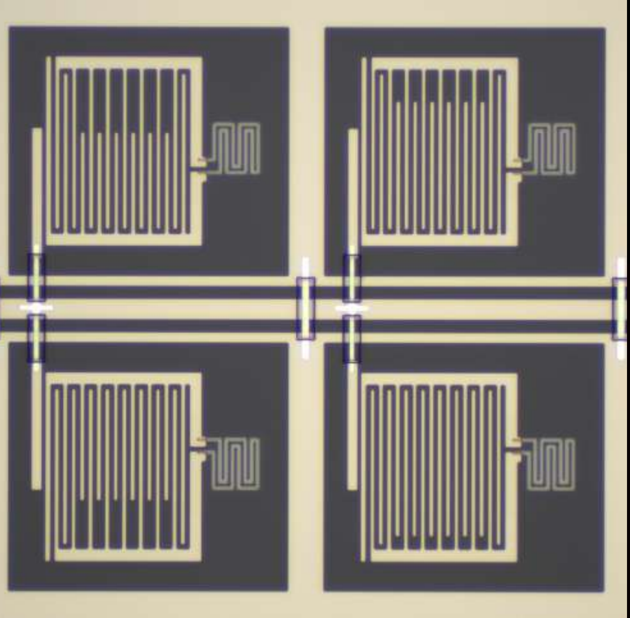
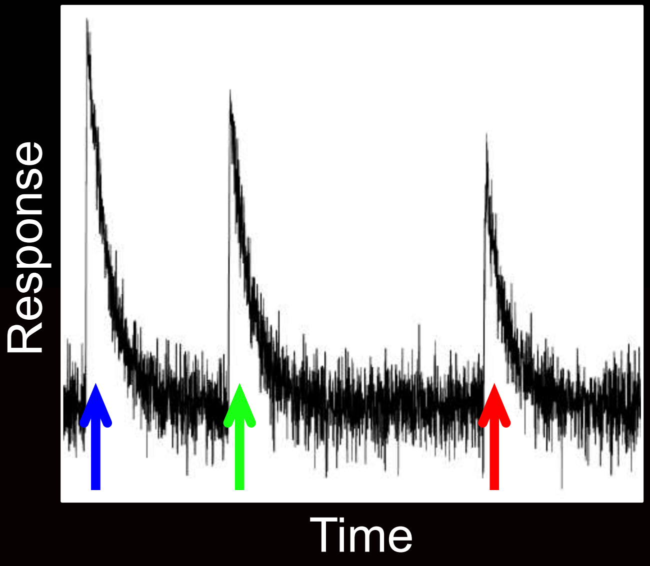
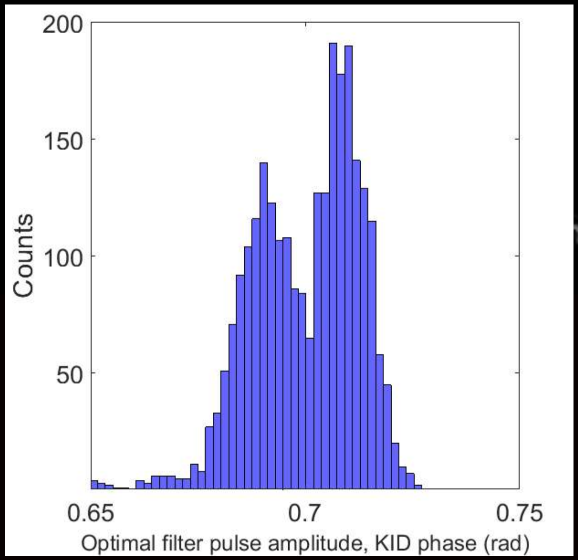
Energy-resolved single photon counting in MKIDs with disordered superconductors







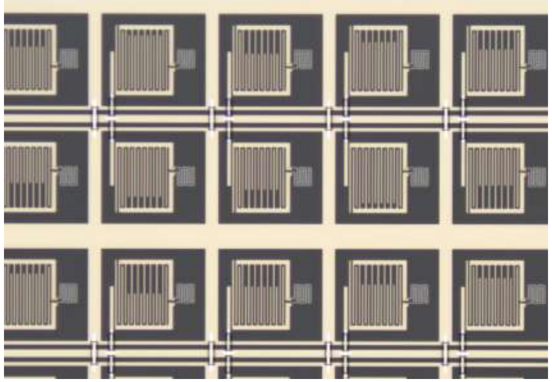
Pieter de Visser | Contact: p.j.de.visser@sron.nl

Outline

- Why energy resolving detectors for visible/near-infrared/mid-infrared?
- Working principle – based on Aluminium detectors
  - Measurement and pulse analysis
  - Energy resolution limits
- Quasiparticle dynamics in MKIDs
  - Equilibrium and non-equilibrium dynamics
  - Role of phonons and phonon-trapping
  - Quasiparticle trapping
- MKIDs with disordered superconductors
- Quasiparticle dynamics in a disordered superconductor
- Open questions (some of them)

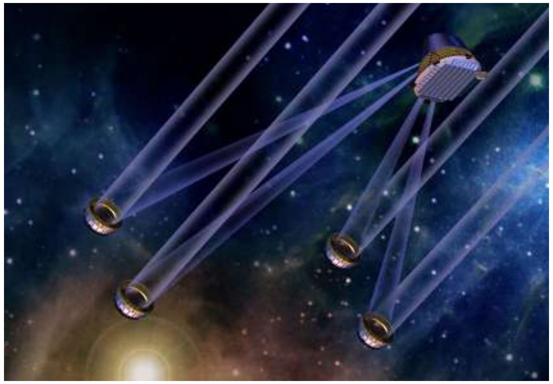
Characterizing Earth-like exoplanets with MKIDs

Integral Field Units



Single photon color resolution without dark counts or read noise

IR single photon detectors



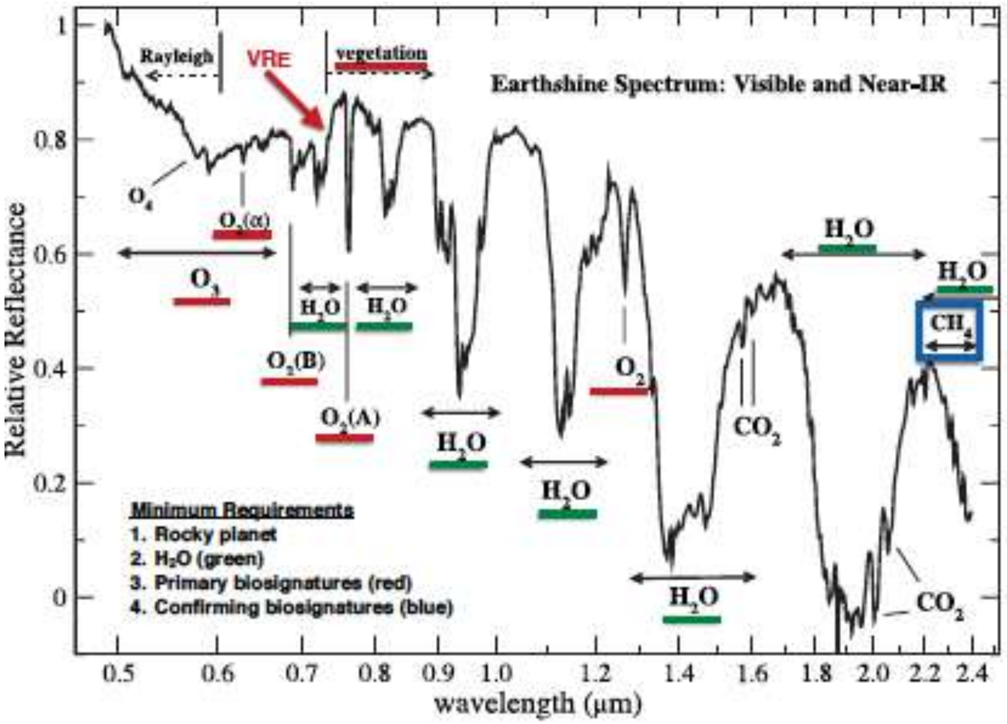
Modular detector arrays for mid-IR interferometer outputs (LIFE)

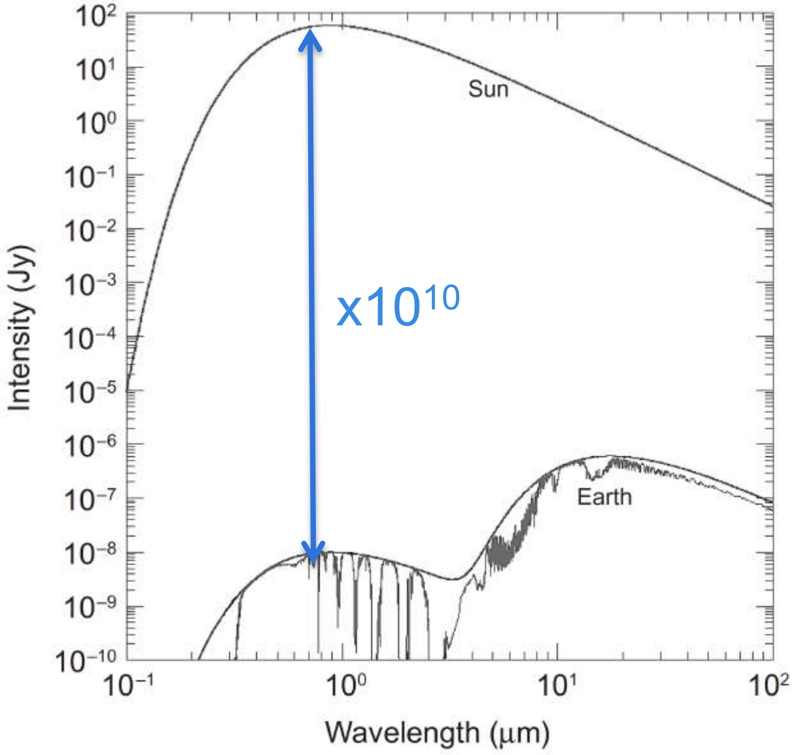
Chromatic wavefront sensors

Real time photon counting with microsecond arrival timing and color information

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 R~100





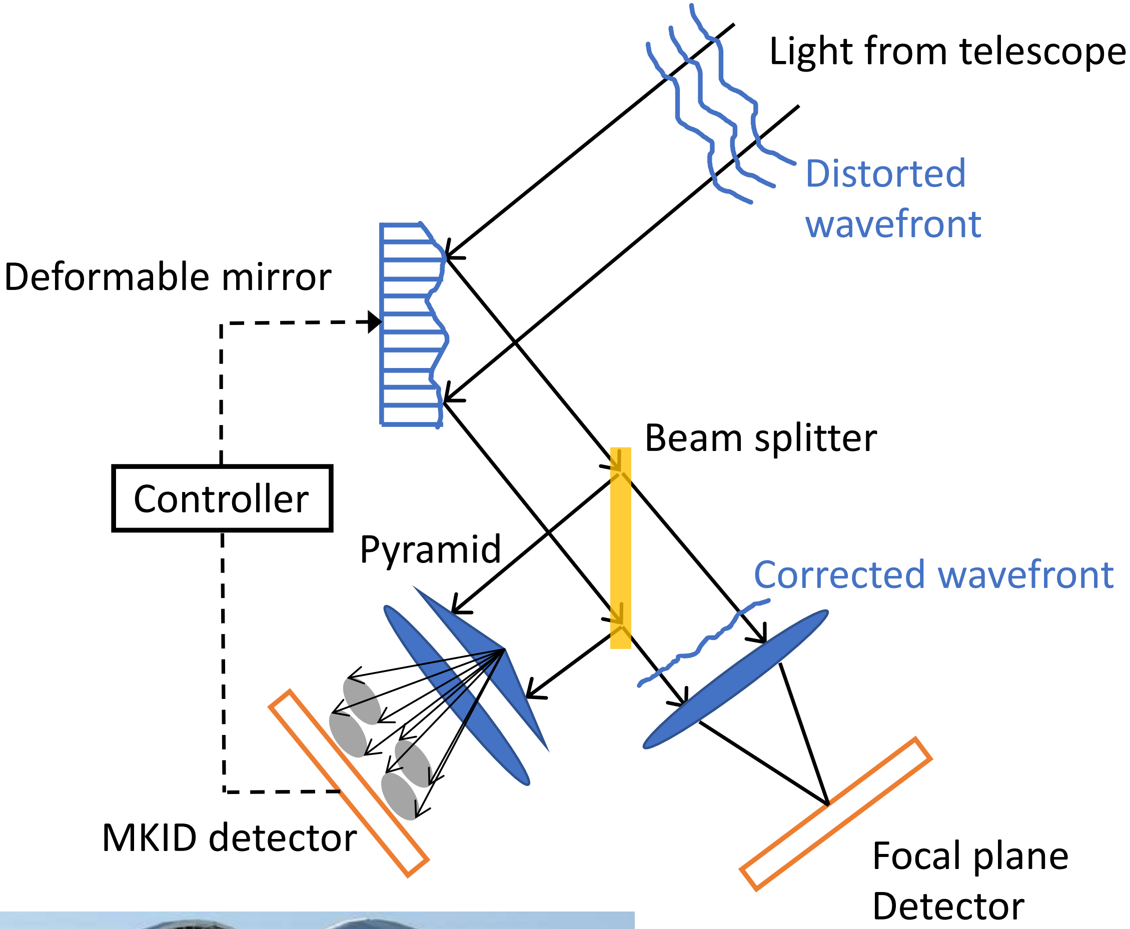
Wavefront sensing

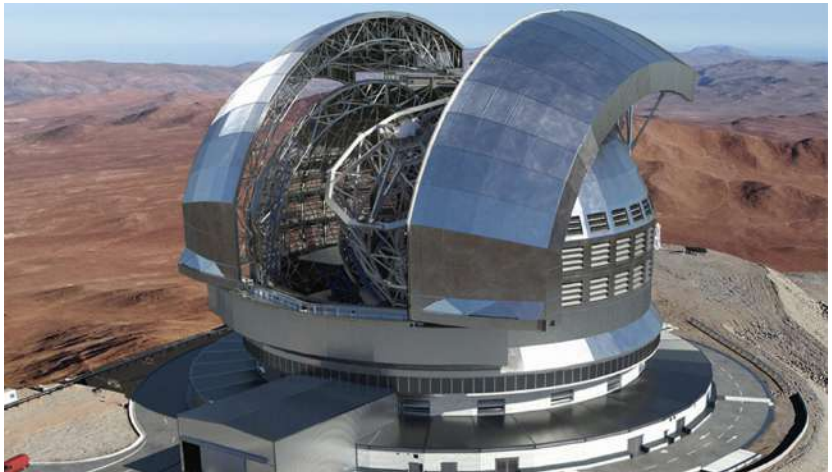
Wavefront errors

- Are chromatic
- Change quickly (~ ms)
- Need a guide star/source which can be faint

Wavefront sensing can be improved by a detector which is:

- Read out real time
- Color resolving
- Photon counting

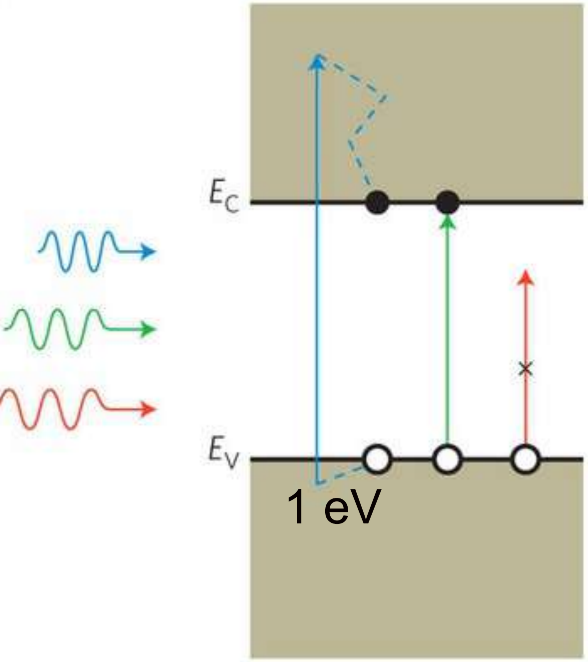


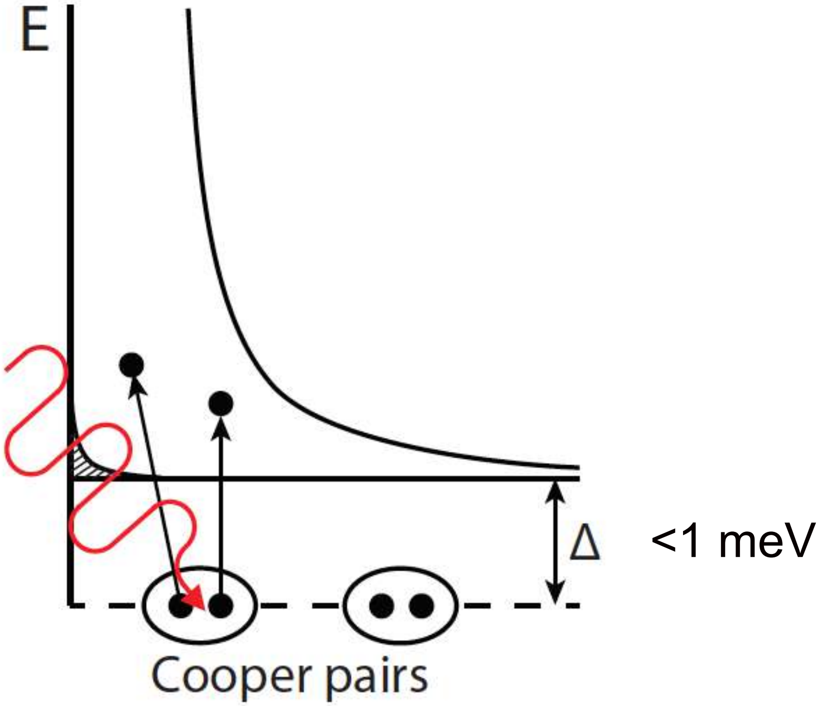


Semiconducting vs superconducting detector

Semiconductor: bandgap ~1 eV => 1 electron per photon

Superconductor: gap <1 meV => 1000’s of ‘electrons’ per photon





Semiconductor

Superconductor

Semiconducting vs superconducting detector

Semiconductor: bandgap ~1 eV => 1 electron per photon

Superconductor: gap <1 meV => 1000's of electrons per photon

Main advantages:

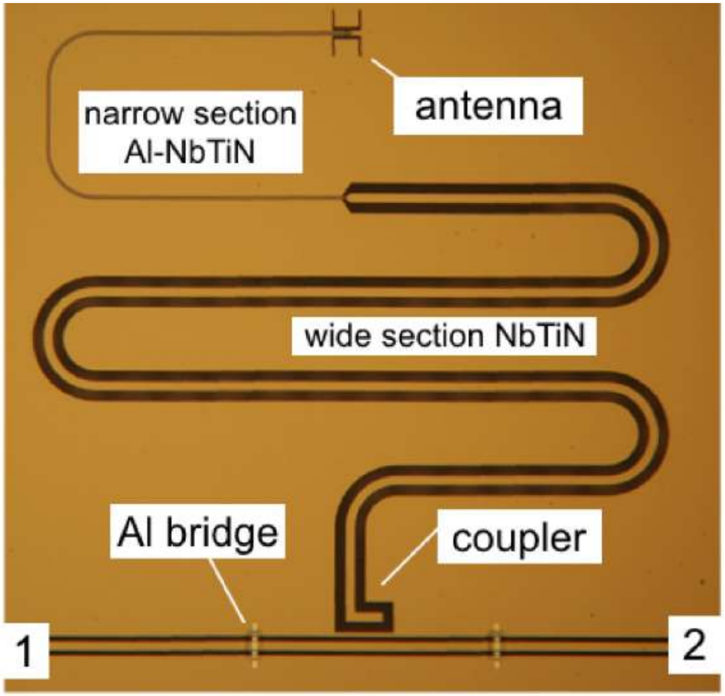
- Colour information preserved - spectroscopy
- No dark-current and no read-noise

Other useful properties:

- Real time readout of the pixels (timing information)
- Can be used for any wavelength above gap frequency

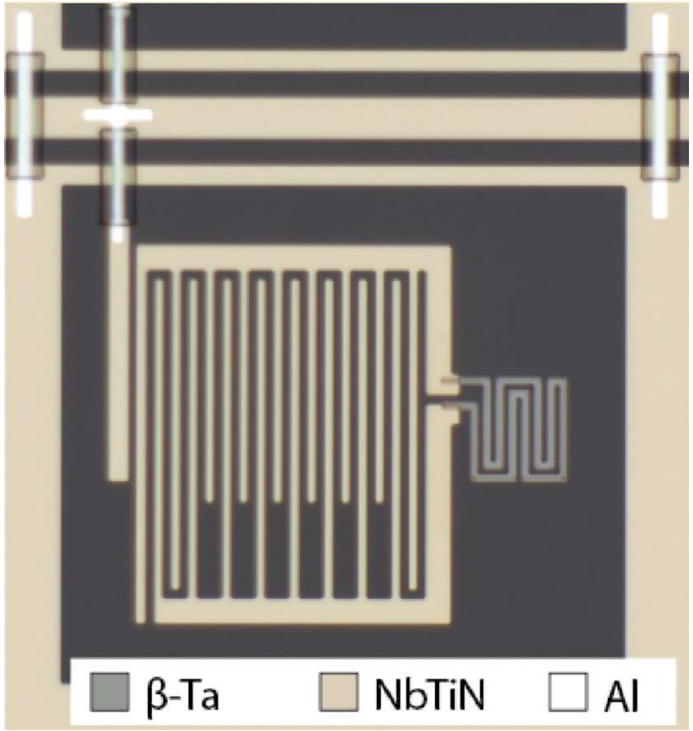
MKIDs, 2 main flavours

Distributed (CPW) resonator with antenna for far-infrared



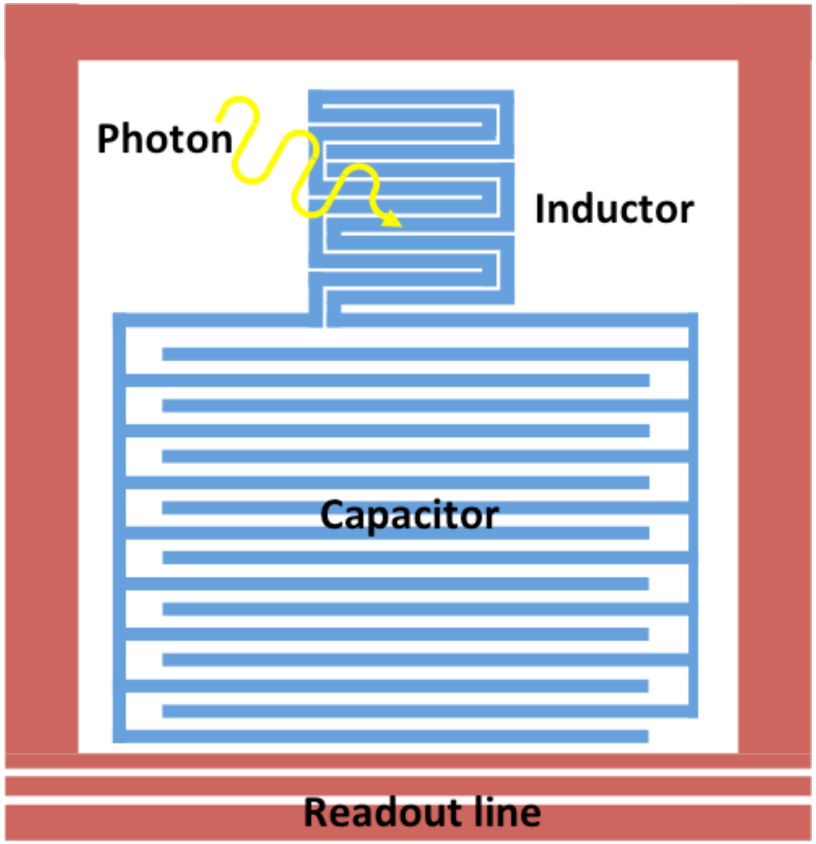
Lumped element resonator.
2 possibilities for inductor:

- Smaller than wavelength (THz, sub-mm)
- (much) larger than wavelength (visible, near-IR)

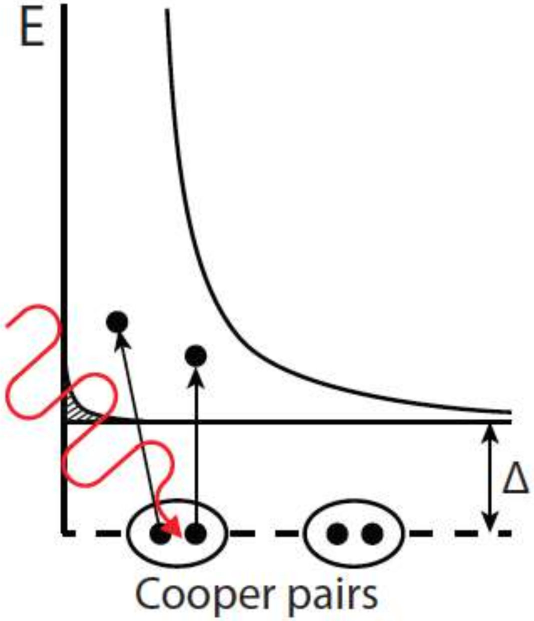


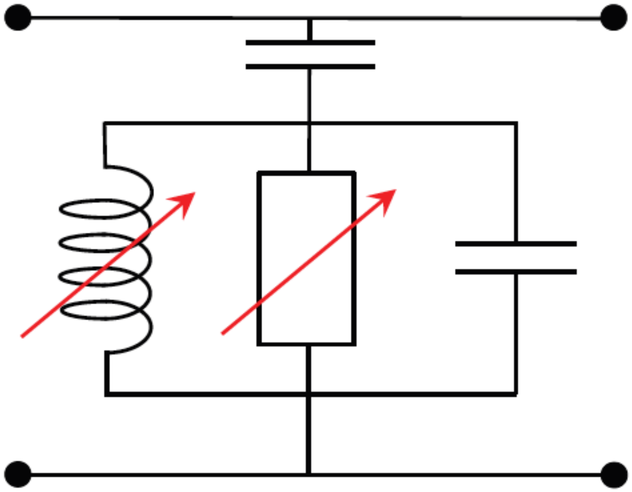
Design: Kevin Kouwenhoven

MKIDs – operation principle

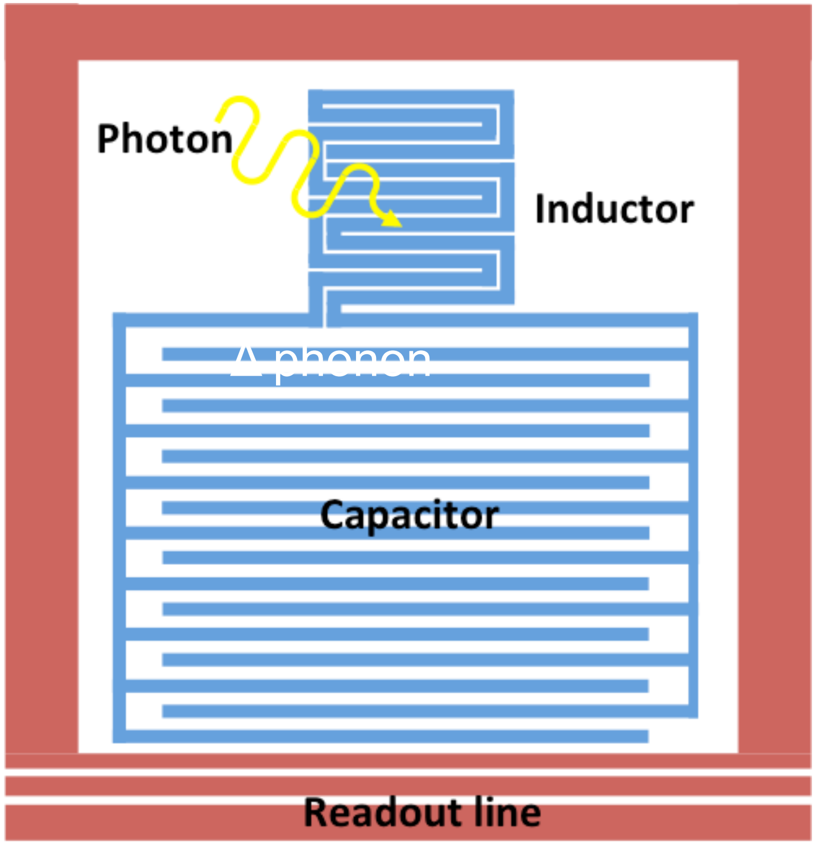


Microwave Kinetic Inductance Detector

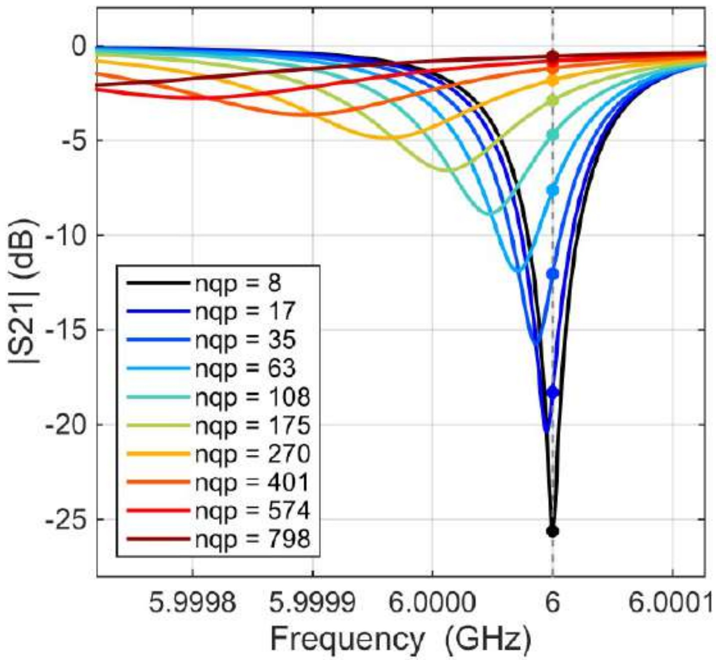


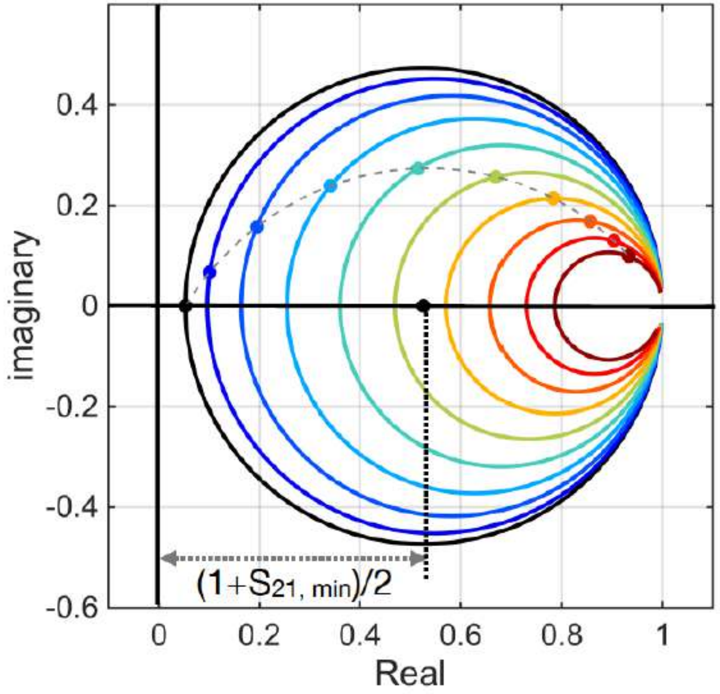


MKIDs – operation principle



Microwave Kinetic Inductance Detector



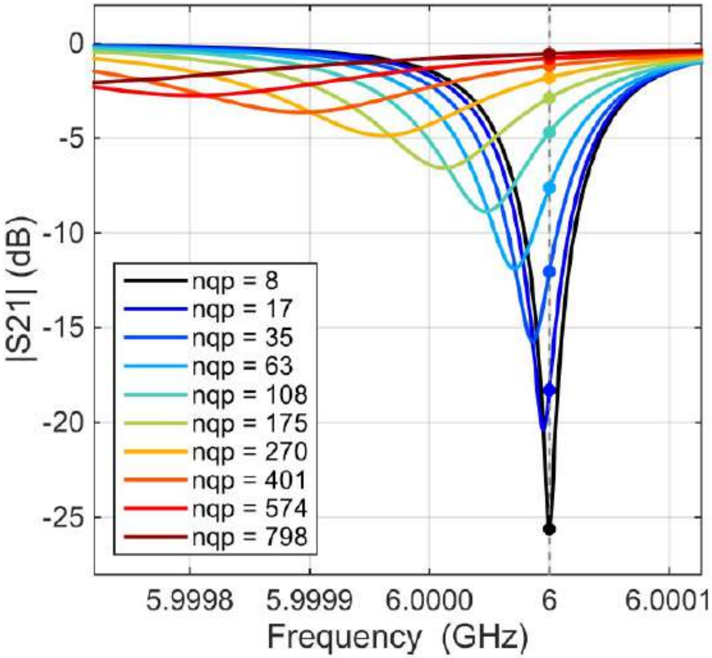


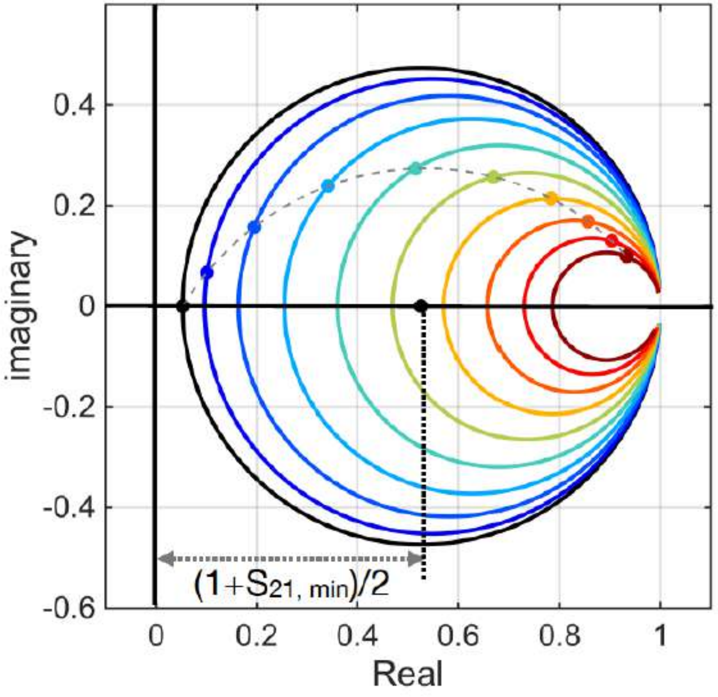
Day et al. Nature 2003

Responsitivity to quasiparticles

$$
\begin{aligned}
\frac{\sigma_1}{\sigma_N} &= \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E)-f(E+\hbar\omega)]g_1(E)dE \\
&+ \frac{1}{\hbar\omega}\int_{min(\Delta-\hbar\omega,-\Delta)}^{-\Delta}[1-2f(E+\hbar\omega)]g_1(E)dE \\
\frac{\sigma_2}{\sigma_N} &= \frac{1}{\hbar\omega}\int_{max(\Delta-\hbar\omega,-\Delta)}^{\Delta}[1-2f(E+\hbar\omega)]g_2(E)dE
\end{aligned}
$$

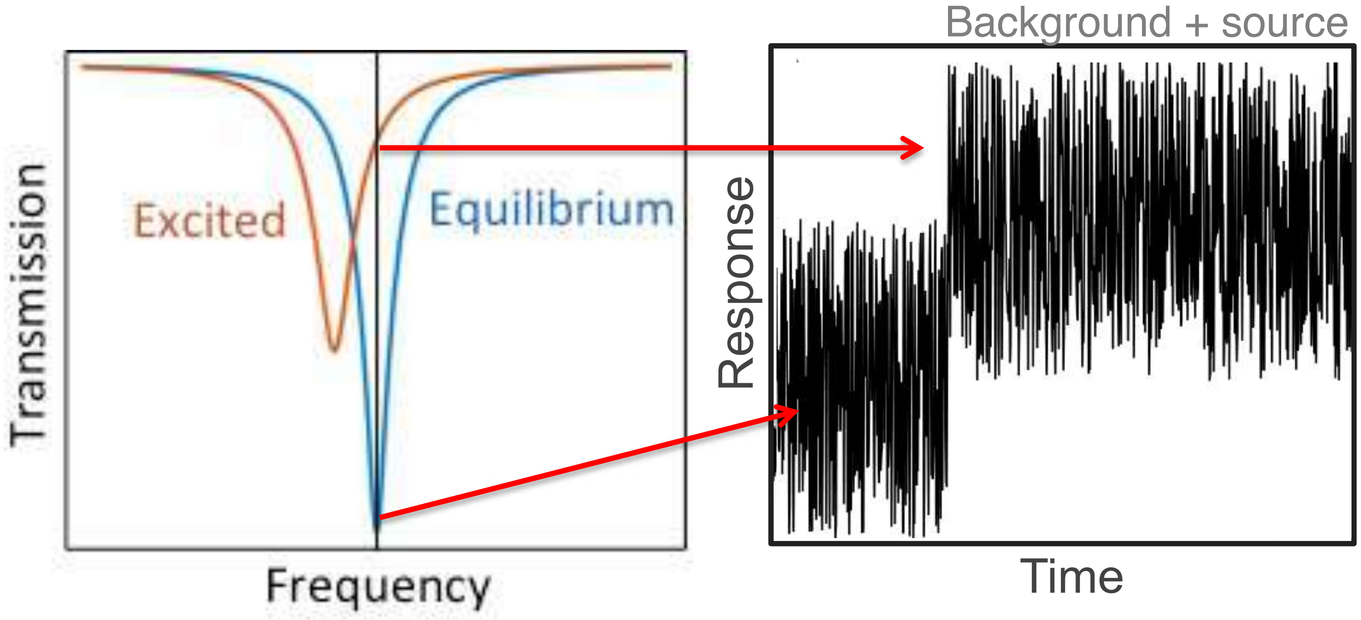
$$
\begin{aligned}
\frac{dA}{dN_{qp}} &= -\frac{\alpha_k\beta Q}{|\sigma|V}\frac{d\sigma_1}{dn_{qp}}; \\
\frac{d\theta}{dN_{qp}} &= -\frac{\alpha_k\beta Q}{|\sigma|V}\frac{d\sigma_2}{dn_{qp}}
\end{aligned}
$$



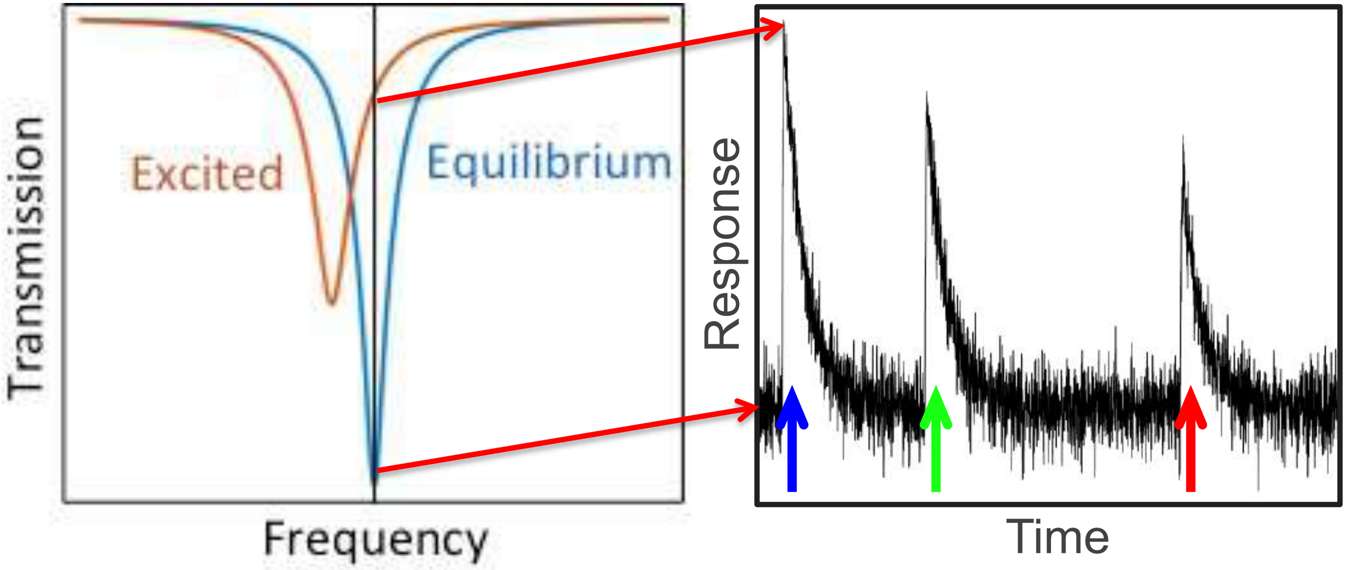


MKID detector – sensitivity in power or in photon energy

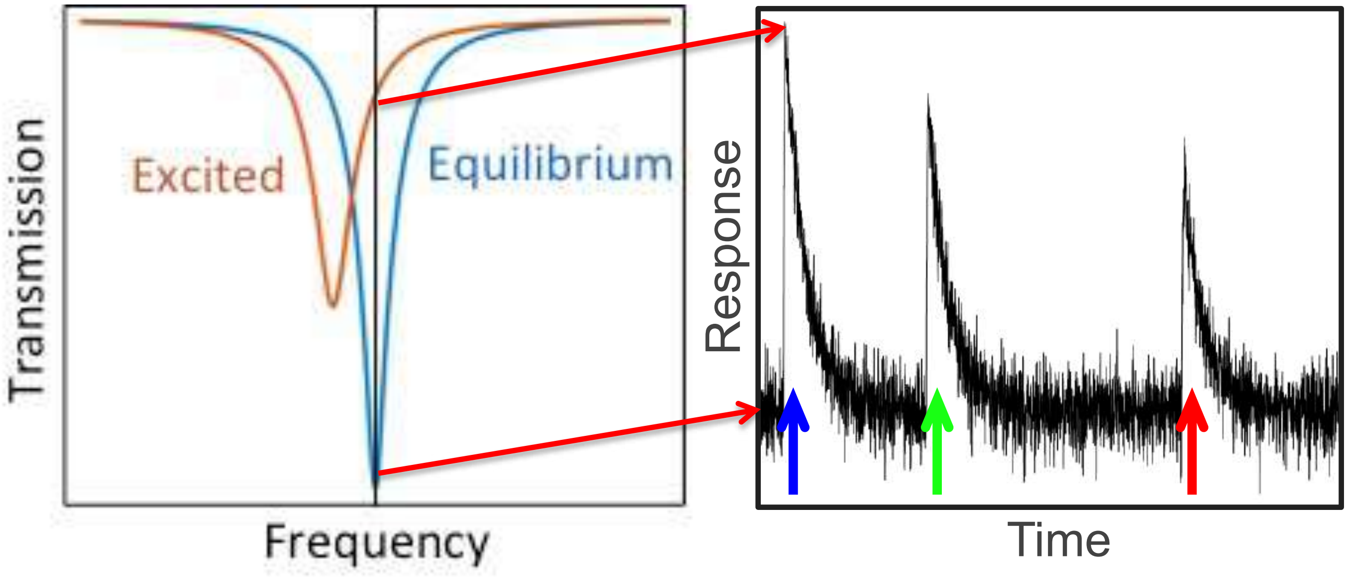
Power integrating



Photon counting
+ Energy resolving



MKID detector – sensitivity in power or in photon energy



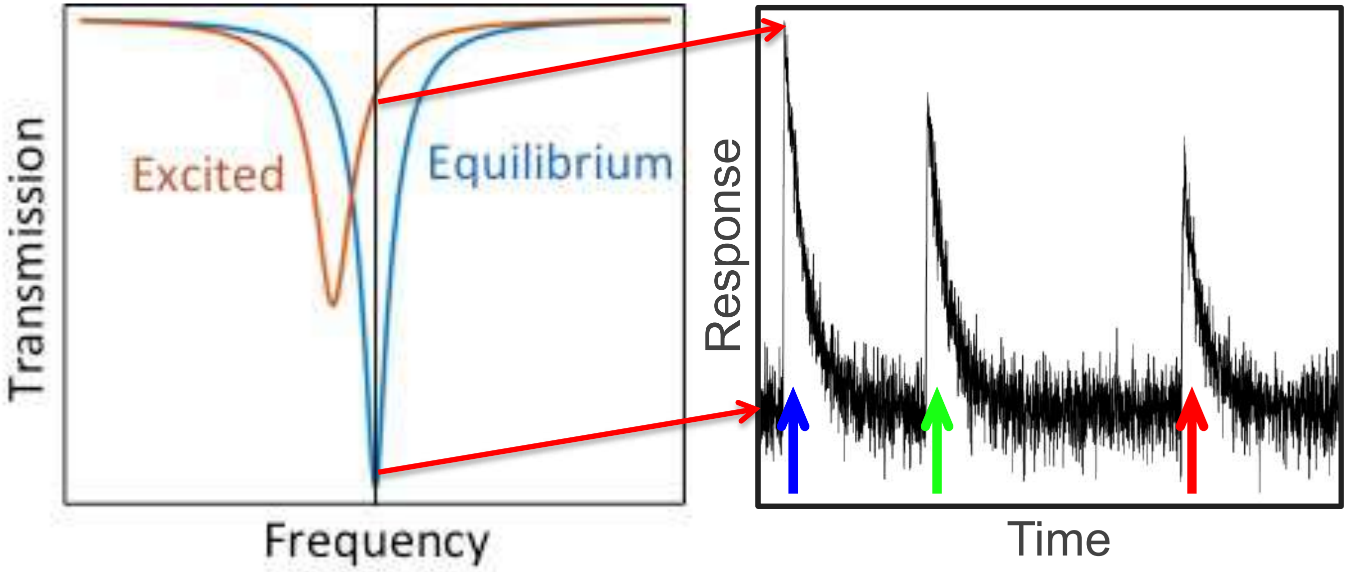
Far-infrared/sub-mm

- Low photon energy
- Many photons / time
- Power detection = change in average signal
- Sensitivity => detect tiny amount of power

Visible/near-infrared

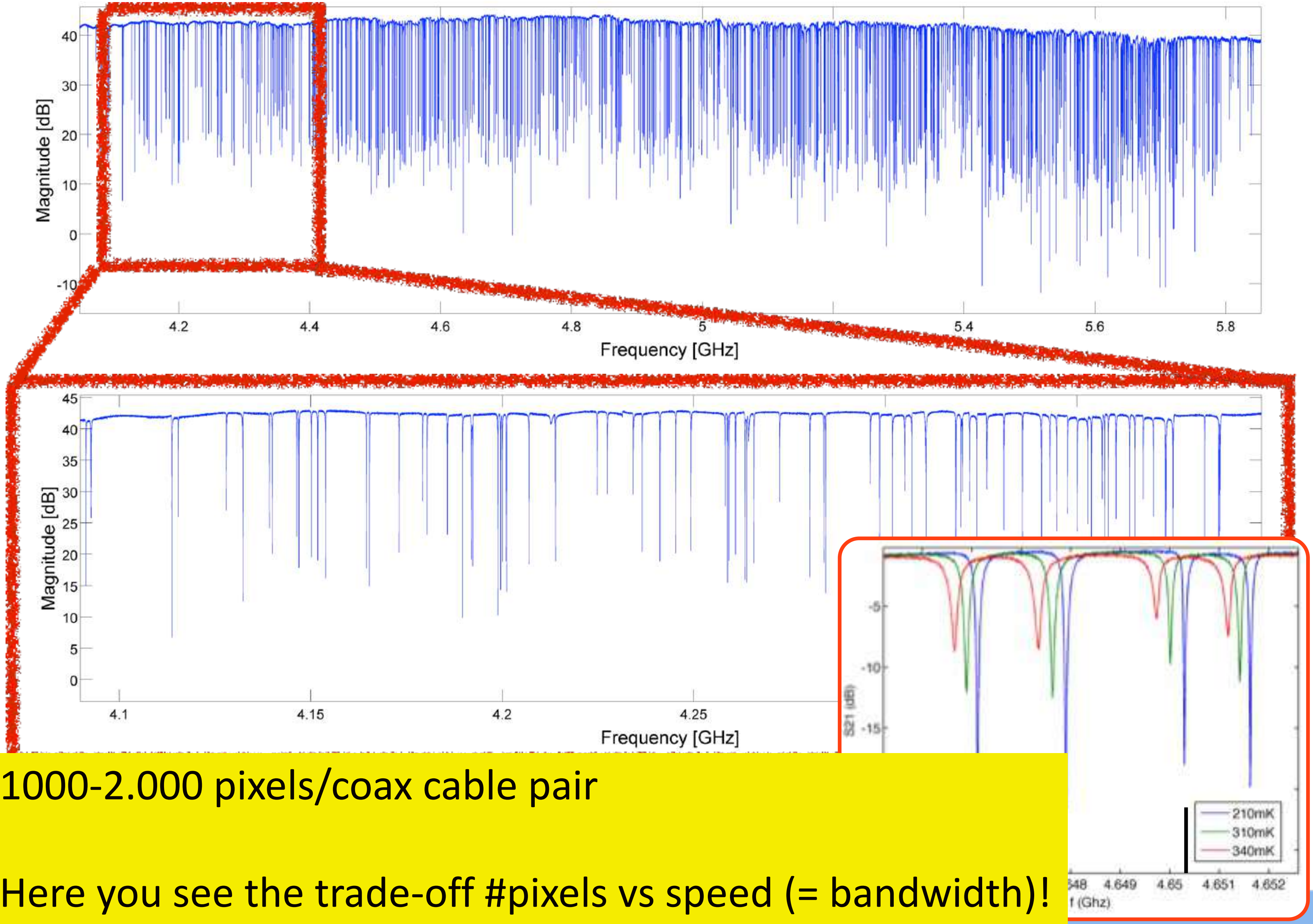
- High photon energy
- Less photons / time
- Photon detection = Pulse for every single photon
- Pulse height => photon energy
- Sensitivity => detect small changes on top of a large pulse

MKID detector – colour information



- Energy resolution => zero dark current and read noise
- Pulse decay time: quasiparticle recombination time (~100 us)
- Pulse rise time: resonator ring-time $\tau = \frac{Q}{\pi f_{res}}$

Multiplexed readout

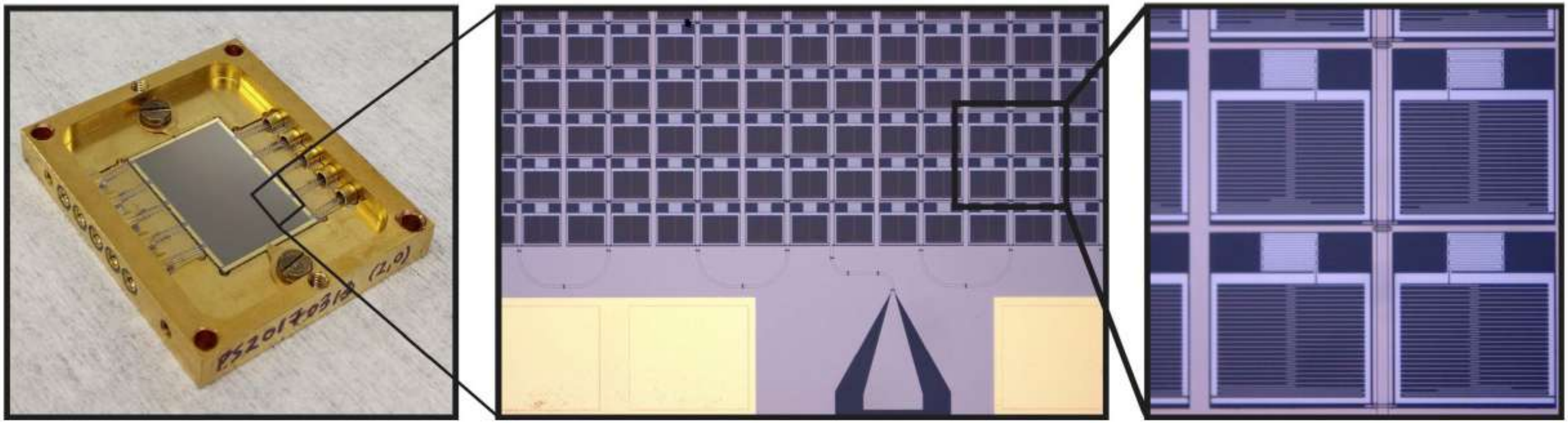


1000-2.000 pixels/coax cable pair

Here you see the trade-off #pixels vs speed (= bandwidth)!

VIS/NIR MKID instruments

- Wavefront sensing with colour sensitivity
- Fringe tracking (on faint sources)
- Spectroscopy
- Time-dependency
- Fluorescence problems in biophysics



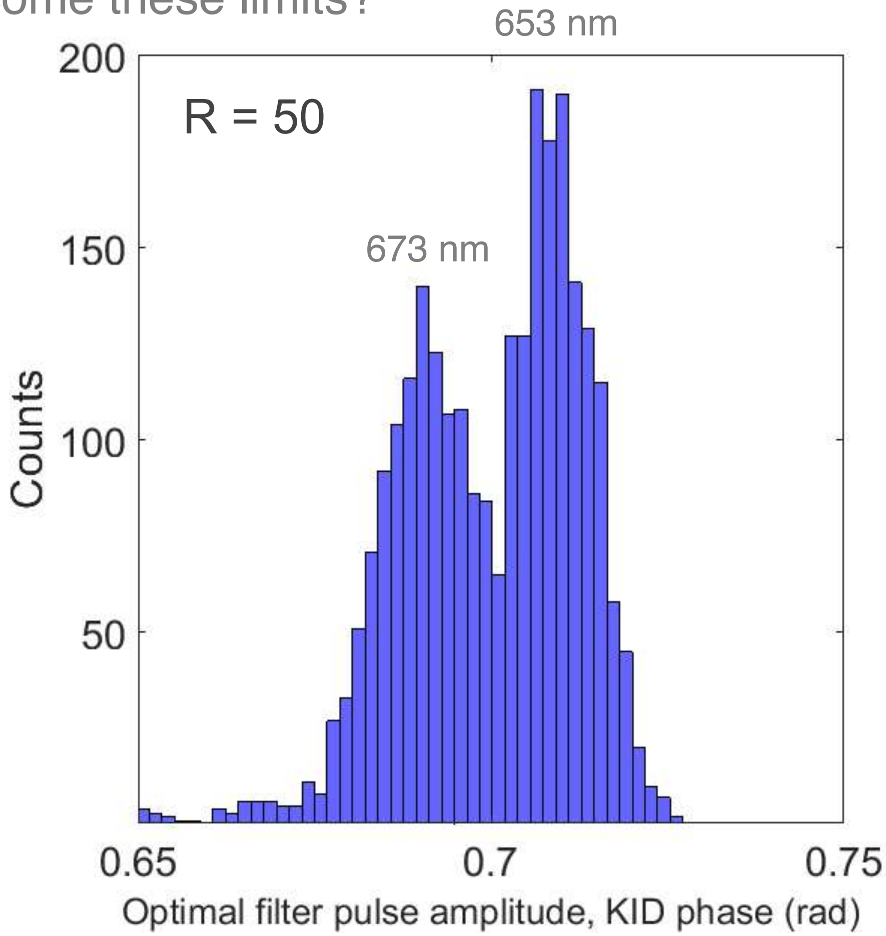
More information:
DARKNESS: Meeker et al, PASP 130 065001 (2018), arXiv:1803.10420
MEC: Walter et al, PASP 132, 125005 (2020), arXiv:2010.12620

Resolving power / energy resolution

Resolving power / energy resolution

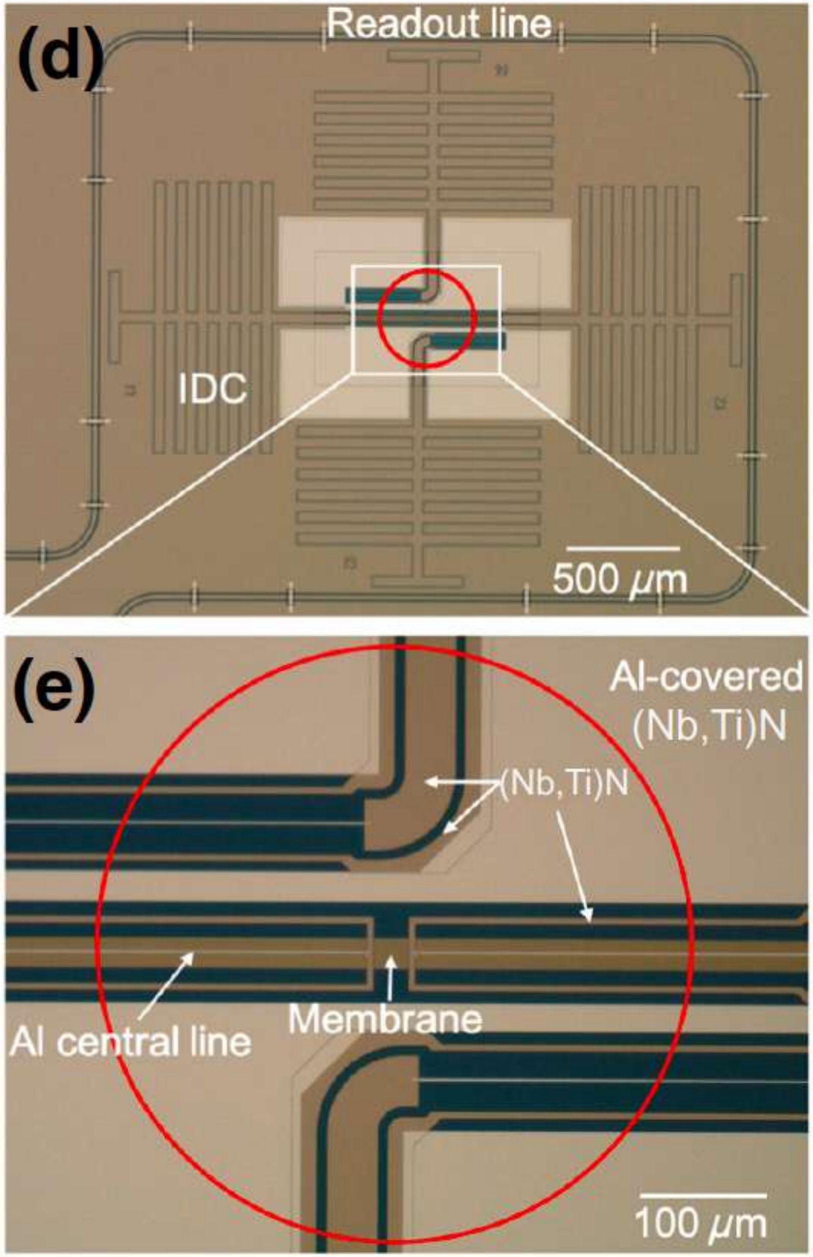
How do we get from single photon hits to a spectrum?

- How do we measure R?
- What limits R?
- How do we overcome these limits?

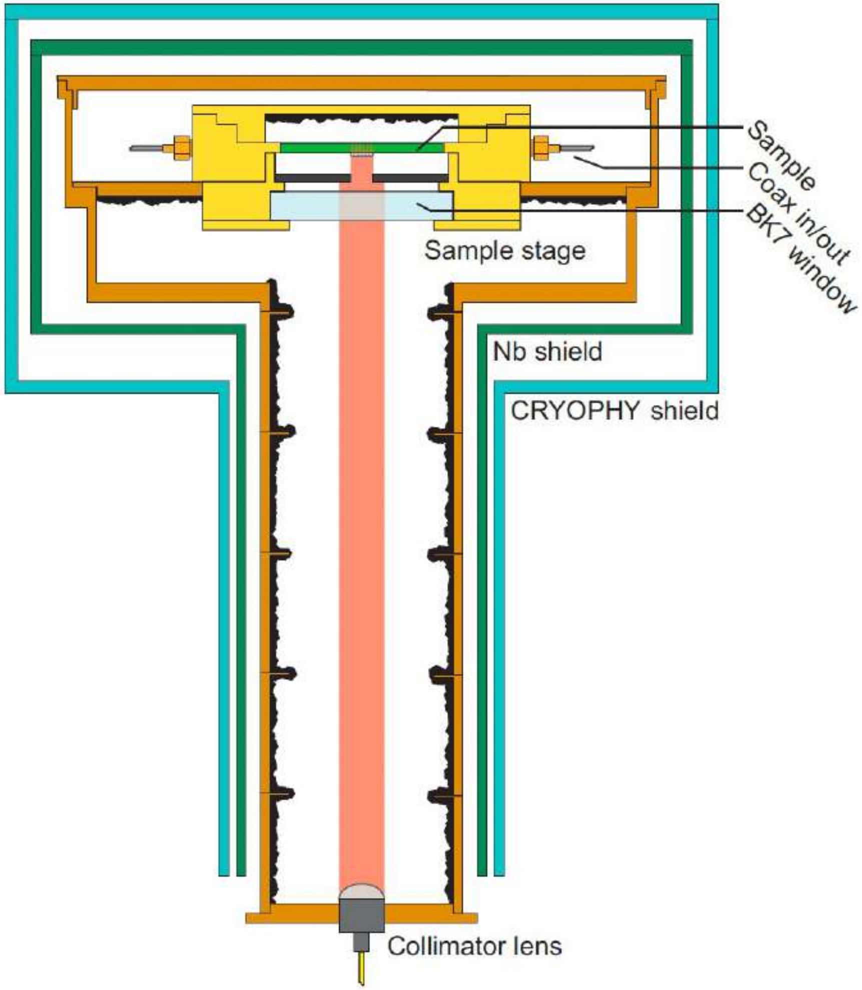


How do we measure energy resolution?

- Hybrid NbTiN/Al MKID, with small Al volume as sensitive element
- This is not an efficient detector, but very sensitive

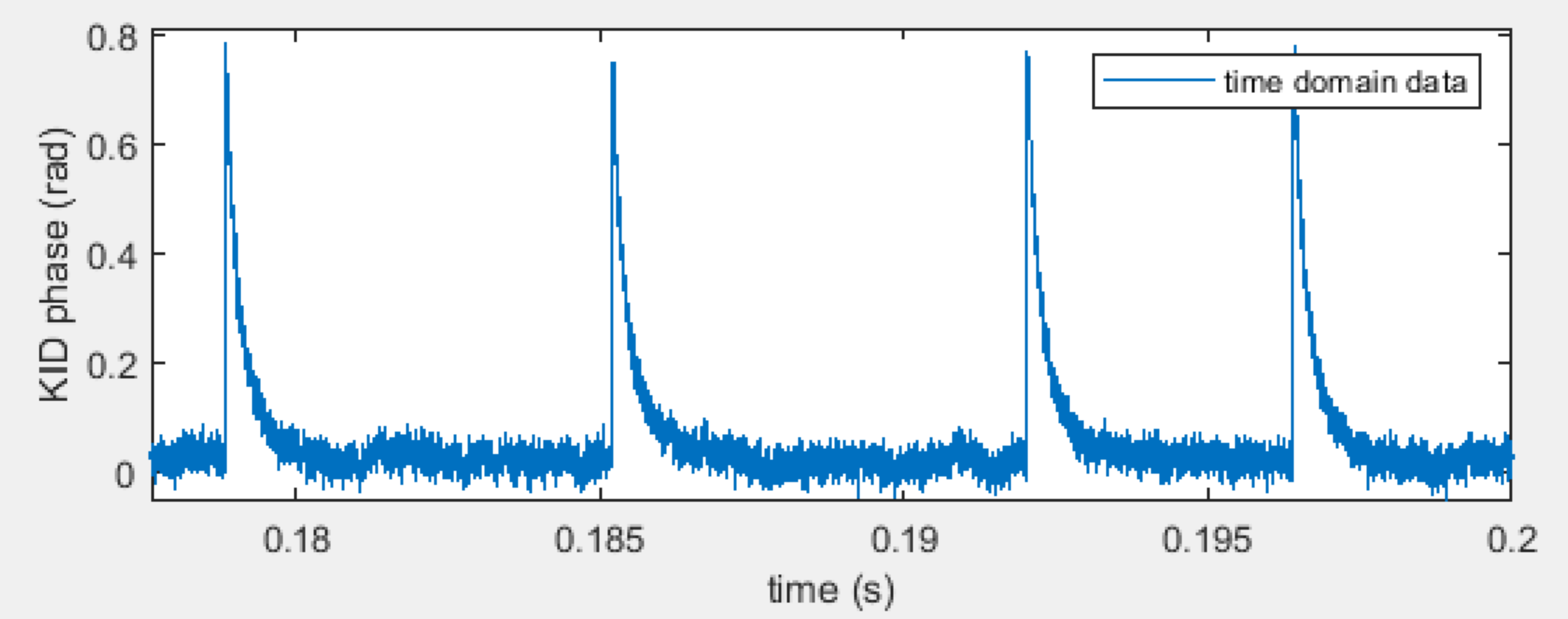


Setup – fiber or window illumination

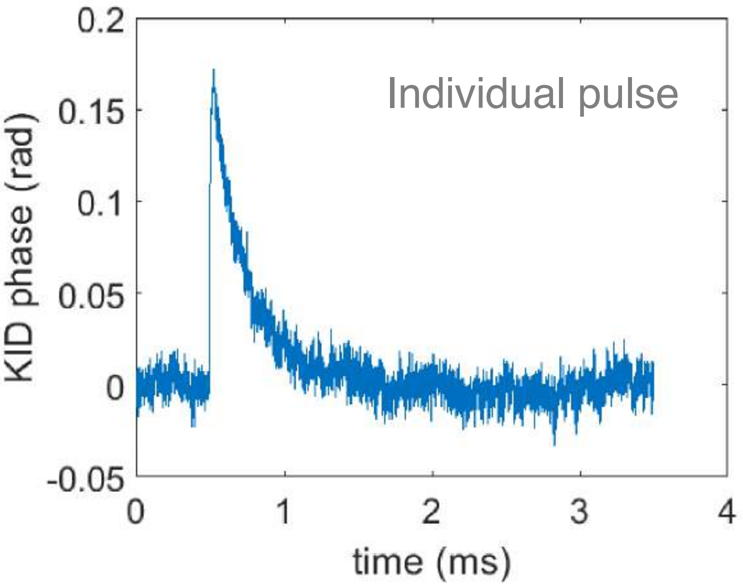


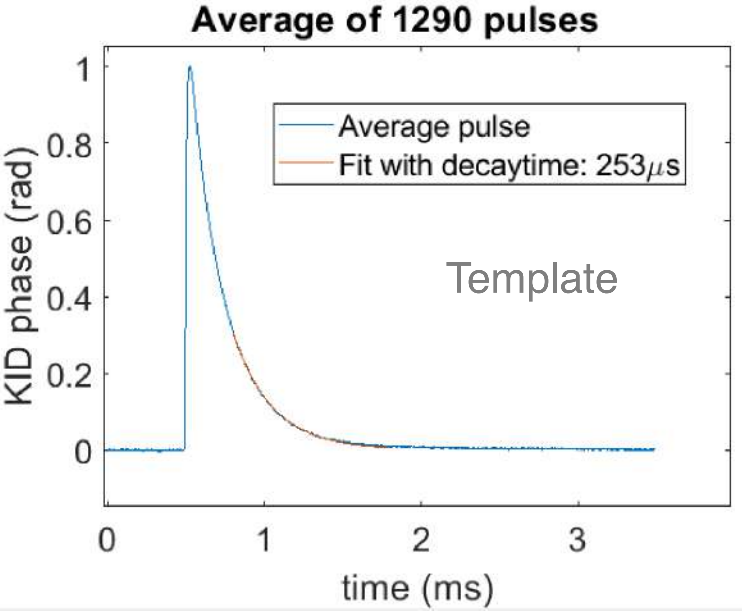
Commercial dilution refrigerator, T>18 mK, typically 100-120 mK for MKIDs.
Interior engineered and produced at SRON.

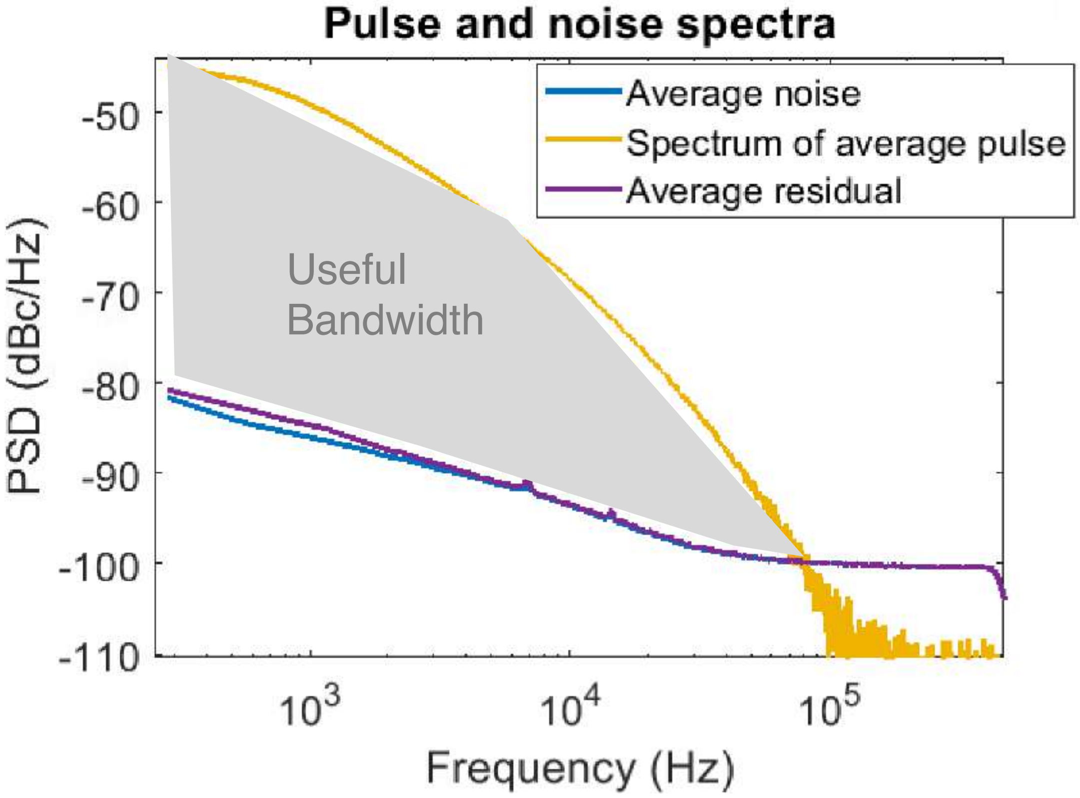
Time trace of KID response with continuous 673 nm illumination



Pulse analysis

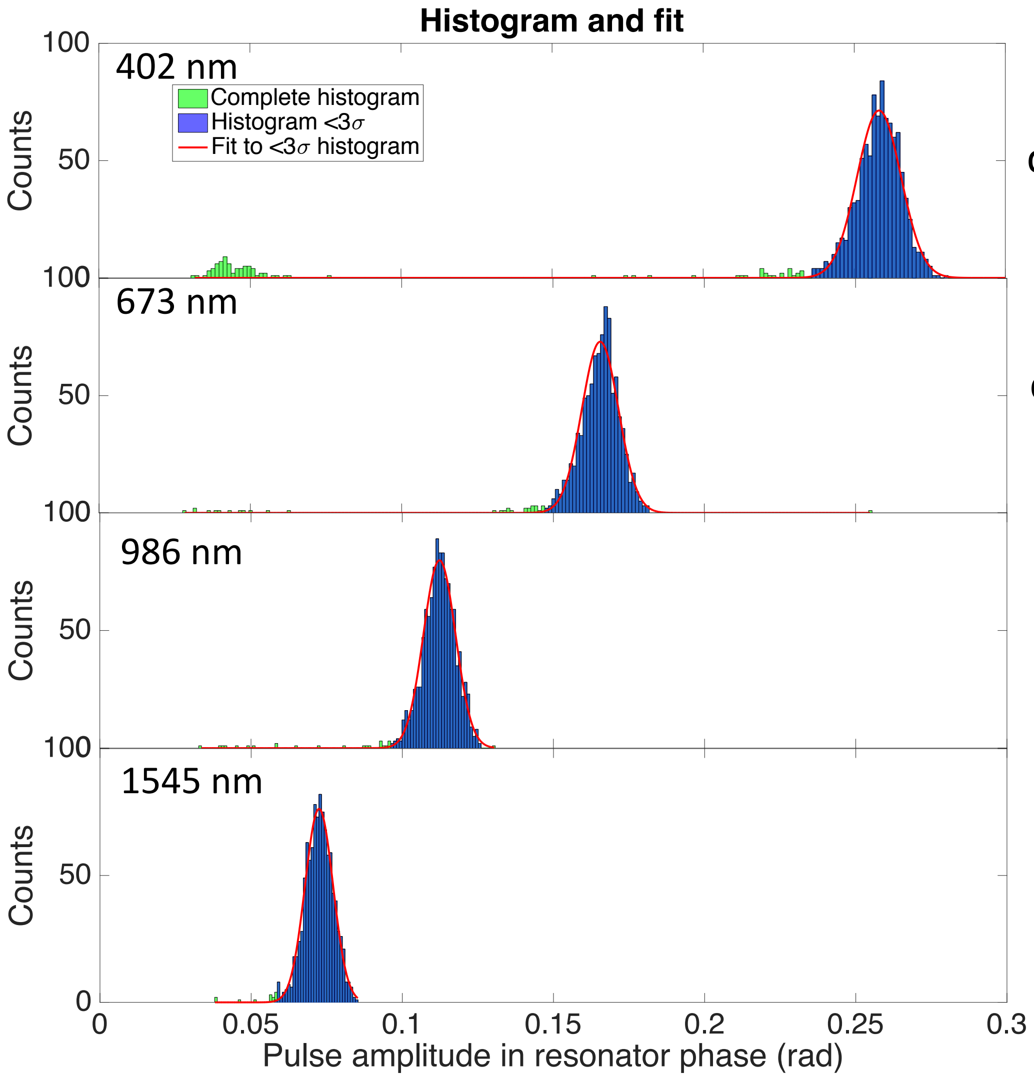






Note: we plot PSDs here where optimal filter uses FTs

Energy resolution of Al KIDs on sapphire



dE = 0.20 eV R = 15.4

dE = 0.16 eV R = 11.5

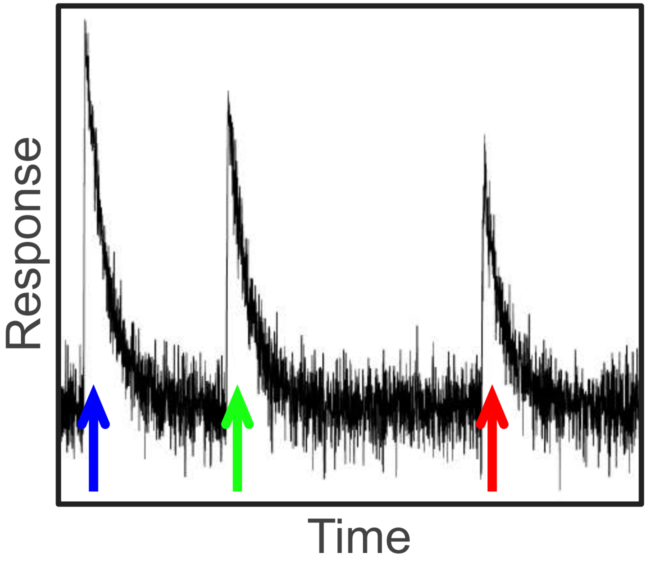
dE = 0.14 eV R = 9.0

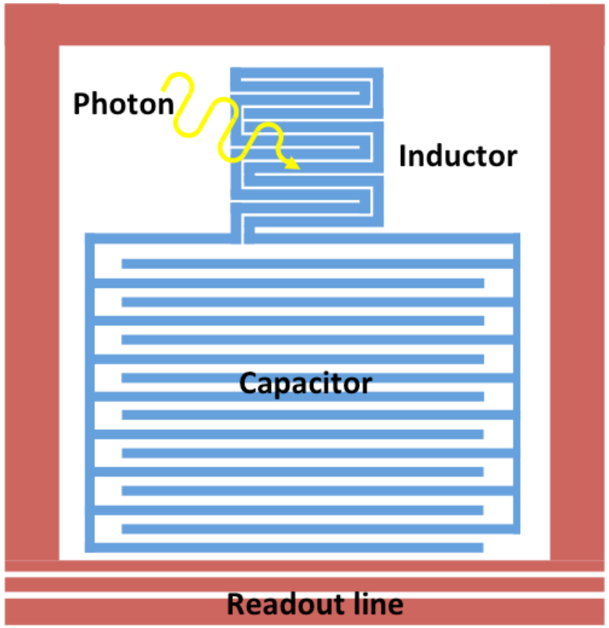
dE = 0.12 eV R = 6.6

What can limit the energy resolution in MKIDs?

Signal / noise

- Volume (low)
- Q-factor (high)
- Kinetic inductance (high)
- Efficiency of creating quasiparticles from photon energy



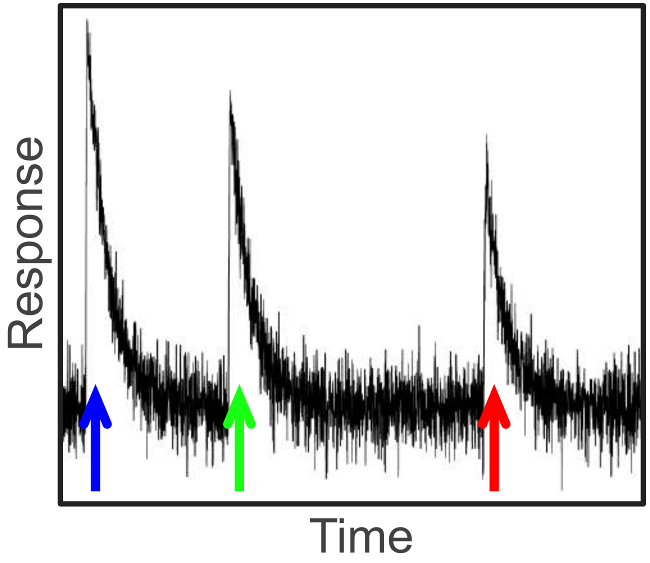


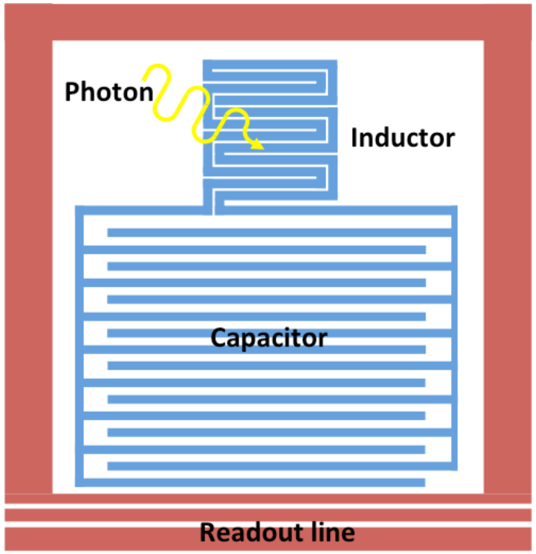
$$dN_{qp} = \frac{\eta E_{photon}}{\Delta}$$

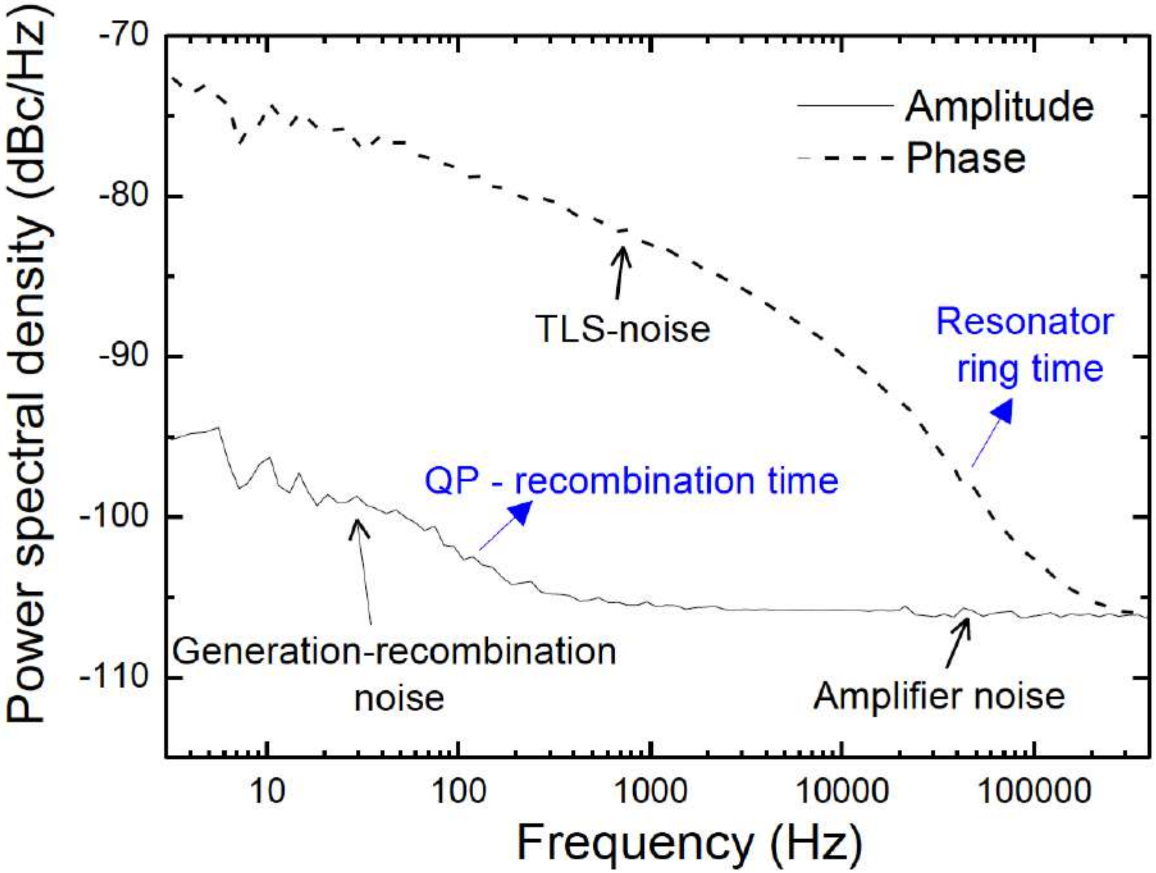
$$\frac{d\theta}{dN_{qp}} \propto \frac{\alpha Q}{V} \frac{d\sigma_2}{dN_{qp}}$$

Signal / **noise**

- Amplifier
- Dielectric two-level-systems
- Generation-recombination of quasiparticles

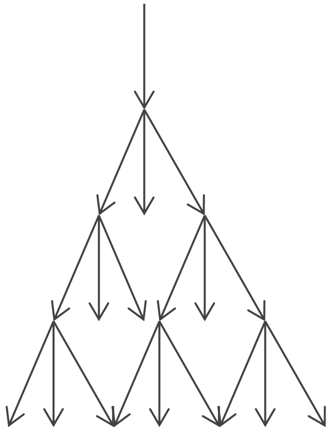


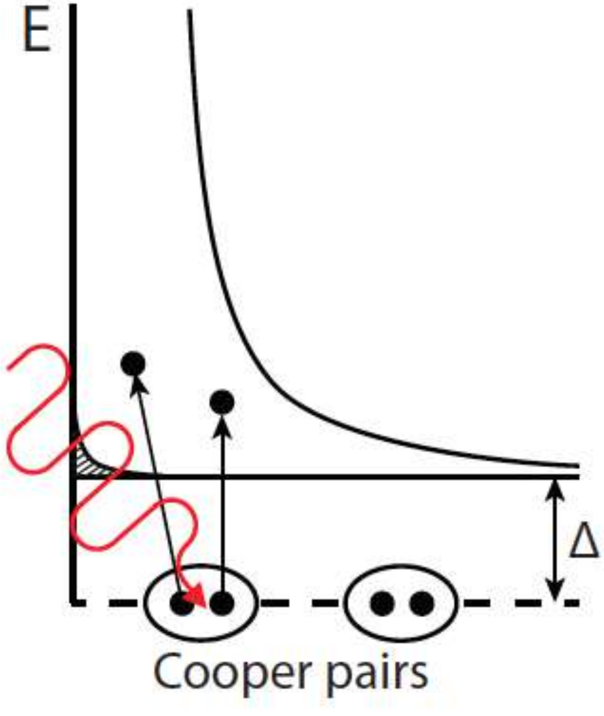


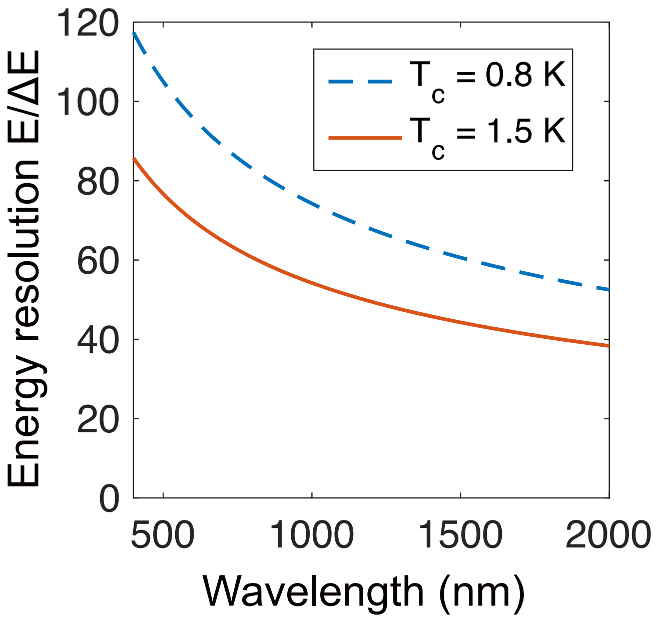


Role of phonons

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







Fano limit

- Statistical limit on how many quasiparticles are created from same photon energy
- Lower gap is the only tunable parameter

Pair-breaking efficiency

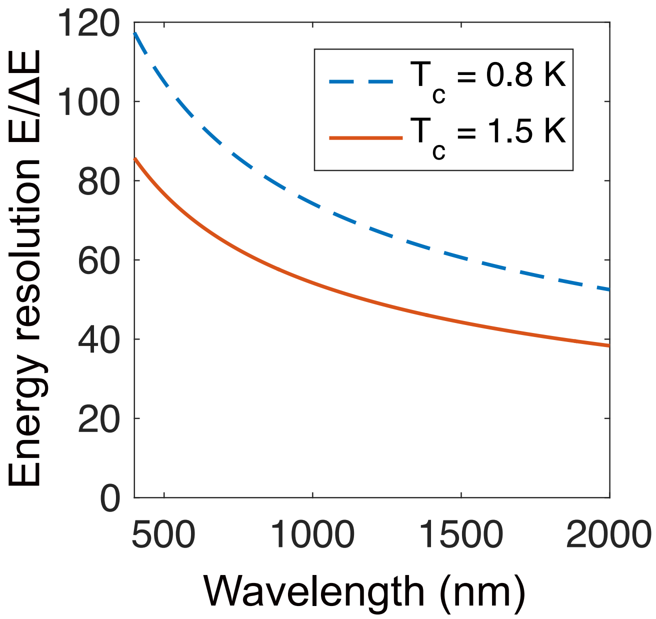
$$R = \frac{1}{2\sqrt{2\ln(2)}}\sqrt{\frac{\eta E}{F\Delta}}$$

Photon energy

Superconductor gap

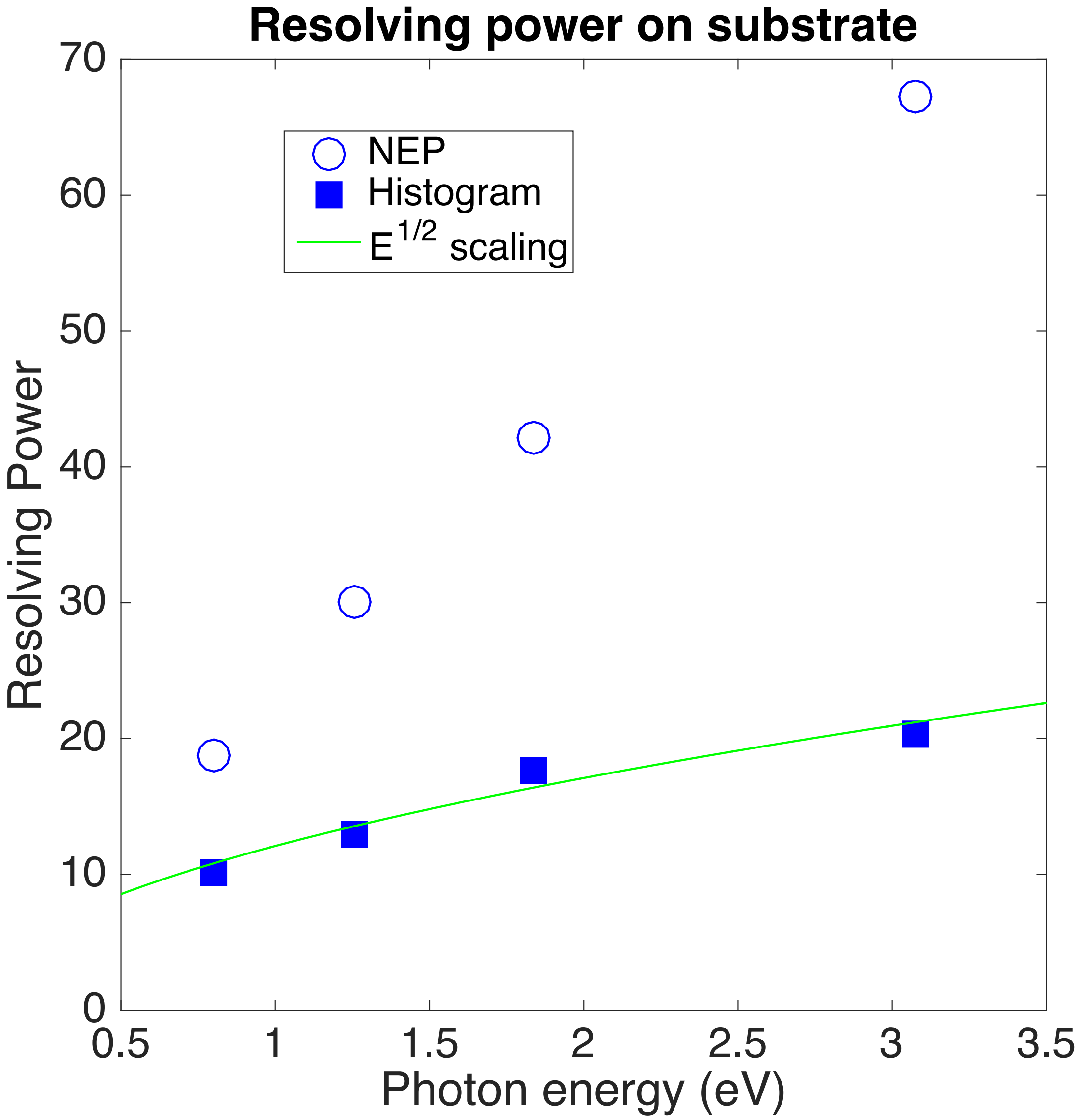
From standard deviation to FWHM

Fano factor F~0.2



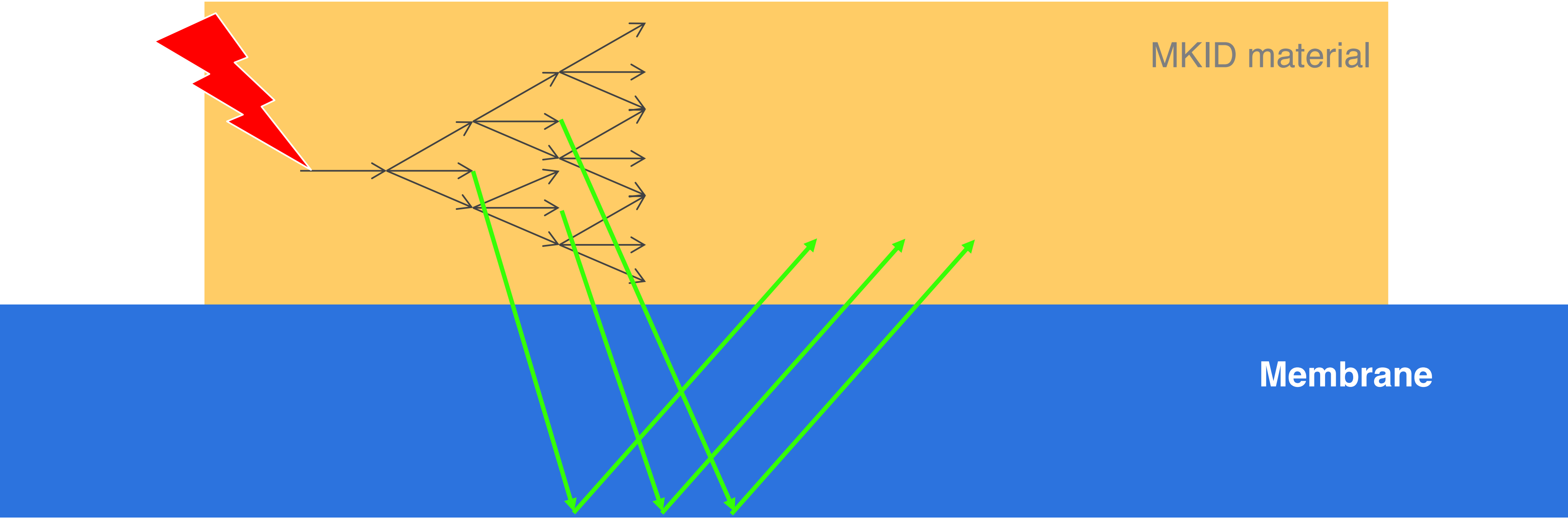
How do we know which mechanism is limiting?

Resolving power Al MKID on substrate



Laser wavelengths:
402 nm
673 nm
986 nm
1545 nm

Phonon recycling with membrane

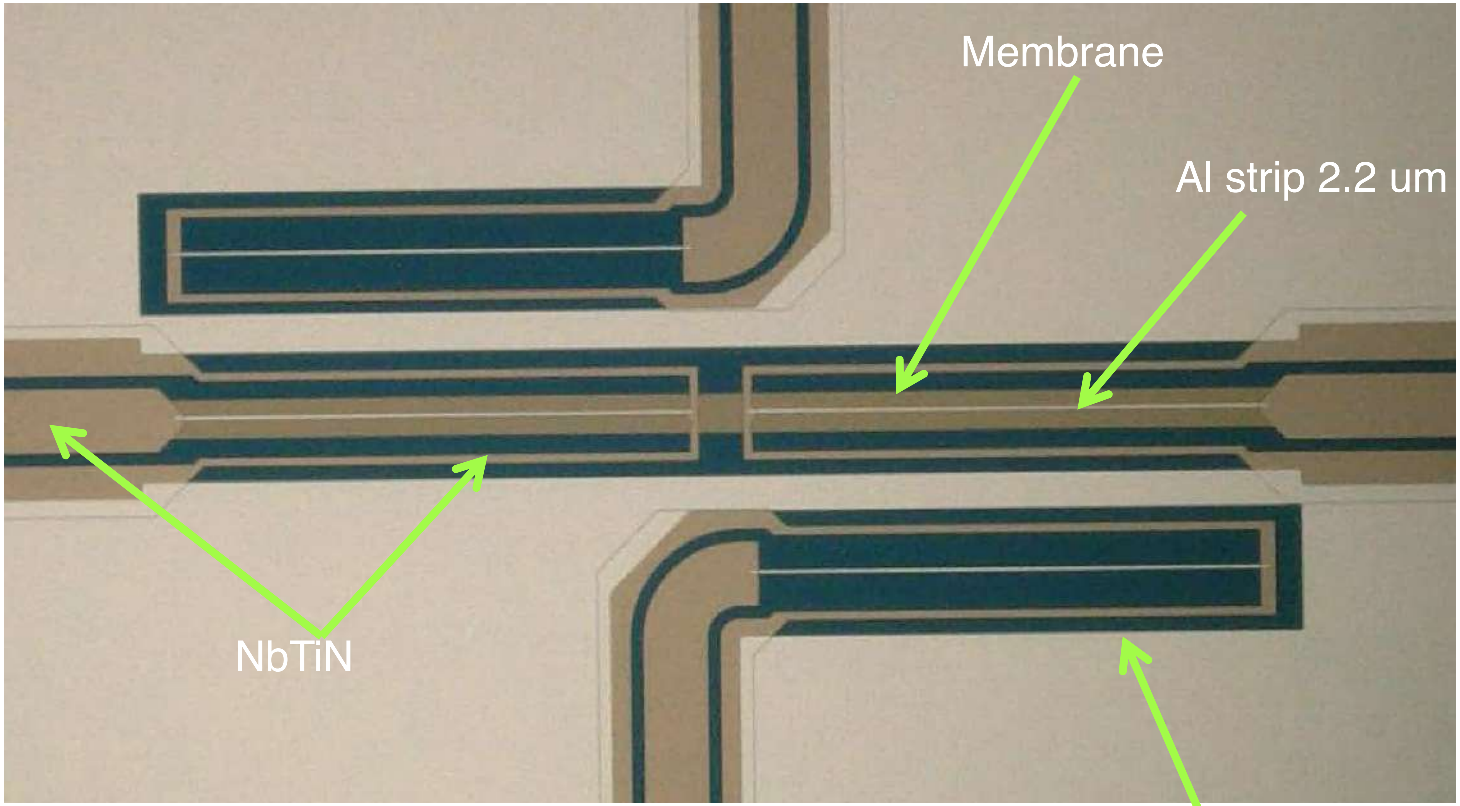


50 nm Alumunium film on 110 nm SiN membrane

Factor >7 better trapping than substrate.

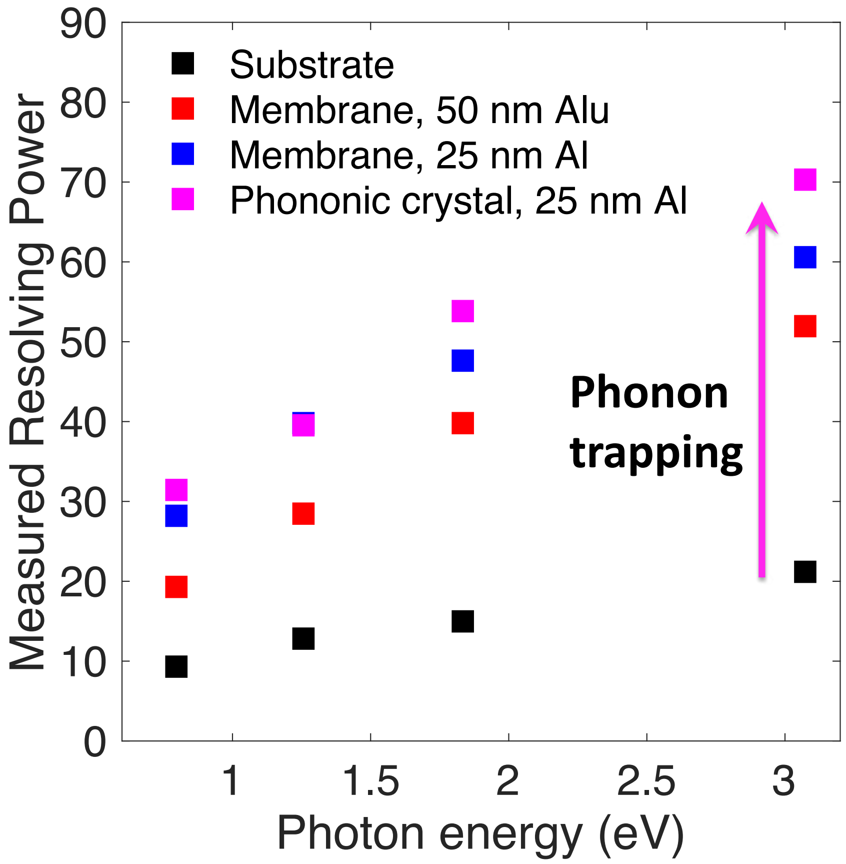
Trap phonons

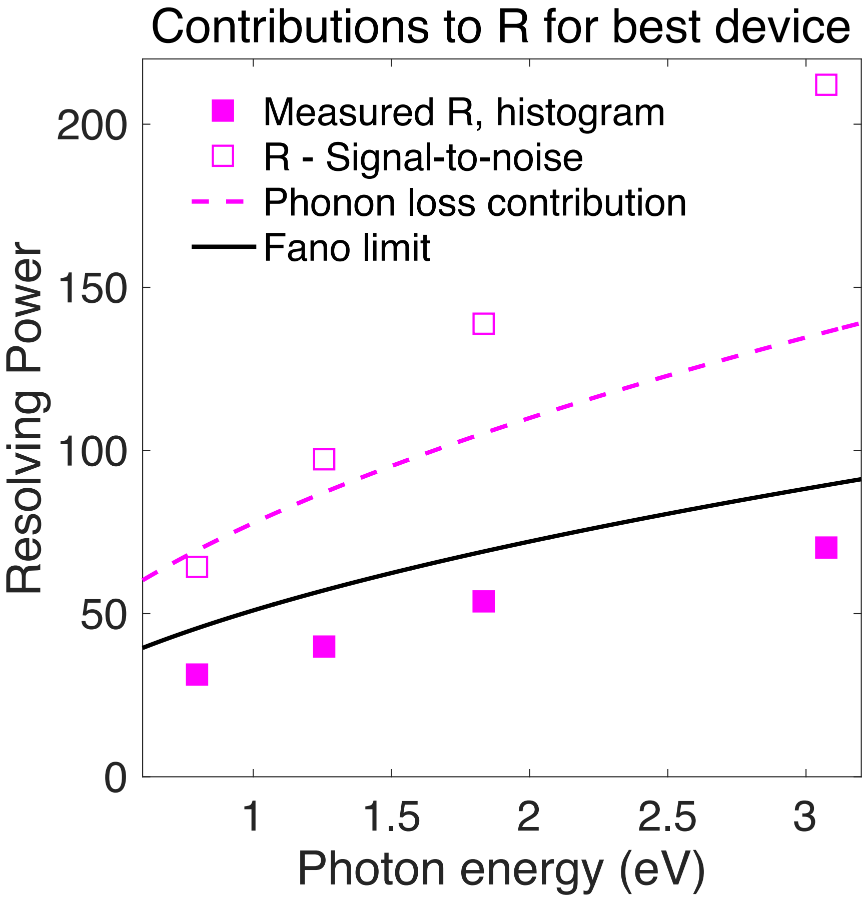
- 50 nm Al film
- 110 nm SiN membrane with 2.2 micron Al strip – aspect ratio
- Geometric retrapping model, factor ~7 longer phonon dwell time



Substrate KID

Measured histogram resolution substrate - membrane



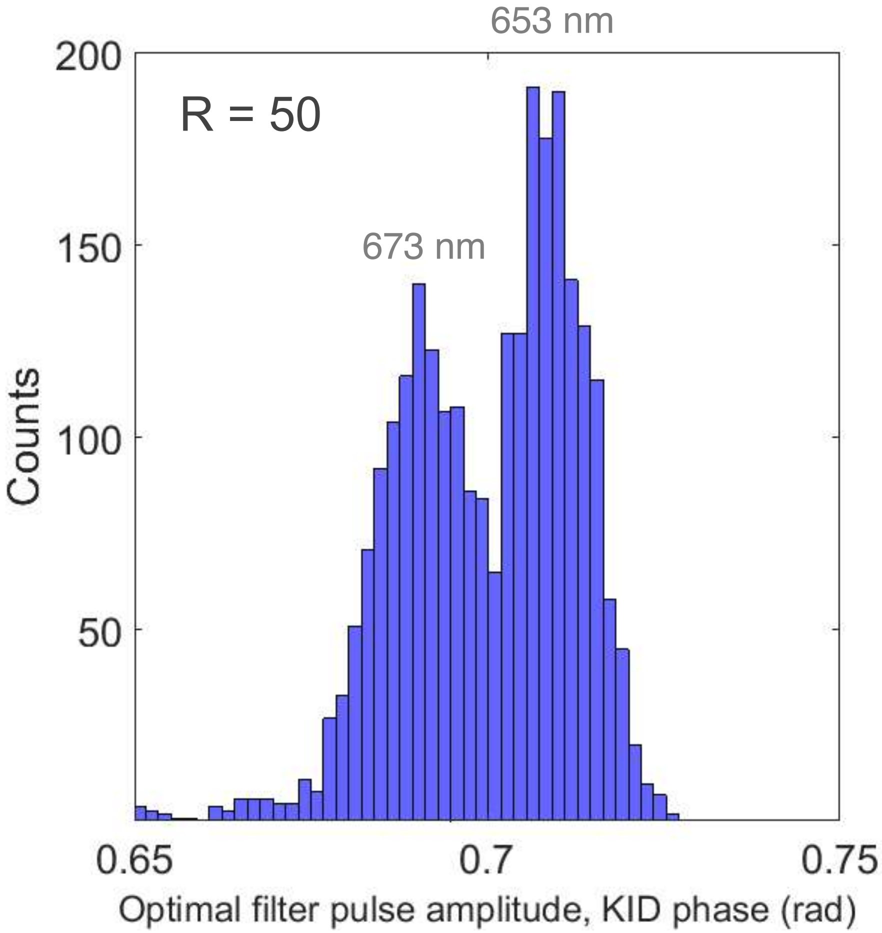


Higher is better

Dominated by Fano fluctuations

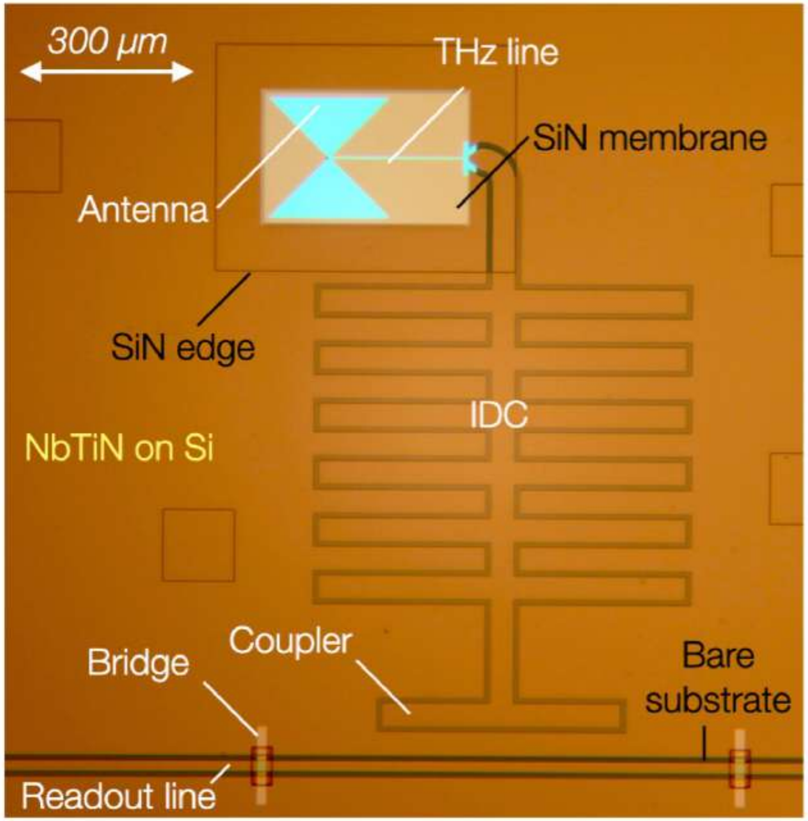
Want to know more?: [Physical Review Applied 16, 034051 (2021)]

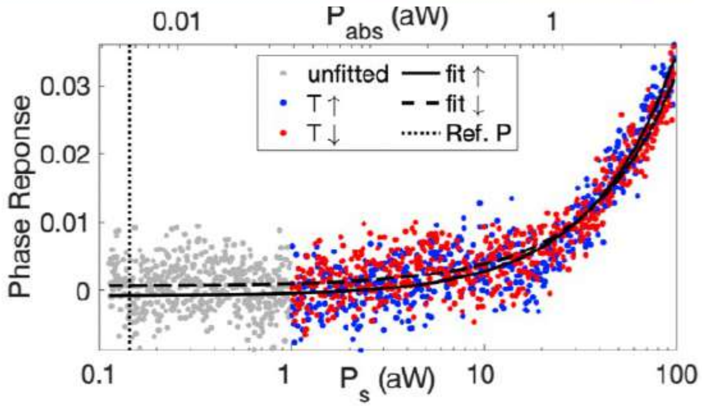
Proof: we can resolve close spectral lines

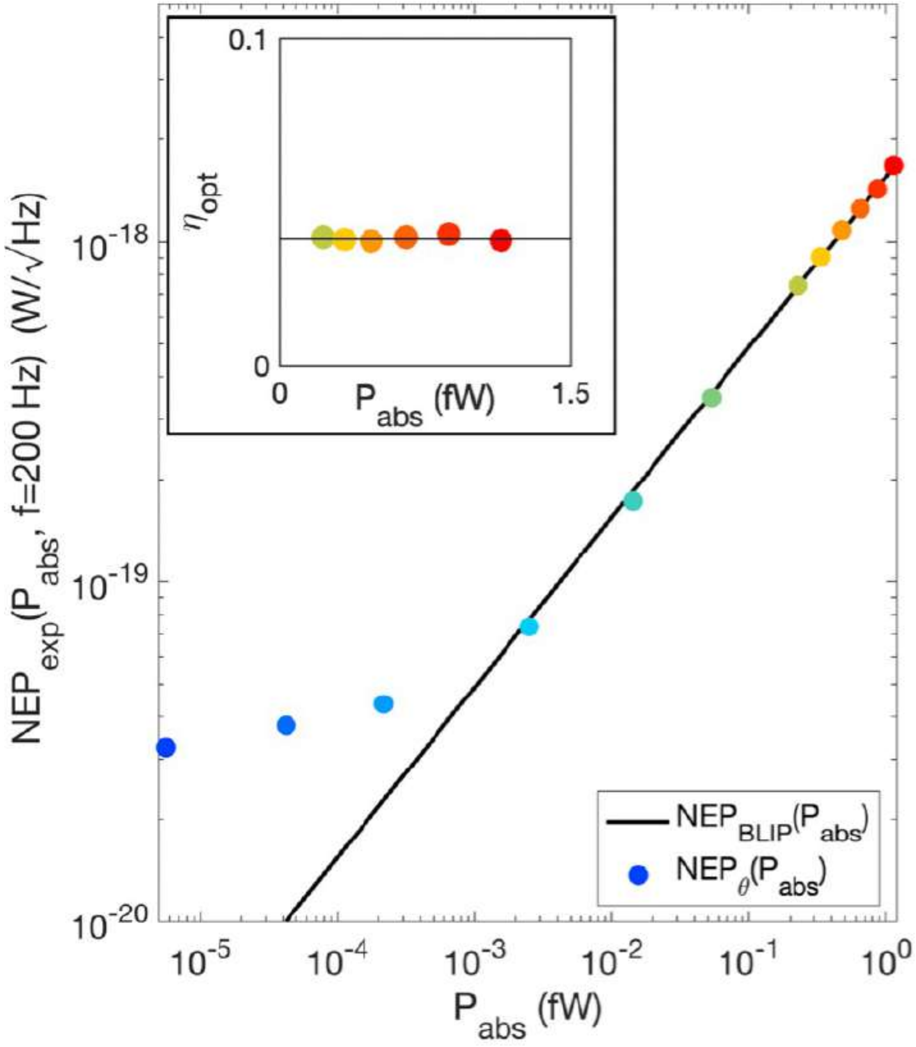


Combination of laser line and a monochromator
Best measured resolving power (at 673 nm)

Very similar Al device is the most sensitive far-infrared MKID

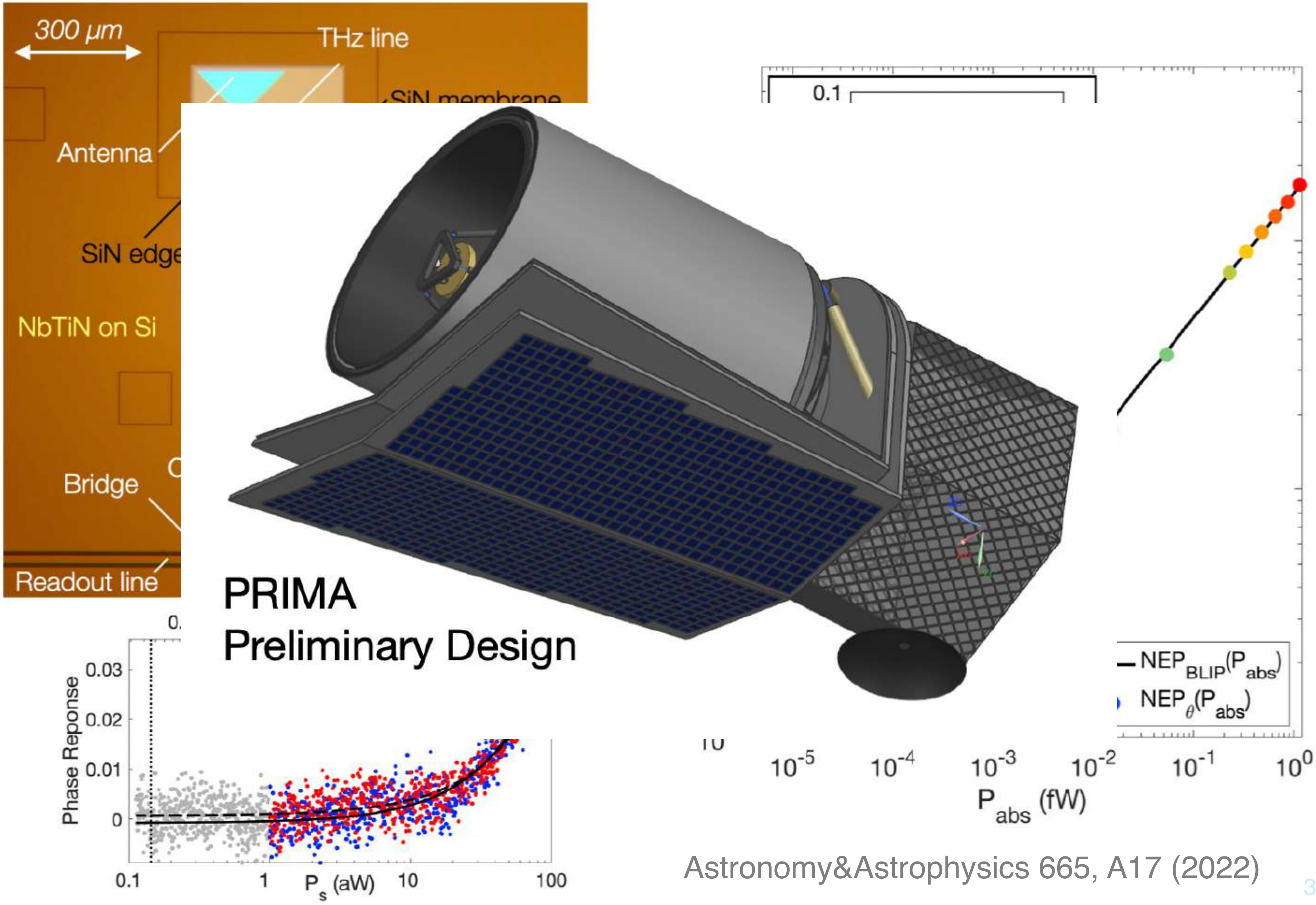






Astronomy&Astrophysics 665, A17 (2022)

Very similar Al device is the most sensitive far-infrared MKID



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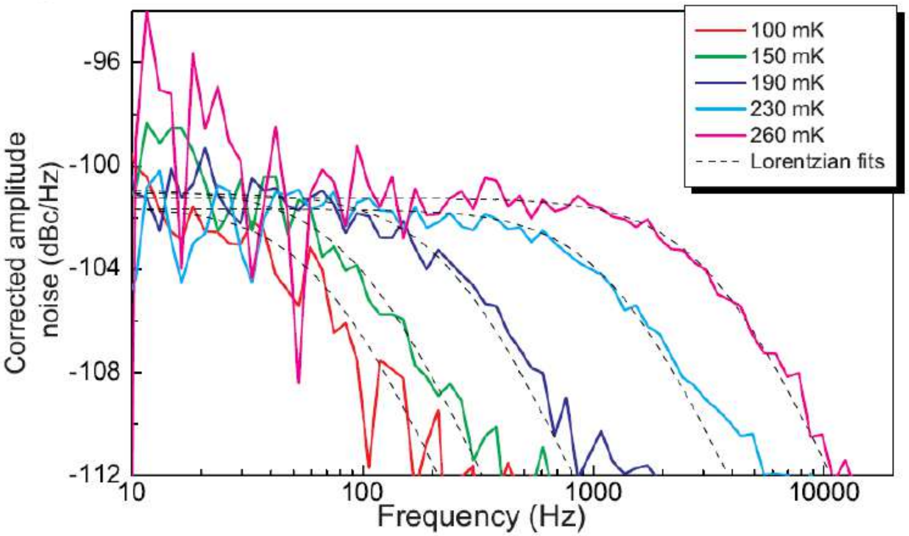
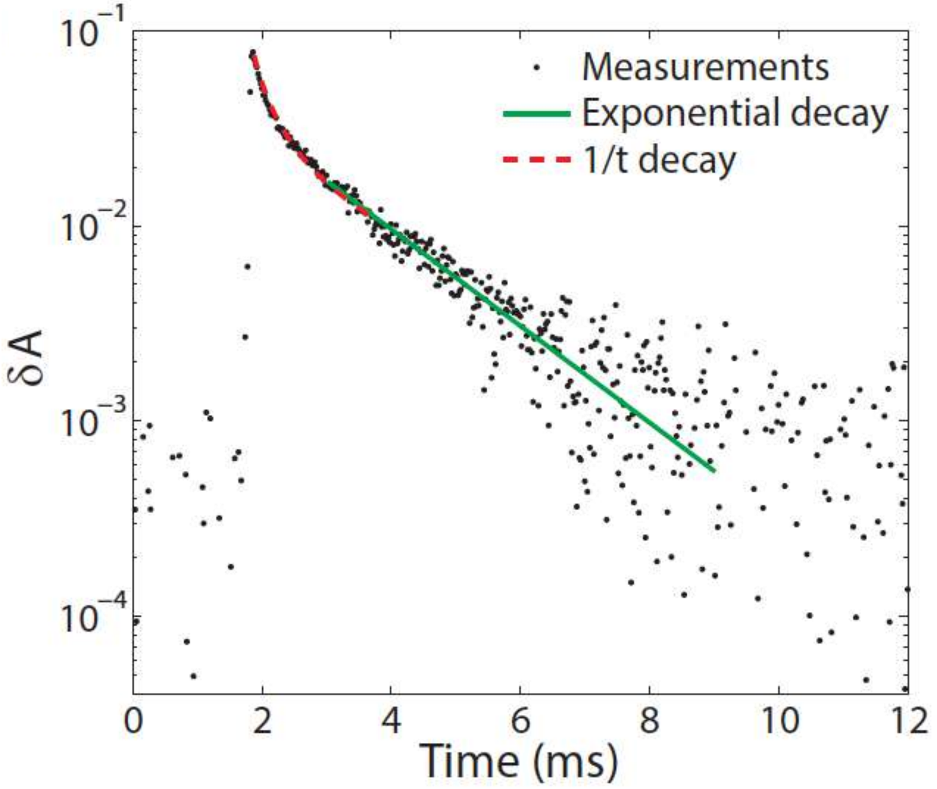
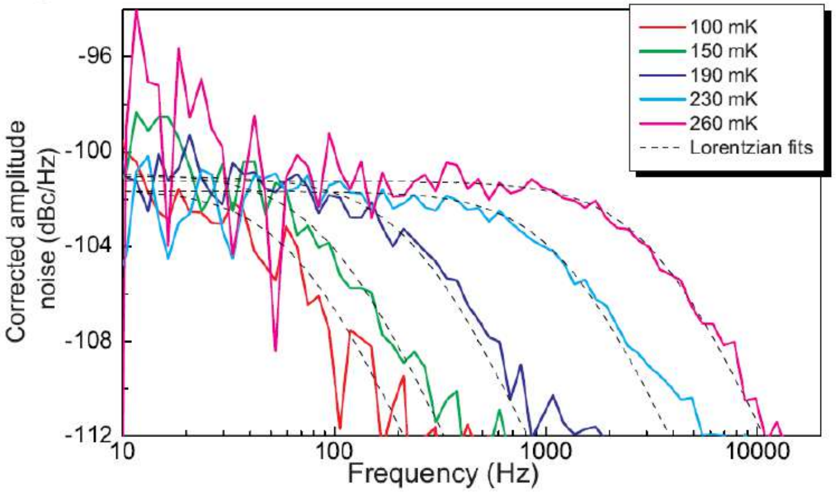
Quasiparticle dynamics probed with MKIDs

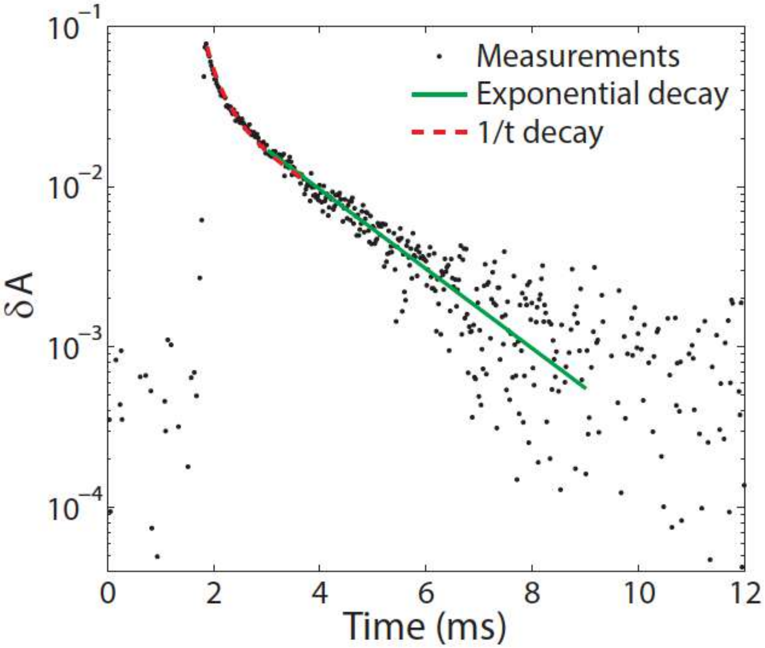
- Generation and recombination of quasiparticles
- Equilibrium (steady state) vs non-equilibrium
- Strong vs weak phonon trapping (membranes)

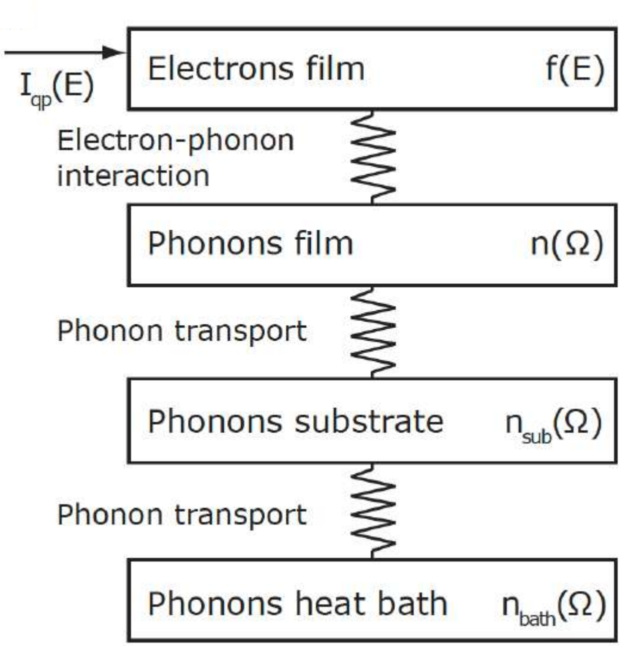


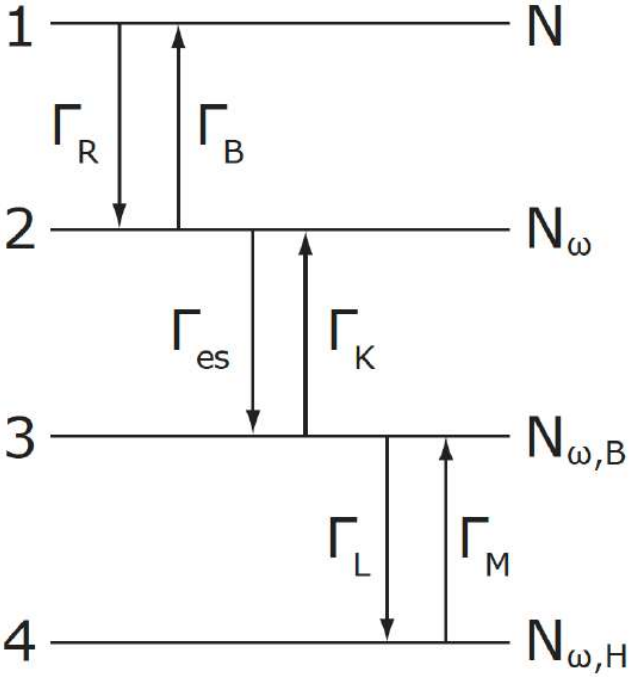


Quasiparticle dynamics



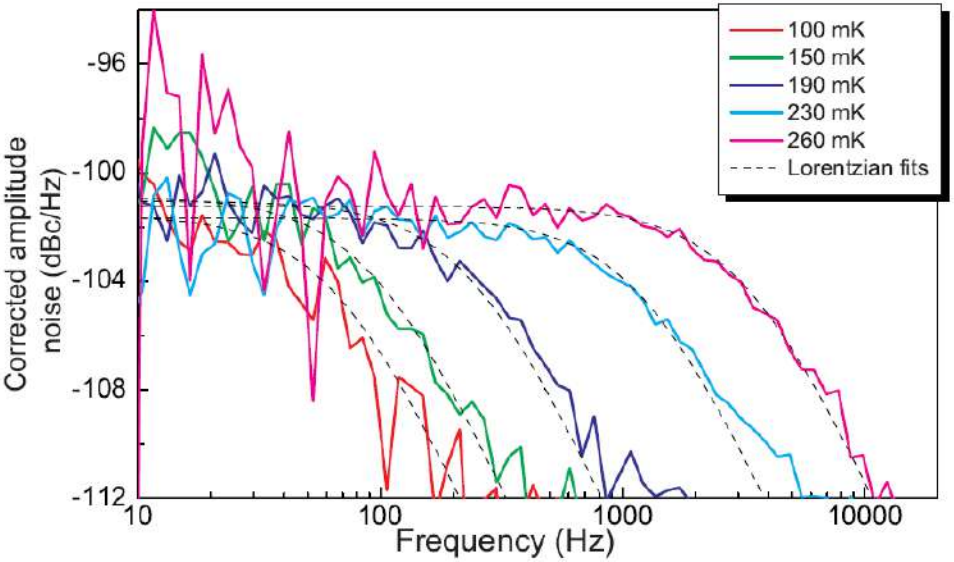




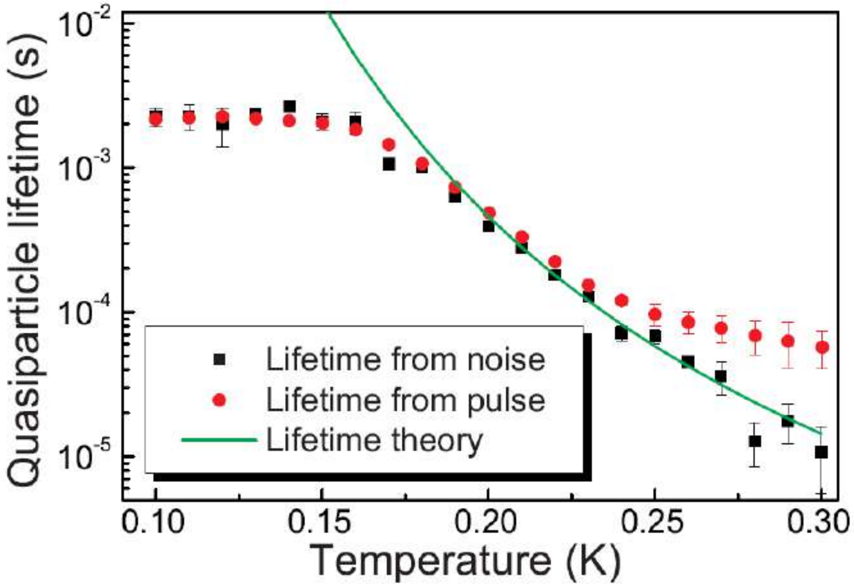


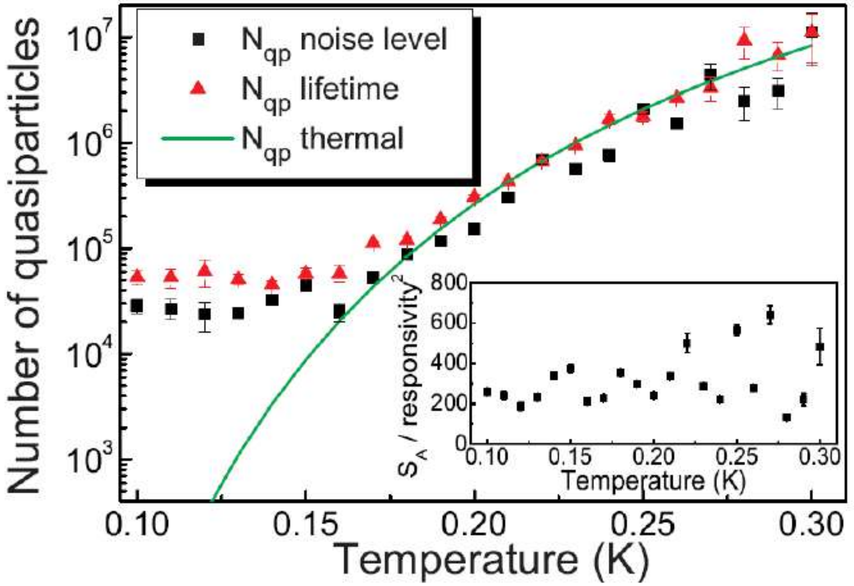
Simple picture

- Nqp and lifetime are connected
- Saturation = excess quasiparticles



$$S_{N_{\mathrm{qp}}}(\omega) = \frac{4\tau_{\mathrm{qp}}N_{\mathrm{qp}}}{1+(\omega\tau_{\mathrm{qp}})^2}$$

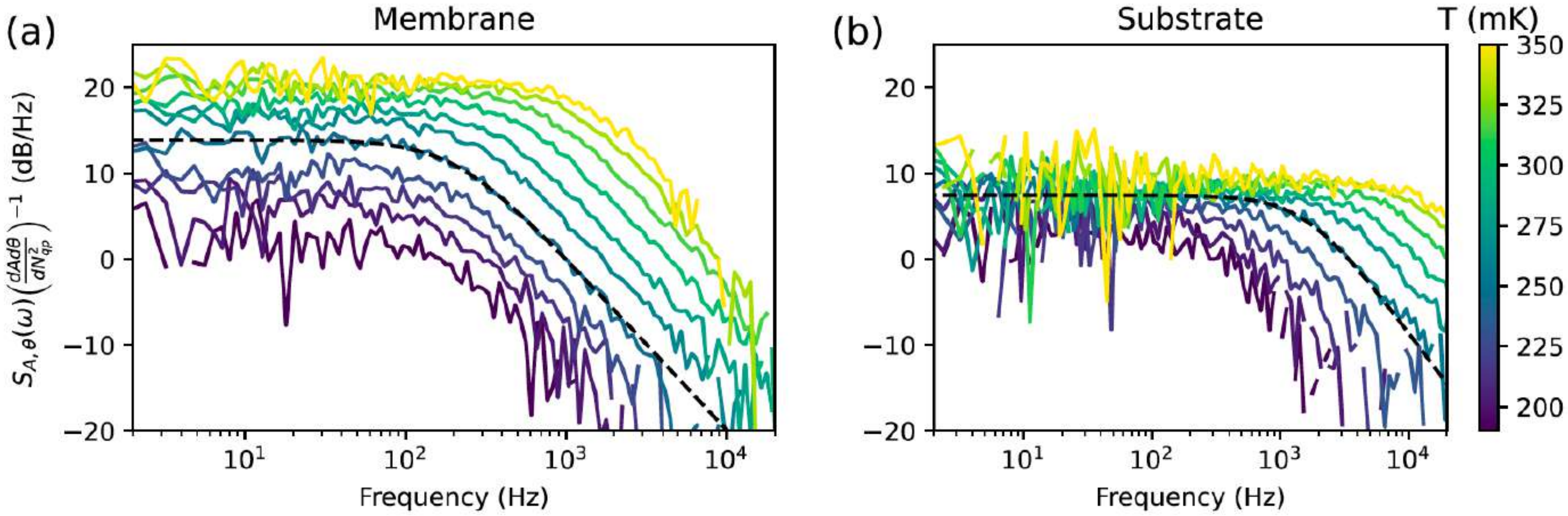




Phys. Rev. Lett. 106, 167004 (2011)
Nature Communications 5, 3130 (2014)

Kaplan et al. Phys. Rev. B 14, 4854–487 (1976)
Wilson, Prober, Phys. Rev. B. 69, 094524 (2004)

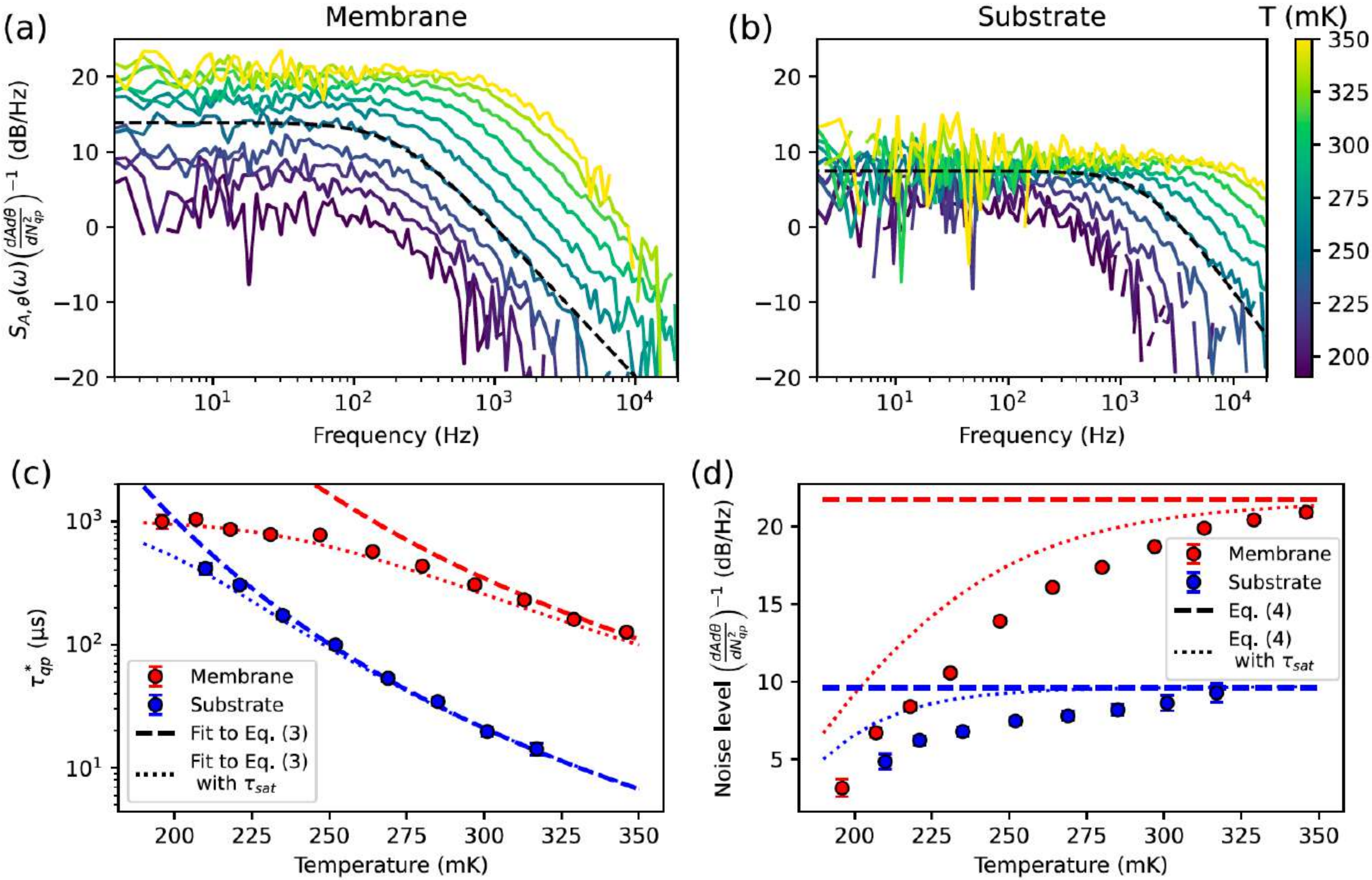
Quasiparticle number and lifetime are disconnected, still Alu



More sensitive device than before, less excess quasiparticles

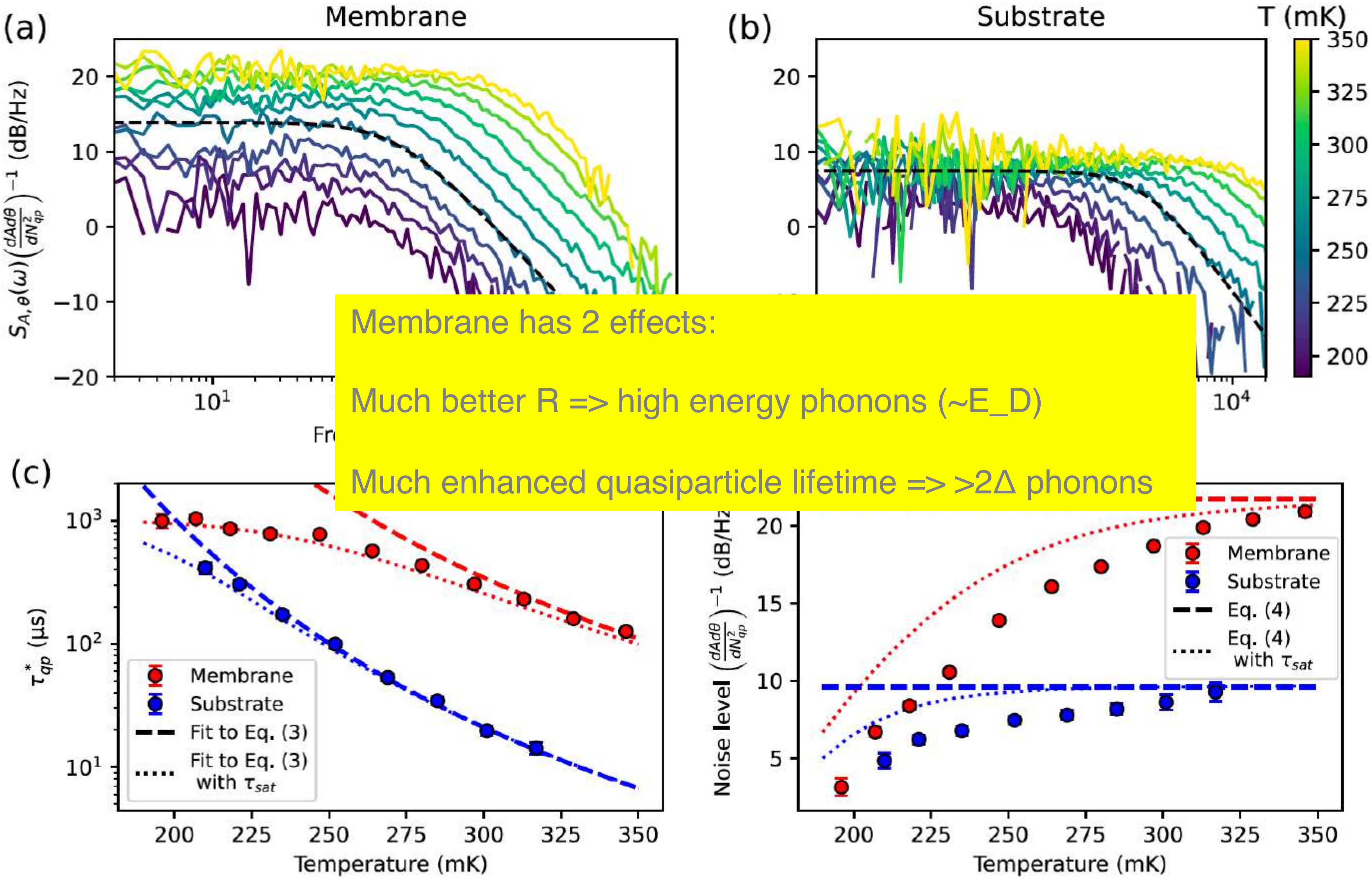
De Rooij et al, Phys. Rev. B 104, L180506 (2021)

Quasiparticle number and lifetime are disconnected



De Rooij et al, Phys. Rev. B 104, L180506 (2021)

Quasiparticle number and lifetime are disconnected



Membrane has 2 effects:

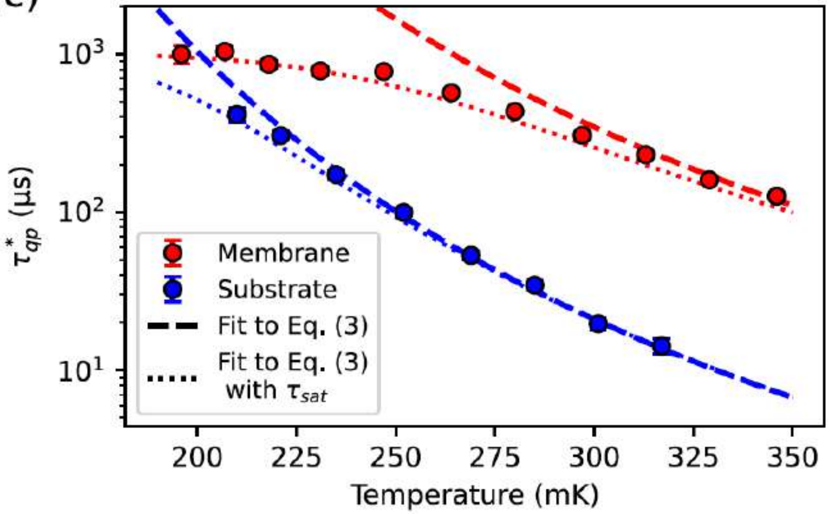
Much better R => high energy phonons (~E_D)

Much enhanced quasiparticle lifetime => >2Δ phonons

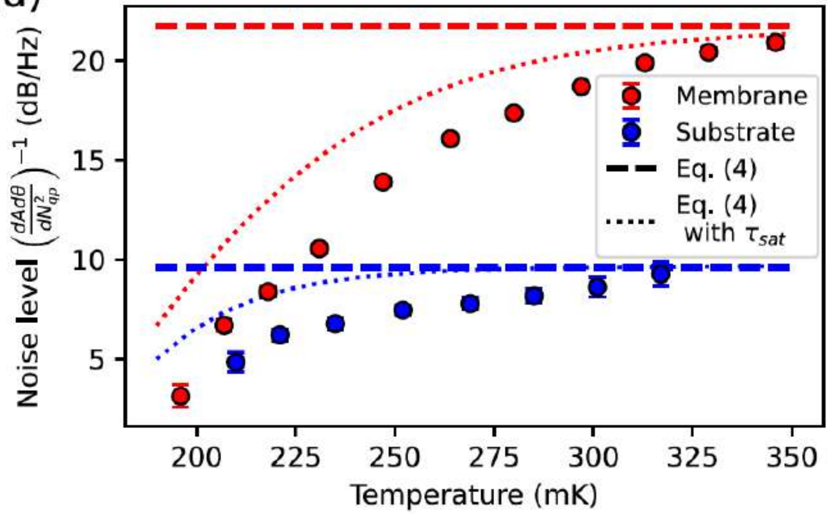
De Rooij et al, Phys. Rev. B 104, L180506 (2021)

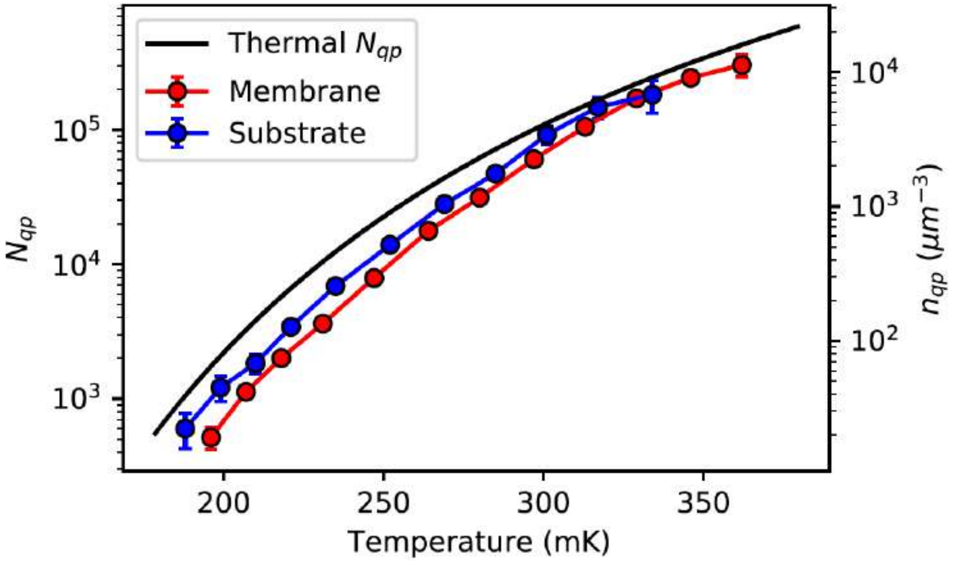
Quasiparticle number and lifetime are disconnected

(c)



(d)

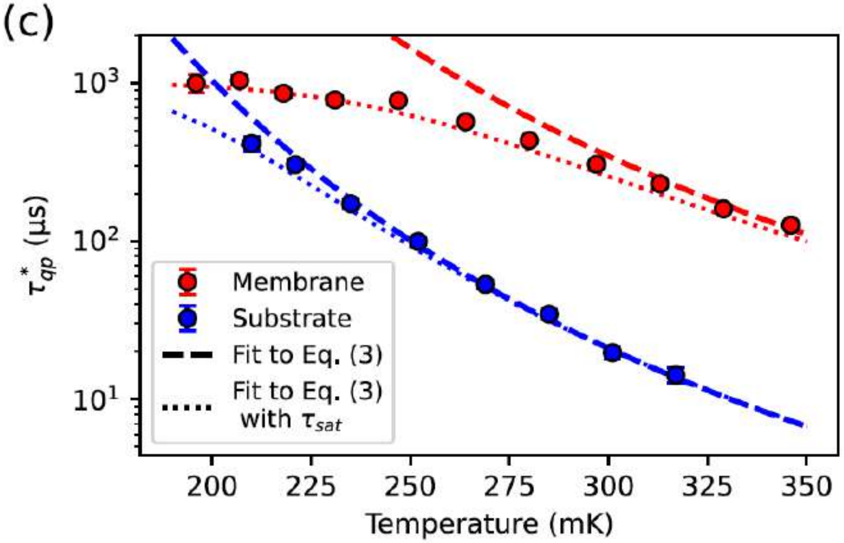


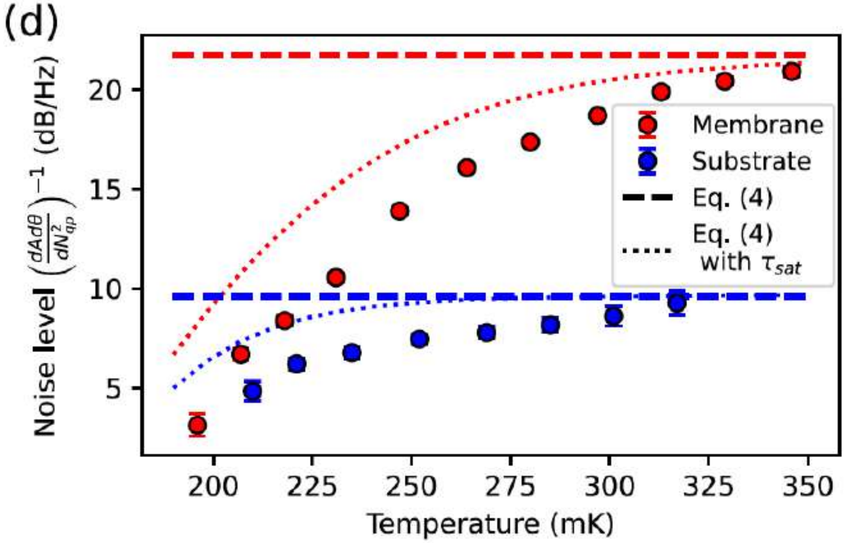


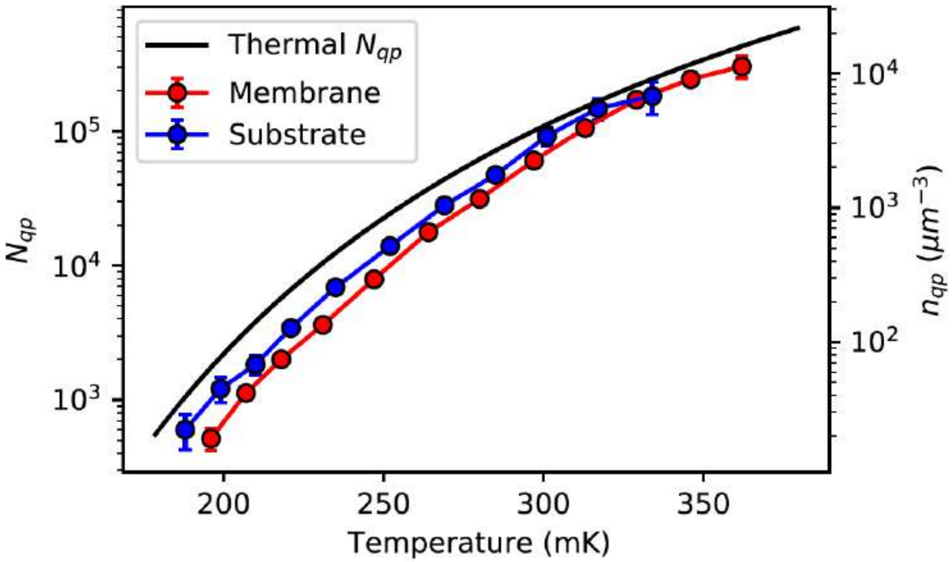
$$S_{N_{\rm qp}}(\omega) = \frac{4\tau^*_{\rm qp} N_{\rm qp}}{1 + (\omega\tau^*_{\rm qp})^2}$$

De Rooij et al, Phys. Rev. B 104, L180506 (2021)

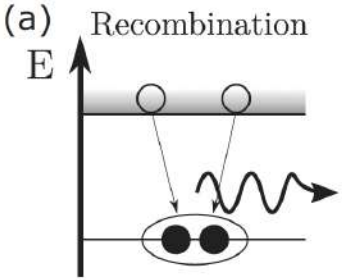
Quasiparticle number and lifetime are disconnected

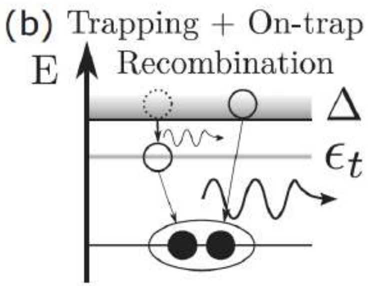






$$S_{N_{\rm qp}}(\omega) = \frac{4\tau^*_{\rm qp} N_{\rm qp}}{1 + (\omega\tau^*_{\rm qp})^2}$$

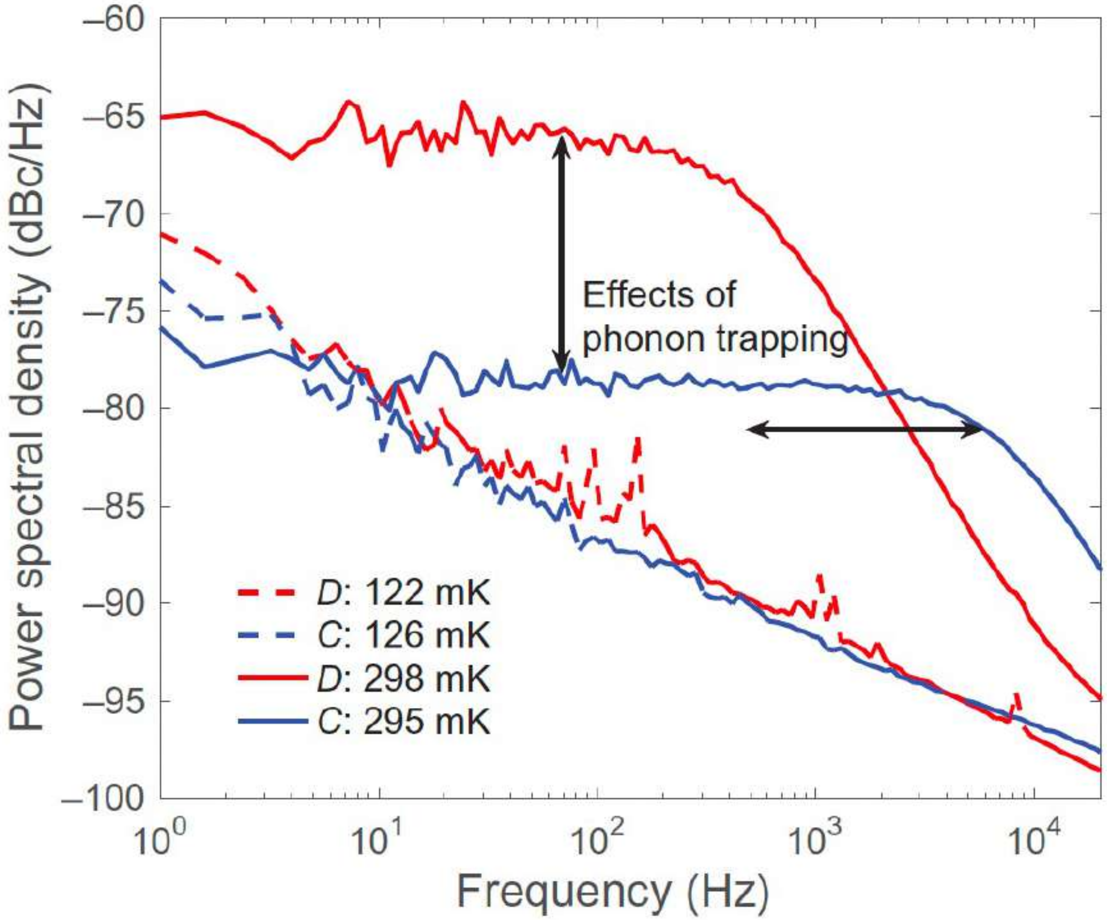




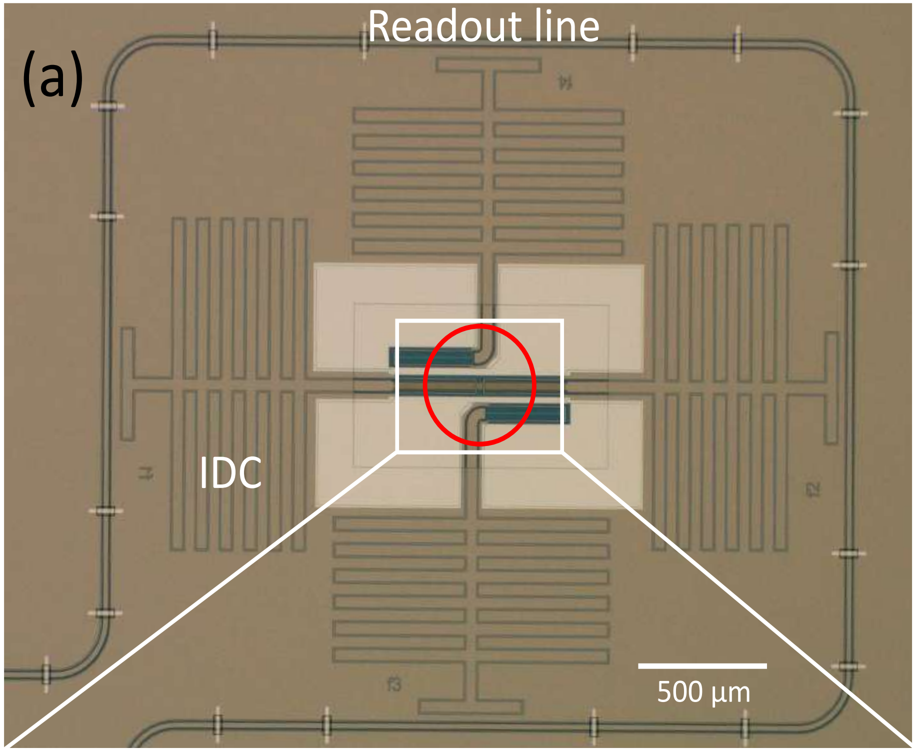
De Rooij et al, Phys. Rev. B 104, L180506 (2021)

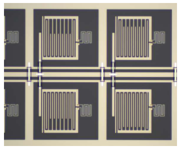
Blessings of this physics

Without strong noise reduction at low temperatures, we could not reach the high signal/noise



So if Aluminium is ideal, why anything else?

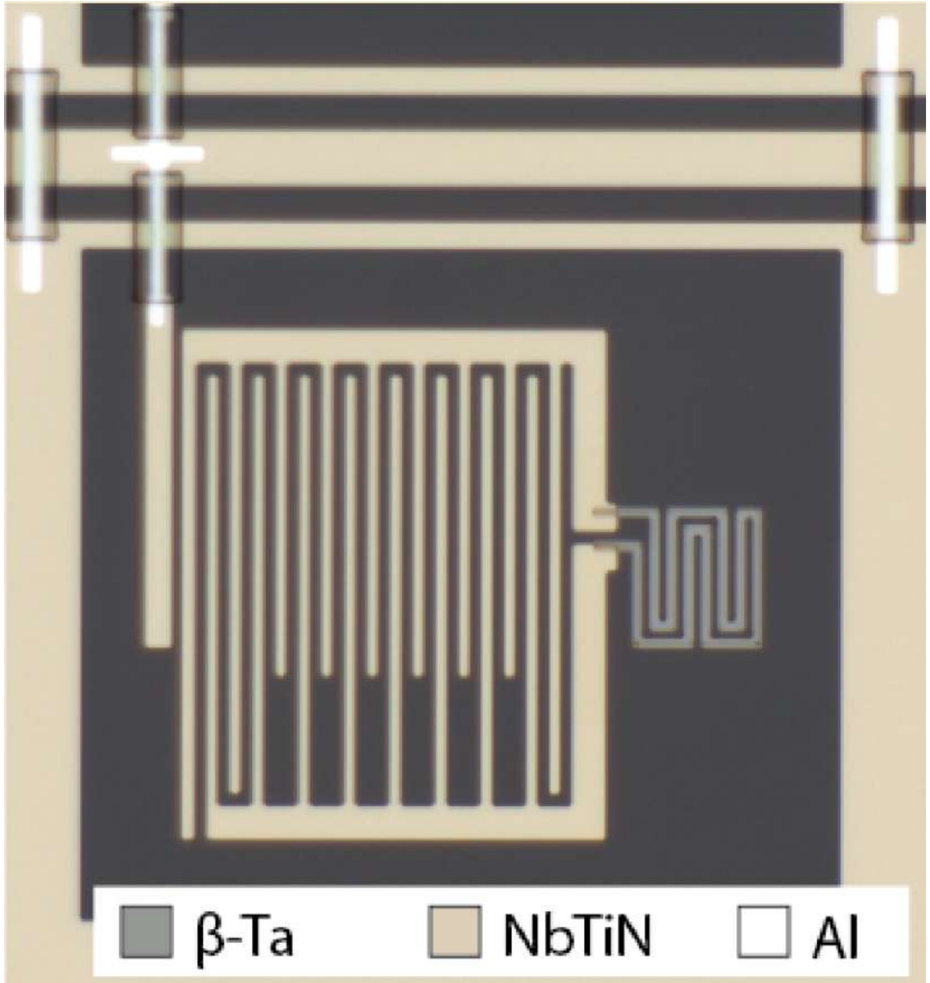




Compact pixel needs high kinetic inductance

Absorption of radiation into the inductor

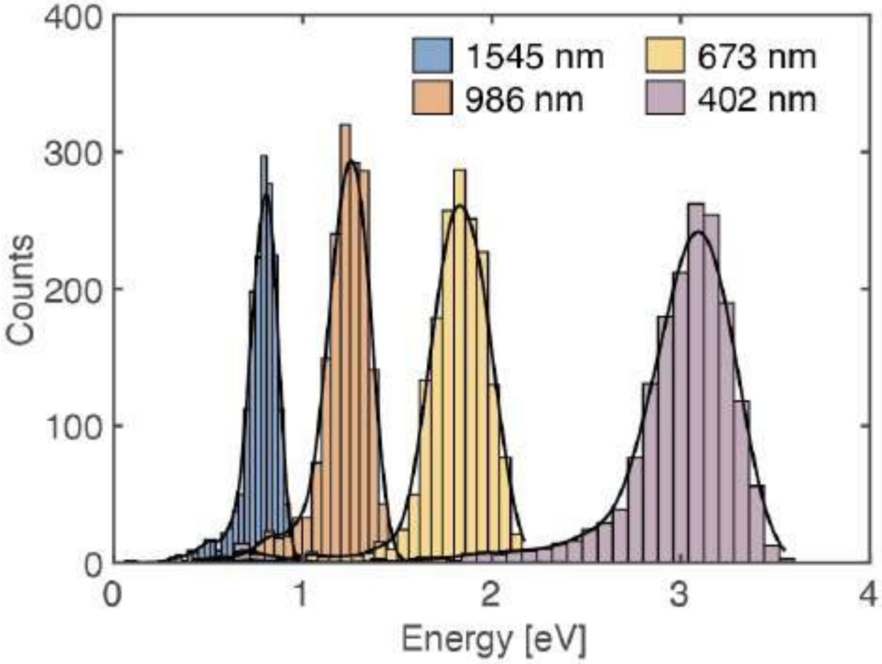
Hybrid device with NbTiN and β-Ta



Robust, insensitive NbTiN (Tc ~15 K) circuitry and capacitor

Sensitive β-Ta inductor, Tc ~ 1 K (150 μeV)

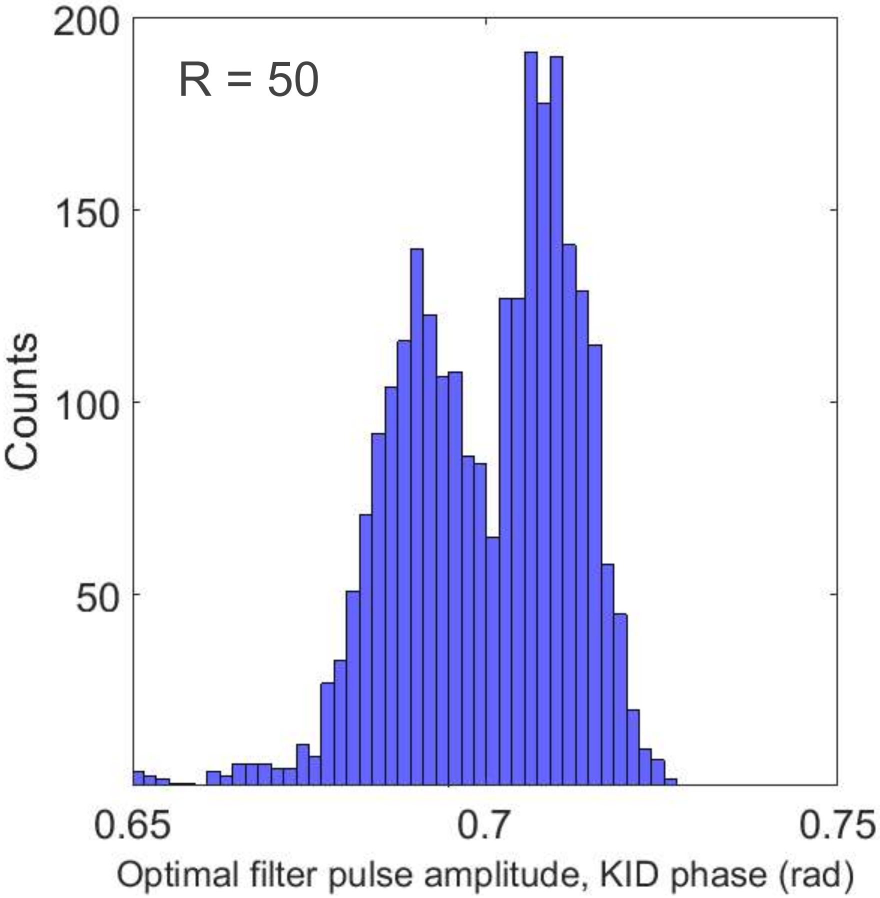
Pixels are 150x150 um



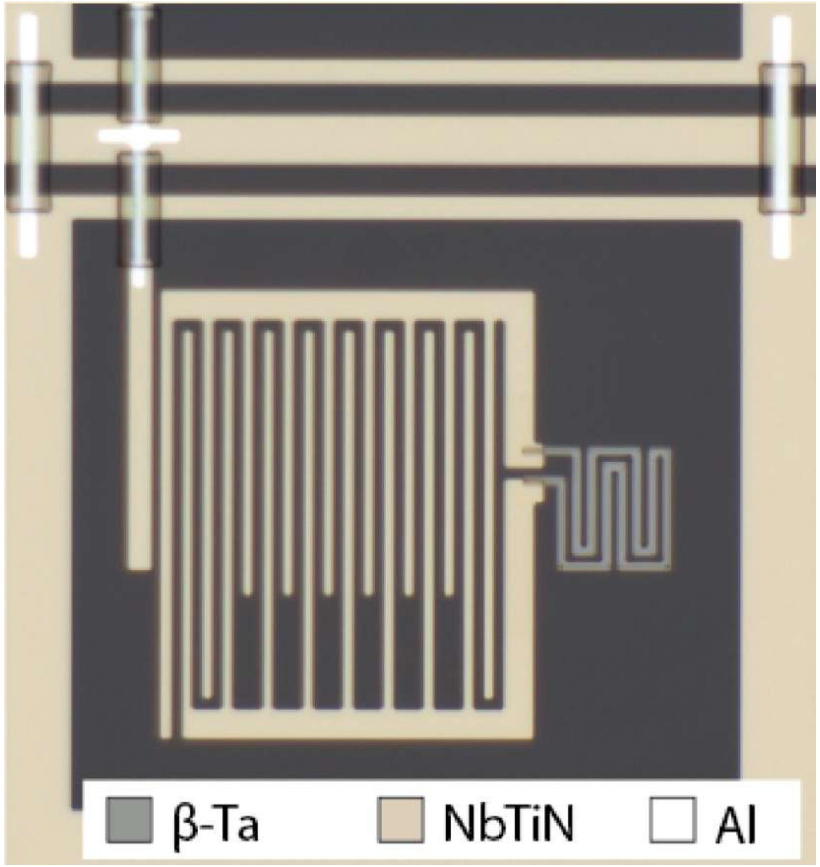
Phys. Rev. Applied 19, 034007 (2023)

Also shown 3.8 um single photon detection

Challenge

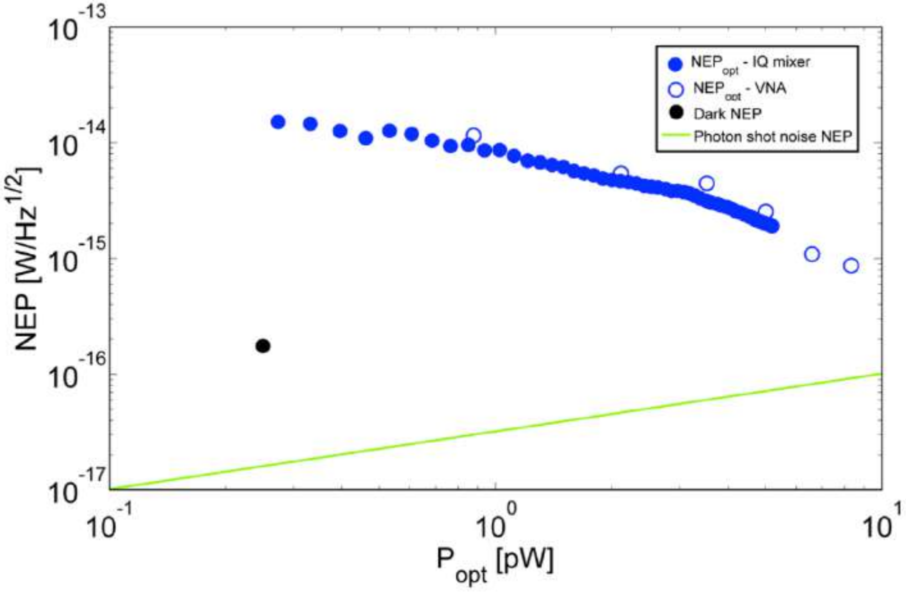

R = 50
Counts
200
150
100
50
0.65
0.7
0.75
Optimal filter pulse amplitude, KID phase (rad)

+


β-Ta
NbTiN
Al

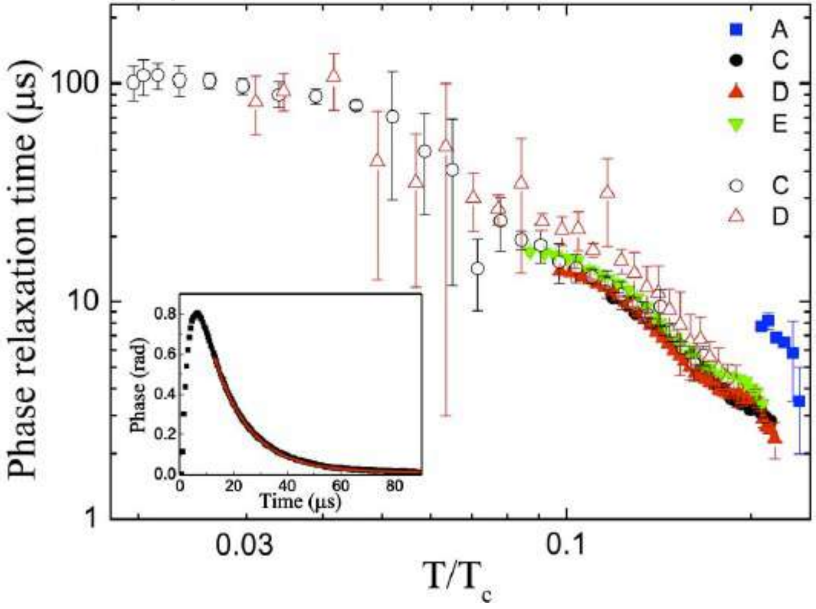
Known problems with disordered MKIDs

TiN devices show hardly any response



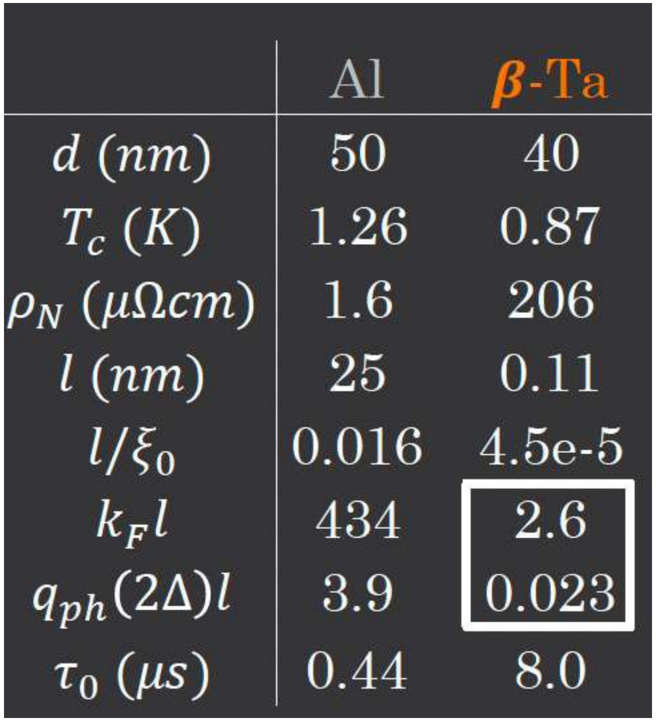
Appl. Phys. Lett. 105, 192601 (2014)

TiN devices with variying disorder all have power law lifetime



IEEE Trans. Superc. 23, 7500404 (2013)

β-Ta



	Al	**β-Ta**
d (nm)	50	40
T_c (K)	1.26	0.87
ρ_N $(\mu\Omega cm)$	1.6	206
l (nm)	25	0.11
l/ξ_0	0.016	4.5e-5
$k_F l$	434	2.6
$q_{ph}(2\Delta)l$	3.9	0.023
τ_0 (μs)	0.44	8.0
L_s (pH)	0.1-1	~100

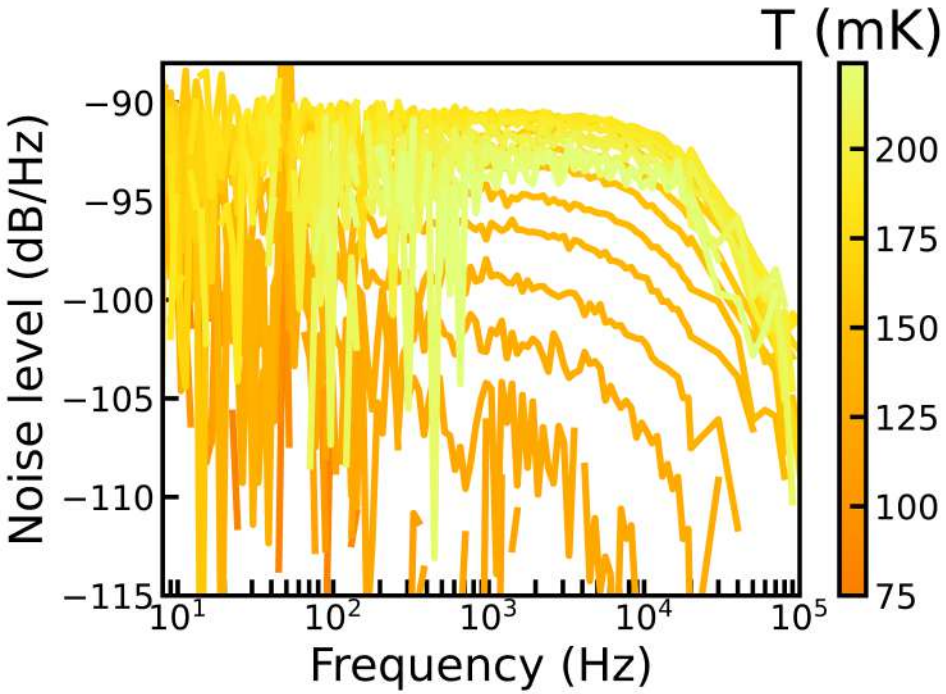
Note: higher L_s is undesirable, because

- qp-response becomes very non-linear
- Mirowave non-linearity too strong

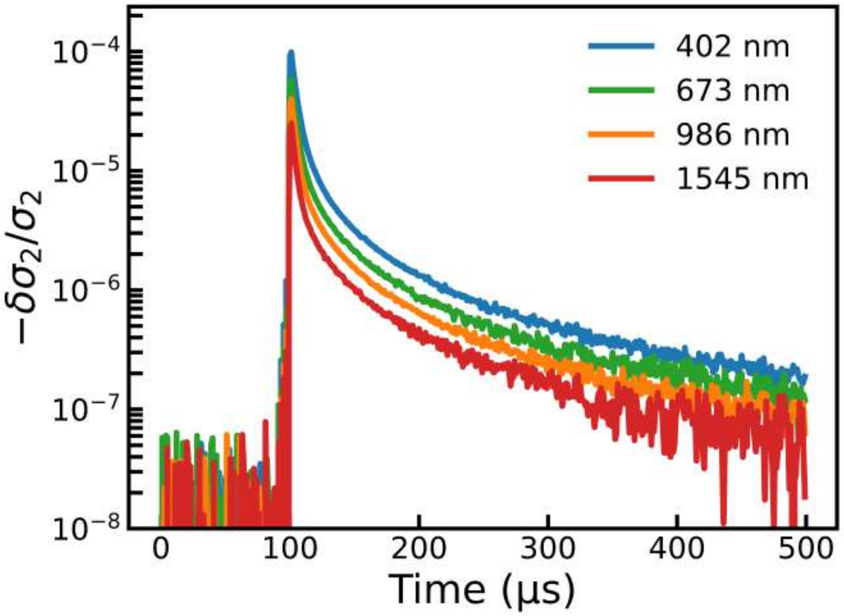
Challenge is not sensitivity alone, but accuracy for a 1-3 eV signal

Quasiparticle dynamics in disordered superconductors

Thermal fluctuations

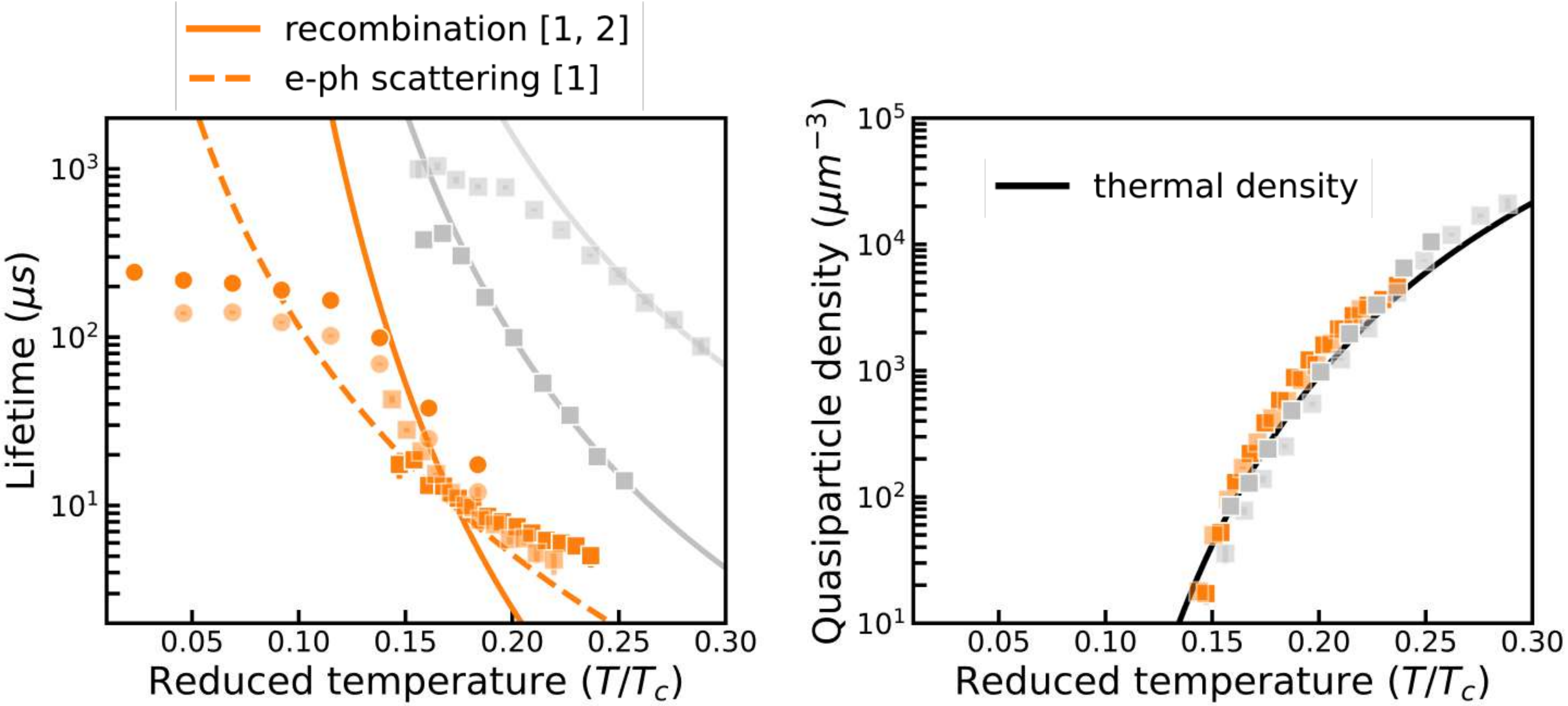


Non-equilibrium

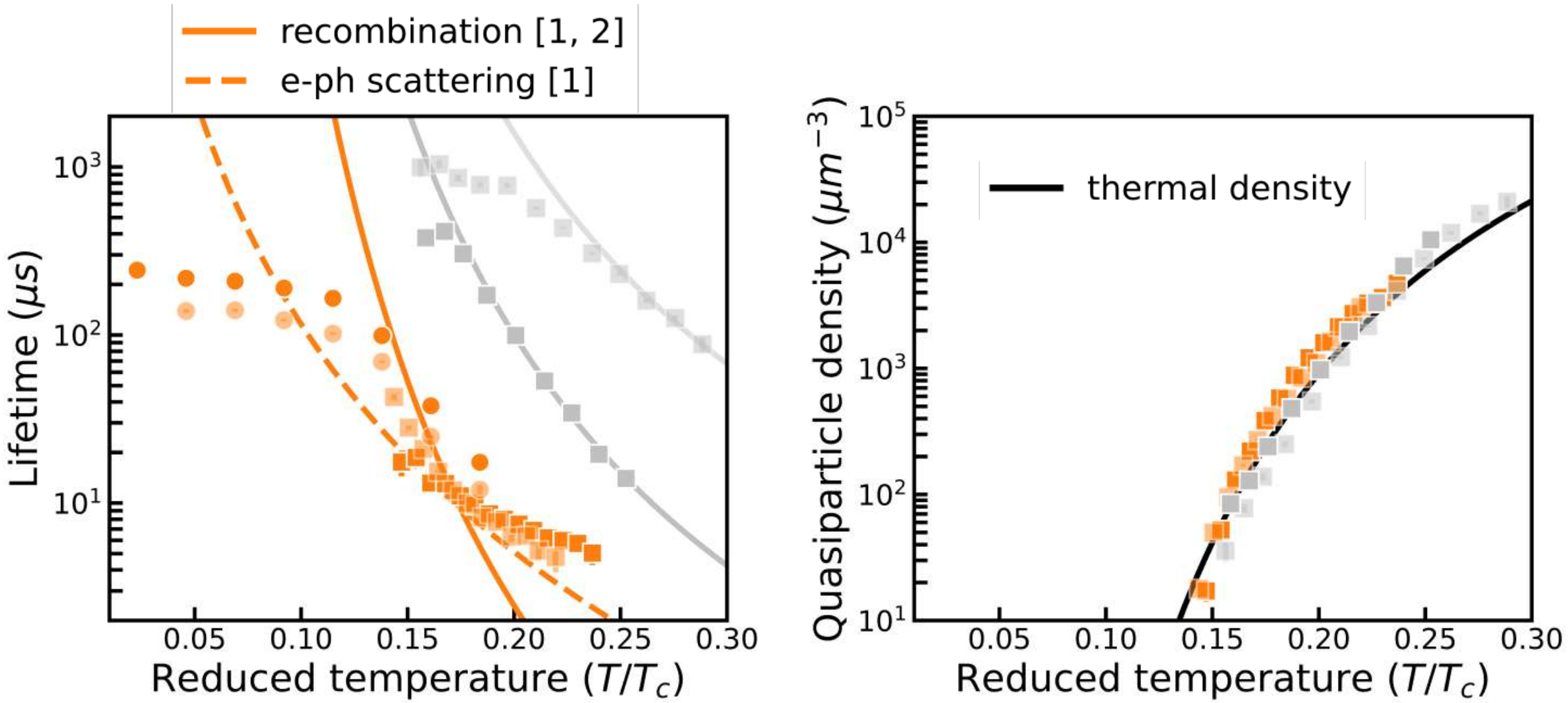


Worst possible pules shape!

Quasiparticle recombination in disordered superconductors



Quasiparticle recombination in disordered superconductors



- Responsivity for both pulse and noise are consistent with QP number fluctuations, not with scattering
- Noise reduction also in T-dependent regime, lifetime does not scale with Nqp, scattering?
- Noise level consistent with thermal quasiparticle density outside saturation regime.
- **NO effect of phonon trapping in T-dependent regime!**

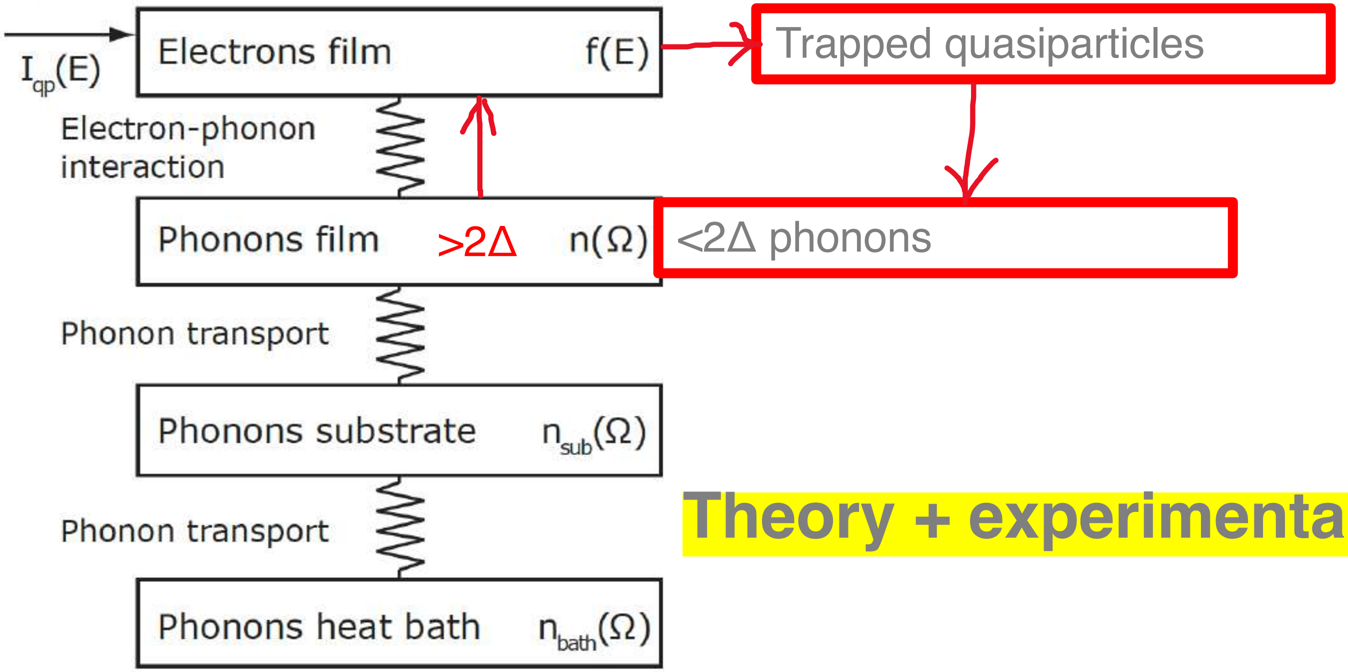
Reizer, Sergeyev, Zh. Eksp. Teor. Fiz. 90, 1056 (1986)

Quasiparticle recombination in disordered superconductors

?? What is ‘the’ microscopic mechanism ??

- First trapping/localisation, loss of energy by a low-E phonon
- Recombination of trapped/localised qp’s (or 1 trapped, 1 free), <2Δ phonon

- Generation of qps, using >2Δ phonon



$I_{qp}(E)$

Electrons film $f(E)$

Trapped quasiparticles

Electron-phonon interaction

Phonons film >2Δ $n(\Omega)$

<2Δ phonons

Phonon transport

Phonons substrate $n_{sub}(\Omega)$

Phonon transport

Phonons heat bath $n_{bath}(\Omega)$

Theory + experimental ideas needed!

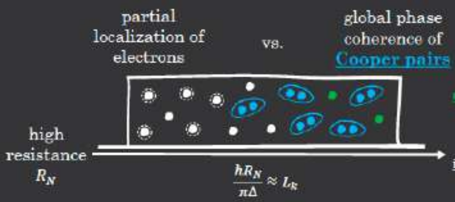
Quasiparticle recombination in disordered superconductors probed with microwave resonators

Steven A. H. de Rooij, Kevin Kouwenhoven, Tonny Coppens, Vignesh Murugesan, David J. Thoen, Jochem J. A. Baselmans and Pieter J. de Visser

s.a.h.de.rooij@sron.nl

SRON Netherlands Institute for Space Research

TU Delft



partial localization of electrons vs. global phase coherence of Cooper pairs

high resistance R_N → high kinetic inductance L_k

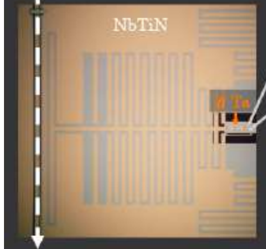
$\frac{\hbar R_N}{\pi\Delta} \approx L_k$

Applications

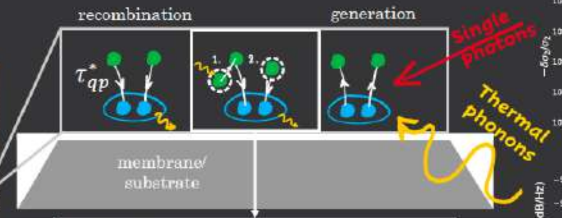
	Quantum circuits	Radiation detectors (MKIDs)
excitations: quasiparticles	decoherence dissipation	dictate the response
high kinetic inductance L_k	non-linearity (replace JJ?) small inductive elements	↑ absorption efficiency ↑ responsivity

How does disorder affect quasiparticle recombination?

Superconducting microwave resonator



$S_{21}(\omega_{res}) \rightarrow \sigma_1 - i\sigma_2$



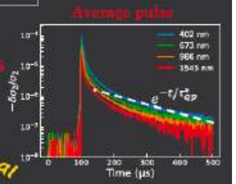
Hypothesis:

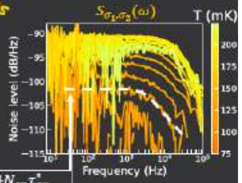
Quasiparticles are trapped and recombine via:

1. detrapping assisted by thermal phonon absorption
2. on-trap recombination into a Cooper pair

→ e-ph scattering limits τ_{qp}^*

→ phonon trapping as no effect ($E_{ph} \lesssim 2\Delta$)

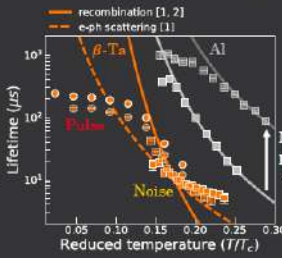




$$\frac{4N_{qp}\tau_{qp}^*}{1+\left(\omega\tau_{qp}^*\right)^2}$$

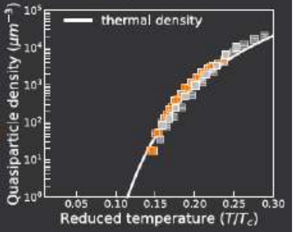
	Al	β-Ta
d (nm)	50	40
T_c (K)	1.26	0.87
ρ_N ($\mu\Omega cm$)	1.6	206
l (nm)	25	0.11
l/ξ_0	0.016	4.5e-5
$k_F l$	434	$\boxed{2.6}$
$q_{ph}(2\Delta)l$	3.9	$\boxed{0.023}$
τ_0 (μs)	0.44	8.0

disordered



Membrane effect: phonon trapping [3]

$\tau_{qp}^* = \tau_{qp}(1 + \tau_{esc}/\tau_{pb})/2$



Conclusion

- The quasiparticle lifetime in disordered β-Ta seems to be limited by electron-phonon scattering at high temperatures, which is slow due to disorder
- Phonon trapping has no effect in β-Ta
- This leads to the hypothesis of trapped quasiparticles and a two-step recombination process:
  1. detrapping; 2. on-trap recombination.

Open questions

- If present, what is the microscopic origin of the quasiparticle trapping?
- How is this trapping related to disorder?
- Do other disordered superconductors show similar behaviour?

References

[1] Reizer, M.Y., Sergeyev, A.V., 1986. Zh. Eksp. Teor. Fiz. 90, 1056.
[2] Kaplan, S.B., et al. 1976. Phys. Rev. B 14, 4854–4873.
[3] Rothwarf, A., Taylor, B.N. 1967. Phys. Rev. Lett. 19, 27–30.

Recent, related work:

[X]

Detection process, our understanding Al vs anything else

Aluminium

β-Ta, TiN, etc

Photon is absorbed, $E>>\Delta$

↓

Photon energy => quasiparticles

↓

How do quasiparticles spread

↓

How does this lead to a
(macroscopic) microwave response

↓

How do quasiparticles recombine

Very sensitive devices

Detection process, our understanding Al vs anything else

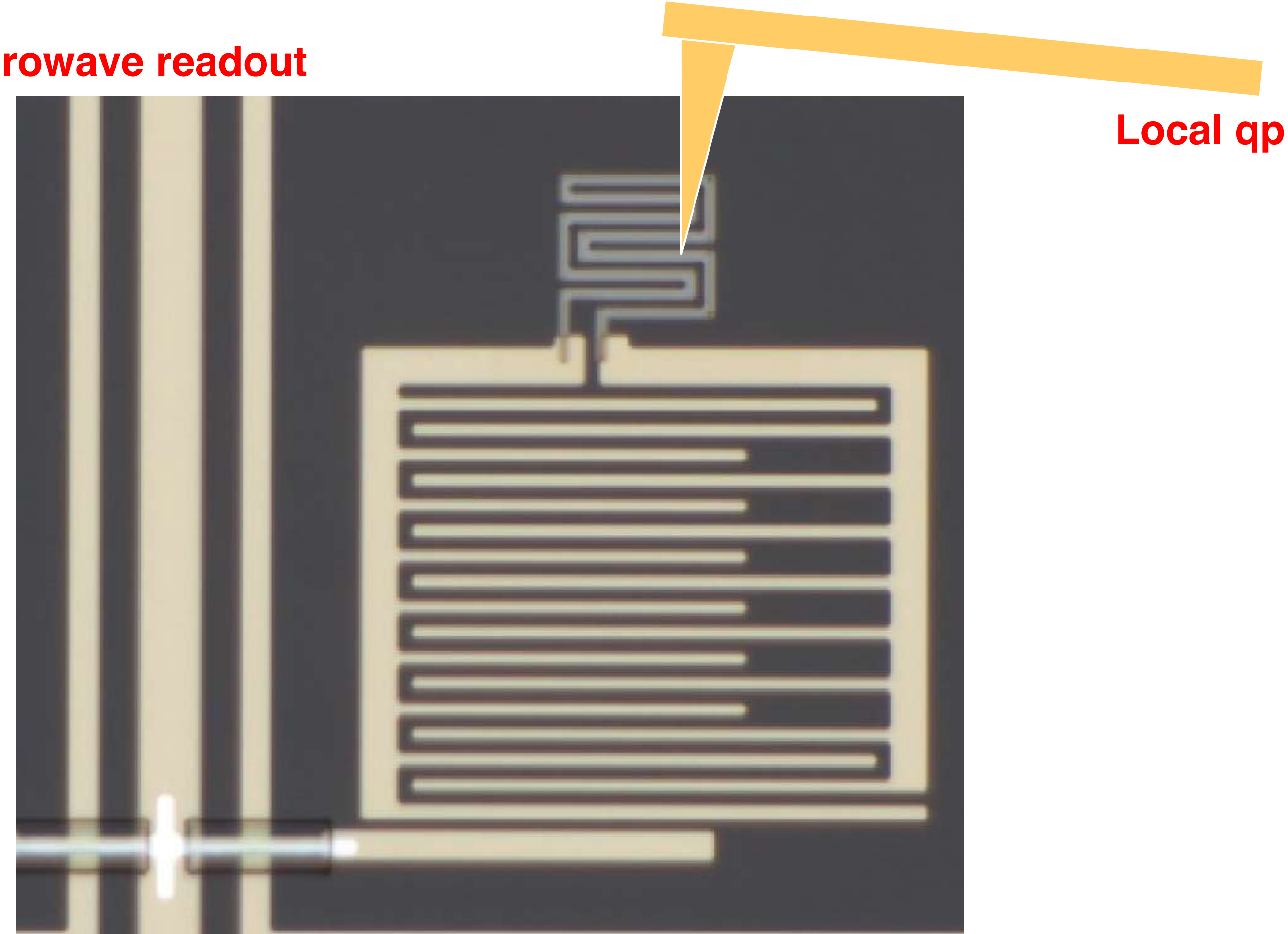
Aluminium		β-Ta, TiN, etc
✅	Photon is absorbed, E>>Δ	✅
✅	Photon energy => quasiparticles	✅
✅	How do quasiparticles spread	✅ ?
✅	How does this lead to a (macroscopic) microwave response	? ?
✅ ?	How do quasiparticles recombine	? ?
✅	Very sensitive devices	? ? ✖ ? ?

Disclaimer: ✅ means we have demonstrated/understand it, not that it is easy

Localised quasiparticles => microscopic response?

STM proposal: local injection of quasiparticles, microwave resonator readout

- Couple local non-equilibrium excitation to resonator response
- Needs to be done at MKID friendly temperatures ~100 mK, to be sensitive enough

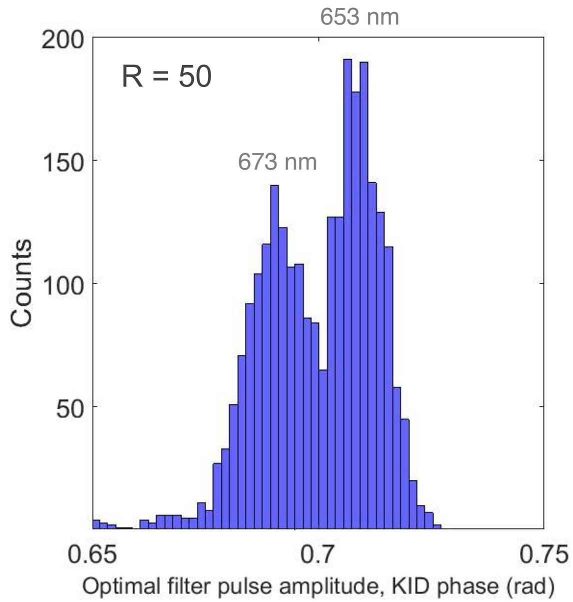


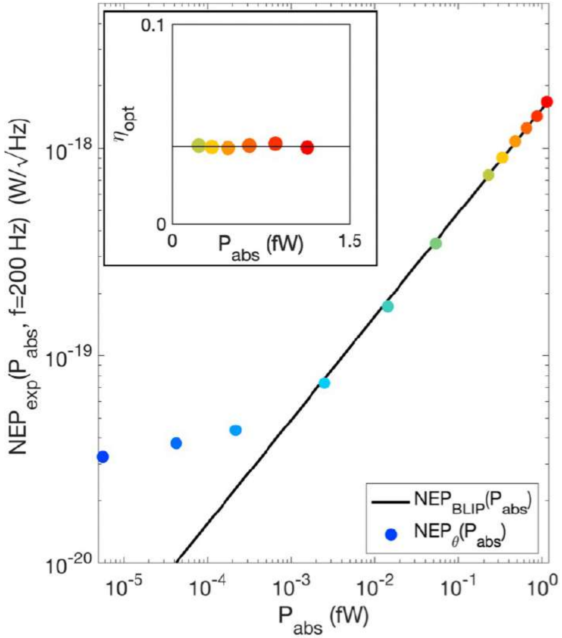
Microwave readout

Local qp injection

Aluminium MKIDs

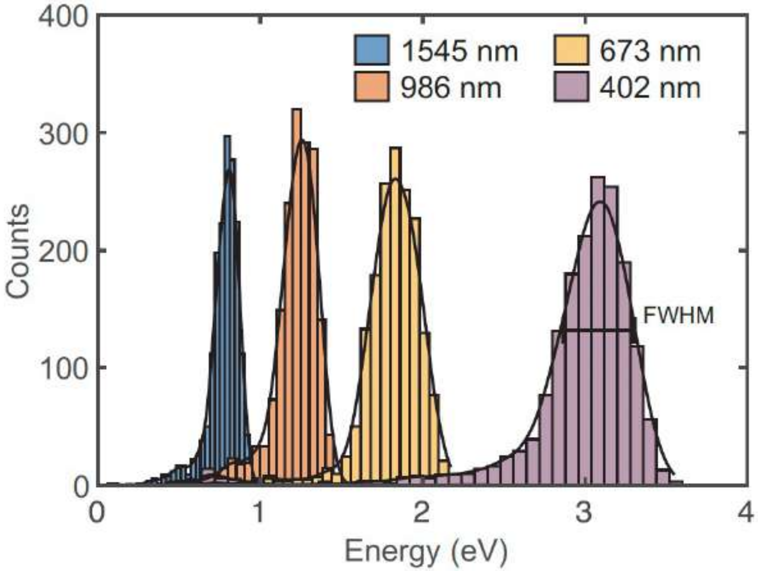
Amazing sensitivity, understood physics

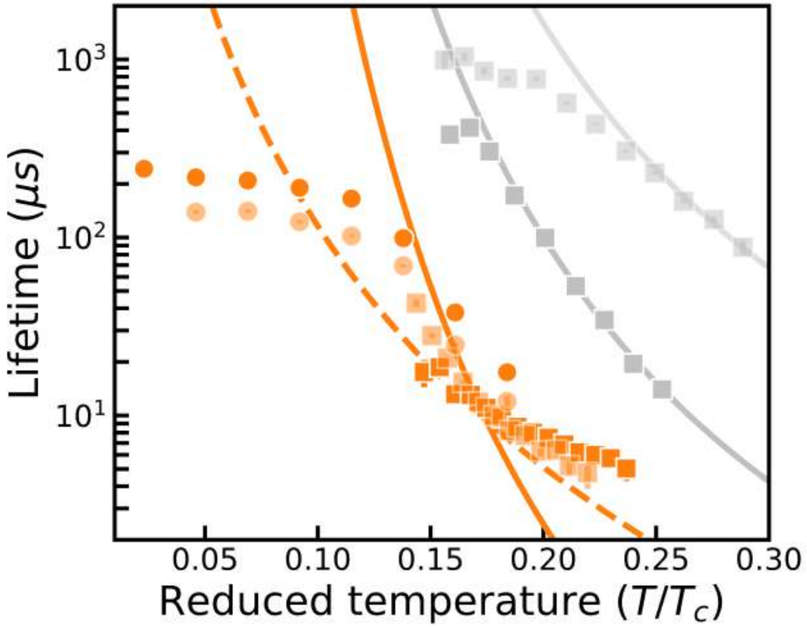




Disordered MKIDs

Poor sensitivity, amazing physics



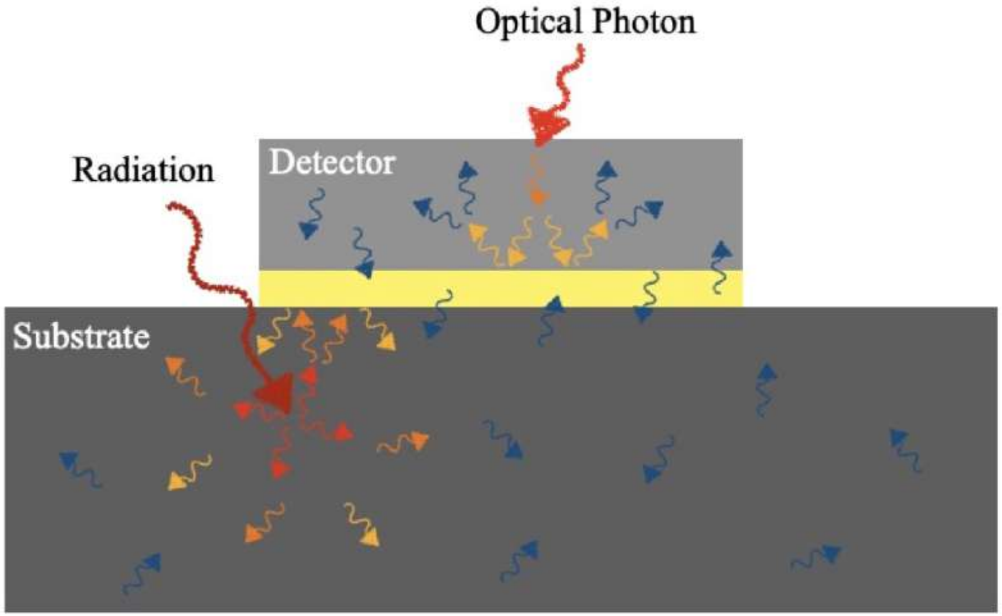


extra

‘Membrane-less’ phonon trapping

Three ways to trap phonons:

- Geometrical – membrane
- Acoustical – phonon reflection from acoustic mismatch (Snell’s law for sound)
- Block available phonon states – materials with different Debye energy



Zobrist et al. arXiv:2204.13669

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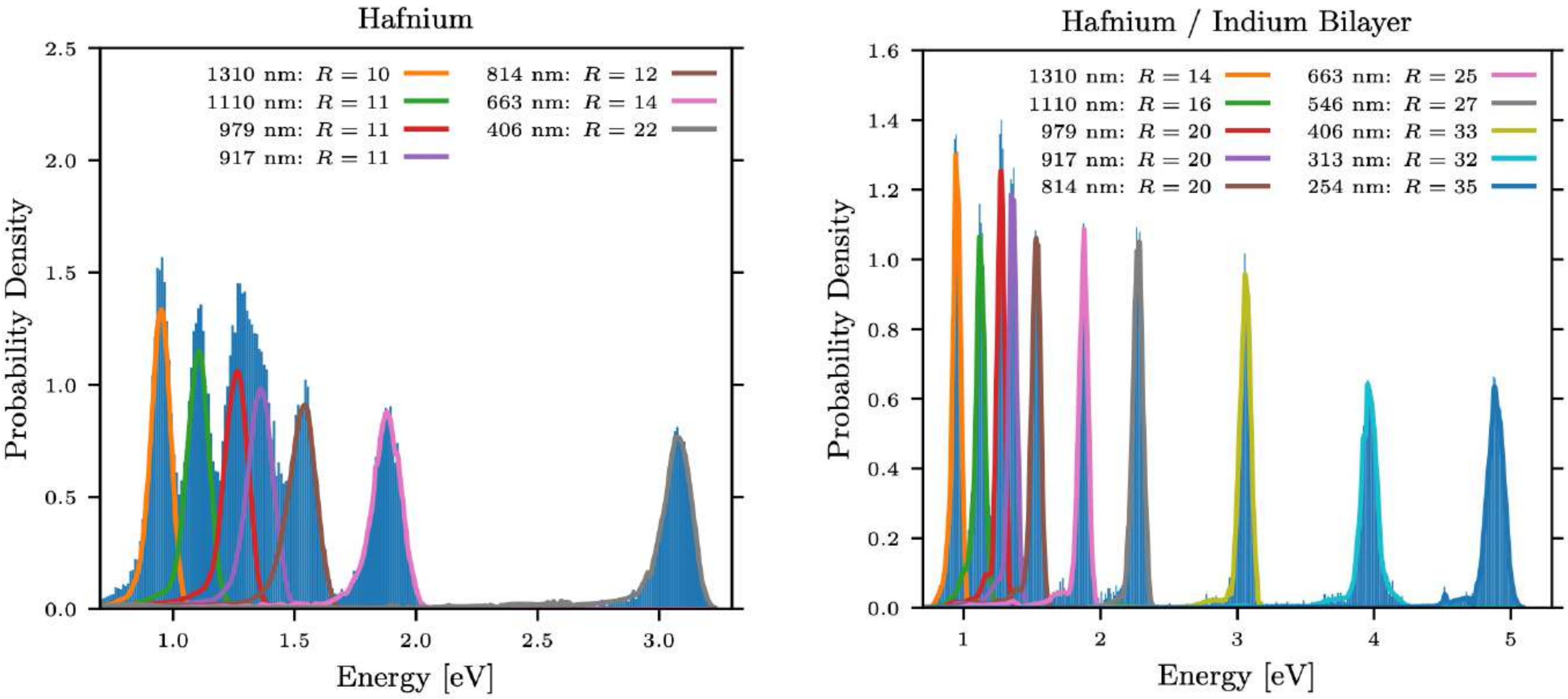
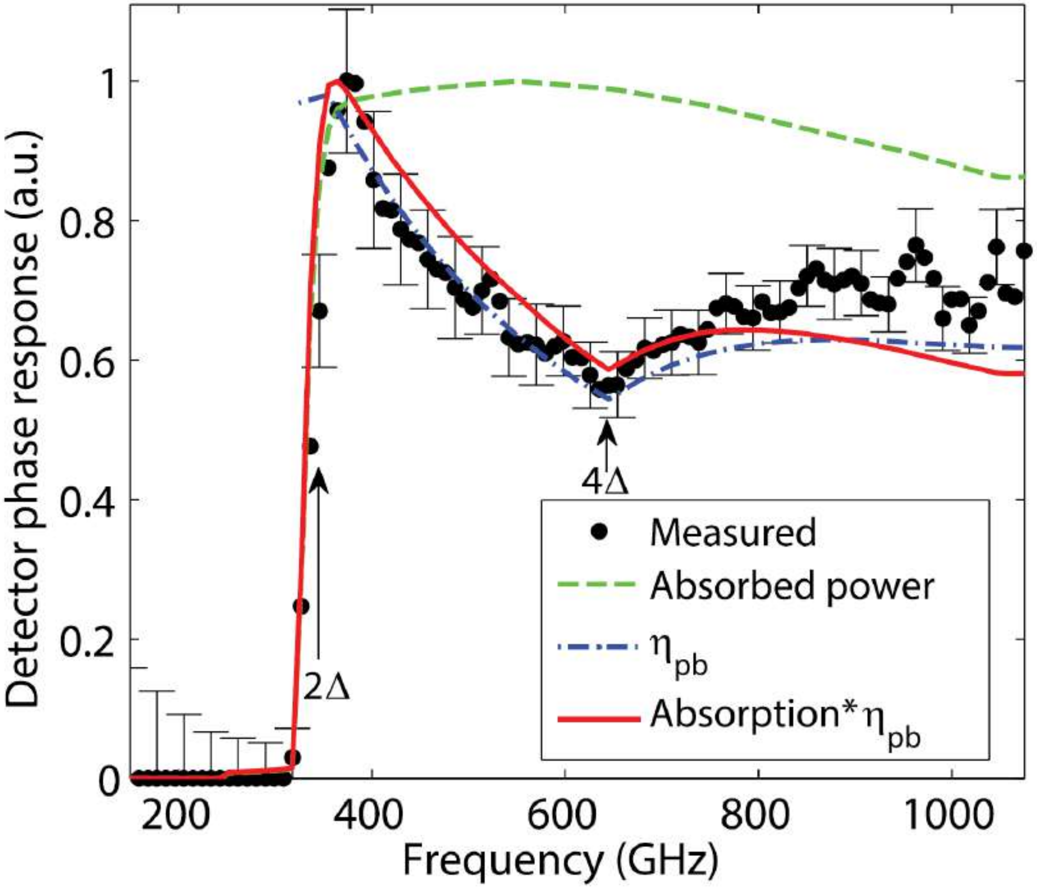


Zobrist et al. arXiv:2204.13669

Pair breaking efficiency = energy from photon going into qps

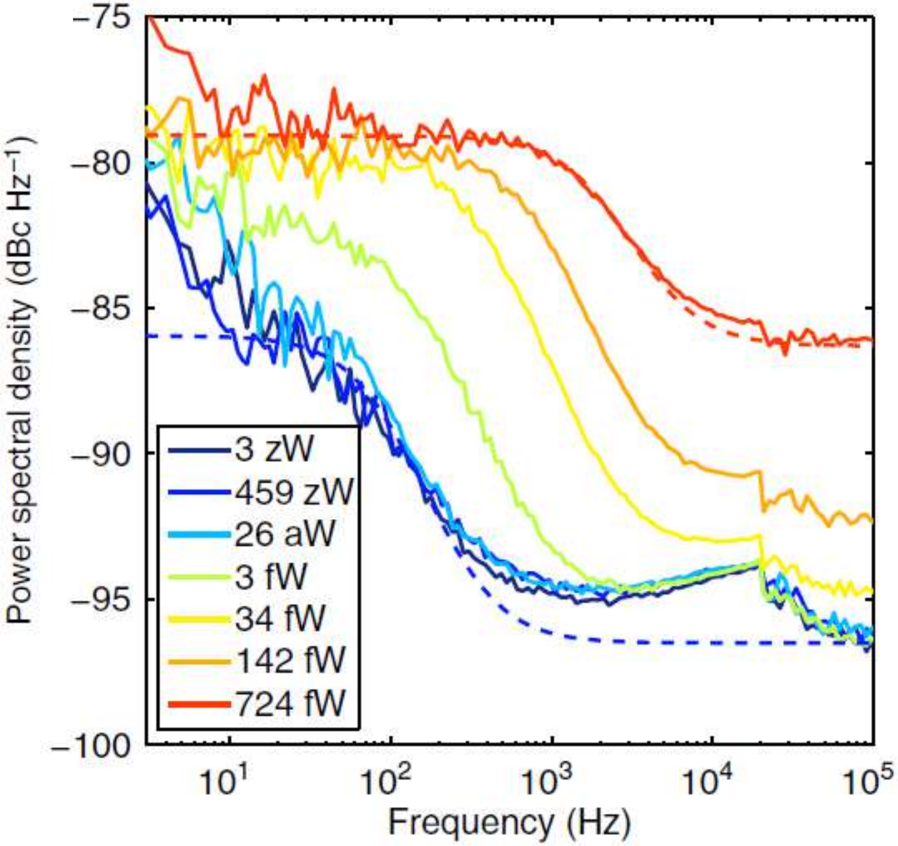
- Efficiency = 1 at 2Δ and for high energies depends on phonon trapping, typically 0.3-0.6

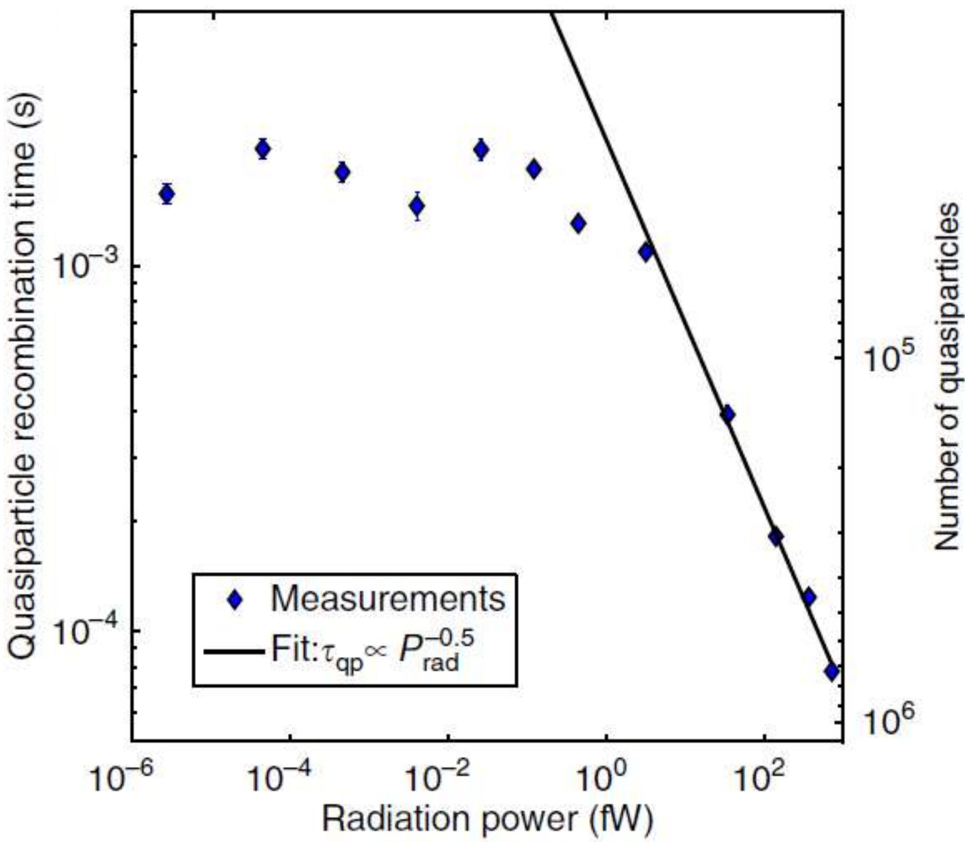


Appl. Phys. Lett. 106, 252602 (2015)

Photon noise

Fluctuations in the photon arrival rate
QP-lifetime from noise scales with sqrt(P) as expected





Noise levels