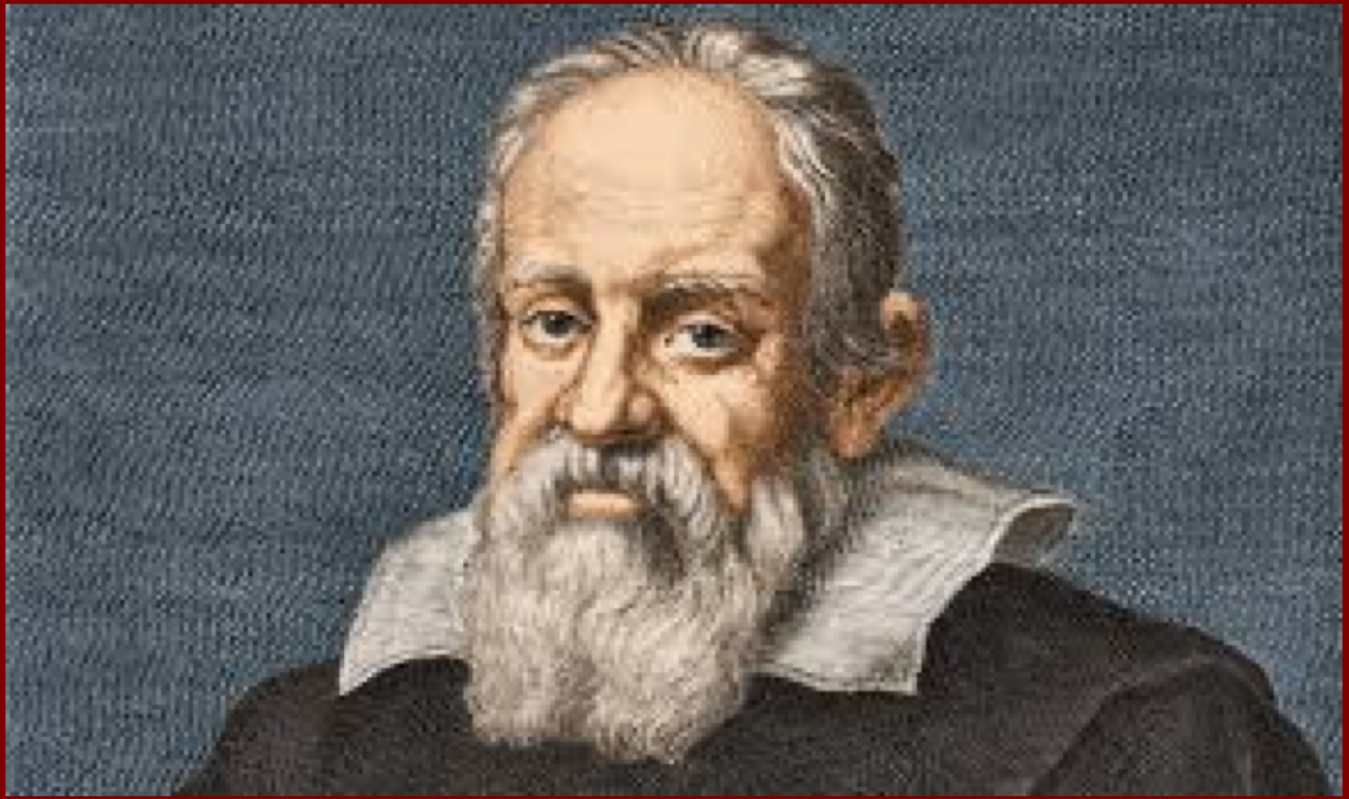
Path to discoveries: Quo Vadis?



Dmitry Budker

Helmholtz Institute
JGU Mainz

UC Berkeley Physics
NSD LBNL

Galileo Galilei Institute, September 04, 2018

Most Serene Prince,

Galileo Galilei most humbly prostrates himself before Your Highness, watching carefully, and with all spirit of willingness, not only to satisfy what concerns the reading of mathematics in the study of Padua, but to write of having decided to present to Your Highness a telescope ("Occhiale") that will be a great help in maritime and land enterprises. I assure you I shall keep this new invention a great secret and show it only to Your Highness. The telescope was made for the most accurate study of distances. This telescope has the advantage of discovering the ships of the enemy two hours before they can be seen with the natural vision and to distinguish the number and quality of the ships and to judge their strength and be ready to chase them, to fight them, or to flee from them; or, in the open country to see all details and to distinguish every movement and preparation.

January 1610

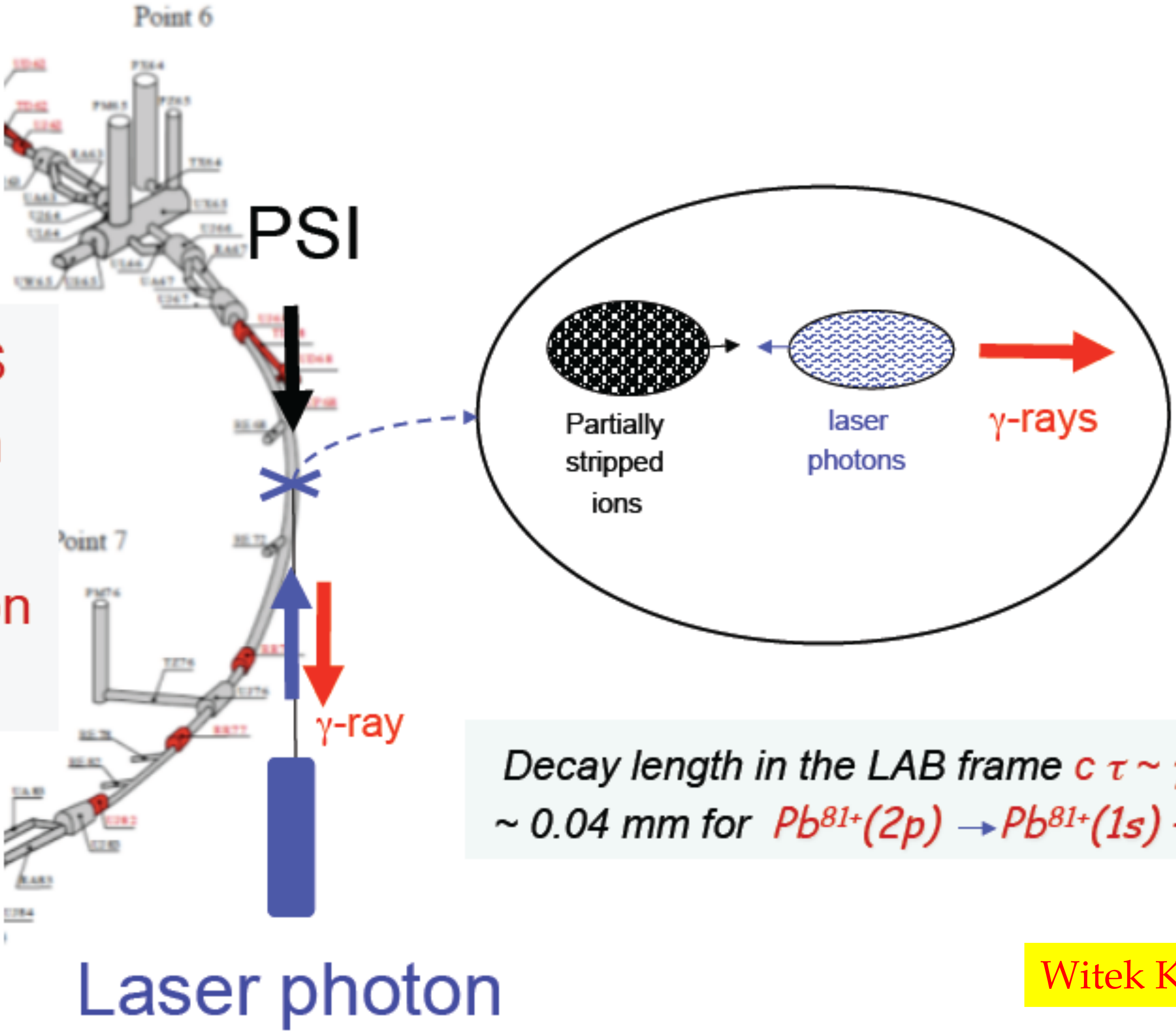
Beware of fake news!

How to make discoveries?

- Following Galileo:
  - New instrumentation and techniques
  - New ideas

The γ-ray source scheme for CERN

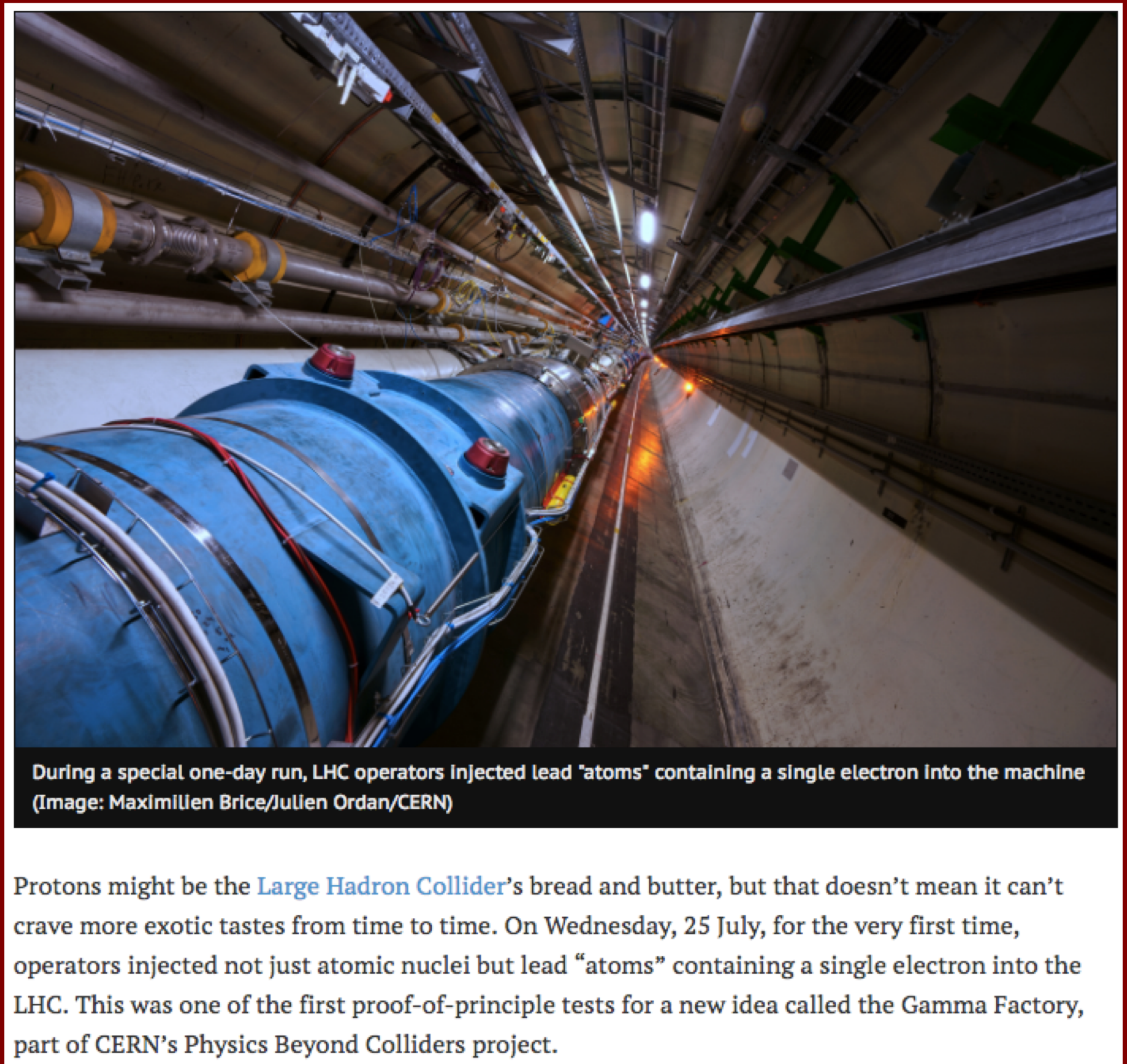
LHC/SPS filled with partially stripped ion bunches



Decay length in the LAB frame $c\,\tau \sim \gamma_L/Z^4$

~ 0.04 *mm for* $Pb^{81+}(2p) \rightarrow Pb^{81+}(1s) + \gamma$

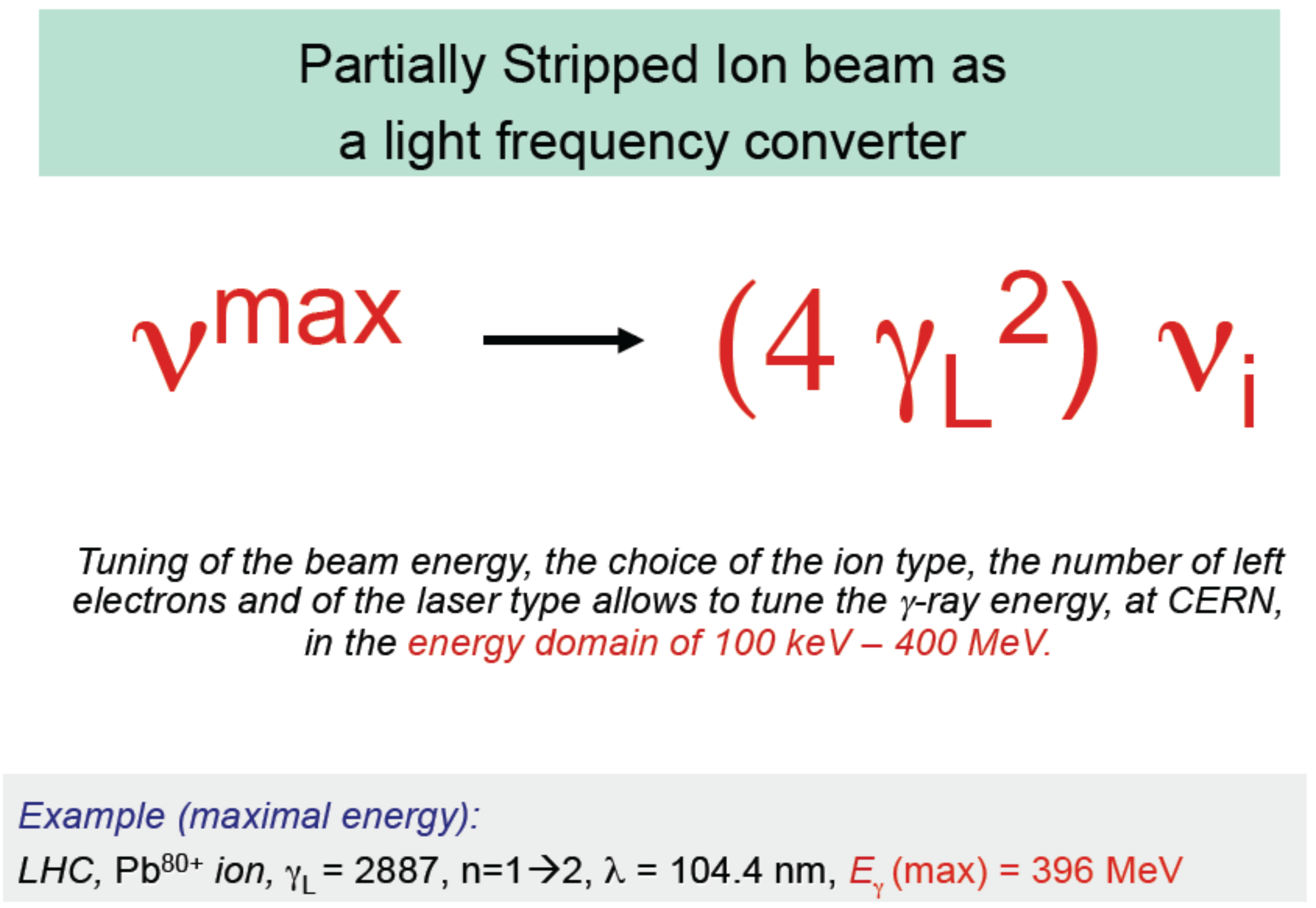
A major recent news from CERN!



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 @ CERN



Partially Stripped Ion beam as a light frequency converter

$$\nu^{\max} \longrightarrow (4\,\gamma_L^{2})\,\nu_i$$

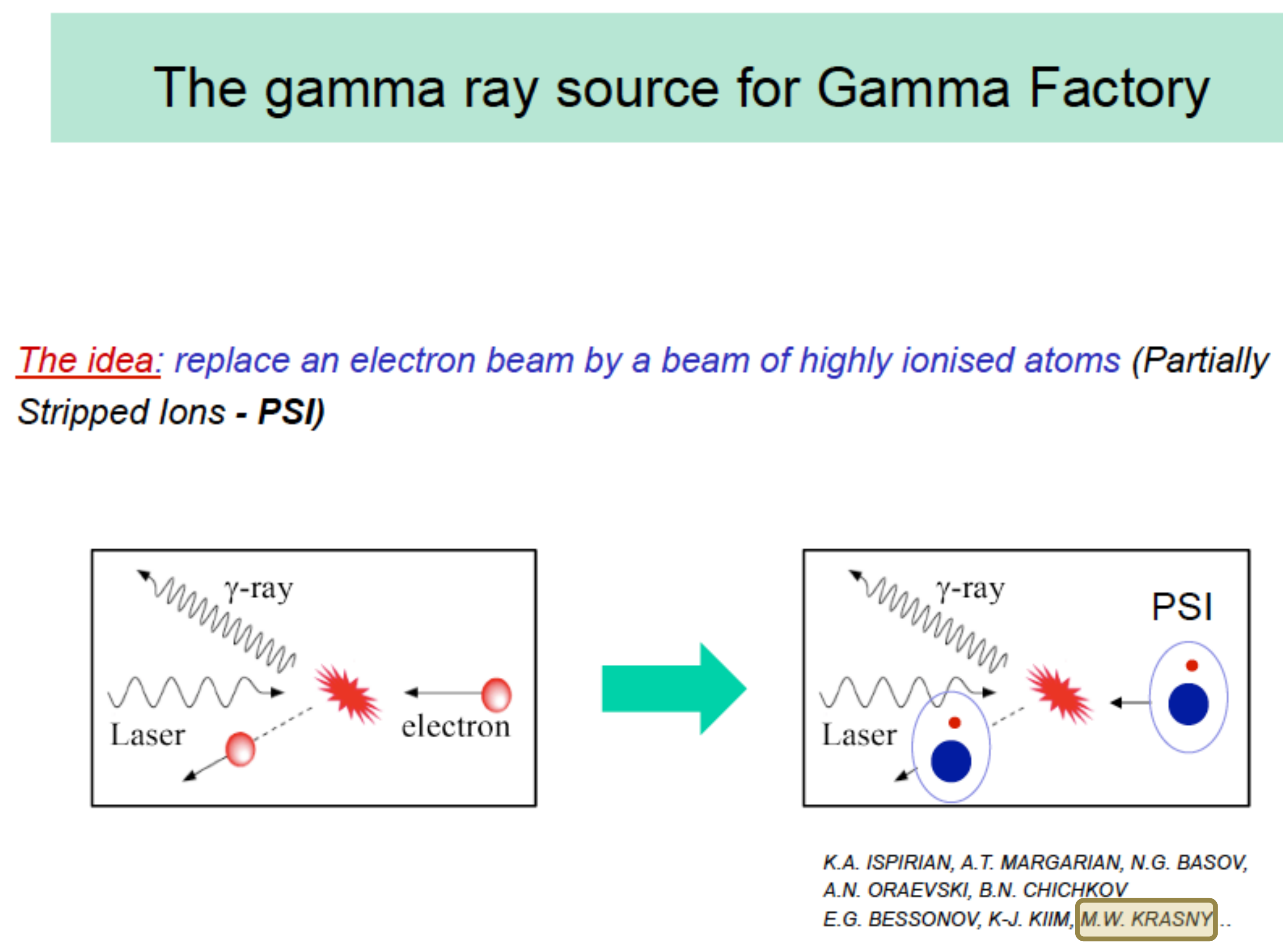
Tuning of the beam energy, the choice of the ion type, the number of left electrons and of the laser type allows to tune the γ-ray energy, at CERN, in the energy domain of 100 keV – 400 MeV.

Example (maximal energy):

LHC, Pb^{80+} *ion*, $\gamma_L = 2887$, $n=1 \rightarrow 2$, $\lambda = 104.4$ nm, $E_\gamma(\max) = 396$ MeV

Witek Krasny

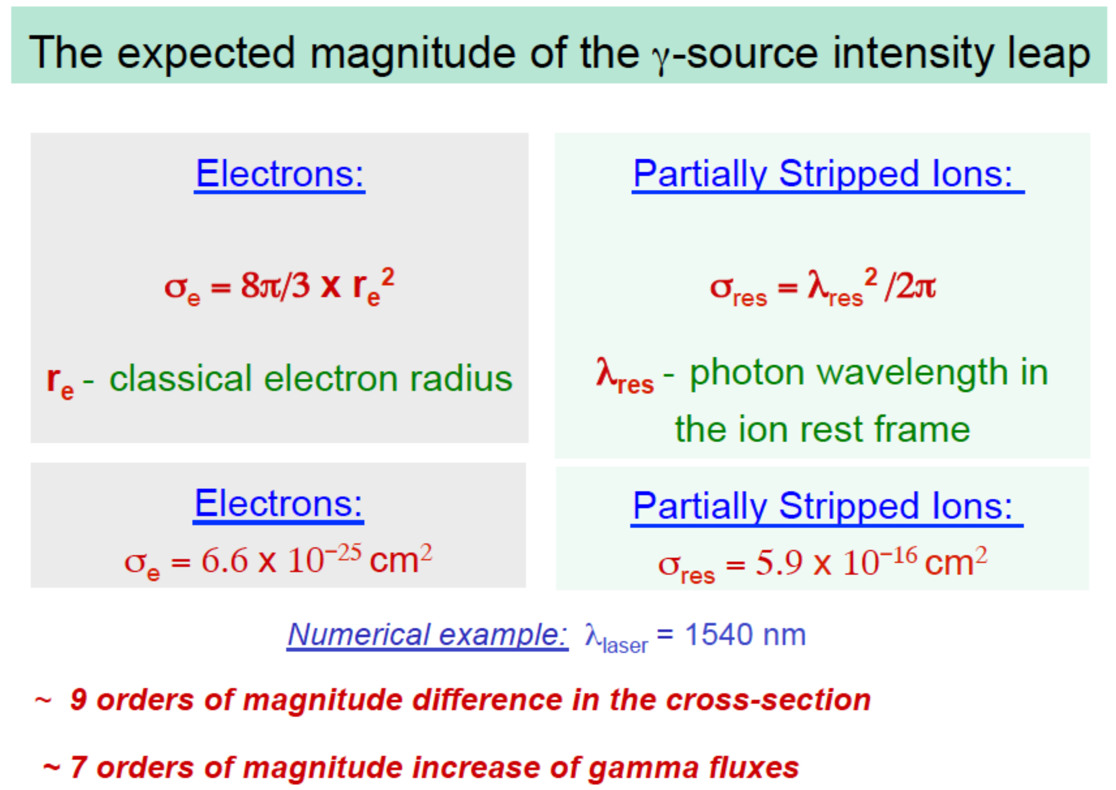
Gamma Factory @ CERN



The gamma ray source for Gamma Factory

*The idea: replace an electron beam by a beam of highly ionised atoms (Partially Stripped Ions - **PSI**)*

K.A. ISPIRIAN, A.T. MARGARIAN, N.G. BASOV, A.N. ORAEVSKI, B.N. CHICHKOV E.G. BESSONOV, K-J. KIIM, M.W. KRASNY...



The expected magnitude of the γ-source intensity leap

Electrons:	Partially Stripped Ions:
$\sigma_e = 8\pi/3 \times r_e^2$	$\sigma_{res} = \lambda_{res}^2/2\pi$
r_e - classical electron radius	λ_{res} - photon wavelength in the ion rest frame
Electrons:	Partially Stripped Ions:
$\sigma_e = 6.6 \times 10^{-25}$ cm^2	$\sigma_{res} = 5.9 \times 10^{-16}$ cm^2

Numerical example: λ_{laser} = 1540 nm

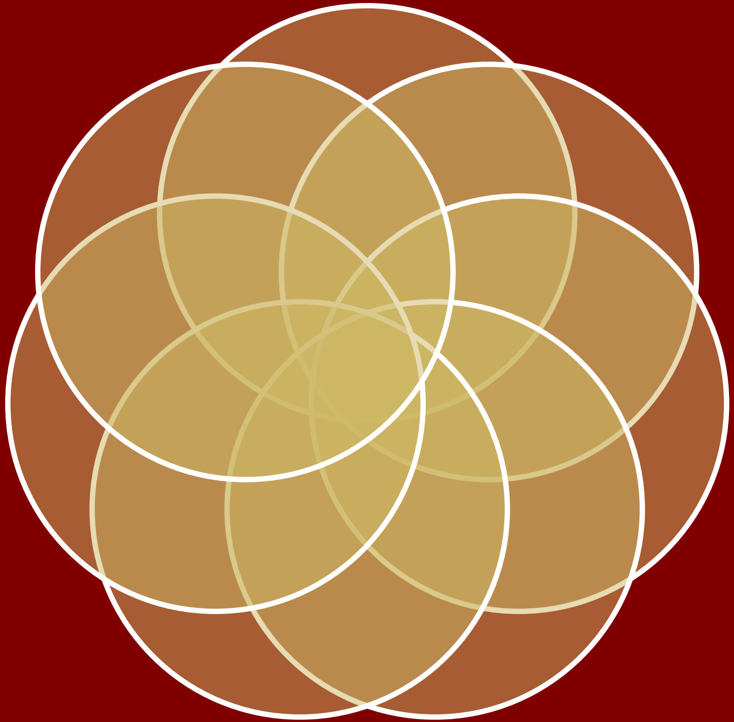
~ 9 orders of magnitude difference in the cross-section

~ 7 orders of magnitude increase of gamma fluxes

Very exciting times for CERN physics!

My gf is gamma factory!

Really Important Questions…



Fundamental Constants?

New particles?

Nuclear (nucleon) masses and radii

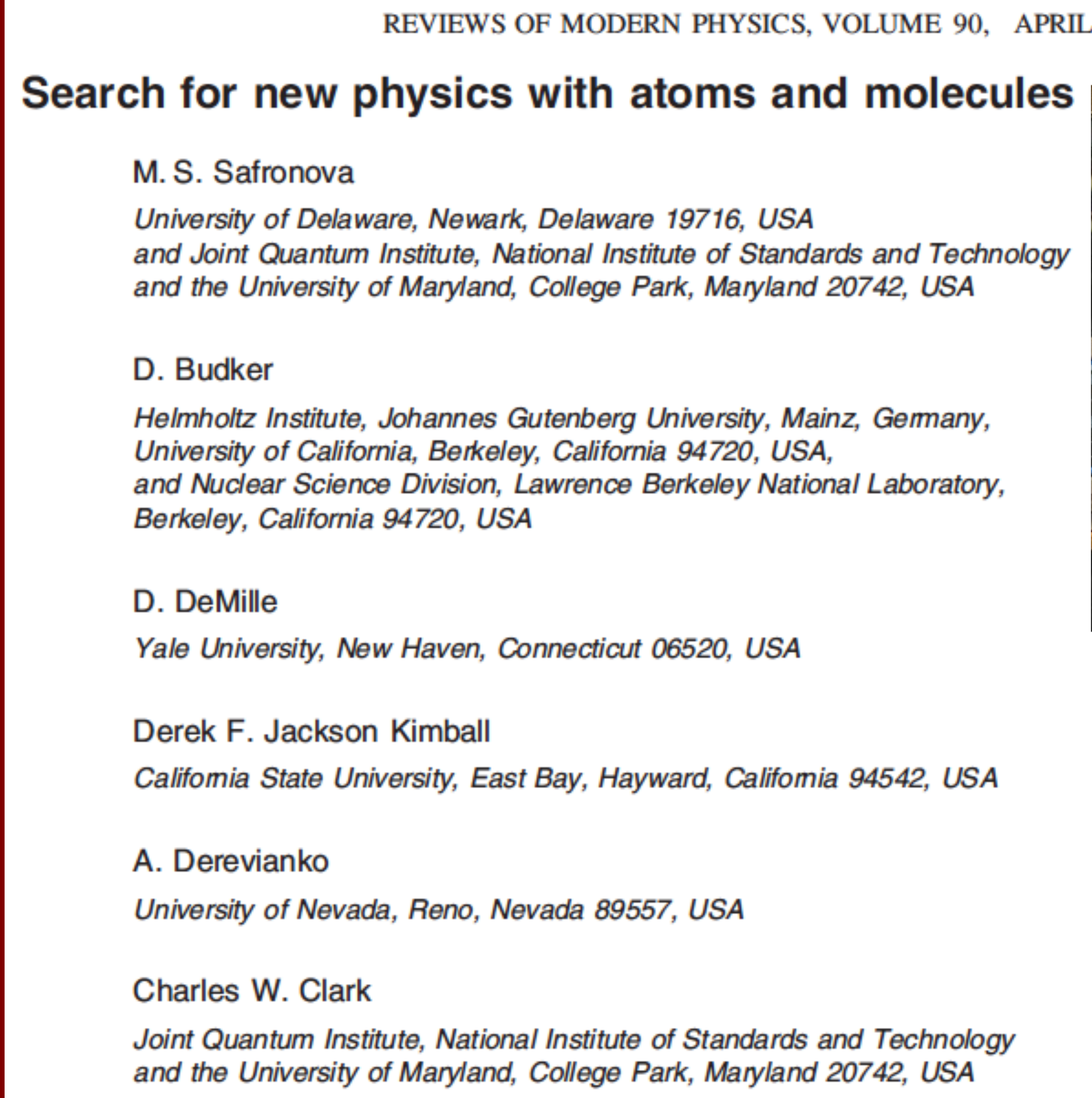
CP Physics, EDMs

Gravity, equivalence

Dark matter, dark energy

Antimatter spectroscopy

… can be addressed by **low-energy** expts



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

Search for new physics with atoms and molecules

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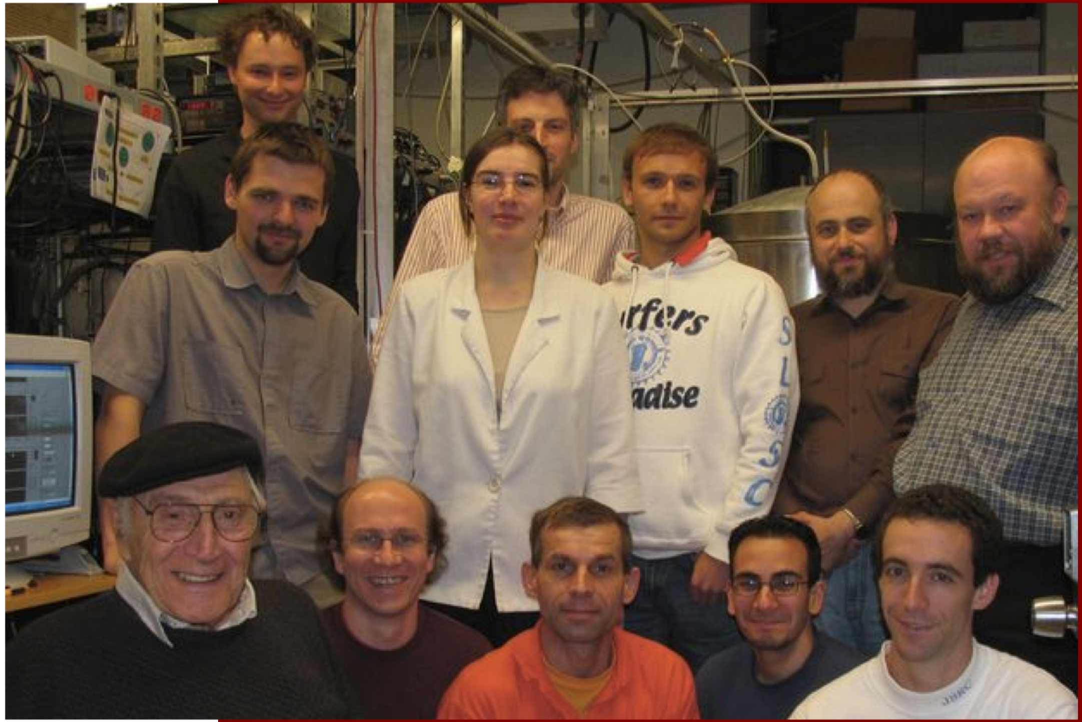
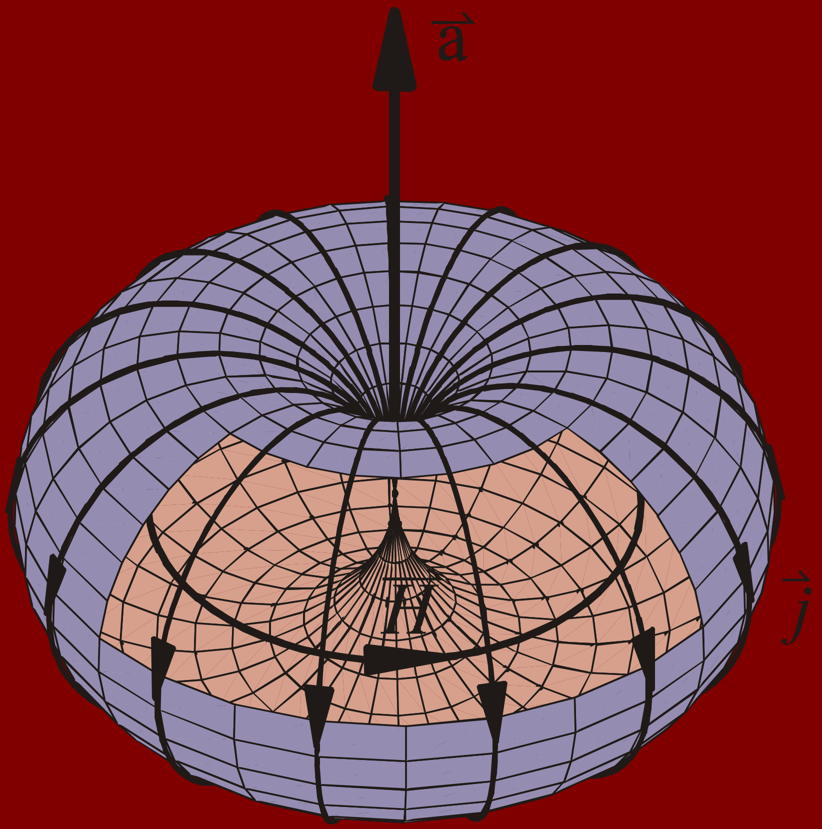
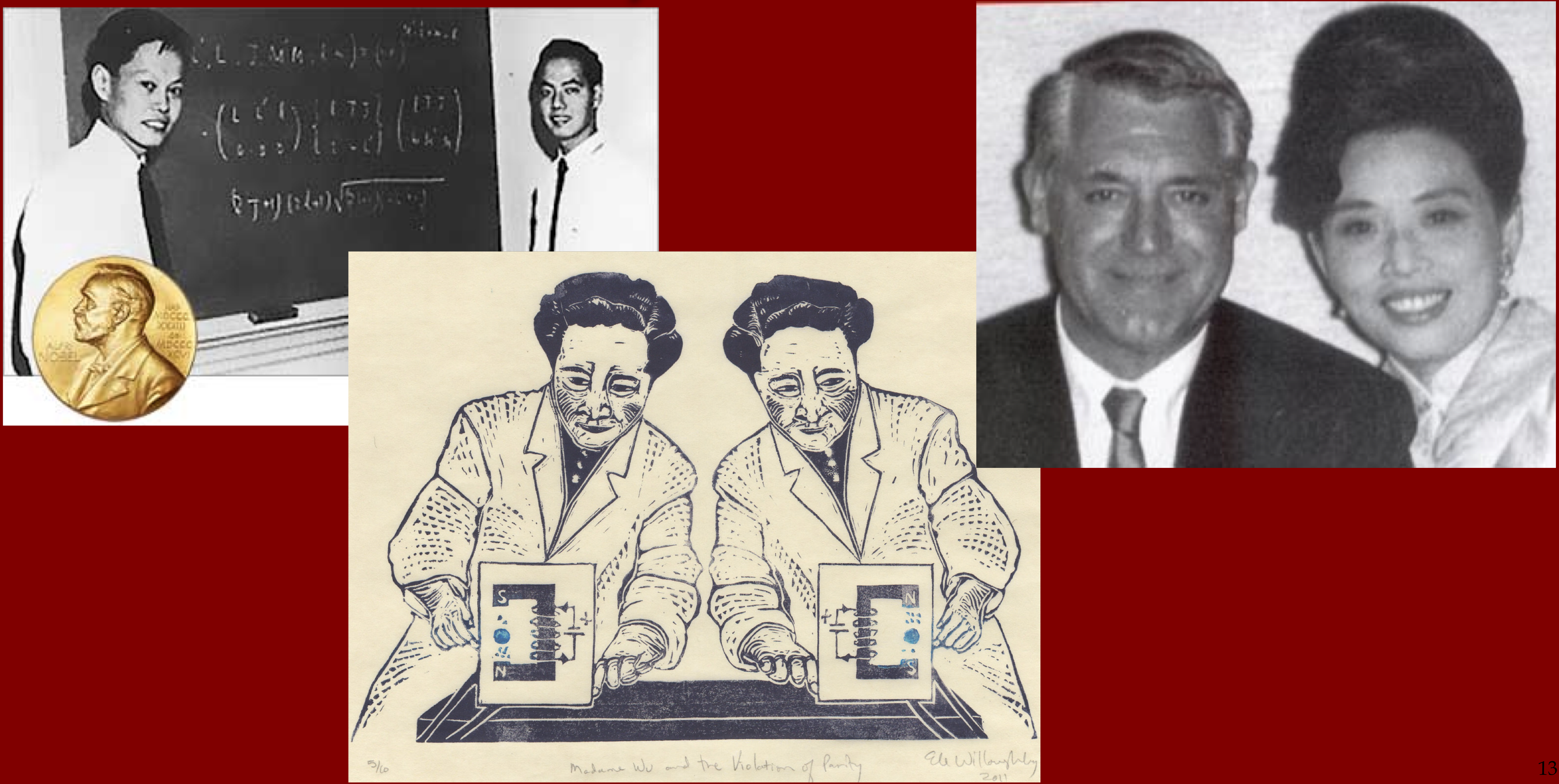


Marianna Safronova with Erwin L. Hahn and the Budker Group, Berkeley, 2006

Parity Violation in Yb (without T-violation)

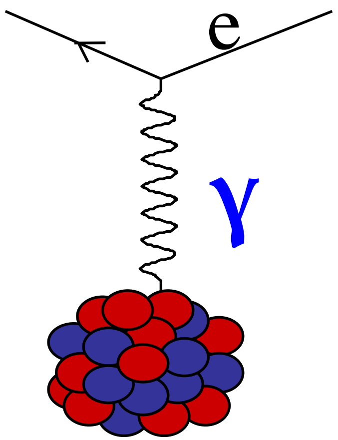


Parity died in 1956



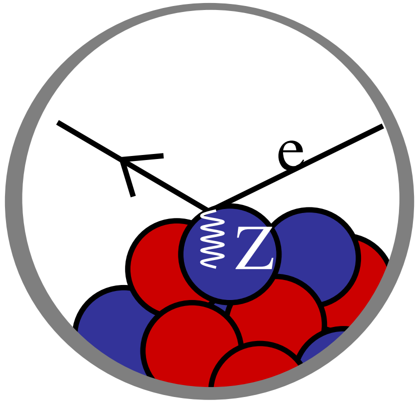
ATOMIC PARITY VIOLATION

- Main Source: Z exchange



Electromagnetic interaction

(conserves parity)

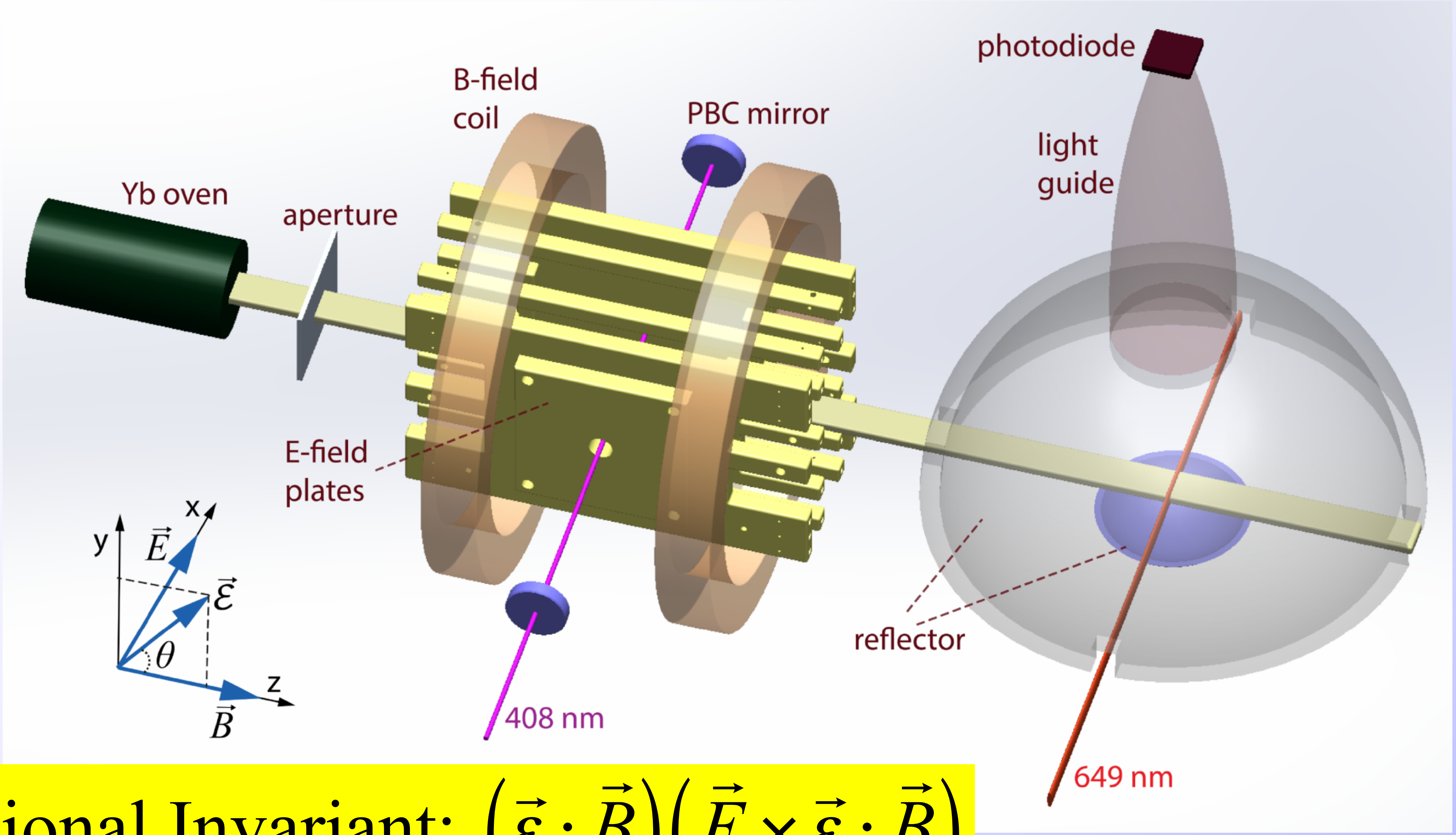


Weak interaction

(violates parity)

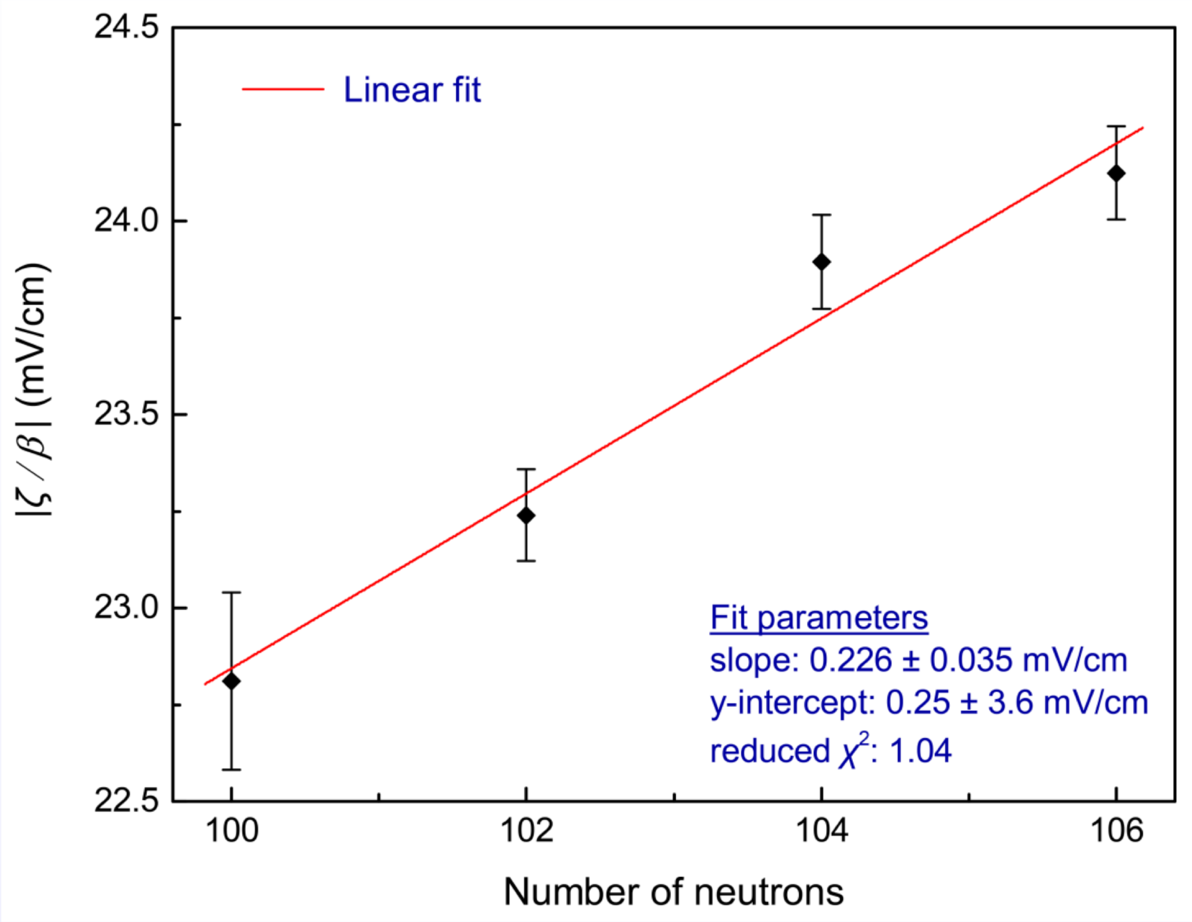
- P-odd, T-even correlation $\boxed{\vec{\sigma} \cdot \vec{p}}$

Yb atomic beam apparatus



Rotational Invariant: $\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$

First observation of isotopic variation of atomic PV



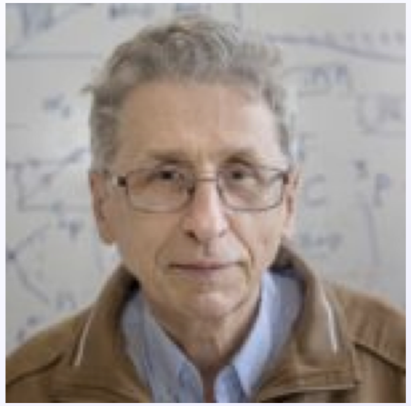
0.5% single isotope accuracy

arXiv:1804.05747

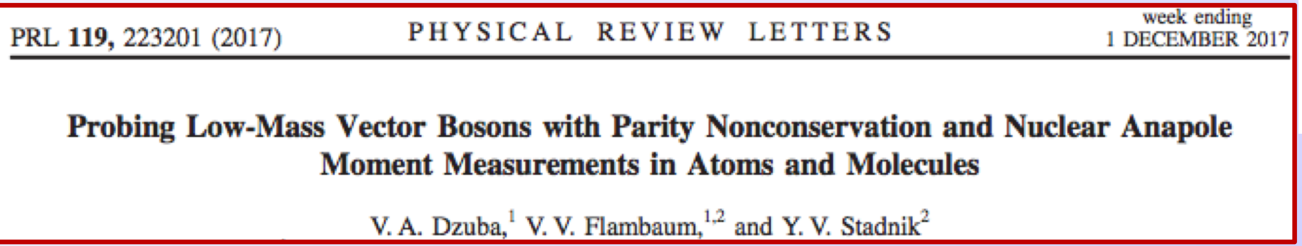
SM: $Q_W \approx -N + Z(1 - 4\sin^2\theta_W)$ → 1% change per neutron around N=103

Observation: 0.96(15) % change per neutron

Implication for light mediators (V.V. Flambaum)



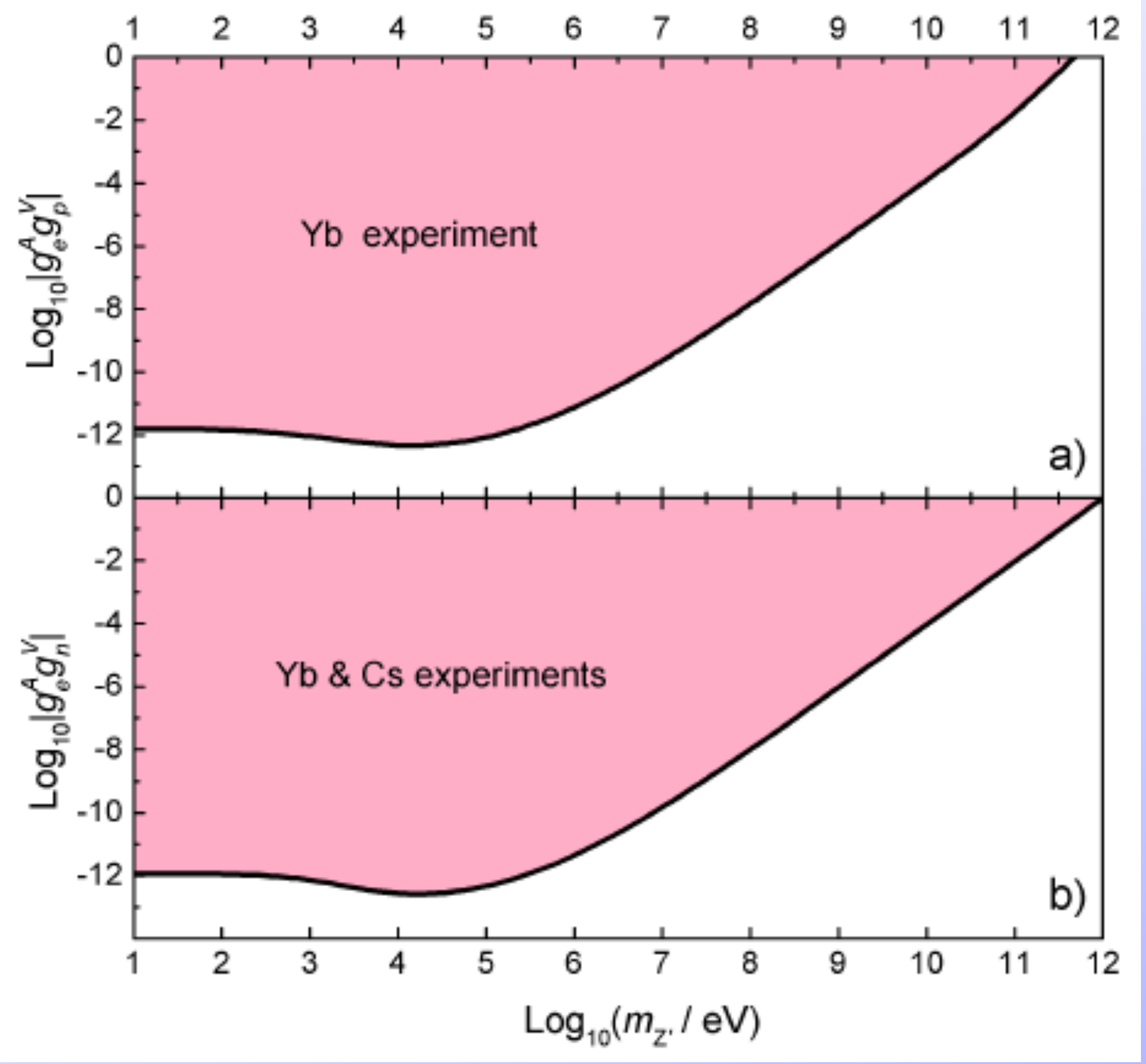
$$\mathcal{L} = Z'_\mu \sum_{f=e,p,n} \bar{f}\gamma^\mu (g_f^V + \gamma_5 g_f^A) f$$



PRL **119,** 223201 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Probing Low-Mass Vector Bosons with Parity Nonconservation and Nuclear Anapole Moment Measurements in Atoms and Molecules

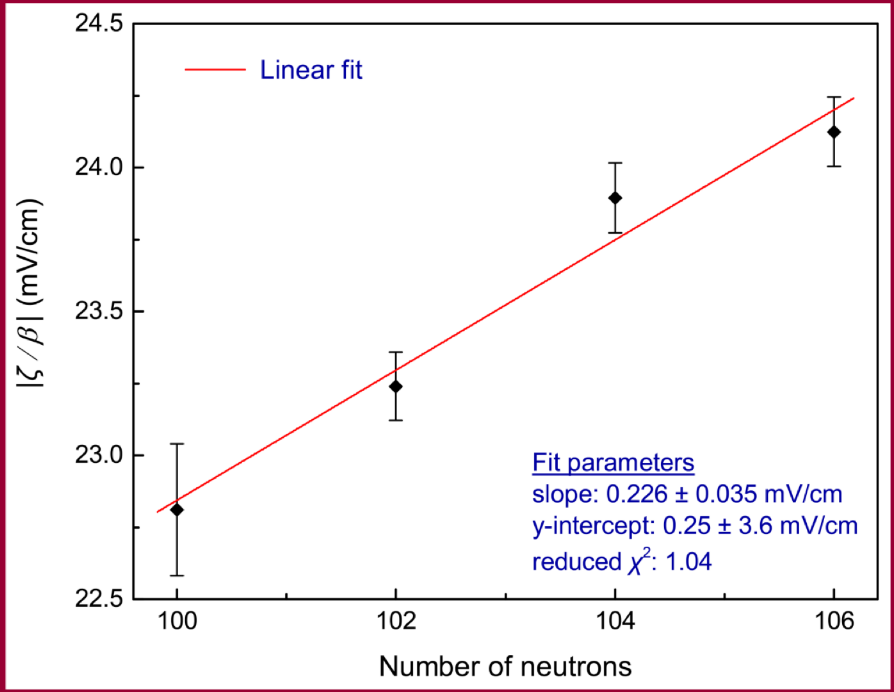
V. A. Dzuba,[1] V. V. Flambaum,[1,2] and Y. V. Stadnik[2]



Reference

D. Antypas, A. Fabricant, J.E. Stalnaker, K. Tsigutkin,
V. V. Flambaum, and D. Budker
Isotopic variation of parity violation in atomic ytterbium
arXiv:1804.05747; accepted to Nature Physics

Summary (PV in Yb)



- Measured PV on a chain of isotopes
- 0.5% accuracy per isotope
- Next stop: anapole moments of ^{171}Yb& ^{171}Yb

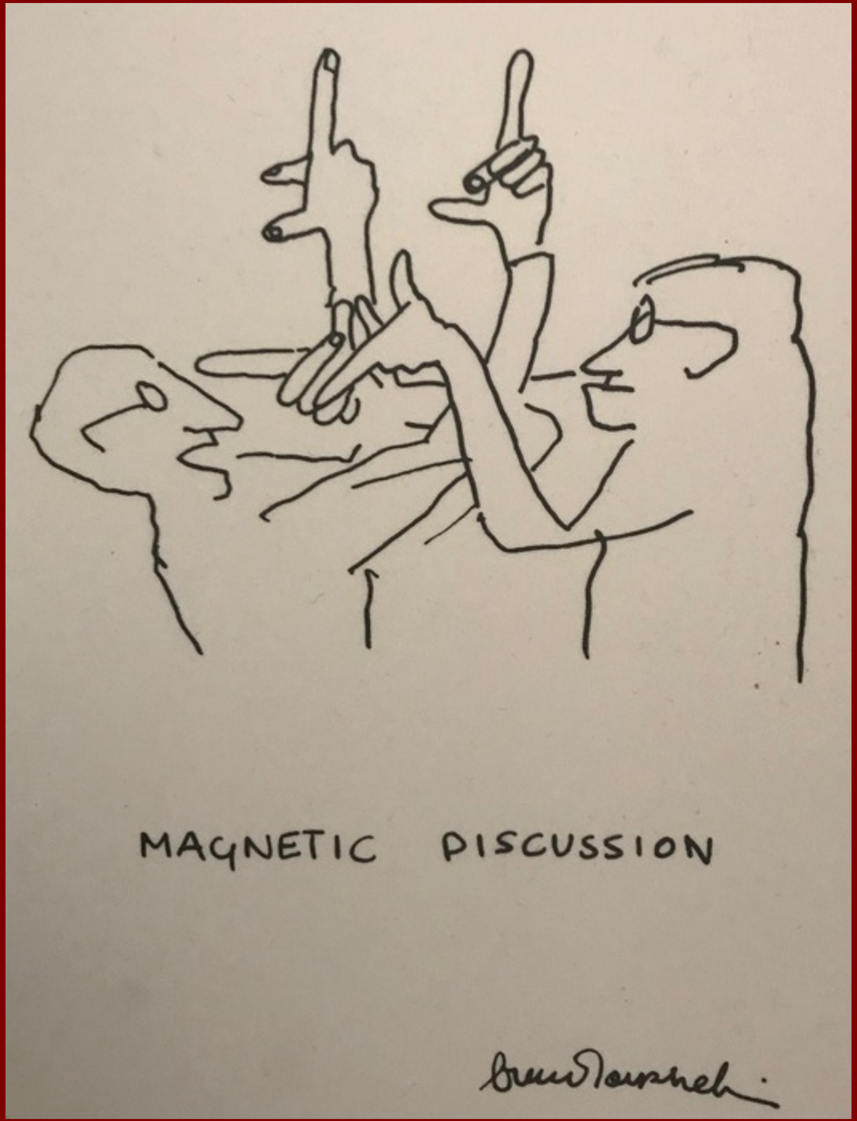

D. Antypas


A. Fabricant


J. Stalnaker


K. Tsigutkin

Axion-like particles (ALPs) search with NMR



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 ???

"Most Wanted" file on DM
What do we know?

- Galactic DM density: ~0.4 GeV/cm^3 (10 GeV/cm^3 d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be bosonic if $m < \sim 20$ eV (1 keV dwarf galaxies)
- "Bosonic Oscillator" with Q ~ $(v/c)^{-2} \sim 10^6$
- Cannot be lighter than ~ 10^{-22} eV
- … (e.g., BEC ?)

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

Gauge Fields

Fermions

$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

Most Searches

(CASPEr-E)

(CASPEr-Wind, GNOME, QUAX)

Dark Matter search with NMR

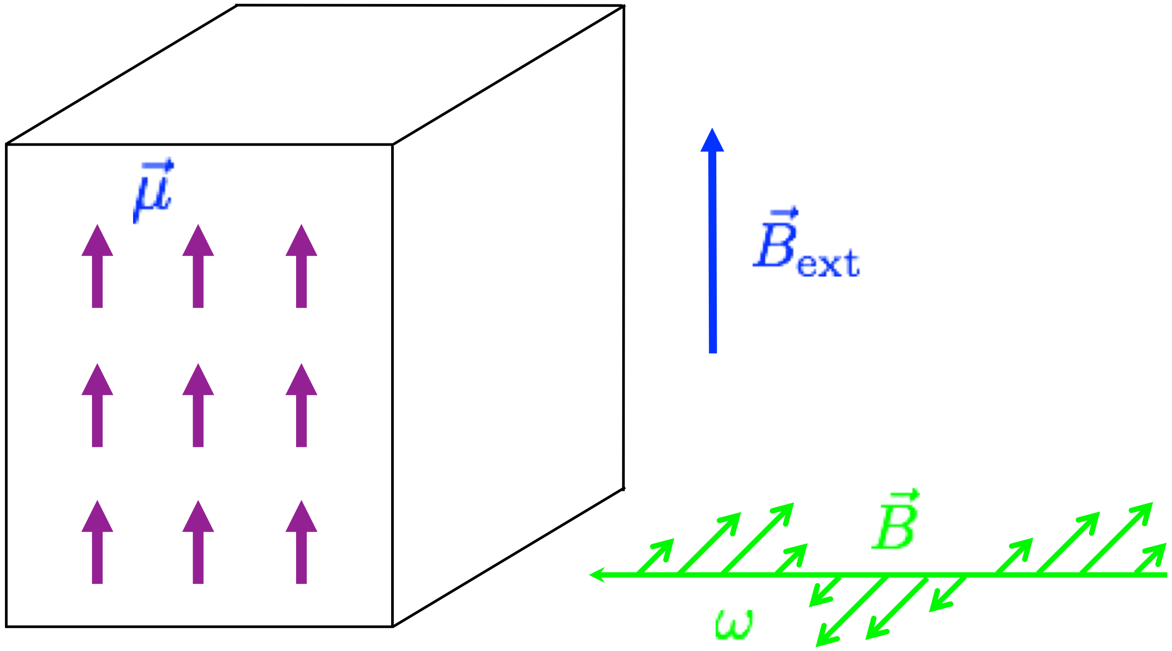
Key Ideas:

- **Dark Matter** could be a "classical" field
- Not screened by shielding
- Oscillating at frequency: mc^2/h
- Relatively narrow line: $\Delta\nu/\ \nu \sim 10^{-6}$

➟ Cosmic Axion Spin-Precession Experiment(s)

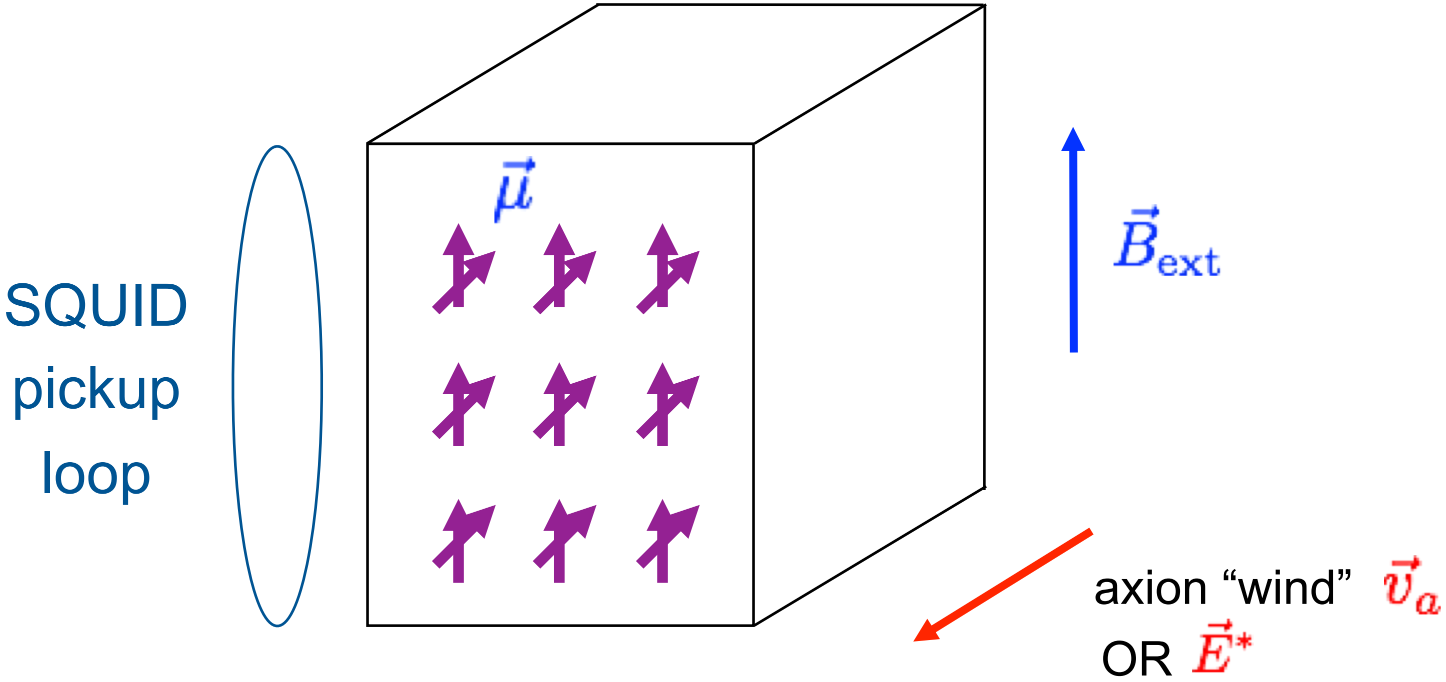
CASPEr

Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\text{ext}} = \omega$

CASPEr



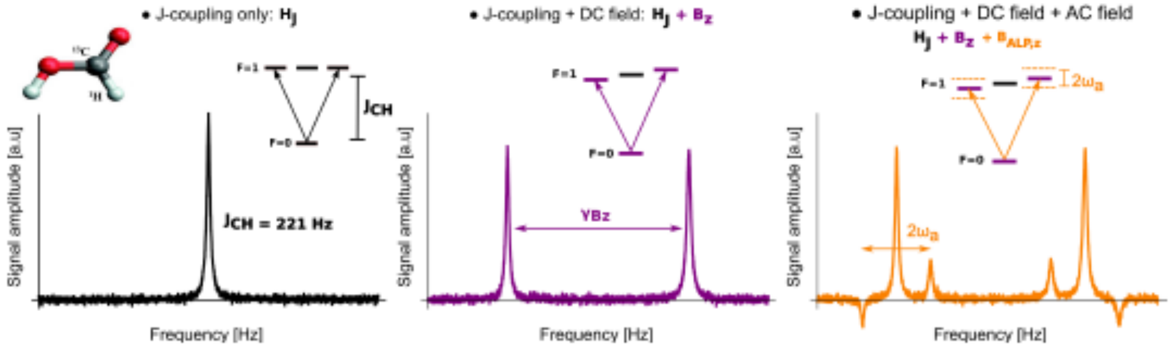
Larmor frequency = axion mass ➔ resonant enhancement

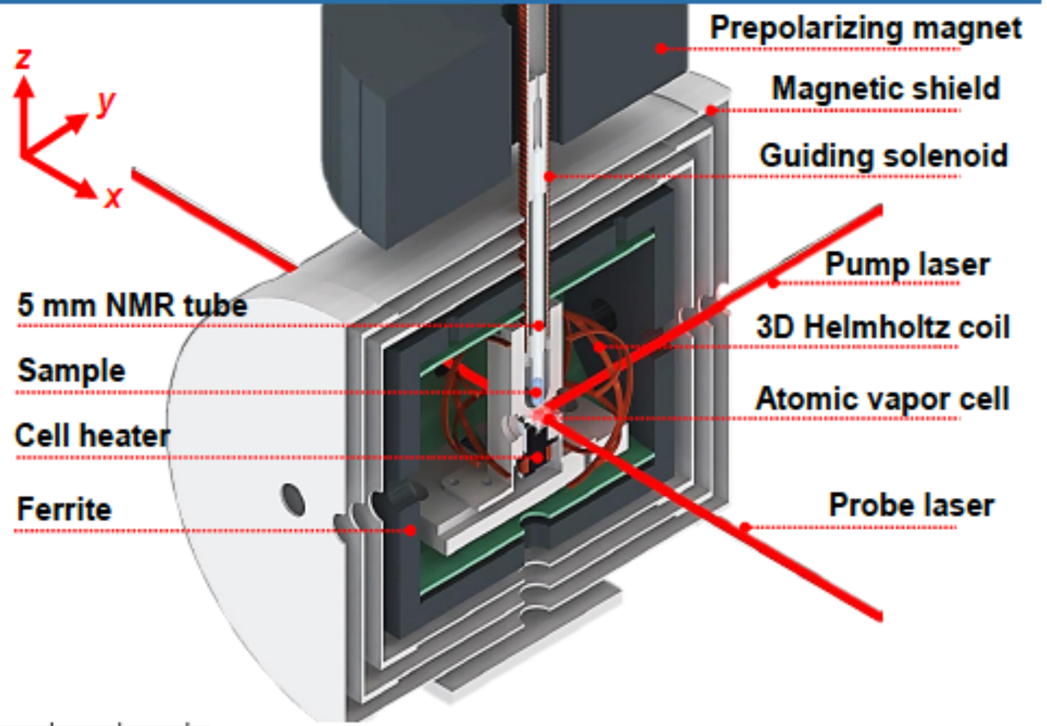
SQUID measures resulting transverse magnetization

Example materials: liquid ^{129}Xe, ferroelectric PbTiO$_3$

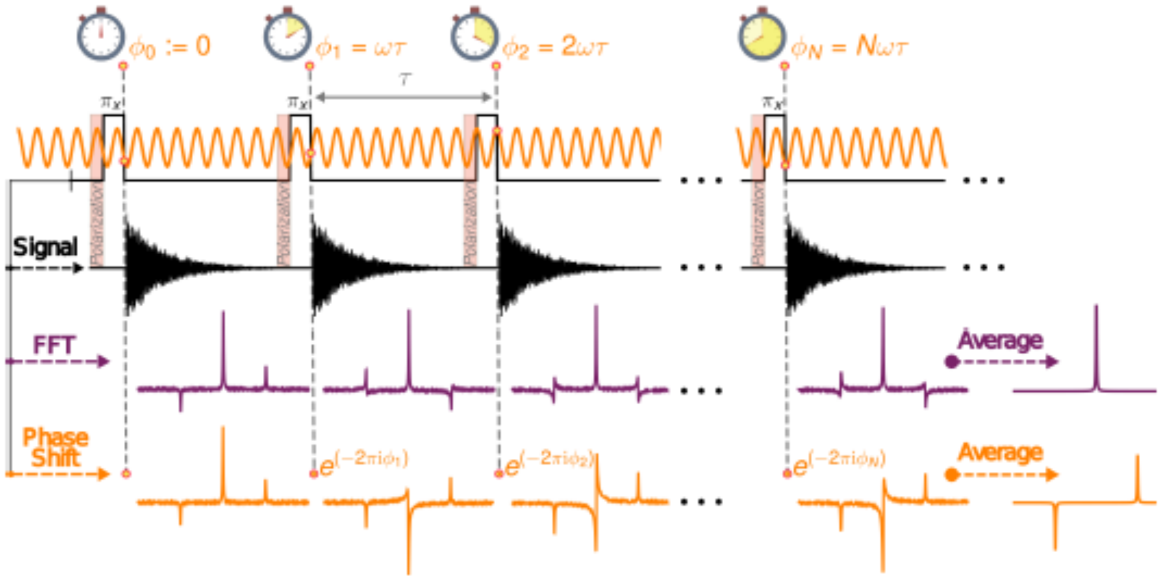
Dark Matter search with ZULF NMR

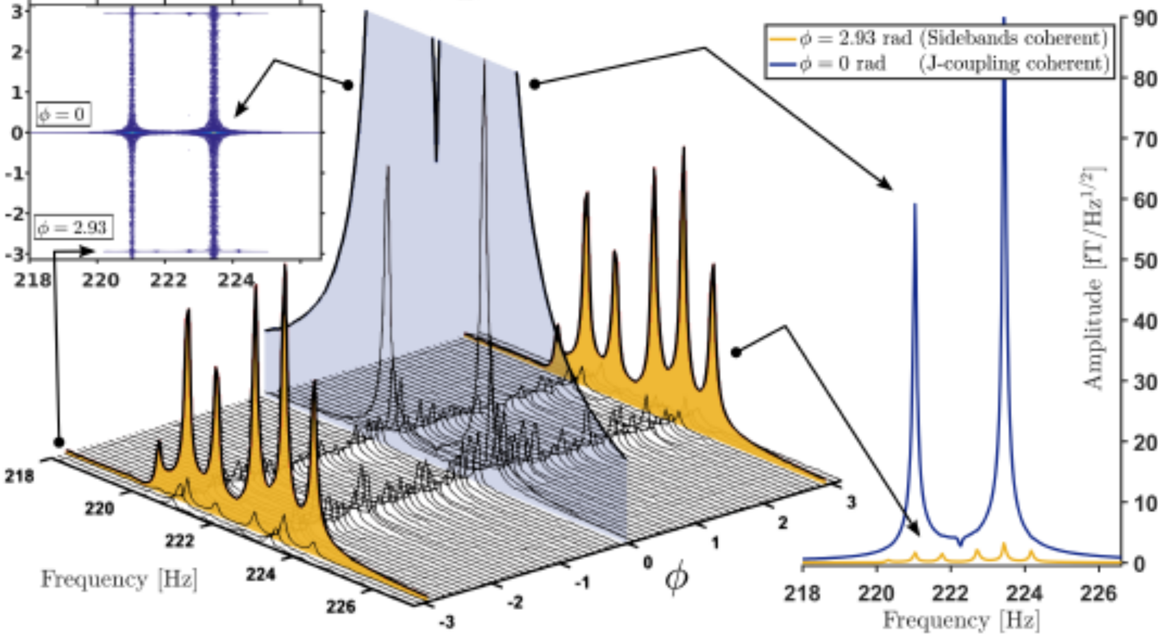
CASPEr With Zero- to Ultralow-Field NMR



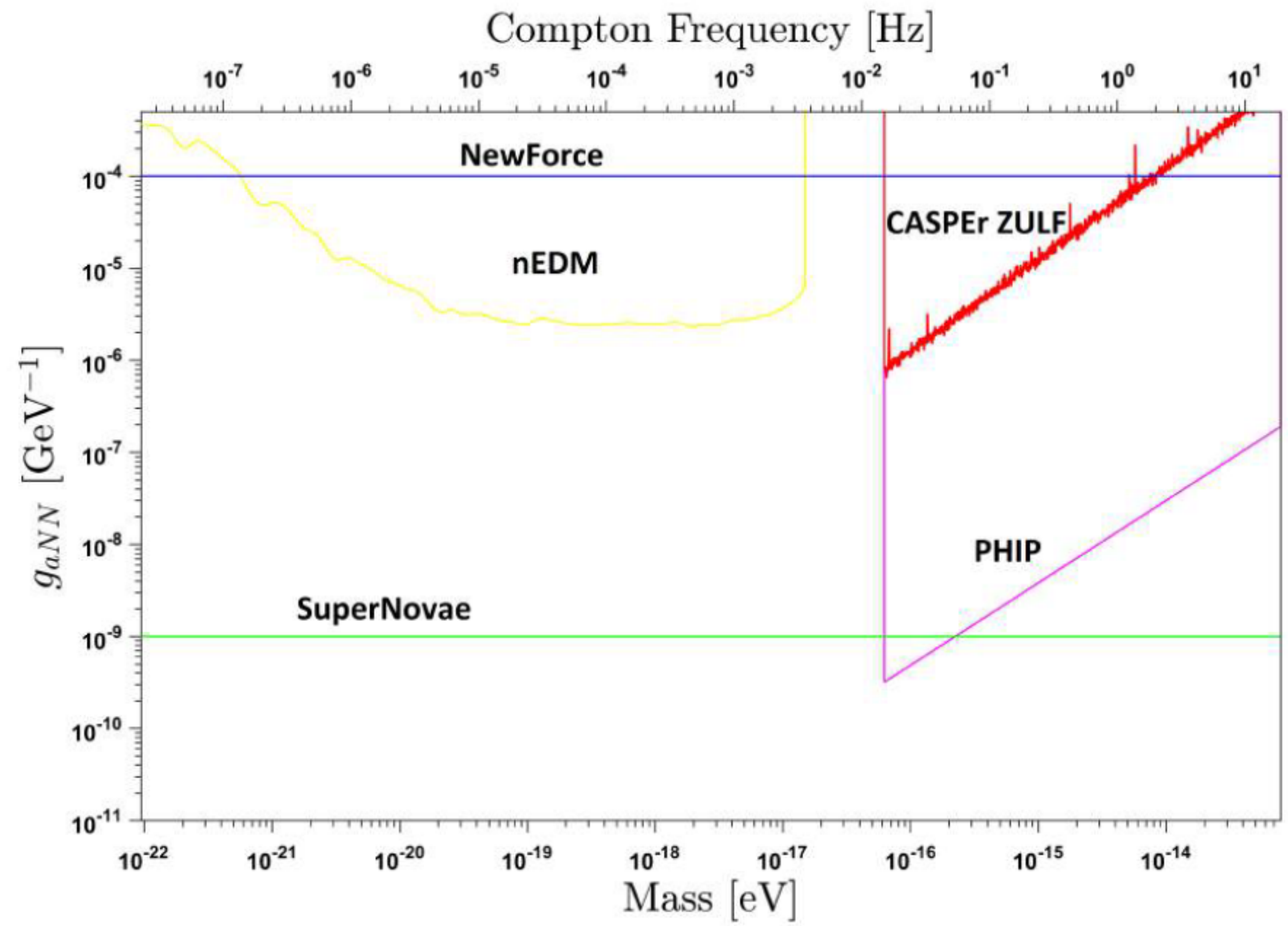


- **Search for dark-matter-induced sidebands**
- **Coherent averaging of arbitrary frequency via post-processing phase cycling**
- **Upcoming sensitivity improvements with PHIP**



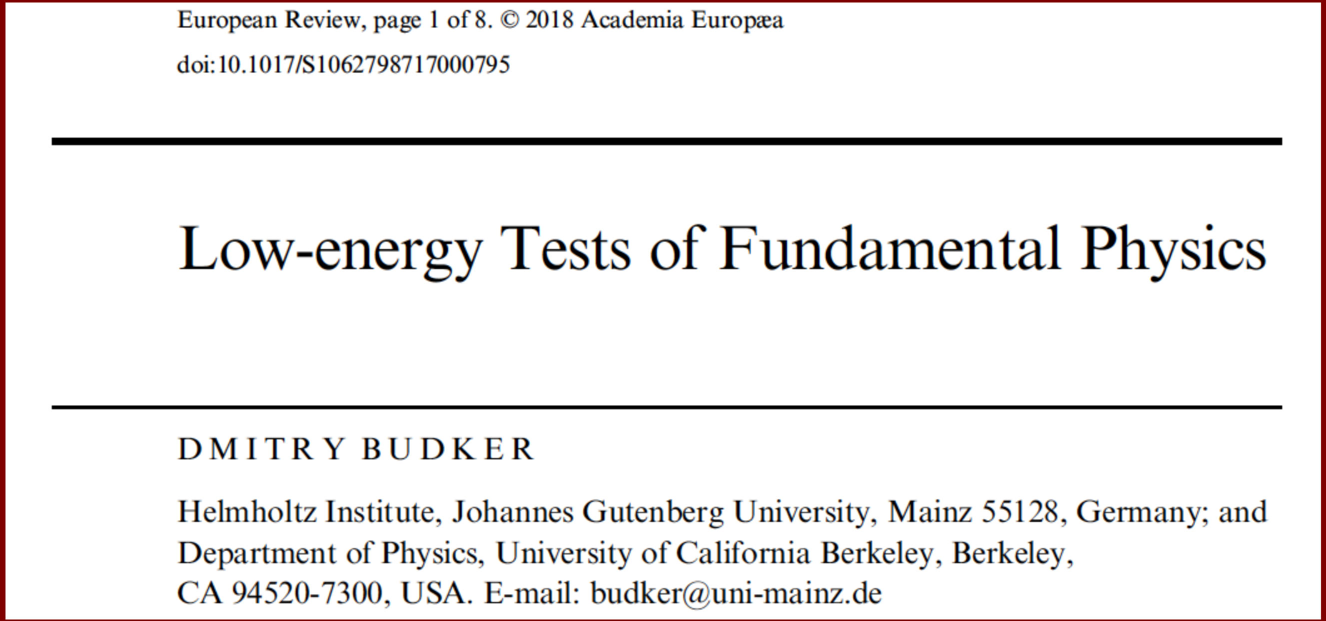


CASPEr ZULF: preliminary results



Personal opinions…

- BSM vs. BBSM physics
- Merger of particle physics, astronomy, cosmology,… in non-collider physics
- Discoveries are around the corner!
- Adopt new technologies or perish



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doi:10.1017/S1062798717000795

Low-energy Tests of Fundamental Physics

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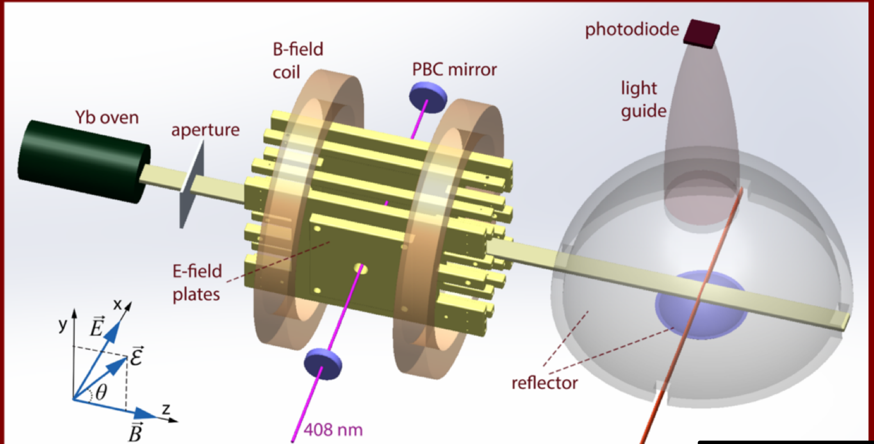
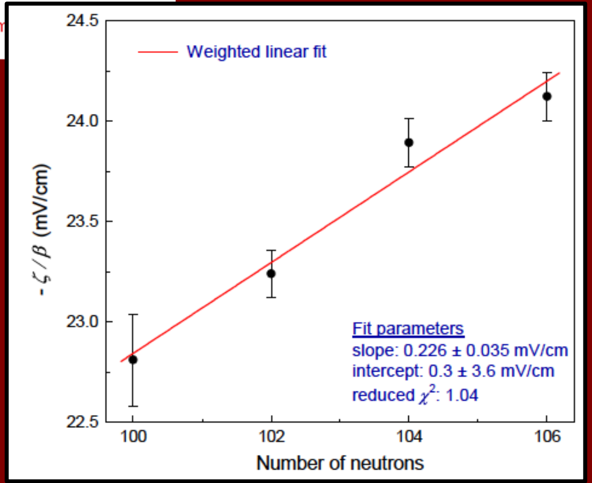
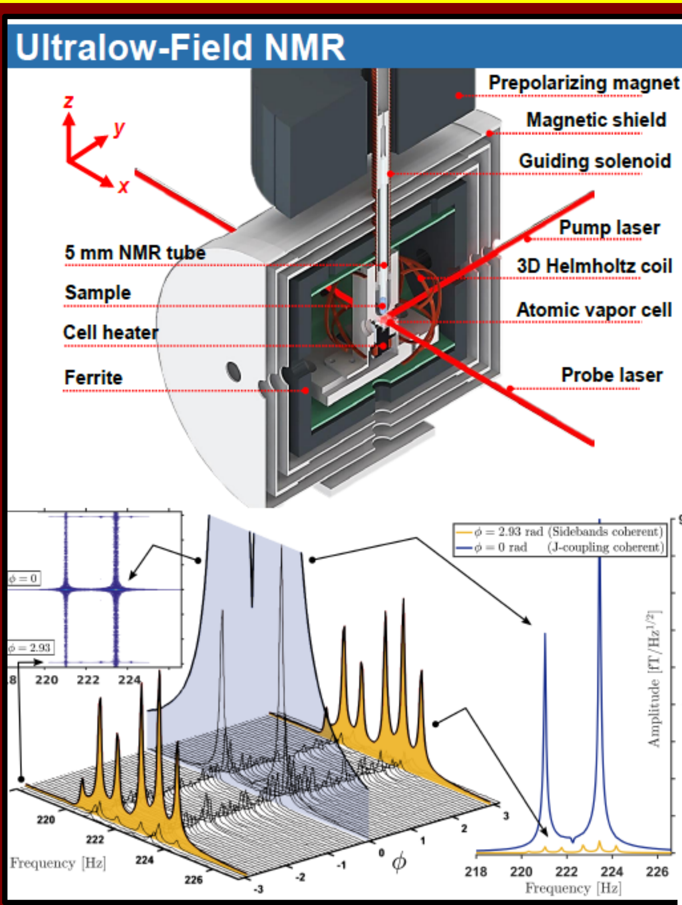
SUMMARY

My is gamma factory!



Parity Violation
in Yb





ALPs search
with CASPEr