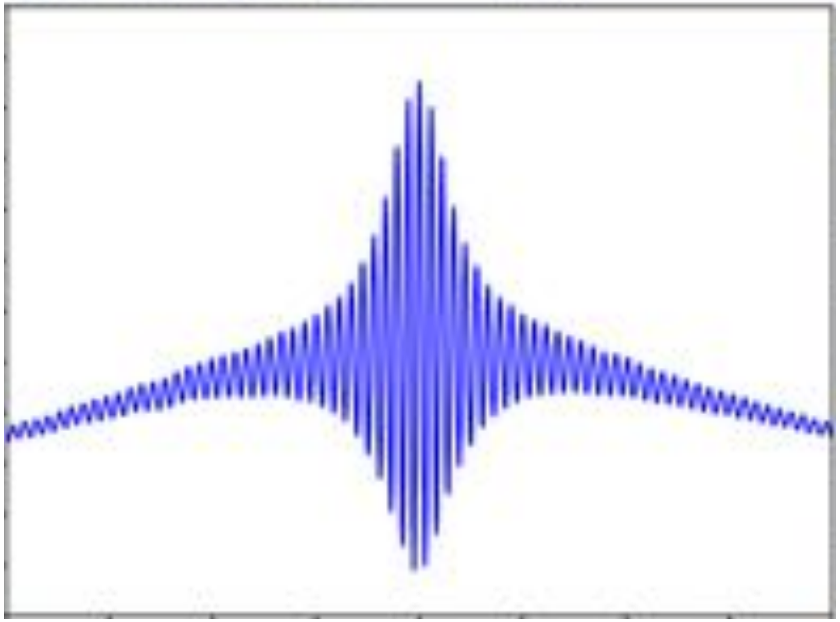
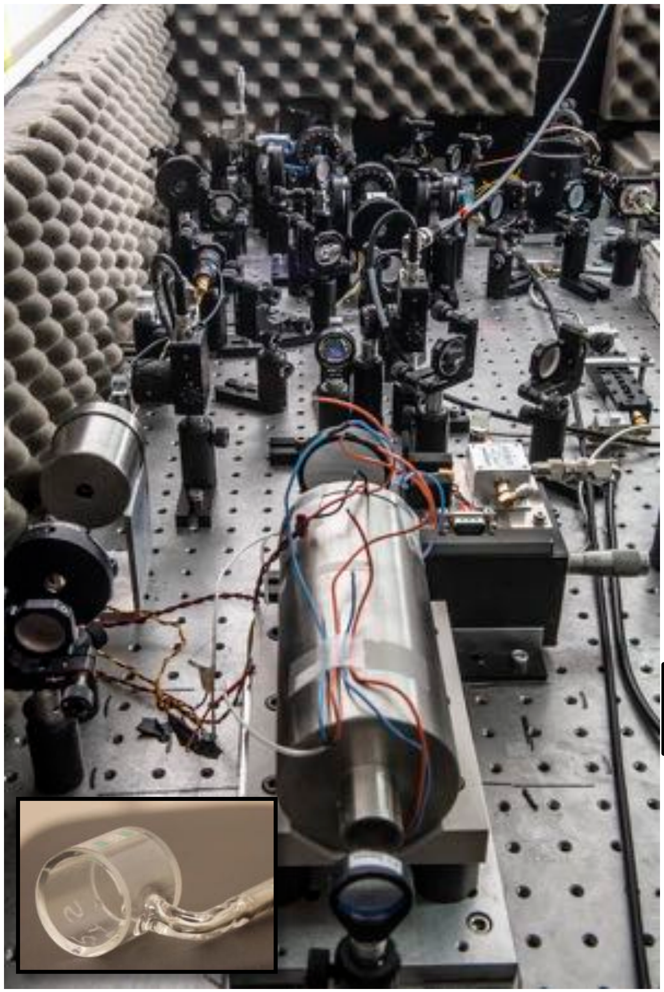
Light shift mitigation in vapor-cell atomic clocks with tailored interrogation

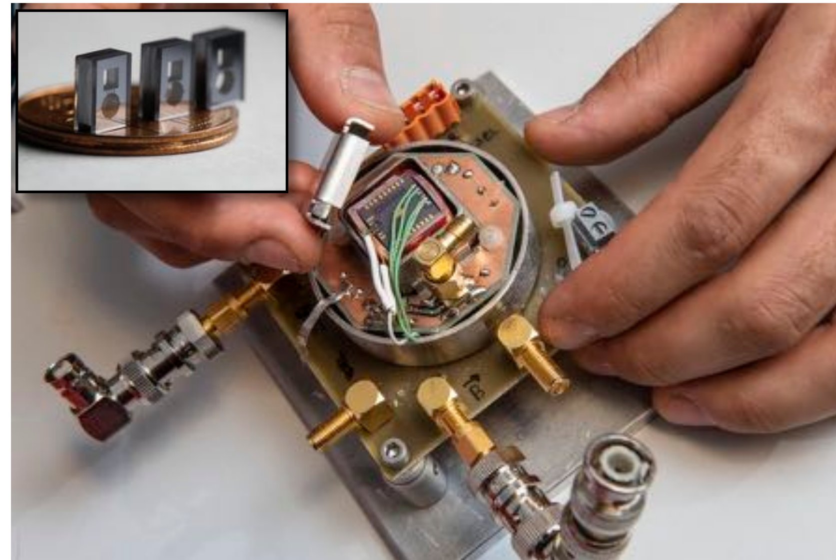


Moustafa ABDEL HAFIZ, Michael PETERSEN, Grégoire COGET, Nicolas PASSILLY, Claudio E. Calosso, Emeric de Clercq, Stéphane GUÉRANDEL, Rodolphe BOUDOT

Coherent population trapping (CPT) clocks at FEMTO-ST

Applications of vapor-cell atomic clocks:
telecom, navigation, instrumentation, …





Miniature CPT atomic clock

Targets:

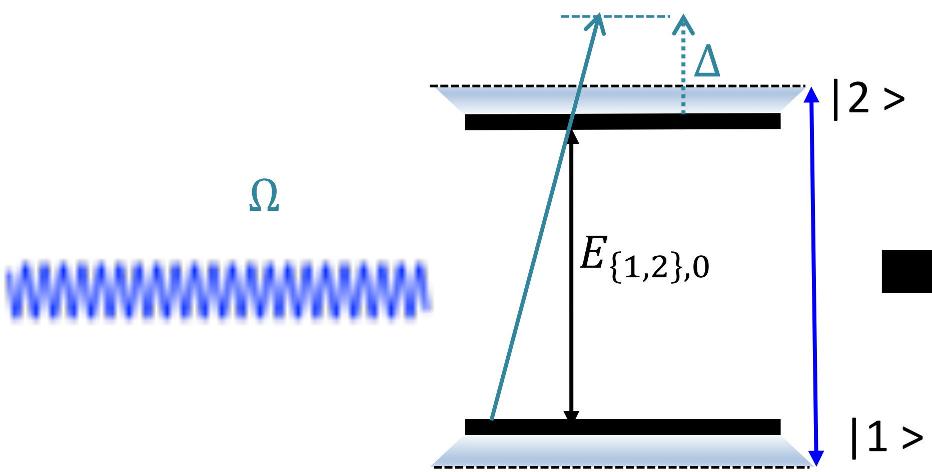
- Allan deviation $\sigma_y(\tau) = \sim$ **10^{-11} at 1 day**
- 15 cm^3 / 125 mW

Compact CPT atomic clock

Targets:

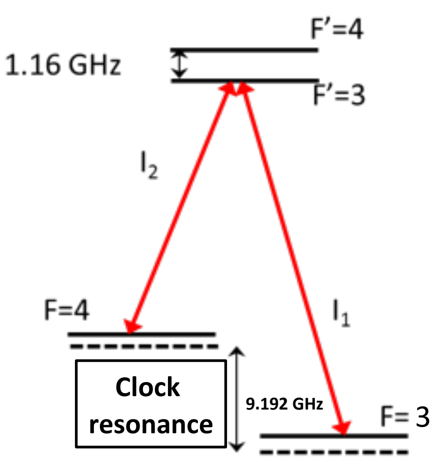
- Allan deviation $\sigma_y(\tau) =$ **few 10^{-13} $\tau^{-1/2}$** up to 1000 s
- < 10^{-14} at 10^4 s, ~ **10^{-14} at 1 day**
- ~ 30 L / 30W

Light shift in a 2-level system



$$E_{\{1,2\}} \approx E_{\{1,2\},0} + \frac{\Omega^2}{4\Delta}$$

In a CPT clock



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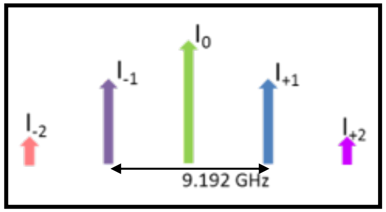


Generation of sidebands by phase/intensity modulation

Light shift depends on detuning and intensity **of each spectral component** of the light

- Complex
- Strongly environment-sensitive

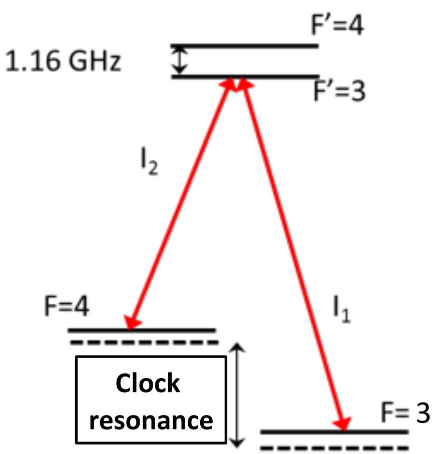
What to do ?

Reduce fluctuations of the field power and frequency

	Sensitivity	Setpoint	Max. to reach 10^{-15} (fract.)
Laser power fluctuations	$2.8\ 10^{-12}$/µW	500 µW	$7\ 10^{-7}$
Laser frequency fluctuations	$4.2\ 10^{-12}$/MHz	335 THz	$8\ 10^{-13}$

➡ Very difficult to reach such stability levels

Reduce sensitivity by compensation



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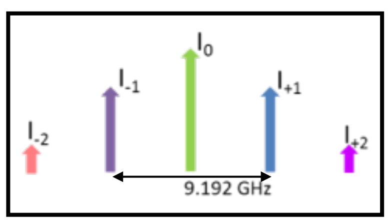
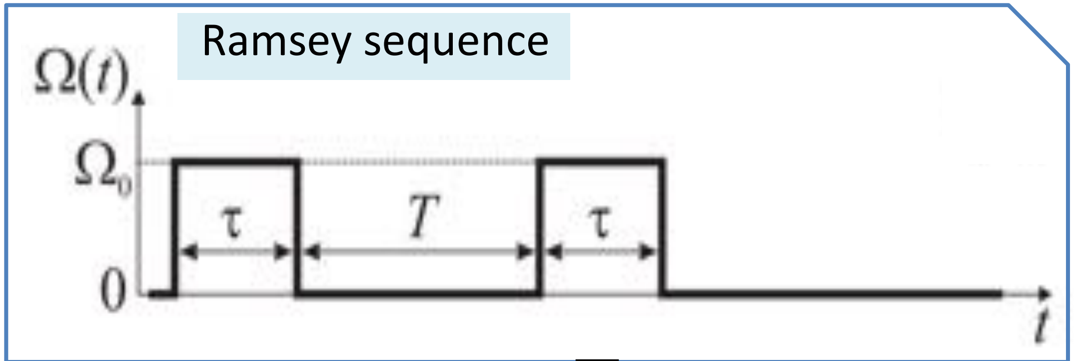
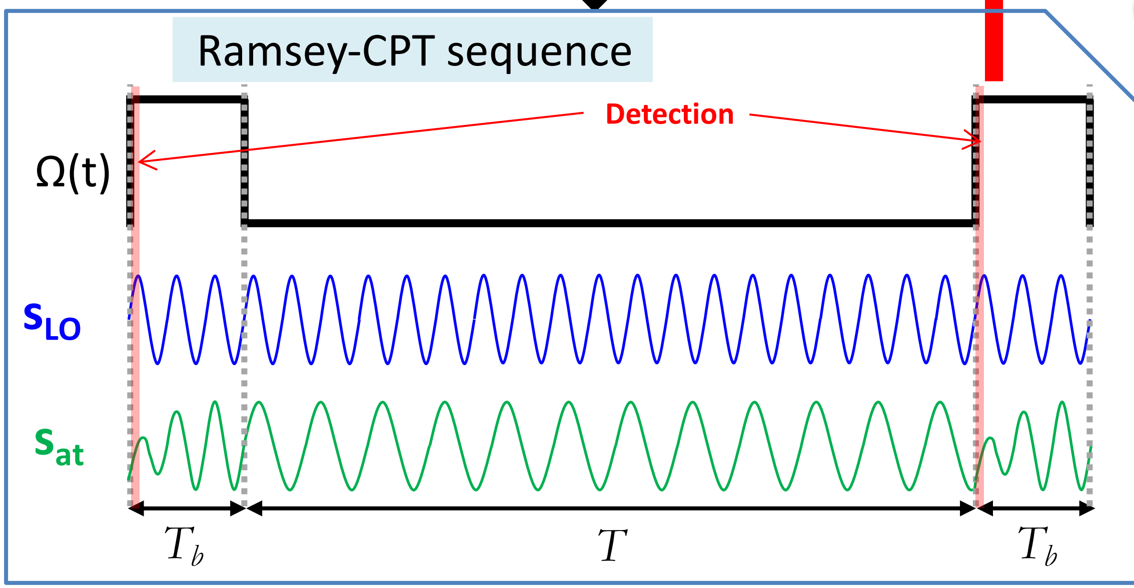


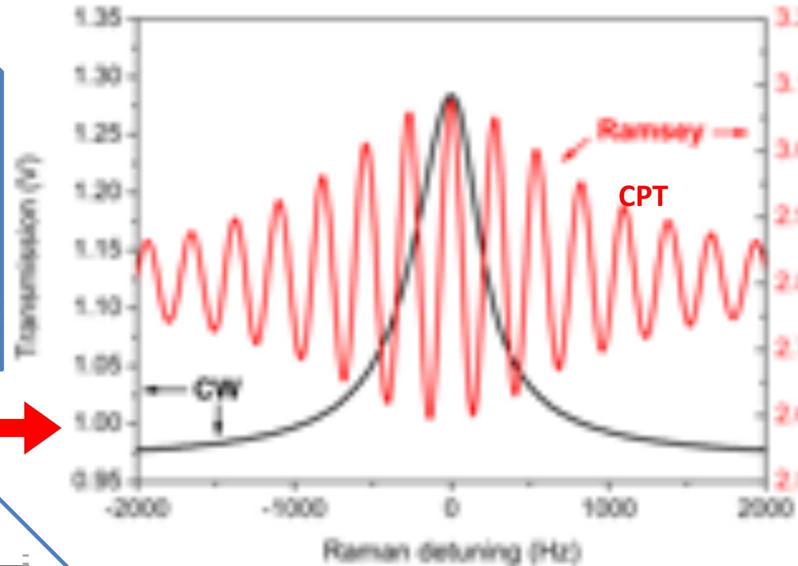
- Tune the modulation depth to change the energy distribution onto the sidebands
- Find a setpoint that compensates positive and negative light shifts

➡ **If exists**, this setpoint may be far from optimal conditions

Sequence tailoring: Ramsey sequence







The Ramsey-CPT fringes represent the phase difference after the free evolution

Atoms are in the dark most of the time

→ <u>Light shift is reduced</u>

BUT there is still residual light shift from light pulses

Beyond two-pulses interferometry

<u>Advanced methods for light shift reduction</u>

- Hyper-Ramsey Yudin et al., *Phys. Rev. A* **82**, 011804 (2010)

➡ Goal: compensate the phase shift imprinted by light during the pulses with another pulse, where the phase is reversed

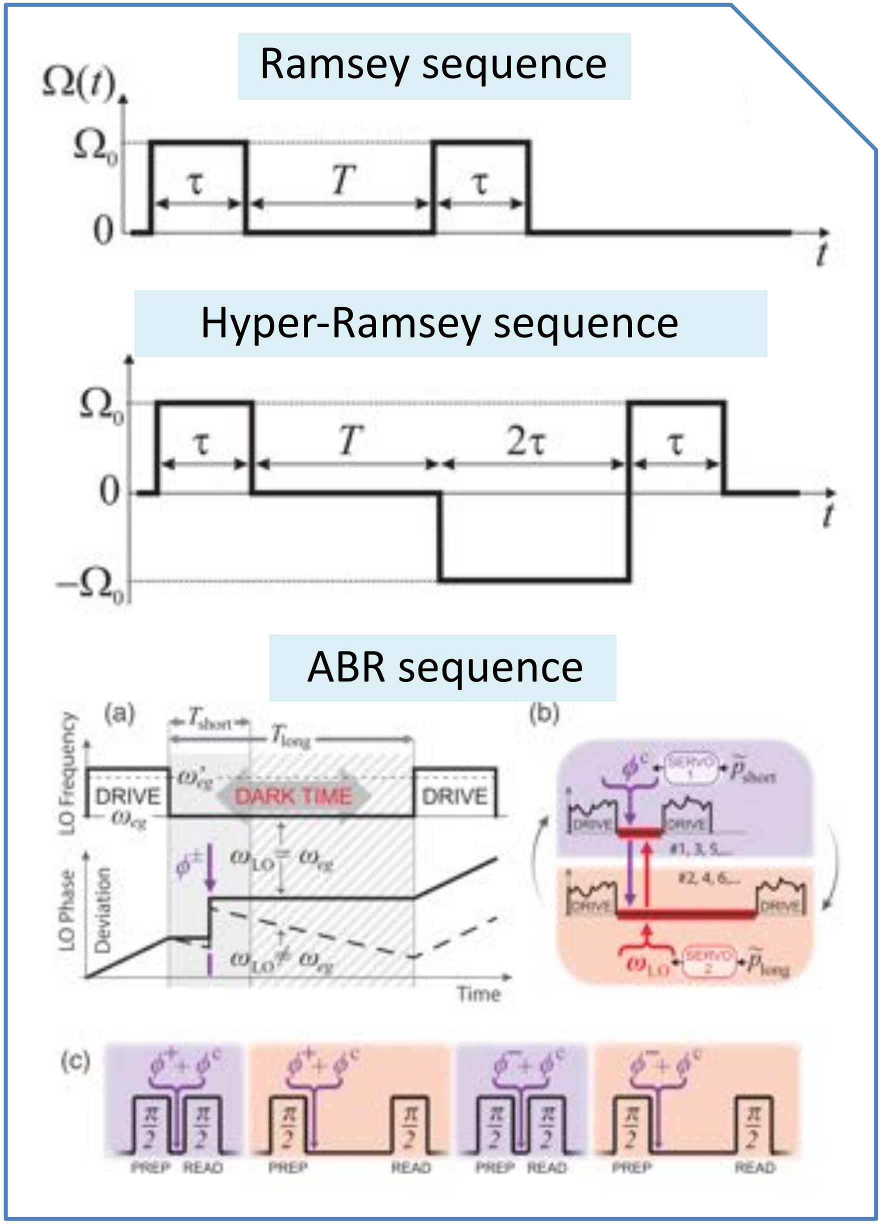
- Modified Hyper-Ramsey
- Generalized Hyper-Ramsey
- Other hybrid schemes…

Zanon et al., *Reports on Progress in Physics* **81** (2018)

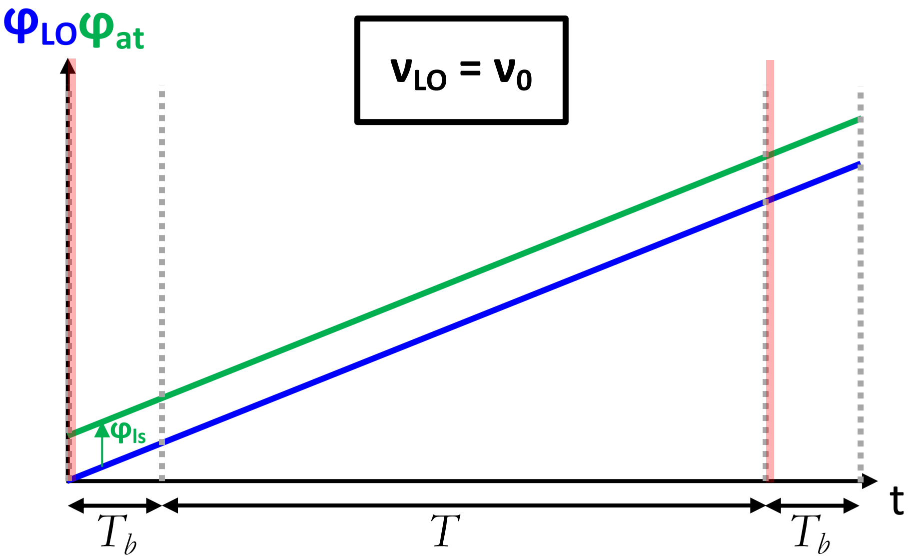
- <u>Autobalanced Ramsey (ABR) spectroscopy</u>

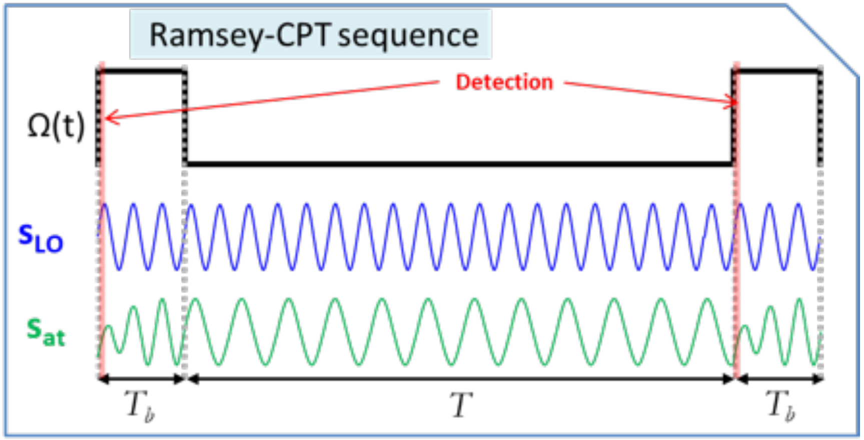
Sanner et al., *Phys. Rev. Lett.* **120**, 053602 (2018)

➡ Main difference: **measurement and live correction of the light shift**

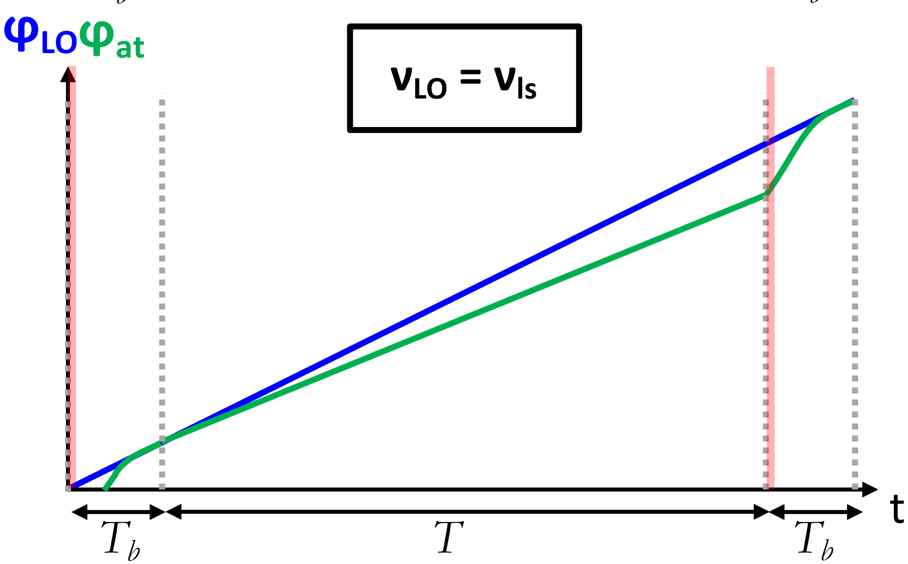


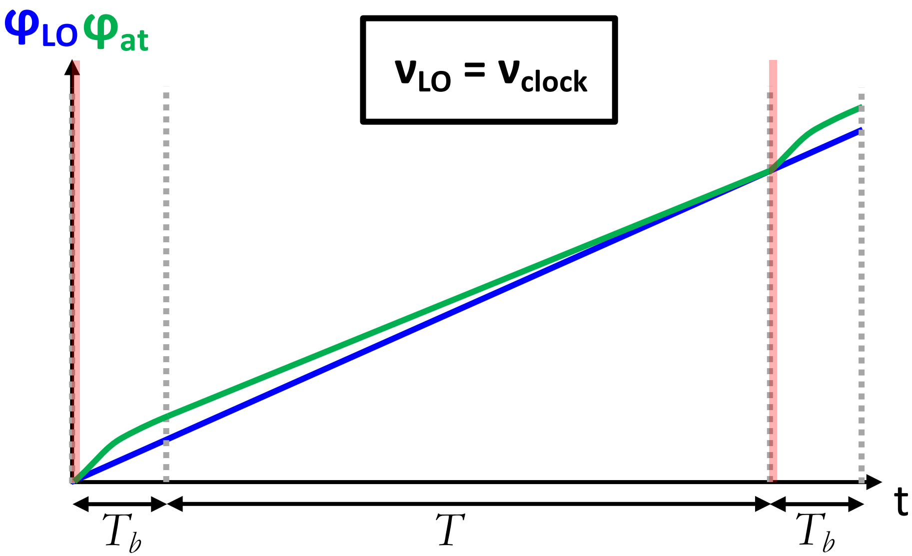
ABR spectroscopy: principle



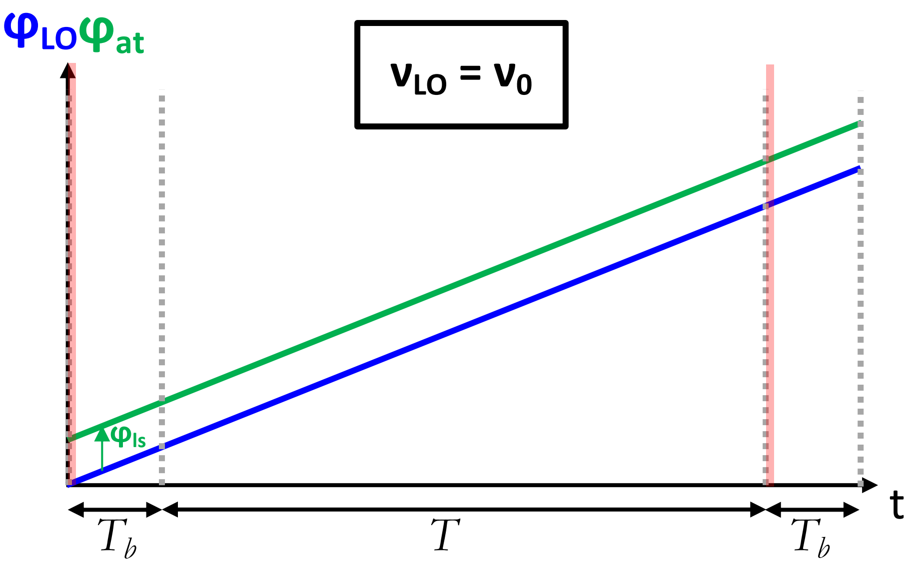


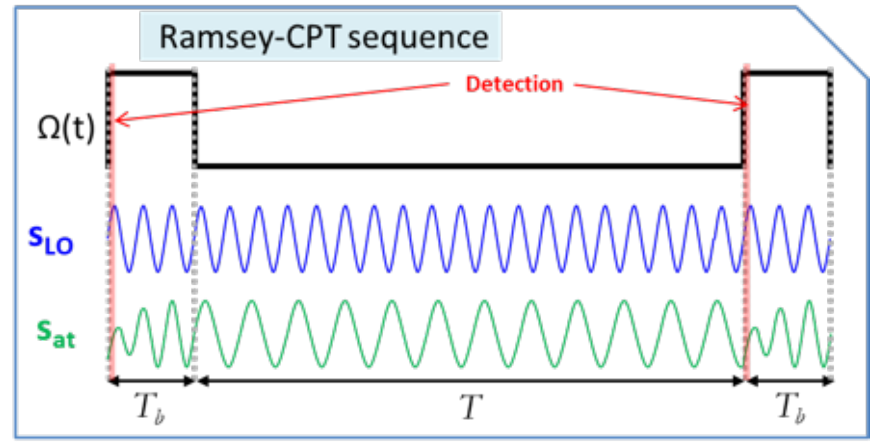
- Frequency = slope of the phase vs time
- Free-evolution atomic frequency during T





ABR spectroscopy: principle





- Frequency = slope of the phase vs time
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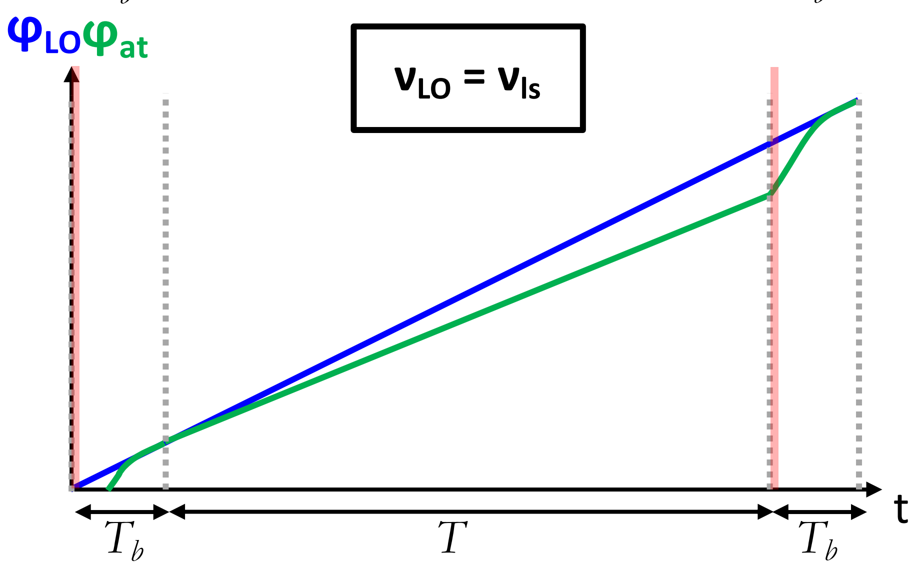
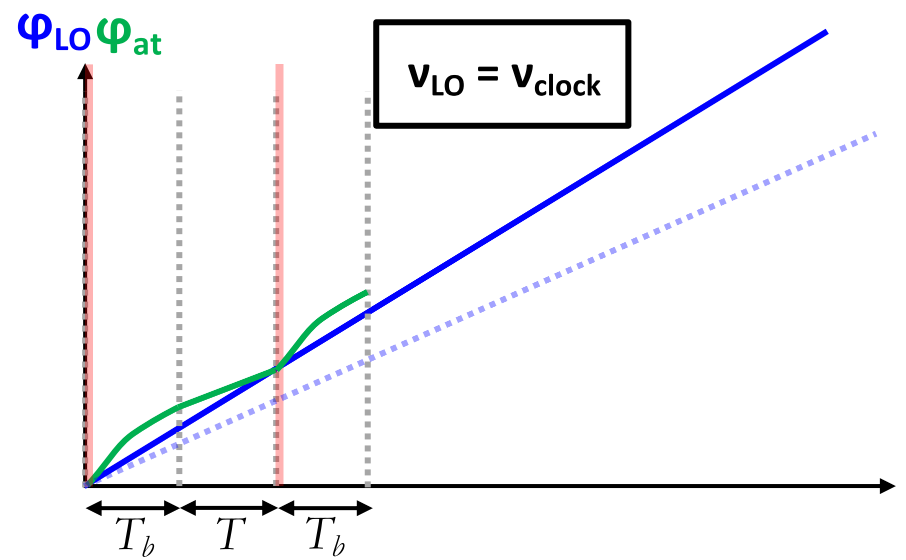


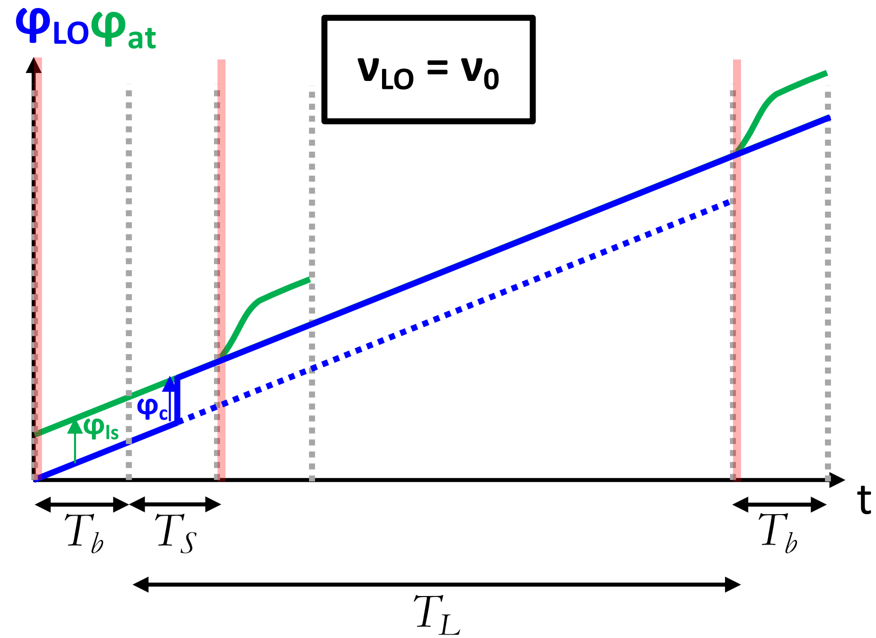


Residual light shift increases with decreasing T

Shift dependent on T is a characteristic of light shifts

➡ Conditions for no light shift whatever T:

- $\nu_{LO} = \nu_0$ ➡ Same slope for LO and free atom
- $\varphi_c = \varphi_{ls}$ ➡ Phase jump corresponding to atomic phase shift

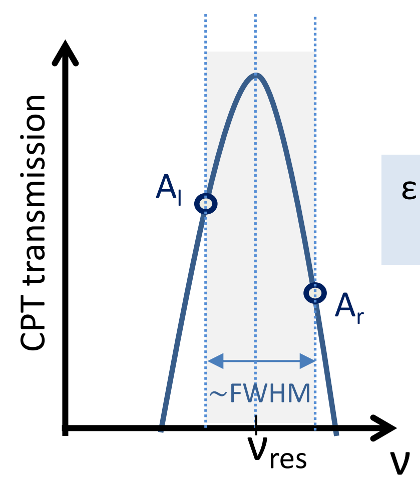


ABR spectroscopy:

- Alternate cycles with dark times T_L and T_S
- Apply a phase jump φ_c during dark times
- Generate associated error signals ε_L and ε_S
- Two servo loops:
  - $\varepsilon_L = 0$ ➡ ν_{LO}
  - $\varepsilon_S = 0$ ➡ φ_c

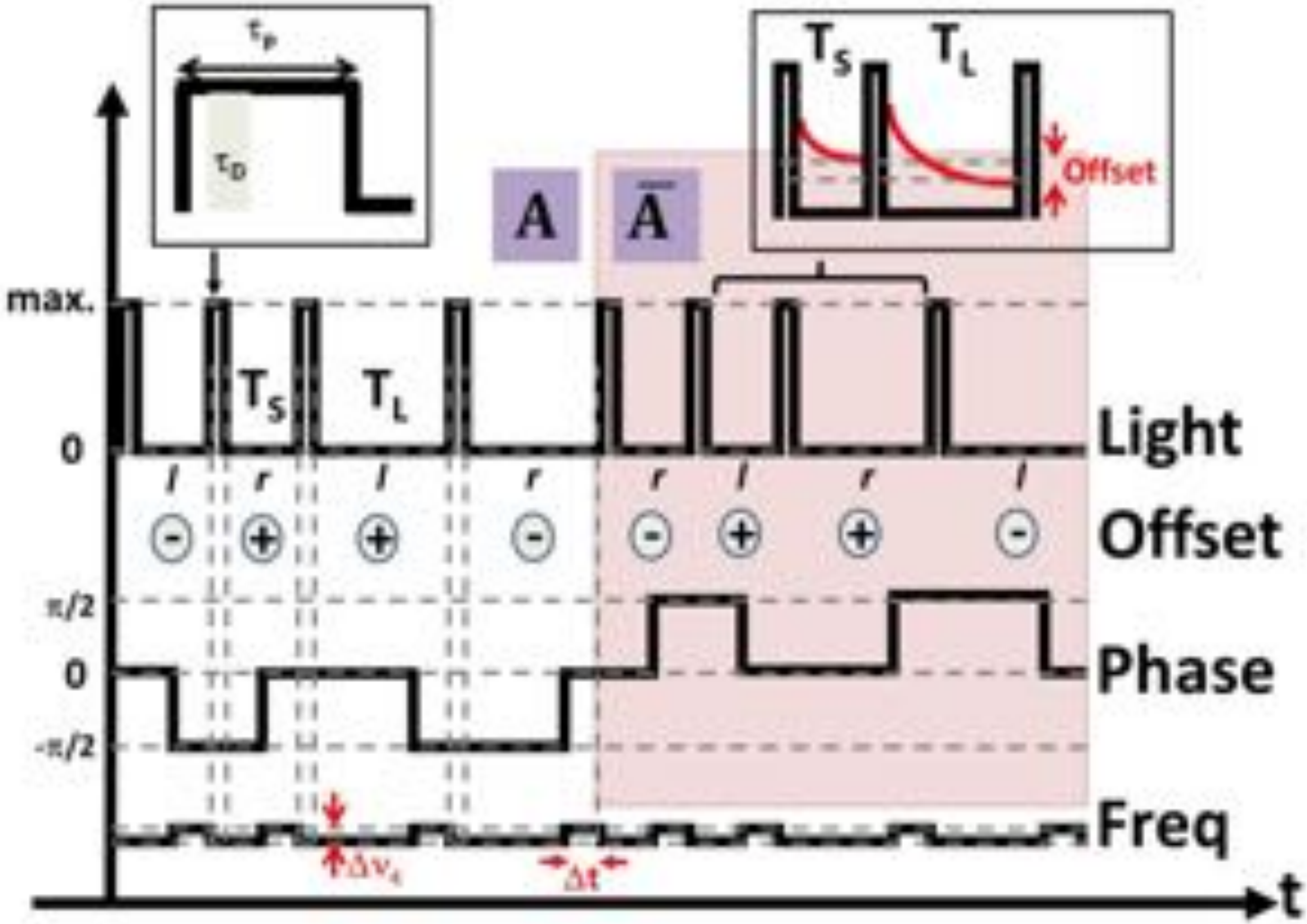
➡ When both servos are on,
$\nu_{LO} = \nu_0$ $\varphi_c = \varphi_{ls}$

Generation of an error signal

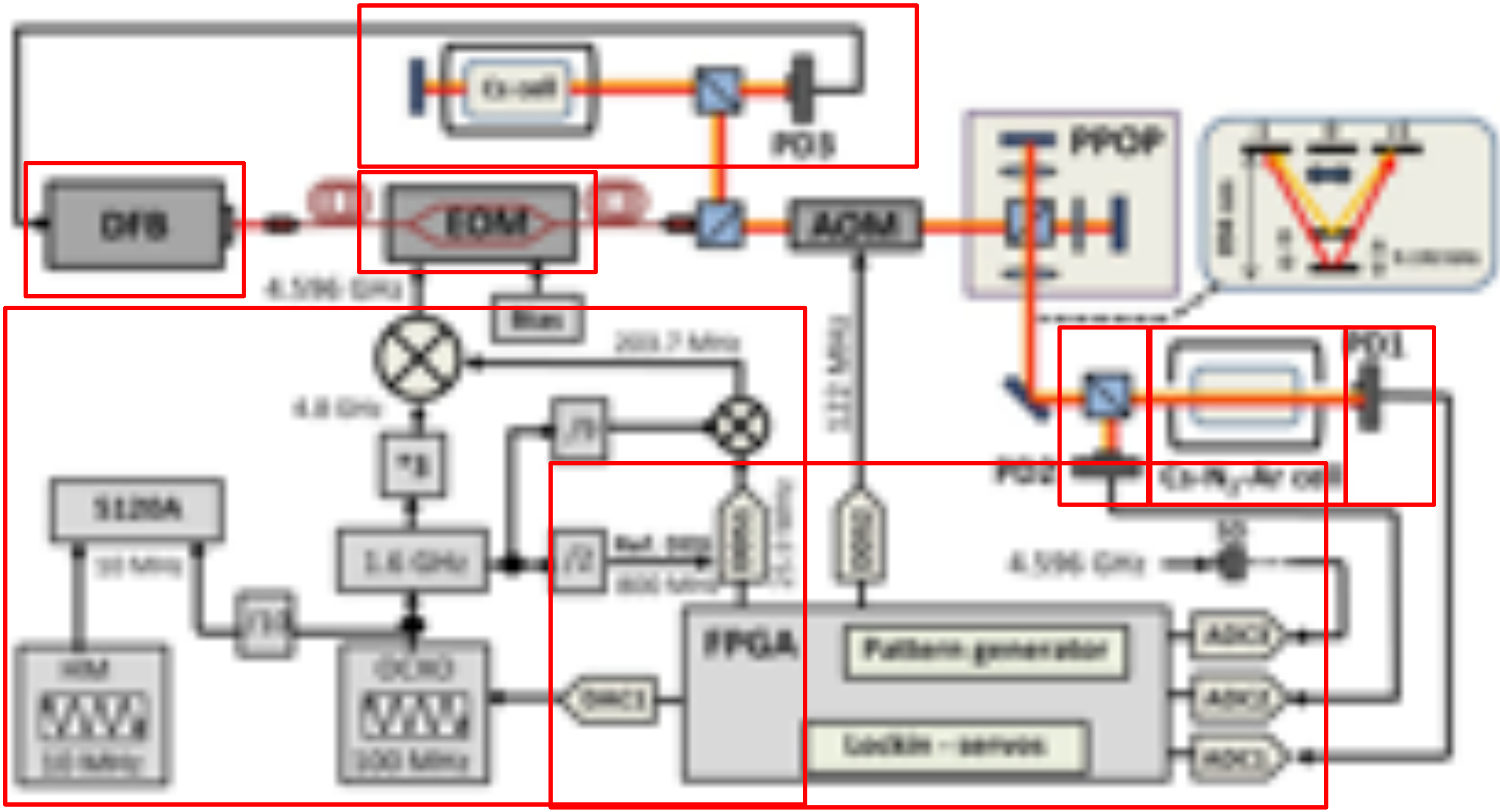


$\varepsilon = A_r - A_l$
$= 0$ when $\nu = \nu_{res}$

ABR-CPT – symmetric sequence



ABR-CPT – setup

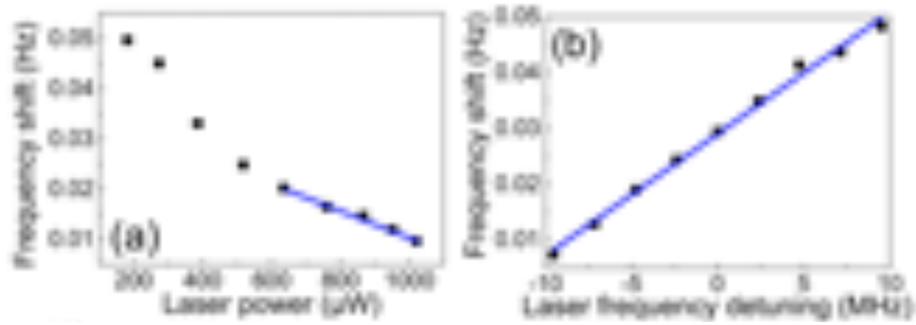


- Laser
- Sidebands generation
- LO signal generation
- Laser frequency stabilization
- Laser intensity stabilization
- Physics package (vapor cell)
- CPT signal detection
- Control electronics

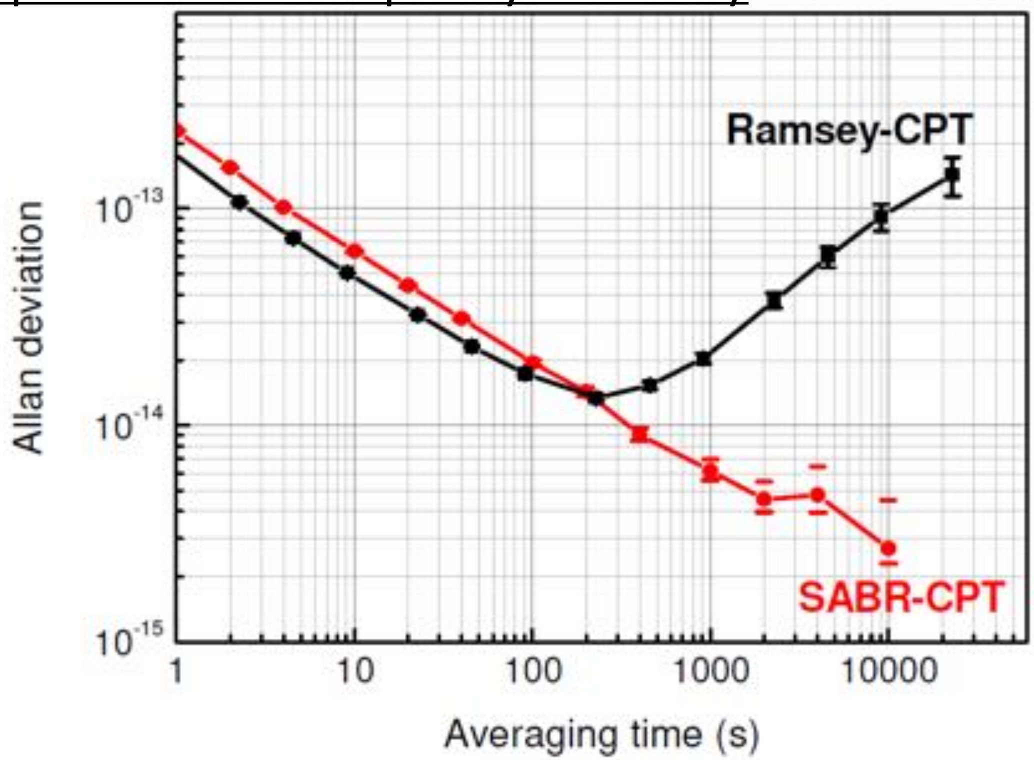
Reduction of sensitivity to light

CW regime	~ $8\ 10^{-12}$/µW
Ramsey-CPT	~ $3\ 10^{-13}$/µW
Autobalanced Ramsey	**~ $3\ 10^{-15}$/µW !!!**

→ **Gain of two orders of magnitude**



Impact on clock frequency instability

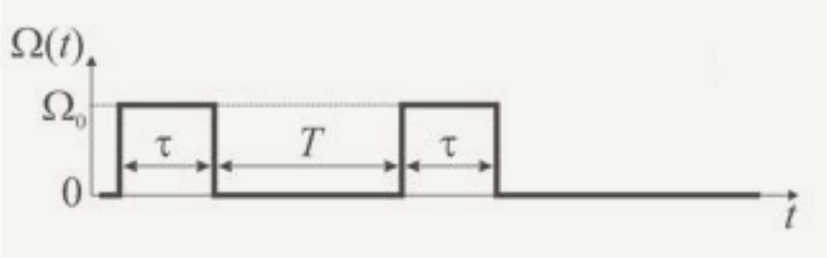


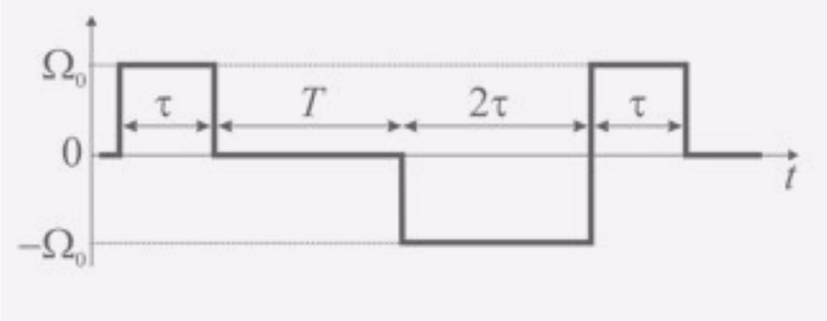
Short term: ~ 2 10^{-13} $\tau^{-1/2}$ @ 1s

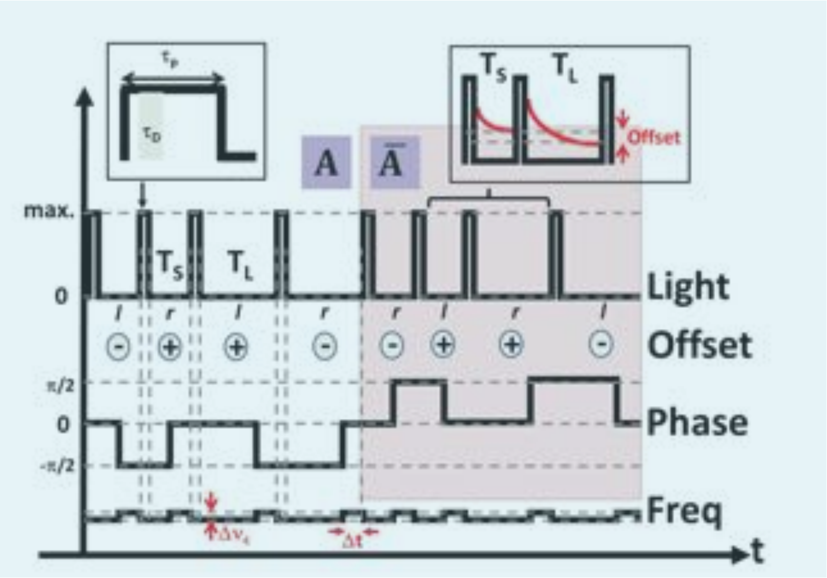
~ 30x improvement @ 10000s

Advanced methods for light shift reduction

- Ramsey spectroscopy
- Hyper-Ramsey
- Autobalanced Ramsey







Sensitivity to incident light power (in a compact CPT clock)

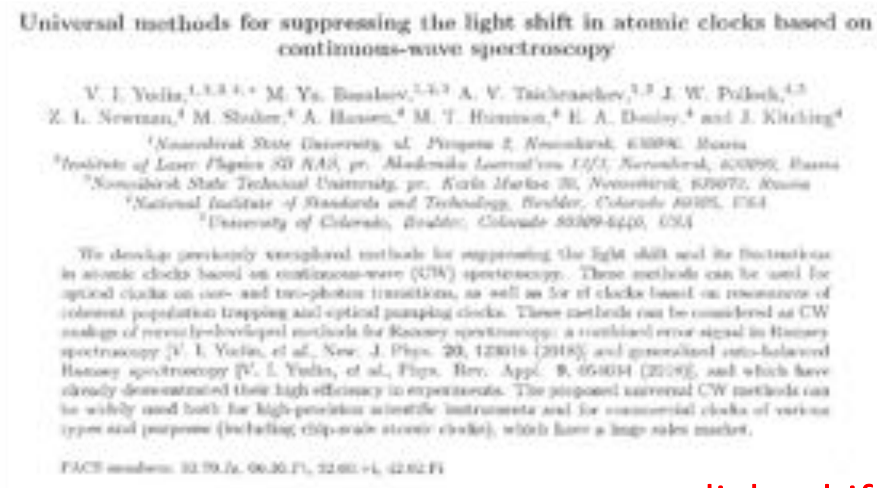
CW regime	$\sim 8\ 10^{-12}/\mu W$
Ramsey-CPT	$\sim 3\ 10^{-13}/\mu W$
Autobalanced Ramsey	**$\sim 3\ 10^{-15}/\mu W$!!!**

But in miniaturized CPT clocks:

- Low laser powers available
- Pulsing light is not easy
- Laser frequency stabilized on CPT cell

Solutions in the CW regime?

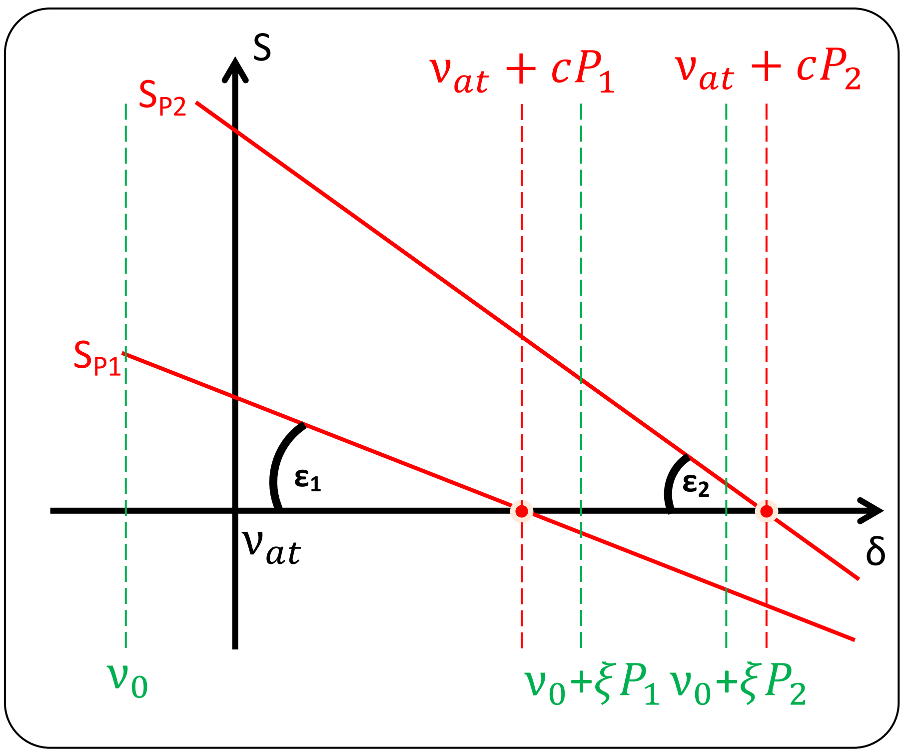
Principle of ACS


Universal methods for suppressing the light shift in atomic clocks based on continuous-wave spectroscopy

V. I. Yudin, M. Yu. Basalaev, A. V. Taichenachev, J. W. Pollock, Z. L. Newman, M. Shuker, A. Hansen, M. T. Hummon, E. A. Donley, and J. Kitching

ν_{at}: light-shift-free c: light-shift coef.

ν_0, ξ: free parameters

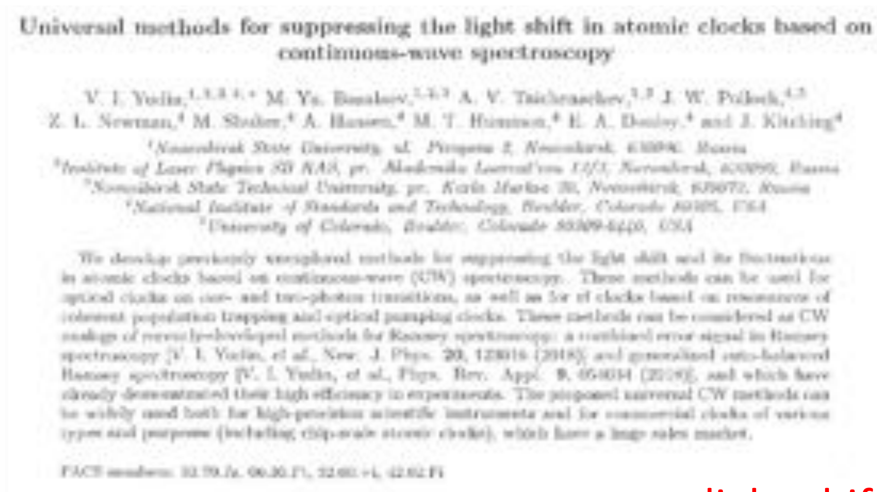


$$\begin{cases} S_{P_1}(\nu_0 + \xi P_1) = 0 & \textbf{@ } \mathbf{P_1} \\ S_{P_2}(\nu_0 + \xi P_2) = 0 & \textbf{@ } \mathbf{P_2} \end{cases}$$

Auto-
Compensated
Shift

- Two servo loops
- Only constraint: linear light shift

Principle of ACS



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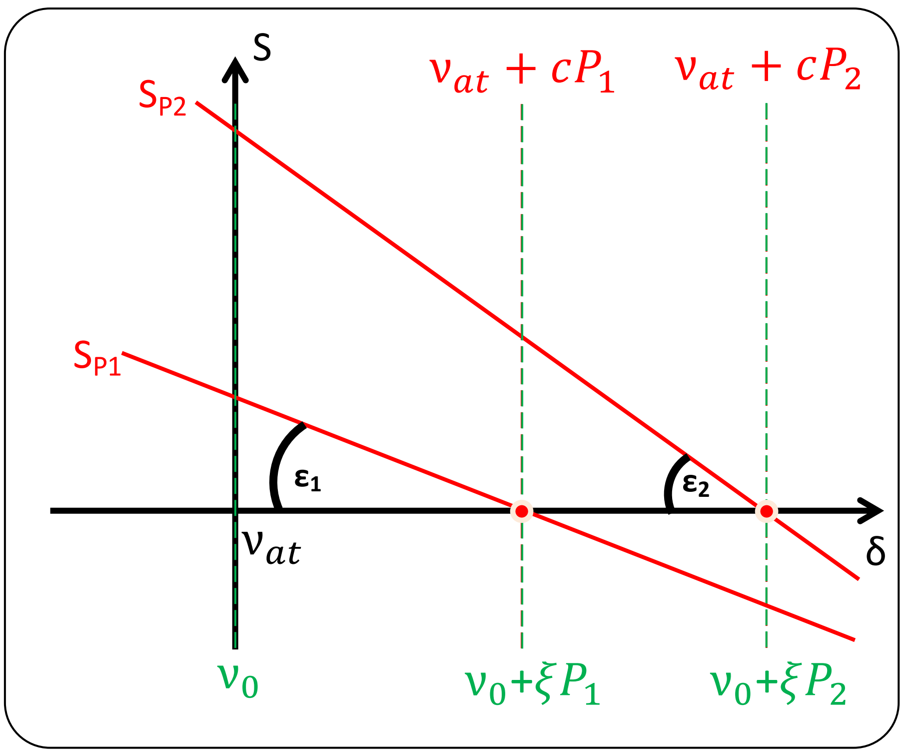
[1]Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090, Russia
[2]Institute of Laser Physics SB RAS, pr. Akademika Lavrent'eva 13/3, Novosibirsk, 630090, Russia
[3]Novosibirsk State Technical University, pr. Karla Marksa 20, Novosibirsk, 630073, Russia
[4]National Institute of Standards and Technology, Boulder, Colorado 80305, USA
[5]University of Colorado, Boulder, Colorado 80309-0440, USA

We develop previously unexplored methods for suppressing the light shift and its fluctuations in atomic clocks based on continuous-wave (CW) spectroscopy. These methods can be used for optical clocks on one- and two-photon transitions, as well as for rf clocks based on resonances of coherent population trapping and optical pumping clocks. These methods can be considered as CW analogs of recently-developed methods for Ramsey spectroscopy: a combined error signal in Ramsey spectroscopy [V. I. Yudin, et al., New. J. Phys. 20, 123016 (2018)] and generalized auto-balanced Ramsey spectroscopy [V. I. Yudin, et al., Phys. Rev. Appl. 9, 054034 (2018)], and which have already demonstrated their high efficiency in experiments. The proposed universal CW methods can be widely used both for high-precision scientific instruments and for commercial clocks of various types and purposes (including chip-scale atomic clocks), which have a large sales market.

PACS numbers: 32.70.Jz, 06.30.Ft, 32.60.+i, 42.62.Fi



ν_{at}: light-shift-free c: light-shift coef.

ν_0, ξ: free parameters

$$\begin{cases} S_{P_1}(\nu_0 + \xi P_1) = 0 & \textbf{@ } \mathbf{P_1} \\ S_{P_2}(\nu_0 + \xi P_2) = 0 & \textbf{@ } \mathbf{P_2} \end{cases}$$

$$\Rightarrow \boxed{\nu_0 = \nu_{at} \,,\, \xi = c}$$

Auto-
Compensated
Shift

- Two servo loops
- Only constraint: linear light shift

Modified error signals

Linear combinations of the original error signals

- S_{LS} is proportional to $\xi - c$
- Both S_{P1} and S_{P2} are exploited in both servos
  - **No "dead time"**

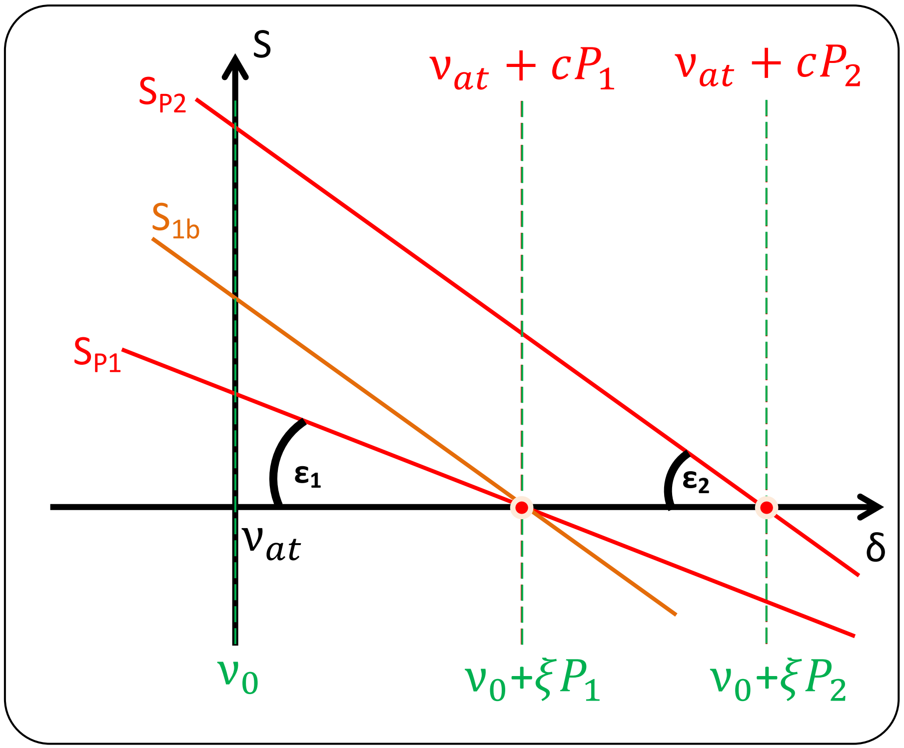
    Prevents degradation of short-term stability
- Independent scaling factors for computation of S_0

$$\begin{cases} S_{LS} = \dfrac{S_{P_2}(\nu_0 + \xi P_2)}{\tan \varepsilon_2} - \dfrac{S_{P_1}(\nu_0 + \xi P_1)}{\tan \varepsilon_1} \\ S_0 = \eta_2 \dfrac{S_{P_2}(\nu_0 + \xi P_2)}{\tan \varepsilon_2} + \eta_1 \dfrac{S_{P_1}(\nu_0 + \xi P_1)}{\tan \varepsilon_1} \end{cases}$$

ν_{at}: light-shift-free c: light-shift coef.

ν_0, ξ: free parameters

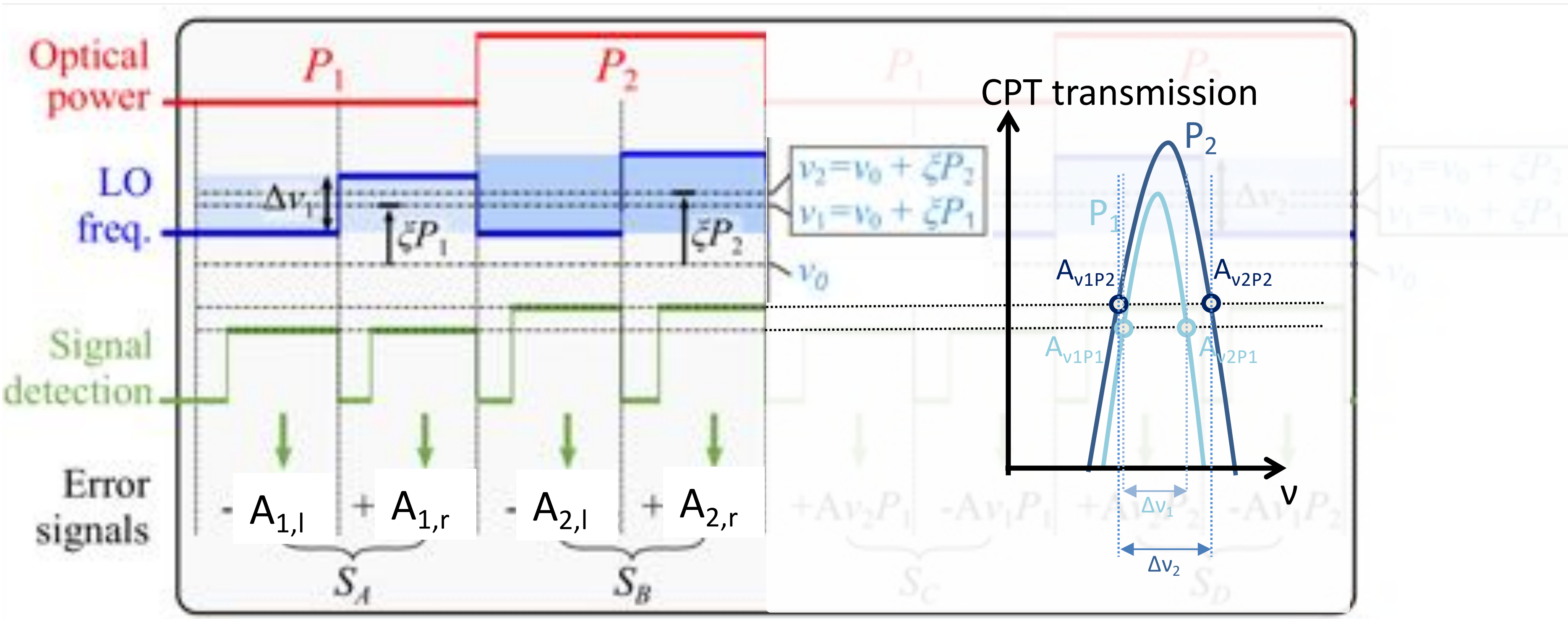
$$\begin{cases} S_{P_1}(\nu_0 + \xi P_1) = 0 \quad \textbf{@ P}_1 \\ S_{P_2}(\nu_0 + \xi P_2) = 0 \quad \textbf{@ P}_2 \end{cases}$$

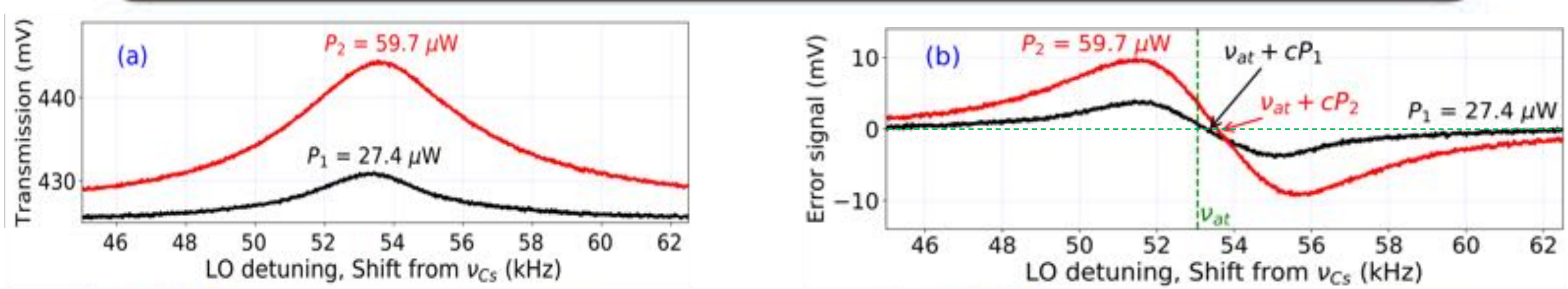


Auto-
Compensated
Shift

- Two servo loops
- Only constraint: linear light shift

Incomplete ACS sequence

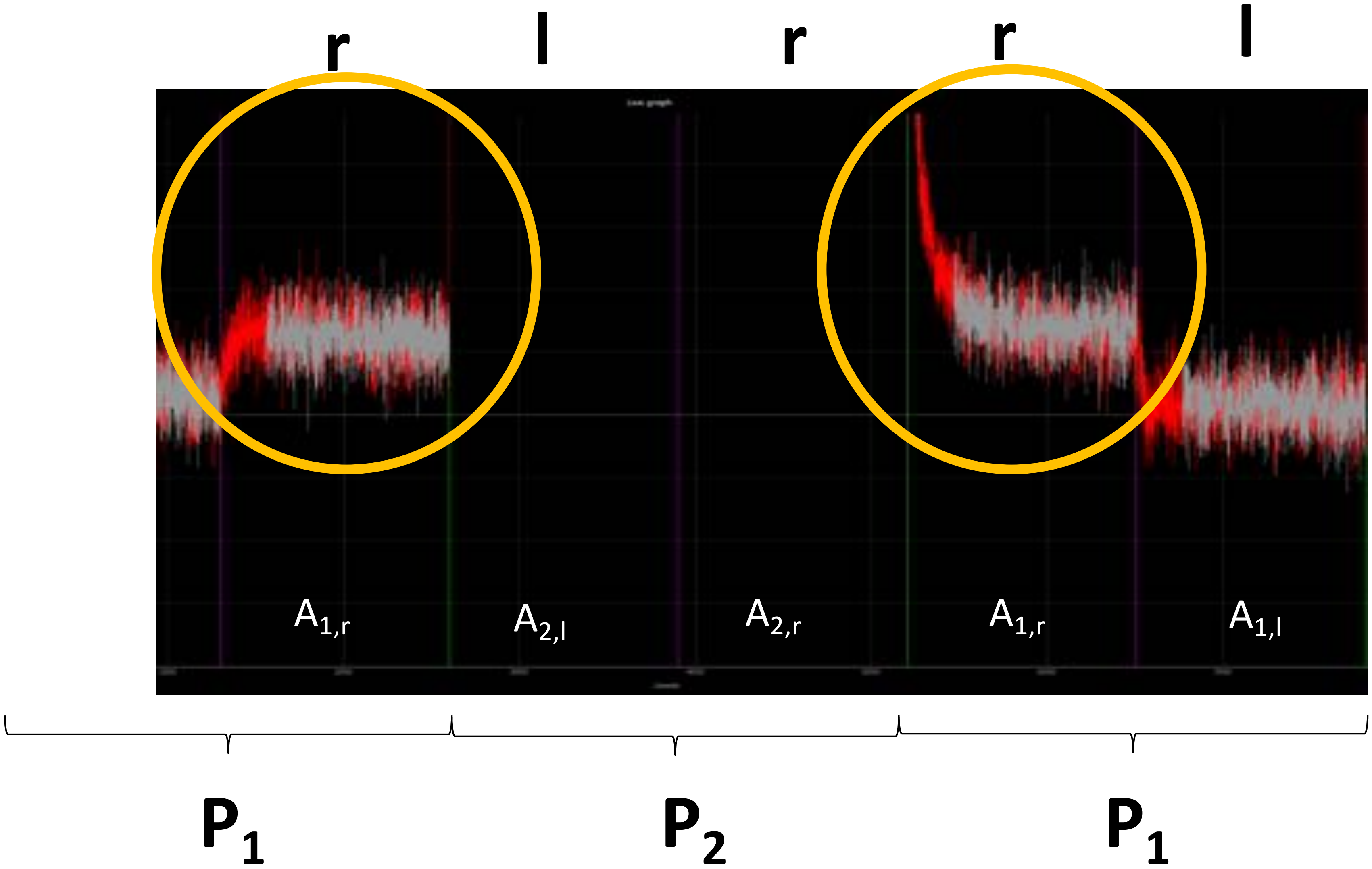




$S_{LS} = (S_B \quad)/D_{e_2} - (S_A \quad)/D_{e_1} = 0$ → Light shift correction (ξ)

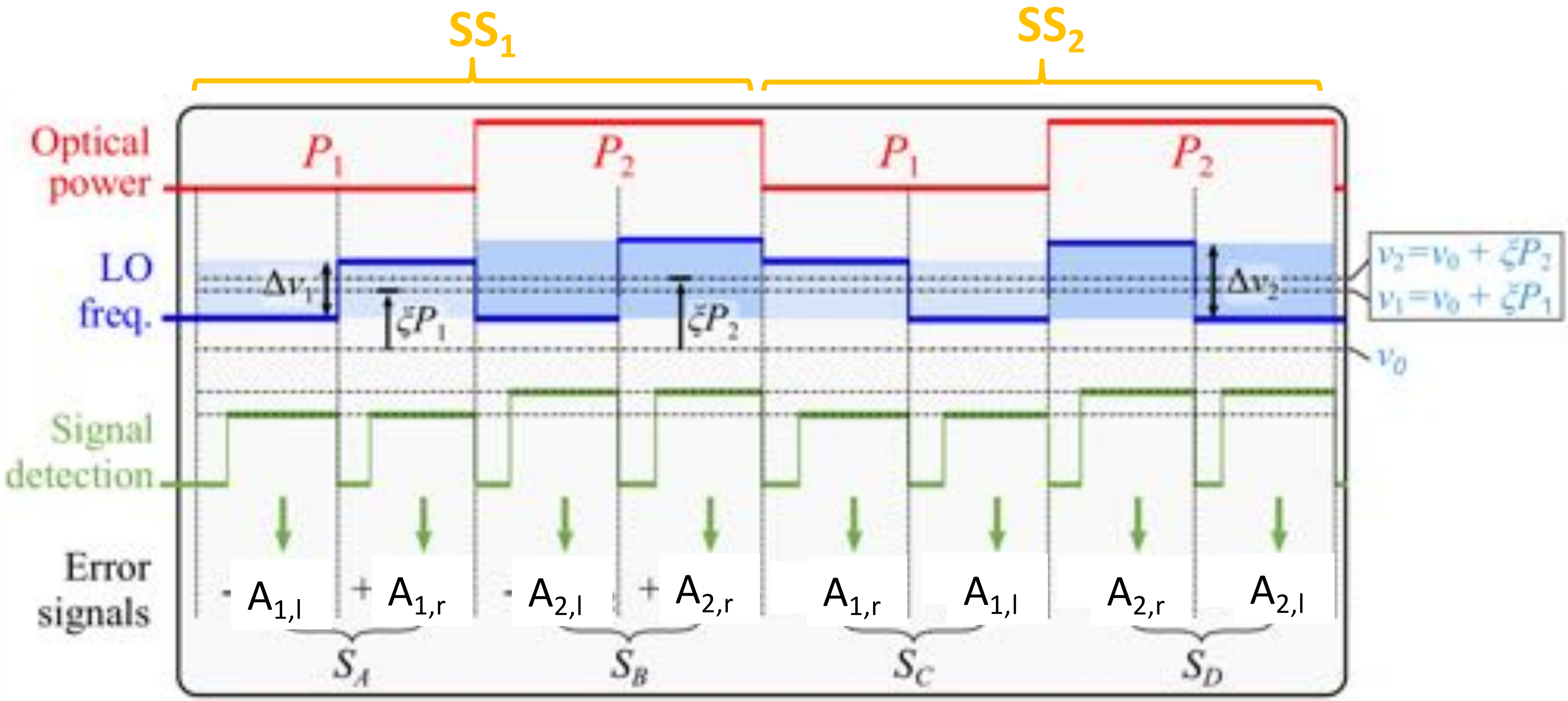
$S_0 = \eta_2\,(S_B \quad)/D_{e_2} + \eta_1\,(S_A \quad)/D_{e_1} = 0$ → Frequency correction (ν_0)

Memory effect



The CPT signal is affected by the atoms history → **Memory shift**

Symmetrized-ACS sequence

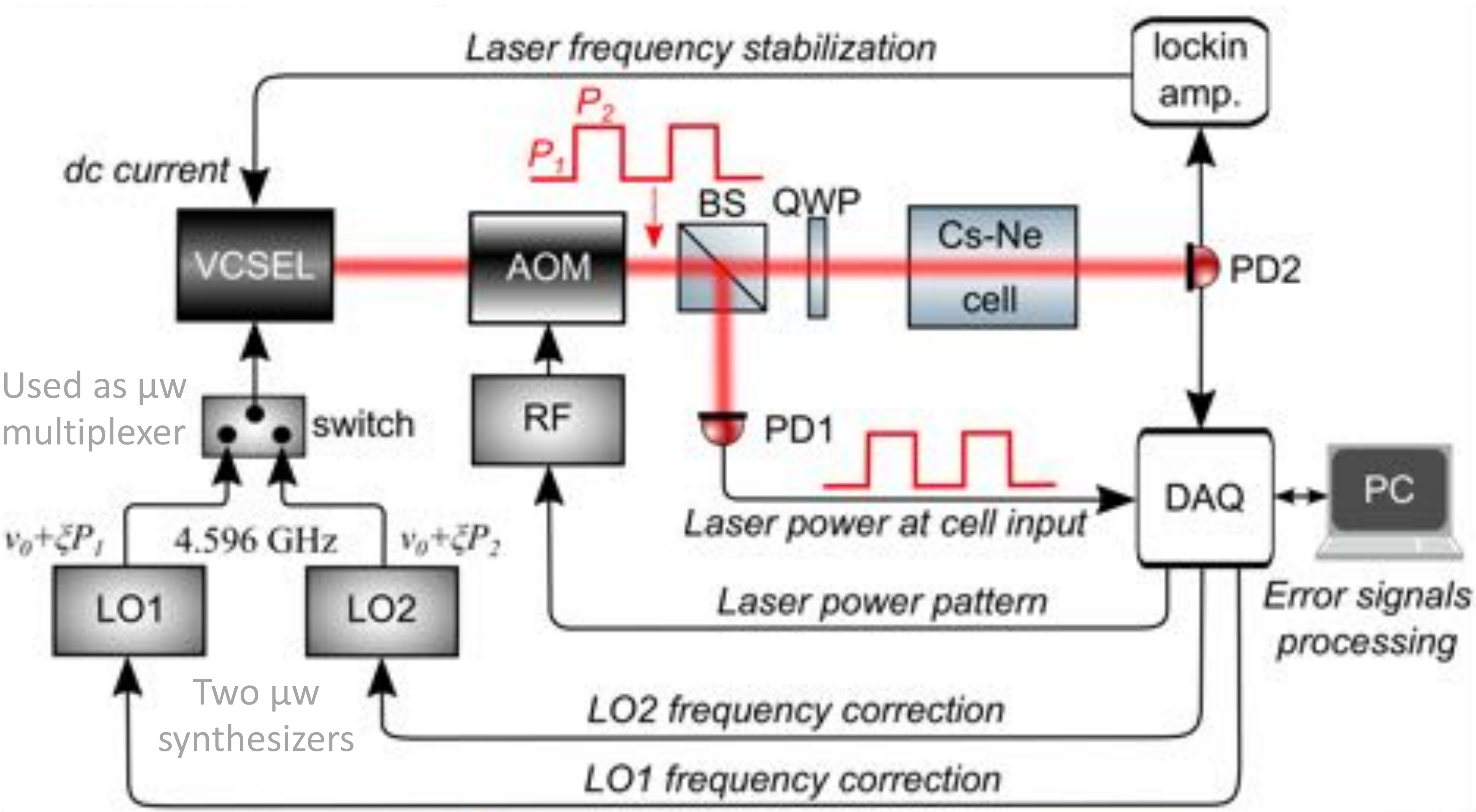


$S_{LS} = (S_B+S_D)/D_{e_2} - (S_A+S_C)/D_{e_1}$ ➔ Light shift correction (ξ)

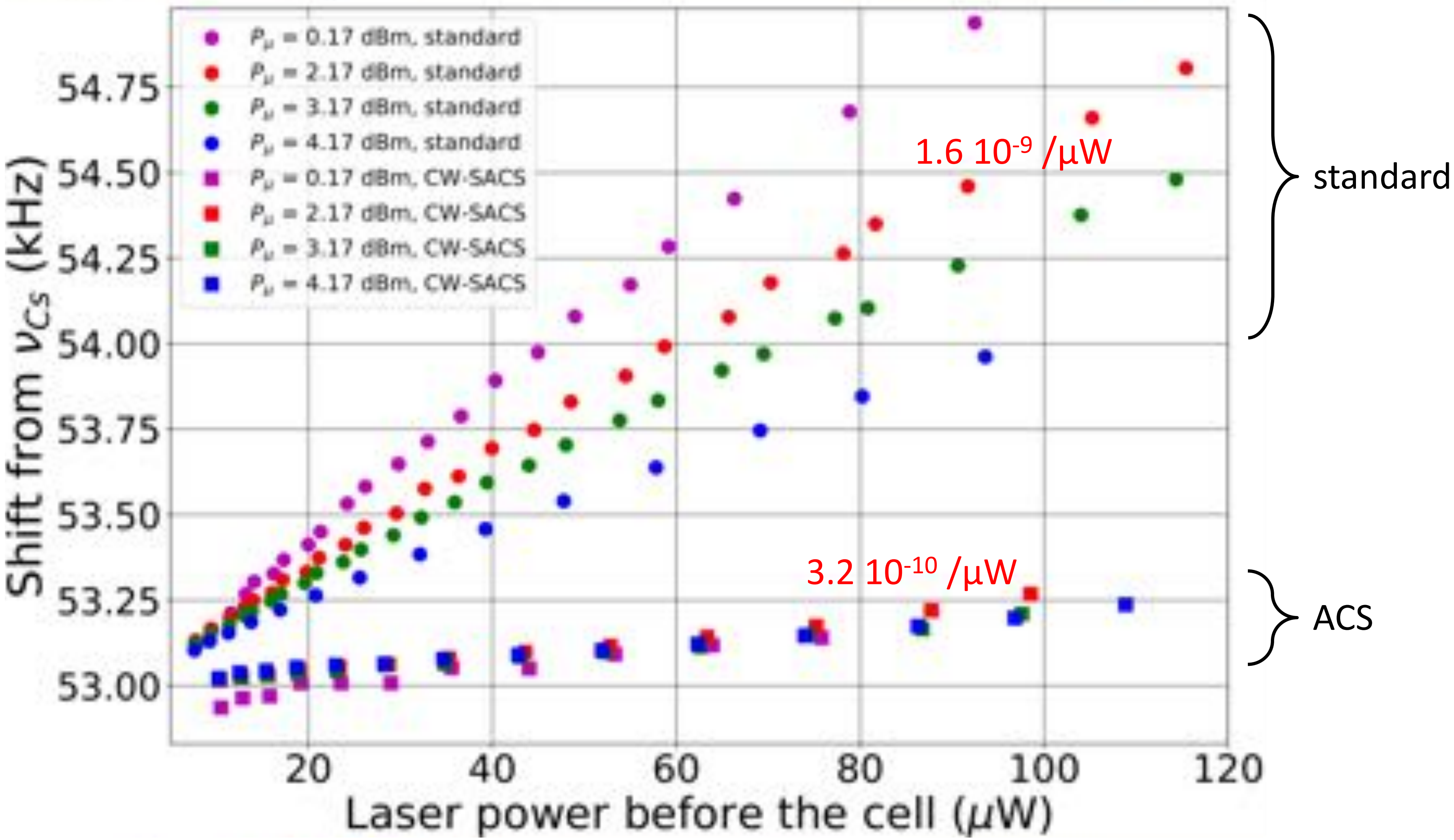
$S_0 = \eta_2\,(S_B+S_D)/D_{e_2} + \eta_1\,(S_A+S_C)/D_{e_1}$ ➔ Frequency correction (ν_0)

Memory shift of sub-sequence 1 is balanced by that of sub-sequence 2

Experimental setup



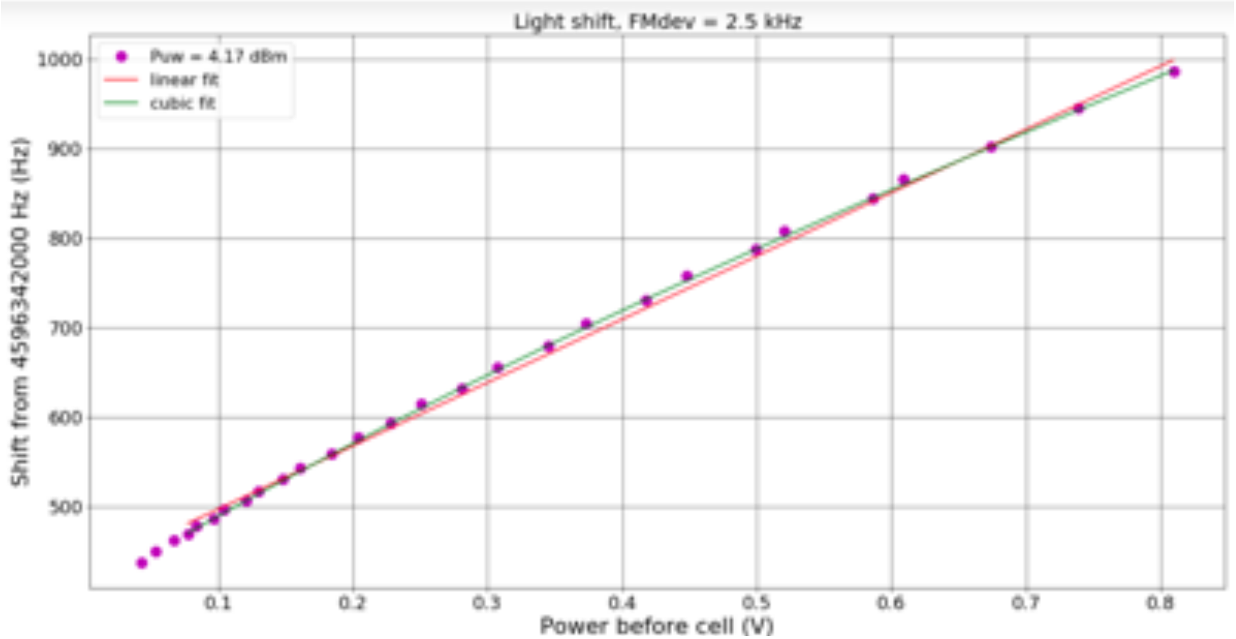
Light shift reduction

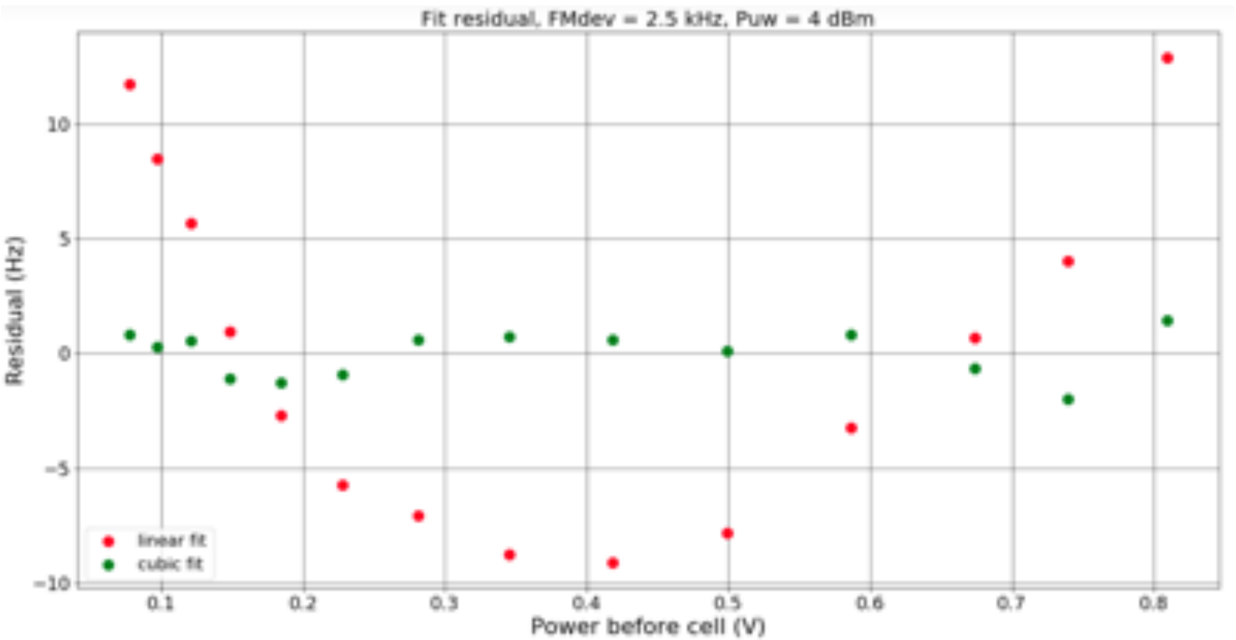


➡ **5 times reduction** in CW-ACS mode

Limited benefit because of non-linearity of the light shift

Non-linear effects





Can we account for the non-linearity with the CW-ACS method ?

We define:

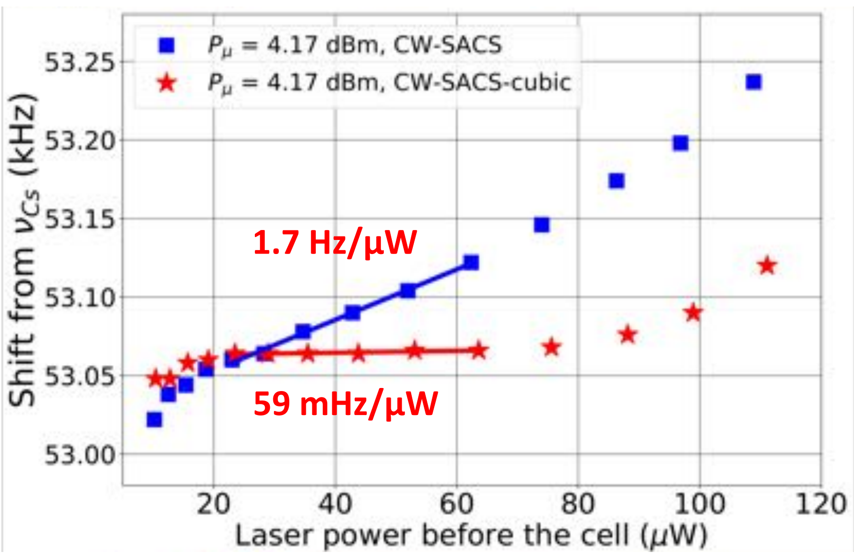
$\nu_1 = \nu_0 + \xi\, P_1 + \beta\, P_1^2 + \gamma\, P_1^3$

$\nu_2 = \nu_0 + \xi\, P_2 + \beta\, P_2^2 + \gamma\, P_2^3$

β, γ fixed by the **local** cubic fit parameters

ν_0, ξ still actively computed by the servos

$$\begin{cases} S_{LS} = \dfrac{S_{P_2}(\nu_2)}{\tan \varepsilon_2} - \dfrac{S_{P_1}(\nu_1)}{\tan \varepsilon_1} = 0 \\ S_0 = \eta_2 \dfrac{S_{P_2}(\nu_2)}{\tan \varepsilon_2} + \eta_1 \dfrac{S_{P_1}(\nu_1)}{\tan \varepsilon_1} = 0 \end{cases}$$



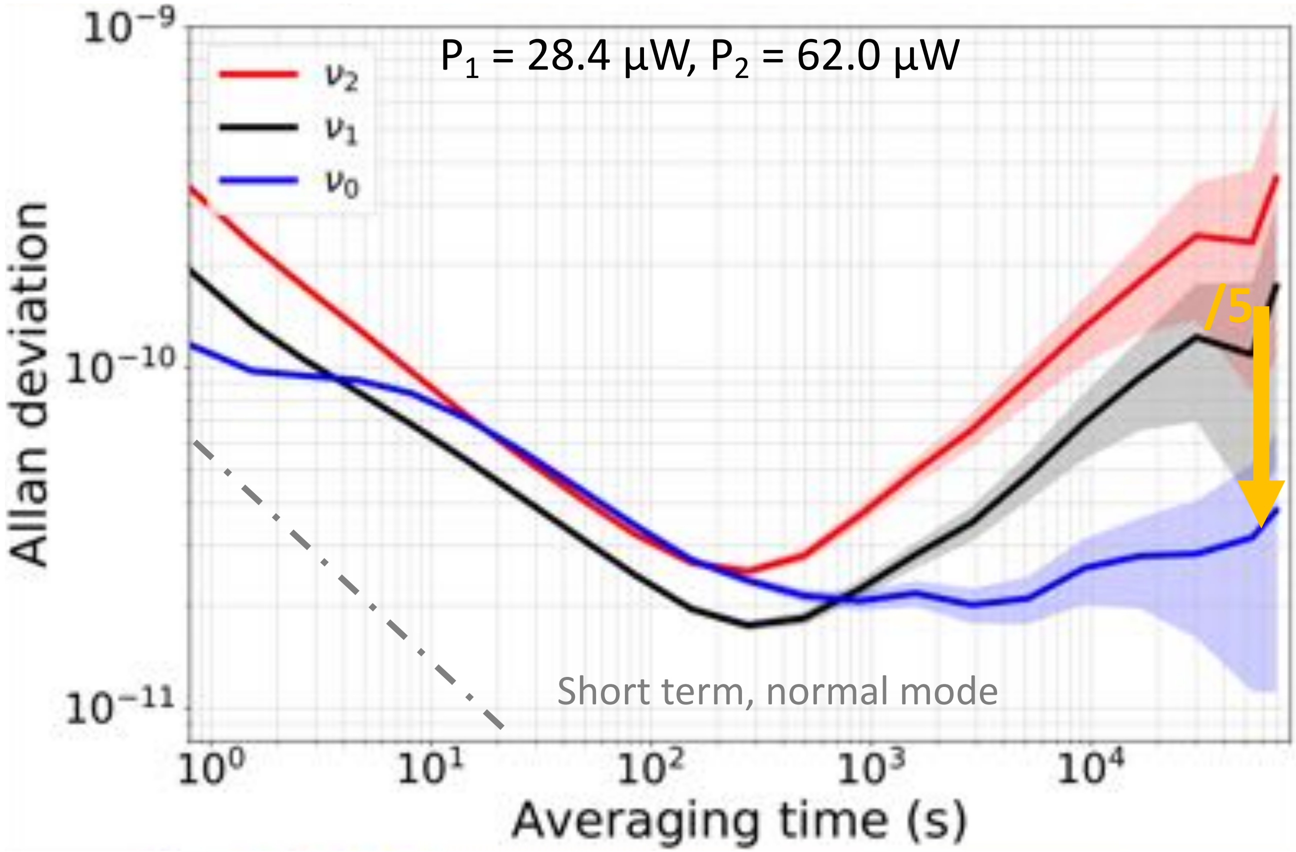
28 times further reduction vs. linear-ACS (170 times vs. standard mode)

Yes, we can! But…

- A simple polynomial law is not universal
- Accuracy is lost if the fit is local

➔ **Robustness goes with knowledge of an analytical function**

Frequency stability measurements



- $\eta_1 = \eta_2 = 0.5$ (no optimization of short-term)
- Short term 5 times worse than in standard operation
  - ❖ Affected by servo gain
- 5 times reduction of the instability @60000 s vs. @P_1 (10 times vs. P_2)
  - ❖ Improvement limited by another unknown long-term effect

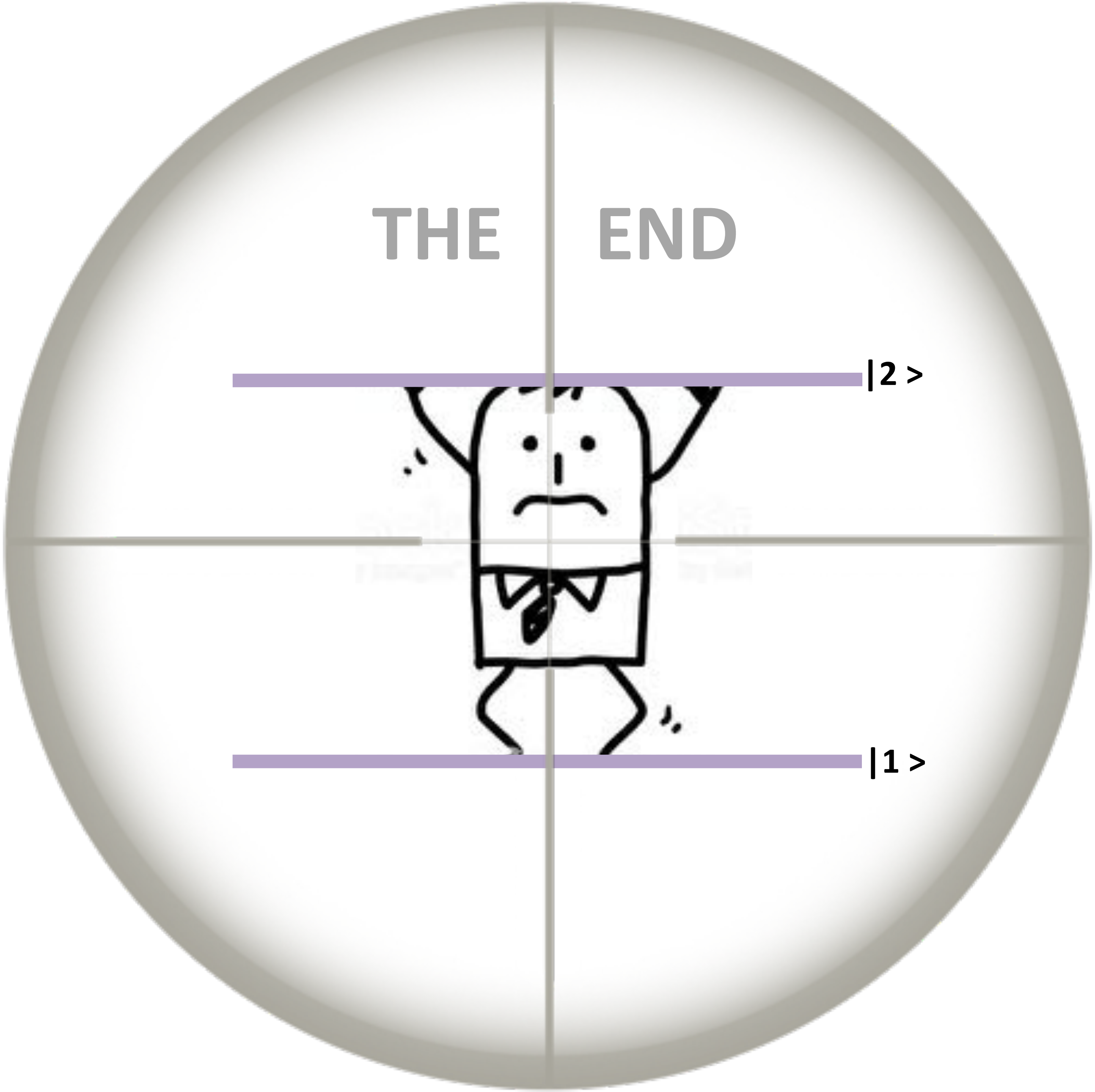
Conclusion

- ✓ Two methods were implemented on a CPT clock in order to reduce light shifts, only playing with the sequence:
  - ✓ In pulsed regime, ABR-CPT → sensitivity / 100
  - ✓ In CW regime, ACS-CPT → sensitivity / 170 with the cubic approximation

- ✓ In both cases, a significant impact was observed on the long-term instability

- ✓ No degradation of the short-term is also possible

- ✓ Symmetrization as a solution for atomic memory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