Novel Designs for Single Photon Detection Based on Quantum and Nanoscale Systems

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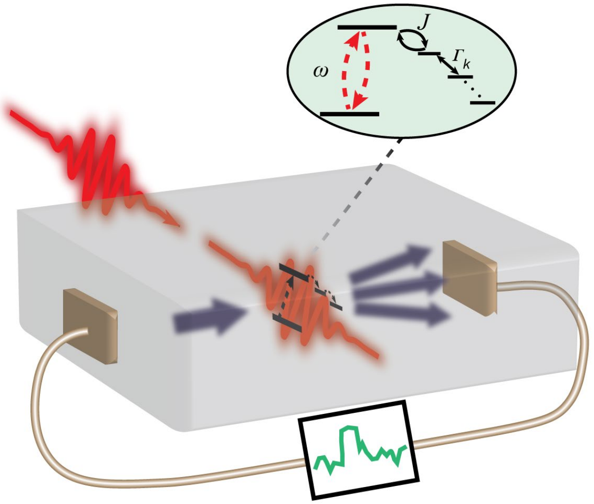

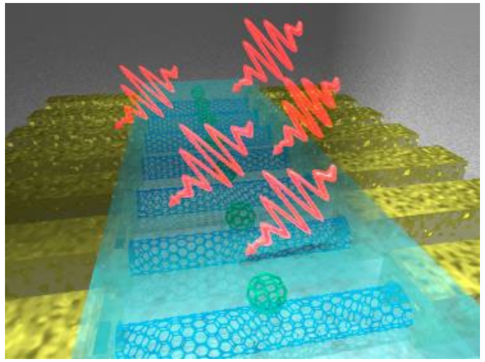

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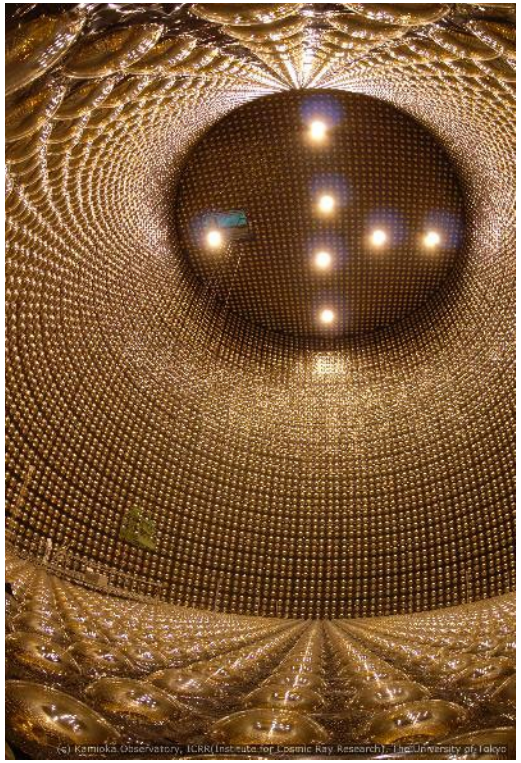
Single Photon Detection is a Critical Enabling Technology

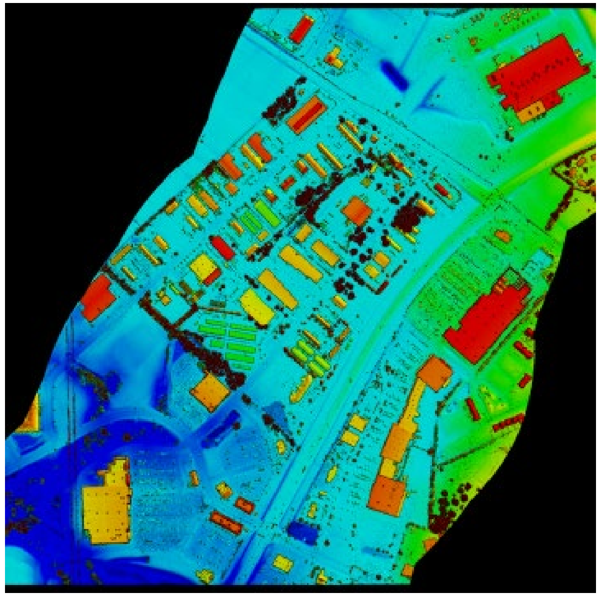
Rare event detection
(*e.g.*, dark matter, neutrinos, electron-proton decay)



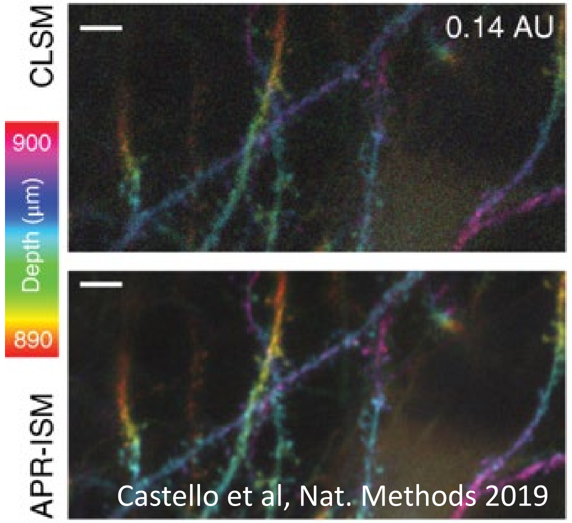
Quantum Key Distribution
Secure communications

Vallone et al, PRL 2015

Single Photon LIDAR
3D terrain and infrastructure mapping



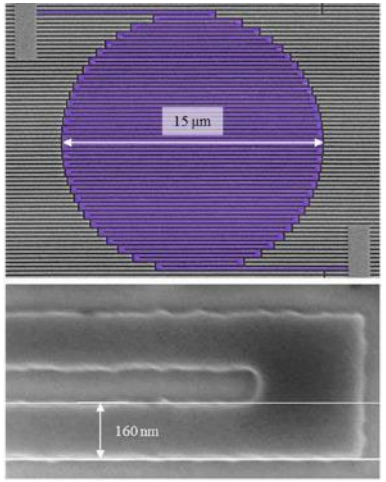
Biological imaging
Neuronal processes mouse brain



Castello et al, Nat. Methods 2019

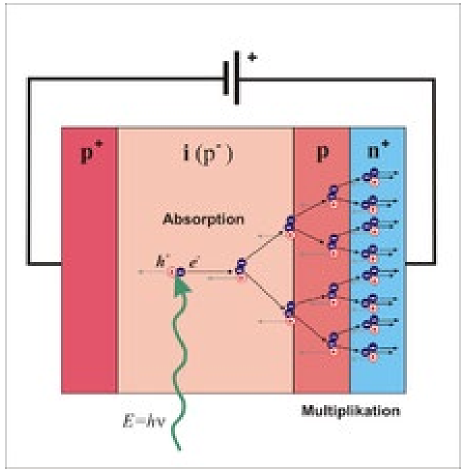
Exquisite Performance for Single Photon Detection

Superconducting Nanowire



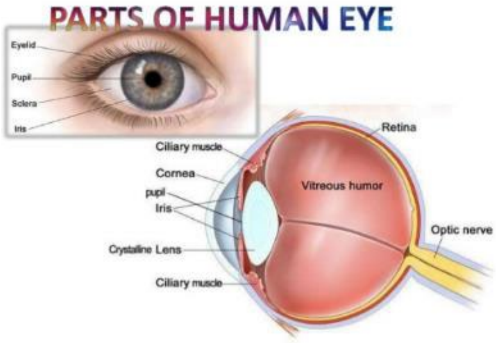
NIST

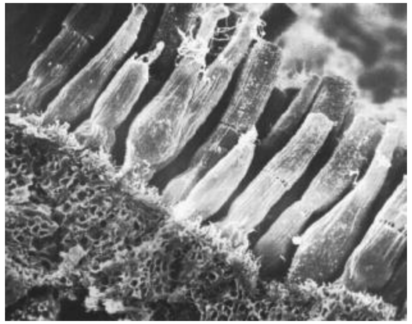
Avalanche Photodiode



Photomultiplier tubes

Hamamatsu

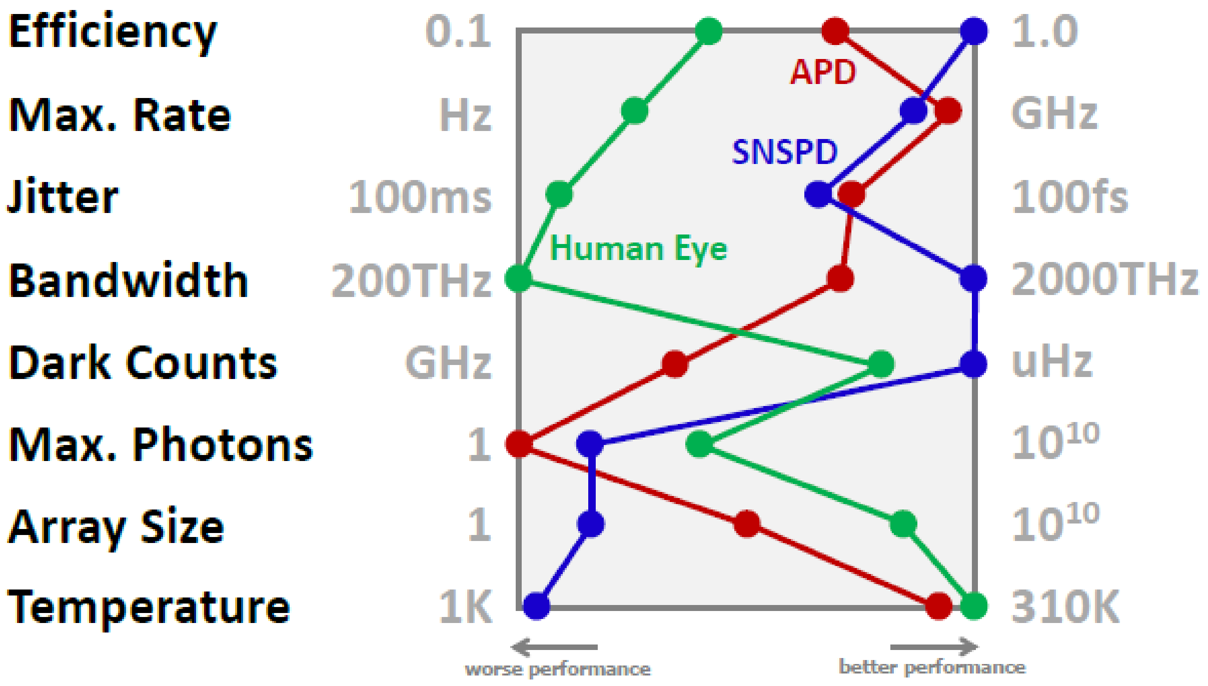




Omikron

Single Photon Detection: *Tinsley et al, Nat. Comm. (2016)*

Trade-Offs for Existing Single Photon Detectors



From Prem Kumar

What are the fundamental limits to single photon detection?

Are there inherent trade-offs?

What is the best architecture, and how do we design it?

Plan for Presentation

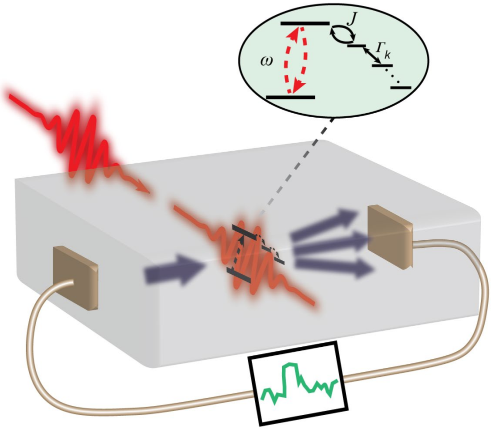
-New general modeling framework

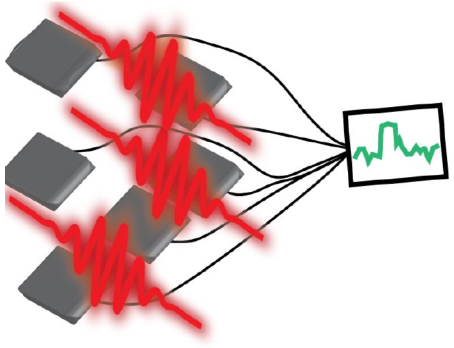
-Novel designs for Photon Number Resolution

-Experiments with molecular and nanoscale systems

-Novel designs for Energy Resolving Detectors

General Modeling Framework from Quantum Optics





-Framework can handle…

- General light field
  - Multiple photons
  - Multiple modes
  - Multiple profiles
- Different types of materials
  - Atoms
  - Molecules
  - Solids

- Complex intermediate states
  - Multiple states
  - Coherent and incoherent
- Broad range of amplification processes

-Generates performance metrics

-Is practical

Young, Sarovar, Léonard, *Phys. Rev. A (2019)*.

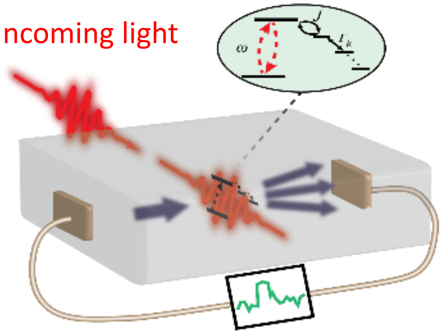
General Modeling Framework

$$\Pi(t) = \mathrm{Tr}_{\mathrm{LIGHT}}\left[\mathcal{K}(t,t_0)\hat{\rho}_{\mathrm{LIGHT}}(t_0)\right]$$

Measurement outcome (e.g. probability)

Depends on detector configuration

Incoming field state



From this, can get performance metrics:

Efficiency: $\Pi(t)$

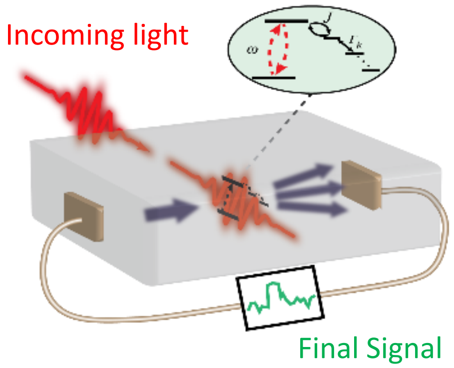
Dark count rate: $\frac{\Pi(0;t_m)}{t_m} + \frac{1}{2t_m} erf\left(2\sqrt{kt_m}\Delta I_{hit}\right)$

Jitter: $\frac{d\Pi(t)}{dt}$

General Modeling Framework

$$\Pi(t) = \mathrm{Tr}_{\mathrm{LIGHT}}\left[\mathcal{K}(t, t_0)\hat{\rho}_{\mathrm{LIGHT}}(t_0)\right]$$

How to get this?



Stochastic quantum master equation for density matrix

$$\dot{\rho}(t) = v_{sys} + v_{l-m} + v_{amp}$$

$$\hat{\rho}_{\mathrm{MATTER}}(t) = \mathrm{Tr}_{\mathrm{LIGHT}}[\mathcal{P}(t, t_0)\hat{\rho}_{\mathrm{TOT}}(t_0)]$$

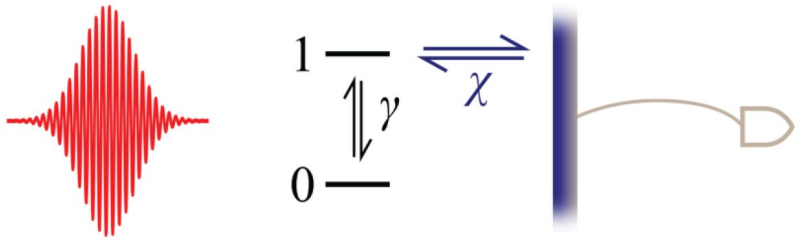
System Architecture

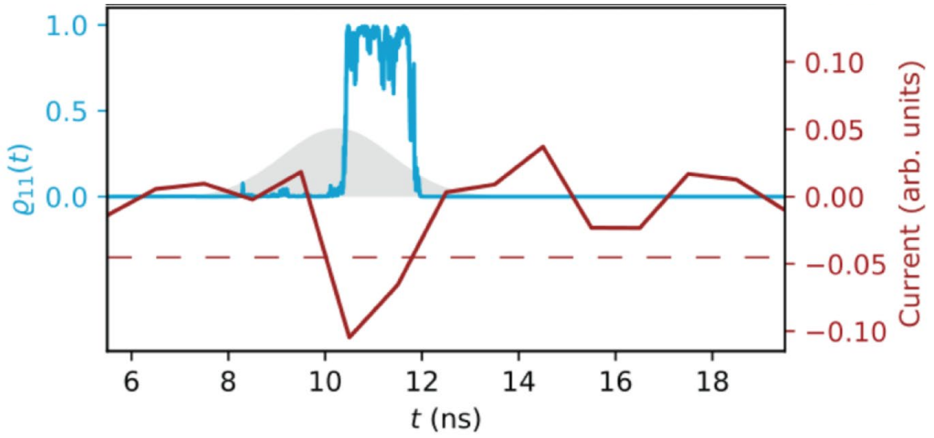
Decoupled detector

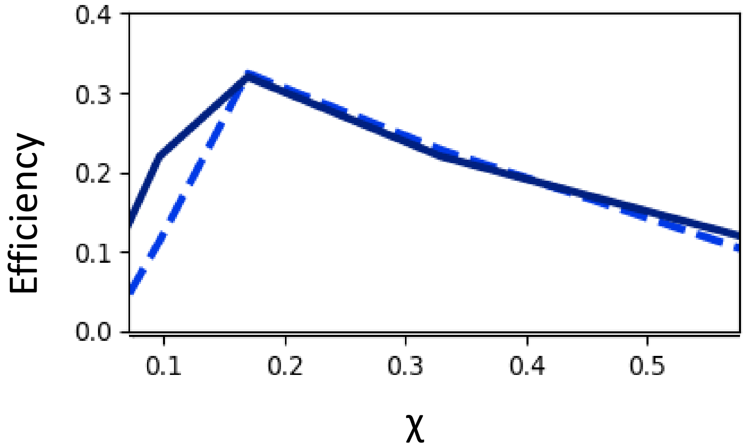
Fully coupled quantum detector

$$I \sim \int \hat{\rho}_{MATTER}(t)dt$$ → Measurement outcome $\Pi(t)$

Fully Quantum Coherent Detector



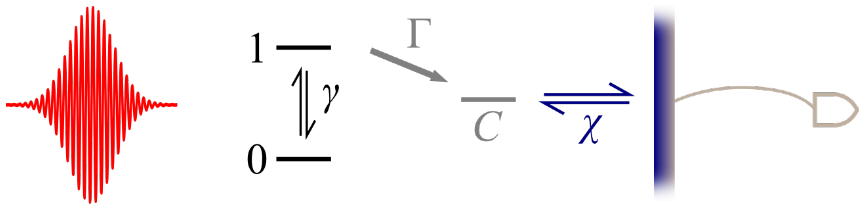


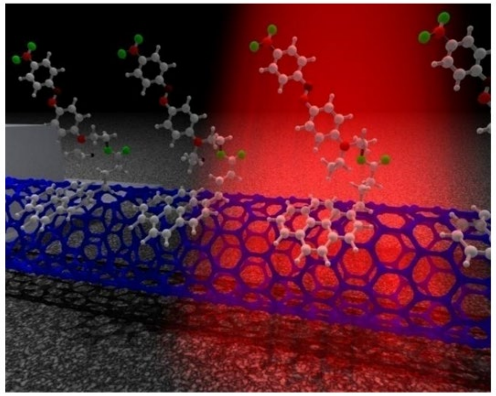


- Measurement backaction quenches absorption
- Detector has limited performance

Young, Sarovar, Léonard, *Phys. Rev. A* (2018).
Royer & Blais, *Phys. Rev. Lett*. (2018).
Helmer et al, *Phys. Rev. A* (2009).

Important Result



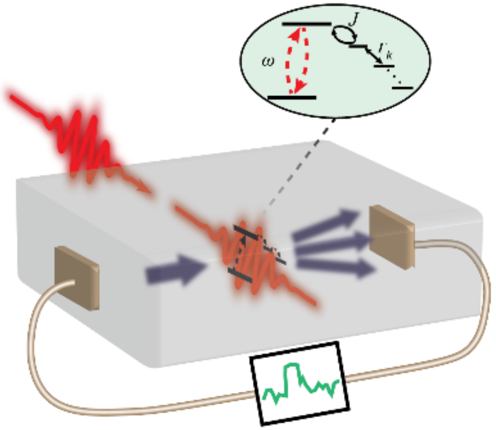


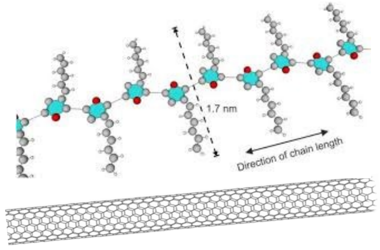
When $\gamma = \Gamma$ and $\gamma^2 + \Gamma^2 \gg 1/\sigma_E$

Perfect detection can exist: 100% efficiency, no additional jitter

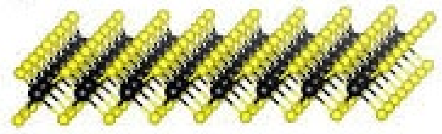
Young, Sarovar, Léonard, *Phys. Rev. A (2018)*.

Extended Systems

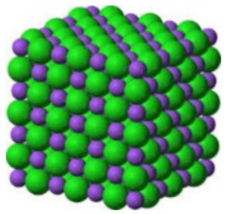




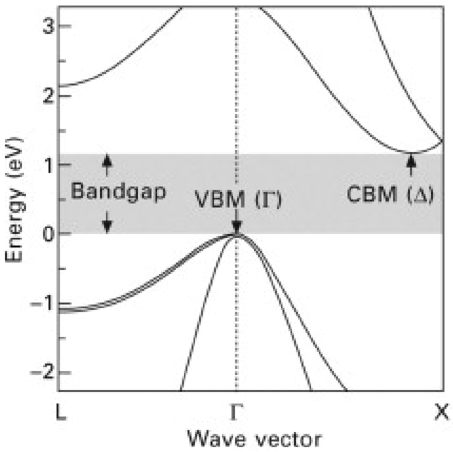
1D

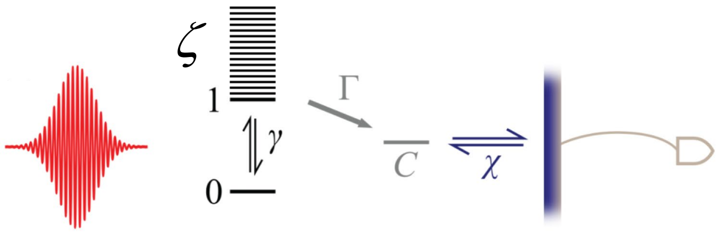


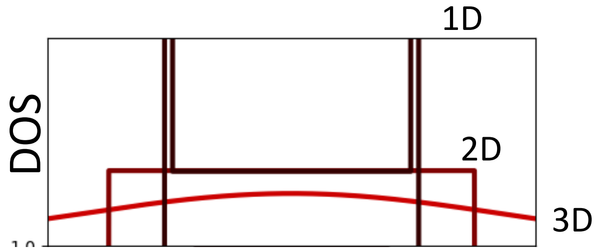
2D



3D



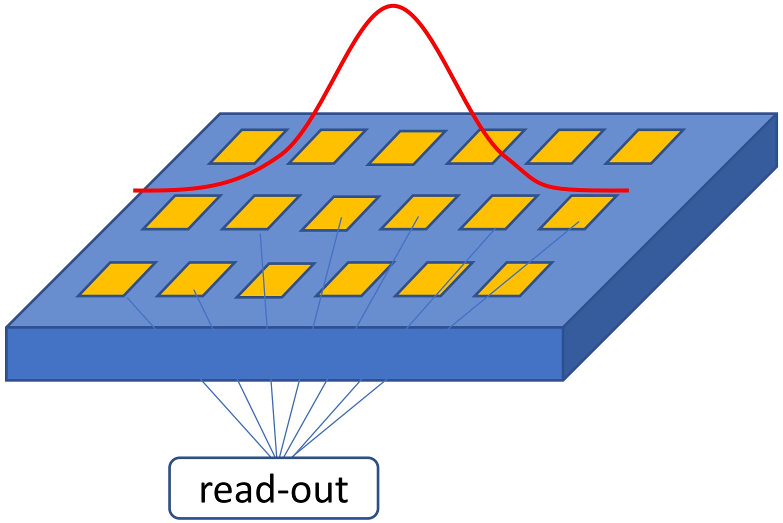




New condition for ideal detection: $\gamma = \Gamma + \zeta$

Young, Sarovar, Léonard, *Phys. Rev. A (2018)*.

Photon Number Resolution



Simple array:

$(\text{efficiency})^N$

$(0.95)^{10} = 60\%$

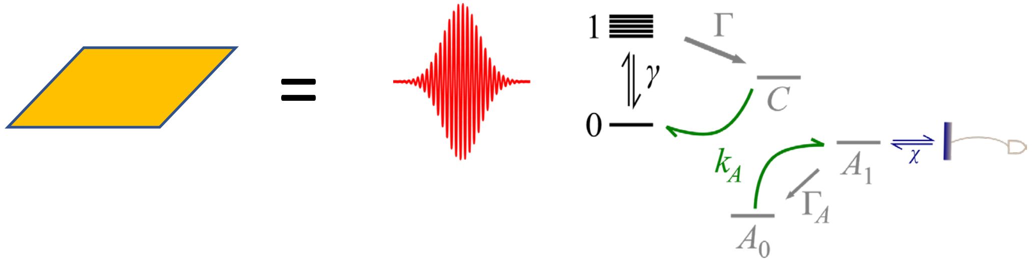
(Even worse than this because two photons can hit the same pixel)

New approach:

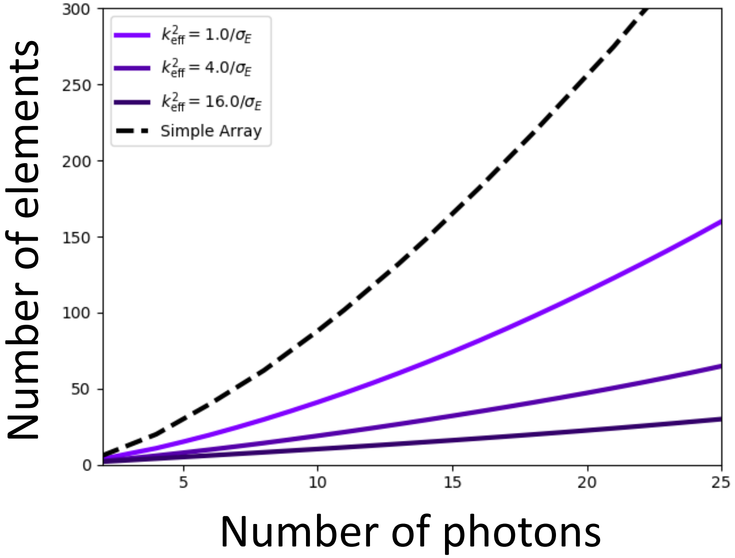
(1) Collective interaction of nanosensors with photon field

+

(2) Designed energetics and kinetic pathways

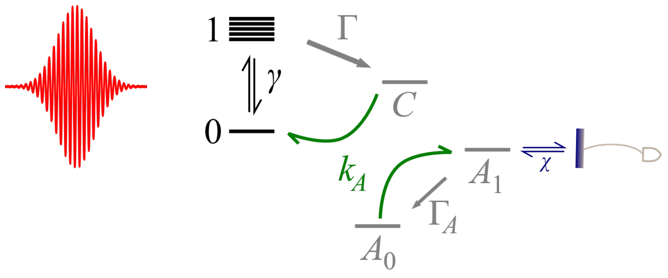


99% efficiency

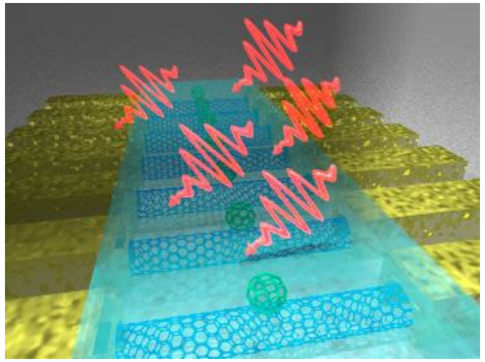


Significant improvement by structuring the system

Design of Physical Realizations for High Performance PNR

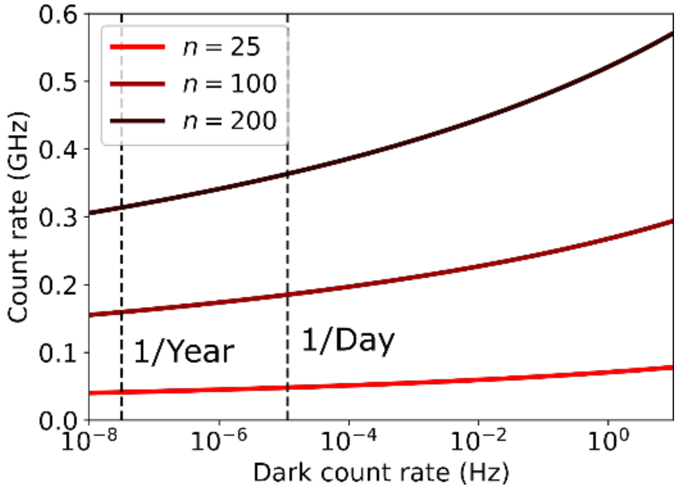


$$\gamma = \Gamma + \zeta$$



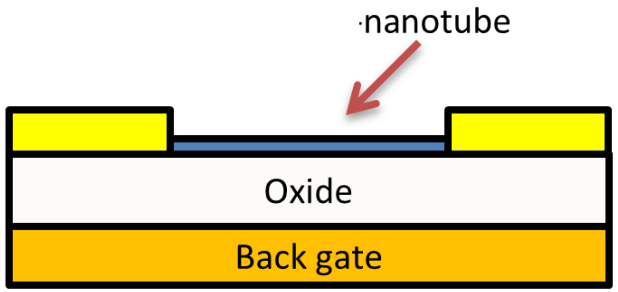
Forster energy transfer
~ picoseconds
~ 100% efficiency

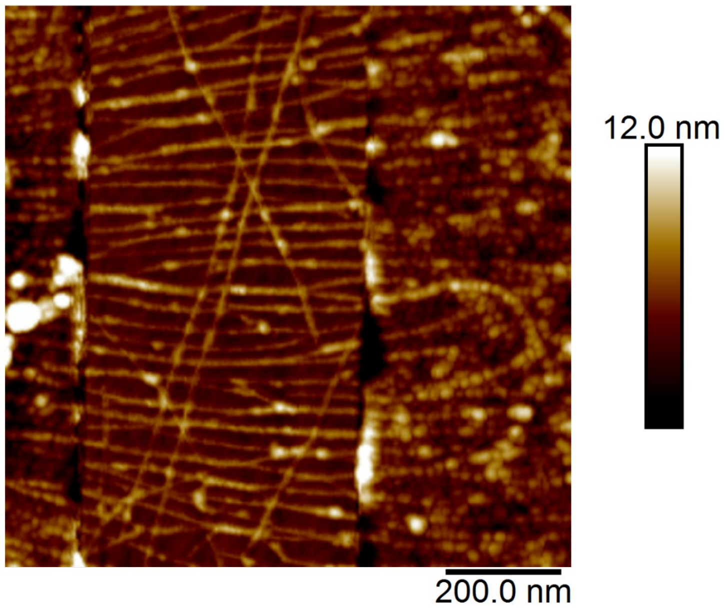
99% efficiency of detecting up to 12 photons



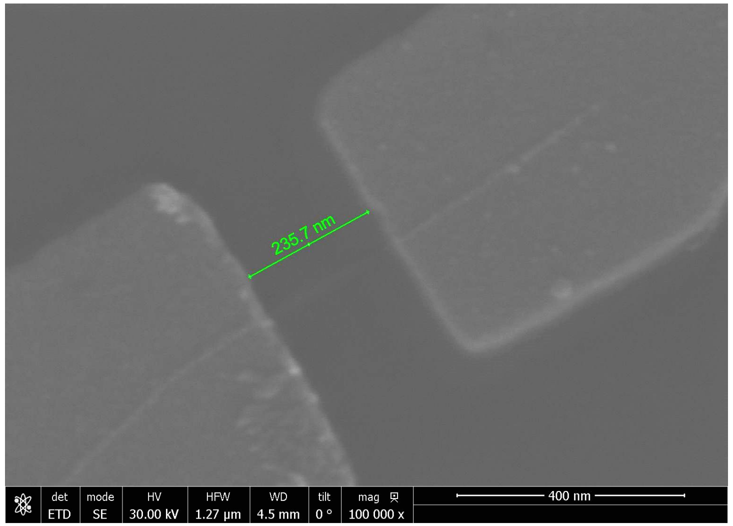
Young, Sarovar, Léonard, *ACS Photonics (2020)*.

Experiments Towards Novel Designs

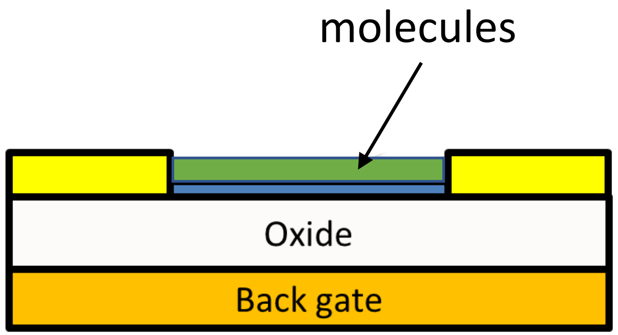


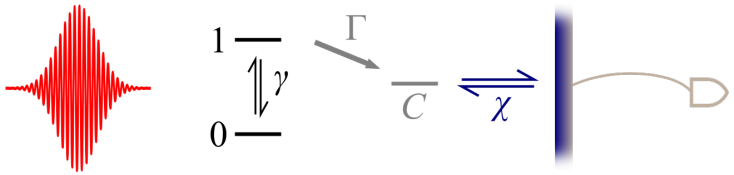


Devices with CNT arrays



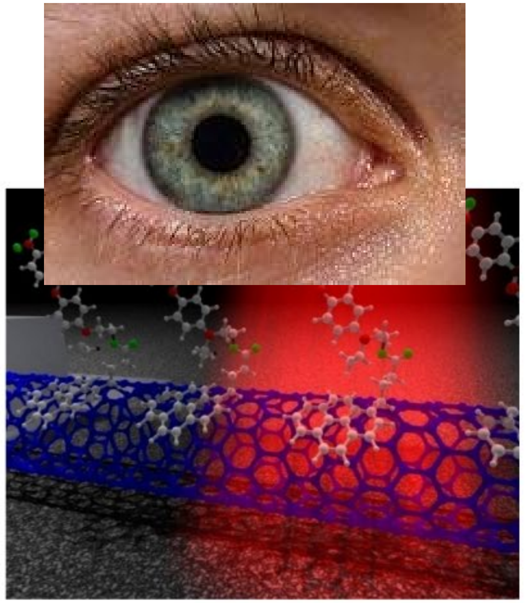
Devices with individual CNT

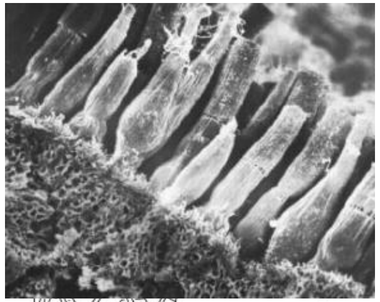




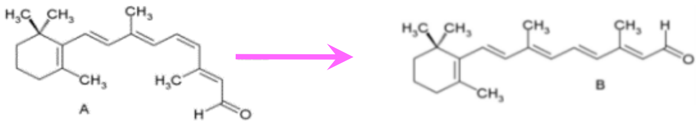
Bergemann & Léonard, *Small* (2018)

Bio-Inspired Design

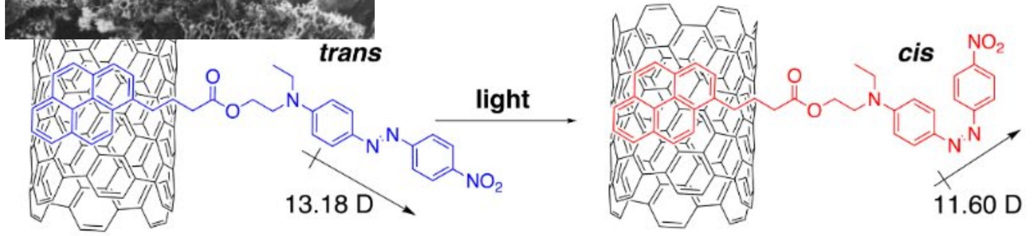


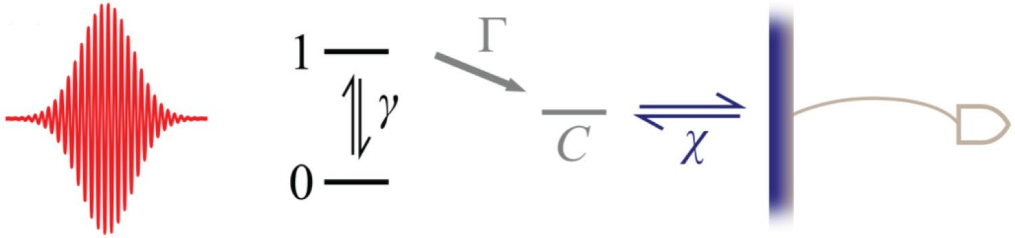


Retinal molecule

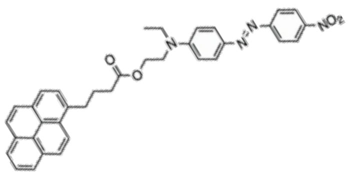


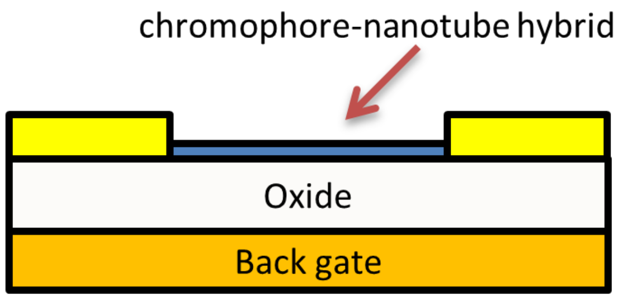
Cis *Trans*

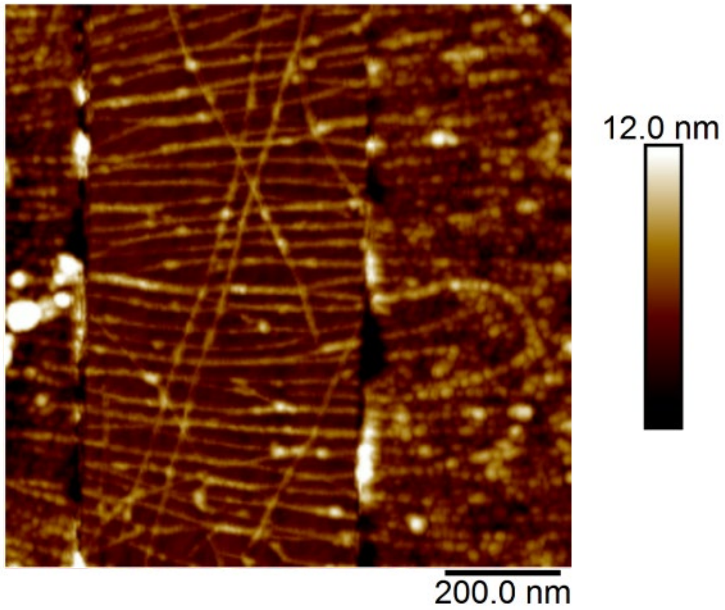


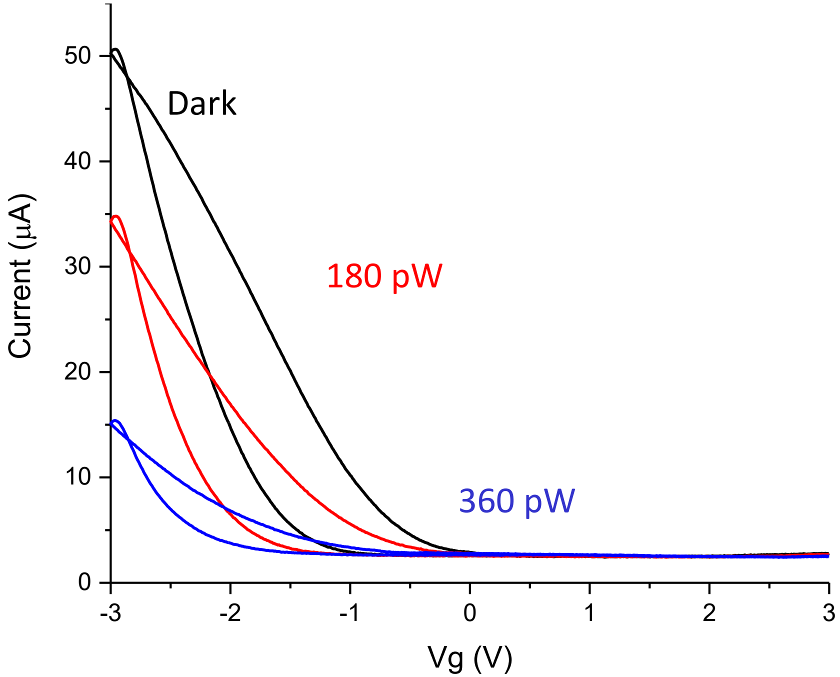


Functionalized Carbon Nanotube Transistors



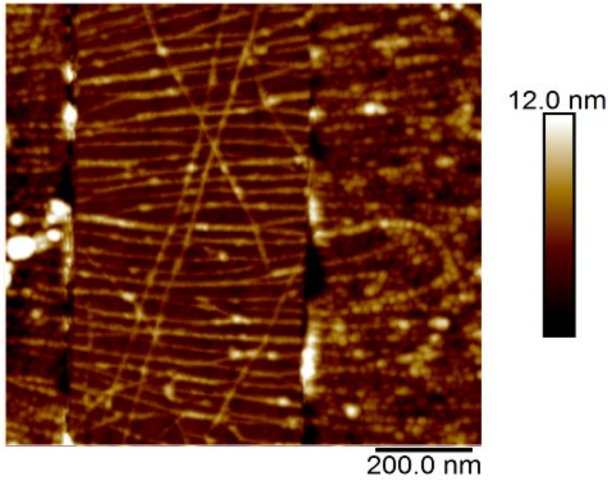


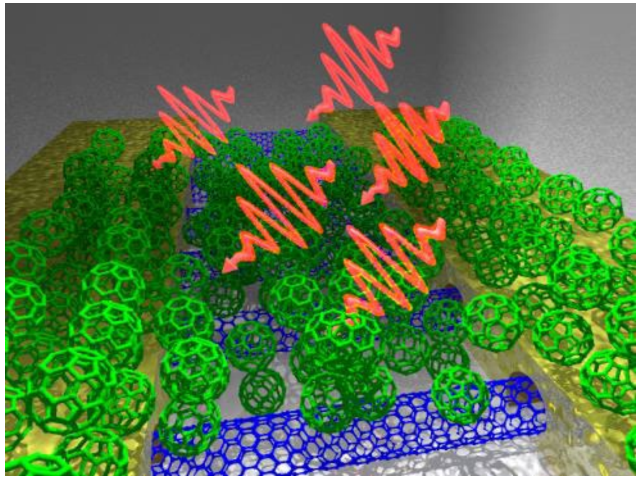


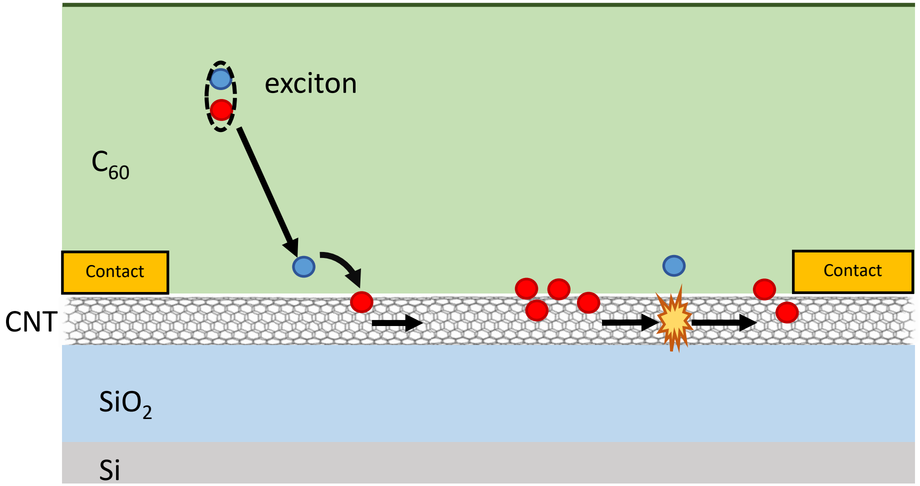


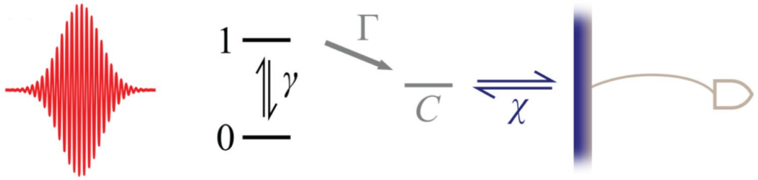
Gain > 10^4 at room temperature

C_{60}/CNT System Achieves Ultrahigh Gain at Room Temperature



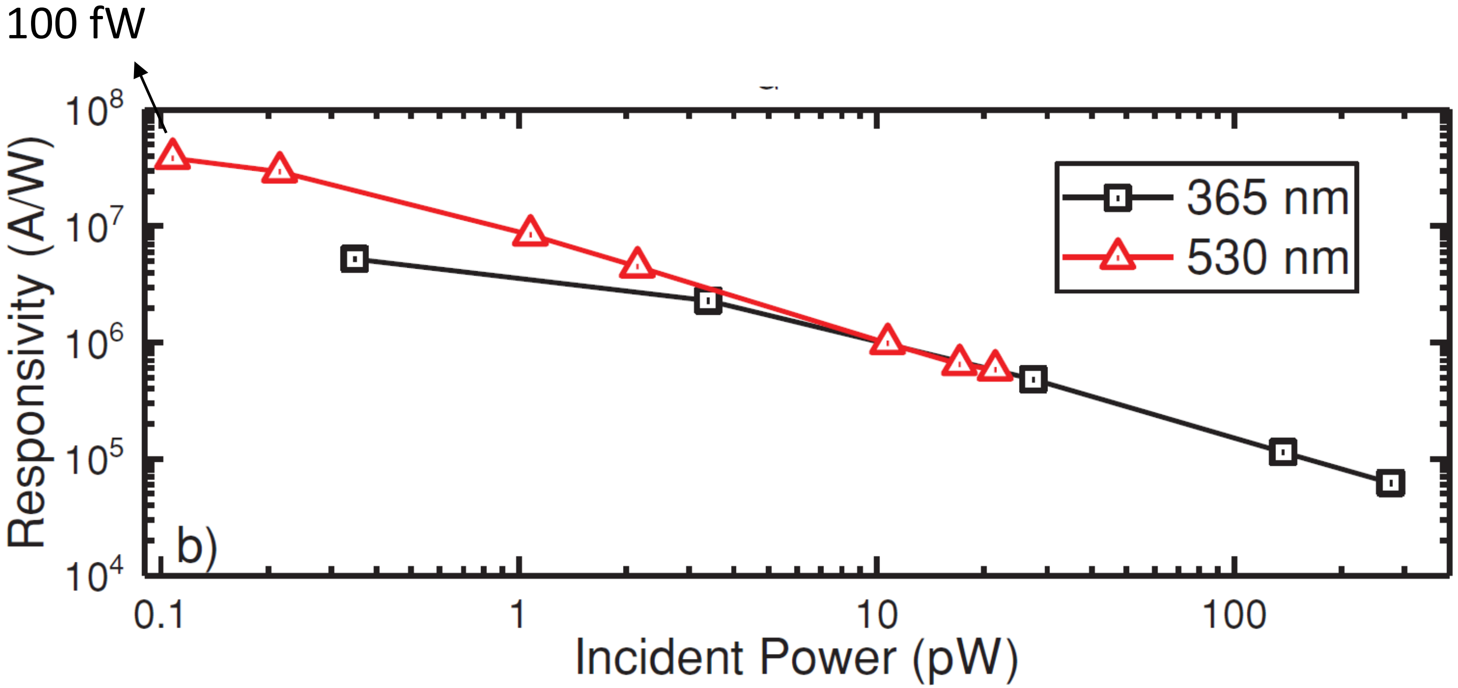






Bergemann & Léonard, *Small* (2018)

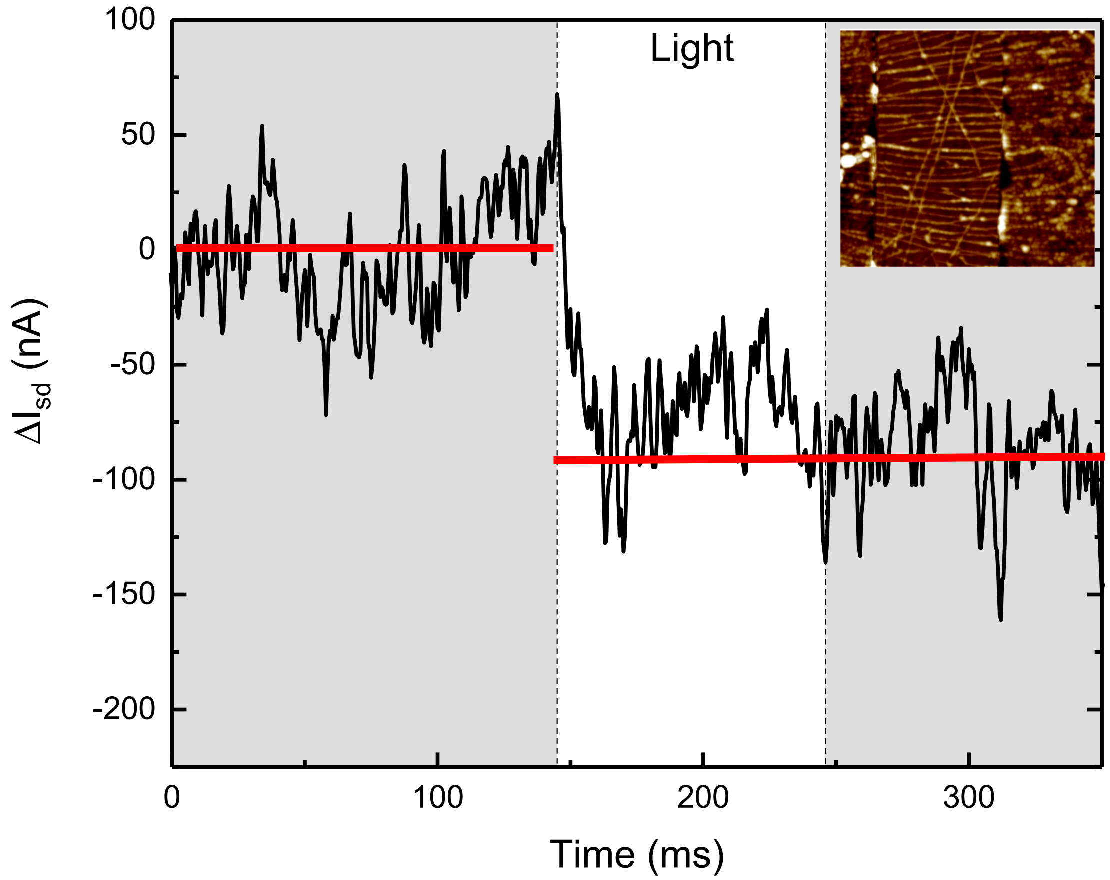
C_{60}/CNT System Achieves Ultrahigh Gain at Room Temperature



- Responsivity > 10^8 A/W
- Gain > 10^8
- Sensitive to UV, visible, and IR

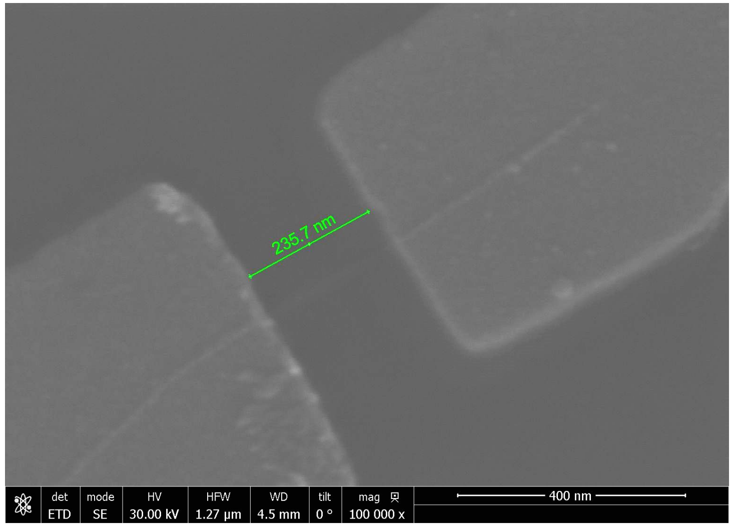
Bergemann & Léonard, *Small* (2018)

Response to Weak Light Pulse



Detection of 40-50 photons per CNT
at room temperature

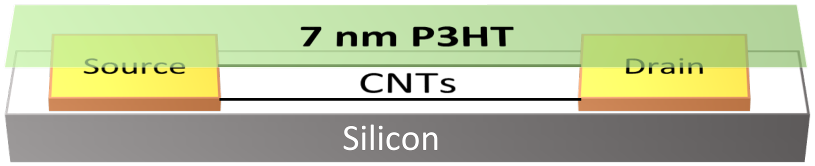
Device with only one CNT

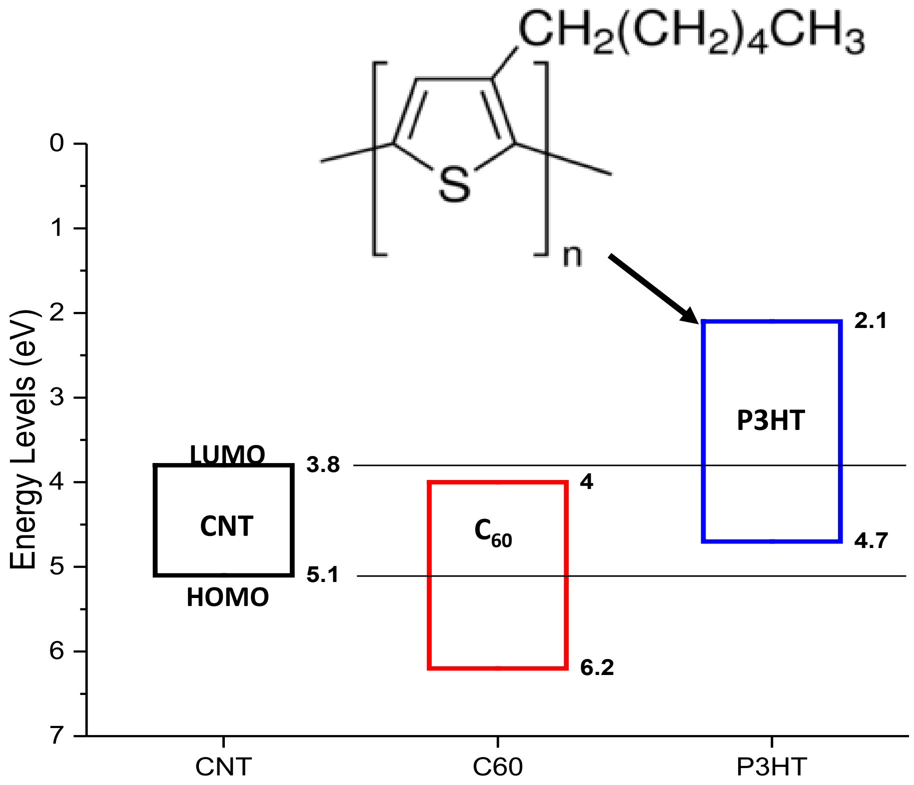


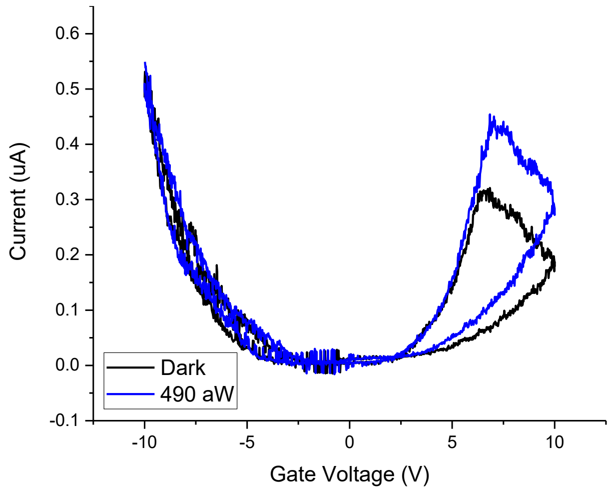
Detection of 200 photons
at room temperature

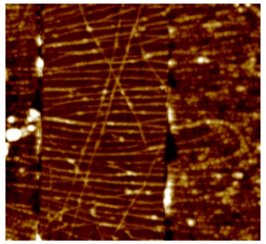
Bergemann & Léonard, *Small* (2018)

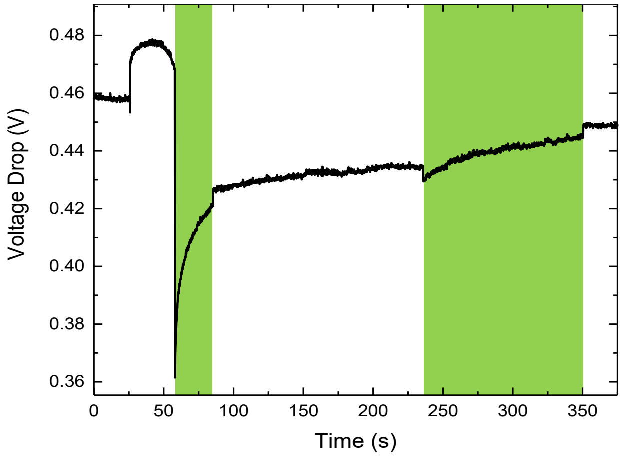
P3HT/CNT System Even More Sensitive











Gain > 10^9 at room temperature

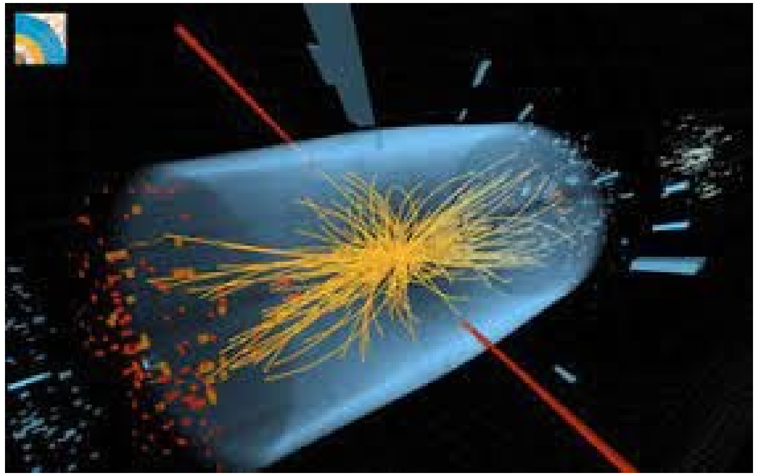
Detection of 8-13 photons/CNT

Bergemann & Léonard, *ACS Nano* (2021)

Frequency-Resolving Single Photon Detection

Example applications for high-energy physics

Reconstruction of photon trajectories in liquid scintillator detectors



High Efficiency
Low jitter
High Frequency resolution

Cosmology: resolving emission lines from galaxies

The DESI Experiment Part II: Instrument Design

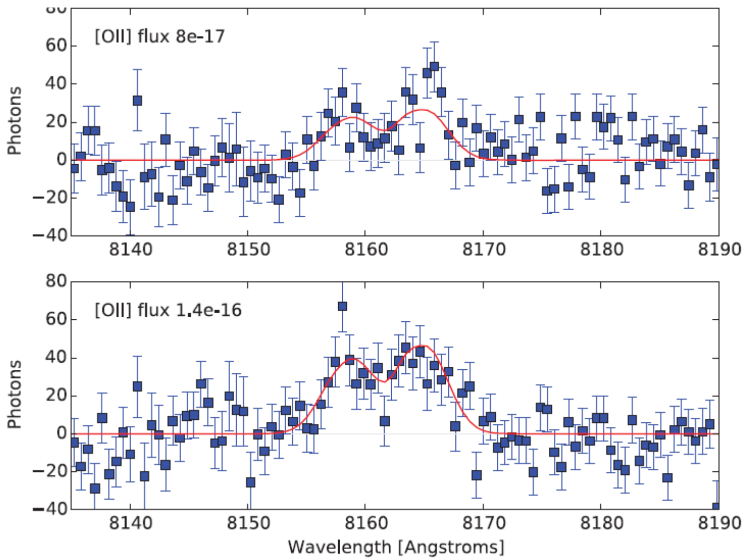
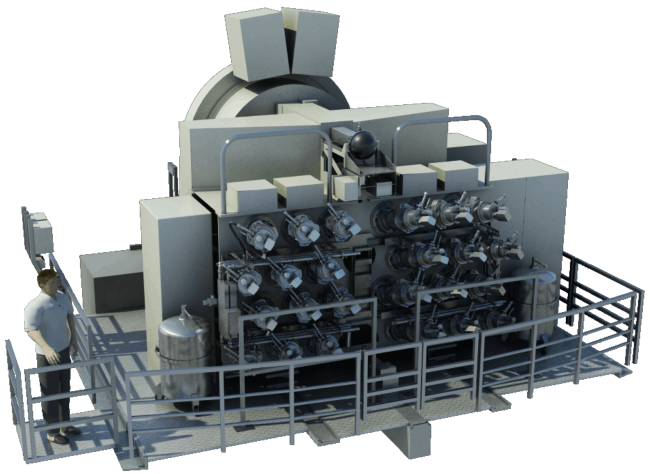


Figure 7.10: A quicksim simulation of the [O II] emission line doublet at a limiting flux of F([O II])=0.8 × 10^{-16} ergs s^{-1} cm^{-2} (top) and the median case of F([O II])=1.4 × 10^{-16} ergs s^{-1} cm^{-2} (bottom) for a reference 1000 second exposure. The simulated emission lines have a velocity width of 70 km/s and a ratio of 1 : 1.3. The red curves represent the input spectra at the resolution of the instrument (expected number of collected photons per pixel row), and the blue squares a random realization of the data with noise.

High Efficiency
High Frequency resolution

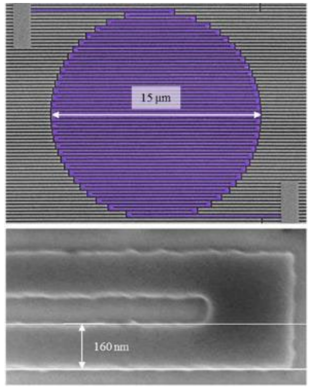
Subwavelength Elements Collectively Interacting with Photon Field

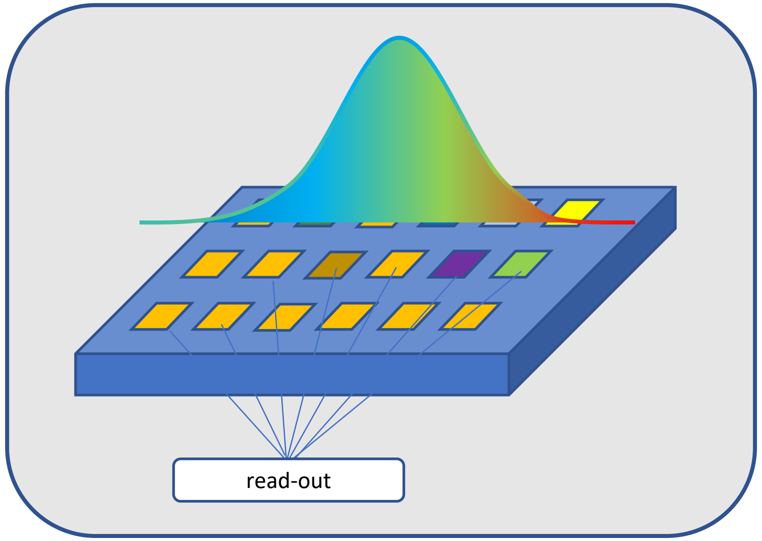
Existing approaches:

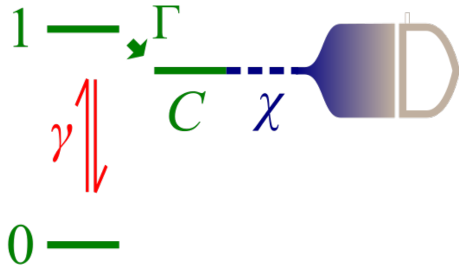


MUSE integral field spectrograph
European Southern Observatory

SNSPDs

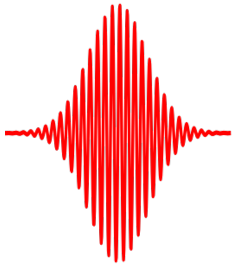


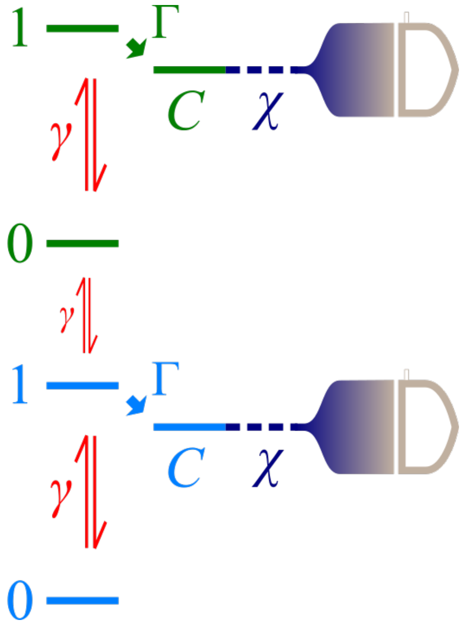




100% efficiency, minimal jitter

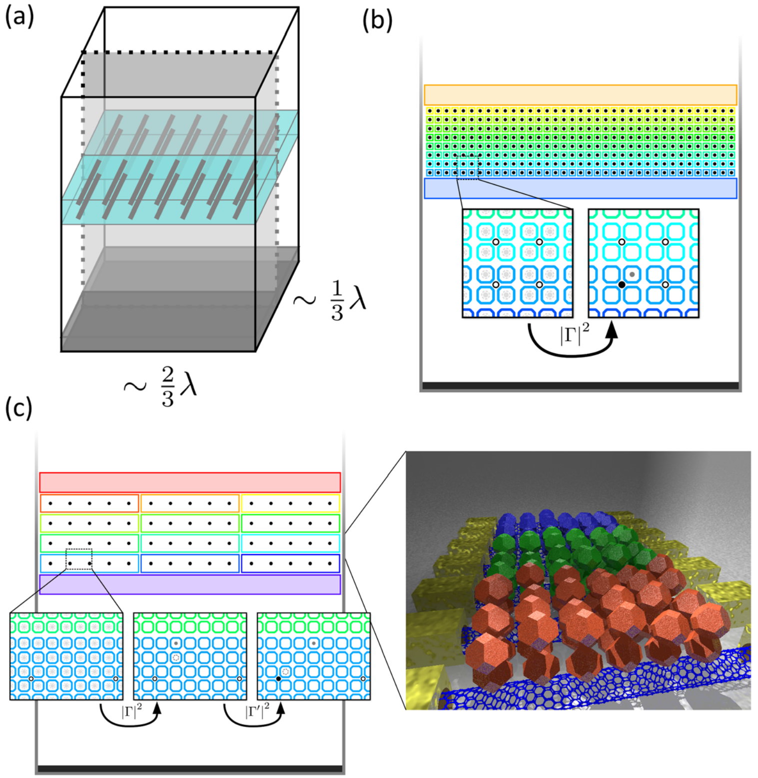
New approach:

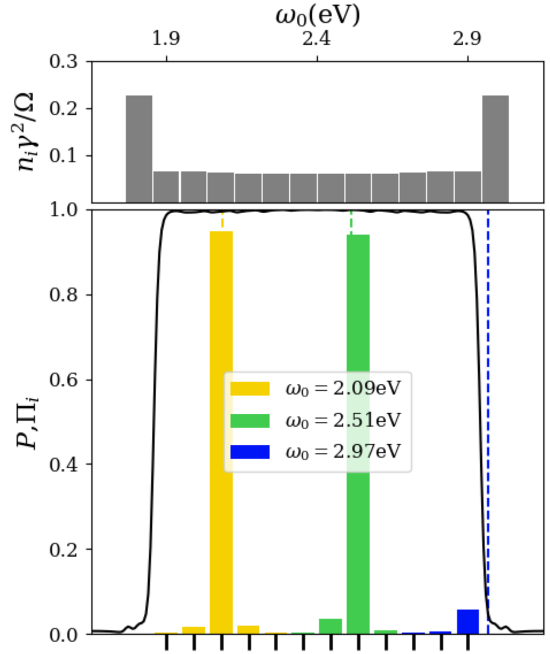




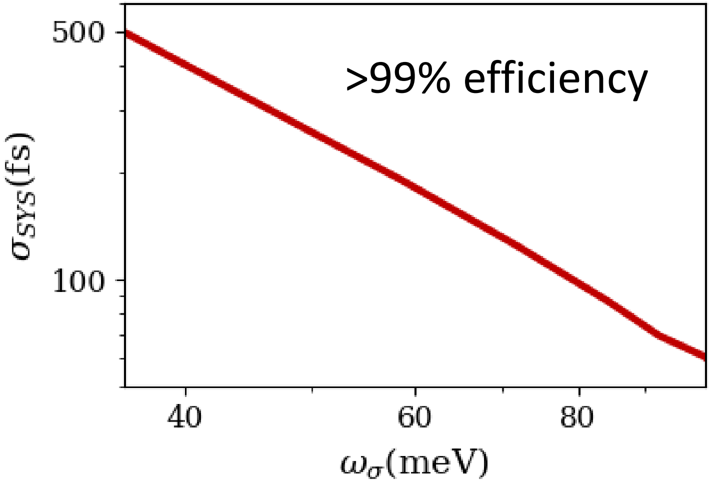
Must still account for collective interaction – the number/optical couplings of elements must be tuned **together** to ensure efficiency at each frequency

Frequency-Resolving Single Photon Detection





Frequency bins



-High efficiency
-Low jitter
-High frequency resolution

Young, Sarovar, Léonard, *arXiv*.

Summary

- New modeling framework allows evaluation and design of photodetectors
- Novel designs emerge with improved performance
- Testing of these designs has already led to ultrahigh gain at room temperature

Future Work

- Develop approaches to reduce noise in experimental systems
- Test new molecule/nanotube combinations
- Integrate with CMOS

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