Search for PQ Axions

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Institute for Basic Science (IBS)

Outline

- Introduction
  - Strong CP-problem, PQ Axion and Dark Matter
- Cosmic Axion Search
  - ADMX
  - HAYSTAC
  - CULTASK
- Solar Axion Search
  - CAST
  - IAXO
- Axion Search in the Laboratory
  - ALP
- Summary


Lavaloza A LIMÓN
3 Unidades de 450 g c/u
Crema Lavaloza AROMA A LIMÓN
Máxima
Metro CREMA LAVALOZA AROMA ALOEVERA 450g
Metro CREMA LAVALOZA AROMA LIMÓN
¡Para que ahorres mucho más!
$5.990
Lavaloza MAXIMA limon crema x3und. x450g c-u
$1.950
Lavaloza MAXIMA limon crema x450g
$3.490
Lavaloza METRO crema aloe x 450g
$3.490
Lavaloza METRO crema aloe x 450g
$12.150
CREMA LAVALOZA AXION ALOE X 3 UND X 450GR PRE
Precio INCREÍBLE
AXION toque de crema con Avena y Vitamina E 640mL
RINDE EL DOBLE*
ESPUMA ACTIVA
AXION 100% EFECTIVO CONTRA LA GRASA Limón 180 mL
AXION 720 mL
AXION Limón 750 mL
ARRANCA LA GRASA IMPOSIBLE
$6.190
Detergente AXION toque crema avena liquido x640m
$2.350
Lavaloza AXION detergente liq. lm. doypa
$11.990
LAVAPLATOS AXION LIMON *750 ML
$6.390
CREMA LAVALOZA AXION AVENA X 450 GR X 2 UND
RINDE HASTA 50% MÁS*
Salvo

In the beginning…

There was **Strong CP-problem**

Non-perturbative effects related to the vacuum structure of QCD leads to a CP violating term in QCD Lagrangian:

$$L_{QCD,\bar{\theta}} = \bar{\theta}\,\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

This would impose an electric dipole moments of neutron for $\theta \neq 0$

But,

Experimental Limits on neutron EDM $d_n < 3\times10^{-26}\, e\cdot\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$

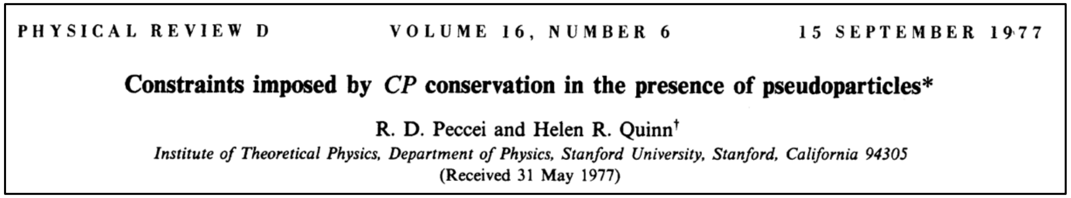
In simple terms: the theory of strong interactions demands a large neutron EDM.
Experiments show it is at least ~ 9-10 orders of magnitude less!

WHY is θ so small?

Strong CP-Problem and PQ Axion

- Pecci-Quinn (1977) introduced a new axial global $U(1)_{PQ}$ symmetry, which is spontaneously broken at an energy scale f_a

$$L_{QCD,\bar{\theta}} = \left(\bar{\theta} - \frac{a(x)}{f_a}\right)\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$



PHYSICAL REVIEW D VOLUME 16, NUMBER 6 15 SEPTEMBER 1977

Constraints imposed by *CP* conservation in the presence of pseudoparticles*

R. D. Peccei and Helen R. Quinn†

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 31 May 1977)

- $\theta = a / f_a$ relaxes to zero…
- CP conservation is preserved "dynamically"

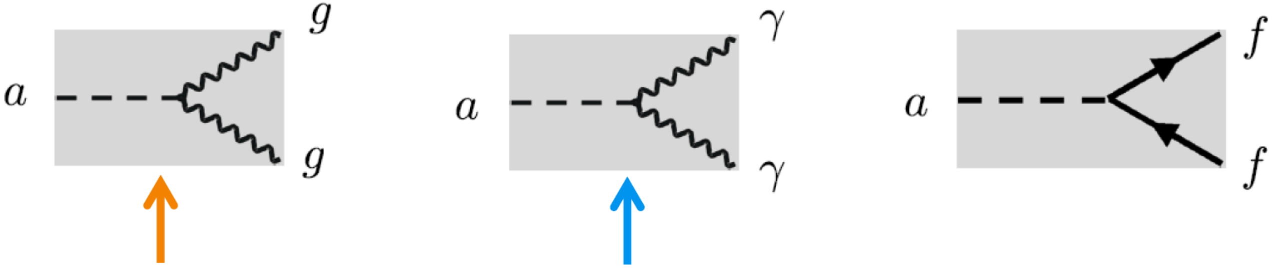
- Weinberg and Wilczek (1978) subsequently pointed out that since a continuous symmetry is broken, there must also be an associated Goldstone boson- the axion

"One needed a particle to clean up a problem…"
-- Franck Wilczek

PQ Axion

- With the PQ symmetry breaking scale f_a
  - ➢ $f_a \gg 10^7$ GeV → $m_a \ll$ eV : “invisible” axion (JinE. Kim, 1979)
  - ➢ Is a pseudo-scalar with spin 0 : behaves like π^0 : $m_a f_a \sim m_\pi f_\pi$
  - ➢ Is very light and weakly interacting
  - ➢ Mass: $m_a \sim 0.6$ eV x (10^7 GeV/ f_a), between 10^{-6} and 10^{-3} eV
  - ➢ Couplings ~ 1/ f_a (hence ~ m_a)

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\; \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$



CP conservation in QCD

Exploited in most experiments

Courtesy A. Ringwald

Axion Dark Matter

- Axions would constitute very cold dark matter in spite of their very low mass

- Very roughly the abundancy of axion cold dark matter is given by:

$$\Omega a / \Omega c \sim (f_a / 10^{12}\mathrm{GeV})^{7/6} = (6\ \mu\mathrm{eV} / m_a)^{7/6}$$

For ma around 10 μeV the axion could make up all of the dark matter!

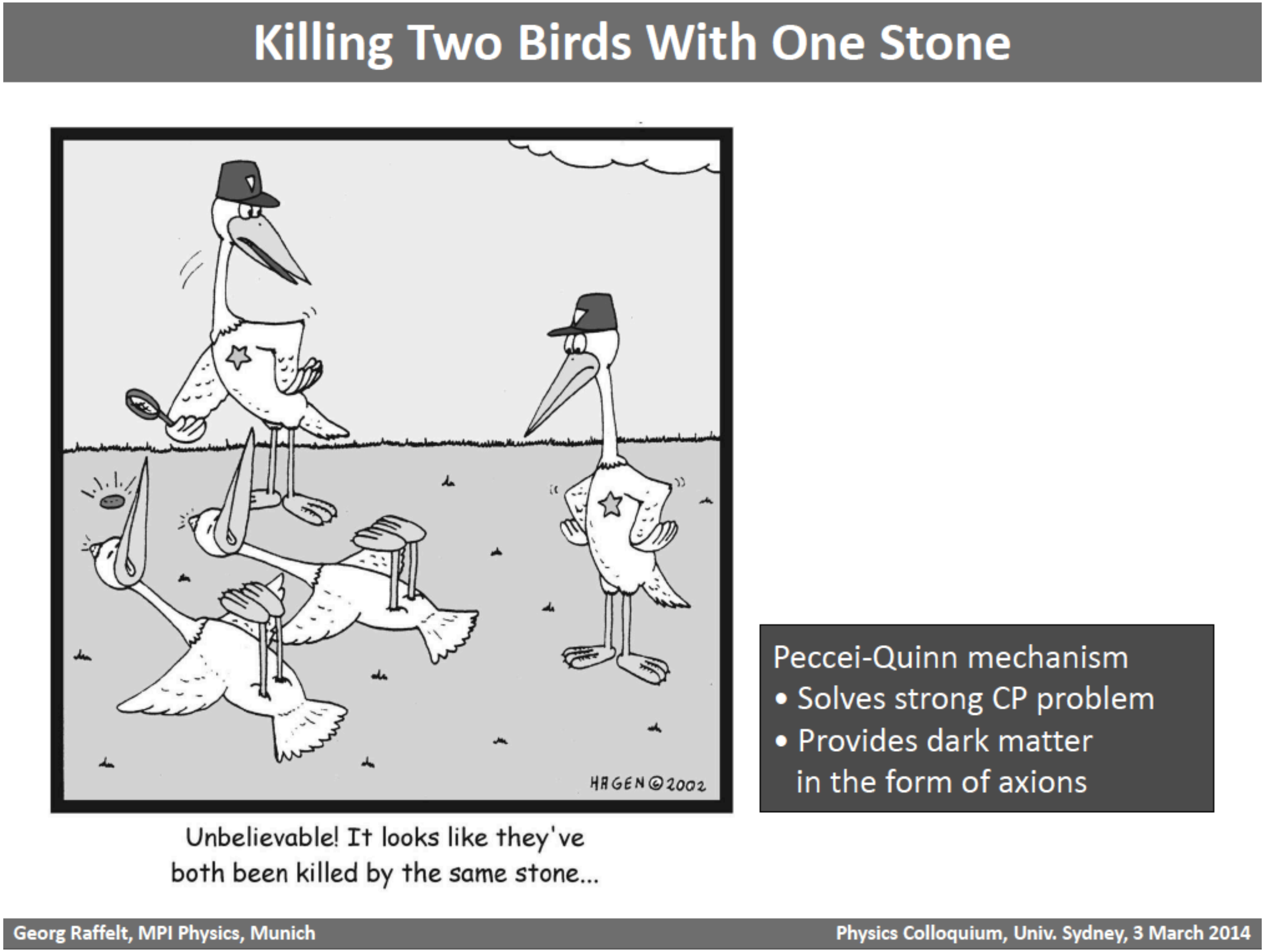
- Axion dark matter could even be similar to a Bose-Einstein condensate.

See for example: https://arxiv.org/abs/1501.05913, Cosmic Axion Bose-Einstein Condensation (Nilanjan Banik, Pierre Sikivie)

- Virial velocity of $\beta \sim 10^{-3}$ (classical)

- Coherence length: $L_{DB} = 1\ \mathrm{m} \times (1\ \mathrm{meV} / m_a)$

Axion Dark Matter



Killing Two Birds With One Stone

Unbelievable! It looks like they've both been killed by the same stone...

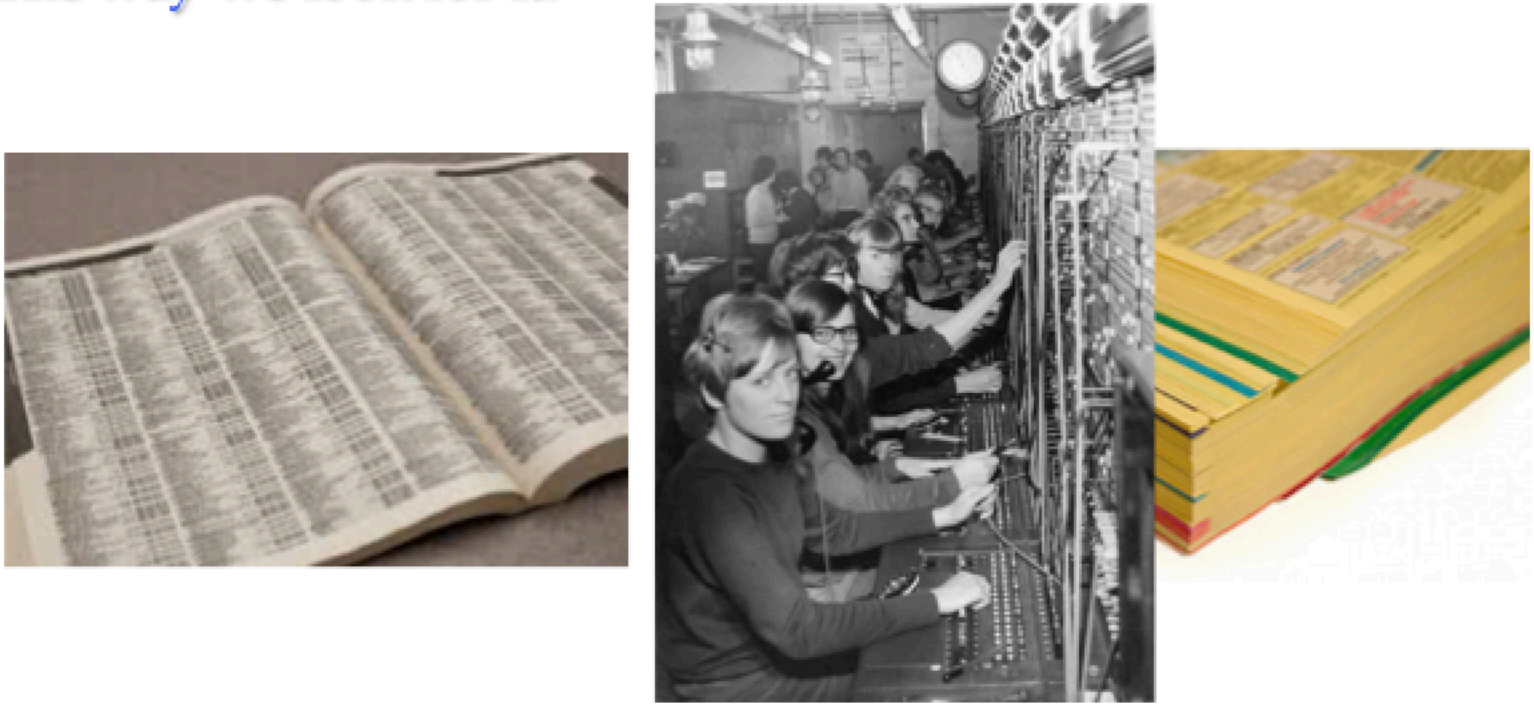
Peccei-Quinn mechanism
- Solves strong CP problem
- Provides dark matter in the form of axions

Georg Raffelt, MPI Physics, Munich

Physics Colloquium, Univ. Sydney, 3 March 2014

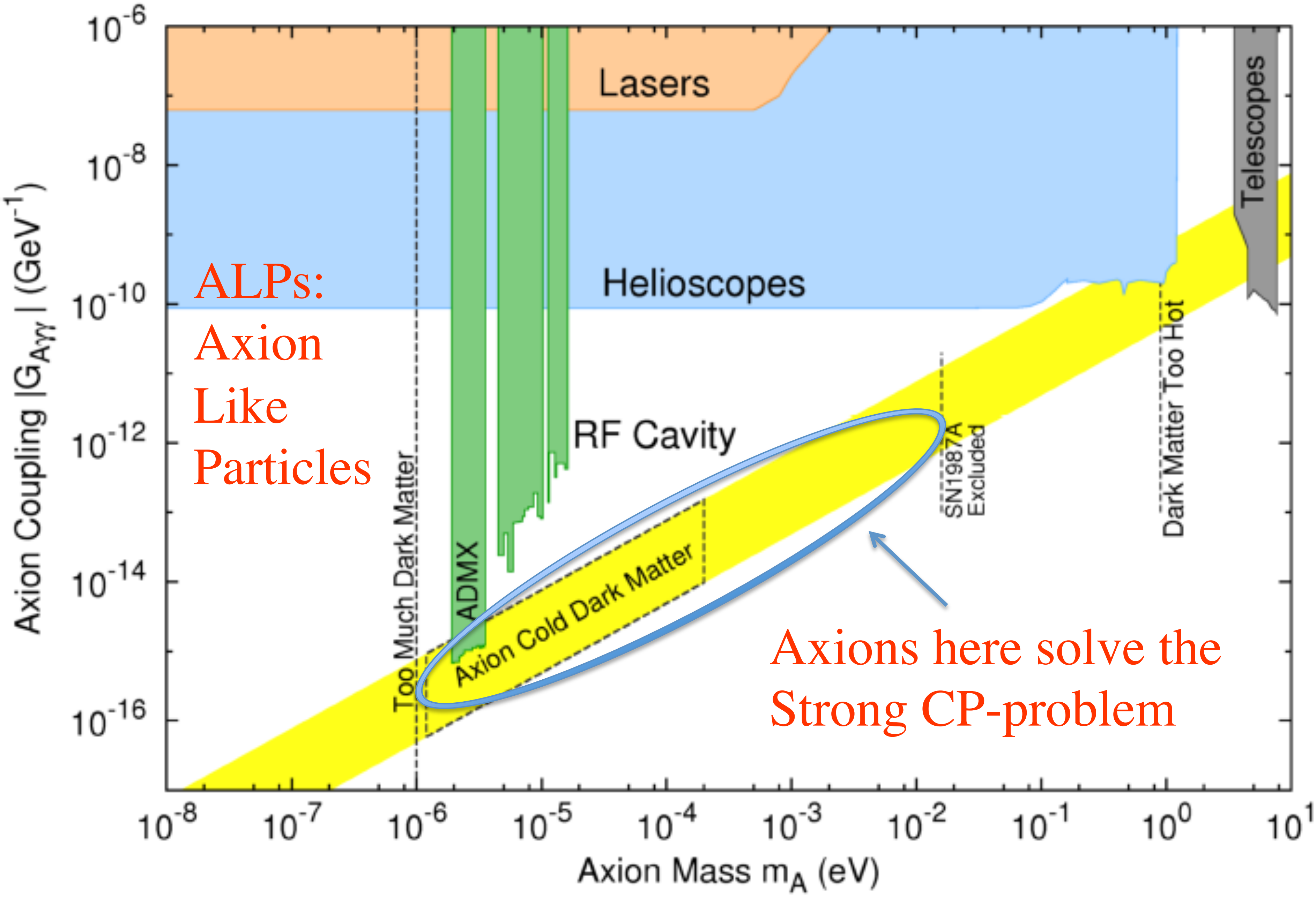
Axion dark matter search

- The axion mass is unknown, like any number in a phone book. The way we look for it:



- Once it's discovered, anyone will be able to dial in… and talk to it.

Axion Landscape



ALPs:
Axion
Like
Particles

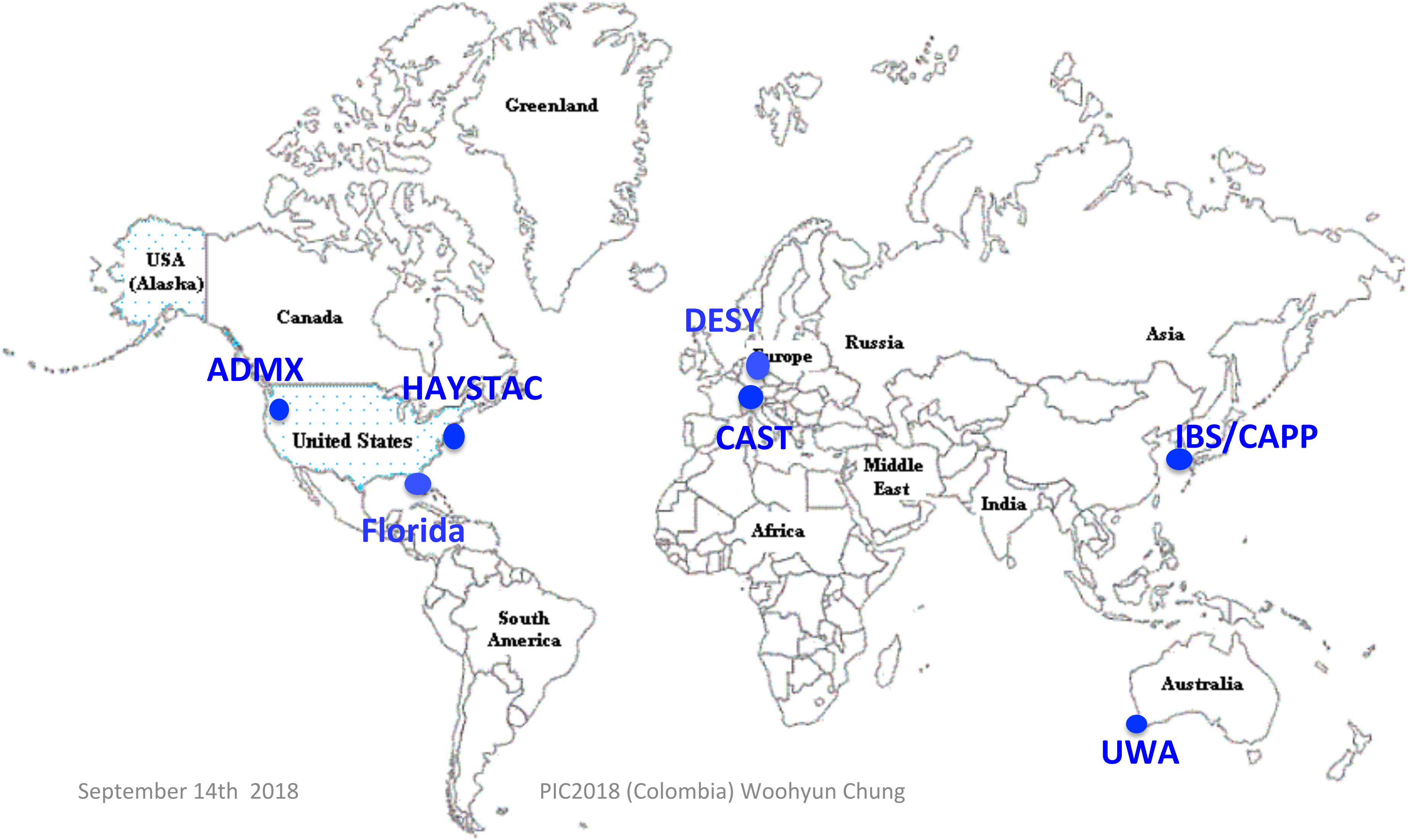
Axions here solve the Strong CP-problem

Axion Search Experiments

- Cosmic Axion Search
  - Haloscopes (Microwave Cavity)
  - Dish Antenna
  - Dielectric Haloscope
  - LC Circuit
  - NMR techniques
  - Atomic Transitions
- Solar axion search
  - Axion Helioscopes
  - Bragg Diffraction Scattering
  - Geomagnetic Conversion
- Laboratory Axion Search
  - Light Shining through Wall
  - Polarization Experiment
  - 5th Force

← Most sensitive so far

Major Axion Activities



Cosmic Axion Search

Cosmic Axion Search

Name	Type	Mass range	Location	Status	Reference
ADMX G2	cavity	10^{-6} to 10^{-5} eV	Seattle	Running	Phys. Rev. Lett. 120, 151301
HAYSTAC	cavity	10^{-5} to 10^{-4} eV	Yale	Running	https://arxiv.org/abs /1803.03690
CULTASK	cavity	10^{-5} to 10^{-4} eV	IBS/CAPP	Running	https://capp.ibs.re.kr/html/capp_en/
KLASH	cavity	2 x 10^{-7} eV	INFN	Proposed	https://arxiv.org/abs /1707.06010
ORGAN	cavity	10^{-4} eV	UWA	Prototype	https://arxiv.org/abs /1706.00209
RADES	cavity	3.5 x 10^{-5} eV	CERN	Prototype	https://arxiv.org/abs /1803.01243
BEAST	capacitive	10^{-11} eV	UWA	Tests	https://arxiv.org/abs /1803.07755
FUNK	dish	(hidden γ search)	KIT	Running	https://arxiv.org/abs /1711.02961
BRASS	dish	10^{-5} to 10^{-2} eV	Hamberg	Proposed	

Cosmic Axion Search

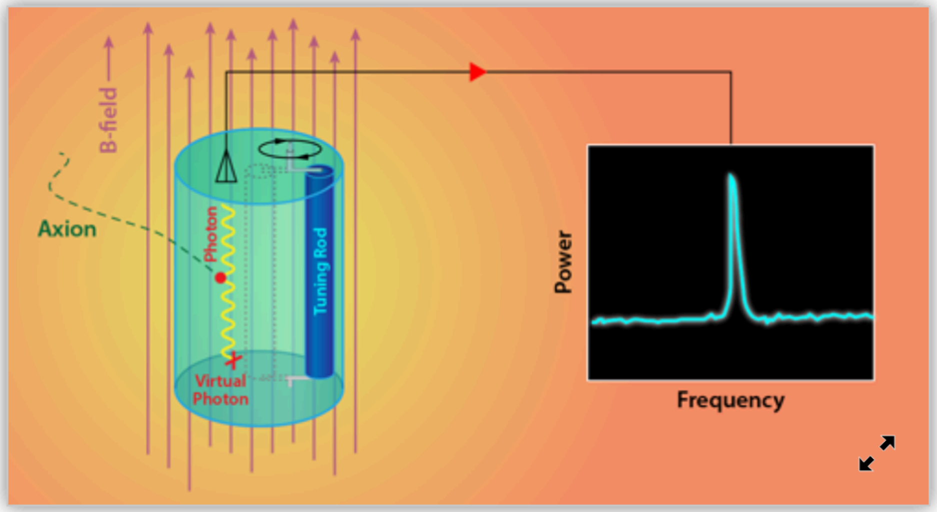
Name	Type	Mass range	Location	Status	Reference
ABRACADABRA	toroid	10^{-14} to 10^{-6} eV	MIT	Prototype	https://arxiv.org/abs /1602.01086
CASPEr-electric	LC Circuit	$<10^{-6}$ eV	Mainz	Proposed	
GNOME	magneto meter	10^{-21} to 10^{-10} eV	Mainz	Running	https://budker.uni-mainz.de/gnome/
CASPEr	NMR	10^{-17} to 10^{-6} eV	Mainz	Proposed	https://arxiv.org/abs /1711.08999
QUAX	NMR	2×10^{-4} eV	INFN	Running	https://doi.org/10.1016/j.dark.2017.01.003

Haloscope

- Conventional axion haloscope technique consists of a high-Q microwave cavity inside a homogeneous magnetic field to trigger the conversion of DM axions into photons.

P. Sikivie, \Experimental tests of the invisible axion,"
Phys. Rev. Lett. 51 (1983) 1415 . 6 , 53 , 61 , 63

$$L_{a\gamma\gamma} = g_{\gamma} \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker

Running Axion Experiments (Haloscope)

ADMX
HAYSTAC
CULTASK

Haloscope

Signal power (conversion):

$$\begin{aligned} P_s &= \kappa \frac{Q}{m_a} g_{a\gamma}^2 B_e^2 |\mathcal{G}_m|^2 V \varrho_a \\ &= 7.2 \times 10^{-23}\mathrm{W} \left(\frac{\kappa}{0.5}\right) \left(\frac{Q}{10^5}\right) \left(\frac{\mu\mathrm{eV}}{m_a}\right) \left(\frac{g_{a\gamma}}{2 \times 10^{-16}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_e}{8\mathrm{T}}\right)^2 \left(\frac{|\mathcal{G}_m|^2}{0.69}\right) \frac{V}{200\mathrm{l}} \tilde{\varrho}_a \end{aligned}$$

Noise power (thermal + amplifier)

$$\begin{aligned} P_n &= T_{sys}\Delta\nu = T_{sys}\frac{m_a}{2\pi Q_a} \\ &= 3.3 \times 10^{-21} \left(\frac{T_{sys}}{K}\right) \left(\frac{m_a}{\mu\mathrm{eV}}\right) \left(\frac{10^6}{Q_a}\right) \end{aligned}$$

Signal to Noise Ratio

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_s}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta\nu}},$$

Scanning Speed

$$\frac{dm_a}{dt} = \frac{Q_a}{Q}\frac{2\pi\Delta\nu}{\Delta t} = \frac{Q_a}{Q}\left(\frac{\mathrm{S}}{\mathrm{N}}\right)^2 \left(\frac{T_{sys}}{P_s}\right)^2$$

Haloscope Detection Scheme

P. Sikivie's Haloscope:

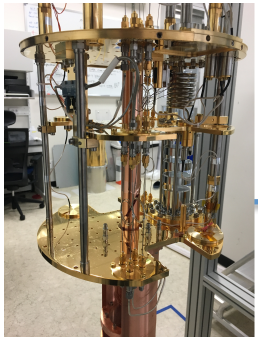
Axion Conversion Power (~10^{-24}W): $$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

Signal to Noise Ratio: $$SNR \equiv \frac{P_{signal}}{P_{noise}} = \frac{P_{a\to\gamma\gamma}}{k_B T_{syst}} \sqrt{\frac{t_{int}}{\Delta f_a}}$$

Scan rate: $$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics

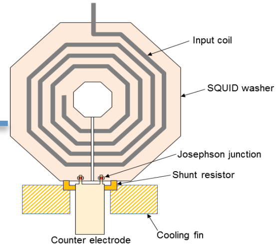
<50mK

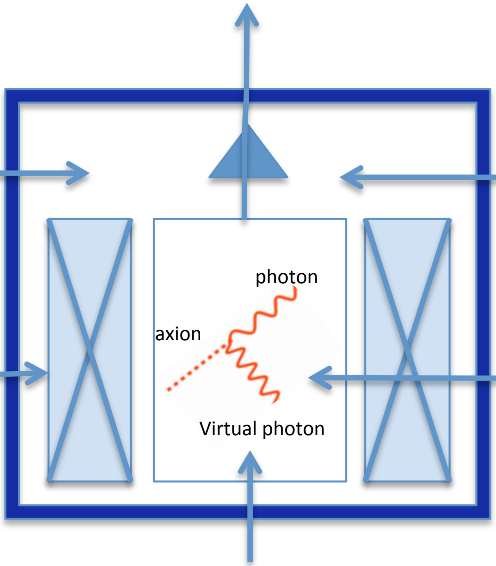


To RF Receiver

SQUID Amplifier

SQUID or JPA (commercial?)

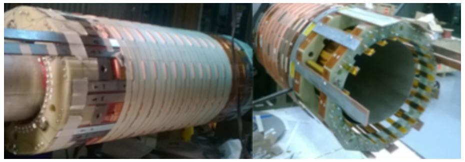




High Field SC Magnet

25T and then 35T

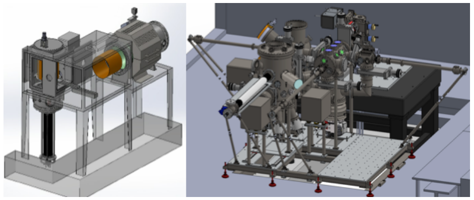
BNL (HTS Technology) Design



High Q Tunable Cavity

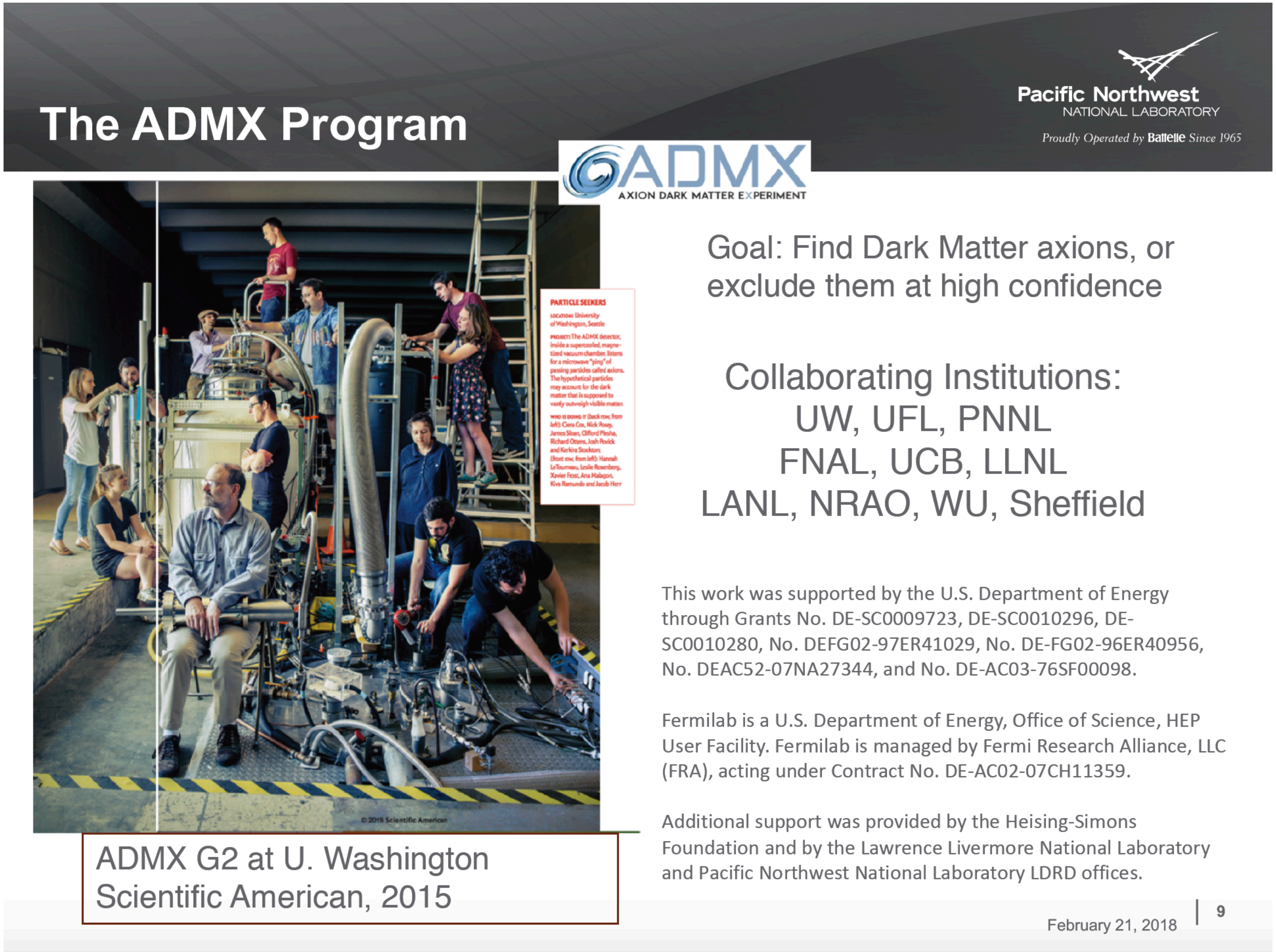
Superconducting Coating

Prof. Jhinhwan Lee of KAIST



(Reverse) Primakoff Effect

ADMX (Haloscope)



The ADMX Program

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by **Battelle** *Since 1965*

ADMX AXION DARK MATTER EXPERIMENT

PARTICLE SEEKERS

LOCATION: University of Washington, Seattle

PROJECT: The ADMX detector, inside a supercooled, magnetized vacuum chamber, listens for a microwave "ping" of passing particles called axions. The hypothetical particles may account for the dark matter that is supposed to vastly outweigh visible matter.

WHO IS DOING IT *(back row, from left)*: Ciera Cox, Nick Posey, James Sloan, Clifford Plesha, Richard Ottens, Josh Povick and Kerkira Stockton; *(front row, from left)*: Hannah LeTourneau, Leslie Rosenberg, Xavier Frost, Ana Malagon, Kiva Ramundo and Jacob Herr

© 2015 Scientific American

ADMX G2 at U. Washington
Scientific American, 2015

Goal: Find Dark Matter axions, or exclude them at high confidence

Collaborating Institutions:
UW, UFL, PNNL
FNAL, UCB, LLNL
LANL, NRAO, WU, Sheffield

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, DE-SC0010296, DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-AC03-76SF00098.

Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

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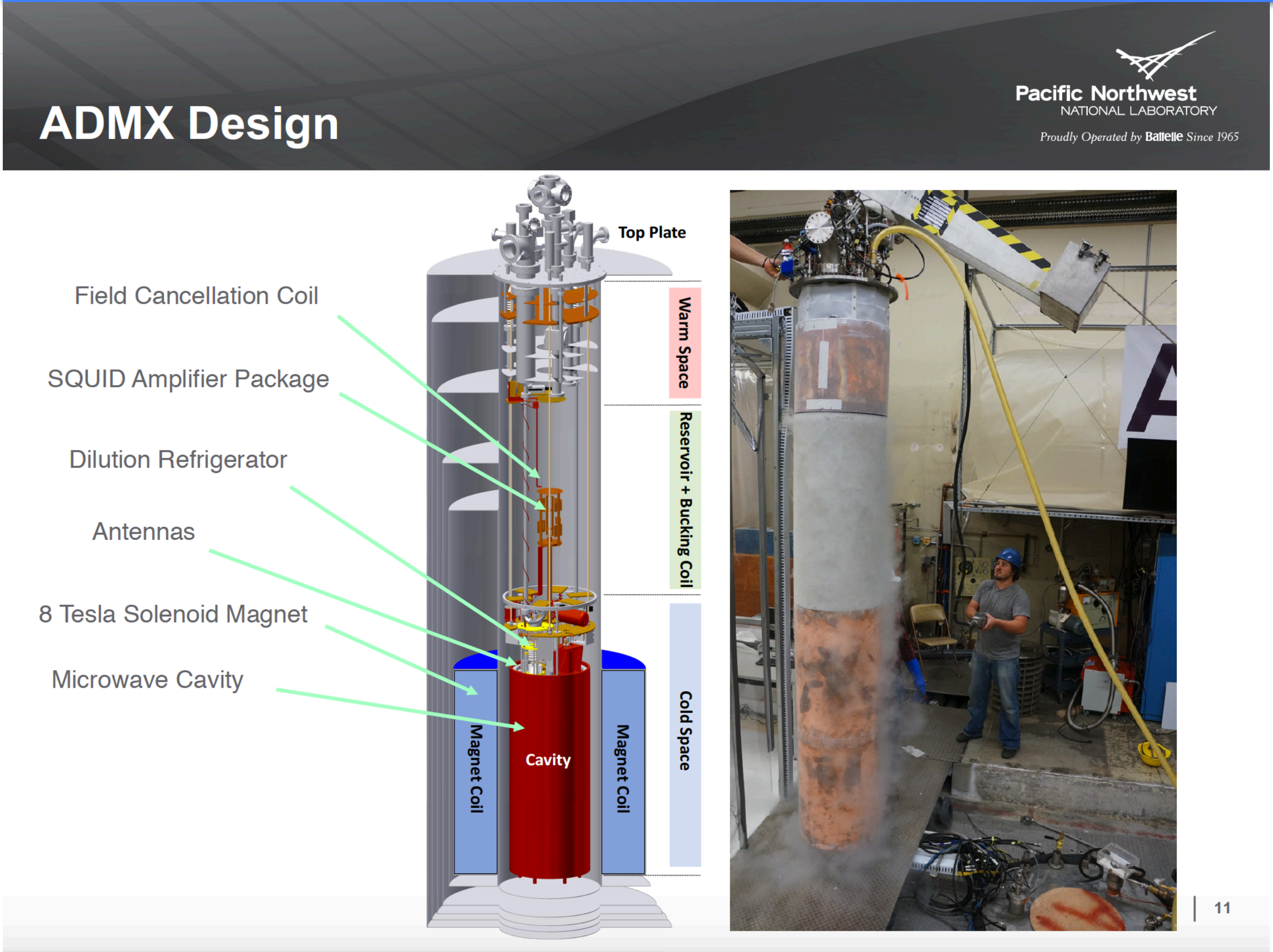
ADMX (Haloscope)



ADMX Design

Pacific Northwest
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Field Cancellation Coil

SQUID Amplifier Package

Dilution Refrigerator

Antennas

8 Tesla Solenoid Magnet

Microwave Cavity

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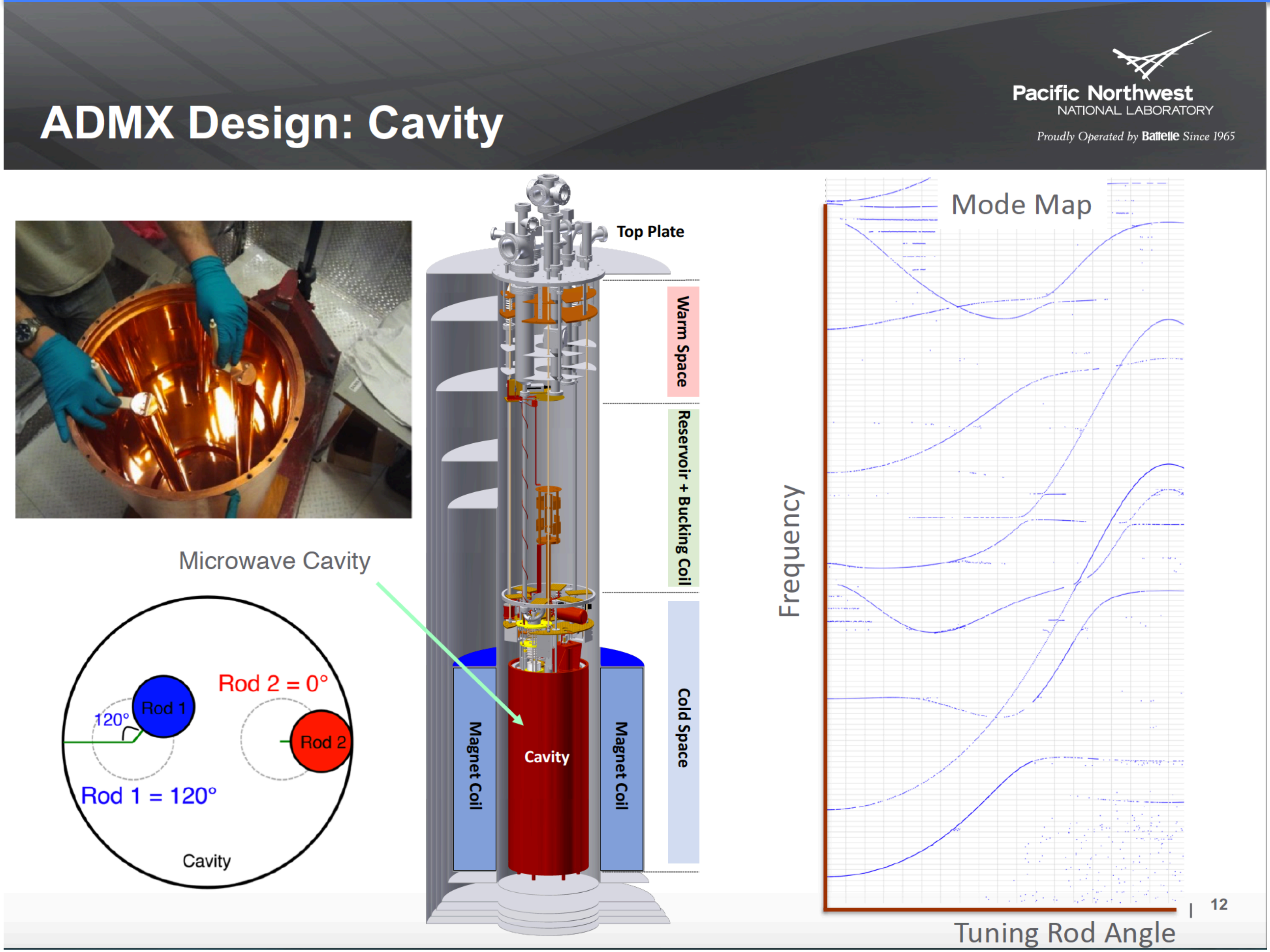
ADMX (Haloscope)



ADMX Design: Cavity

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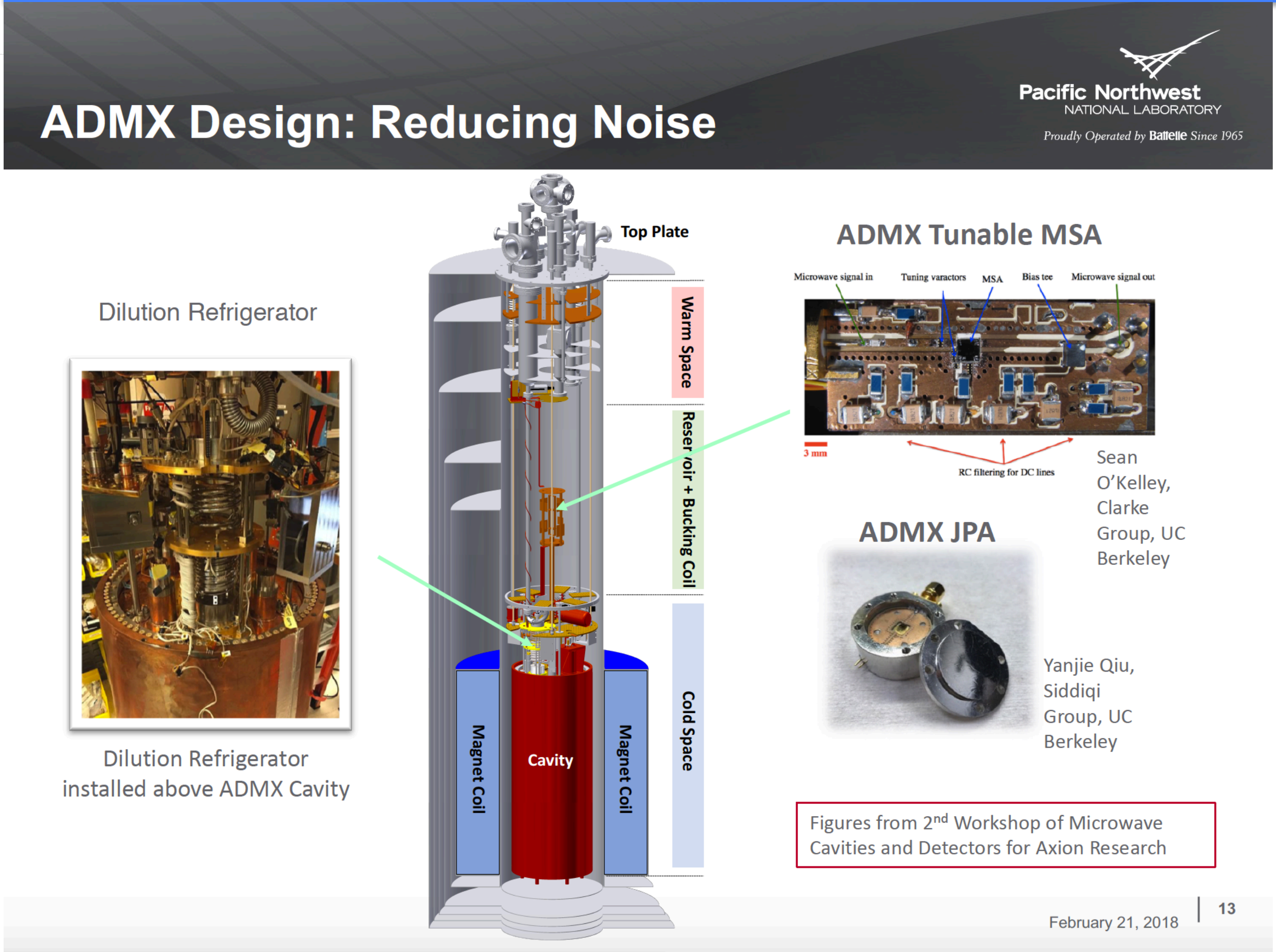
ADMX (Haloscope)



ADMX Design: Reducing Noise

Pacific Northwest NATIONAL LABORATORY
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Dilution Refrigerator

Dilution Refrigerator installed above ADMX Cavity

ADMX Tunable MSA

Sean O'Kelley, Clarke Group, UC Berkeley

ADMX JPA

Yanjie Qiu, Siddiqi Group, UC Berkeley

Figures from 2nd Workshop of Microwave Cavities and Detectors for Axion Research

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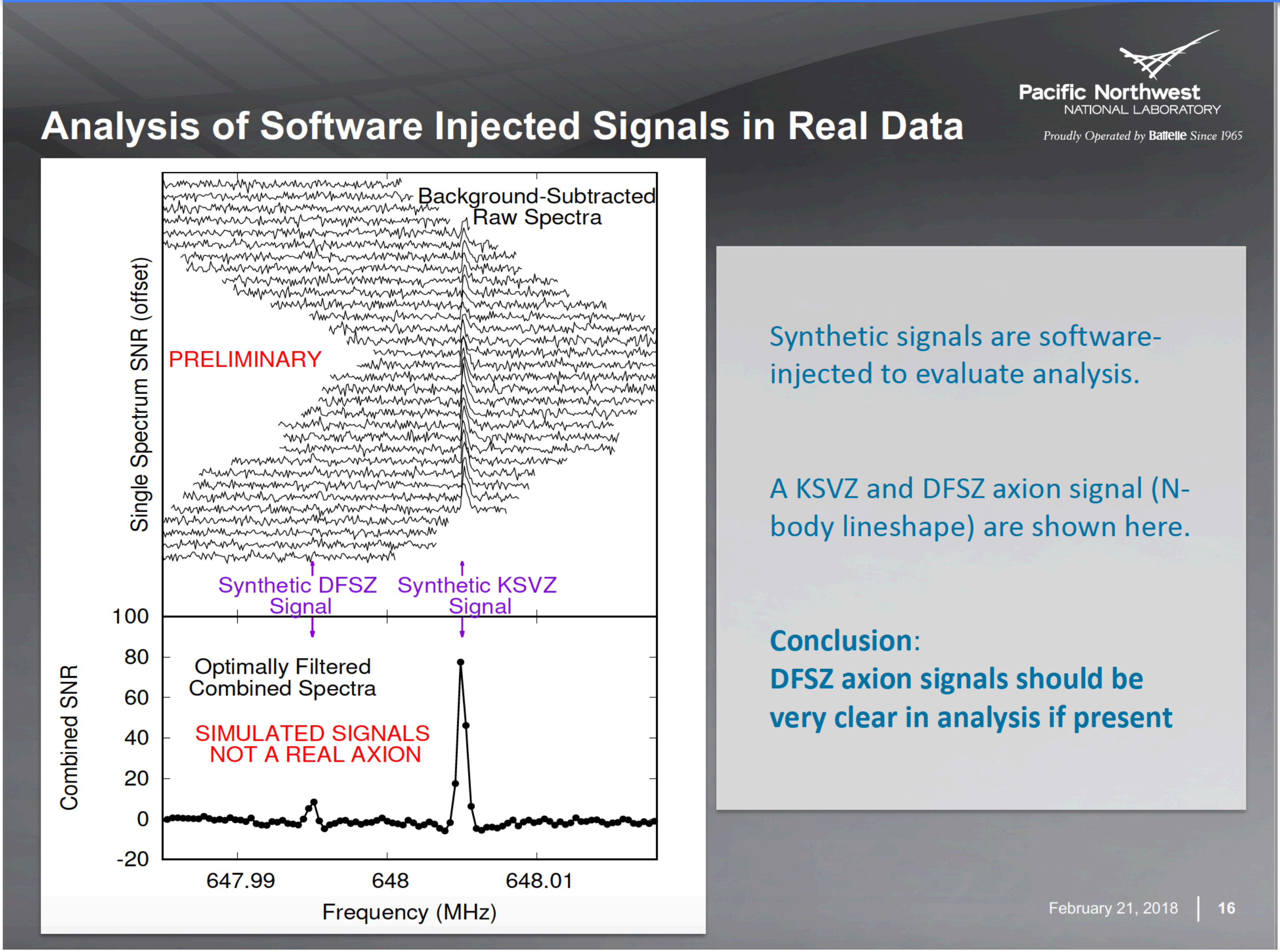
ADMX (Haloscope)



Analysis of Software Injected Signals in Real Data

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Synthetic signals are software-injected to evaluate analysis.

A KSVZ and DFSZ axion signal (N-body lineshape) are shown here.

Conclusion:
DFSZ axion signals should be very clear in analysis if present

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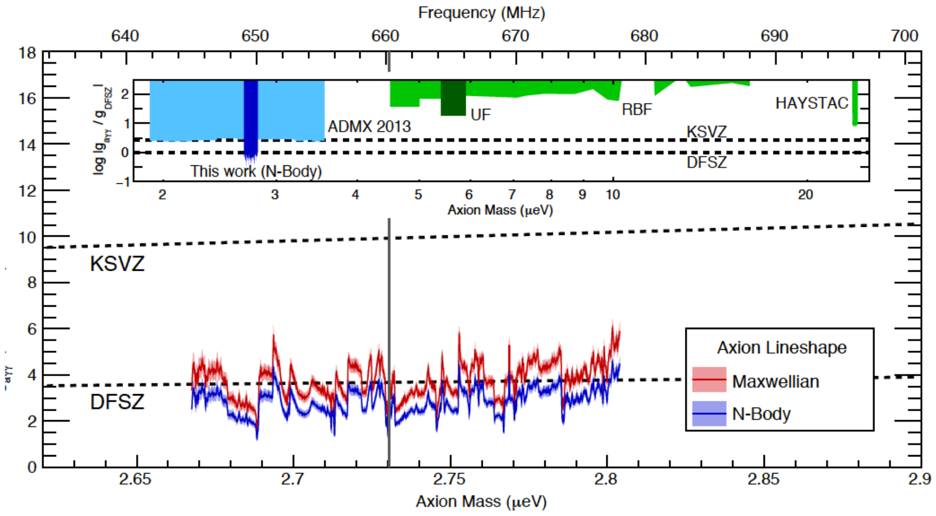
ADMX (Haloscope)

ADMX Exclusion Limits 2017



We didn’t find an axion over this narrow range. More importantly, we could have. This is the first exploration into the plausible DFSZ coupling in the prime mass range for Dark Matter. A discovery could come at any time.

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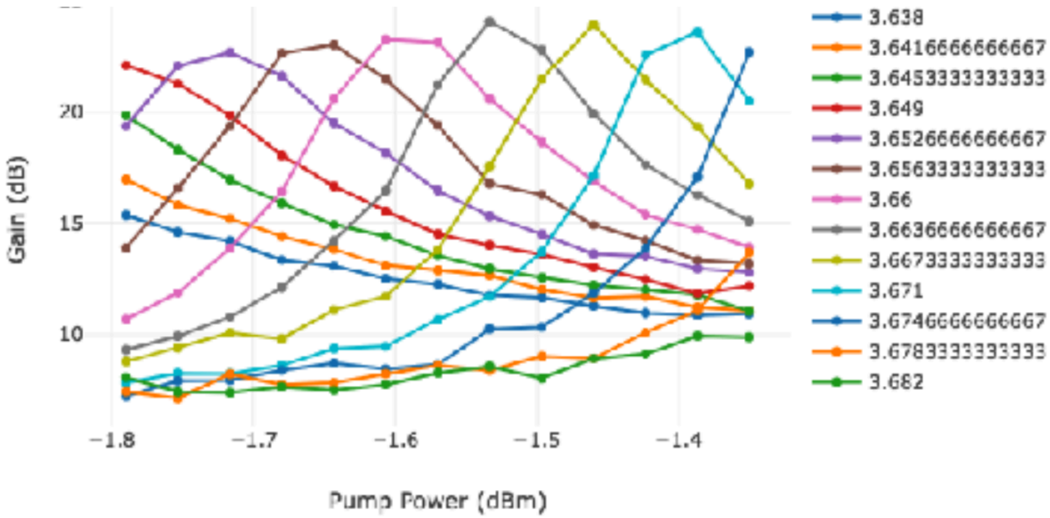
Rybka - ICHEP July 2018

ADMX (Haloscope)

2018 Operations: Electronics

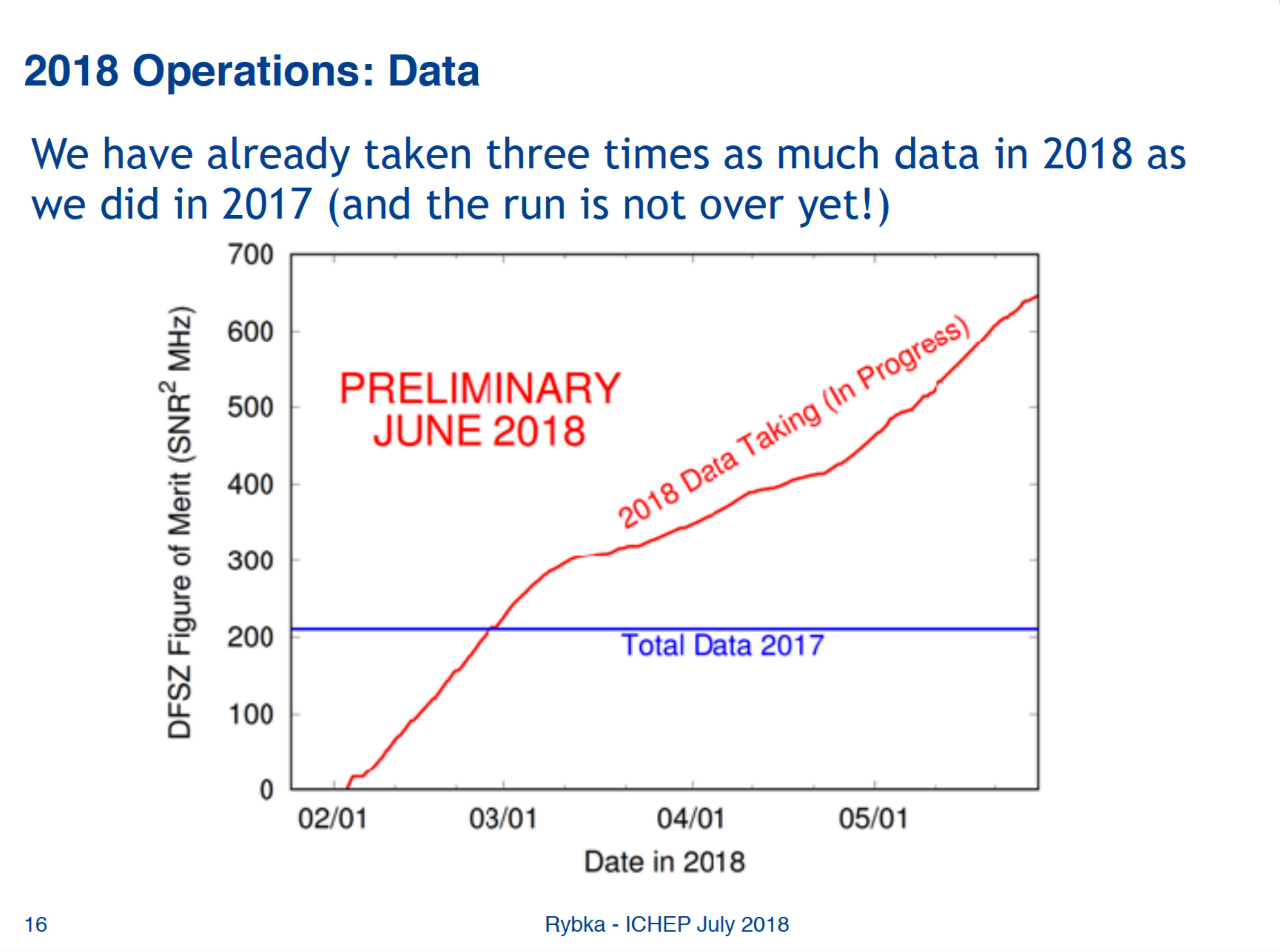
Yanjie Qiu,
Siddiqi Group,
UC Berkeley

Gain Tuning Curves of Operating ADMX JPA



2018 Operations use a Josephson Parametric Amplifier in place of the Microstrip Squid Amplifier

ADMX (Haloscope)



2018 Operations: Data

We have already taken three times as much data in 2018 as we did in 2017 (and the run is not over yet!)

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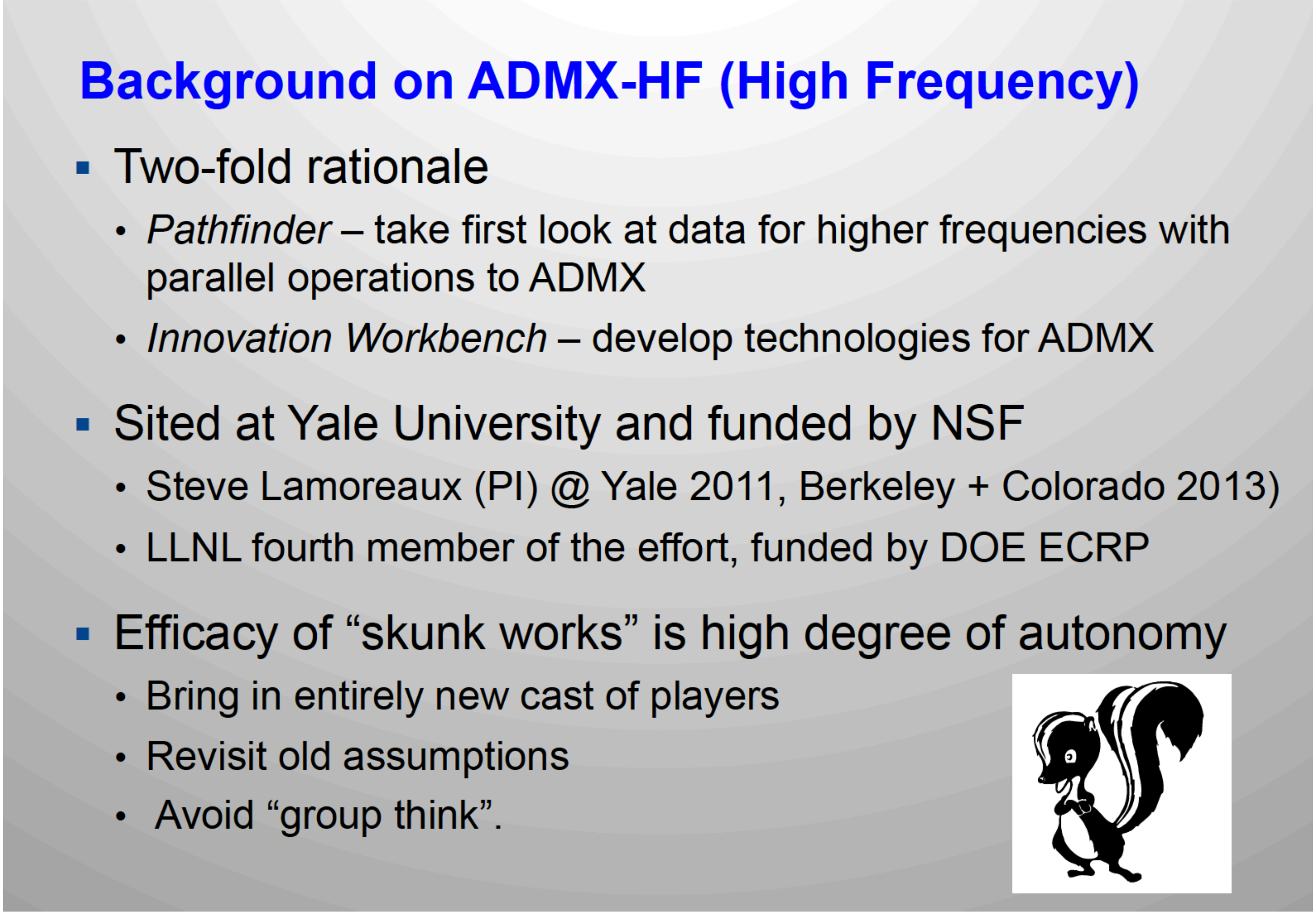
Rybka - ICHEP July 2018

HAYSTAC (Haloscope)



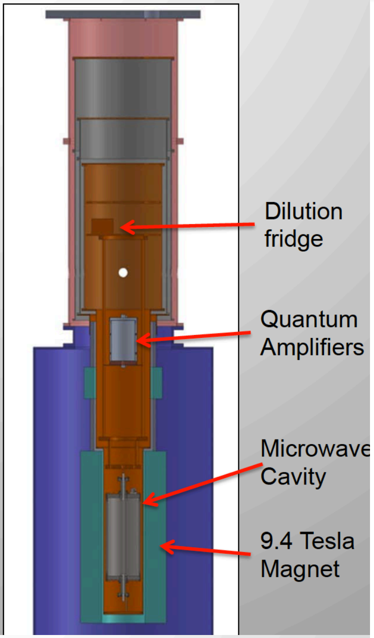
Background on ADMX-HF (High Frequency)

- Two-fold rationale
  - *Pathfinder* – take first look at data for higher frequencies with parallel operations to ADMX
  - *Innovation Workbench* – develop technologies for ADMX
- Sited at Yale University and funded by NSF
  - Steve Lamoreaux (PI) @ Yale 2011, Berkeley + Colorado 2013)
  - LLNL fourth member of the effort, funded by DOE ECRP
- Efficacy of “skunk works” is high degree of autonomy
  - Bring in entirely new cast of players
  - Revisit old assumptions
  - Avoid “group think”.

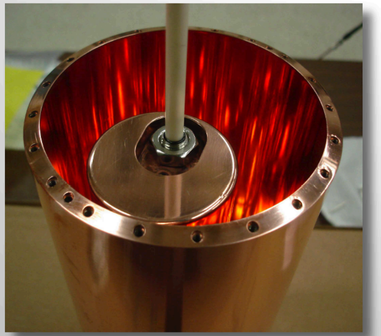
HAYSTAC (Haloscope)

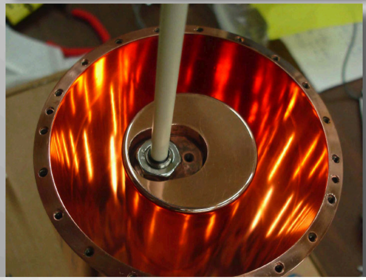
Purchased new magnet from Cryo-Magnetic Instruments.

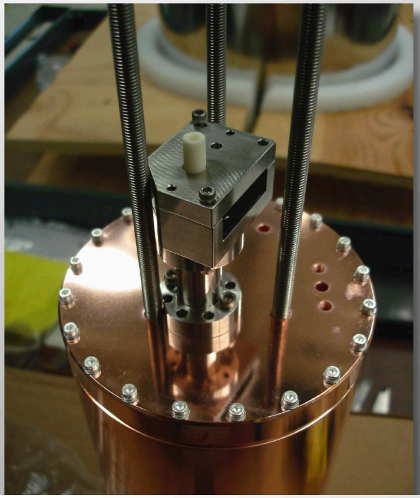
- *9 Tesla / 170 H coil*
- *5” diameter bore*
- *Persistent with bucking region*
- *Designed with highly parallel field (Br < 50 G)*
- *Cryogen free*



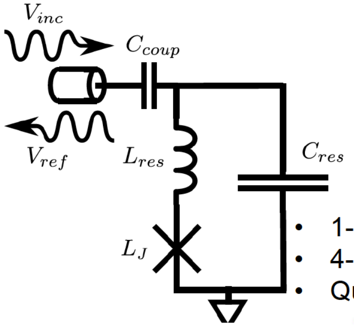
Cavity #2a – Single rod (“internal pivot”) design







Josephson Parametric Amplifiers (JPAs)

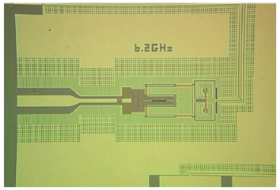


Josephson Junction - a nonlinear inductor

$$L_J = L_{J0} + L_{J2}\left(\frac{I}{I_{crit}}\right)^2$$

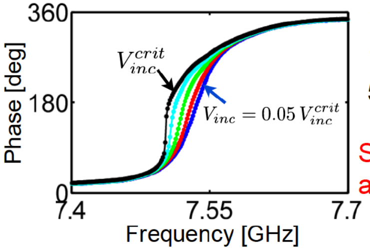
Nonlinear LC circuit

- 1-10 MHz band
- 4-8 GHz tunable range
- Quantum Limited



$$T_n = \hbar\omega / k_B$$

1 GHz = 50 mK
5 GHz = 250 mK



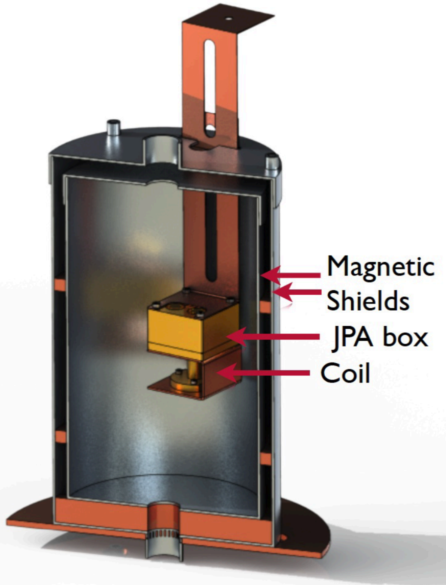
Status: JPA delivered, Installed and Tested to 2 Tesla!

K. Lenhert’s group
U. of Colorado/JILA

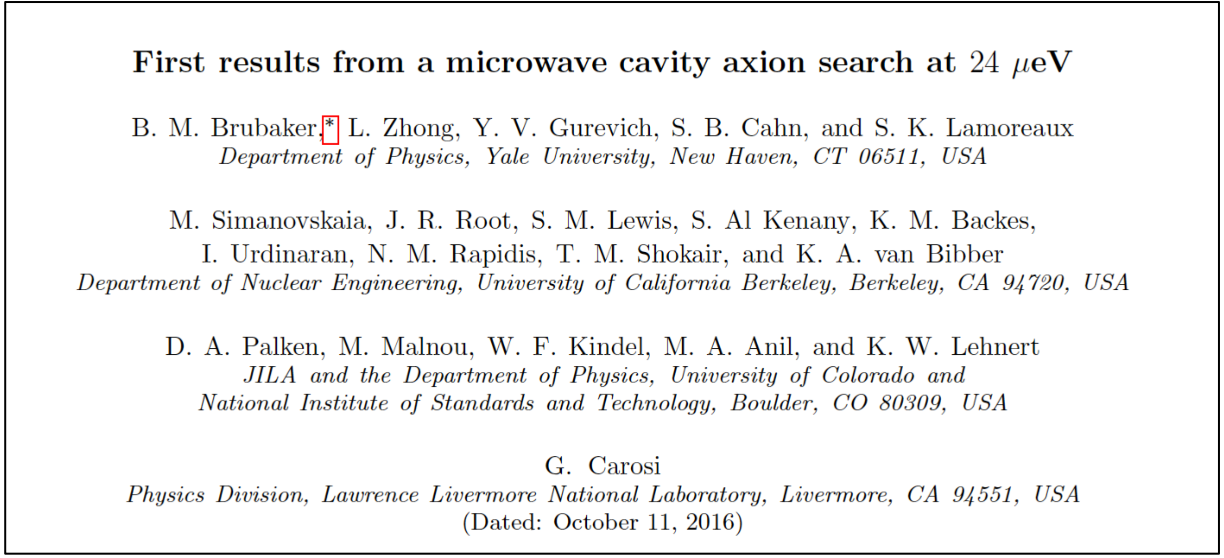
Status – Magnetic Shielding

JPA

- works at ~1Gauss
- ADMX-HF stray field ~100 Gauss



HAYSTAC (Haloscope)



First results from a microwave cavity axion search at 24 μeV

B. M. Brubaker,[*] L. Zhong, Y. V. Gurevich, S. B. Cahn, and S. K. Lamoreaux
Department of Physics, Yale University, New Haven, CT 06511, USA

M. Simanovskaia, J. R. Root, S. M. Lewis, S. Al Kenany, K. M. Backes,
I. Urdinaran, N. M. Rapidis, T. M. Shokair, and K. A. van Bibber
Department of Nuclear Engineering, University of California Berkeley, Berkeley, CA 94720, USA

D. A. Palken, M. Malnou, W. F. Kindel, M. A. Anil, and K. W. Lehnert
JILA and the Department of Physics, University of Colorado and
National Institute of Standards and Technology, Boulder, CO 80309, USA

G. Carosi
Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
(Dated: October 11, 2016)

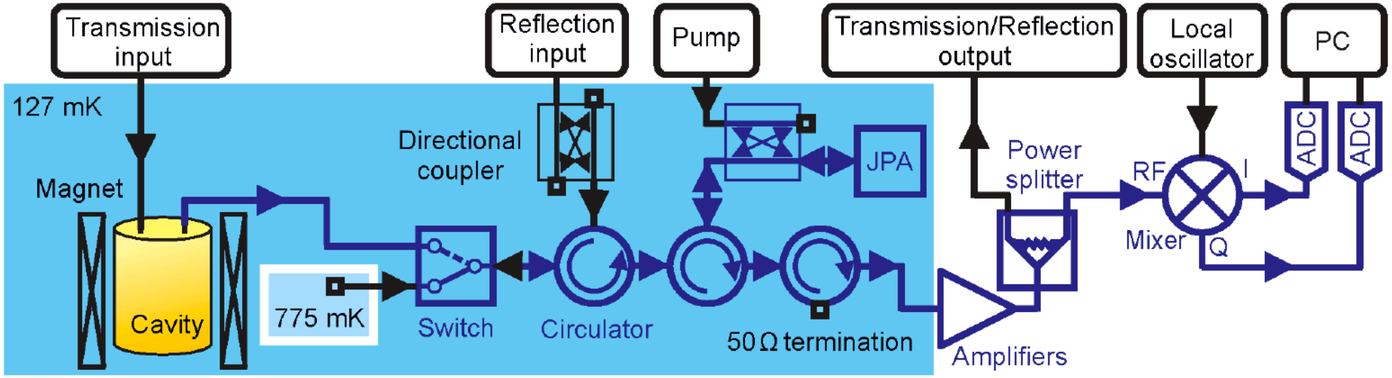


FIG. 1. Simplified receiver diagram: blue arrows indicate the path that a putative axion signal would take through the system, and black arrows indicate other paths. A vector network analyzer (VNA) is used to measure the cavity's frequency response in both transmission and reflection.

HAYSTAC (Haloscope)

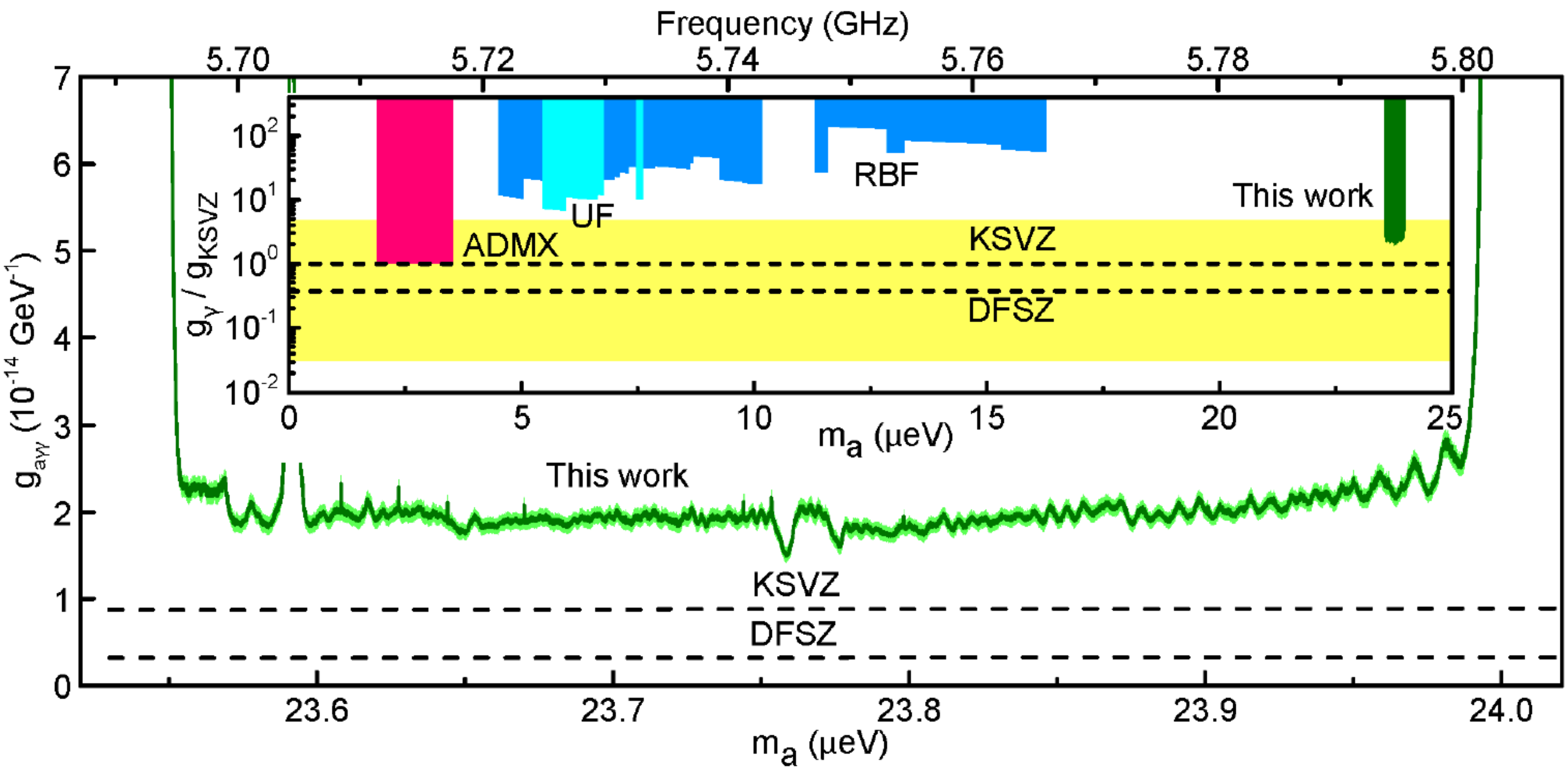


FIG. 3. Our exclusion limit at 90% confidence. The light green shaded region is a 1σ error band. The large notch around 5.704 GHz is the result of cutting spectra around a previously unidentified intruder mode. The narrow notches correspond to frequencies where synthetic axion signals were injected in one of the scans. The inset shows our results (green) together with previous cavity limits from ADMX (magenta, [7]) and early experiments at Brookhaven (RBF, blue, [18]) and the University of Florida (UF, cyan, [19]). The axion model band [13] is shown in yellow.

CULTASK (Haloscope)

IBS/CAPP

Center for Axion and Precision Physics Research (CAPP)

Funded by the Institute for Basic Science (IBS)

15 Oct 2013

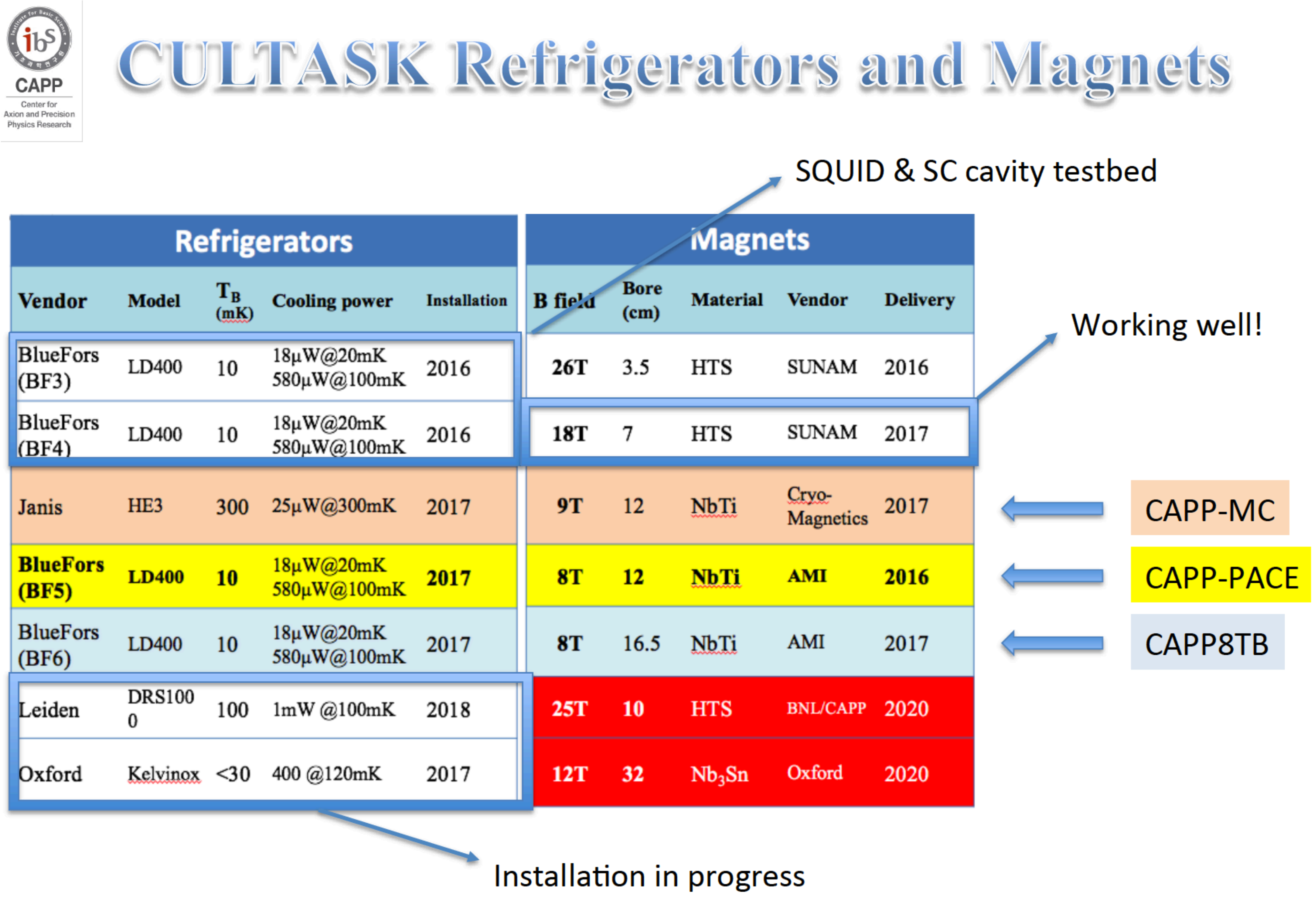
- Led by Director, Yannis Semertzidis
- Annual Budget of ~ $10M
- Physics at CAPP:
  - Dark Matter Axion Search (Cosmic Frontier)
  - Storage Ring Proton EDM (Strong CP Problem, BAU)
  - Muon g-2, J-PARC, COMET, CAST, ARIADNE
- Located at and working with KAIST (Korea Advanced Institute of Science and Technology)
- 50+ members and growing

CULTASK (Haloscope)

CAPP's Axion Research

- Axion Research at CAPP
  - CULTASK (CAPP's Ultra Low Temperature Axion Search in Korea)
    - CAPP-PACE (100%)
    - CAPP8TB (90%)
    - CAPP18T (20%)
    - CAPP12T (10%)
    - CAPP25T (10%)
  - CAPP/CAST
  - ARIADNE & GNOME

CULTASK (Haloscope)



CULTASK Refrigerators and Magnets

SQUID & SC cavity testbed

Working well!

Refrigerators					Magnets				
Vendor	**Model**	**T_B (mK)**	**Cooling power**	**Installation**	**B field**	**Bore (cm)**	**Material**	**Vendor**	**Delivery**
BlueFors (BF3)	LD400	10	18μW@20mK 580μW@100mK	2016	**26T**	3.5	HTS	SUNAM	2016
BlueFors (BF4)	LD400	10	18μW@20mK 580μW@100mK	2016	**18T**	7	HTS	SUNAM	2017
Janis	HE3	300	25μW@300mK	2017	**9T**	12	NbTi	Cryo-Magnetics	2017
BlueFors (BF5)	**LD400**	**10**	18μW@20mK 580μW@100mK	**2017**	**8T**	**12**	**NbTi**	**AMI**	**2016**
BlueFors (BF6)	LD400	10	18μW@20mK 580μW@100mK	2017	**8T**	16.5	NbTi	AMI	2017
Leiden	DRS1000	100	1mW @100mK	2018	**25T**	**10**	HTS	BNL/CAPP	2020
Oxford	Kelvinox	<30	400 @120mK	2017	**12T**	**32**	Nb_3Sn	Oxford	2020

CAPP-MC

CAPP-PACE

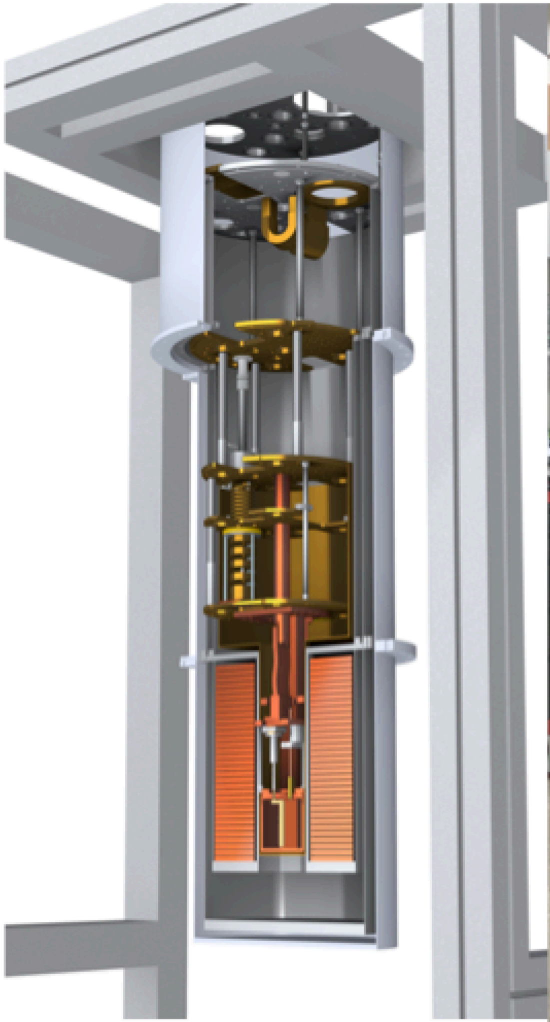
CAPP8TB

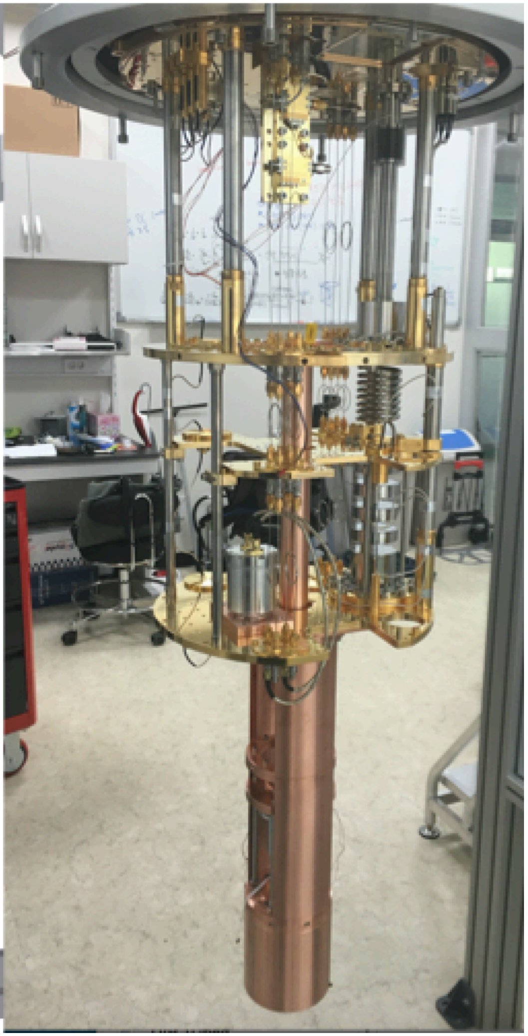
Installation in progress

CULTASK (Haloscope)

CAPP-PACE

parameter	value
Frequency	2.45 – 2.76 GHz
Magnetic Field	8 T
T_{cavity}	< 50 mK
T_{amp}	1 - 1.5 K
Cavity Volume	1.12 litter
Target Sensitivity	KSVZ, 10*KSVZ
DAQ efficiency	0.45
Unloaded Q	~ 80,000
Coupling	1.5 – 2.0
Form Factor	0.55
SNR	5

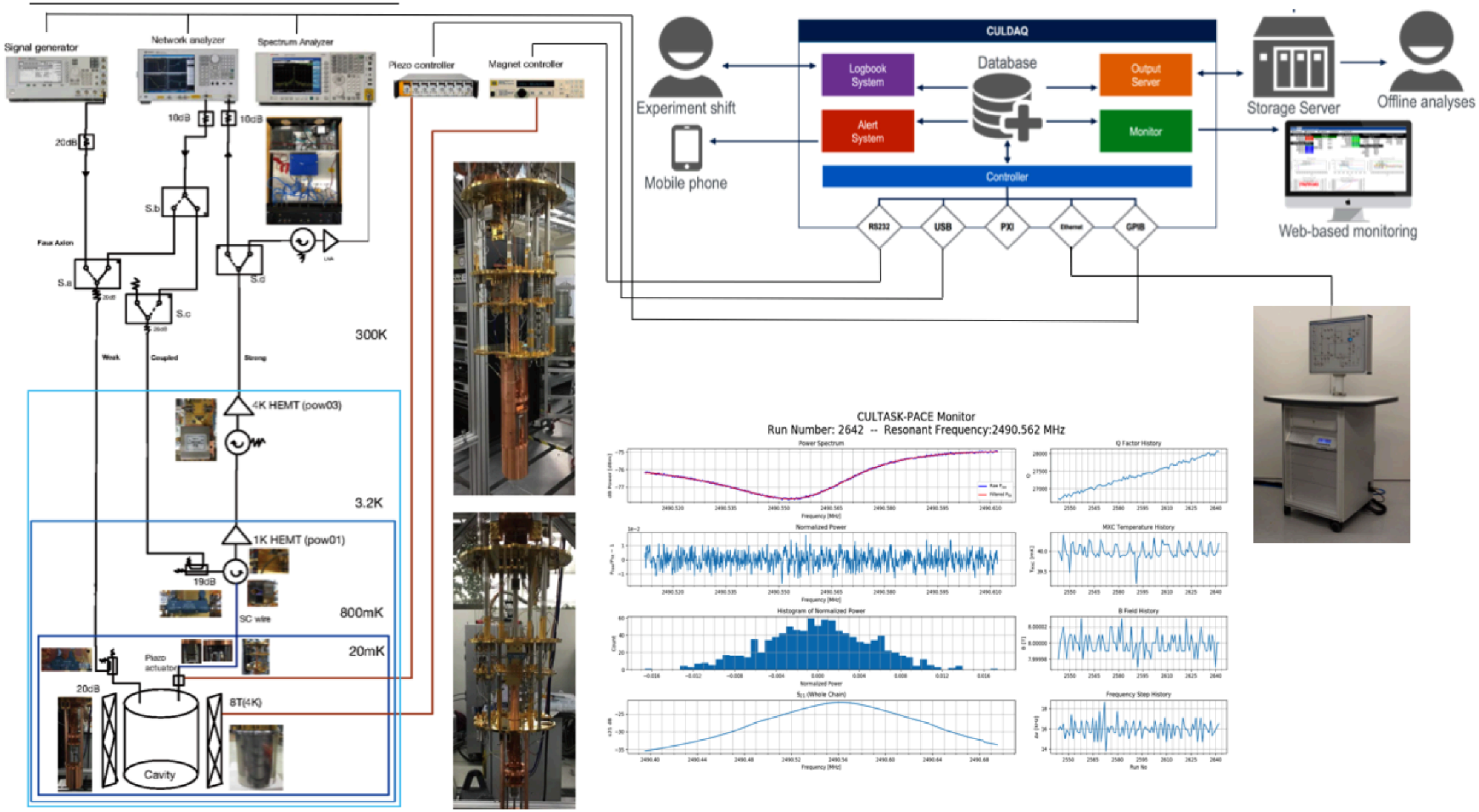




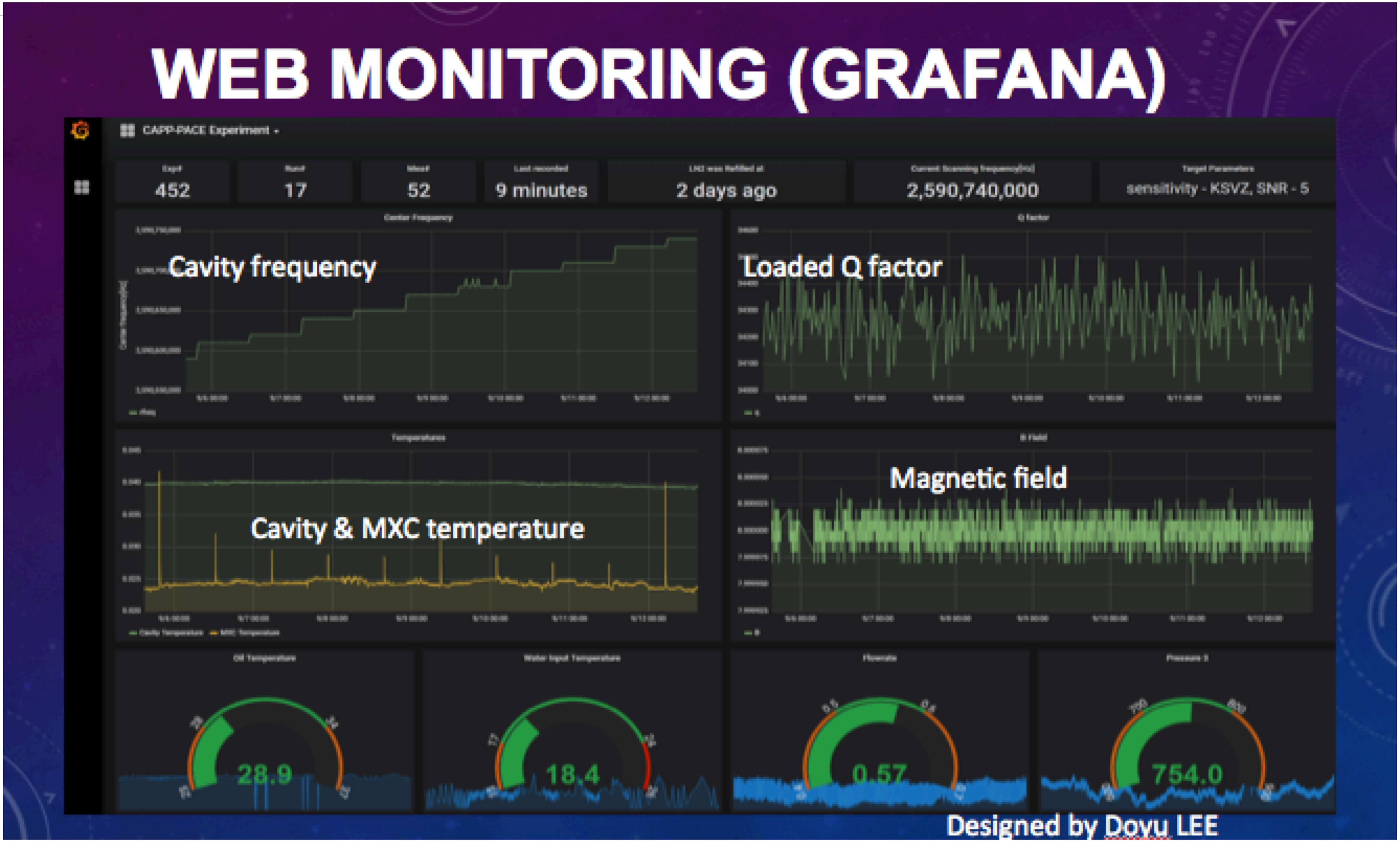
CULTASK (Haloscope)

CAPP-PACE (RF receiver)

RF read-out chain & Controls



CULTASK (Haloscope)



WEB MONITORING (GRAFANA)

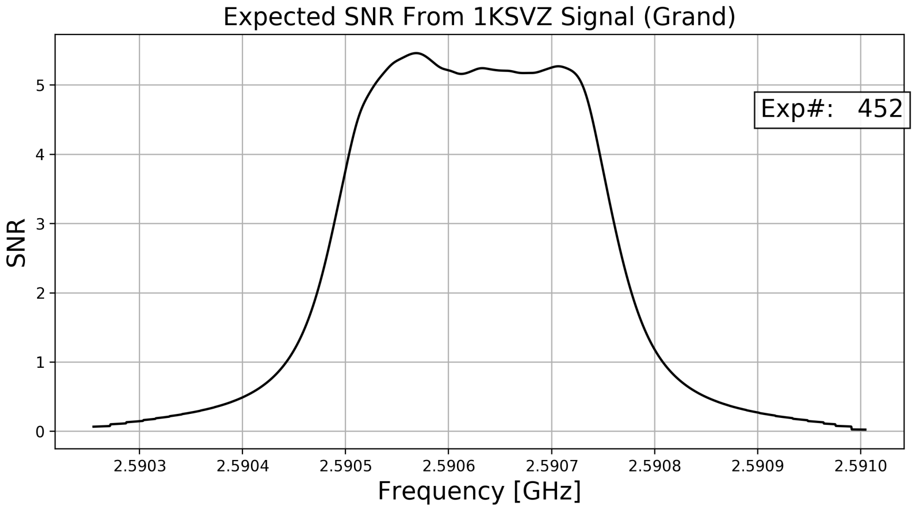
CAPP-PACE Experiment

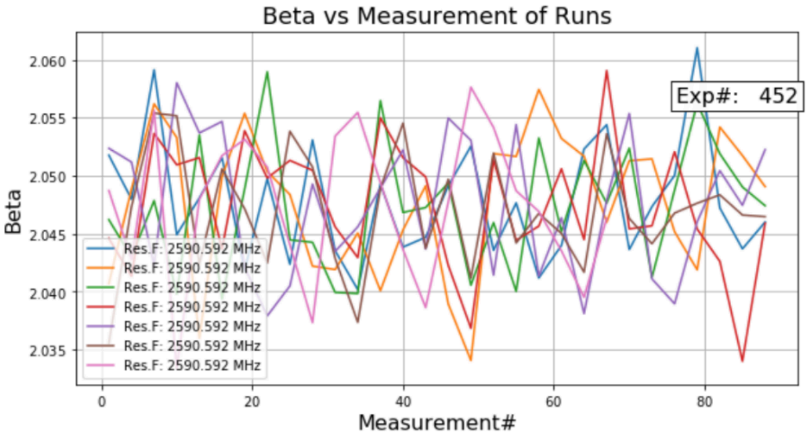
Exp#	Run#	Meas#	Last recorded	LN2 was Refilled at	Current Scanning frequency[Hz]	Target Parameters
452	17	52	9 minutes	2 days ago	2,590,740,000	sensitivity - KSVZ, SNR - 5

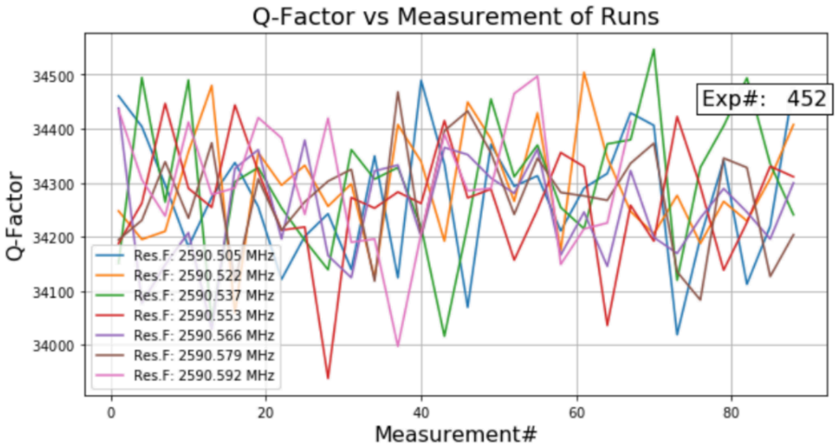
Designed by Doyu LEE

CULTASK (Haloscope)

Data so far (as of yesterday)…







CULTASK (Haloscope)

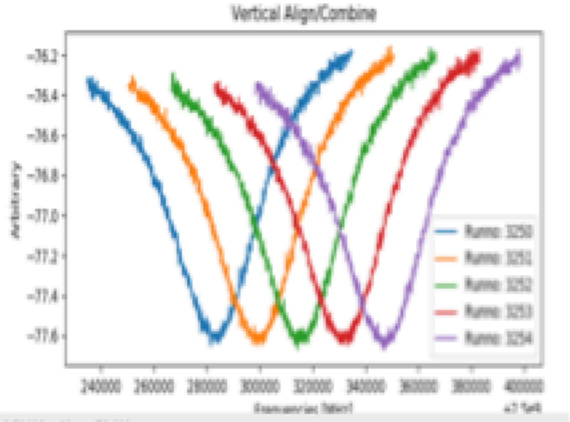
CAPP-PACE R&D

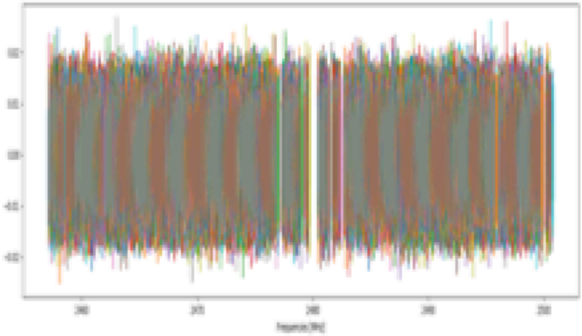
How to improve?

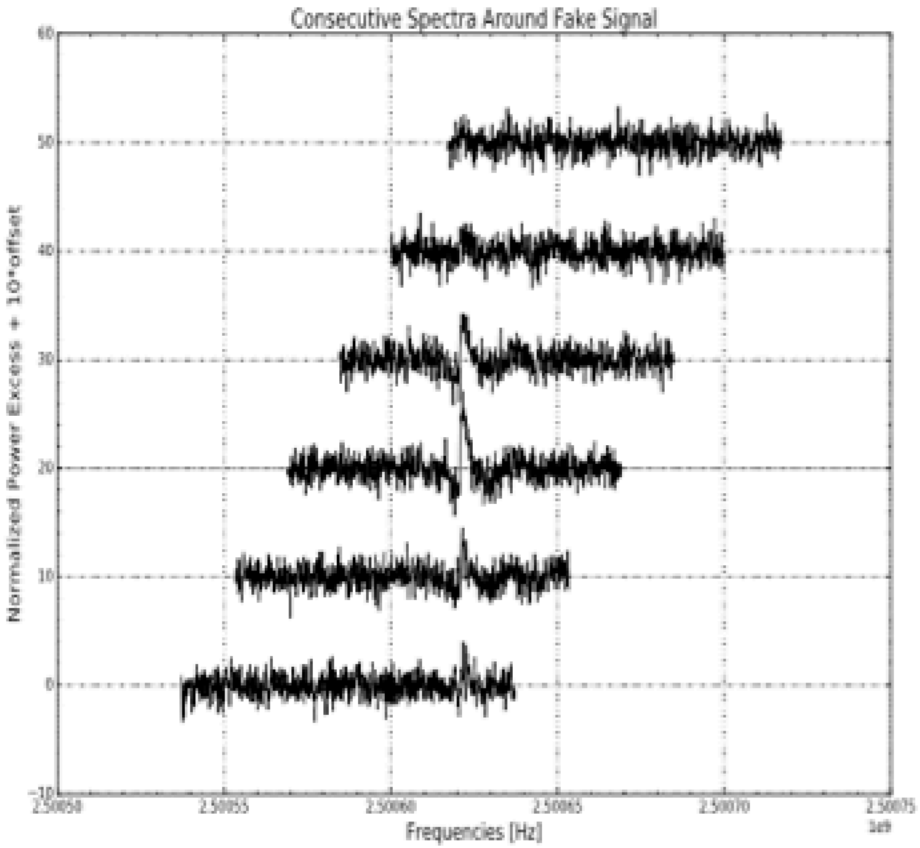
- Maximize B^2V
  - 25T 10cm bore HTS magnet by BNL (2020)
  - 12T 32cm bore LTS magnet by Oxford (2020)
- Higher Frequency
  - Multi-vane cavity
  - Dielectric rings (TM_{030} and TM_{050})
  - Photonic cells
- Scan faster (minimize T_{amp} ← dominating factor)
  - Quantum Amplifier - SQUID or JPA
  - Optimize cryo-RF receiver chain
- Others
  - Improve Q-factor of cavity – pure metal or SC cavity
  - Dead-time-less DAQ

CULTASK (Haloscope)

CAPP-PACE 1st data (2.45- 2.50 GHz)

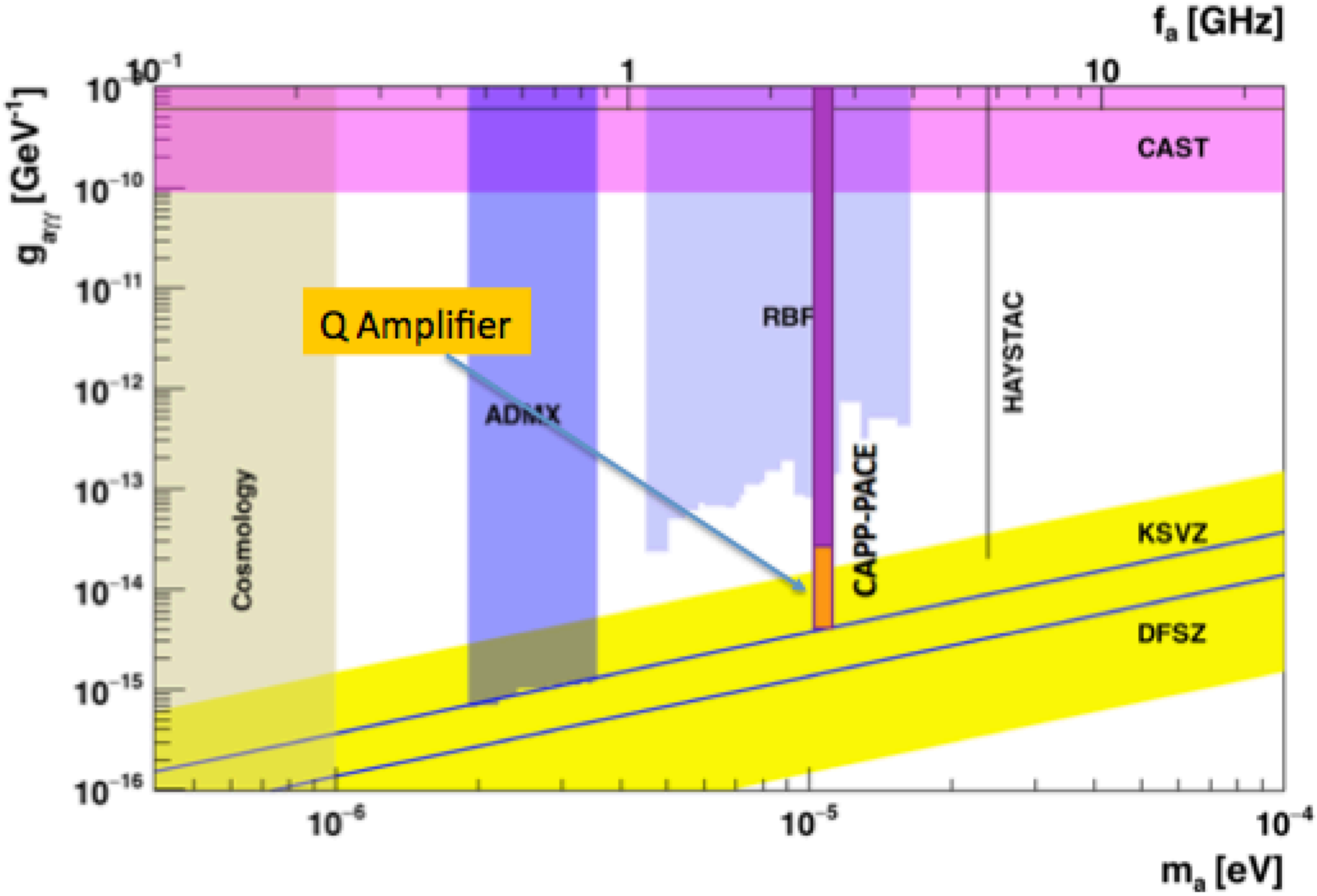






CULTASK (Haloscope)

CAPP-PACE Sensitivity (planned)

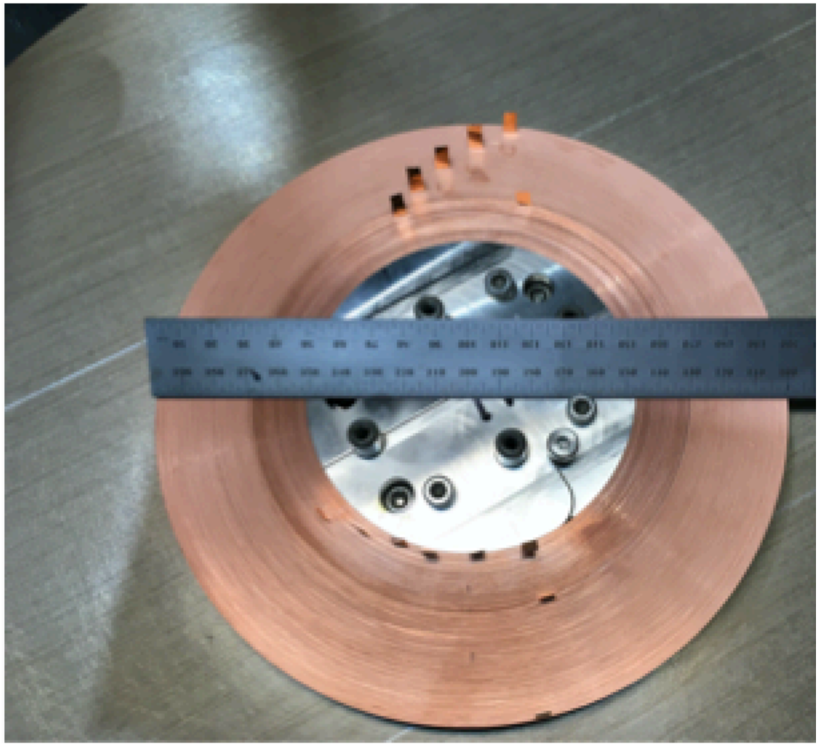


CULTASK (Haloscope)

CAPP-PACE R&D

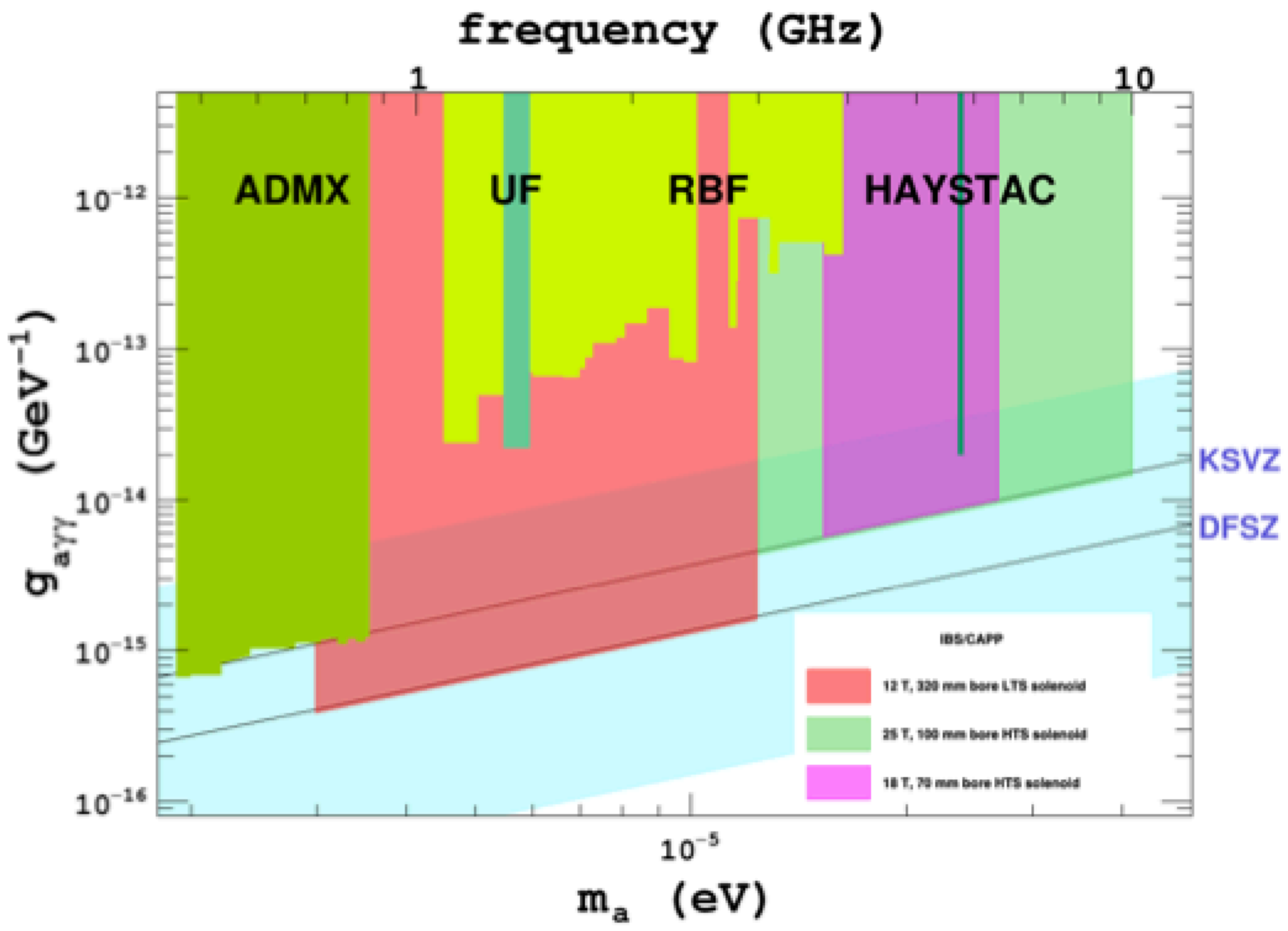
25T 10cm bore HTS magnet by BNL

- The first few (of 28) pancakes wound! - tests in progress
- 5 km of SC tape will be delivered next 5 months

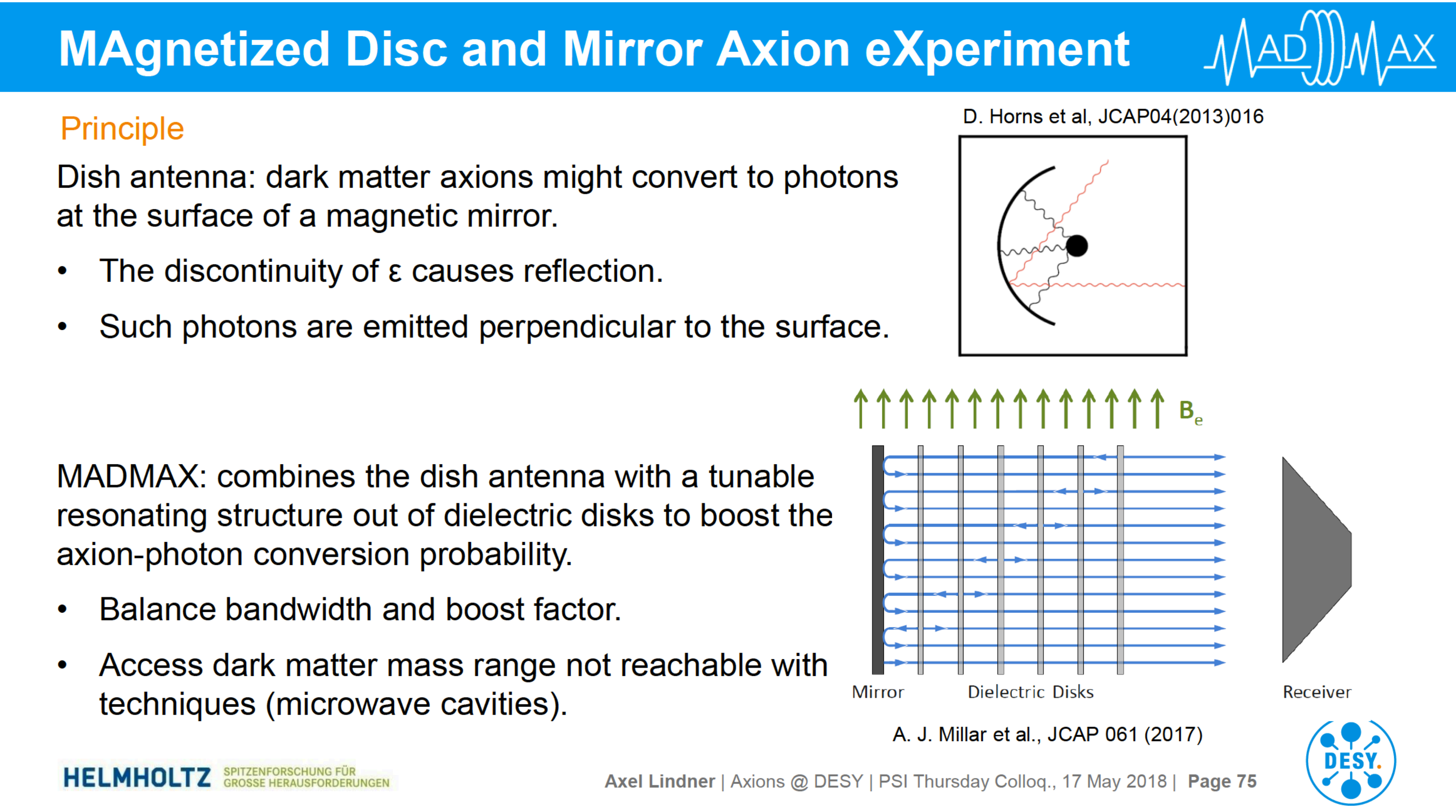


CULTASK (Haloscope)

CULTASK Sensitivity



MADMAX (dish w/ dielectric disk)



MAgnetized Disc and Mirror Axion eXperiment

Principle

Dish antenna: dark matter axions might convert to photons at the surface of a magnetic mirror.

- The discontinuity of ε causes reflection.
- Such photons are emitted perpendicular to the surface.

D. Horns et al, JCAP04(2013)016

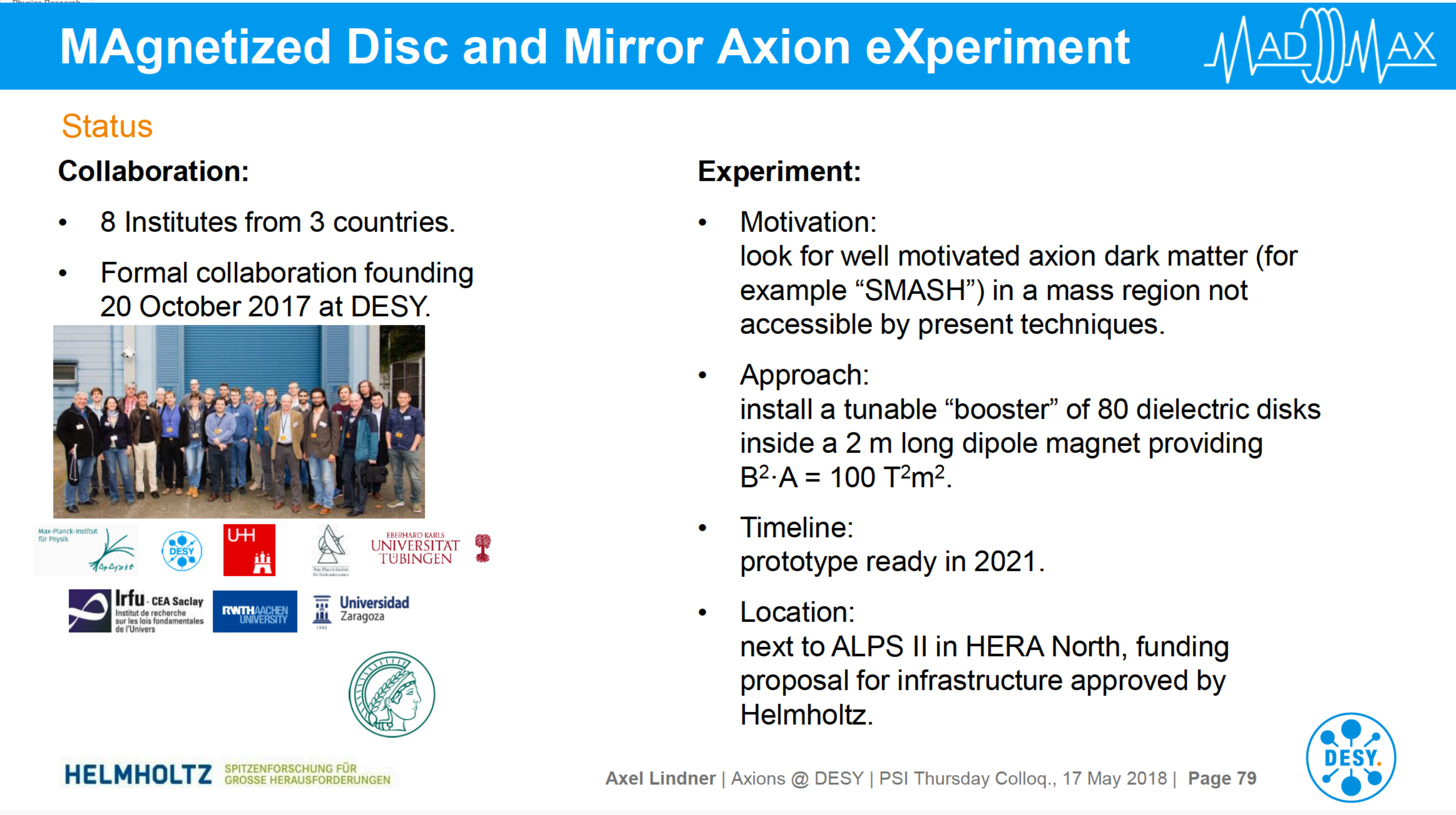
MADMAX: combines the dish antenna with a tunable resonating structure out of dielectric disks to boost the axion-photon conversion probability.

- Balance bandwidth and boost factor.
- Access dark matter mass range not reachable with techniques (microwave cavities).

A. J. Millar et al., JCAP 061 (2017)

Axel Lindner | Axions @ DESY | PSI Thursday Colloq., 17 May 2018 | Page 75

MADMAX (dish w/ dielectric disk)



MAgnetized Disc and Mirror Axion eXperiment

Status

Collaboration:

- 8 Institutes from 3 countries.
- Formal collaboration founding 20 October 2017 at DESY.

Experiment:

- Motivation:
  look for well motivated axion dark matter (for example “SMASH”) in a mass region not accessible by present techniques.
- Approach:
  install a tunable “booster” of 80 dielectric disks inside a 2 m long dipole magnet providing $B^2 \cdot A = 100\ T^2m^2$.
- Timeline:
  prototype ready in 2021.
- Location:
  next to ALPS II in HERA North, funding proposal for infrastructure approved by Helmholtz.

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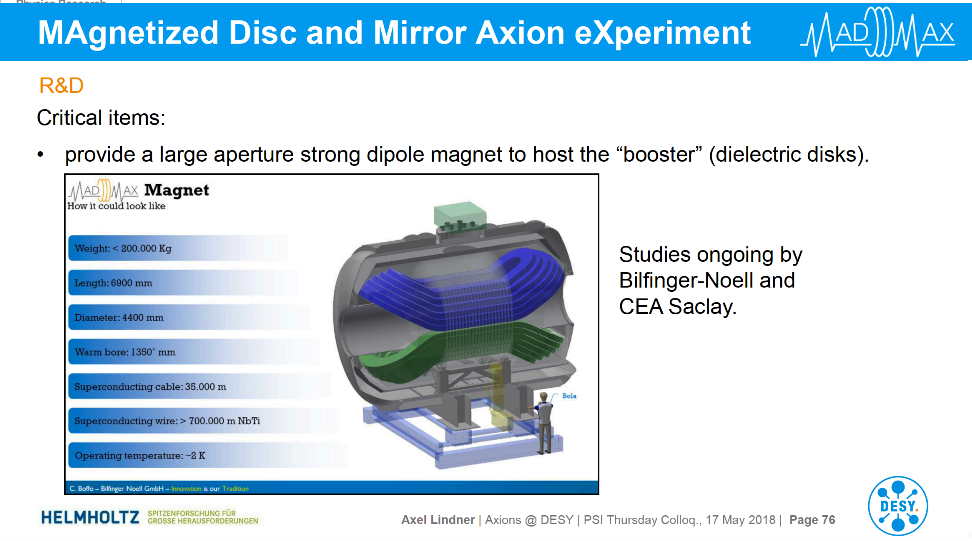
MADMAX (dish w/ dielectric disk)



MAgnetized Disc and Mirror Axion eXperiment

R&D

Critical items:

- provide a large aperture strong dipole magnet to host the “booster” (dielectric disks).

Magnet

How it could look like

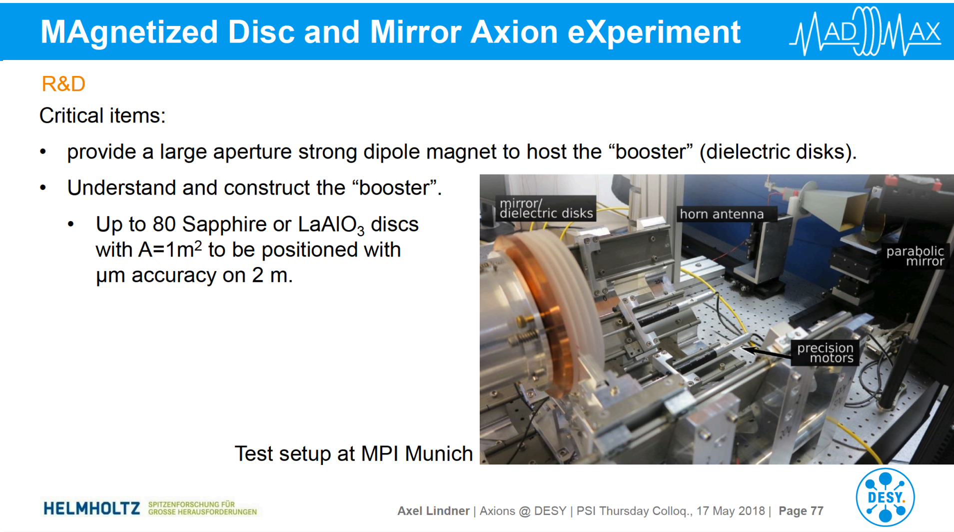
Weight: < 200.000 Kg
Length: 6900 mm
Diameter: 4400 mm
Warm bore: 1350* mm
Superconducting cable: 35.000 m
Superconducting wire: > 700.000 m NbTi
Operating temperature: ~2 K

C. Boffo – Bilfinger Noell GmbH – Innovation is our Tradition

Studies ongoing by Bilfinger-Noell and CEA Saclay.

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Axel Lindner | Axions @ DESY | PSI Thursday Colloq., 17 May 2018 | Page 76



MAgnetized Disc and Mirror Axion eXperiment

R&D

Critical items:

- provide a large aperture strong dipole magnet to host the “booster” (dielectric disks).
- Understand and construct the “booster”.
  - Up to 80 Sapphire or LaAlO$_3$ discs with A=1m^2 to be positioned with µm accuracy on 2 m.

Test setup at MPI Munich

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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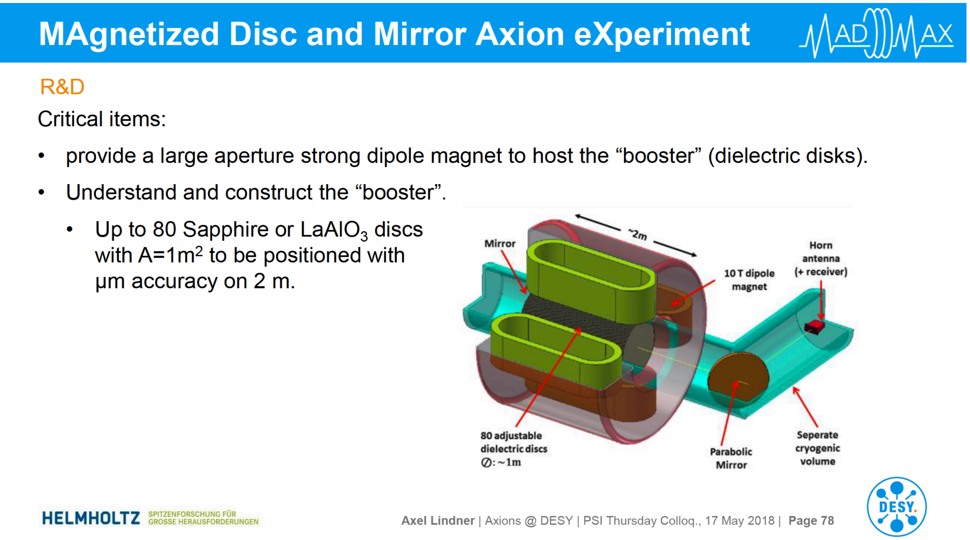

MAgnetized Disc and Mirror Axion eXperiment

R&D

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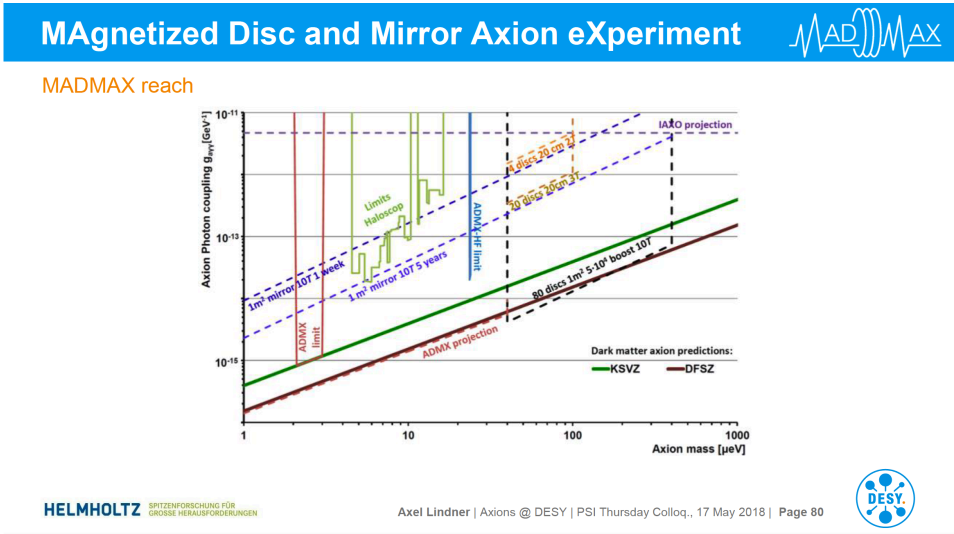
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Axel Lindner | Axions @ DESY | PSI Thursday Colloq., 17 May 2018 | Page 78



MAgnetized Disc and Mirror Axion eXperiment

MADMAX reach

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

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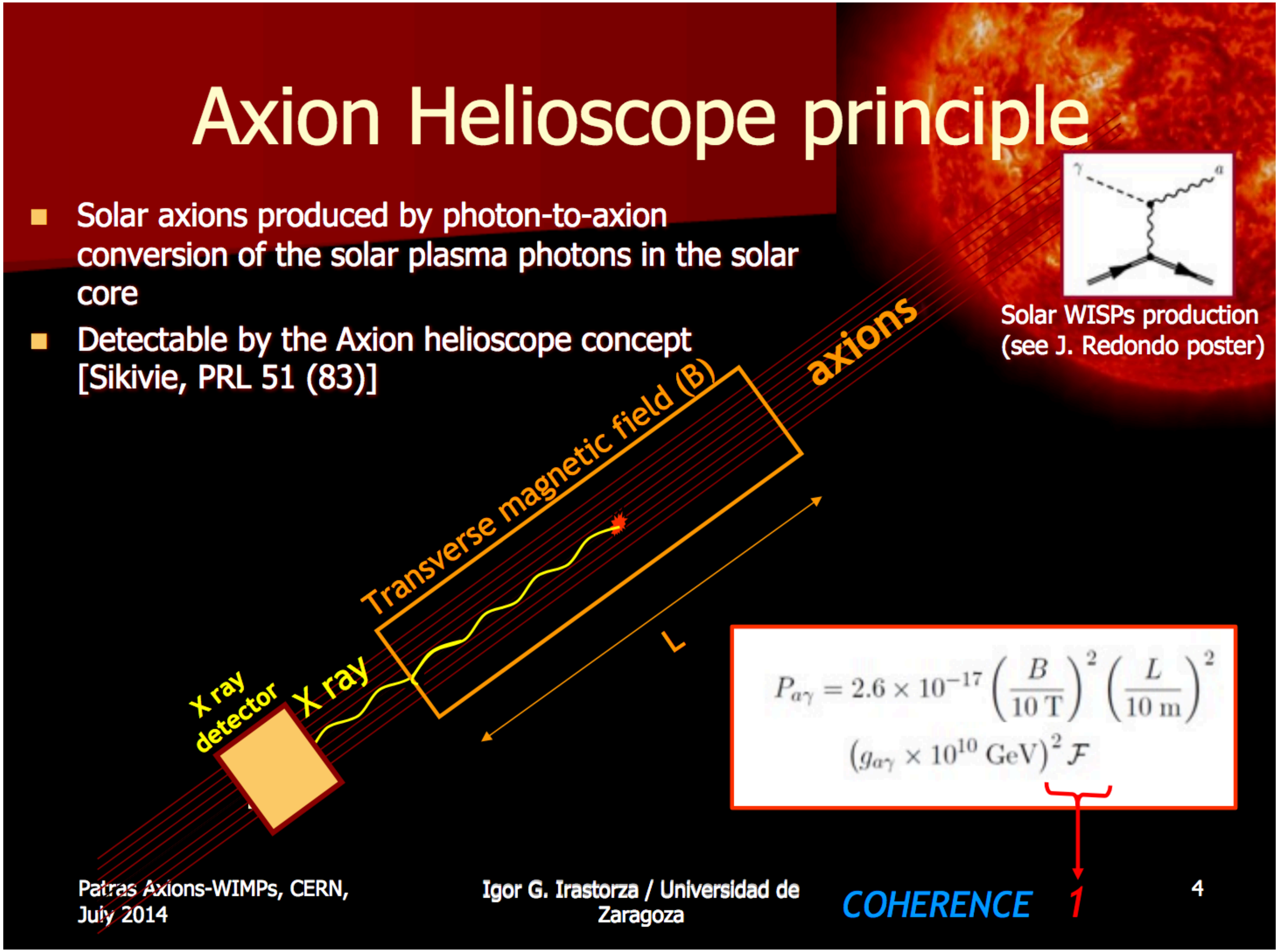
Solar Axion Search (CAST & IAXO)

Solar Axion Search (CAST & IAXO)



Axion Helioscope principle

- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core
- Detectable by the Axion helioscope concept [Sikivie, PRL 51 (83)]

Solar WISPs production (see J. Redondo poster)

$$P_{a\gamma} = 2.6\times 10^{-17}\left(\frac{B}{10\,\mathrm{T}}\right)^2\left(\frac{L}{10\,\mathrm{m}}\right)^2 \left(g_{a\gamma}\times 10^{10}\,\mathrm{GeV}\right)^2 \underbrace{\mathcal{F}}_{1}$$

COHERENCE

Patras Axions-WIMPs, CERN, July 2014

Igor G. Irastorza / Universidad de Zaragoza

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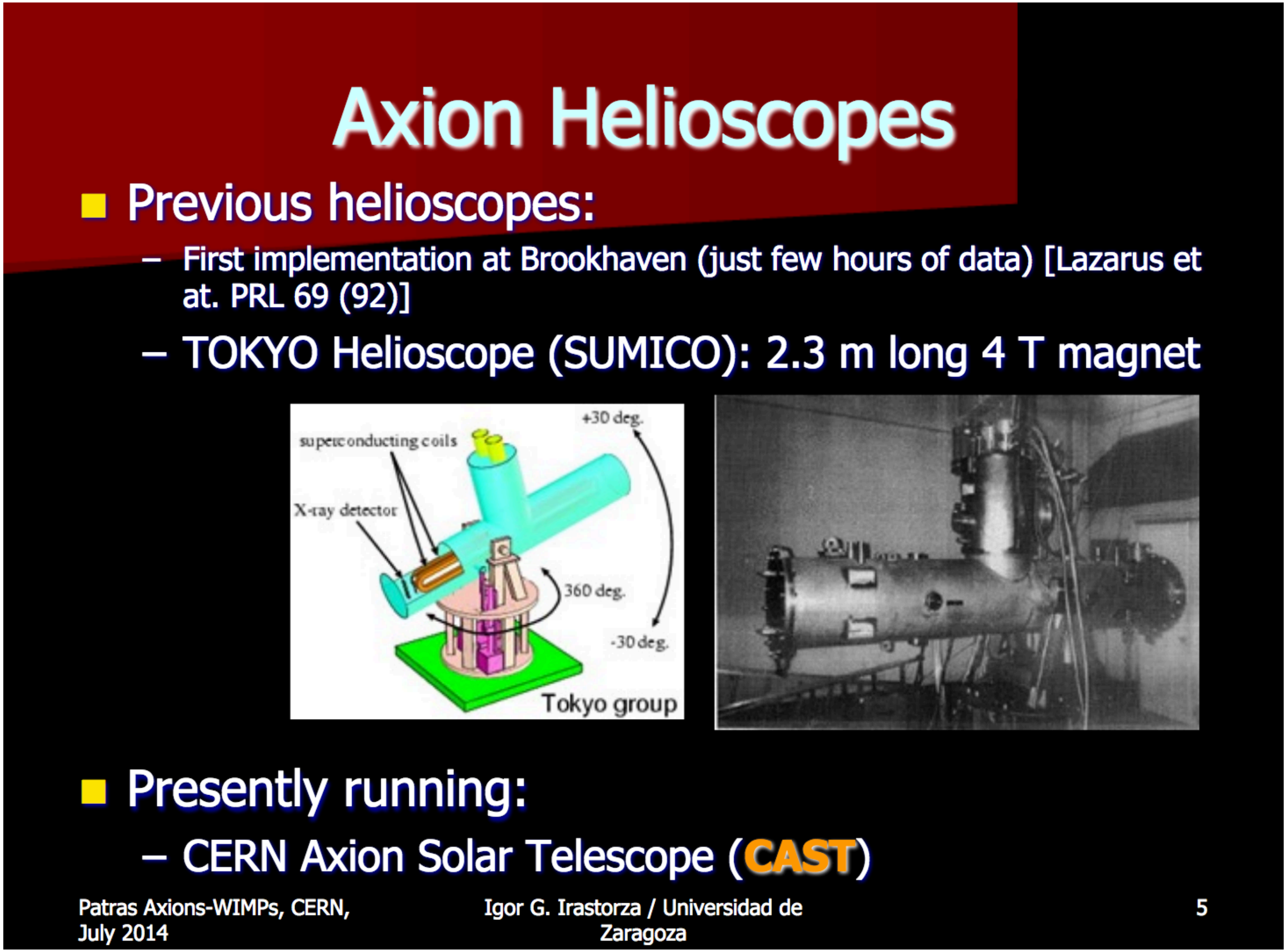
Solar Axion Search (CAST & IAXO)



Axion Helioscopes

- Previous helioscopes:
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

Patras Axions-WIMPs, CERN, July 2014

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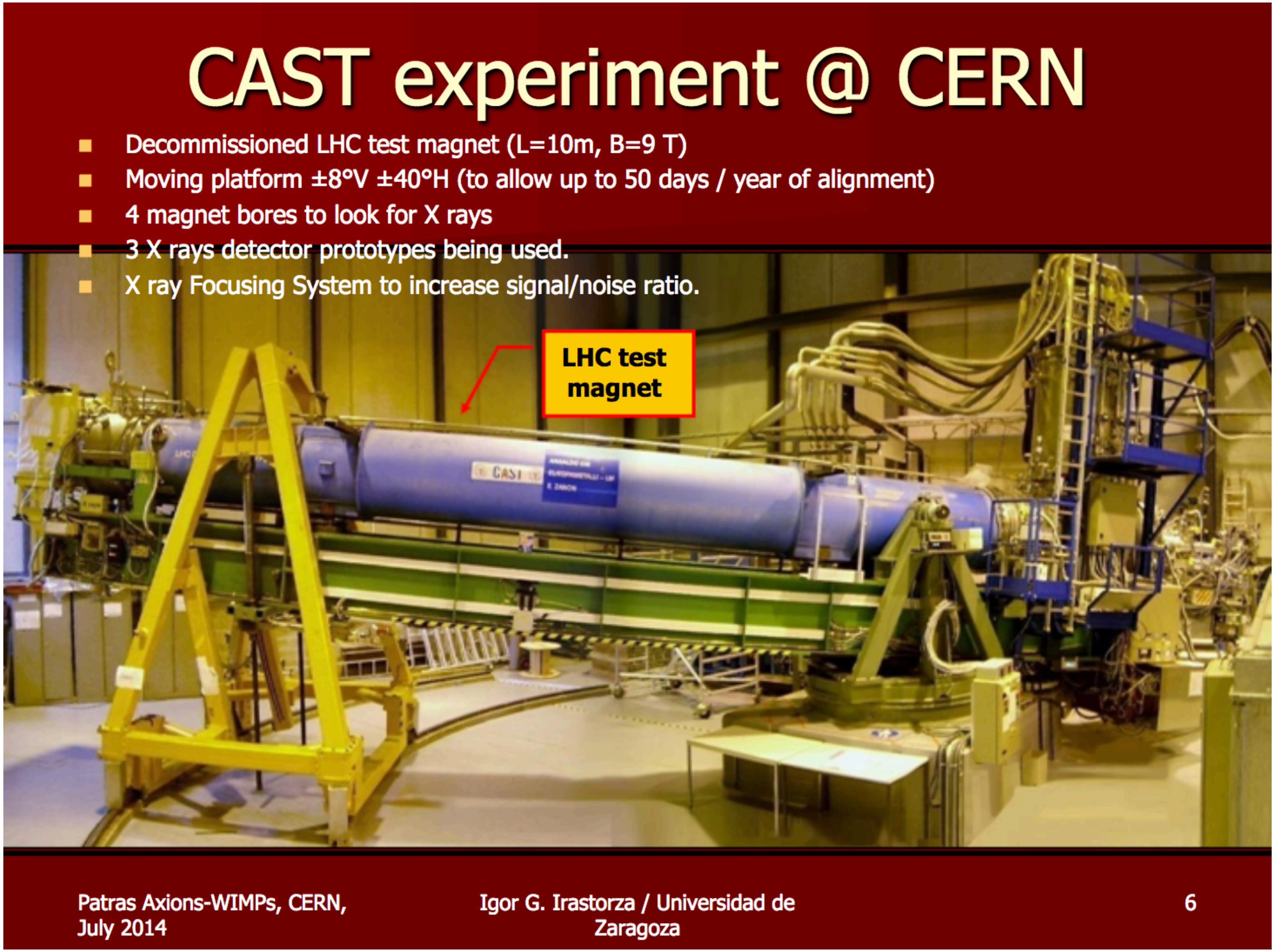
Solar Axion Search (CAST & IAXO)



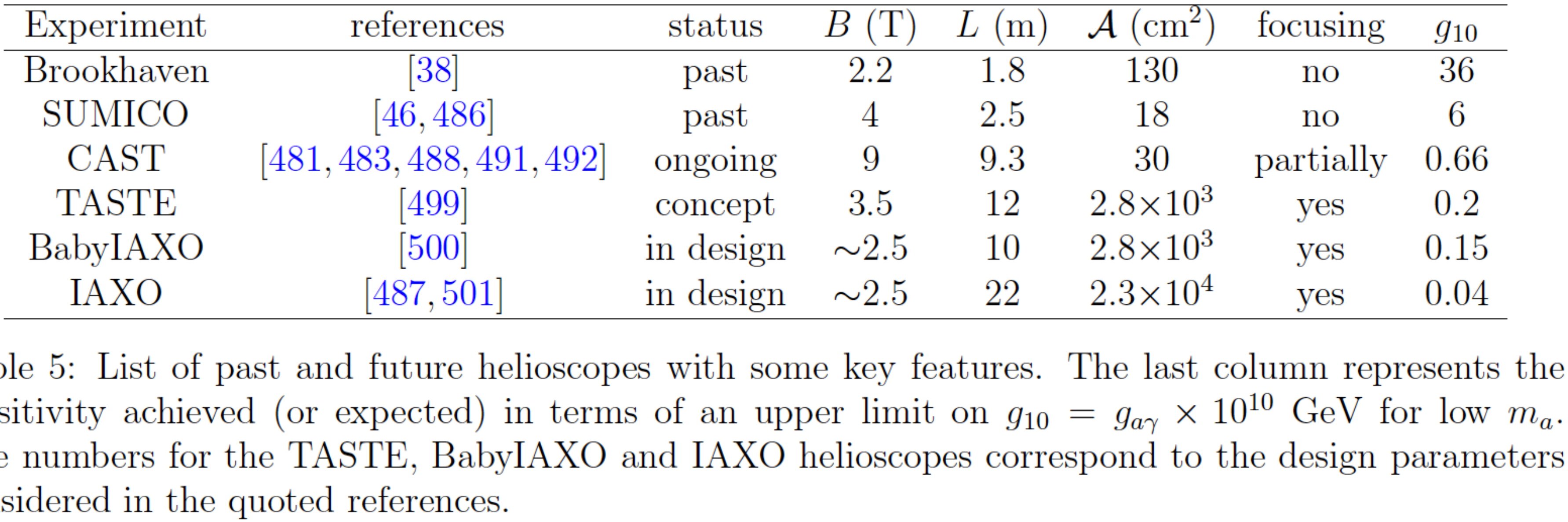
CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.

Patras Axions-WIMPs, CERN, July 2014 Igor G. Irastorza / Universidad de Zaragoza 6

Solar Axion Search (CAST & IAXO)

$$\mathcal{P}(a \to \gamma) = 2.6 \times 10^{-17} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \mathcal{F}(qL),$$



Experiment	references	status	B (T)	L (m)	$\mathcal{A}$ (cm^2)	focusing	g_{10}
Brookhaven	[38]	past	2.2	1.8	130	no	36
SUMICO	[46, 486]	past	4	2.5	18	no	6
CAST	[481, 483, 488, 491, 492]	ongoing	9	9.3	30	partially	0.66
TASTE	[499]	concept	3.5	12	2.8×10^3	yes	0.2
BabyIAXO	[500]	in design	~2.5	10	2.8×10^3	yes	0.15
IAXO	[487, 501]	in design	~2.5	22	2.3×10^4	yes	0.04

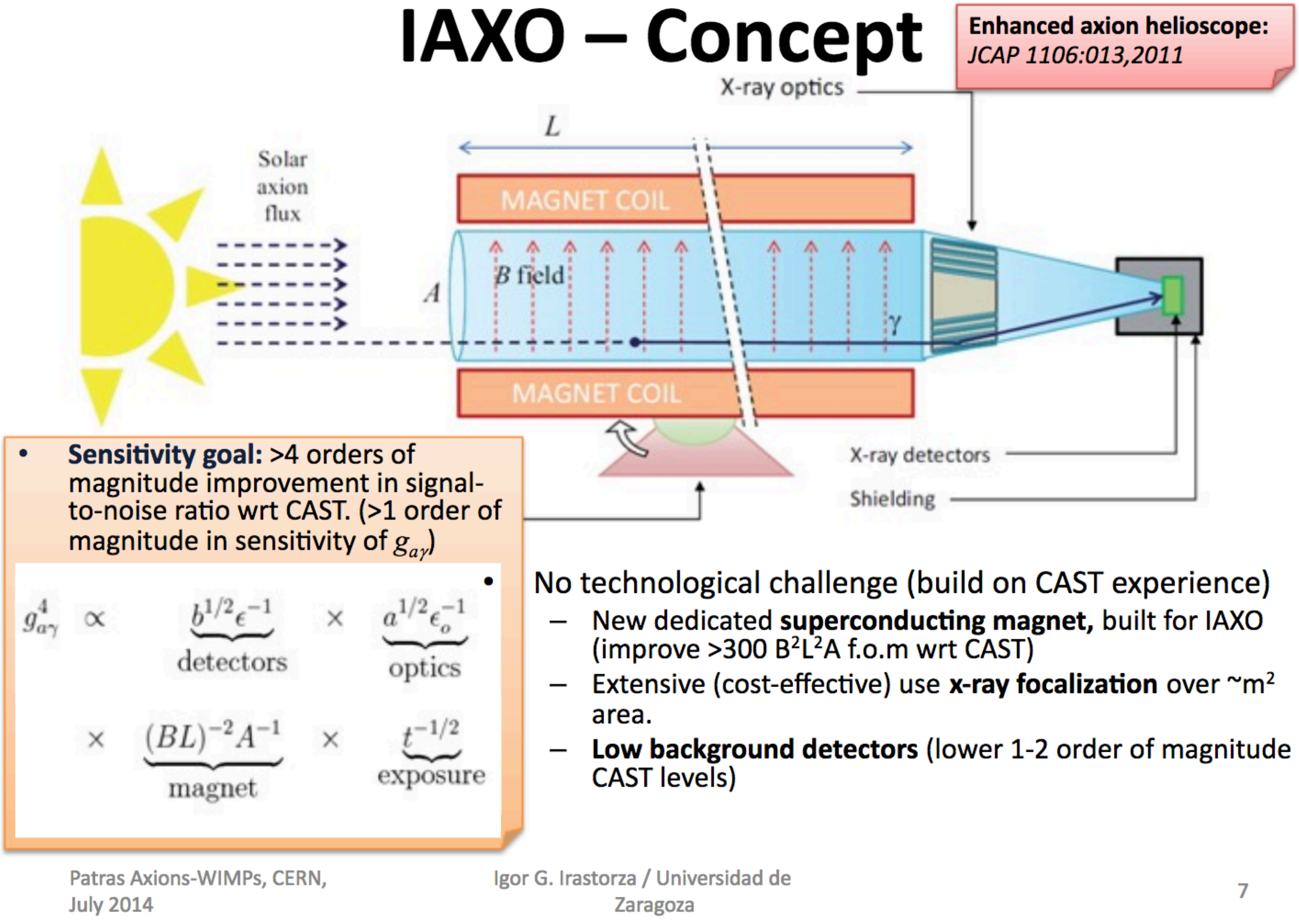
Table 5: List of past and future helioscopes with some key features. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{10} = g_{a\gamma} \times 10^{10}$ GeV for low m_a. The numbers for the TASTE, BabyIAXO and IAXO helioscopes correspond to the design parameters considered in the quoted references.

From

New experimental approaches in the search for axion-like particles

Igor G. Irastorza[1,2] and Javier Redondo[1,3]

Solar Axion Search (CAST & IAXO)



IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011

- **Sensitivity goal:** >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of $g_{a\gamma}$)

$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

- No technological challenge (build on CAST experience)
  - New dedicated **superconducting magnet,** built for IAXO (improve >300 B^2L^2A f.o.m wrt CAST)
  - Extensive (cost-effective) use **x-ray focalization** over ~m^2 area.
  - **Low background detectors** (lower 1-2 order of magnitude CAST levels)

Patras Axions-WIMPs, CERN, July 2014

Igor G. Irastorza / Universidad de Zaragoza

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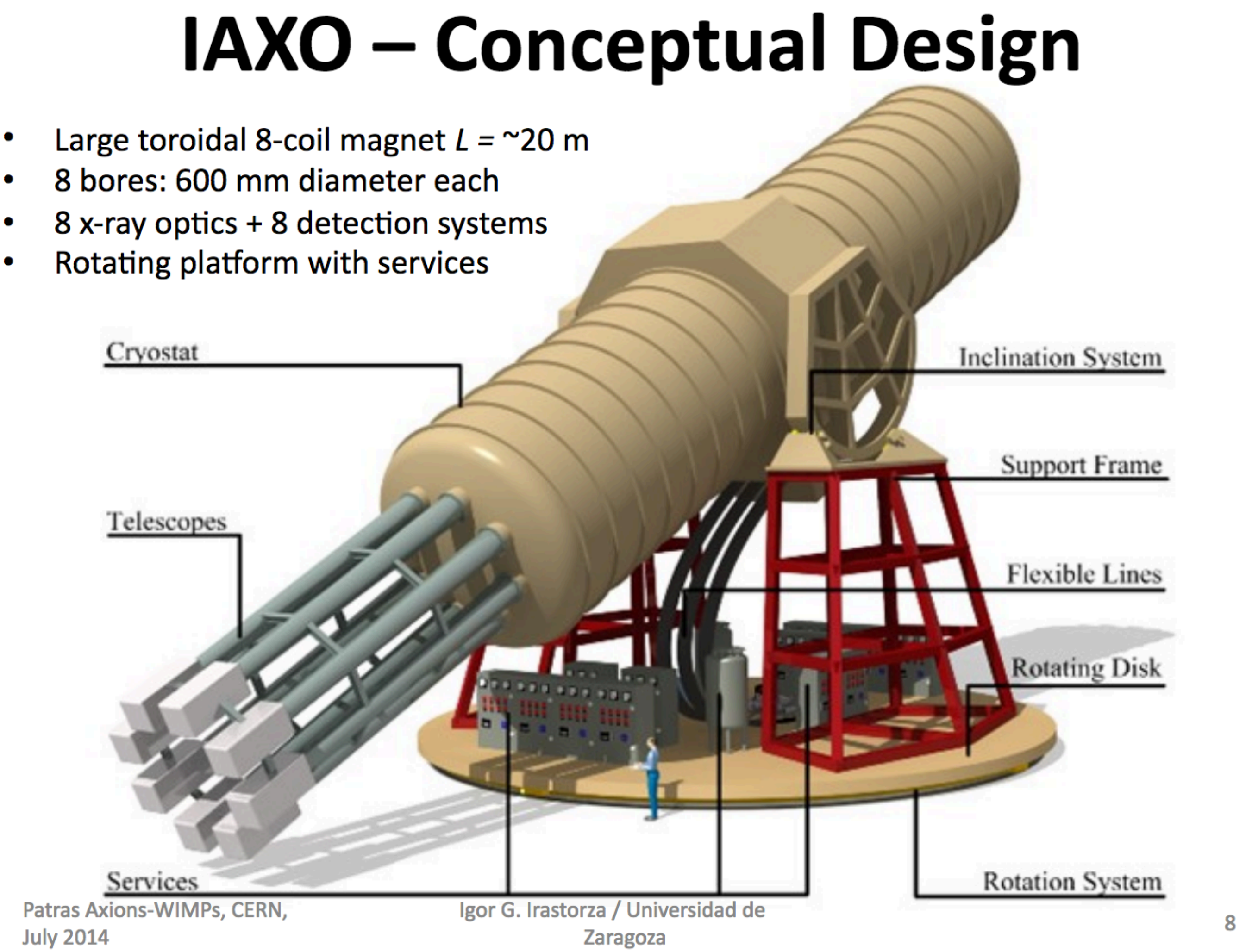
Solar Axion Search (CAST & IAXO)



IAXO – Conceptual Design

- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services

Patras Axions-WIMPs, CERN,
July 2014

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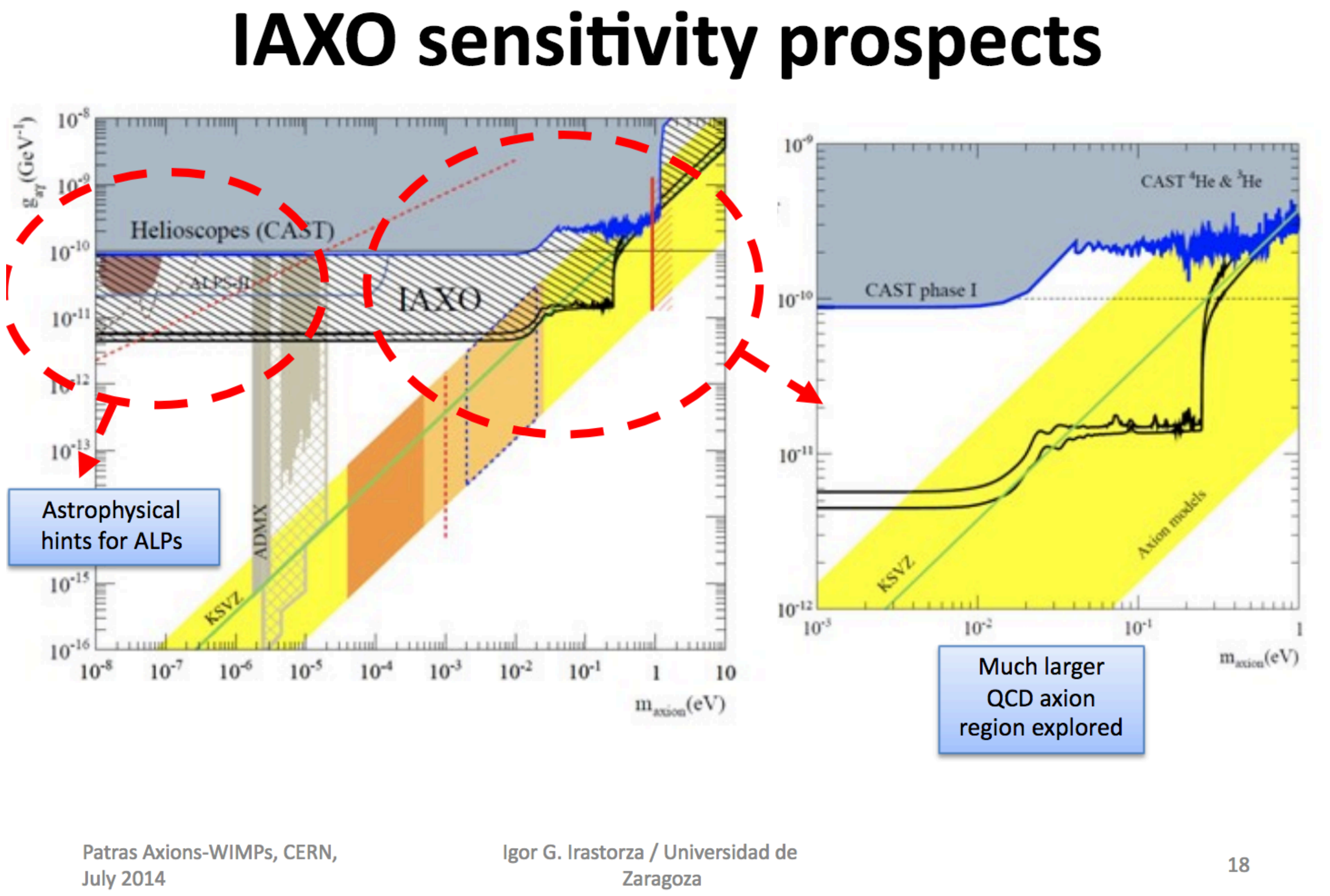
Solar Axion Search (CAST & IAXO)



IAXO sensitivity prospects

Astrophysical hints for ALPs

Much larger QCD axion region explored

Patras Axions-WIMPs, CERN, July 2014

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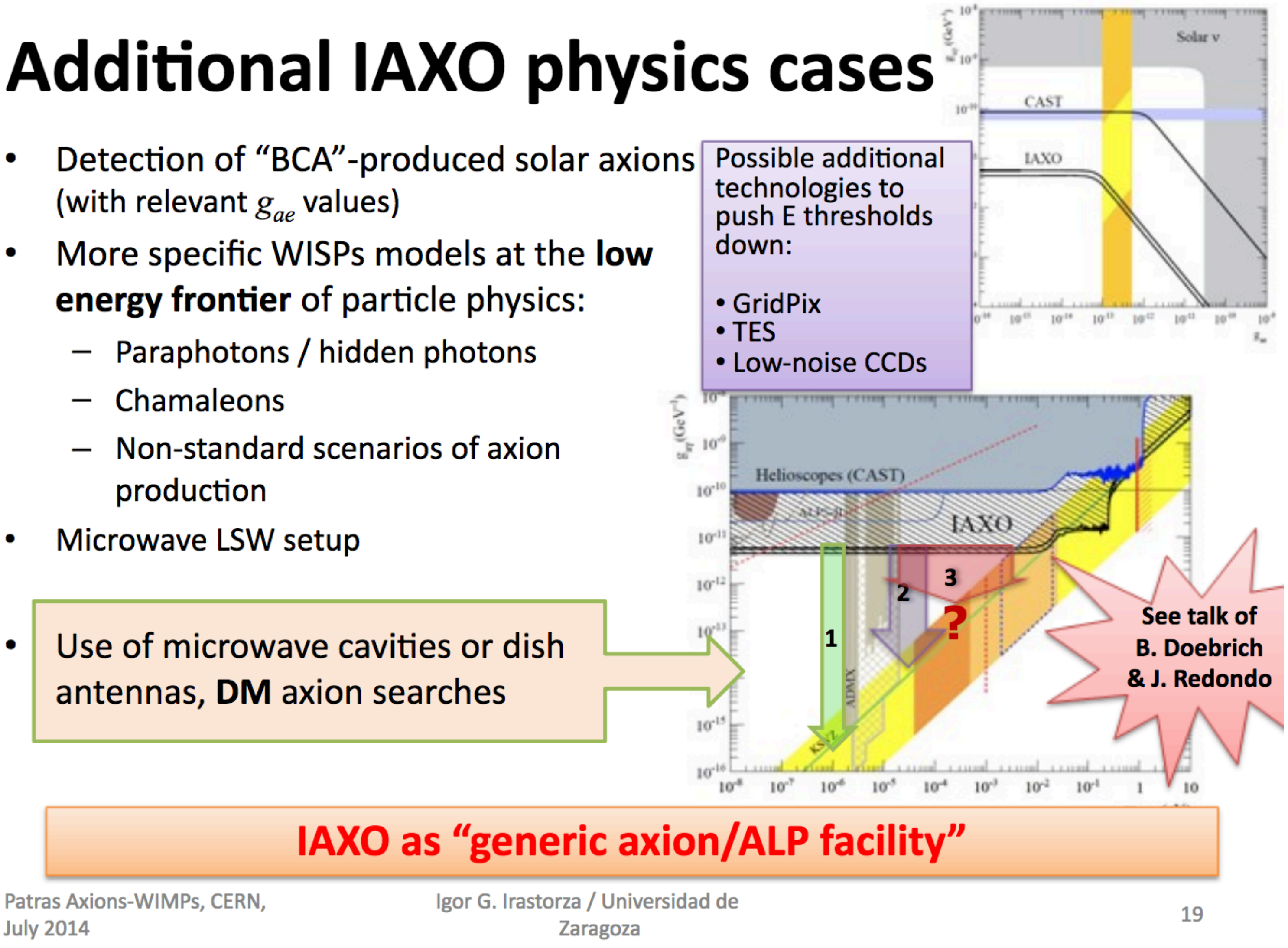
Solar Axion Search (CAST & IAXO)



Additional IAXO physics cases

- Detection of "BCA"-produced solar axions (with relevant g_{ae} values)
- More specific WISPs models at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chameleons
  - Non-standard scenarios of axion production
- Microwave LSW setup
- Use of microwave cavities or dish antennas, **DM** axion searches

Possible additional technologies to push E thresholds down:

- GridPix
- TES
- Low-noise CCDs

See talk of B. Doebrich & J. Redondo

IAXO as "generic axion/ALP facility"

Patras Axions-WIMPs, CERN, July 2014

Igor G. Irastorza / Universidad de Zaragoza

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Axion Search in the Laboratory

Any Light Particle Searches @ DESY in Hamburg

From ALPS I to ALPS II

ALPS I

- based on one HERA proton accelerator dipole magnet,
- initiated 2006 by theory, exp. particle physics and administration,
- approved 2007 and concluded 2010,
- most sensitive ALP search experiment in the lab up to 2014 (surpassed by OSQAR @ CERN using two LHC dipoles).

Jinst Published by IOP Publishing for SISSA Medialab
Received: March 1, 2013
Revised: June 13, 2013
Accepted: July 18, 2013
Published: September 5, 2013

TECHNICAL REPORT

Any light particle search II — Technical Design Report

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[a] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Callinstraße 38, 30167 Hannover, Germany*
[b] *Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, 22607 Hamburg, Germany*
[c] *University of Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany*

E-mail: axel.lindner@desy.de

R Bähre *et al* 2013 *JINST* **8** T09001

ALPS II

- proposed 2011,
  TDR evaluated in 2012,
  directorate decided to continue with the preparatory phase,
- construction phase started in 2017.
- Main goal:
  increase sensitivity on $g_{a\gamma}$ by > 10^3
  to probe for axion-like particles motivated by astrophysics phenomena.

CELL BIOLOGY

Viral vote

Cell **141,** 682–691 (2010)

Why do identical cells often respond differently to the same stimulus? Researchers generally blame noise inherent in biological systems, but there may, in fact, be specific processes at play, according to Ido Golding, now at Baylor College of Medicine in Houston, Texas, and his co-workers.

They watched individual particles of a bacterial virus infect single *Escherichia coli* cells (pictured, top panel, green dots indicate virus particles) — in theory subjecting the cells to the same stimulus. Each virus particle, they found, makes an individual 'decision': to kill the host cell or to become dormant by integrating into the host's DNA. Those decisions are then summed to determine the cell's ultimate fate. Only a unanimous decision by all virus particles to integrate into the DNA of a particular cell keeps that cell alive (red). If even one particle 'votes' for death, the cell bursts (bottom panel, in green). **A.K.**

ELSEVIER

NEUROSCIENCE

Bright eyed

PHYSICS

Not a WISP of evidence

Phys. Lett. B doi:10.1016/j.physletb.2010.04.066 (2010)

In extensions to the standard model, which describes the fundamental particles and forces of physics, some theorists have proposed the existence of very light subatomic particles called WISPs. These could be dark matter, which keeps a spinning galaxy from flying apart.

One way to detect WISPs would be to look for the rare conversion of light particles to WISPs, and later back to photons. In between these conversions, a WISP could zip through any barrier. So Axel Lindner at DESY, the German electron synchrotron in Hamburg, and his colleagues shone green laser light at a 'wall', a thick piece of light-absorbing material, hoping that a few photons might pop out the other side. They increased the chances of a WISP conversion by using optical resonators to boost the power of the laser light and by applying a strong magnetic field. But the researchers did not detect any emerging photons, limiting the chance of a WISP conversion to nearly 1 in 10^{25} — the most sensitive limit yet. **E.H.**

JOURNAL CLUB

Marc Vrakking
Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin

A physicist discusses how to visualize a molecule changing shape.

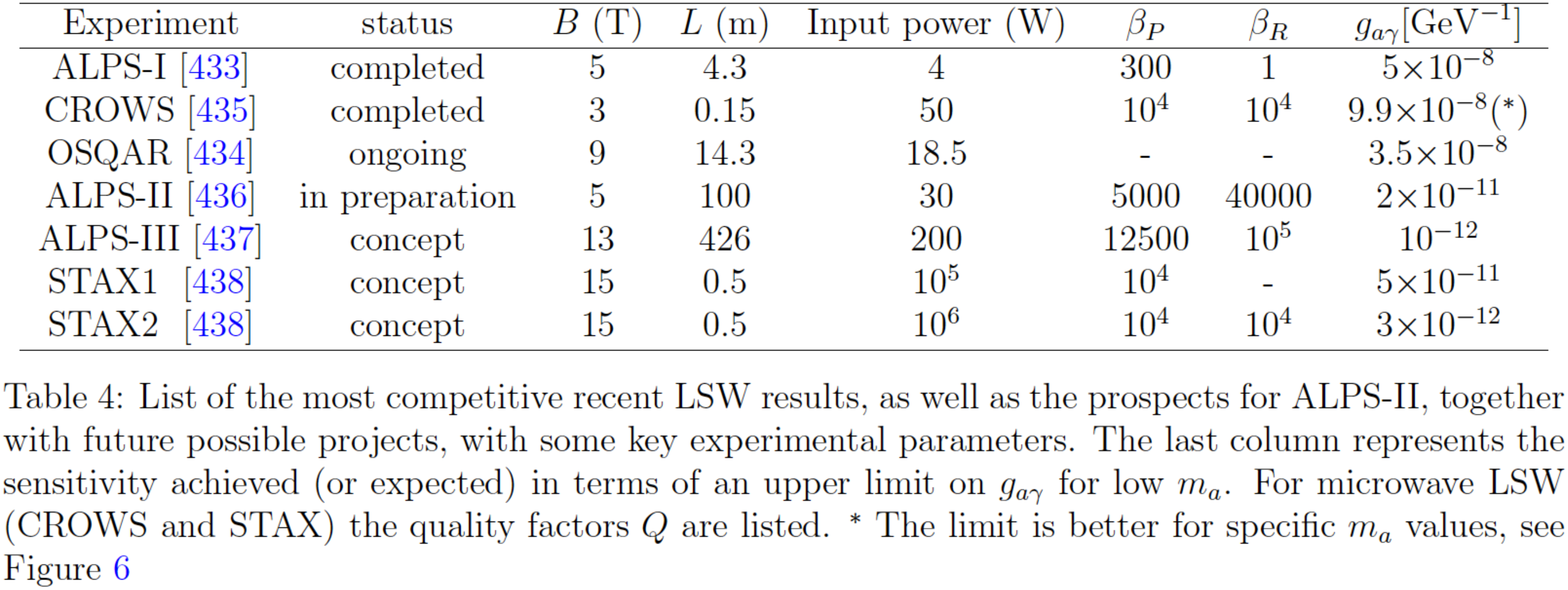
It is the dream of many a chemist to watch a movie of a molecule undergoing structural change. So how can we achieve this? One way is to use the relationship between a molecule's absorption spectrum and its structure to deduce how the structure changes over time. However, a drawback of this technique is its reliance on prior knowledge of the molecular absorption spectrum.

Faton Krasniqi at the Max Planck Advanced Study Group in Hamburg, Germany, and his co-workers present an alternative idea: using photoelectrons ejected from molecules excited by X-ray free-electron lasers to determine molecular structures that change over time (F. Krasniqi *et al. Phys. Rev. A* **81,** 033411; 2010).

They explain how electrons that are ejected and directly detected without any further interaction with the molecule interfere with electrons that scatter off the surrounding atoms in the molecule, thereby creating

Axion Search in the Laboratory

$$\mathcal{P}(\gamma \to a \to \gamma) = \left(\frac{g_{a\gamma} B_e}{\omega}\right)^4 |\mathcal{G}|^2 \beta_P \beta_R,$$



Experiment	status	B (T)	L (m)	Input power (W)	β_P	β_R	$g_{a\gamma}[\mathrm{GeV}^{-1}]$
ALPS-I [433]	completed	5	4.3	4	300	1	5×10^{-8}
CROWS [435]	completed	3	0.15	50	10^4	10^4	9.9×10^{-8}(*)
OSQAR [434]	ongoing	9	14.3	18.5	-	-	3.5×10^{-8}
ALPS-II [436]	in preparation	5	100	30	5000	40000	2×10^{-11}
ALPS-III [437]	concept	13	426	200	12500	10^5	10^{-12}
STAX1 [438]	concept	15	0.5	10^5	10^4	-	5×10^{-11}
STAX2 [438]	concept	15	0.5	10^6	10^4	10^4	3×10^{-12}

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g_{a\gamma}$ for low m_a. For microwave LSW (CROWS and STAX) the quality factors Q are listed. * The limit is better for specific m_a values, see Figure 6

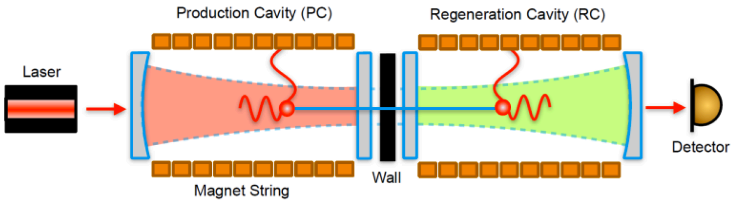
From

New experimental approaches in the search for axion-like particles

Igor G. Irastorza[1,2] and Javier Redondo[1,3]

Axion Search in the Laboratory

ALPS II @ DESY in Hamburg: construction started!



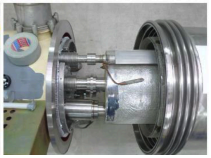
10+10 dipole magnets from the HERA proton accelerator

Production cavity and regeneration cavity, mode matched

$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1T}\frac{l}{10m}\right)^4$$

ALPS II main components: magnets from HERA

- 10+10 dipoles from HERA, each 5.3 T on 8.8 m.
- To be straightened to achieve ≈ 50 mm aperture.
- 10 magnets modified successfully (out of 10).
- The HERA tunnel is being cleared.



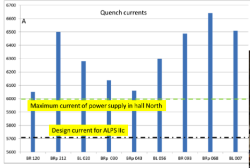


Figure 6.1: Obtained quench currents of straightened HERA dipoles

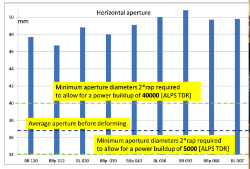
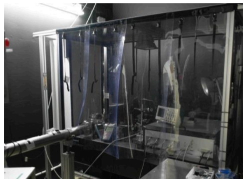


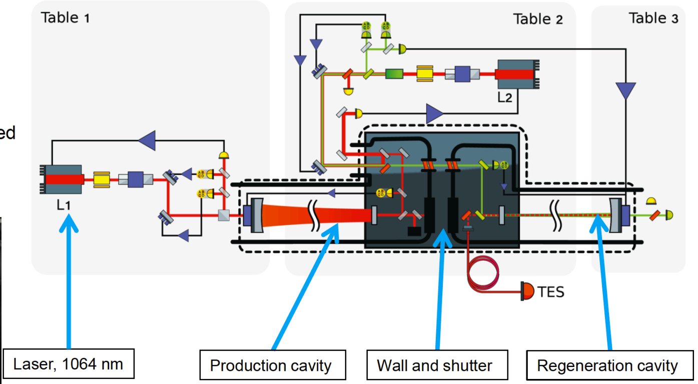
Figure 6.2: Horizontal aperture of HERA dipoles after straightening

ALPS II main components: optics adapted from LIGO

Laser:

- developed for LIGO,
- based on 2 W NPRO by Innolight/Mephisto (Nd:YAG, neodymium-doped yttrium aluminium garnet),
- 1064 nm, 35 W, M^2<1.1

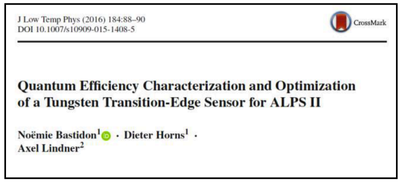




ALPS II main components: detectors

DESY:

- Transition edge sensor (TES) operated at 80 mK.
- Single 1064 nm photon detection demonstrated.



J Low Temp Phys (2016) 184:88–90
DOI 10.1007/s10909-015-1408-5

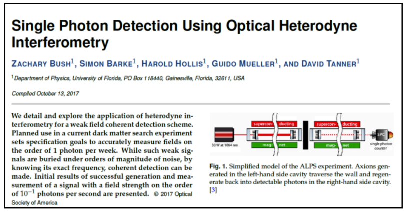
CrossMark

Quantum Efficiency Characterization and Optimization of a Tungsten Transition-Edge Sensor for ALPS II

Noëmie Bastidon[1] · Dieter Horns[1] · Axel Lindner[2]

University of Florida:

- Heterodyne detection scheme.
- 0.1 photons/s detected.



Single Photon Detection Using Optical Heterodyne Interferometry

ZACHARY BUSH[1], SIMON BARKE[1], HAROLD HOLLIS[1], GUIDO MUELLER[1], AND DAVID TANNER[1]

[1] Department of Physics, University of Florida, PO Box 118440, Gainesville, Florida, 32611, USA

Compiled October 13, 2017

We detail and explore the application of heterodyne interferometry for a weak field coherent detection scheme. Planned use in a current dark matter search experiment sets specification goals to accurately measure fields on the order of 1 photon per week. While such weak signals are buried under orders of magnitude of noise, by knowing its exact frequency, coherent detection can be made. Initial results of successful generation and measurement of a signal with a field strength on the order of 10^{-1} photons per second are presented. © 2017 Optical Society of America

Fig. 1. Simplified model of the ALPS experiment. Axions generated in the left-hand side cavity traverse the wall and regenerate back into detectable photons in the right-hand side cavity. [3]

https://arxiv.org/abs/1710.04209

Summary

- **Axion Research is getting mature (discovery potential)**

- **A host of new ideas of detecting dark matter axions have been proposed recently**

- **Major R&Ds have been possible due to fast developing technologies from superconductors and quantum computing**

- **Stay tuned !**

CAPP
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Physics Research

Thank You For Your Attention!