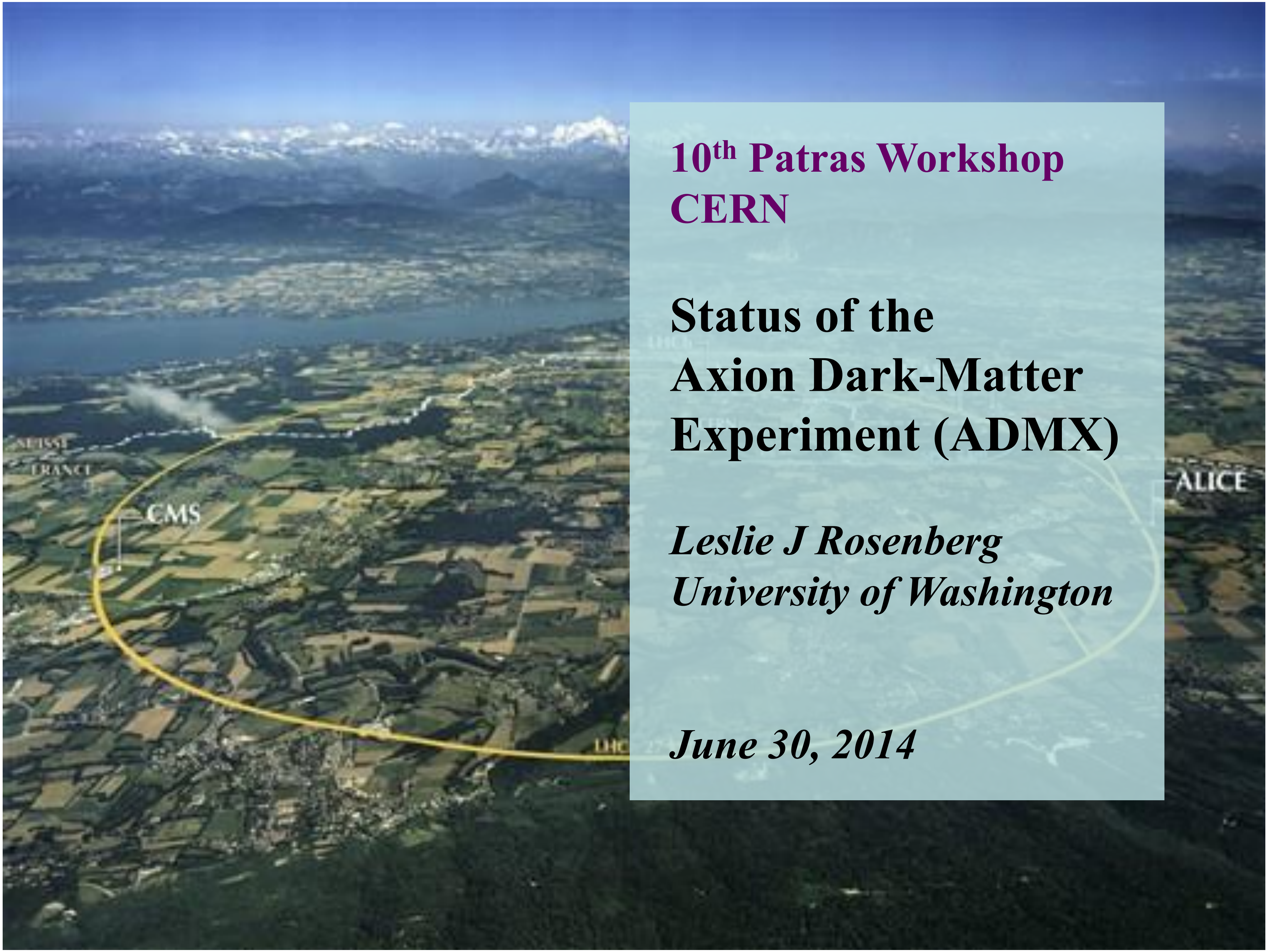


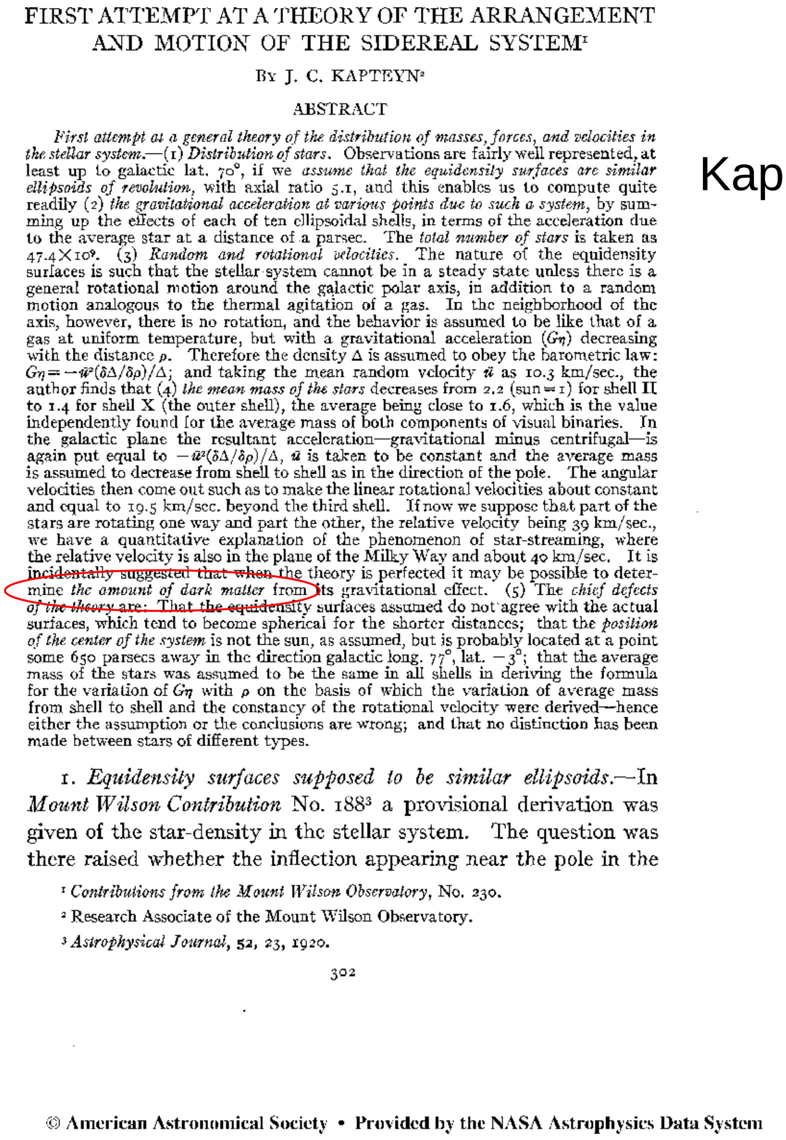
10th Patras Workshop
CERN

Status of the Axion Dark-Matter Experiment (ADMX)

Leslie J Rosenberg
University of Washington

June 30, 2014

What constitutes the dark matter?



FIRST ATTEMPT AT A THEORY OF THE ARRANGEMENT AND MOTION OF THE SIDEREAL SYSTEM[1]

By J. C. KAPTEYN[2]

ABSTRACT

First attempt at a general theory of the distribution of masses, forces, and velocities in the stellar system.—(1) *Distribution of stars.* Observations are fairly well represented, at least up to galactic lat. 70°, if we *assume that the equidensity surfaces are similar ellipsoids of revolution*, with axial ratio 5.1, and this enables us to compute quite readily (2) *the gravitational acceleration at various points due to such a system*, by summing up the effects of each of ten ellipsoidal shells, in terms of the acceleration due to the average star at a distance of a parsec. The *total number of stars* is taken as 47.4×10^9. (3) *Random and rotational velocities.* The nature of the equidensity surfaces is such that the stellar system cannot be in a steady state unless there is a general rotational motion around the galactic polar axis, in addition to a random motion analogous to the thermal agitation of a gas. In the neighborhood of the axis, however, there is no rotation, and the behavior is assumed to be like that of a gas at uniform temperature, but with a gravitational acceleration ($G\eta$) decreasing with the distance ρ. Therefore the density Δ is assumed to obey the barometric law: $G\eta = -\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$; and taking the mean random velocity $\bar{u}$ as 10.3 km/sec., the author finds that (4) *the mean mass of the stars* decreases from 2.2 (sun = 1) for shell II to 1.4 for shell X (the outer shell), the average being close to 1.6, which is the value independently found for the average mass of both components of visual binaries. In the galactic plane the resultant acceleration—gravitational minus centrifugal—is again put equal to $-\bar{u}^2(\delta\Delta/\delta\rho)/\Delta$, $\bar{u}$ is taken to be constant and the average mass is assumed to decrease from shell to shell as in the direction of the pole. The angular velocities then come out such as to make the linear rotational velocities about constant and equal to 19.5 km/sec. beyond the third shell. If now we suppose that part of the stars are rotating one way and part the other, the relative velocity being 39 km/sec., we have a quantitative explanation of the phenomenon of star-streaming, where the relative velocity is also in the plane of the Milky Way and about 40 km/sec. It is incidentally suggested that when the theory is perfected it may be possible to determine *the amount of dark matter* from its gravitational effect. (5) The *chief defects of the theory* are: That the equidensity surfaces assumed do not agree with the actual surfaces, which tend to become spherical for the shorter distances; that the *position of the center of the system* is not the sun, as assumed, but is probably located at a point some 650 parsecs away in the direction galactic long. 77°, lat. −3°; that the average mass of the stars was assumed to be the same in all shells in deriving the formula for the variation of $G\eta$ with ρ on the basis of which the variation of average mass from shell to shell and the constancy of the rotational velocity were derived—hence either the assumption or the conclusions are wrong; and that no distinction has been made between stars of different types.

1. *Equidensity surfaces supposed to be similar ellipsoids.*—In *Mount Wilson Contribution* No. 188[3] a provisional derivation was given of the star-density in the stellar system. The question was there raised whether the inflection appearing near the pole in the

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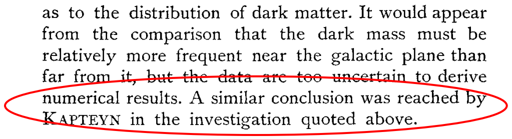
[1] *Contributions from the Mount Wilson Observatory*, No. 230.

[2] Research Associate of the Mount Wilson Observatory.

[3] *Astrophysical Journal*, 52, 23, 1920.

Kapetyn 1922

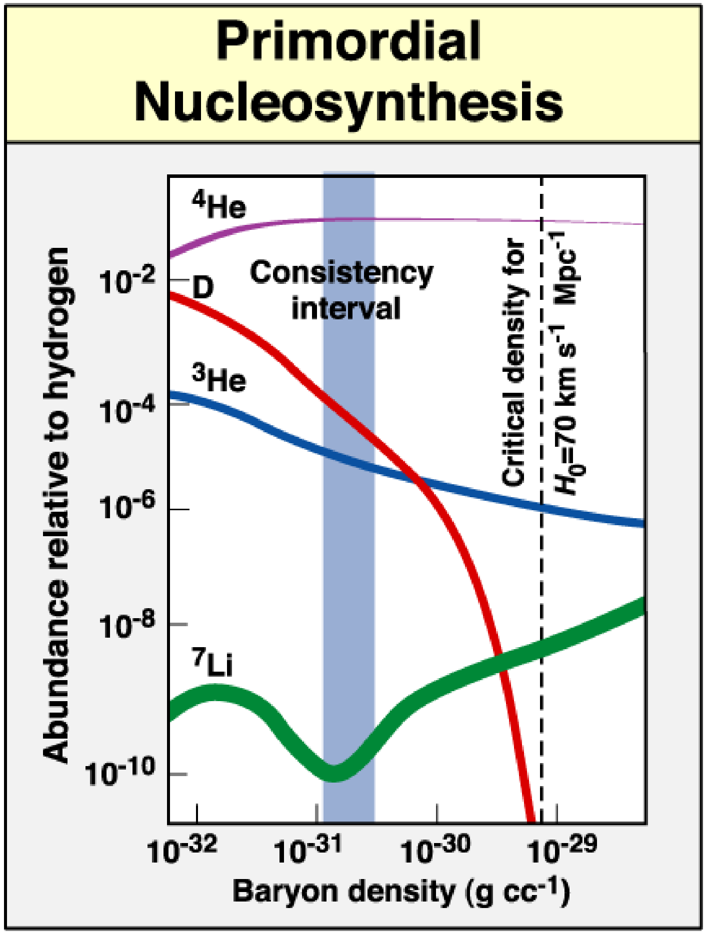


as to the distribution of dark matter. It would appear from the comparison that the dark mass must be relatively more frequent near the galactic plane than far from it, but the data are too uncertain to derive numerical results. A similar conclusion was reached by Kapteyn in the investigation quoted above.

Recognized by
Oort 1932

It's been long appreciated that the light axion is a good dark-matter candidate

(1) From light element abundance:
Dark matter probably isn't bowling balls or anything else made of baryons.



(2) Is dark matter made of, e.g., light neutrinos?
Probably not: fast moving neutrinos would have washed-out structure.
Dark matter is substantially "cold".

(3) "Dark matter: I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…"

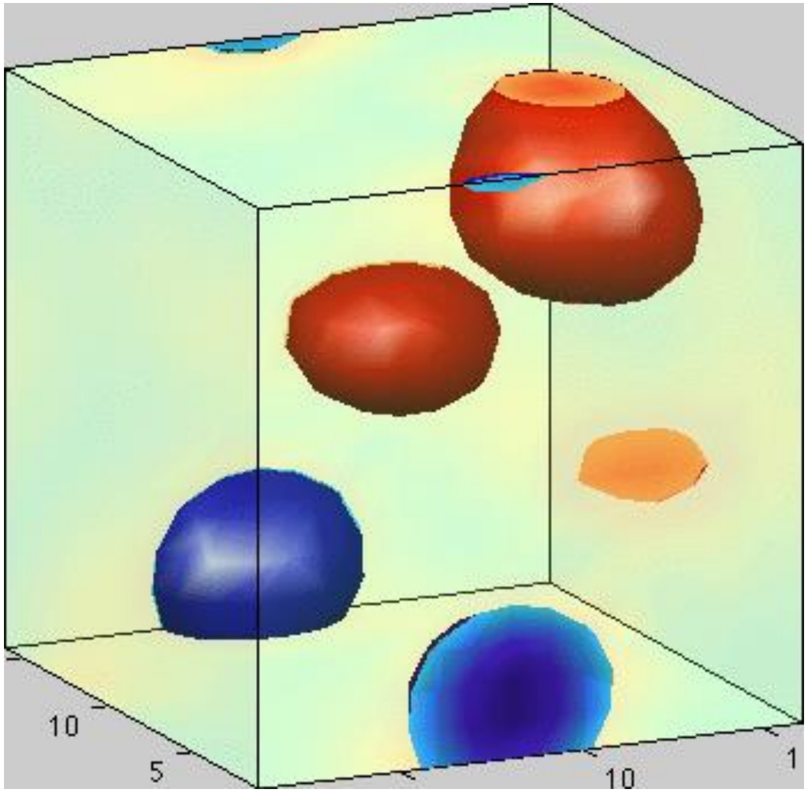
Frank Wilczek in Physics Today

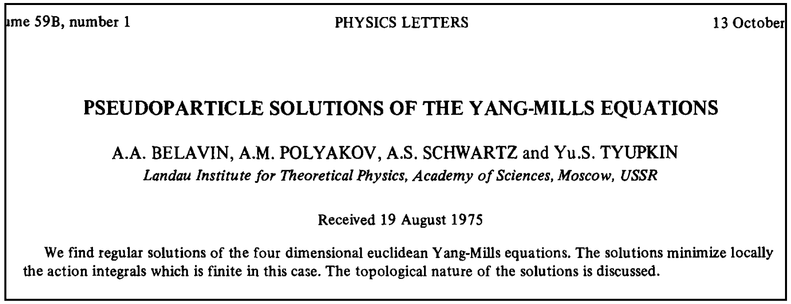
Frank's referring to WIMPS and Axions

Axions? Why does QCD conserve the symmetry CP?

1973: QCD…a gauge theory of color.
QCD theory embedded the observed conservation of C, P and CP.

1975: QCD + “instantons” ⇒ QCD is expected to be hugely CP-violating.




ume 59B, number 1 PHYSICS LETTERS 13 October

PSEUDOPARTICLE SOLUTIONS OF THE YANG-MILLS EQUATIONS

A.A. BELAVIN, A.M. POLYAKOV, A.S. SCHWARTZ and Yu.S. TYUPKIN
Landau Institute for Theoretical Physics, Academy of Sciences, Moscow, USSR

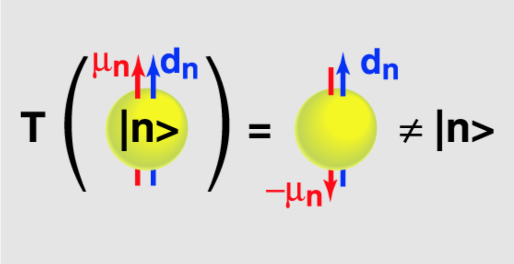
Received 19 August 1975

We find regular solutions of the four dimensional euclidean Yang-Mills equations. The solutions minimize locally the action integrals which is finite in this case. The topological nature of the solutions is discussed.

QCD on the lattice:
CP-violating instantons in 3D
(sort of)

Peccei and Quinn: CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment (~~T~~ + CPT = ~~CP~~); none is unobserved.
(9 orders-of-magnitude discrepancy)

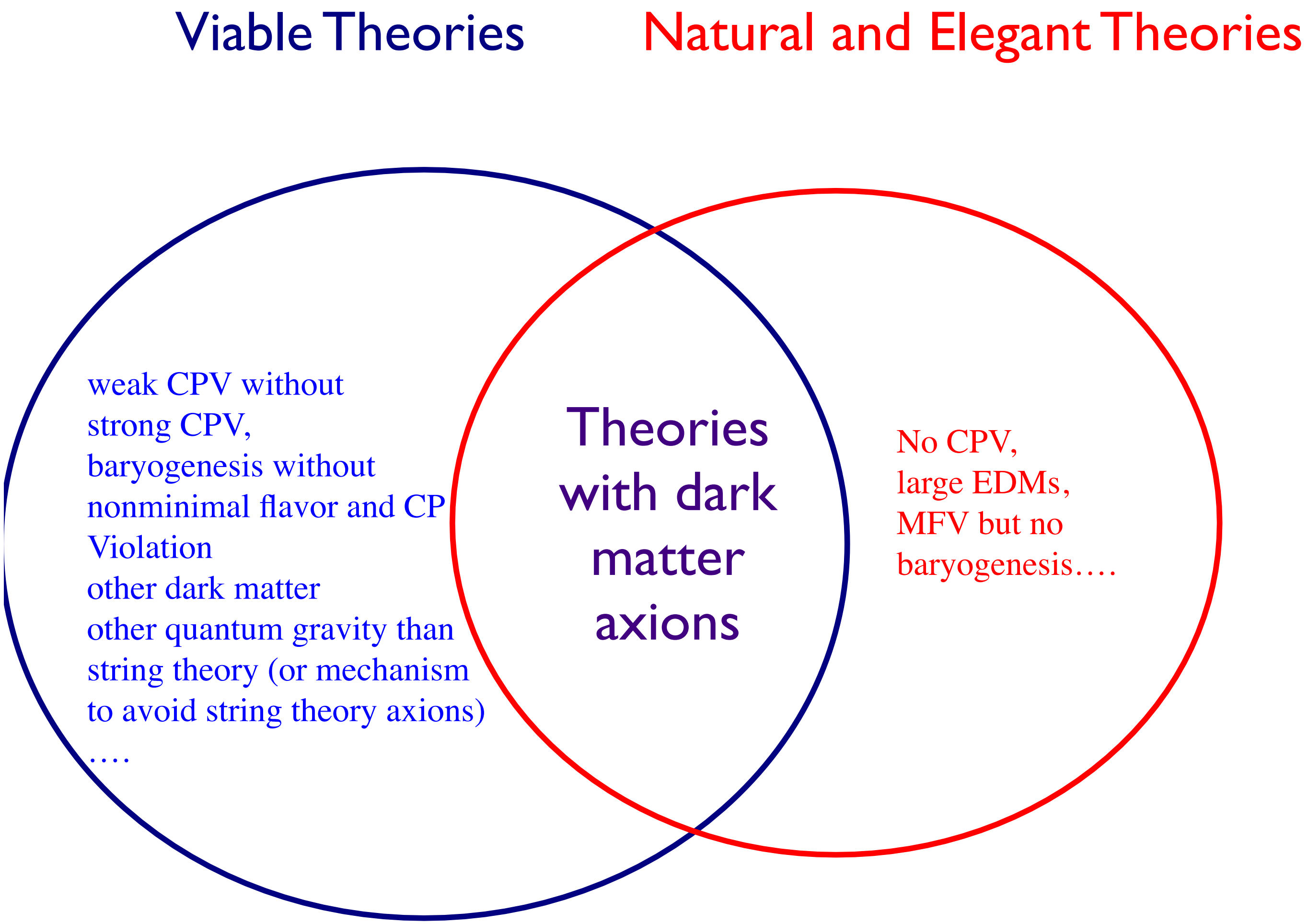


Why doesn’t the neutron have an electric dipole moment?

This leads to the “Strong CP Problem”: Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Recap of axion theory: From A. Nelson



Viable Theories

Natural and Elegant Theories

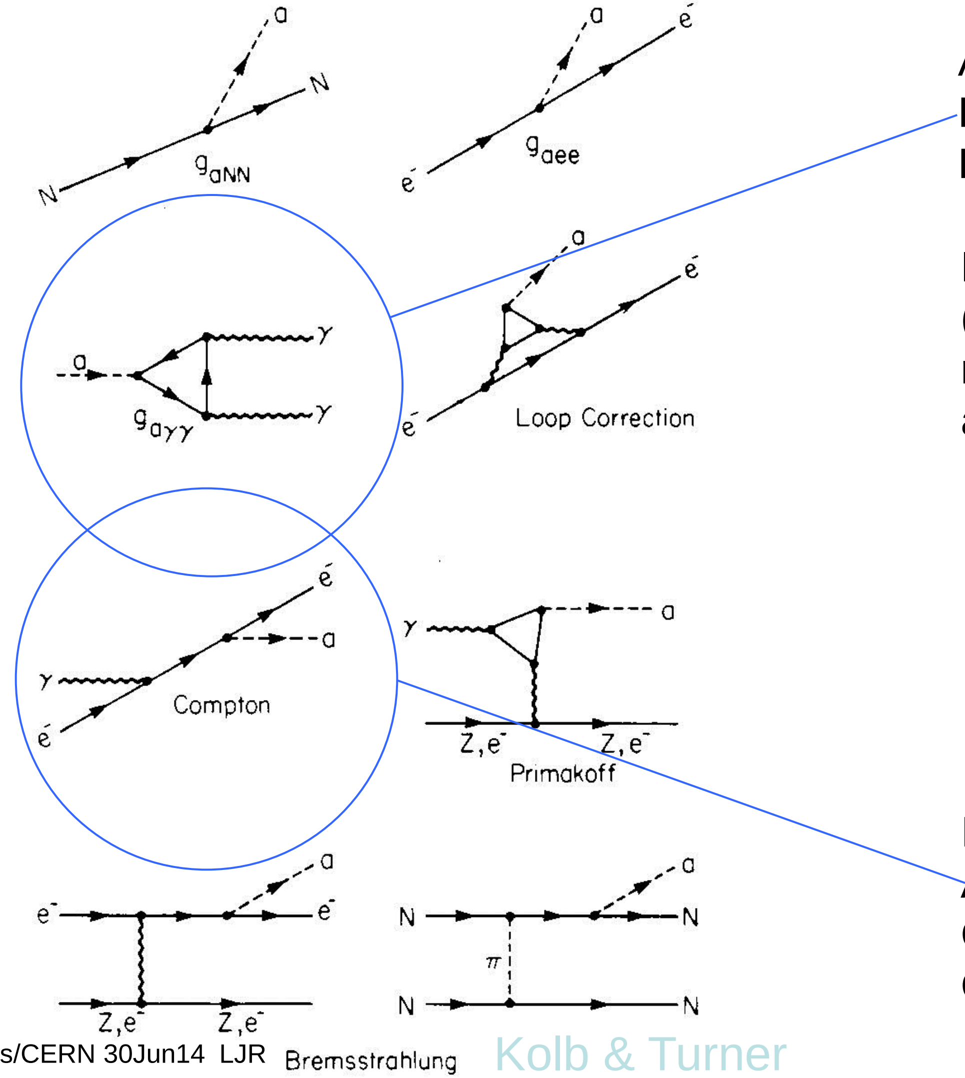
weak CPV without
strong CPV,
baryogenesis without
nonminimal flavor and CP
Violation
other dark matter
other quantum gravity than
string theory (or mechanism
to avoid string theory axions)
….

Theories
with dark
matter
axions

No CPV,
large EDMs,
MFV but no
baryogenesis….

Axions?

Selected axion couplings & the important two-photon coupling



Kolb & Turner

A process with small model uncertainty
Exploited in certain terrestrial searches
Easily calculable

Rate depends on “unification group” (that is, the particles in the loops), ratio of u/d quark masses, and mostly f_{PQ}

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N} - 1.95\right)$$

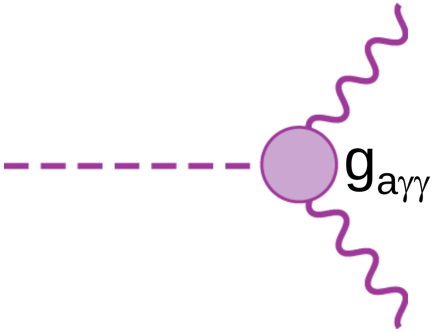
In contrast:
A process with large model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron

RF cavity axion-search experiments

Recall:

The axion couples (very weakly, indeed) to normal particles.

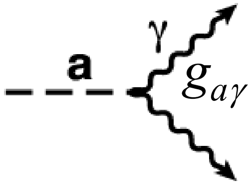
But it happens that the axion 2γ coupling has relatively little axion-model dependence



Axions constituting our local galactic halo would have huge number density ~10^{14} cm^{-3}

Pierre Sikivie's RF-cavity idea (1983): Axion and electromagnetic fields exchange energy

The axion-photon coupling…



…is a source term in Maxwell's Equations

$$\frac{\partial\left(\mathbf{E}^2/2\right)}{\partial t} - \mathbf{E}\cdot\left(\nabla\times\mathbf{B}\right) = g_{a\gamma}\dot{a}\left(\mathbf{E}\cdot\mathbf{B}\right)$$

So imposing a strong external magnetic field B transfers axion field energy into cavity electromagnetic energy.

(Inverse Primakov conversion of axion to photon.)

Properties of the axion

- The Axion is a light pseudoscalar resulting from the Peccei-Quinn mechanism to enforce strong-CP conservation
- f_a, the SSB scale of PQ-symmetry, is the one important parameter in the theory

Mass and Couplings

$$m_a \sim 6\ \mu\mathrm{eV} \cdot \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$$

Generically, all couplings

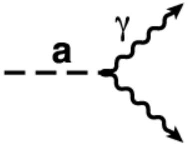
$$g_{aii} \propto \frac{1}{f_a}$$

Cosmological Abundance

$$\Omega_a \sim \left(\frac{5\ \mu\mathrm{eV}}{m_a}\right)^{7/6}$$

(Vacuum misalignment mechanism)

Coupling to Photons



$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = \begin{cases} 0.97 & \text{KSVZ} \\ -0.36 & \text{DFSZ} \end{cases}$$

Axion Mass 'Window'

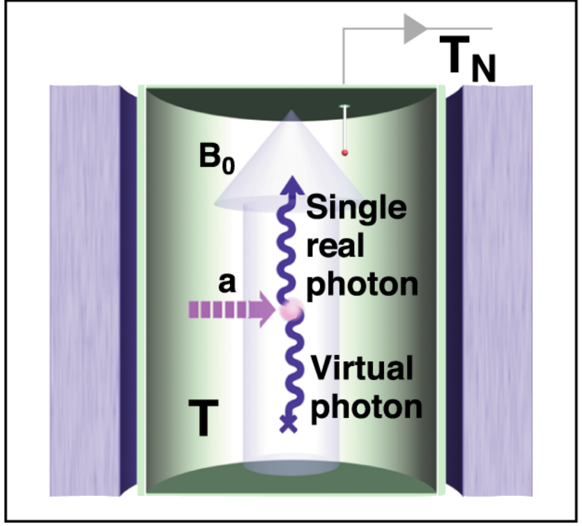
$$10^{-(5\text{ to }6)}\ \mathrm{eV} < m_a < 10^{-(2\text{ to }3)}\ \mathrm{eV}$$

(Overclosure) (SN1987a)

With lower end of window preferred if $\Omega_{CDM} \sim 1$

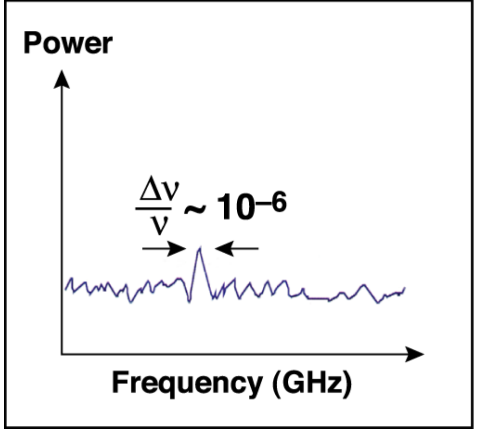
Some experimental details of the RF-cavity technique

Primakoff Conversion



- **The conversion is resonant, i.e. the frequency must equal the mass + K. E.**
- **The total system noise temperature $T_S = T + T_N$ is the critical factor**

Signal



The search speed is quadratic in 1/Ts

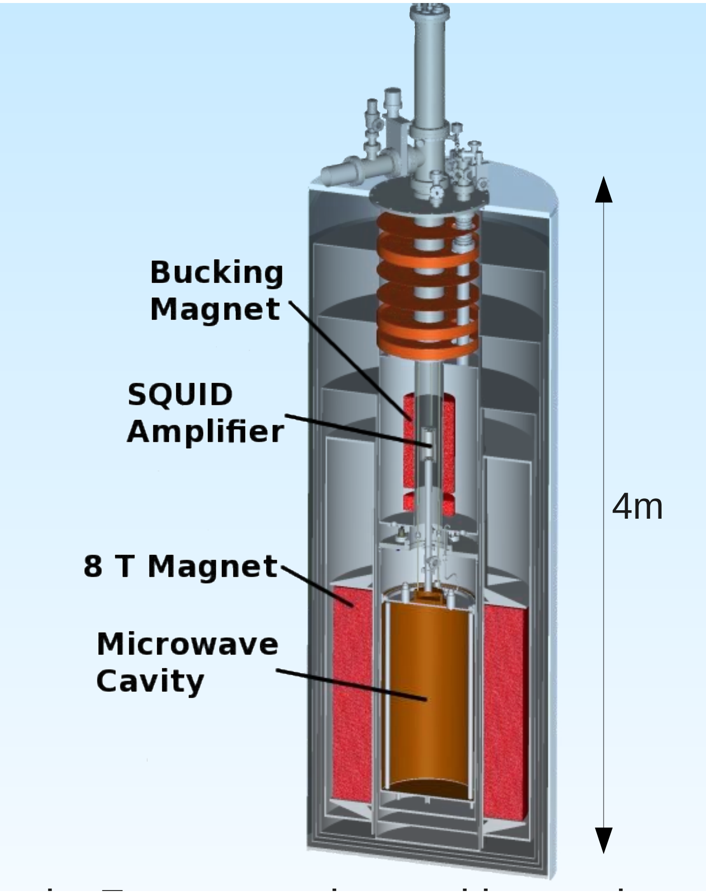
Scaling Laws	
$\frac{d\nu}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$	$g_\gamma^2 \propto \left(B^2 V \cdot \frac{1}{T_S}\right)^{-1}$
For fixed model g^2	**For fixed scan rate $\frac{d\nu}{dt}$**

RF-cavity experiments obey the Radiometer Equation

ADMX: Axion Dark-Matter eXperiment

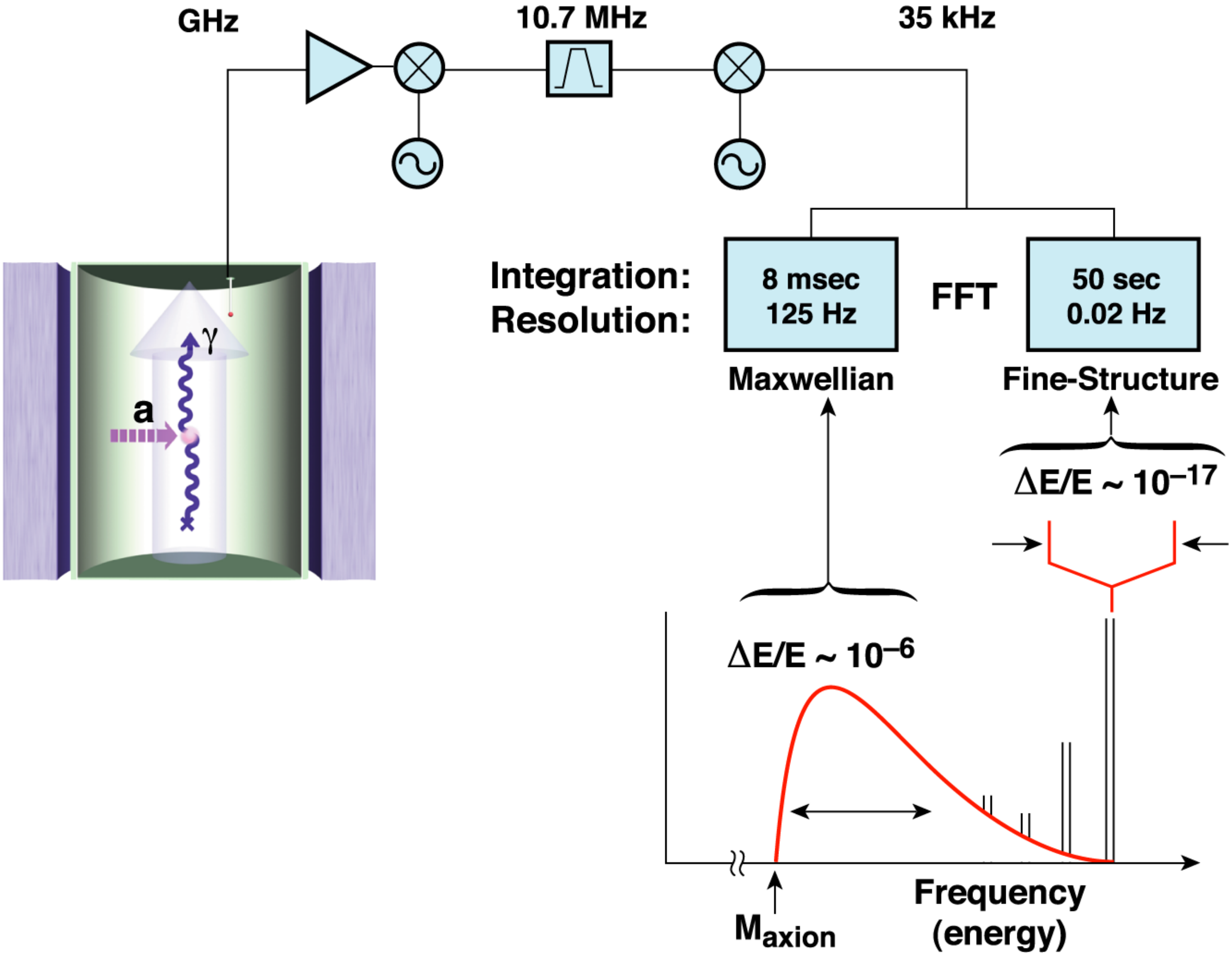
U. Washington, LLNL, U. Florida, U.C. Berkeley,
National Radio Astronomy Observatory, Sheffield U., Yale U.,
U. of Colorado

Magnet with insert

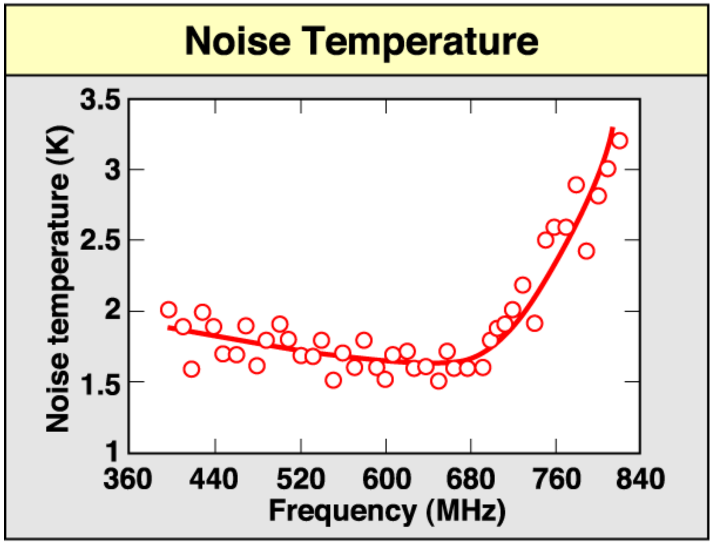


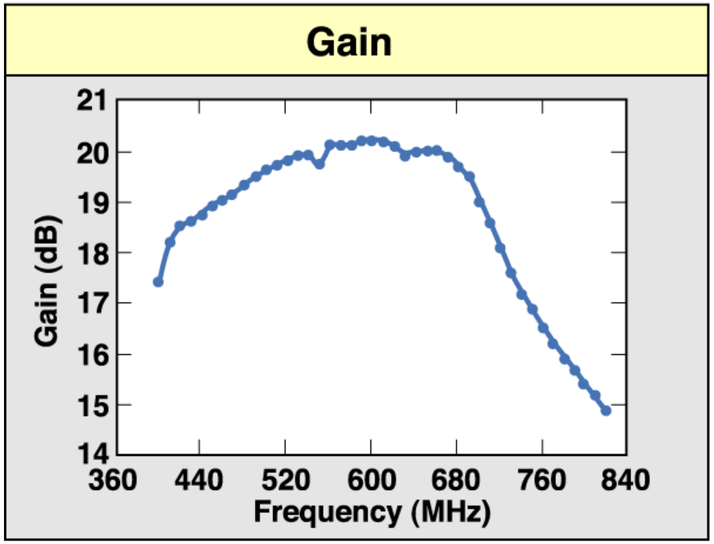
Magnet cryostat

ADMX hardware: Receiver



A brief digression on microwave amplifiers


Noise Temperature


Gain

HFET amplifiers
(Heterojunction Field-Effect Transistor)

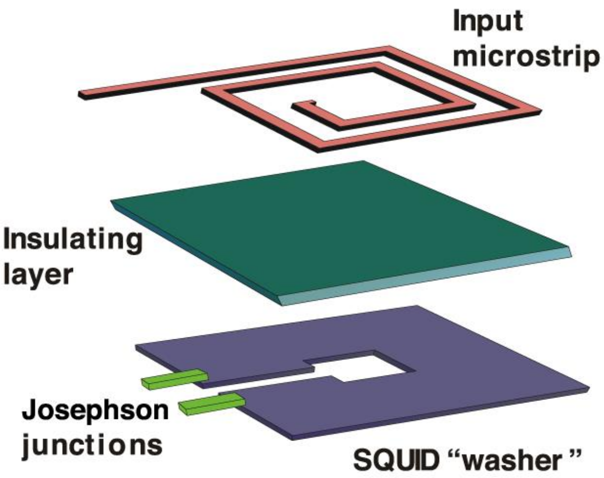
- **A.k.a. HEMT™ (High Electron Mobility Transistor)**
- **Workhorse of radio astronomy, military communications, etc.**

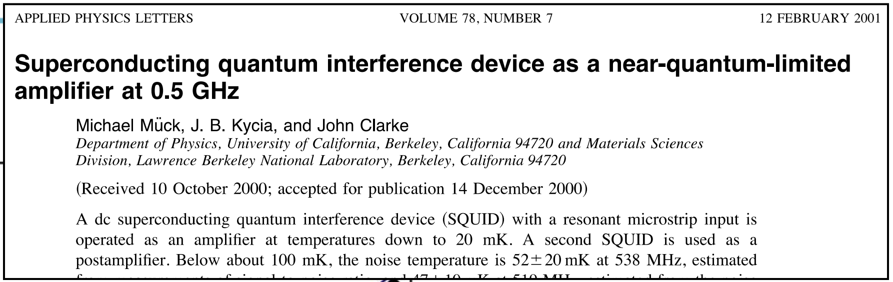
- **Best to date $T_N \gtrsim 1$ K**

But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!

A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!

Quantum-limited SQUID-based amplification



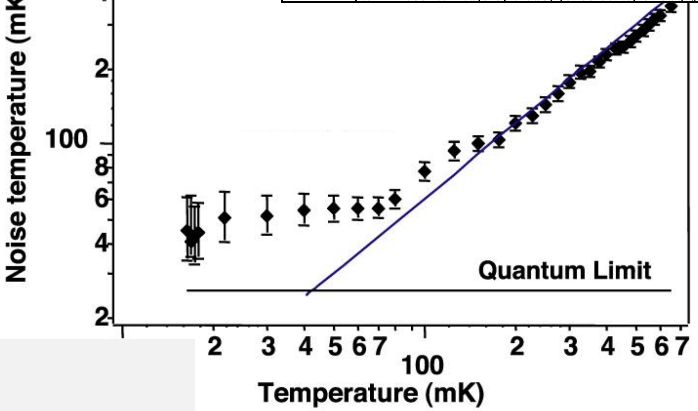

APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

Superconducting quantum interference device as a near-quantum-limited amplifier at 0.5 GHz

Michael Mück, J. B. Kycia, and John Clarke
Department of Physics, University of California, Berkeley, California 94720 and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Received 10 October 2000; accepted for publication 14 December 2000)

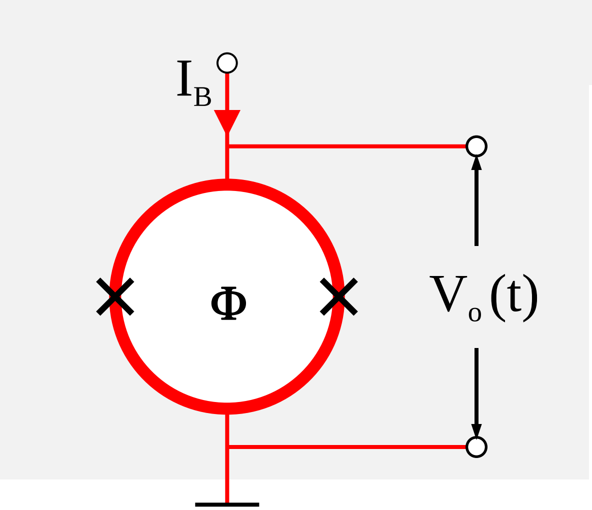
A dc superconducting quantum interference device (SQUID) with a resonant microstrip input is operated as an amplifier at temperatures down to 20 mK. A second SQUID is used as a postamplifier. Below about 100 mK, the noise temperature is 52±20 mK at 538 MHz, estimated

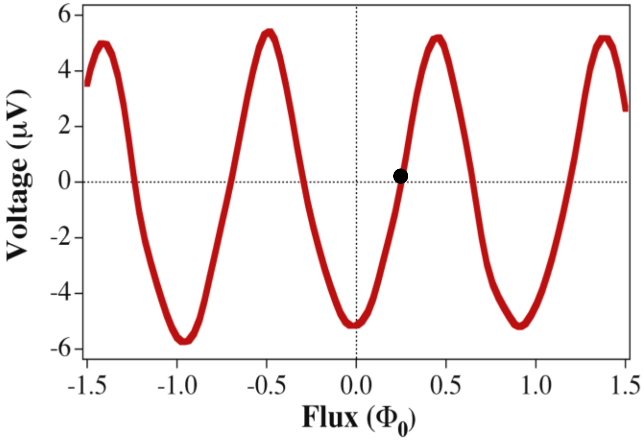


- GHz SQUIDs have been measured with T_N ~50 mK

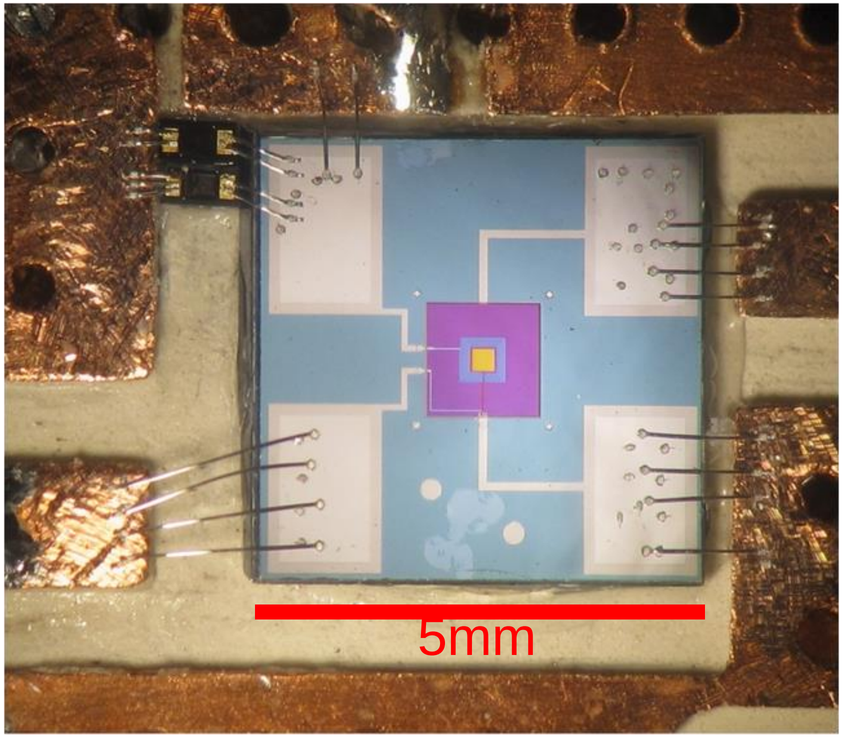
- Near quantum–limited noise

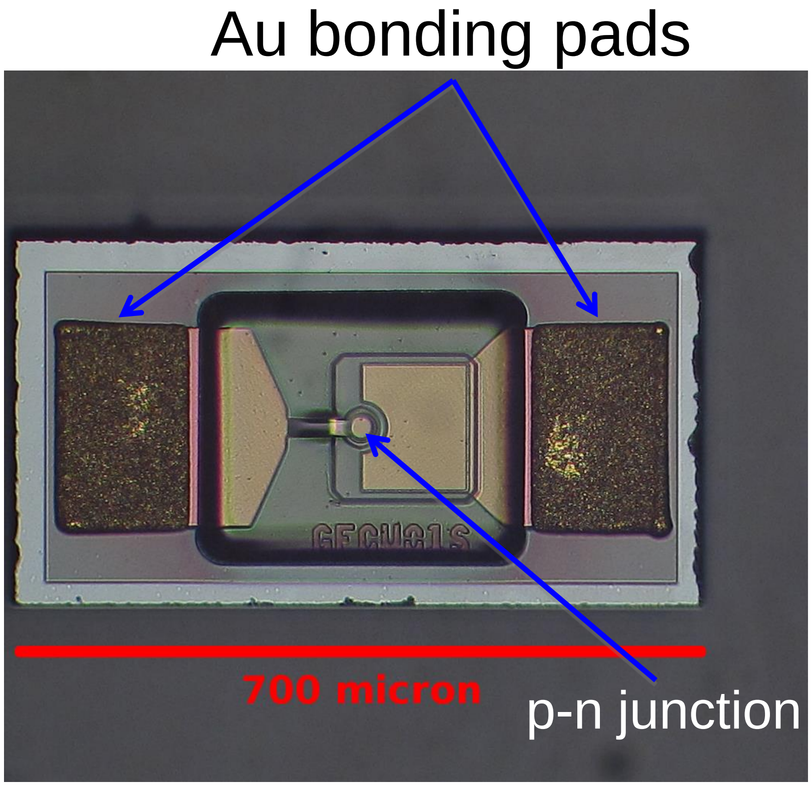
- This provides an enormous increase in ADMX sensitivity



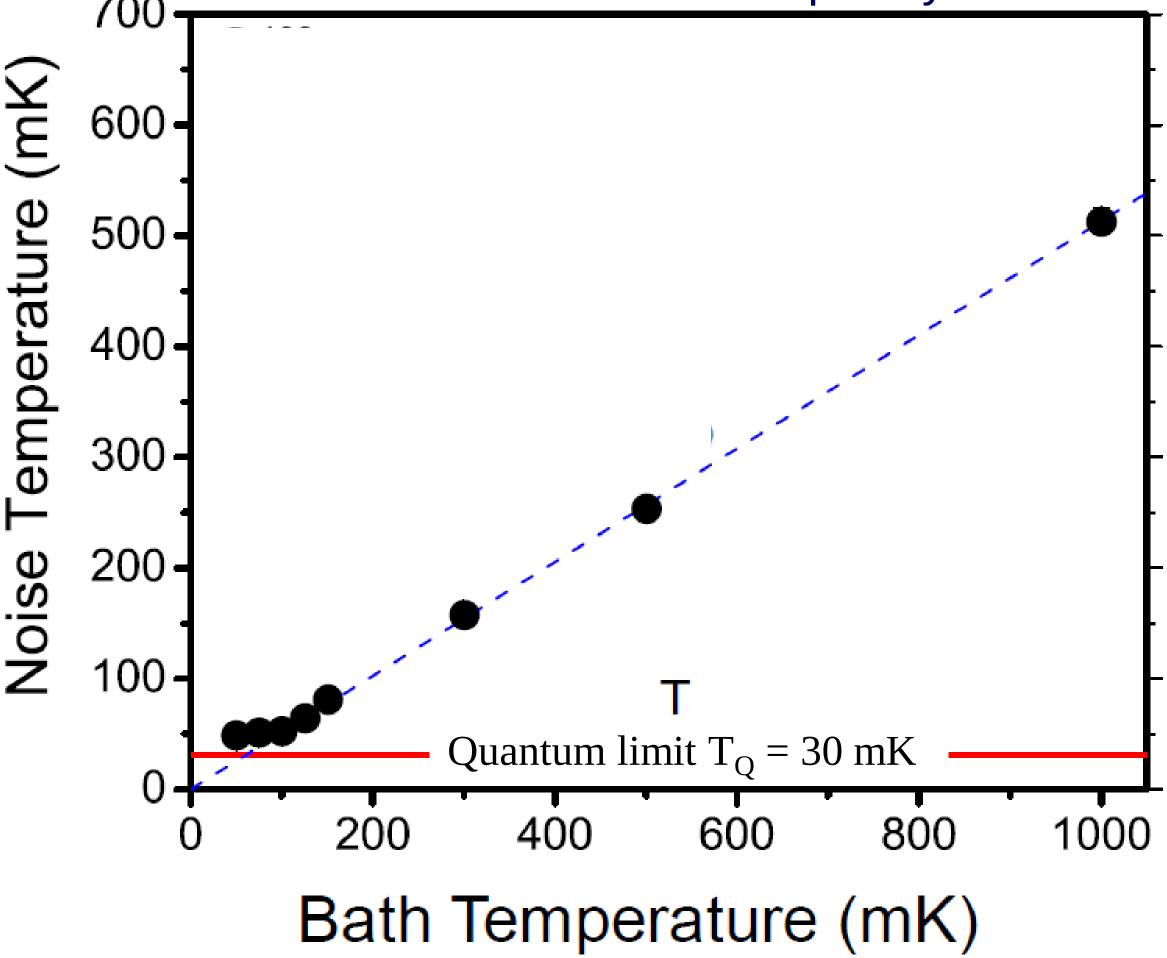


ADMX hardware:
Microstrip SQUID amplifiers with varactor tuning





SQUID amplifiers yield quantum-limited noise

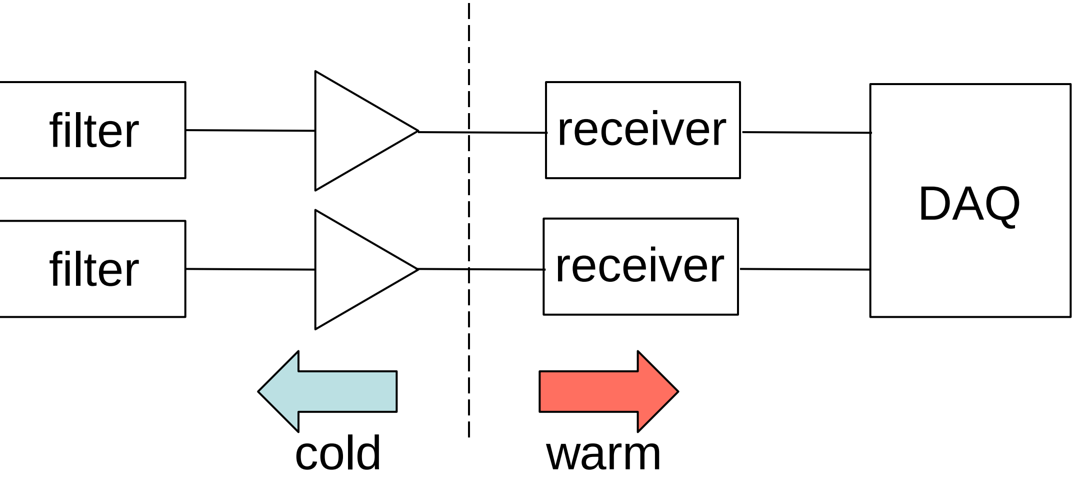


Gain = 20 dB
Frequency 612 MHz

Quantum limit T_Q = 30 mK

Gives speed-up of × 10,000

ADMX hardware: Multi-mode readout



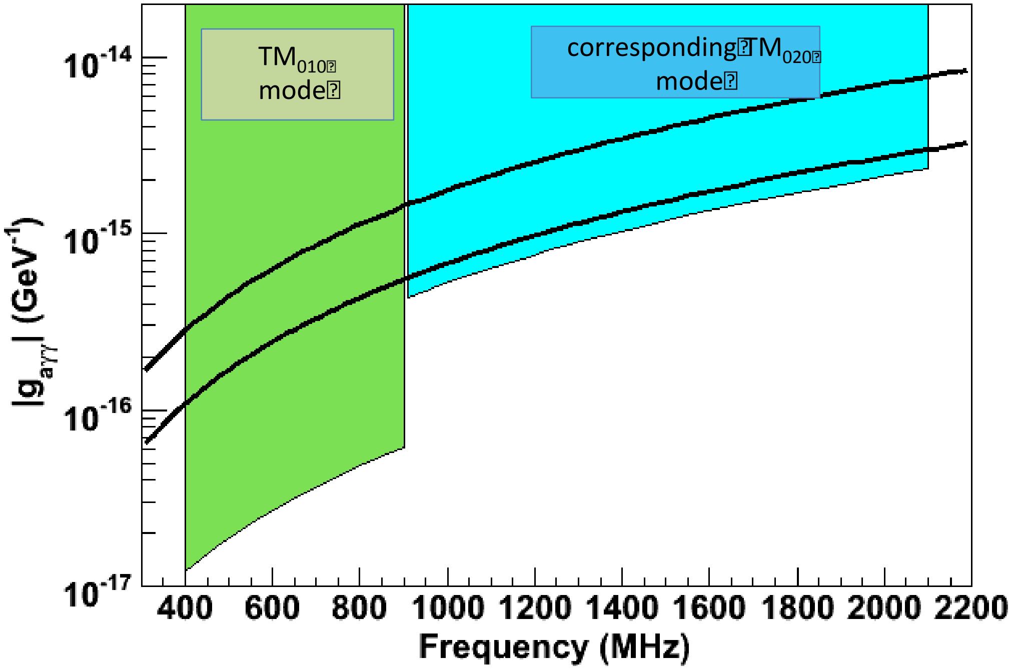
TM_{010} filter receiver

TM_{020} filter receiver

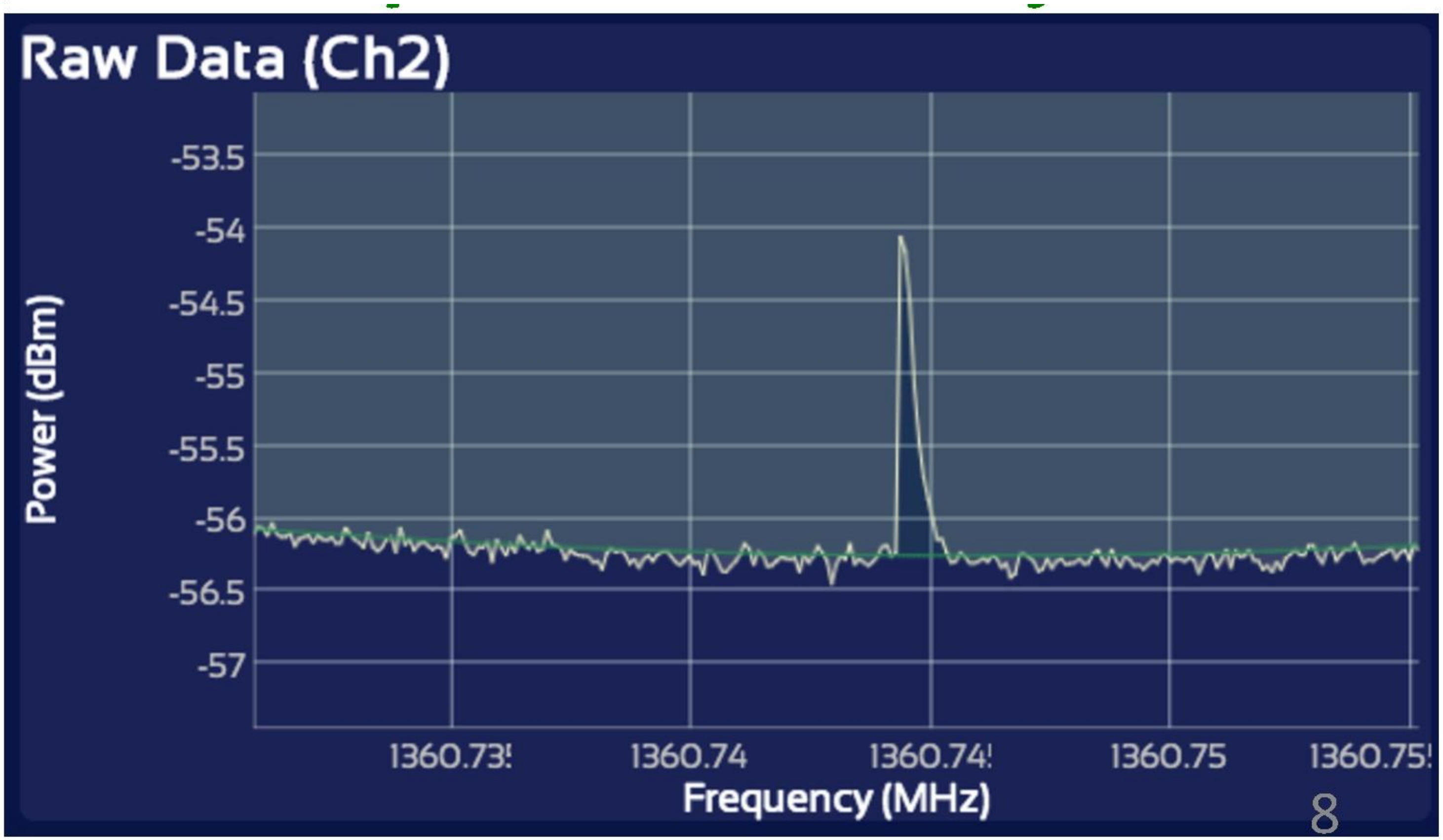
DAQ

cold

warm



Raw data with hardware synthetic axion (✕100)

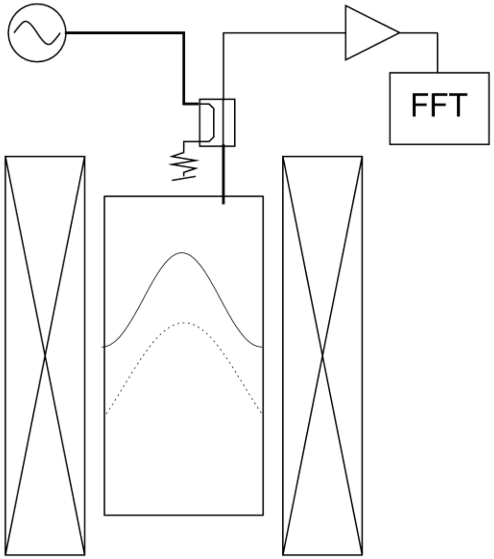


Our confidence limit is our confidence limit

Operations include searches for exotics: “Chameleons”& hidden-sector photons

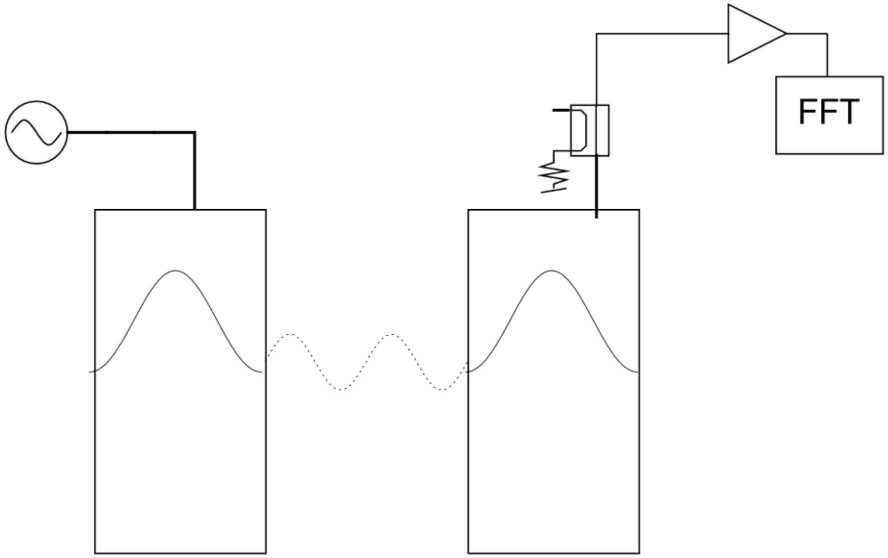
Chameleons

Scalars/pseudoscalars that mix with photons, and are trapped by cavity walls. Arise in some dark energy theories. Detectable by slow decay back into photons in cavity



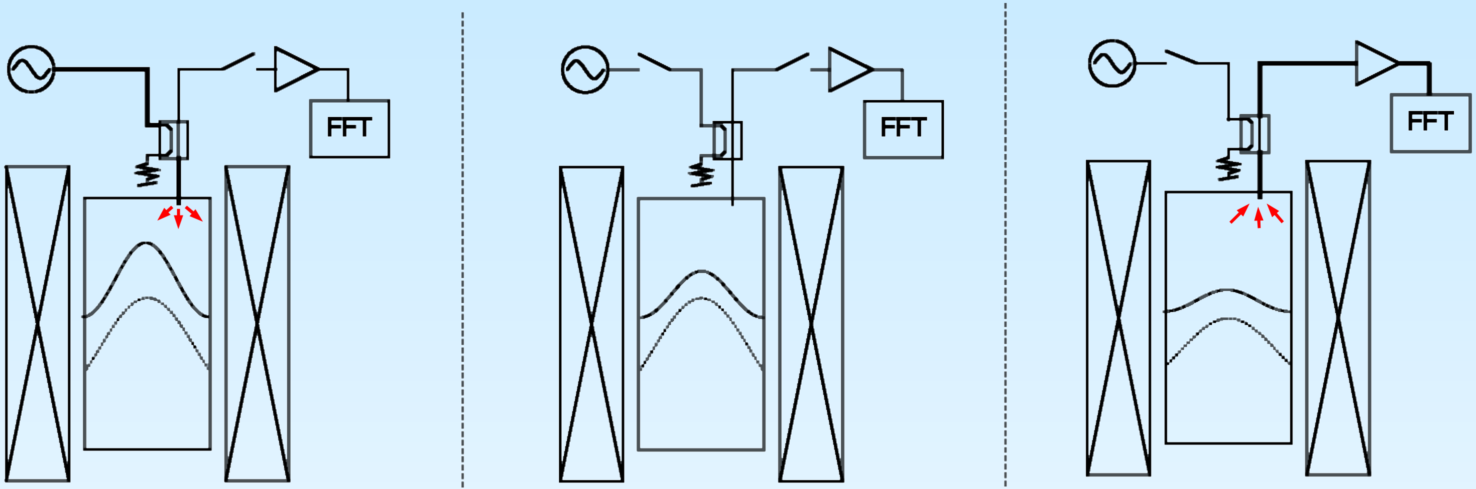
Hidden-sector photons

Vector bosons with photon quantum numbers and very weak interactions. Detectable by reconverting HSPs back into photons in ADMX cavity



Chameleon search in ADMX: Method

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

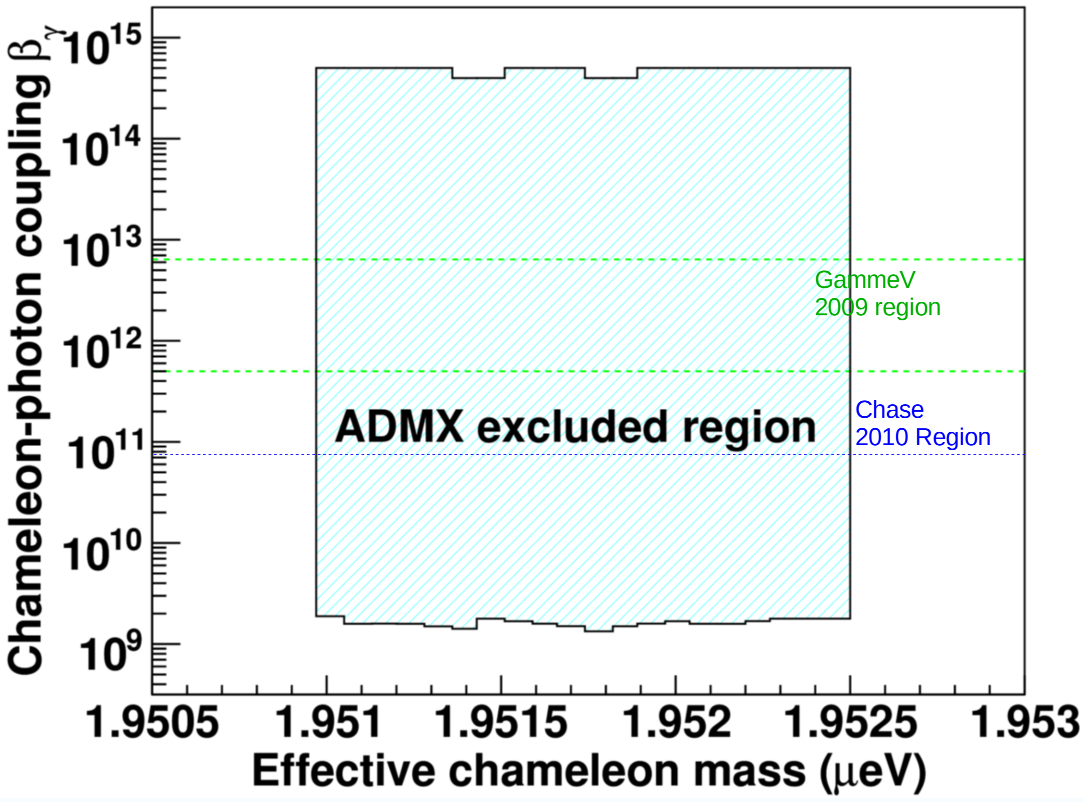
Timescale: 10 minutes
Power in ~25 dBm

Timescale: 100 milliseconds

Timescale: 10 minutes
Sensitivity ~10^{-22} W
Bandwidth ~20 kHz

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

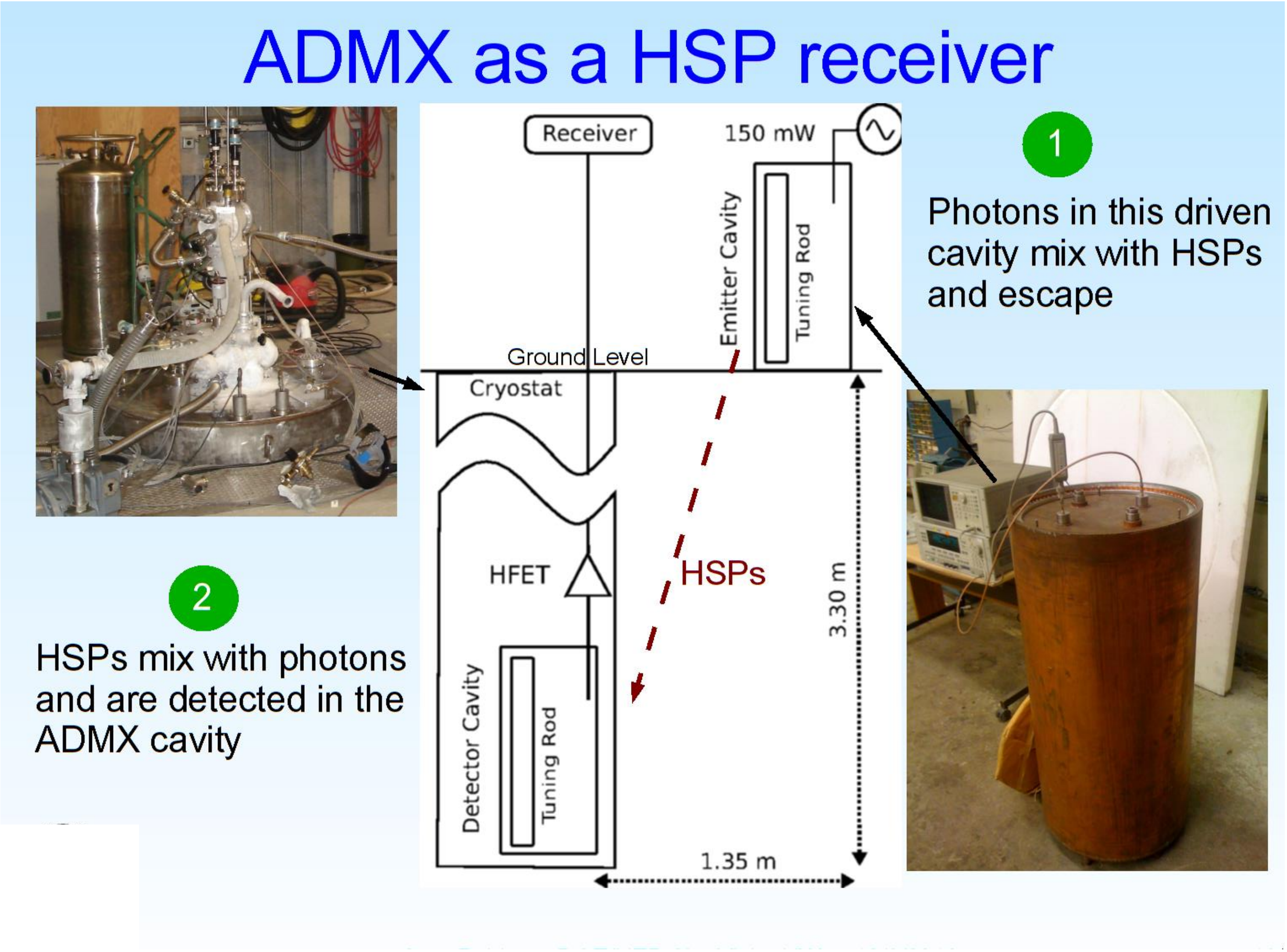
ADMX chameleon bound



Laboratory Dark Energy Search

One day of running set limits 100 times more sensitive than that from FNAL.

Hidden-Sector Photons: Another dark-matter candidate

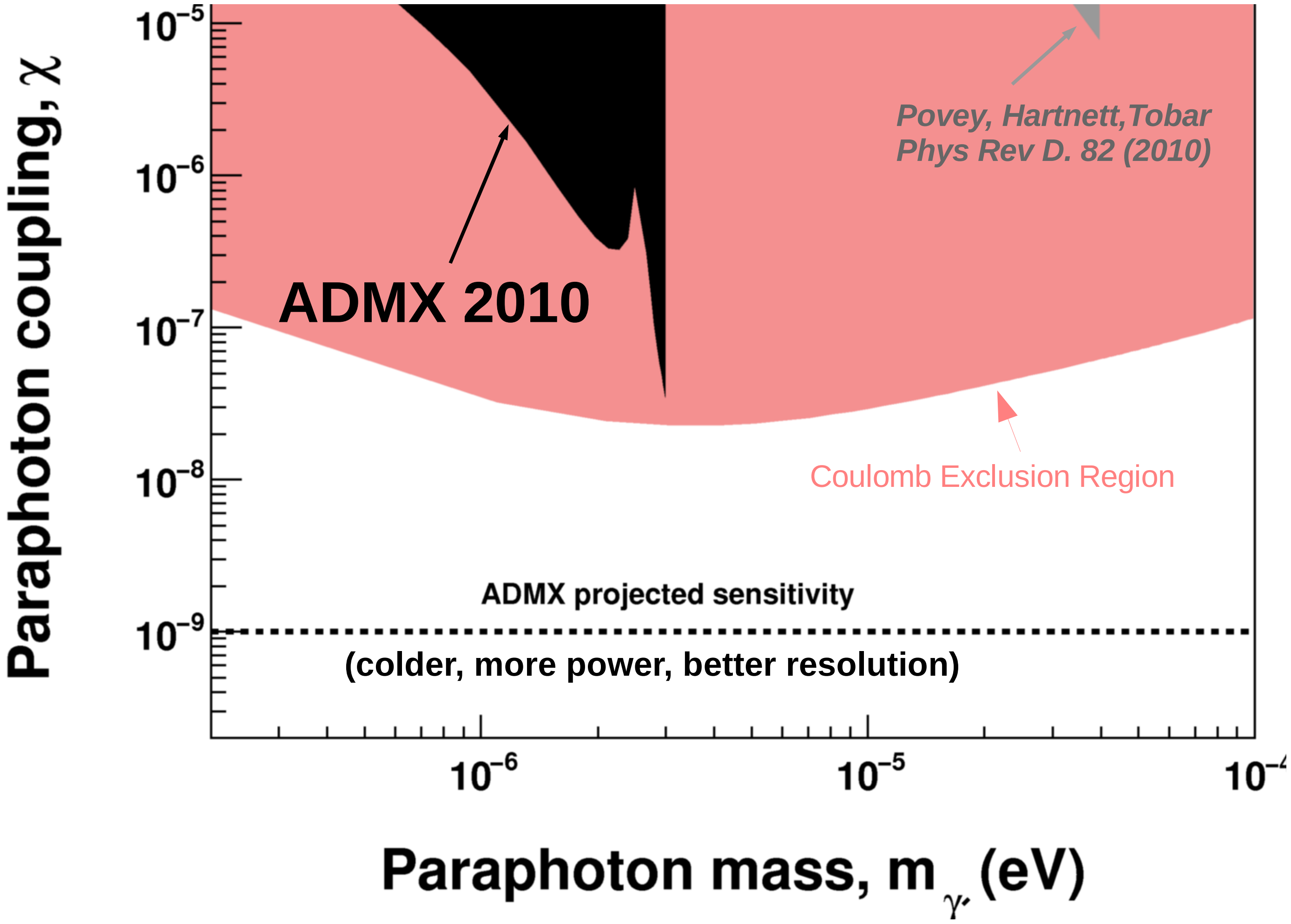


ADMX as a HSP receiver

① Photons in this driven cavity mix with HSPs and escape

② HSPs mix with photons and are detected in the ADMX cavity

ADMX Hidden Sector Photon search in: bound



Next phase projected to extend limits by more than a factor of 10.

Building-up ADMX infrastructure

July 2011

September 2011

June 2012

September 2012

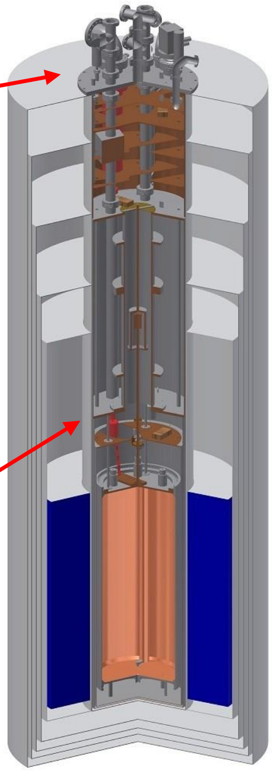
April 2013

April 2014

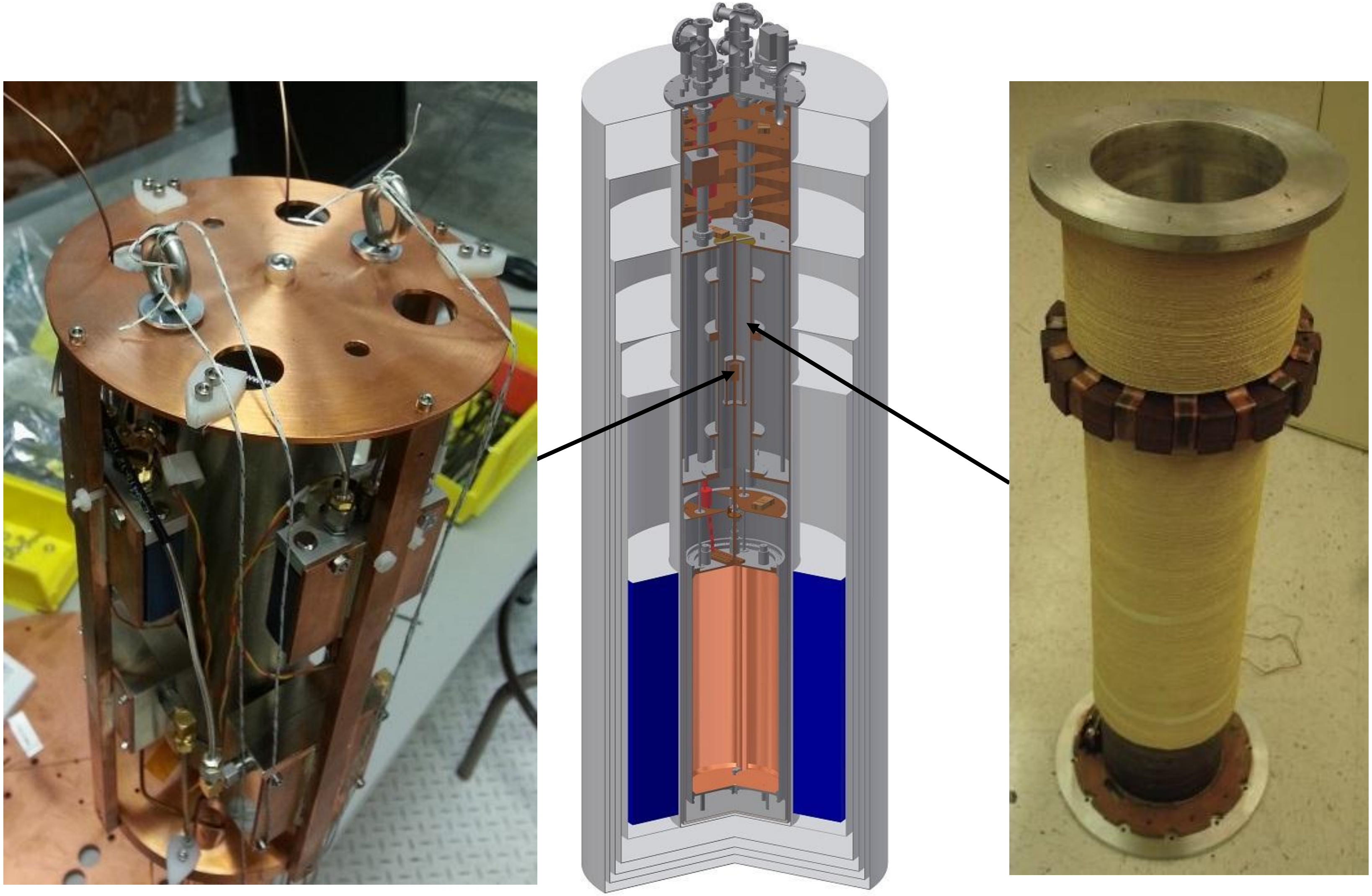
Assembling the ADMX experiment insert

H/53 %%31/)1,)D' =T&9)=1&%

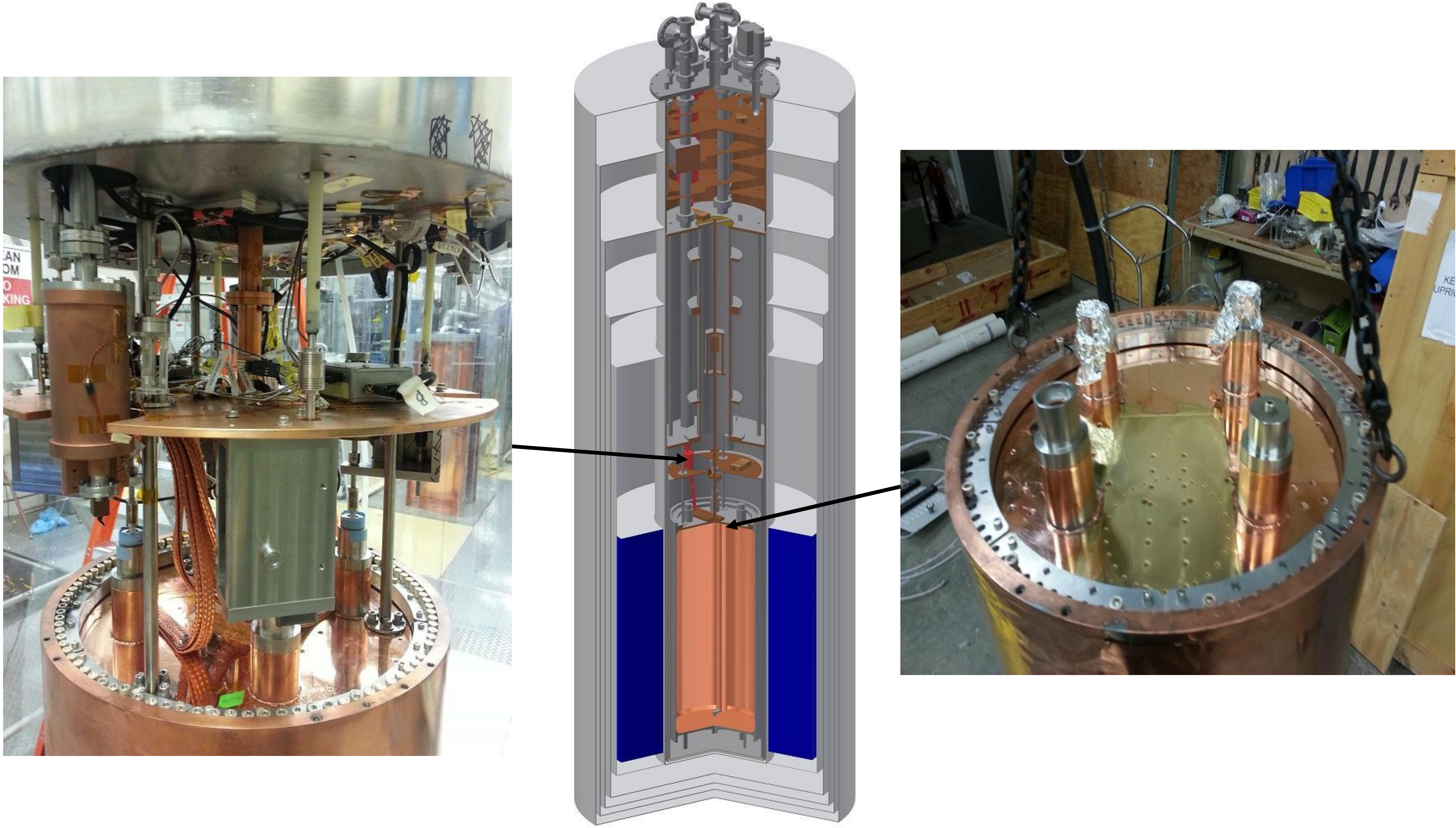
>55$(D%6)1,)31<)8. %,
1,)&5$-3



ADMX quantum-electronics housed in a bucking coil

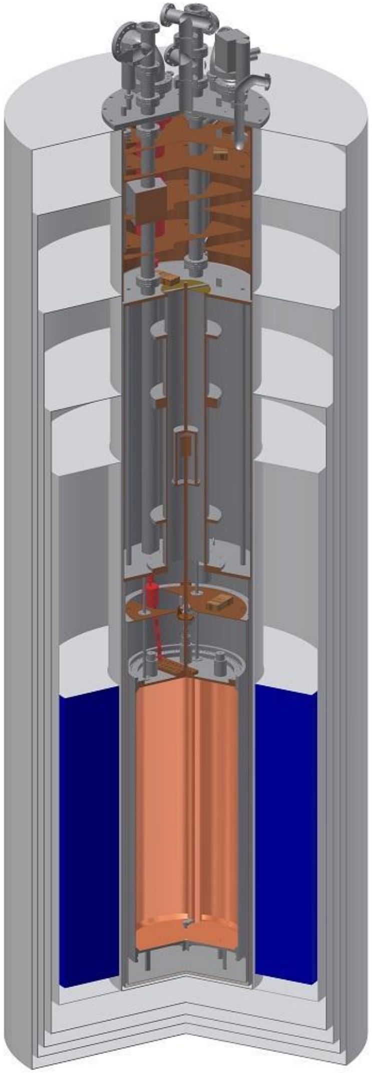


ADMX cavity, tuning and coupling

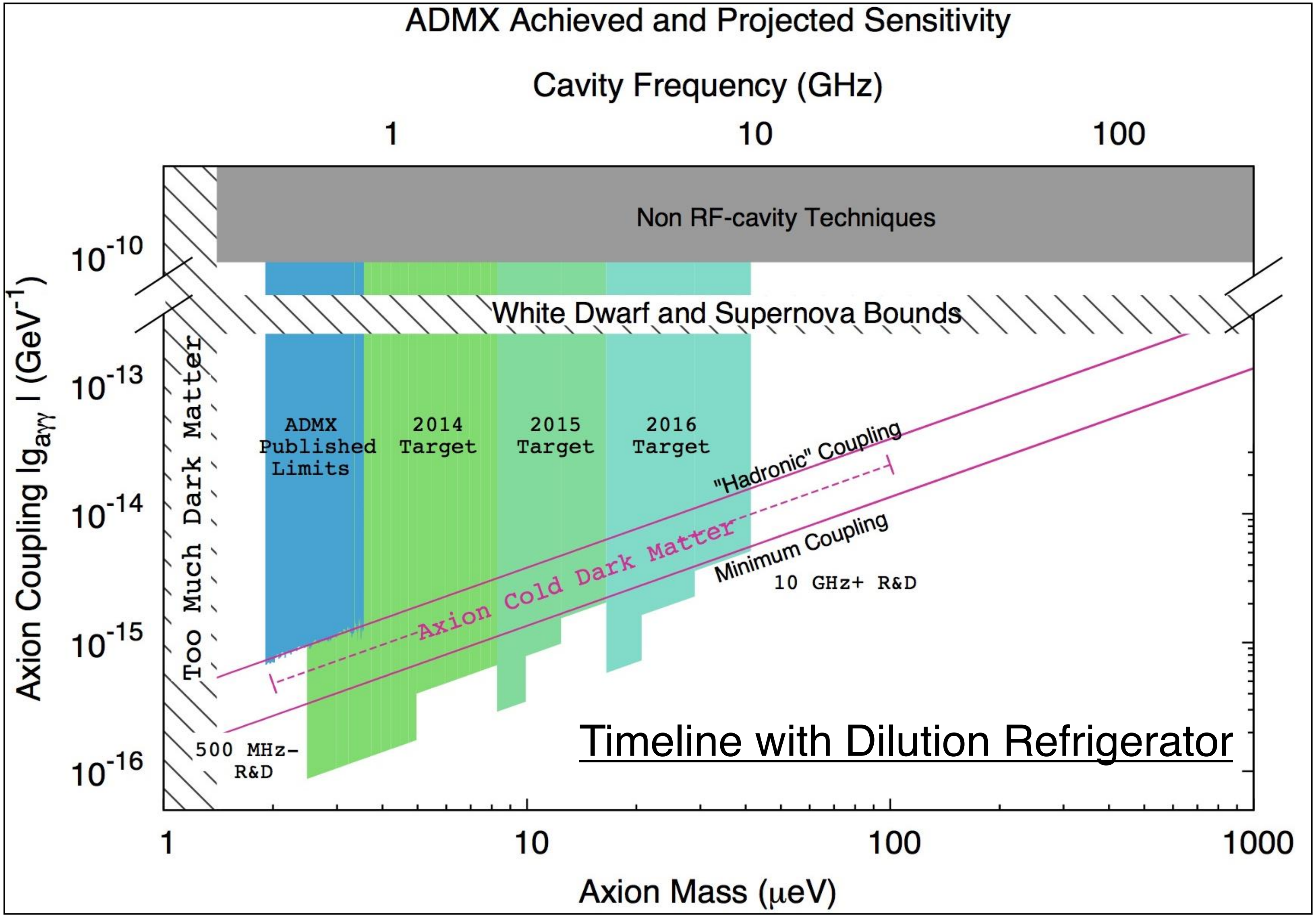


ADMX insert going into and out the magnet bore

Science, Nov. 2013, 552 - 555

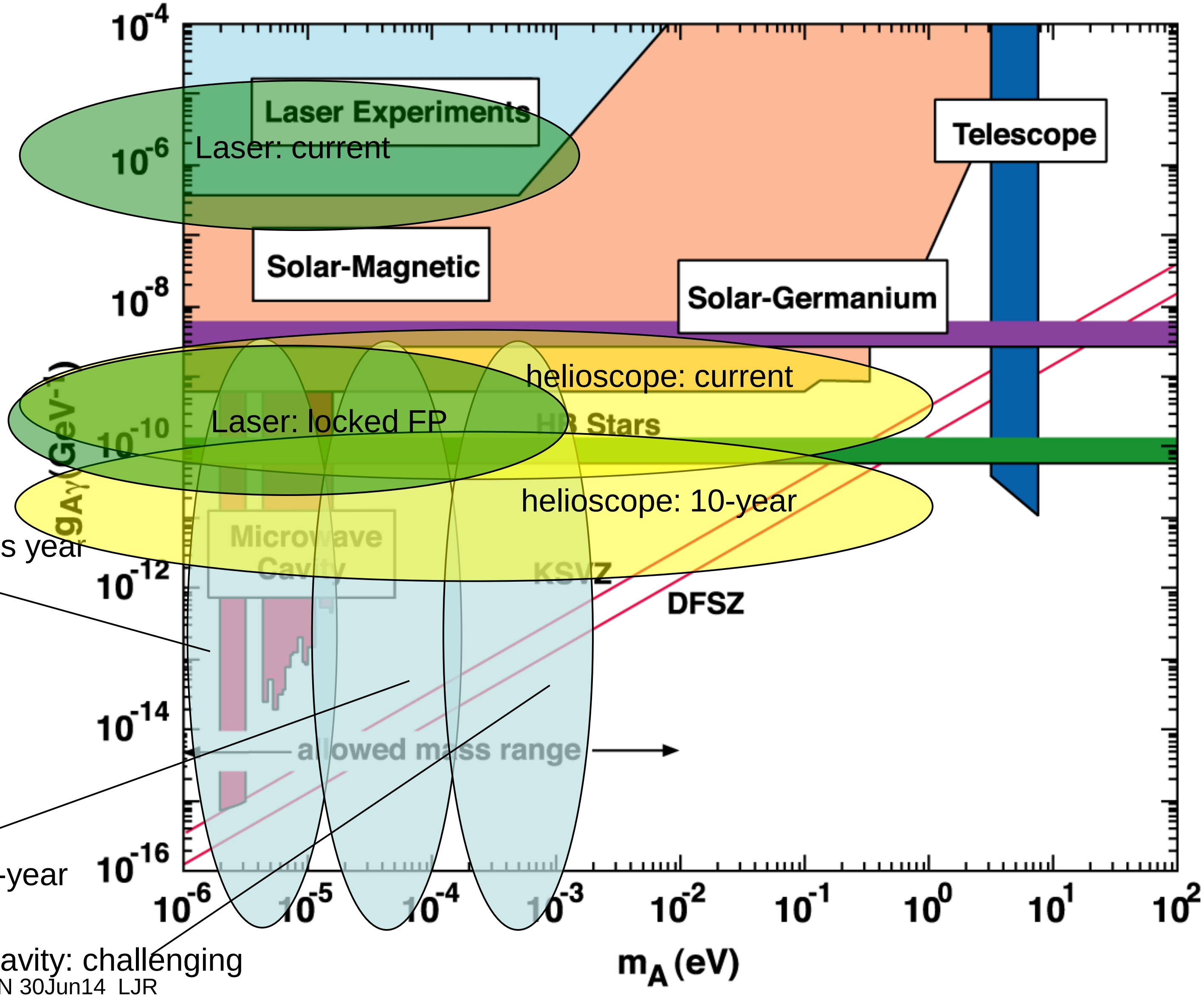


ADMX “Gen 2”: Science Prospects



Timeline with Dilution Refrigerator

ADMX in the context of other key search technologies



Laser: current

helioscope: current

Laser: locked FP

helioscope: 10-year

cavity: this year

cavity: 3-year

cavity: challenging

Conclusions

Axions: A very compelling dark-matter candidate.

- The QCD dark-matter axion is well bounded in mass and couplings.
- The dark-matter axion focus is 1-100 μeV axion masses.

There are many search techniques, but the RF-cavity one is most sensitive.

- ADMX is largest and most mature; several others are on the horizon.
- The next several years will either see a discovery or reject the QCD dark-matter axion hypothesis.

(The space of variant axion (non “QCD”) models is wide open.

- Large efforts are underway for solar axions and laser experiments.
- And ideas are out there for searching for very low-mass & high-mass axions.)

Quite starkly: We have the sensitivity and mass reach to either detect or rule out QCD dark-matter axions at high confidence.

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