Superconducting Technologies for Sensing Extremely Subtle Forces

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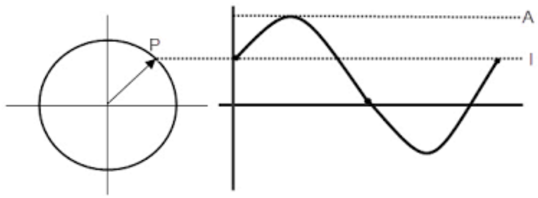
Snowmass Quantum Sensors meeting

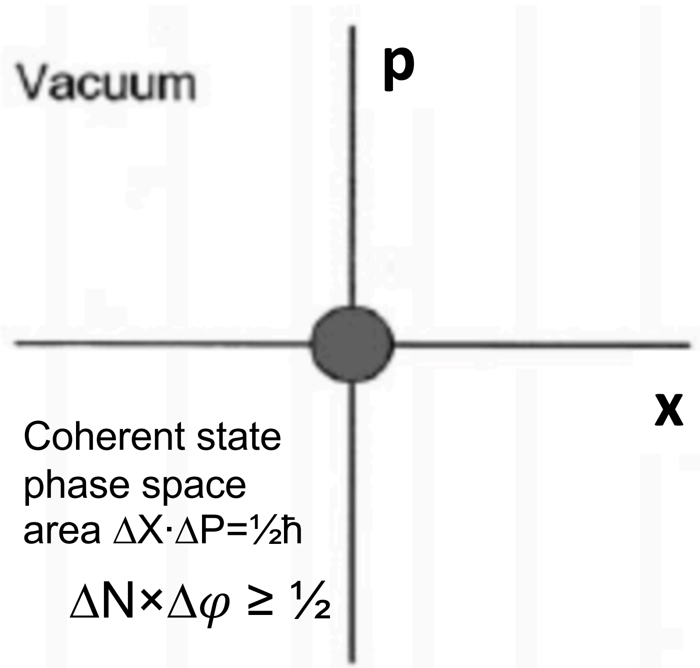
August 19, 2020

- Zero-point noise
- Squeezing
- State transport and transduction
- Single photon detectors
- Measuring arbitrarily small forces
- Cooper pair-breaking detectors



Wavefunction of phasor

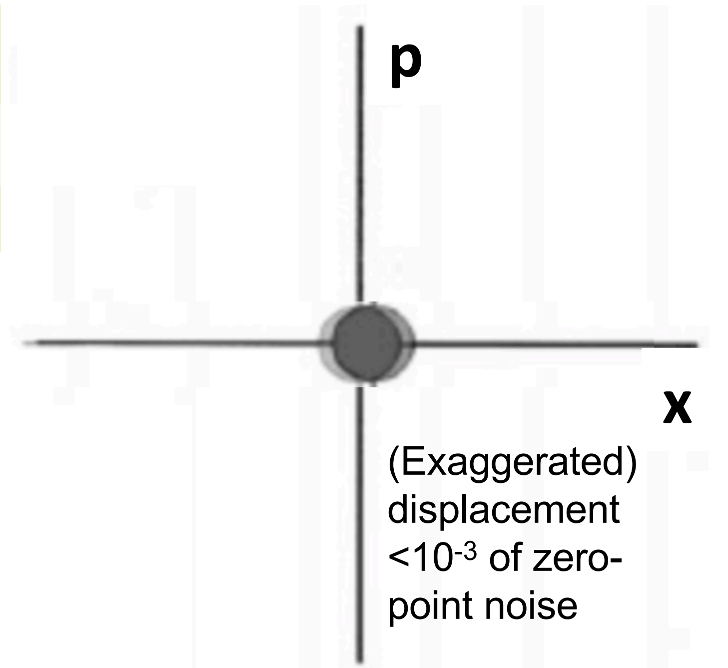
Example: DM axion wave displaces the cavity vacuum state by an amount much smaller than the zero-point vacuum noise



Coherent state phase space area $\Delta X \cdot \Delta P = ½\hbar$

$\Delta N \times \Delta\varphi \geq ½$

Axion-photon mixing induces tiny coherent state displacement $D(g\theta B_0 Q_{cav}/m_a^2)|0\rangle$



(Exaggerated) displacement $<10^{-3}$ of zero-point noise

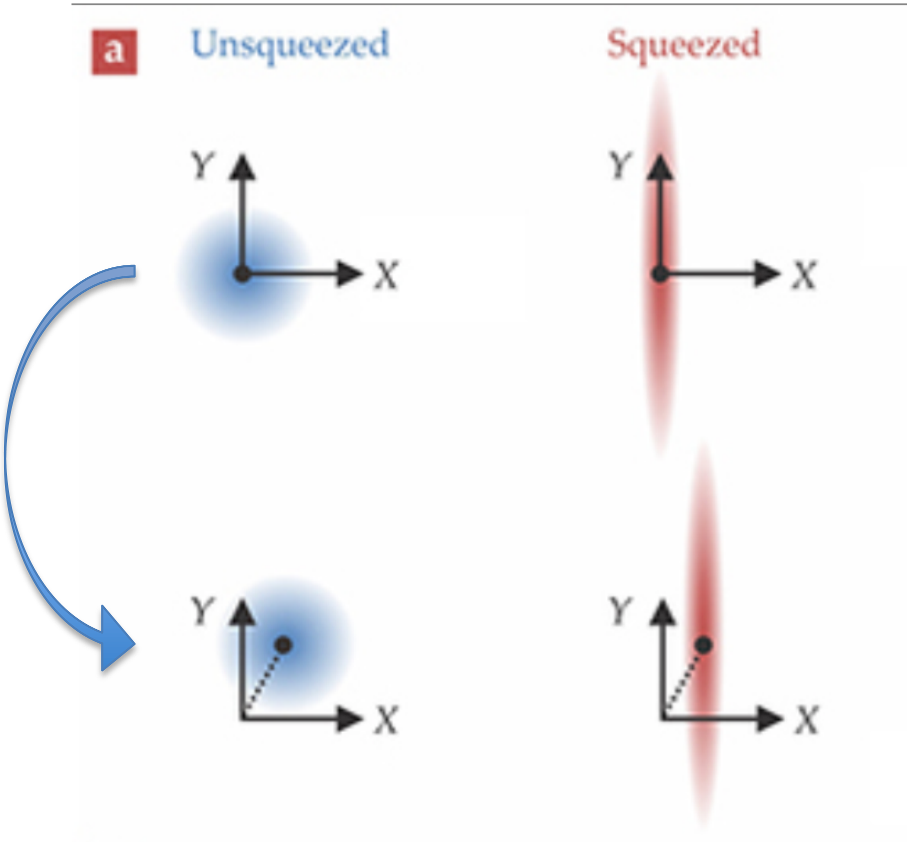
Standard quantum limit: As T→0, even the best phase-preserving amplifiers have an irreducible zero-point noise floor from quantum mechanics (Carlton Caves, 1982)

→ **Measured N = 0 +/- 1 photon per resolved mode**

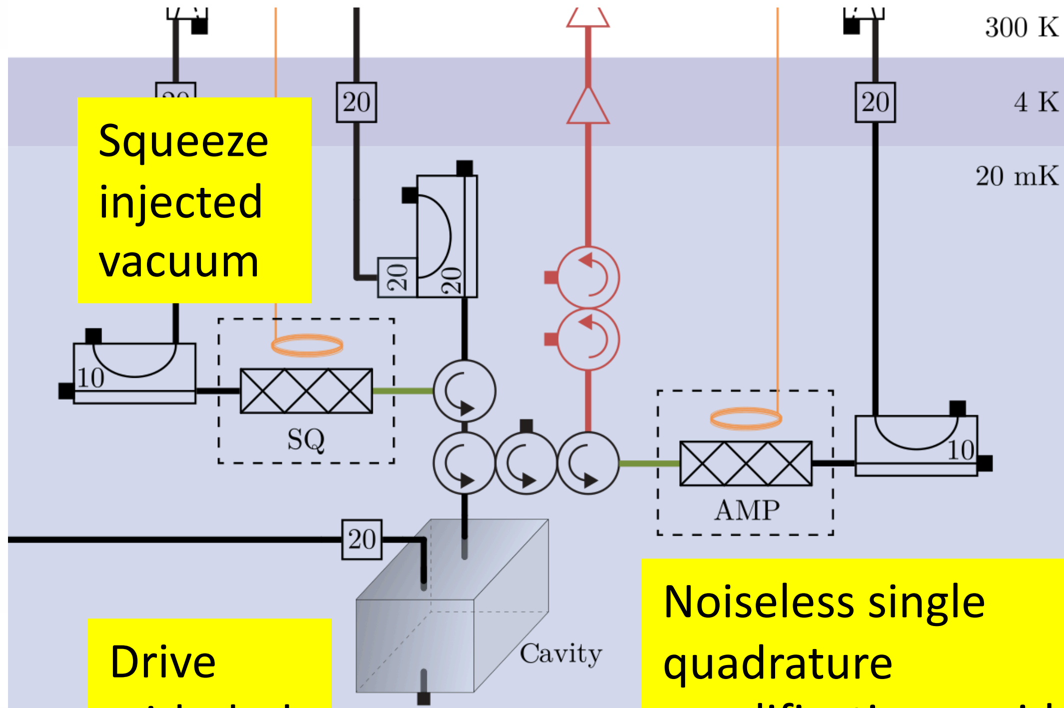
ADMX: expected <N> = 10^{-3} photons. Still need to average 10^6 measurements.

Further improve SNR using non-classical initial probe state prep followed by noiseless readout (single quad. amp. or QND)

(LIGO, HAYSTAC)



M. Malnou et.al (2018)



Squeeze injected vacuum

Drive with dark matter

Noiseless single quadrature amplification avoids simultaneous measurement of non-commuting operators

Need non-reciprocal (T-violating) devices to transport states into and out of the interaction region.

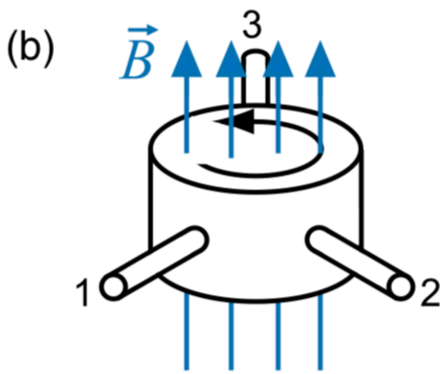
The *ISOLATION* frontier

- After transport of prepared state to the "interaction region":
  - LIGO optical parametric amplification: 9 dB SNR improvement
  - HAYSTAC Josephson parametric amplification 4 dB

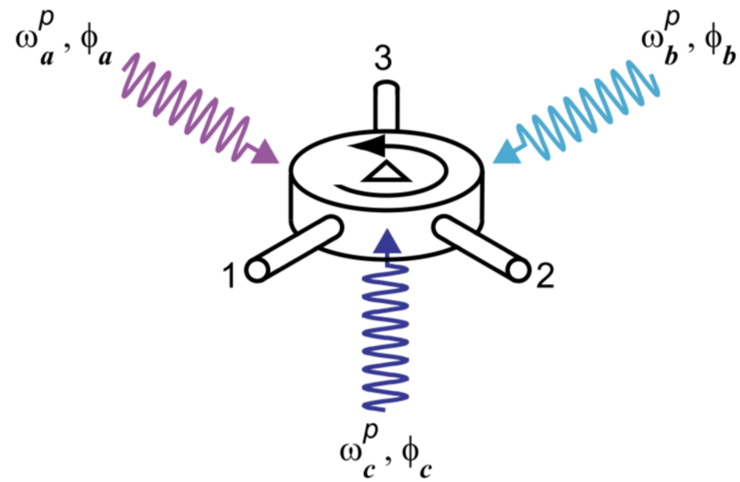
- It is easy to get >20 dB of parametric single quadrature amplification for the initial vacuum squeezing
  - **Losses and decoherence during transport replace squeezed vacuum with unsqueezed vacuum**
  - Even 1% loss per interface (scattering, absorption) is disastrous!

- Compare to In situ measurements:
  - Fermilab-Chicago qubit QND photon counting: 15.7 dB
  - Kasevich (Stanford) QND spin squeezing of Rydberg atoms: 18.5 dB

Measurement of subtle signals requires ultralow loss non-reciprocal devices to transport quantum states

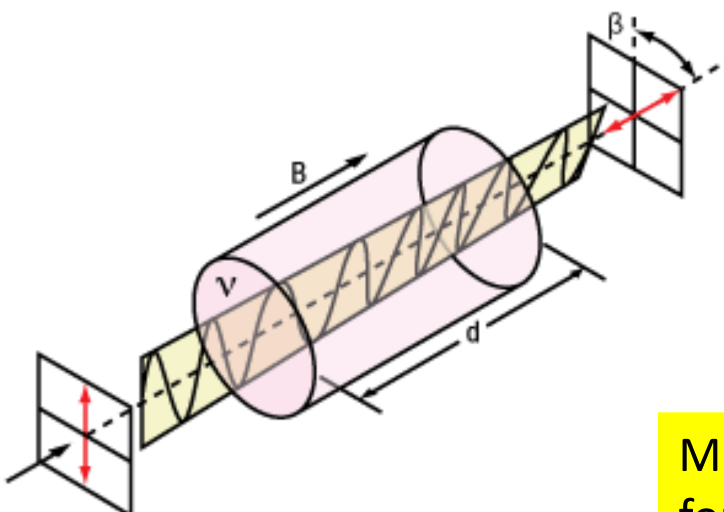


Conventional ferrite-based circulator using **magnetic flux** for T-violation



$$\phi_{tot} = \sum_{i=a,b,c} s_i(\omega_i^p t + \phi_i) = \pi/2$$

Upconverting Josephson circulator using **Berry flux** for T-violation (K. Sliwa et.al, 2015)



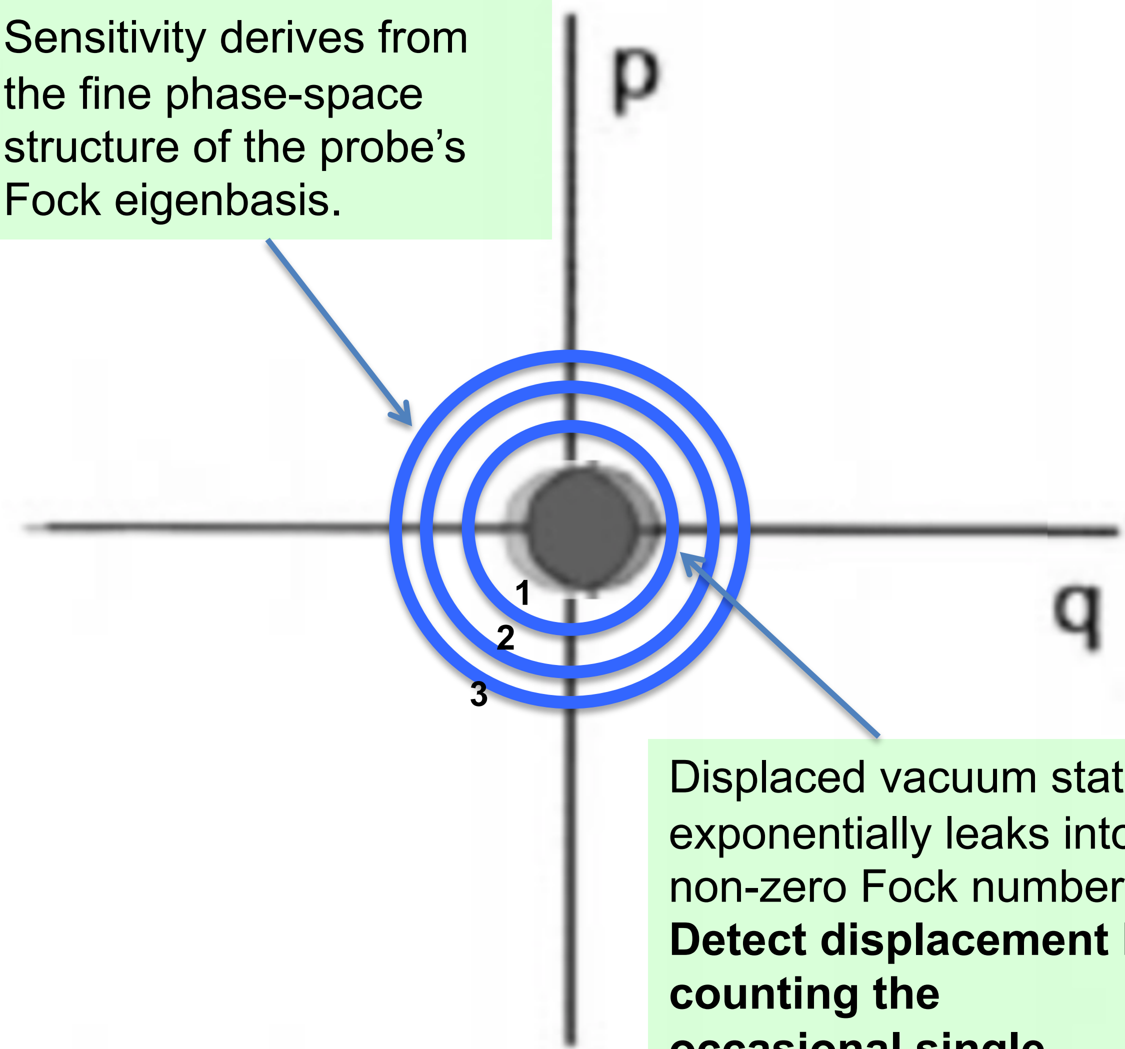
Faraday isolator for optical interferometers

More generally, **unitary up/down-converters** are useful for transducing signals to different frequencies where there exists convenient sensor/amplifier technology.

To reduce readout noise, use photon counting to measure displacement using the Fock basis, i.e. number eigenstates

Avoid zero-point noise by measuring only amplitude and not the conjugate phase observable.
No fundamental limit on how low the noise can go.

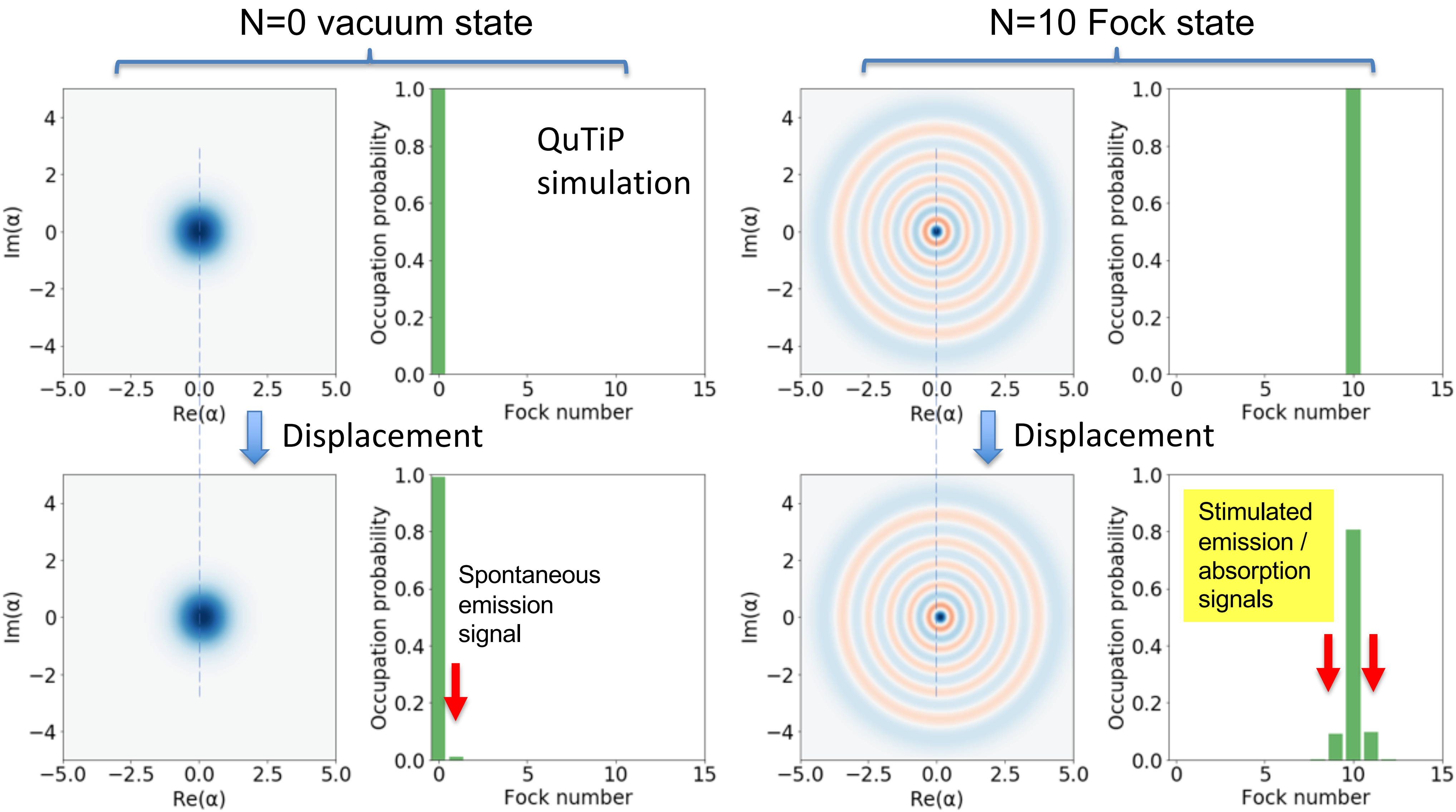
Sensitivity derives from the fine phase-space structure of the probe's Fock eigenbasis.



Displaced vacuum state exponentially leaks into non-zero Fock number. **Detect displacement by counting the occasional single photon.**

- **Quantum nondemolition measurements**
  - Rydberg atoms
  - Superconducting qubits
- **Single photon counting or microcalorimetry with Cooper pair-breaking detectors**
  - Quantum Capacitance Detector
  - MKIDs and KIDs
  - SNSPDs
  - TES's
- Of course, PMTs

QM allows measurement of arbitrarily small forces by employing fine phase space structure in the initial probe state

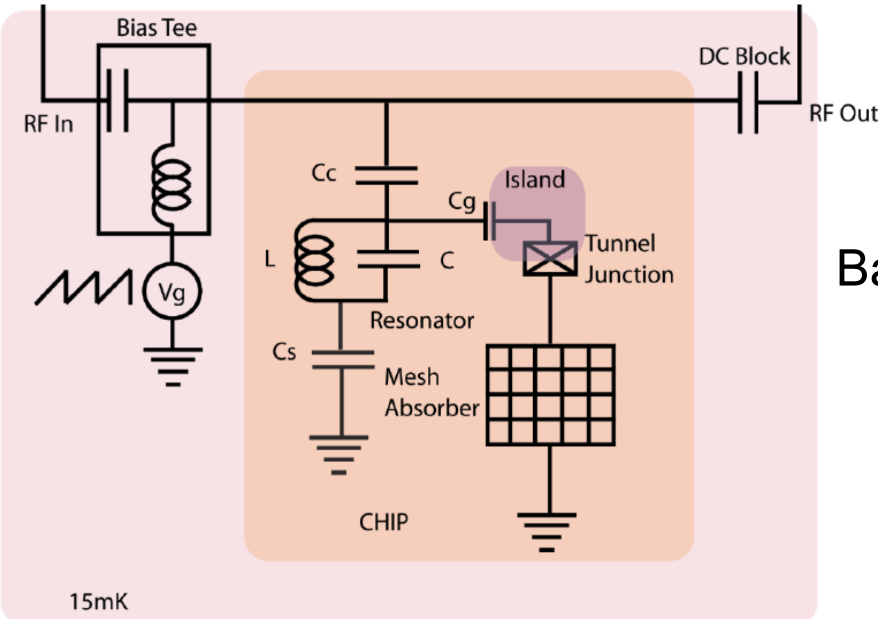


Fermi's Golden Rule applies only to spontaneous emission, so please don't feel limited by beam intensity!

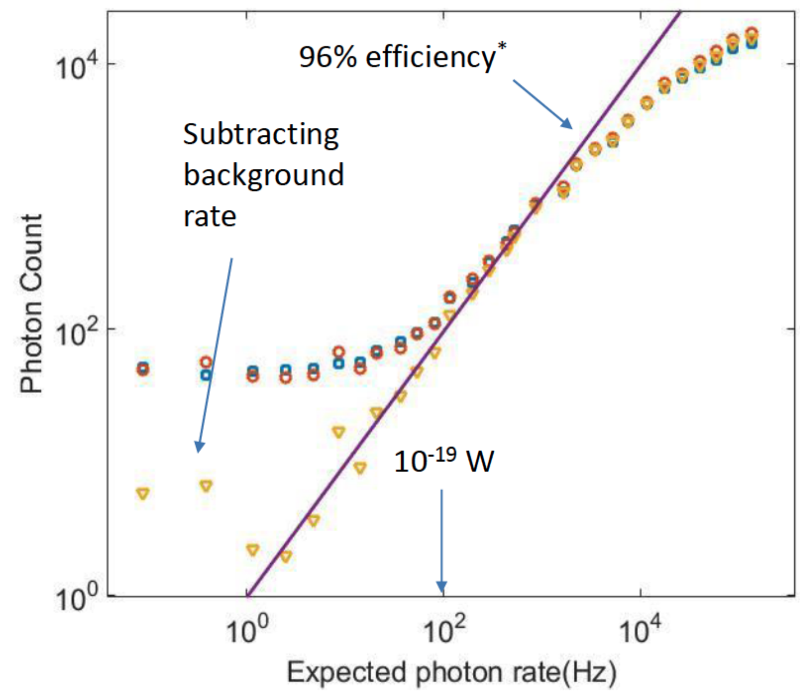
Cooper pair-breaking detectors and backgrounds

Low threshold from tiny energy quantum = 90 GHz = 360 ueV for aluminum

Ex. Quantum Capacitance Detector (Echternach et.al, JPL) for space-based THz astro: Use a Cooper pair box qubit as the sensor. Single THz photon creates 20 broken CPs. Trigger on large burst in the qubit error rate.



Backgrounds



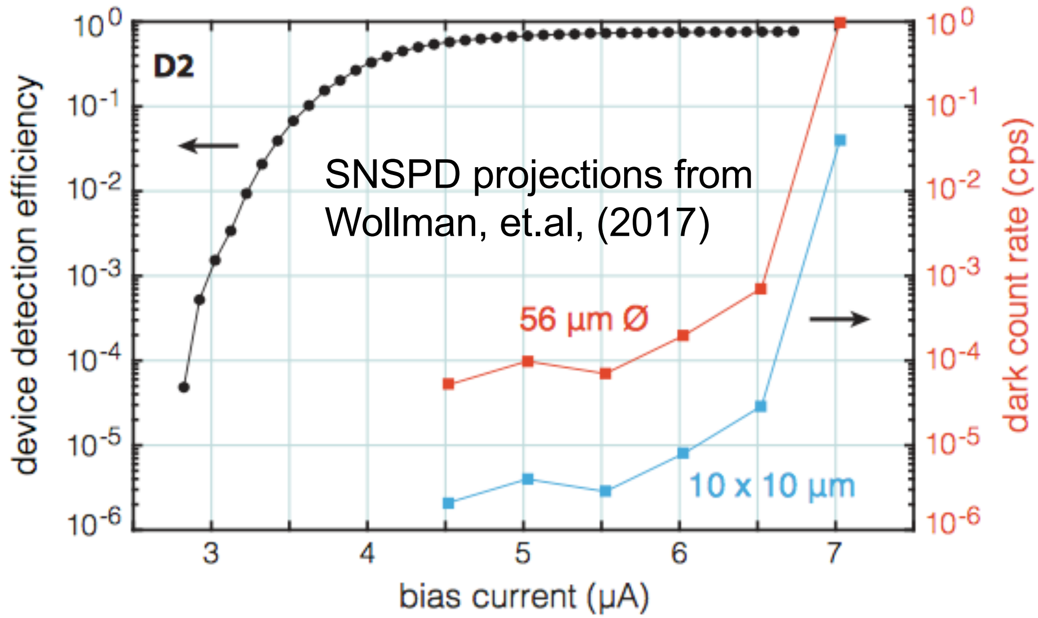
- **Background ~ 100 Hz is due to ambient quasiparticles of unknown origin**
  - 1 QP / micron^3 in all devices to date (qubits, MKIDs, etc), first seen by Martinis in 2002
  - Background rates too high to operate as DM detector. Also prevents going to lower threshold.
  - MIT/PNNL suggests ionizing radiation to blame → **Mitigate with WIMP DM techniques?**
    - Promising results from DEMETRA, operating in CUORE test stand in Gran Sasso.

Thermal backgrounds vanish at higher photon energy

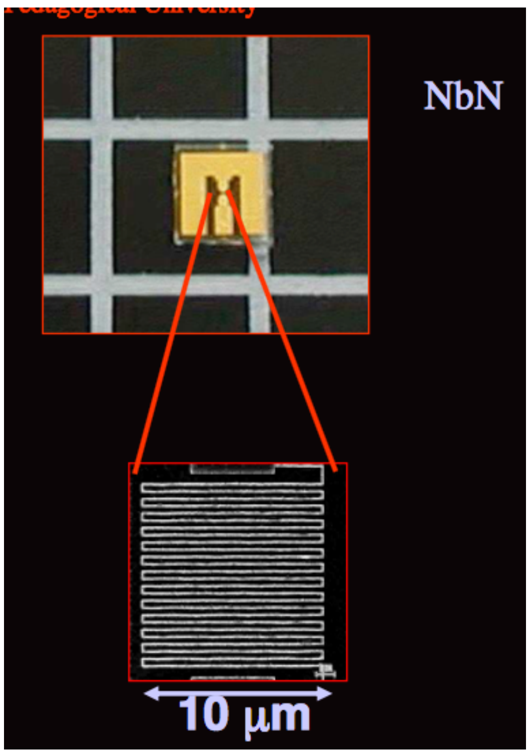
SNSPD: Local energy deposit quenches the meandering current-biased wire.

→ **Dark rates <10^{-5} Hz already achieved for NIR photons**

- Threshold at 60 THz, reduce further by reducing heat capacity by mounting on CMB spiderweb

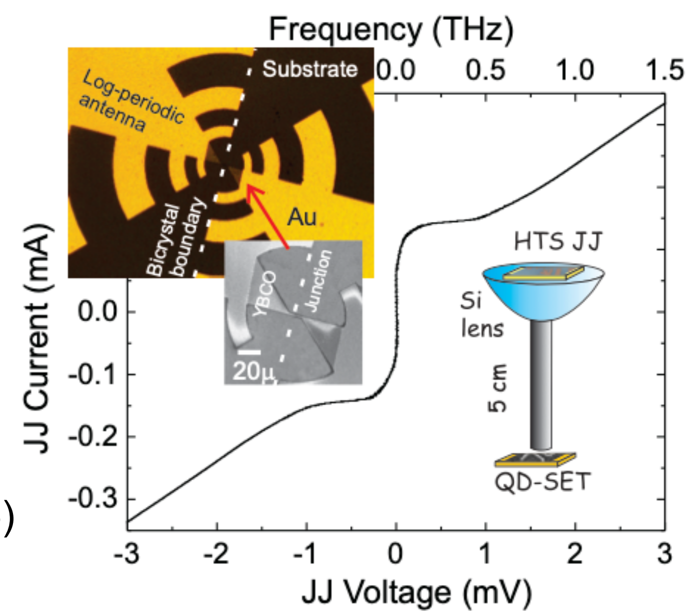


SNSPD projections from Wollman, et.al, (2017)

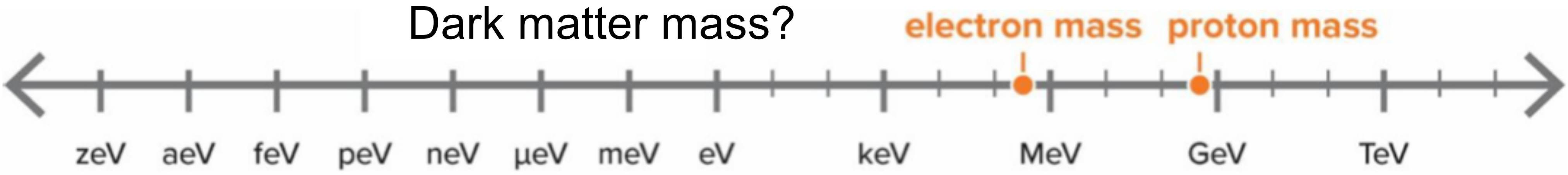


Technical issues:

- Free space optical coupling and quantum efficiency for far infrared
- **Cryogenic single photon sources for calibration**



Tunable AC Josephson THz photon source (Shaikhaidarov et.al, 2016)



Axion Experiments

WIMP Experiments

Yummy low hanging fruit

Quantum-limited amplifiers, upconverters, squeezers

Superconducting qubit QND

Cooper pair breaking single photon detectors

Microalorimeters and reduced threshold WIMP techs (KIDs, TES, etc)

Aaron S. Chou, Snowmass Quantum Sensors, 8/19/2020