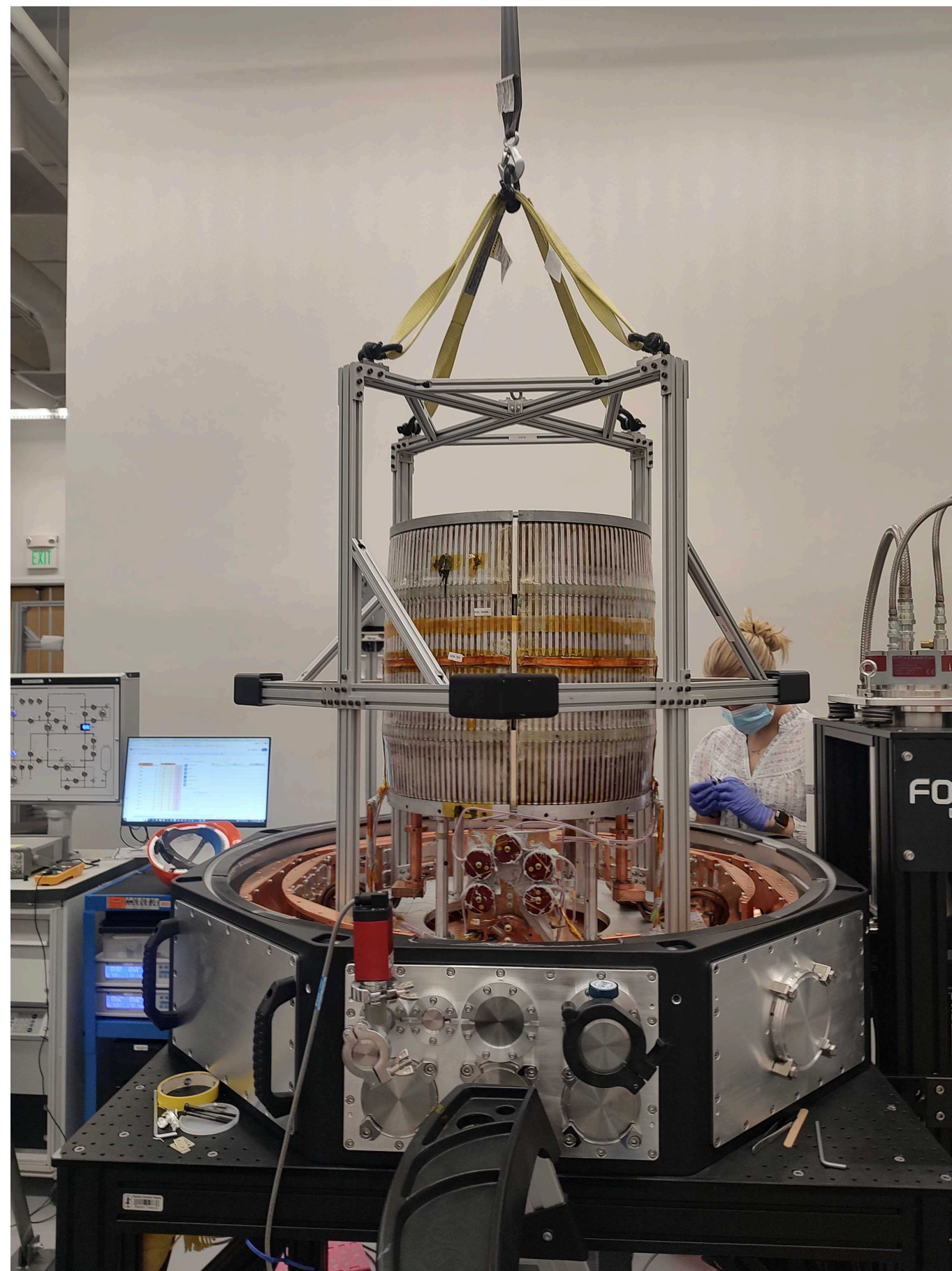


Quantum Probes for a Quantum Universe

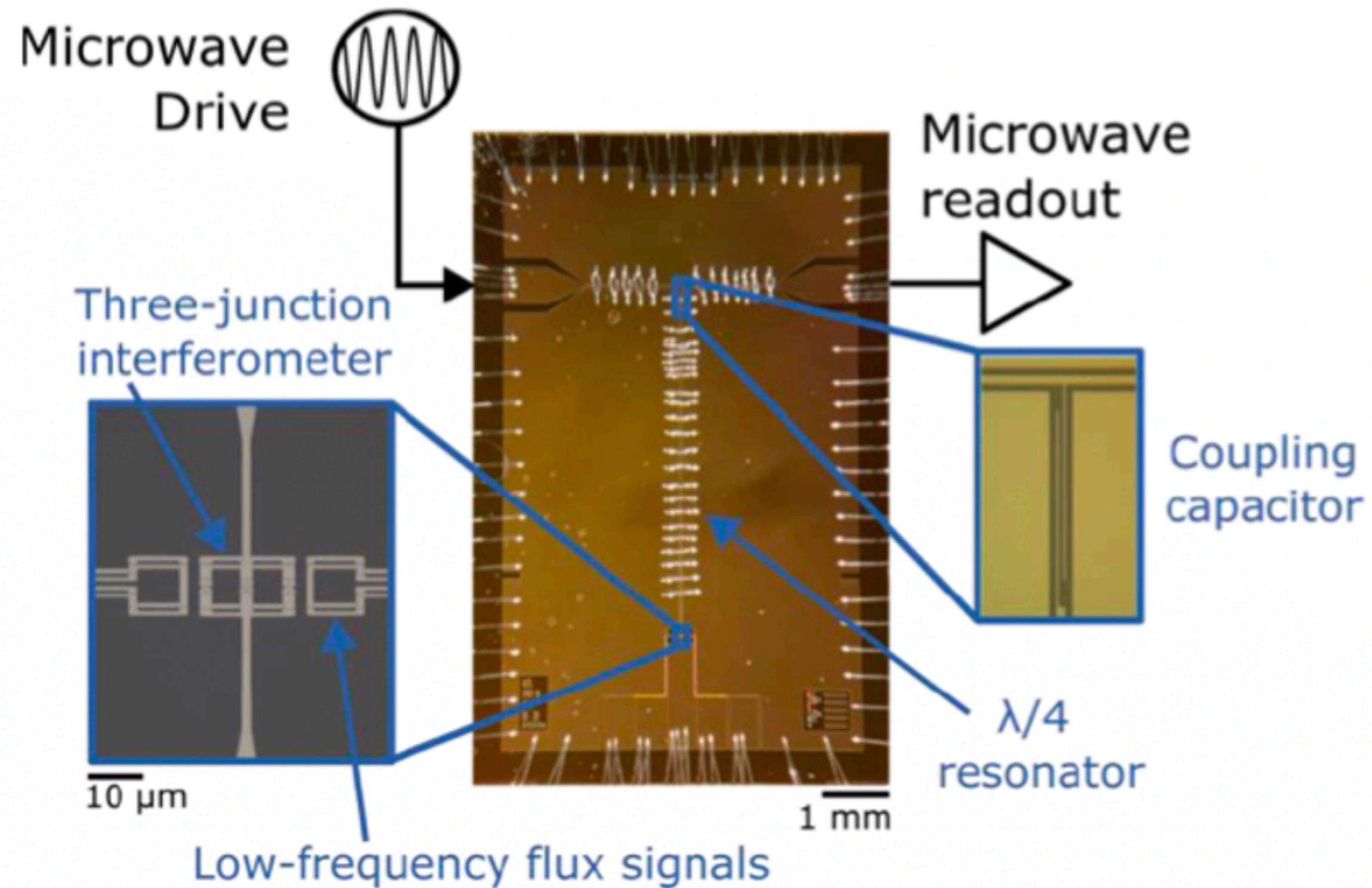
SLAC Summer Institute 2026

Chelsea Bartram

It's been a busy week!

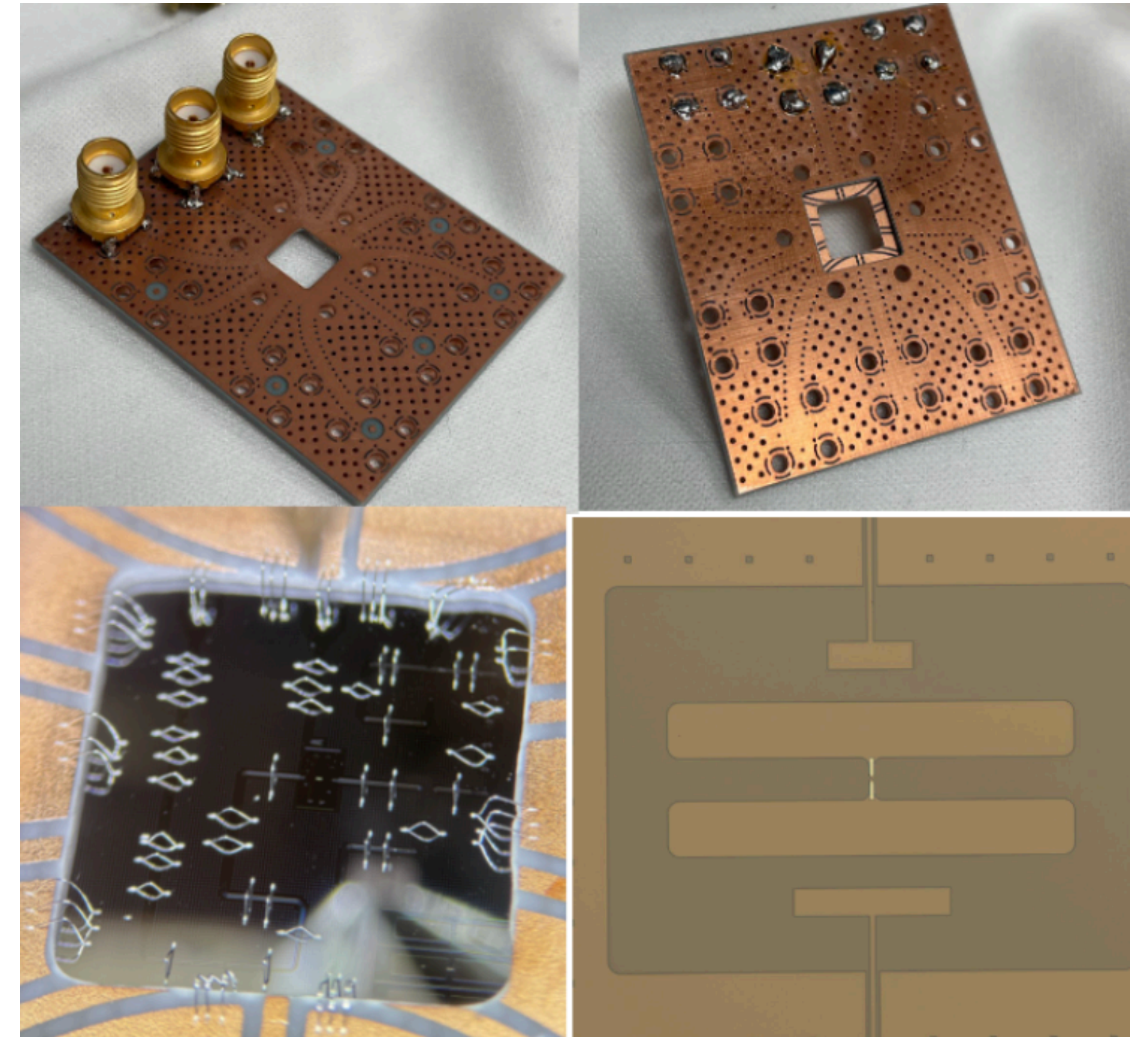


Quantum test beds at Stanford/SLAC



RF Quantum Upconverters

Kuenstner, Stephen E., et al. "Quantum metrology of low-frequency electromagnetic modes with frequency upconverters." *Physical Review Research* 7.1 (2025): 013281.



Single Microwave Photon Detectors

Kuo, Chao-Lin, et al. "Maximizing quantum enhancement in axion dark matter experiments." *Physical Review D* 111.12 (2025): 123018.

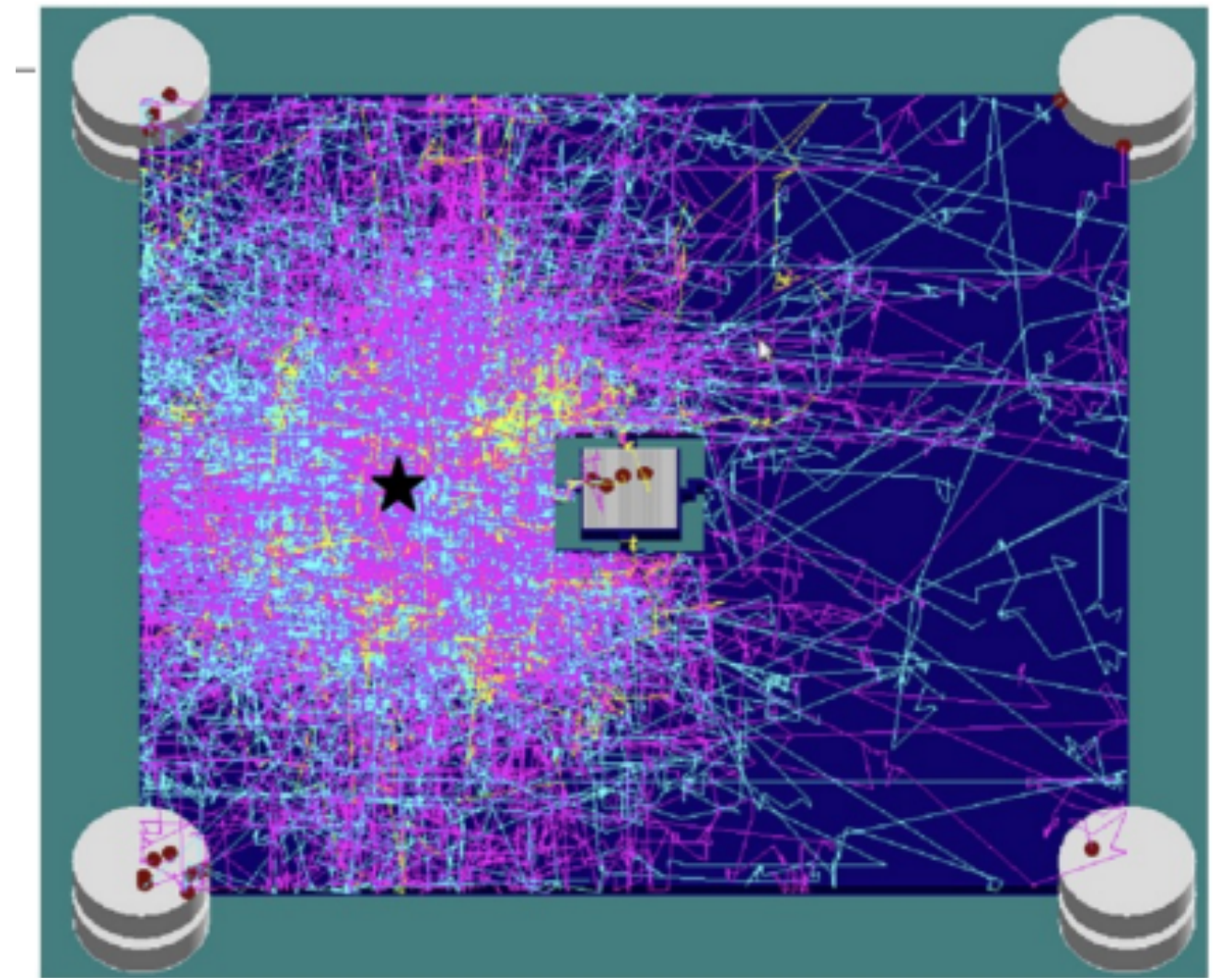
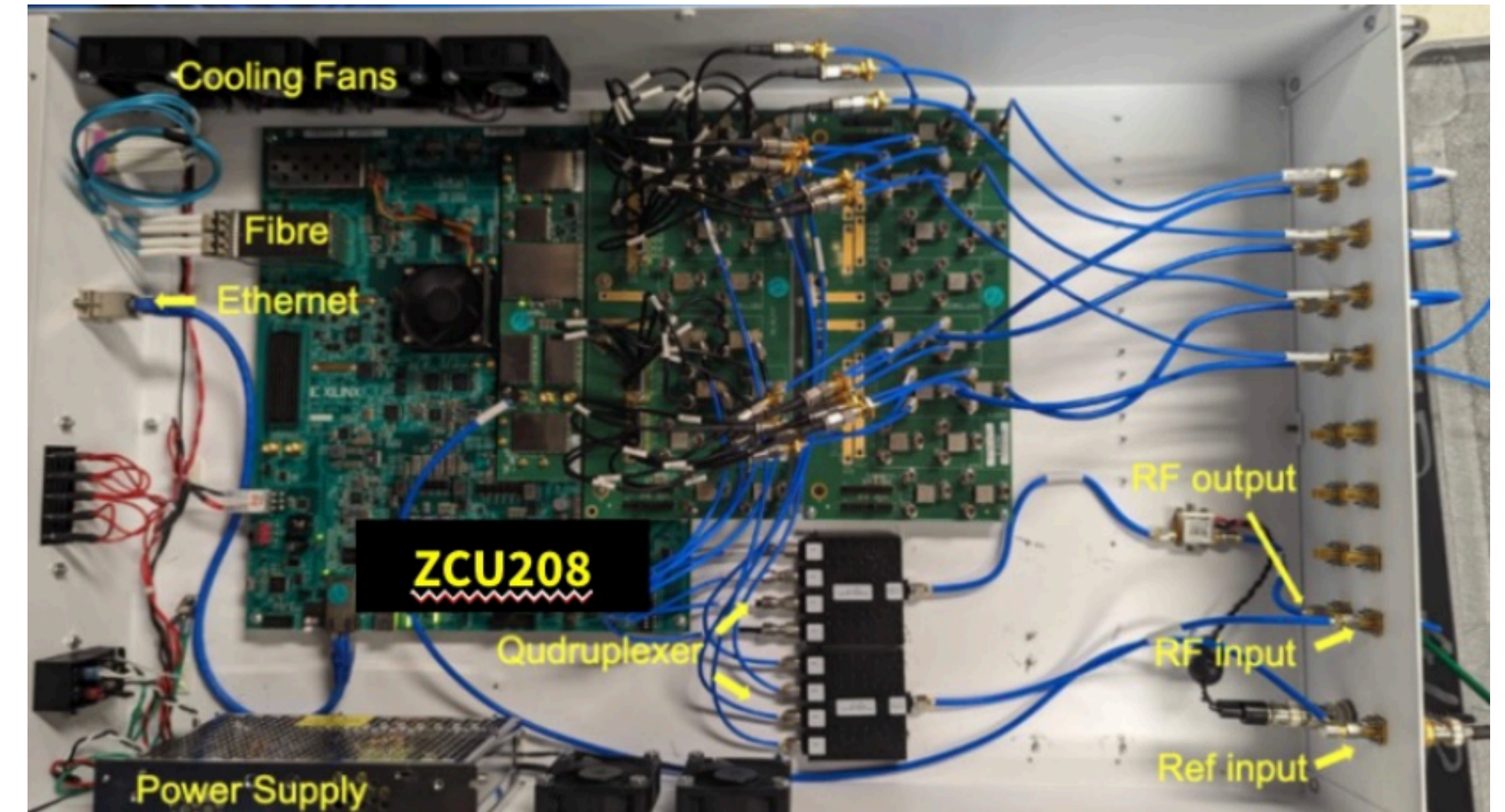
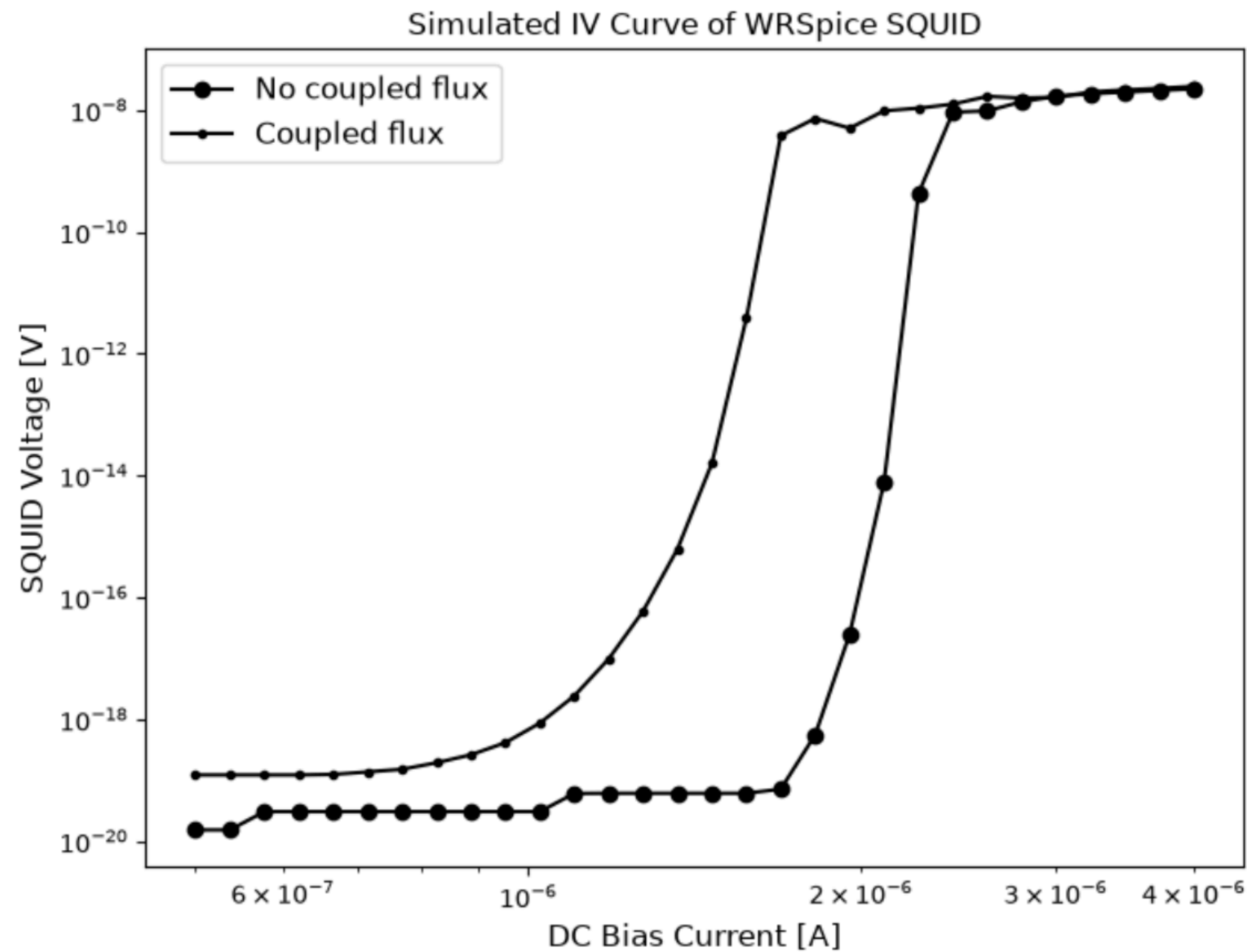
It's been a busy week!

Thanks to all the students and post-docs who volunteered to help!



Projects....

WRSPICE, G4CMP, SMuRF



G4CMP: Condensed Matter Physics Simulation Using the Geant4 Toolkit

What are we calling “quantum”?

Lots of ideas this workshop...

- Dan Carney: John Bell (?)
- Konrad Lehnert: PMTs (?)
- Others?

What is “quantum”?

<https://journals.aps.org/prxquantum/pdf/10.1103/PRXQuantum.4.020101>

A. What is “quantum”?

Do we need to define what is meant by “quantum,” in order to consider how quantum science can be used to search for dark matter? After all, it is the scientific reach of a particular technology that ultimately determines its promise, rather than an arguably arbitrary attribute of “quantumness” [52]. Is a photomultiplier a quantum sensor? It counts photons, quanta of electromagnetic field, with sensitivity beyond the standard quantum limit of a linear amplifier measuring the electromagnetic field. Is a superconducting quantum interference device (SQUID) a quantum sensor? It makes use of the Josephson effect—the quantum interference of the superconducting wave function, split into two paths, interrupted by Josephson junctions. And it has the word “quantum” in the acronym. Answers to such questions are matters of perspective but, inevitably, they do guide the scope of this Perspective. However, it is important to keep in mind that the ultimate focus is on the potential sensitivity improvements, the feasibility, and the scientific merit of an approach.

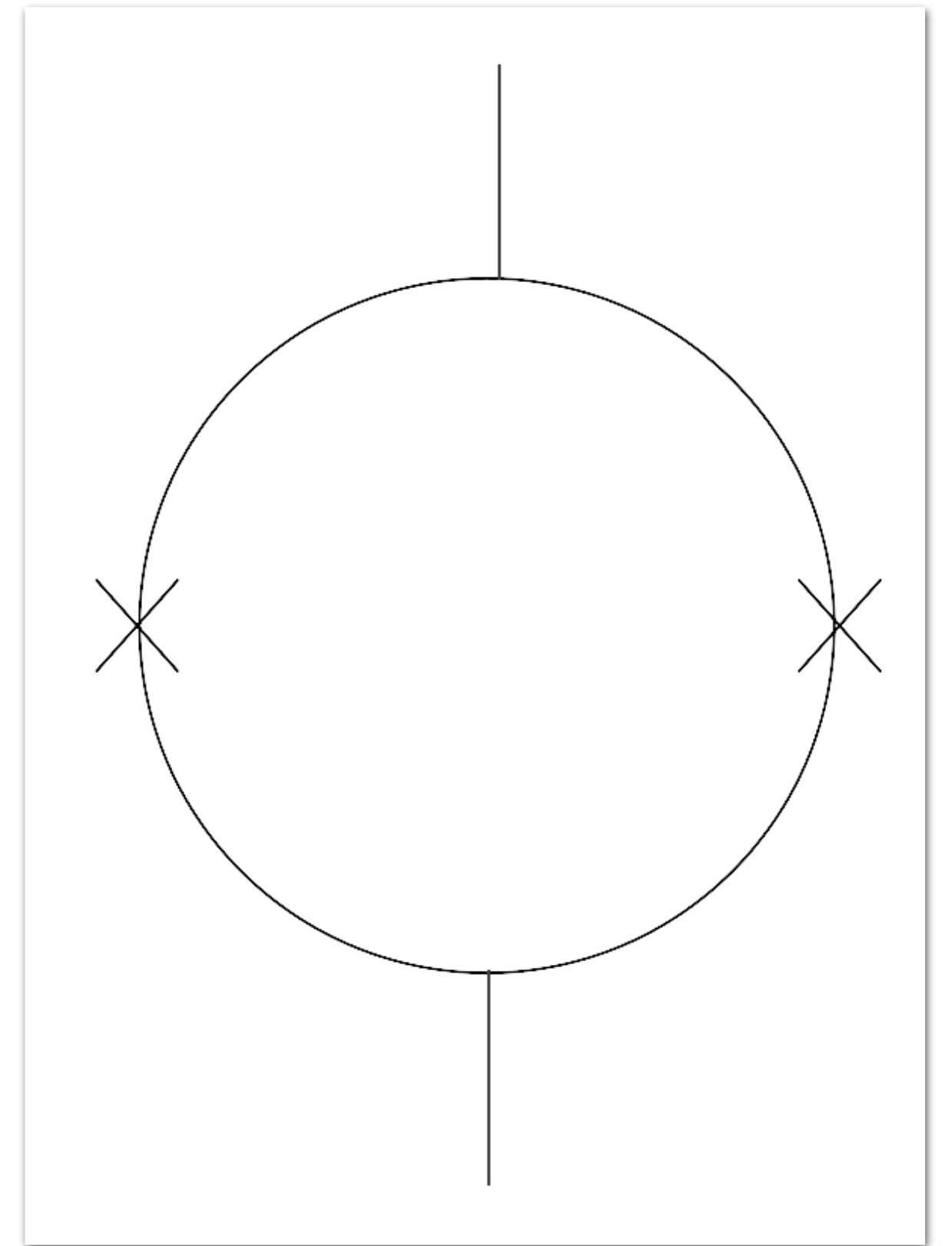
Let us loosely define the “first quantum revolution,” which gave birth to “quantum 1.0” technologies, based on lasers, semiconductor, and superconductor devices. The promise of the “second quantum revolution” is the development of “quantum 2.0” technologies, with the potential to result in impressive performance leaps. For example, a number of approaches aim to evade the standard quantum limit (SQL) of measurement, by making use of entanglement, squeezing, back-action evasion, or strong correlations. More broadly, QIS has developed many ideas for how to optimize preparation, transmission, control, and measurement of correlated quantum states in systems such as spin ensembles, atomic interferometers and clocks, color centers, and superconducting devices.

Sushkov, Alexander O. "Quantum science and the search for axion dark matter." *PRX Quantum* 4.2 (2023): 020101.

Quantum 1.0

At or above the Standard Quantum Limit

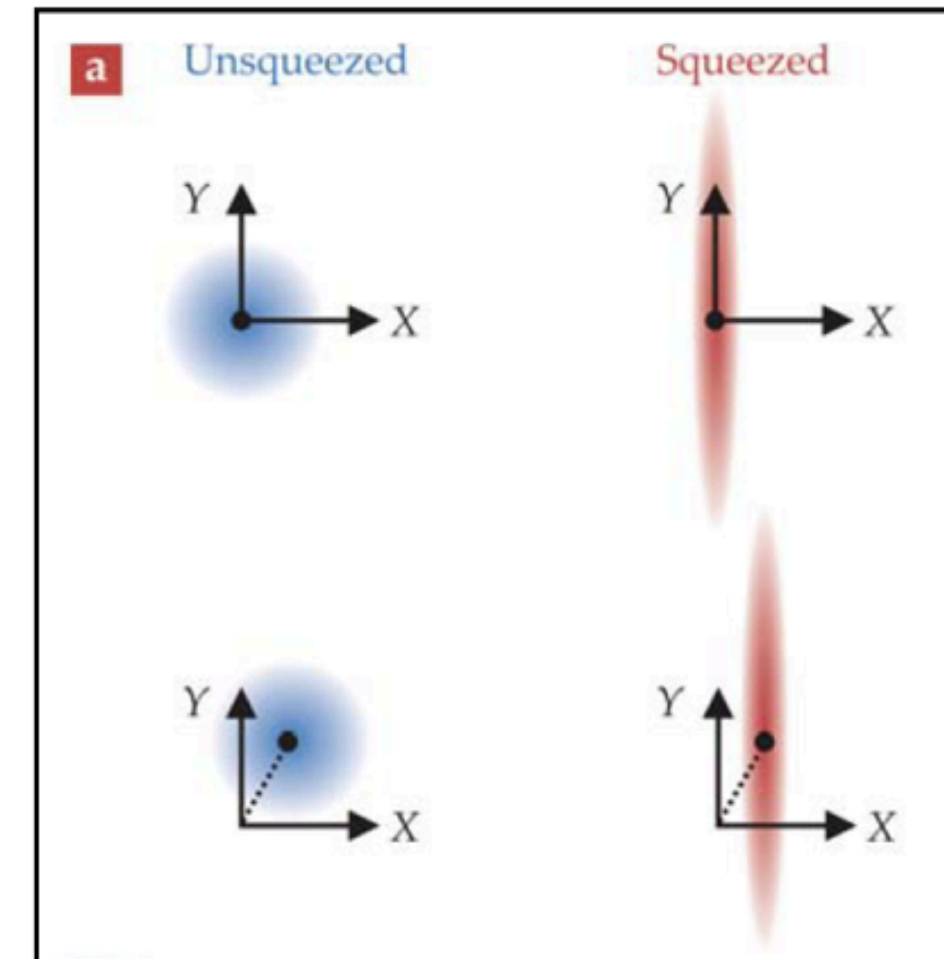
- Josephson junctions: involve quantum mechanical effect through the phase
- Ergo, amplifiers built with Josephson junctions
 - SQUIDs, JPAs, TWPAs
- Semiconductors
- Lasers



Quantum 2.0

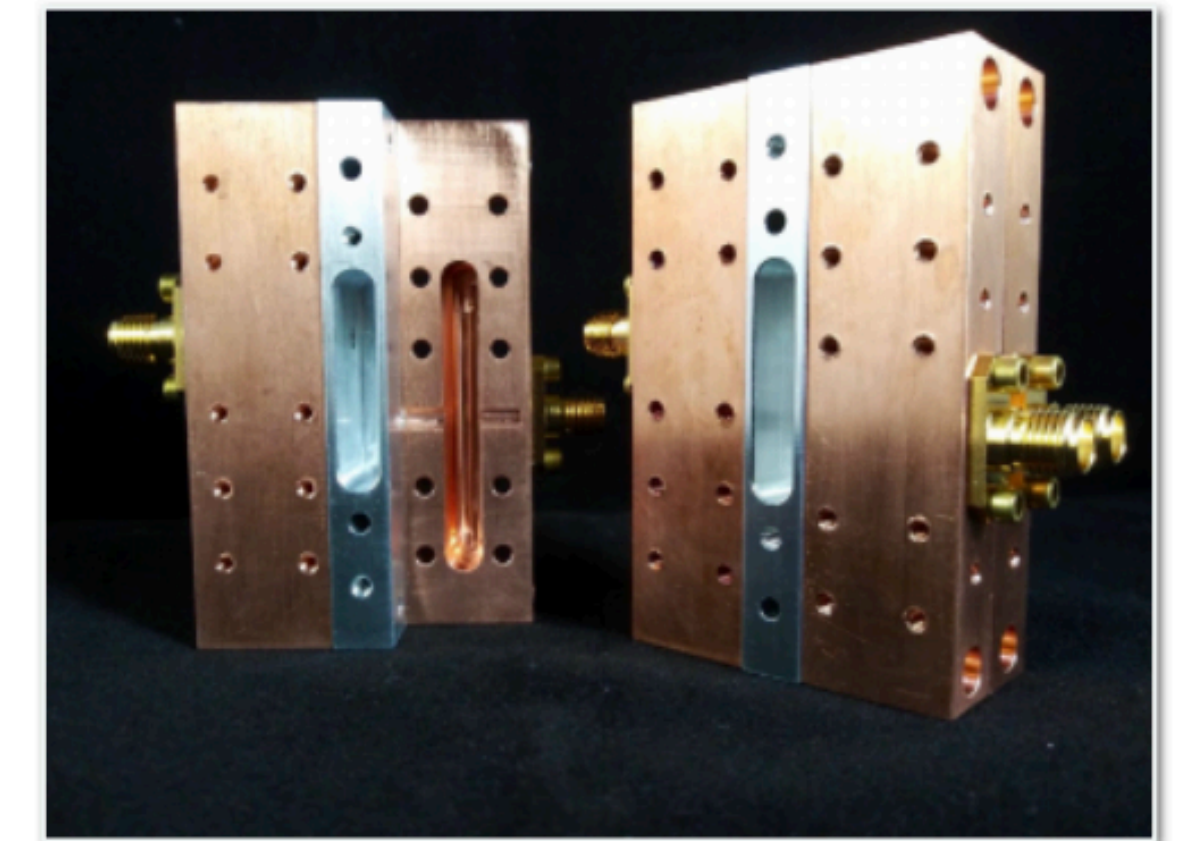
Requires beyond Standard Quantum Limit sensing or sufficiently advanced sensitivity

- Squeezing
- Backaction evasion
- Entanglement
- Photon counting



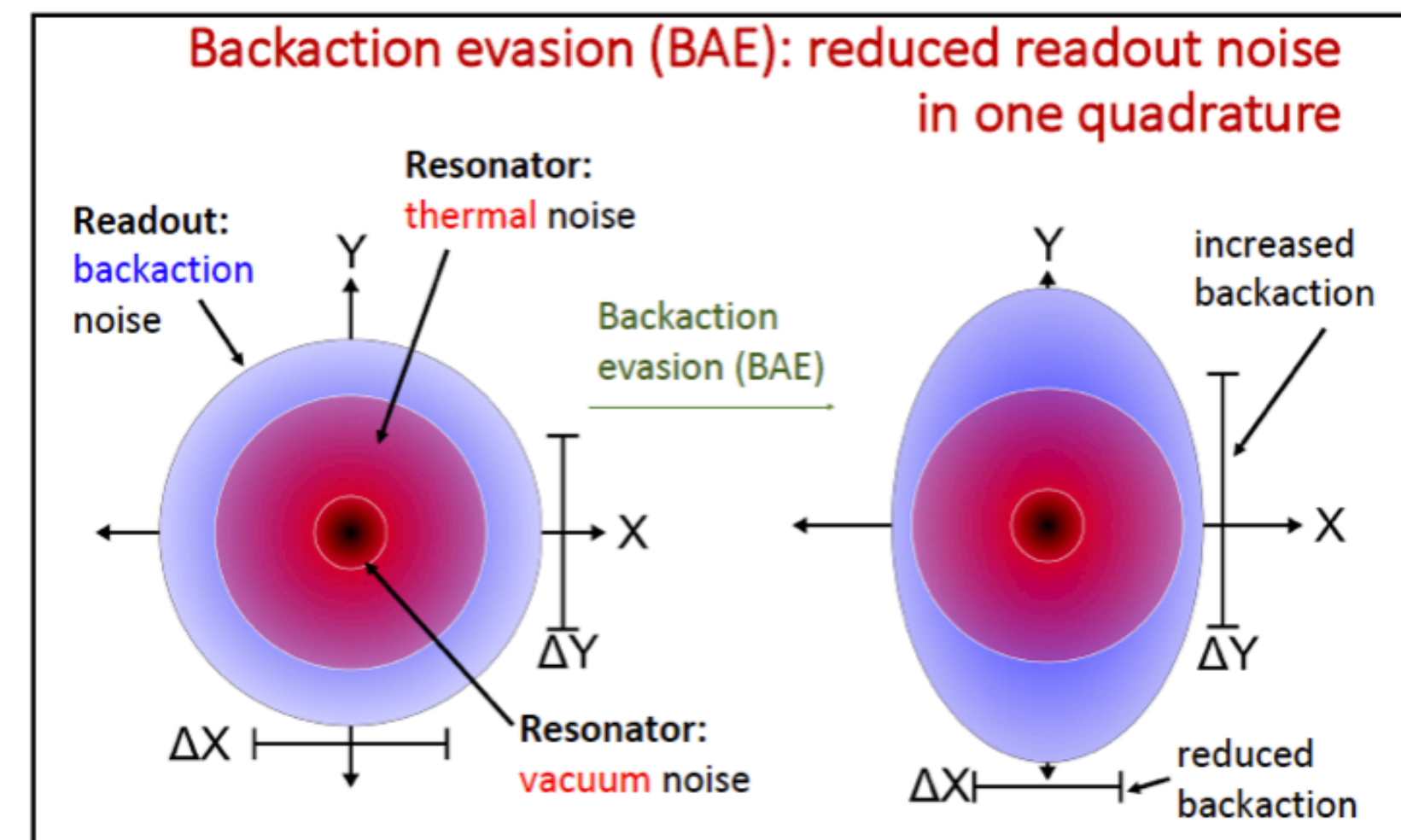
HAYSTAC

[Physics Today](#) 72, 6, 48 (2019);



Hidden photon qubit search

Akash Dixit and Aaron Chou



Quantum Upconverters
- K. Irwin

Yale Quantum Sensing workshop, 2023

<https://arxiv.org/pdf/2311.01930>

Quantum Sensors for High Energy Physics

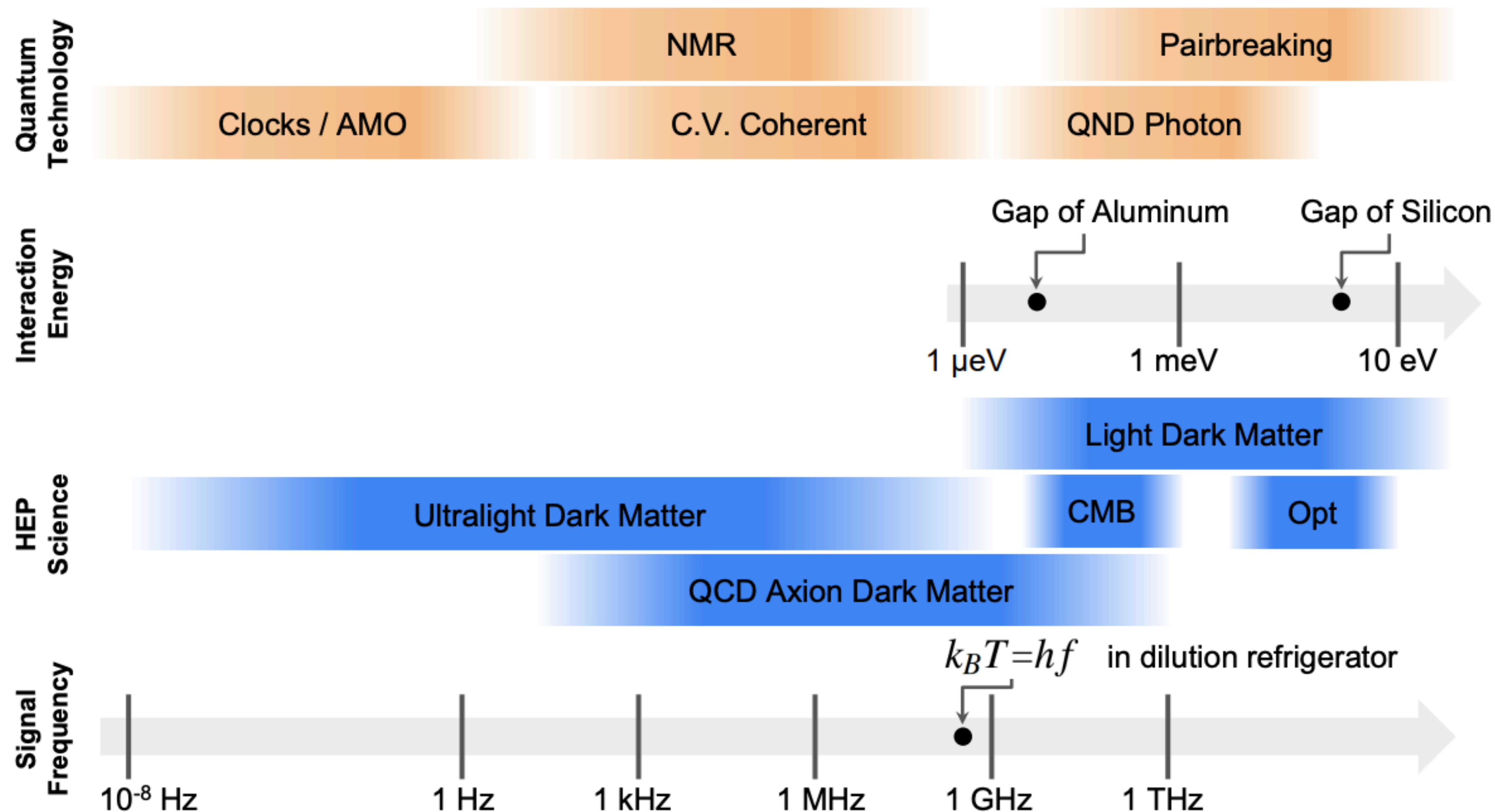
Aaron Chou¹, Kent Irwin^{2,3}, Reina H. Maruyama^{4,5}, Oliver K. Baker⁴, Chelsea Bartram³, Karl K. Berggren⁶, Gustavo Cancelo¹, Daniel Carney⁷, Clarence L. Chang^{8,9,10}, Hsiao-Mei Cho³, Maurice Garcia-Sciveres⁷, Peter W. Graham², Salman Habib¹⁰, Roni Harnik¹, J. G. E. Harris⁴, Scott A. Hertel¹¹, David B. Hume¹², Rakshya Khatiwada^{13,1}, Timothy L. Kovachy¹⁴, Noah Kurinsky³, Steve K. Lamoreaux^{4,5}, Konrad W. Lehnert^{15,16}, David R. Leibbrandt¹⁷, Dale Li³, Ben Loer¹⁸, Julián Martínez-Rincón¹⁹, Lee McCuller²⁰, David C. Moore^{4,5}, Holger Mueller^{21,7}, Cristian Pena¹, Raphael C. Pooser²², Matt Pyle²¹, Surjeet Rajendran²³, Marianna S. Safronova^{24,25}, David I. Schuster^{2,3}, Matthew D. Shaw²⁶, Maria Spiropulu²⁰, Paul Stankus¹⁹, Alexander O. Sushkov²⁷, Lindley Winslow²⁸, Si Xie¹, and Kathryn M. Zurek²⁰

Strong motivation for investing in quantum sensing arises from the need to investigate phenomena that are very weakly coupled to the matter and fields well described by the Standard Model. These can be related to the problems of dark matter, dark sectors not necessarily related to dark matter (for example sterile neutrinos), dark energy and gravity, fundamental constants, and problems with the Standard Model itself including the Strong CP problem in QCD. Resulting experimental needs typically involve the measurement of very low energy impulses or low power periodic signals that are normally buried under large backgrounds.

With a focus on HEP applications, we propose to adopt a broad definition of the term quantum sensor as any new quantum device or technique that has the potential to achieve greater reach towards beyond-the-standard-model physics than that achievable through conventional techniques traditionally used in HEP.

Some definitions used elsewhere such as “Quantum 2.0” as “a class of devices that actively create, manipulate and read out quantum states of matter, often using the quantum effects of superposition and entanglement” highlight an important class of these techniques. These include sensors that evade “Standard Quantum Limits” (SQLs) that are imposed by classical sensors. However, while Quantum 2.0 devices have an important role in HEP applications in the future, focusing only on this category is viewed as too constraining of the future HEP quantum program, which should more broadly explore new experimental quantum techniques and sensing strategies, in particular newly maturing technologies which have leveraged broader investment in R&D from the new QIS programs and from other non-HEP sources.

Yale Quantum Sensing workshop, 2023



Yale Quantum Sensing workshop, 2023

<https://arxiv.org/pdf/2311.01930>

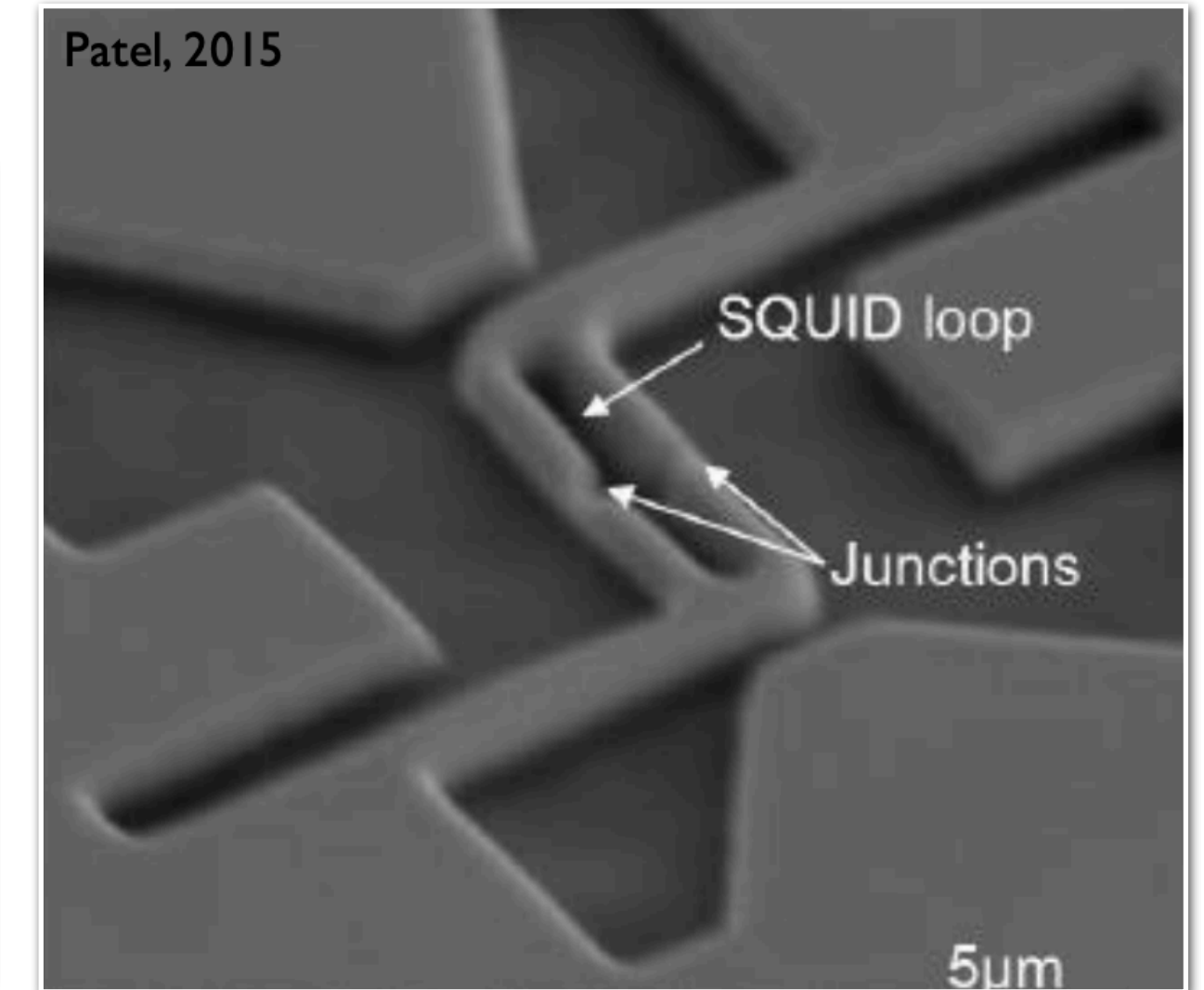
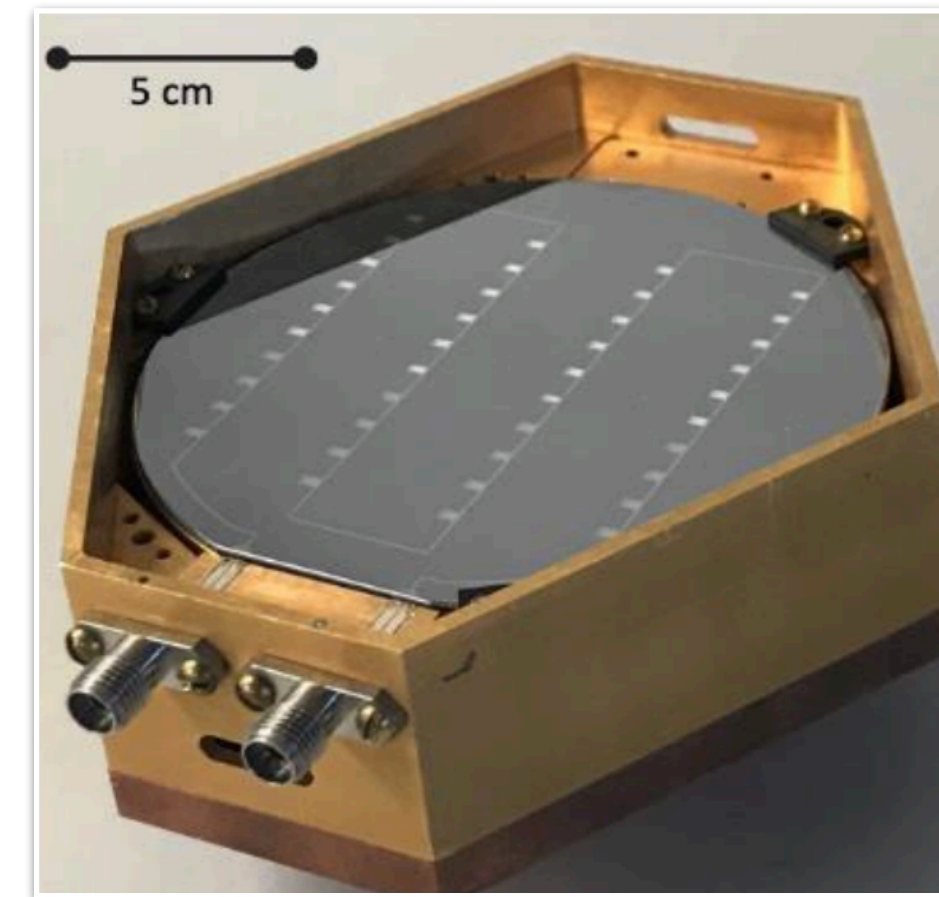
	Dark waves	Dark particles	Cosmology, dark energy, phase transitions	Testing quantum mechanics	Quantum gravity	Telescopes	Collider, fixed target, high event rate	Symmetry violations
SC qubits. SC cavities, SC continuous variables (JPAs, RQUs, KI-TWPAs, etc), squeezing, bae,transduction	x	x		x				x
SC pairbreaking sensors (QCD, TES,MKID, SNSPD)	x	x	x		x	x	x	
Microcalorimetry, single phonon		x						
AMO, clocks, atom and photon interferometry	x	x	x	x	x	x		x
NMR	x	x	x					x
Optomechanics (squeezing, back-action evasion, etc)	x	x		x	x			
Quantum networks	x		x			x		
Sensor arrays, high channel count	x	x	x			x	x	
Quantum materials, metamaterials	x	x				x		
Foundry facilities	x	x	x	x			x	x

Figure 2: Workshop participants populated this table of HEP science targets versus potentially applicable quantum technologies and explored the use cases at each intersection via key questions listed in appendix D.

Where we are now

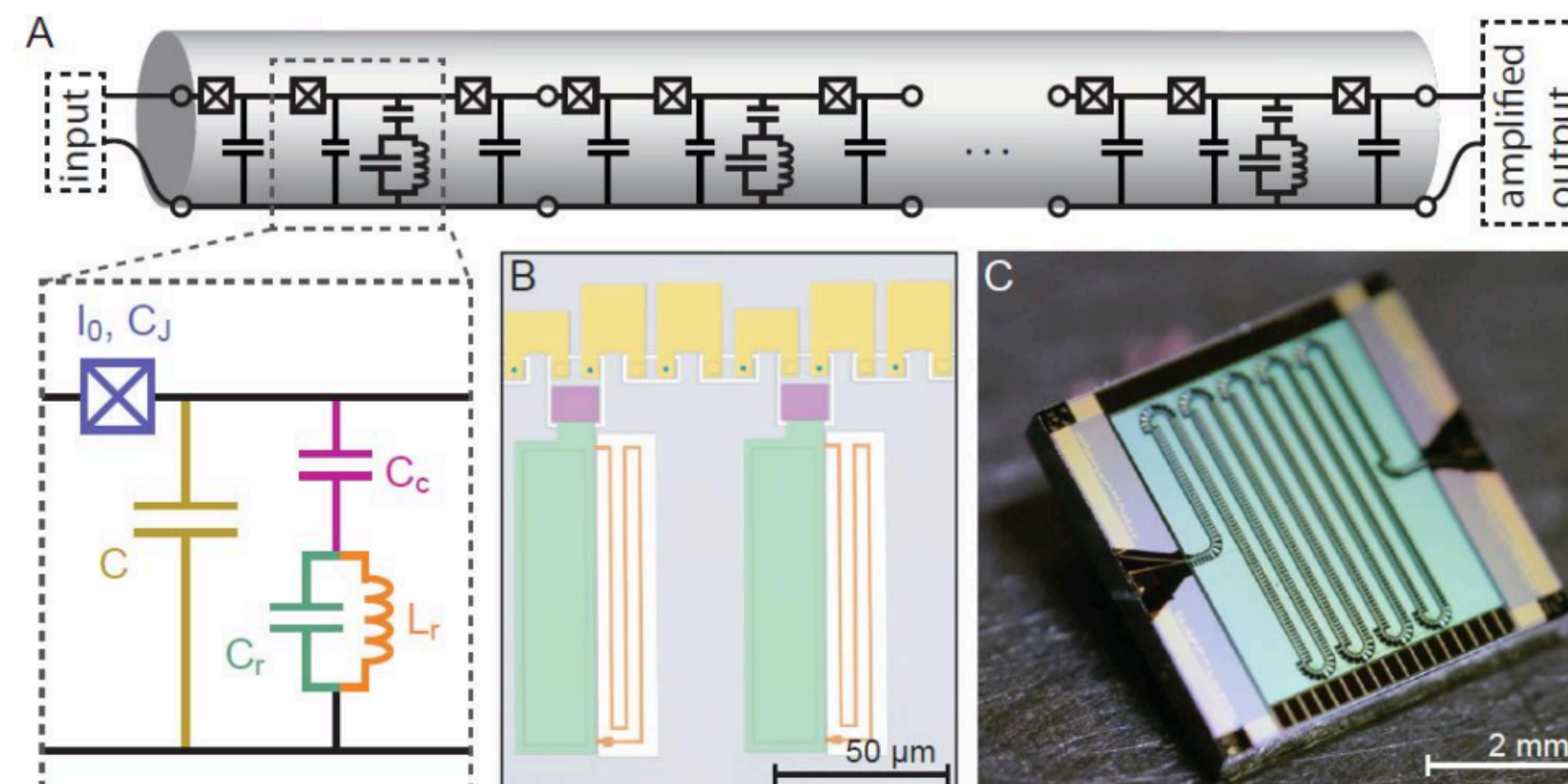
Learned about a zoo of sensors

- TES
- mKIDs
- SNSPDs
- SQUIDS
- JPAs
- TWPAs
- More...



Kevin O'Brien:
continuous
variable amplifiers

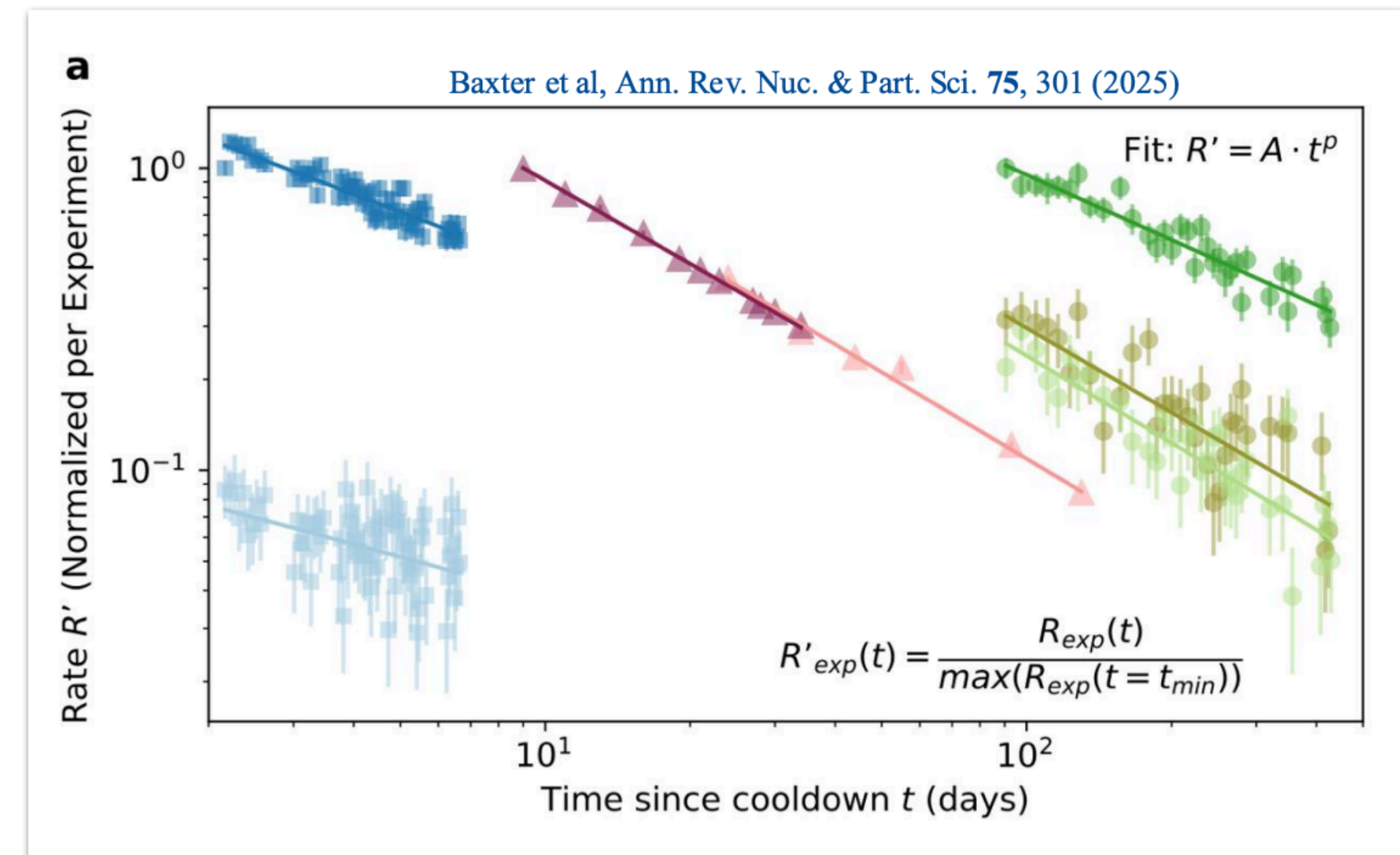
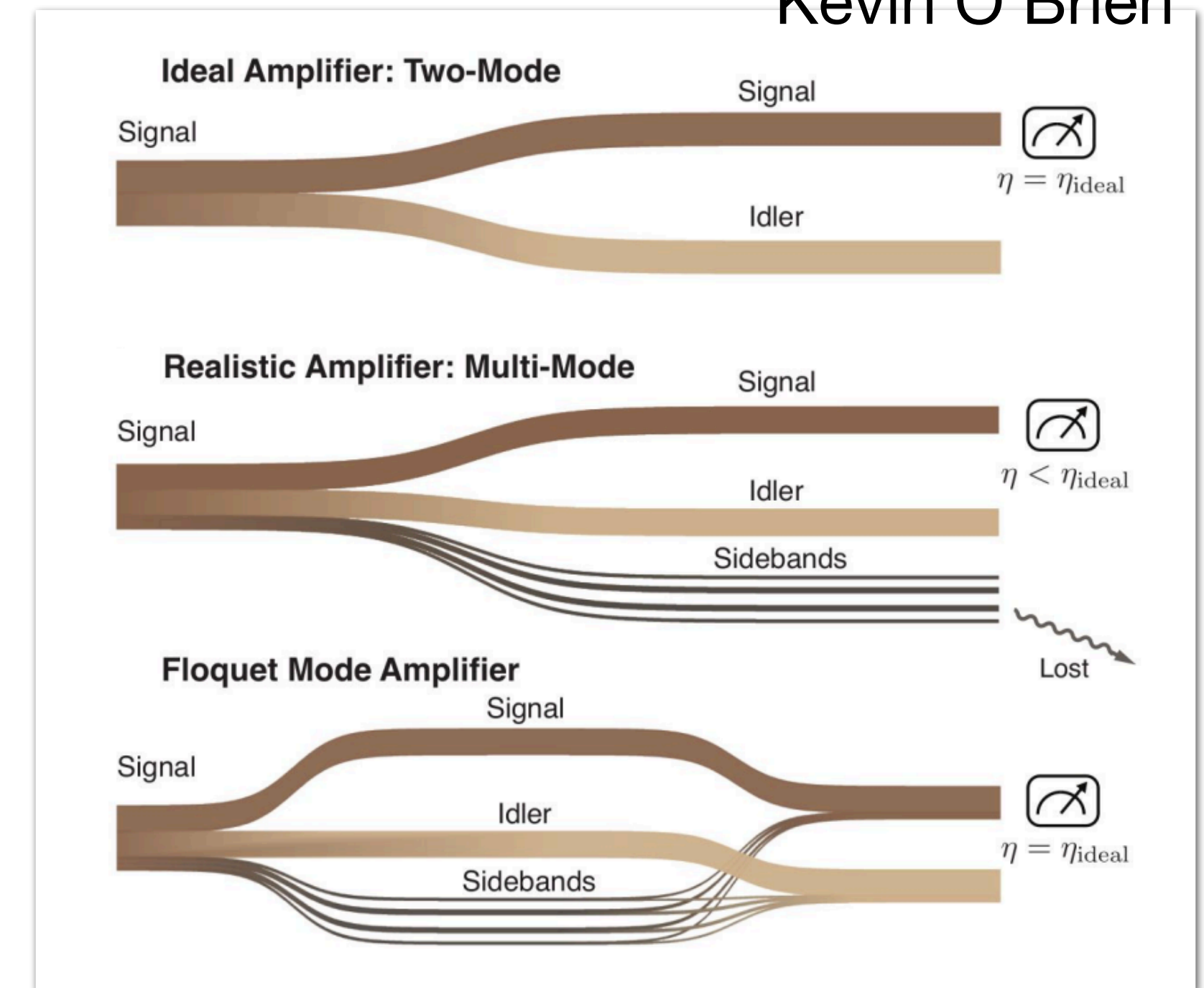
Karthik
Ramanathan: pair
breaking sensors



Sensor development

- Identifying source of low quantum efficiency in continuous variable sensors
- Understanding the low energy excess
- Leveraging the non-linearity of the Josephson junction in new ways (non-linear KIDs)
- Facilities with improved ability to reproduce circuits

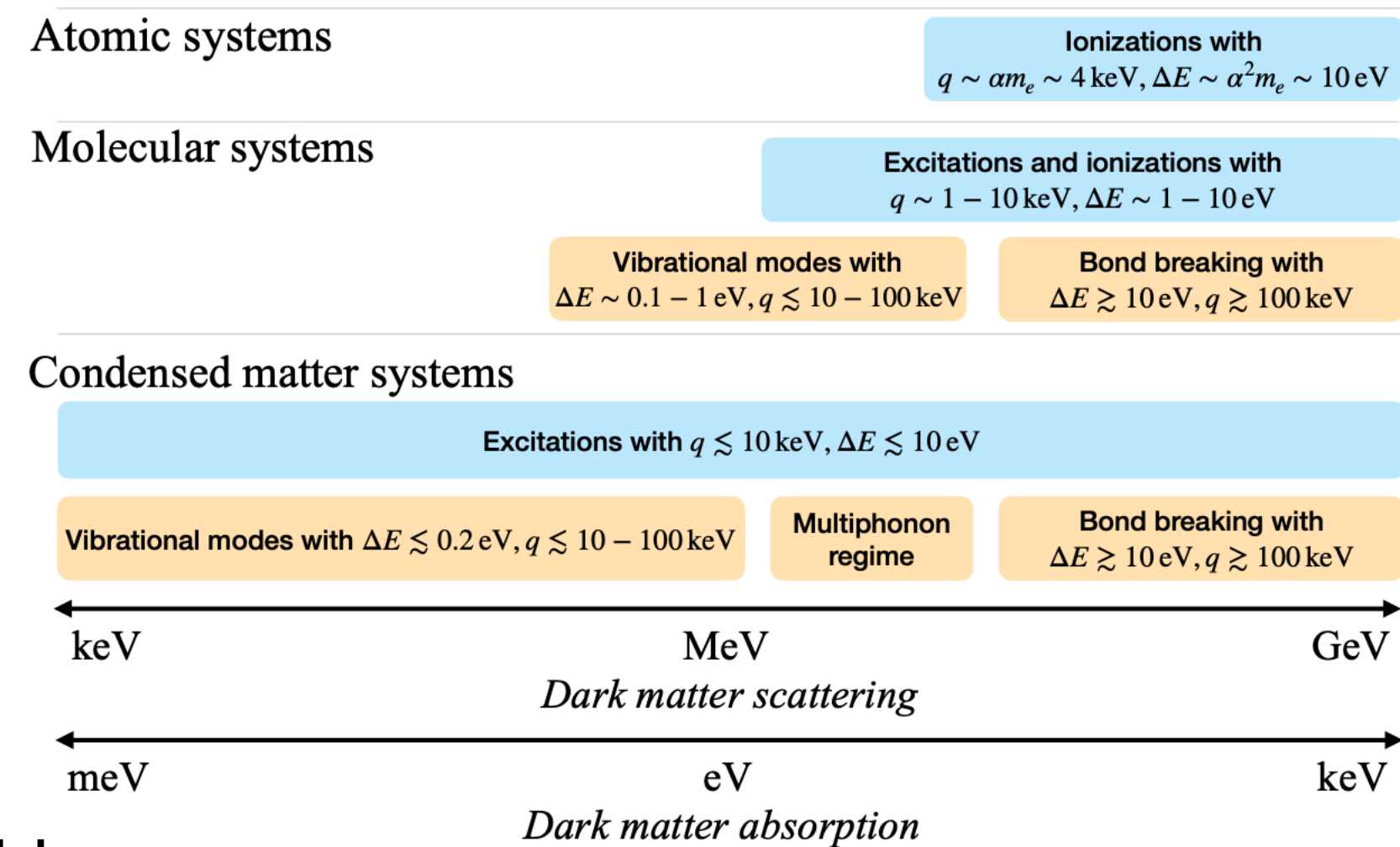
Kevin O'Brien



Dan Baxter

Applications to particle dark matter searches

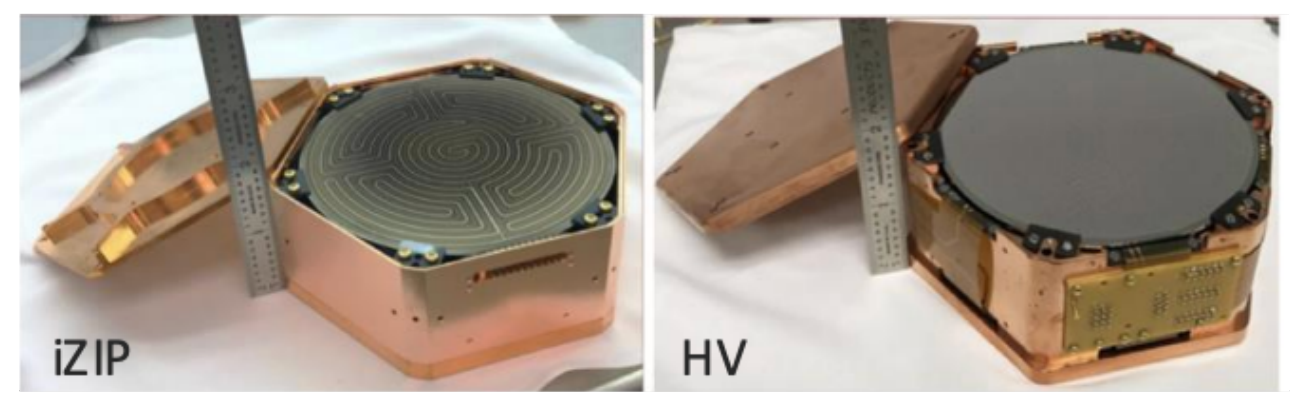
Utilize **diversity of excitation modes in nature** and **advances in neighboring fields** including materials science, quantum sensing.



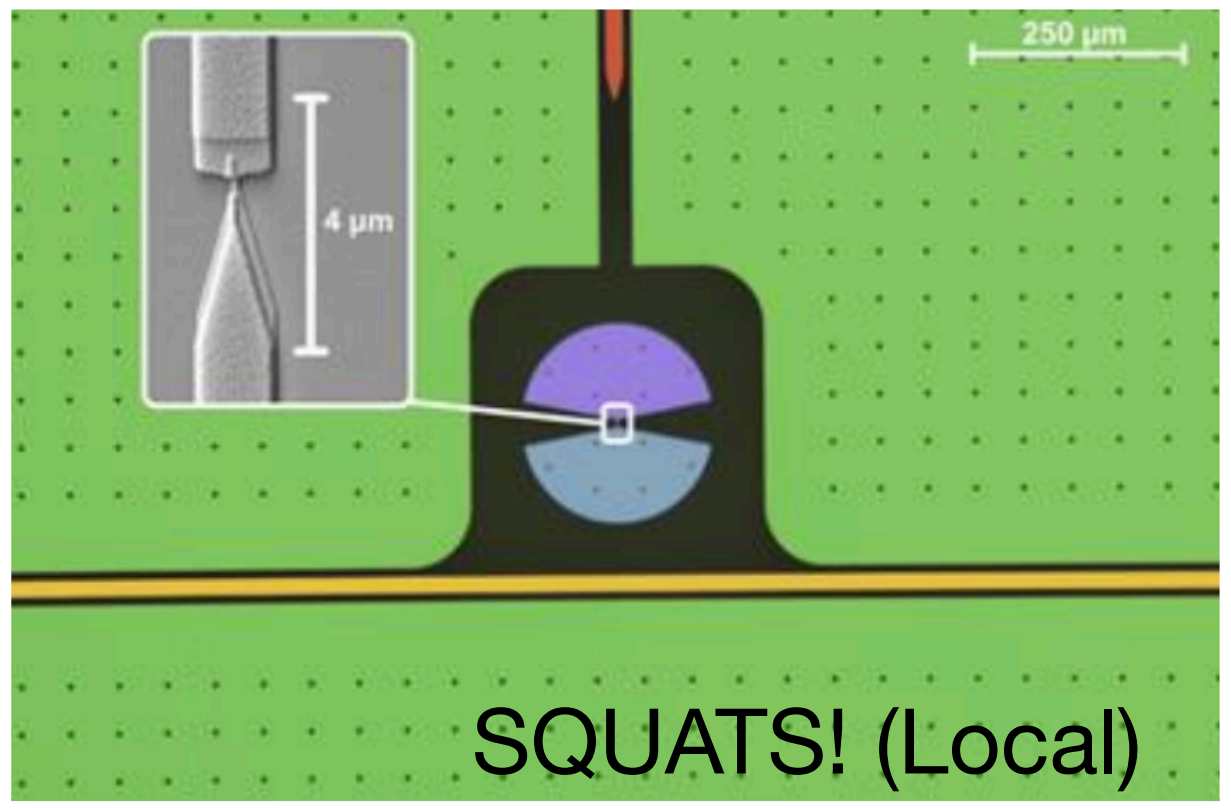
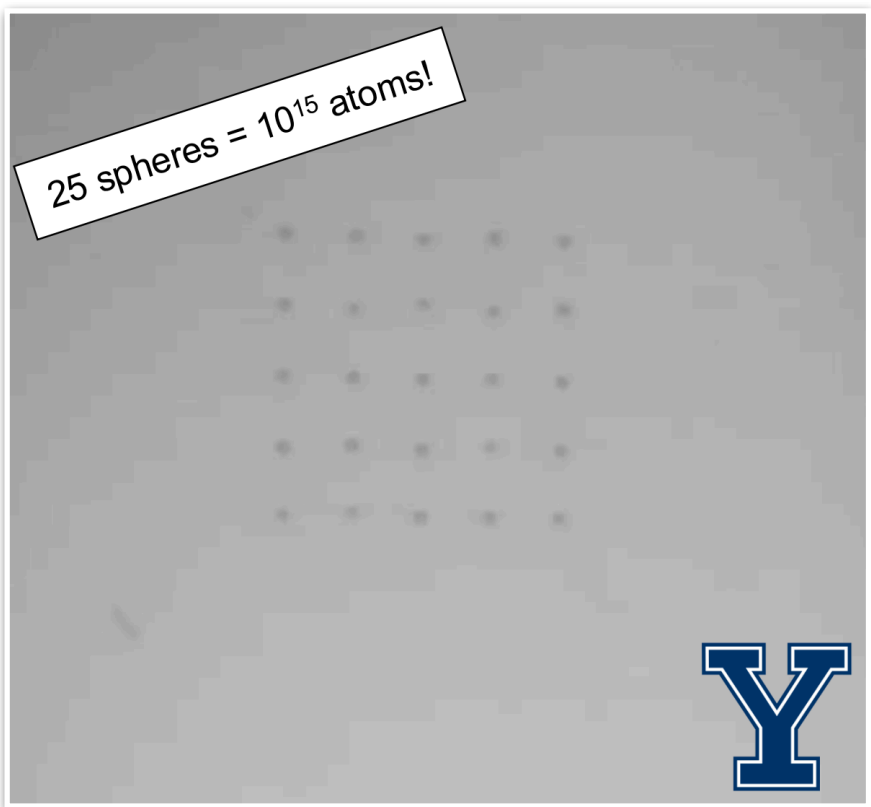
Tonyan Lin

New concepts		technologies	materials		
Atomic clocks	SRF Cavity	Qubits	Skipper CCD	Superfluid He	Polar crystals
NMR	LC Resonators	Metamaterials	TES	Organic molecules	Dirac material
		KIDs	SNSPDs		

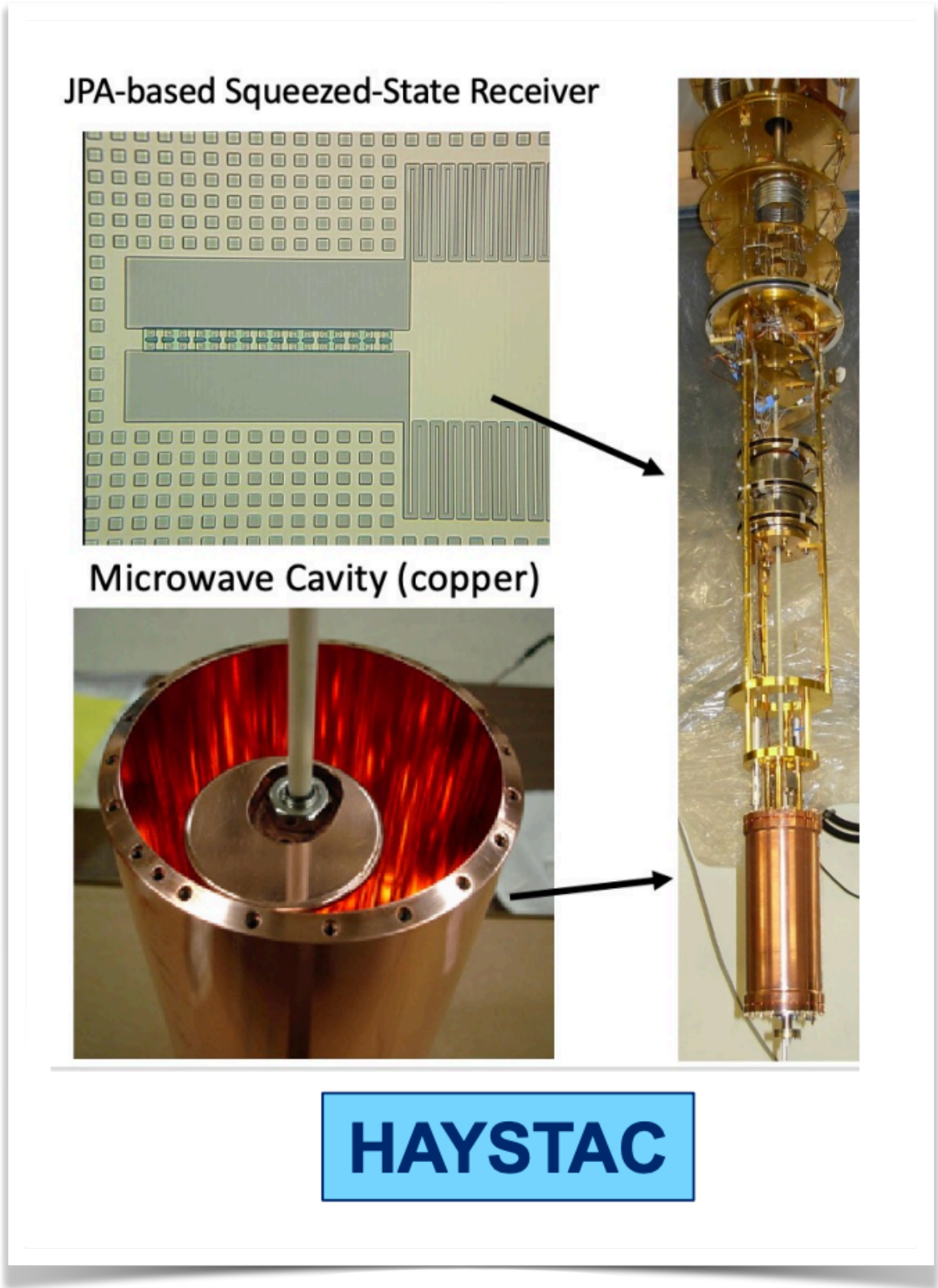
Tonyan Lin



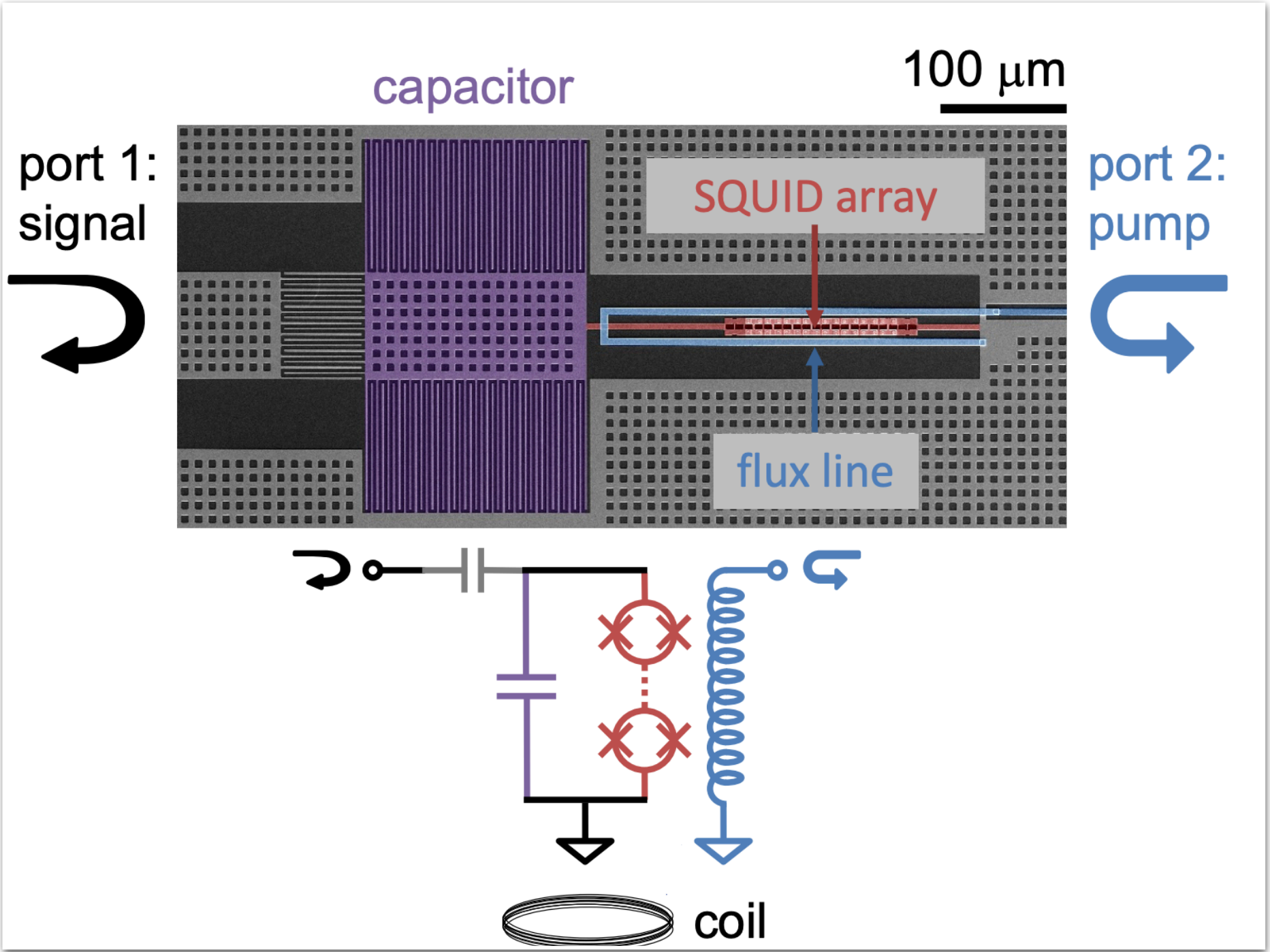
Daniel Baxter, Clarence Chang, David Moore



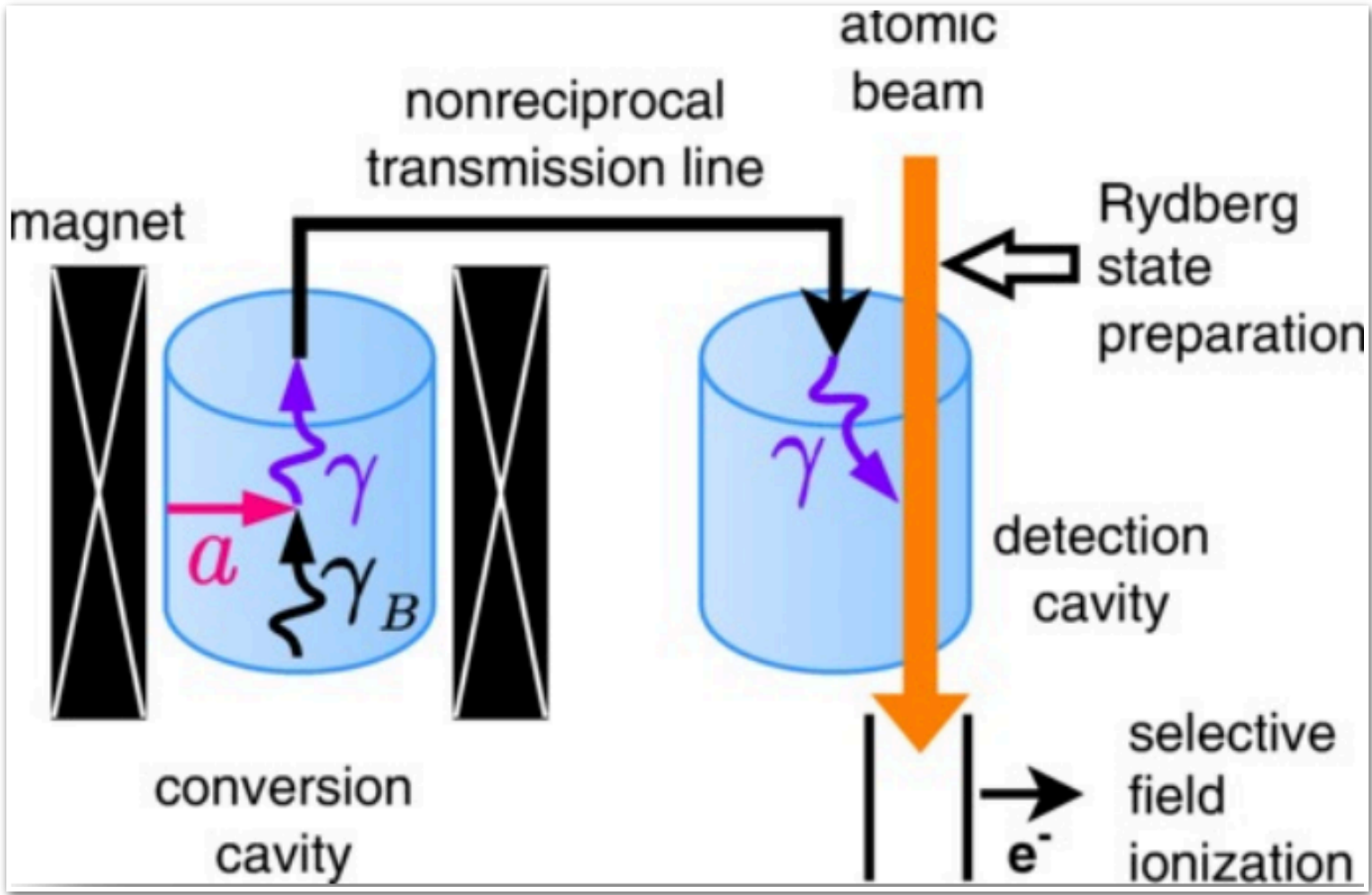
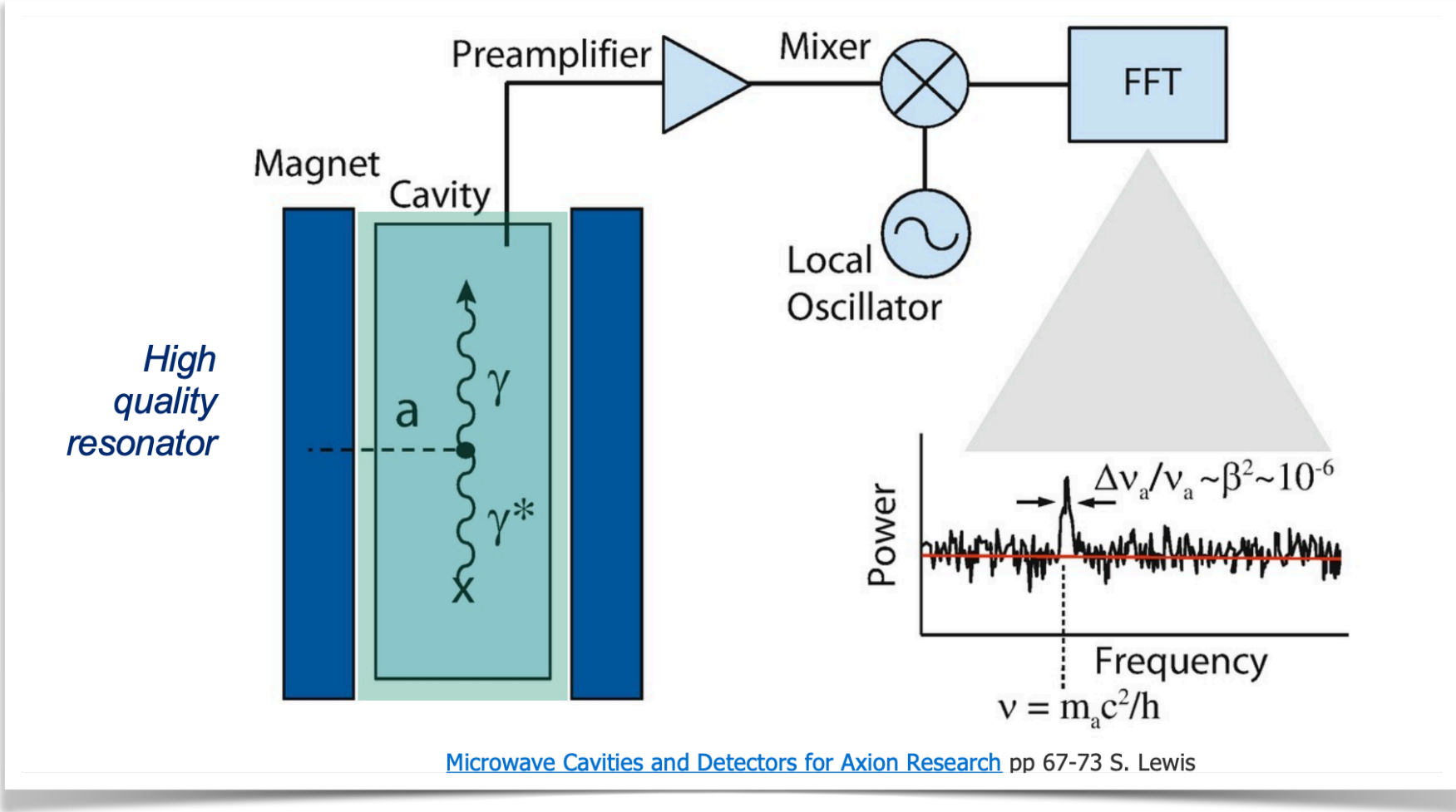
Applications to wavy dark matter searches



Danielle Speller



Konrad Lehnert



Danielle Speller

Applications to astrophysics

C.

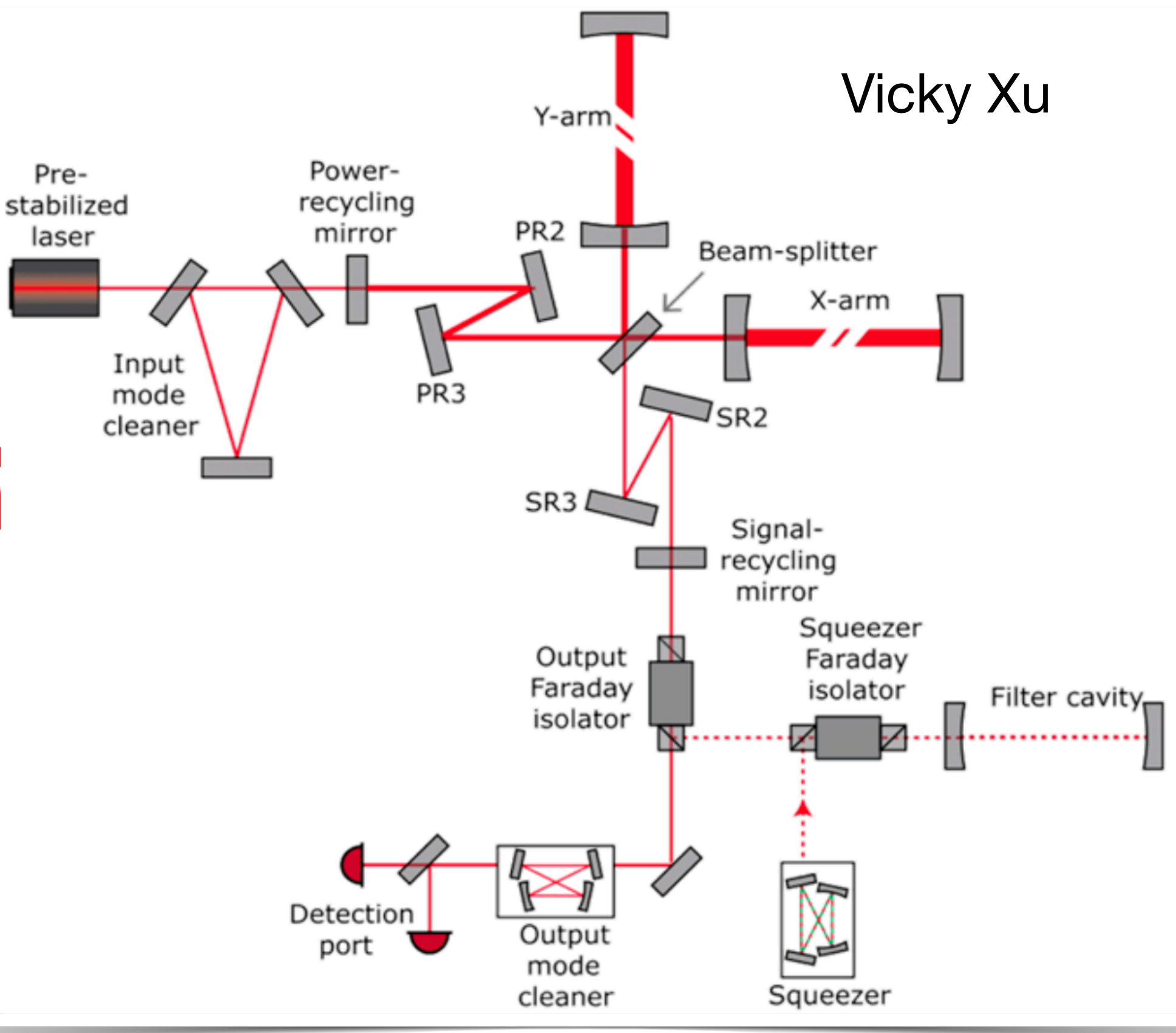

SPIRE-FTS
700 × 400 × 400 mm
resolving power, $R=840$

D.


SOFTS
6 × 1 × 0.5 mm
 $R=1330$

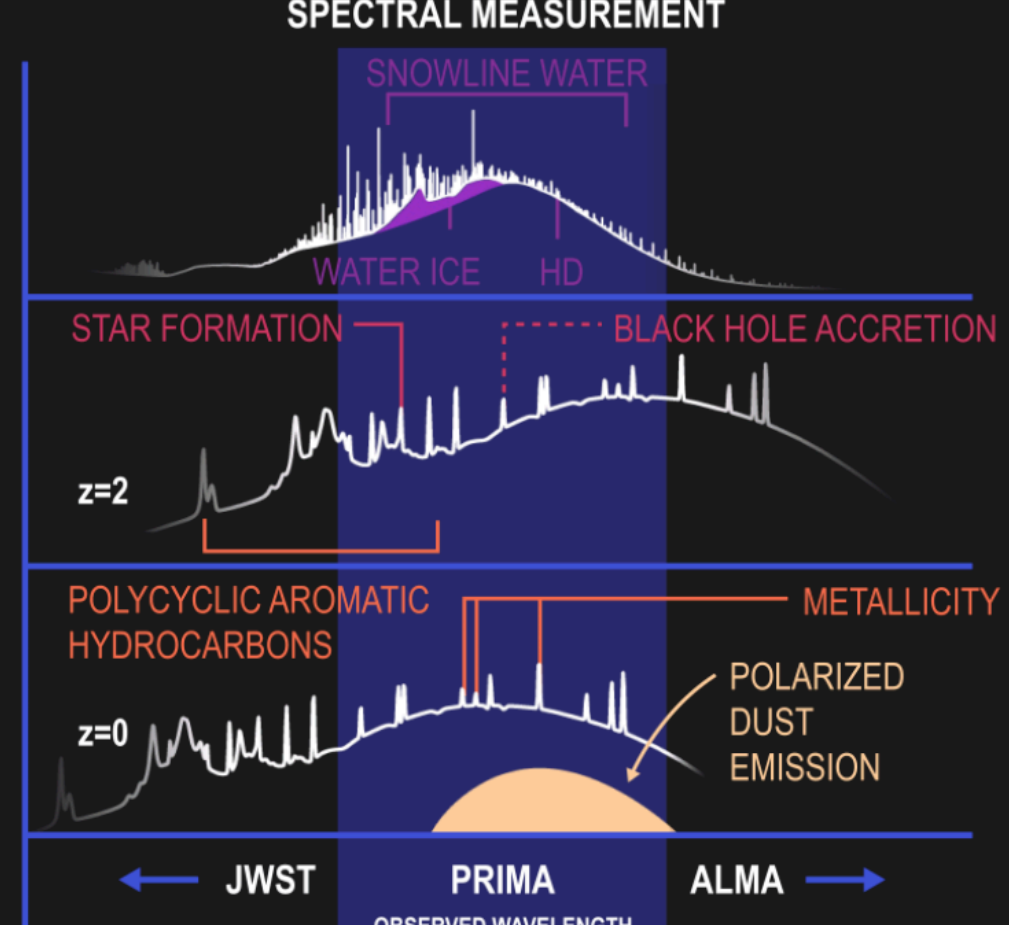
Basu Thakur et al, JLTP, Volume 211, Issue 5-6, p.227-236

Vicky Xu



The diagram illustrates a complex laser interferometer system. It begins with a 'Pre-stabilized laser' that passes through an 'Input mode cleaner' and a 'Power-recycling mirror'. The beam is then split into two paths: a 'Y-arm' and an 'X-arm'. The 'Y-arm' includes a 'PR2' mirror and a 'Beam-splitter'. The 'X-arm' includes a 'PR3' mirror and a 'Beam-splitter'. Both arms recombine at a central 'Beam-splitter'. The resulting beam passes through a 'Signal-recycling mirror' and an 'Output Faraday isolator'. It then enters a 'Squeezer' section, which includes a 'Squeezer Faraday isolator' and a 'Filter cavity'. The final output is directed to a 'Detection port' and an 'Output mode cleaner'. The diagram also shows a 'Squeezer' component at the bottom, which is part of the signal processing chain.

SPECTRAL MEASUREMENT

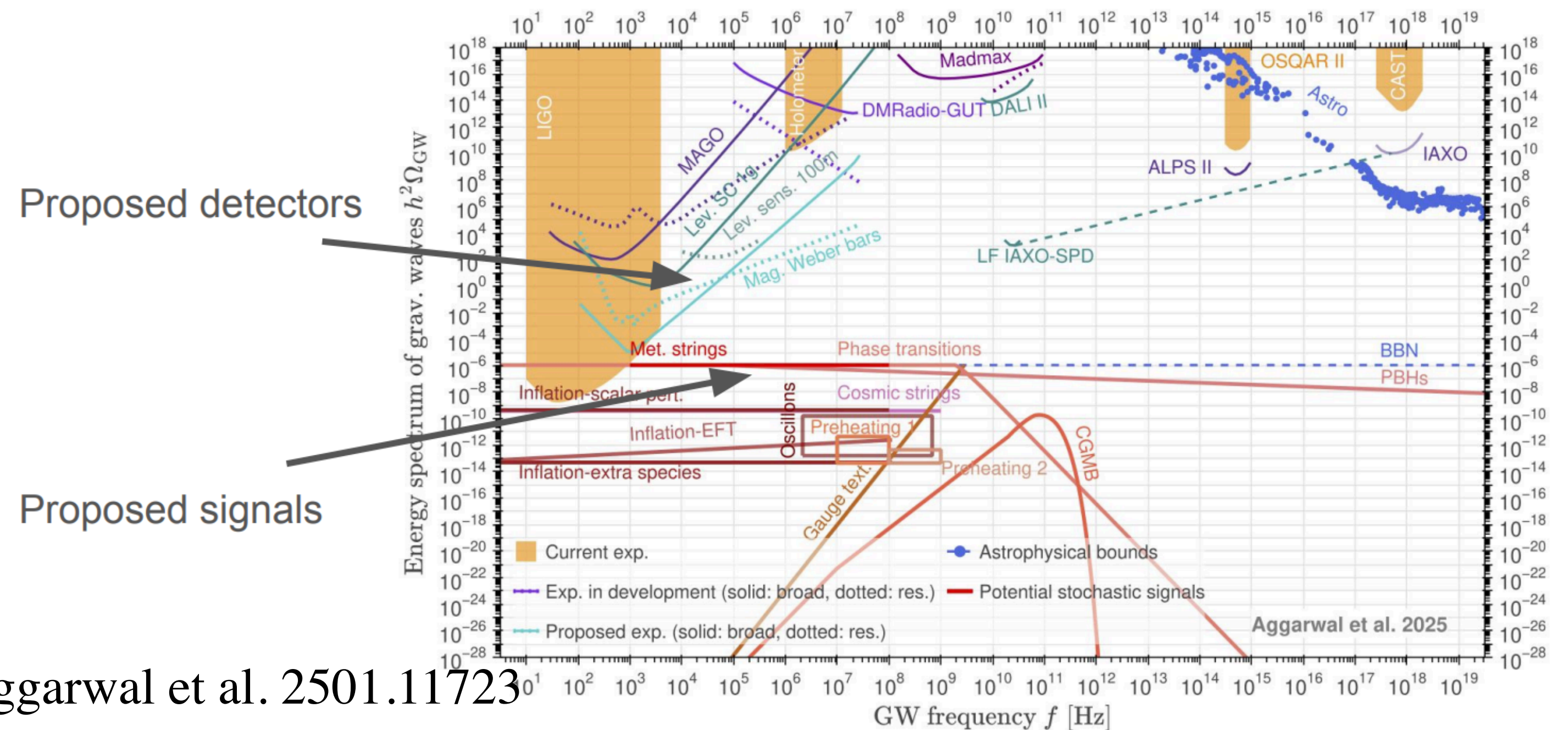
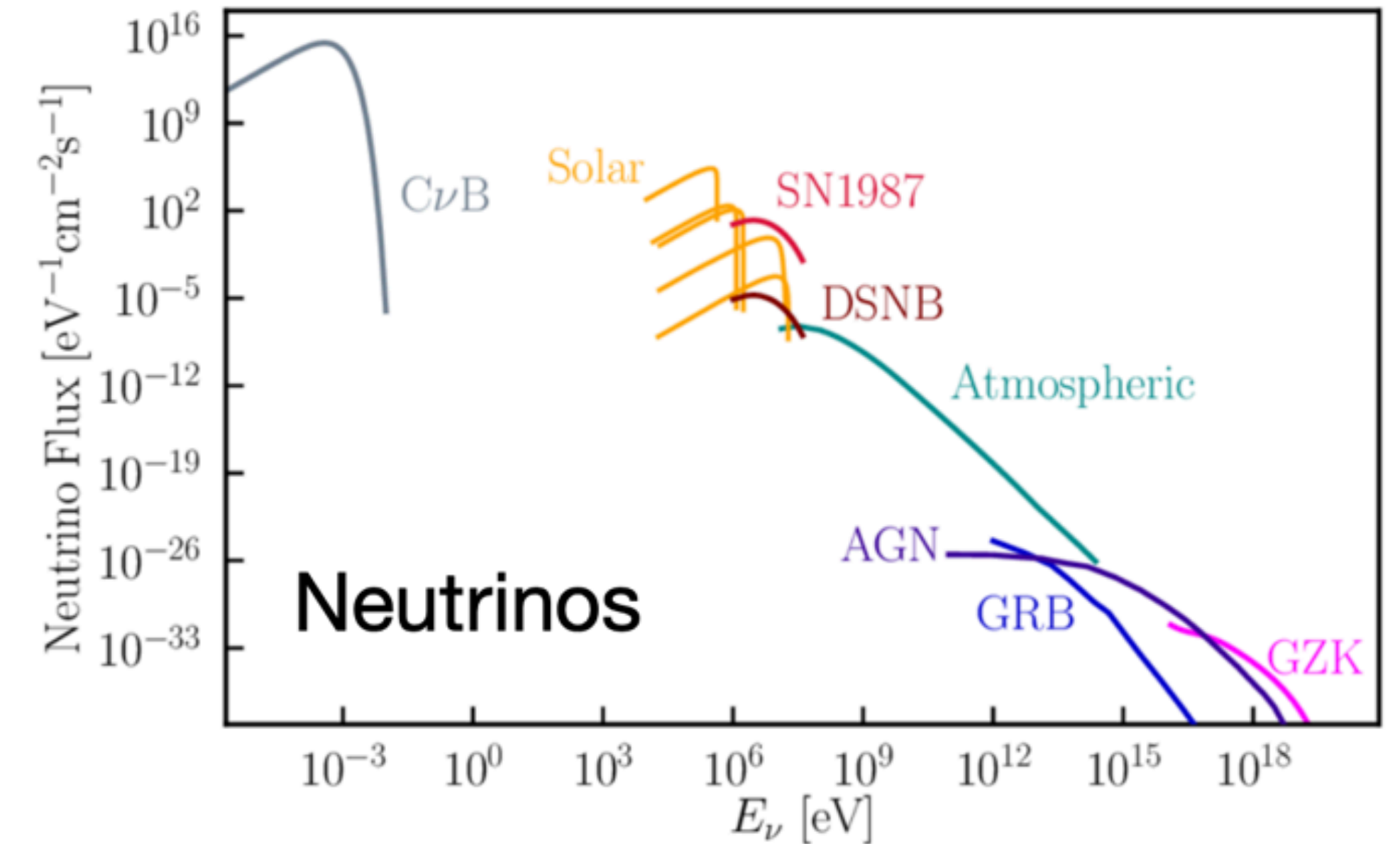
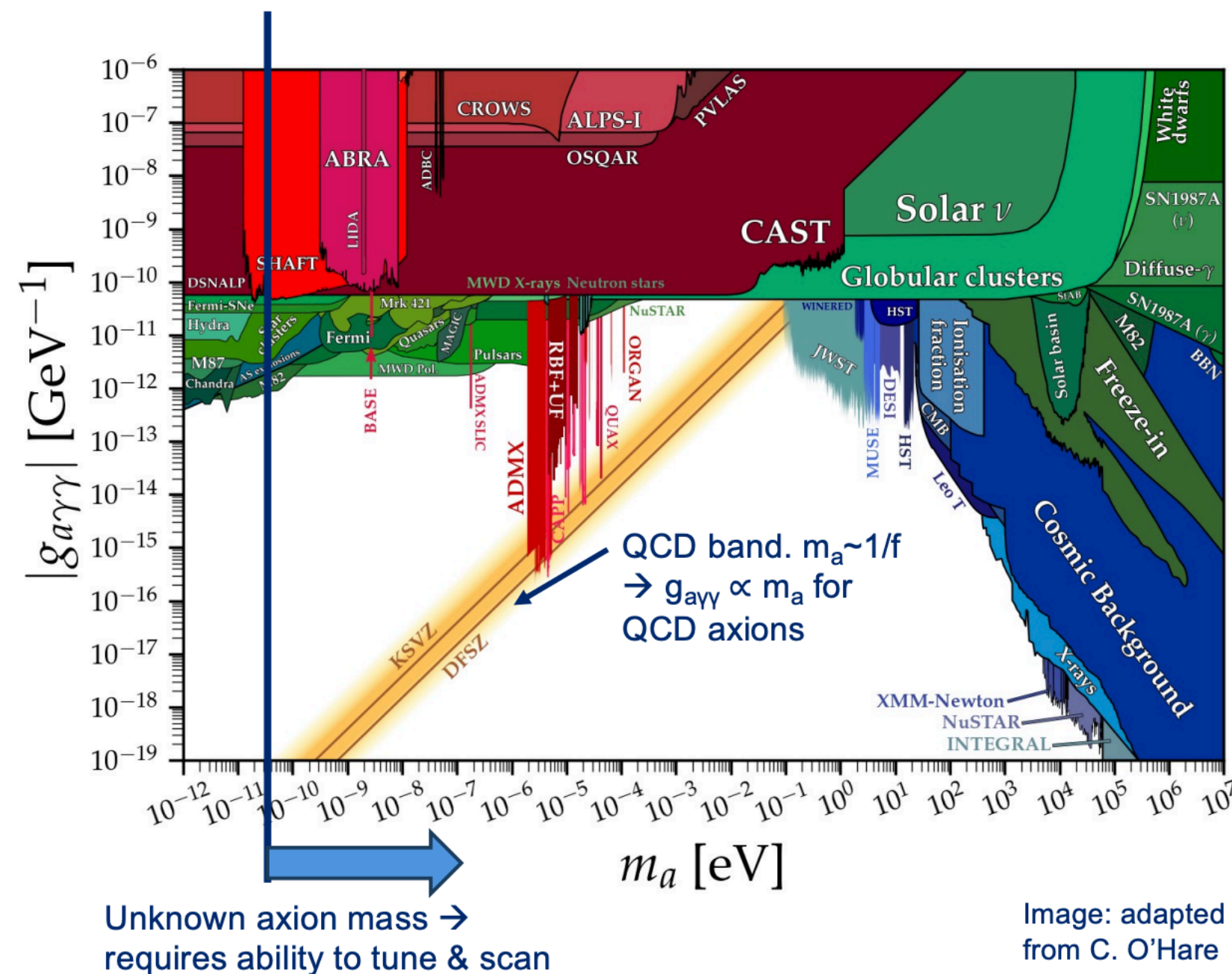


The figure displays three spectral measurement plots. The top plot shows 'SNOWLINE WATER' and 'WATER ICE' features. The middle plot shows 'STAR FORMATION' and 'BLACK HOLE ACCRETION' features. The bottom plot shows 'POLYCYCLIC AROMATIC HYDROCARBONS' and 'METALLICITY' features. The x-axis is labeled 'OBSERVED WAVELENGTH' and ranges from 'JWST' to 'ALMA'. The y-axis is labeled 'SPECTRAL MEASUREMENT'. The plots show various spectral lines and features, with labels indicating the specific astrophysical phenomena being studied.

Ritoban Basu Thakur

A few science drivers

- Cosmic neutrino background
- QCD axion $\rightarrow$ DM density not well known
- Gravitational waves



Aggarwal et al. 2501.11723

Thank you!

