Keck
INSTITUTE FOR SPACE STUDIES
CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

# Developing and Deploying Single Photon Counting Array Detectors

Don Figer, Director, Rochester Imaging Detector Laboratory

Single Photon Counting Detectors
Opening Workshop: January 25-29, 2010
California Institute of Technology
Pasadena, CA 91125

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R·I·T

# Outline

- Motivation for Single Photon Counting Detectors
- Applications
- Current Detector Development Projects
  - photon-counting detector for astrophysics
  - imaging LIDAR detector for planetary missions
  - technology demonstration for exoplanet missions
- Future Directions

# Paul’s Shirt

- “Leave no photon behind….”
- “A photon is a terrible thing to waste….”

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# Motivation for Quantum-Limited Detectors

# This is Why Detectors are Important

$$SNR = \frac{S}{N} = \frac{\eta_{inst} A \frac{\Delta \nu}{h\nu} F_{\nu} t QE_{\nu}}{\sqrt{\left(\eta_{inst} A \frac{\Delta \nu}{h\nu} F_{\nu} t QE_{\nu}\right) + \left(\eta_{inst} A \frac{\Delta \nu}{h\nu} F_{back,\nu} t QE_{\nu}\right) + i_{dark} t + N_{read}^{2}}}.$$

TRANSLATION: Better detectors make more discoveries, solve more problems, cure more people, identify more threats, reduce conflict, and manage resources more effectively.

# Detector Properties and SNR

$$SNR = \frac{S}{N} = \frac{\eta_{inst} A \frac{\Delta\nu}{h\nu} F_\nu \boxed{tQE_\nu}}{\sqrt{\left(\eta_{inst} A \frac{\Delta\nu}{h\nu} F_\nu \boxed{tQE_\nu}\right) + \left(\eta_{inst} A \frac{\Delta\nu}{h\nu} F_{back,\nu} \boxed{tQE_\nu}\right) \boxed{+ i_{dark}} t + \boxed{N_{read}^2}}}.$$

for Quantum-Limited Detectors, $i_{dark} \to 0, N_{read} \to 0, QE_\nu \to 1.$

$\tau =$ exposure time to reach a particular SNR. Solve SNR equation for t.

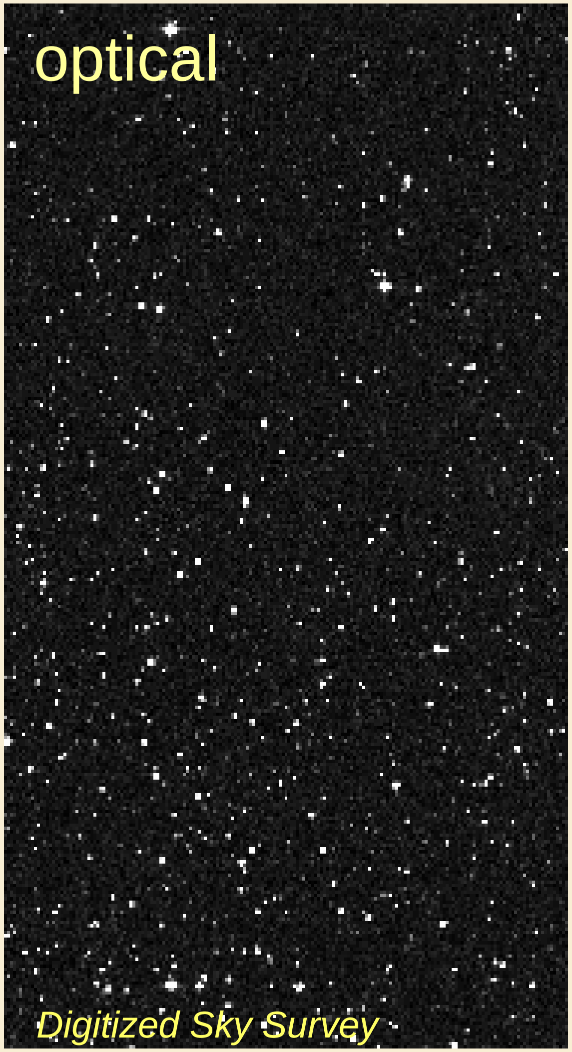
$$\tau = \frac{SNR^2 (N_\gamma QE + n_{pix} N_{\gamma,background} QE + n_{pix} i_{dark}) + \sqrt{SNR^4 (N_\gamma QE + n_{pix} N_{\gamma,background} QE + n_{pix} i_{dark})^2 + 4 N_\gamma^2 n_{pix} (QE\, N_{read}\, SNR)^2}}{2 (N_\gamma QE)^2}$$

$$\tau \xrightarrow{SNR=1 \text{ and } N_{\gamma,background}=0 \text{ and } i_{dark}=0} \frac{N_{read}\sqrt{n_{pix}}}{N_\gamma QE}.$$

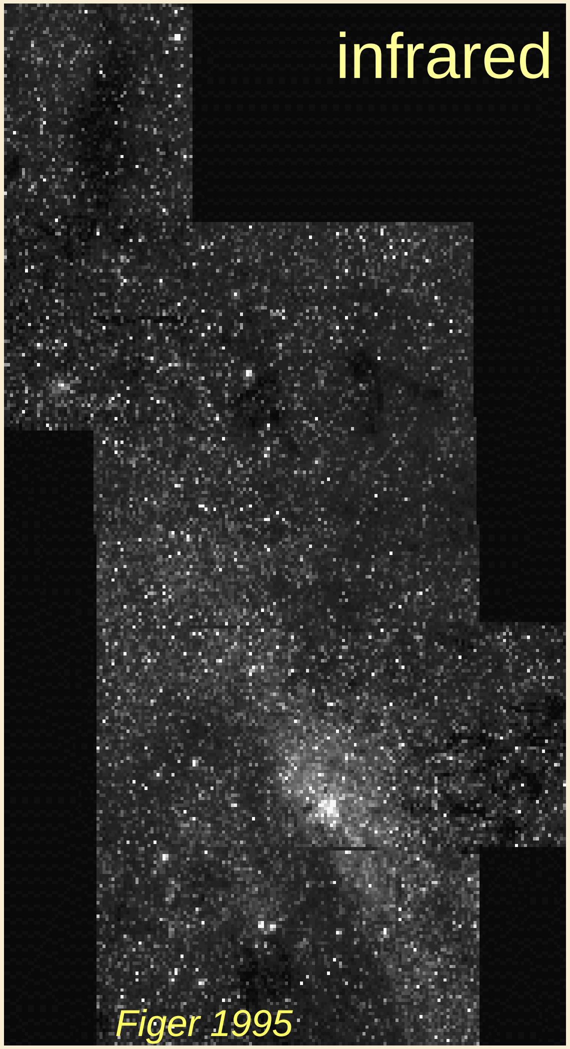
# Quantum-Limited Imaging Detectors

- limited by the information carried by a photon
  - existence in time and space (x, y, z, t)
  - wavelength ($\lambda$)
  - polarization
- "easier said than done….."

# Where is the Center of the Galaxy?



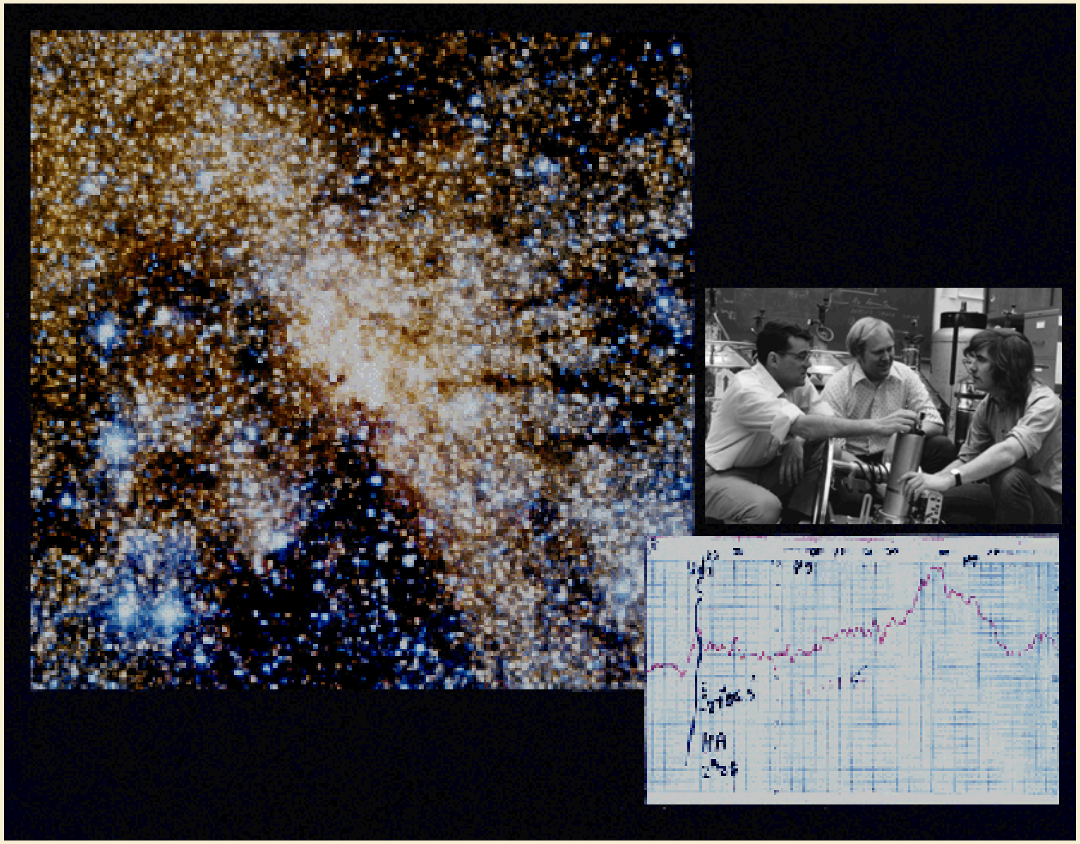
*Digitized Sky Survey*



*Figer 1995*

# Make Discoveries: Galactic Center

**El Centro Galáctico: 1967-1994**

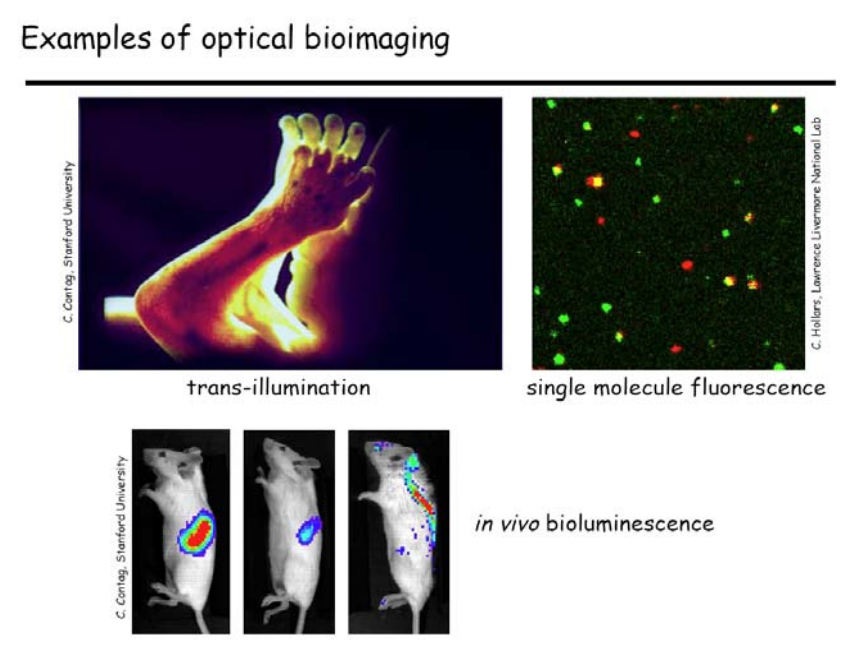


**Gatley/NOAO/KPNO, (PtSi array) G. Neugebauer & E. E. Becklin/Caltech (PbS)**

# ”Imaging” Detectors for non-imaging Applications: Spectroscopy

Figer et al. 2000

# Cure People



## Examples of optical bioimaging

C. Contag, Stanford University

trans-illumination

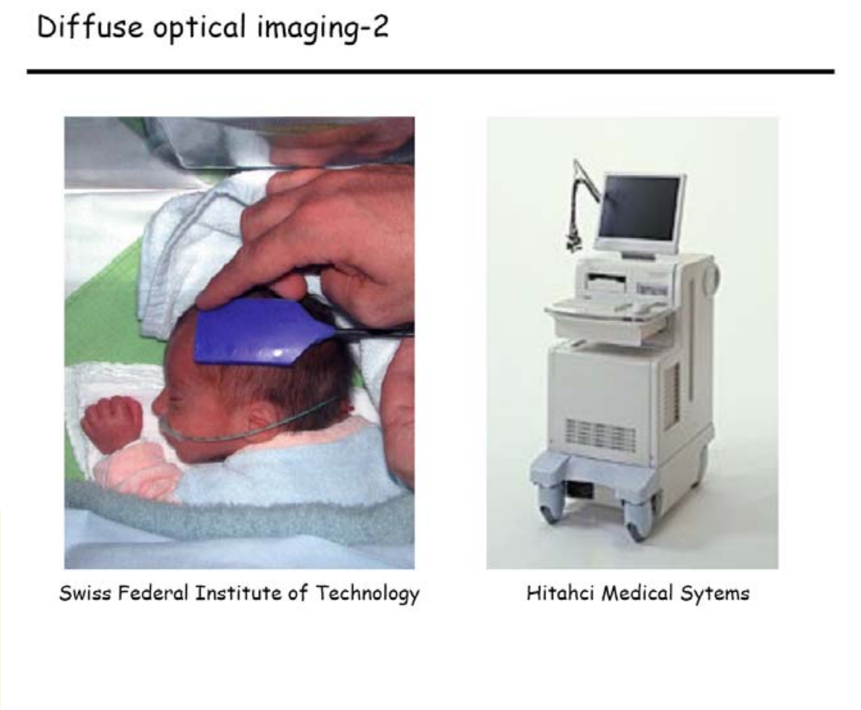
C. Hollars, Lawrence Livermore National Lab

single molecule fluorescence

C. Contag, Stanford University

*in vivo* bioluminescence

*breast cancer detection*



## Diffuse optical imaging-2

Swiss Federal Institute of Technology

Hitahci Medical Sytems

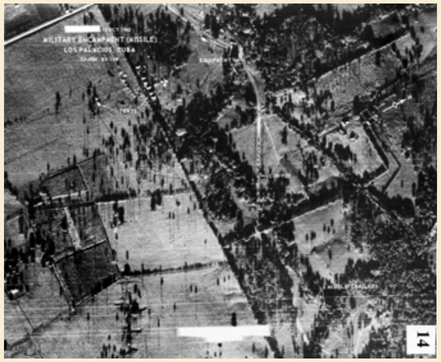
# Identify Threats

- Threats to national security assets
  - inter-continental ballistic missiles
  - anti-satellite kill vehicle
  - orbital debris
  - laser blinding systems

- Threats to people/homeland
  - bio/chem hazards
  - dirty bombs

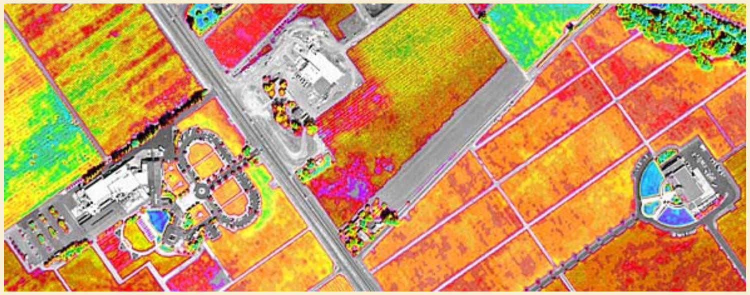
# Reduce Conflict

- Monitoring
  - treaty compliance
  - nuclear proliferation
  - arms buildup
- Enabling pre-emptive strikes
- Enabling conflict resolution



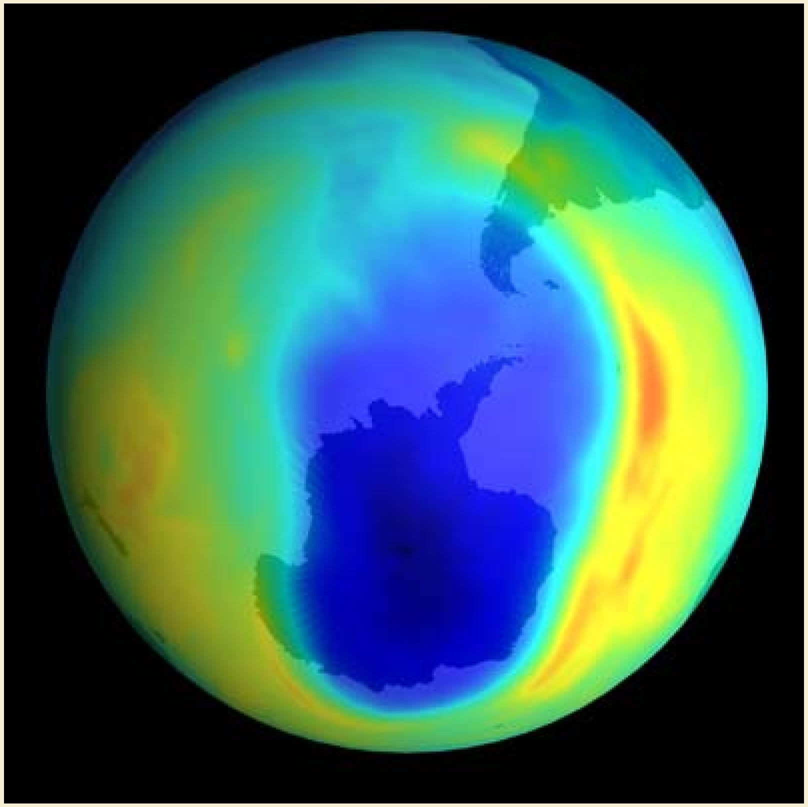
# Manage Resources

Water



Vegetation

Forests



Atmosphere (e.g. ozone)

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# Enter Photon-Counting Detectors

- Sensitivity in low light
- High speed imaging and multi-spectral data for dynamic targetting and discrimination
- Maintain near-ideal performance in very bright lighting
- Enable high range resolution 3D imaging
- Note that many applications can become low light applications with higher resolutions:
  - high-speed imaging, target identification/tracking
  - LIDAR across long distances
  - spectroscopy
  - fast wavefront sensing

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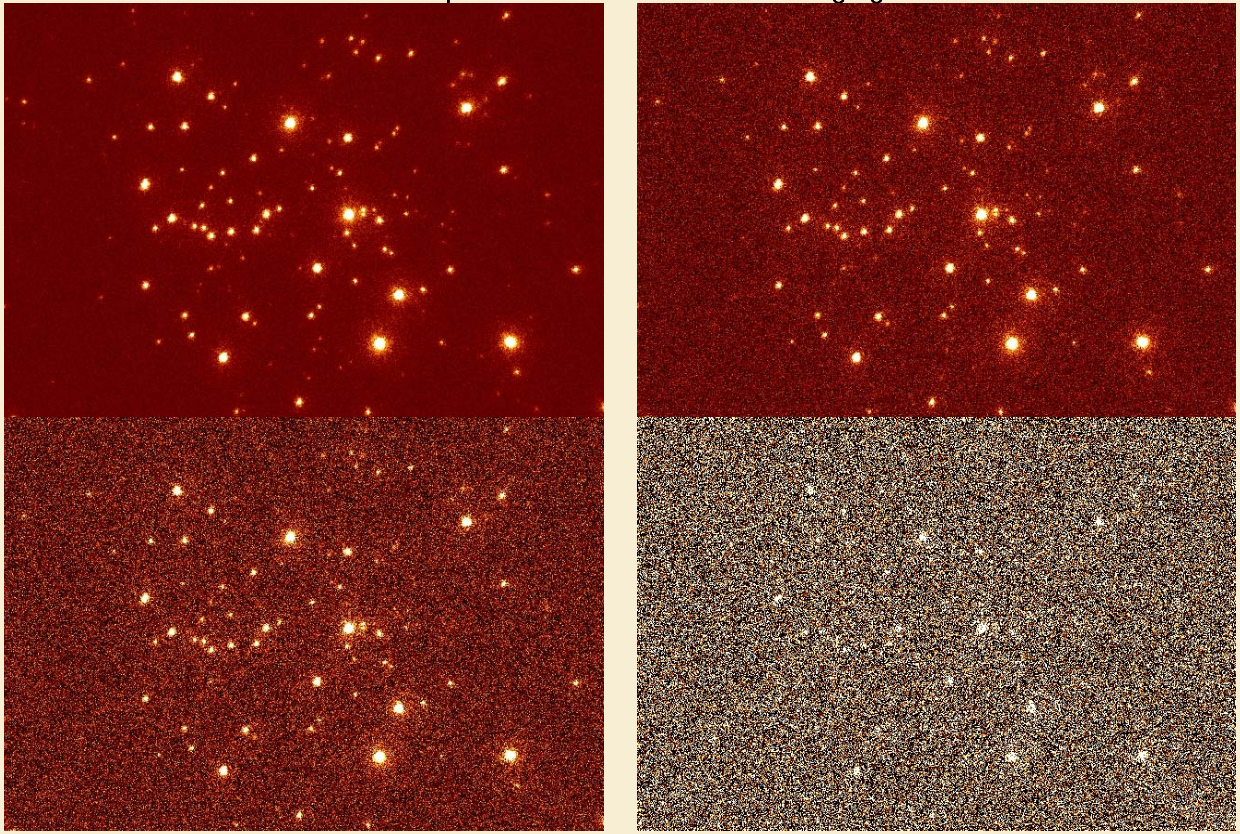
# Outer Space Applications

# Read Noise

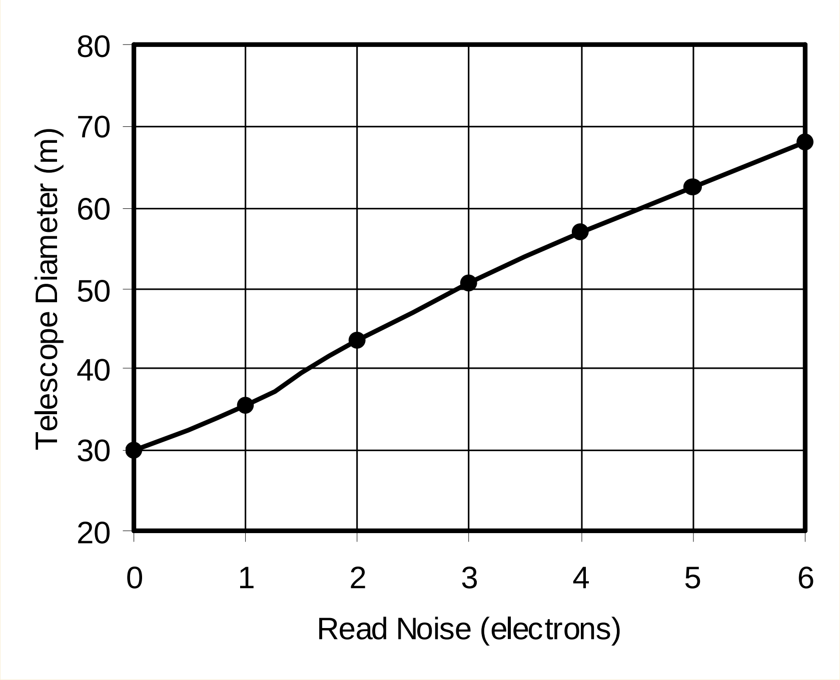


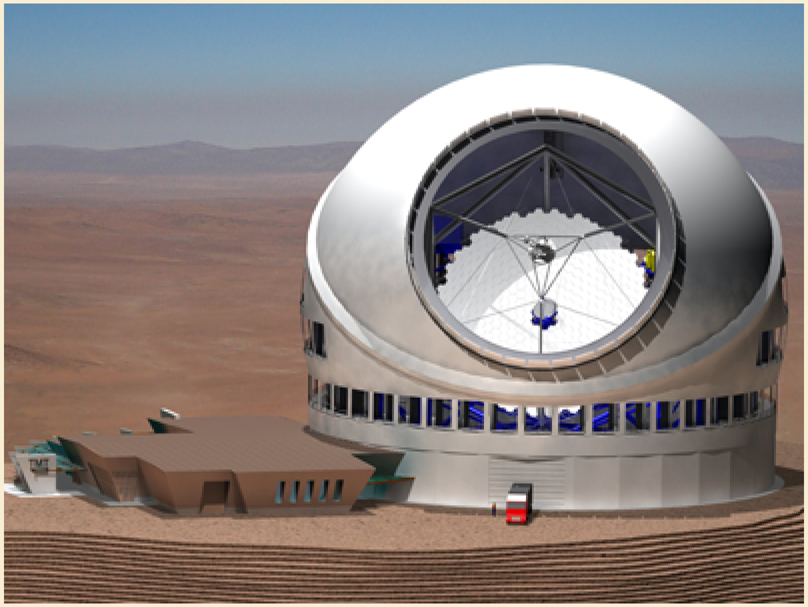
The Importance of Read Noise in Imaging

*Images of the Arches cluster near the Galactic center, based on real data obtained with Keck/LGSAO. Each image has synthetic shot noise and increasing read noise (left to right and top to bottom: 0, 5, 10, 100 electrons).*

# Aperture vs. Read Noise

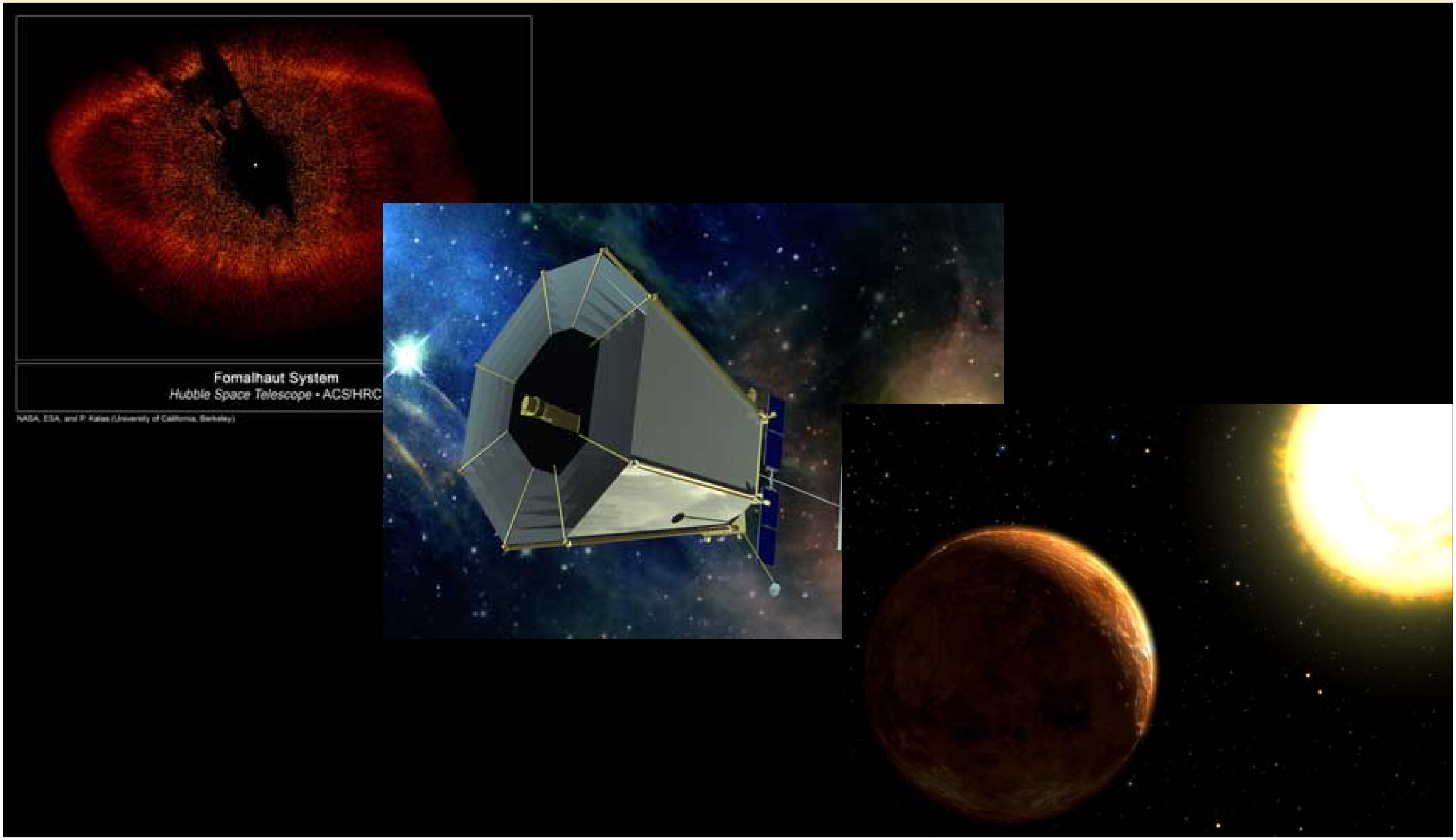
**Effective Telescope Size vs. Read Noise**





*This plot shows a curve of constant sensitivity for a range of telescope diameters and detector read noise values in low-light applications. A 30 meter telescope and zero read noise detector would deliver the same signal-to-noise ratio as a 60 meter telescope with current detectors.*

# Finding an "Earth"



# Very Low Light Level - ExoPlanet Imaging

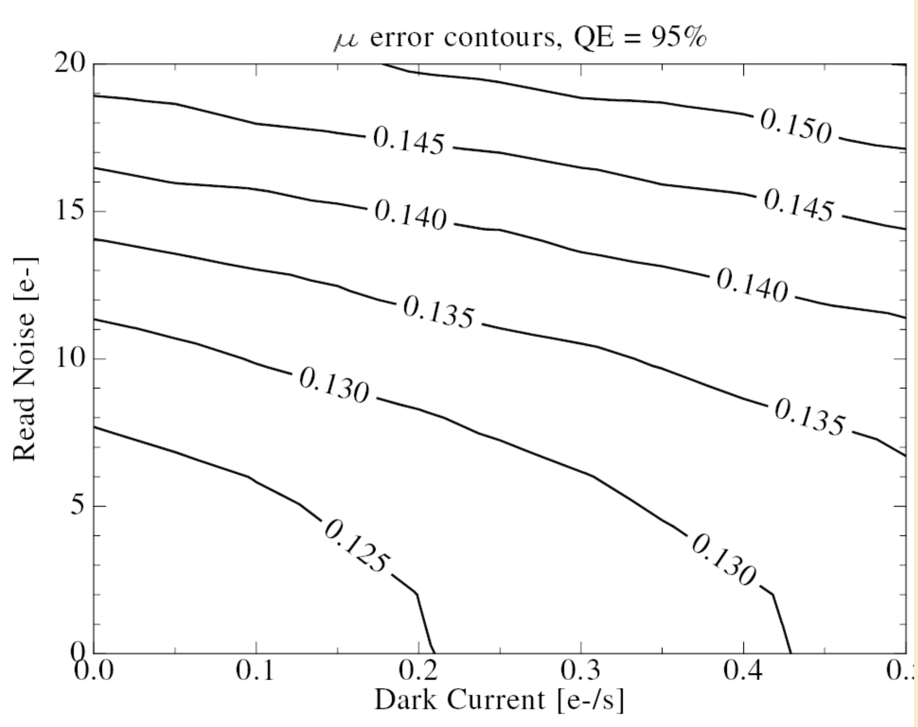
- The exposure time required to achieve SNR=1 is dramatically reduced for a zero read noise detector, as compared to detectors with state of the art read noise.

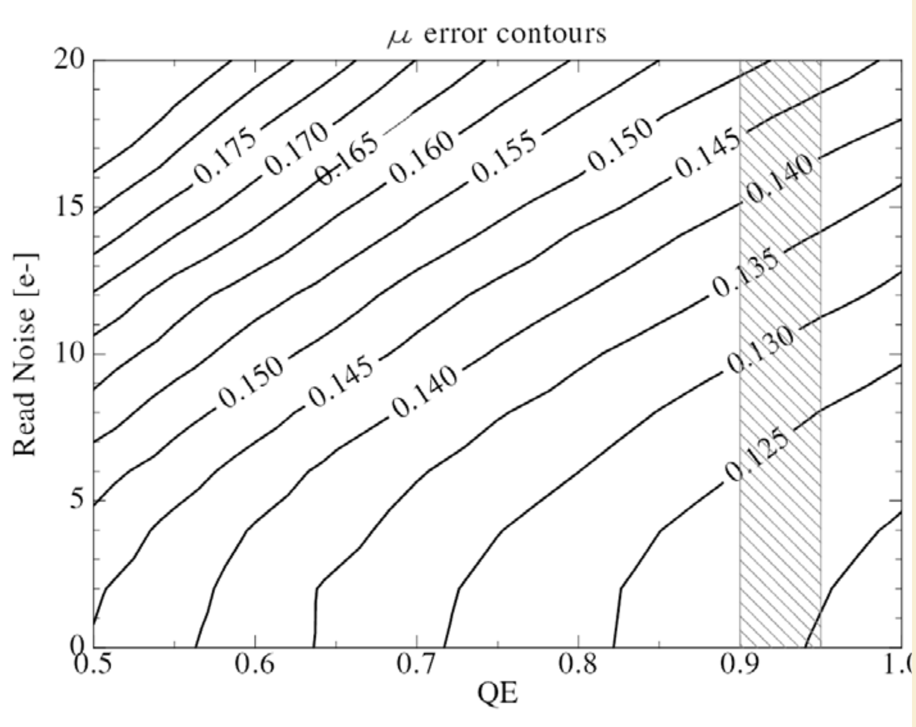
**Exposure Time (seconds) for SNR = 1**

| FOM | | Quantum Efficiency | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100% |
| read noise | 0 | 6,600 | 2,300 | 1,311 | 900 | 680 | 544 | 453 | 388 | 338 | 300 |
| | 1 | 7,159 | 2,674 | 1,591 | 1,123 | 865 | 703 | 591 | 510 | 448 | 400 |
| | 2 | 8,486 | 3,457 | 2,141 | 1,547 | 1,209 | 992 | 841 | 730 | 645 | 577 |
| | 3 | 10,148 | 4,363 | 2,760 | 2,016 | 1,587 | 1,309 | 1,113 | 968 | 857 | 768 |
| | 4 | 11,954 | 5,312 | 3,402 | 2,500 | 1,976 | 1,633 | 1,392 | 1,212 | 1,074 | 964 |
| | 5 | 13,830 | 6,281 | 4,053 | 2,990 | 2,369 | 1,961 | 1,673 | 1,459 | 1,293 | 1,161 |
| | 6 | 15,745 | 7,259 | 4,709 | 3,484 | 2,764 | 2,291 | 1,956 | 1,706 | 1,513 | 1,359 |
| | 7 | 17,684 | 8,244 | 5,368 | 3,979 | 3,161 | 2,621 | 2,239 | 1,954 | 1,734 | 1,558 |

mag_star=5, mag_planet=30, R=100, i_dark=0.0010

# Hunt for Dark Energy





Brown 2007, PhD Thesis

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# Inner Space Applications

# Biophotonics

- Defined as using photons for biomedical purposes
- Applications
  - – cognitive functioning
  - – brain hematoma
  - – breast cancer
- Hardware systems

# Motivation for Biophotonics

- Alternate modalities
- Low mass, cost, power, volume
- Safe

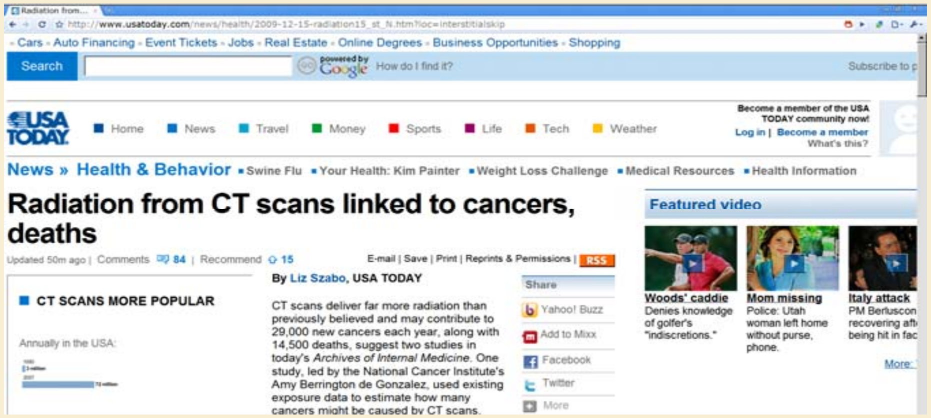
WOMEN'S HEALTH

**Exposure to Mammography Radiation Raises Chance for Breast Cancer in Women at Risk**

By Drucilla Dyess
Published: Thursday, 3 December 2009

Young women already at high risk of developing breast cancer, due to family history or genetic mutation, could be increasing their risk for the disease by having yearly mammograms. Ironically, exposure to mammography radiation may be the most harmful to the very

Find the diet that best suits your needs a lifestyle



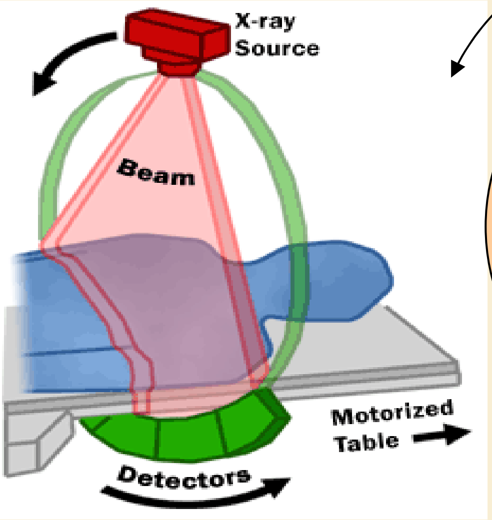
**Radiation from CT scans linked to cancers, deaths**

By Liz Szabo, USA TODAY

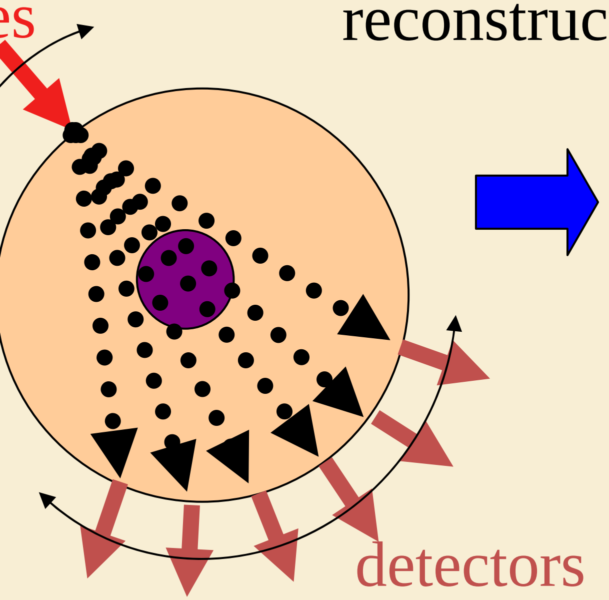
CT scans deliver far more radiation than previously believed and may contribute to 29,000 new cancers each year, along with 14,500 deaths, suggest two studies in today's *Archives of Internal Medicine*. One study, led by the National Cancer Institute's Amy Berrington de Gonzalez, used existing exposure data to estimate how many cancers might be caused by CT scans.

# Ballistic Photons

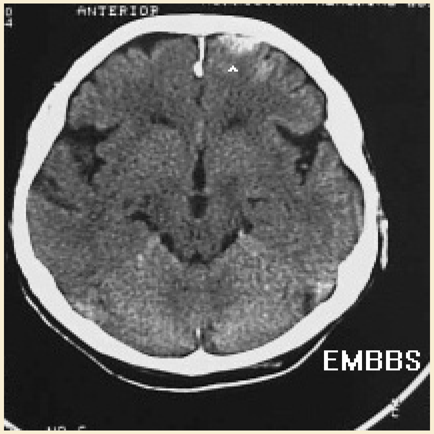
CT-scan (x-ray)



sources



numerical reconstruction



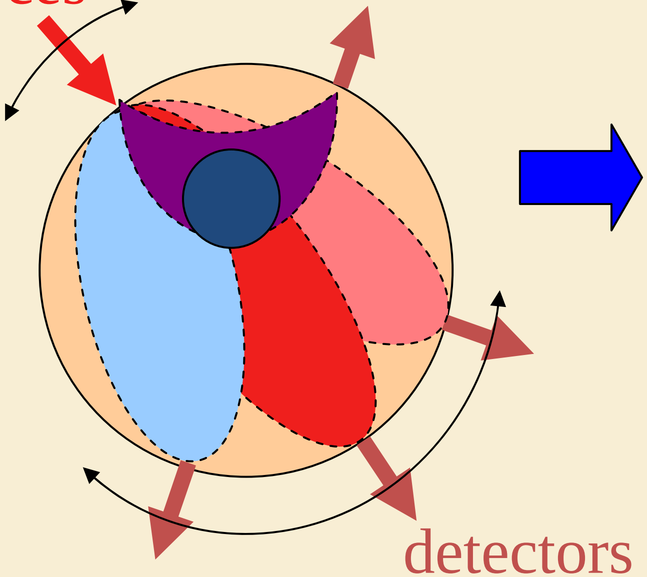
detectors

scattering << absorption ⇒ paths = straight lines

(courtesy F. Bevilacqua)

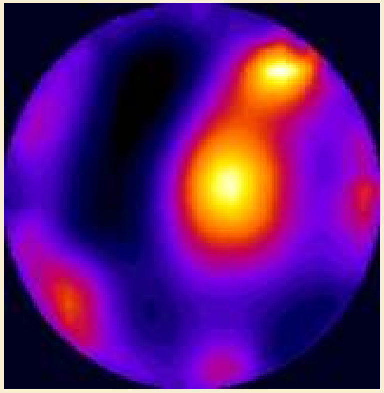
# Scattered Photons

near-infrared light



sources

detectors

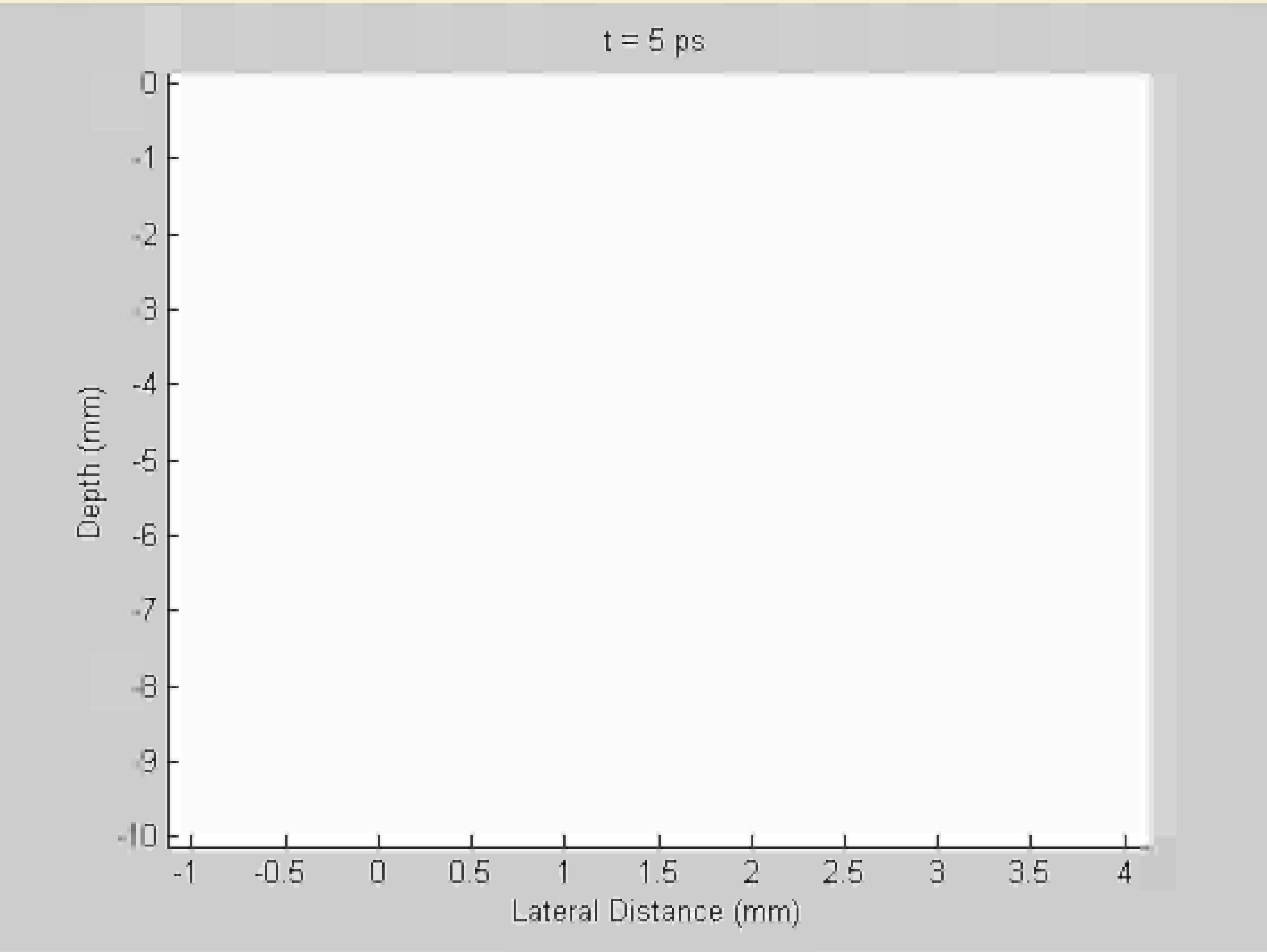


scattering >> absorption ⇒ broad probability of paths

(courtesy F. Bevilacqua)

http://www.medphys.ucl.ac.uk/research/borg/index.htm

# Diffuse Photon Propagation



# Diffuse Optical Imaging (Phantom)

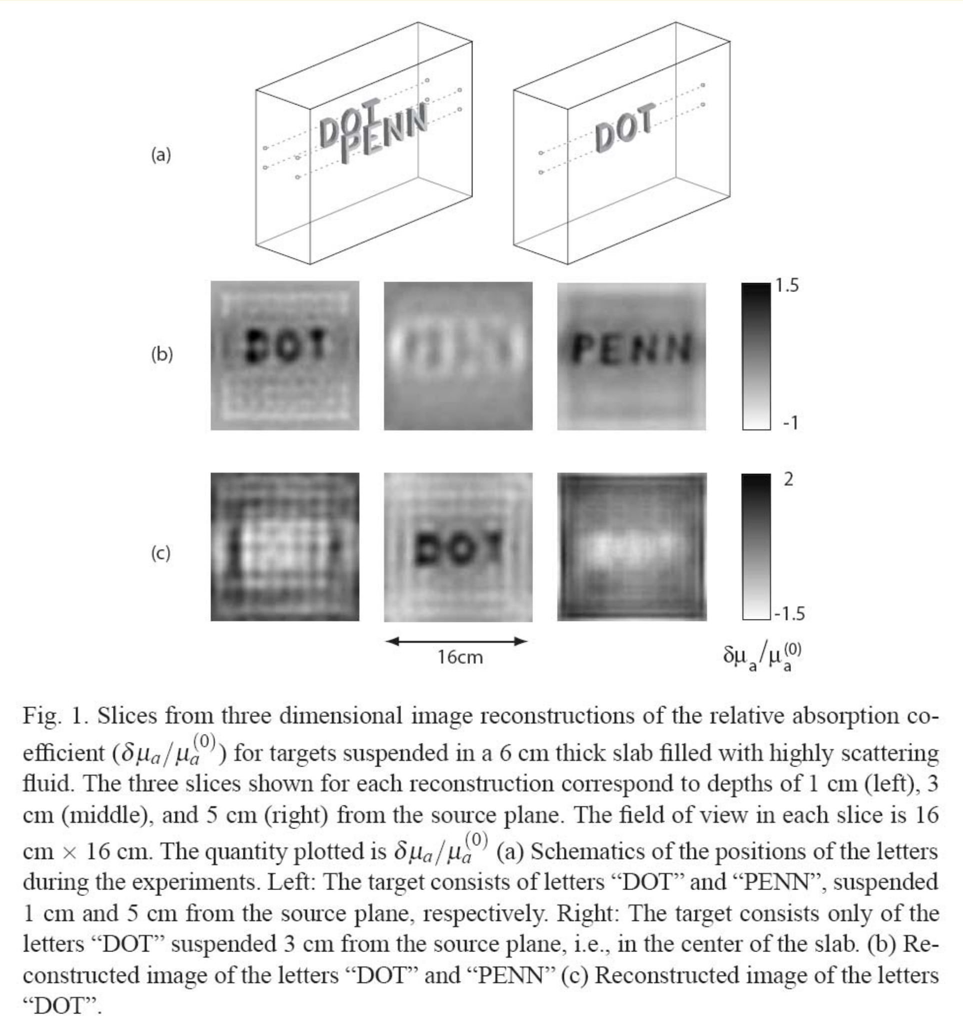
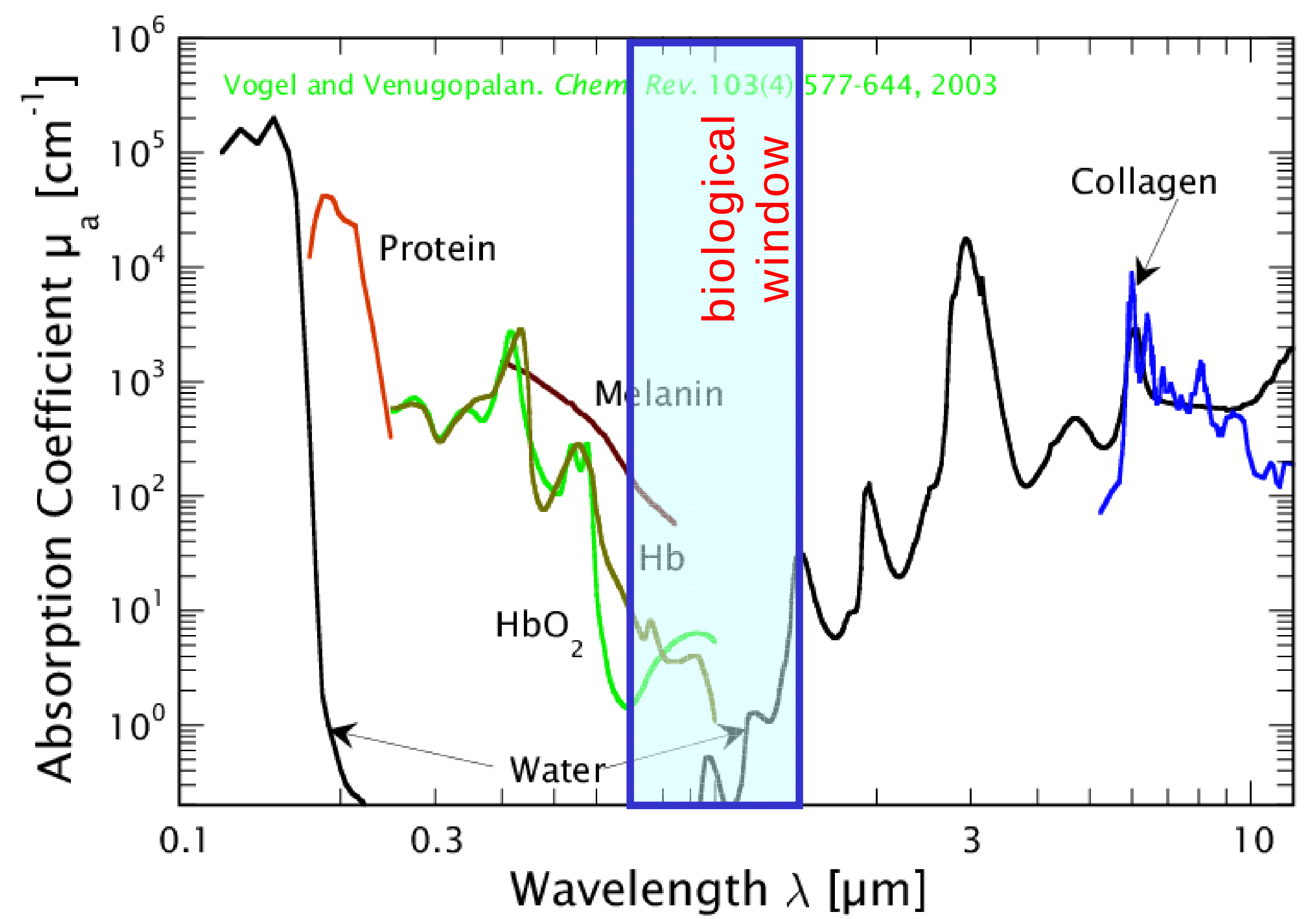


Fig. 1. Slices from three dimensional image reconstructions of the relative absorption coefficient $(\delta\mu_a/\mu_a^{(0)})$ for targets suspended in a 6 cm thick slab filled with highly scattering fluid. The three slices shown for each reconstruction correspond to depths of 1 cm (left), 3 cm (middle), and 5 cm (right) from the source plane. The field of view in each slice is 16 cm × 16 cm. The quantity plotted is $\delta\mu_a/\mu_a^{(0)}$ (a) Schematics of the positions of the letters during the experiments. Left: The target consists of letters "DOT" and "PENN", suspended 1 cm and 5 cm from the source plane, respectively. Right: The target consists only of the letters "DOT" suspended 3 cm from the source plane, i.e., in the center of the slab. (b) Reconstructed image of the letters "DOT" and "PENN" (c) Reconstructed image of the letters "DOT".

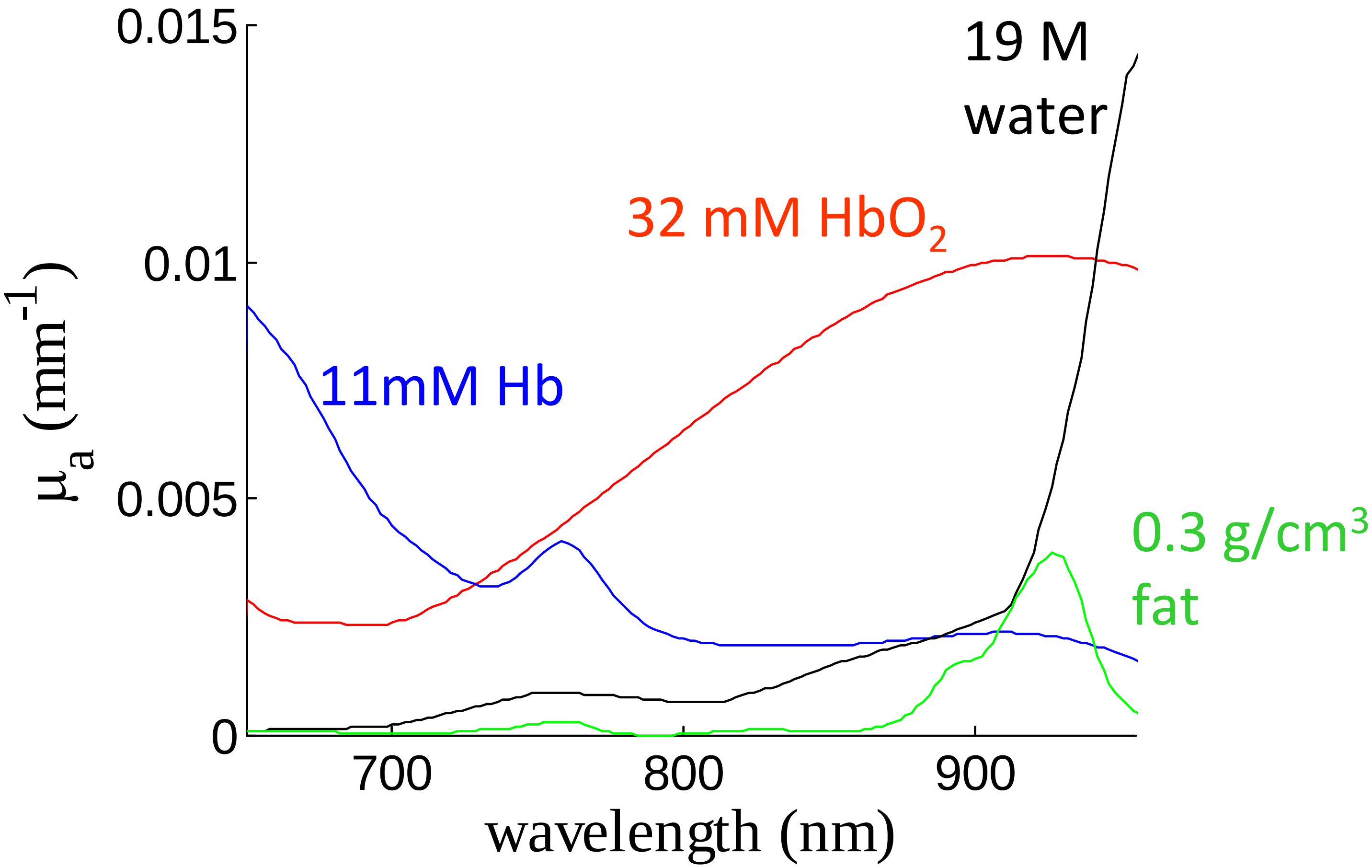
Konecky et al. 2008, Optics Express

# Spectroscopy in Biological Tissue



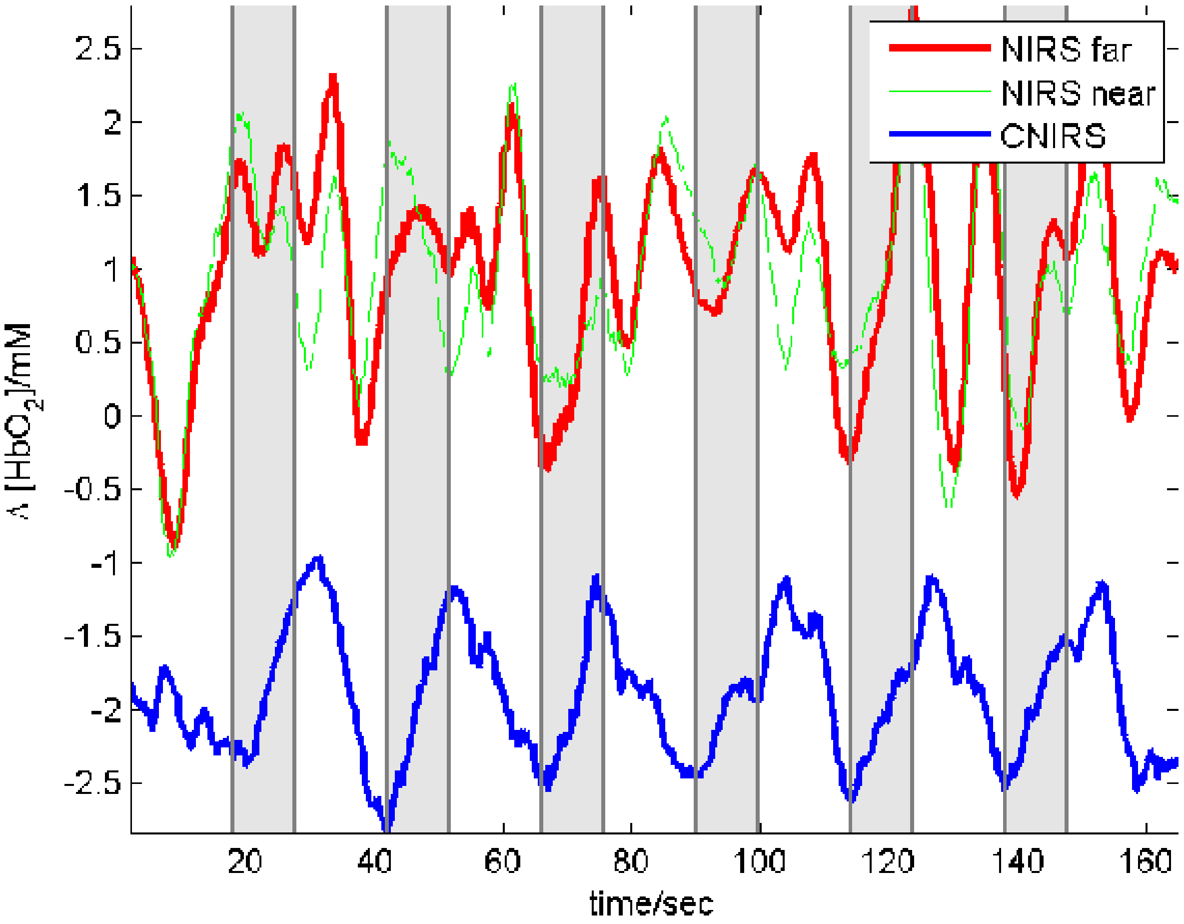
courtesy V. Venugopalan, http://www.osa.org/meetings/archives/2004/BIOMED/program/#educ

# Important Near-IR Absorbers

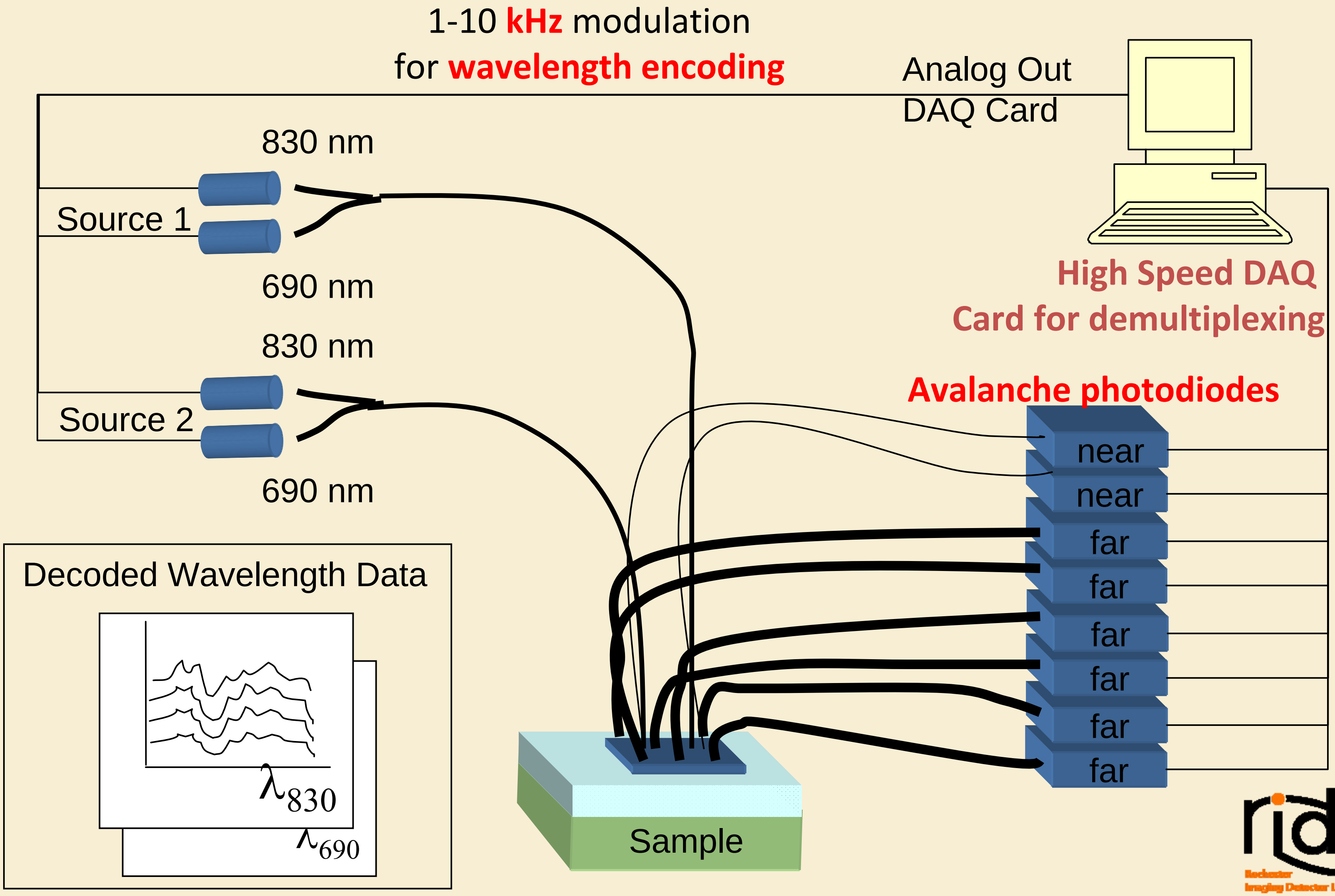


# What is He Thinking?

# Response to Visual Stimulation



# Brain Monitoring System Layout



1-10 **kHz** modulation
for **wavelength encoding**

Analog Out
DAQ Card

830 nm

Source 1

690 nm

830 nm

Source 2

690 nm

**High Speed DAQ**
**Card for demultiplexing**

**Avalanche photodiodes**

near
near
far
far
far
far
far
far

Sample

Decoded Wavelength Data

$\lambda_{830}$

$\lambda_{690}$

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# Cognitive Functioning

**Fig. 1** Wireless imaging instrument attached to a newborn infant's head. The squares (blue) represent the detector locations, while the circles (red) depict source locations, each equipped with light emitting diodes at two wavelengths (730 and 830 nm). The electronics to the right includes a Bluetooth device for wireless transmission, drivers for the light emitting diodes, filters, analog-to-digital converters, a microprocessor, and a power supply based on a battery. The instrument weighs as little as 40 g, has a sample rate of 100 Hz, and the battery lasts for approximately 3 h. The wireless technology is comfortable to wear, easy to apply, and enables measurements in moving subjects and everyday situations. (Color online only.)

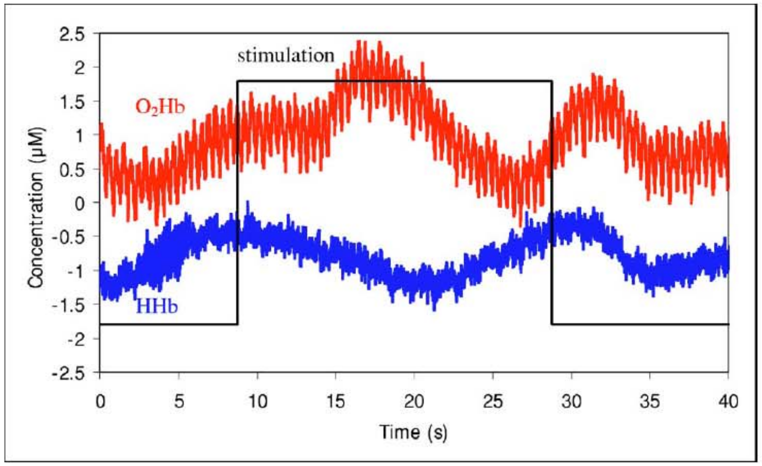
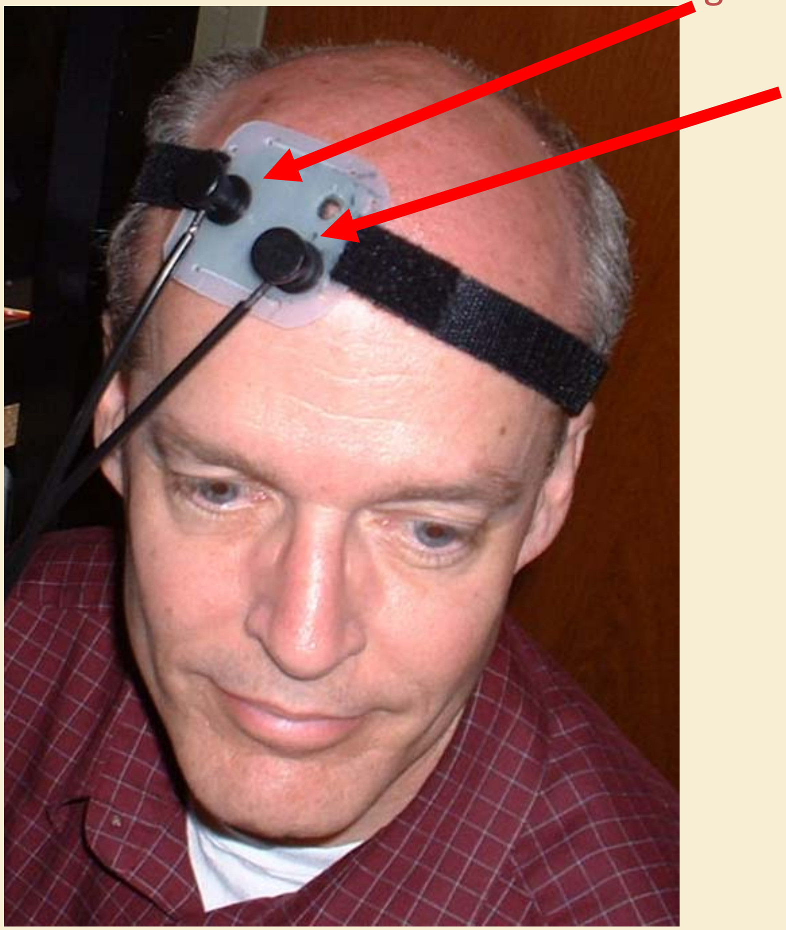


**Fig. 2** A sample of a functional NIRs measurement with a 100-Hz sampling rate in a healthy neonate. The upper trace (red) depicts $O_2Hb$, and the lower trace (blue) HHb and the straight line (black) depict the duration of the visual stimulation. A number of physiological phenomena can be observed: (1) The arterial pulsations are visible in the $O_2Hb$ tracing. The pulsations can be used to calculate the heart rate and arterial oxygen saturation. (2) Approximately every 10 s, there are fluctuations in the blood circulation (the so-called slow vasomotion). These changes are particularly evident in the $O_2Hb$ tracing. (3) The $O_2Hb$ increases and the HHb decreases during the stimulation. This corresponds to a typical functional cortical activation. Although the slow vasomotion partially masks the activation, the measurement can be repeated several times and thus the functional activation can be revealed statistically. (Color online only.)

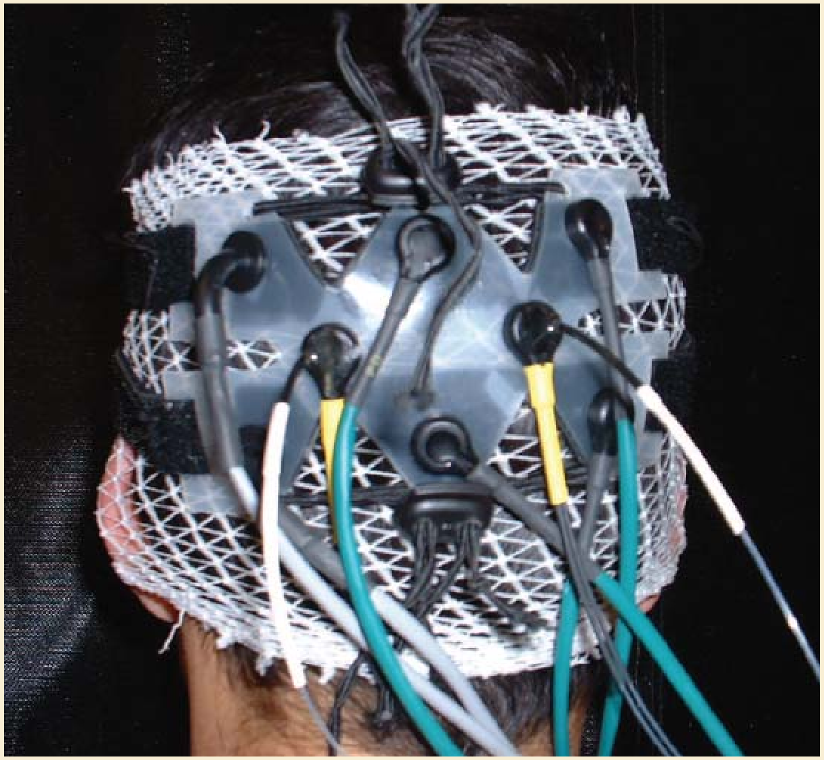
Wolf et al. 2007, Journal of Biomedical Optics

# Cerebral Blood Monitoring

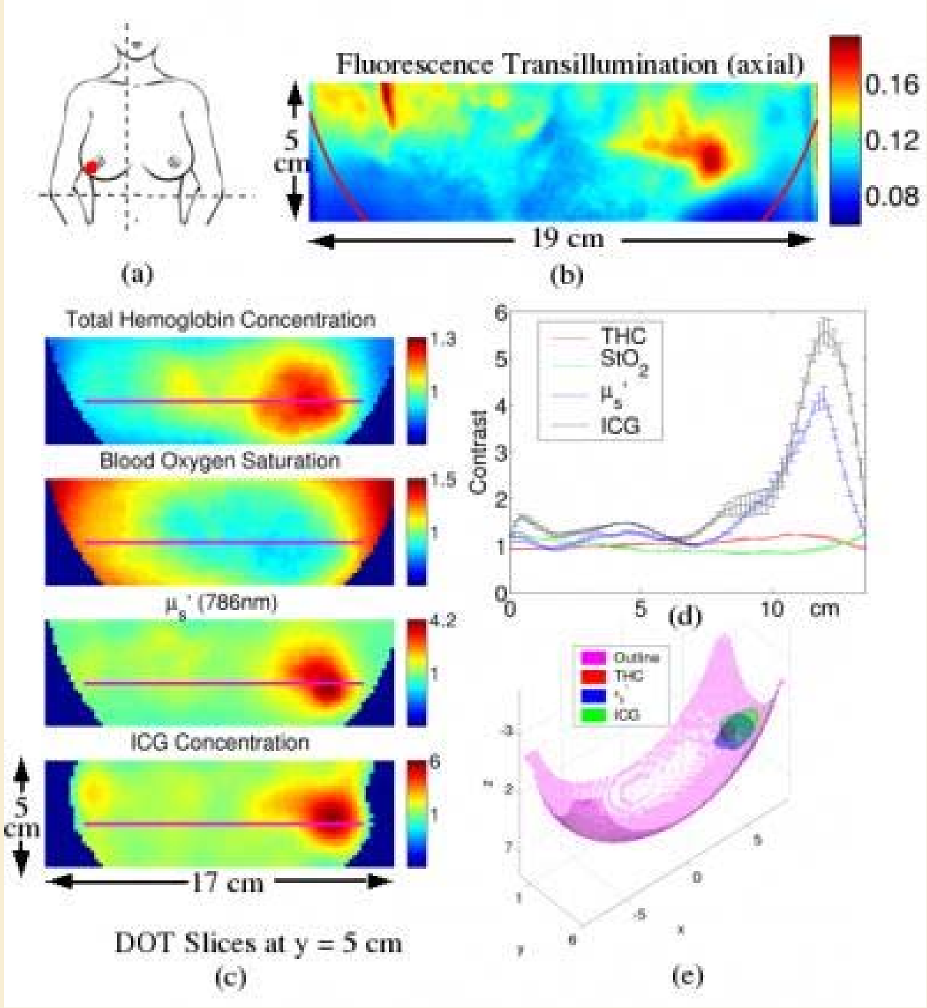


light in (690, 830 nm)

light out

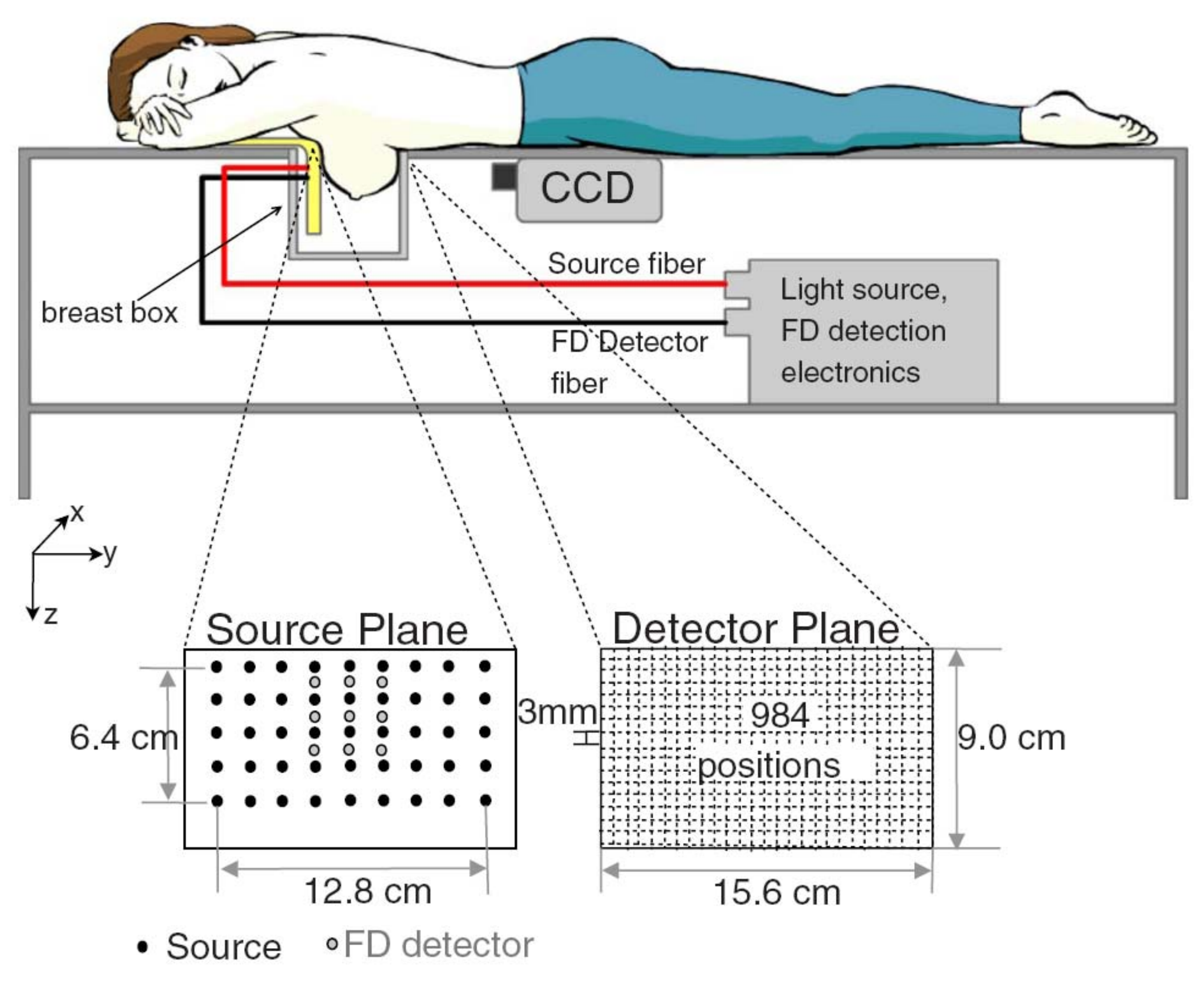


# Breast Cancer Detection



Tromberg et al., 2009

# Parallel Plate Breast Scanner



Choe et al. 2009, Journal of Biomedical Optics

# Typical Detector

- Hamamatsu ~few element silicon avalanche photodiode modules
- Frequency rolloff in low MHz to GHz
- Spectral response out to 1000 nm

# Heavily Multiplexed Systems!

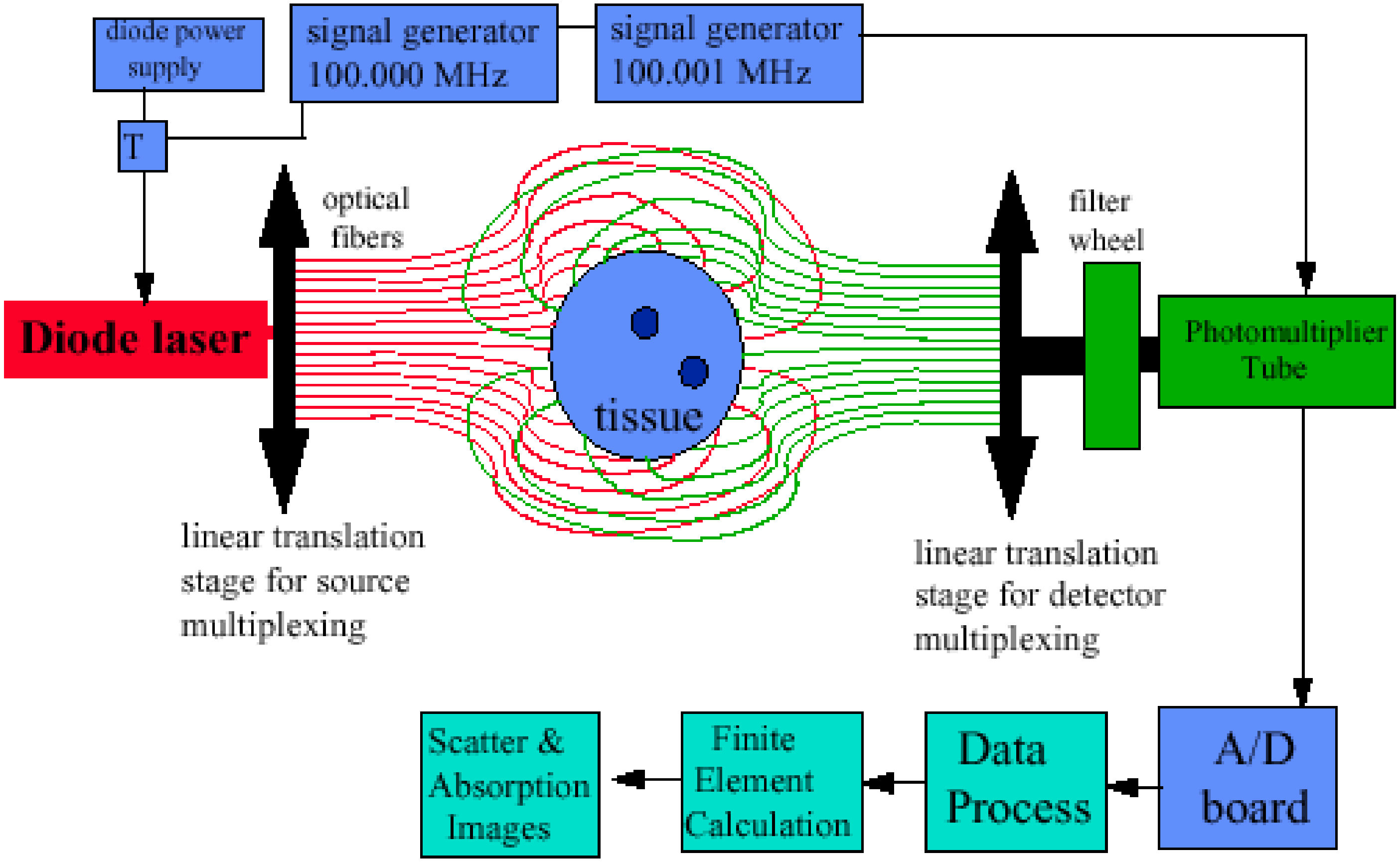
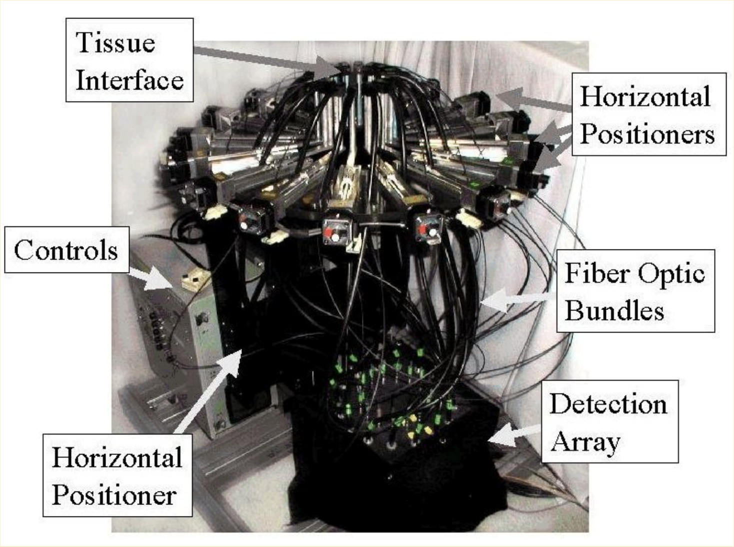


Fig. 1. Schematic of the automated imaging instrument including hardware and software processing. Source optical fibers are indicated in red and detector optical fibers in green.

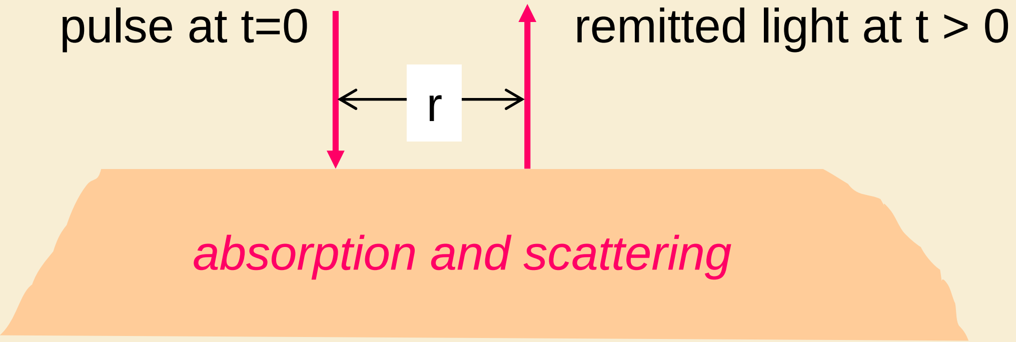
B. W. Pogueet al, Opt. Express **1**, 391-403 (1997),
http://www.opticsexpress.org/abstract.cfm?URI=OPEX-1-13-391

# Optical Multiplexing Hardware



http://www-nml.dartmouth.edu/nir/instrumentation.html

# Time-resolved Measurements

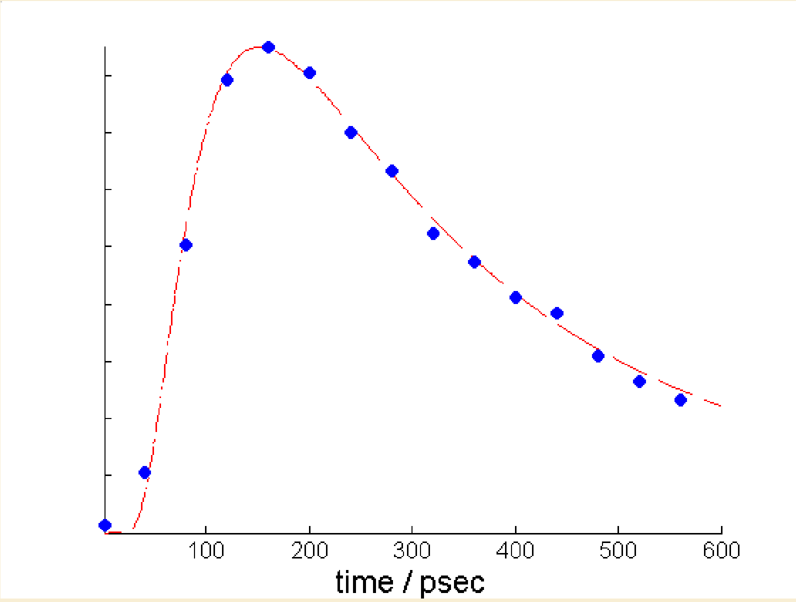


pulse at t=0

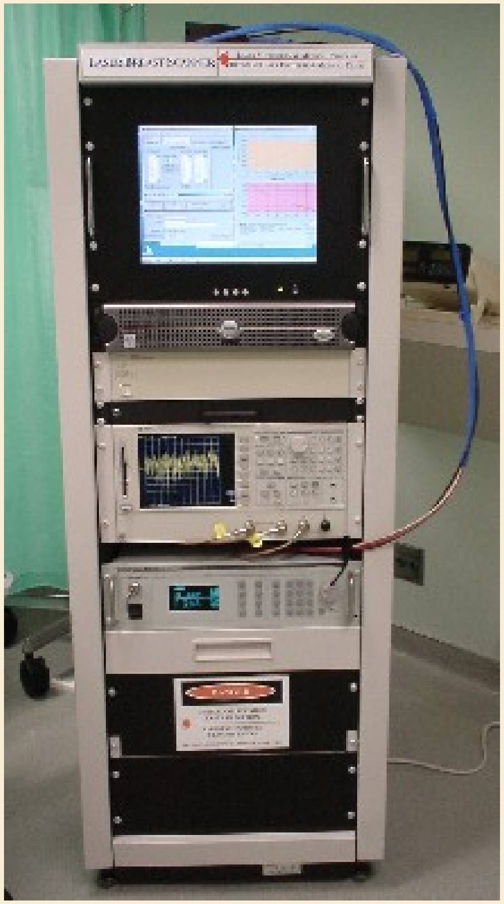
r

remitted light at t > 0

*absorption and scattering*



# Hand-Held Optical Breast Scanner



(courtesy F. Bevilacqua)

***Pham, TH., et al. Review of Scientific Instruments, 71 , 1 – 14, (2000).***
***Bevilacqua, F., et al. Applied Optics, 39, 6498-6507, (2000).***
*Jakobowski et al., J. Biomed. Opt., 9(1), 230-238 (2004).*

# Hand-Held Optical Breast Scanner

*Measurement of breast tissue optical properties* B. J. Tromberg and others 663

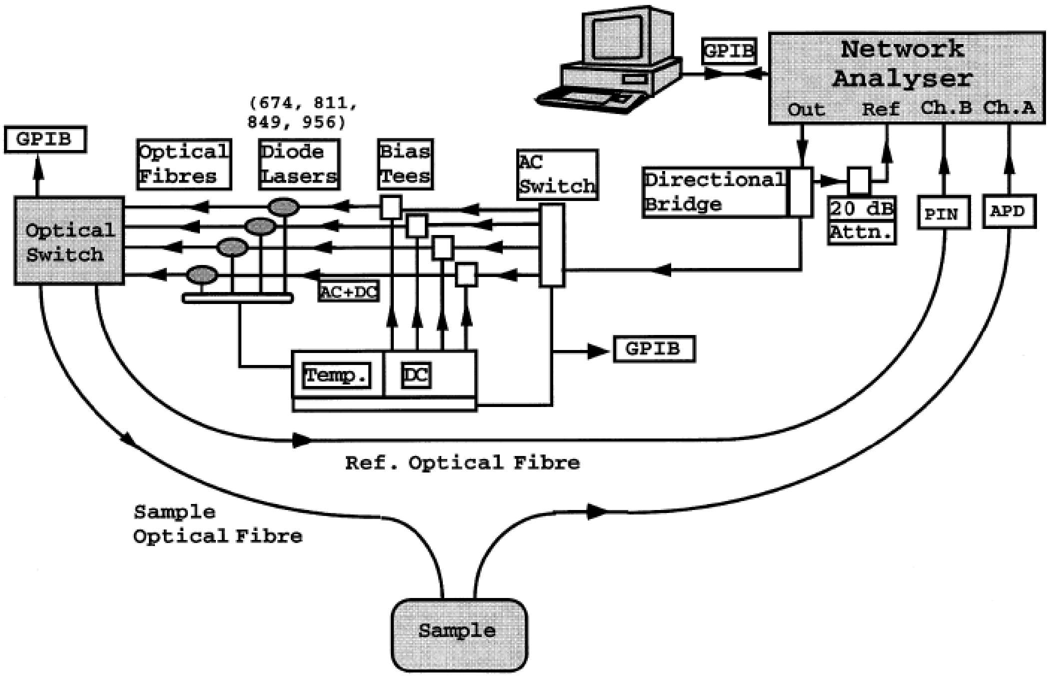
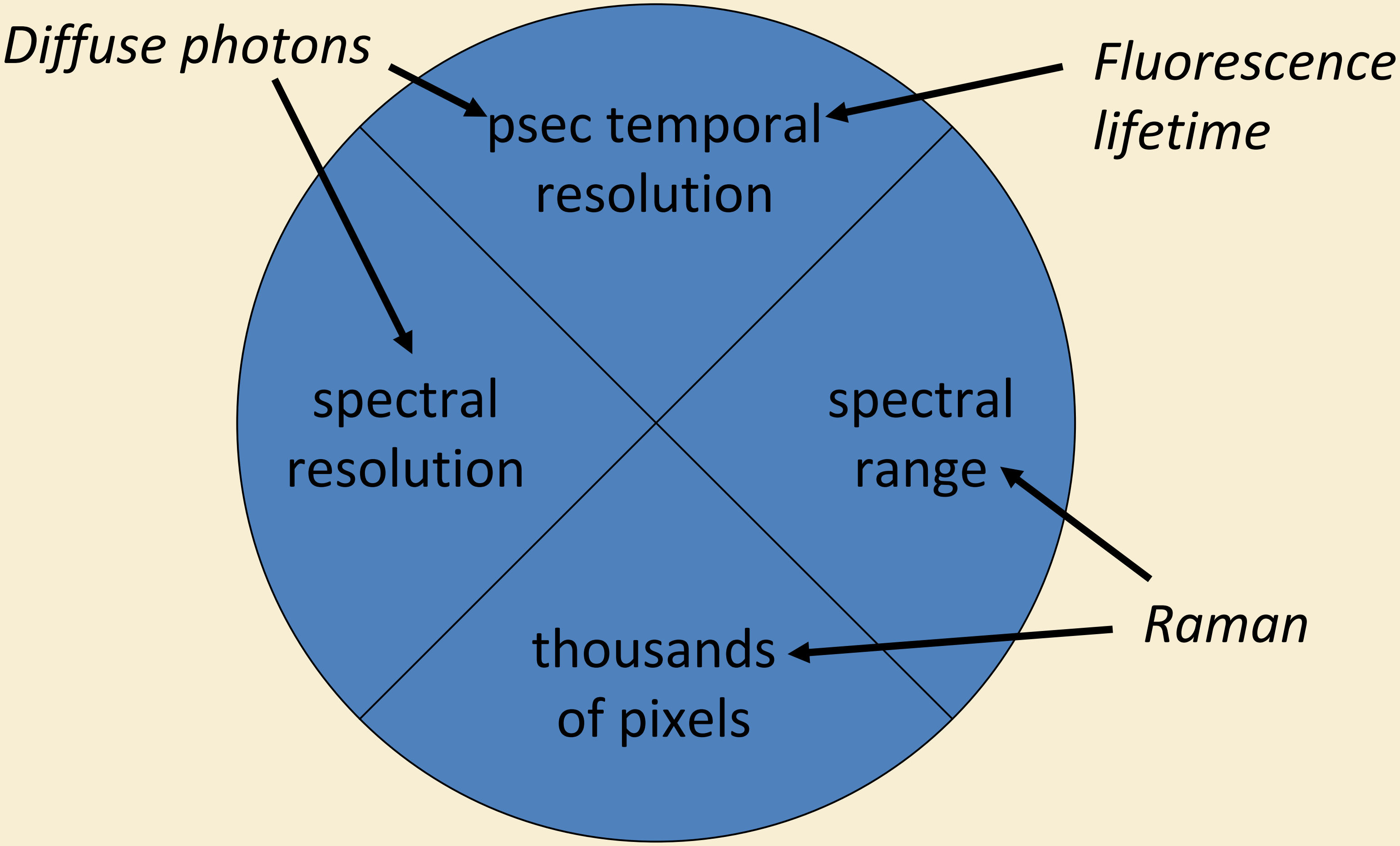


Figure 1. Multiwavelength, multifrequency FDPM instrument.

# Benefits of QLIDs for Biomedical Optics



*Diffuse photons*

*Fluorescence lifetime*

psec temporal resolution

spectral resolution

spectral range

thousands of pixels

*Raman*

# Summary

- biomedical spectroscopy: characterize tissue, biofluids, cells
- frequently in near-IR
- multiple factors driving sub-nsec time resolution
- many-many-channel sensing: a game-changer
- get past the Si bandgap cutoff
- spectral resolution at each pixel: good for diffuse spectroscopy

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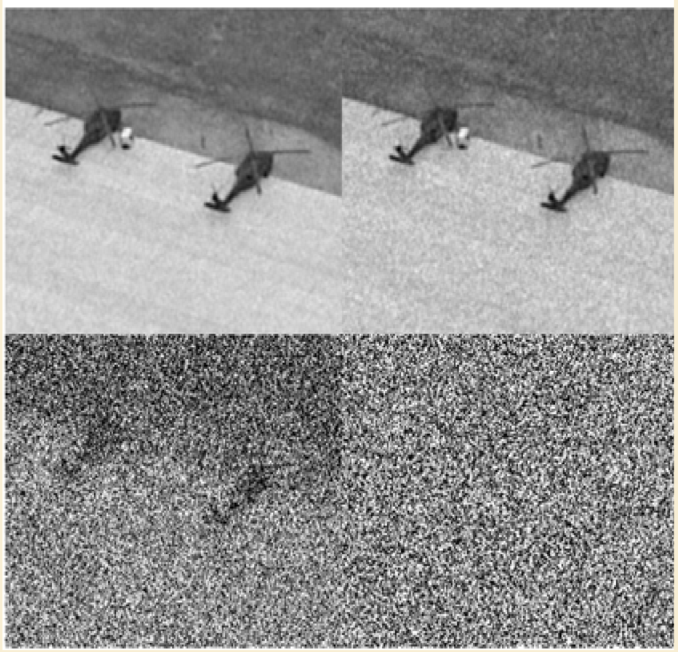
# Middle Space Applications

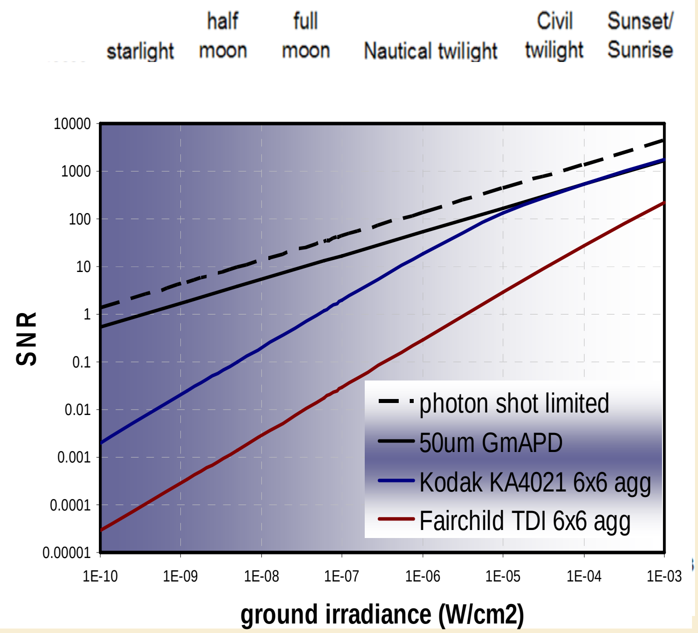
# Read Noise and SNR

*Figure 4. Image simulations of four different strawman system designs*



Simulated full moon images of Bolling AFB representing (top-left) ideal photon limited, (top-right) GmAPD, (lower-left) Kodak KA-4021, and (lower-right) Fairchild 10121 TDI sensors.

*Figure 5. Dependence of SNR on sky illumination for strawman system designs.*



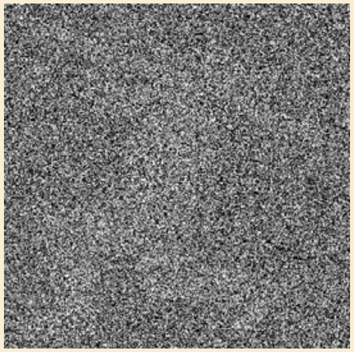
Curves demonstrating the sensitivity of a shot noise limited 50um pitch 100% QE sensor, a 50um pitch Gm-APD sensor, a 6x6 aggregated 8um pitch Kodak KA4021 sensor, and a 6x6 aggregated 8um pitch Fairchild 128 stage TDI sensor.

# Strawman System Simulation

| ***Parameter*** | ***Ideal Detector*** | ***Gm-APD*** | ***Kodak KA4021*** | ***Fairchild linear TDI*** |
|---|---|---|---|---|
| Read noise (e-) | 0 | 0 | 25 | 40 |
| Effective frame/line rate (Hz) | 5 | 5 | 5 | 6500 |
| Coadds/TDI | 5 | 5 | 5 | 128 |
| Eff. Integration (s) | 1.00 | 1.00 | 1.00 | 0.02 |
| Native pitch (um) | 50 | 50 | 8 | 8 |
| Aggregation | 1x1 | 1x1 | 6x6 | 6x6 |

# Low SNR and Target Recognition

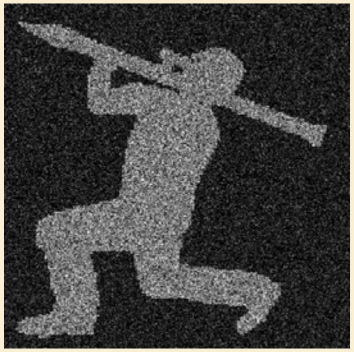
- Point-like targets are difficult to recognize at low SNR.
- Extended targets are much easier to recognize at low SNR.



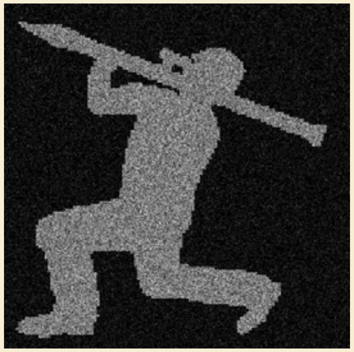
SNR=0.5

SNR=1

SNR=2



SNR=5

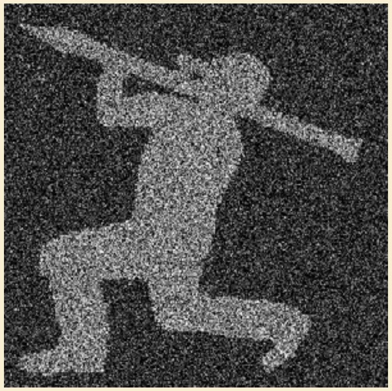


SNR=10

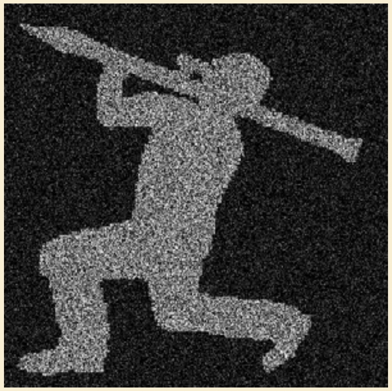
# Read Noise and Target Recognition

- Read noise in the background influences target recognition.

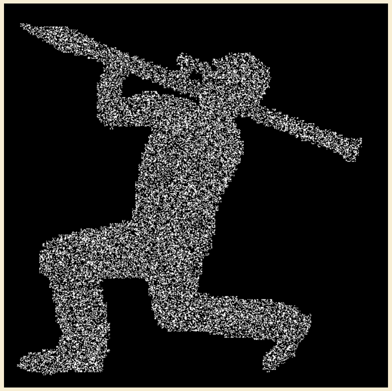
SNR=0.6, RN=3



SNR=0.8, RN=2



SNR=1.1, RN=1



SNR=0.7, RN=0

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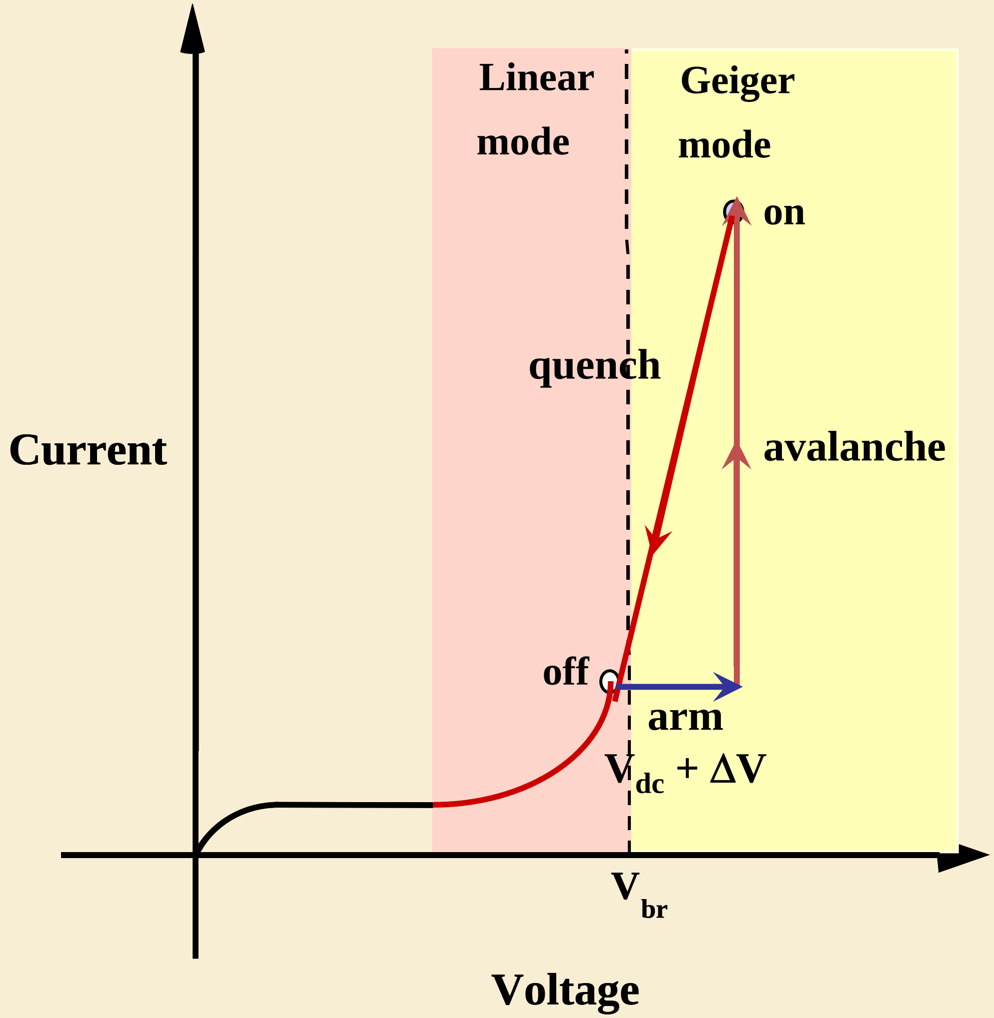
# Photon-Counting Detector

# Introduction to Photon-Counting Detectors

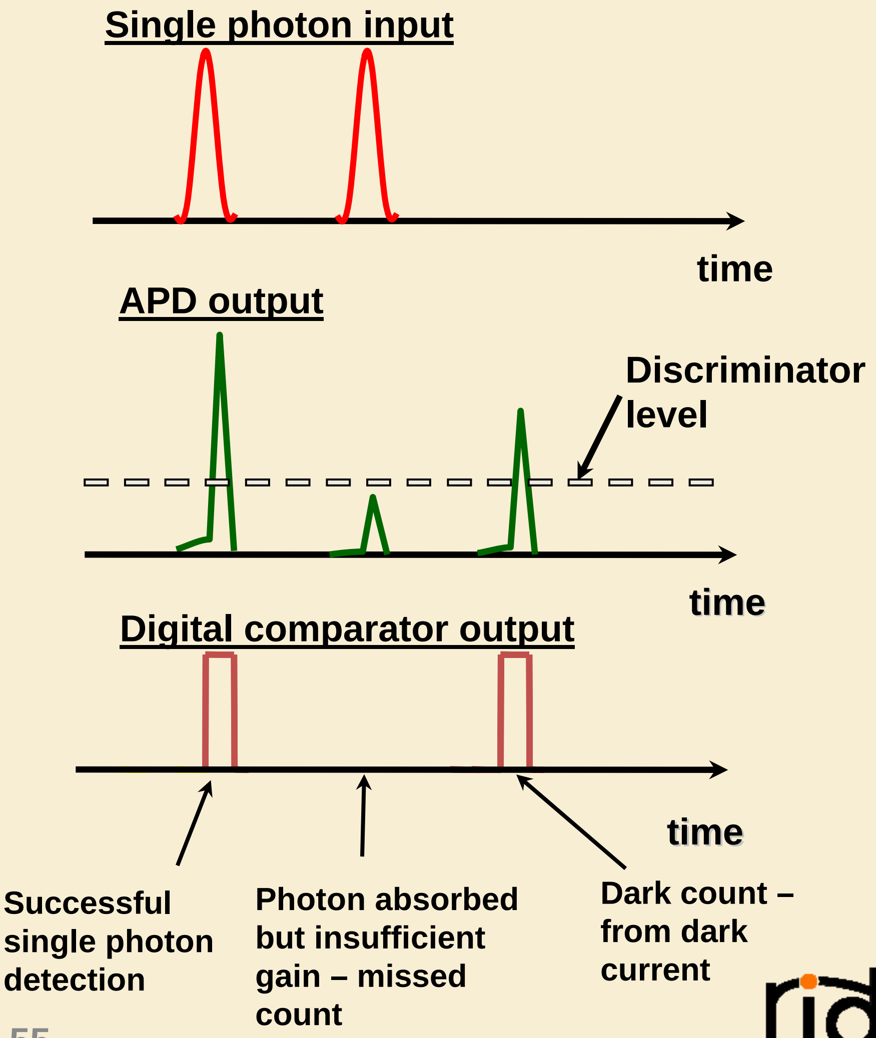
- Photon-counting detectors detect individual photons.
- They typically use an amplification process to produce a large pulse for each absorbed photon.
- Current devices typically have one element (pixel).
- These types of detectors would be useful in low-light and high dynamic range applications
  - nighttime surveillance
  - daytime imaging
  - faint object astrophysics
  - high time resolution biophotonics
  - real-time hyperspectral monitoring of urban/battlefield environments
  - orbital debris identification and tracking

# Operation of Avalanche Diode



# Performance Parameters

- ✓ Photon detection efficiency (PDE)
  - ➢ The probability that a single incident photon initiates a current pulse that registers in a digital counter
- ✓ Dark count Rate (DCR)/Probability (DCP)
  - ➢ The probability that a count is triggered by dark current instead of incident photons



Successful single photon detection

Photon absorbed but insufficient gain – missed count

Dark count – from dark current

# Zero Noise Detector Project

| | |
|---|---|
| Goals | To design, fabricate, develop, and test a large scale, operational, megapixel array detector that has zero read noise. |
| Schedule | October 2008 – October 2012 |
| Budget | $2,839,191 |
| Sponsor | Gordon and Betty Moore Foundation |
| Collaborators | MIT Lincoln Laboratory |

# Zero Noise Detector Project Goals

- Operational
  - Photon-counting
  - Wide dynamic range: flux limit to >$10^8$ photons/pixel/s
  - Time delay and integrate
- Technical
  - Backside illumination for high fill factor
  - Moderate-sized pixels (25 μm)
  - Megapixel array

# Zero Noise Detector Specifications

*Optical (Silicon) Detector Performance*

| *Parameter* | *Phase 1 Goal* | *Phase 2 Goal* |
|---|---:|---:|
| *Format* | **256x256** | **1024x1024** |
| *Pixel Size* | **25 µm** | **20 µm** |
| *Read Noise* | **zero** | **zero** |
| *Dark Current (@140 K)* | **$<10^{-3}$ $e^-$/s/pixel** | **$<10^{-3}$ $e^-$/s/pixel** |
| *QE[a] Silicon (350nm,650nm,1000nm)* | **30%,50%,25%** | **55%,70%,35%** |
| *Operating Temperature* | **90 K – 293 K** | **90 K – 293 K** |
| *Fill Factor* | **100%** | **100%** |

**[a] Product of internal QE and probability of initiating an event. Assumes antireflection coating match for wavelength region.**

# Zero Noise Detector Specifications

*Infrared (InGaAs) Detector Performance*

| *Parameter* | *Phase 1 Goal* | *Phase 2 Goal* |
|---|---:|---:|
| *Format* | **Single pixel** | **1024x1024** |
| *Pixel Size* | **25 µm** | **20 µm** |
| *Read Noise* | **zero** | **zero** |
| *Dark Current (@140 K)* | **TBD** | **$<10^{-3}$ $e^{-}$/s/pixel** |
| *QE[a] (1500nm)* | **50%** | **60%** |
| *Operating Temperature* | **90 K – 293 K** | **90 K – 293 K** |
| *Fill Factor* | **NA** | **100% w/o µlens** |

**[a] Product of internal QE and probability of initiating an event. Assumes antireflection coating match for wavelength region.**

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# Zero Noise Detector Project Status

- A 256x256x25μm readout circuit has been fabricated.
- InGaAs test diodes have been fabricated and tested.
- Silicon GM-APD arrays have been fabricated and will be bump-bonded to the new readout circuit.
- Photon-counting electronics are being built.
- Testing will begin in early 2010.
- Depending on results, megapixel silicon or InGaAs arrays will be developed.

# Technology Demonstration for Exoplanet Missions

- NASA funded TDEM to mature technologies for exoplanet missions (e.g. TPF).
- RIT/LL have been awarded a grant to evolve single photon counting array detectors for exoplanet missions.
- The two-year project will produce about a dozen 256x256 GMAPD imaging arrays and test them in the presence of high energy radiation (60 MeV protons).

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# Imaging LIDAR Detector

# Introduction to LIDAR

- LIght Detection And Ranging (LIDAR) measures photon time-of-flight, and thus distance to a target.
- LIDAR detectors typically have one element and are scanned.
- A LIDAR "imaging" detector is pixellated and can be used to produce a 3D data set.

# A LIDAR Imaging Detector for NASA Planetary Missions

| ***Parameter*** | ***Current*** | ***Goal*** |
|---|---:|---:|
| ***Space-Qualifiable*** | NO | YES |
| ***Scalable to Large Format*** | NO | YES |
| ***CMOS ROIC Timing Resolution*** | 250 ps | 250 ps |
| ***Pixel Size*** | 50 μm | 50 μm |
| ***Multiplied Dark Current (@140 K)*** | unknown | $<10^{-3}$ $e^{-}$/s/pixel |
| ***QE (350nm,650nm,1000nm)***[a] | 45%,65%,5% | 45%,65%,10% |
| ***Operating Temperature*** | 293 K | 90 K – 293 K |
| ***Radiation Limit*** | unknown | 50 Krad(Si)[b] |
| ***Technology Readiness Level***[c] | 2 | 4 |

- These arrays will be back-illuminated and bump bonded, enabling high performance in a space-qualifiable focal plane.
- The design of the ROIC will be finished by the end of 2009, with fabrication starting in early 2010.
- Funding: $546,000
- Duration:  3 years (2008-2010)

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# Future Directions

# Future Directions

- In the short term, we plan to develop the GM-APD detectors
  - final fabrication
  - lab testing
  - field testing
  - radiation testing
- In the medium term, we plan to deploy detectors for
  - astrophysics, planetary science
  - biophotonics
  - defense
- In the long term, we plan to develop multi-mode quantum-limited detectors.

# Biomedical Experiments Sensor Testbed

- Proposal for BEST
- Build and use a testbed for deploying new photonic detectors for biomedical purposes
- Prototype, phantoms, trials, commercialization
- Partners
  - RIT
  - Rochester General Hospital System
  - Carestream Health (ex-Kodak)
  - Beckman Laser Institute (UC Irvine)

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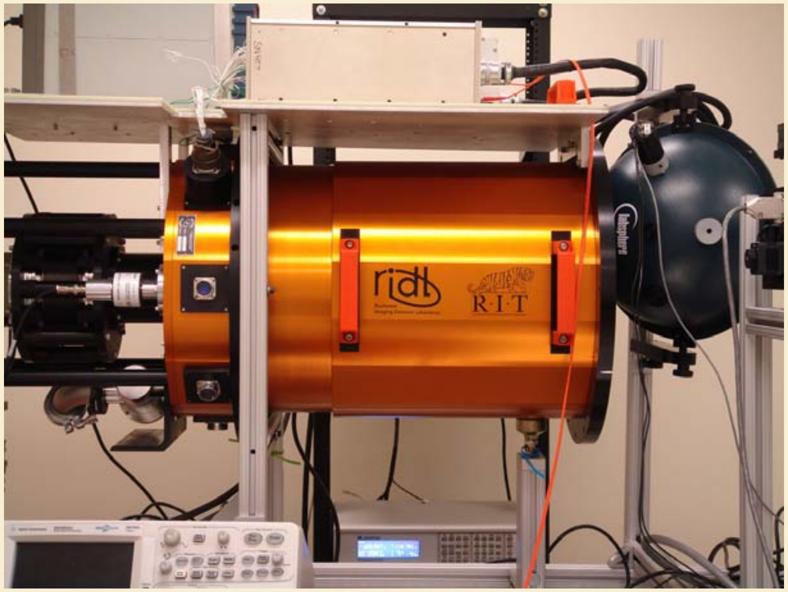
# Personnel and Facilities

# Facilities for Data Collection

- Lab testing in RIDL
- Field testing at KPNO 2.1m Telescope



# RIDL Facility: Clean/ESD Systems

# RIDL Facility: Probe Station

# RIDL Personnel

**Don Figer**

Director

**Zoran Ninkov**

Professor

**Dan Smialek**

Lab Coordinator

**Brian Ashe**

Engineer

**Don Stauffer**

Engineer

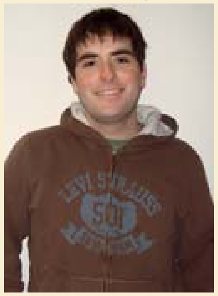
**Brandon Hanold**

Engineer

**Tom Montagliano**

Engineer

**John Frye**



Programmer

***Graduate Students***

**Max Bobrov**

Programmer

**Christine Trombley**

Grad. Student

**Kim Kolb**

BAE Grad. Fellow

**Brian Glod**

Programmer

***Undergraduate Students***

**Chris Maloney**

Lab Assistant

**Alicia Evans**

Lab Assistant

**Matthew Simpson**

Lab Assistant