Low Energy Particle Physics With Microwaves

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Outline

- Microwave Review
- ADMX Experiment
  - Dark Matter Axion Search
  - Chameleons Search
  - Hidden Sector Photon Search
- Project 8 Experiment

Microwave Scales

Length: 1 meter – 1 millimeter

Frequency: 300 MHz – 300 GHz

Photon Energy: 1 μeV – 1 meV

Why Microwaves?

Exquisite Power Sensitivity

Precision Frequency Measurement

Power Sensitivity

Radiometer Equation:

$$noise = k_B T \sqrt{\frac{B}{t}}$$

Boltzmann's constant

bandwidth (Hz)

Temperature (K)

Integration time (s)

For example, at room temperature, a minute of integration on a 1 Hz wide signal is sensitive to powers of 10^{-21} Watts

(1 zeptowatt)

There are electronics and quantum limitations to this, I'll touch on that later

ADMX

Axion **D**ark **M**atter e**X**periment

University of Washington
LLNL
University of Florida
UC Berkeley
NRAO
Sheffield University

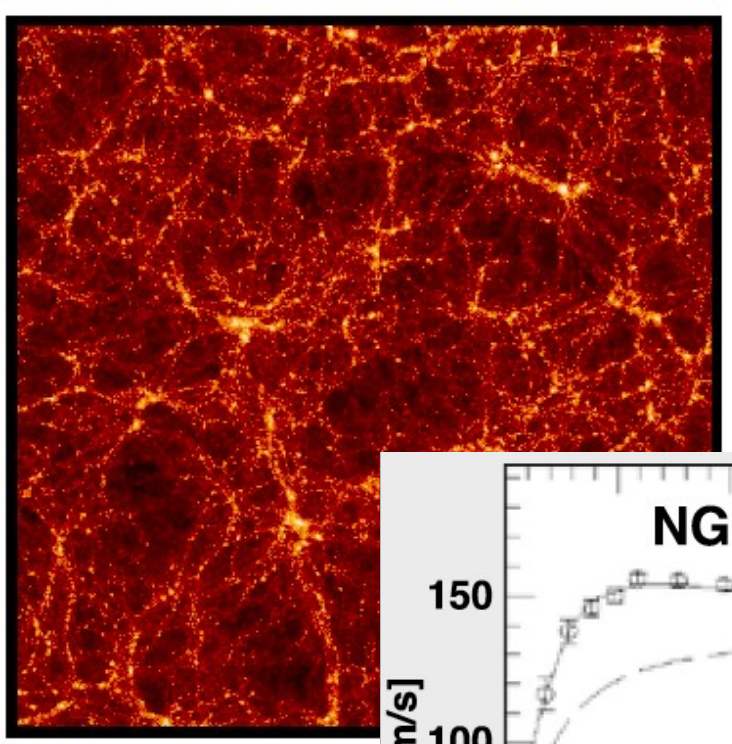
Using microwave technology to probe low energy, weakly coupled particle physics

ADMX Axion Search

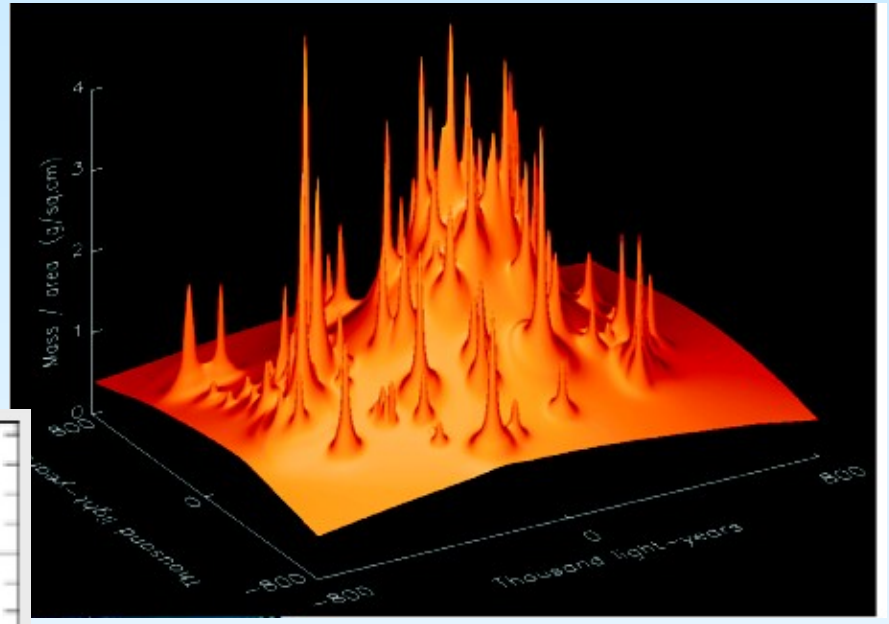
ADMX's primary mission

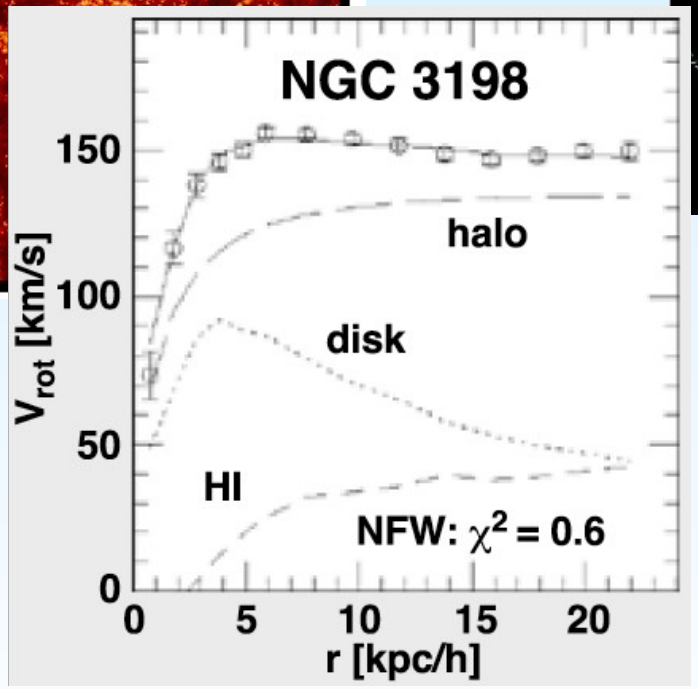
Dark Matter

Model growth of structures



Lensing of background objects as a probe





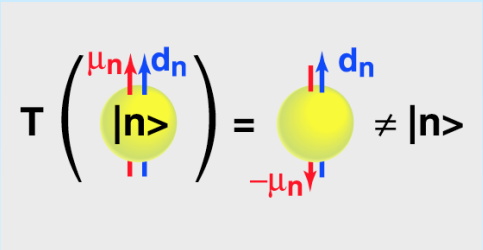
Dynamics

Observations at all scales provide compelling evidence for dark matter, but its nature remains a mystery

Axions

The Strong CP Problem

Lack of neutron electron dipole moment indicates strong force is CP invariant



edm<3·10^{-26} e-cm
Baker et al.
PRL 97 2006

How can the weak force be CP violating but the strong force remains CP invariant? O(10^{-10}) cancellation required

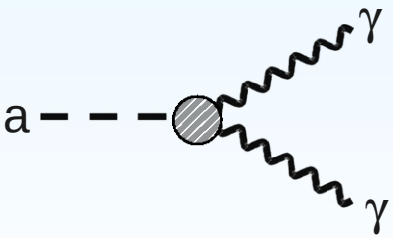
The Peccei-Quinn Solution

Add a dynamic field, spontaneously broken, which cancels any strong CP violation

This results in a new pseudo-goldstone boson, the Axion

-Weinberg, Wilczek

Has a photon coupling

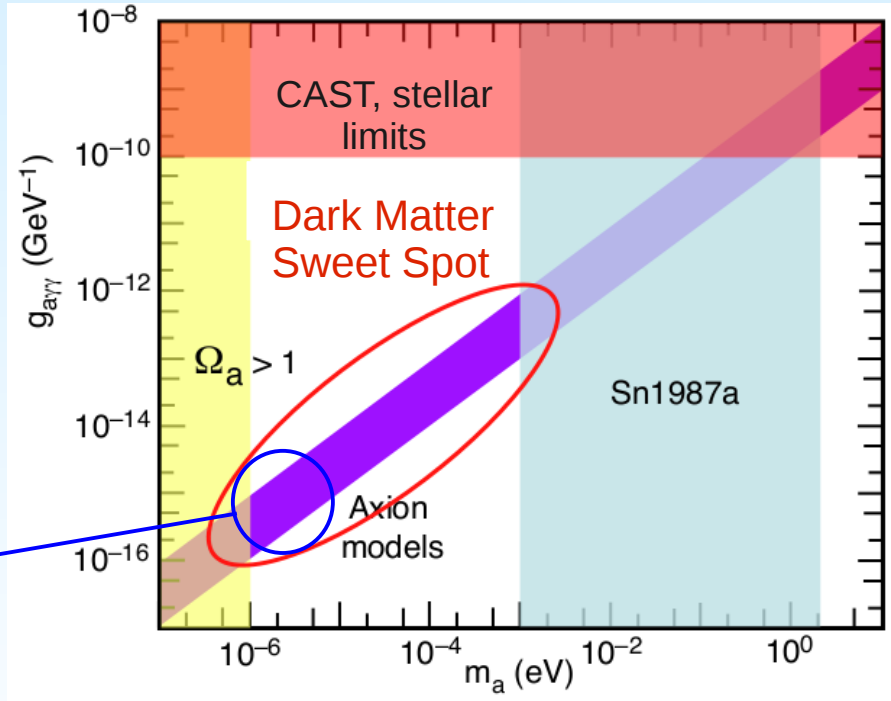


Axions as Dark Matter

When Peccei-Quinn symmetry is broken, a large number of axions are produced. (Vacuum misalignment mechanism)

With the right conditions, this makes enough Axions to account for dark matter

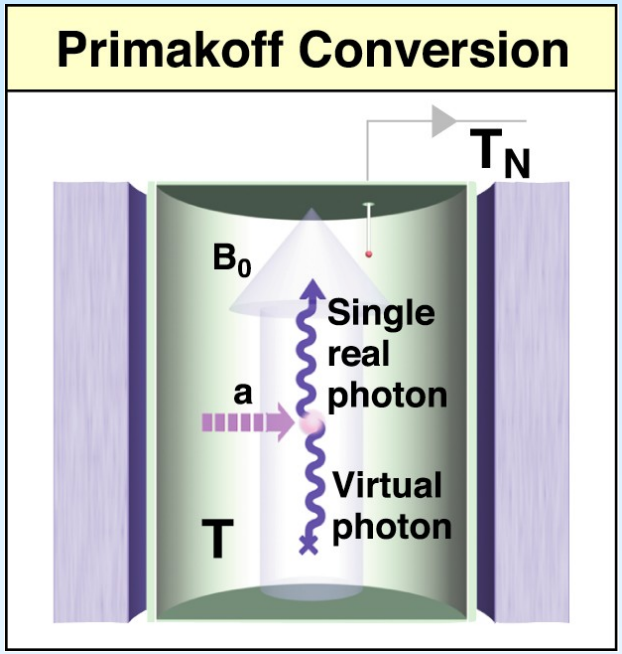
m_a<1 μeV
Makes too much
Dark Matter



ADMX
Target Region

m_a>1 meV
Disfavored
by SN1987a

Axion Haloscope



Dark Matter Axions will convert to photons in a magnetic field.

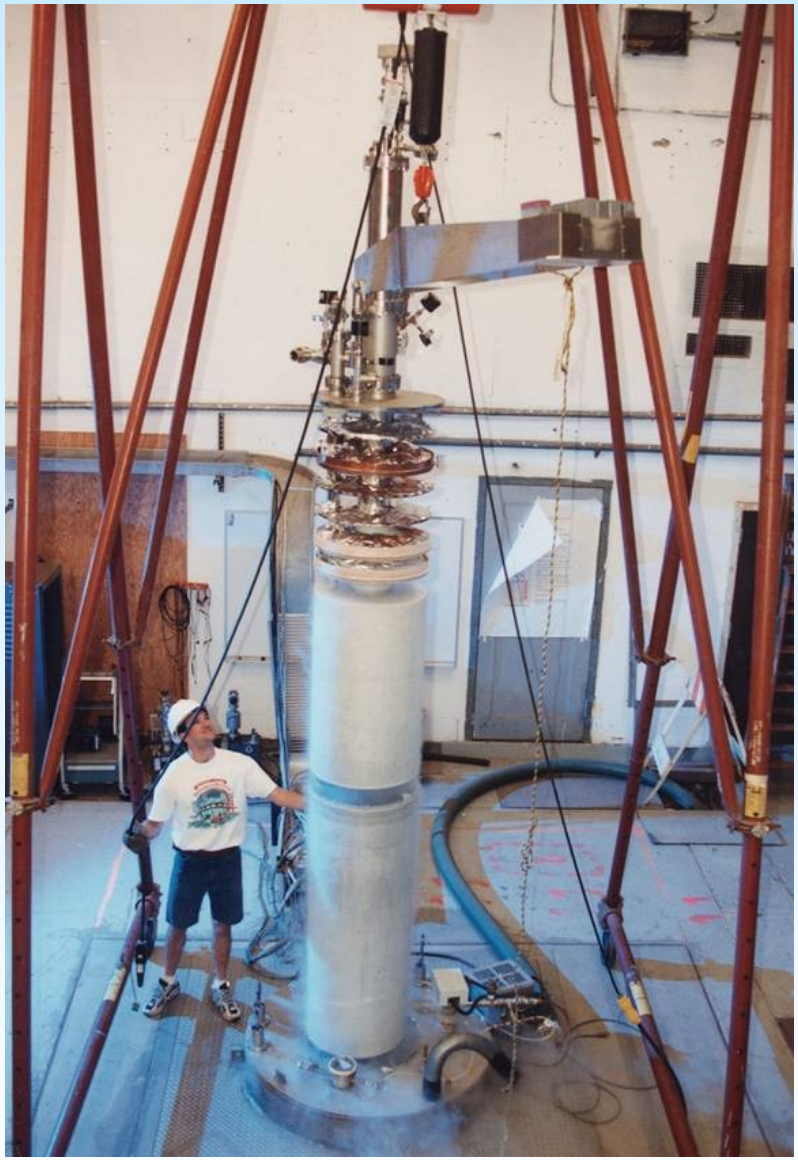
The measurement is enhanced if the photon's frequency corresponds to the cavity's resonant frequency.

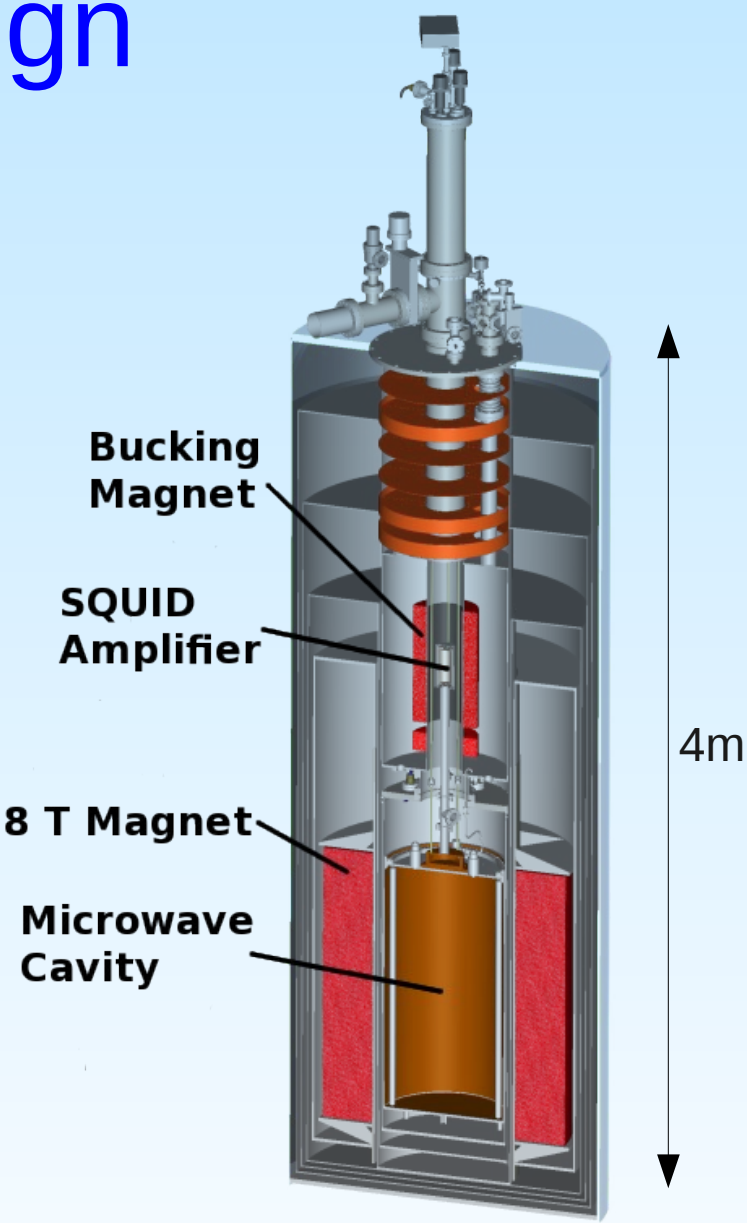
See: Sikivie, Phys. Rev. Lett. 1983

You Want:
-Large Cavity Volume
-High Magnetic Field
-High Cavity Q

You Don't Want:
-High Thermal Noise
-High Amplifier Noise

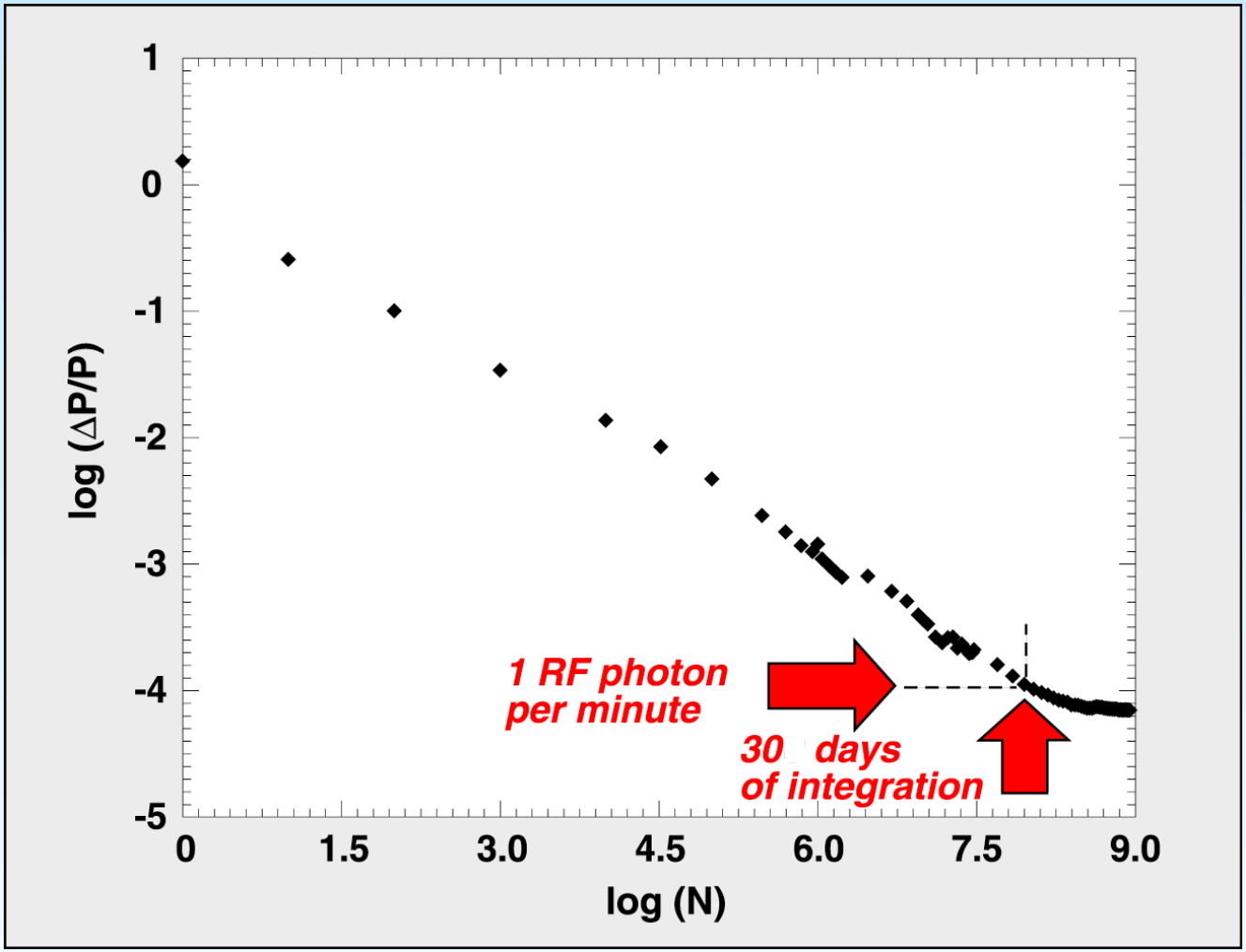
ADMX Design





Cavity Frequency changed by moving metal rods (not shown) inside cavity

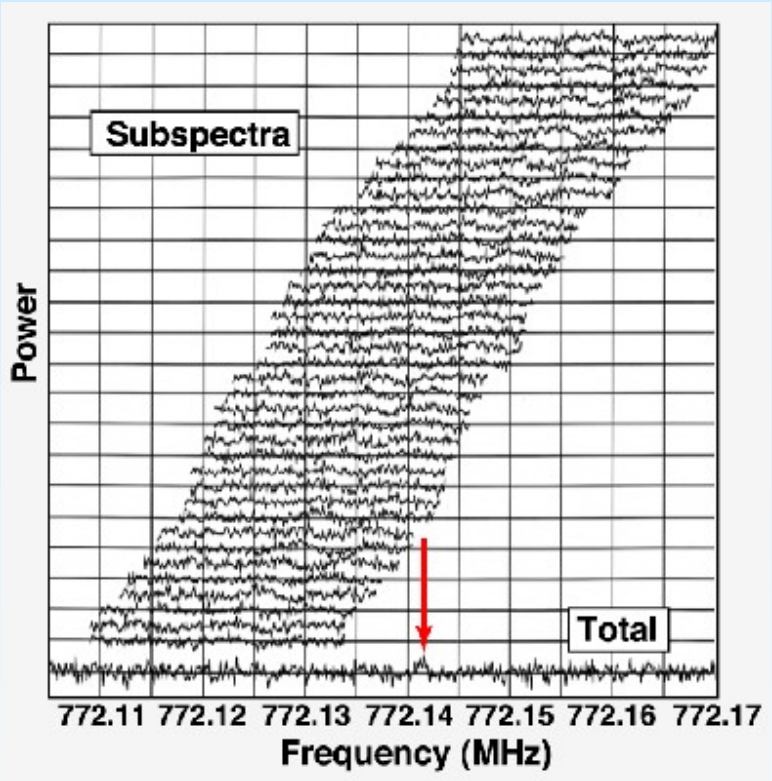
ADMX Power Sensitivity



Power sensitivity to 1/100 Yoctowatt

Systematics limited only after 1 month integration

Scanning for Axions



ADMX Has demonstrated the power sensitivity needed to detect axions, but we need to explore phase space on a realistic timescale

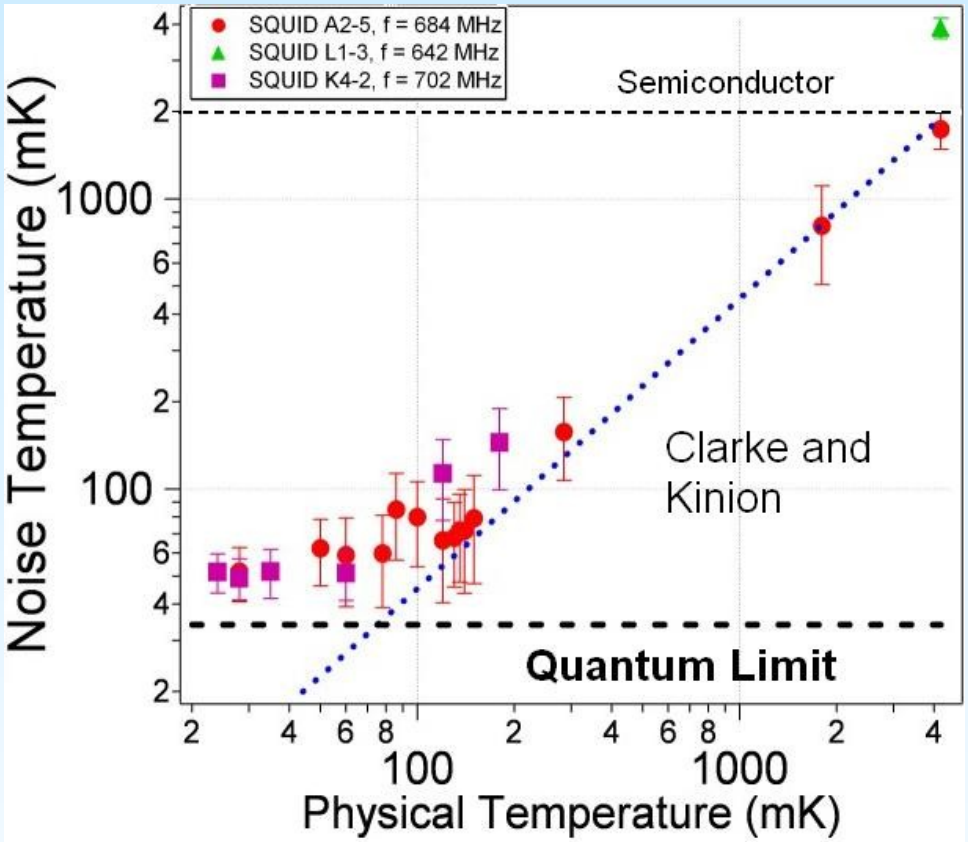
Power spectra are 25 kHz wide. Cavity is tuned and power spectra are averaged. Axions would appear as excess power peaks

$$noise = k_B T \sqrt{\frac{B}{t}}$$

For a fixed SNR, a factor of 10 lower temperature lets us spend 1/100th the time on each subspectrum, so we scan 100 times as fast

ADMX SQUID

The ADMX SQUID is all about lowering the noise temperature



Semiconductor Limit: 2 K

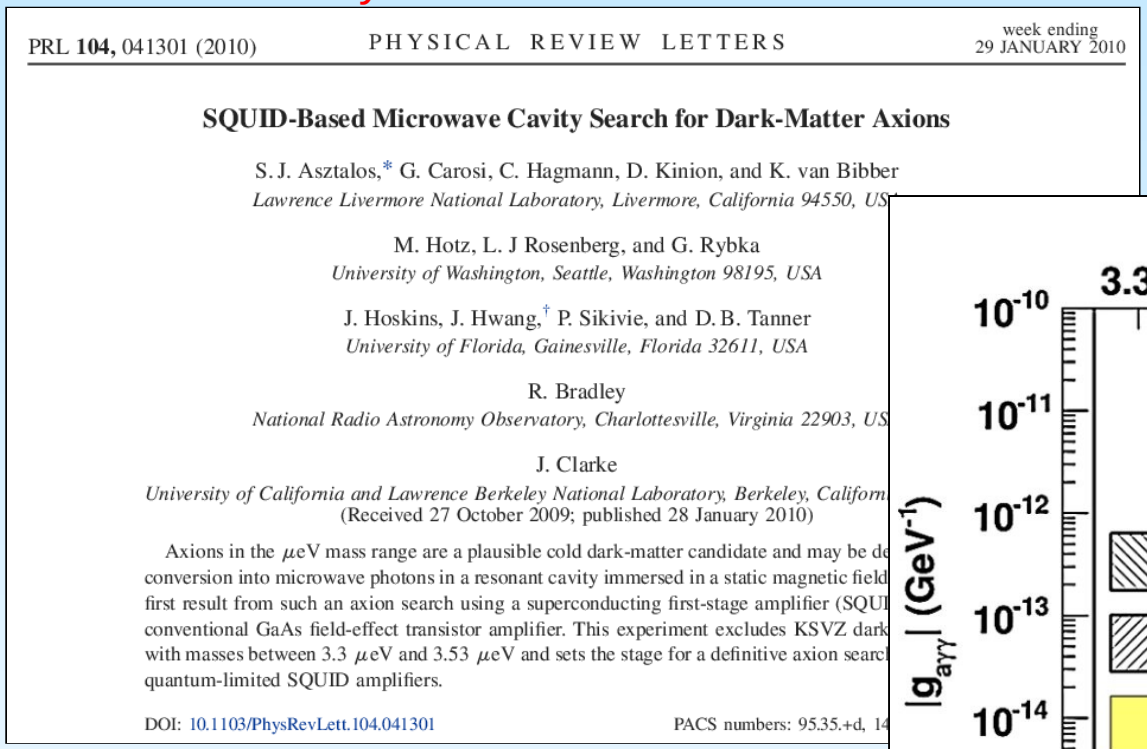
(2009) Amplifier Noise Temperature: 1K

SQUID limit: 50 mK (Planned 2013)

With the SQUID, noise is limited only by physical temperature, down to 50 mK

Recent Results

DOI: 10.1103/PhysRevLett.104.041301



PRL **104,** 041301 (2010) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2010

SQUID-Based Microwave Cavity Search for Dark-Matter Axions

S. J. Asztalos,* G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber
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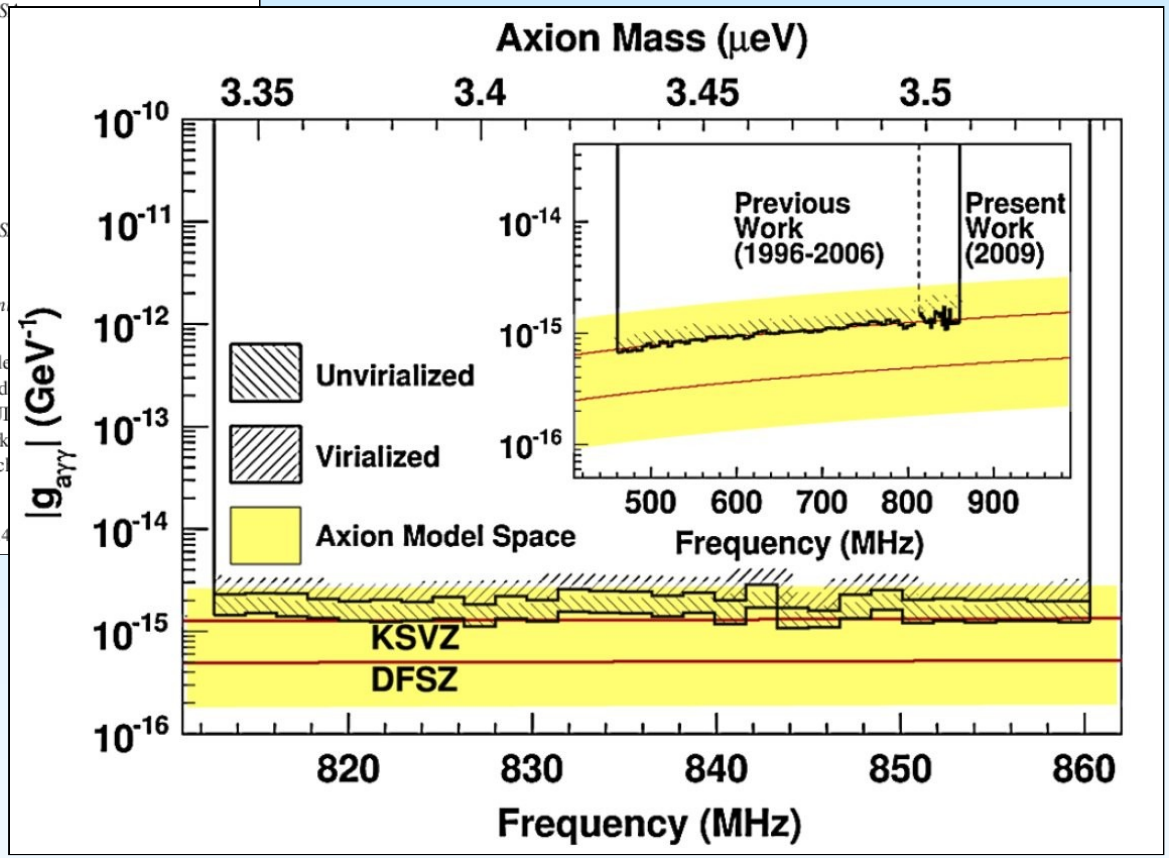
(Received 27 October 2009; published 28 January 2010)

Axions in the μeV mass range are a plausible cold dark-matter candidate and may be de conversion into microwave photons in a resonant cavity immersed in a static magnetic field first result from such an axion search using a superconducting first-stage amplifier (SQUI conventional GaAs field-effect transistor amplifier. This experiment excludes KSVZ dark with masses between 3.3 μeV and 3.53 μeV and sets the stage for a definitive axion searc quantum-limited SQUID amplifiers.

DOI: 10.1103/PhysRevLett.104.041301 PACS numbers: 95.35.+d, 14

Excludes optimistically coupled axions over 48 MHz



Covered 812 – 860 MHz = 48 MHz

Total Run Time: 19 months

Continuous Data Collecting: 8 months

SQUID Amplifier operational (shielded) in high field region

860-890 MHz data yields similar limit, publication in progress

The Next Phase

There is still much to be done

We have not covered the axion mass range.

We have not excluded all reasonable axion models.

We want a definitive search: are Axions Dark matter, or aren't they?

Phase 2 Plan in a Nutshell

Drop temperature 4K -> 100 mK

Scan over masses faster

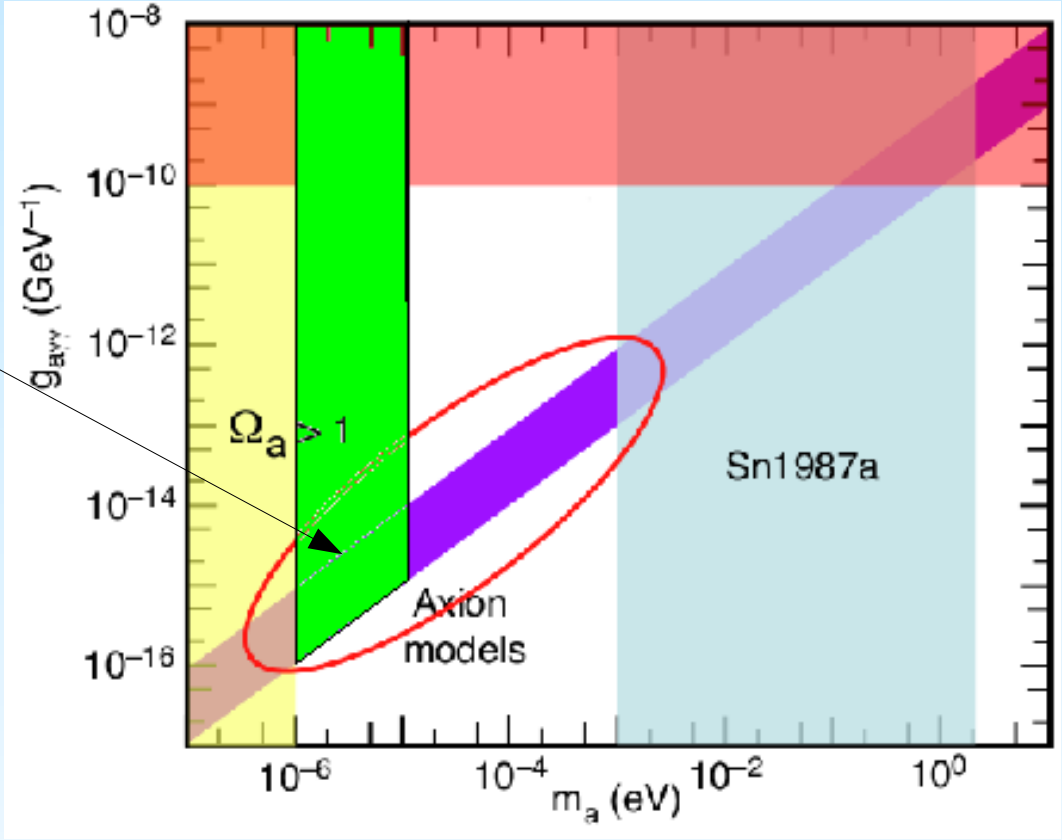
Be sensitive to pessimistic models

“Phase 2” Targets

Goal: first decade of axion mass, with pessimistic couplings

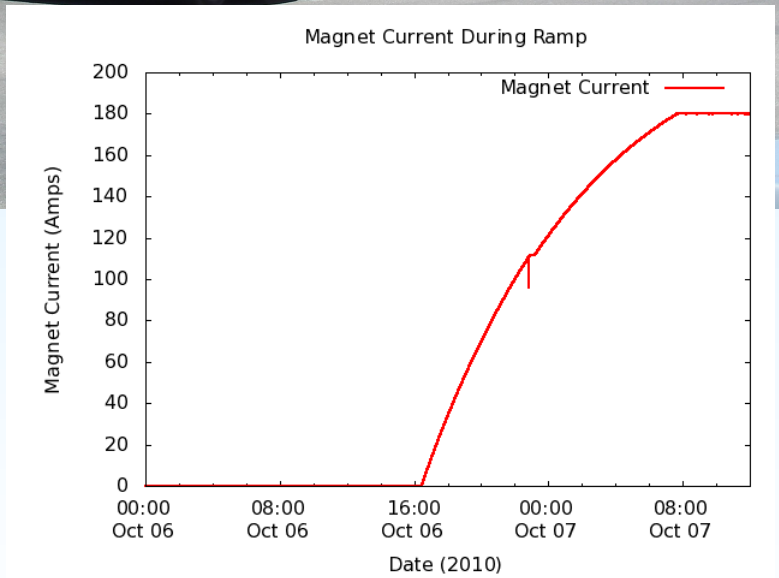
Timescale: ~1 year of continuous running

Target start date: ~2014 (funding permitting)



Higher masses require cavity R&D, but have no fundamental roadblocks

ADMX moved University of Washington



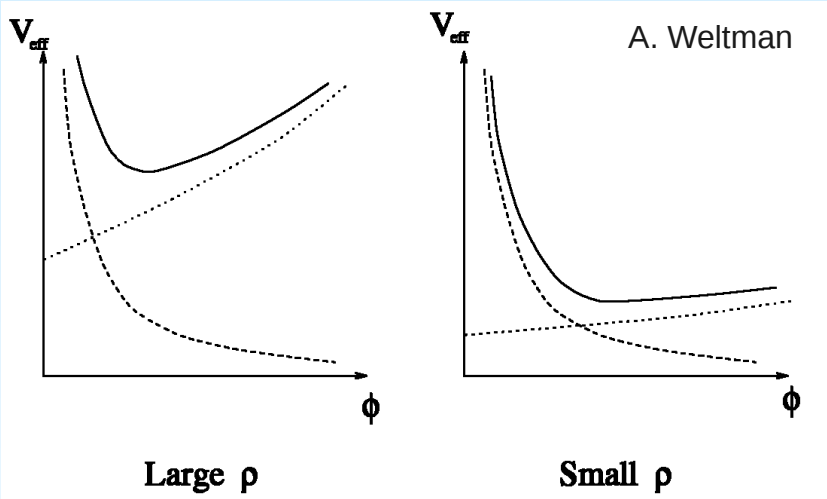
ADMX Scalar Chameleon Search

Axions aren't the only game in town

Chameleons

What they are

Exotic particle with nonlinear self coupling
Effective Mass depends on local energy density



For example:

$$V(\phi) = \Lambda^{\varepsilon} e^{\Lambda^{\varepsilon+n}/\phi^{\varepsilon}} + \frac{\beta}{M_{Pl}} \phi F^{\mu\nu} F_{\mu\nu}$$

Khoury and Weltman, PRL 93.171104 (2004)

Why do we care?

Candidate for dark energy

Laboratory Chameleon Search Technique

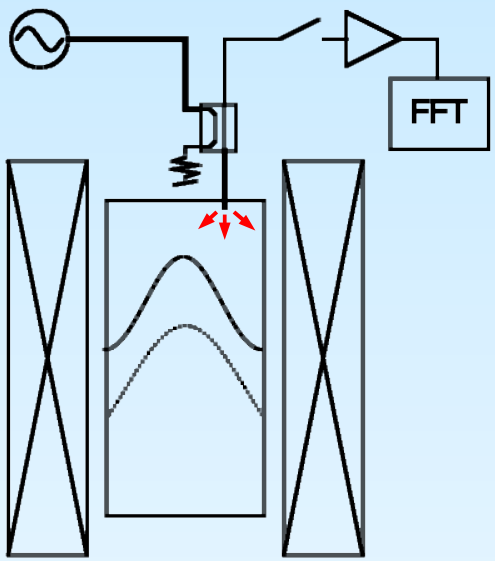
Suppose a chameleon has the properties:

- Large mass in solid matter ← Necessary to avoid short-range gravity deviations
- Small mass in vacuum ← Both model and experiment dependent
- Couples to photons

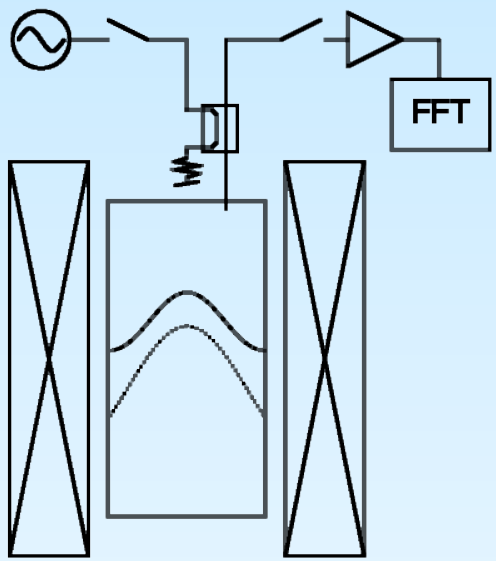
One might see them with this type of experiment

1) Put photons in a box
2) Photos mix with chameleons
3) Remove the photons from the box
4) Look for the “afterglow” produced as chameleons mix back Into photons

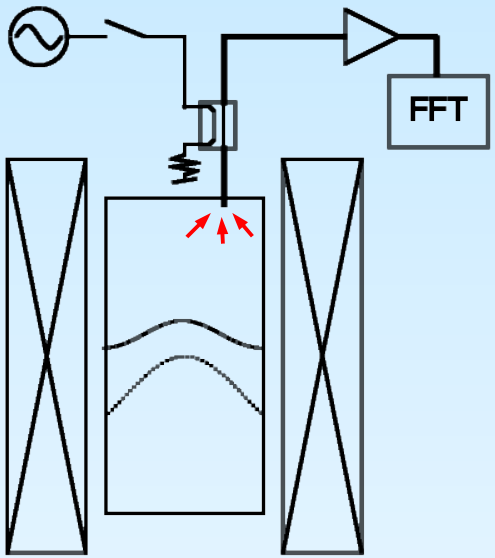
ADMX as a chameleon-photon regenerator



Step 1: Injected RF power excites E&M and chameleon modes



Step 2: Power is turned off, E&M modes decay



Step 3: Chameleon modes slowly decay into E&M modes which are detected through antenna

Timescale: 10 minutes

Power in ~25 dBm

Timescale: 100 milliseconds

Timescale: 10 minutes

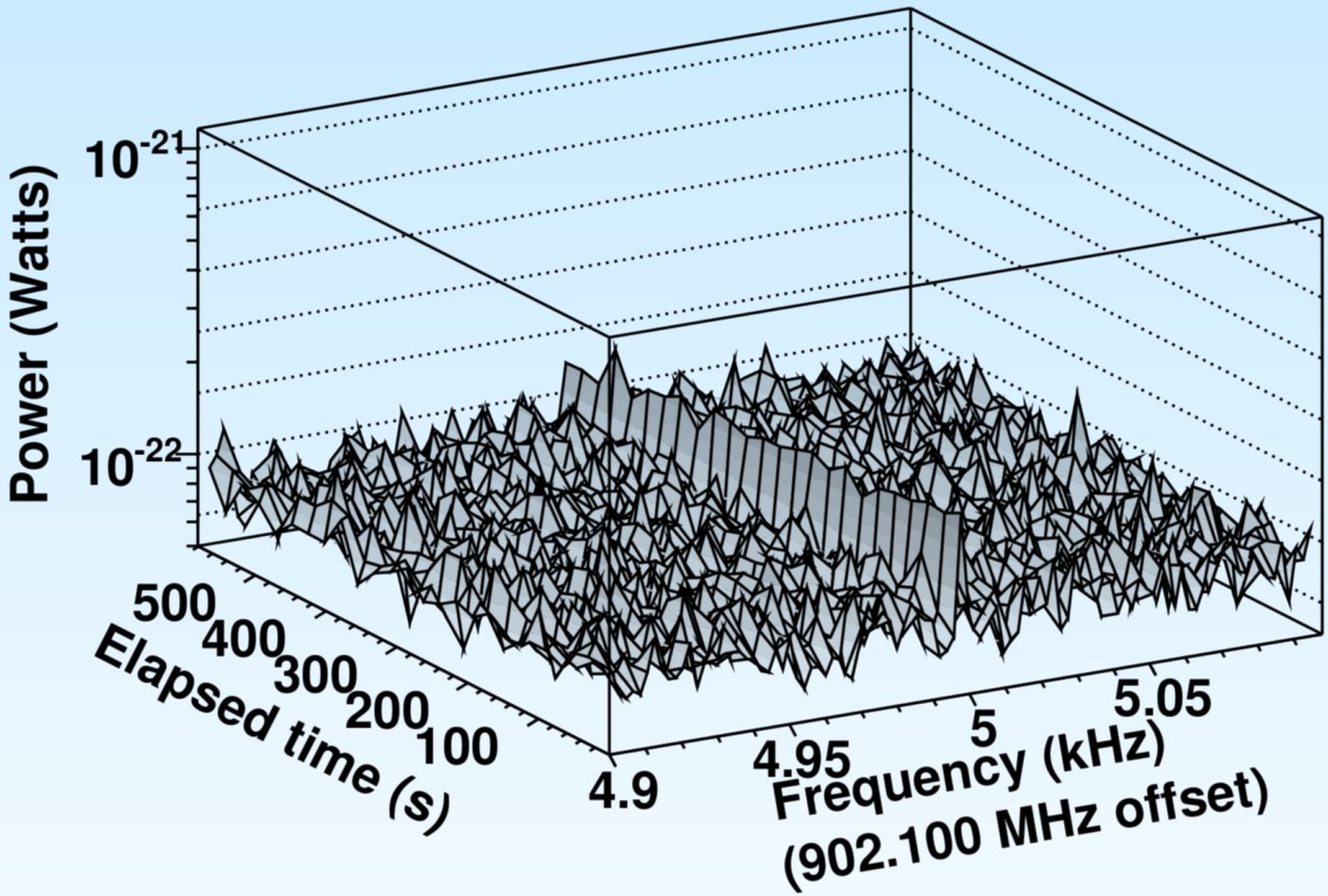
Sensitivity ~10^{-22} W

Bandwidth ~20 kHz

(Step 4: tune rods ~10 kHz and repeat)

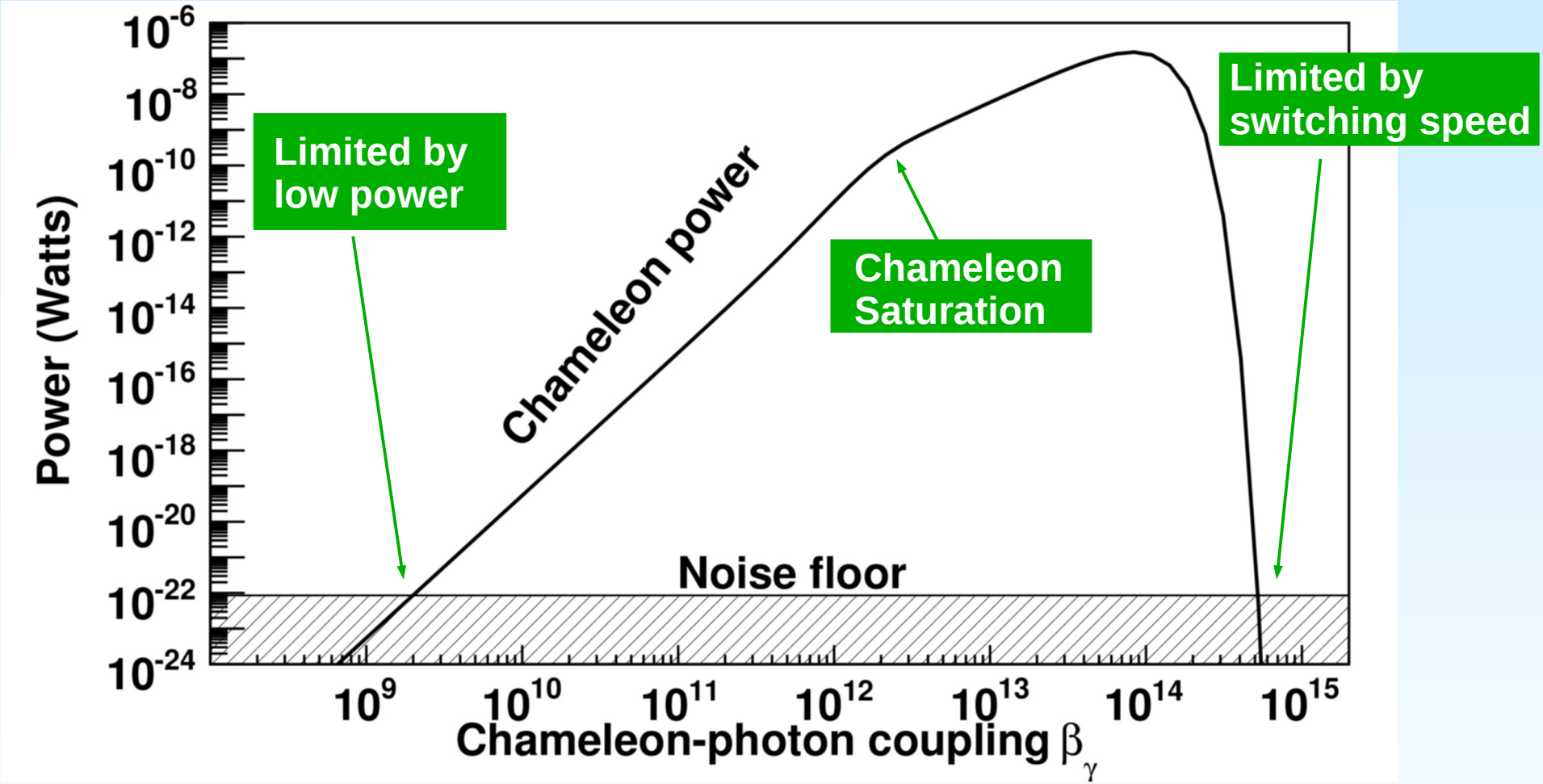
Total Run Time: 1 Day

Simulated Chameleon Signals



Simulated signal with $\beta_y = 2 \cdot 10^{-9}$

Chameleon Sensitivity



Results

PRL **105,** 051801 (2010) PHYSICAL REVIEW LETTERS week ending 30 JULY 2010

Search for Chameleon Scalar Fields with the Axion Dark Matter Experiment

G. Rybka, M. Hotz, and L. J Rosenberg
University of Washington, Seattle, Washington 98195, USA

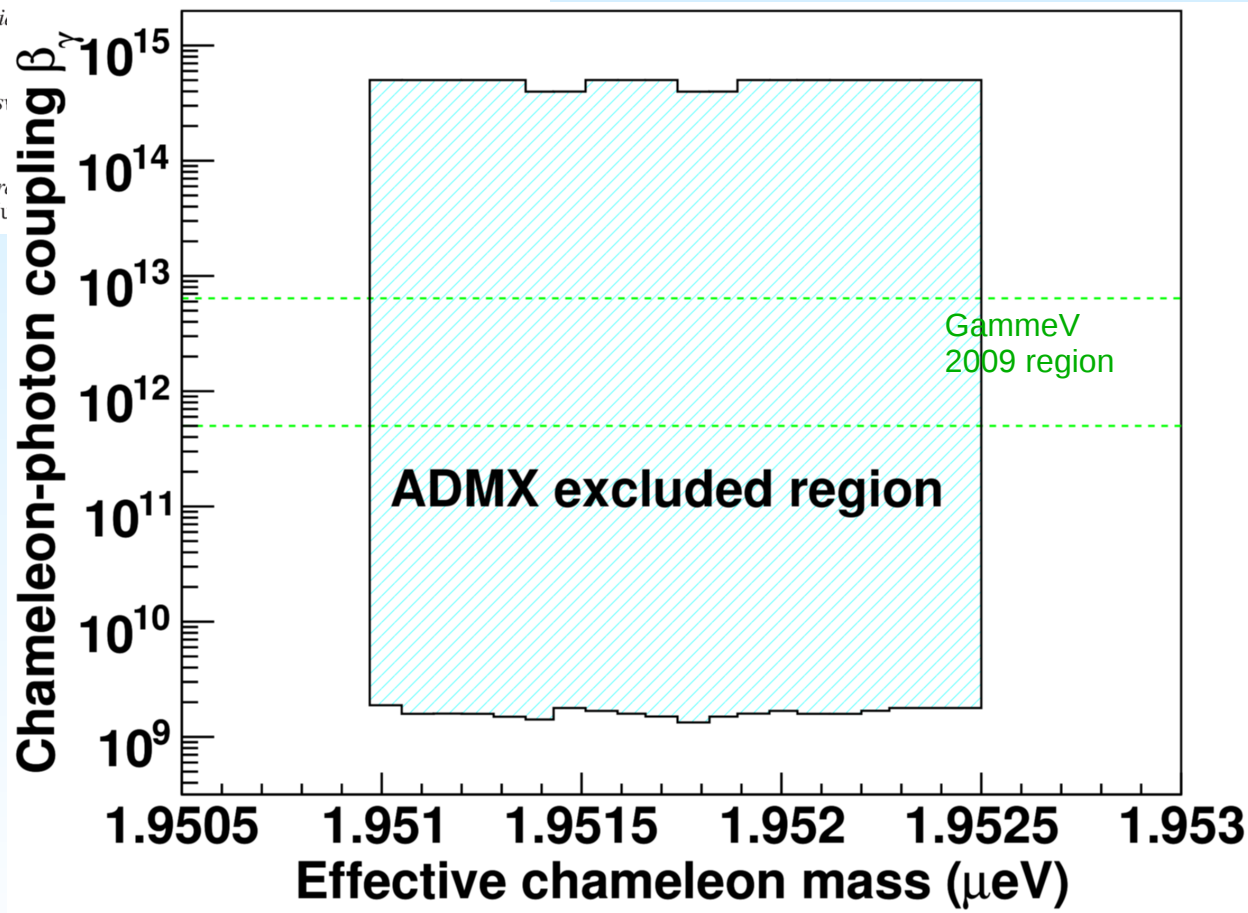
S. J. Asztalos,* G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber†
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

J. Hoskins, C. Martin, P. Sikivie, and D. B. Tanner
University of Florida, Gainesville, Flori

R. Bradley
National Radio Astronomy Observatory, Charlottes

J. Clarke
University of California and Lawrence Berkeley National Labor
(Received 26 April 2010; revised manuscript received 28 Ju

5 orders of magnitude in coupling



Caveats:

Setup dependent "effective mass"

Assumes chameleon containment

Cavity Searches in Context

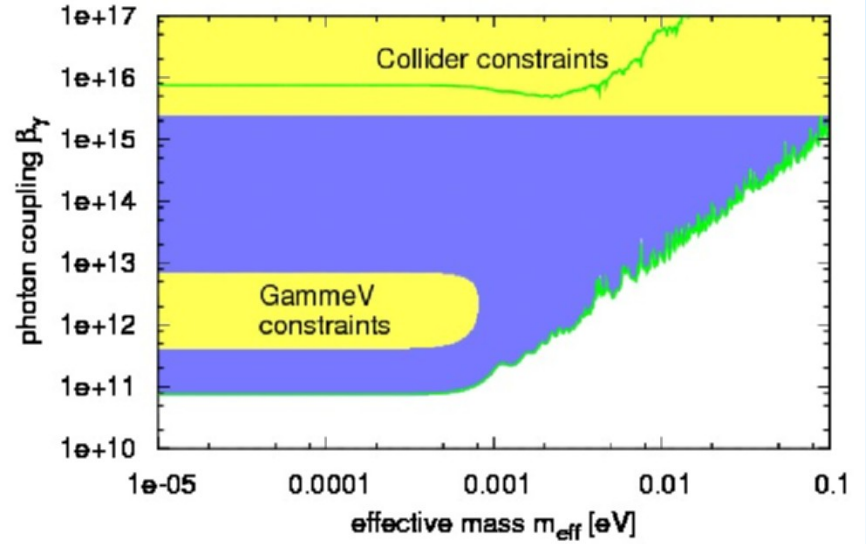
ADMX Mass Search Range (1 day of running): 10^{-9} eV

Gammev/Chase Search Range (4 days of running): 10^{-3} eV

ADMX can get more sensitive to coupling, but won't run any faster

Good news for Fermilab!

Without a precise theoretical prediction, CHASE will find chameleons long before cavity searches



Steffen et al. arxiv:1010.0998

(Though cavities may be able to measure their properties more precisely)

ADMX Hidden Sector Photon Search

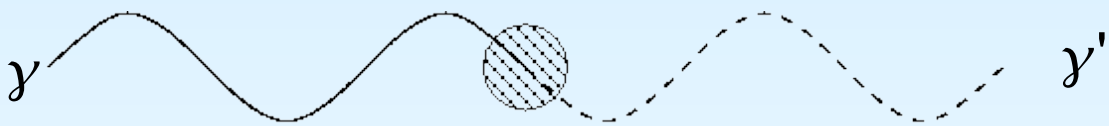
In case the hidden sector prefers vectors

Hidden Sector Photons

New U(1) symmetries that mix with photons
are popular features in post-standard model physics

A variety of motivations

"Hidden Sector Photon" or "paraphoton"

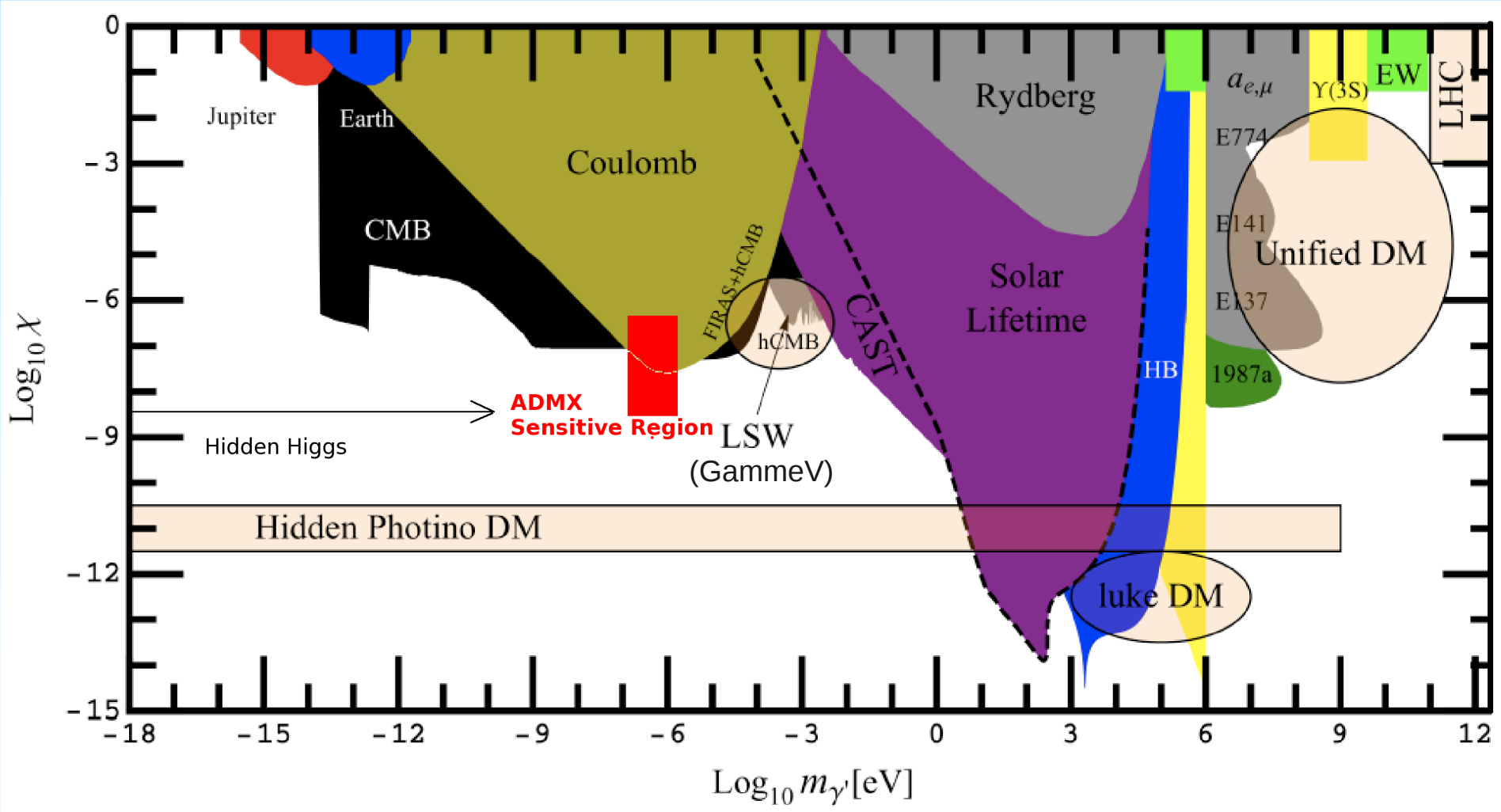


$$L = \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{2} \chi F^{\mu\nu} B_{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 B_\mu B^\mu$$

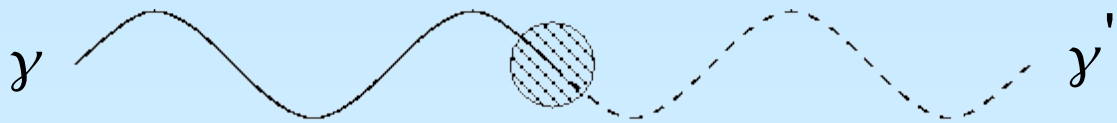
mixing parameter mass

Two Paramaters in phenomonology

HSPs: The Big Picture

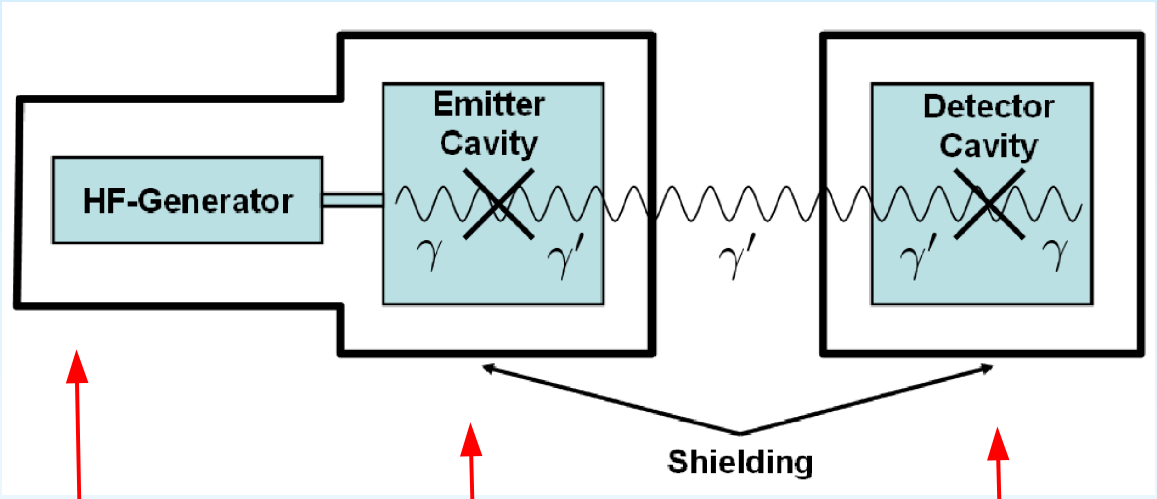


HSP Cavity Searches



Light HSPs couple nearby electromagnetic resonant cavities

See: Jaeckel and Ringwald, Phys. Lett. B 659 (2008) 509

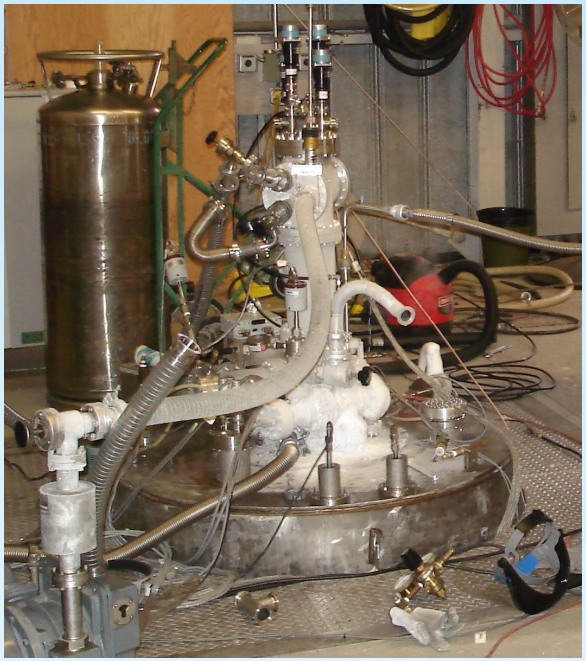


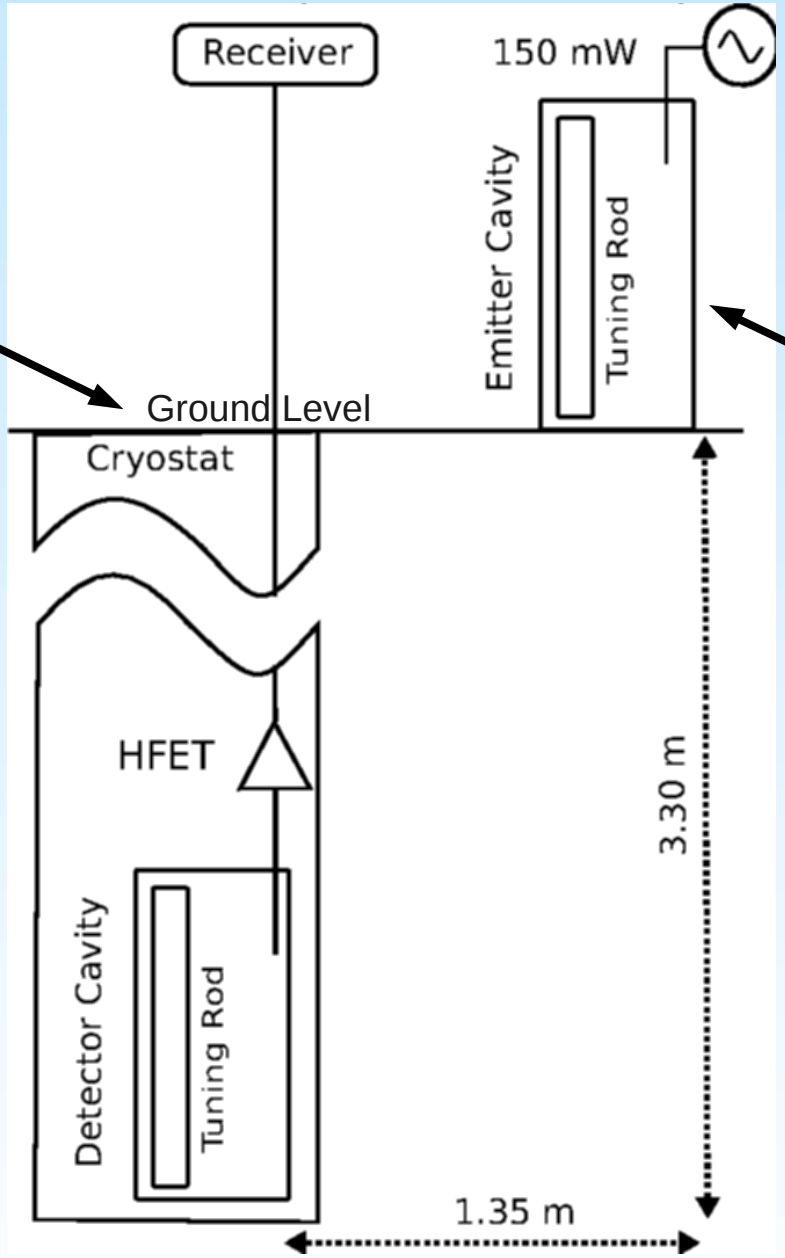
Standard test equipment

We have spare cavities

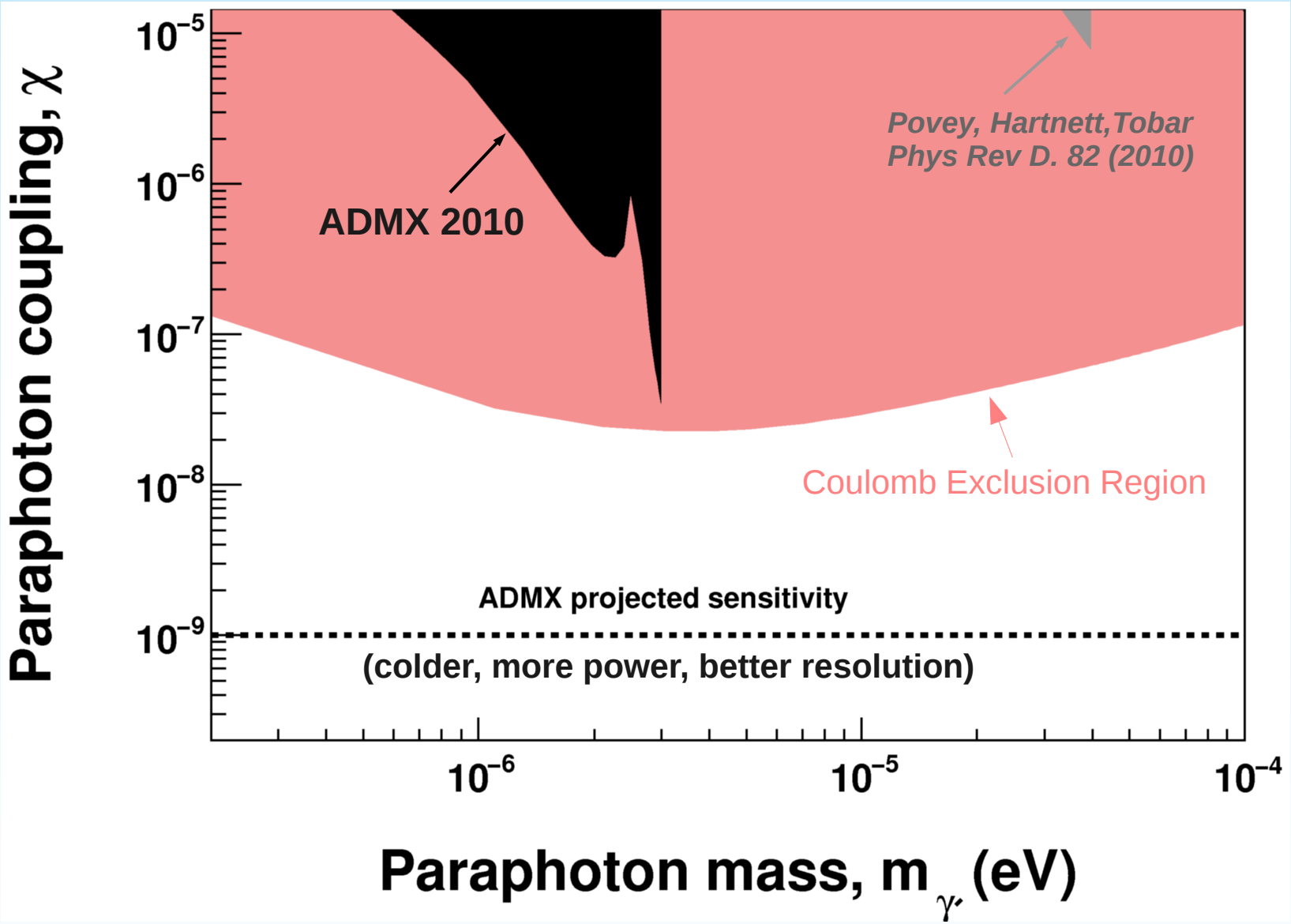
ADMX is one of these

ADMX as a HSP receiver





HSP Results



arXiv:1007-3766 (accepted by PRL)

Project 8

An entirely different experiment, using similar technology but looking at particles we actually know exist

PROJECT 8

Using microwaves to measure the neutrino mass

Collaborators

University of Washington: Hamish Robertson, Peter Doe, Leslie Rosenberg, Michael Miller, Gray Rybka, Brent Vandevender, Laura Bodine

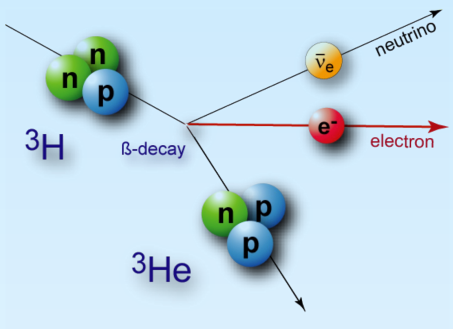
UCSB: Ben Monreal, Michelle Leber, Matthew Bahr

MIT: Joe Formaggio, Noah Oblath

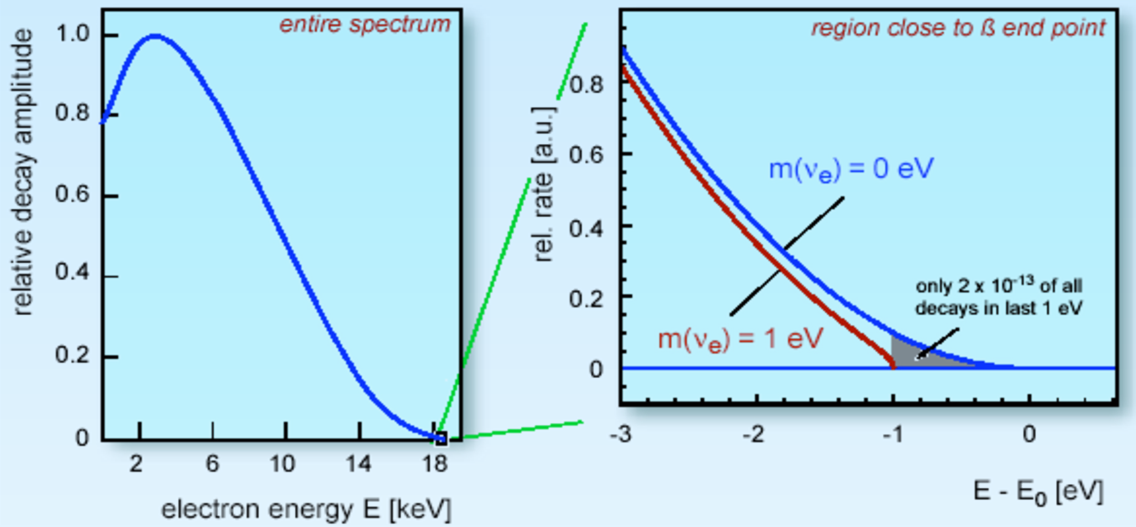
NRAO: Rich Bradley

Measuring the Neutrino Mass

The most promising direct method of measuring the neutrino mass is measuring the deviation of the Tritium decay elecron spectrum endpoint



$$^3H \rightarrow {}^3He^+ + e^- + \nu_e$$



The current limitation on this method is electron energy resolution

The KATRIN experiment will be the pinnacle of the MAC-E spectrometer method with a resolution of 1 eV (1 in 10^5)

How can we do better?

The Project 8 Idea

PHYSICAL REVIEW D **80,** 051301(R) (2009)

Relativistic cyclotron radiation detection of tritium decay electrons as a new technique for measuring the neutrino mass

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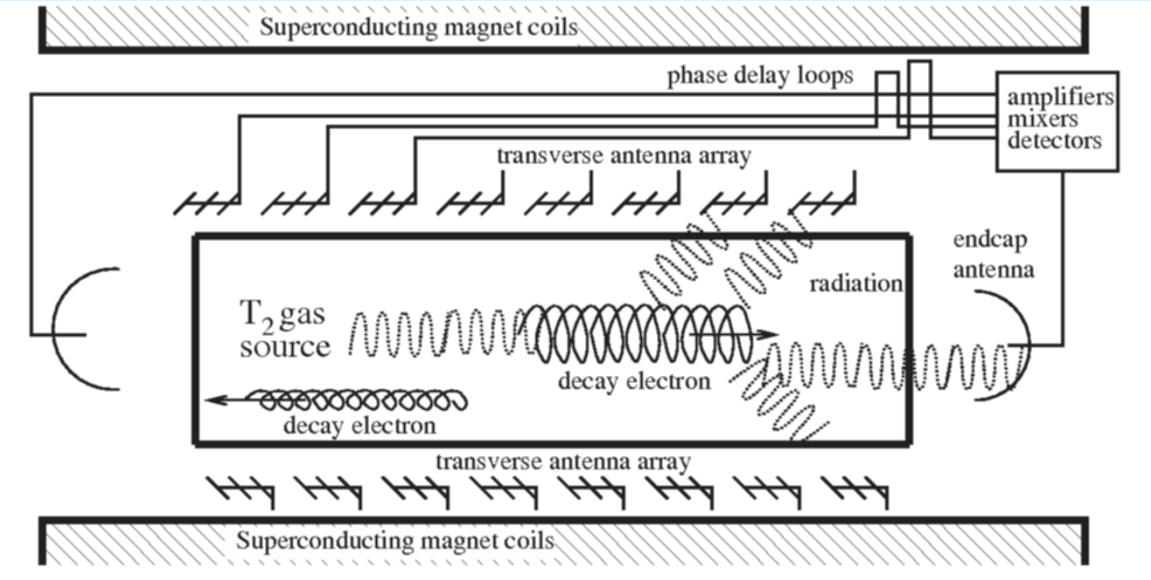
Joseph A. Formaggio
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge Massachusetts, USA
(Received 18 April 2009; published 9 September 2009)



- **Allow Tritium to decay in a magnetic field**
- **Measure frequency of electron cyclotron radiation**
- **Use frequency to calculate energy**

Frequency is something that can be measured very accurately

Numbers for Context

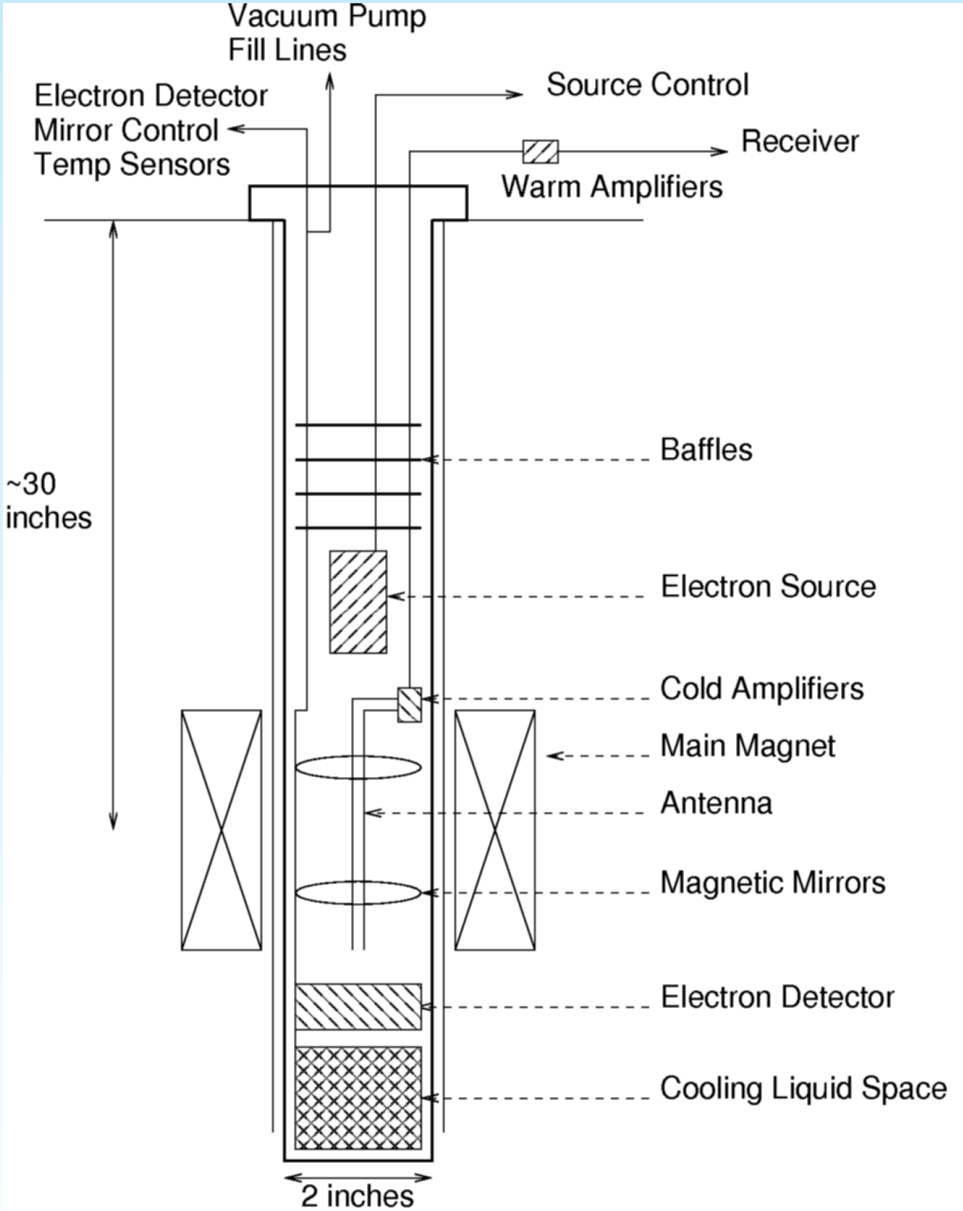
Consider an 18 keV Electron in a 1 tesla Field

Cyclotron Frequency	**27 GHz**
Desired Frequency Resolution	**50 kHz**
Minimum Measurement Time	**40 μs**
Power Emitted in Cyclotron Radiation	**10^{-15} W**
Thermal Noise (77 K) in Desired Bandwidth	**5×10^{-17} W**
Fraction of electrons at endpoint	**1 in 10^{13}**

The Path To Project 8

1) Demonstrate we can detect cyclotron radiation from a single electron
2) Demonstrate energy resolution from cyclotron radiation is superior to other methods
3) Demonstrate there are no killer systematics to scaling up
4) Build the Project 8 neutrino mass experiment

Prototype: Overview



Demonstrate we can detect cyclotron radiation from a single electron

We Need:

- Magnet
- Electron Source
- Electron Trap
- Antenna & Receiver
- Analysis

Prototype: Source

Krypton 83m gas produces a monoenergetic electron in the energy of interest

activation — decay — Internal conversion

$^{nat}Kr \longrightarrow {}^{83}Rb \longrightarrow {}^{83m}Kr \longrightarrow {}^{83}Kr$

produced at CENPA

λ=86 days

λ=1.8 hours

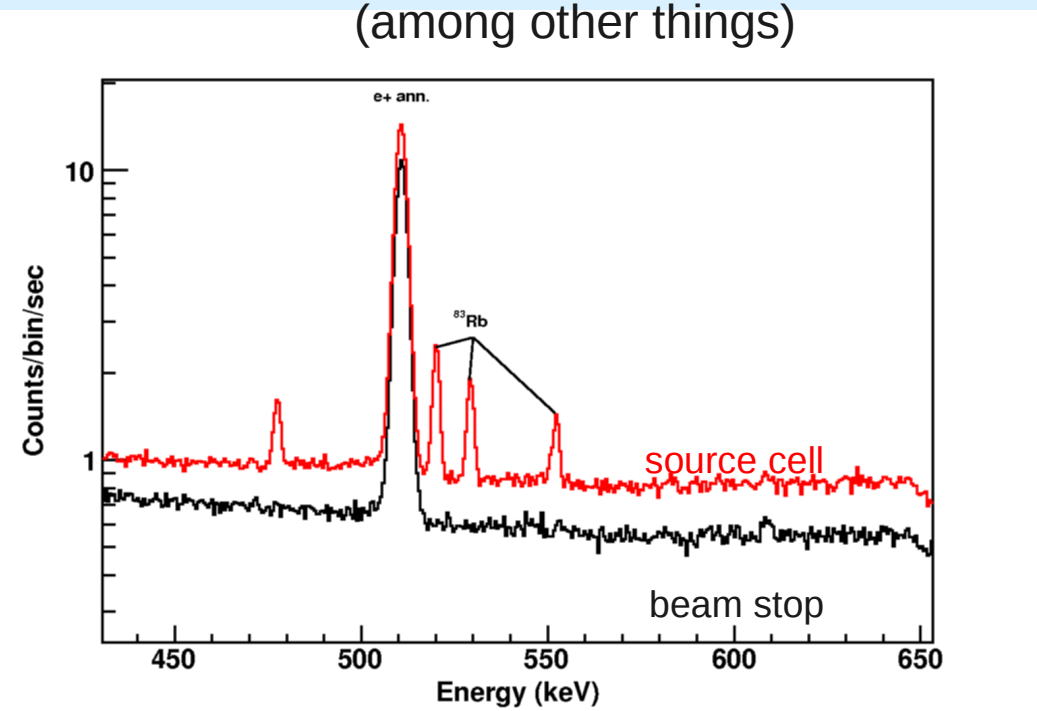
produces 17.8 keV conversion electron (among other things)

Benefits

- Gaseous-easy to get in trap
- Stored as ^{83}Rb
- Convenient half-life
- Monoenergetic

Hassles

- High freezing temperature
- Requires beam-time

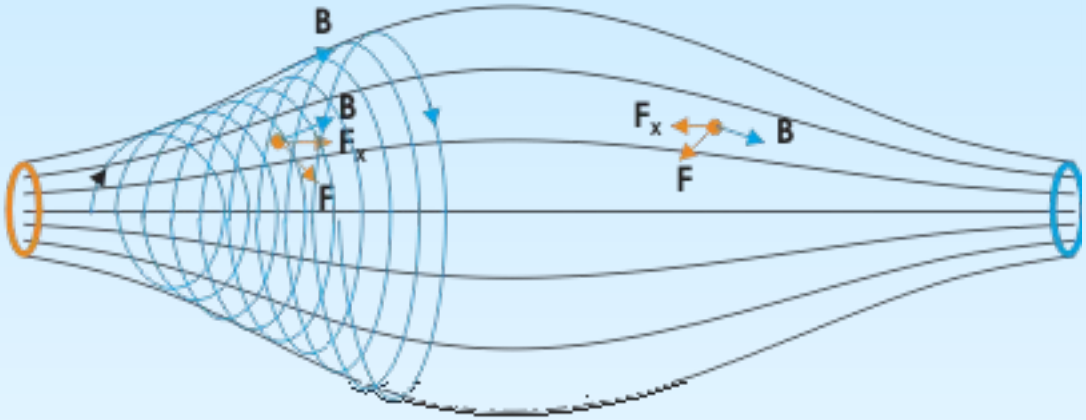


Rb production at CENPA demonstrated April, 2010

Thanks, Brent VanDevender and Noah Oblath

Prototype: Trap

Electric fields change the electron's energy, ruling out Penning traps
A magnetic bottle is a much more attractive solution



But a changing magnetic field strength will also change the frequency

We will have to deal with this in analysis

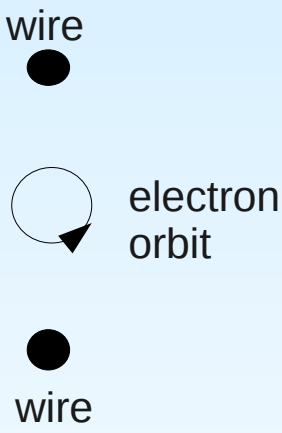
Prototype: Antenna

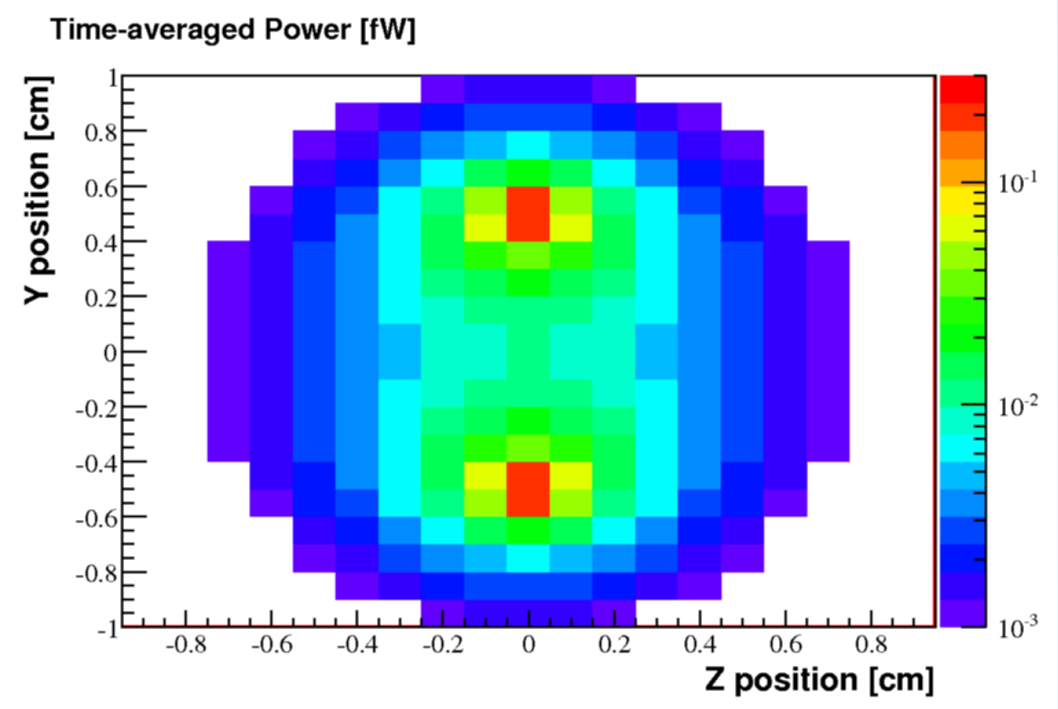
27 GHz = 1.1 cm wavelength

Uncomfortably between far field antenna and capacitive electrons

Two wire transmission lines are attractive antenna candidates

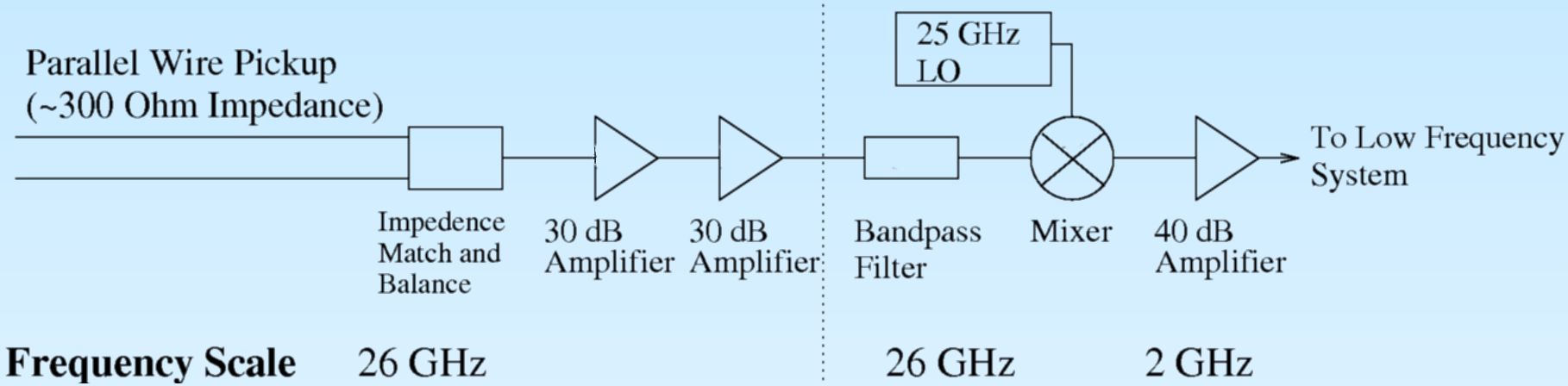
Voltage is excited by charge moving between wires, signal is carried down line



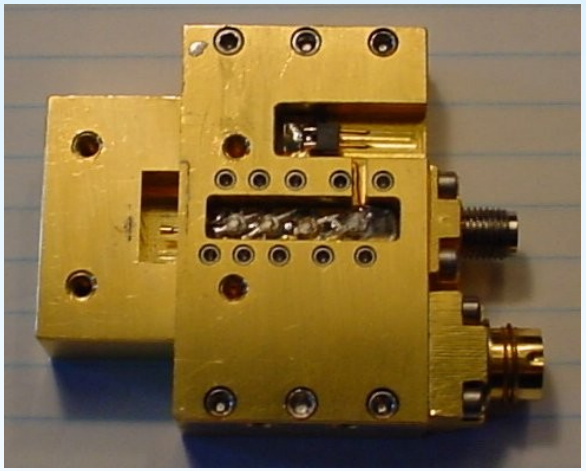


Concern: “Magnetron” motion can move electron out of high gain regions. Would strips be better?

Prototype: Receiver



SNR Depends entirely on noise temperature



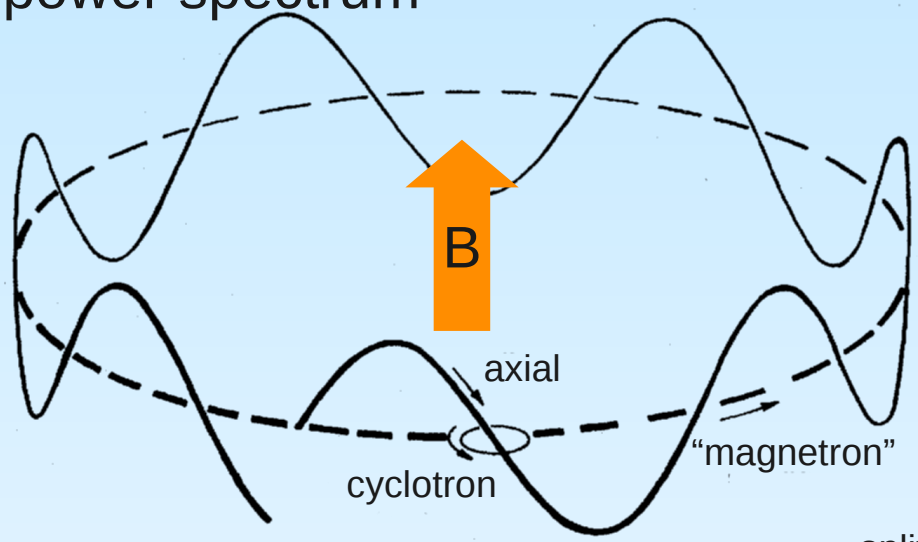
NRAO (Richard Bradley) is providing extremely low noise temperature (15 K) microwave amplifiers

Total noise temperature = 77K (physical) + 15K (amp) = 92 K

Prototype: Analysis

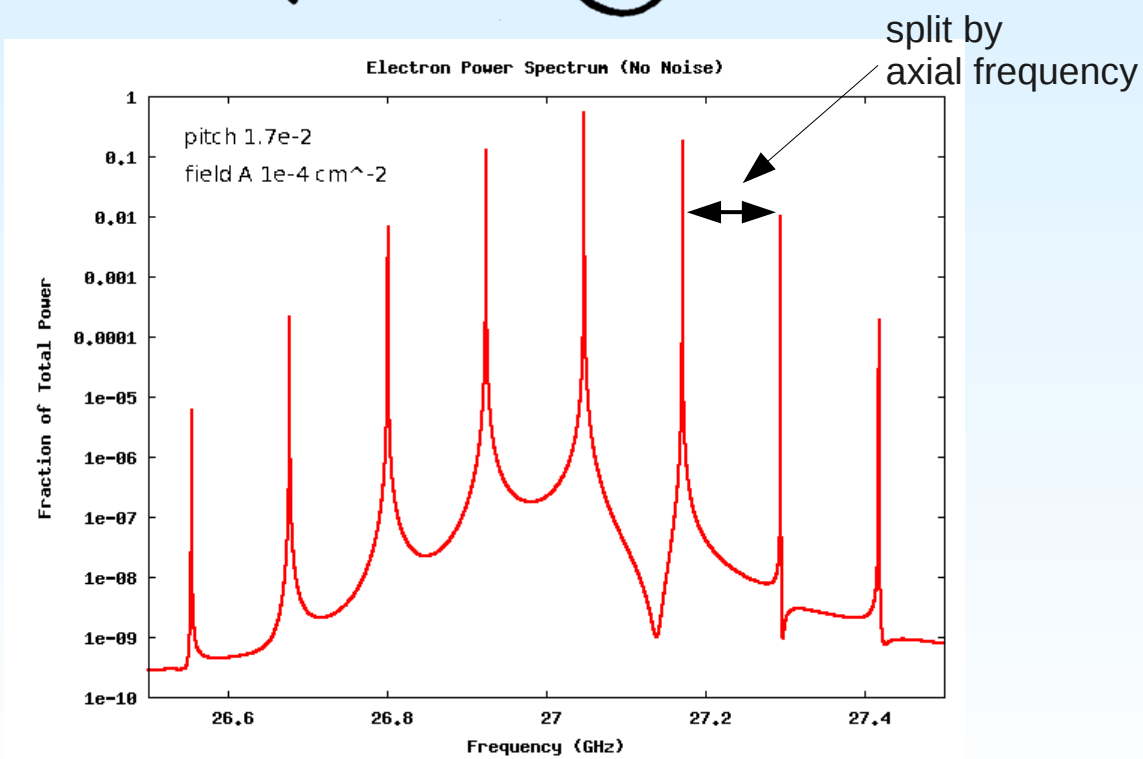
Fundamental contributions to power spectrum

- Cyclotron Motion
- Axial Motion
- "Magnetron" Motion
- Doppler Shift



Frequency mixing spreads out signal and decreases SNR

But it also can remove inhomogeneous magnetic field effects



Prototype: Status and Plans

Magnet: Obtained from Van Dyck & Dehmelt's g-2 experiment

Source: Rb production ready when needed

Trap: Under development

Antenna: Under development. Receiver parts en route

Analysis: Under development; tied to trap and antenna

We hope to have the prototype together this Winter!

Summary

ADMX utilizes the exquisite power sensitivity of microwave technology to search for beyond the standard model physics

Dark Matter Axions

Scalar Chameleons

Hidden Sector Photons

Project 8 utilizes the precision of microwave frequency measurement in a bid to measure the neutrino mass

Microwave technology may be the key to unlocking the 'hidden sector' frontier