Fermilab PAC, 11/10/16

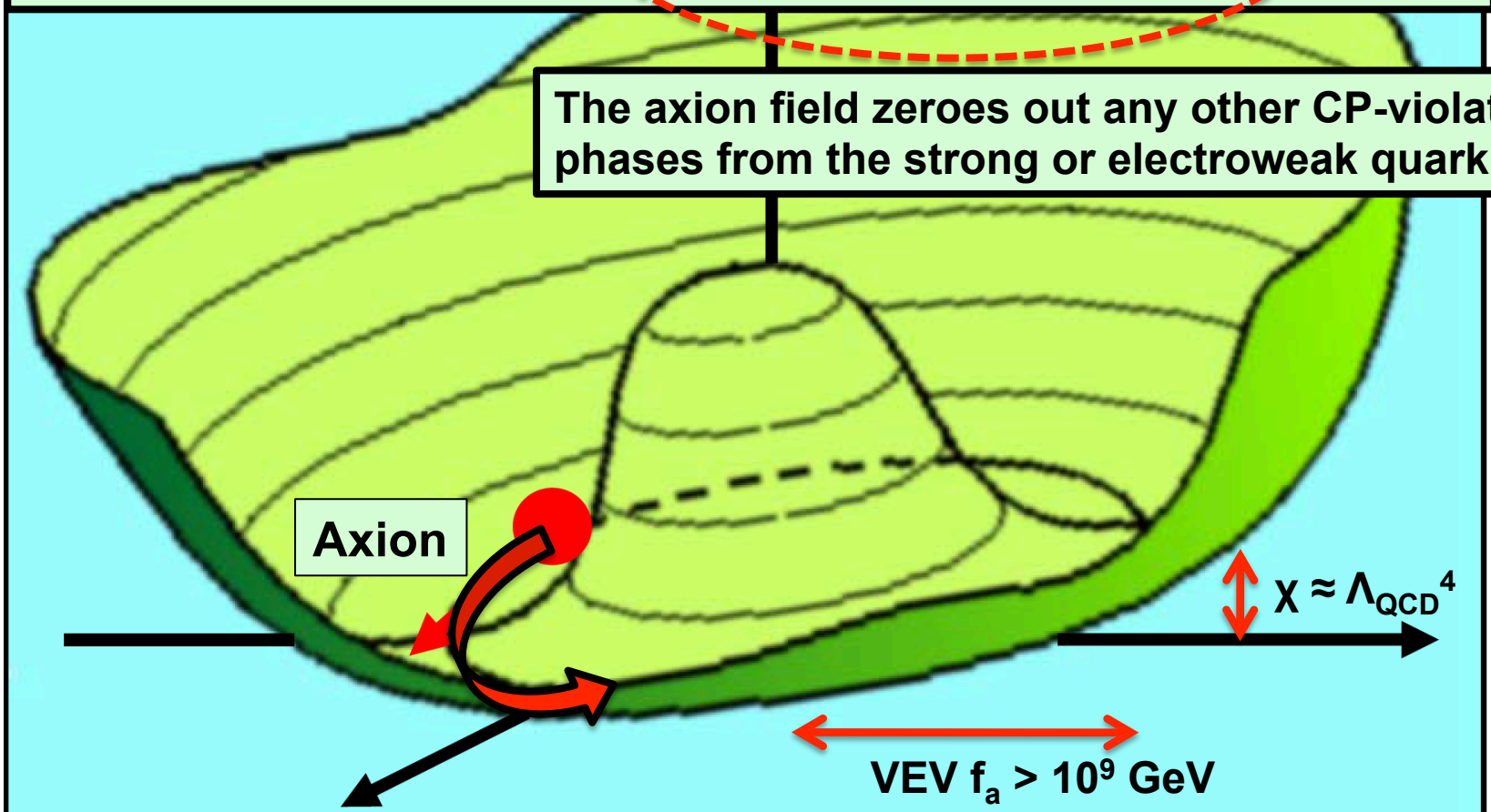
Axion Dark Matter Outlook

Aaron S. Chou
FNAL

Explaining the vanishing neutron EDM

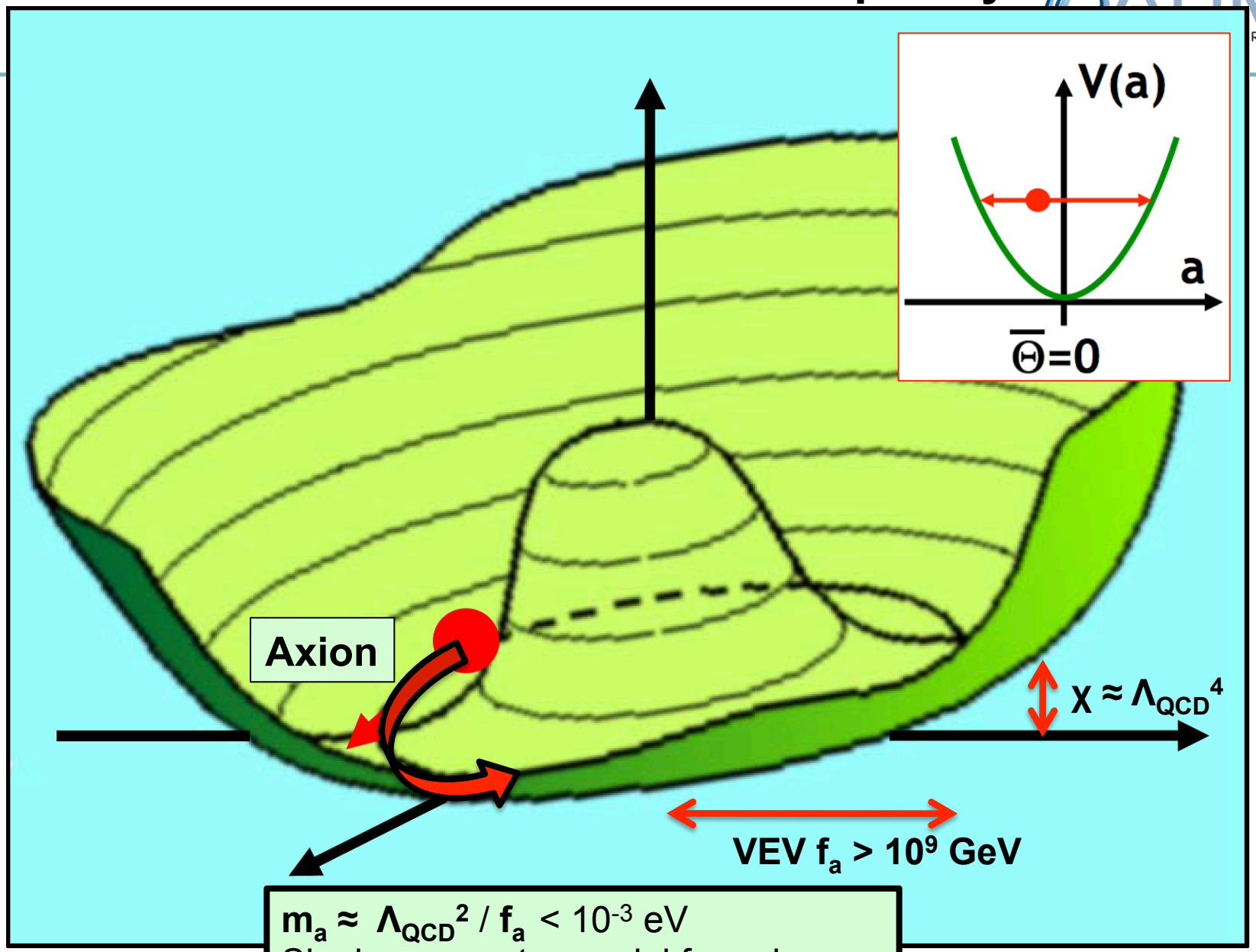
$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G\tilde{G} \rangle$$

The axion field zeroes out any other CP-violating phases from the strong or electroweak quark sector.



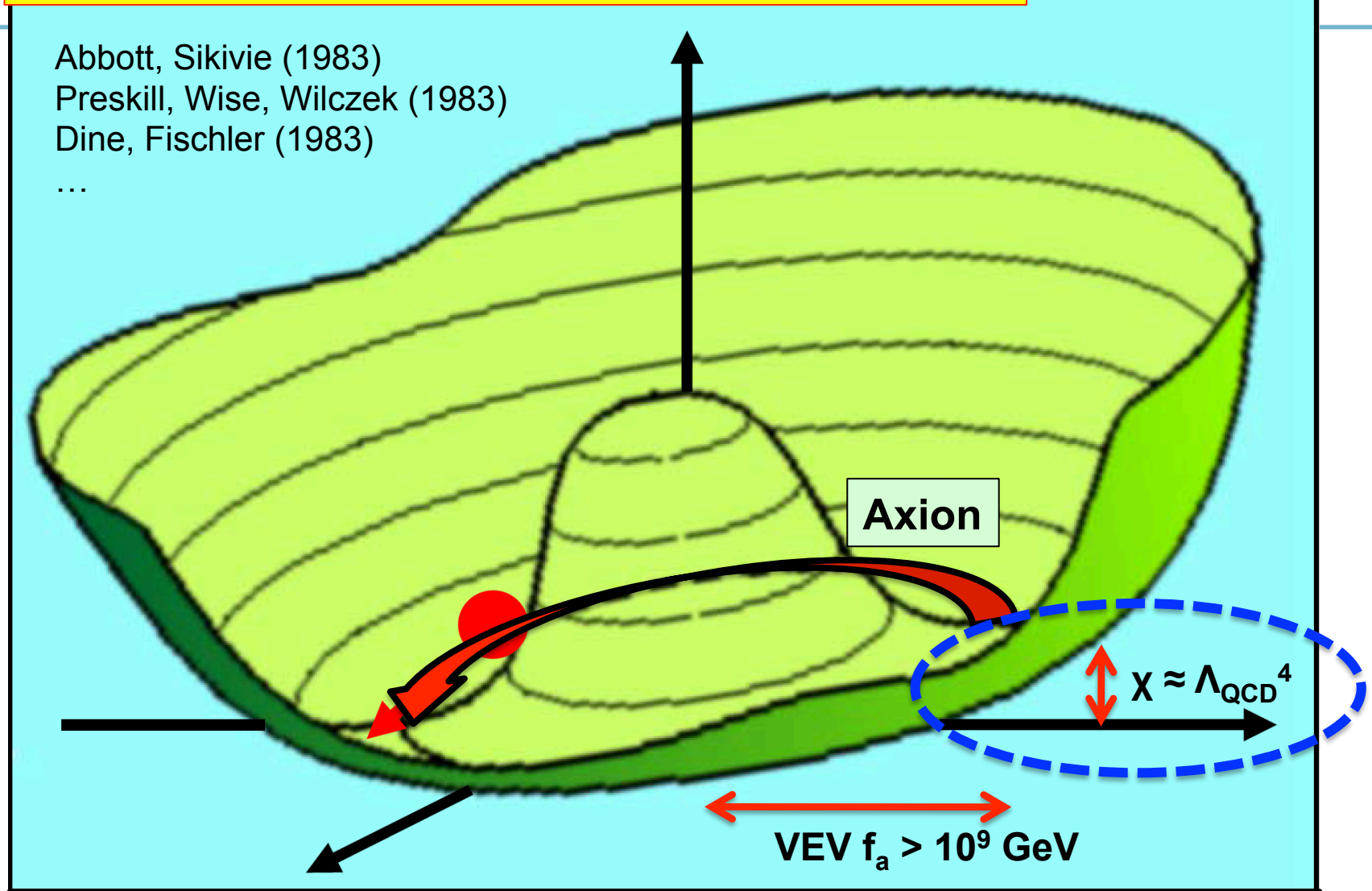
The neutron EDM vanishes, solving the **strong CP fine-tuning problem**.

Axion mass = harmonic oscillator frequency



$m_a \approx \Lambda_{QCD}^2 / f_a < 10^{-3}$ eV
Single parameter model for axions

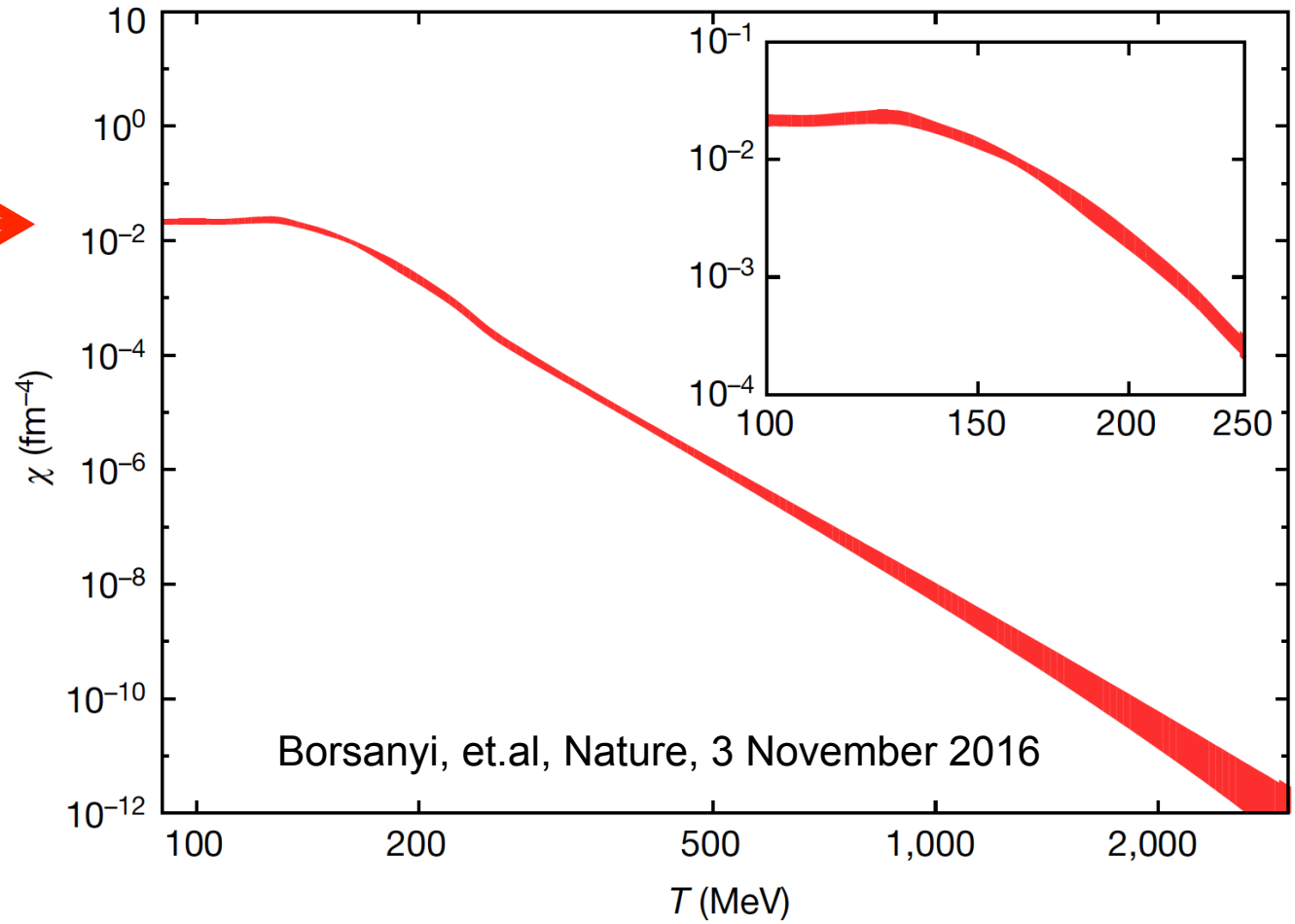
The initial potential energy density is released as ultracold dark matter



Initial axial **theta angle θ_0**, determines the available potential energy to be converted into axion dark matter.

Latest lattice result for QCD topological susceptibility agrees with naïve estimate

$\chi = d^2V/d\theta^2$
$\approx \Lambda_{QCD}^4$



This gives the QCD potential energy density available to convert into DM axions.

Bucket of dark matter is dumped into the red-shifting photon bath at time $1/H \approx 1/m_a$

Non-DM density redshifting away →

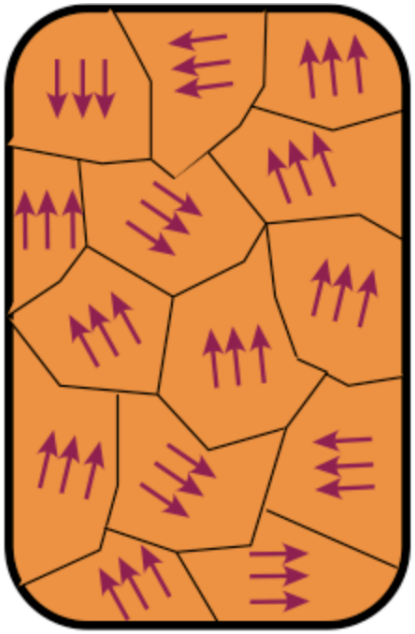
Global warming

For a bucket filled to the level $\langle \sin^2 \theta_0 \rangle \times \chi$ of fish,
dumping it too late creates an improper balance of fish/water.

If you are going to procrastinate and dump it late, you better not have too many fish in that bucket since there is not a lot of water left!

→ **Small m_a requires small $\langle \sin^2 \theta_0 \rangle$ to avoid overproducing dark matter.**

Fullness of bucket depends on whether the axion phase transition happens before or after inflation



Ferromagnetic spin domains

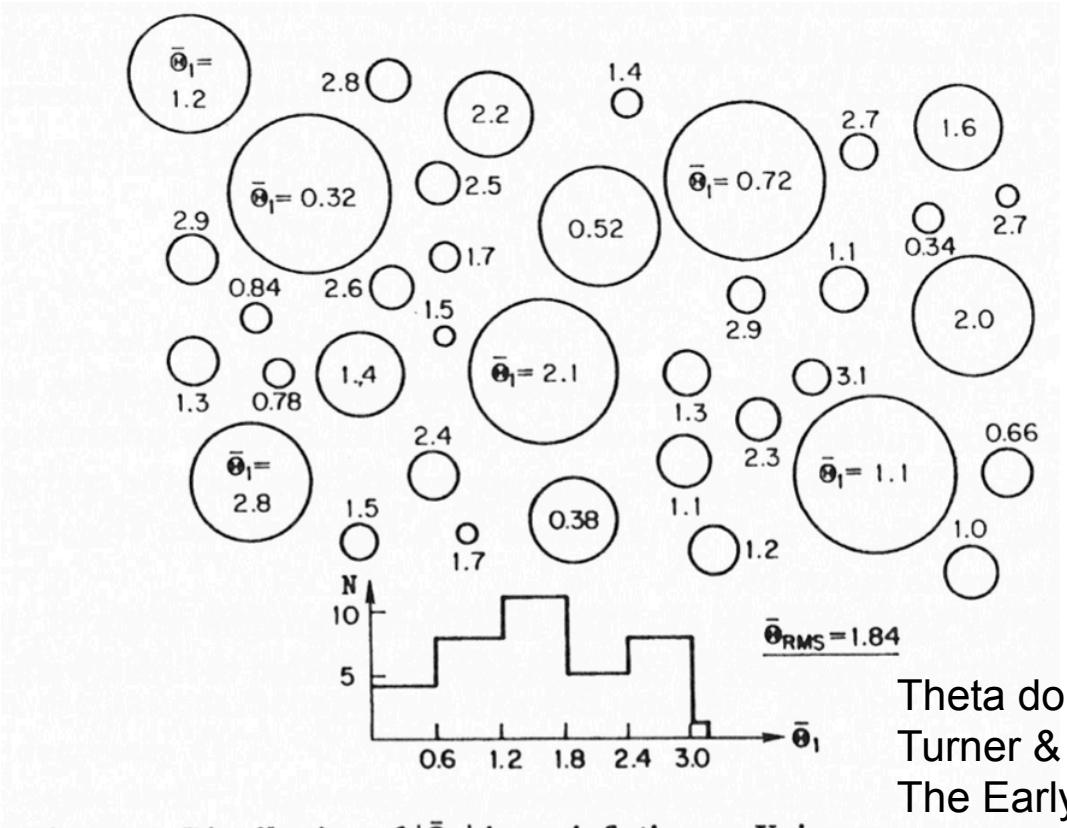
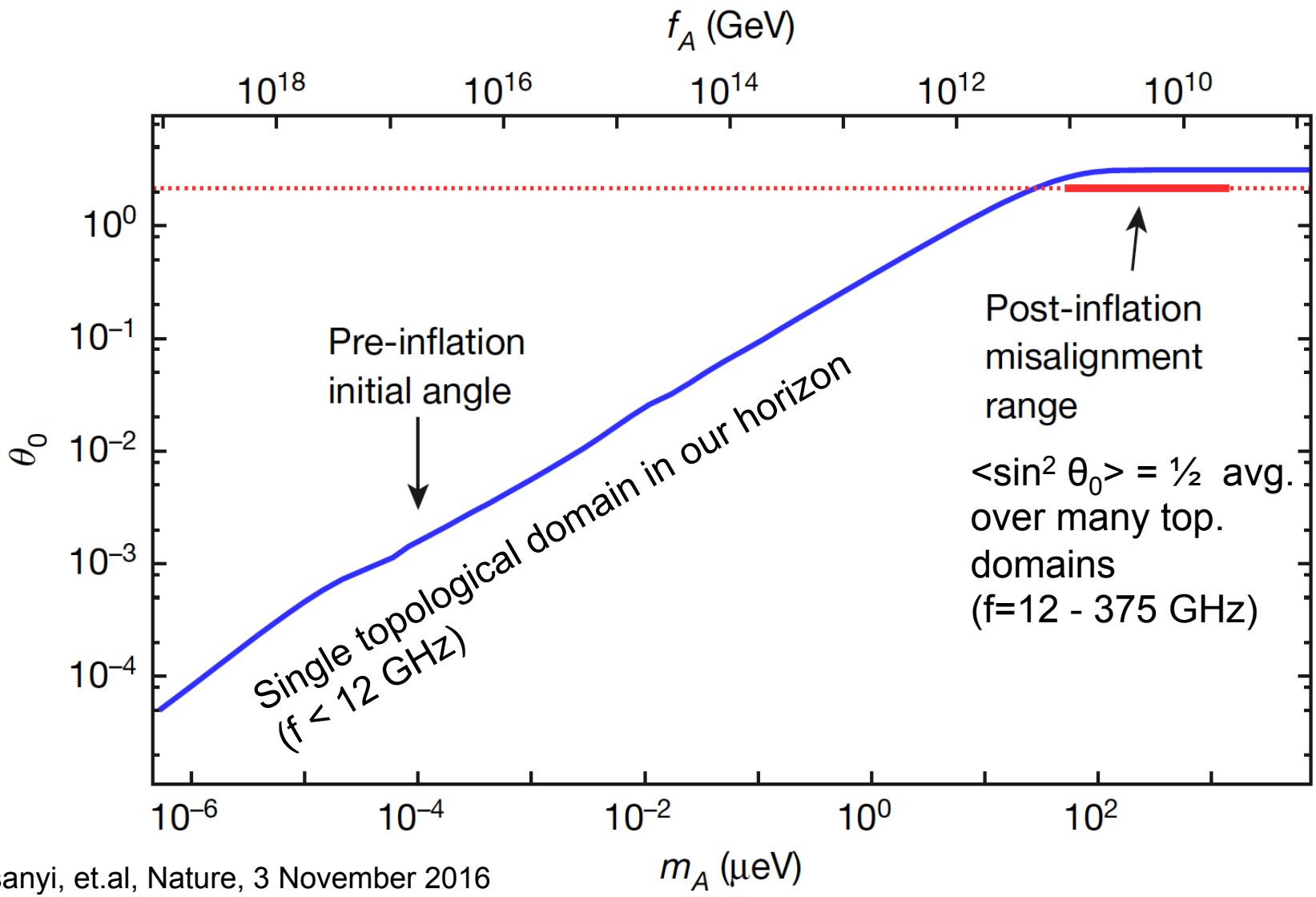


Fig. 10.9: Distribution of $|\bar{\Theta}_1|$ in an inflationary Universe.

Theta domains, Turner & Kolb The Early Universe

- If axion phase transition occurs **pre-inflation**, bubbles are inflated, and we live in one which by chance can have θ<1.
- If axion phase transition occurs **post-inflation**, many bubbles are contained within our horizon, and so we get average value $\langle \sin^2\theta \rangle \times \Lambda_{QCD}^4$ of dark matter.

New lattice results give crisp dividing line at m_a=50 μeV between pre- vs post-inflationary axion phase transition



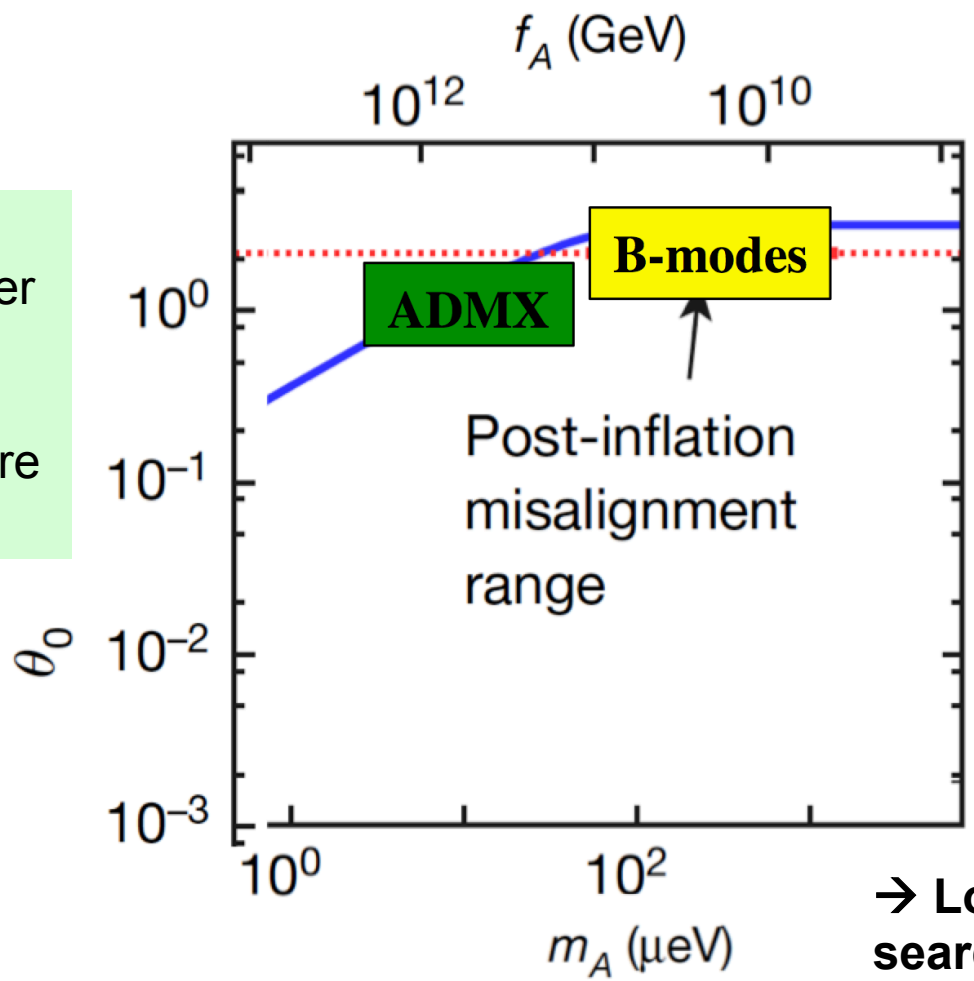
Borsanyi, et.al, Nature, 3 November 2016

ADMX and CMB B-modes are complementary probes of cosmic inflation

B-modes are observable only if the scale of inflation $E_{inf} > 10^{16}$ GeV:

$$V^{1/4} \sim (r/0.01)^{1/4} \times 10^{16}\ \mathrm{GeV}$$

If ADMX-G2 observes a lower mass axion, $E_{inf} < 10^{12}$ GeV, and B-modes are not detectable.

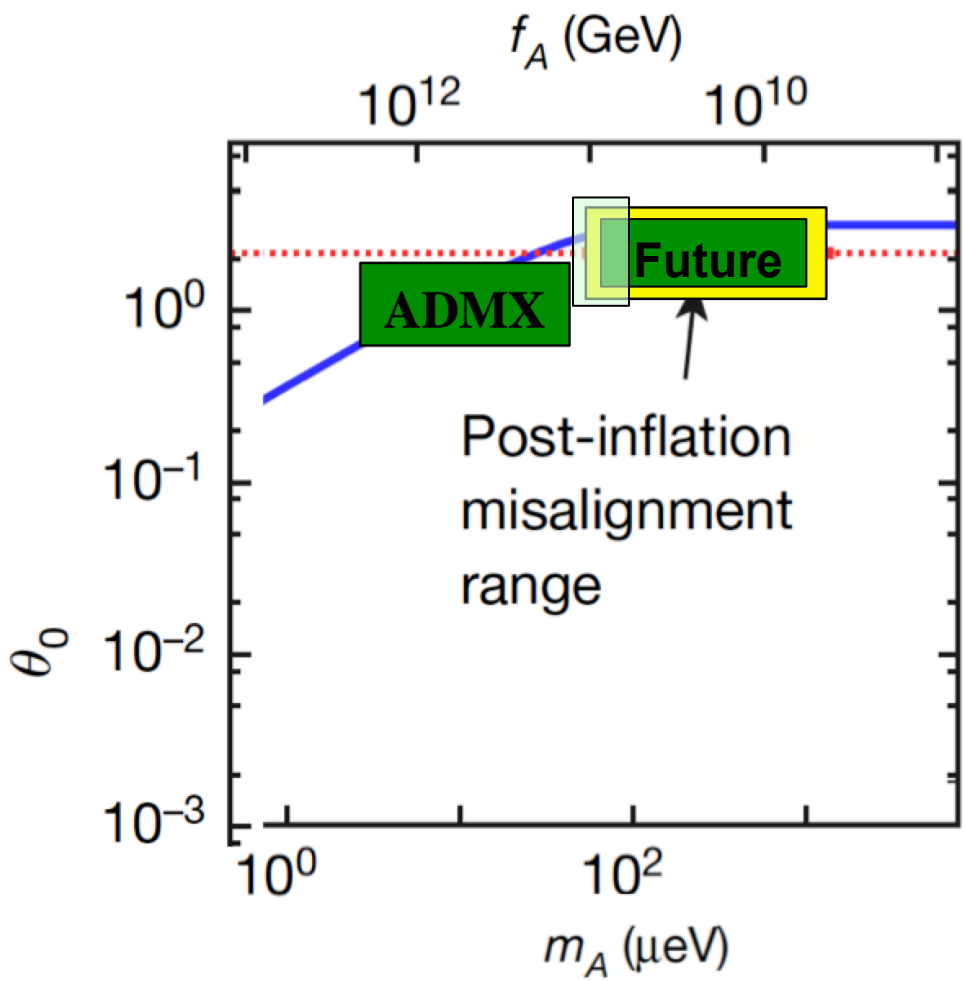


If CMB inflationary B-modes are seen, then $E_{inf} > 10^{16}$ GeV and dark matter axion masses are too high to be seen by ADMX-G2.

→ Lower mass axion searches can probe low scale inflation!

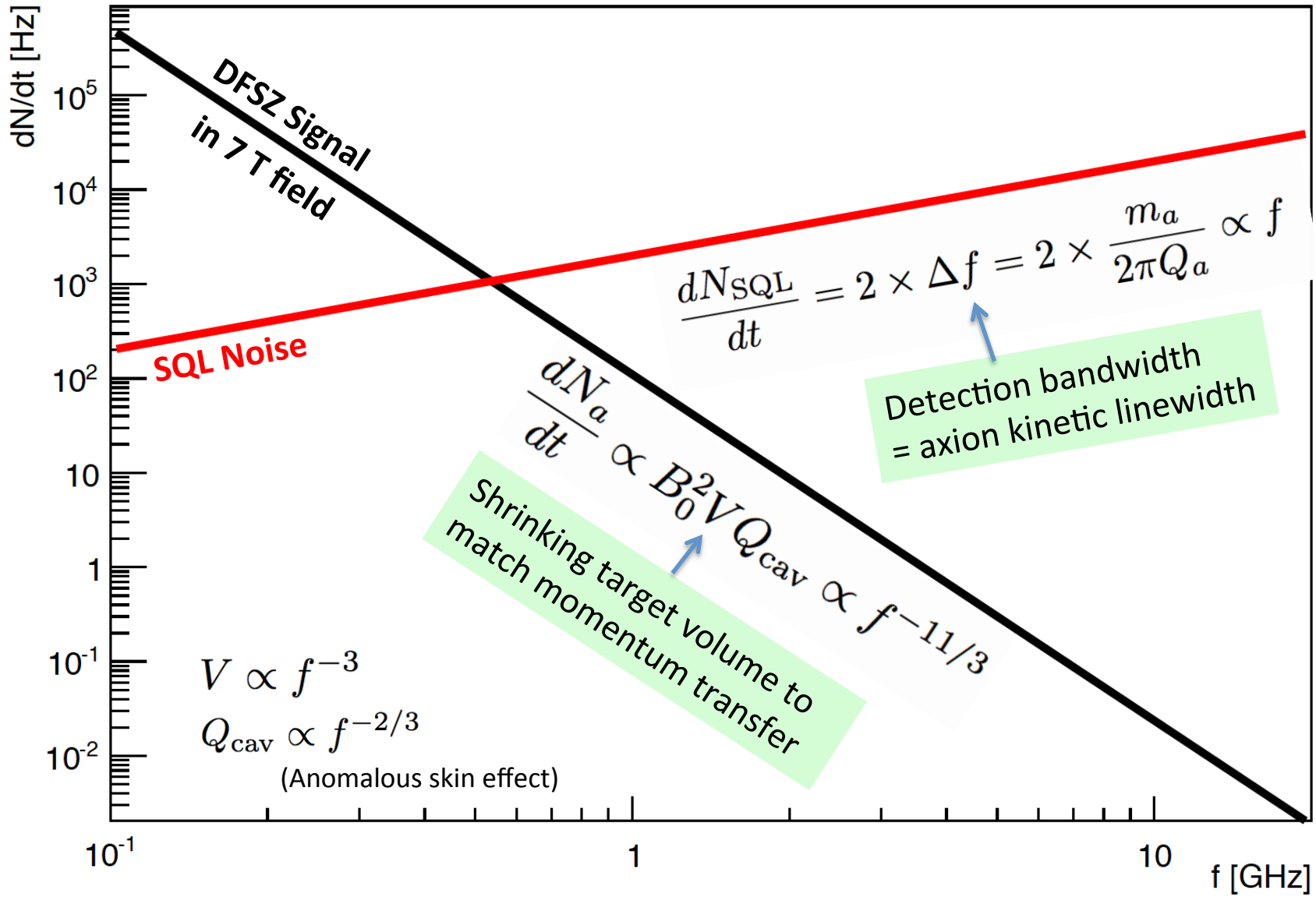
A future axion experiment should focus on higher mass to study the same class of "simple" inflationary models using independent probes

The natural next step is 10-20 GHz, or 40-80 μeV.

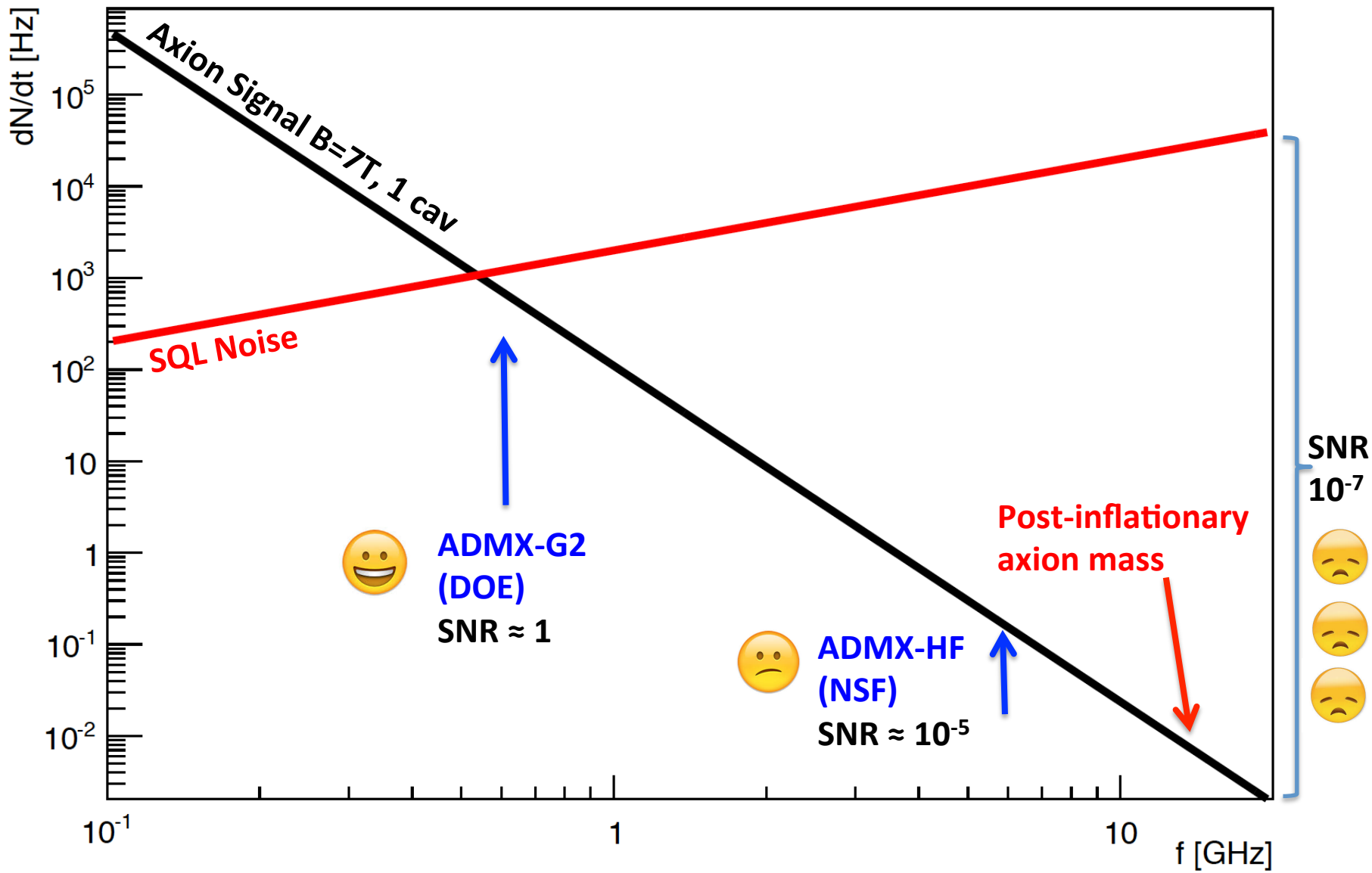


What prevents us from immediately going to higher frequencies?

DFSZ axion signal photon rate for single volume≈λ³ cavity vs. Standard Quantum Limit readout noise

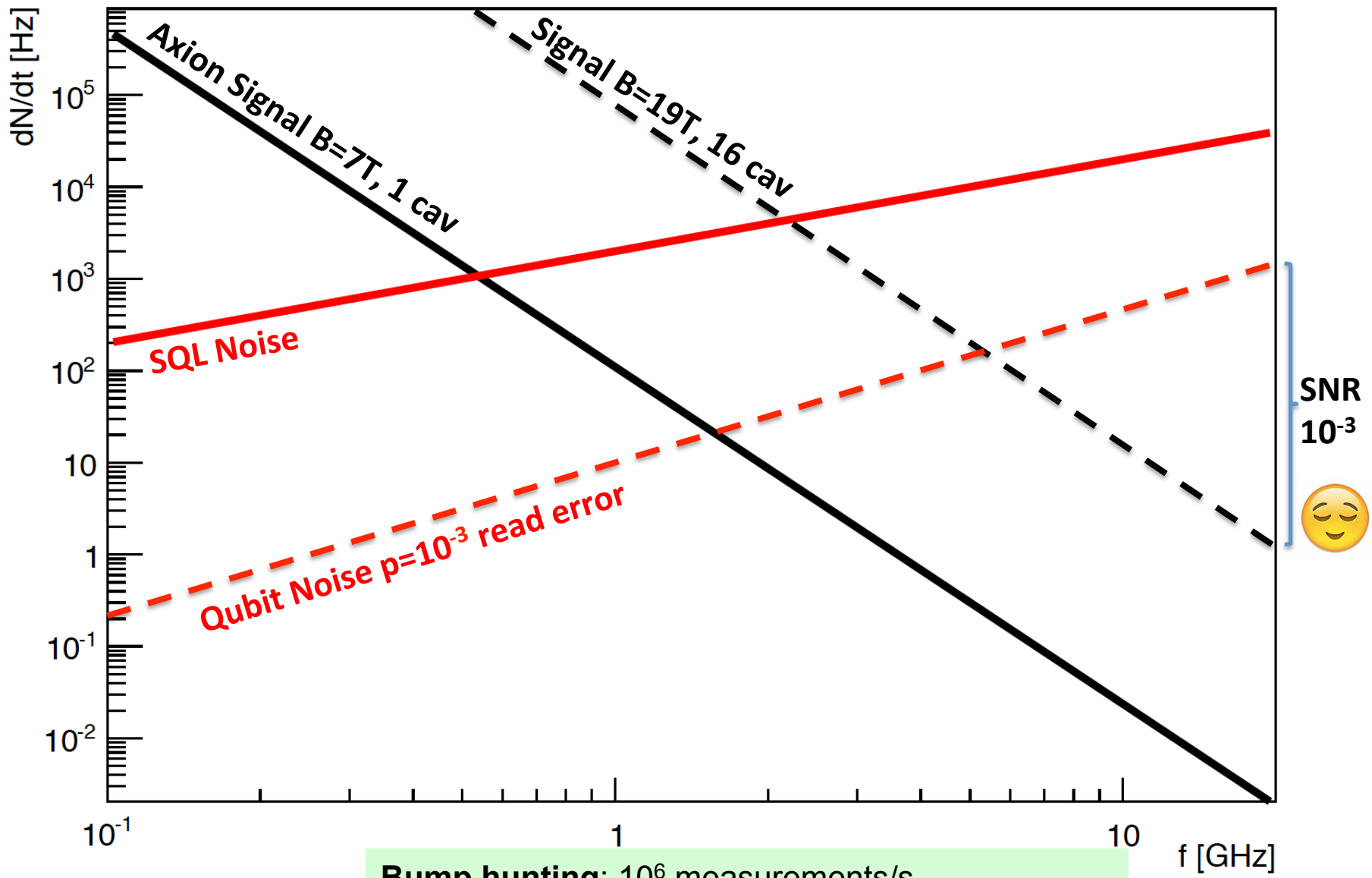


ADMX-G2 is currently looking under the lamp post where the Signal/Noise ratio is favorable



If CMB experiments see B-modes, what is our plan for getting to f>10 GHz?

Plausible 10-20 GHz search strategy: higher B field, more larger cavities, reduce noise using Qubit detector



Bump hunting: 10^6 measurements/s
→ obtain sensitivity to 0.1% excess in few seconds

Ingredients for 10-20 GHz axion DM search

- **Higher field magnet**
  - Utilize FNAL core competency in superconducting magnets
- **Larger volume, high-Q, cryogenic RF cavities**
  - Utilize FNAL core competency in accelerator RF cavities, cryogenics
- **Lower noise RF photon detectors**
  - Utilize Chicagoland expertise and infrastructure in superconducting electronics

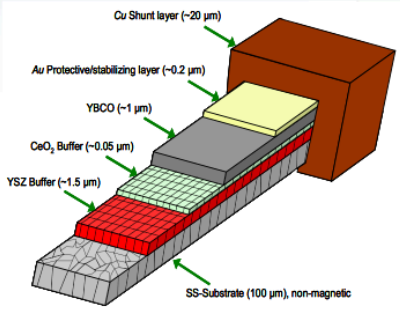
Ingredient #1: Higher field, smaller bore magnet
Utilize Fermilab core competency in superconducting magnets

- Signal strength scales as B^2
- At higher frequencies, axion Compton wavelength is smaller so the natural cavity size is also smaller.
  - Large B is easier with small bore

- Most risk-free way of increasing signal strength, but expensive.

20 GHz axion experiment possible with existing commercial NMR YBCO magnet technology

1.1 GHz = 25.85 T, $12M



- 89 mm RT bore
  Very similar to 1.2 GHz, except for inner sections

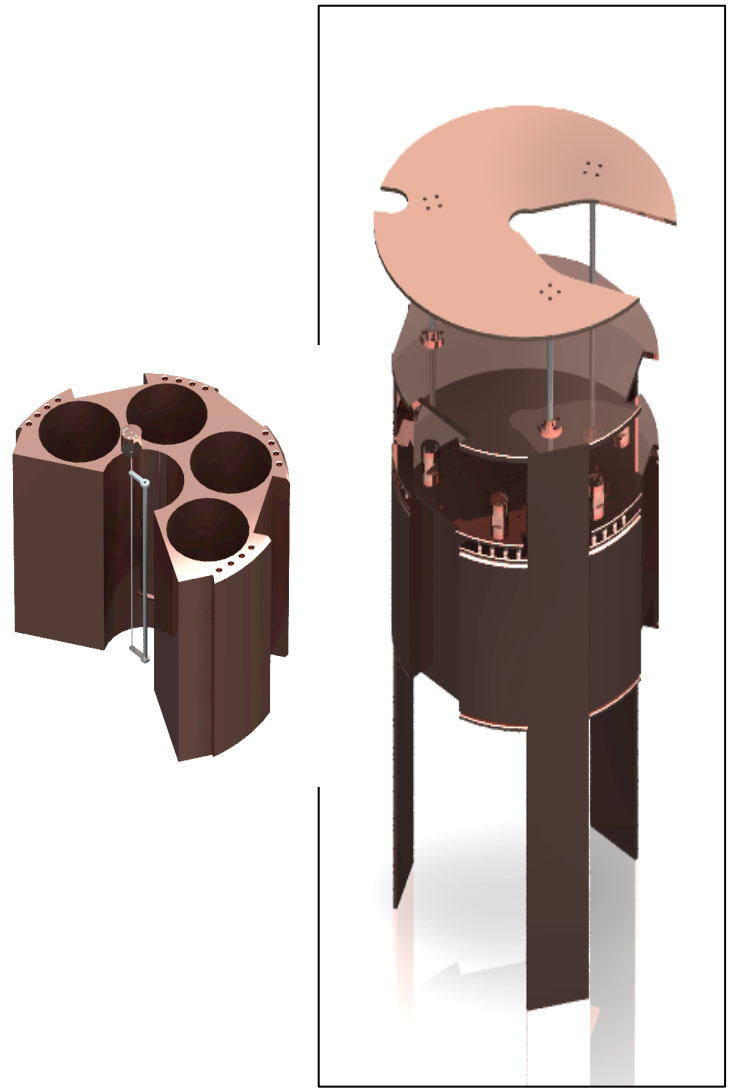
Fermilab expertise in superconducting magnets and cryogenics can be used for customizing/procuring magnet and integrating 20mK cryostat.
(It is non-trivial to maintain a sufficiently large sample space for cold cavities.)

Ingredient #2: Larger volume, high-Q RF cavities
Utilize Fermilab core competency in accelerator RF cavities

Simplest idea: power combine lots of cavities, operated in parallel and tuned to the same frequency.

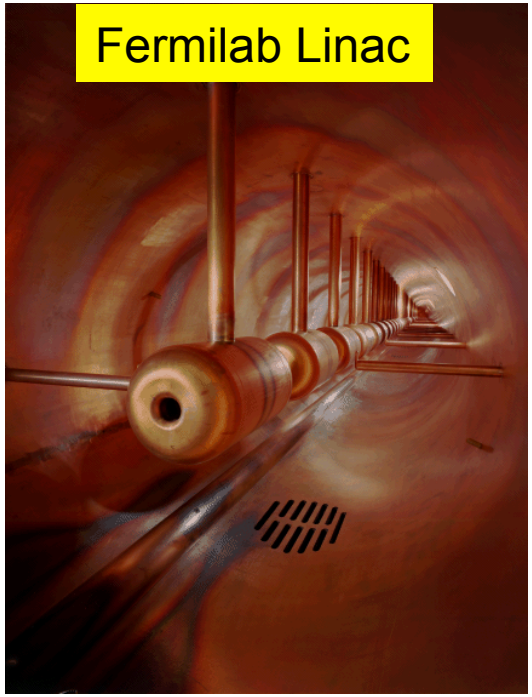
Cost and complexity scale at least linearly with N_{cav}, i.e. as (frequency)^3 !

Okay for small N_{cav}, but not indefinitely scalable.



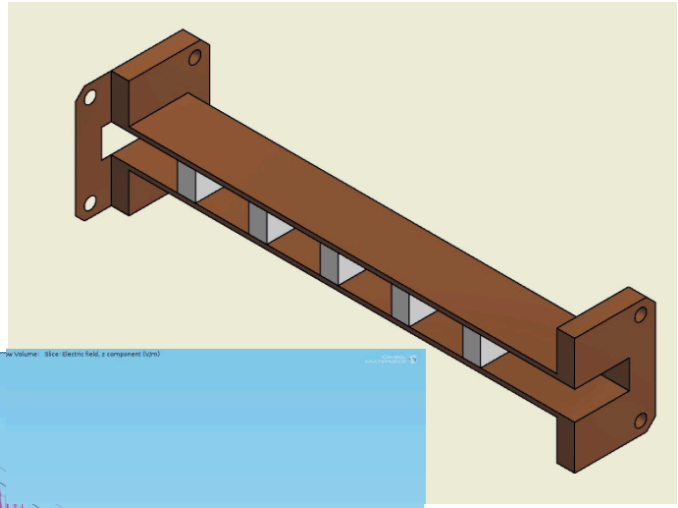
The axion DM community has engaged the accelerator RF community to transfer accelerator cavity technology

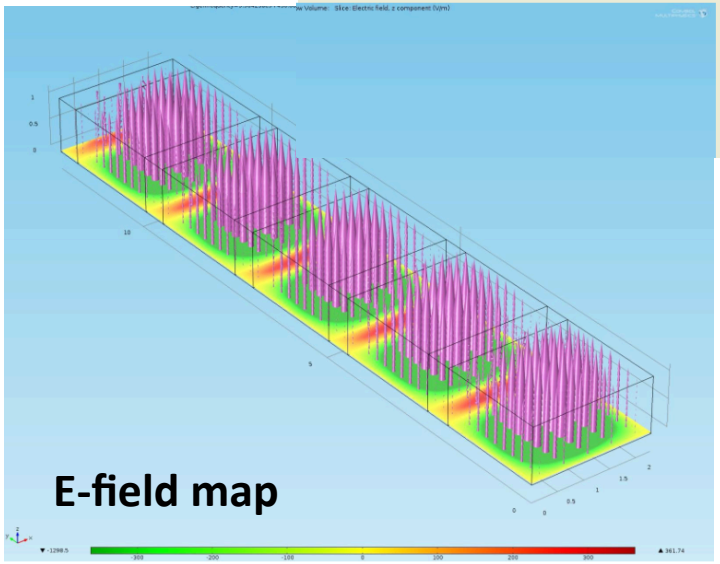
Same physical process as acceleration, but time reverse!
Accelerators transfer power from RF cavity → charged particle beam;
Axion detectors transfer power from charged particle beam → RF cavity.
Both require electric gradient to be in-phase with the particle beam.



Alvarez drift tube linac (1945) uses periodic conducting shields to block out-of-phase RF

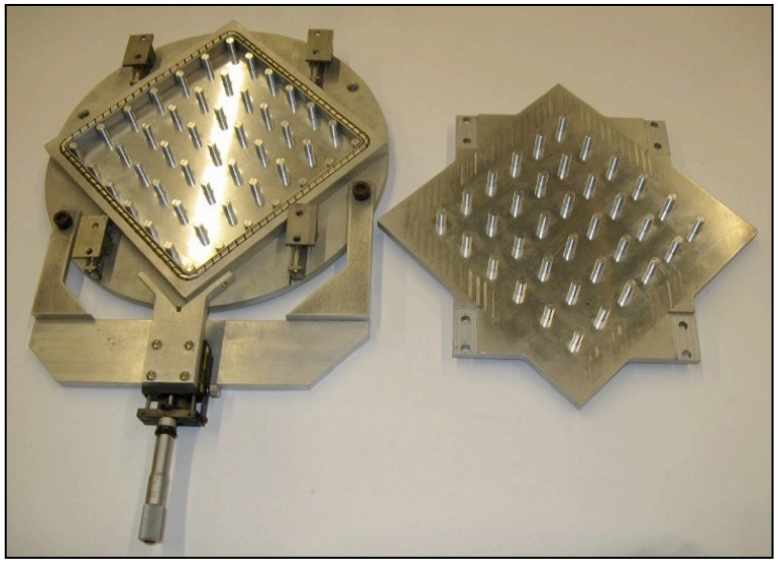
Orpheus axion resonator concept (Rybka, UW) uses periodic dielectric to suppress out-of-phase RF



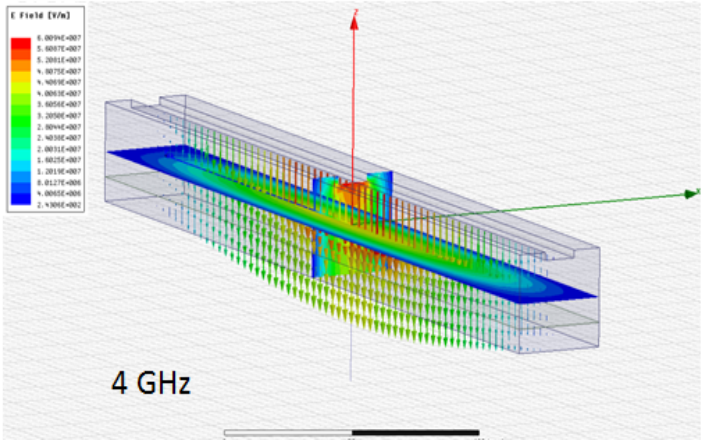


Funding for cross-disciplinary collaboration from Heising-Simons Foundation.

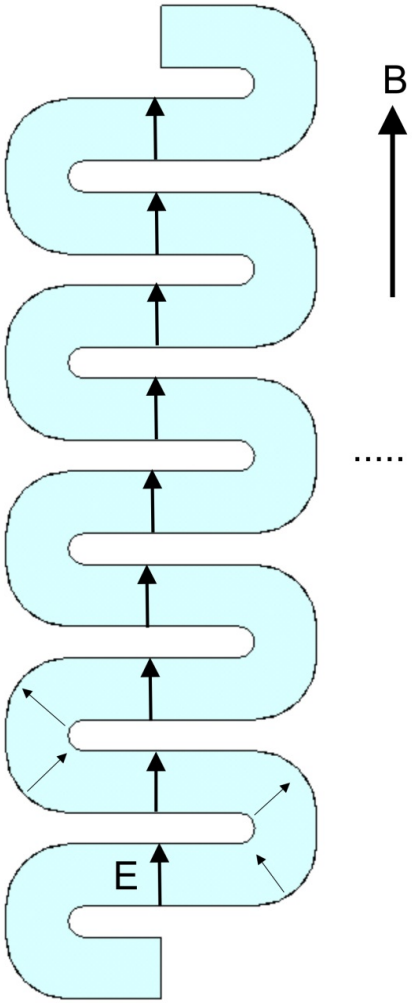
Some other large volume axion cavity concepts inspired by particle accelerator RF cavity designs



Photonic bandgap cavities (Carosi, LLNL)



Ridged waveguide (Moretti, FNAL AD)

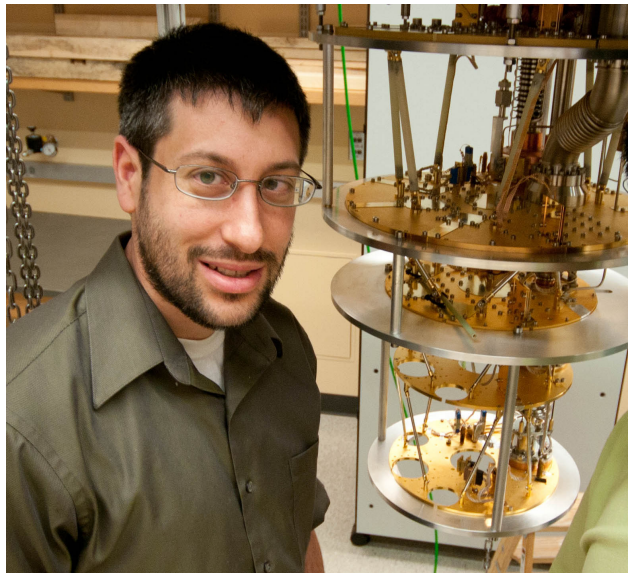


Folded traveling wave tube (Kazakov, FNAL TD)

Ingredient #3: Lower noise photon detectors

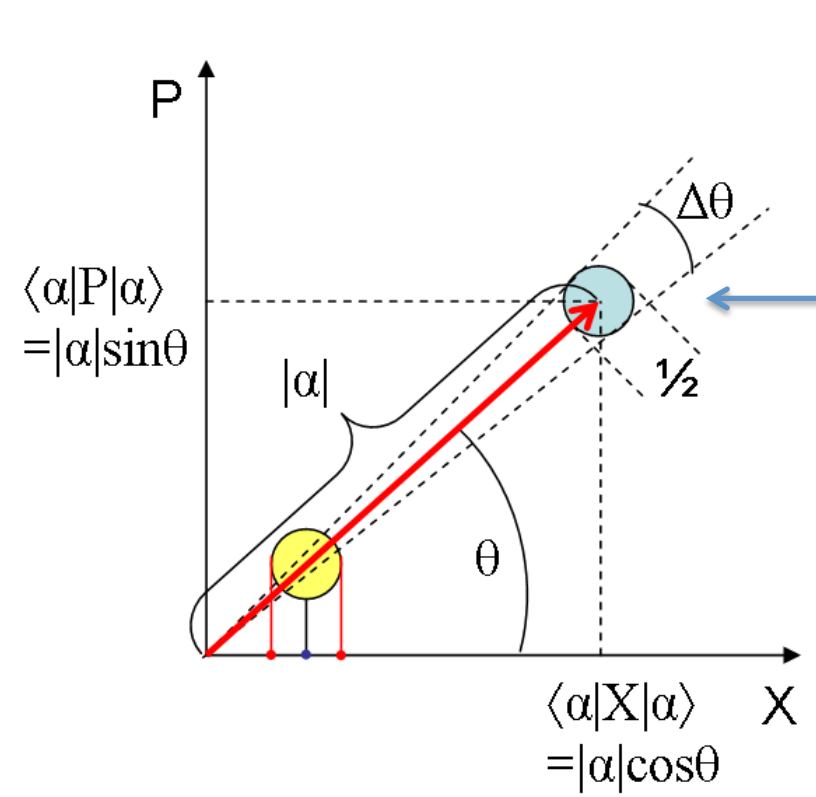
- Utilize Chicagoland expertise and infrastructure in superconducting electronics
  - U.Chicago: new Pritzker nanofab facility, quantum computing
  - FNAL: milliKelvin test stands, MKIDs, SPT, SRF materials expertise
  - ANL: superconducting fab user facility, SPT
  - Northwestern U: superconducting materials expertise

Brand-new Pritzker Nanofab



Superconducting qubits at D.Schuster lab (UC)

Quantum-limited amplifiers suffer from zero-point readout noise – the Standard Quantum Limit (SQL)



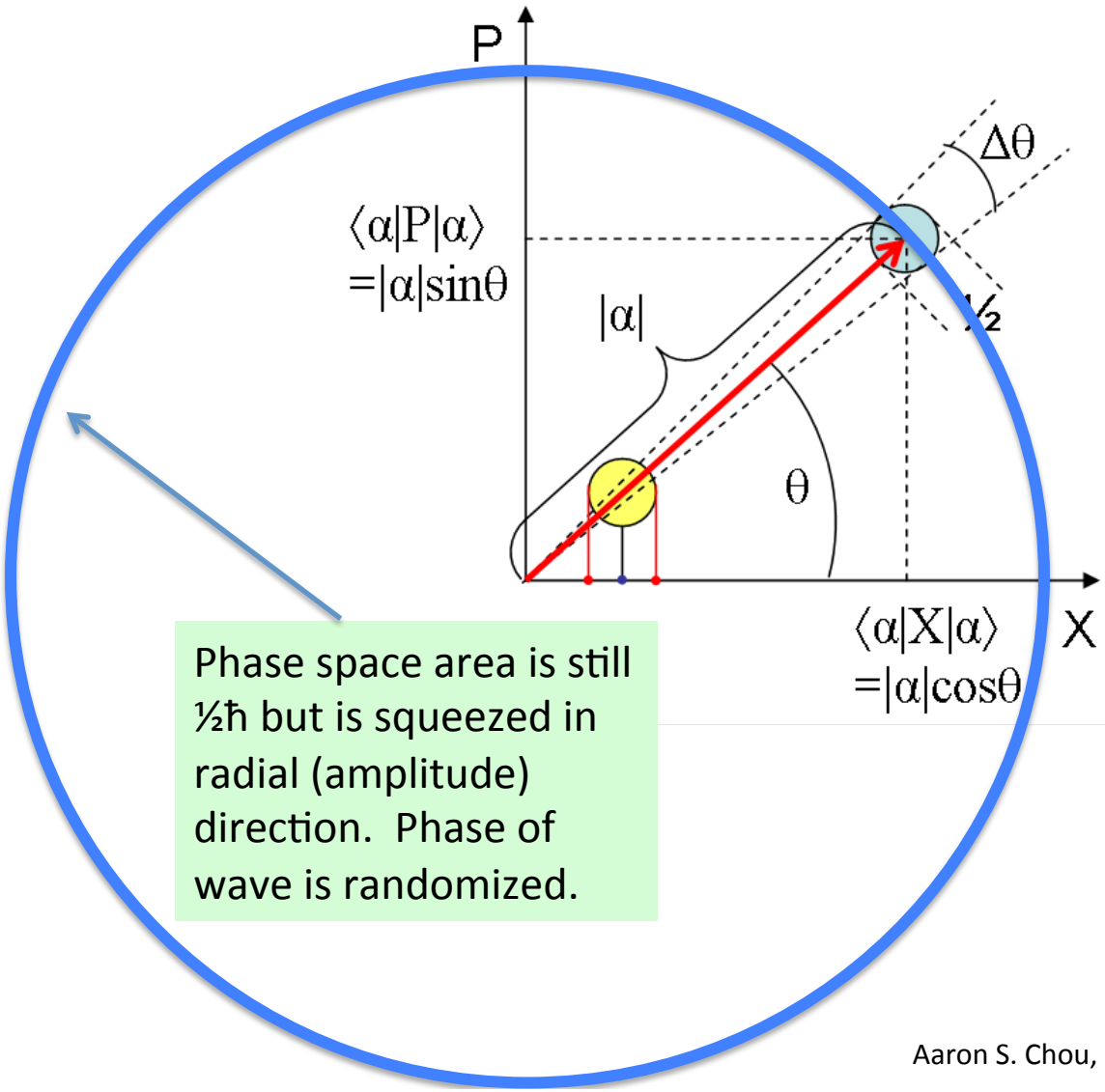
½ ħ= quantum of phase space area.
Simultaneous measurement of wave amplitude and phase gives irreducible zero-point noise in measurement.
(Caves, 1982)

Thermal noise = kT of energy per resolved mode
→ **Quantum noise = 1 photon per resolved mode in the T=0 limit.**

Noise photon rate exceeds signal rate in high frequency dark matter axion searches. Need new sensor technology….

Quantum non-demolition (QND) single photon detection can do much better

Number operator commutes with the Hamiltonian→ all backreaction is put into the phase. Measure exact photon number. Noise = shot noise, thermal backgrounds, read noise.



Demonstrated with Rydberg atoms, (Haroche/Wineland Nobel Prize 2012)

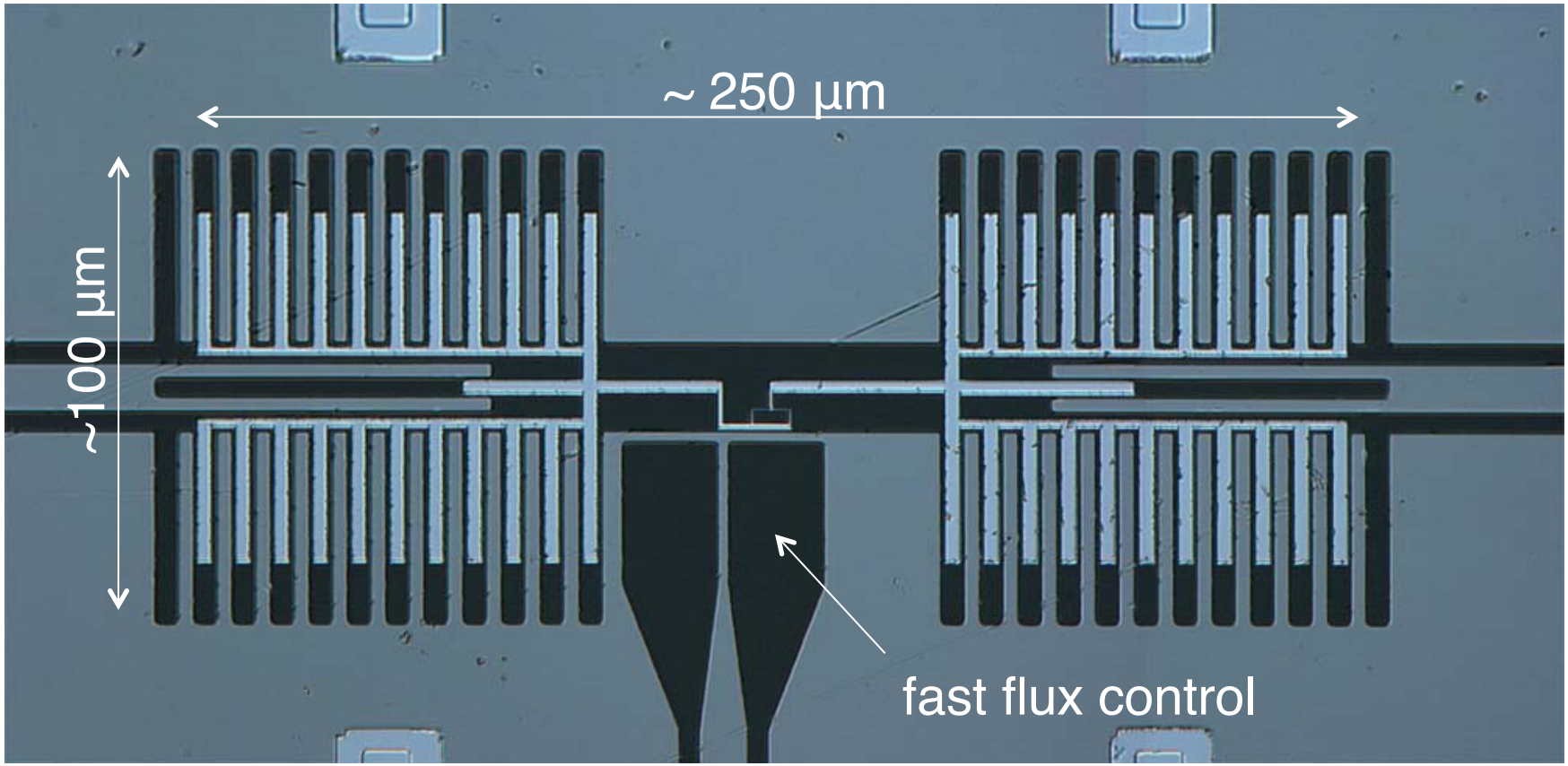
Implementation using solid state artificial atom qubits, (D.Schuster et.al, 2007)

Proposed for axion search: (Lamoreaux, et.al, 2013, Zheng, et.al, 2016)

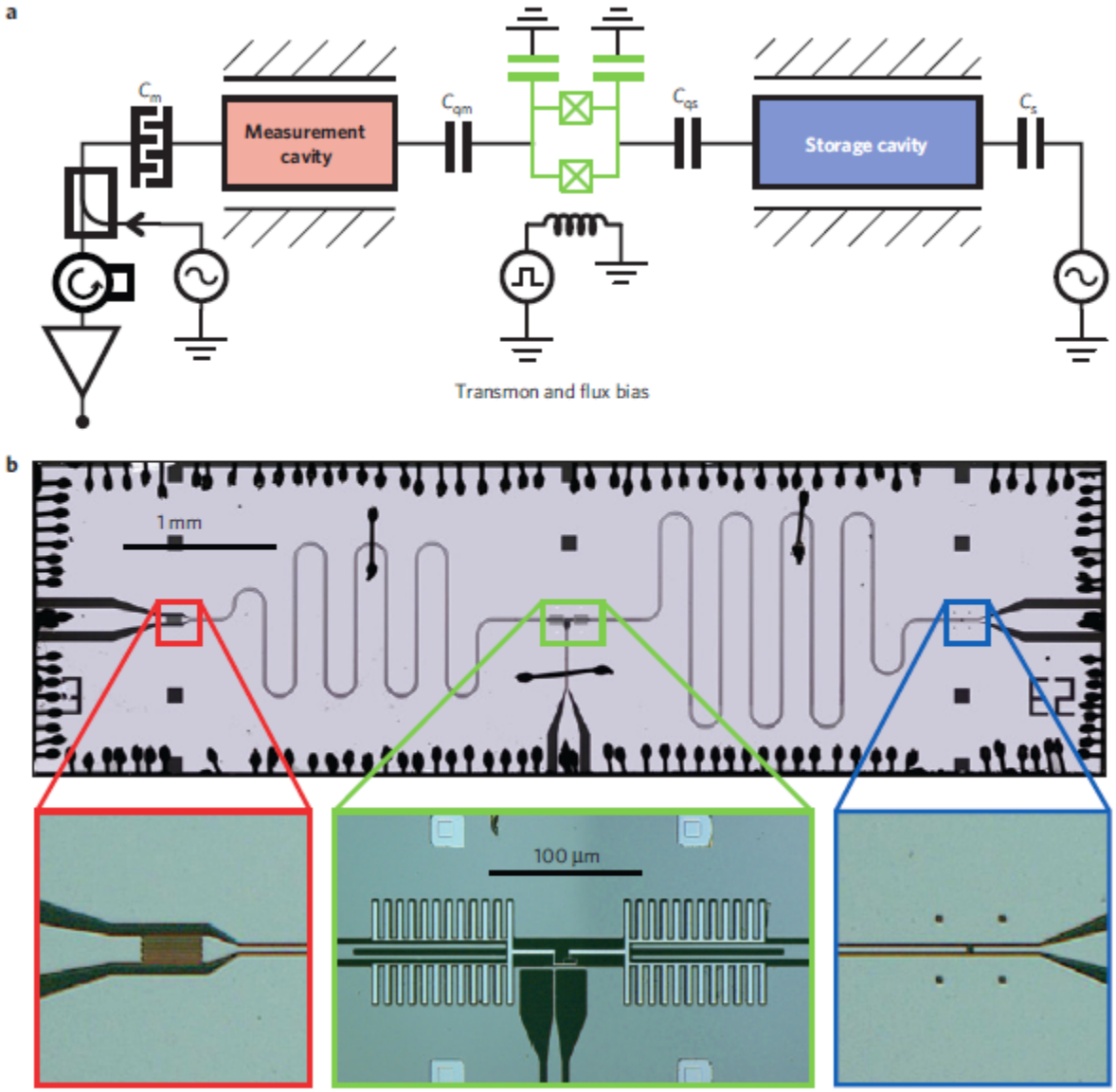
Use solid-state superconducting qubits as "artificial atom" photon detectors

Qubit-based single microwave photon detection technology pioneered by D.Schuster (UC) via DOD-funded quantum computing research

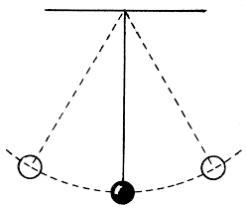
- An end-coupled "transmon" qubit with ~40 legs



QND Detector = qubit + fast cavity



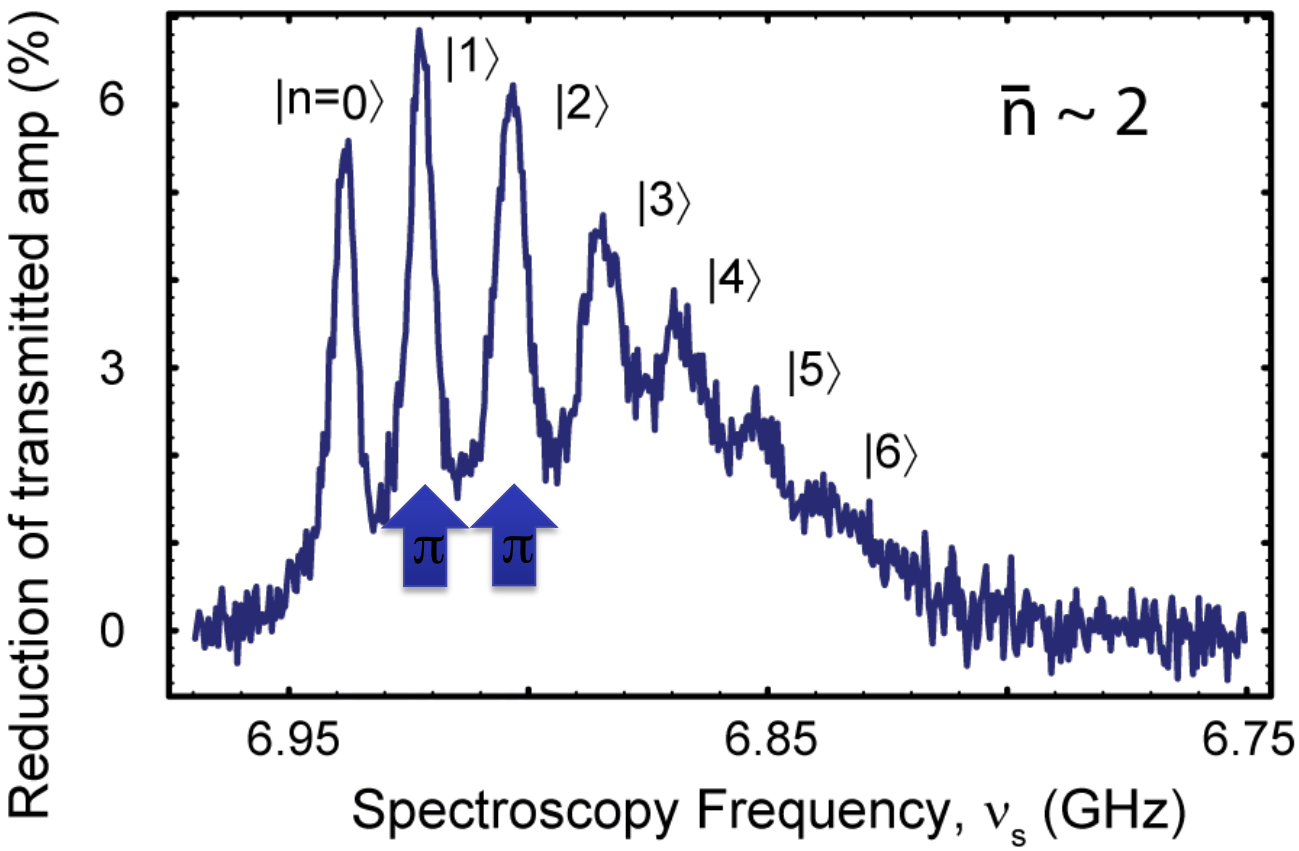
Readout frequency shift



Axion DM

Sensing photon number with a qubit

$$H \approx \hbar\omega_r a^\dagger a + \frac{\hbar}{2}(\omega_a' + 2\chi a^\dagger a)\sigma_z$$



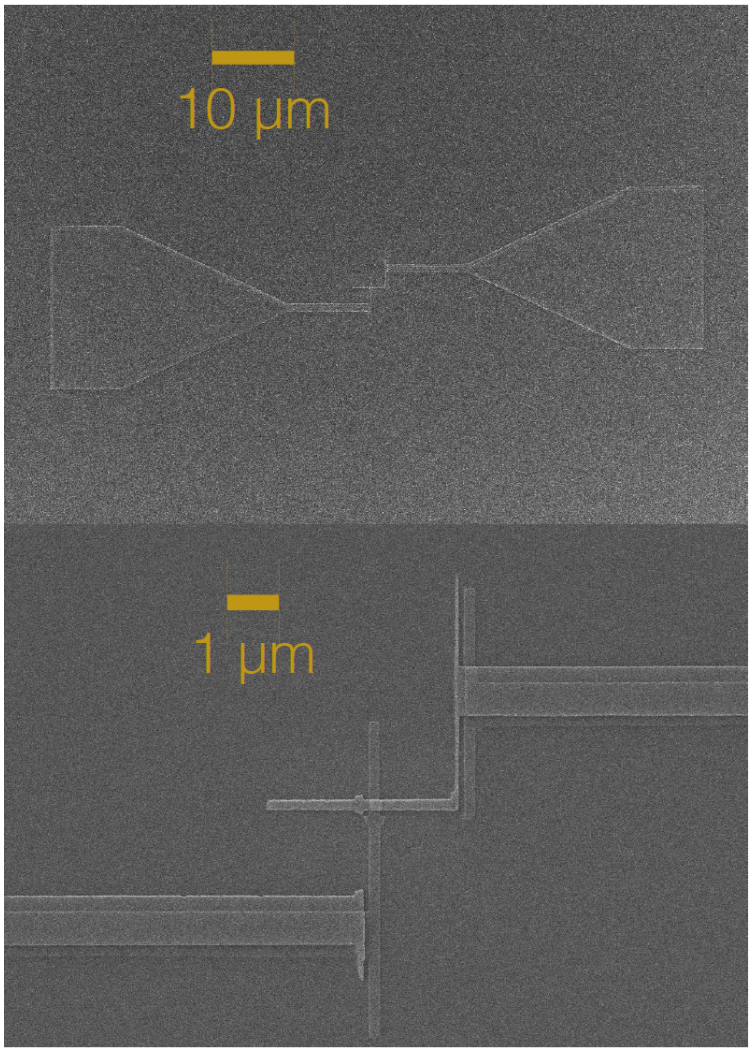
- Qubit transition frequency depends on photon number in cavity

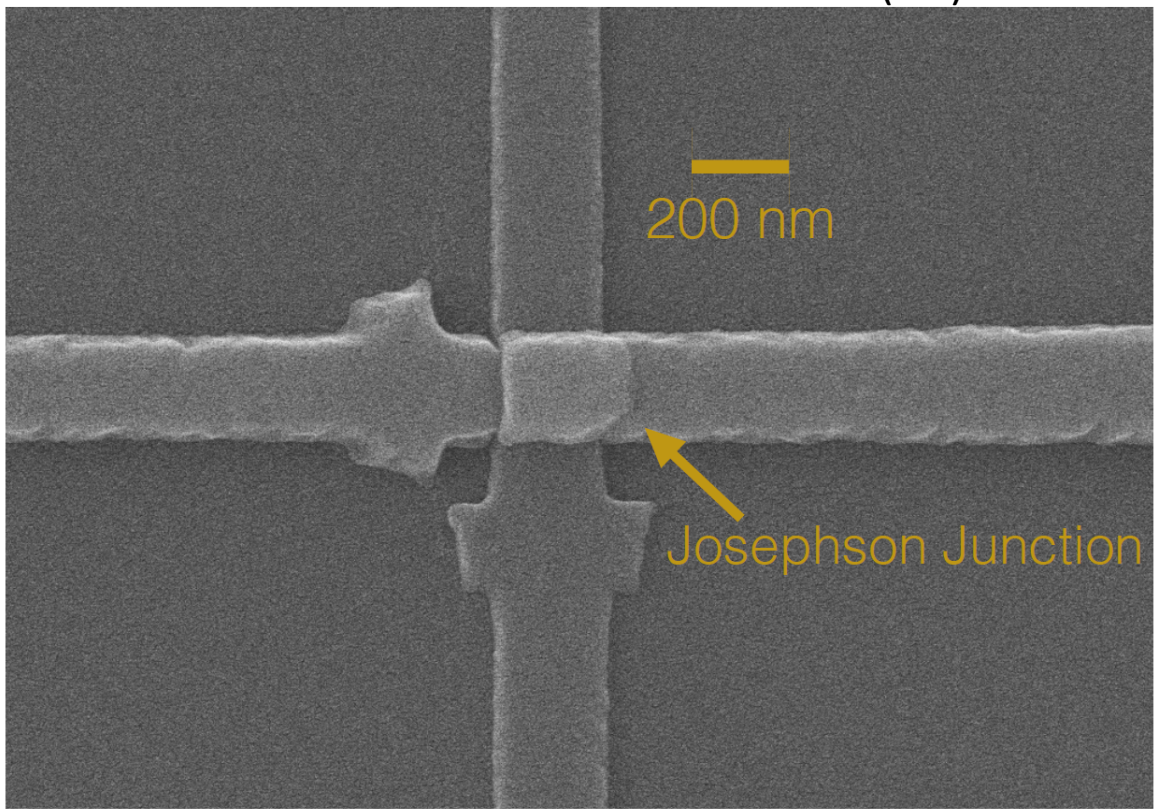
- Just like matter-effects in neutrino oscillations sense potential energy of interaction with background particles

Theory: J. Gambetta, A. Blais, …, S. Girvin, and R. J. Schoelkopf, *PRA 94 123602 (2005)*
Experiment: D. I. Schuster, … , S. M. Girvin, R. J. Schoelkopf, Nature (London) **445** 515 (2007)

3-D transmon qubit for axion detector being fabricated at Pritzker nano-fab facility

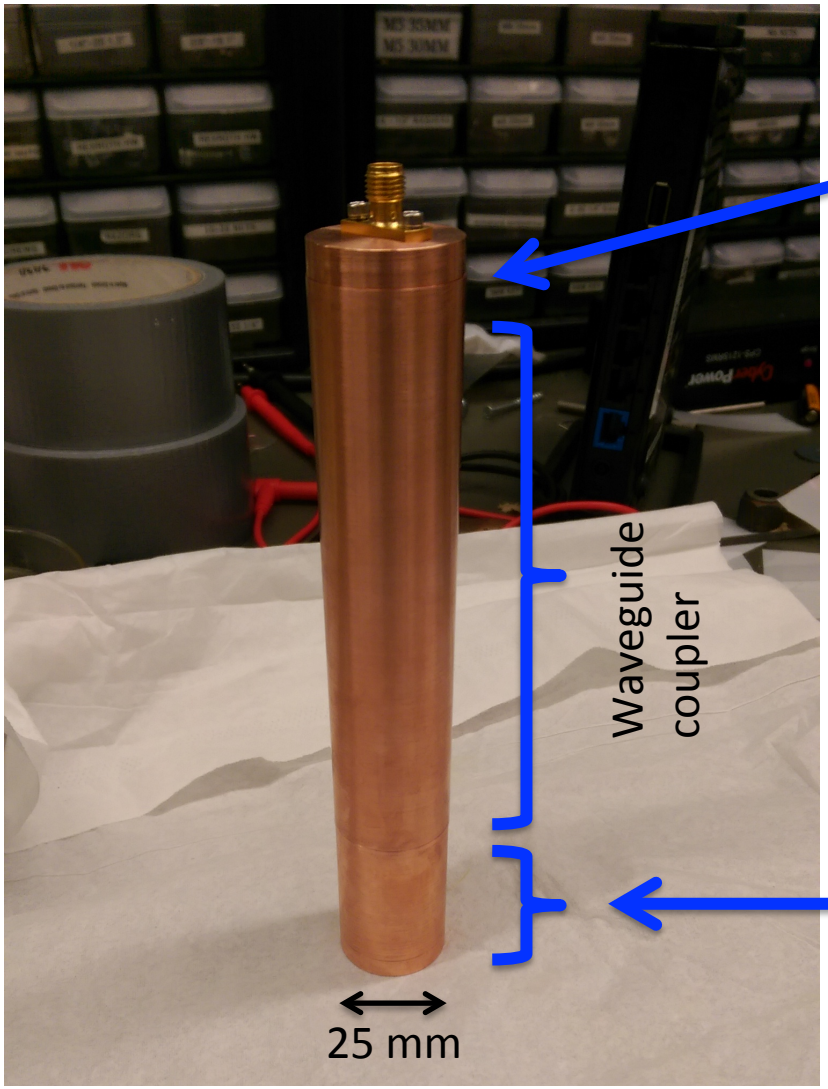
Akash Dixit (UC)

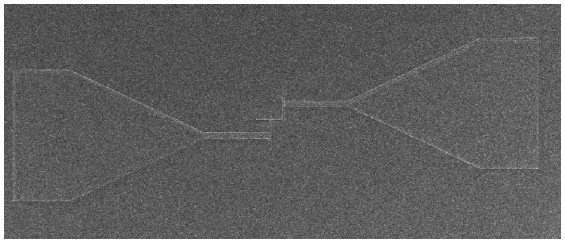




Scanning electron microscopy after Al deposition

Prototype for 10 GHz axion QND detector





Superconducting qubit in field-free bucking coil region acts as an **amplitude→frequency transducer** for QND measurements.

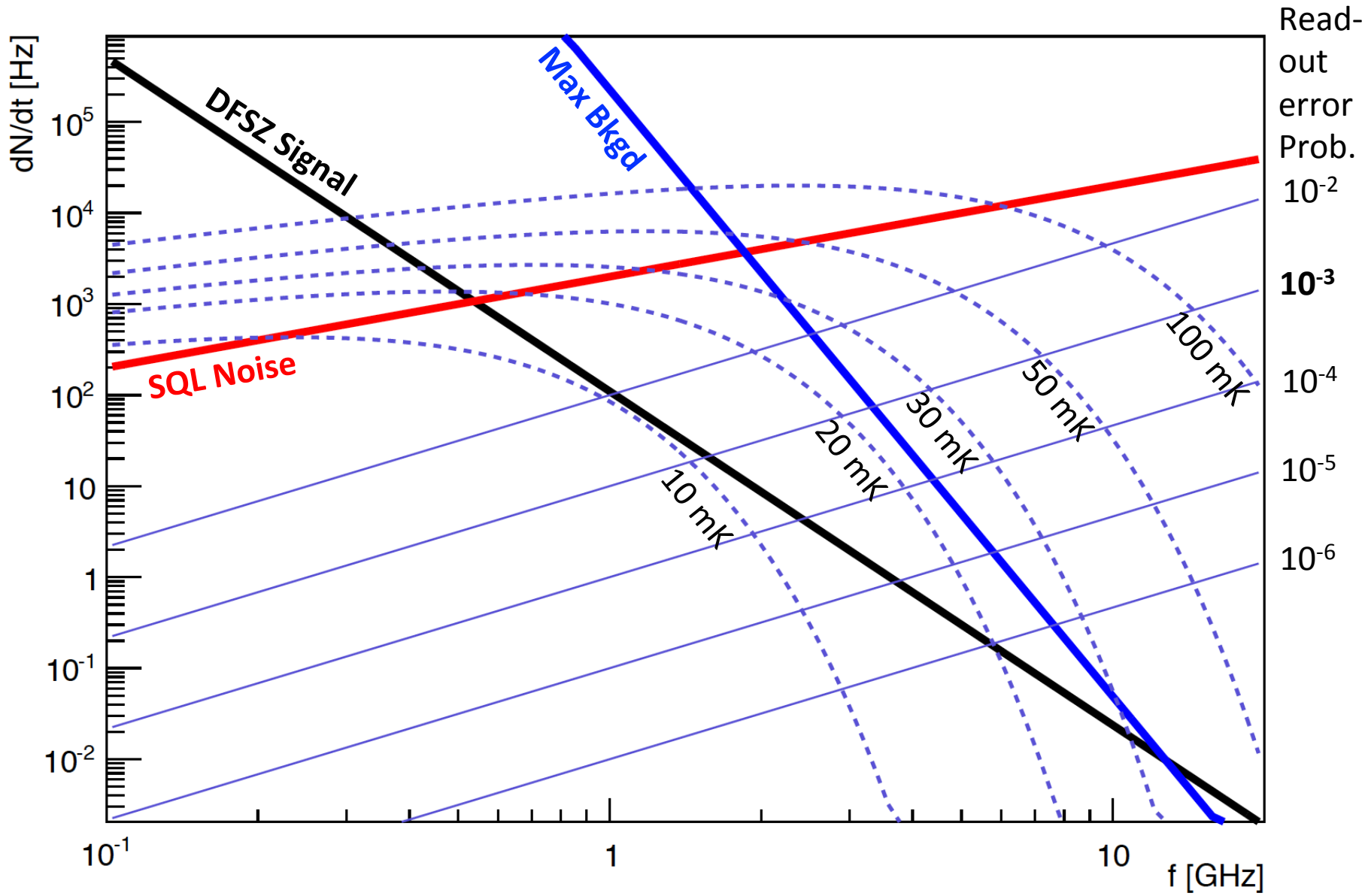
Qubit frequency shifts by 10 MHz per photon deposited in axion cavity. **Successful "spin-flip" of qubit confirms presence of cavity photon.**

Axion scattering cavity dipped into high B-field region

Akash Dixit, Aaron Chou, David Schuster (UC), R&D in progress.

Funded by Heising-Simons Foundation

Projected qubit sensor noise levels



Enabling technology transfer from quantum computing to HEP

Panel recommends new program to support collaboration between DOE-supported labs & non-DOE quantum scientists.

Led by OHEP Connections initiative

Also:
Heising-Simons Foundation,
Detector R&D funding,
LDRD funding

Aaro

A two-way street for technology transfer

- U.Chicago and other DOD-funded qubit researchers transfer high QE, low dark rate single photon detectors to HEP
  - This is possibly the enabling technology for future axion searches, neutrino mass measurements, etc.

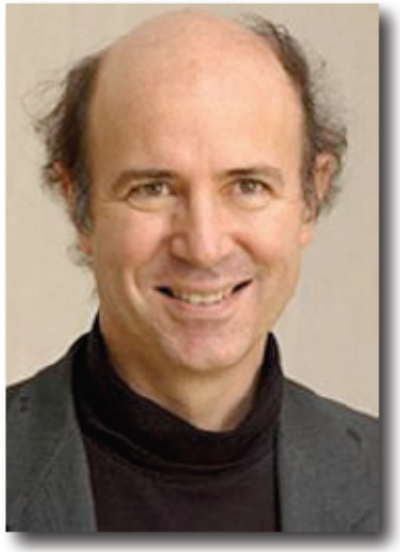
- Fermilab transfers SRF cavity processing techniques to quantum computing community to improve qubit lifetimes
  - **Could this be the enabling technology for quantum computing?**

Private foundation funding follows the guidance of VIPs

HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

"If the axion does not exist, please tell me how to solve the strong CP problem."
Frank Wilczek



"Axions may be intrinsic to the structure of string theory."
Ed Witten

Through current axion initiative, providing funding R&D for ADMX-G2, ADMX-HF, CASPEr.

(Including support for Chou's student Akash Dixit for qubit R&D, LLNL cavity workshops)

Take-aways

- Operating ADMX-G2 at lower frequencies will probe a unique and interesting range of axion masses and provide valuable experience for future projects.
  - **Science topics: neutron EDM, dark matter, scale of cosmic inflation**

- Next generation axion DM experiments should target the 10-20 GHz band and R&D in the next 3-5 years will be critical to determining the best techniques for improving the signal/noise ratio to enable the experiment.

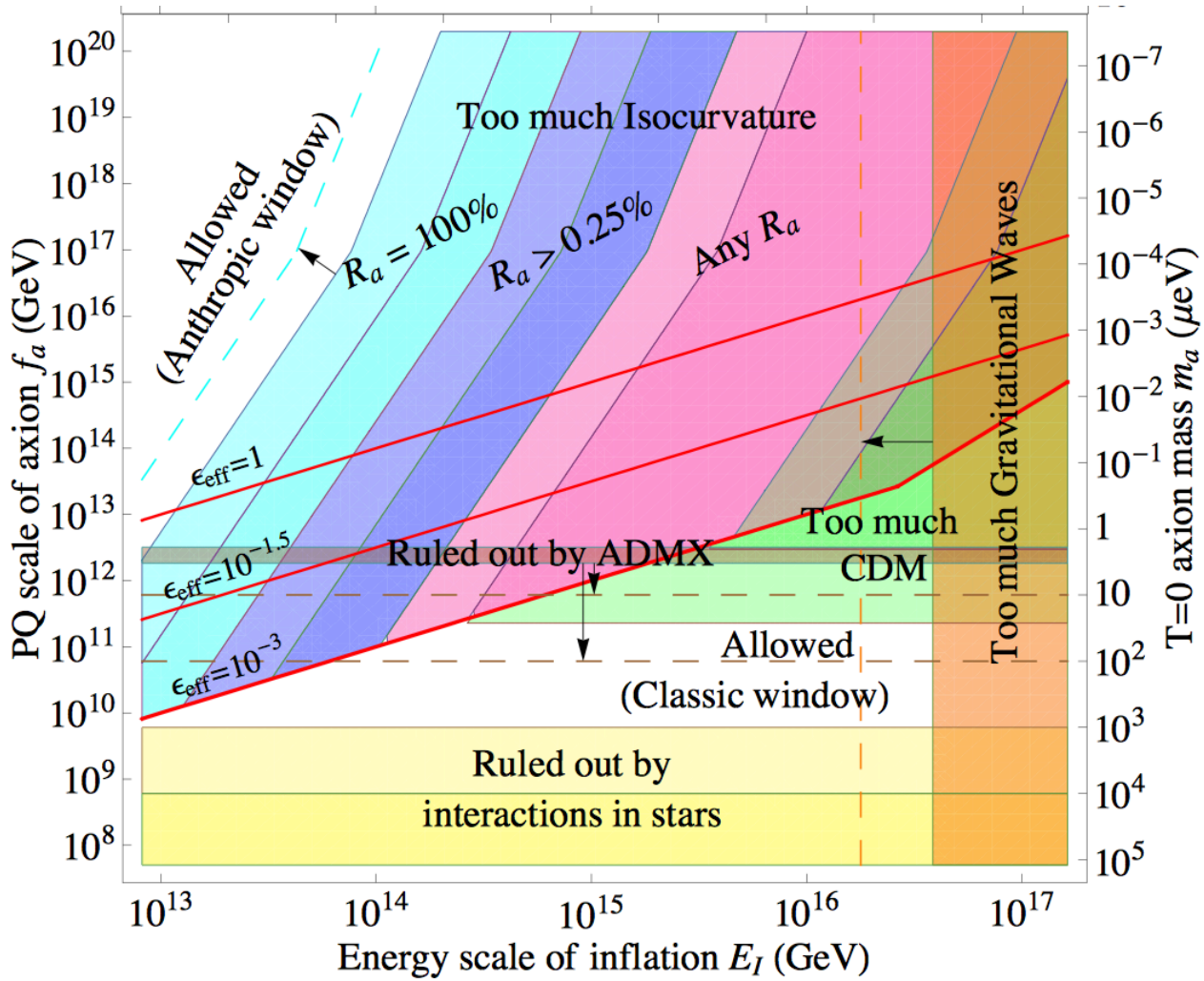
- Fermilab core competencies are well-suited to address the technical challenges:
  - High field superconducting magnets
  - High-Q, large volume RF cavities, cryostats,
  - Chicagoland expertise/infrastructure in superconducting electronics
    - The enabling technology may be the qubit-based single microwave photon detector (FNAL/LLNL/U.Chicago R&D collaboration)

Backup slides

Axions + cosmic inflation = CMB isocurvature

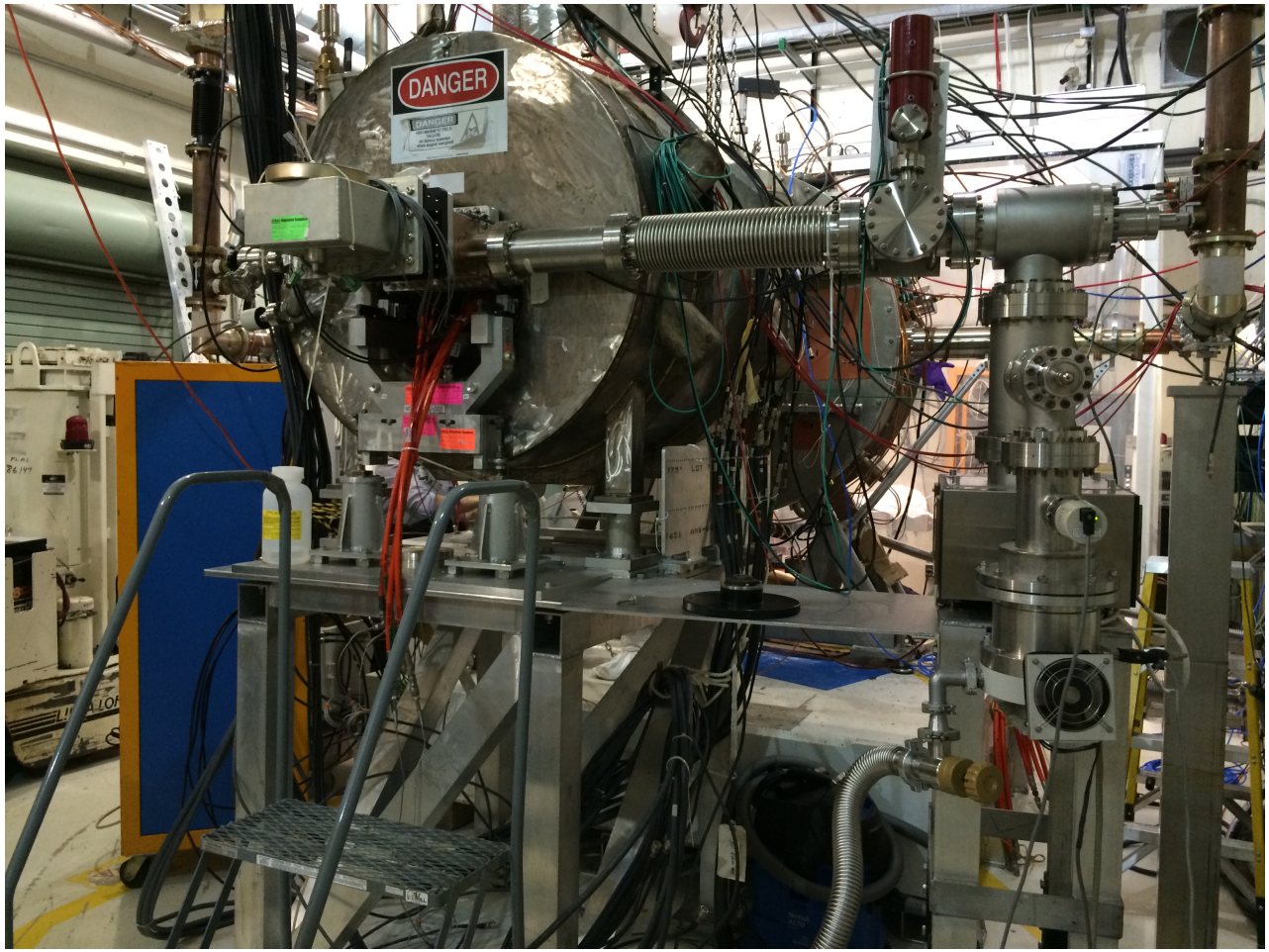
$\delta\theta^2 \approx H_I^2/f_a^2$ (Seckel & Turner, 1985)

Hertzberg, Tegmark, Wilczek (2010)



Inflation creates a spectrum of radiation in the form of gravitational waves and axionic waves (isocurvature perturbations in CMB). **Neither has yet been detected.**

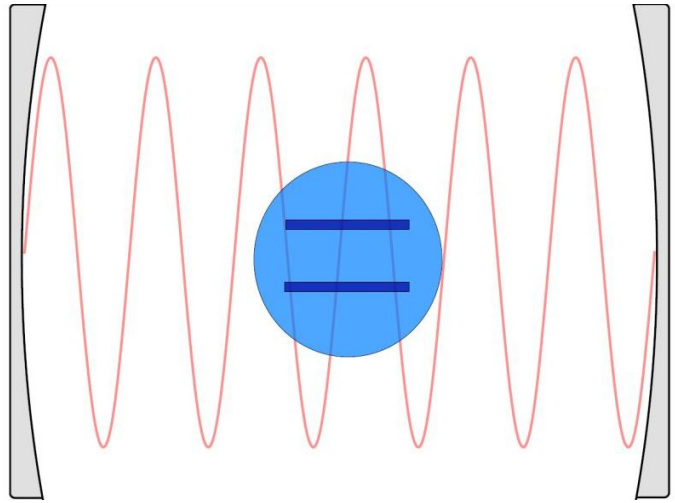
Fermilab's MuCool test stand is secretly an axion experiment



Copper RF cavity operated inside a superconducting 5T solenoid.
This looks just like a 800 MHz axion experiment.

Cavity QED:
Use 2-level atom to measure cavity photon population

Linear cavity
Bosonic oscillator,
Number operator = $a^\dagger a$



2-level "atom"
Fermionic oscillator,
Number operator = σ_z

The 1st order non-linearity in (number operator)^2 in the undiagonalized Hamiltonian is:

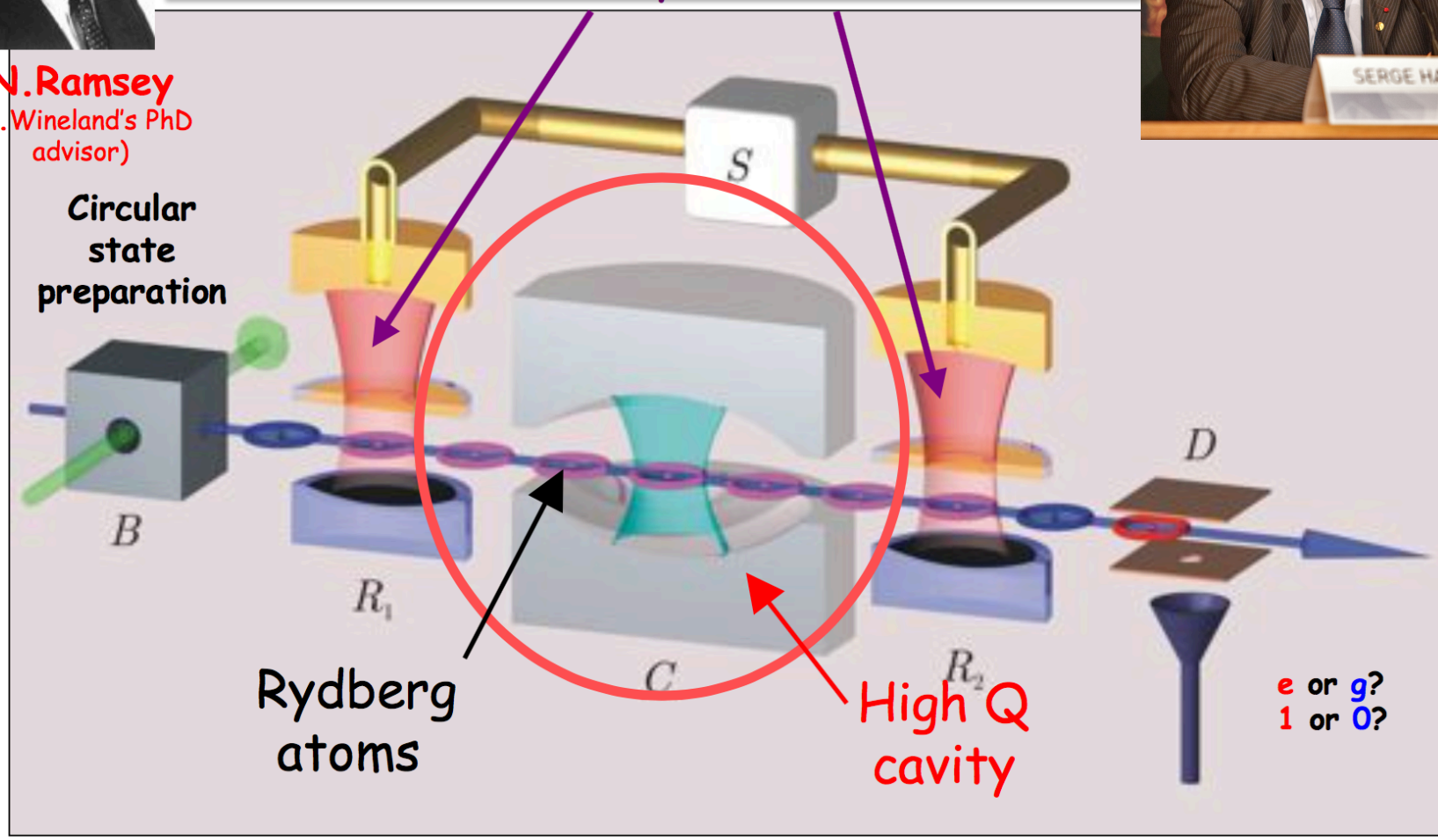
$$H \approx \hbar\omega_r \left(a^\dagger a + 1/2\right) + \frac{\hbar}{2}\left(\omega_a + \boxed{\frac{2g^2}{\Delta} a^\dagger a} + \frac{g^2}{\Delta}\right)\sigma_z$$

$\Delta = \omega_r - \omega_a$

The atom frequency depends on the cavity resonator's occupation number!
This product of number operators commutes with H and allows QND measurement.

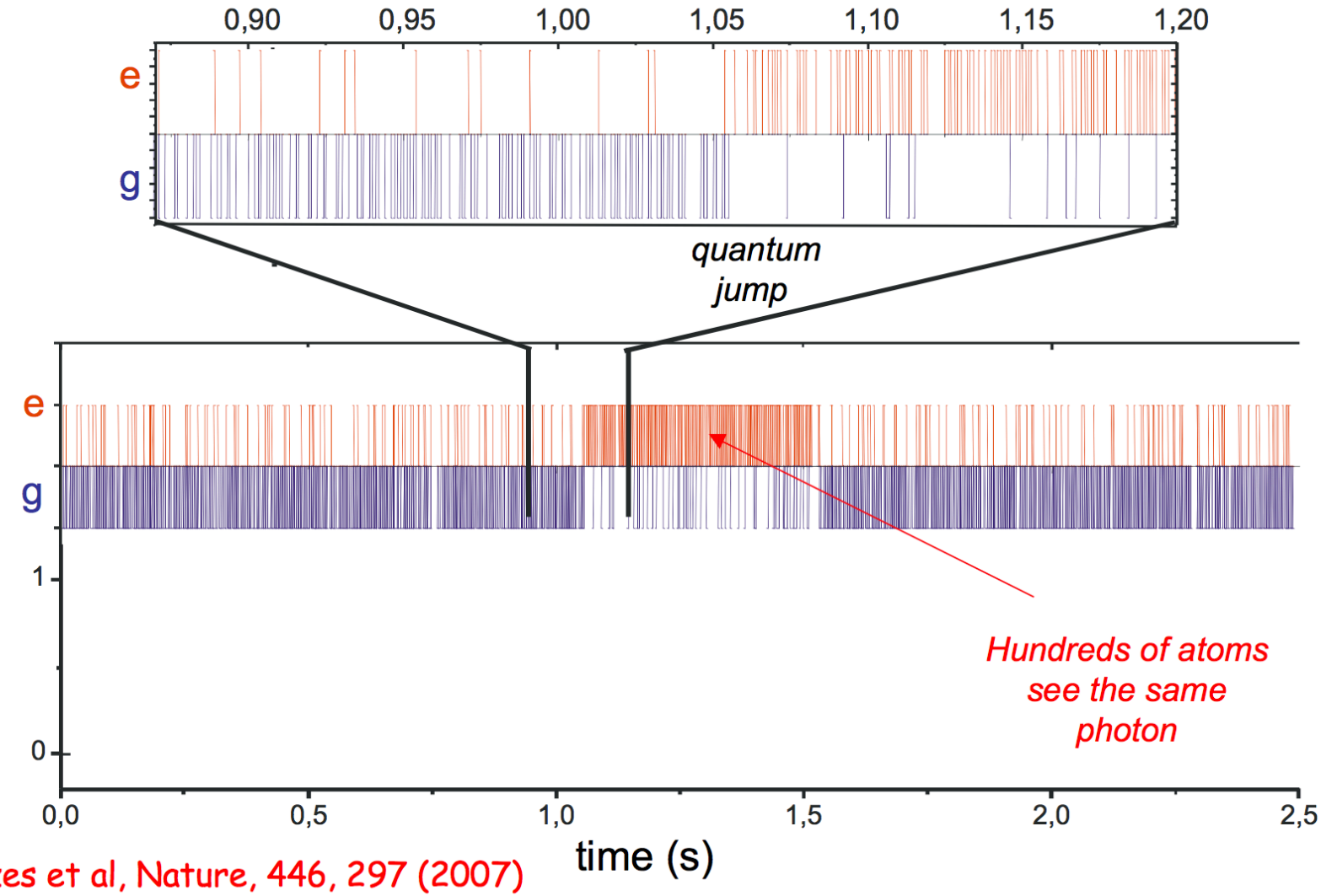
N.Ramsey
(D.Wineland's PhD advisor)

Serge Haroche 2012 Nobel Prize:
Atoms acts an amplitude→ frequency transducers.
They probe the cavity photon number without any net absorption of photons.
Analogous to neutrino "matter effects."



An atomic clock delayed by photons trapped inside

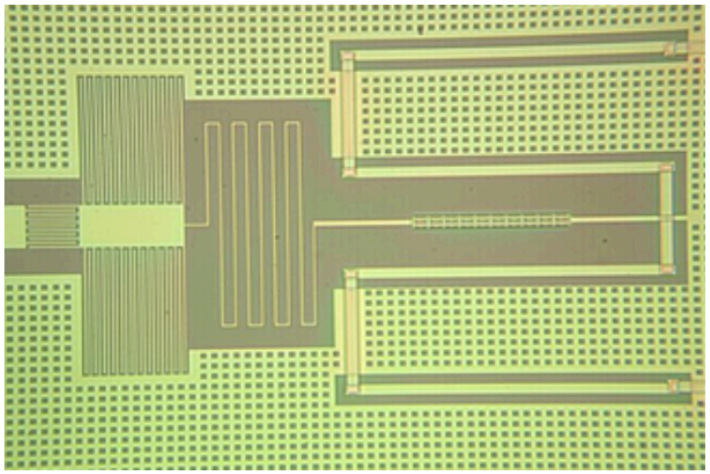
Birth, life and death of a photon



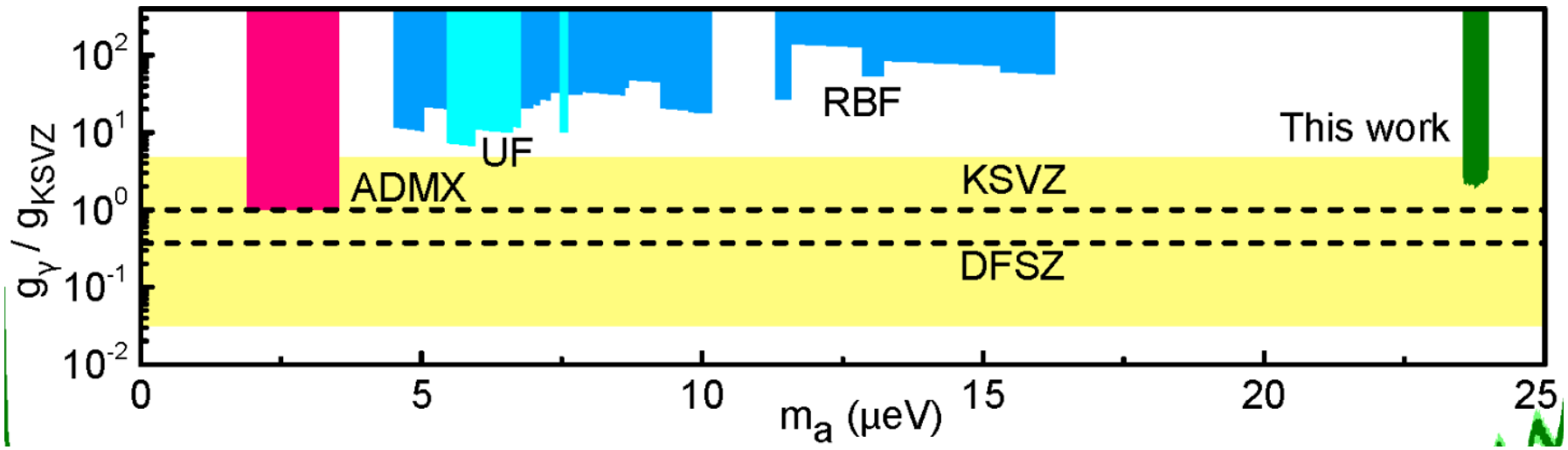
S.Gleyzes et al, Nature, 446, 297 (2007)

Other on-going axion DM R&D efforts

- ADMX-HF (NSF, Heising-Simons)
  - Goal: demonstrate operability of quantum-limited Josephson parametric amplifier near large magnetic field. Not quite there yet.
  - Strategy: purchase larger magnet to enable axion search at ~6 GHz

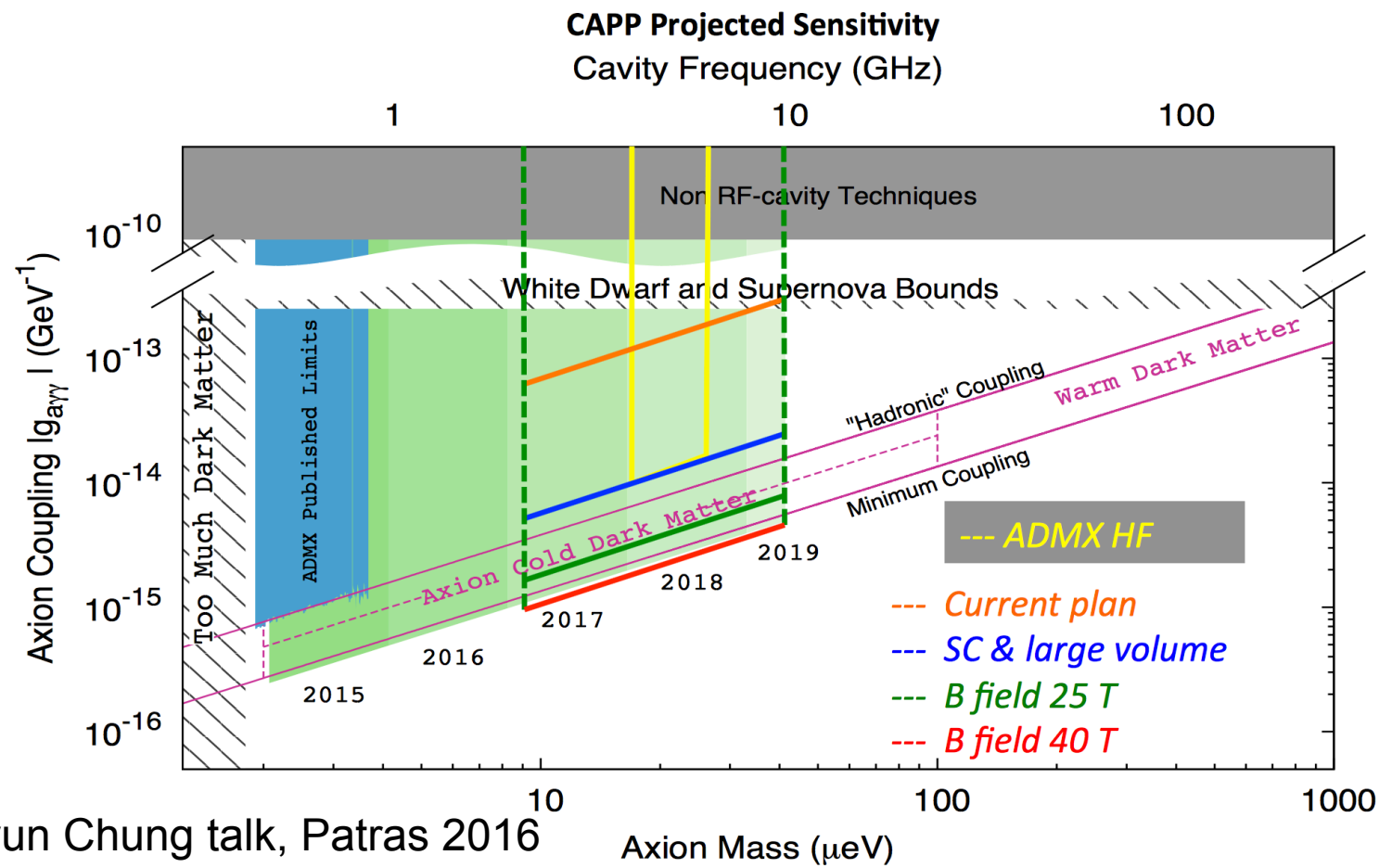


arXiv:1610.02580



Other on-going axion DM R&D efforts

- CULTASK (Center for Axions and Precision Physics, IBS South Korea)
  - Goal: explore all possibilities for exploring 2-10 GHz mass range
  - Status: Purchased 2 dilution refrigerators, small magnet to obtain operational experience



Woohyun Chung talk, Patras 2016