Searching for Axions and Dark Photons with SNSPDs in the BREAD experiment

Christina Wang (Caltech)
on behalf of the BREAD collaboration

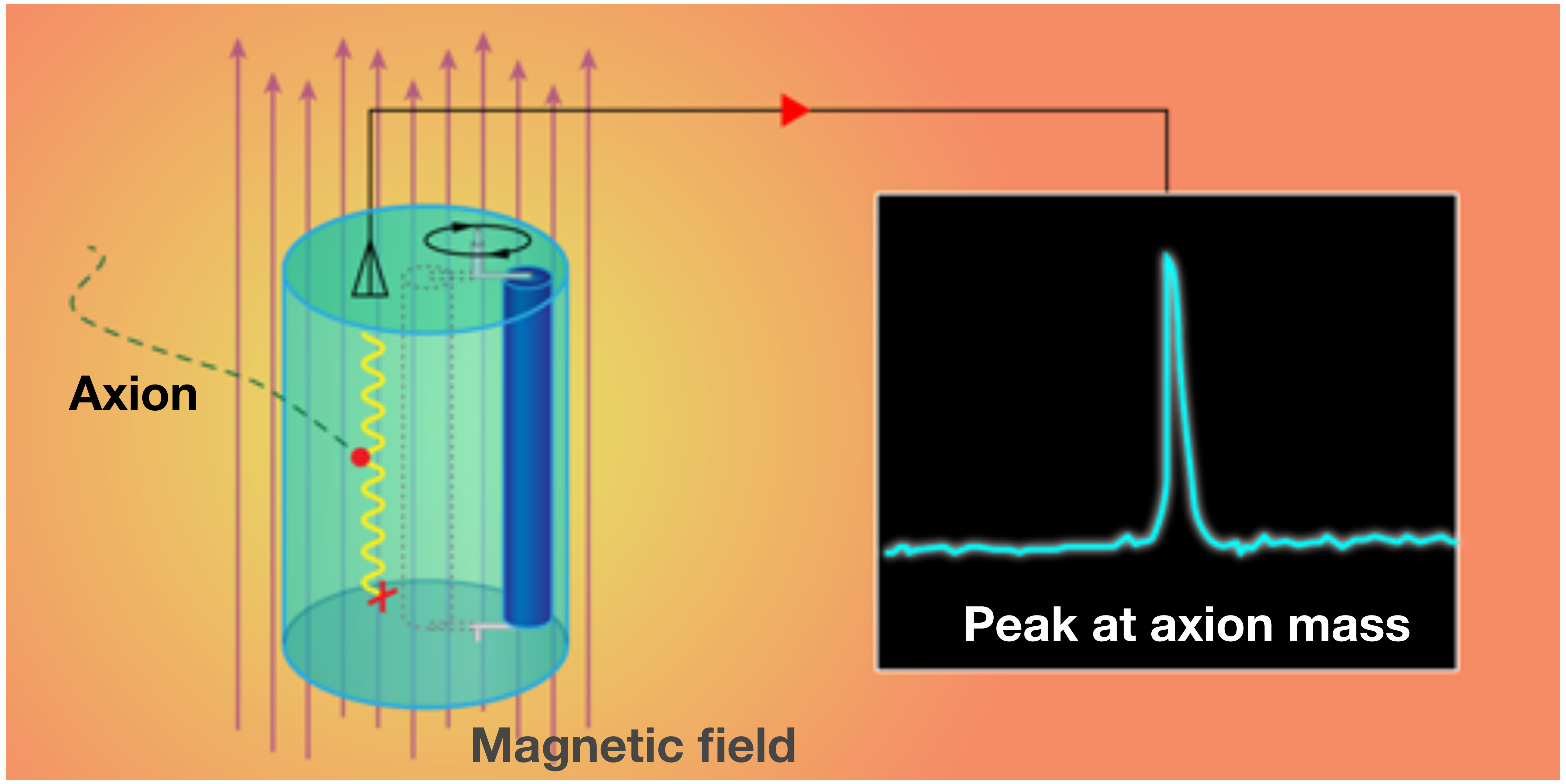
2022 CPAD Workshop
11/30/2022

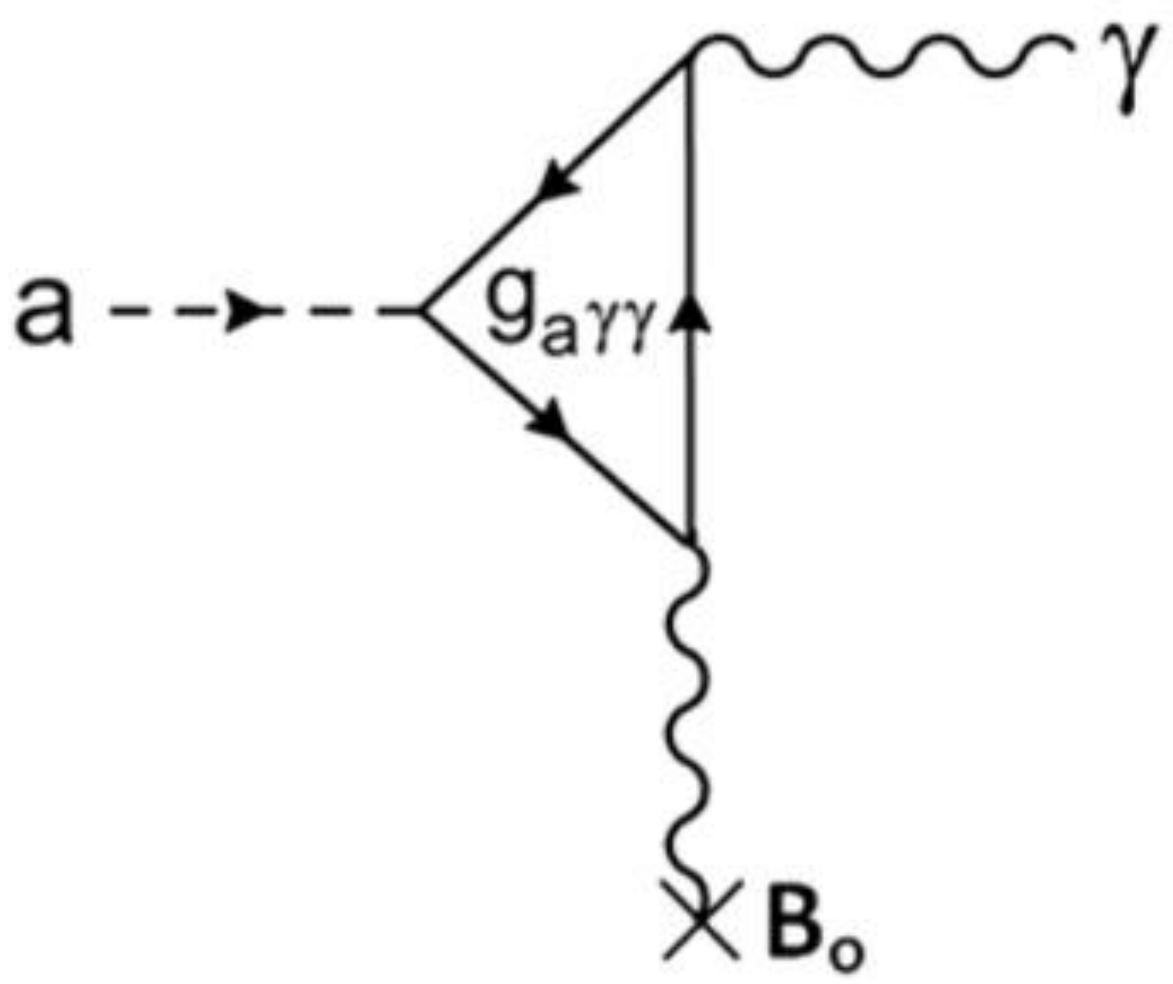
Caltech

BREAD COLLABORATION

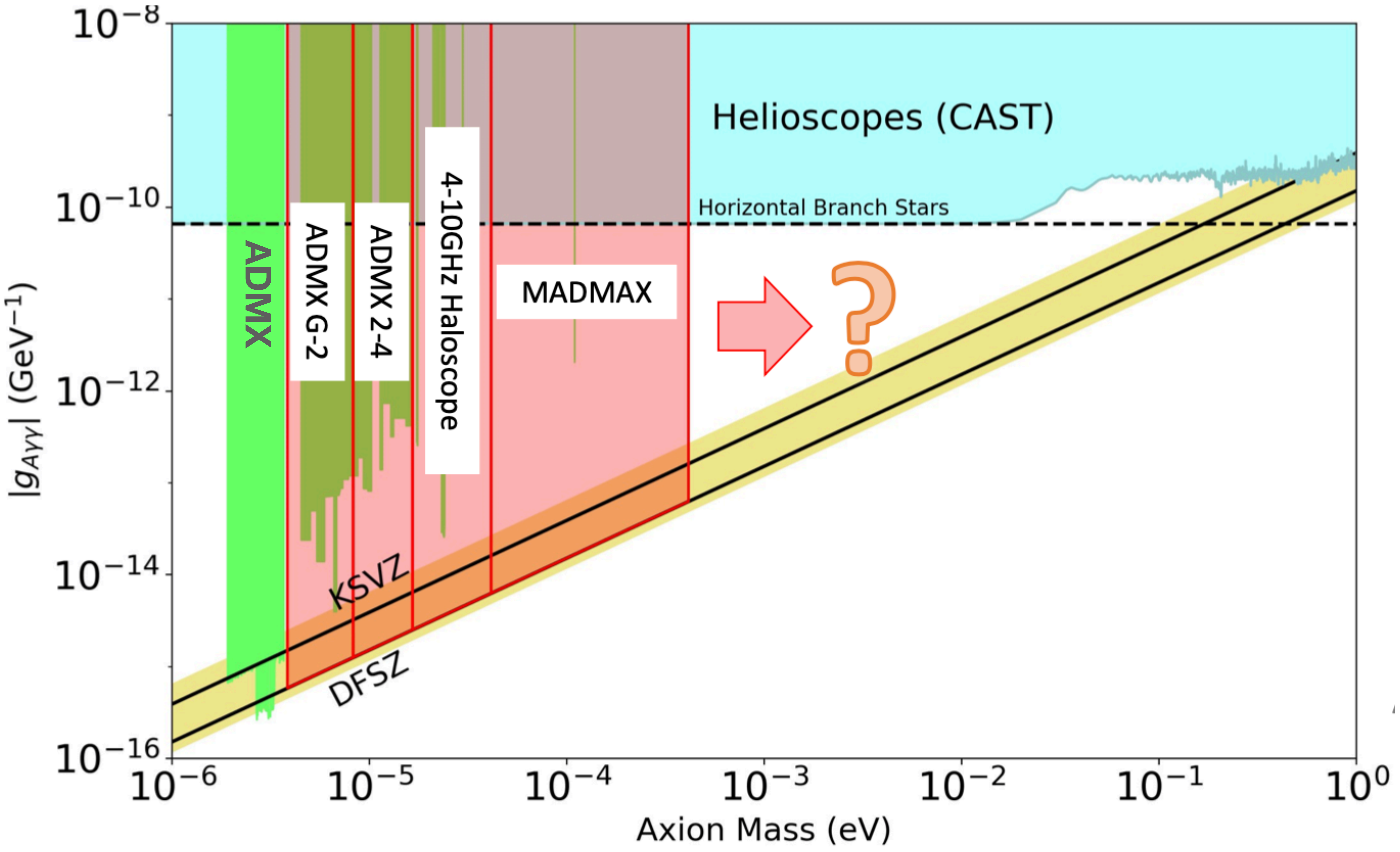
Axions

- Axions are well-motivated dark matter candidates that were initially introduced to explain the strong CP problem
- Under external magnetic field, axion induces electric field with frequency proportional to axion mass
- Current axion detection experiments, like ADMX, use resonant cavity to detect ~μev mass axions
  - However, the cavities are tuned to unknown axion mass
  - Higher mass → Smaller cavity ($V \sim m_a^{-3}$) has much smaller Q-factor ($Q \sim m_a^{-1}$) and acceptance for axions



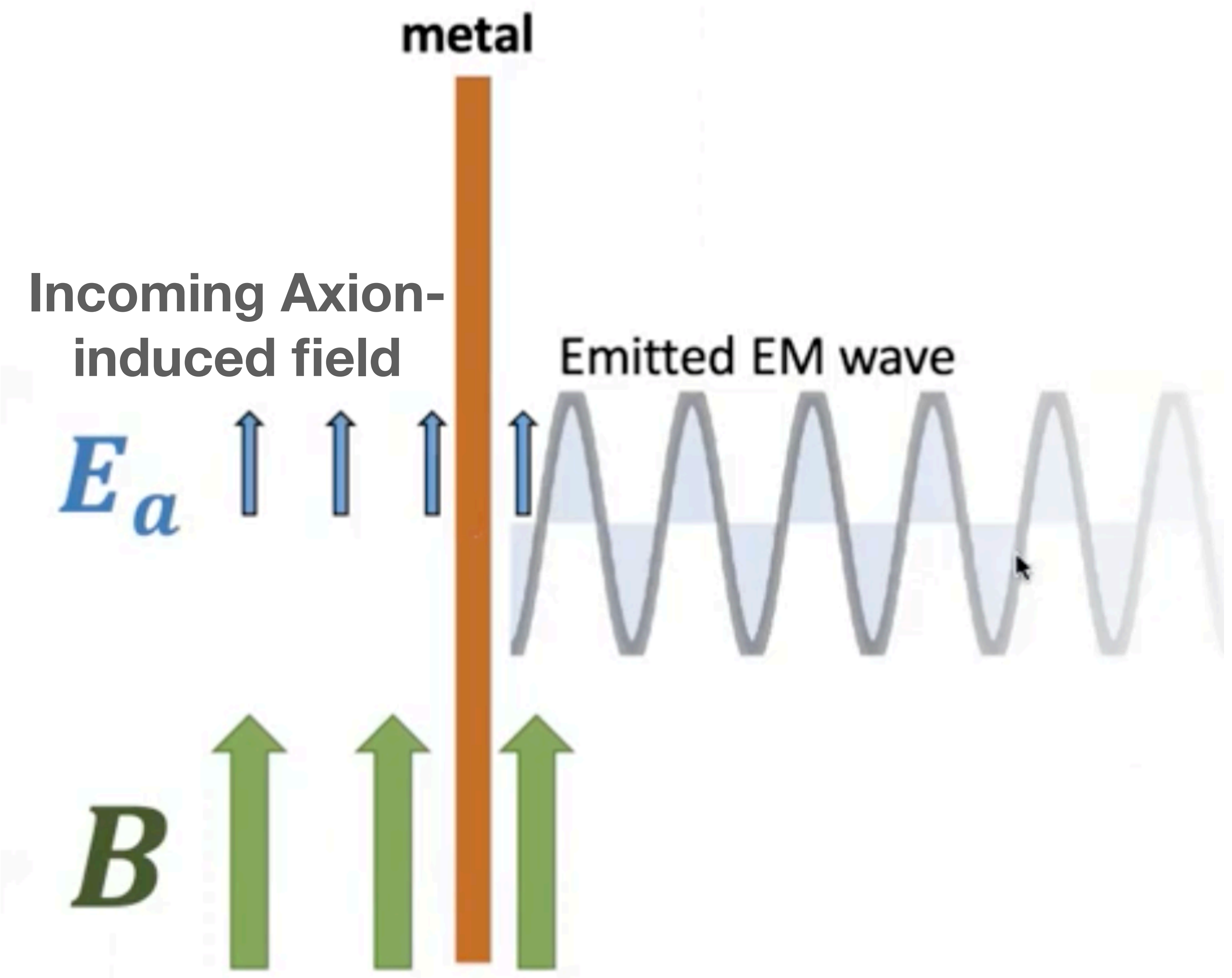


meV Axions are Unexplored



BREAD: Broadband Reflector Experiment for Axion Detection

- Axion or dark photons that couple to photons would induce a small EM field that causes discontinuity at conducting surfaces
- To satisfy the $E_{||} = 0$ boundary condition, a compensating EM wave will be emitted perpendicular to the surface
    - Emitted photon energy equals DM mass
    - Dark photon signal converts to EM even without B field



Dark photon signal:

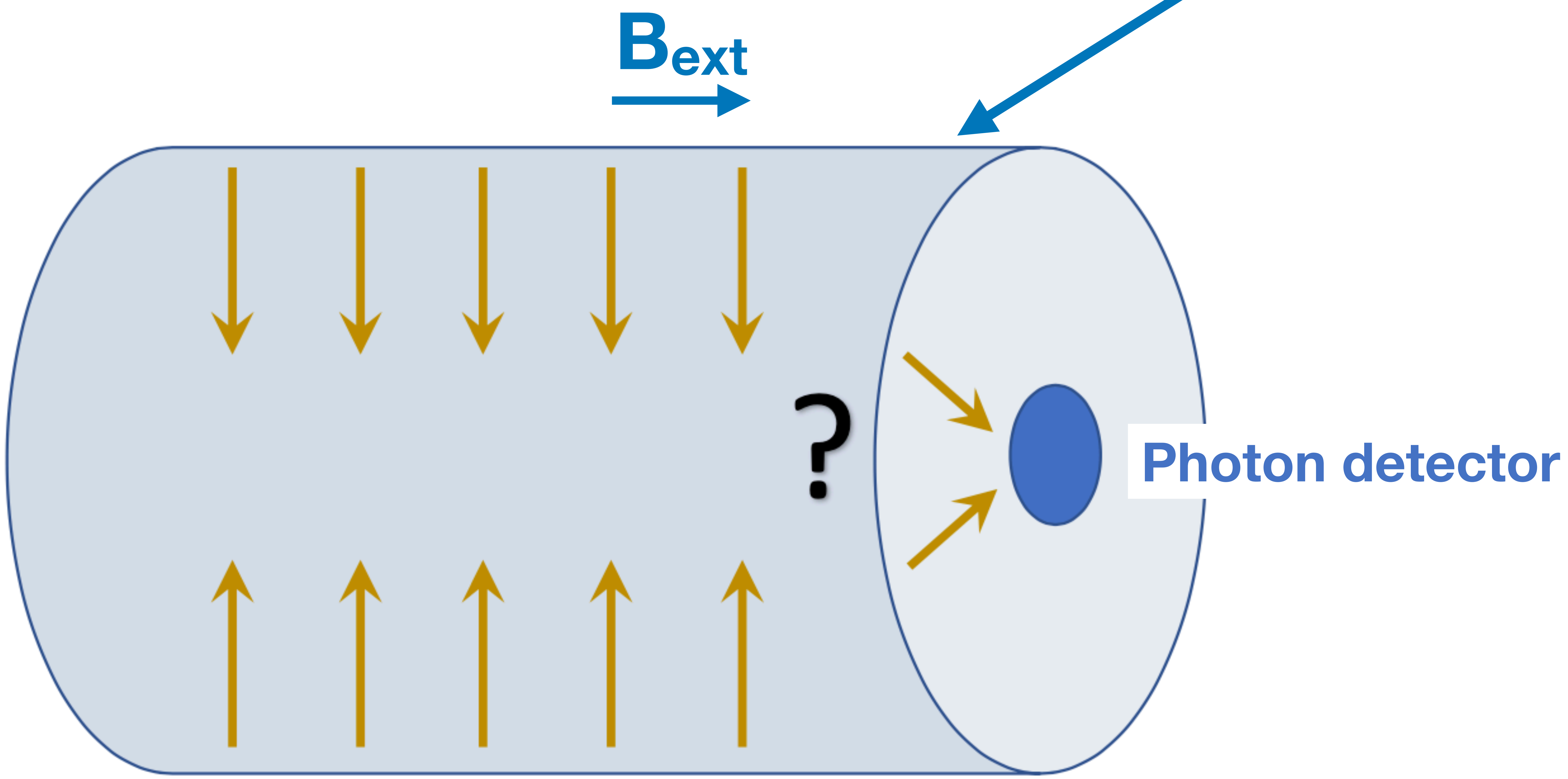
$$P_{A'} = 2.2 \times 10^{-23}\mathrm{W}\frac{\alpha_{pol}^2}{2/3}\left(\frac{\kappa}{10^{-14}}\right)^2\frac{\rho_{DM}}{0.45\mathrm{GeV/cm^3}}\frac{A_{dish}}{10\mathrm{m^2}}$$

Axion signal:

$$P_a = 8.8 \times 10^{-23}\mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\mathrm{GeV^{-1}}}\frac{\mathrm{meV}}{m_a}\right)^2\left(\frac{B}{10T}\right)^2\frac{\rho_{DM}}{0.45\mathrm{GeV/cm^3}}\frac{A_{dish}}{10\mathrm{m^2}}$$

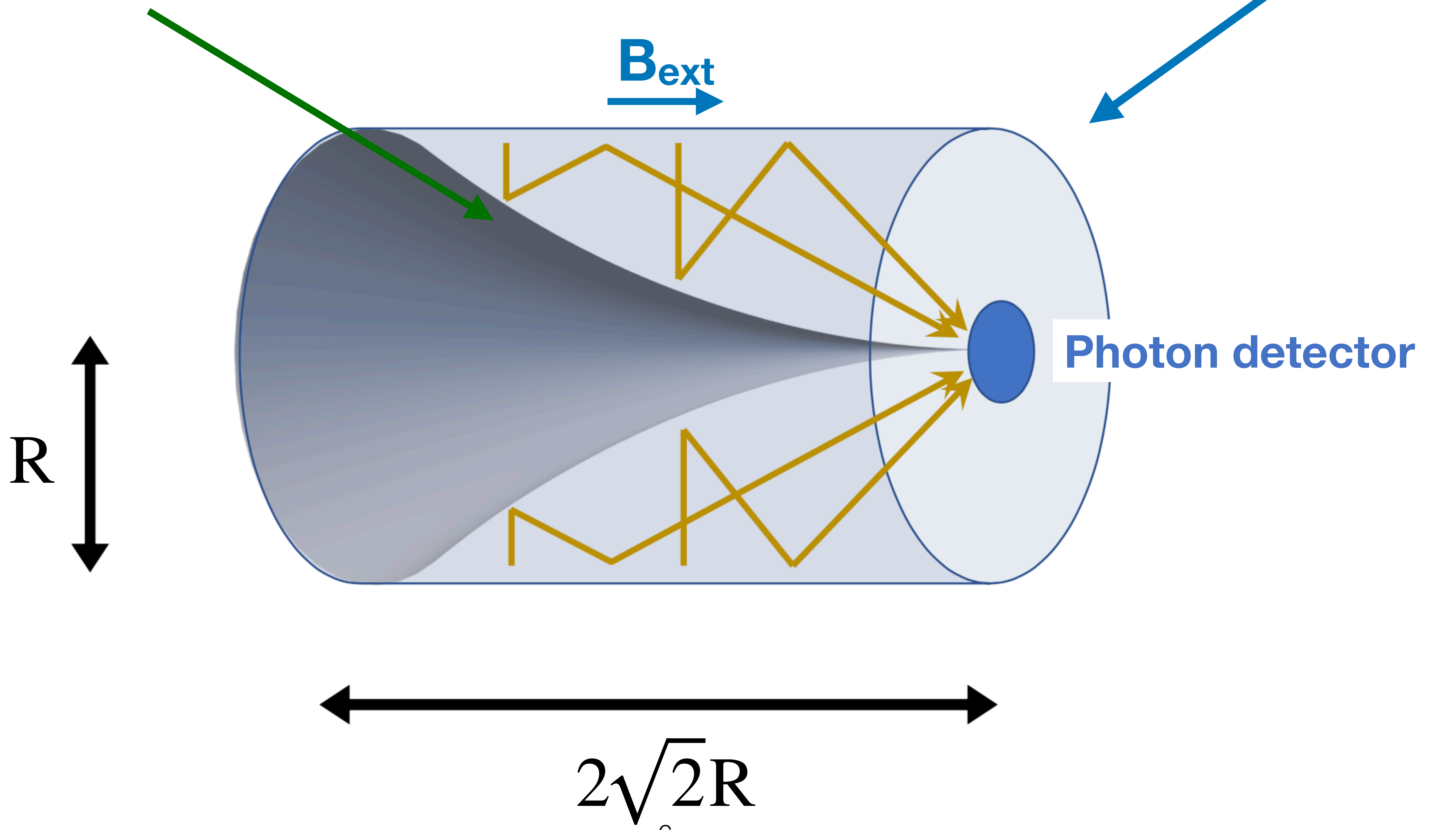
BREAD Detector Concept

- Since an external B field is needed, its convenient to build a **cylindrical surface** that would fit in a solenoid

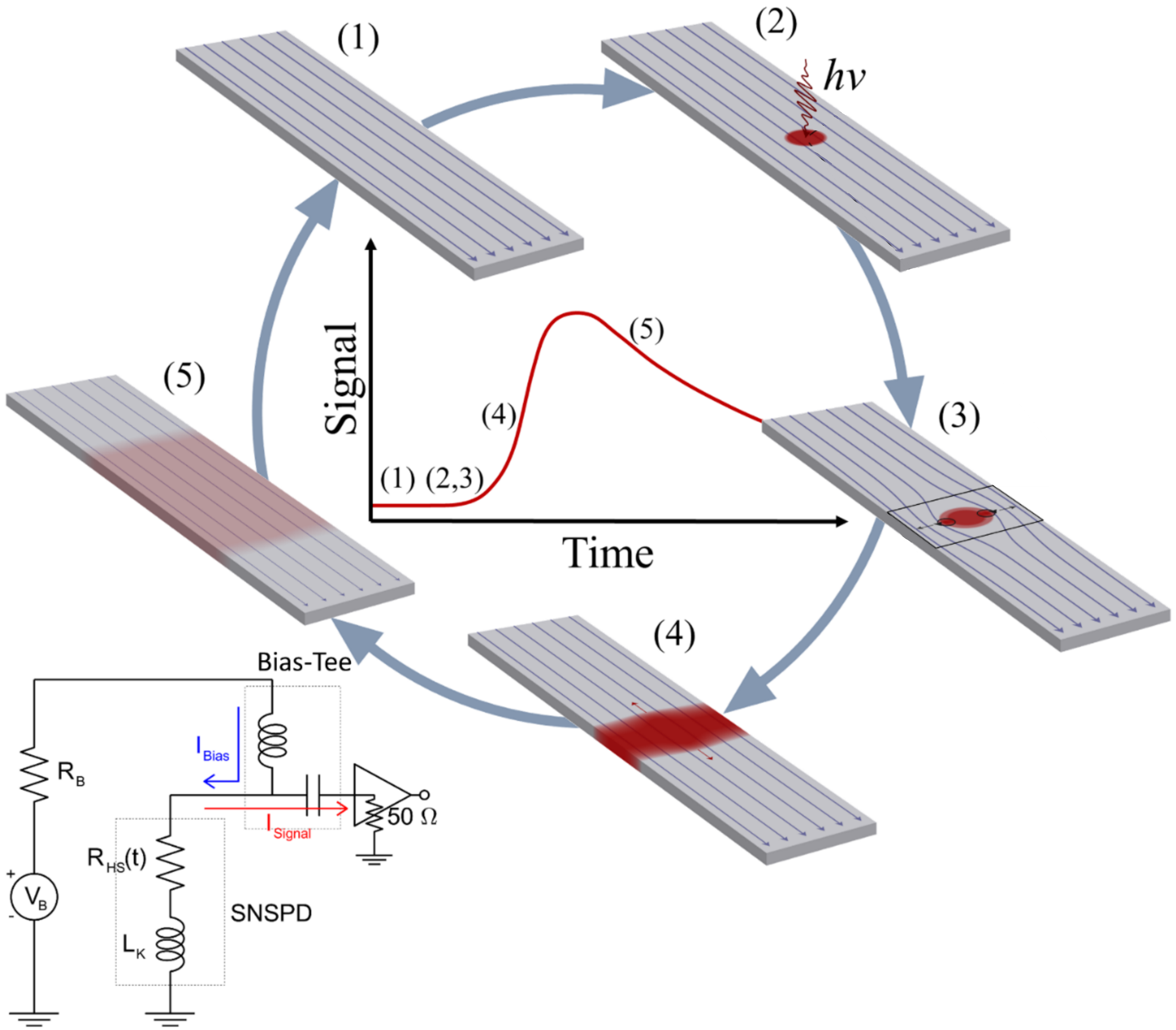


BREAD Detector Concept

- Since an external B field is needed, its convenient to build a **cylindrical surface** that would fit in a solenoid
- A **parabolic mirror** is added to focus the photons to a vertex



Superconducting Nanowire Single Photon Detector (SNSPD) for BREAD

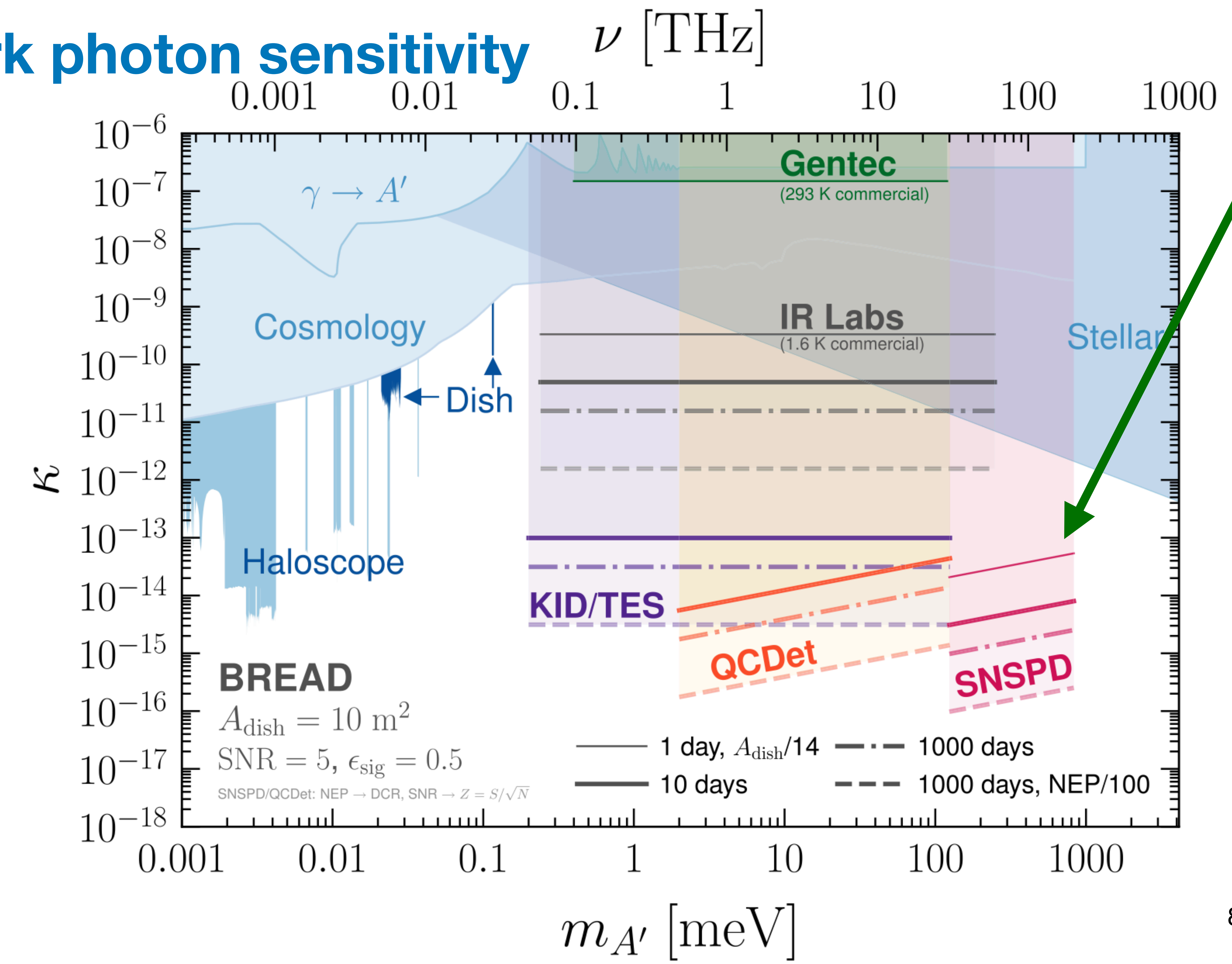


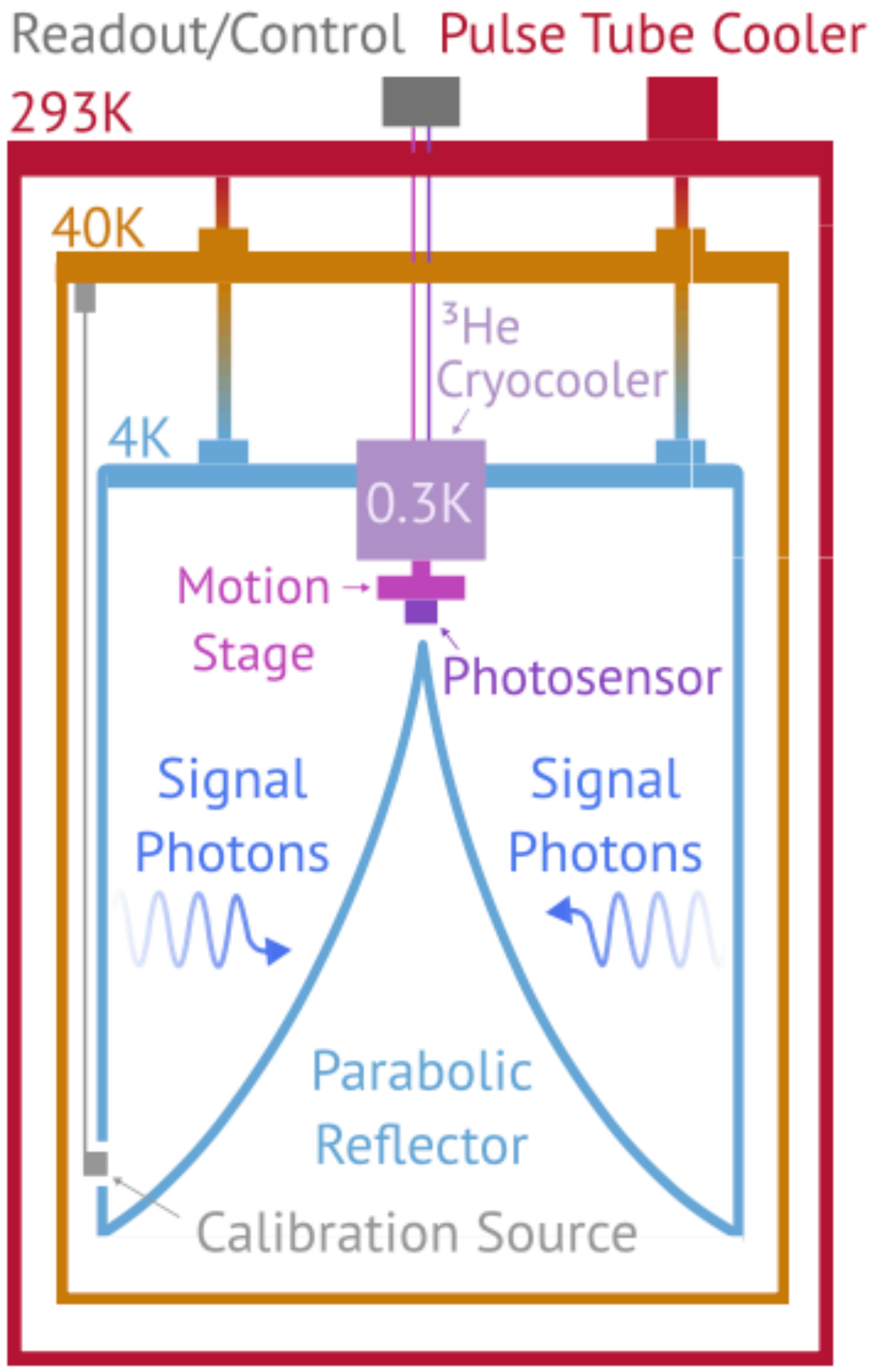
- SNSPDs satisfy the photosensor requirements for BREAD:
  - Broad spectral response: ultraviolet to infrared → sensitive to 0.1 - 1 eV dark photon/axions mass
  - Low noise: DCR < 10^{-3} Hz
  - mm^2-size active area
- Detection Mechanism:
  - Operating temperature : 1-4 Kelvin
  - Single photon triggers detector out of superconducting state
  - Resistance quickly (ps) jumps to few kΩ → bias current into readout

Pilot Experiment with SNSPDs

- Currently planning for pilot dark photon search at IR frequencies with SNSPD (doesn't need external B field) at Fermilab
- SNSPD provides unique sensitivity for 0.1 - 1 eV dark photon mass
- **We can already explore previously unconstrained regions by running the pilot experiment with 1 day**

Dark photon sensitivity



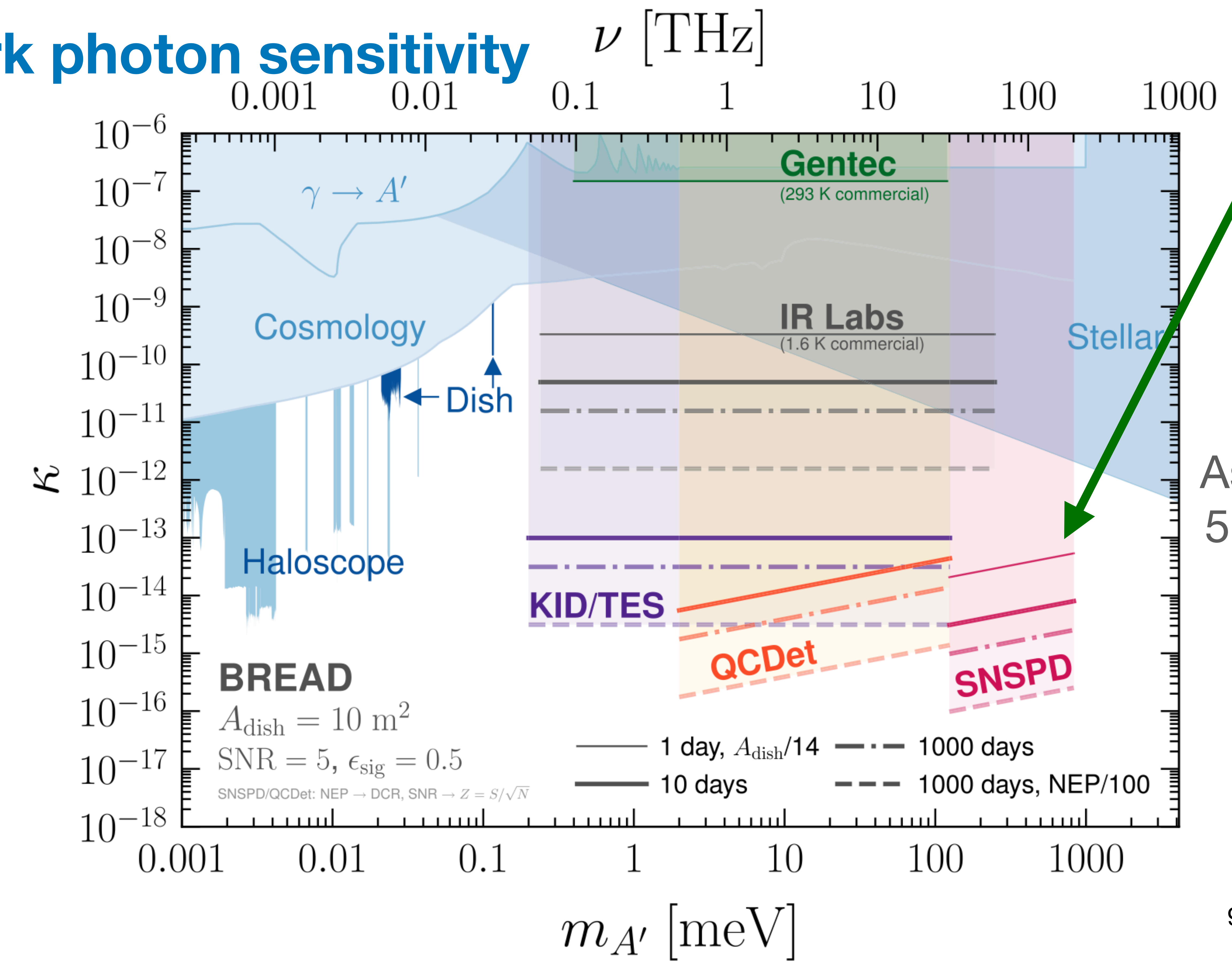


R = 20 cm

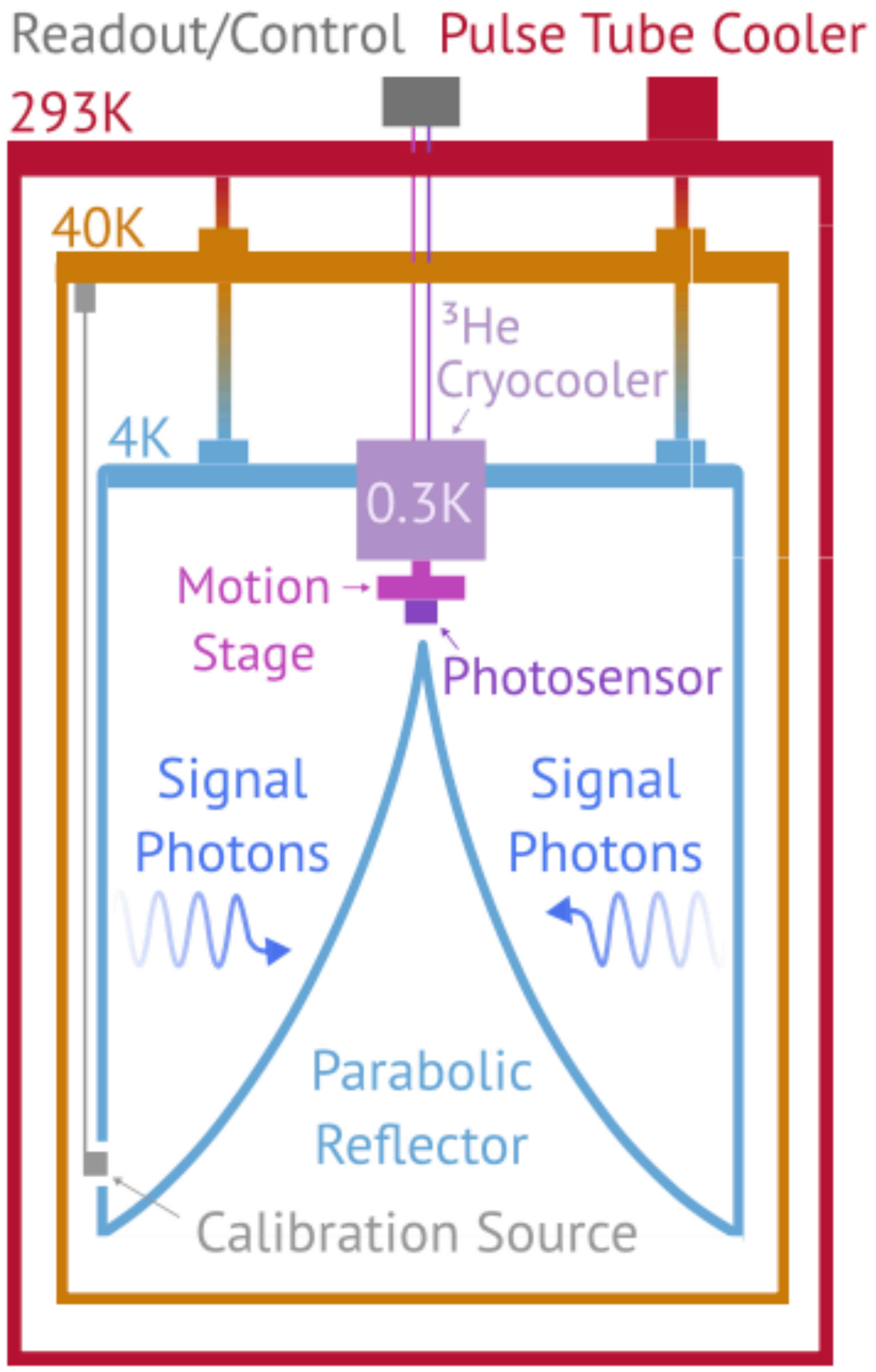
Pilot Experiment with SNSPDs

- Currently planning for pilot dark photon search at IR frequencies with SNSPD (doesn't need external B field) at Fermilab
- SNSPD provides unique sensitivity for 0.1 - 1 eV dark photon mass
- **We can already explore previously unconstrained regions by running the pilot experiment with 1 day**

Dark photon sensitivity



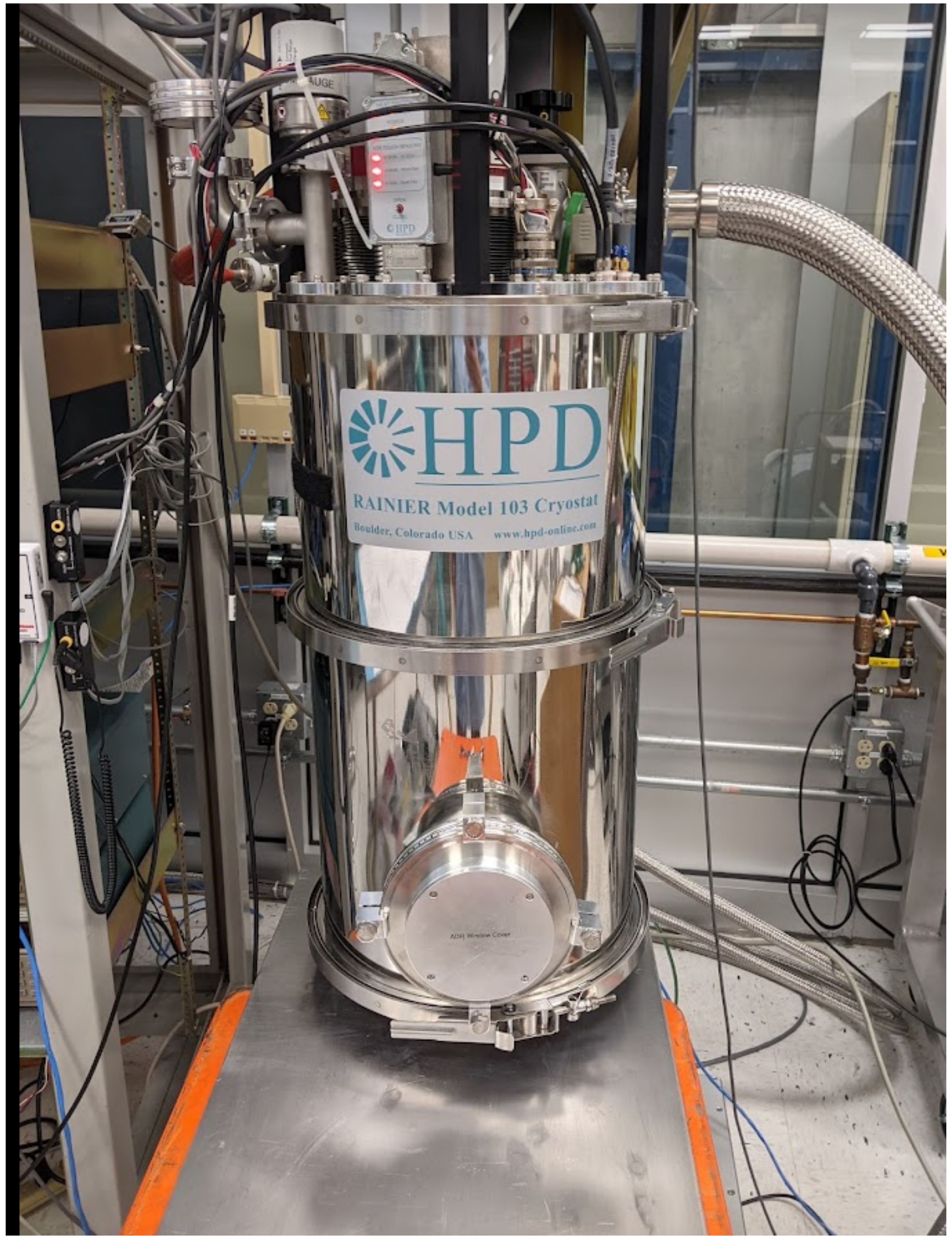
Assuming DCR ~1e-4
50% signal efficiency



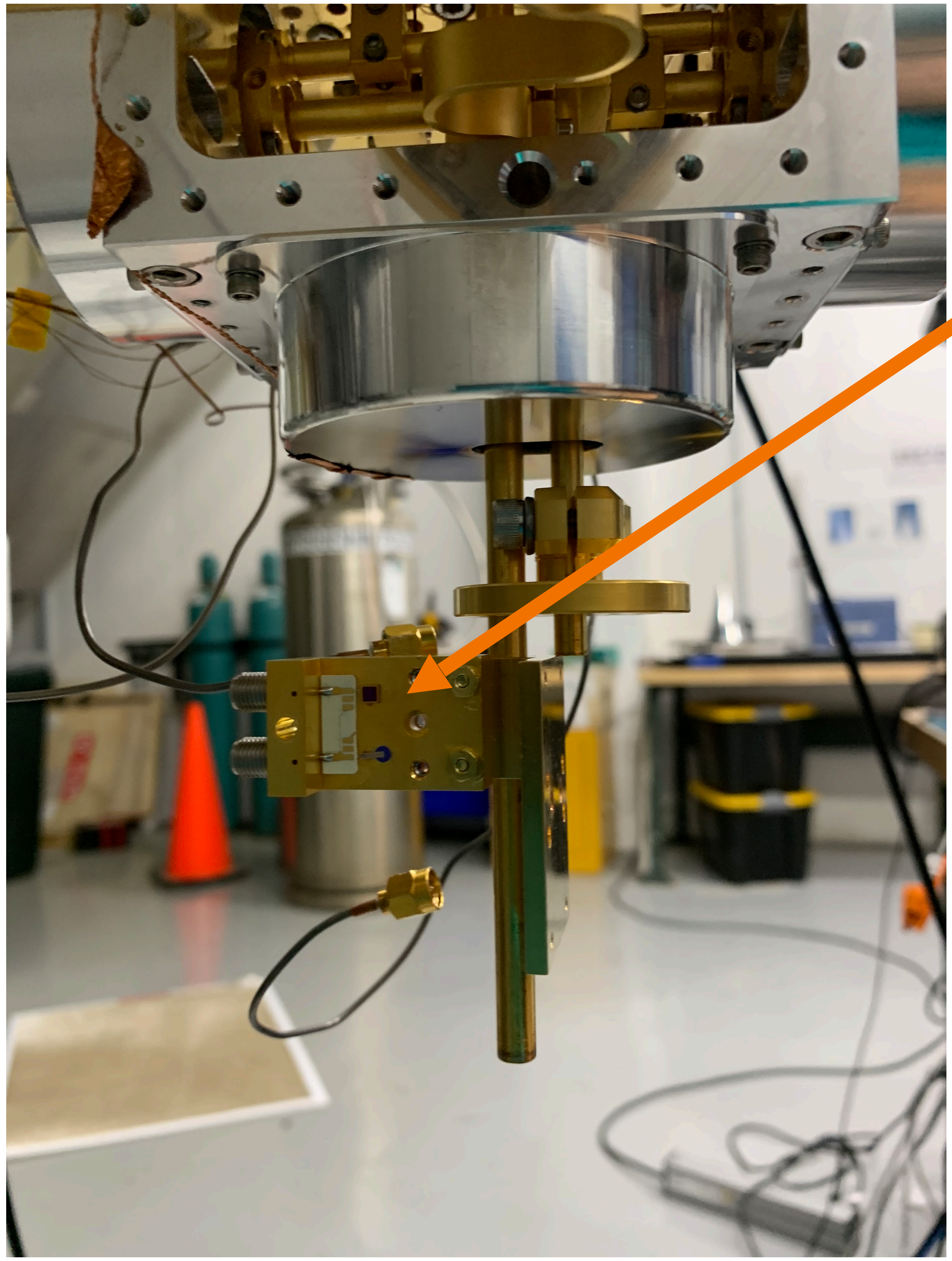
R = 20 cm

ADR Test Stand at FNAL

- I will focus on SNSPD testing at FNAL for the rest of the talk
  - Details on the design and testing of the reflector in **Gabriel Hoshino's talk**
- The sensors are mounted in an Adiabatic Demagnetization Refrigerator (ADR) cryostat in FNAL
  - Base temperature is 0.2K
- Capable of external illumination with laser diode of 4 wavelengths in the range 0.6-1.6 microns to calibrate SNSPDs
  - Cryostat has a sapphire window to allow illumination by an external source



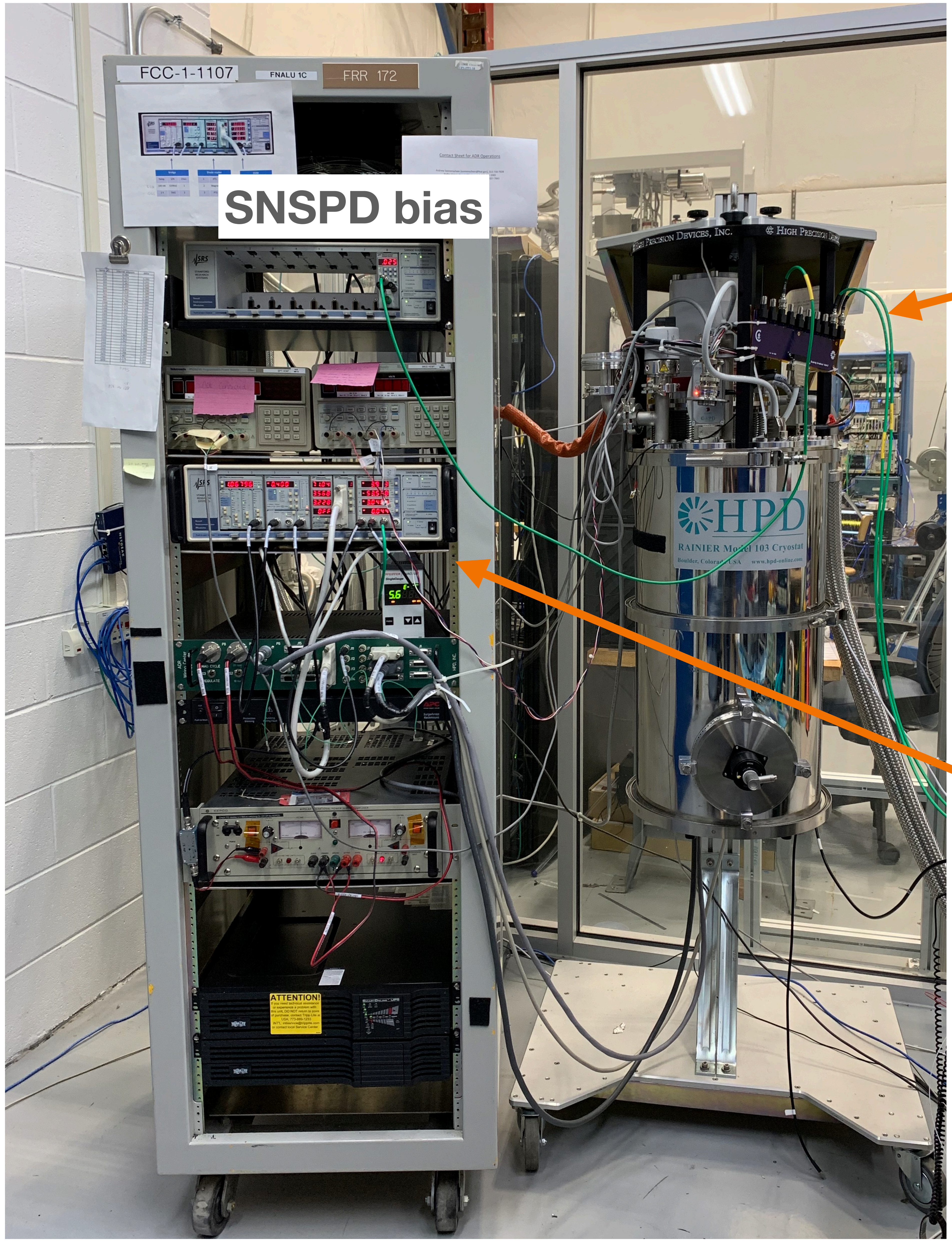
SNSPDs in ADR



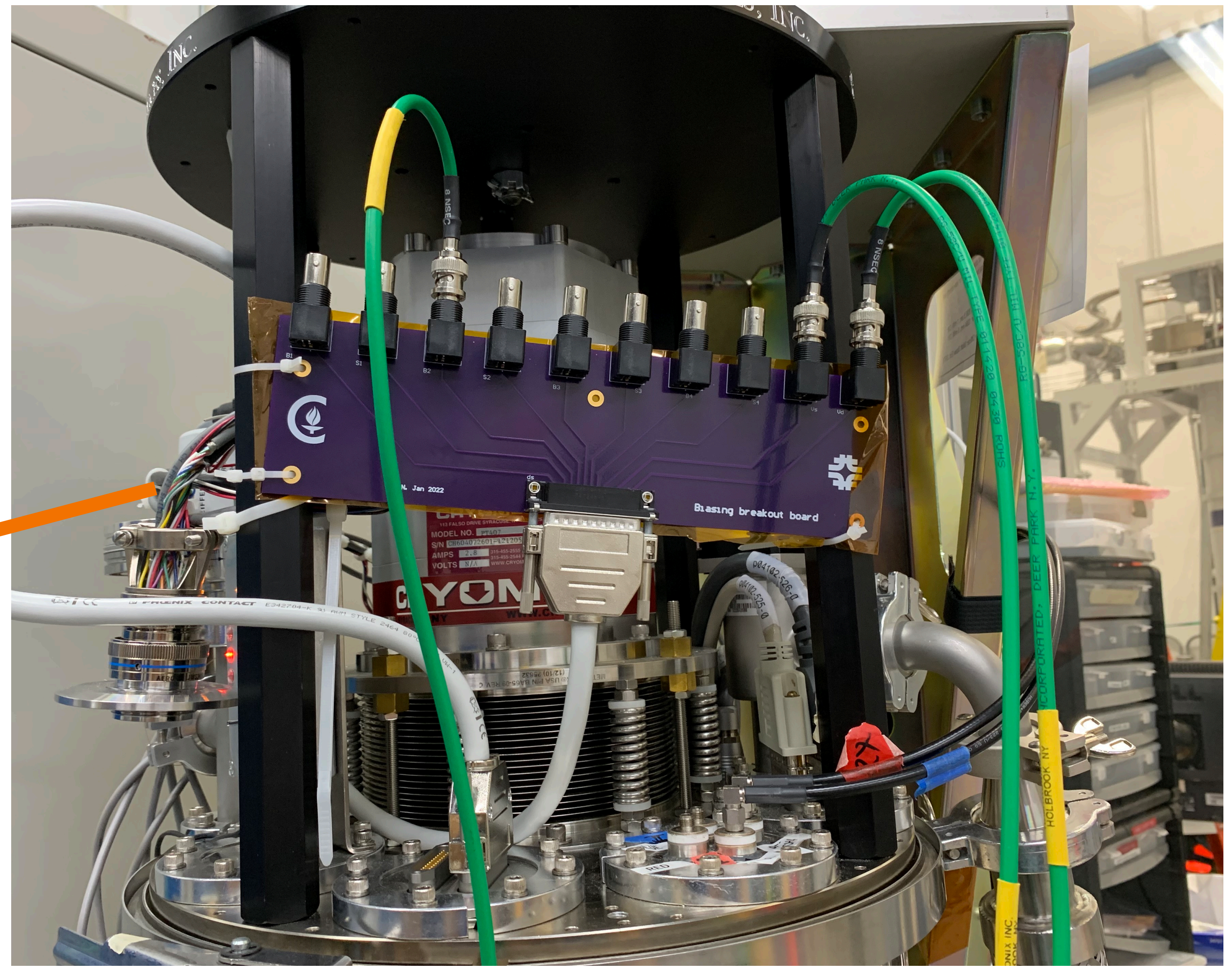
JPL SNSPDs

- We have received SNSPDs from MIT/JPL for testing purpose
  - Test the ADR, electronics, DAQ with the test SNSPDs
- We will start testing 8-channel mm^2 SNSPD

Electronics

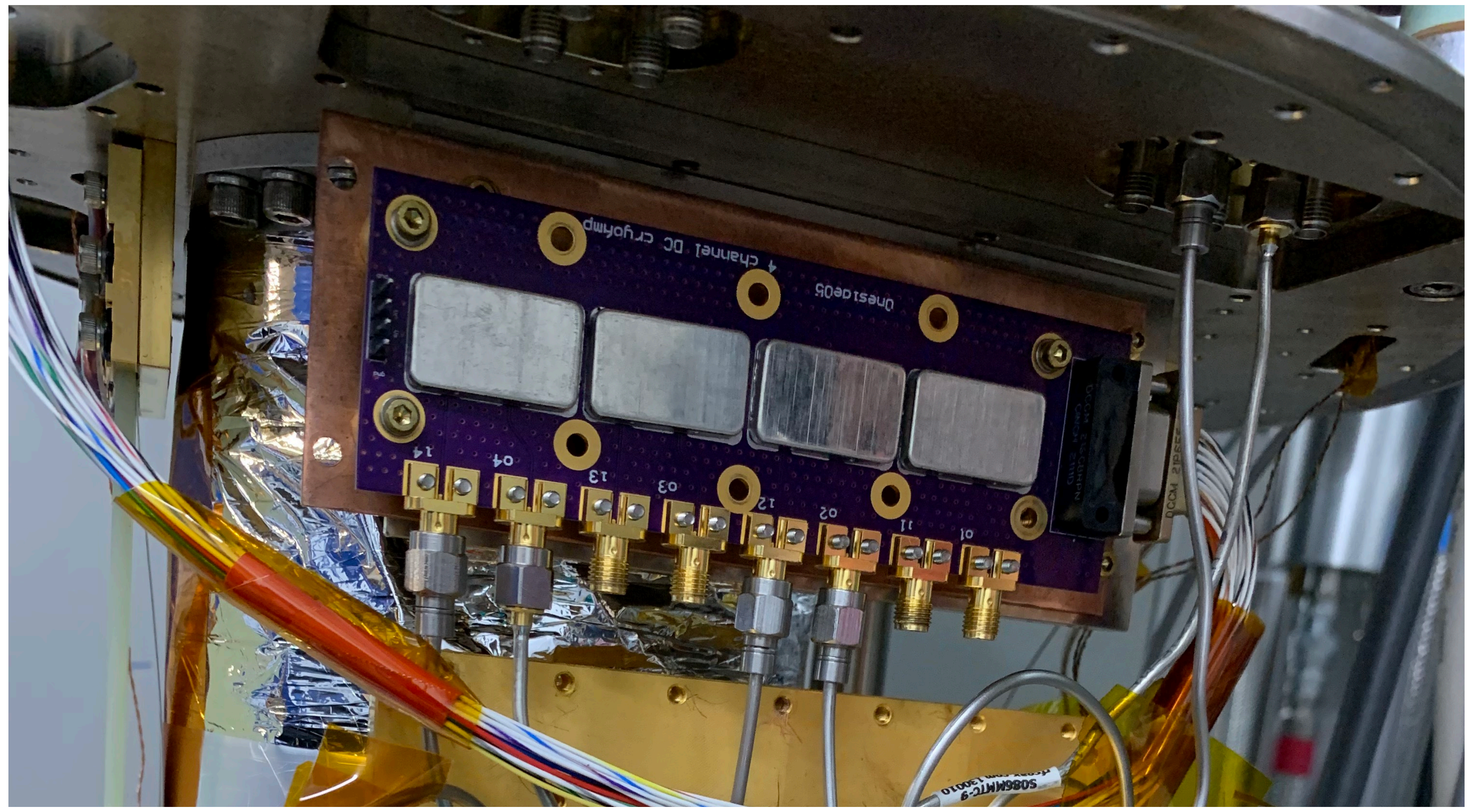


Temperature &
pressure monitors

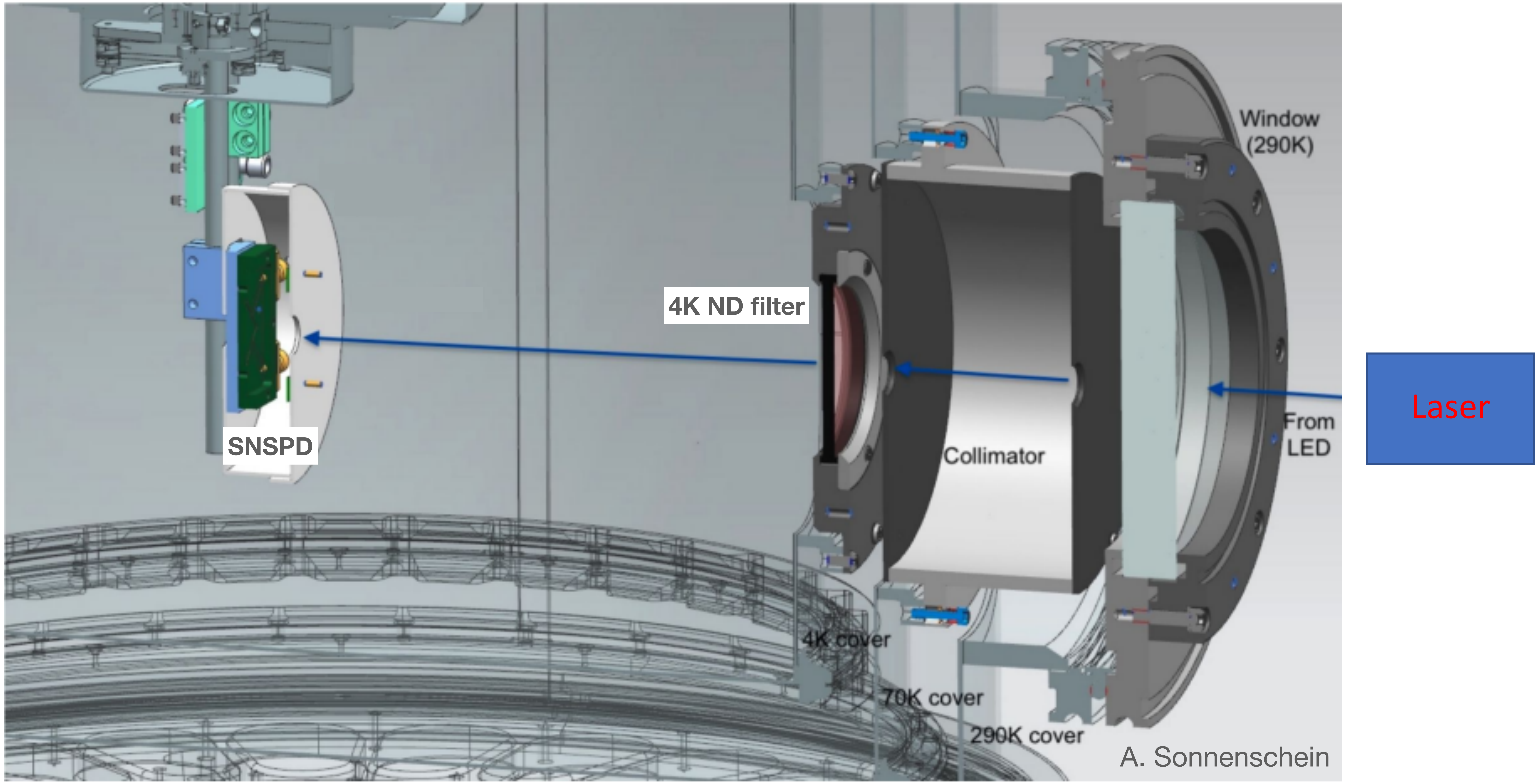


Biasing breakout board
(provides bias for SNSPDs and the cryo-amp)

Low noise 4-channel amplifier at 70 K
~30 dB gain from 10-500MHz

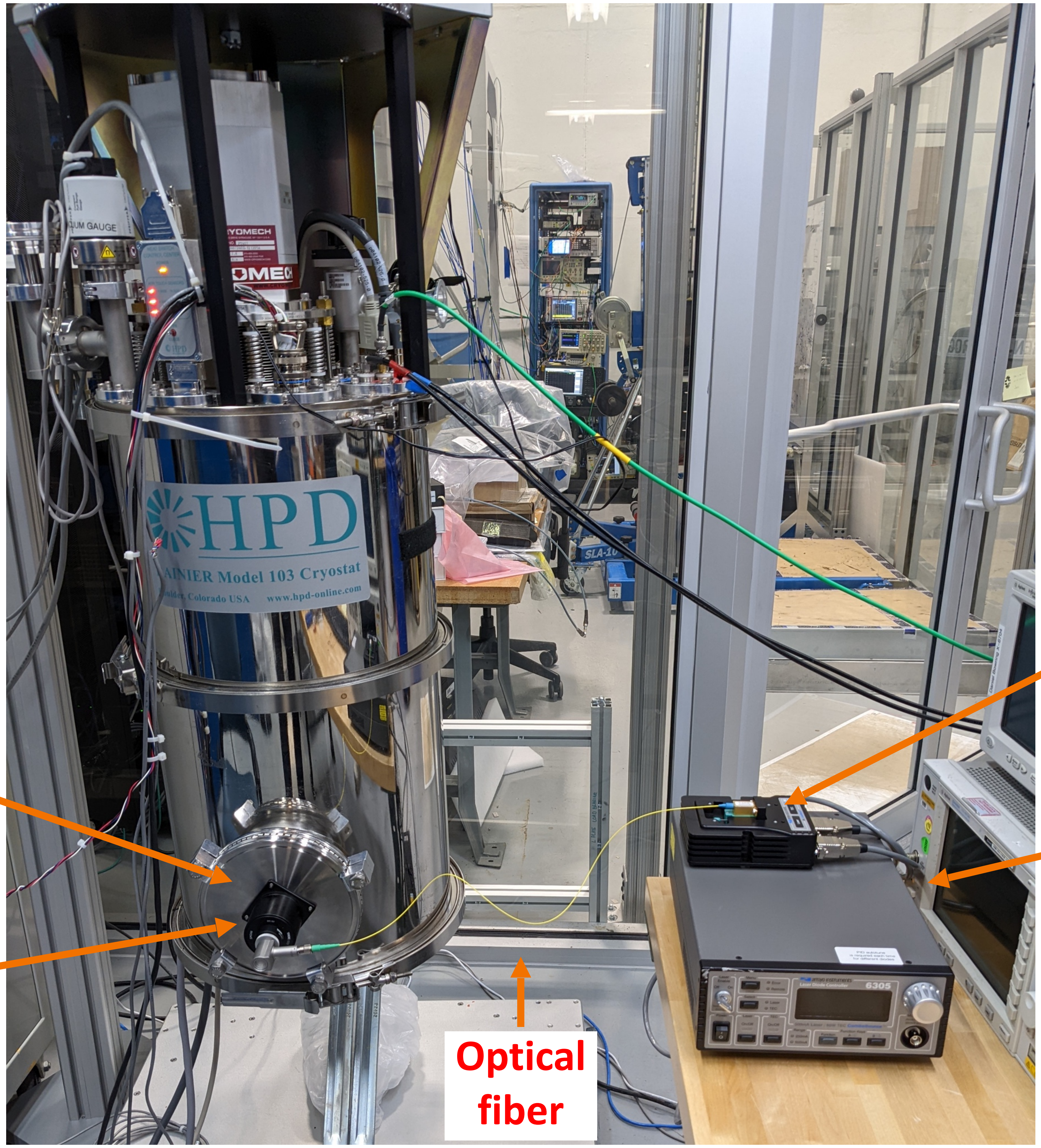


Calibration of Sensors in ADR with External Laser



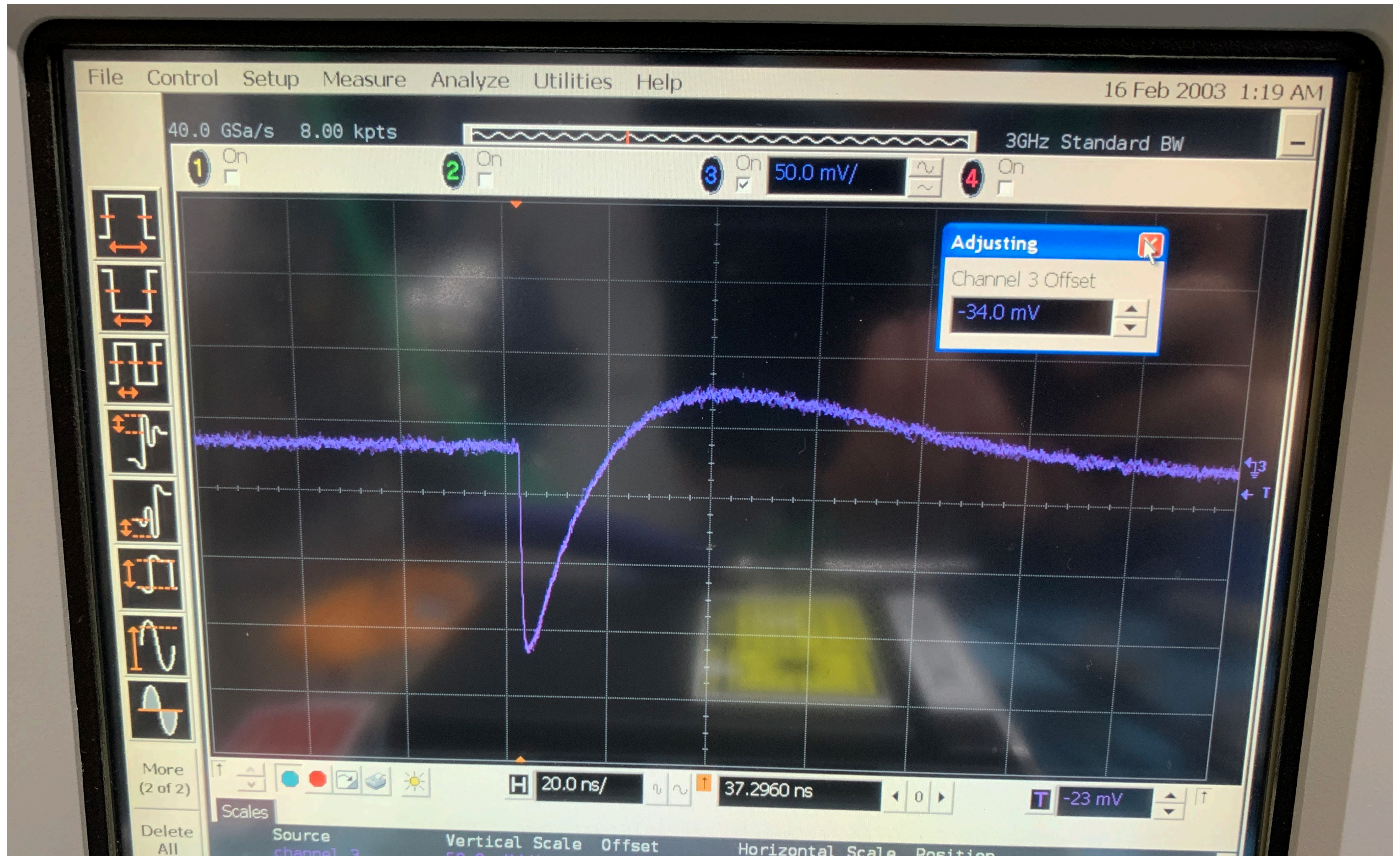
ND filter suppresses wavelength < 700 nm by 1e-4

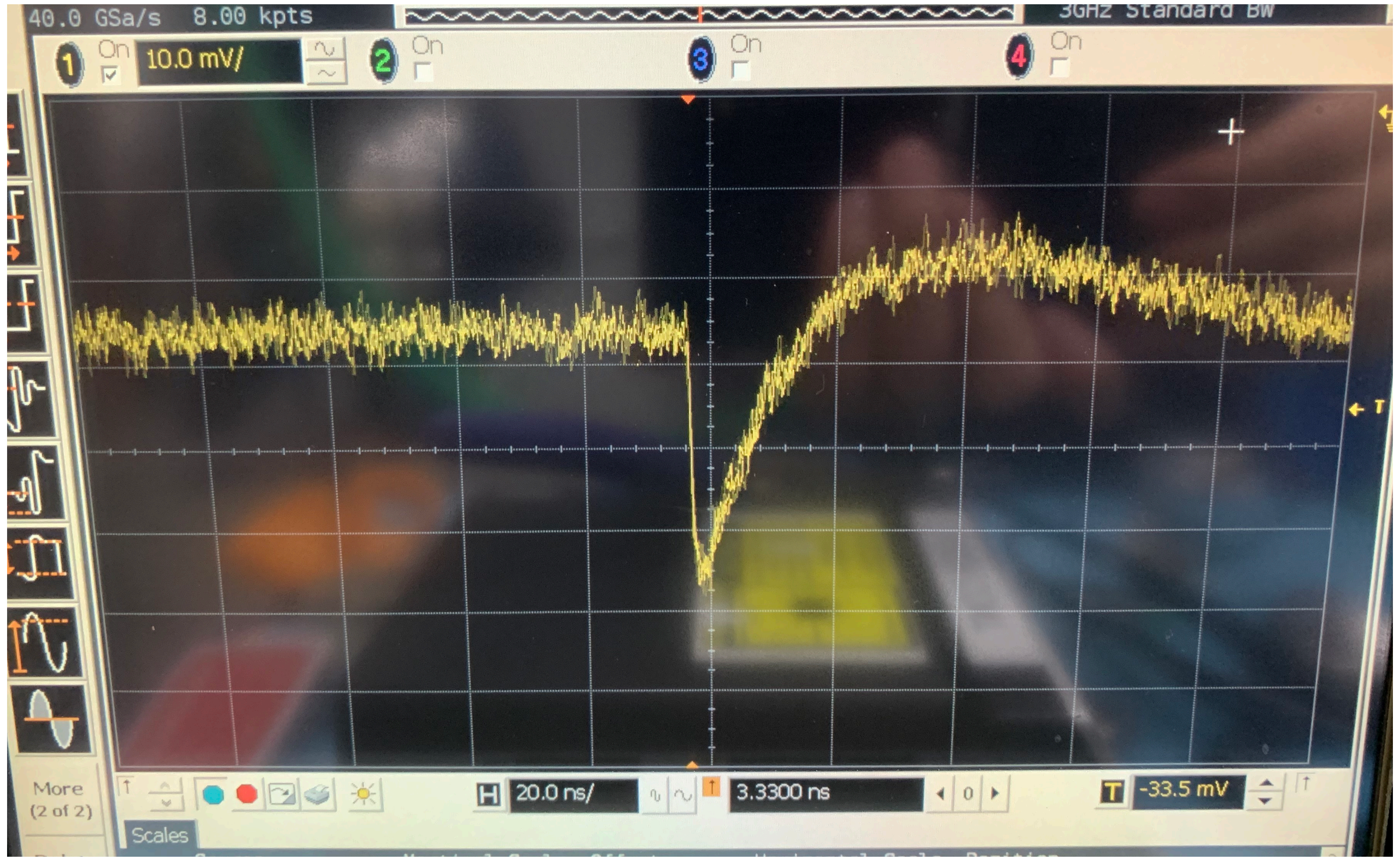
Calibration of Sensors in ADR with External Laser

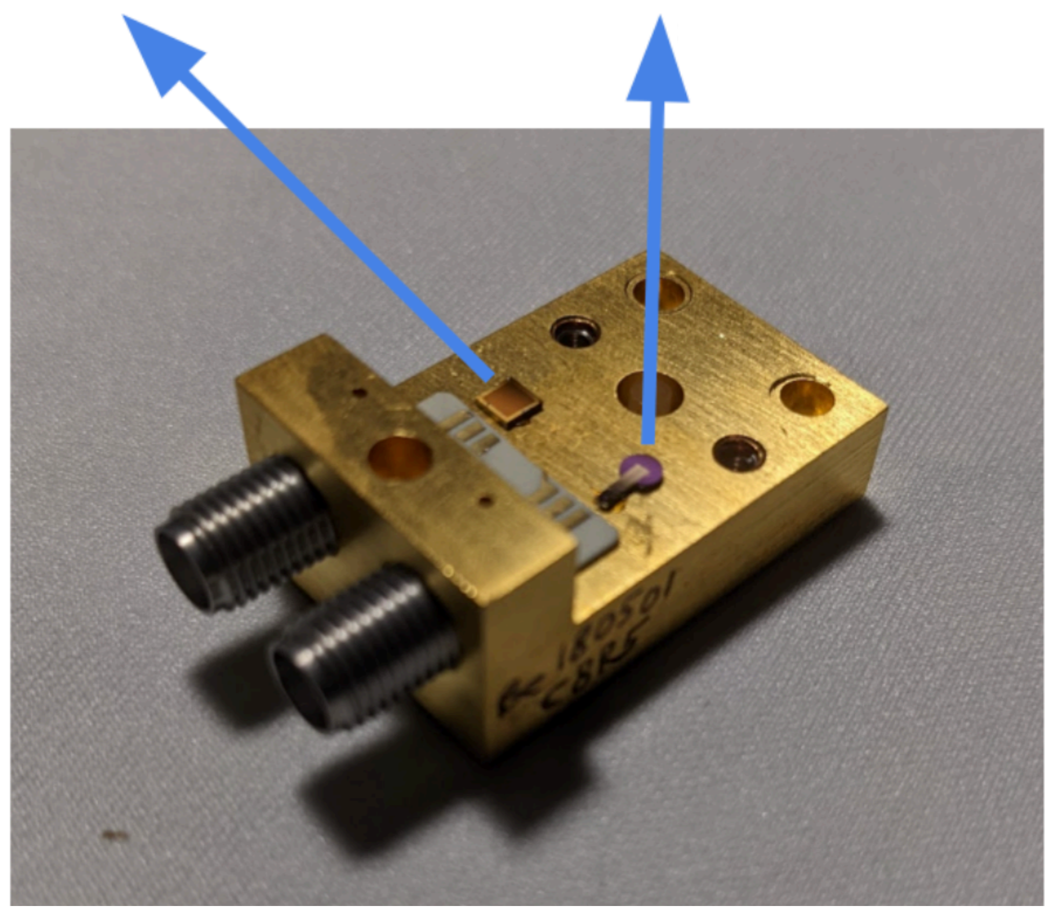


First Pulses from SNSPDs with ADR

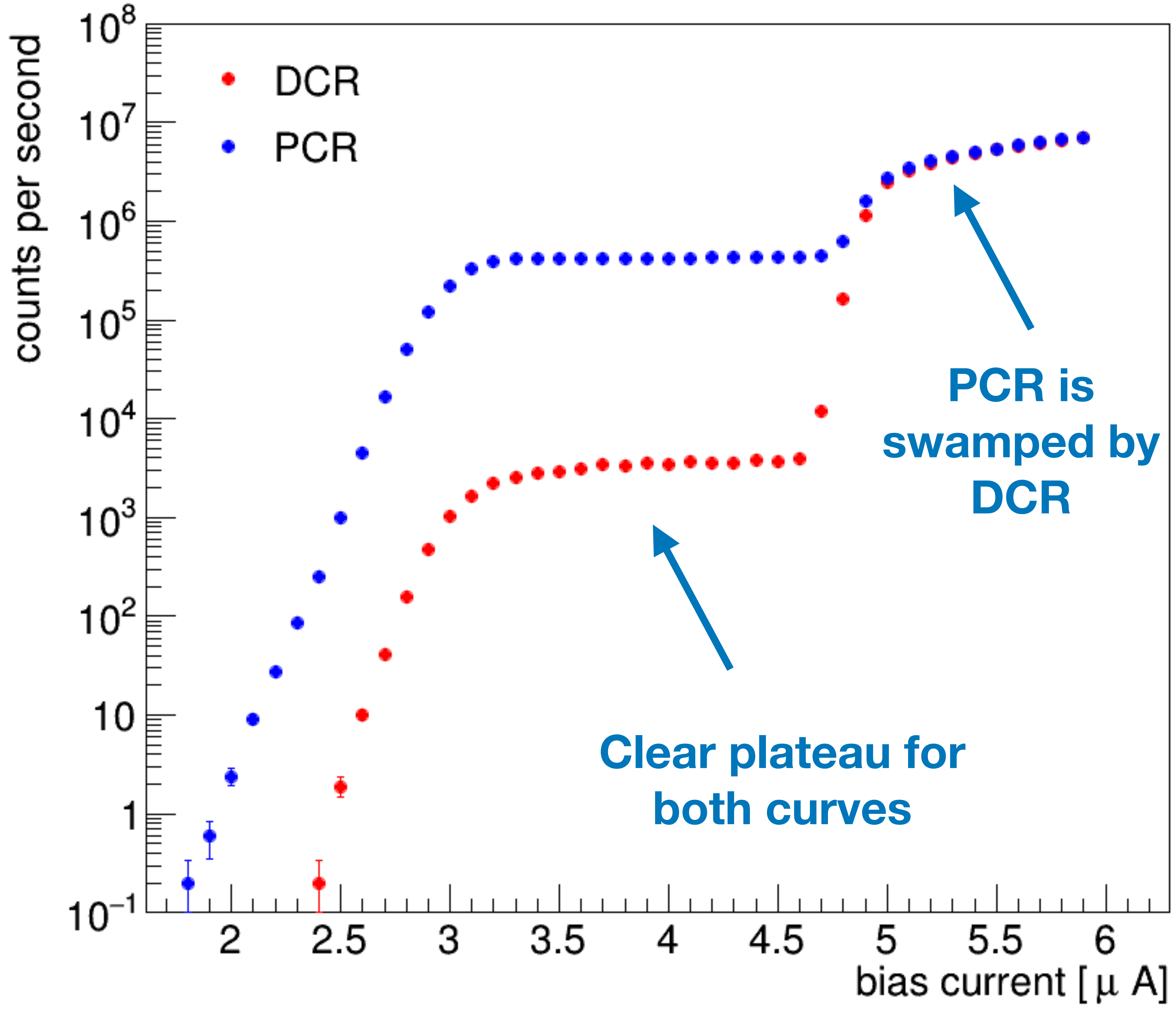
Cooled down the ADR to 0.8K and saw first pulses from both JPL SNSPDs







Photon Count Rate & Dark Count Rate

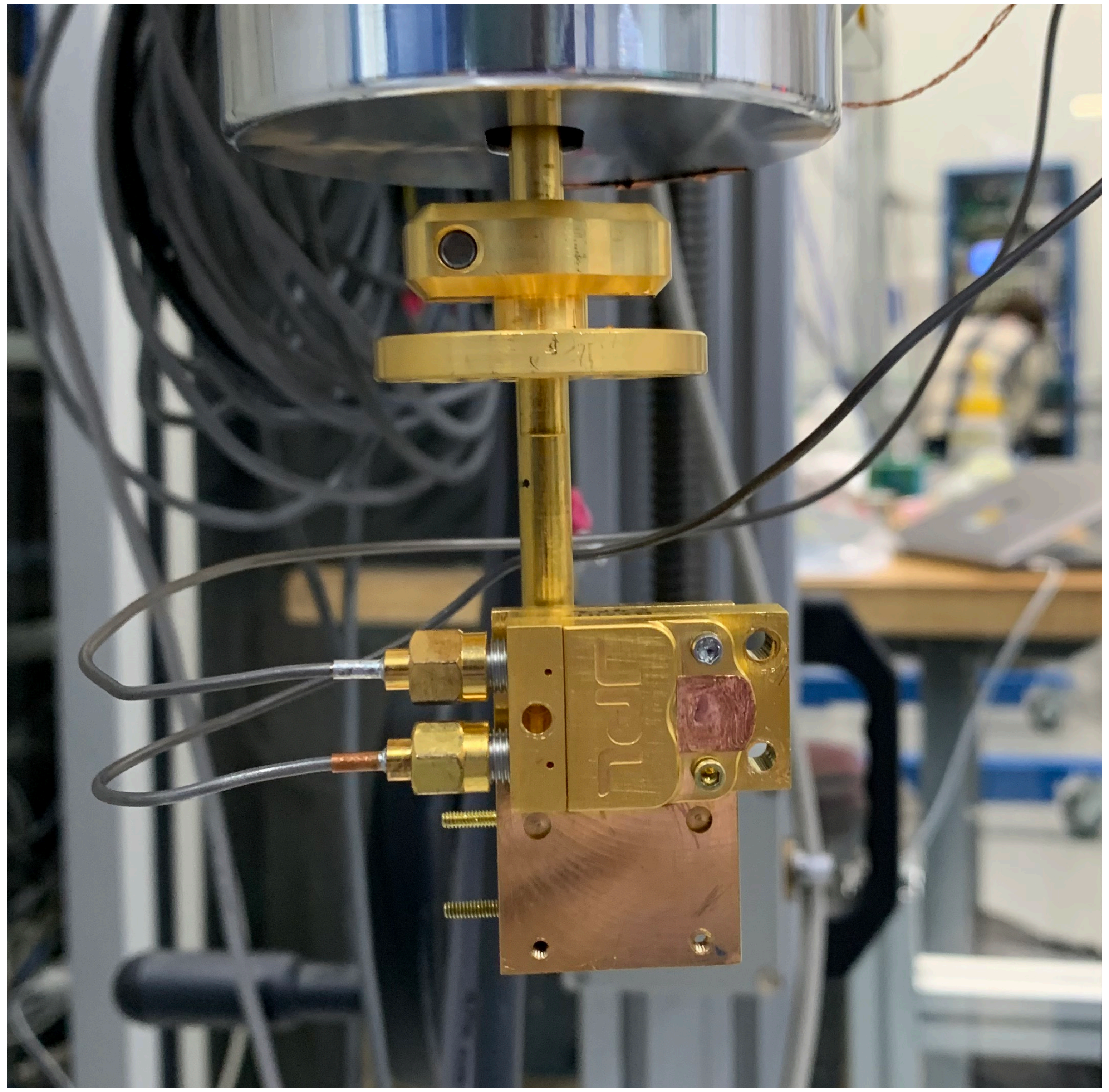


- We measured the **dark count rate** and **photon count rate** with 1300nm diode
- We observed a **clear plateau** from 3-5 uA for both DCR and PCR curves → **detector operating as expected**

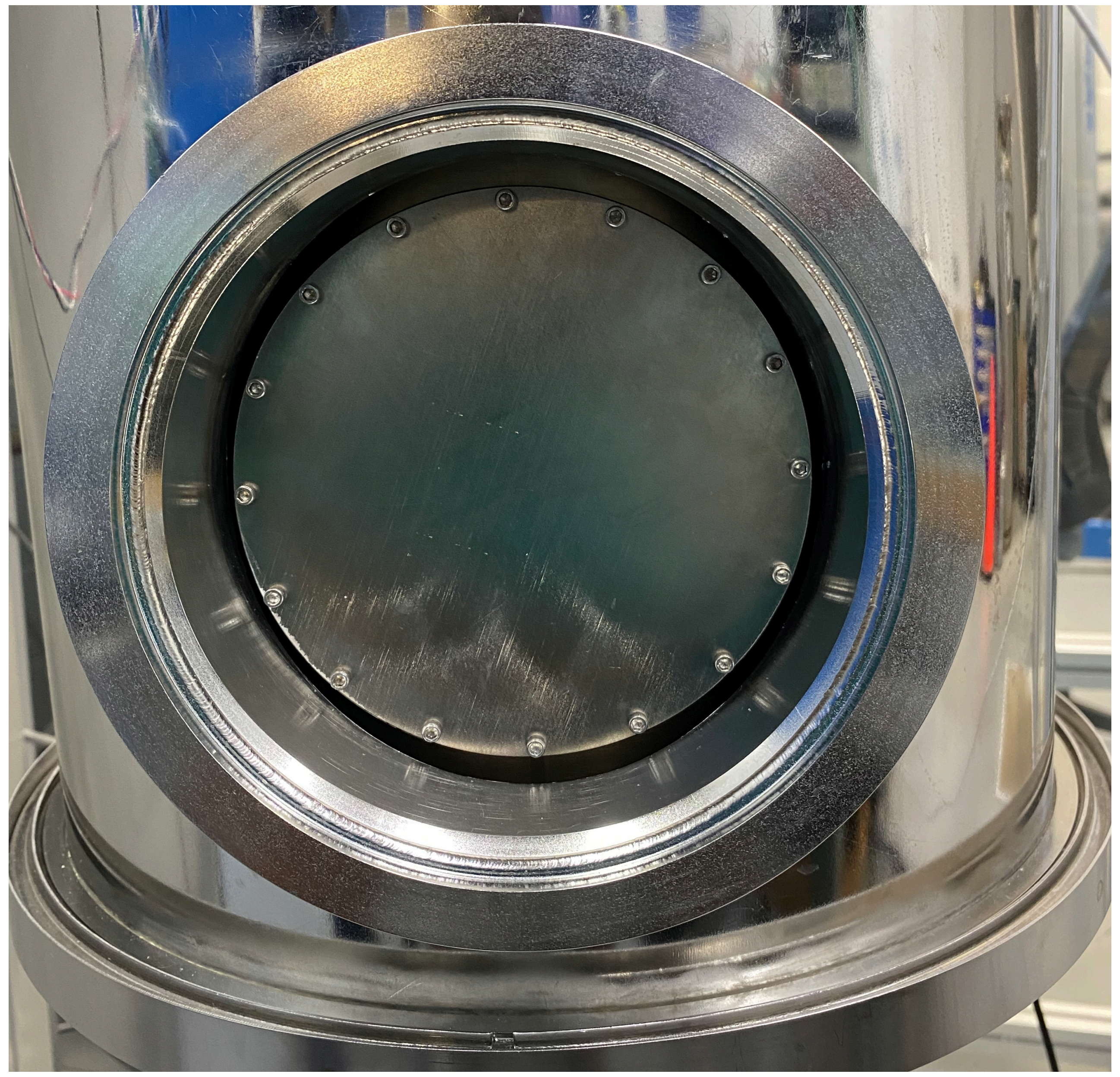
Dark Count Rate Measurements

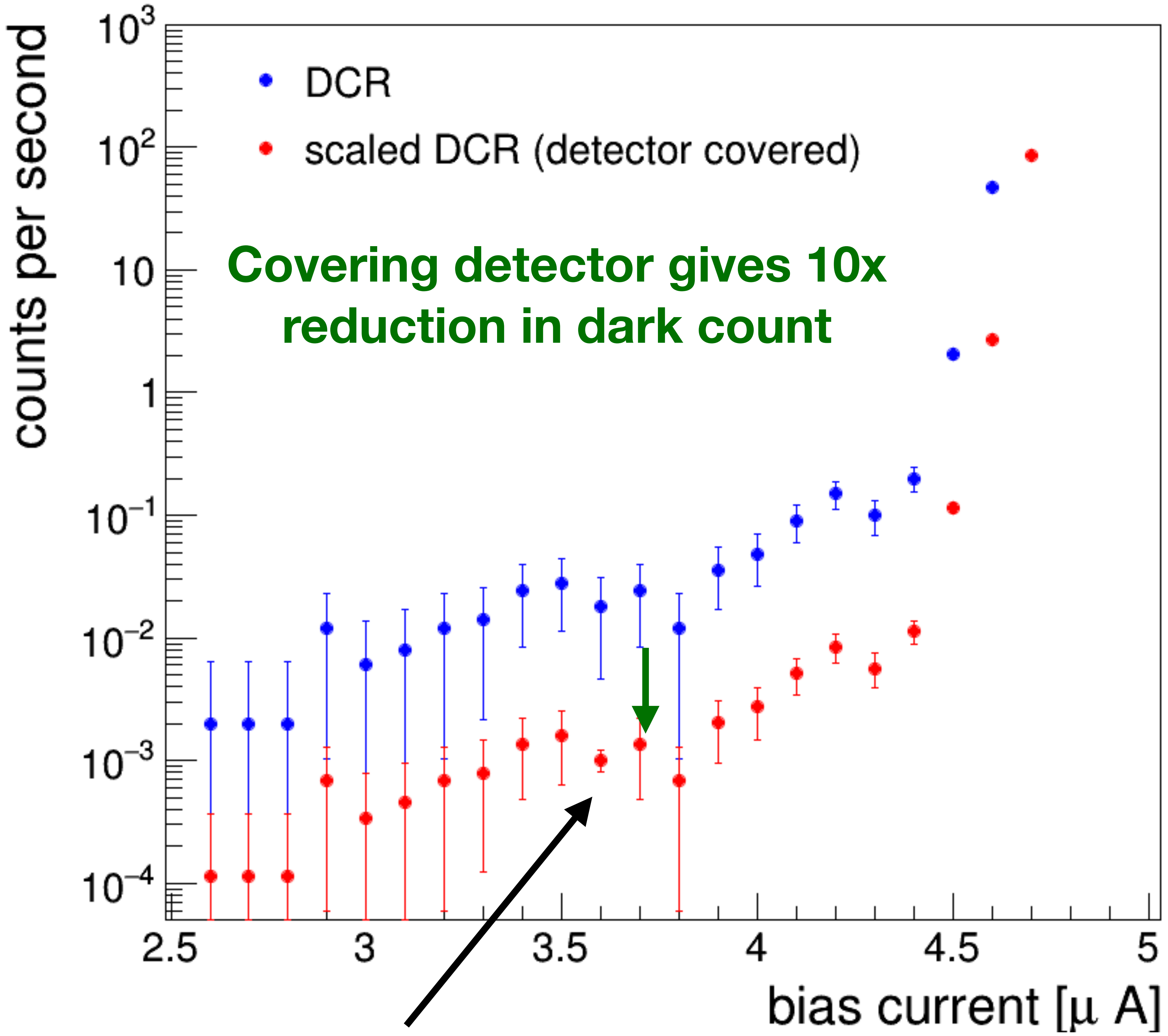
- We expect the large DCR is due to photons coming through the sapphire window
- Measured the DCR after added a shielding at 70K and the SNSPD shield → 1e-3 DCR!

Covered SNSPDs



Add radiation shield at 70K





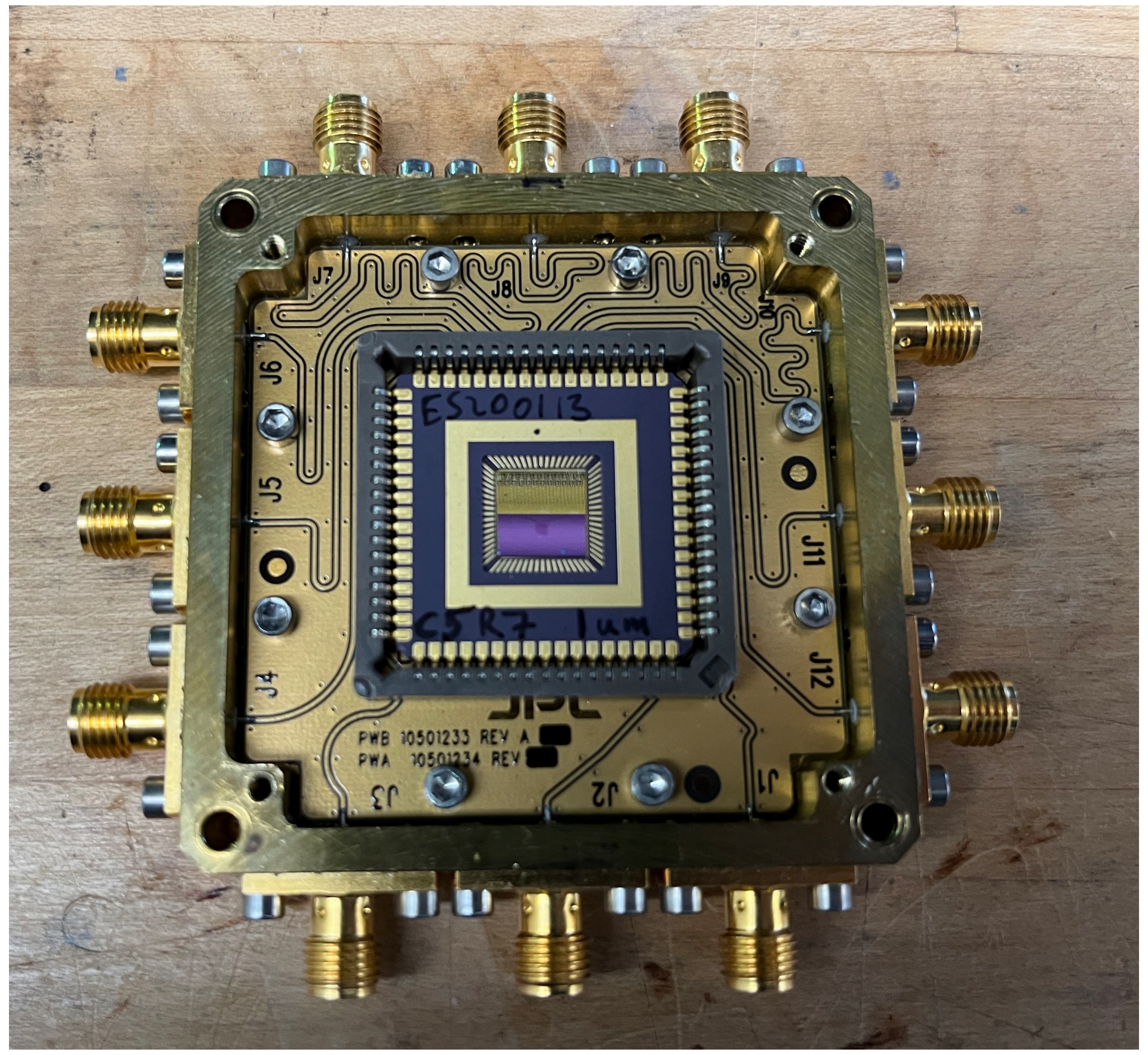
Only measured dark count at 3.6 uA

Other points are scaled from DCR without lid on due to long integration time

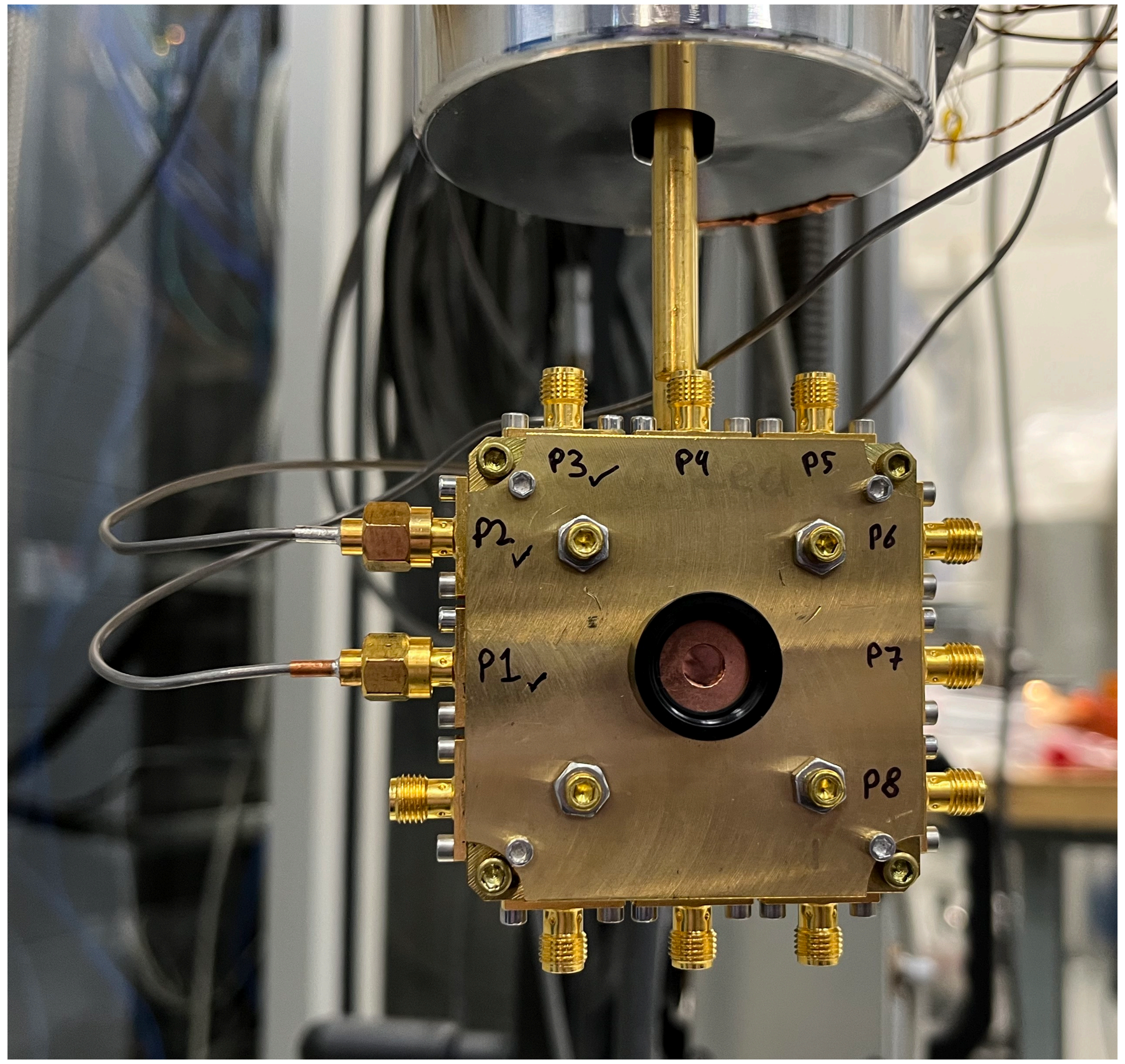
Towards mm^2 SNSPD Active Area

- Have started testing first 8-channel mm^2 SNSPD → saw first pulses from mm^2-SNSPD
- Will measure dark count rate and PCR curve for mm^2 SNSPD

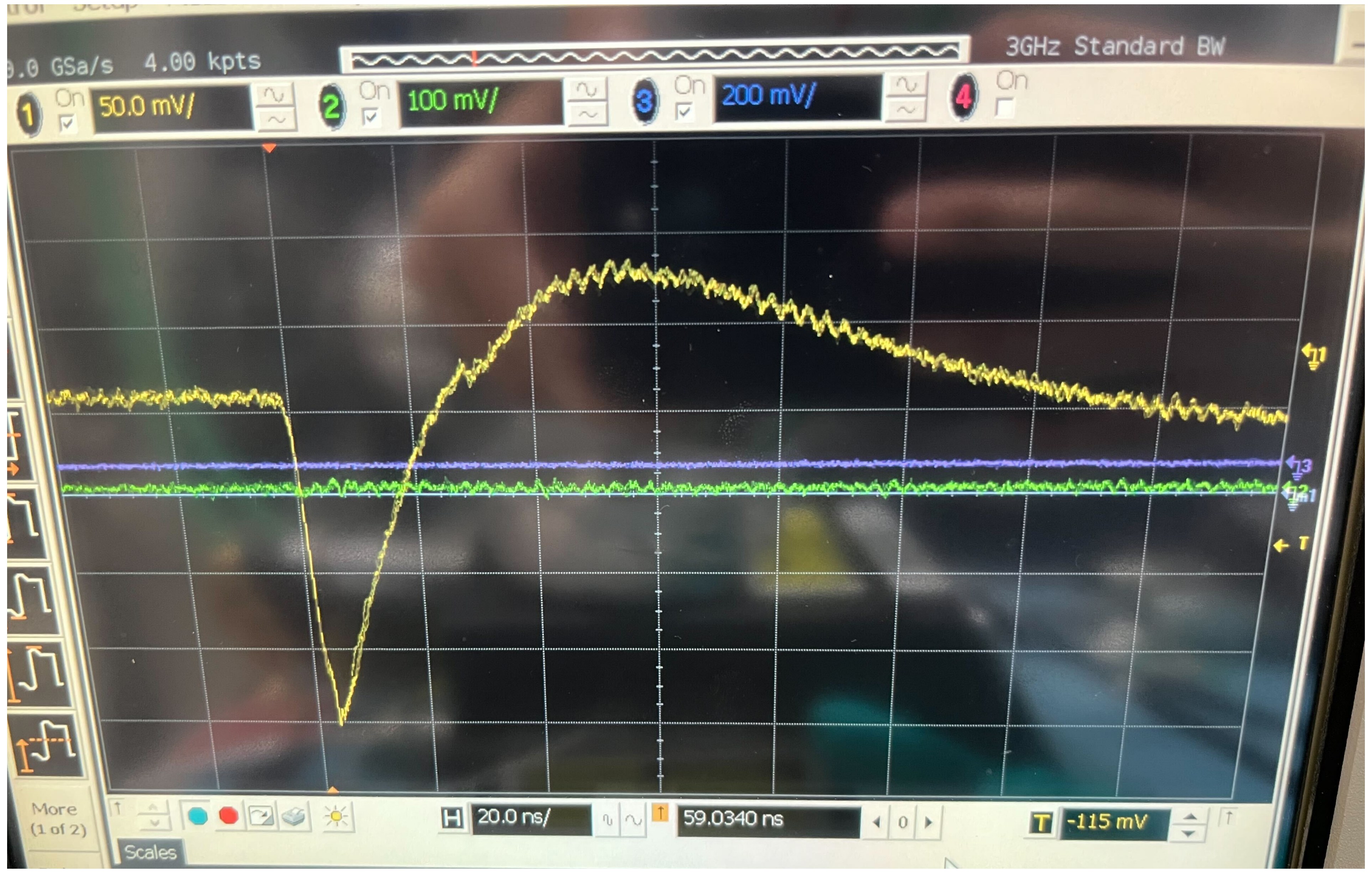
mm^2 SNSPD without lid



mm^2 SNSPD on ADR cold finger

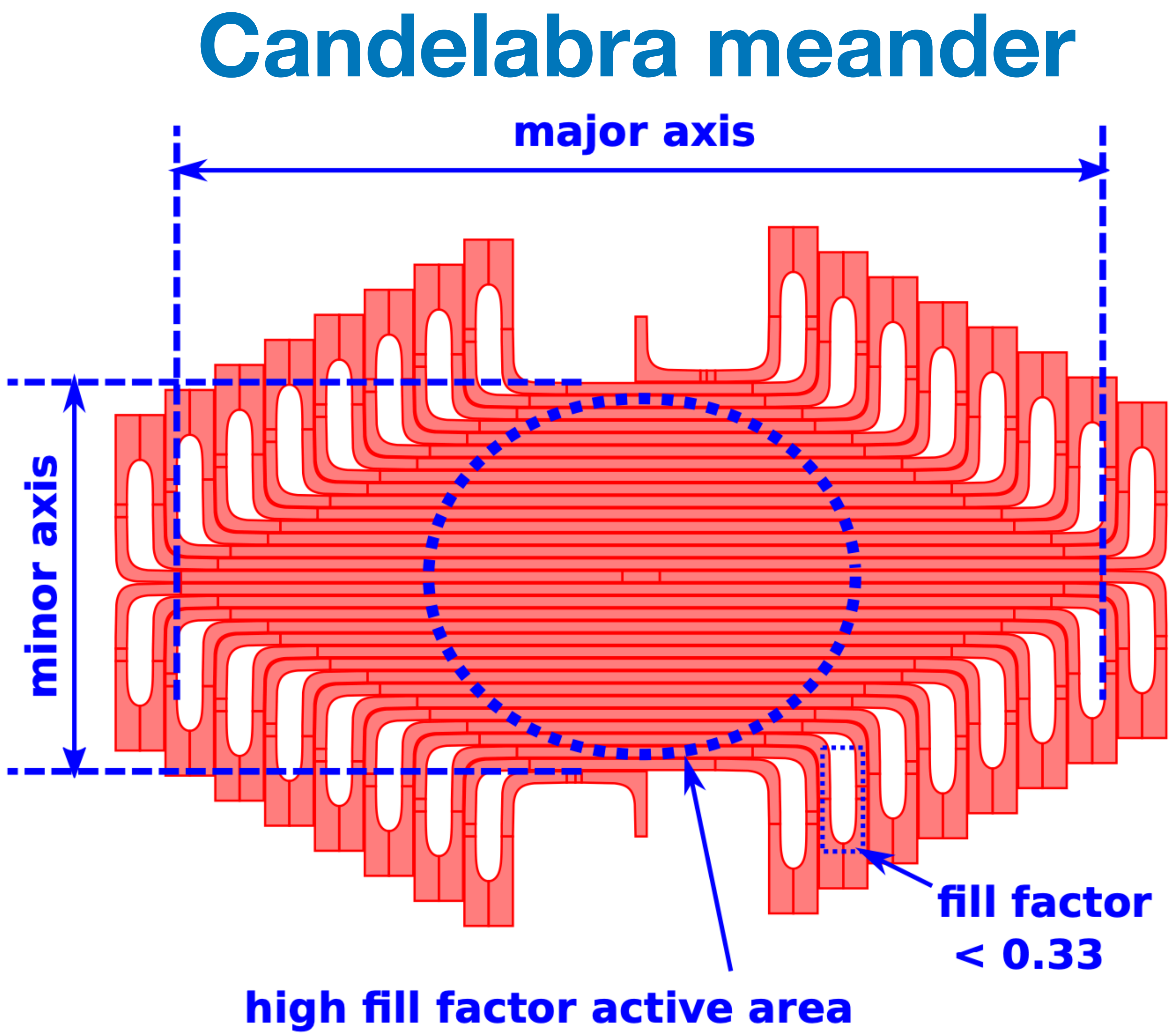


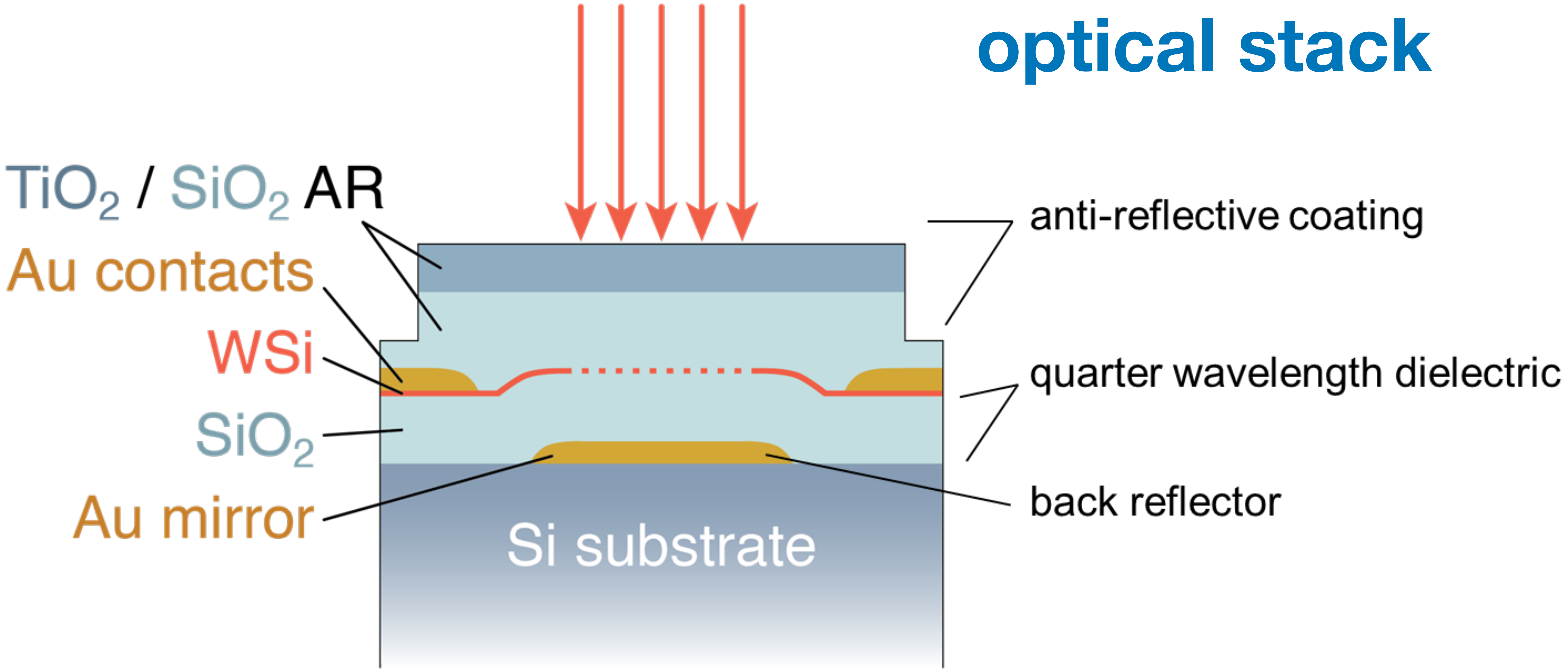
first pulses from mm^2-SNSPD



Future SNSPD Improvements

- Improvement on SNSPD designs could increase the efficiency (more details in Jamie Luskin's talk)
  - Increase fill factor by exploring new geometry: Candelabra meander
    - Place nanowire bends outside of high fill-factor active area to minimize current crowding
  - Design optical stack optimized for photon absorption





arXiv:2202.05942

Summary

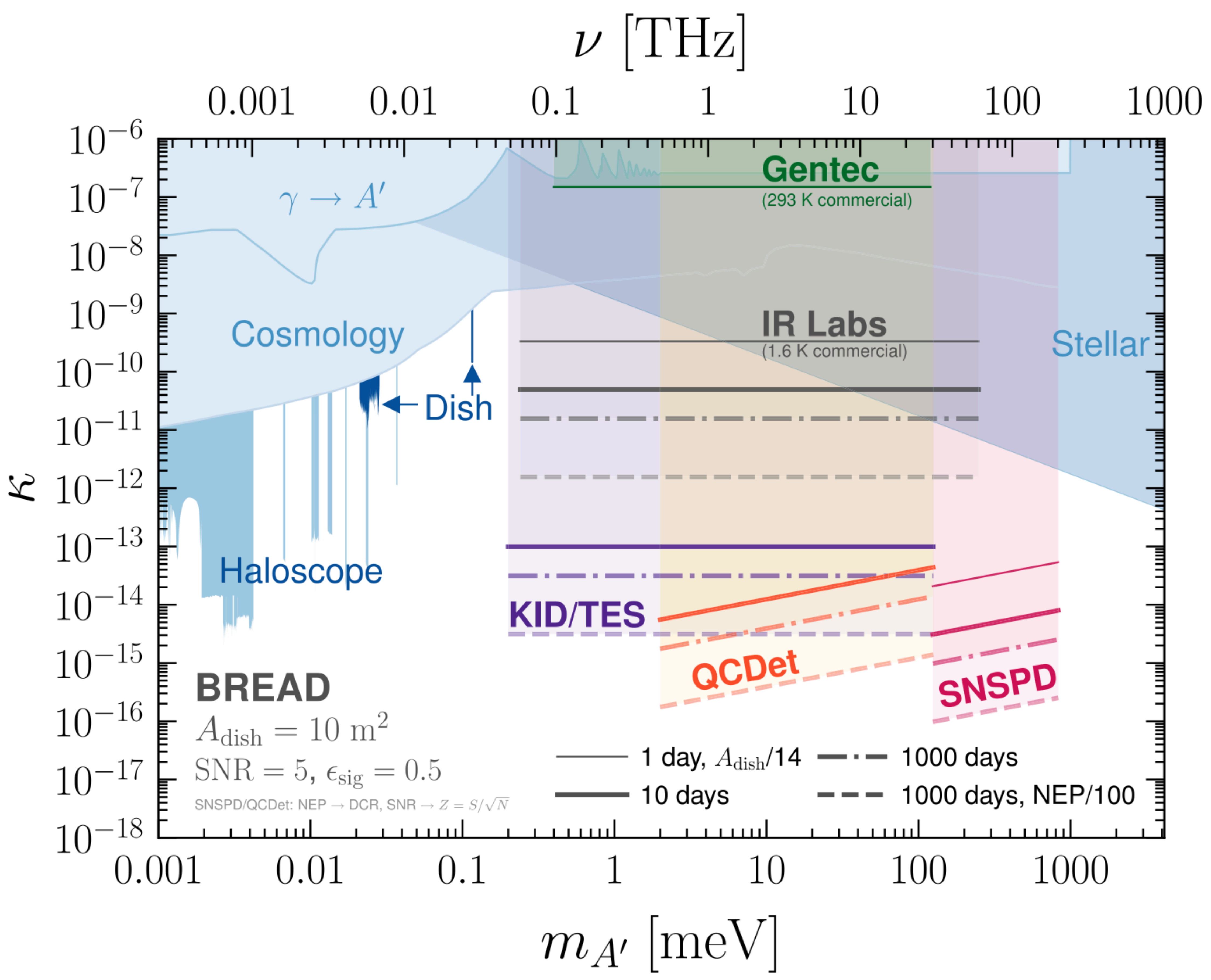
- Pilot BREAD experiment is progressing well towards an optical experiment with SNSPDs
- Pilot dark photon experiment (no magnetic field) can already set best limit for 0.1-1 meV
- Characterization of large area SNSPD (mm^2) in terms of photon and dark count rate will begin soon
- Developing system to measure calibrated efficiency as function of photon wavelength and incident angle: critical for BREAD
- Integrating novel BREAD concept to search for axions and dark photons with latest generation superconducting photon detectors

Backup Slides

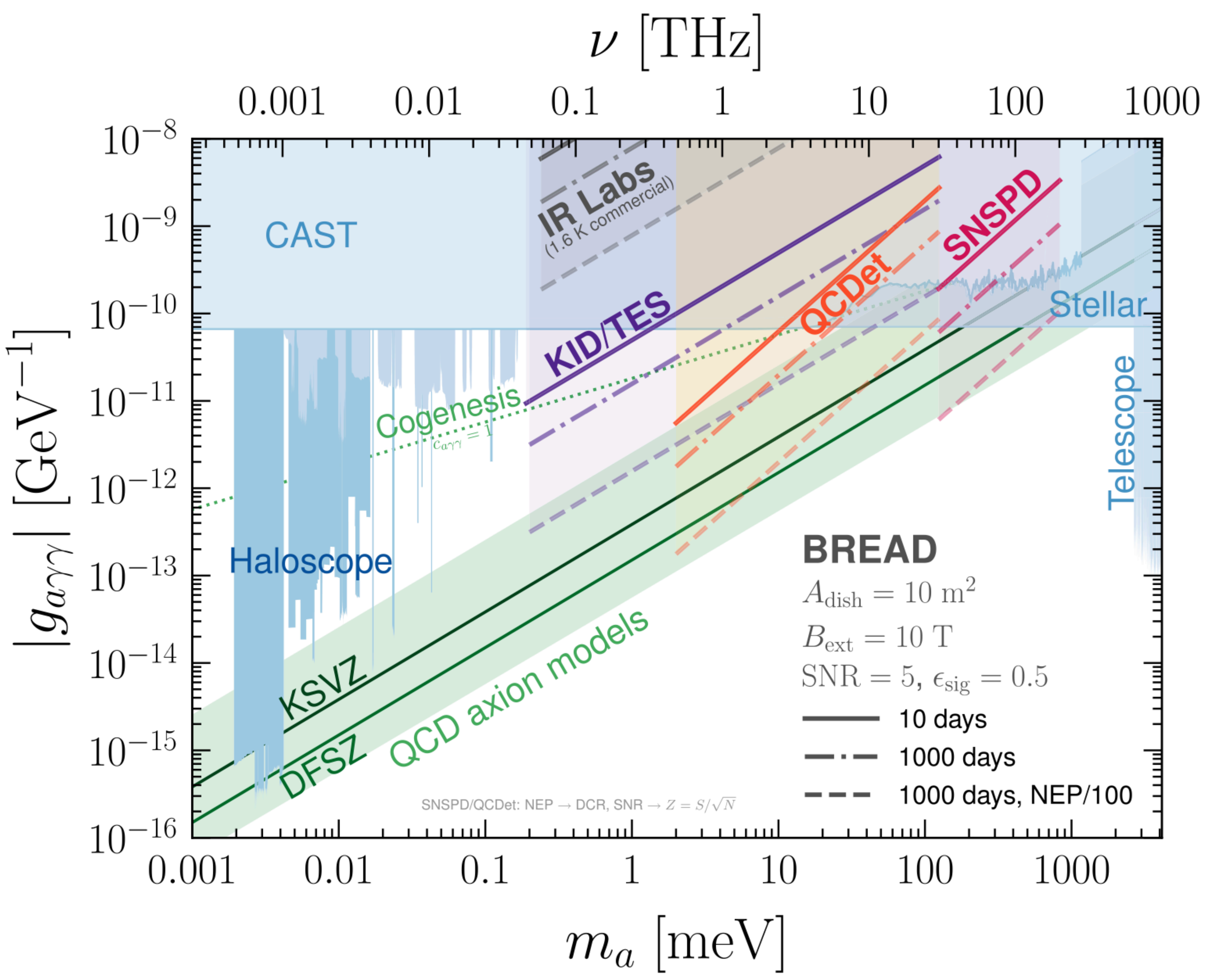
Projected Sensitivity

Phys. Rev. Lett. 128, 131801

Dark photon



Axion



- SNSPD provides unique sensitivity for 0.1-1 eV dark photons and axions due to its sensitivity for 1-10um photons

$$Z = \frac{N_{\text{signal}}}{\sqrt{N_{\text{noise}}}} = \frac{\epsilon_s R_{\text{DM}} \Delta t}{\sqrt{\text{DCR}\Delta t}}.$$

Requiring $Z = 5$ for DM reach implies the coupling sensitivity is related to the DCR by

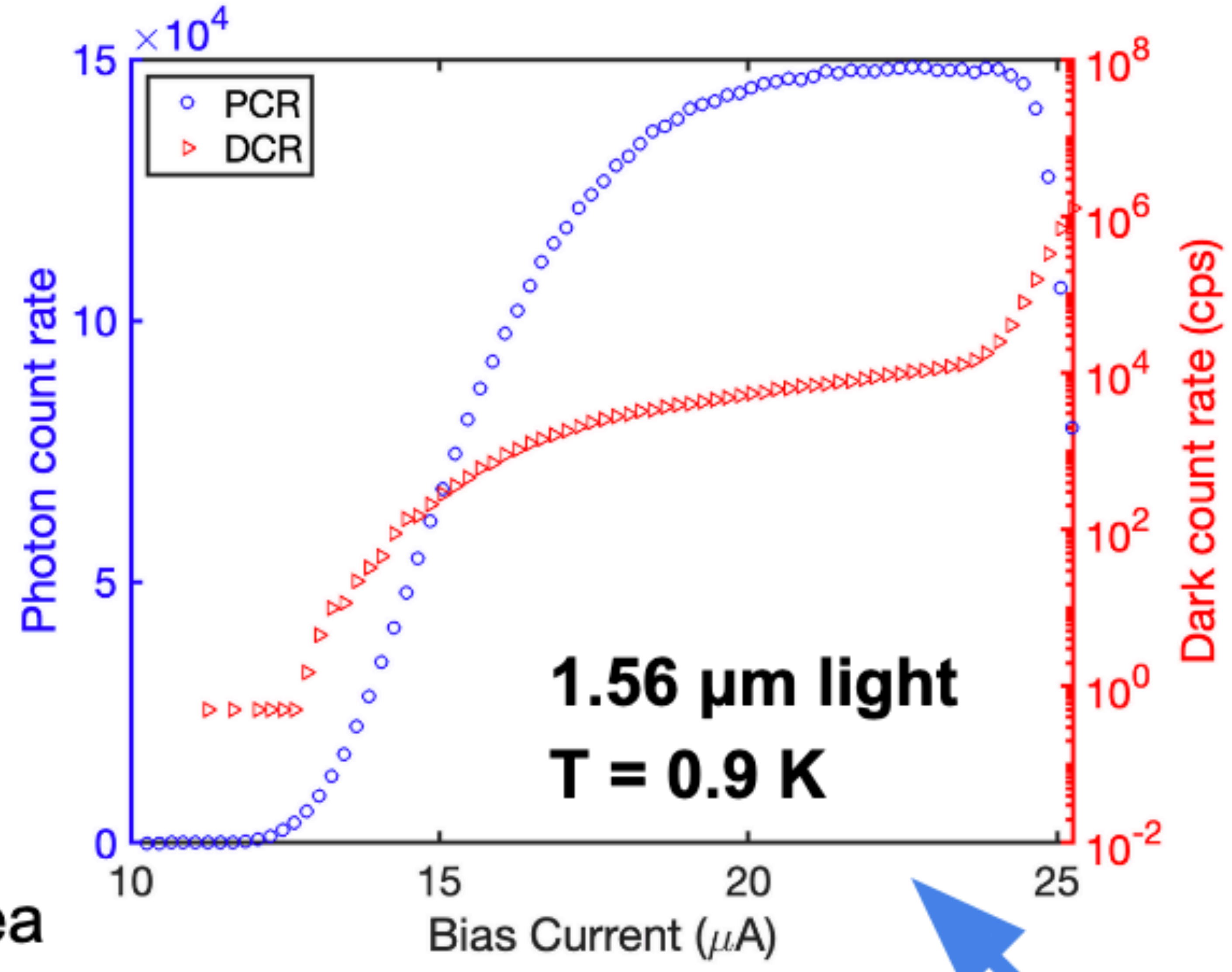
$$\left\{ \begin{array}{c} \left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2 \end{array} \right\} = \left\{ \begin{array}{c} \frac{3.0}{\text{GeV}^2} \left(\frac{m_a}{\text{meV}}\right)^3 \left(\frac{10\,\text{T}}{B_{\text{ext}}}\right)^2 \\ 11.9 \frac{2/3}{\alpha_{\text{pol}}^2} \frac{m_{A'}}{\text{meV}} \end{array} \right\} \left(\frac{\text{hour}}{\Delta t}\right)^{1/2}$$

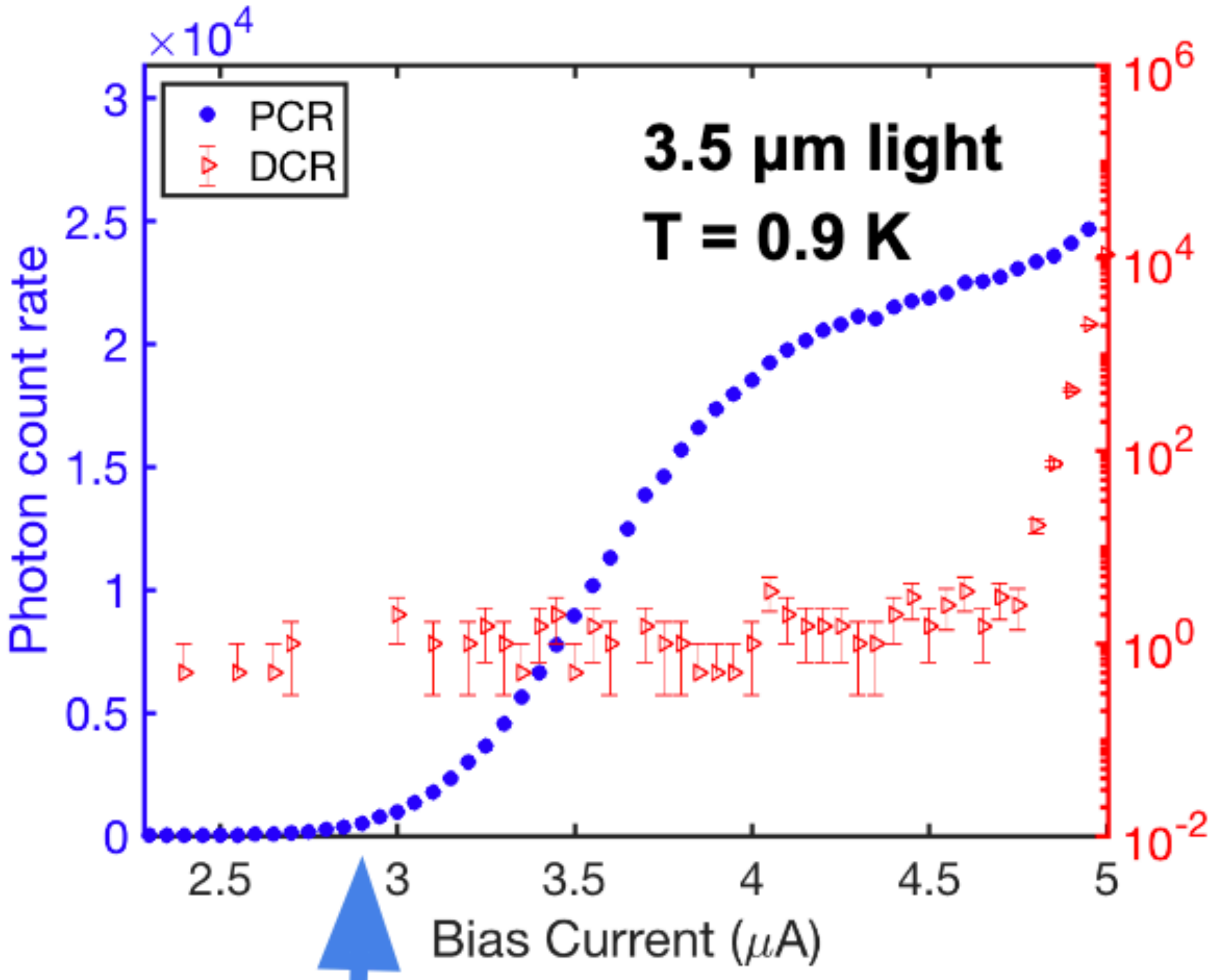
$$\times \frac{10\,\text{m}^2}{A_{\text{dish}}} \frac{Z}{5} \frac{0.5}{\epsilon_s} \left(\frac{\text{DCR}}{10^{-2}\,\text{Hz}}\right)^{1/2} \frac{0.45\,\text{GeV/cm}^3}{\rho_{\text{DM}}}. \tag{11}$$

In photon counting regimes, it is more convenient to consider the DM-induced rate $R_{\rm DM}$ of emitted photons given by $P_{\rm DM}/m_{\rm DM}$:

$$\left\{ \begin{matrix} \dfrac{R_a}{0.55\,{\rm Hz}} \\ \dfrac{R_{A'}}{0.14\,{\rm Hz}} \end{matrix} \right\} = \left\{ \begin{matrix} \left(\dfrac{g_{a\gamma\gamma}}{10^{-11}\,{\rm GeV}^{-1}}\right)^2 \left(\dfrac{\rm meV}{m_a}\right)^3 \left(\dfrac{B_{\rm ext}}{10\,{\rm T}}\right)^2 \\ \dfrac{\alpha_{\rm pol}^2}{2/3} \left(\dfrac{\kappa}{10^{-14}}\right)^2 \dfrac{\rm meV}{m_{A'}} \end{matrix} \right\} \times \frac{\rho_{\rm DM}}{0.45\,{\rm GeV/cm}^3} \frac{A_{\rm dish}}{10\,{\rm m}^2}. \tag{9}$$

JPL test devices





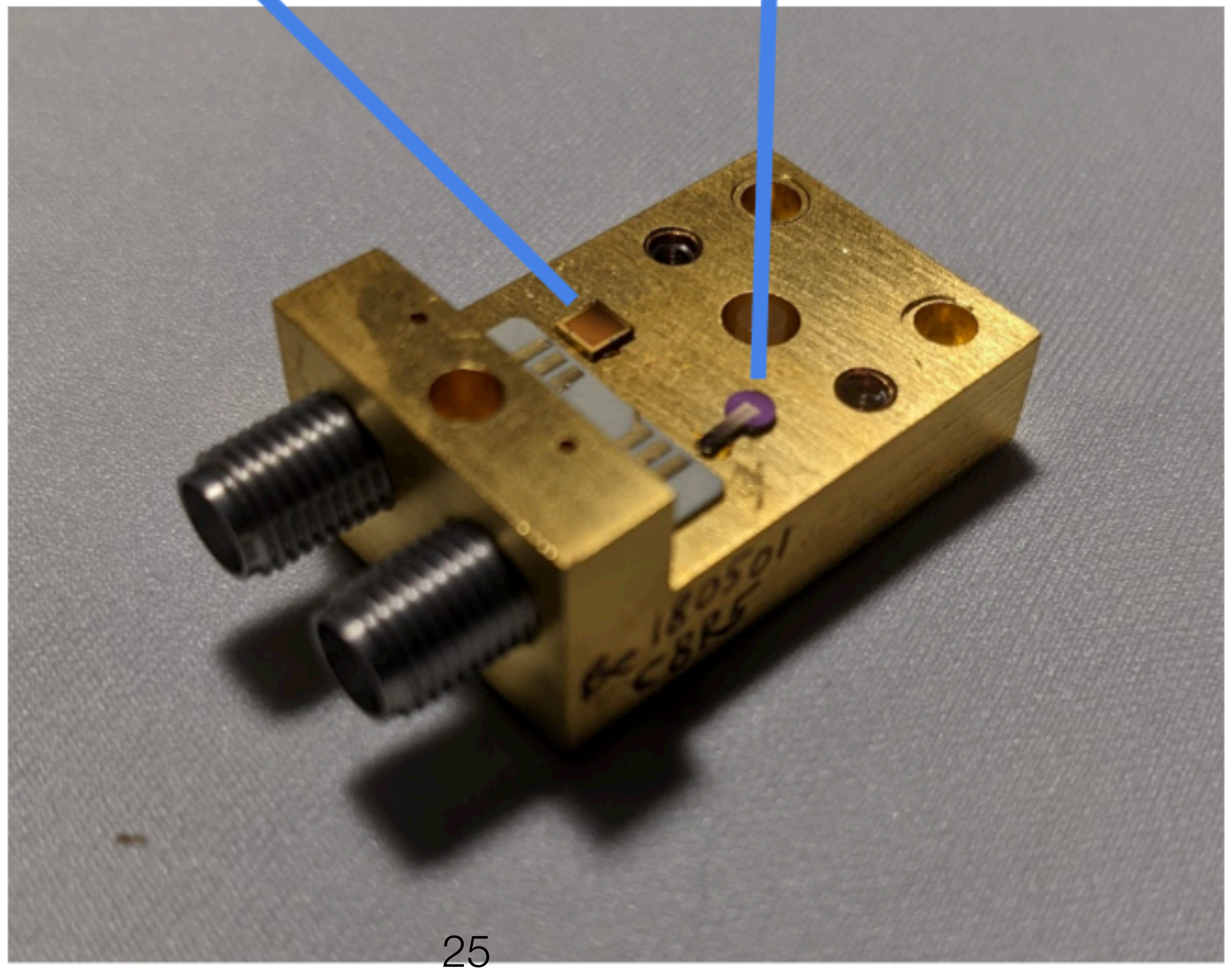
<u>B201116 C4R2</u>
NbTiN 240 nm-wide meander
44x44 μm square active area
Res: 9.09 MOhm

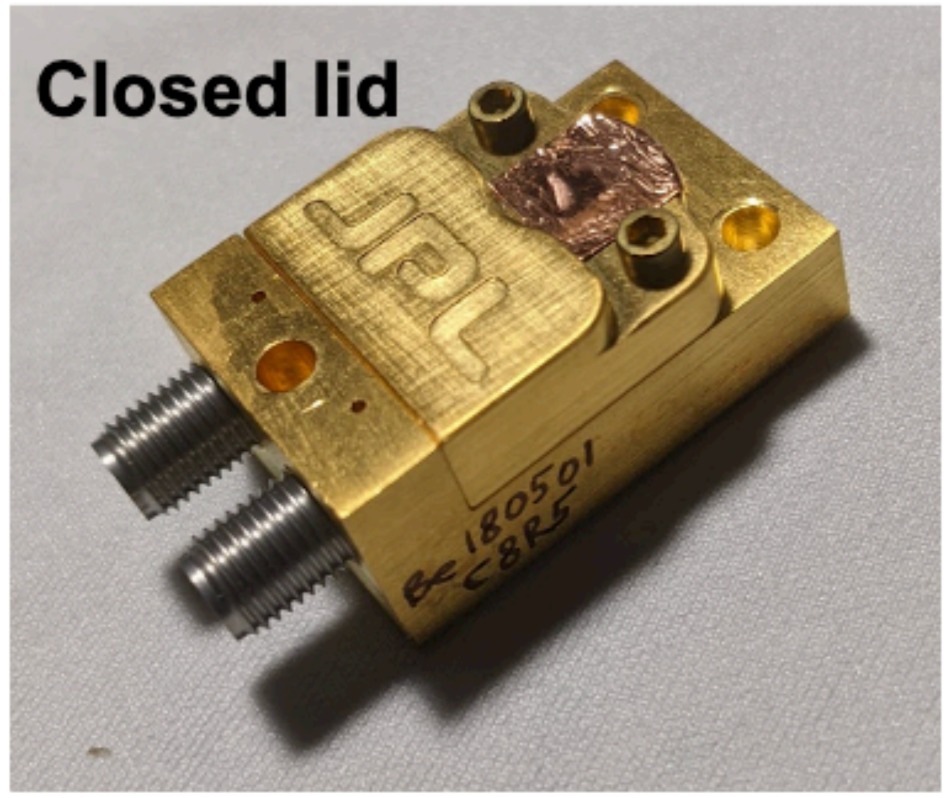
No optical stack

This data was collected with a die next to this one, thus response is expected to the similar, but this device is untested

<u>Be180501 C8R5</u>
WSi single pixel meander with 80 nm-wide wires
22 μm circular active area
Res: 5.46 MOhm

Optical cavity designed for 1550 nm. The plateau will be even longer for this wavelength



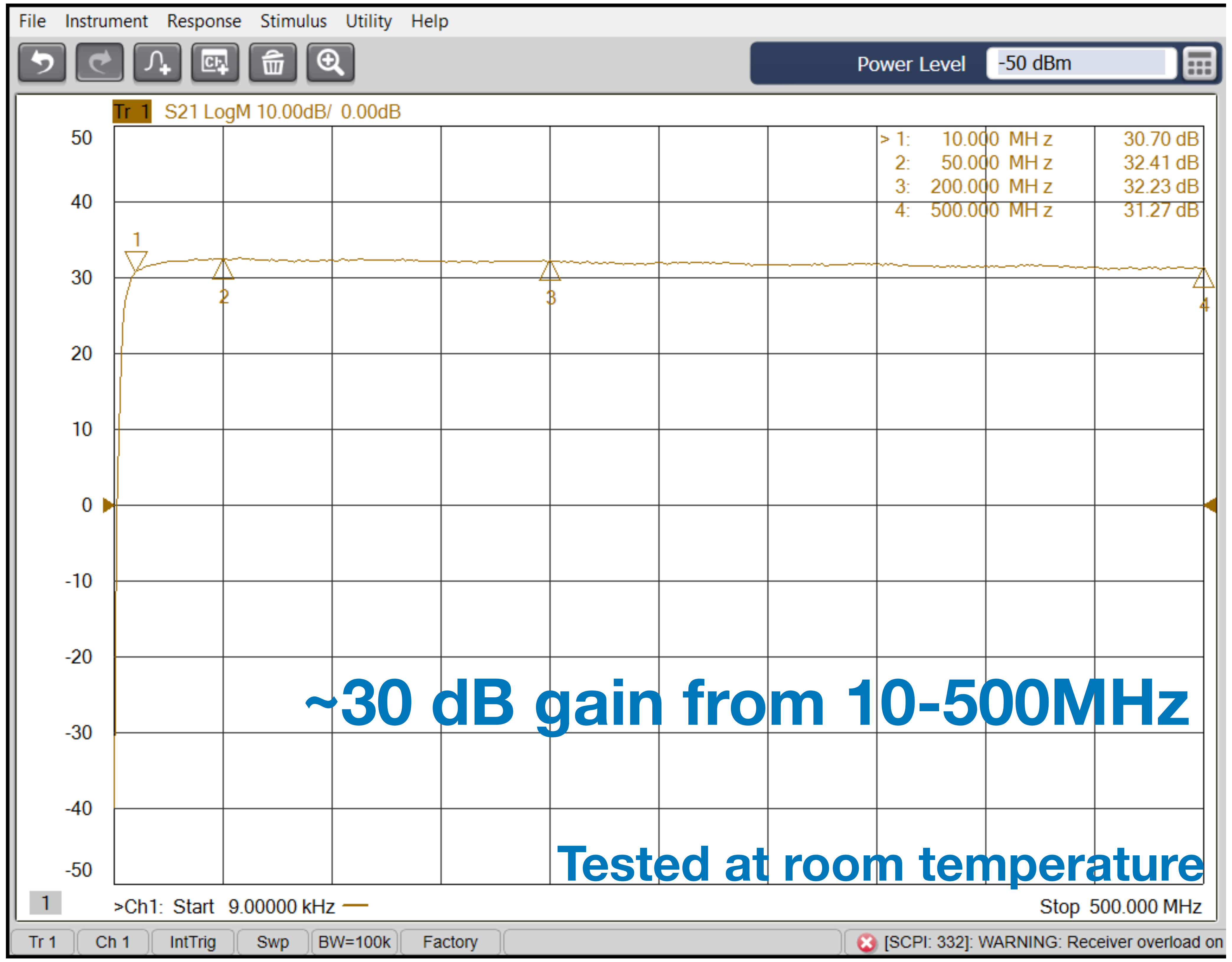


Boris Korzh, Andrew Beyer, Bruce Bumble, Matt Shaw

jpl.nasa.gov

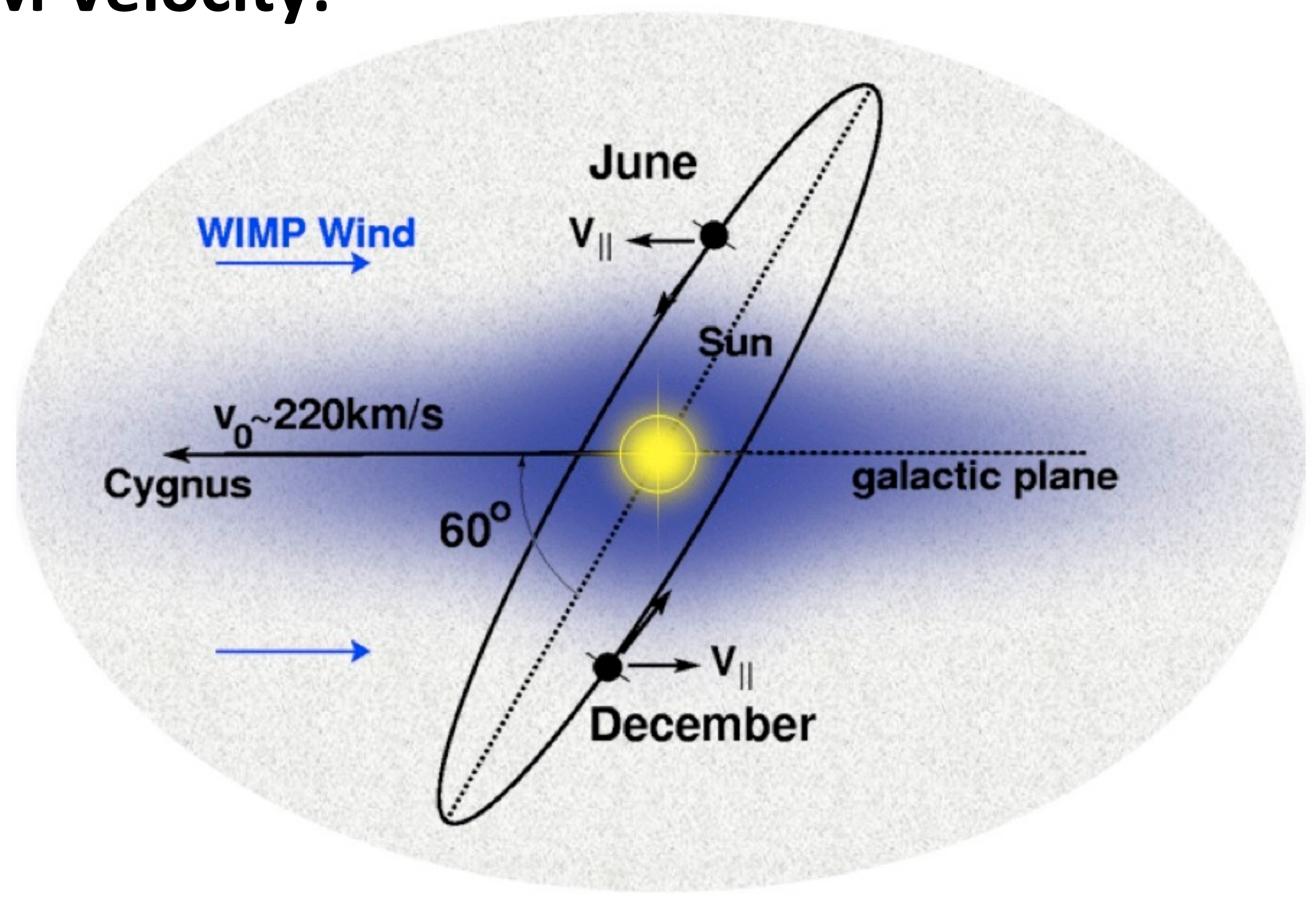
Cryogenic Amplifiers

- Low noise 4-channel amplifier at 70 K
- Designed by Lautaro Narvaez
- Populated and characterized by myself at Caltech



Velocity Effect

CDM Velocity:



[https://www.hep.ucl.ac.uk/darkMatter/pictures/wind.jpg]

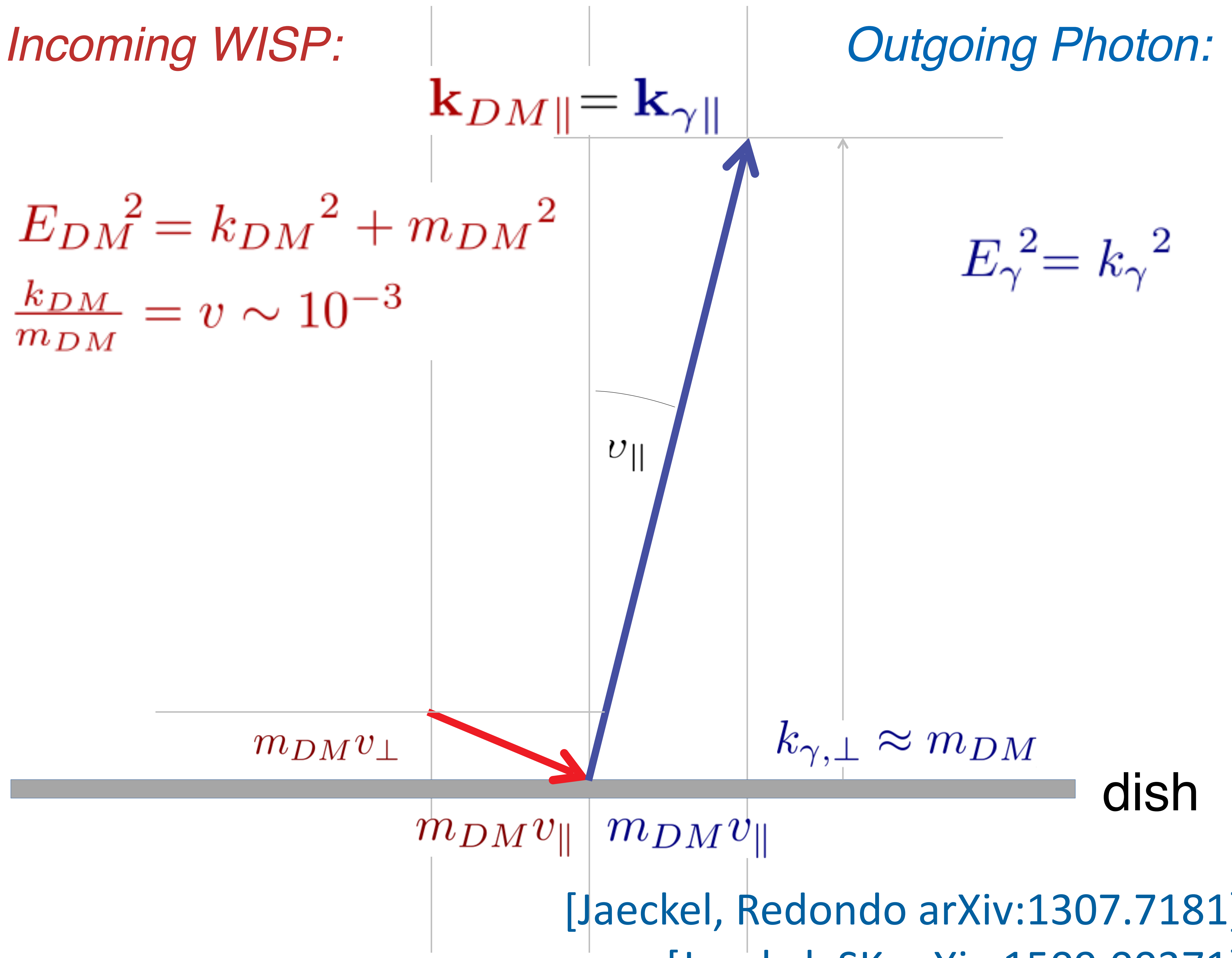
Standard Halo Model:

$$f(\boldsymbol{v}) = \frac{1}{(2\pi\sigma_v^2)^{3/2}} \exp\left(-\frac{|\boldsymbol{v}-\boldsymbol{v}_{\rm lab}|^2}{2\sigma_v^2}\right) \frac{\Theta(v_{\rm esc}-|\boldsymbol{v}|)}{N_{\rm esc}}$$

$$|\boldsymbol{v}_{\rm lab}| \sim 220\,{\rm km\,s^{-1}},\ \sigma_v \sim 156\,{\rm km\,s^{-1}}$$

DM velocity $\sim v \sim 10^{-3}c$

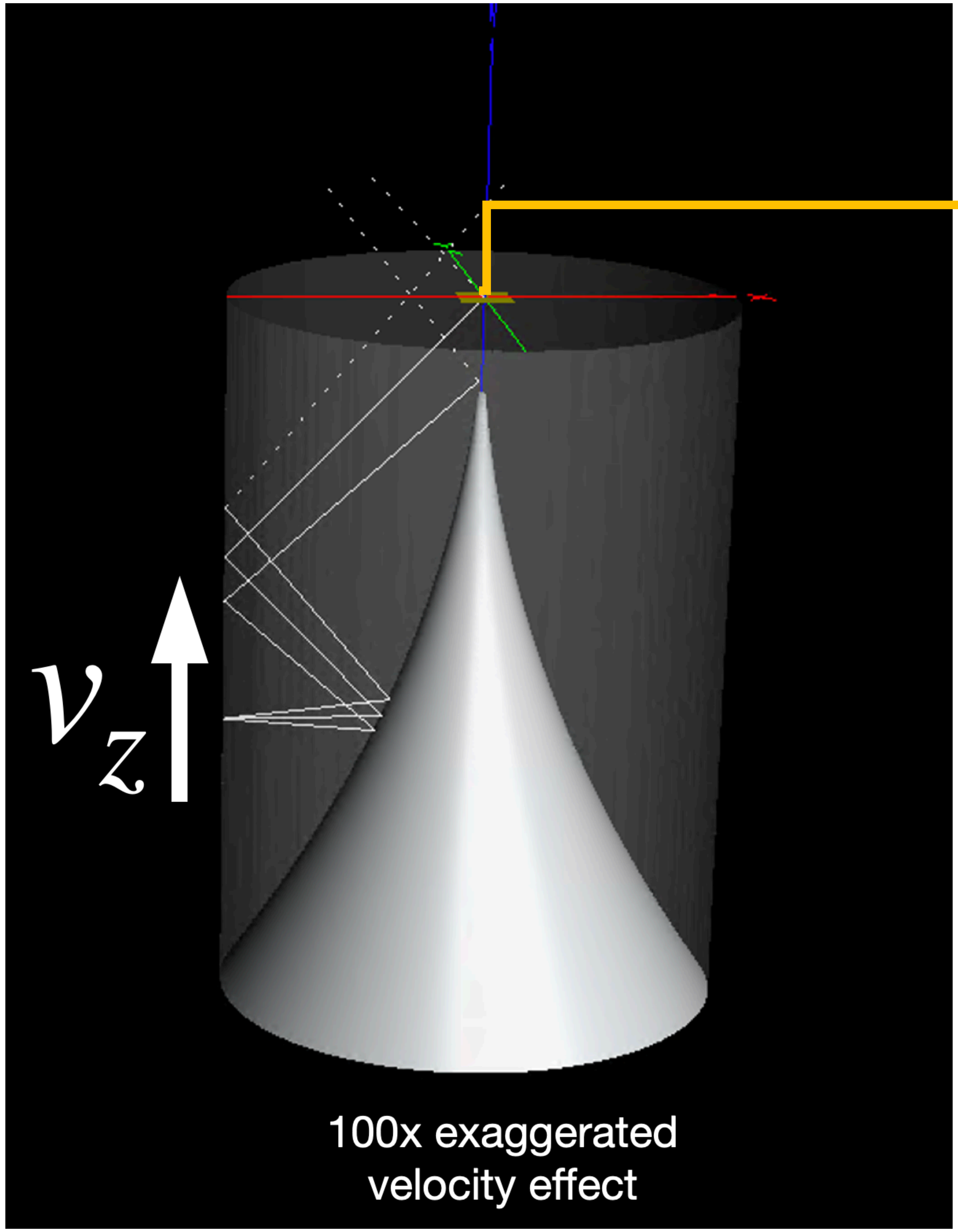
For Dish Antenna:

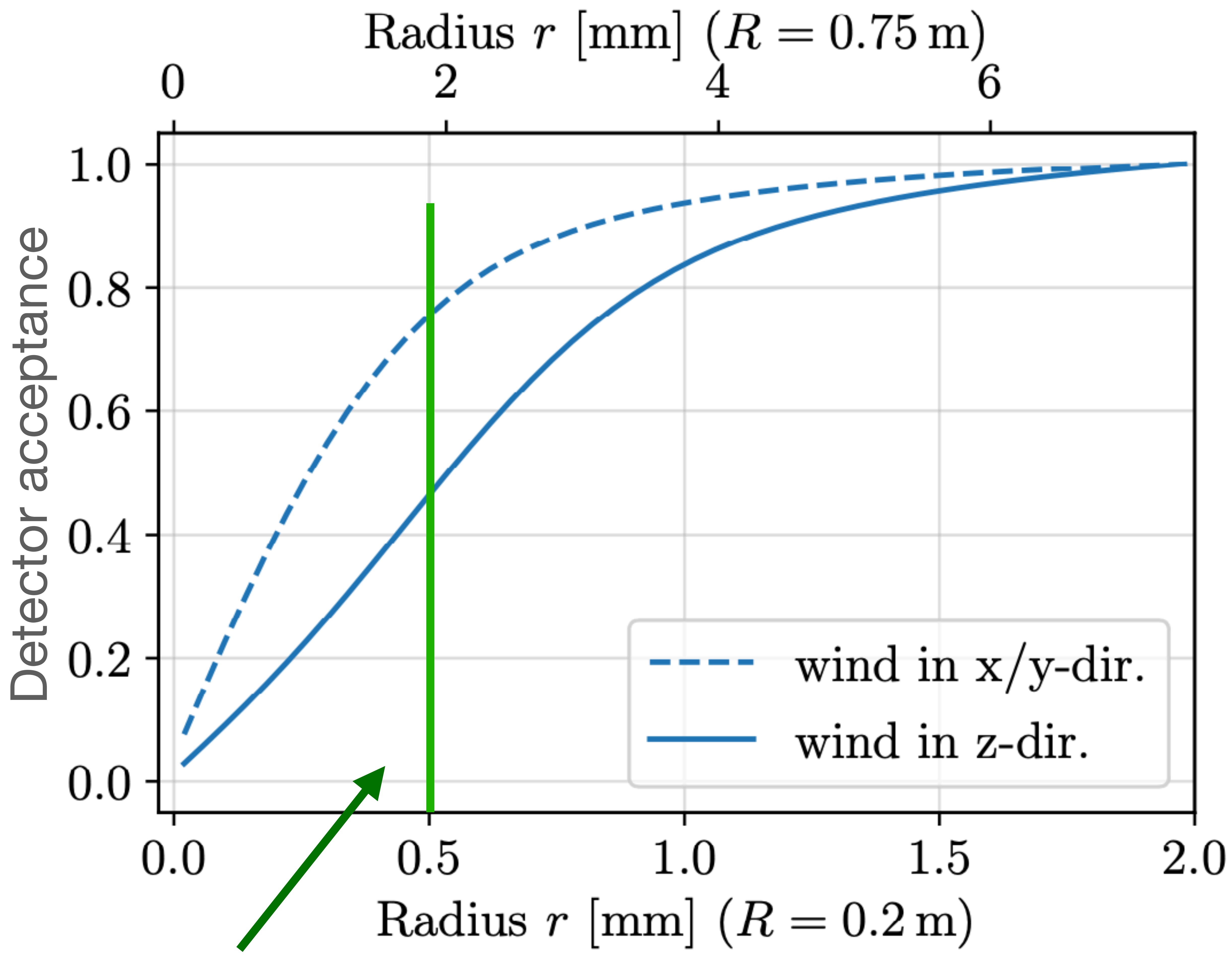


[Jaeckel, Redondo arXiv:1307.7181]
[Jaeckel, SK arXiv:1509.00371]

outgoing angle $\sim v \sim 10^{-3}c$

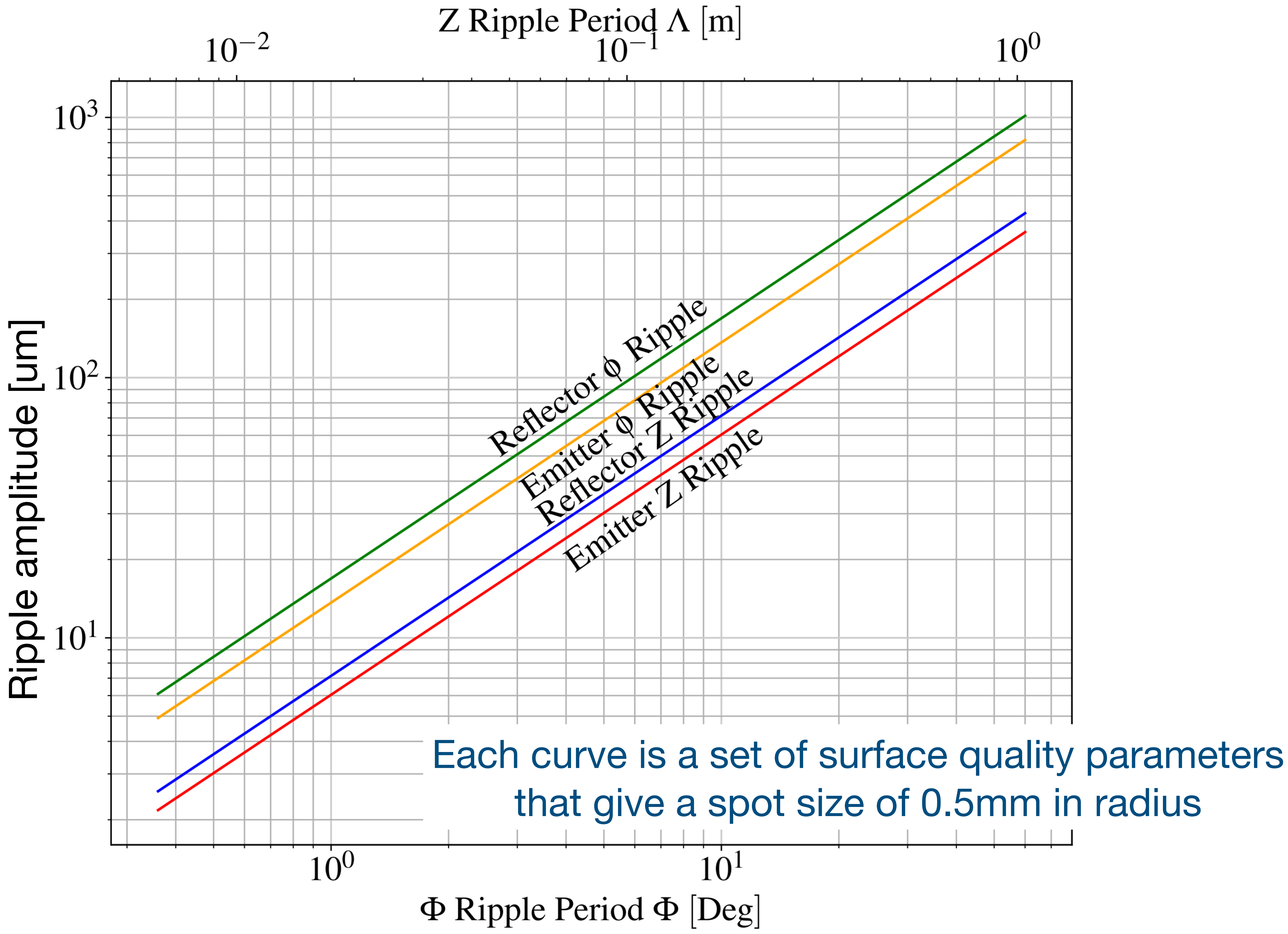
InfraBREAD: Velocity Effects





1mm² SNSPD captures 45-75% of signal

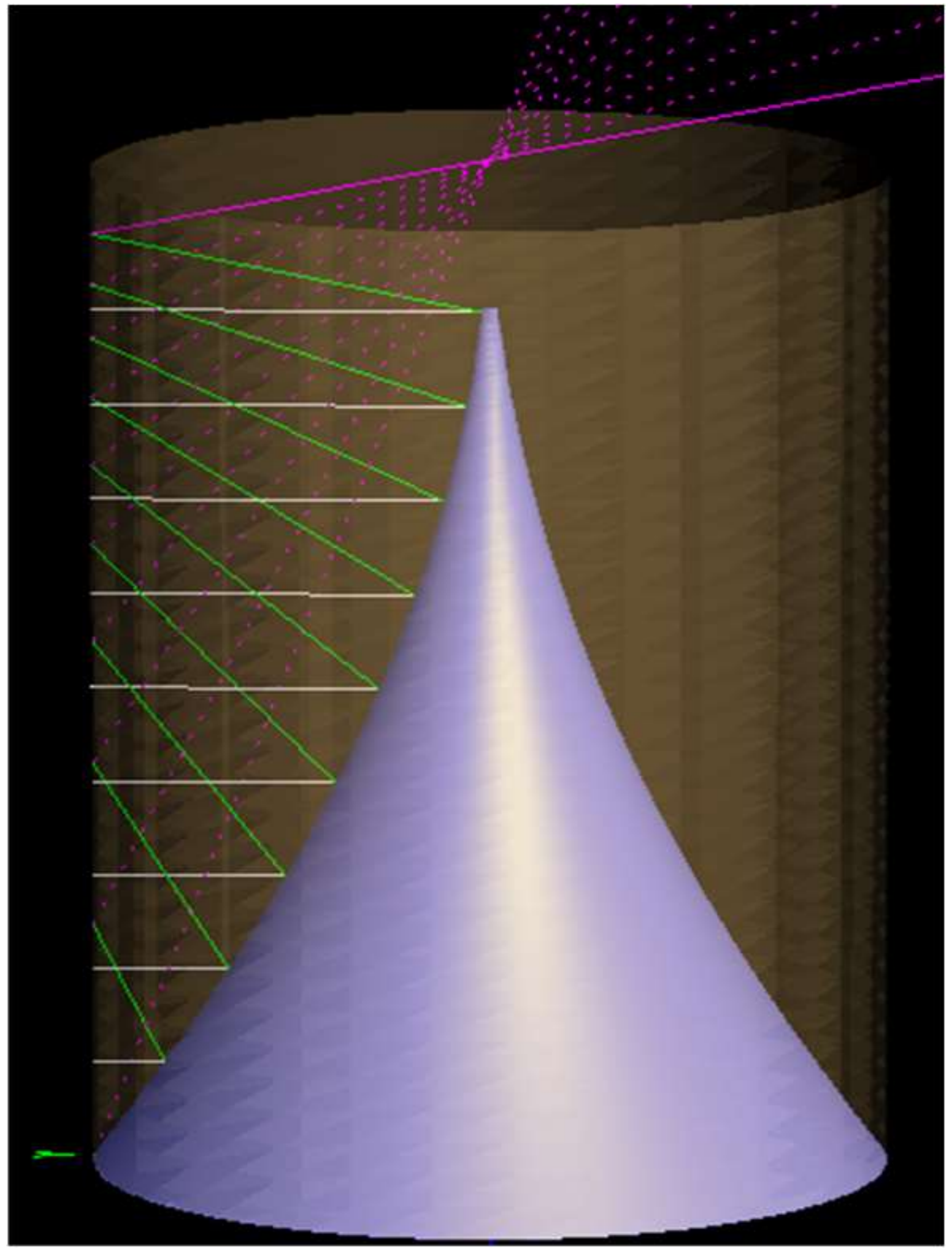
InfraBREAD: Mechanical Requirements



- Used ray tracing simulation to study mechanical requirements
- Sinusoidal perturbations (ripples) cause a broadening of the focal spot.
- Diamond turning to achieve requirements

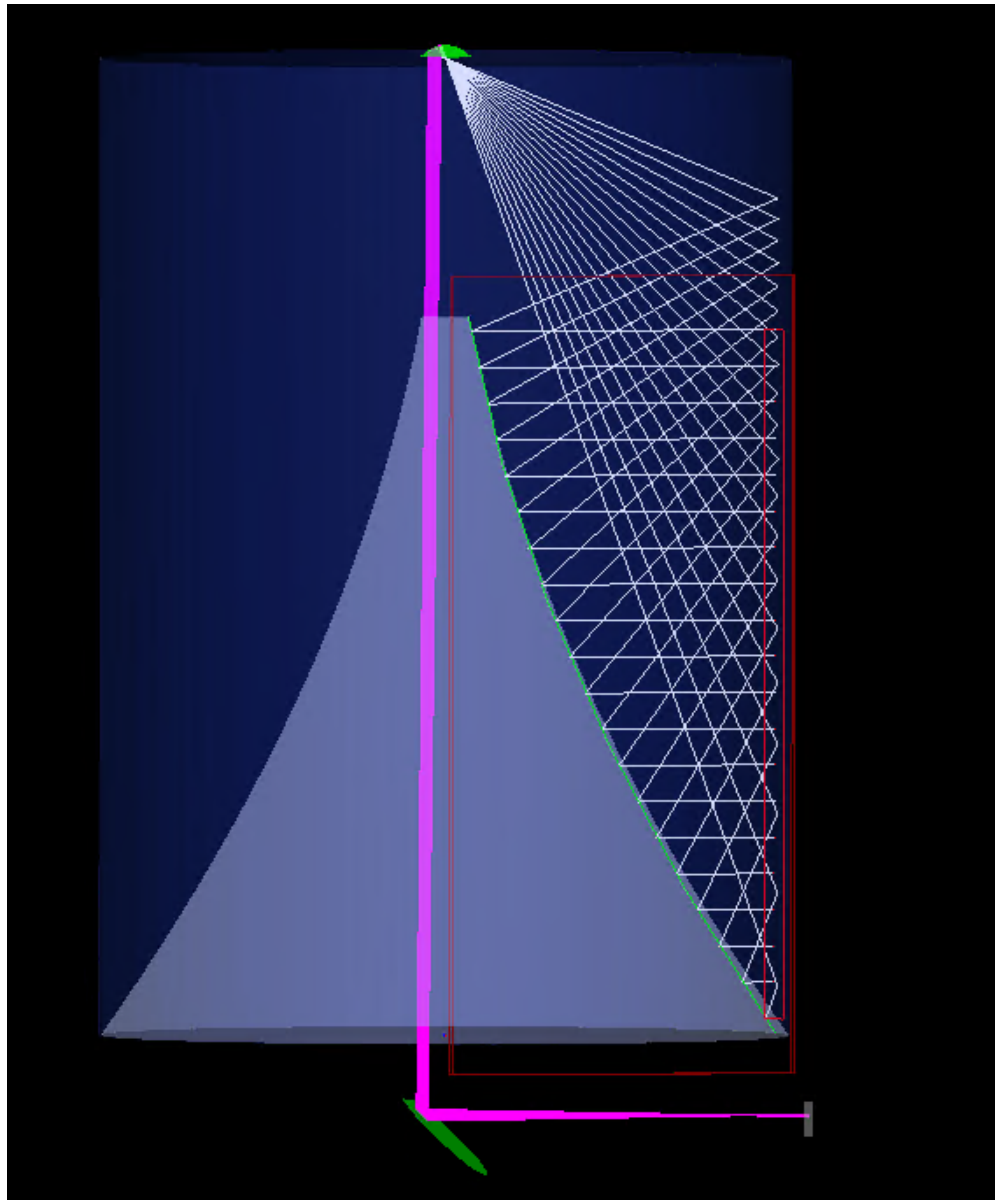
InfraBREAD: Different Design Paths

Centered Detector



Incident Rays
from wide angles

Secondary Mirror(s)



Incident Angle
Adjustable

TABLE I. Illustrative photosensor performance: spectral energy E, operating temperature T_{op}, active area A_{sens}. Bolometers (photocounters) report noise equivalent power NEP (dark count rate DCR).

Photosensor	$\frac{E}{\text{meV}}$	$\frac{T_{\text{op}}}{\text{K}}$	$\frac{\text{NEP}}{\text{W}/\sqrt{\text{Hz}}}$	$\frac{A_{\text{sens}}}{\text{mm}^2}$
GENTEC [97]	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$
IR LABS [98]	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2
KID/TES [99, 100]	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2
QCDet [101, 102]	[2, 125]	0.015	$\frac{\text{DCR}}{\text{Hz}} = 4$	0.06^2
SNSPD [103, 104]	[124, 830]	0.3	$\frac{\text{DCR}}{\text{Hz}} = 10^{-4}$	0.4^2

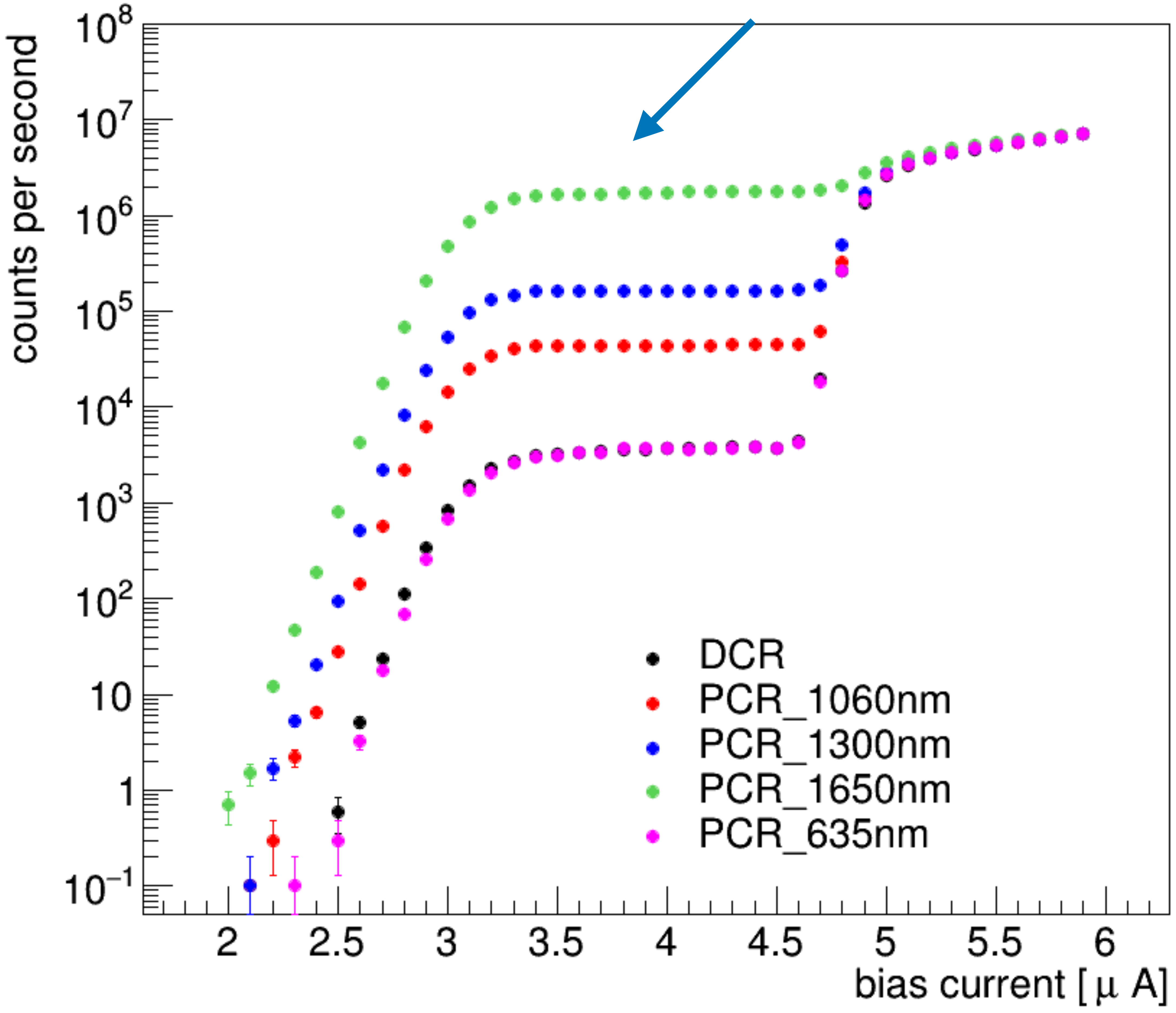
BREAD program

BREAD	Pilot	Stage 1	Stage 2a	Stage 2b
Axion a	—	✓	✓	✓
Dark photon A'	✓	✓	✓	✓
Experimental parameters				
A_{dish} [m^2]	0.7	10	10	10
B_{ext} [T]	—	10	10	10
ϵ_s	0.5	0.5	0.5	0.5
Δt [days]	10	10	1000	1000
NEP [W Hz$^{-1/2}$]	10^{-14}	10^{-18}	10^{-20}	10^{-22}
Coupling sensitivity (SNR = 5)				
$\left\|g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\mathrm{KSVZ}}\right\|$	—	280	9.0	0.90
$\left\|g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\mathrm{DFSZ}}\right\|$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07

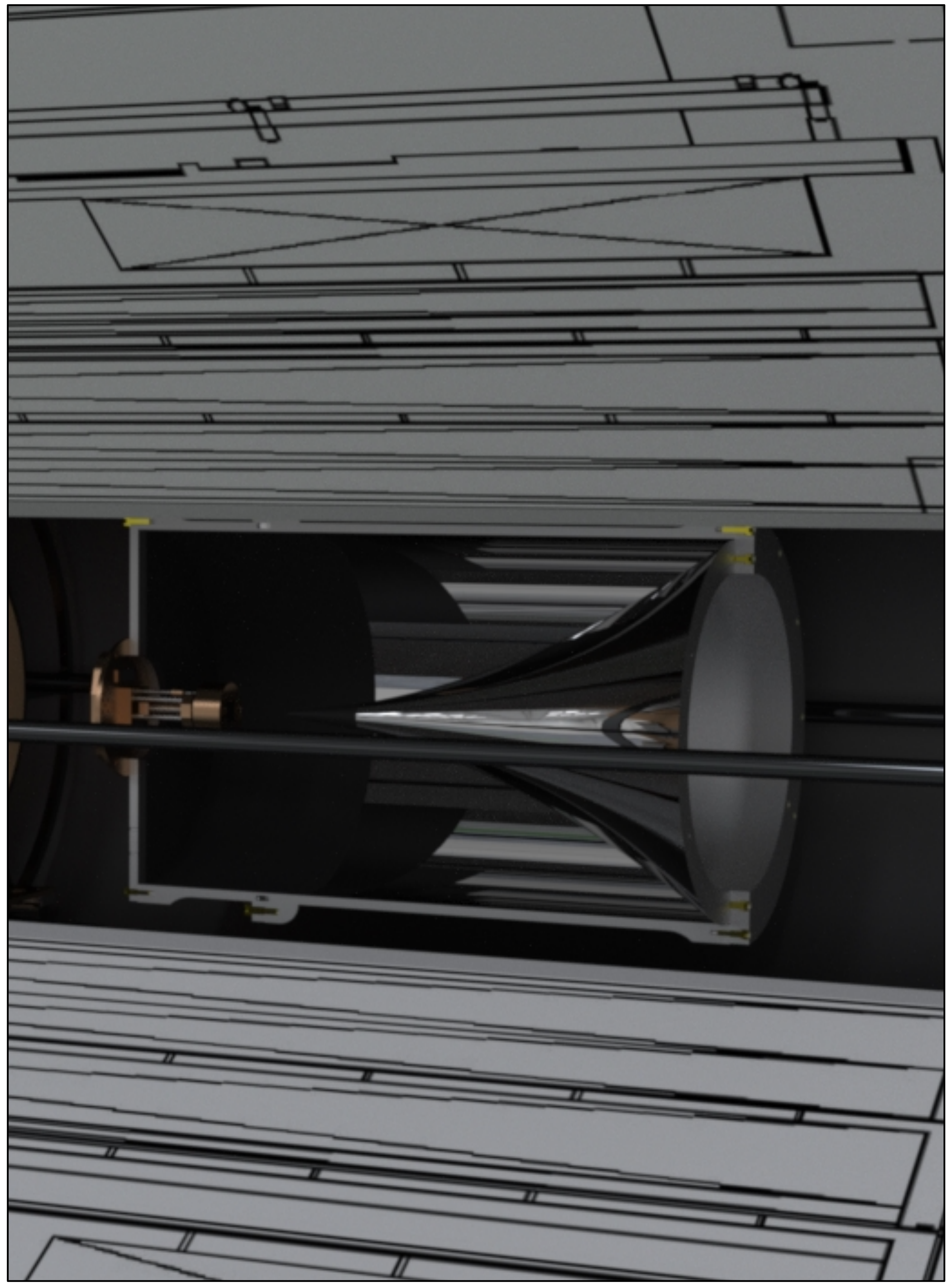
PCR for Various Wavelengths

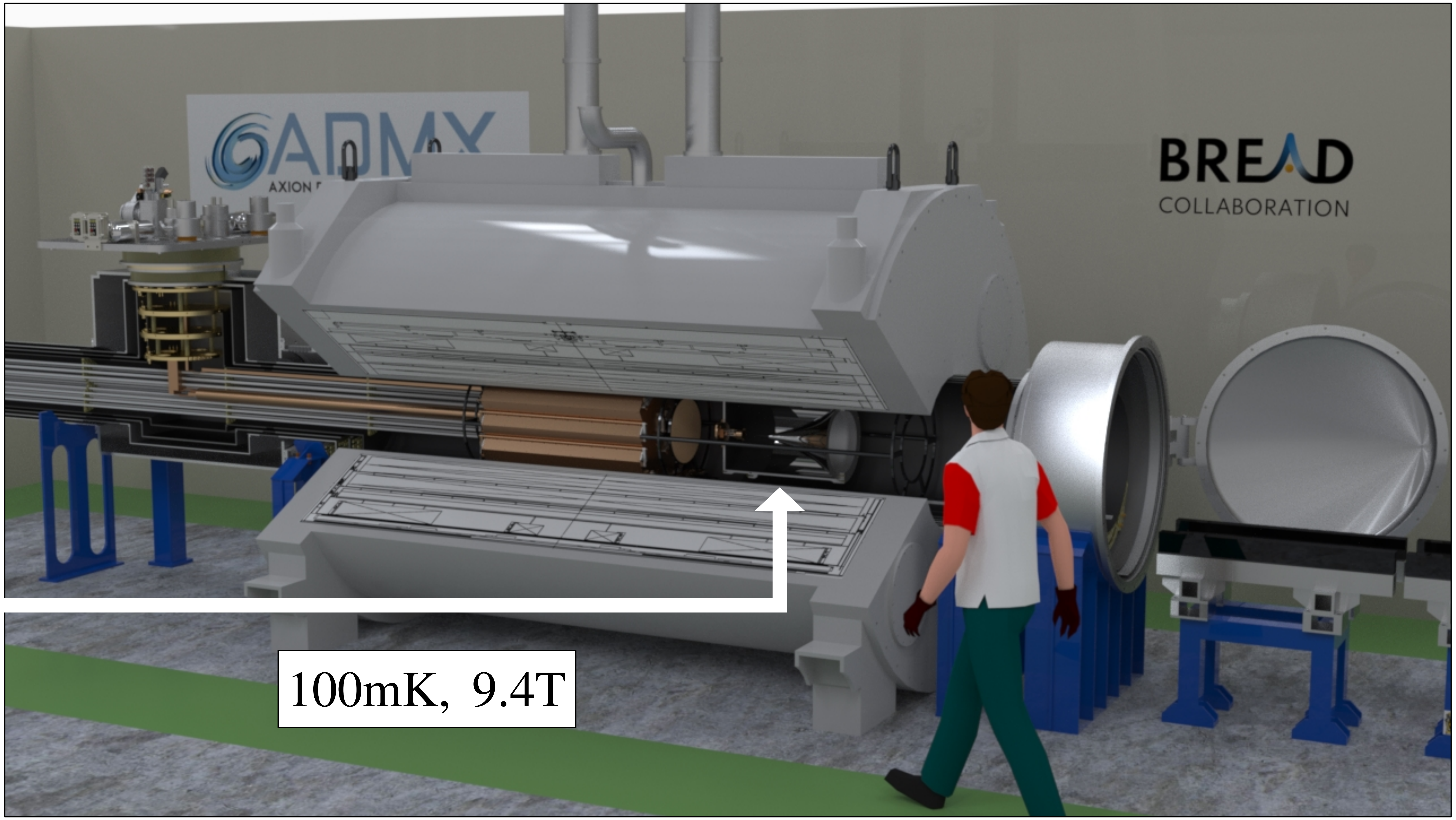
- Repeated the measurement of photon count rate with laser diodes of different wavelengths at the same power of 2 mW
    - λ: 635, 1060, 1300, and 1650nm
- Clear plateau from 3-4.5uA for all wavelengths
- For λ > 1um, observe photons counts above the DCR
- Low counts for 635 nm is due to the ND filter that attenuates 635 nm photons by 1e-4

Clear plateau for all curves



Vision: Large-Scale BREAD

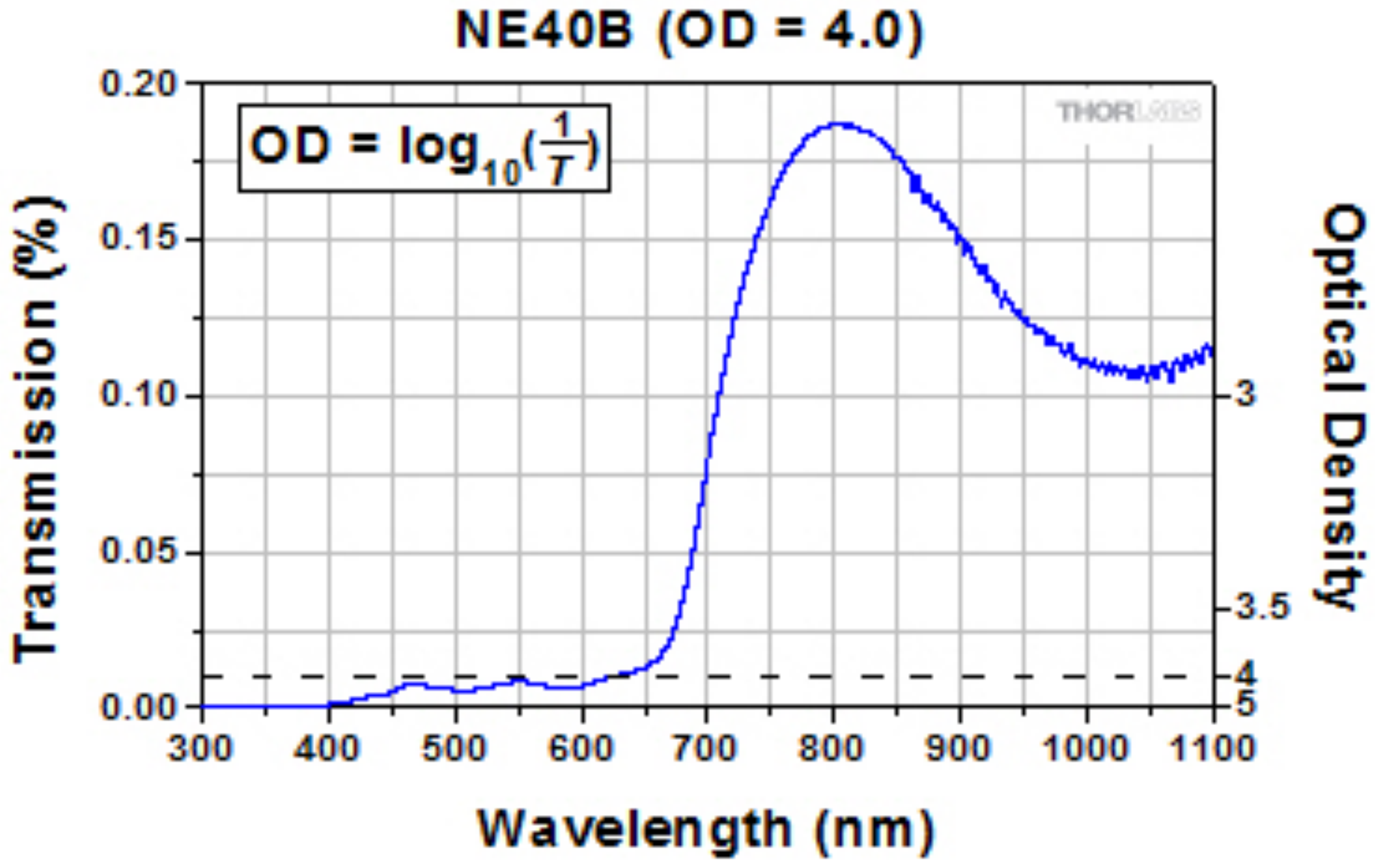




larger-scale version (A ~ 4 m²) as side-experiment to ADMX-EFR at Fermilab

ND Filter at 4K

- Unmounted Ø25 mm Absorptive ND Filter, Optical Density: 4.0
- https://www.thorlabs.com/thorproduct.cfm?partnumber=NE40B



213 DIL LaserMount

$345
US List Price*
How to Buy

Click here for larger image(s)

At-a-Glance

- 14-pin DIL Lasers
- 8-pin mini-DIL Lasers (electrical only)
- Zero insertion force (ZIF) connection
- Solder-less wiring
- Passive cooling

Manuals and Downloads

Overview

The 213 DIL LaserMount is an excellent choice for electrical connection and passive cooling of DIL laser modules.

Mini-DIL Support

The 213 can also be used for mini-DIL lasers, although only electrical connections can be made.

Quick Laser Connections

The 213 makes connections to the laser quick with a zero insertion force socket… simply slide the laser into the socket, screw the device to the mount for passive cooling, and close the lead clamp to make electrical connection. The lead clamps are user replaceable for easy maintenance in production applications.

Accessories

Beyond the mount itself, the 213 works with our optional fiber tray, device cover, and fan base:

The 200-TRAY fiber tray bolts directly to the top of the mount and makes fiber management simple.

The 200-C cover enhances the stability of the laser by minimizing the impact of ambient air currents.

The 200-FAN fan base significantly increases the heat sink performance, from 3°C/W to 1.5°C/W.

Easy Wiring

The underside of the mount houses a simple screw terminal wiring setup, with all wires color coded, and the terminals clearly marked to

RC08APC-P01
Reflective Collimator with Patch Cord Shown Mounted to a Ø1/2" Post

Products Home / Fiber Components / Collimation / Coupling / Reflective Collimators / SMA-Connectorized Protected Silver Reflective Collimato

RC08SMA-P01 - Protected Silver Reflective Collimator, 450 nm - 20 µm, Ø8.5 mm Beam, SMA

Zoom

Complete Product Details

Part Number:	RC08SMA-P01 -Ask a technical question
Package Weight:	0.21 lbs / Each
Available:	Today
RoHS:	RoHS✓
Price:	$653.60
Add To Cart:	Qty : 1 Add To Cart
Release Date:	Dec 17, 2010

Drawings and Documents:

- Auto CAD PDF
- Auto CAD DXF
- Solidworks
- eDrawing
- Step
- Zemax (ZAR)
- RoHS — RoHS✓
- REACH — REACH✓

Download all support documents

Download

Building a

One-Click
available fr
purchase r

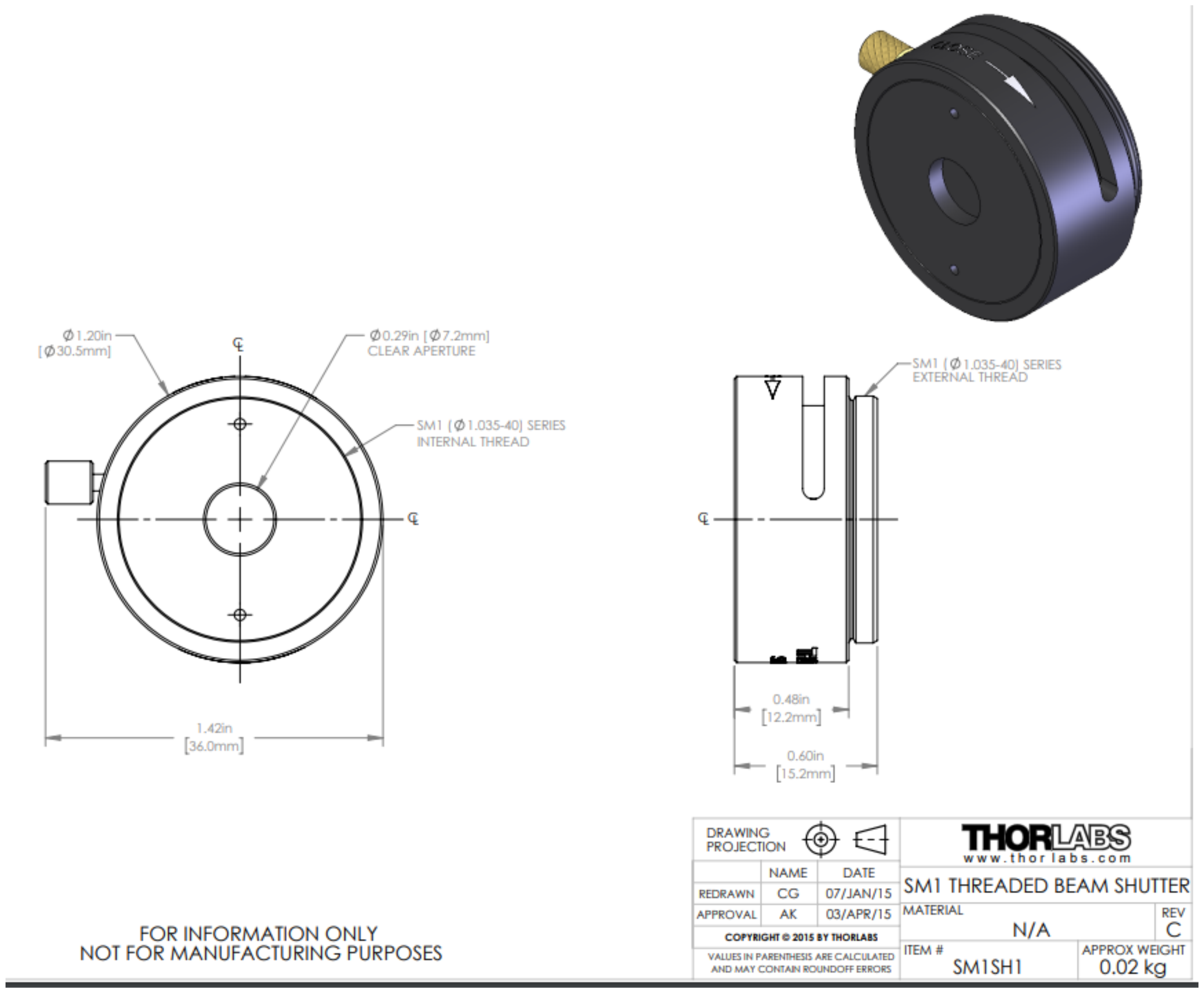
**Warranty (
and Condi**

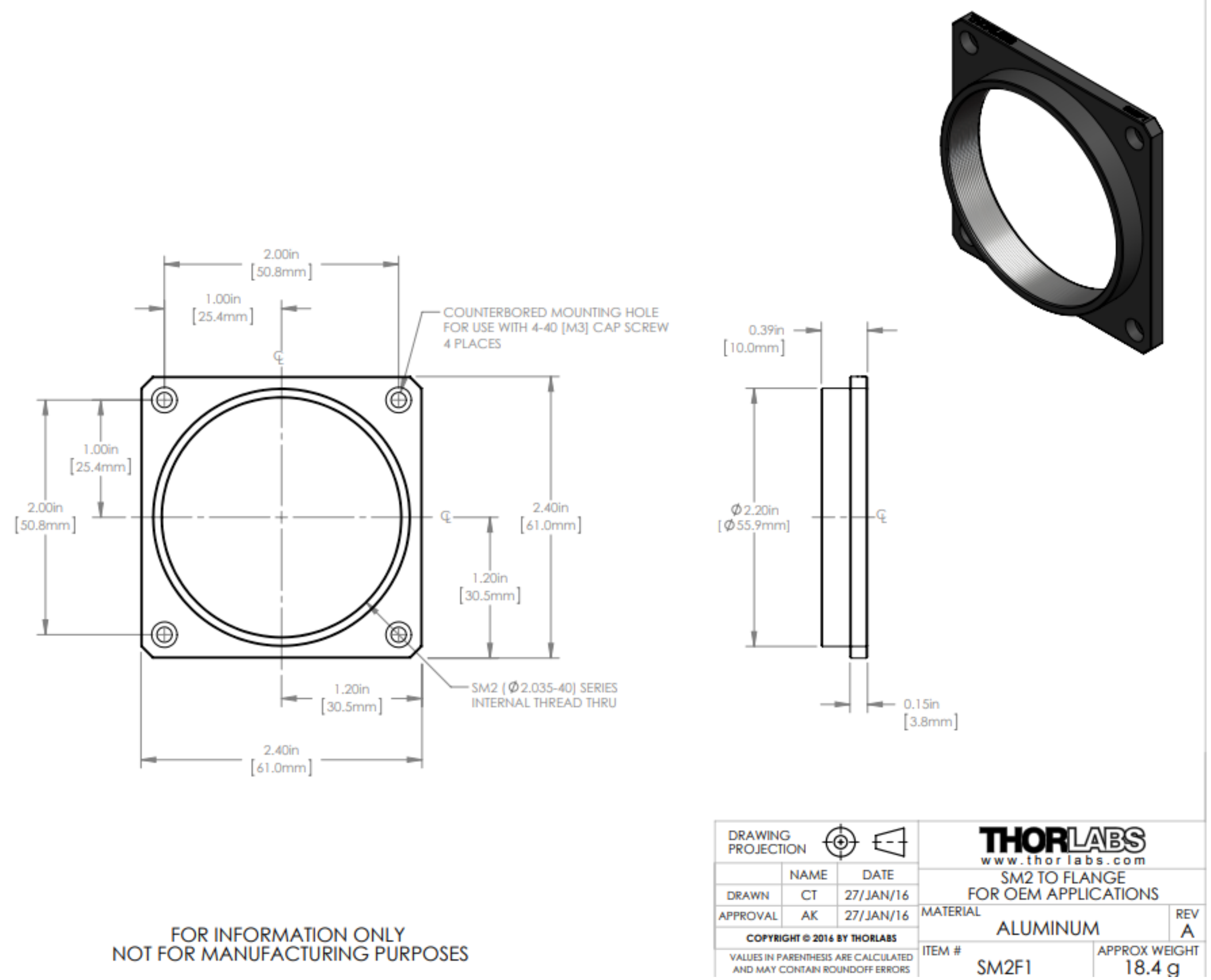
Two year w
sources ar
year or (to
number of

Share this Product Print Friendly Add favorite Watch for updates

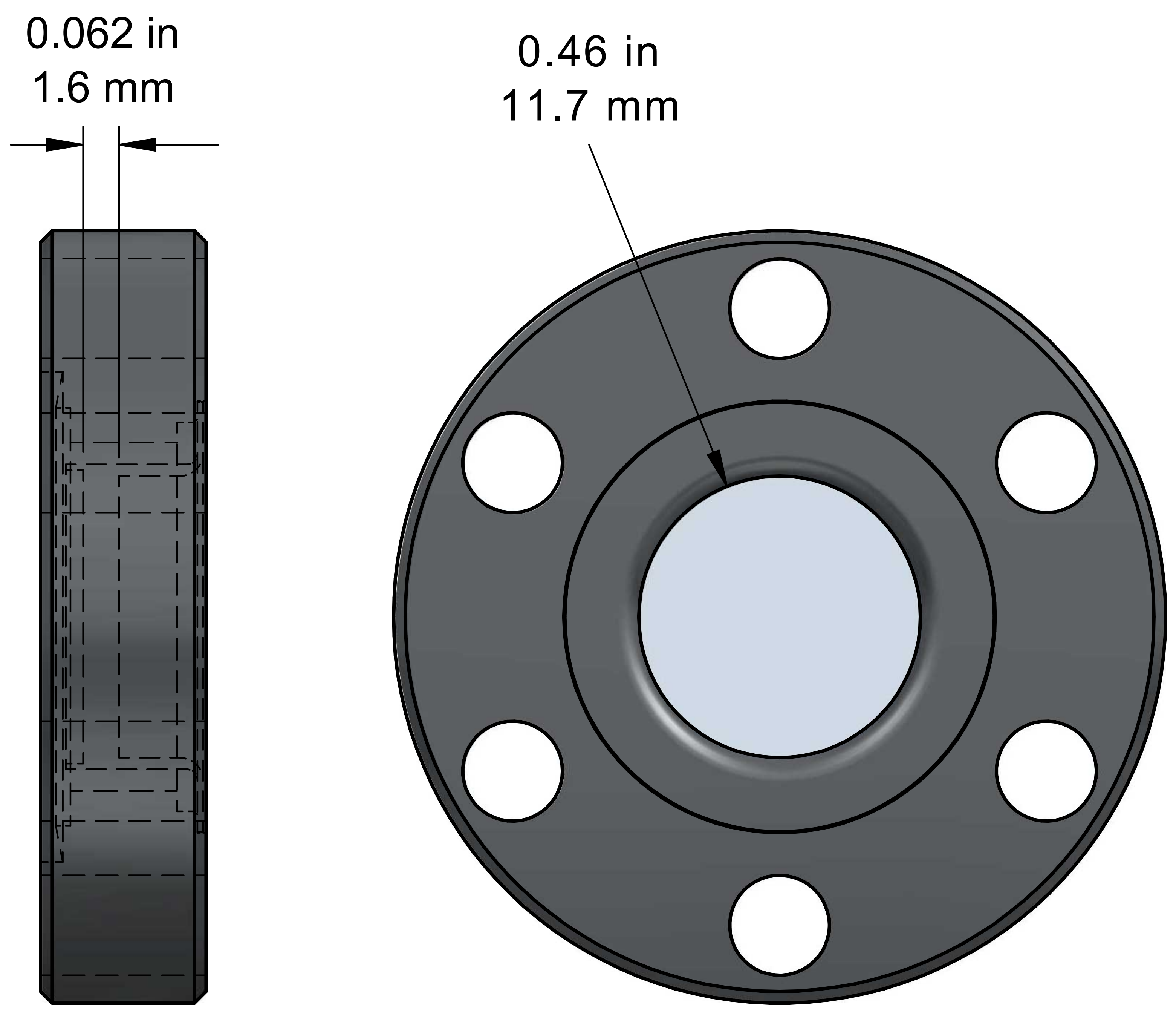
Product Feedback - Let us know what you think about our RC08SMA-P01 product. Click here to leave us your feedback.

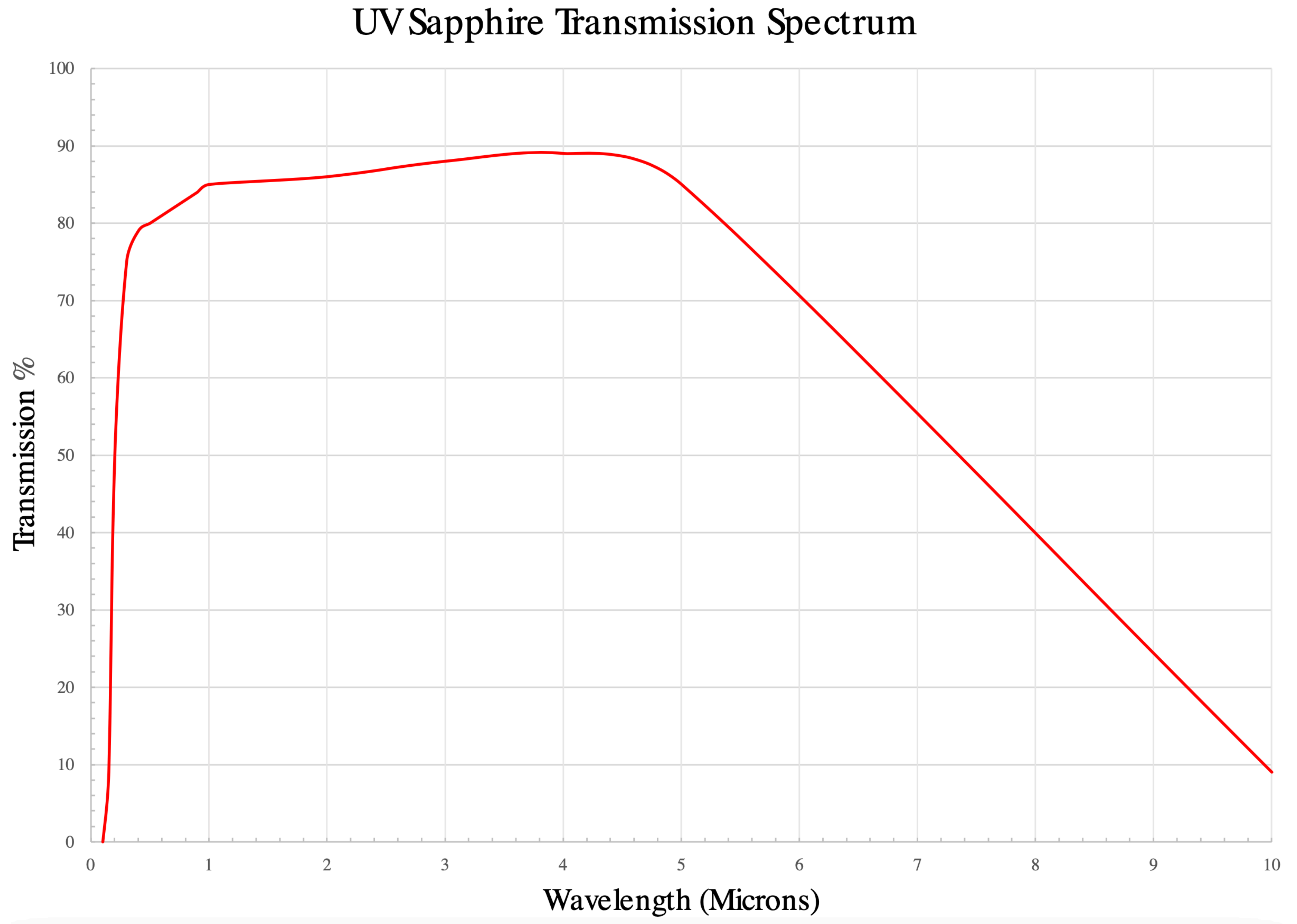
Optical shutter and mounting flange





Sapphire Window





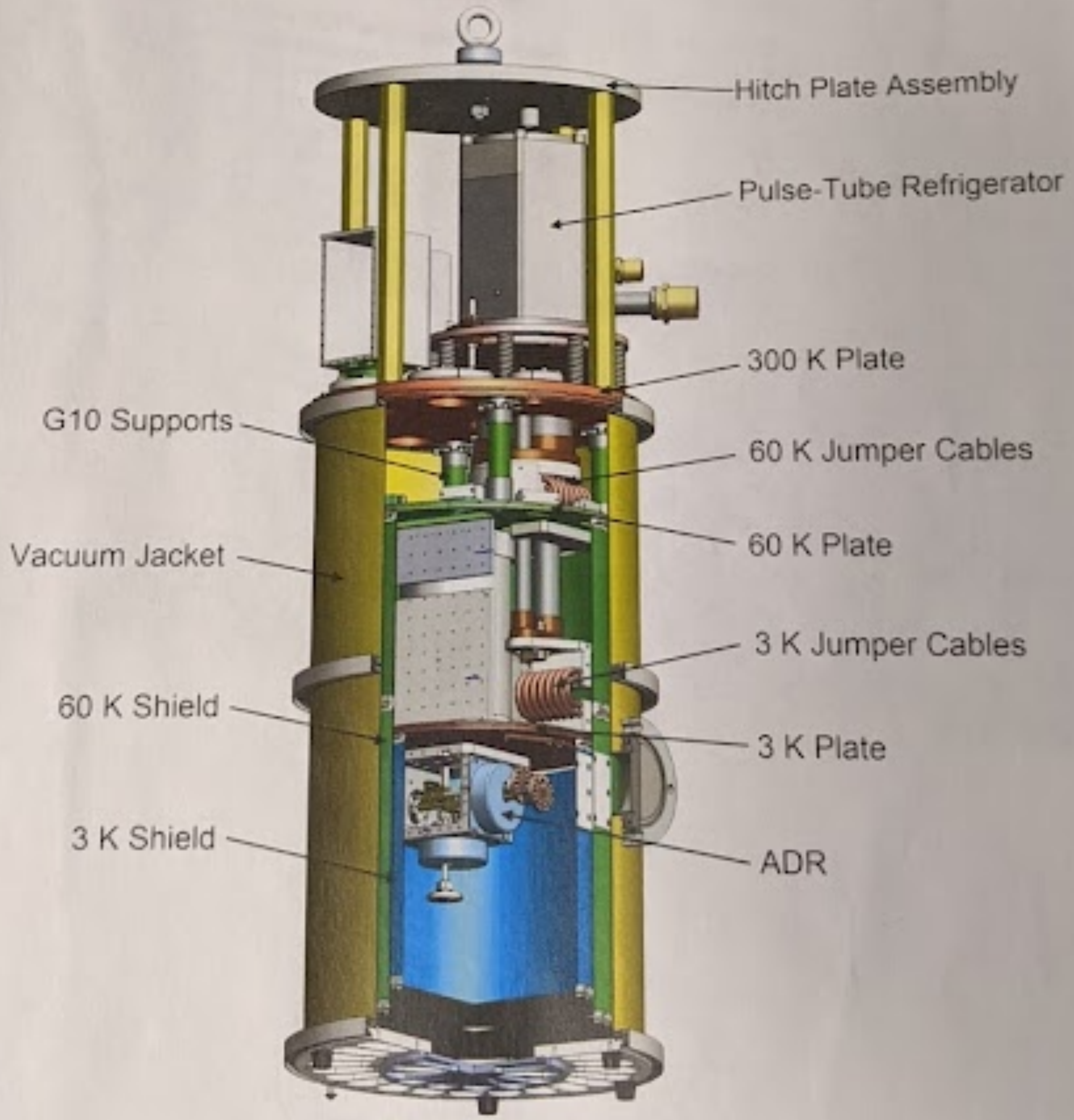
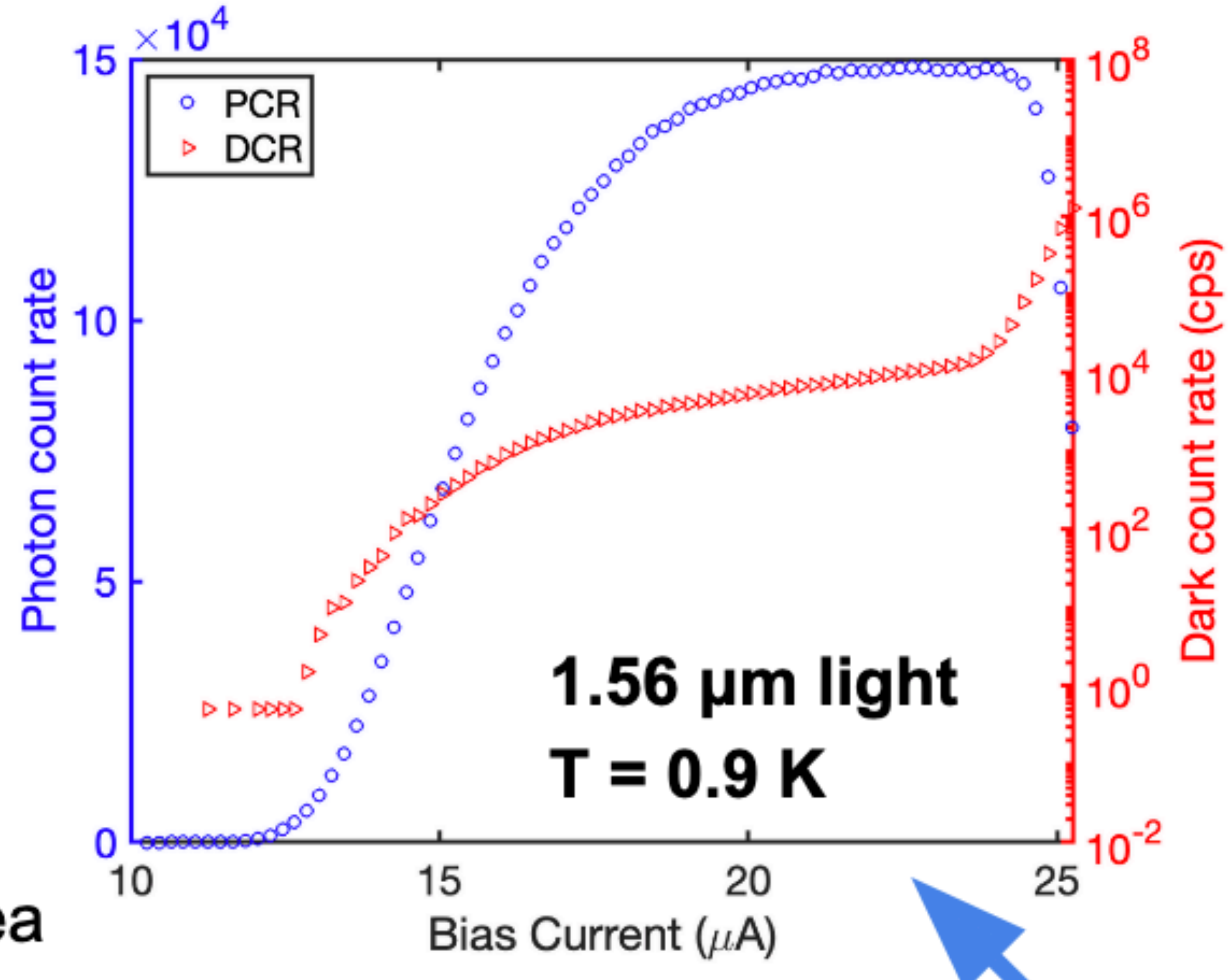
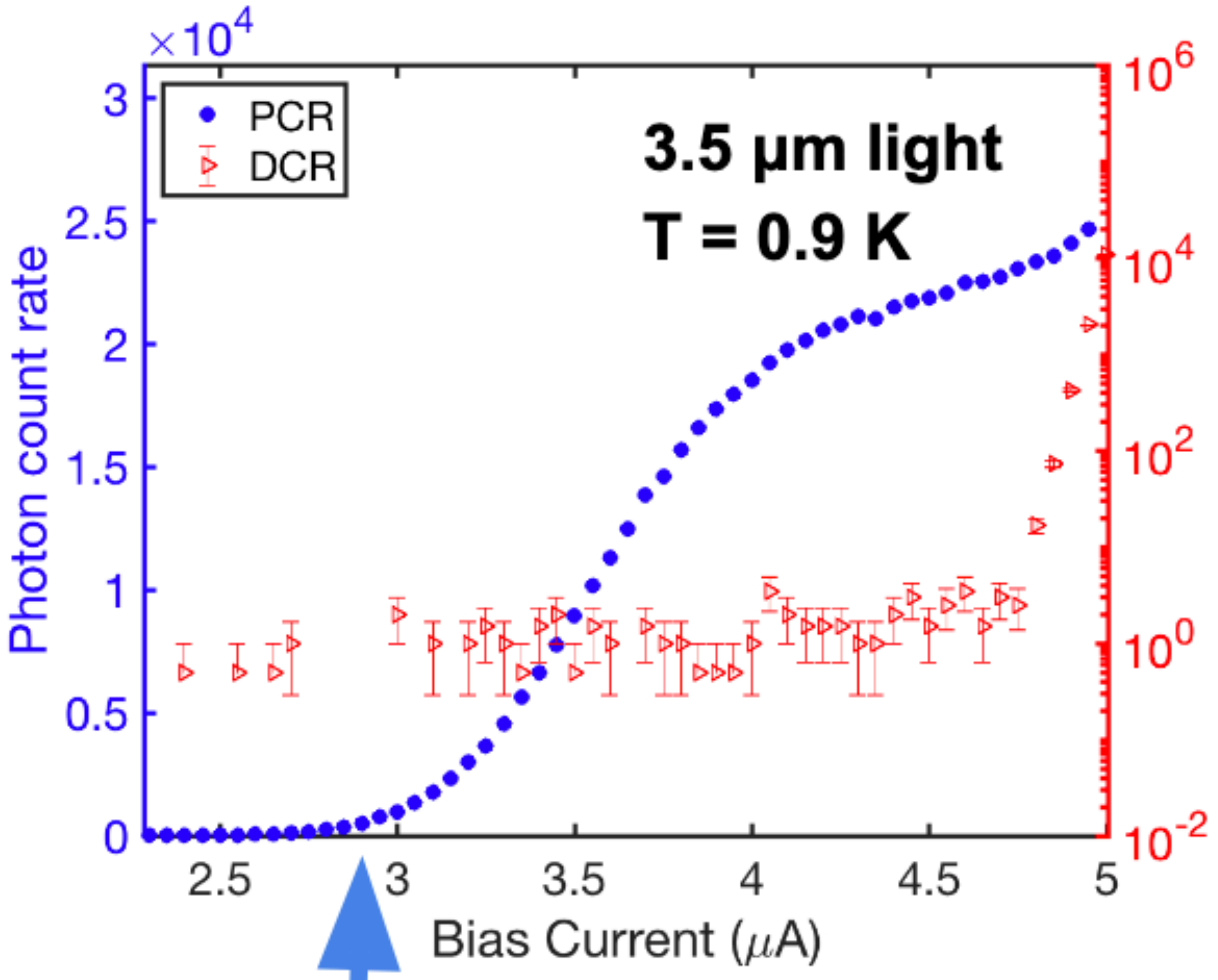


Figure 1: Cut-away view of the Model 103 Rainier

JPL test devices





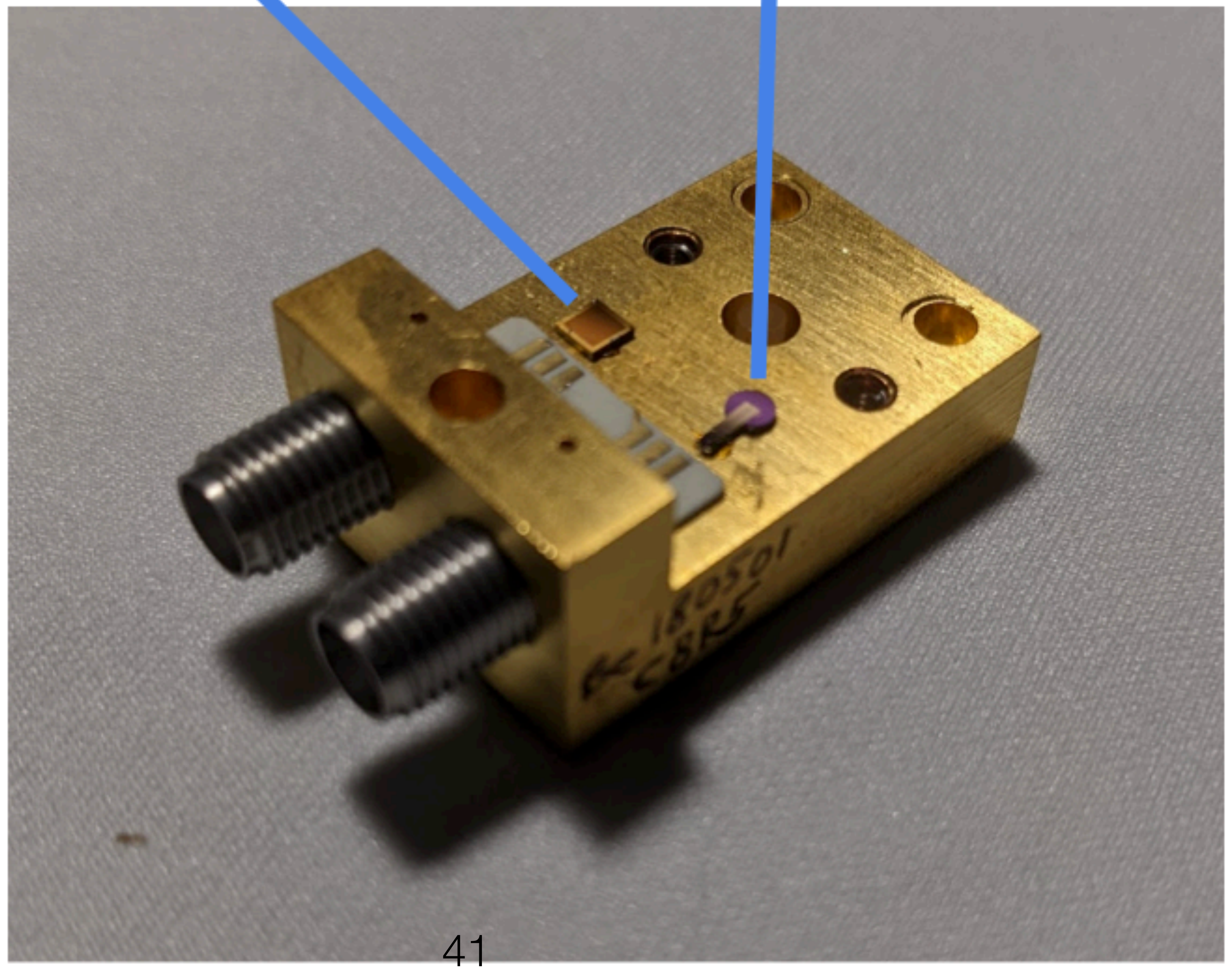
Be180501 C8R5
WSi single pixel meander with 80 nm-wide wires
22 µm circular active area
Res: 5.46 MOhm

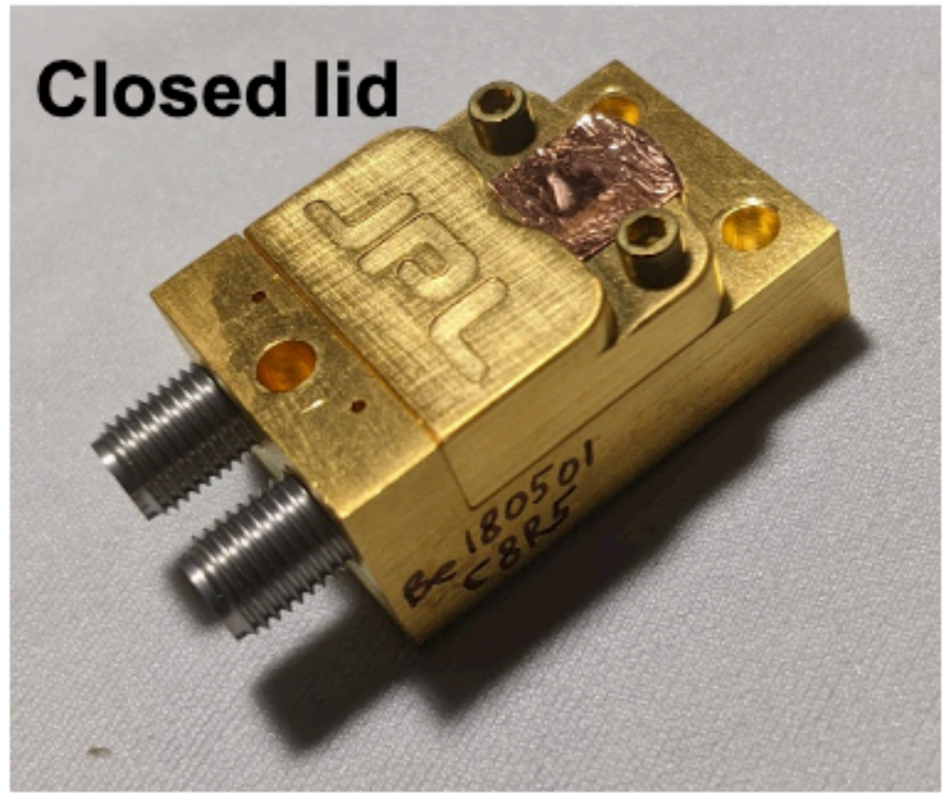
Optical cavity designed for 1550 nm. The plateau will be even longer for this wavelength

B201116 C4R2
NbTiN 240 nm-wide meander
44x44 µm square active area
Res: 9.09 MOhm

No optical stack

This data was collected with a die next to this one, thus response is expected to the similar, but this device is untested





Boris Korzh, Andrew Beyer, Bruce Bumble, Matt Shaw

jpl.nasa.gov

Shwabian Time Tagger

- Can set threshold for signal pulse in software
- Record counts per second
- Can record 70M tags/s
- Data transfer over USB