Approaching the neutron EDM through ultracold mercury

Simon Stellmer

University of Bonn

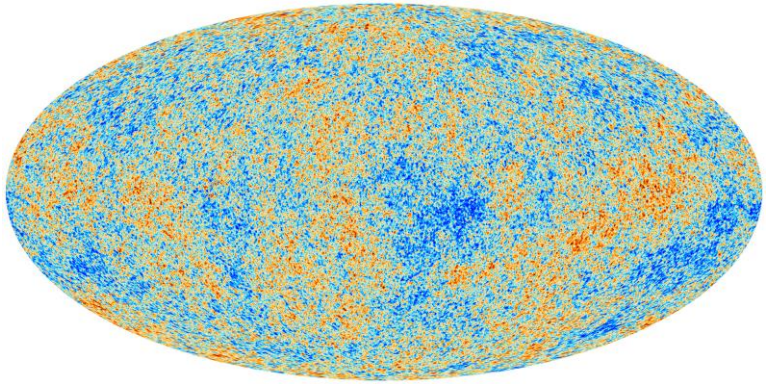
Workshop *EDMs: complementary experiments and theory connections* | 05.03.2024

UNIVERSITÄT BONN

QUANTUM METROLOGY
RESEARCH GROUP

Baryogenesis and the search for EDMs

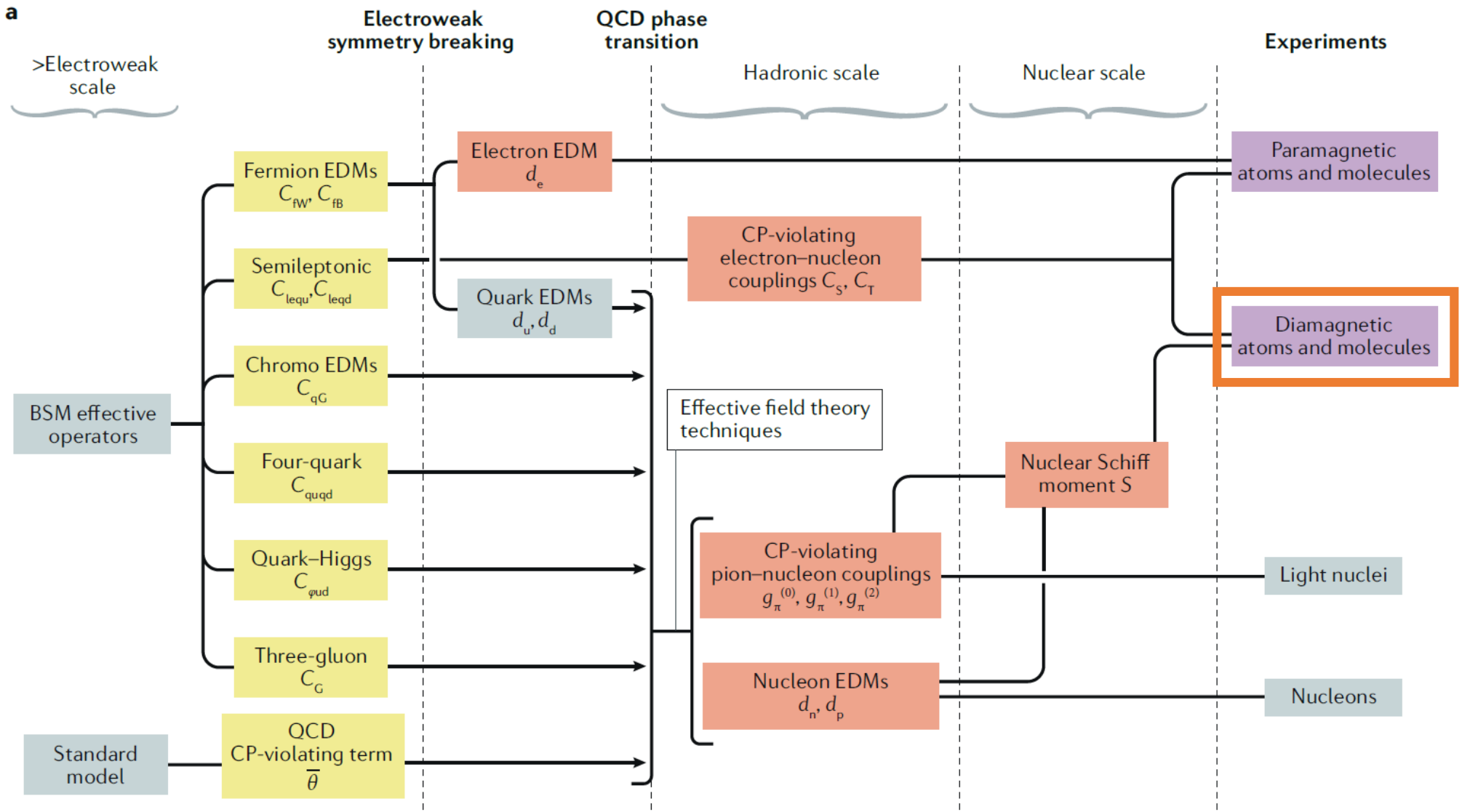
Baryogenesis and the search for EDMs



Arthur Schawlow

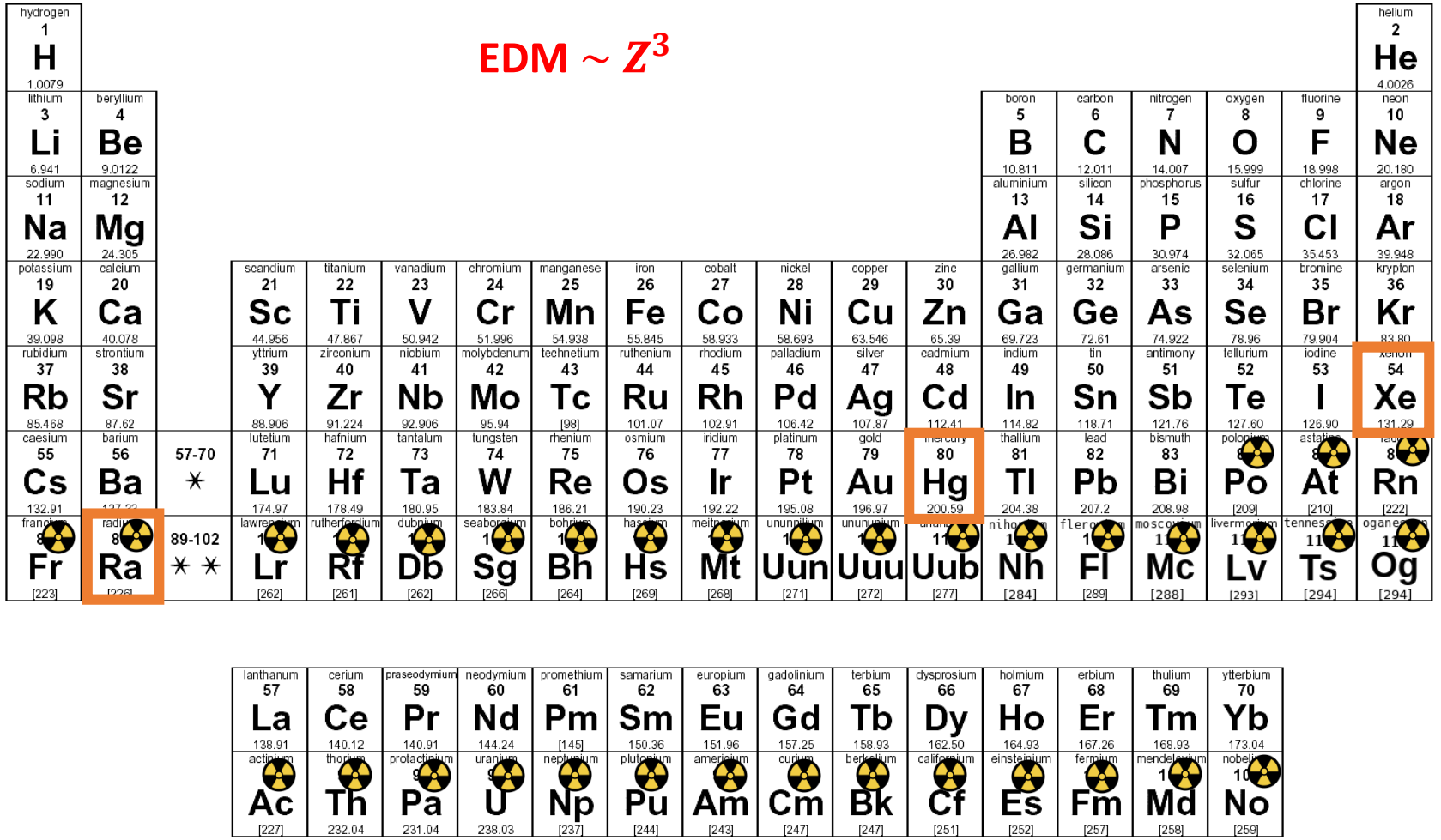
“Never measure anything but frequency!”

Baryogenesis and the search for EDMs

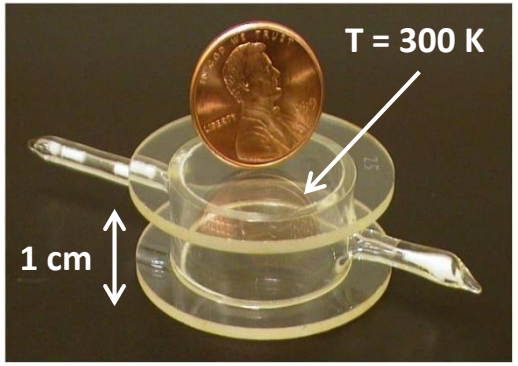


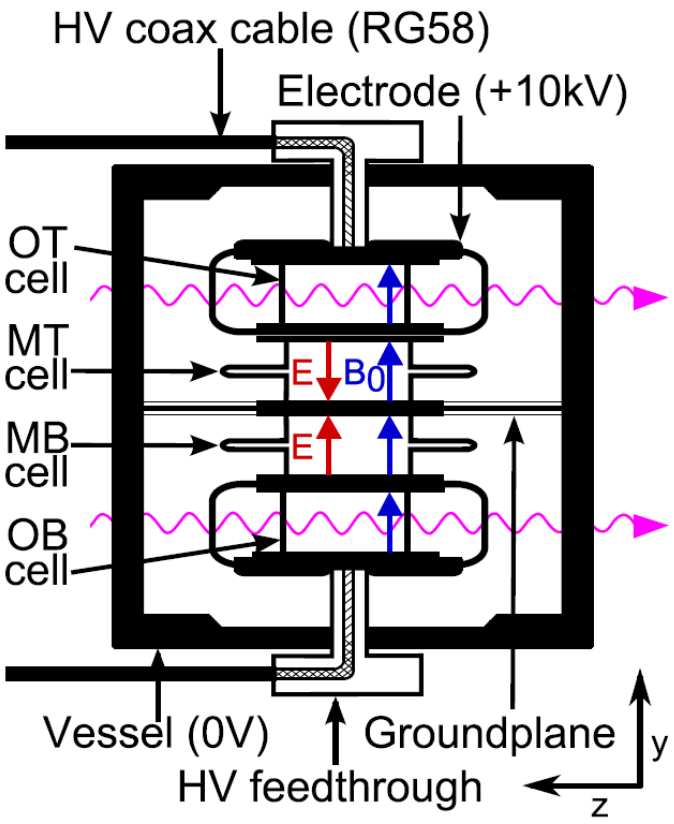
Nature Reviews Physics **1**, 510 (2019)

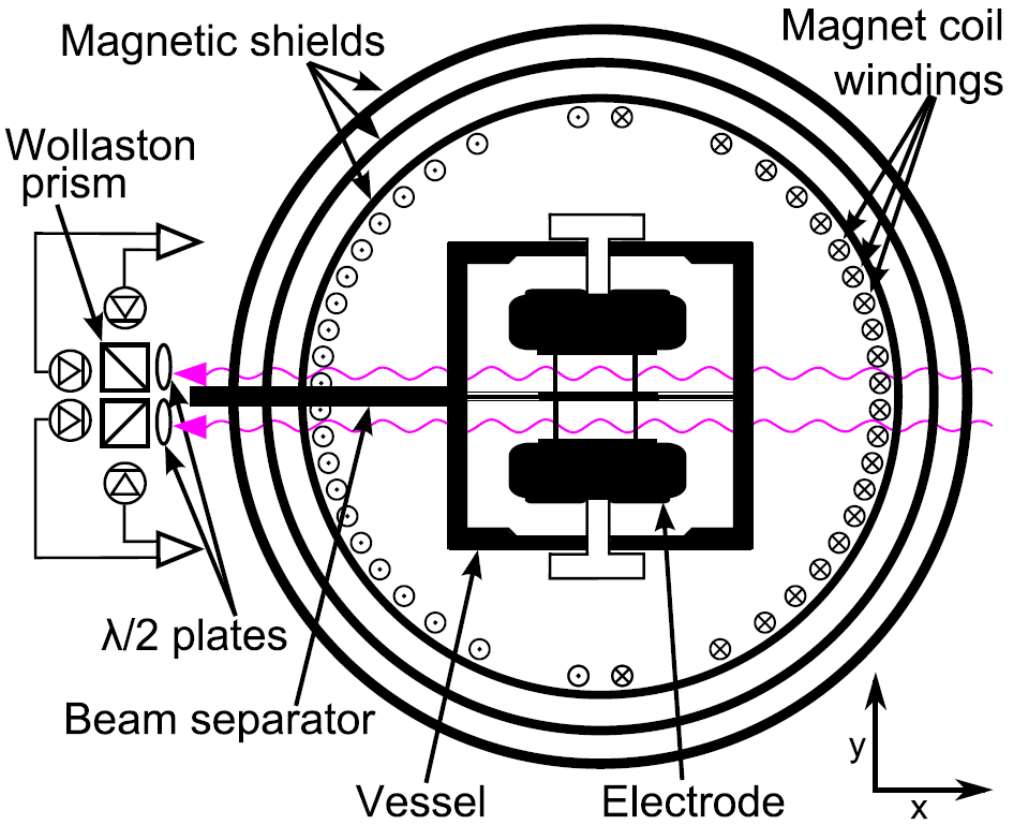
Baryogenesis and the search for EDMs



Mercury EDM measurements







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

Mercury EDM measurements

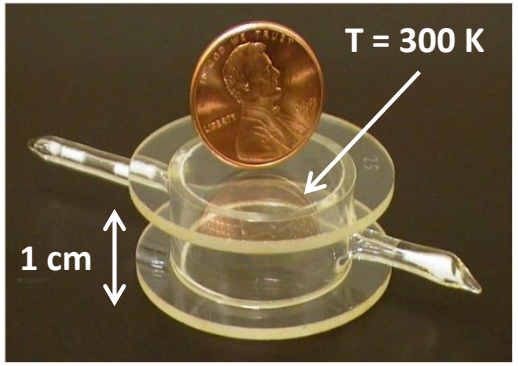


TABLE II. Systematic effects on the measured EDM value. All entries are specified in units of (10^{-31} e cm). The final value for the systematic error bar is the quadrature sum of the listed effects, 1.48×10^{-30} e cm.

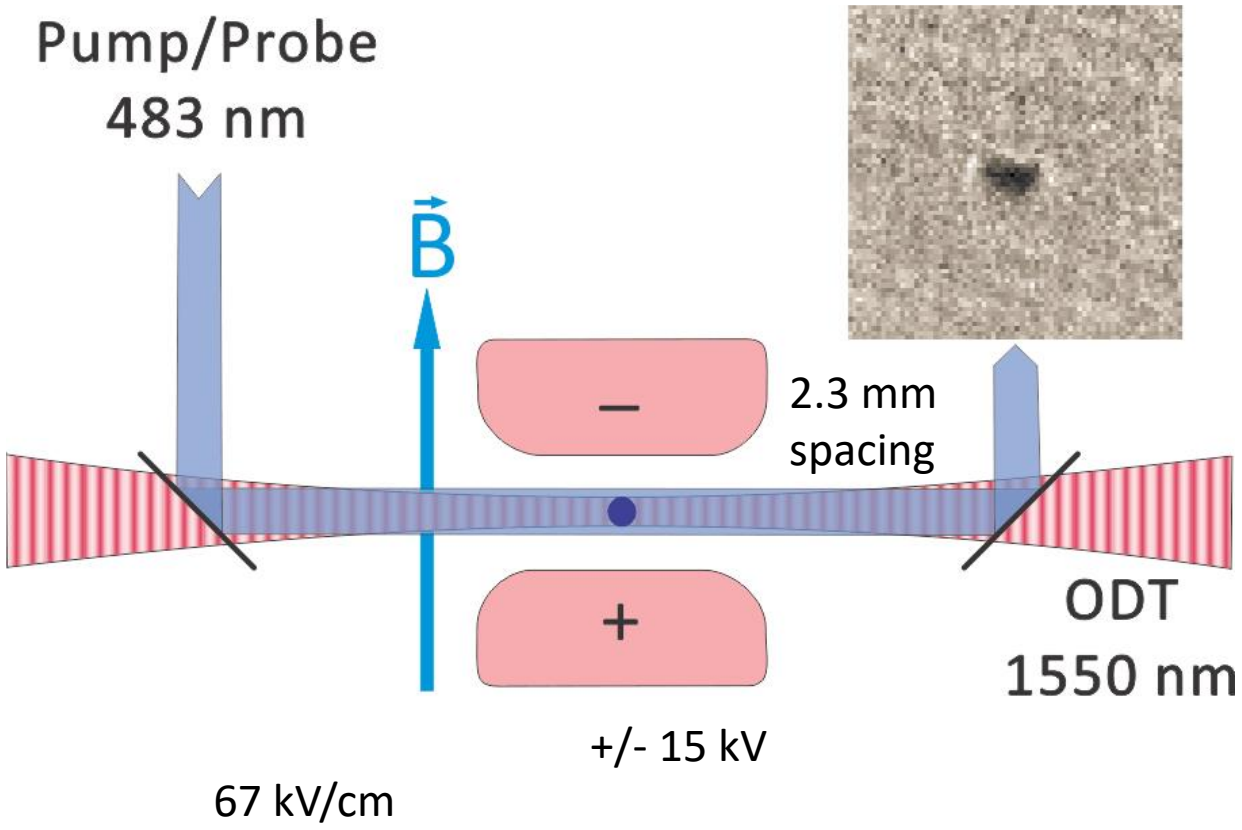
Effect	Syst.	Effect	Syst.
Axial cell motion	12.62	Parameter correlations	2.33
Radial cell motion	3.36	$\mathbf{v} \times \mathbf{E}/c$ fields	2.29
Leakage currents	5.02	Charging currents	1.83
$\mathbf{E}^2$ effects	3.04	Geometric phase	0.06

TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{\mathrm{Hg}}/(1.9\ \mathrm{fm}^2)$	1.6×10^{-26} e cm	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{\mathrm{Hg}}/(0.2\ \mathrm{fm}^2)$	2.0×10^{-25} e cm	[21]
$\bar{g}_0$	$\mathbf{S}_{\mathrm{Hg}}/(0.135\ e\,\mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22,23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\ \mathrm{cm}^{-1})$	5.7×10^{-27} cm	[25]
C_S	$\mathbf{d}_{\mathrm{Hg}}/(5.9 \times 10^{-22}\ e\,\mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{\mathrm{Hg}}/(6.0 \times 10^{-23}\ e\,\mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{\mathrm{Hg}}/(4.89 \times 10^{-20}\ e\,\mathrm{cm})$	1.5×10^{-10}	see text

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

Radium EDM measurements

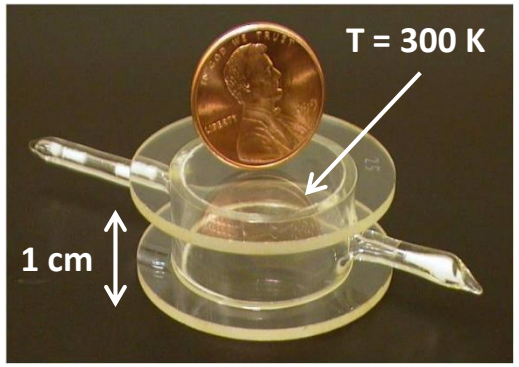


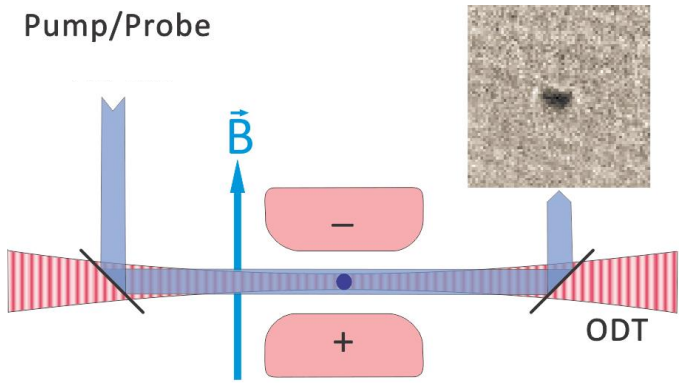
200 atoms

Phys. Rev. Lett. **114**, 233002 (2015)

The quMercury experiment in Bonn

The quMercury experiment



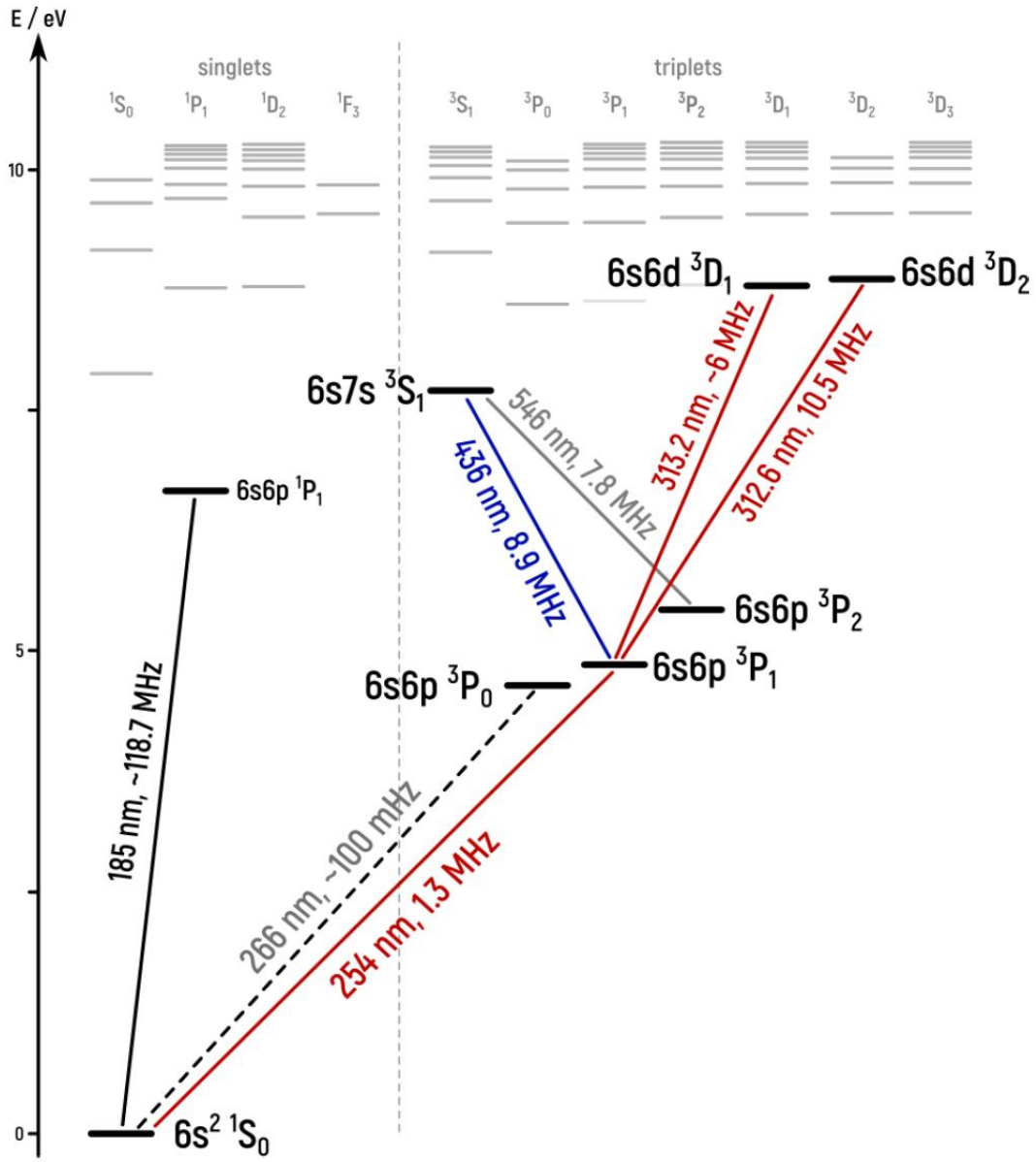


Sensitivity:

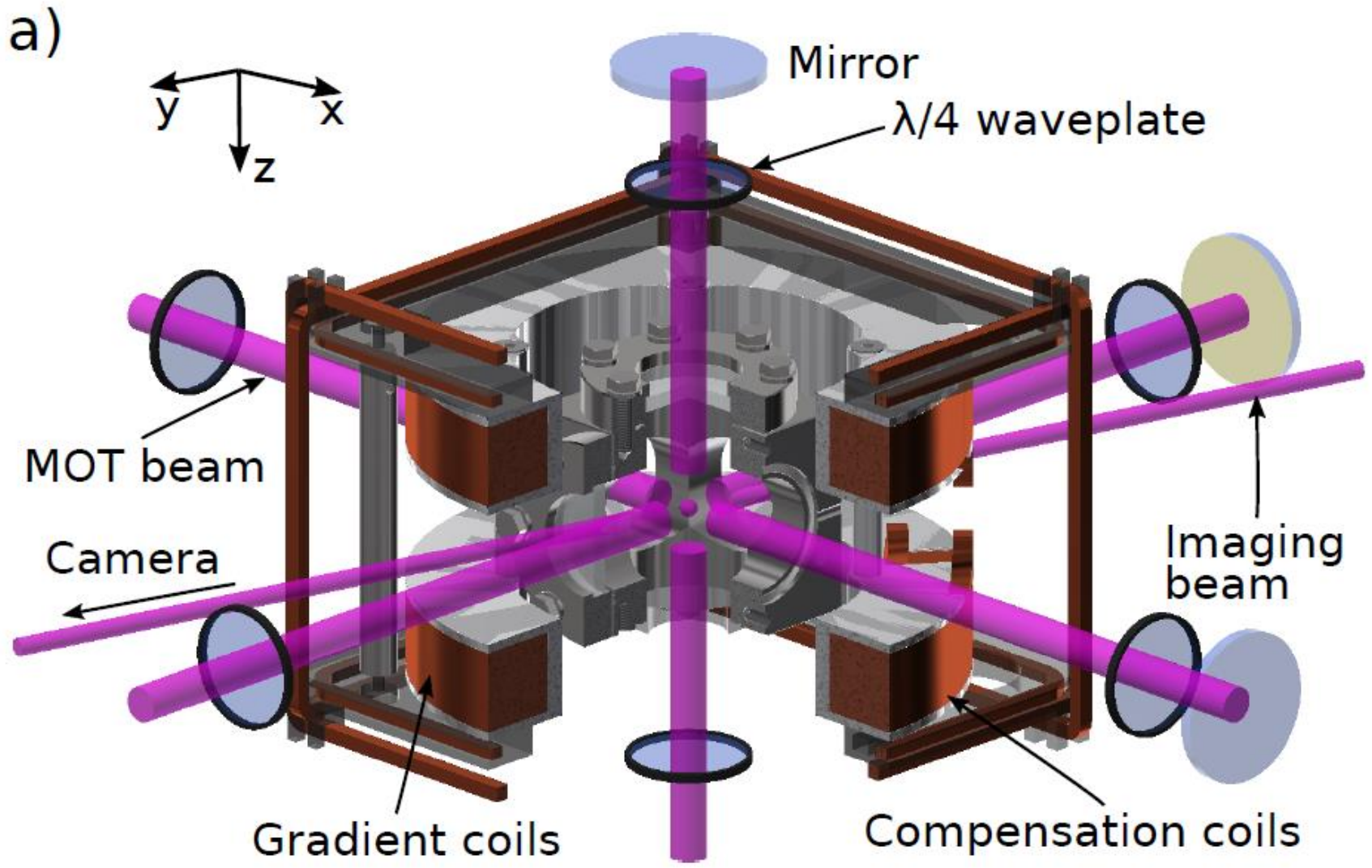
$$\delta d = \frac{\hbar}{2E\sqrt{2N\tau T}}$$

	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			

The quMercury experiment

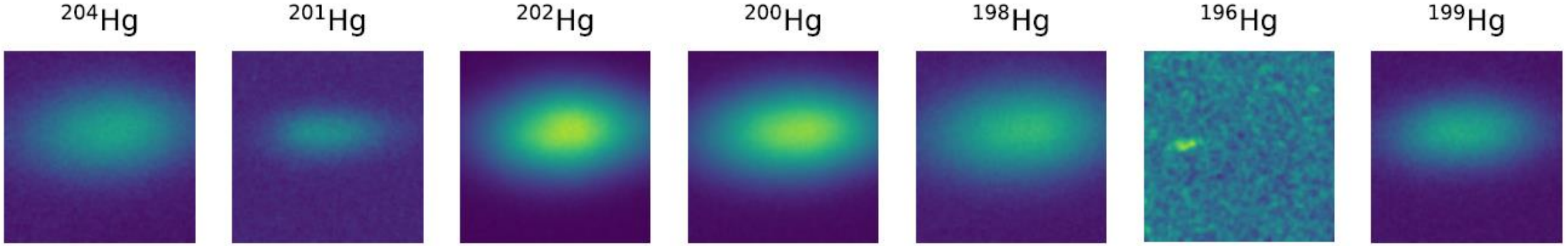


The quMercury experiment



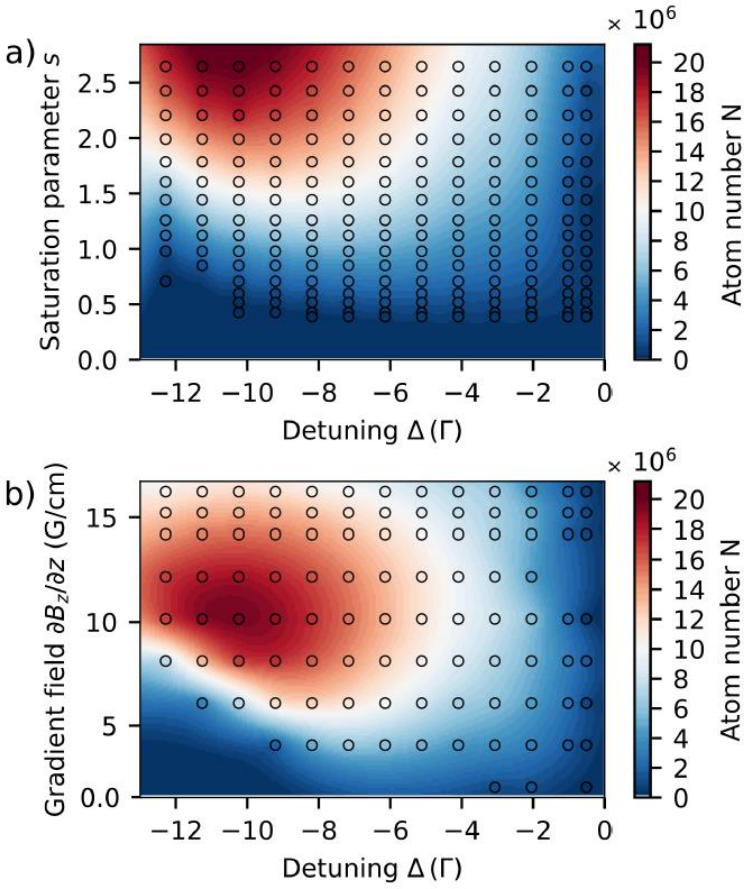
Phys. Rev. A **105**, 033106 (2022)

The quMercury experiment

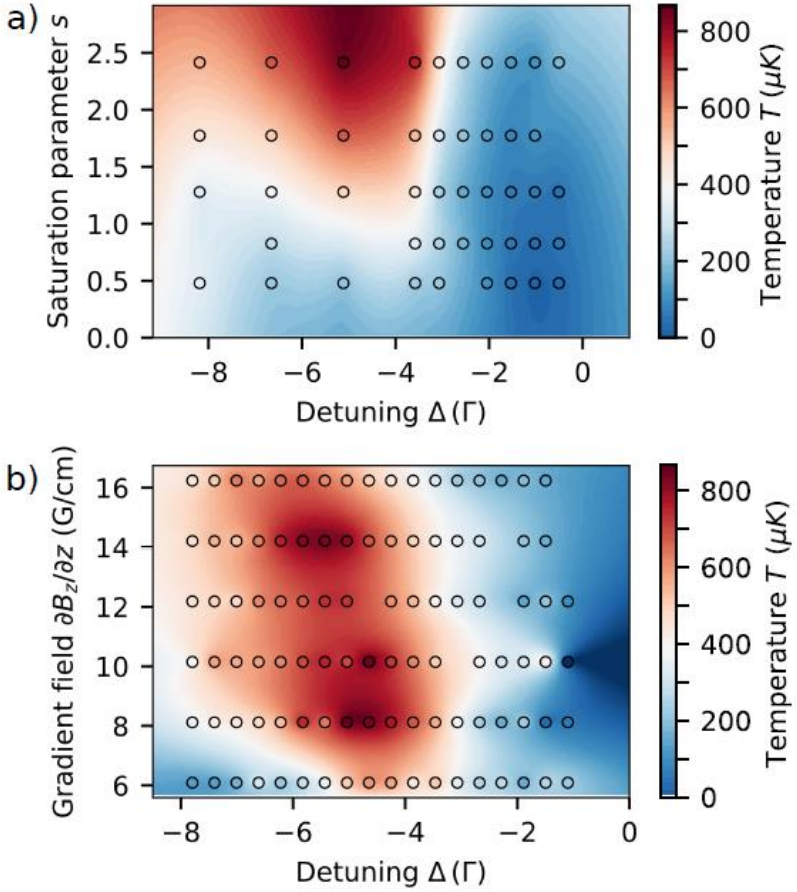


The quMercury experiment

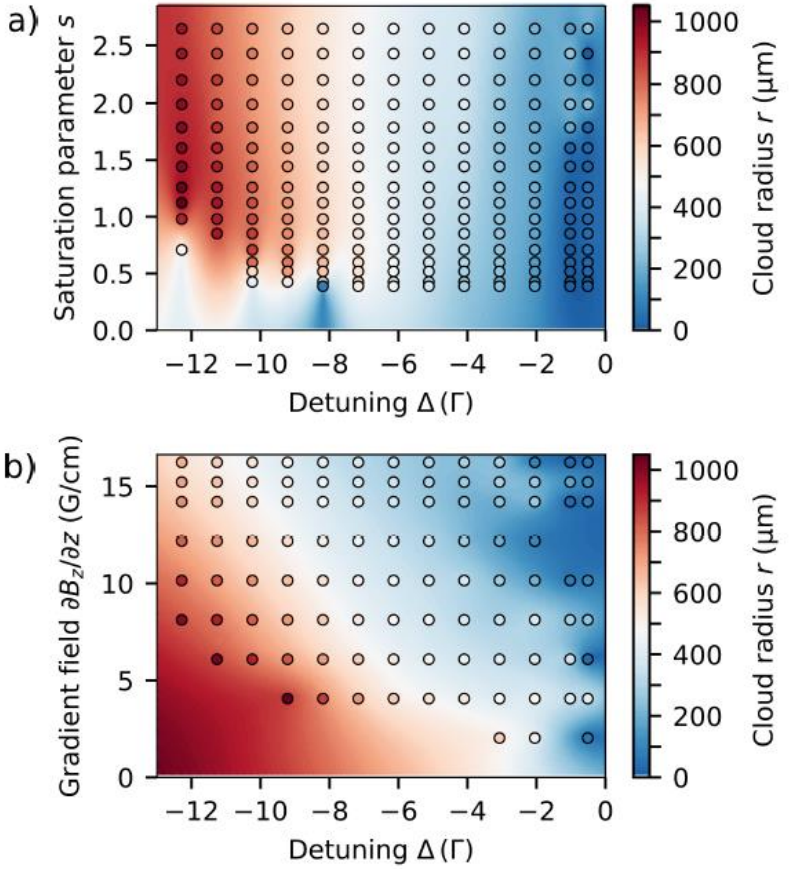
Atom number



Temperature

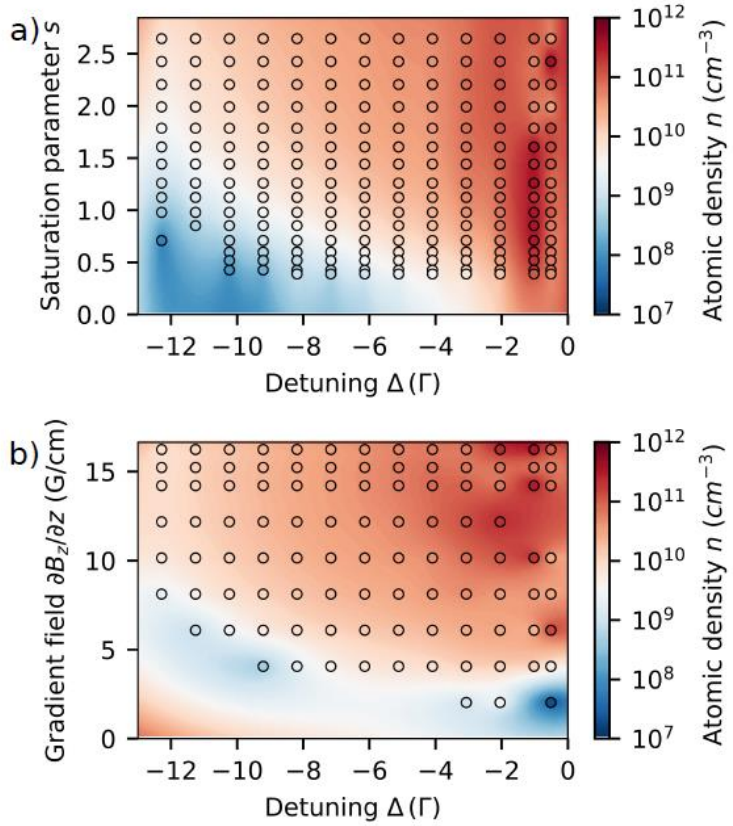


Cloud size (density)

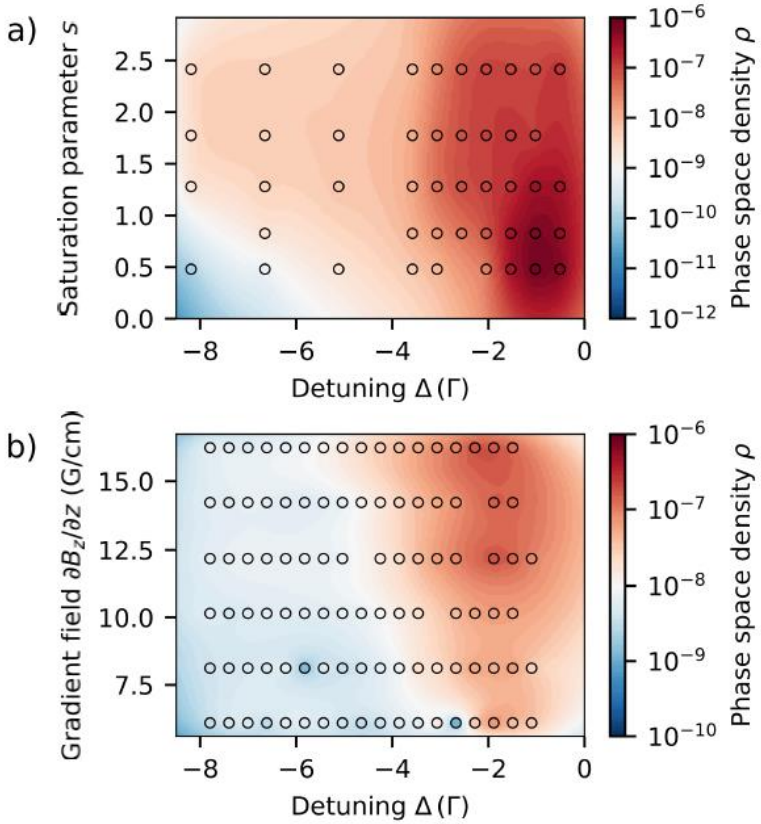


The quMercury experiment

Density

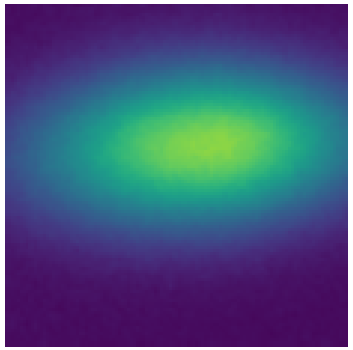


Phase-space density



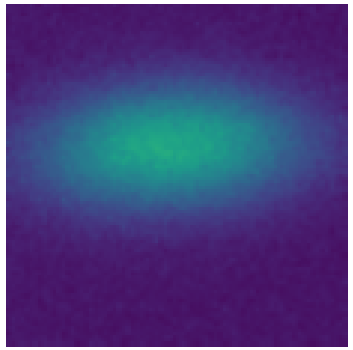
The quMercury experiment

^{200}Hg

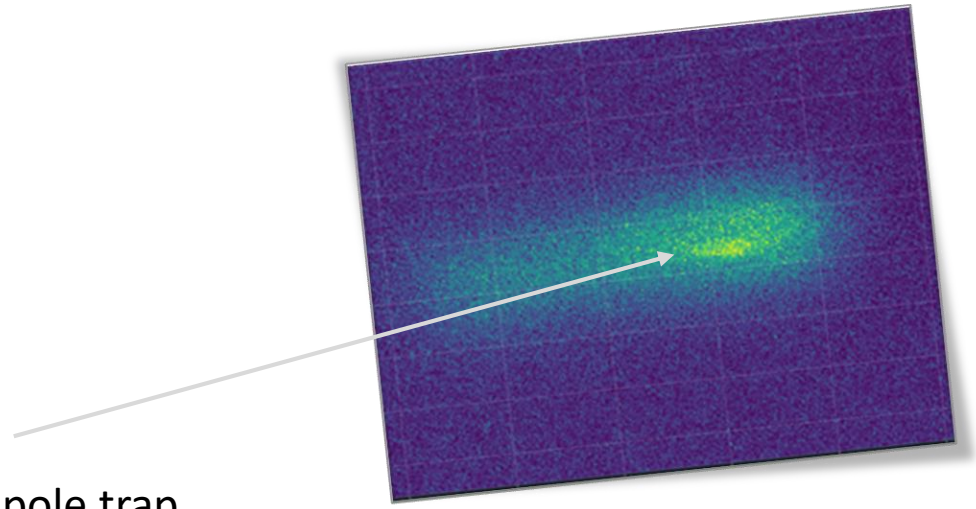


10^8 atoms
200 µK temperature

^{199}Hg



5 x 10^6 atoms
30 µK temperature



dipole trap
loading

Isotope shift spectroscopy

Isotope shift spectroscopy

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

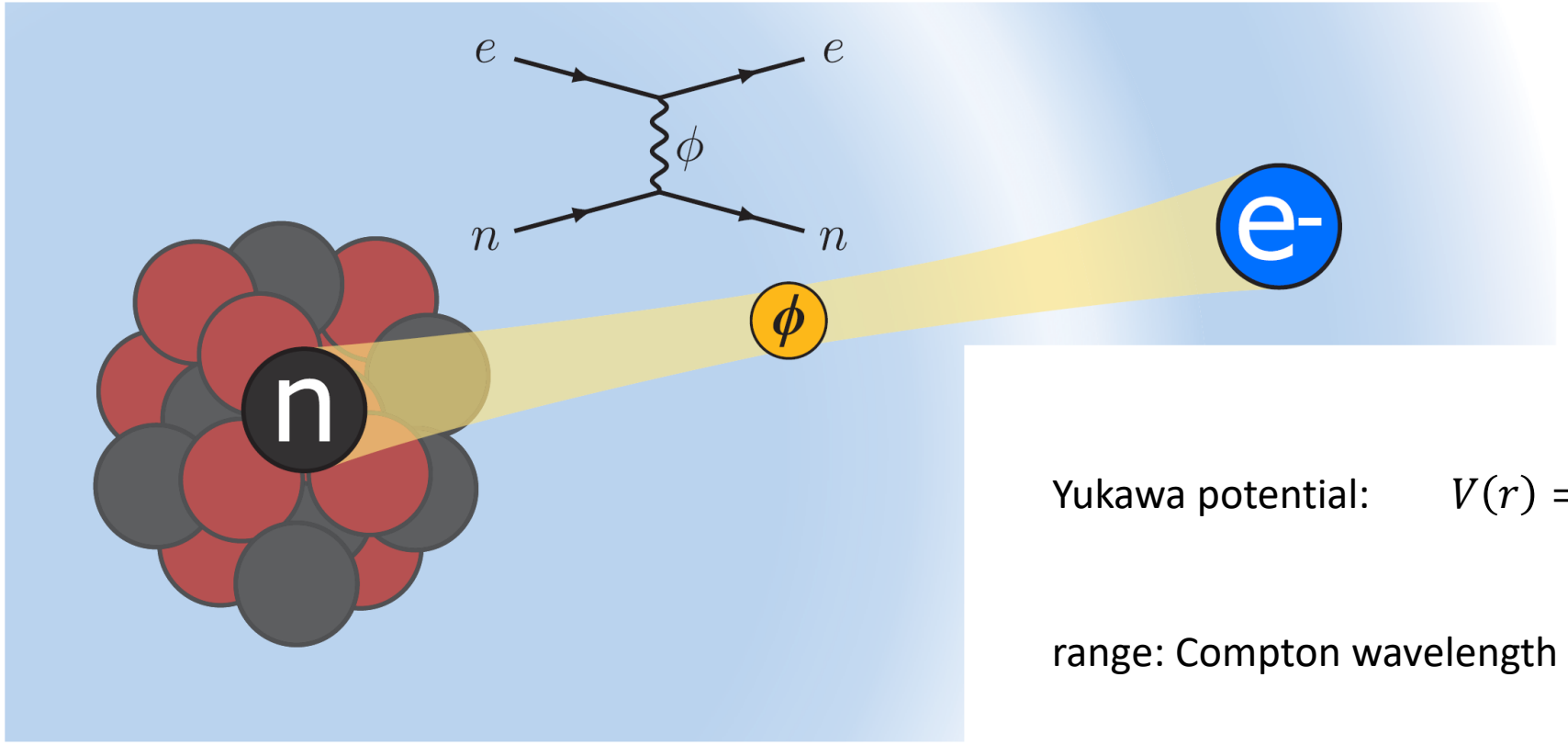
$$\nu_{\alpha ji} = F_\alpha \, \delta\langle r^2 \rangle_{ji} + K_\alpha \, \mu_{ji} + G_\alpha \left(\delta\langle r^2 \rangle_{ji}\right)^2 + \upsilon_{ne} \, D_\alpha \, a_{ji}$$

field shift	*mass shift*	*higer-order terms*	*New Physics*
(GHz scale)	(MHz scale)	(kHz scale)	(Hz - kHz scale)

isotopes i, j
transitions α, β

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, Kyoto, 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** + **new physics**

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

field shift	*mass shift*	*higer-order terms*	*New Physics*
(GHz scale)	(MHz scale)	(kHz scale)	(Hz - kHz scale)

isotopes i, j
transitions α, β

Some magic math:

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**

$$\tilde{\nu}_{\beta ji} = F_{\beta\alpha}\,\tilde{\nu}_{\alpha ji} + K_{\beta\alpha} + G_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2 + \upsilon_{ne}\,D_{\beta\alpha}\,\tilde{\alpha}_{ji}$$

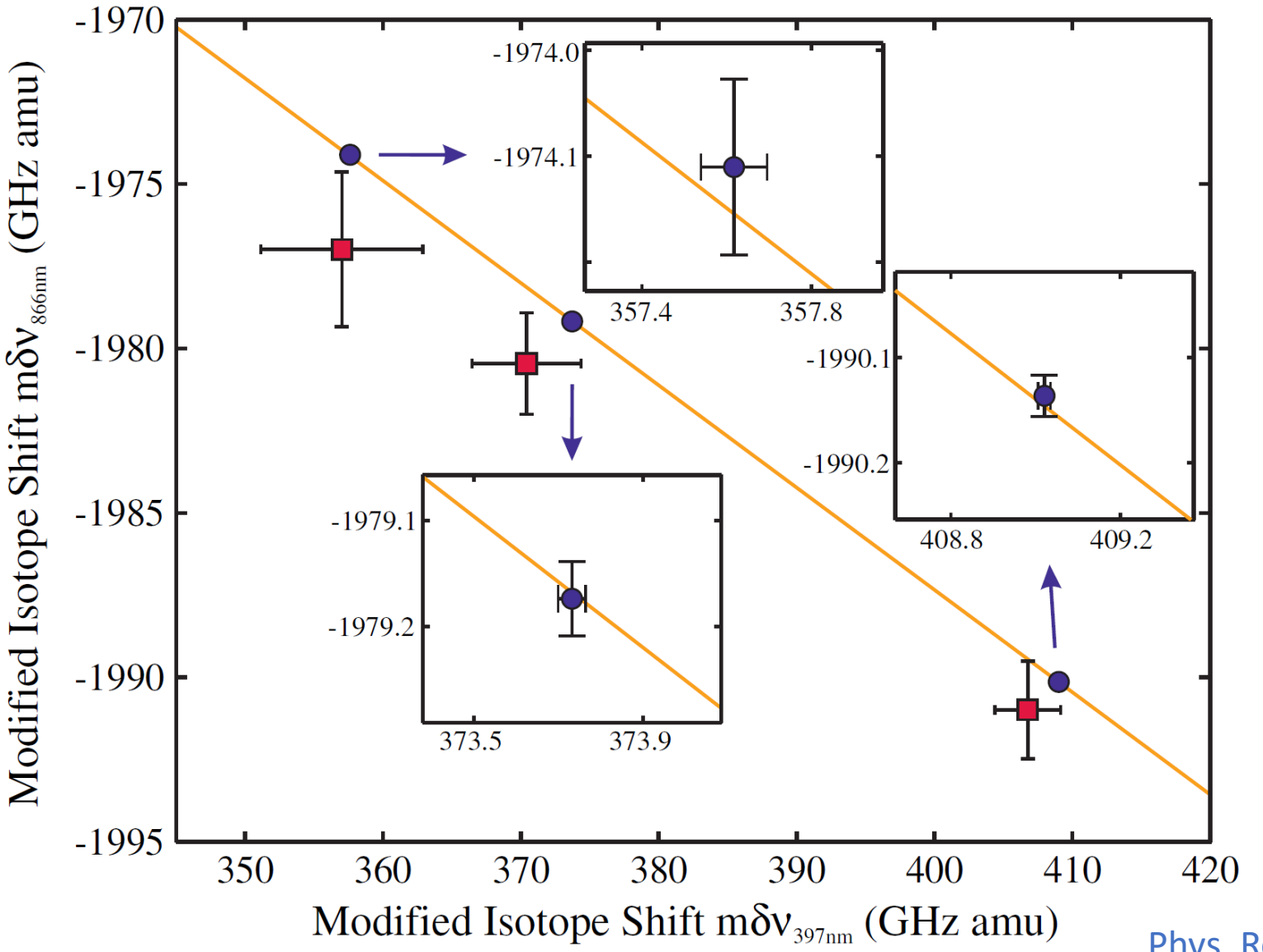
isotopes i, j
transitions α, β

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

-> graphical representation: **King plot**

Isotope shift spectroscopy

A random example: Calcium ions

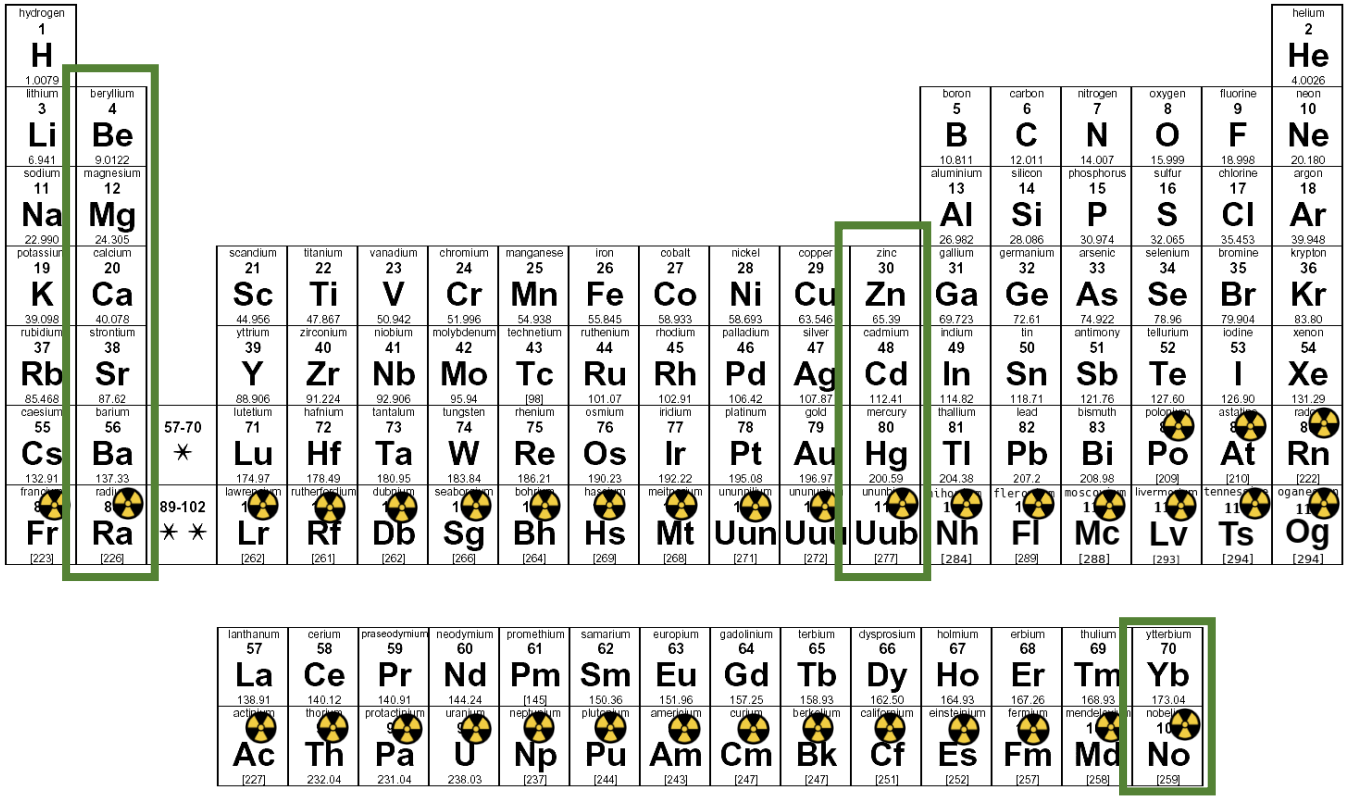


Phys. Rev. Lett. **115**, 053003 (2015)

Isotope shift spectroscopy

Desiderata:

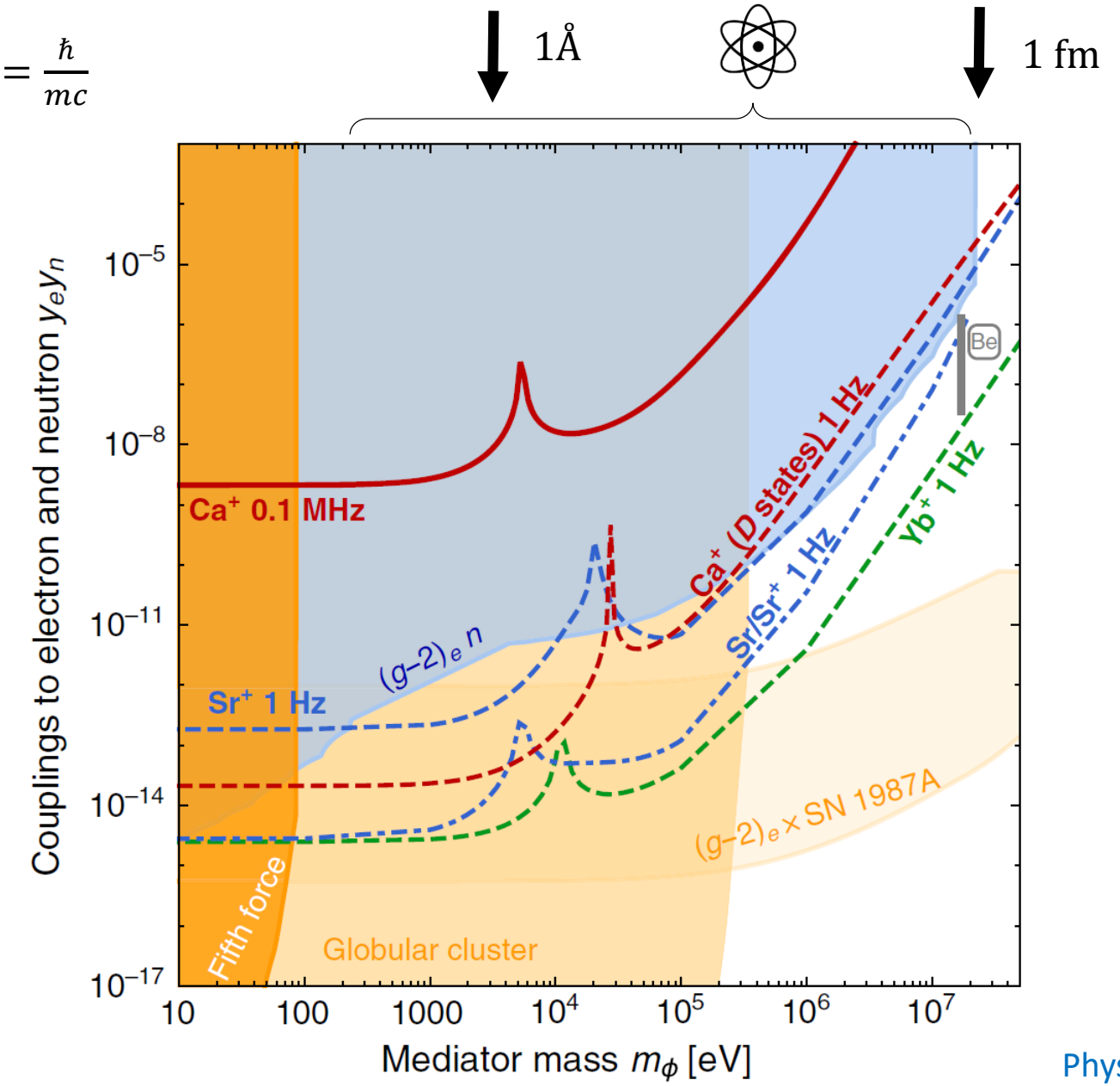
- element that can be laser-cooled & trapped
  - could be atoms or ions or HCIs
- as many isotopes as possible
  - stable
  - large spread of neutron numbers
- $I = 0$ to steer clear of hyperfine structure
- as many optical transitions as possible
  - the narrower, the better
  - connecting different orbitals



→ **Ca, Ba, Zn, Cd, Hg, & Yb**

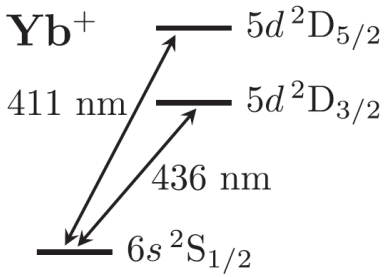
Isotope shift spectroscopy

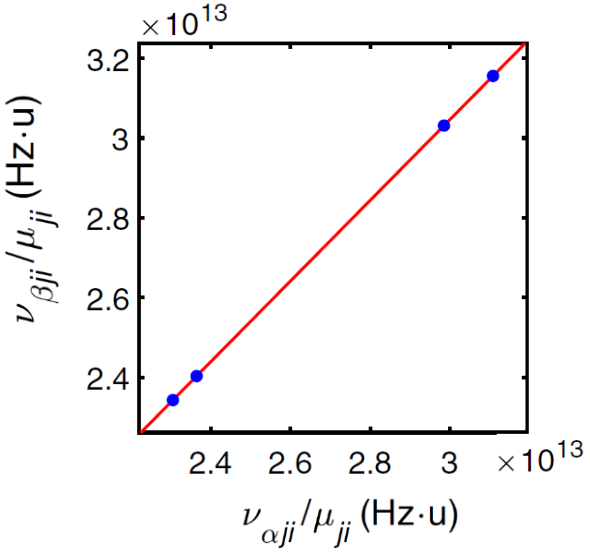
range: $R = \frac{\hbar}{mc}$

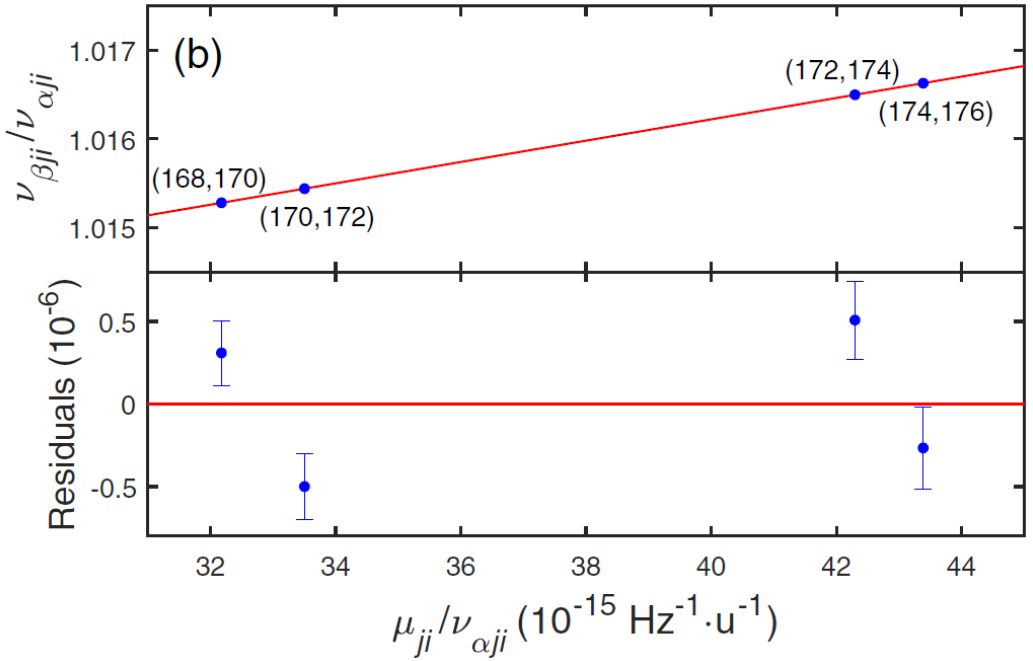


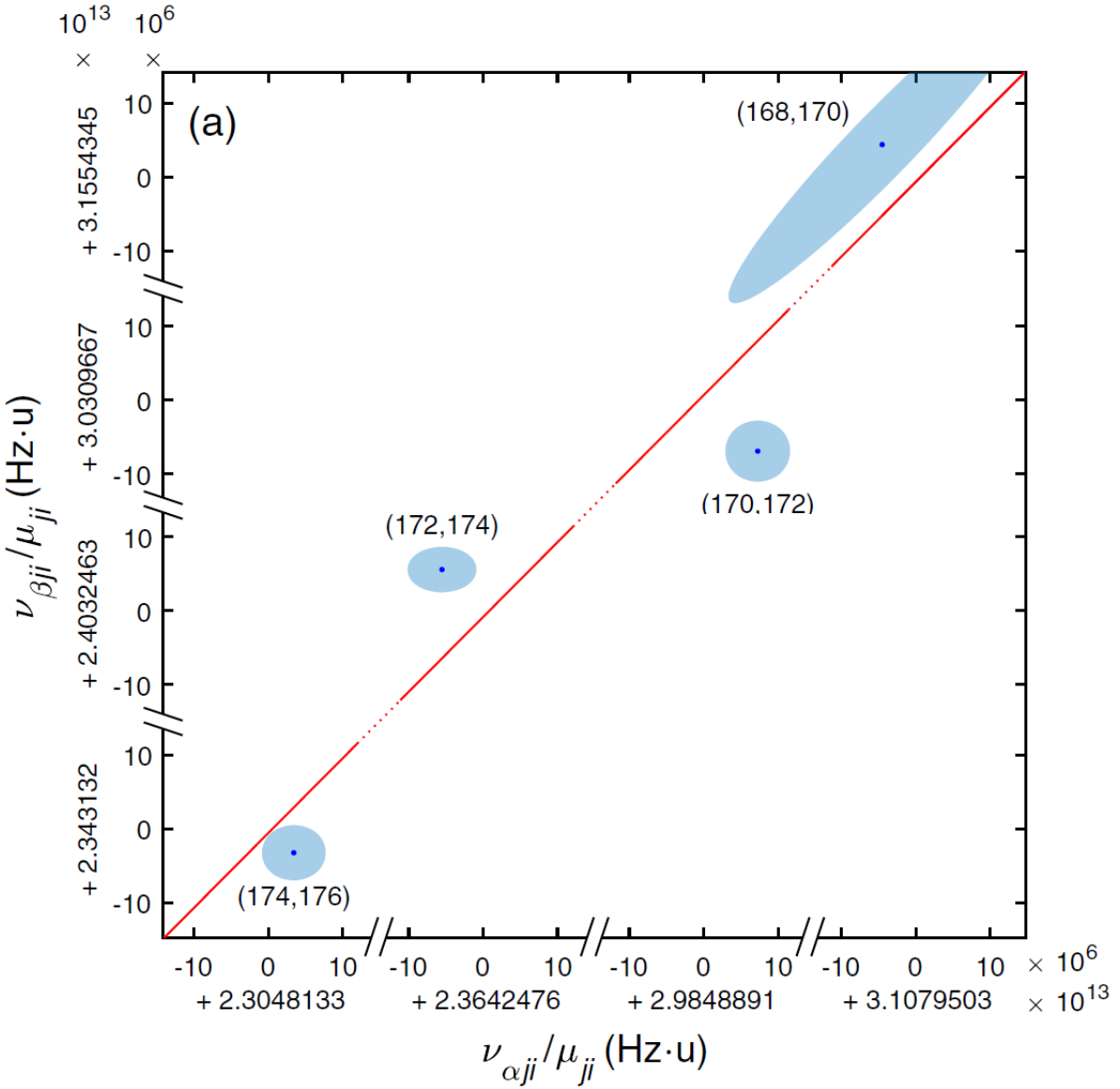
Phys. Rev. Lett. **120**, 091801 (2018)

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-So...

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

N. L. Figueroa[1], J. C. Berengut[2], V. A. Dzuba[2], V. V. Flambaum[2], D. Budker[1], D. Antypas[1,*]

[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 $6s^2\,{}^1S_0 \rightarrow 5d6s\,{}^1D_2$ 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

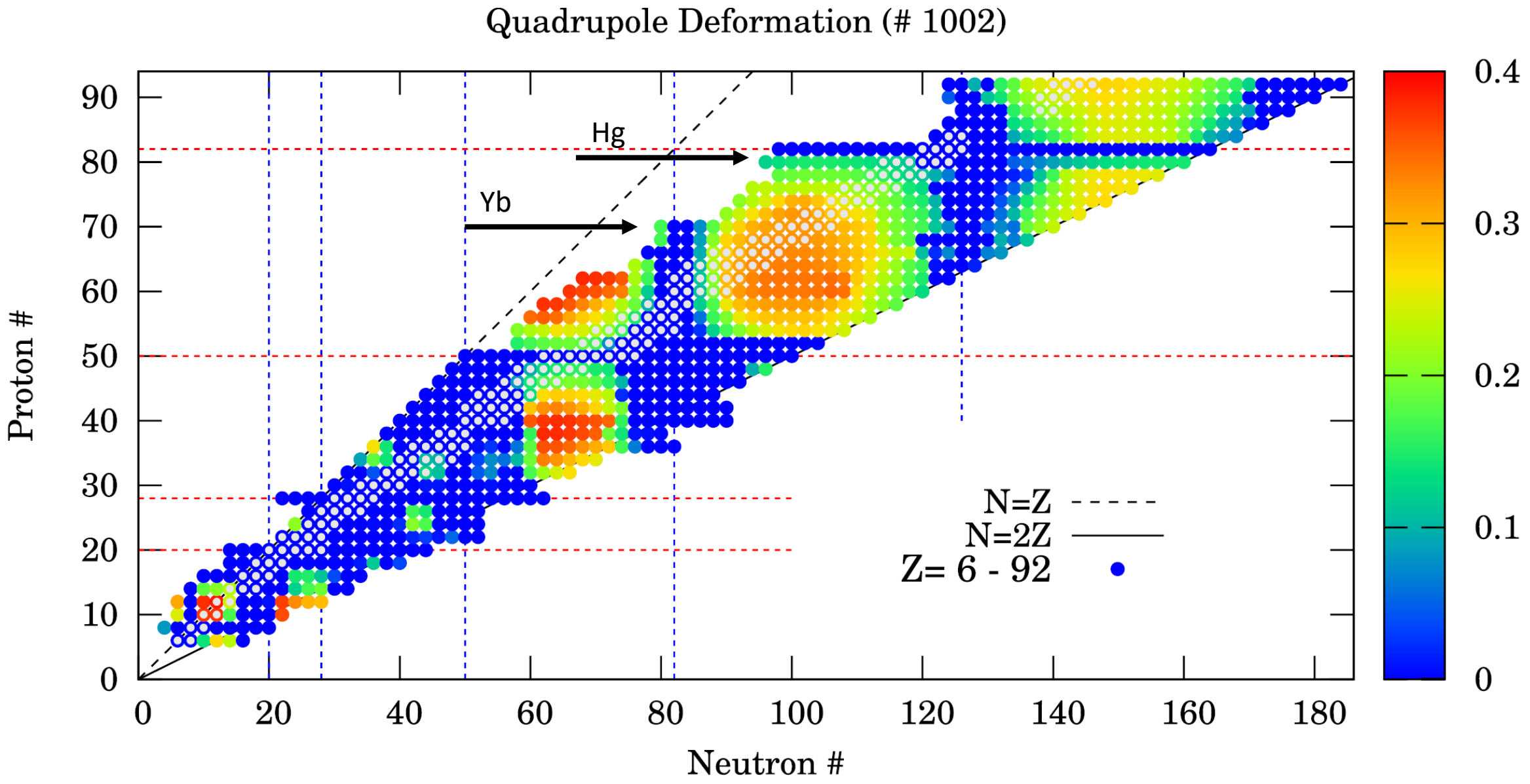
$$+ G'_{\beta\alpha}\delta\langle r^4\rangle_{ji} + \cdots$$

$$\tilde{\nu}_{\beta ji} = F_{\beta\alpha}\,\tilde{\nu}_{\alpha ji} + K_{\beta\alpha} + G_{\beta\alpha}\left(\delta\langle r^2\rangle_{ji}\right)^2 + \upsilon_{ne}\,D_{\beta\alpha}\,\tilde{\alpha}_{ji}$$

field shift	mass shift	second-order field shift	New Boson
linear	offset	**nonlinear / quadratic**	**nonlinear**

$$|\,😢\,\rangle + |\,👍\,\rangle$$

Isotope shift spectroscopy

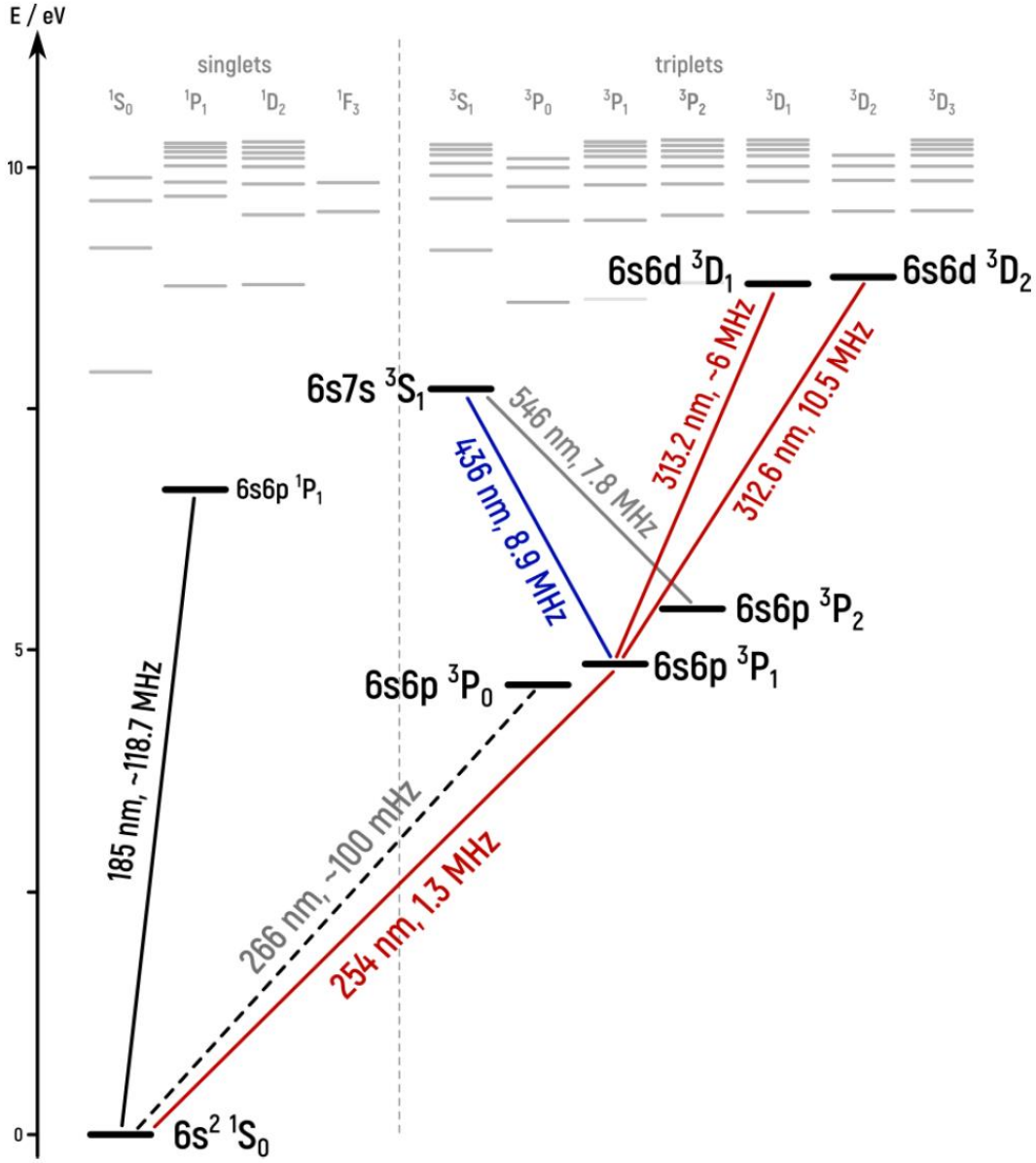


Phys. Scr. **92**, 04005 (2017)

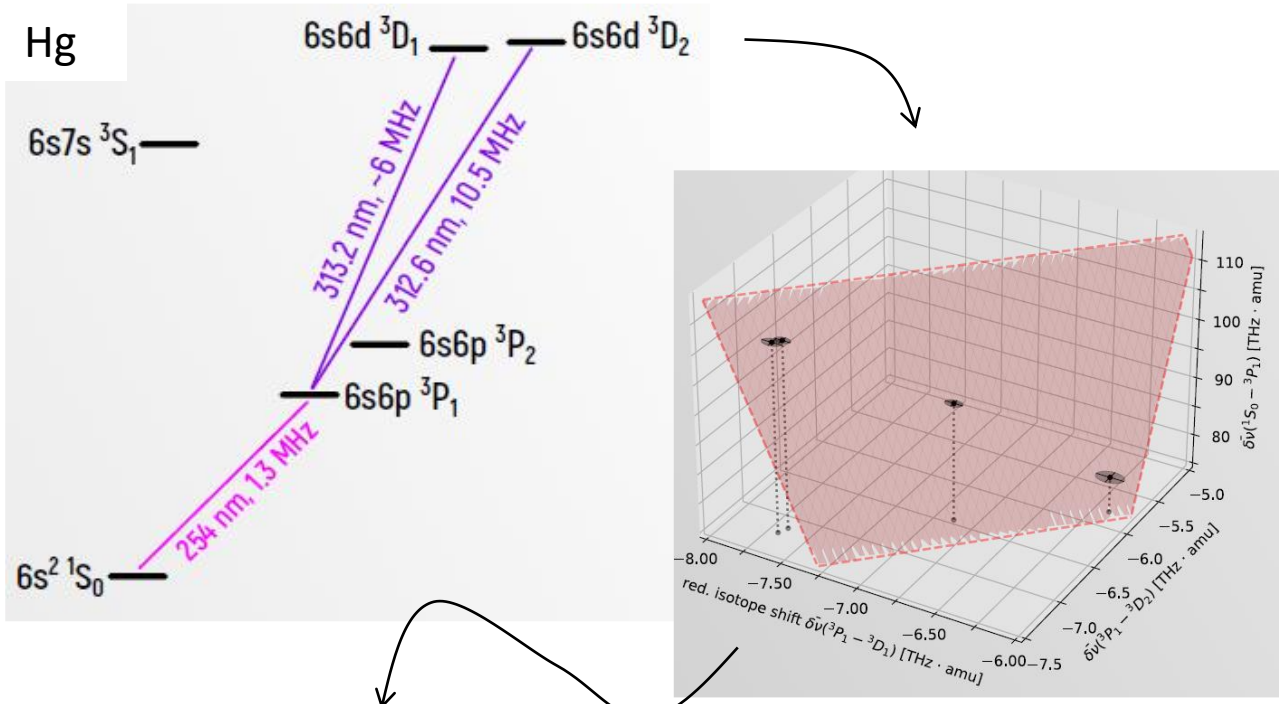
Isotope shift spectroscopy: Mercury

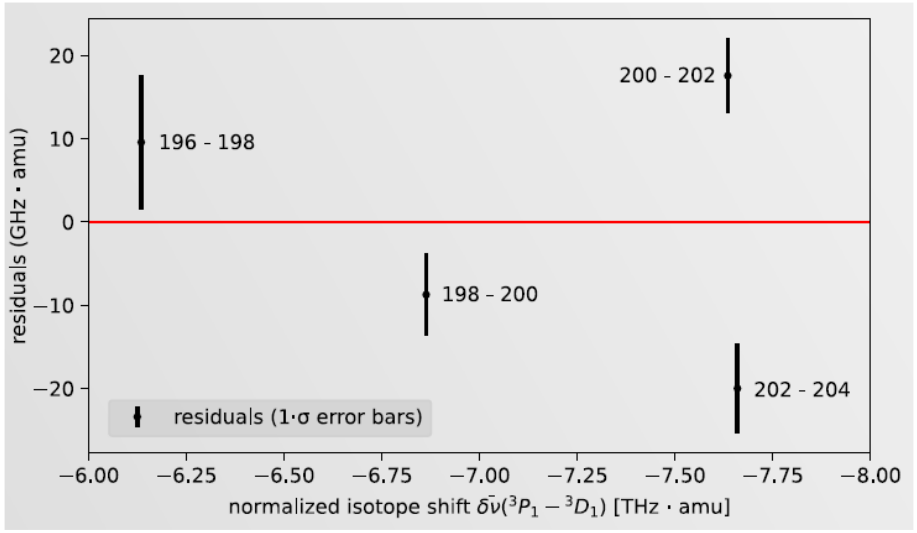
Mercury:

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



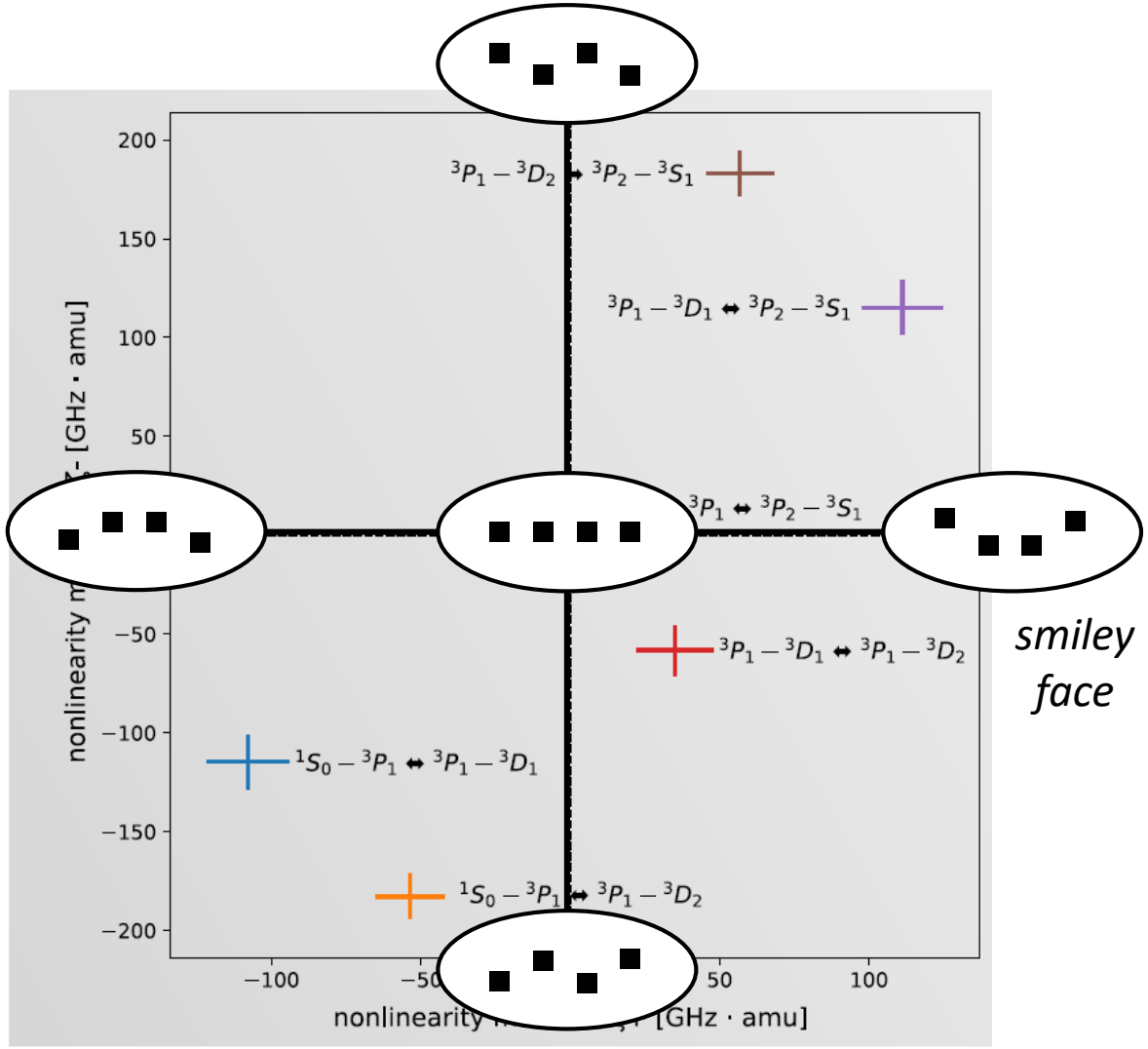
Isotope shift spectroscopy: Mercury





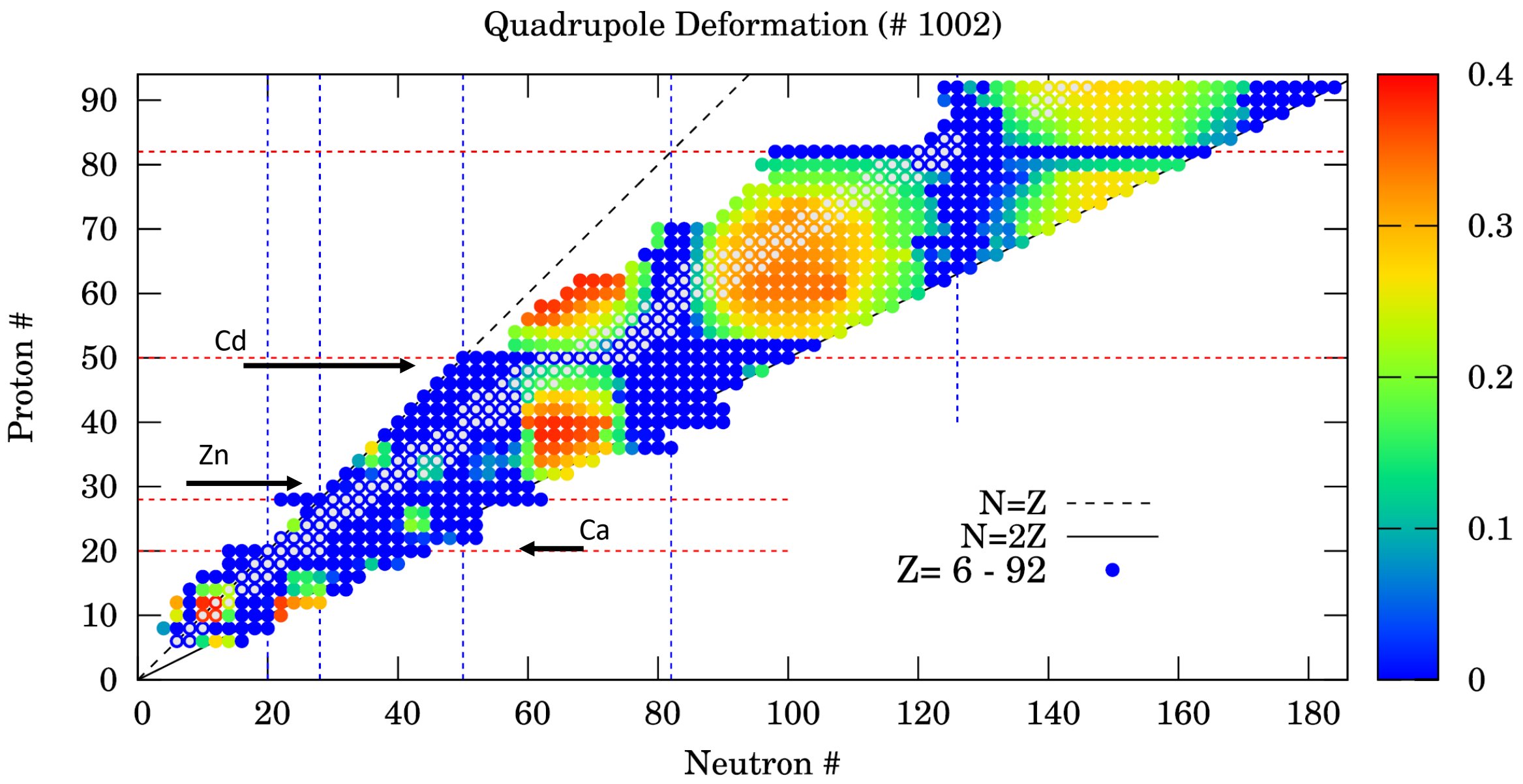
Nonlinearity measure:

zig zag



smiley face

Isotope shift spectroscopy

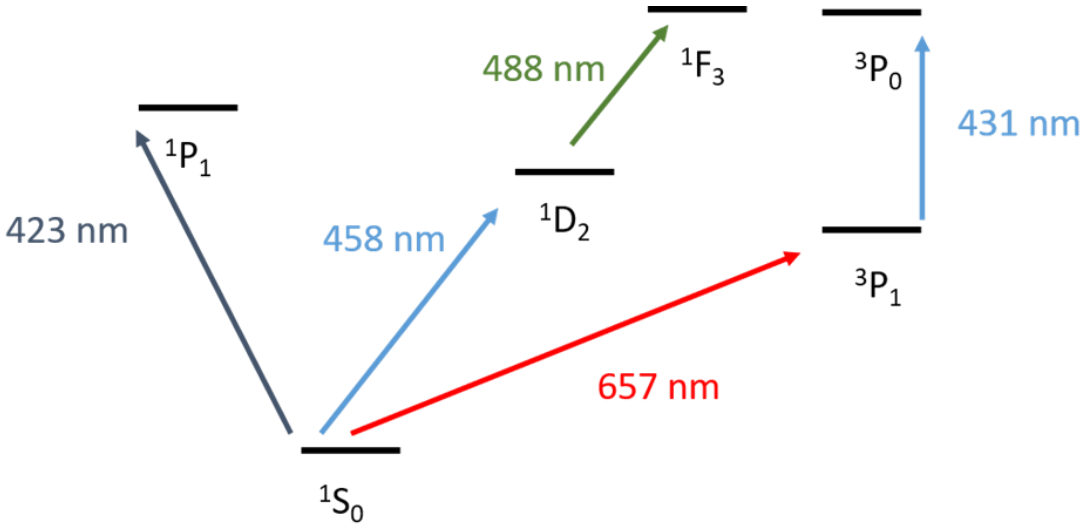


Phys. Scr. **92**, 04005 (2017)

Isotope shift spectroscopy: Calcium and Zinc

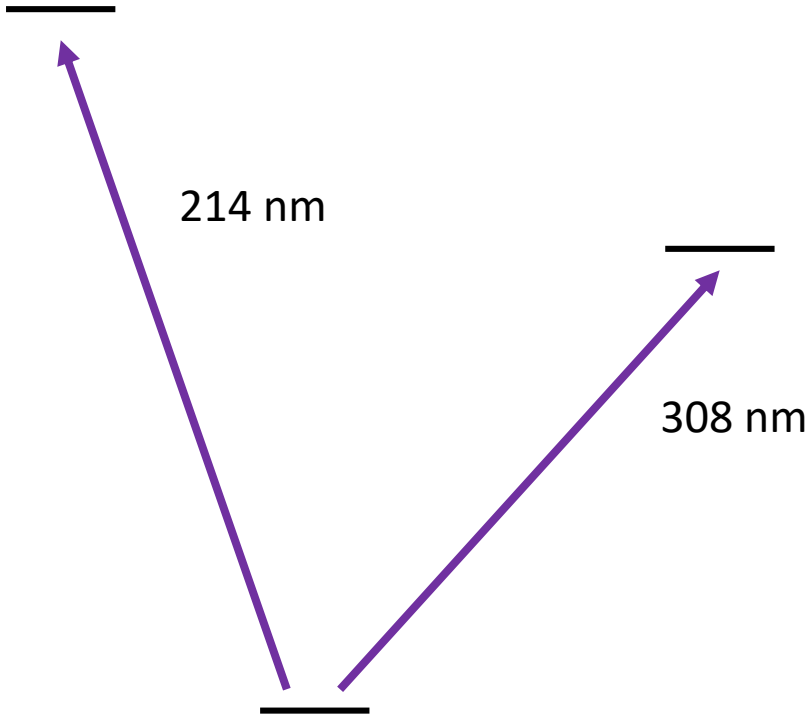
Calcium:

- 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



Zinc:

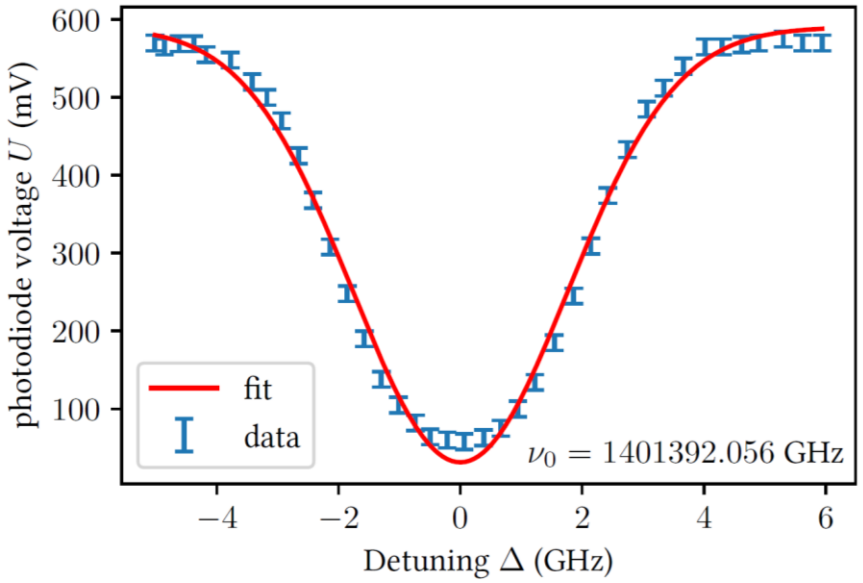
- 4 stable bosonic isotopes
- near the Z= 28 shell closure
- deep-UV transitions

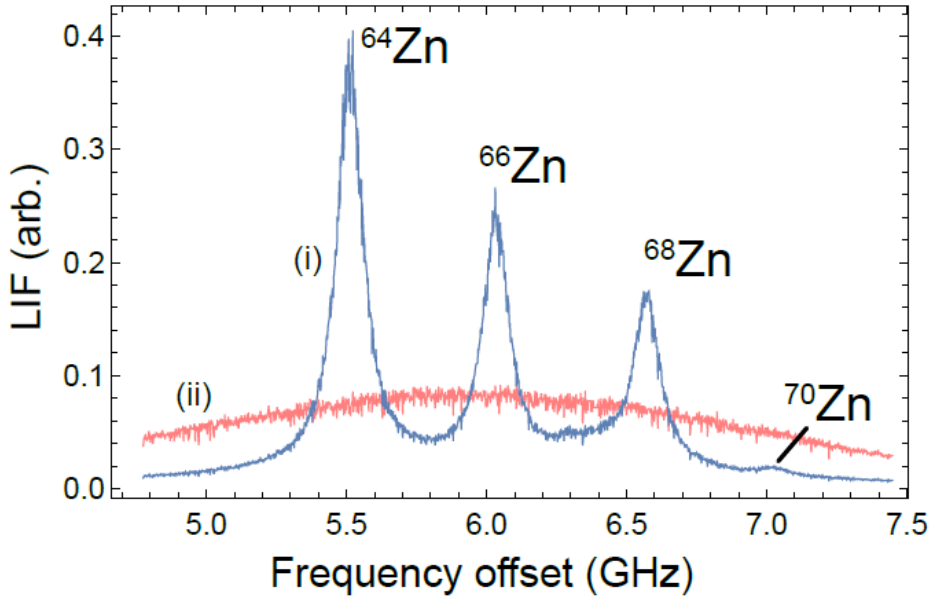


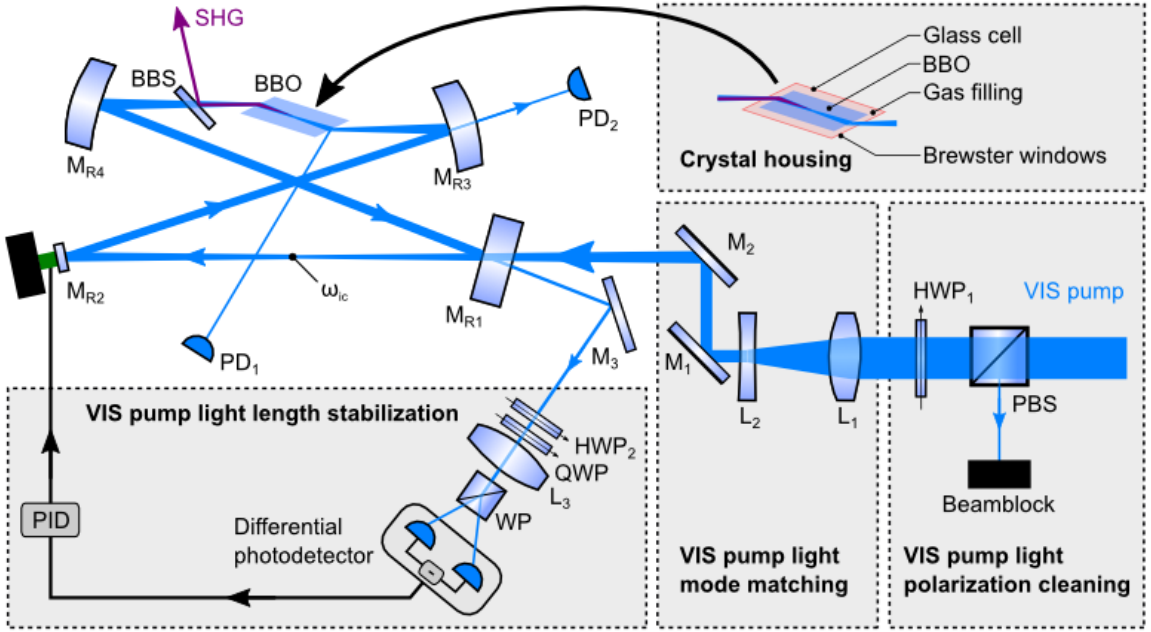
Deep-UV laser development

UV laser development: 214 nm

Zinc







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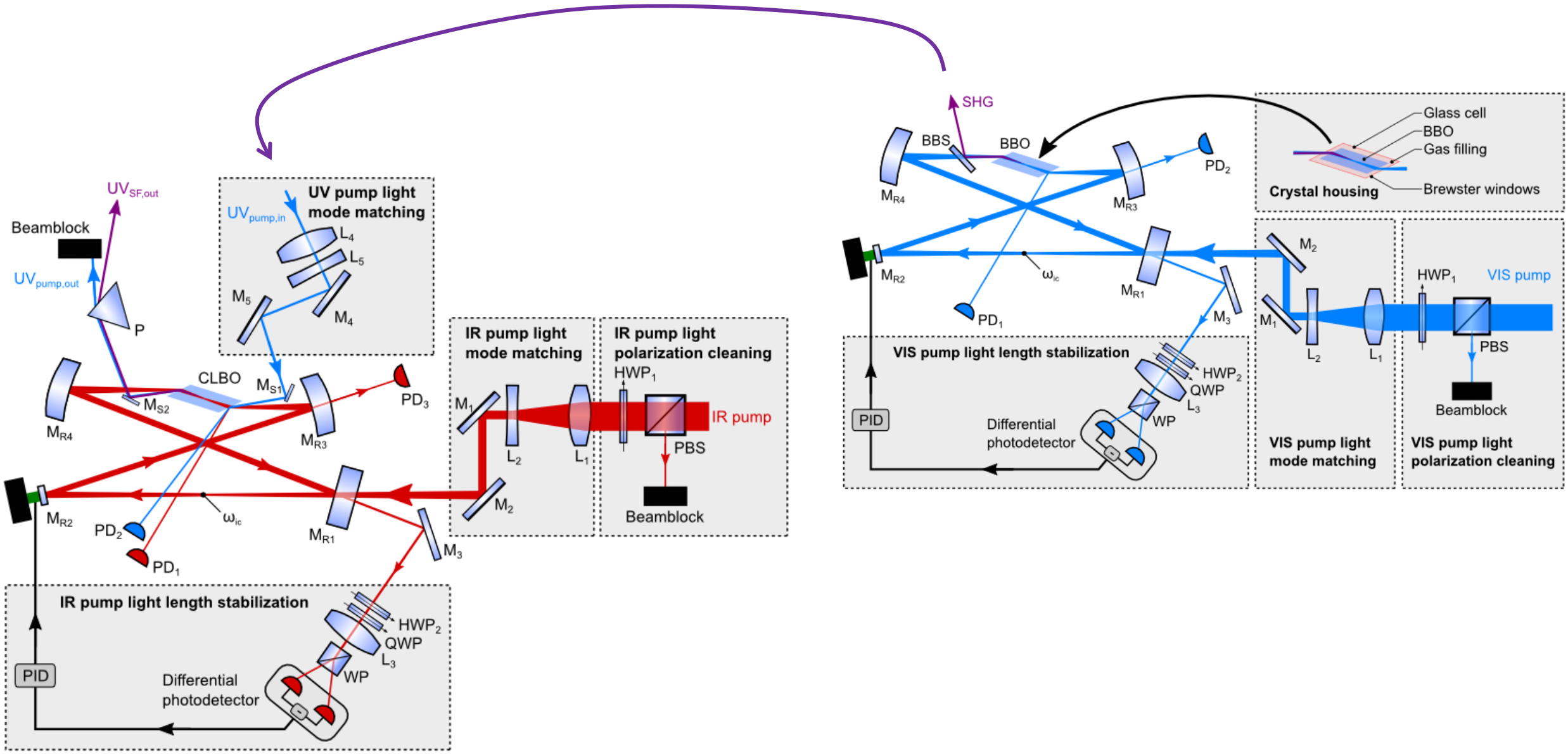
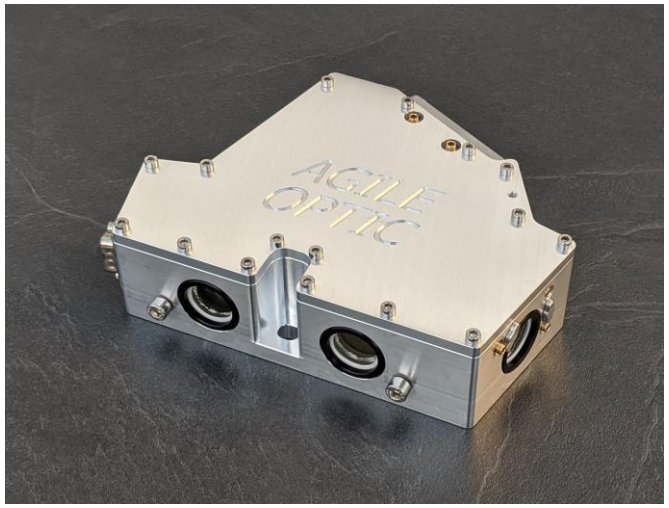
UV laser development: 185 nm



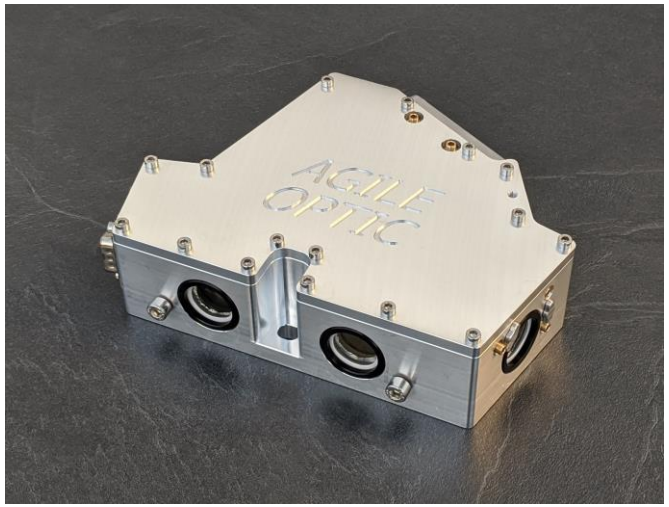
UV laser development: 254 nm and beyond

6 W at 1016 nm



3 W at 508 nm

+ wide tunability
+ high intensity stability
+ high frequency stability



300 mW at 254 nm

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