DARK MATTER EFFORTS AT FERMILAB

52nd Annual Users' meeting
Fermilab

Rakshya Khatiwada
06/13/2019

OUTLINE

Dark Matter

Direct detection efforts at Fermilab

(SENSEI, SuperCDMS, LZ, ADMX)

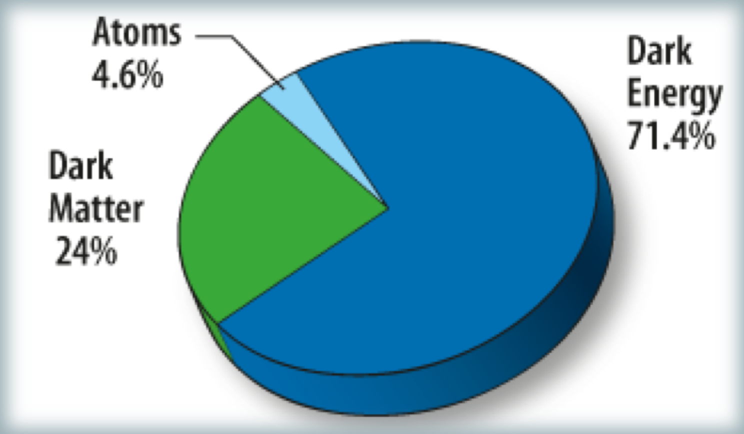
Conclusion

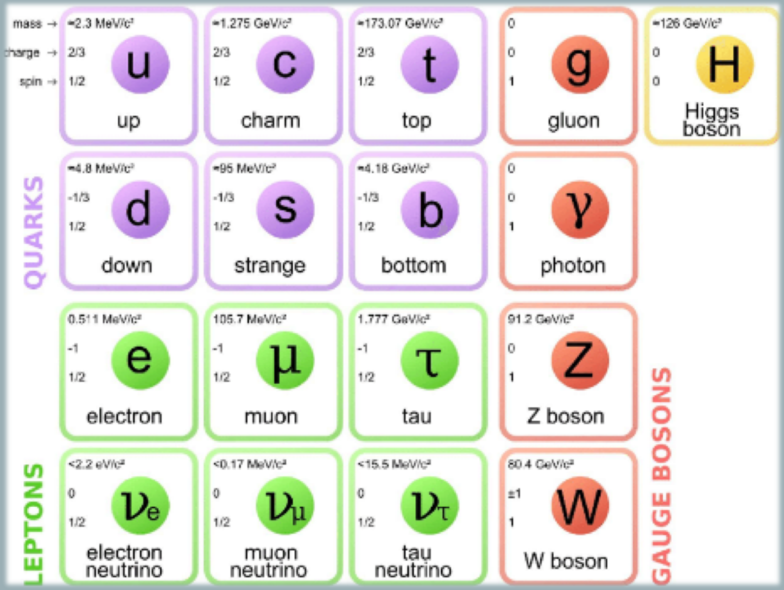
DARK MATTER

Clearly the next big piece of the puzzle in the universe

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

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



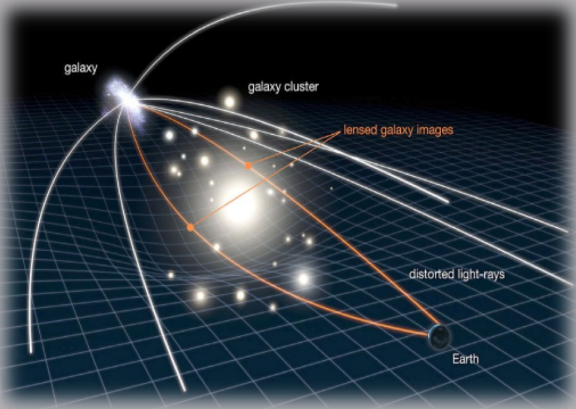


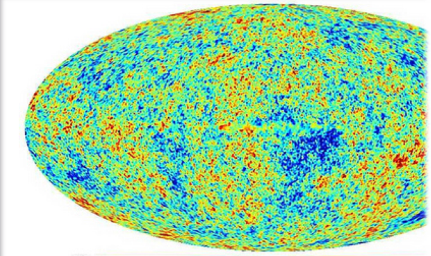
mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

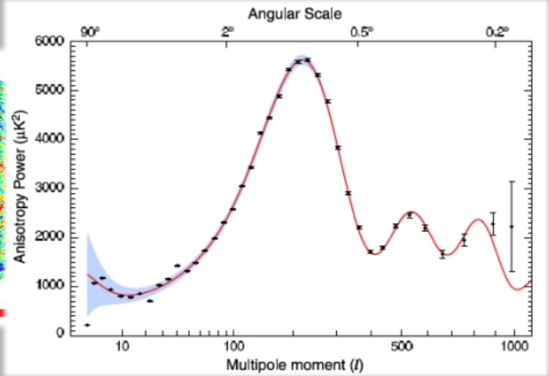
EVIDENCE OF DARK MATTER

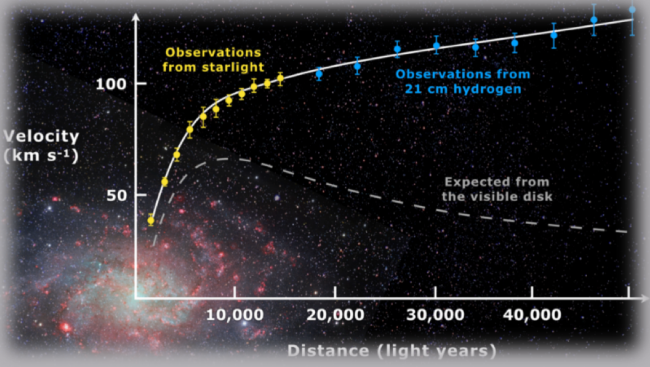
Gravitational lensing: Light bent by galaxies

Shape of the CMB power spectrum: fluctuation of the CMB temperature vs. angular scale – indicates existence of dark matter. Comparison of model with dark matter and observation matches





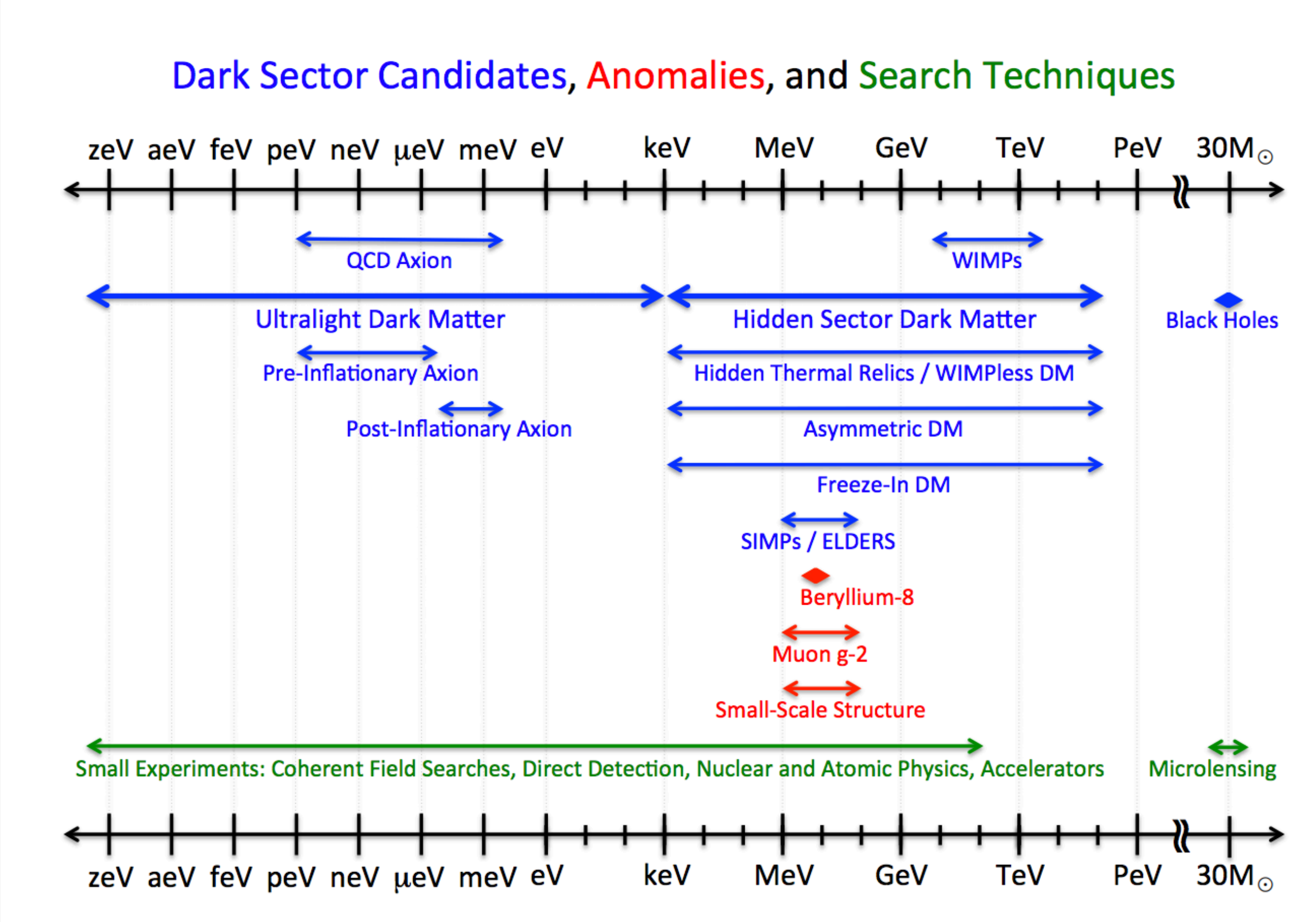




Galaxy clusters/rotation curve: Orbital speed of galaxy and stars vs. distance from the center

DARK MATTER CANDIDATES

US Cosmic vision



Dark Sector Candidates, Anomalies, and Search Techniques

QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

SIMPs / ELDERS

Beryllium-8

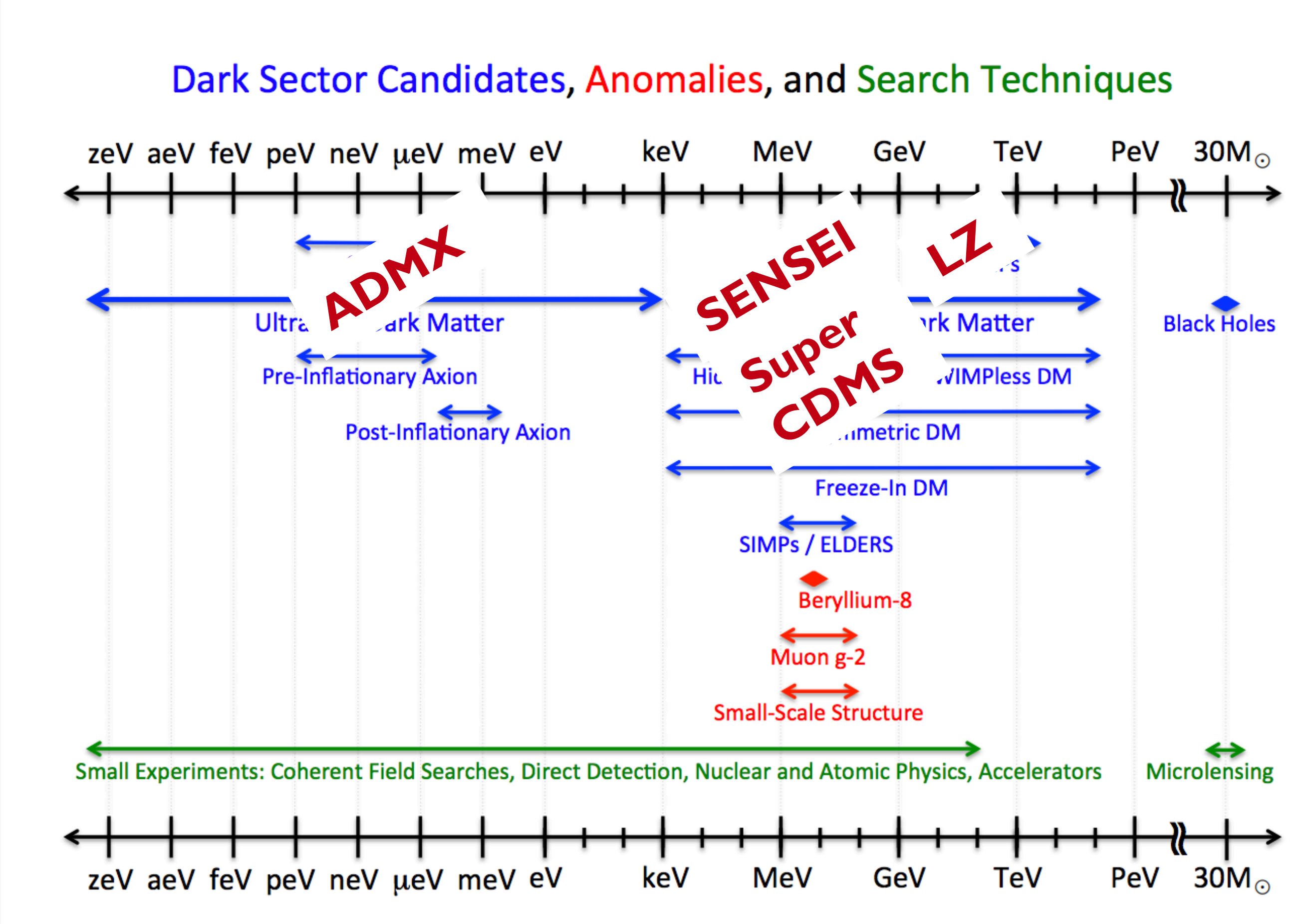
Muon g-2

Small-Scale Structure

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

Microlensing

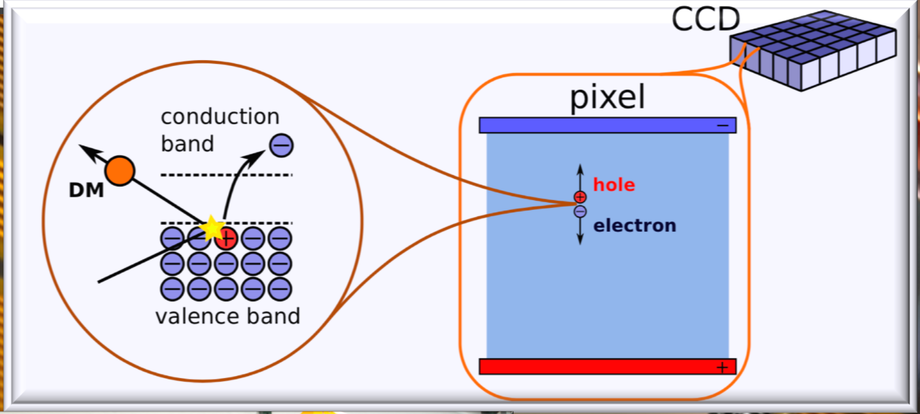
DARK MATTER EFFORTS AT FERMILAB



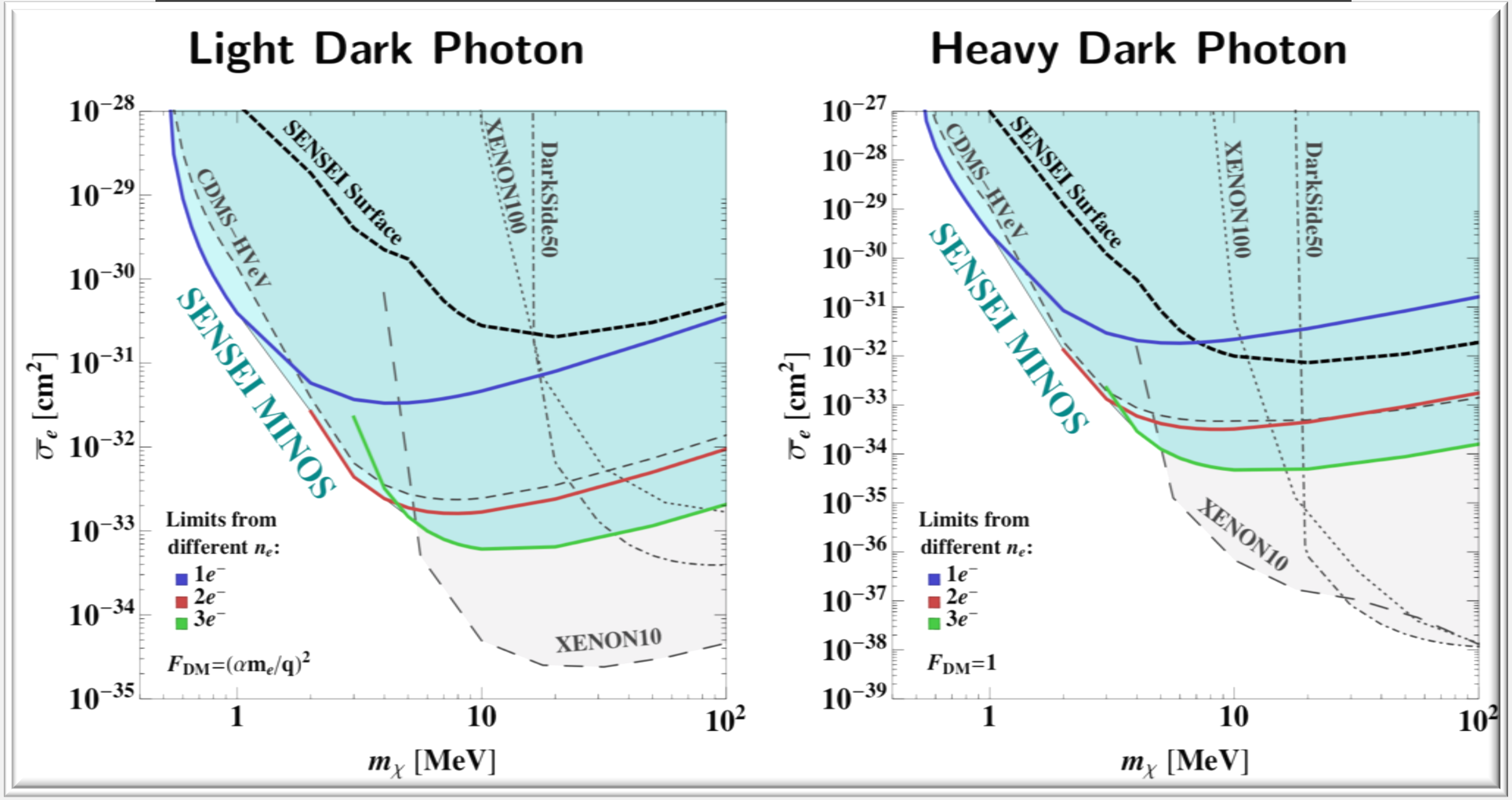
SENSEI

(Sub-Electron-Noise Skipper CCD Experimental Instrument)

- Detect DM-e interaction by measuring the ionization produced by the electron recoil
- Use electrons in the CCD as the target
- Single electron counting detector
- Fermilab leads the experiment
- Has world’s best limits at low mass sub-GeV dark matter
- Prototype run with 0.1 gm CCD sensor at MINOS in 2019
- Next step 10 and 100 gram ~ R and D ongoing
- Projected improvement: 5 to 6 orders of magnitude



SENSEI SENSITIVITY



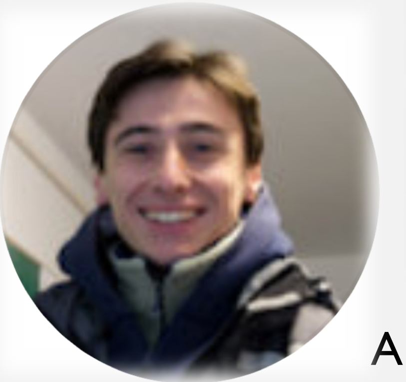
SENSEI TEAM AT FERMILAB

Juan Estrada

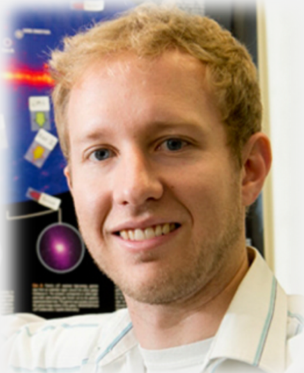
Mike Crisler

Guillermo Fernandez

Javier Tiffenberg



Miguel Sofo Haro



Alex Drlica-Wagner

SUPERCDMS SNOLAB

DM-nuclei elastic scattering -measure phonons (Ge/Si crystal Lattice vibrations) and ionization (charge)

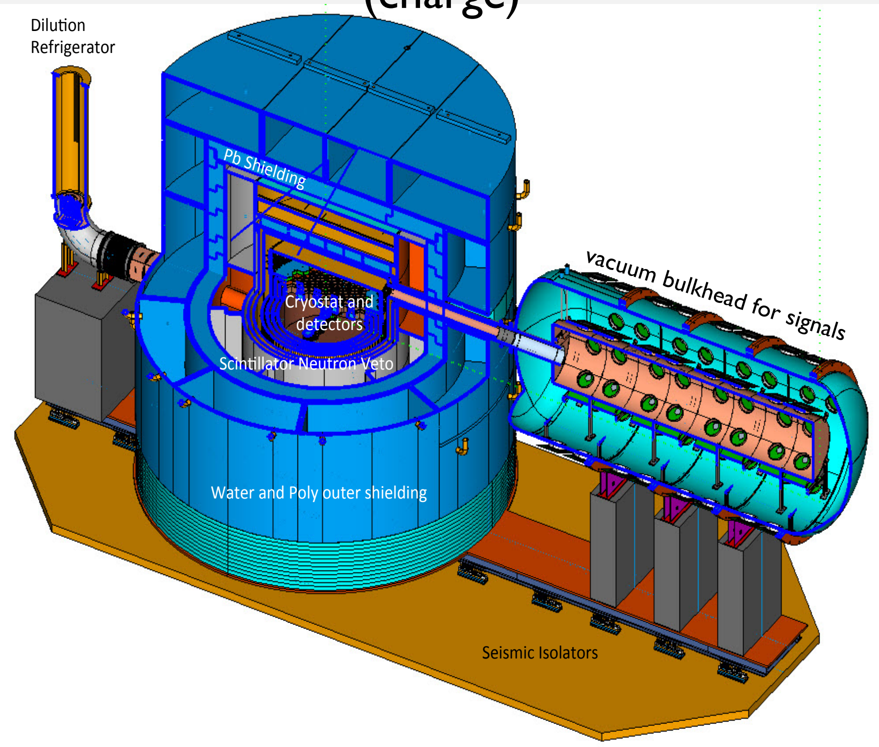
Lab G (ongoing):

- Cryogenic and calibration system design and construction
- Warm electronics design and fabrication
- Infrastructure preparation for the experiment

Anticipate another result using a new device recently run at Northwestern !

Timeline:

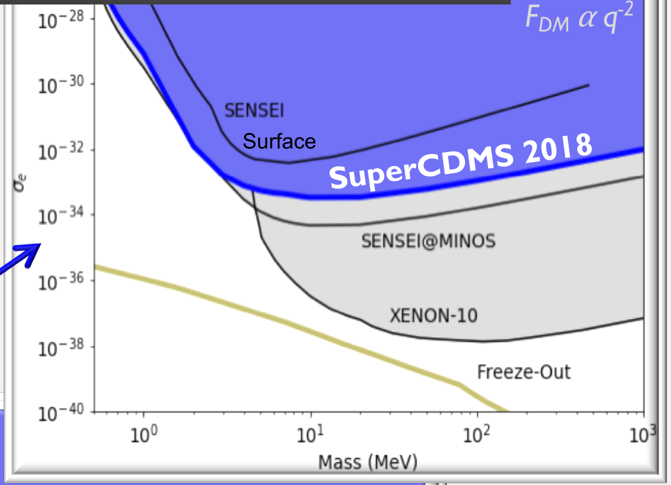
- Construction and testing at Fermilab in 2019
- Install and Commission at SNOLAB in 2020
- First physics run in 2021!

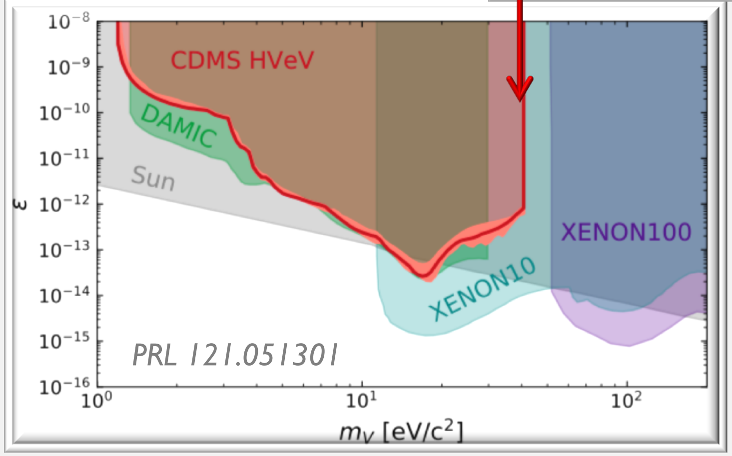


SUPERCDMS SNOLAB SENSITIVITY

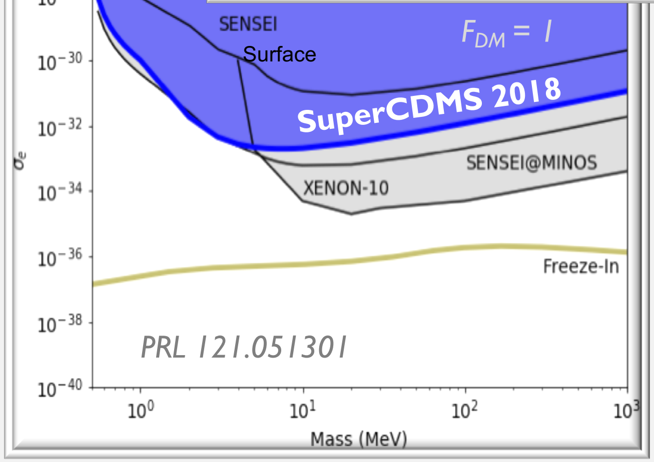
2018: Demonstrated world-leading dark matter sensitivity with a prototype Si detector that measured single e/h pairs.

dark photon kinetic mixing and electron-scattering dark matter





PRL 121.051301



PRL 121.051301

SUPERCDMS SNOLAB TEAM AT FERMILAB

Lauren Hsu

Daniel Bauer

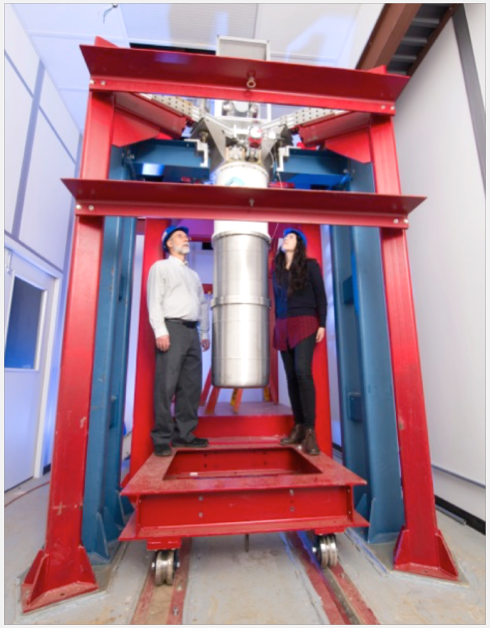
Patrick Lukens

Noah Kurinsky

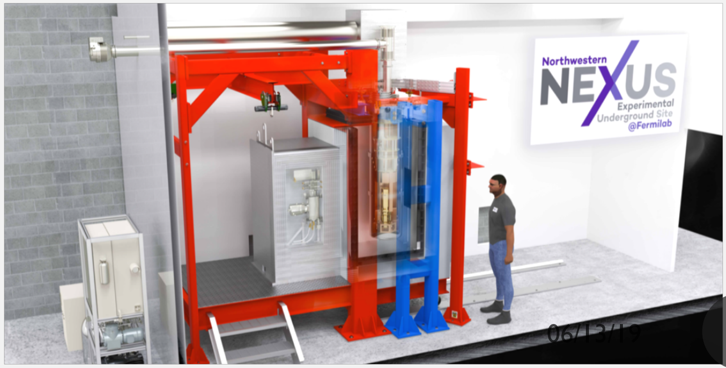
NEXUS

Facility for Calibration and Future Sub-GeV Dark Matter Searches

NEXUS facility currently being installed in MINOS near detector hall

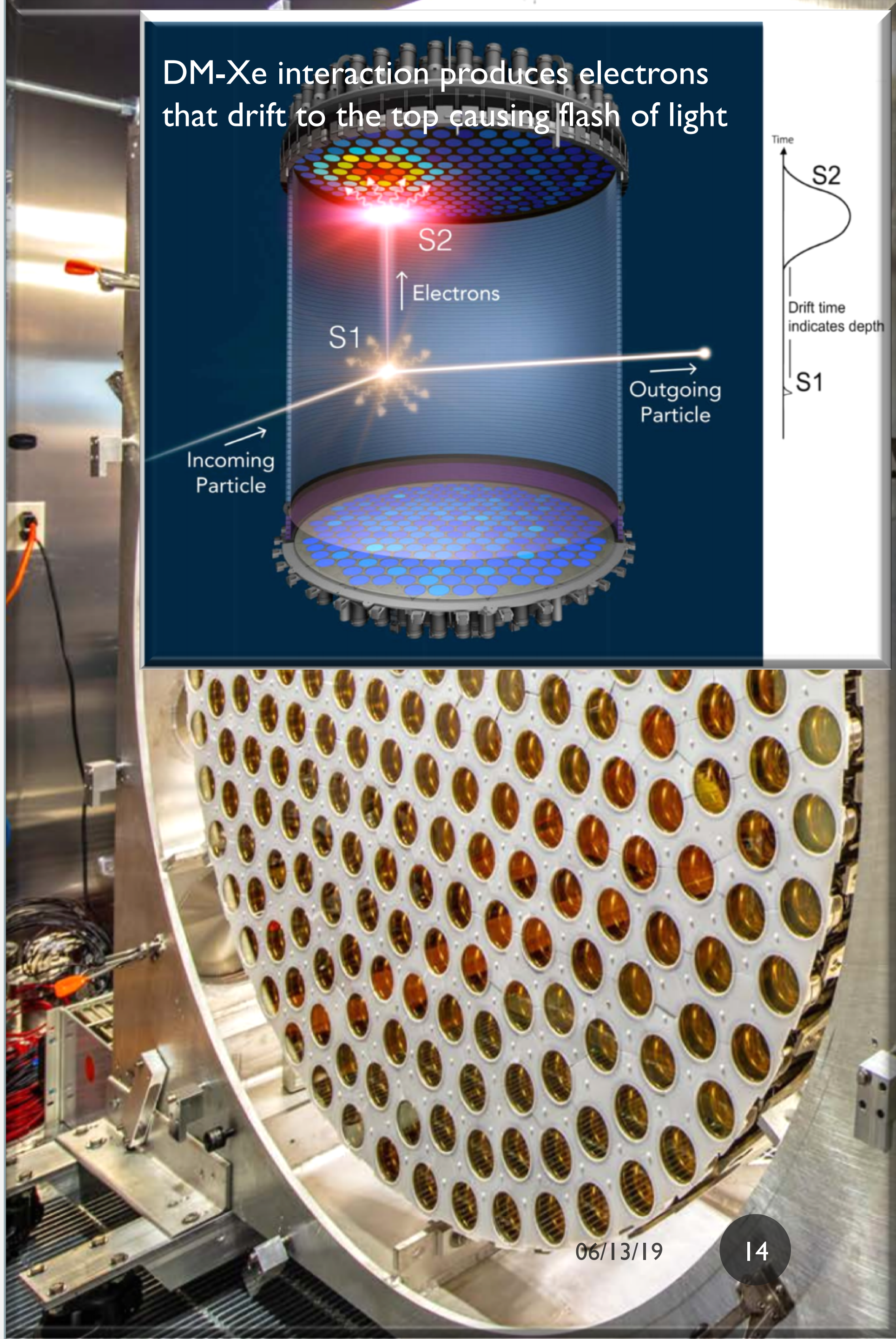


- Will allow low background for nuclear-recoil calibration and dark matter searches
- Dilution refrigerator and large experimental volume (33 cm D X 53 cm H)
- Already doing its first R&D now
- A collaboration between Fermilab and Northwestern University SuperCDMS
- Available to other cryogenic experiments



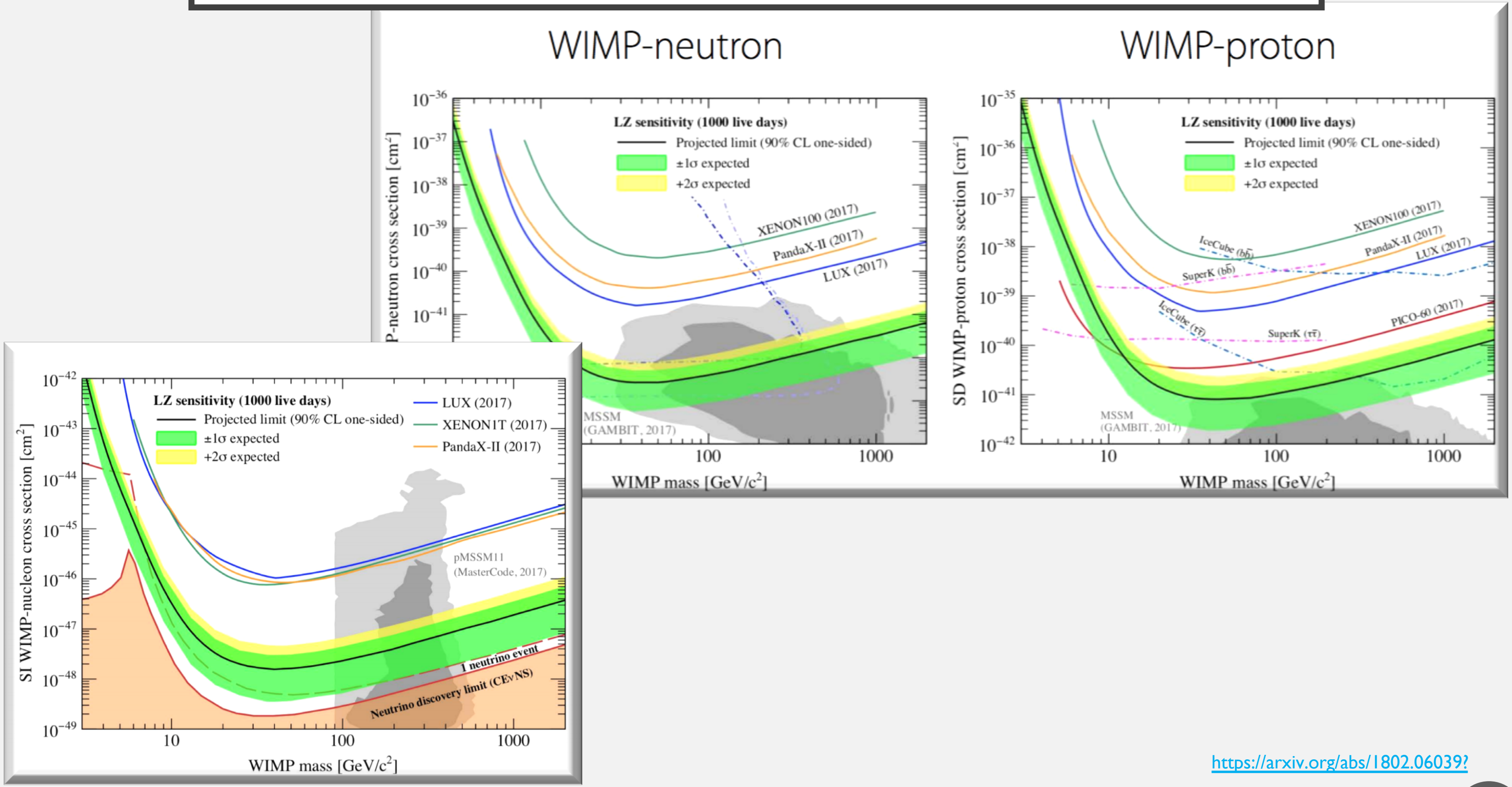
LZ
(LUX-ZEPLIN)

- Low radioactivity Titanium vessel fabricated in Italy received
- PMT array testing complete
- TPC forward field region completed
- HV grids arrived at SURF from Stanford~ May 2019, more arriving this month
- 7 ton Xenon at hand in SLAC
- Xenon tower (cooling and liquifaction system) from Fermilab is in place
- TPC integration now underway ~ June 2019
- Data taking expected ~ early 2020
- Preliminary sensitivity plots are published



DM-Xe interaction produces electrons that drift to the top causing flash of light

LZ PROJECTED SENSITIVITY



WIMP-neutron

WIMP-proton

https://arxiv.org/abs/1802.06039?

LZ TEAM AT FERMILAB


Eric Dahl

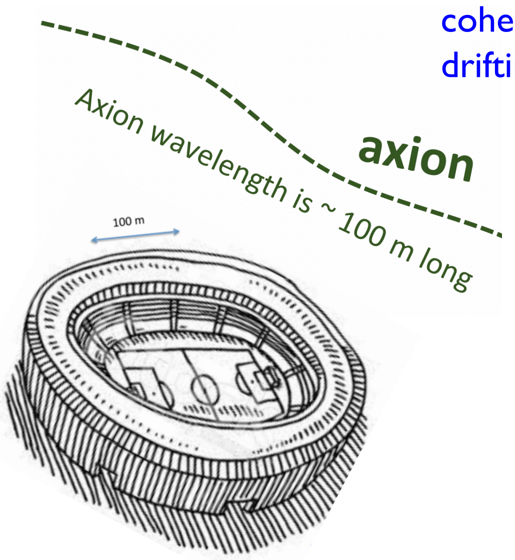

Hugh Lippincott


Alissa Monte

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**

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

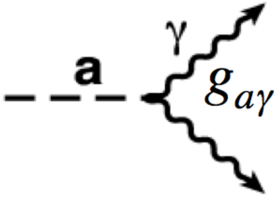
$$\vec{\nabla}\times\vec{B}_r - \frac{d\vec{E}_r}{dt} = \vec{J}_a$$

- ***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!***

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

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

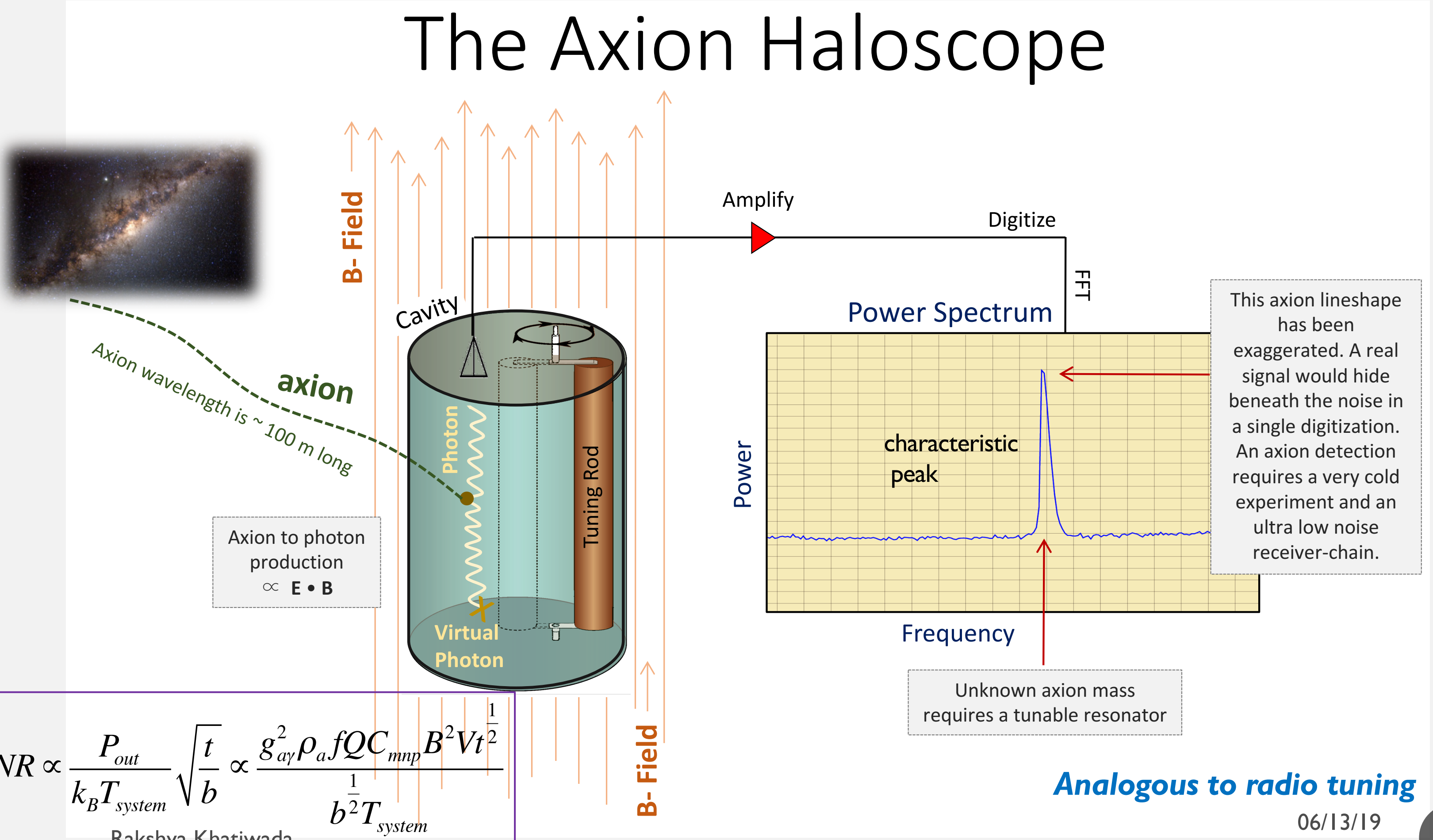


$$\boxed{\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}a\vec{E}\cdot\vec{B},}$$

Serge Brunier@NASA

HOW TO DETECT AXIONS?

The Axion Haloscope



Axion to photon production $\propto$ **E • B**

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

Analogous to radio tuning

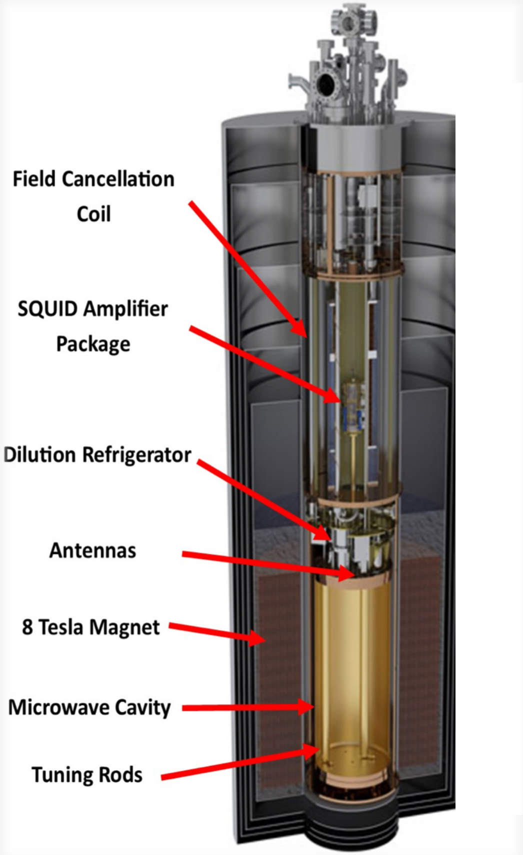
$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

Rakshya Khatiwada

06/13/19

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

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

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

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

**Determines the sensitivity of the experiment*

**The most involved aspect of analysis*

ADMX PRELIMINARY RESULTS 2018/19

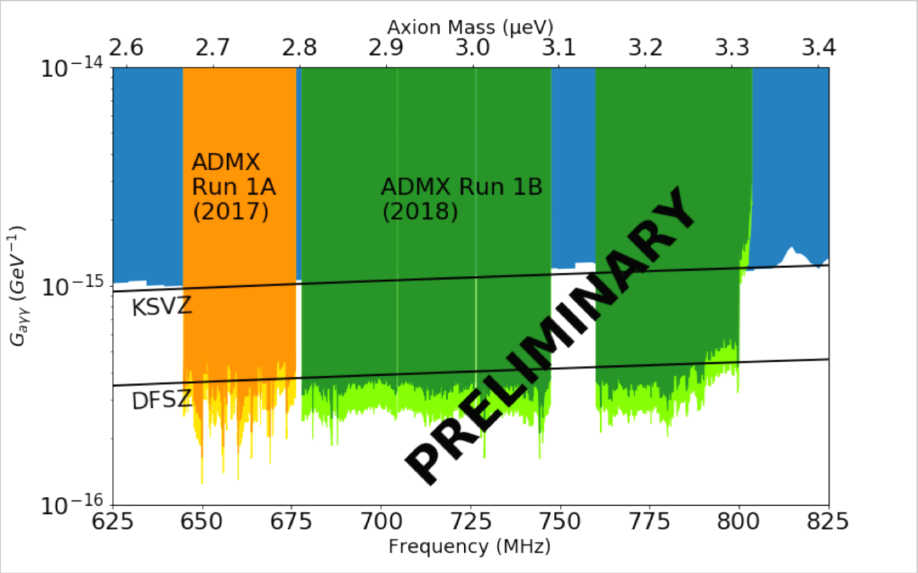
=> x4 more frequency covered than 2017

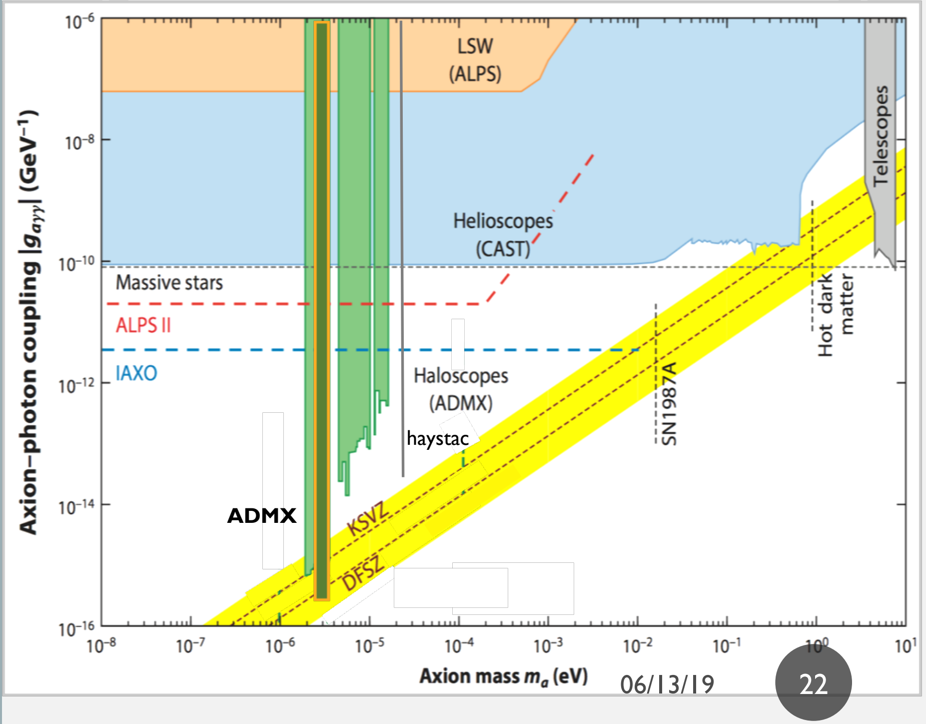
=> DFSZ sensitivity -- 680 to 800 MHz

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

=> Stay tuned for results – paper out mid 2019

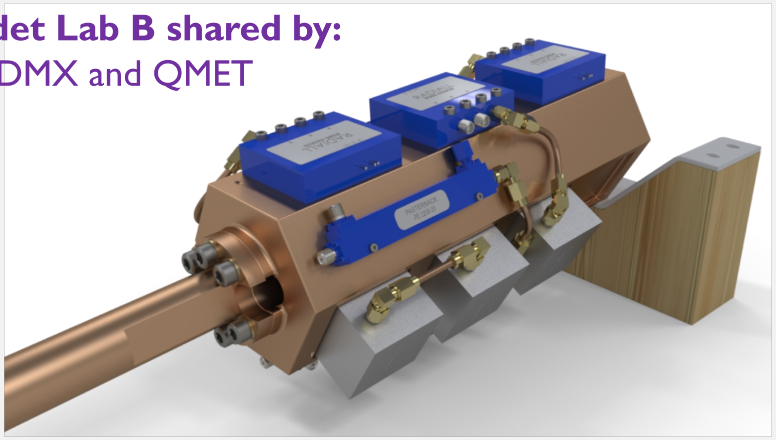
=> Analysis being finalized

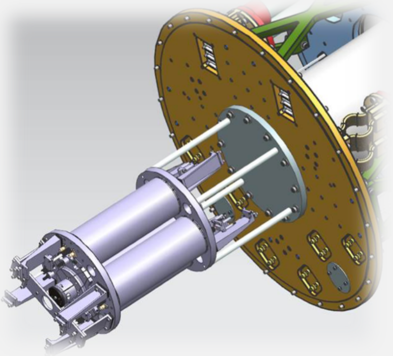


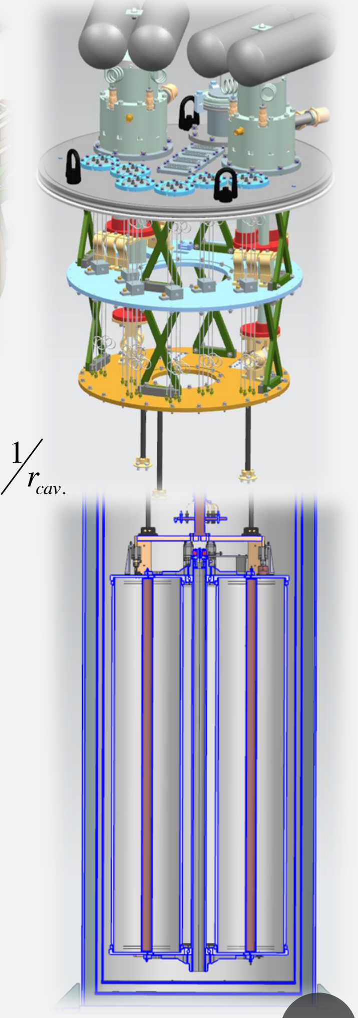


ADMX AT FERMILAB

Sidet Lab B shared by:
ADMX and QMET







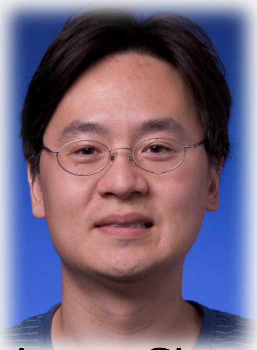
$f_{cav.} \propto 1/r_{cav.}$

- New detector (Run 1c) designed and fabricated at Fermilab, delivered to University of Washington
- **Run1c starting this summer** (800-1200 MHz)(3.3-5 μeV)

- Higher frequency multi-cavity array 4K test stand ready in the summer 2019
- 4 cavity array (mechanical tuning, motors) to be tested ~ later 2019
- Expected involvement of various collaborating institutions at Fermilab
- Targeted for >2 GHz (>8 μeV) axions

ADMX TEAM AT FERMILAB


Andrew Sonnenschein


Aaron Chou


Daniel Bowering

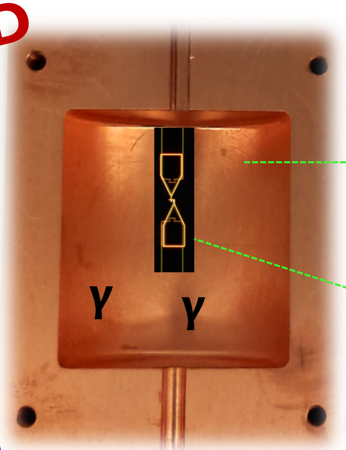

Rakshya Khatiwada


William Wester

QUANTUM METROLOGY (QMET) BASED SENSOR FOR DARK MATTER DETECTION

DOE QuantiSED Initiative

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

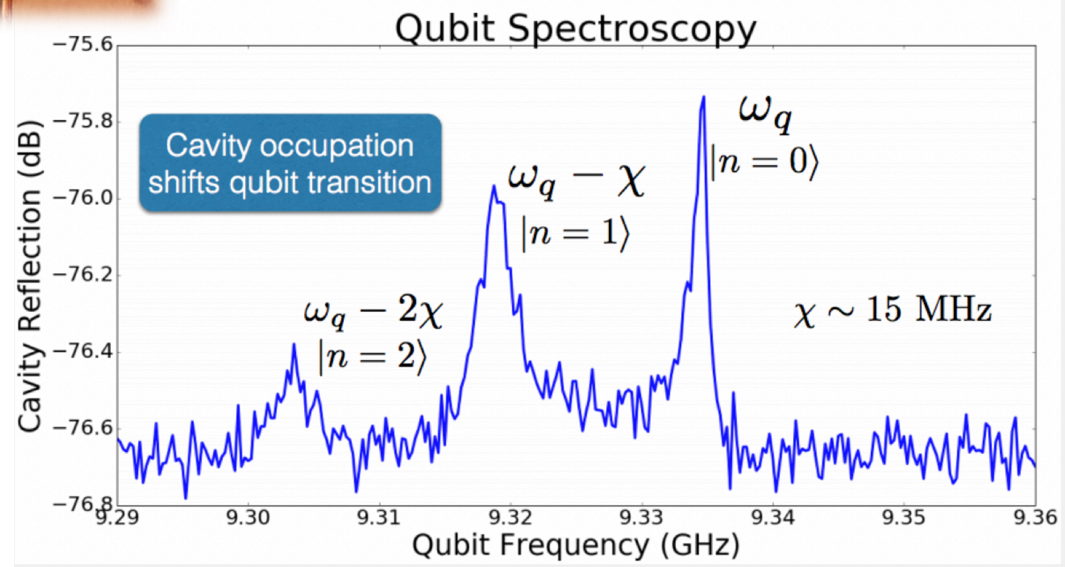


readout cavity

qubit/single JJ /nonlinear oscillator

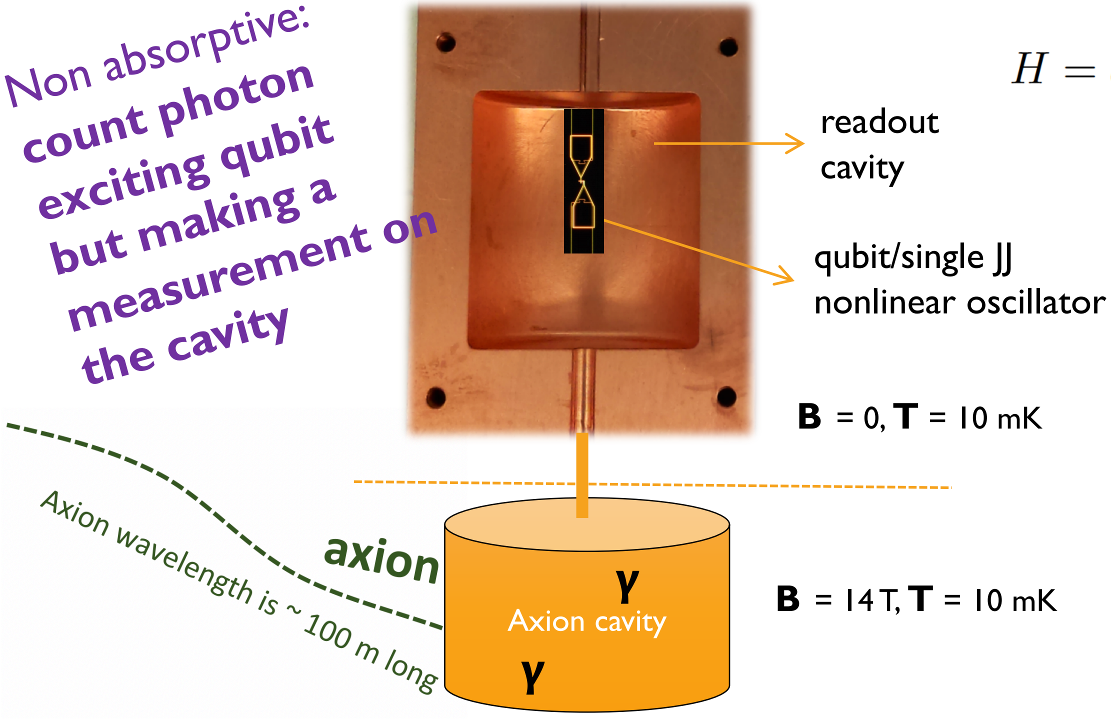
$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

cavity qubit mixed



QUBIT BASED SINGLE PHOTON DETECTOR

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

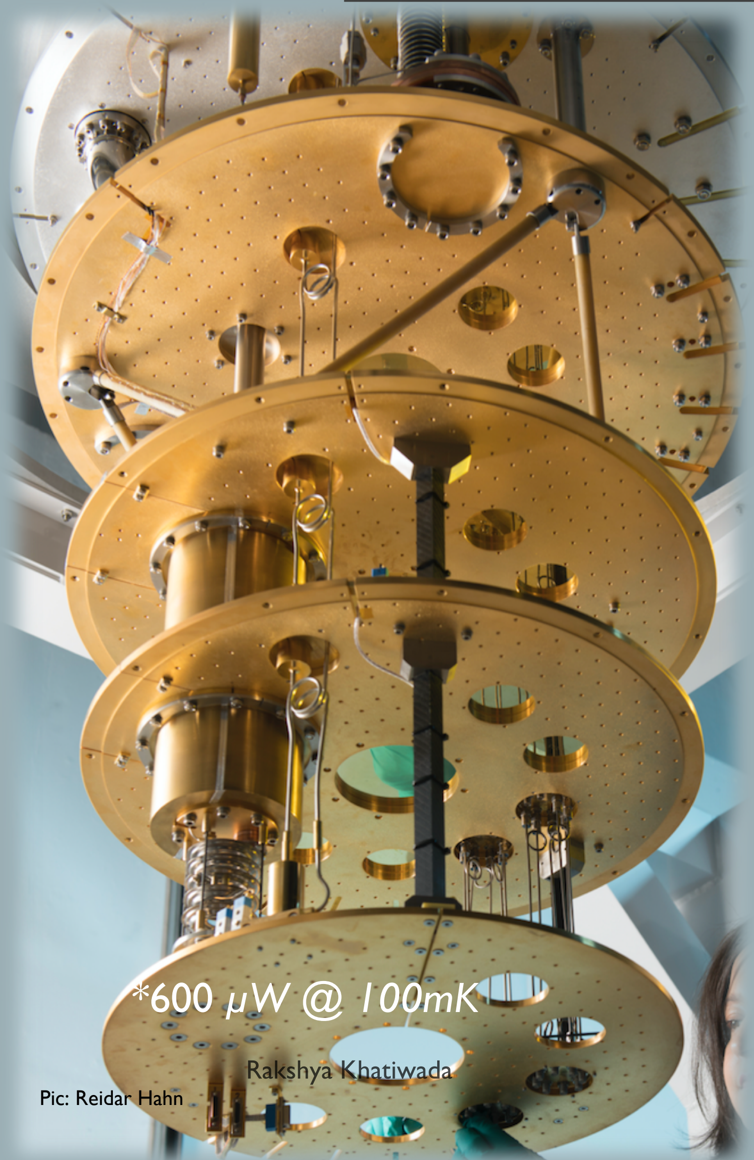


$$H = \underbrace{\omega_c a^\dagger a}_{\text{cavity}} + \underbrace{\omega_q \sigma_z}_{\text{qubit}} + \underbrace{2\frac{g^2}{\Delta} a^\dagger a \sigma_z}_{\text{mixed}}$$

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



*600 μW @ 100mK

Pic: Reidar Hahn

Rakshya Khatiwada

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

U Chicago

The plan:

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

Fermilab

*integration of magnet and the axion cavity

=>Use magnetic shielding for qubit sensors

=>Use high quality factor axion cavity (compatible with magnet)

Boulder

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

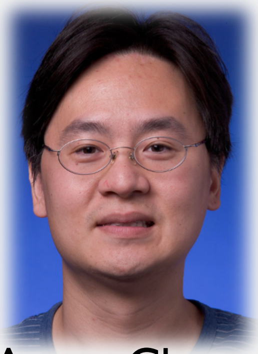
=>Ultimately establish a standalone axion detector

Fermilab

Multiple years' plan!

Targeted for >40 μeV axions

QMET AT FERMILAB



Aaron Chou

Daniel Bowering

Rakshya Khatiwada

Funded by DOE
Early Career Award

DARK MATTER THEORY EFFORTS

Fermilab Cosmic Physics Center
Recent Theory Highlights (2019)

Dark matter & dark radiation from primordial black holes (Hooper, Krnjaic, McDermott)

MeV scale dark matter and big bang nucleosynthesis (Blinov et. al.)

Producing millicharged particles in neutrino experiments (Tsai et. al.)

Numerical simulations of cosmic reionization history (Gnedin et. al.)

Constraining neutrino self interactions that explain the Hubble tension (Blinov, Krnjaic, McDermott)

Neutrino-philic forces and extra cosmological neutrino species (Hooper, Krnjaic et. al.)

Gravitational direct detection of ultra heavy dark matter using quantum sensors (Krnjaic et. al)

Dark matter annihilation signatures from early forming microhalos (Hooper et. al)

Excess in the antiproton spectrum from annihilating dark matter (Hooper et. al.)

NOT A COMPREHENSIVE LIST

DARK MATTER SEARCH SUMMARY

- Fermilab active in all DOE generation-2 dark matter projects
- These projects are more sensitive than ever before with hardware optimization and implementation of novel background suppression techniques
- World leading projected and current operating sensitivity
- Data taking expected: 2019, 2020 and 2021
- Future high sensitivity to dark matter necessitates quantum science based novel devices and sensors along with superconducting technology – without these, dark matter 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 &

Fermilab

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Heising-Simons Foundation

University of Washington, Dept. of Physics

Additional slides

AXION PRODUCTION

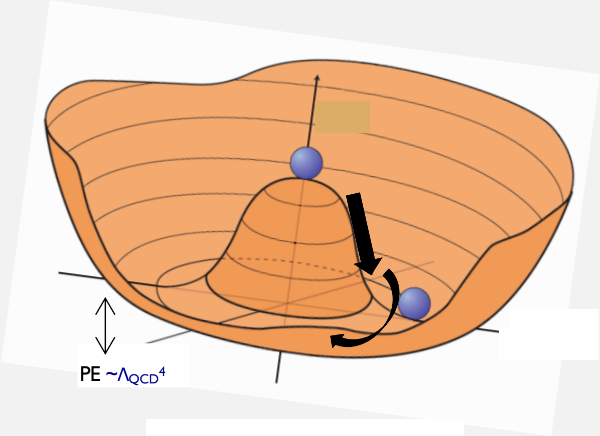
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE ~Λ_{QCD}^4 released, makes up dark matter

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

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

--- f_a unknown

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



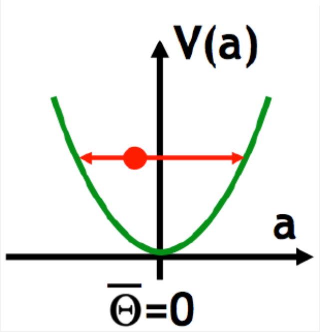


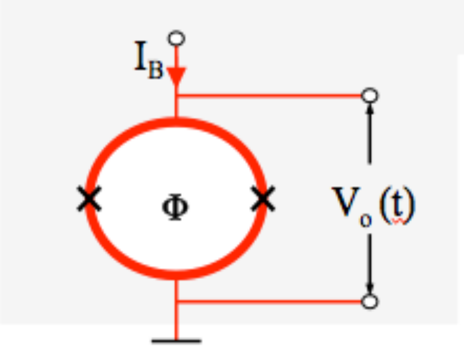
Fig 1:J. Ellis et al; arxiv:1201.6045v1

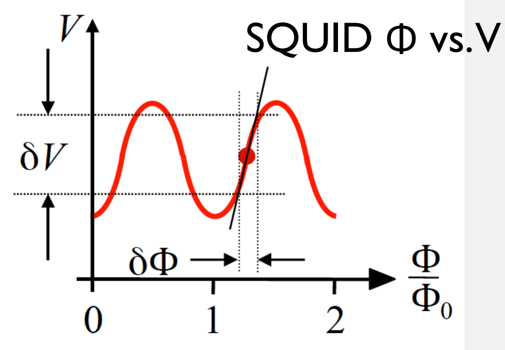
SQUID AMPLIFIERS

MSA

JPA

Based on dc SQUID





Microstrip SQUID Amplifier

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

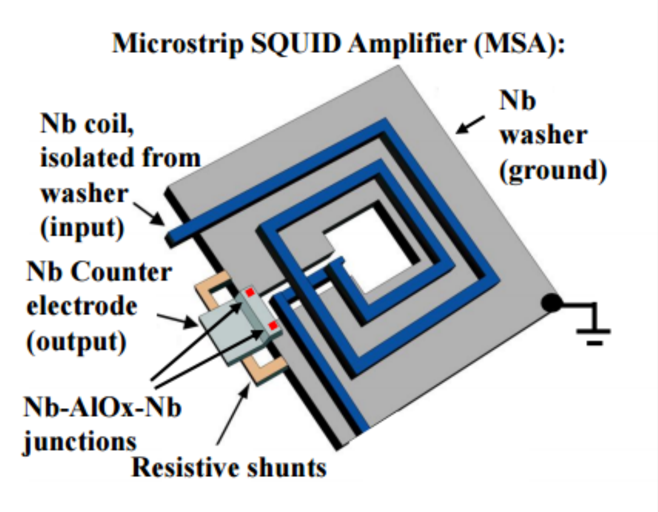
Josephson Parametric Amplifier

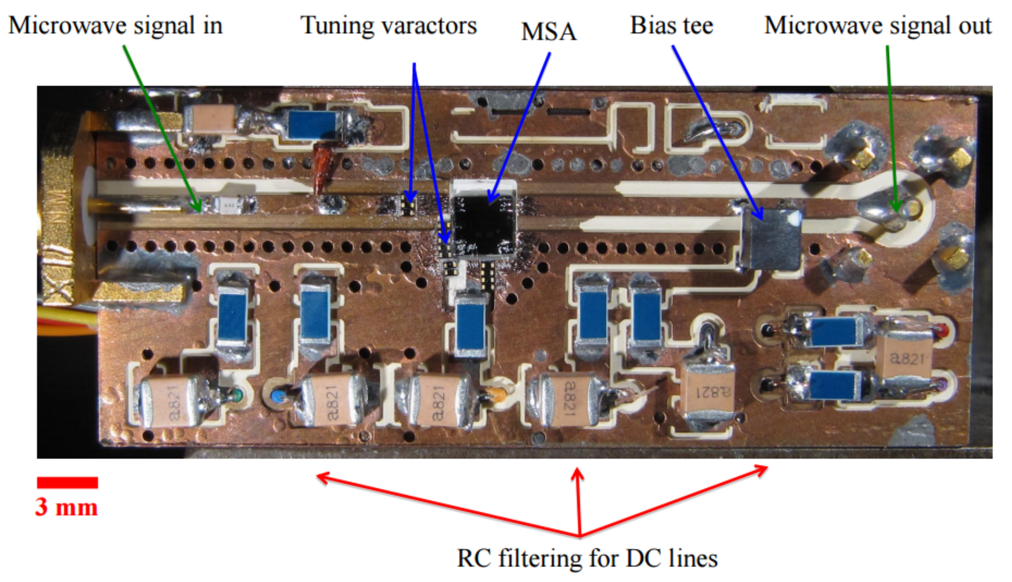
- Oscillator whose inductance is modulated
- shunted by a parallel plate C with

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

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

MSA



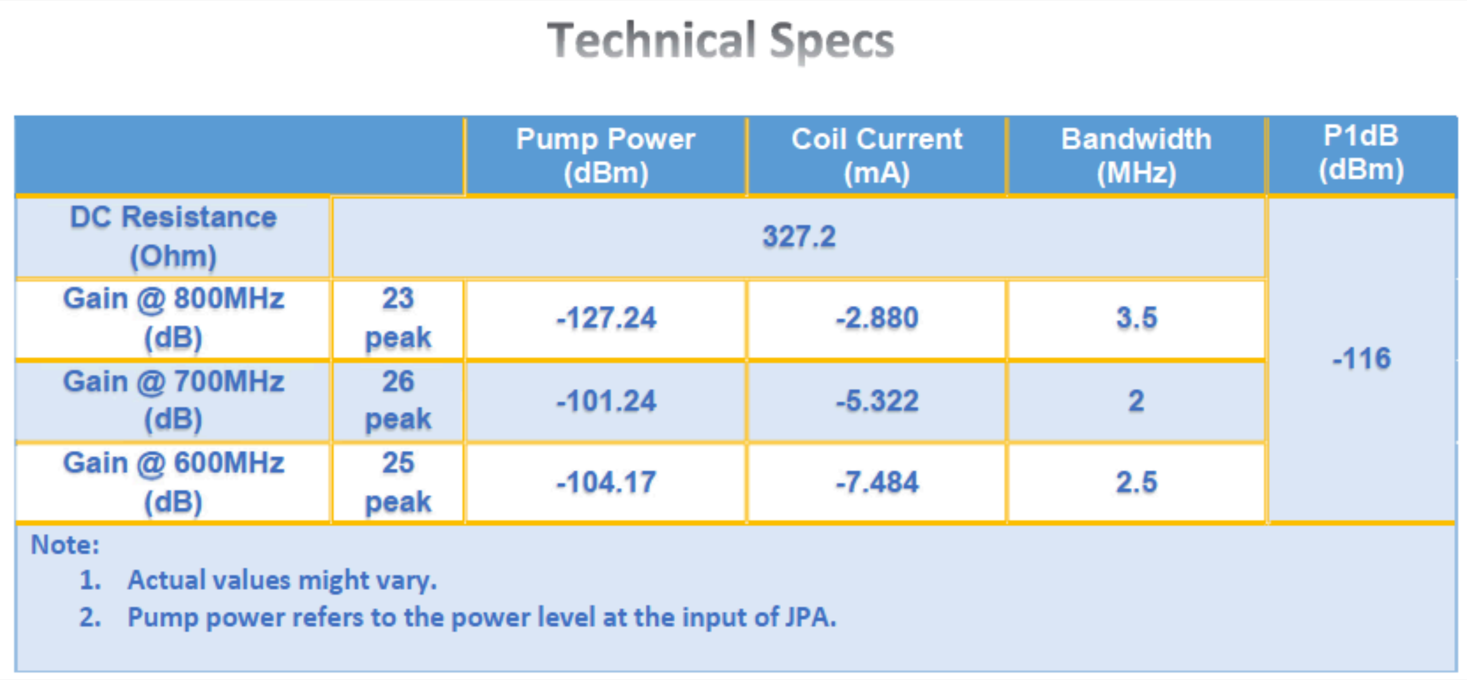


JPA Al SQUID produced by shadow evaporation Technique

Substrate is oxidized silicon 300 micron thick.

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

JPA



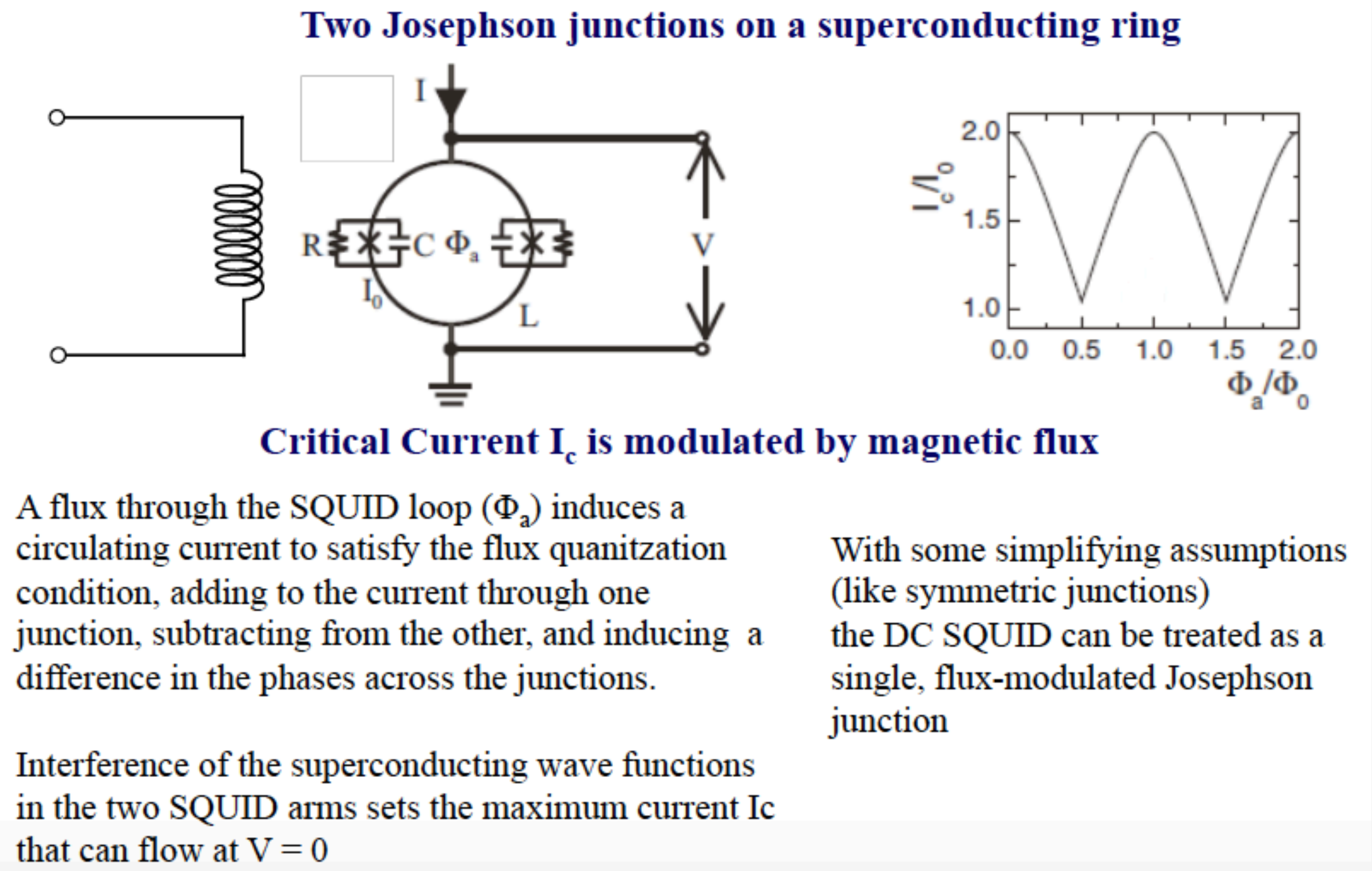
Technical Specs

		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

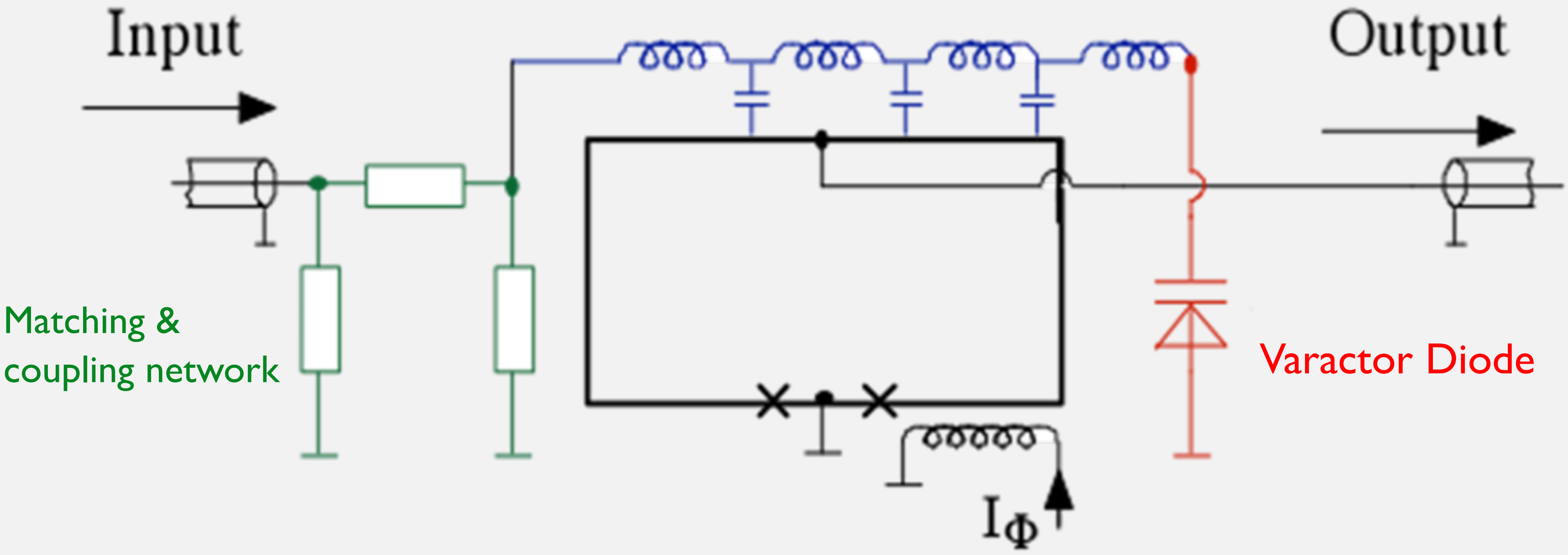
A flux through the SQUID loop (Φ_a) induces a circulating current to satisfy the flux quanitzation condition, adding to the current through one junction, subtracting from the other, and inducing a difference in the phases across the junctions.

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



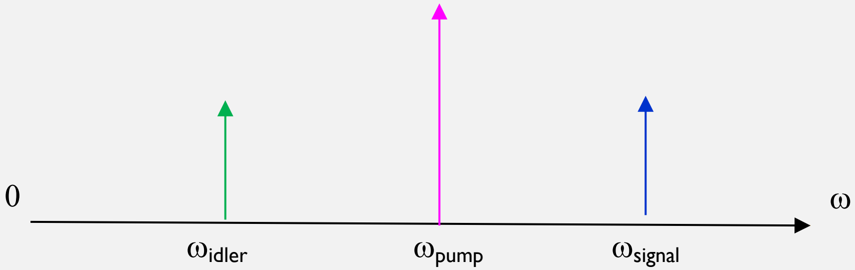
- Varying the capacitance modifies the phase change on reflection, effectively changing the length of the microstrip
- As the phase changes from a node to anti-node, the standing wave changes from λ/2 to λ/4, and the resonant frequency varies by a factor of 2
- Varactors must be GaAs (Si freezes out),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

Courtesy: Sean O'Kelley, UC Berkeley

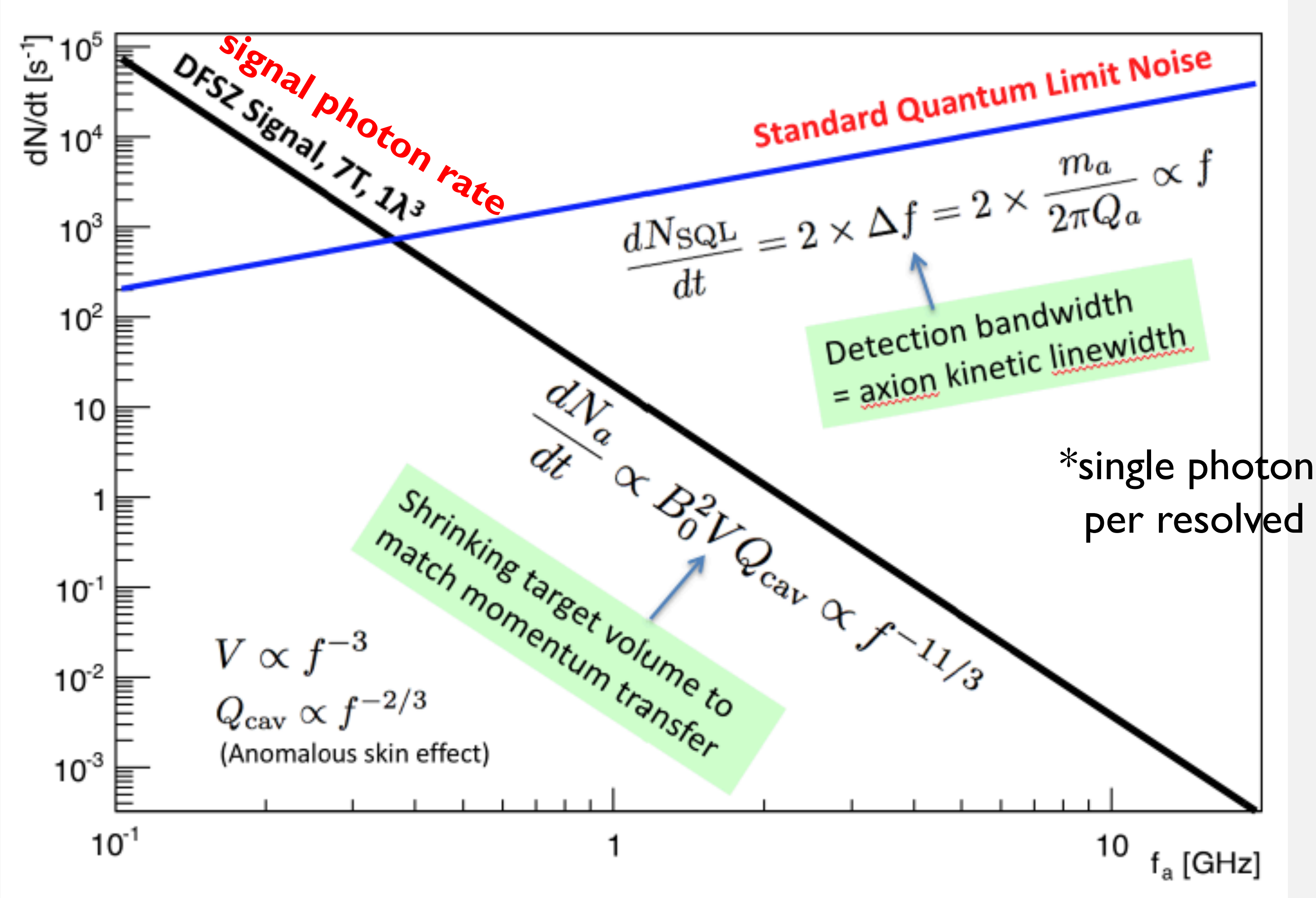
JPA

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

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



LIMITATION OF QUANTUM AMPLIFIERS

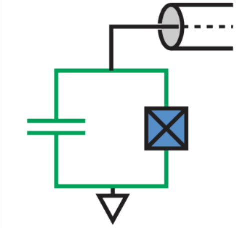


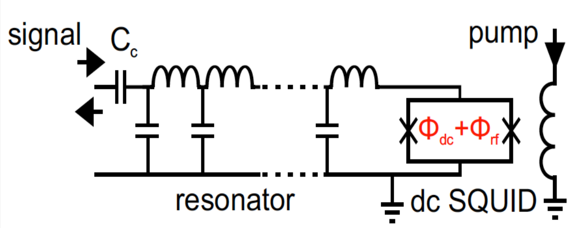
*single photon of noise
per resolved mode

JOSEPHSON PARAMETRIC AMPLIFIER (JPA)

- Parametric amplifier: Oscillator whose resonance frequency is modulated

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



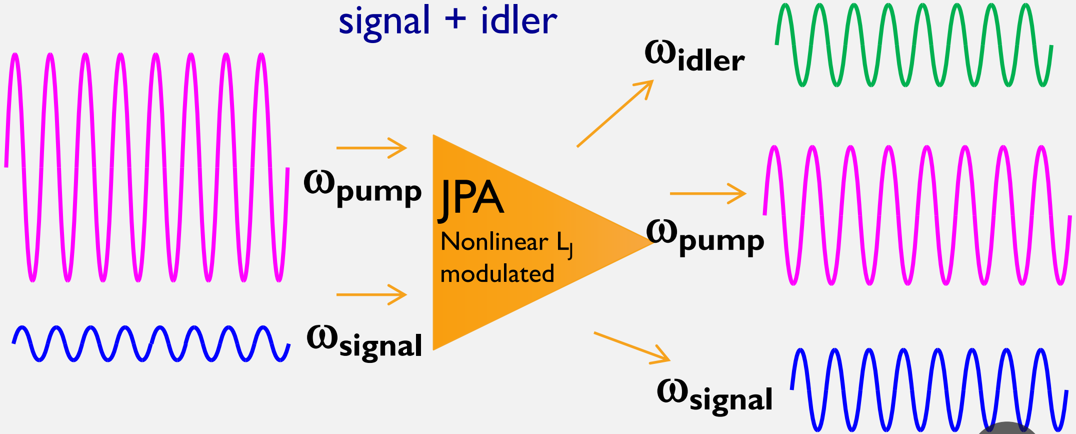


- Oscillating system a λ/4 resonator

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

- Inductance varied with SQUID (flux dependent nonlinear inductor)
- Energy transfer from pump to two normal modes of swing
- Noise – Quantum Limit

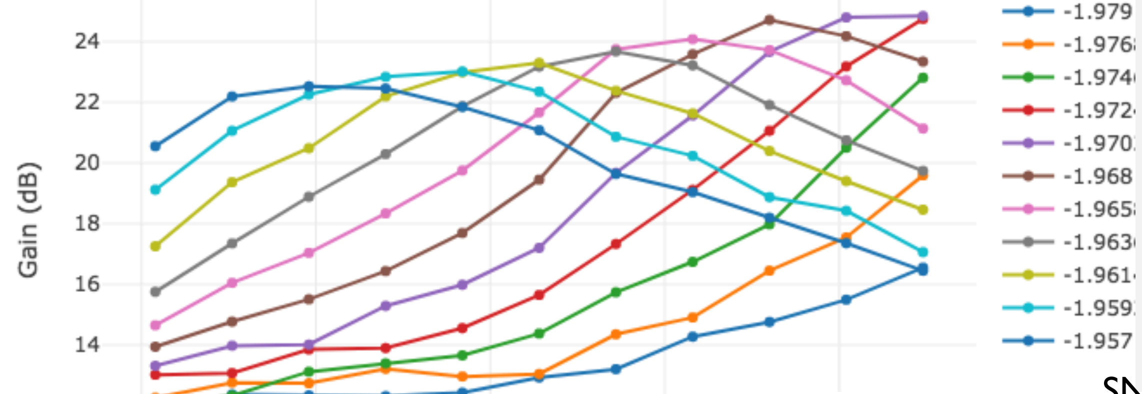
two normal modes of swing:
signal + idler



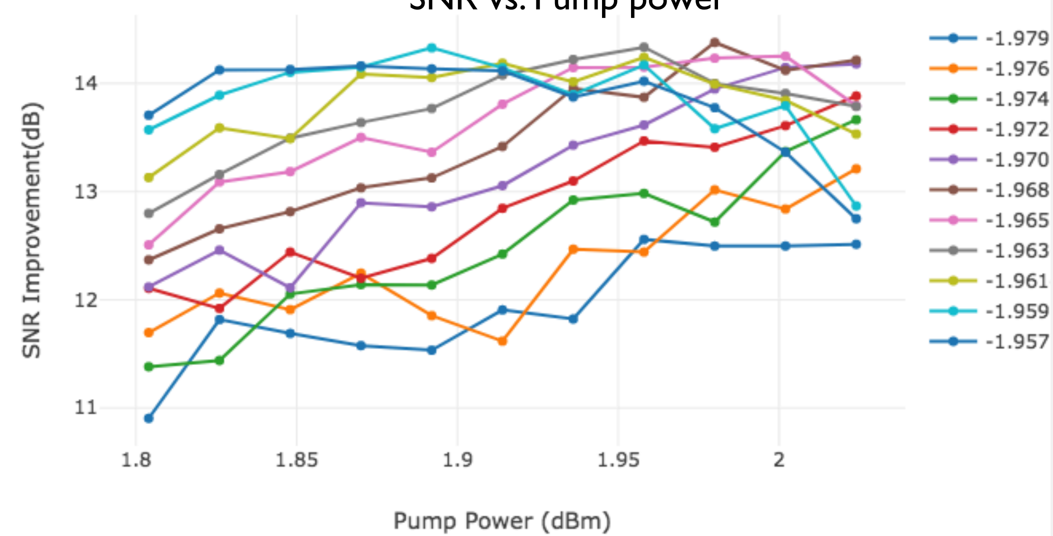
Paramp schematic: L. Zhong et al., "Squeezing with a fluxdriven Josephson parametric amplifier," New J. Phys. 15, 125013 (2013).

JPA OPERATION -- BIASING

Gain vs. Pump power



SNR vs. Pump power



Current run started January 2

-- 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

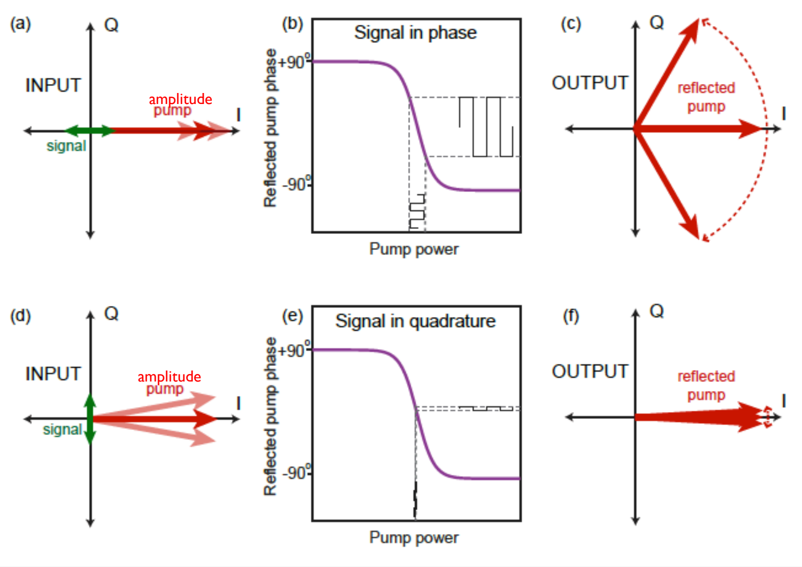
*Vector difference between output state<

input – deamplified state

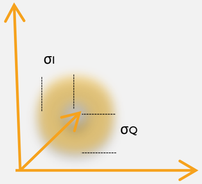
*Input noise in the out of phase/quadrature

de-amplified causing < noise than QL in

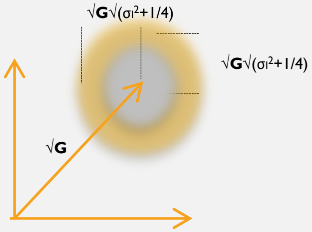
total

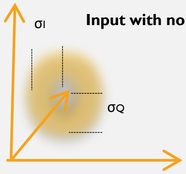


Input with noise

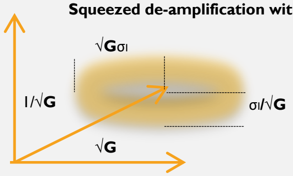


amplification with noise + ½ photon vacuum fluctuation noise





Squeezed de-amplification with noise



Pump schematic: D. H. Slichter

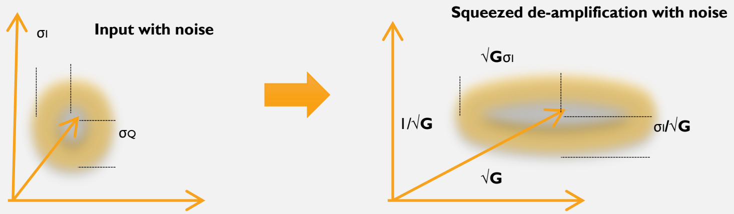
SUB-QUANTUM-NOISE-LIMITED JPAS CONTD.

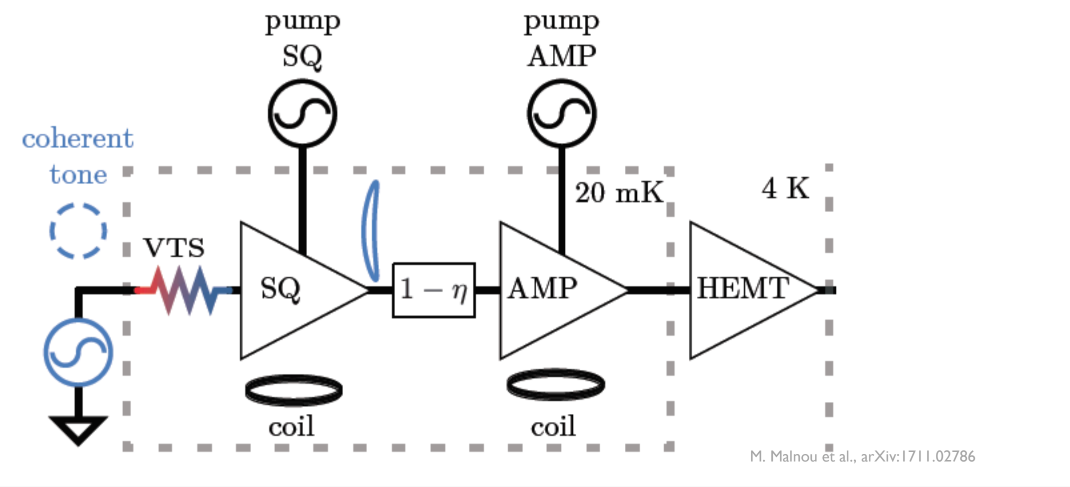
*Amplify the Squeezed state with lower than quantum noise at the input

*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

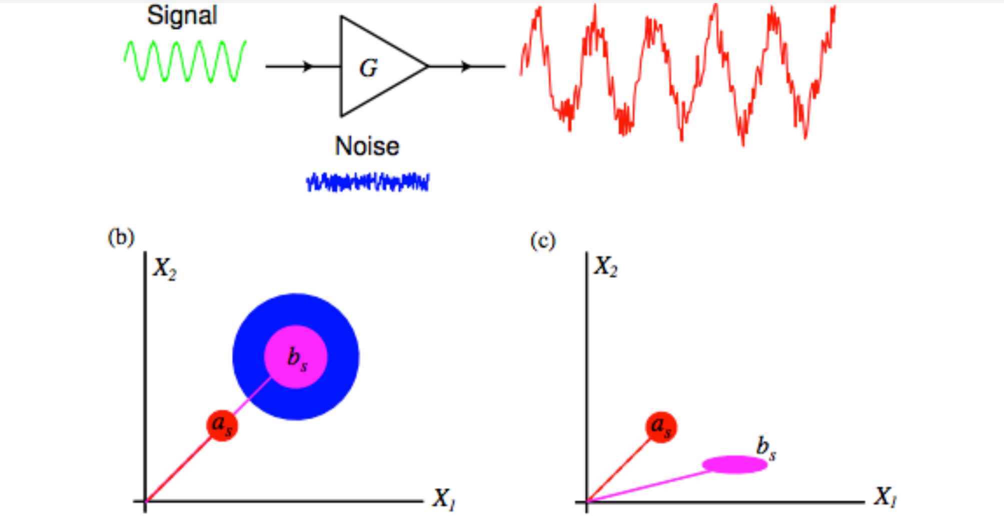


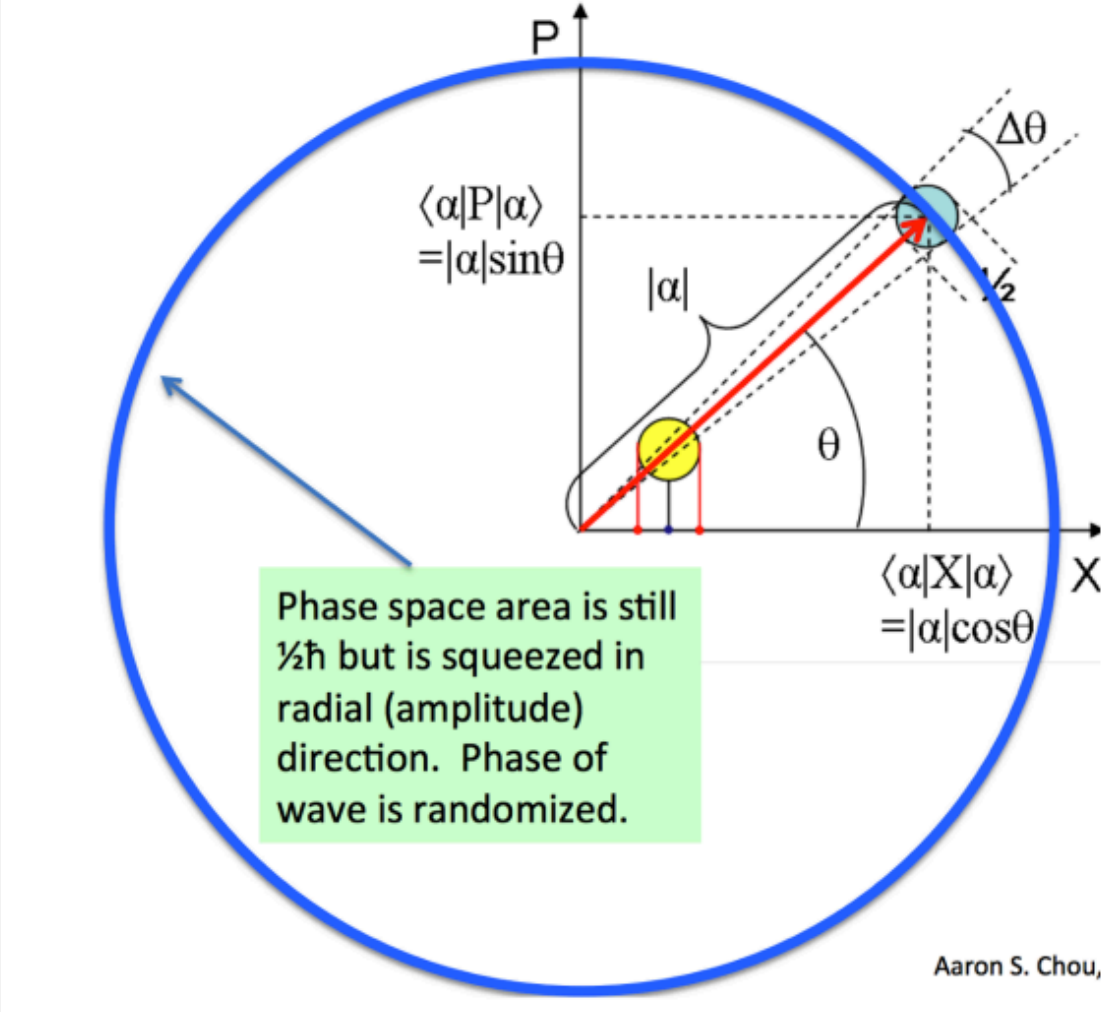
Figure 1.1: (a) In general, the amplification process will degrade the signal to noise ratio by adding certain amount of noise to the signal before amplifying it. (b) Quantum mechanics places a restriction on the minimum amount of this added noise when the amplifier amplifies both quadratures of the 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



Phase space area is still ½ħ but is squeezed in radial (amplitude) direction. Phase of wave is randomized.

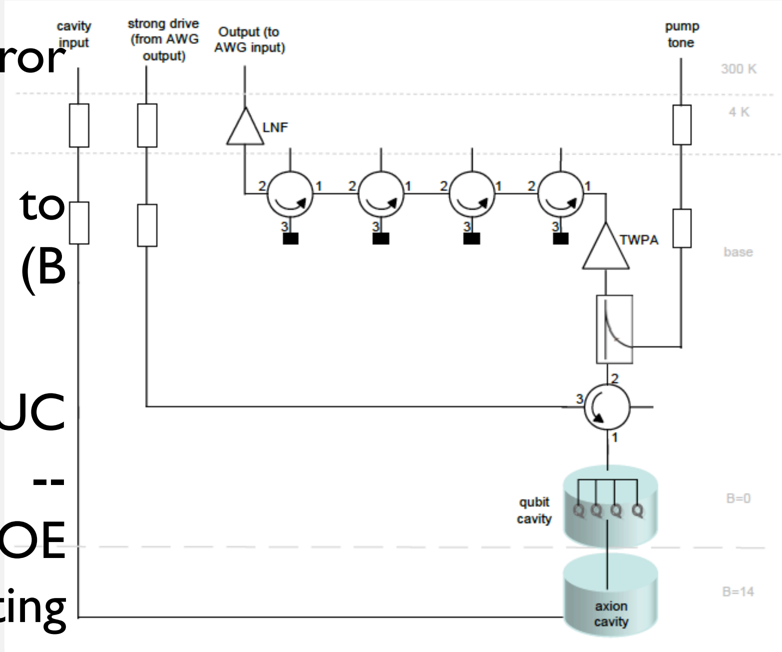
Aaron S. Chou,

No zero point noise limit of Quantum amps.

-- count the photons

SINGLE PHOTON COUNTING AXION DETECTOR

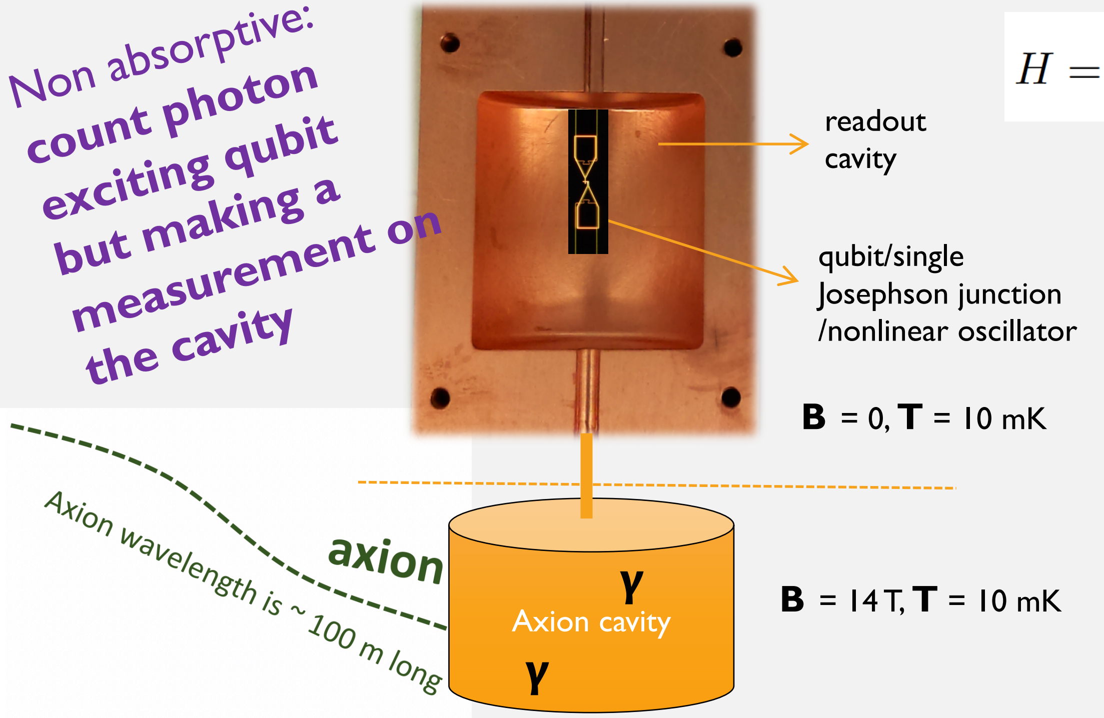
- Technique needs more maturity
- qubit readout error reduction
- needs tailoring to axion detection (B field)
- Fermilab, UC Boulder and Yale -- part of DOE quantum computing and sensors initiative



QUBIT BASED SINGLE PHOTON DETECTOR

Non absorptive:

count photon exciting qubit but making a measurement on the cavity



B = 0, **T** = 10 mK

B = 14 T, **T** = 10 mK

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

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

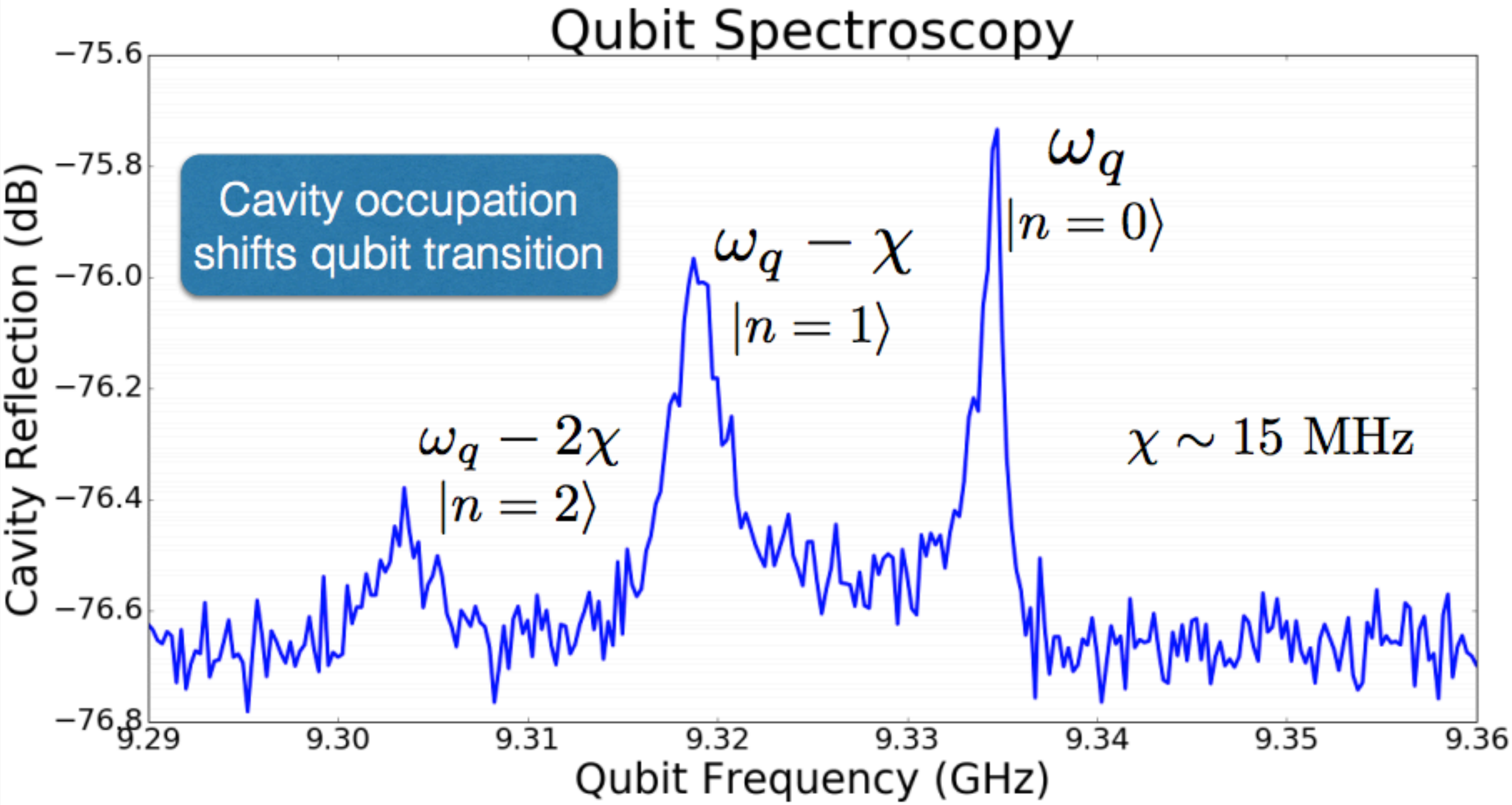
$$H = \omega_c a^\dagger a + (\omega_q + 2\frac{g^2}{\Delta} a^\dagger a)\sigma_z$$

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

*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 !

Cavity Dependent Qubit



Qubit Spectroscopy

Cavity occupation shifts qubit transition

$\chi \sim 15$ MHz

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.