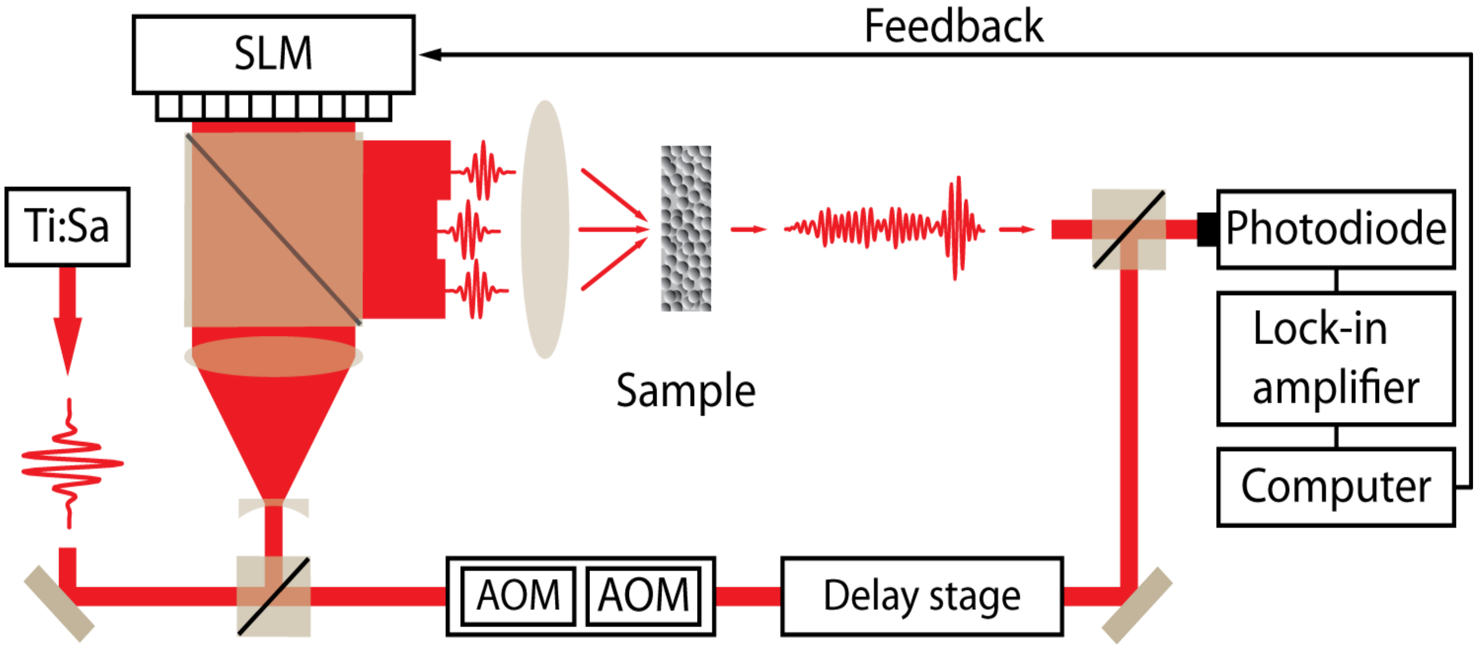


Fink, et al. Rep. Prog. Phys. (2000)

Johnson, et al. Phys. Rev. E (2003)

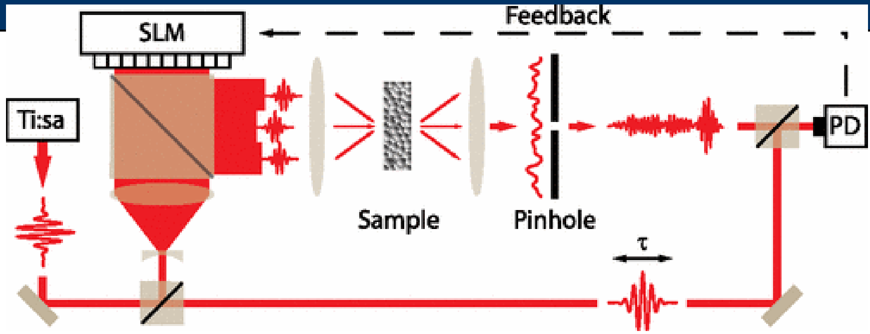
Bypassing diffusion (space – time)

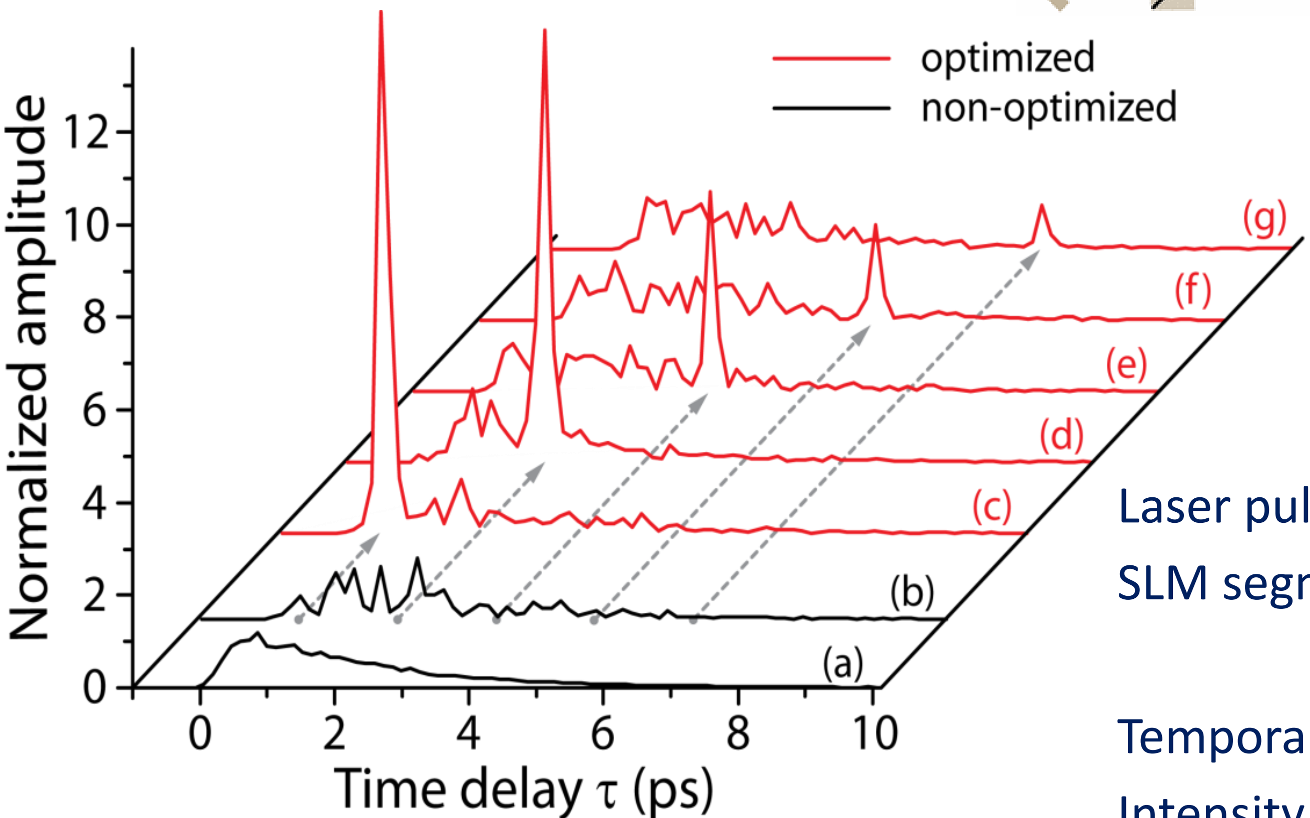




Aulbach, Gjonaj, et al, Phys. Rev. Lett. (2011)

Time focusing



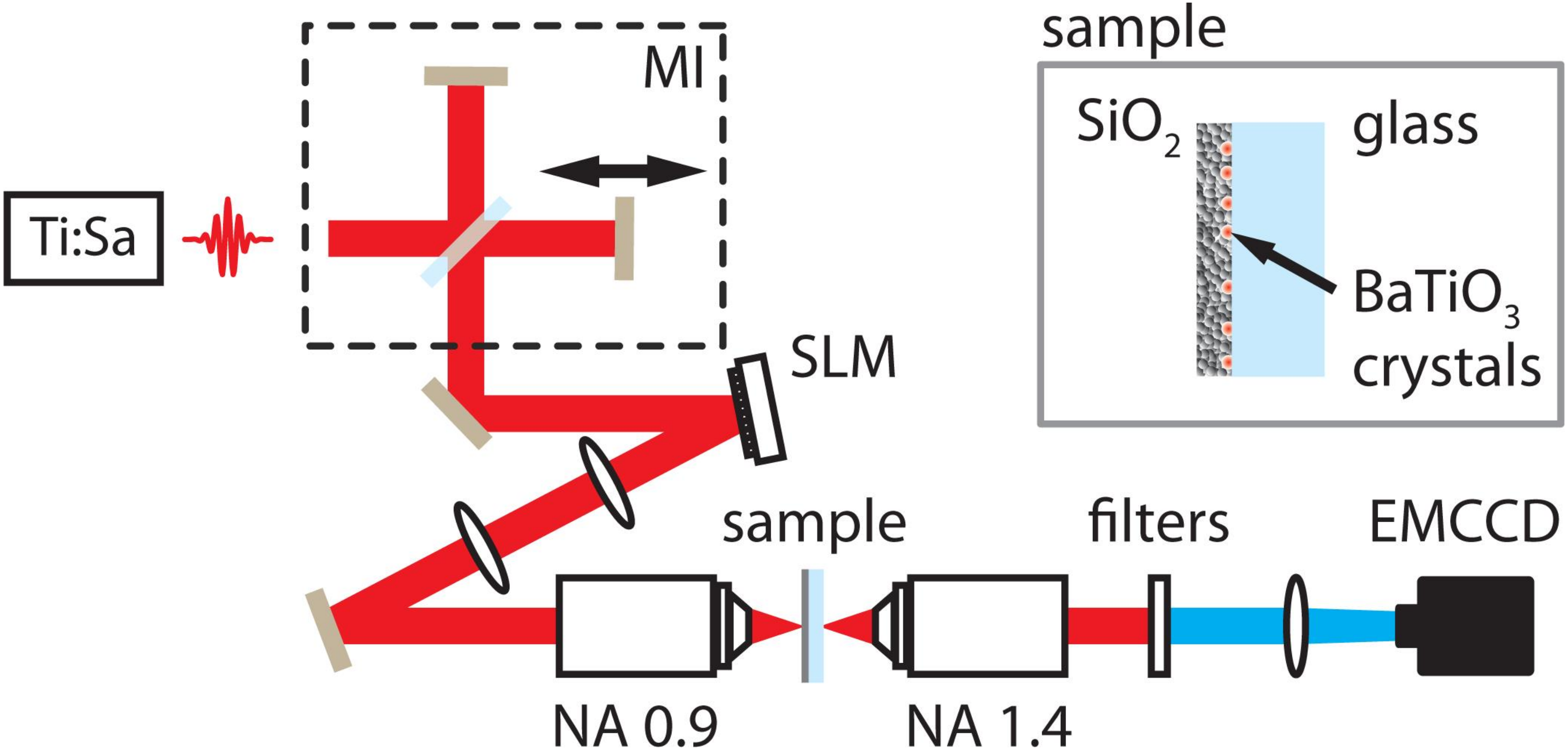


Laser pulse	~ 64 fs
SLM segmentation N	~ 300
Temporal focusing	~ 115 fs
Intensity enhancement	~ 10^2 - 10^3

Aulbach, Gjonaj, et al, Phys. Rev. Lett. (2011)

Space-time addressing of targets

Second Harmonic particles (size 200 nm)

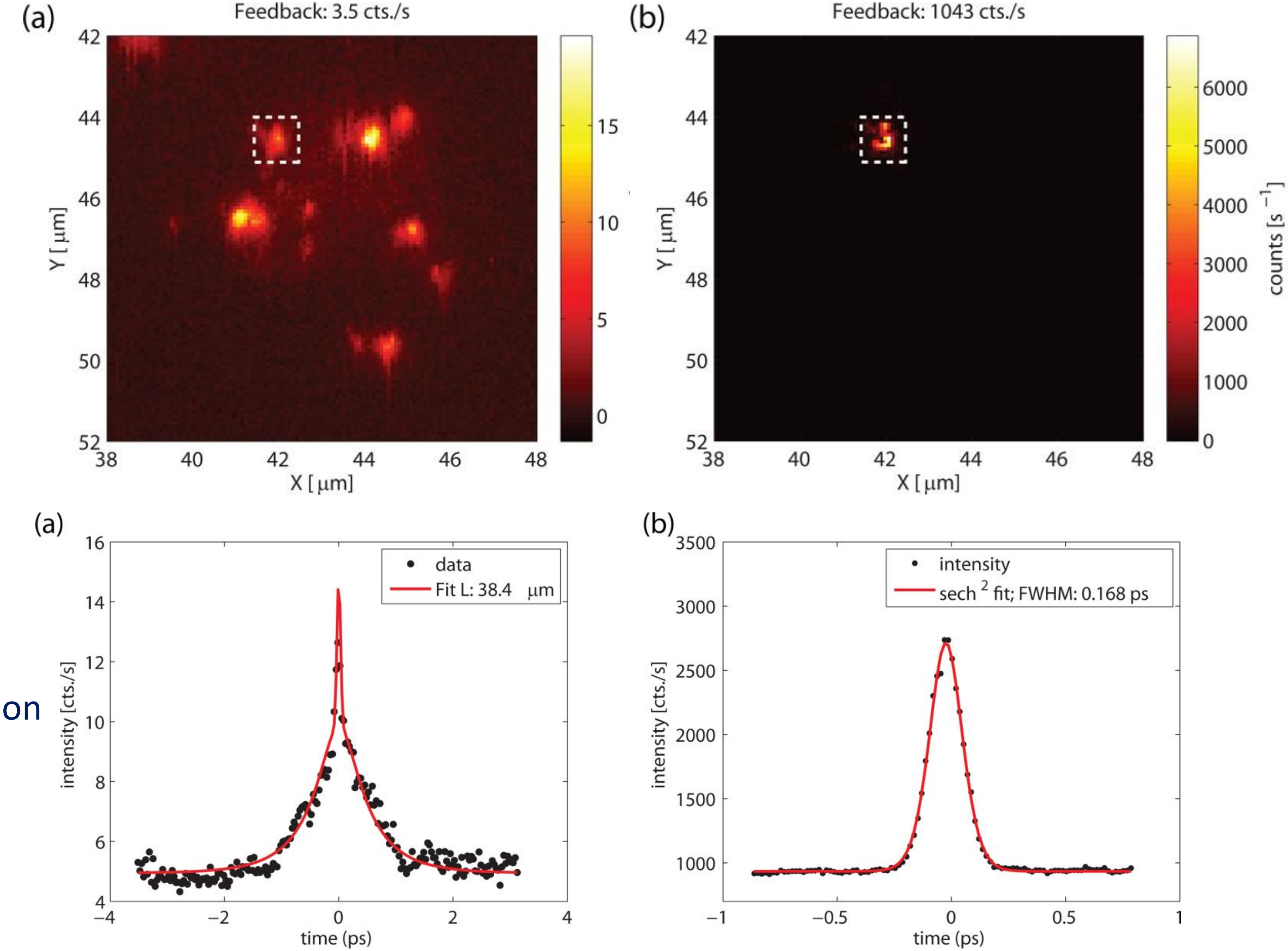


Aulbach, Gjonaj, et al, Opt. Exp. (2012)

Space-time focusing

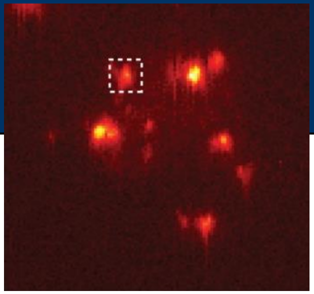
SH images (@ 2ω)

Autocorrelation (@ 2ω)



Aulbach, Gjonaj, et al, Opt. Exp. (2012)

Reproducibility



Part. #	τ_{pulse}(fs)	η_{exp}	η_{model}	η_{cw}
1	110	$2.5 \cdot 10^2$	$3.1 \cdot 10^2$	$1.6 \cdot 10^4$
2	102	$0.7 \cdot 10^2$	$3.2 \cdot 10^2$	$1.7 \cdot 10^4$
3	111	$2.7 \cdot 10^2$	$2.7 \cdot 10^2$	$1.4 \cdot 10^4$
4	104	$0.7 \cdot 10^2$	$2.9 \cdot 10^2$	$1.5 \cdot 10^4$
5	109	$3.0 \cdot 10^2$	$3.8 \cdot 10^2$	$2.0 \cdot 10^4$
6	109	$5.5 \cdot 10^2$	$6.5 \cdot 10^2$	$2.4 \cdot 10^4$

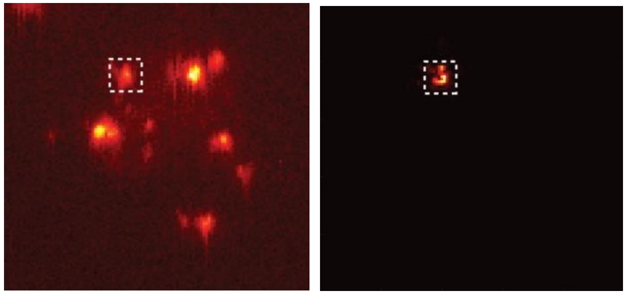
The enhancement, η, depends on the SLM segmentation.

We contained the SLM segmentation to N = 800,
because above it (N > 1000) the particles are burned and destroyed

Biomedical opportunities

Depth ~ **10 - 100** mean free paths

Tissue equivalent **0.1 - 5 cm**



- ❑ **Can we burn inside?**

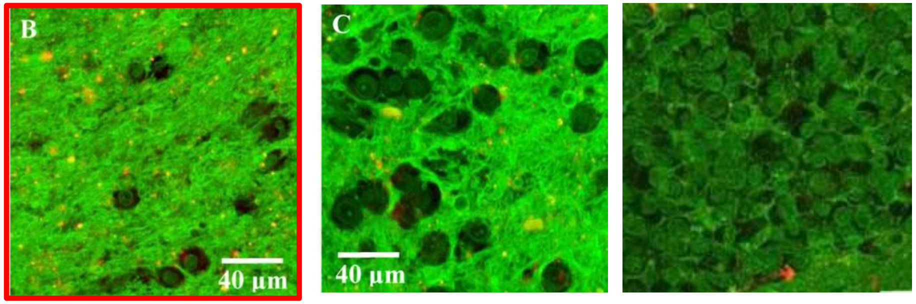
  Nanoparticle labelling ?

- ❑ **Can we image inside (THG)?**

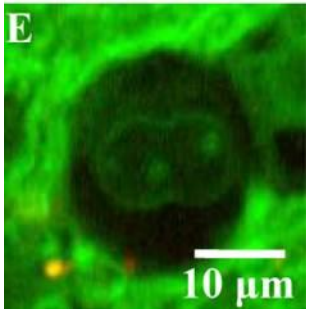
  Focusing and memory effect?

Human brain tumour (dark)

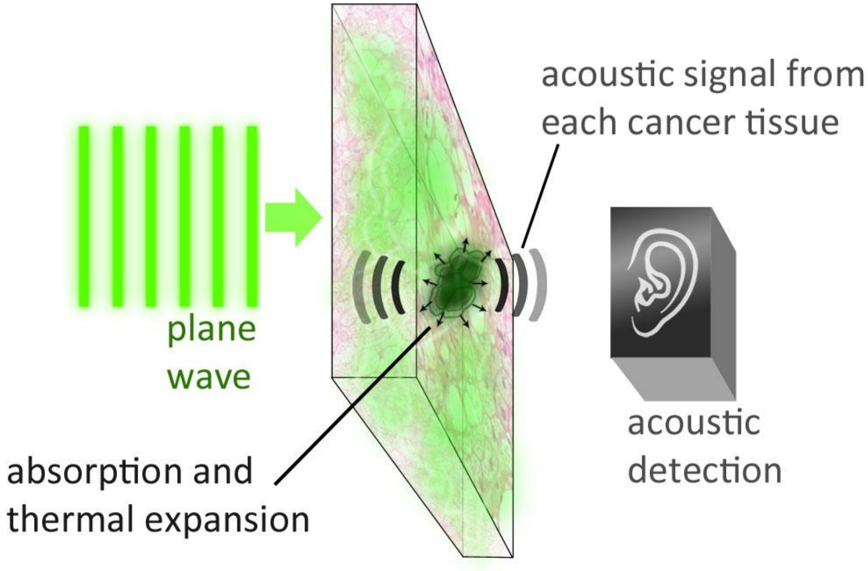
Intra-operational THG image (40 mW)



- ❑ Intra-operational (in depth)
  - High tumour density: CUT MORE
  - Low tumour density: CLOSE UP
- ❑ Early stage (in depth)
  - Degeneration: YES/NO



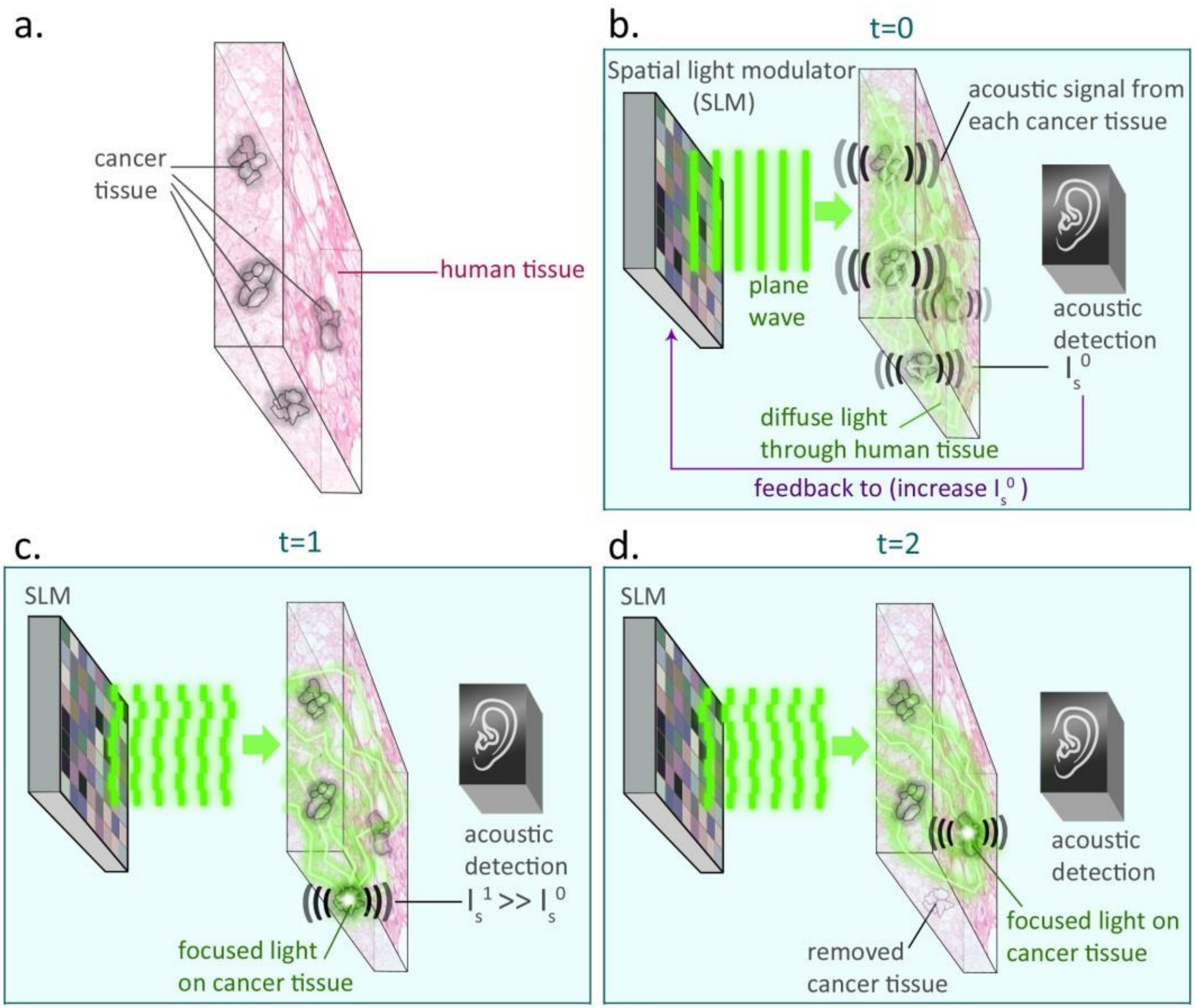
The right feedback



- **Challenges/requisitions:**
  - Diffusion of light by tissue
  - Local power delivery
  - Specificity – tumours only

  - Photoacoustic contrast
    Multi-sensorial (light, sound)
    Single detector (image-free)
    Only optical diffusion

Ant-burning of tumours



Therapy, imaging & sensing

- **Photoacoustics space-time focusing:**
  - Contrast agents: Hemoglobin – brain, eye, breast
    Melanin – skin, lymph nodes, circulating tumor cells
    External – dyes, plasmonic particles
  - Imaging : SHG, **THG**, (memory effect - high res, limited range)
  - Sensing: Oxygen saturation of Hemoglobin (sO_2), temperature

One case of success is sufficient!

Conclusions

- **Generic**
  - Microscopy is important and is challenging
  - ‘SIM is the future’ – *Betzig said.*
- **Specific to this work**
  - High index materials (n>3) are great for SIM
  - A double Moire illumination is the way to go
  - 5x better resolution (down to 45nm)
  - Relatively simple and fast
  - The required control is feasible