Detecting Dark Matter with Superconducting Nanowires

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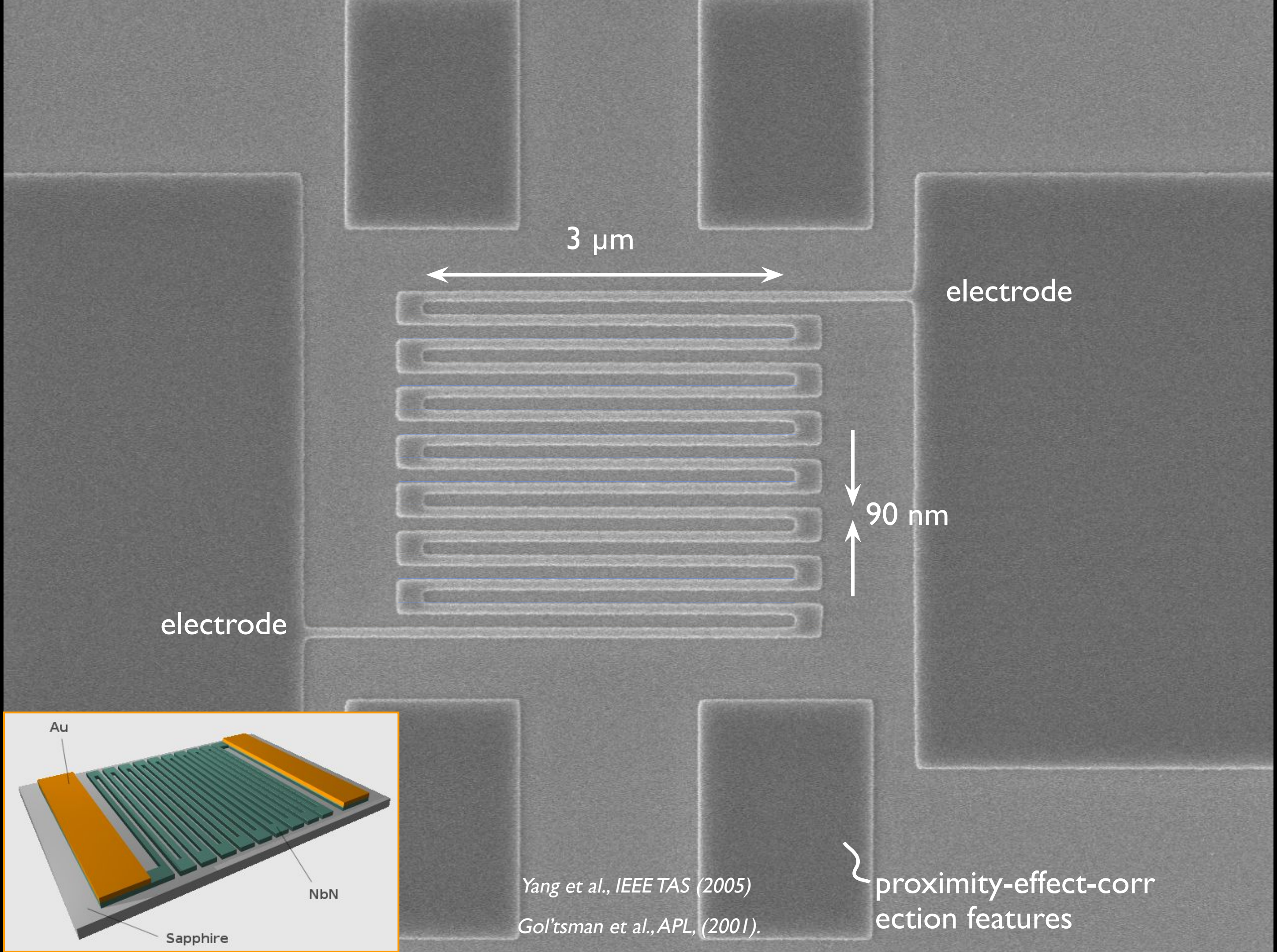
Excess Workshop, Feb 17, 2022



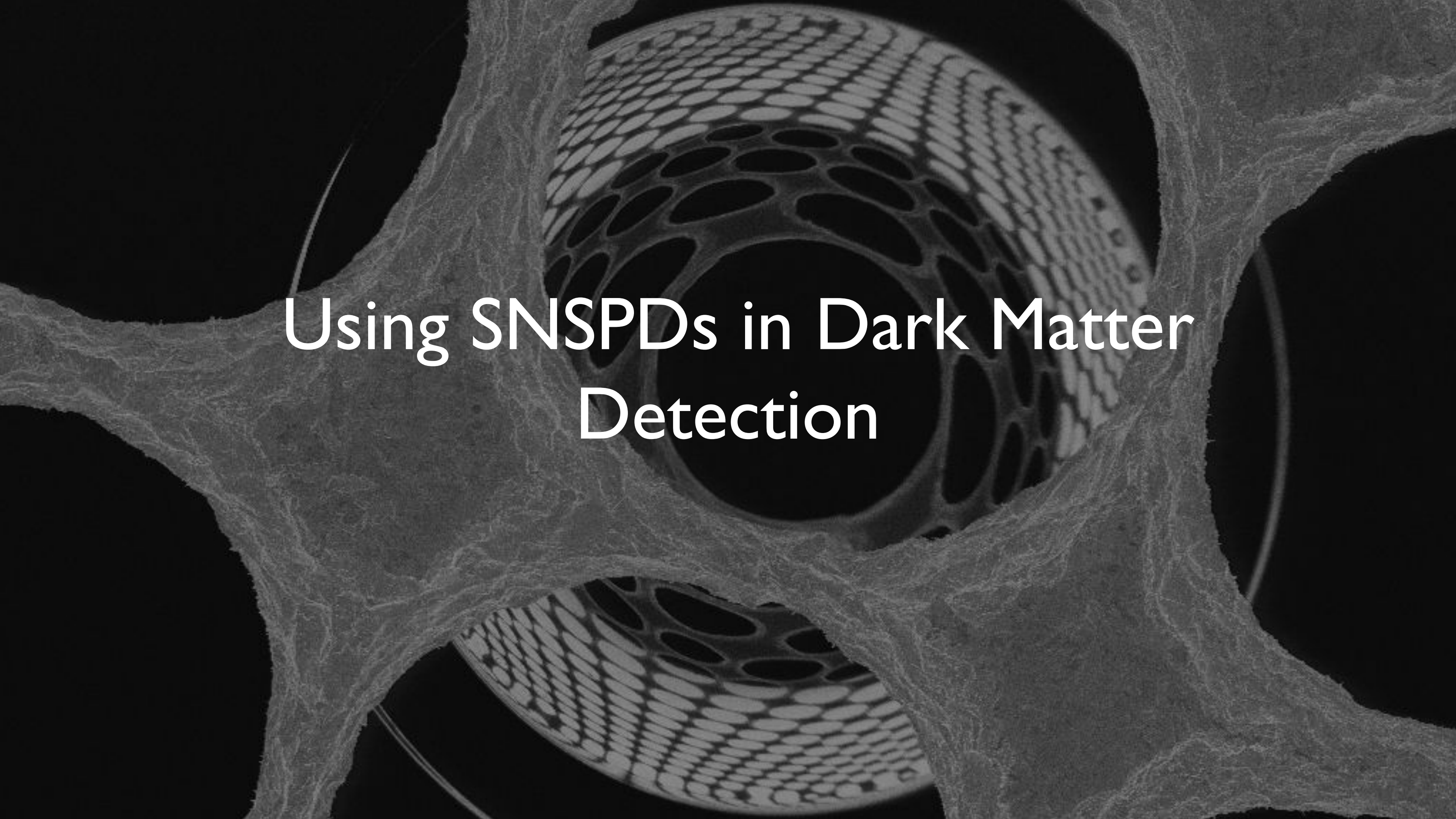
Yang et al., IEEE TAS (2005)

Gol'tsman et al., APL, (2001).

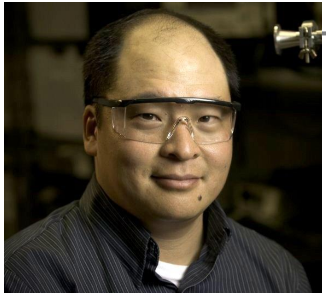
Why are SNSPDs Particularly good for DM Search?

- Infrared efficiency for single photons up to 15 µm: single photon sensitivity
- Efficiency: Competes with transition-edge sensors (98%)
- Dark-count rate (~ 1 per day)
- Convenient fabrication, shielding, amplification, operating temperature ($\geq$ 1 K)

Using SNSPDs in Dark Matter Detection



Dark-Matter Collaborators



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Yonit Hochberg

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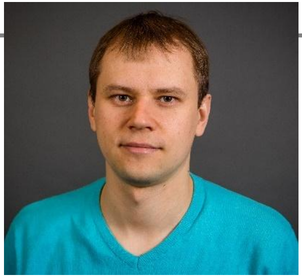

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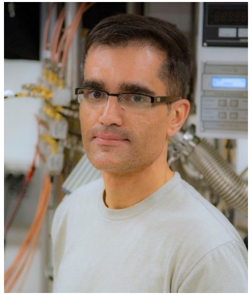

Varun Verma

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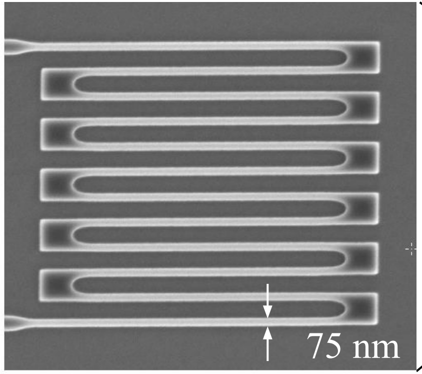
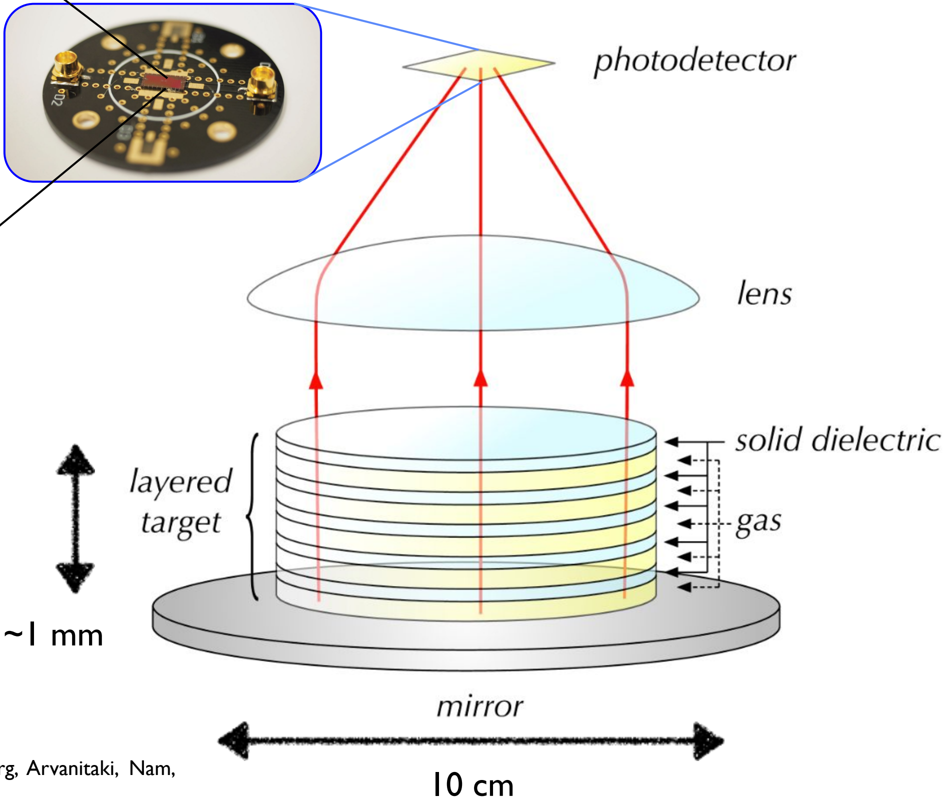
Nanowire Detection of Photons from the Dark Side



Dark-Matter Detector Concept

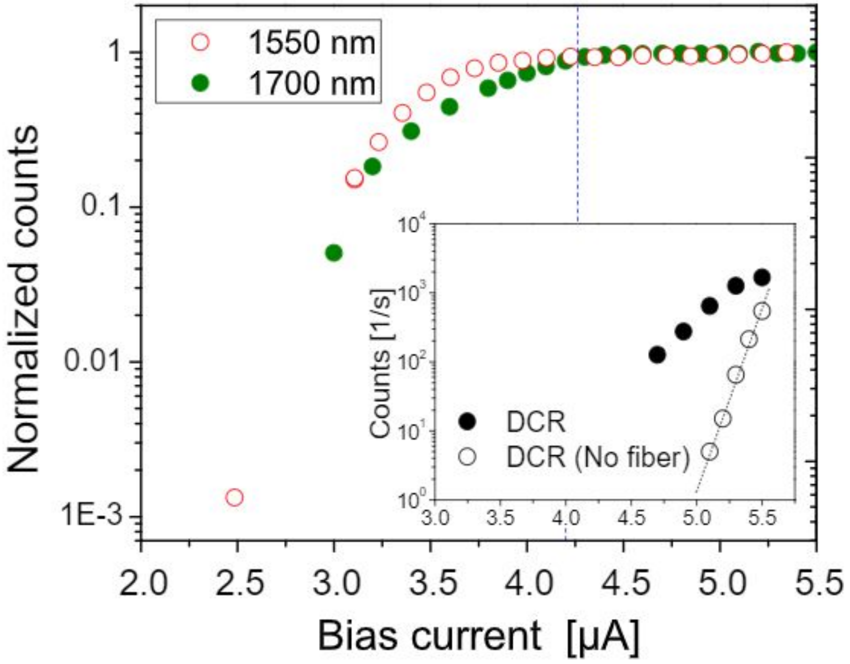


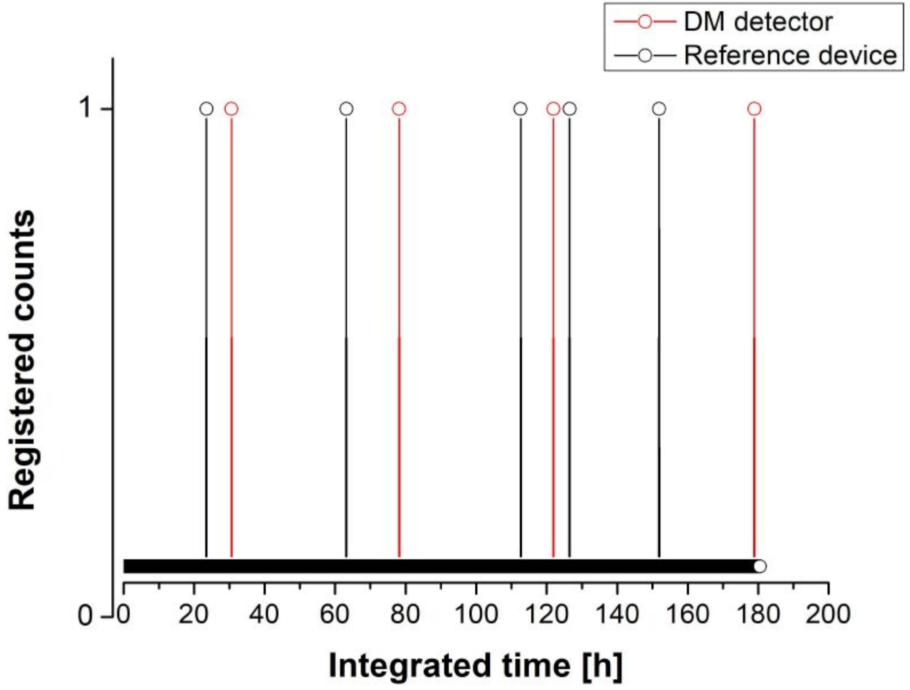
Karl K. Berggren (MIT), Sae Woo Nam (NIST), Asimina Arvanitaki (Perimeter), Ilya Charaev (MIT), Jeffrey Chiles (NIST), Andrew E. Dane (MIT), Ken Van Tilburg (NYU/IAS), Masha Baryakhtar (Perimeter), Robert Lasenby (Stanford University), Junwu Huang (Perimeter)

M. Baryakhtar, J. Huang, R. Lasenby, PRD 2018 (Proposal/Theory)
Chiles, Charaev, Lasenby, M. Baryakhtar, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren 2110.01582

Data collected from 180 hours

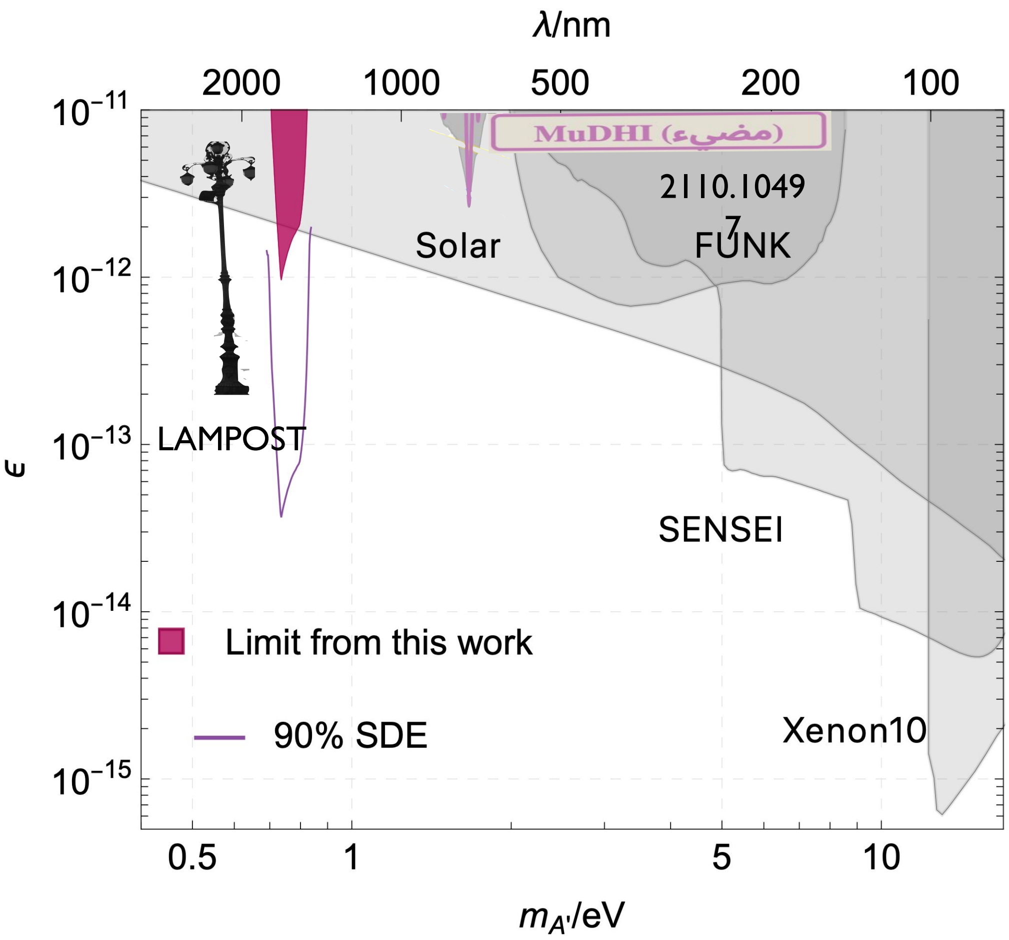
- Confirmed robust alignment strategy
- Confirmed efficient photon detection at 1550 and 1700 nm
- Cooled down to 300 mK in sorption-type cryostat





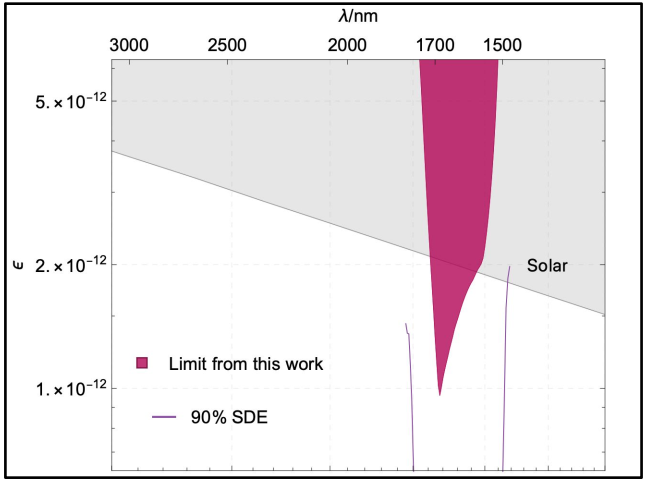
arXiv:2110.01582

Current experiment progress/limits



arXiv:2110.01582

- Prototype cuts into new parameter space with ~1 week of runtime
- Factor of ~100x increase in signal possible with relatively minor updates
- Background veto could lead to additional >10x decrease in background



Could the Detector Itself be a DM Target?

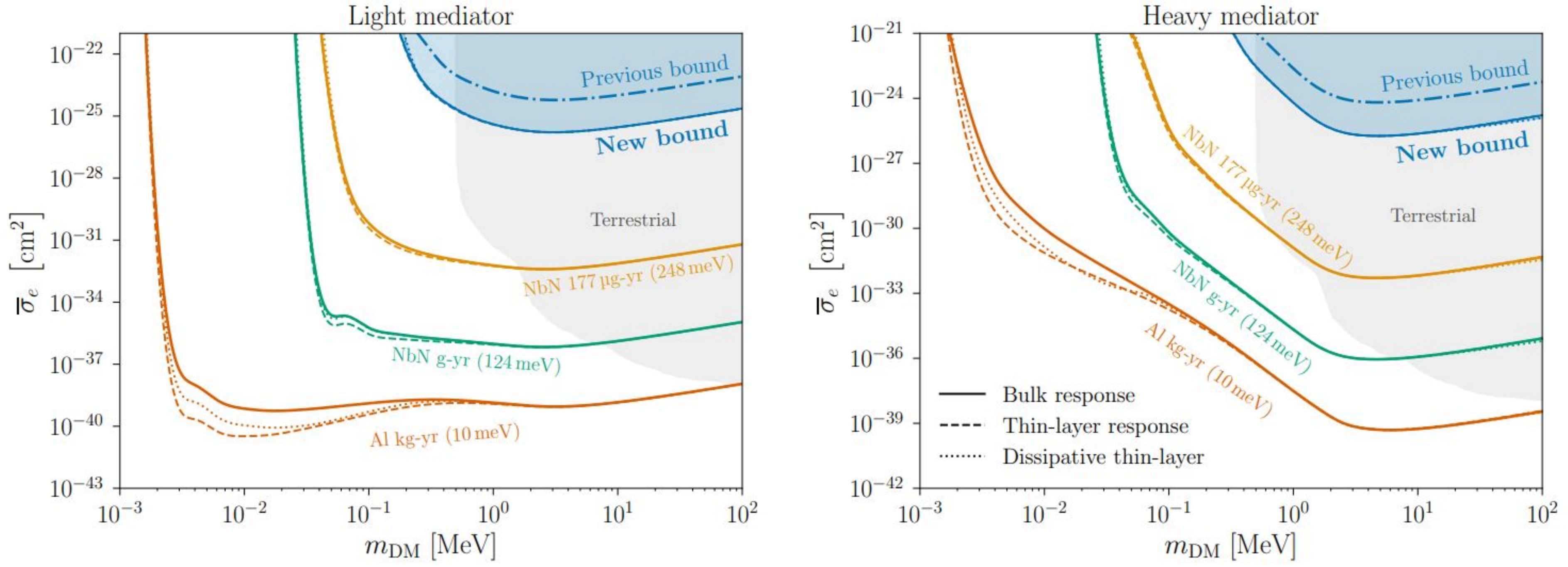
Inspired by related proposals, as well as preceding work:

[Hochberg et al, 2017],

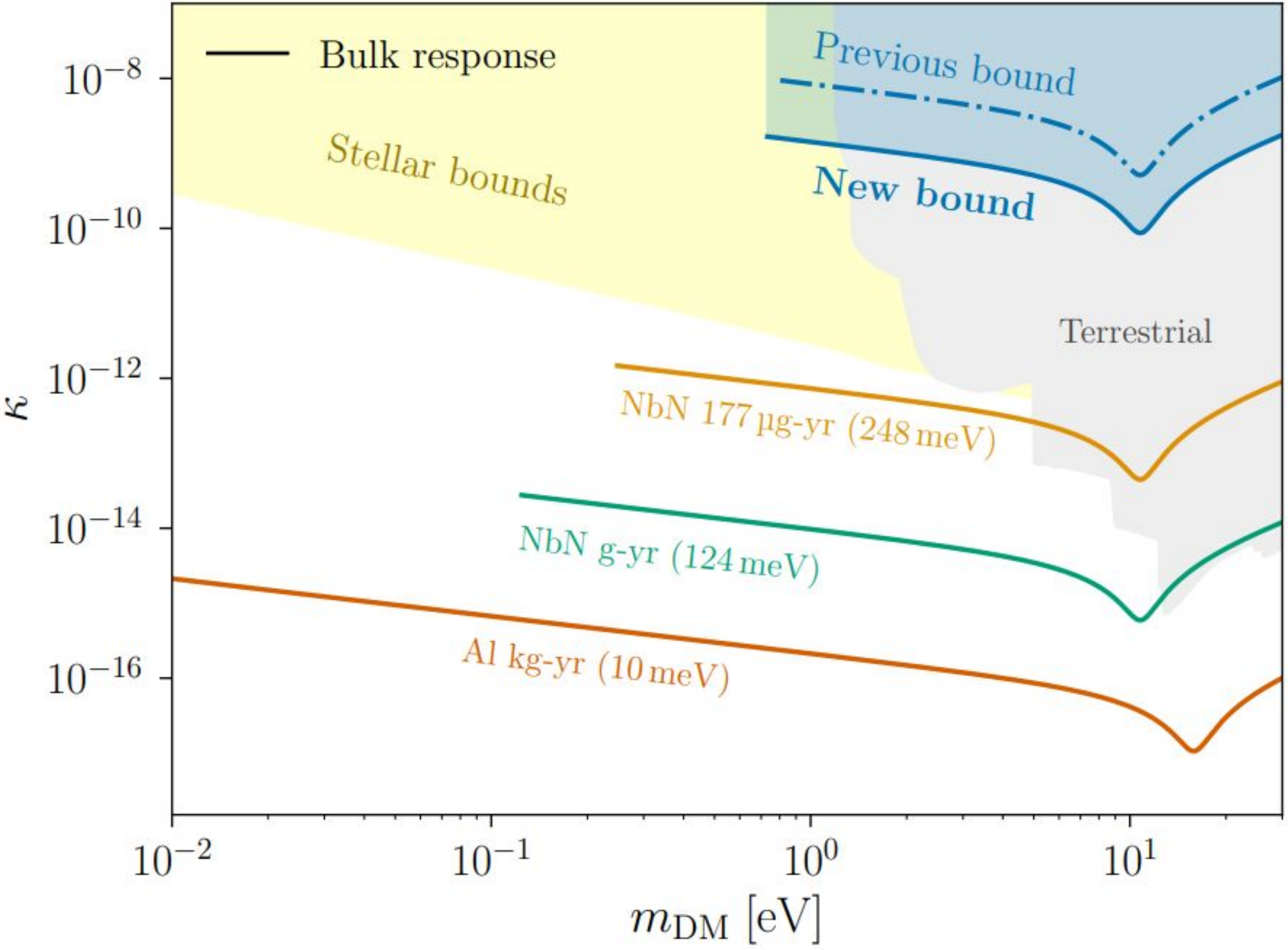
[Hochberg, Zhao, Zurek, + w/ Pyle, + w/ Lin, 2015]

Hochberg et al. arXiv:2110.01586 [hep-ph]

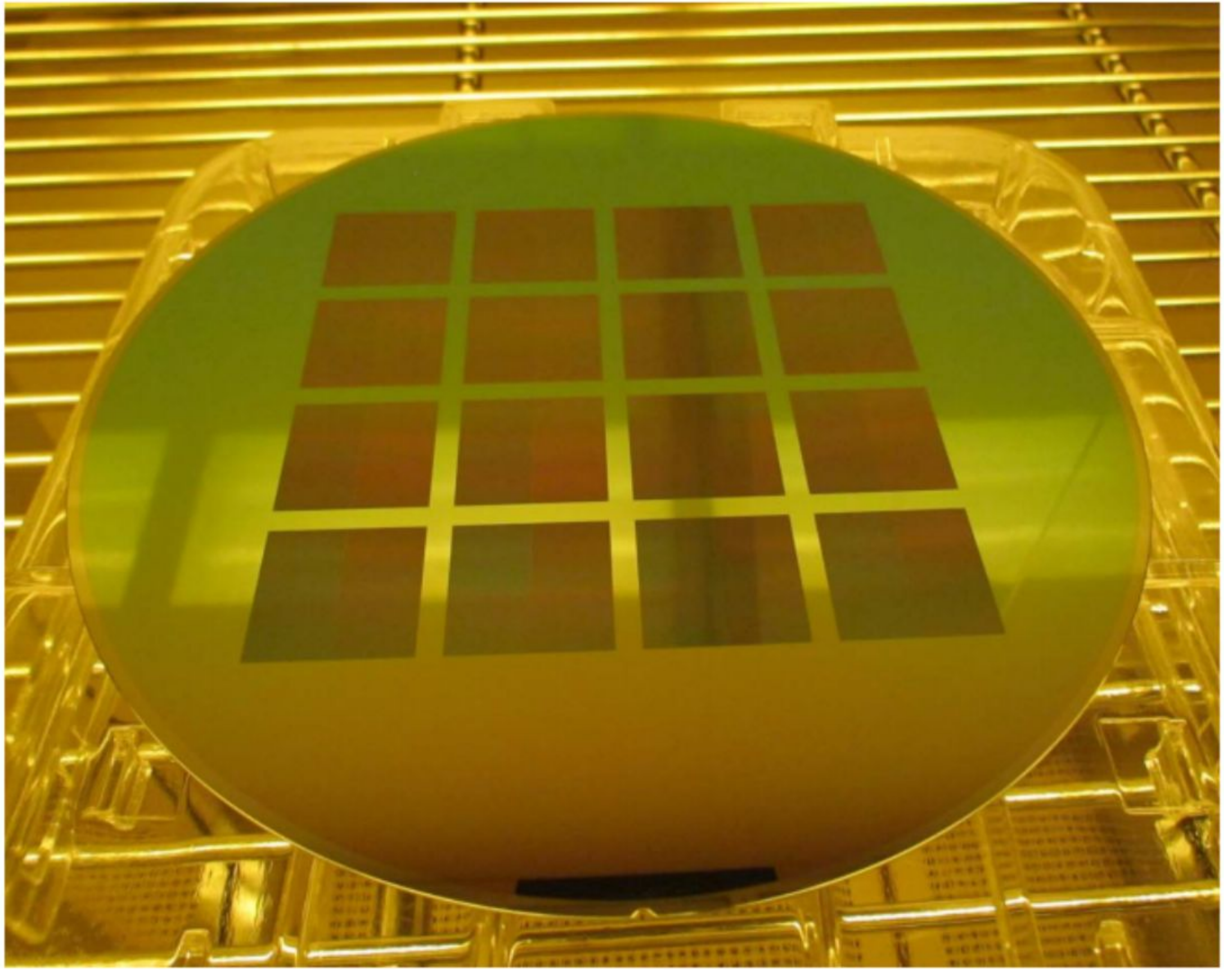
DM Scattering in NbN



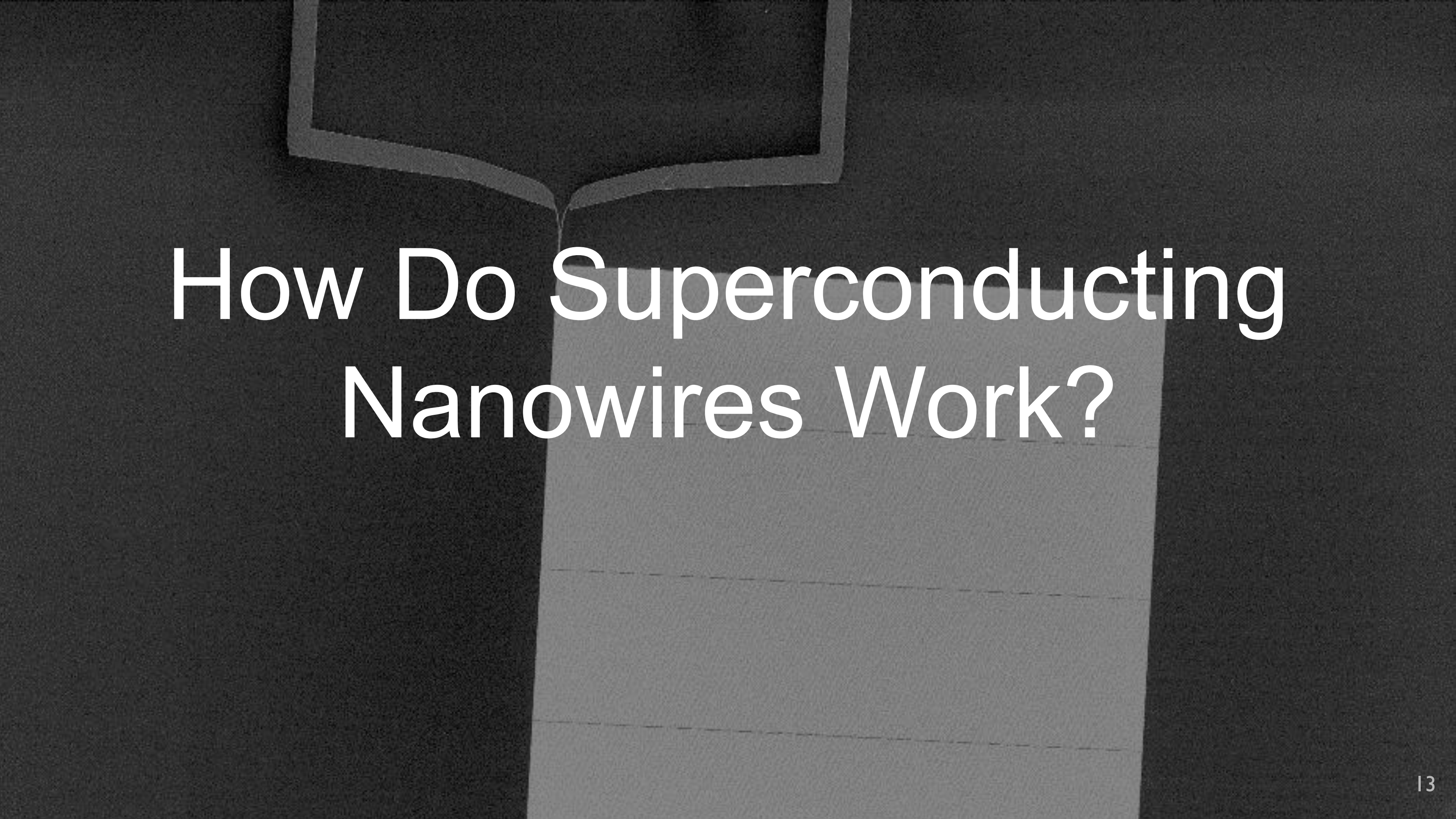
Hochberg et al. arXiv:2110.01586 [hep-ph]



image, courtesy of Mark Schattenburg, fabricated at MIT Lincoln Lab

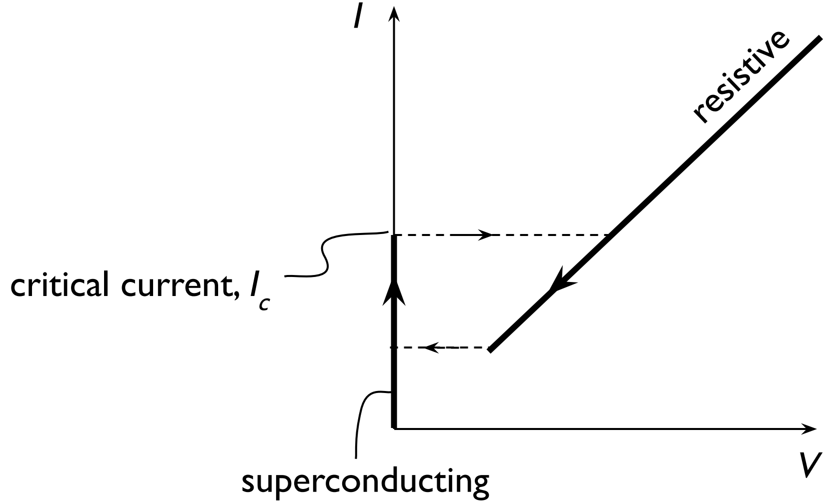


200 mm-diameter silicon wafer with 16 cat gratings.

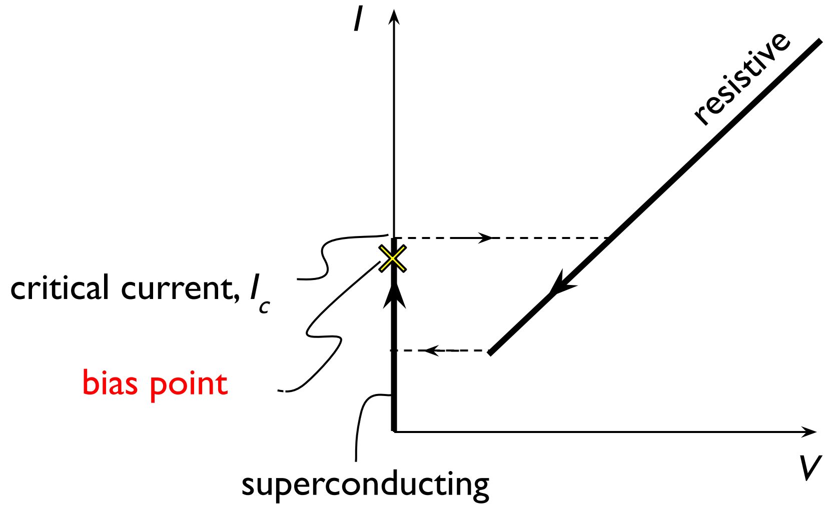


How Do Superconducting Nanowires Work?

Comparison-Based Device



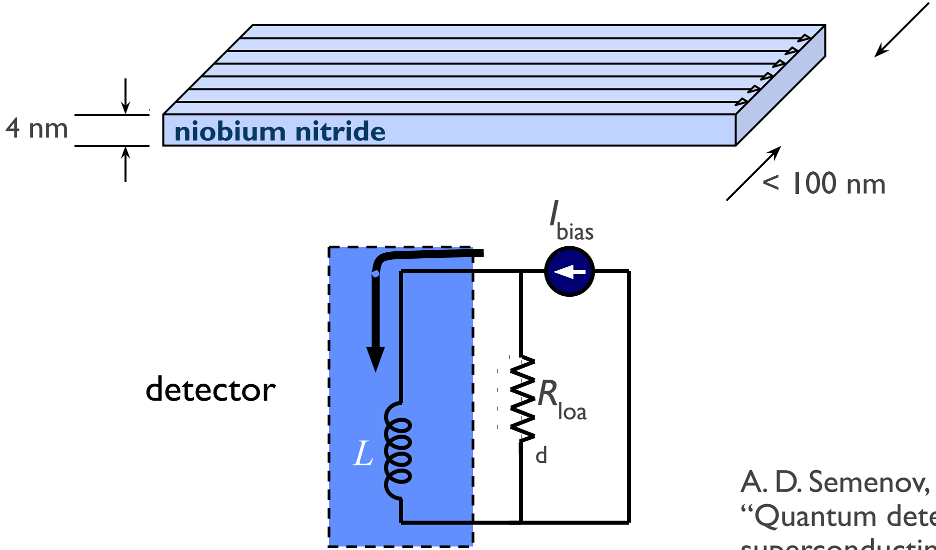
Comparison-Based Device



Current Bias

Critical Temperature ~ 11 K

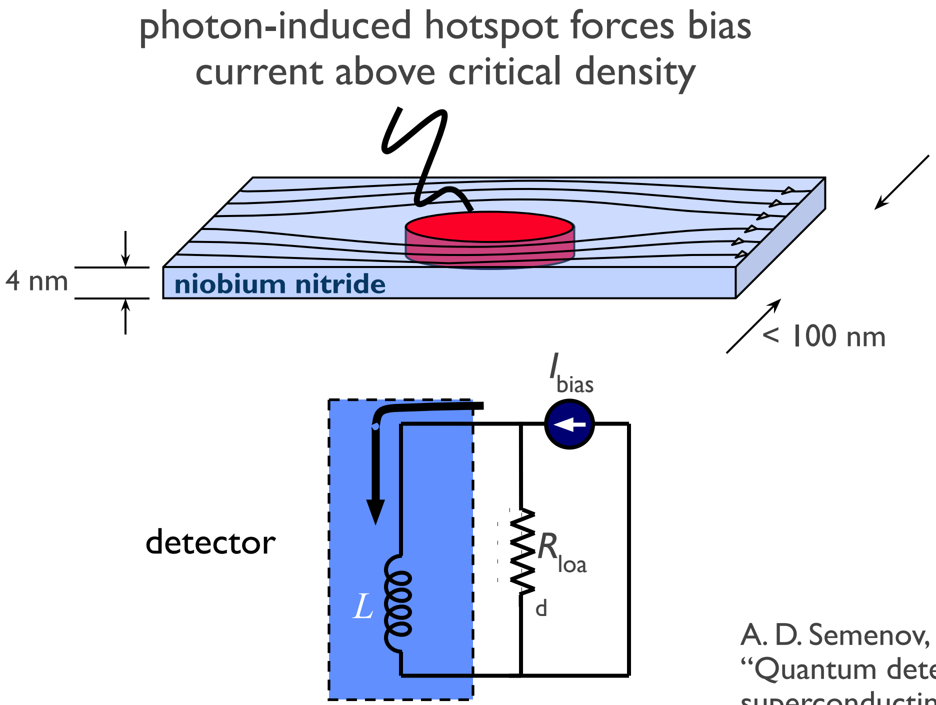
superconductor is biased near its transition



A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica* C, *vol. 351*, pp. 349–356, 2001

Absorption

Critical Temperature ~ 11 K

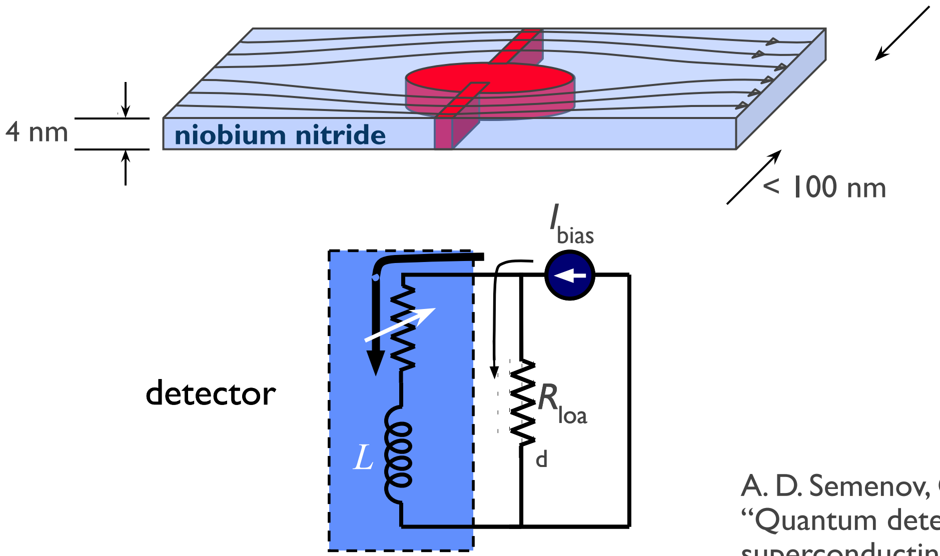


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica*

Breakdown

Critical Temperature ~ 11 K

resistive barrier spans nanowire

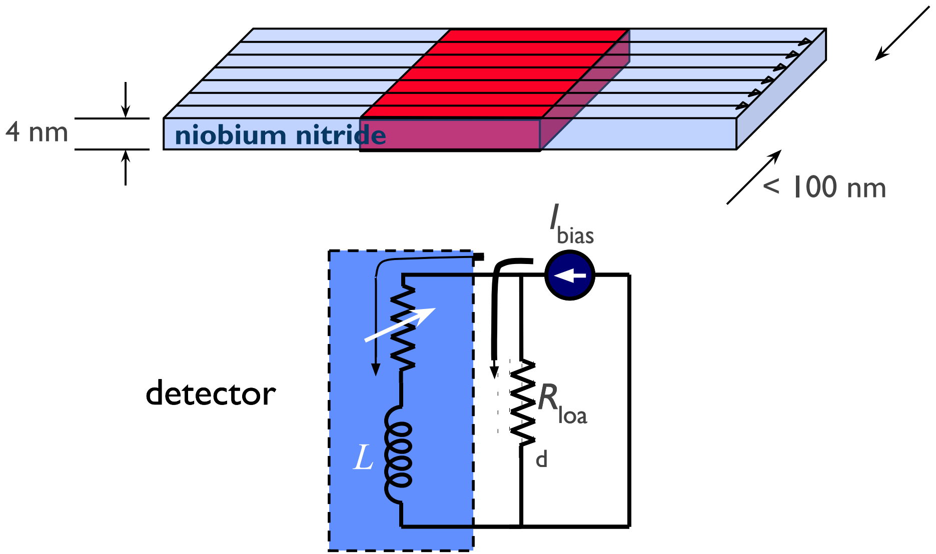


A. D. Semenov, G. N. Gol'tsman, and A. A. Korneev, "Quantum detection by current carrying superconducting film," *Physica*

Acceleration/Heating

Critical Temperature ~ 11 K

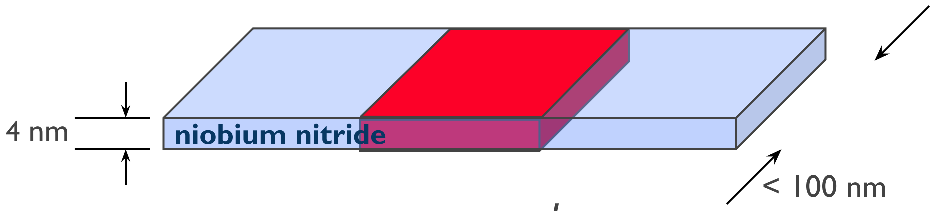
resistance grows from heating

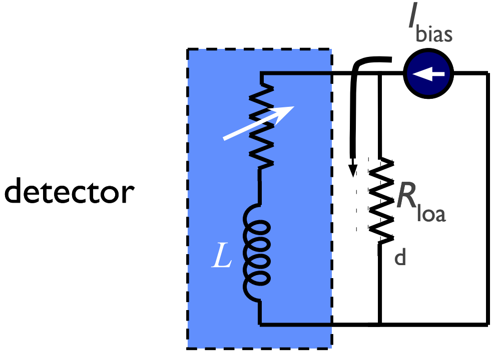


Diversion of Current

Critical Temperature ~ 11 K

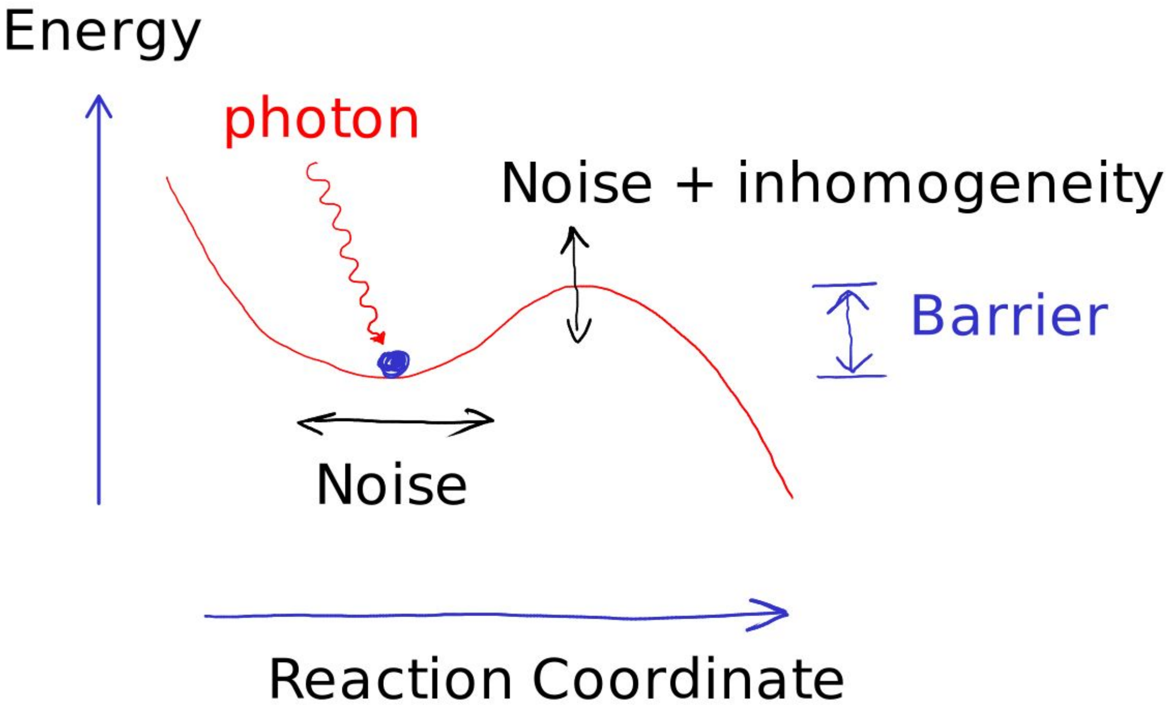
current is diverted



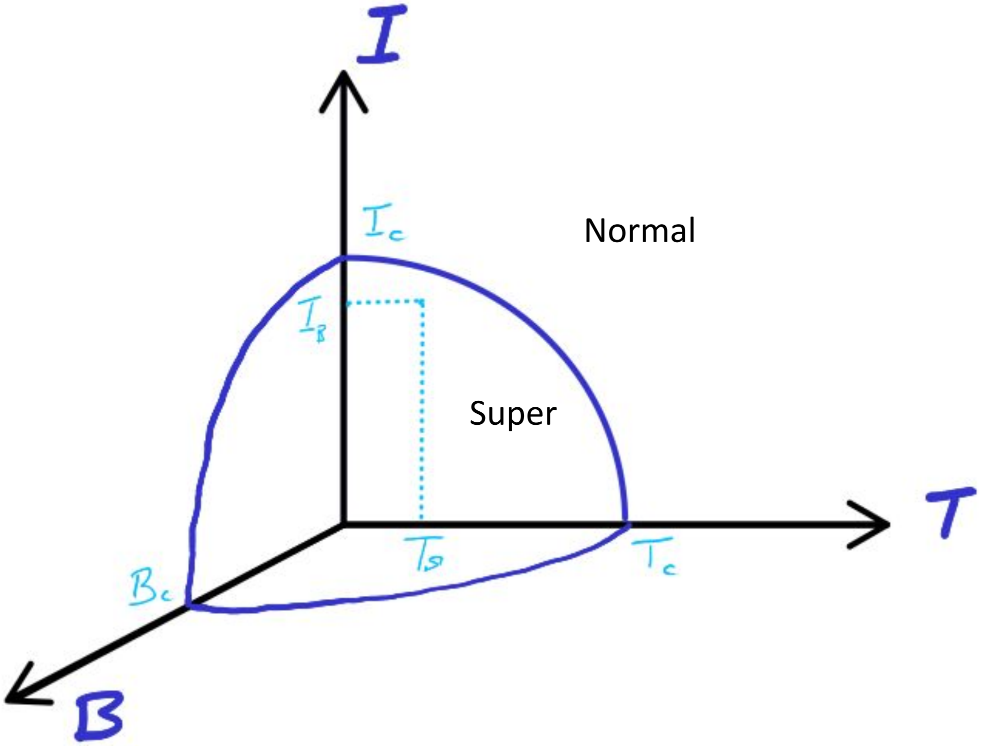


IR Sensitivity

- Toy-model of detection process
- Particle must have sufficient energy to excite system over barrier
- Inhomogeneity and noise prevent lowering barrier below certain value

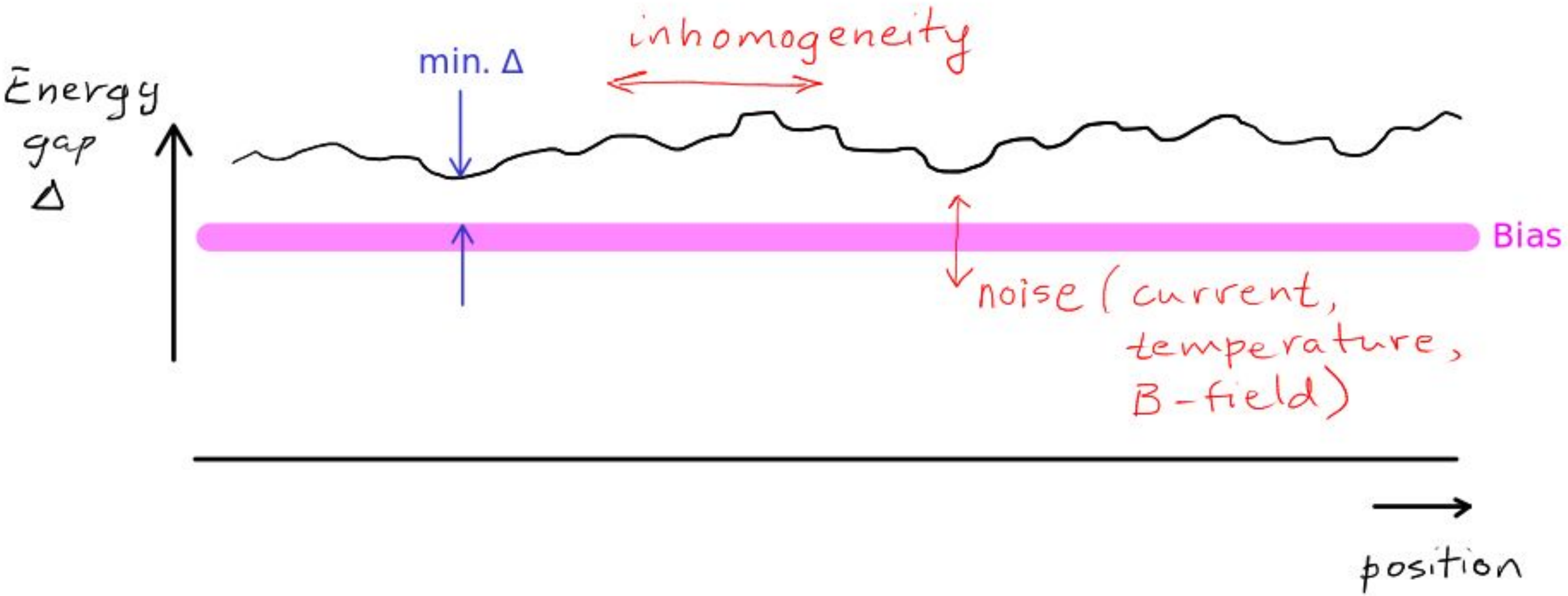


How is barrier determined?

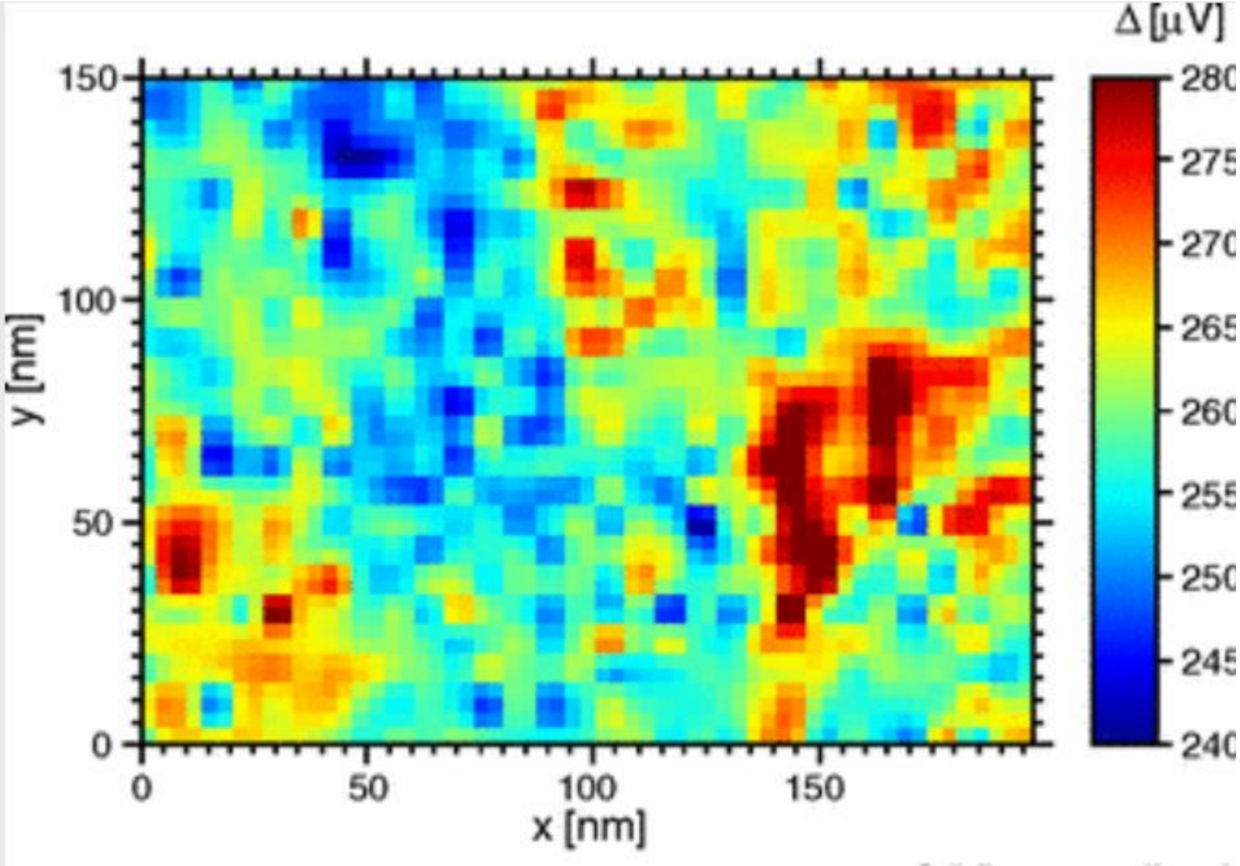


- Current and temperature are used to lower superconducting barrier
- Remaining barrier can be made arbitrarily low in the absence of biasing noise

Noise and Inhomogeneity



Intrinsic Inhomogeneity ~ 40 μV (6.4 yJ)



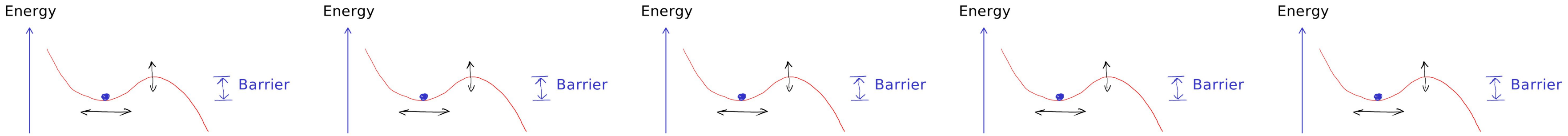
Sacepe, PRL, 2008

Current-Bias Noise

- Thermal Noise/Shot Noise
  - Naive calculations of shot noise (which are certainly incorrect) suggest a major effect
    - $\sqrt{(2\, B \cdot q \cdot 10\mu A)} \approx 0.2\ \mu A$
  - Shot noise in Josephson junctions has been carefully studied
  - Shot noise in normal metal wires is well understood (Landauer '93)
  - Shot noise in superconducting wires does not seem to be well understood by our community (maybe just me?) and might even be an open problem in theoretical condensed-matter physics (that maybe no one except us cares about…)

Thermal Fluctuations

- Independent thermal fluctuations
  - Berlin Theory (Semenov '20) is that a nanowire can be modeled as a large number of thermally independent fluctuations, thus correct model is of large # of detectors…

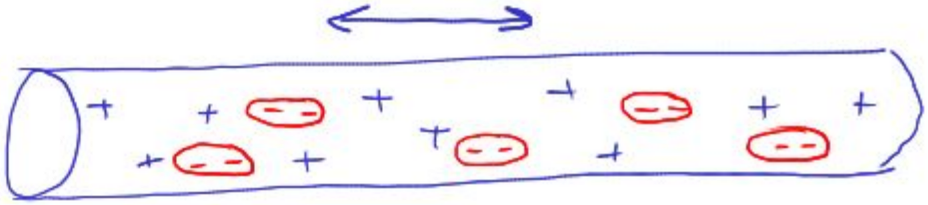


- All the "detectors" contribute to noise, but only one at a time detects a photon

Thermal Instability: Cryocoolers often exhibit significant thermal fluctuation, which isn't always addressed in detector systems

Mechanical Vibrations

- When a wire moves, a current is induced in it due to inertia of the electrons
- While this effect is small (O(1e-6)) for our current devices, it scales as 1/Δ, thus could become important for low-T_c materials.
- Has not been carefully considered for SNSPDs



Magnetic-field Noise

- Likely a small effect because critical fields are Tesla-scale, while fluctuations are 1e-5 Tesla scale
- Estimated suppression of I_C with field is $\approx 10^{-4}$ A/T (Charaev '18)
- Background B-field noise is likely ~ nT scale or lower (and thus is negligible). However, it may vary with frequency, and local EMI effects could result in larger effects
- Has not been carefully studied (to my knowledge)

Superconductivity Team in QNN Group

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Thank you to Lara Ranieri and Rinske Wijtmans for assistance in preparing these slides for presentation

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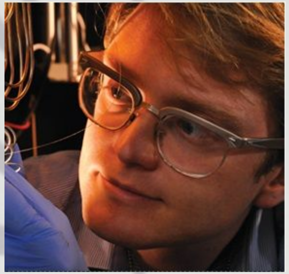

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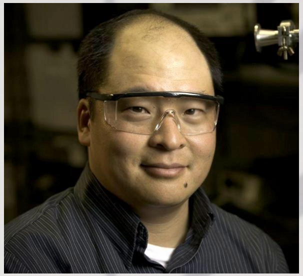

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- Edward Ramirez (JPL)
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- Brian Noble (UNF)
- William Strickland (UNF)

- Varun Verma (NIST)
- Jeff Chiles (NIST)
- Adriana Lita (NIST)

SNSPD SUPPORT

- **Dept. of Energy (primary sponsor of this work)**
  - Ongoing collaborations with Brookhaven/Fermilab/ Argonne
- U.S. Air force Office of Scientific Research
- U.S. Office of Naval Research
- DARPA DETECT and
- IARPA
- NASA
- NSF
- Skoltech
- Many U.S. and international fellowships

Thank You!

- To the hundreds (thousands?) of PIs, post-docs, students, technicians who have supported this field over decades, and the thousands of administrators/facilities workers/family members who have supported them.
- The major institutions that have been involved in this field include (in random order).
    - U. of Rochester, Moscow State Pedagogical University, Delft University of Technology, Karlsruhe Institute of Technology, National Institute of Standards and Technology, Yale University, University of Waterloo, University of British Columbia, Caltech Jet Propulsion Laboratory, EPFL Lausanne, MIT Lincoln Laboratory, Michigan State University, National Institute of Information and Communications Technology (NICT) in Kobe Japan, Nanjing University, Shanghai Institute of Microsystem and Information Technology (SIMIT), Heriot Watt University, Glasgow University, University of Roma TRE, Italian National Research Council (Rome, Naples)*, KTH Royal Institute of Technology, Los Alamos National Lab, Chalmers University, EPFL, Eindhoven University of Technology, The Technion, Argonne National Lab, and others that have slipped my mind...

Apologies in advance to anyone I neglected to mention.

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END OF PRESENTATION

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