BREAD COLLABORATION

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

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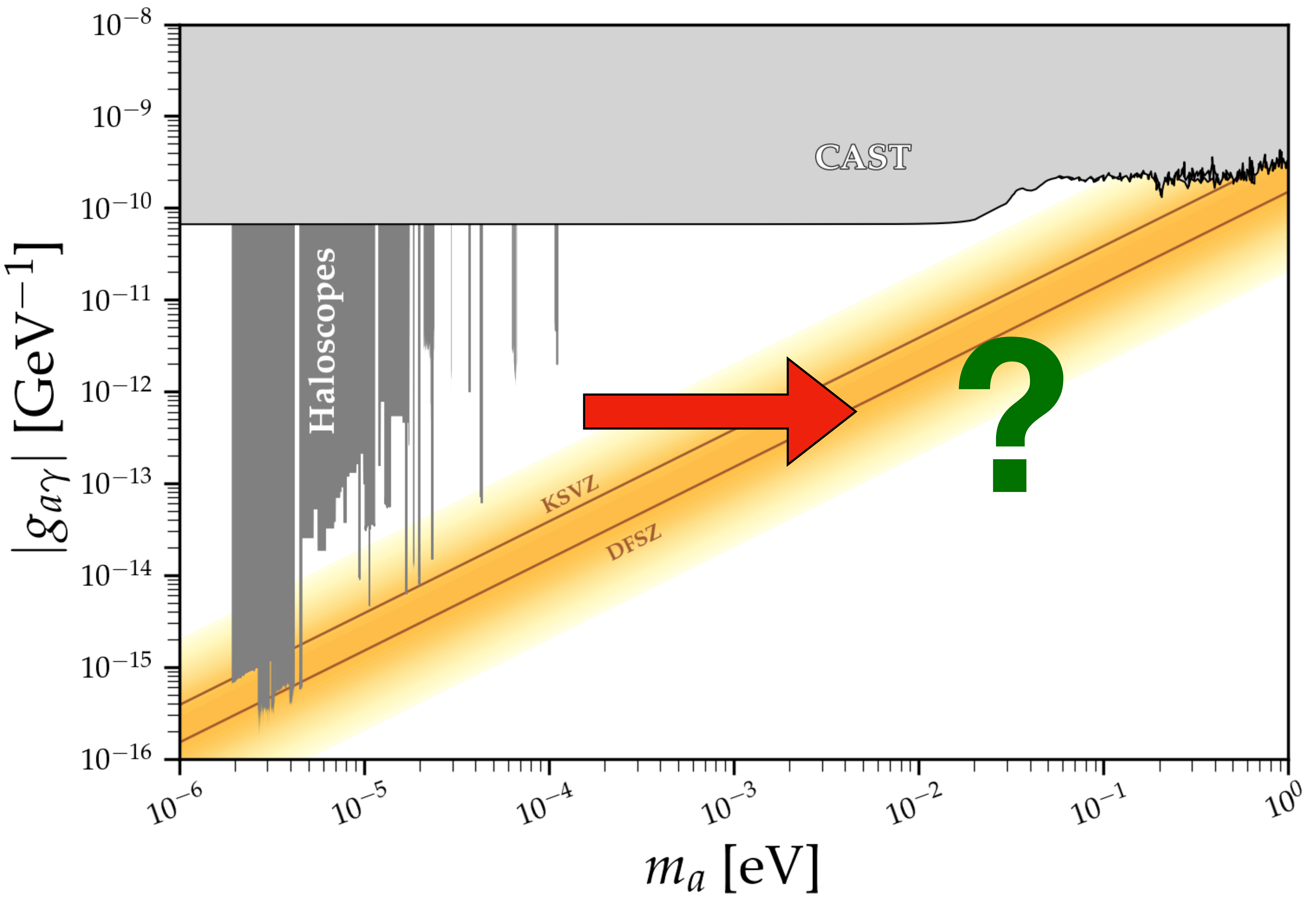
on behalf of the BREAD collaboration

2024 Dark Wave Lab Workshop
04/16/2024

Caltech

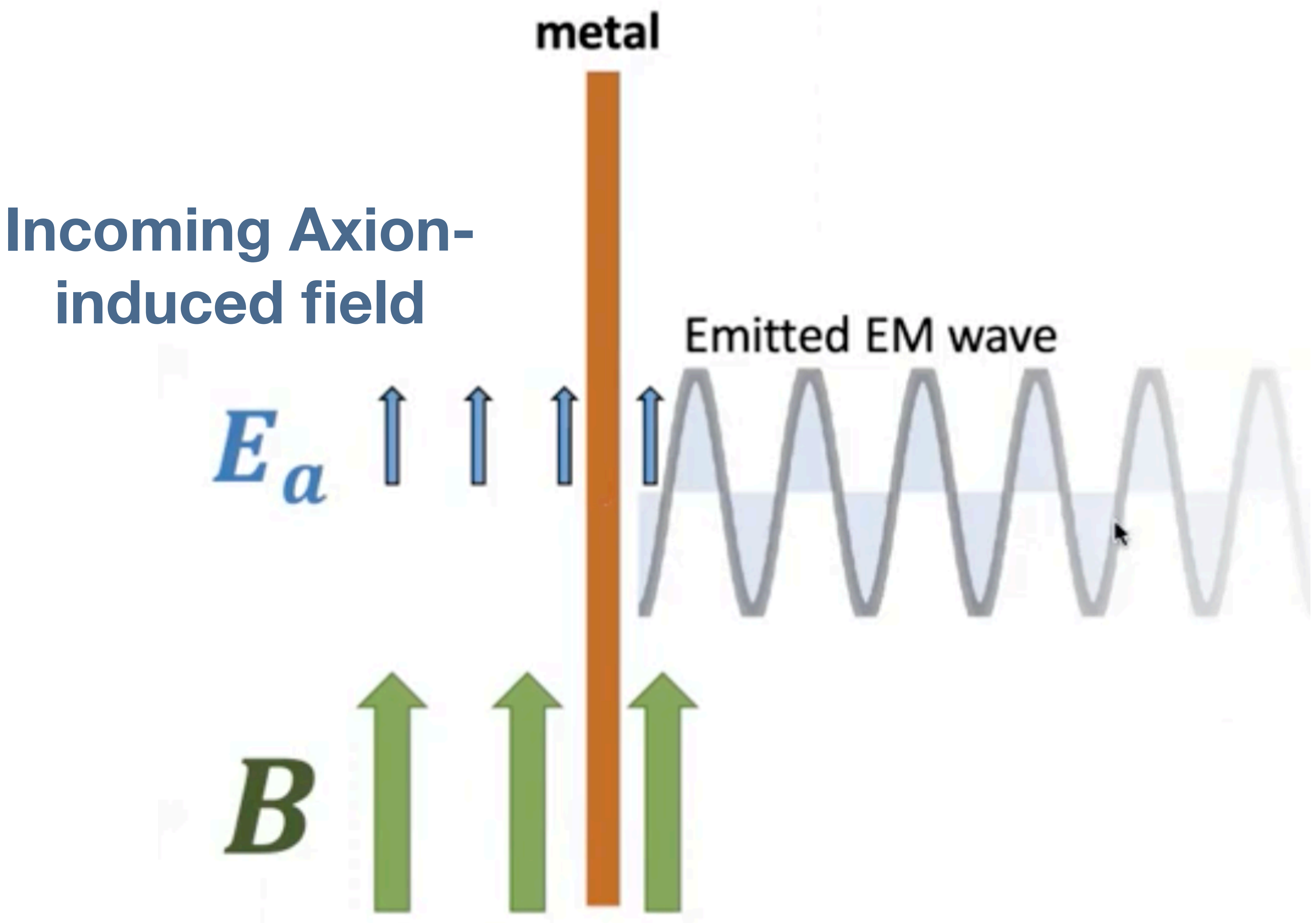
Fermilab

High Mass Axions are Unexplored



BREAD: Broadband Reflector Experiment for Axion Detection

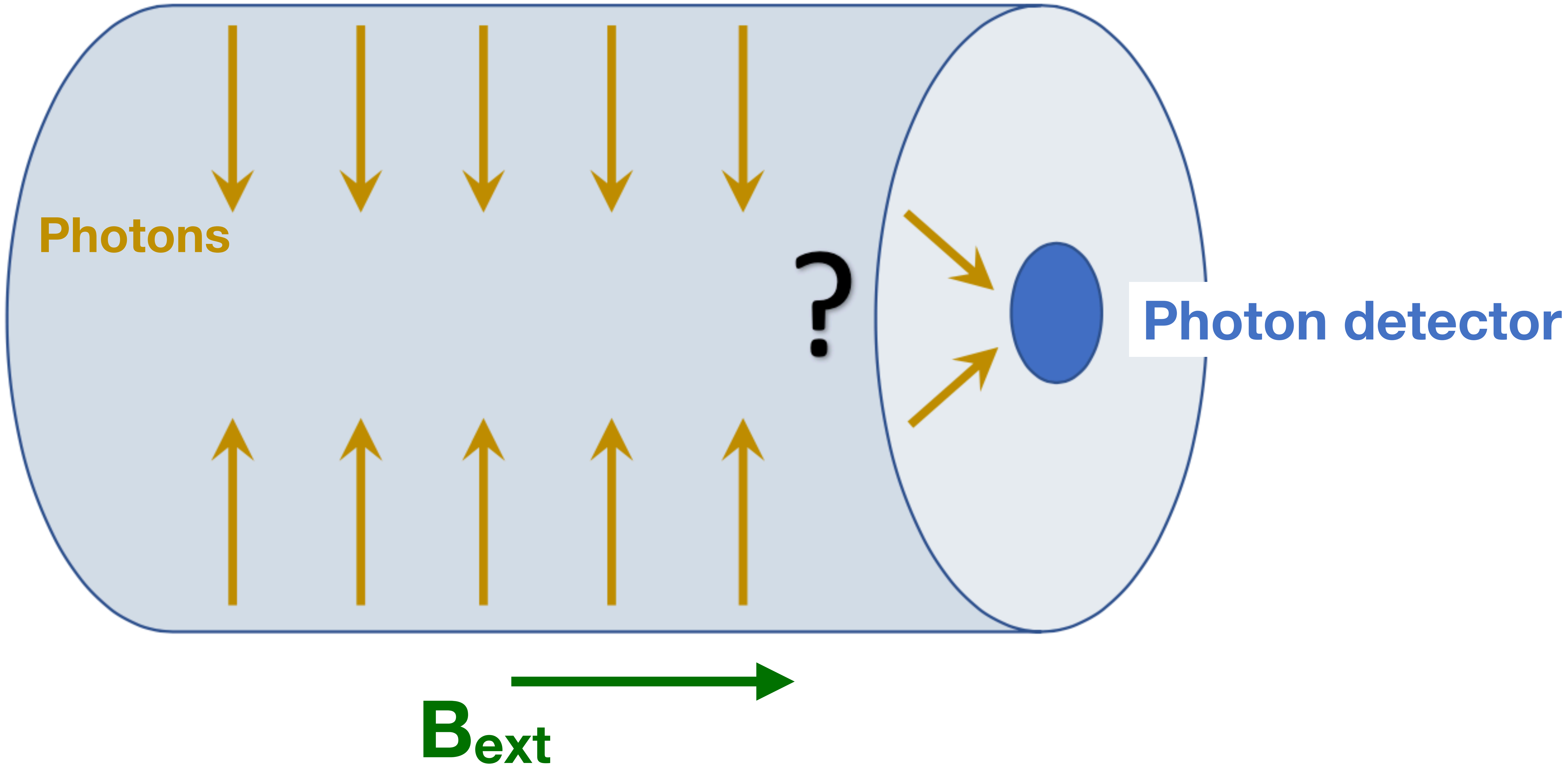
- Axion-induced EM field causes discontinuity at conducting surfaces
- To satisfy the $E_{||} = 0$ boundary condition, an additional EM wave emitted ⊥ to the surface
  - Emitted photon energy equals DM mass
  - For dark photon converts to photons without the need of B field



Phys. Rev. Lett. 128, 131801

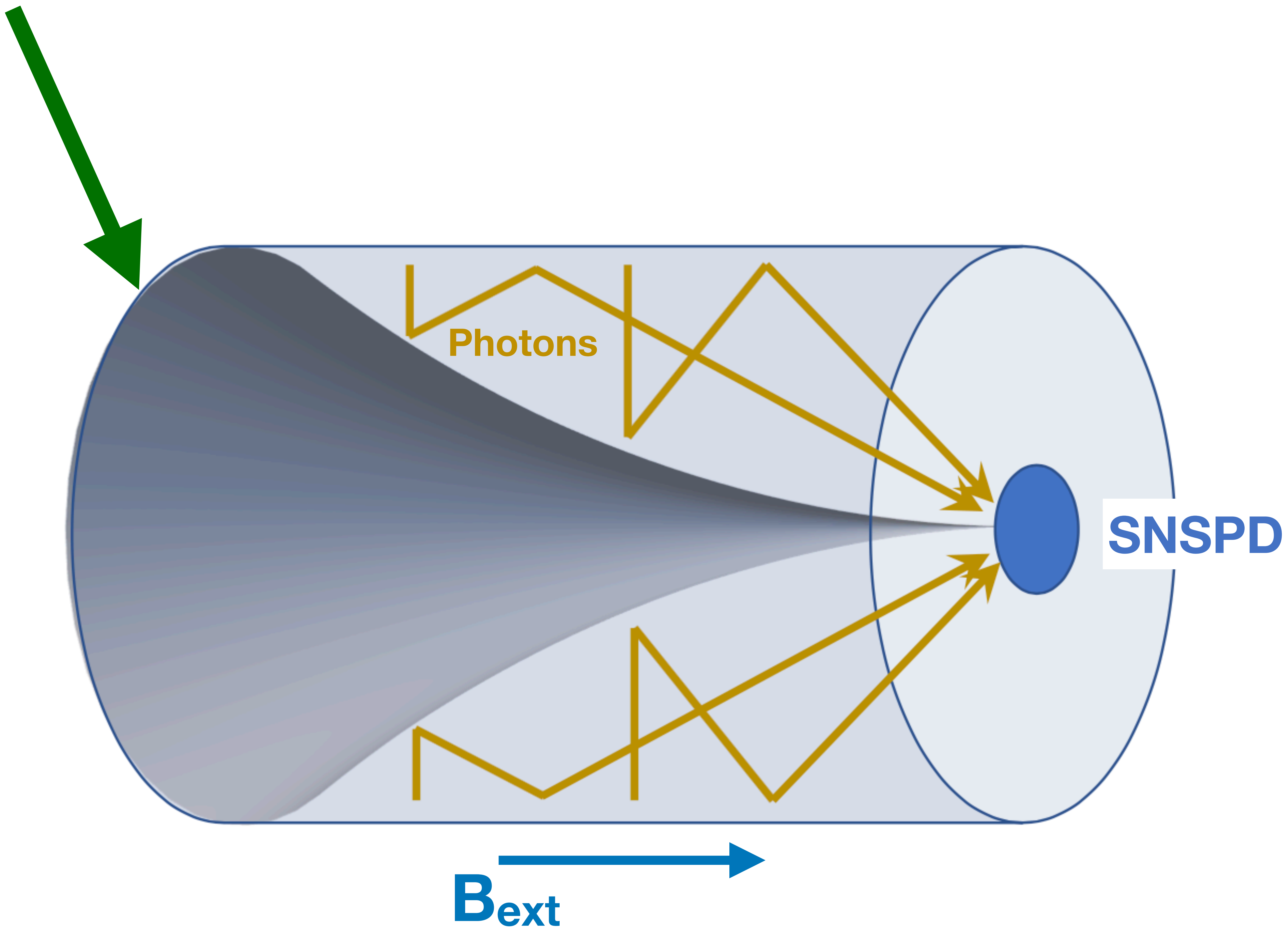
BREAD Detector Concept

- Cylindrical surface is convenient for solenoidal B field

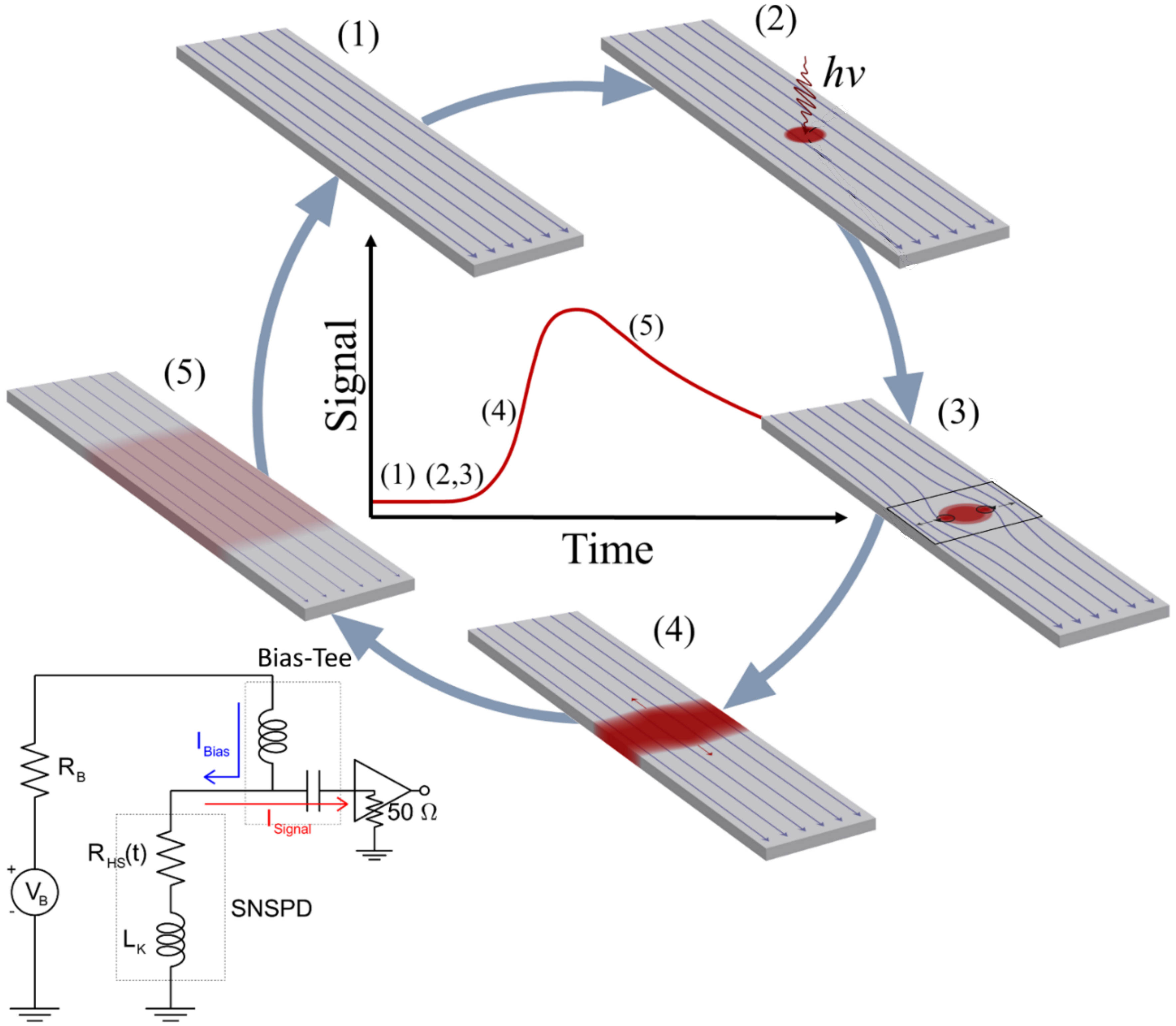


BREAD Detector Concept

- Cylindrical surface is convenient for solenoidal B field
- A **parabolic mirror** focuses the photons to a vertex

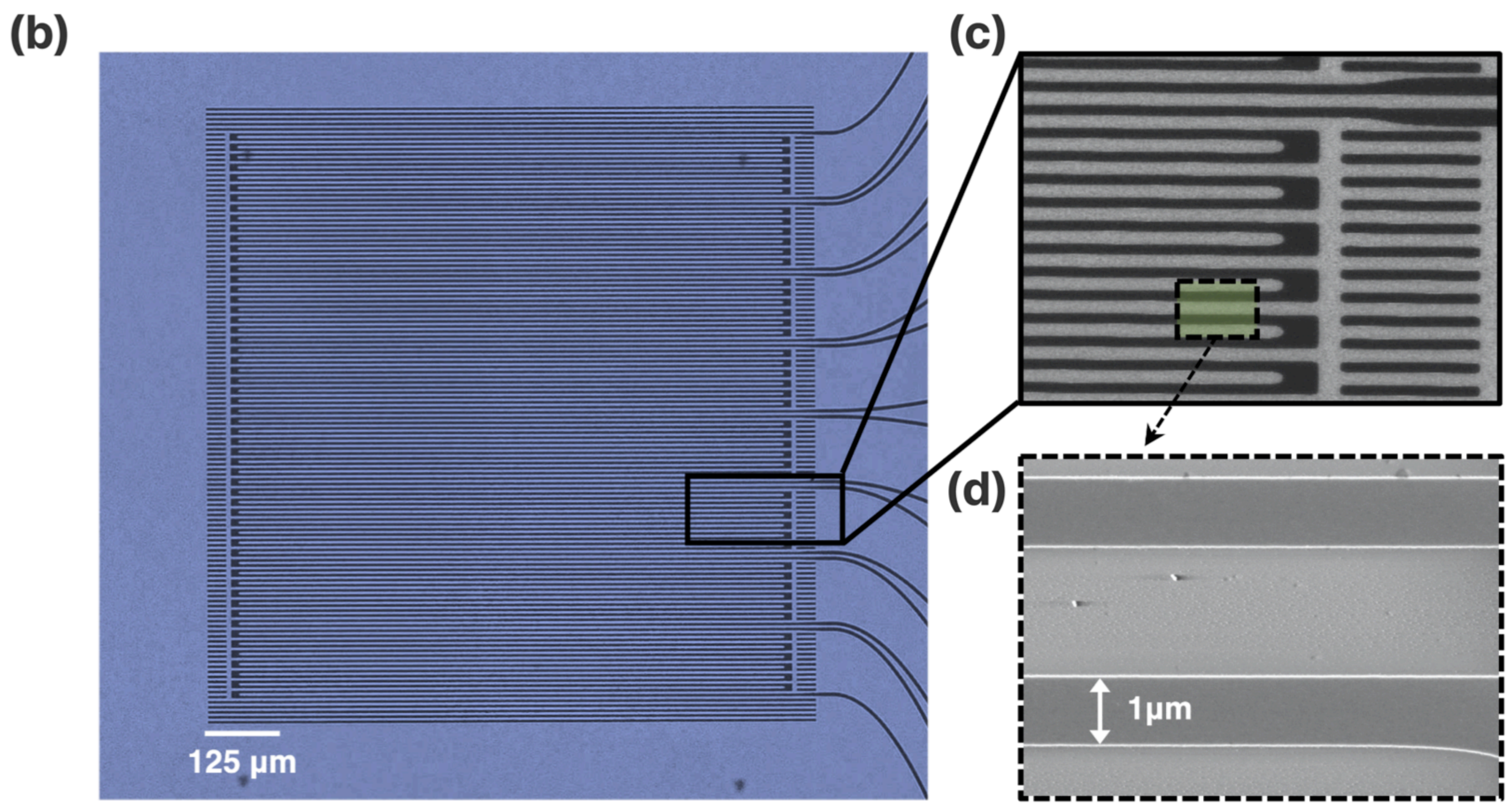


Superconducting Nanowire Single Photon Detector (SNSPD)



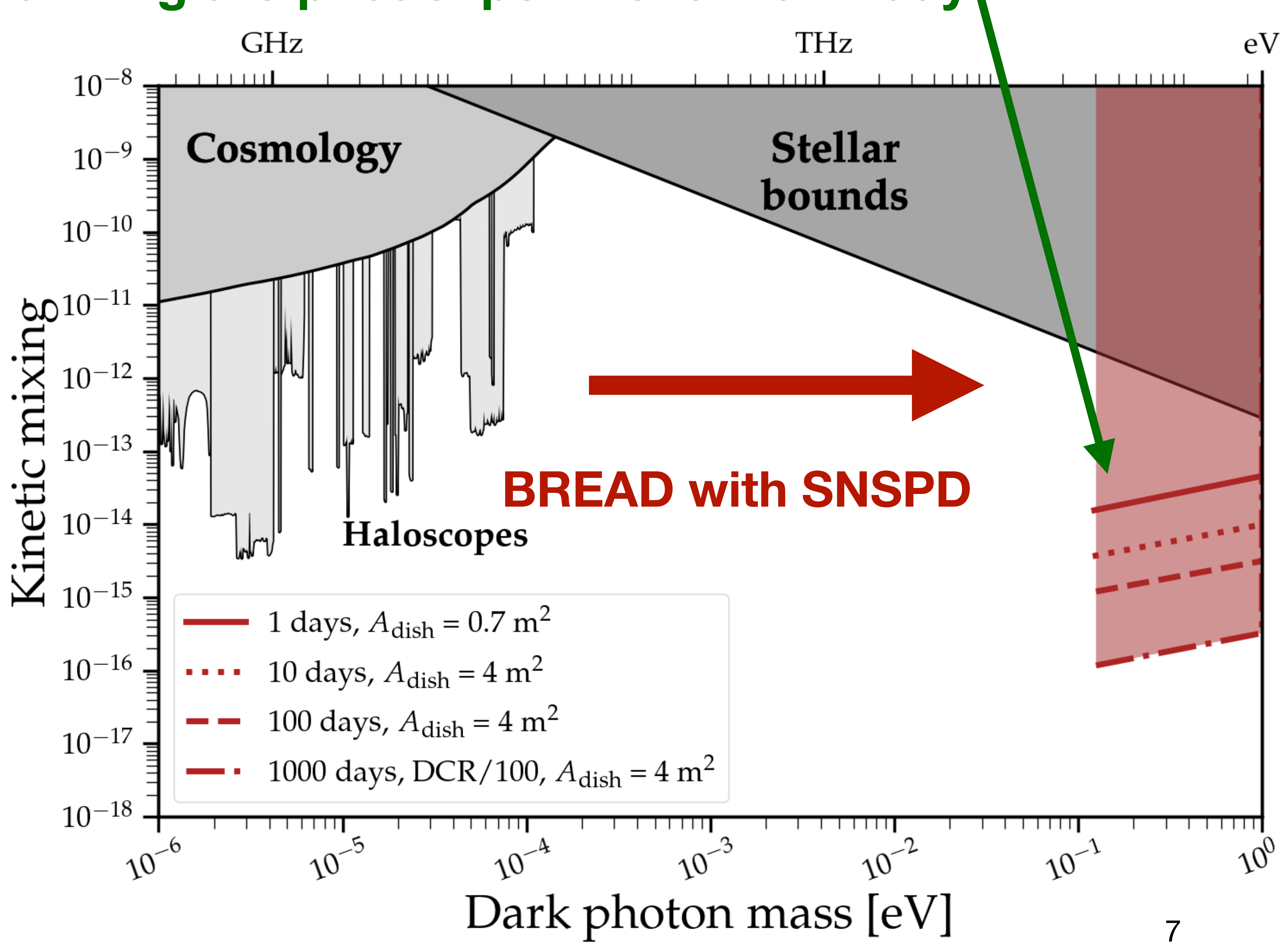
- Detection Mechanism:
  - Operating at 1-4 K
  - Incident single photon triggers detector out of superconducting state
  - Resistance quickly (ps) jumps to few kΩ → bias current into readout

- SNSPDs satisfy the photosensor requirements for BREAD:
  - Broad spectral response: ultraviolet to near infrared → sensitive to 0.1 - 1 eV dark photon/axions mass
  - Low noise: DCR < 10^{-3} Hz
  - mm^2-size active area

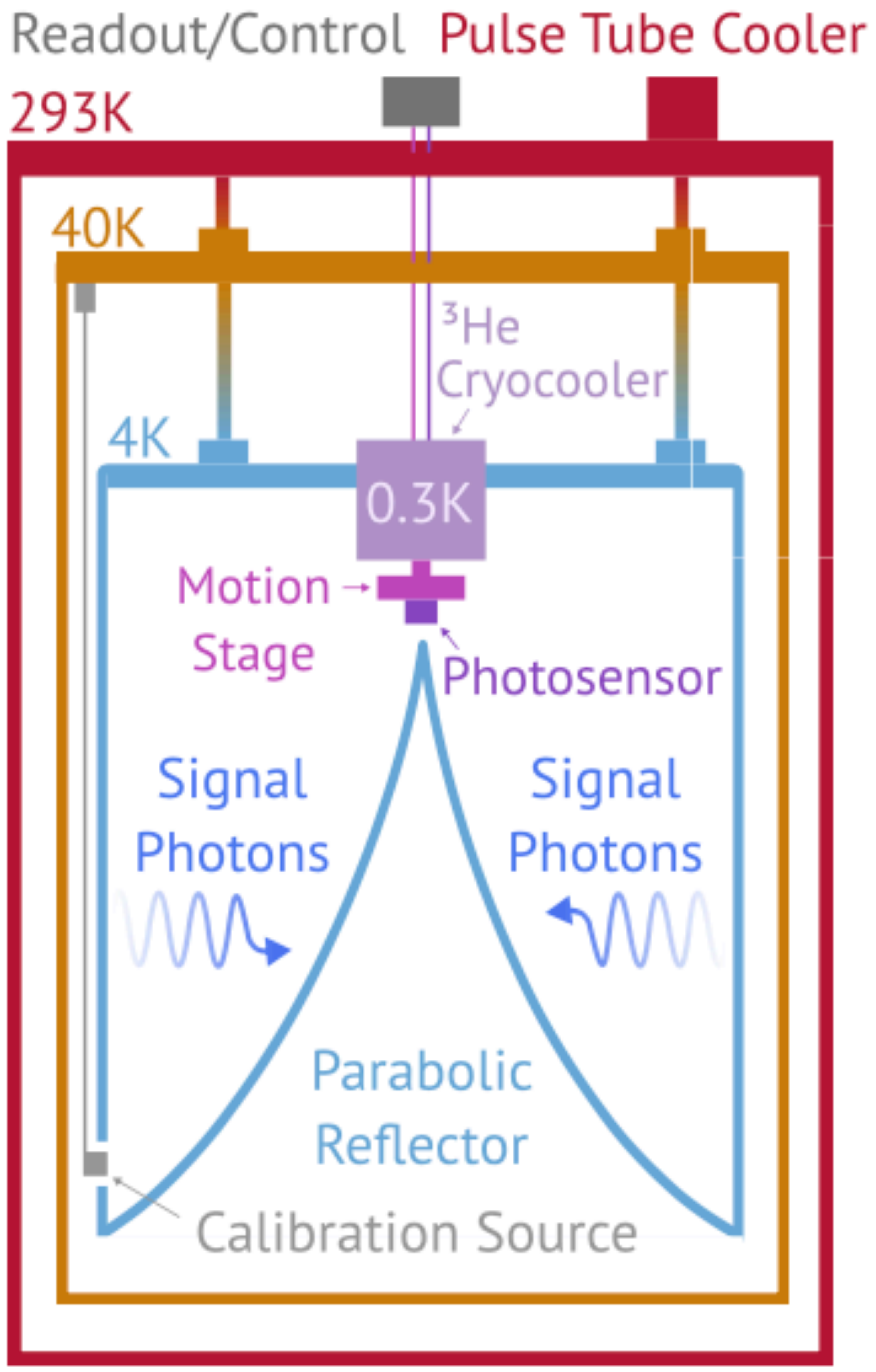


Pilot Experiment with SNSPDs

- Currently planning for pilot dark photon search 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**



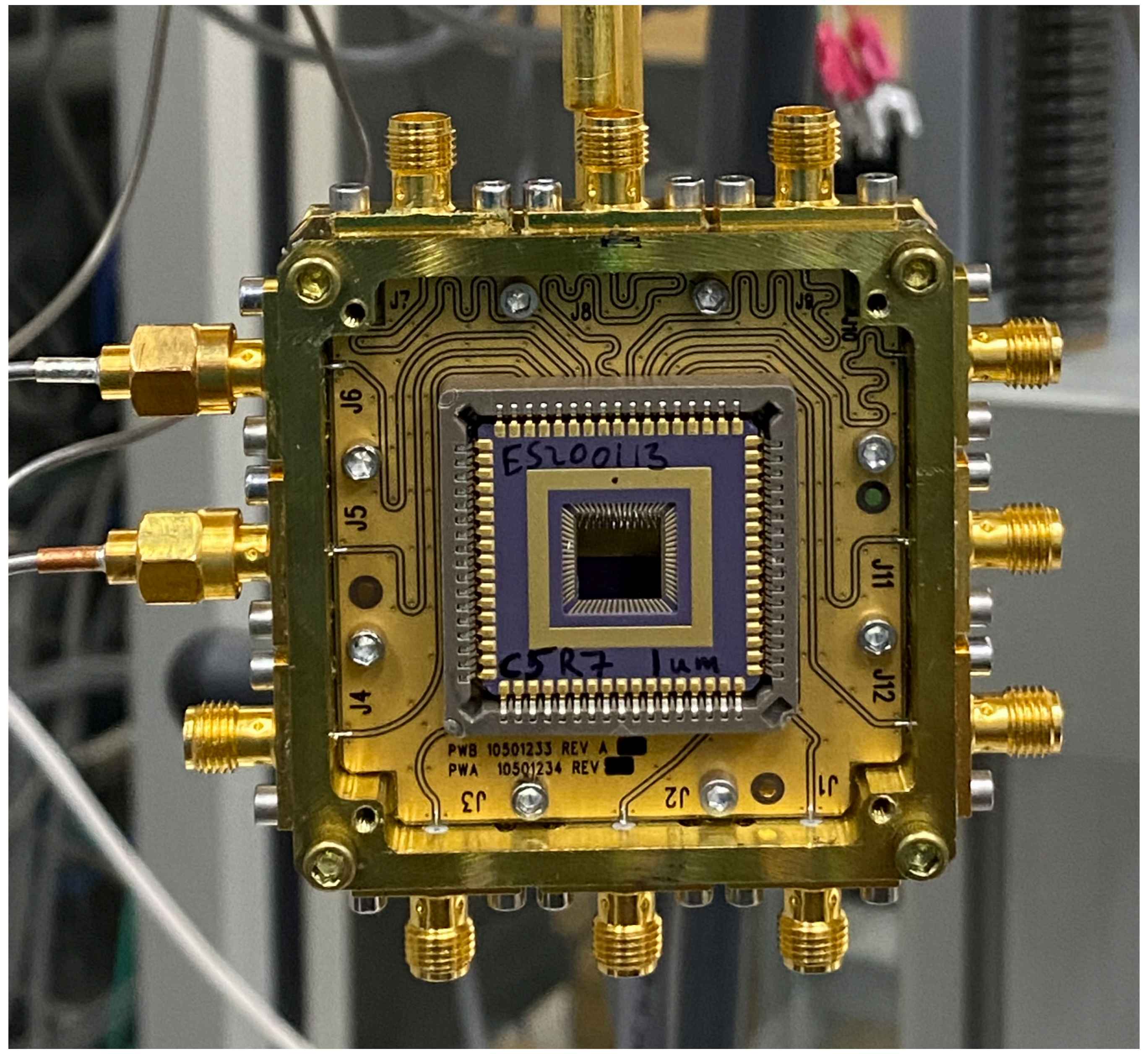
R = 20 cm

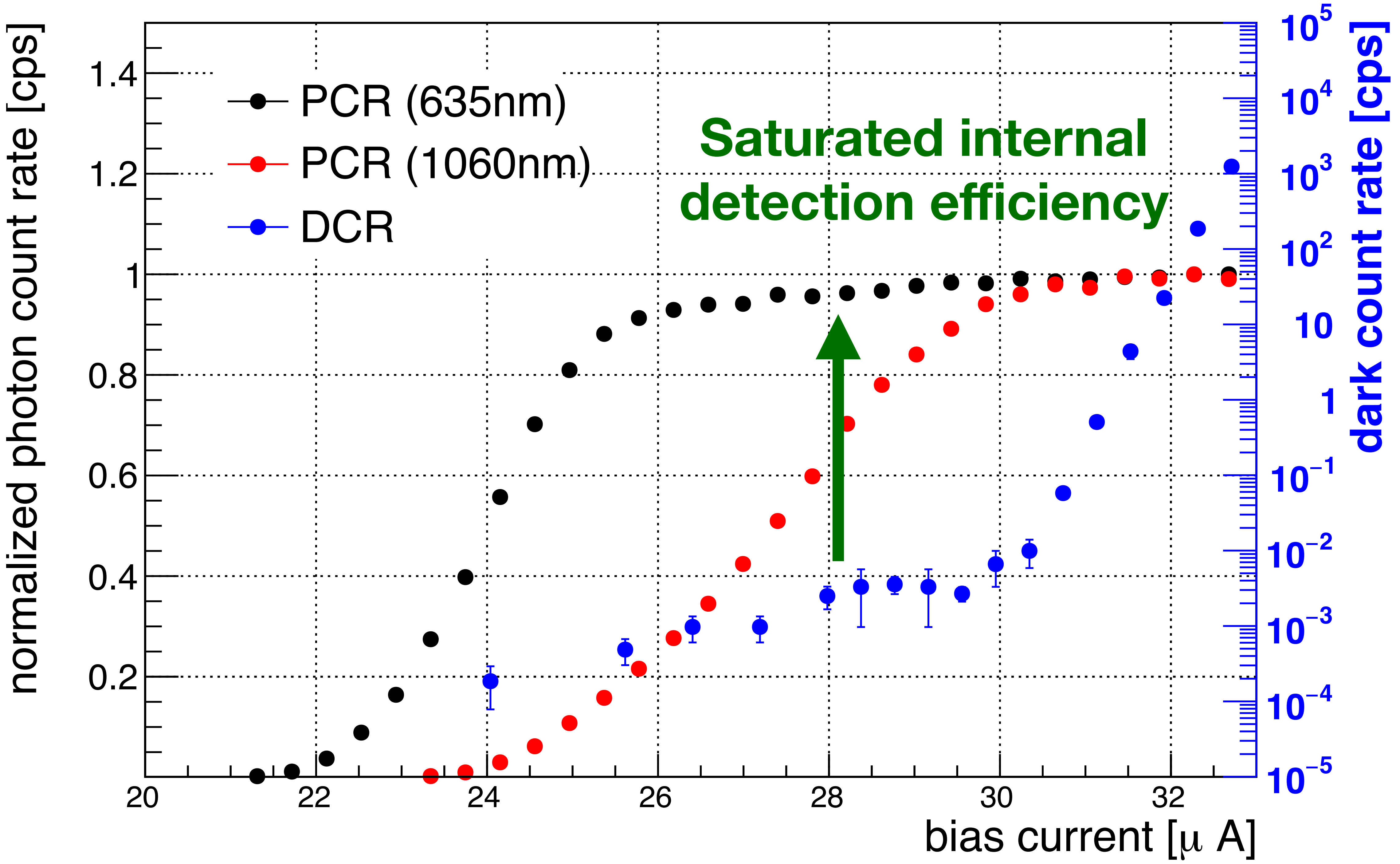


Status of the Pilot Bread Experiment — SNSPD Characterization

- Characterizing 8-channel mm² SNSPDs developed by collaborators at JPL
- The sensors are mounted in an Adiabatic Demagnetization Refrigerator (ADR) cryostat at Fermilab
- **Measured saturated internal detection efficiency and DCR of 1e-3 cps**
  - Working with JPL to develop new SNSPD in new dark box with higher efficiency and lower dark count
- **Developing system to measure calibrated efficiency to prepare for the pilot dark photon experiment**

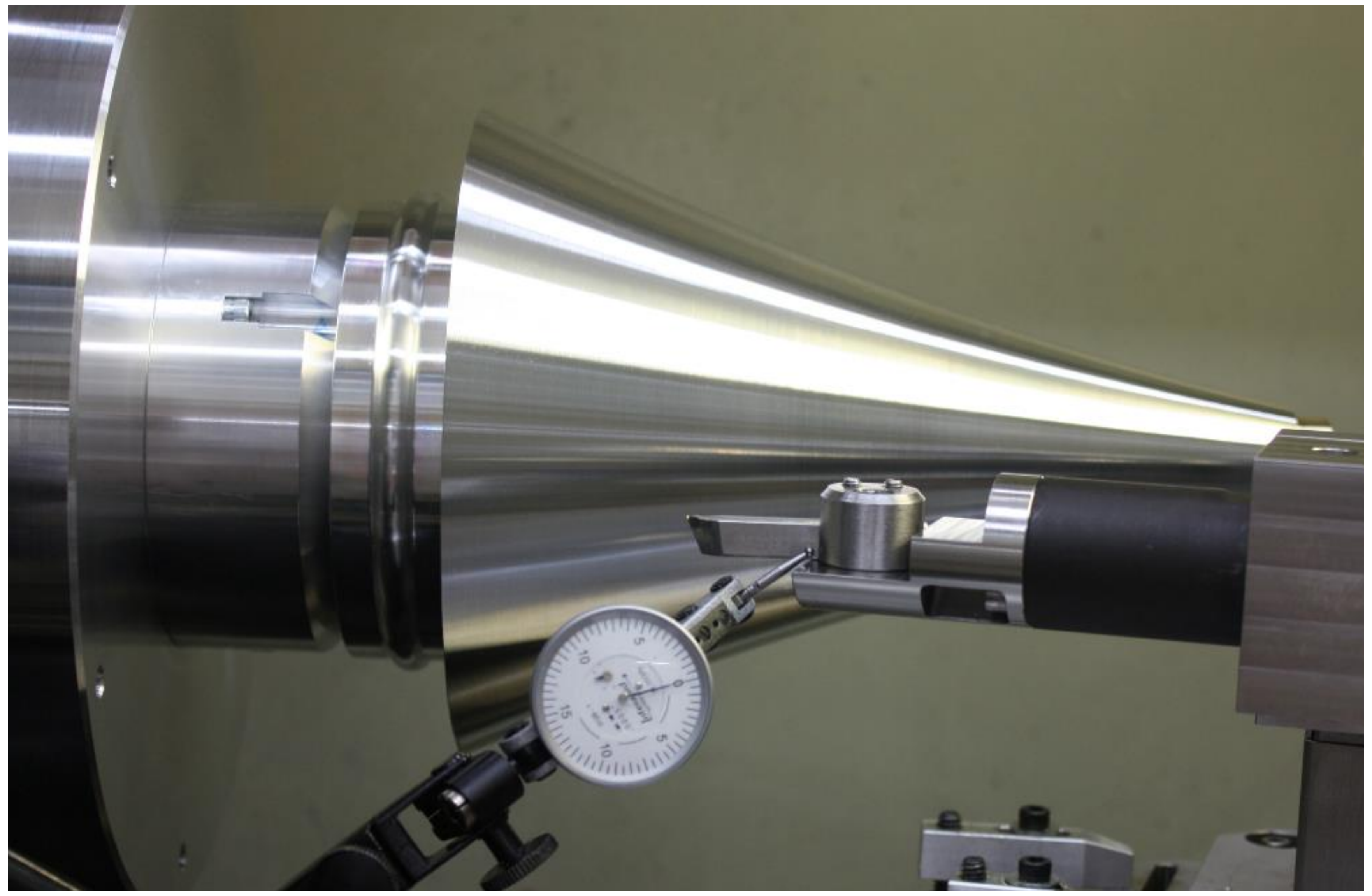
mm² SNSPD on ADR cold finger

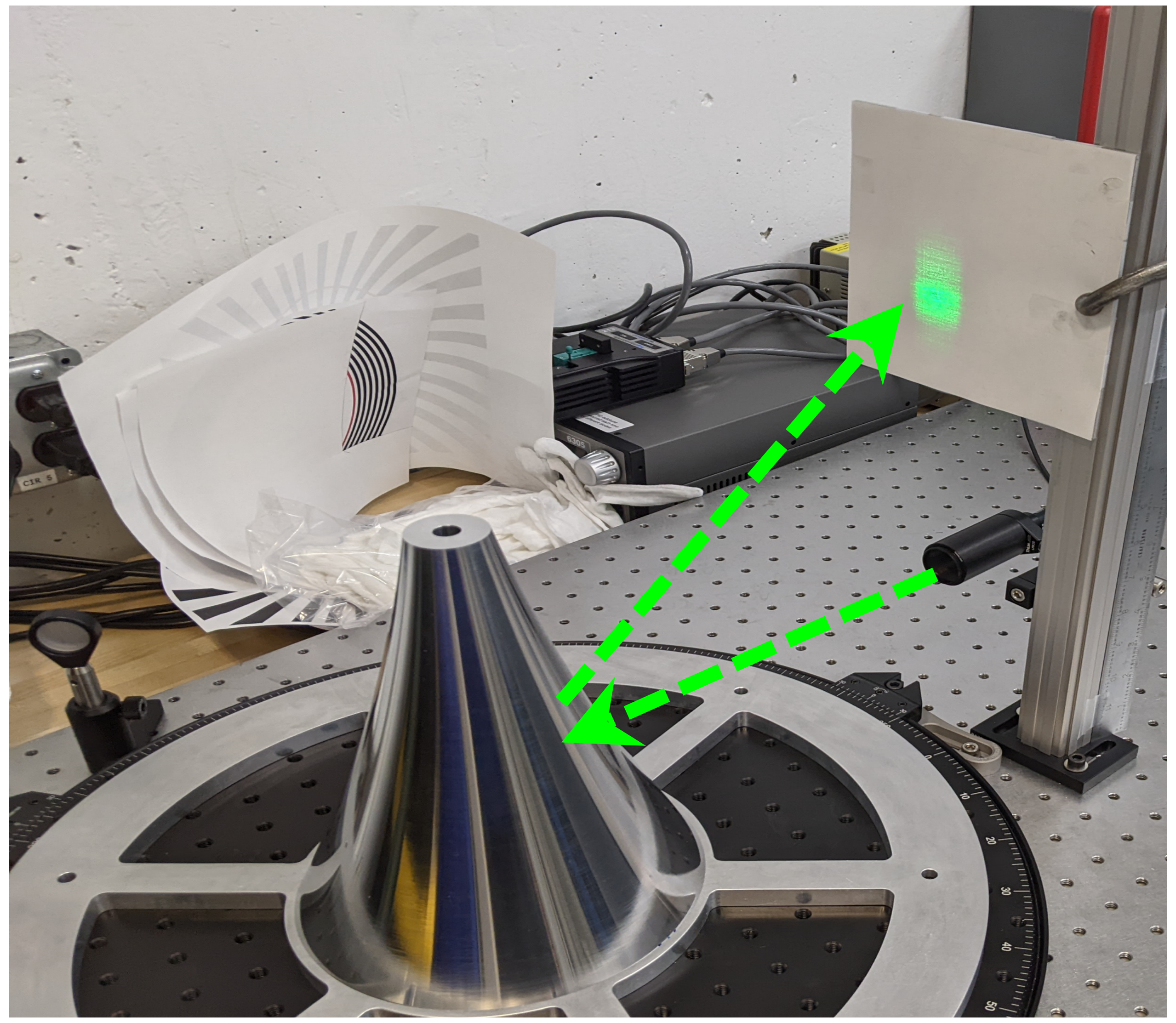




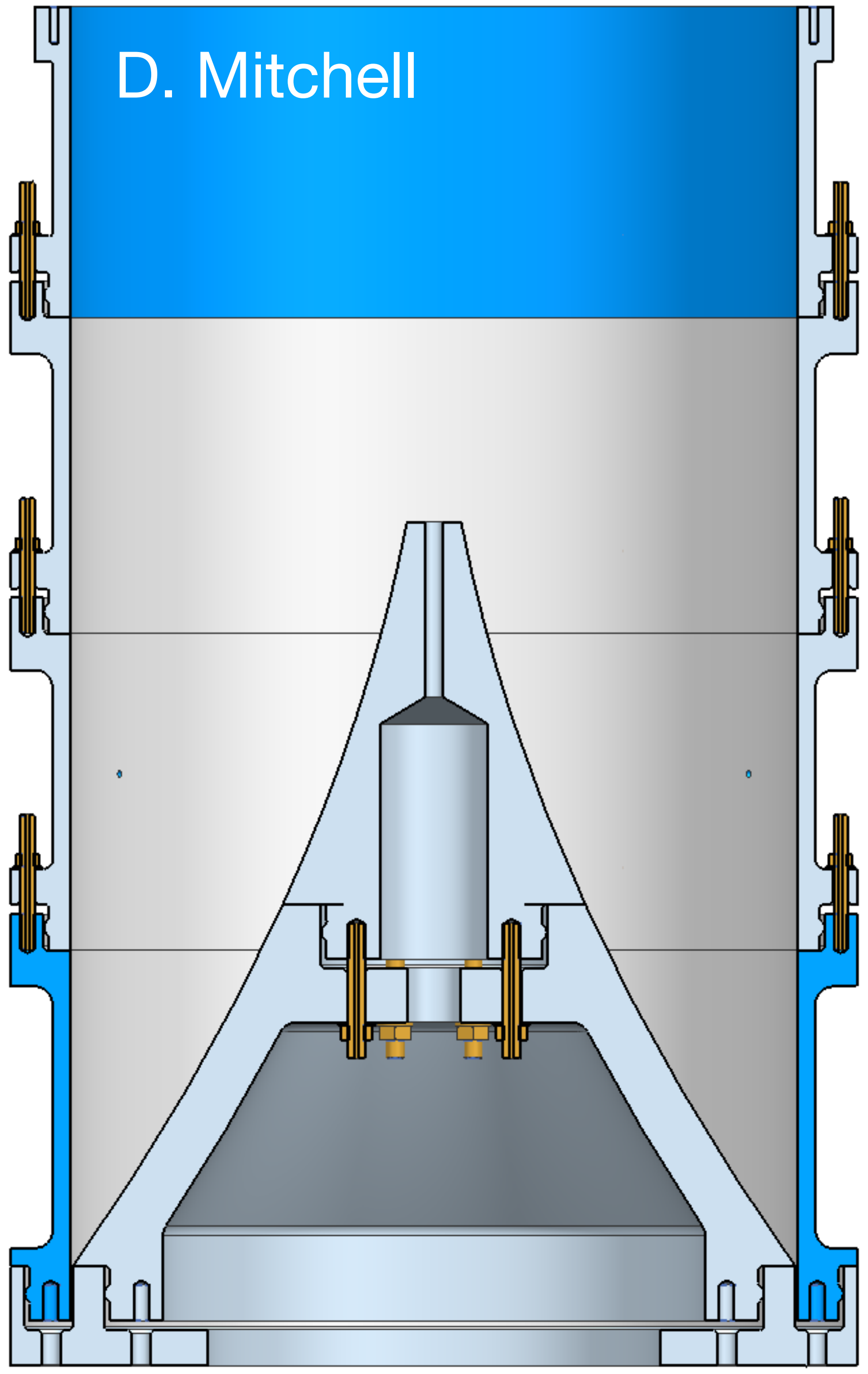
Status of the Pilot Bread Experiment — Reflector & Integration

- At optical wavelengths, need best possible focusing to limit size of photosensor.
- Reflector fabricated with diamond turning to achieve μm-level precision and smoothness
  - Top segment of the reflector diamond turned at LLNL and tested at FNAL
    - 90% optical efficiency and 25 nm roughness achieved within specification
- Plan to mount the setup in a dilution fridge in SQMS, working with engineers for optimized thermal and mechanical solution



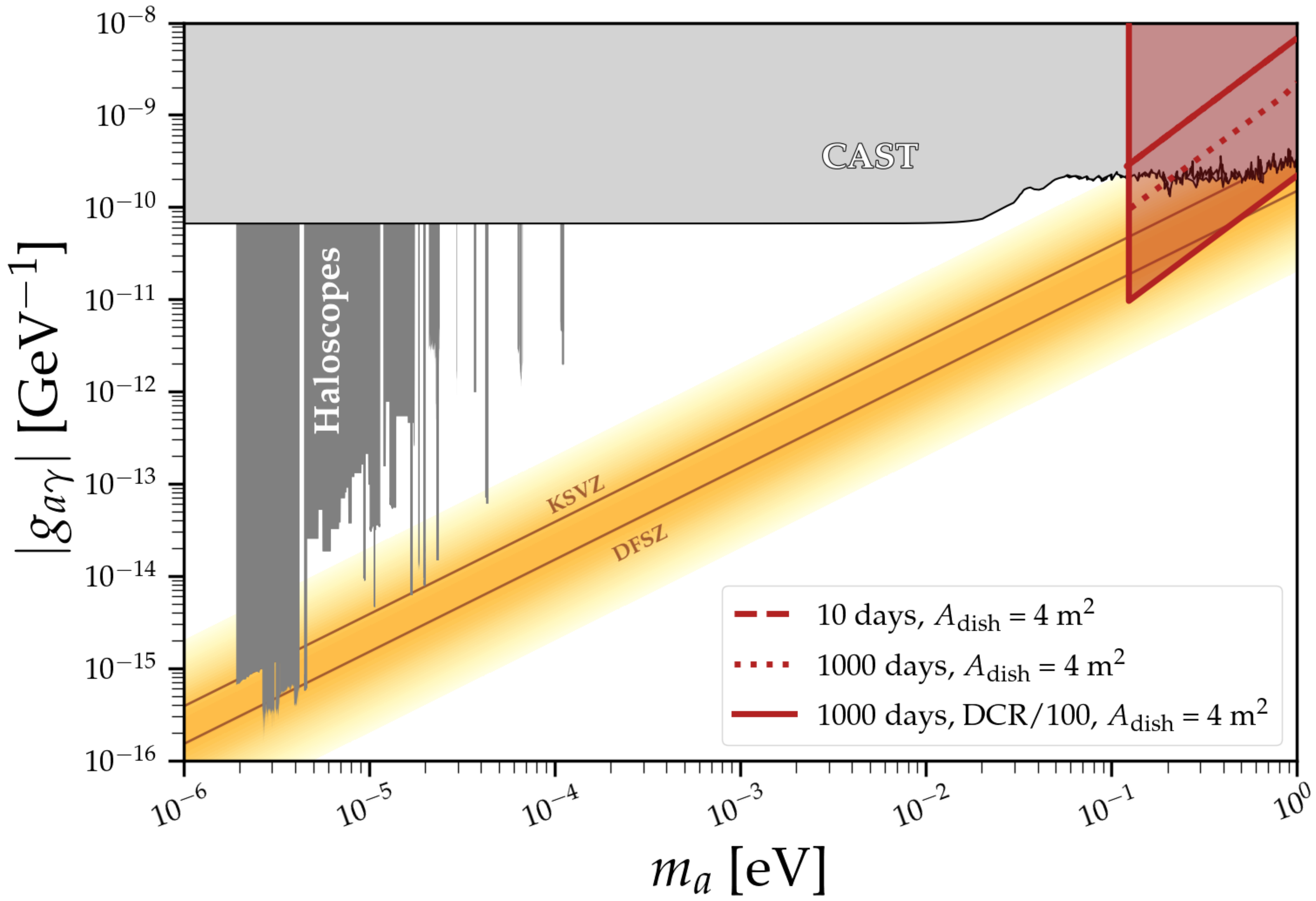


Measuring focal spot dispersion with laser

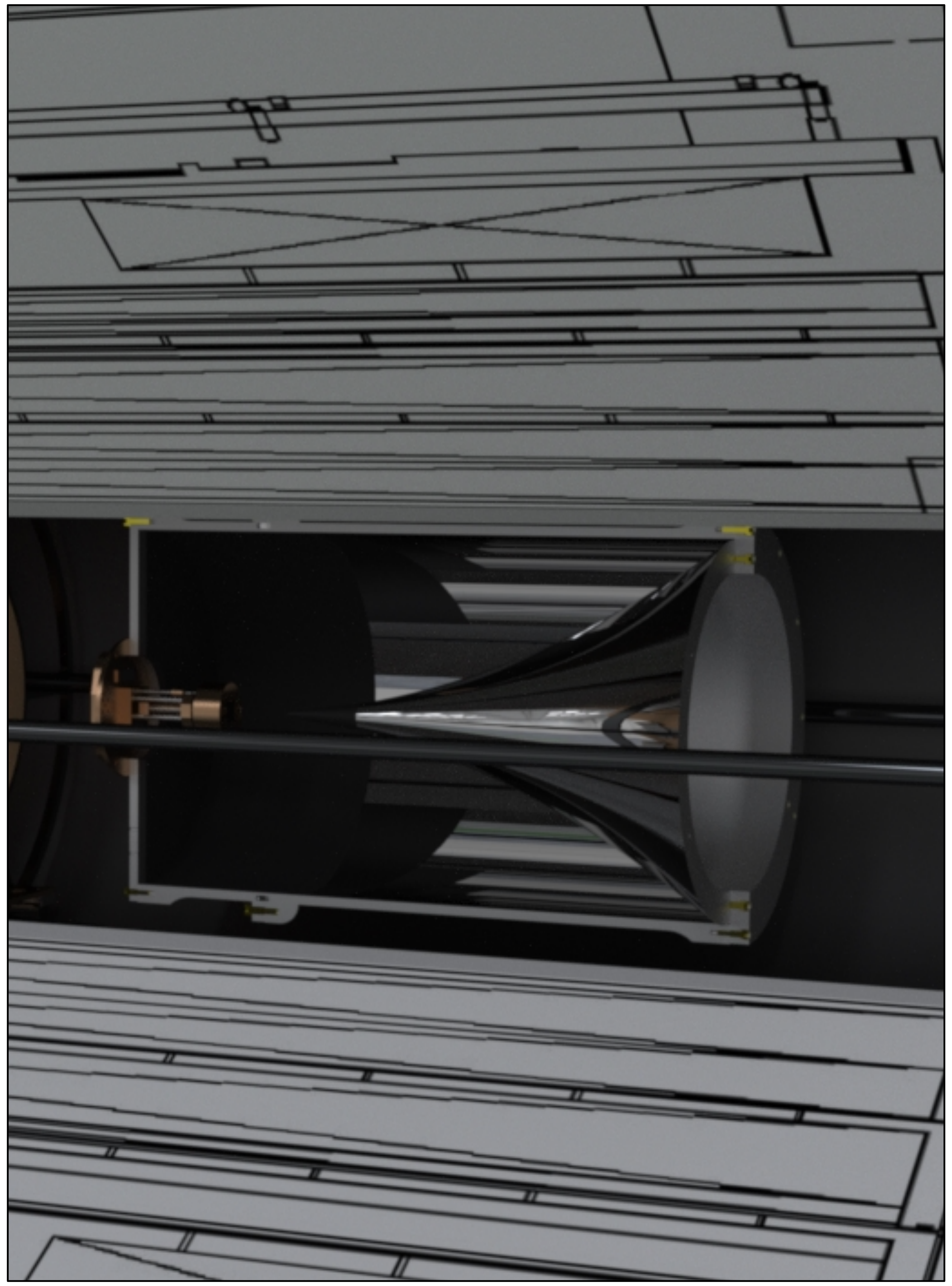


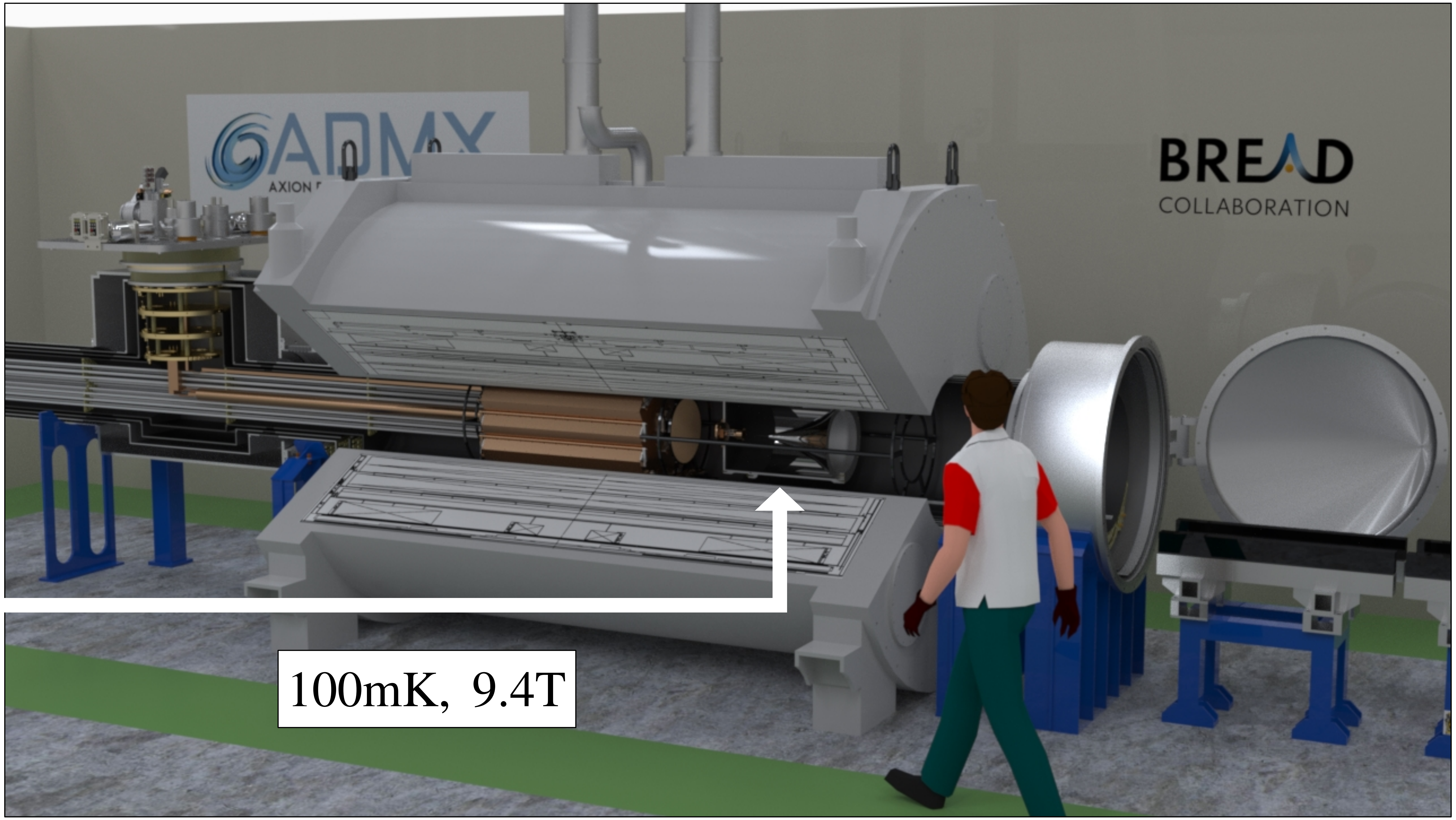
Large-Scale Bread Experiment for Axions

- SNSPD provides unique sensitivity for 0.1 - 1 eV axion masses



Vision: Large-Scale BREAD

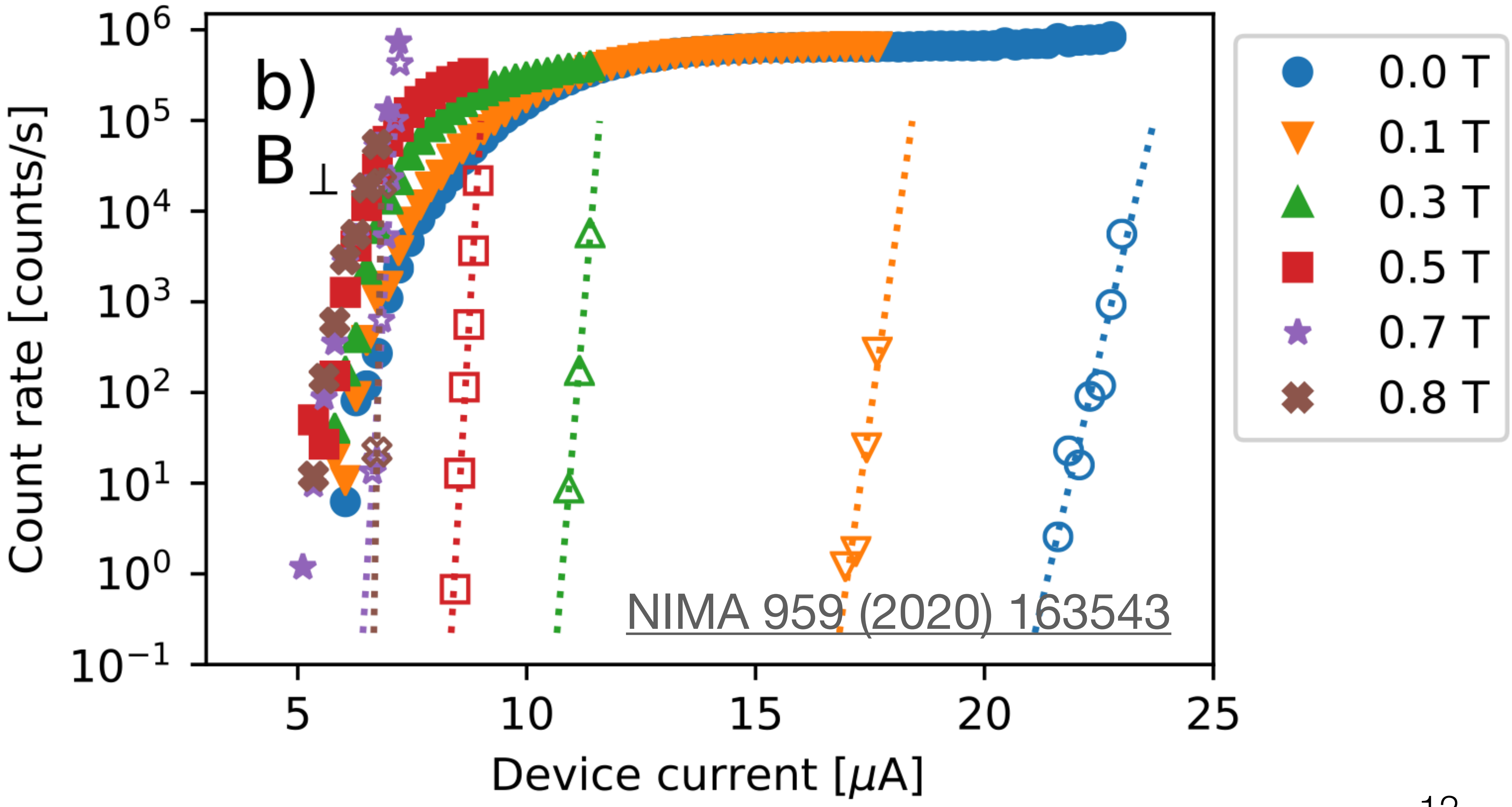


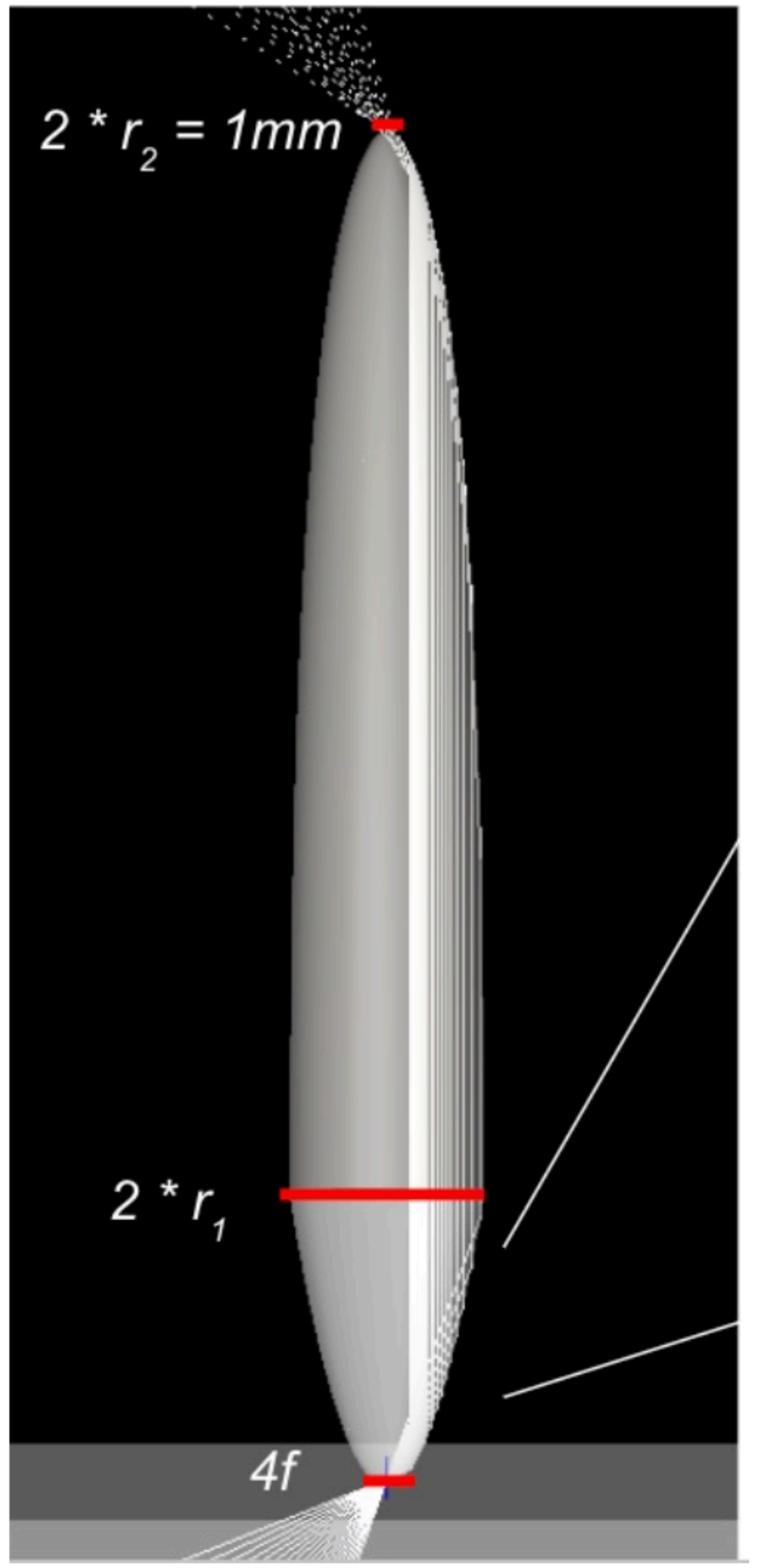


larger-scale version (A ~ 4 m²) as side-experiment to ADMX-EFR

InfraBread for Axions

- **Require sub-Kelvin cryostat and related infrastructure in the Dark Wave Lab**
- **R&D needed to operate SNSPD in magnetic field**
  - Require sensor development & characterization inside strong B field
- **Alternatively, guide the signal photons to lower or zero B field regions for detection**
  - Performing simulation study to guide photons to outside of the magnet

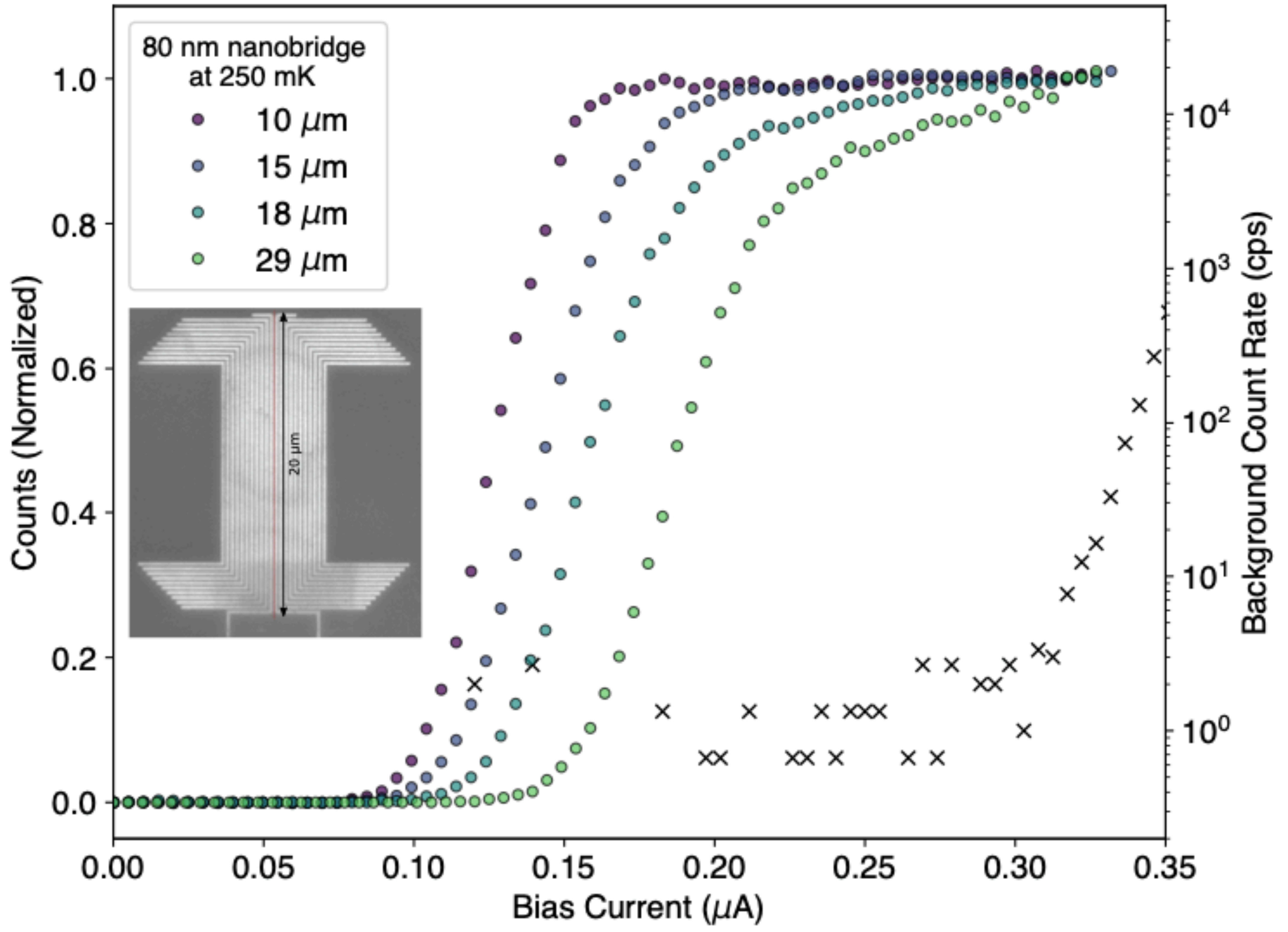




Paraboloid to Winston Cone setup to guide the photons outside of the solenoid

Future SNSPD Improvements: Lowering the Energy Threshold

- **To further improve the reach to lighter mass → lowering the energy threshold**
- Increasing silicon concentration in WSi → lower energy threshold
- Recent demonstration of SNSPD can detect photons up to 29μm / 0.04 eV



https://arxiv.org/pdf/2308.15631.pdf

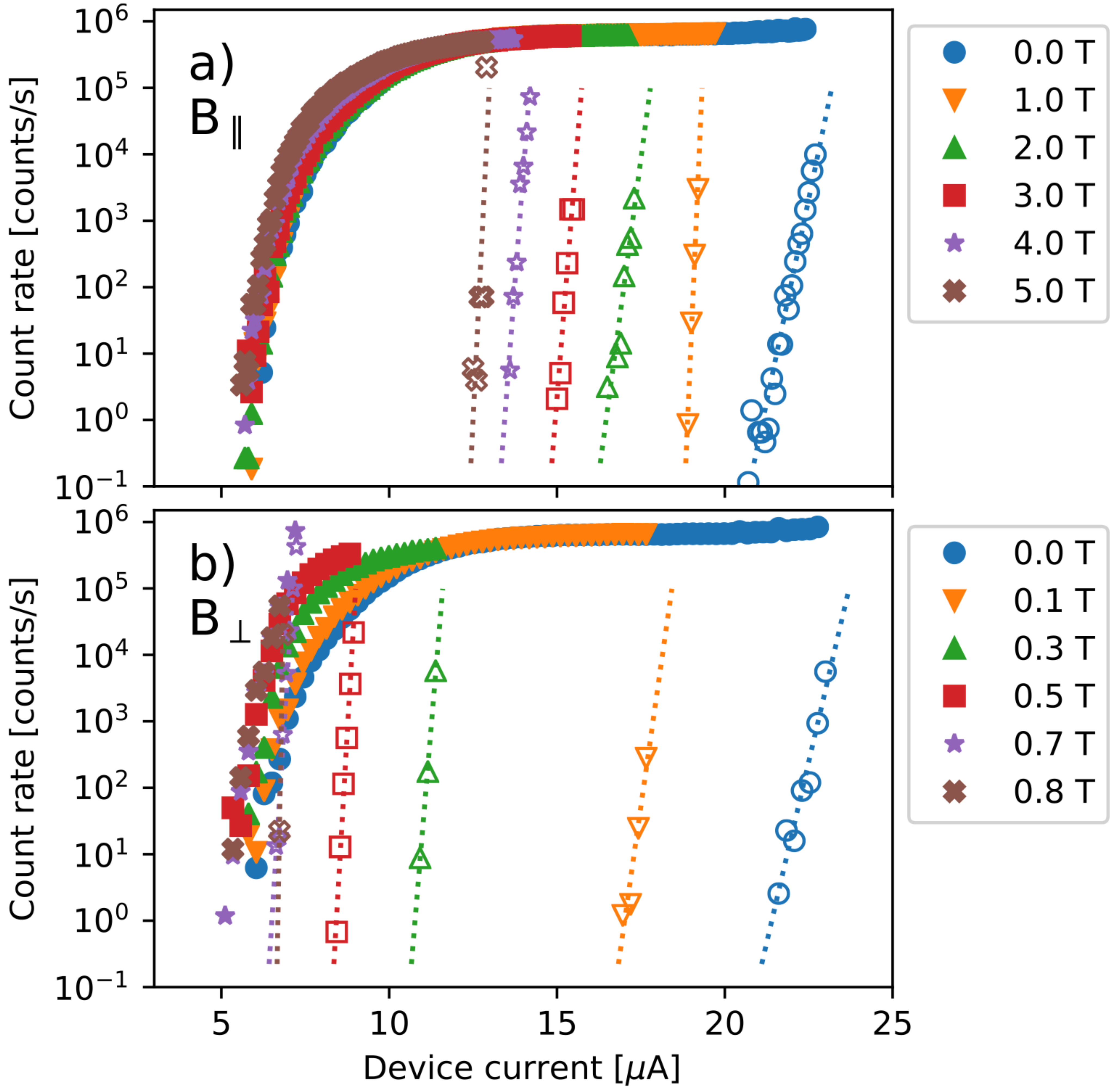
Summary

- Presented current progress of the pilot BREAD experiment using SNSPDs that can set best limit for 0.1-1 eV dark photon
    - Developing system to measure SNSPD calibrated efficiency, fabricating and characterizing reflector, and integrating the system to SQMS fridge
- Access to sub-K cryostat and magnet in the Dark Wave Lab is essential to the next large-scale BREAD experiment for axions

Backup Slides

SNSPD in Magnetic Field

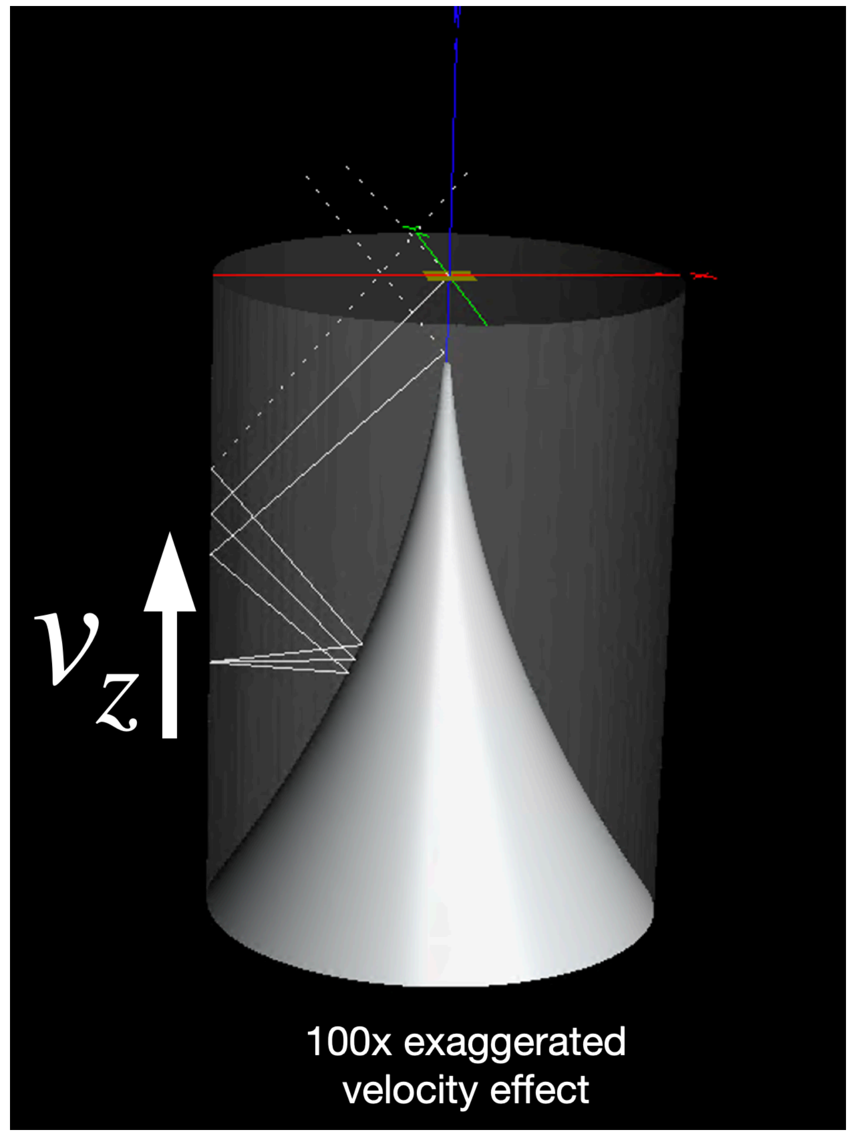
- Signal efficiency is mostly similar in different B field, while dark count rate increases significantly



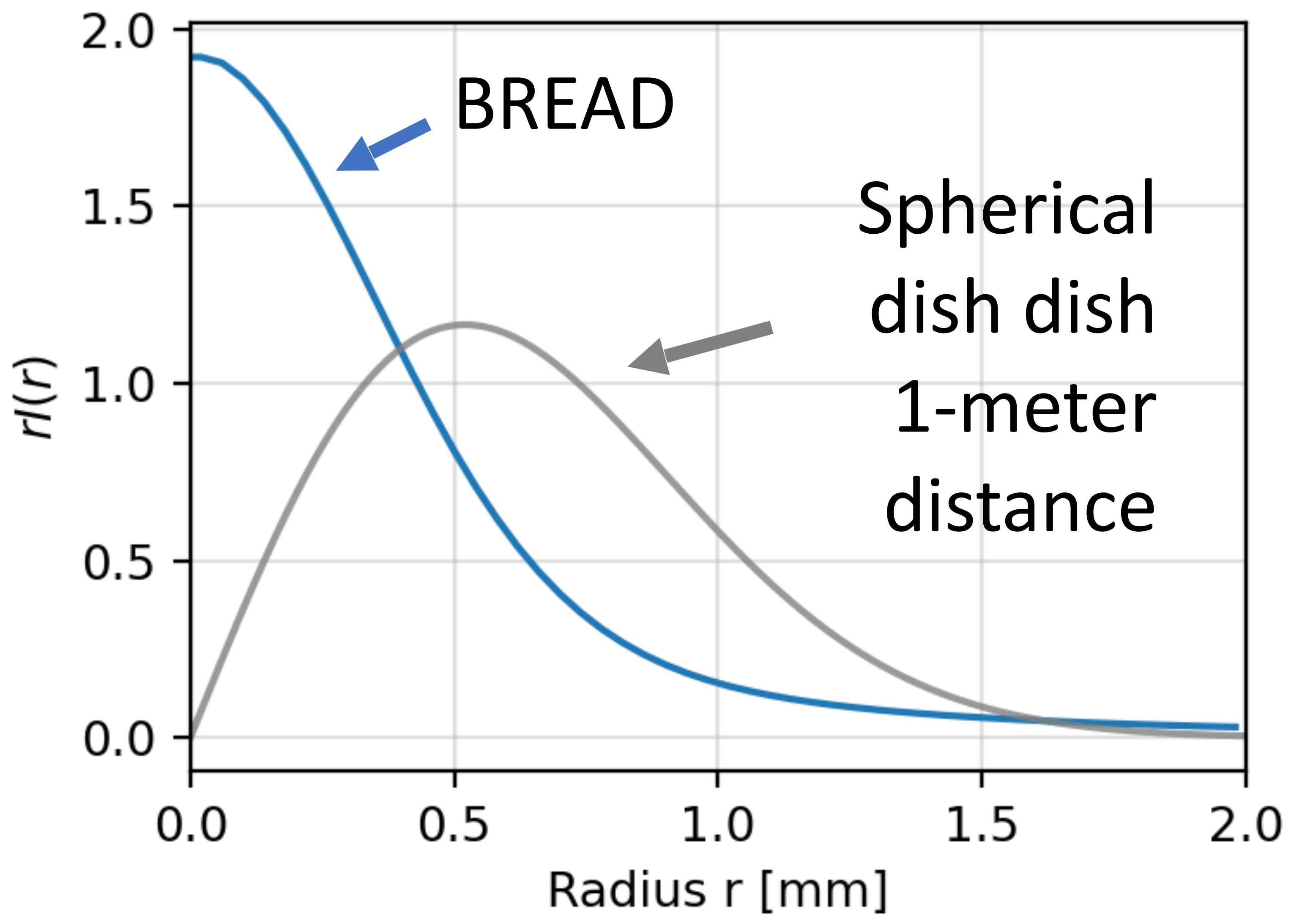
NIMA 959 (2020) 163543

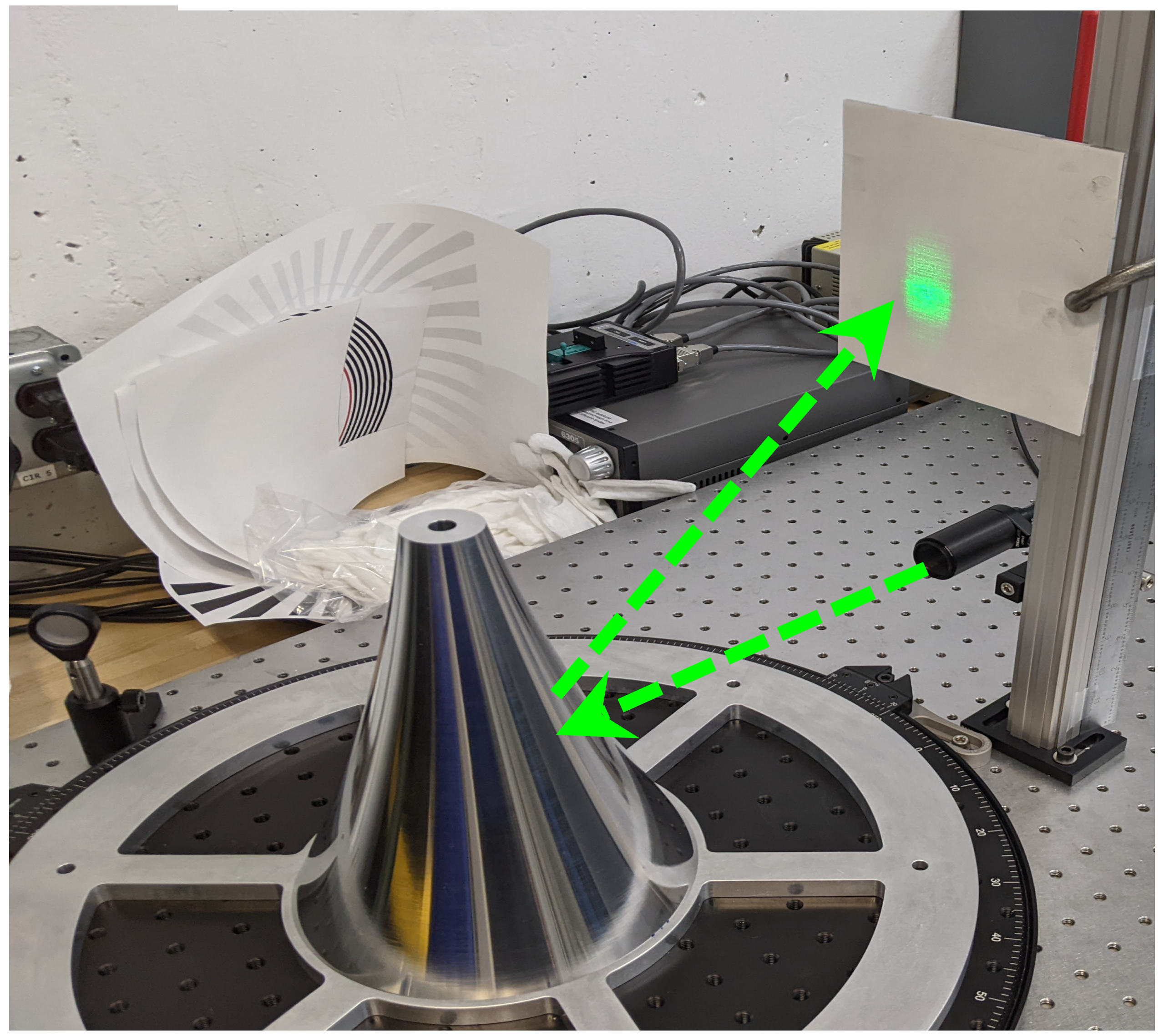
InfraBREAD Dish Requirements

- At optical wavelengths, need best possible focusing to limit size of photosensor.
- Dark matter velocity dispersion limits focal spot to ~ 1 mm for a meter scale device.
- Reflector surface deviations need to be controlled at few micron level.
- Achievable by industry standard optical machining process (single point diamond turning) on various substrates (e.g. aluminum)



Focal plane Intensity Distribution

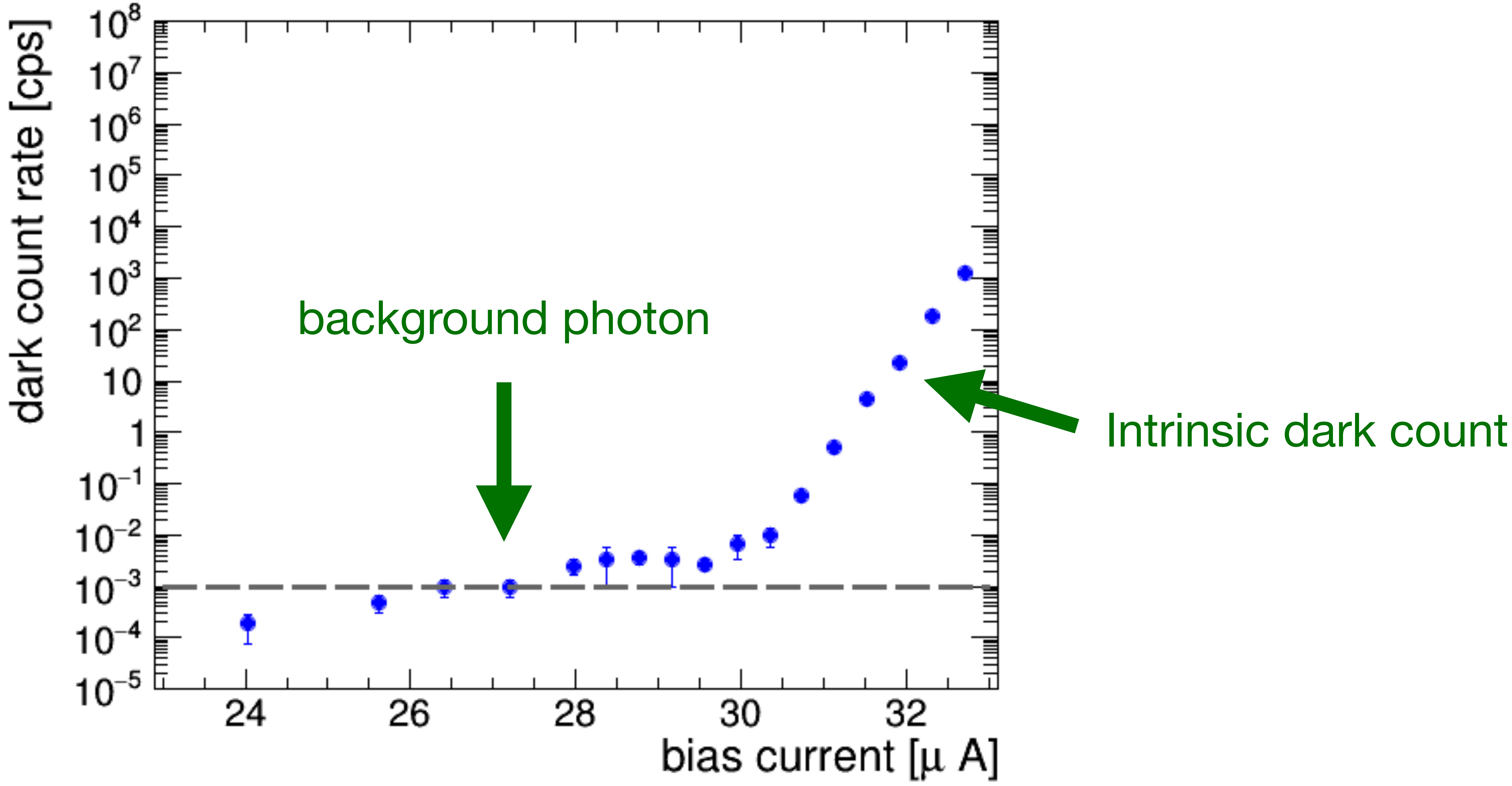




Measuring focal spot dispersion with laser

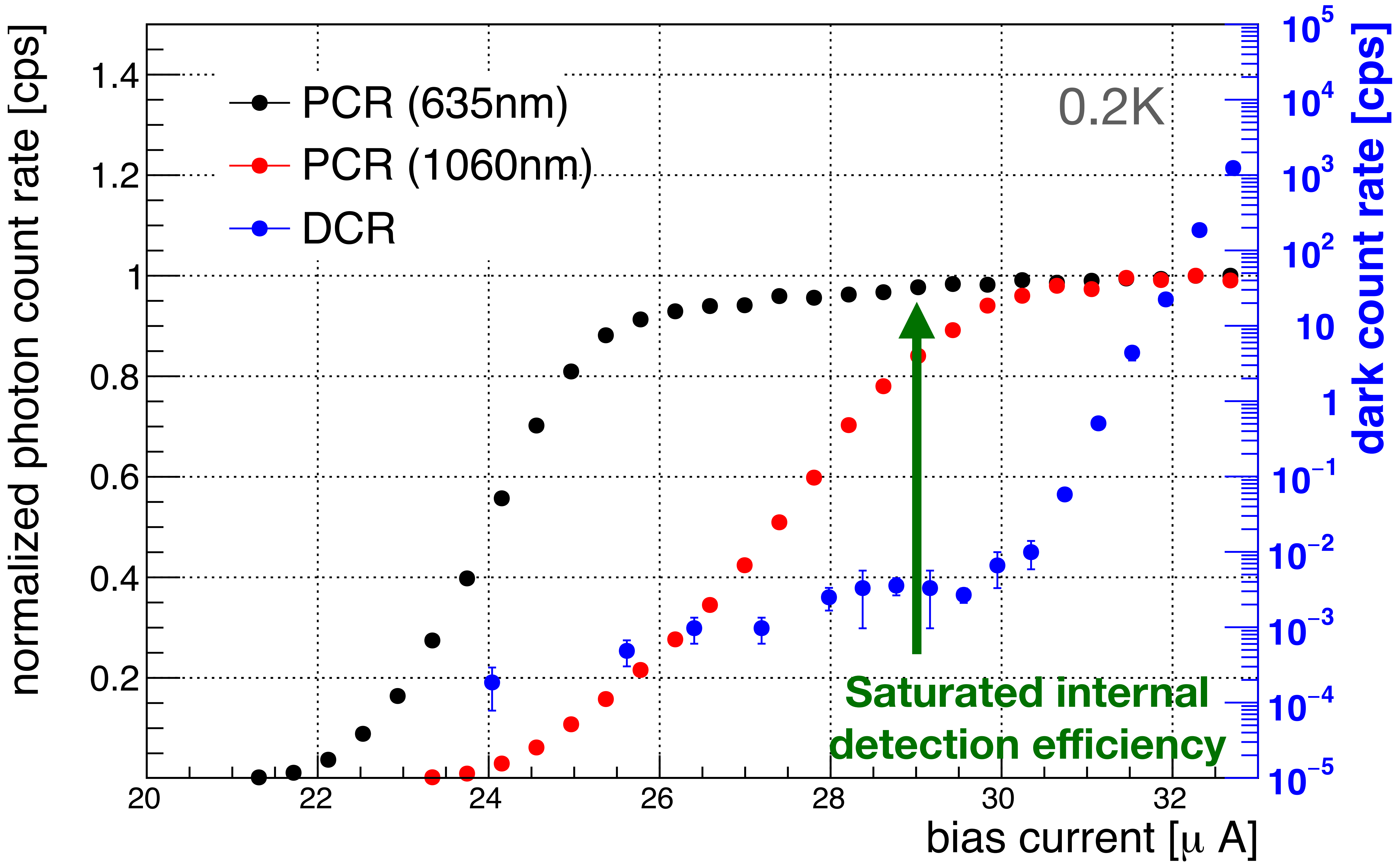
Background Rate Measurement

- **Measured the DCR with shielding at every stage → < 1e-3 cps**
- Working on new dark box for SNSPD to further reduce the noise floor in DCR



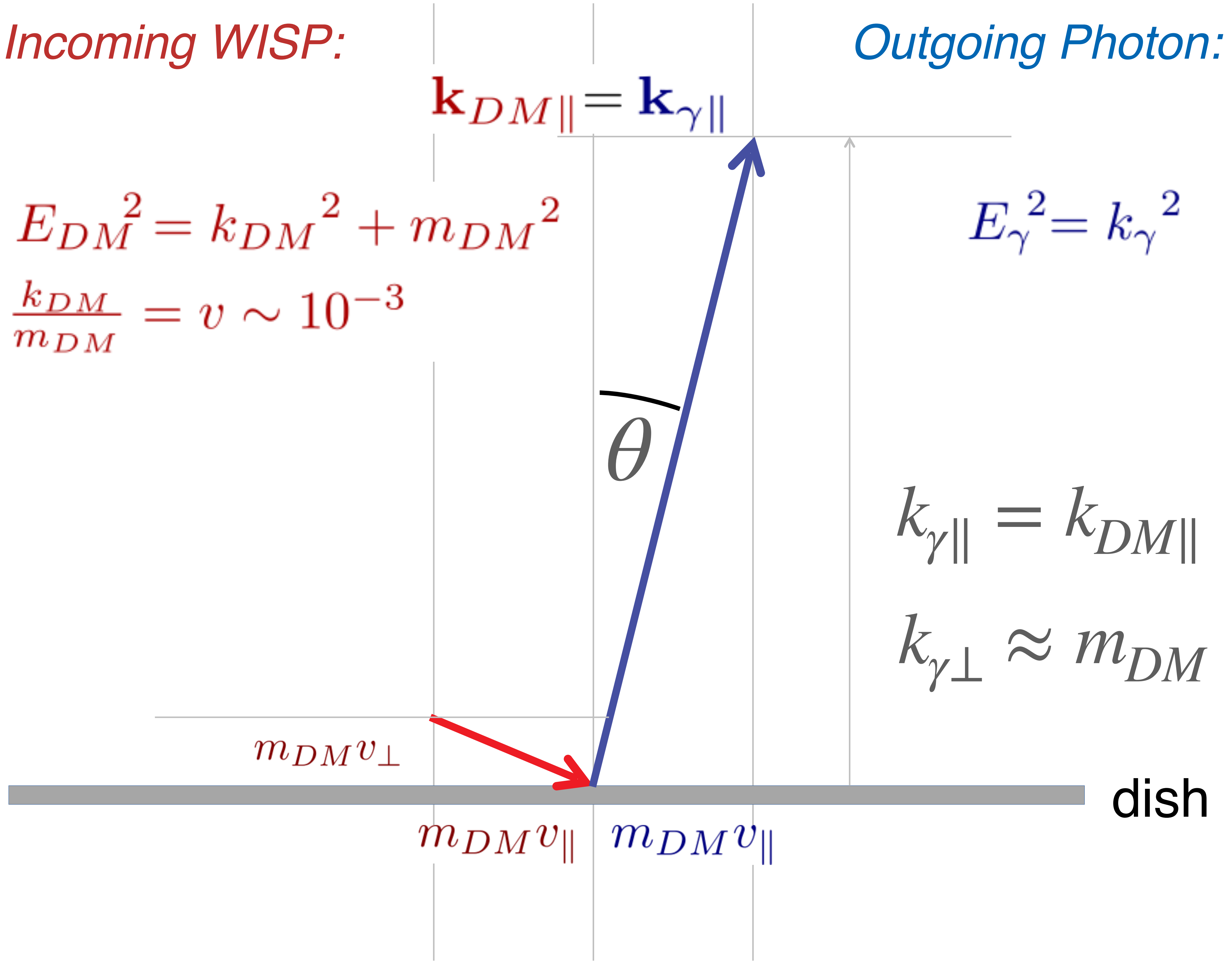
Photon Count Rate & Dark Count Rate

- Internal detection efficiency saturated for both 635 and 1060 nm
- Saturation occurs at a lower bias current for higher photon energy



Velocity Effect

For Dish Antenna:

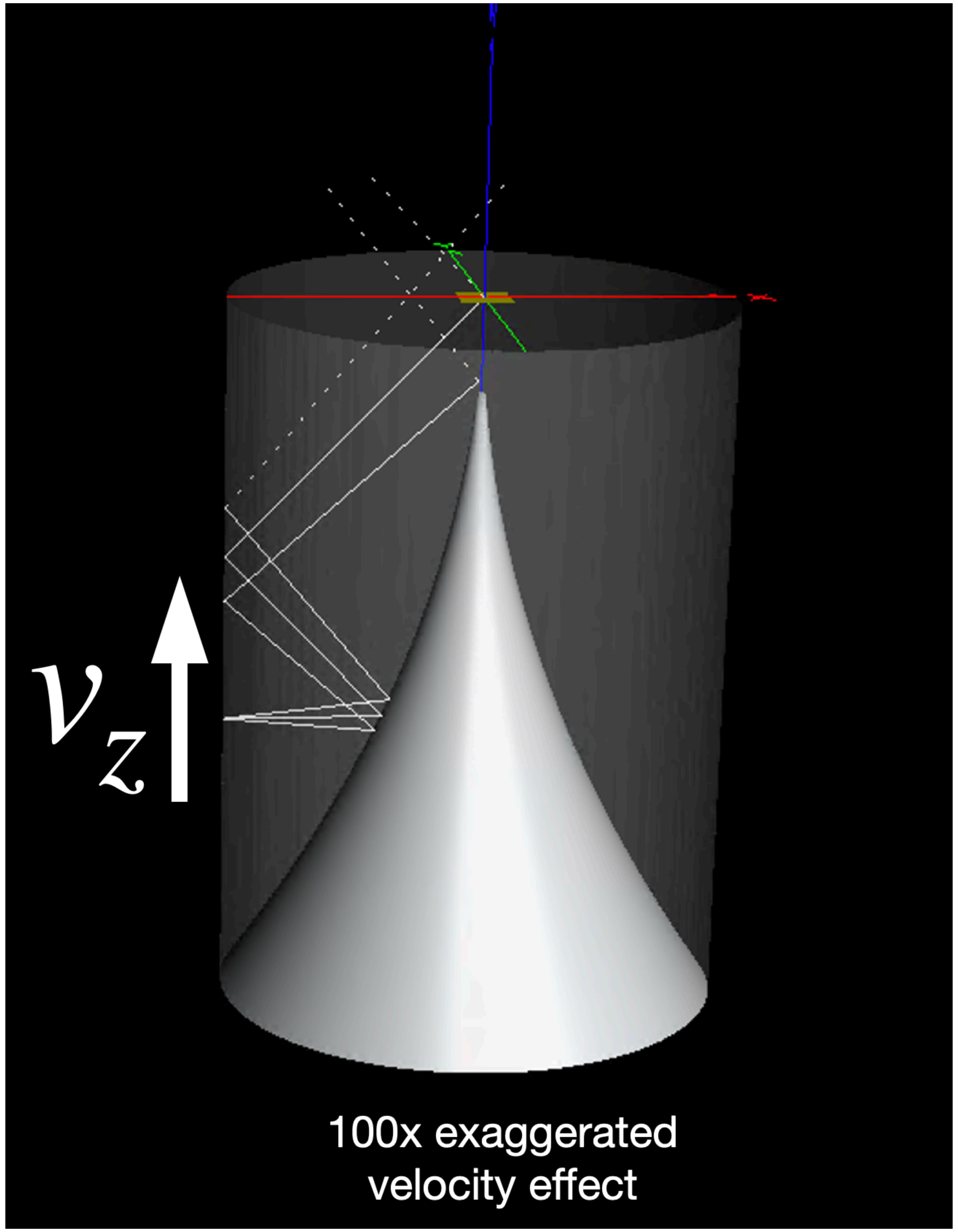


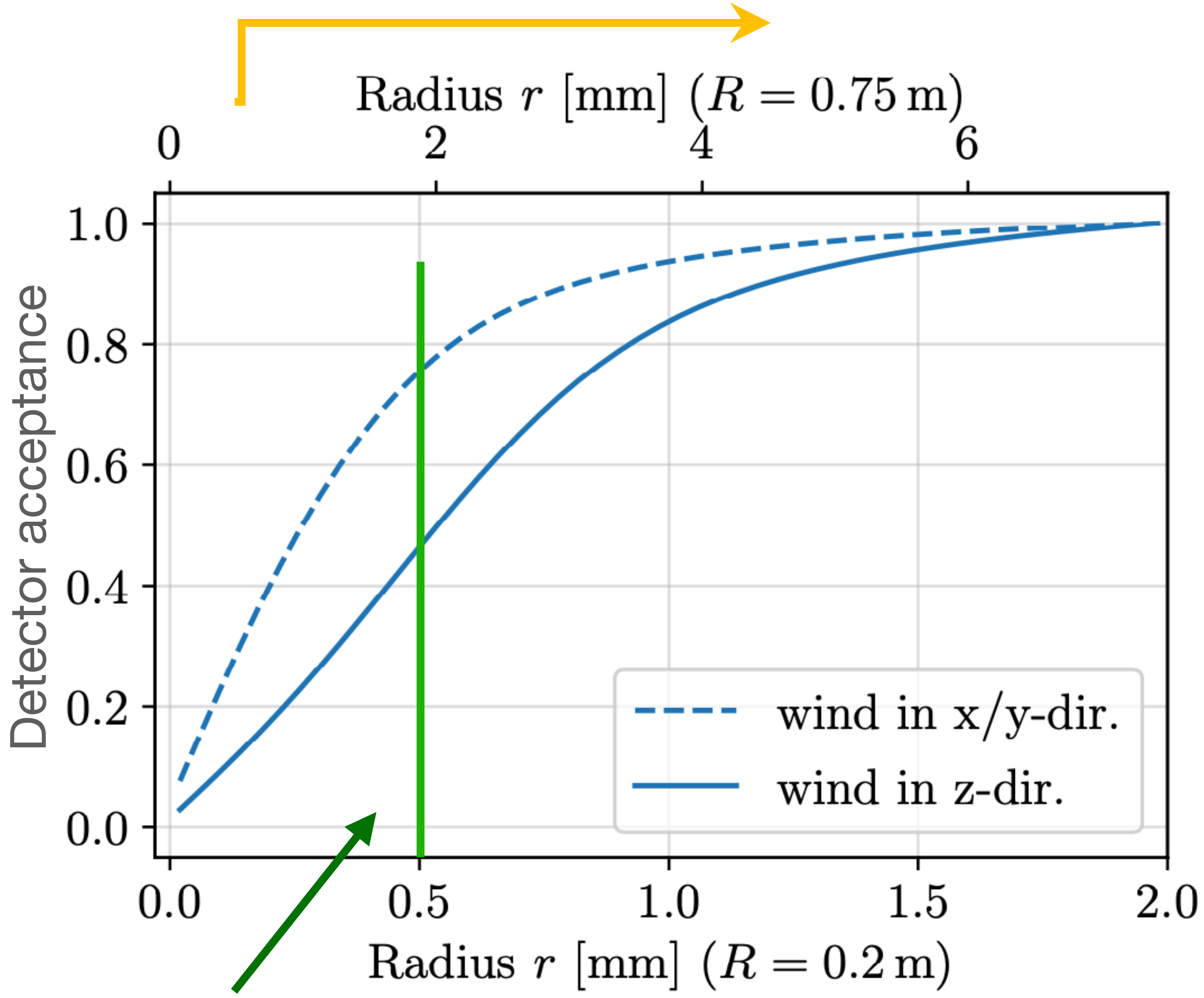
By requiring $E_\| = 0$ and energy conservation, photon wave vector can be calculated

→ outgoing angle $\theta \approx v \sim 10^{-3}$

[Jaeckel, Redondo arXiv:1307.7181]

InfraBREAD: Velocity Effects





1mm² SNSPD captures 45-75% of signal

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:

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

$$\left\{\begin{matrix}\left(\frac{g_{a\gamma\gamma}}{10^{-12}}\right)^2 \\ \left(\frac{\kappa}{10^{-15}}\right)^2\end{matrix}\right\} = \left\{\begin{matrix}\frac{3.0}{\mathrm{GeV}^2}\left(\frac{m_a}{\mathrm{meV}}\right)^3\left(\frac{10\,\mathrm{T}}{B_{\mathrm{ext}}}\right)^2 \\ 11.9\frac{2/3}{\alpha_{\mathrm{pol}}^2}\frac{m_{A'}}{\mathrm{meV}}\end{matrix}\right\}\left(\frac{\mathrm{hour}}{\Delta t}\right)^{1/2} \times \frac{10\,\mathrm{m}^2}{A_{\mathrm{dish}}}\frac{Z}{5}\frac{0.5}{\epsilon_s}\left(\frac{\mathrm{DCR}}{10^{-2}\,\mathrm{Hz}}\right)^{1/2}\frac{0.45\,\mathrm{GeV/cm^3}}{\rho_{\mathrm{DM}}}. \quad (11)$$

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)				
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{KSVZ}}\rvert$	—	280	9.0	0.90
$\lvert g_{a\gamma\gamma}/g_{a\gamma\gamma}^{\text{DFSZ}}\rvert$	—	740	23	2.3
$\kappa/10^{-14}$	8400	22	0.7	0.07

Thermal Photon Background