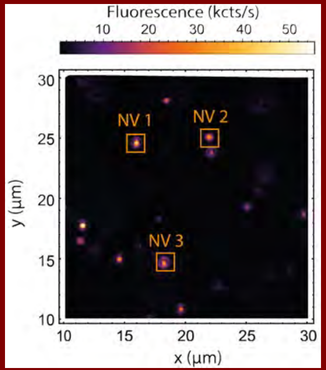
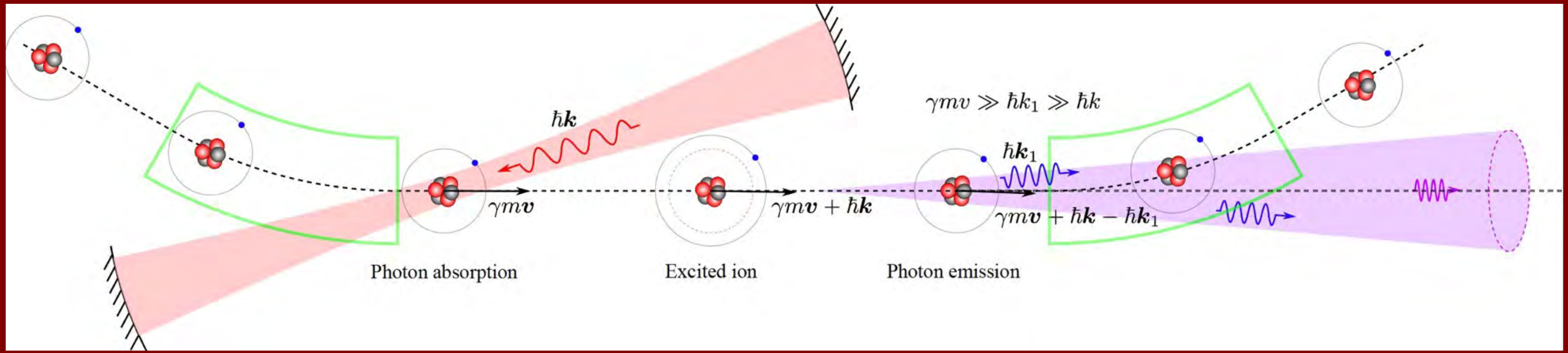
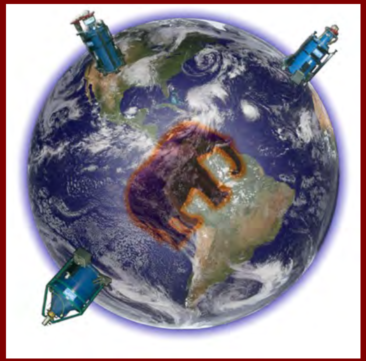
In search for ultralight bosonic dark matter
and other adventures







Dmitry Budker

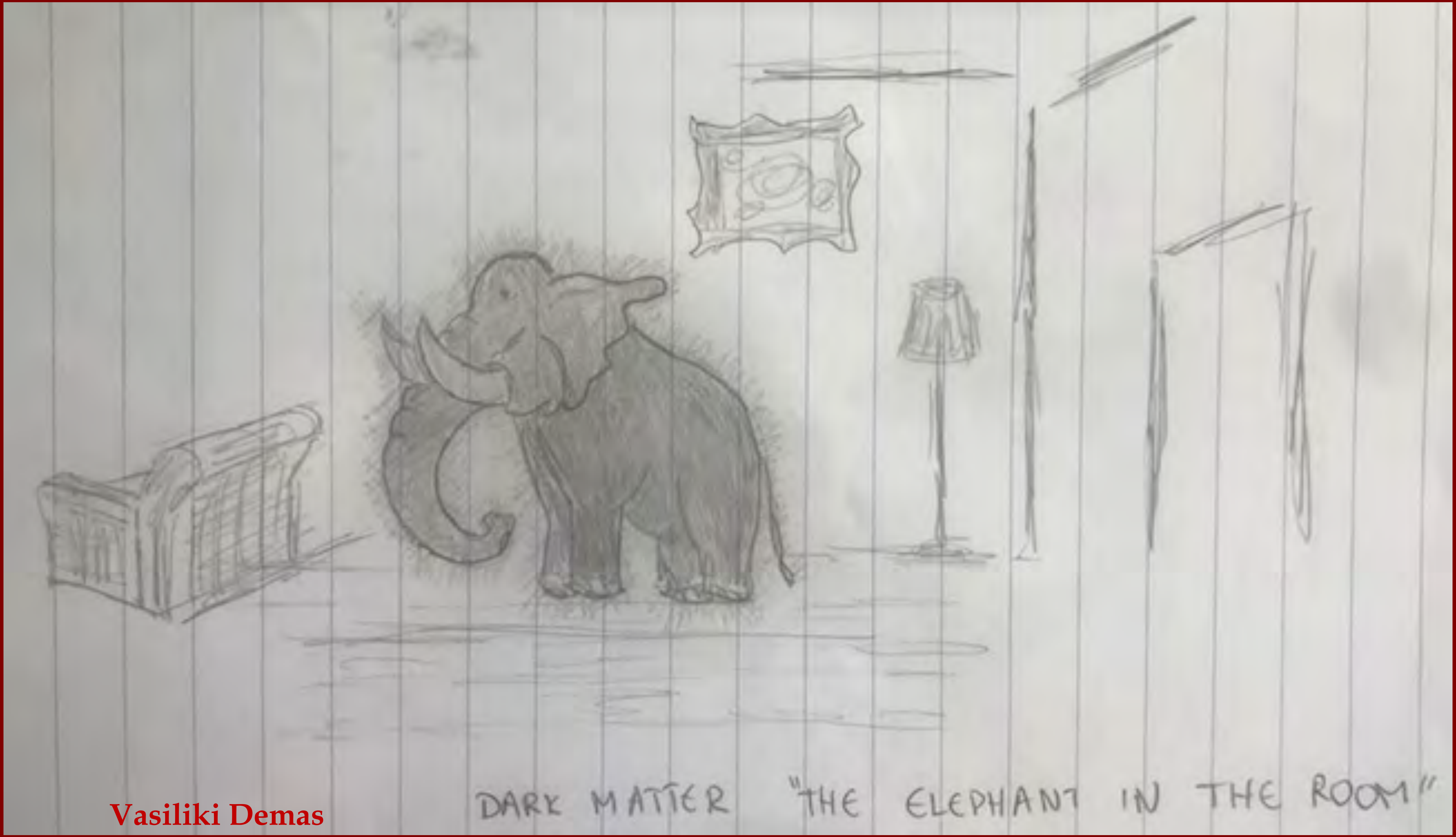
Helmholtz Institute, Johannes Gutenberg University, Mainz

&

Department of Physics, UC Berkeley

Wright Lab Quantum Sensing Workshop

April 08, 2022 (via Zoom)



Vasiliki Demas

More Elephants!

Matter-antimatter Asymmetry

Similar amount of matter and DM

Dark Energy

Strong-CP problem

Hierarchy problem

One and the same Elephant ?

So what is DM or what mimics it ?

- A gross misunderstanding of gravity (MOND, …) ???
- Proca MHD (finite photon mass) ☹?
- Black holes, dark planets, interstellar gas, … ☹?
- WIMPS ☺
- Ultralight bosonic particles
  - Axions (pseudoscalar) ☺
  - ALPs (pseudoscalar) ☺
  - Dilatons (scalar) ☺
  - Vector particles ☺
  - Tensor particles ???
- Antiquark Nuggets (AQN) !!!☺!!!

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 CF2 Whitepaper
New Horizons: Scalar and Vector Ultralight Dark Matter

Quantum Sensors for High Precision Measurements of Spin-dependent Interactions

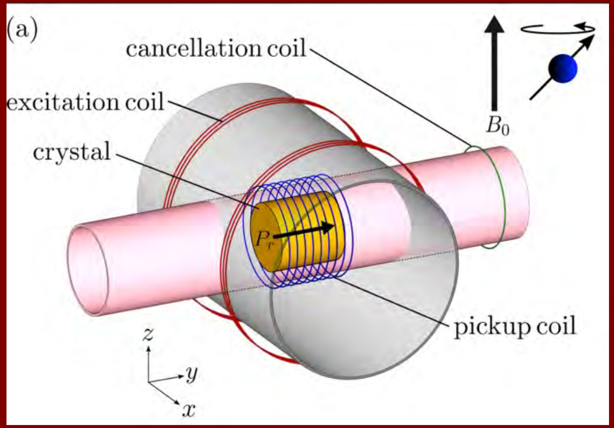
Snowmass2021 CF2 Wavelike Dark Matter Axion White Paper

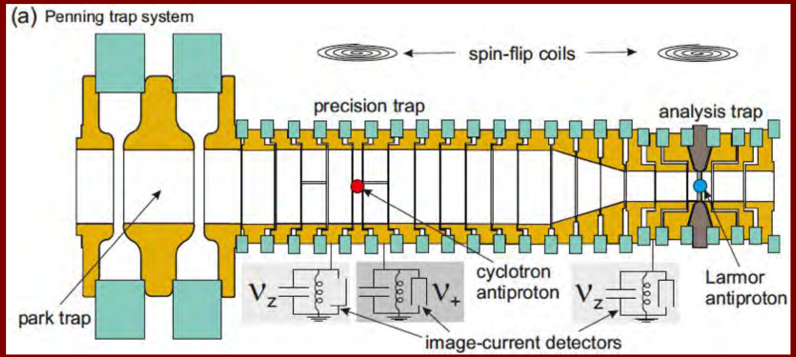
Snowmass White Paper: Precision Studies of Spacetime Symmetries and Gravitational Physics

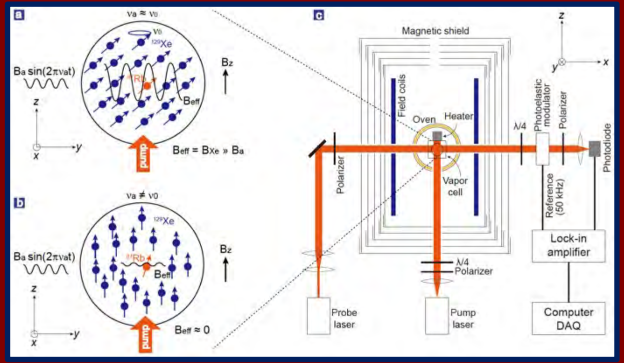
Searching for Ultralight Bosonic (and other) DM

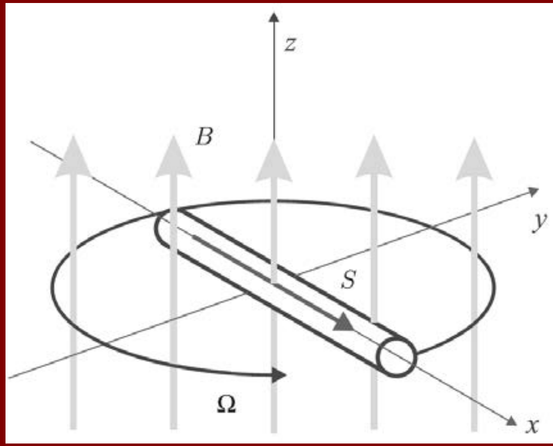
- NMR (CASPEr)
- Spin-based sensors for DM: masers, spin amplifiers
- Spin-based sensors for fifth-force searches (single NV, cells)
- GNOME, clock networks, hybrid networks
- Gravimeters
- Atomic spectroscopy
- Antimatter

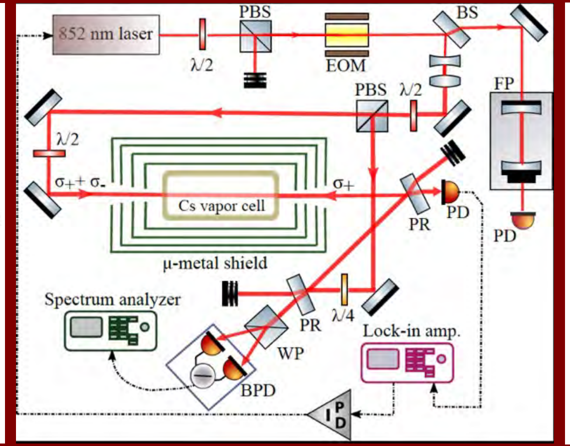
- Levitated magnets

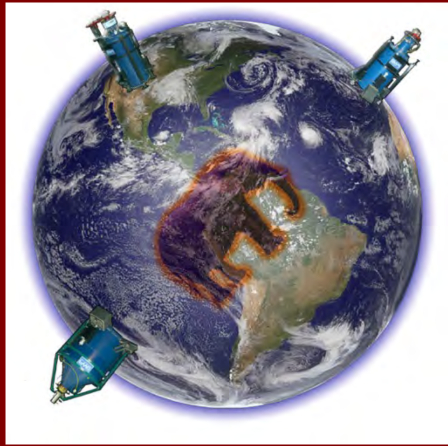


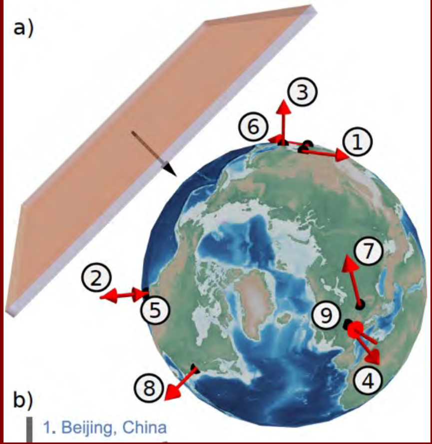


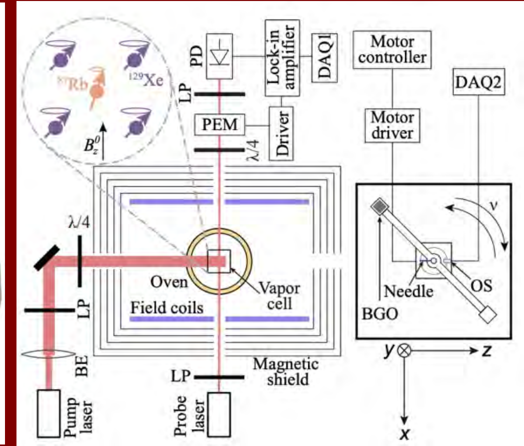










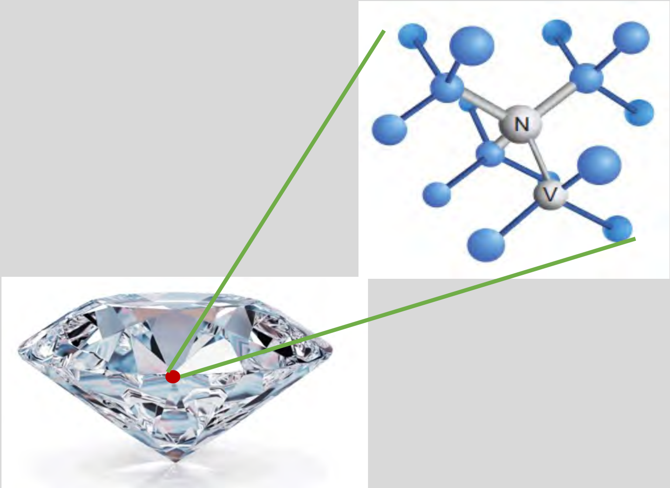


GNOME NETWORK 2017

Animation: Arne Wickenbrock

THE SMALLEST "TABLETOP"
ATOMIC SCALE

Utilizing single-spin sensor to search for exotic interactions



NV centers in diamond: single-spin sensors

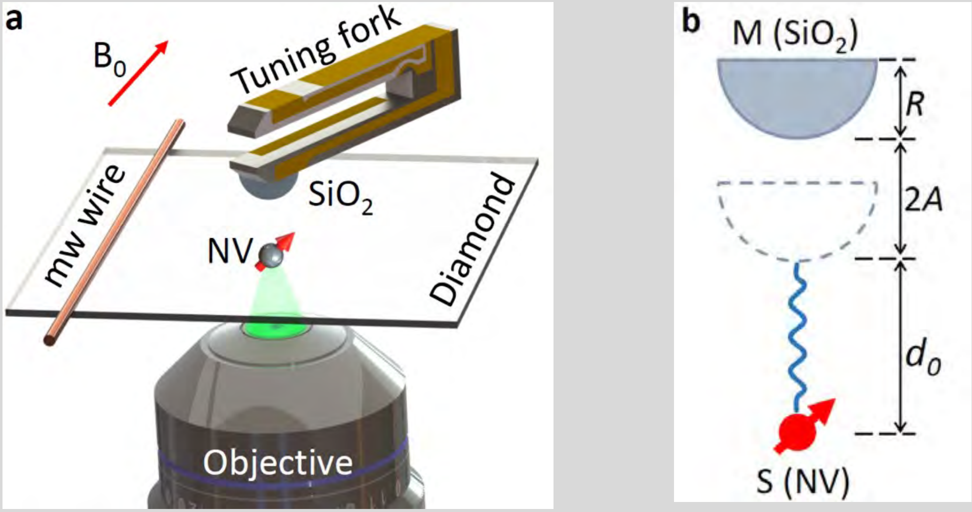


Diagram of the setup: NV sensor + AFM

Features

- ✓ Atomic scale
- ✓ Near surface

→ Shorter force range

- ✓ Precise quantum control → Good sensitivity
- ✓ NV + AFM → Cancel unwanted signals

Prof. Xing Rong (USTC)

The latest catalog of EXOTIC potentials

PHYSICAL REVIEW A **99**, 022113 (2019)

Revisiting spin-dependent forces mediated by new bosons: Potentials in the coordinate-space representation for macroscopic- and atomic-scale experiments

Pavel Fadeev,[1] Yevgeny V. Stadnik,[1] Filip Ficek,[2] Mikhail G. Kozlov,[3,4] Victor V. Flambaum,[1,5] and Dmitry Budker[1,6,7]

PHYSICAL REVIEW A **105**, 022812 (2022)

Pseudovector and pseudoscalar spin-dependent interactions in atoms

Pavel Fadeev,[1,*] Filip Ficek,[2] Mikhail G. Kozlov,[3,4] Dmitry Budker,[1,5] and Victor V. Flambaum[1,6]

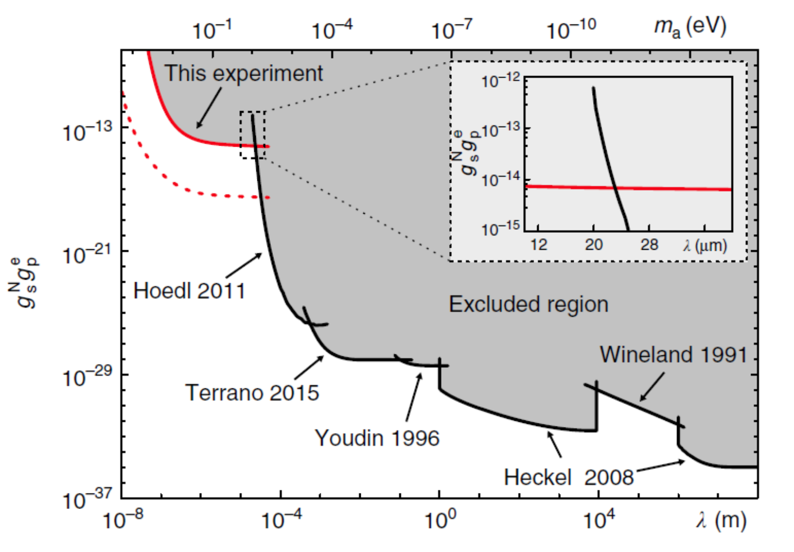
Previous catalogs:

- J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984)
- B. A. Dobrescu and I. Mocioiu, J. High Energy Phys. 11 (2006)

Several searching results with NV sensors

Monopole-dipole interaction

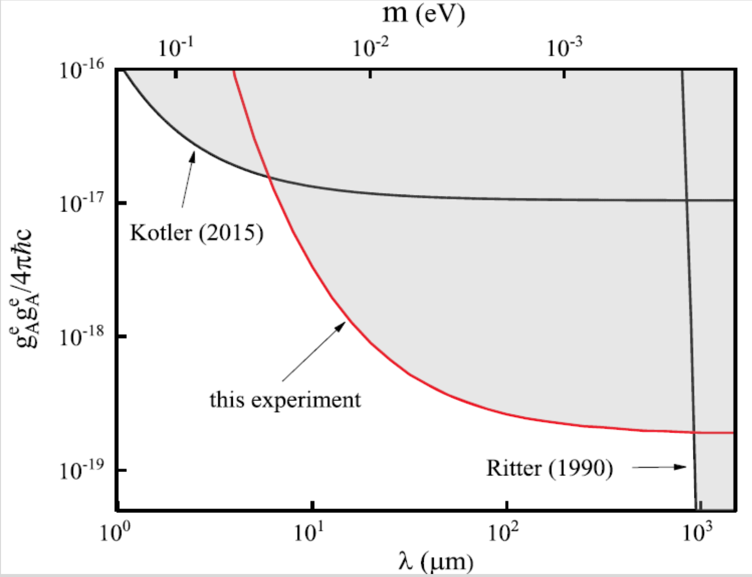
$$V_{\rm sp}(\mathbf{r}) = \frac{\hbar^2 g_s^N g_p^e}{8\pi m}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}}\boldsymbol{\sigma}\cdot\mathbf{e}_r,$$



Nature Communications 9,739 (2018)

Dipole-dipole interaction

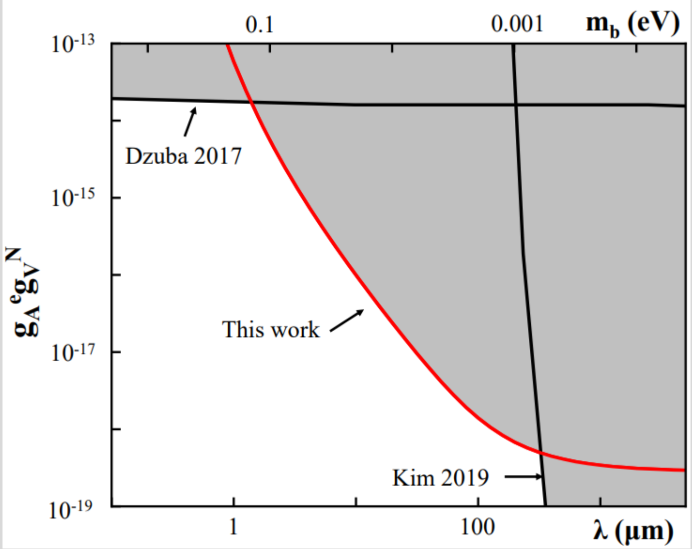
$$H_2 = \frac{g_A^e g_A^e}{4\pi\hbar c}\frac{\hbar c}{r}(\vec{\sigma_1}\cdot\vec{\sigma_2})e^{-\frac{r}{\lambda}},$$



Phys. Rev. Lett. 121, 080402 (2018)

Velocity-dependent monopole-dipole interaction

$$V = g_A^e g_V^N \frac{\hbar}{4\pi}(\boldsymbol{\sigma}\cdot\boldsymbol{v})\left(\frac{e^{-\frac{r}{\lambda}}}{r}\right),$$



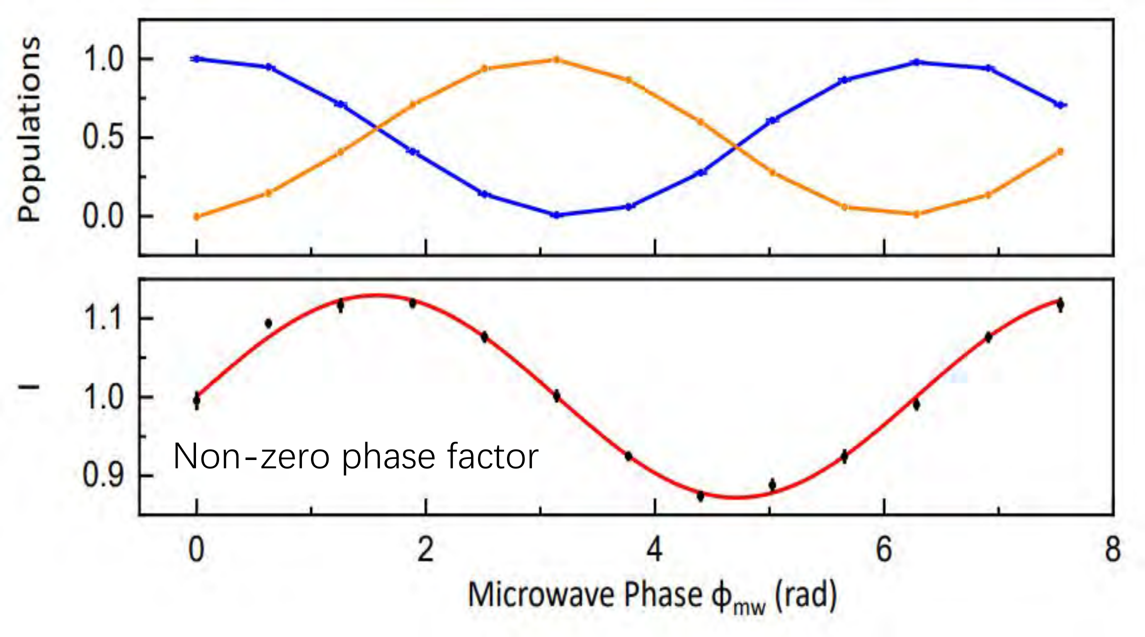
arXiv : 2009.09257 (2020)

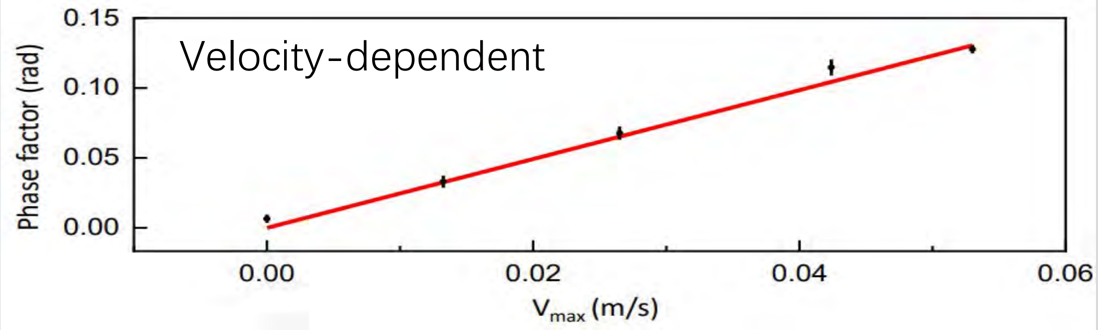
Prof. Xing Rong (USTC)

One search yields nonzero signal !

Velocity-dependent monopole-dipole interaction

$$V = f^{\perp}\frac{\hbar^2}{4\pi m_e c}\boldsymbol{\sigma}\cdot\boldsymbol{v}\times\hat{r}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda}},$$





We analyzed several possible sources of the observed signal and they cannot explain the nonzero signal. Further experiments are being carried out to figure out the possible source of this signal.

Possible sources	Contribution to the phase factor (rad)
Tuning fork	$< 10^{-3}$
Charges on the mass	$< 10^{-4}$
Casimir Force	$< 10^{-5}$
Diamagnetism of the mass	$< 10^{-10}$
Effect due to the moving dielectric	$< 10^{-15}$
Nuclear spin in the mass	$< 10^{-15}$

arXiv : 2010.15667 (2020)

Prof. Xing Rong (USTC)

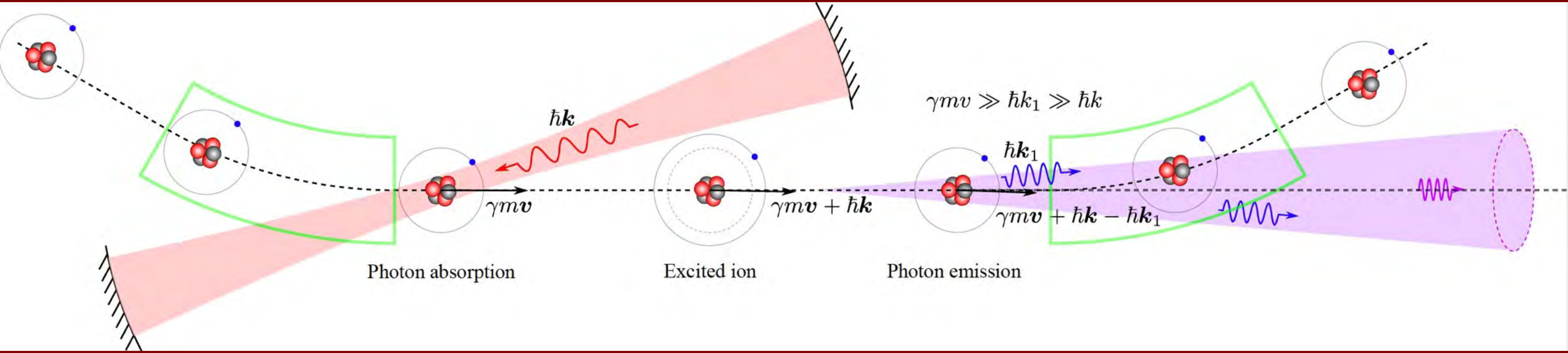
THE LARGEST "TABLETOPS"

THE UNIVERSE

SPACE NETWORKS

GLOBAL NETWORKS

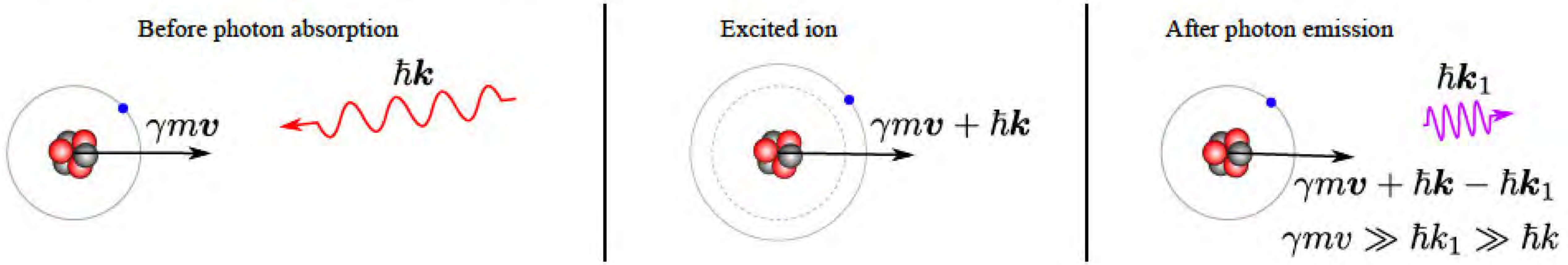
Gamma Factory @ CERN



- Proposal: M. W. Krasny (2015)
- Up to 10^{17} photons/s with energies up to 400 MeV
- Physics with primary, secondary, and tertiary beams
- "Table-top" physics with the LHC ?

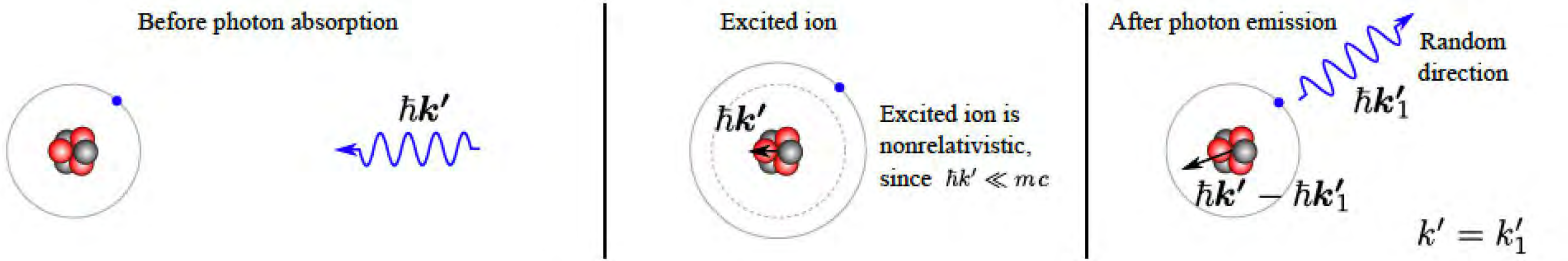
Photon scattering on relativistic ions

In the laboratory reference frame:



Photon-energy boost: $2\gamma_L \times 2\gamma_L$
backward emission angle: $1/\gamma_L$

In the initial ion reference frame:



Photon-energy boost: $2\gamma_L$

PSI @ LHC

Is this possible?

A major news from CERN! (July 2018)

During a special one-day run, LHC operators injected lead "atoms" containing a single electron into the machine (Image: Maximilien Brice/Julien Ordan/CERN)

Protons might be the Large Hadron Collider's bread and butter, but that doesn't mean it can't crave more exotic tastes from time to time. On Wednesday, 25 July, for the very first time, operators injected not just atomic nuclei but lead "atoms" containing a single electron into the LHC. This was one of the first proof-of-principle tests for a new idea called the Gamma Factory, part of CERN's Physics Beyond Colliders project.

Gamma Factory PBC study group

90 scientists
35 institutes
>10 countries

A. Abramov[1], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], H. Bartosik[2], E.G. Bessonov[5], N. Biancacci[2], J. Bieroń[6], A. Bogacz[7], A. Bosco[1], R. Bruce[2], D. Budker[8], K. Cassou[9], F. Castelli[10], I. Chaikovska[9], C. Curatolo[11], P. Czodrowski[2], A. Derevianko[12], K. Dupraz[9], Y. Dutheil[2], K. Dzierżęga[6], V. Fedosseev[2], N. Fuster Martinez[2], S. M. Gibson[1], B. Goddard[2], A. Gorzawski[13,2], S. Hirlander[2], J.M. Jowett[2], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[14,2], F. Kroeger[15], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], D. Manglunki[2], B. Marsh[2], A. Martens[9], J. Molson[2], D. Nutarelli[9], L. J. Nevay[1], A. Petrenko[2], V. Petrillo[10], W. Płaczek[6], S. Redaelli[2], S. Pustelny[6], S. Rochester[8], M. Sapinski[16], M. Schaumann[2], M. Scrivens[2], L. Serafini[10], V.P. Shevelko[5], T. Stoehlker[15], A. Surzhikov[17] I. Tolstikhina[5], F. Velotti[2], G. Weber[15], Y.K. Wu[18], C. Yin-Vallgren[2], M. Zanetti[19,11], F. Zimmermann[2], M.S. Zolotorev[20] and F. Zomer[9]

1 *Royal Holloway University of London Egham, Surrey, TW20 0EX, United Kingdom*
2 *CERN, Geneva, Switzerland*
3 *Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russia*
4 *A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia*
5 *P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia*
6 *Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland*
7 *Center for Advanced Studies of Accelerators, Jefferson Lab, USA*
8 *Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany*
9 *LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*
10 *Department of Physics, INFN–Milan and University of Milan, Milan, Italy*
11 *INFN–Padua, Padua, Italy*
12 *University of Nevada, Reno, Nevada 89557, USA*
13 *University of Malta, Malta*
14 *LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France*
15 *HI Jena, IOQ FSU Jena and GSI Darmstadt, Germany*
16 *GSI, Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
17 *Braunschweig University of Technology and Physikalisch-Technische Bundesanstalt, Germany*
18 *FEL Laboratory, Duke University, Durham, USA*
19 *University of Padua, Padua, Italy*
20 *Center for Beam Physics, LBNL, Berkeley, USA*

CERN Physics Beyond Colliders

Prof. Dr.
Witold Krasny

GF group is open to everyone willing to contribute to this initiative!

FEATURE ARTICLE

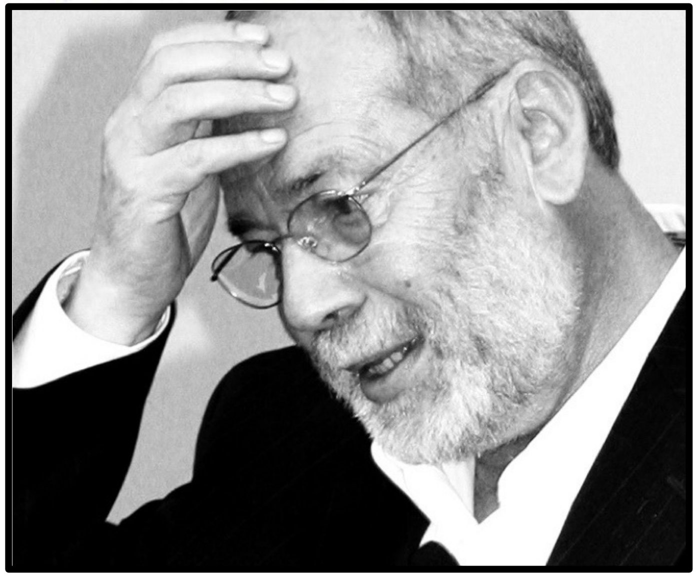
Ann. Phys. (Berlin) 2020, 2000204

annalen der physik

www.ann-phys.org

Atomic Physics Studies at the Gamma Factory at CERN

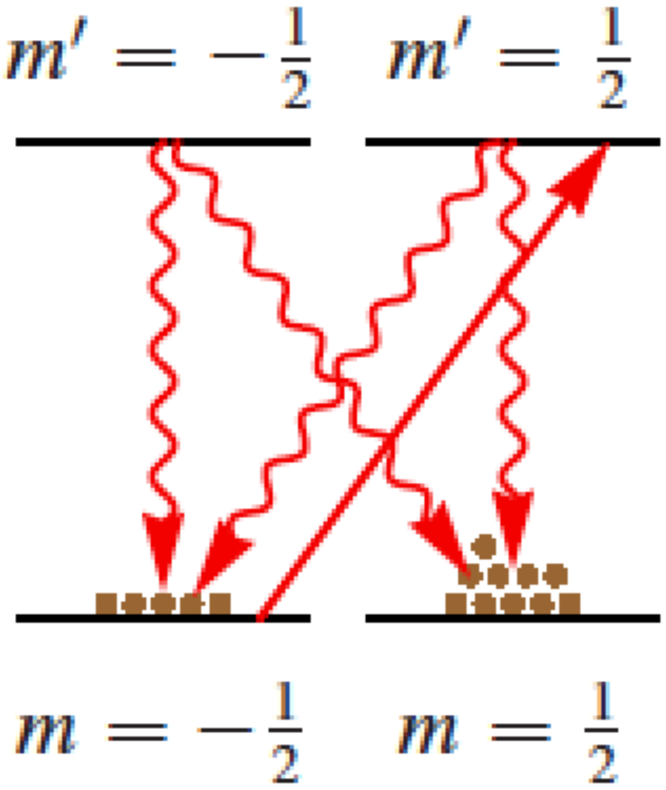
Dmitry Budker, José R. Crespo López-Urrutia, Andrei Derevianko, Victor V. Flambaum, Mieczyslaw Witold Krasny, Alexey Petrenko, Szymon Pustelny, Andrey Surzhykov, Vladimir A. Yerokhin, and Max Zolotorev*



duality

Light Source ↔ Giant Ion Trap

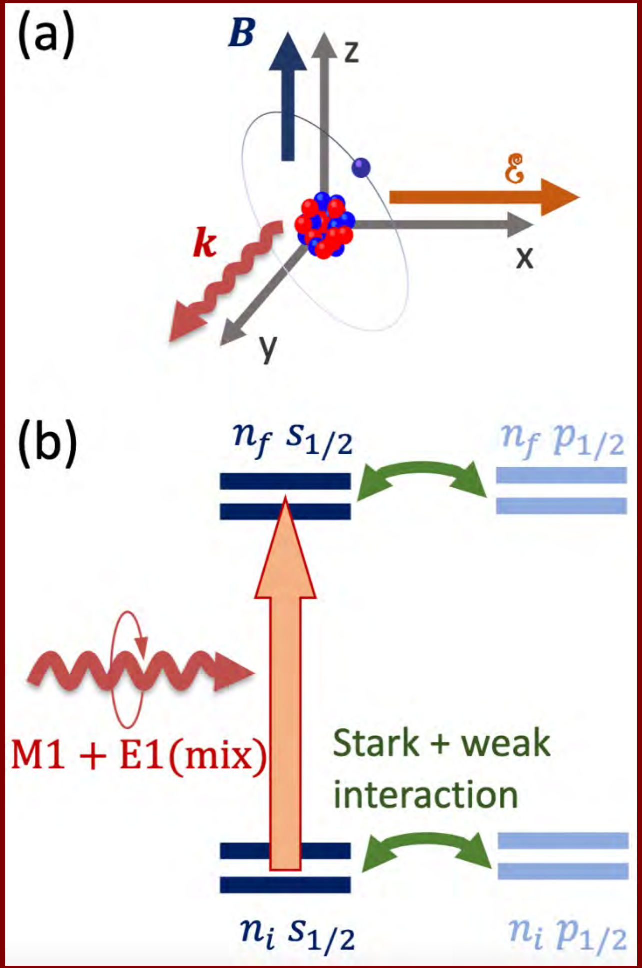
Optical Pumping of PSI



- Single-path polarization via optical pumping
- Both electronic and nuclear polarization
- Will polarization survive a round trip?
- If yes ☞ measure static and oscillating **EDM**
- Regardless ☞ nuclear-spin dependent parity violation

Parity–violation studies with partially stripped ions

*Jan Richter[1, 2], Anna V. Maiorova[3,4], Anna V. Viatkina[1, 2, 5, 6], Dmitry Budker[5, 6, 7], and Andrey Surzhykov[1, 2, 8, *]*



- H-like and Li-like PSI
- Stark-PNC interference
- Circular dichroism
- $\sim 10^{-6}$ for all Z

RESEARCH ARTICLE

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Local Lorentz Invariance Tests for Photons and Hadrons at the Gamma Factory

DOI: 10.1002/andp.202100141

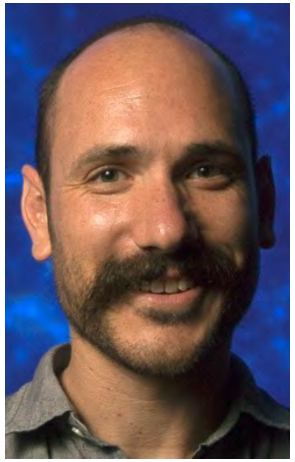
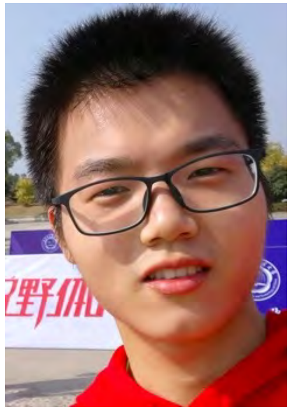
B. Wojtsekhowski and Dmitry Budker*

State-of-the-art:

- Two-way speed via rotating cavities: $\delta c_2/c < 10^{-18\,(20)}$
- One-way speed via asymmetric optical ring: $\delta c_1/c < 10^{-14}$
- One-way speed via e^+e^- beam orbit shape: $\delta c_1/c < 5{\cdot}10^{-15}$
  W. Bergan *et al* PRD 101, 032004 (2020)

@ GF: one-way speed to $\delta c_1/c < 10^{-17}$





Expanding Nuclear Physics Horizons with Gamma Factory

Ann. Phys. (Berlin) 2021, 2100284
arXiv:2106.06584

Dmitry Budker
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany and
Department of Physics, University of California, Berkeley, California 94720, USA

Julian C. Berengut
School of Physics, University of New South Wales, Sydney 2052, Australia and
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Victor V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany and
The New Zealand Institute for Advanced Study, Massey University Auckland, 0632 Auckland, New Zealand

Mikhail Gorchtein
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Junlan Jin
Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Felix Karbstein
Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany and
Theoretisch-Physikalisches Institut, Abbe Center of Photonics,
Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, 07743 Jena, Germany

Mieczyslaw Witold Krasny
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France and
CERN, Geneva, Switzerland

Yury A. Litvinov
Gesellschaft für Schwerionenforschung GSI, 64291 Darmstadt, Germany

Adriana Pálffy and Hans A. Weidenmüller
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

Vladimir Pascalutsa and Marc Vanderhaeghen
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany

Alexey Petrenko
CERN, Geneva, Switzerland and
Budker Institute of Nuclear Physics, Novosibirsk, Russia

Andrey Surzhykov
Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany and
Technische Universität Braunschweig, 38106 Braunschweig, Germany

Peter G. Thirolf
Fakultät für Physik, Ludwig-Maximilians-Universität München, 85748 Garching, Germany

Vladimir Zelevinsky
Department of Physics and Astronomy, Michigan State University,
640 S. Shaw Lane, East Lansing, MI 48824, USA and
National Superconducting Cyclotron Laboratory, Michigan State University,
640 S. Shaw Lane, East Lansing, MI 48824, USA

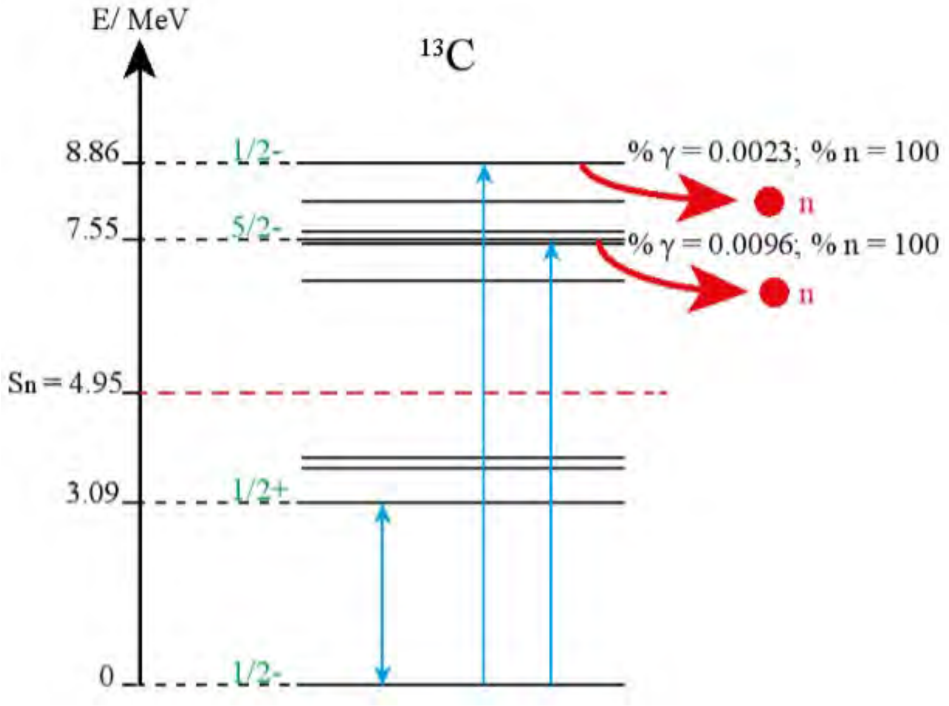
(Dated: February 16, 2021)





Nuclear physics at the ɧgf: examples

- High-resolution spectroscopy of γ-resonances
- Fano effect in γ-resonances
- Giant resonances, pigmy resonances
- (γ, α) reactions: astrophysical S-factors
- Nuclear E1 polarizabilities, e.g., $^{208}\mathrm{Pb}(\gamma, \gamma')$
- Parity-violating photophysics
- Lepton-pair photoproduction (e^+,e^- and μ^+, μ^-)
- Interaction of nuclear and electronic degrees of freedom (influence of the electron shell on nuclear lifetimes and electron bridge)



Photofission

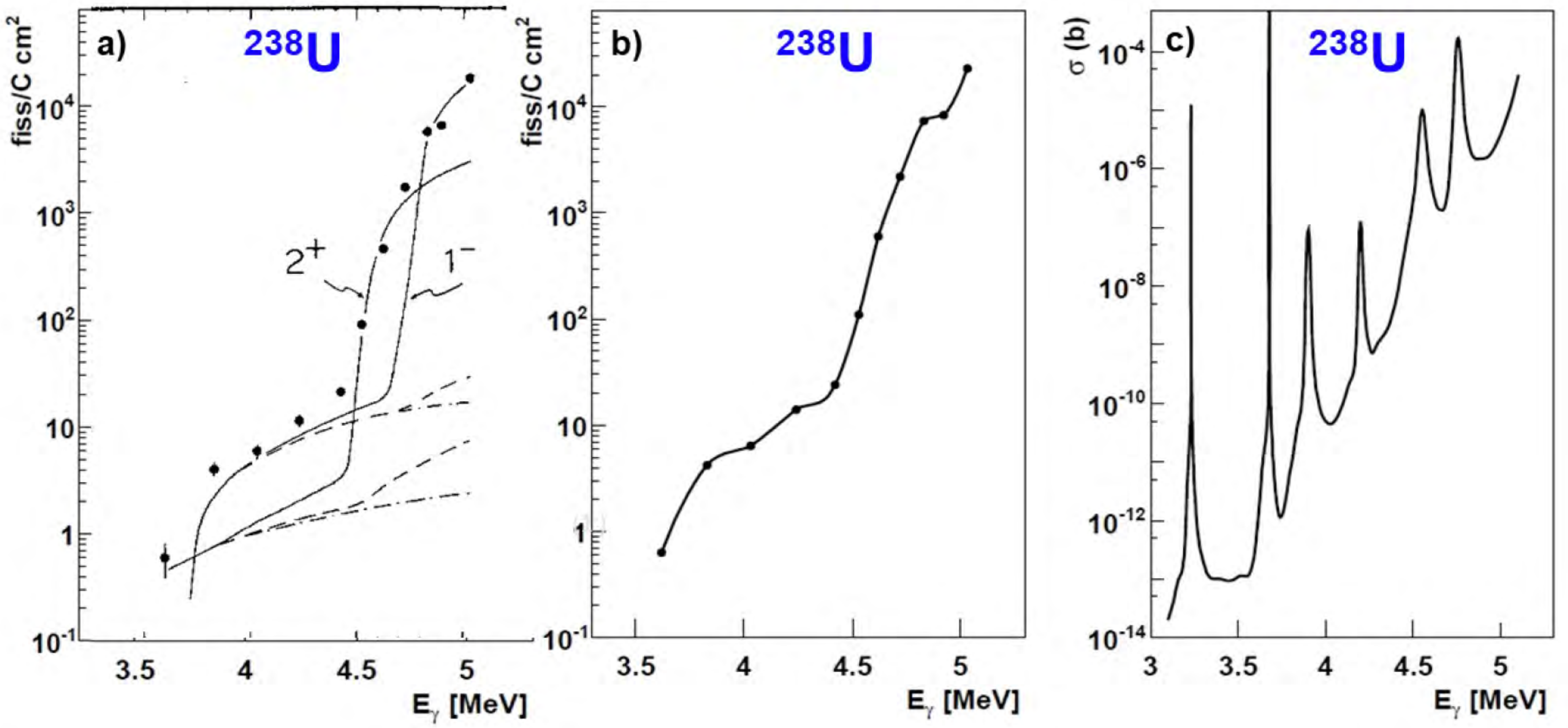


FIG. 12. a) Photofission yield for ^{238}U as a function of the excitation energy: experimental data (full symbols) and 2^+ and 1^- contributions from model calculations (labelled solid lines) [235]. b) Photofission yield data from a) (solid line to guide the eye) as accessible with bremsstrahlung photons of an effective bandwidth $\Delta E \sim 300$ keV. c) Expected photofission yield of ^{238}U when using a γ beam of $\Delta E/E \sim 10^{-6}$, based on resonances tentatively reported in an early photofission experiment with li[Screenshot]n [236]. Figure adapted from | G. Bellia *et al.* Z.Physik A **314**, 1, 43-47 (1983)

PHYSICAL REVIEW C **103**, 054603 (2021)

Resonance photoproduction of pionic atoms at the proposed Gamma Factory

Victor V. Flambaum
School of Physics, University of New South Wales, Sydney 2052, Australia;
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany;
and Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany

Junlan Jin*
Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

Dmitry Budker
Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany;
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany;
and Department of Physics, University of California, Berkeley, California 94720, USA

(Received 3 November 2020; revised 23 February 2021; accepted 13 April 2021; published 3 May 2021)

We present a possibility of direct resonance production of pionic atoms (Coulomb bound states of a negative pion and a nucleus) with a rate of up to $\approx 10^{10}$ per second using the gamma-ray beams from the Gamma Factory

$$\gamma + {}^{A}_{Z_i}\mathrm{X} \rightarrow \left({}^{A}_{Z}\mathrm{X}' + \pi^-\right)_{nl}$$

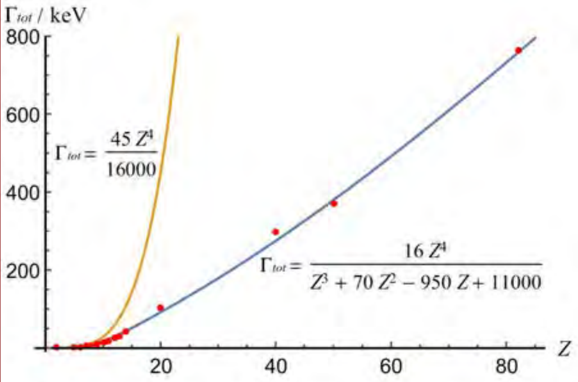


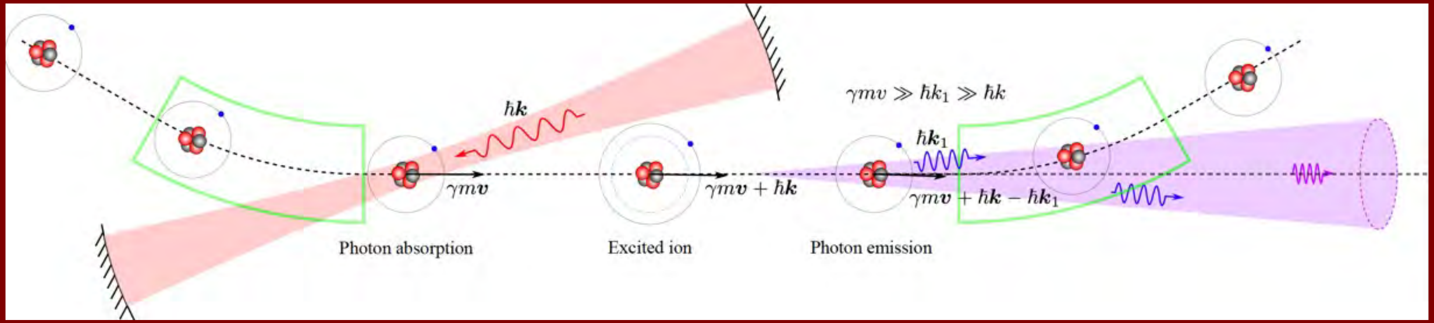
FIG. 4. Fitting of 1*s* width data from Refs. [8,36] shown as red dots on the graph. When width data for different isotopes with the same atomic number Z are given, the average value of the widths is used for the fitting. Data for ^{40}Ca and ^{90}Zr are from Ref. [33]. 1*s* width for ^{4}He is from Ref. [34]. The yellow curve and blue curve represent Eqs. (18) and (19), respectively.

TABLE I. Parameters of the ${}^{A}_{Z_i}\mathrm{X}(\gamma, \pi^-){}^{A}_{Z}\mathrm{X}'$ reaction for light nuclei. Data for the free π^- production at threshold ($\sigma_{p=0}$) in the third column are from Refs. [20–26]. Here ${}^{A}_{Z}\mathrm{X}'_{g.s.}$ means the final nucleus is in the ground state. σ_0 is the resonant cross-section for bound π^- production. The last column gives the production rate of pionic atom ${}^{A}_{Z}\mathrm{X}'$ in the 1*s* state expected at the GF by use of Eq. (17) (see Sec. II D).

${}^{A}_{Z_i}\mathrm{X}$	${}^{A}_{Z}\mathrm{X}'_{g.s.}$	$\sigma_{p=0}$ (μb)	σ_0 (μb)	$10^3 \times \Gamma_\gamma/\Gamma_{\mathrm{tot}}$	Rate (s^{-1})
${}^{7}_{3}\mathrm{Li}$	${}^{7}_{4}\mathrm{Be}_{g.s.}$	8	1200	9.05	6.0×10^9
${}^{11}_{5}\mathrm{B}$	${}^{11}_{6}\mathrm{C}_{g.s.}$	4	260	1.90	2.7×10^9
${}^{12}_{6}\mathrm{C}$	${}^{12}_{7}\mathrm{N}_{g.s.}$	4	200	1.50	2.6×10^9
${}^{14}_{7}\mathrm{N}$	${}^{14}_{8}\mathrm{O}_{g.s.}$	0.2	8	0.057	1.3×10^8

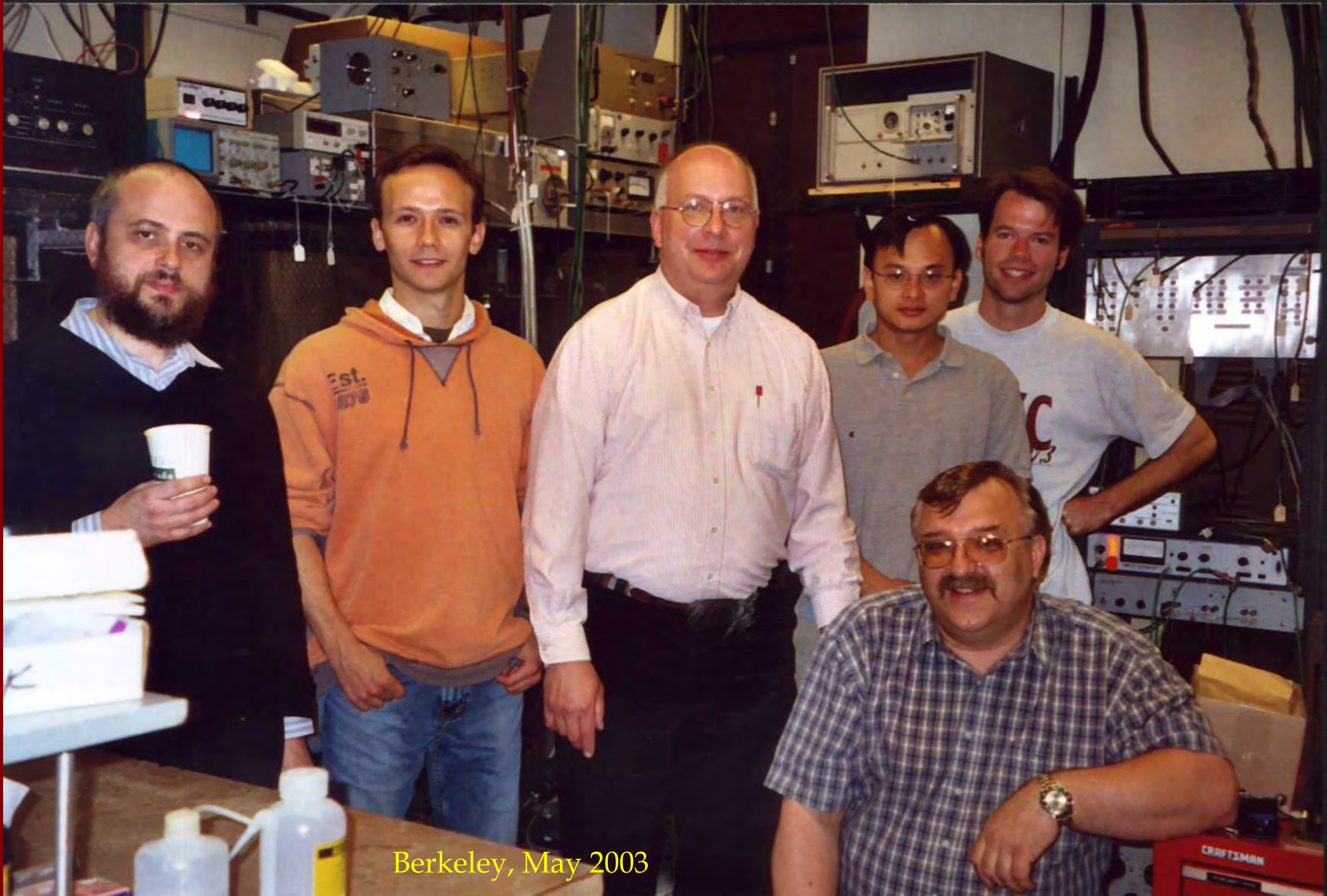
Excellent prospects of precision physics with

- The Gamma Factory @ CERN



Q: What is important in (quantum) science?

A: the Wright connections!



Berkeley, May 2003

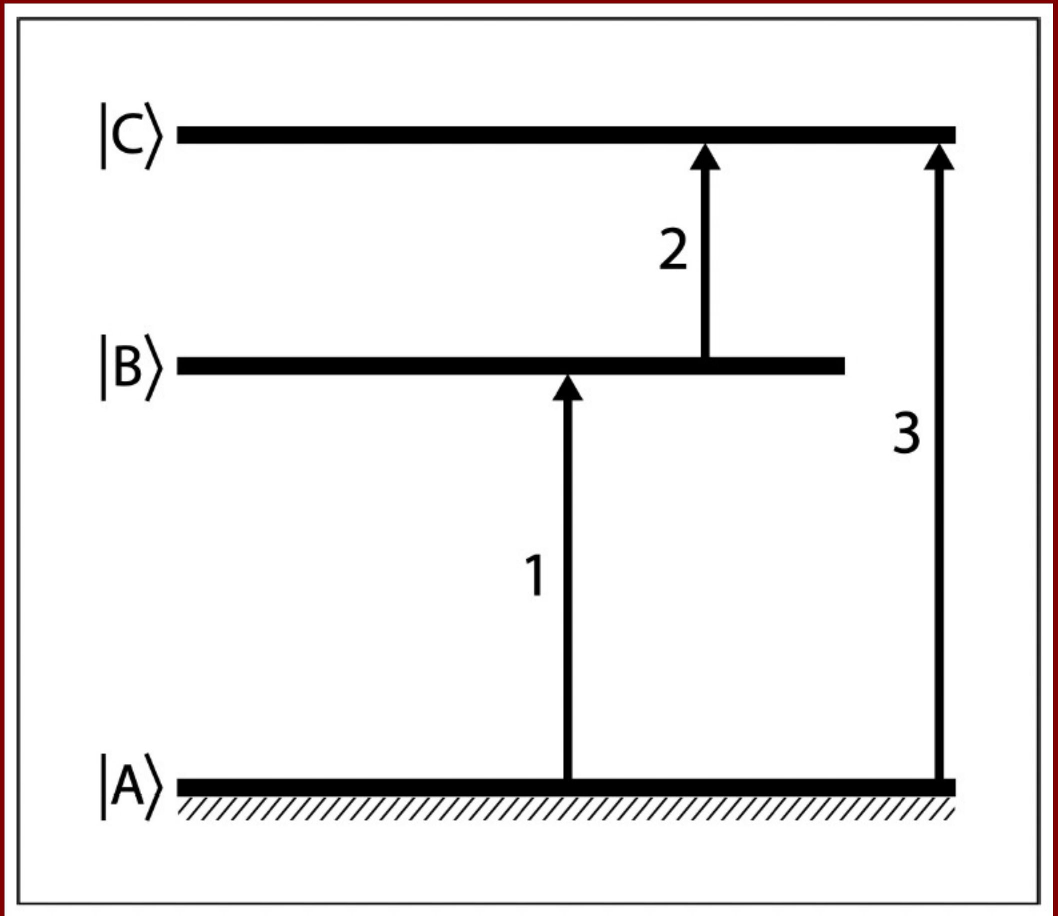
A proposed test of quantum mechanics with three connected atomic clock transitions

Mark G. Raizen
Department of Physics, The University of Texas at Austin, Austin, Texas, 78712

Gerald Gilbert
MITRE-Princeton, 200 Forrestal Road, Princeton, NJ 08540

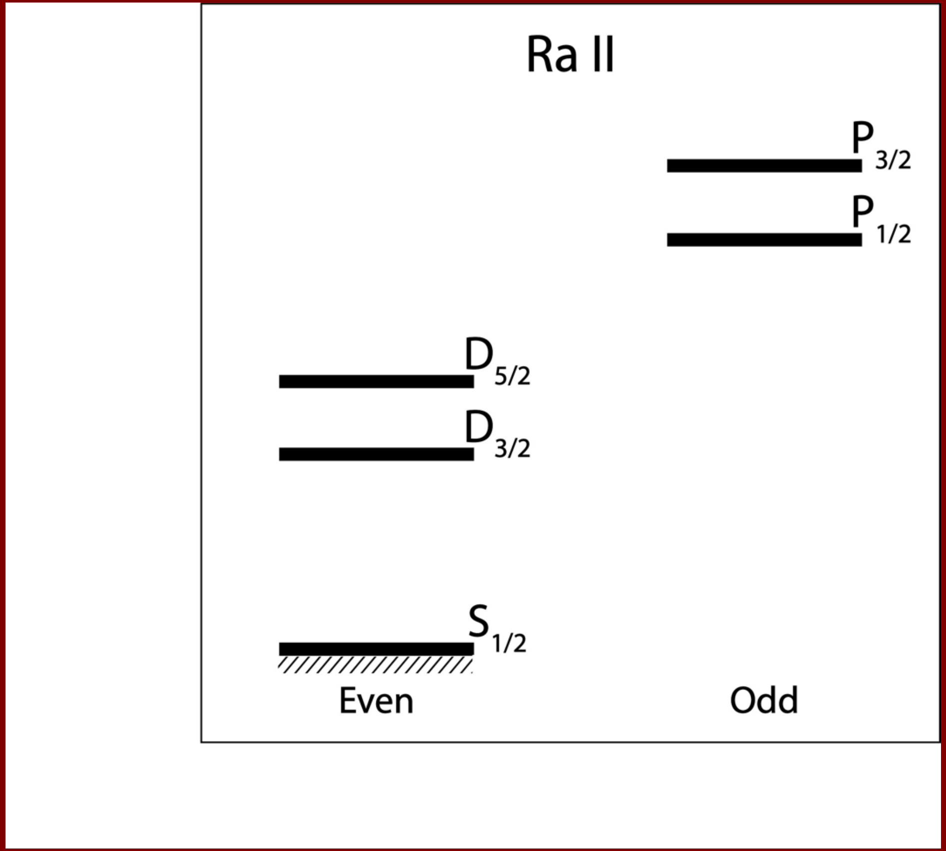
Dmitry Budker

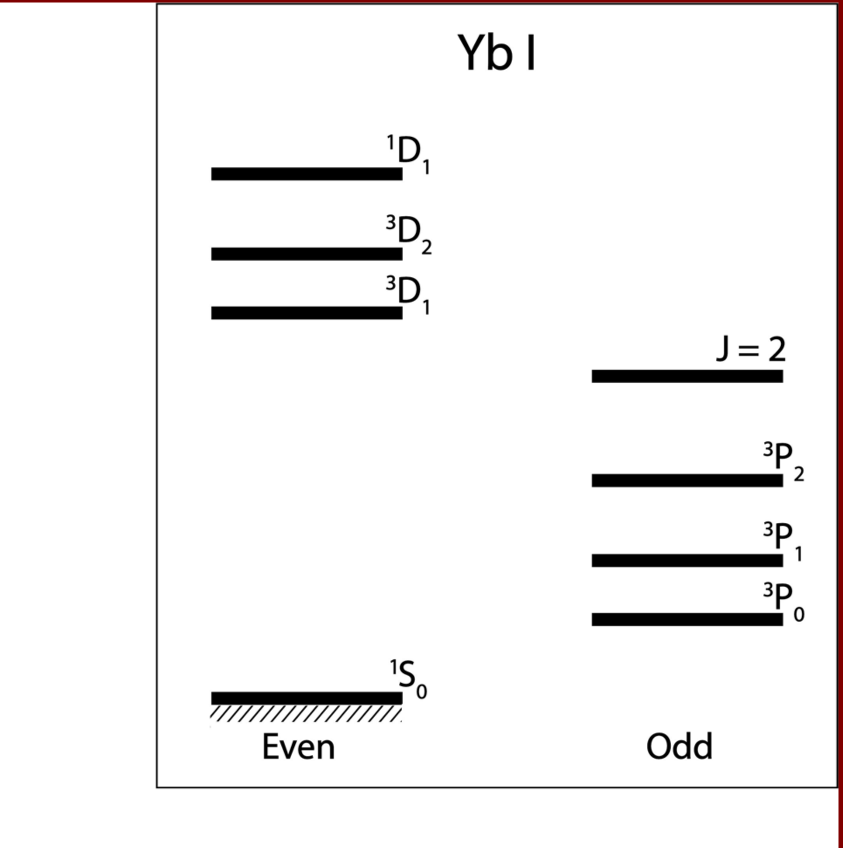
arXiv:2203.10269



Prof. Steven Weinberg
1933-2021

$$1+2 \stackrel{?}{=} 3$$





State		Energy (cm^{-1}) [6]	Lifetime
$4f^{14}6s^2$	$^1S_0$	0	
$4f^{14}6s6p$	$^3P_0$	17 288.439	≈20 s [11]
	$^3P_1$	17 992.007	866 ns [12]
	$^3P_2$	19 710.388	≈9 s [13]
$4f^{13}5d6s^2$	J=2	23 188.518	≈1 min [11, 14]
$4f^{14}5d6s$	$^3D_1$	24 489.102	329 ns [12]
	$^3D_2$	24 751.948	460 ns [9]
	$^1D_2$	27 677.665	6.7 μs [9]

- Molecules
- Nuclei

TABLETOP: as big or small as you wish!

- *D. Aybas, et al, Search for axion-like dark matter using solid-state nuclear magnetic resonance, Phys. Rev. Lett.* **126**, *141802 (2021)*
- *M. Jiang, H. Su, A. Garcon, X. Peng, and D. Budker, Search for axion-like dark matter with spin-based amplifiers,* Nature Physics (2021) *arXiv:2102.01448 (2021)*
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- *S. Afach, et al, Search for topological defect dark matter using the global network of optical magnetometers for exotic physics searches (GNOME); Nature Physics* (2021) *arXiv:2102.13379*
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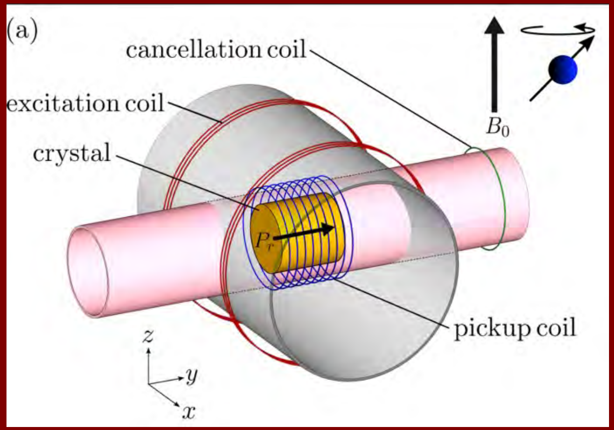
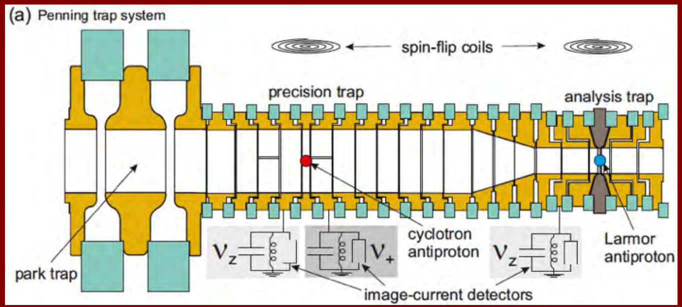
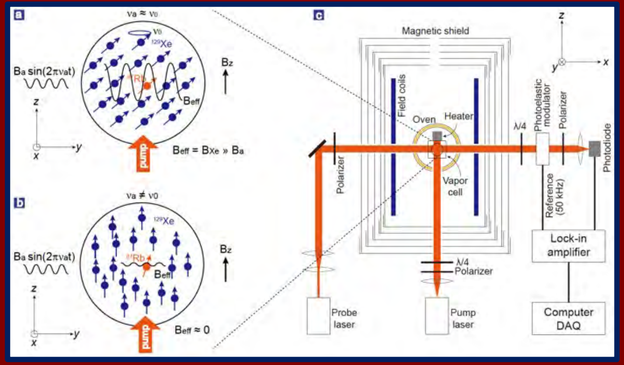
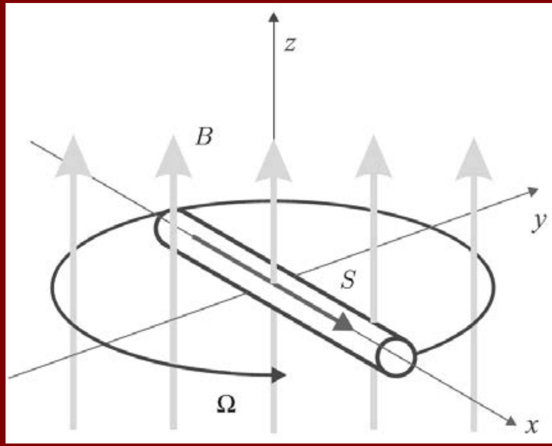
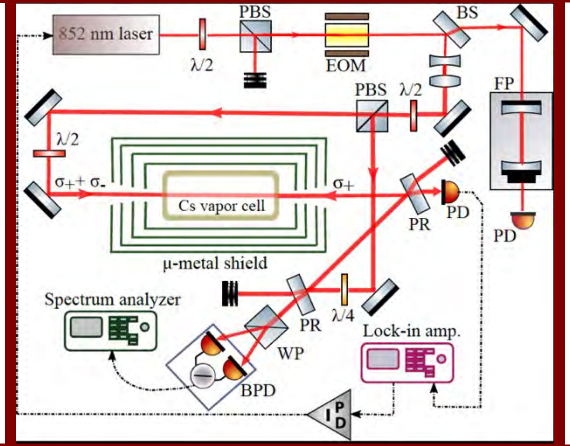
- P. Fadeev, *et al,* Ferromagnetic Gyroscopes for Tests of Fundamental Physics, *Quant. Sci. Tech*. **6**(2) 024006 (2021)
- C. Smorra, *et al,* Direct limits on the interaction of antiprotons with axion-like dark matter. Nature **575**, 310-314 (2019)

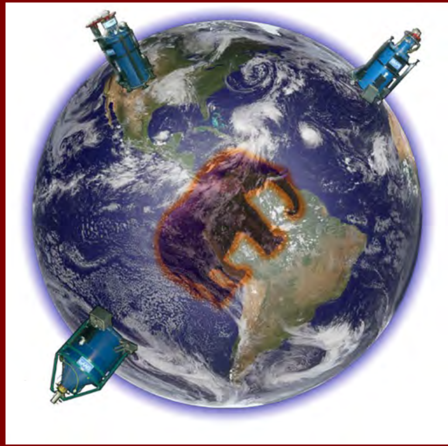


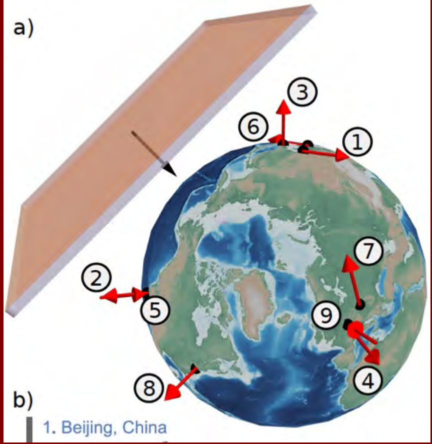


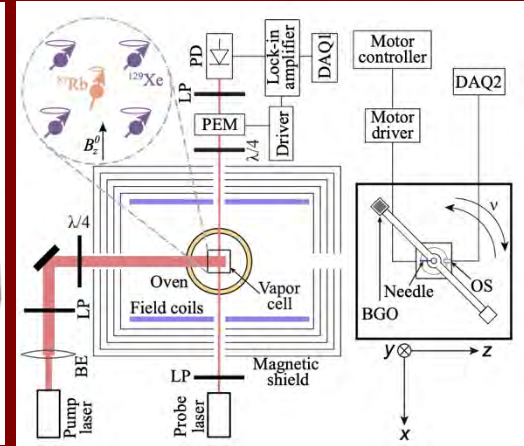








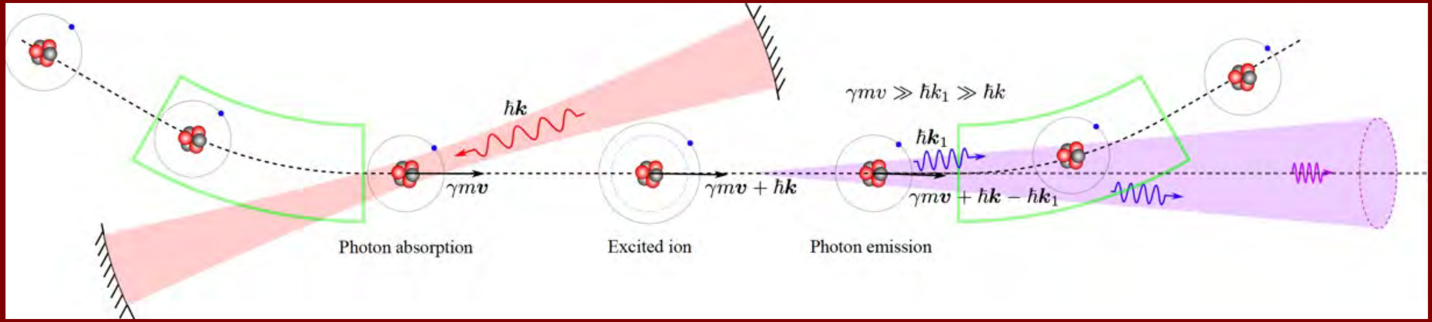




Summary

- Searches for UBDM

- The Gamma Factory



$$1+2 \stackrel{?}{=} 3$$

- Weinberg's QM extension