AMO Applications to HEP

John Gillaspy

Program Director

Atomic, Molecular and Optical Physics—Experiment

National Science Foundation

HEPAP 11/30/2018
Gaithersburg

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Context: my personal background

1980: Big Electron Accelerator

SLAC
NATIONAL ACCELERATOR LABORATORY

1990: Little Electron Accelerator
Precision Measurements

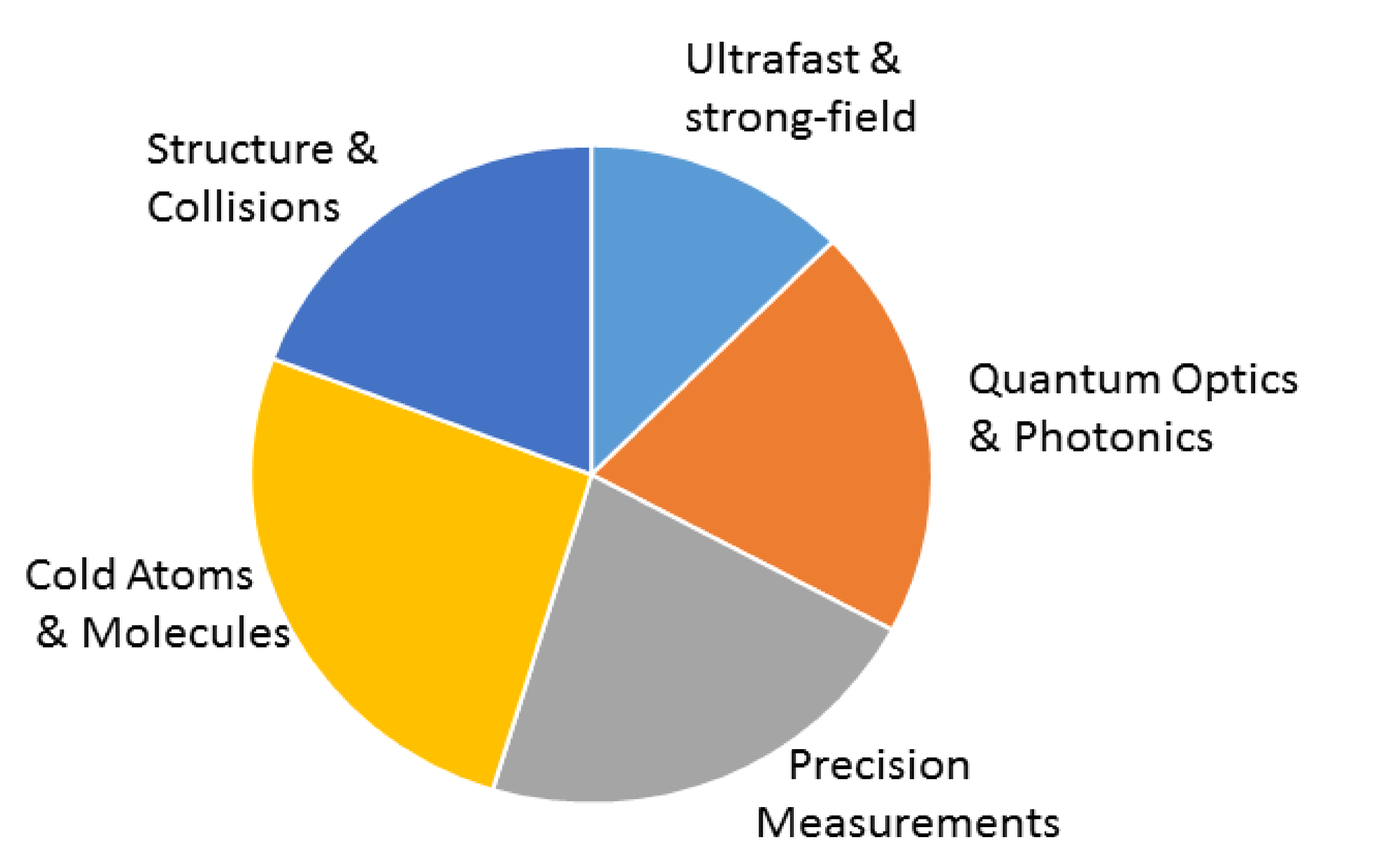
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

2014: AMO Program

NSF

Context: NSF AMO-E portfolio (2015-2018)

$18M/year



I. Intense Lasers
II. Precision Measurements

I. Intense Lasers

(particle acceleration, vacuum pair production)

- 2018 Nobel Prize shared by Gerard Mourou for CPA (NSF's AMO Program supported Mourou's work in ultrafast laser research; U Mich 1991-2006)
- Key technology to produce the most extreme laser light intensities: equivalent to focusing all of the sunlight reaching the earth onto tip of a pencil (10^20 W/cm2)
- Currently supporting, e.g. Zenghu Chang (UCF) & Wendell Hill (UMD)

World's shortest pulses: around 50 attoseconds (40-50x10^{-18} s)

I. Lasers for Particle Acceleration
II. Precision Measurements

Technology Breakthrough Underlying Many Precision Measurements

Atomic Clock Precision

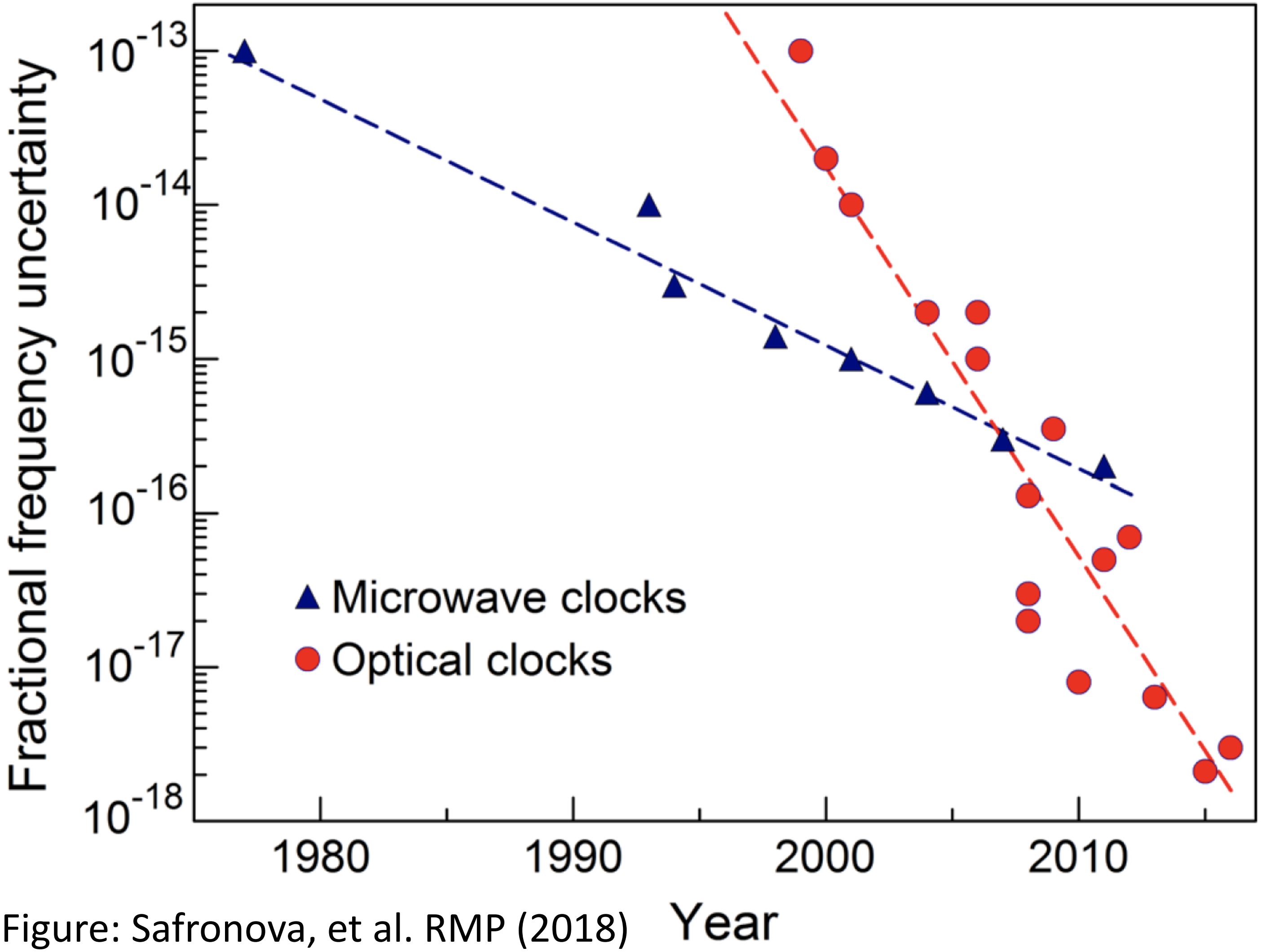


Figure: Safronova, et al. RMP (2018)

NSF funds clock work at universities (supplementary to NIST)
e.g. Kurt Gibble, Penn State

Technology Breakthrough Underlying Many Precision Measurements

Atomic Clock Precision

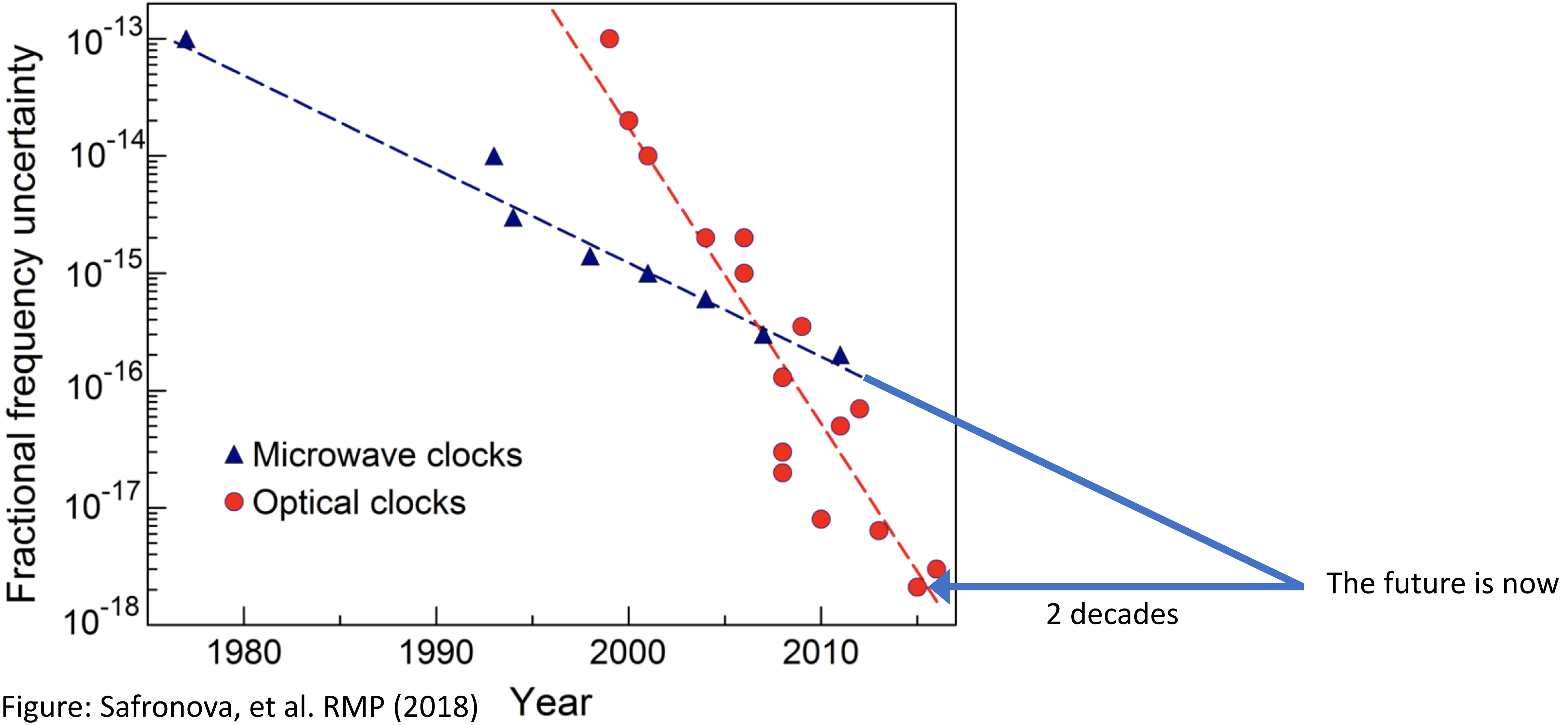
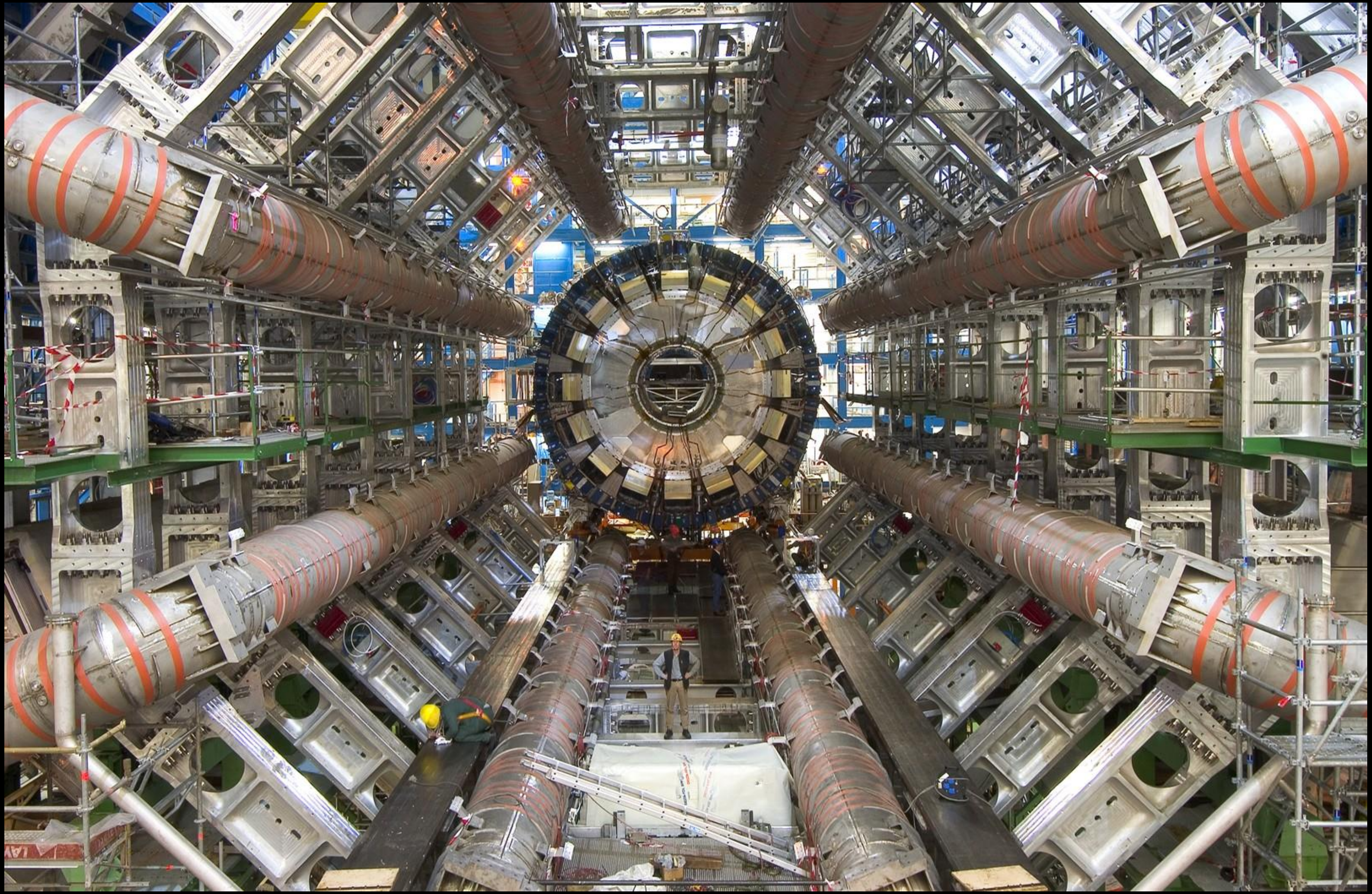


Figure: Safronova, et al. RMP (2018)

Precision Measurements

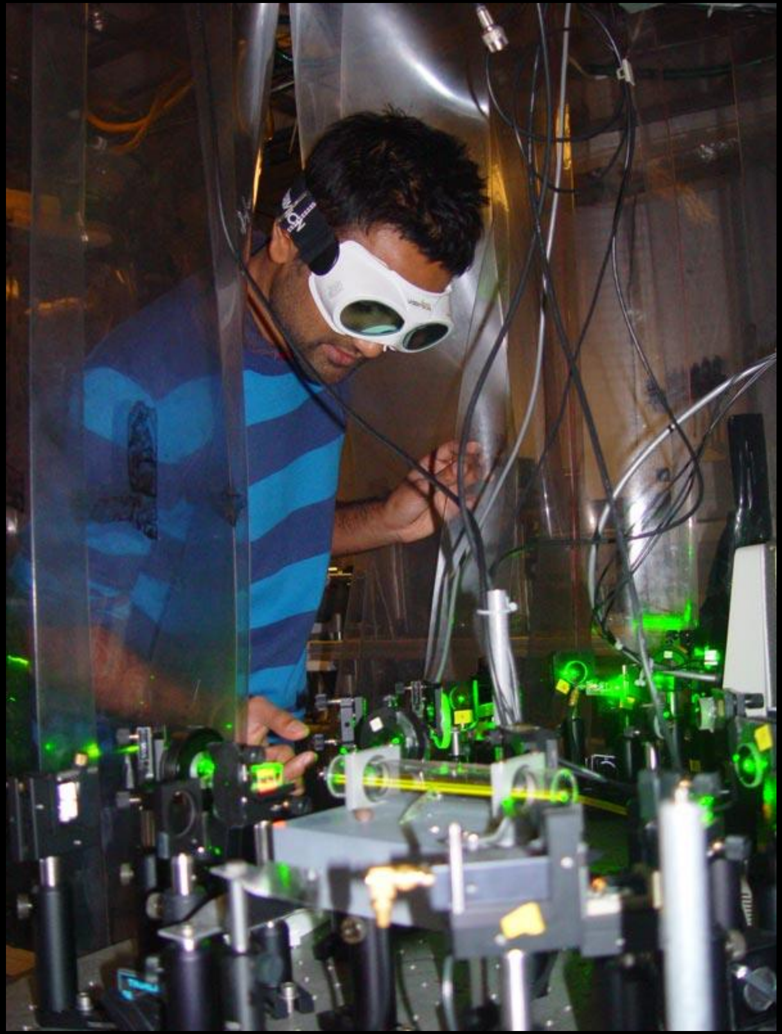
- Virtual Particles
- Fundamental Symmetries
- Fundamental Constants
- Search for new forces (or deviations from scaling of known forces)
- Quantum Detectors
- Misc "beyond the Standard Model of Particle Physics" searches (e.g. tests of Bell's inequality).

High Energy Particle Detector
(on the mass shell)



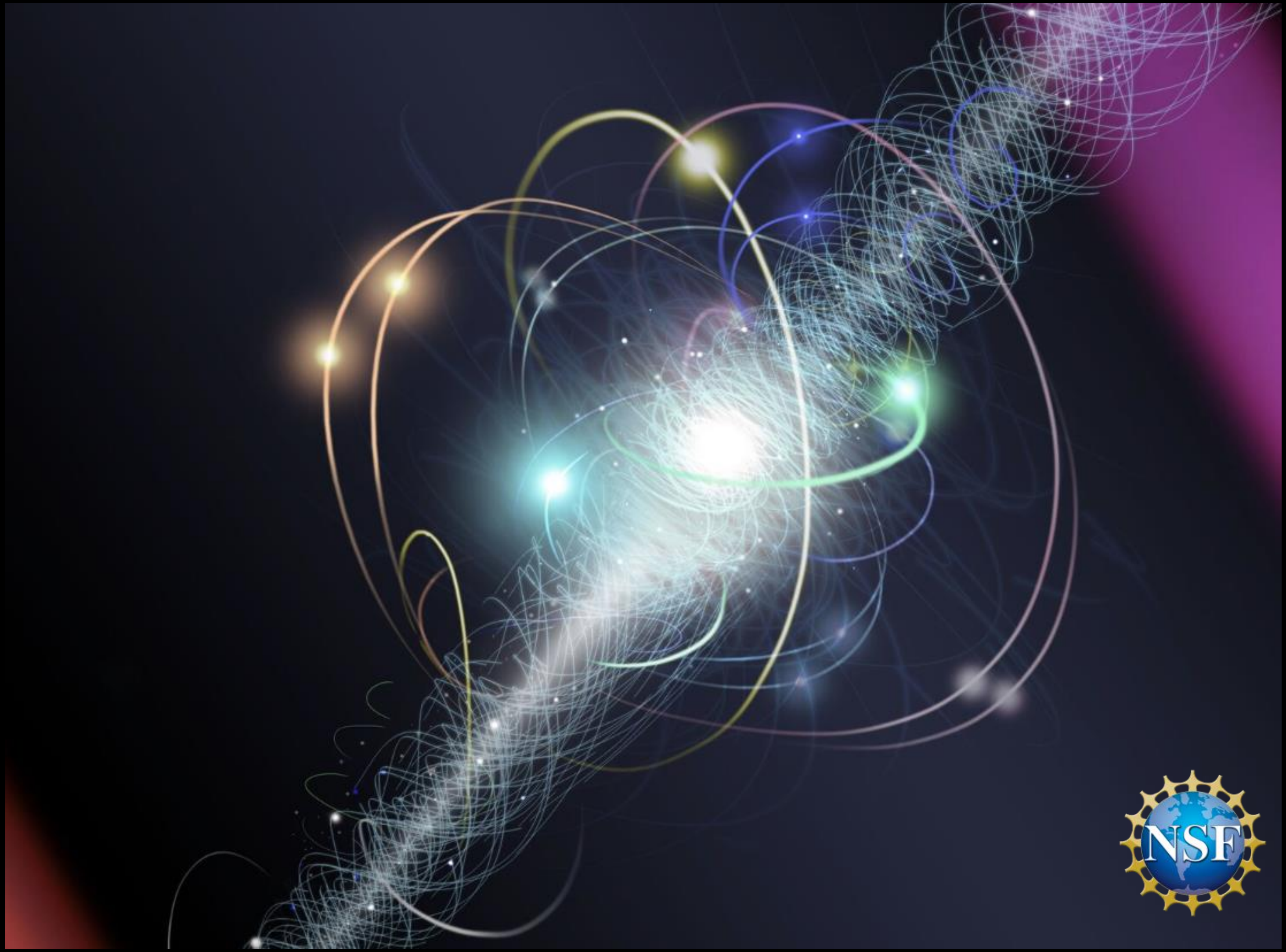
ATLAS at LHC

Virtual Particle Experiment
(off the mass shell)



EDM (Tarbutt Lab)

Virtual Particles



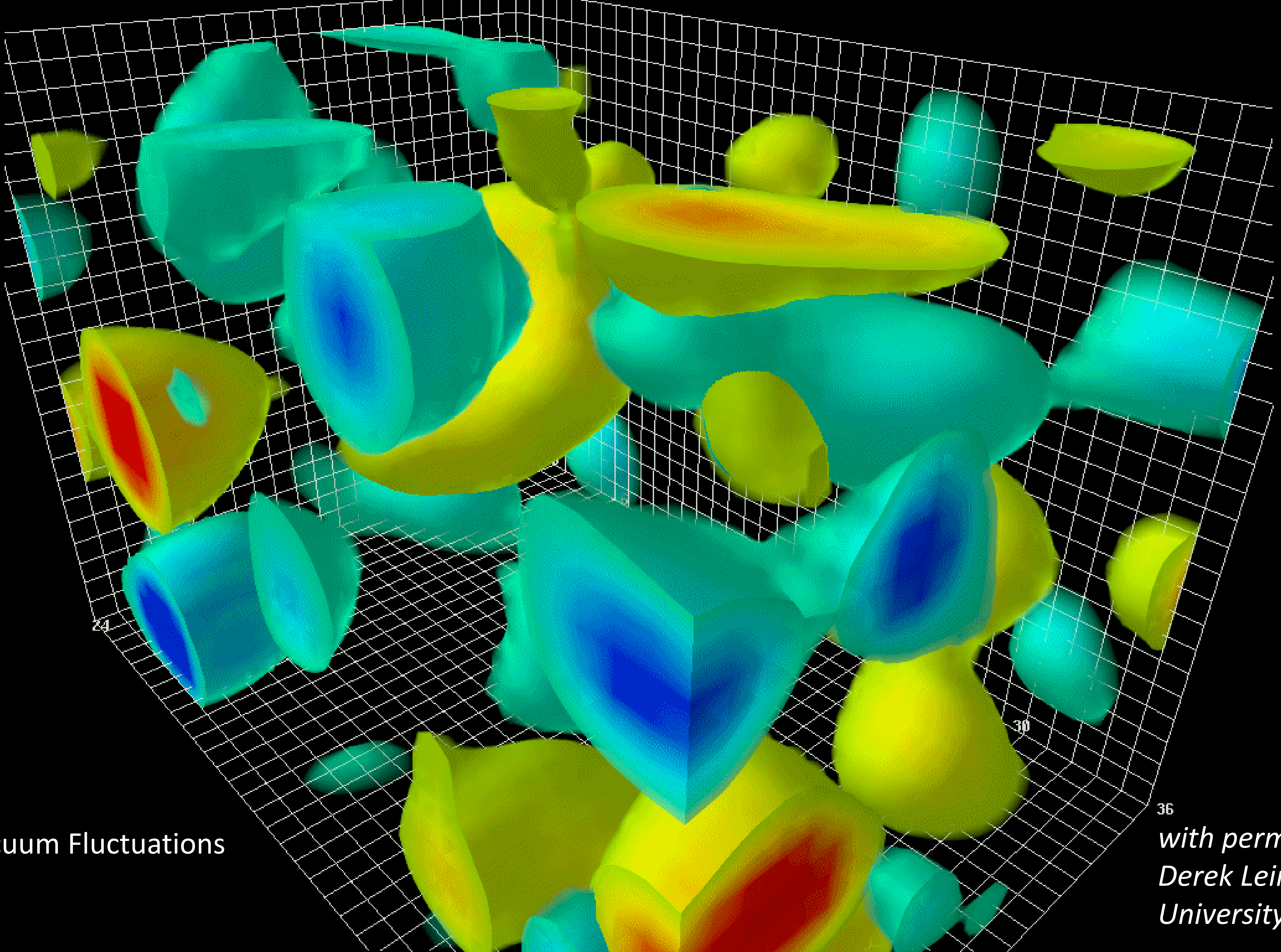
ACME-II (Nature, 2018)
search for electron EDM
(electric dipole moment)
DeMille (1404146)

EPP co-fund

Saul Gonzalez

Cornell (PFC 1734006)

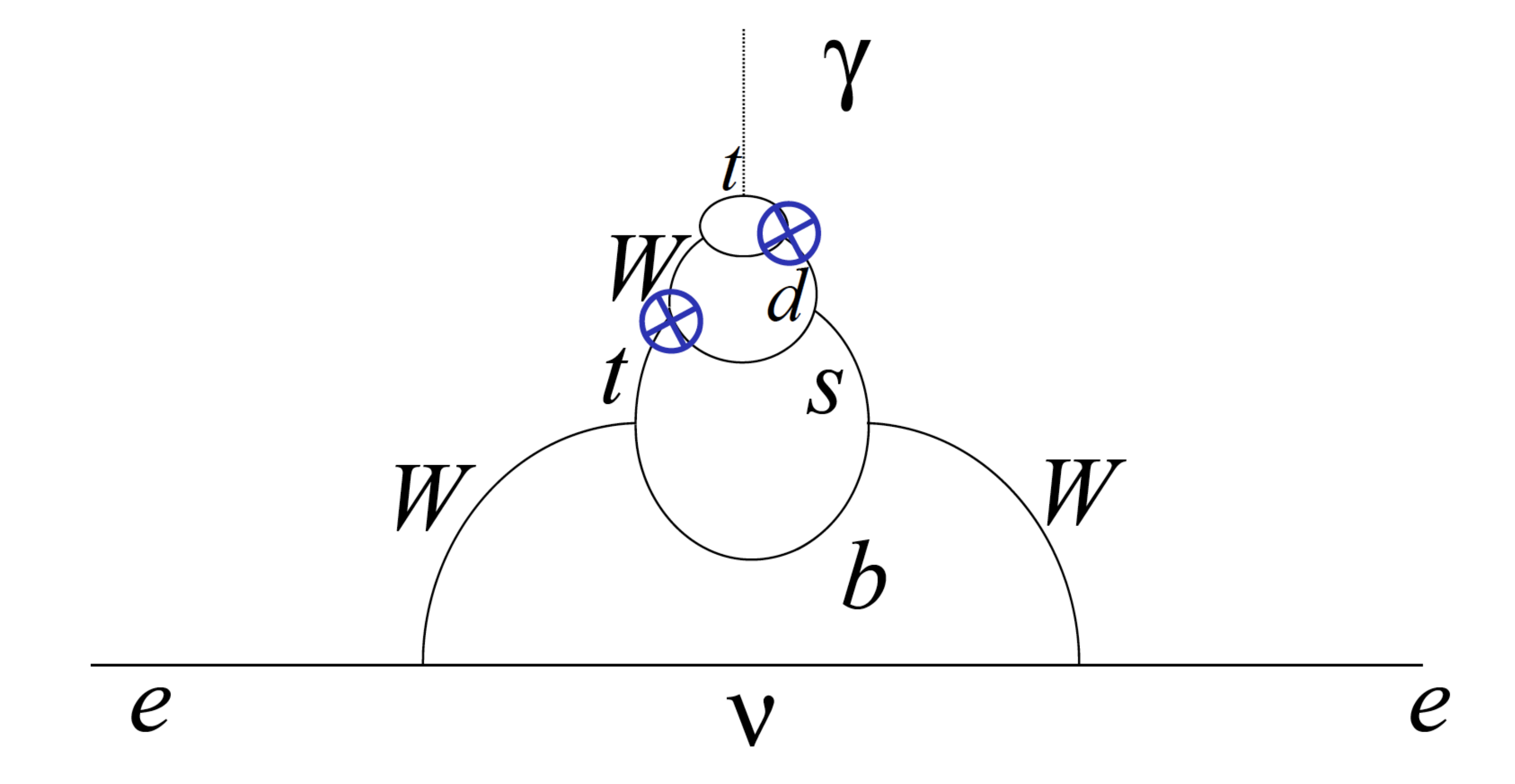
Weiss (1607517)



Quantum Vacuum Fluctuations
(QCD)

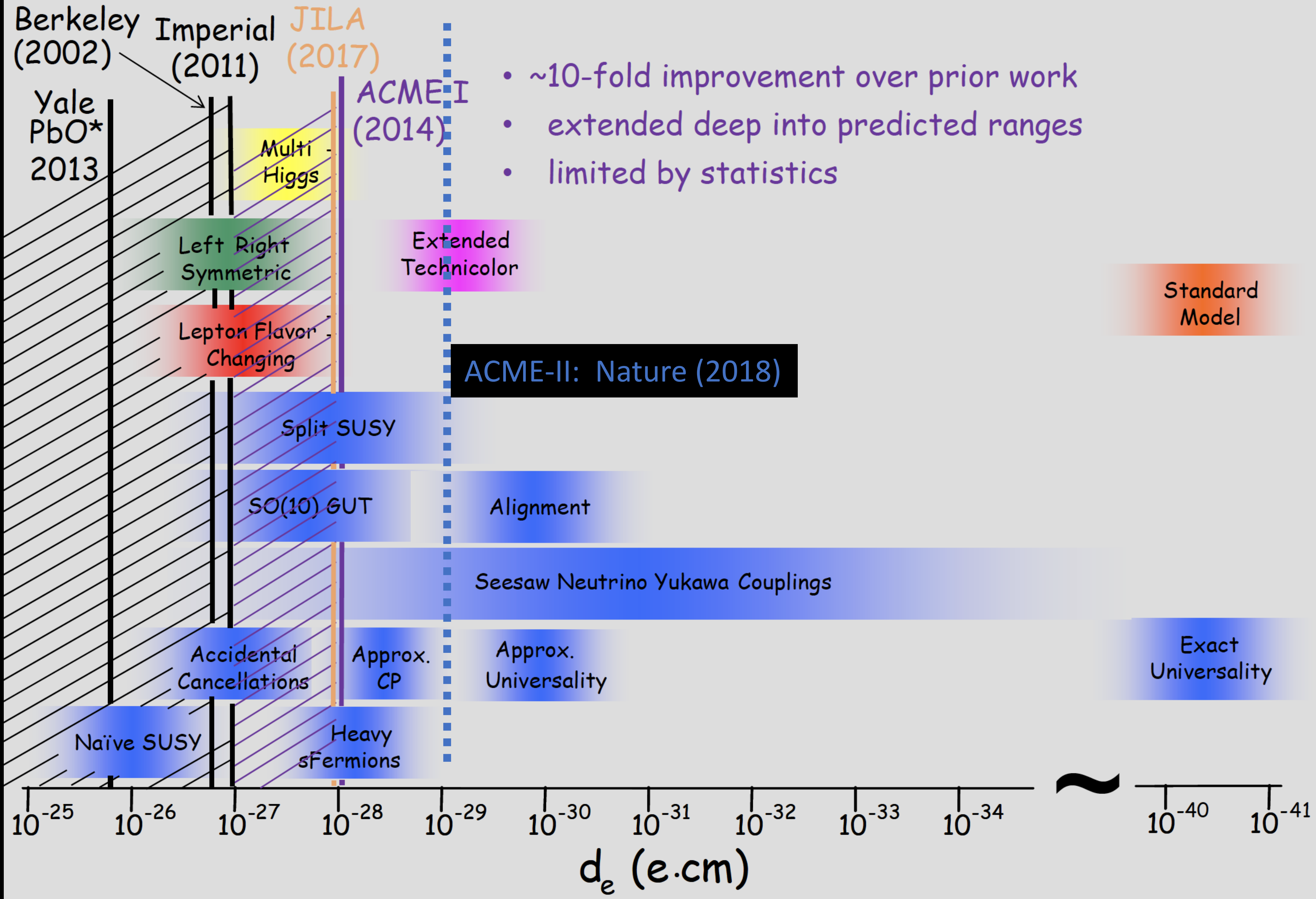
with permission from
Derek Leinweber
University of Adelaide

Standard Model eEDM
(extremely small)



4-loop Feynman diagram involving quarks; CP-violating components of the CKM matrix

Upper bound on electron EDM from ACME I



- ~10-fold improvement over prior work
- extended deep into predicted ranges
- limited by statistics

“This result implies that a broad class of conjectured particles, if they exist and time-reversal symmetry is maximally violated, have masses that greatly exceed what can be measured directly at the Large Hadron Collider.”

--ACME-II, Nature **562**, 355 (2018)

A positive signal could provide a strong motivation to build a higher energy collider (ACME-II: 3–30 TeV c^{-2} cf. LHC 13 TeV c^{-2})

Caveats and Loopholes in AMO constraints

Impact of EDMs in particle physics

J. Feng: "Naturalness and the status of SUSY", Annu. Rev. Nucl. Part. Sci. (2013)

"All of the constraints shown are merely indicative and subject to significant loopholes and caveats"

From Dave DeMille's 2018 DAMOP talk

Implications for ACME-II limit on the SUSY partner to the top quark

Interpreting the Electron EDM Constraint

Cari Cesarotti,[a] Qianshu Lu,[a] Yuichiro Nakai,[b] Aditya Parikh,[a] and Matthew Reece[a]
[a] Department of Physics, Harvard University, Cambridge, MA, 02138
[b] Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854

October 22, 2018

https://arxiv.org/abs/1810.07736

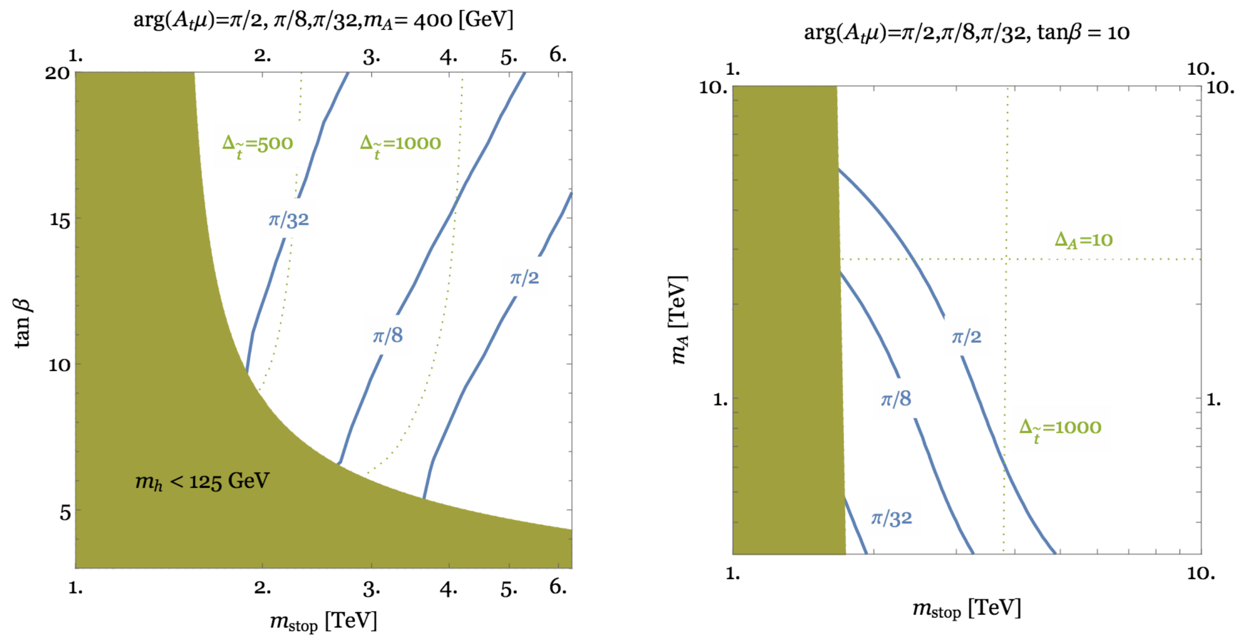


Figure 7: The implication of the EDM bound in the ACME II experiment on the stop parameter space in the MSSM where the 125 GeV Higgs mass is realized by stop loops with a large A-term. The horizontal axis is the common stop mass $m_{\rm stop} = m_{\tilde{Q}_3} = m_{\tilde{u}_3}$. The vertical axes show $\tan\beta$ and m_A in the left and right panels respectively. We fix $m_A = 400$ GeV in the left panel and $\tan\beta = 10$ in the right panel. The phase is taken to be $\arg(A_t\mu) = \pi/2, \pi/8, \pi/32$. The parameter $|\mu|$ is 350 GeV. The green region is excluded by the small Higgs mass with any values of the A-term. The blue curves denote the ACME II constraint. The green dotted curve describes the degree of fine-tuning defined in (5.1).

Precision Measurements

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FUNDAMENTAL SYMMETRIES:

- Discrete (CPT, Permutation)
- Continuous (Local Lorentz Invariance)

Antimatter:

Positronium:
1807054   Tom (1S-2S spectroscopy)

Anti-hydrogen
1836330 Gabrielse, Harvard (AMO Program)
1806305 Fajans, Berkeley (Plasma Program)

Local Lorentz Invariance
PHY 1507160

Entanglement enhanced precision test of local Lorentz invariance

Eli Megidish,[1] Joseph Broz,[1] Nicole Greene,[1] and Hartmut Häffner[1]

[1] *Department of Physics, University of California, Berkeley, California 94720, USA*

The high degree of control available over individual atoms enables precision tests of fundamental physical concepts. In this paper we study how entangled states can be leveraged to enhance a precision test of local Lorentz invariance of the electron. Employing high-fidelity entanglement of a pair of trapped $^{40}Ca^+$-ions, we find that the sensitivity can be improved by a factor of two. The sensitivity of our measurements nearly reaches the projection noise limit set by quantum mechanics. Our measurements improve the previous best limit for local Lorentz invariance of the electron using $^{40}Ca^+$-ions by factor of two to about 5×10^{-19}.

https://arxiv.org/abs/1809.09807

NB: Connection with Quantum Leap

- This (PHY 1507160), and many other Precision Measurement awards in the NSF AMO-E program (e.g. ACME), exploit uniquely quantum ("classically impossible") effects such as entanglement, superposition, squeezing, etc.

- As such, they could reasonably be construed to fall under the general rubric of institutional or national quantum initiatives (although they are supported as part of NSF's longstanding "core" quantum research in AMO, not part of new "quantum leap" programs).

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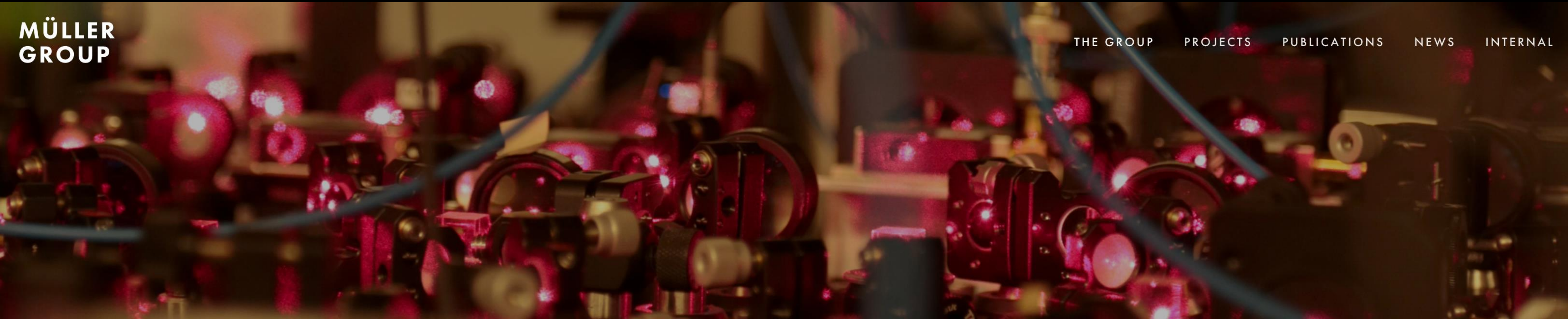
Changes in Fundamental Constants

EPP co-fund

- 1806583 Mueller (h/m; fine structure constant; atom interferometry)
- 1806223 Hanneke (search for change in m_p/m_e; molecular ion vibration)
- 1707575 Gupta (h/m; fine structure constant; atom interferometry with Yb BEC)
- 1607565 Gabrielse (electron g-2, fine structure constant)
- 1806494 Takacs (Rydberg constant in Highly Charged Ions)

EPP & ENP co-fund



Precision Measurements

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Search for new forces:

- 1806297 Hunter A Search for Long-Range Spin-Spin Interactions and Optical Forces in TlF

  (associated with an ultralight vector meson or a dark photon)

- 1404325 Romalis Precision Measurements with Nuclear Spins

  (spin-gravity interaction with energy sensitivity at the Planck scale)

- 1708160 Mueller Corrections to the gravitational force from cosmological Dark Energy

Precision Measurements

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- ★ Quantum Detectors
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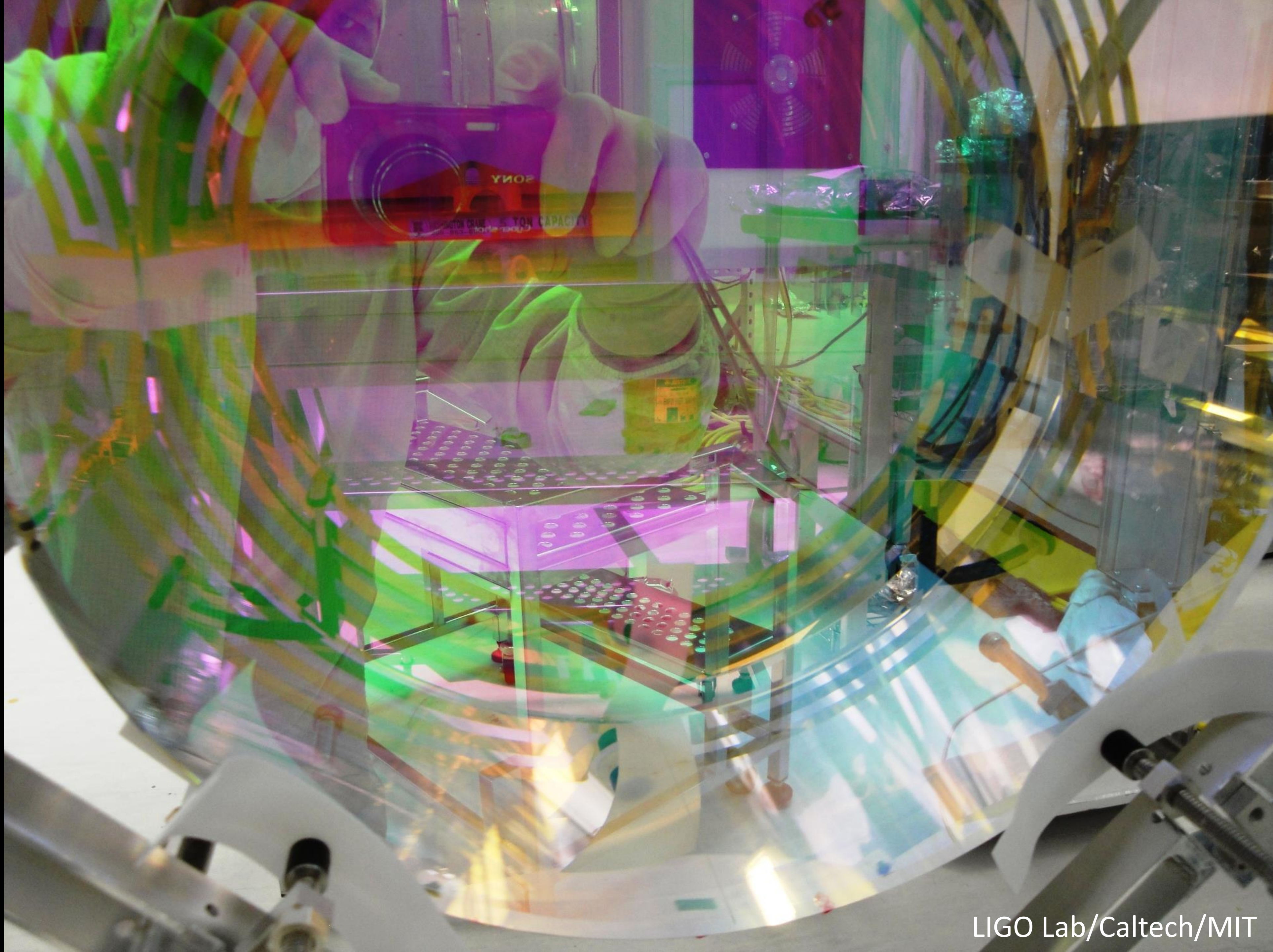
LIGO

Mavalvala, MIT;
squeezed light



LIGO Lab/Caltech/MIT

Precision Measurements

- Virtual Particles
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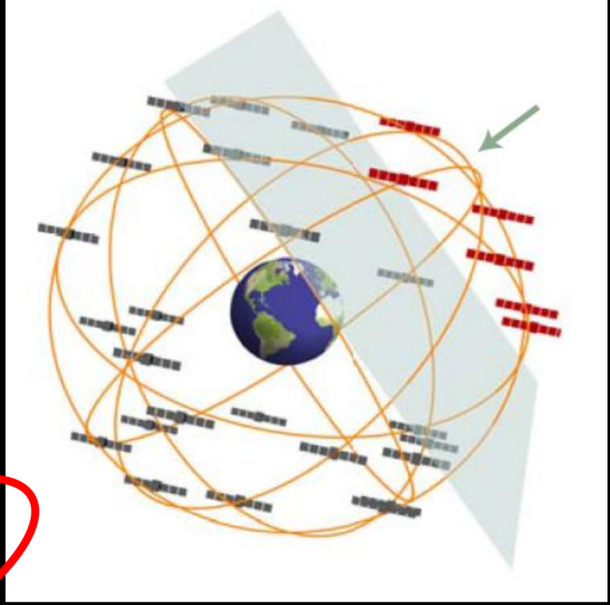
Misc “beyond the Standard Model of Particle Physics” searches (e.g. tests of Bell’s inequality).

- 1541160 Kaiser Testing Bell's Inequality . . .
- 1844337 Blinov Remote Entanglement of Trapped Ions and Loophole-Free Bell Inequality

AMO & Dark Matter



- GNOME (using network of atomic magnetometers to search for low mass dark matter). Stalnaker/Kimball 1707875/1707803

PA co-fund

- GPS.DM (GPS satellite network as a planet-sized detector to search for clumps of low mass dark matter, changing fundamental constants). Derevianko 1806672

PA co-fund

- Optically Searching for New Physics from a Dark Sector Using Optically Levitated Microspheres Moore 1653232

PA co-fund

Co-funded with Jim Whitmore

AMO-nuclear

Proton Size Puzzle, EDM, detectors . .

- 1654610 Singh (NSCL, Michigan State)
  single atom microscope to detect rare nuclear reactions; atoms captured inside a thin film of frozen neon
- 1649324 Fairbank (Colorado State University)
  to detect one barium atom in five tons of liquid xenon using laser spectroscopy (for neutrino mass; nEXO detector)
- 1707573 Heckel (University of Washington)
  EDM in ^{199}Hg

Co-fund with
Nuclear Physics
Allena Opper, NSF PD

For More Info:
Workshops

Fundamental Physics Innovation AWARDS

APS physics | GORDON AND BETTY MOORE FOUNDATION

Home | Scientific Scope | Lectureship Awards | Visitor Awards | Convening Awards | Grant Publicity

Scientific Scope of the Fundamental Physics Innovation Awards

The Standard Model describing nature's matter and force particles is known to be incomplete, and the conventional techniques for discovering new particles (colliders, large detectors, etc.) are becoming prohibitively expensive. Given the challenge posed by open questions such as the nature of dark matter and dark energy, it is important to find alternative ways to test well motivated theories that aim to solve the important problems of fundamental physics.

Precision instruments create a timely opportunity to search for new physics beyond the Standard Model by measuring small signals in cost-effective experiments that are often well suited to university-scale laboratories. Novel instruments and methods that use quantum mechanics to achieve new measurement capabilities – so called quantum technologies – have exploded over the past two decades and lie at the core of this emerging opportunity. The range of instrumentation is broad, spanning current and emerging techniques from, for example, atomic and optic... inter... few.

Whil... desig... expe... the a... signa... visits... learn...

Gran... suite... instru... facili... of lov... resea... or ac...

WORKSHOP ON OPPORTUNITIES IN FUNDAMENT...

The workshop took place in Palo Alto, California on October 24-25, 2016.

The workshop and report have been funded by the Gordon and Betty Moore Fou...

Workshop organizers from the Gordon and Betty Moore Foundation Science Pr...

Ernie Glover, Program Officer

Irena Kotikova, Program Associate

Workshop Scientific Advisors:

2016

49th Annual DAMOP Meeting
May 28 - June 1, 2018 • Ft. Lauderdale, FL

Precision-measurement Searches for New Physics

Third annual workshop of the Group on Precision Measurements and Fundamental Constants

May 28, 2018

2018

Table-Top Experiments with Skyscraper Reach

2017

Workshop at MIT

August 9-11, 2017

Goal

The goal of the workshop is to bring together a diverse set of scientists from the particle physics, nuclear physics, and AMO communities to discuss new ideas for small-scale experiments that can search for new physics beyond the Standard Model. These experiments push the boundaries of the sensitivity frontier, as a complement to LHC searches at energy frontier.

For More Info:

Papers

REVIEW

Probing the frontiers of particle physics with tabletop-scale experiments

David DeMille,[1*] John M. Doyle,[2*] Alexander O. Sushkov[3,4*]

The field of particle physics is in a peculiar state. The standard model of particle theory successfully describes every fundamental particle and force observed in laboratories, yet fails to explain properties of the universe such as the existence of dark matter, the amount of dark energy, and the preponderance of matter over antimatter. Huge experiments, of increasing scale and cost, continue to search for new particles and forces that might explain these phenomena. However, these frontiers also are explored in certain smaller, laboratory-scale "tabletop" experiments. This approach uses precision measurement techniques and devices from atomic, quantum, and condensed-matter physics to detect tiny signals due to new particles or forces. Discoveries in fundamental physics may well come first from small-scale experiments of this type.

DeMille *et al.*, *Science* **357**, 990–994 (2017)   8 September 2017

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for new physics with atoms and molecules

M. S. Safronova

University of Delaware, Newark, Delaware 19716, USA
and Joint Quantum Institute, National Institute of Standards and Technology
and the University of Maryland, College Park, Maryland 20742, USA

D. Budker

Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,
University of California, Berkeley, California 94720, USA,
and Nuclear Science Division, Lawrence Berkeley National Laboratory,
Berkeley, California 94720, USA

D. DeMille

Yale University, New Haven, Connecticut 06520, USA

Derek F. Jackson Kimball

California State University, East Bay, Hayward, California 94542, USA

A. Derevianko

University of Nevada, Reno, Nevada 89557, USA

Charles W. Clark

Joint Quantum Institute, National Institute of Standards and Technology
and the University of Maryland, College Park, Maryland 20742, USA

Interpreting the Electron EDM Constraint

Cari Cesarotti,[a] Qianshu Lu,[a] Yuichiro Nakai,[b] Aditya Parikh,[a] and Matthew Reece[a]
[a] Department of Physics, Harvard University, Cambridge, MA, 02138
[b] Department of Physics and Astronomy, Rutgers University, Piscataway, NJ 08854

October 22, 2018

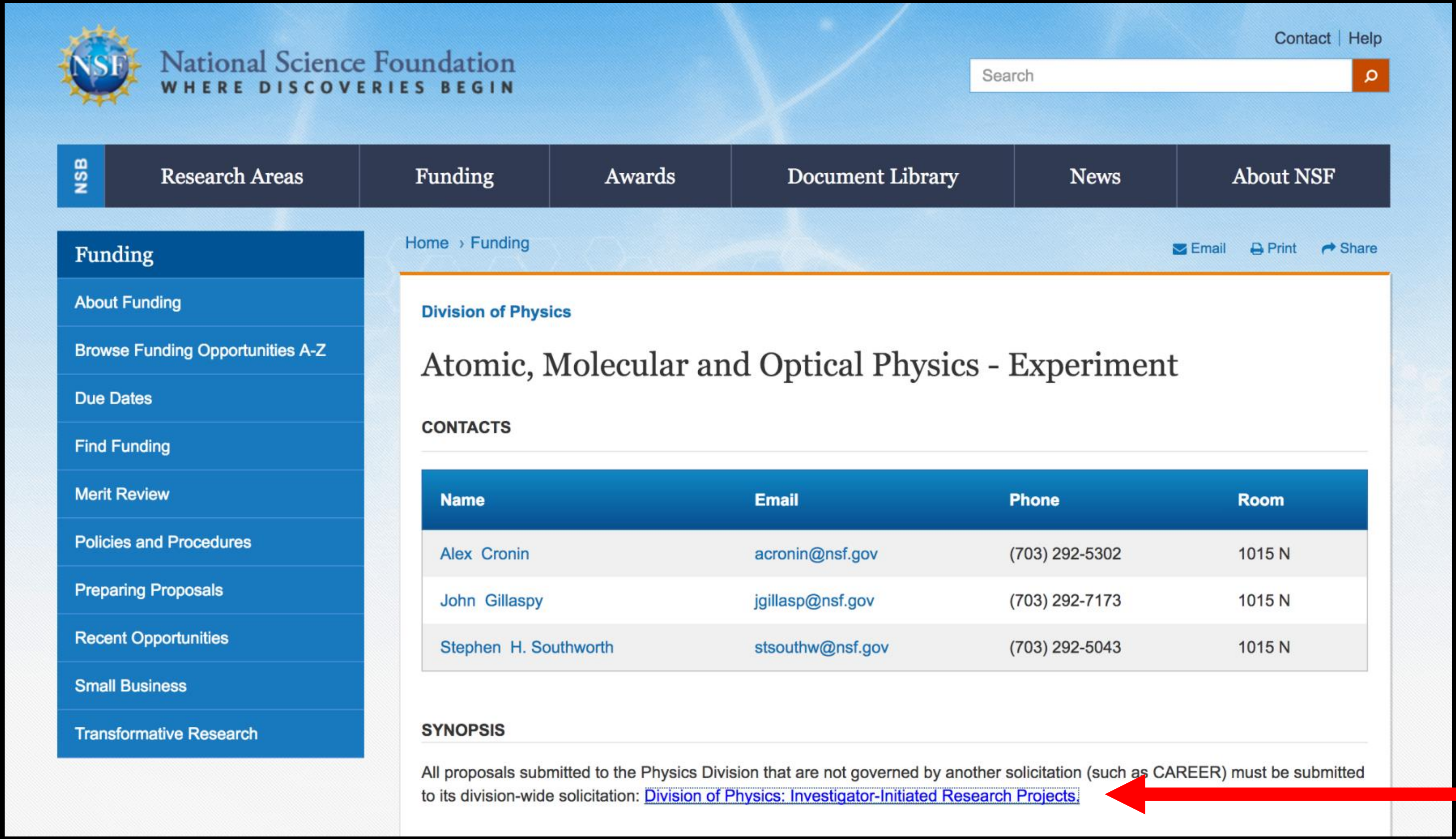
https://arxiv.org/abs/1810.07736

Give someone a fish and they will eat today.

Teach someone to fish and they will eat forever

Fishing for Active NSF AMO Awards:

Google: NSF AMO-E



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Division of Physics

Atomic, Molecular and Optical Physics - Experiment

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John Gillaspy	jgillasp@nsf.gov	(703) 292-7173	1015 N
Stephen H. Southworth	stsouthw@nsf.gov	(703) 292-5043	1015 N

SYNOPSIS

All proposals submitted to the Physics Division that are not governed by another solicitation (such as CAREER) must be submitted to its division-wide solicitation: Division of Physics: Investigator-Initiated Research Projects.

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Division of Physics

Division of Physics: Investigator-Initiated Research Projects (PHY)

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Saul Gonzalez Martirena	sgonzale@nsf.gov	(703) 292-2093	

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What Has Been Funded (Recent Awards Made Through This Program, with Abstracts)

Map of Recent Awards Made Through This Program

News

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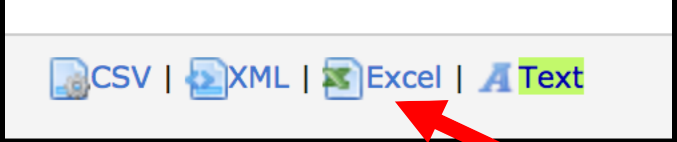
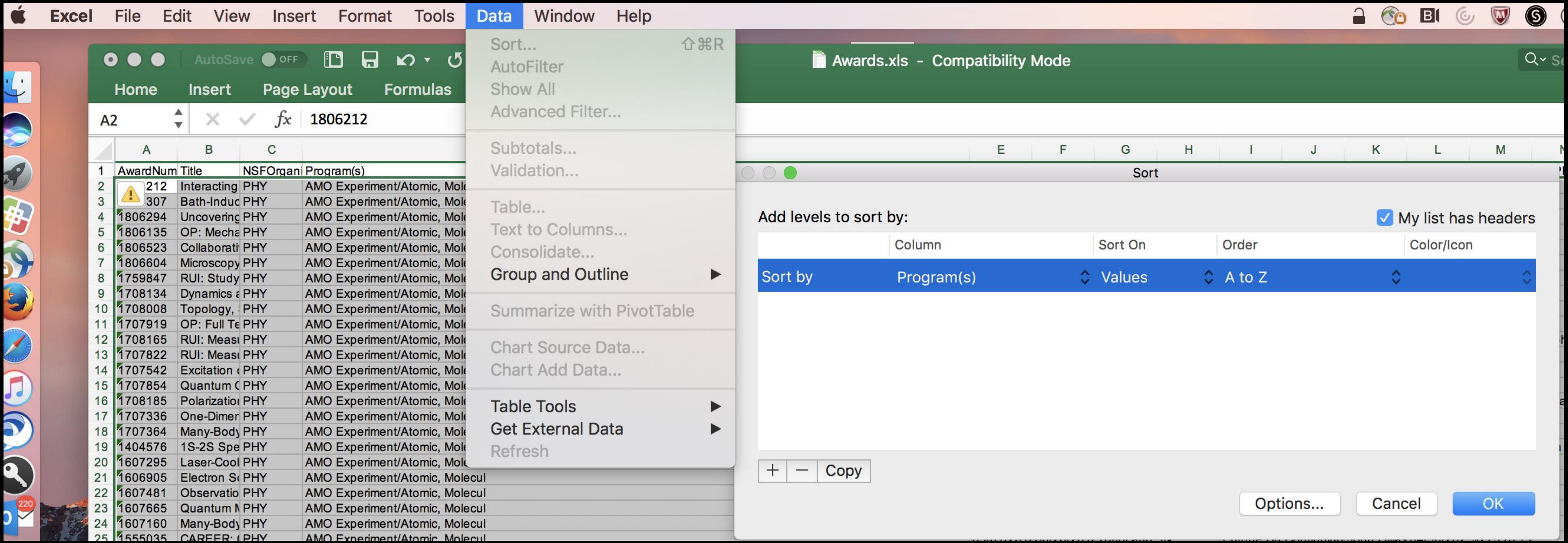


Click Here and sort by Program



FY18 Precision Measurement Awards

- 1806583 Mueller (h/m; fine structure constant; atom interferometry)
- 1807054 Tom (positronium 1S-2S spectroscopy; Rydberg measurement; CPT test)
- 1806672 Derevianko (dark matter search with GPS clocks)
- 1806305 Fajans (antihydrogen; CPT tests; freefall)
- 1836330 Gabrielse [Supplement/1310079] (antihydrogen; CPT tests; antiproton magnetic moment)
- 1806223 Hanneke (search for change in m_p/m_e; molecular ion vibrational modes)
- 1806297 Hunter (Lorentz invariance; search for long-range spin-spin interactions; cooling TlF)
- 1806768 Munday (Casimir torque)
- 1802952 Gratta (gravity at small scales)
- 1806686 Geraci (gravity at micron scale; laser-cooled trapped microspheres)
- 1806494 Takacs (highly charged ions; towards a Rydberg measurement)
- 1806777 Sell (atomic state lifetimes; Rb, Cs, Yb)
- 1806209 Leibrandt (quantum logic spectroscopy; molecular ions)
- 1752685 Olmschenk (state lifetimes; La++ ions & telecom light)

FY17 Precision Measurement Awards

- 1654425 Yost (laser cooling atomic hydrogen)
- 1653232 Moore (searching for new physics with optically levitated microspheres)
- 1654610 Singh (single atom detection for nuclear astrophysics)
- 1707575 Gupta (h/m; fine structure constant; atom interferometry with Yb BEC)
- 1708165 Gearba (measurement of critical parameters of atomic ion clocks)
- 1707573 Heckel (search for an EDM of 199Hg)
- 1707803 Stalnaker (collaborative: dark matter search with GNOME)
- 1707875 Kimble (collaborative: dark matter search with GNOME)
- 1707840 Mavalvala (optomechanical squeezing; LIGO inspired; foundations of quantum measurement)
- 1708160 Mueller (gravitational Aharonov-Bohm effect; atom interferometry tests of gravity)

FY16 Precision Measurement Awards

- 1555232 Williams (spectroscopy of Be isotopes)
- 1607295 Gibble (Cd optical atomic clock)
- 1607429 Redshaw (special relativity tests; chip-trap mass spectrometer)
- 1607571 Sackett (tune-out wavelength spectroscopy; atom interferometry)
- 1607603 Elliott (atomic parity violation; two-pathway coherent control)
- 1607762 Guzman (search for violations of the spin statistics theorem using Sr)
- 1607517 Weiss (search for the electron EDM; Cs and Rb optical lattice traps)
- 1607565 Gabrielse (lepton magnetic moments and fine structure constant)
- 1607749 Mohideen (Casimir force measurements)
- 1649324 Fairbank (Single Ba atom detection in solid Xe)

FY15 Precision Measurement Awards

- 1507160 Haeffner (search for anomalous physics with precision measurements)
- 1519265 Hunter (search for long-range spin-spin interactions with TlF)
- 1531107 Sell (precision measurements of excited state atomic lifetimes)
- 1506424 Blewitt (dark matter search with GPS clocks)
- 1506431 Geraci (gravity at the micron scale with laser-cooled trapped microspheres)