Verifying QED through precision measurement of the metastable Helium tune-out frequency

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Quantum Electrodynamics (QED)

- Quantum electrodynamics (QED) is one of the most rigorously tested theories of modern physics for which He - the simplest multi-electron atom - is a key test-bed (more complex atoms e.g. alkalis, are intractable)
- Energy levels can be determined via a power series expansion of the fine-structure constant α to a high level of accuracy
- Ultrahigh resolution lasers and frequency combs have enabled measurement of He transition *intervals* with an accuracy exceeding one part in 10^{11} to test QED theory – and stood the test!
- Transition *rates* are much harder to measure, and theoretical calculations are similarly constrained in accuracy: difficult to challenge QED – thus far.

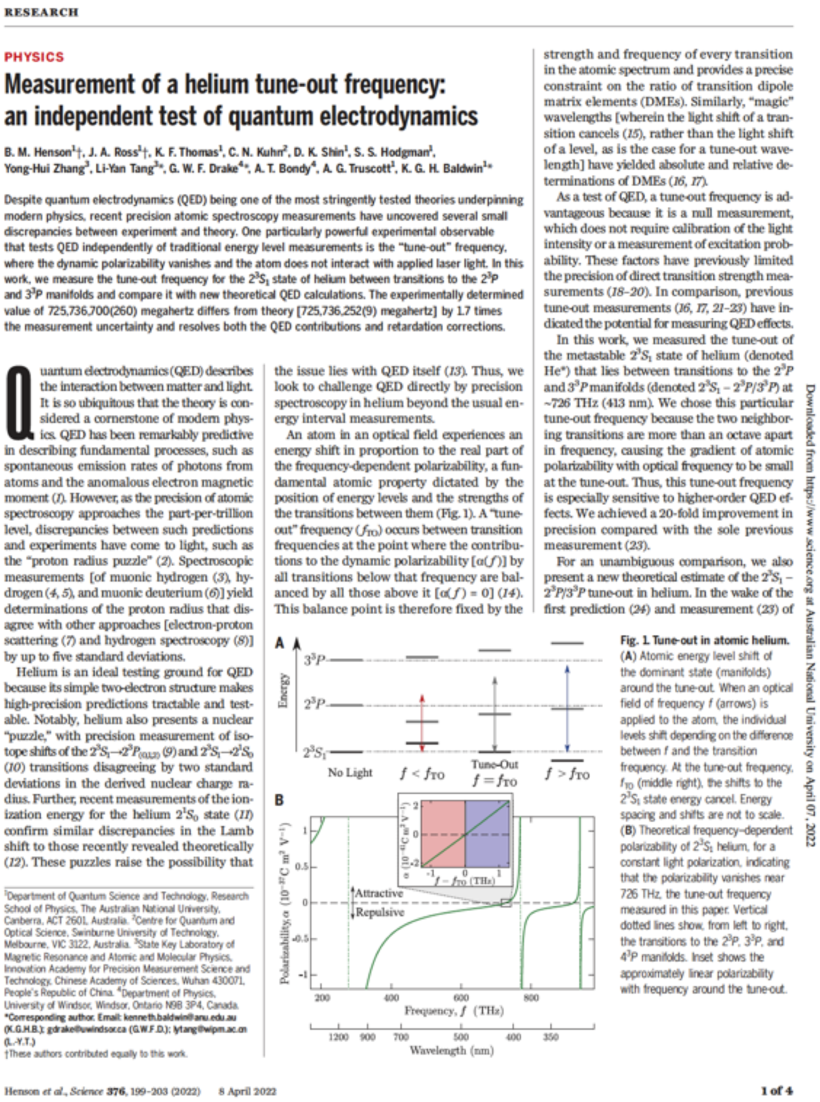
QED and the proton radius puzzle

- Discrepancies in the proton radius arose in spectroscopy of muonic- and electronic-hydrogen (involving QED) which differ by ~5σ [Pohl et al. **Nature** 466, 213-216 (2010), H. Fleurbaey et al., **PRL** 120, 183001 (2018), N. Bezginov et al., **Science** 365, 1007 (2019)] – the "proton radius puzzle" – new physics?

- Helium also has a nuclear "puzzle," with ^{3}He and ^{4}He isotope shifts of the $2^3S_1 \rightarrow 2^3P_{(0,1,2)}$ (X. Zheng et al., **PRL** 119, 263002 (2017)) and $2^3S_1 \rightarrow 2^1S_0$ (R. J. Rengelink et al., **Nat. Phys.** 14, 1132–1137 (2018)) transitions disagreeing by 2σ in the nuclear charge radius – *but recent news*: arxiv.org/abs/2306.02333

- More stringent tests of QED using different experiments are therefore important to provide independent validation or otherwise of QED.

Measuring the He* tune-out frequency to test QED



PHYSICS

Measurement of a helium tune-out frequency: an independent test of quantum electrodynamics

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Despite quantum electrodynamics (QED) being one of the most stringently tested theories underpinning modern physics, recent precision atomic spectroscopy measurements have uncovered several small discrepancies between experiment and theory. One particularly powerful experimental observable that tests QED independently of traditional energy level measurements is the "tune-out" frequency, where the dynamic polarizability vanishes and the atom does not interact with applied laser light. In this work, we measure the tune-out frequency for the 2^3S_1 state of helium between transitions to the 2^3P and 3^3P manifolds and compare it with new theoretical QED calculations. The experimentally determined value of 725,736,700(260) megahertz differs from theory [725,736,252(9) megahertz] by 1.7 times the measurement uncertainty and resolves both the QED contributions and retardation corrections.

Quantum electrodynamics (QED) describes the interaction between matter and light. It is so ubiquitous that the theory is considered a cornerstone of modern physics. QED has been remarkably predictive in describing fundamental processes, such as spontaneous emission rates of photons from atoms and the anomalous electron magnetic moment (*1*). However, as the precision of atomic spectroscopy approaches the part-per-trillion level, discrepancies between such predictions and experiments have come to light, such as the "proton radius puzzle" (*2*). Spectroscopic measurements [of muonic hydrogen (*3*), hydrogen (*4*, *5*), and muonic deuterium (*6*)] yield determinations of the proton radius that disagree with other approaches [electron-proton scattering (*7*) and hydrogen spectroscopy (*8*)] by up to five standard deviations.

Helium is an ideal testing ground for QED because its simple two-electron structure makes high-precision predictions tractable and testable. Notably, helium also presents a nuclear "puzzle," with precision measurement of isotope shifts of the $2^3S_1 \rightarrow 2^3P_{(0,1,2)}$ (*9*) and $2^3S_1 \rightarrow 2^1S_0$ (*10*) transitions disagreeing by two standard deviations in the derived nuclear charge radius. Further, recent measurements of the ionization energy for the helium 2^1S_0 state (*11*) confirm similar discrepancies in the Lamb shift to those recently revealed theoretically (*12*). These puzzles raise the possibility that the issue lies with QED itself (*13*). Thus, we look to challenge QED directly by precision spectroscopy in helium beyond the usual energy interval measurements.

An atom in an optical field experiences an energy shift in proportion to the real part of the frequency-dependent polarizability, a fundamental atomic property dictated by the position of energy levels and the strengths of the transitions between them (Fig. 1). A "tune-out" frequency (f_{TO}) occurs between transition frequencies at the point where the contributions to the dynamic polarizability [$\alpha(f)$] by all transitions below that frequency are balanced by all those above it [$\alpha(f) = 0$] (*14*). This balance point is therefore fixed by the strength and frequency of every transition in the atomic spectrum and provides a precise constraint on the ratio of transition dipole matrix elements (DMEs). Similarly, "magic" wavelengths [wherein the light shift of a transition cancels (*15*), rather than the light shift of a level, as is the case for a tune-out wavelength] have yielded absolute and relative determinations of DMEs (*16*, *17*).

As a test of QED, a tune-out frequency is advantageous because it is a null measurement, which does not require calibration of the light intensity or a measurement of excitation probability. These factors have previously limited the precision of direct transition strength measurements (*18*–*20*). In comparison, previous tune-out measurements (*16*, *17*, *21*–*23*) have indicated the potential for measuring QED effects.

In this work, we measured the tune-out of the metastable 2^3S_1 state of helium (denoted He*) that lies between transitions to the 2^3P and 3^3P manifolds (denoted $2^3S_1 - 2^3P/3^3P$) at ~726 THz (413 nm). We chose this particular tune-out frequency because the two neighboring transitions are more than an octave apart in frequency, causing the gradient of atomic polarizability with optical frequency to be small at the tune-out. Thus, this tune-out frequency is especially sensitive to higher-order QED effects. We achieved a 20-fold improvement in precision compared with the sole previous measurement (*23*).

For an unambiguous comparison, we also present a new theoretical estimate of the $2^3S_1 - 2^3P/3^3P$ tune-out in helium. In the wake of the first prediction (*24*) and measurement (*23*) of

Fig. 1. Tune-out in atomic helium. (**A**) Atomic energy level shift of the dominant state (manifolds) around the tune-out. When an optical field of frequency *f* (arrows) is applied to the atom, the individual levels shift depending on the difference between *f* and the transition frequency. At the tune-out frequency, f_{TO} (middle right), the shifts to the 2^3S_1 state energy cancel. Energy spacing and shifts are not to scale. (**B**) Theoretical frequency–dependent polarizability of 2^3S_1 helium, for a constant light polarization, indicating that the polarizability vanishes near 726 THz, the tune-out frequency measured in this paper. Vertical dotted lines show, from left to right, the transitions to the 2^3P, 3^3P, and 4^3P manifolds. Inset shows the approximately linear polarizability with frequency around the tune-out.

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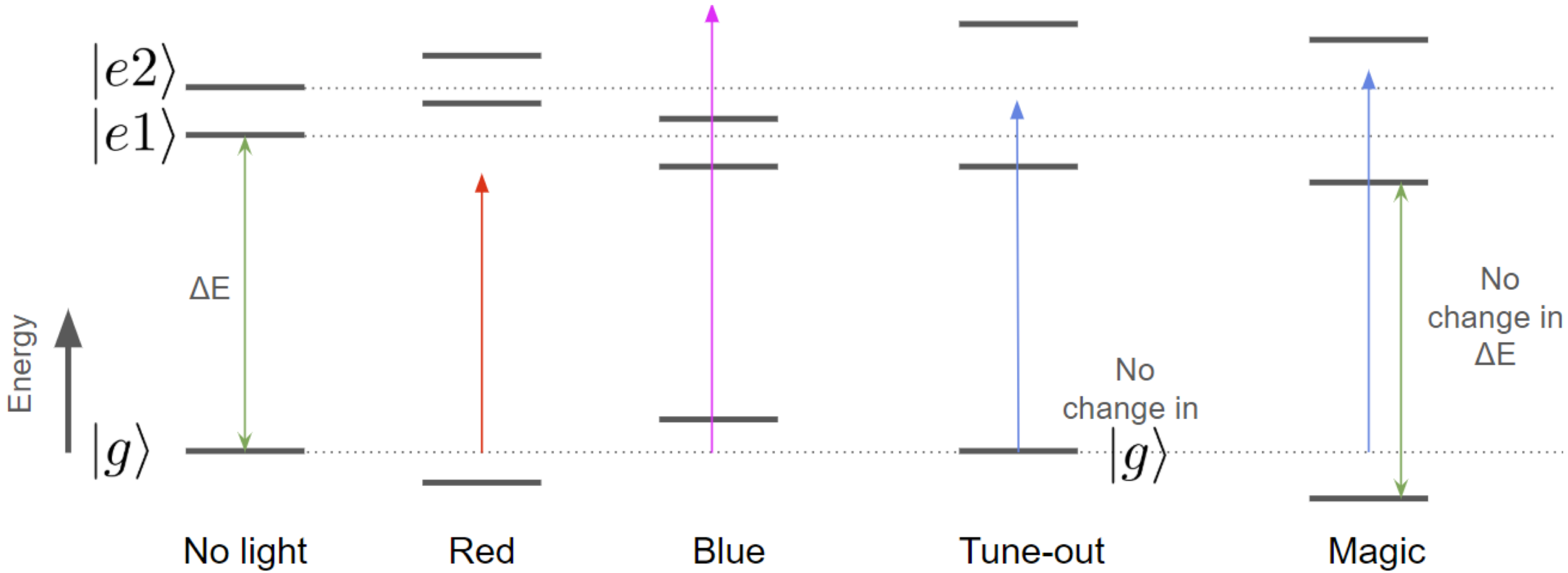
Henson *et al.*, *Science* **376**, 199–203 (2022)   8 April 2022   **1 of 4**

Science **376**, 199 - 203 (2022)

Tune-out and magic frequencies



The tune-out frequency is the frequency at which the atom no longer scatters photons, and so it becomes "invisible"

Metastable Helium

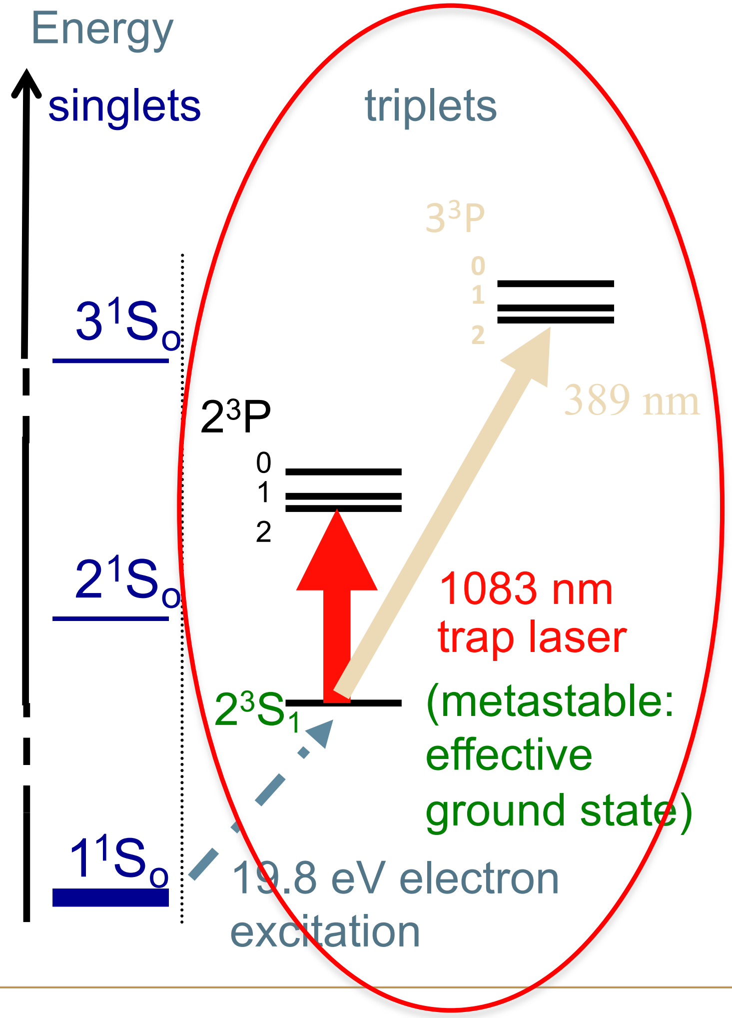
Metastable 2^3S_1 helium (He*) :

- A long lived (~8000s) state that acts as an effective “ground state” for atom optics
  Hodgman et al. PRL **103**, 053002 (2009)
- Has ~20 eV of internal energy enabling efficient *single particle detection* e.g. microchannel plate

See: “Metastable helium: Atom optics with nano-grenades”, K.G.H. Baldwin, *Cont. Phys.* **46**, 105 (2005)

He* BEC apparatus used for :

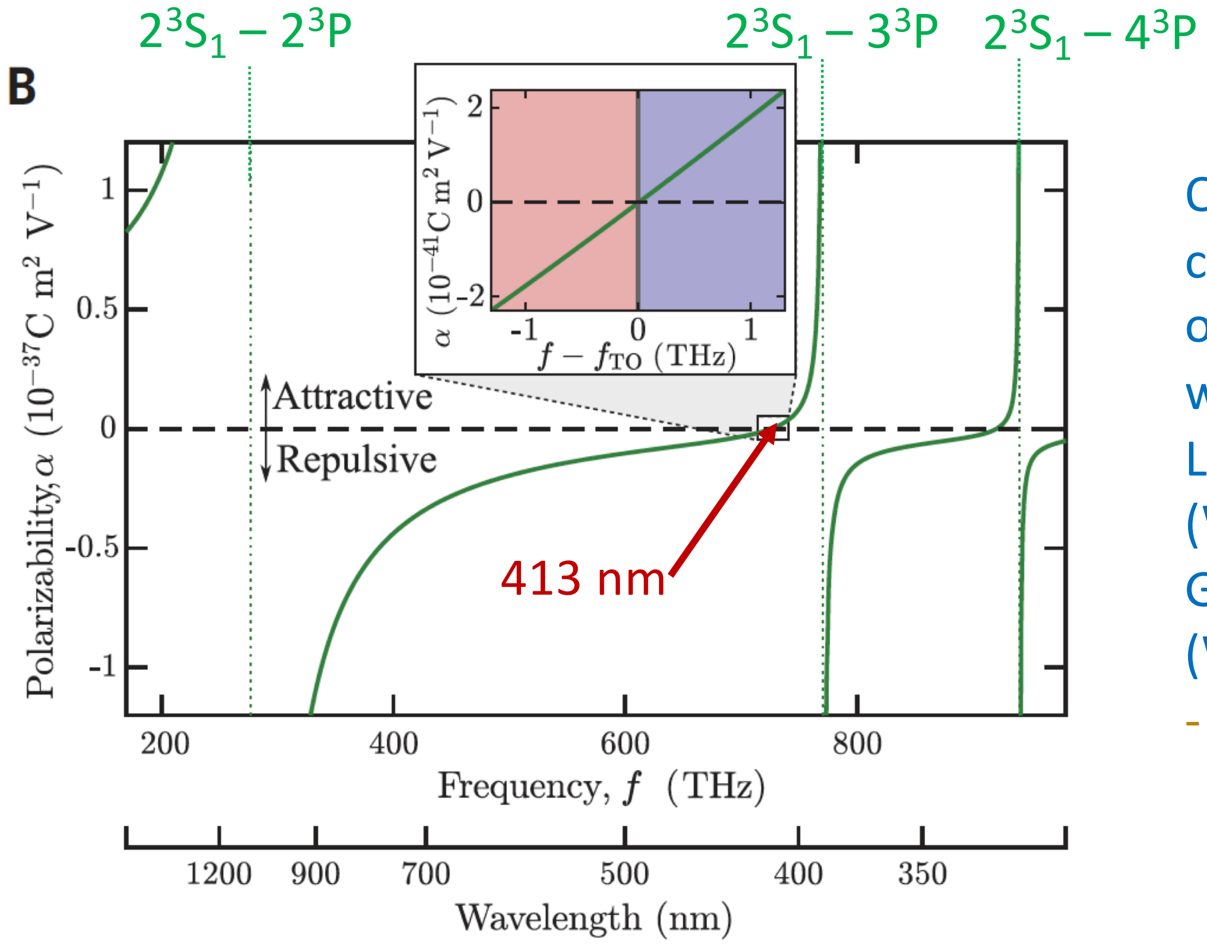
- Atomic physics: He* lifetimes, QED studies
- Atom lasers and atom guiding
- Quantum statistics and Bell’s inequalities
- Ghost imaging



Tune-out frequency calculation

First estimate of the 413 nm tune-out performed by Jim Mitroy (Darwin) & Li-Yan Tang (Wuhan) PRA, 2013

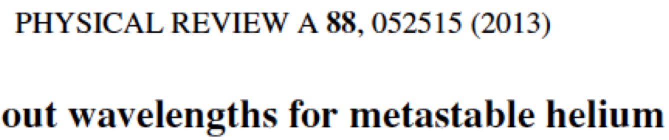
- 220ppm accuracy



Our present collaboration on QED theory with:
Li-Yan Tang (Wuhan) &
Gordon Drake (Windsor)

- 0.012ppm accuracy

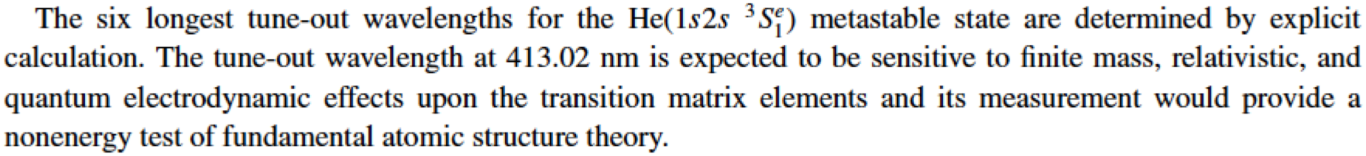
He* tune-out theory



PHYSICAL REVIEW A **88**, 052515 (2013)

Tune-out wavelengths for metastable helium

The tune-out ratio of transition strengths is more sensitive to QED contributions



The six longest tune-out wavelengths for the He(1*s*2*s* $^3S_1^e$) metastable state are determined by explicit calculation. The tune-out wavelength at 413.02 nm is expected to be sensitive to finite mass, relativistic, and quantum electrodynamic effects upon the transition matrix elements and its measurement would provide a nonenergy test of fundamental atomic structure theory.

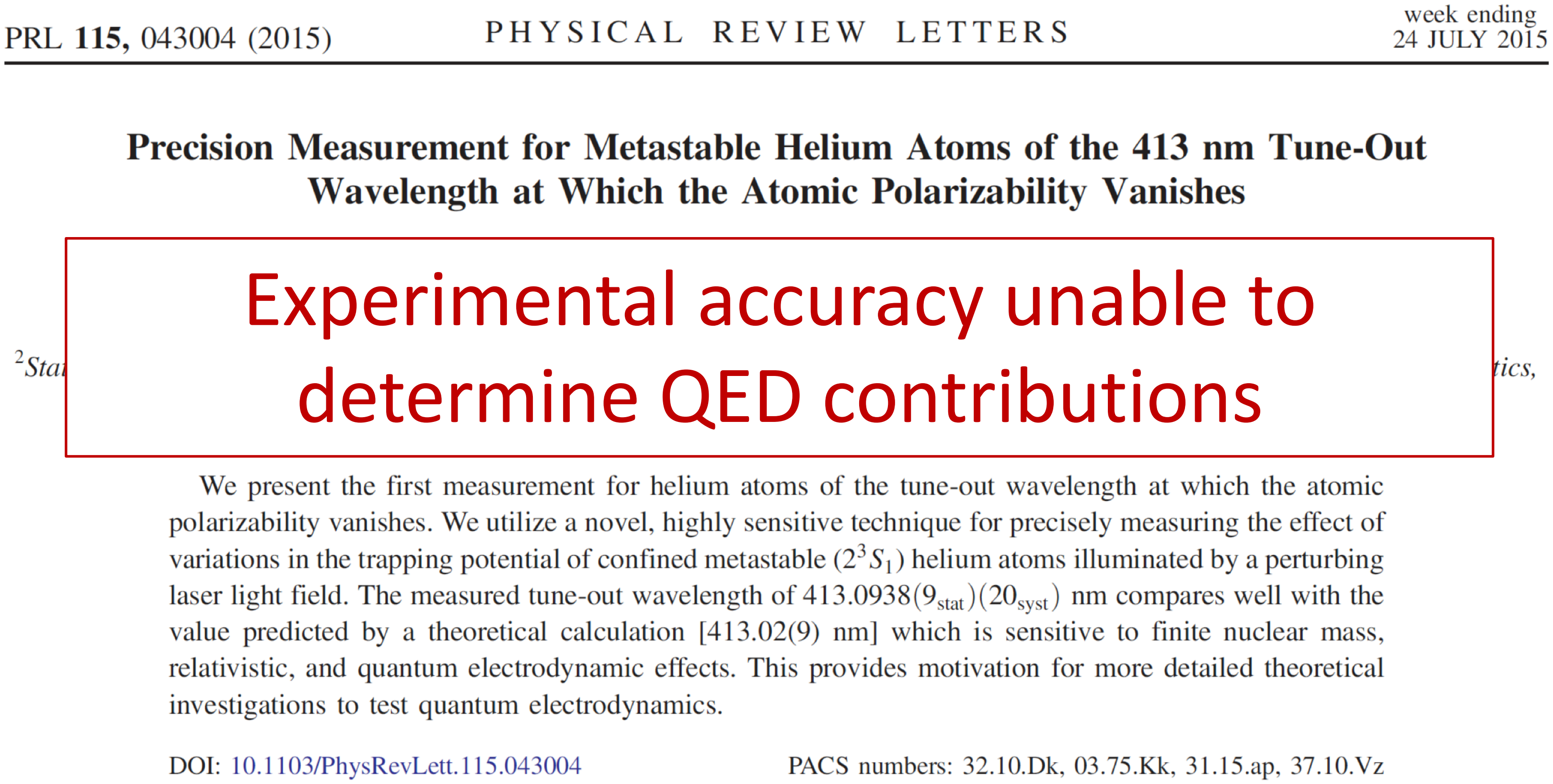
"Suppose the tune-out frequency can be determined to an absolute accuracy of 0.0001 nm, then the fractional uncertainty in the derived structure information would be 1.8 x 10^{-6}. This would constitute the most precise measurement of transition rate information ever made for helium …….. A measurement of the 413.02-nm tune-out wavelength at an accuracy of 0.0001 nm would have the potential to probe QED effects in an atomic structure model of the helium metastable state."

He* tune-out measurements at ANU

- 2013 – PRA **88**, 052515 *Tune out wavelengths for metastable helium*, J. Mitroy and L.-Y. Tang. Predict test of QED ~220 ppm
- 2015 – PRL **115**, 043004. First He* tune-out measurement ~5 ppm – insufficient to test QED, and theory only ~220 ppm

- 2018 – Australian Research Council grant with Li-Yan Tang and Gordon Drake (which improved theory to ~0.012 ppm)
- 2022 – Science **376**, 199. Measurement of He* tune-out at ~0.36 ppm which tests the QED contribution of ~10 ppm

First experimental 413nm detection



PRL **115,** 043004 (2015) PHYSICAL REVIEW LETTERS week ending 24 JULY 2015

Precision Measurement for Metastable Helium Atoms of the 413 nm Tune-Out Wavelength at Which the Atomic Polarizability Vanishes

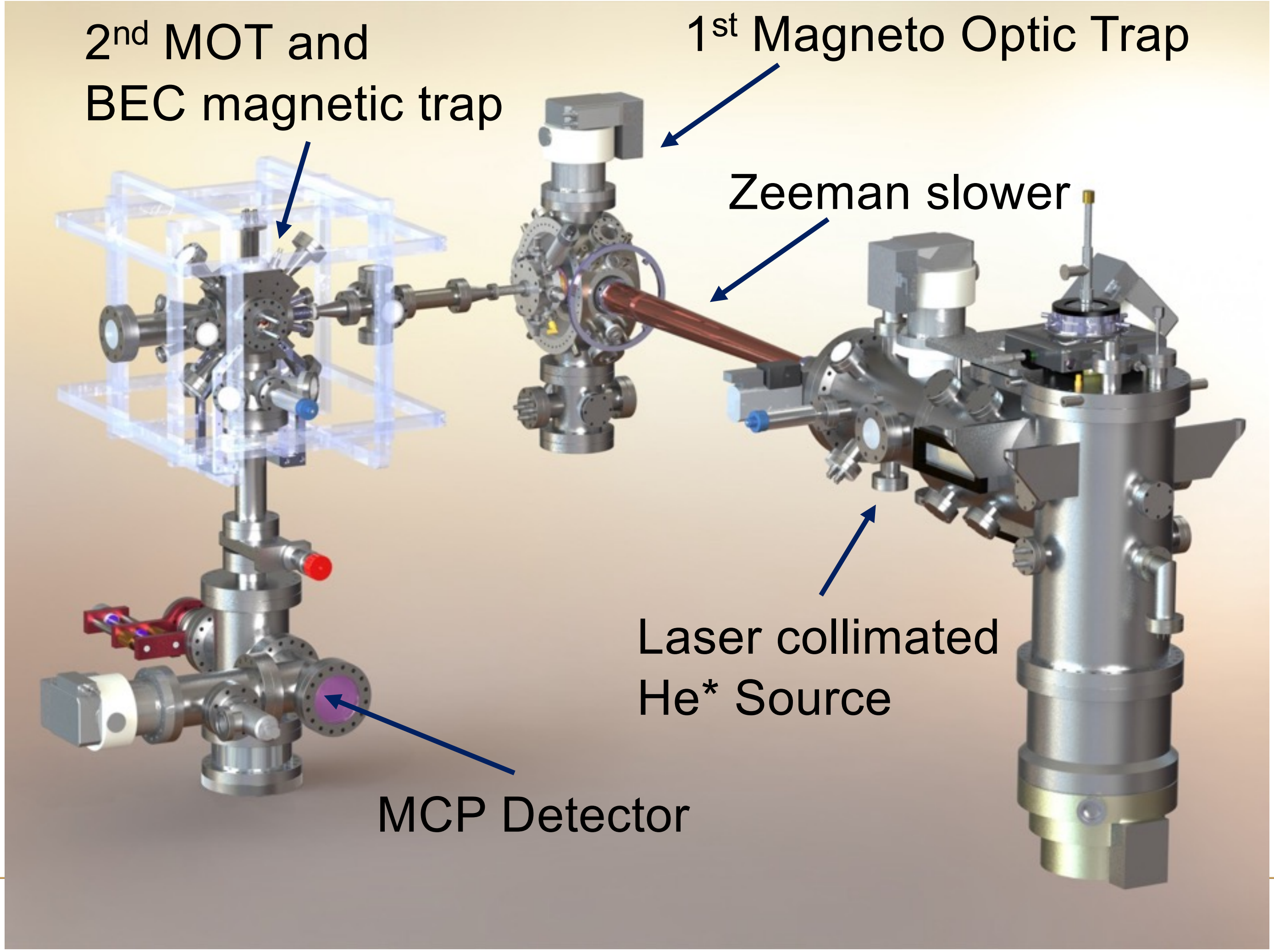
Experimental accuracy unable to determine QED contributions

^{2}*Sta* … *tics,*

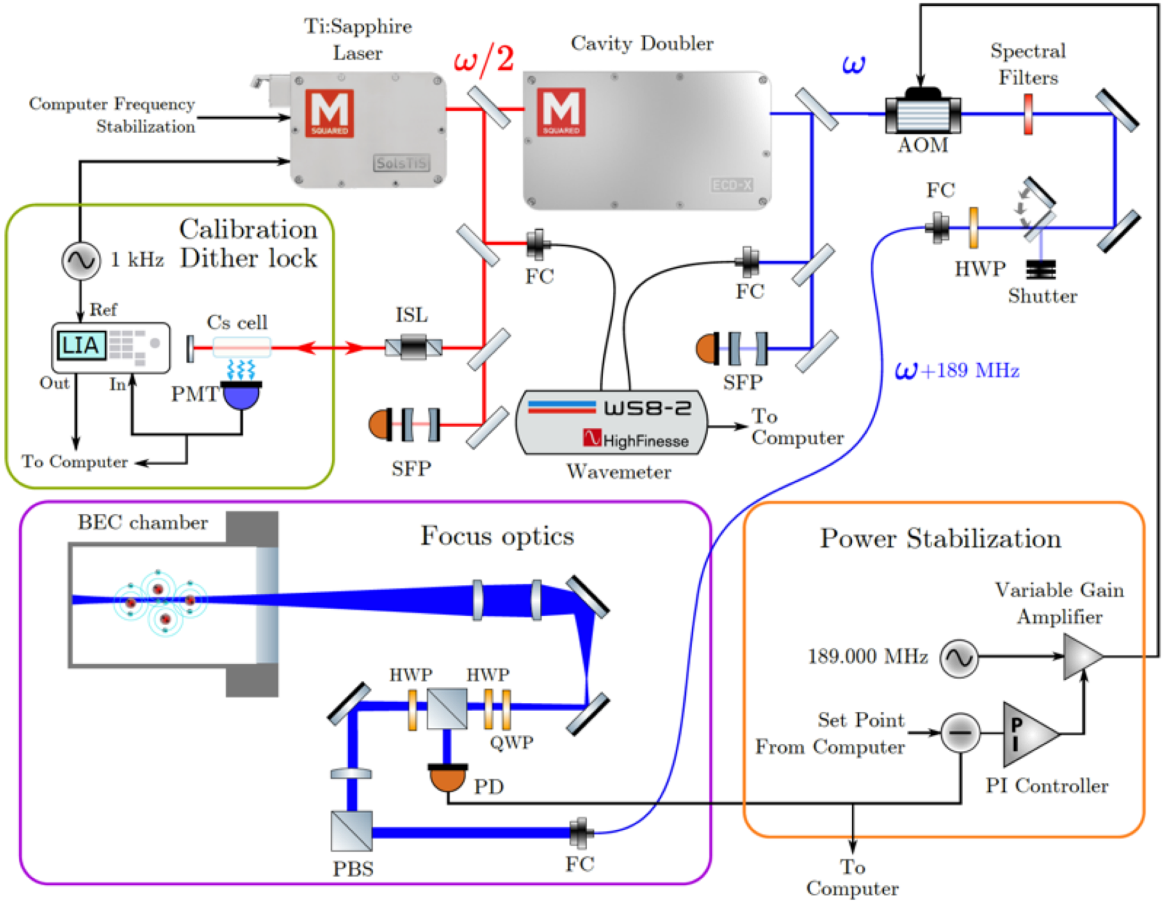
We present the first measurement for helium atoms of the tune-out wavelength at which the atomic polarizability vanishes. We utilize a novel, highly sensitive technique for precisely measuring the effect of variations in the trapping potential of confined metastable (2^3S_1) helium atoms illuminated by a perturbing laser light field. The measured tune-out wavelength of $413.0938(9_{\mathrm{stat}})(20_{\mathrm{syst}})$ nm compares well with the value predicted by a theoretical calculation [413.02(9) nm] which is sensitive to finite nuclear mass, relativistic, and quantum electrodynamic effects. This provides motivation for more detailed theoretical investigations to test quantum electrodynamics.

DOI: 10.1103/PhysRevLett.115.043004 PACS numbers: 32.10.Dk, 03.75.Kk, 31.15.ap, 37.10.Vz

Experimental apparatus



New 413nm probe laser system

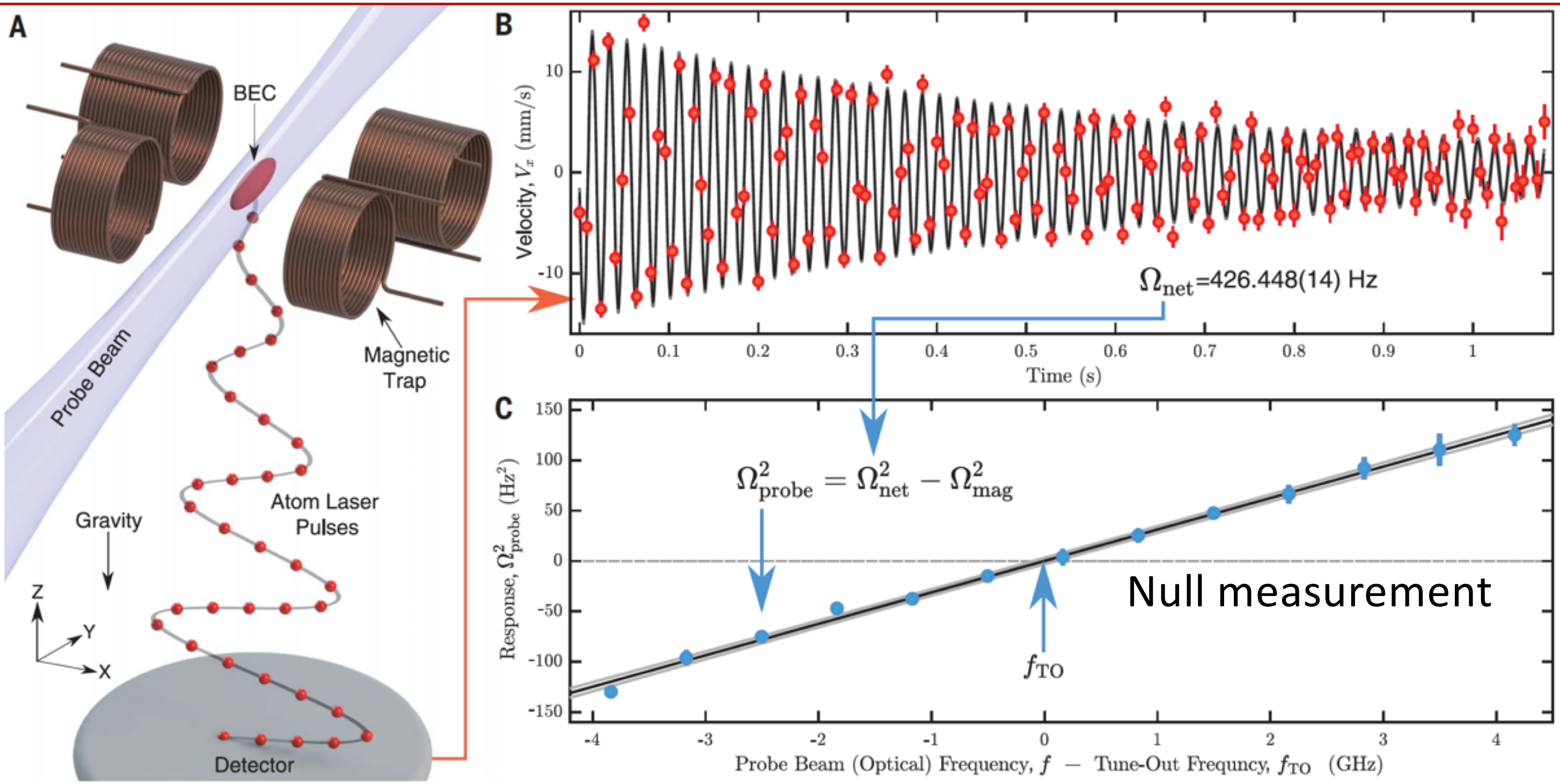


- More power
- Greater stability
- Spectral purity
- Cs cell reference

New atom laser trap frequency measurement

Experimental sensitivity is 10^{-35} Joule!

Precision ~20 better than previously, enabling determination of QED contributions



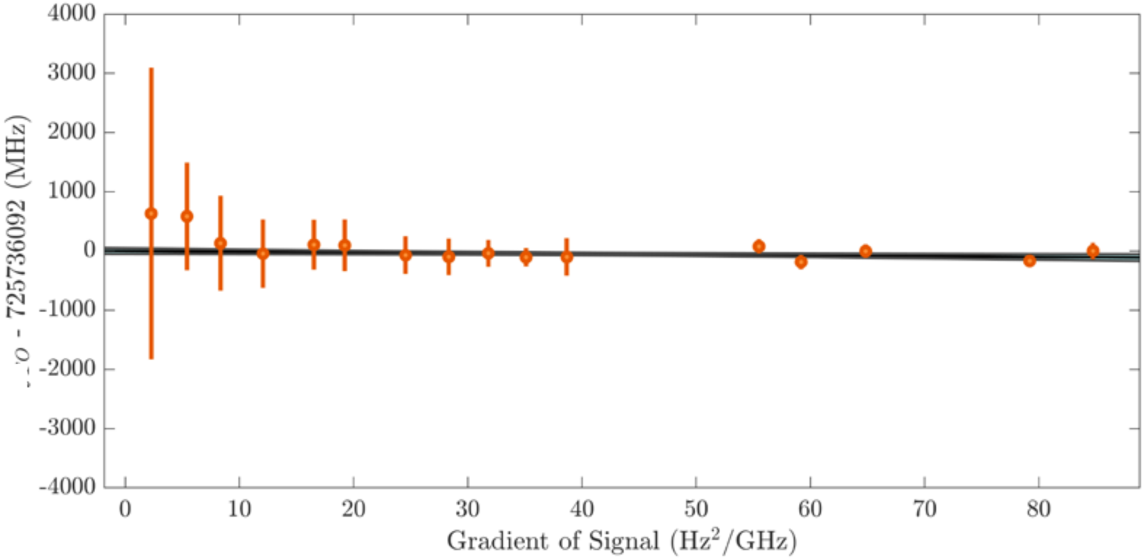
Ω_{net}=426.448(14) Hz

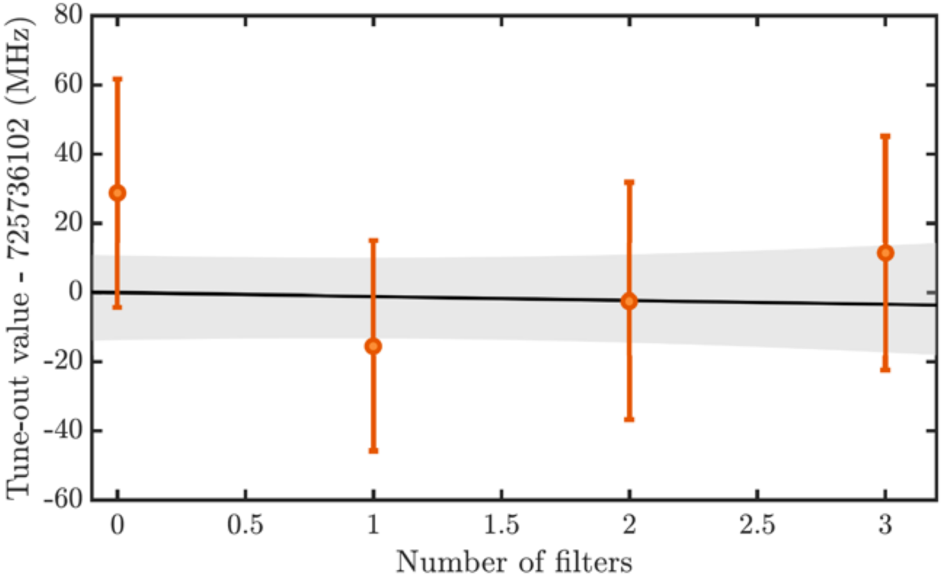
$$\Omega^2_{\mathrm{probe}} = \Omega^2_{\mathrm{net}} - \Omega^2_{\mathrm{mag}}$$

Null measurement

Systematic effects

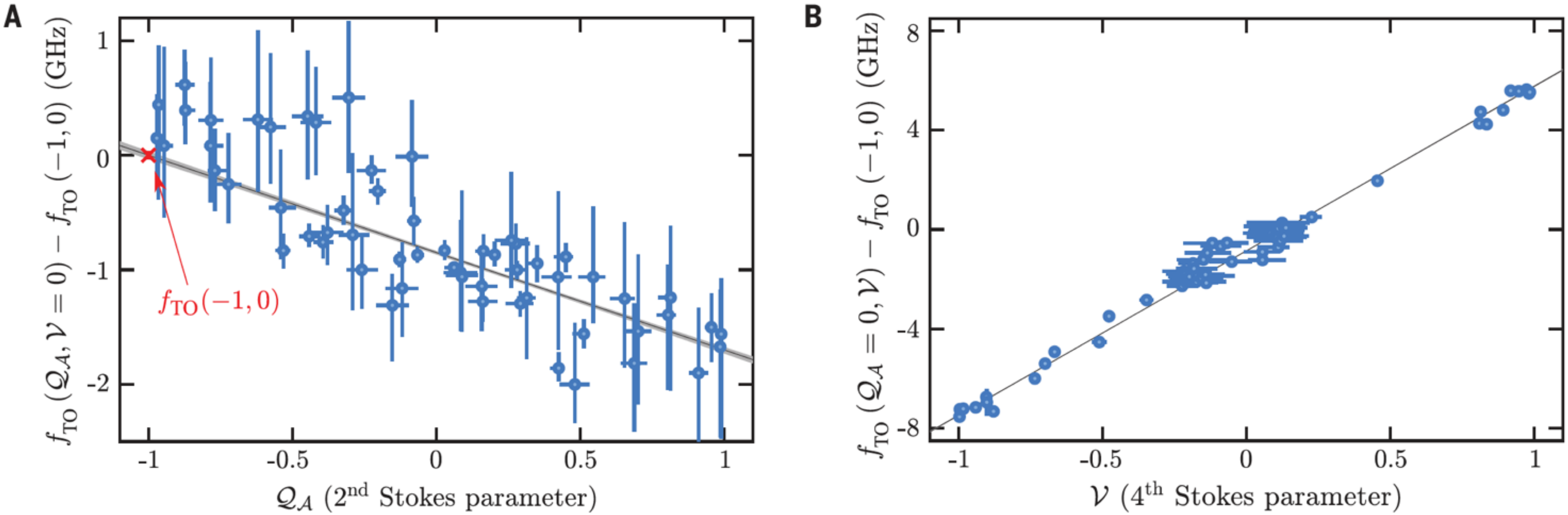
Probe laser intensity



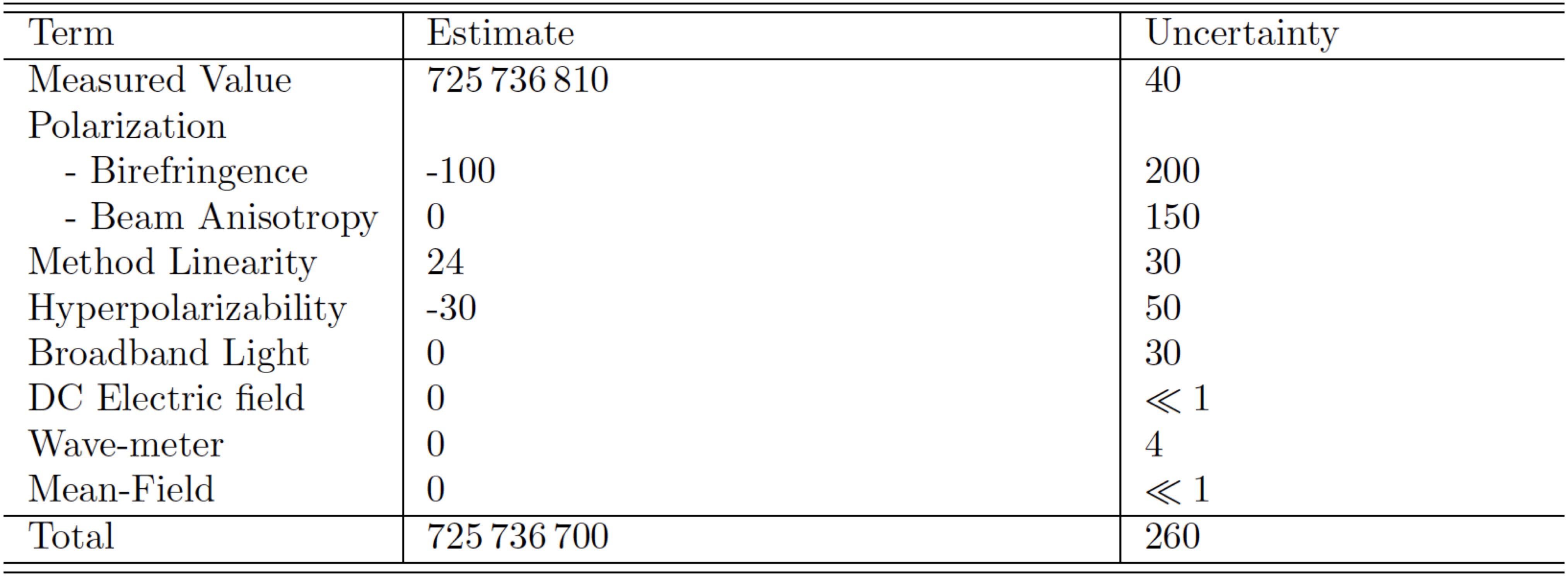


Broadband light

Effect of laser polarisation

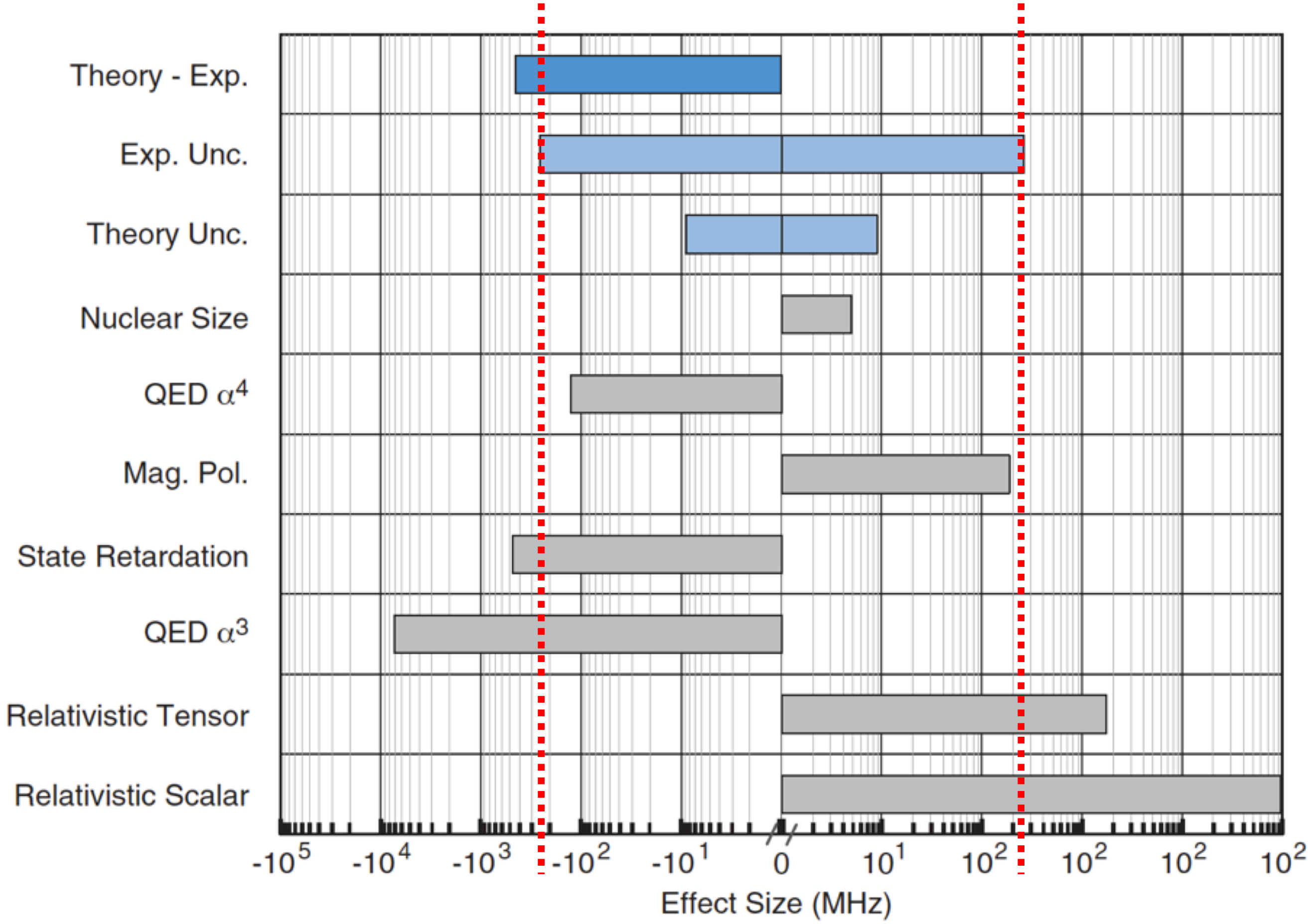


Experimental error budget (MHz)



Term	Estimate	Uncertainty
Measured Value	725 736 810	40
Polarization		
- Birefringence	-100	200
- Beam Anisotropy	0	150
Method Linearity	24	30
Hyperpolarizability	-30	50
Broadband Light	0	30
DC Electric field	0	$\ll 1$
Wave-meter	0	4
Mean-Field	0	$\ll 1$
Total	725 736 700	260

Contributions – theory and expt.



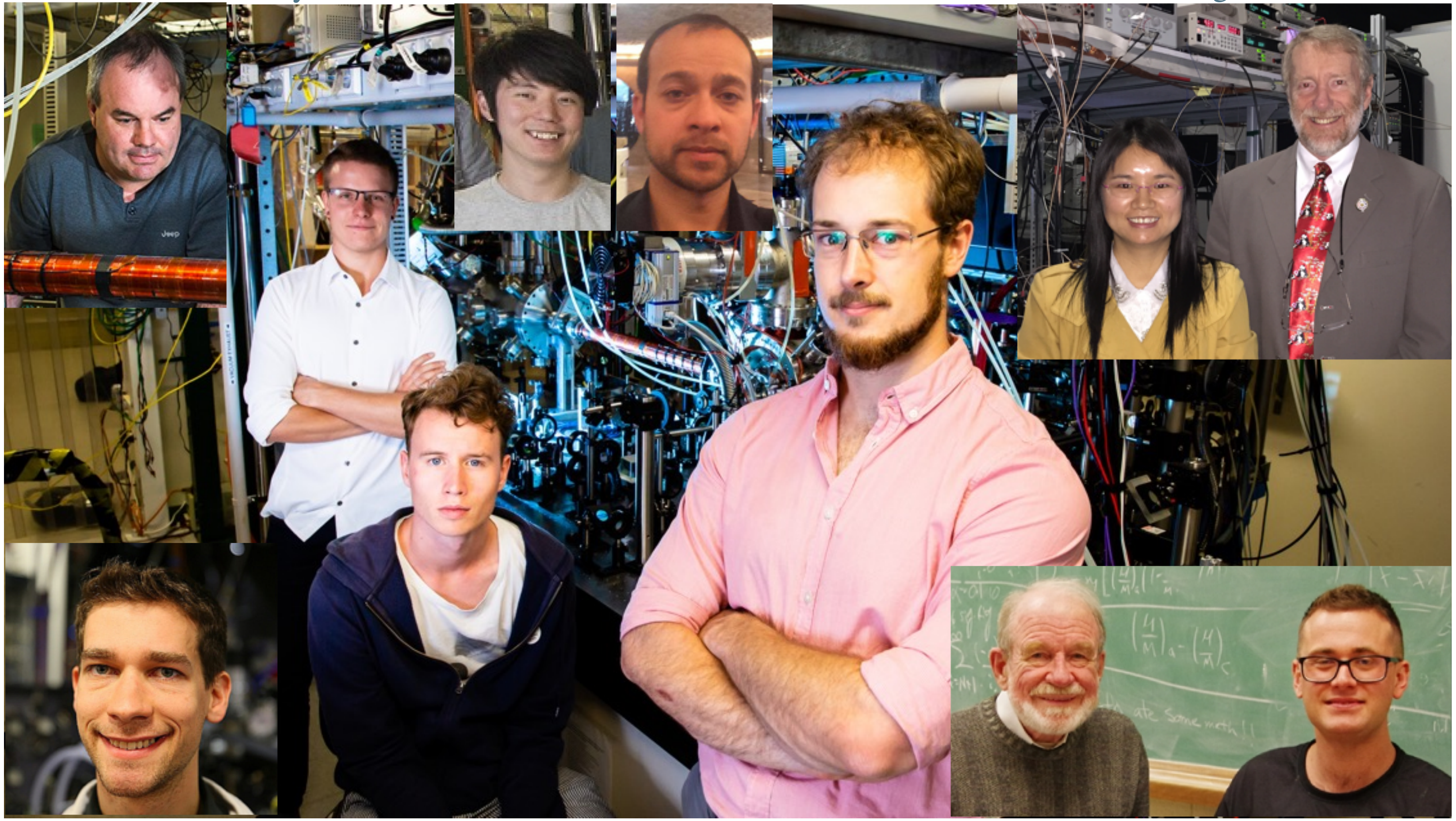
Conclusions

- “measurement of the 413.02nm tune-out wavelength at an accuracy of 0.0001 nm [~0.24 ppm] would have the potential to probe QED effects”
  – J Mitroy & L-Y Tang (PRA, 2013)
- Our theory calculation is now accurate to ~0.012 ppm: 725,736,252(9) MHz
- Our experiment is now accurate to ~0.36 ppm: 725,736,700(260) MHz
- Experiment has been able to resolve (by a factor of almost 30) QED contributions ~10 ppm and (by a factor of 2) retardation corrections ~0.7 ppm
- The current discrepancy between theory and experiment is ~1.7σ
- Without retardation correction, discrepancy is ~0.1σ
- Using a new and completely independent method, and within the above uncertainties – QED is alive and well!

The He* tune-out team

(Yong-Hui Zhang)

Andrew Truscott Bryce Henson David Shin Carlos Kuhn Li-Yan Tang Ken Baldwin



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THANK YOU!

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