# QUAntum LImited PHotons In the Dark Experiment @ Far Infra Red

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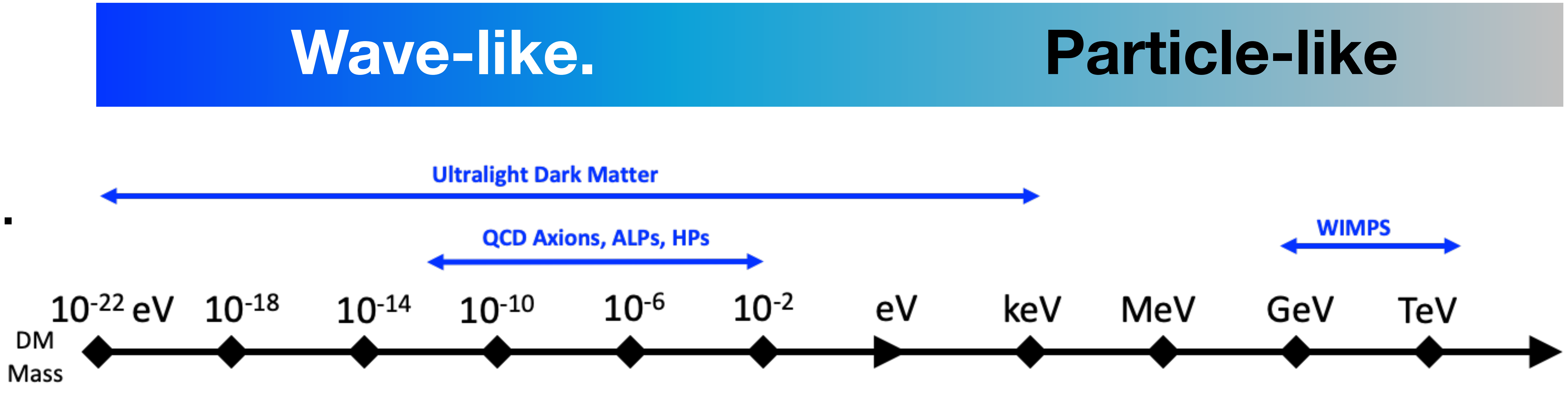
Wave Dark Matter, Annual Review of Astronomy and Astrophysics, Vol. 59:247-289 (September 2021) and Direct detection of dark matter—APPEC committee report (2021) & FERMILAB-PUB-23-681-T (2023)

# Dark Matter



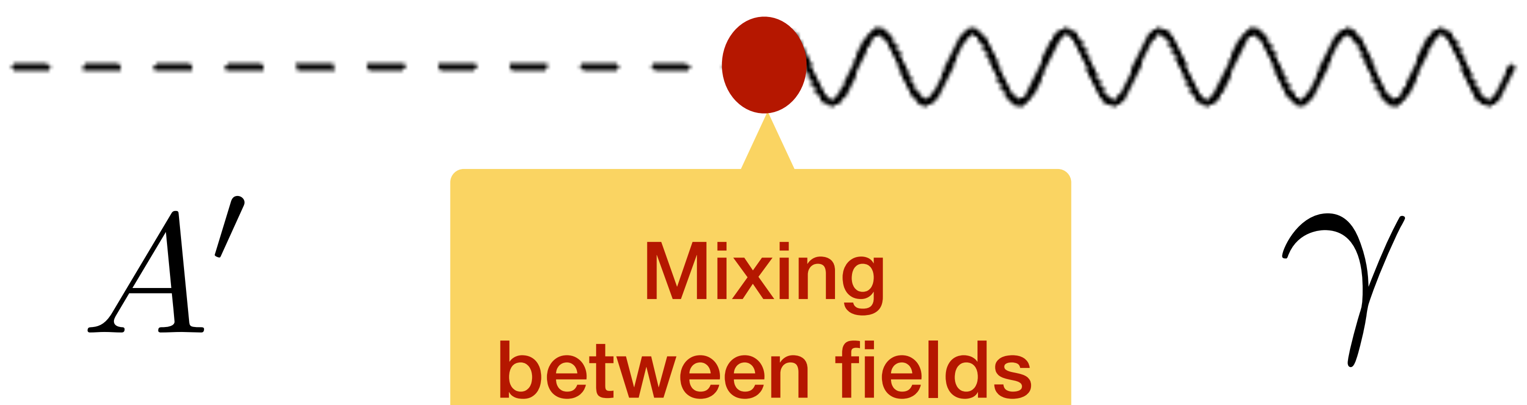

**Wave-like:** Large number densities, (sub)eV masses. Detection via photo-conversion methods.

**1 THz**

Far Infra Red: ~0.3 - 30 THz
1 THz ↔ 4.13 meV

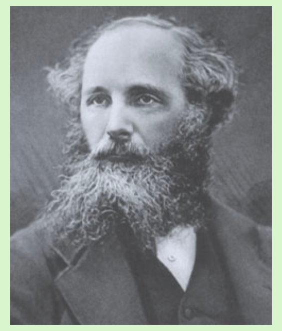
**Hidden Photons, e.g.:** SM photons mix with dark sector/ massive hidden-photons.

New massive field terms




Mixing between fields

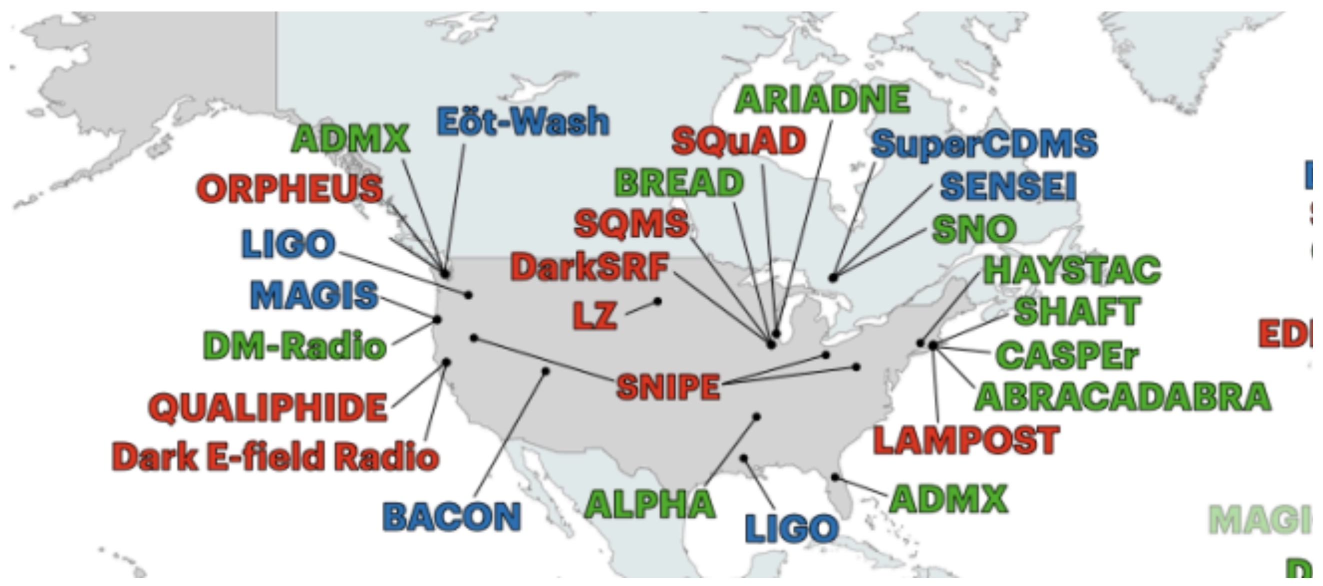
$\chi$



Maxwell

**Technical need:** FIR / THz photon counting detectors

# QUALPHIDE

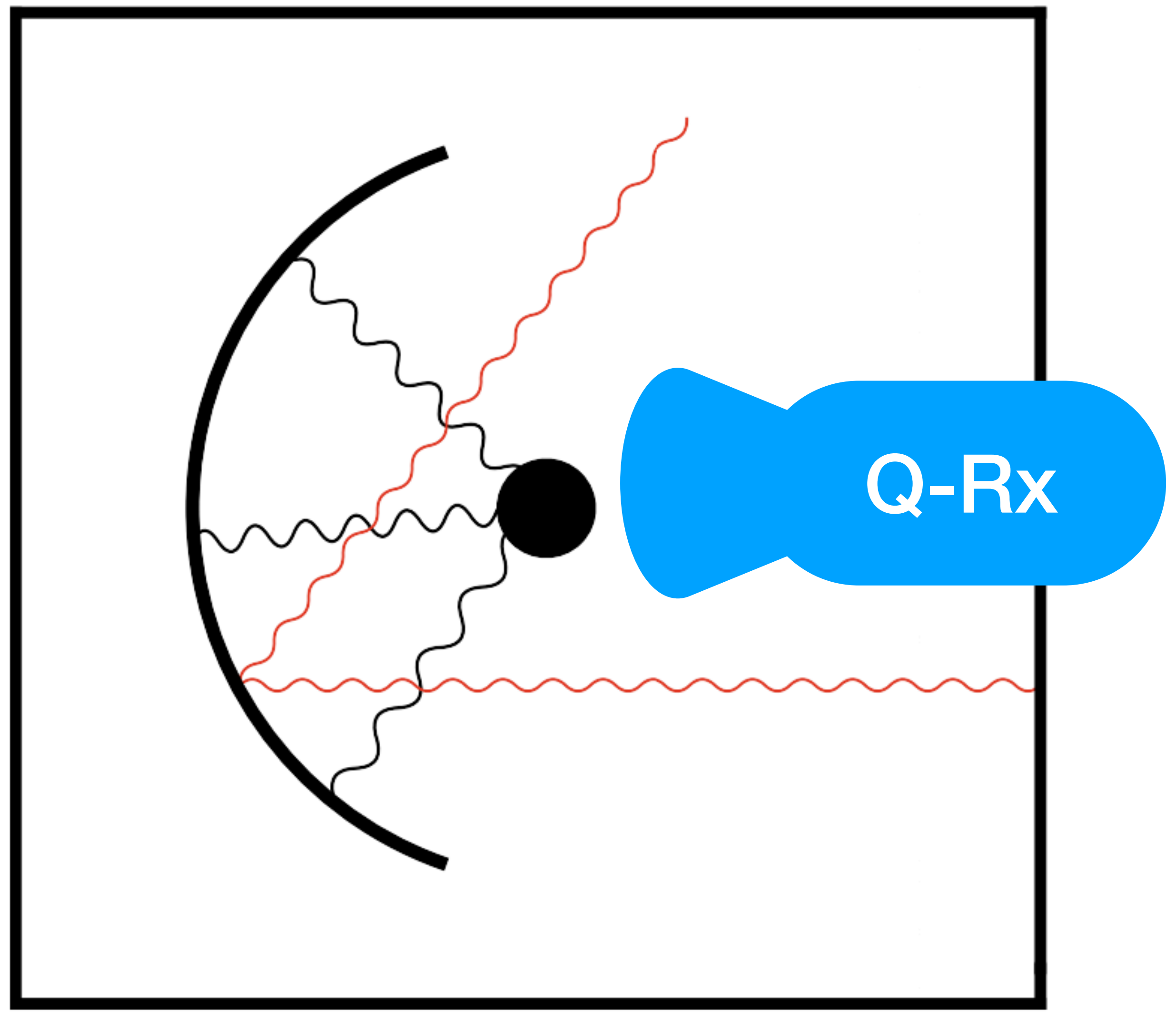



JCAP01(2016)005, JCAP04(2013)016 and
Broadband Solenoidal Haloscope for Terahertz Axion Detection (Phys. Rev. Lett. 128, 131801).
Also, e-Print: 2503.20432 [hep-ph]

Oscillating hidden-photon E-field → boundary condition on conducting surface sources standard $E_\perp$ field.

Metallic dish focuses such HP sourced photons

Background mitigation: $k_B T_{back} \ll m_{\mathrm{DM}} c^2$




$$h\nu \approx m_{\mathrm{DM}} c^2$$

$$P_{\mathrm{focus}} \sim \chi^2 \rho_{\mathrm{DM}} A_{\mathrm{Dish}}$$

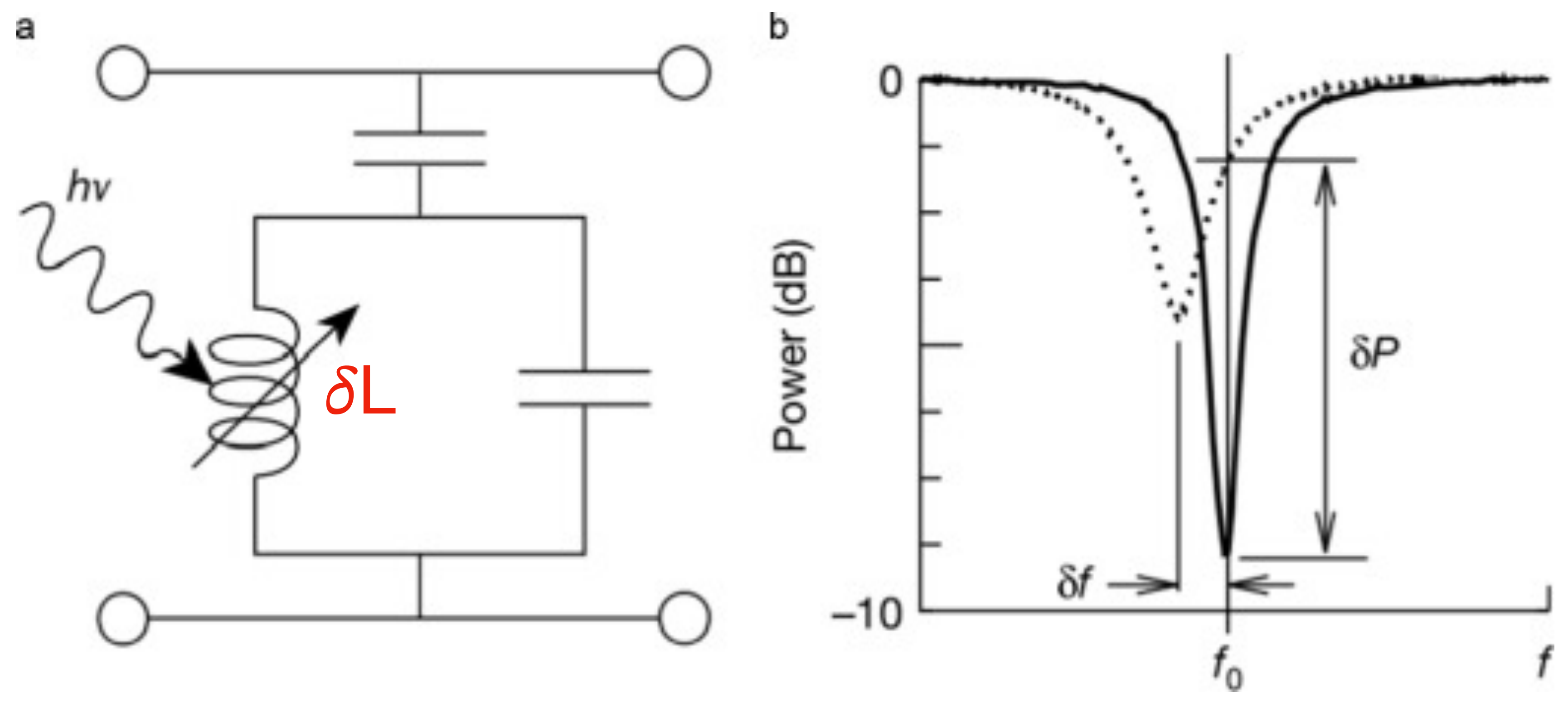
**QUALIPHIDE :** Quantum-Receiver (Q-Rx) test-bed to *qualify* GHz-THz sensor technologies for hidden photon searches and extendable to axions, ALPs etc.

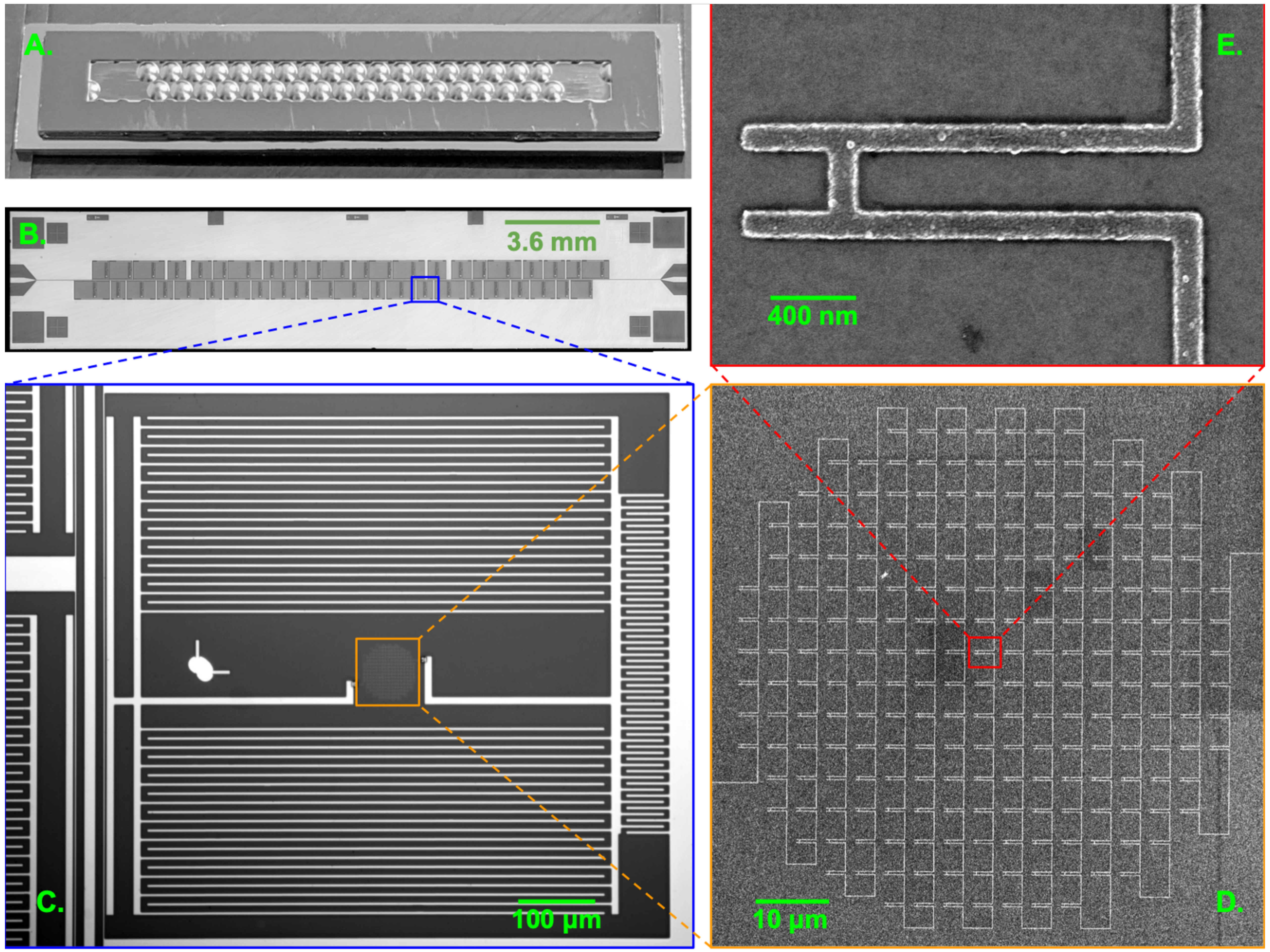
We use coherent detection at $10^{0\text{-to-}2}$ GHz, & photon counting at $10^{3\text{-to-}4}$ GHz.

# FIR KIDs

Kinetic Inductance Detectors (KIDs) made at JPL for FIR Astrophysics

**Day et al** Phys. Rev. X **14**, 041005 – **Published 7 October, 2024**




A) KID array with lenslets. B—D) Device micrographs with successive zoom-ins on absorber

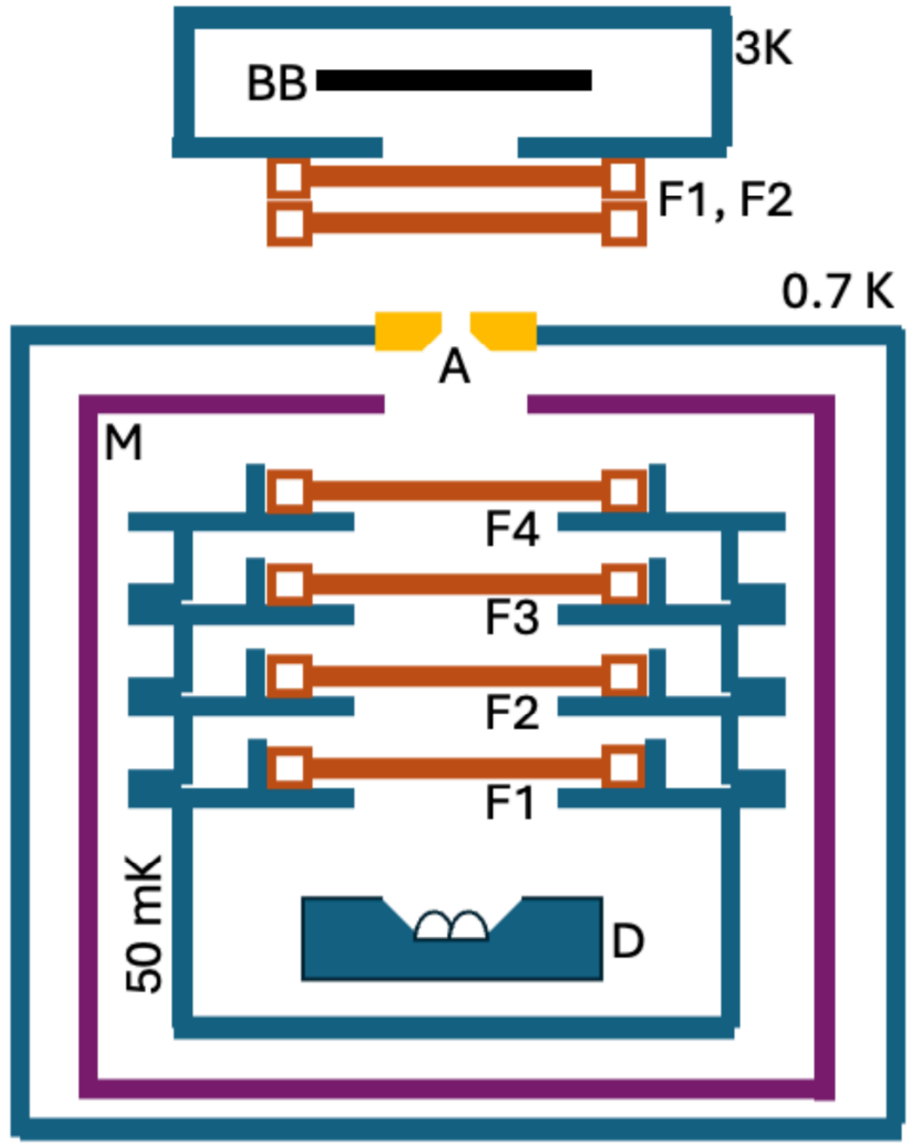
KIDs are nano fabricated superconducting LC resonators

High-energy photon absorption breaks Cooper-pairs →δL →δf

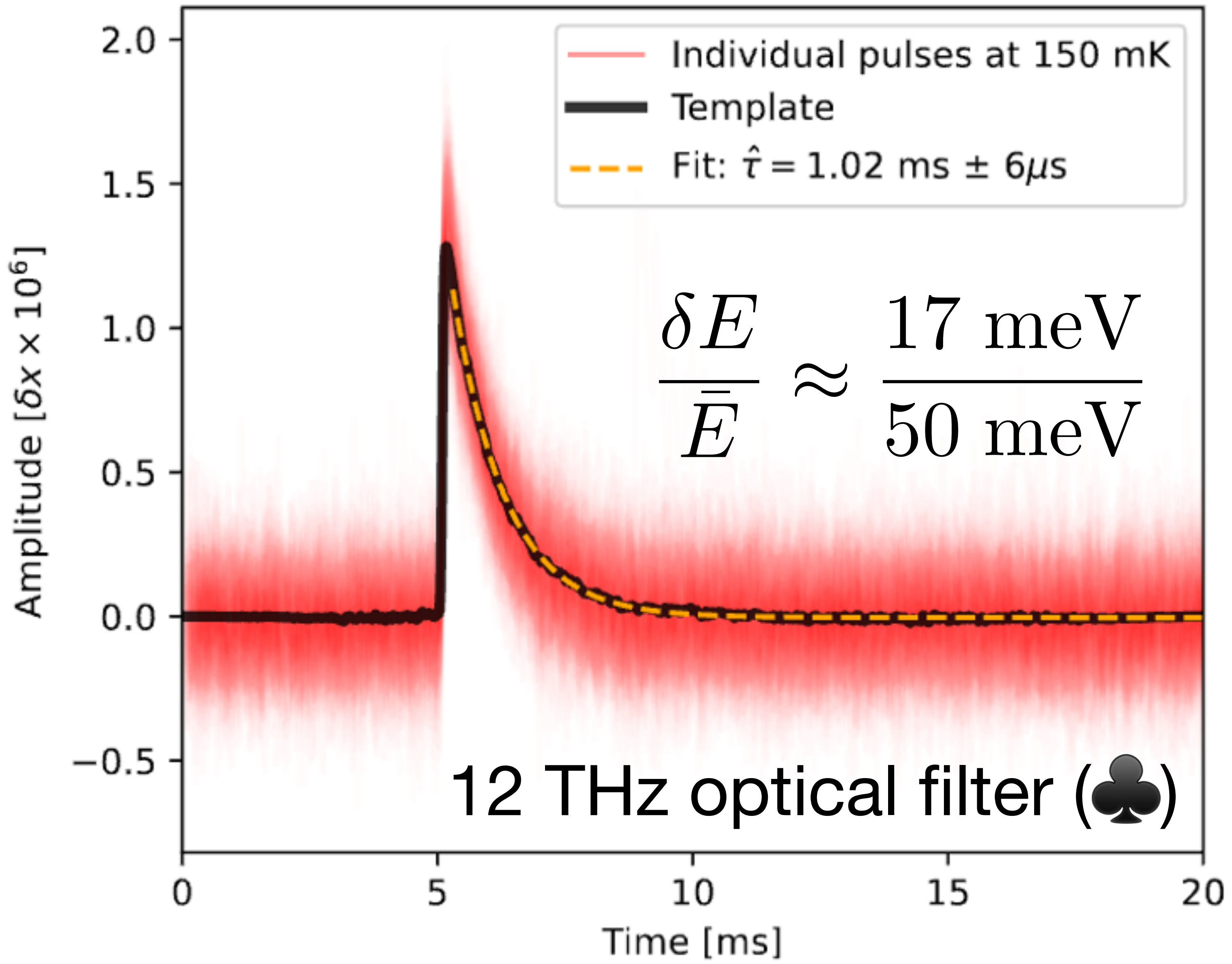
In these KIDs, the absorber itself is a low volume Al inductor, O(10) $\mu m^3$

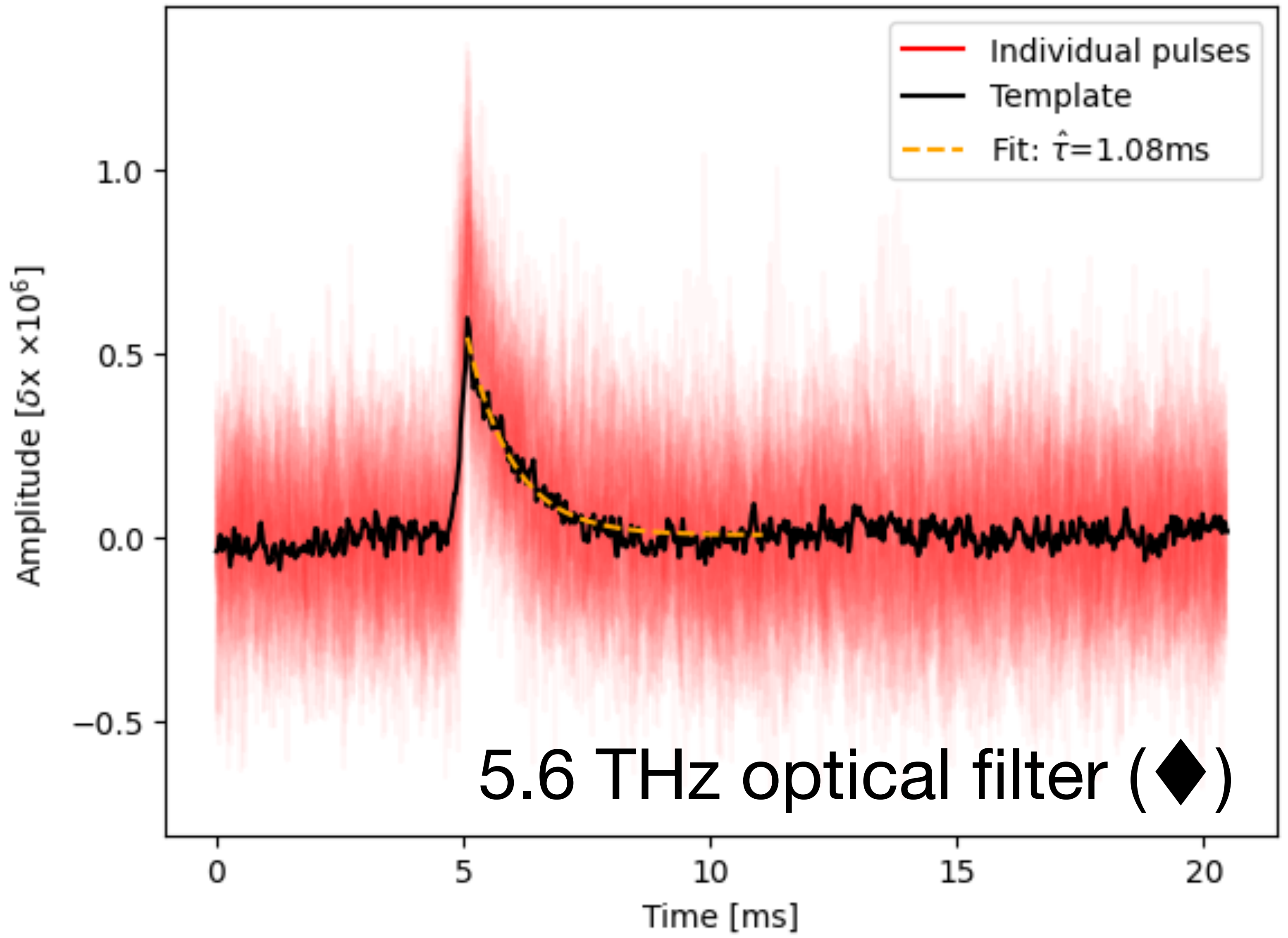
# FIR KIDs

Measurement & calibrations with blackbody & optical filters

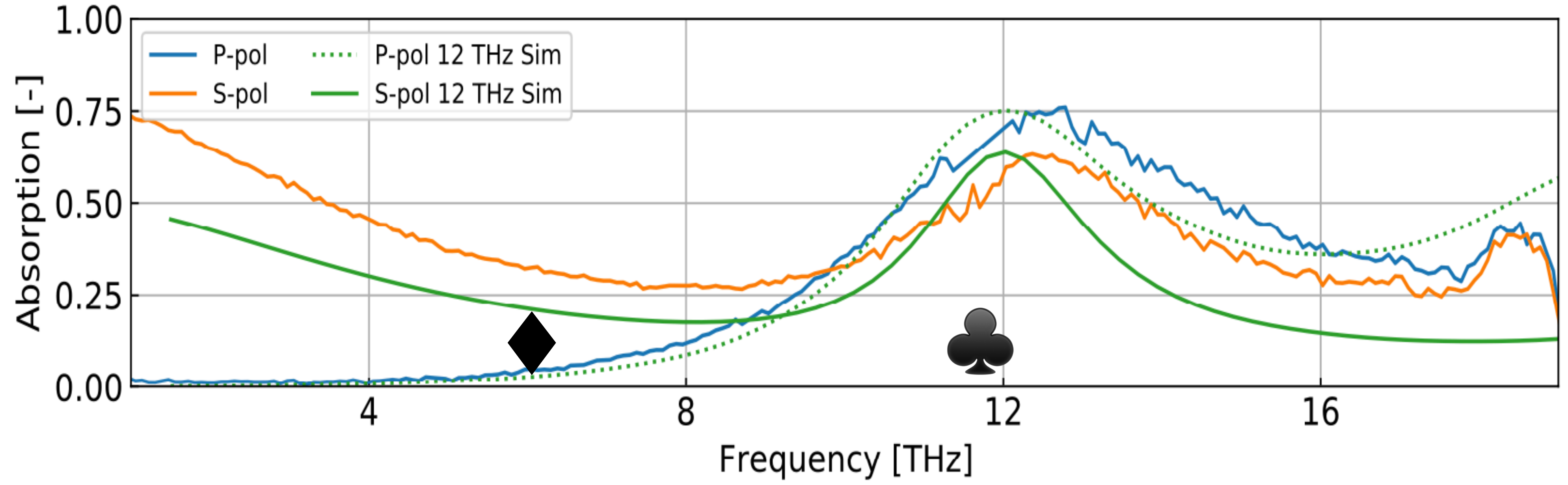



## Single photon pulses

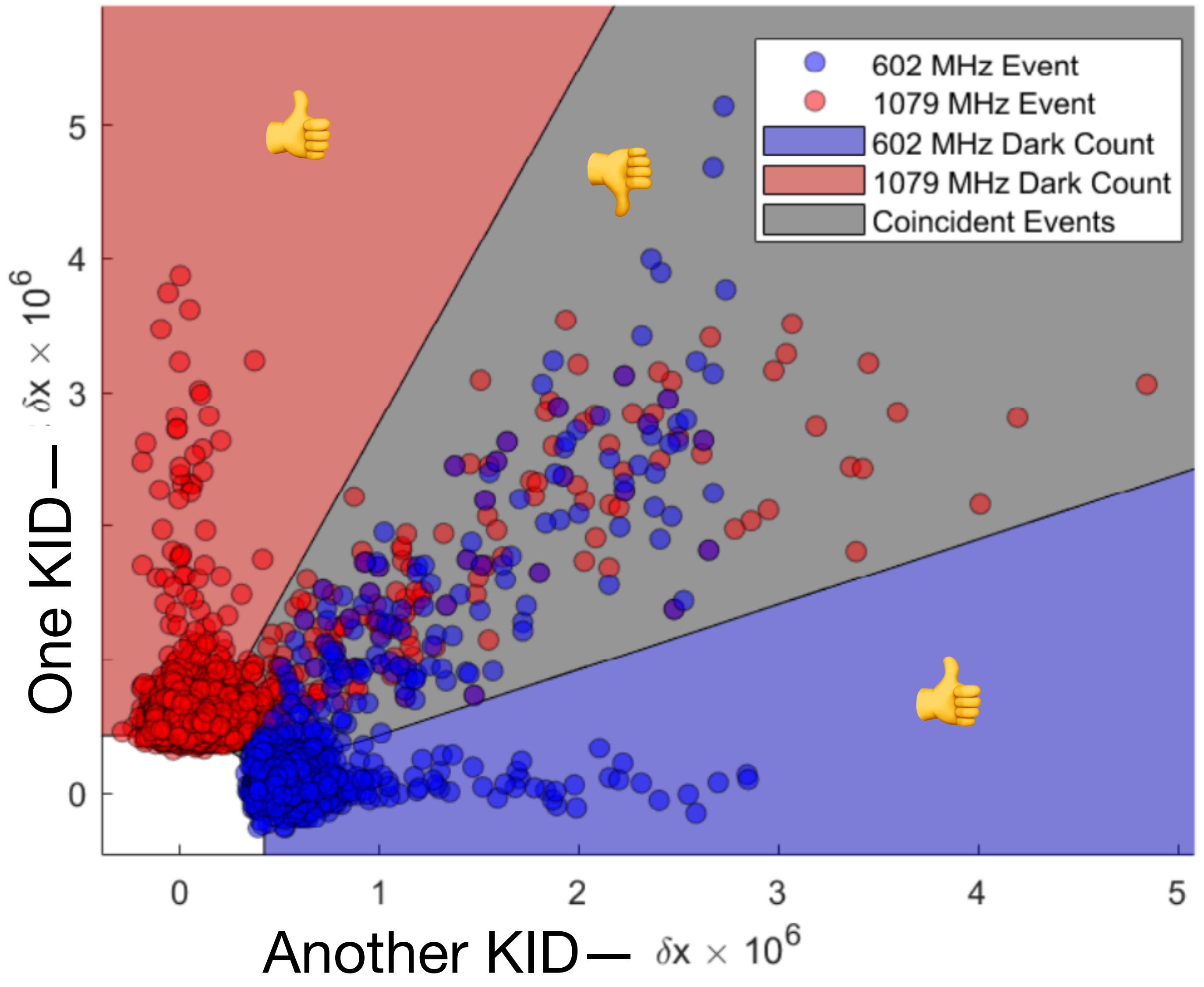



## THz Absorption profile



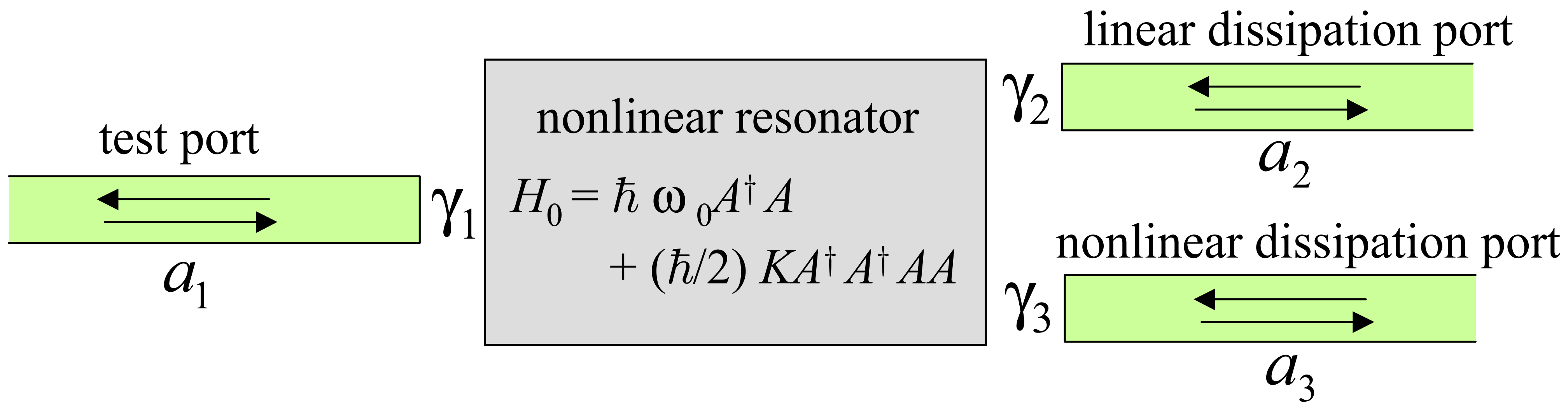

## Veto-ing against coincident pulses, dark count rate is 5 mHz

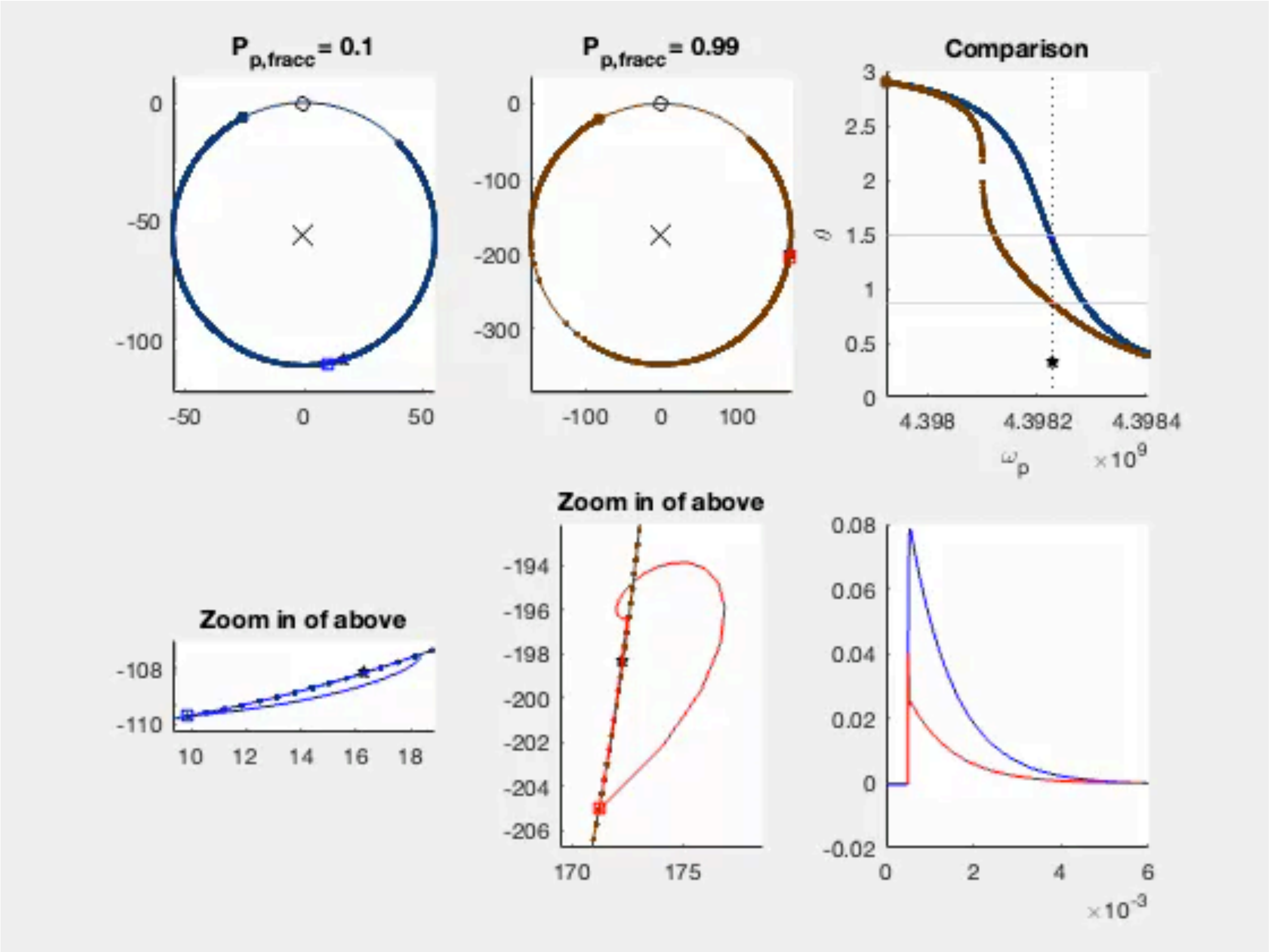



$$\text{NEP} \sim h\nu\sqrt{\text{DCR}} \approx 5 \times 10^{-22} \text{W}/\sqrt{\text{Hz}}$$

# NLKIDs

**N**on **L**inear **KIDs**:
Kerr nonlinearity couples a strong pump to a weak signal



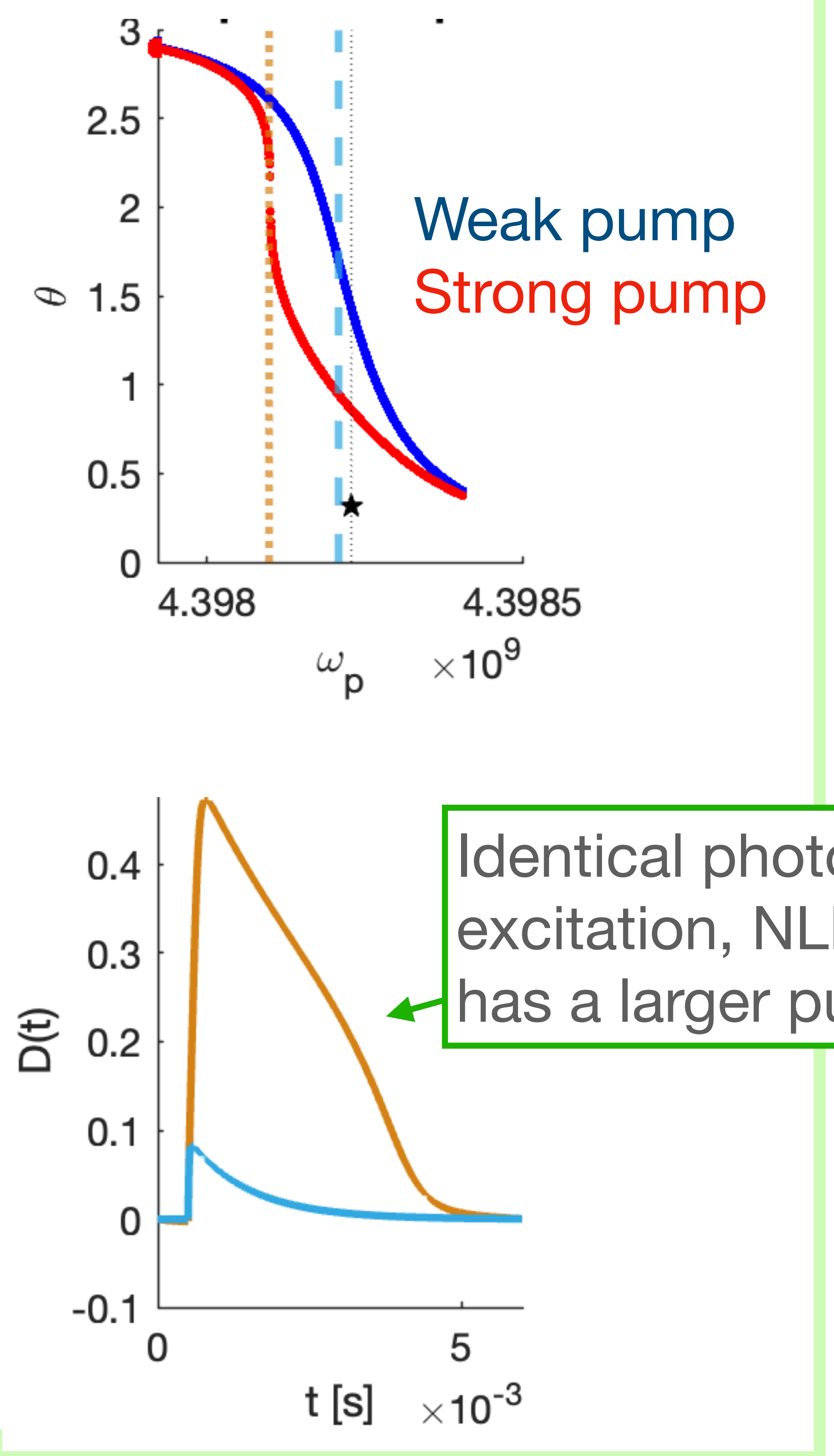




Only one tone per KID, and we have in situ amplification

J. Lightwave Technol. 24, 5054-5066 and Phys. Rev. E **74**, 046619

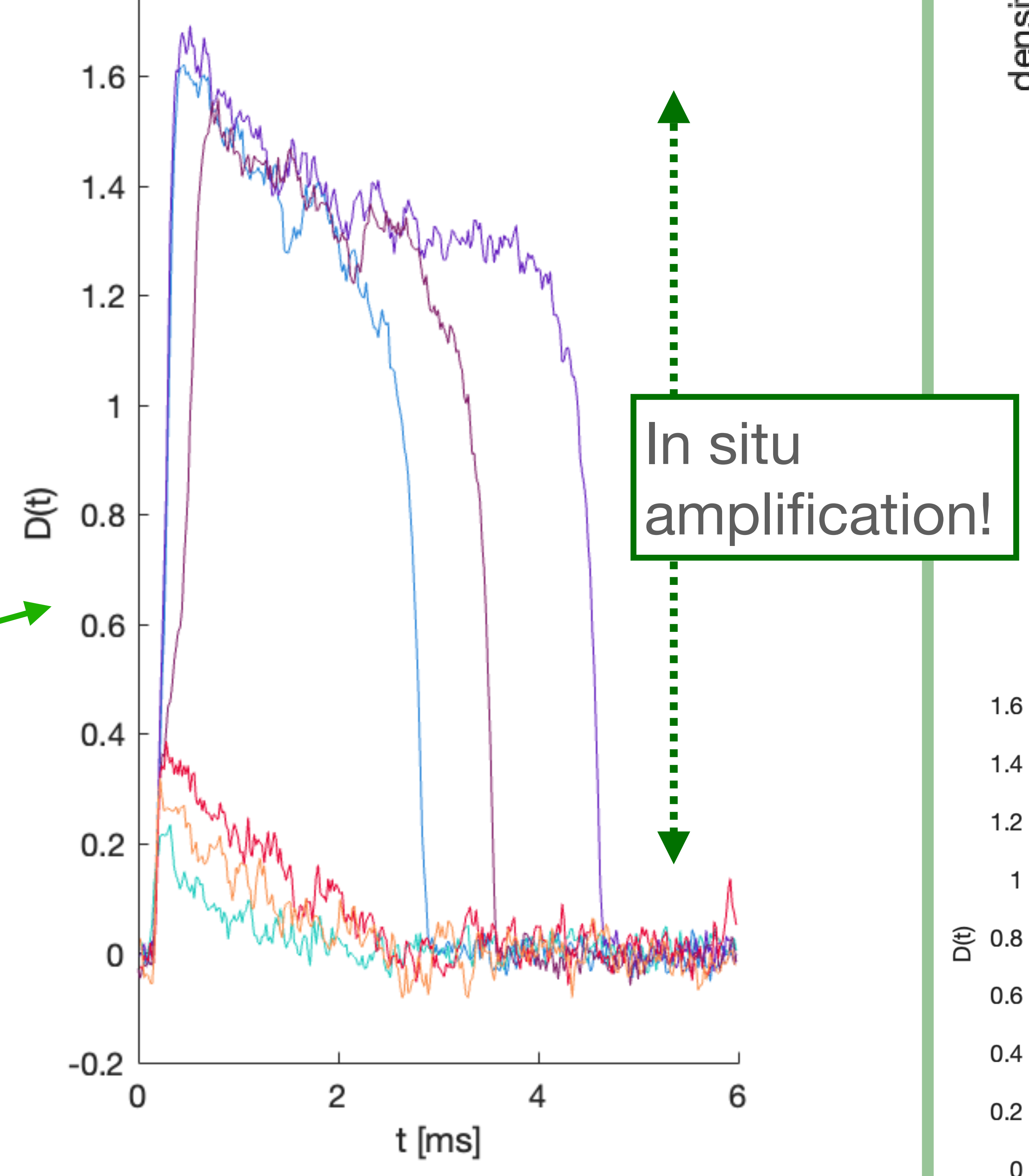
# NLKIDs

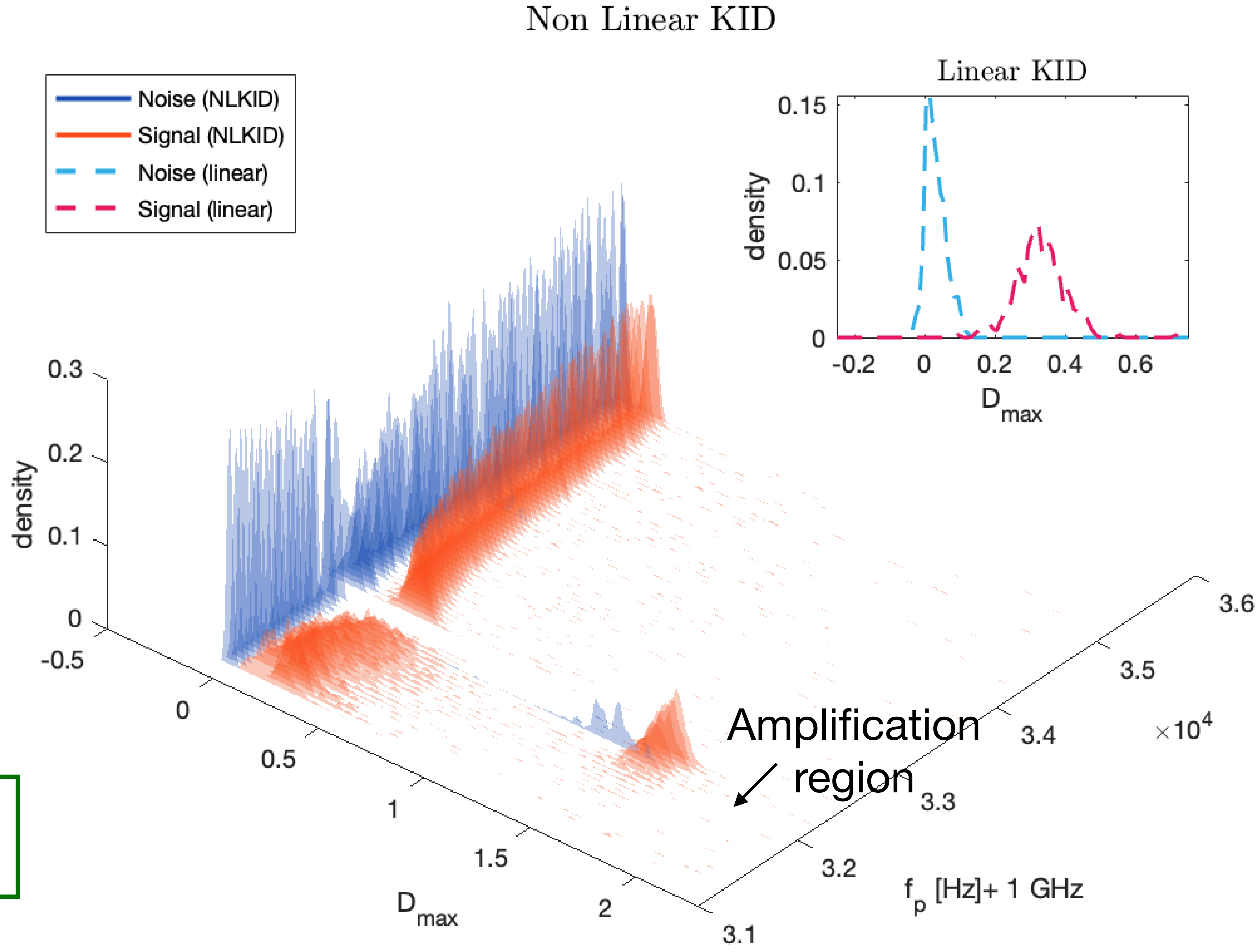
## Quantum Optics simulation

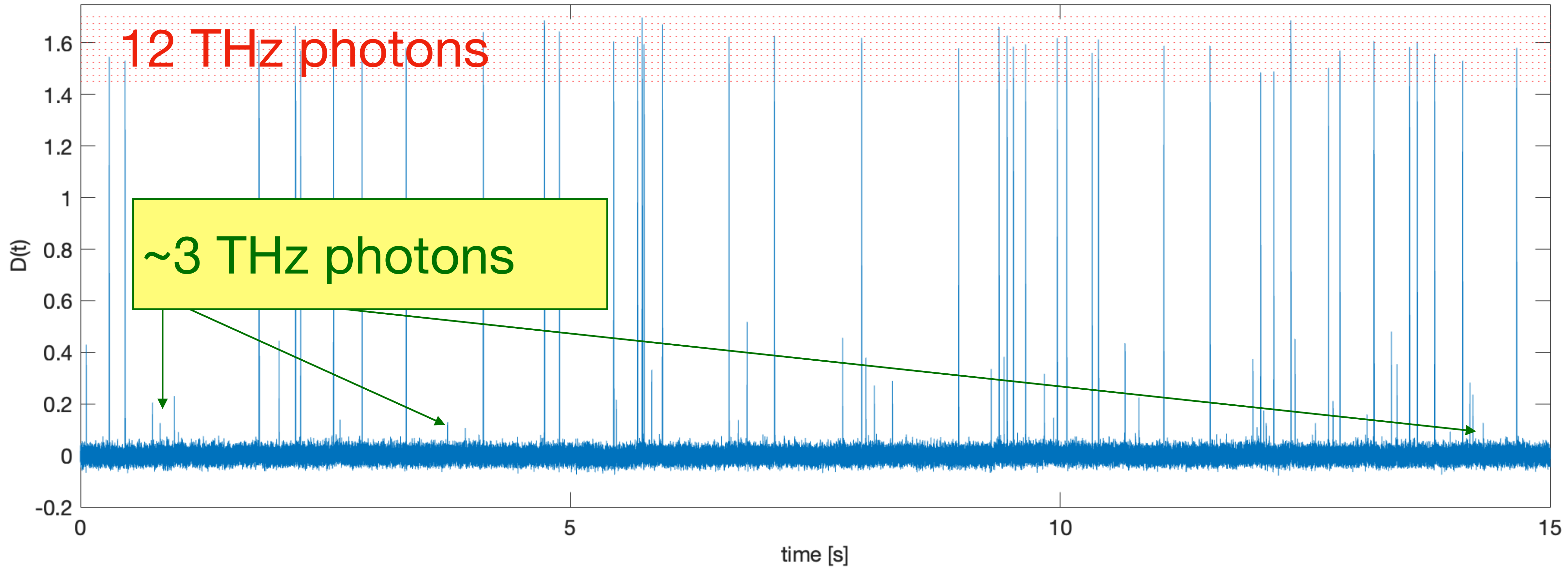



## Data

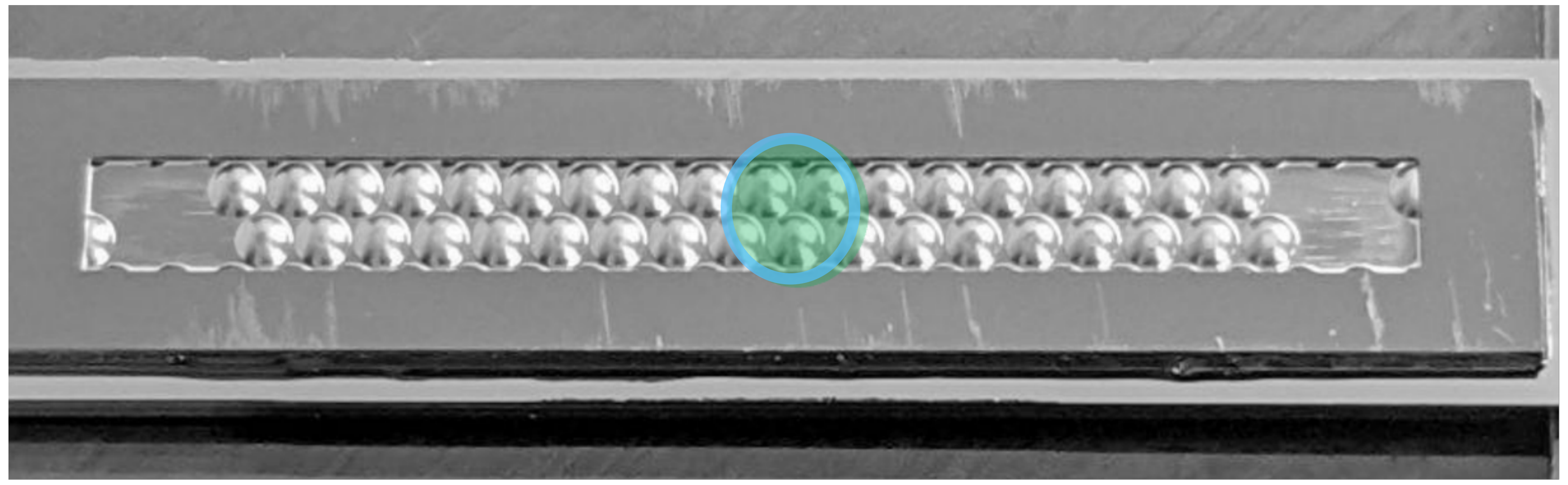
12 THz pulses in our NLKID, strong pump power but varying pump frequencies

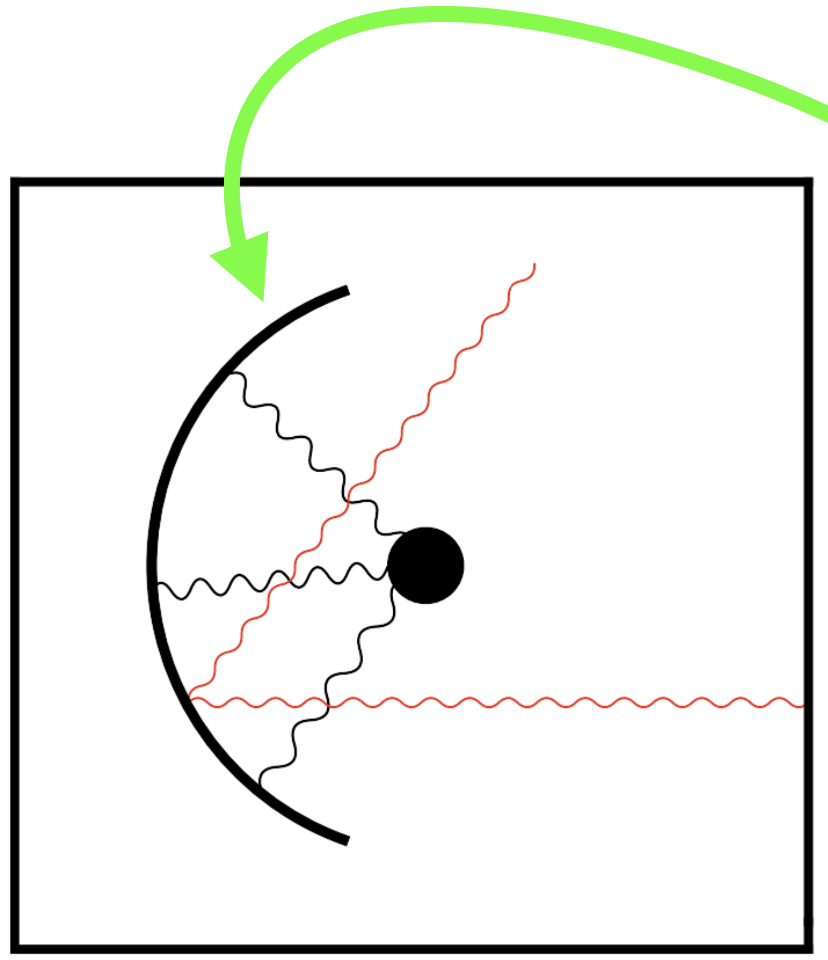


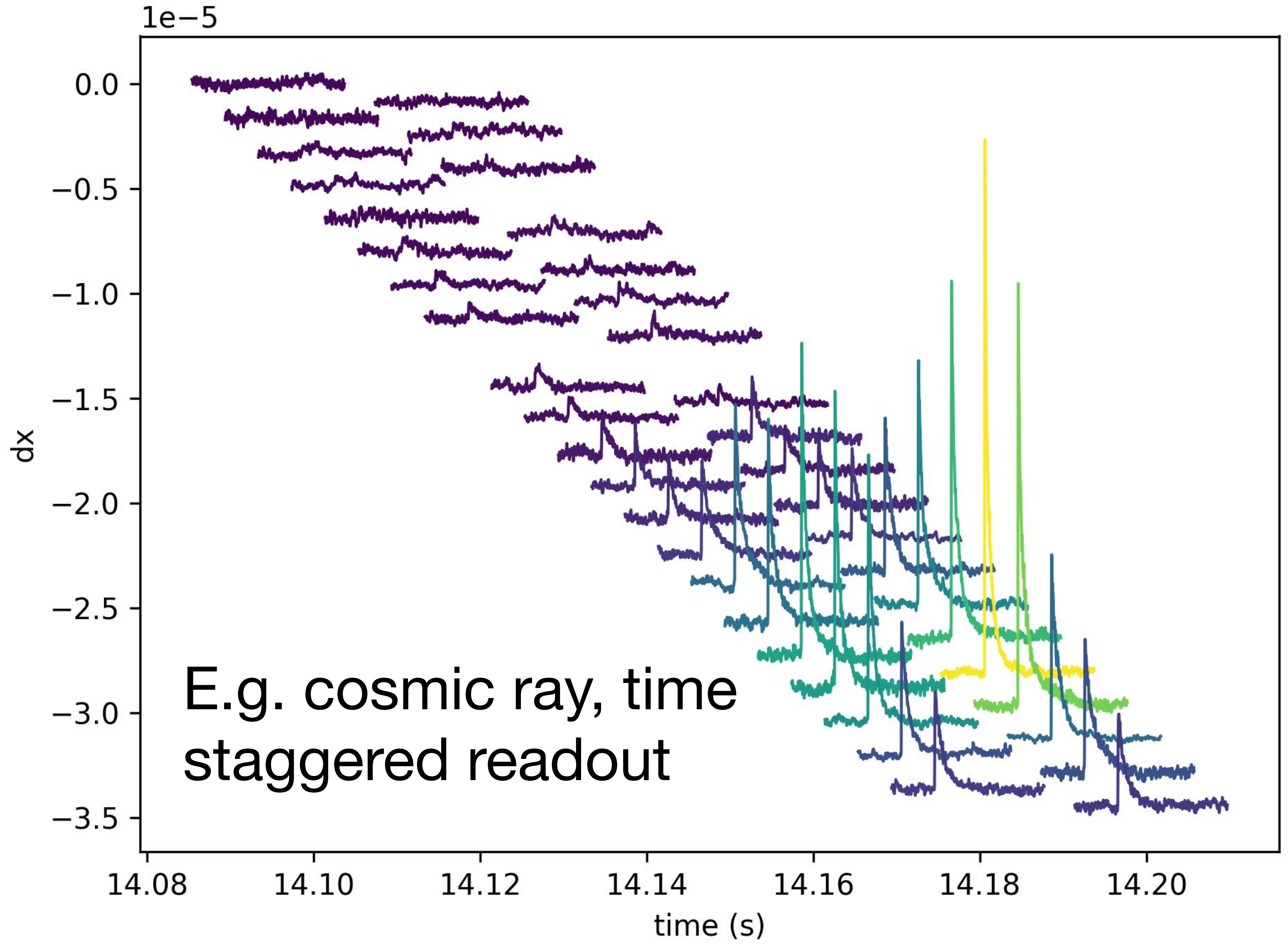
# QUALIPHIDE @ FIR

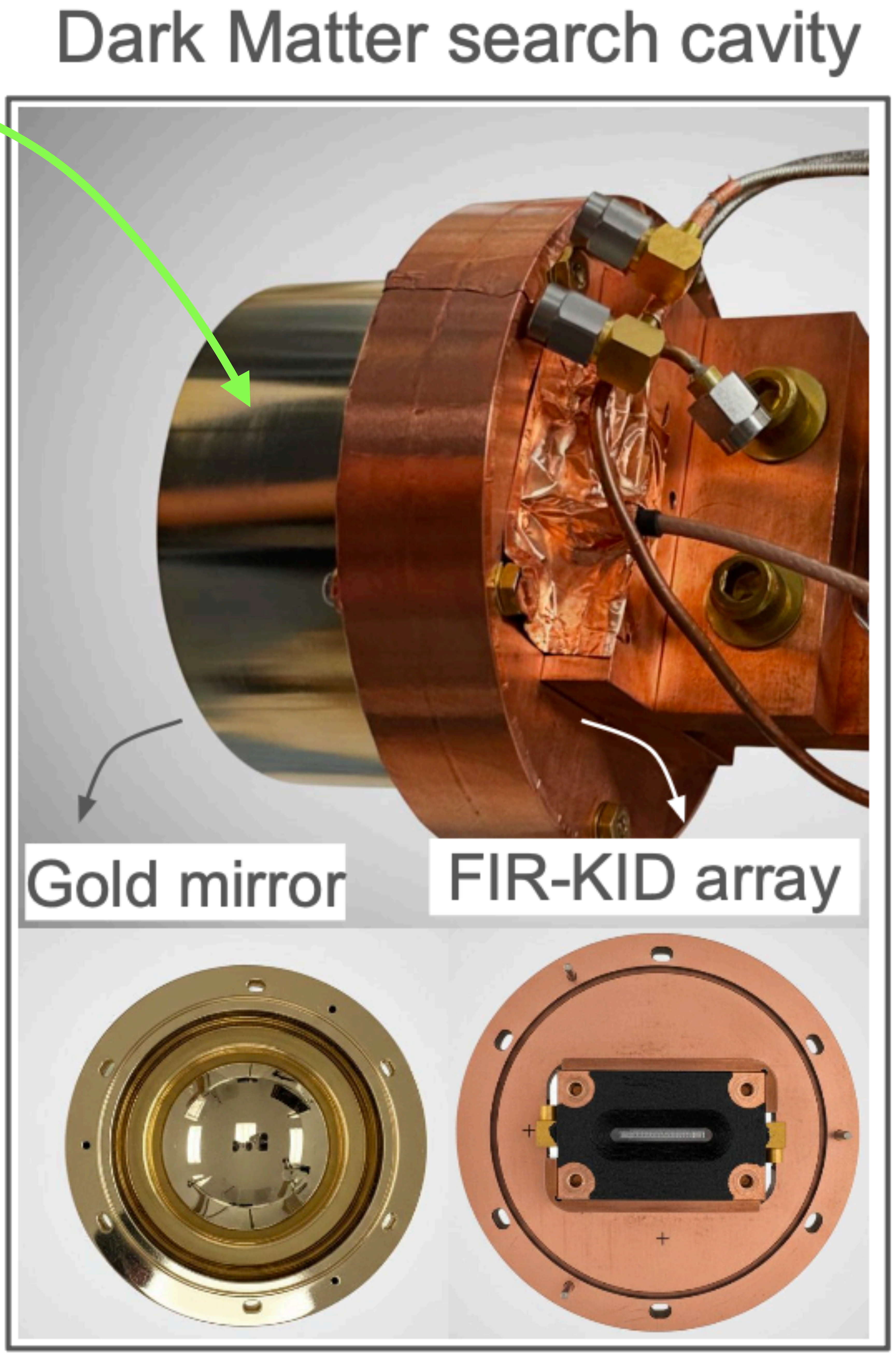




4 central pixels of FIR-KID array form the signal channels.

Other pixels serve as background monitors to lower DCR to ~mHz



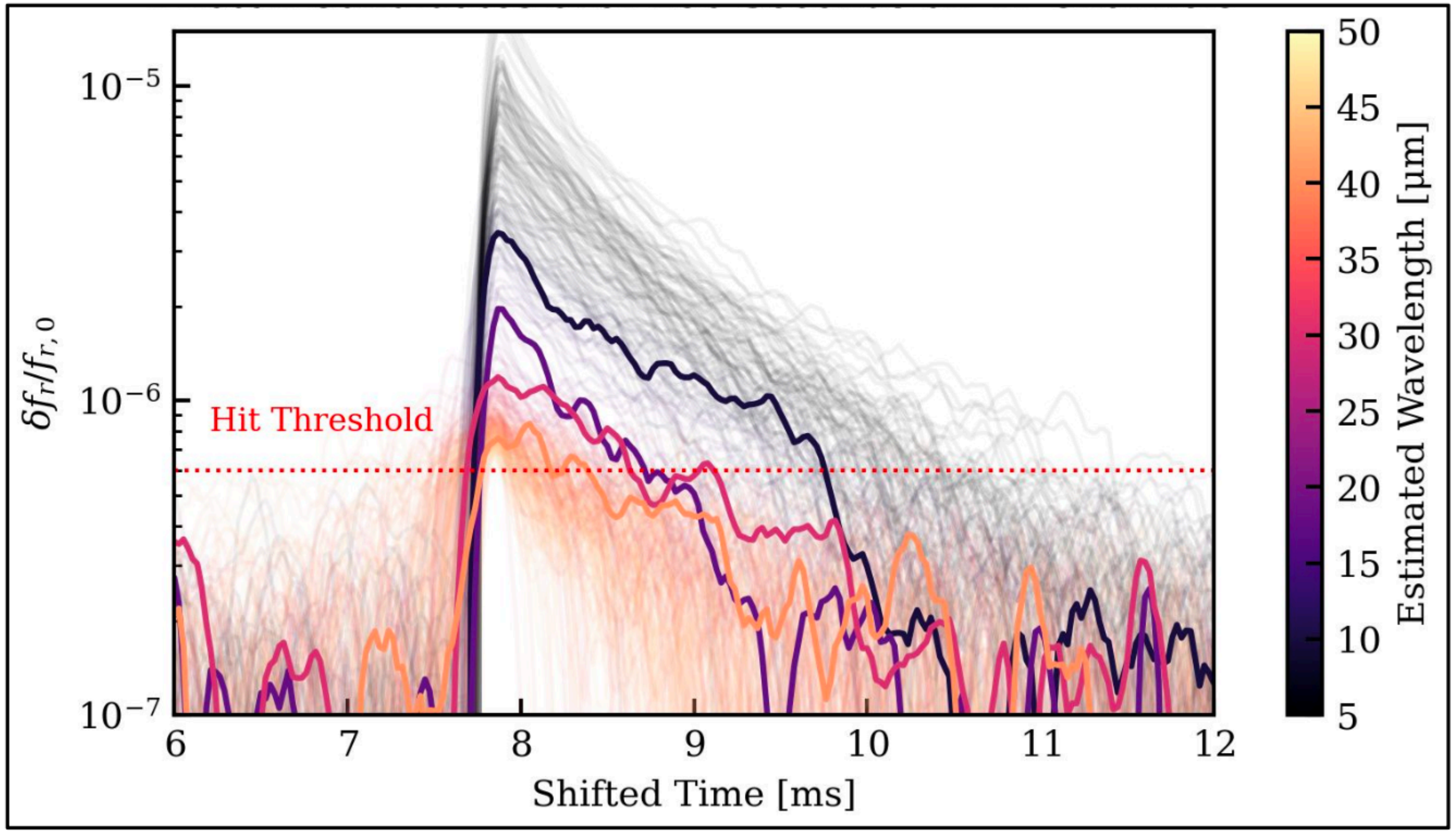



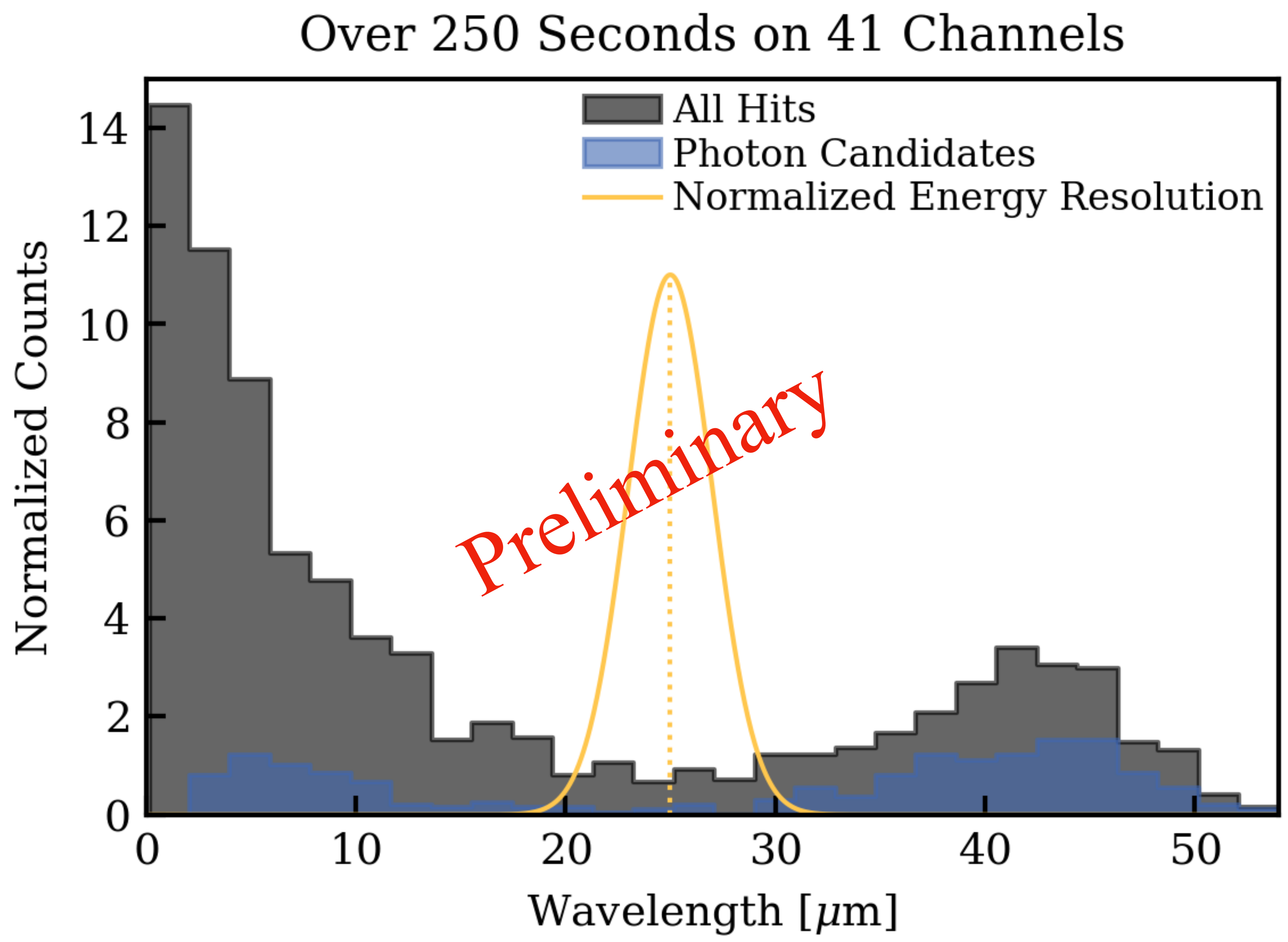
# QUALIPHIDE @ FIR

Engineering data set captures 5-50 $\mu$m photon pulses in linear mode.

Additionally, NLKID mode data set augments science reach at lower masses

Measured single far infrared photon pulses

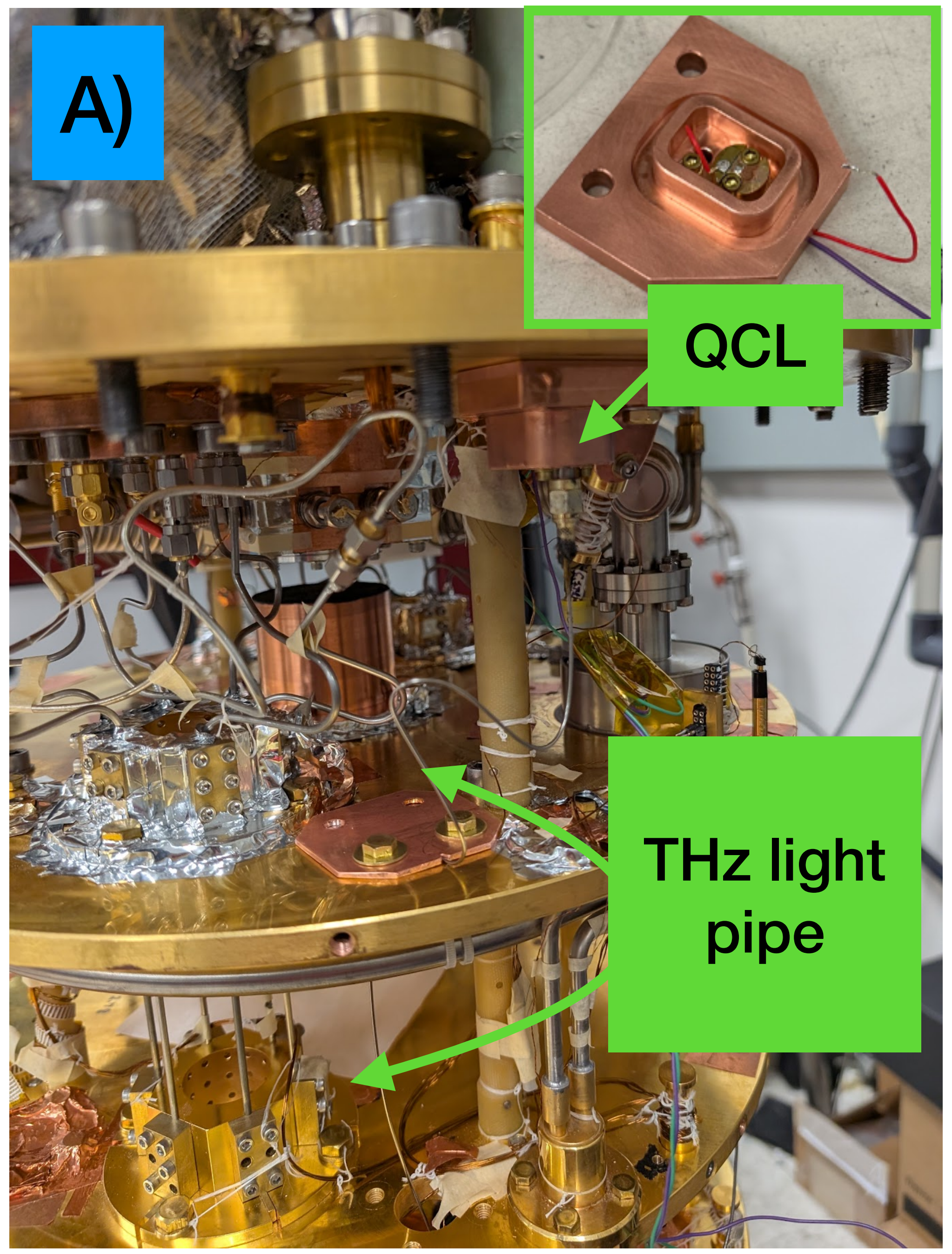


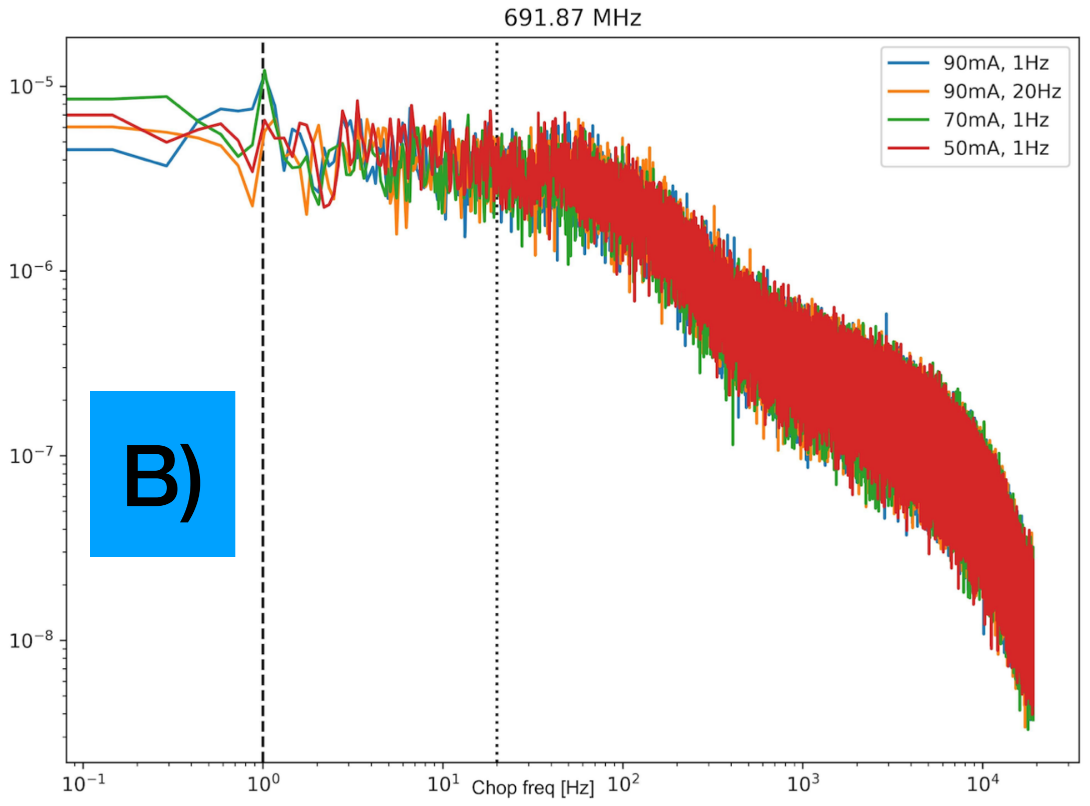



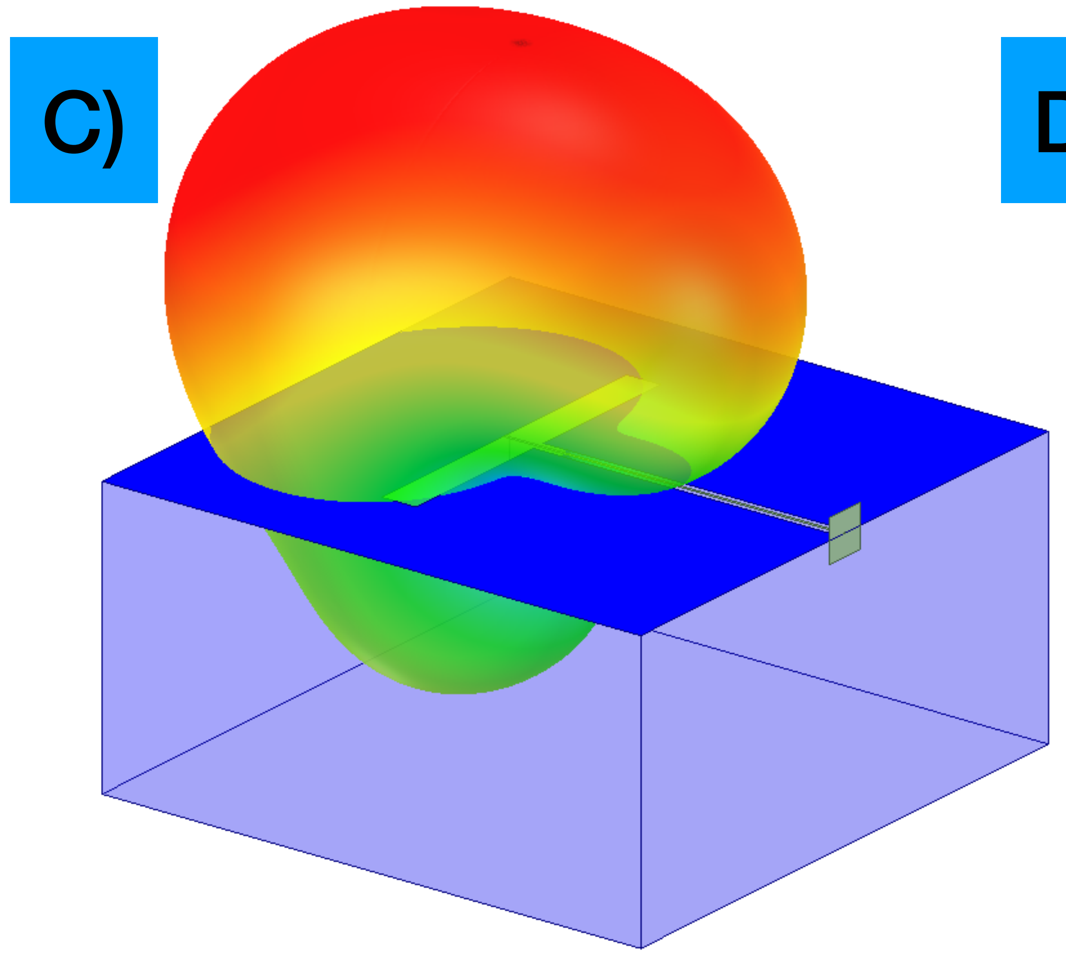
# QUALIPHIDE @ FIR

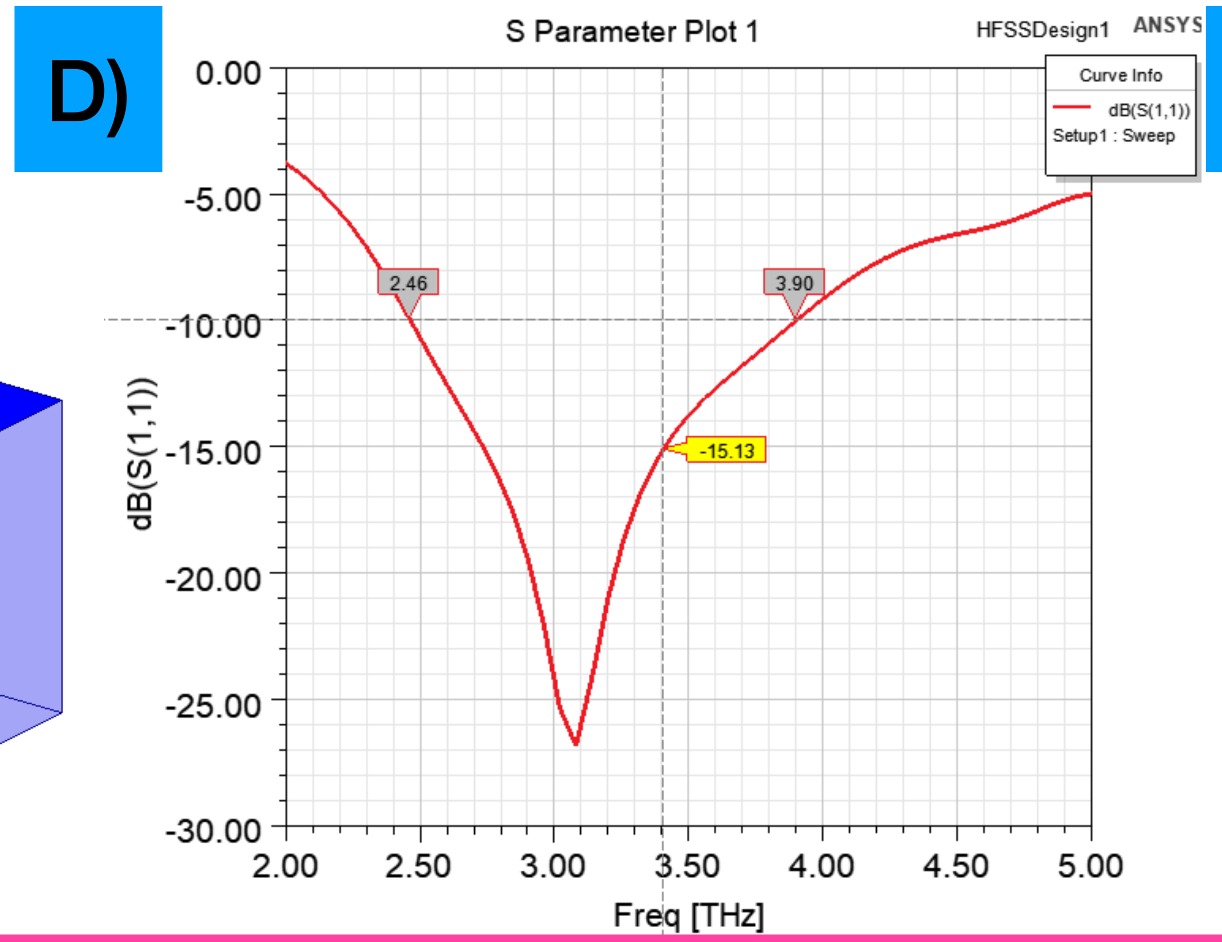
QCL @ 1.2-6 THz setup in the cryostat and measured modulated low-flux response with KIDs (A & B). C-F: 3.4 THz antenna coupled KID design. C-E show antenna and KID absorption simulation, and F shows the designed array with zoom-in of the above elements.

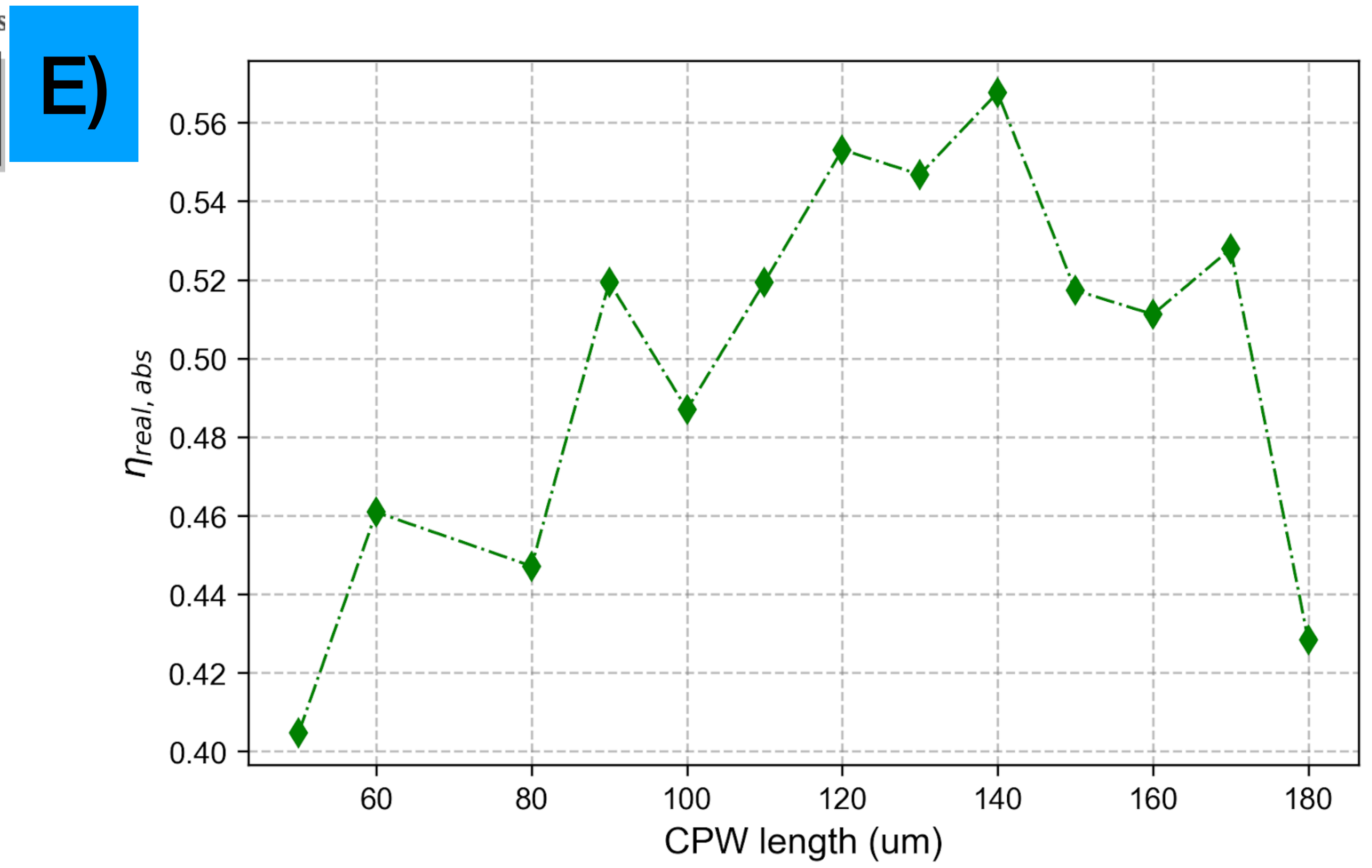
QCL setup at 4K and low flux 3.4 THz measurements



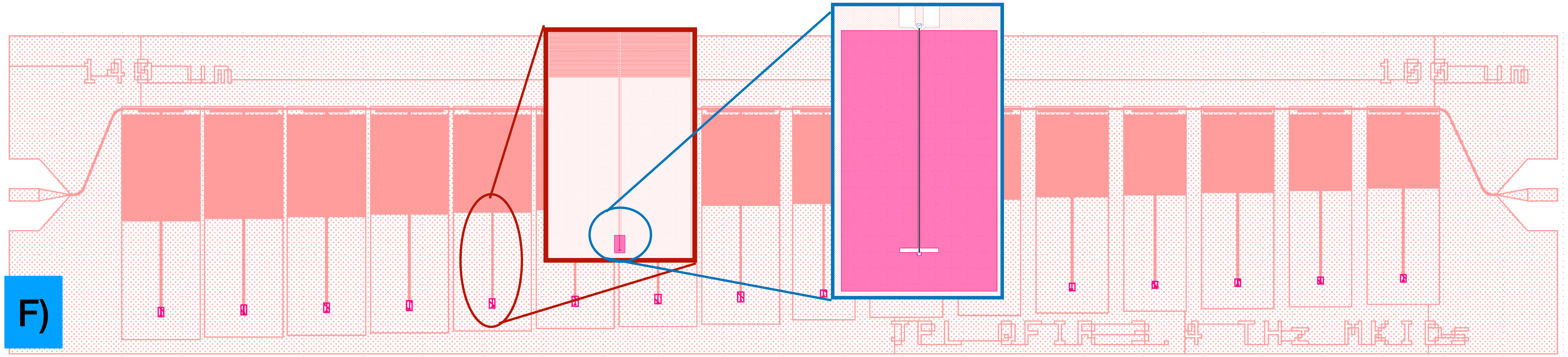



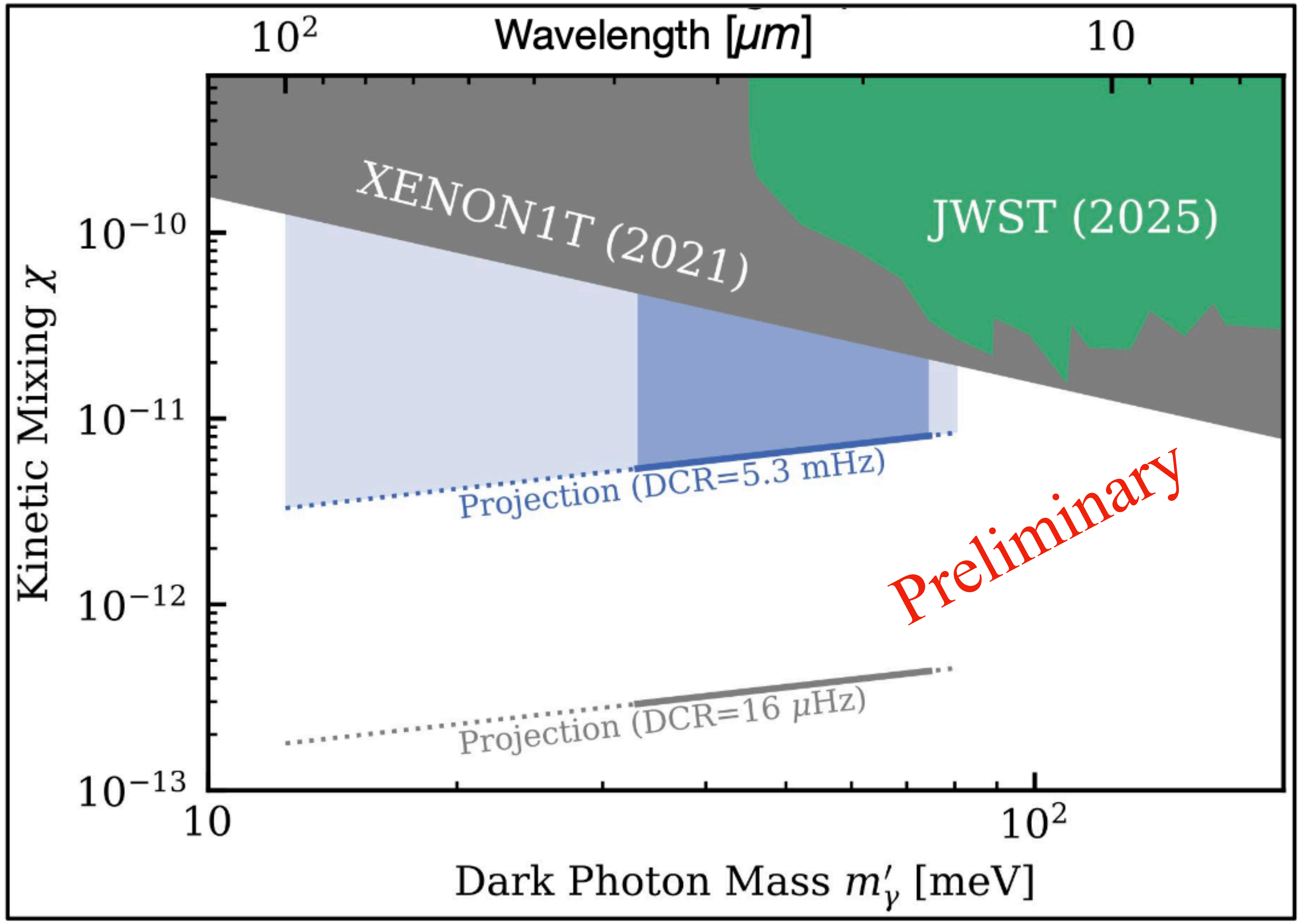




Slot antenna design + KID absorption calculation




3.4 THz KID array design

# QUALIPHIDE @ FIR




L.Yuan (internal)

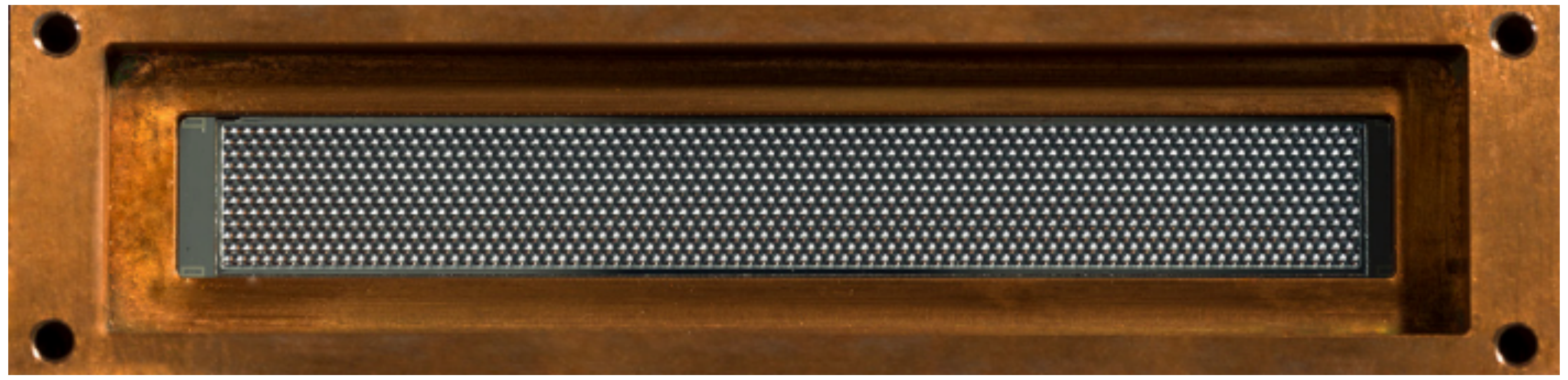
Blue: mean 5.3 mHz DCR on core pixels, ignores energy distribution

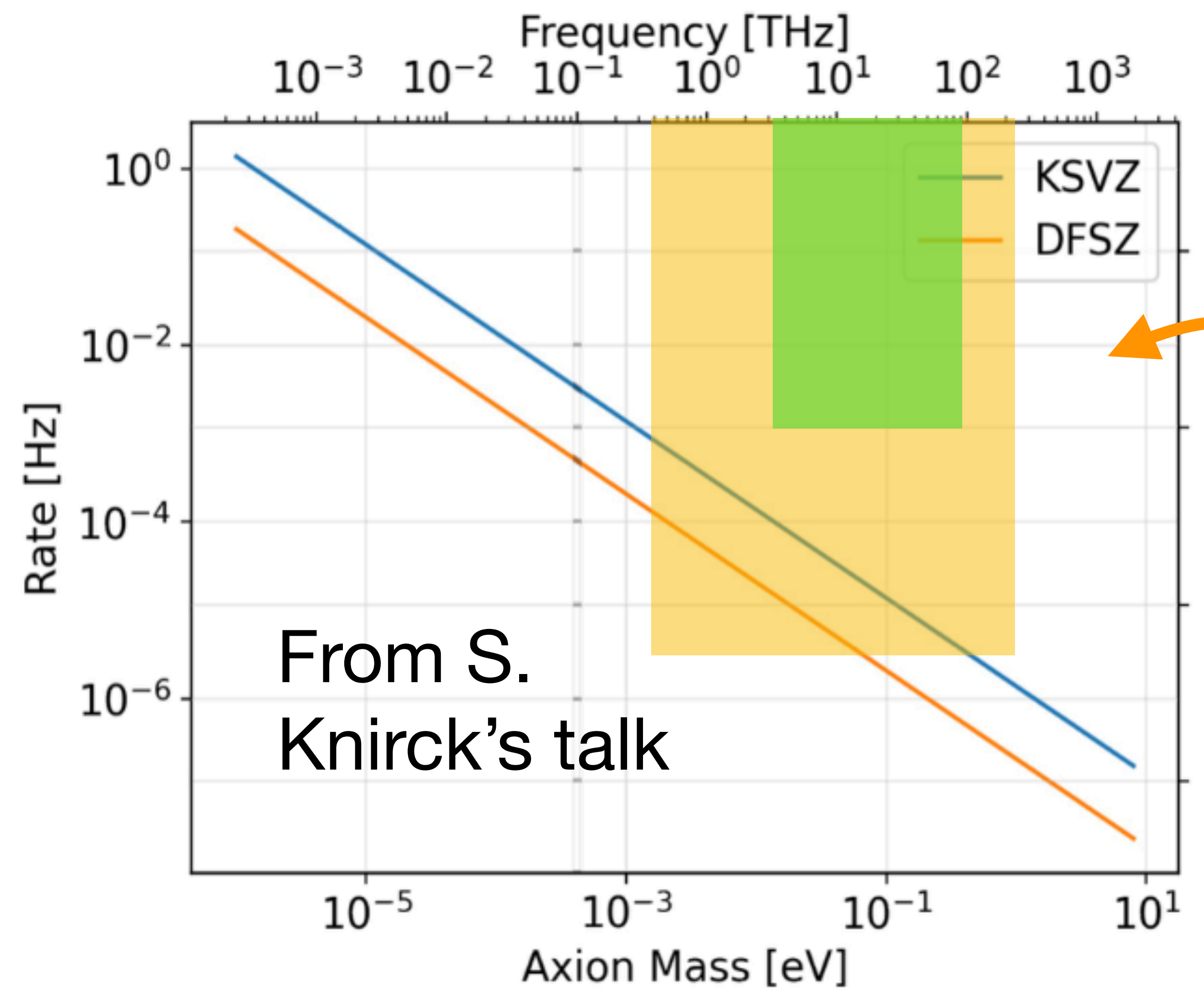
Gray: a "signal-given-background" model indicates a final limit approaching 16 $\mu$Hz DCR, ~$10^3$ better than state of the art

Likelihood, w/ energy distribution, forms final limits — underway.

# QUALIPHIDE @ FIR

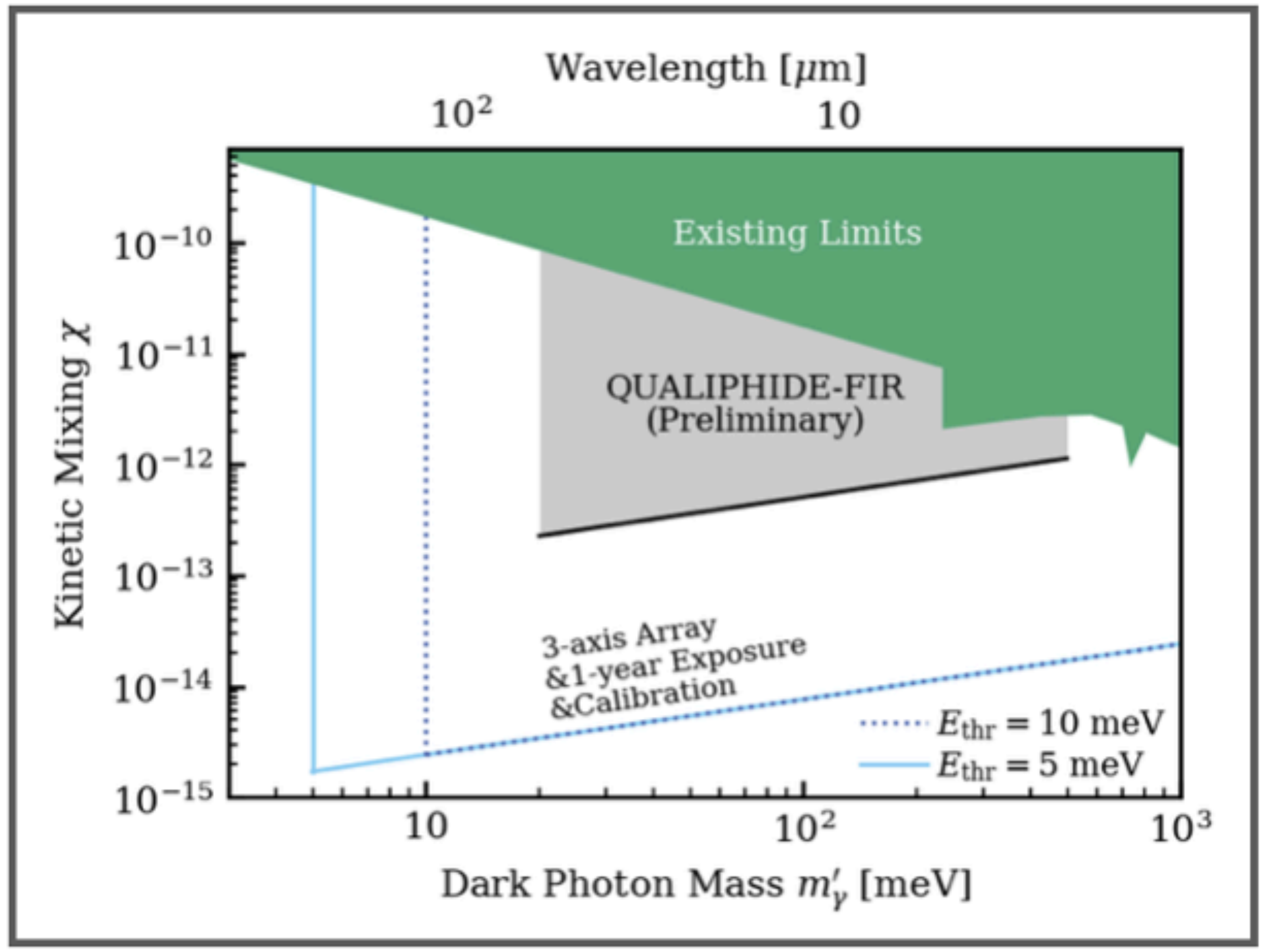
JPL has already scaled the 44 pixel device to 1008 pixels, ~80% operating in single photon counting mode

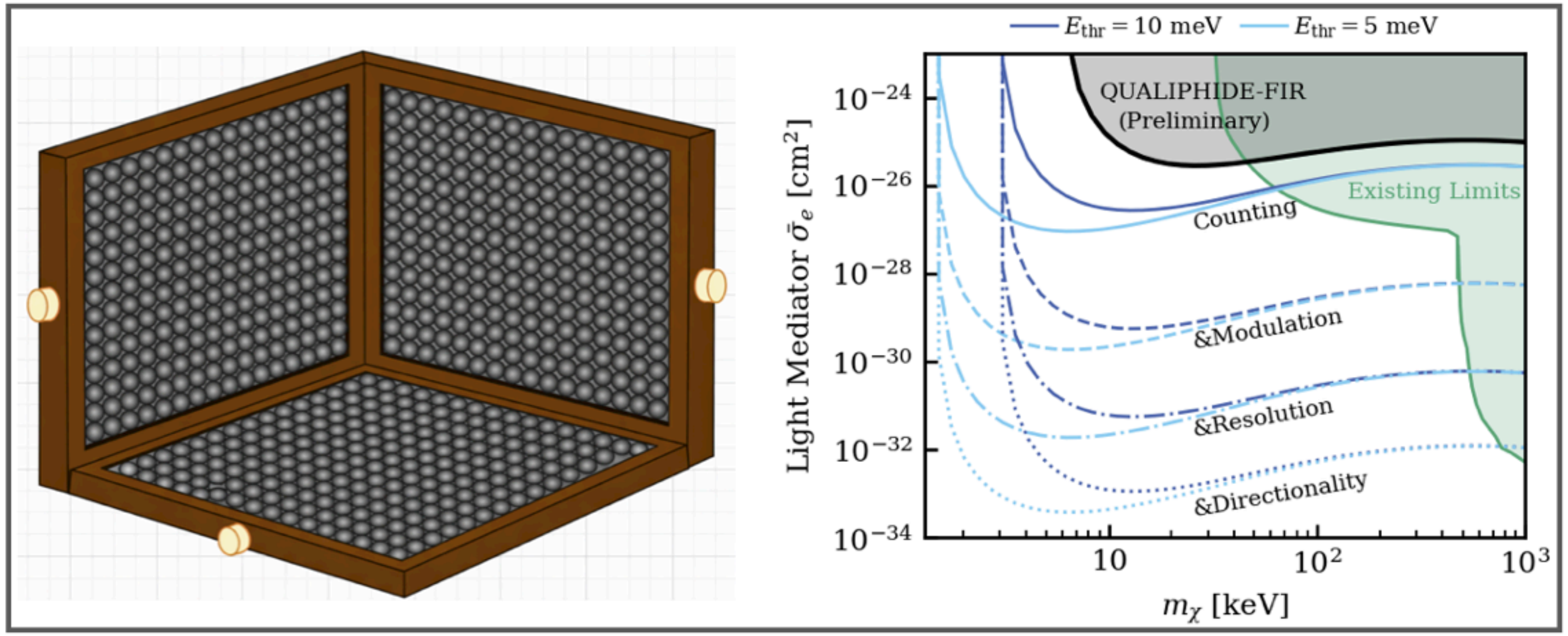





Goal-1: Push to lower (1 THz) and higher (100 THz) energies … but more importantly show the ~10 uHz DCR is realizable

Goal-2: Make a bigger version of QUALIPHIDE & simultaneously use these arrays for e-recoil DM searches



# Conclusions

*Collaborations & questions welcome!*

QUALIPHIDE-FIR slated to provide world-leading sensitivity to 10-100 meV dark matter/ hidden photons, with photon counting KIDs.

Novel NLKIDs enables lower energy searches.

DOE integration, e.g. BREAD, enables much deeper dark matter searches.

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Caltech

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Arjun Ghosh (GS)

UNIVERSITY OF OXFORD

Nikita Klimovich (PI)
Boon Kok Tan (Co-I)

# Back up slides

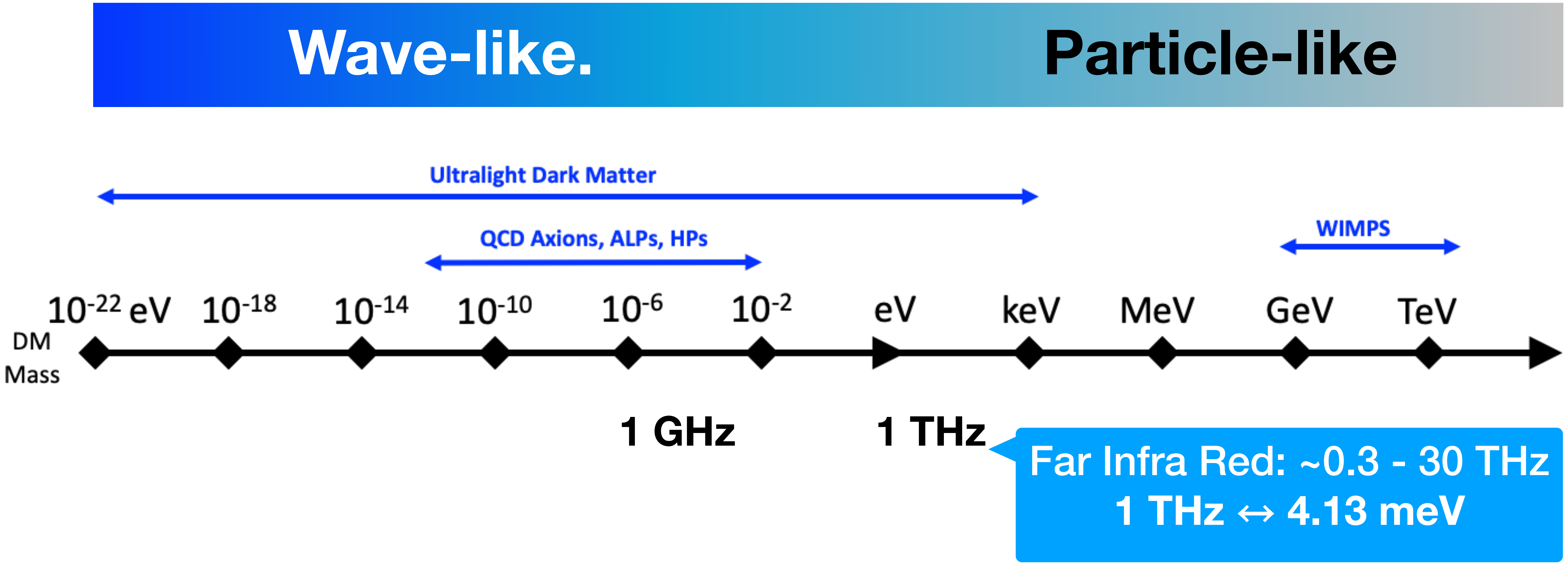
Wave Dark Matter, Annual Review of Astronomy and Astrophysics, Vol. 59:247-289 (September 2021) and Direct detection of dark matter—APPEC committee report (2021) & FERMILAB-PUB-23-681-T (2023)

# Dark Matter

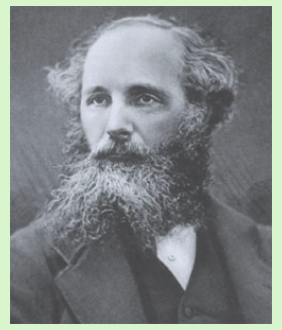
**Wave-like:** Large number densities, (sub)eV masses. Detection via photo-conversion methods.

**Hidden Photons, e.g.:** SM photons mix with dark sector/ massive hidden-photons.

**Technical need:** FIR / THz photon counting detectors




$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m_{\gamma'}^2}{2}\tilde{X}_{\mu}\tilde{X}^{\mu} + J^{\mu}A_{\mu}$$



Maxwell

Mixing between fields

New massive field terms

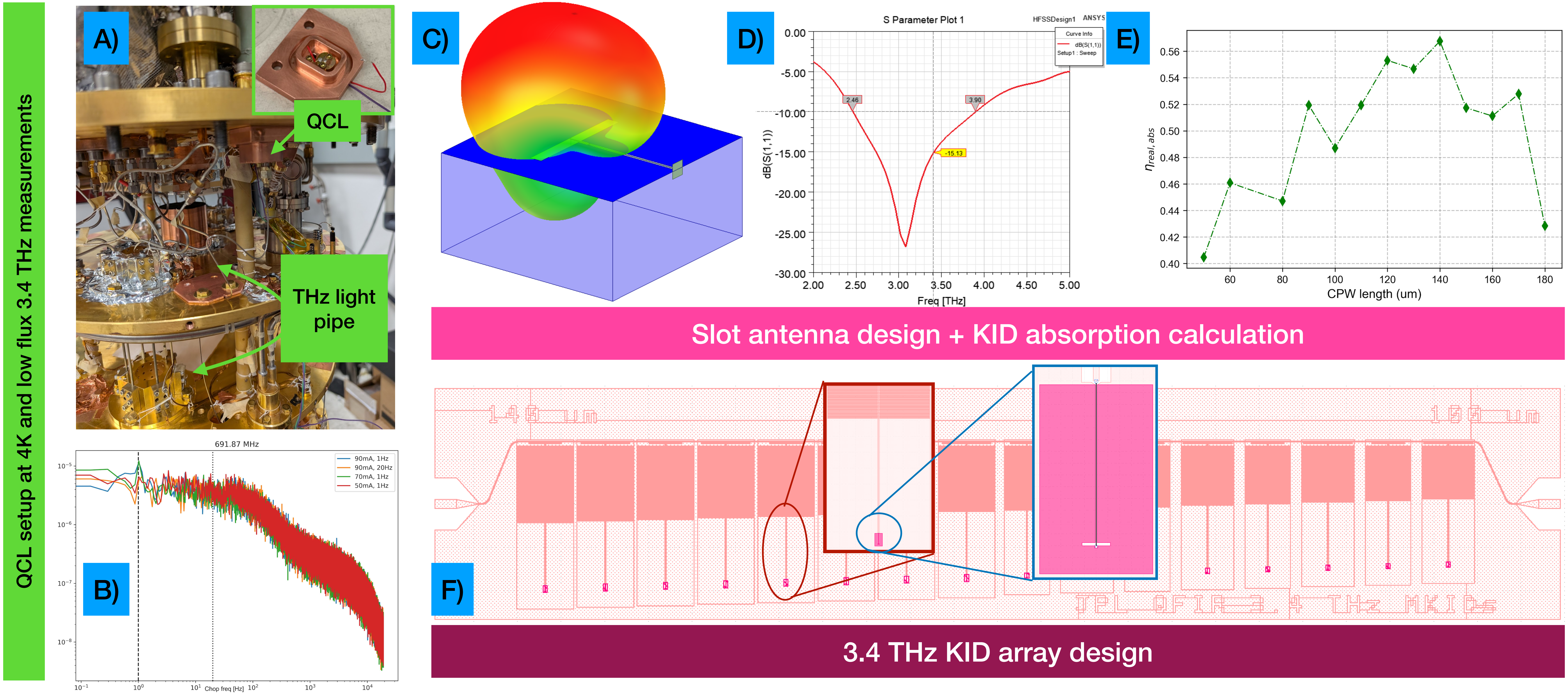
# From GHz to THz

*"Photon counting surpasses the standard quantum limit…"**
*~ Sushkov, PRX Quantum 4, 020101 – 22 May, 2023*

At $10^{\pm 1}$ THz designing high volume cavities are difficult and coherent measurements can be worse than SQL over wide bands.

So, every photon counts and we build photon counting THz detectors.

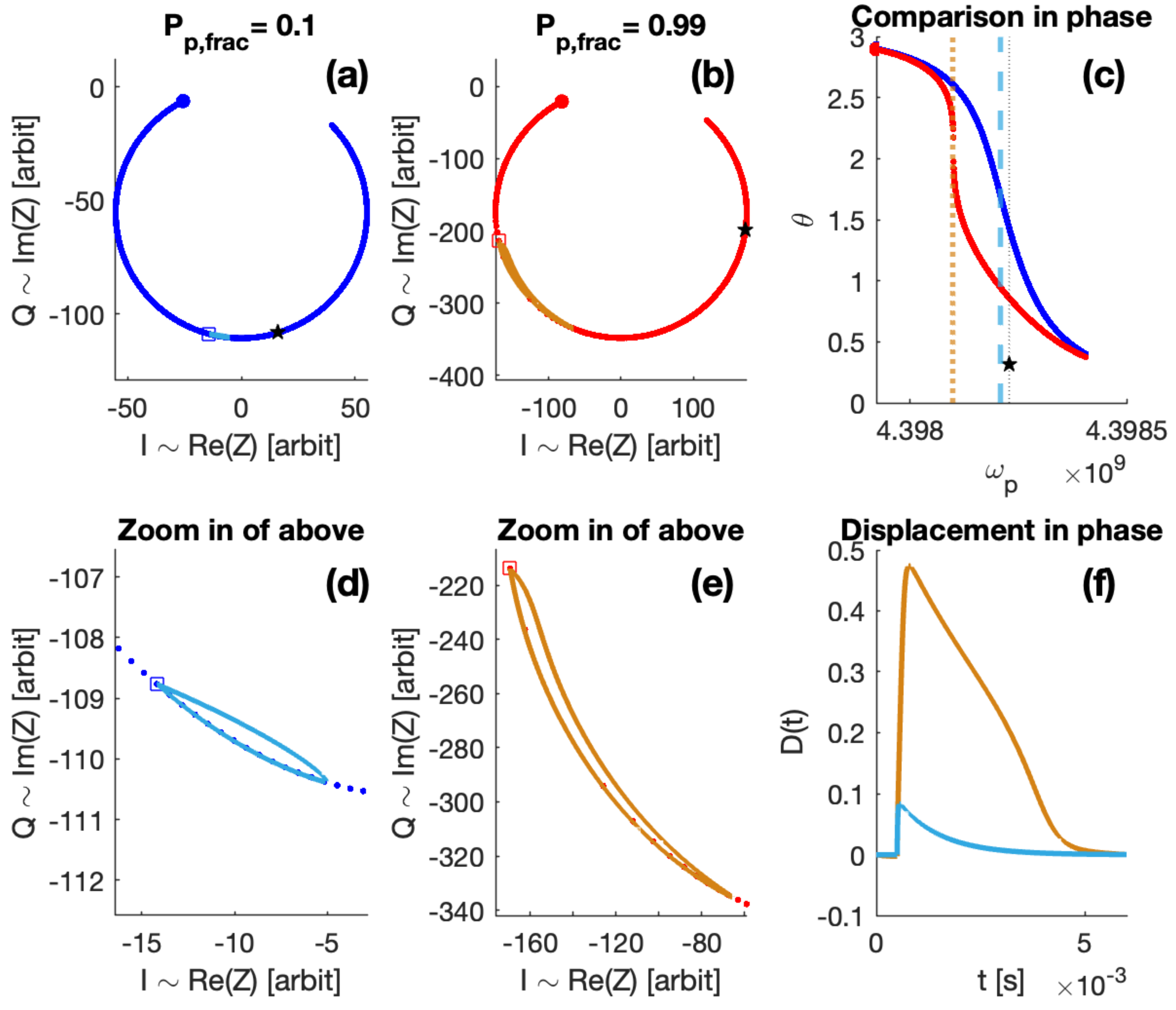
*Noise Equivalent Power of radiometric vs photometric measurements.*

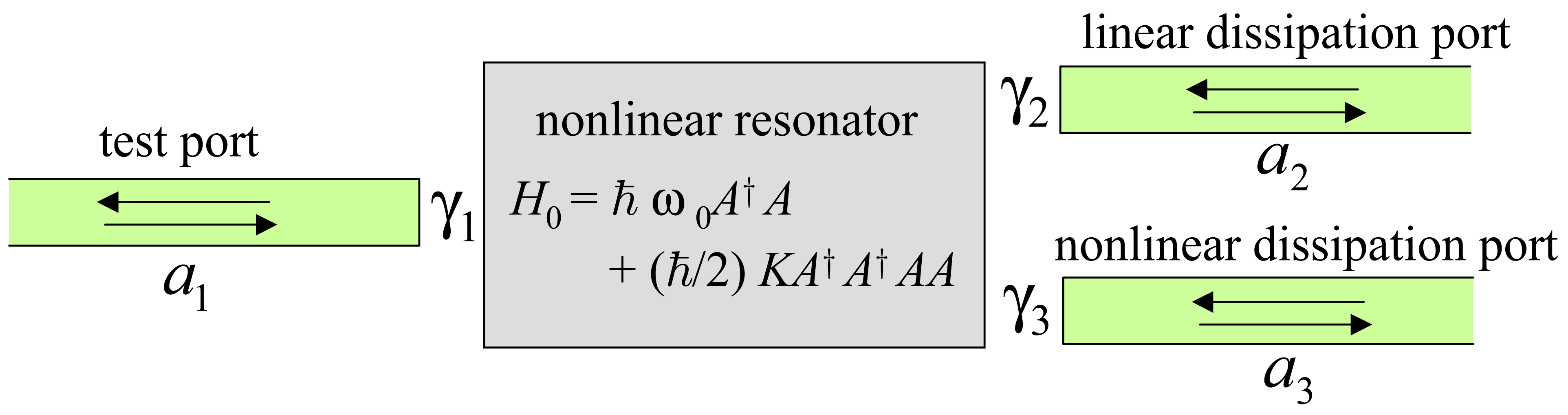


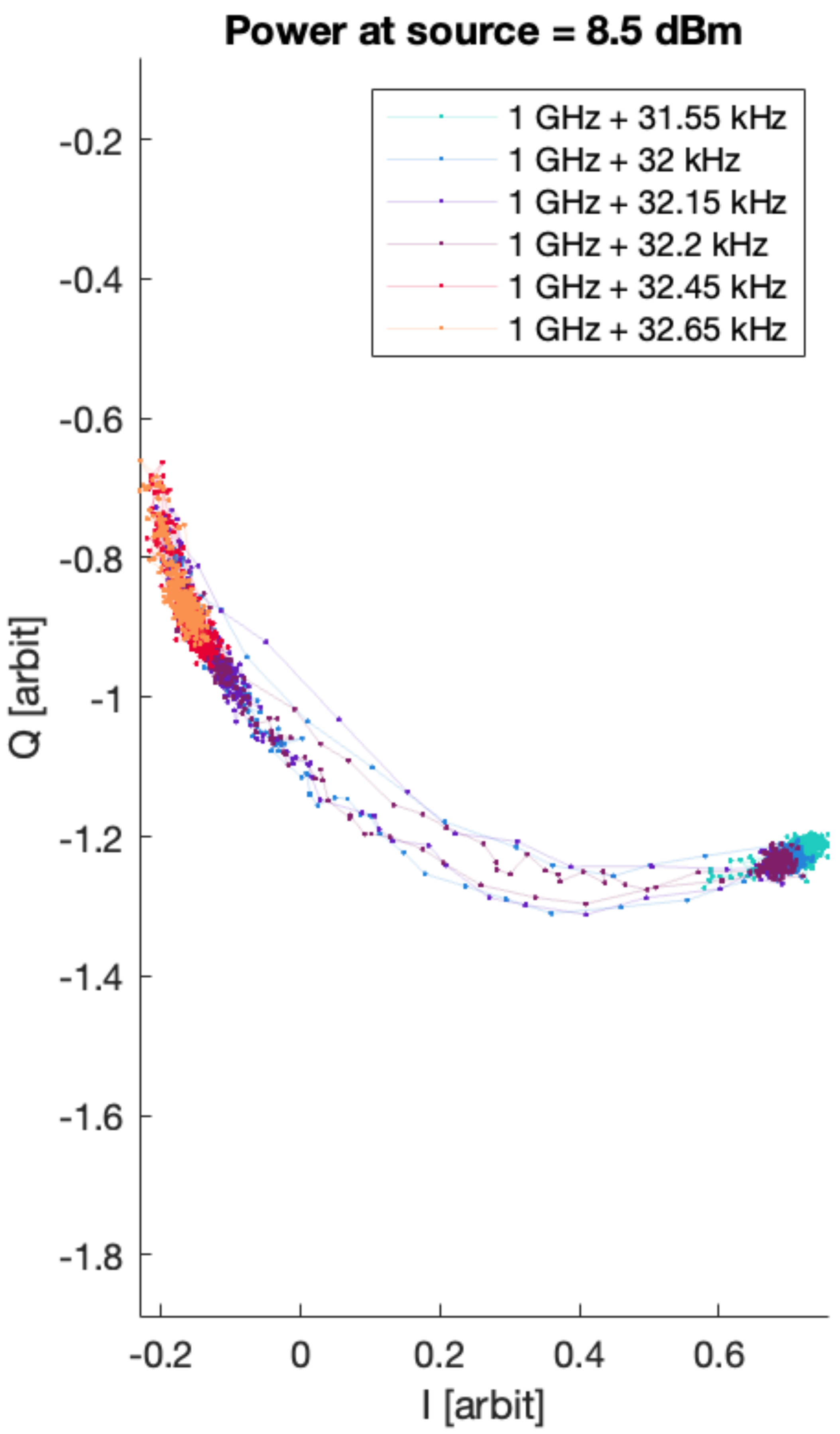

QCL @ 3.4 THz setup in the cryostat and measured modulated low-flux response with KIDs (A & B). C-F: 3.4 THz antenna coupled KID design. C-E show antenna and KID absorption simulation, and F shows the designed array with zoom-in of the above elements.

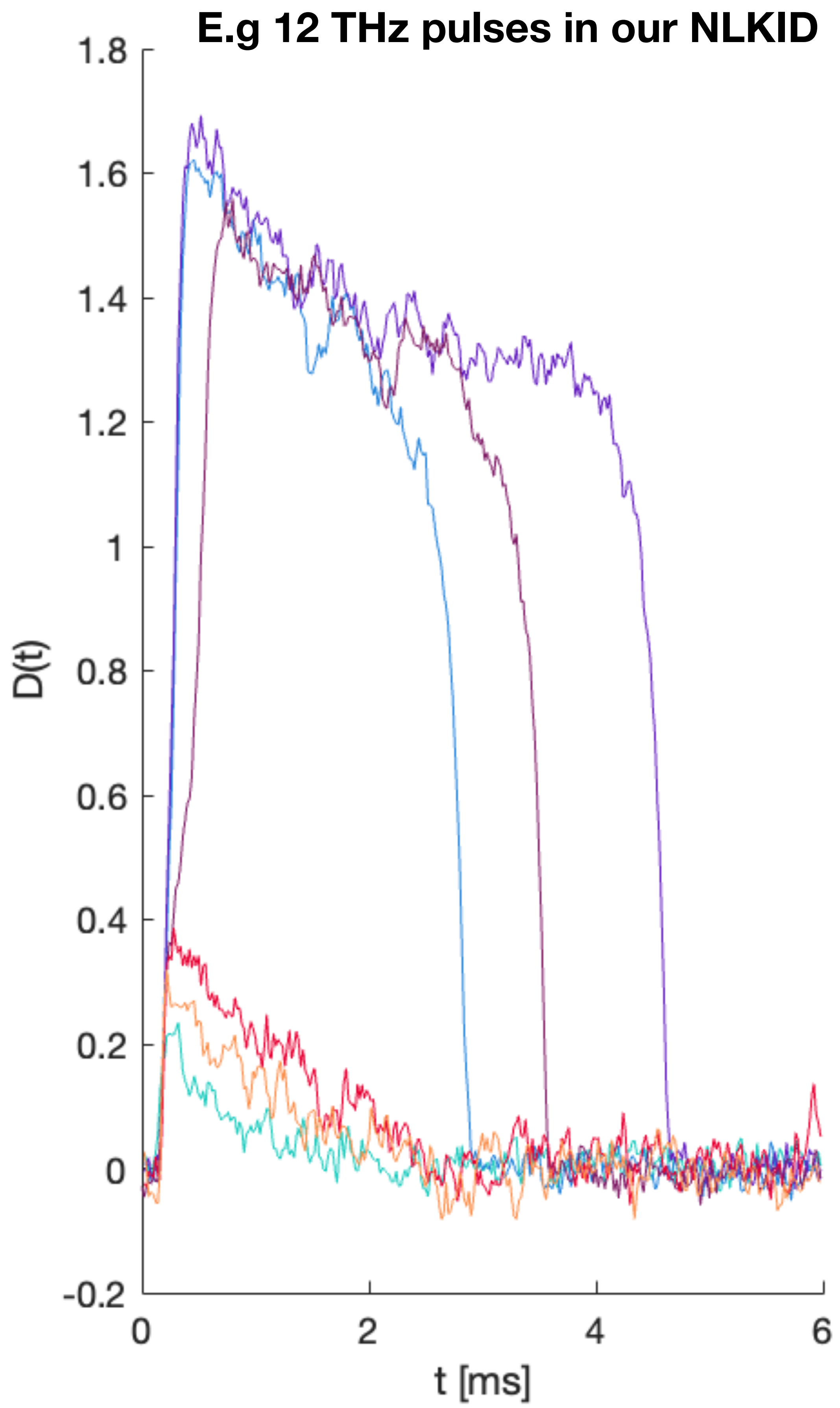
# NLKIDs

## Pulse is amplified via optimally coupling pump power to signal power



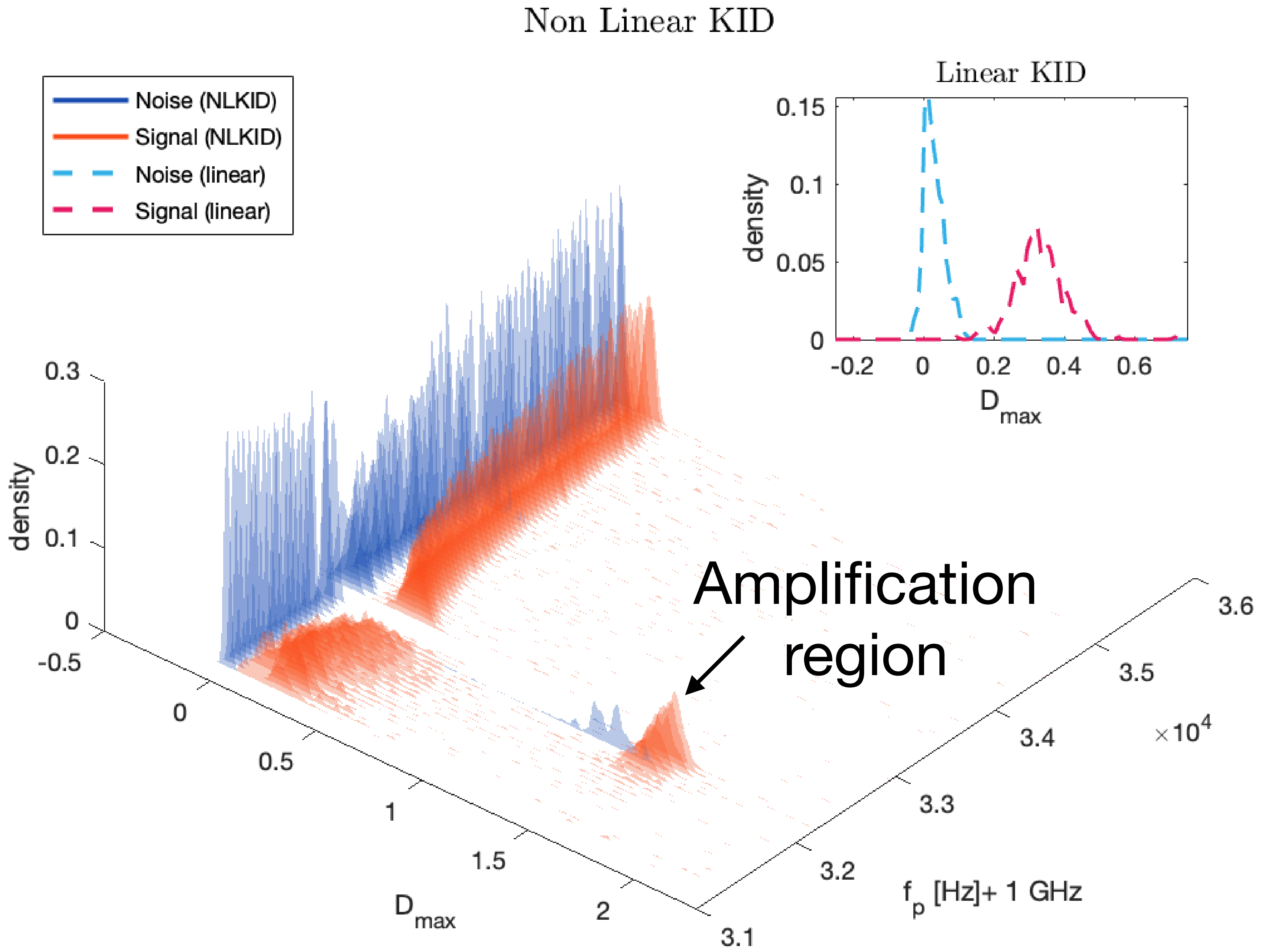



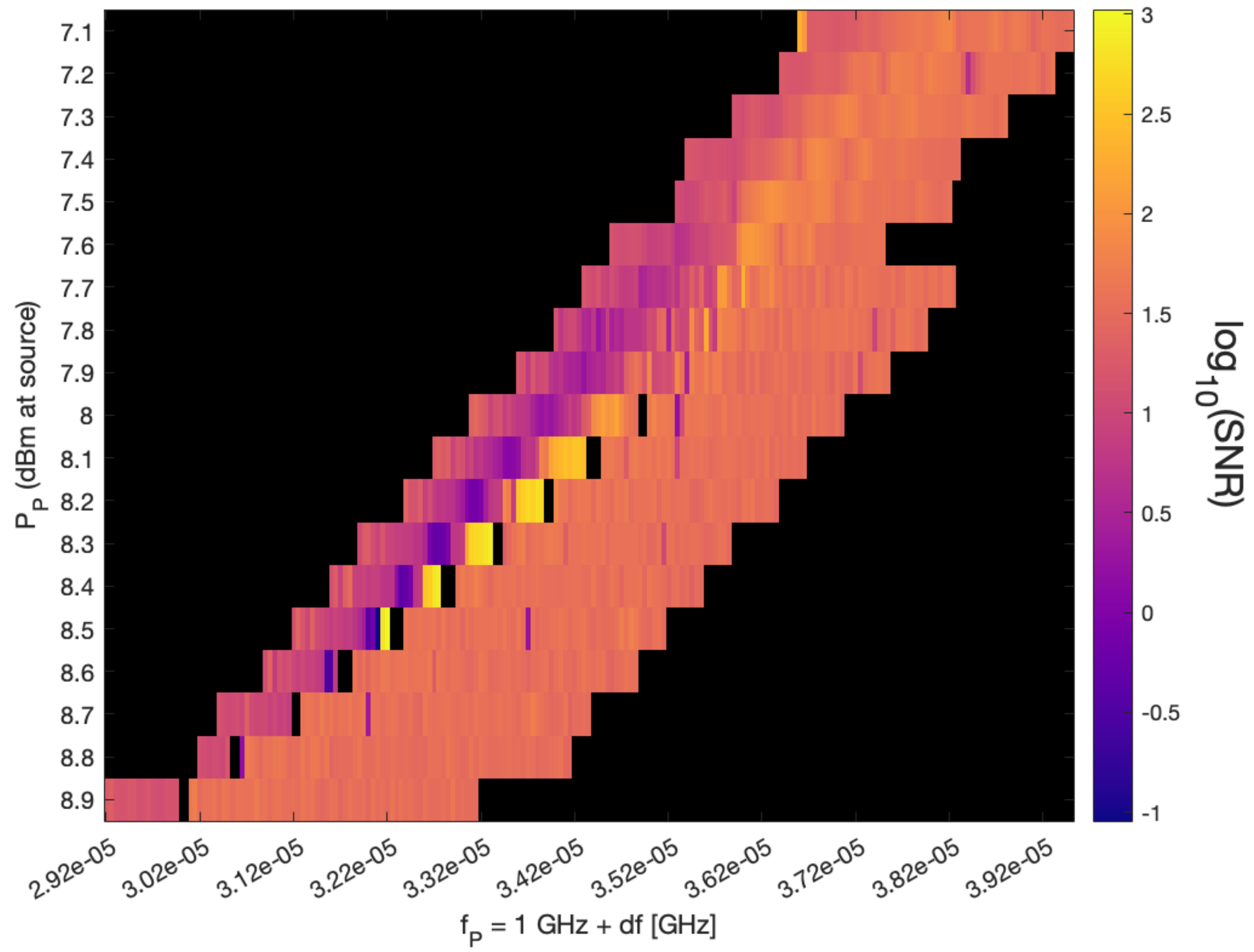

Top-left: Simulation of a **Non-Linear Kinetic Inductance Detector** responding to THz photons. Right: NLKID data

# NLKIDs @ 3 THz

A)

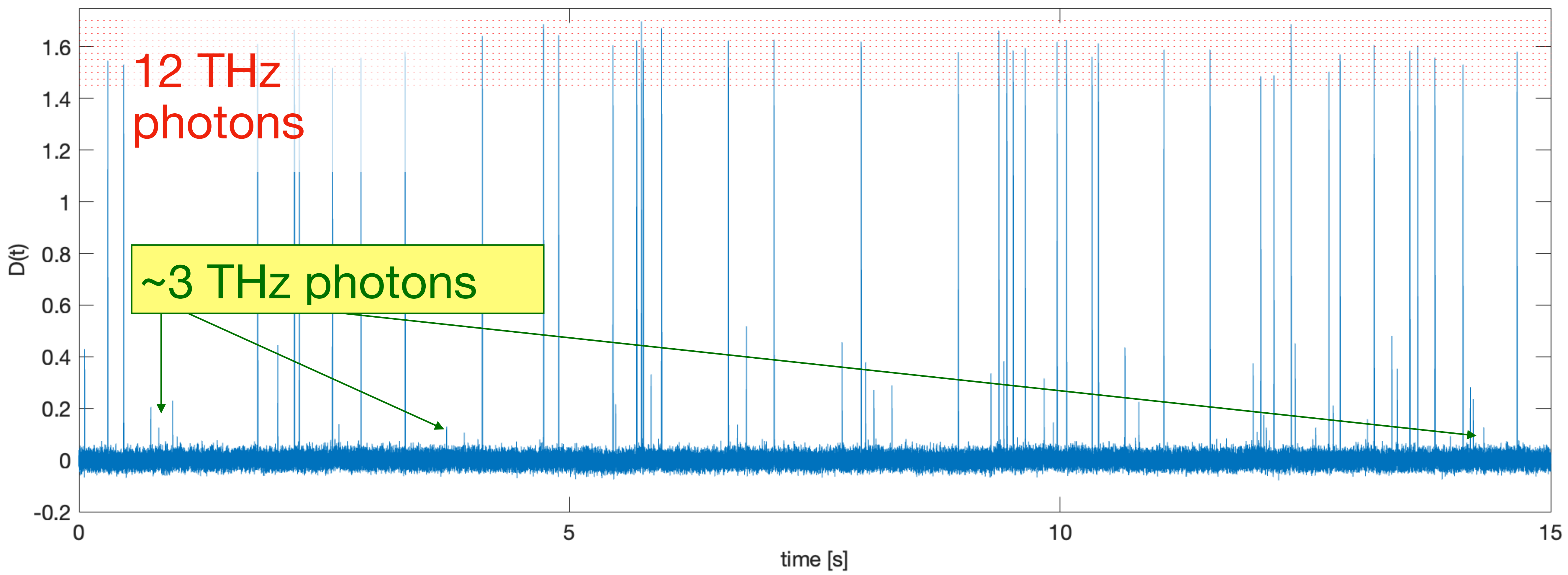



B)




NLKID response in 12 THz maximization mode

C)




A) Optimization holding pump power and varying pump frequency reveals a high amplification region. Compared to linear operations, single photons are measured with much larger pulse amplitudes without increasing noise.

B) Signal to Noise ratio from comprehensive pump tuning. We can easily enhance SNR from ~20 to > 1000.

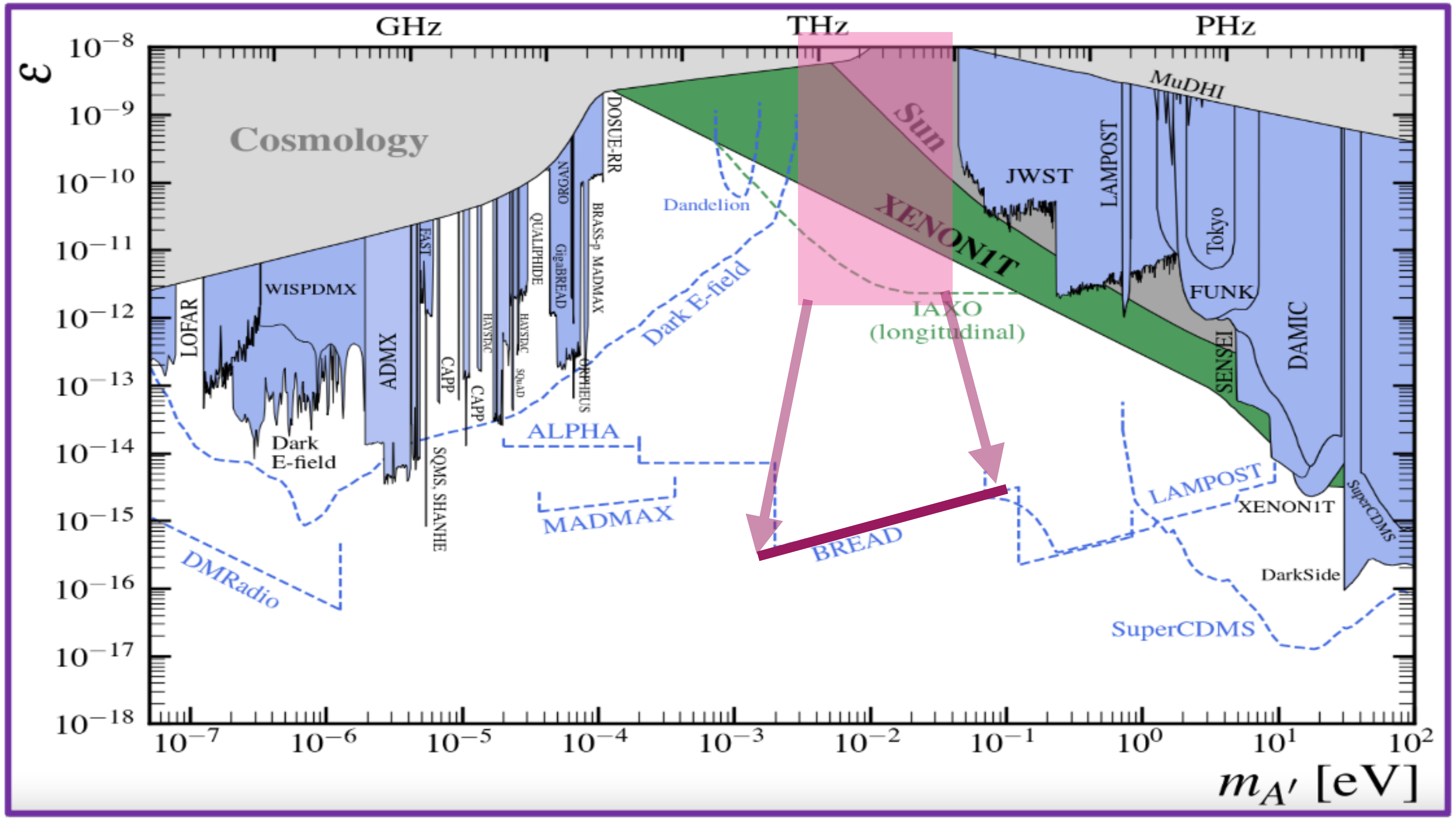
C) Amplification of the 12 THz photons (red) also “extracted” few-THz photons. This leads to a new form of natively multiplexed photon counting detector in the THz.

# QUALIPHIDE @ FIR

Once this demonstration science run is done ….

1) Future plans to have such single-photon sensing KIDs operate down to 0.6 THz *(need to secure R&D $$)*

2) Integrate our detectors with BREAD and other major DM search experiments



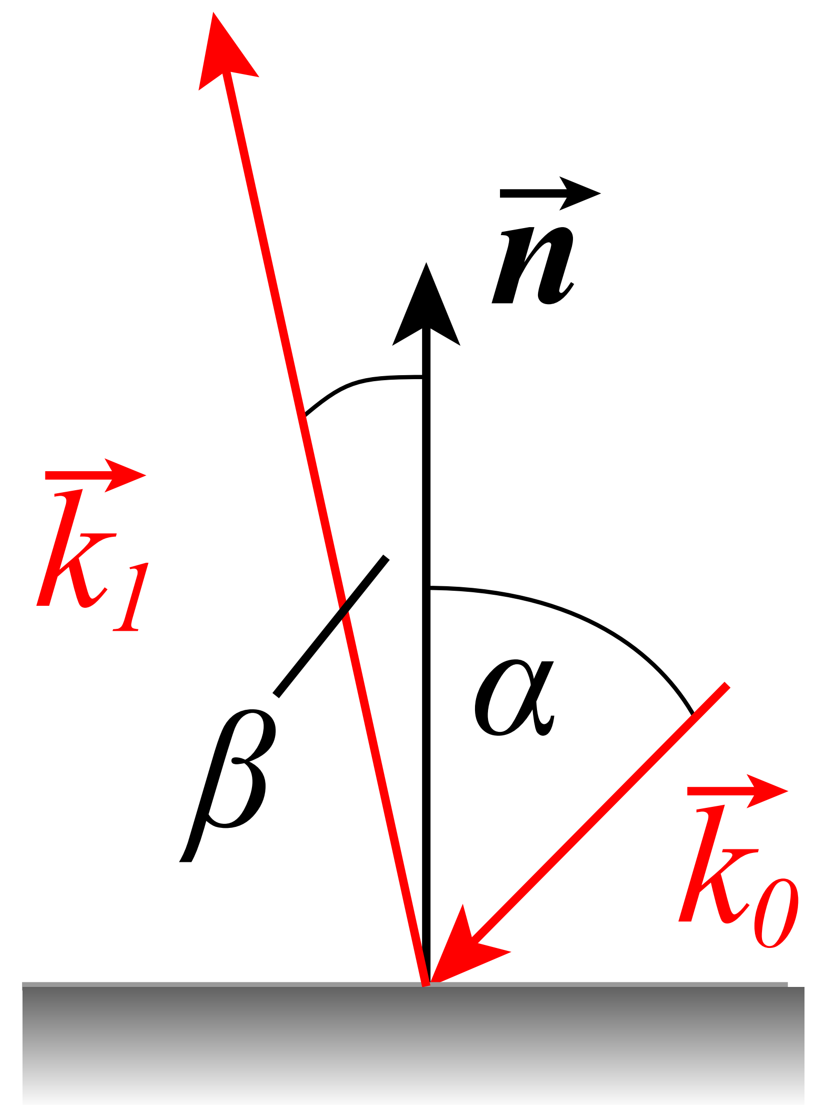

$$\chi_{sens} \approx 2.4 \times 10^{-12} \left[\frac{R_{\gamma,\mathrm{sens}}}{3\,\mathrm{mHz}}\right]^{\frac{1}{2}} \left[\frac{f_\gamma}{12\,\mathrm{THz}}\right]^{\frac{1}{2}} \left[\frac{150\,\mathrm{cm}^2}{A_{\mathrm{sens}}}\right]^{\frac{1}{2}} \left[\frac{N_{\mathrm{sens}}}{4}\right]^{\frac{1}{2}} \left[\frac{0.25}{\epsilon_f}\right]^{\frac{1}{2}}$$

# Hidden Photons

See papers by Dieter Horns and Stefan Knirk and others arXiv:1212.2970, 2203.14915 and references therein. Related experiments, WISPDMX, FUNK, MADMAX, BREAD etc.

HPs and photons are always mixing.

$$\begin{pmatrix} \mathbf{E} \\ \mathbf{E}_{\text{hid}} \end{pmatrix}_{\text{emitted}} = \mathbf{E}_{\text{DM},\parallel} \begin{pmatrix} 1 \\ \chi \end{pmatrix} \exp(-i(\omega t - \mathbf{k}_1 \mathbf{x}))$$




$$\mathbf{k}_{\parallel,1} = \mathbf{k}_{\parallel,0}$$

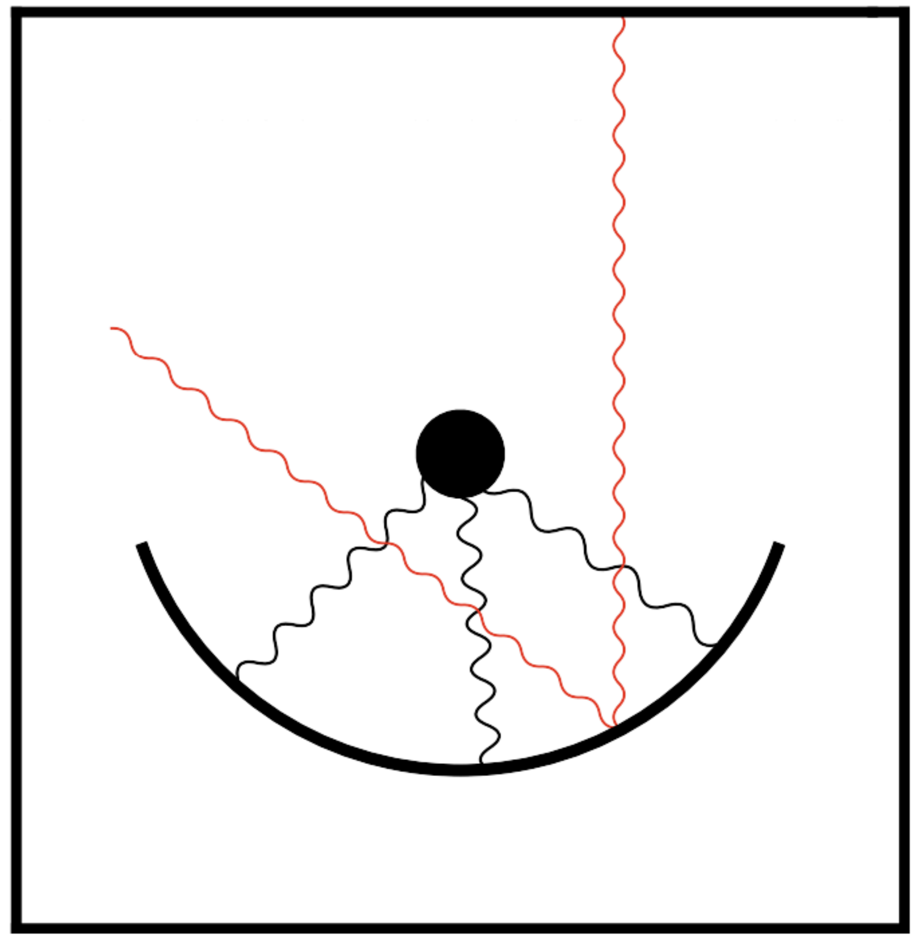
**Symmetry breaking at the metallic surfaces:**
boundary conditions imposed on classical E-field
… leads to HP production

HP energy largely driven by HP mass

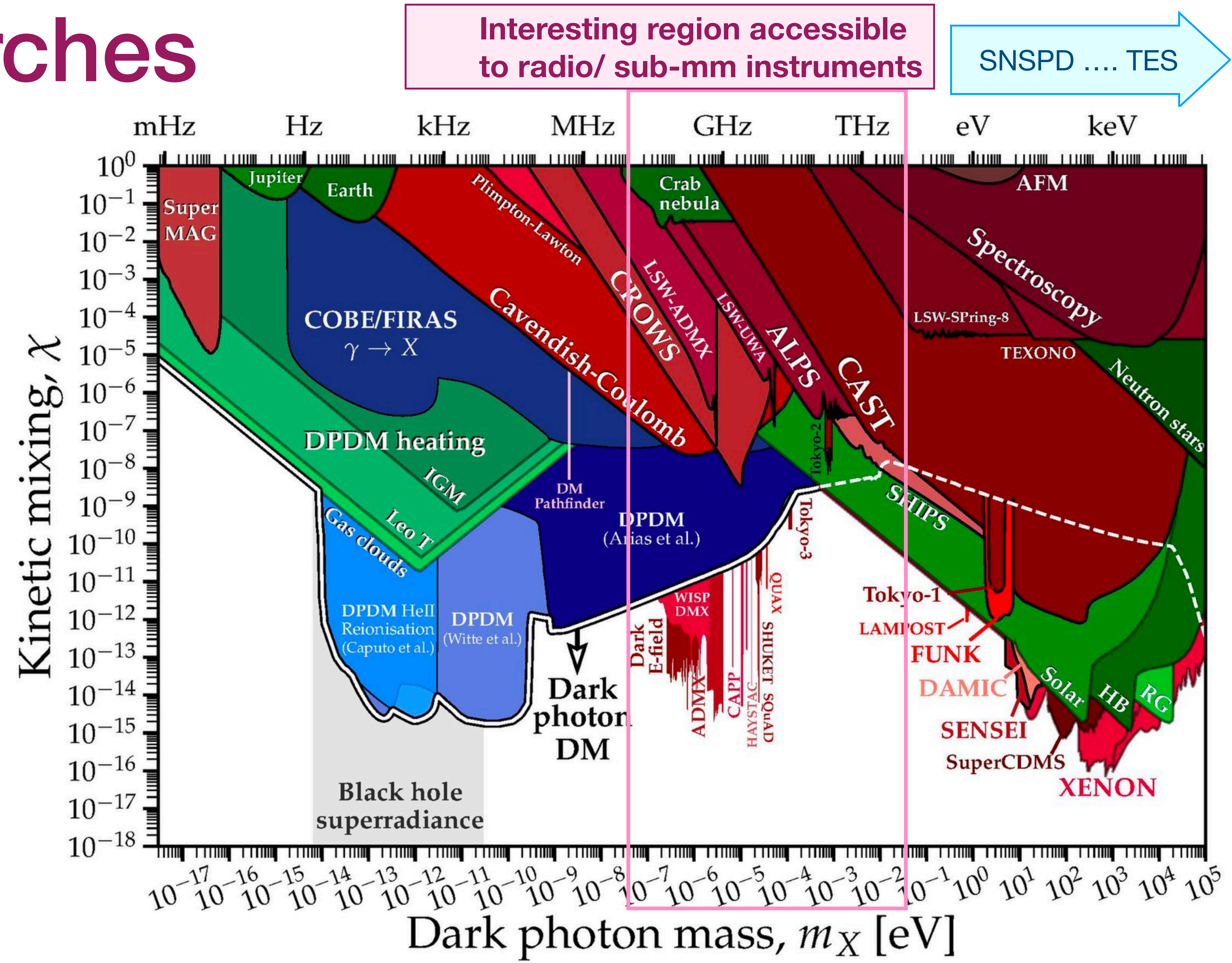
$$\mathbf{k}_1 = \sqrt{m_X^2 + |\mathbf{k}_{\perp,0}|^2}\ \mathbf{n} + \mathbf{k}_{\parallel,0}$$

Angle ~normal, 0.1% scatter from f(v)

# HP-Dish searches



$$P_{\rm centre} \sim \chi^2 \rho_{\rm CDM} A_{\rm dish}$$



# Our approach

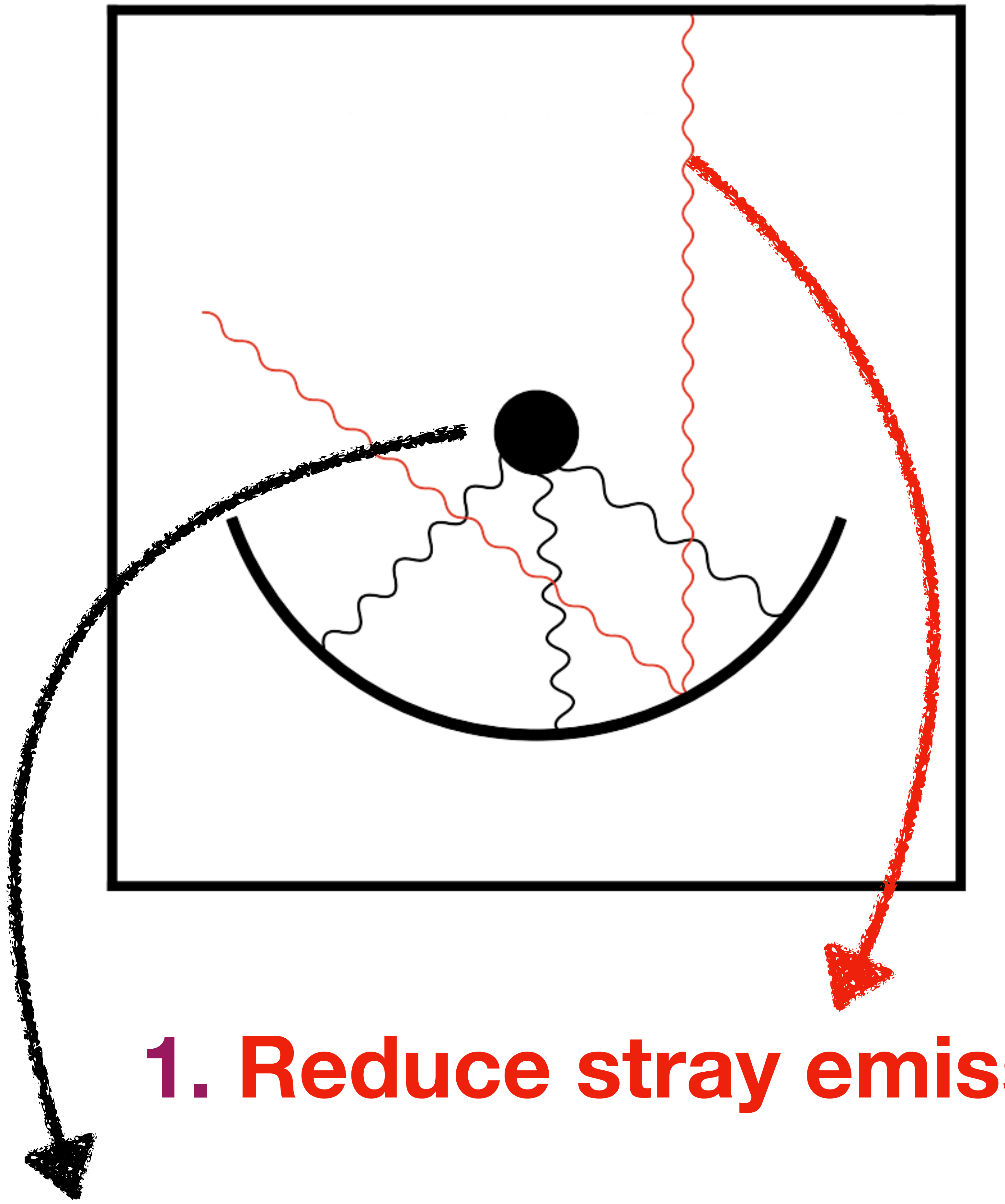
1. Since the experiments are all in the GHz-THz range, cryogenics makes sense

**Lower T, v_peak below signal band**

$$\nu_{peak-background} \approx 60\mathrm{GHz} \times (T/K)$$

*Same idea as CMB receiver design*

We operate at ~20 mK and the estimate for the background NEP is 10^-23 W/rt.Hz, sufficiently low for performing HP searches > GHz



**1. Reduce stray emissions**

**2. Improve photo detection to the standard quantum limit**

# Our approach

2. Not background photon noise limited, **amplify the signal to the standard quantum limit**

Again, constraint on operating temp. We have T = 0.02K

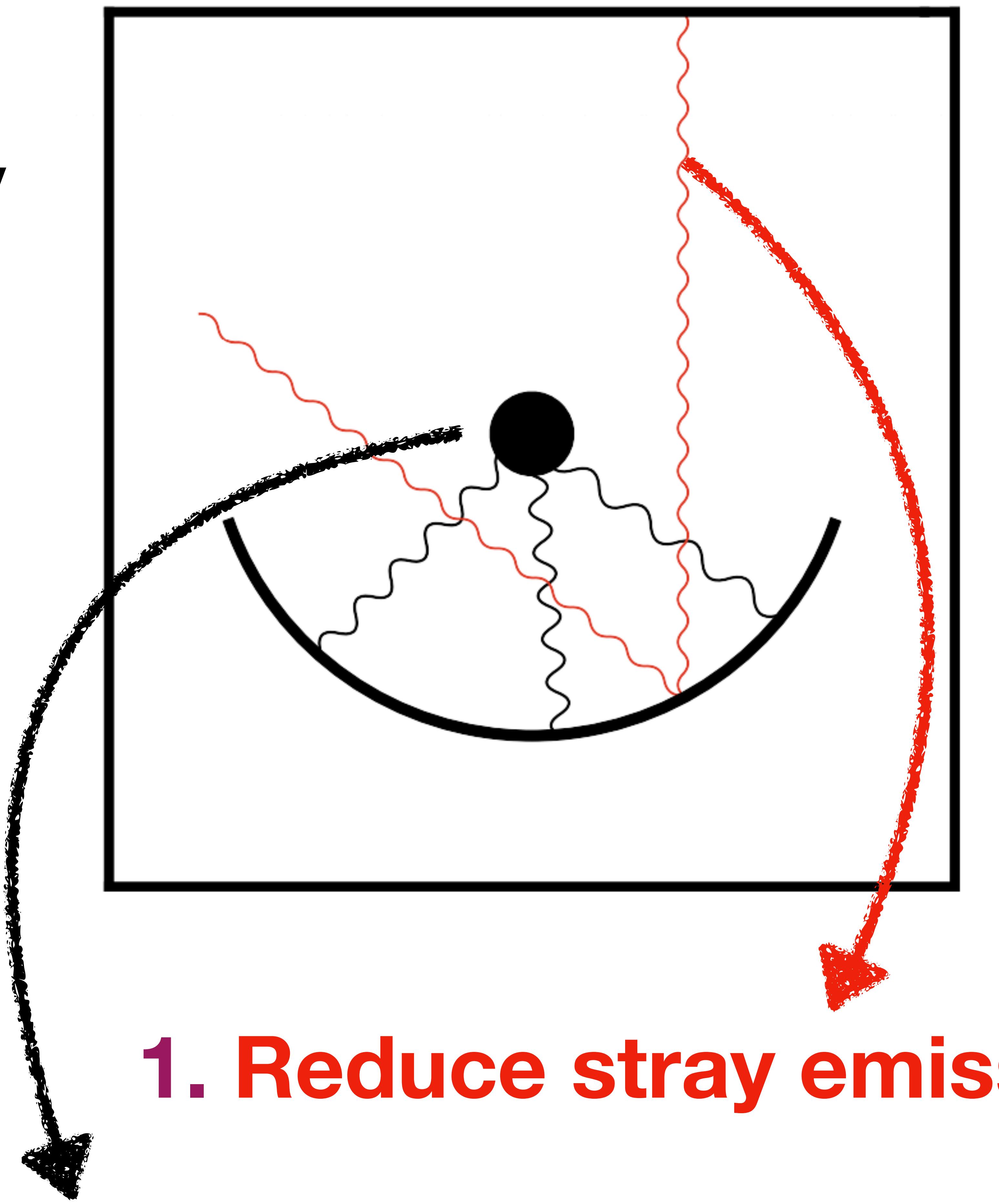
$$\frac{1}{2}h\nu \gg kT$$

Lower the system temperature to SQL, i.e., use parametric amplifier

$$\mathrm{SNR} = \frac{P_{\mathrm{det}}}{k_{\mathrm{B}}T_{\mathrm{sys}}}\sqrt{\tau/\Delta}$$

$$T_{\mathrm{sys}} = h\nu/k \cdot N_{quanta}$$

At SQL (N_quanta = 0.5)
5 GHz, Tsys = 0.12 K
50 GHz, Tsys = 1.2 K
0.5 THz, Tsys = 12 K



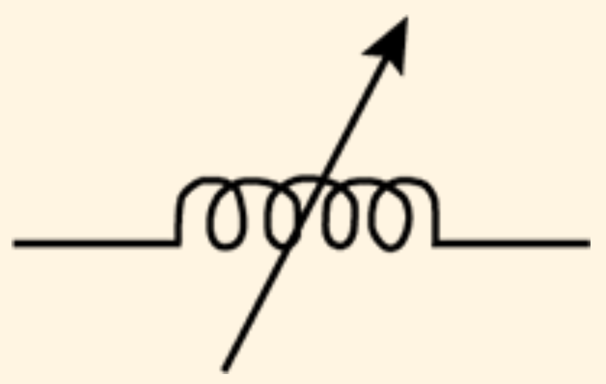
1. Reduce stray emissions

**2. Improve photo detection to the standard quantum limit**

# Non Linear Kinetic Inductance (NLKI)

Inertia of Cooper-pairs leads to **kinetic inductance**, or lag w.r.t oscillating EM fields… depends **nonlinearly** on current in thin-film superconductors like NbTiN, MgB2

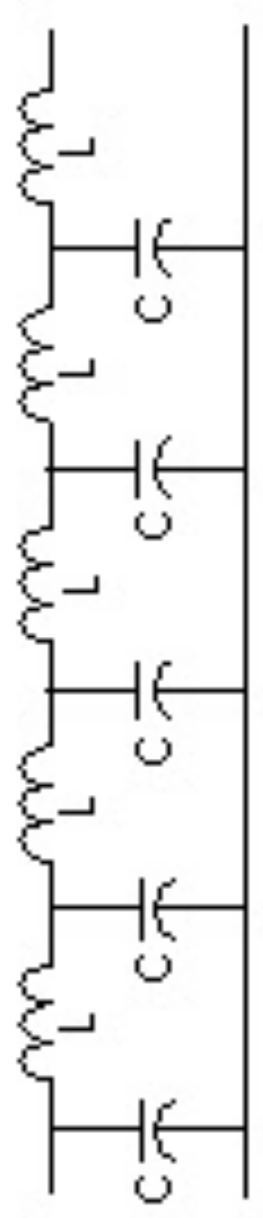
$$\mathcal{L}(I) = \mathcal{L}_0\left(1+\left(\frac{I}{I_*}\right)^2 \dots\right) =$$

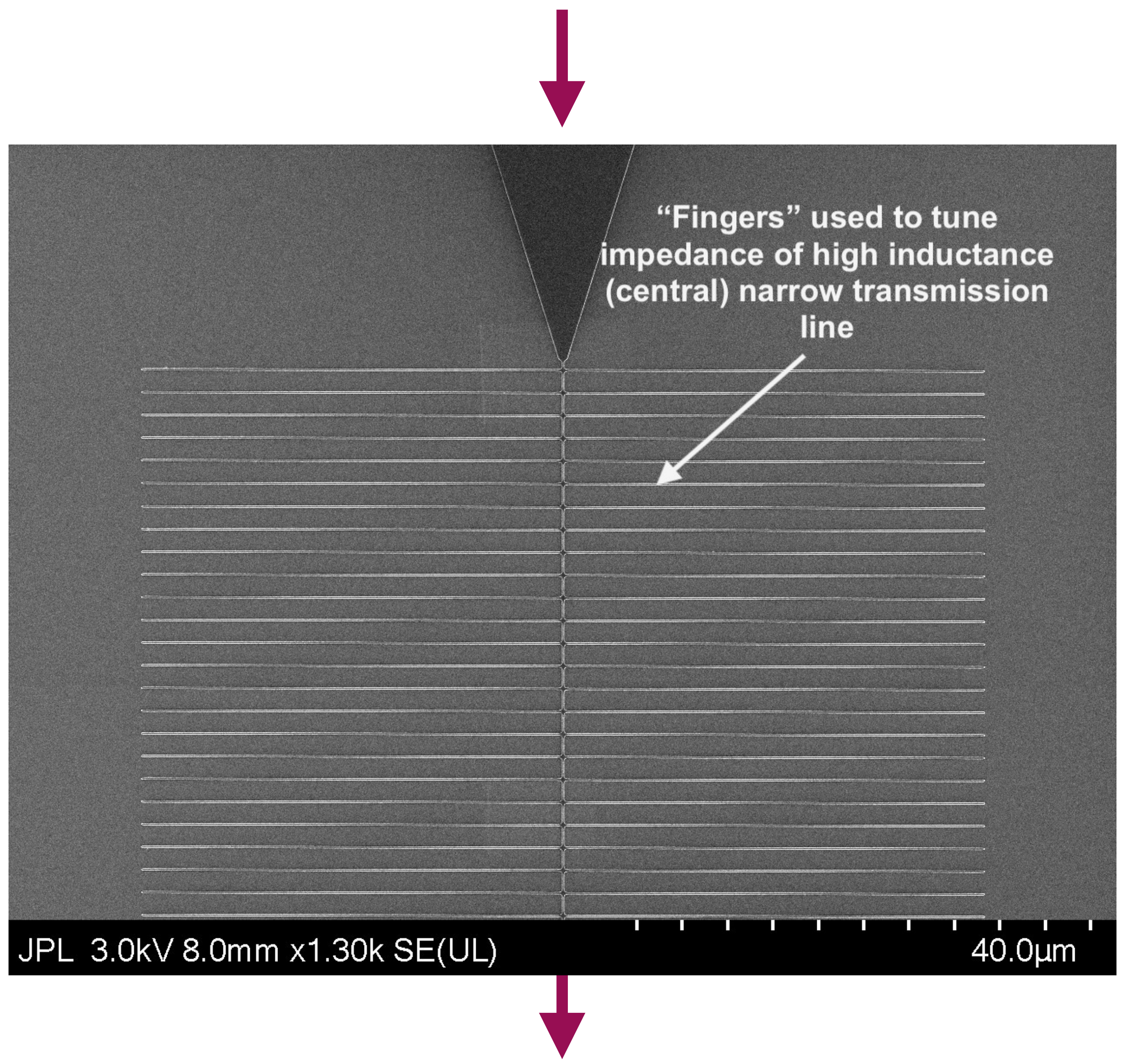


Transmission line = ladder of inductors and capacitors, i.e., “waveguides” in GHz-THz

*30nm thin, 250nm wide NbTiN lines with capacitative fingers for impedance matching*

Modulating fingers 👉🏼 dispersion engineering … enables Kinetic Inductance Traveling Wave Parametric Amplifiers (KI-TWPA)

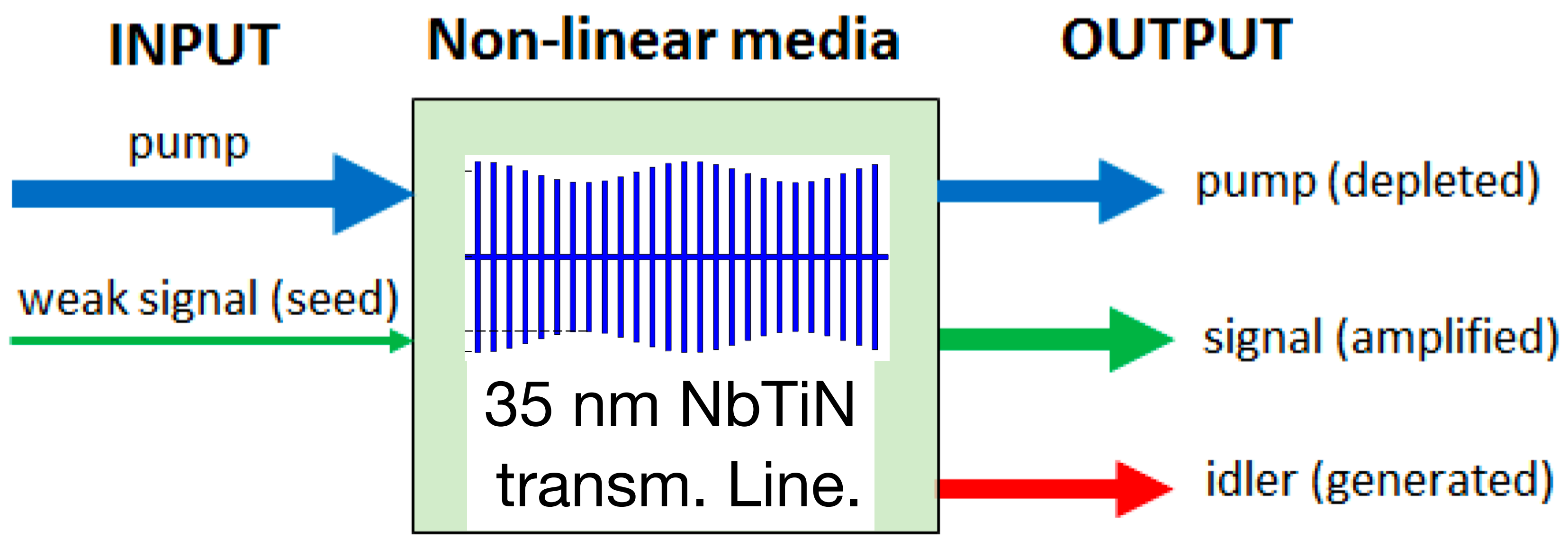




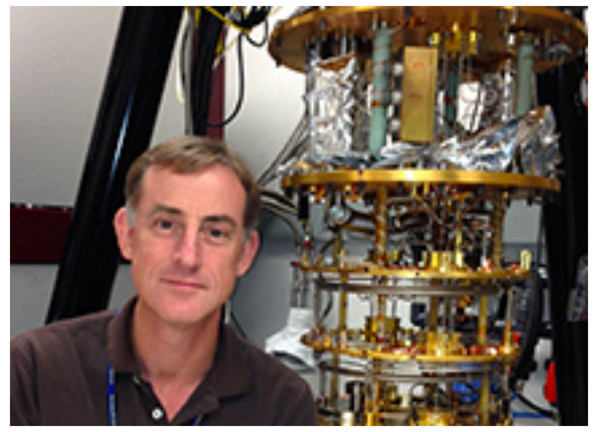
# KI-TWPA

Current driven nonlinearity -> 3 and 4 wave mixing

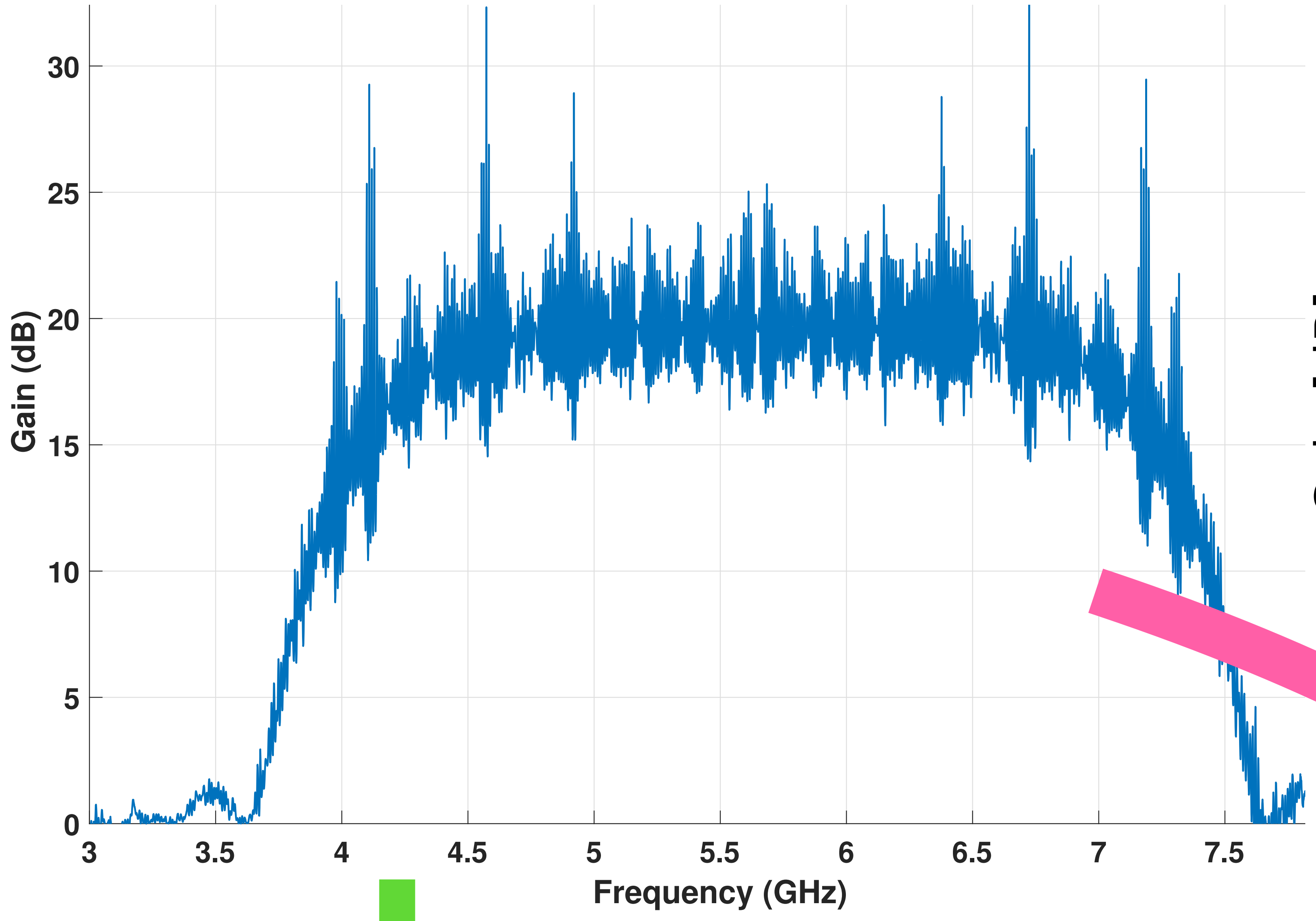
$$\mathcal{L}(I) \approx \mathcal{L}_0 \left(1 + \left(\frac{I}{I_*}\right)^2 + \left(\frac{I}{I'_*}\right)^4 + \ldots\right)$$



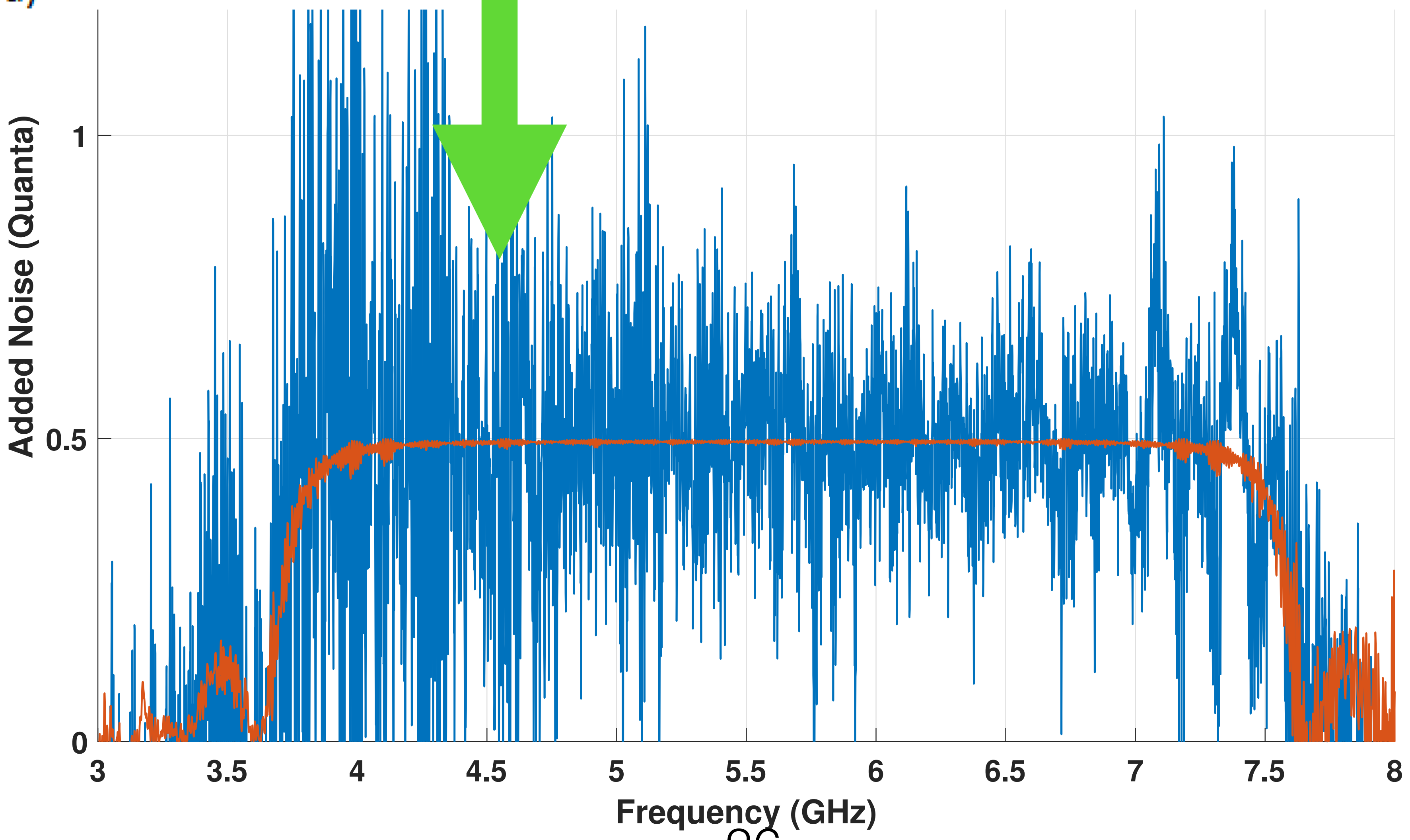

High kinetic inductance enables high gain and compact scalable TWPAs

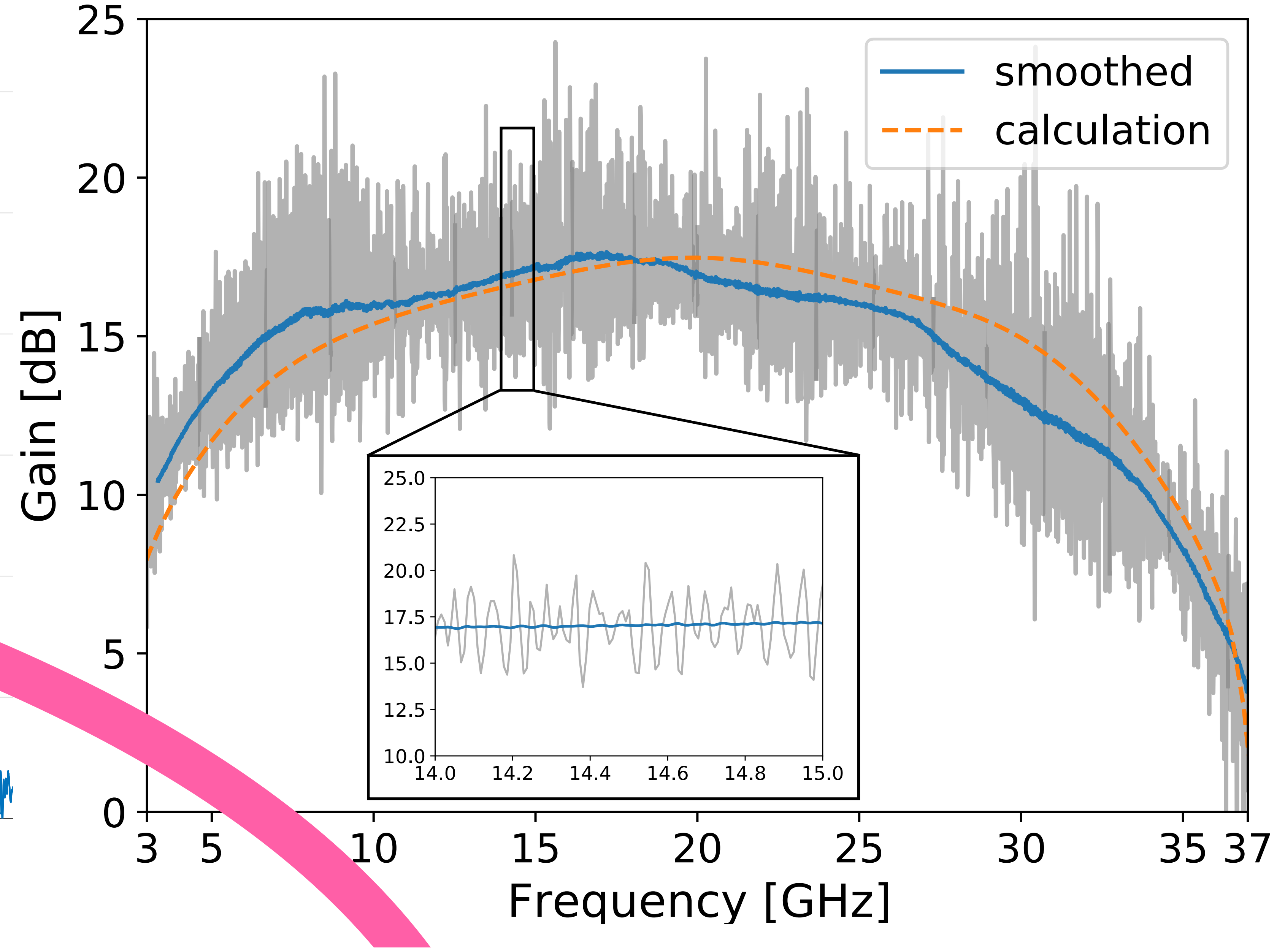


*Peter Day, JPL*

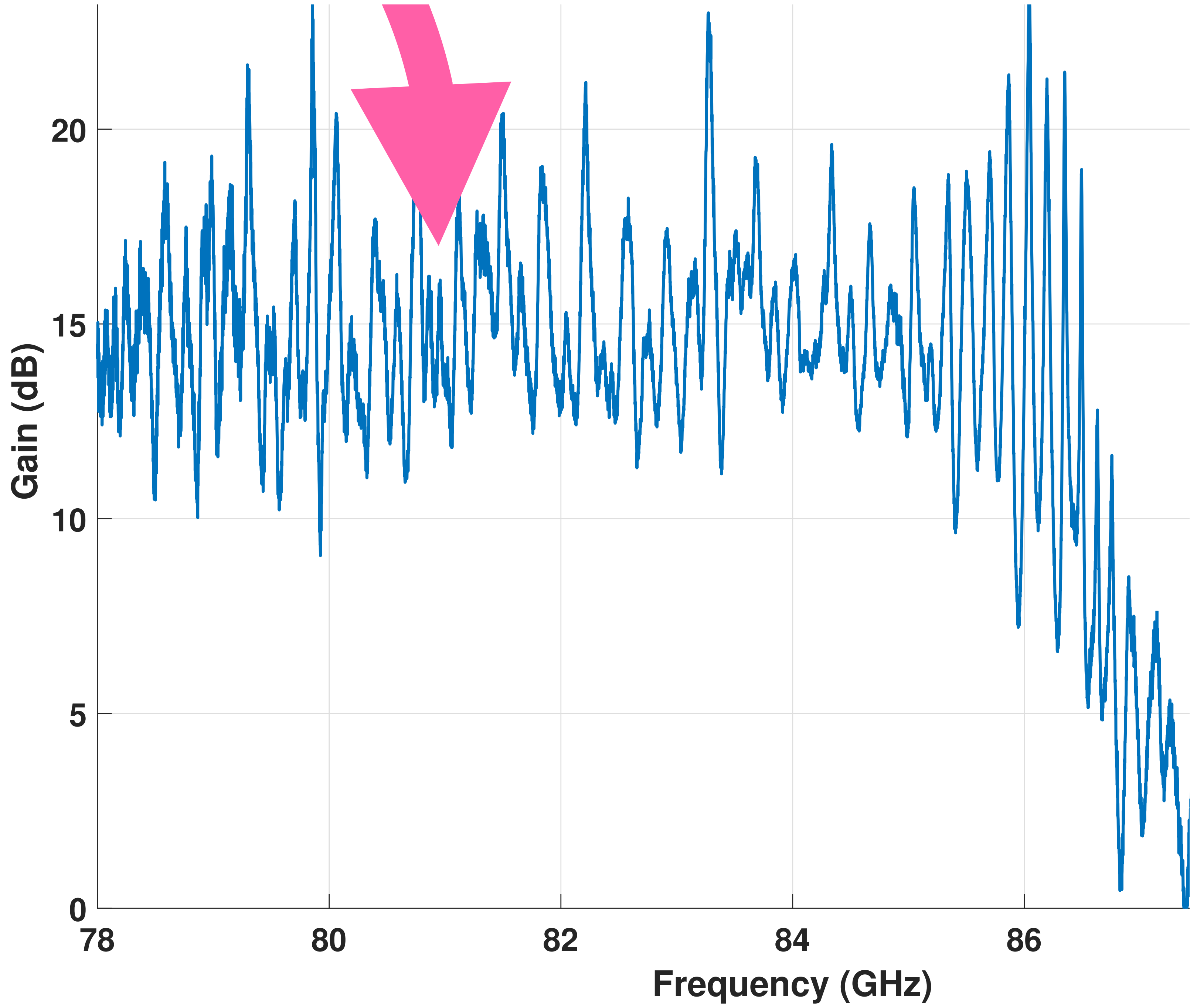



**Gain translates to noise quanta, SQL = 0.5**

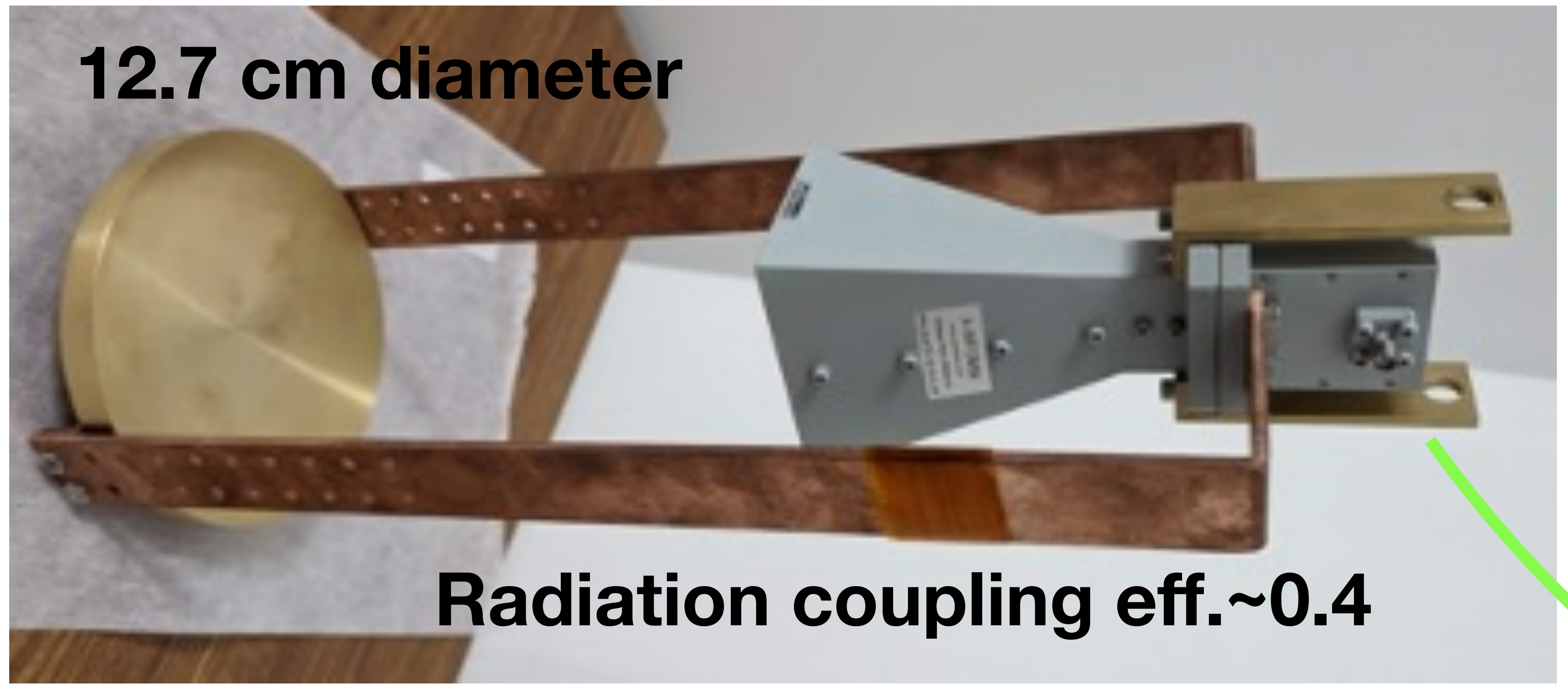


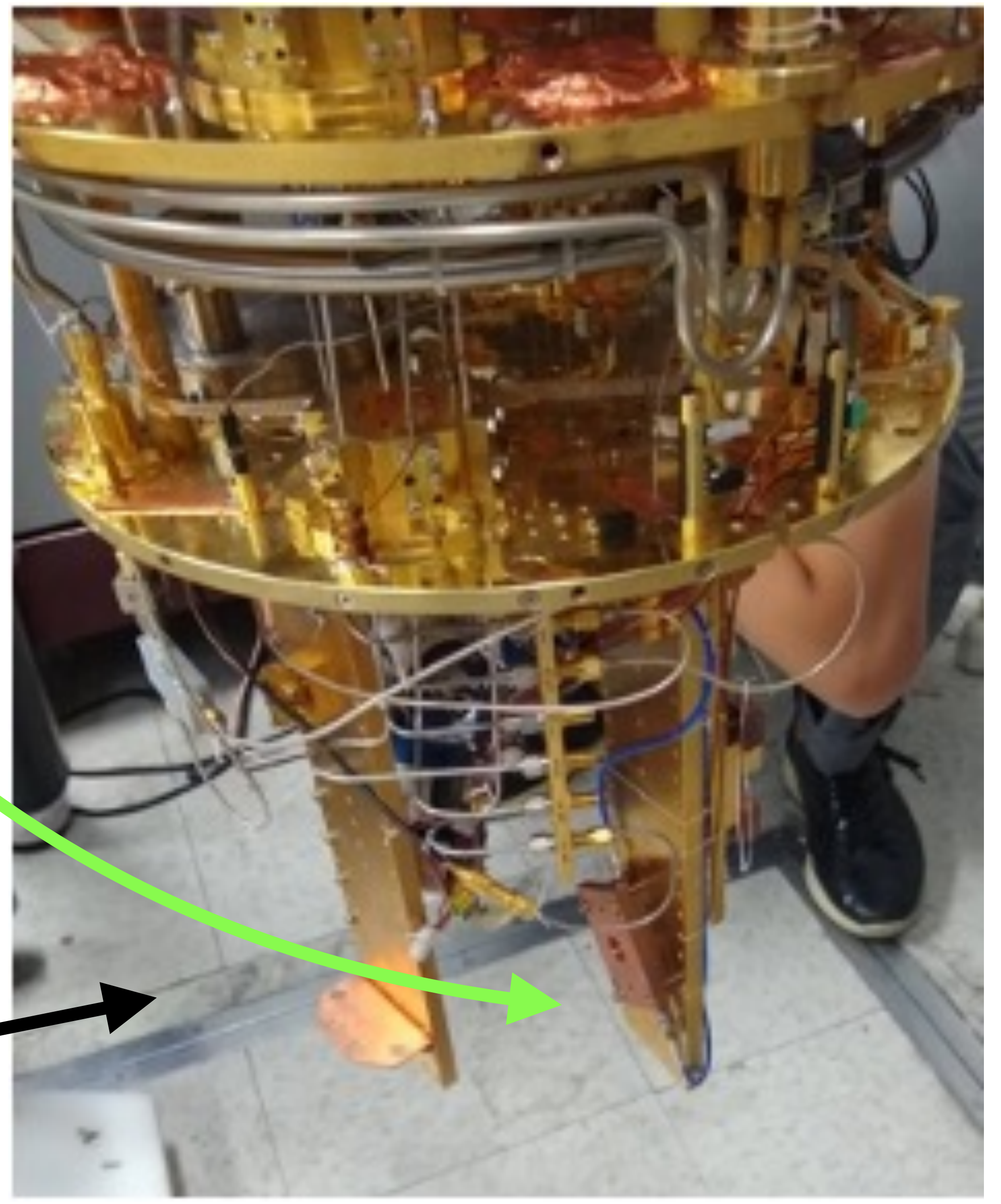



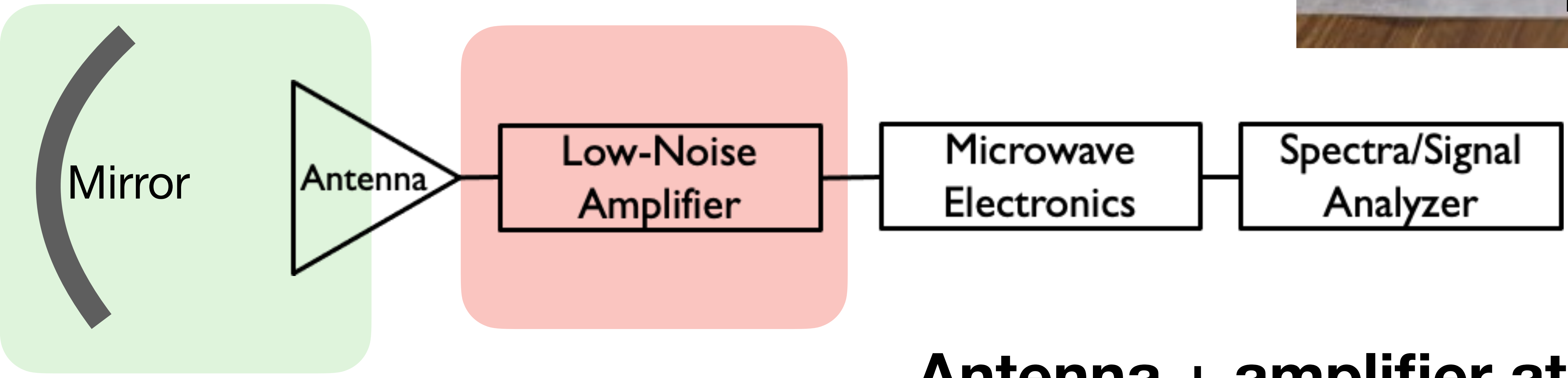

**Ever increasing freq. coverage**



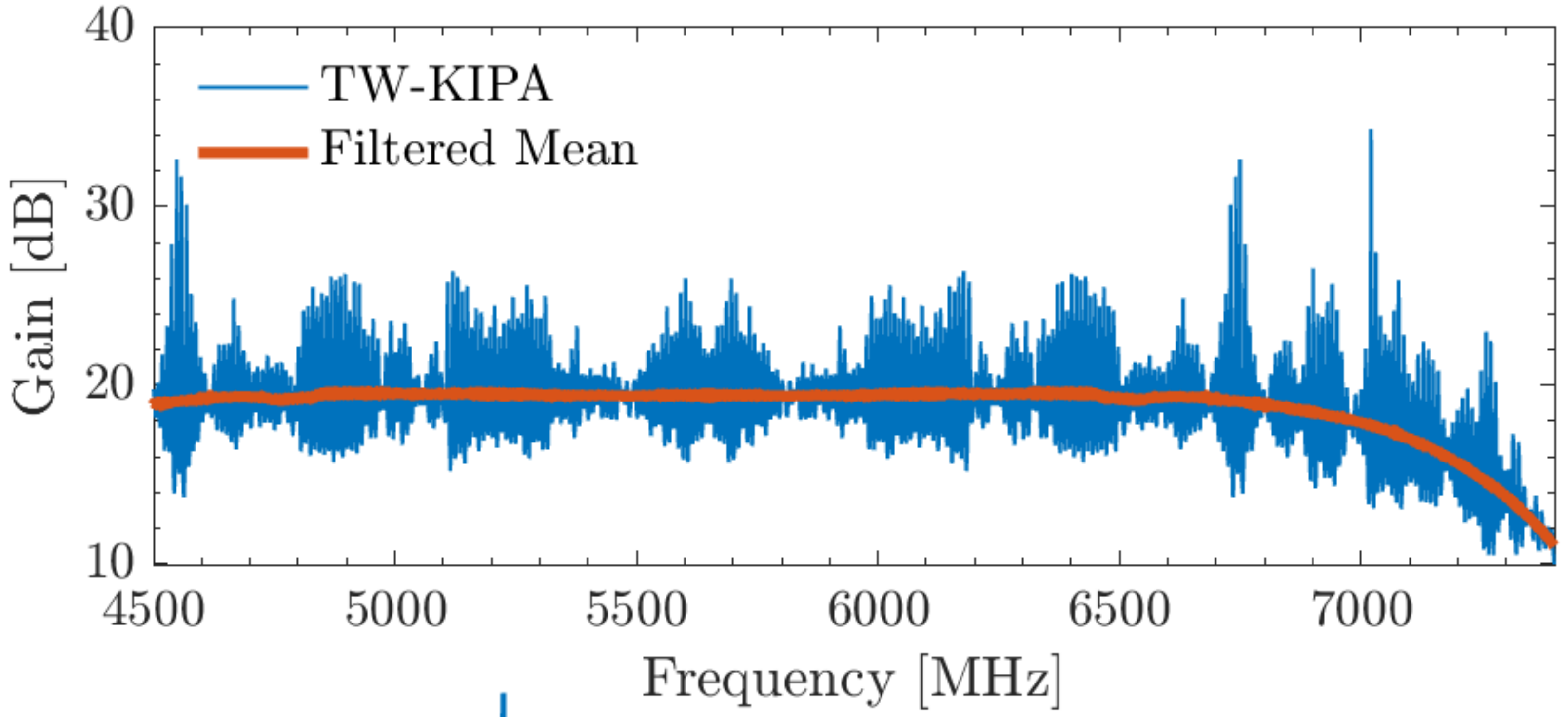
# QUALIPHIDE



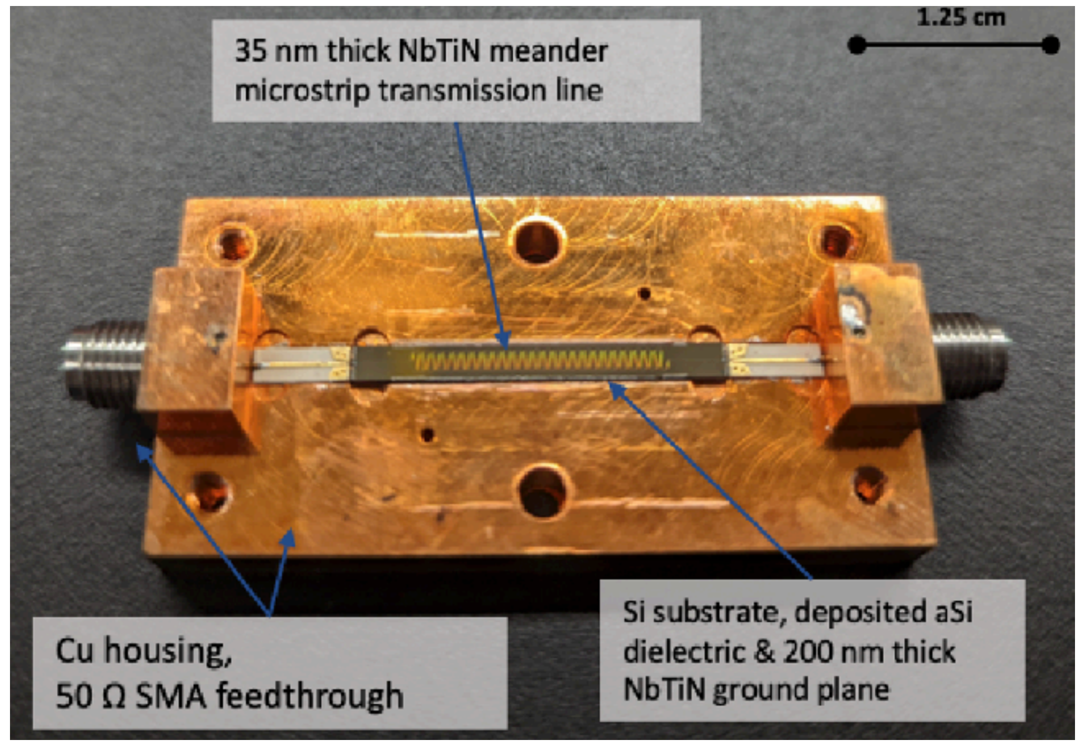



**Antenna + amplifier at 20 mK**



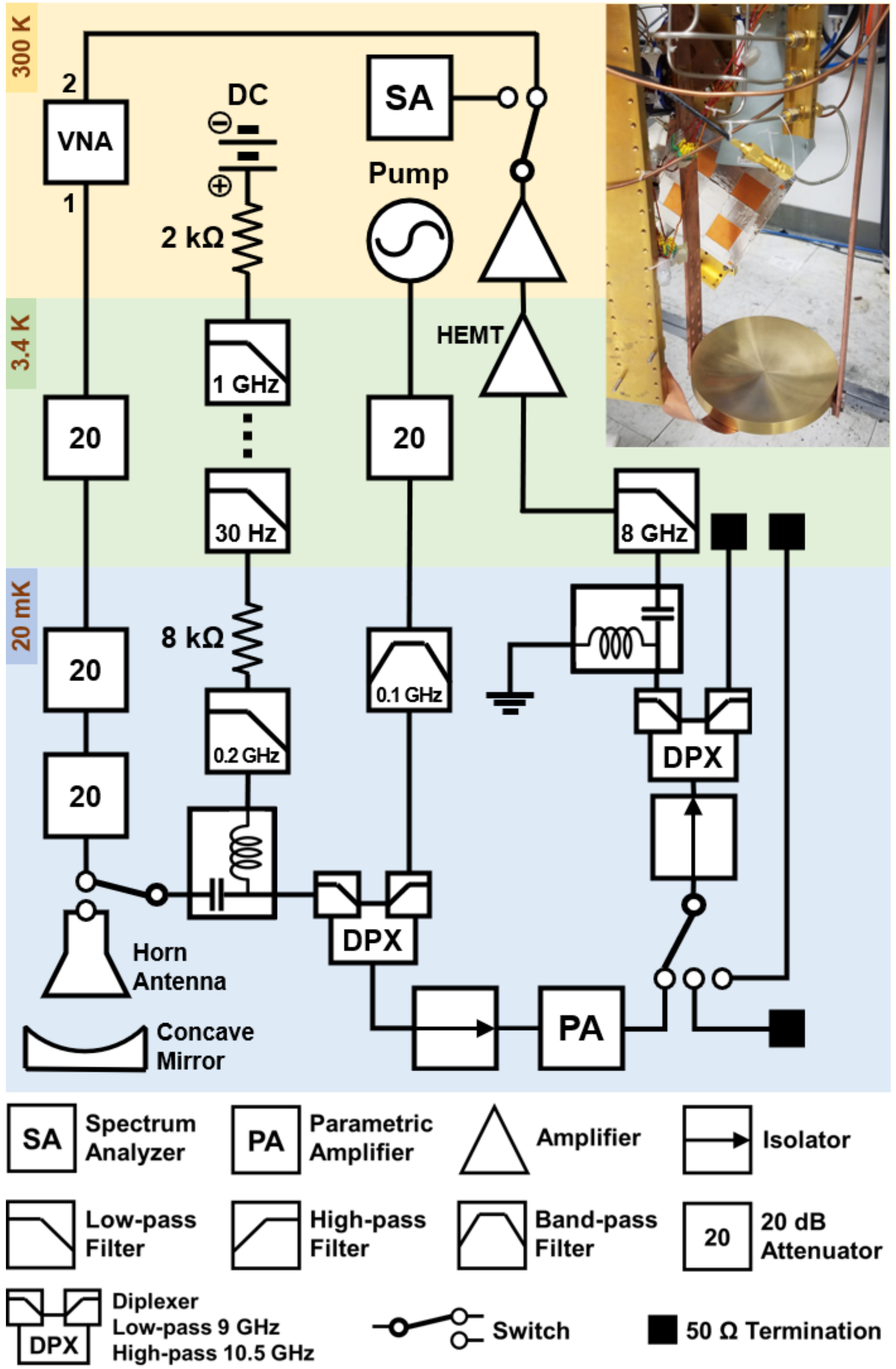

Focus of parabolic mirror at antenna waist

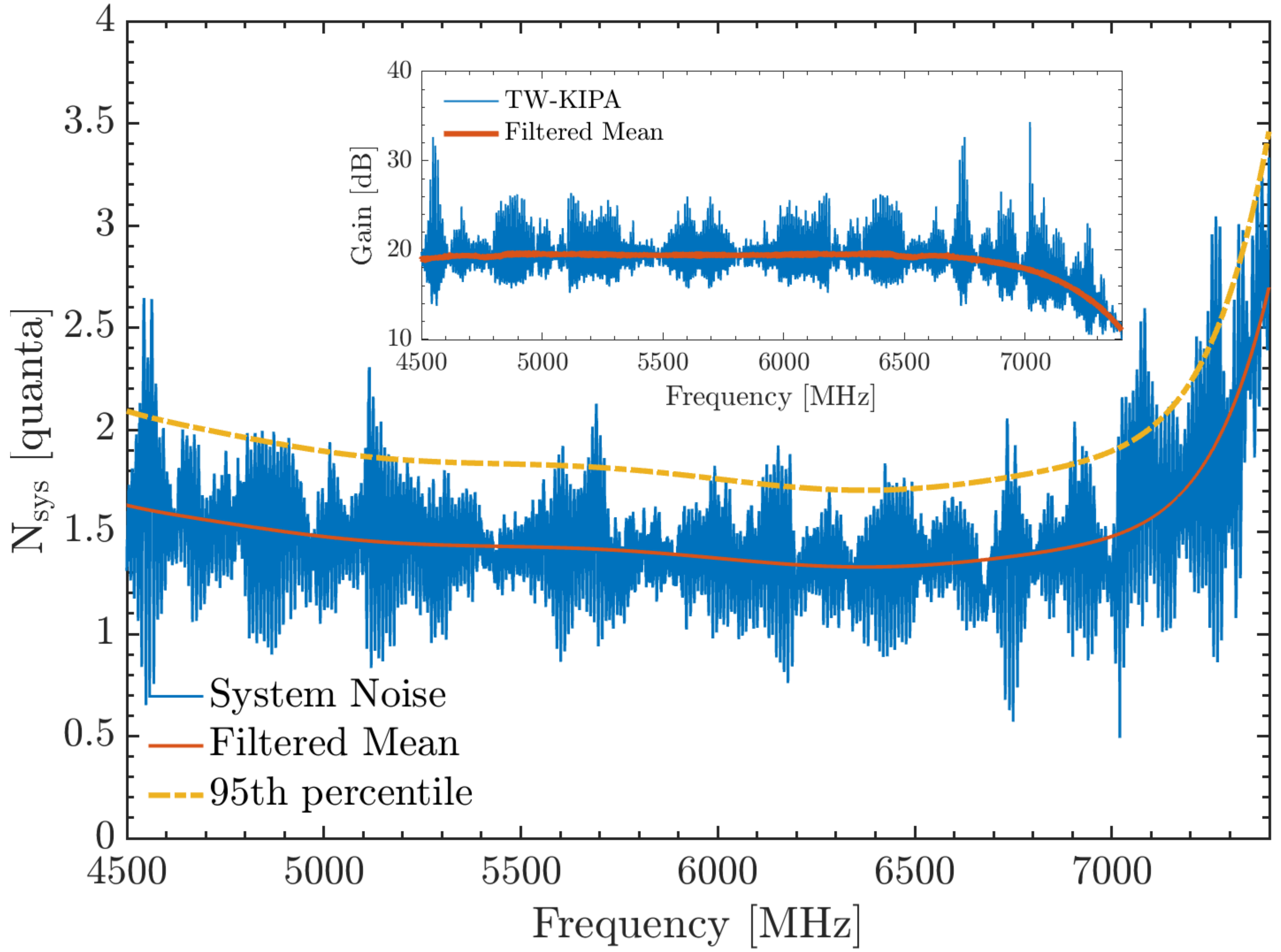
Traveling Wave Parametric Amplifier (TWPA).




KITWPAs with > 15 dB gain demonstrated in 4-10 GHz, 27-40 GHz and 75-110 GHz (ongoing work)

# QUALIPHIDE



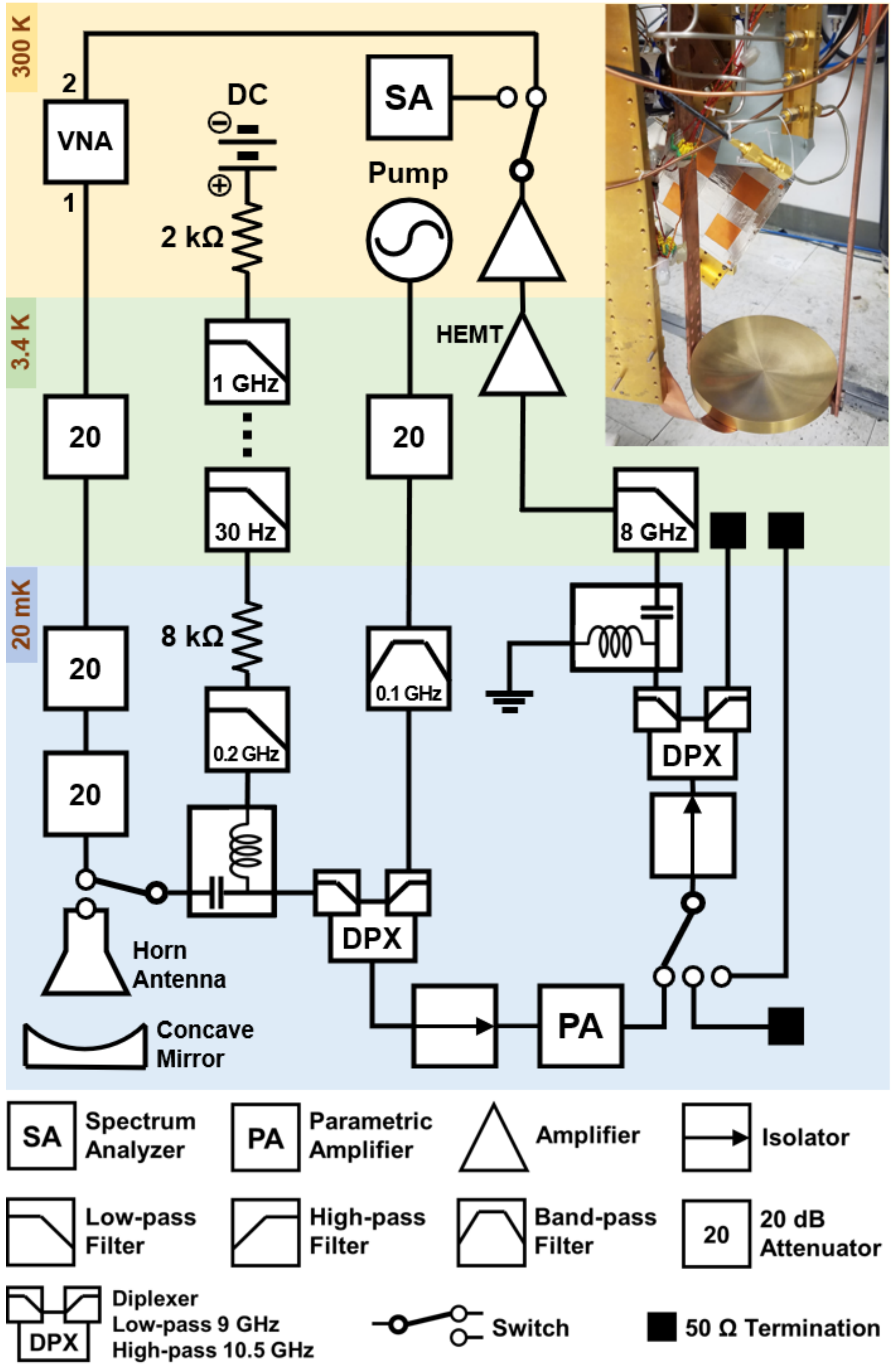



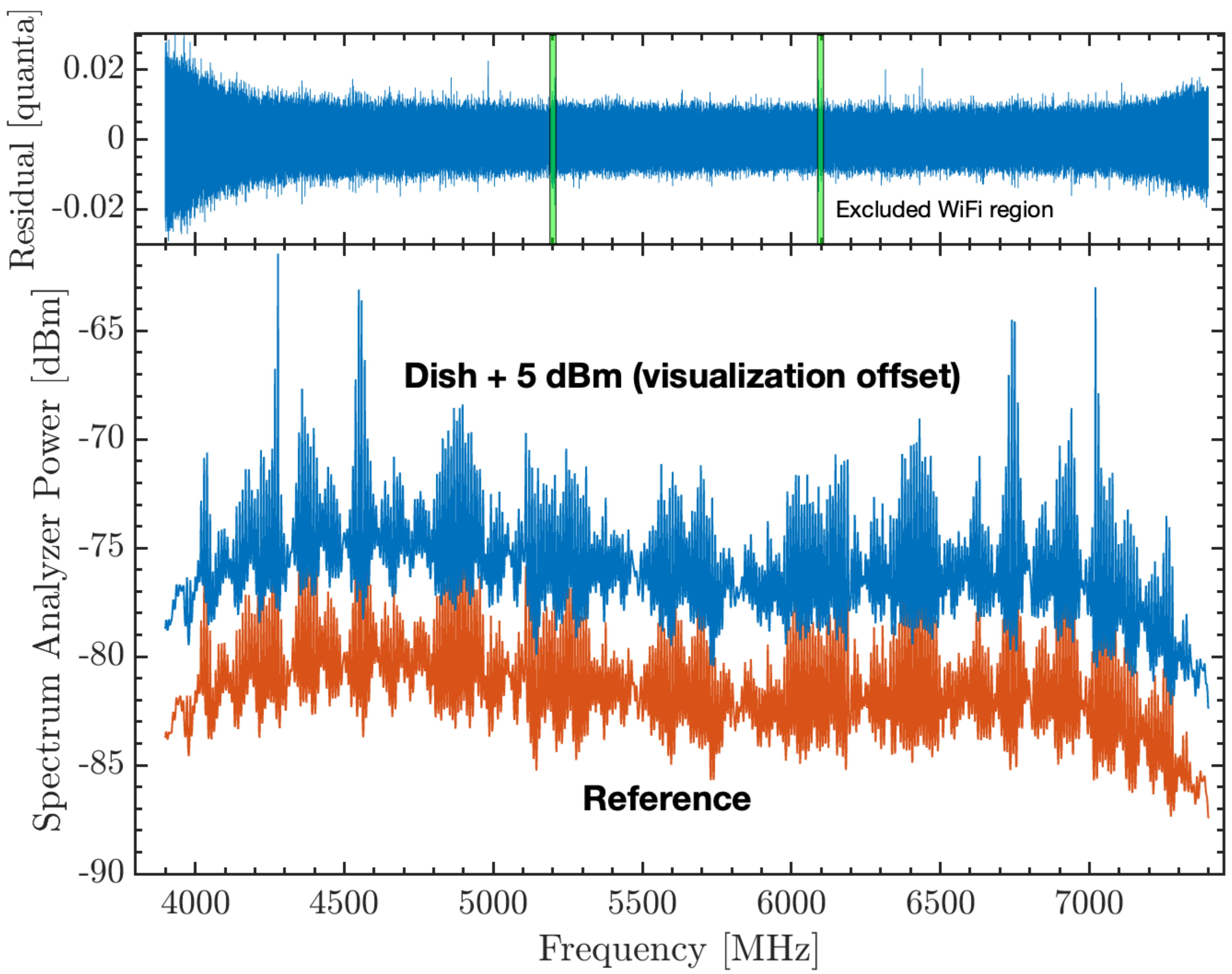

Achieved sensitivity ~2 quanta of noise (top)

Experimental setup (left) built for VNA calibration of system S-parameters + cold/hot load Y-factor measurements, all of this allows us to quote the noise in units of “quanta”.

# QUALIPHIDE

**Major effort by Ramanathan and Klimovich**




Total freq. / mass scan range 3.9-7.4 GHZ

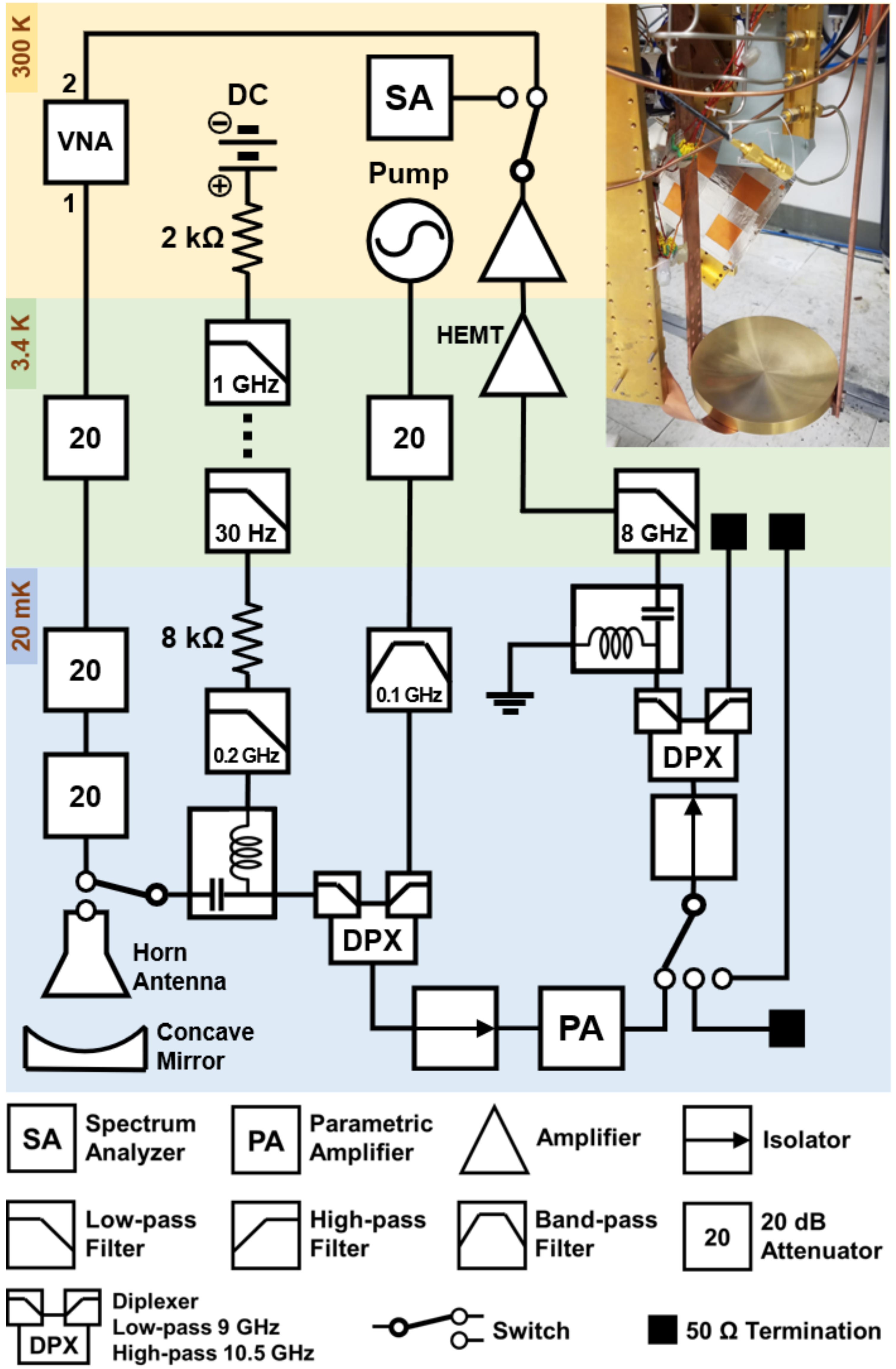
SA setup optimized freq. bins based on DM astrophysical dispersion… 762 Hz bins with 5.5 mins/bin

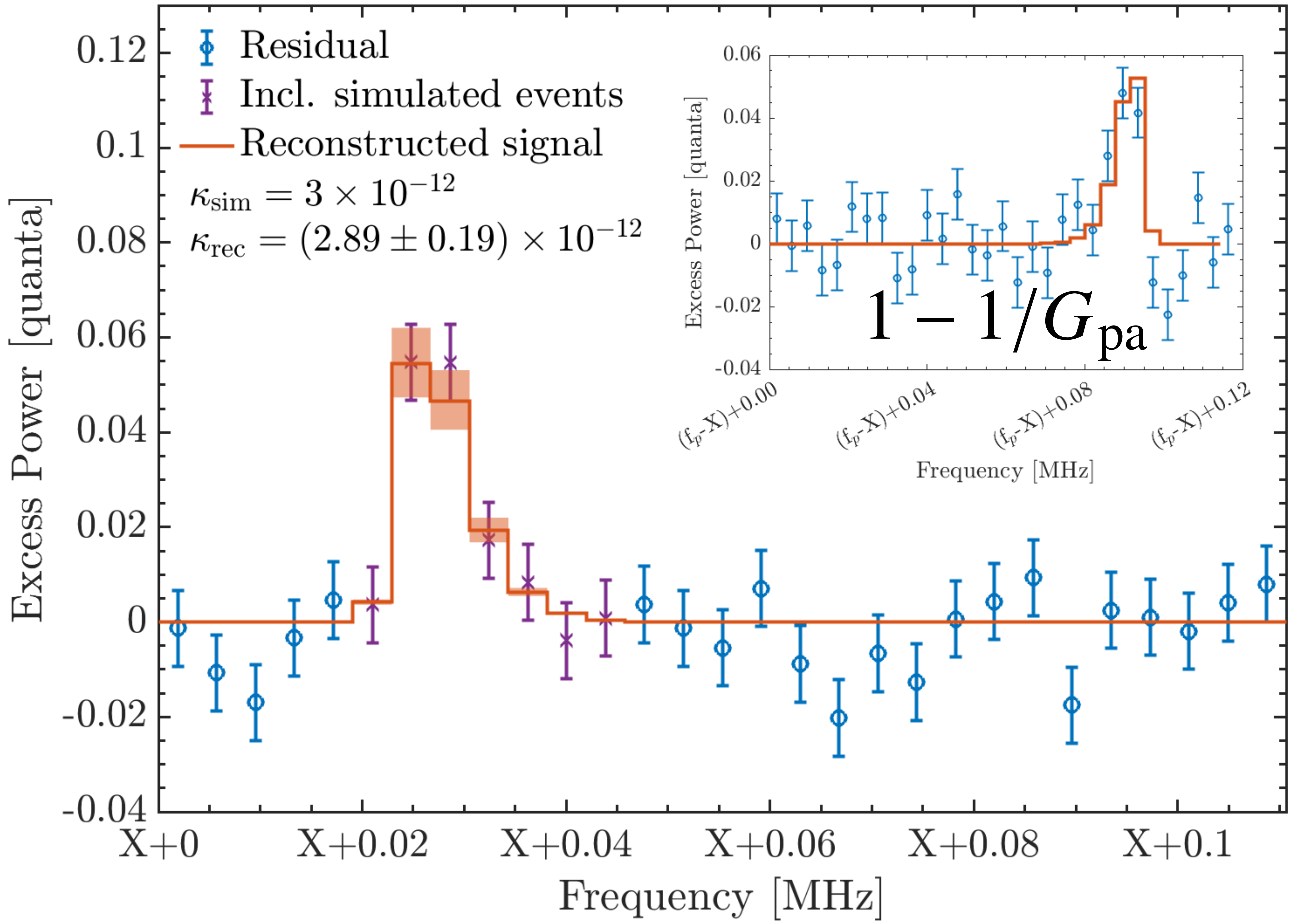
Data taken for reference-load only and mirror only sets

Analysis done with log-likelihood hypothesis testing. Additional tests with fake signals, MCMCs etc. done to make final parameter-search limits

# QUALIPHIDE

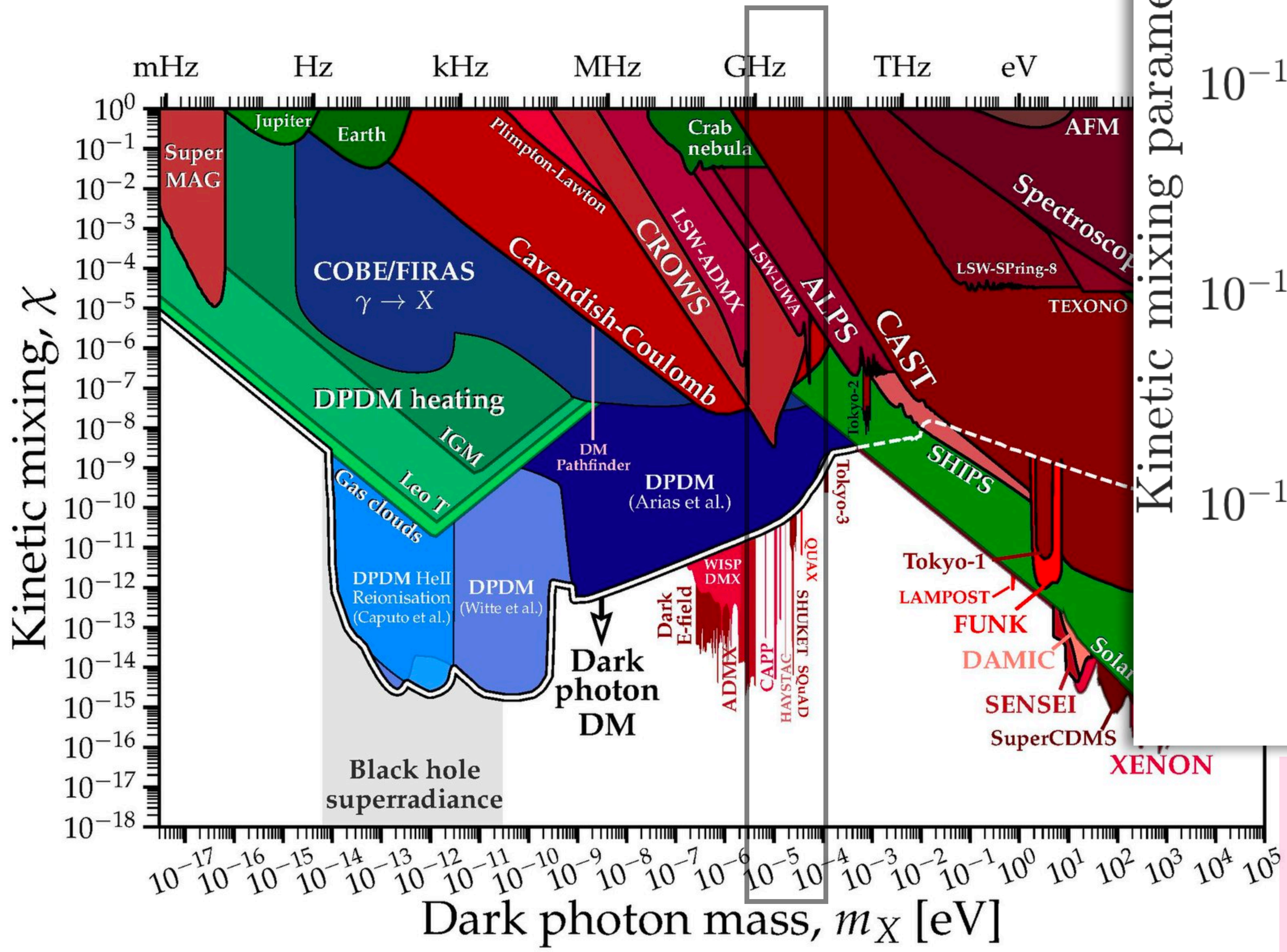
**Major effort by Ramanathan and Klimovich**

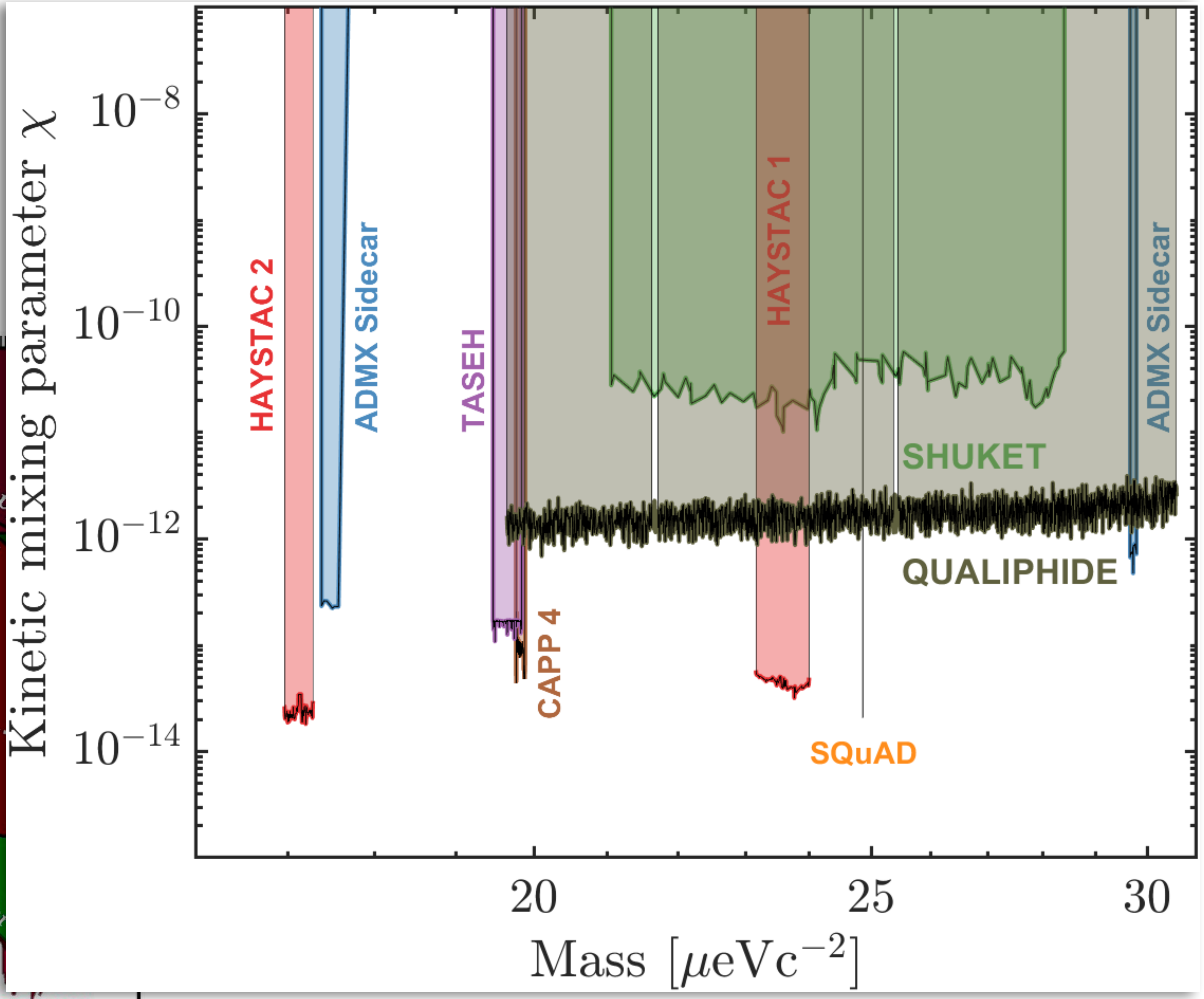



Idler part of “signal” as well, with different gain
This helps improves weak signal search
Example shown of injected signal and reconstruction

# QUALIPHIDE

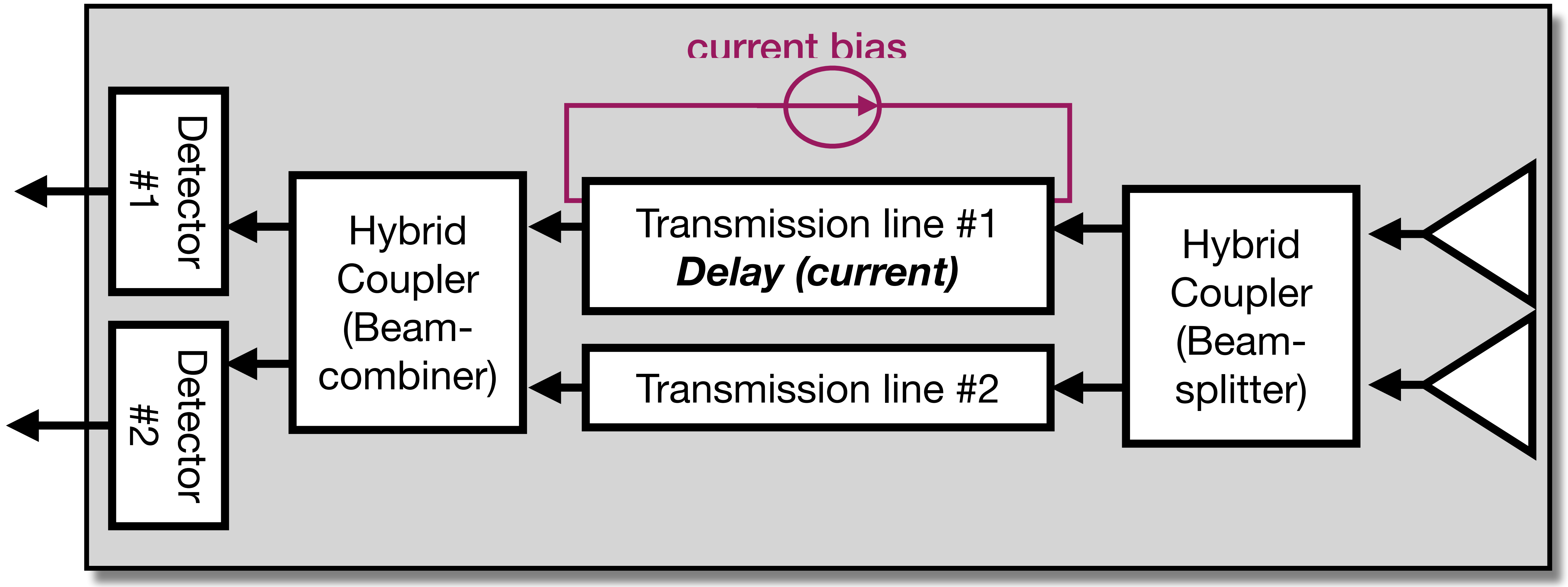


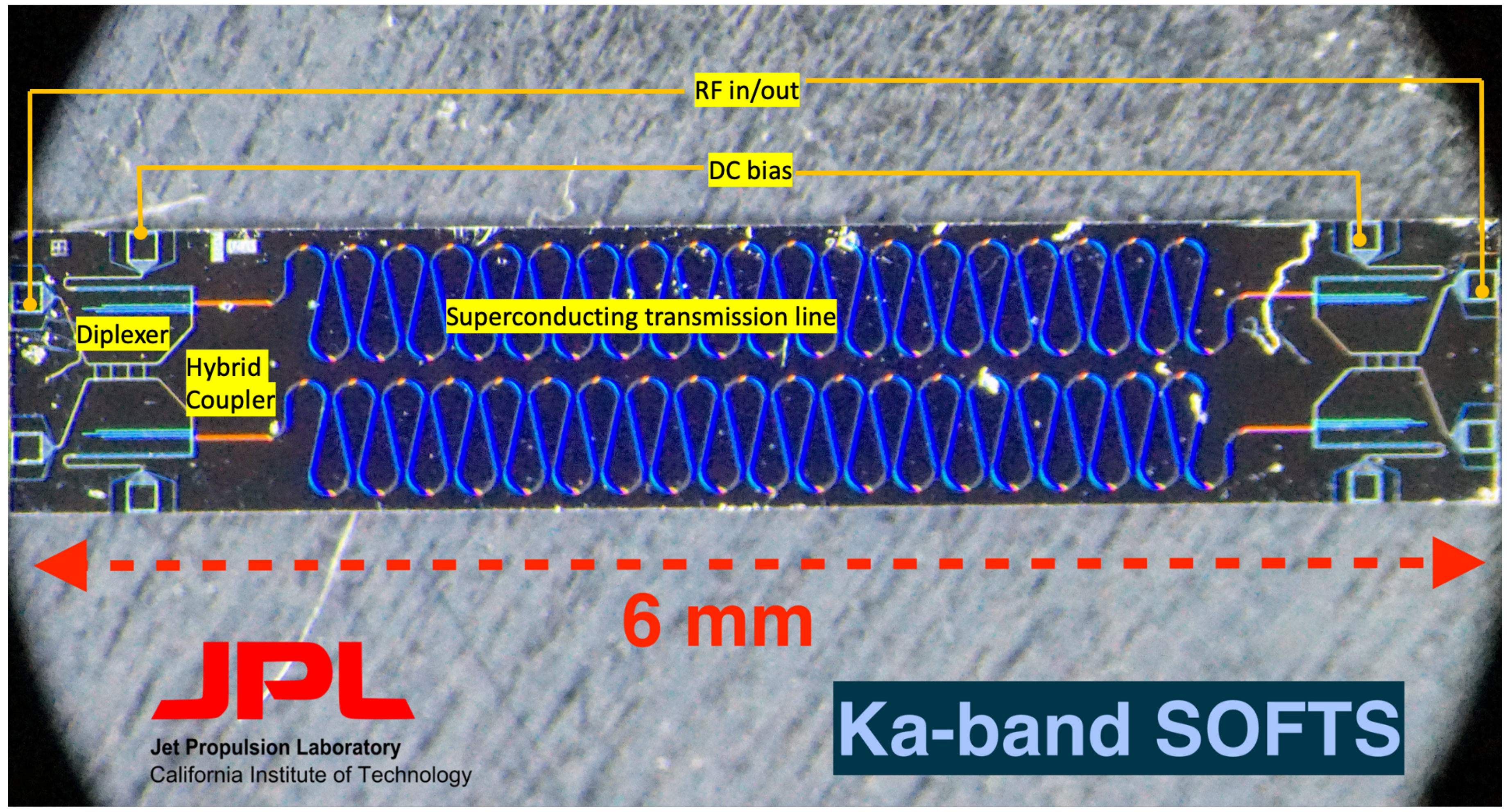

**We have surveyed a much larger mass -sensitivity range than most experiments**

**Our experiment's costs were orders of magnitude lower than all others**

# Other spectrometers




## Superconducting On-Chip Fourier Transform Spectrometer (SOFTS)



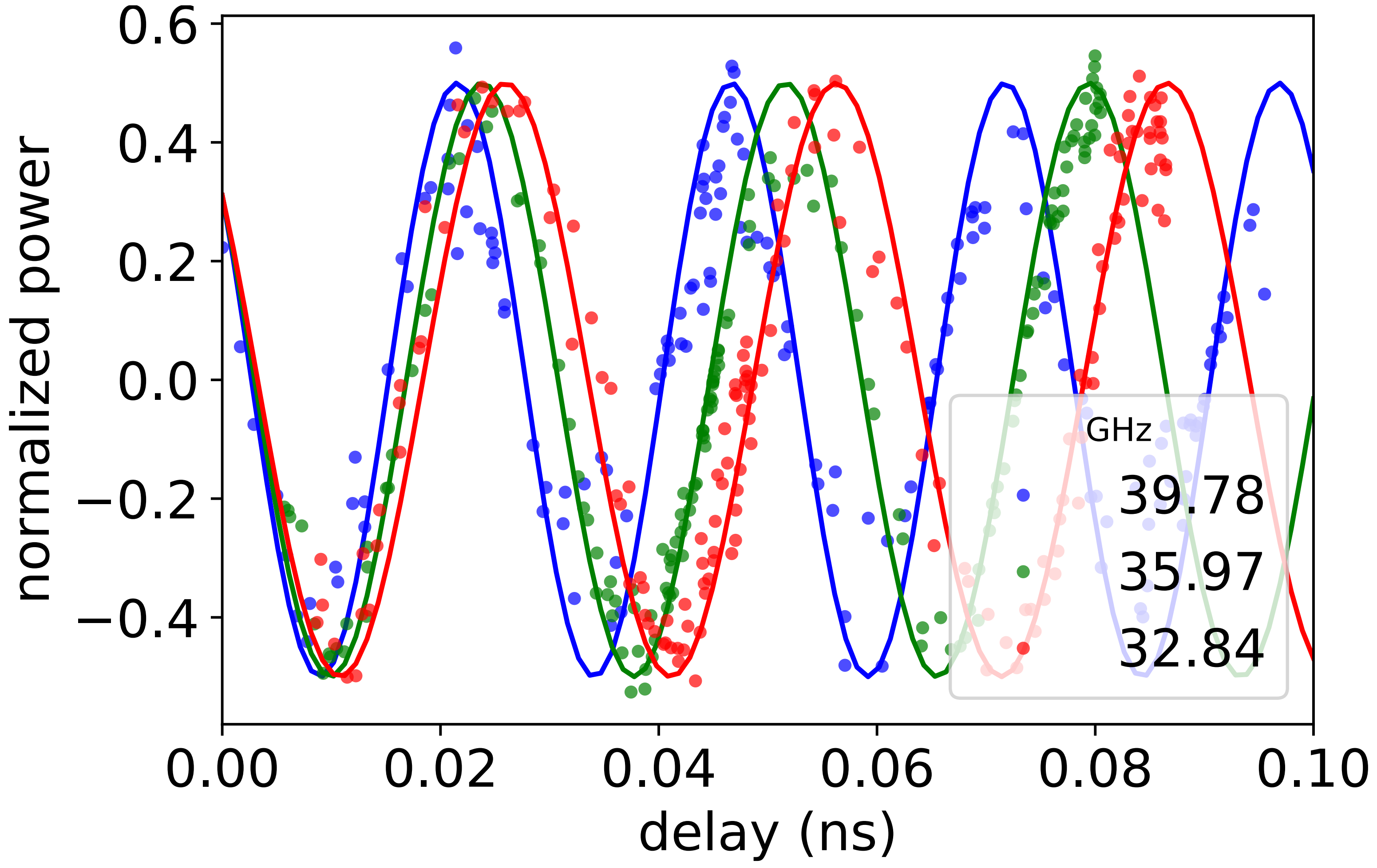

No frequency conversion

Modulate phase delay w/ DC control:

$$\Delta\tau = \sqrt{\mathcal{L}(I)\mathcal{C}} \qquad \mathcal{L}(I) \approx \mathcal{L}_0\left(1 + \left(\frac{I}{I_*}\right)^2 + \left(\frac{I}{I'_*}\right)^4 + \dots\right)$$

Two lines in Mach Zehnder format 👉🏽 FTS on chip, high efficiency w/o opto-mechanical baggage

$$P_{FTS} \sim P(\nu)(1 \pm \cos(2\pi\nu\Delta\tau))$$

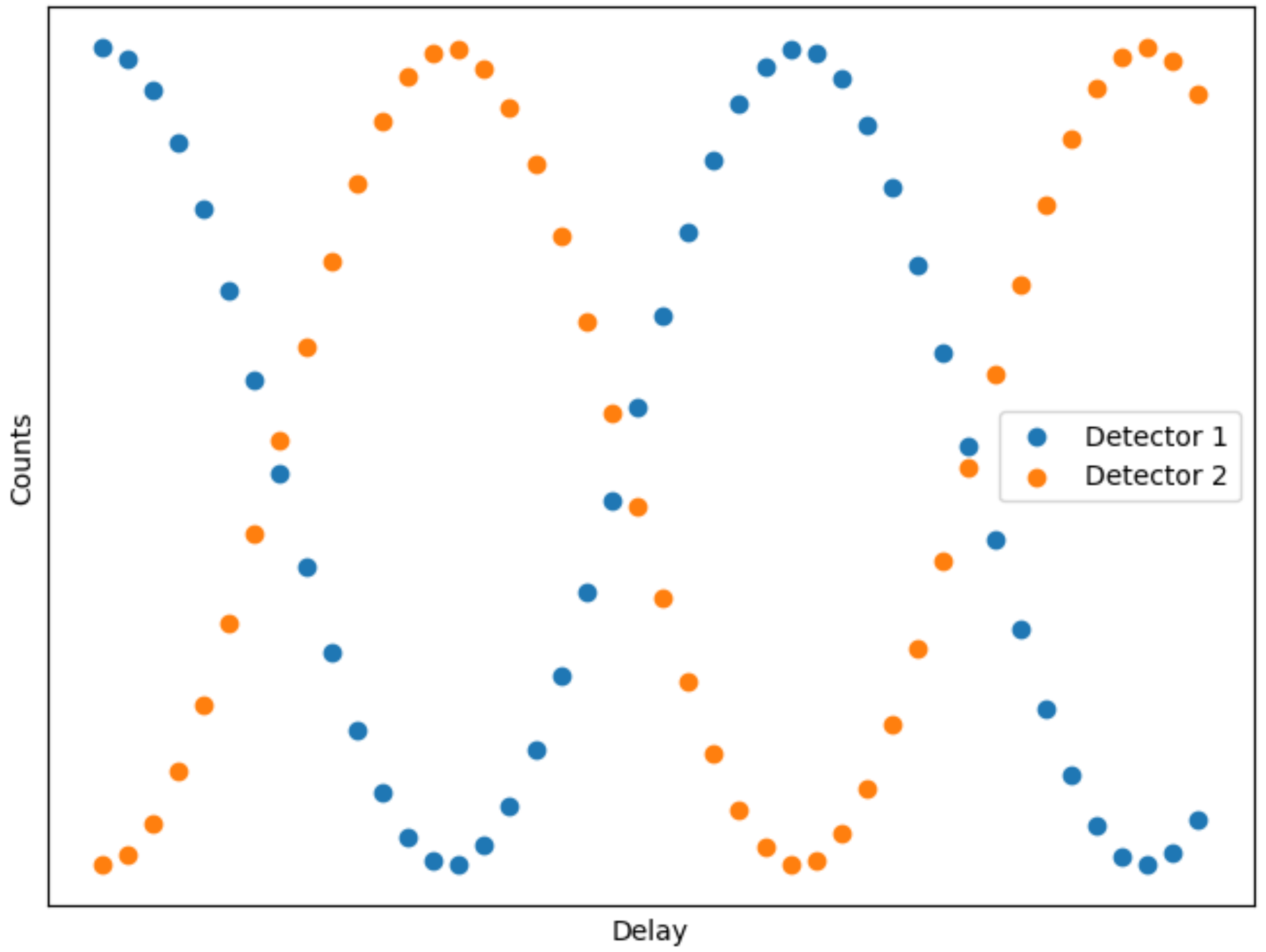


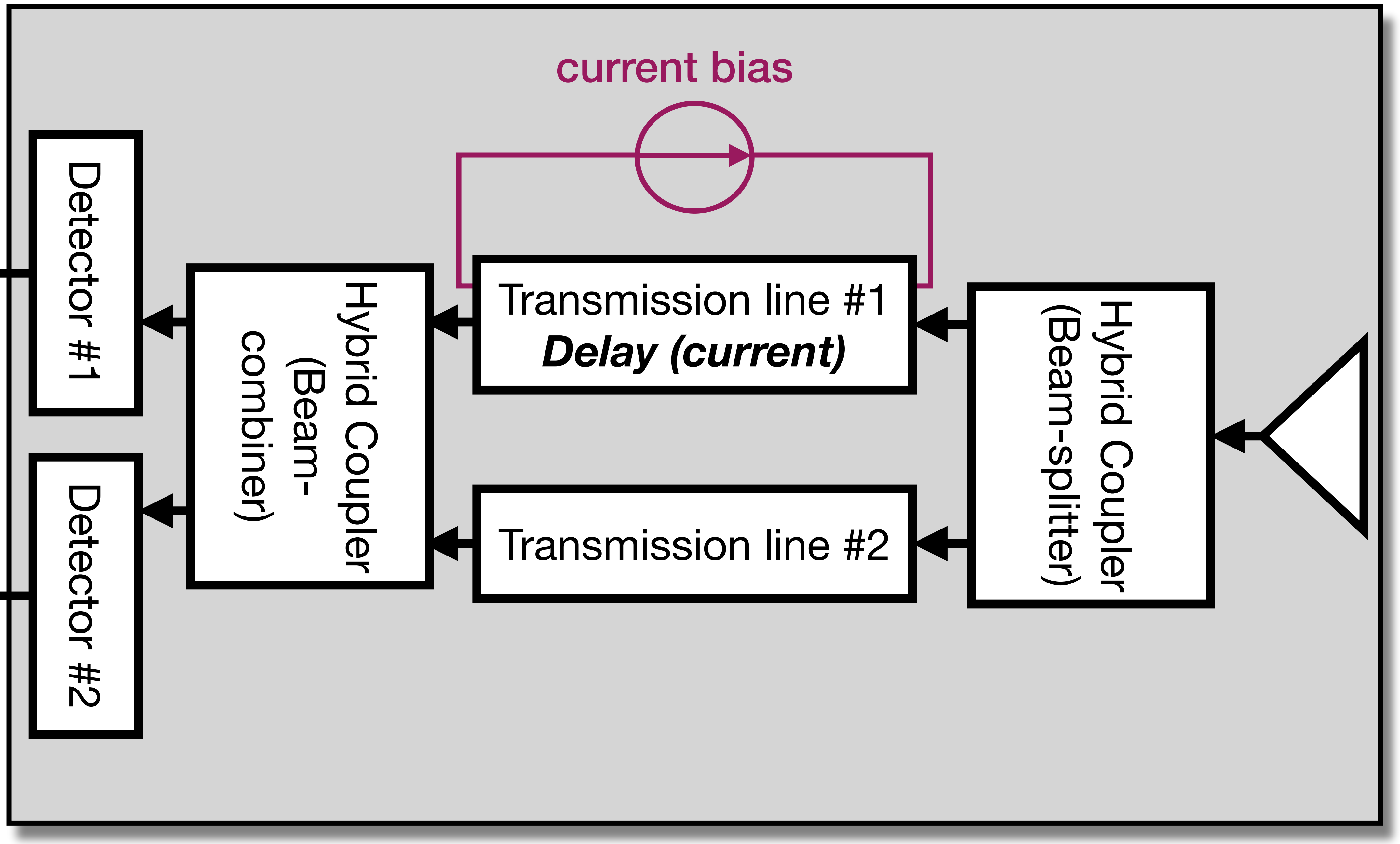
# Hidden Photon search

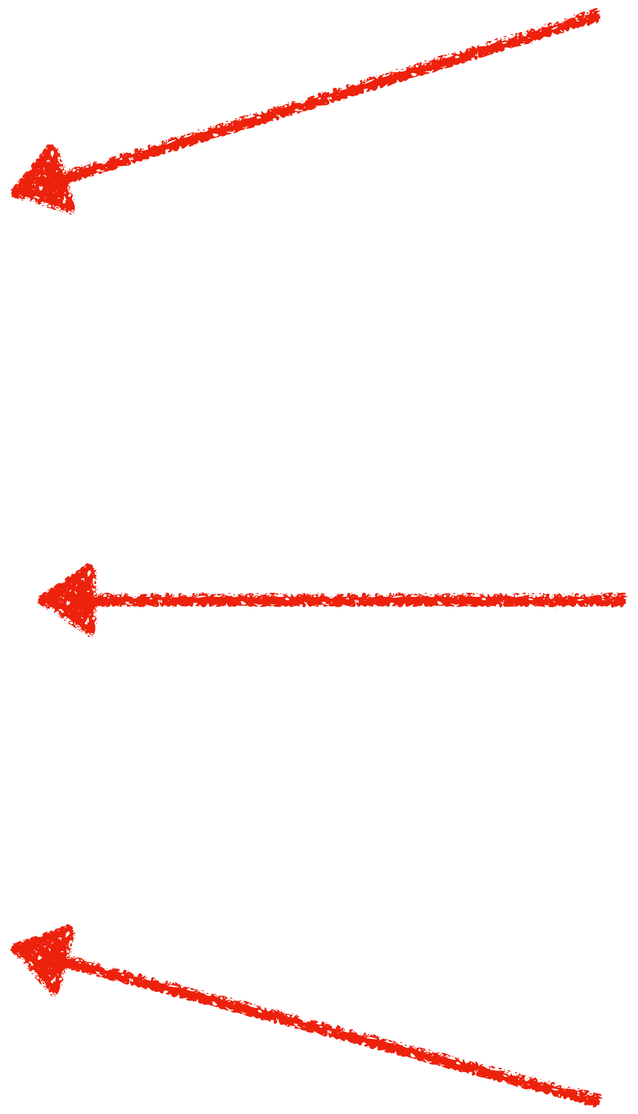
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m_{\gamma'}^2}{2}\tilde{X}_\mu\tilde{X}^\mu + J^\mu A_\mu$$

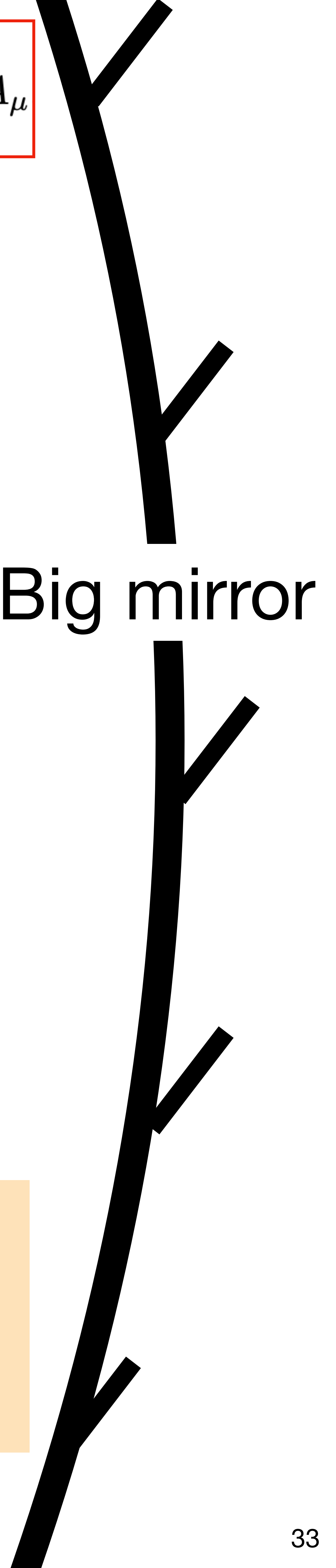
Real photons from hidden photons

## Sketch of SOFTS with BREAD-like setup






SOFTS will work in a broad-band

If the whole system is sub-kelvin, then at 0.1-1 THz we expect no real backgrounds… likely limited by dark count of detectors

One 100-GHz photon/s ~ $6*10^{-23}$ W

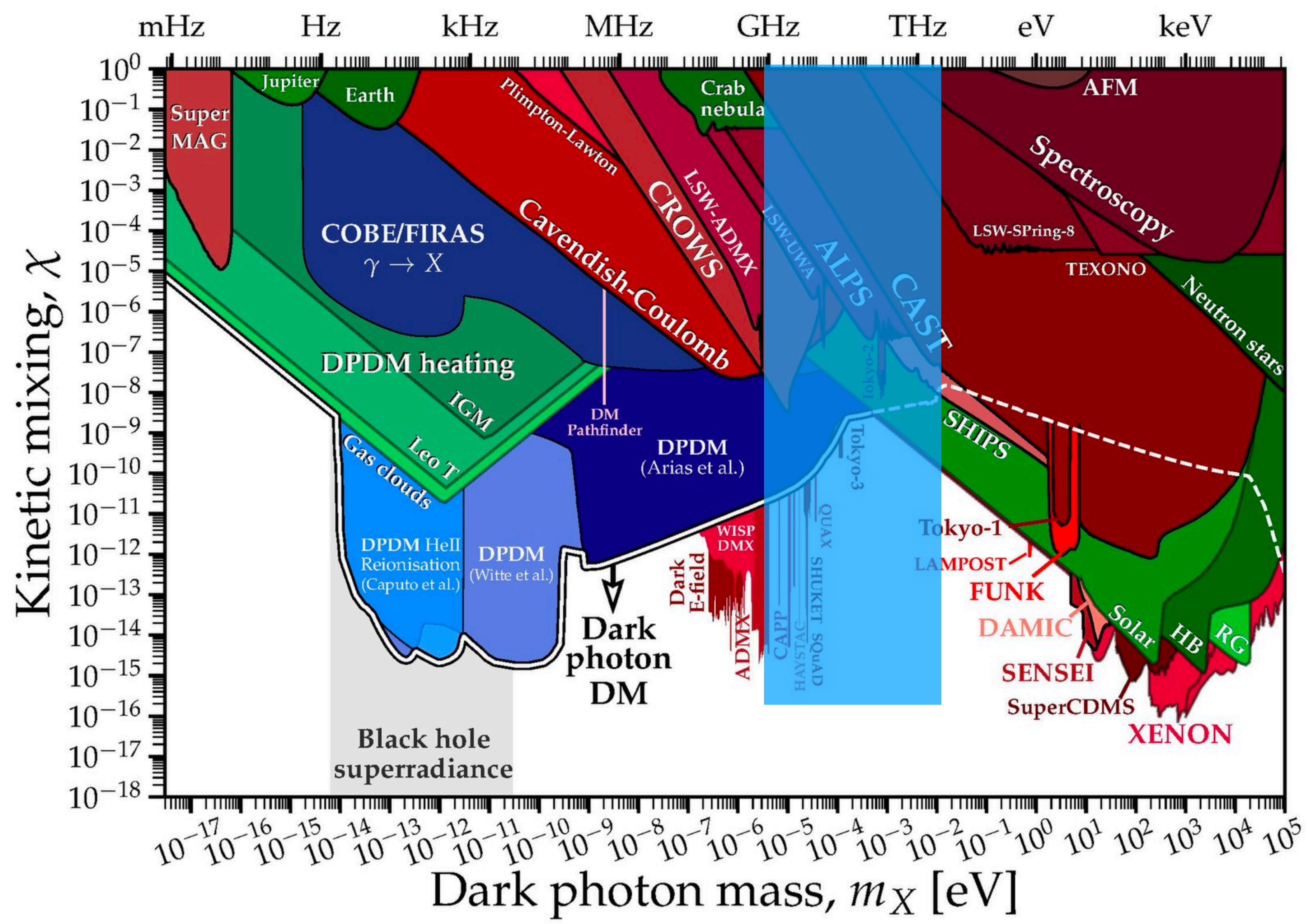
Sensitivity calculations under way, estimate $\chi$ ~$10^{-13}$

# QUALIPHIDE

**Going beyond spare-parts…**

Given the simple execution, we can envision extensions to this program with *some* funding.

These experiments use devices made for *other** science applications, operations are parasitic and brief, <u>and yields new results in new fields !</u>




Future qualifications for QUALIPHIDE

Wants for improvement **(i)** larger mirror [< m^2] & optimized horns **(ii)** dedicated cryostat space **(iii)** NbTiN TWPAs in Ka & W-bands **(iv)** electronics for higher frequencies **(v)** one PhD student

Our approach can make rapid impact in the GHz-THz window where experimental constraints are lacking, and cheaply



**funded NASA / NSF research related to astrophysics*

# QUALIPHIDE

New cosmological (structure formation) simulations indicate axions / wave-like DM likely have mass ~65 ueV, or in 10-20 GHz band.

KI-TWPAs can be easily made to operate here and our experiment can be extended.

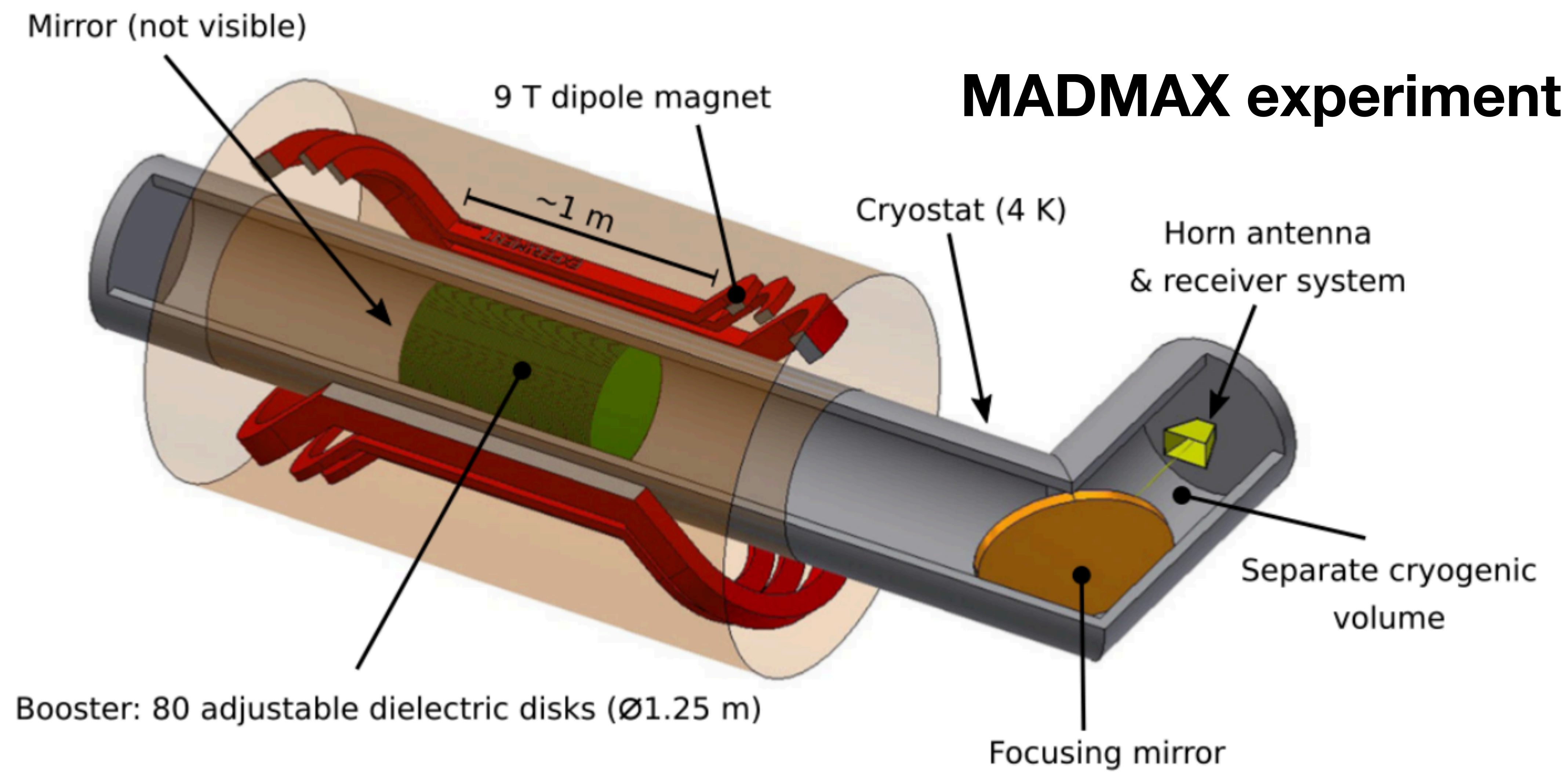
We can increase the scope of axion/ HP searches using B-fields and meta-material stacks for resonant enhancements. Such meta-material stack have similarity with filters considered in sub-mm telescopes

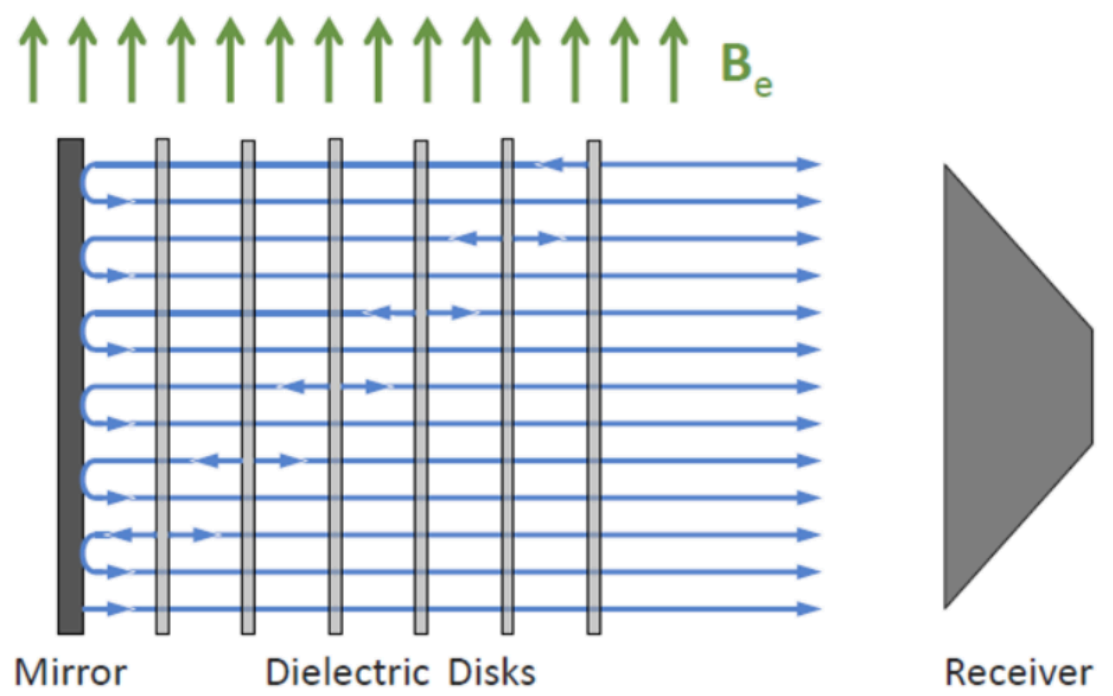
**Dark matter from axion strings with adaptive mesh refinement**

Malte Buschmann, Joshua W. Foster, Anson Hook, Adam Peterson, Don E. Willcox, Weiqun Zhang & Benjamin R. Safdi

*Nature Communications* **13**, Article number: 1049 (2022) | Cite this article

**MADMAX experiment**




**https://madmax.mpp.mpg.de/**

**arXiv: 2003.10894**

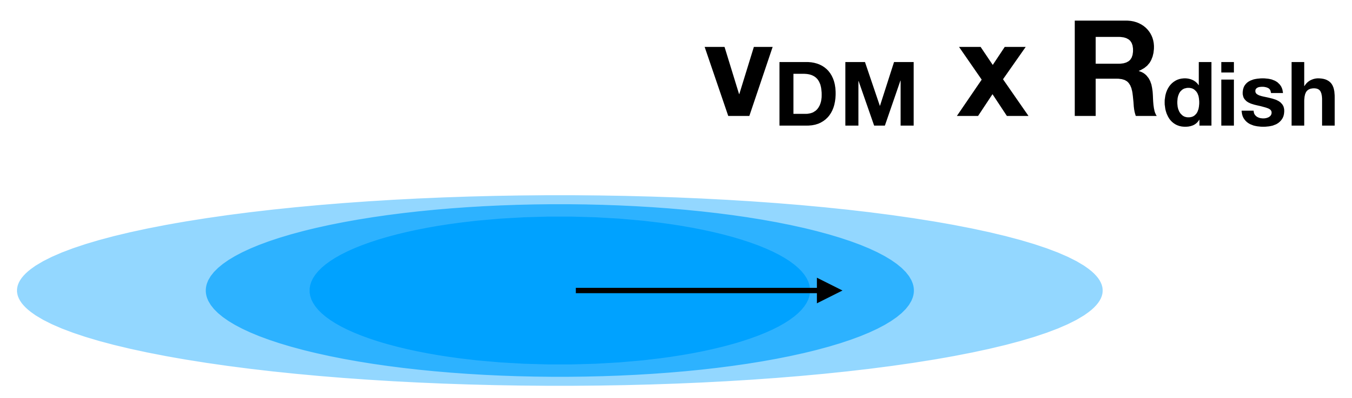
# QUALIPHIDE

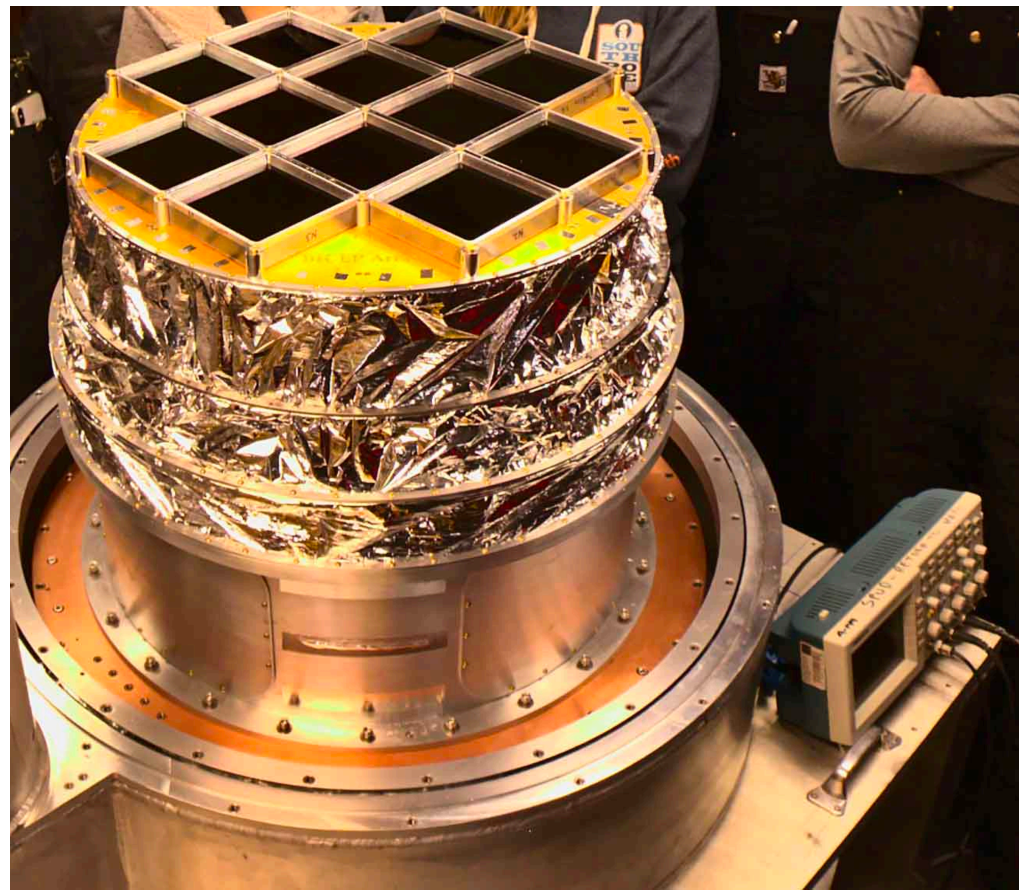
Astrophysical distribution of DM implies imperfect focusing, driven by velocity-scale ($v_{DM}$)

Directional imaging with multiple feeds can be done — easier at higher frequencies

Such multi-feed measurements can (?) also help with the famous DM-wind method of truly understanding the origin of the signal

**Many interesting and exciting approaches lie ahead that extend the QUALIPHIDE method to search for broad ranges of wave-like DM**



Dark Matter search cavity
Gold mirror
FIR-KID array
Measured single far infrared photon pulses
Hit Threshold
$\delta f_r/f_{r,0}$
Shifted Time [ms]
Estimated Wavelength [μm]
Sensitivity
Wavelength [μm]
XENON1T (2021)
JWST (2025)
No background subtraction, DCR=5.3 mHz
QUALIPHIDE-FIR
40 hrs, ideal background subtraciton
Kinetic Mixing χ
Dark Photon Mass $m'_\gamma$ [meV]
Existing Limits
QUALIPHIDE-FIR
(Preliminary)
3-axis Array
&1-year Exposure
&Calibration
$E_{thr}$ = 10 meV
$E_{thr}$ = 5 meV
Counting
&Modulation
&Resolution
&Directionality
Light Mediator $\bar{\sigma}_e$ [cm²]
$m_\chi$ [keV]