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Application of LIGO Technology to Biomedical Optics

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LIGO Seminar
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11AM

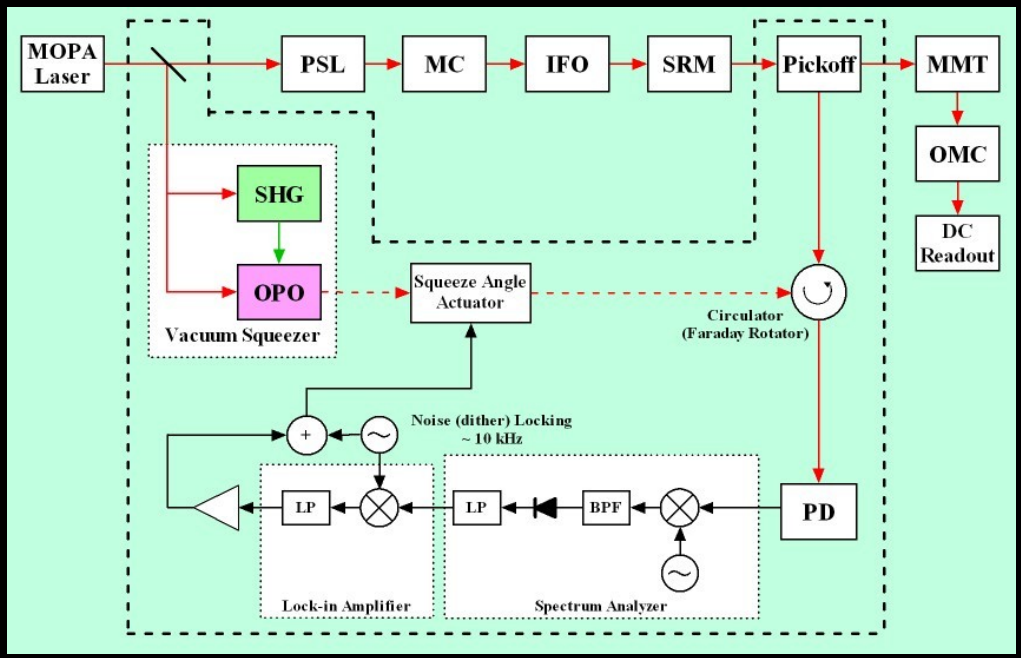
LIGO-G060597-00-Z

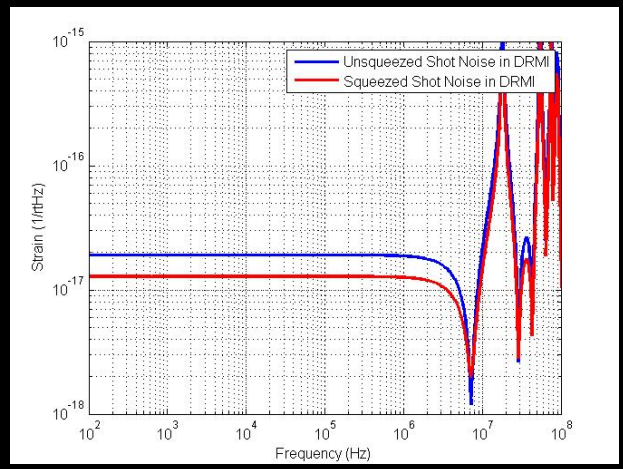
Outline

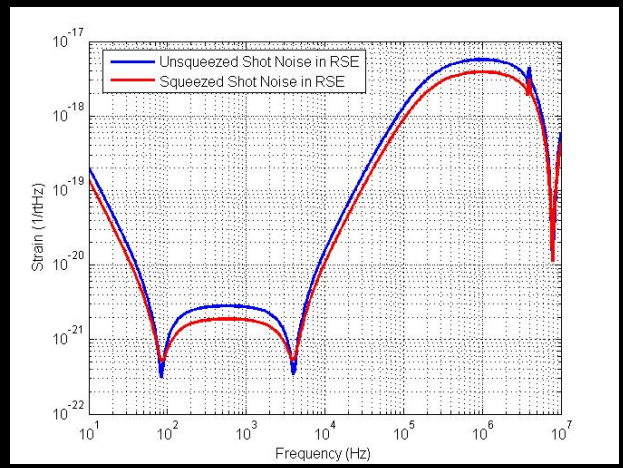
1. A quick report on my research on squeezing-enhanced gravitational-wave interferometers at 40m
2. Optical interferometry in biomedical optics
3. Quantitative imaging using interferometry
4. Measurement of surface tension of red blood cells by quantitative phase microscopy
5. How LIGO technology can be applied to biomedical optics

Squeezing-Enhanced GW Interferometers at 40m

Goal: To Experimentally Demonstrate a Squeezing-Enhanced GW Interferometer in the Advanced LIGO Configuration in the GW Band







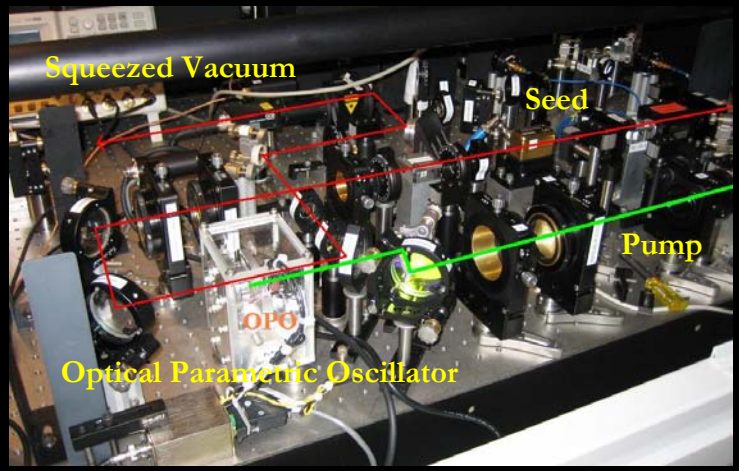
Interface to 40m

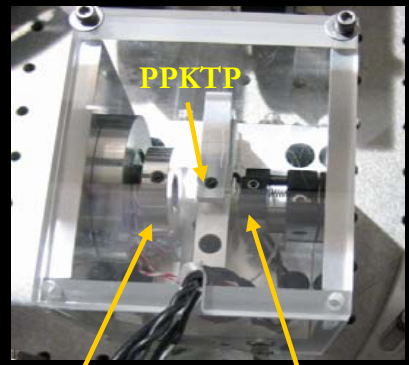
- Squeezer based on MOPA Laser
- Squeezed vacuum injected into the dark port via the circulator
- Squeeze angle locked to reduce broadband shot noise

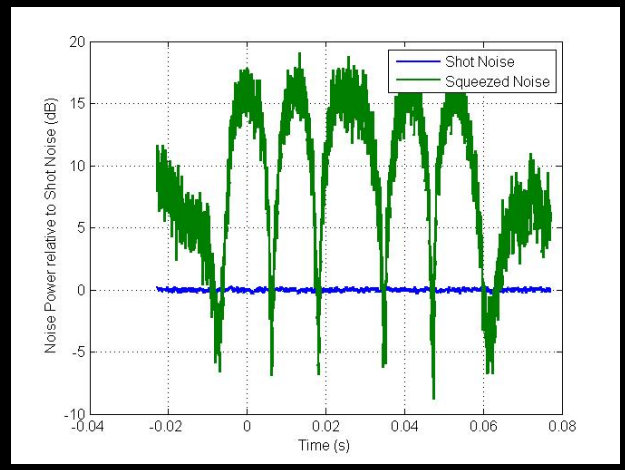
DRMI/RSE Quantum Noise Budget

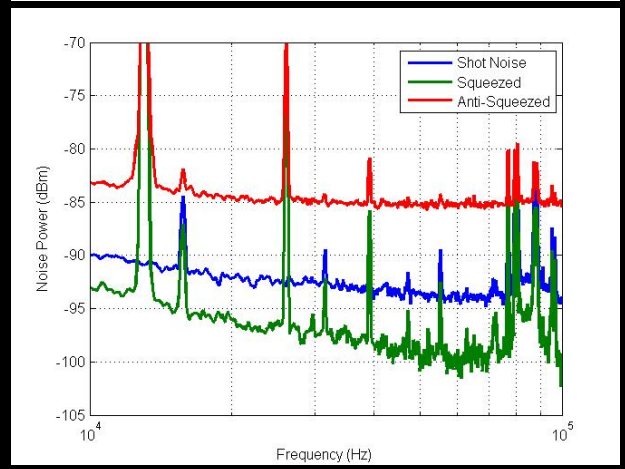
- Input Power to BS = 700mW
- Homodyne Angle = 0
- Squeeze Angle = $\pi/2$
- Initial Squeezing Level = 5dB
- Injection Loss = 10%
- Detection Loss = 10%

Squeezing-Enhanced GW Interferometers at 40m



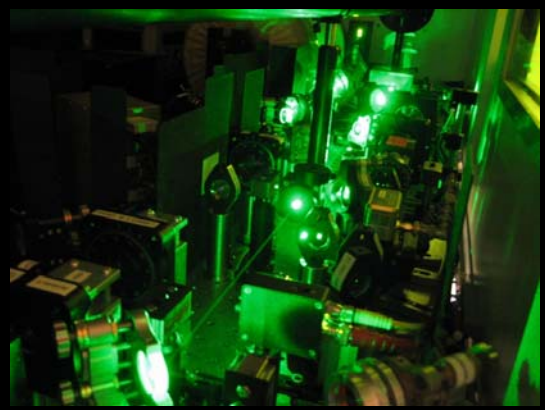






Generation of Squeezed Vacuum in Optical Parametric Oscillation

- Vacuum seed squeezed in presence of pump in OPO
- 2.2 cm OPO cavity with a PPKTP crystal in the middle
- Squeezed vacuum injected to the dark port of the 40m IFO
- Pump field generated by second-harmonic generation (SHG)



Squeezing Result

- About 6.0 dB of scanned squeezing
- About 4.5 dB of broadband squeezing/reduction of shot noise
- Locking stability to be improved

Injection of squeezed vacuum to the 40m IFO to be tested in a month or two..

Optical Interferometry in Biomedical Optics

- **Optical Coherence Tomography (OCT)**
  - Non-invasive optical tomographic (3D) imaging technique
  - Uses low-coherence interferometry (superluminescent diodes or femtosecond lasers as a light source)
  - mm penetration (approx. 2-3mm in tissue)
  - Sub-μm axial and lateral resolution
  - Invented by J. Fujimoto's group at MIT in 1991 [Huang et al., Science, 254, 5035 (1991), Drexler et al., Nature Medicine, (2001)]
  - Used in many biomedical applications, especially in ophthalmology and dermatology

- **Quantitative Phase Microscopy**
  - Non-invasive phase imaging technique
  - Uses CW
  - Nanometer sensitivity
  - High contrast
  - Useful for investigation of cellar dynamics (motility, growth, membrane motion, etc)

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Optical Coherence Tomography (OCT)

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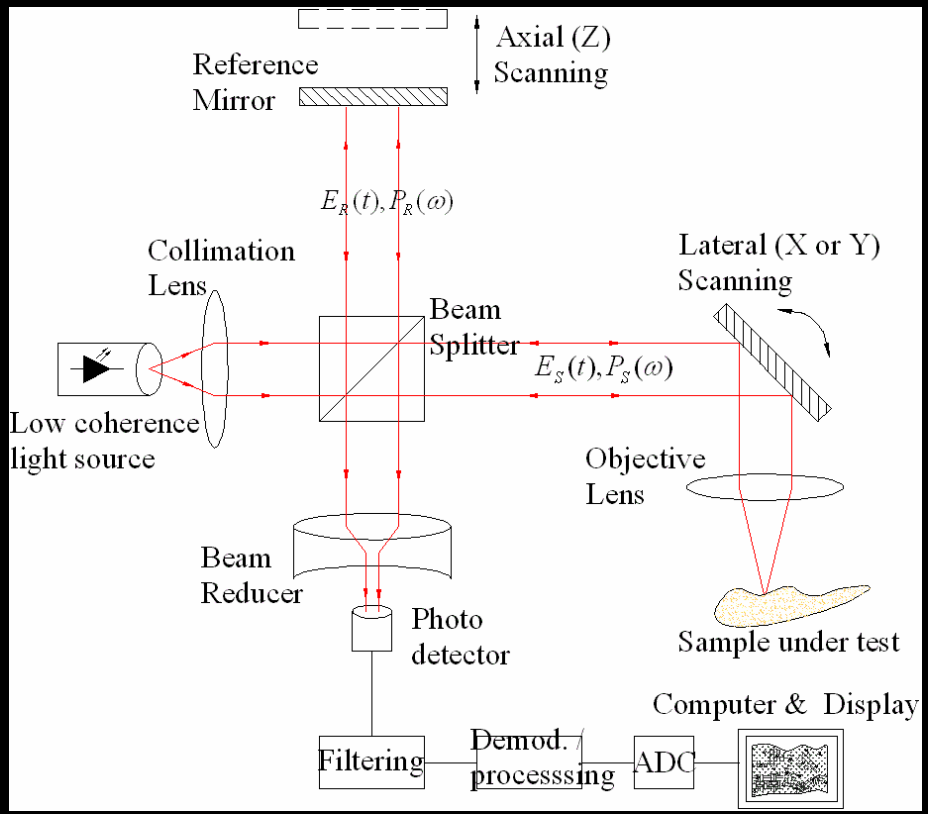

- Interferometry with a low coherent light source
- The light is split into and recombined from reference and sample arms.
- The path-length of the reference arm is translated longitudinally.
- Interference is achieved only when the path difference between the arms lies within the coherence length of the light source.

$$I = I_R + I_S + 2\sqrt{I_R I_S}\,|G(\tau)|\cos\frac{4\pi}{\lambda_0}(L_R - L_S)$$

$$G(\tau) = \exp\left[-\left(\frac{\pi\Delta\nu\tau}{2\sqrt{\ln 2}}\right)^2\right]\exp(-i2\pi\nu_0\tau)$$

Coherence length or axial resolution

$$l_c = \frac{2c\ln 2}{\pi}\cdot\frac{1}{\Delta\nu} \approx 0.44\frac{\lambda_0^2}{\Delta\lambda}$$

- ν_0 = center frequency of the light source
- $\Delta\nu$ = FWHM
- τ = optical time delay between the arms

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Optical Coherence Tomography (OCT)

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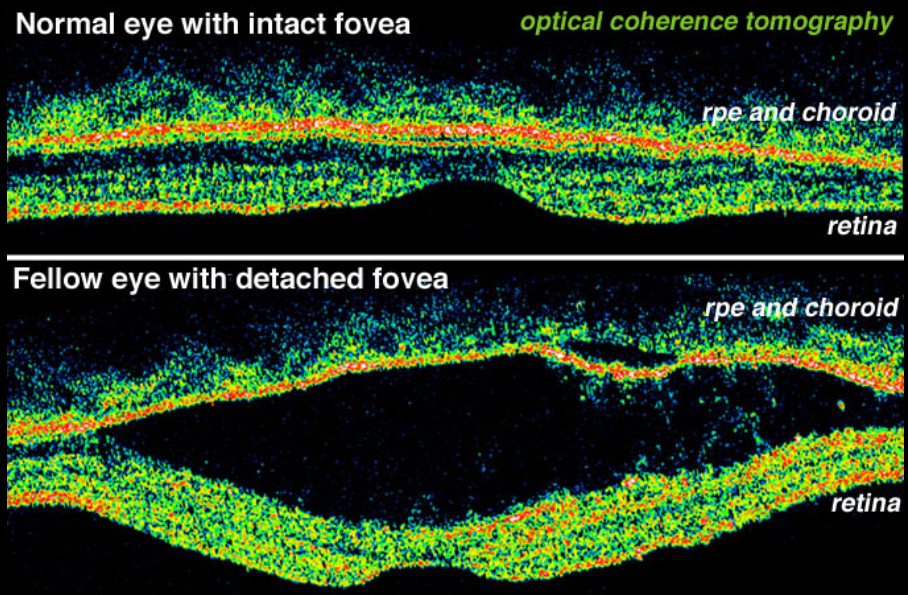
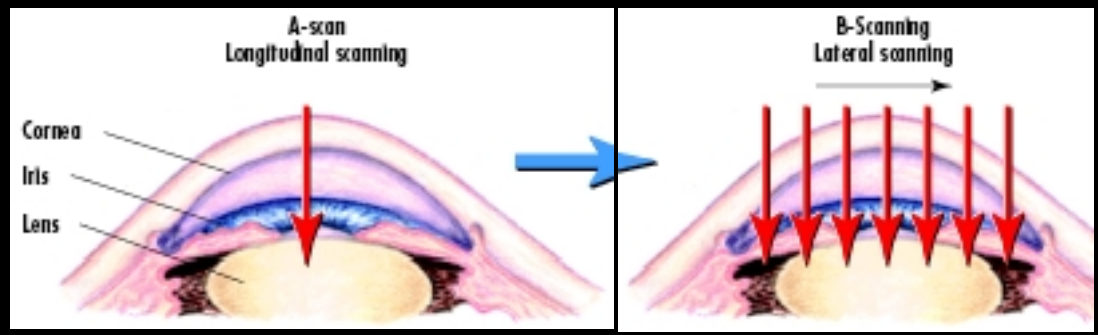


Fig. 31b. Optical coherence tomography (OCT) images of the patient's normal macula and of the retina in the other eye with the macular detachment.

Carl Zeiss Inc.

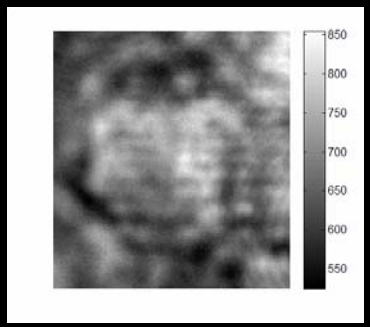


Quantitative Phase Imaging

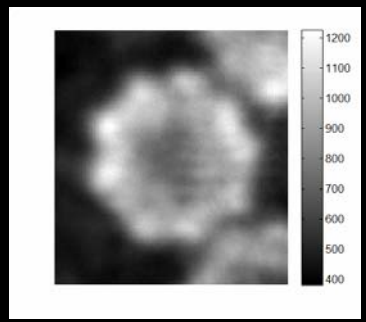
- **Advantages over biochemical methods**
  - Non-invasive
  - No preparation
  - Fast
  - Quantitative

- **Advantages over conventional microscopes**
  - Quantitative
  - Cells are transparent → they are phase objects
  - High contrast
  - High axial sensitivity
  - High time resolution (high speed)

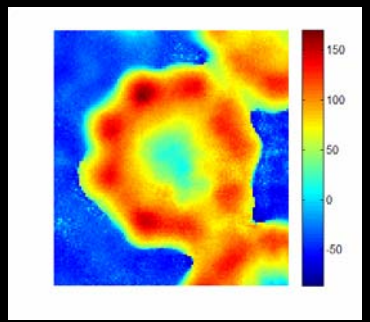
Bright Field



Phase Contrast



Quantitative



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Apparatus of Quantitative Phase Microscope

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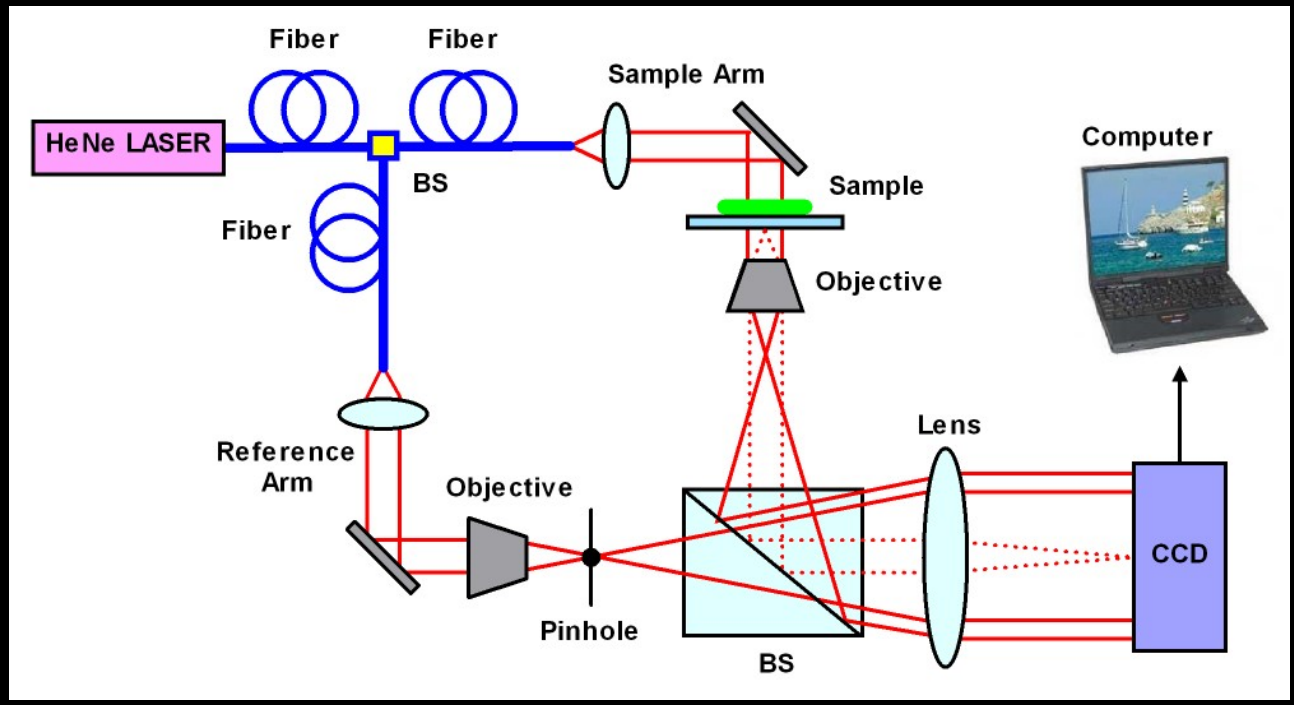

- LASER: a few mW at 633nm
- Fiber: mode-cleaner
- Objective: 100X, NA = 1.2
- Transverse resolution: 0.3μm
- Pinhole: low-pass filter
- CCD: digital hologram
- Post-processing on the computer

Reference Arm is purposely misaligned to Sample Arm in one of the transverse directions to create a (spatially) high frequency fringe.

T. Ikeda, G. Popescu, R. R. Dasari, and M. S. Feld, Opt. Lett., 30, 1165 (2005)

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Extraction of Sample Phase Content

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$$I(x) = I_R + I_S(x) + 2\sqrt{I_R I_S(x)}\cos[qx + \phi(x)]$$

↓ **High-pass filtering**

$$I(x) = 2\sqrt{I_R I_S(x)}\cos[qx + \phi(x)]$$

↓ **Weak dependence of the fields on x**

$$I(x) = 2\sqrt{I_R I_S}\cos[qx + \phi(x)]$$

↓ **Demodulation at q and low-pass filtering**

$$I(x) = 2\sqrt{I_R I_S}\cos\phi(x)$$

↓ **Kramers-Kronig relation**

$$z(x) = \frac{1}{2}I(x) + i\frac{P}{2\pi}\int_{-\infty}^{\infty}\frac{I(x')}{x - x'}dx'$$

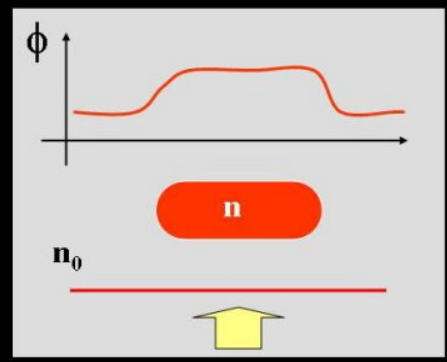
↓ **Take the ratio of Im[z(x)] and Re[z(x)]**

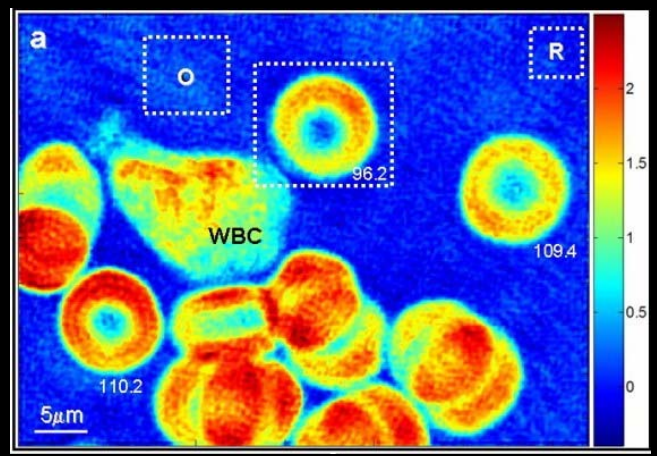
$$\phi(x) = \tan^{-1}\frac{\mathrm{Im}[z(x)]}{\mathrm{Re}[z(x)]}$$

Red blood cells (RBCs):

- optically homogeneous

$$\phi = 2\pi\frac{h}{\lambda}(n_{cell} - n_{plasma})$$





Red Blood Cells (RBCs)

Why interested in RBCs?

- Membrane integrity → Cell shape
- Shape
  - → Indicator of health
  - → Pathology (sickle cell disease, alcoholism, etc)
- Simple, flexible, dynamic
- Membrane mechanics and fluctuations not well understood

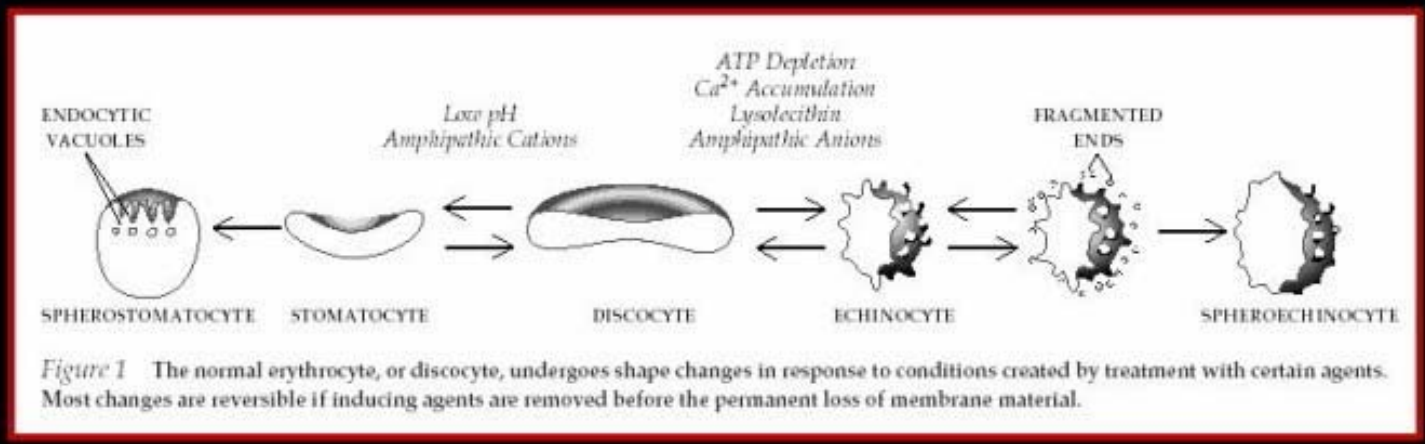


Figure 1 The normal erythrocyte, or discocyte, undergoes shape changes in response to conditions created by treatment with certain agents. Most changes are reversible if inducing agents are removed before the permanent loss of membrane material.

WebMD Scientific American [2001]

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Apparatus of Phase-Locked Quantitative Phase Microscope

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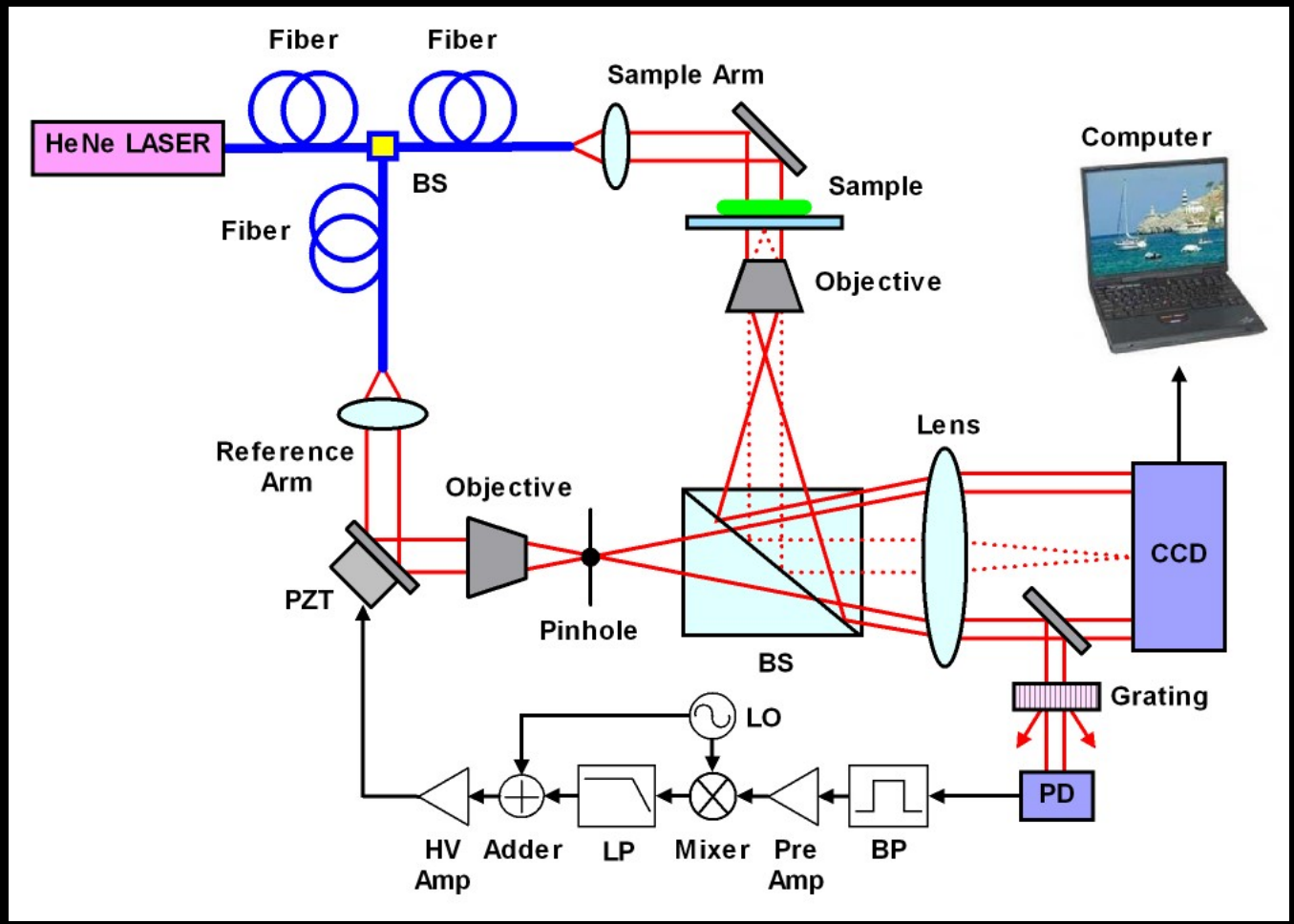

- Amplitude grating as a high-pass filter to extract only the component of the light that matches the fringe frequency
- Dither locking with a PZT in Reference Arm helps investigate cellar activity at nm sensitivity
- Long-term observation of cellar activity at a high speed is possible with a high speed CCD camera

G. Popescu, T. Ikeda, K. Goda, C. A. Best, M. Laposata, S. Manley, R. R. Dasari, K. Badizadegan, and M. S. Feld, Phys. Rev. Lett., 97, 218101 (2006)

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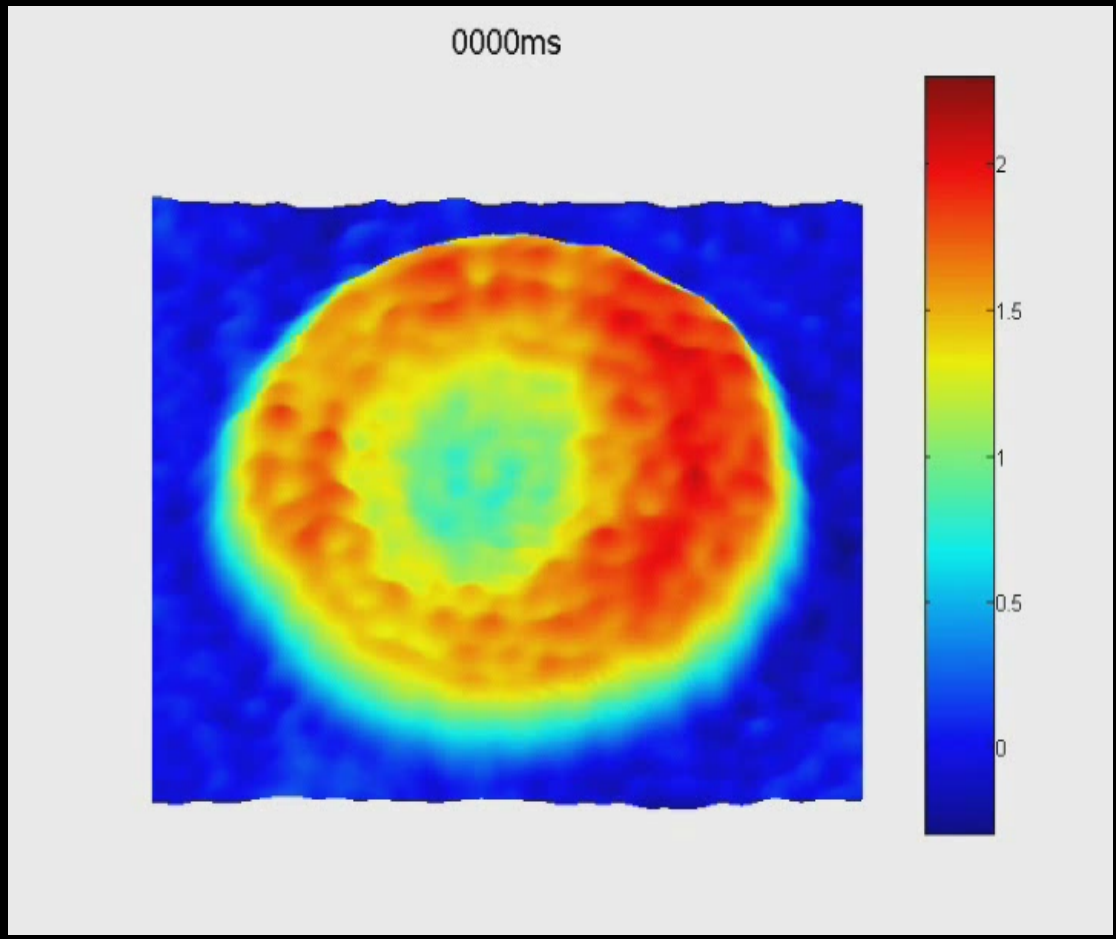
RBC Fluctuations

170 frames at 10.3ms/ frame

Normal Cell



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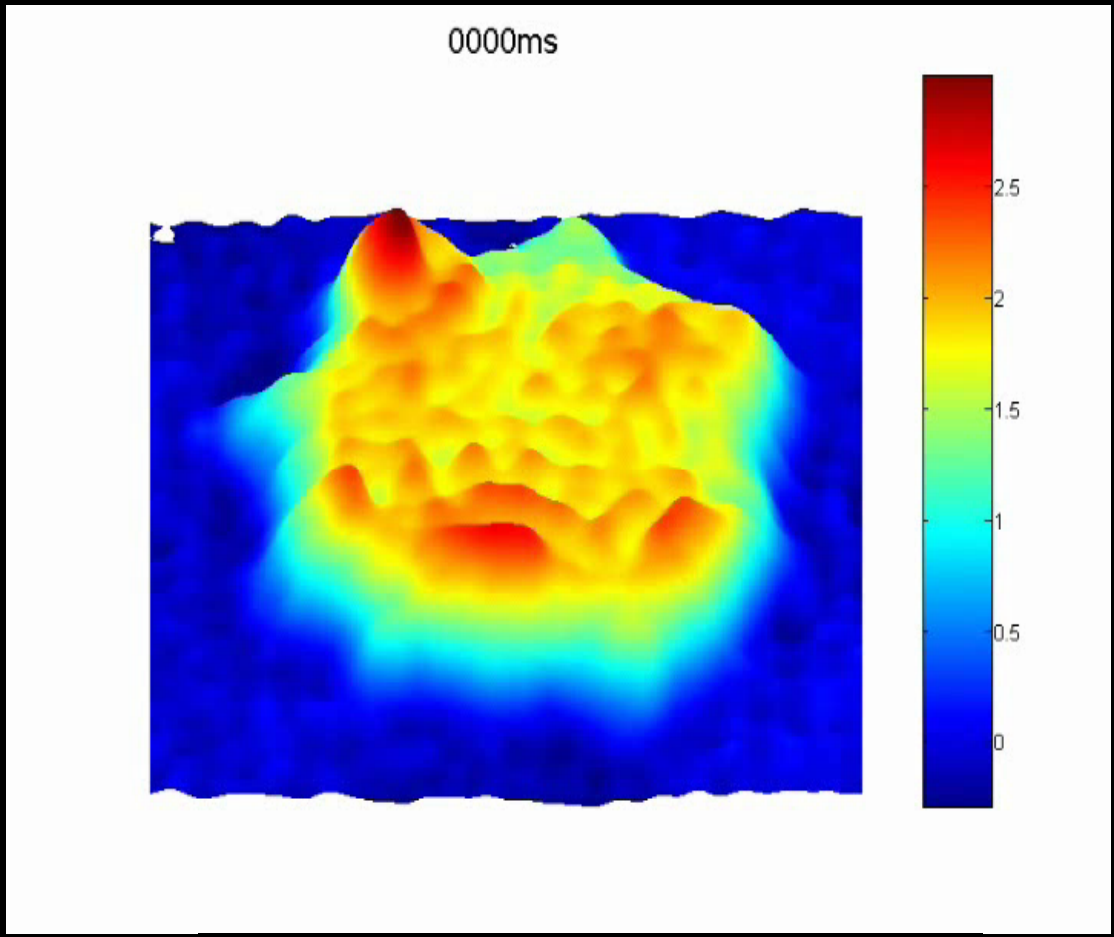
RBC Fluctuations

170 frames at 10.3ms/ frame

Echinocyte



- Echinocyte = crenated red blood cell

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Analysis of Surface Tension

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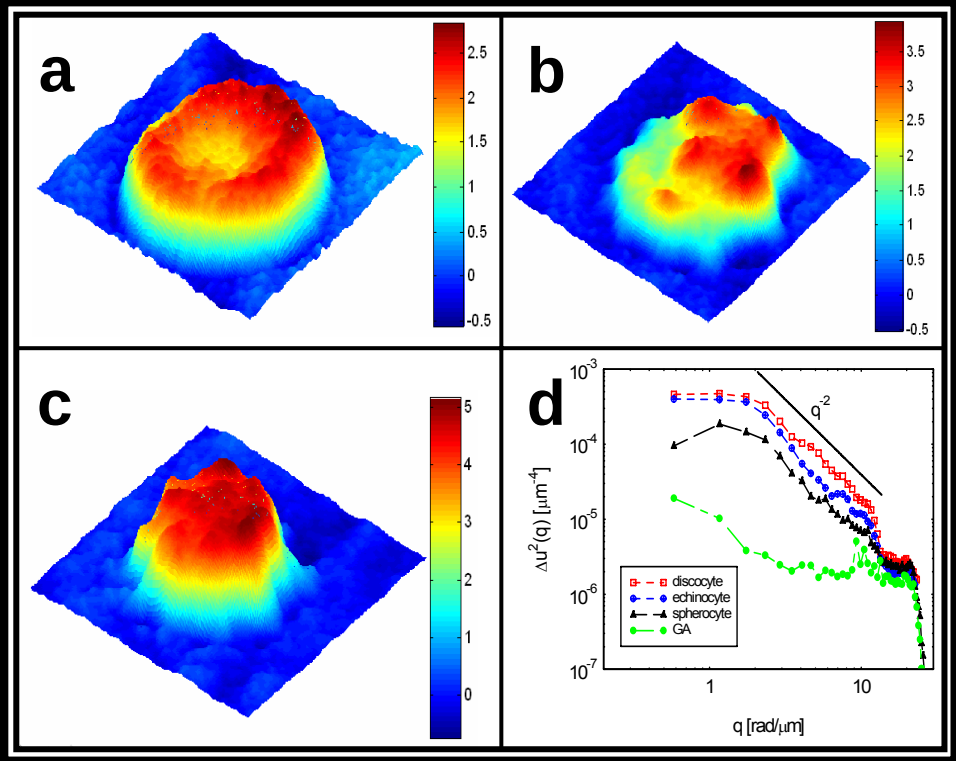
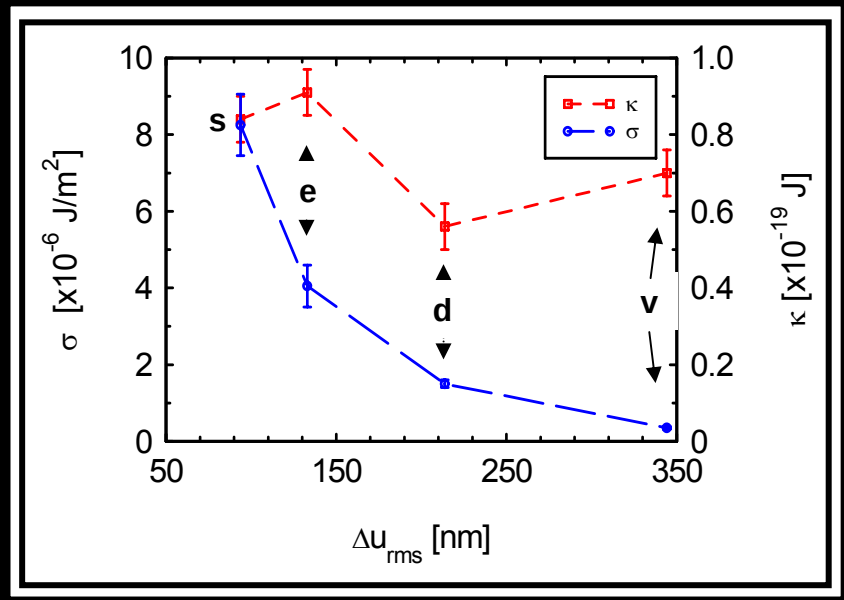




$$\left\langle \Delta u^2(q) \right\rangle \propto \frac{K_B T}{k_c q^4 + \sigma q^2}$$

$$l_c \propto \sqrt{\frac{\kappa}{\sigma}}$$

$\kappa = bending$

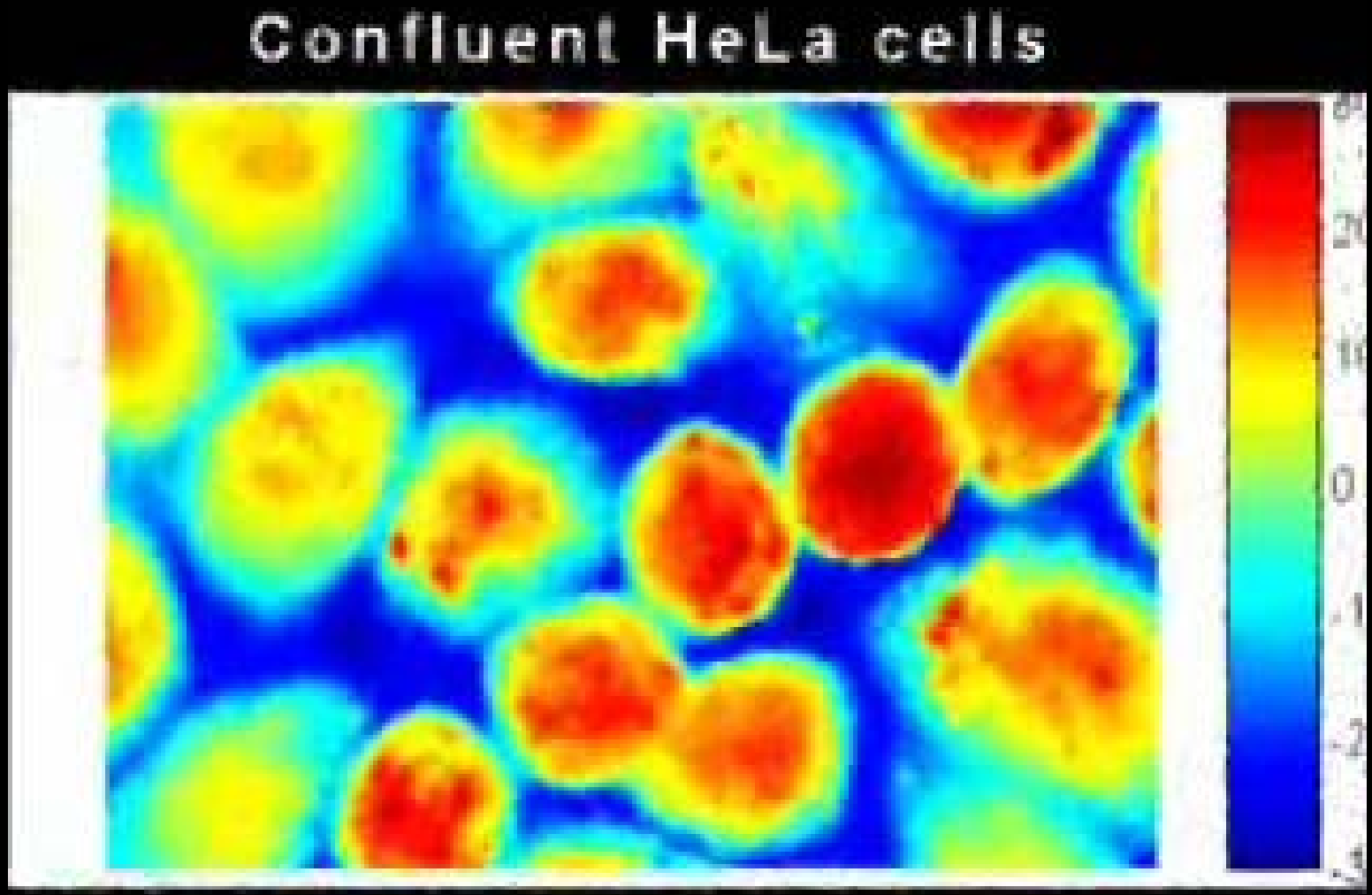
$\sigma = tension$

s - spherocytes
e - echinocytes
d - discocytes
v - vesicles

- Tension increases from discocyte to spherosyte
- Measurement of surface tension can be used as a medical diagnostic tool

G. Popescu, T. Ikeda, K. Goda, C. A. Best, M. Laposata, S. Manley, R. R. Dasari, K. Badizadegan, and M. S. Feld, Phys. Rev. Lett., 97, 218101 (2006)

Some More Movies



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How LIGO Technology Can Be Applied to Biomedical Optics

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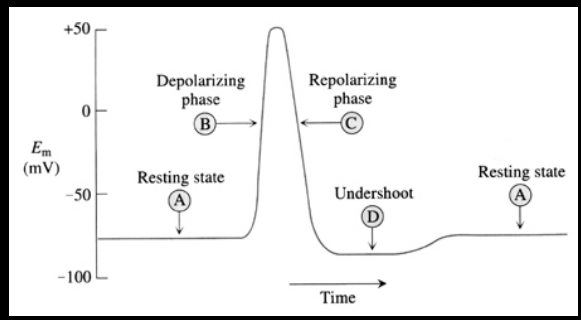
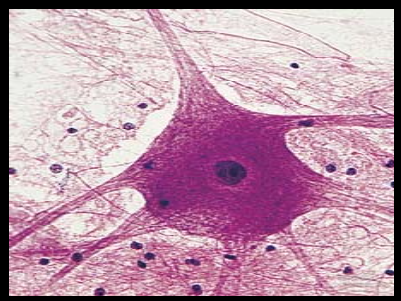
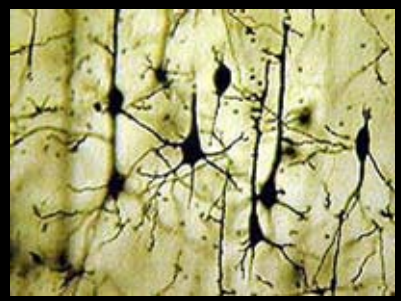
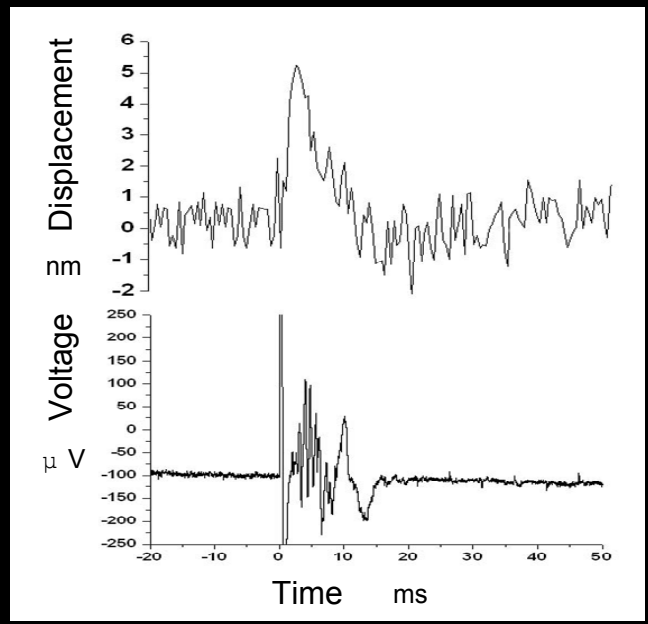
- Increase detector sensitivity
  - By Noise Reduction
  - By Feedback Control
  - By inventing a new low-noise configuration



- Another Example (Detection of Neuron Swelling)
  - Neuron axons swell during the propagation of action potential.
    [I. Tasaki et al., Science, 210, 338 (1980)]
  - Neuron axons become birefringent during the propagation of action potential.







C. Fang-Yen, M. C. Chu, H. S. Seung, R. R. Dasari, and M. S. Feld, Opt. Lett., 29, 2028 (2004)