The Proton Radius Puzzle
- precision spectroscopy at extremes -

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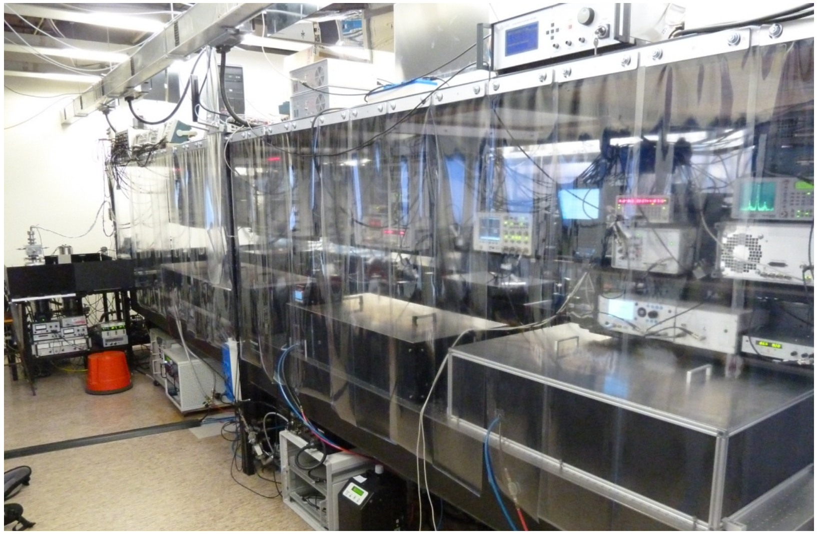


LaserLaB Amsterdam

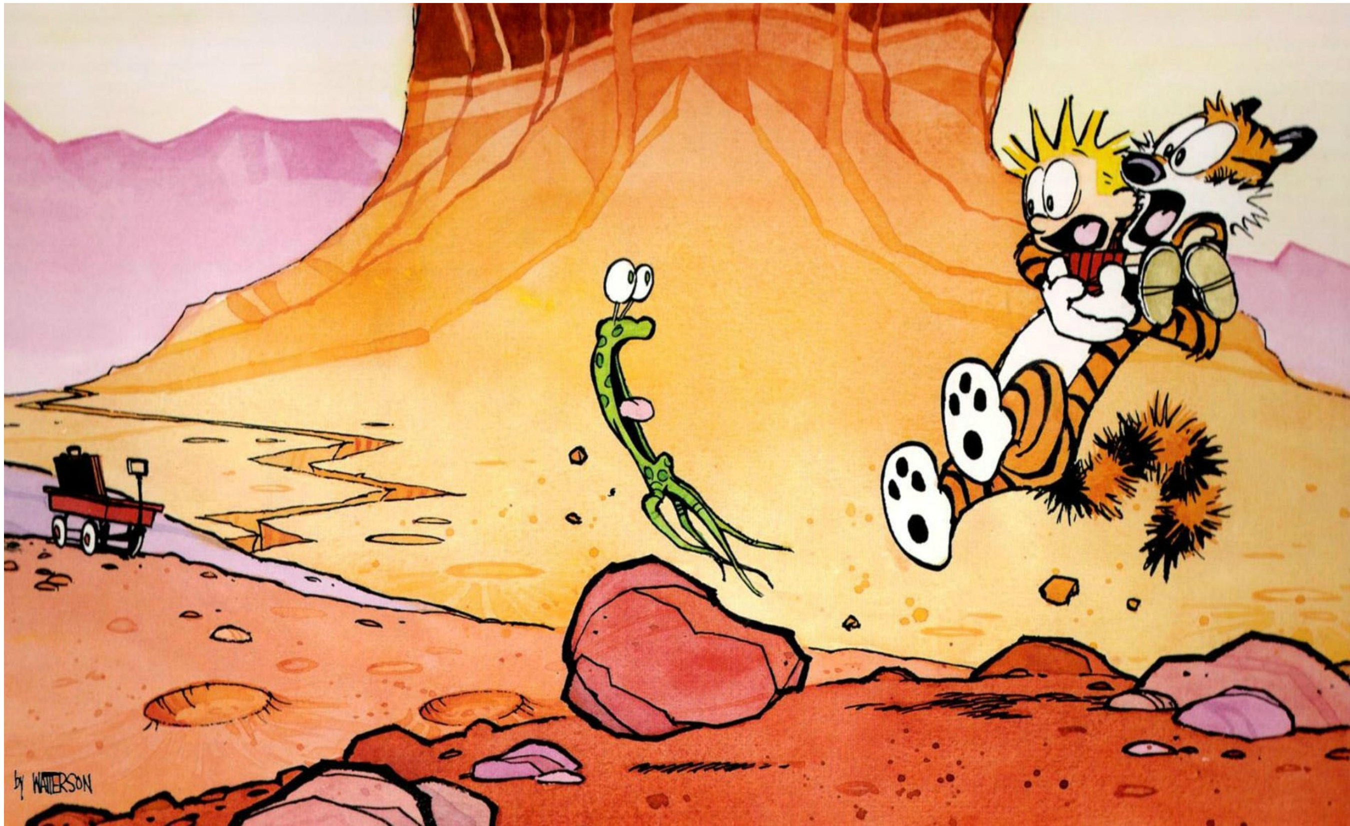
€ from:

Nikhef Colloquium 23 September 2016

Outline

LaserLaB Amsterdam

- ☐ **Proton Radius & Deuteron Radius Puzzle**
- ☐ **Precision revolution: frequency comb lasers**
- ☐ **Ramsey-comb excitation: power and accuracy combined**
- ☐ **Deep-UV Ramsey-comb excitation of Kr and H2**
- ☐ **Prospects for He+ 1S-2S spectroscopy**
- ☐ **Summary**



Calvin & Hobbes
meet an alien from
another planet ...

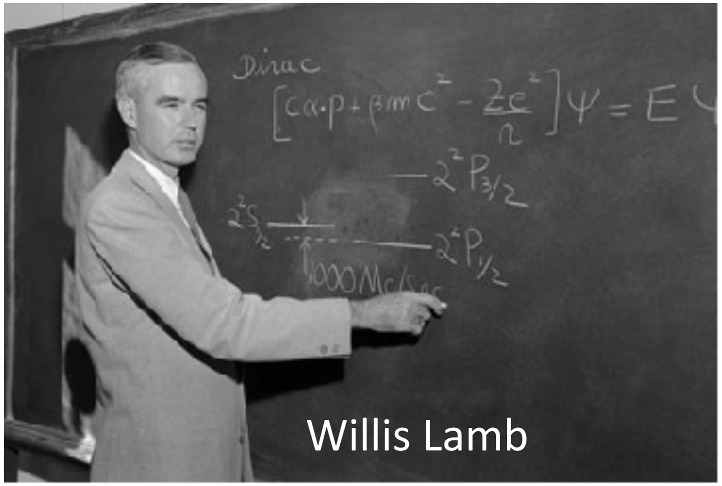
Cartoon by
Bill Watterson

Precision tests at the atomic scale

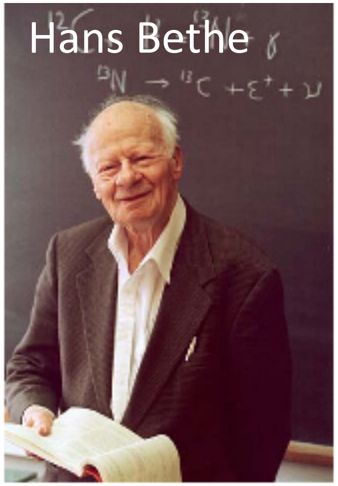
QED:

First seen as 'Lamb shift' in 2S-2P in hydrogen by W. Lamb in 1947

1.0576 GHz (microwaves)



Willis Lamb



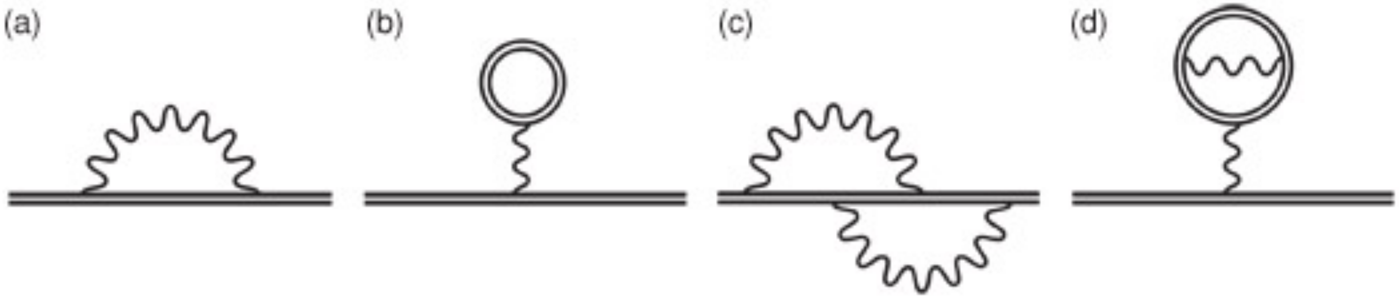
Hans Bethe

First calculation by Bethe (1947)

Heisenbergs uncertainty principle:

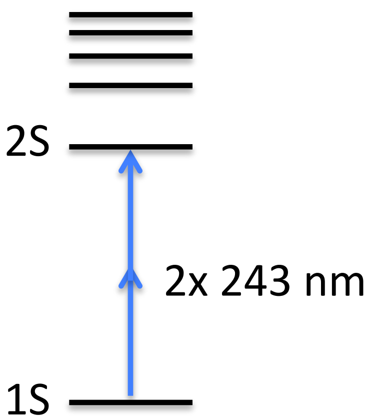
$$\Delta E\ \Delta t \geq h/4\pi$$

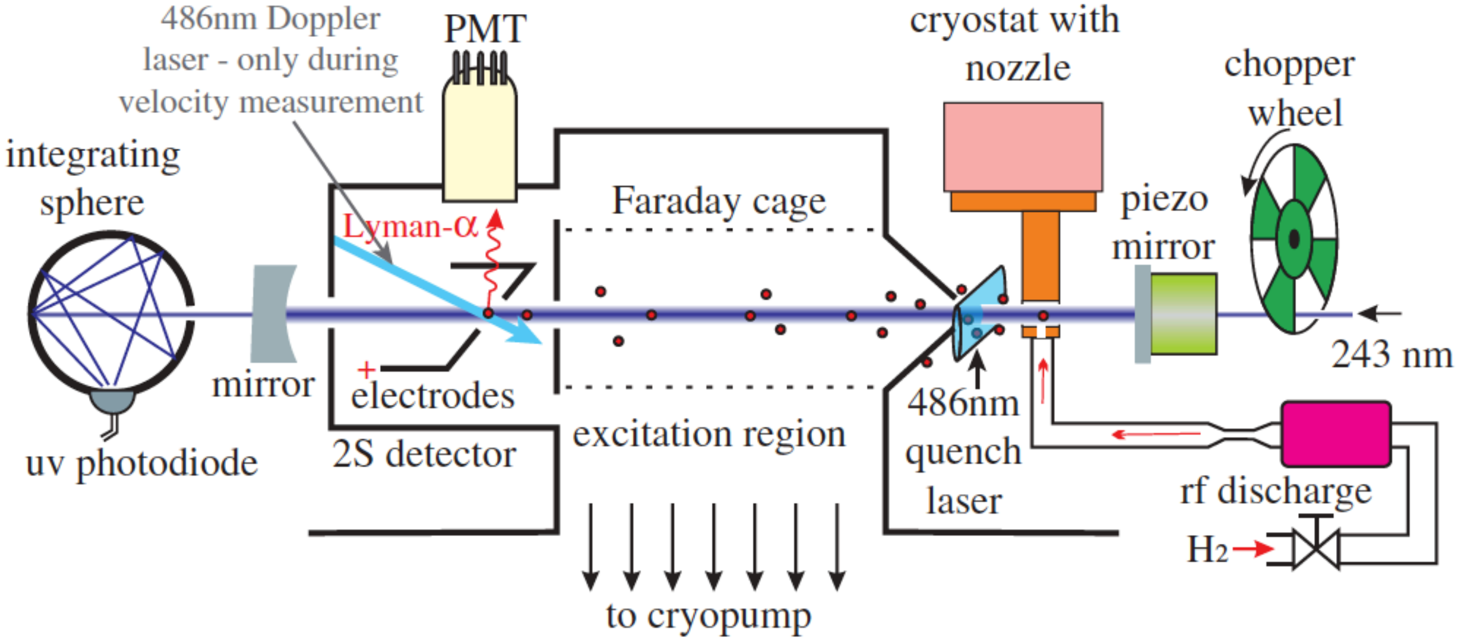
(a) Self-interaction
(b) vacuum-polarization
(c) Two-loop
(d) ....



Physics Nobel Prize in 1965 for Schwinger, Feynman, and Tomonaga

MPQ 1S-2S hydrogen experiment in 2011





1S-2S: 2 466 061 413 187 035 (10) Hz

C.G. Parthey et al.,
PRL **107**, 203001 (2011)

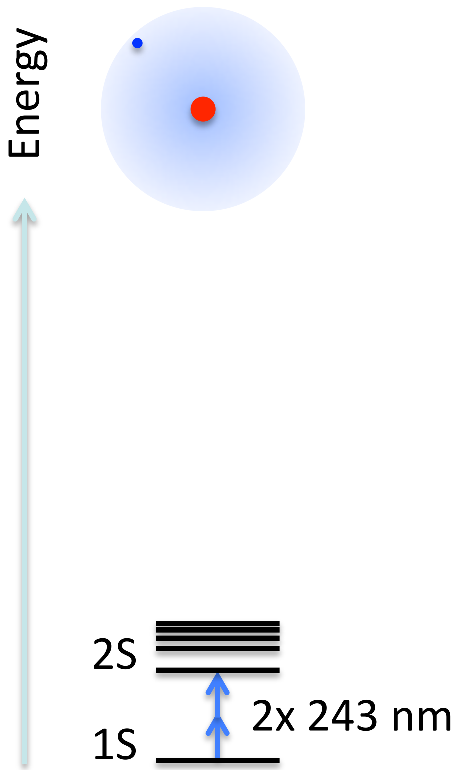
The 1S-2S values for H

		Scaling	H (kHz)
Theory	$\Delta\upsilon_{1S\text{-}2S}$	Z^2	$2.466\ldots\times10^{12}$
	$\Gamma_{1S\text{-}2S}$	Z^4	1.3×10^{-3}
	$\Delta L_{1S\text{-}2S}$	$Z^{\geq3.7}$	7 127 887(44)
	Finite size	Z^4r^2	1102(44)
	(nucl. pol.)		(2)
	$B_{60}+B_{7i}$	$Z^{\geq6}$	-8(3)
	Test $B_{60}+B_{7i}$		25%
	Rel. acc. $\Delta L_{1S\text{-}2S}$		6.3 ppm
Experiment	$\Delta\upsilon_{1S\text{-}2S}$		246606143187.035(10)
	$\delta L(\delta R_\infty)_{1S\text{-}2S}$	Z^2	16
	Rel. $\delta L(\delta R_\infty)$		2.2 ppm

H 1S-2S from
C.G. Parthey et al.,
PRL **107**, 203001 (2011)

Hydrogen spectroscopy testing QED?

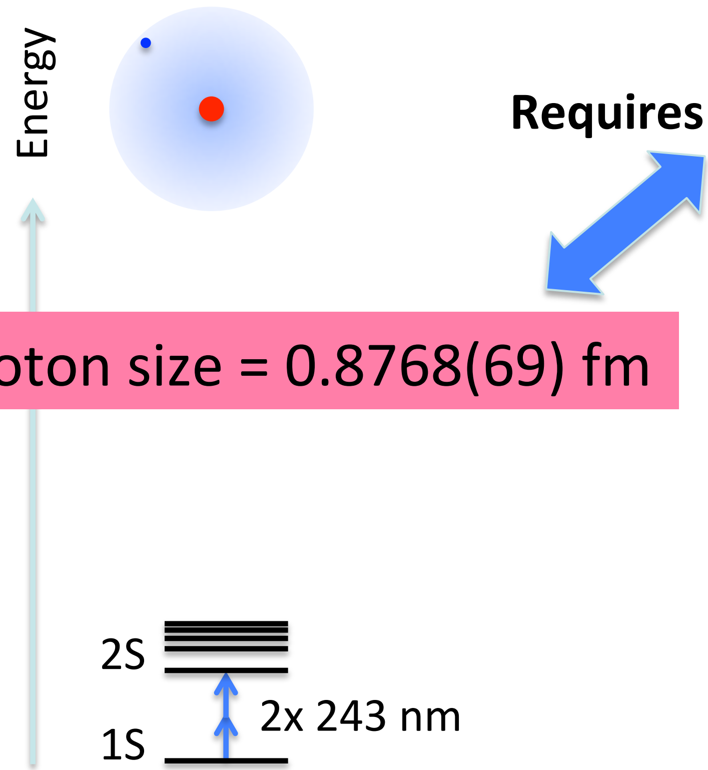
Hydrogen (H)



C.G. Parthey et al.,
PRL **107**, 203001 (2011)
1S-2S: 2 466 061 413 187 035 (10) Hz

Obtain the proton radius instead?

Hydrogen (H)



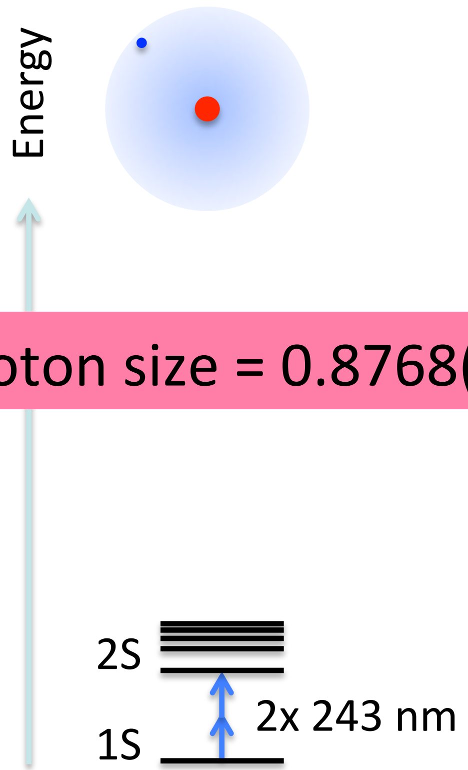
Requires Rydberg constant

proton size = 0.8768(69) fm

C.G. Parthey et al.,
PRL **107**, 203001 (2011)
1S-2S: 2 466 061 413 187 035 (10) Hz

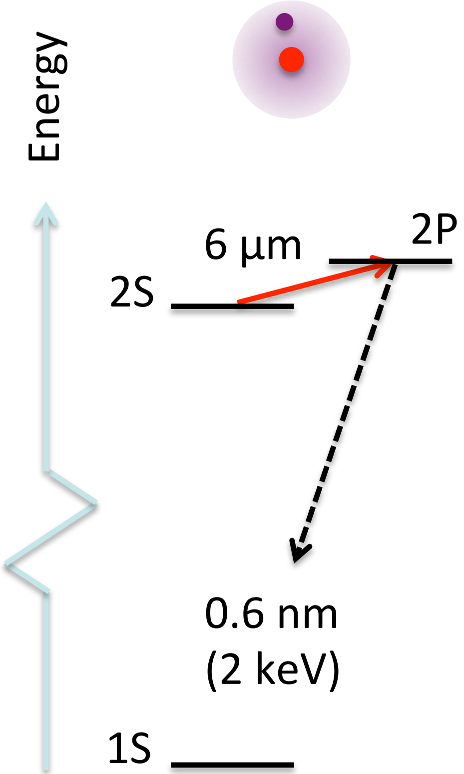
Muonic hydrogen at PSI Switserland

Hydrogen (H)



proton size = 0.8768(69) fm

Muonic hydrogen (μH)



C.G. Parthey et al.,
PRL **107**, 203001 (2011)
1S-2S: 2 466 061 413 187 035 (10) Hz

R. Pohl et al,
Nature, vol. **466**, pp. 213-216 (2010)
Science **339**, 417-420 (2013).

Muonic hydrogen 2S-2P spectrum

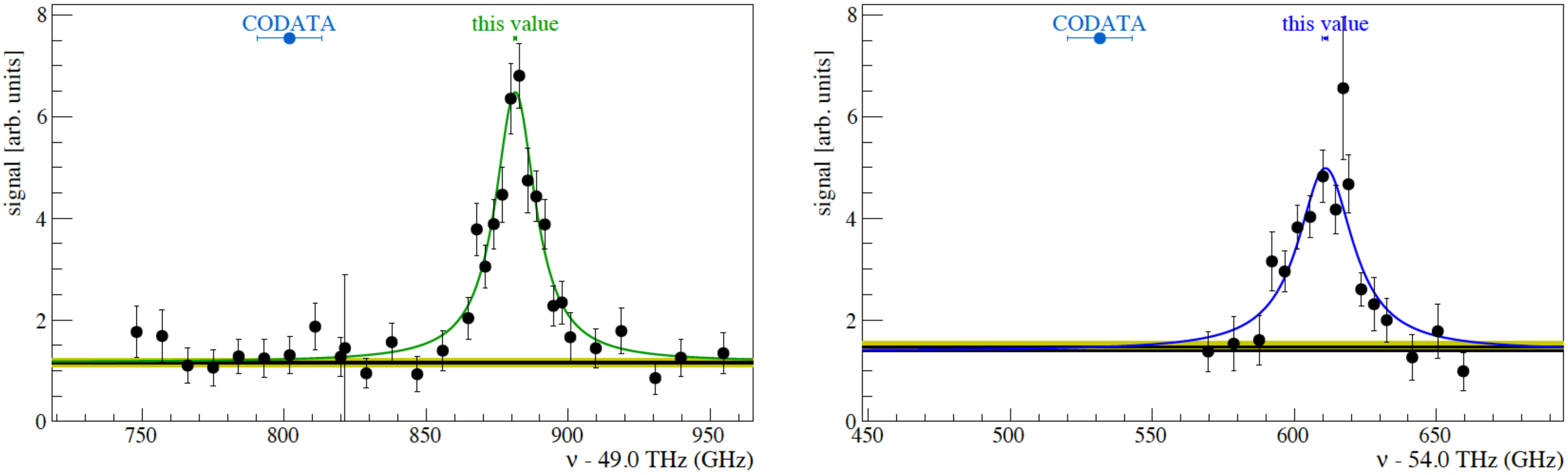
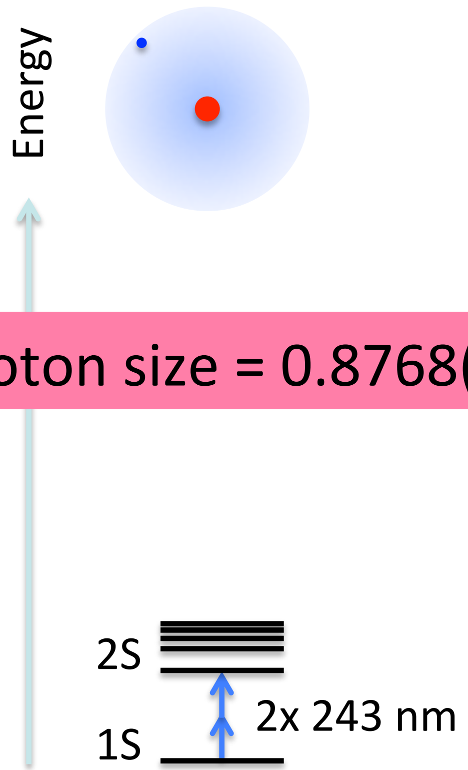


Fig. 2. Two resonances measured in μp see Fig. 1(a). Left: $2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$ transition from the F=1 triplet state near $\lambda = 6.0\,\mu$m (49881.35 ± 0.65 GHz). Right: The $2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}$ transition from the F=0 singlet state near $\lambda = 5.5\,\mu$m (54611.16 ± 1.03 GHz). The horizontal bar indicates the background level (with uncertainty), including data taken without laser. The expected resonance positions calculated using the CODATA value of r_E(p) are 80 GHz below the observed positions.

arXiv paper 1609.03440

Proton size 4% smaller?

Hydrogen (H)



proton size = 0.8768(69) fm

C.G. Parthey et al.,
PRL **107**, 203001 (2011)
1S-2S: 2 466 061 413 187 035 (10) Hz

Muonic hydrogen (μH)

8 July 2010 | www.nature.com/nature | £10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

OIL SPILLS
There's more to come

PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

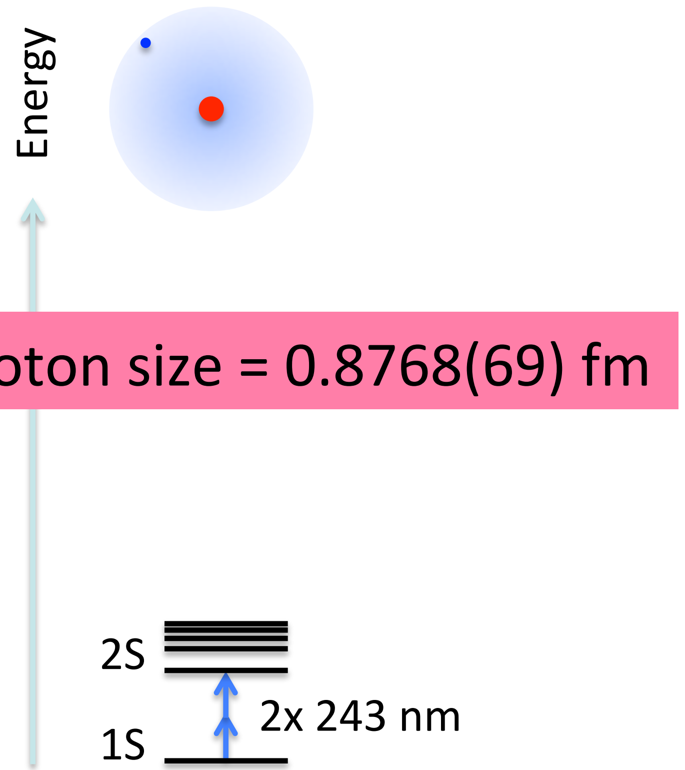
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent

NATUREJOBS
Researchers for hire

Nature, vol. **466**, pp. 213-216 (2010)
Science **339**, 417-420 (2013).

Conflicting proton radii ?!?

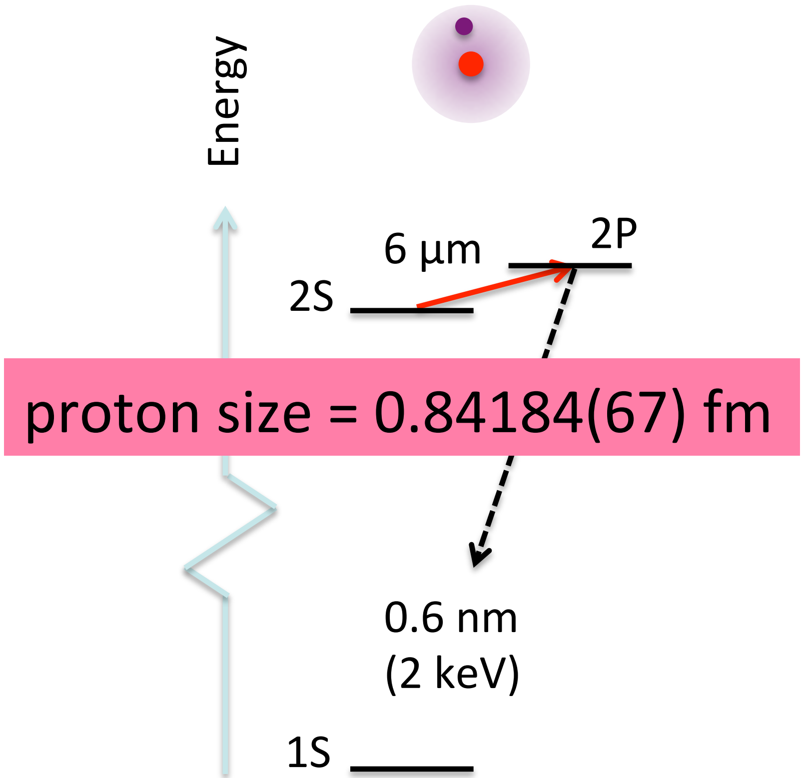
Hydrogen (H)



proton size = 0.8768(69) fm

C.G. Parthey et al.,
PRL **107**, 203001 (2011)
1S-2S: 2 466 061 413 187 035 (10) Hz

Muonic hydrogen (μH)

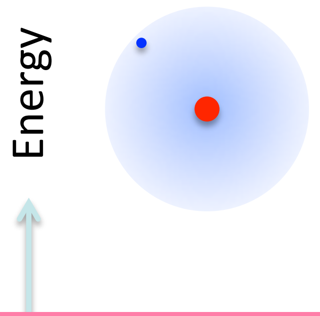


proton size = 0.84184(67) fm

R. Pohl et al,
Nature, vol. **466**, pp. 213-216 (2010)
Science **339**, 417-420 (2013).

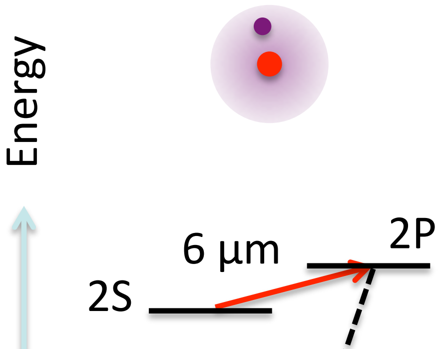
Proton size or Rydberg constant?

Hydrogen (H)



proton size = 0.8768(69) fm

Muonic hydrogen (μH)



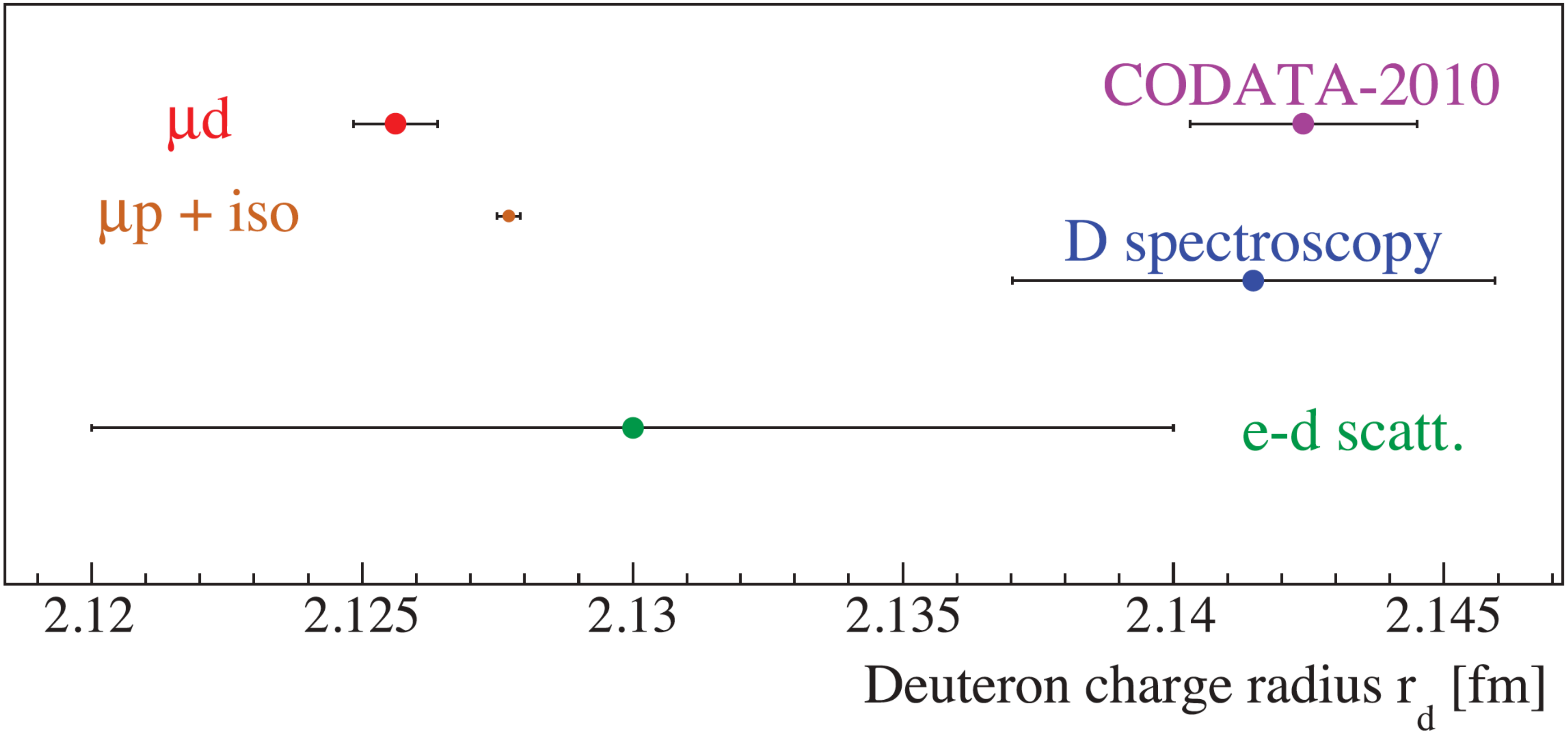
proton size = 0.84184(67) fm

R. Pohl et al., “Laser spectroscopy of muonic deuterium”, Science 353, 669 (2016):

$$r_d = 2.12562(78)\ \text{fm}$$

difference is **7.5σ** with CODATA: $r_d = 2.1424(21)$ fm

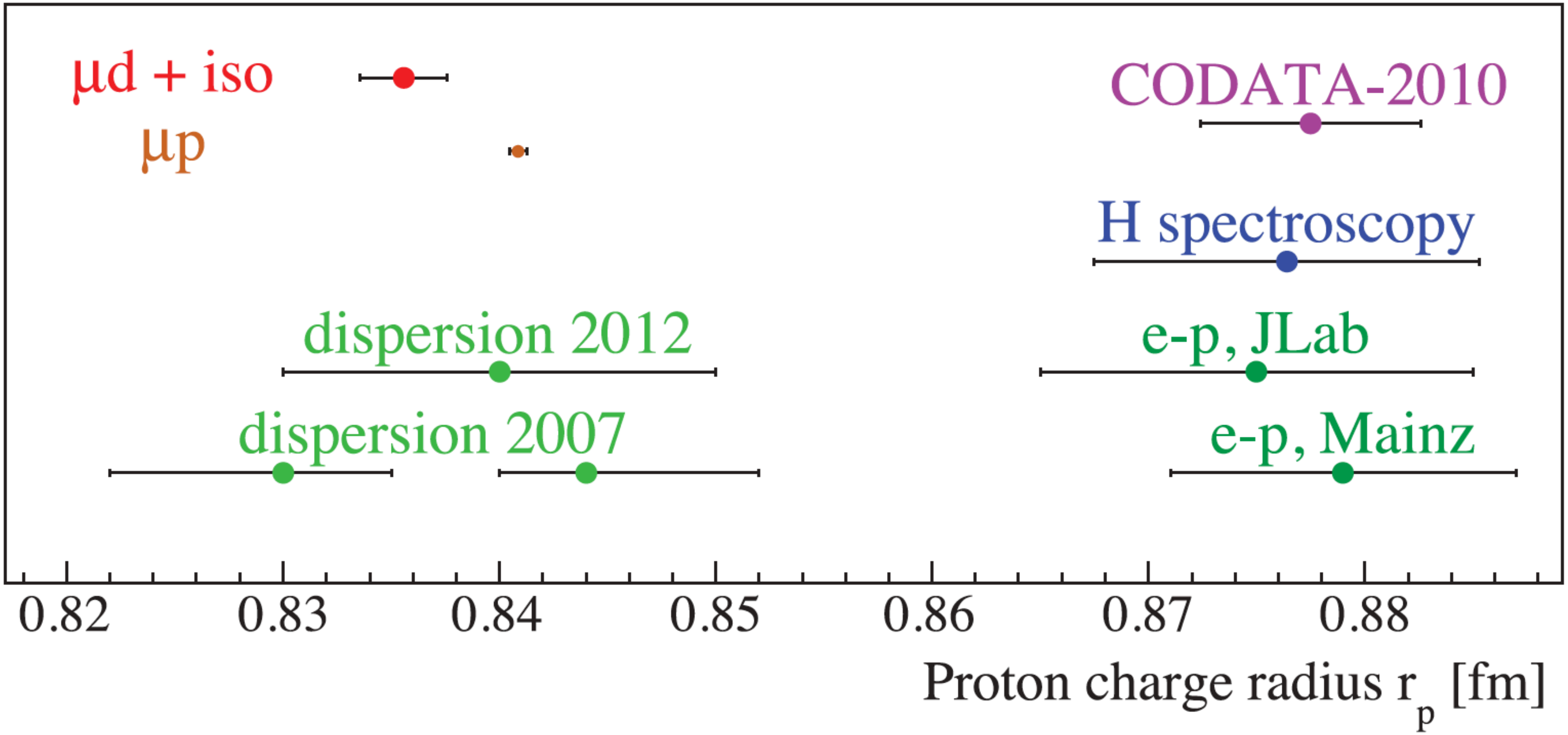
Deuteron charge radius, Aug. 2016



See also arXiv: 1607.03165 (August 2016)

R. Pohl et al., Science 353, 669 (2016)

Proton charge radius, August 2016



R. Pohl et al., Science 353, 669 (2016)

Solutions ?

Shift of Rydberg constant CODATA-2010 value by 7σ ?

good: $r_p(\mu p)$ and $r_p(H)$ in agreement
bad: difference $r_d(\mu p)$ and $r_d(H,D)$ still 2.5σ off
bad: still $r^2_d - r^2_p$ value off by 2.6 σ between (H,D) vs. (μp, μd)

QED in H and D is off by 110 kHz ? (=44σ of claimed accuracy of 2.5 kHz)

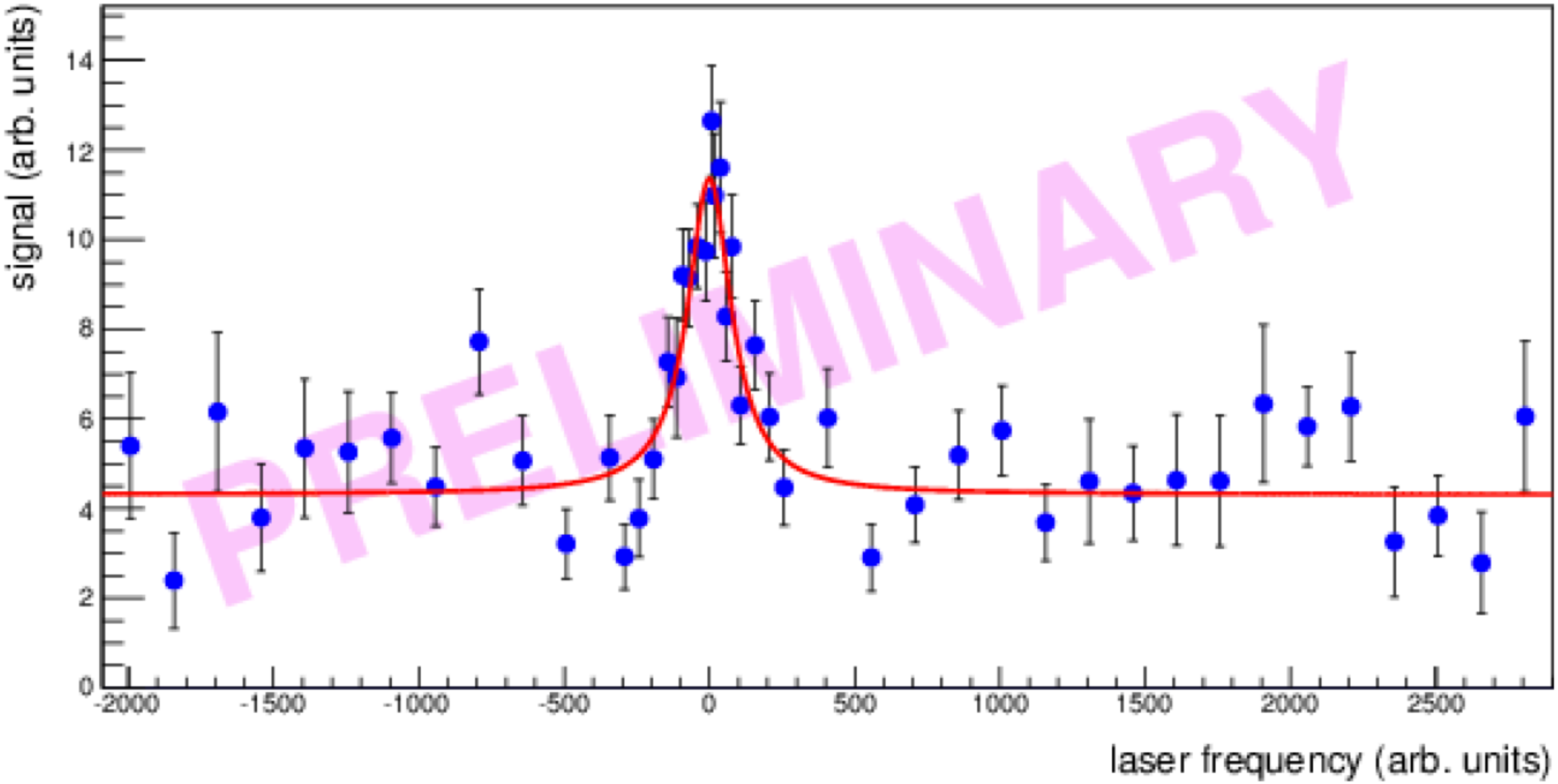
good: agreement between r_p and r_d from H & D & μp & μd
good: Rydberg constant unaffected
bad: still $r^2_d - r^2_p$ value off 2.6 by σ between (H,D) vs. (μp, μd)
bad: extreme shift of QED

Shift of all muonic spectroscopy of 14σ (=80 GHz for μp and 104 GHz for μd) or theory missing term in muonic atoms; off by 160σ in μp and 20σ in μd ?

good: $r_p(\mu p)$ and $r_p(H)$ in agreement, and also $r_d(\mu p)$ and $r_d(H,D)$
bad: extreme shifts of either theory or experiment

Pohl et al. Science 2016: "**Ultimately, only new experiments can shed more light on the proton and deuteron radius discrepancies**"

Preliminary muonic ^{4}He+ (2S-2P)



From arXiv paper 1609.03440 (12 September 2016) with first result in it on muonic 4He

Preliminary muonic ^{4}He+ (2S-2P)

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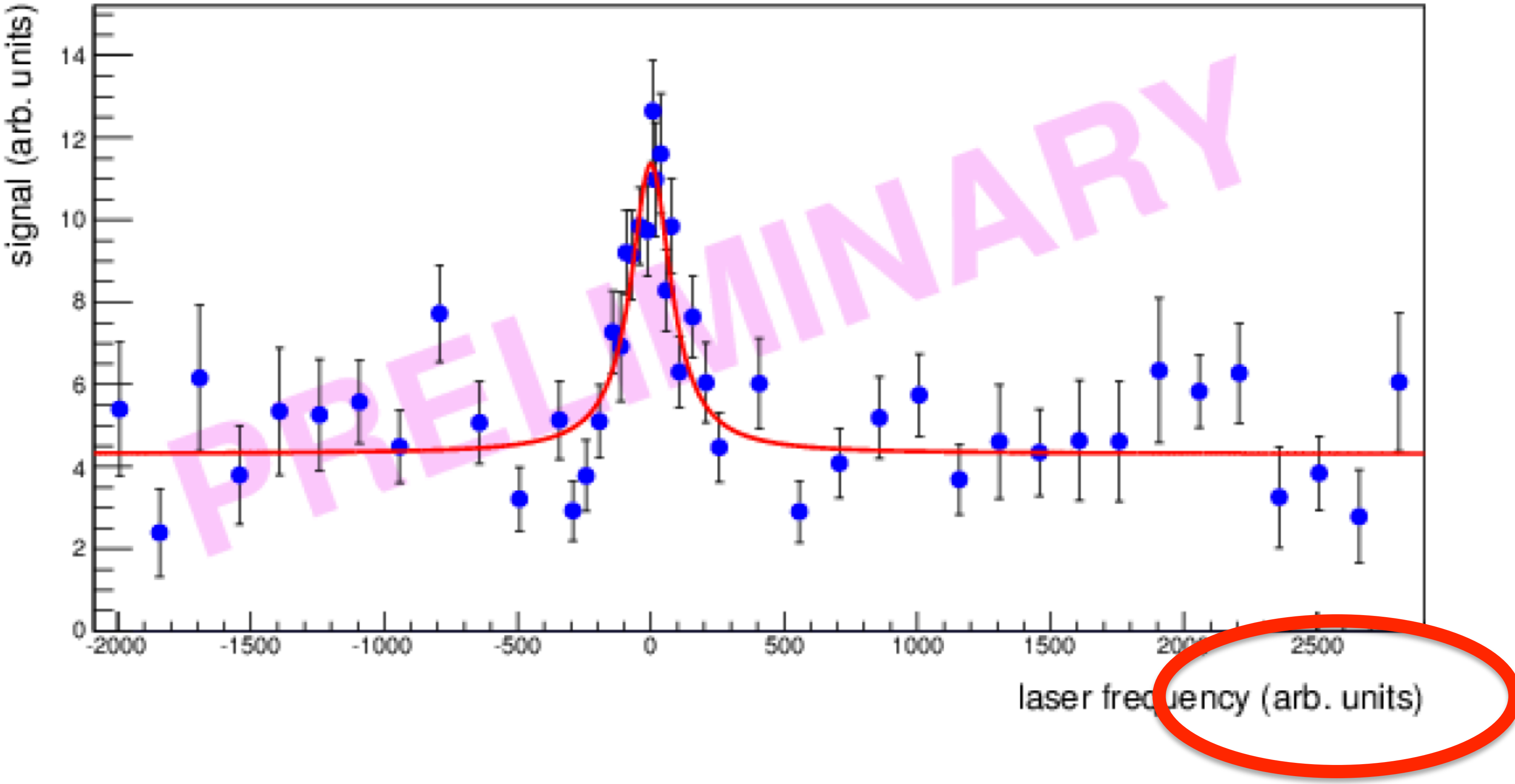
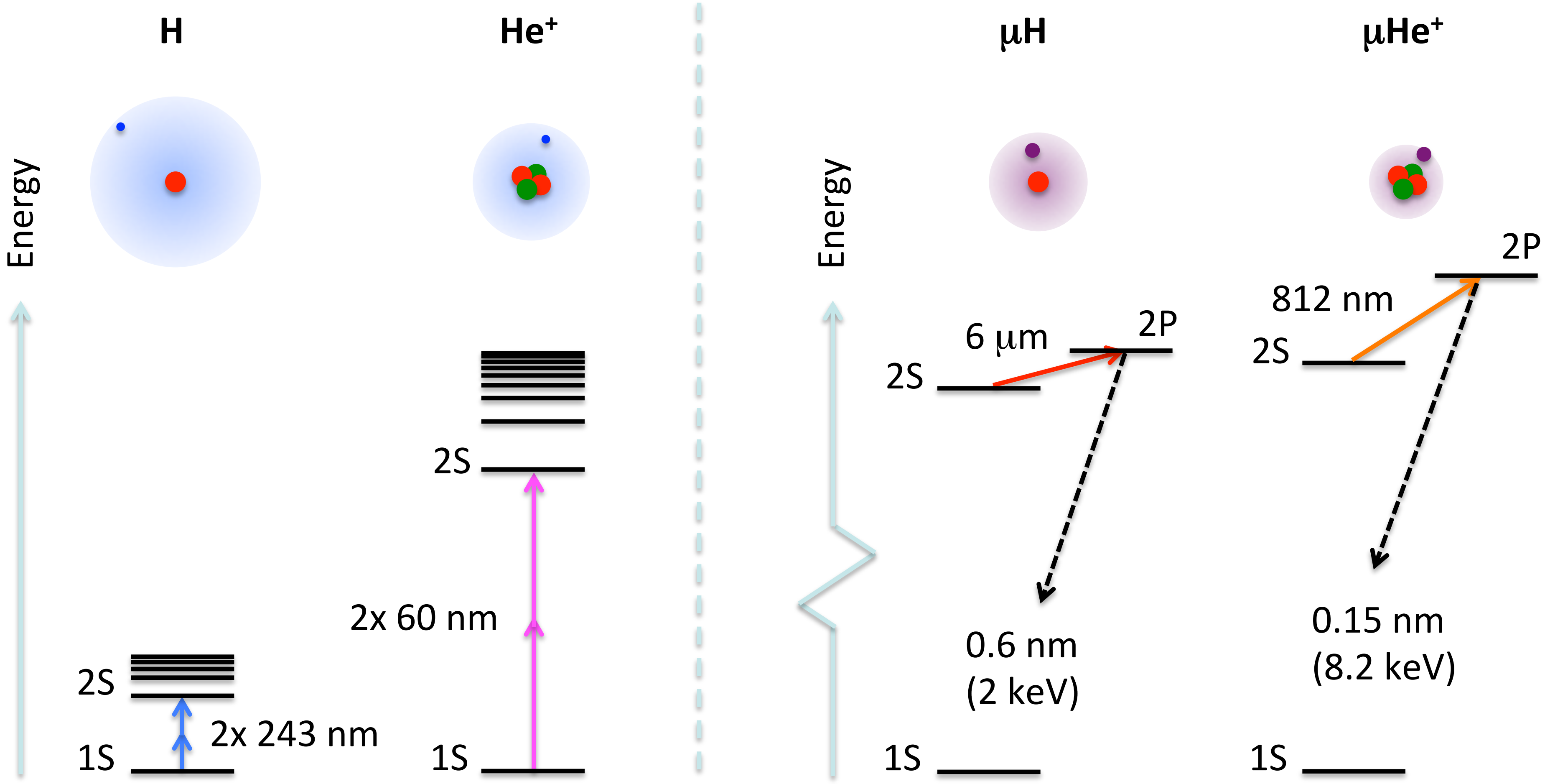


From arXiv paper 1609.03440 (12 September 2016) with first result in it on muonic 4He

Normal vs. muonic matter



The 1S-2S values for H and He+

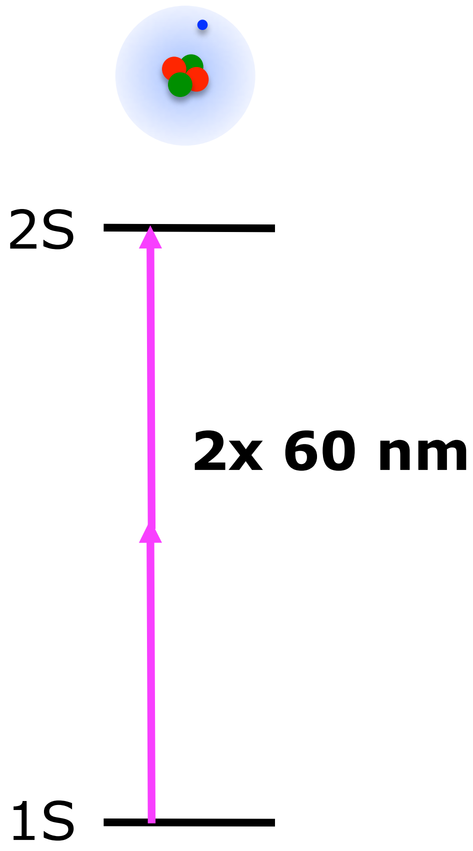
LaserLaB Amsterdam

		Scaling	H (kHz)	He$^+$ (kHz)
Theory	$\Delta\upsilon_{1S-2S}$	Z^2	$2.466...\times10^{12}$	$9.869...\times10^{12}$
	Γ_{1S-2S}	Z^4	1.3×10^{-3}	83×10^{-3}
	ΔL_{1S-2S}	$Z^{\geq3.7}$	7 127 887(44)	93 856 127(348)*
	Finite size	Z^4r^2	1102(44)	62 079(295)
	(nucl. pol.)		(2)	(40 or 15**)
	$B_{60}+B_{7i}$	$Z^{\geq6}$	-8(3)	-543(185)
	Test $B_{60}+B_{7i}$		25%	7% or 4%***
	Rel. acc. ΔL_{1S-2S}		6.3 ppm	3.7 ppm****
Experiment	$\Delta\upsilon_{1S-2S}$		246606143187.035(10)	**not measured**
	$\delta L(\delta R_\infty)_{1S-2S}$	Z^2	16	65
	Rel. $\delta L(\delta R_\infty)$		2.2 ppm	0.7 ppm

H 1S-2S from
C.G. Parthey et al.,
PRL **107**, 203001 (2011)

Targets precision spectroscopy in (X)UV

He$^+$



Aim: <1 kHz

1:10^{13}

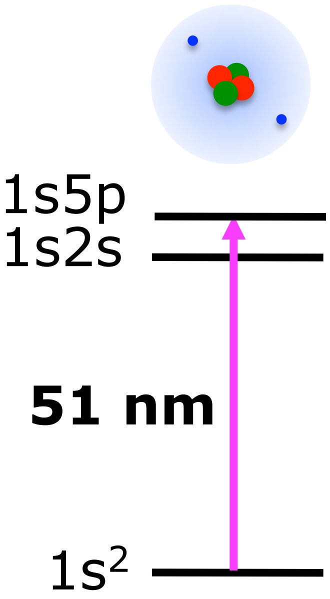
never measured

Targets precision spectroscopy in (X)UV

LaserLaB Amsterdam

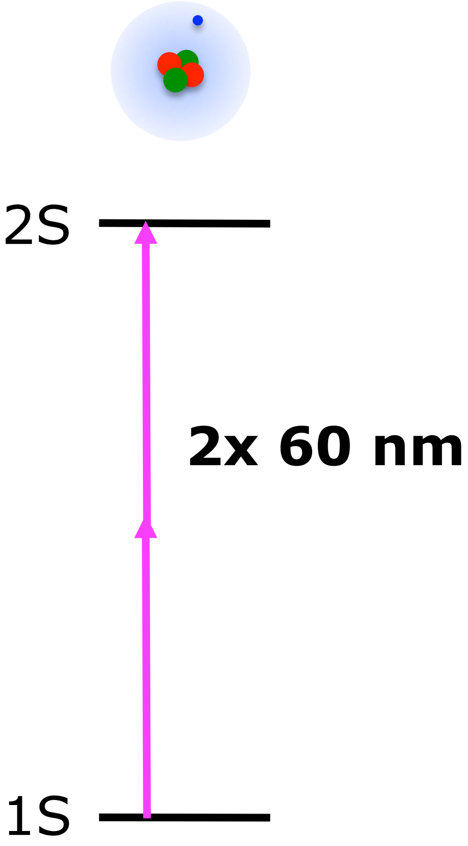
Ramsey spectroscopy,
comb assisted

He



6 MHz
1:10^9
PRL 105, 063001 (2010)

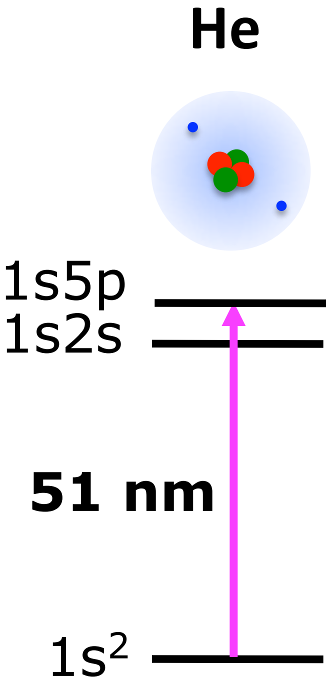
He$^+$



Aim: <1 kHz
1:10^{13}
never measured

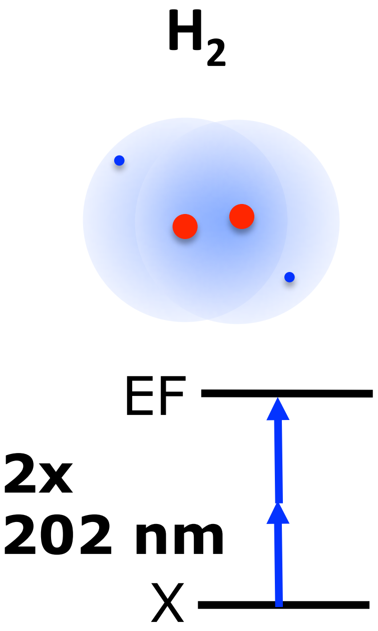
Targets precision spectroscopy in (X)UV

Ramsey spectroscopy,
comb assisted

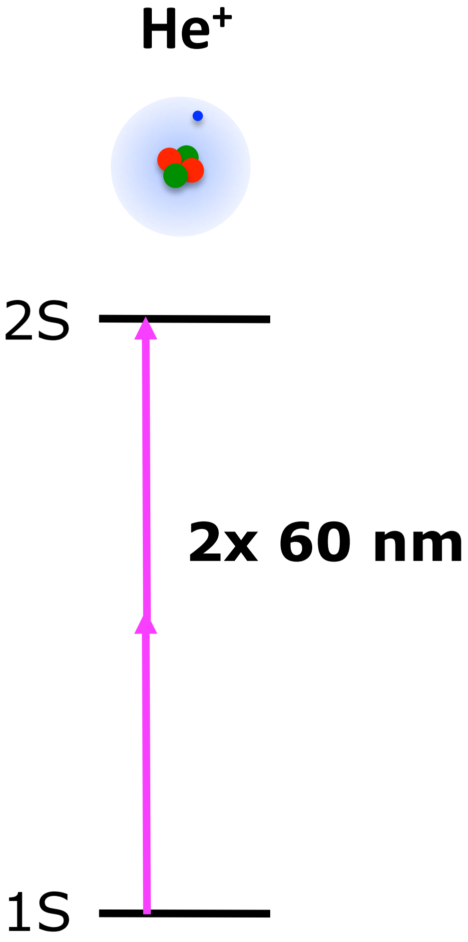


6 MHz
1:10^9
PRL 105, 063001 (2010)

Ramsey-comb spectroscopy

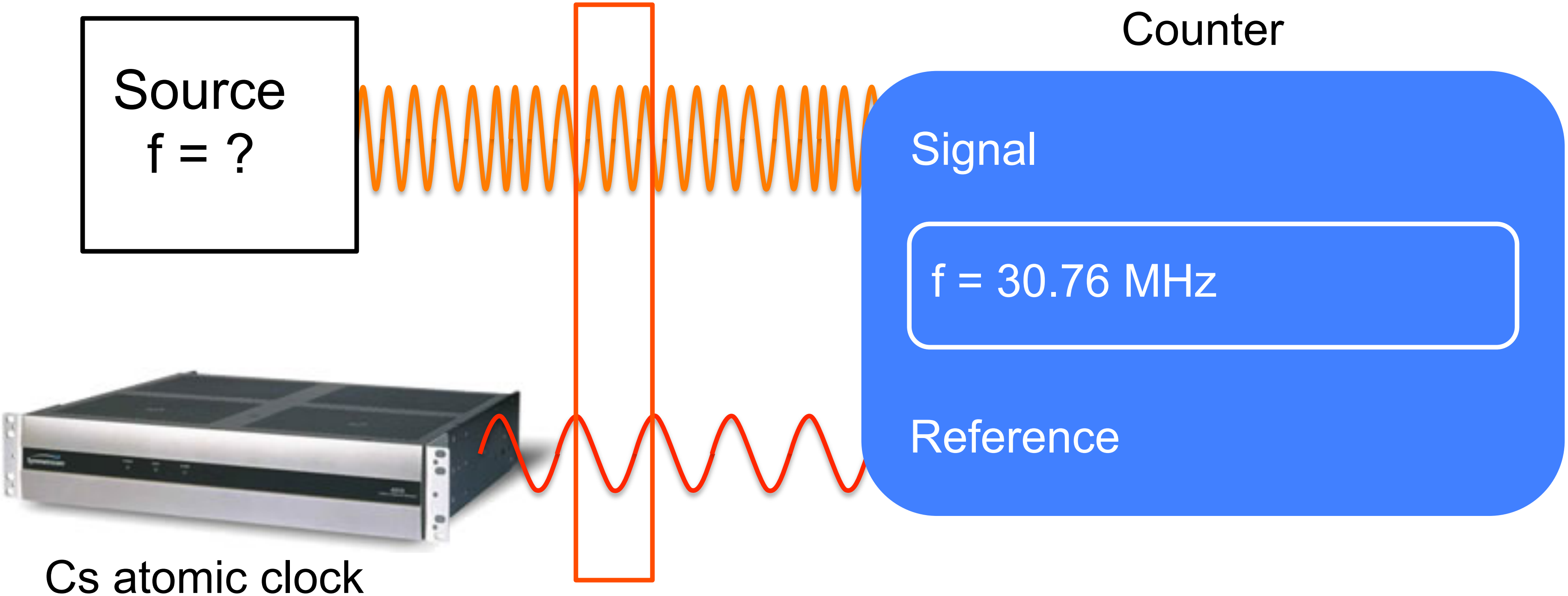


Aim: <25 kHz = better than 1:10^{11}
current accuracy ~ 3MHz
J. Chem. Phys. **130**, 174306 (2009)



Aim: <1 kHz
1:10^{13}
never measured

Comparing frequencies



Source
f = ?

Counter

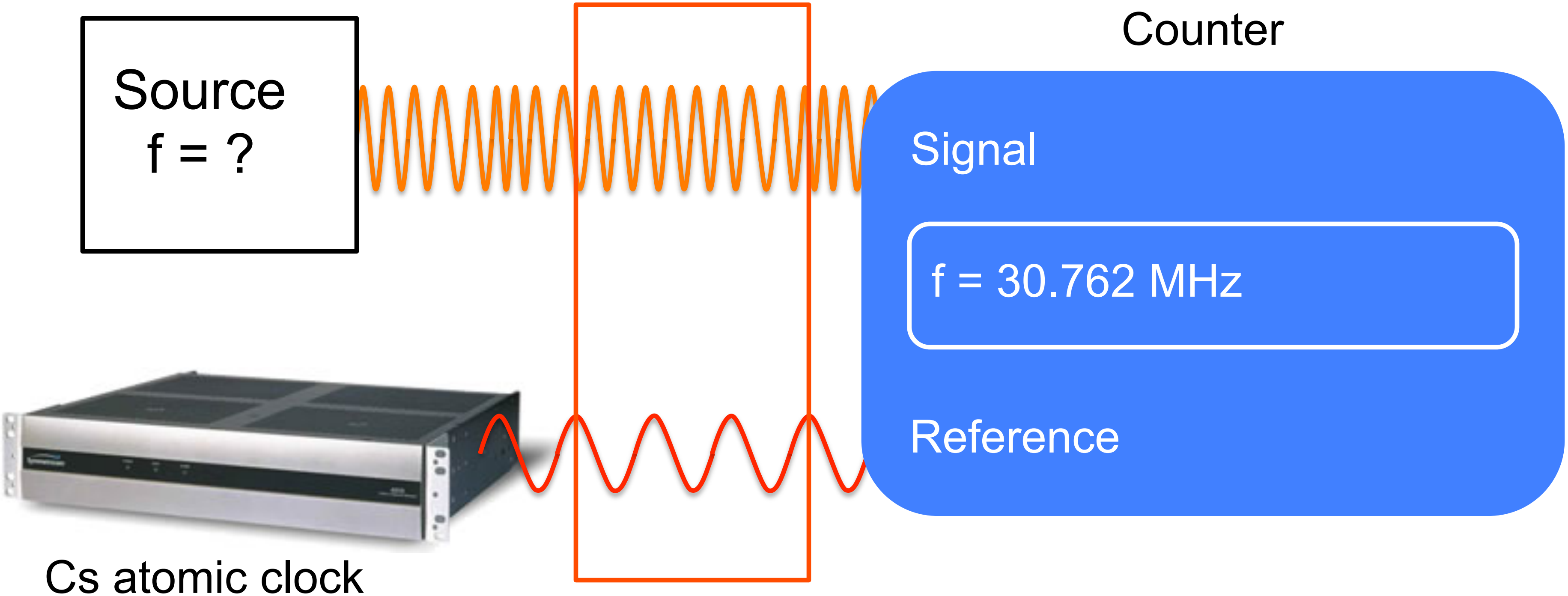
Signal

f = 30.76 MHz

Reference

Cs atomic clock
10 MHz

Comparing frequencies



Source
f = ?

Counter

Signal

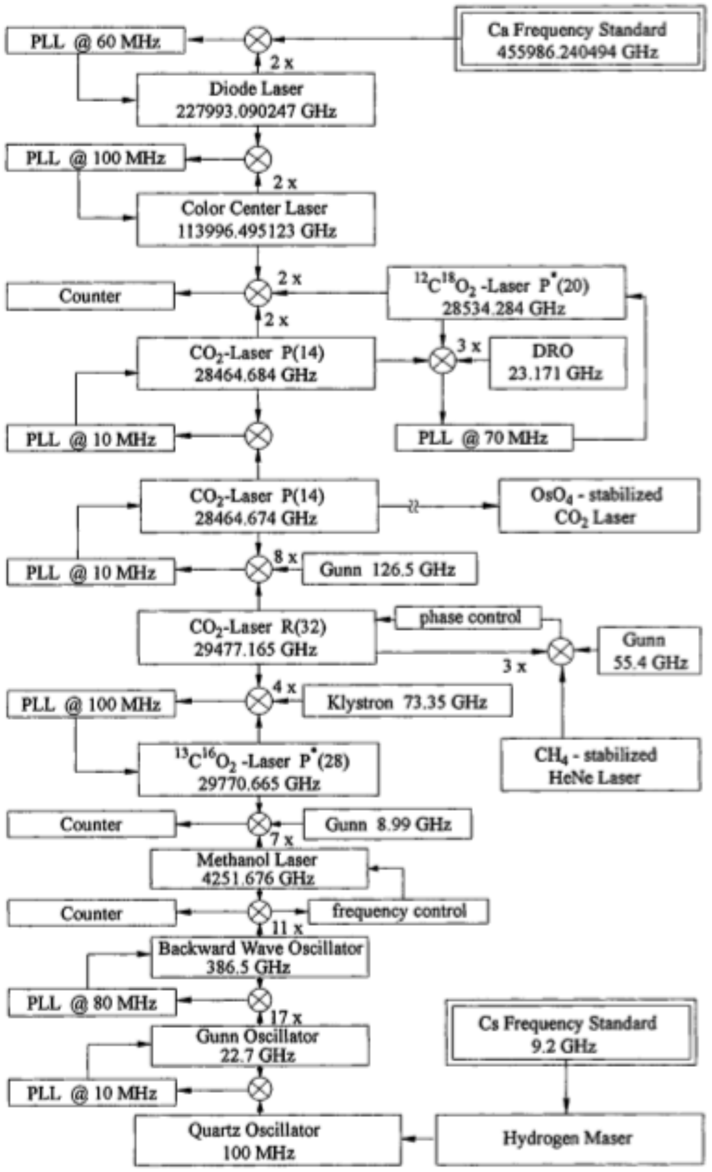
f = 30.762 MHz

Reference

Cs atomic clock
10 MHz

OK for microwaves up to 100 GHz,
but optical frequencies at 100’s of PHz or even THz ???

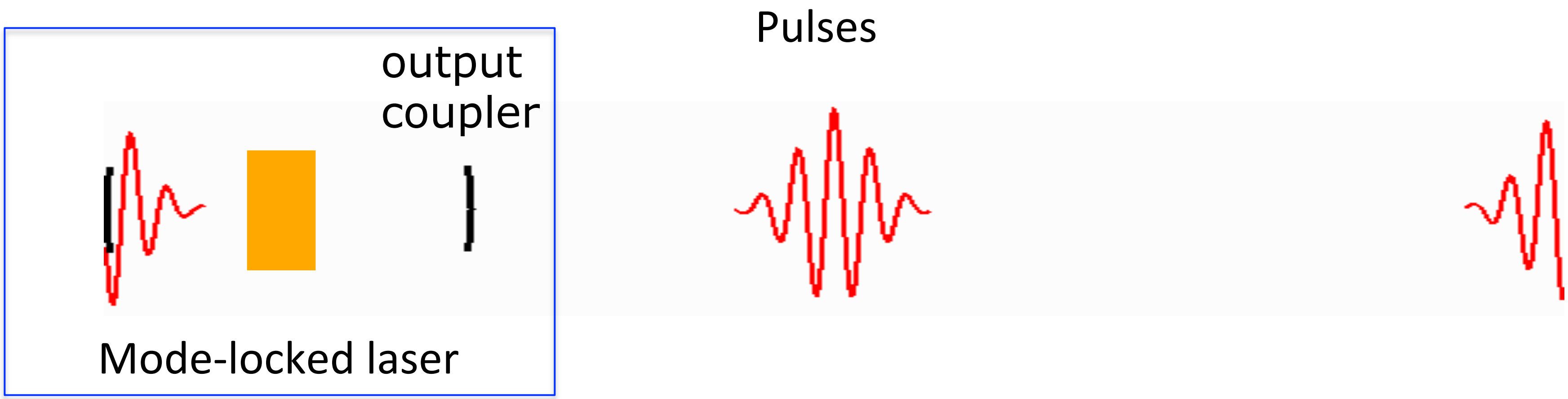
Frequency chain PTB in 1996



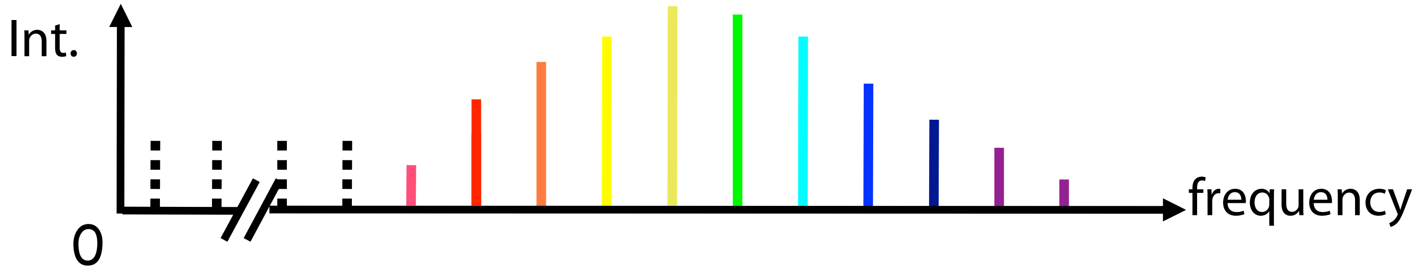
- ❑ Complicated!
- ❑ Exotic lasers
- ❑ Loads of electronics
- ❑ Many people needed to keep it going
- ❑ Big! (>6 m table)
- ❑ Just for 1 frequency!

Other 'Frequency Chains'
in e.g. Paris (BNM-SYRTE),
Munich (MPQ), NIST

Frequency comb lasers

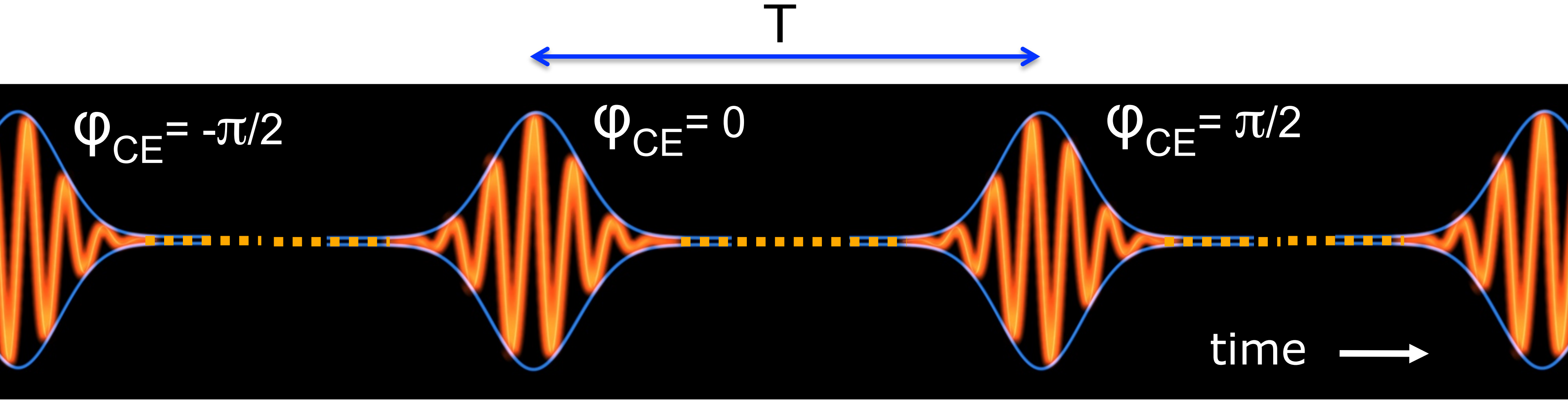


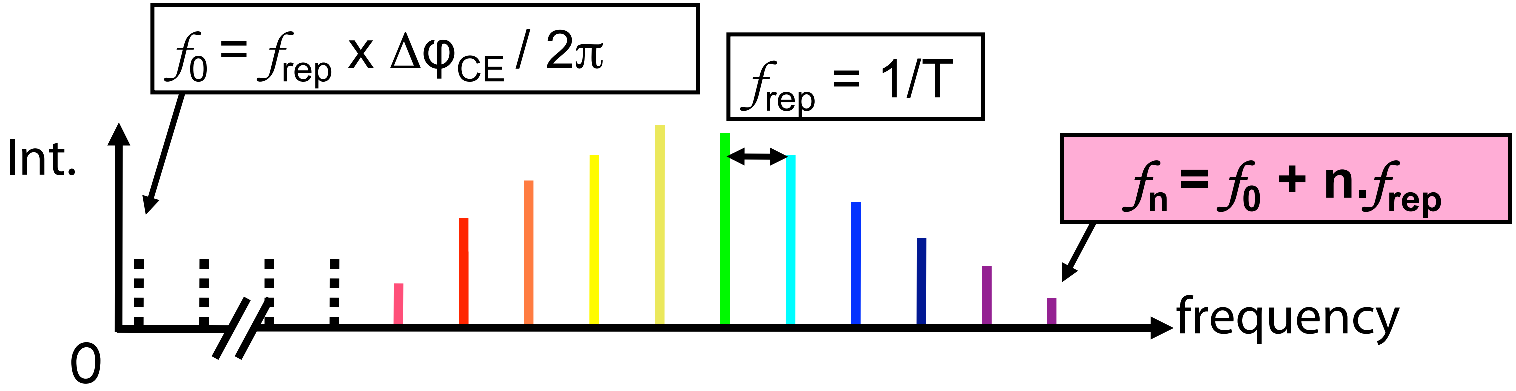
Laser modes



R. Holzwarth et al. PRL 85, 2264 (2000),
D.J. Jones et al. Science 288, 635 (2000)

FC's – infinite pulse trains



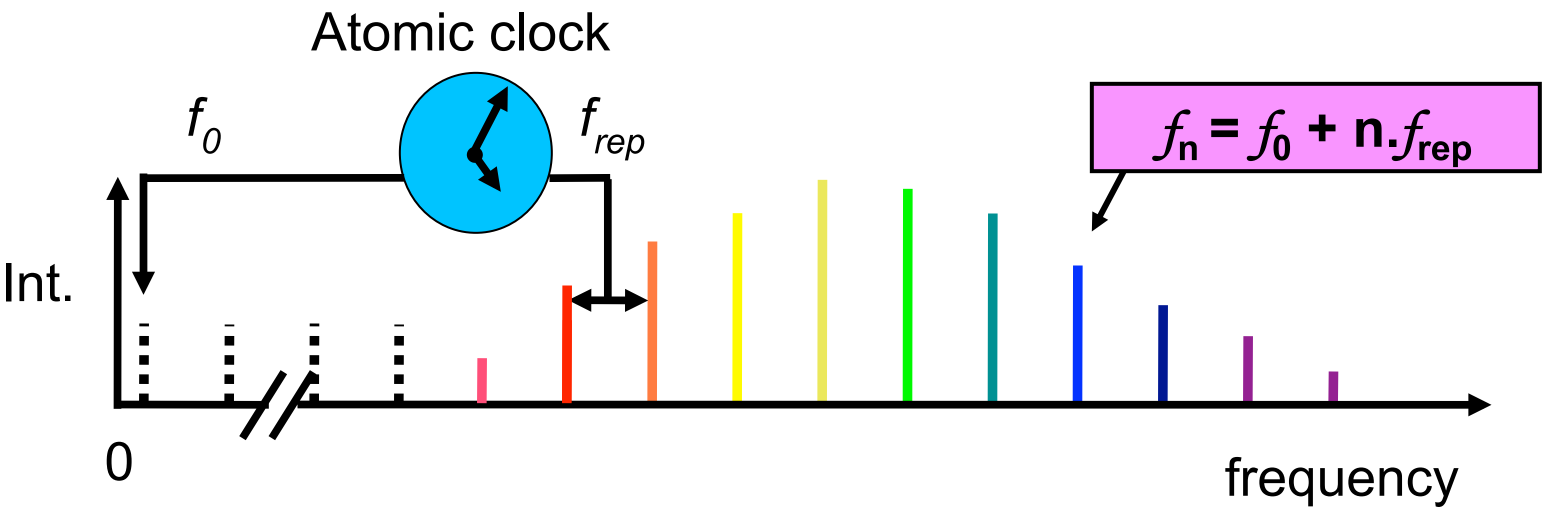


$f_0 = f_{rep} \times \Delta\varphi_{CE} / 2\pi$

$f_{rep} = 1/T$

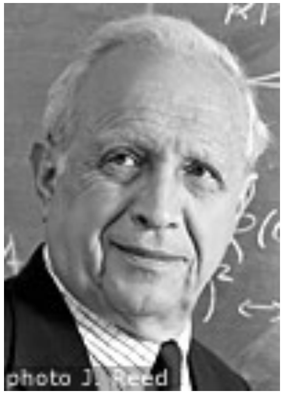
$f_n = f_0 + n.f_{rep}$

Fully referenced frequency comb



$f_n = f_0 + n.f_{rep}$

Nobel prize
2005
Physics

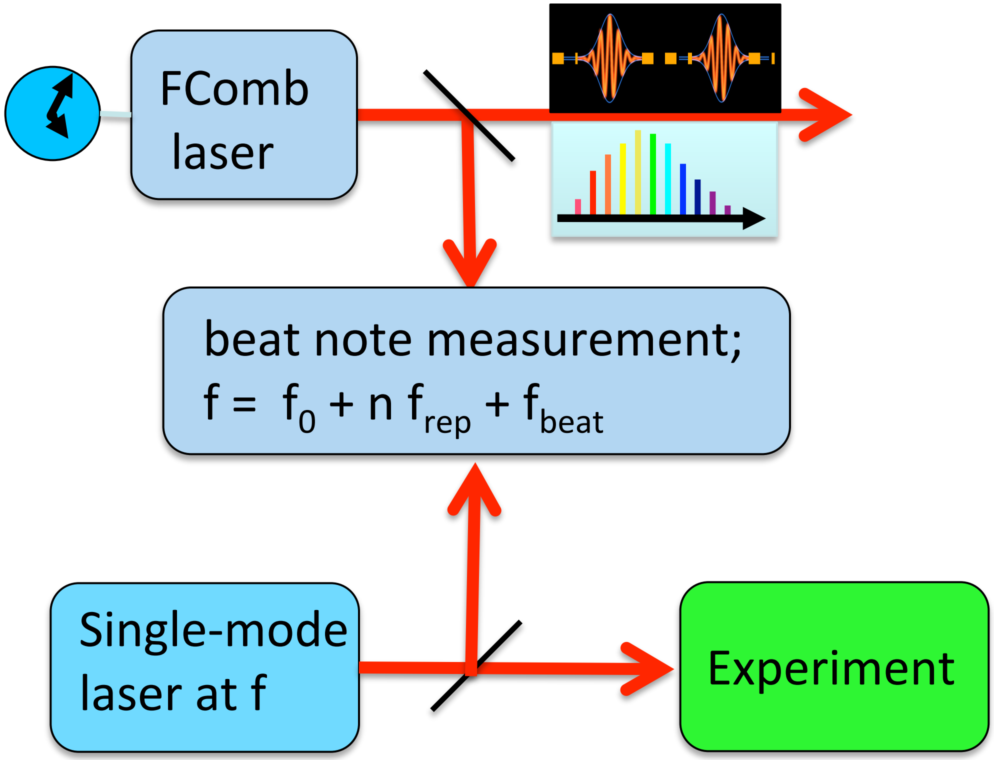


R.J. Glauber

J. Hall

T.W. Hänsch

Comb calibration - traditional



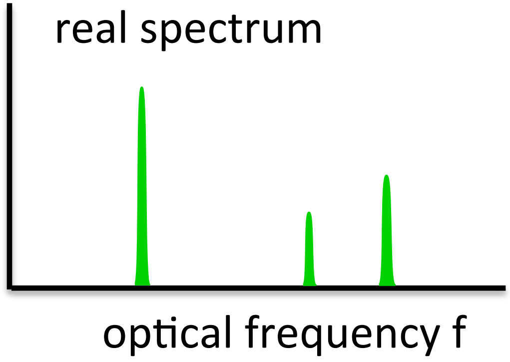
FComb laser

beat note measurement;

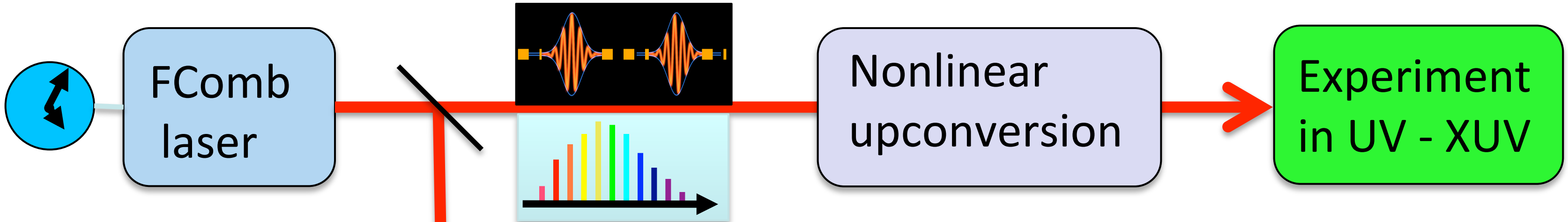
$f = f_0 + n\, f_{rep} + f_{beat}$

Single-mode laser at f

Experiment



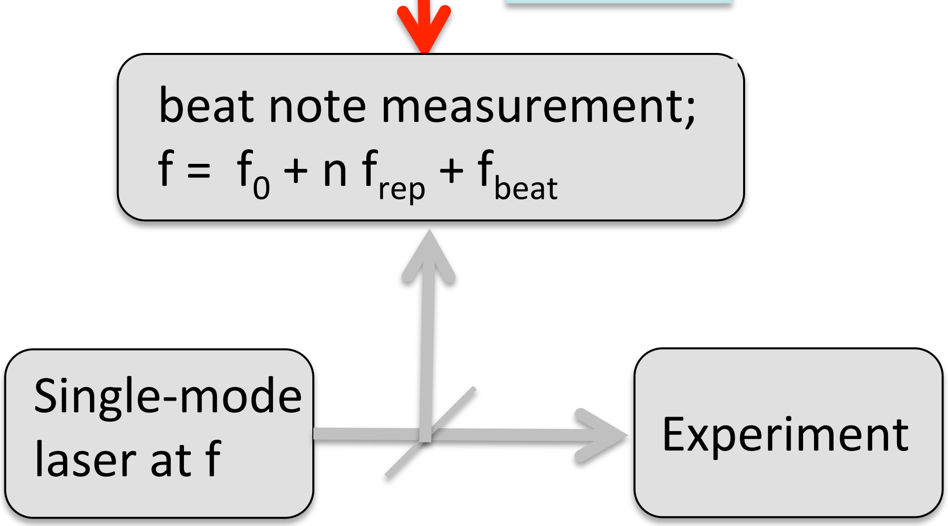
Direct comb excitation – single comb



FComb laser

Nonlinear upconversion

Experiment in UV - XUV

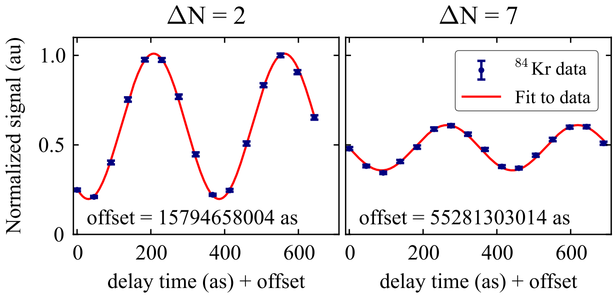


beat note measurement;

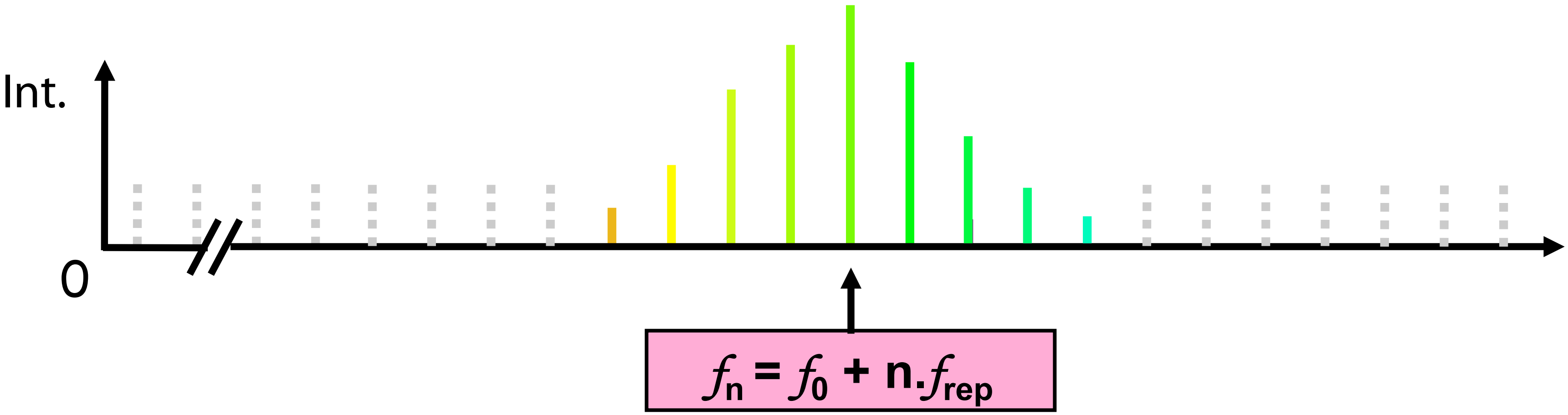
$f = f_0 + n f_{rep} + f_{beat}$

Single-mode laser at f

Experiment

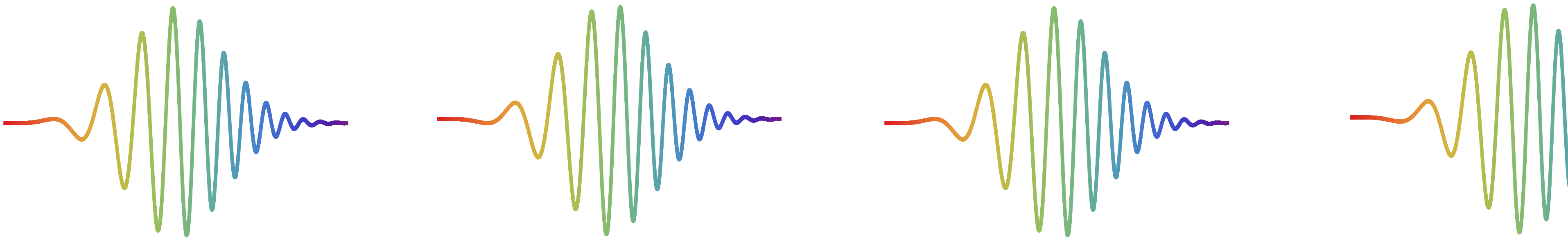


The essential beauty of frequency combs

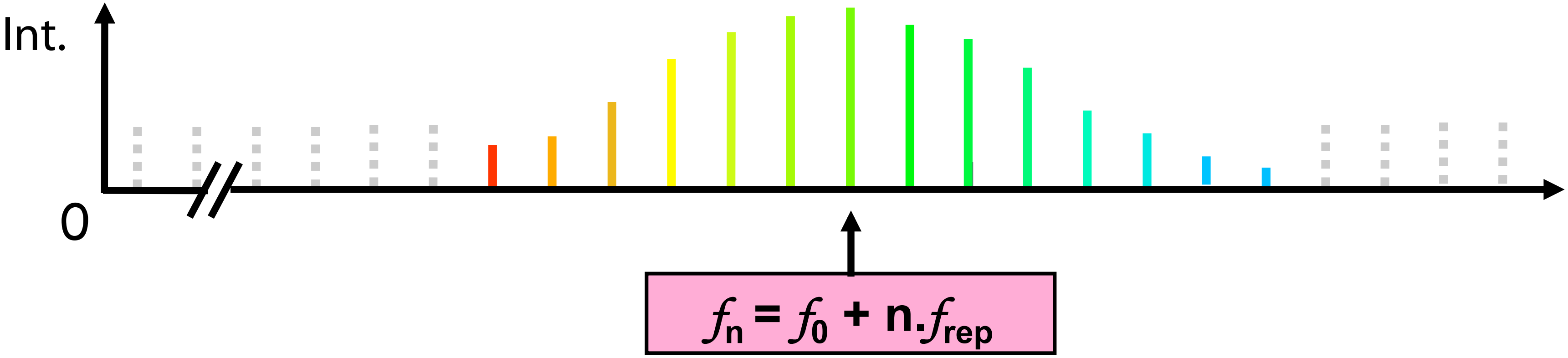


$f_n = f_0 + n.f_{rep}$

Equal chirp & broadening? – no problem!

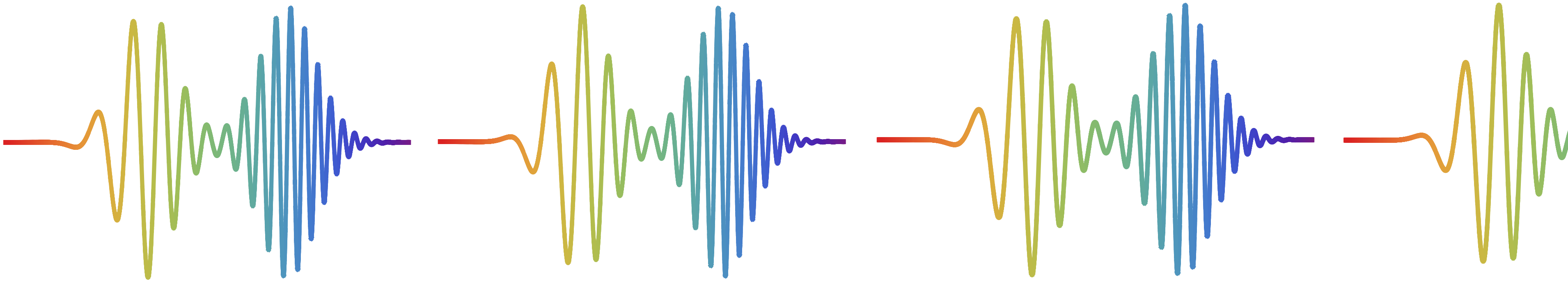


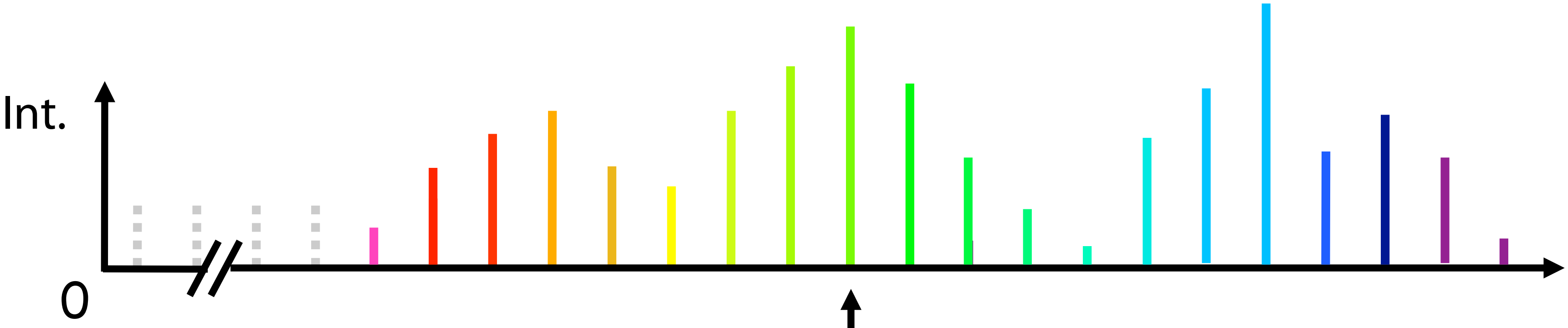
Phases and amplitudes changed, but frequencies at the same position!



$f_n = f_0 + n.f_{rep}$

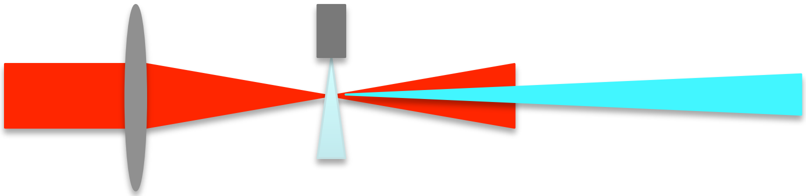
Terrible but equal pulse distortion = OK!





$f_n = f_0 + n.f_{rep}$

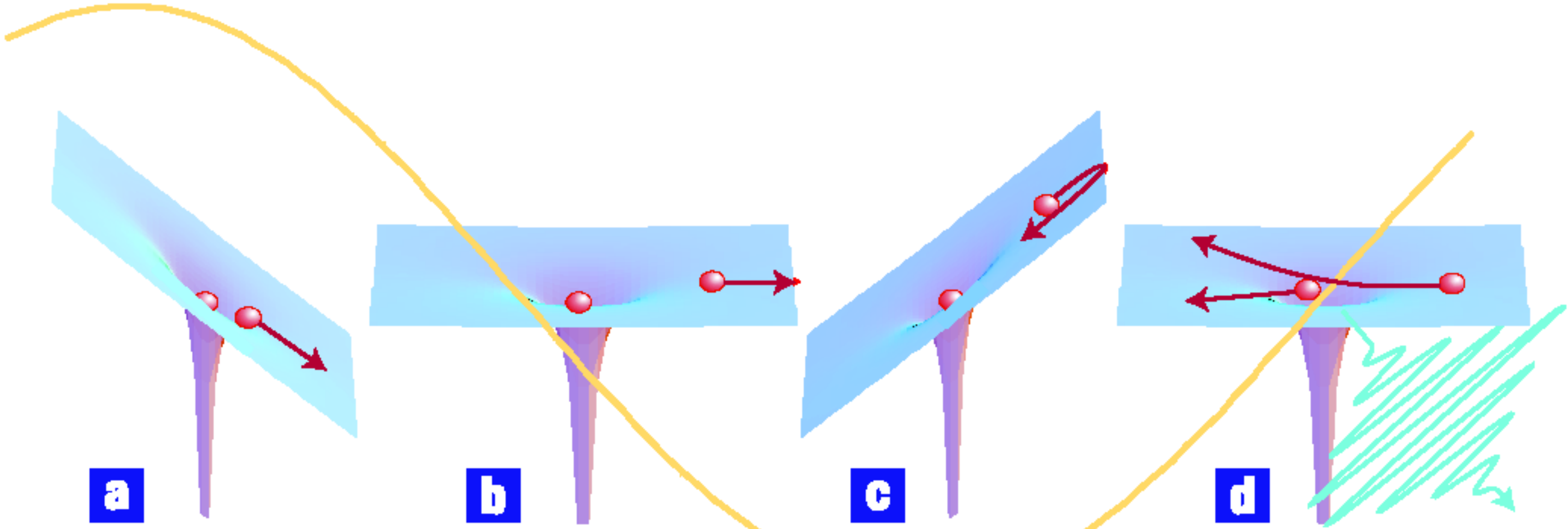
XUV? Upconversion through HHG



Near-infrared

Extreme ultraviolet

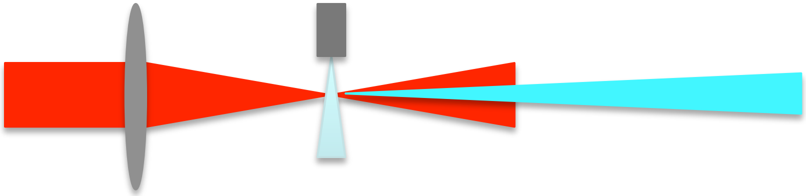
peak power ~10^{14} W/cm^2



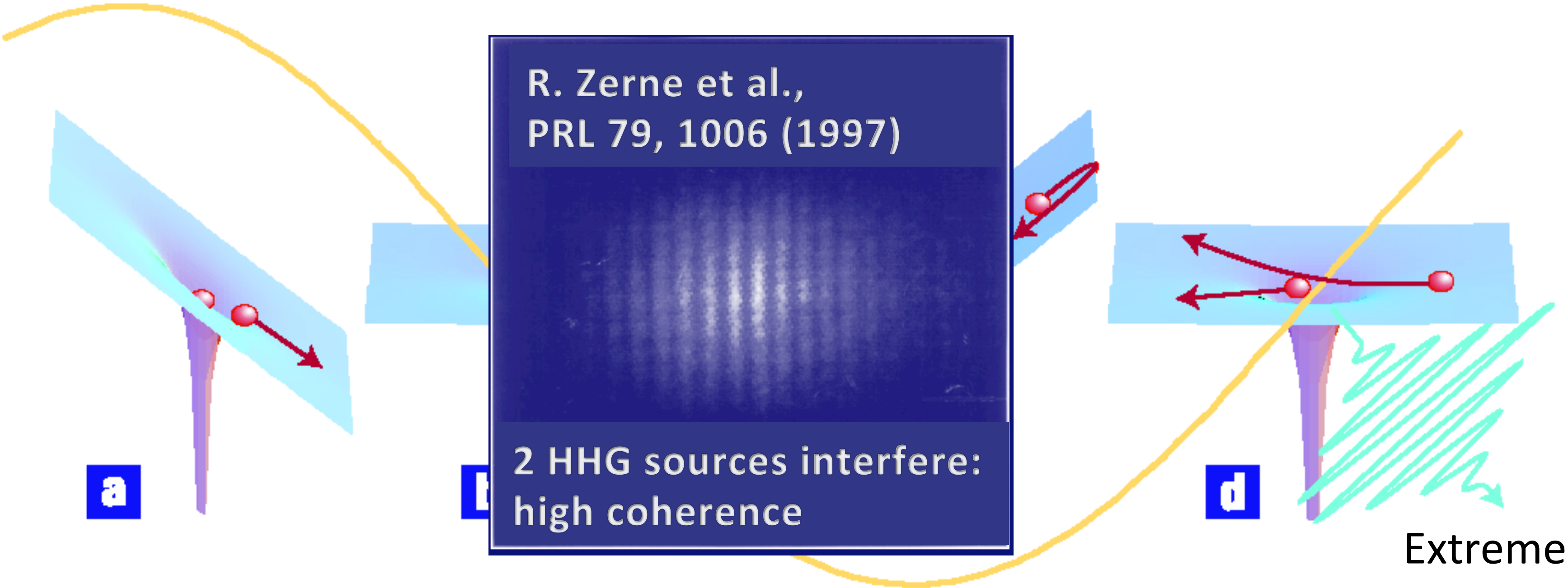
Extreme ultraviolet

Corkum & Krausz, Nature Physics 3, 381 (2007)

Laser upconversion through HHG



peak power ~10^{14} W/cm^2

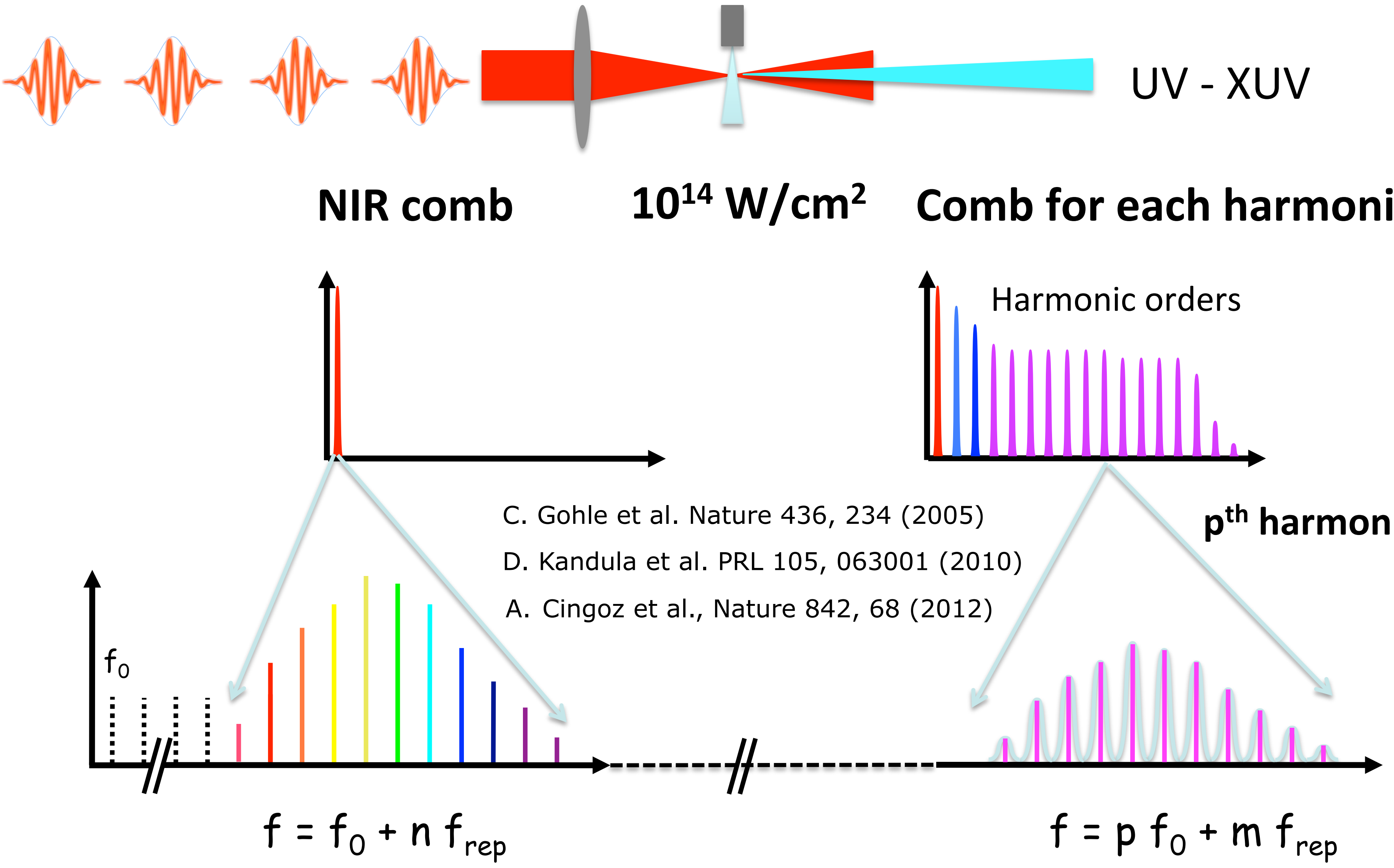


R. Zerne et al.,
PRL 79, 1006 (1997)

2 HHG sources interfere:
high coherence

Corkum & Krausz, Nature Physics 3, 381 (2007)

Comb upconversion through HHG



UV - XUV

NIR comb

10^{14} W/cm^2

Comb for each harmonic

Harmonic orders

pth harmonic

C. Gohle et al. Nature 436, 234 (2005)

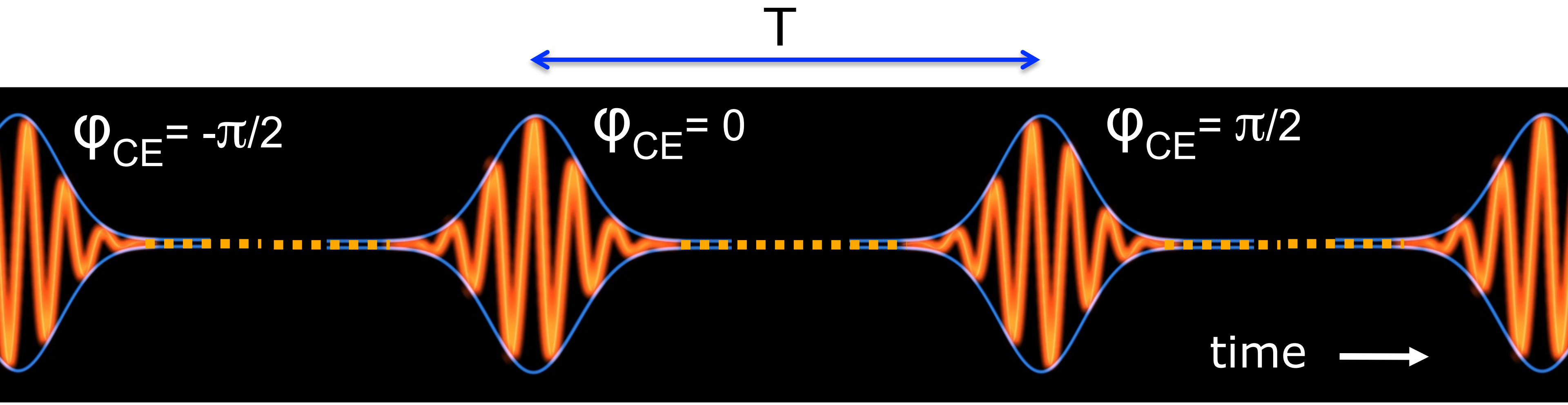
D. Kandula et al. PRL 105, 063001 (2010)

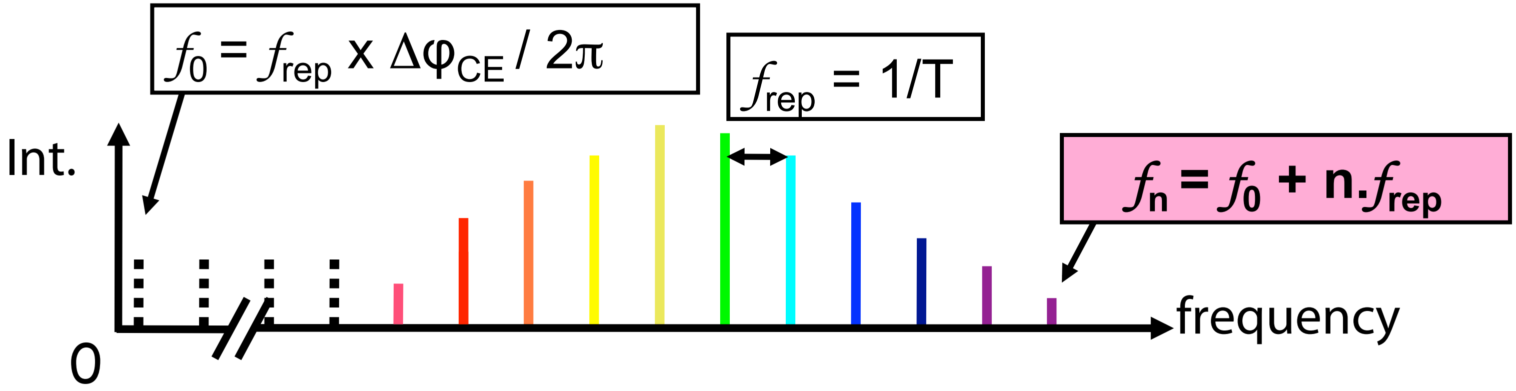
A. Cingoz et al., Nature 842, 68 (2012)

$$f = f_0 + n\, f_{rep}$$

$$f = p\, f_0 + m\, f_{rep}$$

FC's – infinite pulse trains

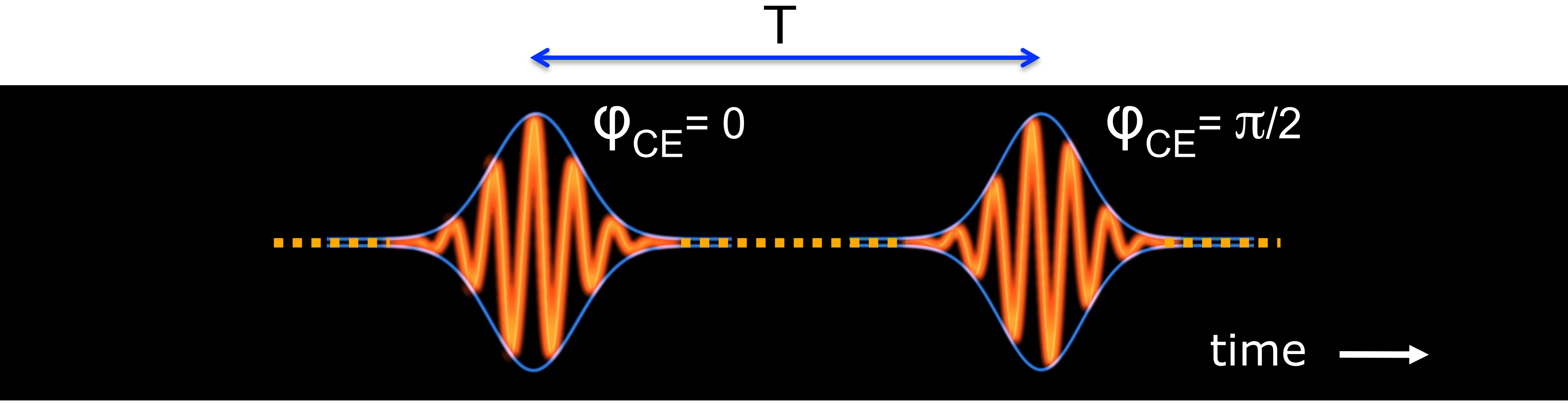



$f_0 = f_{rep} \times \Delta\varphi_{CE} / 2\pi$

$f_{rep} = 1/T$

$f_n = f_0 + n.f_{rep}$

Heresy! 2 pulses, but mJ energy



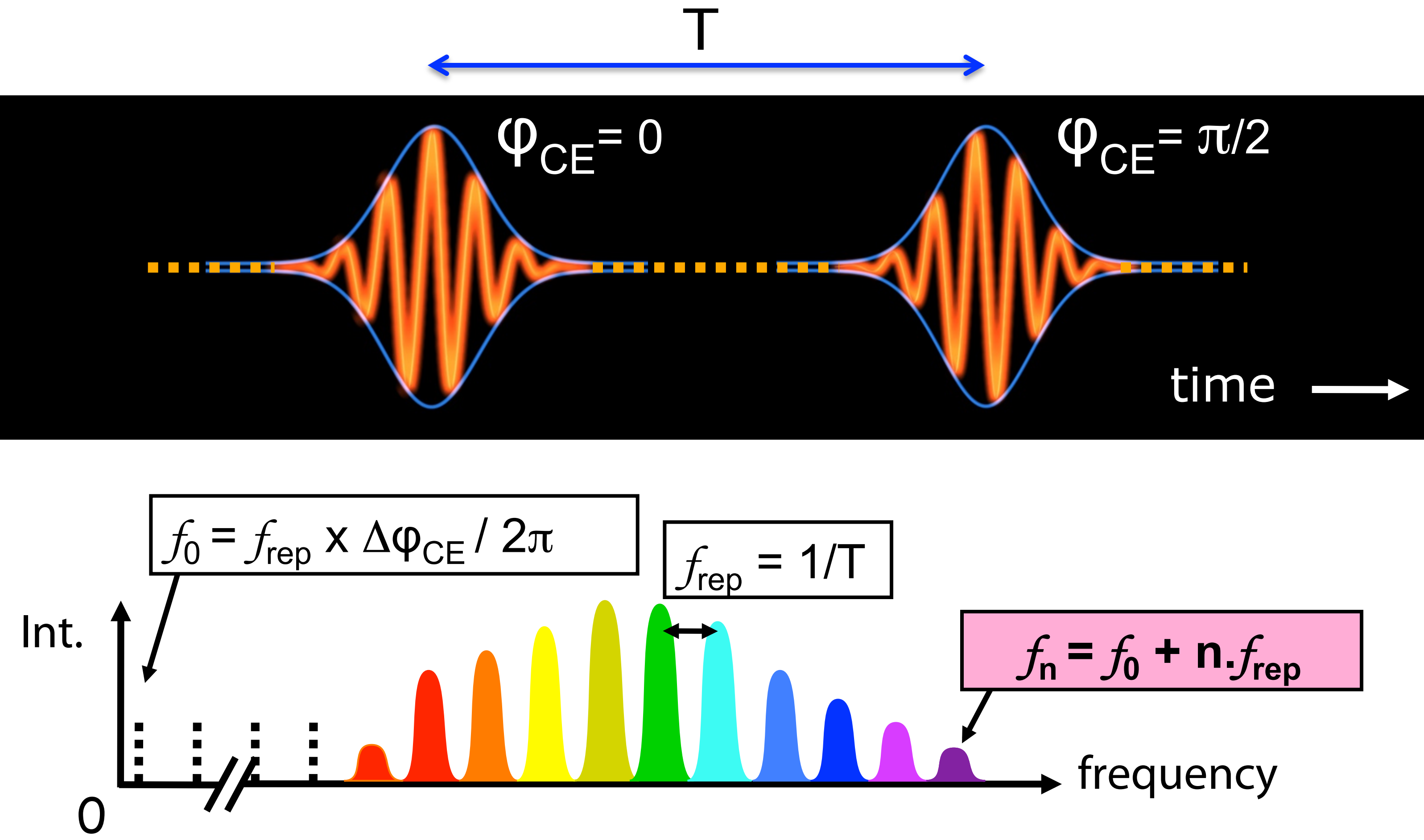
The Black Knight with
chopped-off limbs...

"Monty Python
and the Holy Grail"

(1975)

Let's call it a draw!

Heresy! 2 pulses, but mJ energy

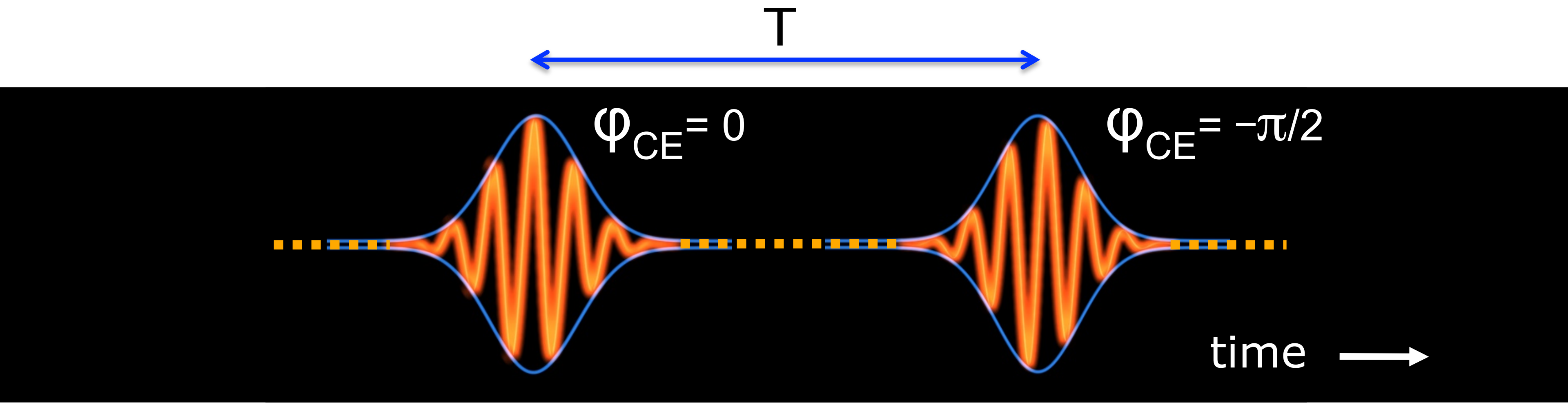


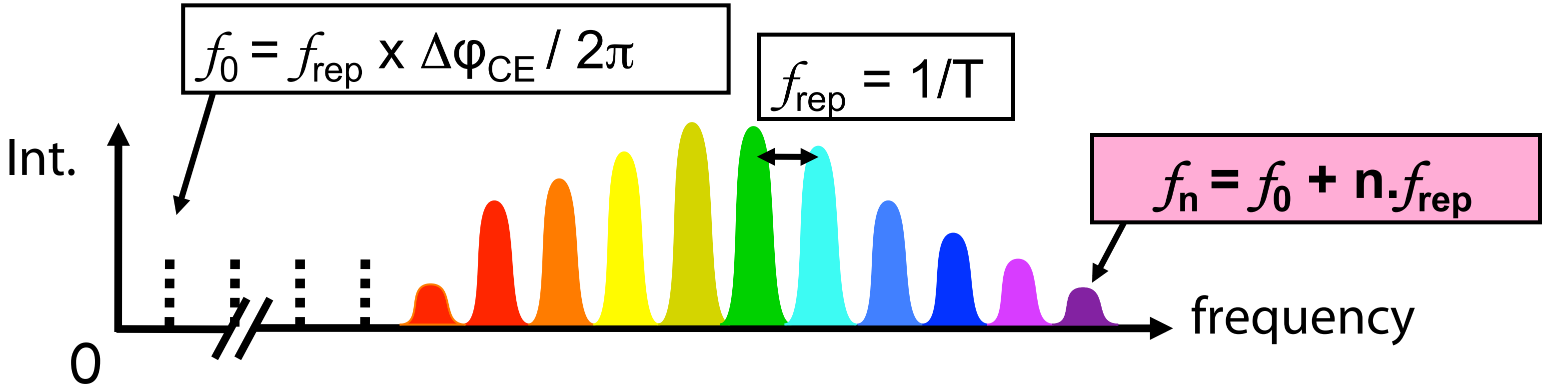
$f_0 = f_{rep} \times \Delta\varphi_{CE} / 2\pi$

$f_{rep} = 1/T$

$\mathbf{f_n = f_0 + n.f_{rep}}$

Heresy! 2 pulses, but mJ energy





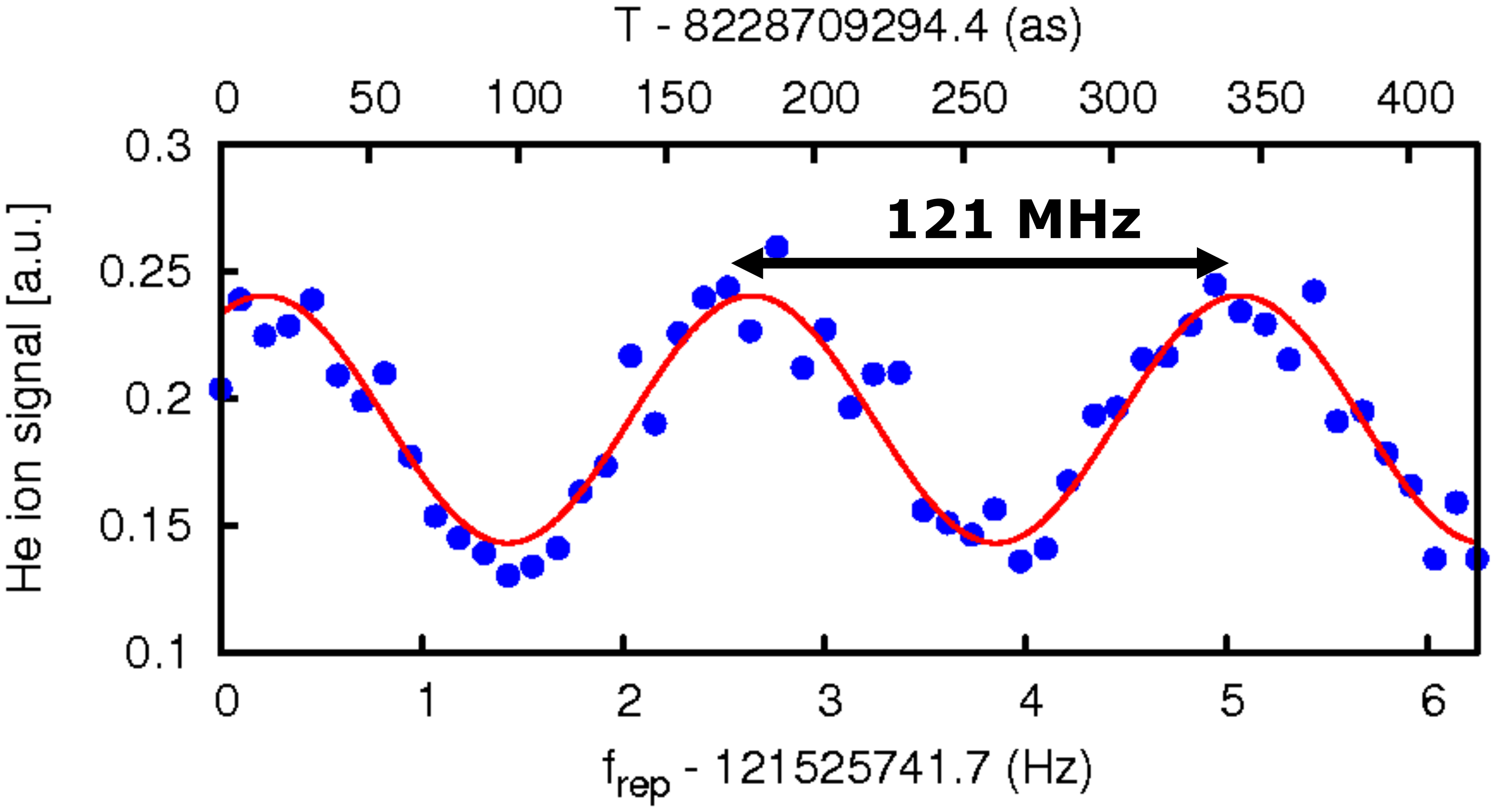
$f_0 = f_{rep} \text{ x } \Delta\varphi_{CE} / 2\pi$

$f_{rep} = 1/T$

$\boldsymbol{f_n = f_0 + n.f_{rep}}$

Spectroscopy of He $1s^2\ ^1S_0 – 1s5p\ ^1P_1$ at 51 nm

LaserLaB Amsterdam



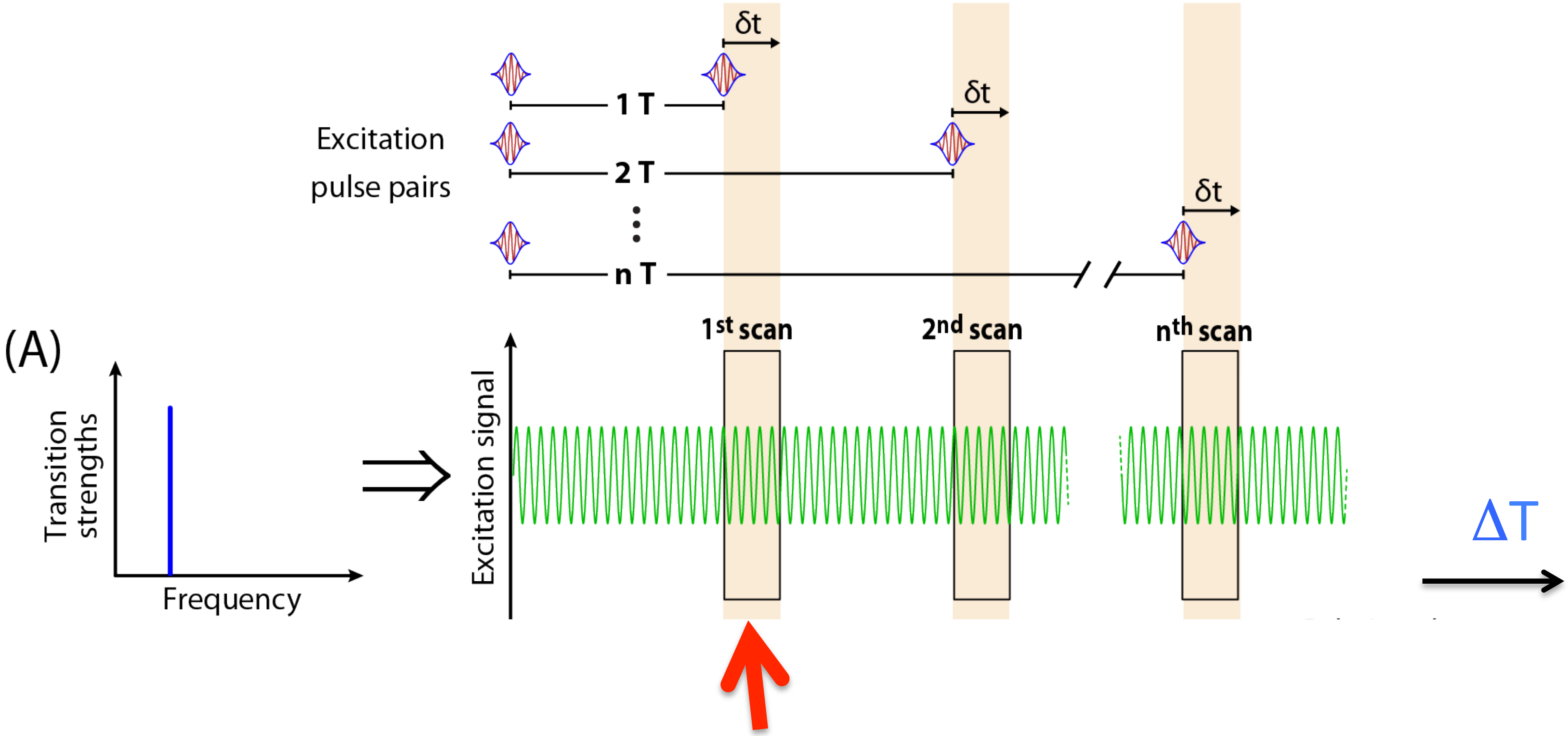
Accuracy 6 MHz at 51 nm

D. Kandula et al. PRL **105**, 063001 (2010)
D. Kandula et al. PRA **84**, 062512 (2011)

Dominik Kandula

Christoph Gohle

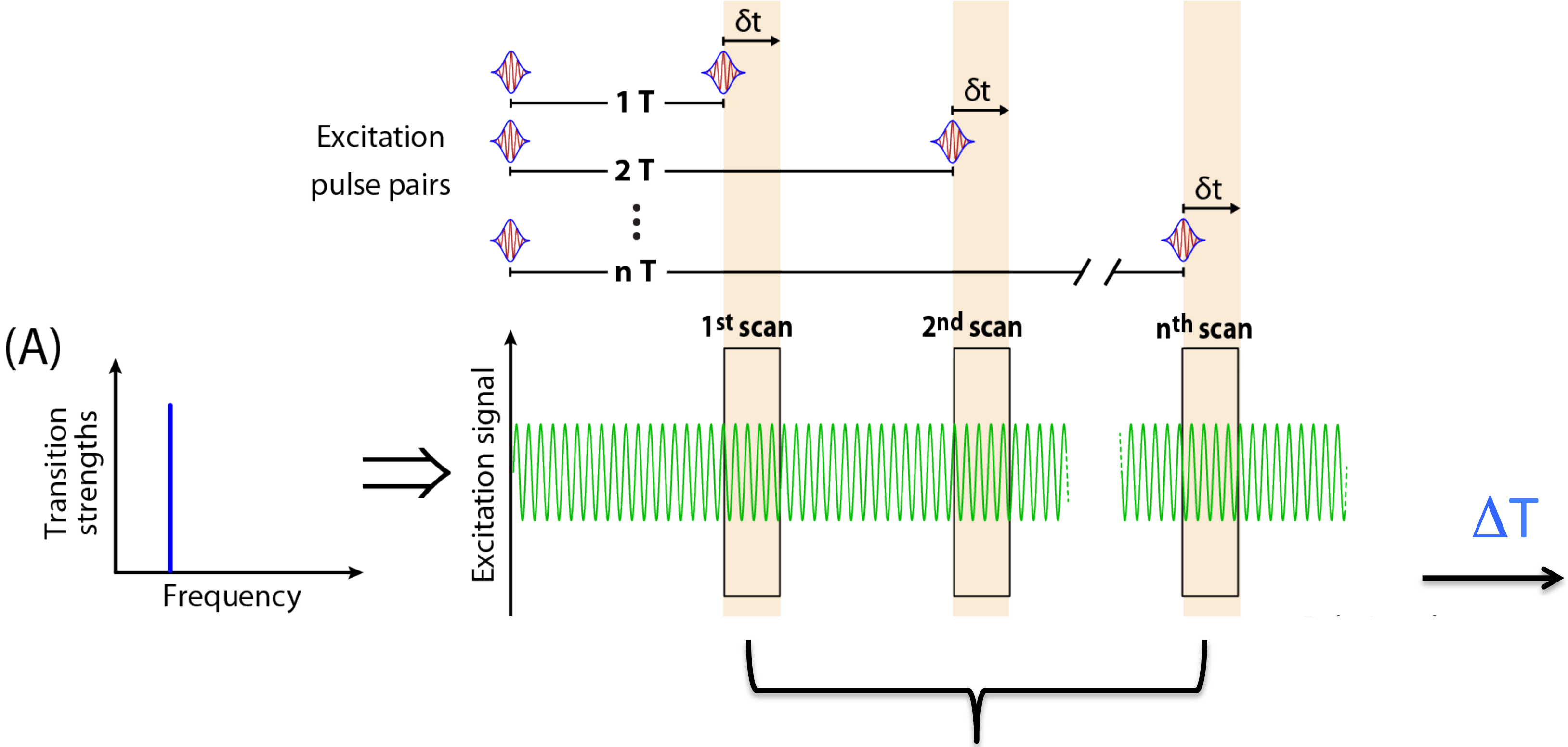
From Ramsey ...



$$\text{Signal} = \cos(2\pi f_{tr}\,\Delta T - \phi_s)$$

$$\text{Error of } \Delta f_{tr} = \Delta\phi_s / 2\pi\,\Delta T$$

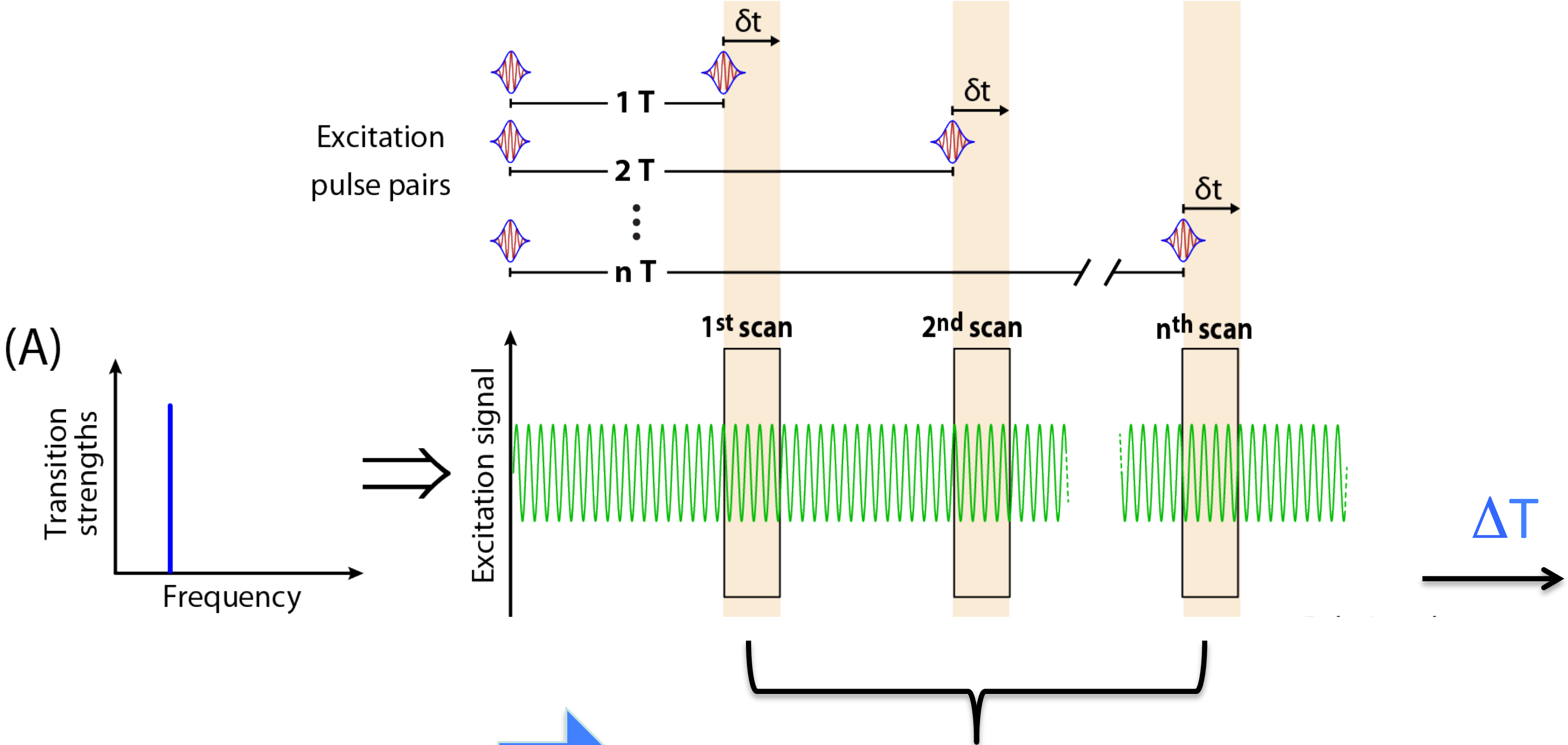
From Ramsey to Ramsey-comb



$$\text{Signal} = \cos(2\pi f_{tr}\,\Delta T - \phi_s)$$

$$\text{Error of } \Delta f_{tr} = \Delta\phi_s \,/\, 2\pi\,\Delta T$$

Constant phase = comb precision!



Constant phase ϕ_s

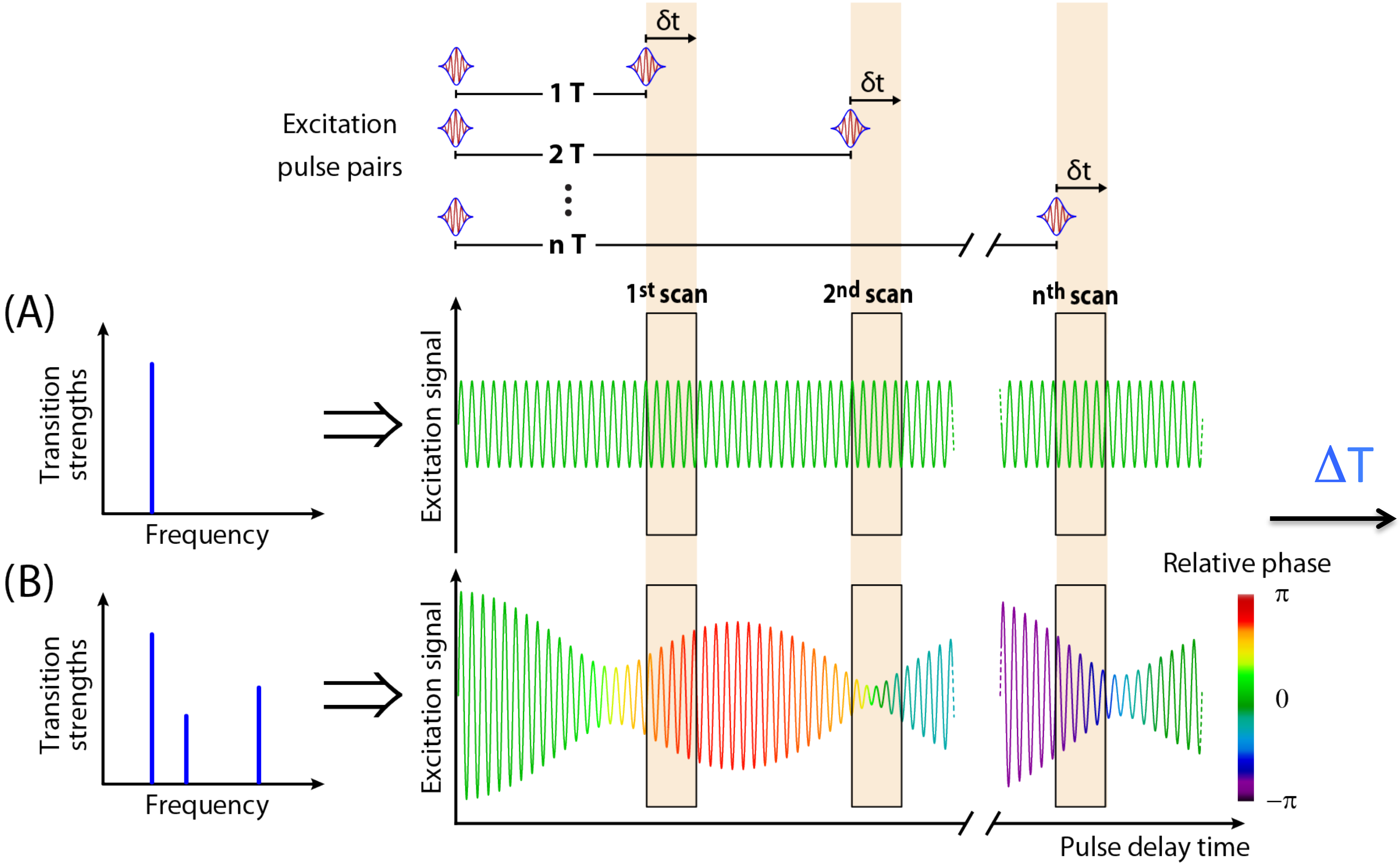
Better than λ / 2000

Accuracy recovered,
& also suppression of
AC Stark effect!

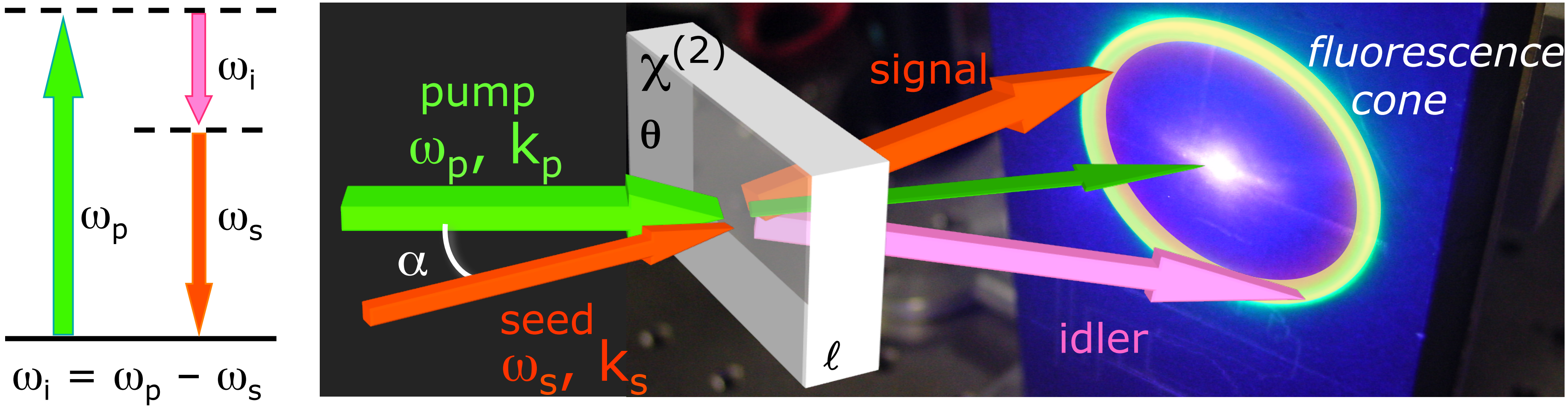
$$\text{Signal} = \cos(2\pi f_{tr}\, \Delta T \cancel{+ \phi_s})$$

$$\text{Error of } \Delta f_{tr} = \cancel{\Delta\phi_s} \,/\, 2\pi\, \Delta T$$

Complex spectra possible



Parametric amplification to mJ

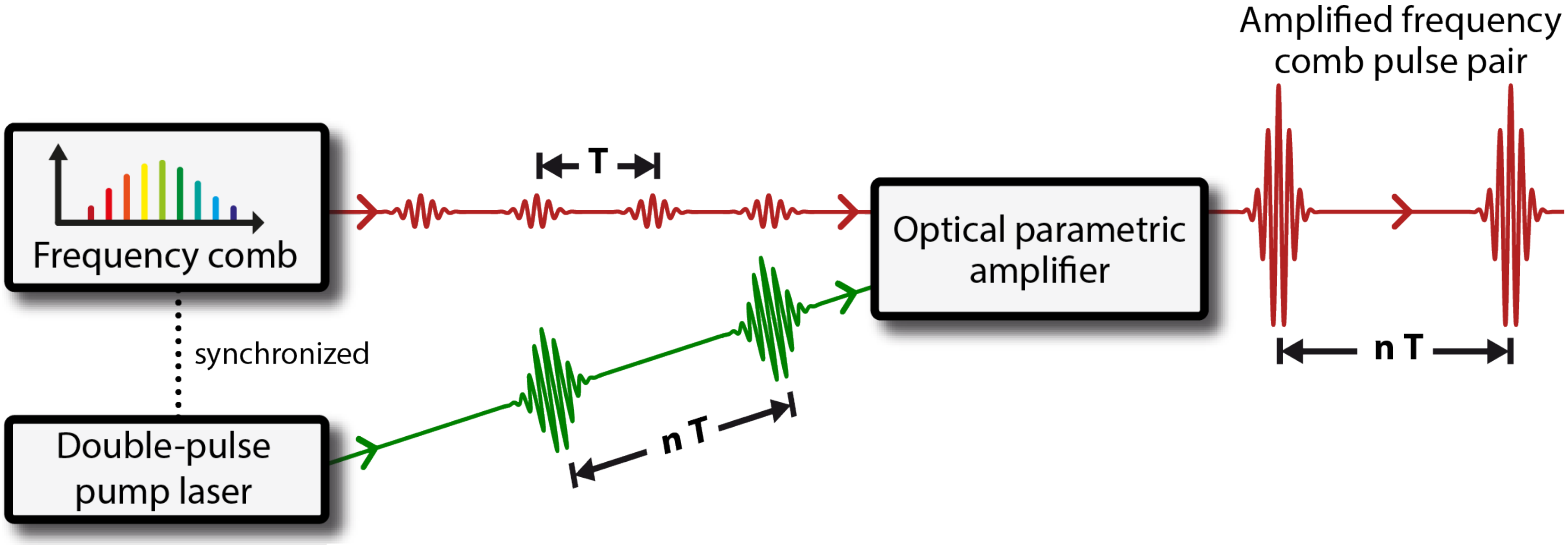


BBO crystals pumped by 532 nm 50 ps at intensities of 7 GW/cm^2

- ☐ Tuning over 700-1000 nm with little effort
- ☐ Bandwidth adjustable from 300 nm to 0.2 nm
- ☐ No memory effect (no dissipation)
- ☐ **Two comb pulses amplified by two synchronized equal pump pulses; microradian pointing sensitivity!**

Power & accuracy: Ramsey-comb excitation

LaserLaB Amsterdam



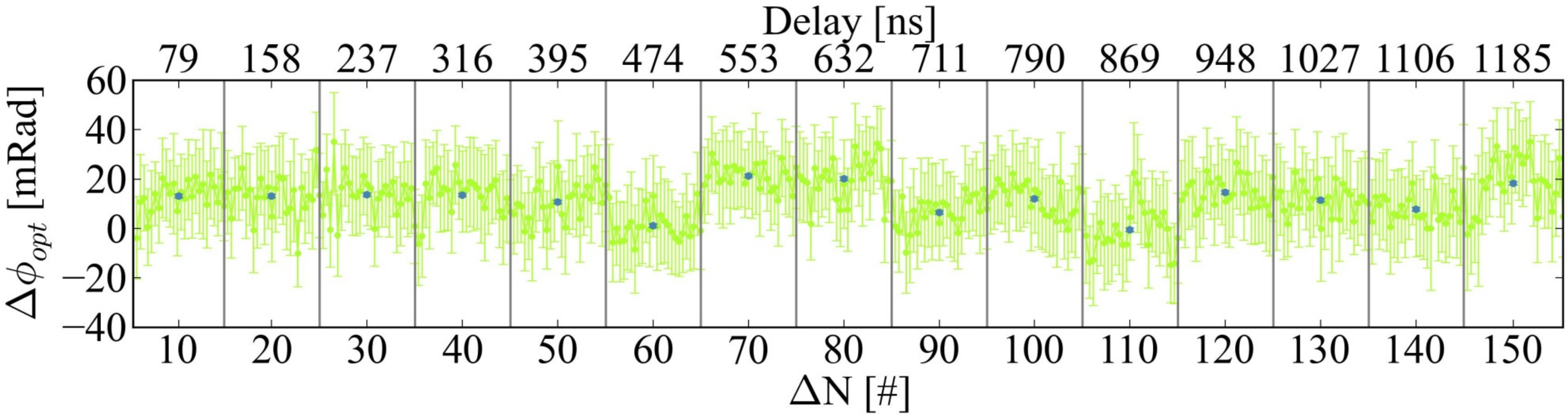
J. Morgenweg, K.S.E. Eikema, Laser Physics Letters **9**, 781-785 (2012)
J. Morgenweg, K.S.E. Eikema, Optics Express **21**, 5275-5286 (2013)
J. Morgenweg, I. Barmes, K.S.E. Eikema, Nature Physics **10**, 30-33 (2014)

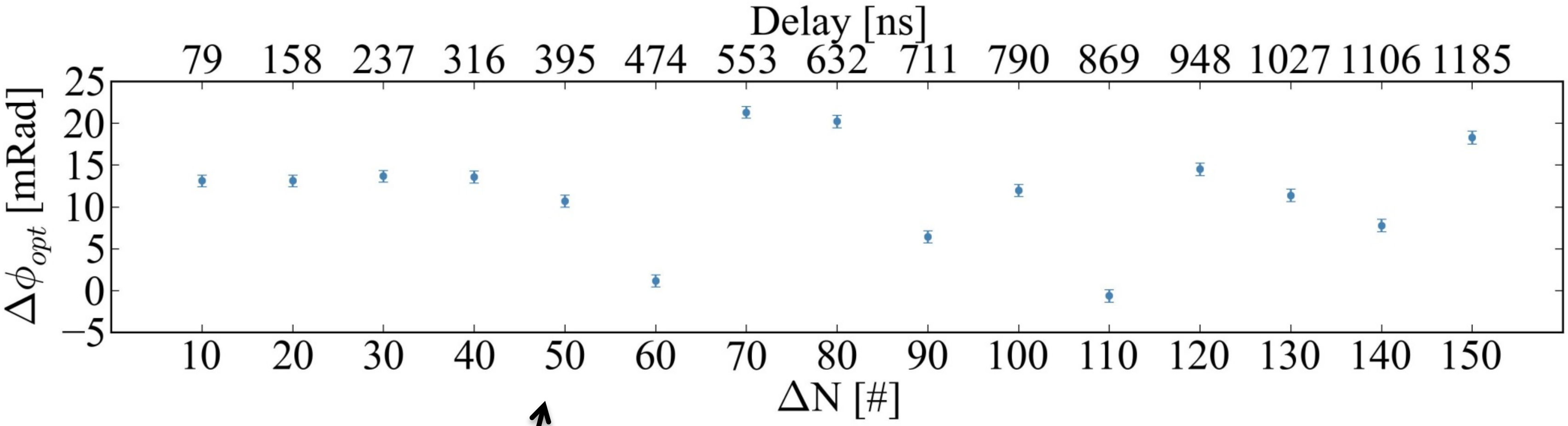
Jonas Morgenweg

Ramsey-comb spectroscopy advantages

- ☐ Combines high pulse energy with kHz accuracy (or even better)
- ☐ Signal well defined in time: efficient signal detection
- ☐ Analysis purely based on phases in the time domain: no lineshape
- ☐ Constant phase effects eliminated, including the AC-Stark effect!
- ☐ High energy pulses = easy frequency (up)conversion to UV and XUV
- ☐ High power gives a lot of flexibility when looking for signal

Phase difference of the amplified pulses

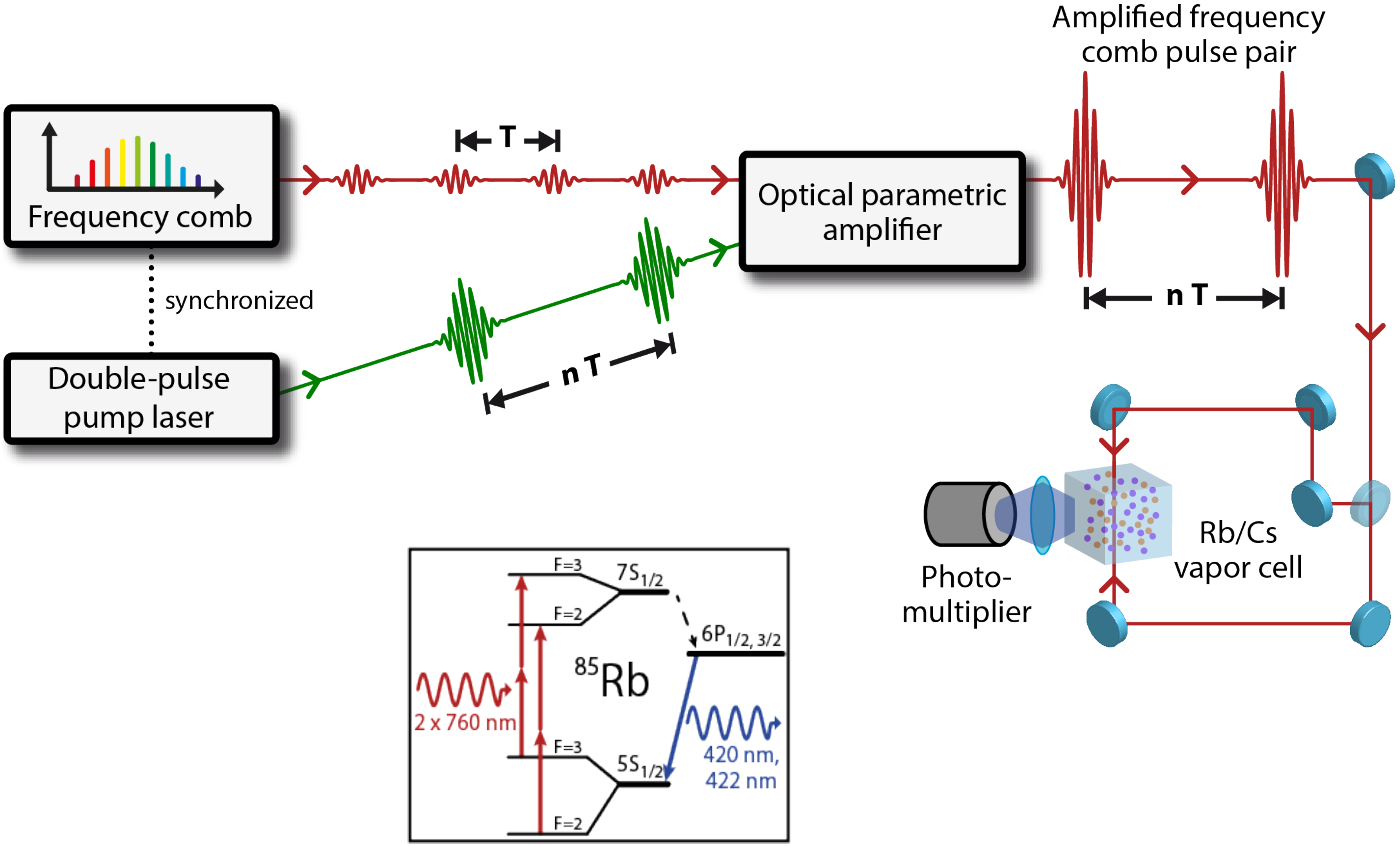




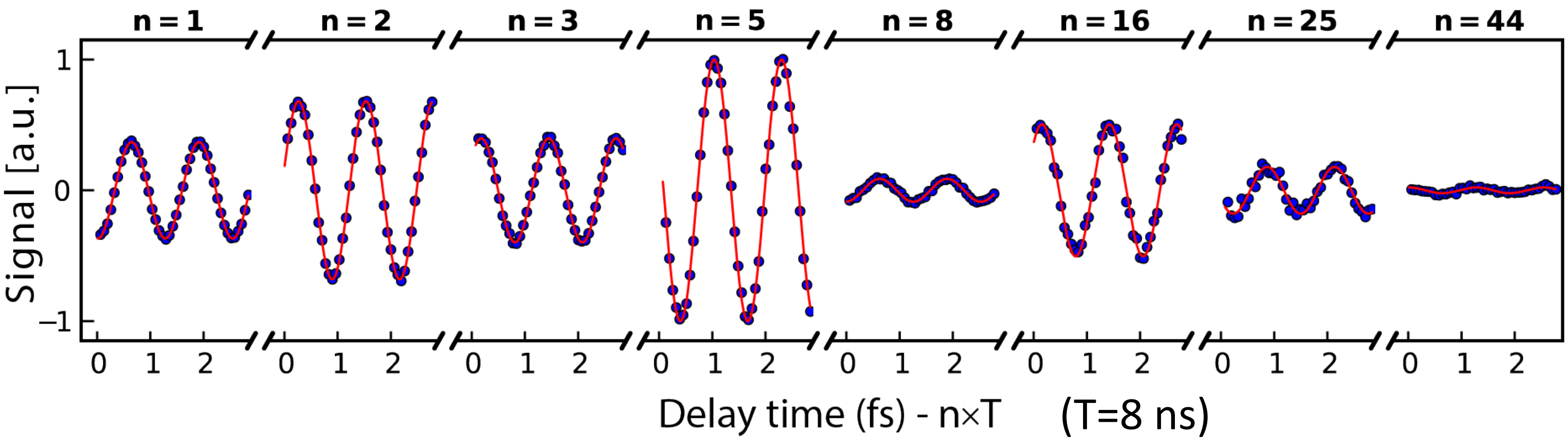
Older measurement; variation after 400 ns mostly due to the measurement method

Ramsey-Comb spectroscopy test

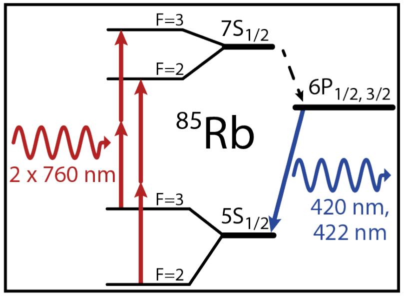
LaserLaB Amsterdam

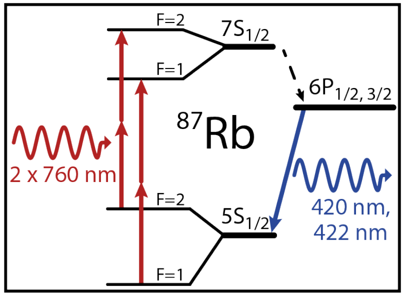


Rubidium signal at different delays


Rubidium, 5S-7S (2 x 760 nm)

- Two-photon Ramsey-signals at multiple macro-delays n×T
- Amplitude modulation from multiple resonances





kHz-level accuracy in Rb and Cs

Frequency description		Result [kHz]
^{85}Rb, 5S$_{1/2}$ - 7S$_{1/2}$	Center of gravity	788,796,960,604(4)$_{\mathrm{stat}}$(3)$_{\mathrm{sys}}$
	Hyperfine A$_{7S}$	94,684(2)$_{\mathrm{stat}}$(2)$_{\mathrm{sys}}$
^{87}Rb, 5S$_{1/2}$ - 7S$_{1/2}$	Center of gravity	788,797,092,128(6)$_{\mathrm{stat}}$(3)$_{\mathrm{sys}}$
	Hyperfine A$_{7S}$	319,761(6)$_{\mathrm{stat}}$(3)$_{\mathrm{sys}}$
^{133}Cs, 6S$_{1/2}$ - 9S$_{1/2}$	Center of gravity	806,761,363,429(5)$_{\mathrm{stat}}$(3)$_{\mathrm{sys}}$
	Hyperfine A$_{9S}$	109,999(3)$_{\mathrm{stat}}$(1)$_{\mathrm{sys}}$

Publications:

J. Morgenweg, I. Barmes and K.S.E. Eikema, Nature Physics **10**, 30-33 (2014)

J. Morgenweg and K.S.E. Eikema, PRA **89**, 052510 (2014)

Compares well with previous full-reprate direct comb excitation:

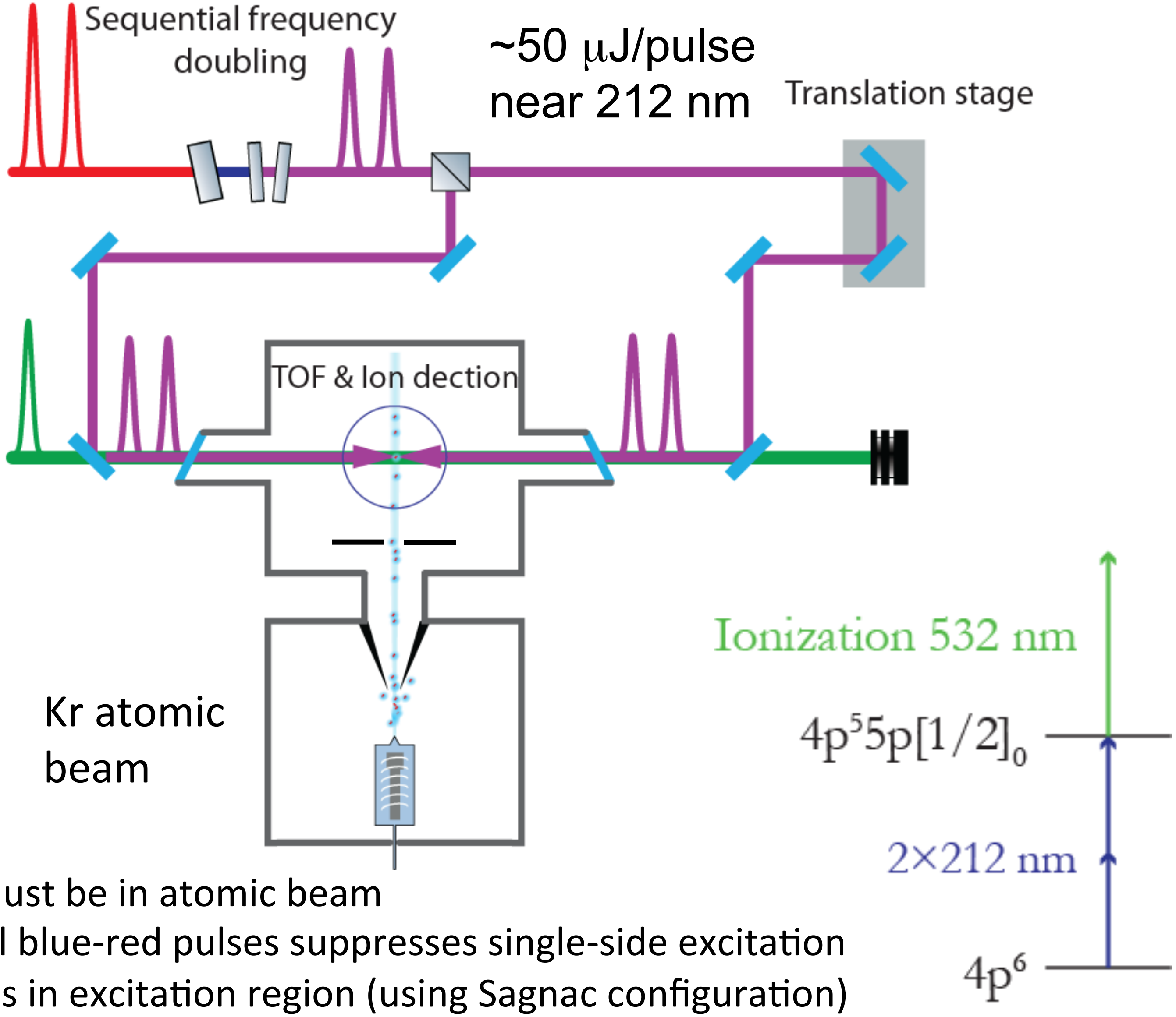
I. Barmes, S.Witte and K.S.E. Eikema:

Nature Photonics **7**, 18 (2013) and PRL **111**, 023007 (2013)

Kr excitation at 2x 212 nm

1.5 mJ/pulse
near 848 nm

~50 μJ/pulse
near 212 nm



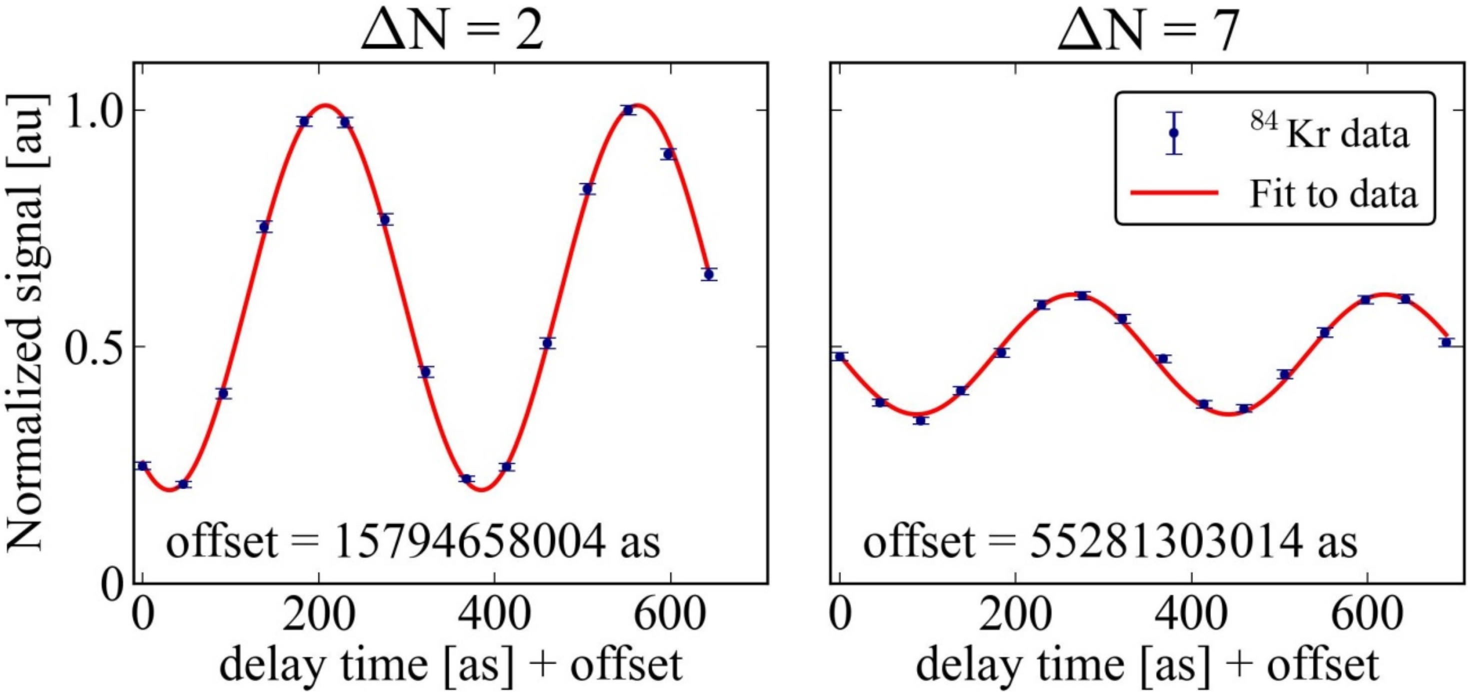
Kr atomic
beam

- ☐ Collision point must be in atomic beam
- ☐ Coherent control blue-red pulses suppresses single-side excitation
- ☐ Overlap of beams in excitation region (using Sagnac configuration)

Results in krypton at 212 nm

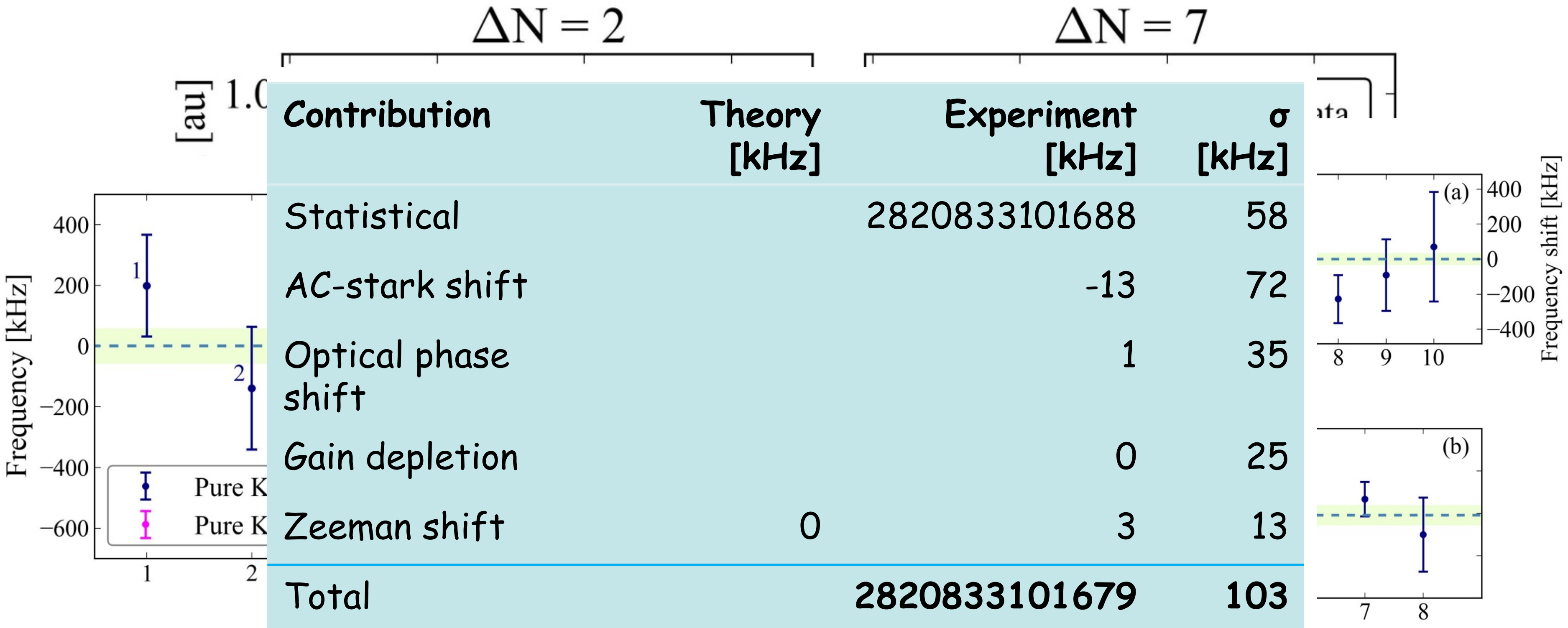
LaserLaB Amsterdam

- Ramsey-interference signals
- Account for all systematic effects



Results in krypton at 212 nm

- Ramsey-interference signals
- Account for all systematic effects

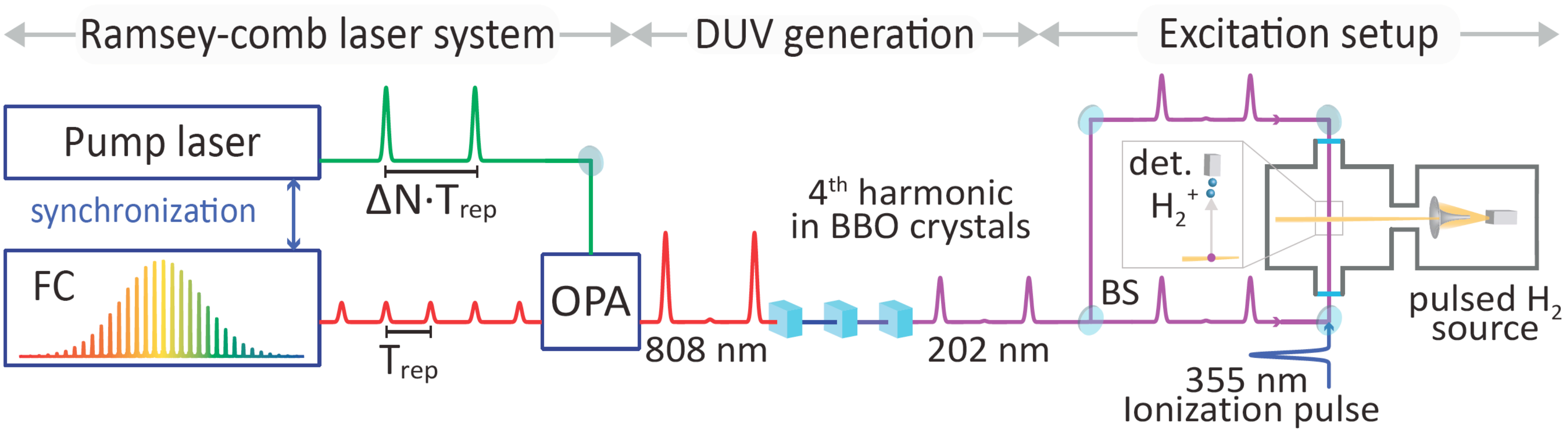


Contribution	Theory [kHz]	Experiment [kHz]	σ [kHz]
Statistical		2820833101688	58
AC-stark shift		-13	72
Optical phase shift		1	35
Gain depletion		0	25
Zeeman shift	0	3	13
Total		**2820833101679**	**103**

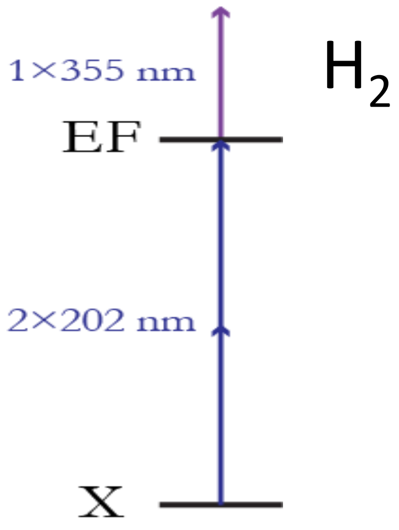
Improvement of 34 times over previous measurements

Accepted by PRL September 2016.

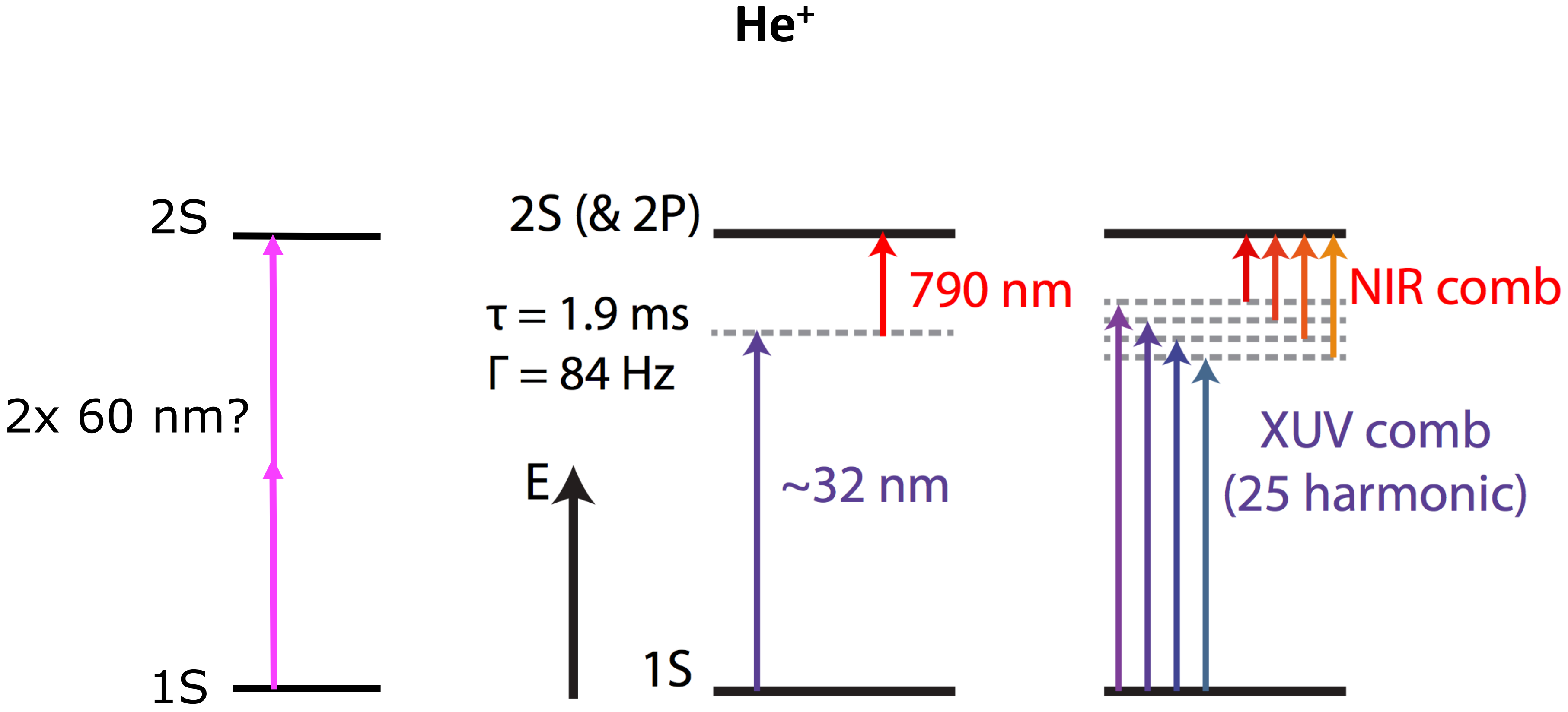
Next: H_2 (X-EF) spectroscopy at 2x202 nm



- Excitation 2x202 nm, tens of μJ/pulse
- Beam ~1 mm diameter
- Ionization with 355 nm pulse
- Single-sided excitation suppressed by λ/4 plates and chirped pulses

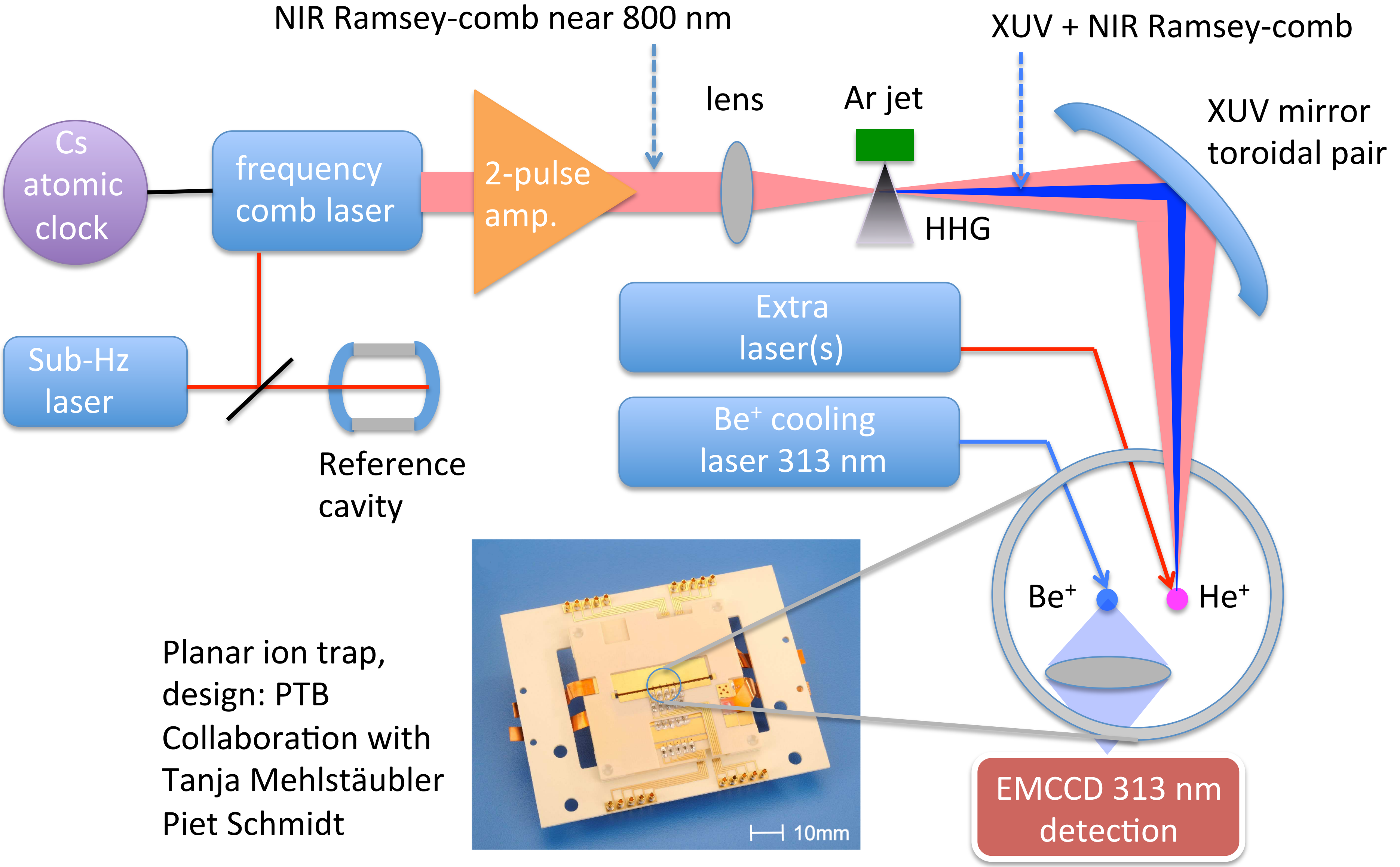


And of course 1S-2S excitation of He+ !



After applying a bunch of tricks the target accuracy is ~ 1kHz or better...

Setup 1S-2S excitation of He+



NIR Ramsey-comb near 800 nm

XUV + NIR Ramsey-comb

Cs atomic clock

frequency comb laser

2-pulse amp.

lens

Ar jet

HHG

XUV mirror toroidal pair

Sub-Hz laser

Reference cavity

Extra laser(s)

Be^+ cooling laser 313 nm

Be^+

He^+

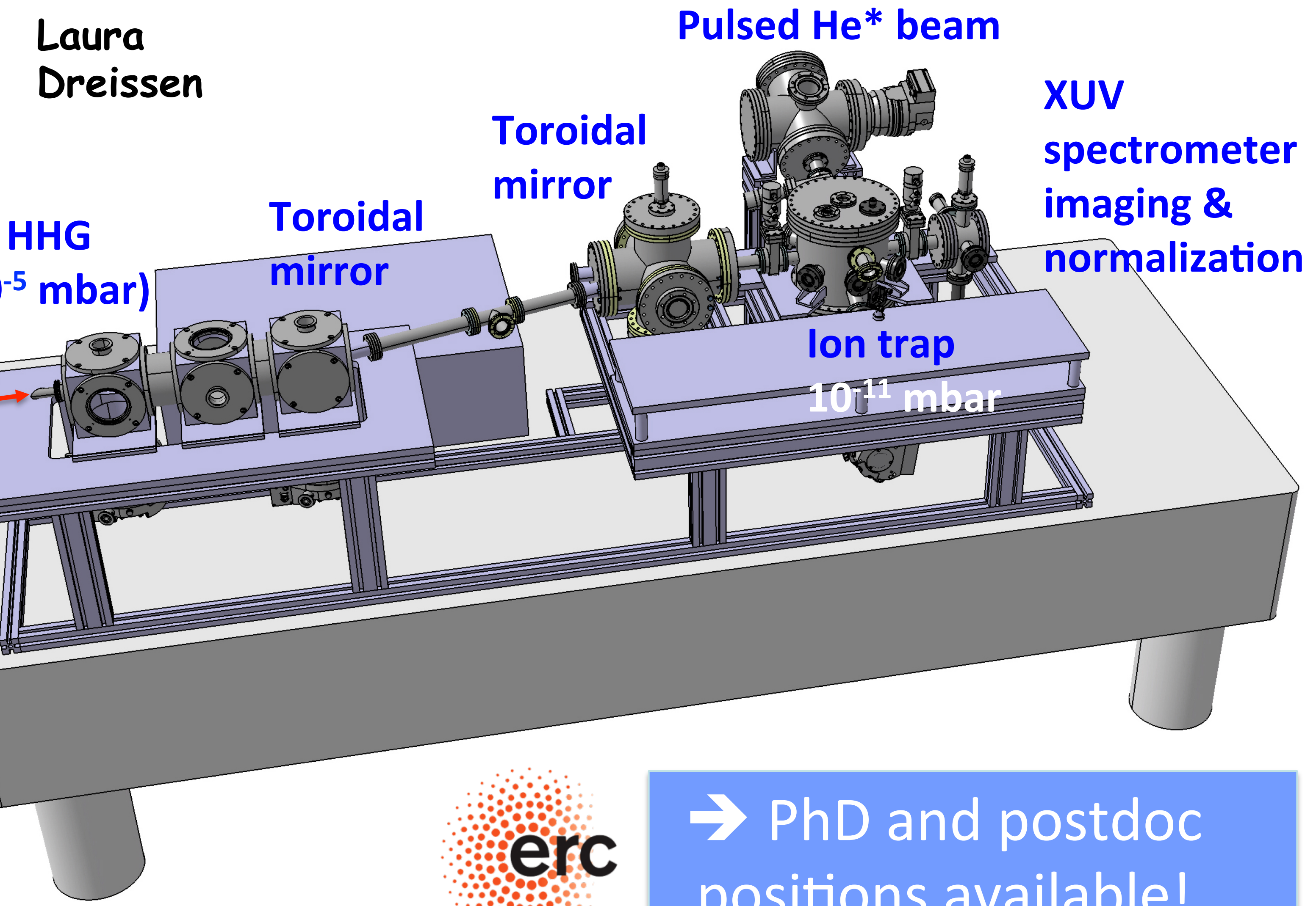
EMCCD 313 nm detection

Planar ion trap,
design: PTB
Collaboration with
Tanja Mehlstäubler
Piet Schmidt

Design He+ experiment vacuum setup

LaserLab Amsterdam

Laura Dreissen



→ PhD and postdoc positions available!

Thanks to all involved:

LaserLaB Amsterdam

Current coworkers

Robert Altmann

Laura Dreissen

Sandrine Galtier

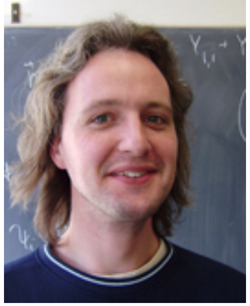
Itan Barmes

Stefan Witte

Wim Ubachs

Recent former coworkers

Jonas Morgenweg



Tjeerd Pinkert

Axel Ruehl

Dominik Kandula

Christoph Gohle

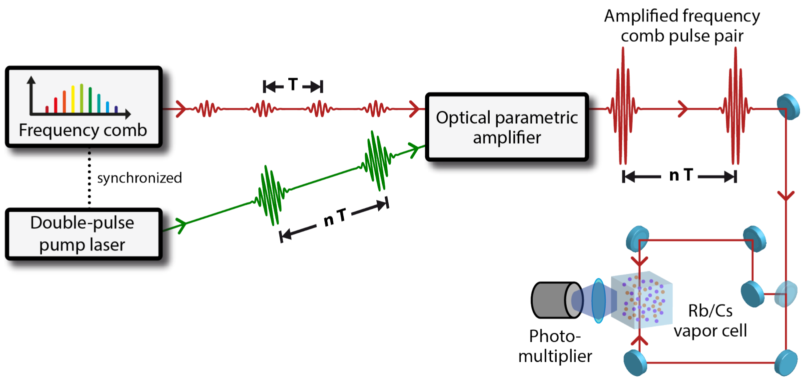
Anne Lisa Wolf

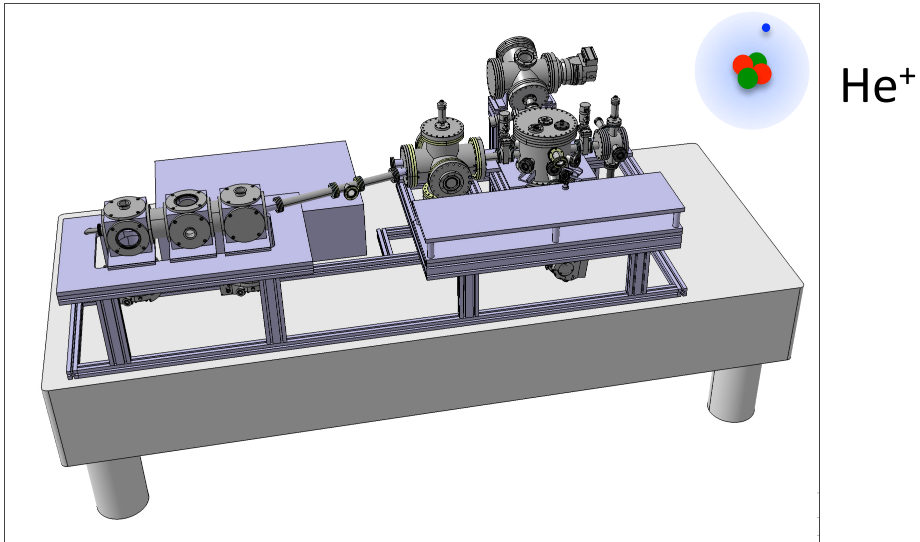
Summary

- Proton Radius Puzzle in a confusing state
- More measurements in muonic and electronic systems required

- Ramsey-comb spectroscopy enables precision measurements at ever shorter wavelengths; now deep-UV demonstrated
- Extension of Ramsey-comb spectroscopy to 30 nm seems feasible

- Good prospects for contributions to the proton radius puzzle by Ramsey-comb spectroscopy of H_2 (X-EF) & He^+ (1S-2S)





Avoiding delay dependent phase shifts in HHG