

Two-photon laser spectroscopy of antiprotonic helium and the antiproton-electron mass ratio

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**Asacusa collaboration at CERN's
Antiproton Decelerator**

(* University of Tokyo)



Funding agencies: European Research Council – Ministry of Education, Culture, Sports, Science and Technology, Japan – Austrian Federal Ministry of Science – OTKA Hungarian Scientific Research Fund – European Science Foundation (EURYI) – Monbukagakusho – Munich Advanced Photonics Cluster of the Deutsche Forschungsgemeinschaft



Outline

- ~~Where/who we are~~ (see previous talk by Ryu Hayano)
 - Antiprotonic helium:
 - ... what it is, how to create it.
 - ... motivation, why we care at all
 - Our scientific goal
 - Experimental method, layout
 - Latest results, compare to earlier
 - Interpretation of results
- } Historical context



CPT Symmetry: proton - antiproton

- To test CPT: compare properties of particles-antiparticles
- No CPT violation observed so far – the quest is towards continuously higher precisions, to discover something "in the next digit"
- High-precision antiproton experiments:
 - Cyclotron frequencies in a Penning trap: $q/m \sim 9 \times 10^{-11}$ (TRAP @ LEAR, ATRAP @ AD)
 - spin-flip in Penning trap $\mu_{\bar{p}}/\mu_p \sim 5 \times 10^{-6}$ (aim: 10^{-9})
ATRAP@AD (recently), BASE@AD (future)
 - Antihydrogen spectroscopy – future
(ASACUSA, ATRAP, ALPHA @ AD)
 - Antihydrogen gravitation – future
(GBAR, AEGIS @ AD)
 - What other high-precision measurements can we do with antiprotons besides Penning traps?
LASER SPECTROSCOPY OF ANTIPROTONIC HELIUM!



Alternative way to trap $\bar{P}$: exotic atom

- $\bar{P}$ stops in material – replaces an electron in an atomic orbit – cascades down immediately (and annihilates)
- Emitted radiation: X-ray. Spectrum $\rightarrow m_{\bar{P}}$ (precision: 5×10^{-5})

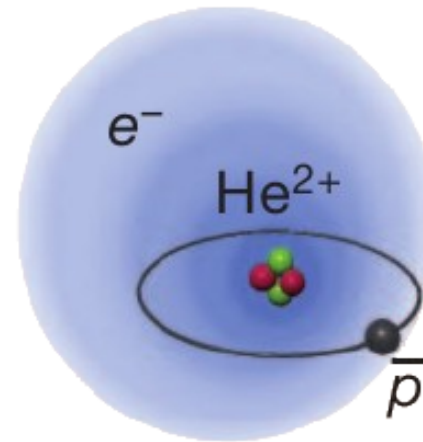


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Antiprotonic helium (same story?)

- $\bar{P}$ replaces one electron:
nucleus + $\bar{P}$ + electron
in high Rydberg state ($n \sim 38$, $l \sim n-1$)



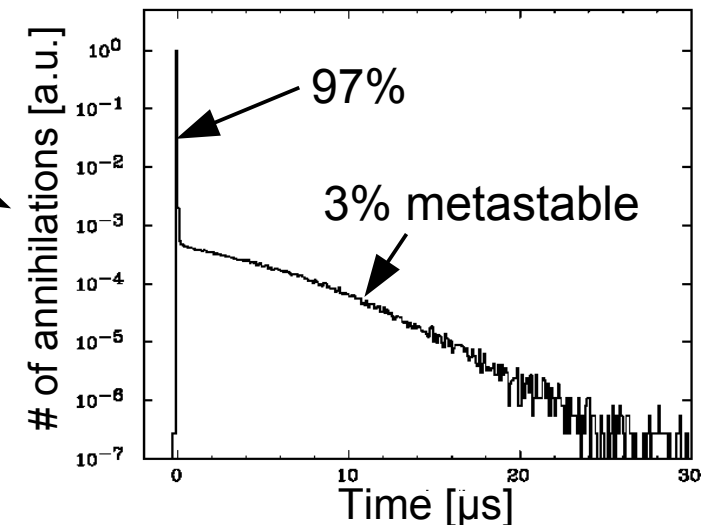
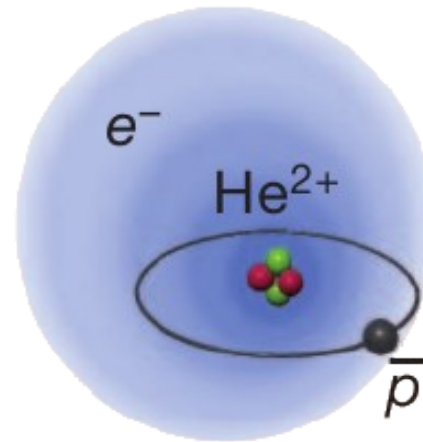
Alternative way to trap $\bar{P}$: exotic atom

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Unique!

Antiprotonic helium (~~same story?~~)

- $\bar{P}$ replaces one electron:
nucleus + $\bar{P}$ + electron
in high Rydberg state ($n \sim 38$, $l \sim n-1$)
- $\sim 3\%$ in metastable states
(lifetime: 3-4 μs , enough for experimenting)
- antiproton's atomic transitions are in the **visible range**
(laser spectroscopy, high precision)
- **Simple enough** for 10^{-9} calculations, or better
(see next talk by V. Korobov)



What exactly can we learn from $\bar{\text{P}}\text{-He}$ spectroscopy? Scientific goal

- Measure atomic transition frequencies of antiprotonic helium: ν_{exp}
- Compare it to theoretical 3-body calculations: ν_{th}
[V.I. Korobov, for example: *Phys. Rev. A* 77 (2008) 042506]
(see next talk)
- Interpretation:

Frequency is function of many constants: $\nu_{\text{th}}(m_{\text{He}}, q, m_e, m_{\bar{\text{p}}})$

Use this hydrogen-like parametrization:

$$\nu_{n,l \rightarrow n',l'} = R c \frac{m_{\bar{\text{p}}}^*}{m_e} Z_{\text{eff}}^2(n, l, n', l') \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

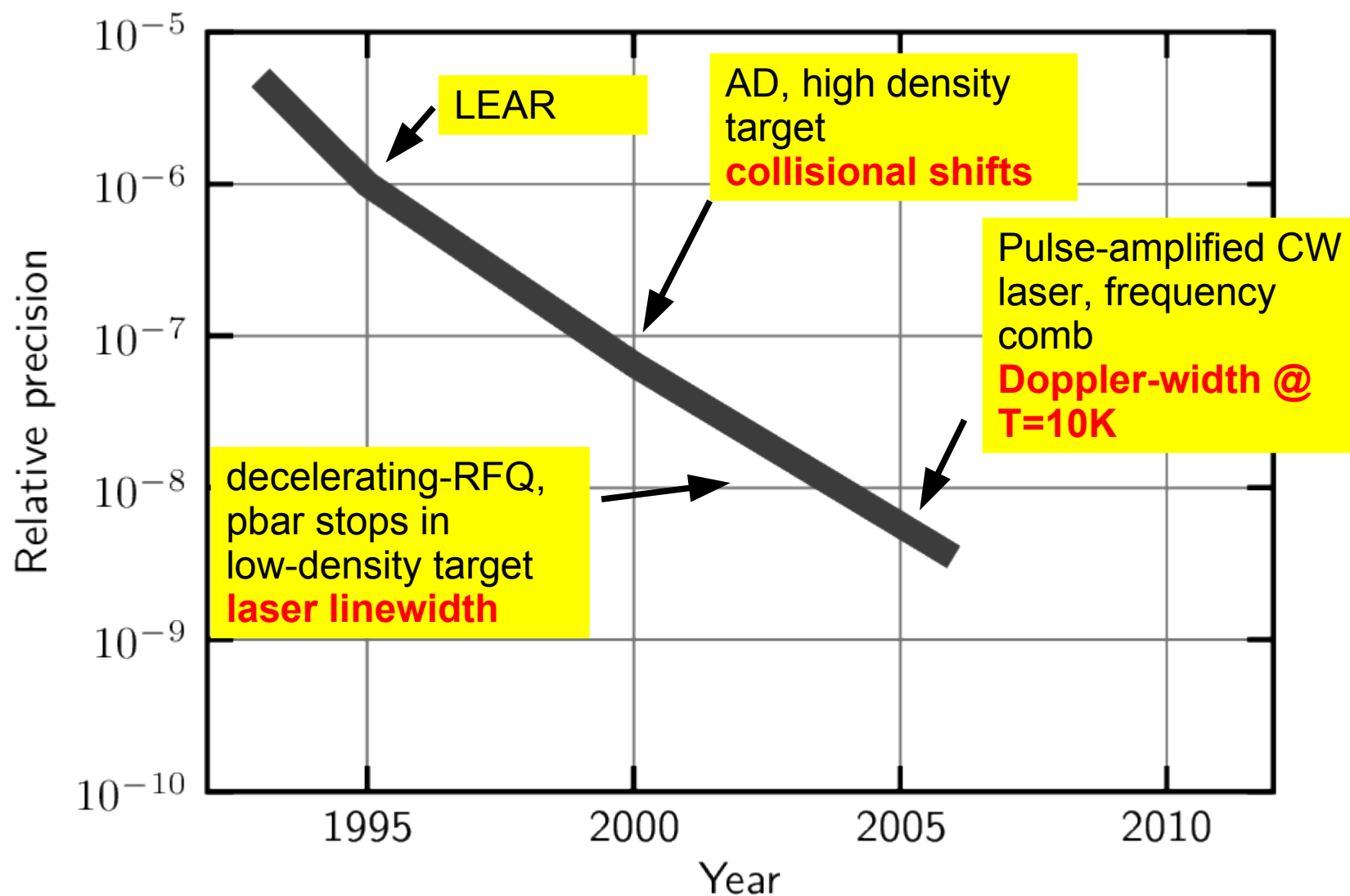
Known to extremely high precision

Screening by electron; use QED to calculate

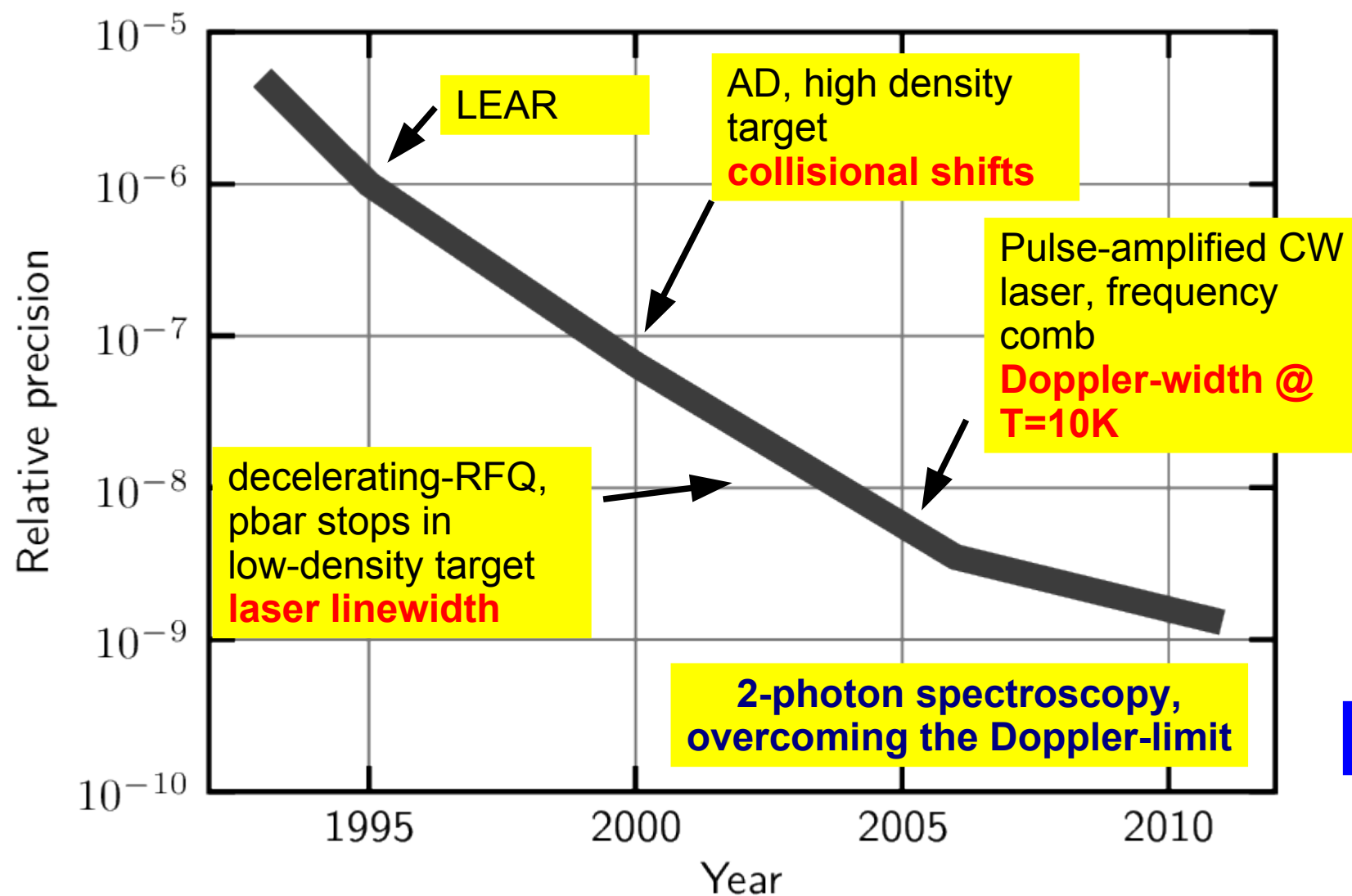
Let $\nu_{\text{th}}(m_{\bar{\text{p}}}/m_e) \equiv \nu_{\text{exp}} \Rightarrow m_{\bar{\text{p}}}/m_e$ – a dimensionless fundamental constant



Long history, continuously increasing precision



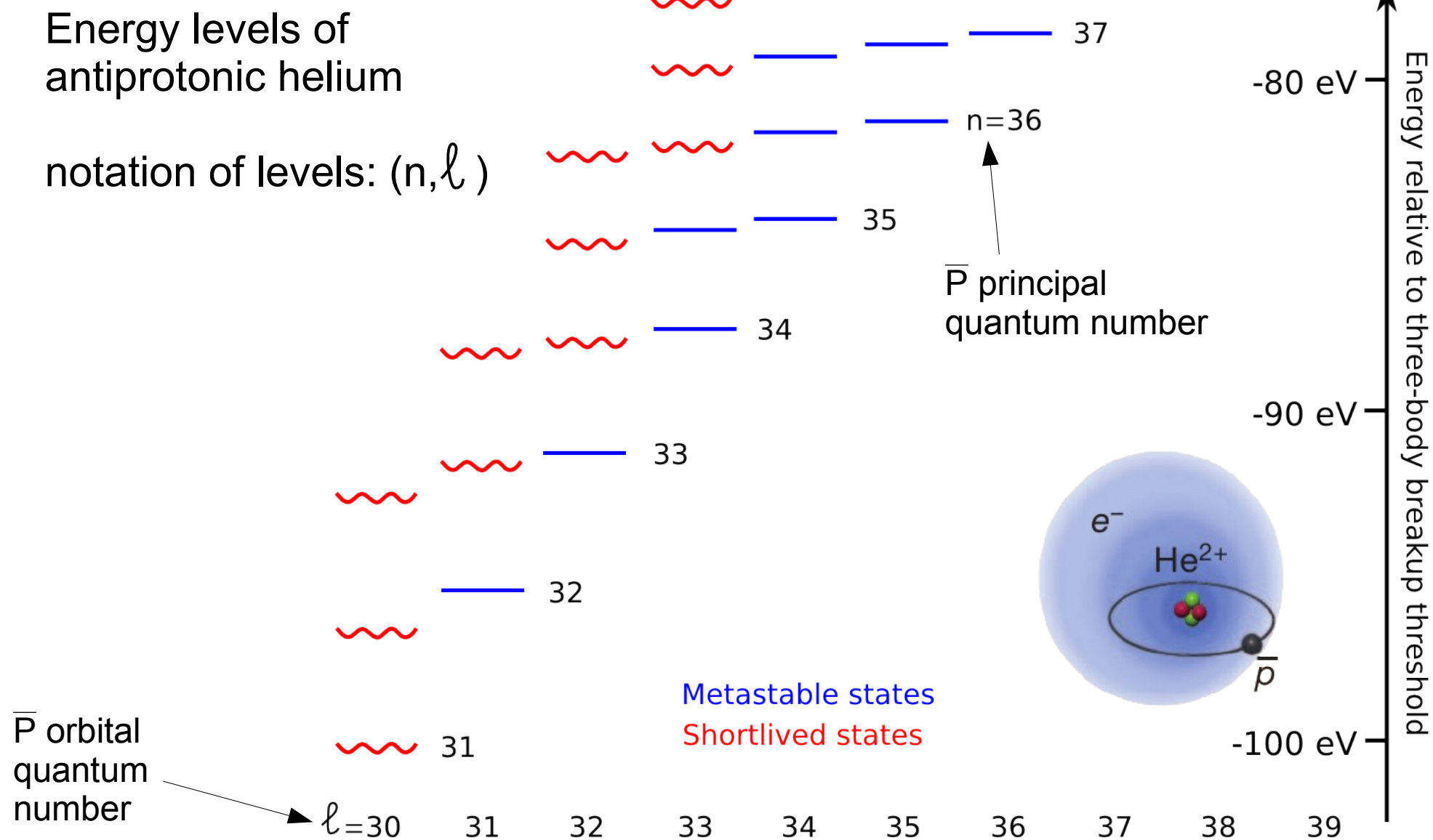
Long history, continuously increasing precision



This talk...



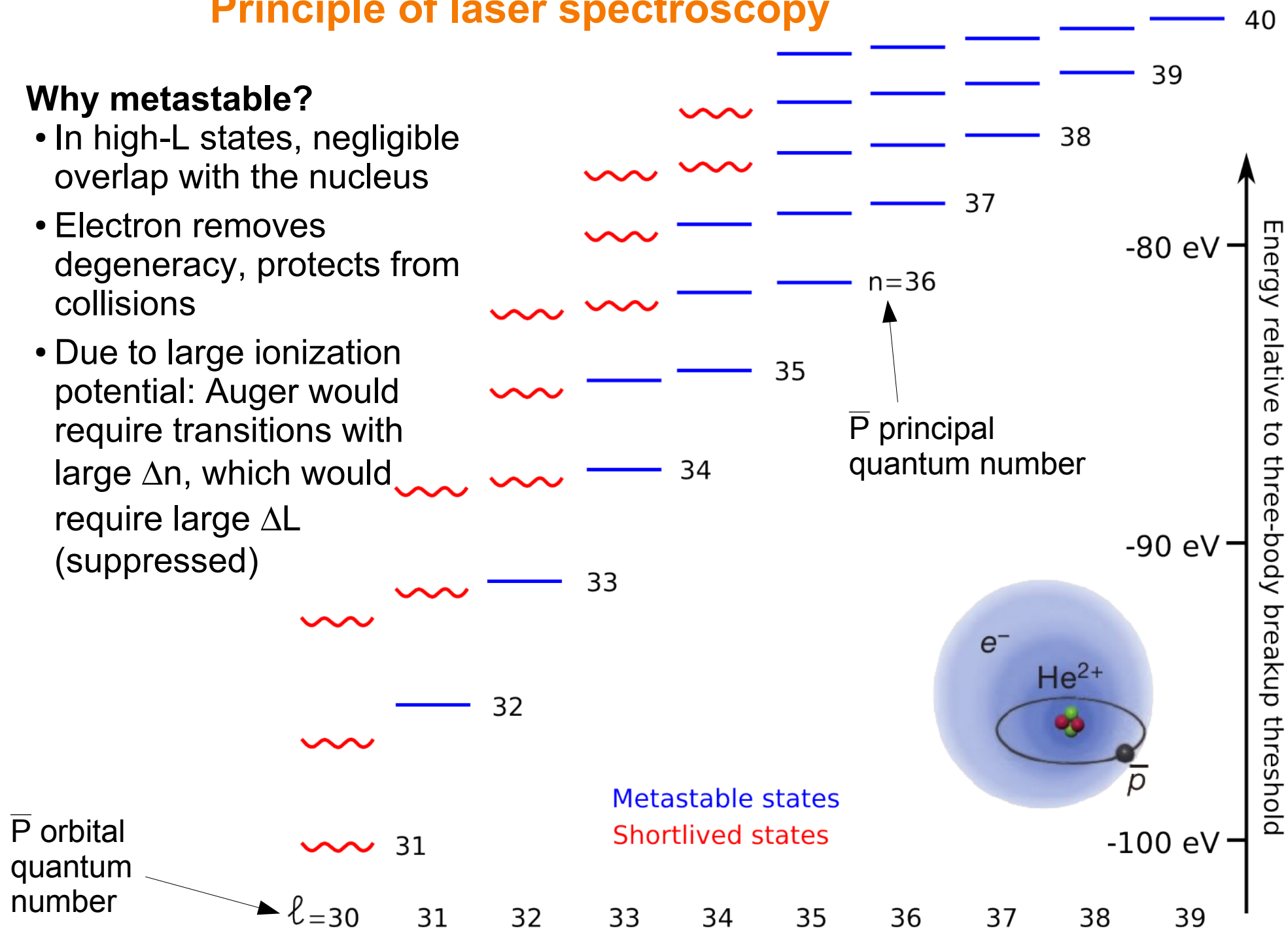
Principle of laser spectroscopy



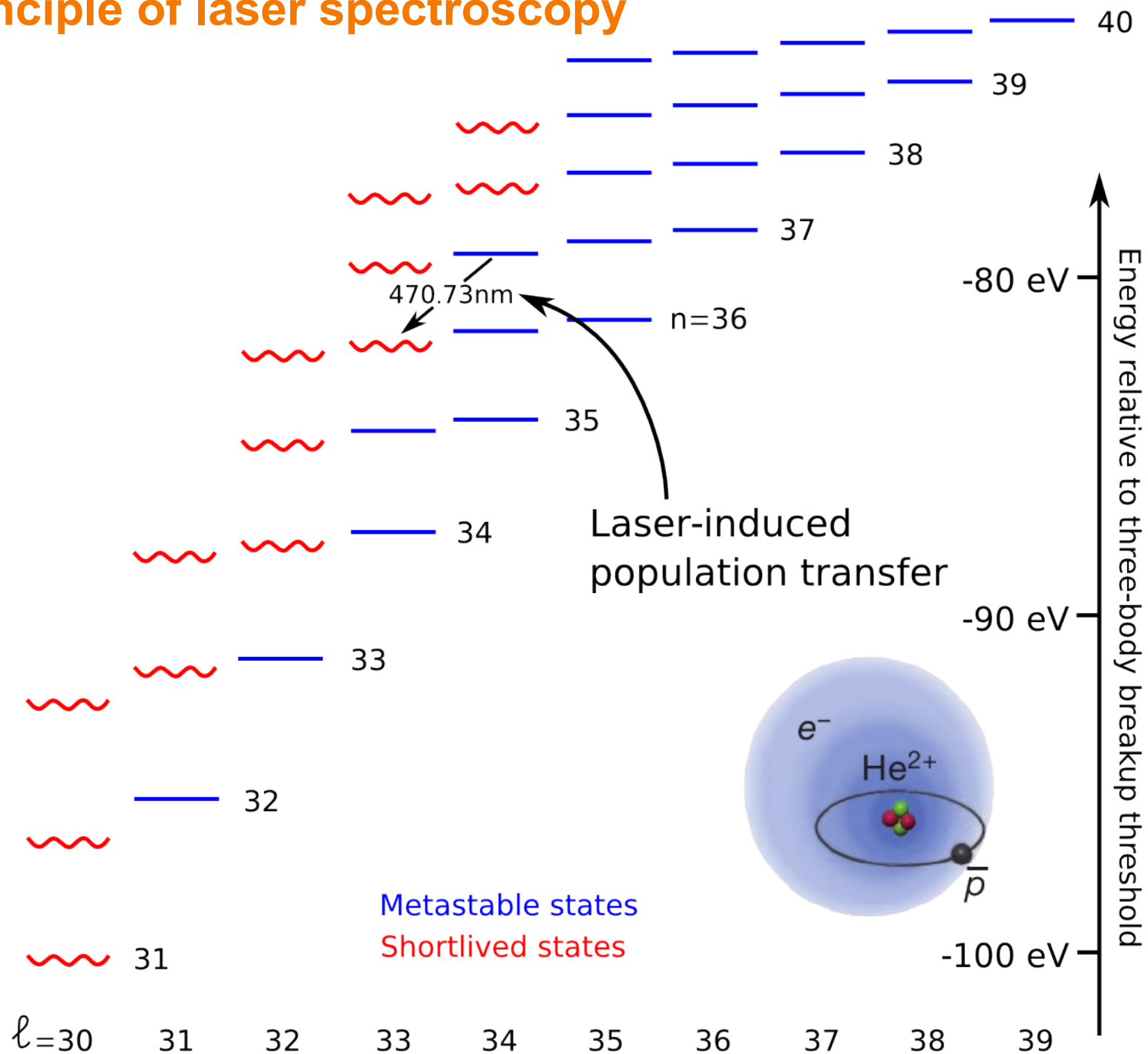
Principle of laser spectroscopy

Why metastable?

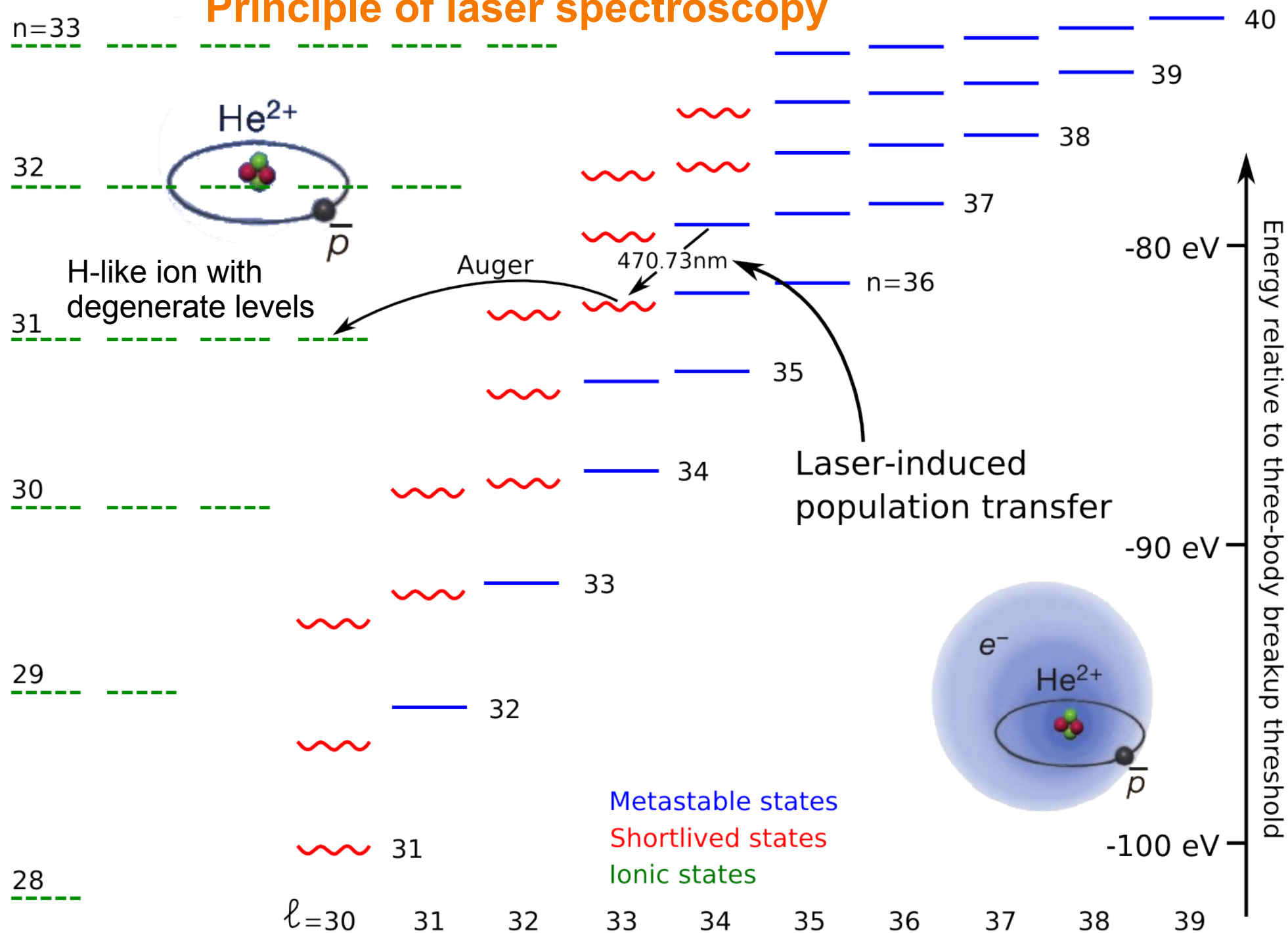
- In high-L states, negligible overlap with the nucleus
- Electron removes degeneracy, protects from collisions
- Due to large ionization potential: Auger would require transitions with large Δn , which would require large ΔL (suppressed)



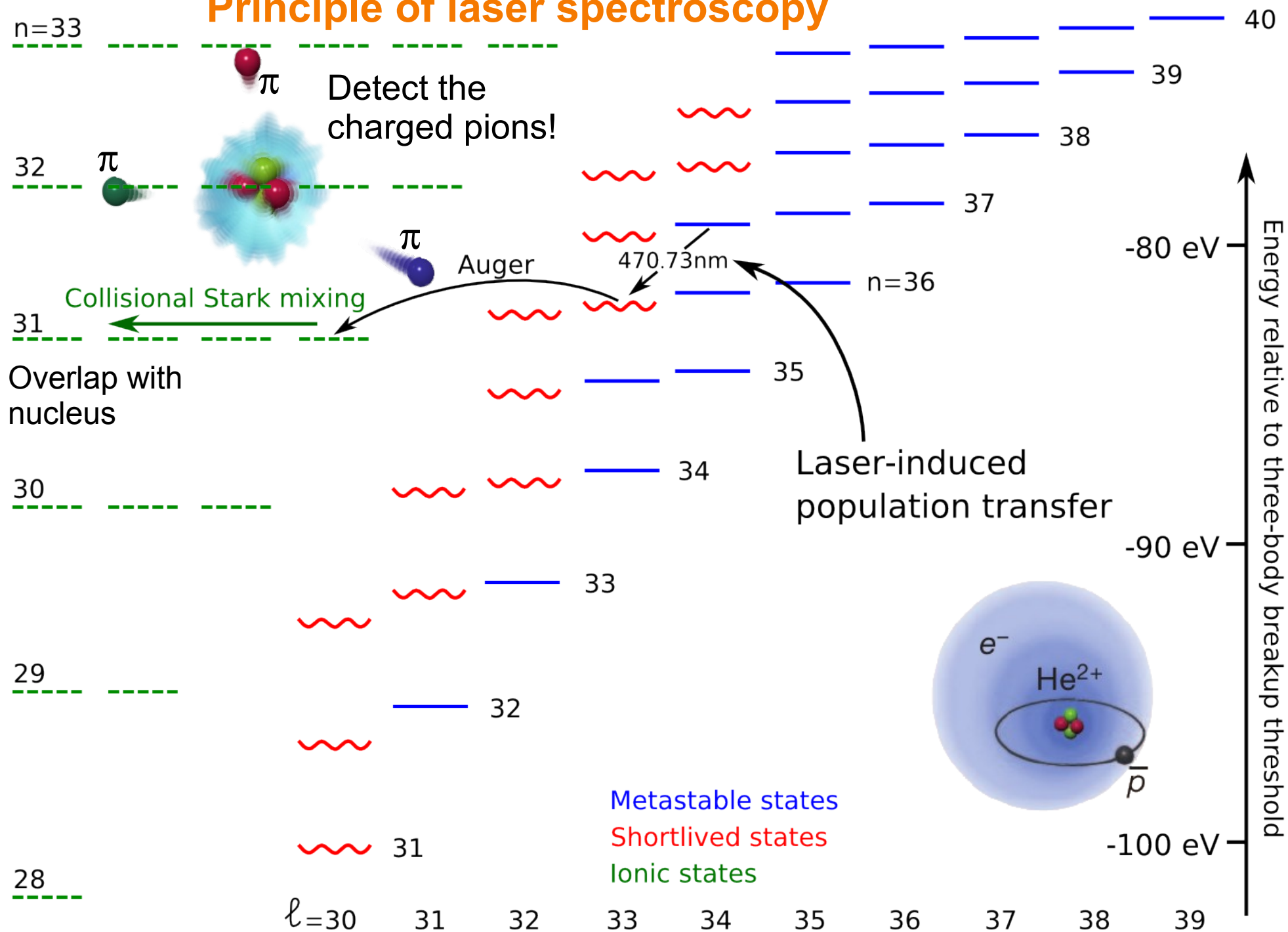
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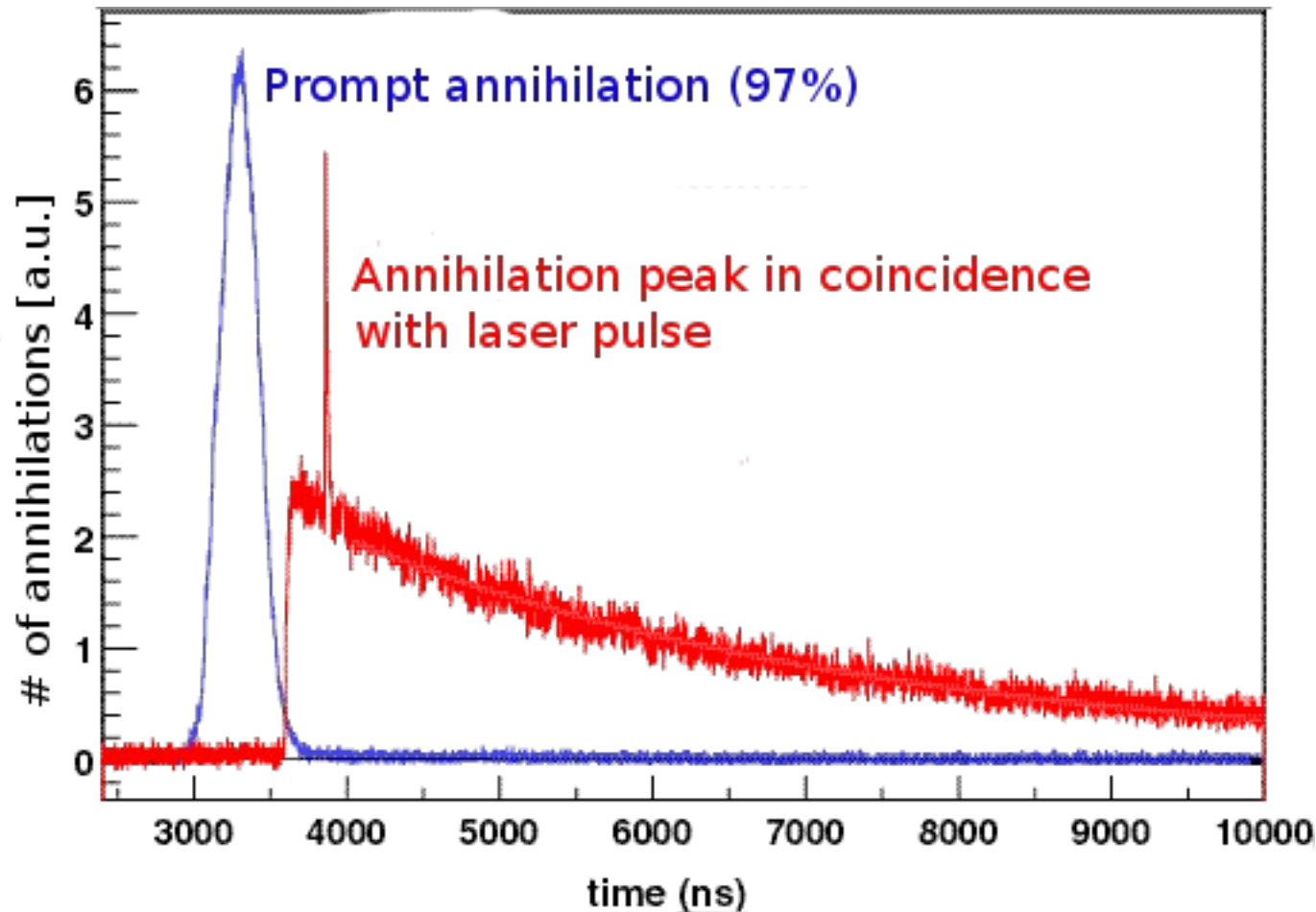
Principle of laser spectroscopy



Principle of laser spectroscopy



Principle of laser spectroscopy



To measure the resonance lineshape:

- Scan laser frequency
- Register peak area vs. laser frequency



The big and the small....



Size 3 meters

Lifetime 70 years

Heartbeat rate 28/minute



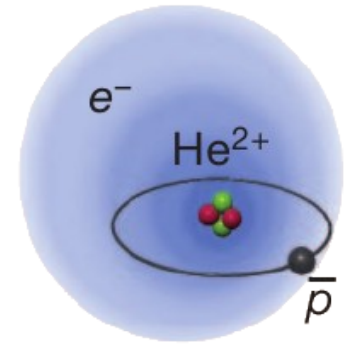
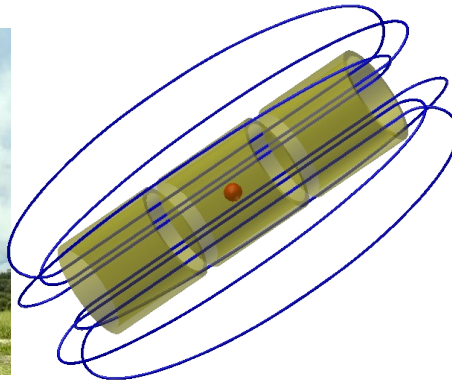
8 cm

1 year

550/minute



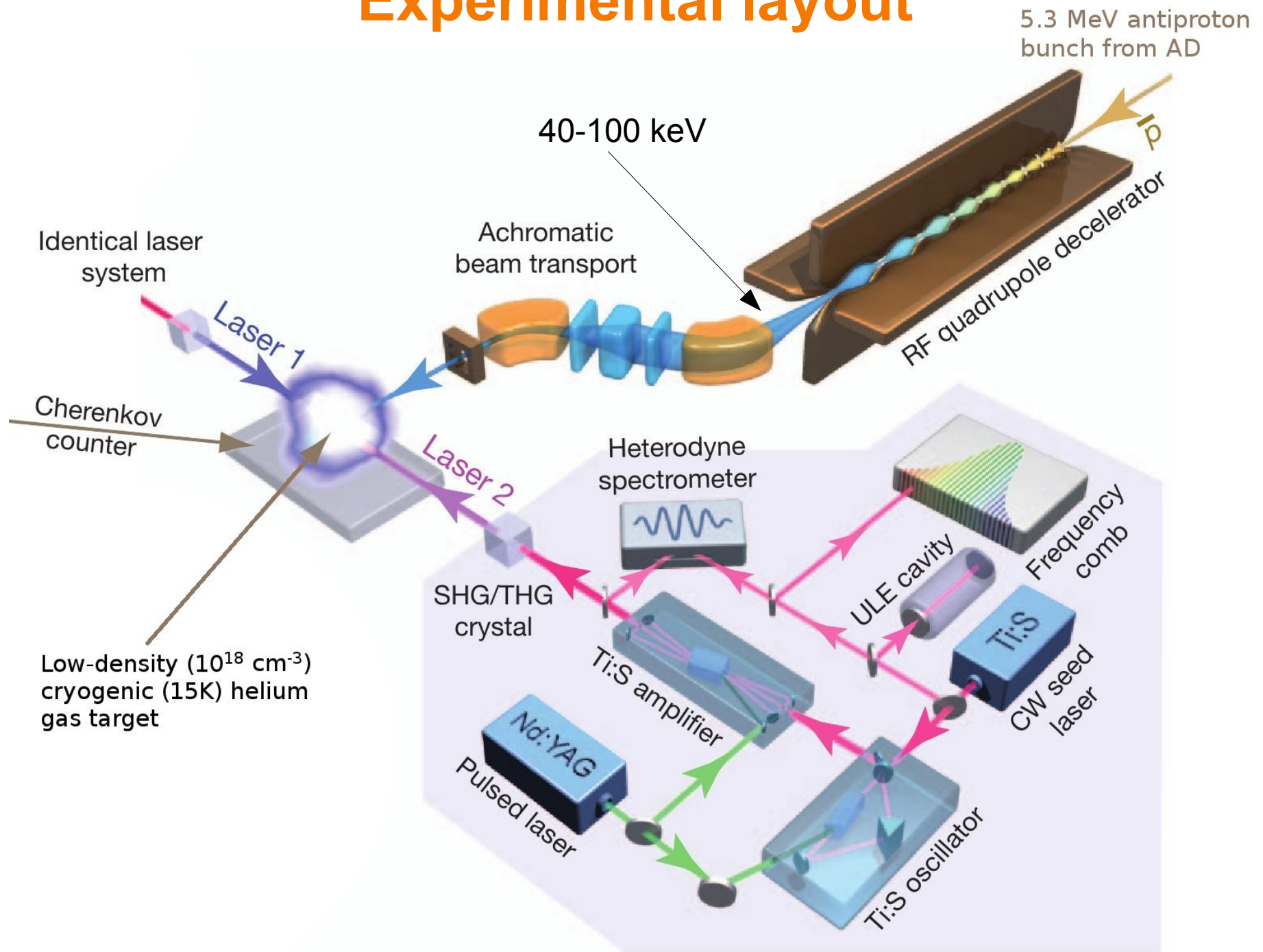
The big and the small....

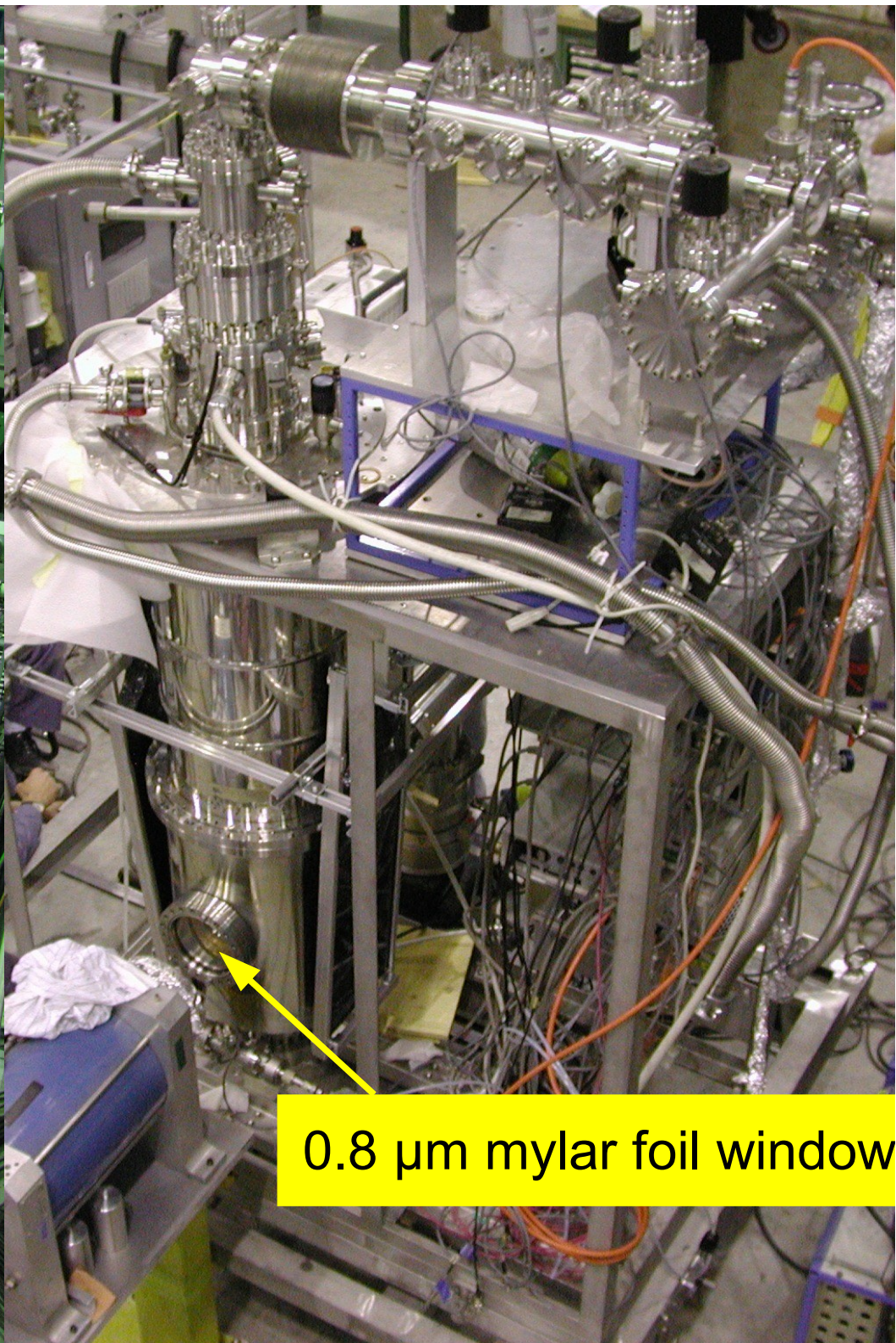
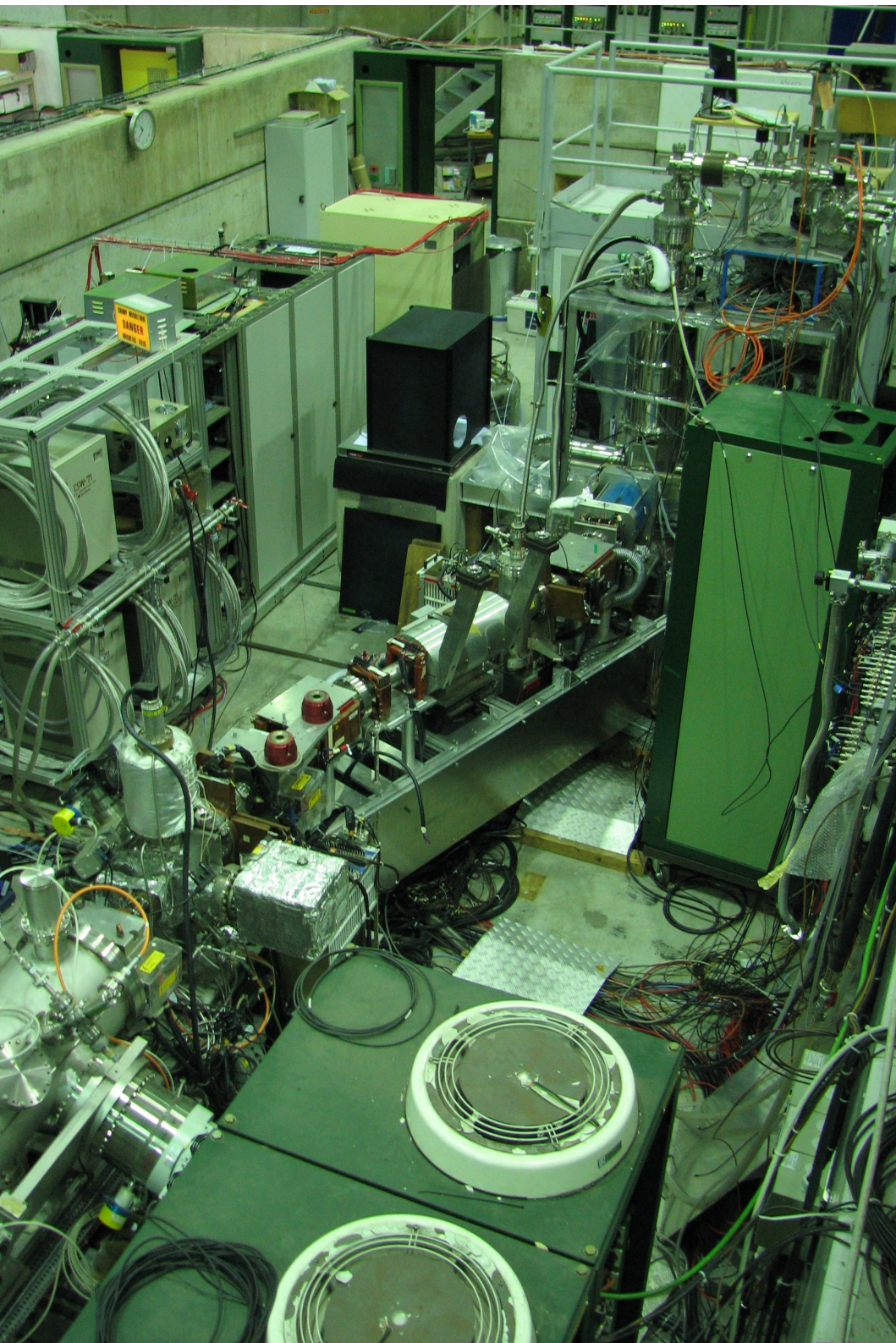


Size	3 meters	~cm	8 cm	32 pm
Lifetime	70 years	several months	1 year	2-3 microseconds
Heartbeat rate	28/minute	magnetron, axial, cyclotron 10 kHz - 100 MHz	550/minute	$\bar{p}$ atomic transition 300-1100 THz
		Man-made, care is needed to make it precise		Nature-made, perfect
		Easy to calculate		More difficult to calculate (but possible)



Experimental layout





0.8 μm mylar foil window

The heart of the experiment: Pulse-amplified CW laser system

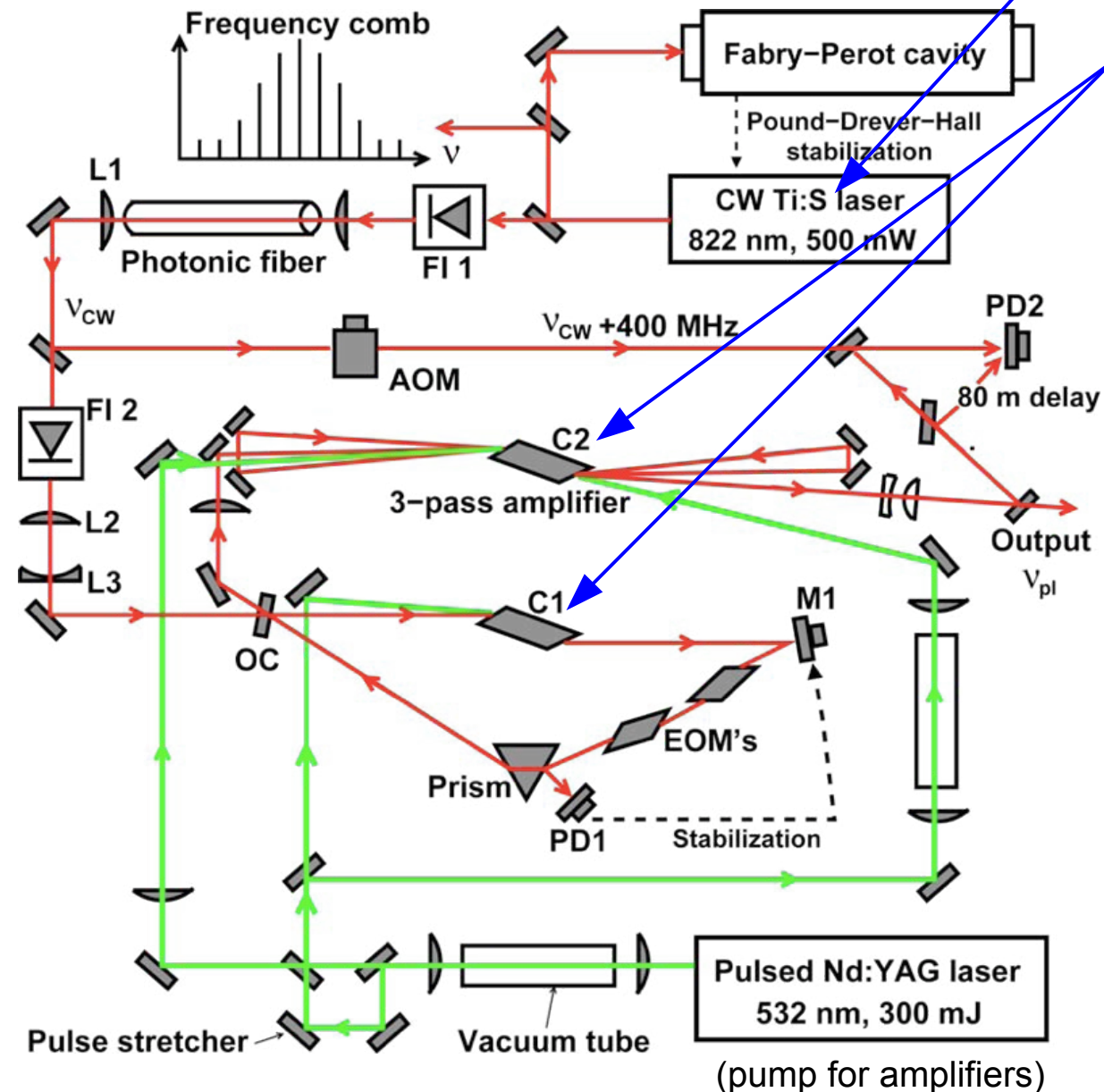
1) CW seed stabilized/measured by frequency comb

2) pulse-amplified

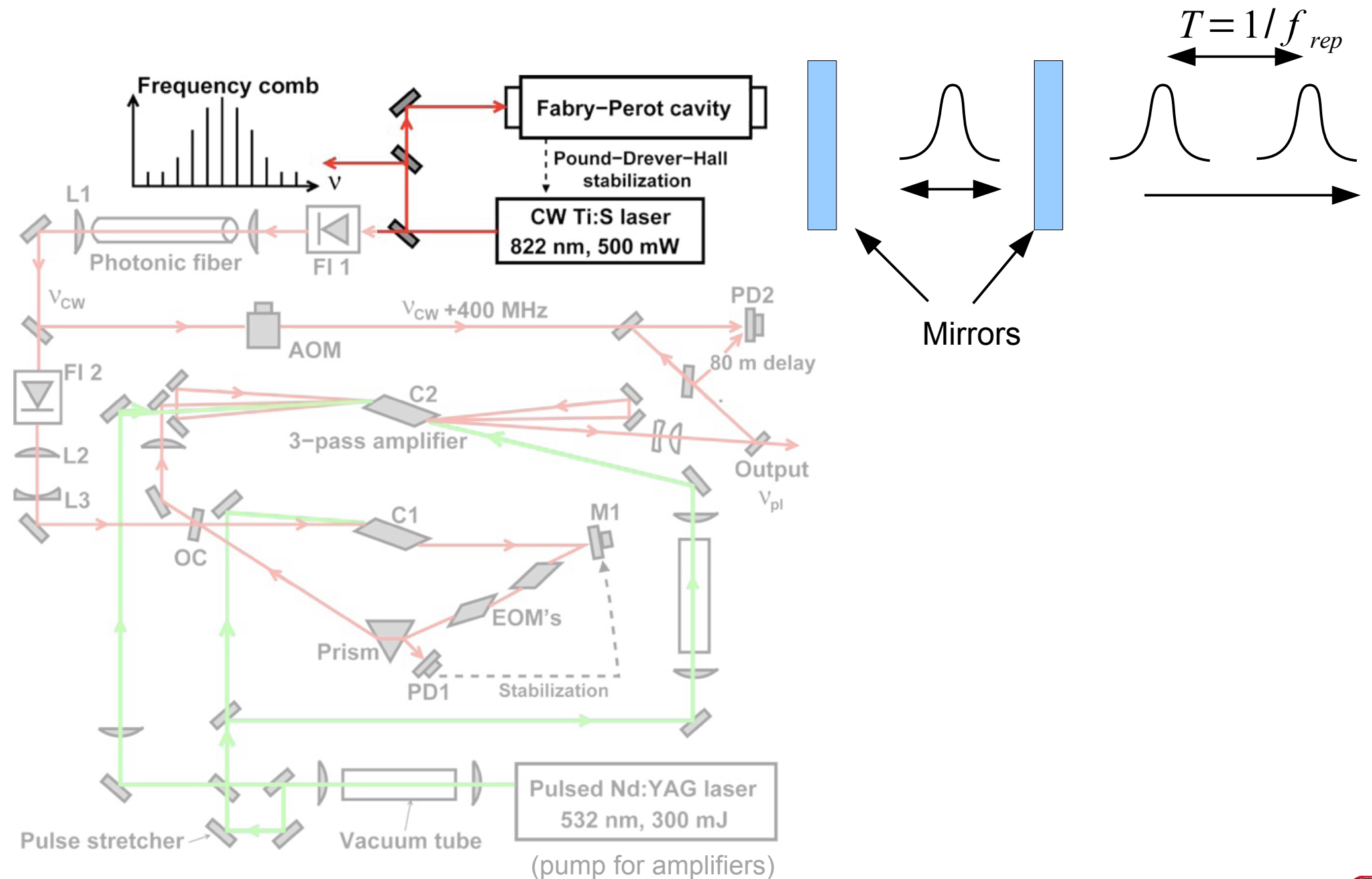
3) frequency doubled/tripled

$E=60-100$ mJ
linewidth = 6 MHz
pulselength = 30-100 ns

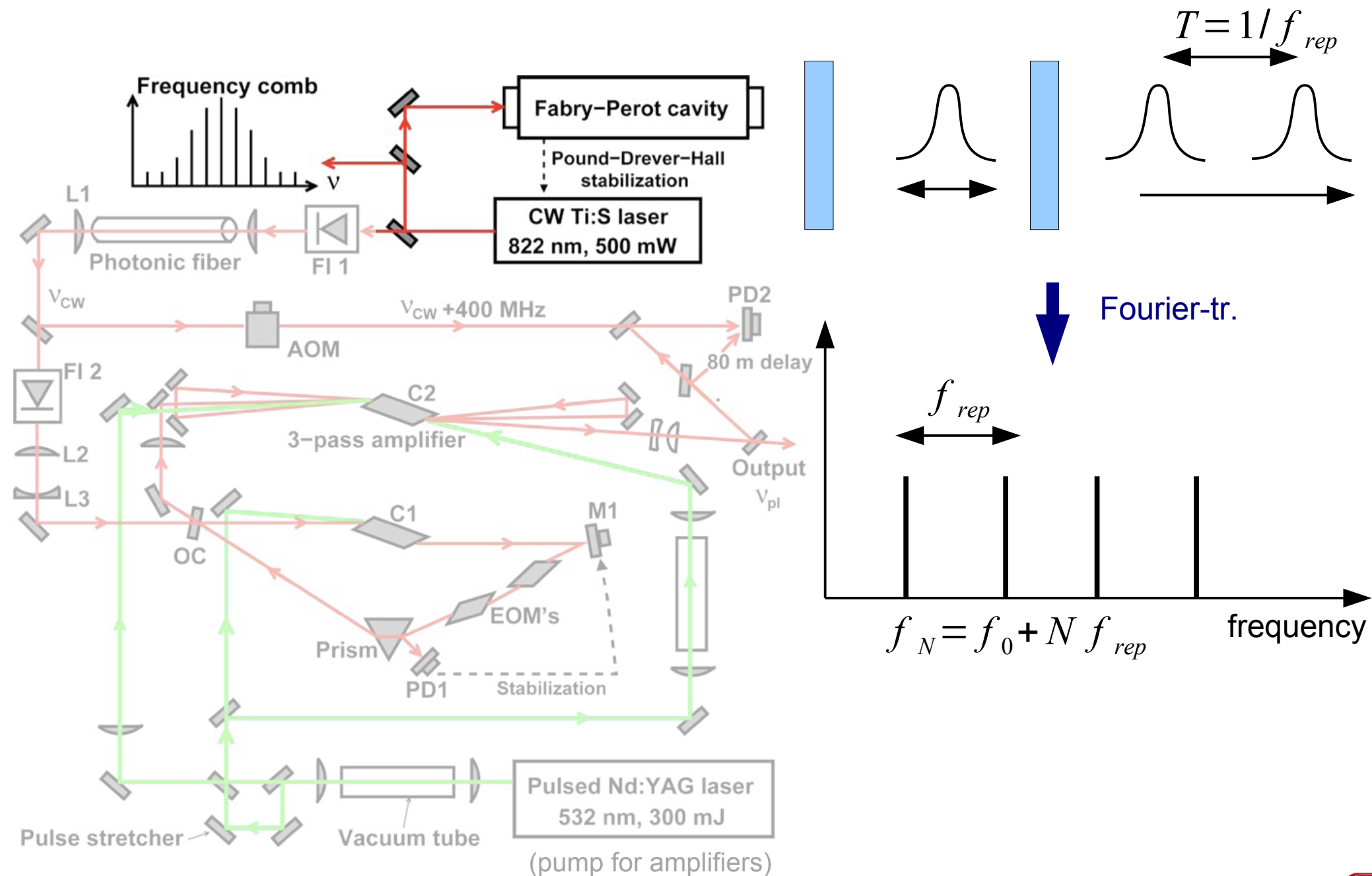
"... highest resolution reported so far for a nanosecond laser..."
[M. Hori, A. Dax, *Optics Letters* 34,1273 (2009)]



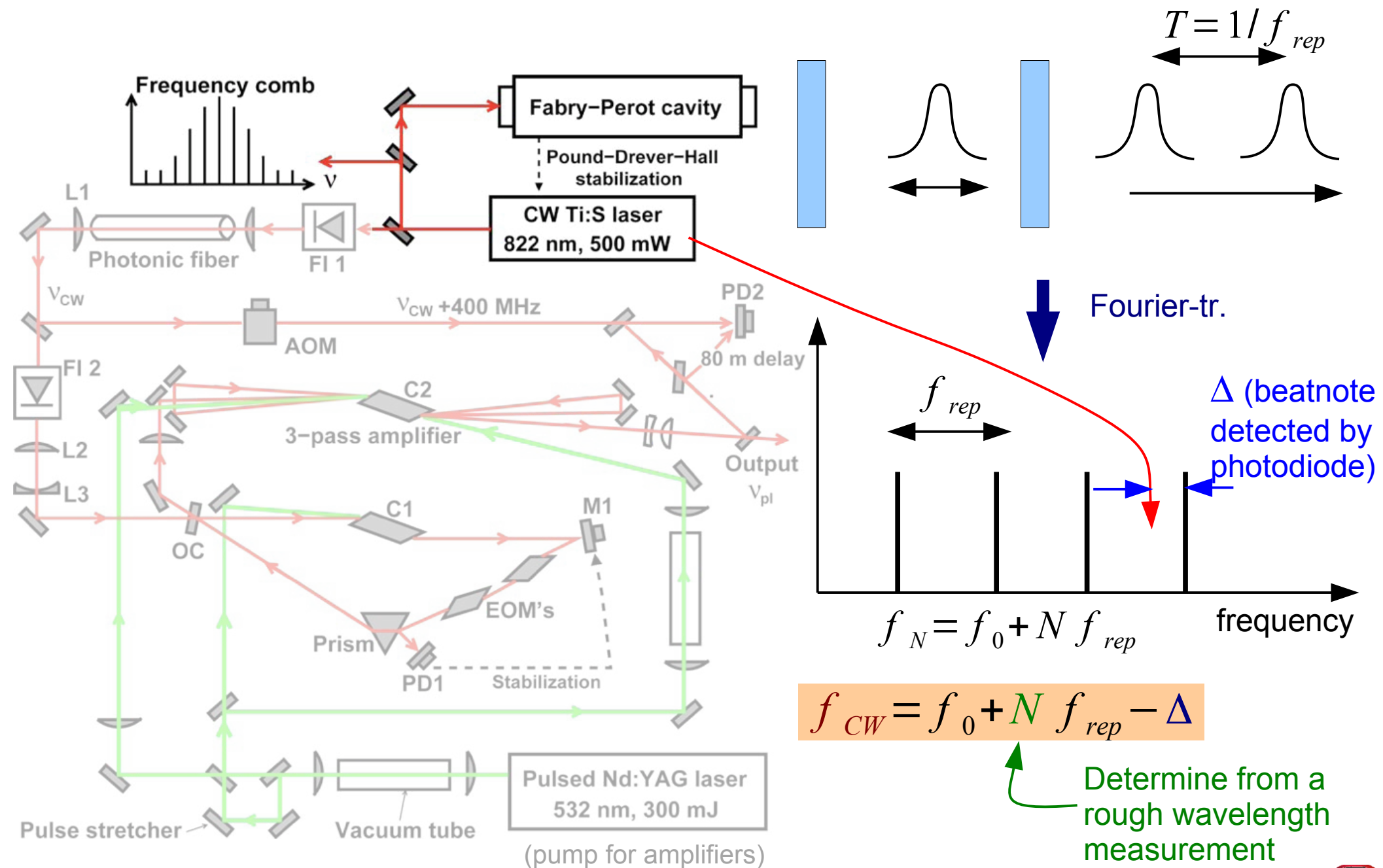
Frequency measurement by the frequency comb



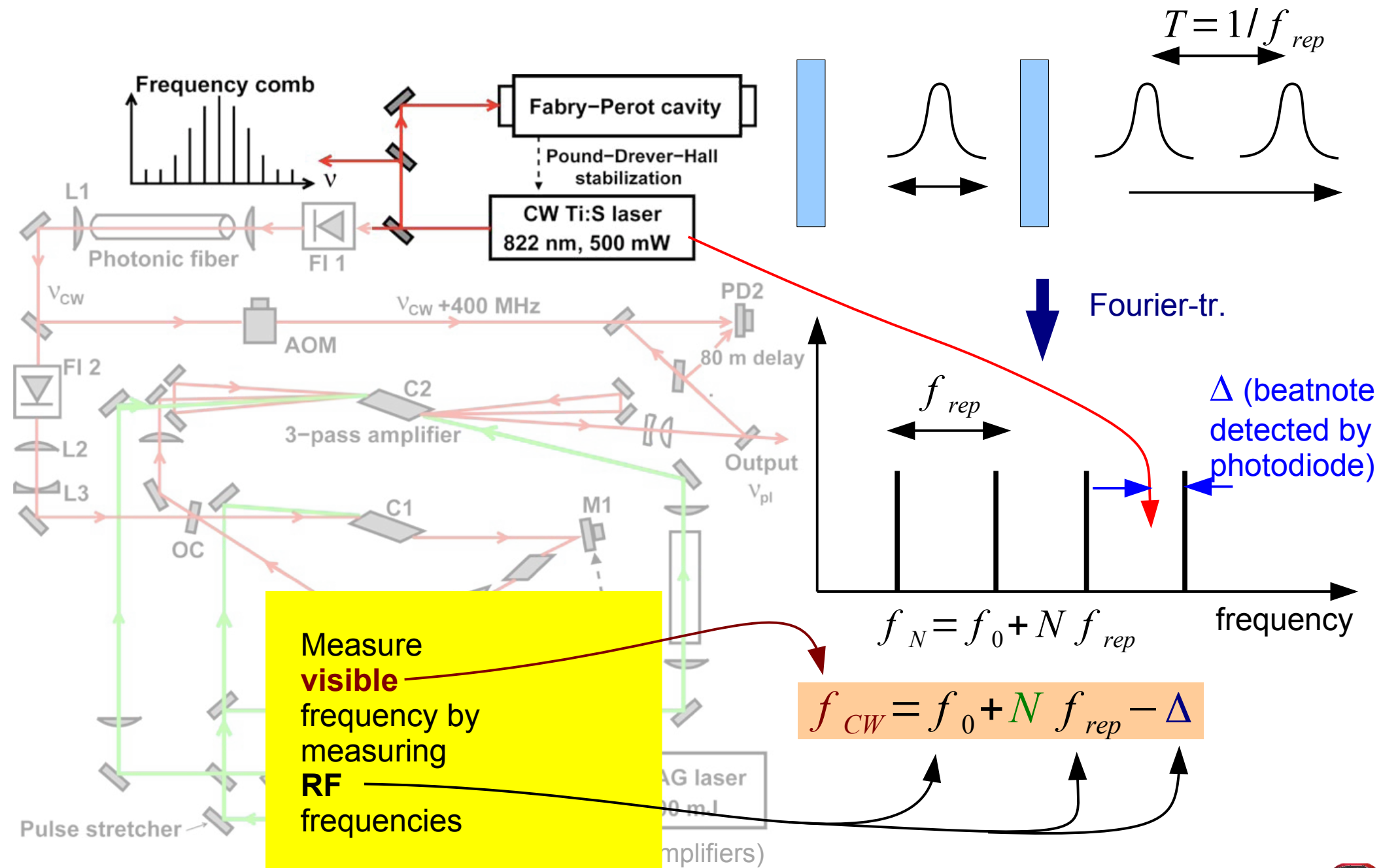
Frequency measurement by the frequency comb



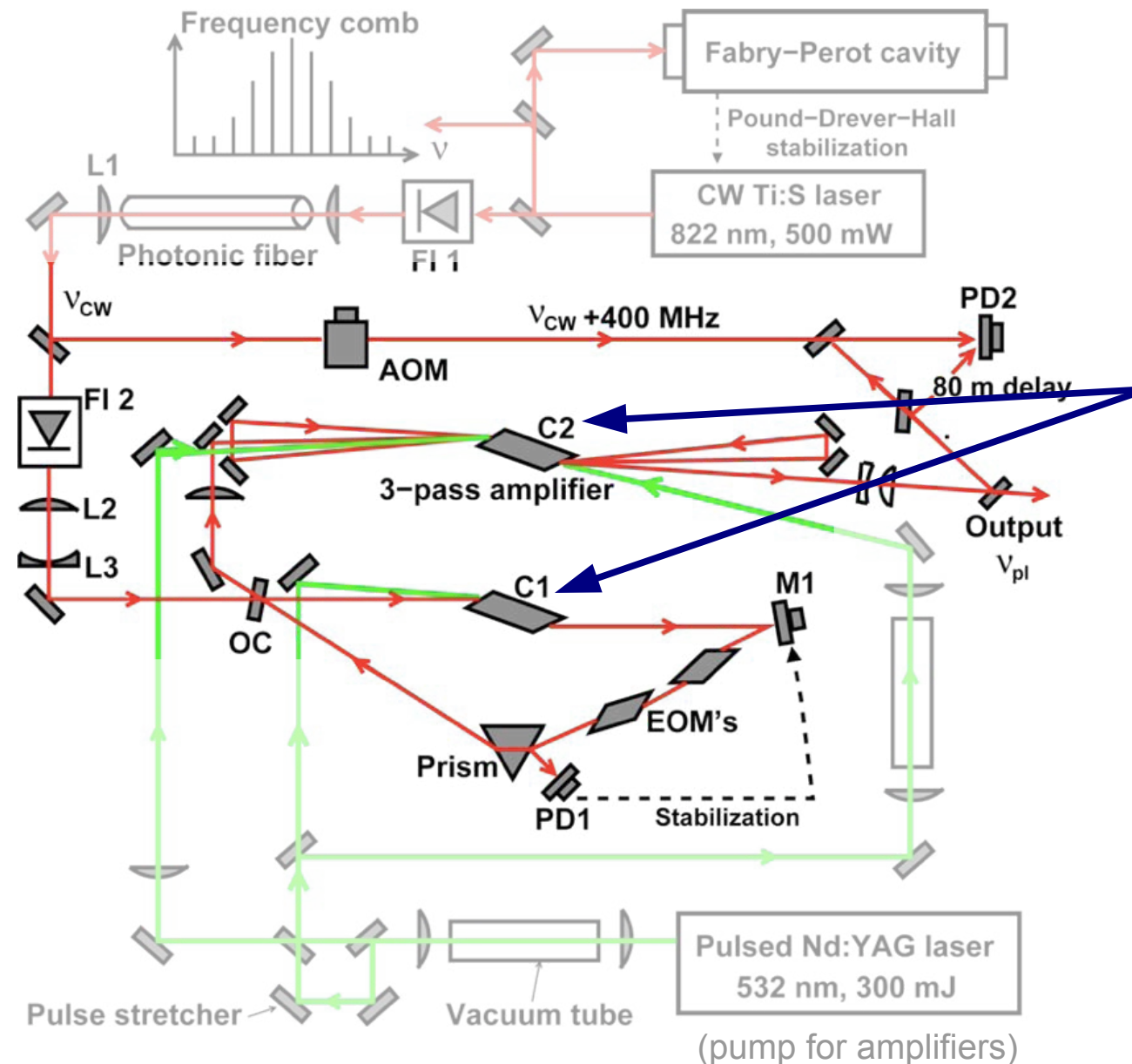
Frequency measurement by the frequency comb



Frequency measurement by the frequency comb



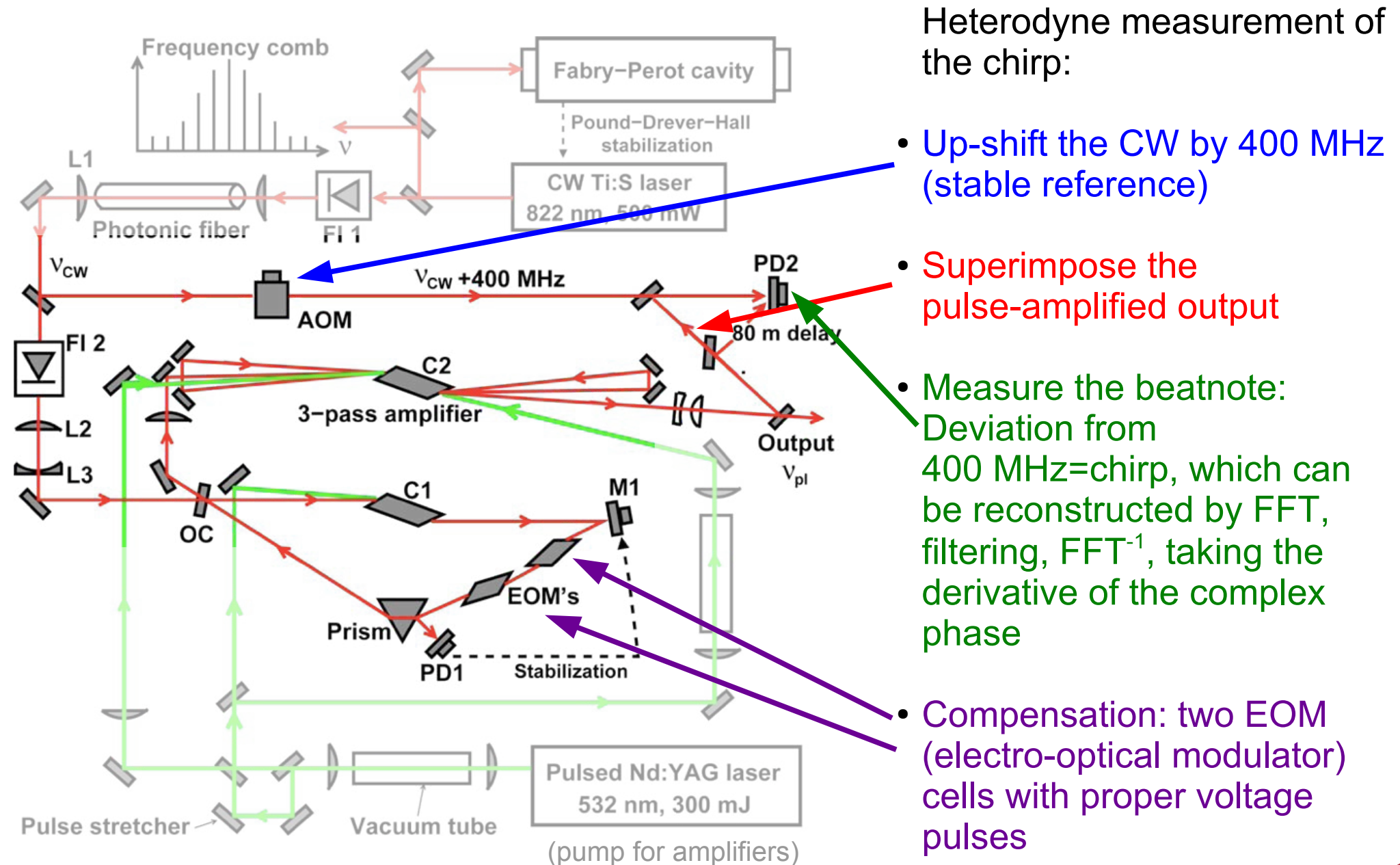
Measurement & compensation of the chirp



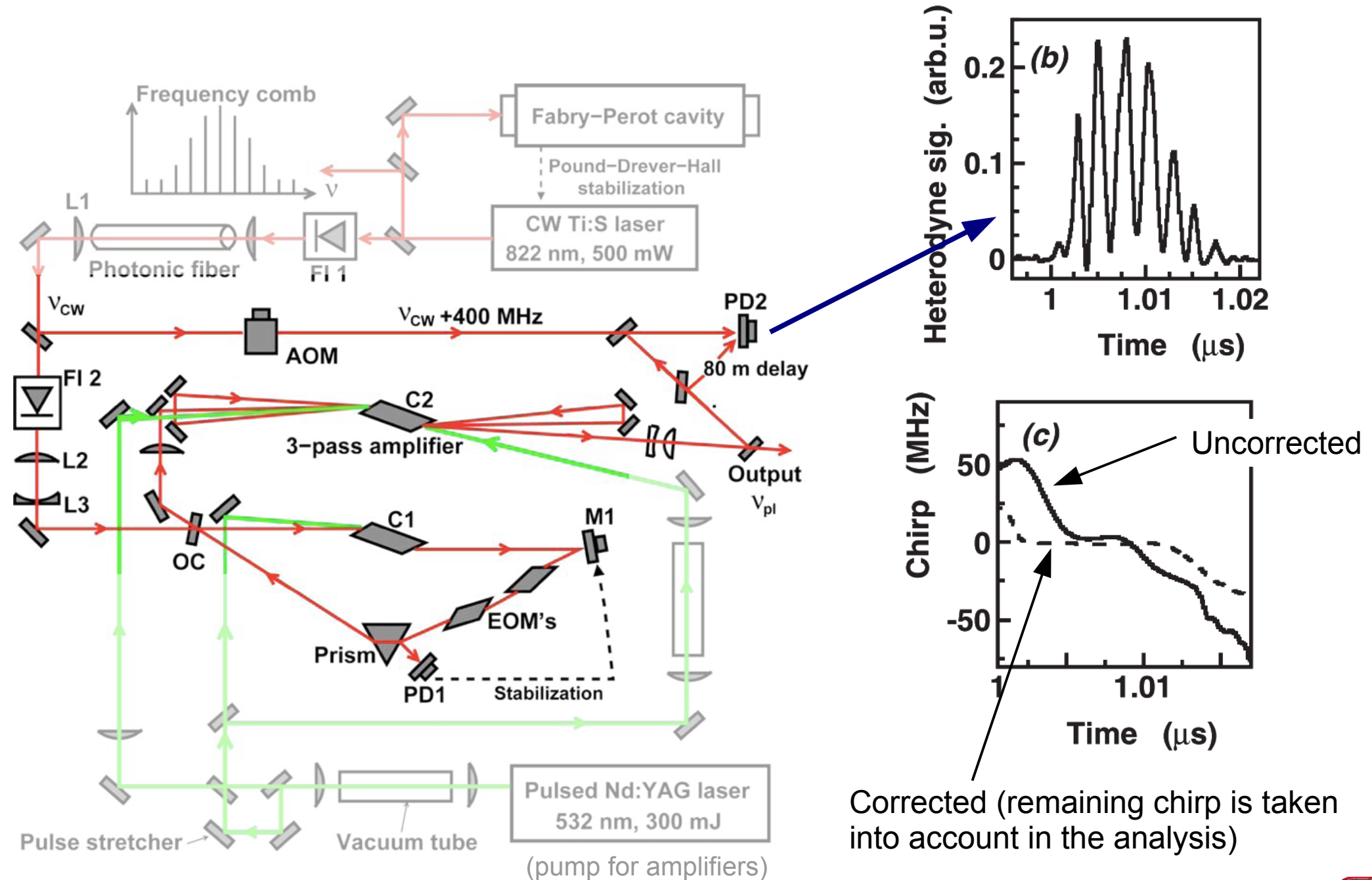
- Even though the CW seed laser is very stable...
- ...the pulse amplification introduces a frequency drift ("chirp") during the pulse.
- due to the sudden change of refractive index in the amplification cells



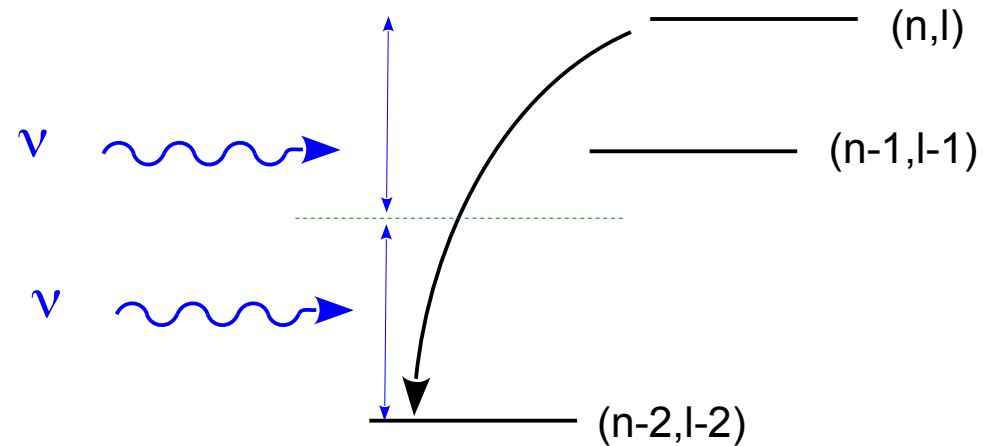
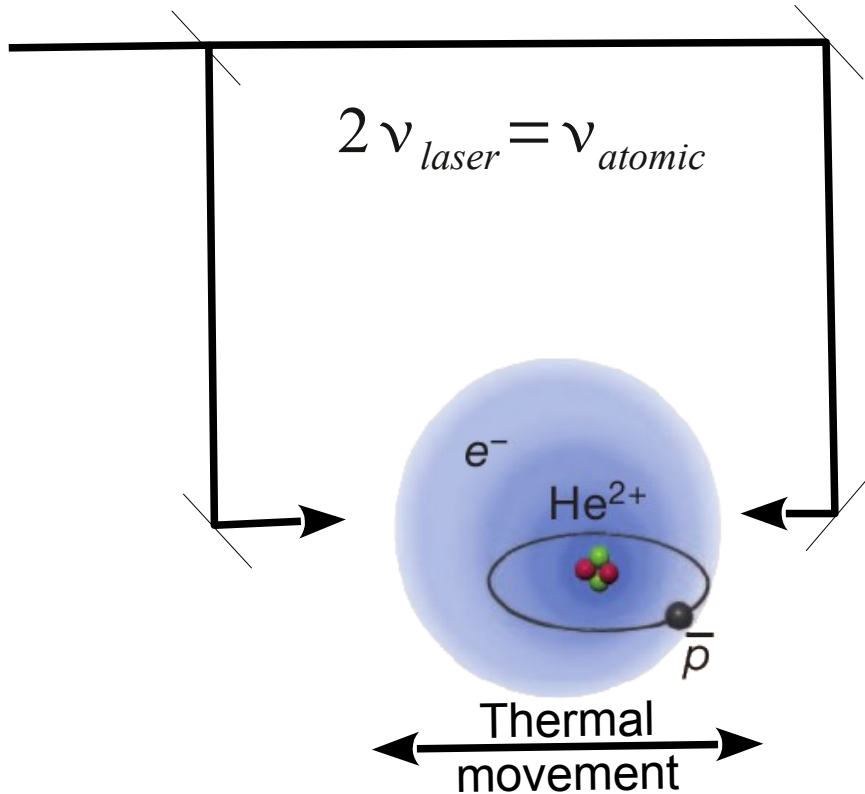
Measurement & compensation of the chirp



Measurement & compensation of the chirp



2-photon spectroscopy: one-color

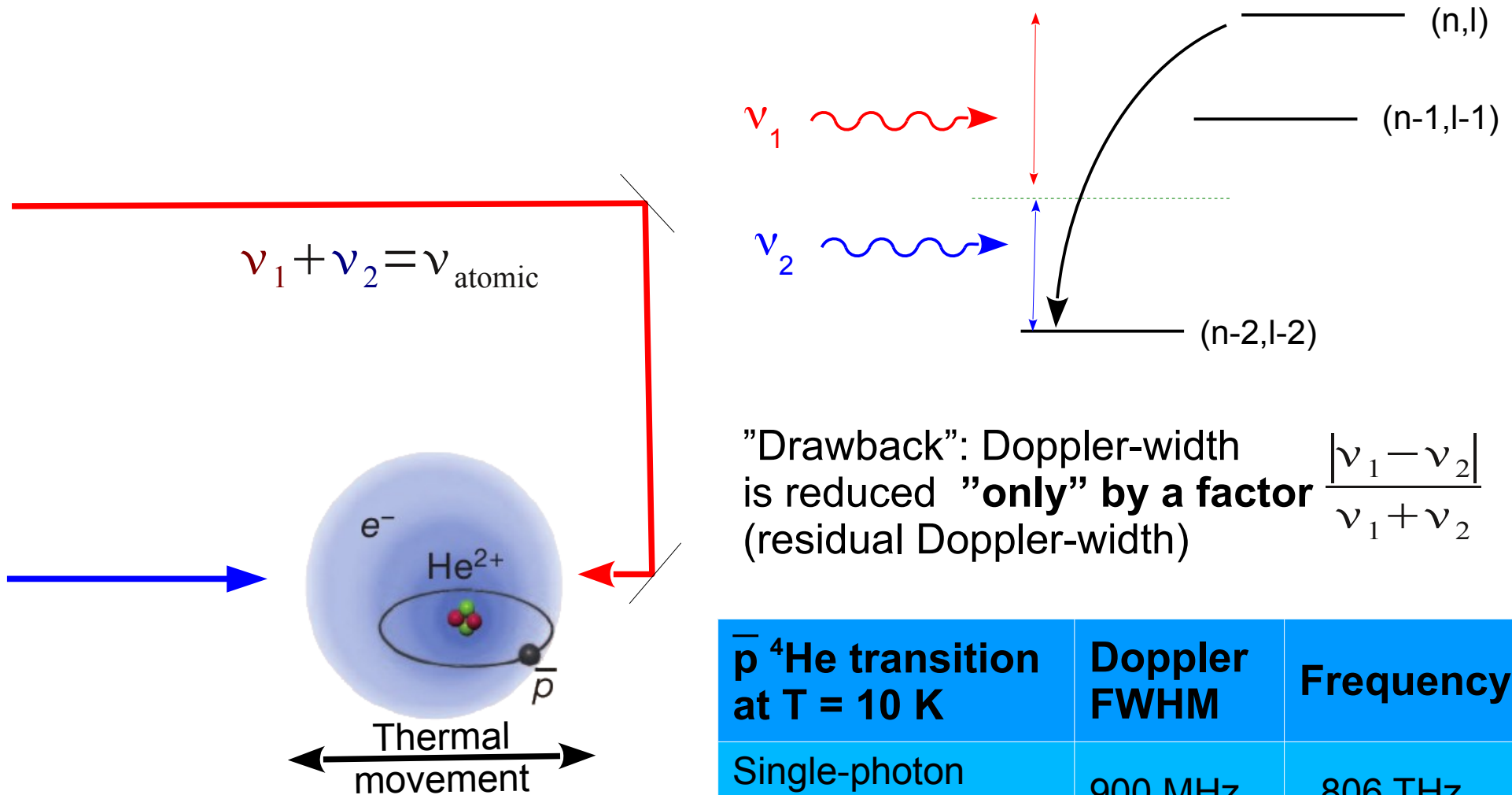


Red/blue shifts (due to thermal motion) cancel each other to first order

Problem:
transition probability is small $\rightarrow$
would need gigawatt scale lasers



2-photon spectroscopy: two-colors

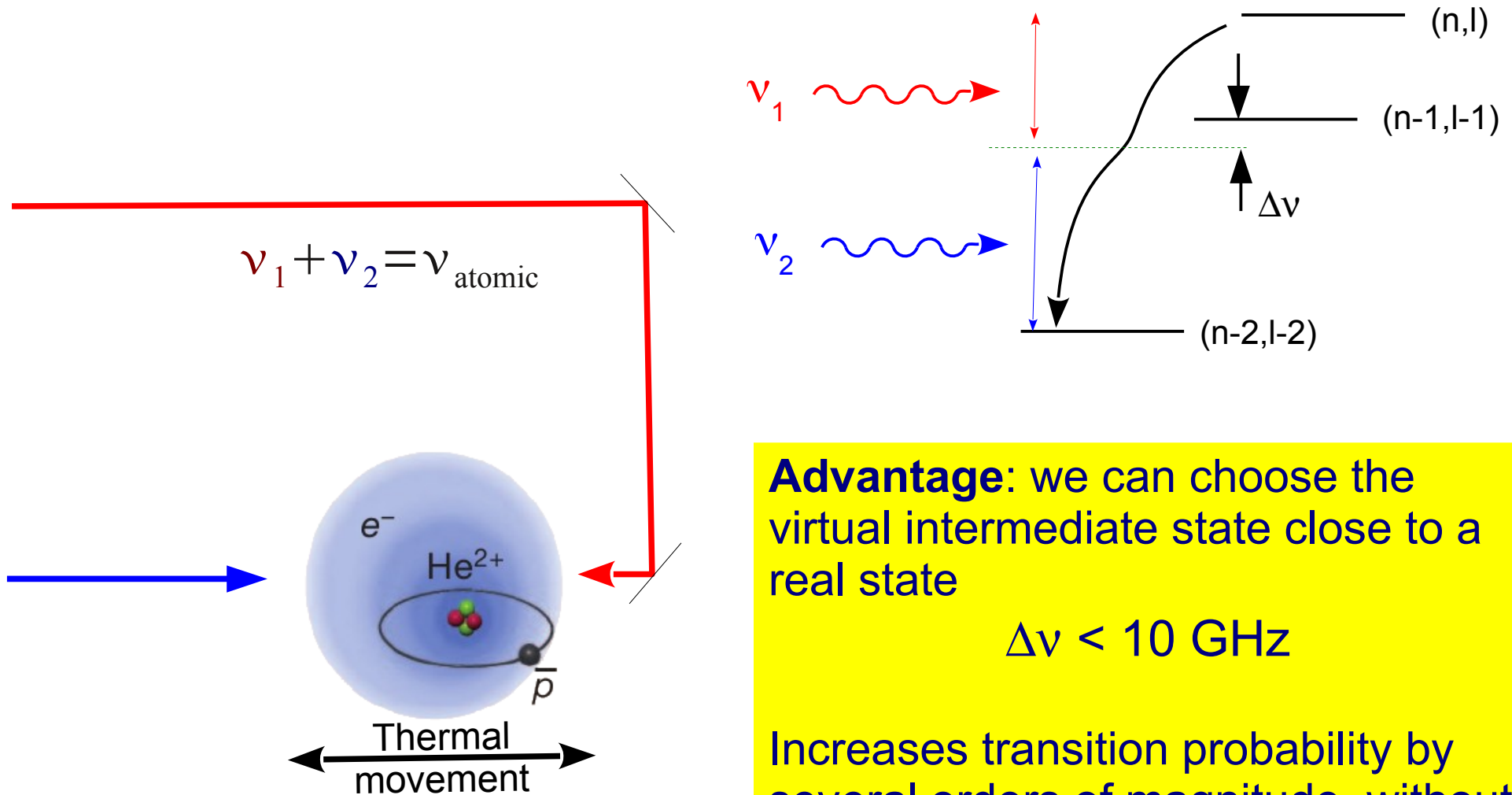


"Drawback": Doppler-width is reduced **"only"** by a factor $\frac{|\nu_1 - \nu_2|}{\nu_1 + \nu_2}$ (residual Doppler-width)

$\bar{p}$ ⁴ He transition at T = 10 K	Doppler FWHM	Frequency
Single-photon (35,33) → (34,32)	900 MHz	806 THz
Two-photon (36,34) → (34,32)	100 MHz	1525 THz



2-photon spectroscopy: two-colors



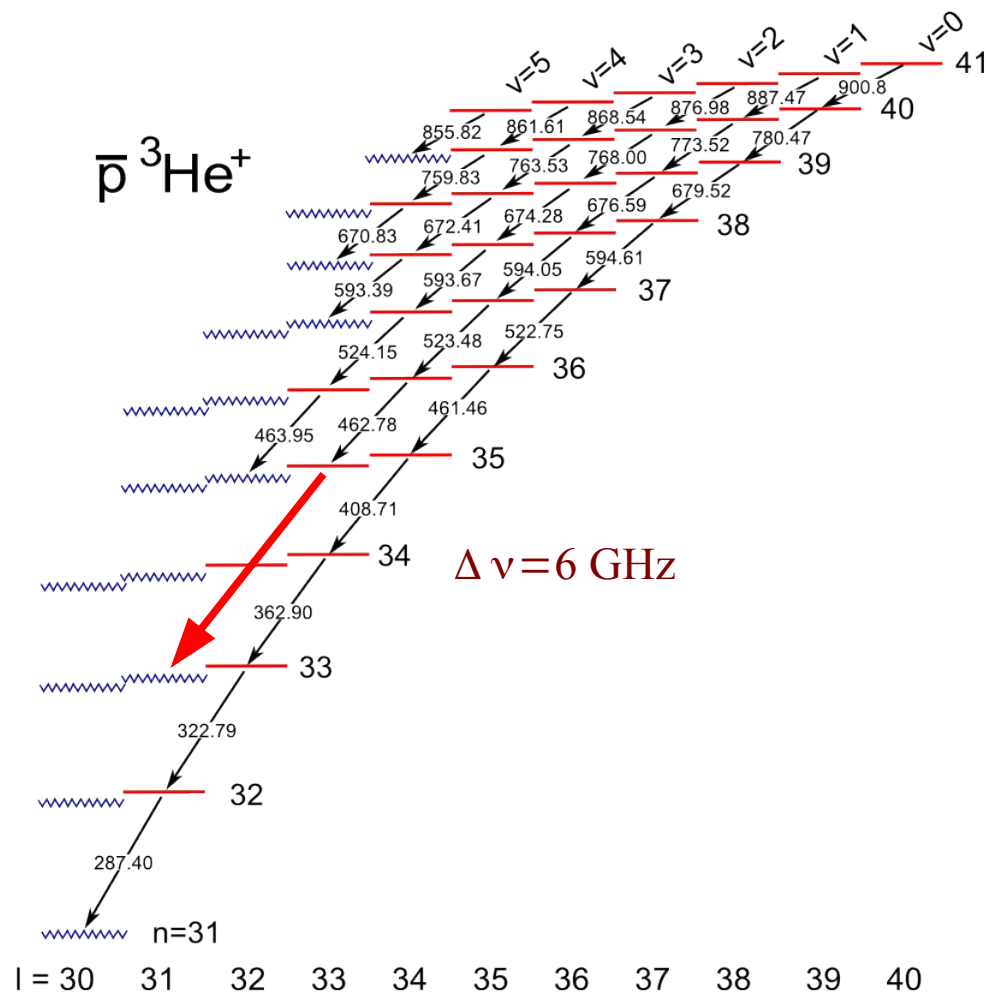
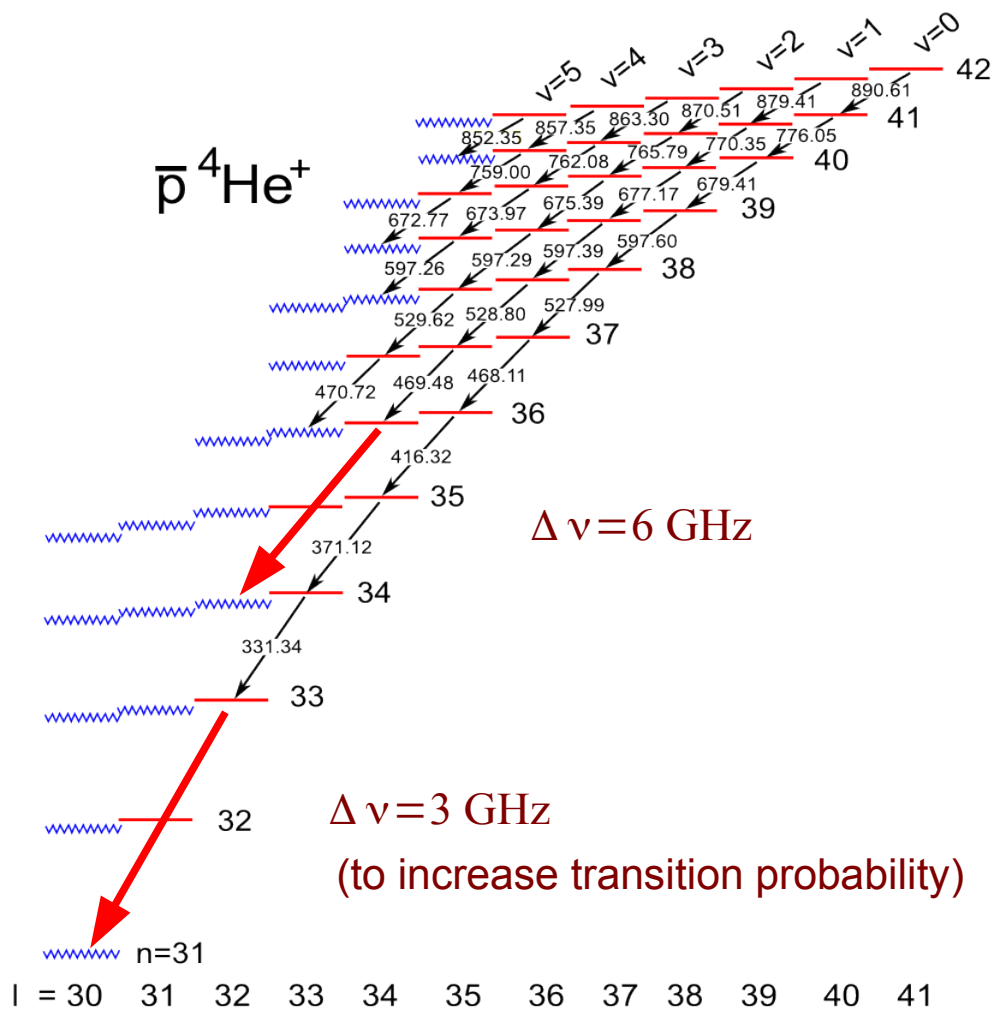
Advantage: we can choose the virtual intermediate state close to a real state

$$\Delta\nu < 10 \text{ GHz}$$

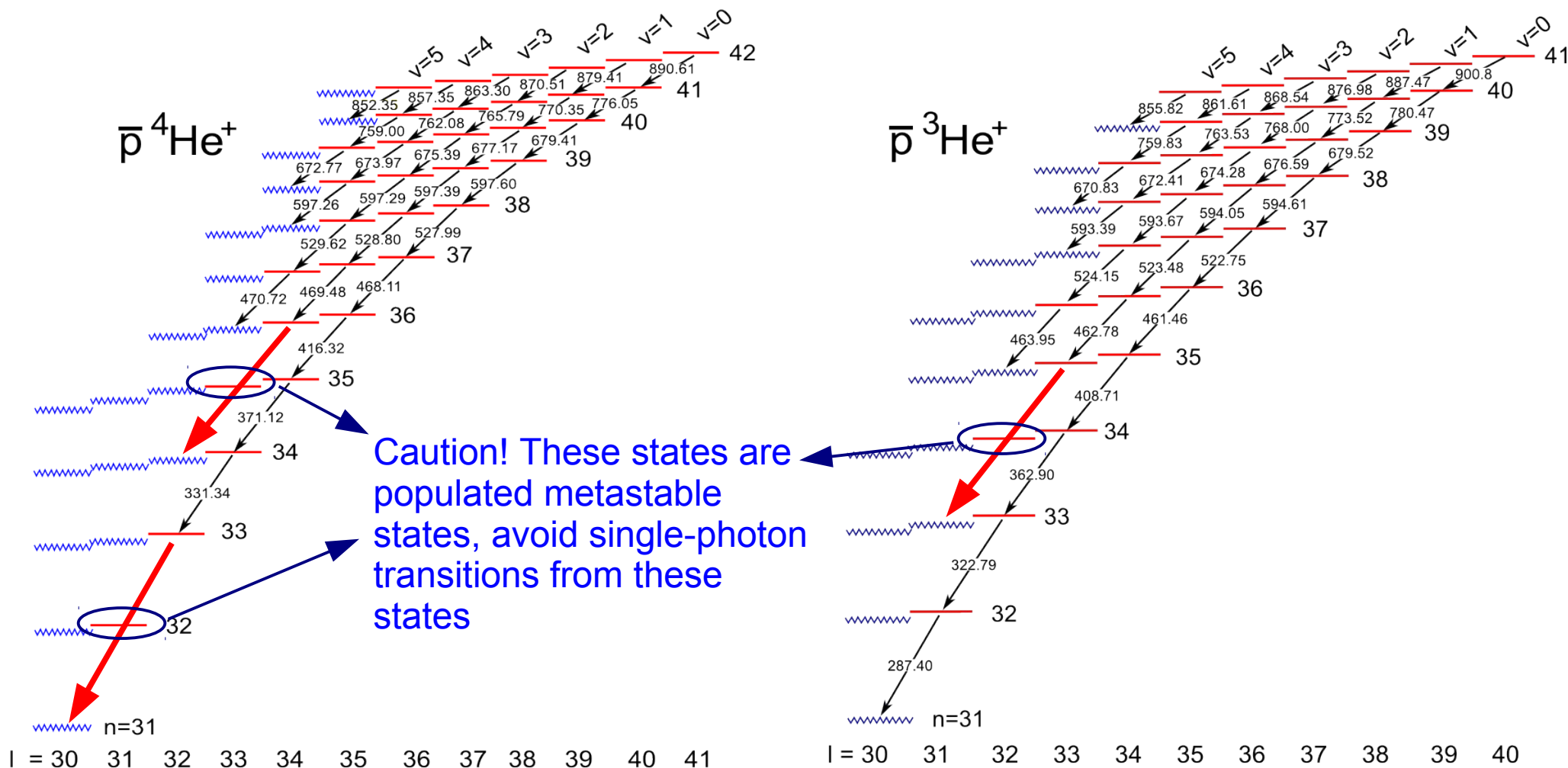
Increases transition probability by several orders of magnitude, without really involving the population of the intermediate state (if not "too" close)



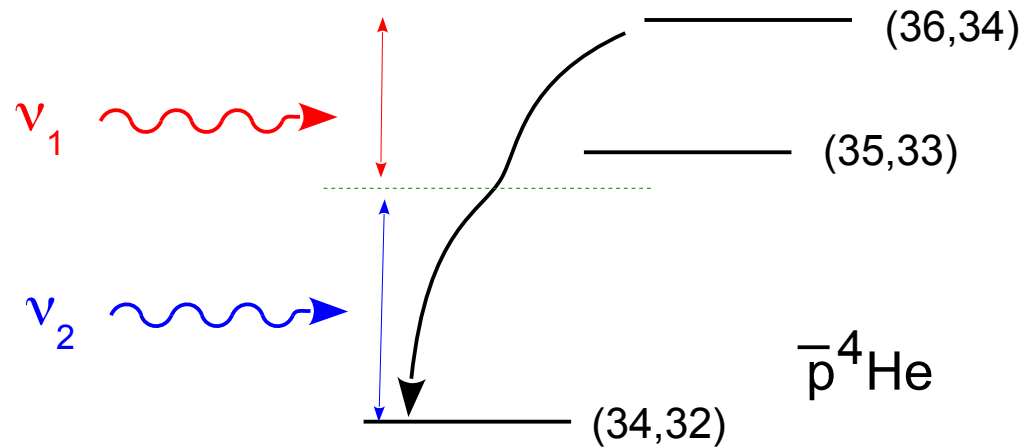
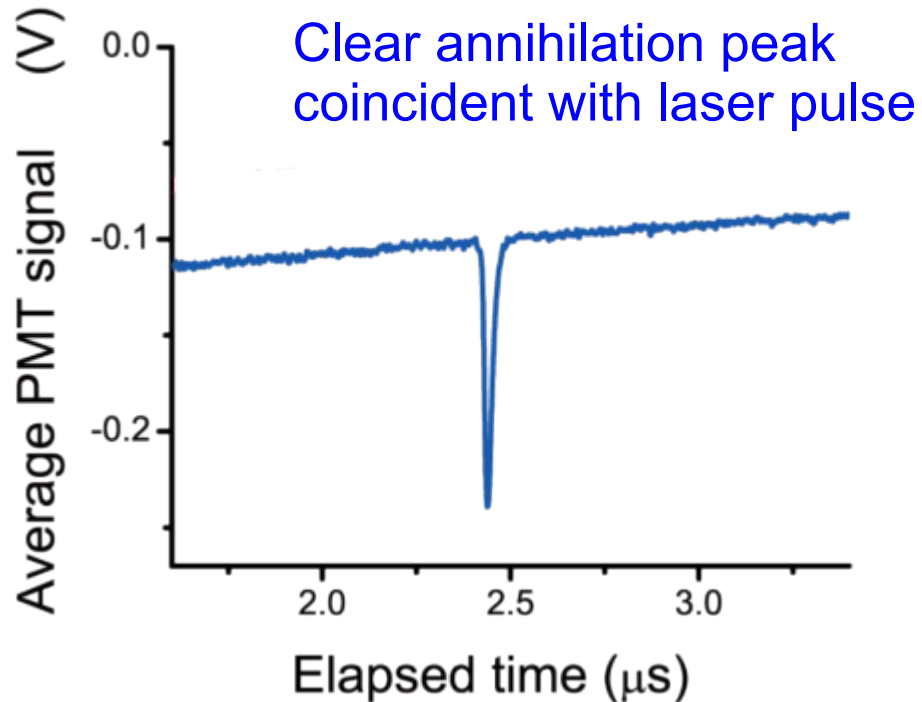
Measured three 2-photon transitions



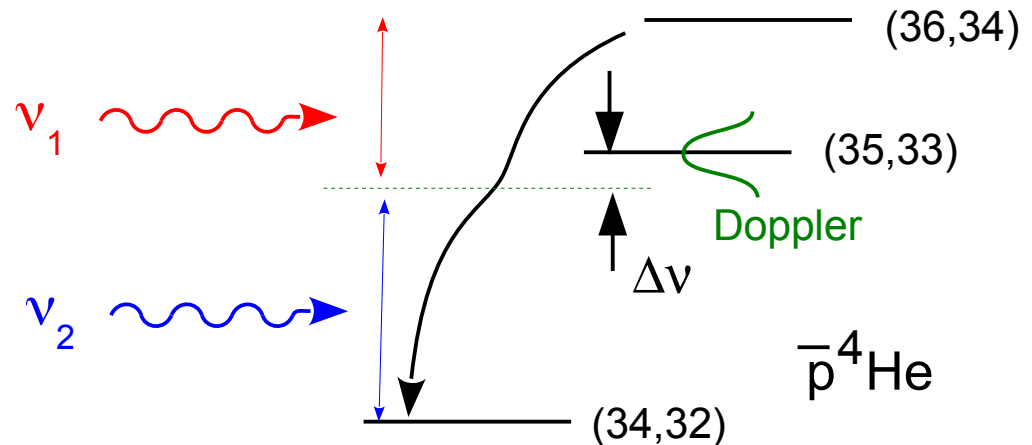
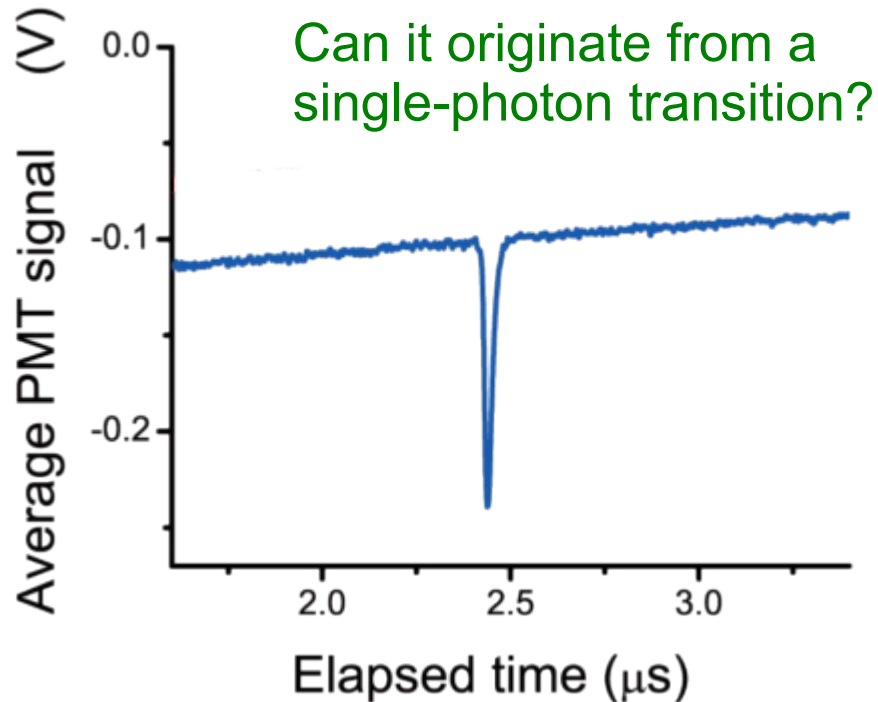
Measured three 2-photon transitions



2-photon spectroscopy: annihilation signal



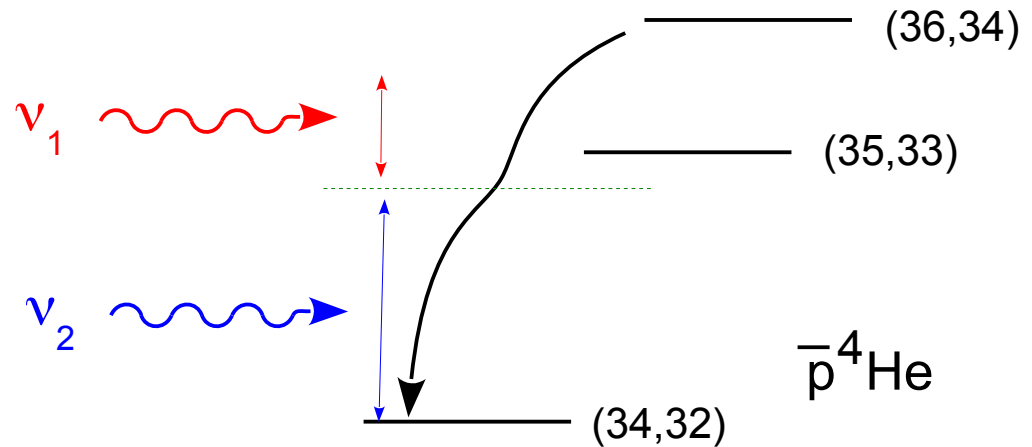
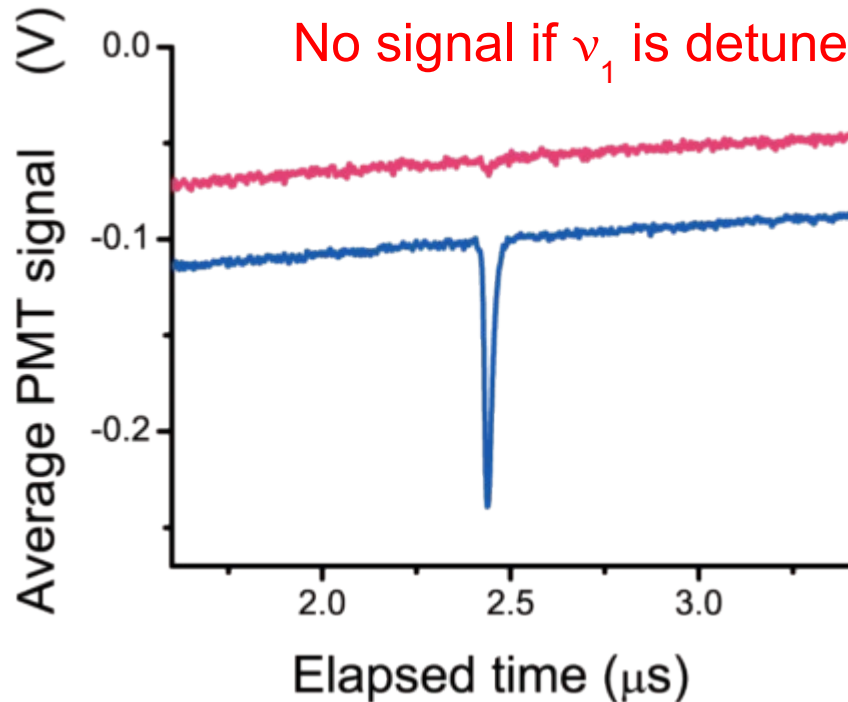
2-photon spectroscopy: not a 1-photon signal?



Doppler bandwidth typically 0.4 – 1 GHz $\ll \Delta\nu = 6$ or 3 GHz
Should be OK!



2-photon spectroscopy: not a 1-photon signal?



Our signal is clearly a 2-photon signal



AC Stark shift?

Intense laser fields can shift two-photon transition frequencies proportionally to:

$$\frac{\Omega_1^2 - \Omega_2^2}{\Delta \nu}$$

Rabi frequencies between parent and virtual intermediate states (depends on laser intensity)

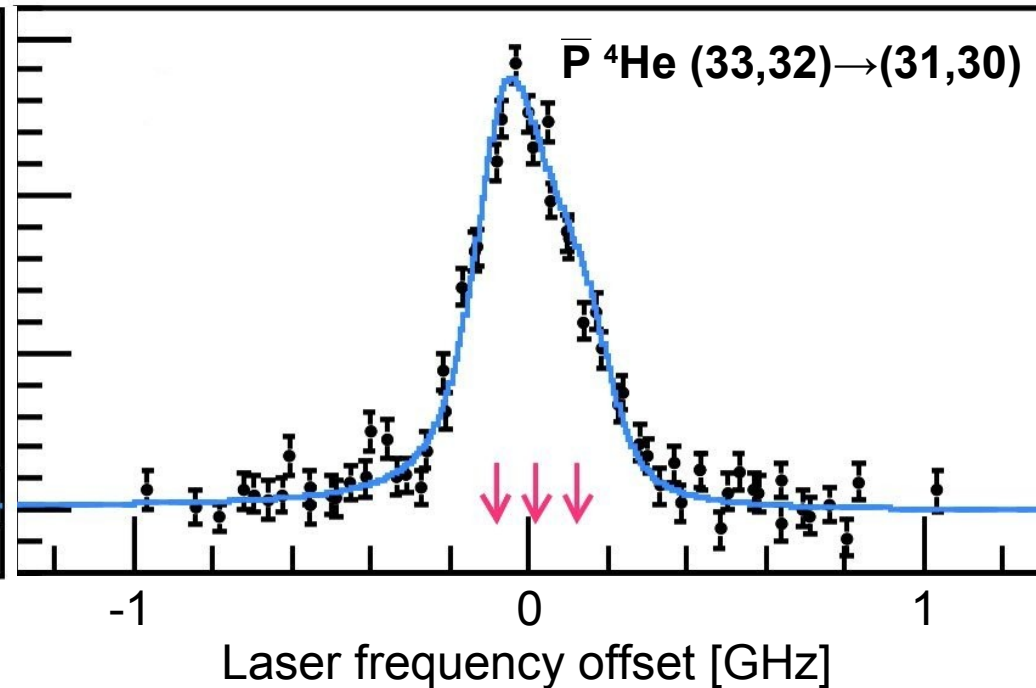
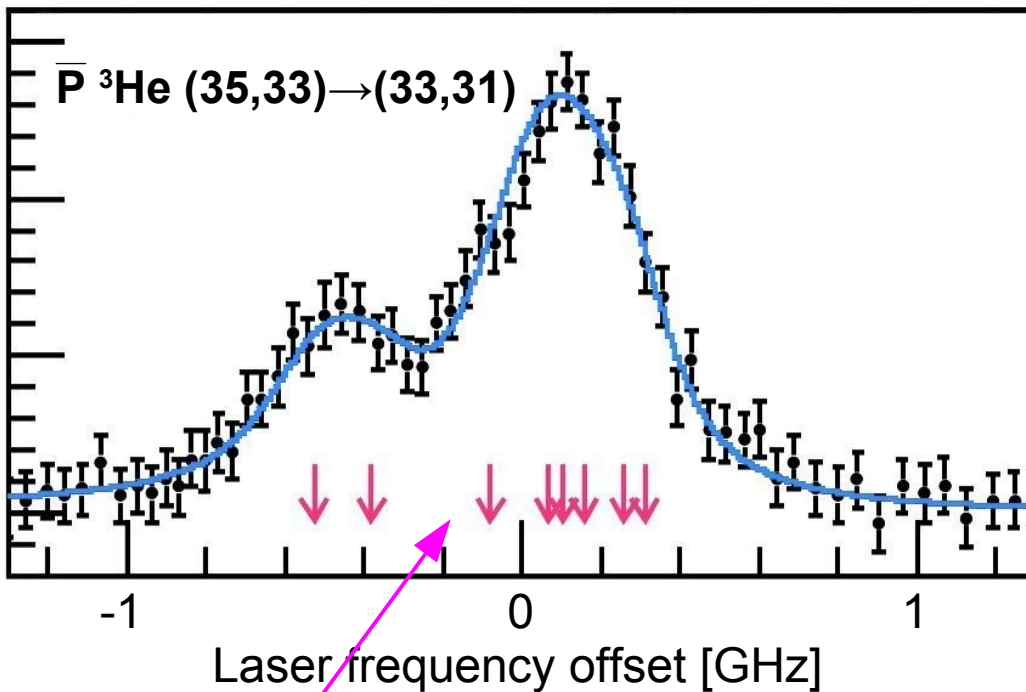
detuning from the real intermediate state

Minimize it by

- adjusting laser intensities such that $\Omega_1 \sim \Omega_2$ (<5 MHz)
- average results with $\pm \Delta \nu$ (<0.5 MHz)



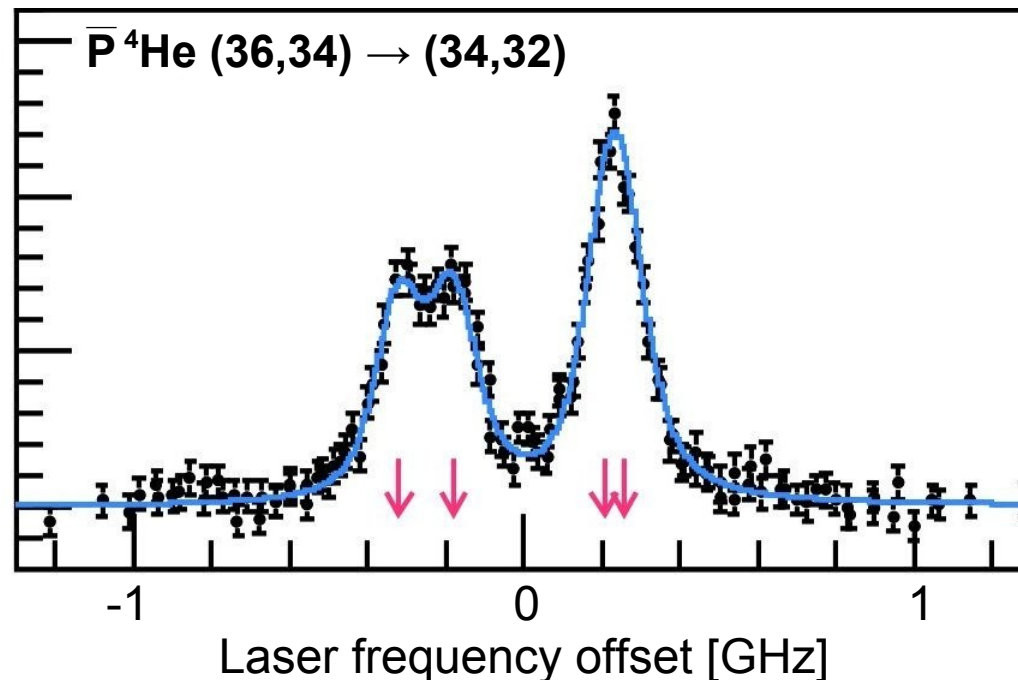
Measured resonance profiles



Hyperfine lines caused by the interaction between $S_e \ell_{\bar{P}} (S_{^3\text{He}})$

Fitting function: numerical simulation of the optical rate equations

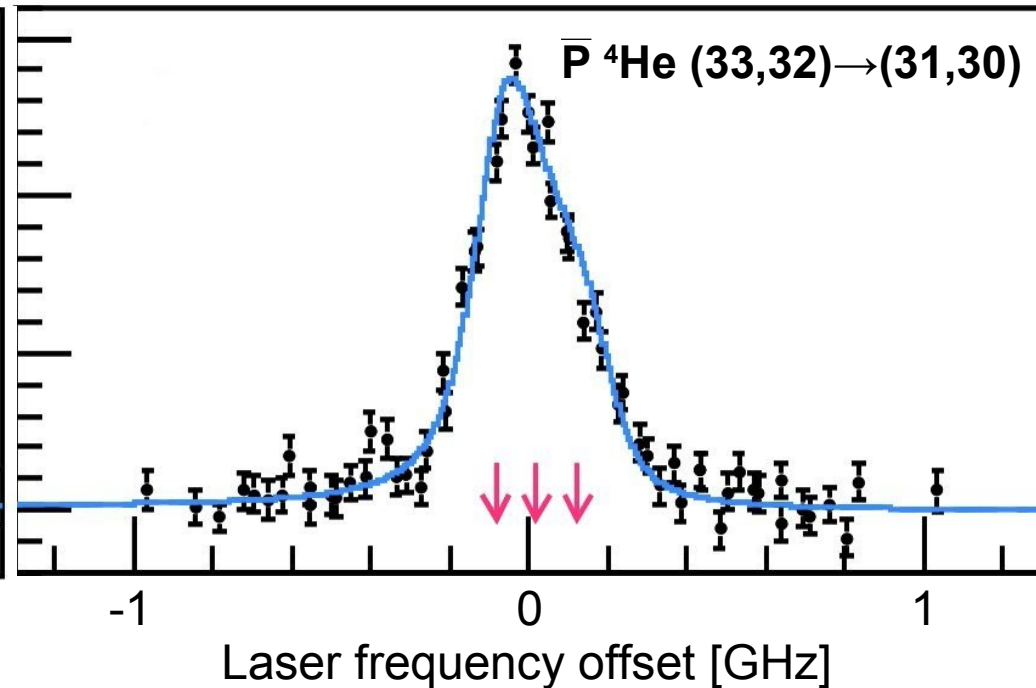
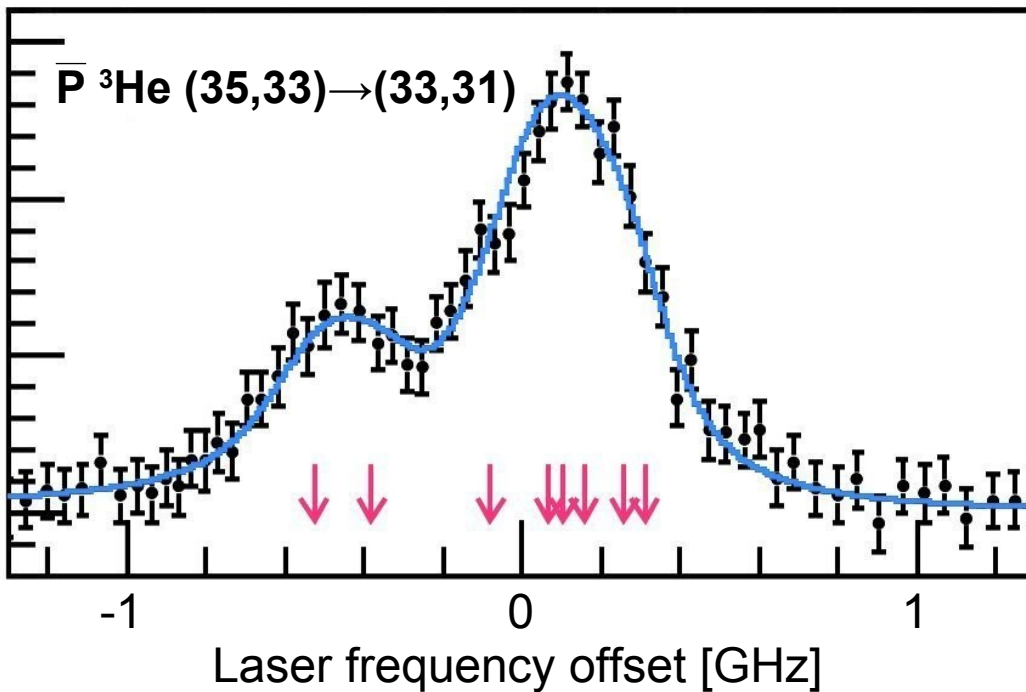
[Nature 475 (2011) 484]



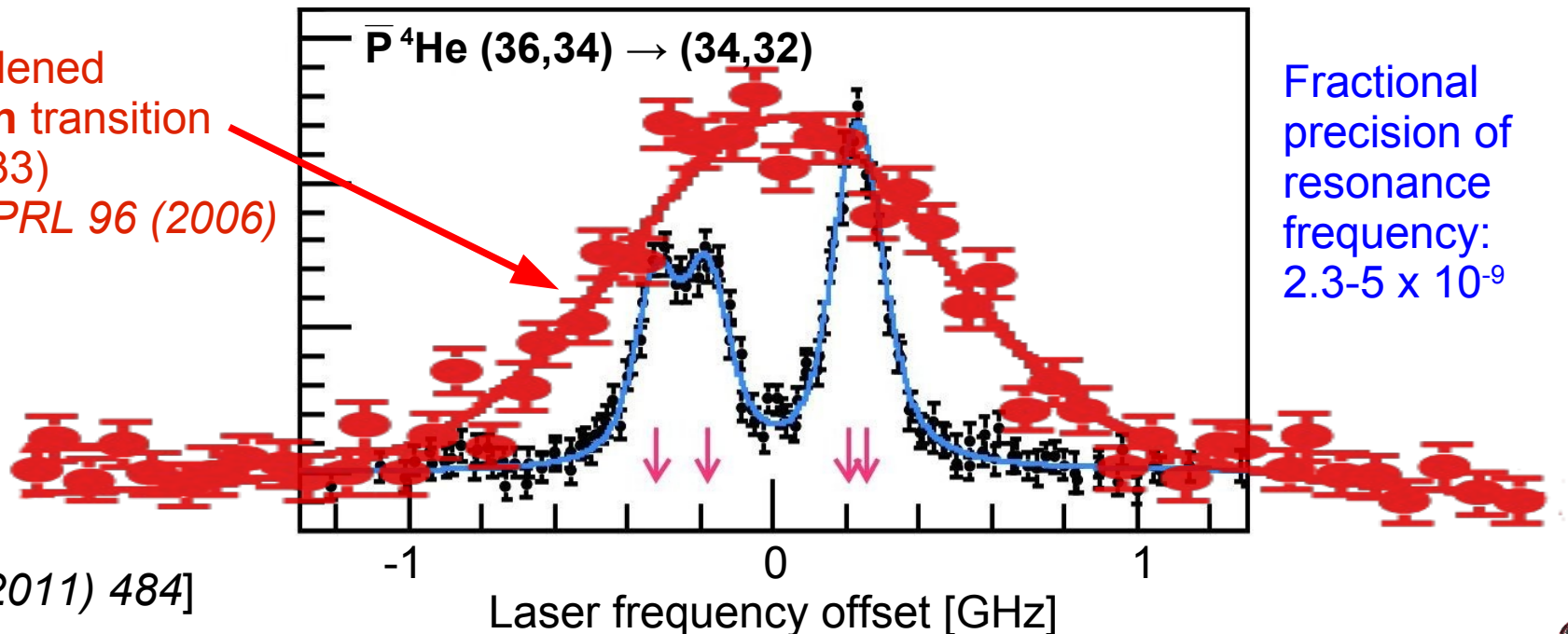
Fractional precision of resonance frequency: $2.3\text{-}5 \times 10^{-9}$



Measured resonance profiles



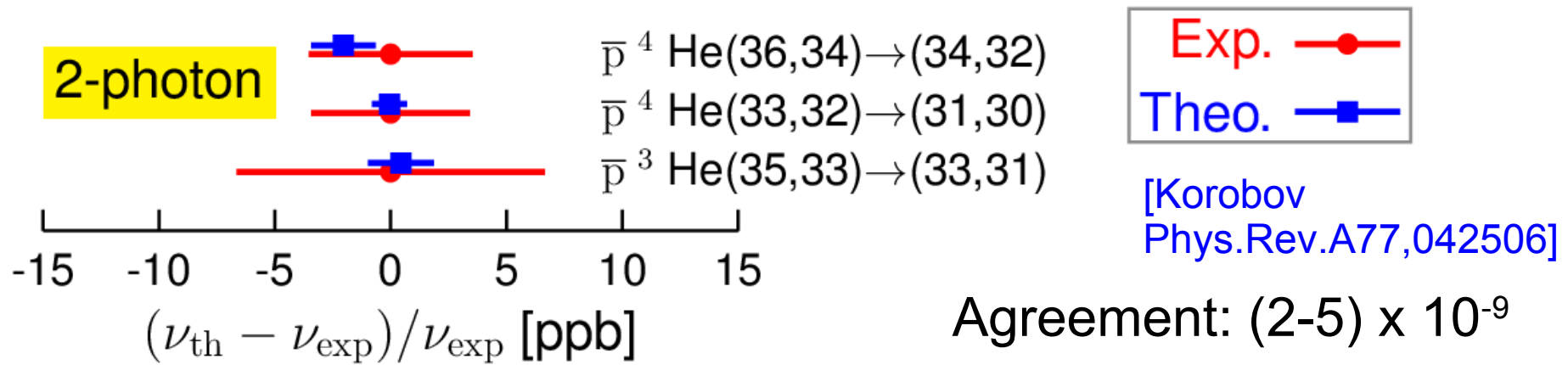
Doppler-broadened
single-photon transition
 $(36,34) \rightarrow (35,33)$
[M.Hori et.al. PRL 96 (2006)
243401]



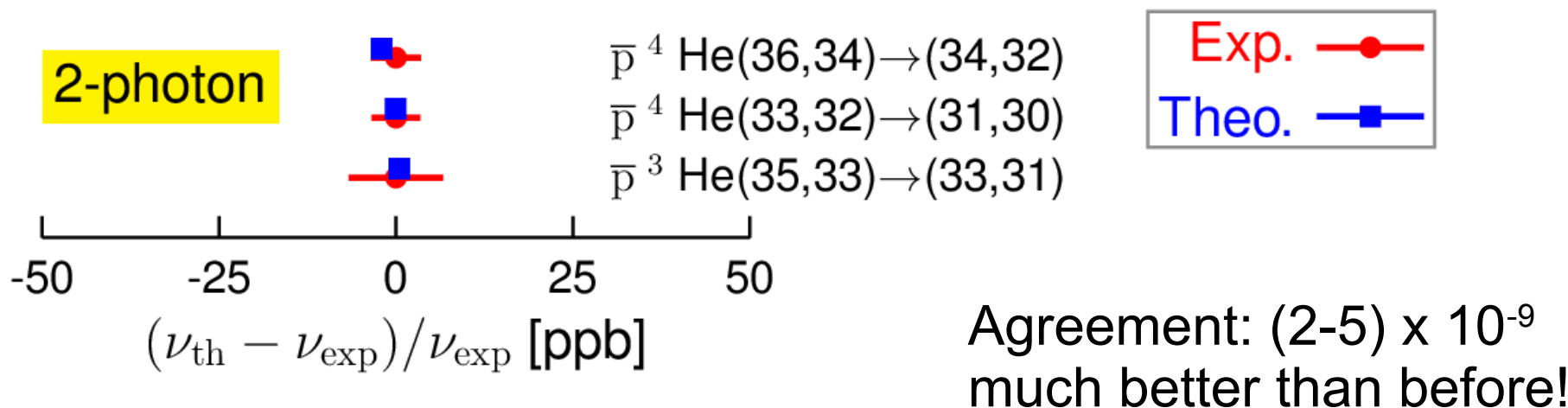
[Nature 475 (2011) 484]



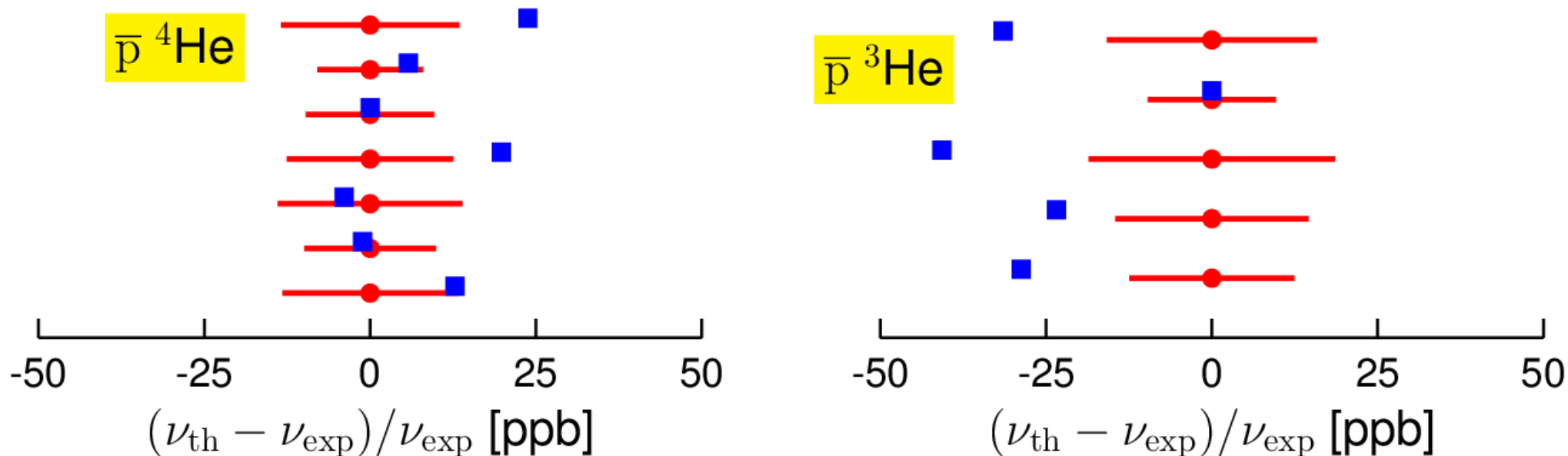
Transition frequencies: exp - theo



Transition frequencies: exp - theo

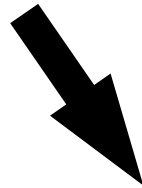


Comparison to earlier results: **1-photon** [*PRL* 96 (2006) 243401]



The antiproton-electron mass ratio from 2-photon spectroscopy

Minimize $\sum_{i = \text{transitions}} \frac{[\nu_{th}^{(i)}(m_{\bar{p}}/m_e) - \nu_{exp}^{(i)}]^2}{\sigma^{(i)}}$



$$m_{\bar{p}}/m_e = 1836.1526736 \cdot (1 \pm 1.3 \cdot 10^{-9})$$

[*Nature* 475 (2011) 484]



The (anti)proton-electron mass ratio

Washington Penning trap

PRL75(1995)3598

GSI/Mainz electron g-factor in $^{12}\text{C}^{5+}$

PRL88(2002)011603

GSI/Mainz electron g-factor in $^{16}\text{O}^{7+}$

PRL92(2004)093002

CODATA2002 average

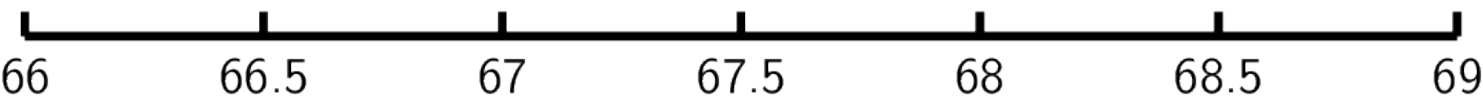
proton

CPT test: compare proton-antiproton

Antiprotonic helium 1-photon

PRL96(2006)243401

Earlier 1-photon
result!



$$(m_{p,\bar{p}}/m_e - 1836.152)/10^{-5}$$



The (anti)proton-electron mass ratio

Washington Penning trap

PRL75(1995)3598



GSI/Mainz electron g-factor in $^{12}\text{C}^{5+}$

PRL88(2002)011603



GSI/Mainz electron g-factor in $^{16}\text{O}^{7+}$

PRL92(2004)093002



proton

Antiprotonic helium 1-photon

PRL96(2006)243401

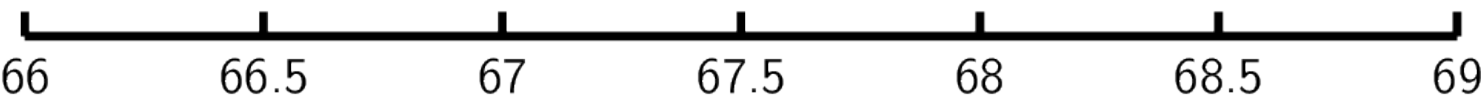


CODATA2006 average



Assume CPT, proton=antiproton
Average of 4 expts. gave the "official"
proton-electron mass ratio in 2006

Earlier 1-photon
result!



$$(m_{p,\bar{p}}/m_e - 1836.152)/10^{-5}$$



The (anti)proton-electron mass ratio

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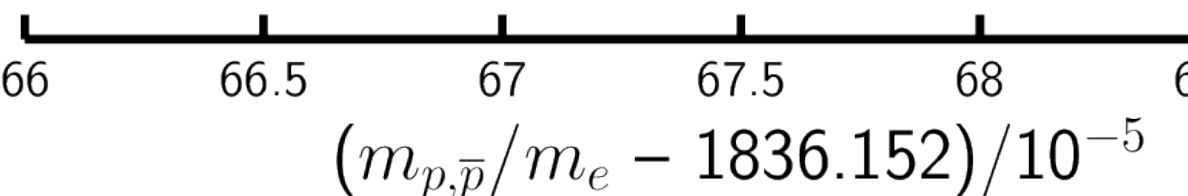
REVIEWS OF MODERN PHYSICS, VOLUME 80, APRIL-JUNE 2008

CODATA recommended values of the
fundamental physical constants: 2006

Peter J. Mohr, Barry N. Taylor, and David B. Newell

"...assume that CPT is a valid
symmetry, [.....] take the masses of
the antiproton and proton to be
equal and use the data to determine
the proton-electron mass ratio.

Since the proton relative atomic mass
is known more accurately than the
electron relative atomic mass from
other experiments, the mass ratio
yields information primarily on the
electron relative atomic mass..."



The (anti)proton-electron mass ratio

Washington Penning trap
PRL75(1995)3598

GSI/Mainz electron g-factor in $^{12}\text{C}^{5+}$
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CODATA2002 average

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CPT test: compare proton to antiproton (2-photon)

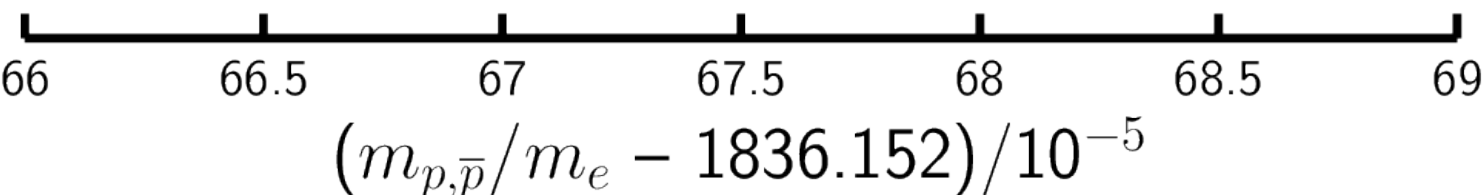
- Use CODATA2002 proton value (they included our results later)

- Agreement 1.3×10^{-9}

- Precision of $\bar{P}/e$ is approaching P/e

Antiprotonic helium 2-photon
Nature475(2011)484

Latest 2-photon result!



The (anti)proton-electron mass ratio

Washington Penning trap

PRL75(1995)3598

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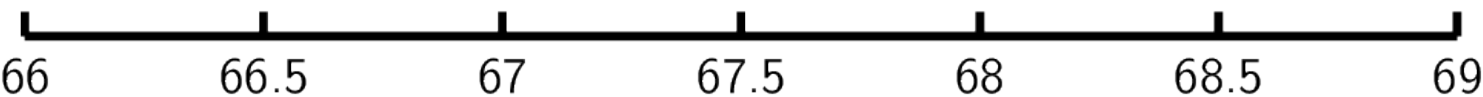
Antiprotonic helium 1-photon

PRL96(2006)243401

Antiprotonic helium 2-photon

Nature475(2011)484

CODATA2010 average



$$(m_{p,\bar{p}}/m_e - 1836.152)/10^{-5}$$

Assume CPT, proton=antiproton
Average of 3 proton expts. and our 1-
and 2-photon results gives the
current "official" proton-electron mass
ratio



The (anti)proton-electron mass ratio

Washington Penning trap
PRL75(1995)3598

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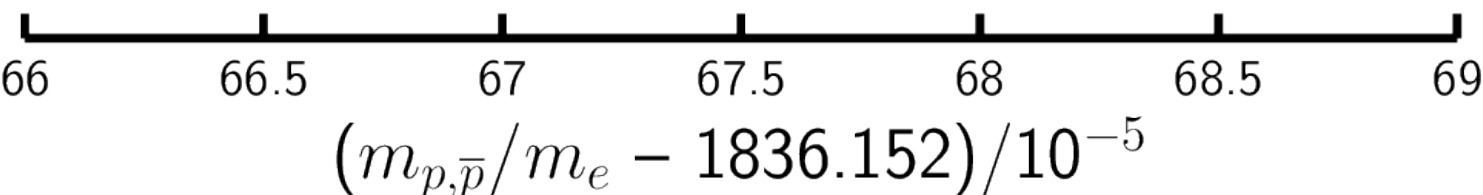
Antiprotonic helium 1-photon
PRL96(2006)243401

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and 2-photon results gives the
current "official" proton-electron mass
ratio

Using our 2-photon result
to determine electron
atomic mass:
 $m_e = 0.0005485799091(7)\text{u}$

CODATA2010 average



SUMMARY

- First 2-photon spectroscopy of antiprotonic helium:
 $m_{\bar{p}}/m_e = 1836.1526736 \cdot (1 \pm 1.3 \cdot 10^{-9})$
- It is approaching the precision of m_p/m_e
- CPT test: agreement with proton-electron mass ratio: 1.3×10^{-9}
- Assuming CPT, determine electron relative atomic mass :
 $m_e = 0.0005485799091(7)u$
- Among others, antiprotonic helium spectroscopy contributes to the current "official" proton-electron mass ratio

WE HOPE

to be able to determine $m_{\bar{p}}/m_e$ to an accuracy competing with m_p/m_e in the near future (....)



Thanks for your attention...

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