MICRO-523: Optical Detectors

Week Three: Optical Methods – Selected Examples

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Based on MICRO-523, P.-A. Besse, 2023

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EPFL

Outline

Emphasis of lecture

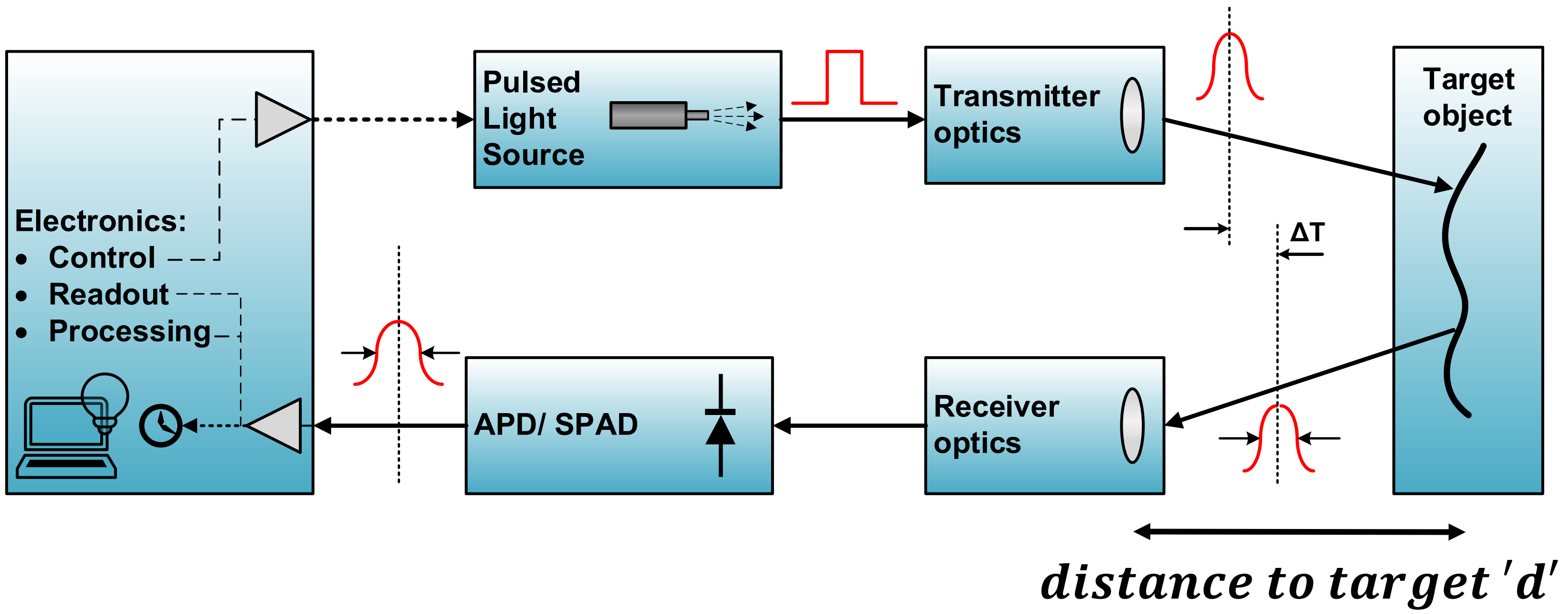
1. Think of the full chain and include the illuminator and back-end processing as well.

   See also Week 1 slide “Take-home Messages/W1-2: Components of an optical system”

2. Choose detector as function of measurement set-up.

3. Explore new applications enabled by enhanced detector features (e.g. single-photon detector arrays).

3.1 Time-of-Flight Measurements



Common applications

- **Proximity sensing**
- **Range-finding**
- **3D imaging in scanning or flash mode**

Ambient Light

$$d = \frac{c\Delta T}{2}, \text{ c is speed of light}$$

D-TOF system: TOF is 'directly' measured

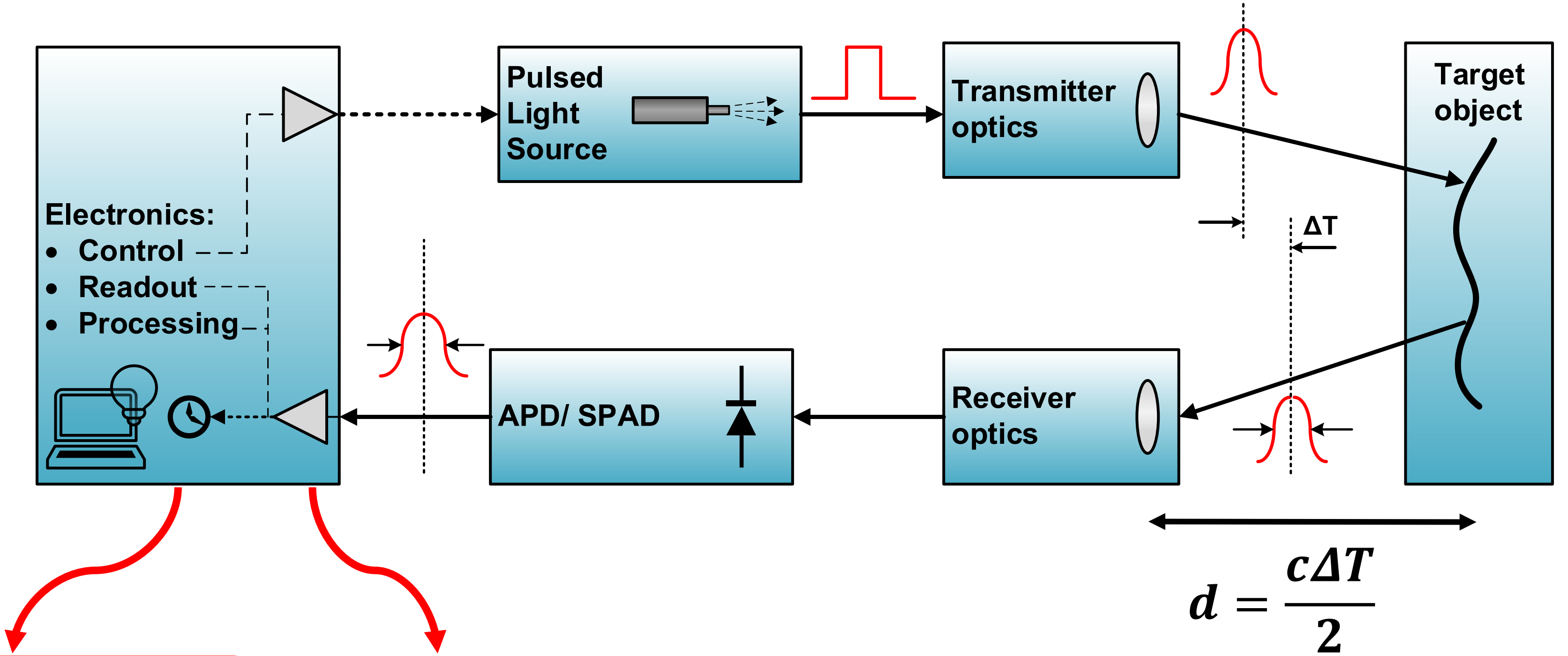
Usually: small # of back-reflected photons

ToF precision ➔ Averaging Example

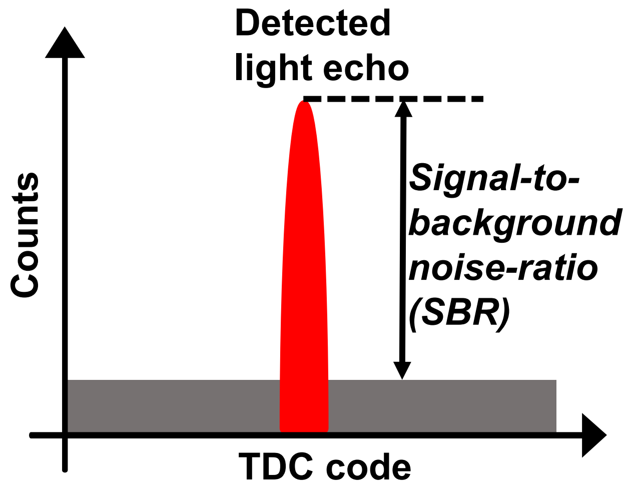
Δt=1ns → L=15 cm

Δt=1ps → L=0.15 mm

3.1 Time-of-Flight Measurements



$$d = \frac{c\Delta T}{2}$$



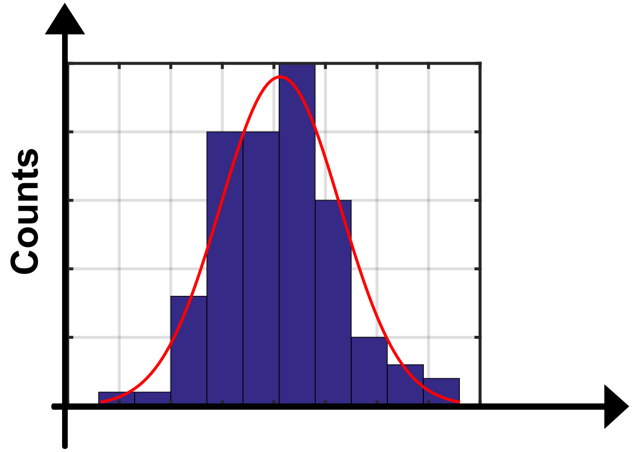
- time-to-amplitude converters (TACs)
- time-to-digital converters (TDCs)

Time-stamping circuits

- Transimpedance amplifier- comparators
- Avalanche quenching circuits

Typical front-end circuits

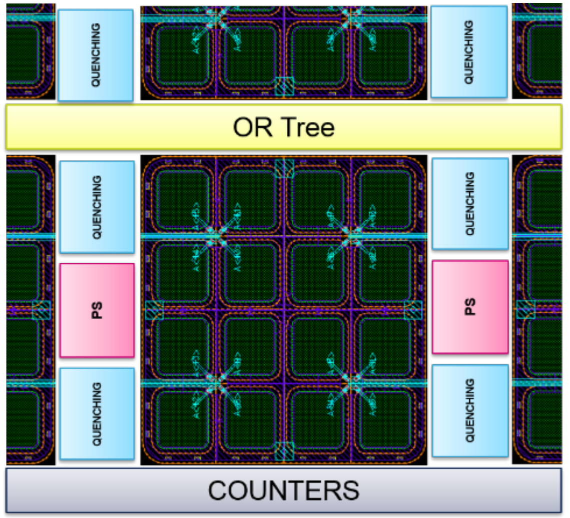
Histogram of time of arrival of reflected photons from target



Time-correlated single-photon counting (TCSPC)

3.1 Examples of Range Finders/Photon counters based on CMOS SPADs

Market "push"- available off-the-shelf

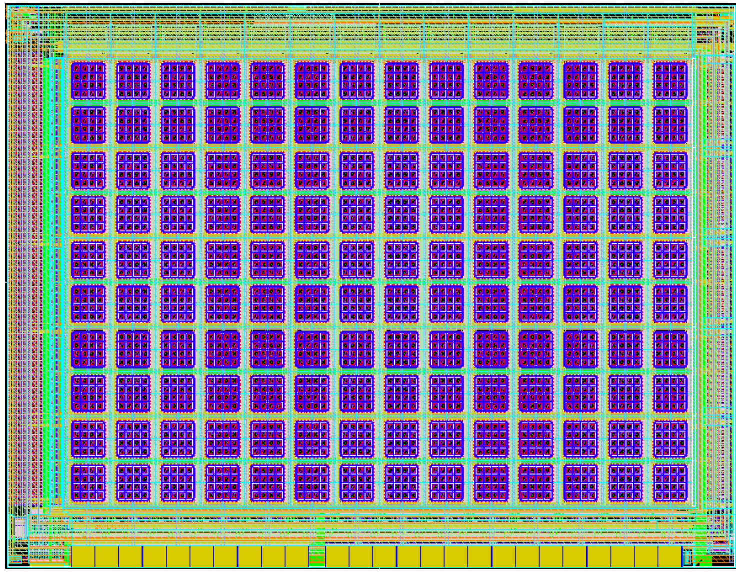


VL53L5, Compact Integrated Module

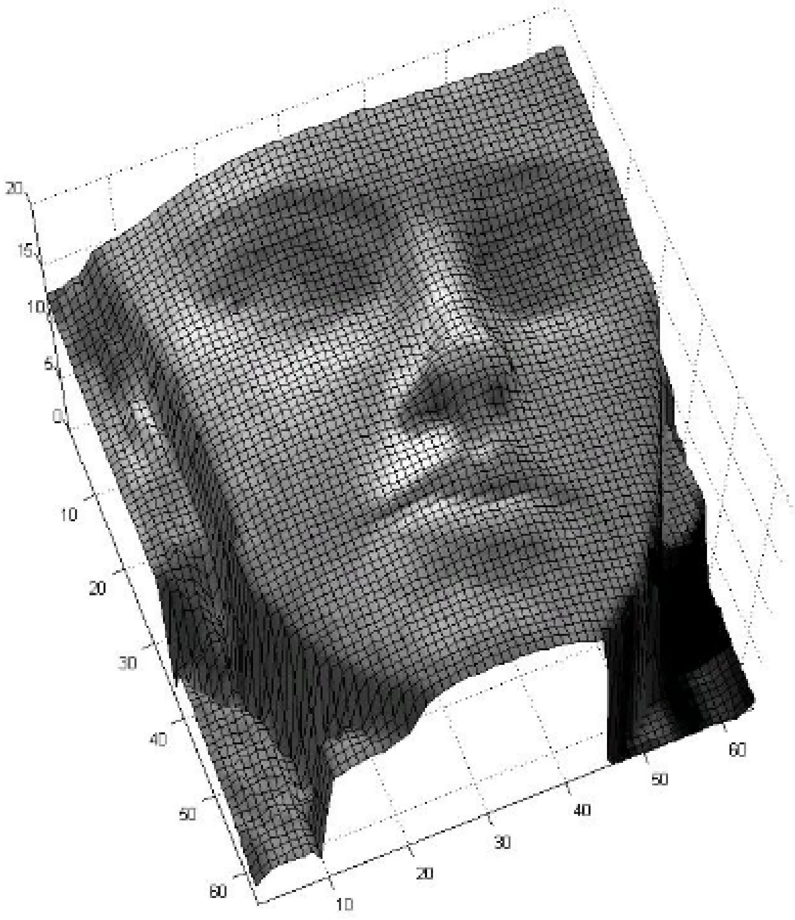
- Class 1 certified 940nm invisible VCSEL
- 61° diagonal, square FoV

Ranging Capabilities

- Up-to 64 (8x8) ranging zones
- Up-to 4m ranging per zone

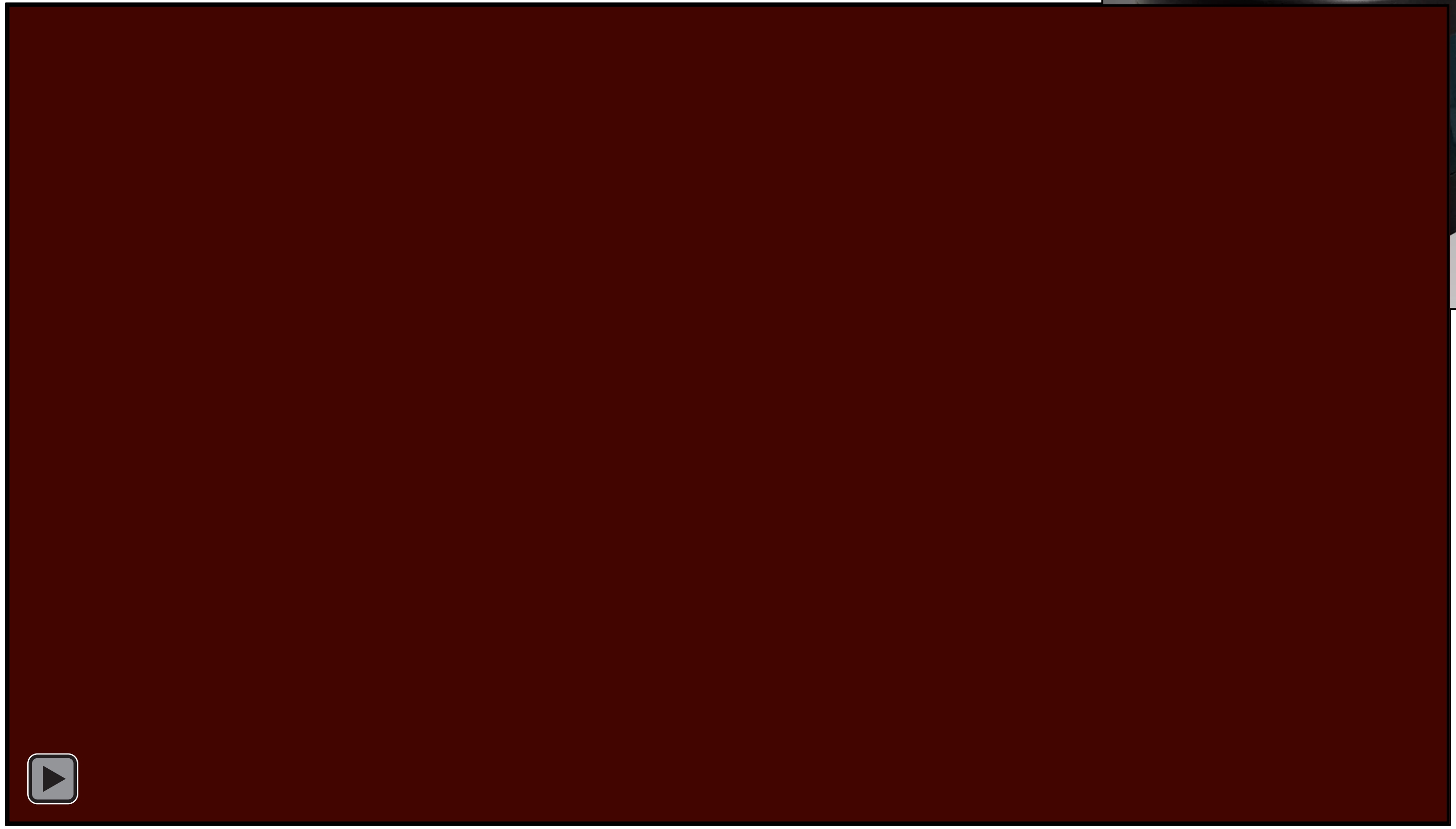


3.1 Examples of 3D-imagers



cm/mm level precision

Light Detection and Ranging



[G. Wetzstein, ISSW 2018]
[Velodyne, 2018, https://www.youtube.com/watch?v=KxWrWPpSE8I]

Outline

3.2.1 Lock-in Amplifier: Principle

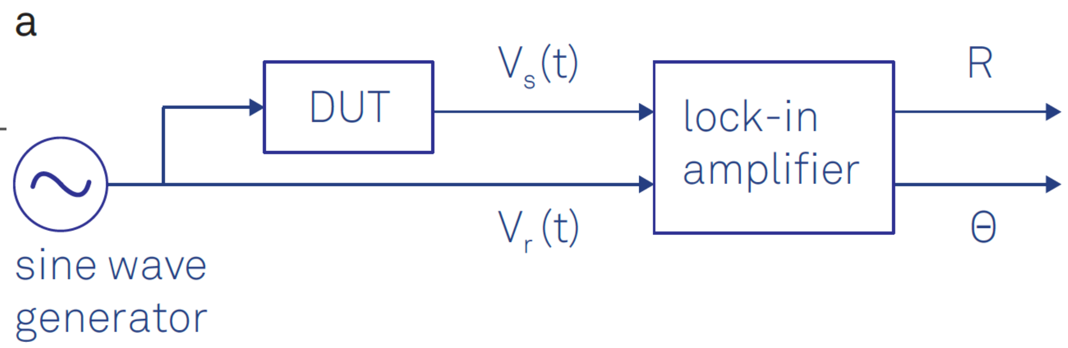
$$V_s(t) = R \cdot \cos(2\pi f_s t + \phi_s)\,, V_r(t) = \cos(2\pi f_r t)$$

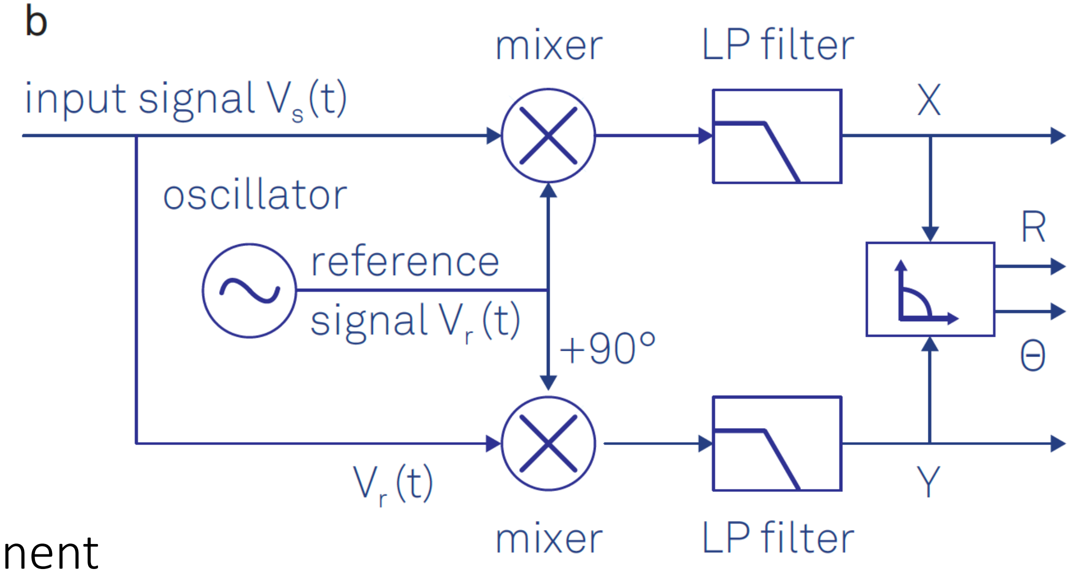
Mixing: $V_s(t) \cdot V_r(t)$

-> Two components at $(f_s\text{-}f_r)$ and $(f_s\text{+}f_r)$.

If $f_r\text{=}f_s$: $(f_s\text{-}f_r)$= 0 Hz and $(f_s\text{+}f_r)$=2f. -> DC component is measurement goal* (in-phase component, X), the 2f component can be cancelled with an appropriate low-pass filter

R, Θ_r calculated by transformation from Cartesian to Polar coords

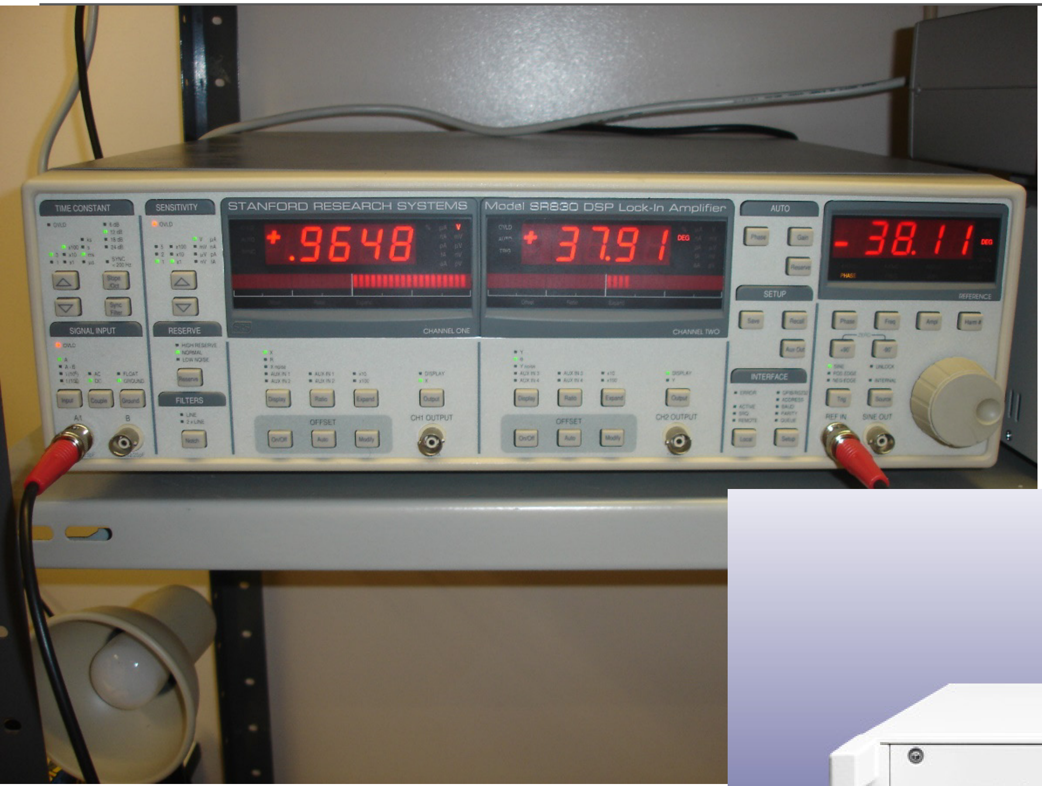




*contribution from any signal that is not at the same frequency as the reference signal is attenuated close to zero.

EN Wikipedia *Lock-in amplifier; Zurich Instruments Lock-in white paper*

3.2.1 Lock-in Amplifier: Examples

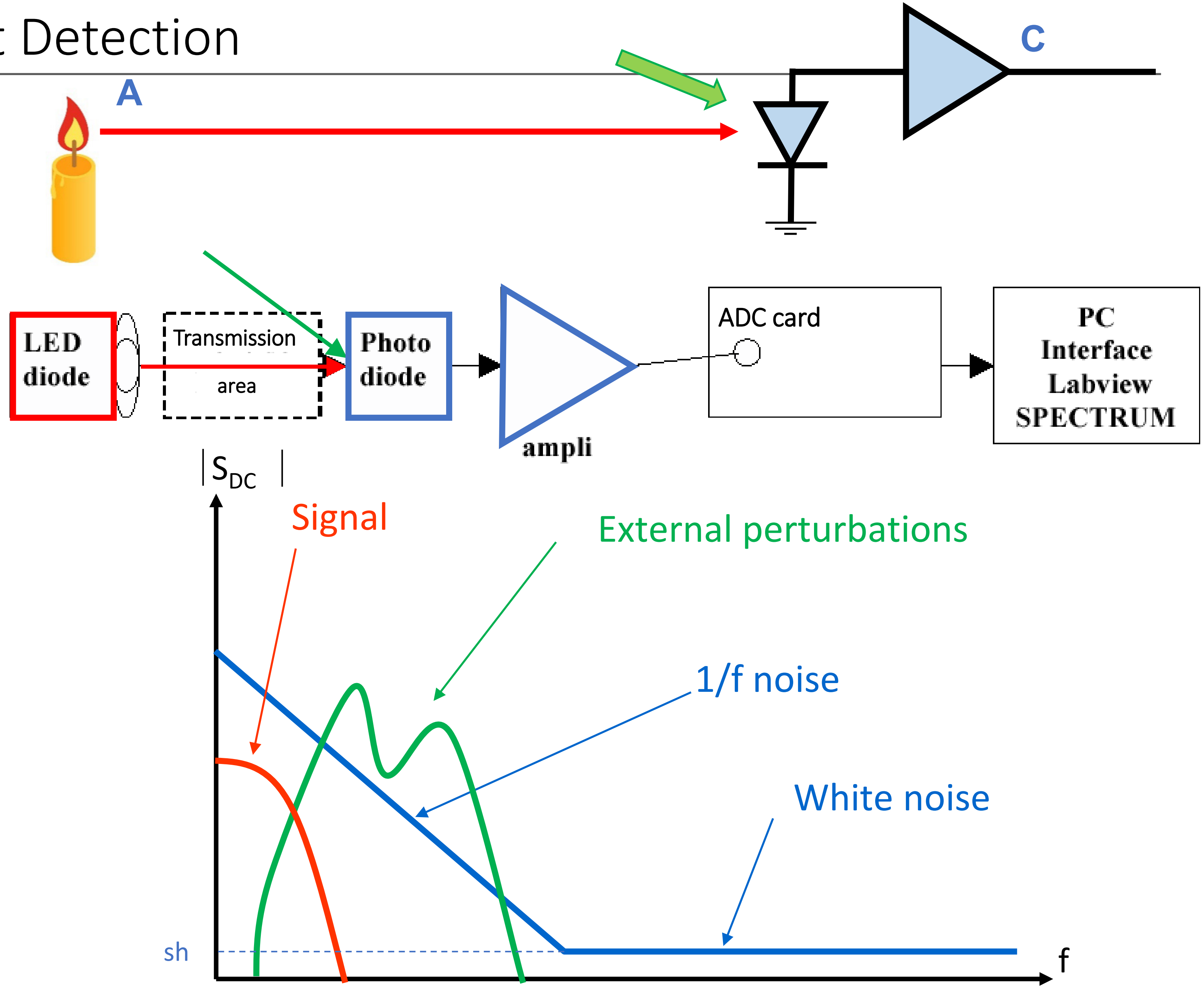


Stanford Research Instruments, Analog Lock-in
By Nuno Nogueira (Nmnogueira) - Self-made, CC BY-SA 2.5, https://en.wikipedia.org/w/index.php?curid=13431432

Zurich Instruments, Digital Lock-in

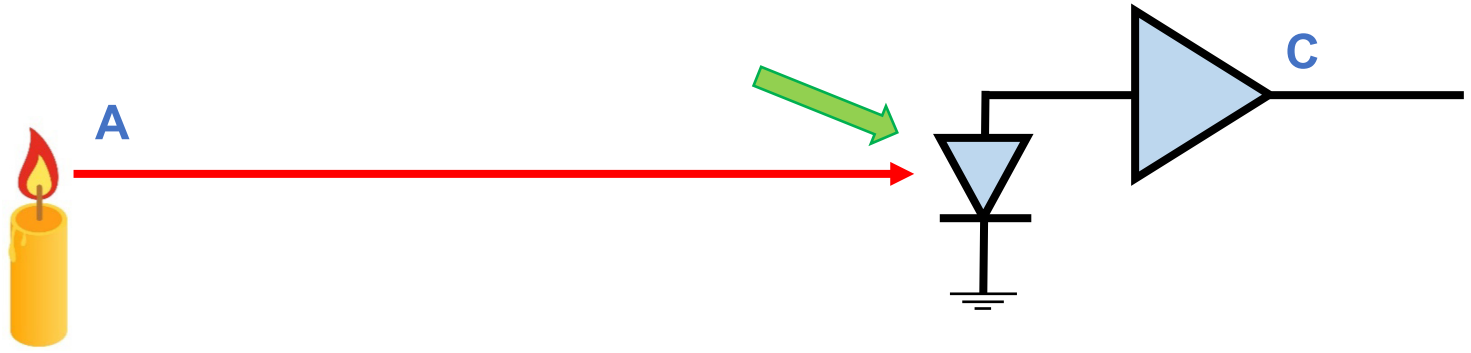
📖 EN Wikipedia *Lock-in amplifier*

3.2.2 Direct Detection

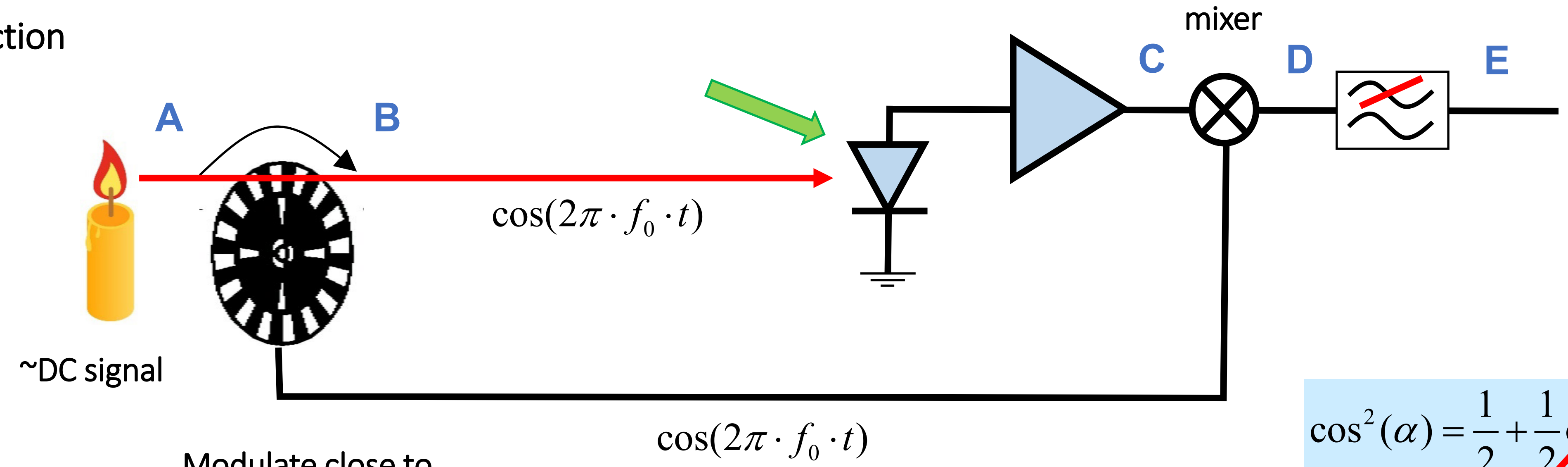


3.2.2 Direct vs. synchronous detection

Direct detection



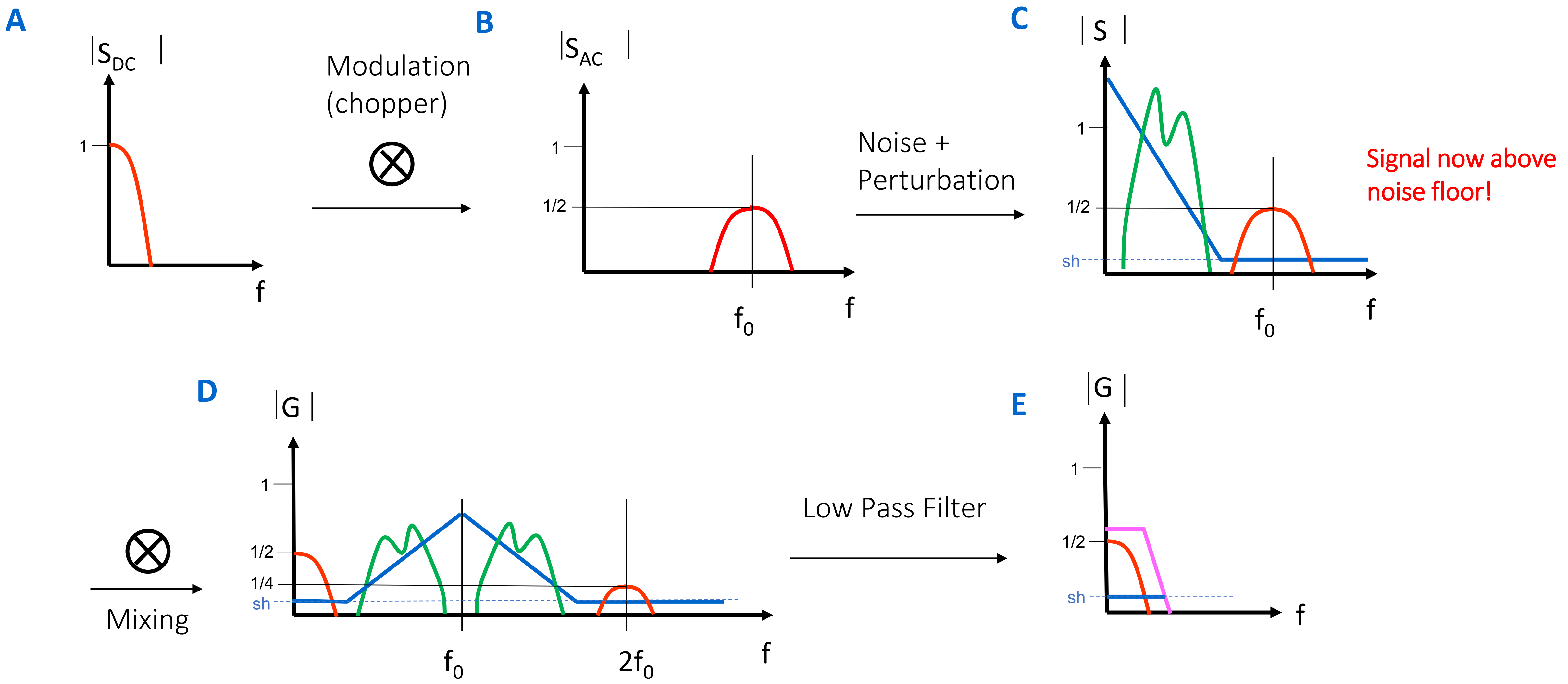
Synchronous detection



Modulate close to light source

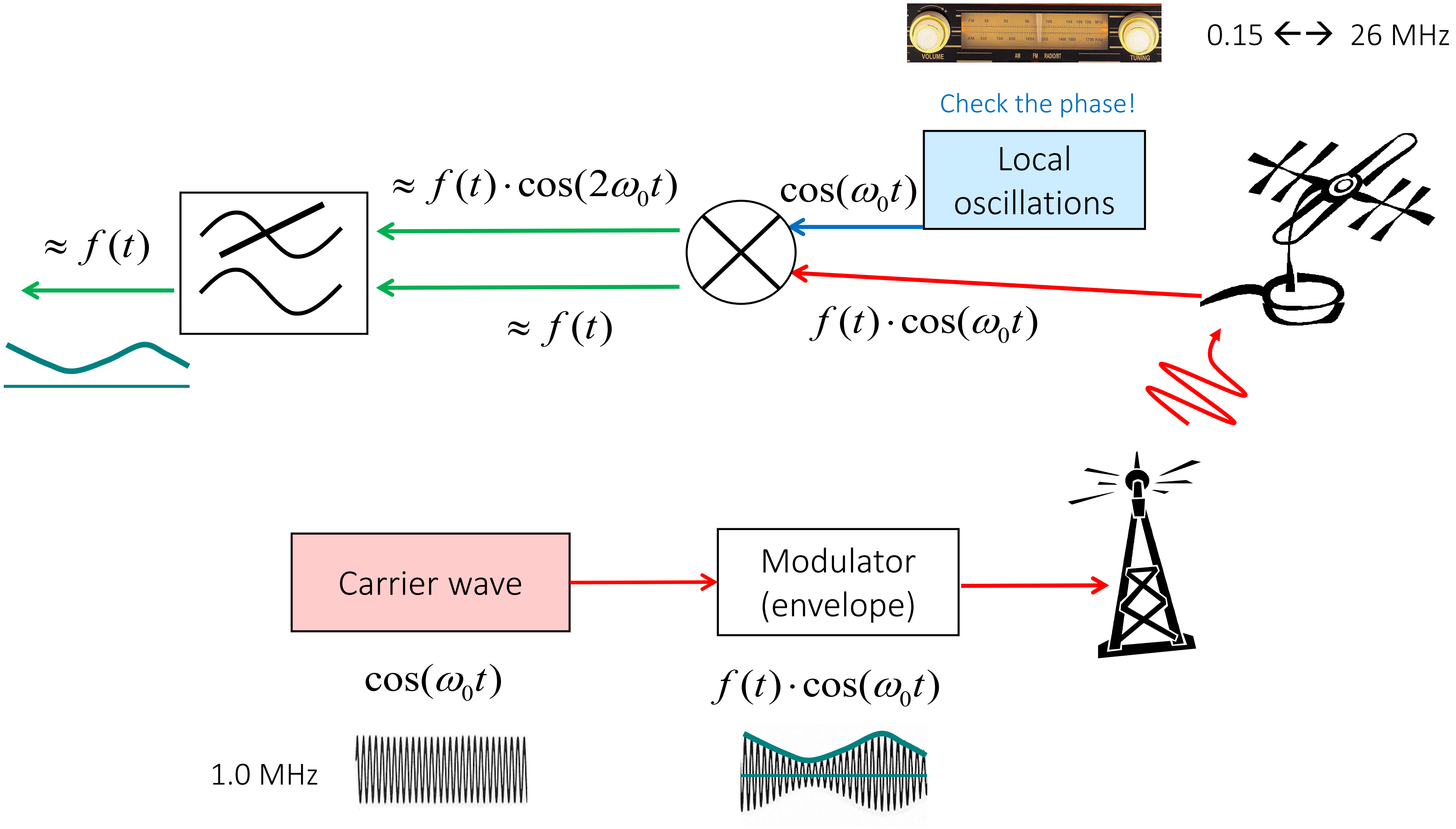
$$\cos^2(\alpha) = \frac{1}{2} + \frac{1}{2}\cos(2\alpha)$$

3.2.3 Synchronous Detection: Spectral Analysis (sinusoidal modulation)

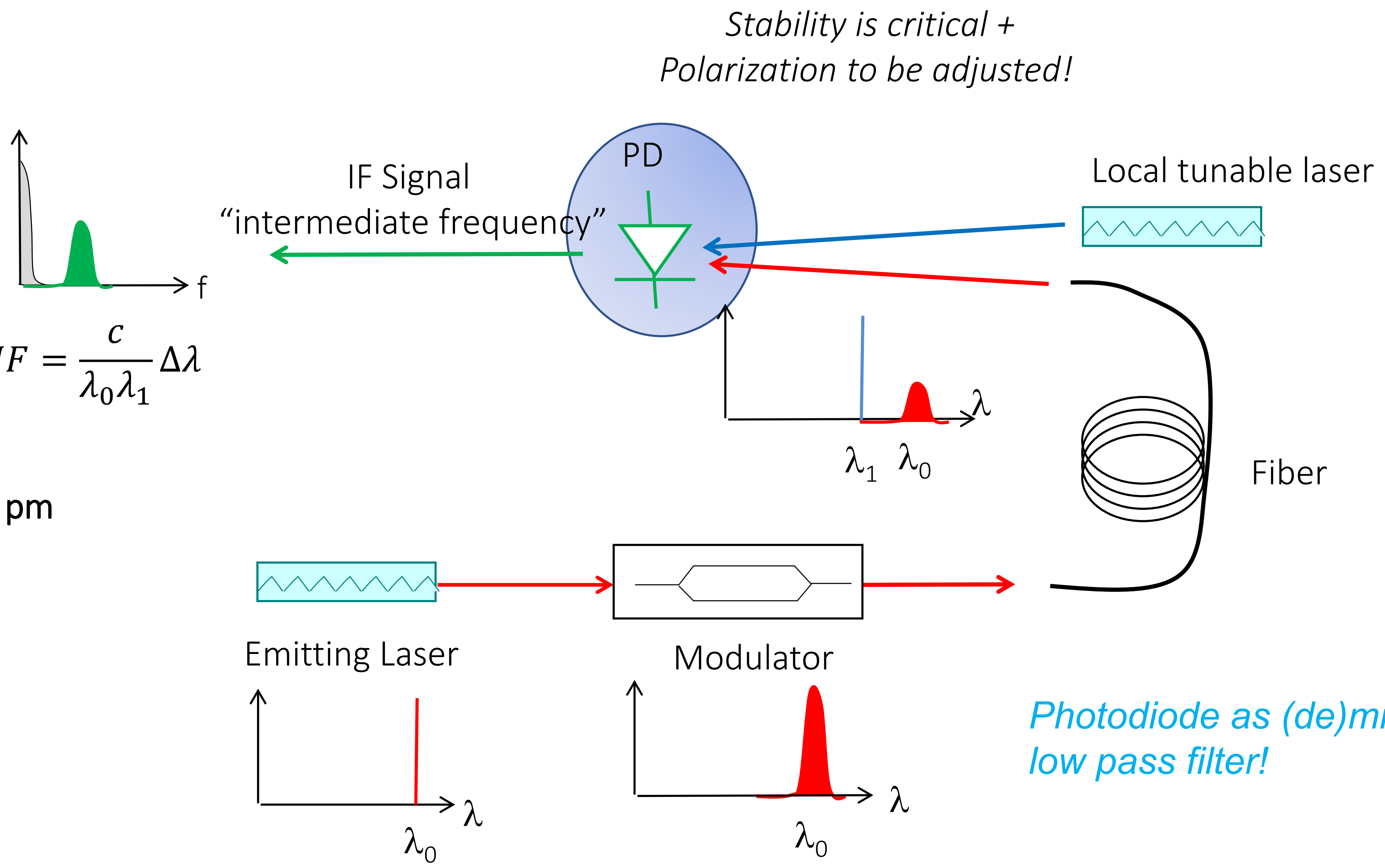


Outline

3.3 Electronics: AM Radio



3.3 Similar Method in Optics: Heterodyne Detection



$$IF = \frac{c}{\lambda_0 \lambda_1} \Delta\lambda$$

λ_0= 1 μm
1GHz → $\Delta\lambda$=3 pm

Photodiode as (de)mixer and low pass filter!

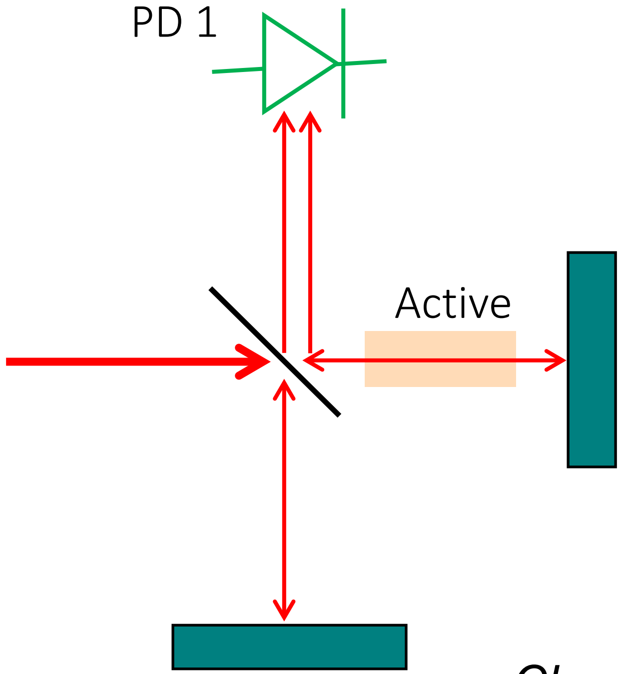
Outline

3.4 Interferometers: Homodyne detectors

Very long coherence length

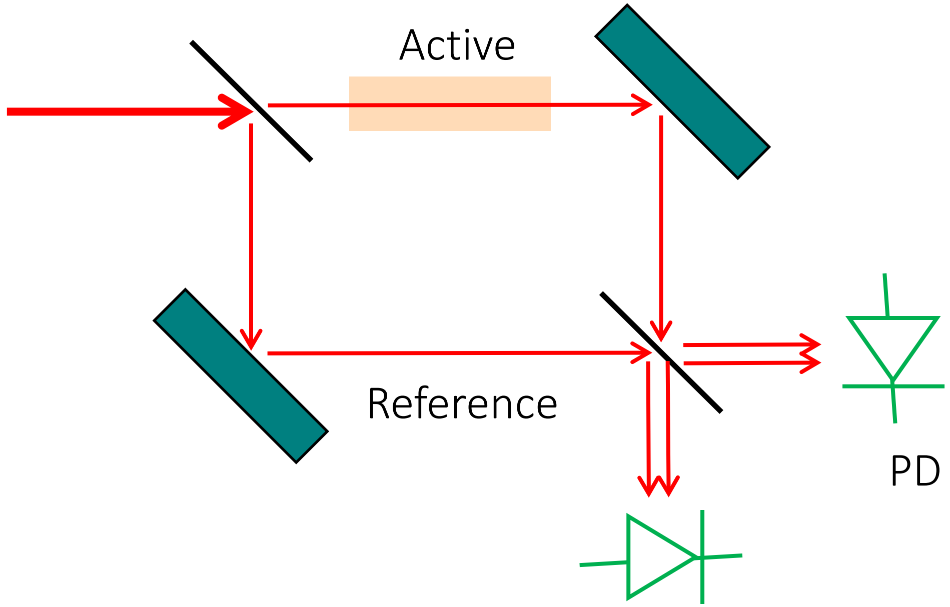
«Homodyne»

Michelson



Reference

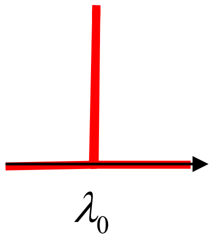
Mach-Zehnder



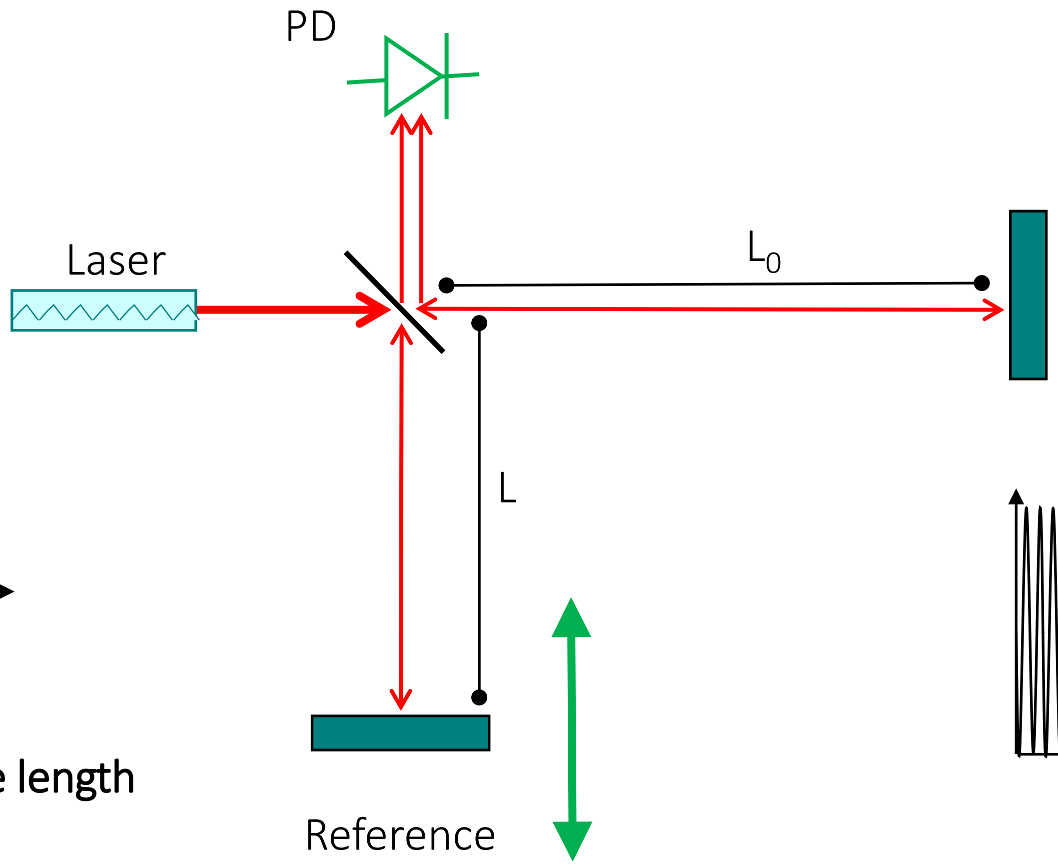
PD 1

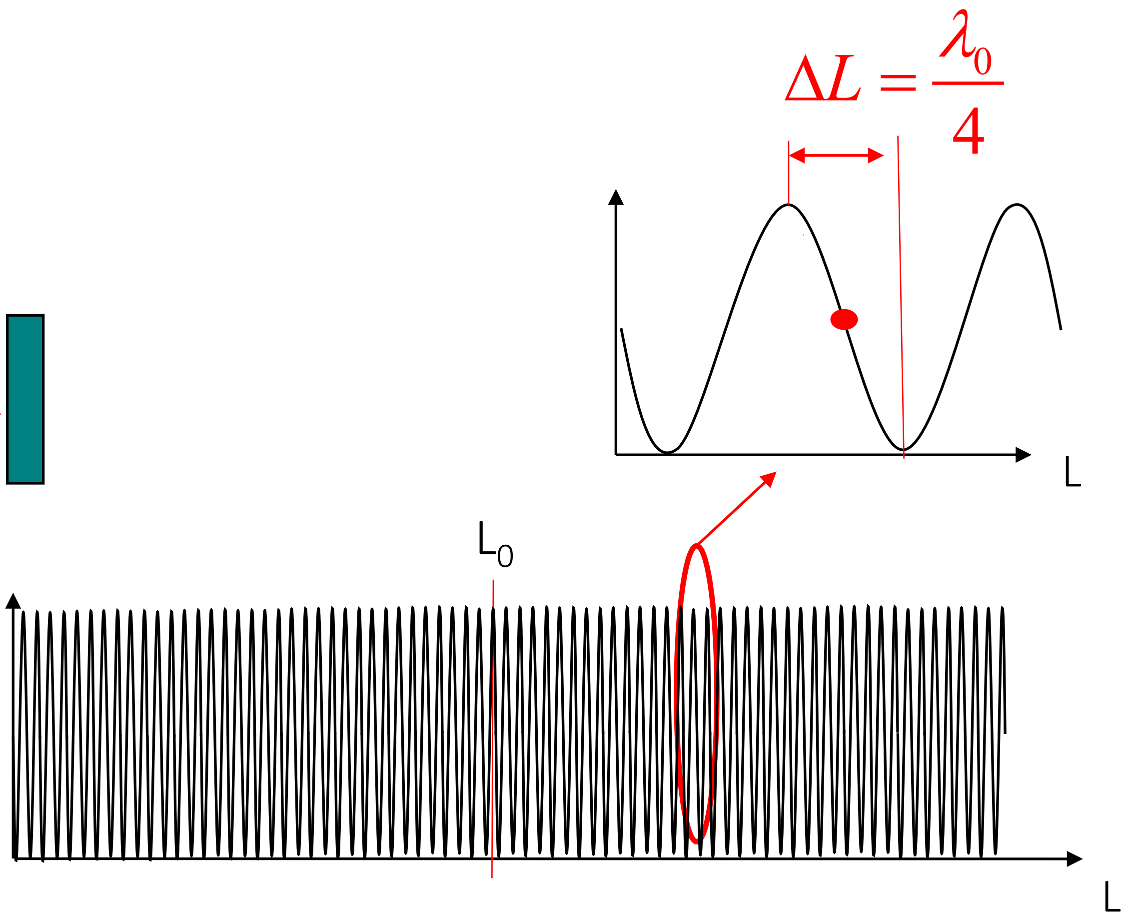
Change in refractive index (or change in length)
→ phase variation Δφ → sinusoidal intensity variations

3.4 Michelson Interferometer



Very long
coherence length



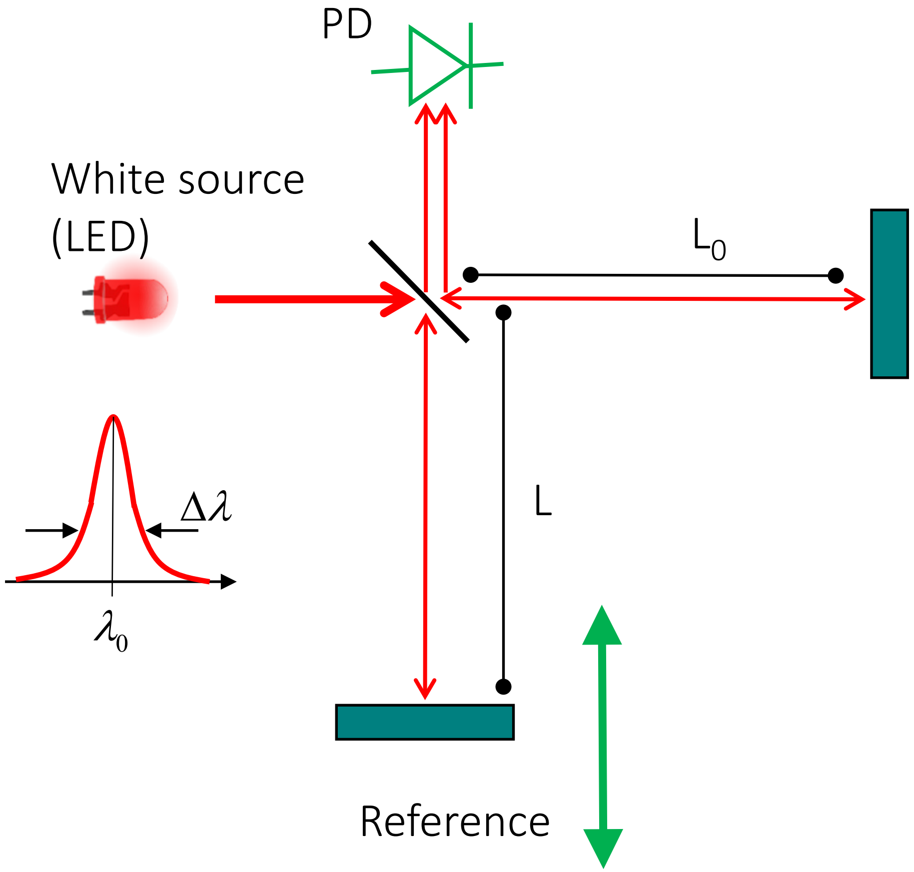


- Counting of interference fringes
- High resolution in a single fringe

Detection of very small ΔL (nm) possible!

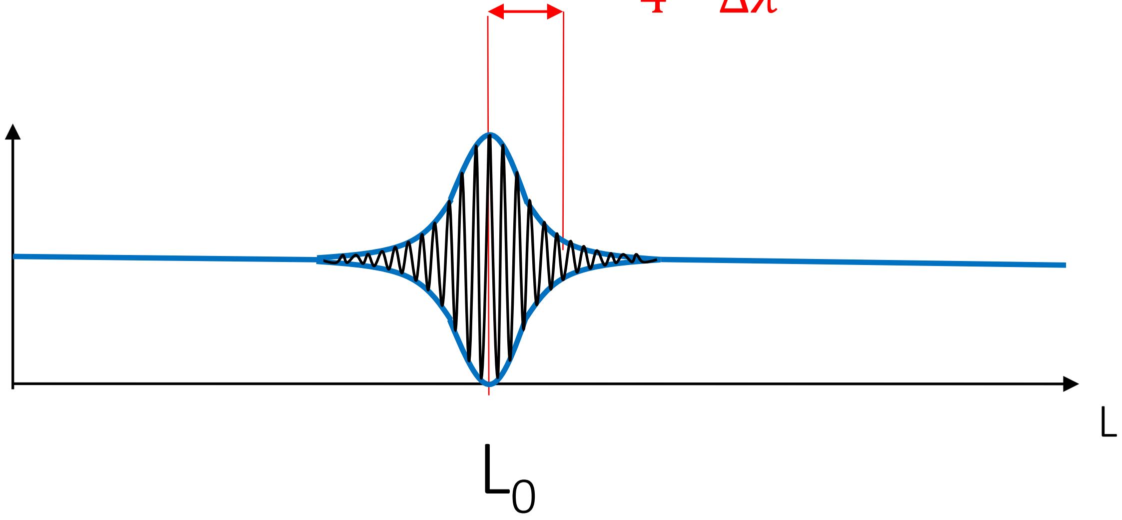
3.4 Optical Coherence Tomography (OCT)

Coherence time = time delay during which the light is still able to interfere with a delayed copy of itself



Low coherence source = large bandwidth → very short coherence length

Coherence length (/2): $\Delta L \cong \frac{\lambda_0}{4} \cdot \frac{\lambda_0}{\Delta\lambda}$

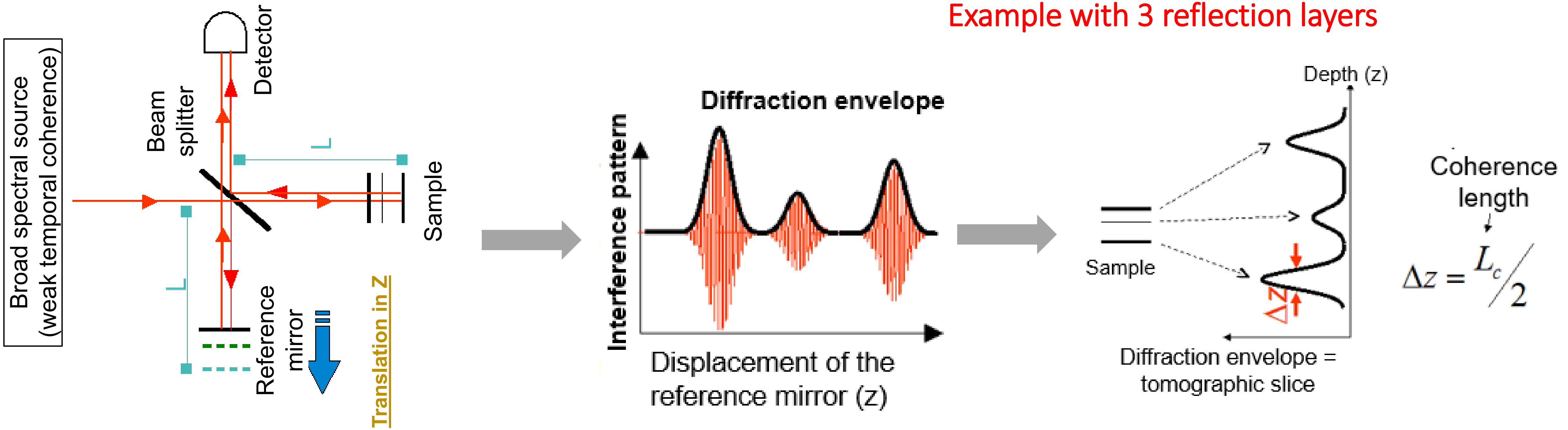


Envelope detection around L_0

3.4 Optical Coherence Tomography (OCT)

Very short coherence length

Example with 3 reflection layers



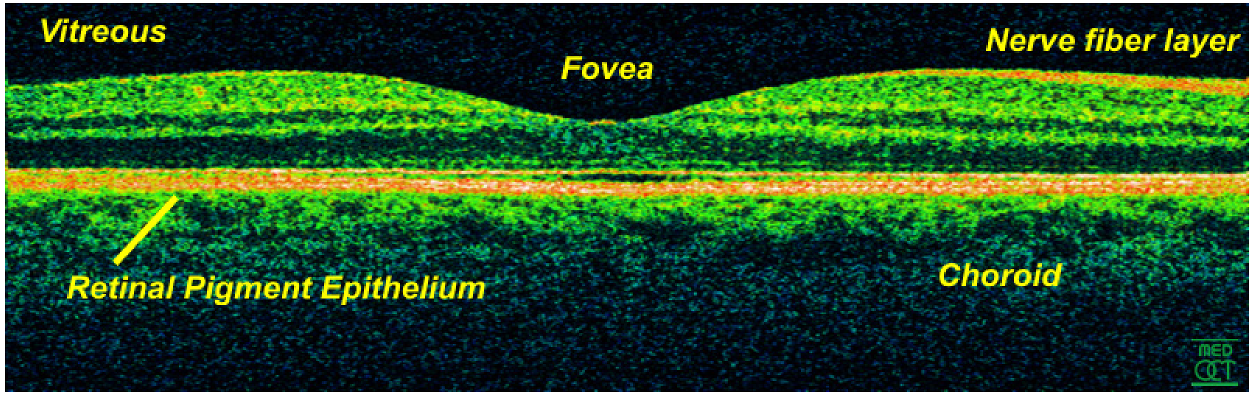
Time-domain OCT (scanning reference mirror)

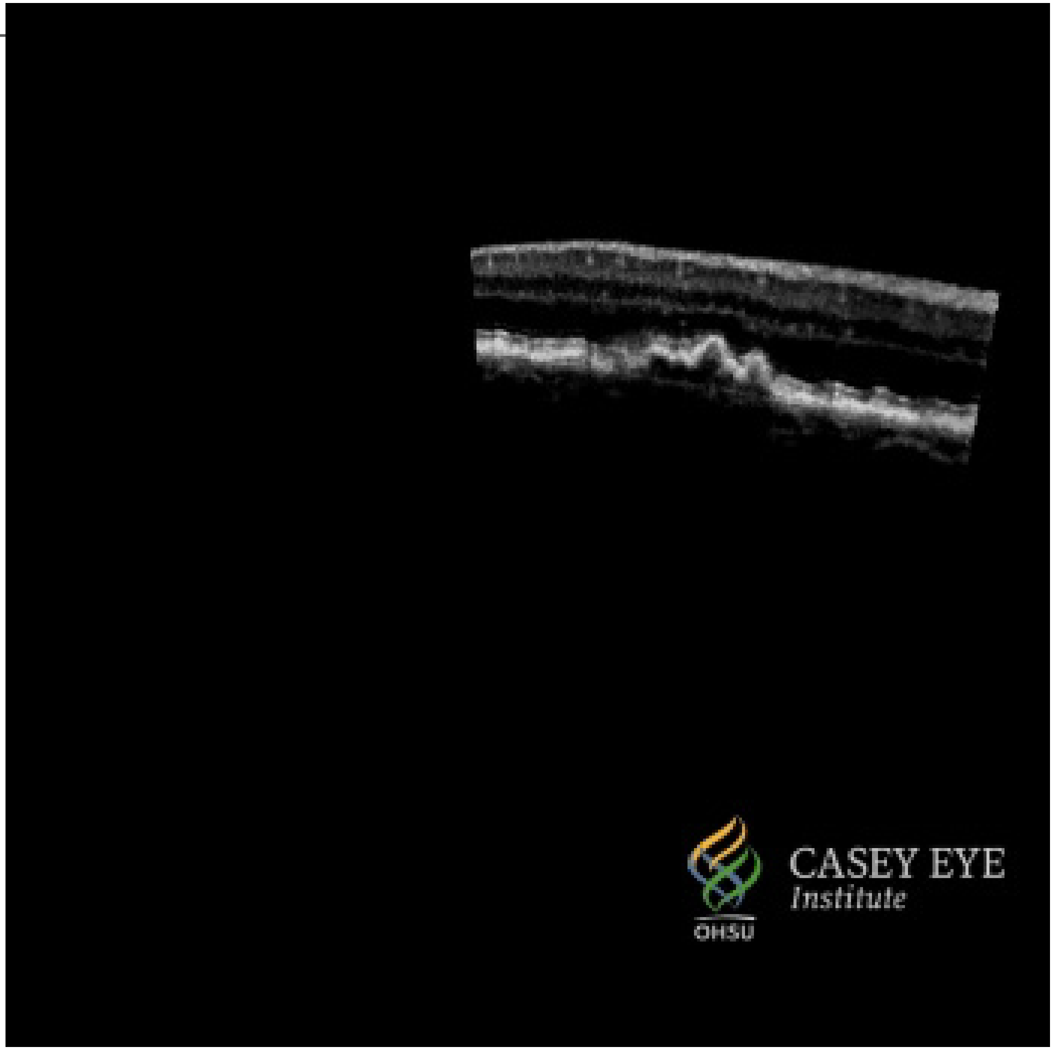
www.lesia.obspm.fr/Resultats-et-images.html

3.4 Optical Coherence Tomography (OCT)

ZEISS CIRRUS 6000 OCT

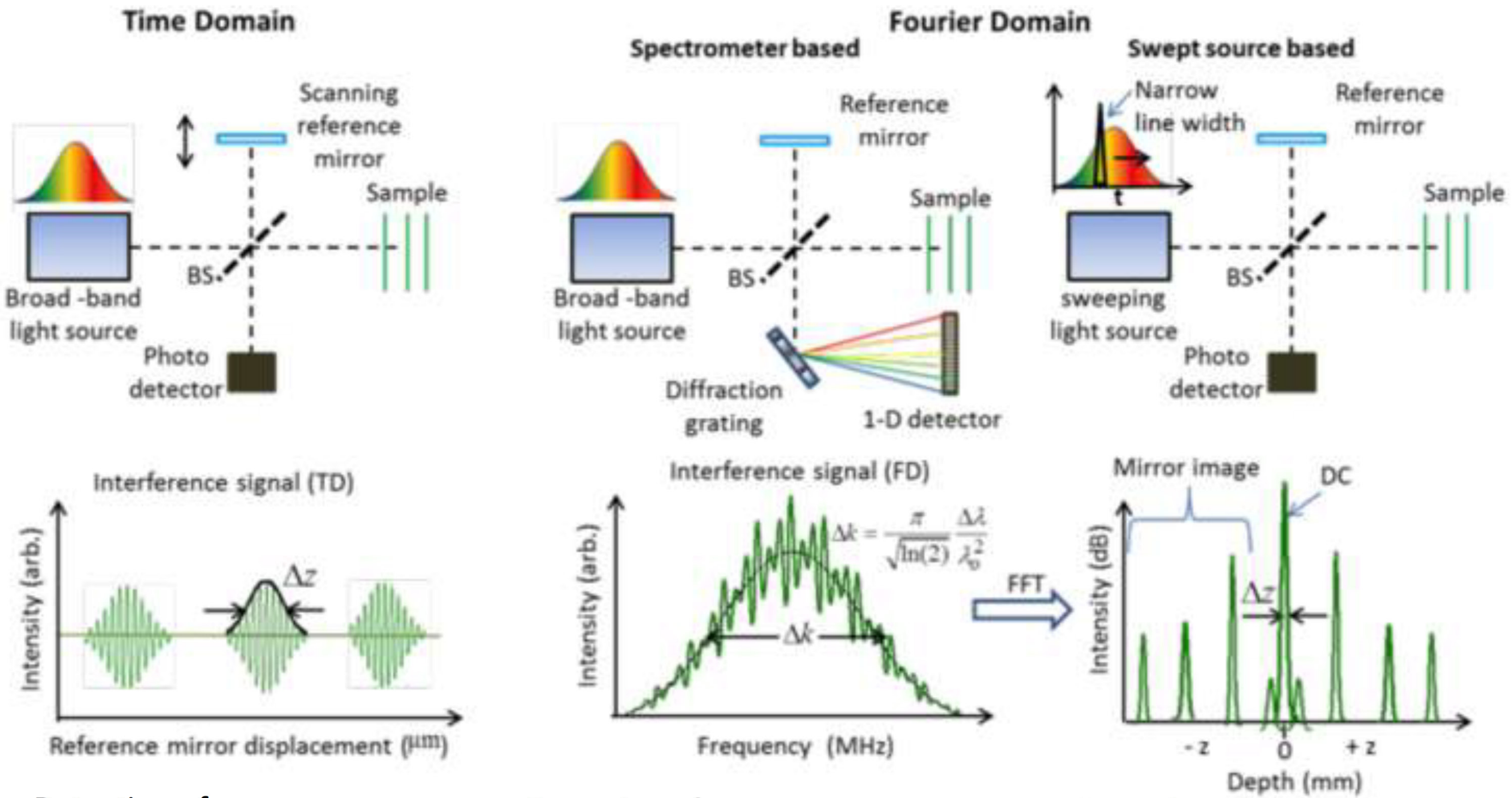
3.4 Optical Coherence Tomography (OCT)





Detection Process

EPFL



Detection of photo-electron current with bandwidth B

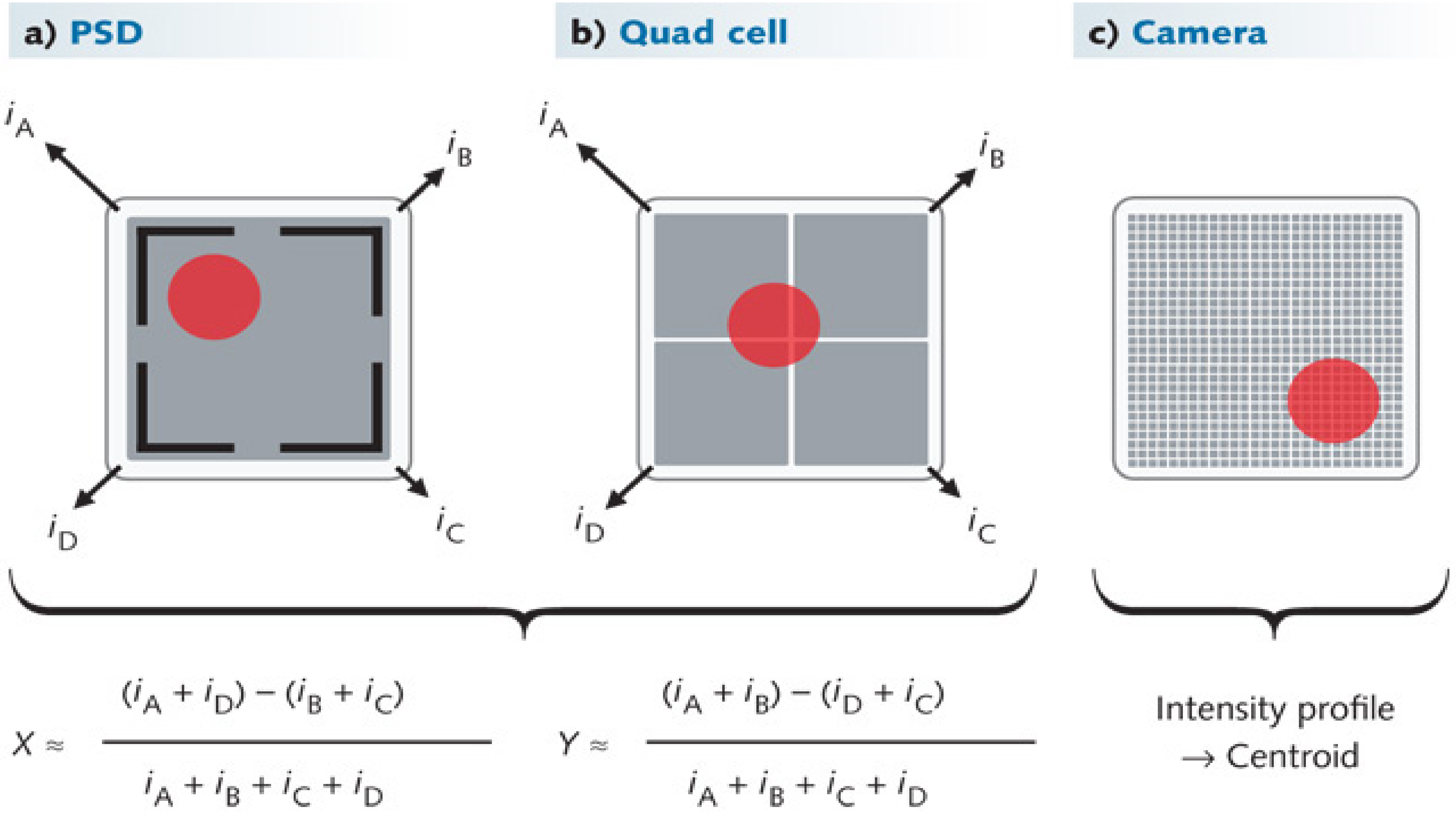
Detection of photo-electron number during integration time τ_{A_scan}

Detection of photo-electron current with bandwidth B

rainer.leitgeb@meduniwien.ac.at

Outline

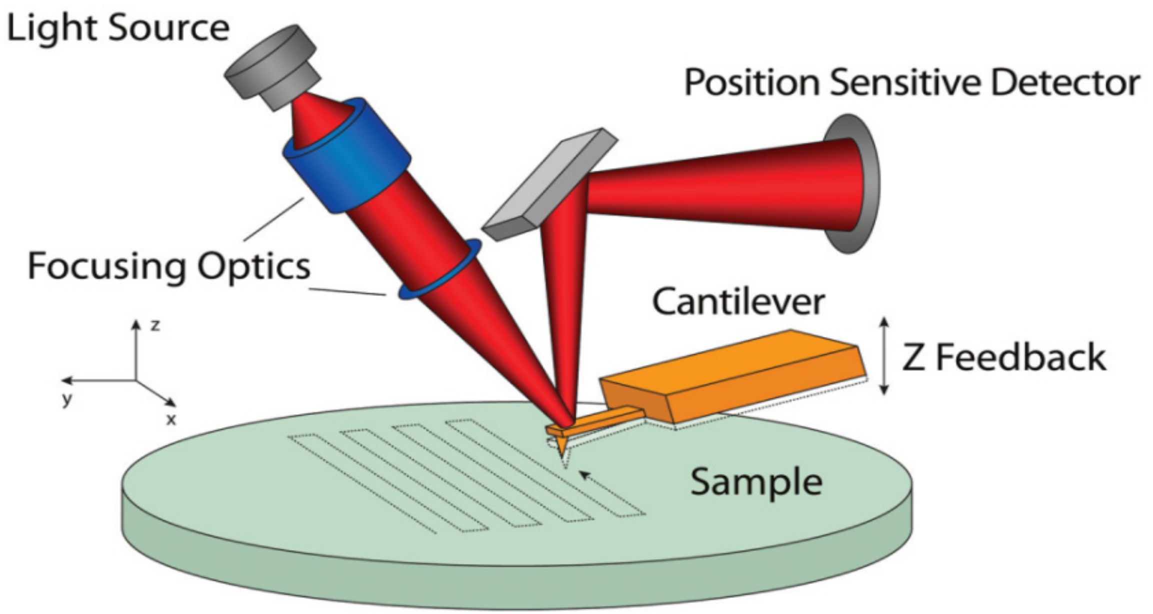
3.5 2D Position-Sensitive Detectors



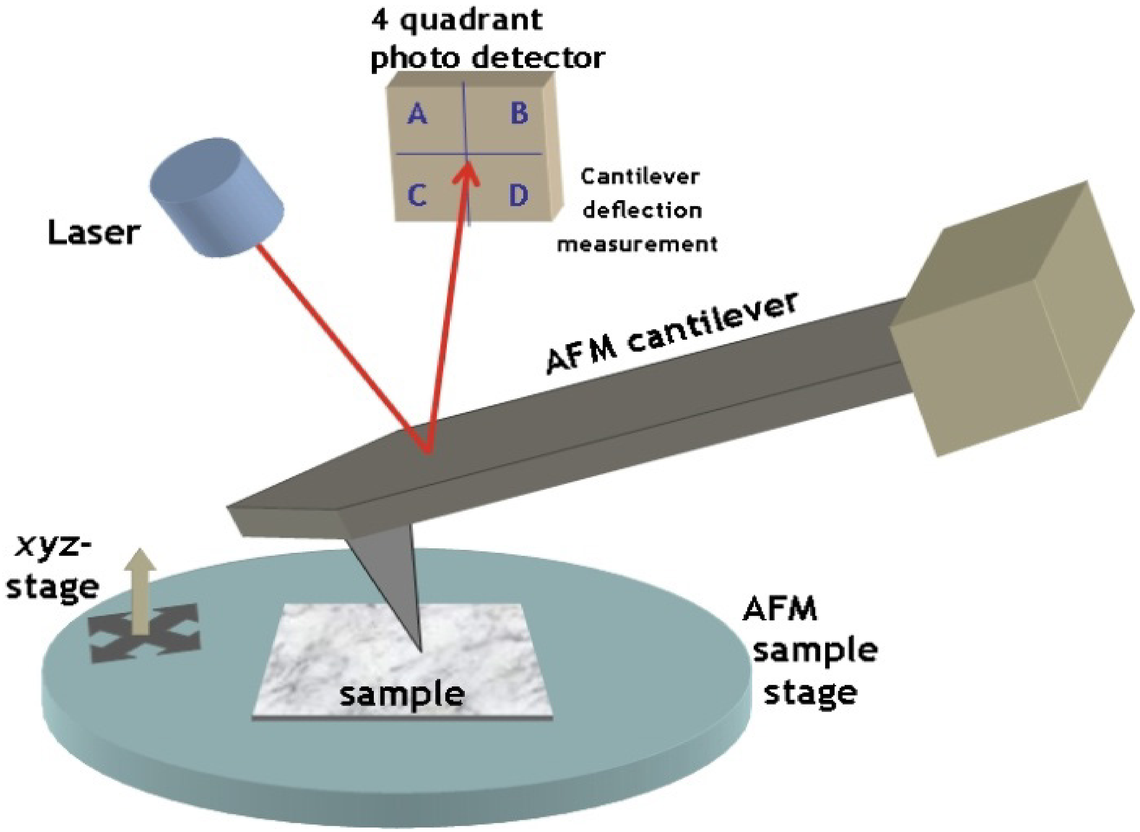
A. Cordes, A. Davidson “Detectors: CMOS cameras allow robust active stabilization of laser beams”, Laser Focus World, 2011

3.5 Example: AFM

Atomic Force Microscopy (AFM)



Asylum Research, « Combined AFM/optical », app. note 12



http://en.wikipedia.org/wiki/File:AFMsetup.jpg

Take-Home Messages/W3-1

3.1 **Synchronous detection**:

- Explain the principle of “synchronous detection”.
- What are its advantages? Which detectors would you use?

3.2 **Interferometers/OCT**:

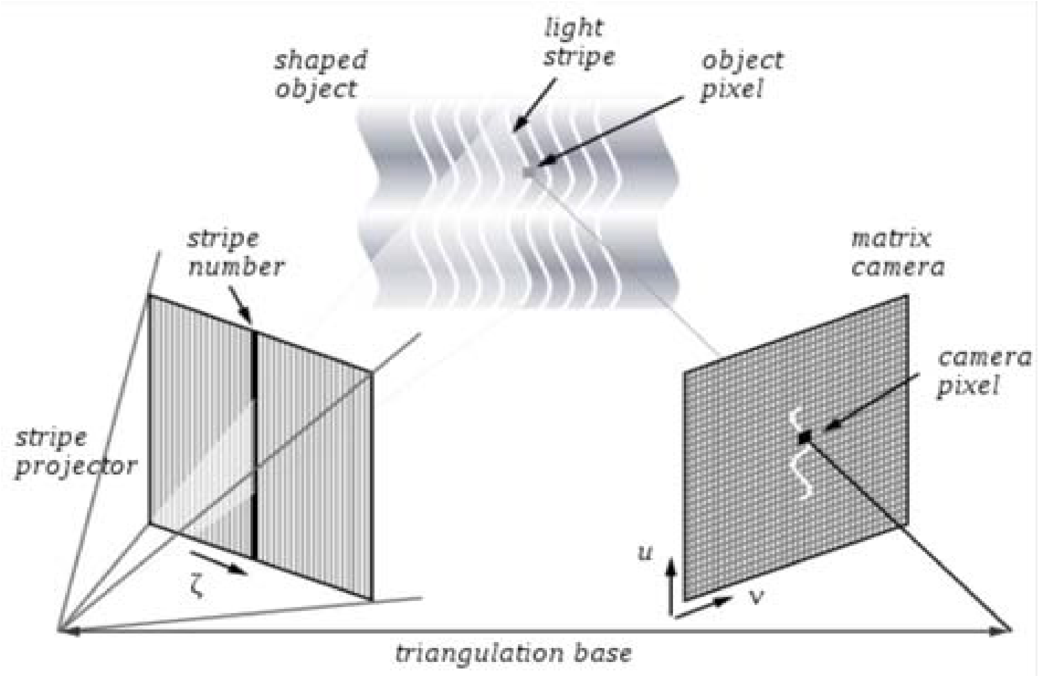
- Provide examples of interferometers.
- What are the working principles of interferometers/OCT devices? Which detectors would you use?

3.3 **Optical position sensors:**

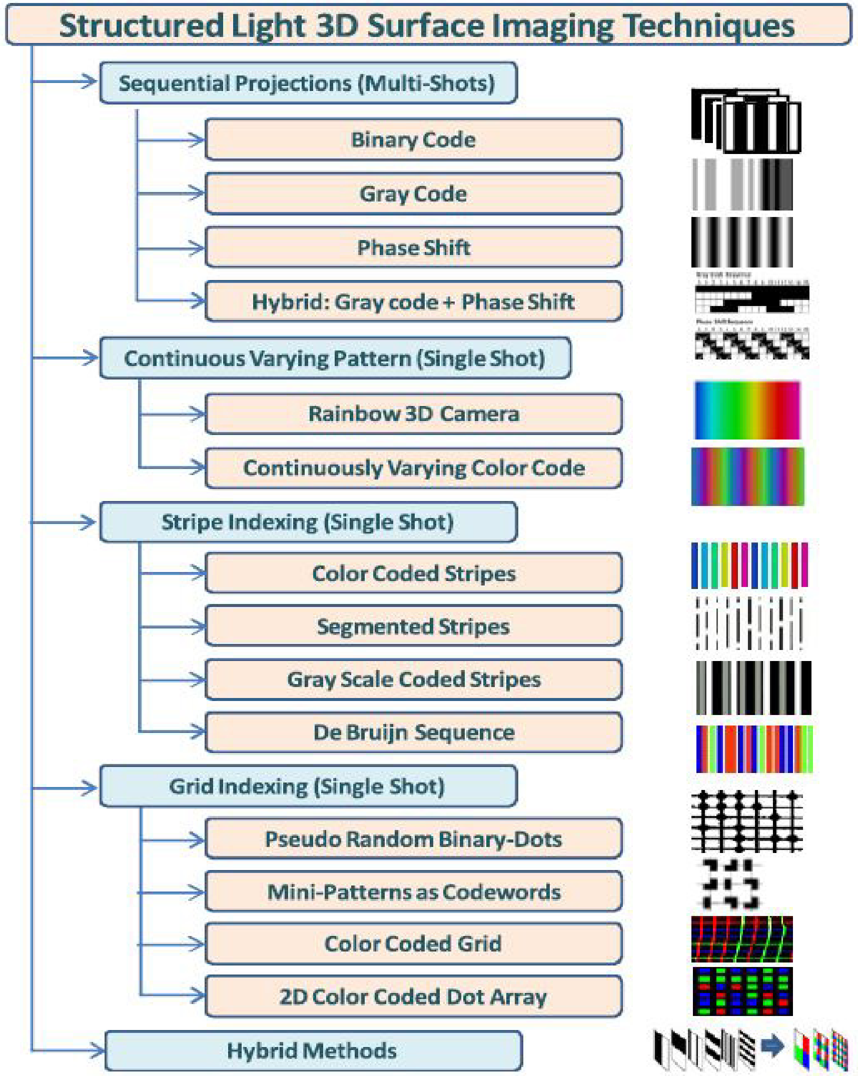
- Explain optical position sensors.
- Give example of such sensor’s applications.

Outline

3.6 3D Imaging using Structured Light



http://en.wikipedia.org/wiki/Structured-light_3D_scanner

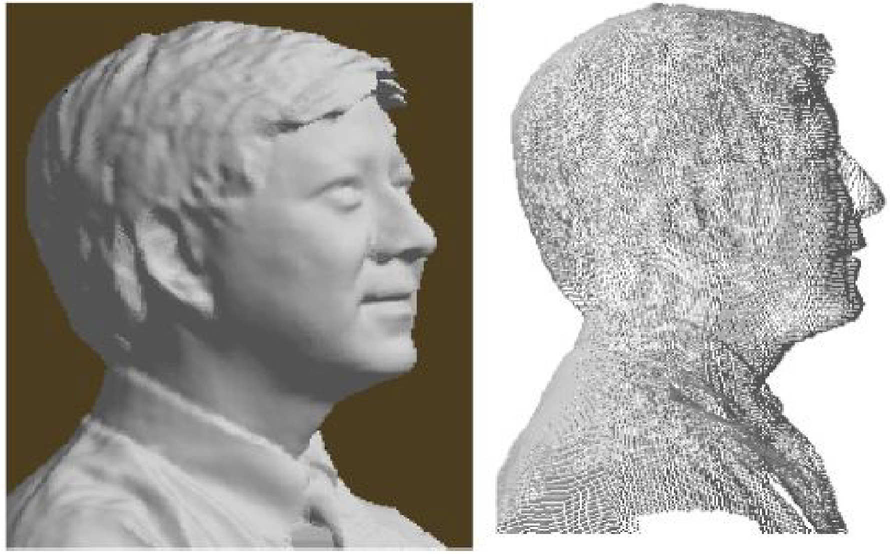


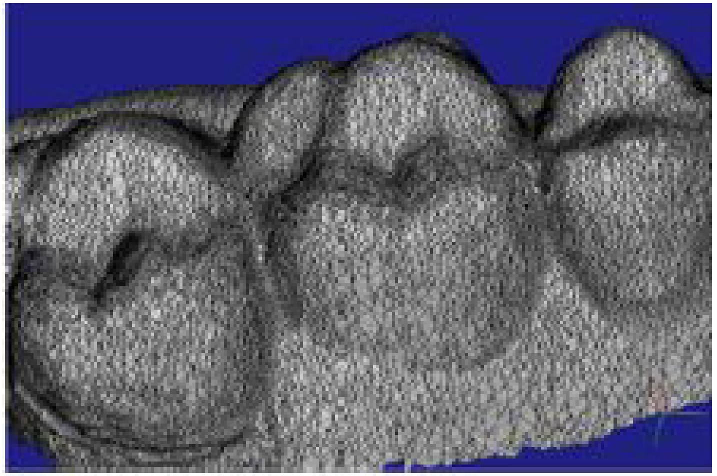
J. Geng, « Structured-light 3D surface imaging: a tutorial », Advances in Optics and Photonics 3, 128–160 (2011)

Any curvature will deform the straight lines…

3.6 Structured Light: Examples/1

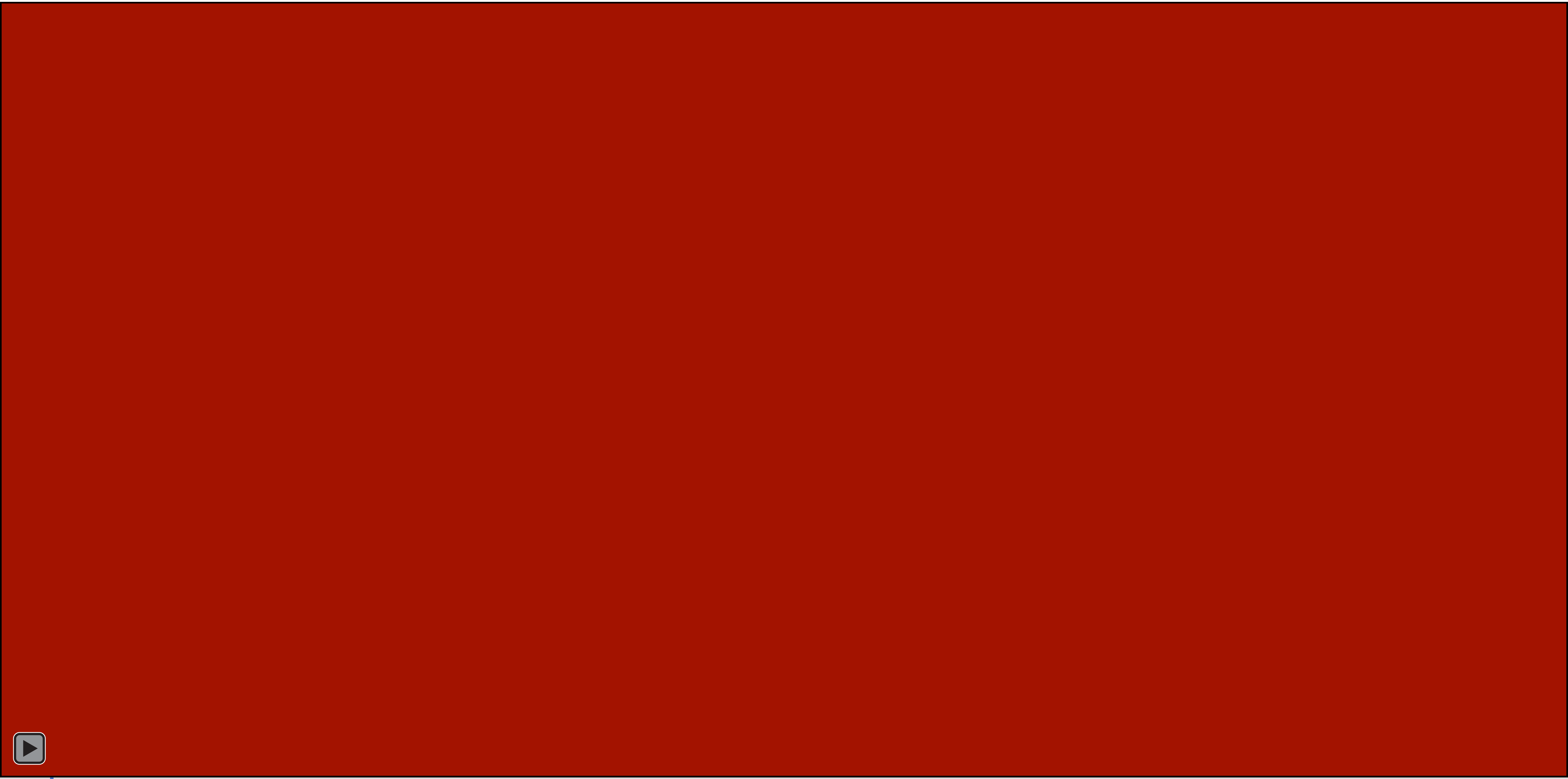
http://en.wikipedia.org/wiki/Structured-light_3D_scanner





J. Geng, « Structured-light 3D surface imaging: a tutorial », Advances in Optics and Photonics 3, 128–160 (2011)

3.6 Structured Light: Examples/2



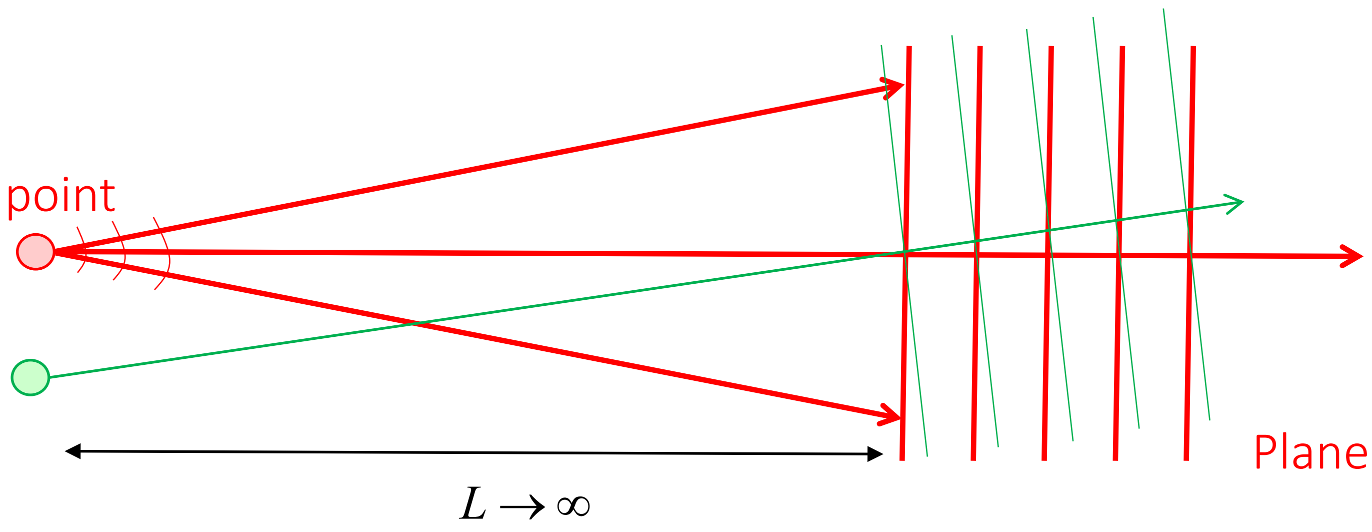
Outline

3.7 The Propagation of Light

A) Propagation to infinity

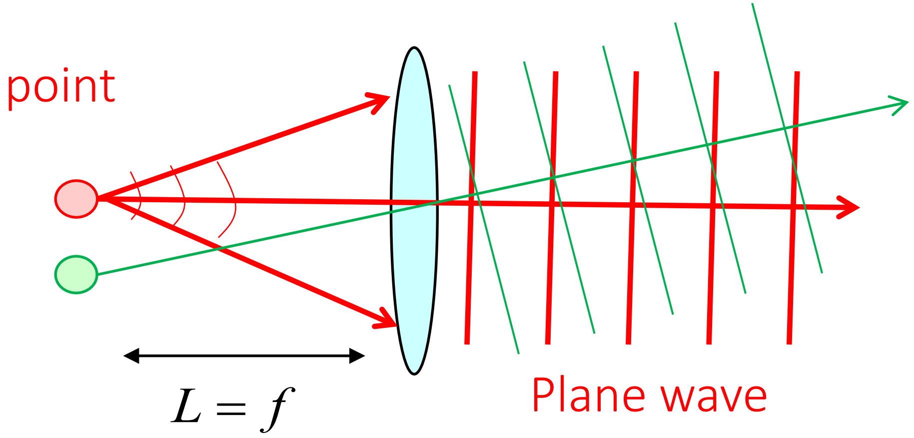
Point source: at ∞ → plane wave

Move the point laterally: different angle → phase shift



B) With a lens at the focal point

Basically the same effect!

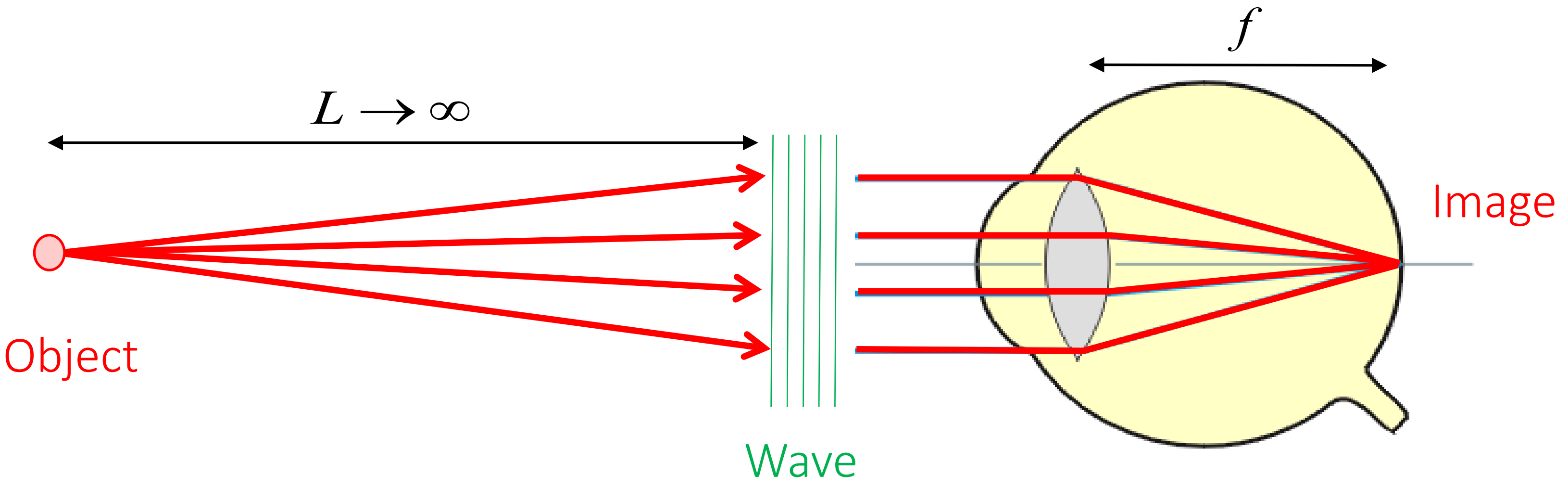


<u>Approximation</u>:

Fourier transform!

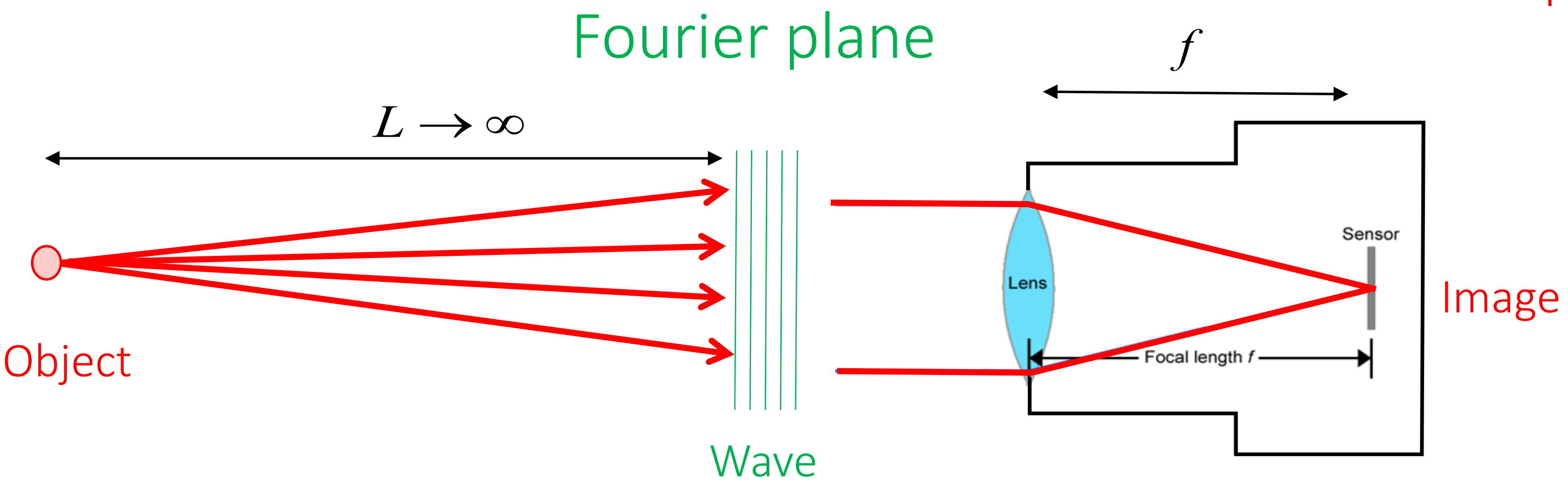
3.7 Vision and Photography «at infinity»

A) Vision

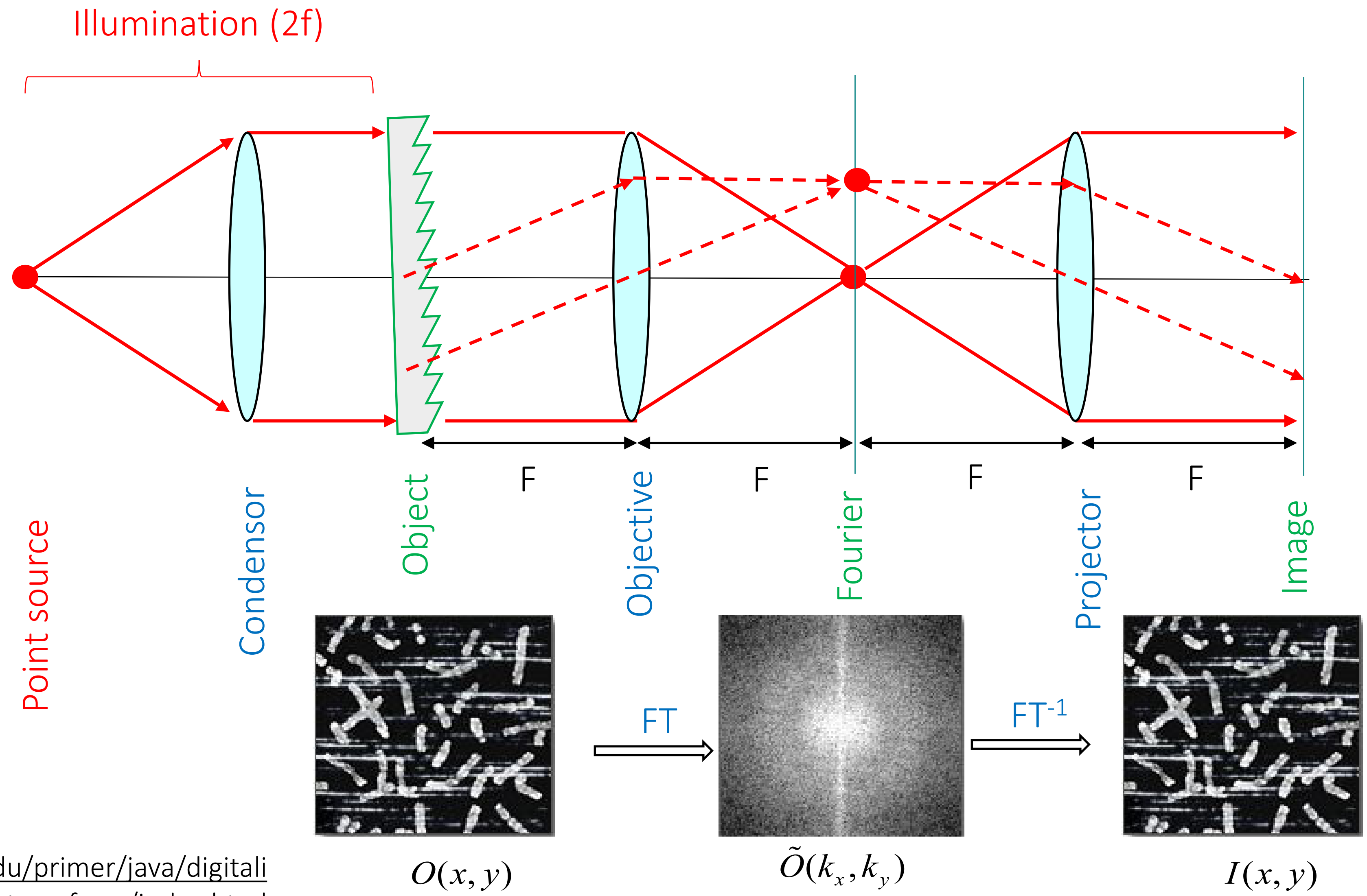


FT -> IFT

B) Photography



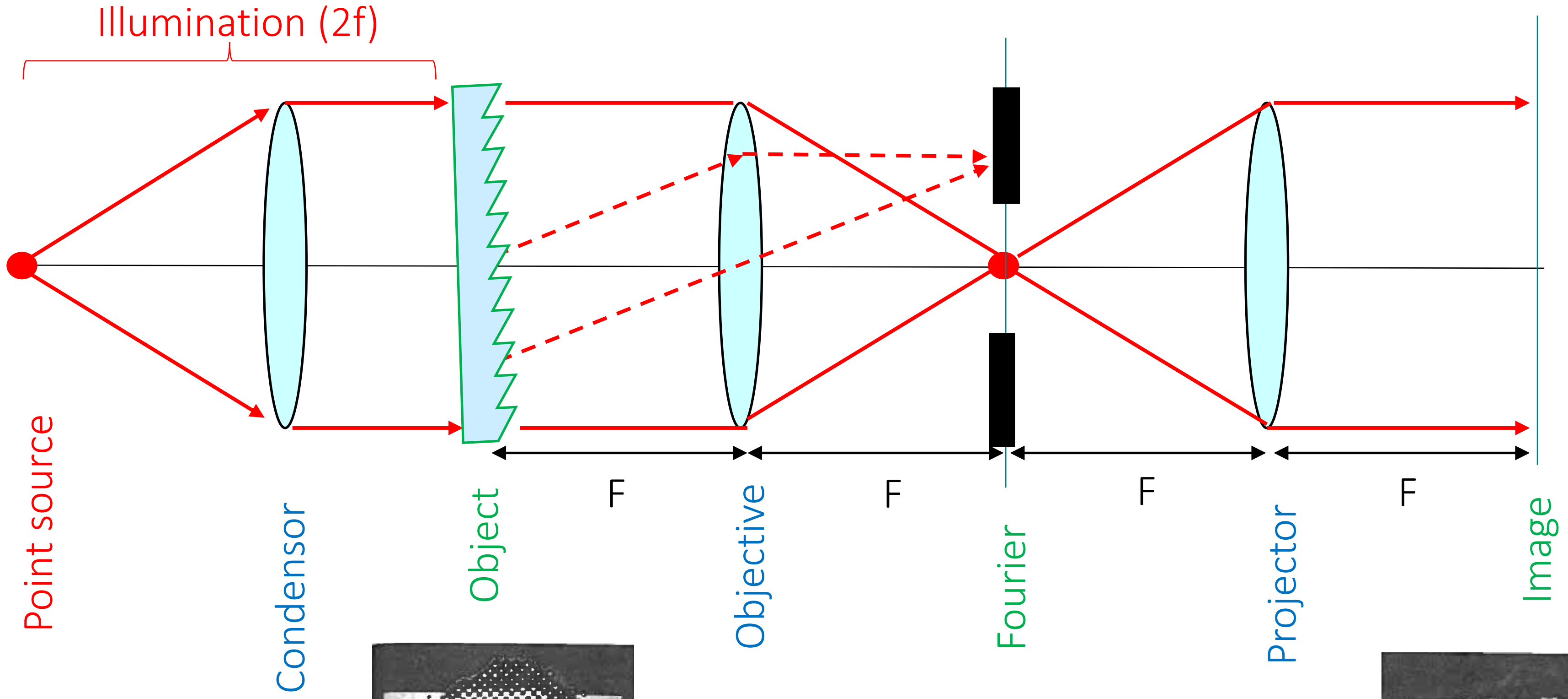
3.7 Basics of Fourier Optics: 4f Setup

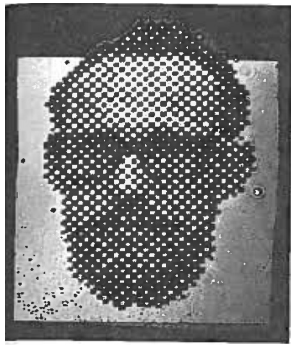


Could implement purely optical image processing!

http://micro.magnet.fsu.edu/primer/java/digitalimaging/processing/fouriertransform/index.html

3.7 Fourier Optics – Smooth (4f): Low Pass Filter



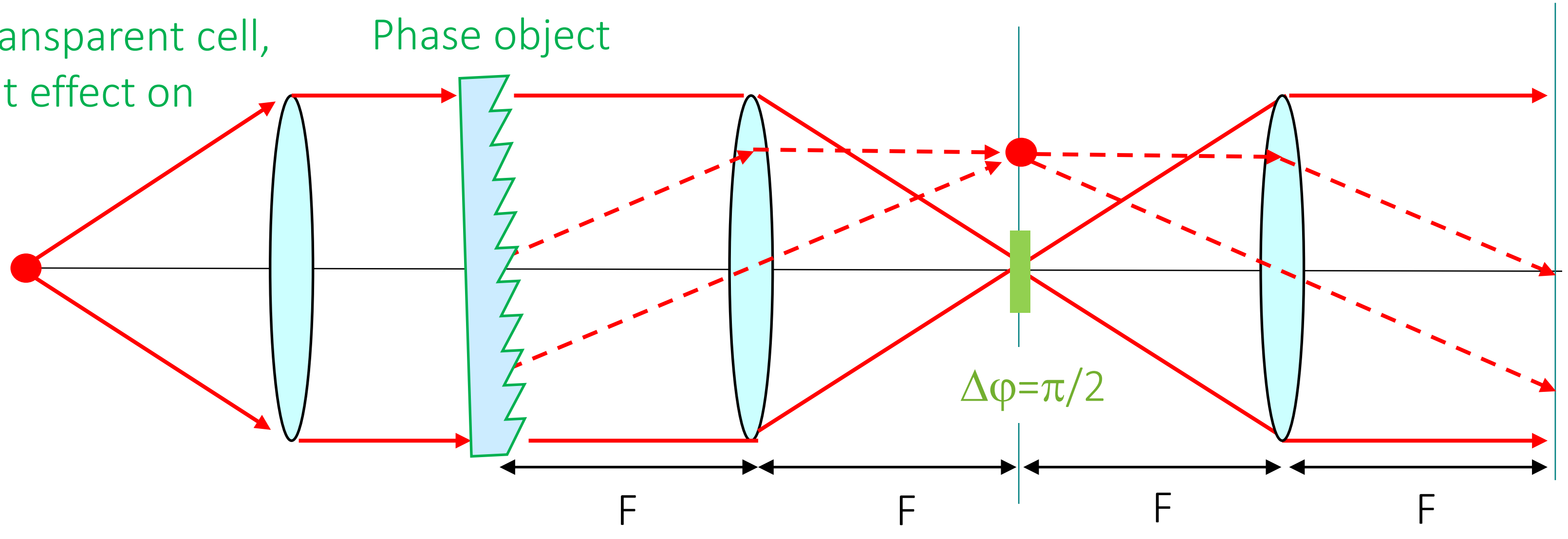


Only low spatial frequencies

A. Phillips, American Journal of Physics, 37, 536 (1969).

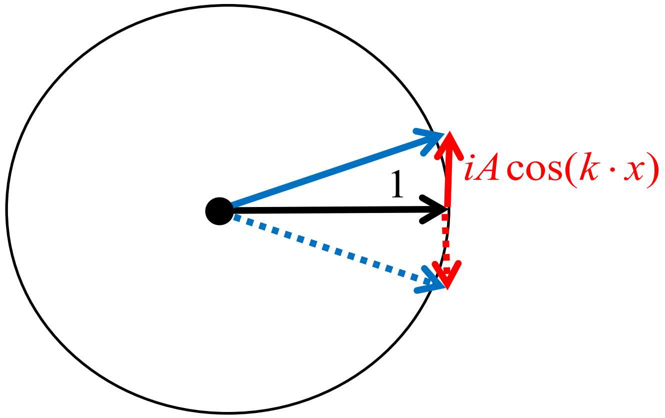
3.7 Fourier Optics – Phase Contrast (4f): Zernike

Example: almost transparent cell, small *n* contrast but effect on the phase

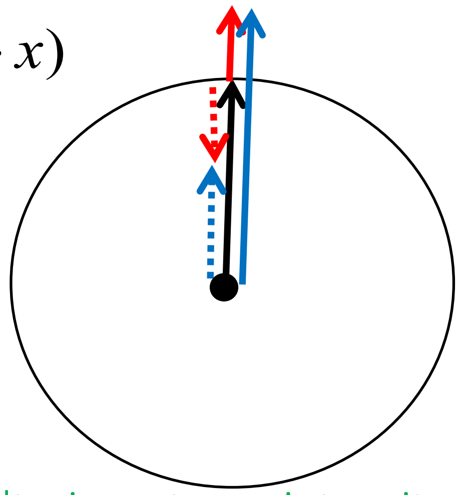


Frederik Zernike
Nobel Prize in Physics
1953

$$e^{iA\cos(k\cdot x)} \rightarrow 1 + iA\cos(k\cdot x)$$



Before filtering: small phase difference, intensity = 1

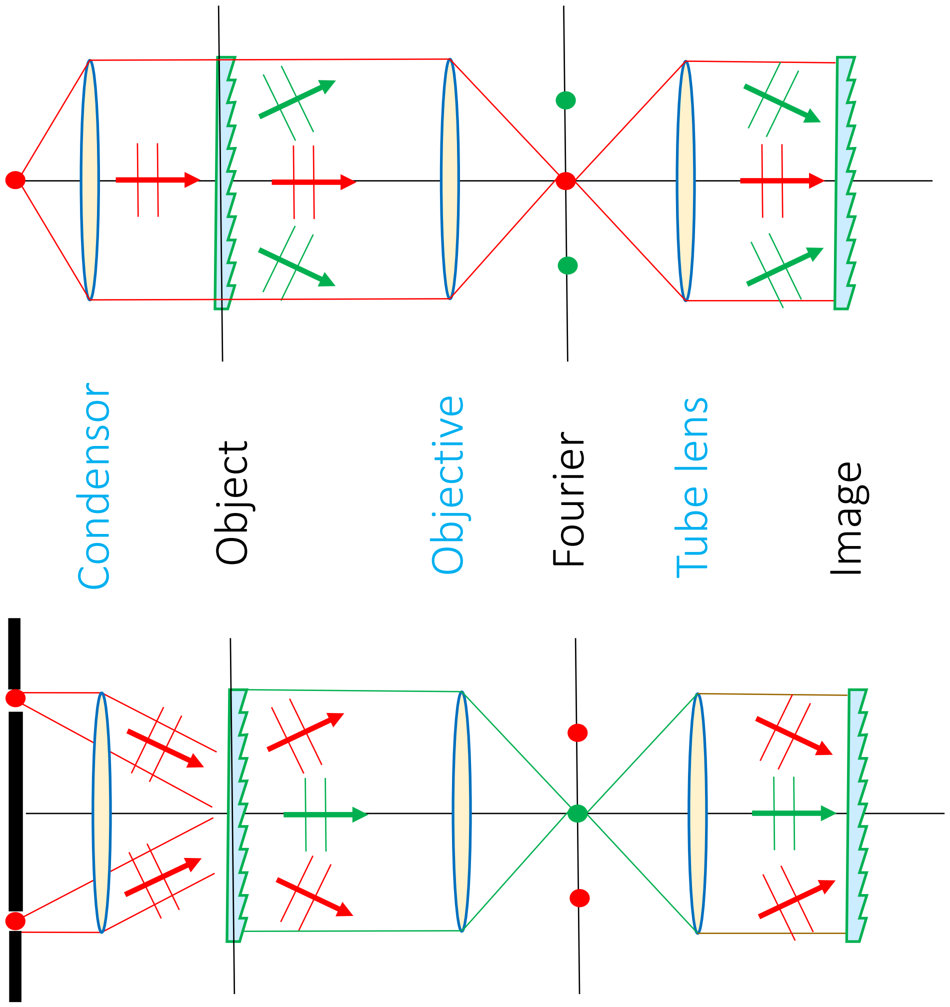


After filtering: strong intensity difference

Outline

3.8 Microscopy: Annular Illumination

Point illumination (hard to implement in practice)



Zero order light (undeflected)

Deflected light

Zero order blocked → darkfield

Zero order $\pi/2$ shifted → phase contrast

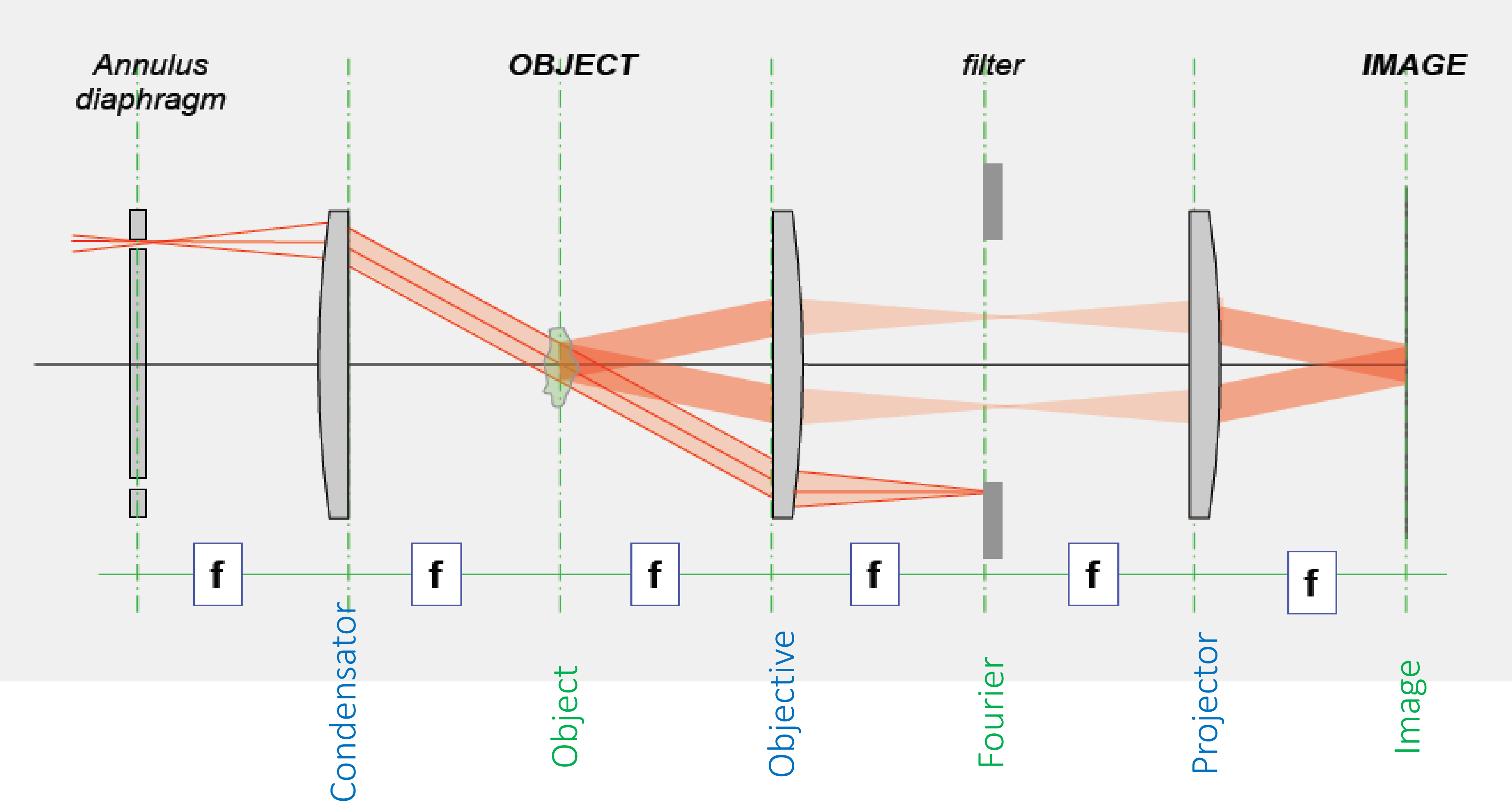
Annular illumination (ring → cone of light)

Zero order light

Deflected light

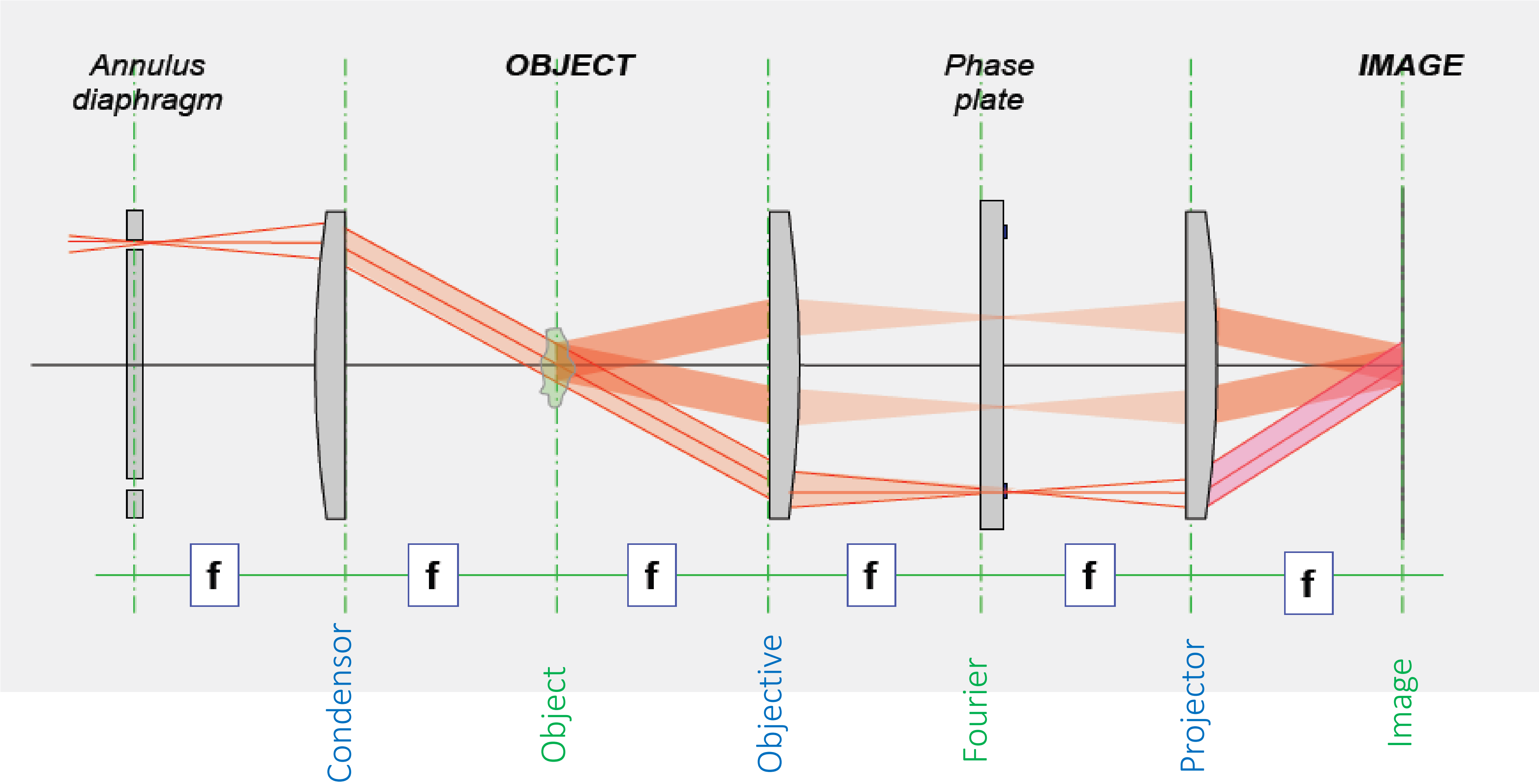
Increased brightness

3.8 Darkfield Microscopy («Edge Enhancement»)



T. Lasser, M. Leutenegger, « Cours Biomicroscopy II », 2012, STI, EPFL

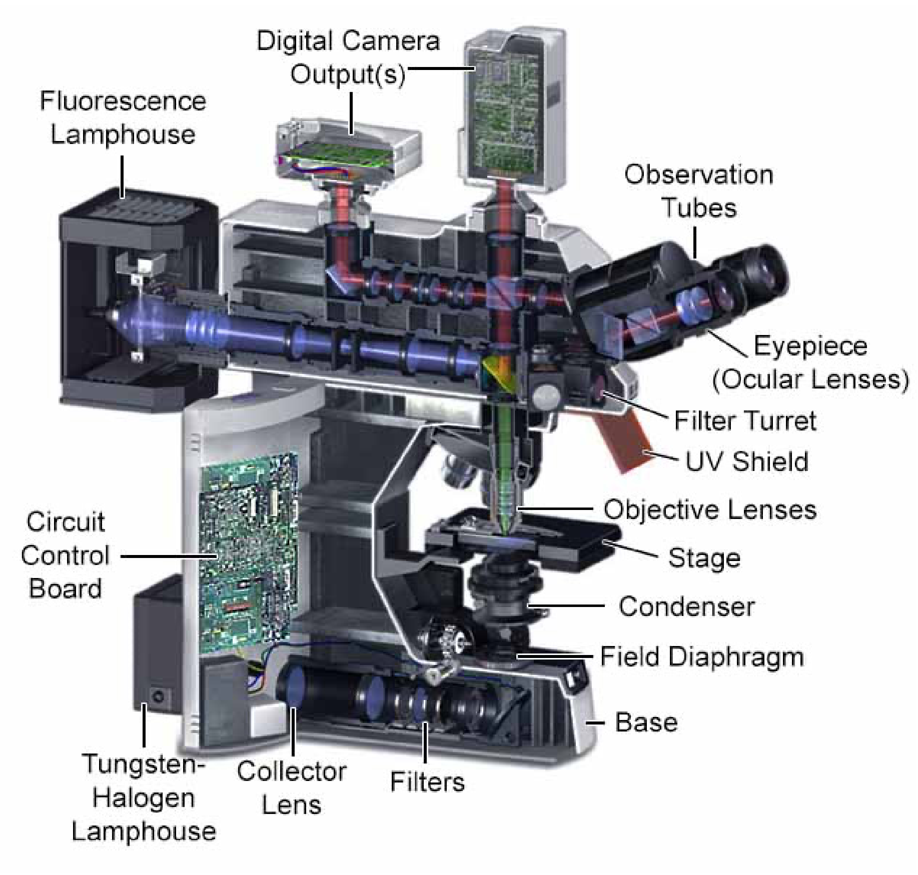
3.8 Phase Contrast Microscopy: Zernike



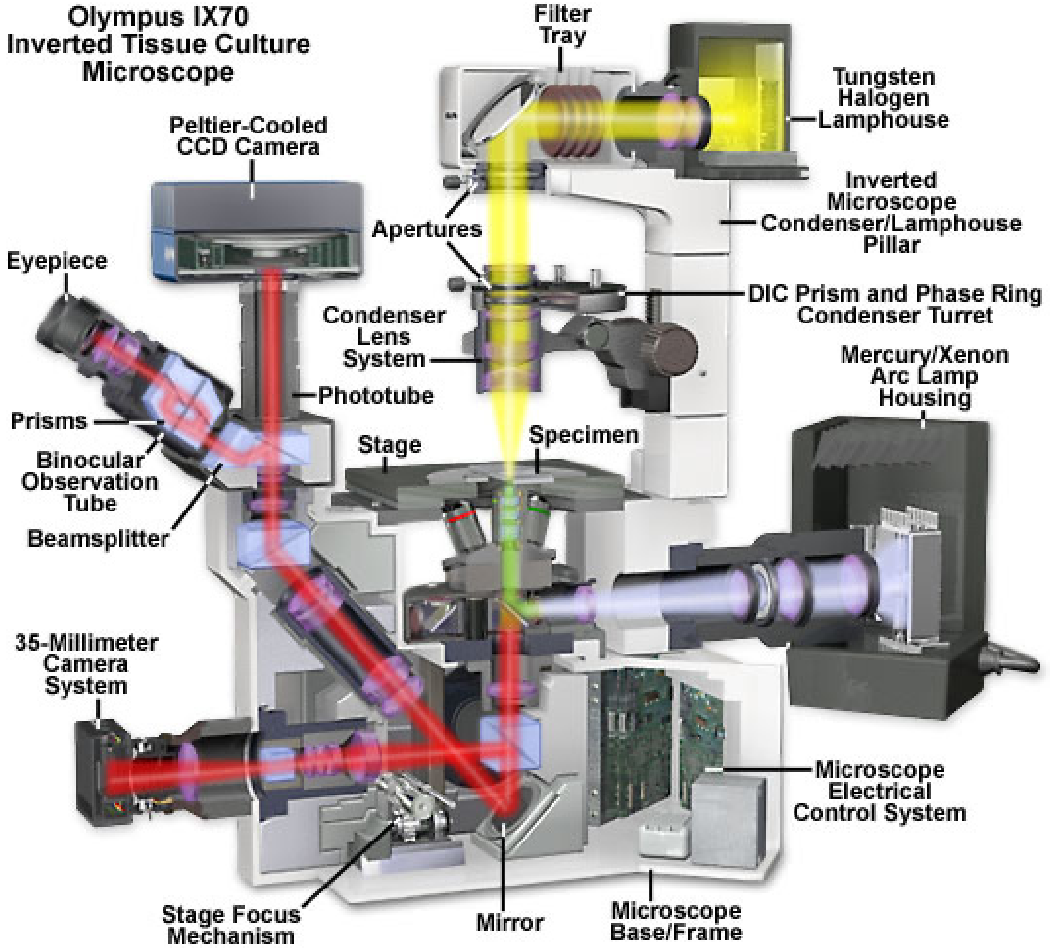
T. Lasser, M. Leutenegger, « Cours Biomicroscopy II », 2012, STI, EPFL

3.8 Microscopy Examples

Upright microscope

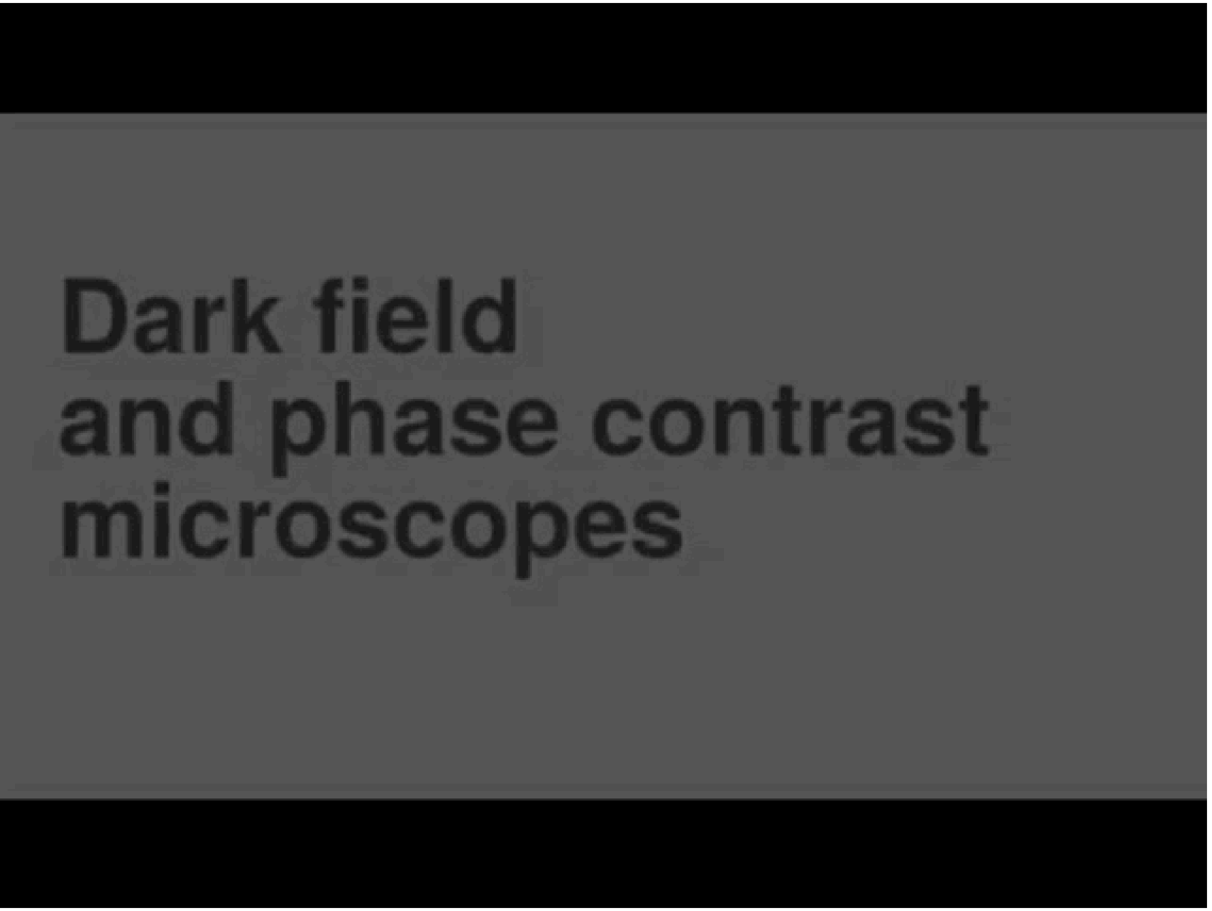


Inverted microscope

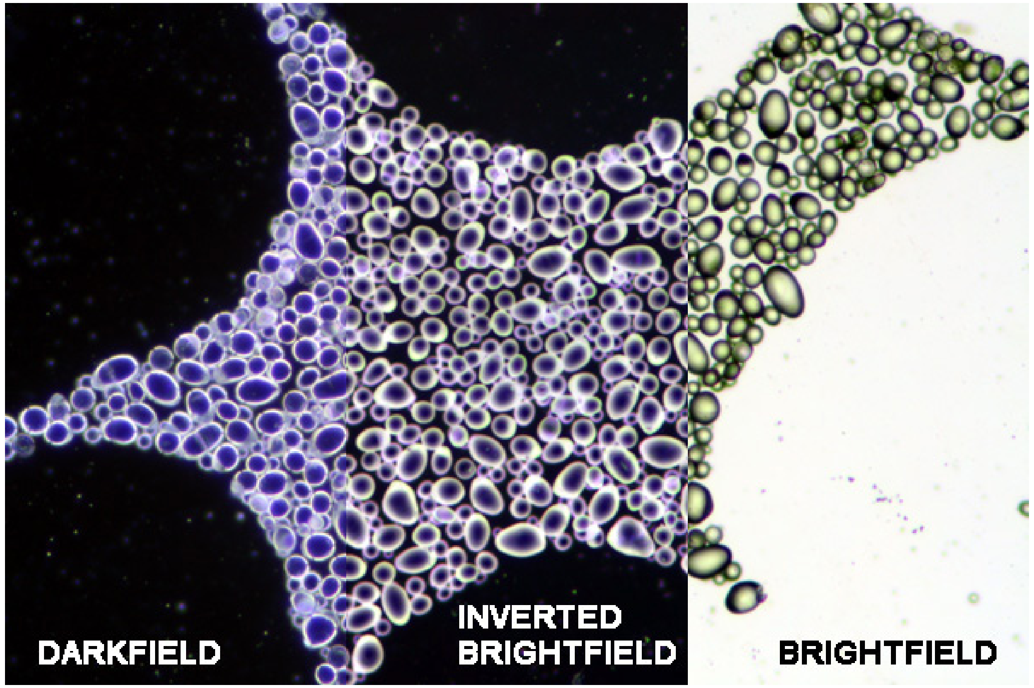


G. Fantner, EPFL, MICRO-428 Week 6

3.8 Microscopy Examples: Darkfield and phase contrast

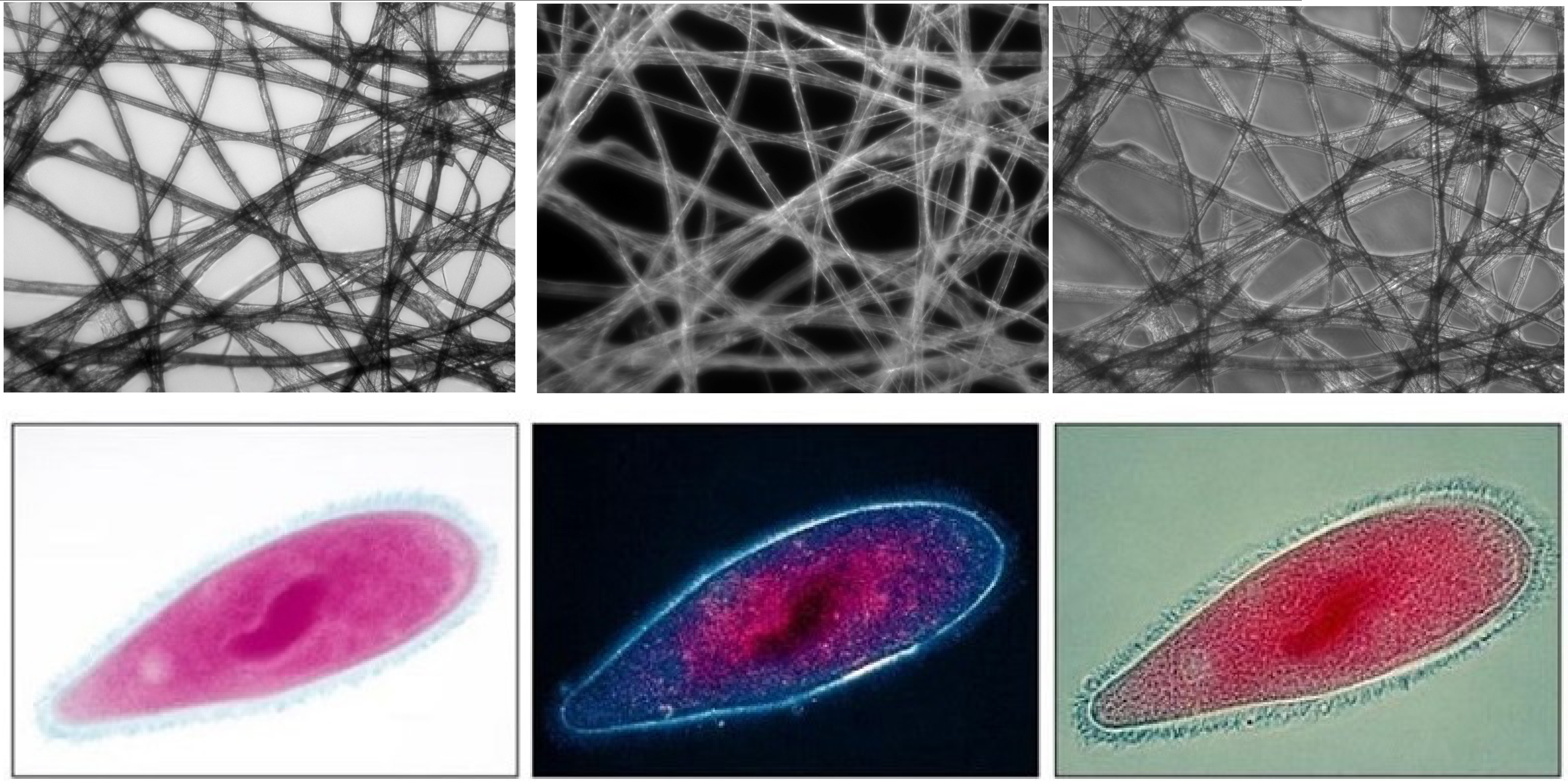


https://www.youtube.com/watch?v=vr4tYUnaHNQ



G. Fantner, EPFL, MICRO-428 Week 6

3.8 Microscopy: Examples of different modes

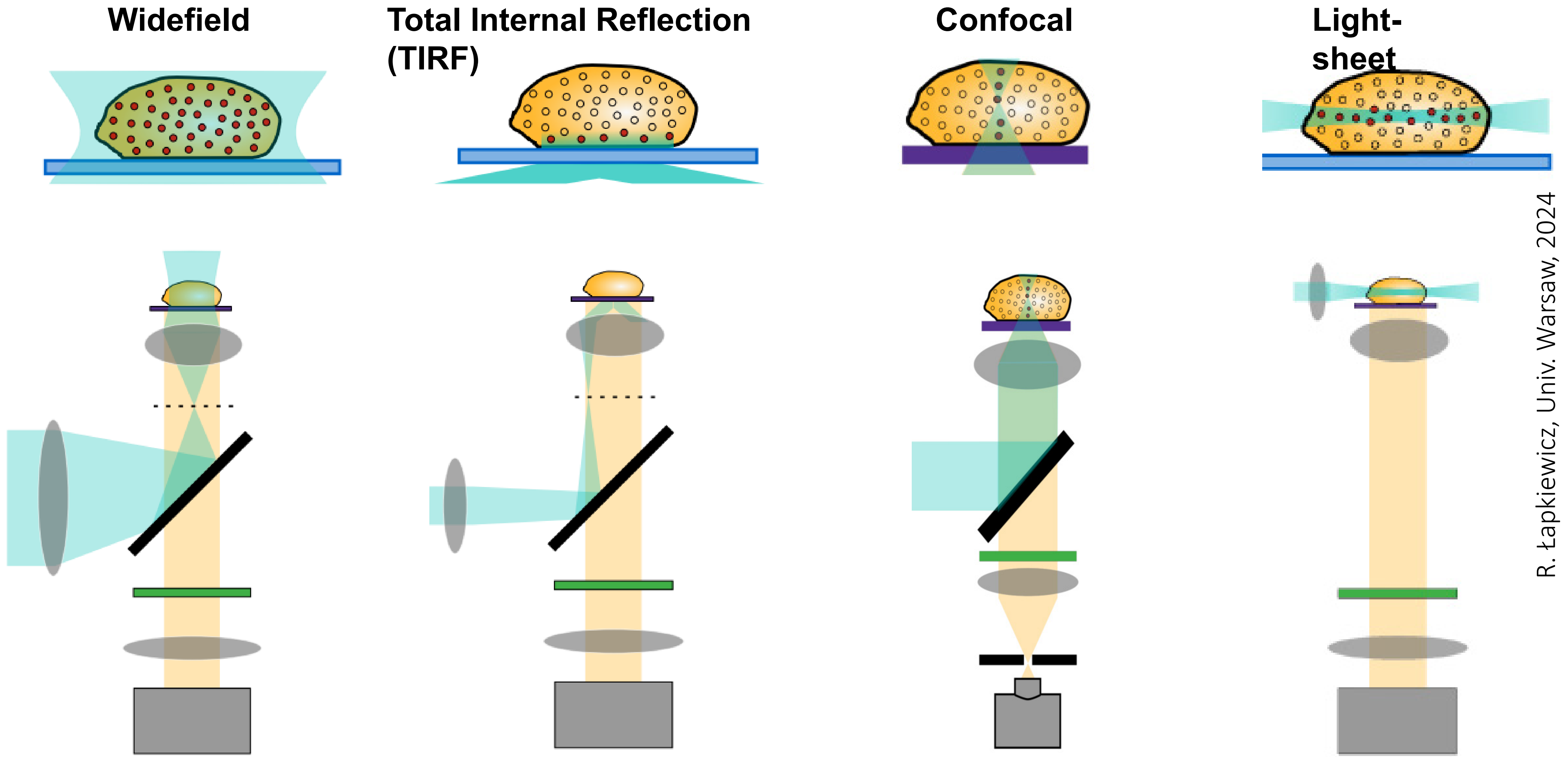


Brightfield Darkfield Phase-contrast

G. Fantner, EPFL, MICRO-428 Week 6

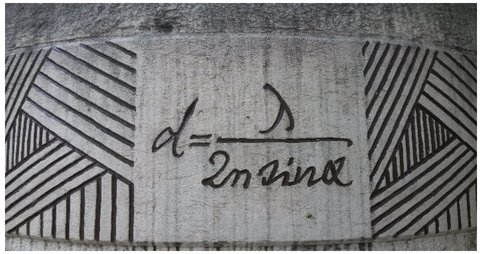
3.8 More Microscopy set-ups

Main fluorescence microscopy modalities: 3D imaging and sectioning

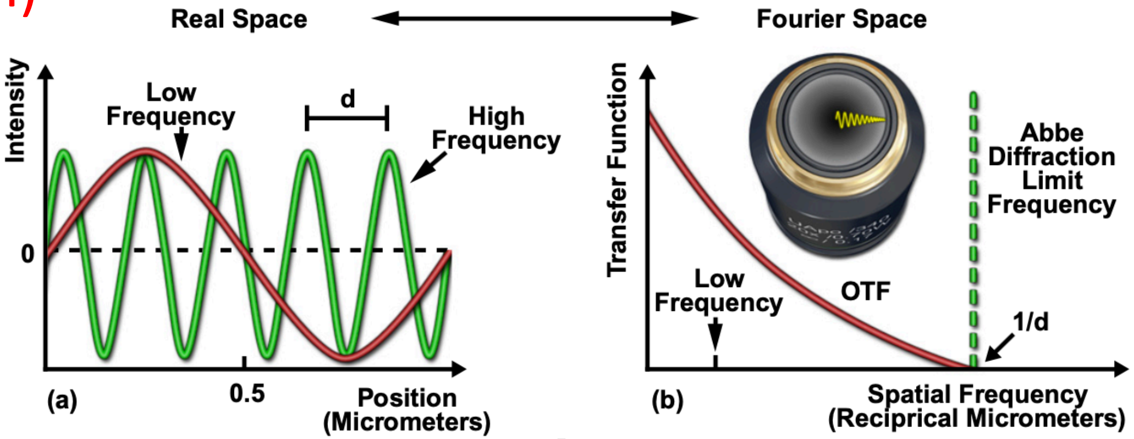


Outline

3.9 Microscopy: Superresolution techniques



A microscope has a maximum (spatial) bandwidth = Abbe diffraction limit!



In 2D the bandwidth can be plotted in Fourier space as a circle → the larger the circle, the higher the achievable spatial resolution.

Original image | Power spectrum with mask that filters low frequencies | Result of inverse transform | Power spectrum with mask that passes low frequencies | Result of inverse transform

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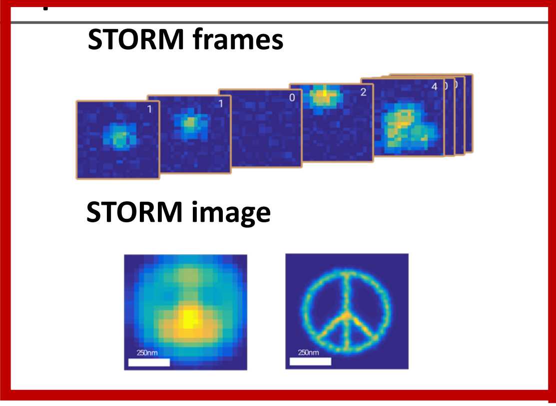
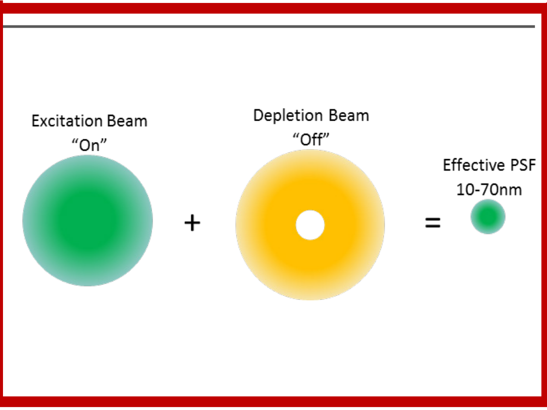
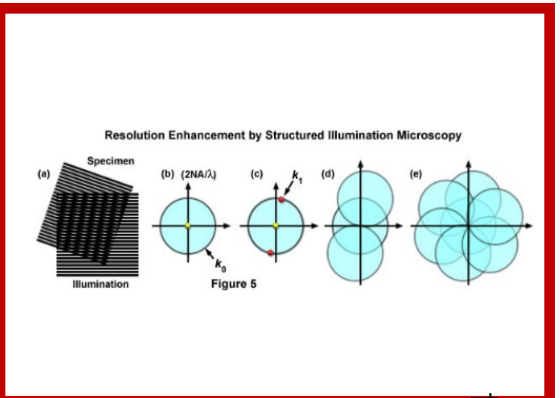
3.9 Superresolution techniques







How to break Abbe's limit?

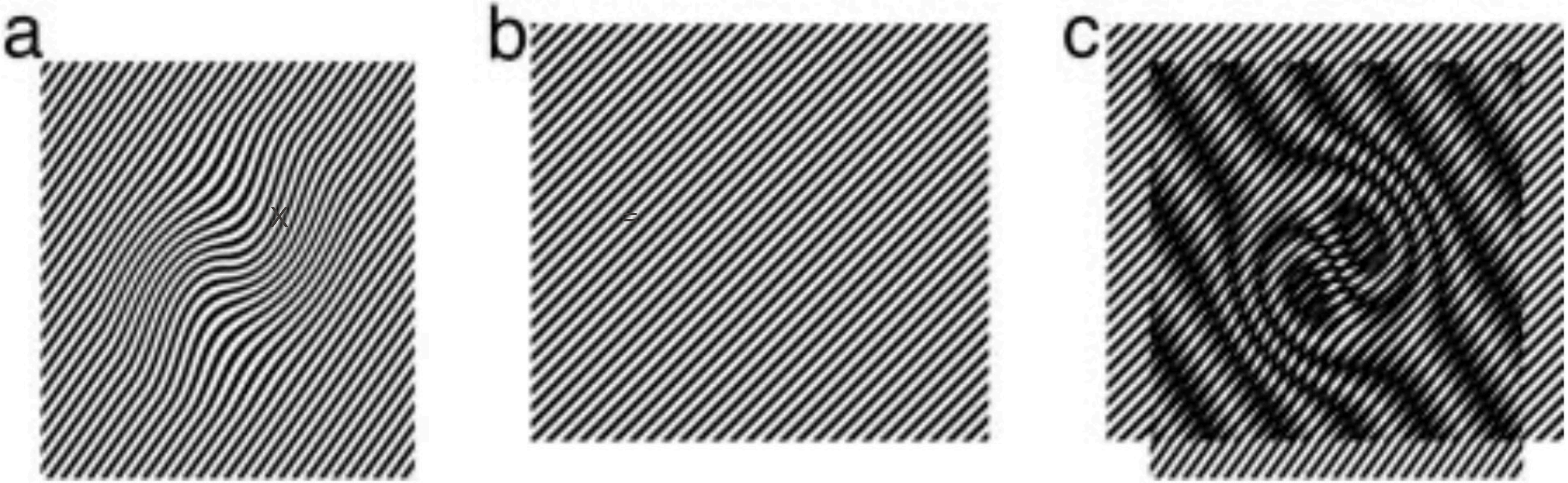
→ break at least one of Abbe's assumptions

	PALM\STORM	STED	SIM\ISM
• **Linear response**	✓ ✗	✗	✓
• **Uniform illumination**	✓	✗	✗
• **Far-field detection**	✓	✓	✓
• **Time independent image**	✗	✓	✓
• **Classical light**	✓	✓	✓

R. Łapkiewicz, Univ. Warsaw, 2024

3.9 Structured Illumination Microscopy (SIM)

Frequency mixing is done by illuminating the sample not with a uniform illumination, but with a striped pattern of known frequency.



$$A_\omega \cos(\omega_{sample} x) \times \cos(\omega_{ill} x)$$
$$= \frac{A_\omega}{2} \cos\left((\omega_{sample} - \omega_{ill})x\right) + \frac{A_\omega}{2} \cos\left((\omega_{sample} + \omega_{ill})x\right)$$

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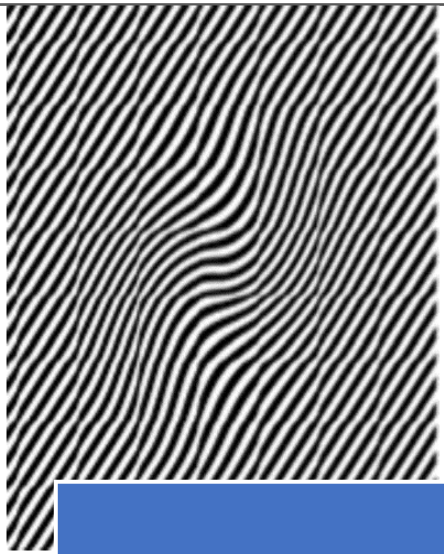
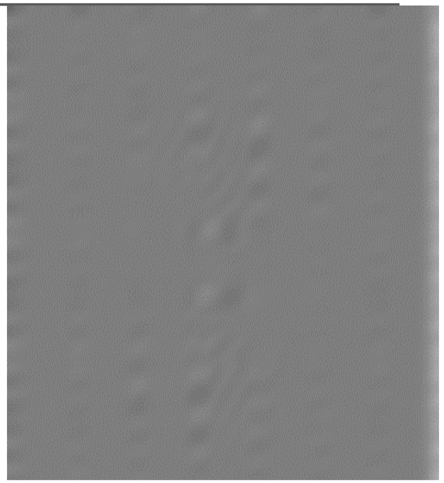
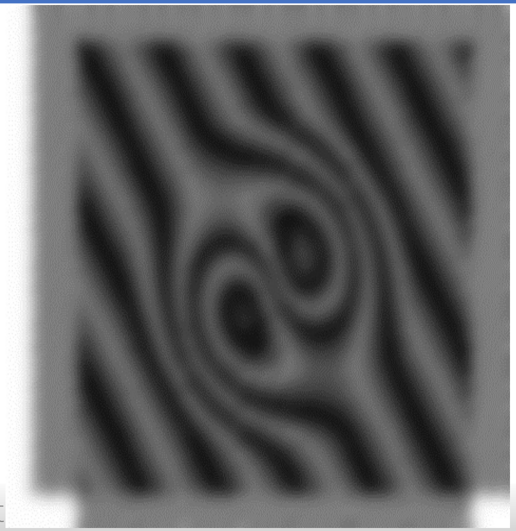
3.9 Structured Illumination Microscopy (SIM)



Microscope removes high frequencies



$$A_\omega \cos(\omega_{sample} x) \times \cos(\omega_{ill} x)$$
$$= \frac{A_\omega}{2} \cos\left((\omega_{sample} - \omega_{ill})x\right) + \frac{A_\omega}{2} \cos\left((\omega_{sample} + \omega_{ill})x\right)$$



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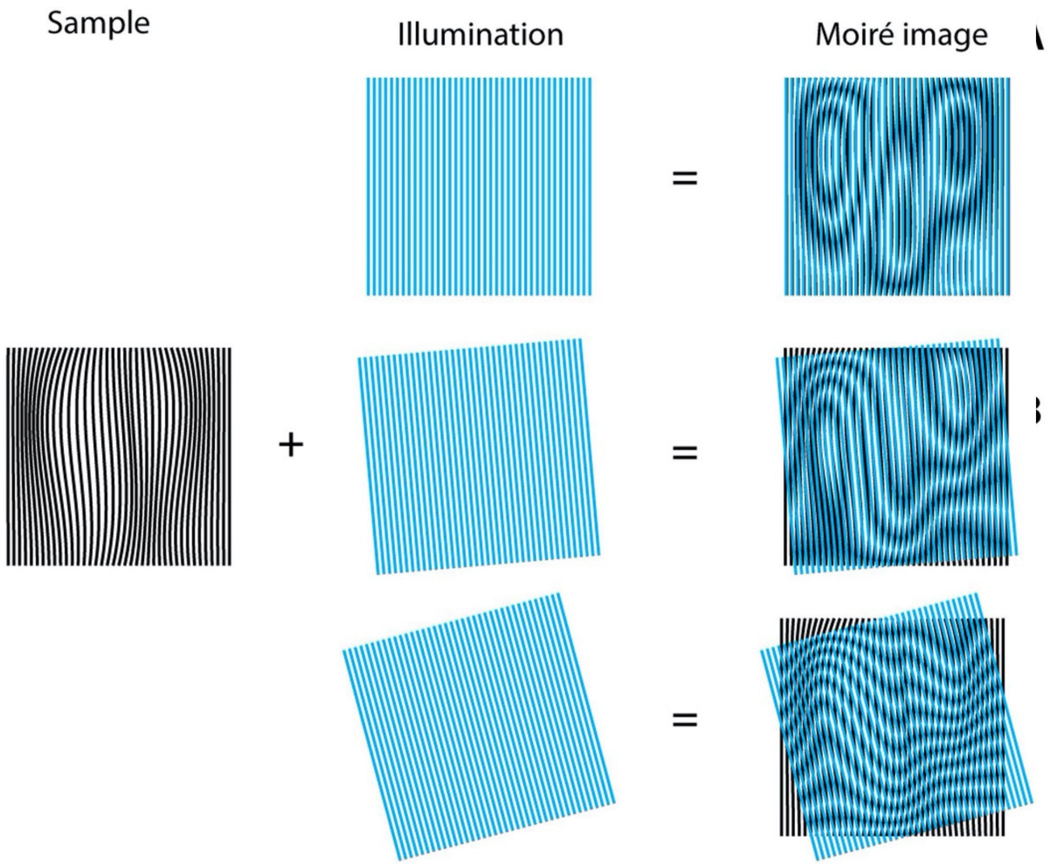
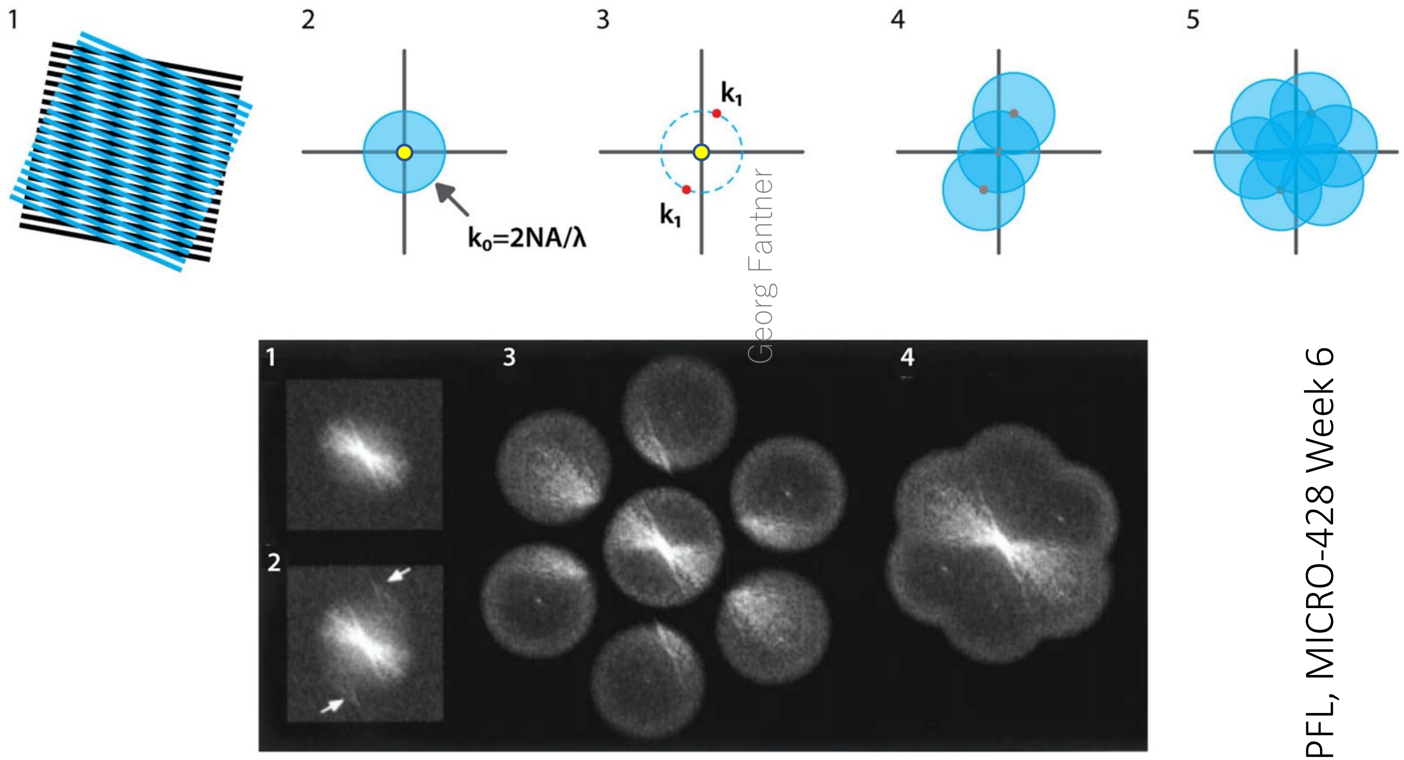
3.9 Structured Illumination Microscopy (SIM)

We can do the structured illumination with different displacements and rotations.





Each image with striped illumination expands the imaged Fourier space in a different direction. Reassembling the Fourier transforms of the individual images results in information with twice the frequency content.

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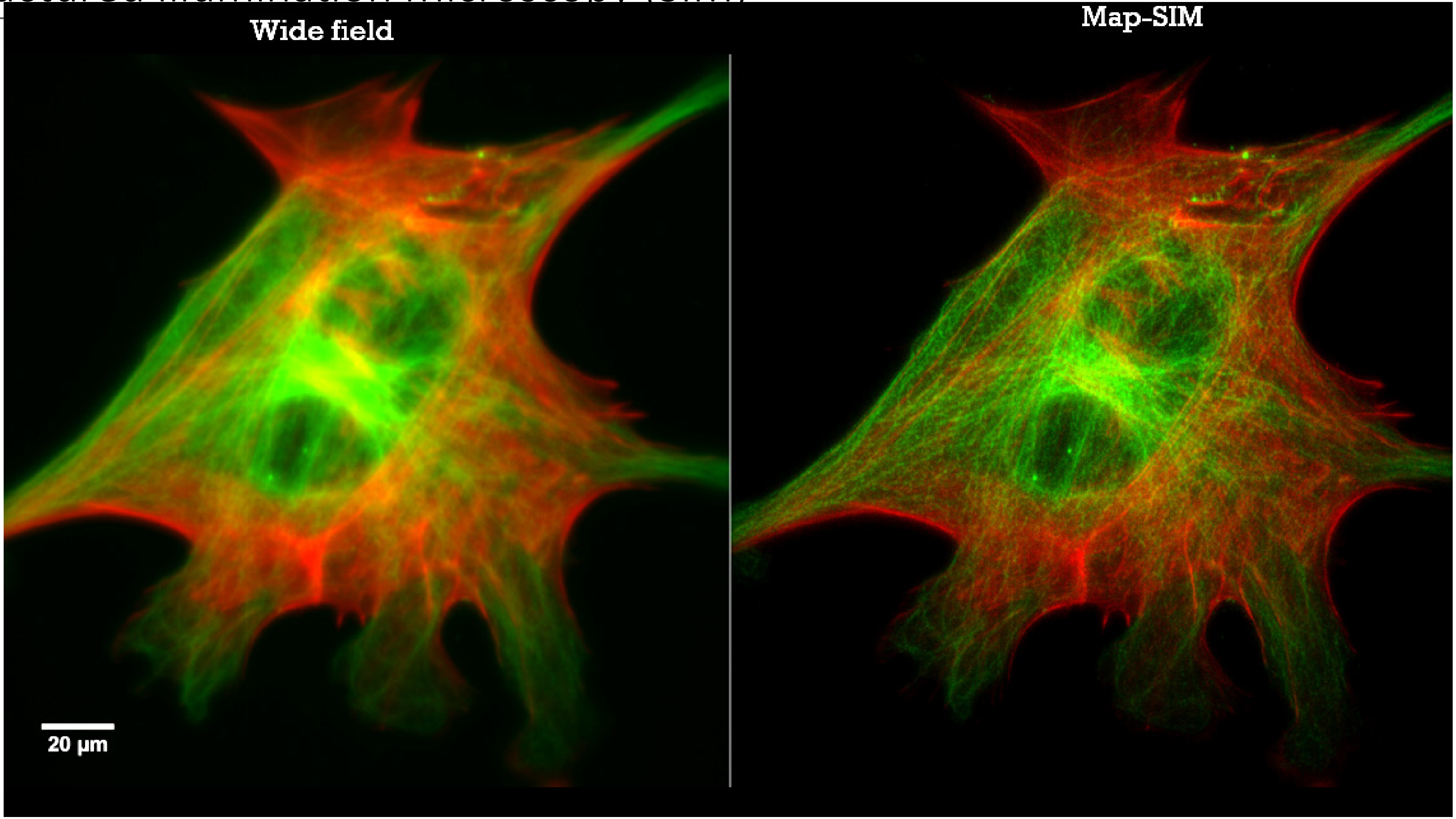
3.9 Structured Illumination Microscopy (SIM)



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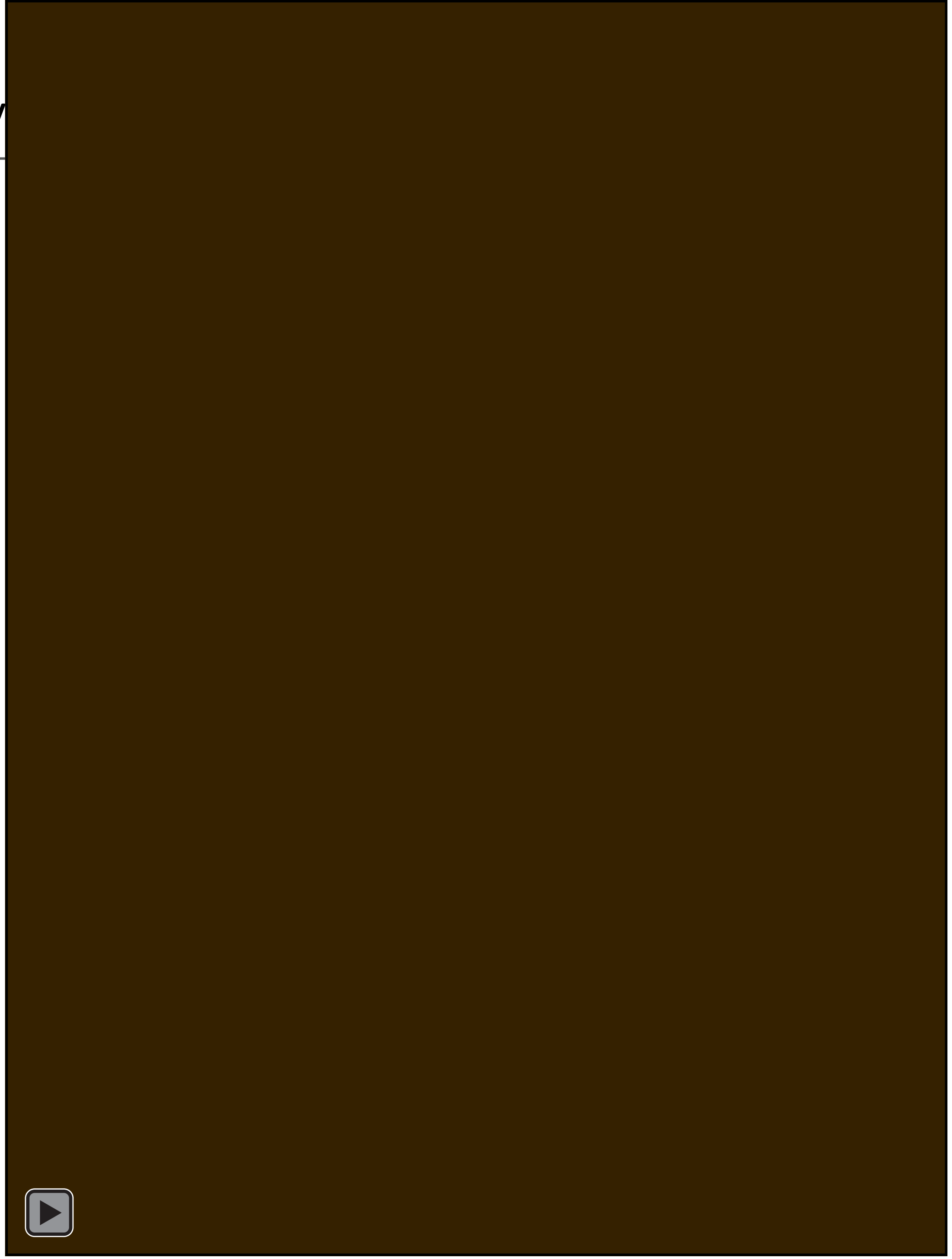
3.9 Single molecule localization microscopy

STORM - Stochastic Optical Reconstruction Microscopy

Basic principle: Separate spatially overlapping light sources *in time*

→ plot the centre of each light source as a dot, sum them all up → reconstruct a superresolved image.



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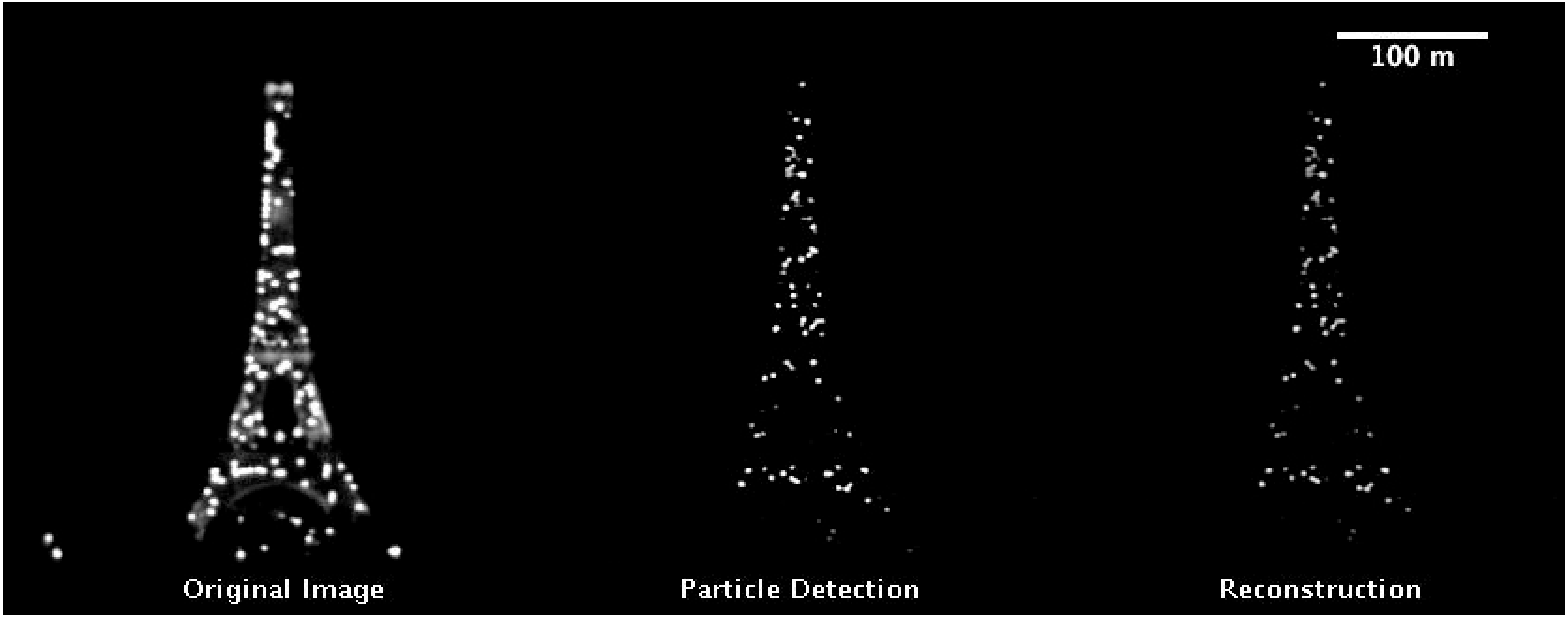
3.9 Single molecule localization microscopy



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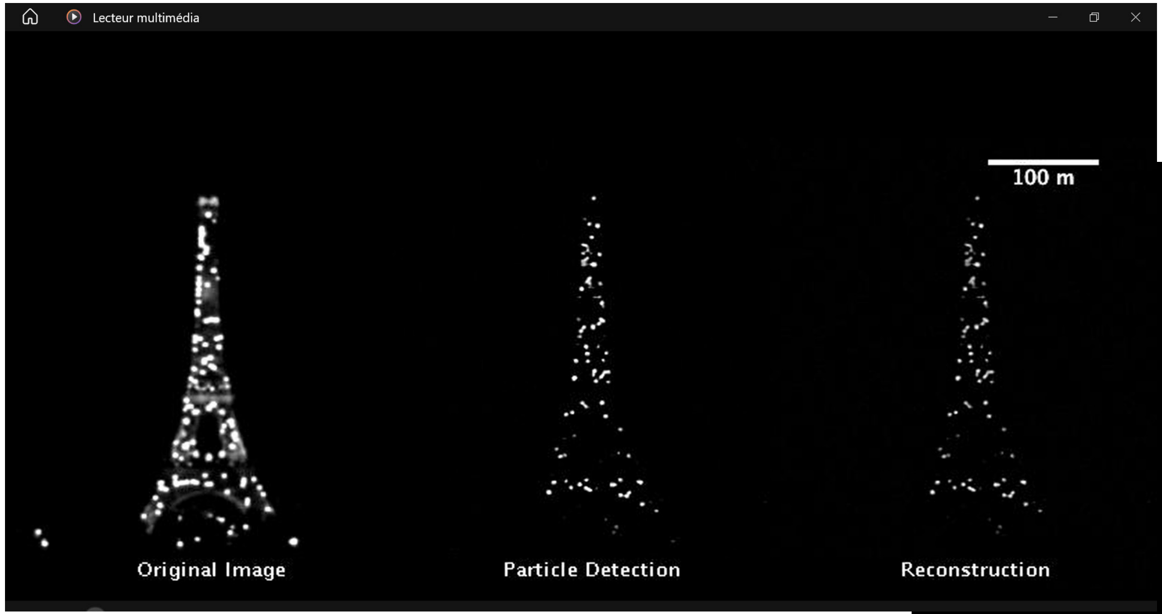
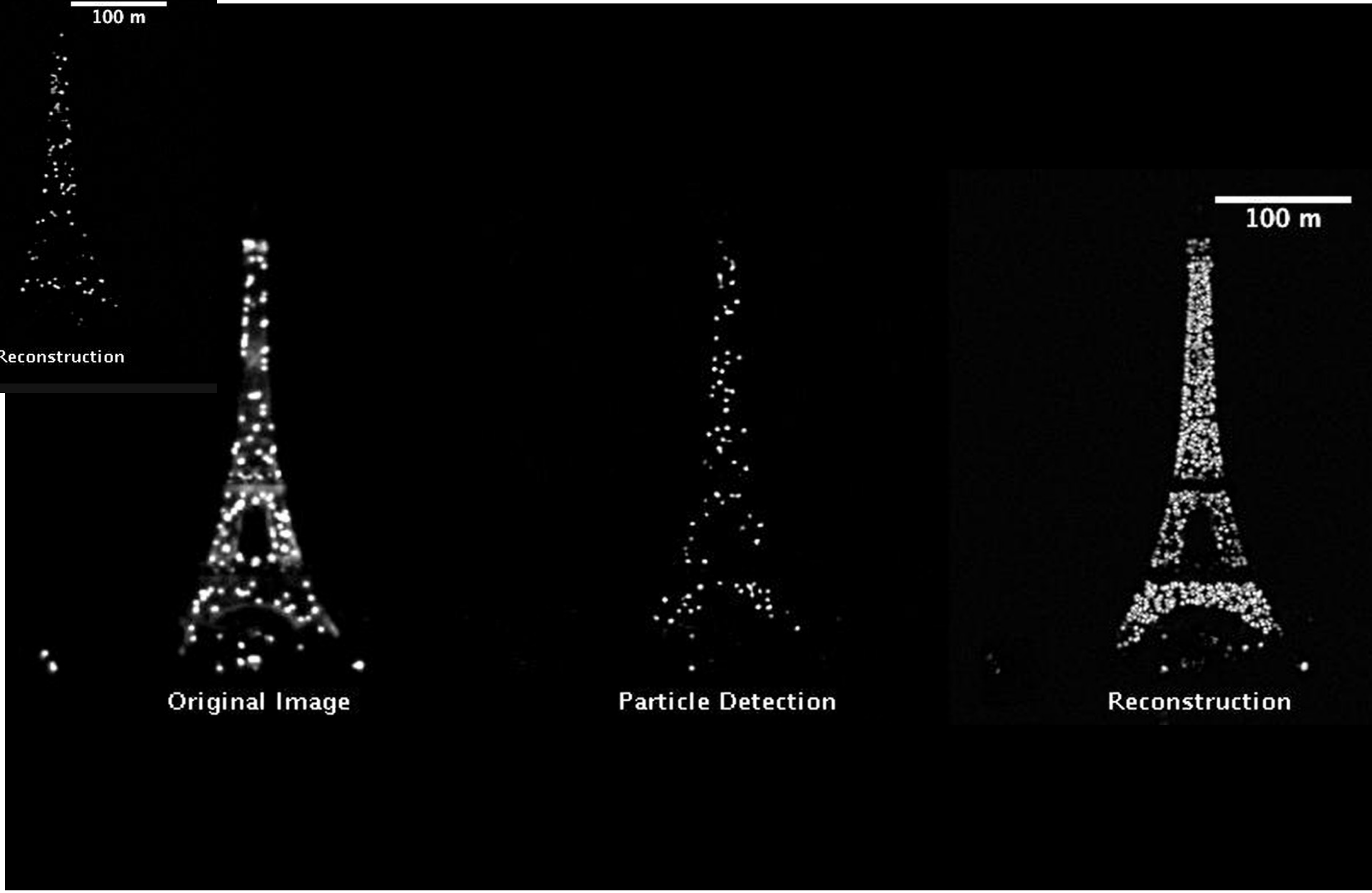
https://www.youtube.com/watch?v=RE70GuMCzww

3.9 Single molecule localization microscopy





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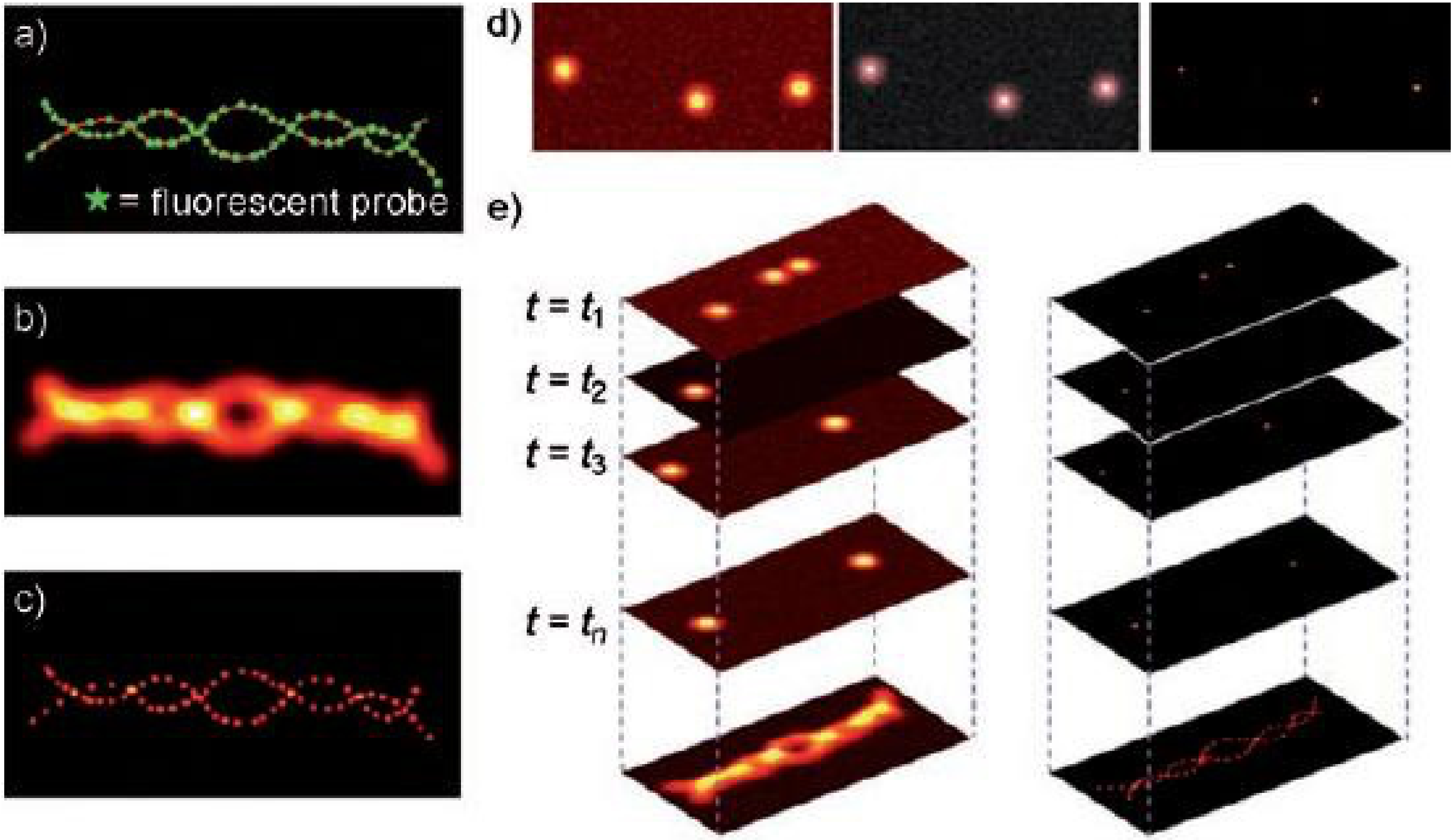
https://figshare.com/articles/dataset/QuickPALM_STORM_over_the_Eiffel_Tower/7284584

3.9 Single molecule localization microscopy



http://bme240.eng.uci.edu/students/08s/mkotlarc/images/PALM2.JPG

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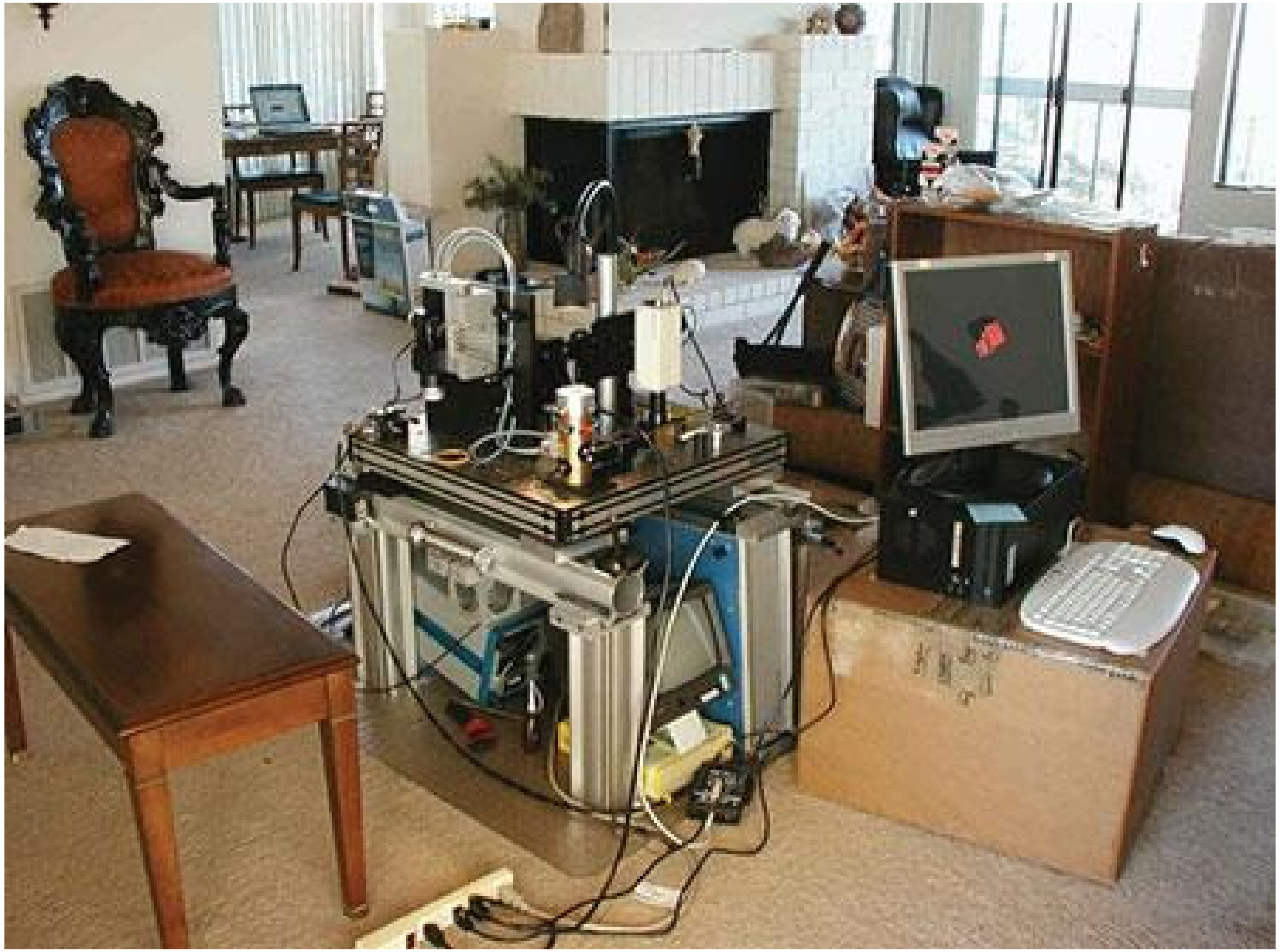
3.9 Single molecule localization microscopy



Eric Betzig's friend's living room setup

PALM (Photoactivated Localization Microscopy)
Localization microscopy

📖 R. Łapkiewicz, Univ. Warsaw, 2024

E. Betzig et al. Science. 313 (5793): 1642–1645 (2006).

Eric Betzig – Nobel Lecture. NobelPrize.org

Take-Home Messages/W3-2

3.4 **Fourier optics:**

- In Fourier optics, explain the « 4F » setup and give an application example.

3.5 **Microscopy:**

- Explain different microscope configurations, in particular widefield vs. Scanning (confocal).
- Which detectors would you use for each implementation?

3.6 **Superresolution Microscopy:**

- Provide examples of underlying principles and implementations and corresponding detectors.

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- Victoria Chalain, EPFL MA

Additional slide material:

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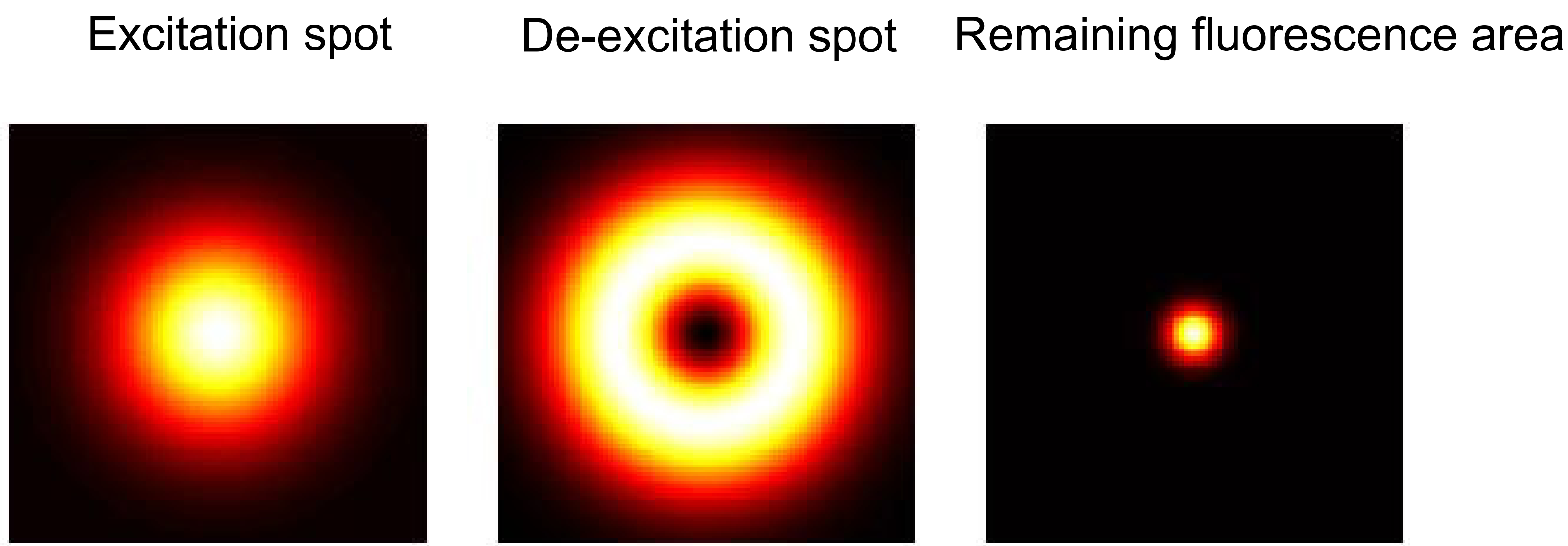
- Georg Fantner, EPFL STI LBNI
- Radek Łapkiewicz, Quantum Imaging Lab, Faculty of Physics, University of Warsaw
- Preethi Padmanabhan, formerly EPFL

Appendix 3.1: Superresolution microscopy: STED

A3.1: Superresolution microscopy: STED

STimulated Depletion Emission microscopy (STED)

- Scanning confocal microscopy technique
- Size of emitting area of the spot is reduced by depleting fluorescence in specific regions of the sample while leaving a centre focal spot active to emit fluorescence.



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A3.1: Superresolution microscopy: STED

When scanning the STED beam, only the fluorophores inside the excitation spot are excited.

Those fluorophores that also are inside the STED doughnut are stimulated to emit. This emission occurs at a wavelength red-shifted from the normal fluorescence. These red shifted photons can be filtered out from the detected signal.

Only the fluorophores that fall inside the excitation beam, but NOT in the STED doughnut are used for image reconstruction.

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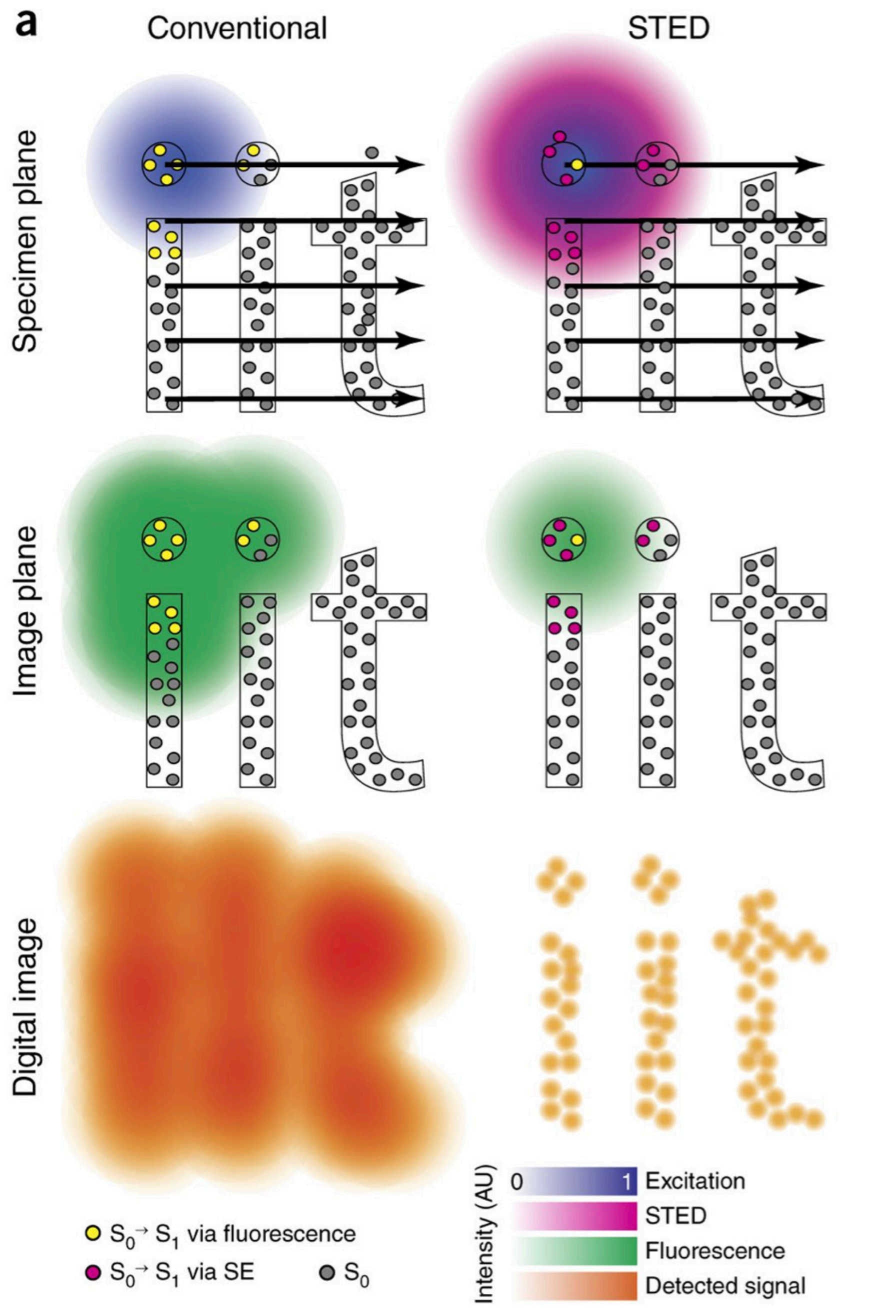
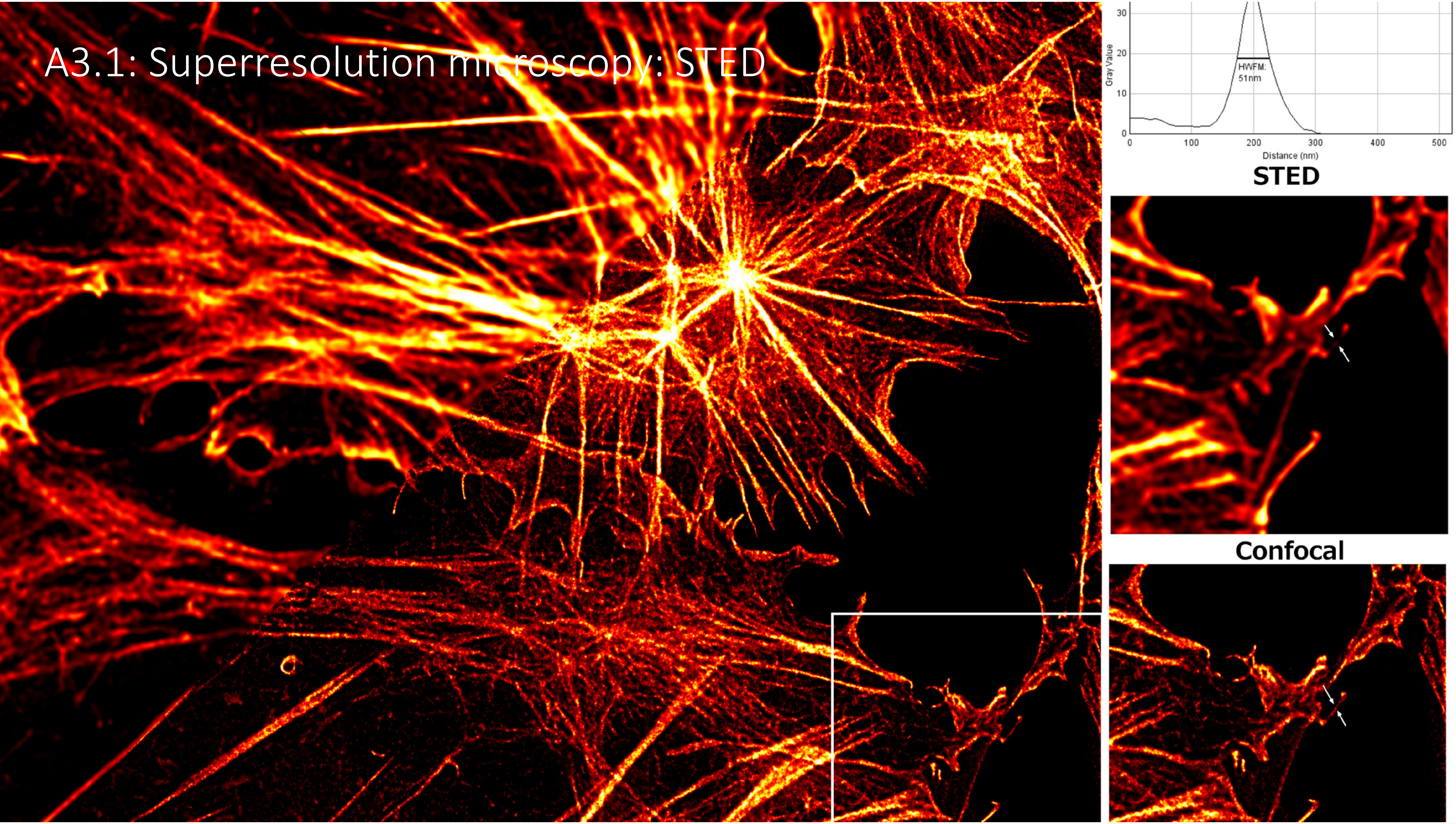


Vicidomini et al. Nature Methods volume 15, pages173–182(2018)

A3.1: Superresolution microscopy: STED



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Exercises – Week 3

Exercise 3.1: Superresolution microscopy

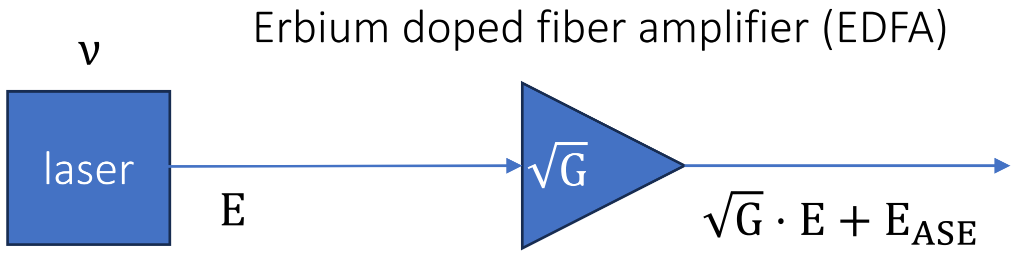
Questions

- Which kind of different microscope configurations exist (in particular widefield vs. Scanning confocal)?

  → Which kind of microscopy superresolution techniques exist?

- Which type of photonic detector would you use?

Exercise 3.2: Optical amplification noise effect on detection



ASE: amplified spontanoues emission

G: power gain

n_{sp}: spontaneous emission factor

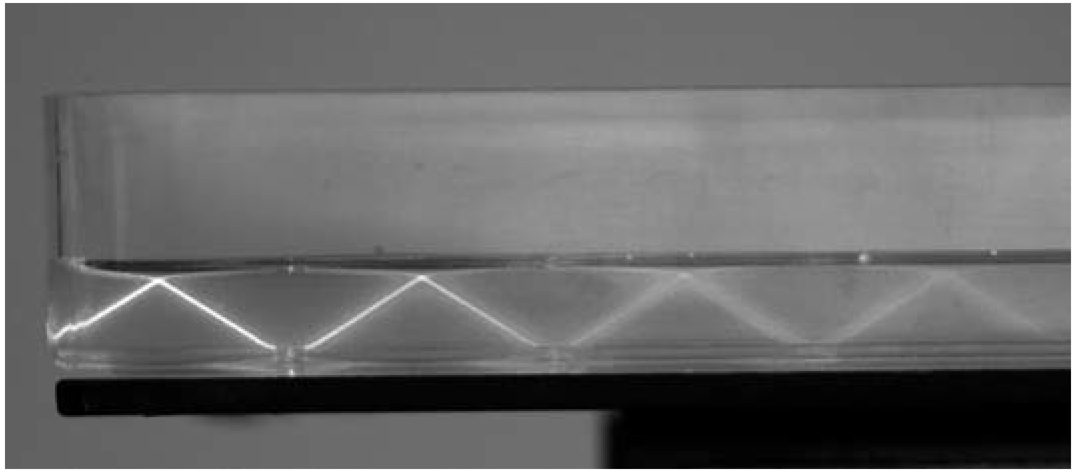
h: Planck's constant

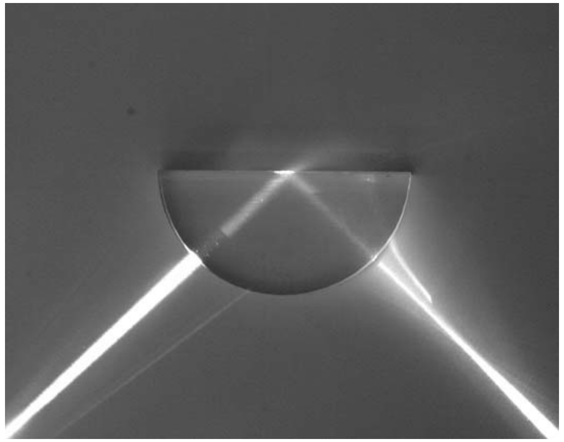
B_o: optical bandwidth

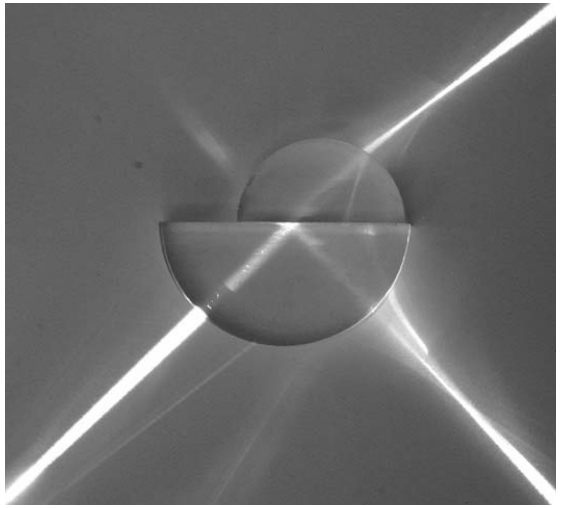
- Neglect all other noise terms apart from ASE
- Use for optical power $P = |E|^2$
- **Sketch the power spectral density [Watt/Hz] and highlight ν, P, P_{ASE}, B_o for G=0, G=25 and G=100**
- **What is the ratio between the signal at frequency ν and noise ? how can we improve the signal to noise ratio?**

Exercise 3.3: Rain Sensor

Design a rain sensor for a car windshield based on these experiments.

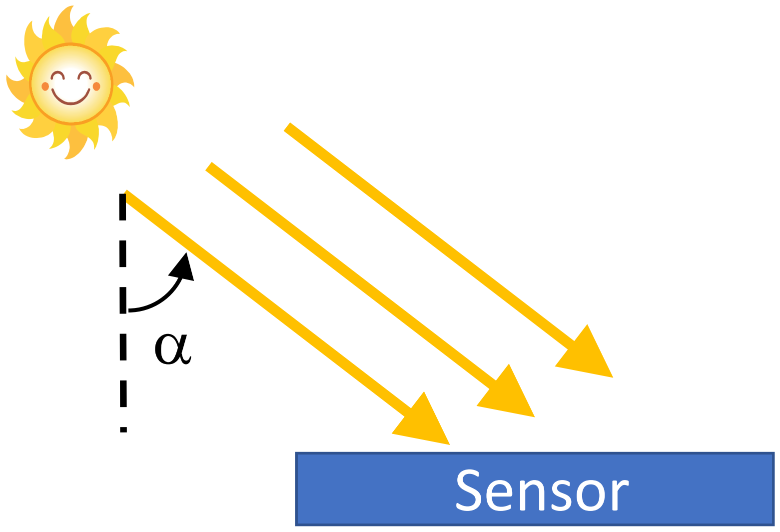






Hints: water presence → total internal reflection
What happens when there is a gap?

Exercise 3.4: Sun Sensor



Hint: sun at ∞, α to be determined
Make it as easy as possible → PSD?

Design a sensor to measure the azimuth and the elevation of the sun!

A potential application could be to guide a satellite.

1) Location sensor:
   -S.W. Janson «micro/nanotechnology for picosatellites», 22nd Annual AIAA/USU Conference on small satellites, paper SSC08-VII-6

2) Camera:
   -N. Xie, A. Theuwissen, «Low-power high-accuracy micro-digital sun sensor by means of a CMOS image sensor», Journal of Electronic Imaging 22(3), 033030 (Jul–Sep 2013)