Nanowire Detection of Photons from the Dark Side

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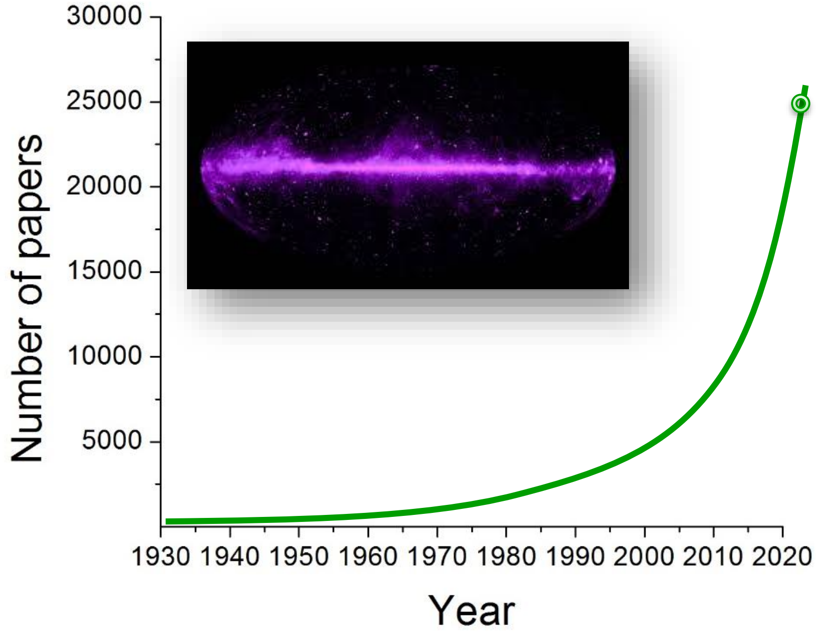
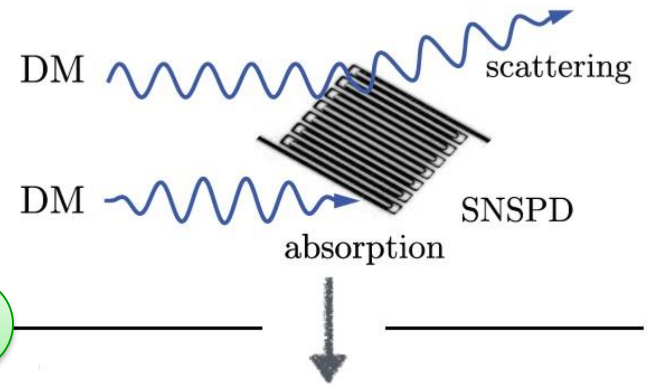
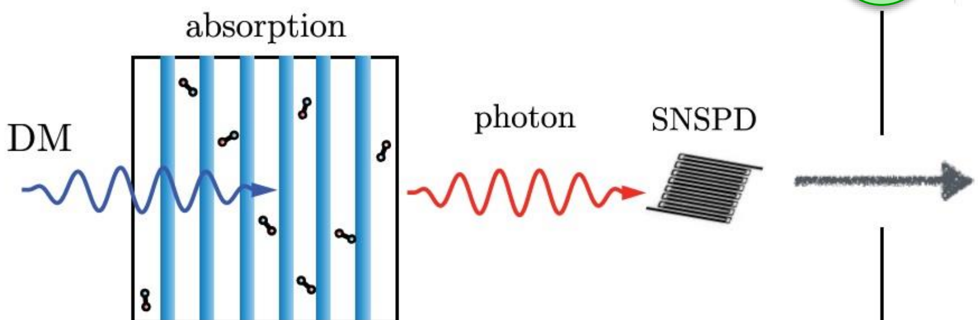
Dark-Matter Searching using superconducting nanowire

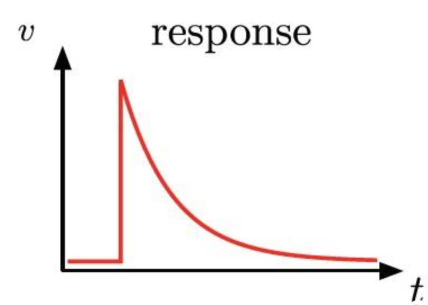
Mass ranging 10 meV – 10 eV



Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo and K. K. Berggren, "Detecting Dark Matter with Superconducting Nanowires," arXiv:1903.05101 [hep-ph], submitted to PRL





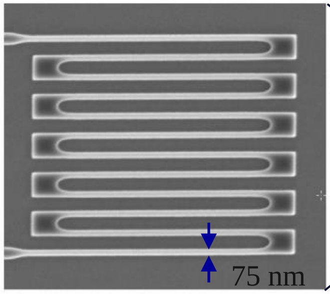


Masha Baryakhtar, Junwu Huang, Robert Lasenby, Phys.Rev. D98 (2018) no.3, 035006 (arXiv:1803.11455)

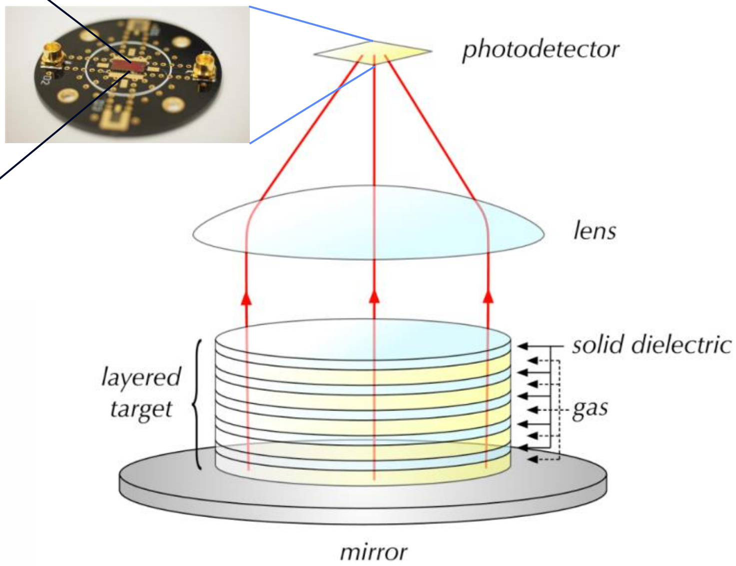
Dark-Matter Searching using superconducting nanowire

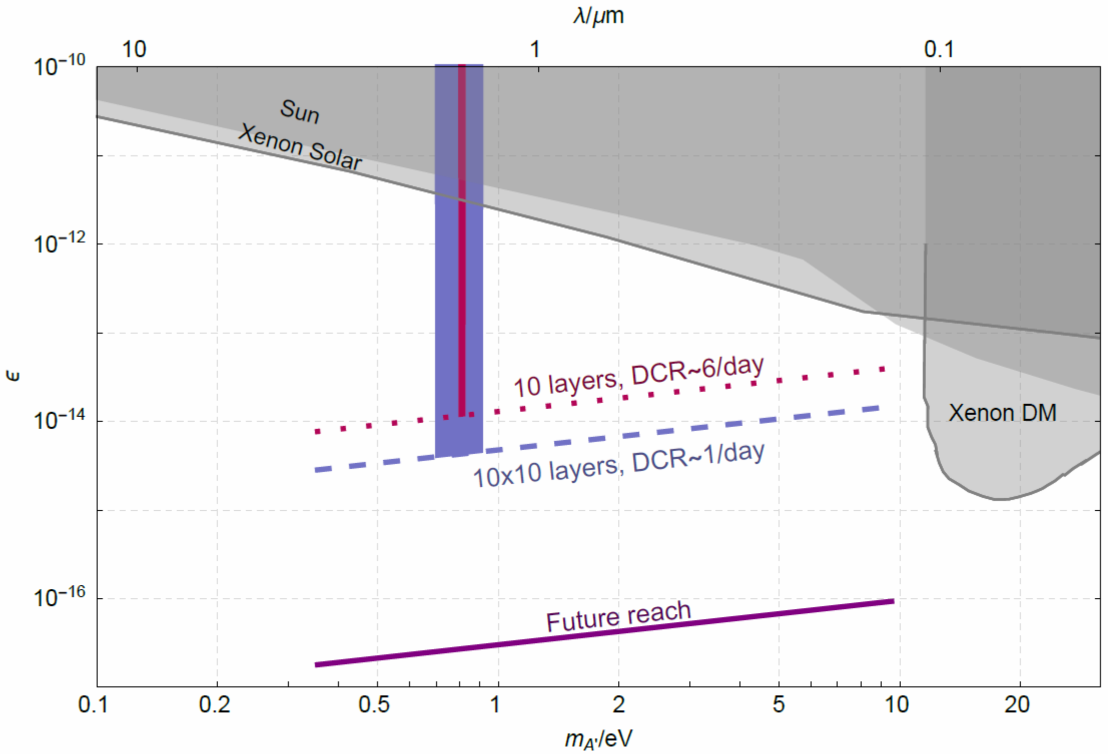
Collaboration of fundamental physics theorists, device designers, and system integrators and engineers:
(1) Use quantum interference of dark matte to build up population in a single-photon state;
(2) Use detector technology perfected for quantum-optics to sense photon.

superconducting detector



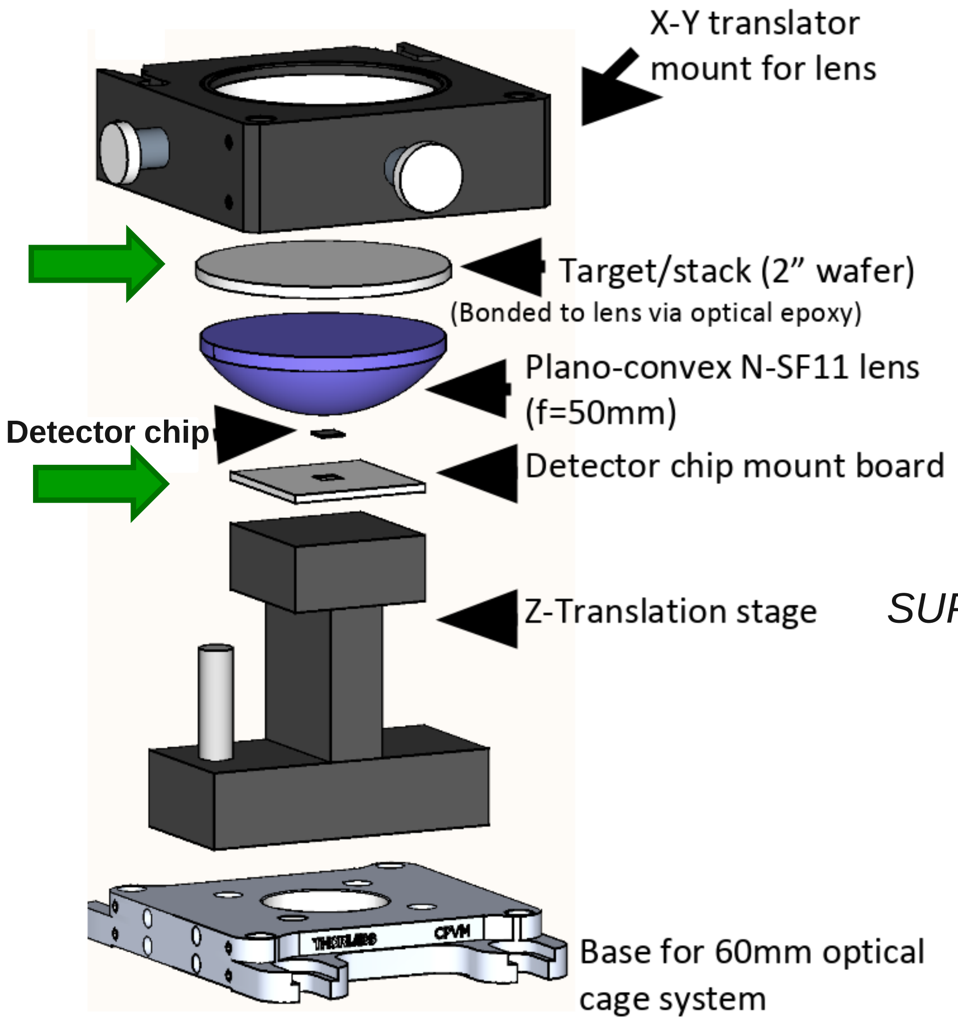
Dark-Matter Detector Concept



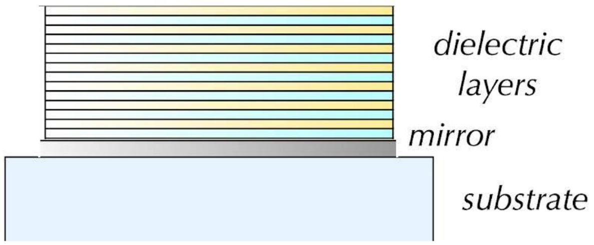


Key advantage of these detectors is low Dark Count Rate (DCR). Depending on number of layers in target, and achievable DCR, reach of experiment could extend well beyond what is possible today

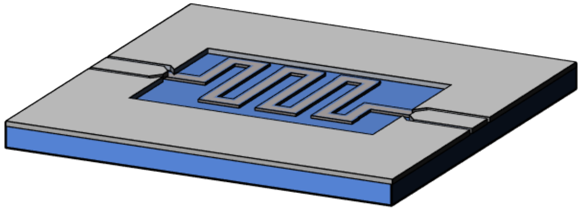
Multilayer optical haloscope



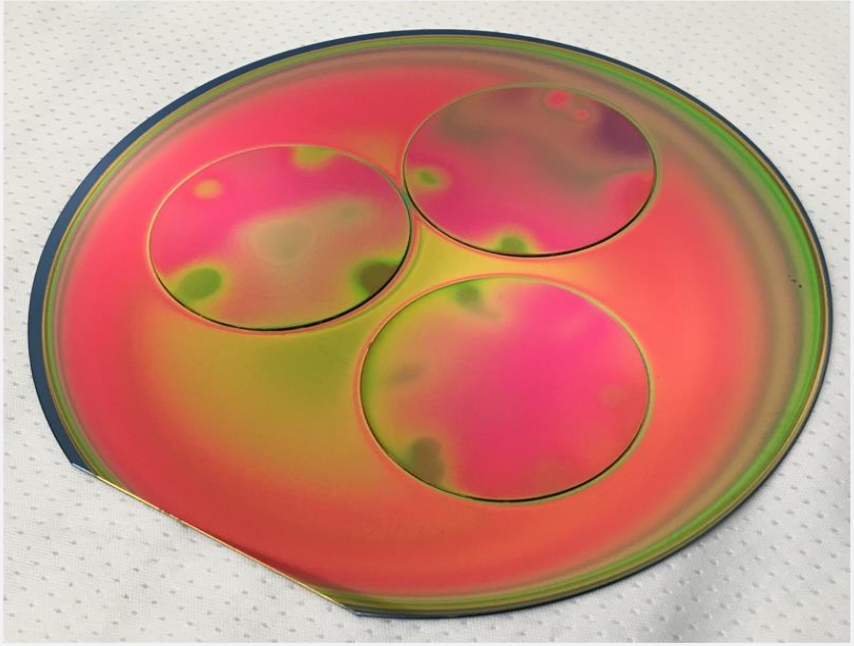
MULTILAYER OPTICAL TARGET



SUPERCONDUCTING NANOWIRE SINGLE-PHOTON DETECTOR (SNSPD)

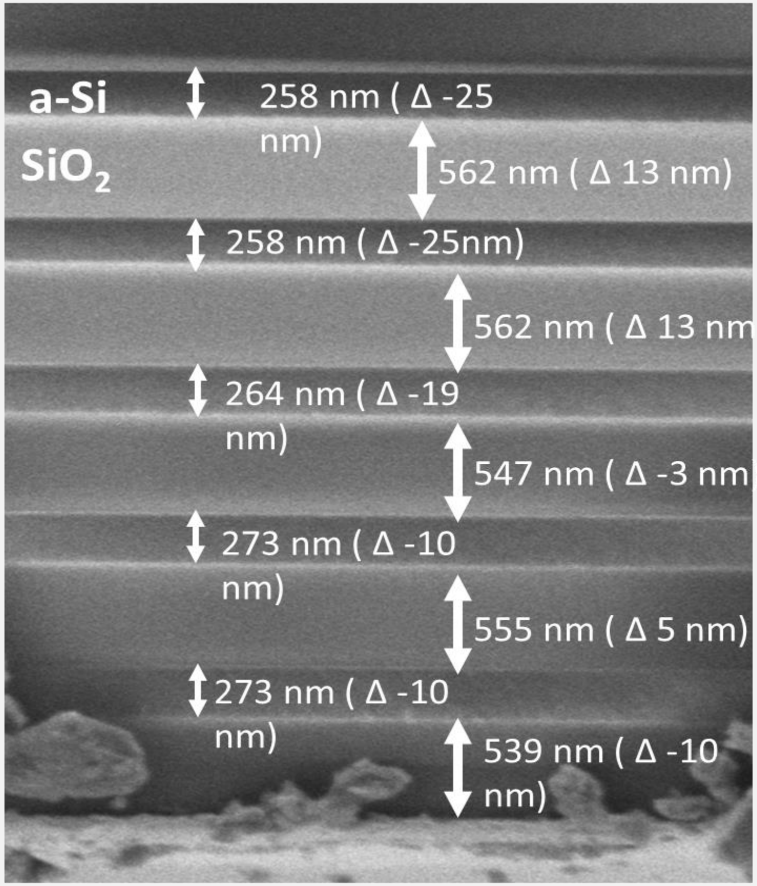


Multilayer optical target

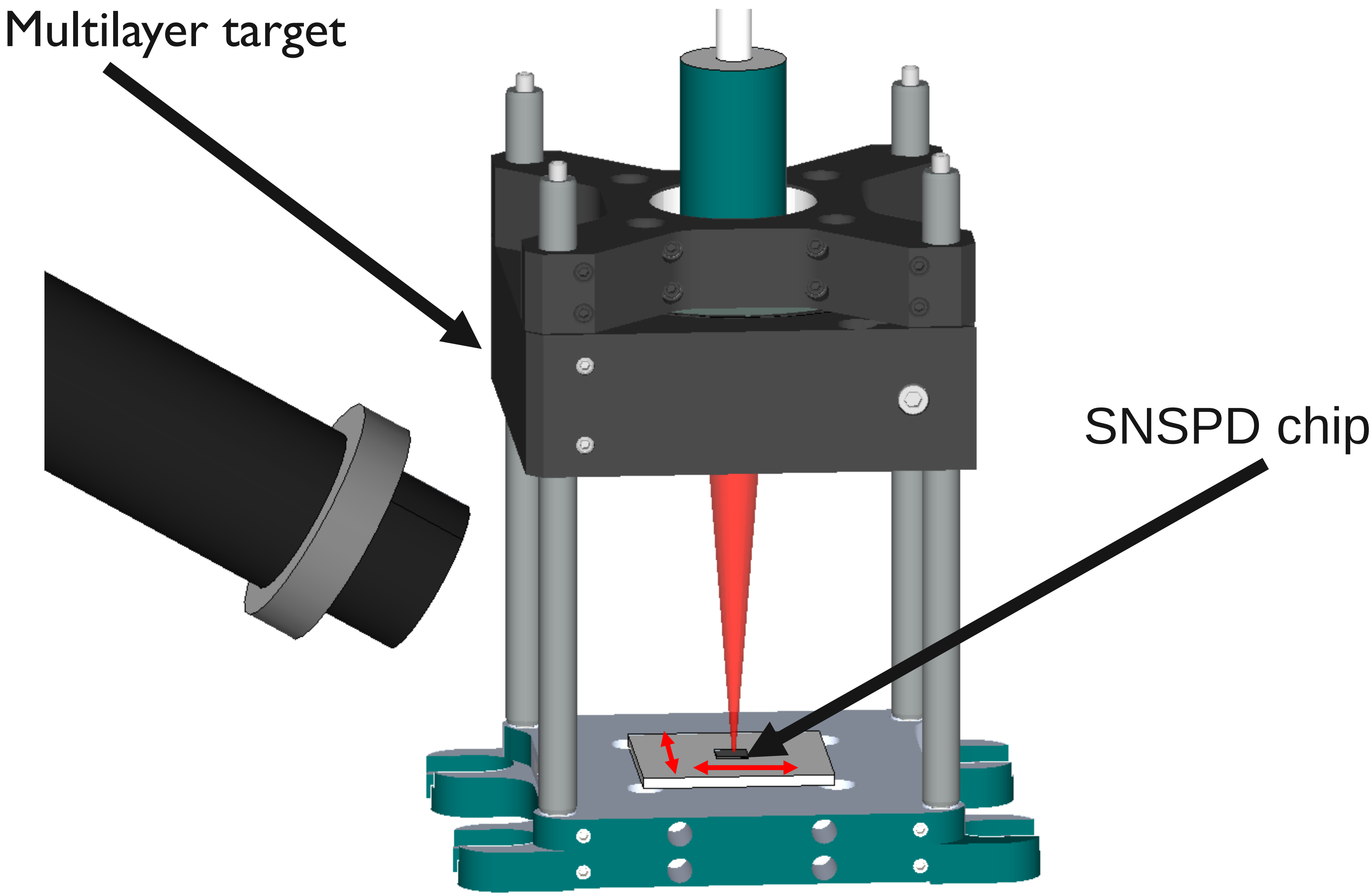


- Confirms blueshift due to reduced layer thicknesses (mainly a-Si)
- Thermal or electrical effects of mounted samples vs. wafers

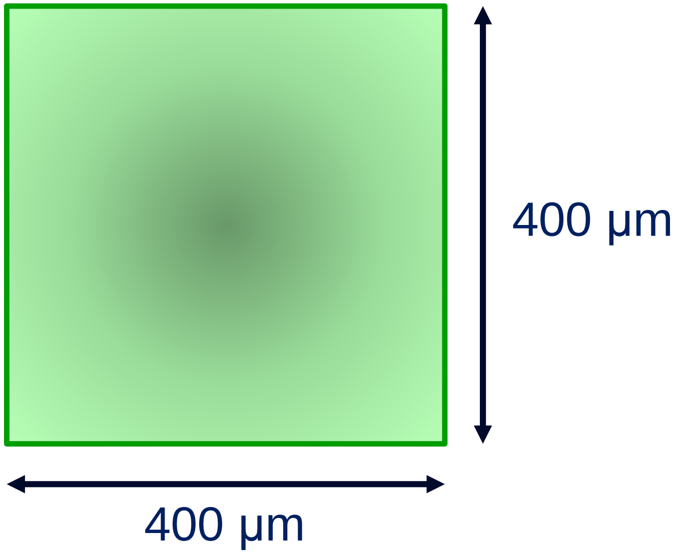
SEM inspection



Why do we need large-area SNSPD?



Fabrication of large area SNSPD

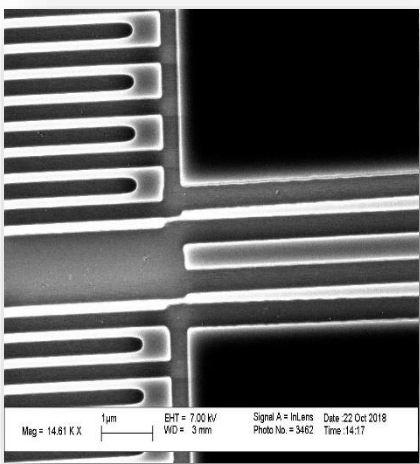


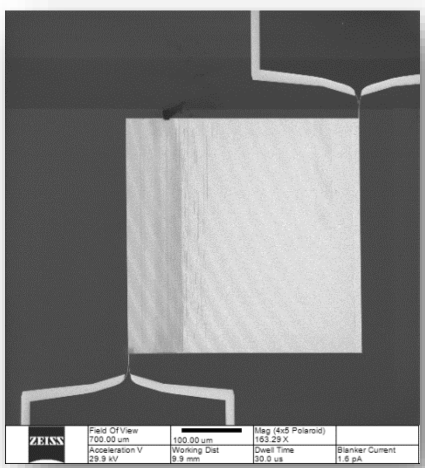
High probability of defects

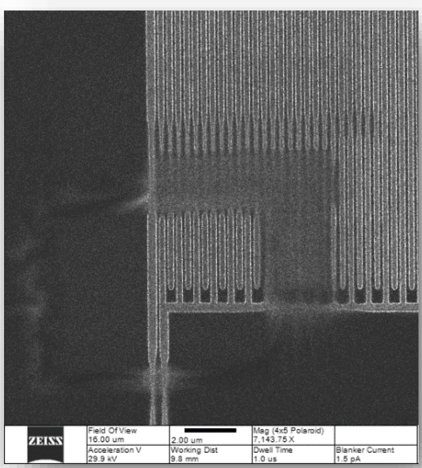
- Cross-section variations: non-uniformity of the thickness or width of the film
- Nanowire edge defects or internal structural defects
- Current-crowding

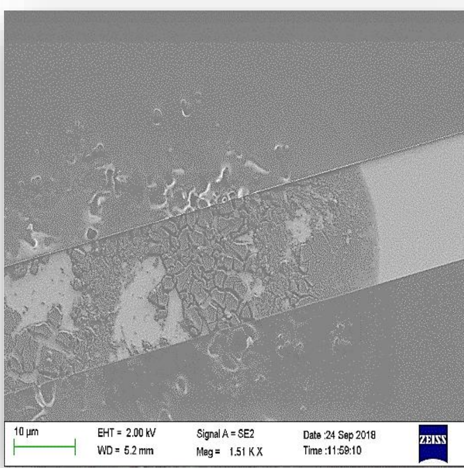
Requirements

- Long-term stability of electron-beam parameters and long-term suppression of external acoustic, mechanic, and electro-magnetic interferences
- Uniformity of resist

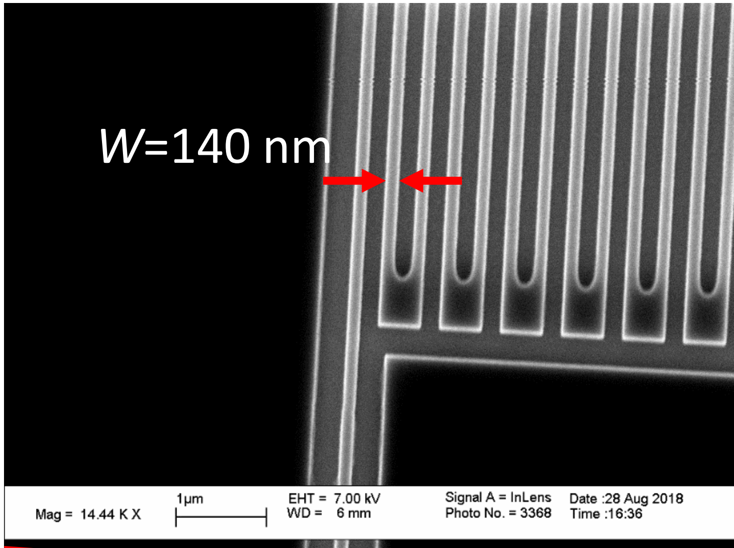


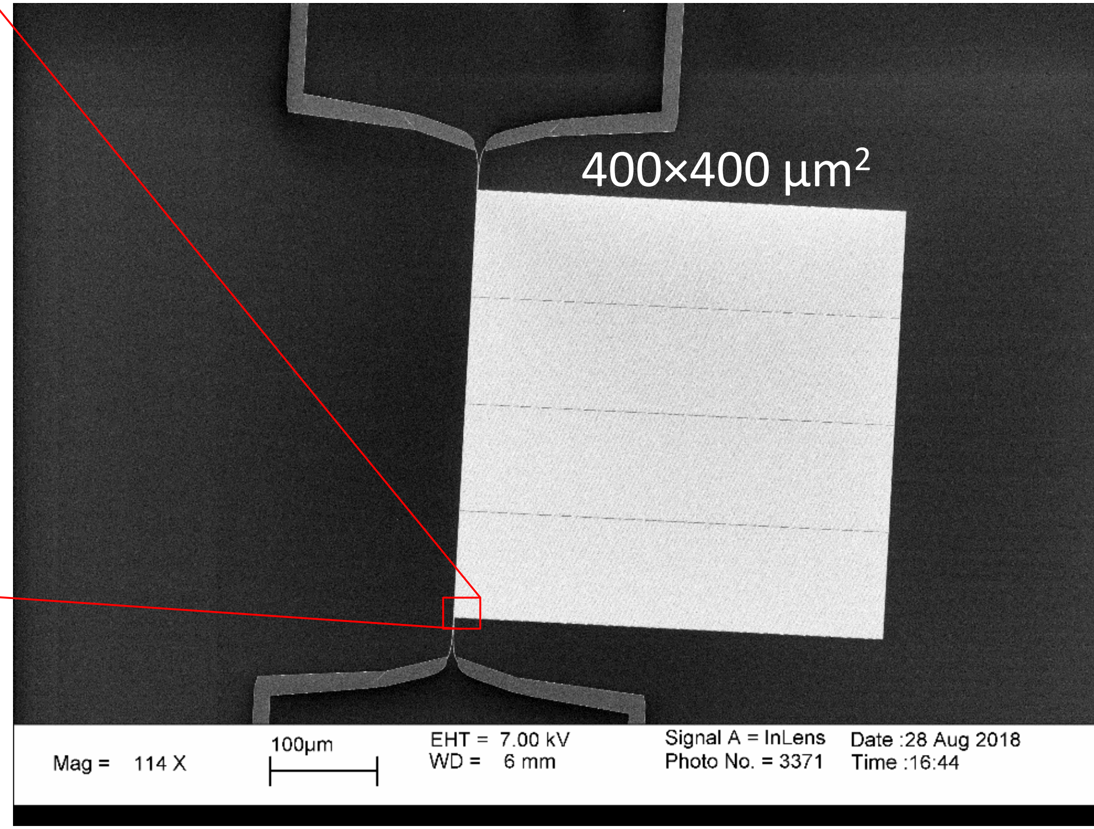


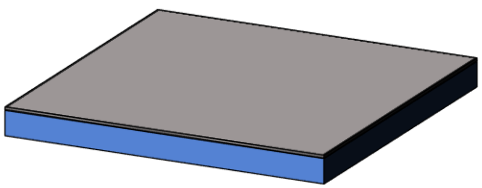




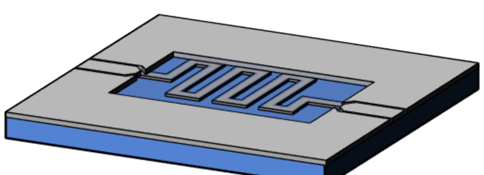
Superconducting nanowires





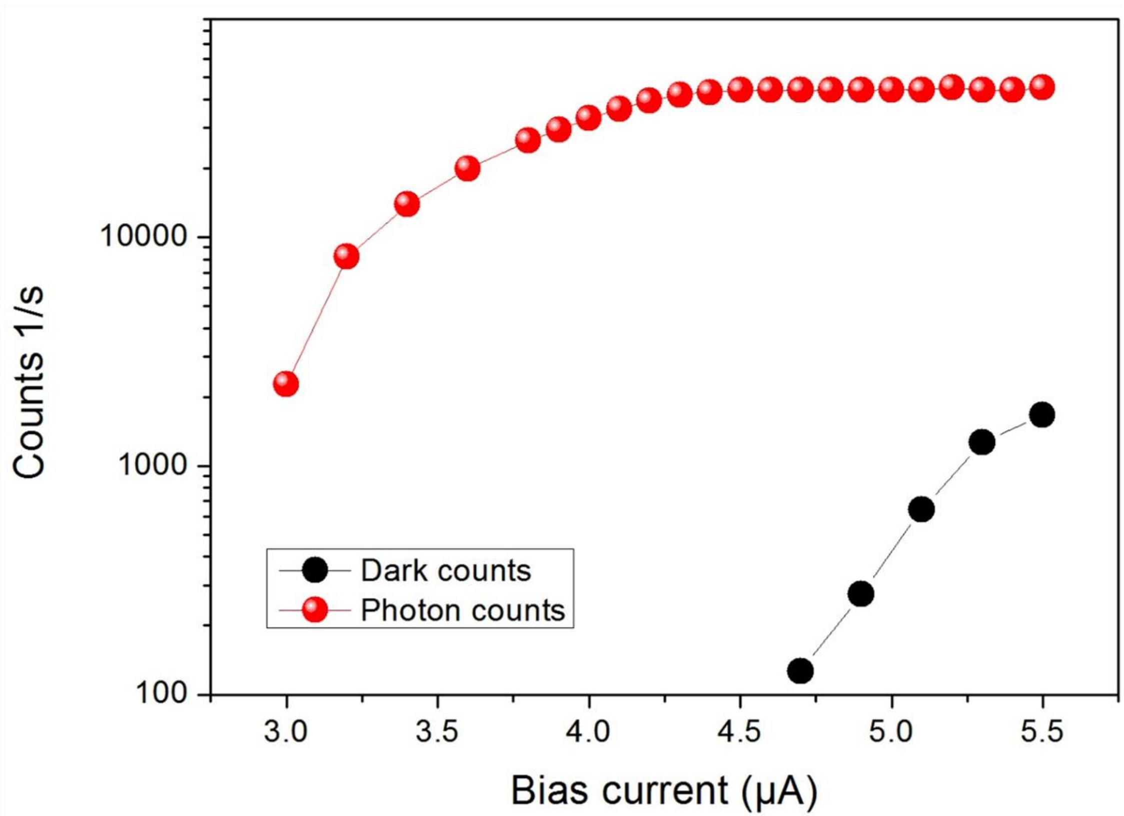


Deposition of 7 nm WSi film on silicon oxide substrate



Pattern WSi nanowires using e-beam lithography and reactive ion etching

Optical response



Critical current	**5.5 μA**
Bath temperature	**300 mK**
Wavelength	**1550 nm**

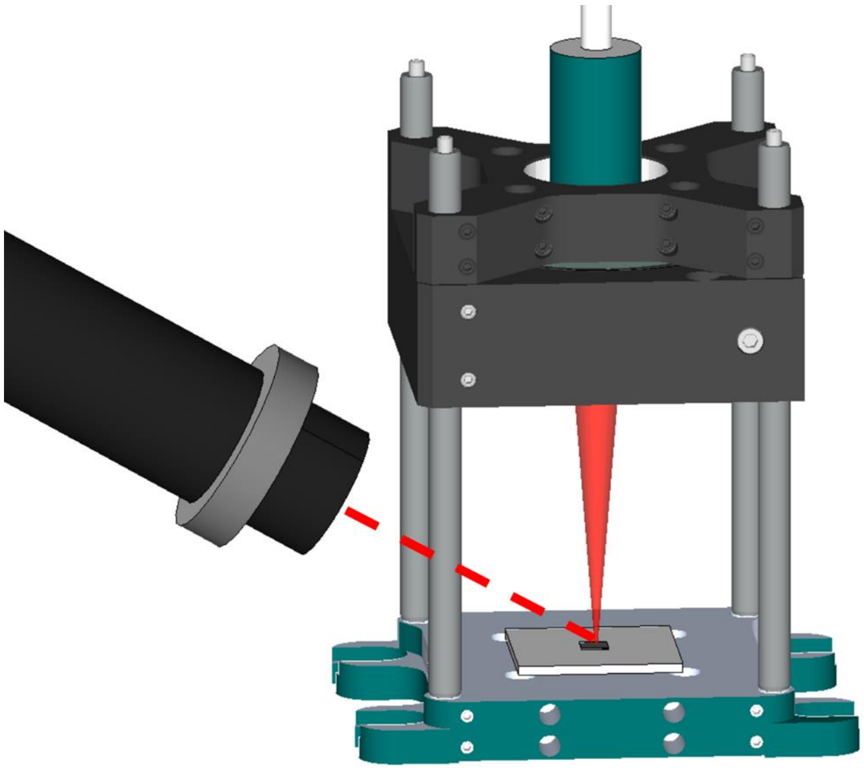
Preliminary testing of WSi *prototype device* in a fiber-coupled package

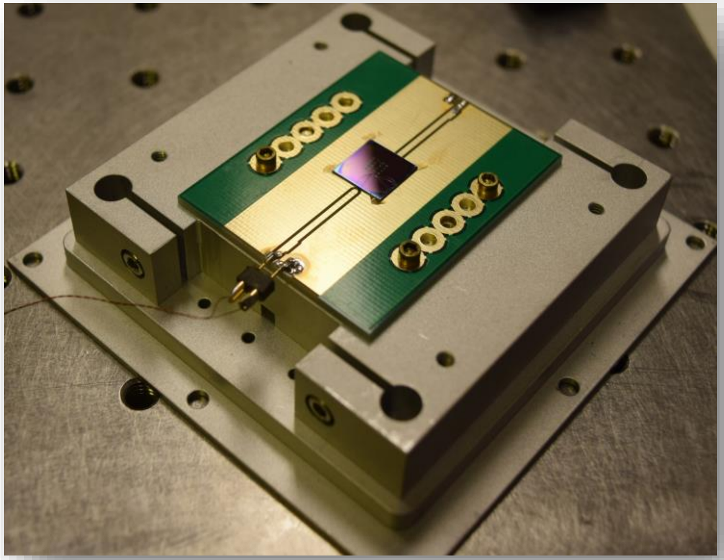
Dark count events due to:

- Current crowding
- Blackbody photons

Quick recap of optomech assembly

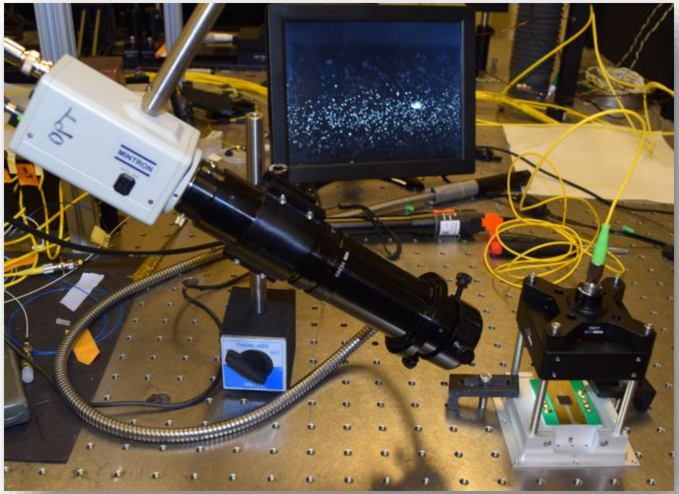
- Target: multilayer stack on SiO2 substrate
- Bonded to glass lens / self aligned
- Alignment of target -> detector confirmed by collinear laser light imaged off-axis



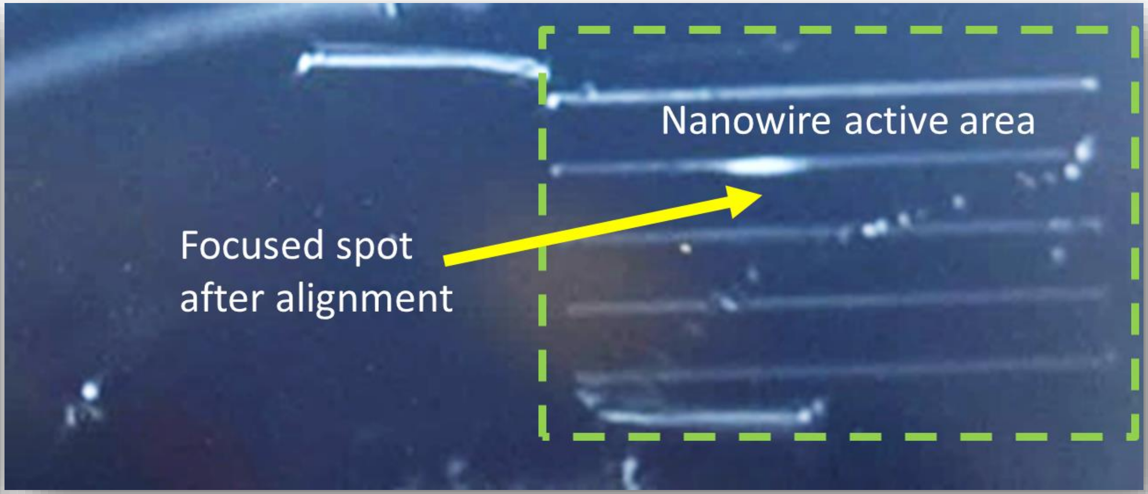


Quick recap of optomech assembly

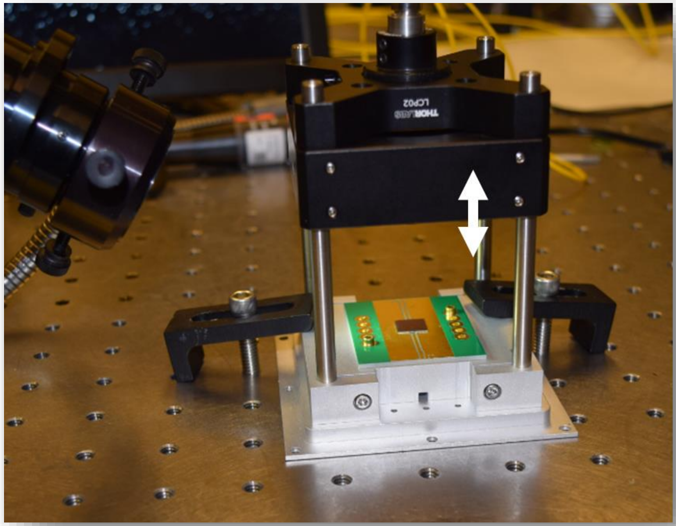
1. Build optical alignment setup

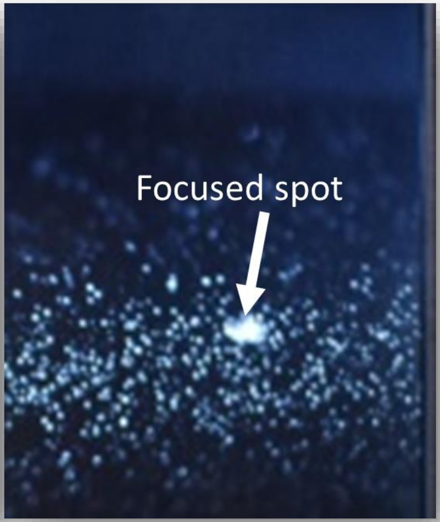


3. Align/mount detector to optical axis

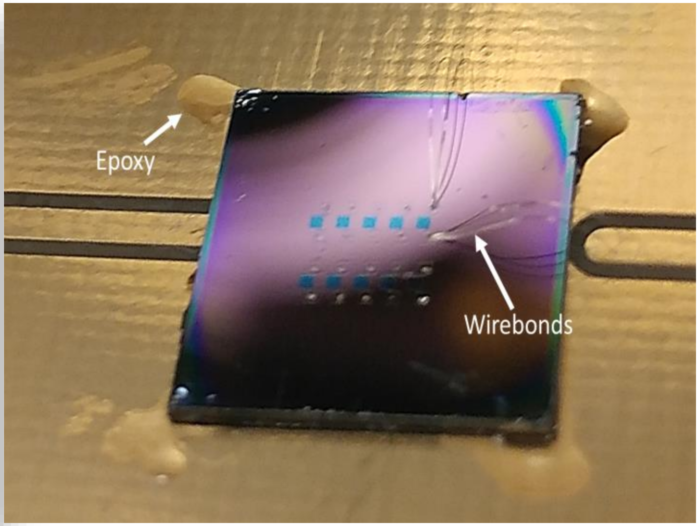


2. Fix focal distance

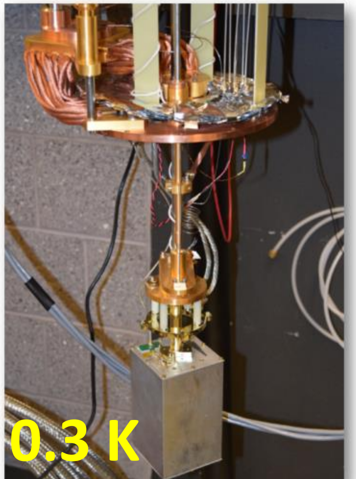


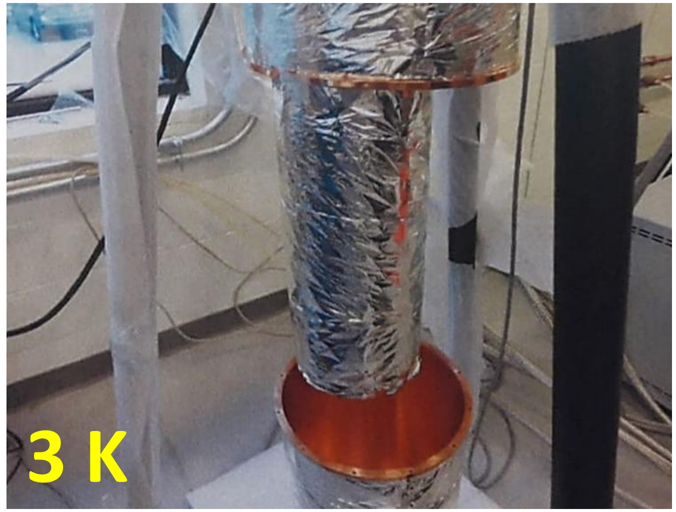


4. Wire-bond chip to electrical breakout

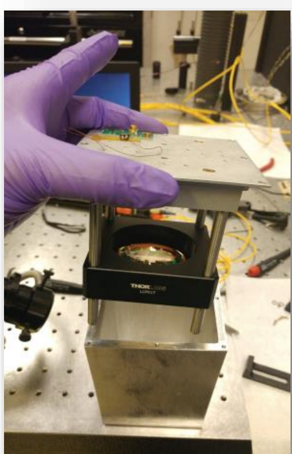


Dark-count experiment with optical haloscope





Assembled haloscope with device prototype

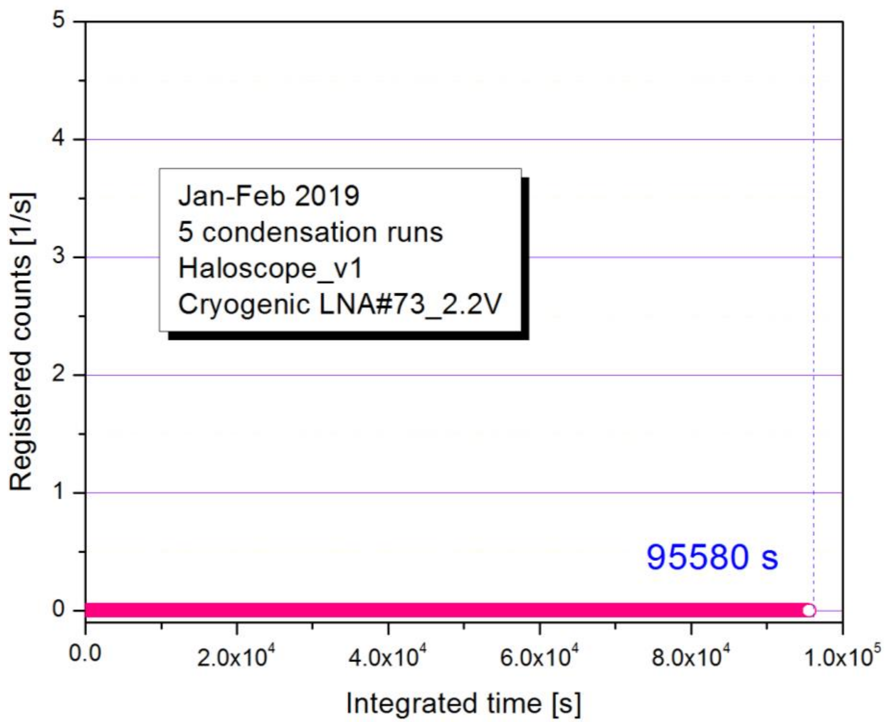


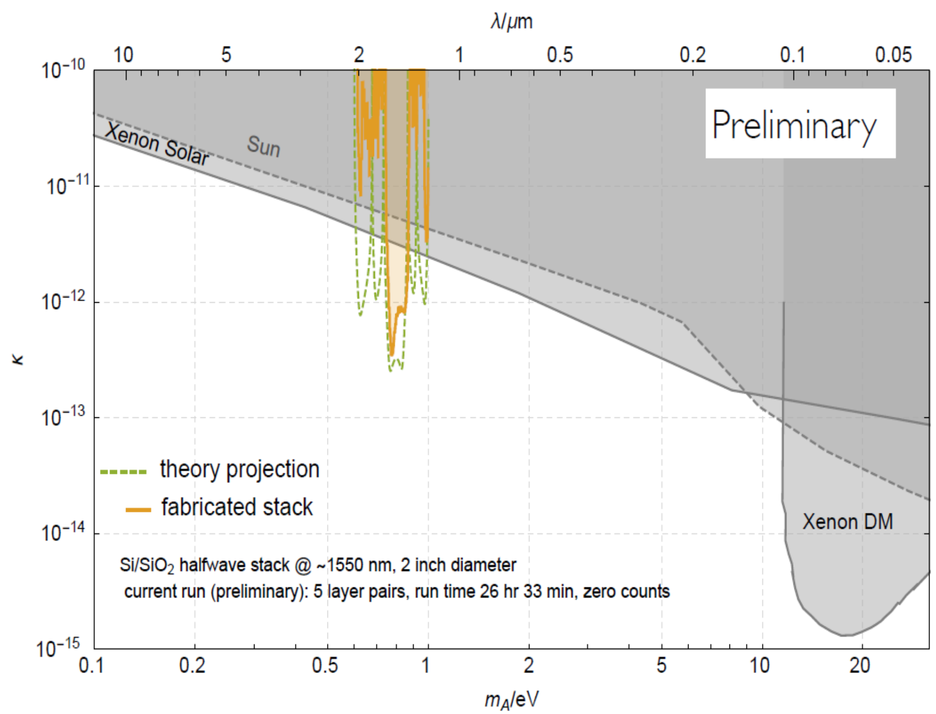
Optical fiber connection removed

Multi-layer superinsulation (apr. 100 layers in total) on 3 K and 40 K <u>radiation shields</u>

Dark-count experiment with optical haloscope

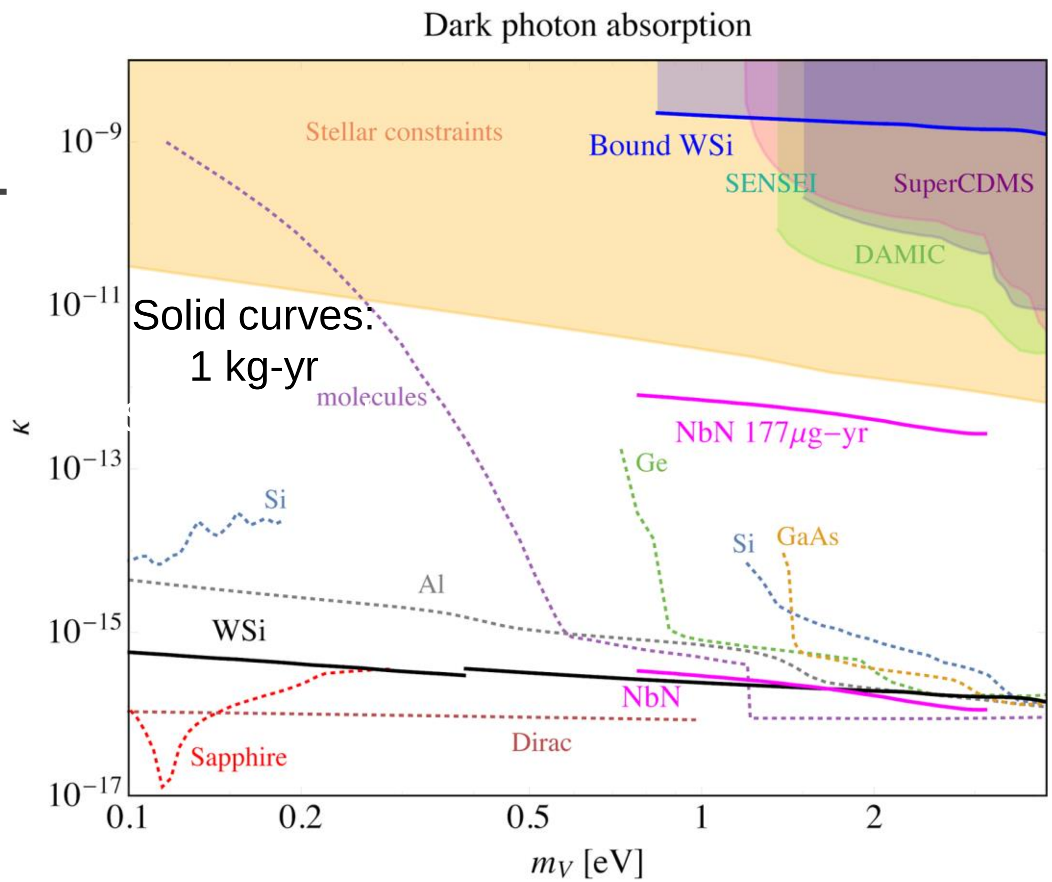
PRELIMINARY EXPERIMENTAL RESULTS



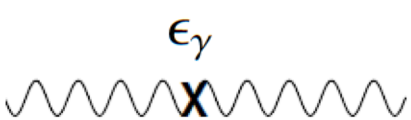


Dark-count experiment with SNSPD

SNSPDs as target + sensor

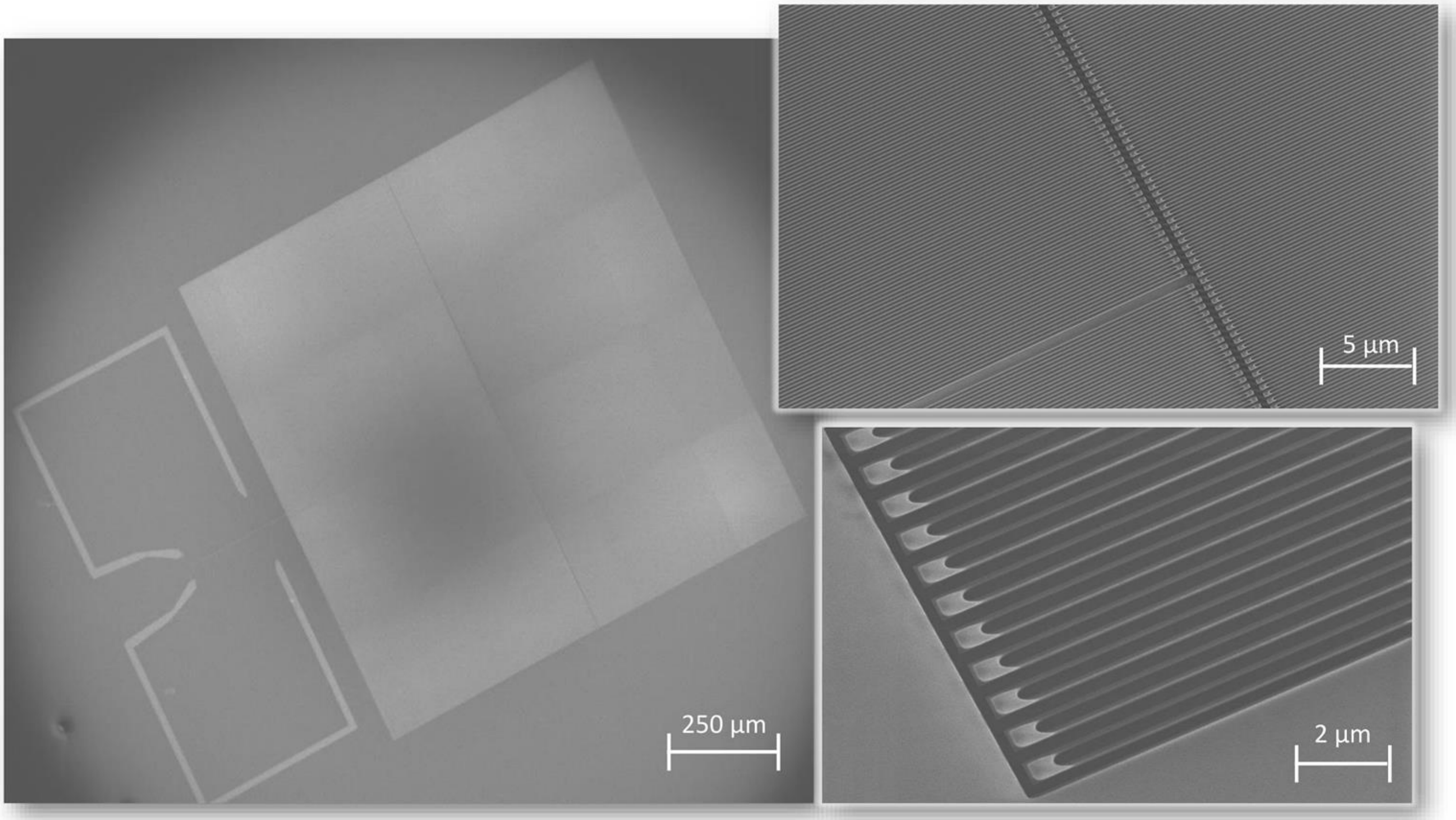


Absorption of kinetically mixed dark photon

dark photon  **photon**

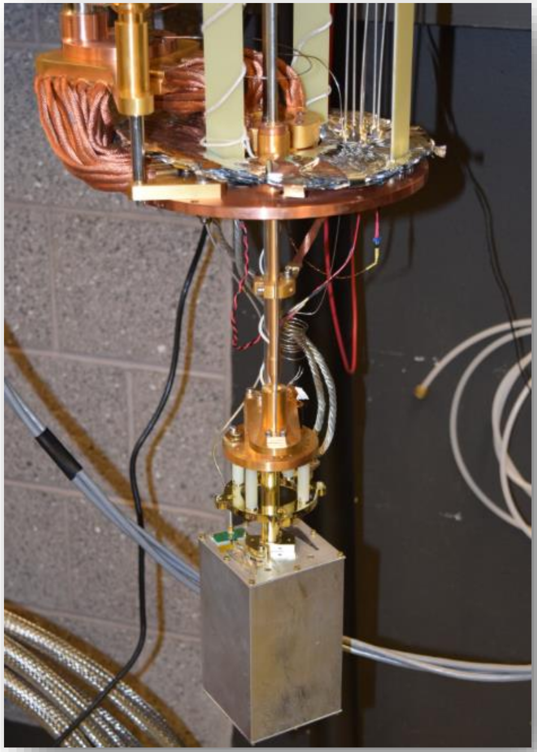
Dark-count experiment with SNSPD

SNSPDs as target + sensor



Conclusions

- Dark matter detection with multilayer optical haloscopes and SNSPD
- Superconducting nanowire detectors
  - 400x400 um^2 area
  - No dark counts in > 90 000 seconds
- Multilayer optical target
  - 1 dB optical loss
- Optomechanical assembly
  - Self-aligned optical axis, minimal positioning of detector chip required
- First experimental run
  - Collecting data



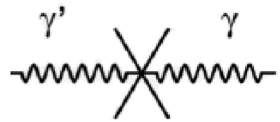
Appendix

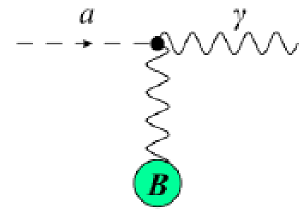
Early indications:

- Stars moving near the galactic plane should be quickly enough to escape the gravitational pull of the luminous mass in galaxy;
- Measurement of the mass of the cluster using standard mass to luminosity ratios gave a total mass for the cluster approximately 2% of this value;
- Rotation curves extreme deviate from predictions due to Newtonian gravity and the luminous matter distribution;
- Gravitational lensing

Searching for light bosonic dark matter

- Photon can convert into axion (dark photon) and back through E . B (kinetic mixing) term



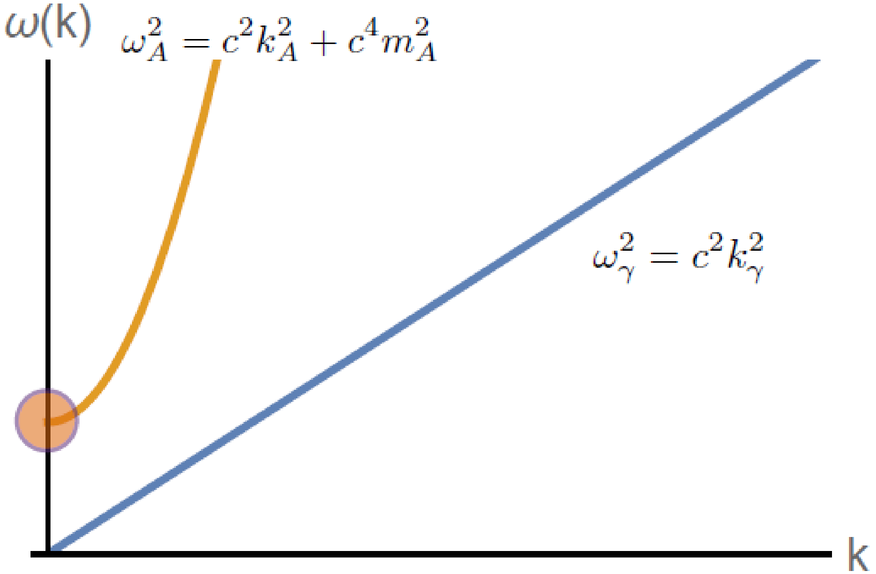


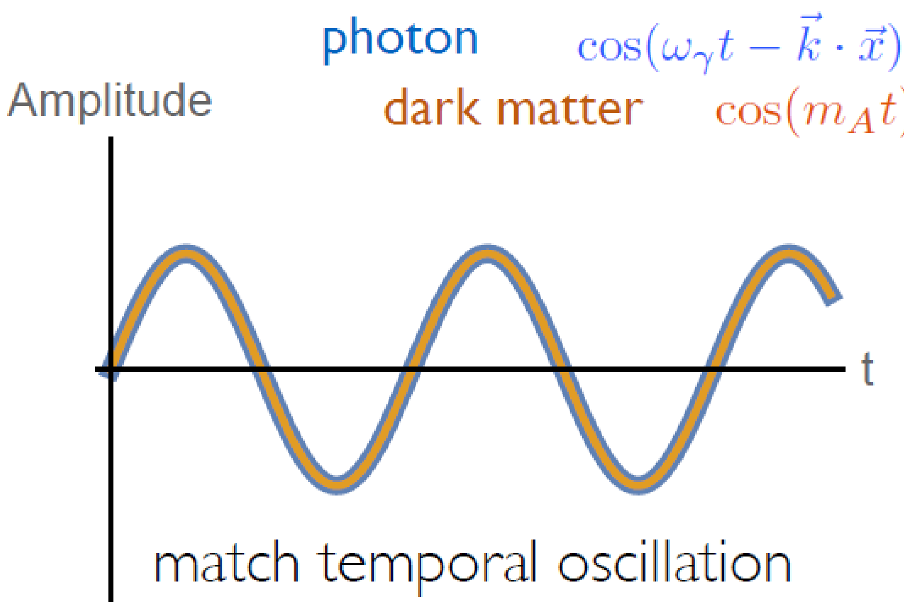
- Why haven't we seen photons from DM conversion?
  - Mismatch in dispersion relation: photons relativistic while dark matter is massive with a small velocity in our galaxy
  - Impossible to conserve both energy and momentum

$$\omega_A = \omega_\gamma \Rightarrow k_\gamma \sim 0$$ ✘

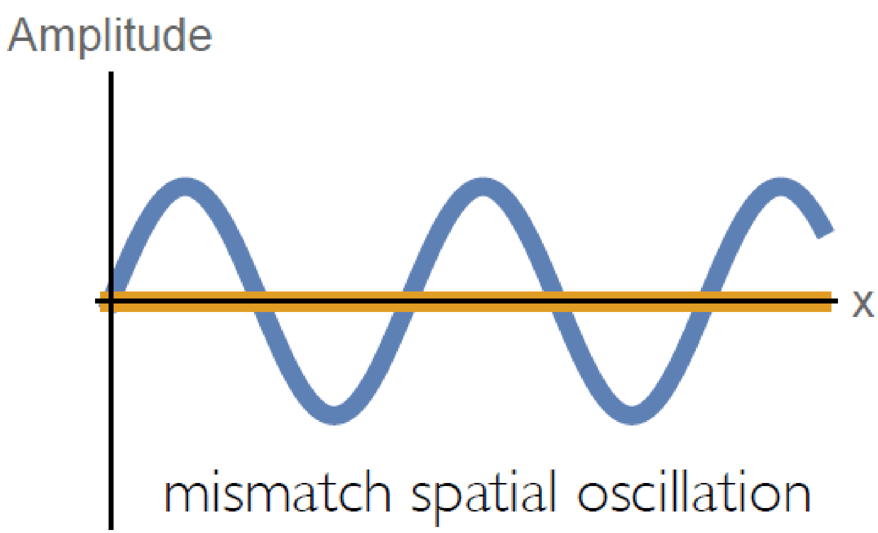
Masha Baryakhtar et al., Phys. Rev. D **98, 035006**

Light bosonic dark matter



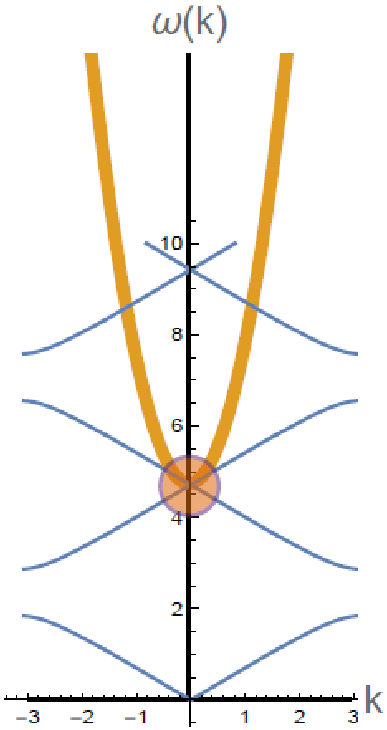


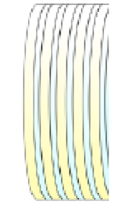
Mismatch in dispersion relation: photons relativistic while dark matter nonrelativistic with a small velocity in our galaxy



Masha Baryakhtar et al., Phys. Rev. D **98, 035006**

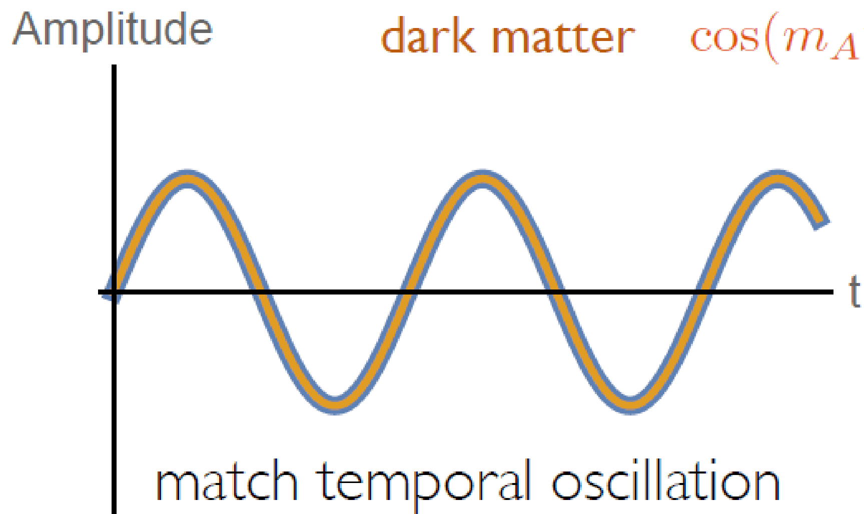
Light bosonic dark matter



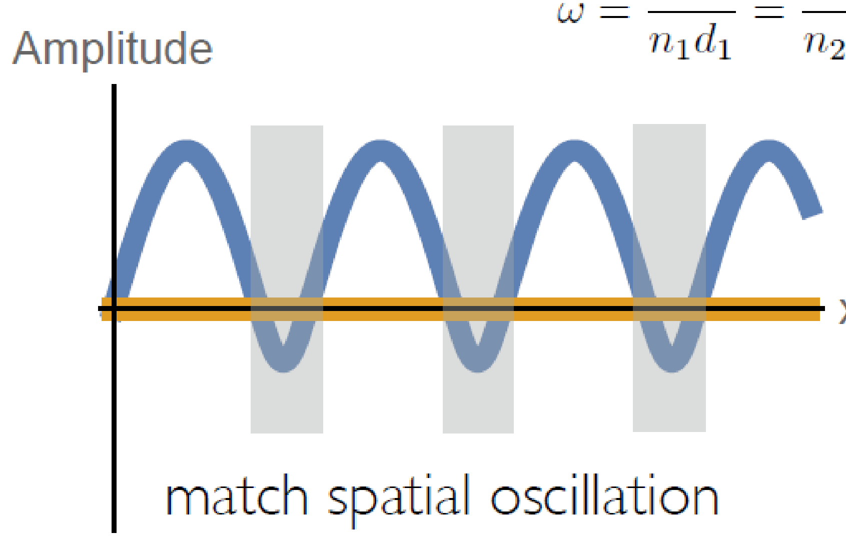


photon $\cos(\omega_\gamma t - k_n x)\eta_n(x)$

dark matter $\cos(m_A t)$

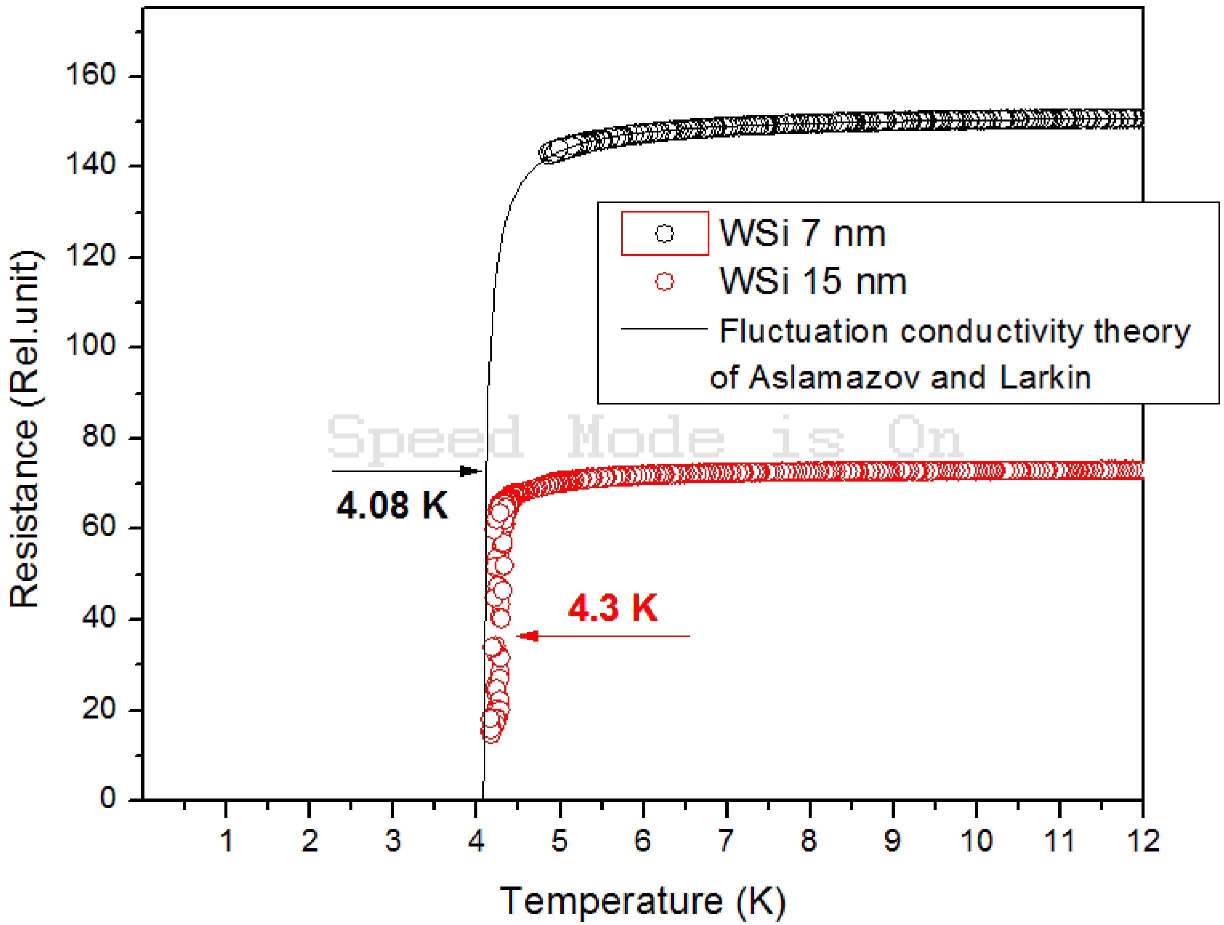


$$\omega = \frac{\pi}{n_1 d_1} = \frac{\pi}{n_2 d_2}$$

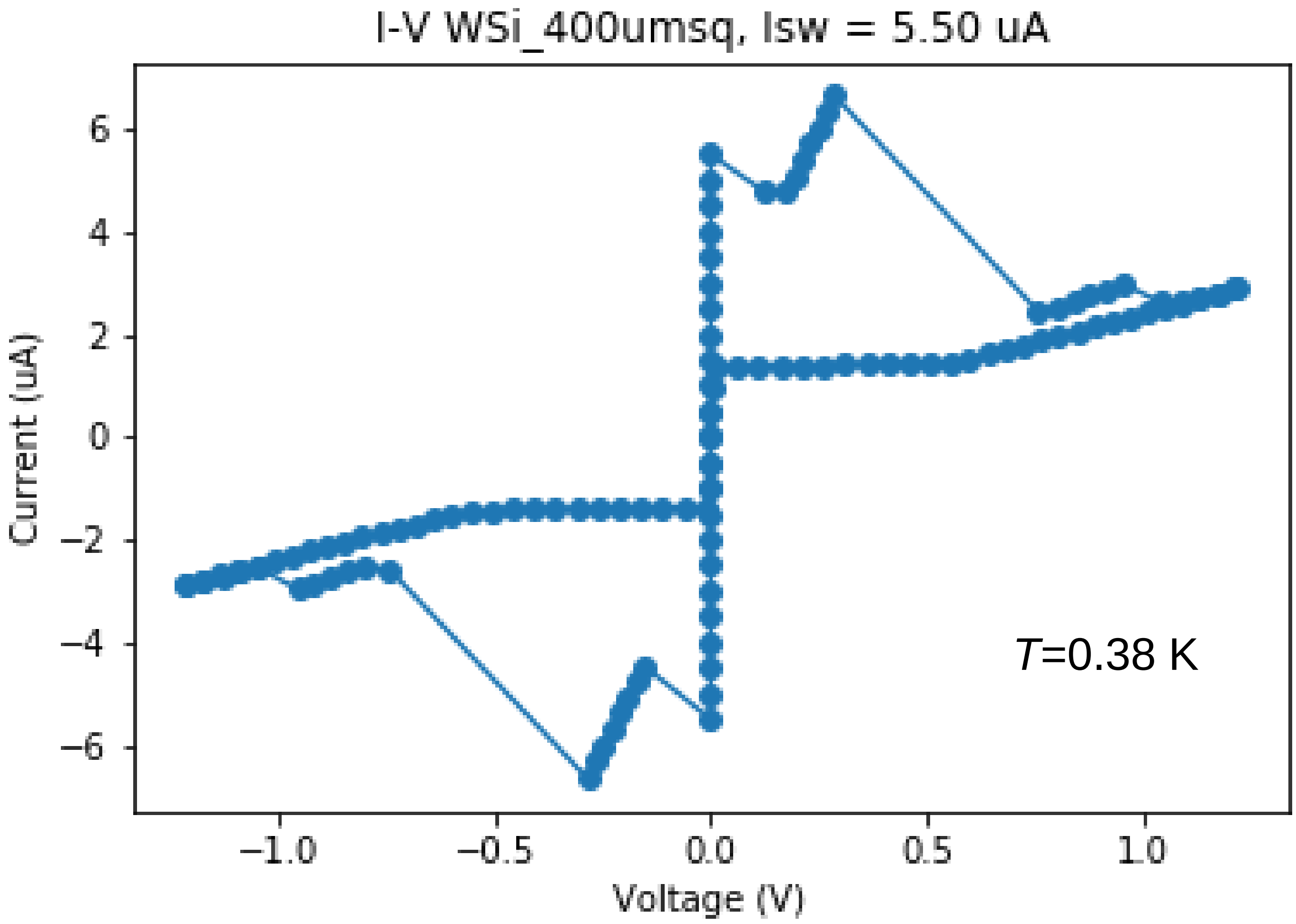


- Add periodicity in one dimension to correct momentum mismatch
- Periodic index of refraction changes free solutions of photon modes
- Nonzero spatial overlap with zero-momentum waves

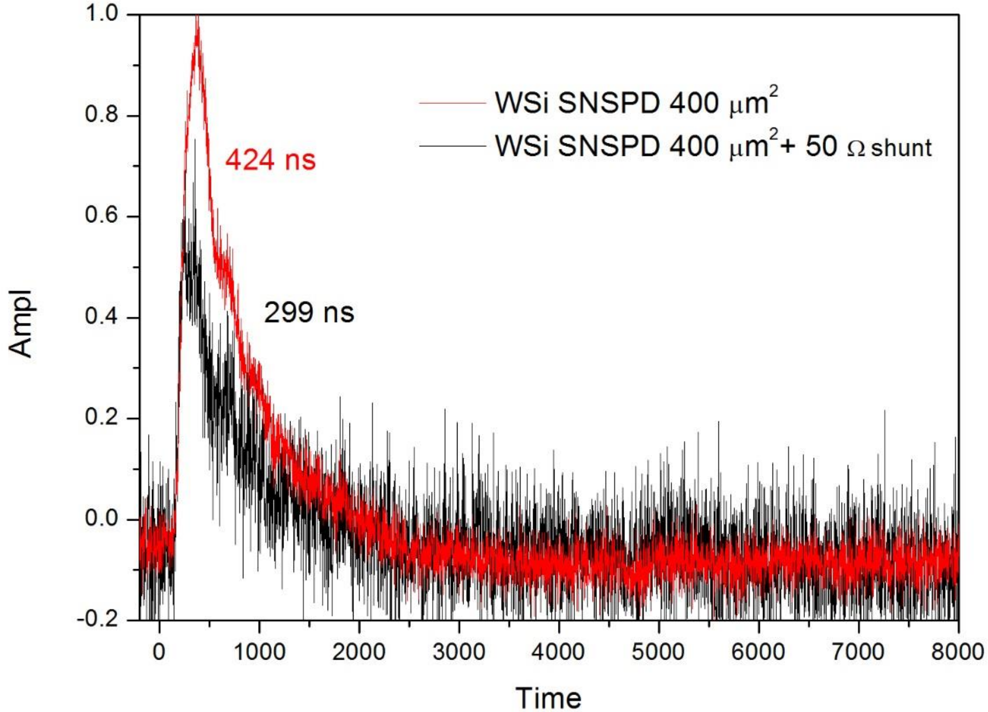
WSi films (provided by NIST)



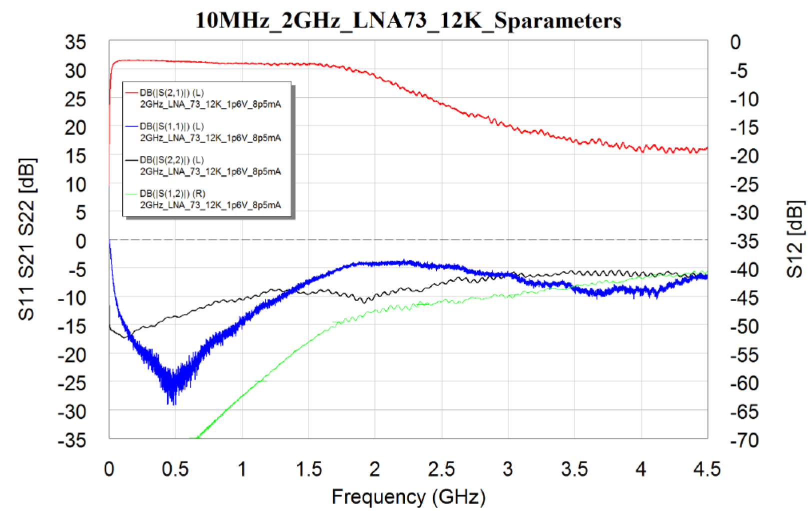
SNSPD 400*400 μm^2



Optical response

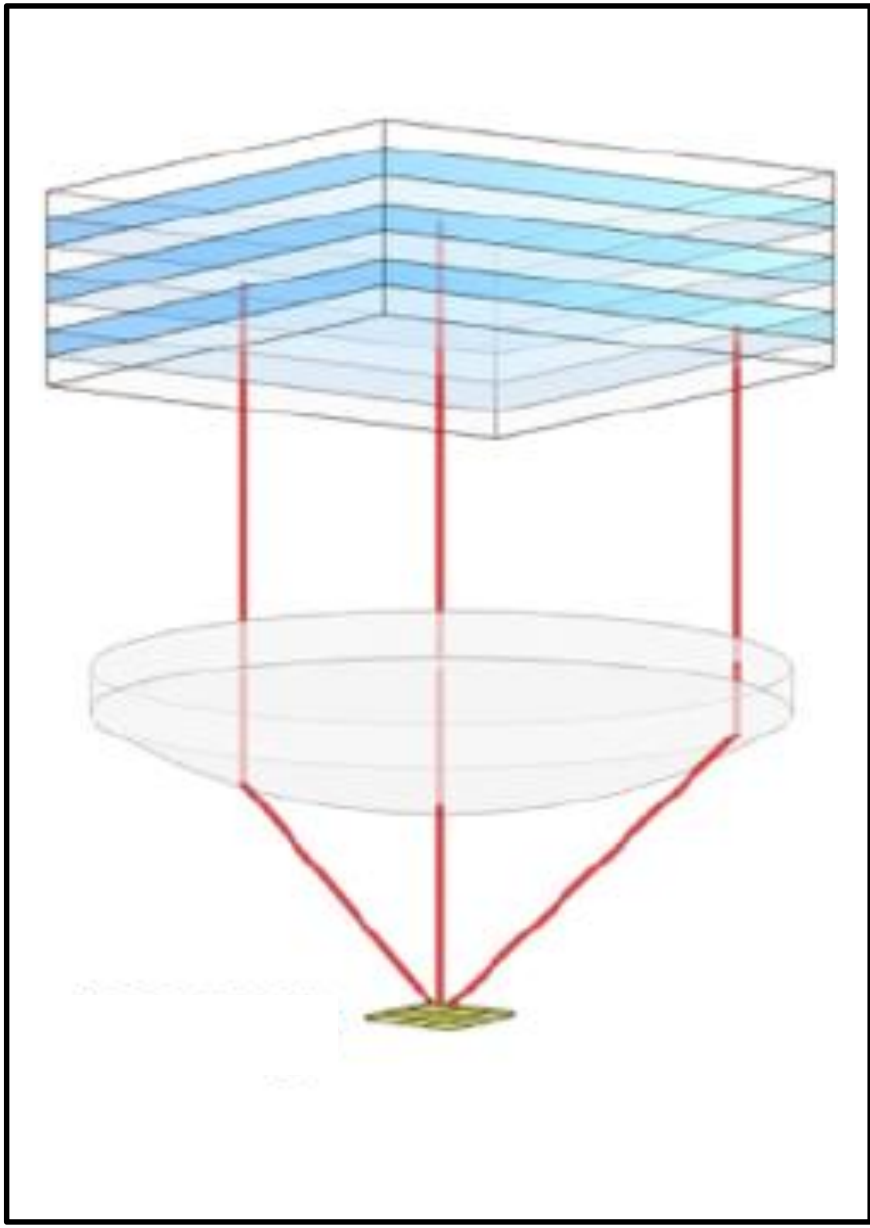


Cryogenic LNA



Multilayer optical haloscope design

- **3 major aspects**

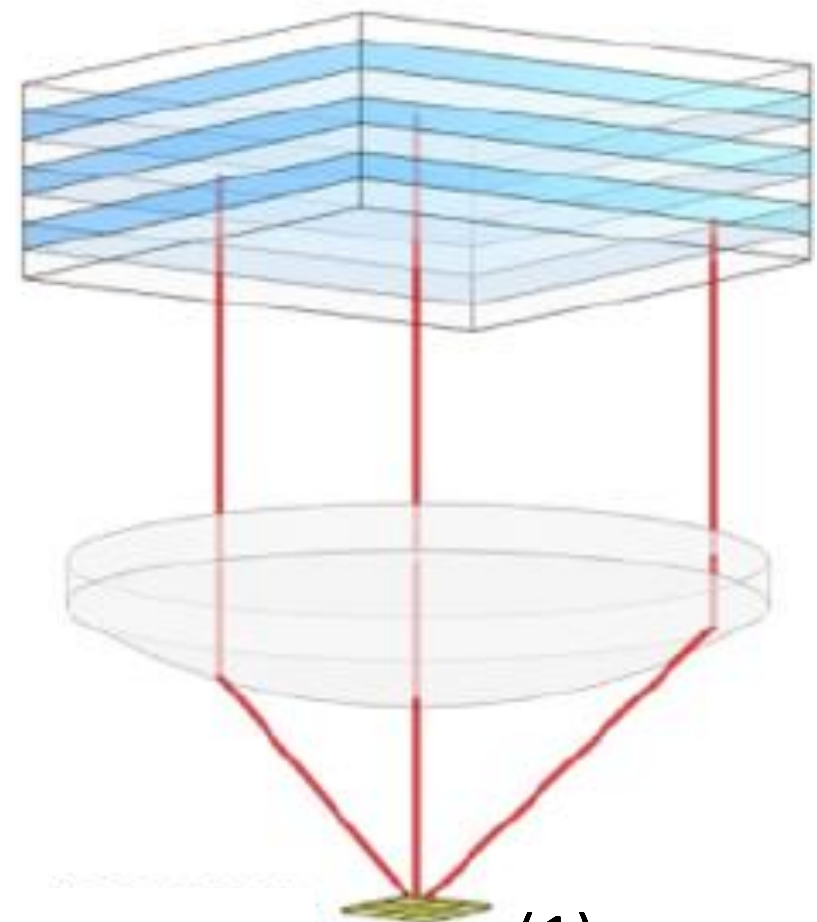


Multilayer optical haloscope design

- **3 major aspects**
  1. Detector

     -Pick up the signal with low noise

     -Provide large area to ease alignment



(1)

Multilayer optical haloscope design

- **3 major aspects**
  1. Detector

     -Pick up the signal with low noise

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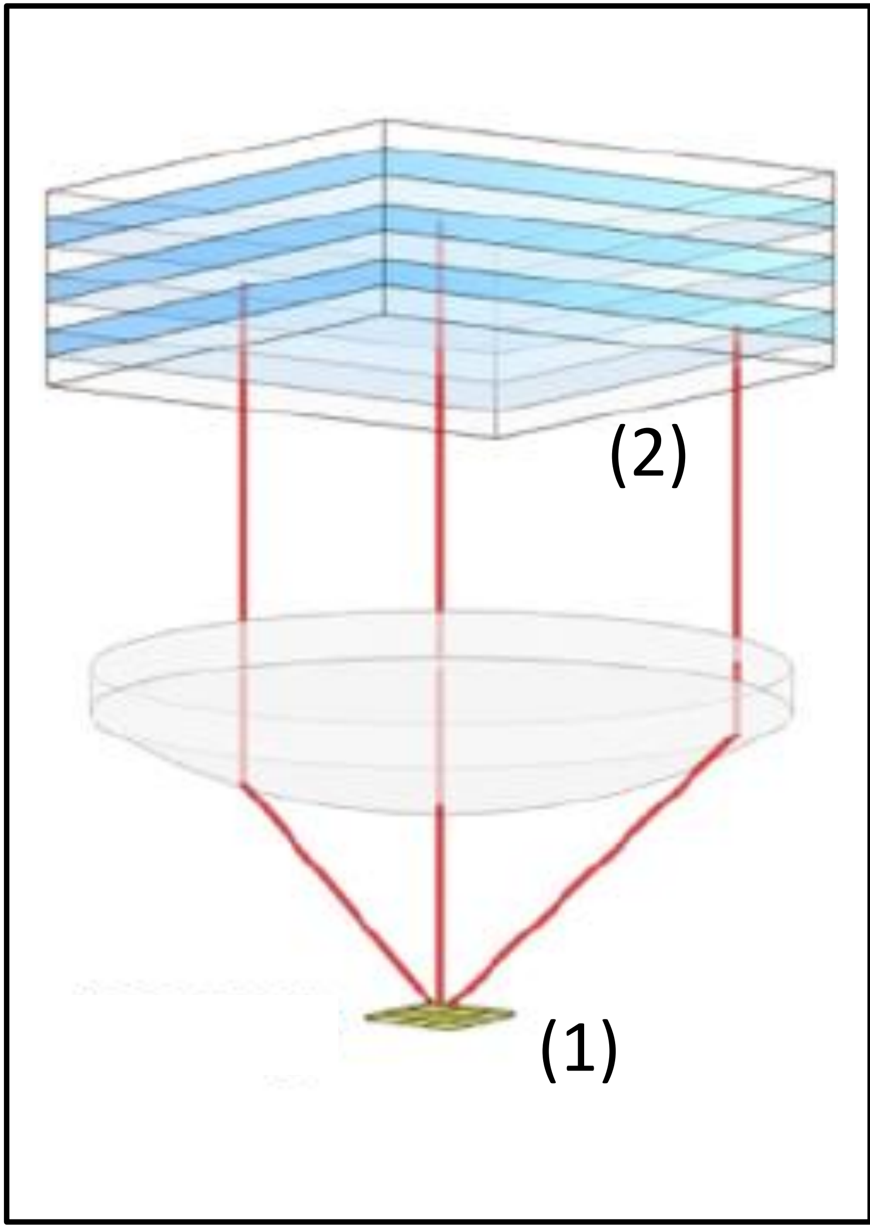
  2. Multilayer target

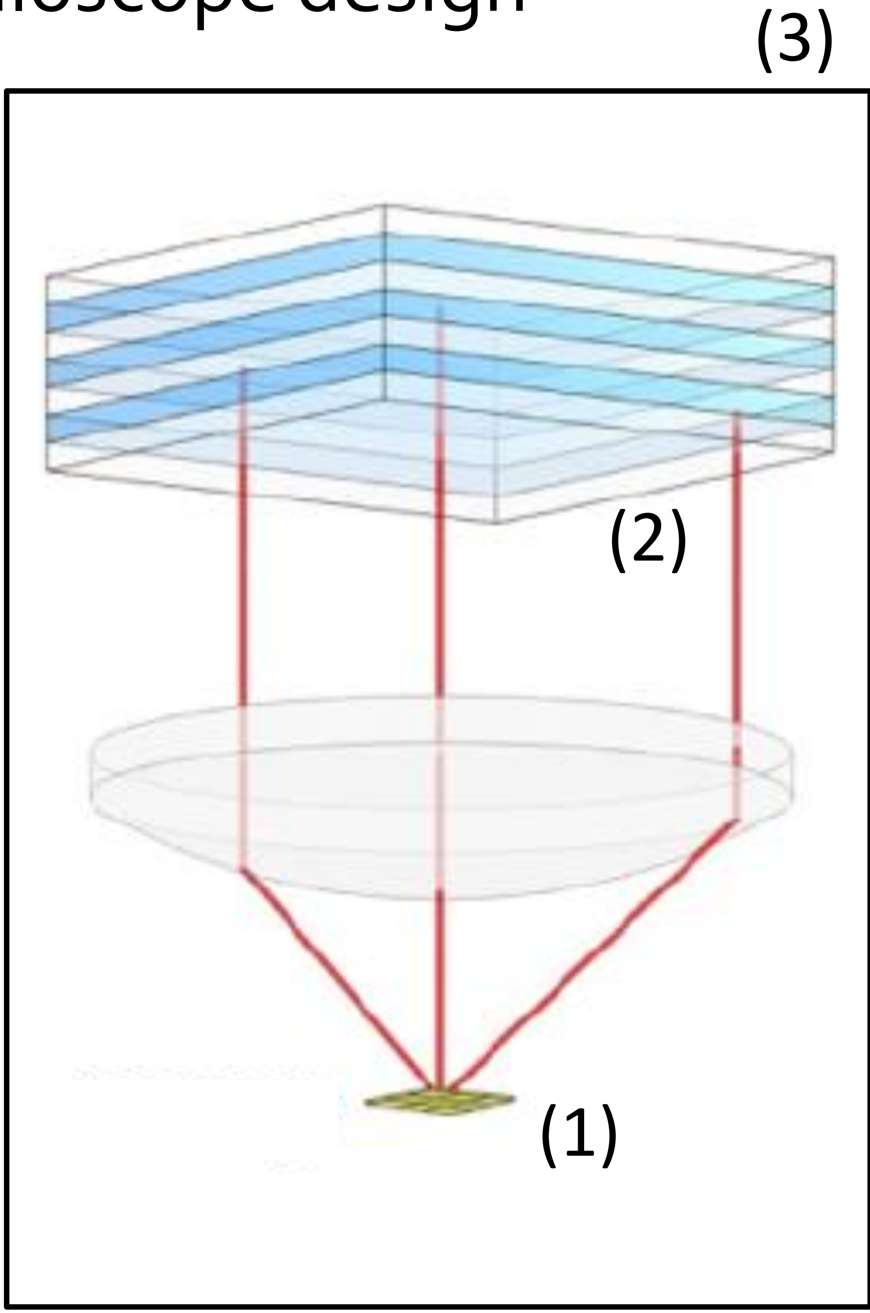
     -Convert DM to SM photons

     -Precisely engineered thin film coating for phase matching



Multilayer optical haloscope design

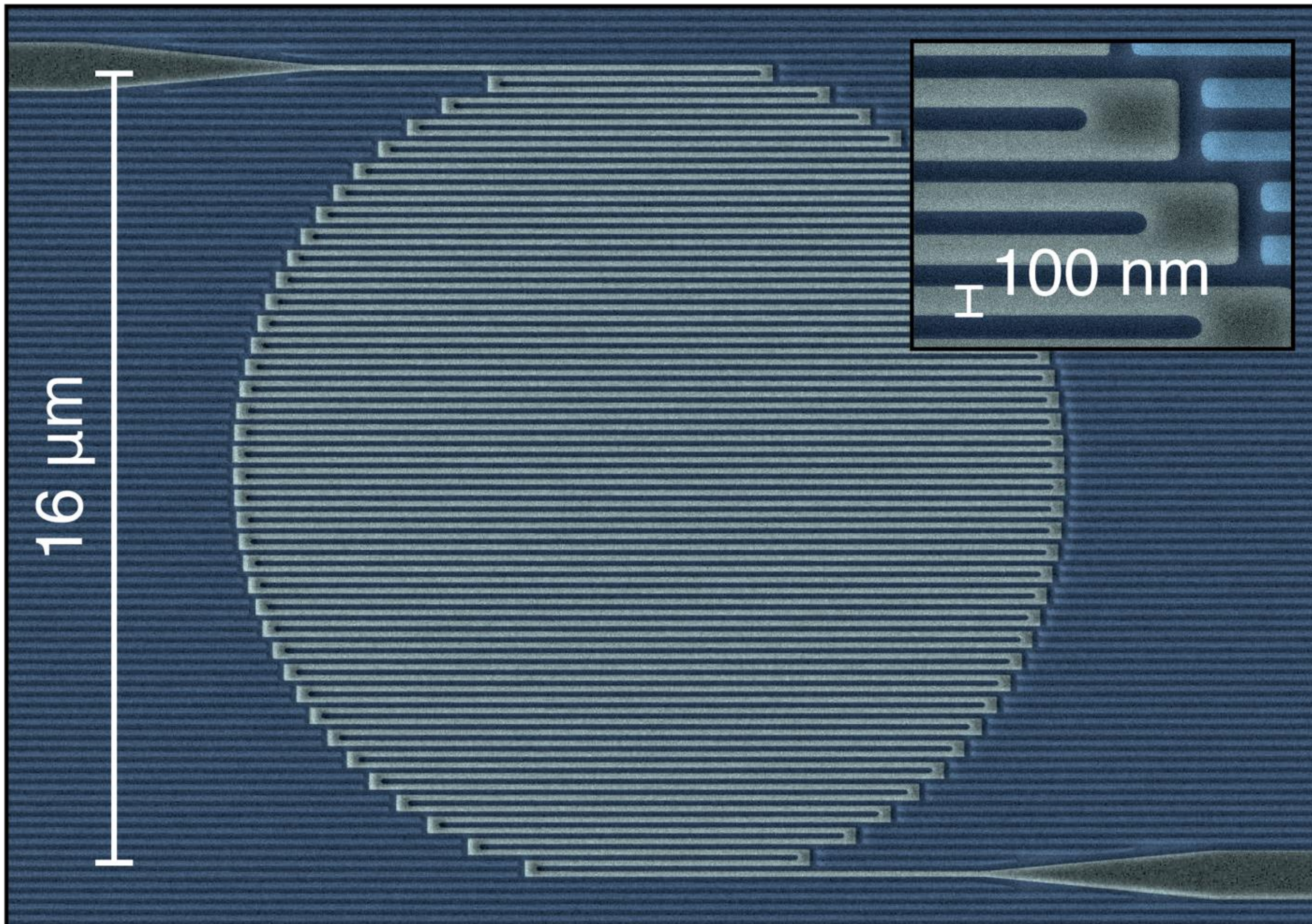
- **3 major aspects**
  1. Detector
     -Pick up the signal with low noise
     -Provide large area to ease alignment
  2. Multilayer target
     -Convert DM to SM photons
     -Precisely engineered thin film coating for phase matching
  3. Optomechanical assembly
     -Align all elements (lens, target, detector)



Superconducting nanowire single photon detectors (SNSPDs)

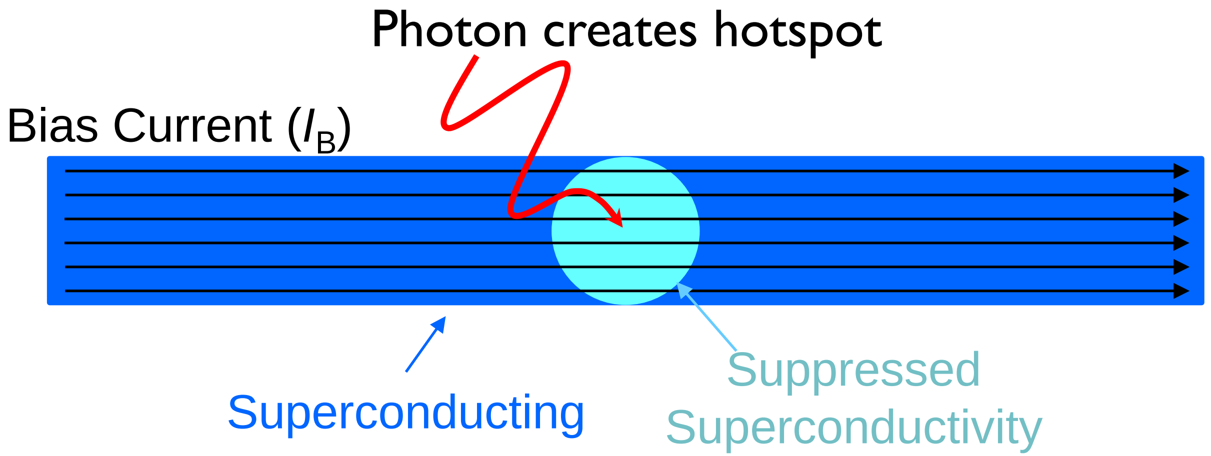
Superconducting Nanowire Single-Photon Detector

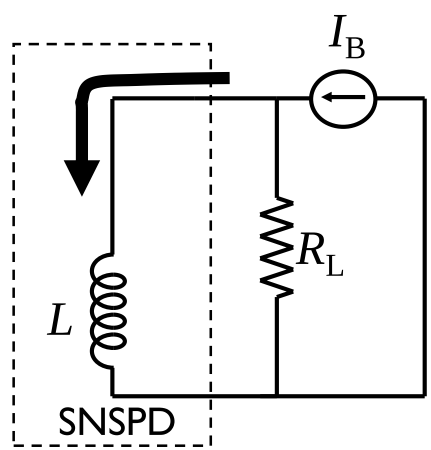
- Meandered wire of superconducting thin film with a small bias current



V. Verma (NIST)

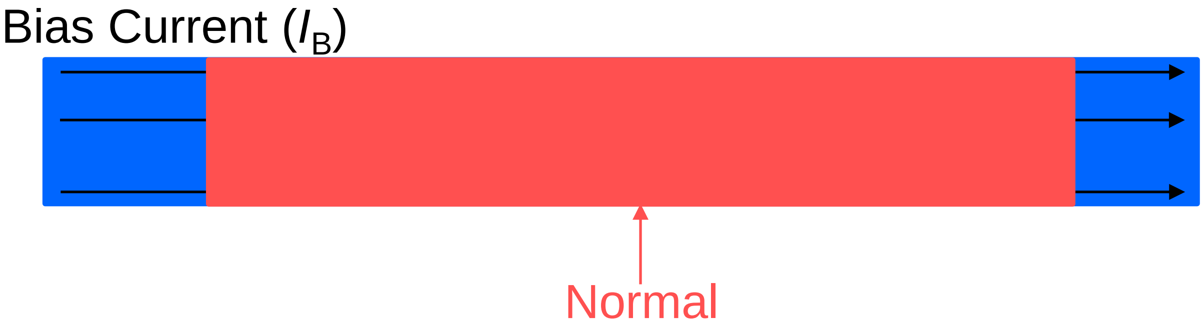
Superconducting Nanowire Single-Photon Detector

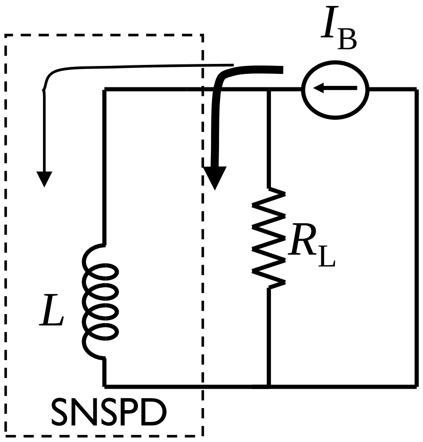




Anomalously, large Inductance, L

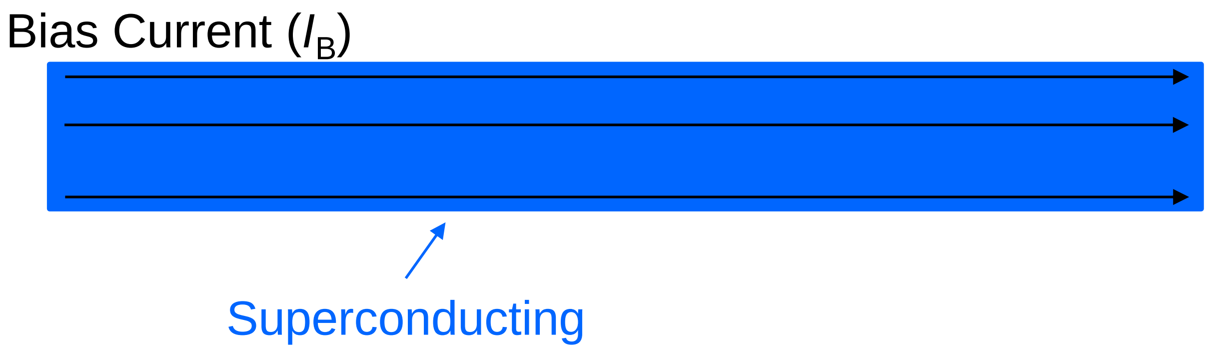
Superconducting Nanowire Single-Photon Detector

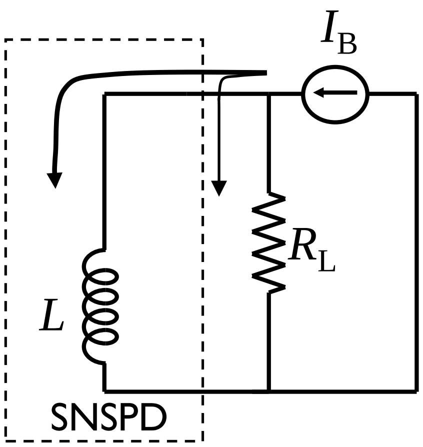




Superconducting Nanowire Single-Photon Detector

Superconductivity is restored



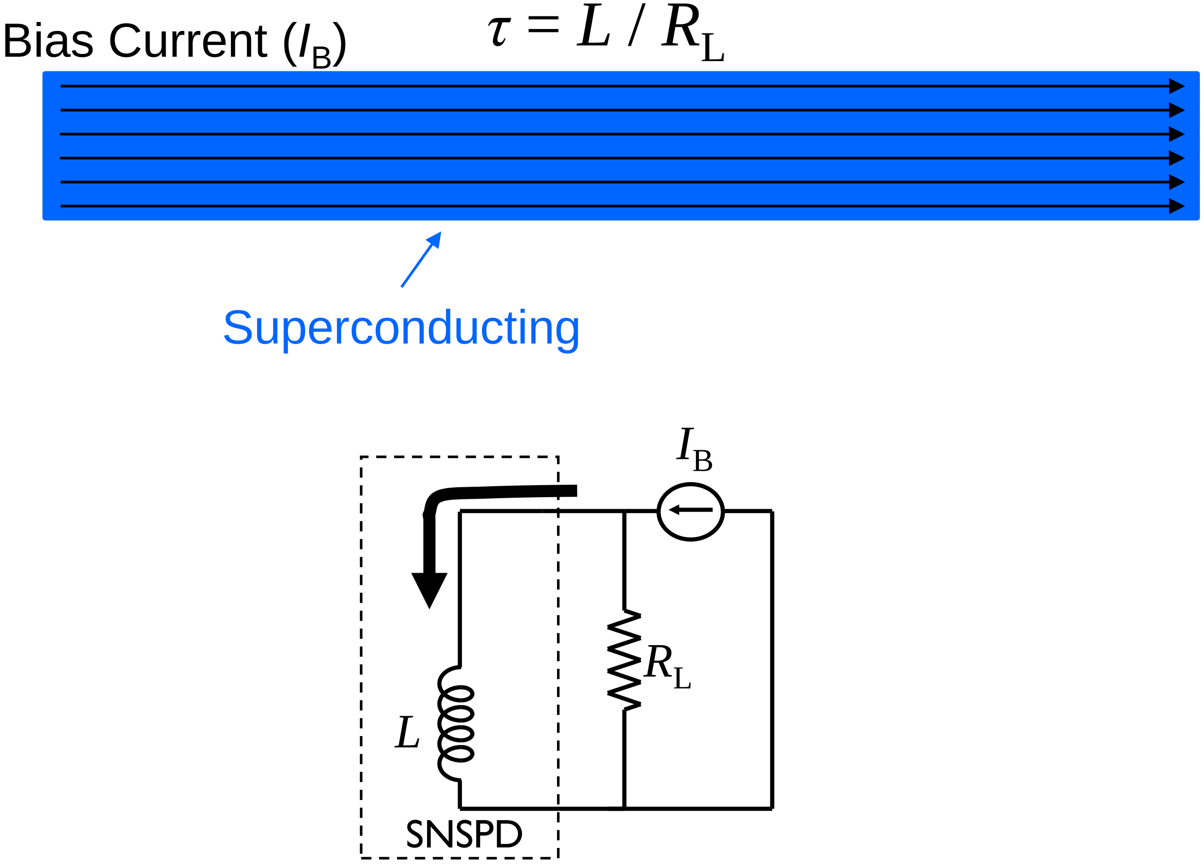


Anomalously, large Inductance, L

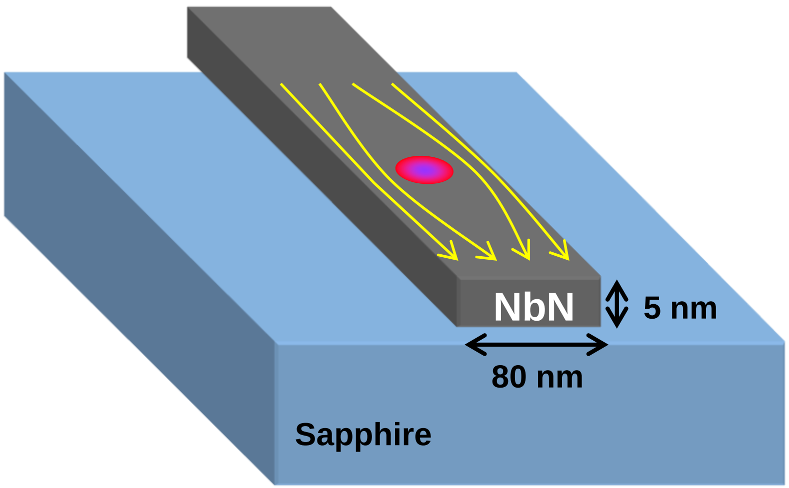
Superconducting Nanowire Single-Photon Detector

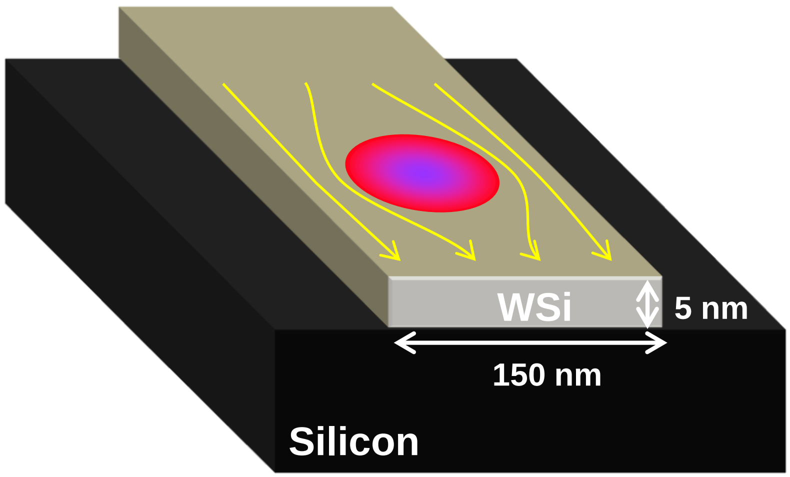
Bias Current Restored

$$\tau = L / R_L$$



SNSPD materials: Amorphous Alloys (WSi, MoSi, MoGe)



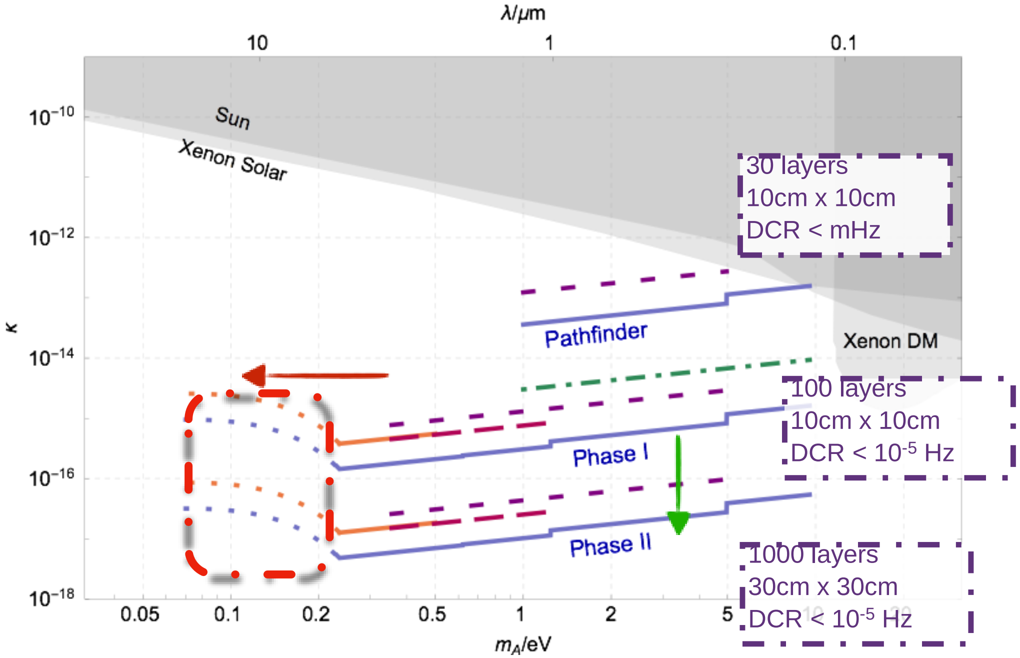


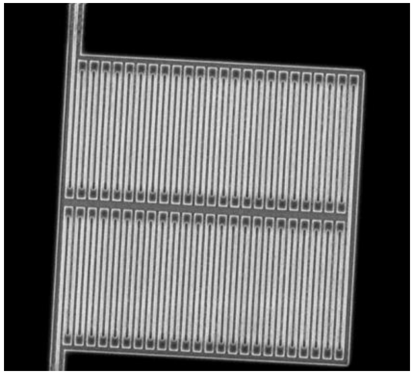
Lower superconducting gap + Lower carrier density = Larger "hotspot" → Wider wires
Amorphous → More uniform material (fewer constrictions)

- **Larger devices**
- **Better yield**

- **Lower temperature**

Multilayer optical haloscopes
Future Reach: Single photon detector R&D





Requirement: A single photon counter of low dark count rate (DCR) and surface area ~(100 μm)^2

Currently demonstrated: DCR and environmental background rates below 10^{-4} Hz at 1550 nm

Current R&D: Improve detector efficiency, increase area, characterize DCR and environmental backgrounds

Future:

- Extend detector capabilities
- Demonstrate single photon sensitivity down to 50 meV energies

Future: Achieve DCR of O(10^{-6} Hz), and mitigate environmental backgrounds to this level

Axion and hidden photon dark matter detection with multilayer optical haloscopes, Masha Baryakhtar, Junwu Huang, Robert Lasenby, Phys.Rev. D98 (2018) no.3, 035006 (arXiv:1803.11455).