Laser spectroscopy to probe physics within and beyond the standard model

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Particle Physics Seminar | 27.10.2022

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QUANTUM METROLOGY RESEARCH GROUP

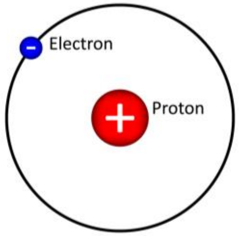
Arthur Schawlow

"Never measure anything but frequency!"

1. Electron-proton mass ratio $\mu = m_e/m_p$

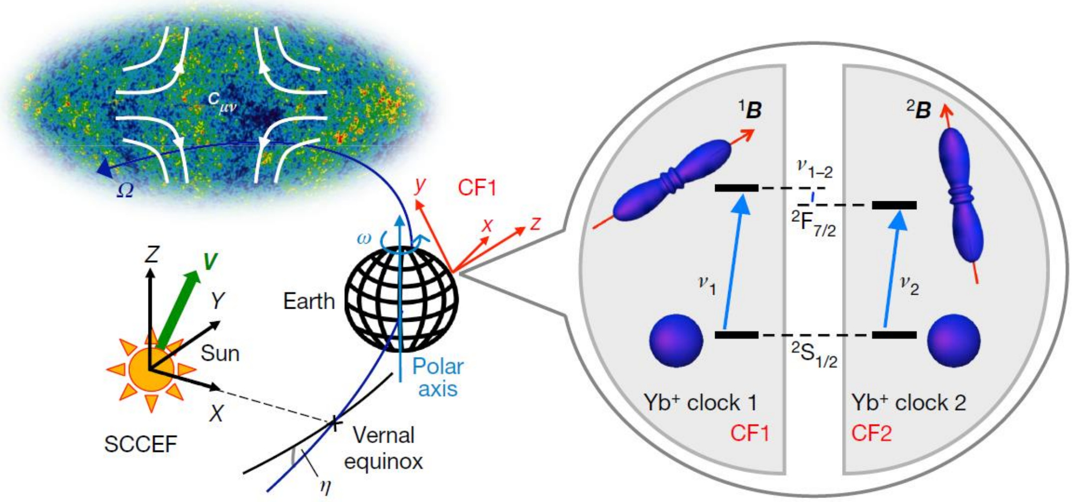
(by comparing the energy of various transitions over time)

$$\left(\frac{1}{\mu}\right)\left(\frac{d\mu}{dt}\right) = -0.5(1.6) \times 10^{-16}/\mathrm{yr}$$



Phys. Rev. Lett. **113**, 210802 (2014)

2. Lorentz invariance

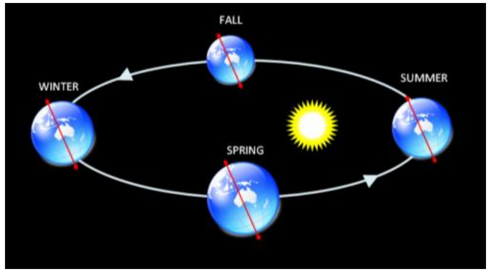


$$2.8\ (4.2) \times 10^{-18}$$

Nature **567**, 204 (2019)

3. Local position invariance

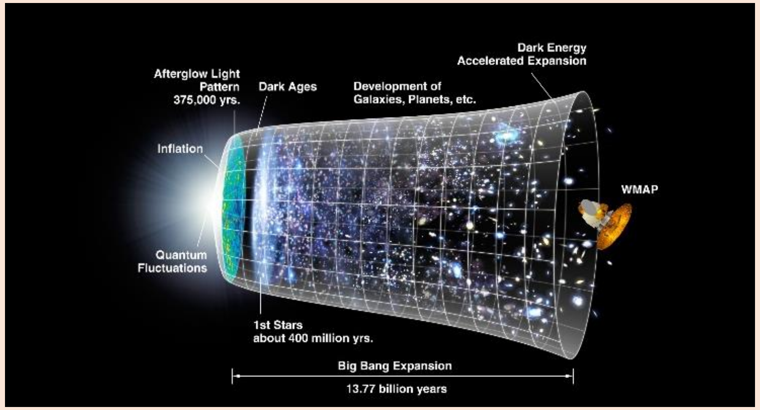
$$\left(\frac{c^2}{\alpha}\right)\left(\frac{d\alpha}{d\Phi}\right) = 14(11) \times 10^{-9}$$



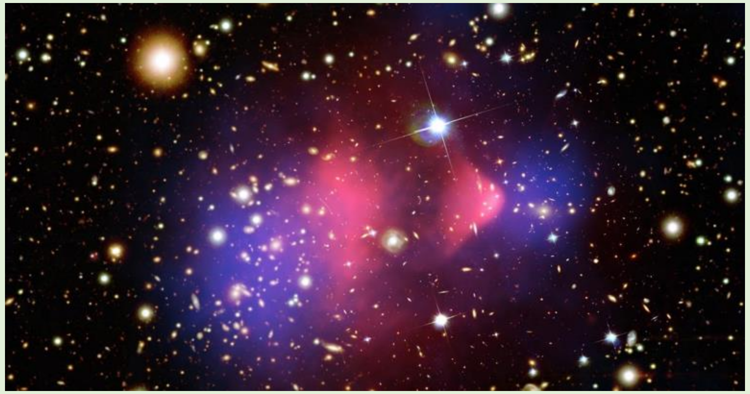
Phys. Rev. Lett. **126**, 011102 (2021)

Grand challenges in fundamental physics

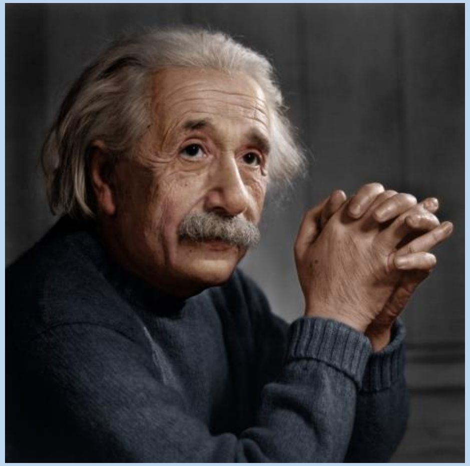
Baryon asymmetry



New particles

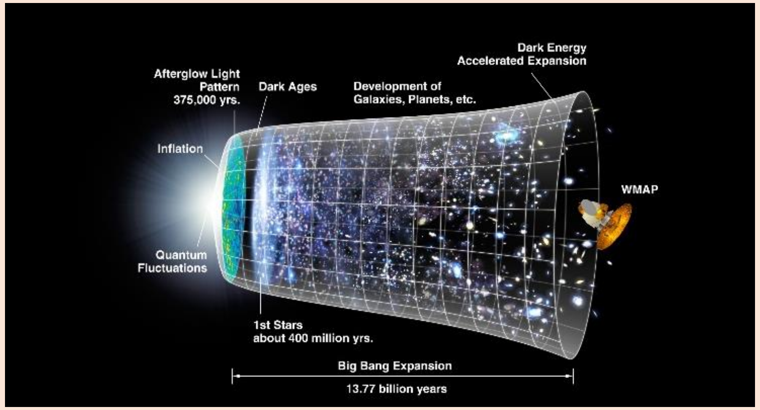


Test of special relativity



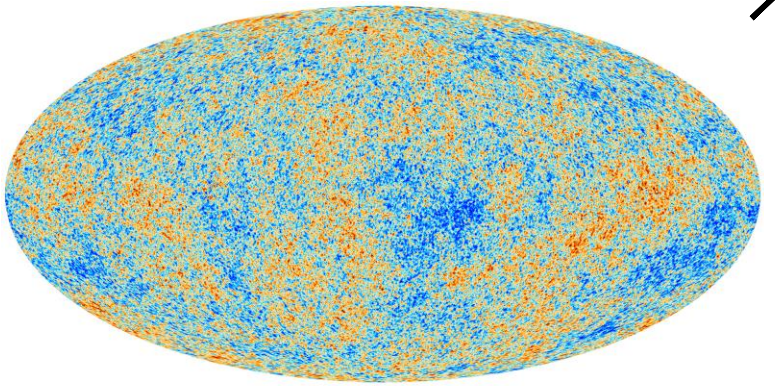
images: wikipedia

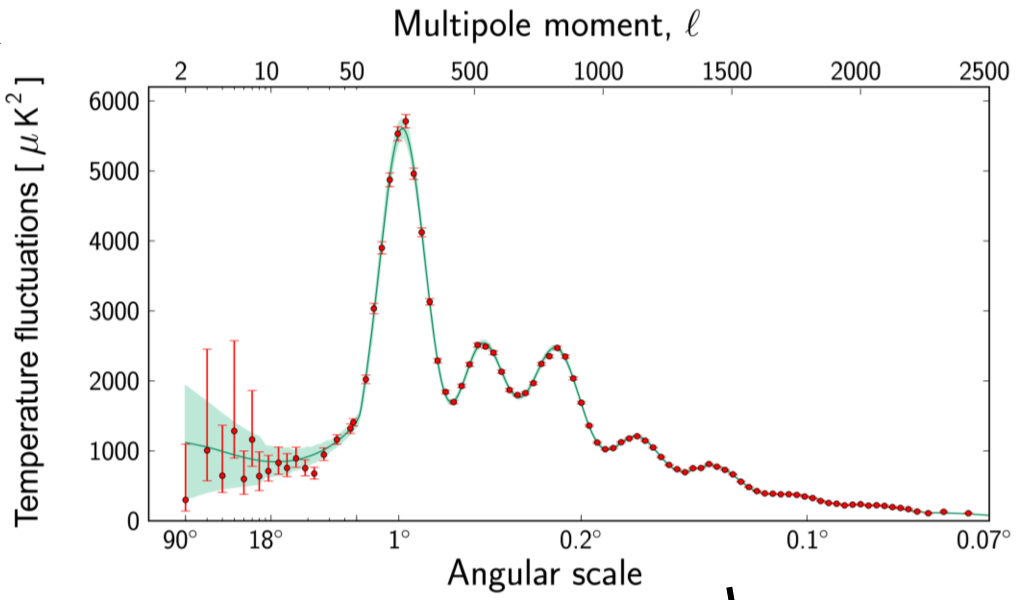
Baryon asymmetry



Baryogenesis and the search for EDMs

Baryogenesis and the search for EDMs





Baryon asymmetry:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

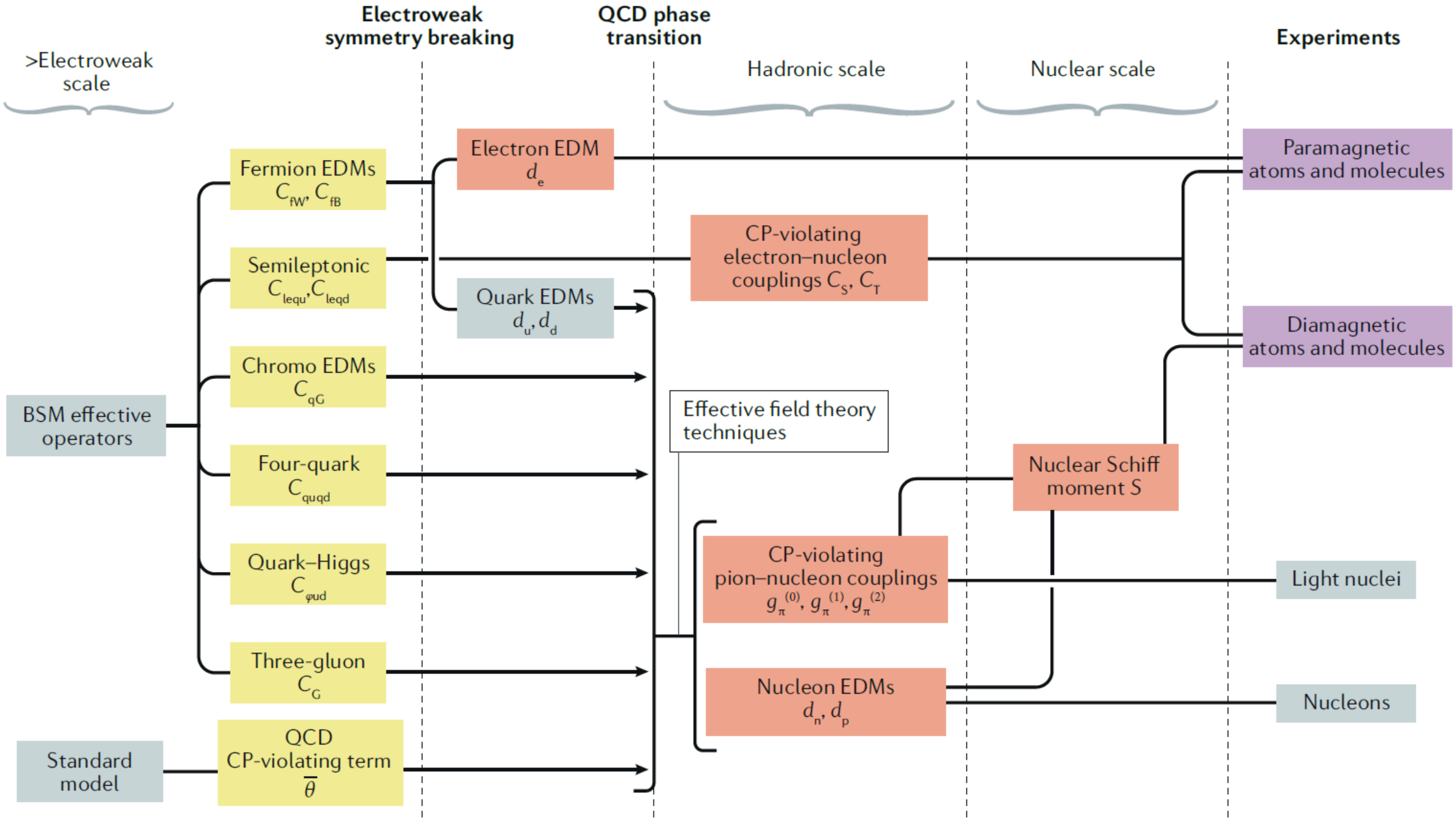
Standard model prediction: $\eta \sim 10^{-18}$

CMB measurements: $\eta = 6.11(30) \times 10^{-10}$

-> 8 orders of magnitude tension

-> 5% uncertainty on the measurement !!!

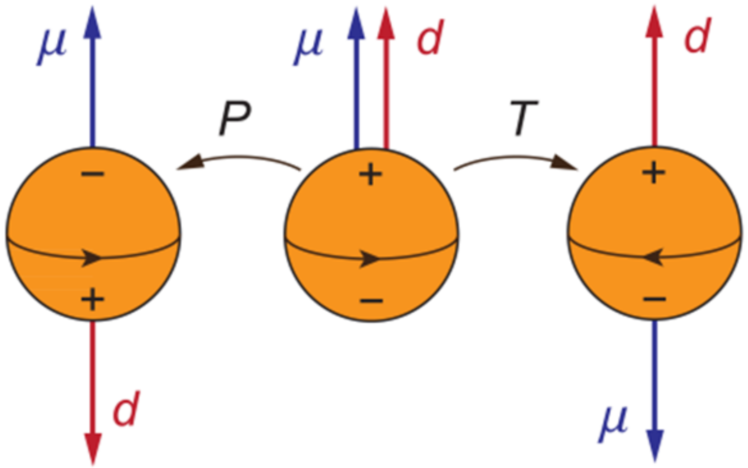
Baryogenesis and the search for EDMs



Nature Reviews Physics **1**, 510 (2019)

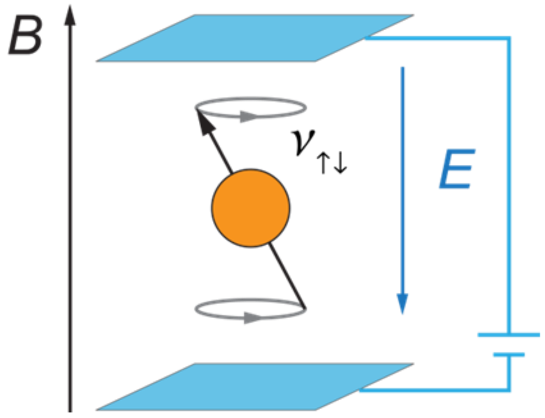
Baryogenesis and the search for EDMs

General idea:



T-violation is equivalent to CP-violation (because of CPT!)

General concept:



Larmor frequency:

$$h\nu = |2\mu B \pm 2dE|$$

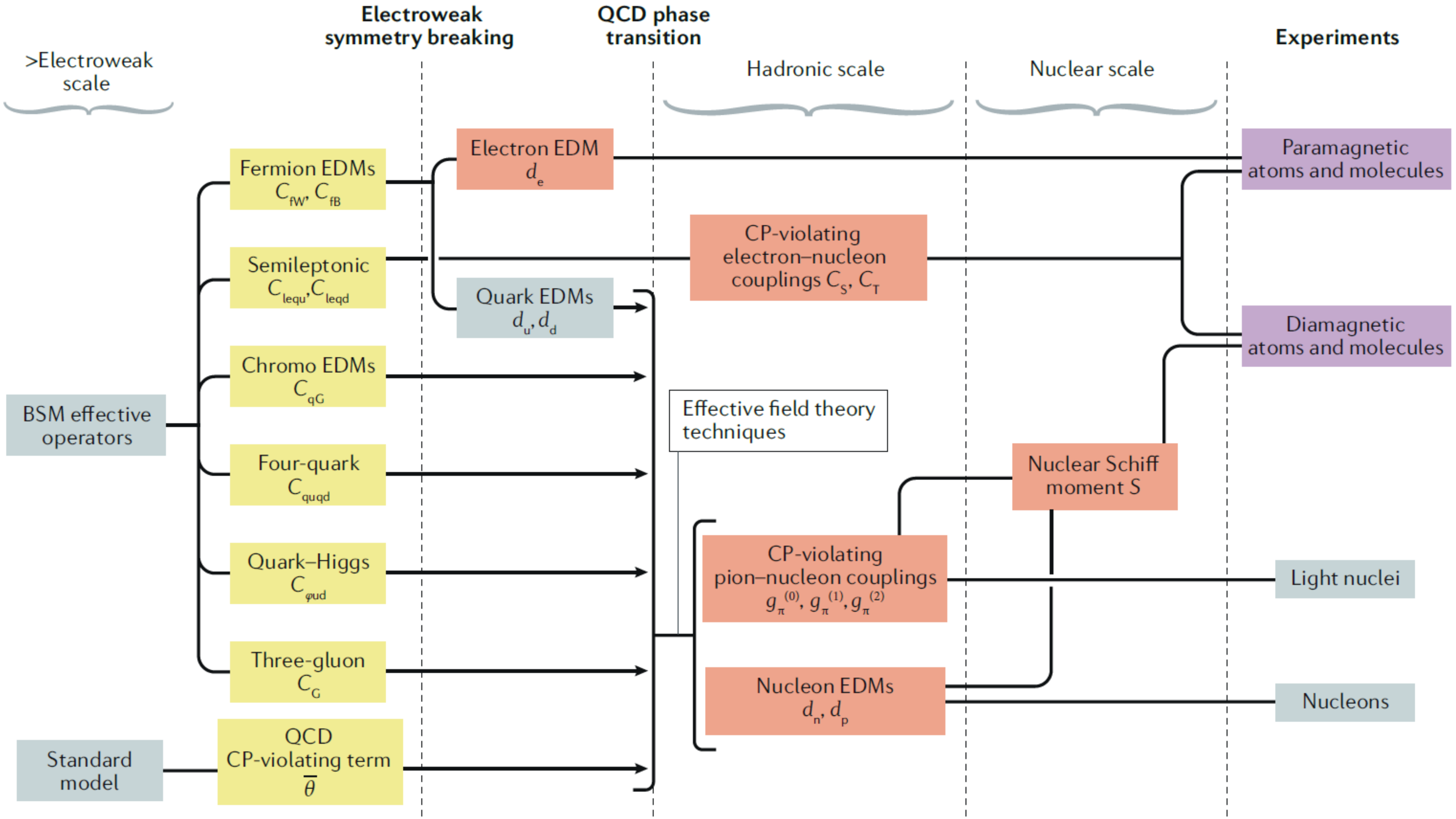
Dipole moment:

$$d = \frac{h\,\Delta\nu}{4E}$$

Sensitivity:

$$\delta d = \frac{\hbar}{2E\,\sqrt{2N\tau T}}$$

Baryogenesis and the search for EDMs



Baryogenesis and the search for EDMs

Electron EDM (e.g. Stanford, Imperial College, Harvard, JILA, …)

ACME 2018 result: $d_e = \left(4.3 \pm 3.1_{stat} \pm 2.6_{syst}\right) \times 10^{-30}\ e\ \text{cm}$

$|d_e| < 1.1 \times 10^{-29} e\ \text{cm}$

Nature **562**, 355 (2018)

In typical models, where d_e is produced by one- or two-loop diagrams, for $\sin(\phi_T) \approx 1$ our result typically limits time-reversal-symmetry-violating new physics to energy scales above $\Lambda \approx 30$ TeV or $\Lambda \approx 3$ TeV, respectively[4–8].

Atomic EDM (e.g. U Washington, Argonne NL, Mainz/ Heidelberg/PTB, Bonn, …)

2016 result: $d_{\text{Hg}} = \left(2.20 \pm 2.75_{stat} \pm 1.48_{syst}\right) \times 10^{-30}\ e\ \text{cm}$

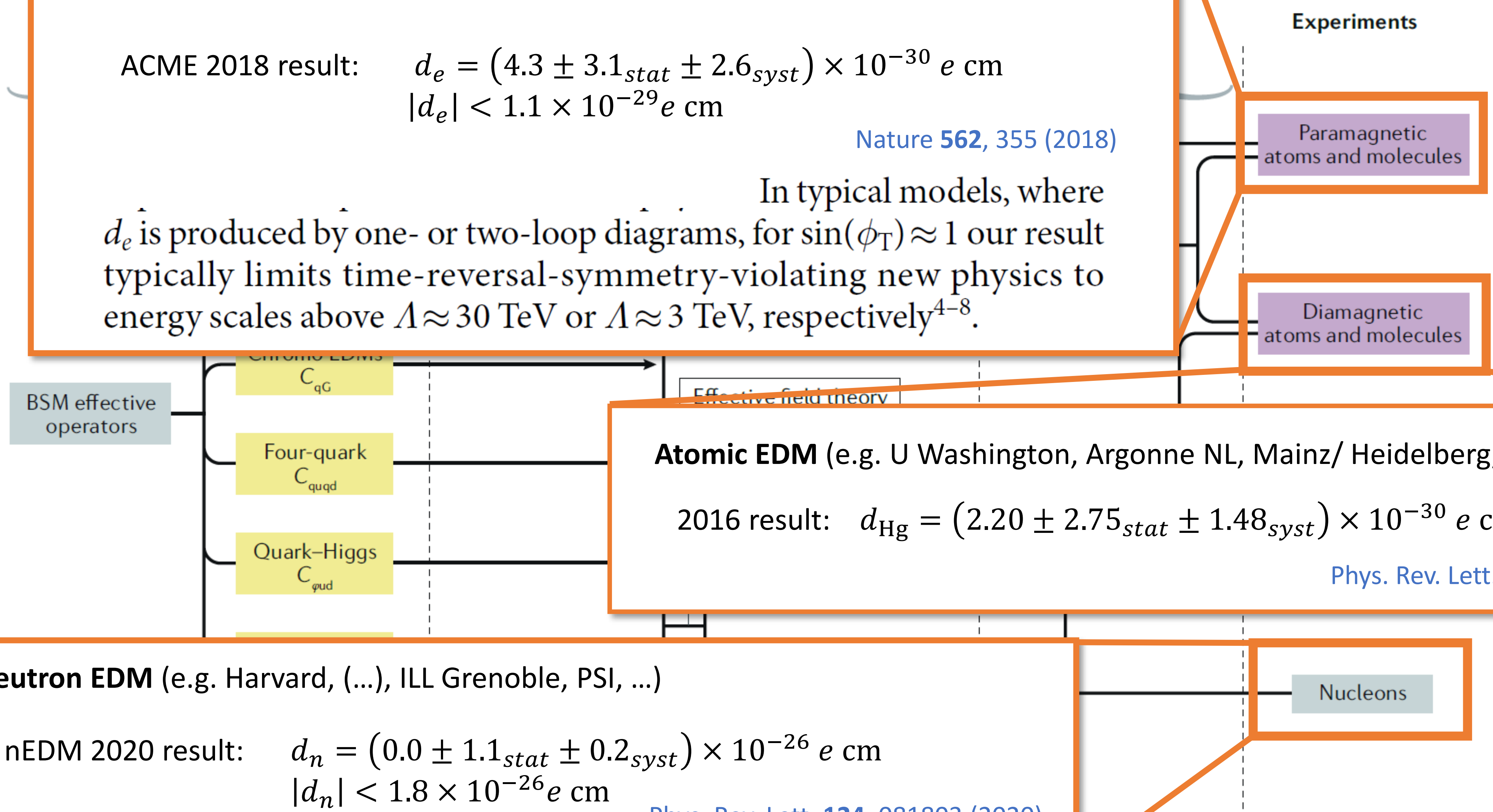
Phys. Rev. Lett. **116**, 161601 (2016)

Neutron EDM (e.g. Harvard, (…), ILL Grenoble, PSI, …)

nEDM 2020 result: $d_n = \left(0.0 \pm 1.1_{stat} \pm 0.2_{syst}\right) \times 10^{-26}\ e\ \text{cm}$

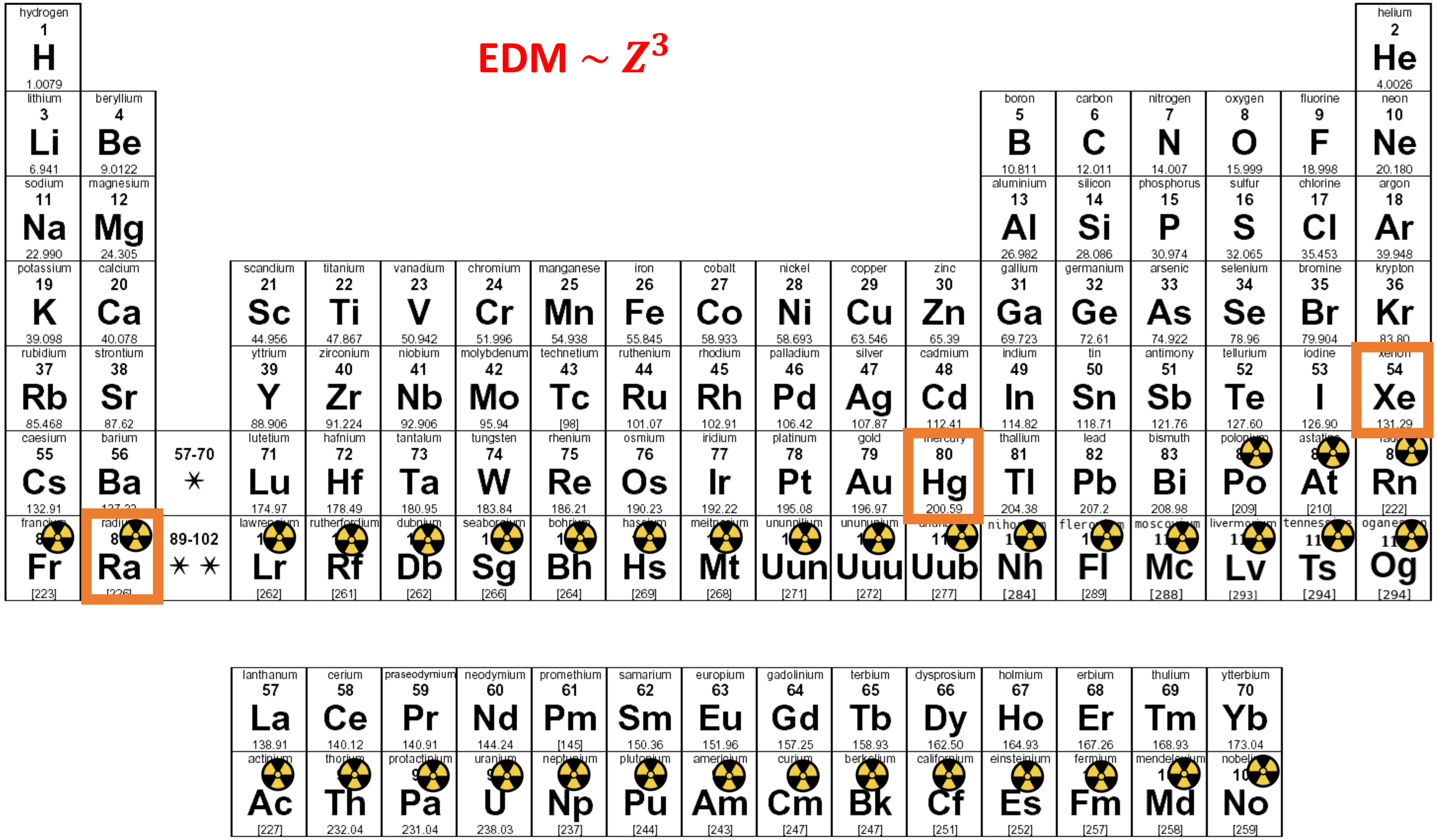
$|d_n| < 1.8 \times 10^{-26} e\ \text{cm}$

Phys. Rev. Lett. **124**, 081803 (2020)

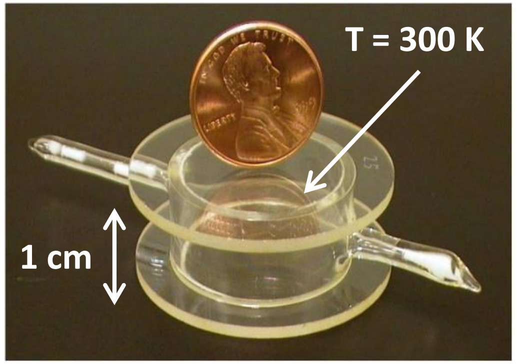


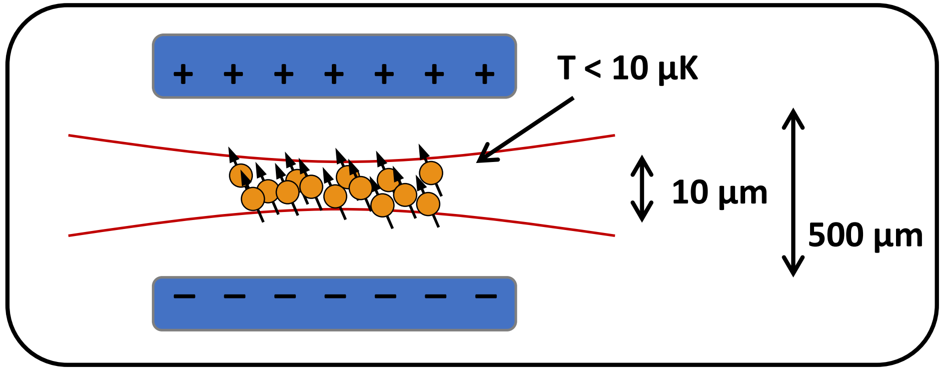
A new approach: ultracold atoms

EDM $\sim Z^3$



A new approach: ultracold atoms





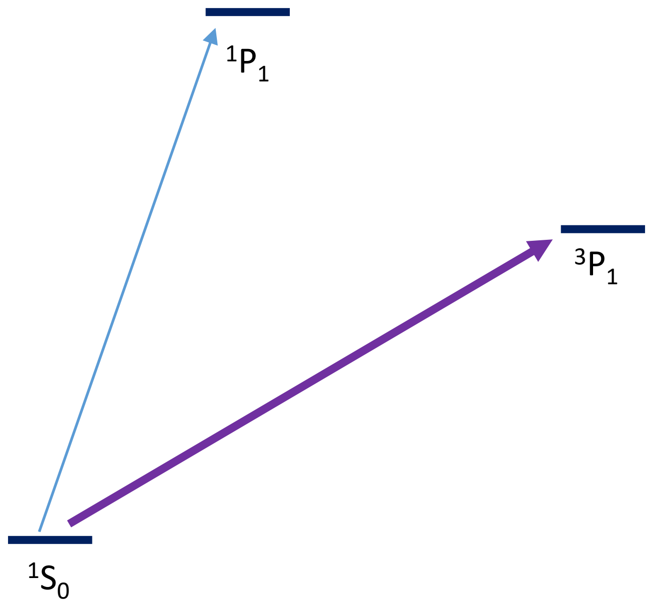
Sensitivity:

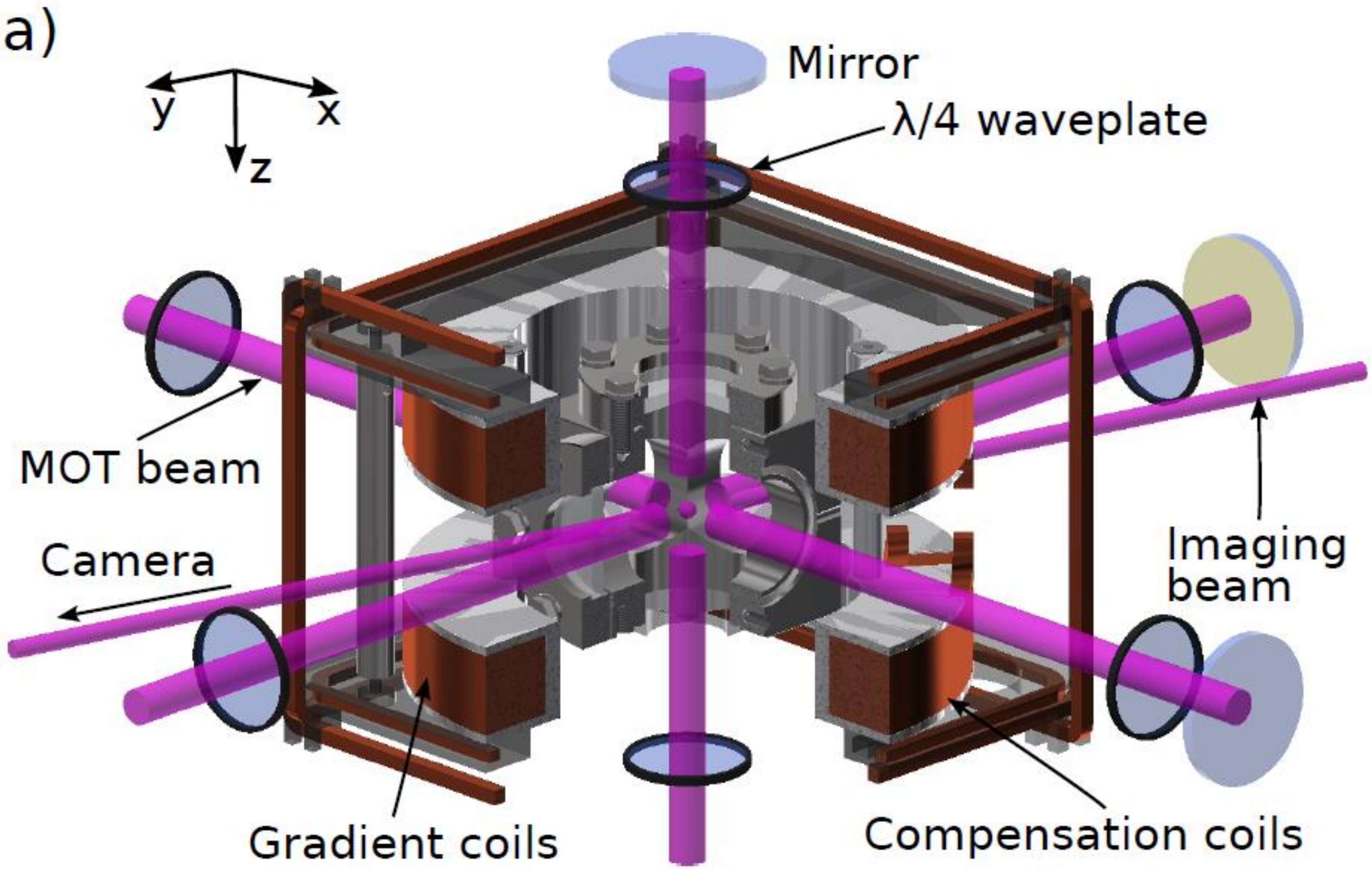
$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$

	Seattle (2016)	quMercury		
		conservative	**optimistic**	**Heisenberg**
voltage	15 kV	10 kV	30 kV	30 kV
electrode gap	1.1 cm	0.5 mm	0.5 mm	1 mm
E-field	13.6 kV/cm	200 kV/cm	600 kV/cm	300 kV/cm
spin decoherence τ	100 s	100 s	300 s	100 s
atom number N	2×10^{14}	10^{6}	10^{8}	10^{7}
measurement time T	10 months	3 months	3 months	3 months
design sensitivity δd	(2×10^{-33} e cm)	1.5×10^{-28} e cm	7.6×10^{-31} e cm	2.6×10^{-33} e cm
experimental sensitivity δd	7.4×10^{-30} e cm			

A new approach: ultracold atoms

254-nm laser system:
Toptica FHG,
200 – 300 mW



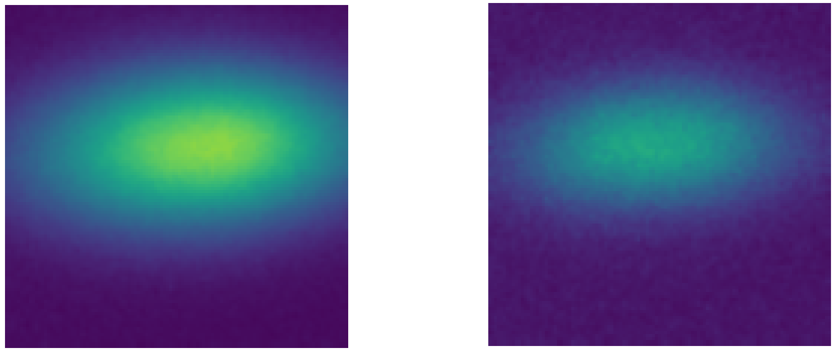


Phys. Rev. A **105**, 033106 (2022)

A new approach: ultracold atoms

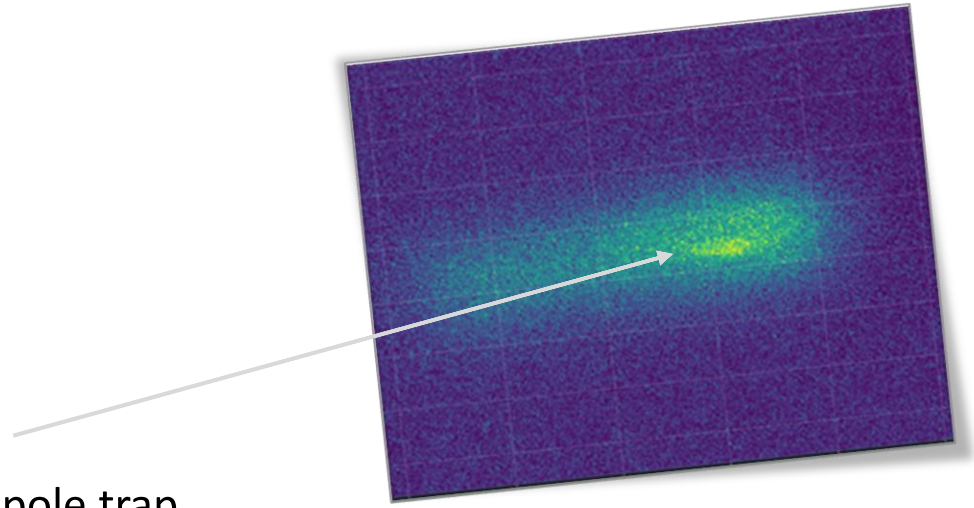
Magneto-optical trapping of mercury

^{200}Hg ^{199}Hg



10^8 atoms
200 µK temperature

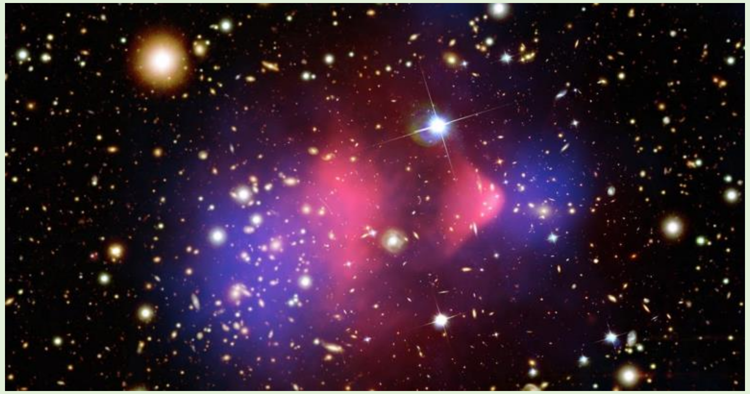
5×10^6 atoms
30 µK temperature



dipole trap loading

Next steps: optimization, scattering properties, evaporative cooling, quantum degeneracy, electric field plates, …

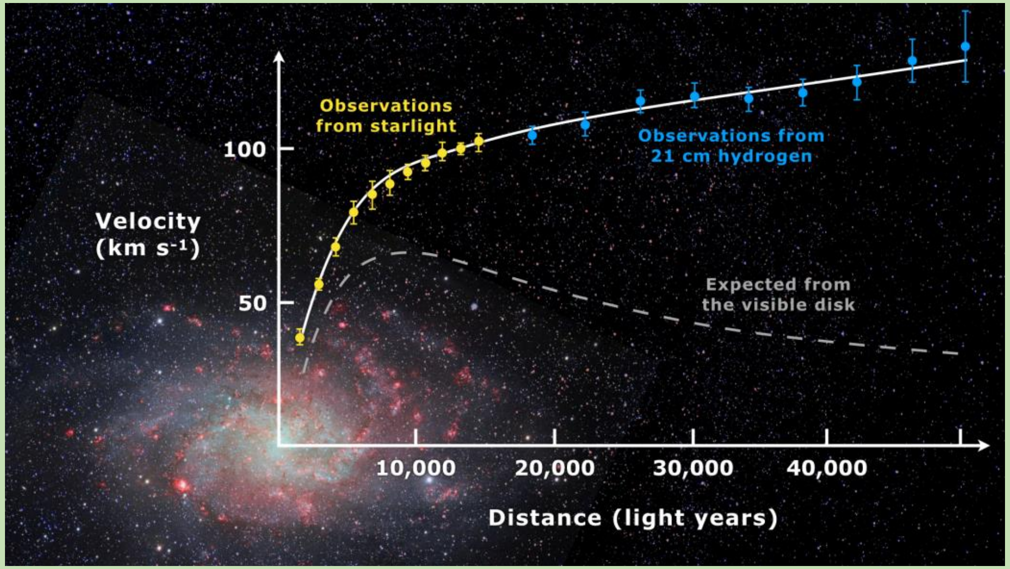
Dark matter



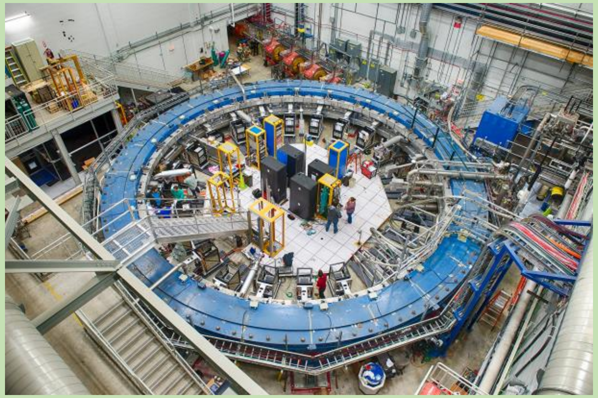
images: wikipedia

Search for new particles

Dark matter



Muon g-2



Fermilab (2021):

$$\frac{g-2}{2} = 0{,}001\,165\,920\,40\,(54)$$

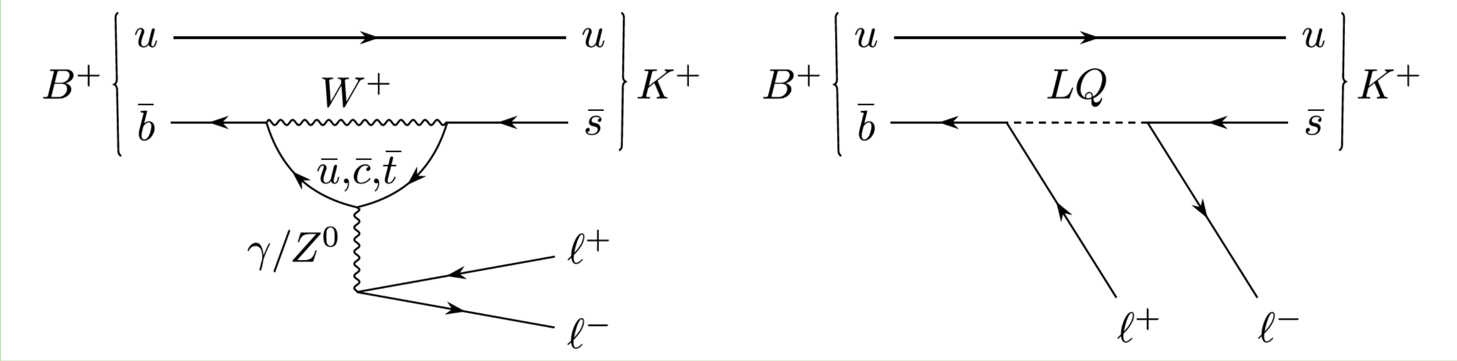
3.3 σ from SM calculations

Lepton universality

LHCb (2021):

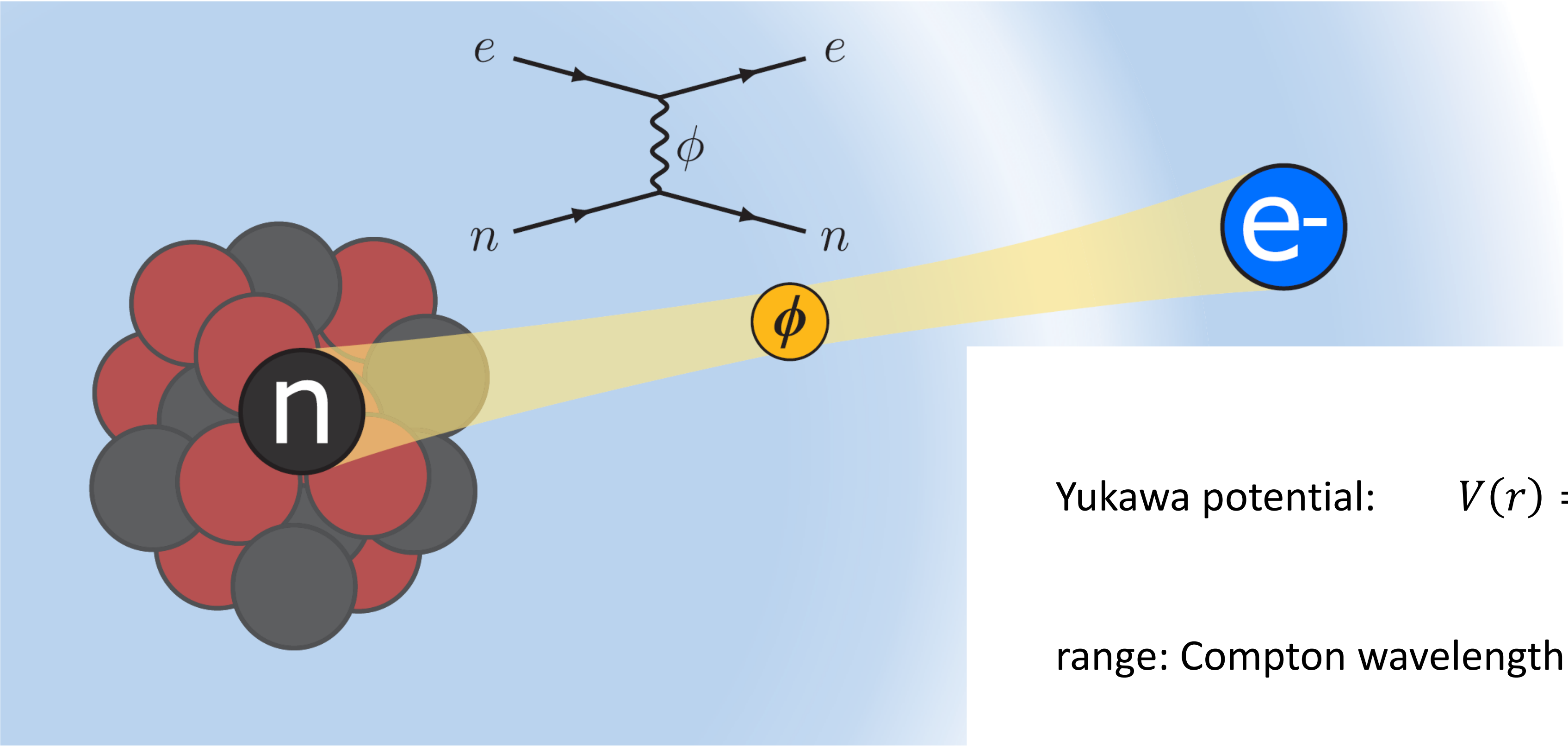
$$B^+ \to K^+\mu^+\mu^-$$
$$B^+ \to K^+e^+e^-$$

ratio: $R_K = 0.85(4)$



Isotope shift spectroscopy

Here:
Precision spectroscopy of optical transitions to search for a fifth force



Yukawa potential: $V(r) = \pm\, e^{-r/R}\, \frac{1}{R}$

range: Compton wavelength $R = \frac{\hbar}{mc}$

Experimental work:
MIT, Mainz, JQI, PTB, Stanford, Rice, Torun, Bonn, FHI, …

Proposal: Phys. Rev. Lett. **120**, 091801 (2018)
MIT work: Phys. Rev. Lett. **125**, 123002 (2020)

Isotope shift spectroscopy

Isotope shift, depends on electronic orbital properties + **nuclear properties**

$$\boldsymbol{\nu_{\alpha ji}} =$$

isotopes i, j
transitions α, β

Isotope shift spectroscopy

Isotope shift, depends on electronic orbital properties + nuclear properties

$$\boldsymbol{\nu_{\alpha ji}} = \boldsymbol{F_\alpha}\ \boldsymbol{\delta\langle r^2\rangle_{ji}}$$

field shift

(GHz scale)

isotopes i, j
transitions α, β

Isotope shift spectroscopy

Isotope shift, depends on electronic orbital properties + **nuclear properties**

$$\nu_{\alpha ji} = F_{\alpha}\, \delta\langle r^2 \rangle_{ji} + K_{\alpha}\, \mu_{ji}$$

field shift *mass shift*

(GHz scale) (MHz scale)

isotopes i, j
transitions α, β

Isotope shift spectroscopy

Isotope shift, depends on electronic orbital properties + nuclear properties

$$\nu_{\alpha ji} = F_\alpha\,\delta\langle r^2\rangle_{ji} + K_\alpha\,\mu_{ji} + G_\alpha\left(\delta\langle r^2\rangle_{ji}\right)^2$$

field shift (GHz scale)

mass shift (MHz scale)

second-order field shift (kHz scale)

isotopes i, j
transitions α, β

Isotope shift spectroscopy

Isotope shift, depends on electronic orbital properties + nuclear properties + new physics

$$\boldsymbol{\nu_{\alpha ji} = F_\alpha\, \delta\langle r^2\rangle_{ji} + K_\alpha\, \mu_{ji} + G_\alpha \left(\delta\langle r^2\rangle_{ji}\right)^2 + v_{ne}\, D_\alpha\, a_{ji}}$$

field shift	*mass shift*	*second-order field shift*	*New Boson*
(GHz scale)	(MHz scale)	(kHz scale)	(Hz - kHz scale)

isotopes i, j
transitions α, β

Then:

1. Normalize by the mass shift μ_{ij}
2. Use a second optical transition β to remove the $\delta\langle r^2\rangle_{ji}/\mu_{ij}$ field shift term

Isotope shift spectroscopy

Isotope shift
relation between
two optical transitions,

depends on **electronic orbital properties** + **nuclear properties** + **new physics**

$$\tilde{\boldsymbol{\nu}}_{\beta ji} = \boldsymbol{F}_{\beta\alpha}\,\tilde{\boldsymbol{\nu}}_{\alpha ji} + \boldsymbol{K}_{\beta\alpha} + \boldsymbol{G}_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2 + \boldsymbol{\upsilon}_{ne}\,\boldsymbol{D}_{\beta\alpha}\,\tilde{\boldsymbol{a}}_{ji}$$

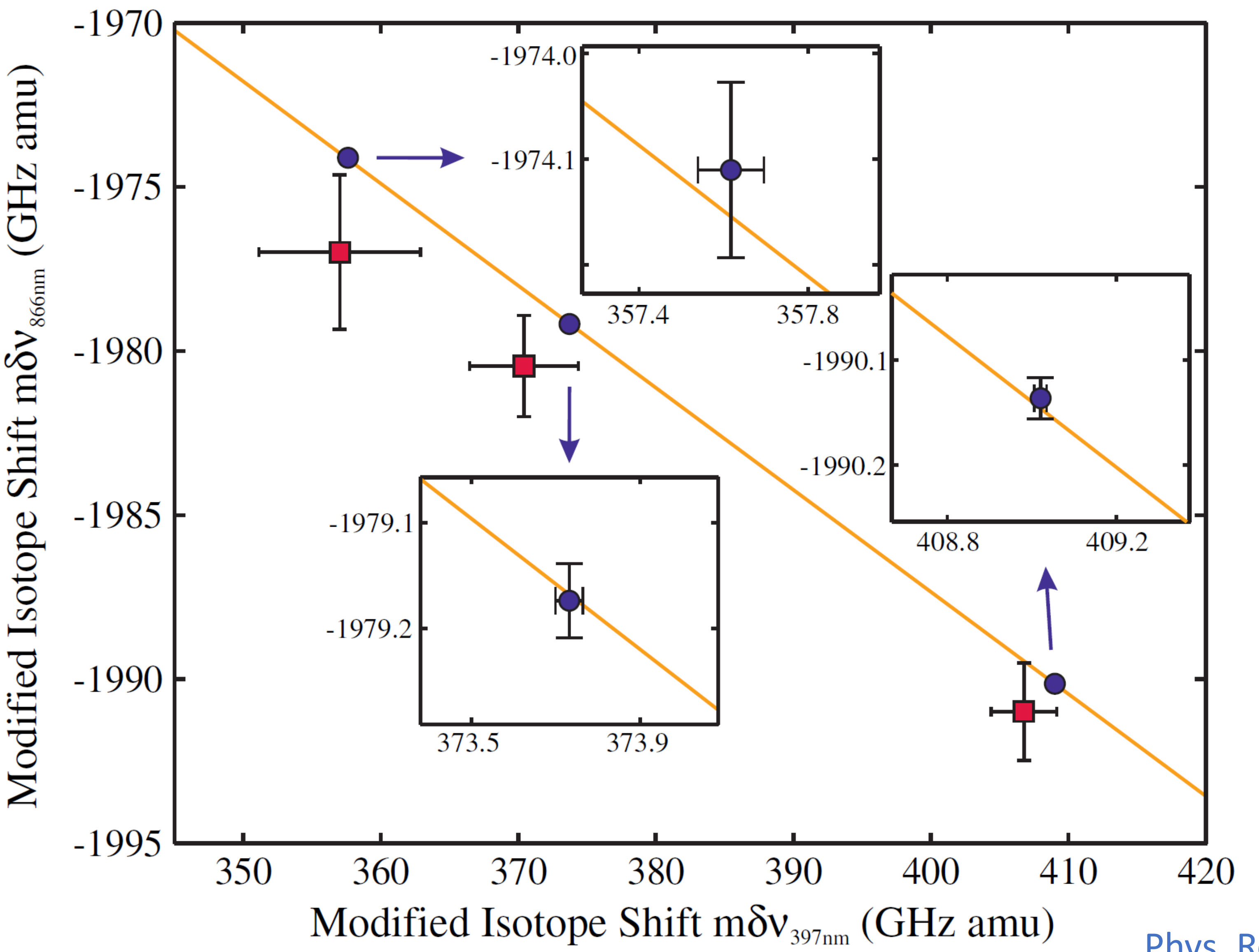
field shift	*mass shift*	*second-order field shift*	*New Boson*
(GHz scale)	(MHz scale)	(kHz scale)	(Hz - kHz scale)
linear	offset	**nonlinear / quadratic**	**nonlinear**

isotopes i, j
transitions α, β

-> graphical representation: **King plot**

Isotope shift spectroscopy

A random example: Calcium ions



Phys. Rev. Lett. **115**, 053003 (2015)

Isotope shift spectroscopy

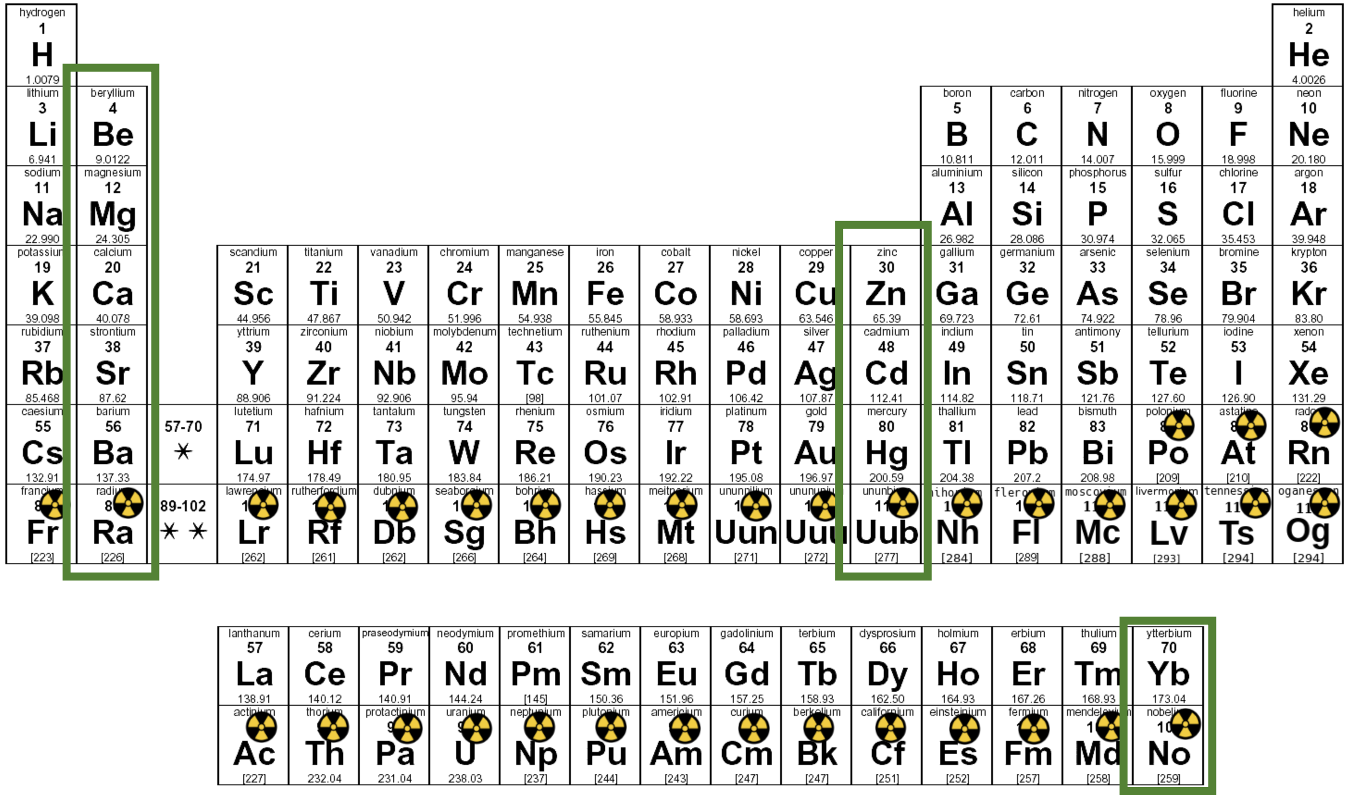
Desiderata:

- element that can be laser-cooled & trapped
  - could be atoms or ions (also HCIs)

- as many isotopes as possible
  - stable
  - large spread of neutron numbers

- $I = 0$ to steer clear of hyperfine structure

- as many optical transitions as possible
  - the narrower, the better
  - connecting different orbitals



→ **Ca, Ba, Zn, Cd, Hg, & Yb**

Isotope shift spectroscopy

$$\underbrace{\tilde{\nu}_{\beta ji} = F_{\beta\alpha}\,\tilde{\nu}_{\alpha ji}}_{\text{linear}} + \underbrace{K_{\beta\alpha}}_{\text{offset}} + \underbrace{G_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2}_{\text{nonlinear / quadratic}} + \underbrace{\upsilon_{ne}\,D_{\beta\alpha}\,\tilde{a}_{ji}}_{\text{nonlinear}}$$

field shift | *mass shift* | *second-order field shift* | *New Boson*

linear | offset | **nonlinear / quadratic** | **nonlinear**

Checklist:

- N isotopes (at least 4)
- N-1 differences between isotopes (at least 3)
- N-2 optical transitions (at least 2 for a 2D King plot)
- 1 „DOF“ used up for the mass shift („mass of nucleus“)
- 1 „DOF“ used up for the field shift („size of nucleus“)

-> 1 „DOF“ left for nonlinear terms

Isotope shift spectroscopy

$$\underbrace{\tilde{\nu}_{\beta ji} = F_{\beta\alpha}\,\tilde{\nu}_{\alpha ji}}_{\text{linear}} + \underbrace{K_{\beta\alpha}}_{\text{offset}} + \underbrace{G_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2}_{\text{nonlinear / quadratic}} + \underbrace{v_{ne}\,D_{\beta\alpha}\,\tilde{a}_{ji}}_{\text{nonlinear}}$$

field shift | *mass shift* | *second-order field shift* | *New Boson*

linear | offset | **nonlinear / quadratic** | **nonlinear**

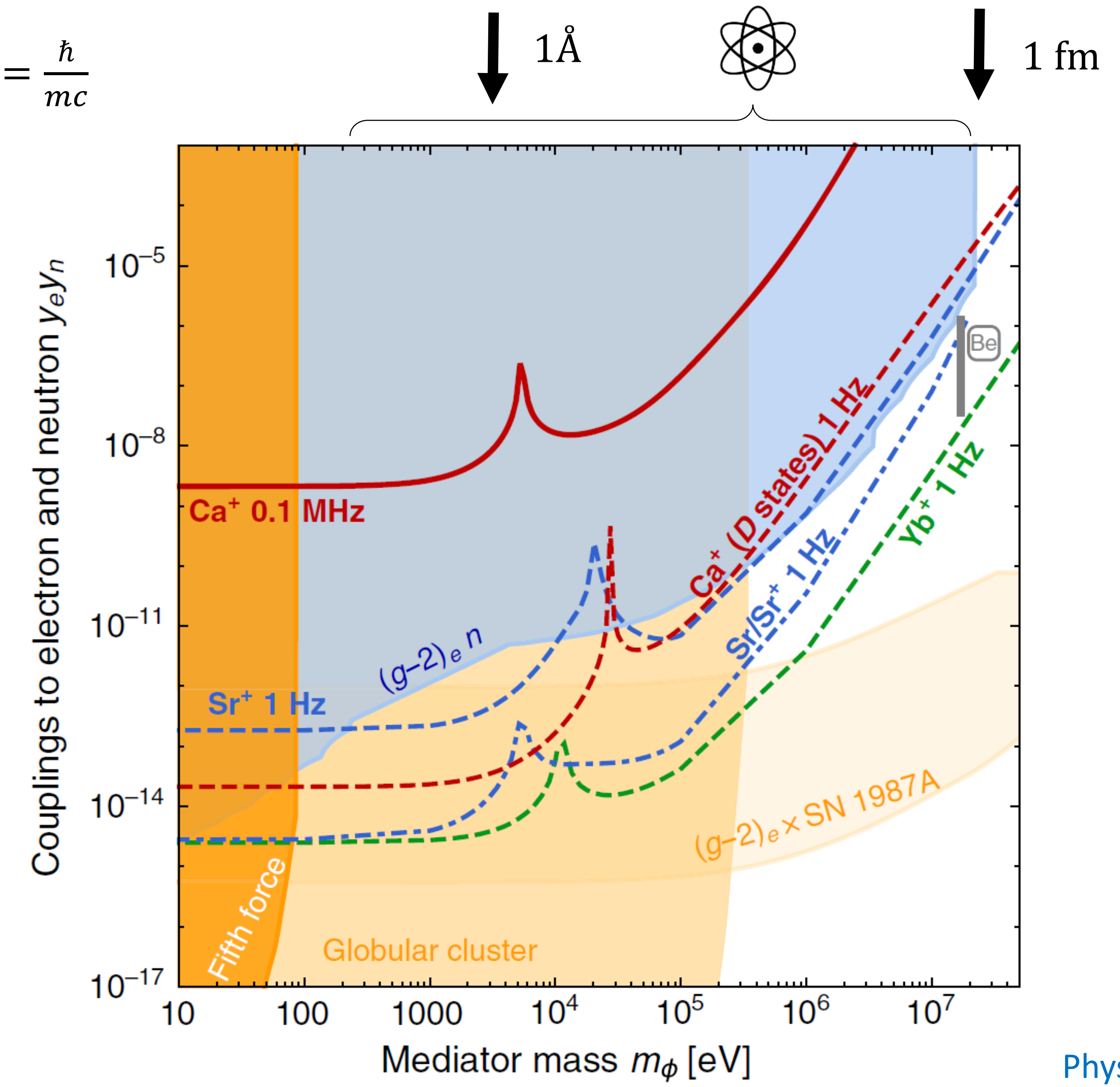
Checklist:

- N isotopes (at least 5)
- N-1 differences between isotopes (at least 4)
- N-2 optical transitions (at least 3 for a 3D King plot)
- 1 „DOF“ used up for the mass shift („mass of nucleus“)
- 1 „DOF“ used up for the field shift („size of nucleus“)
- 1 „DOF“ used up for the second-order field shift

-> 1 „DOF“ left for nonlinear terms

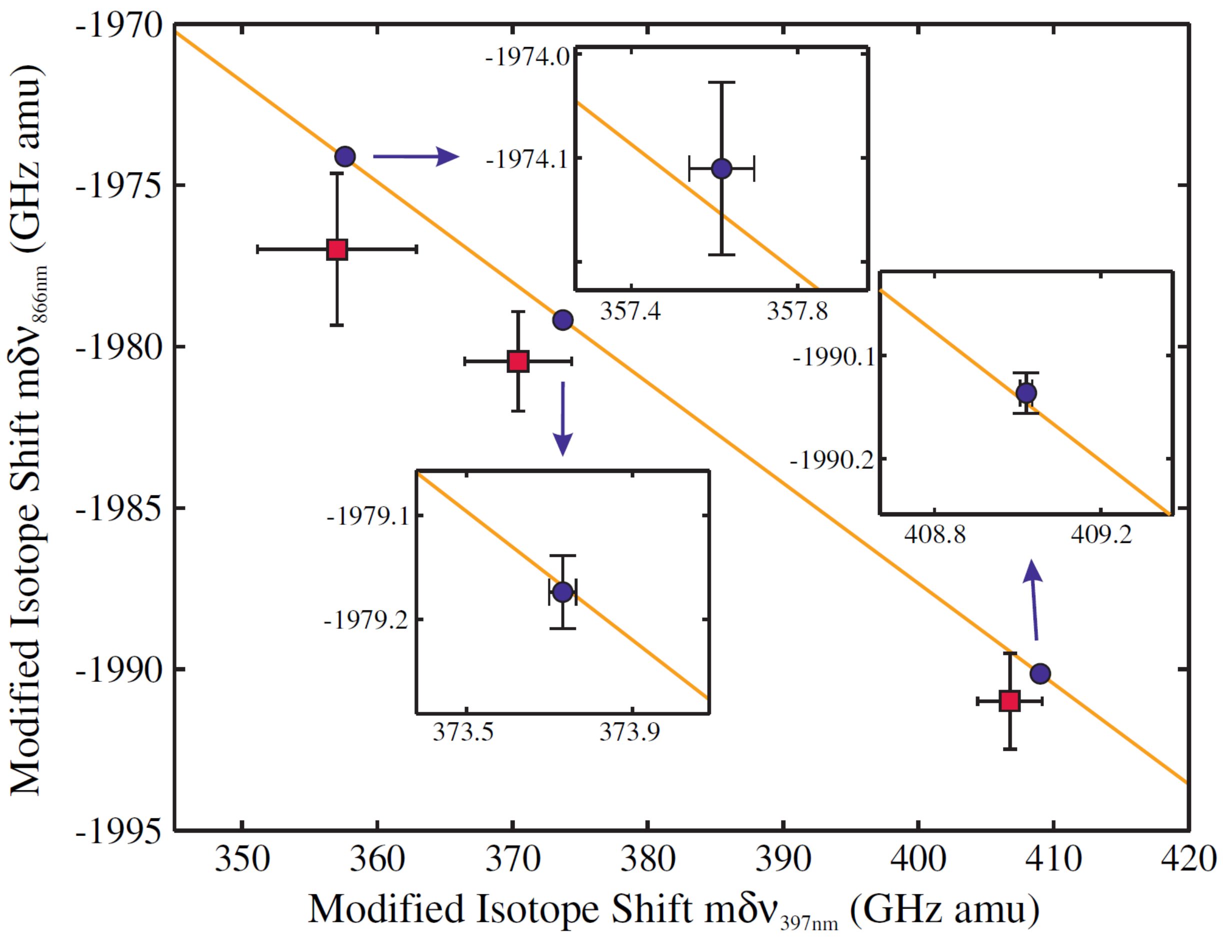
Isotope shift spectroscopy

range: $R = \frac{\hbar}{mc}$

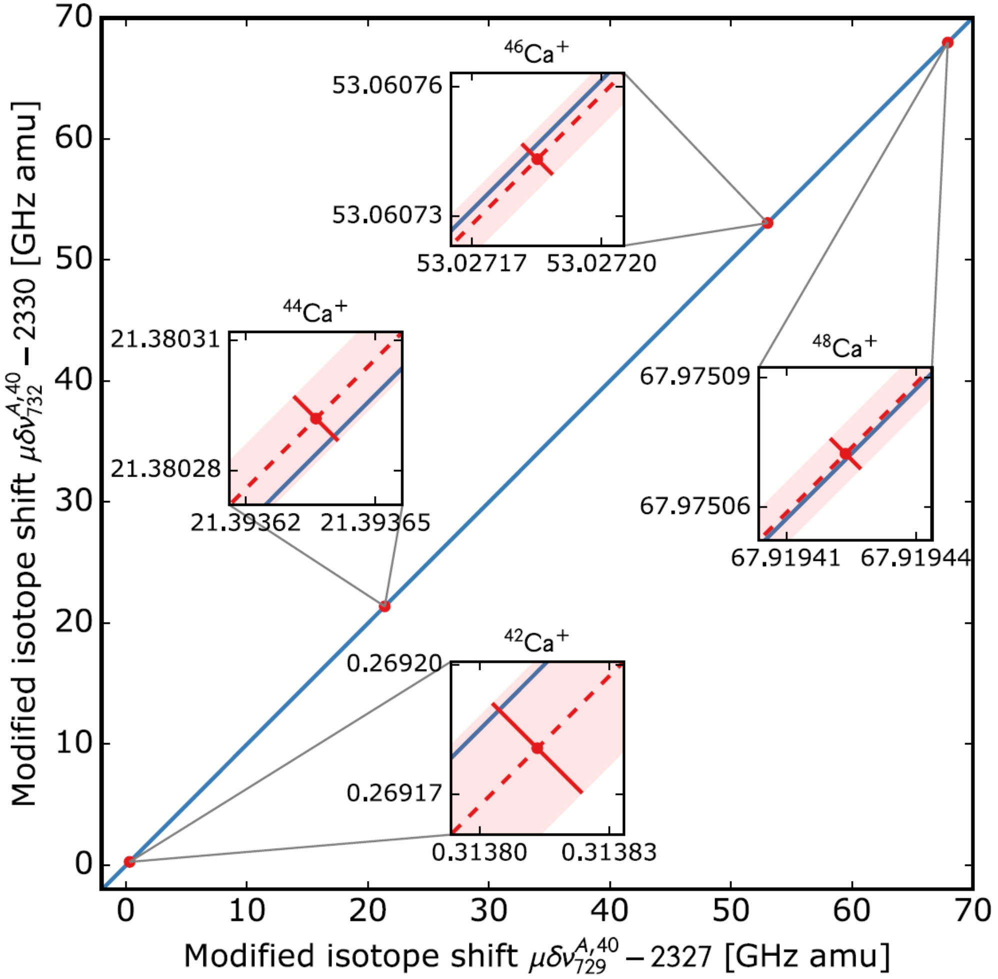


Phys. Rev. Lett. **120**, 091801 (2018)

Isotope shift spectroscopy: Calcium

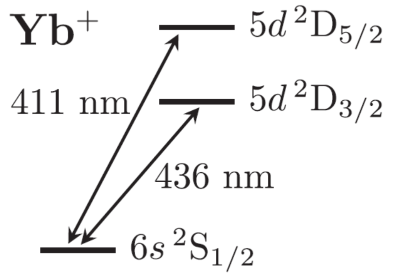


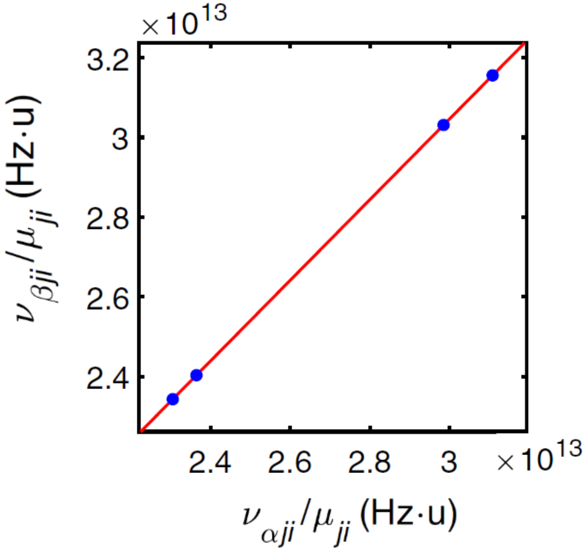
Phys. Rev. Lett. **115**, 053003 (2015)

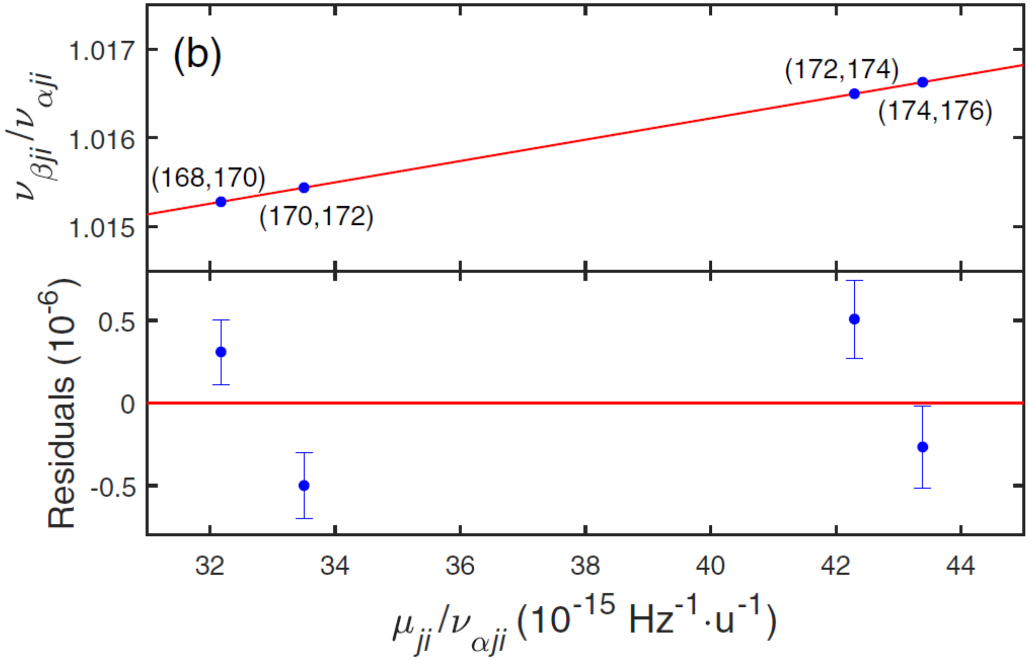


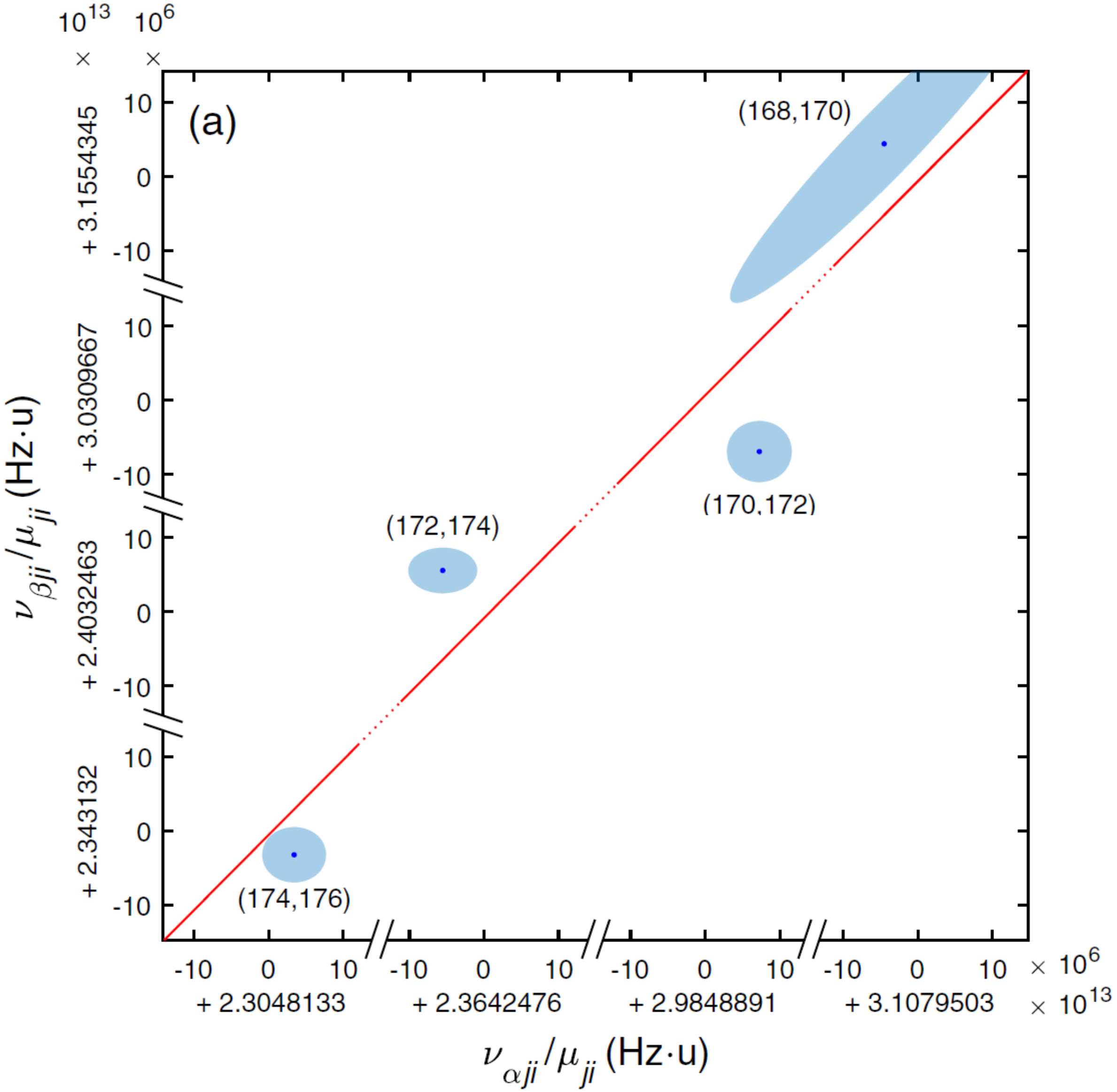
Phys. Rev. Lett. **125**, 123003 (2020)

Isotope shift spectroscopy: Ytterbium









Phys. Rev. Lett. **125**, 123002 (2020)
+ more recent work at MIT, PTB, Mainz…

Isotope shift spectroscopy: Ytterbium

PHYSICAL REVIEW LETTERS **125**, 123002 (2020)

Editors' Suggestion

Evidence of Two-Sou…

Precision determination of isotope shifts in ytterbium and implications for new physics

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[1] *Johannes Gutenberg-Universität Mainz, Helmholtz-Institut Mainz, GSI Helmholtzzentrum für Schwerionenforschung, 55128 Mainz, Germany*

[2] *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia*

(Dated: February 1, 2022)

We report measurements of isotope shifts for the five spinless Yb isotopes on the $6s^2\,{}^1S_0 \to 5d6s\,{}^1D_2$ transition using Doppler-free two-photon spectroscopy. We combine these data with existing measurements on two transitions in Yb^+ [Phys. Rev. Lett. 125, 123002 (2020)], where deviation from King-plot linearity showed hints of a new bosonic force carrier at the 3σ level. The combined data strongly reduces the significance of the new-physics signal. We show that the observed nonlinearity in the joint Yb/Yb^+ King-plot analysis can be accounted for by the deformation of the Yb nuclei.

Isotope shift spectroscopy: Ytterbium

quadrupole deformations

$$+ G'_{\beta\alpha}\delta\langle r^4\rangle_{ji} + \dots$$

$$\tilde{\nu}_{\beta ji} = \underbrace{F_{\beta\alpha}\,\tilde{\nu}_{\alpha ji}}_{\text{linear}} + \underbrace{K_{\beta\alpha}}_{\text{offset}} + \underbrace{G_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2}_{\textbf{nonlinear / quadratic}} + \underbrace{\upsilon_{ne}\, D_{\beta\alpha}\,\tilde{a}_{ji}}_{\textbf{nonlinear}}$$

field shift

mass shift

second-order field shift

New Boson

linear

offset

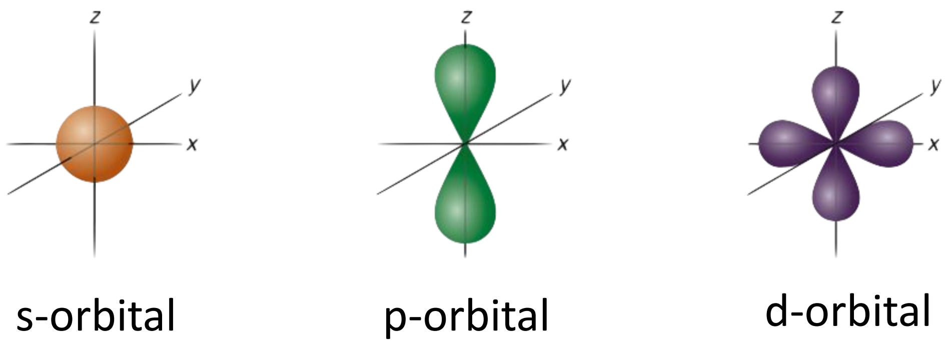
nonlinear / quadratic

nonlinear

Isotope shift spectroscopy: Mercury

Now what?

(1) Move away from s-orbitals



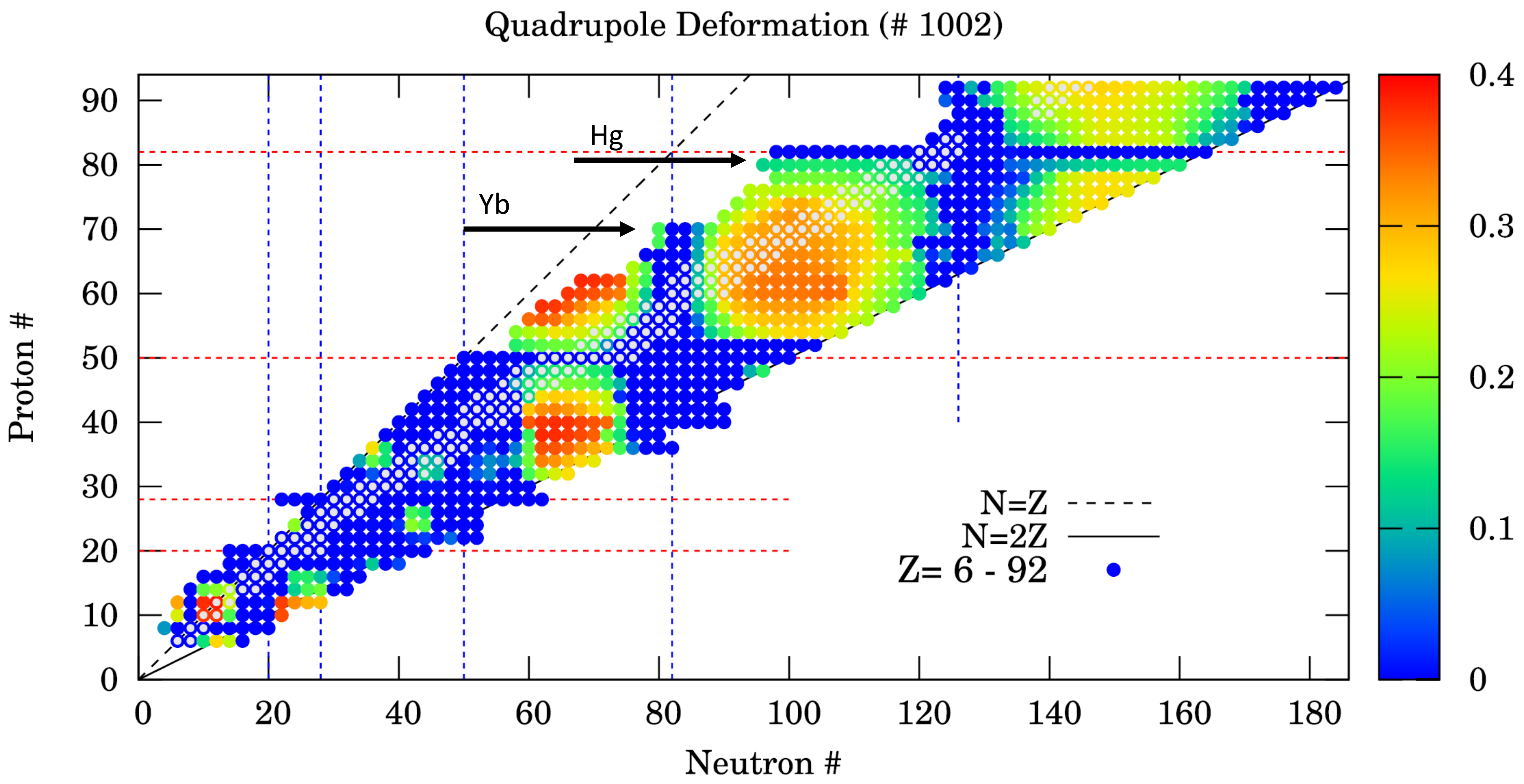
Suppression of field shift for non-*s* states in relativistic atoms:

$$\frac{(Z\alpha)^2}{3} \approx \frac{1}{10} \qquad \text{for mercury}$$

$$\frac{(Z\alpha)^2}{3} \approx \frac{1}{140} \qquad \text{for calcium}$$

(2) Search for nuclei with less quadrupole deformations

Isotope shift spectroscopy: Mercury

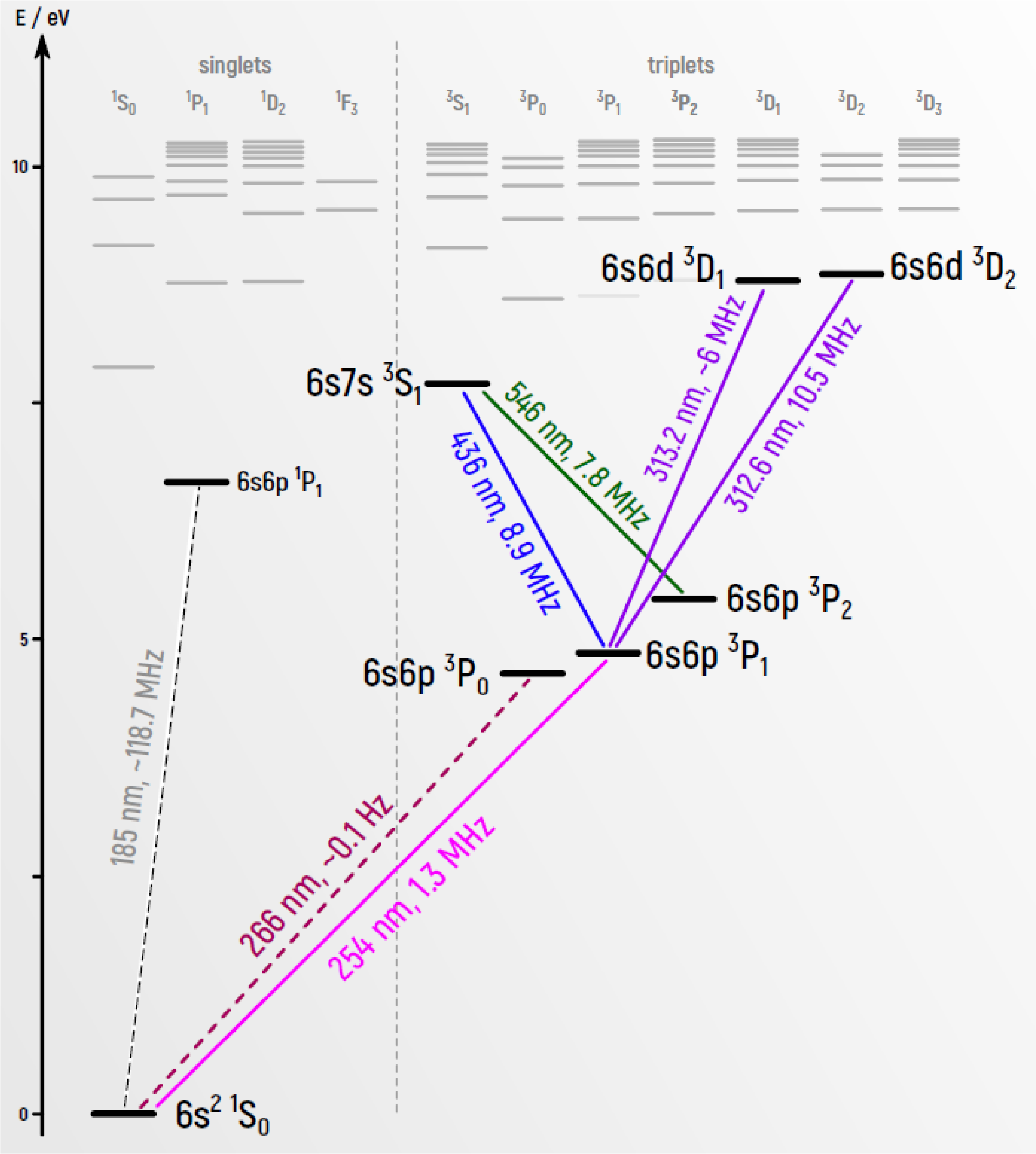


Phys. Scr. **92**, 04005 (2017)

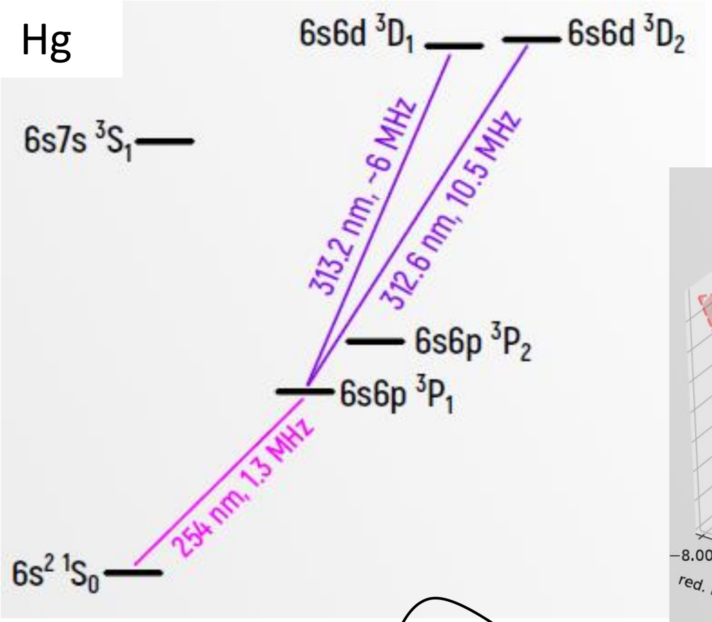
Isotope shift spectroscopy: Mercury

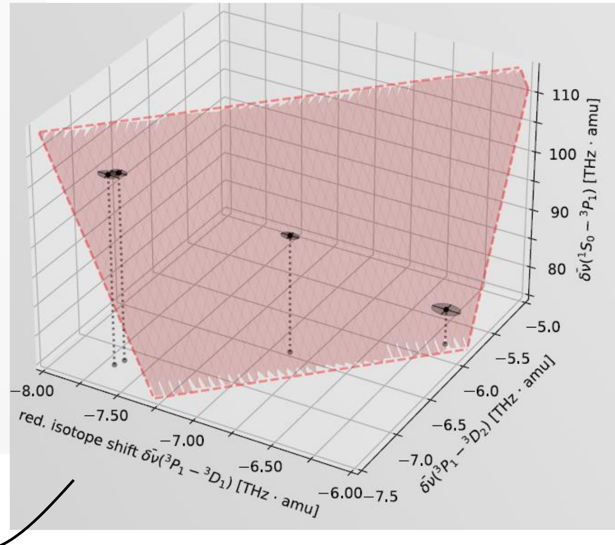
Mercury:

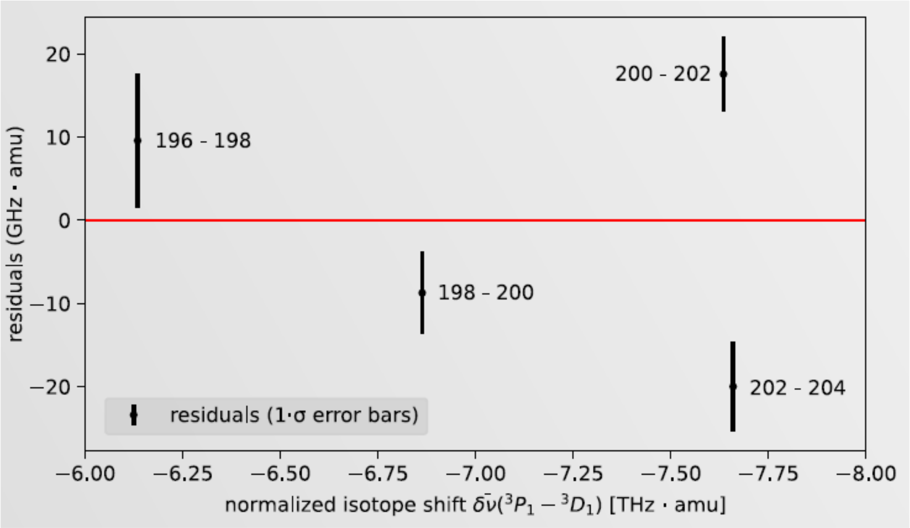
- 5 suitable isotopes
- Lots of transitions
- **Less quadrupole deformations than Yb**



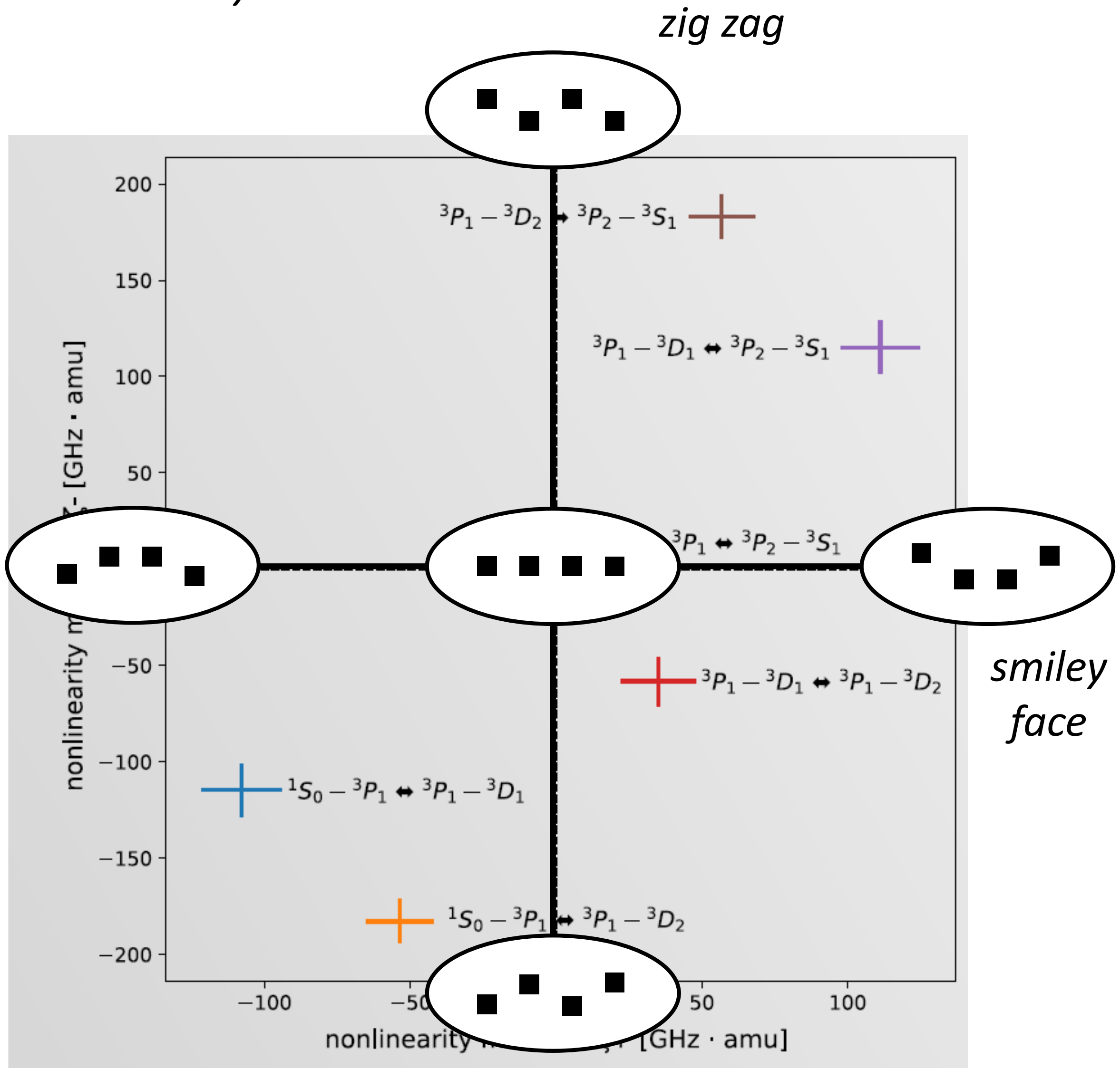
Isotope shift spectroscopy: Mercury



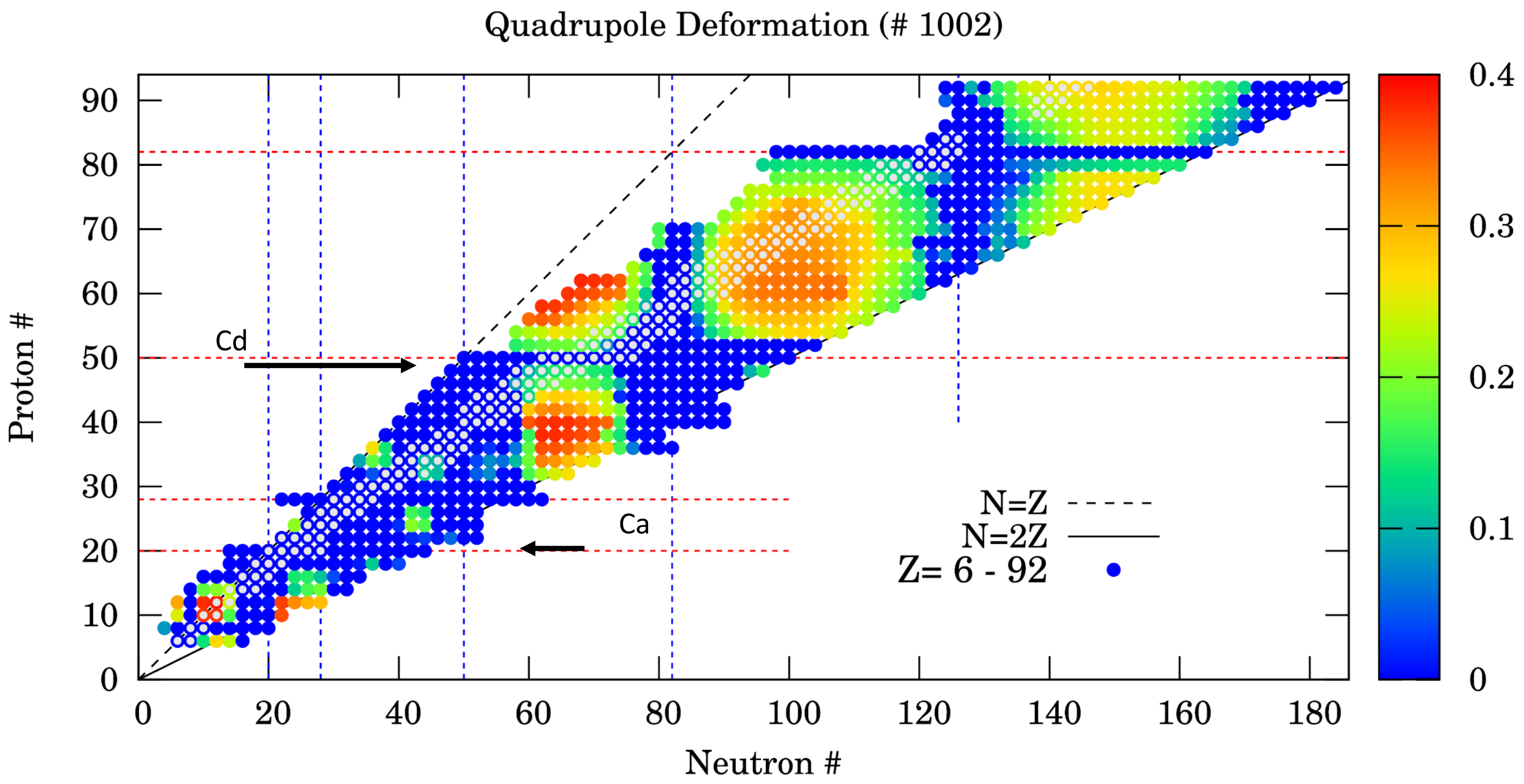




Nonlinearity measure:



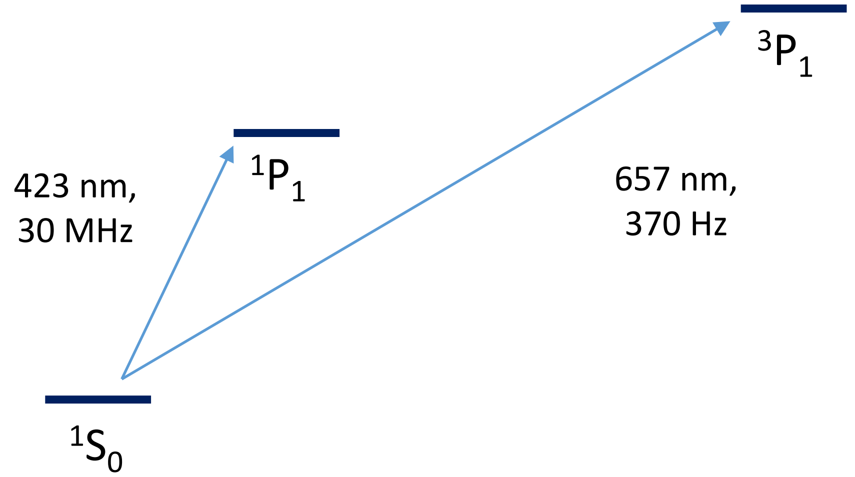
Isotope shift spectroscopy



Isotope shift spectroscopy: back to Calcium

Calcium:

- 5 stable bosonic isotopes
- nuclear shell closures at $N = 20$ and $N = 28$
- lots of very narrow transitions
- Compare with Ca^+ ions and HCI
- masses have been measured (last week!)



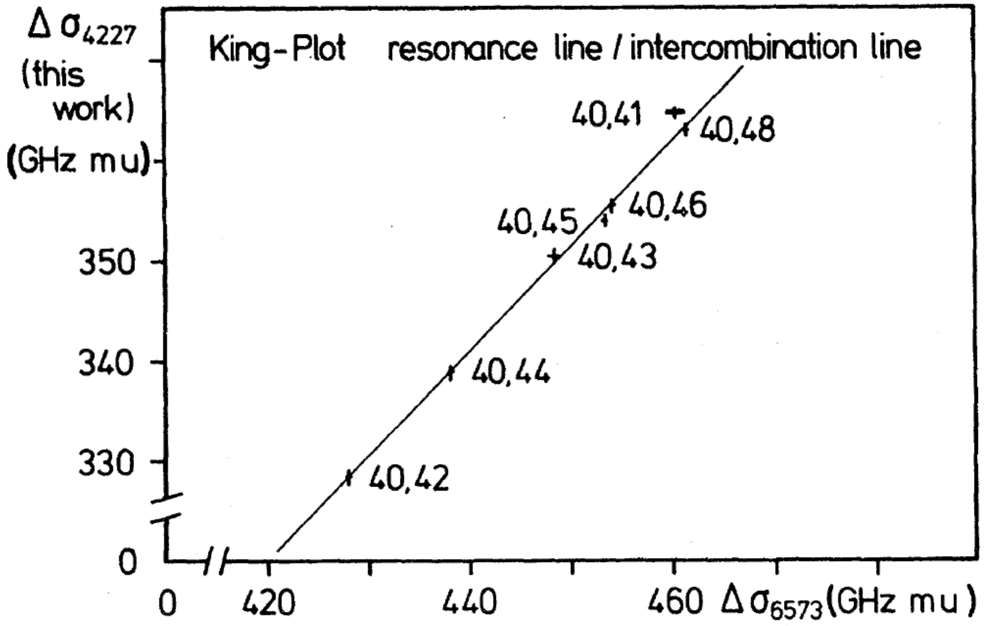
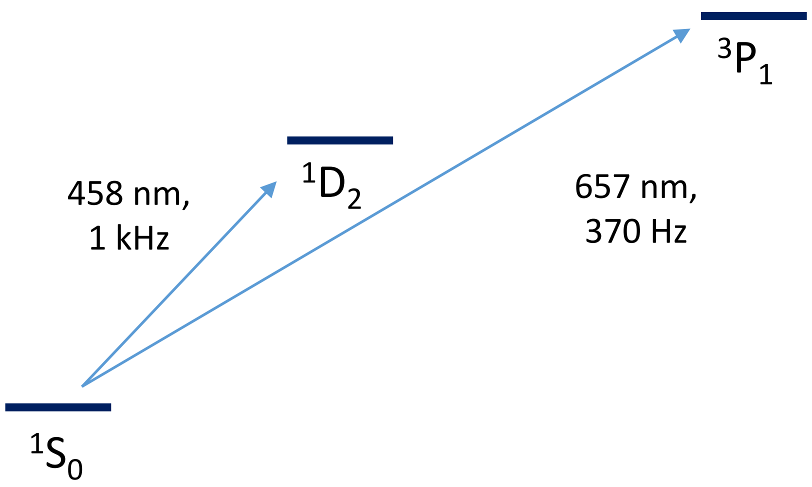


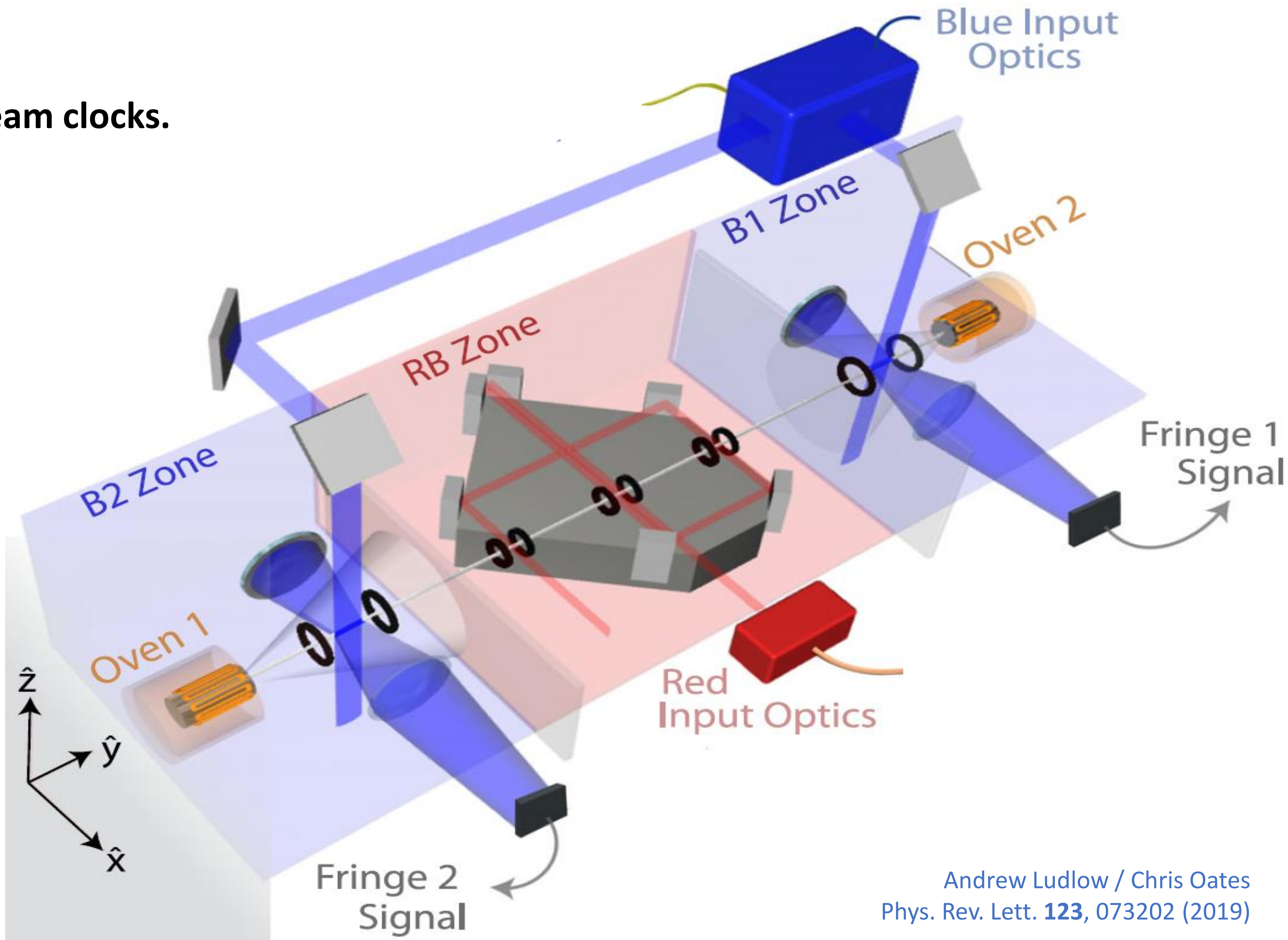
FIG. 2. King diagram with the isotope shifts of the CaI intercombination line $^1S_0$-$^3P_1$ ($\Delta\sigma = A'A/(A'-A) \times \delta\nu$).

Phys. Rev. C **26**, 2194 (1982)

Isotope shift spectroscopy: back to Calcium

A new approach:
simultaneous operation of two calcium beam clocks.



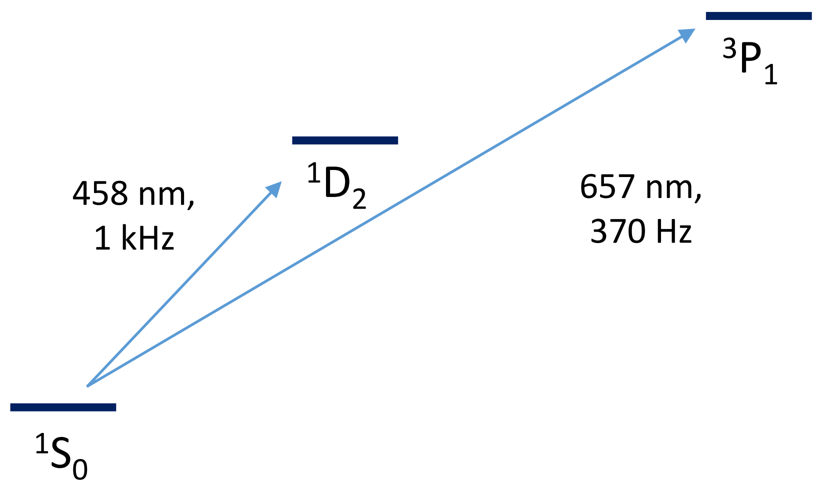


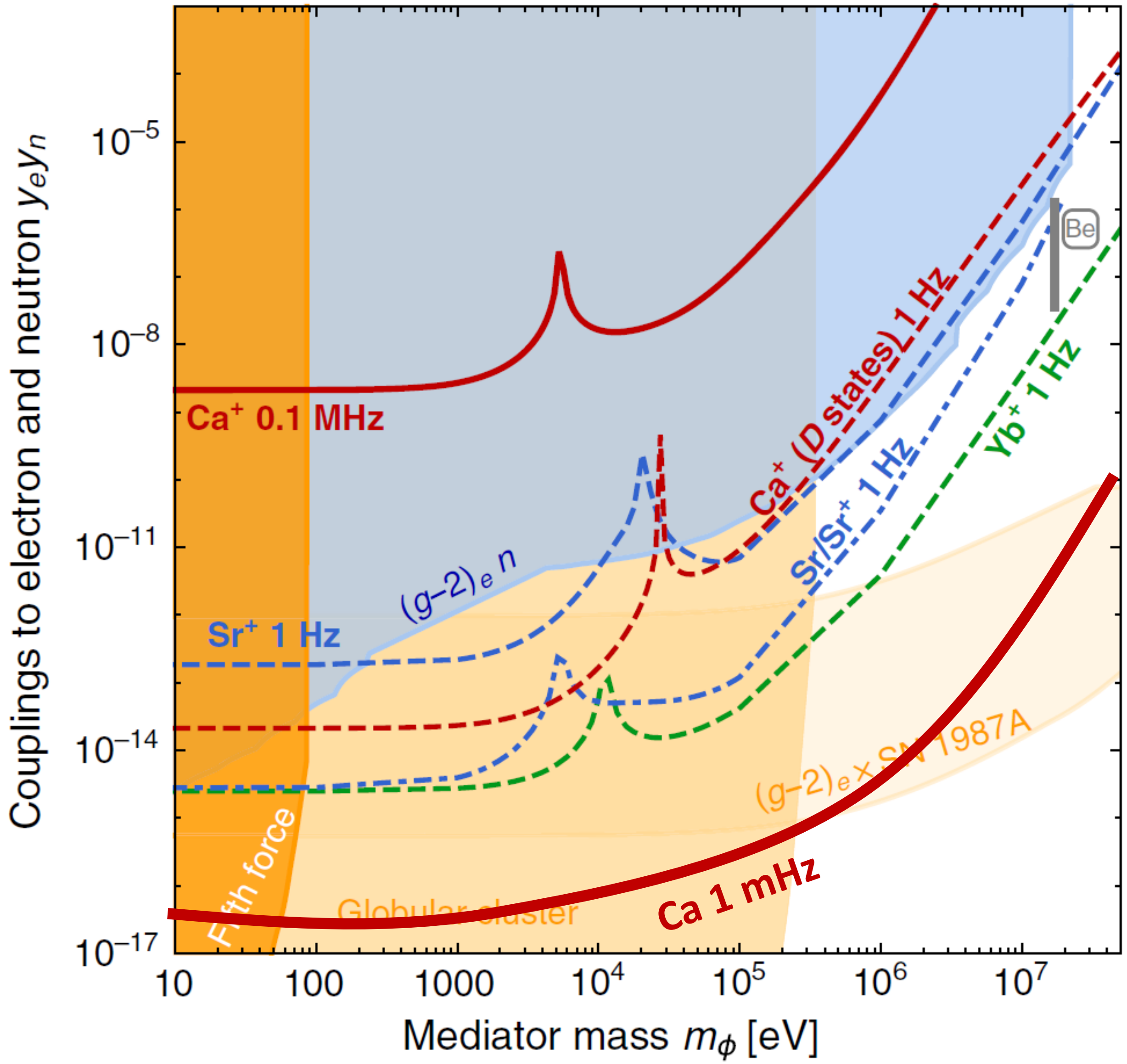
Andrew Ludlow / Chris Oates
Phys. Rev. Lett. **123**, 073202 (2019)

Isotope shift spectroscopy: back to Calcium

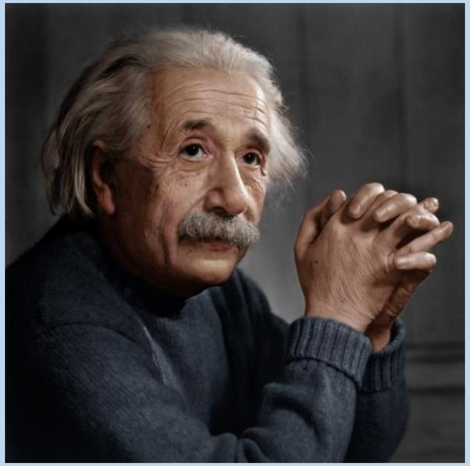
A new approach:
simultaneous operation of two calcium beam clocks.

- target instability: 10^{-16}
- target sensitivity: mHz range



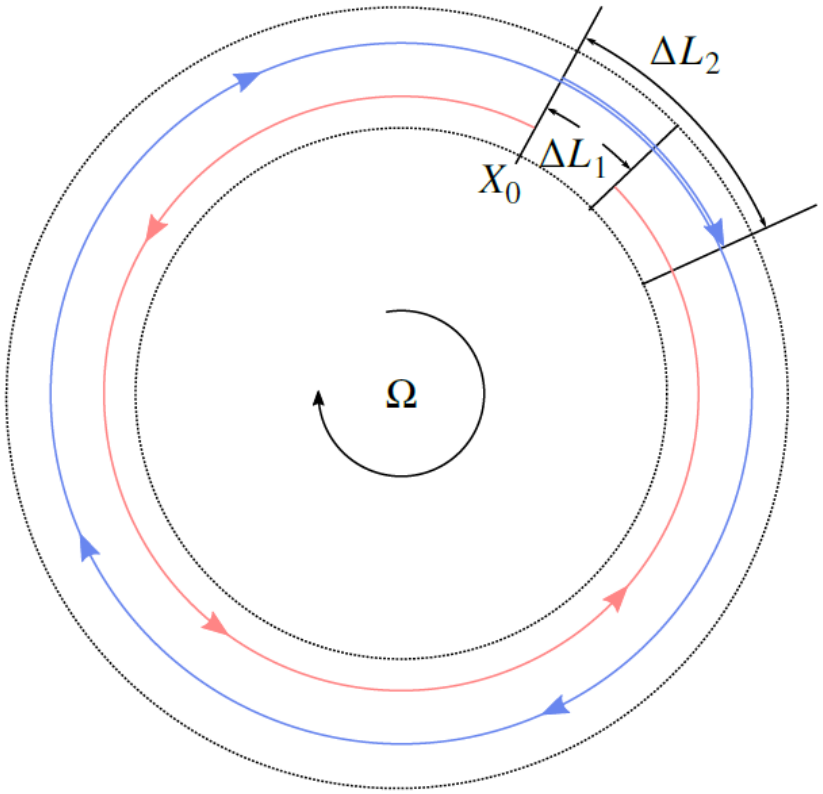


Test of special relativity



images: wikipedia

The Sagnac effect

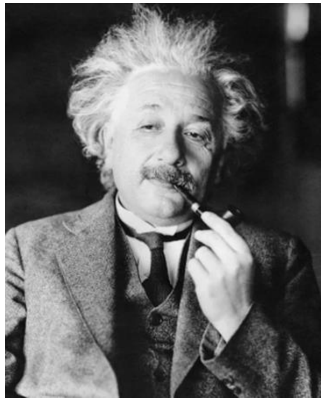


$$
\begin{aligned}
\Delta\tau &= \tau_1 - \tau_2 \\
&= \frac{4\pi R^2\Omega}{c^2 - (\Omega R)^2} \\
&= \frac{4\pi R^2\Omega}{c^2}\sum_{k=0}^{\infty}\left(\frac{\Omega R}{c}\right)^{2k} \\
&= \frac{4\pi R^2\Omega}{c^2}\left(1 + \left(\frac{\Omega R}{c}\right)^2 + O\left(\left(\frac{\Omega R}{c}\right)^4\right)\right)
\end{aligned}
$$

(1) For small rotation rates:

$$\Delta\tau = \frac{4A\Omega}{c^2}$$

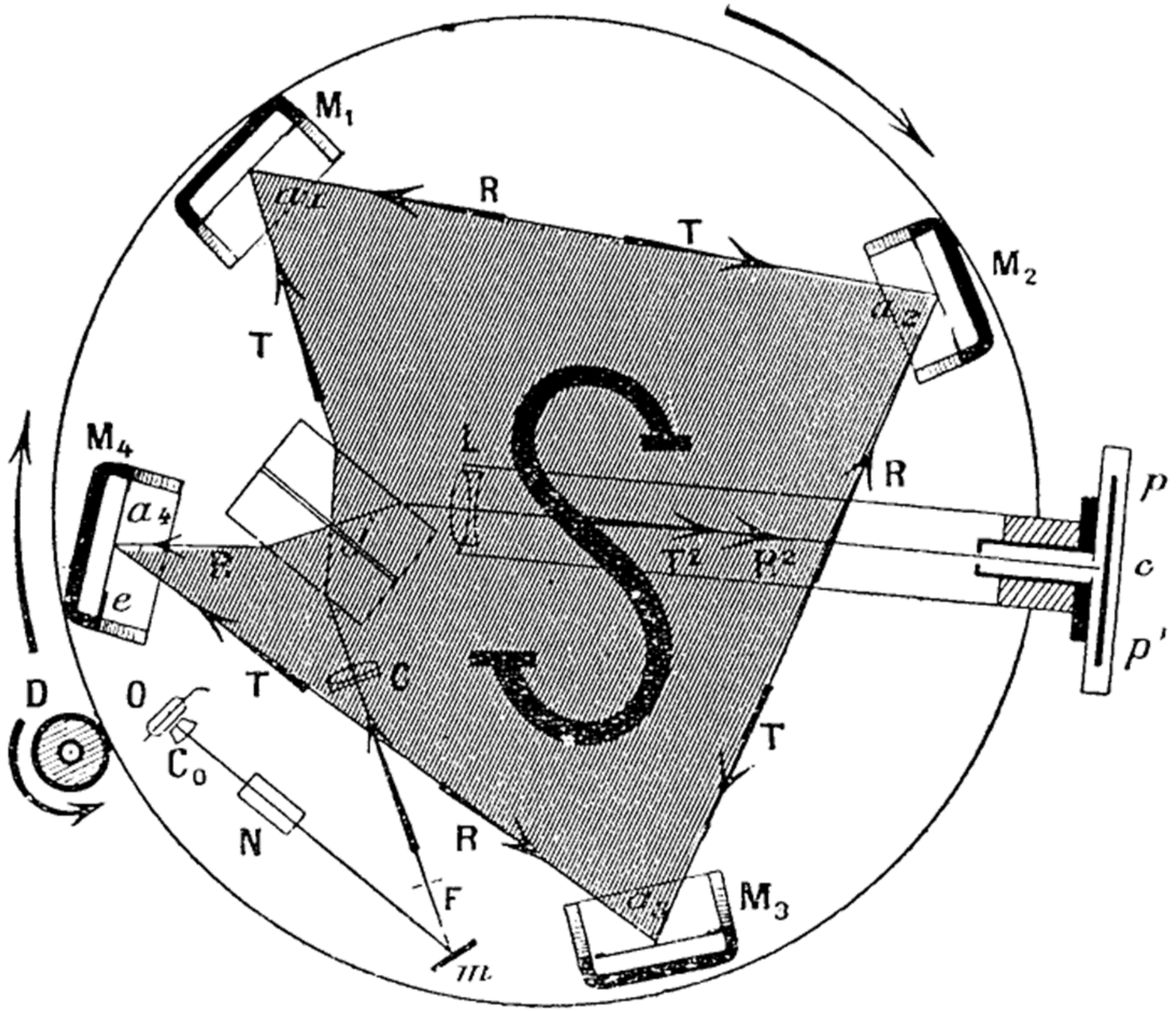
The Sagnac effect (1913)



Albert Einstein

Max von Laue

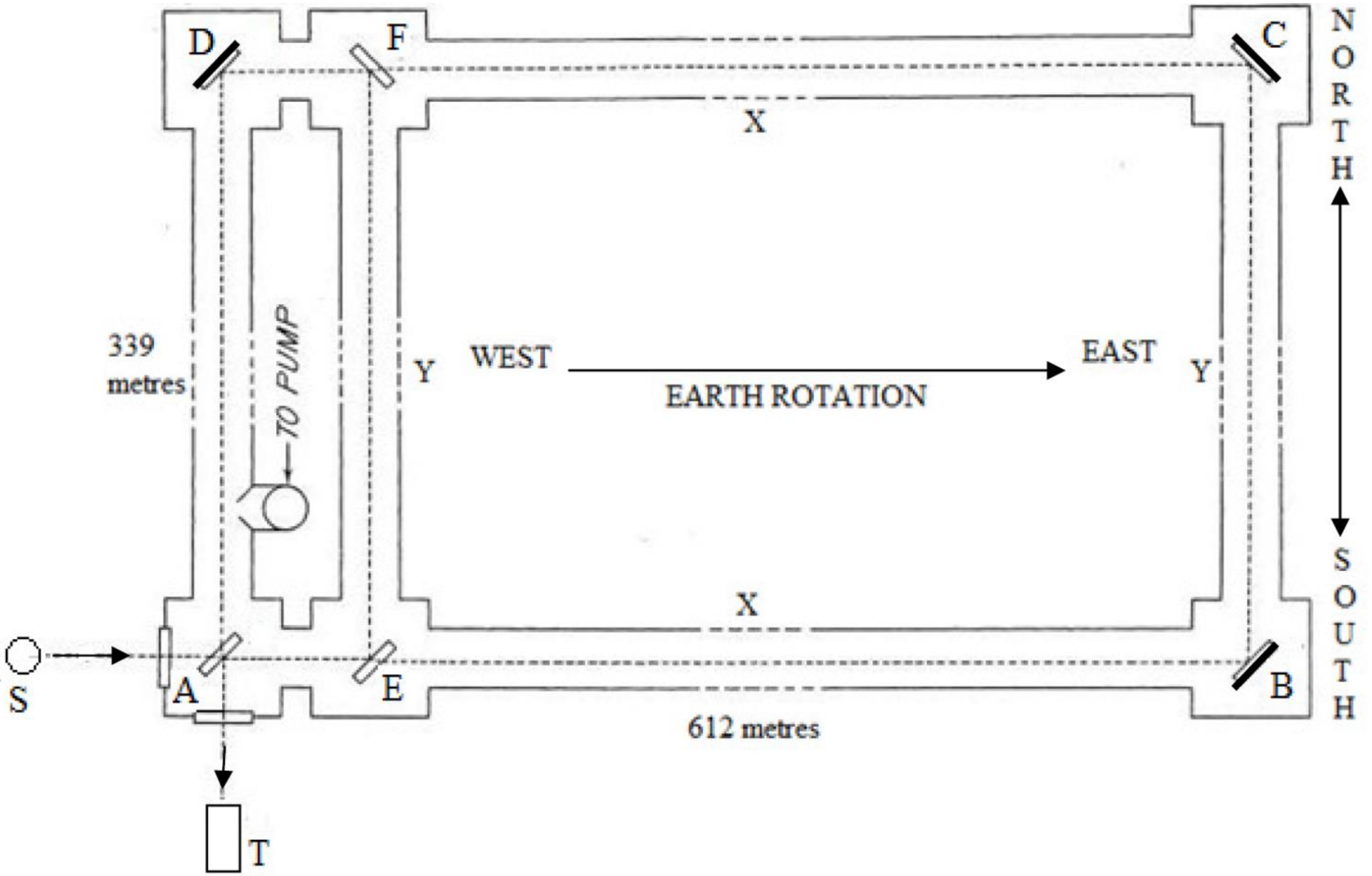
George Sagnac



The Michelson-Gale experiment (1925)

Albert A. Michelson

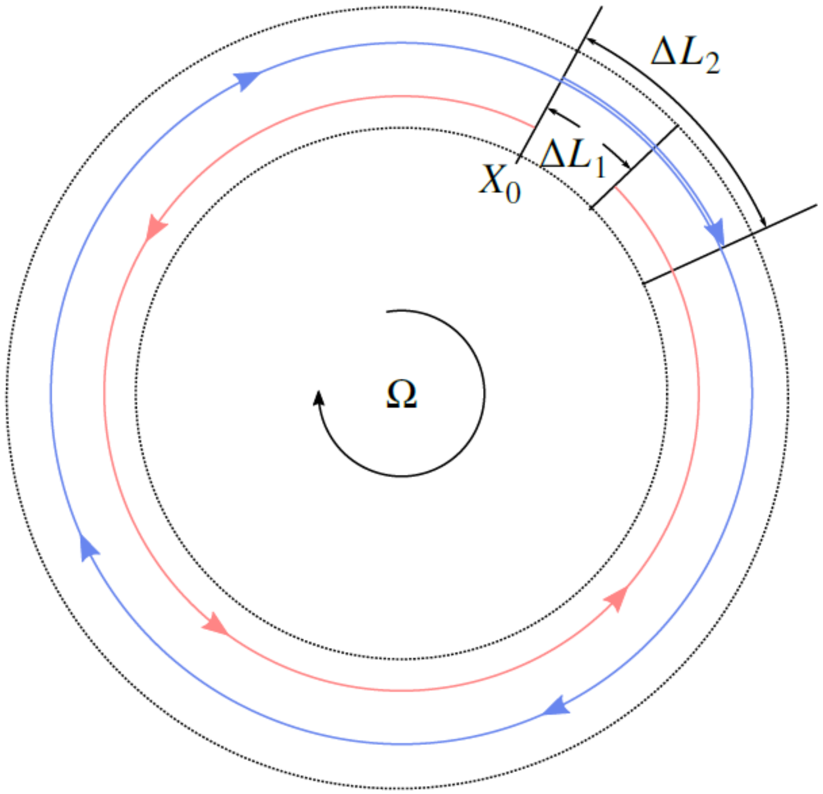
Henry G. Gale



calculated shift: 0.237 periods
measured shift: 0.230(5) periods

-> Earth is rotating! (*Cheers to Foucault (1851)!)*
-> First time that Sagnac is used for Earth rotation

The Sagnac effect



$$\begin{aligned}\Delta\tau &= \tau_1 - \tau_2 \\ &= \frac{4\pi R^2\Omega}{c^2 - (\Omega R)^2} \\ &= \frac{4\pi R^2\Omega}{c^2}\sum_{k=0}^{\infty}\left(\frac{\Omega R}{c}\right)^{2k} \\ &= \frac{4\pi R^2\Omega}{c^2}\left(1 + \left(\frac{\Omega R}{c}\right)^2 + O\left(\left(\frac{\Omega R}{c}\right)^4\right)\right)\end{aligned}$$

(1) For small rotation rates:

$$\Delta\tau = \frac{4}{c^2}\vec{A}\,\vec{\Omega}$$

(2) From phase to frequency:

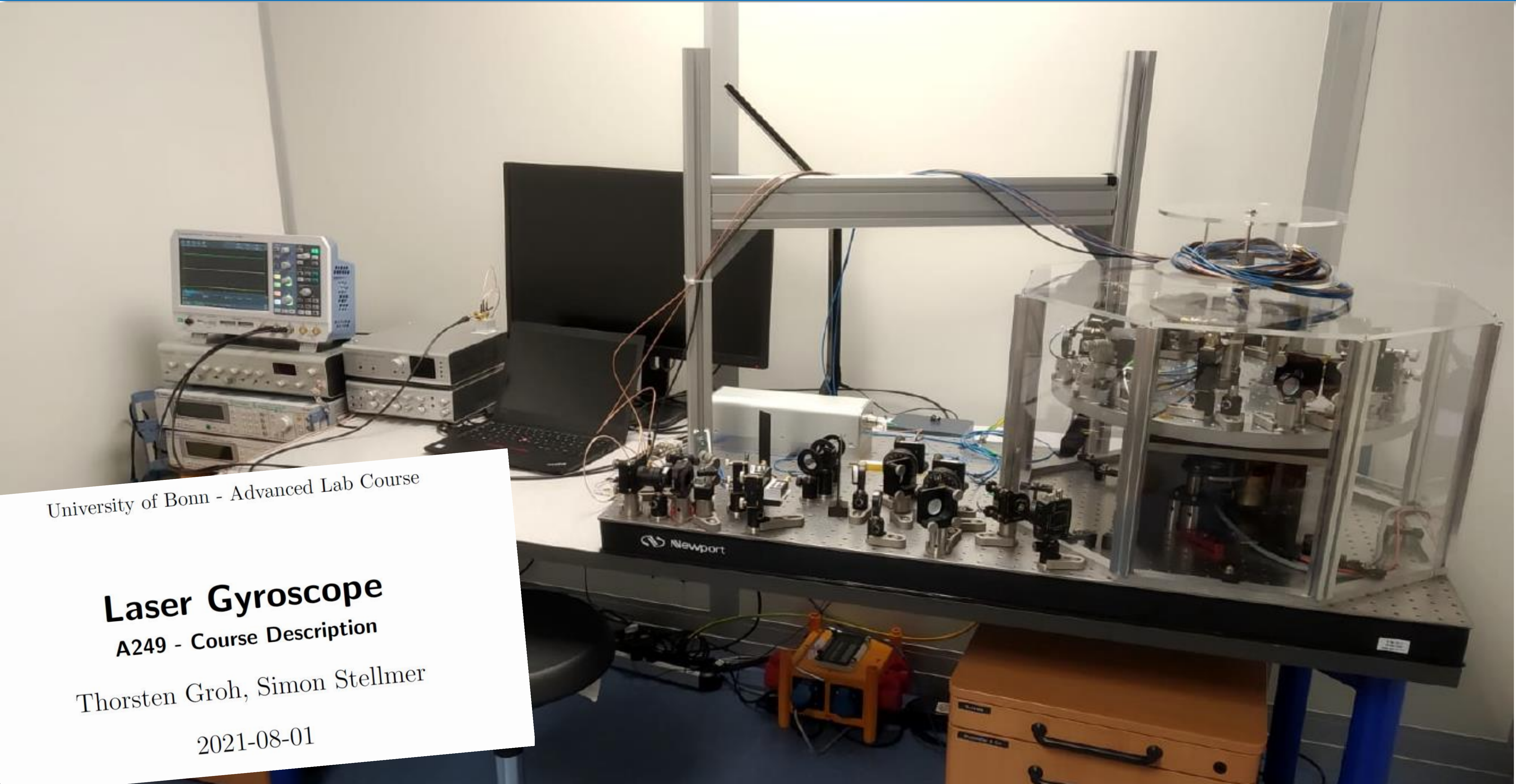
$$f_{Sagnac} = \frac{4}{\lambda\, S}\vec{A}\,\vec{\Omega}$$

(3) Consider a square of arm length L:

$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega\,\sin\theta$$

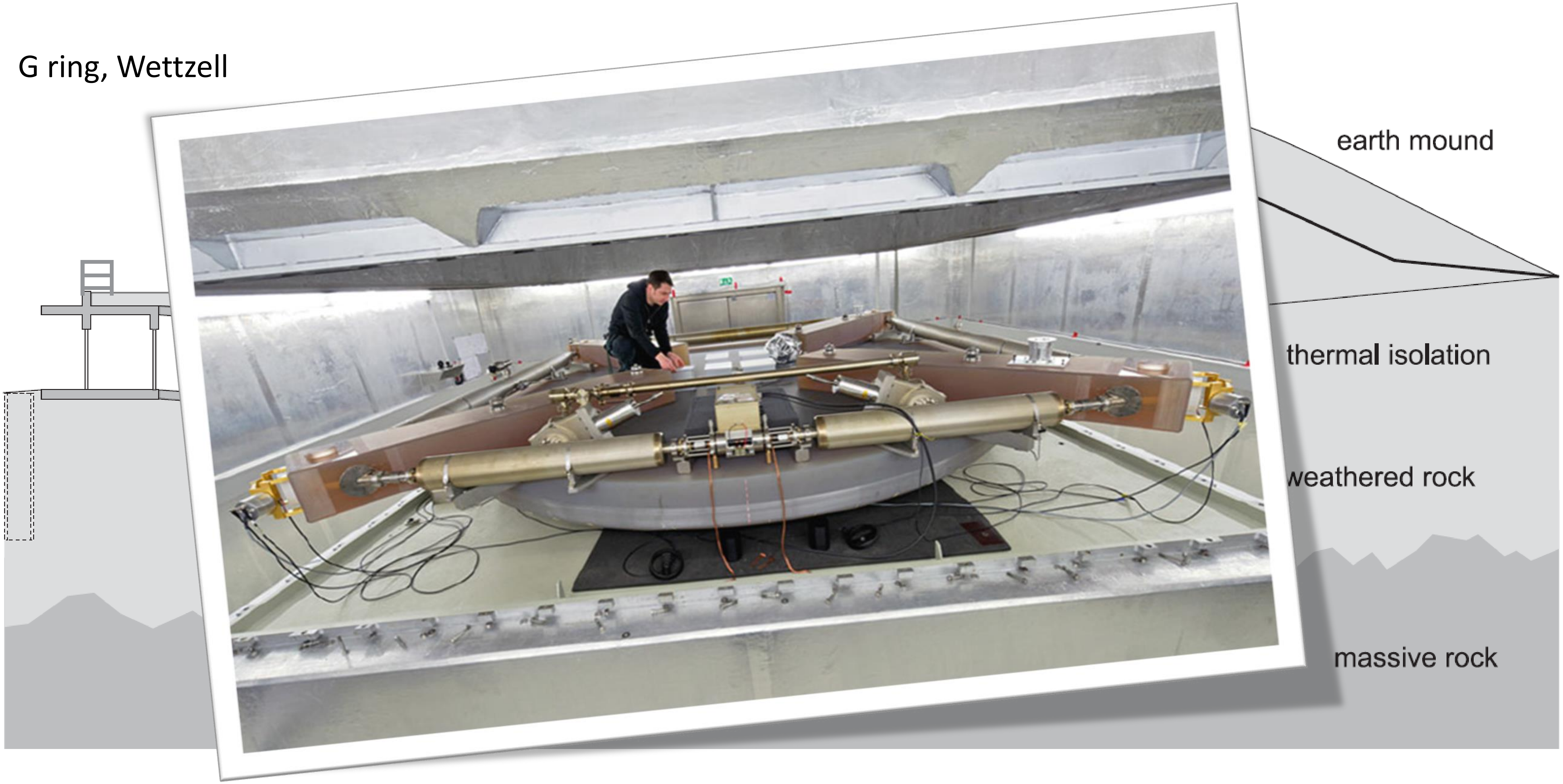
„scale factor" $\in \mathbb{N},\ \mathcal{O}\,(10^7)$

The Sagnac effect



The G Ring at Wettzell

G ring, Wettzell

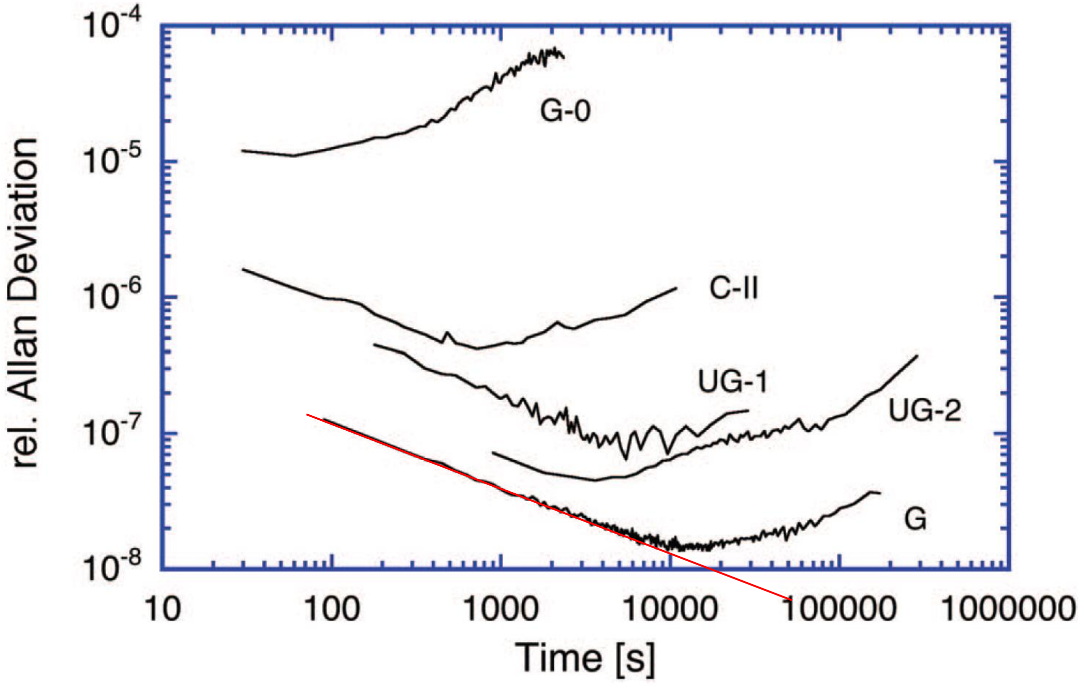


The G Ring at Wettzell

Sensitivity:

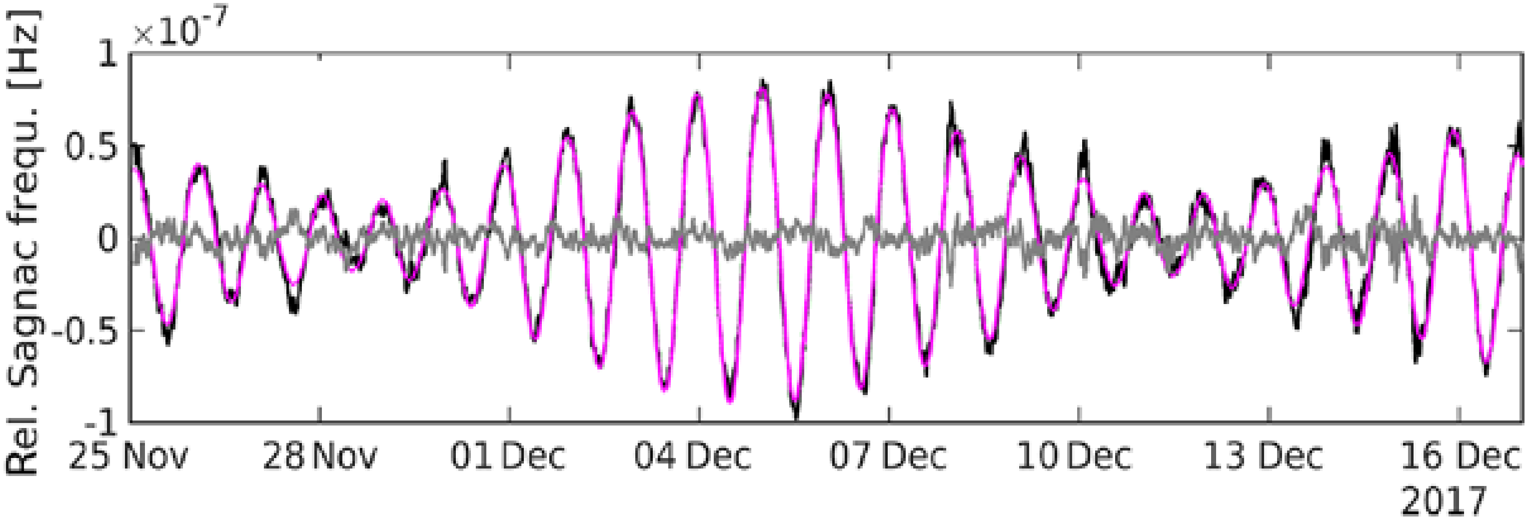
$$\delta\Omega = \frac{1}{4}\frac{c\lambda}{L^2\,F}\sqrt{\frac{h\nu}{P}\,\frac{1}{\tau}}$$

G ring (Wettzell): $\delta\Omega = 12\ \mathrm{prad/s/\sqrt{Hz}}$



Take-home message:
10^{-8} within 3 hours

Earth rotation…
tidal effects !



sub-diurnal
variations !

Test of special relativity

$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega_E\,\sin\theta$$

Test of special relativity

Sagnac frequency:
Our observable, at the 10^{-9} level

$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega_E\,\sin\theta$$

Test of special relativity

Sagnac frequency:
Our observable, at the 10^{-9} level

Earth rotation rate

$$f_{Sagnac} = \frac{L}{\lambda}\, \Omega_E \, \sin\theta$$

IERS: International Earth Rotation Service (= astronomy)

The contributed observations used in the preparation of this Bulletin are available at <http://www.usno.navy.mil/USNO/earth-orientation/eo-info/general/input-data>. The contributed analysis results are based on data from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), the Global Positioning System (GPS) satellites, Lunar Laser Ranging (LLR), and meteorological predictions of variations in Atmospheric Angular Momentum (AAM).

COMBINED EARTH ORIENTATION PARAMETERS:

IERS Rapid Service

	MJD	x	error	y	error	UT1-UTC	error
		"	"	"	"	s	s
22 10 14	59866	0.25701	.00009	0.23208	.00009	-0.005444	0.000014
22 10 15	59867	0.25408	.00009	0.23040	.00009	-0.005177	0.000013
22 10 16	59868	0.25116	.00009	0.22886	.00009	-0.004895	0.000014
22 10 17	59869	0.24810	.00009	0.22721	.00009	-0.004671	0.000016
22 10 18	59870	0.24528	.00009	0.22512	.00009	-0.004559	0.000016
22 10 19	59871	0.24299	.00009	0.22296	.00009	-0.004593	0.000017
22 10 20	59872	0.24079	.00009	0.22122	.00009	-0.004790	0.000019

Last week

Error on pole coordinates: 0.09 mas = 2.7 mm

Error in length-of-day: ~ 10 μs

10 μs / 24 hours = 10^{-12}

Test of special relativity

Sagnac frequency:
our observable, at the 10^{-9} level

Earth rotation rate:
from VLBI, at the 10^{-12} level

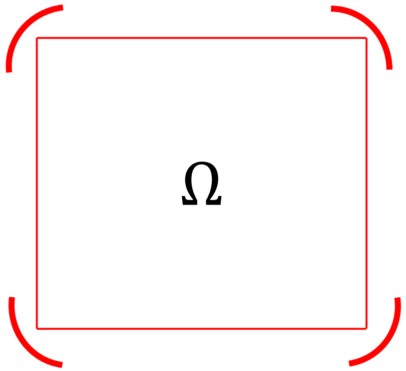
$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega_E\ \sin\theta$$

Scale factor

Test of special relativity

longitudinal mode
number N

$$\frac{L}{2\,\lambda} \cong N = \frac{f}{FSR}$$



Measured with a frequency comb:

$f = 473\,612\,701.08 \pm 0.15$ MHz

$FSR = 18.734\,385\,26 \pm 2$ MHz

$\rightarrow \; N = 25\,280\,397.23 \pm 0.28$

$\rightarrow \; P = 16.002\,252\,12$ m

$\cong$: see Applied Optics **56**, 1124 (2017)

Test of special relativity

Sagnac frequency:
our observable, at the 10^{-9} level

Earth rotation rate:
from VLBI, at the 10^{-12} level

$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega_E\,\sin\theta$$

Projection onto rotation axis

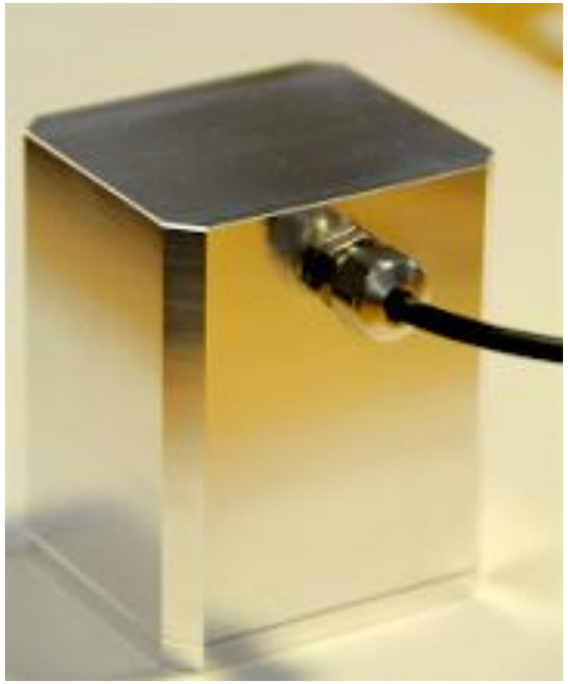
Scale factor:
integer number (25 280 397)

Test of special relativity

(1) Use IERS data to fix pole coordinates to within 0.1 mas (3 x 10^{-10})

(2) Use on-site VLBI, LL, SLR, GNSS etc. to determine G ring position (= latitude θ) to better than 10 cm (1 x 10^{-8})

(3) Use tiltmeters to level the ring laser at sub-nrad precision (< 10^{-9})



Tiltmeter

Space-geodetic techniques

Test of special relativity

Sagnac frequency:
our observable, at the 10^{-9} level

Earth rotation rate:
from VLBI, at the 10^{-12} level

$$f_{Sagnac} = \frac{L}{\lambda}\,\Omega_E\,\sin\theta$$

Scale factor:
integer number (25 280 397)

Projection onto rotation axis:
10^{-8} to 10^{-9} level

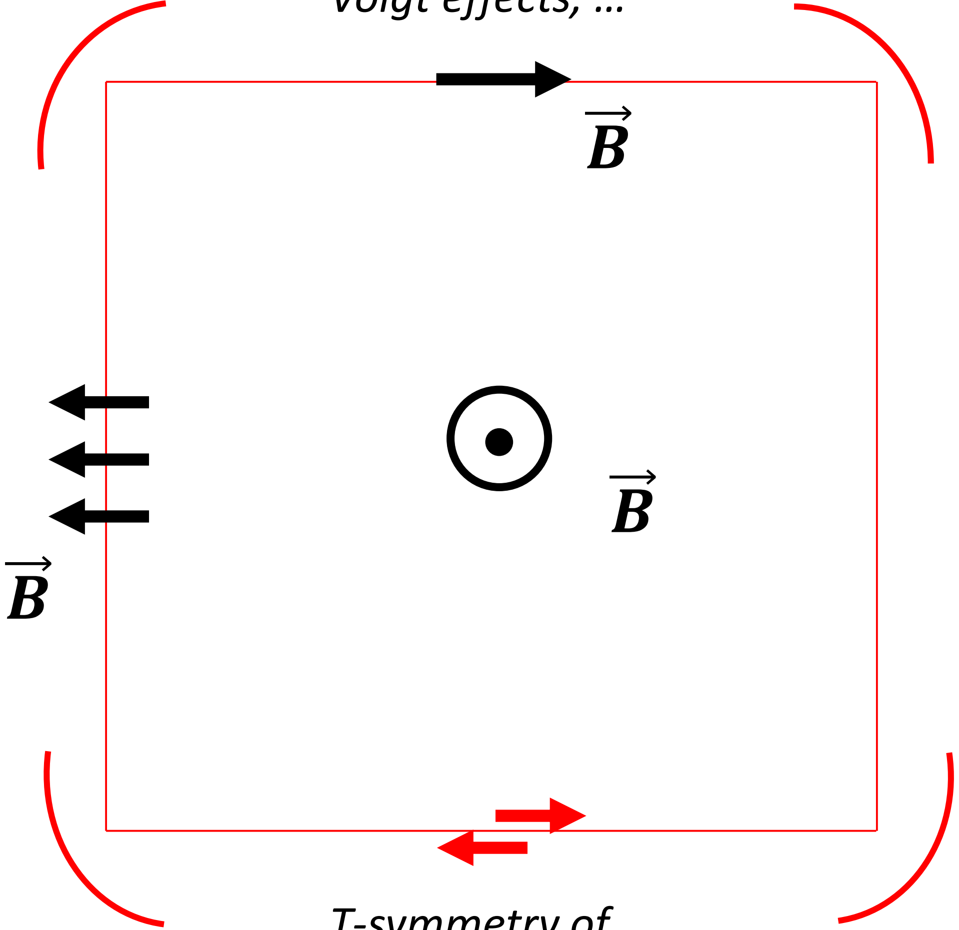
The GeoSensor

The GeoSensor

Magnetooptics

Faraday / Cotton-Mouton / Voigt effects, …

Birefringence of the vacuum

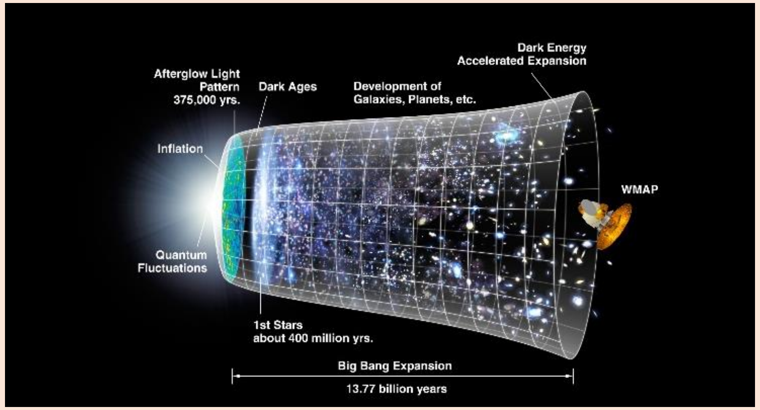


Aharonov-Bohm / Aharonov-Casher / Berry, …

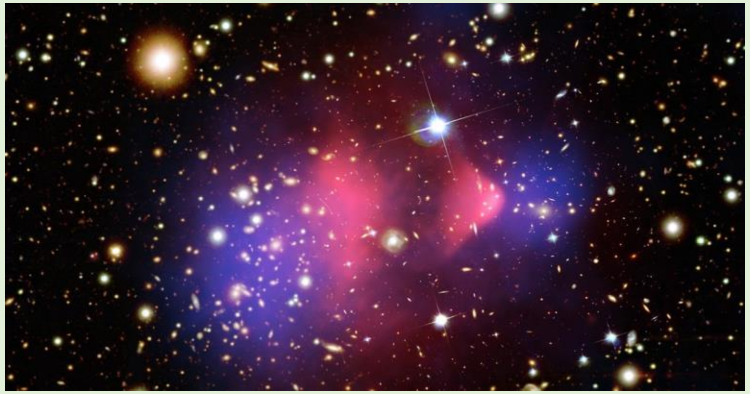
T-symmetry of electromegnetism

Grand challenges in fundamental physics

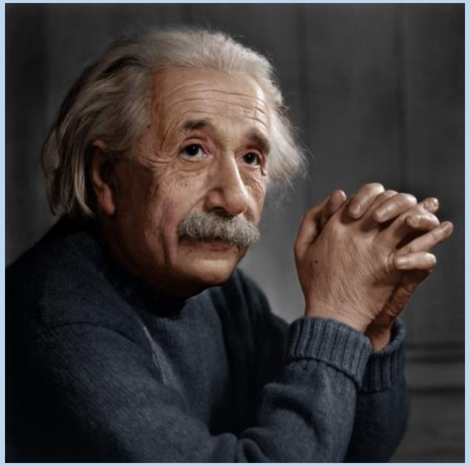
Baryon asymmetry



New particles



Test of special relativity



images: wikipedia

Thanks to a great team

PhDs
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Felix Affeld
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Lara Becker

QUANTERA
QuantumGuide
UVQuanT
Bundesministerium für Bildung und Forschung
Bundesamt für Kartographie und Geodäsie
FULBRIGHT
TRA MATTER
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DFG Deutsche Forschungsgemeinschaft
ML4Q
SFB/TR 185
CLONETS CLOCK NETWORK SERVICES
Max-Planck-Institut für Radioastronomie
UNIVERSITÄT BONN