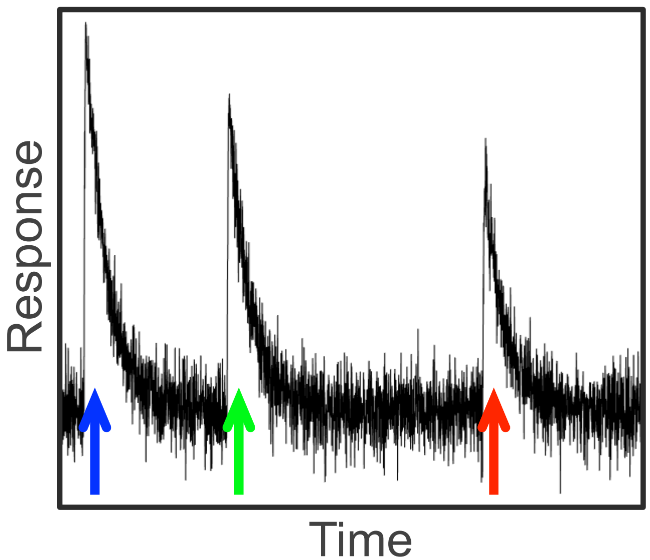
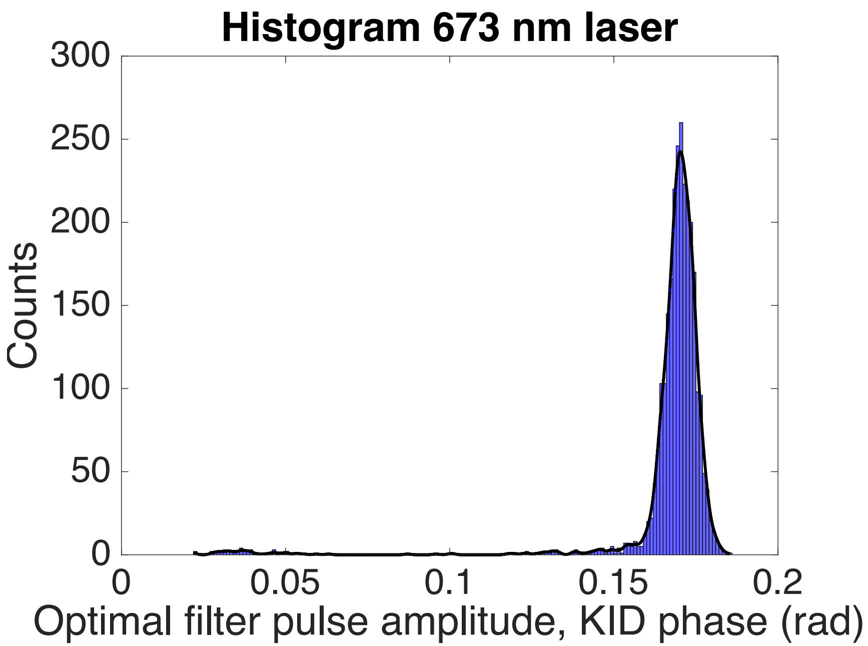
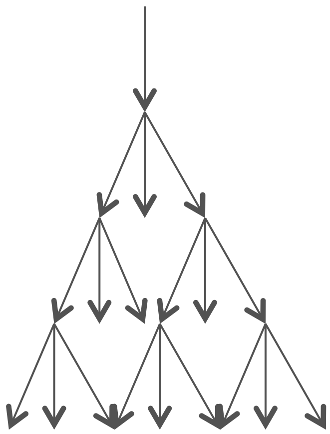
Energy resolution of aluminium MKIDs at visible/near-infrared wavelengths







Pieter de Visser
Vignesh Murugesan
David Thoen
Jochem Baselmans

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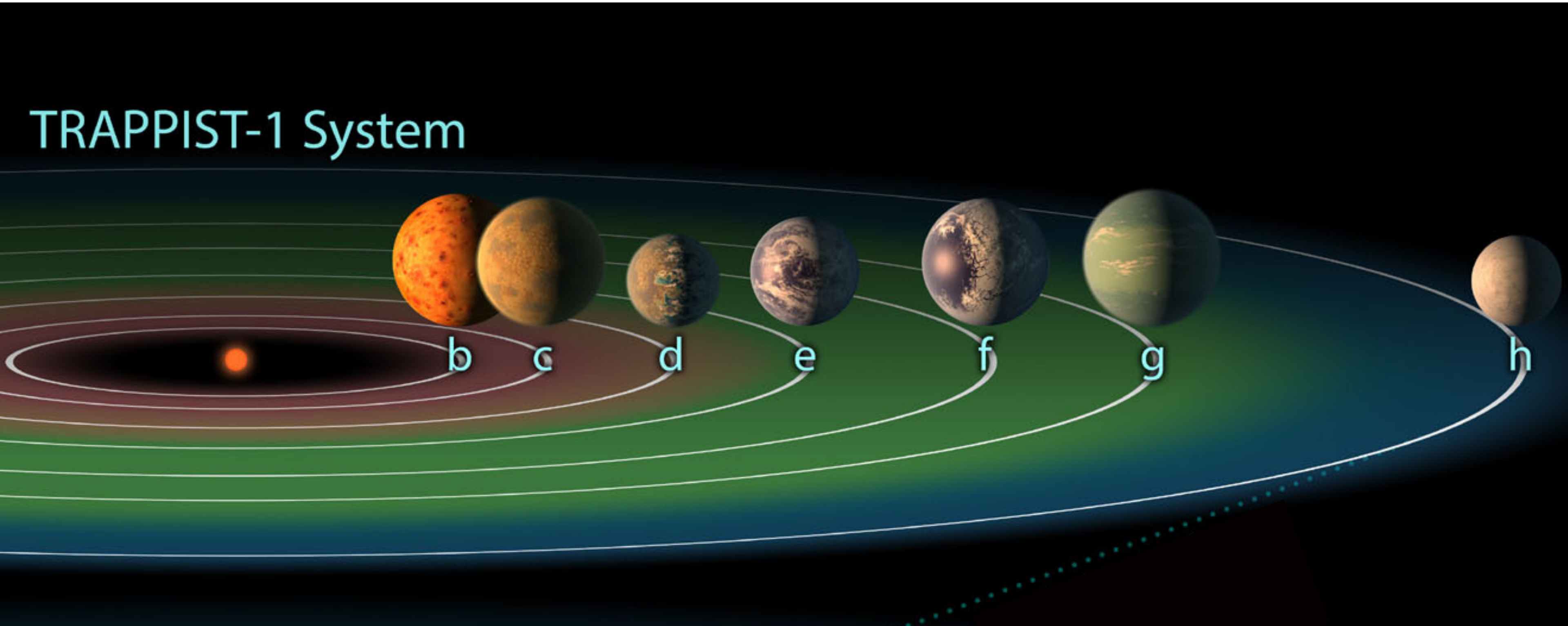
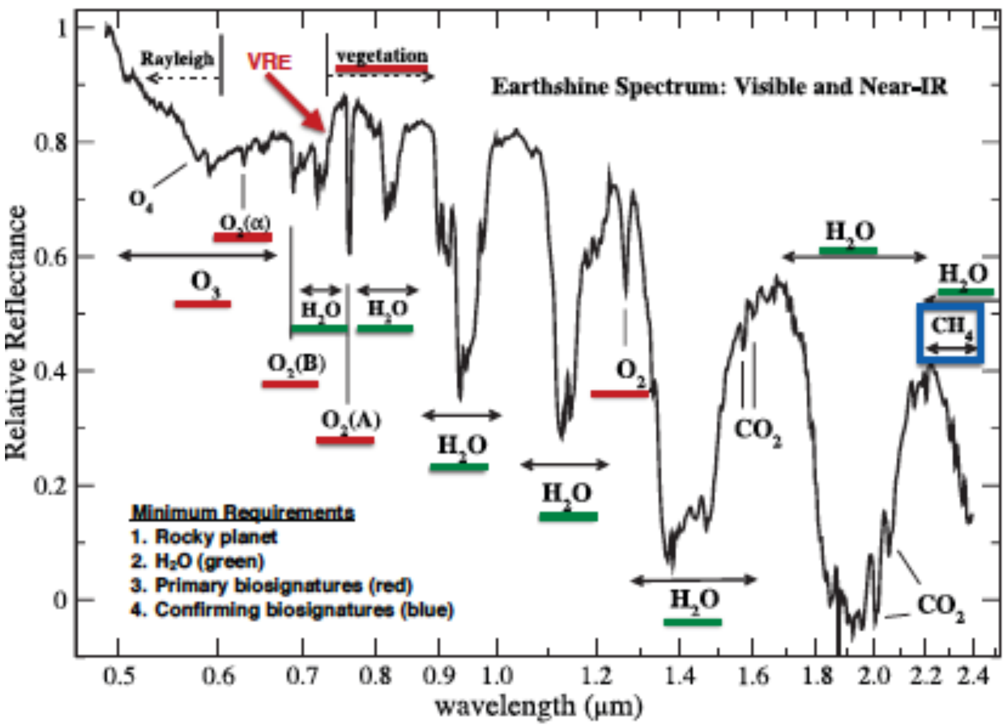
Are we alone?

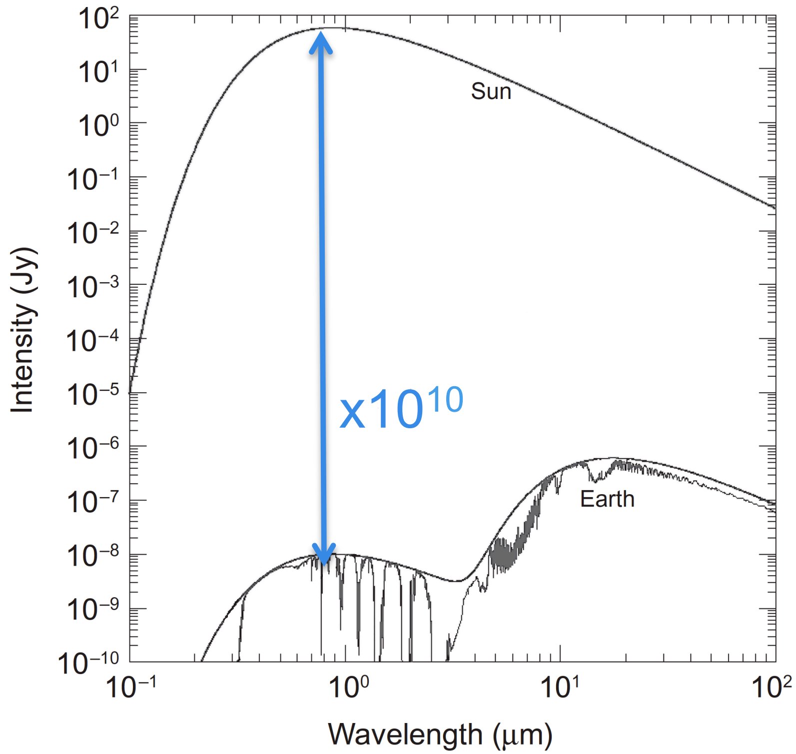
- 1000’s of exoplanets found
- Several dozen in habitable zone
- Now is the time to find out what ‘lives’ on these planets



Breath analysis: a spectrum of the planet's light

- 10^{10} larger signal from star than planet => null the star
- Still only <1 photon/second from planet
- Detector required with zero noise and ideally R~100





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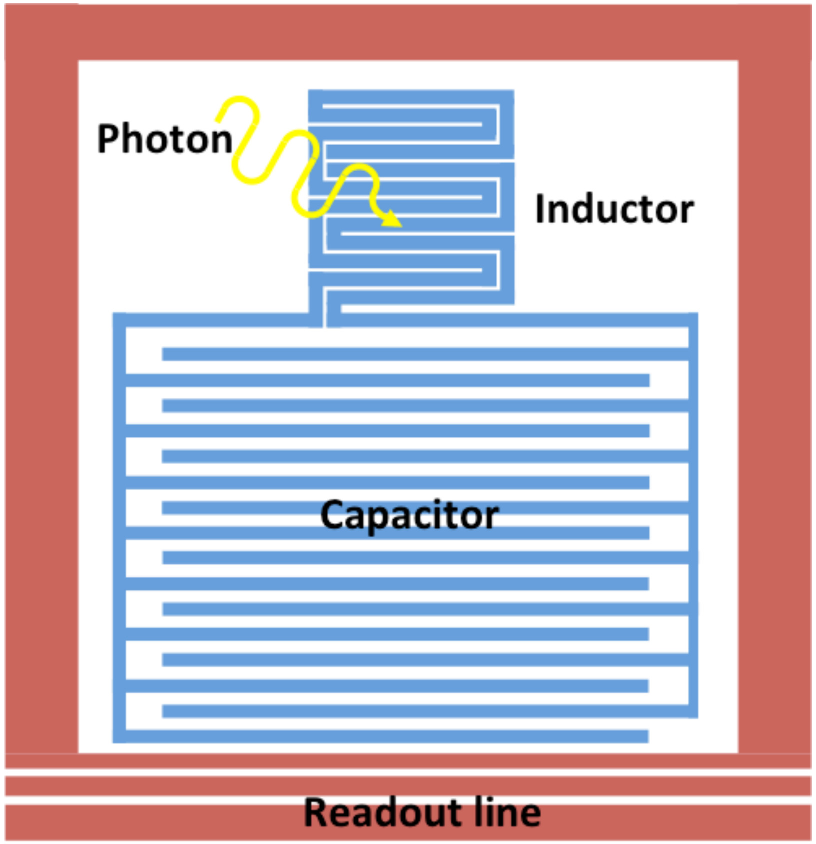
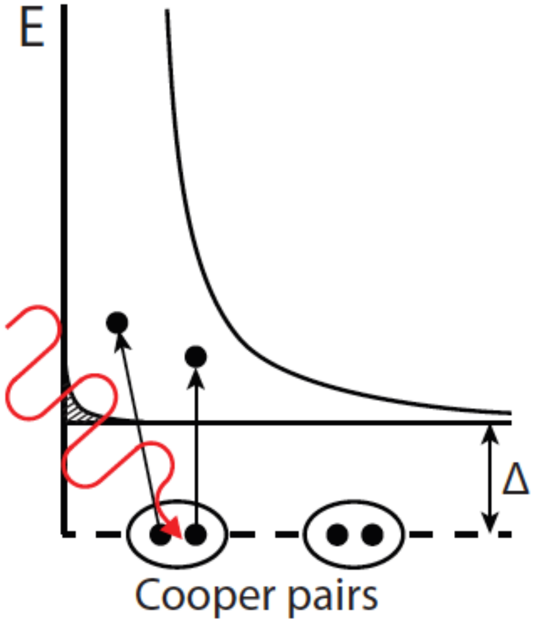
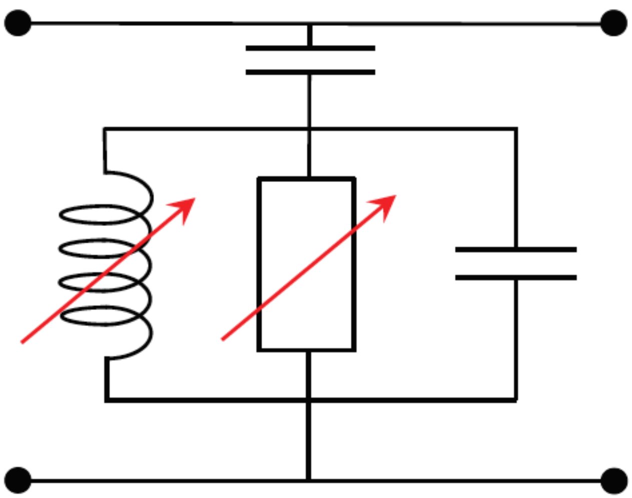
Solution: superconducting detectors







Microwave Kinetic Inductance Detector

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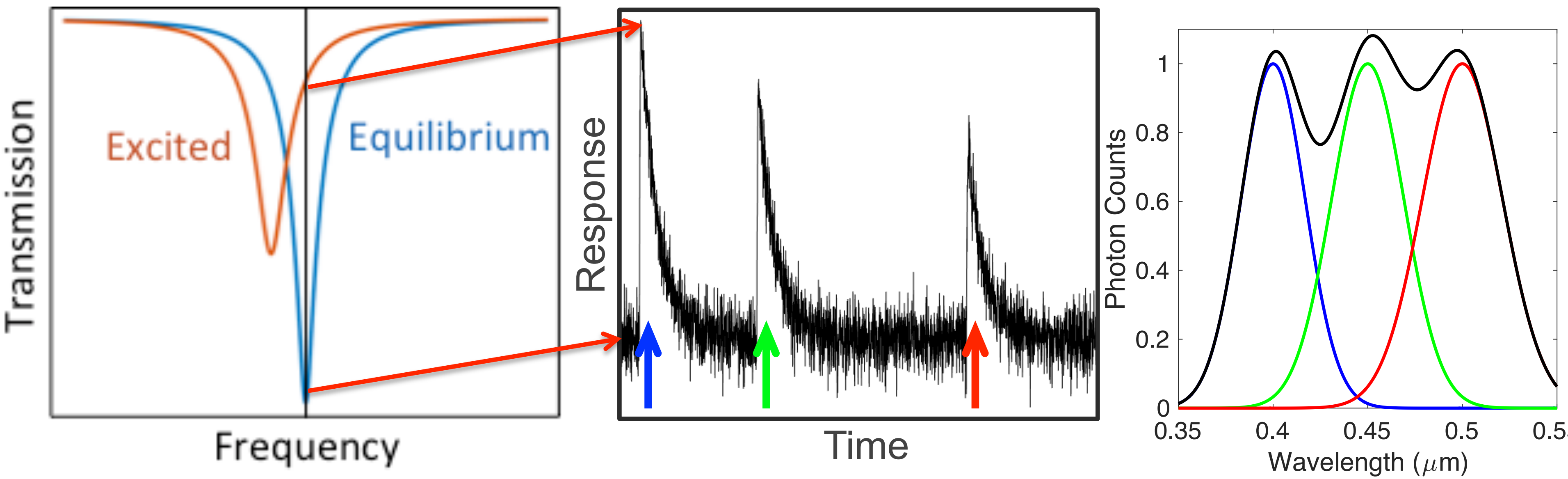
MKID detector – colour information



Energy resolution = zero dark current and read noise

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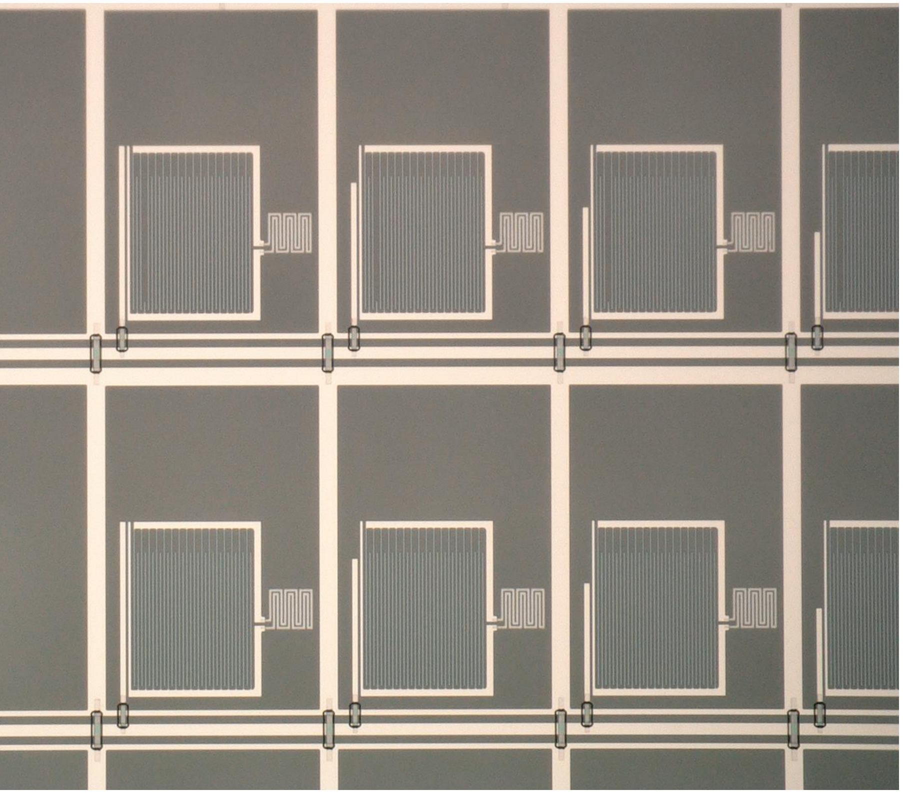
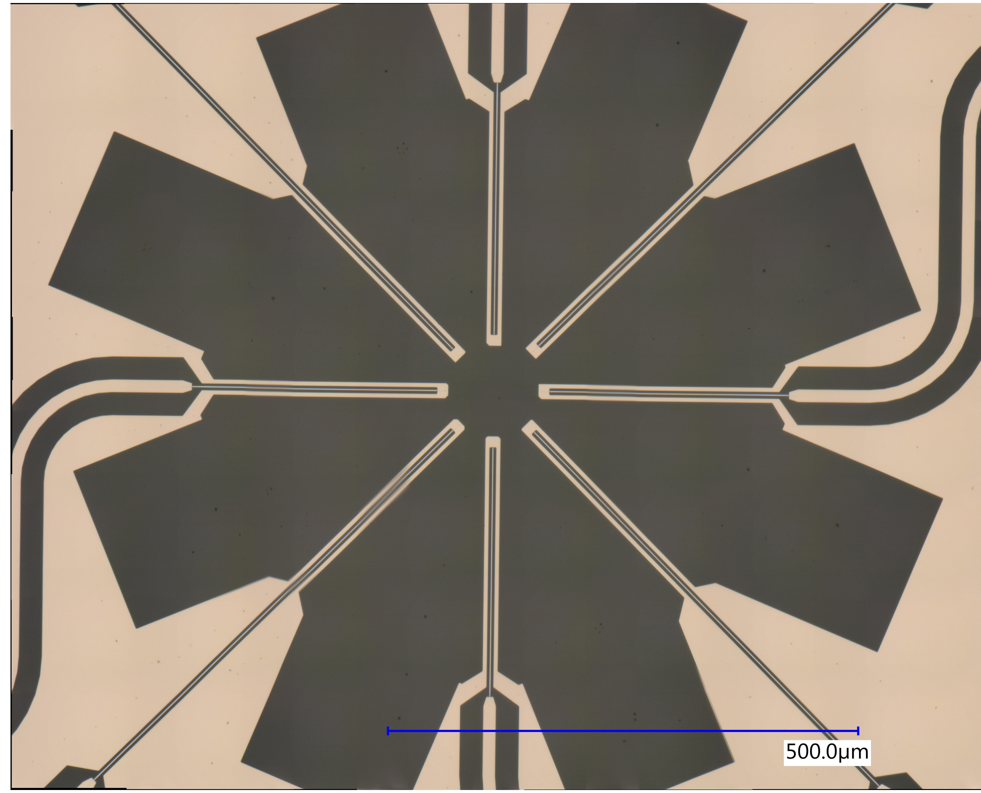
SRON visible/near-IR MKIDS research in two directions





Improving quantum efficiency
NbTiN/TiN hybrid LEKIDs

+ readout electronics
+ lens coupling

Energy resolution / sensitivity
NbTiN/Al hybrid CPW KIDs

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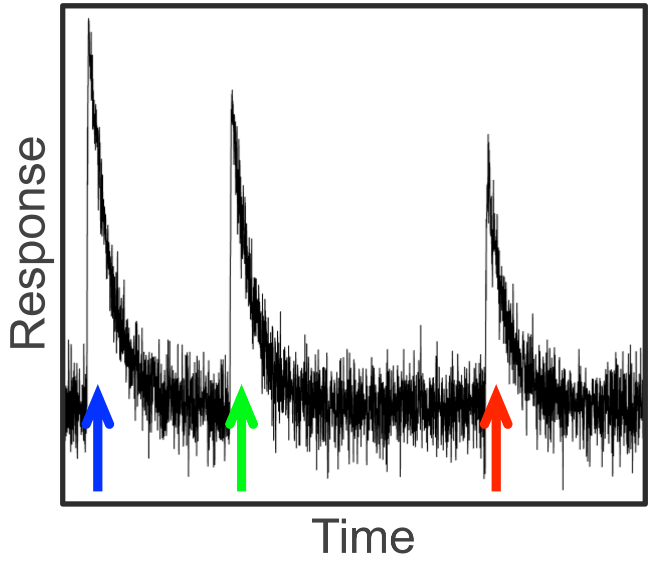
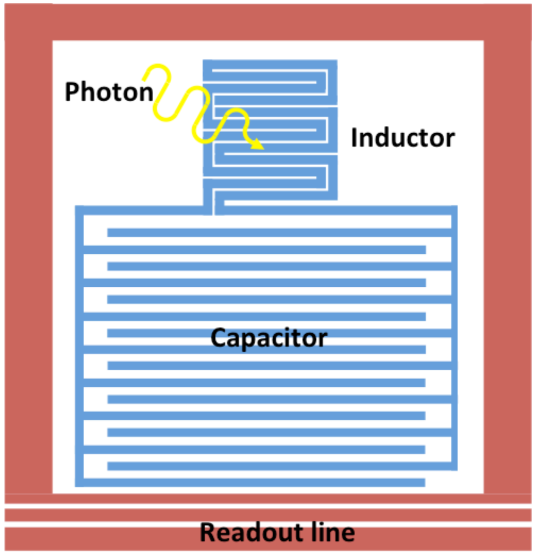
Energy resolution limits

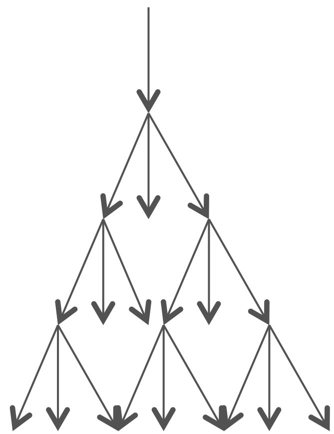
- Signal-to-noise
  - Volume
  - Q-factor
  - Kinetic inductance
  - Noise
  - *Timing*
  - *Nonlinearities*
- Current density uniformity vs. quasiparticle-diffusion
- Hot phonon loss
- Again phonons – Fano limit

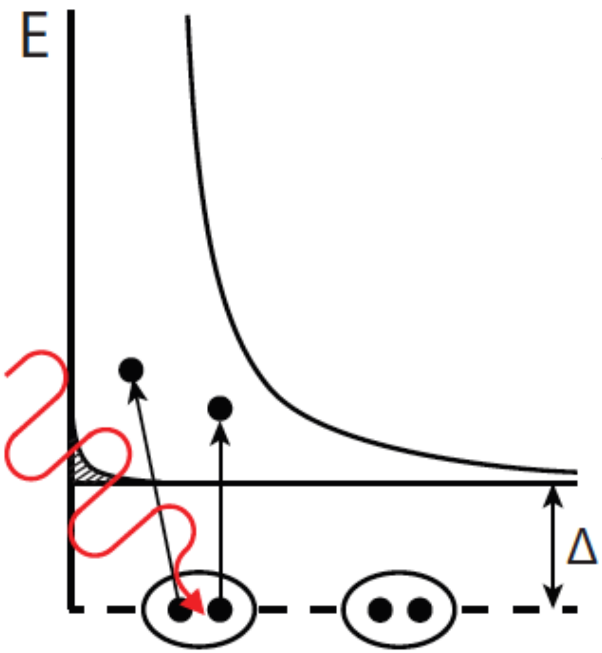




Role of phonons

- Convert 1-3 eV excitation into few thousand ~0.2 meV quasiparticle excitations
- Electron-phonon interaction
- Hot phonon loss
- Fano statistics in best case

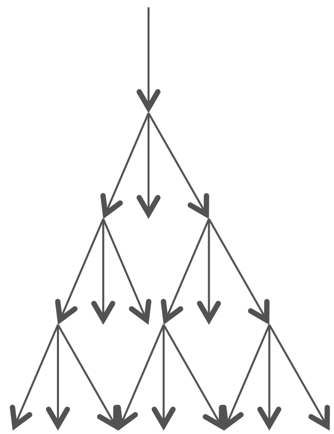


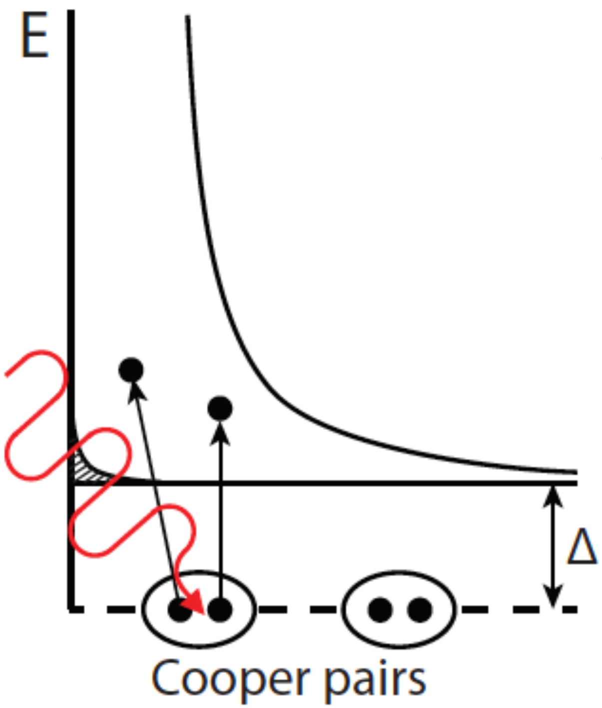


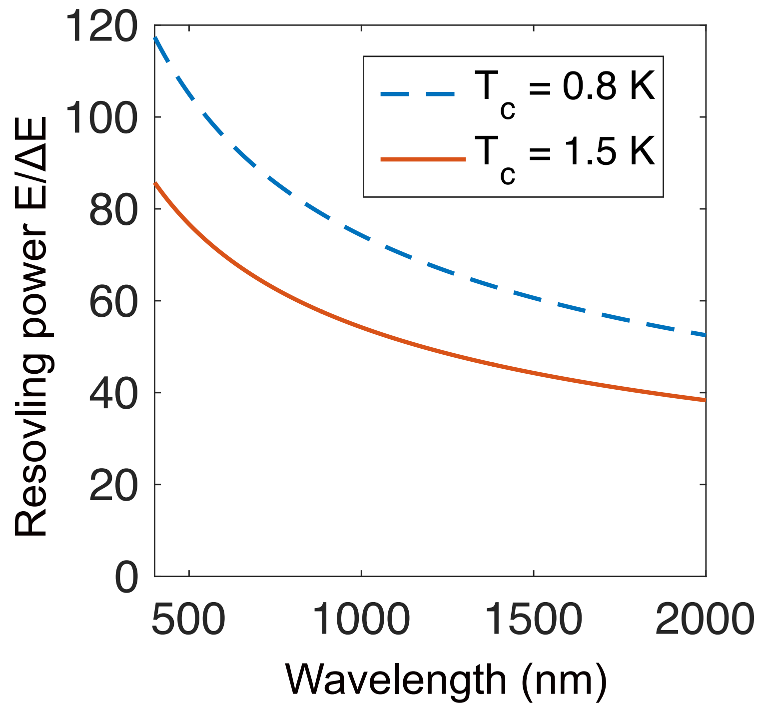
$$R = \frac{1}{2\sqrt{2\ln(2)}}\sqrt{\frac{\eta E}{F\Delta}}$$

Role of phonons

- Convert 1-3 eV excitation into few thousand ~0.2 meV quasiparticle excitations
- Electron-phonon interaction
- Hot phonon loss
- Fano statistics in best case







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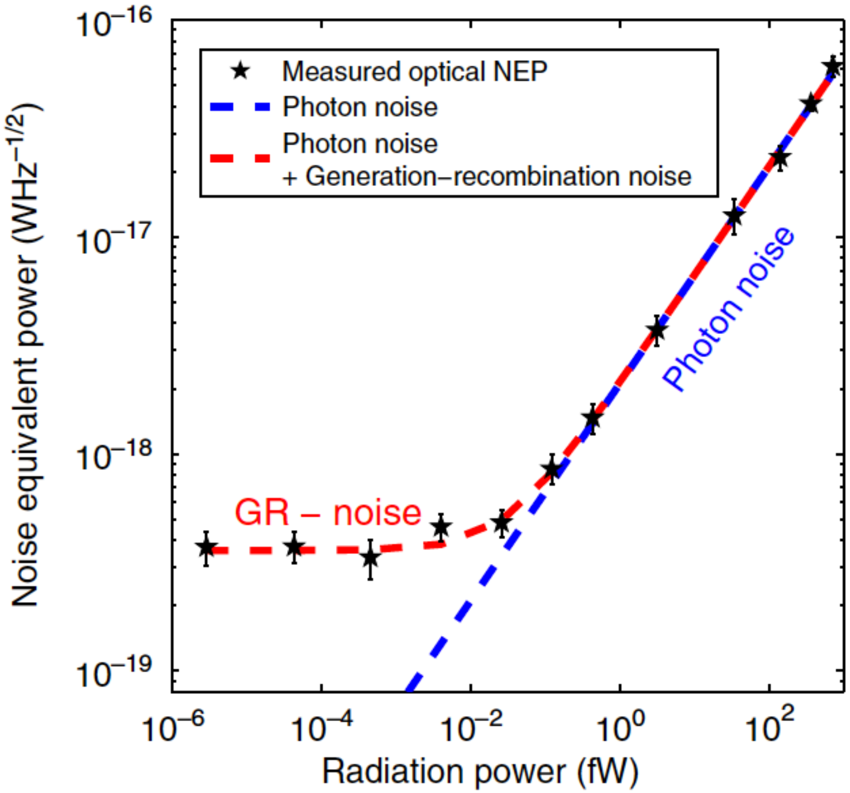
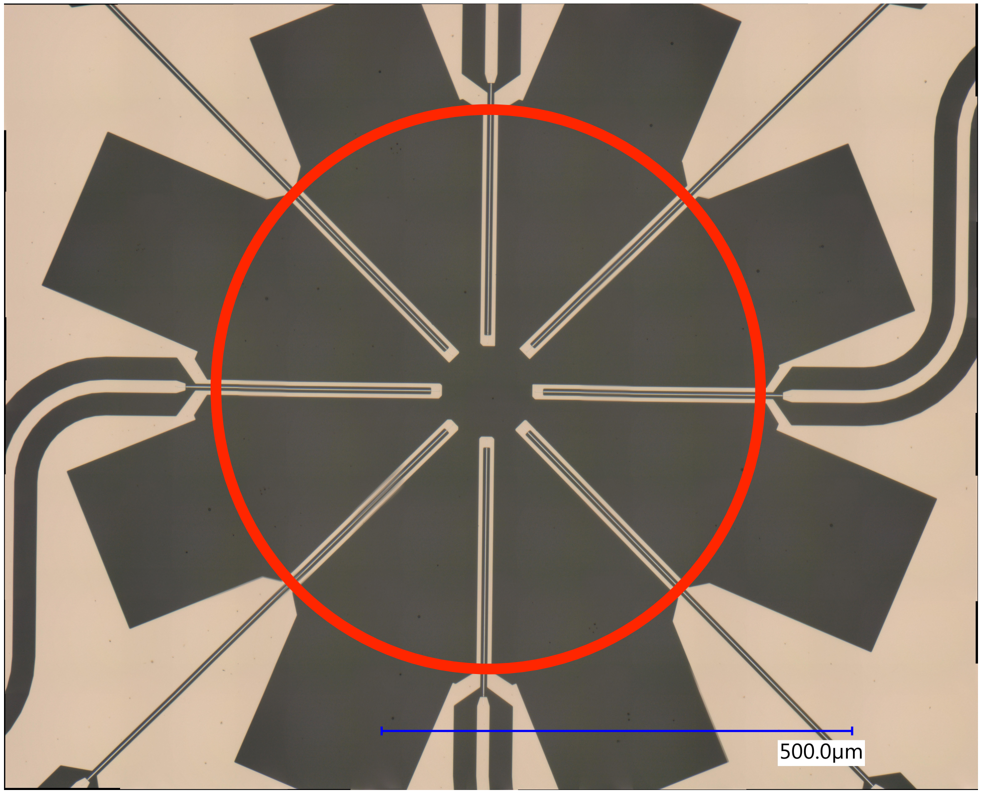
NbTiN-Al E-resolution study

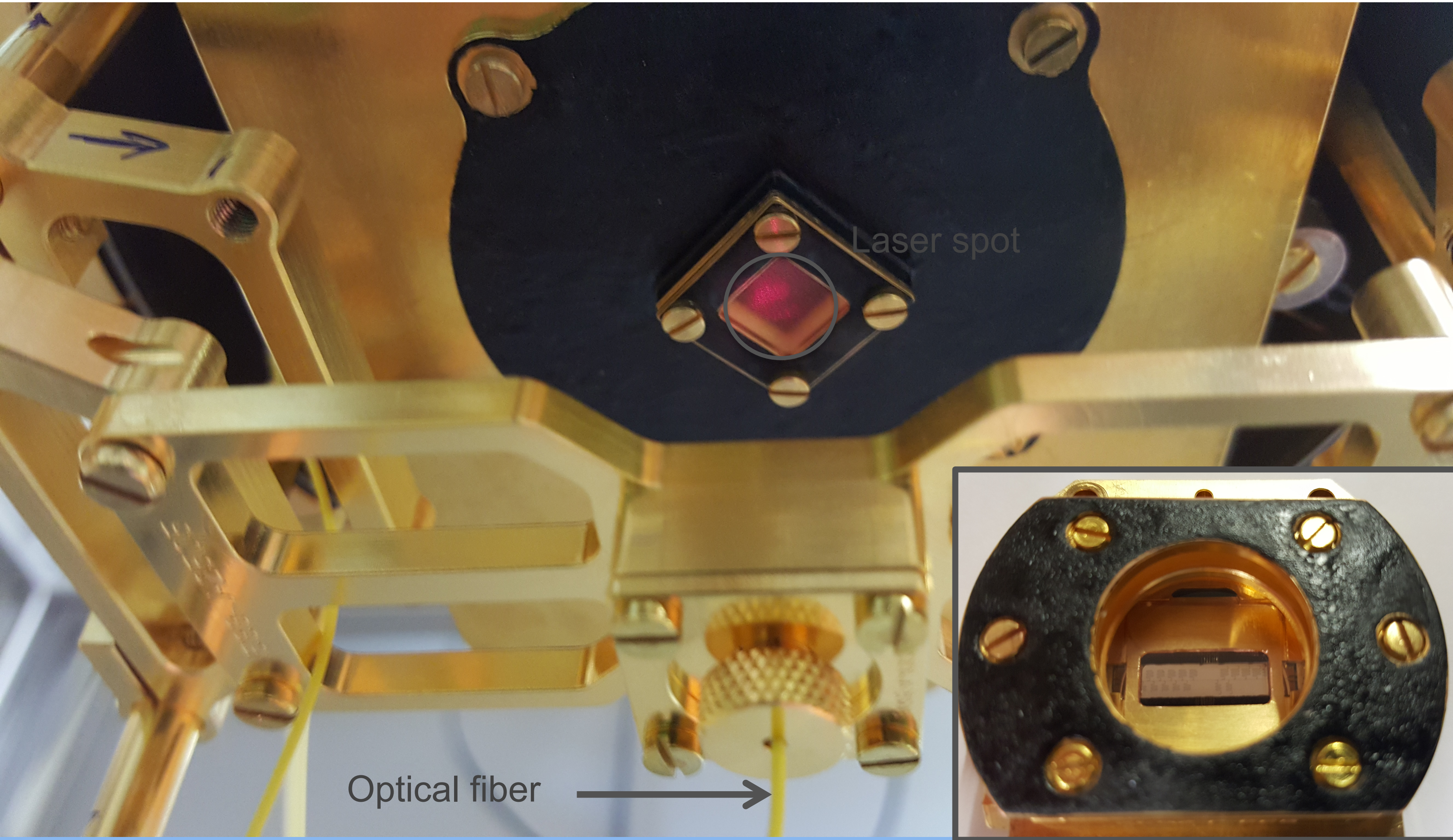
- THz NEP promises R~60 at 400 nm
- Al KIDs are the only ones we really understand in detail
- This is NOT an efficient VIS/NIR detector



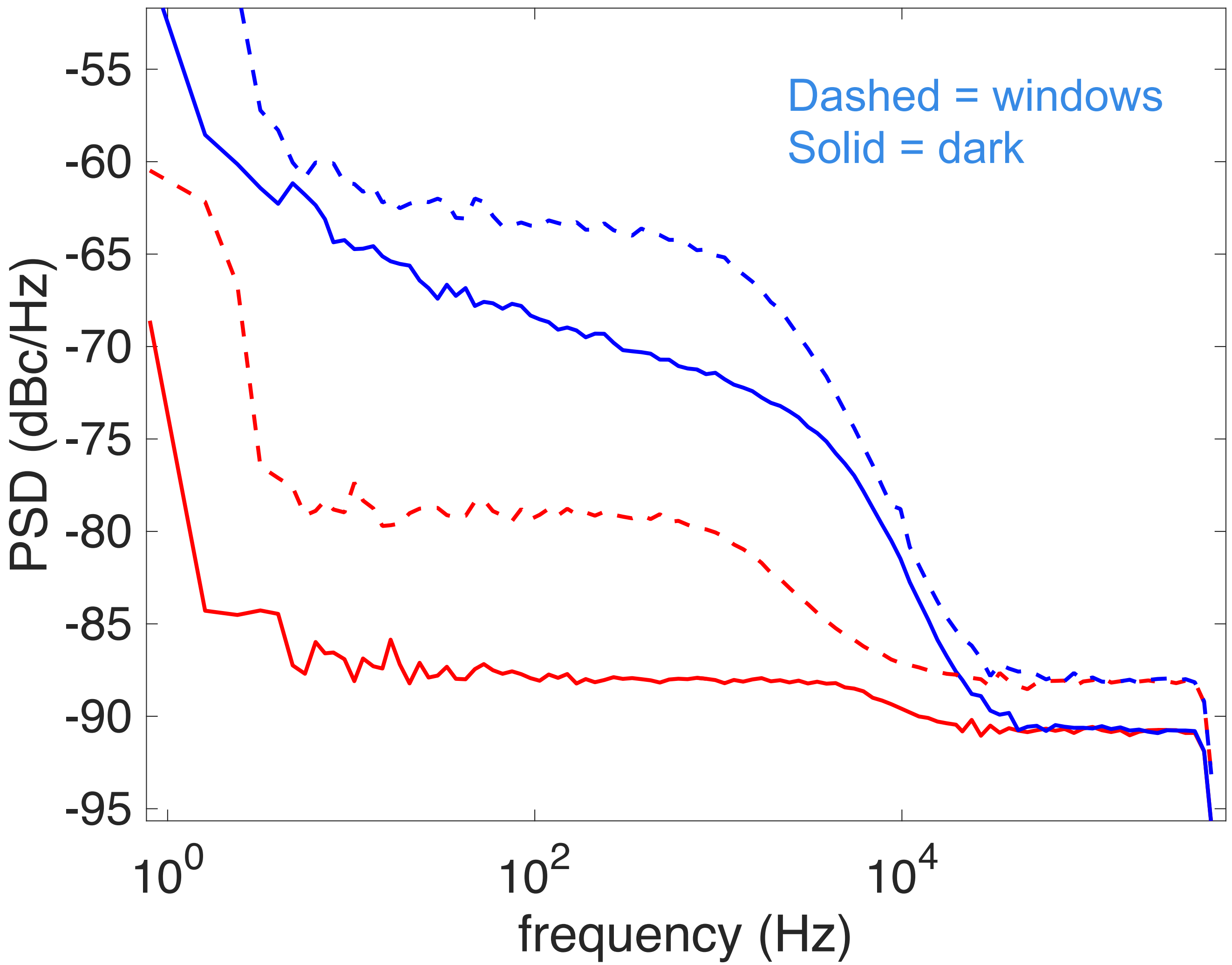


Nature Comms 5, 3130 (2014)
A&A, 601, A89 (2017)

Setup 4 K –> 100 mK

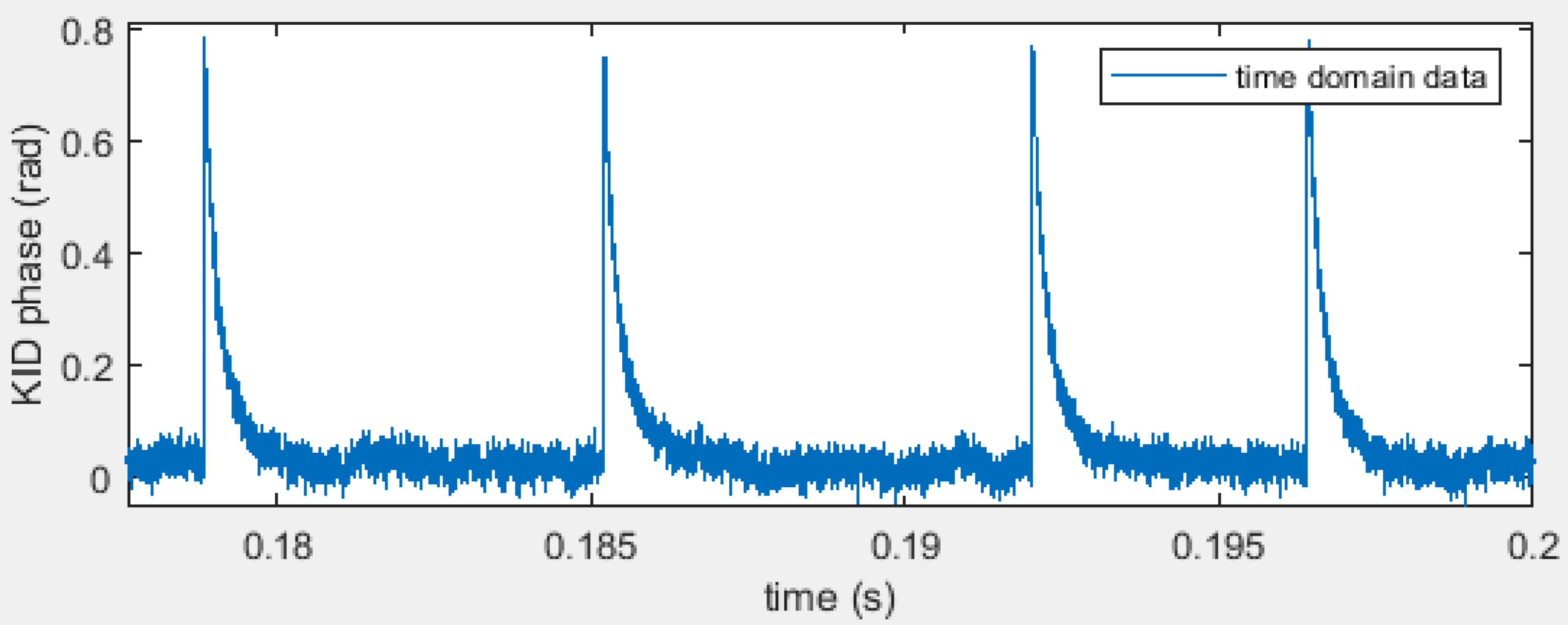


4 K stray light



Optical fiber directly coupled to 100 mK box

Time trace of KID response with continuous 673 nm illumination



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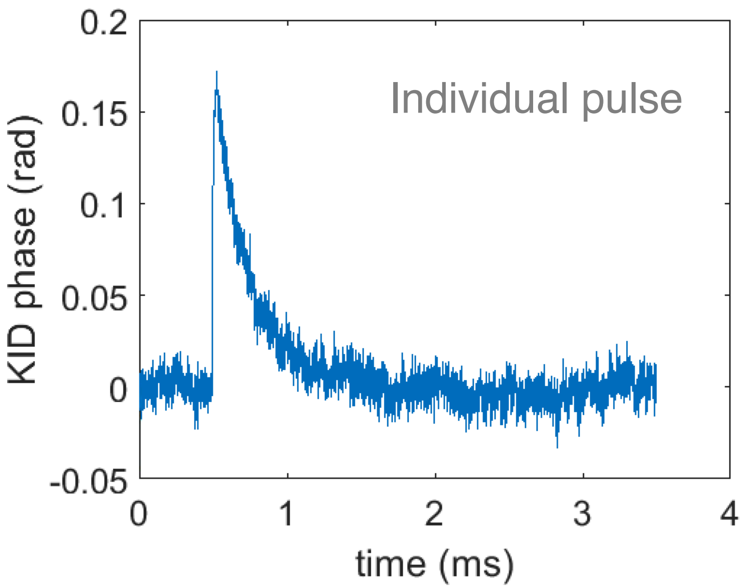
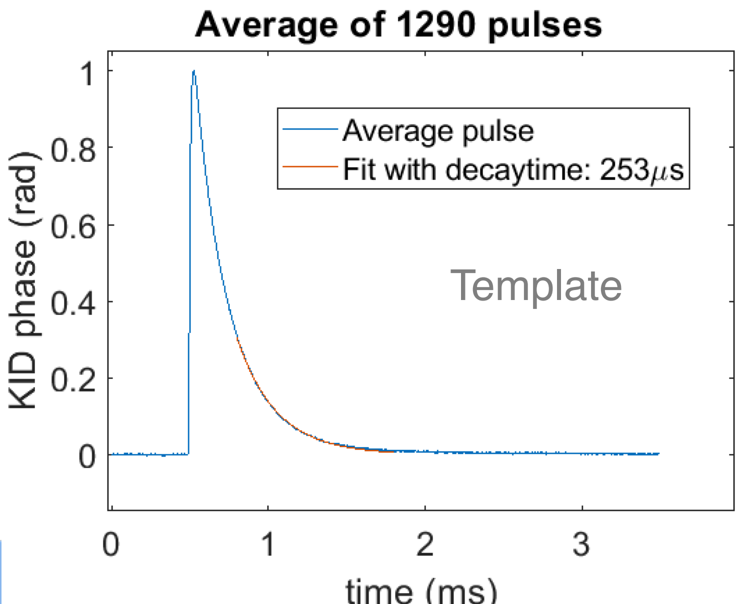
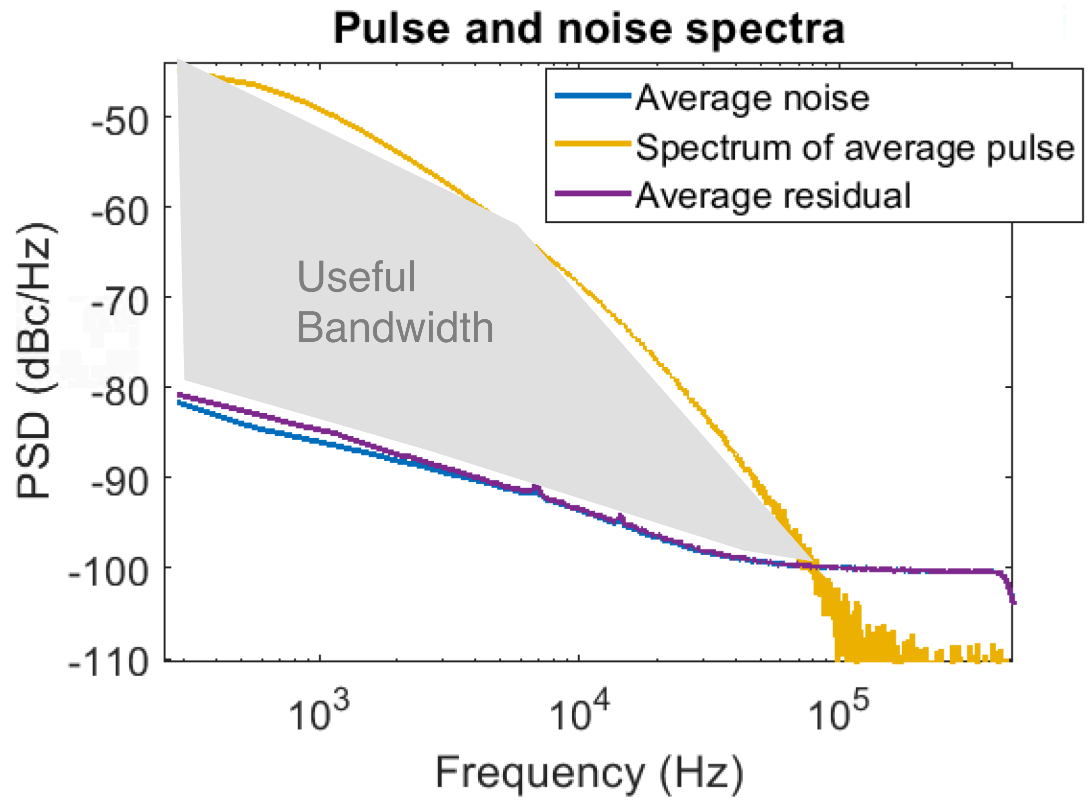
Pulse analysis





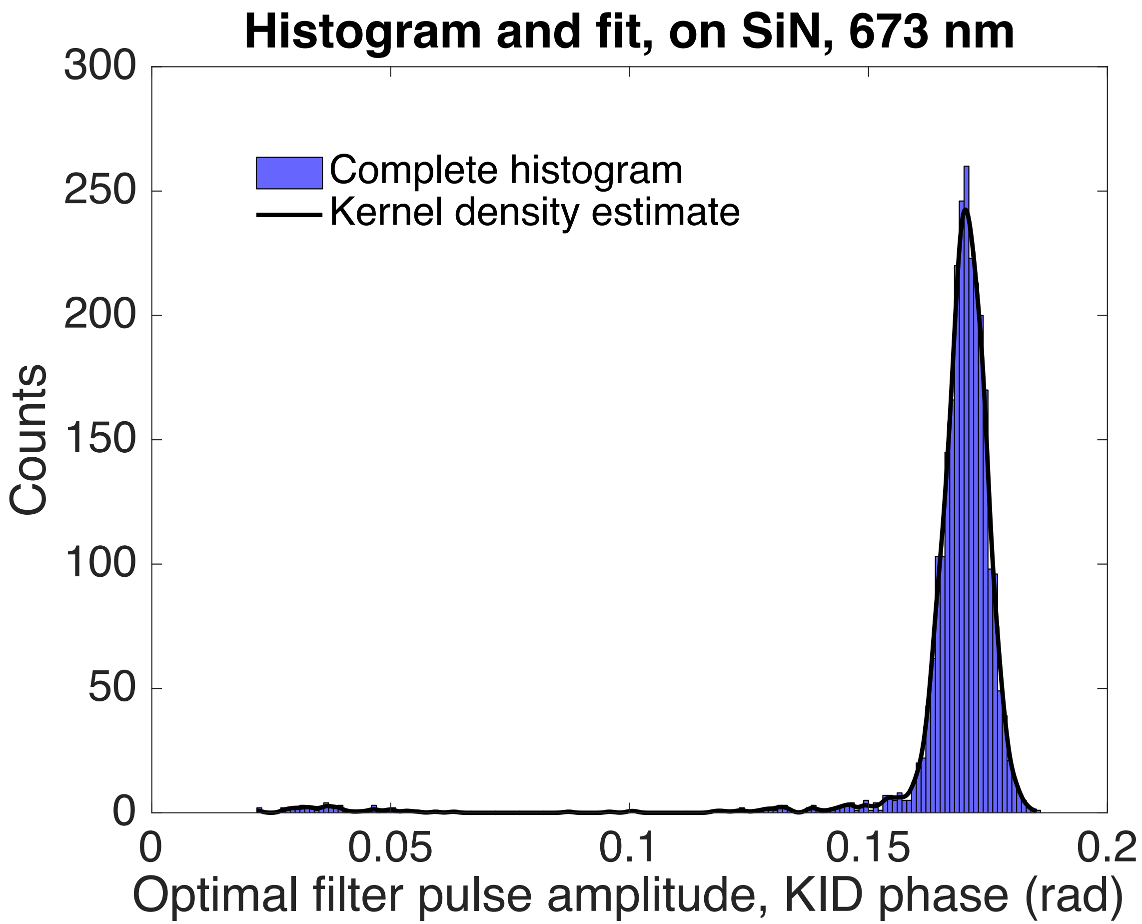


Linear optimal filter in frequency
DC component left out

KID Phase only for now

Histogram

- Kernel density estimate of FWHM (+-5% uncertainty)
- Without low-E hits we get same FWHM with Gaussian fit



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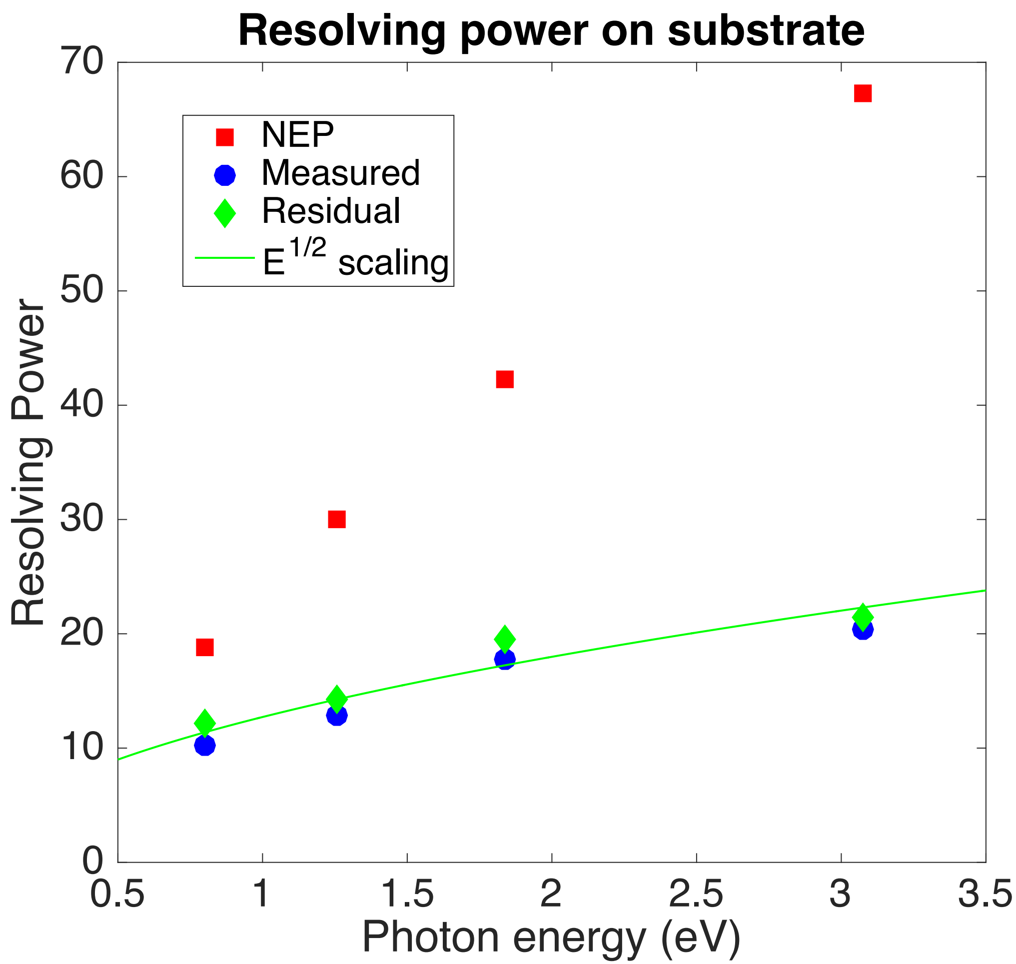
Resolving power Al MKID on substrate



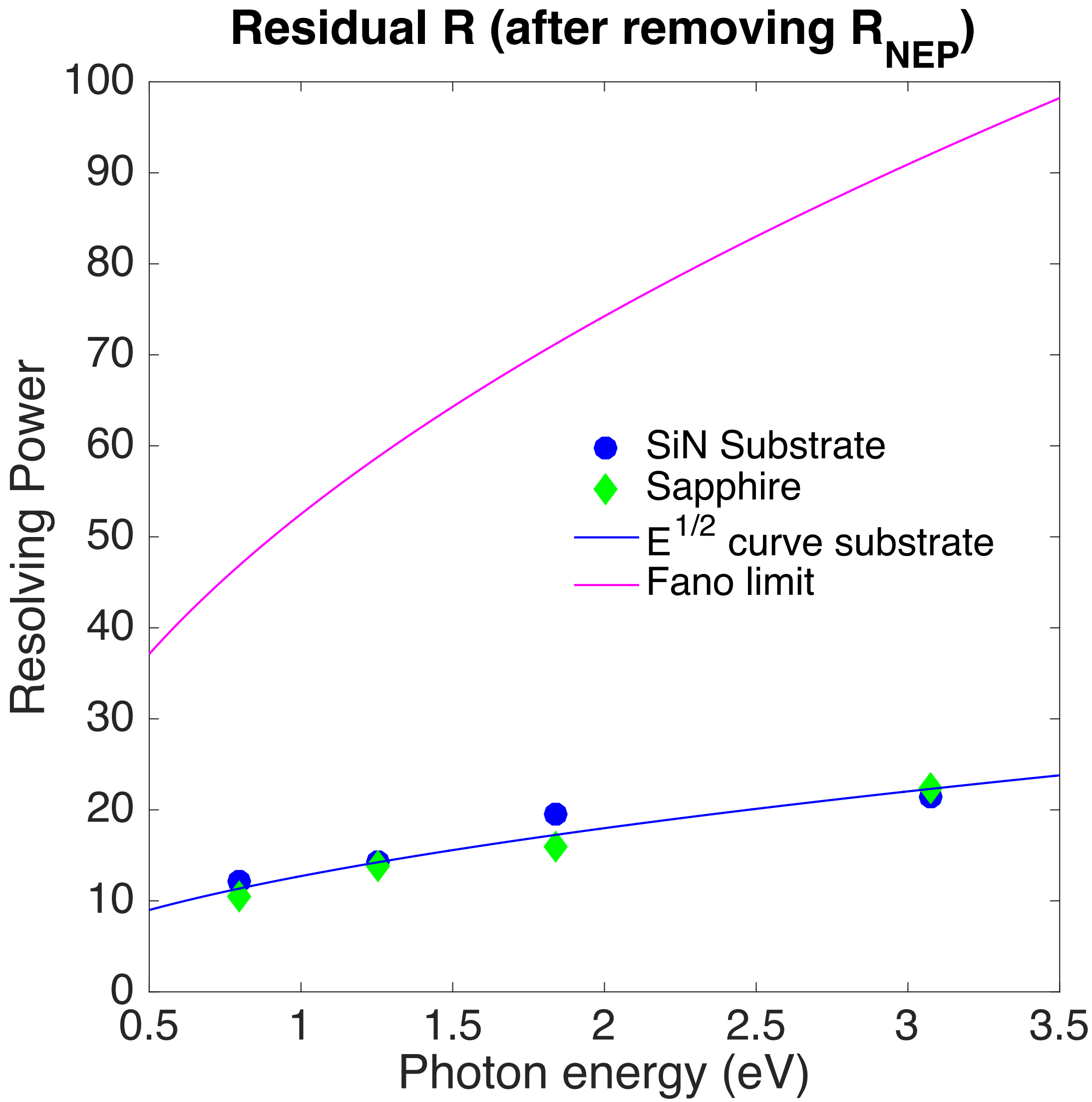
Laser wavelengths:
402 nm
673 nm
986 nm
1545 nm

dE = 0.08 – 0.15 eV

Factor 2-3 between NEP (signal-to-noise) and histogram measurement

Phonons?

$$(1/R_{meas})^2 = (1/R_{NEP})^2 + (1/R_{Not\text{-}NEP})^2$$



Trap phonons

- Thicker superconducting film keeps phonons longer
- 150 nm Al film destroys responsivity ✗

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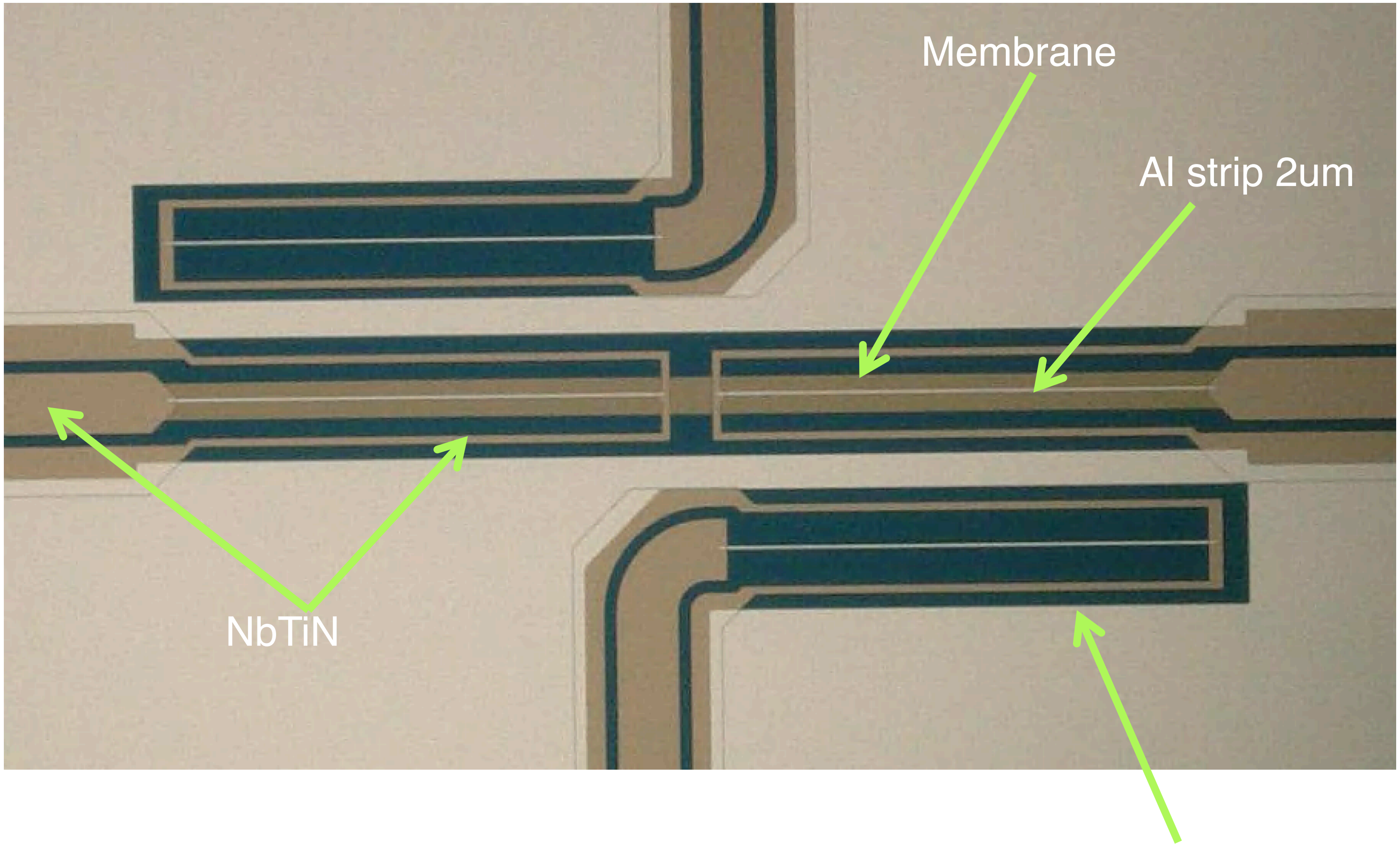
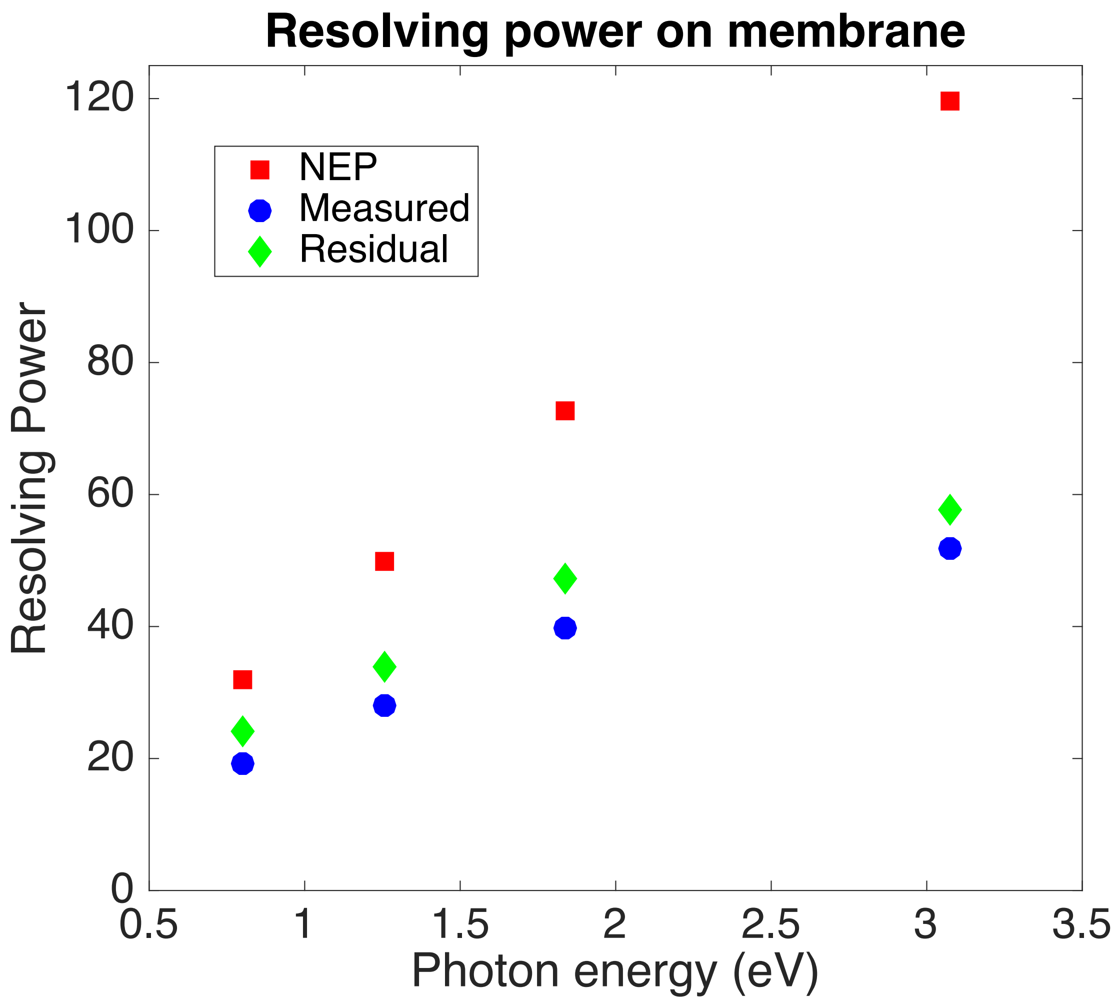
Trap phonons

- 50 nm Al film
- 120 nm SiN membrane with 2 micron Al strip – aspect ratio
- Geometric retrapping model, factor ~10 longer phonon dwell time



Resolving power



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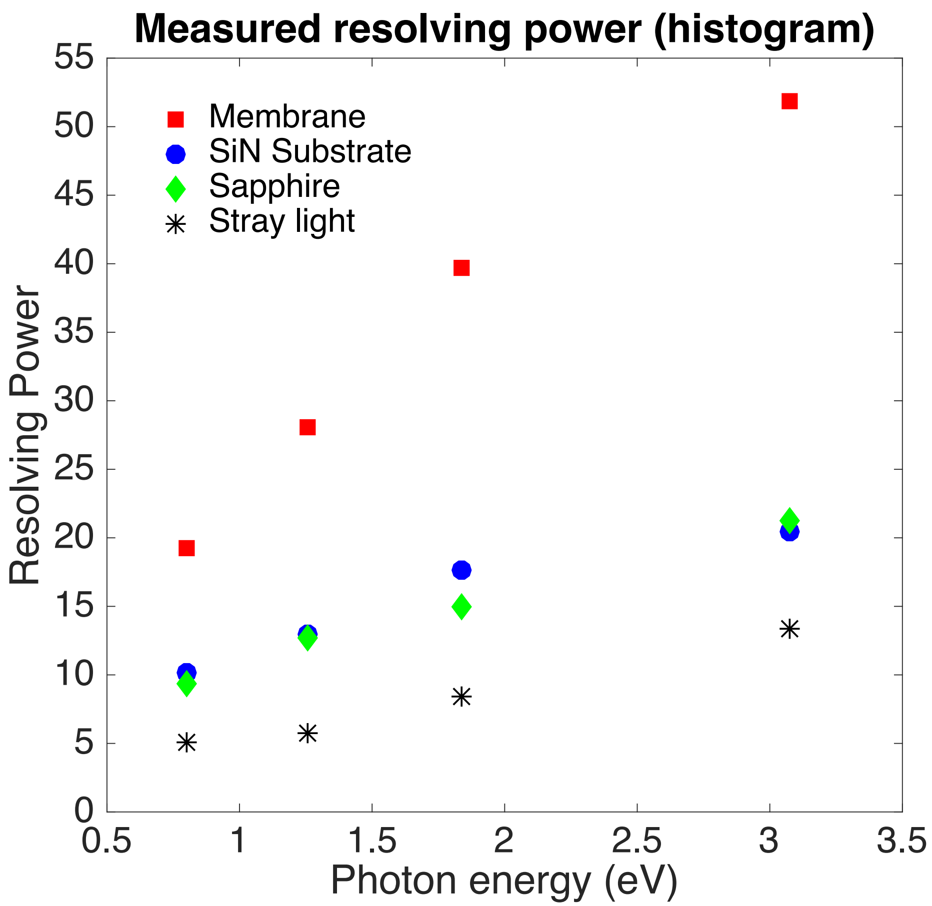
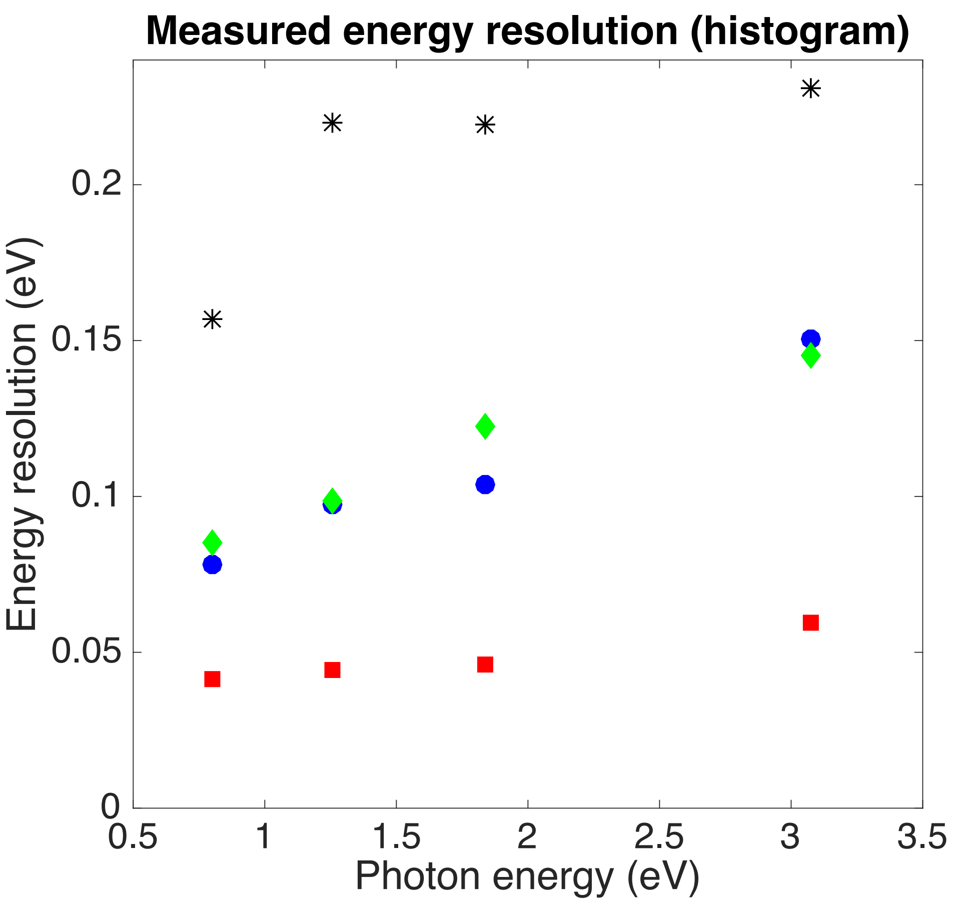
Measured histogram resolution substrate - membrane



Higher is better



Lower is better, lowest 41 meV

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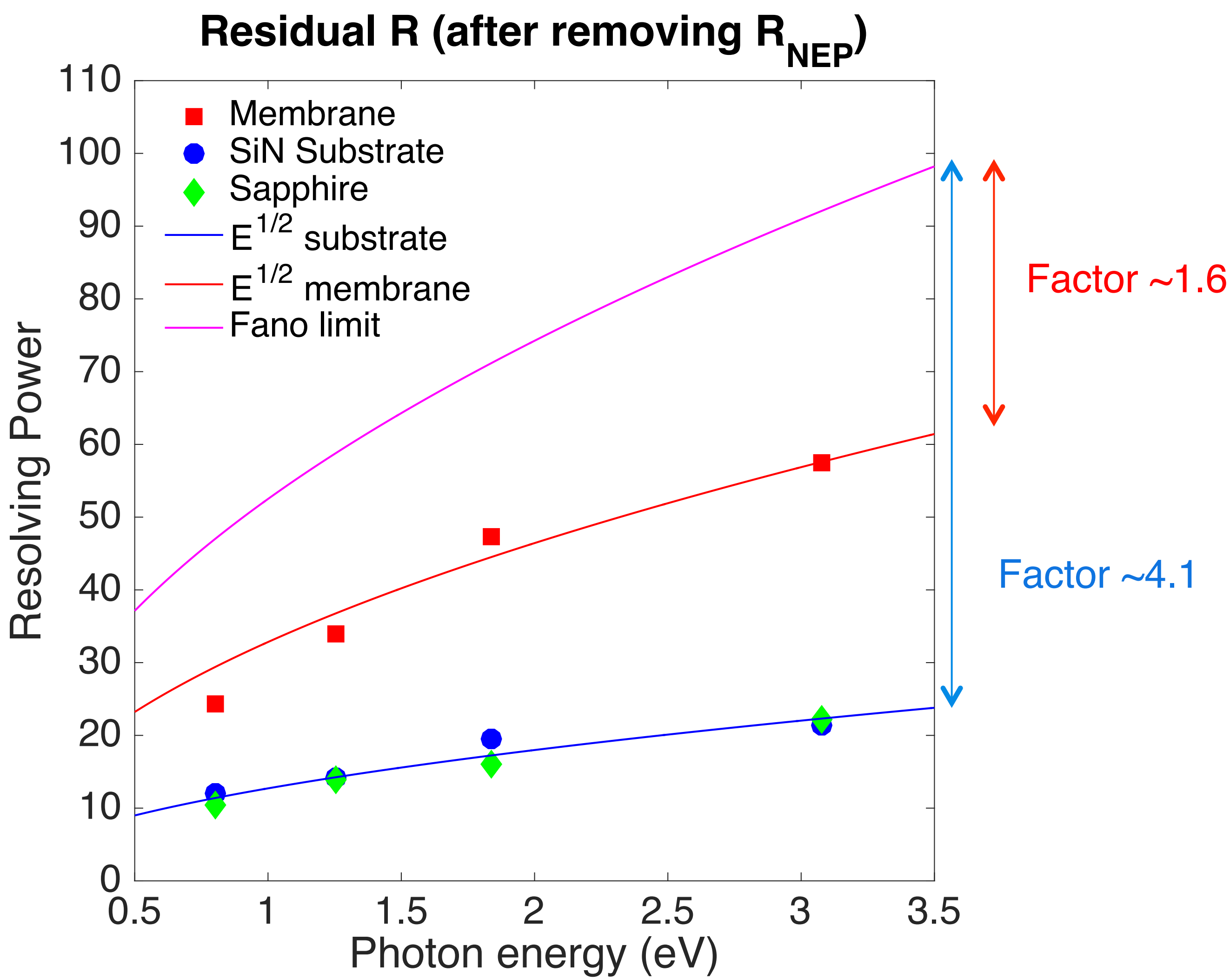
Resolving power

$$(1/R_{meas})^2 = (1/R_{NEP})^2 + (1/R_{Not\text{-}NEP})^2$$



Gained factor 2.6 in R, effective factor 6.7 in phonon trapping
Still factor of 5 better phonon trapping needed for Al MKID

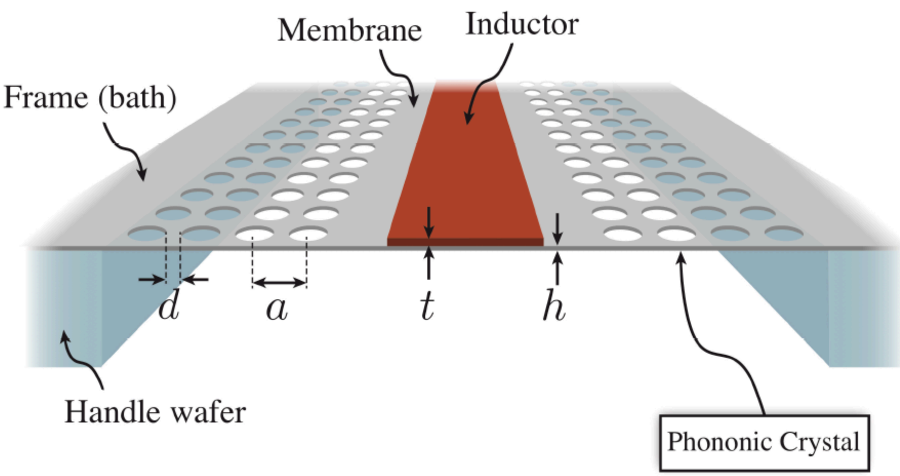
What is next?

- For this data:
  - Different ways of pulse filtering
  - Readout power dependence

- Towards Fano limit for Aluminium:
  - Design and control the phonon flow
  - Further improve the NEP ($dE^2 = dE_{Fano}^2 + dE_{NEP}^2 + \ldots$)

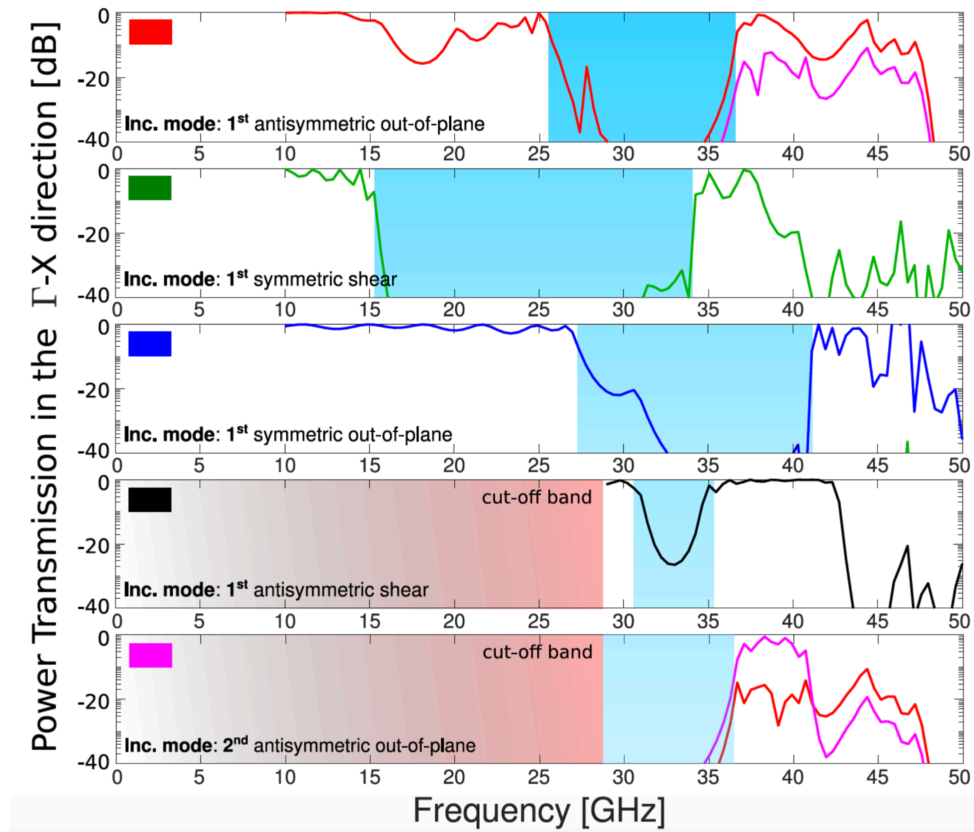
- Implement this in practical (LEKID) detectors:
  - Understand and quantify electron-phonon coupling in TiN, PtSi, etc.
  - How to combine fast with phonon trapping?
  - How to combine membranes with AR coatings?

Towards Fano limit: understand and design the phonon flow



Rostem, PdV, Wollack,
Physical Review B 98, 014522 (2018)

Talk on Friday at 12.00



Puurtinen et al. This proceedings

Poster Tuesday

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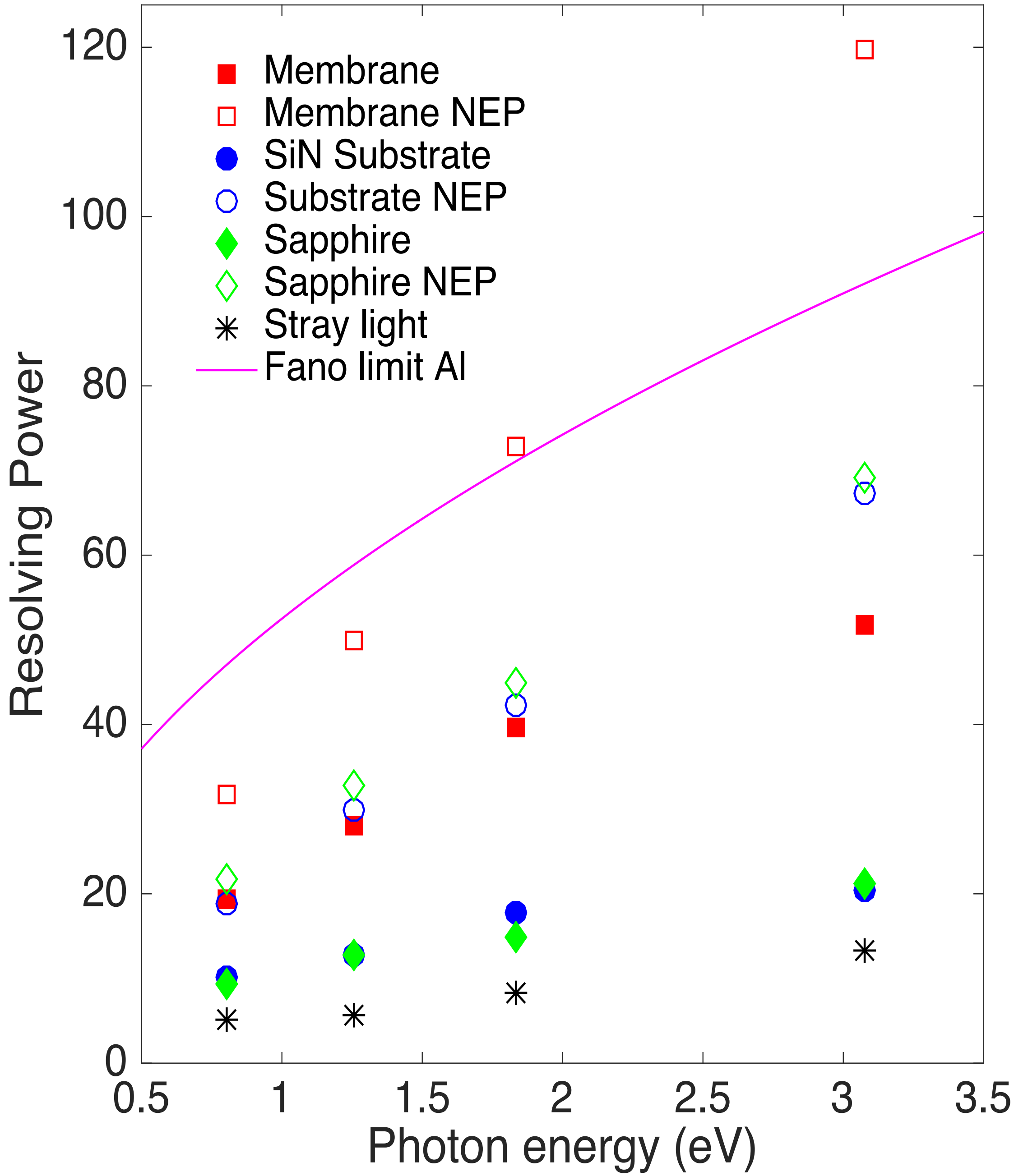
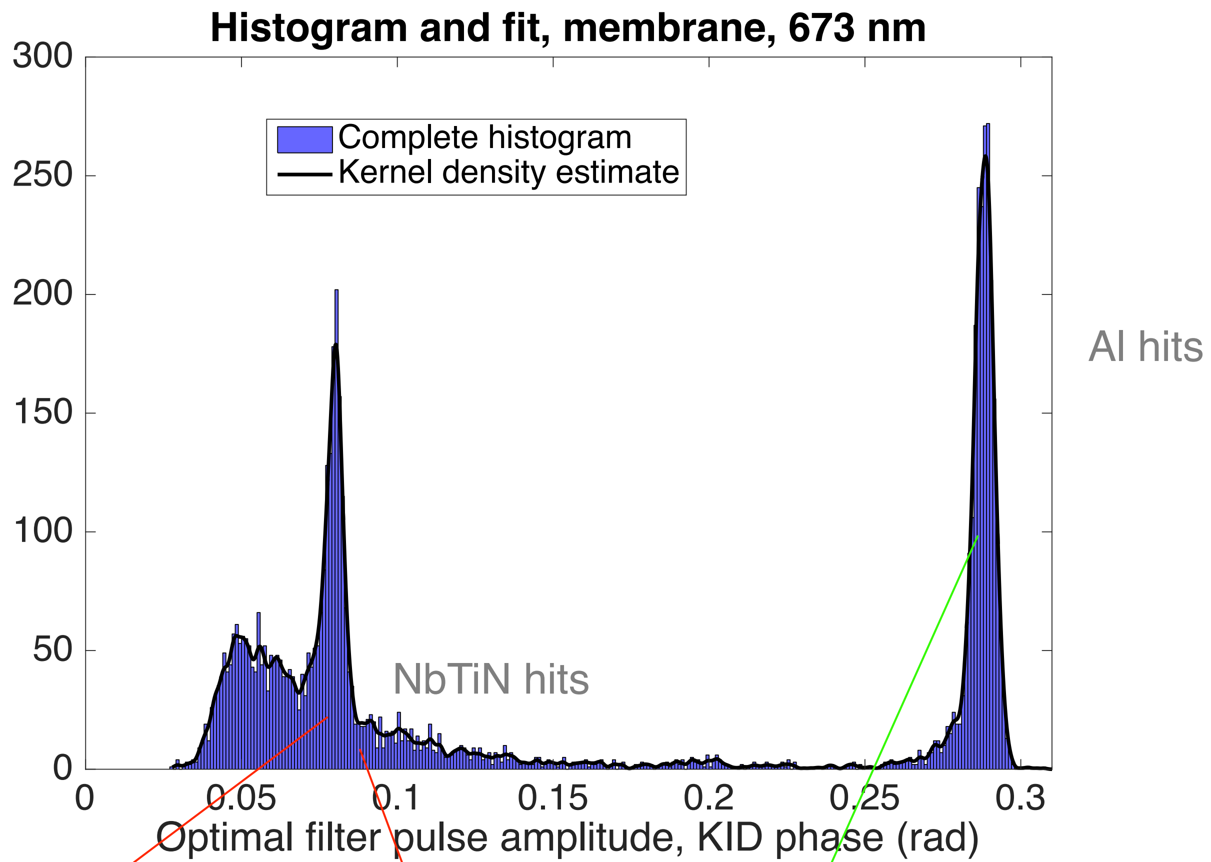
Summary



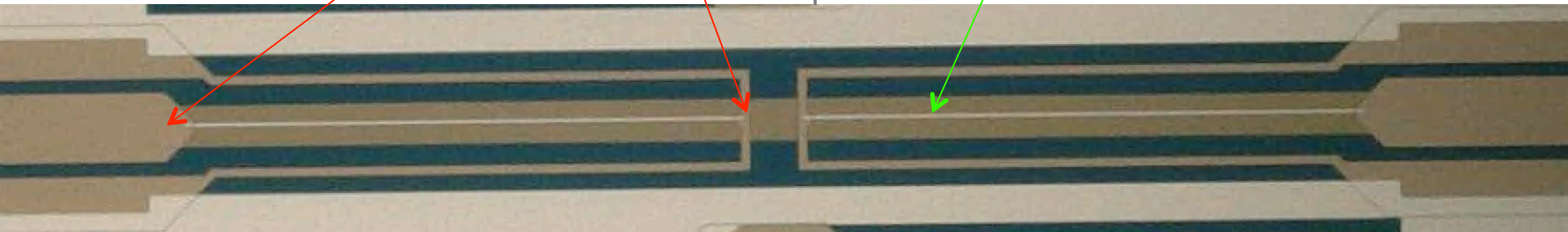
Membrane
Membrane NEP
SiN Substrate
Substrate NEP
Sapphire
Sapphire NEP
Stray light
Fano limit Al
Resolving Power
Photon energy (eV)
0
20
40
60
80
100
120
0.5
1
1.5
2
2.5
3
3.5

Extra

Low E hits due to NbTiN on membrane

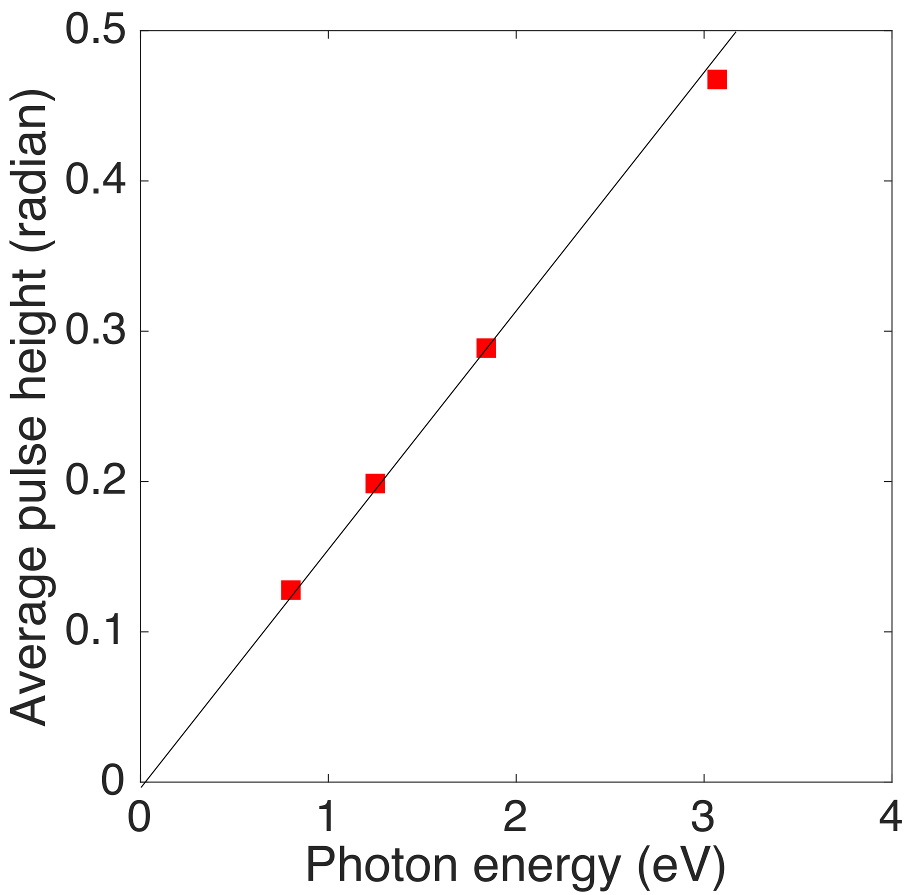


Hits in NbTiN ON membrane (small pieces) are seen as low-E hits
Low E hits not there for substrate KIDs on same chip



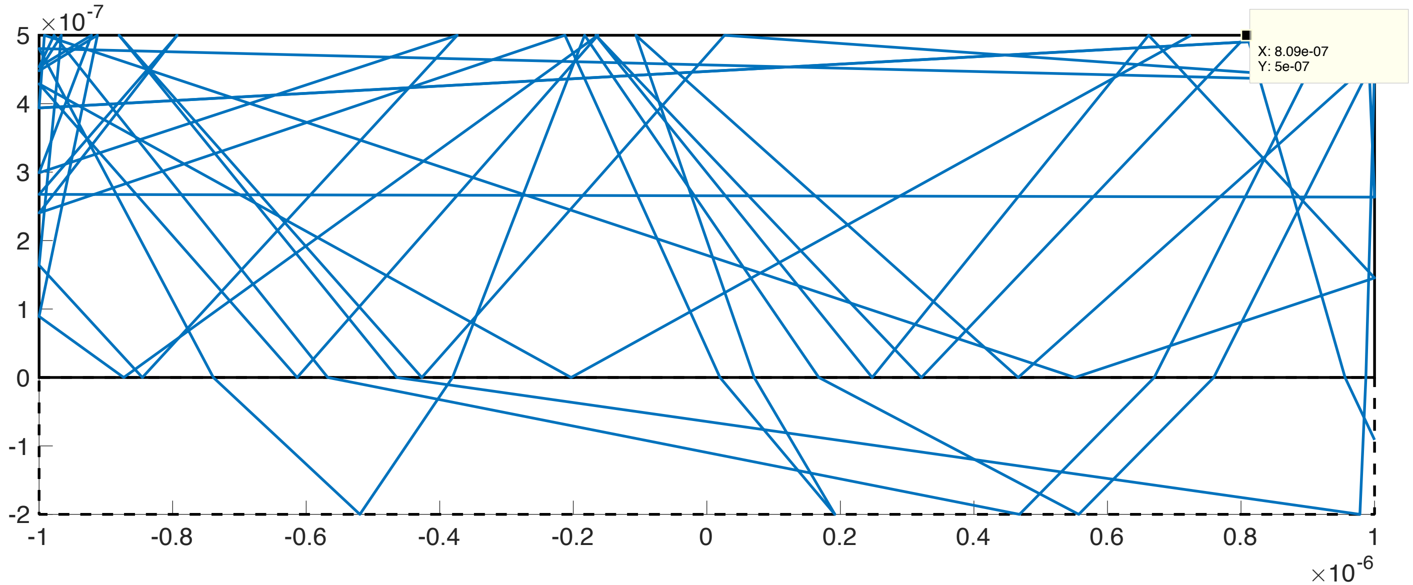
Average pulse height on membrane

- Almost linear response vs energy



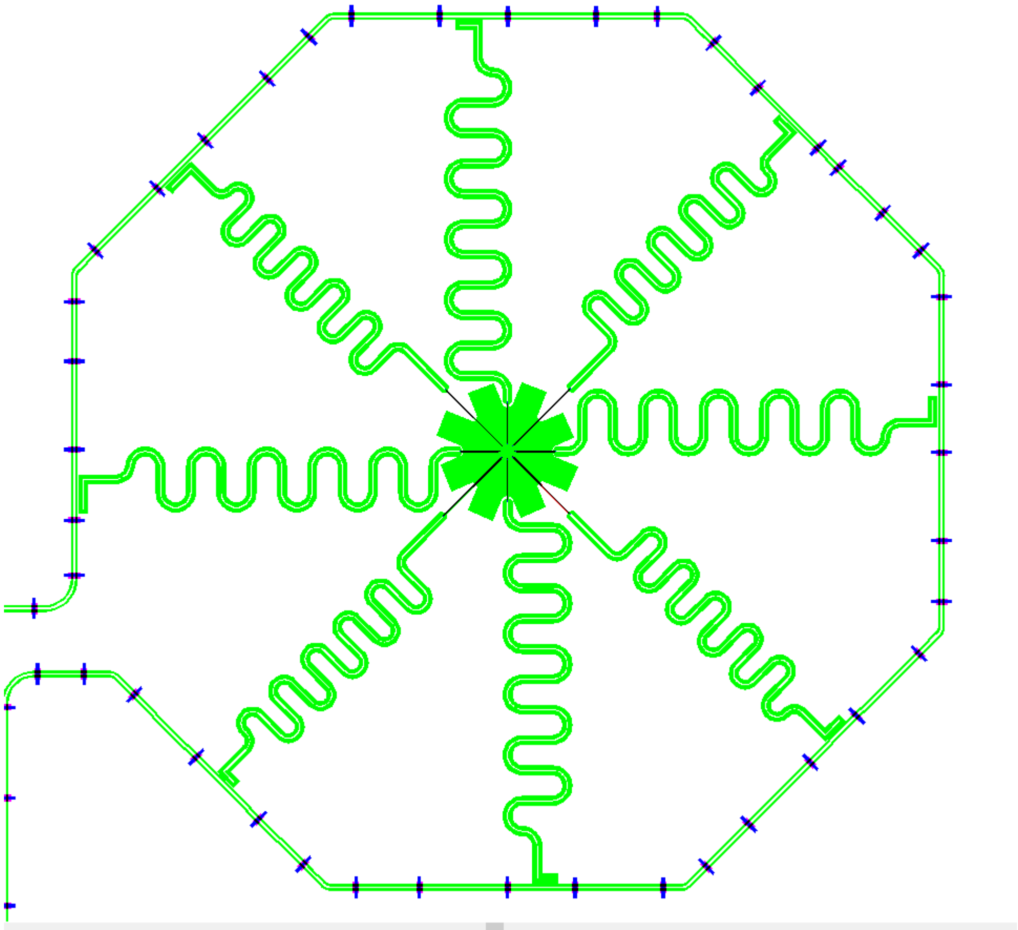
Trap phonons

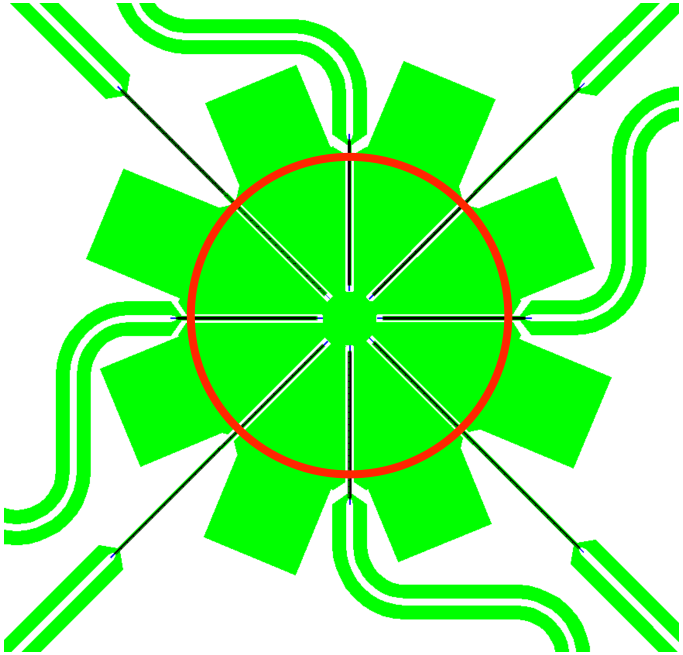
- 120 nm SiN membrane with 2 micron wide, 50 nm Al strip – aspect ratio
- Geometric retrapping model, factor ~10 longer phonon dwell time



Example simulation for very thin (20 nm) membrane and 50 nm film

New design, remove groundplane, 0.5 mm aperture to reduce groundplane absorption





Aperture of 0.5 mm in front of chip to reduce heating

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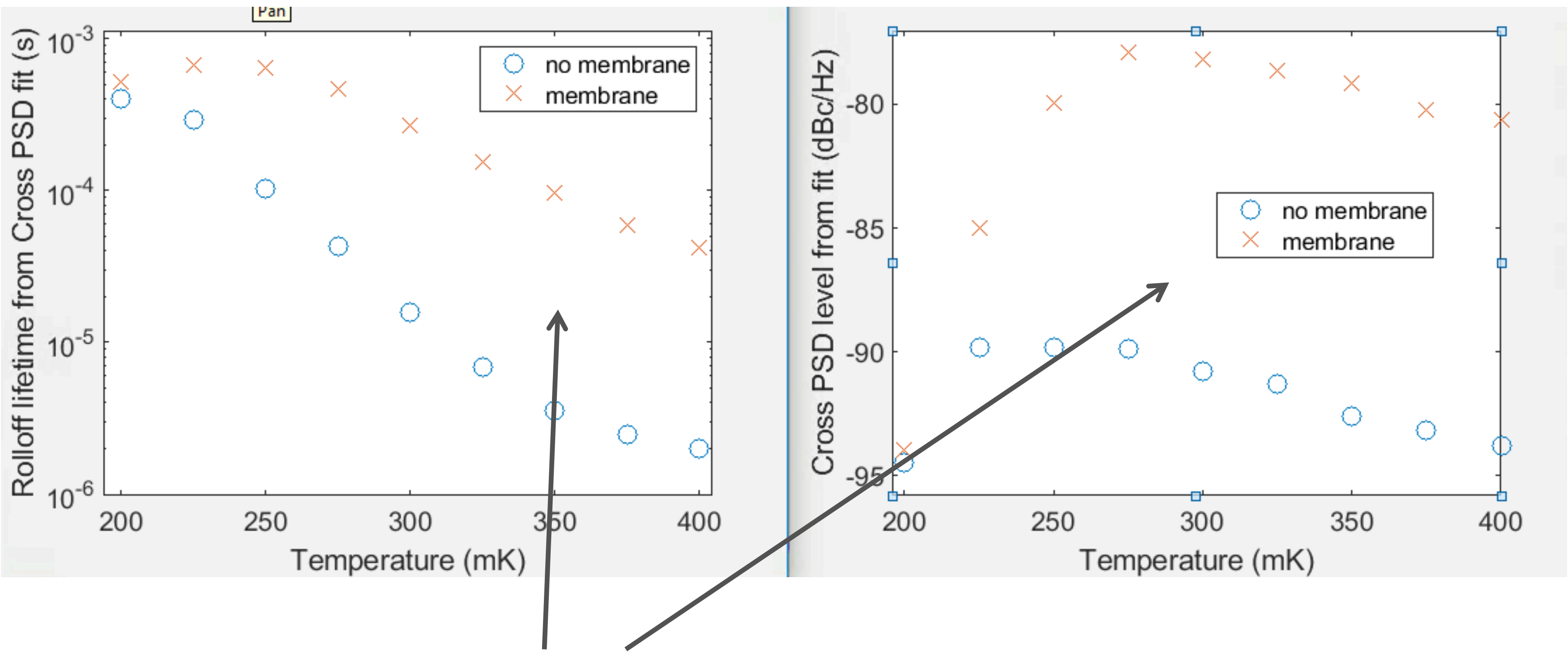
Proof of phonon trapping from GR noise



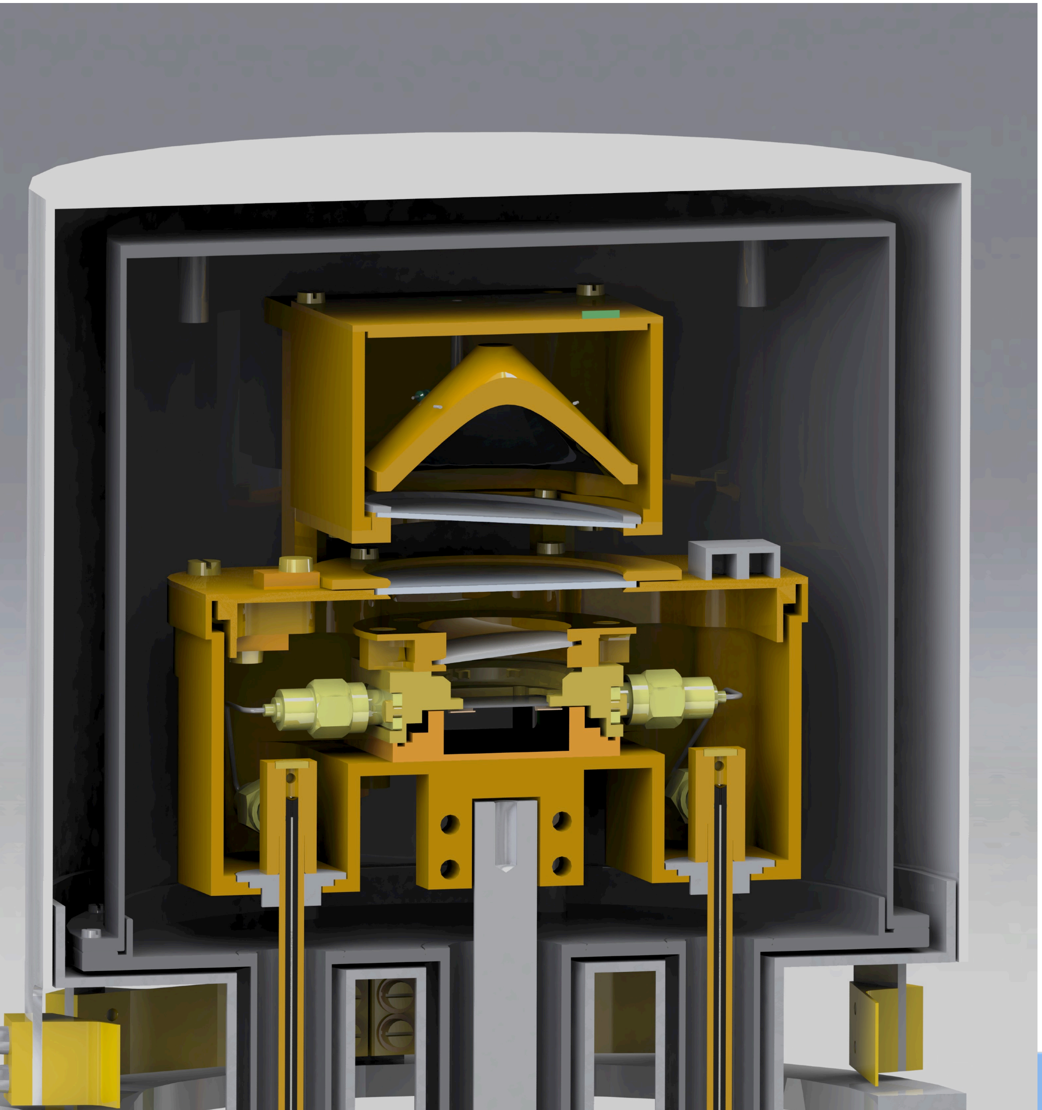
Factor of 10-15 enhancement in noise level and lifetime

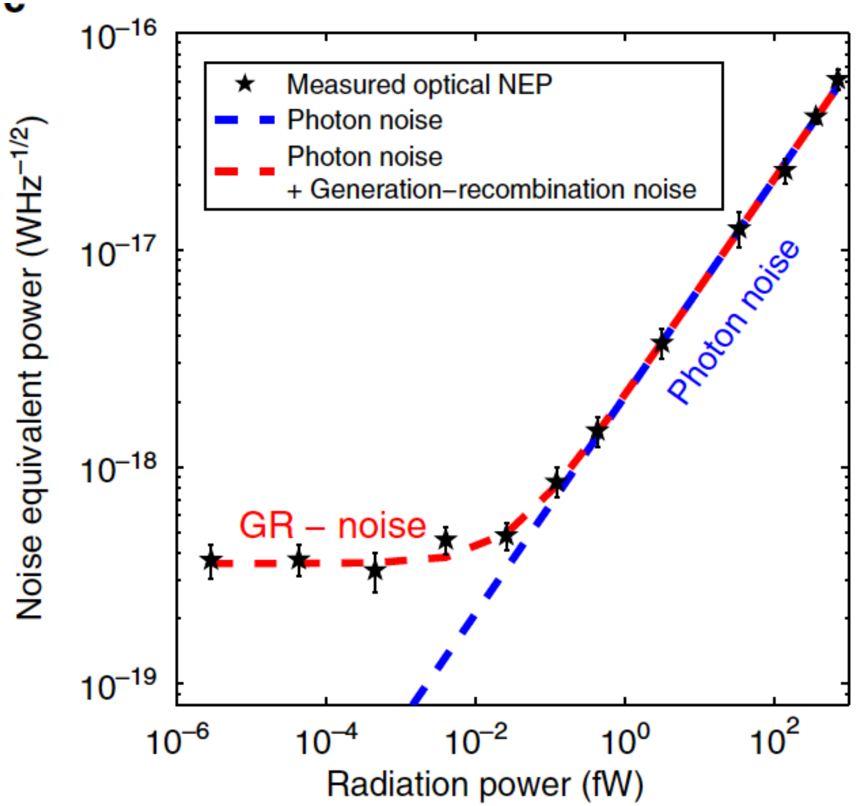
However, this is an equilibrium (or steady state) probe for a non-equilibrium (pulse) problem.

This is in contrast to power integrating detectors, where the pulse-lifetime is the non-equilibrium probe for a steady state problem.

Very dark setup ⇔ visible light

MKIDs are very sensitive – they see everything!





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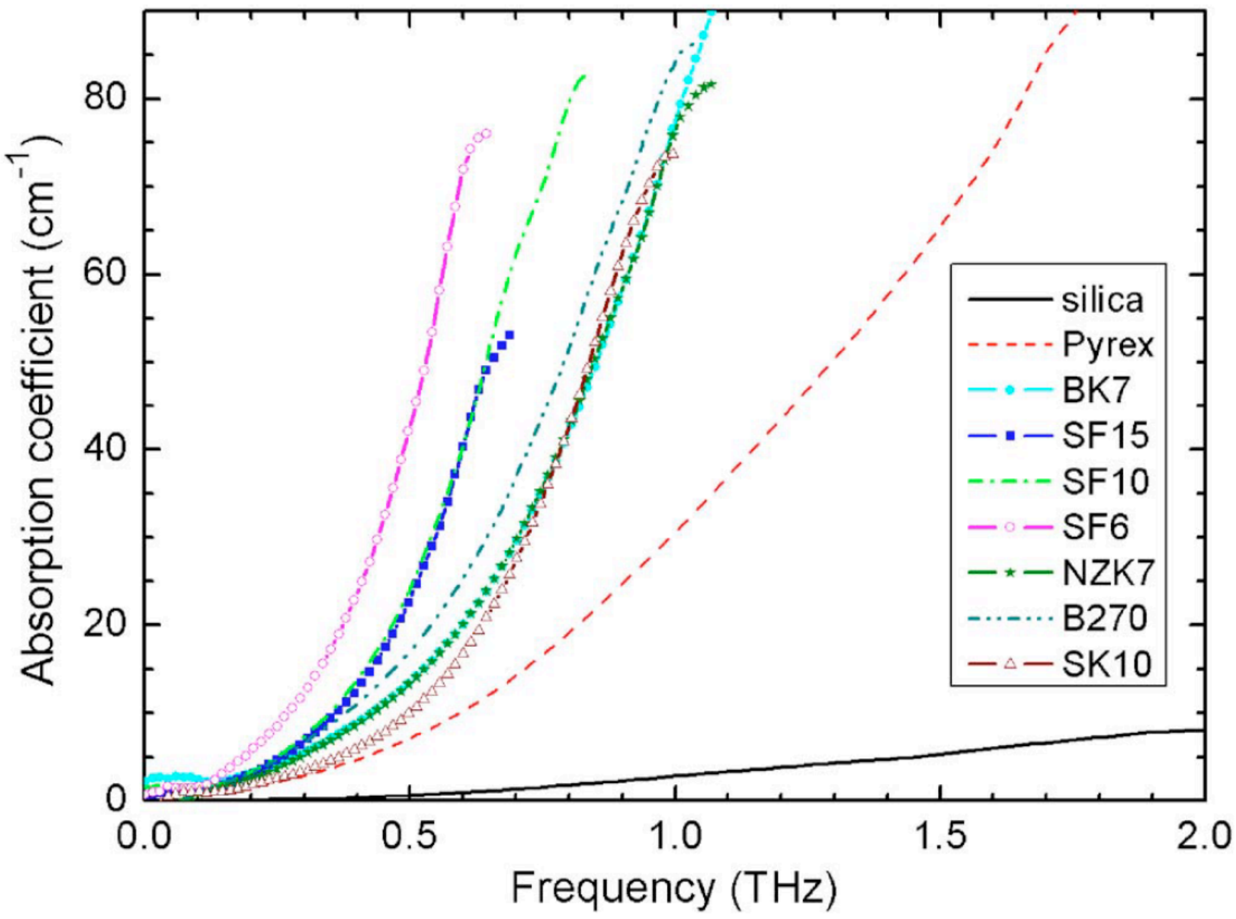
A&A, 601, A89 (2017)

Glasses are transparent below ~500 GHz



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