QUANTUM DEVICES FOR AXION HALOSCOPES

University of Freiburg

Pic: visitfreiburg.de

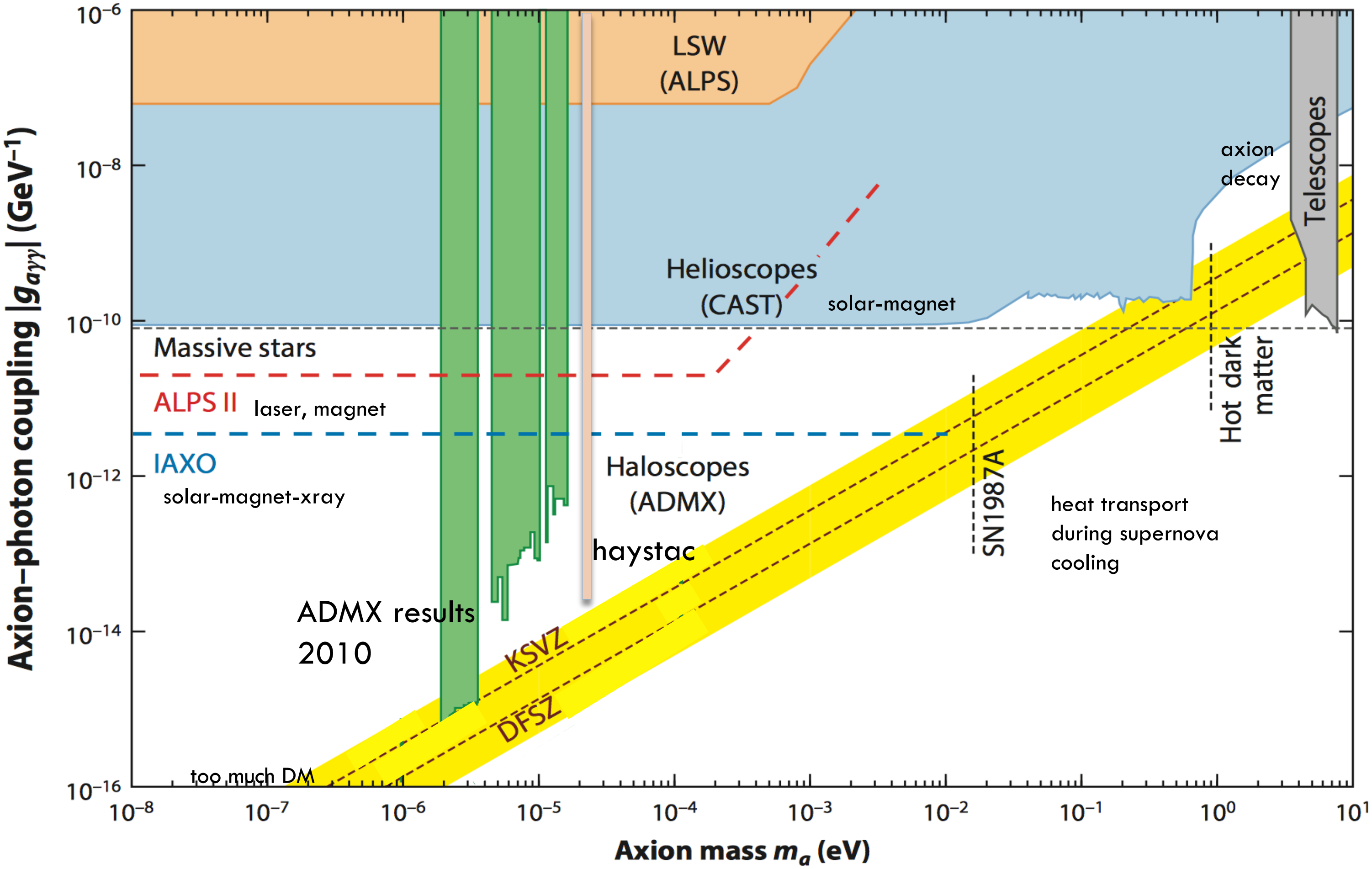
06/03/2019

Rakshya Khatiwada Fermilab

Outline

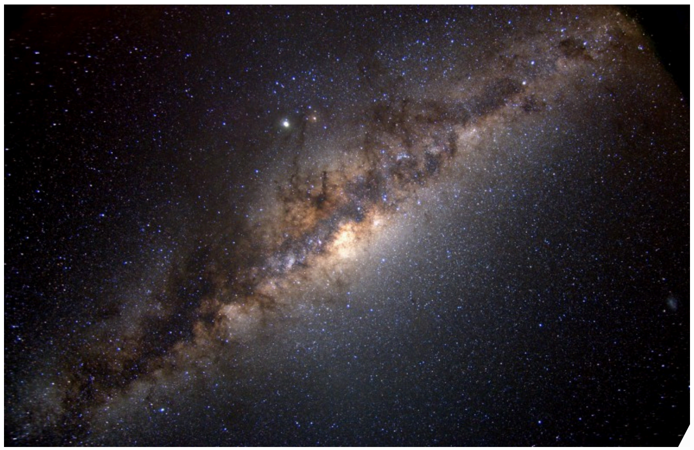
- ❑ Axion haloscope – Axion Dark Matter eXperiment (ADMX)
- ❑ Quantum electronics
- ❑ ADMX results 2018
- ❑ Future axion searches using quantum technology
- ❑ Conclusion

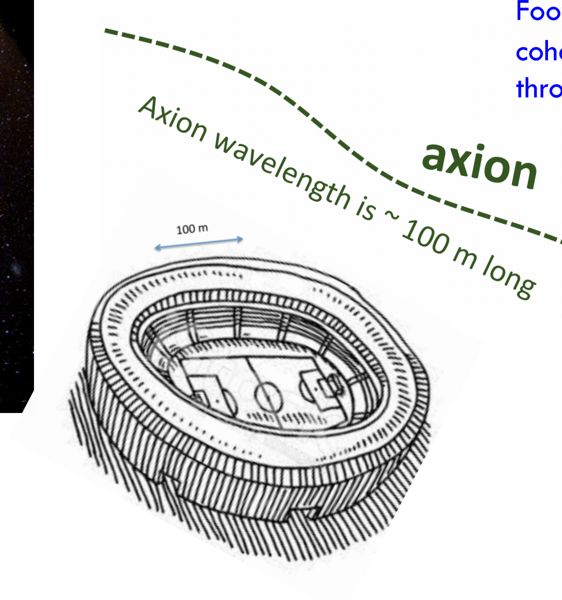
Axion searches overview



Graham, et. al (2016)

Axion in the galactic halo





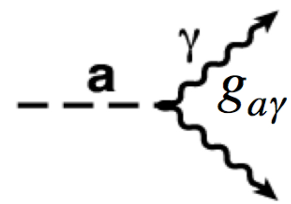
Football stadium sized clumps of coherently oscillating axions drifting through the detector

Oscillating electric current
In external **B**

$$\boldsymbol{J_a}(t) = g_{a\gamma}\boldsymbol{B_0}a_0e^{-i\omega t}$$

$$\vec{\nabla} \times \vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

$m_a c^2 = h\nu$



- *Big bang-> Milkyway halo-> gravitational potential-> Maxwell Boltzmann distribution of v (**mean 10^{-3}c ~ local virial velocity)***
- *# density local galactic halo ≈ 10^{14} cm^{-3}*

  -- (ρ= 450 MeV/cm^3)
- *Lifetime 10^{42} years!*

β_{virial} (local galactic) ~ 10^{-3}c :

$\lambda_{\text{De Broglie}}$ *(coherent) ~ 100 m,*

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B},$$

Serge Brunier@NASA

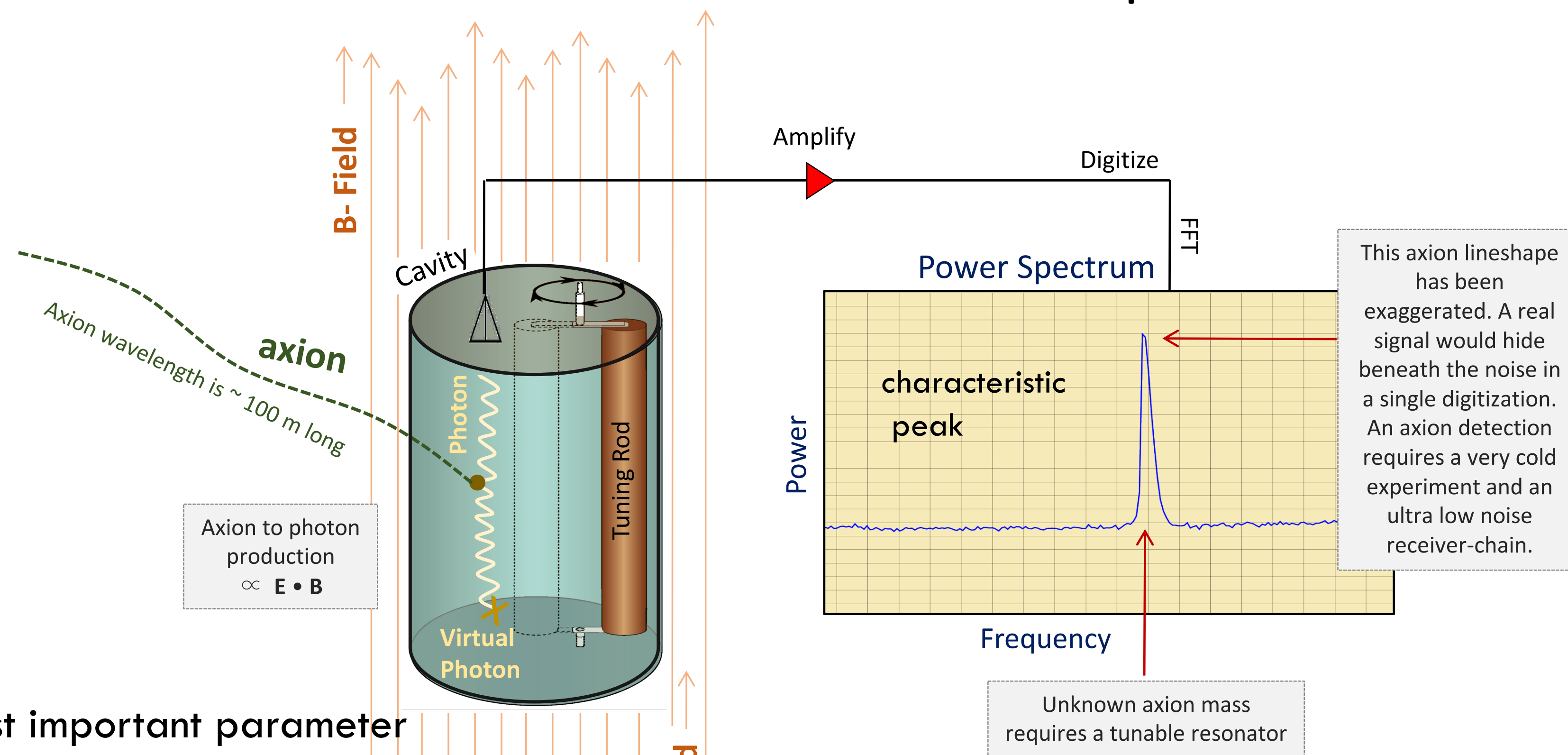
A good axion detector

- Tunable in frequency since mass of axion unknown f_{PQ}
- Low thermal photon background => very cold (dil. fridge)
- Low added electronics noise => quantum technology

ADMX => World's most sensitive RF receiver

Sensitivity: 10^{-26} Watts

The Axion Haloscope

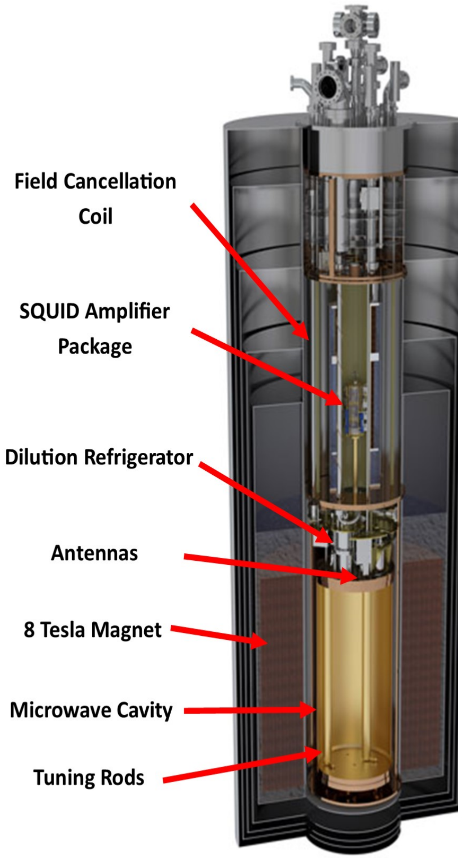


Most important parameter

$$SNR \propto \frac{P_{out}}{k_B T_{system}}\sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

C. Boutan

ADMX detector



Field cancellation coil: cancels the residual magnetic field around the SQUID electronics

Superconducting QUantum Interference Device (SQUID) amplifiers: amplifies the signal while being quantum noise limited

Dilution refrigerator: cools the insert to ~ 90mK

Antennas: pick up signal

Magnet: facilitates the axion conversion to photons, 8T

Microwave Cavity: converts axions into photons, tunable

Quantum amplifiers

Why quantum amps.?

Intrinsically low noise (superconducting technology)

⇒ low resistance elements

⇒ low thermal dissipation

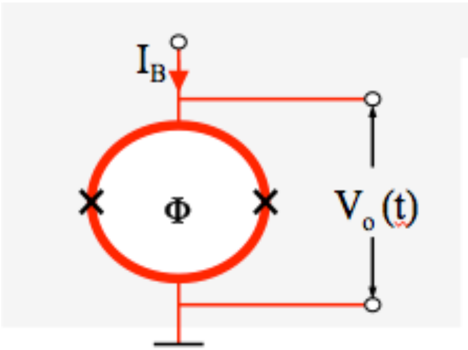
⇒ Add very low added noise during amplification

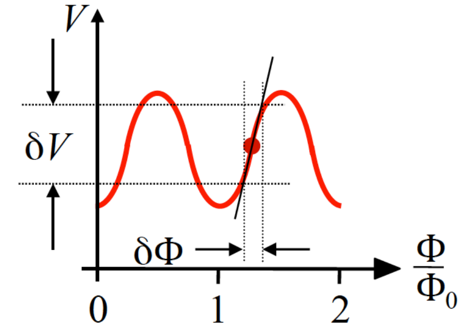
=> Tunable in frequency

Josephson Parametric Amplifier

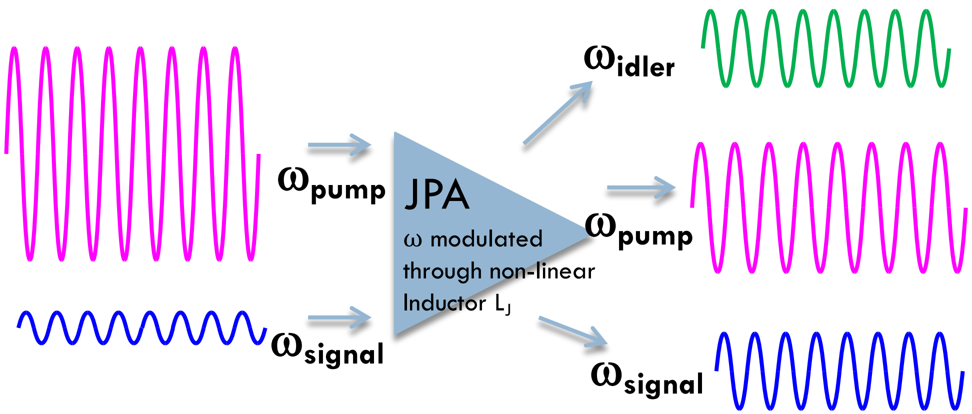
JPA

dc SQUID





- Energy transfer from pump to two normal modes of swing



Only limited by Quantum Noise

What is quantum noise?

Similar to $\Delta x \Delta p \geq \hbar/2$

Δx: *position*
Δp: *momentum*

48 mK ($h\omega/k_B$ @1GHz)

Electromagnetic wave phase and amplitude measurement uncertainty

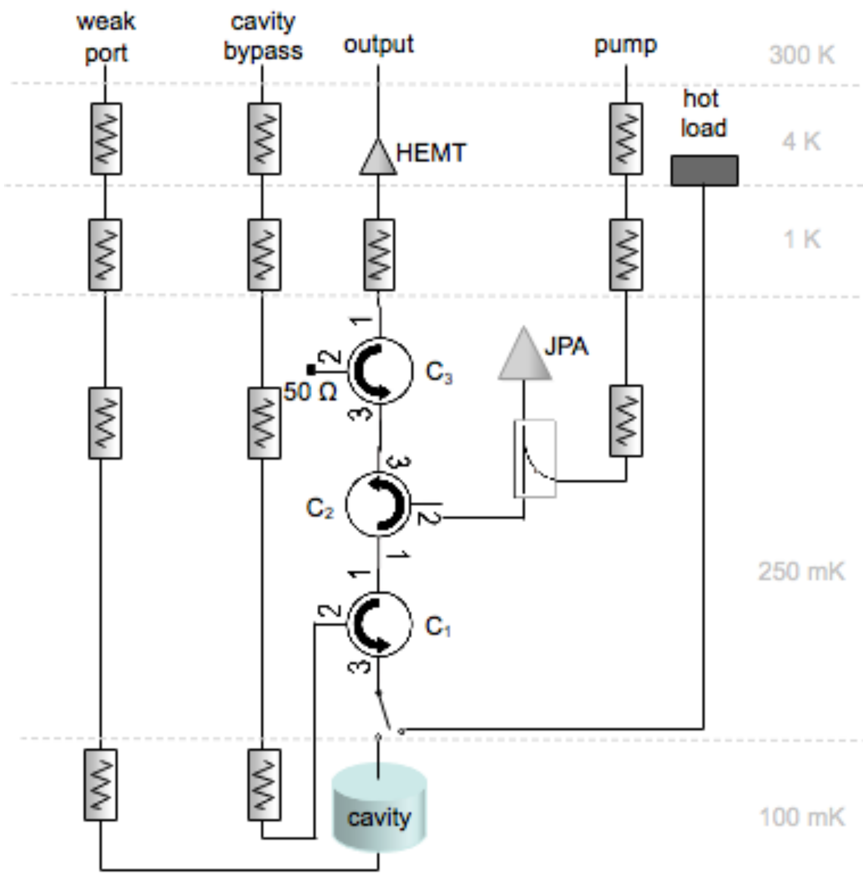
$$T_{system} = T_{amps.} + T_{physical}$$

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

*Determines the sensitivity of the experiment

*The most involved aspect of analysis

Cryogenic electronics

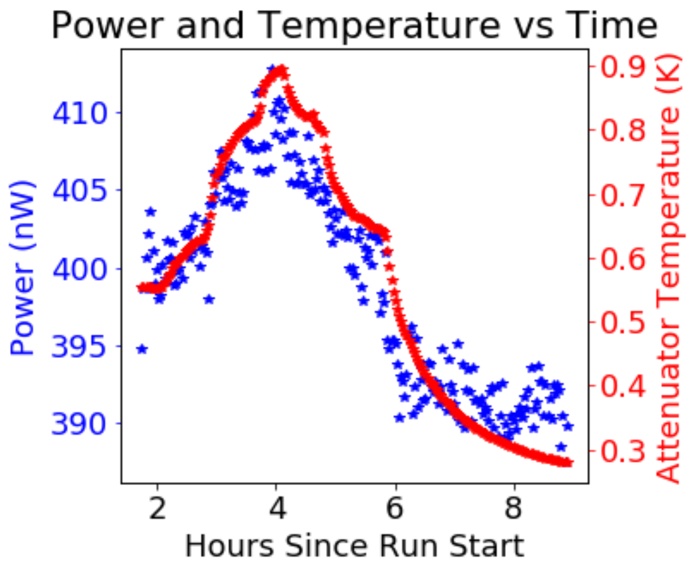


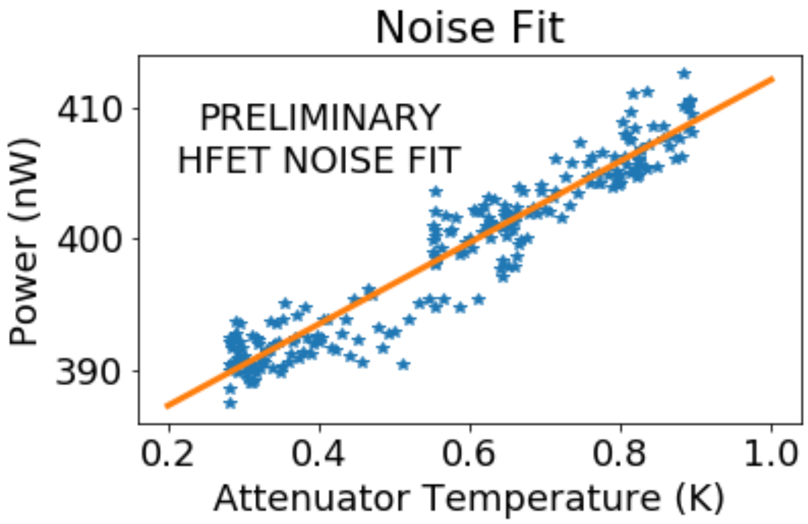
Most important analysis parameter

$$T_{system} = T_{physical} + T_{amps} + T_{HFET}/G_{amps}$$

Characterize the contributions from HFETs and Quantum amps.

HFET noise characterization

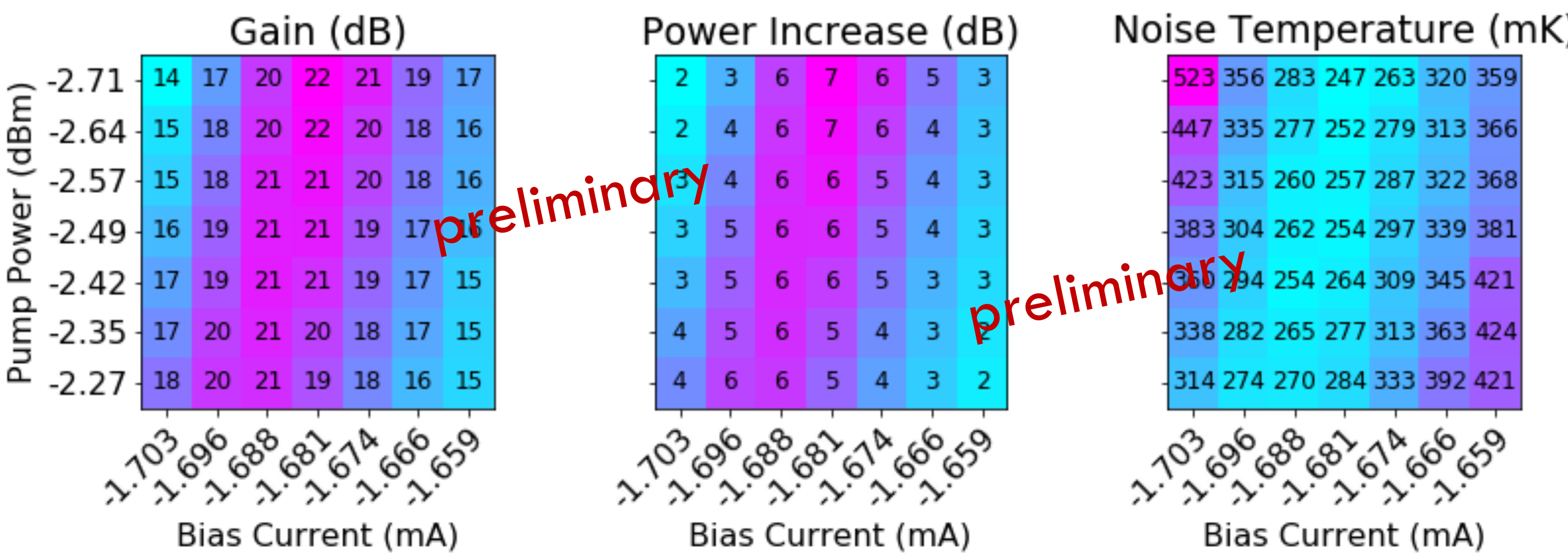




Quantum amps.' noise temperature

Optimize amps. for the lowest noise temperature

Involves series of amps. bias procedures



T_{amps} ~ 125 mK

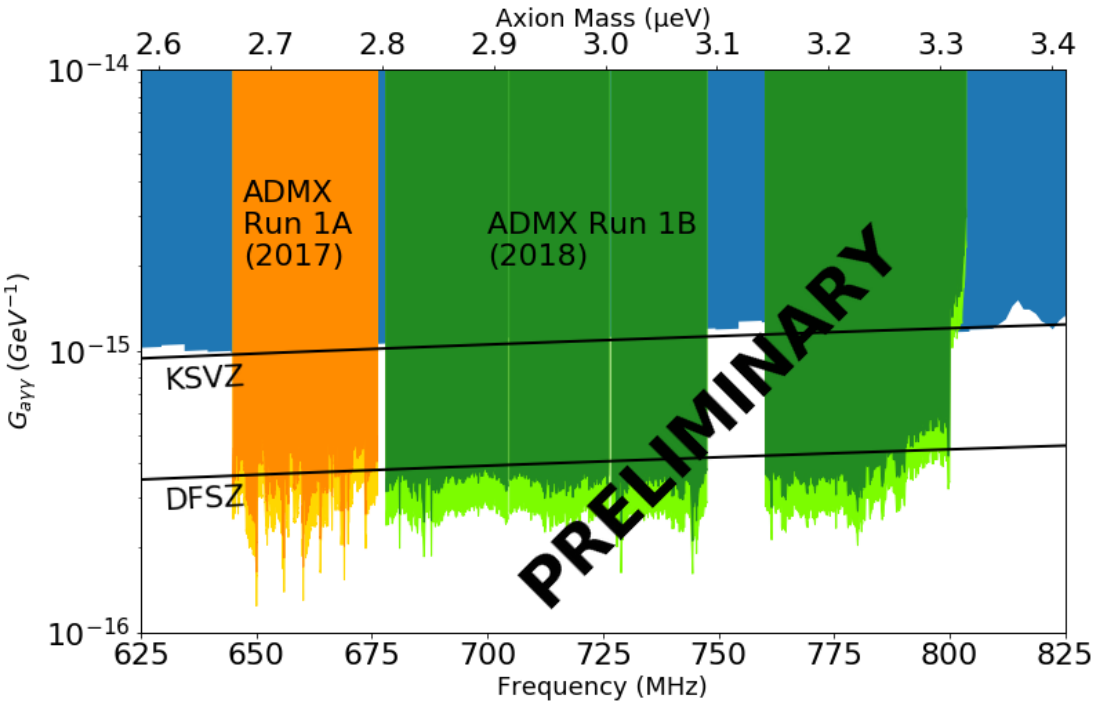
T_{HFET} ~ 25 mK

$T_{physical}$ ~ 100 mK

T_{system} ~ 250-350 mK

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

ADMX preliminary results 2018/19



*x4 more frequency covered than 2017 DFSZ sensitivity -- 680 to 800 MHz

*Axion mass covered to this date: 2.66 to 3.3 µeV

*Stay tuned for results – paper out mid 2019

Prof. Gray Rybka's talk on June 06, at 15:10

Future direction: key parameters

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

$$T_{system} \propto T_{amps.} \propto {}^{h\omega}/_{k_B}$$

*48 mK at 1 GHz
n x 48 mK at n GHz

*other techniques that add < QL

***qubit based single-photon detection**

***Squeezed quantum vacuum JPAs--<QL noise**

*powerful magnet?

*existing magnets – small volume
-- need High B and V

*Design study in progress at UF & FSU -- costly

$$f_{cav.} \propto {}^{1}/_{r_{cav.}}$$

***multi-cavity array**
-- power combine

*too many cavities

*photonic band-gap, open resonators, cavity-qubit

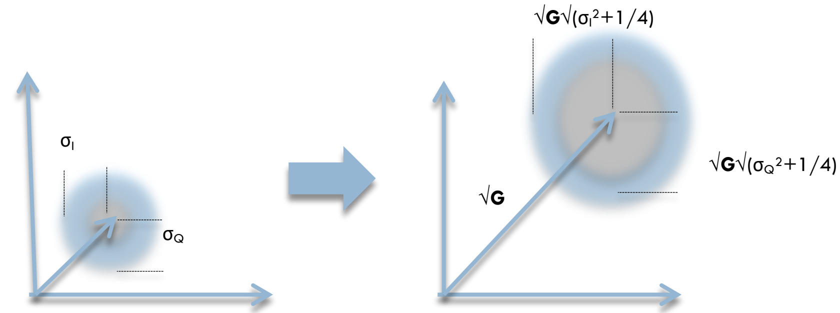
Multi-cavity array with squeezed vacuum

Squeezed parametric amplification

*Nonlinearity causes change in pump power to cause pump phase shift – transfer function of JPA

Input with noise

amplification with noise + ½ photon vacuum fluctuation noise



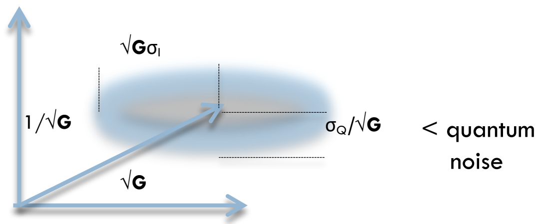
*Input noise in the out of phase/quadrature de-amplified causing **< noise than Quantum Limit in total** !

Exploring this idea for

10s of μeV Axion searches

Multi-cavity array

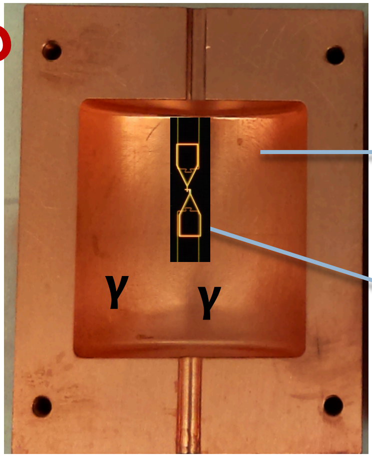
Squeezed de-amplification with noise



Beyond ADMX Generation-2

qubit based single photon detector

Fermilab QuantiSED Initiative



readout cavity

qubit/single Josephson junction /nonlinear oscillator

RF amplitude to qubit frequency transducer with single photon sensitivity

$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

cavity — qubit — mixed

ω_c: cavity frequency
a^+a: photon occupation #
ω_q: qubit frequency
σ_z: electric dipole (josephson junction)
g ~ **d.E**: cavity-qubit coupling
Δ: detuning/ω_q-ω_c
g^2/Δ: Stark shift

$$H = \omega_c a^\dagger a + (\omega_q + 2\frac{g^2}{\Delta} a^\dagger a)\sigma_z$$

$$H = (\omega_c + 2\frac{g^2}{\Delta}\sigma_z) a^\dagger a + \omega_q \sigma_z$$

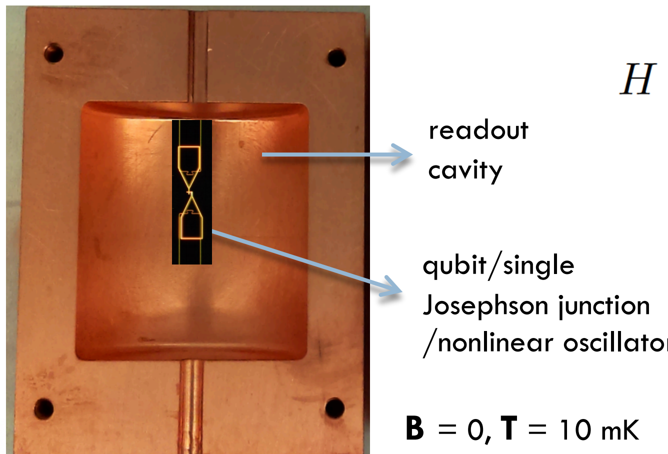
Non absorptive: **count photon exciting qubit but making a measurement on the cavity**

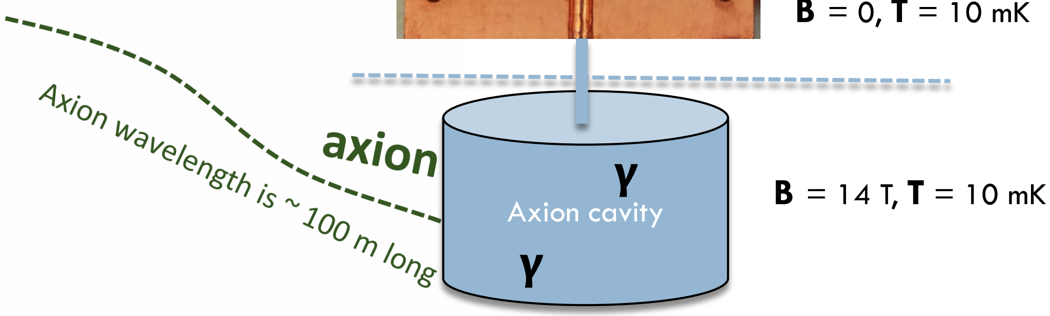
*presence of photon in the "readout cavity" shifts the qubit frequency of excitation
*Excite the qubit using a Pi pulse corresponding to the shifted frequency
*Measure this excitation by looking at the "readout cavity" frequency shift
*Frequency shift is quantized in units of the photon number
=> Tells how many photons are present in the cavity

-- photon counting !

qubit based single photon detector

Non absorptive:
count photon exciting qubit but making a measurement on the cavity





$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

cavity　　qubit　　mixed

ω_c: cavity frequency
a^+a: photon occupation #
ω_q: qubit frequency
σ_z: electric dipole (josephson junction)
g ~ **d.E:** cavity-qubit coupling
Δ: detuning/ω_q-ω_c
g^2/Δ: Stark shift

$$H = \omega_c a^\dagger a + (\omega_q + 2\frac{g^2}{\Delta} a^\dagger a)\sigma_z$$

$$H = (\omega_c + 2\frac{g^2}{\Delta}\sigma_z) a^\dagger a + \omega_q \sigma_z$$

*presence of photon in the "readout cavity" shifts the qubit frequency of excitation
*Excite the qubit using a Pi pulse corresponding to the shifted frequency
*Measure this excitation by looking at the "readout cavity" frequency shift
*Frequency shift is quantized in units of the photon number
=> Tells how many photons are present in the cavity

-- photon counting !

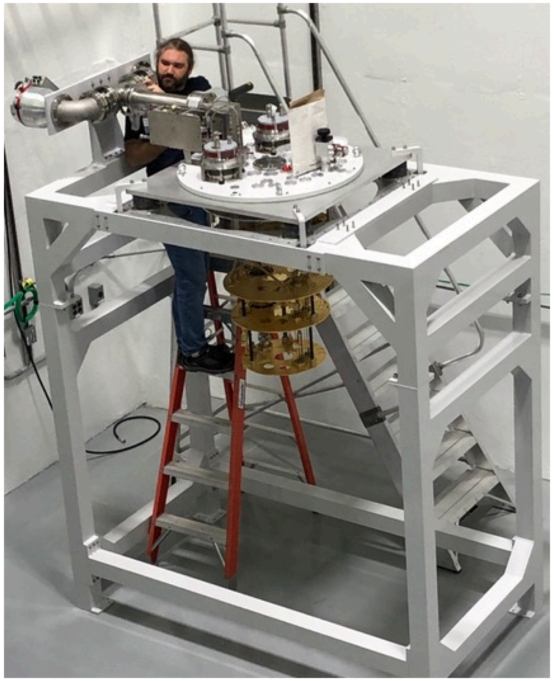
photon counting detector

What has been done:

*Single qubit-cavity has been successfully readout

$\Rightarrow$ error rates ~ 1%

U Chicago



What remains to be done:

*multiple qubit readout to reduce error rate and integration time and for reliable signal

*integration of magnet and the axion cavity

Fermilab

=>Use magnetic shielding for qubit sensors

=>Use high quality factor axion cavity (compatible with magnet) – resonance buildup of the signal

=>Stimulated emission with axion cavity prepared with known number of photon ~ enhances signal by a factor of N+1

Boulder

=>Ultimately establish a standalone axion detector

Multiple years' plan!

Targeted for >40 μeV axions

Axion search summary

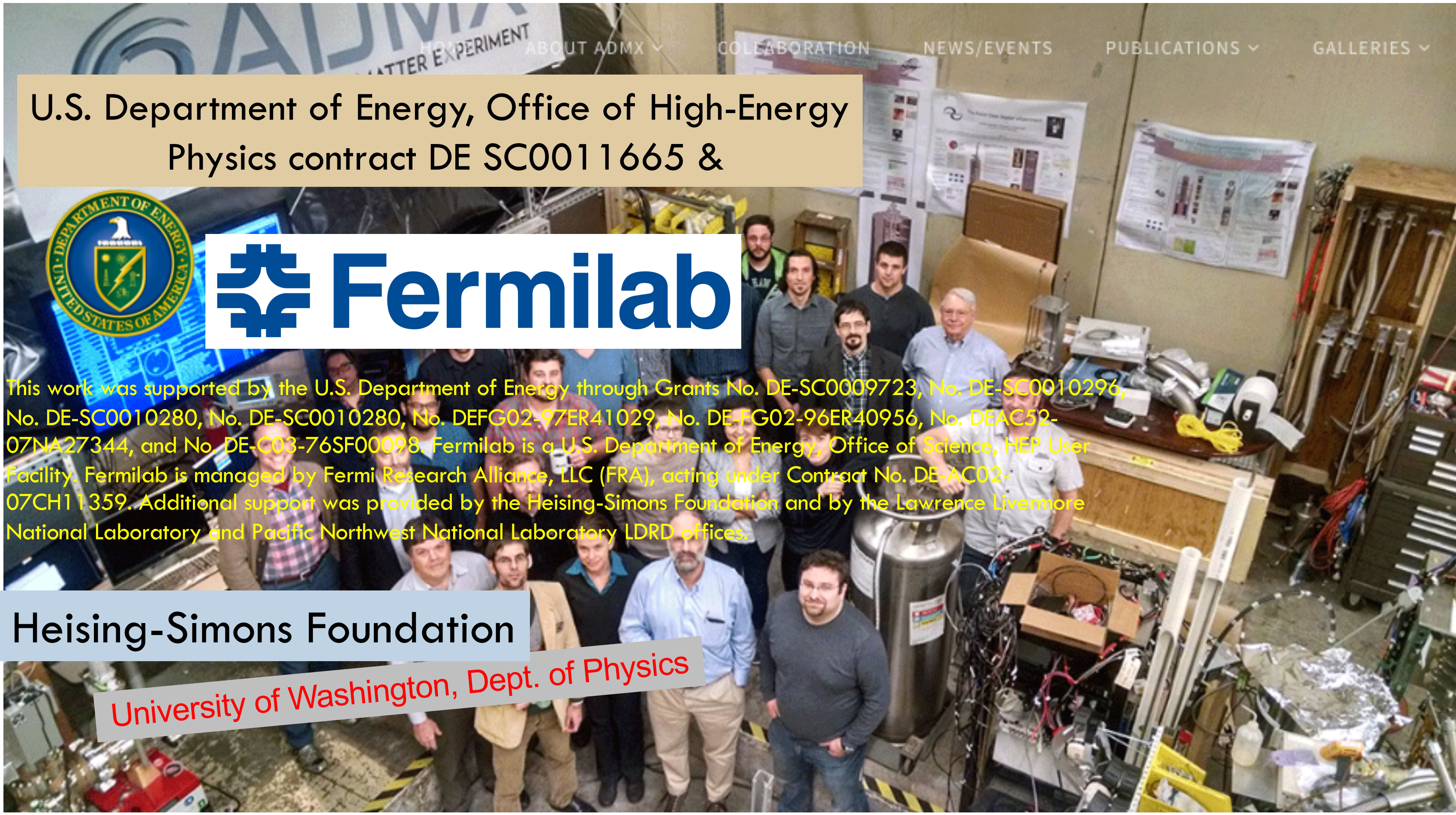
- ADMX DFSZ sensitivity -- forefront of Axion Dark Matter search
- Future direction for axion search:

  -- alternatives to single cavity haloscope (multi-cavity array)

  -- high field magnet

  ---- investigation of quantum science based novel methods and technology – without these, axion search impossible in a reasonable amount of time

Acknowledgement



U.S. Department of Energy, Office of High-Energy Physics contract DE SC0011665 &

Fermilab

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-C03-76SF00098. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

Heising-Simons Foundation

University of Washington, Dept. of Physics

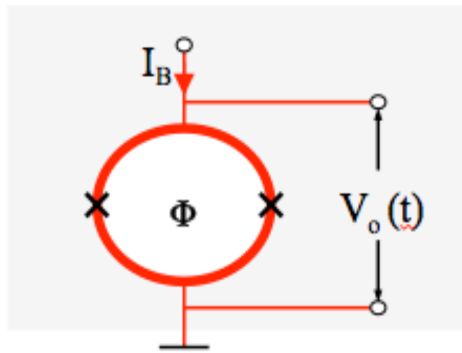
Additional slides

SQUID amplifiers

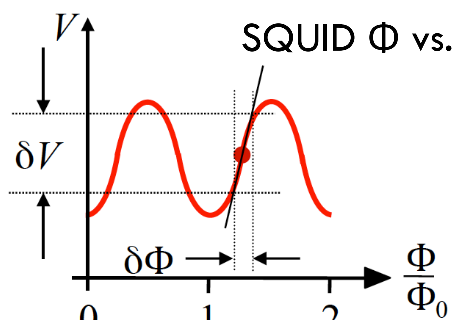
MSA

JPA

Based on dc SQUID



SQUID Φ vs. V



Microstrip SQUID Amplifier

- Resonator inductively coupled to SQUID
- Tunable: varactor tuning effectively changes the length of the resonator
- Tunability ~100 MHz/device

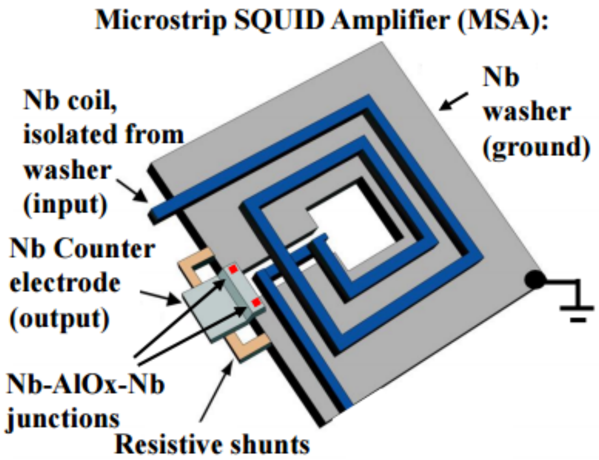
Josephson Parametric Amplifier

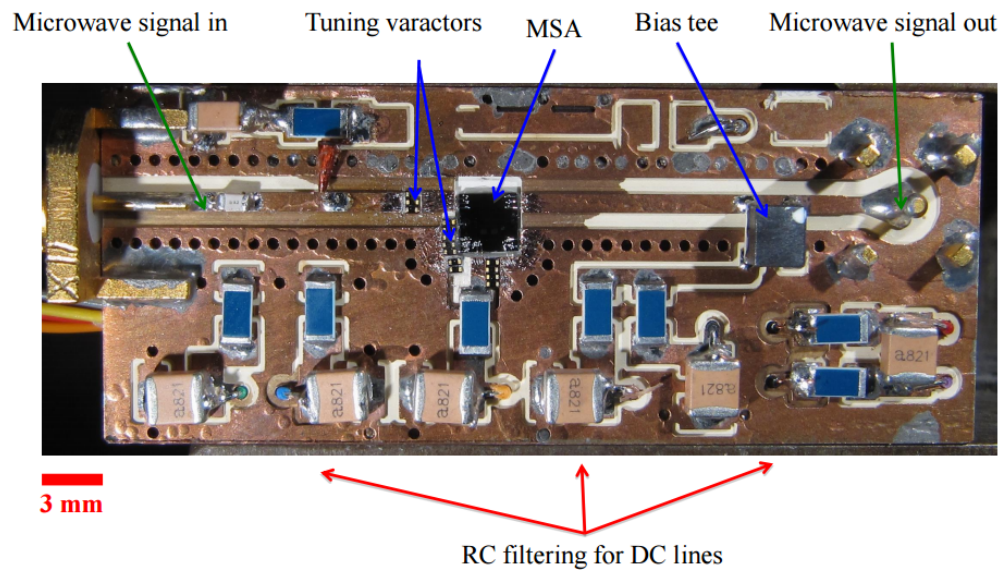
- Oscillator whose inductance is modulated
- shunted by a parallel plate C with

$$\omega_0 = \frac{1}{2\pi\sqrt{(C(L_{stray} + L_{SQUID}))}}$$

- amplifies weak signal by pumping
- Tunability ~ several 100 MHz/device

MSA





JPA Al SQUID produced by shadow evaporation Technique

Substrate is oxidized silicon 300 micron thick.

Resonator and antenna patterned from sputterred 50 nm thick Nb film.

JPA

Technical Specs

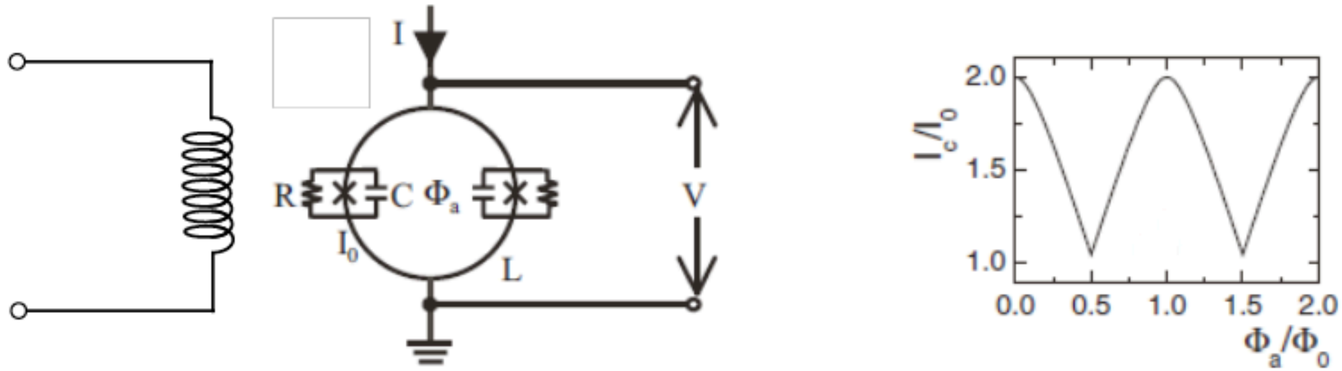
		Pump Power (dBm)	Coil Current (mA)	Bandwidth (MHz)	P1dB (dBm)
DC Resistance (Ohm)	327.2				-116
Gain @ 800MHz (dB)	23 peak	-127.24	-2.880	3.5	
Gain @ 700MHz (dB)	26 peak	-101.24	-5.322	2	
Gain @ 600MHz (dB)	25 peak	-104.17	-7.484	2.5	

Note:

1. Actual values might vary.
2. Pump power refers to the power level at the input of JPA.

MSA contd.

Two Josephson junctions on a superconducting ring



Critical Current I_c is modulated by magnetic flux

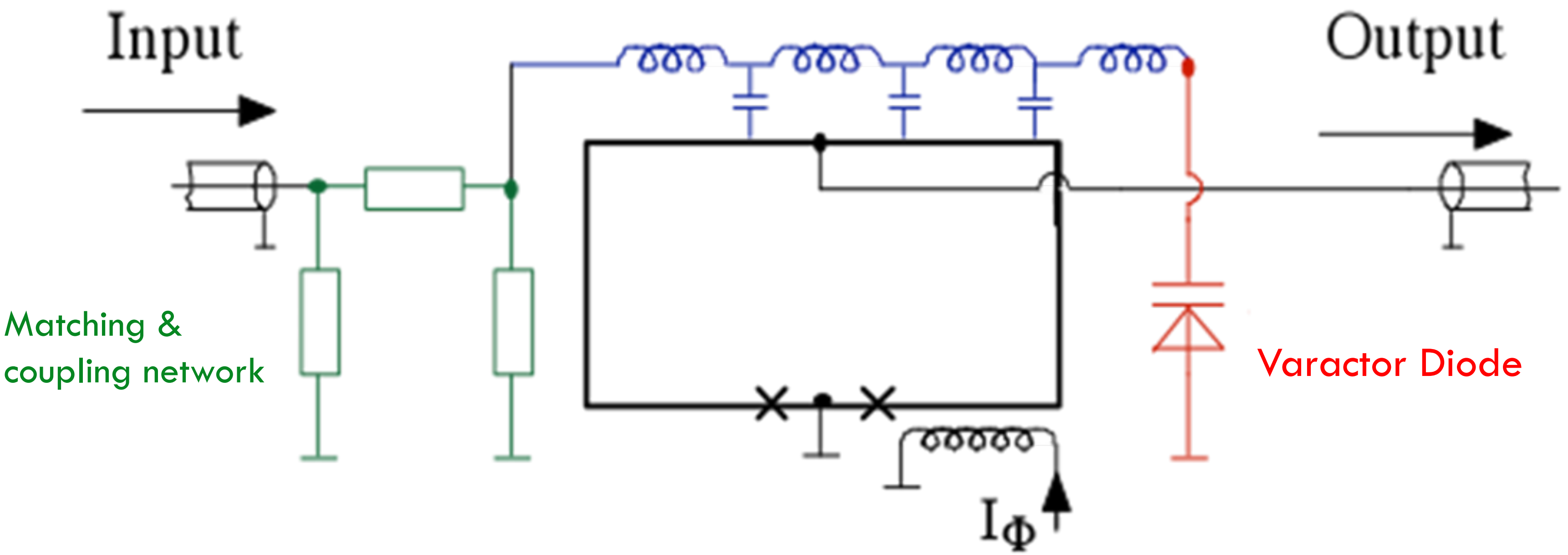
A flux through the SQUID loop (Φ_a) induces a circulating current to satisfy the flux quanitzation condition, adding to the current through one junction, subtracting from the other, and inducing a difference in the phases across the junctions.

Interference of the superconducting wave functions in the two SQUID arms sets the maximum current Ic that can flow at V = 0

With some simplifying assumptions (like symmetric junctions) the DC SQUID can be treated as a single, flux-modulated Josephson junction

Courtesy of Sean O'Kelley

MSA Schematic



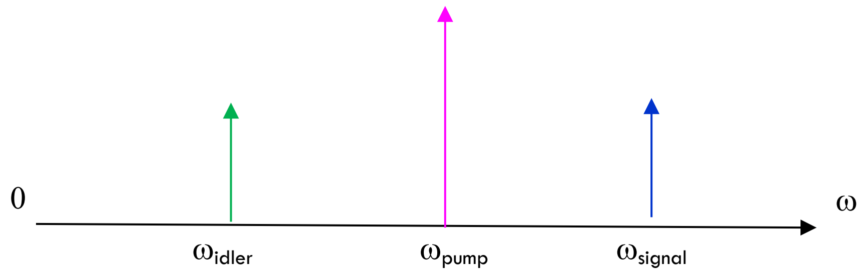
- Varying the capacitance modifies the phase change on reflection, effectively changing the length of the microstrip
- As the phase changes from a node to anti-node, the standing wave changes from $\lambda/2$ to $\lambda/4$, and the resonant frequency varies by a factor of 2
- Varactors must be GaAs (Si freezes out), high Q, very low inductance

Courtesy: Sean O'Kelley, UC Berkeley

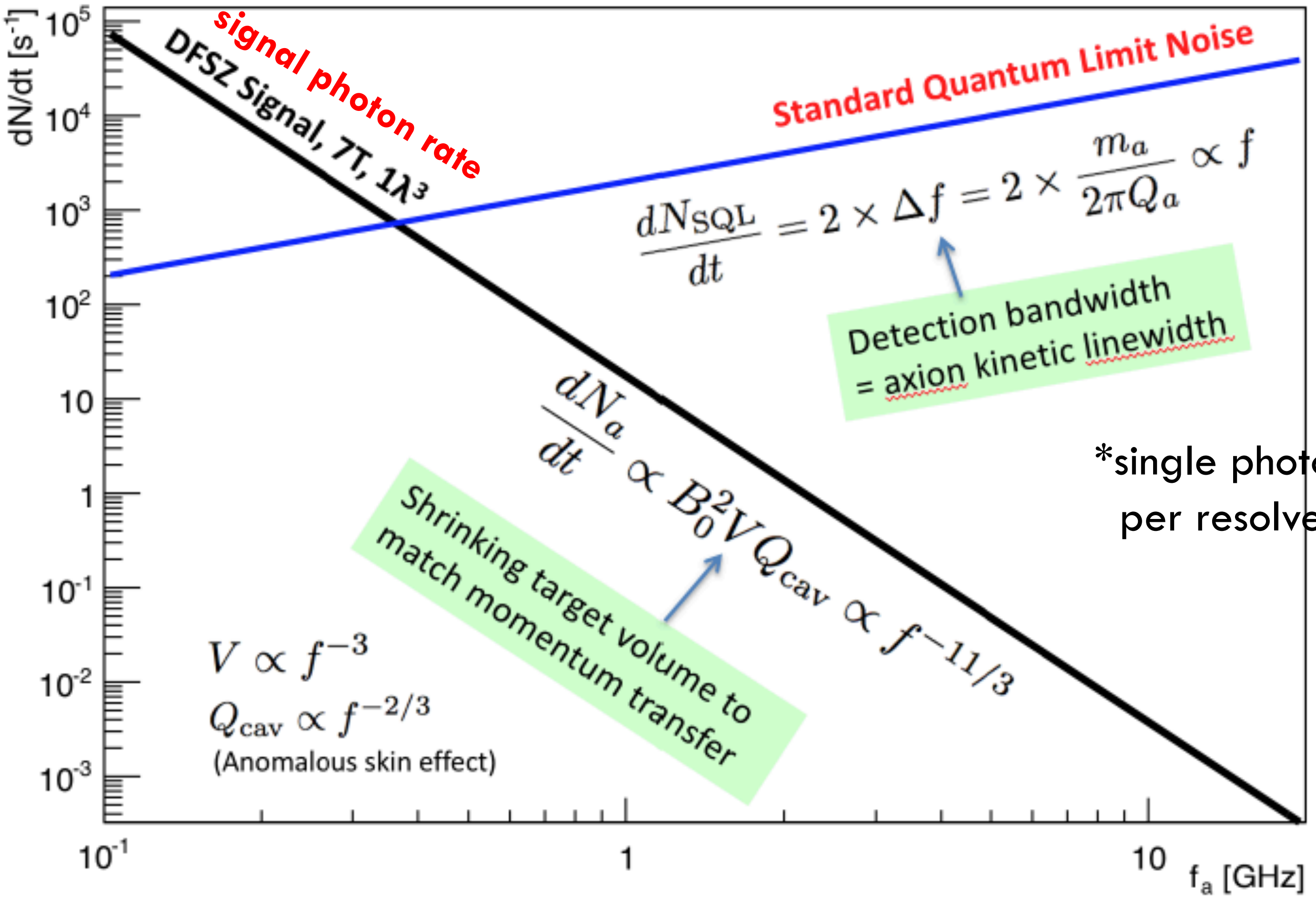
JPA

phase preserving Paramp: $\omega_{signal} \neq \omega_{idler}$

$2\omega_{pump} = \omega_{signal} + \omega_{idler}$



Limitation of quantum amplifiers

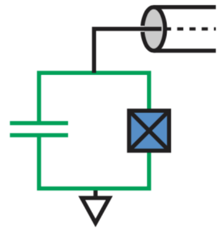


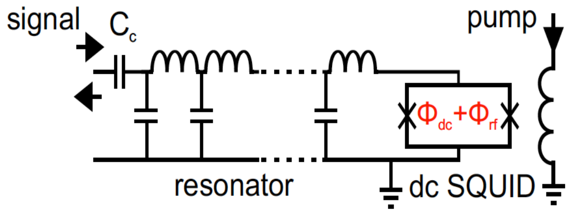
*single photon of noise per resolved mode

Josephson Parametric amplifier (JPA)

- Parametric amplifier: Oscillator whose resonance frequency is modulated

$$\omega_0 = \frac{1}{2\pi\sqrt{(C(L_{stray} + L_{SQUID}))}}$$





- Oscillating system a λ/4 resonator

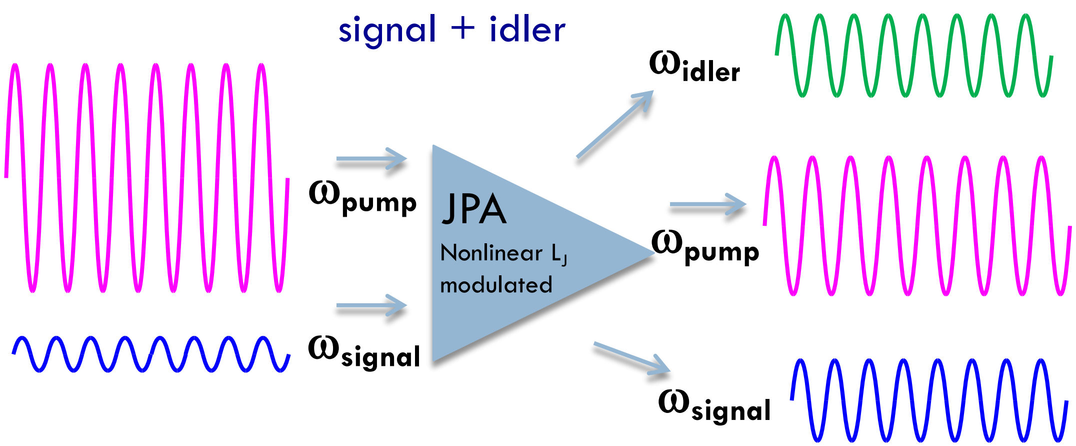
$$L(I) = \frac{\Phi_0}{2\pi I_0\sqrt{1-(I/I_0)^2}}$$

- Inductance varied with SQUID (flux dependent nonlinear inductor)

two normal modes of swing:
signal + idler

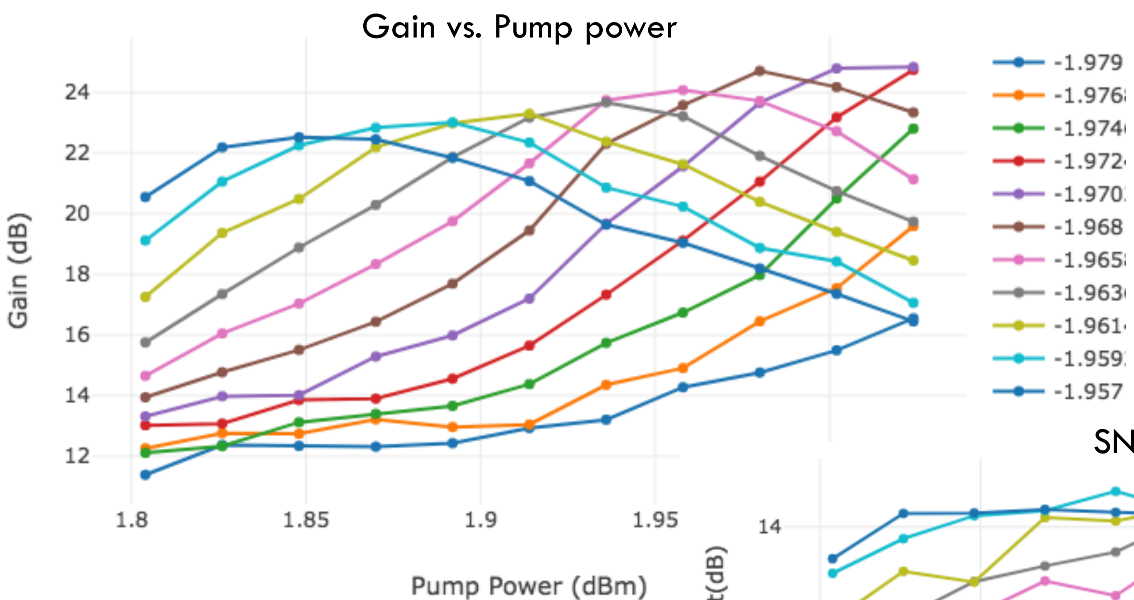
- Energy transfer from pump to two normal modes of swing

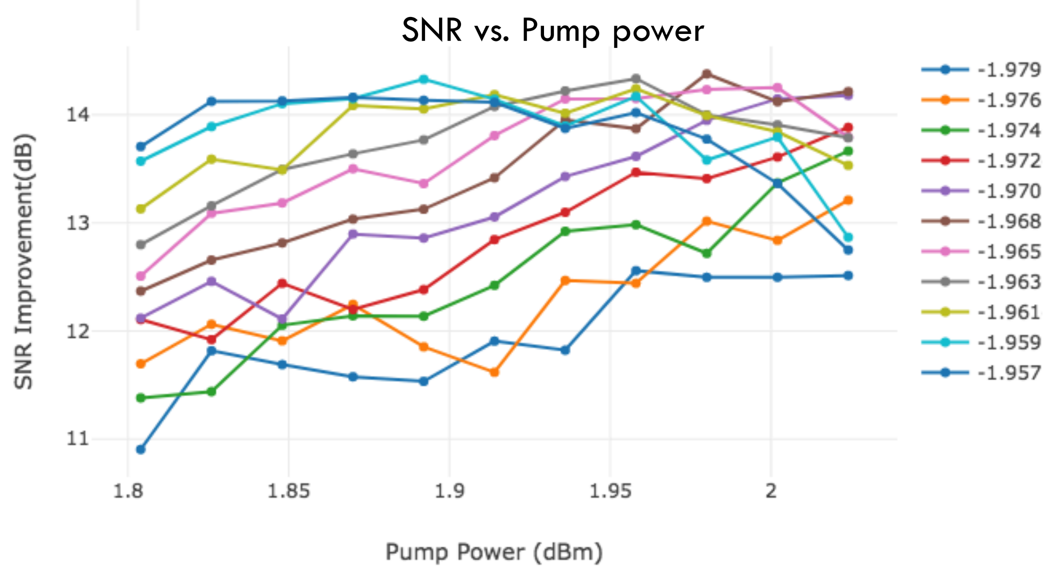
- Noise – Quantum Limit



Paramp schematic: L. Zhong et al., “Squeezing with a fluxdriven Josephson parametric amplifier,” New J. Phys. 15, 125013 (2013).

JPA operation -- biasing





Current run started January 2018

-- x4 more data
680-800 MHz (JPA)
-- covered 680-800 MHz – Oct
-- T_{system} < 500 mK

Sub-quantum-noise-limited JPAs

Phase sensitive JPA amplification

*Nonlinearity causes change in pump power

to cause pump phase shift -- transfer

function of JPA

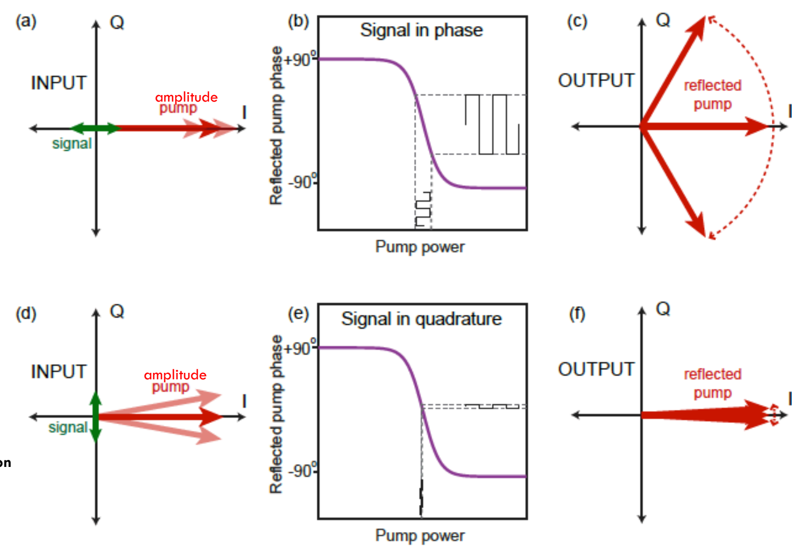
*Vector difference between output state<

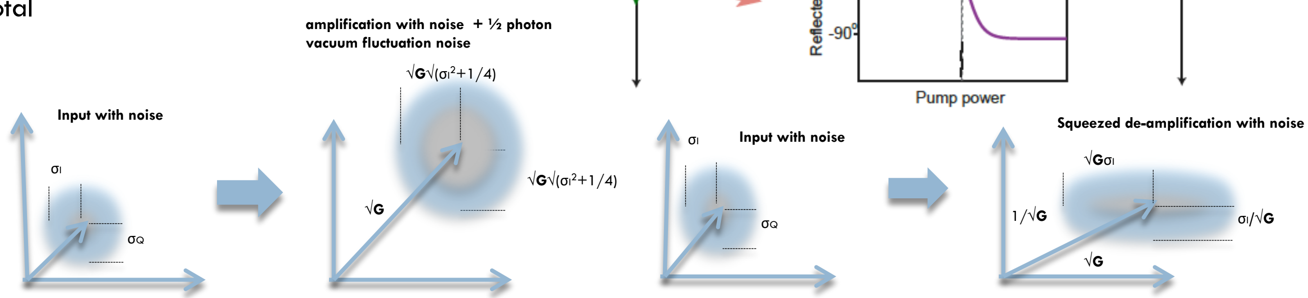
input – deamplified state

*Input noise in the out of phase/quadrature

de-amplified causing < noise than QL in

total





Pump schematic: D. H. Slichter

Sub-quantum-noise-limited JPAs contd.

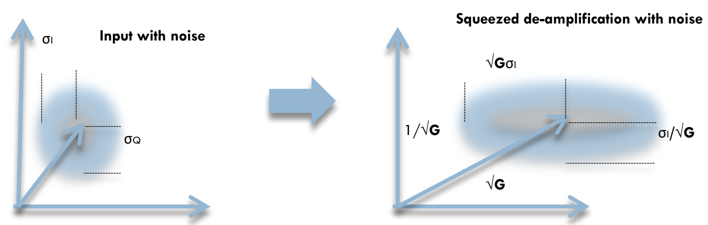
34

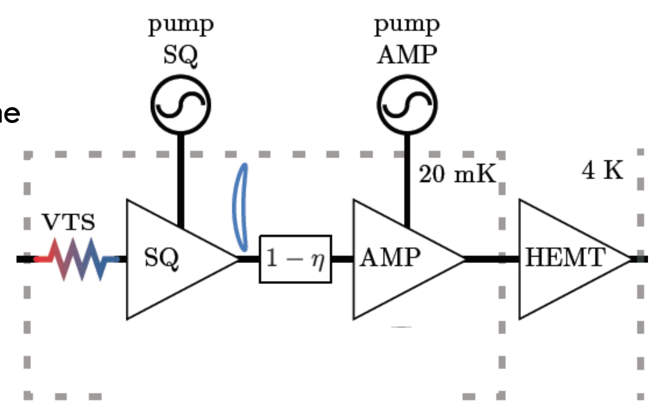
*Amplify the Squeezed state with lower than quantum noise at the input

*There have been a few ideas proposed for Axion search
-- not satisfactory

*High losses between two JPAs
*Feeding squeezed state into the cavity not well understood

*Further R&D necessary
--viability test
*>4GHz





M. Malnou et al., arXiv:1711.02786

Squeezed states/ultra noiseless amps.

- JPA-nonlinear-phase insensitive (measures both amplitude and phase of the signal)– by definition, quantum noise limited since simultaneous measurement on amplitude and phase.
- Ultra noiseless amps (degenerate/squeezed state para amp.) —phase sensitive (measures one or the other)– no limit from quantum noise since not measuring two quantities simultaneously

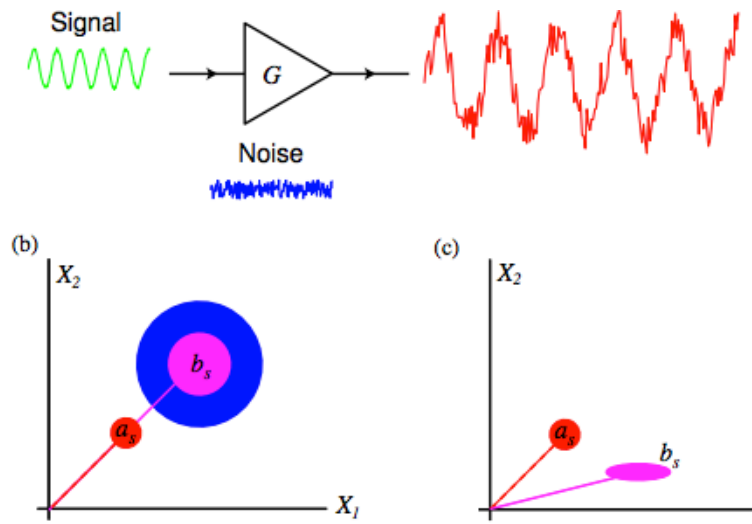


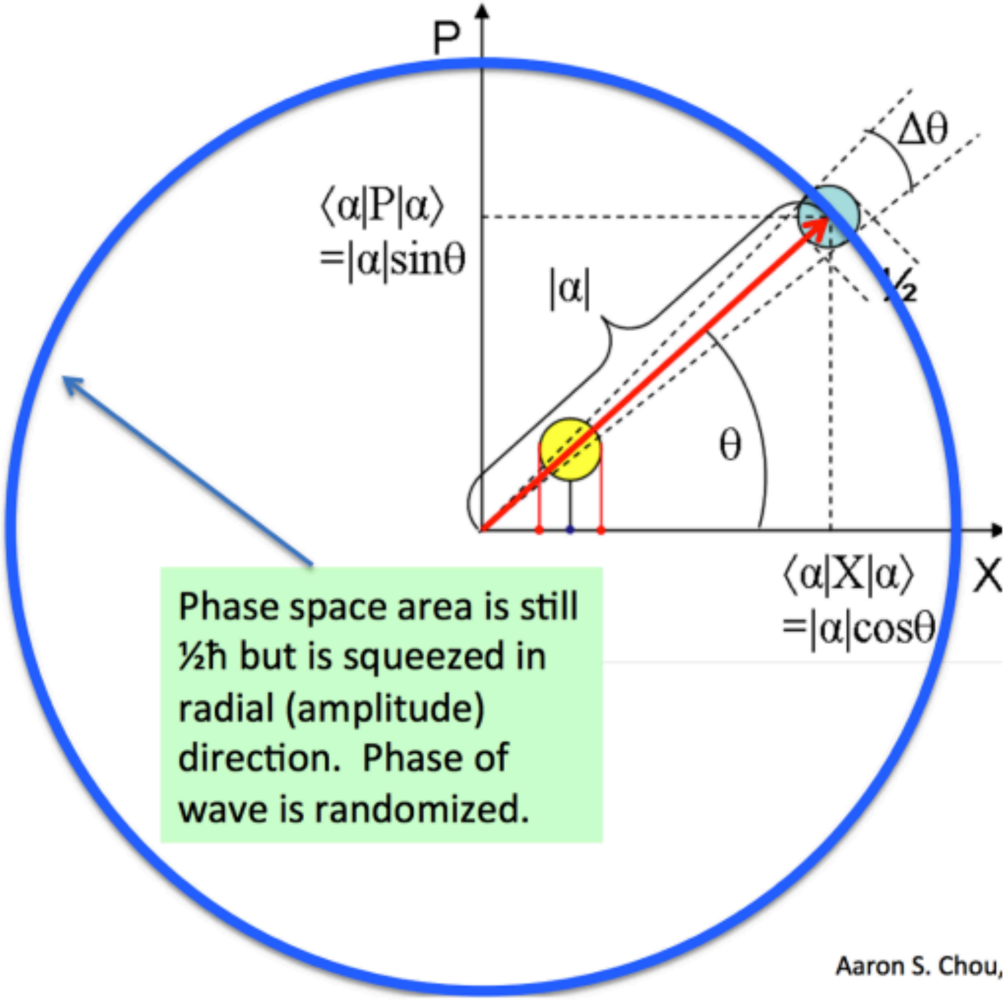
Figure 1.1: (a) In general, the amplification process will degrade the signal to noise ratio by adding certain amount of noise to the signal before amplifying it. (b) Quantum mechanics places a restriction on the minimum amount of this added noise when the amplifier amplifies both quadratures of the signal. When an amplifier achieves this limit, it is said to be quantum limited. (c) On other hand, if the amplifier is a phase-sensitive amplifier, and only amplifies one of the quadratures, then it can do that ideally without adding any noise.

Castellano-thesis

Analogy of electromagnetic field

- EM field denoted by $a^{+}a$ -- creation and anhilation operators (don't commute)
- Harmonic oscillator in its lowest position, there is spread in the values of position and momenta called "zero-point motion" of the oscillator.
- Analogous to the operators are the amplitude and phase of an electromagnetic wave/signal.

QND photon counting advantage

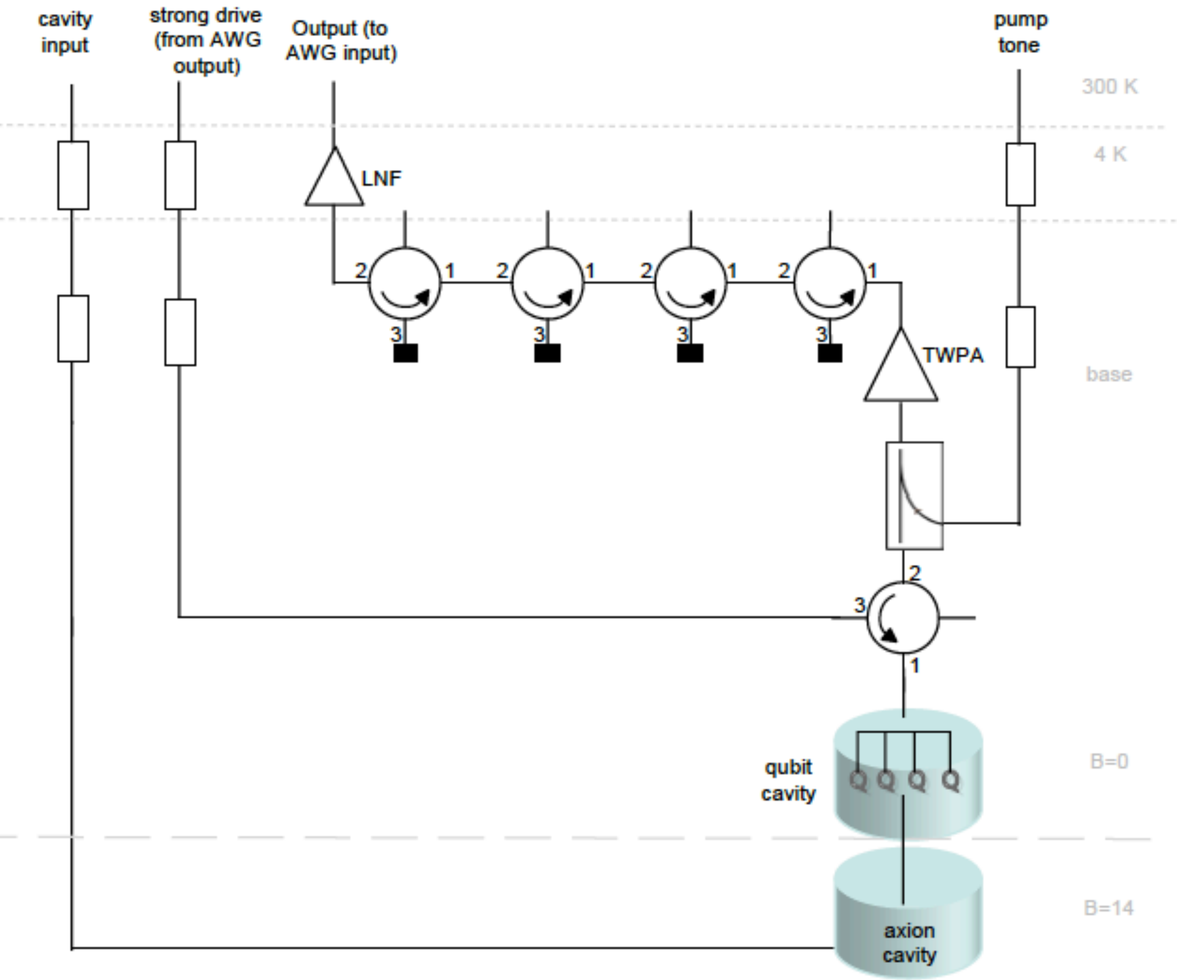


No zero point noise limit of Quantum amps.

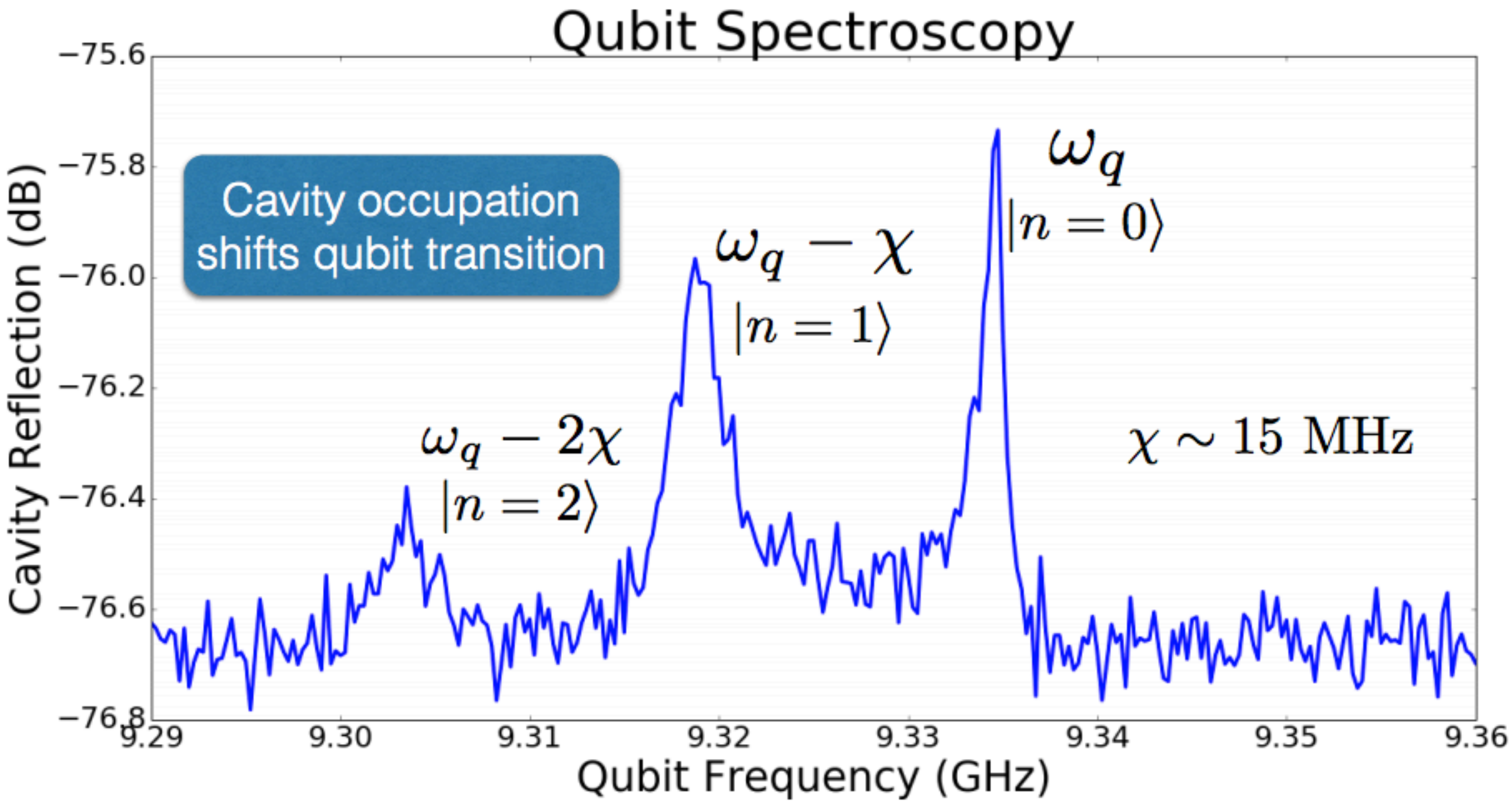
-- count the photons

Single photon counting axion detector

- Technique needs more maturity
- qubit readout error reduction
- needs tailoring to axion detection (B field)
- Fermilab, UC Boulder and Yale -- part of DOE quantum computing and sensors initiative



Cavity Dependent Qubit



Akash Dixit

Cavities etc.

- Photonic bandgap: Isolate a single mode using a defect in an open periodic lattice of metal and/or dielectric rods. Well defined TM010 mode, much higher volume at a given frequency than conventional cylindrical cavity. Challenge is to make them tunable. Work at UC Berkeley.

  Open resonators retain high Qs at high frequencies. Cold prototype under construction at 20 GHz.

  Photon counting method is not limited by Quantum noise limit --10 GHz
  Qubit – axion cavity – currently under development at U Chicago/Fermilab

ADMX operations

Live Analysis – Automatic scanning

1. Cavity frequency scanned until a desired signal-to-noise level is reached.
2. Regions with power above trigger threshold are flagged as potential statistical anomalies, external RF leakage, synthetic injected axions
3. Rescan persistent candidates to see if they persist.
4. If they persist have a couple of checks.
    a. Switch to resonant mode that doesn't couple to axions (TEM mode).
    b. Turn B-Field down (axion power should scale as B^2).

Further Offline Analysis

- Ability to vary the bin size from time-series data.
- High Resolution analysis to look for ultra-sharp lines.