THE MOST SENSITIVE MICROWAVE RECEIVER FOR AXION DARK MATTER SEARCH

LTD-18

Milan, Italy,

Photo by Getty Images/Westend61

07/22/2019

Rakshya Khatiwada, Fermilab

DARK MATTER

Weakly interacting – can't be detected with observational astrophysics tools – doesn't reflect, absorb or emit light

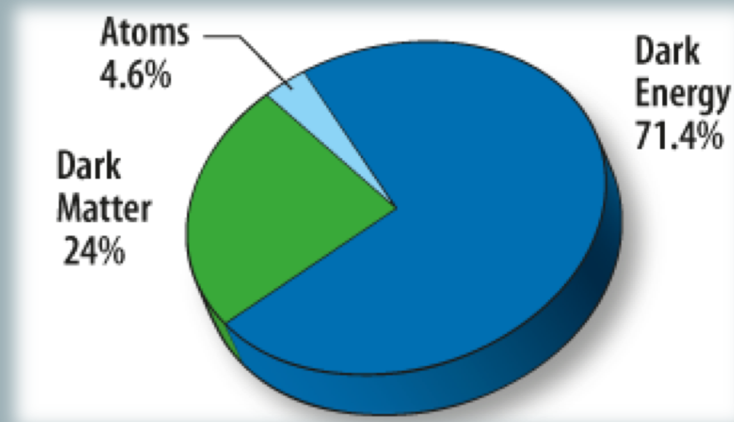
Makes up large structures of the universe – **forms clumps – cold dark matter**

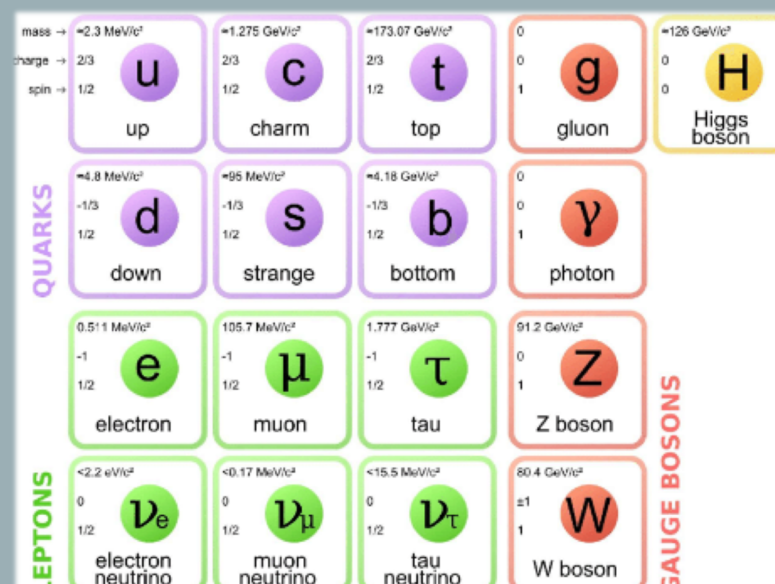
Proof of existence:

-- Gravitational lensing

-- CMB power spectra

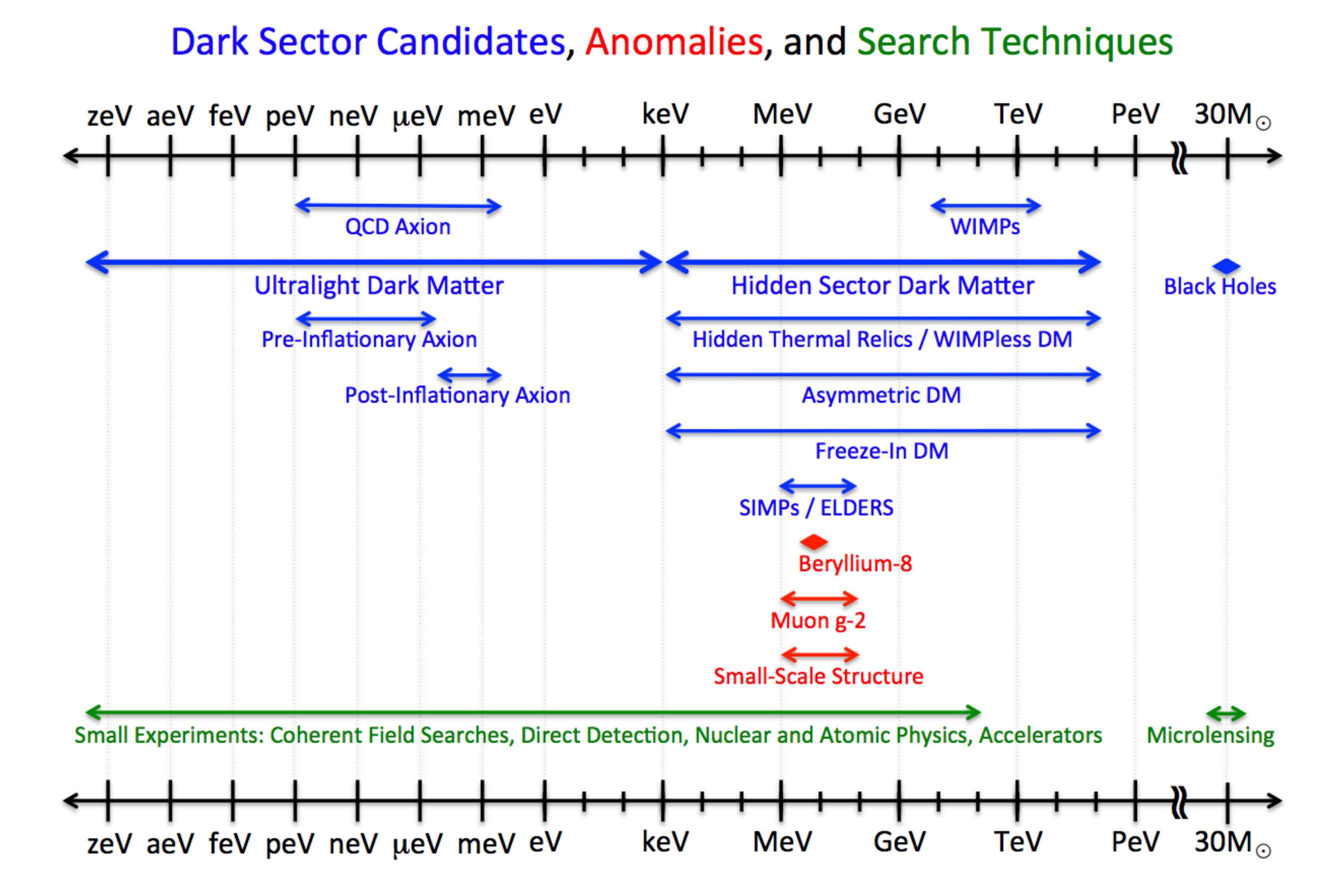
-- Galaxy rotation curves etc.





DARK MATTER CANDIDATES

US Cosmic vision



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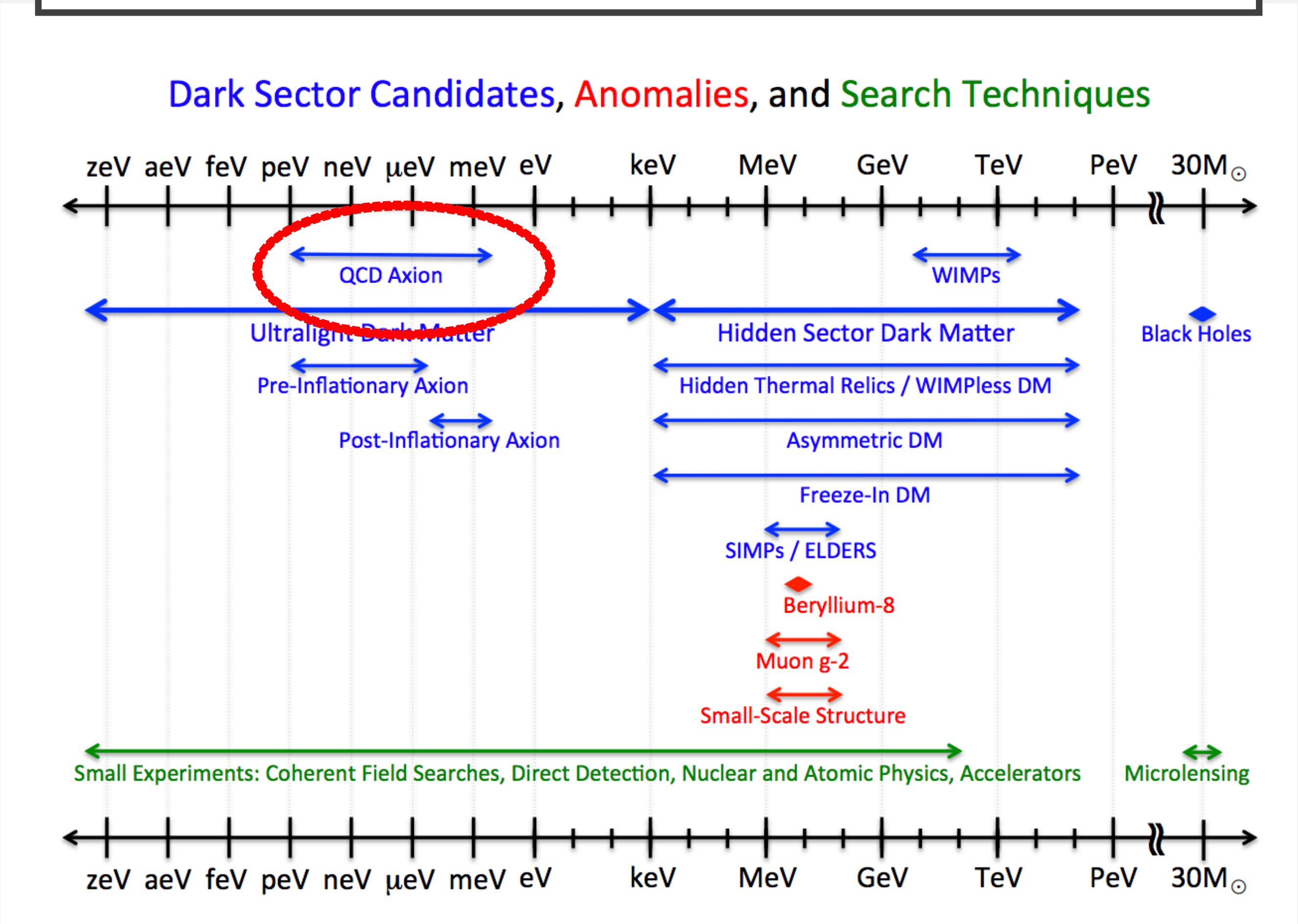
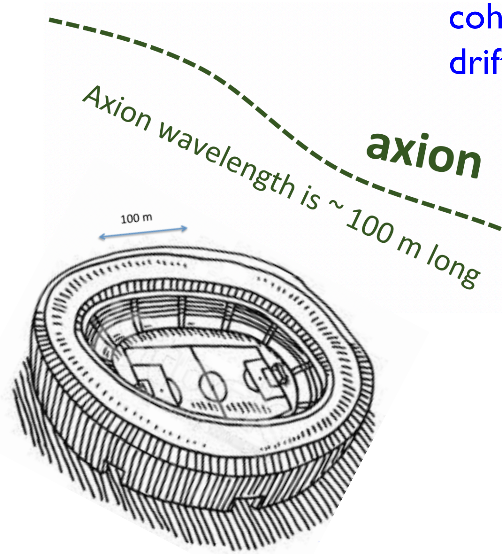


AXION DARK MATTER EXPERIMENT

(ADMX)

AXION IN THE GALACTIC HALO

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



Oscillating electric current
In external **B**

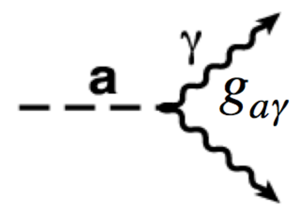
$$\boldsymbol{J_a}(t) = g_{a\gamma}\boldsymbol{B_0}a_0 e^{-i\omega t}$$

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

- ***Produced around Inflation***
- ***Misalignment mechanism***
- ***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!***
- QCD axion mass $m_a \sim \Lambda_{QCD}^2/f_a$ --- f_a unknown

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

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



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

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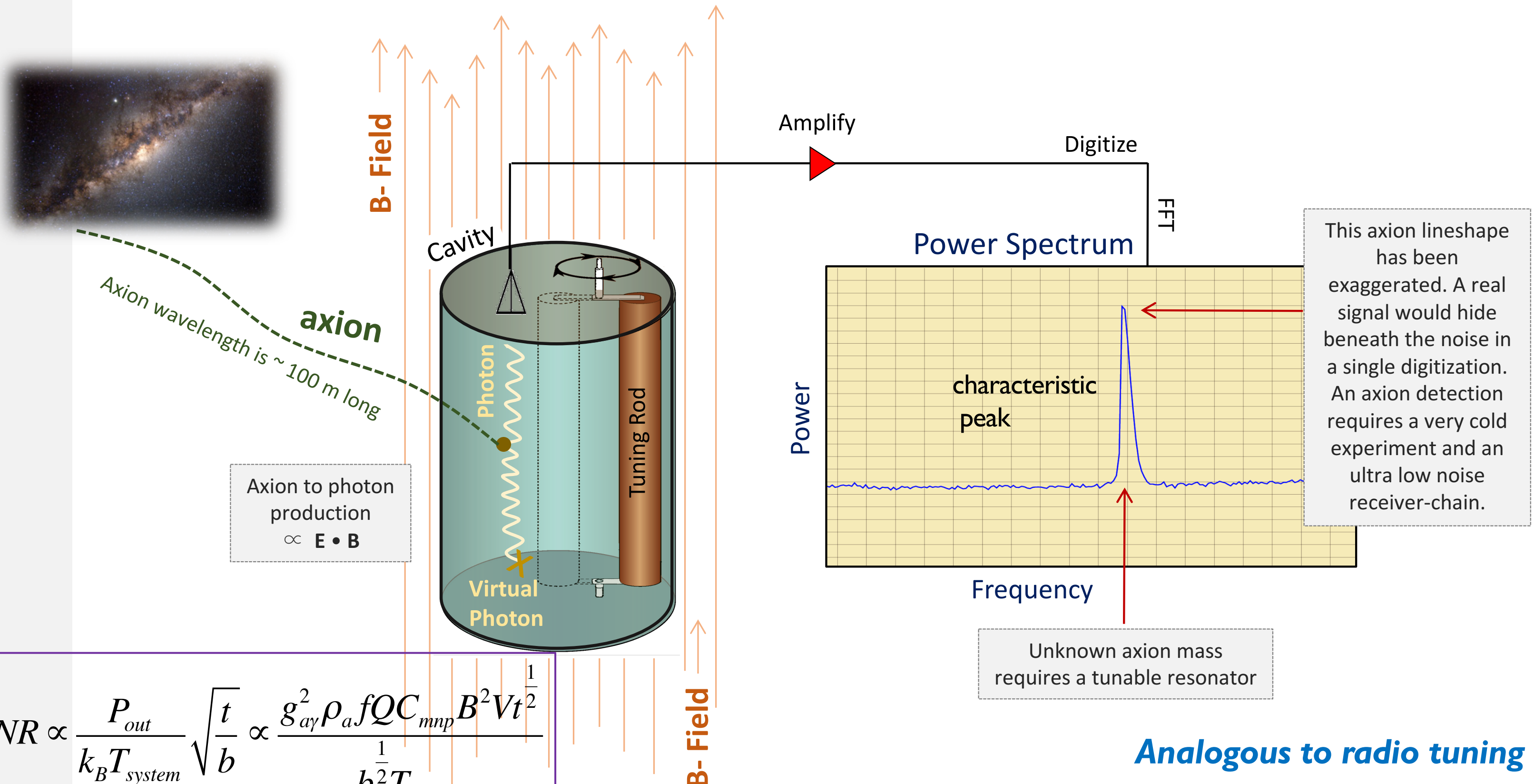
HOW TO DETECT AXIONS?

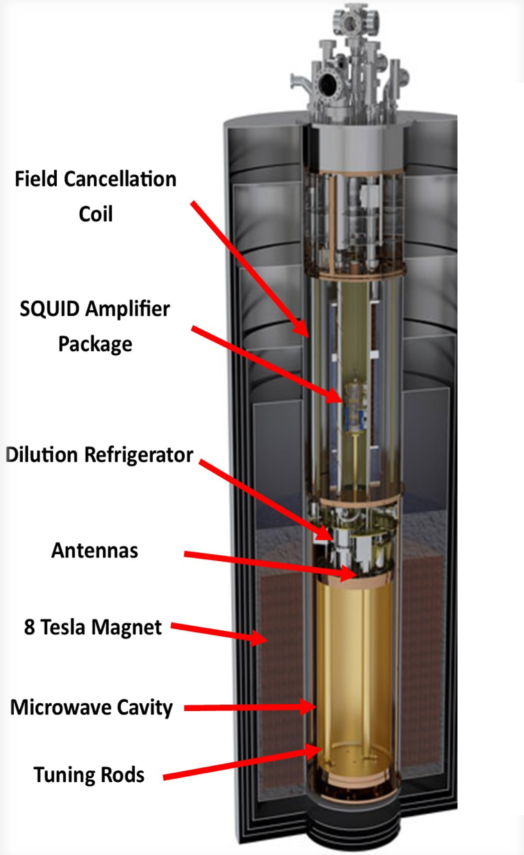
The Axion Haloscope



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

Serge Brunier@NASA
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)

$\Rightarrow$ low resistance elements

$\Rightarrow$ low thermal dissipation

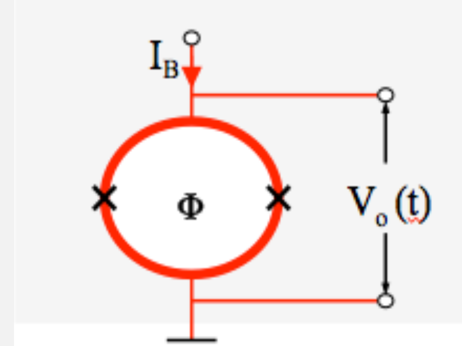
$\Rightarrow$ Add very low added noise during amplification

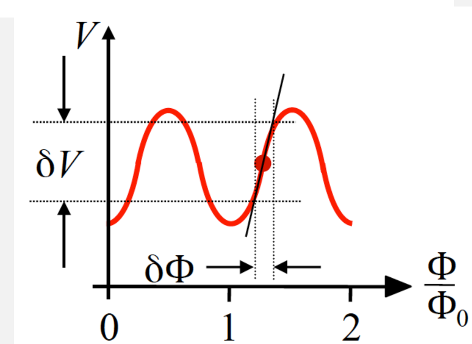
=> Tunable in frequency

Josephson Parametric Amplifier

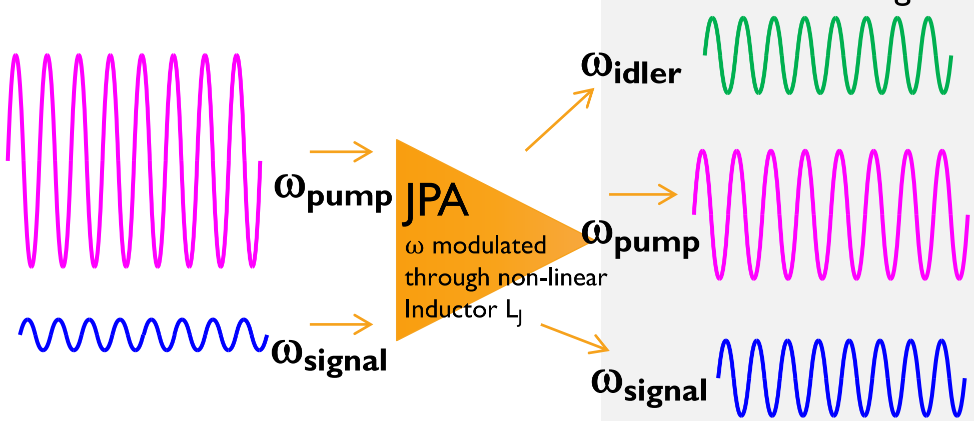
JPA

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)

Note: increases with frequency

Electromagnetic wave phase and amplitude measurement uncertainty

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

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

**Determines the sensitivity of the experiment*
**The most involved aspect of analysis*

ADMX PRELIMINARY RESULTS 2018/19

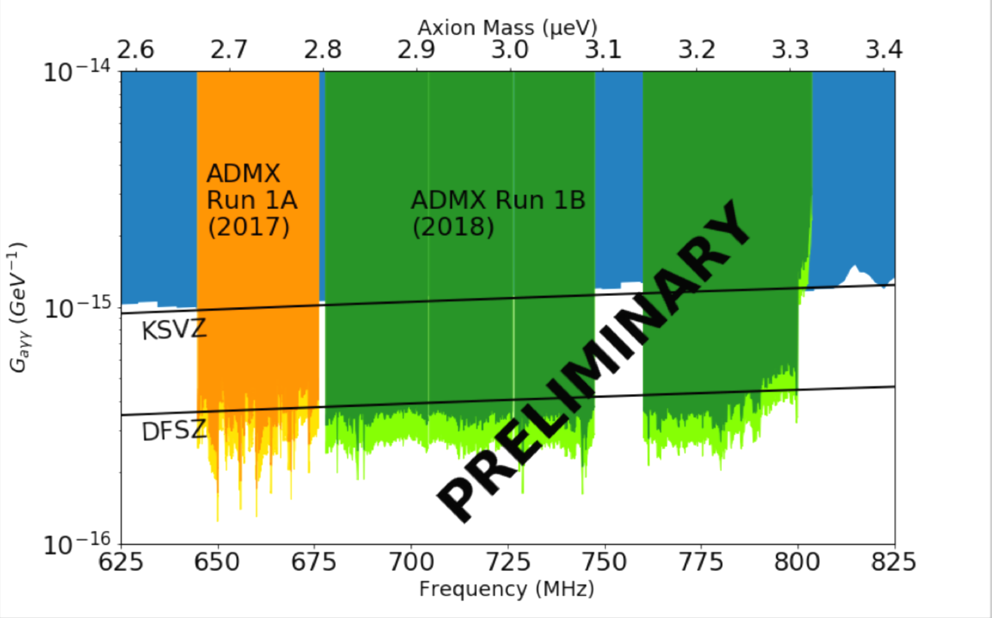
=> x4 more frequency covered than 2017

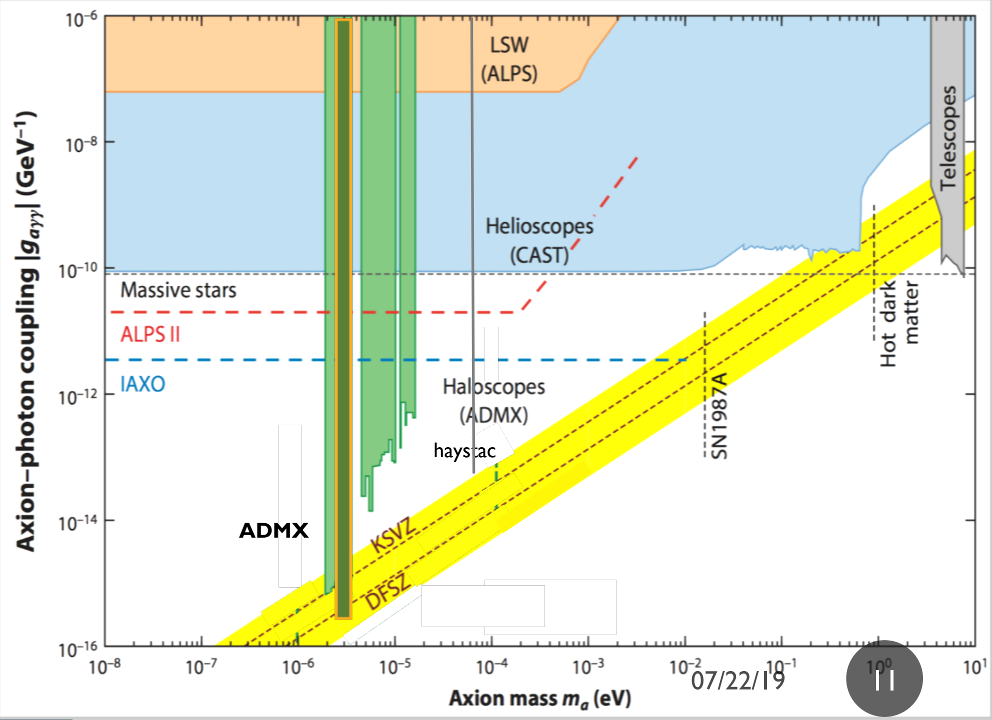
=> DFSZ sensitivity -- 680 to 800 MHz

=> Axion mass probed to this date: 2.66 to 3.3 μeV

=> Stay tuned for results – paper out 2019

=> 2019 run will start soon





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

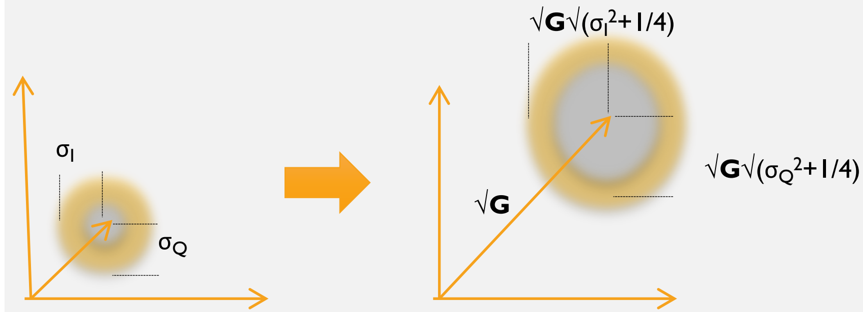
*Nonlinearity causes change in pump power to cause pump phase shift – transfer function of JPA

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

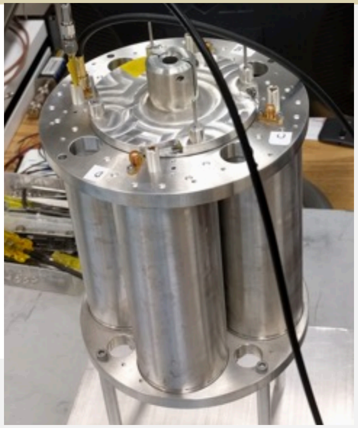
****Exploring this idea for 10s of μeV Axion searches***

Input with noise

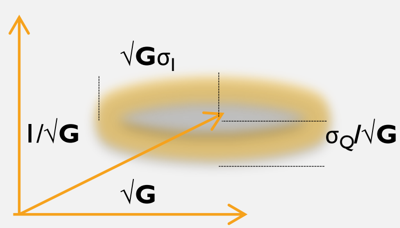
amplification with noise + ½ photon vacuum fluctuation noise



four cavity array



Squeezed de-amplification with noise

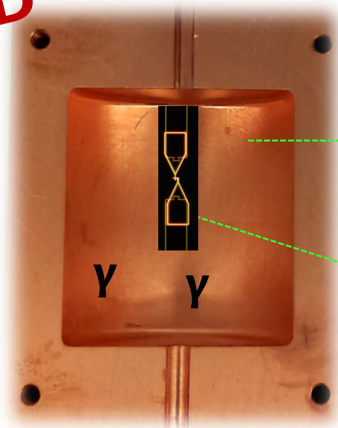


< quantum noise

QUBIT BASED SENSOR FOR DARK MATTER DETECTION

DOE QuantiSED Initiative

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

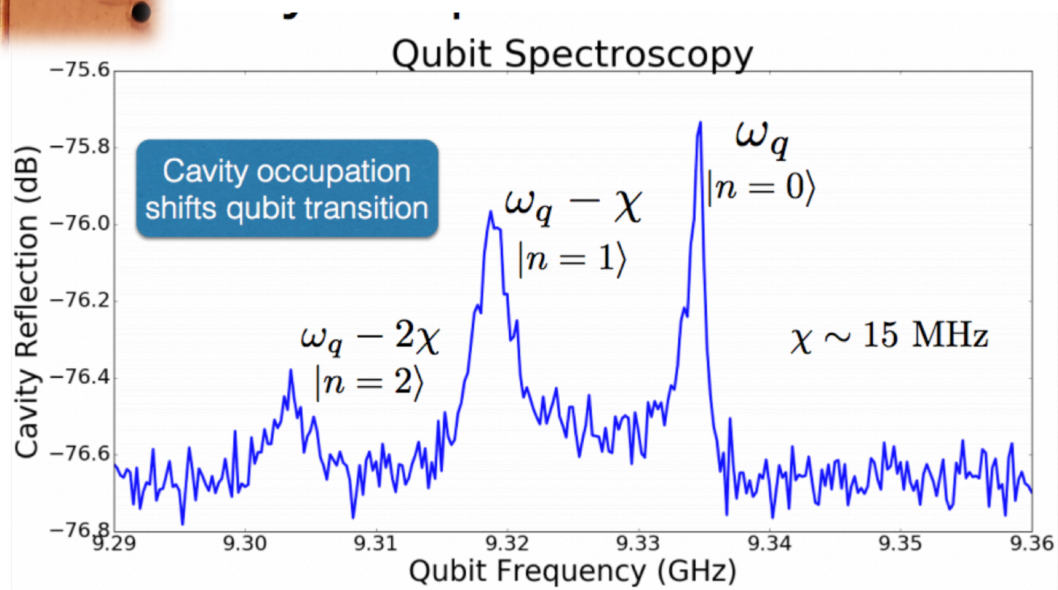


$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

readout cavity

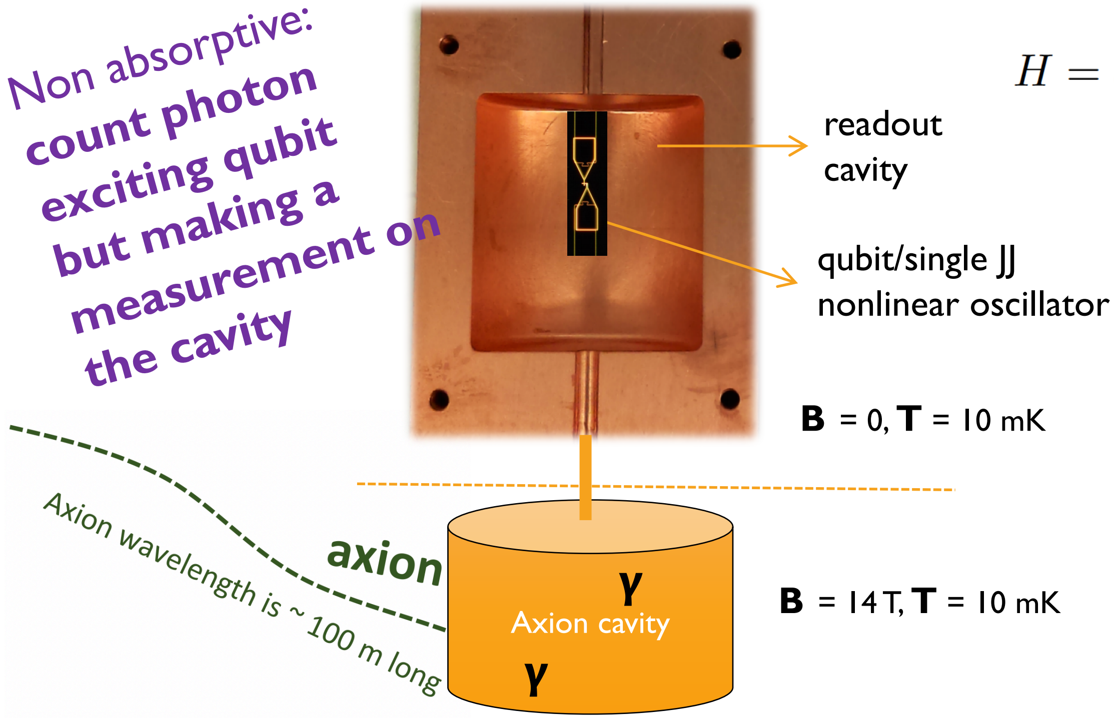
cavity | qubit | mixed

qubit/single Josephson Junction /nonlinear oscillator



QUBIT BASED SINGLE PHOTON DETECTOR

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



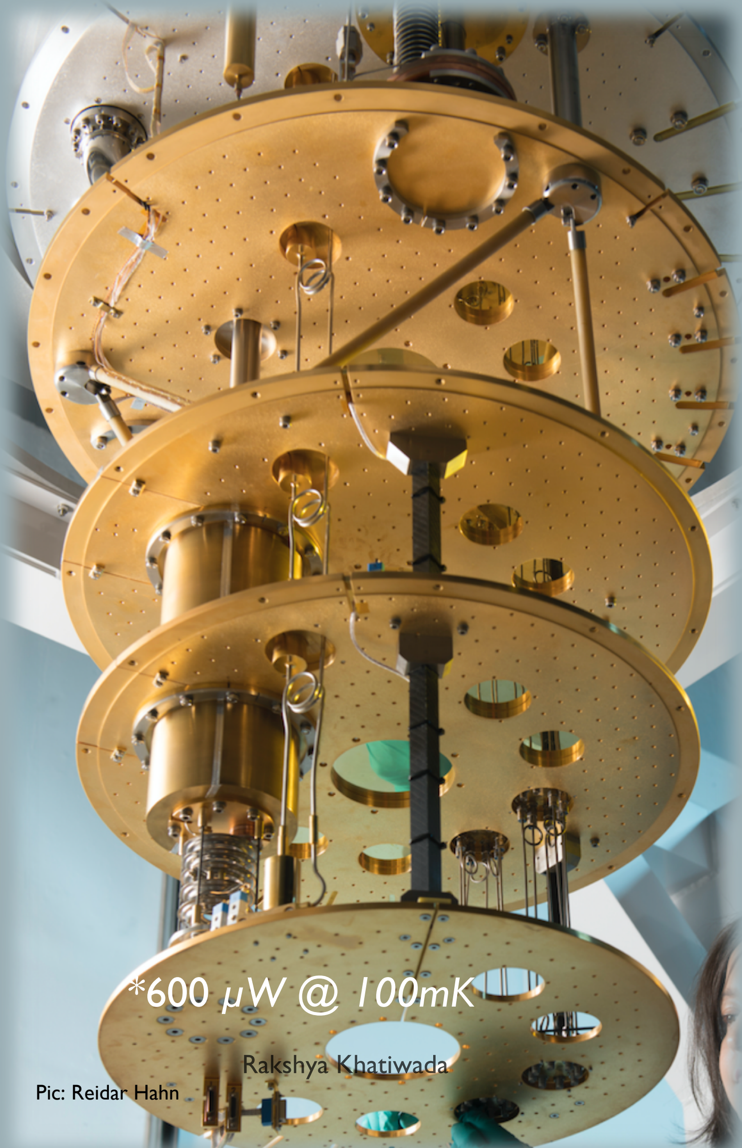
$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

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

Photon # counting evades the quantum noise limit

PHOTON COUNTING DARK MATTER DETECTOR



Pic: Reidar Hahn

*Single qubit-cavity readout
⇒ error rates ~ 1%

U Chicago

The plan:

*multiple qubit readout -- reduce error rate and integration time

Fermilab

*integration of m cavity

Aaron Chou
25th July
Time: 13:45

=>Use magnetic ensors

=>Use high quali (compatible with magnet)

Boulder

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

=>Ultimately establish a standalone axion detector

Fermilab

Multiple years' plan!

Targeted for >40 μeV axions

DARK MATTER SEARCH SUMMARY

- ADMX DFSZ sensitivity -- forefront of Axion Dark Matter search
- Next run taking place this year ~ 2019
- Future direction for axion search:

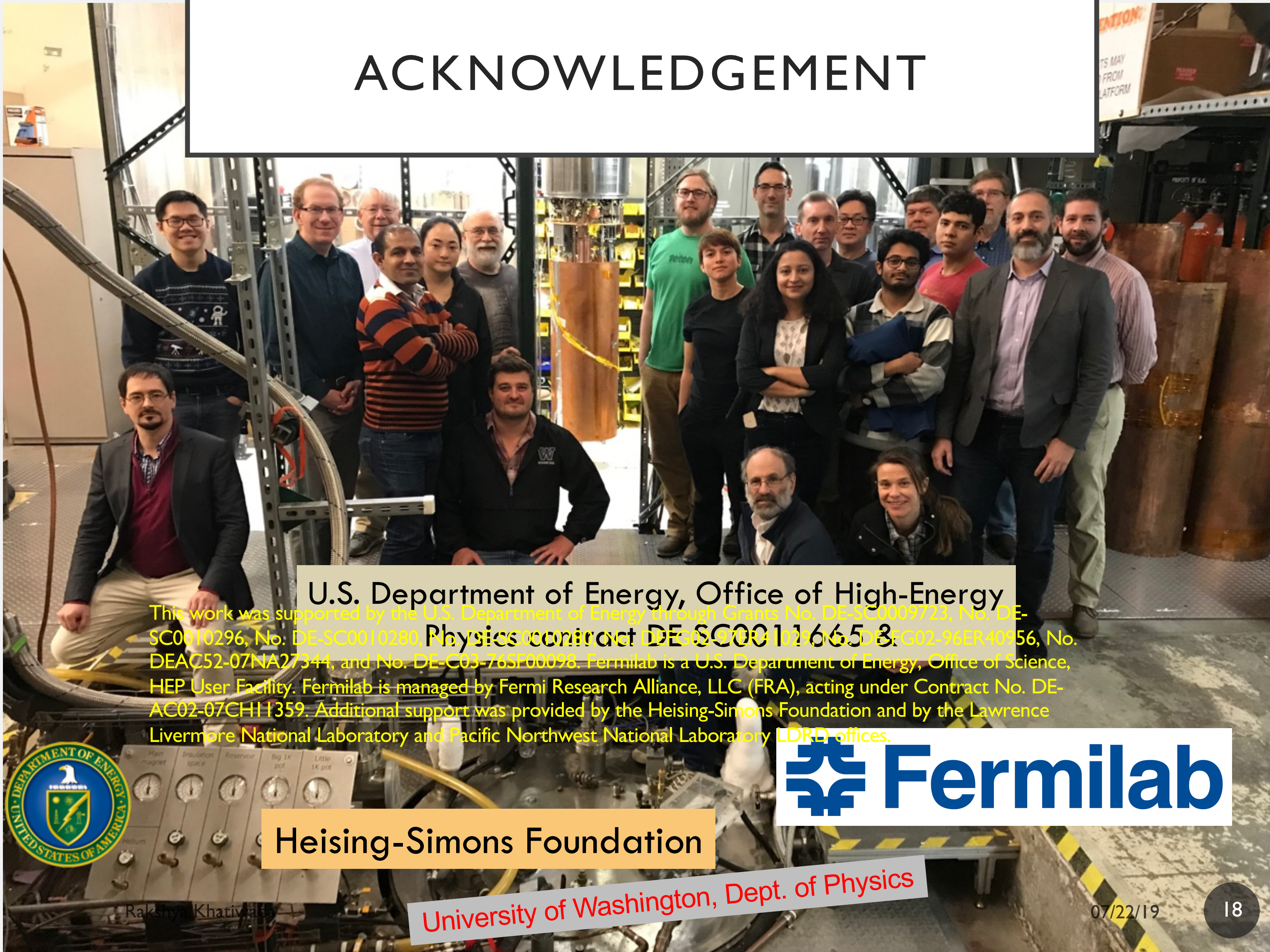
  -- alternatives to single cavity

  haloscope (multi-cavity array)

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

Serge Brunier@NASA

ACKNOWLEDGEMENT



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

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Fermilab

Heising-Simons Foundation

University of Washington, Dept. of Physics

Additional slides

AXION PRODUCTION

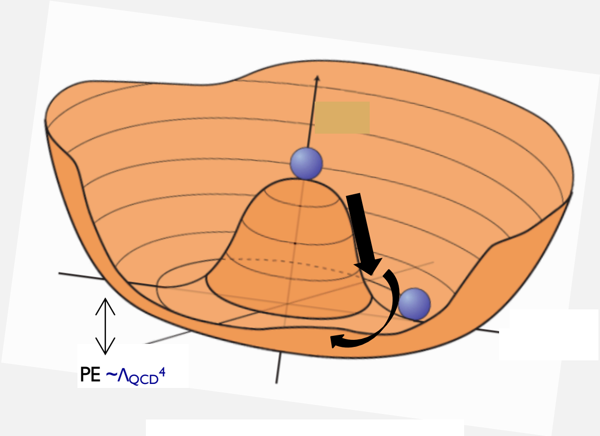
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by $\Lambda_{QCD}{}^4$
- PE $\sim\Lambda_{QCD}{}^4$ released, makes up dark matter

-- oscillation of the QCD θ angle about its minimum--vacuum energy to axions

- QCD axion mass $m_a \sim \Lambda_{QCD}{}^2/f_a$
  $\sim (200\ \text{MeV})^2/f_a$

--- f_a unknown

$\Rightarrow$GHz frequencies at $f_a \sim 10^{13}$ GeV scale



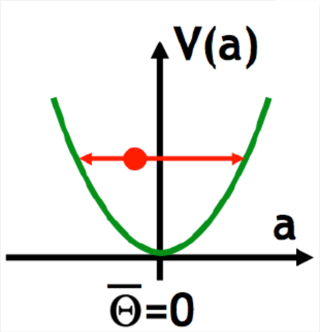
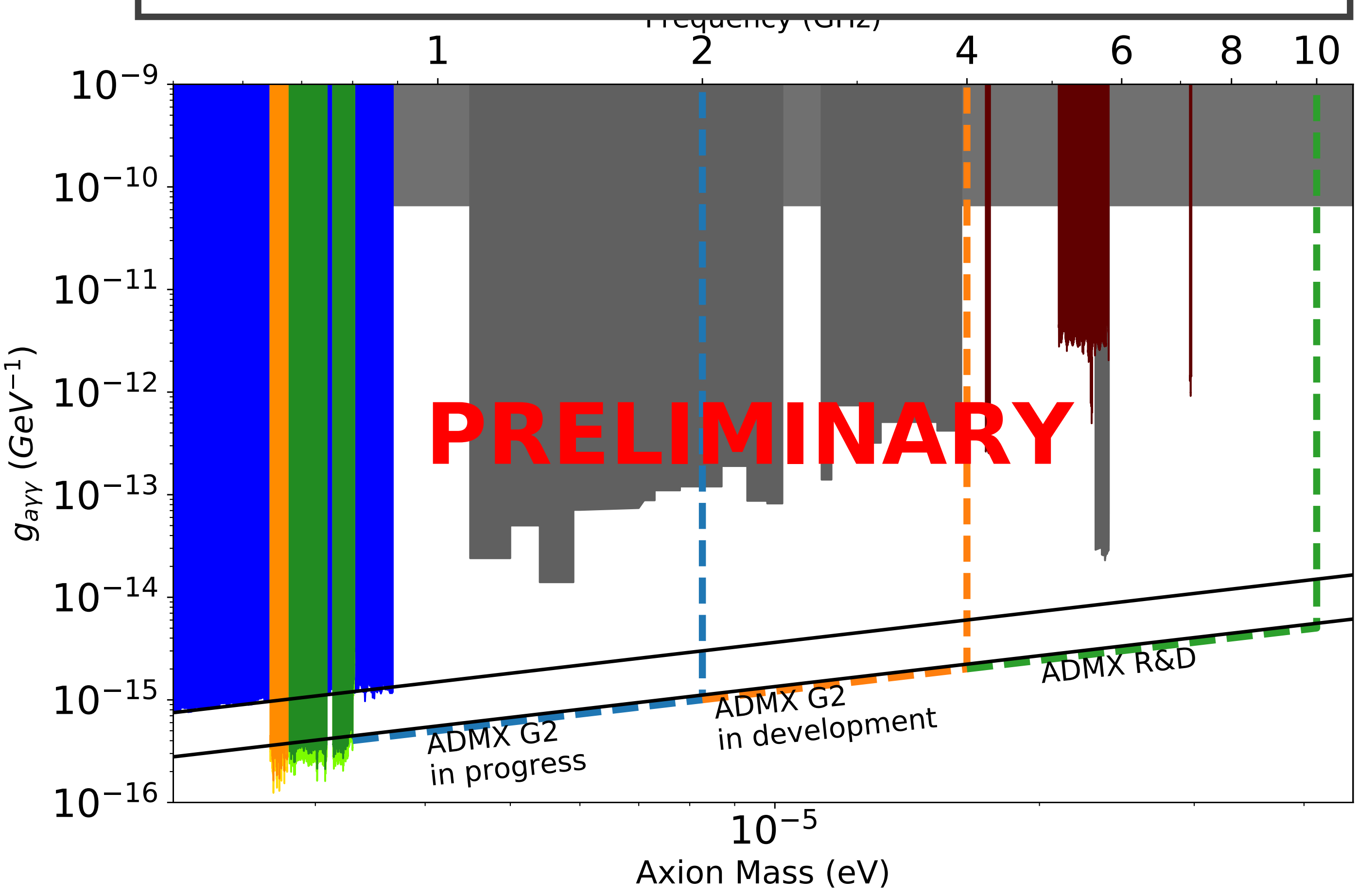
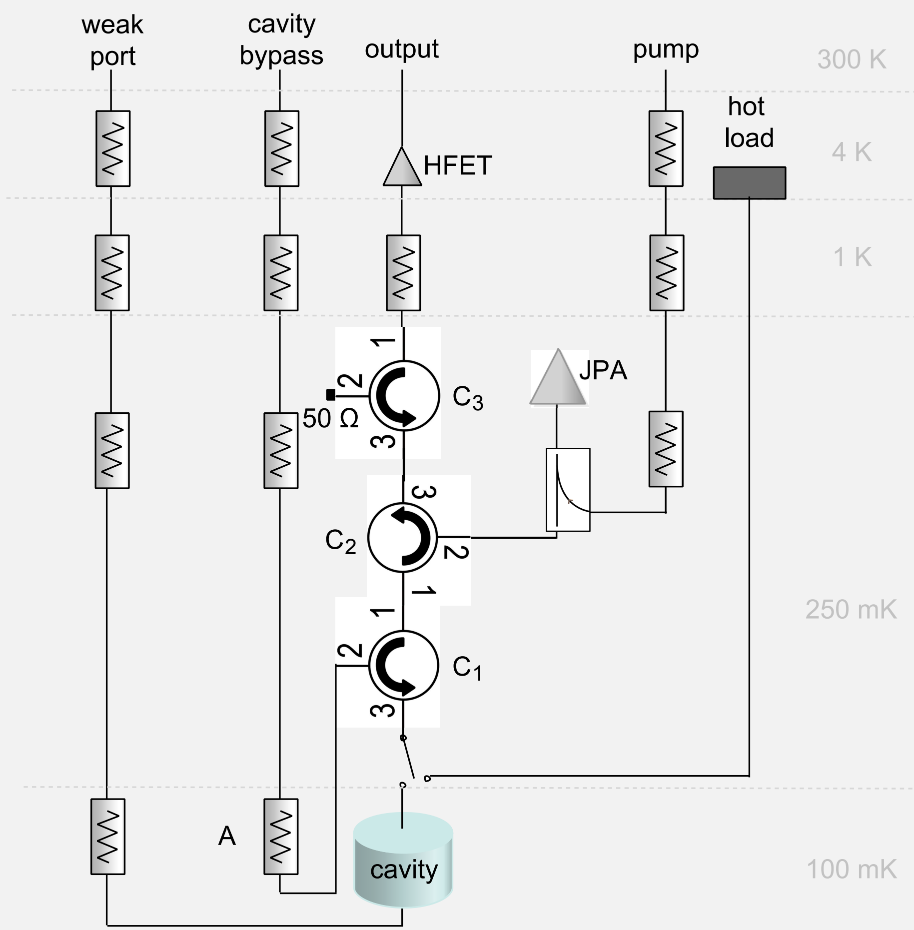


Fig 1:J. Ellis et al; arxiv:1201.6045v1

ADMX G2 FUTURE PLAN

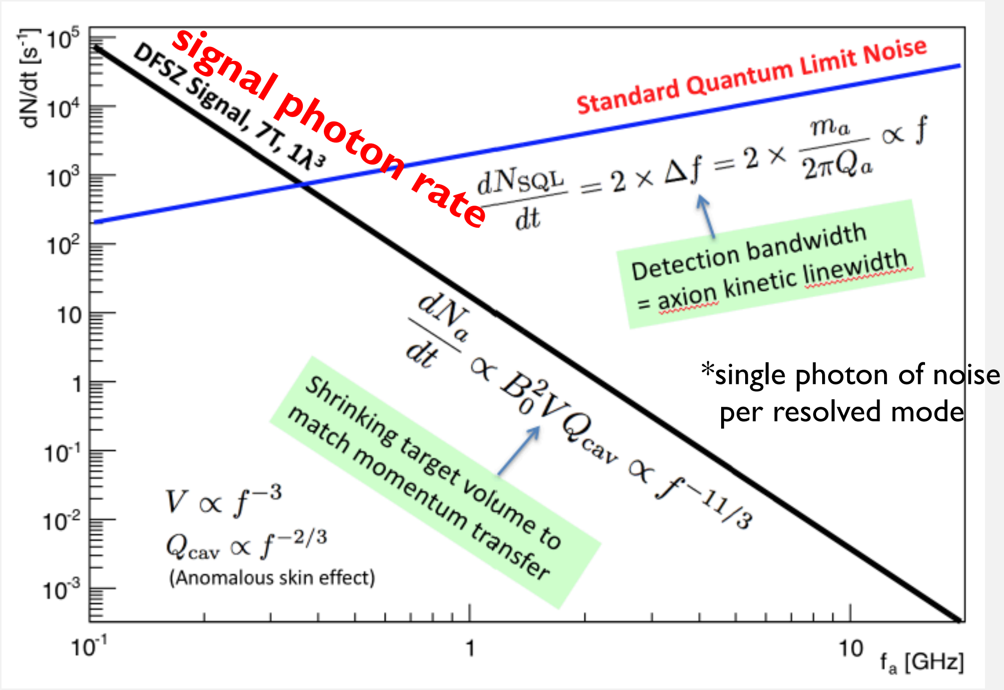


RF LAYOUT



weak port
cavity bypass
output
pump
300 K
hot load
4 K
HFET
1 K
1
2
C3
50 Ω
3
JPA
3
C2
2
1
1
250 mK
2
C1
3
A
cavity
100 mK

LIMITATION OF QUANTUM AMPLIFIERS



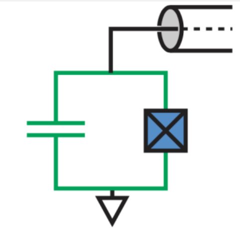
Photon counting procedure

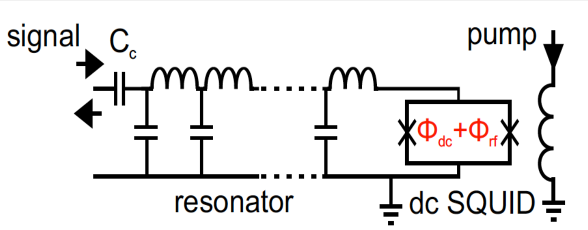
1. Wait 1 cavity lifetime (1micro second)
2. Attempt to excite qubit at one photon shifted frequency (so its insensitive to other # of photons)
3. Readout the qubit to check if it has been excited (200 nsec to 2 micro secs)
4. Wait for the qubit to decay (20 to 50 micro secs) or reset the qubit based on its state.

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

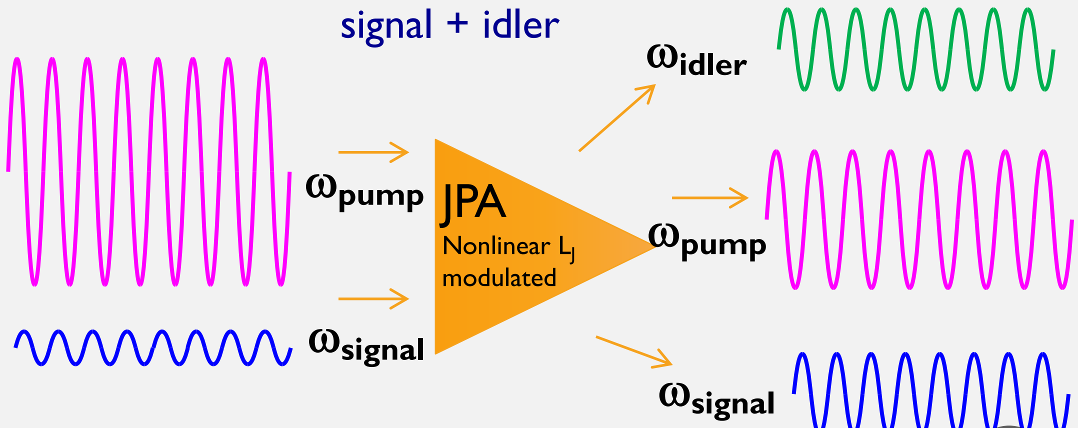
$$L(I) = \frac{\Phi_0}{2\pi I_0\sqrt{1-(I/I_0)^2}}$$

- Inductance varied with SQUID (flux dependent nonlinear inductor)

- Energy transfer from pump to two normal modes of swing

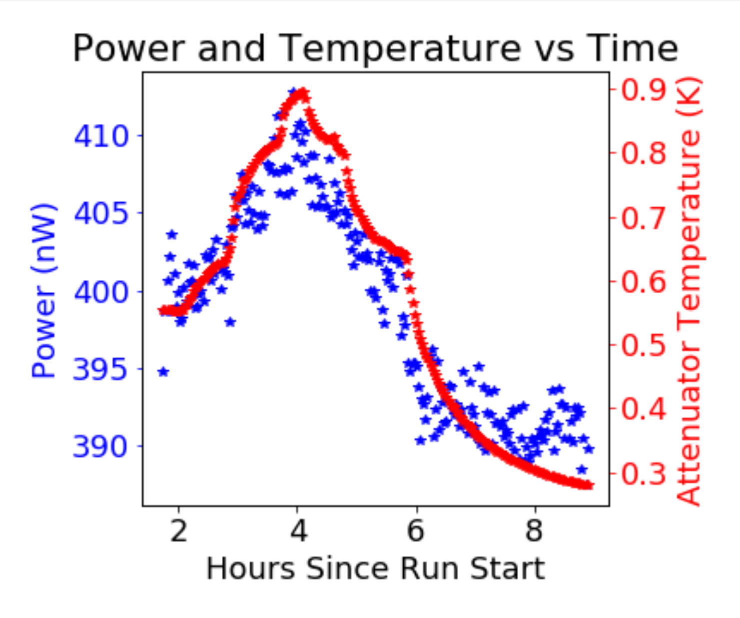
- Noise – Quantum Limit

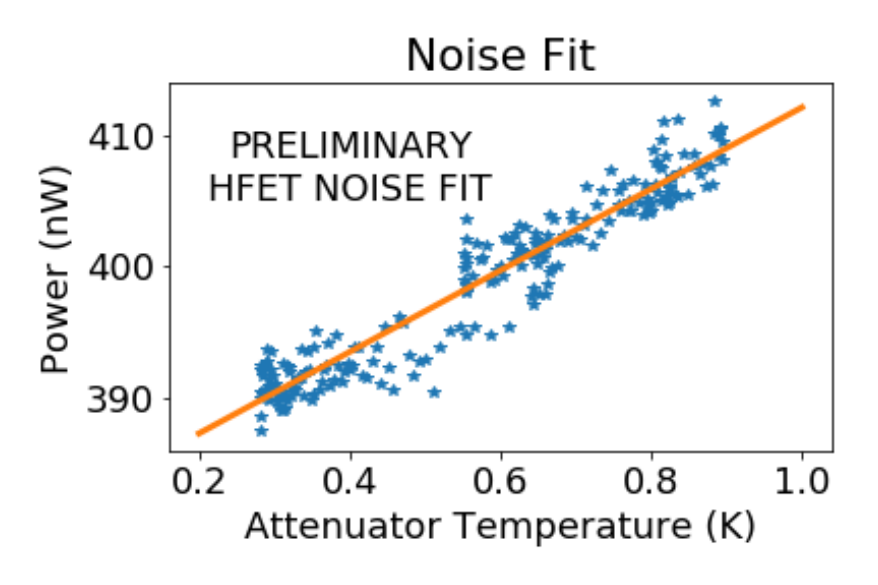
two normal modes of swing:
signal + idler



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

HFET NOISE CHARACTERIZATION

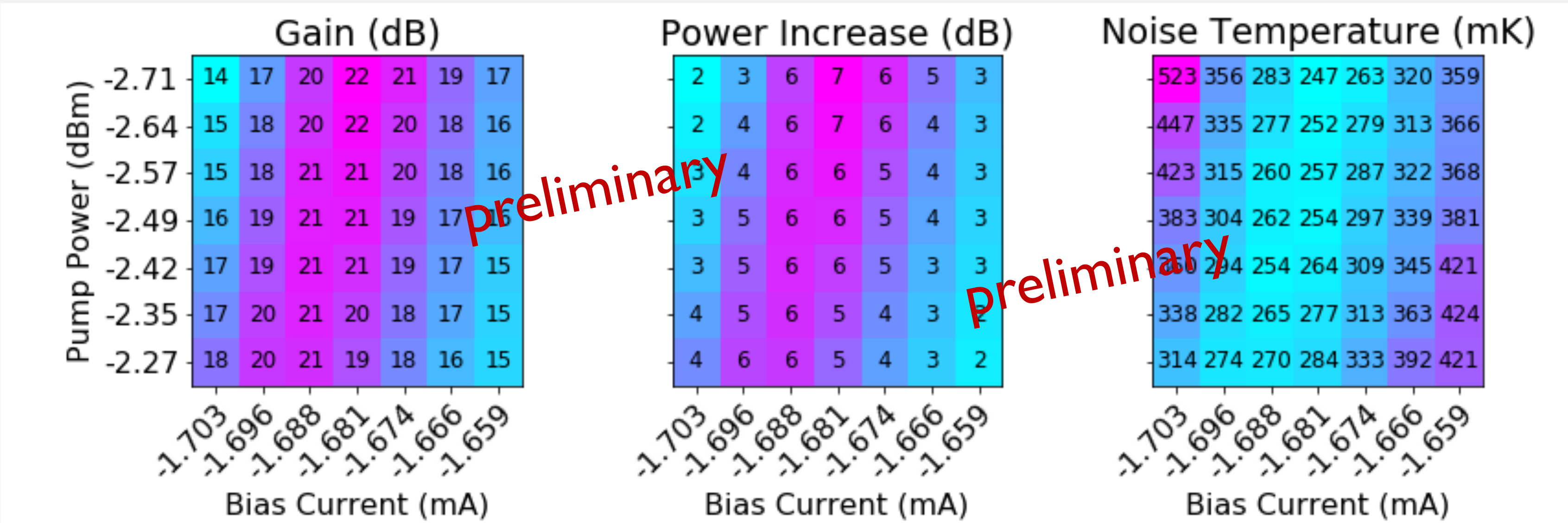




QUANTUM AMPS.' NOISE TEMPERATURE

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

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

SUB-QUANTUM-NOISE-LIMITED JPAS

Phase sensitive JPA amplification

*Nonlinearity causes change in pump power

to cause pump phase shift -- transfer

function of JPA

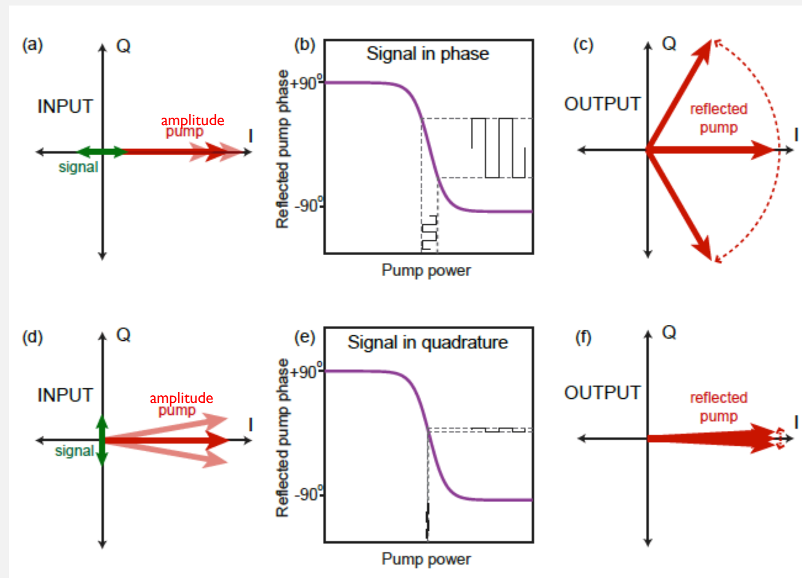
*Vector difference between output state<

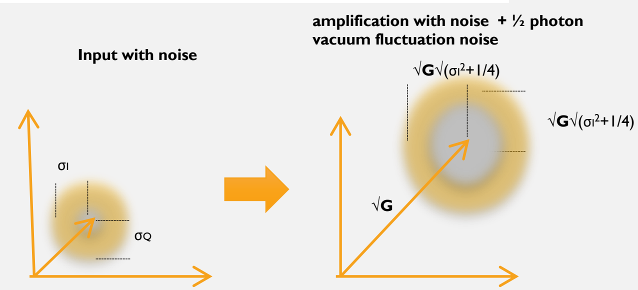
input – deamplified state

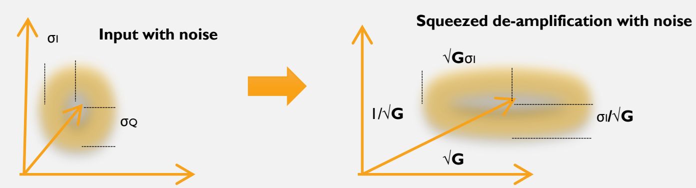
*Input noise in the out of phase/quadrature

de-amplified causing < noise than QL in

total



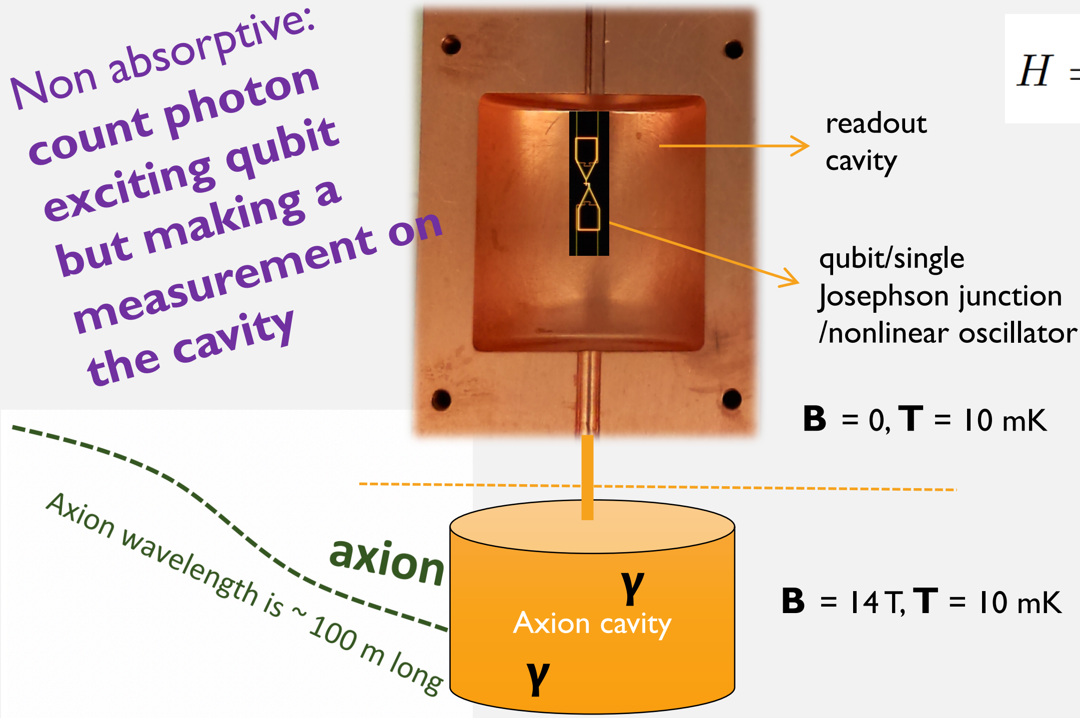




Pump schematic: D. H. Slichter

QUBIT BASED SINGLE PHOTON DETECTOR

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



$$H = \underbrace{\omega_c a^\dagger a}_{\text{cavity}} + \underbrace{\omega_q \sigma_z}_{\text{qubit}} + \underbrace{2\frac{g^2}{\Delta} a^\dagger a \sigma_z}_{\text{mixed}}$$

ω_c: cavity frequency
a^+a: photon occupation #
ω_q: qubit frequency
σ_z: electric dipole (josephson junction)
$g \sim$ **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 !

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

DATA TAKING/ANALYSIS STEPS

- Tune the cavity resonance TM_{010} to the desired mass of Axion (photon frequency), tune the SQUID amps. to match this.
- NA checks at this frequency: antenna coupling, Q_{cav}
- SA (Digitize): Record noise power spectra data for 100s in a BW of 25kHz centered at TM_{010}
- For one bin with this BW (25kHz), use at least 20 overlapping noise power spectra
- Background receiver transfer function shapes were removed to 95% of least-deviant power bins using Savitsky Golay filter shapes (length 121, polynomial order 4) – removes signal much broader than axions.
- Power scaled to known T_{sys} and weighted by Q_L to produce excess power in each bin for Axion signal
- This excess power is then convolved using two astrophysical signal shapes—Maxwellean predicted by Standard Halo Model and N-body shape.
- When the data were statistically consistent with no Axion signal, the Power equation is used to put the limits on the coupling.
- Frequencies with >3σ above the mean power were flagged candidates for rescan/analysis
- If persists, individually checked for RF interference

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.