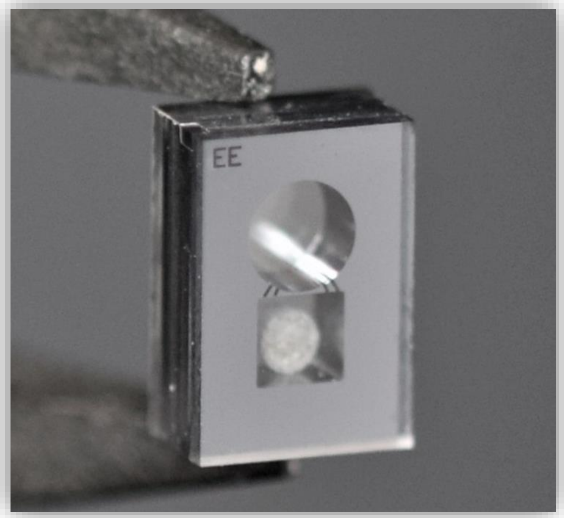
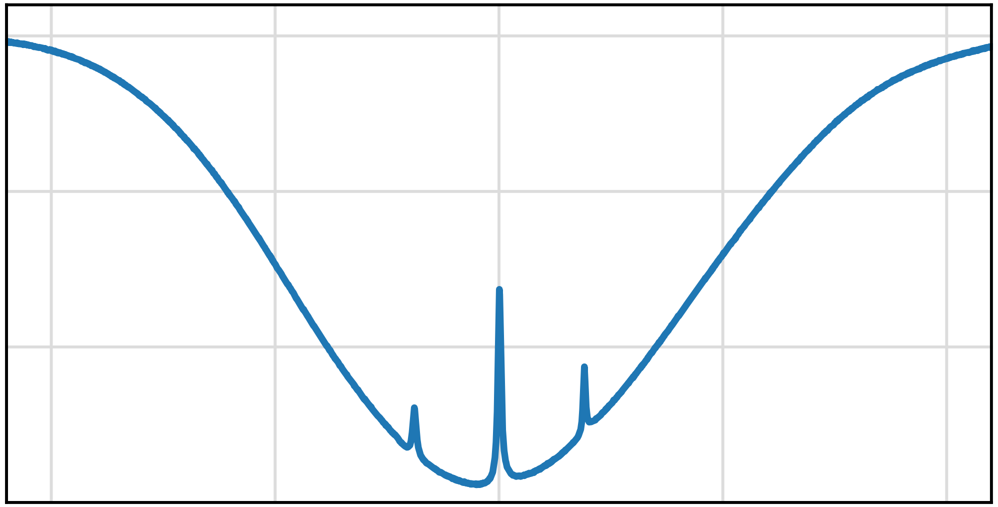
femto-st SCIENCES & TECHNOLOGIES

Microcell-based optical frequency references

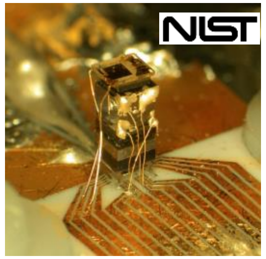




Rodolphe Boudot, Carlos Manuel Rivera-Aguilar, Emmanuel Klinger, Martin Callejo, Quentin Tanguy, Andrei Mursa, Nicolas Passilly

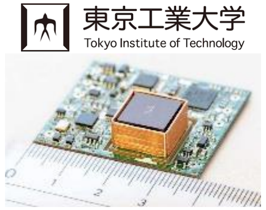
+ many thanks: J. Millo, P. Roset

Motivations & Applications



[1]

[2]



[3]

[4] Not CPT

[5]

Commercial **microwave CSACs** are compact and low-power, used in navigation, communications, instrumentation.

Typical perfs: < 120 mW, < 20 cm^3, a few 10^{-11} at 1 day

Short-term limited by the laser (VCSEL) FM noise
Long-term limited by light-shifts and buffer-gas shifts

Probing optical transitions in microfabricated cells

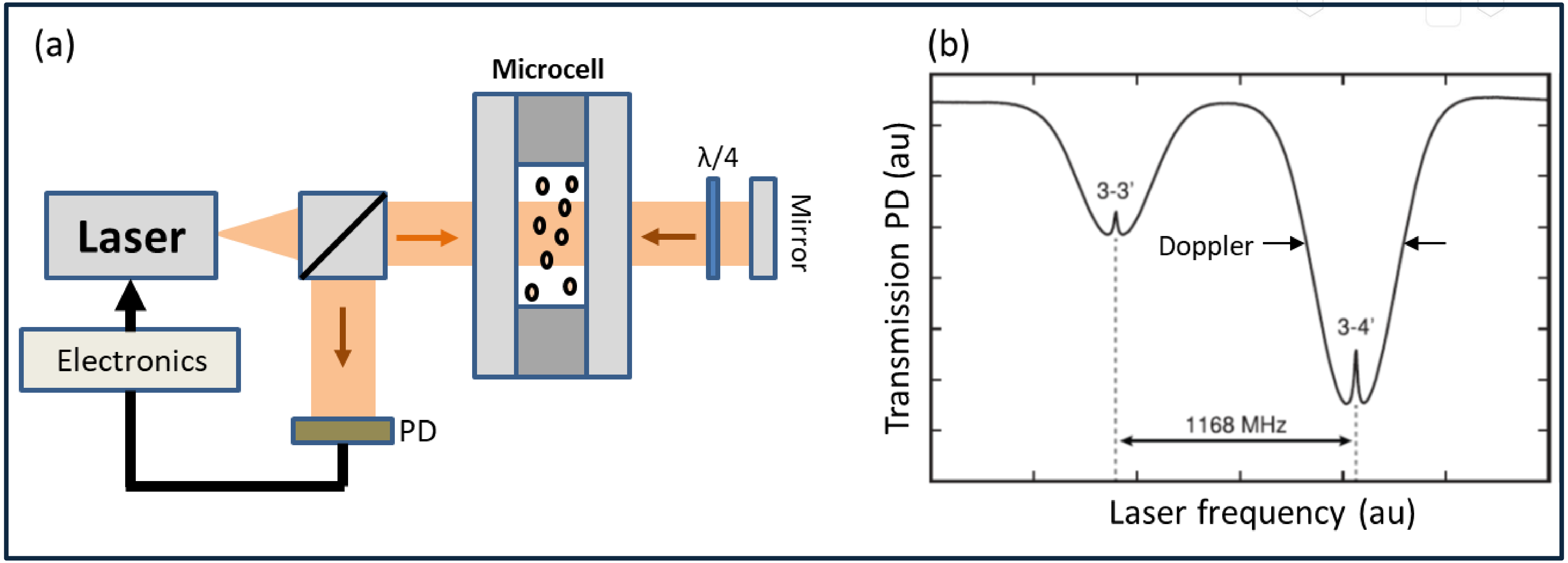
$$\boxed{\sigma_y(\tau) = \frac{\Delta\nu}{\nu_0}\frac{1}{S/N}\tau^{-1/2}}$$

Favor optical transitions over microwave: ↑ ν_0
Use narrow optical transitions (clean cell atmosphere): ↓ $\Delta\nu$
Reduce technical noise (use low-FM-noise lasers): ↑ S/N

*Note: Requires microcombs for optical to microwave conversion

[1]: S. Knappe *et al*., Appl. Phys. Lett. **85**, 9, 1460 (2004)
[2]: https://www.microchip.com/en-us/product/csac-sa65
[3]: H. Zhang *et al*., IEEE Journ. Solid State Circuits 54, 11, 3135 (2019).
[4]: https://www.safran-group.com/products-services/mro-50-ruggedized-rubidium-oscillator
[5]: https://www.syrlinks.com/en/produits/all/time-frequency/mems-micro-atomic-clock-mmac

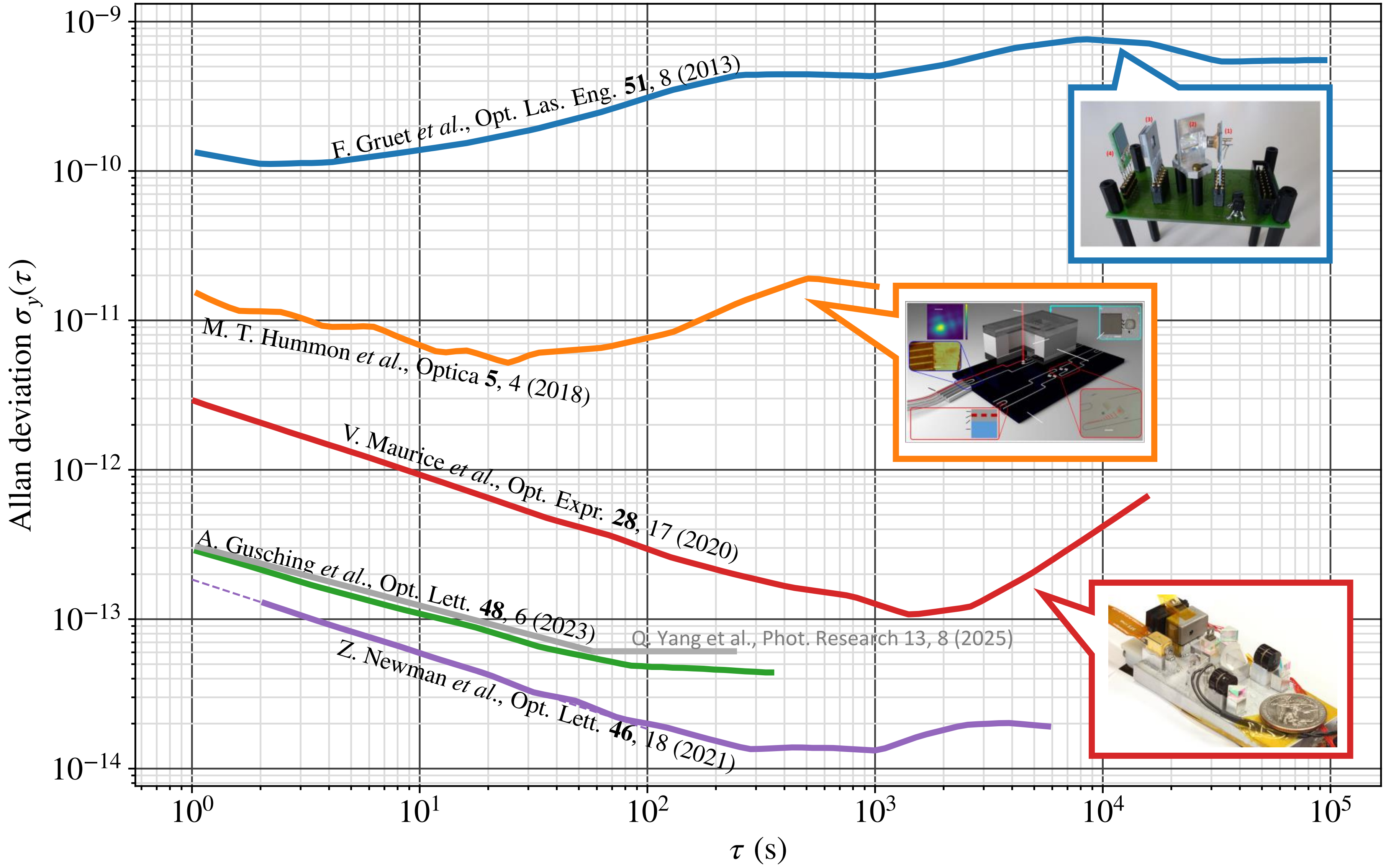
Sub-Doppler spectroscopy



Simple architecture: 1 laser + 1 vapor cell / No laser cooling, no UHV

High potential for miniaturization with MEMS cells and integrated lasers/photonics

State of the Art in Microcell Optical References



Main techniques used

Linear absorption in buffer gas microcell

Saturated absorption (SAS)

Dual-frequency Sub-Doppler spectroscopy

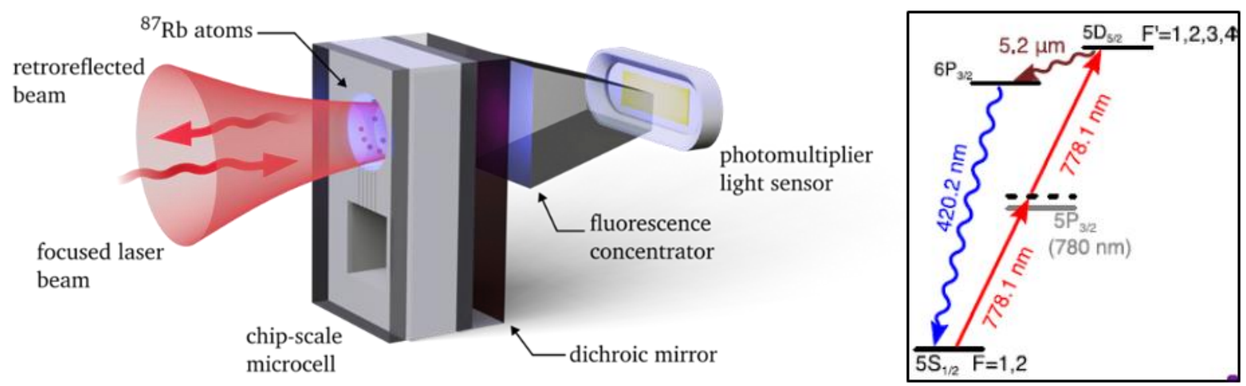
Rb Two photon spectroscopy (DBR laser 778 nm) (ECDL laser 778 nm)

Rb 780 nm + MTS

Microcell-based optical references at FEMTO-ST

Rb two-photon transition (778 nm)

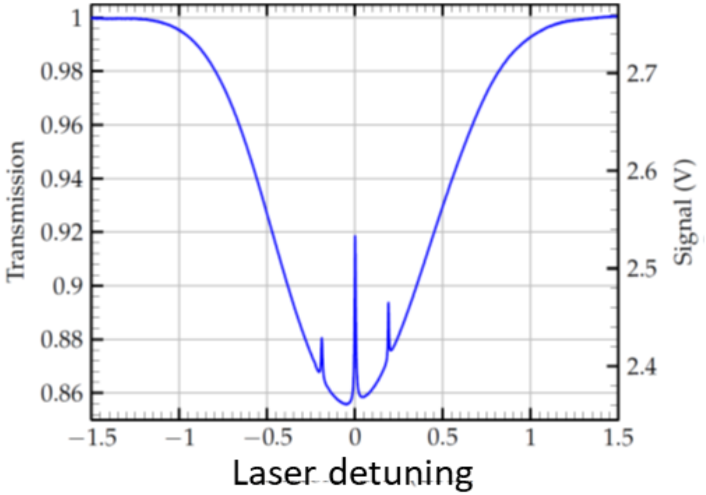
Natural linewidth : 330 kHz



M. Callejo et al., JOSAB 42, 1, 151 (2025)

Cs atom $6S_{1/2} - 7P_{1/2}$ (459 nm)

Natural linewidth : 1 MHz



E. Klinger et al., Opt. Lett. 49, 8, 1953 (2024)
E. Klinger et al., Appl. Phys. Lett. 126, 124003 (2025)

Two-photon Rb optical reference at 778 nm

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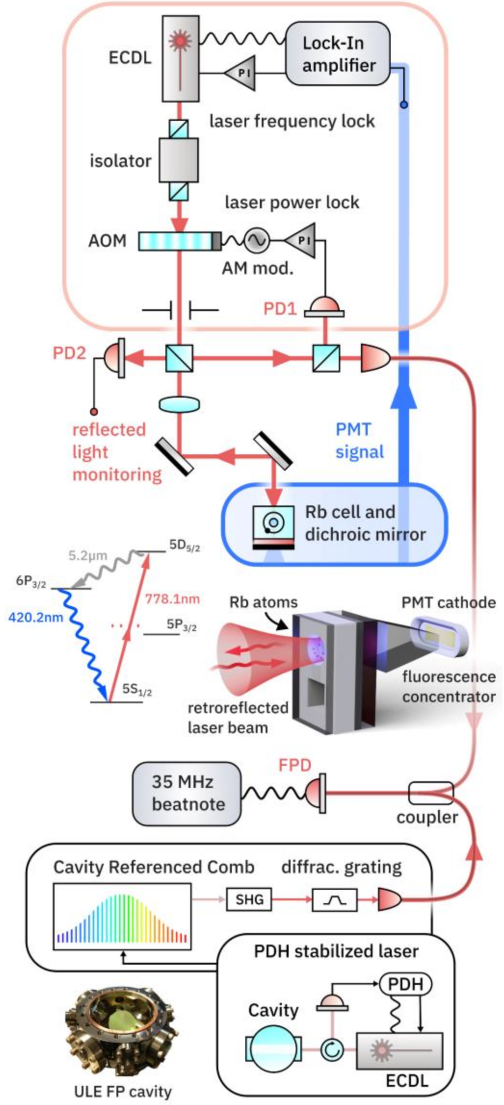
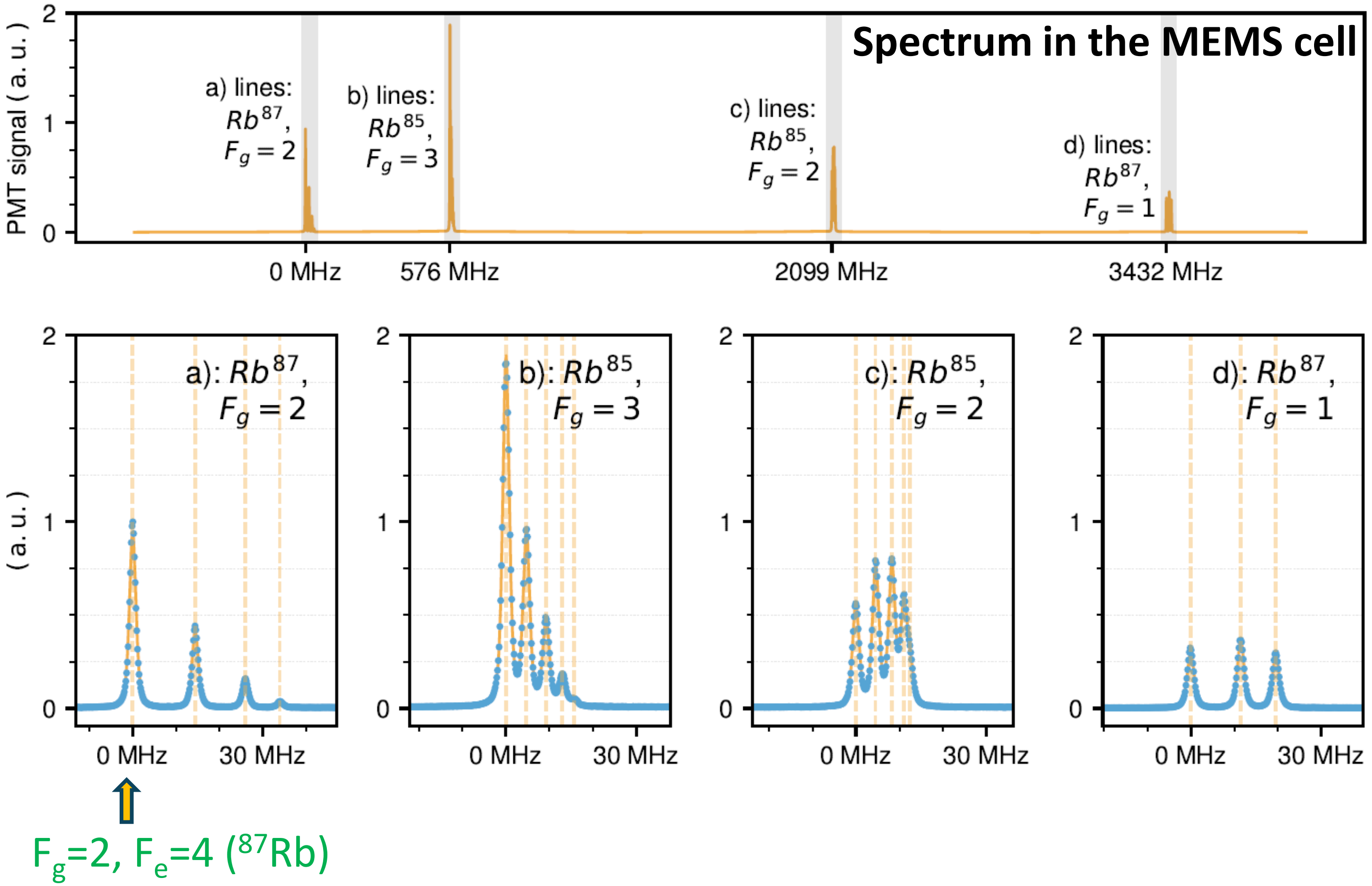


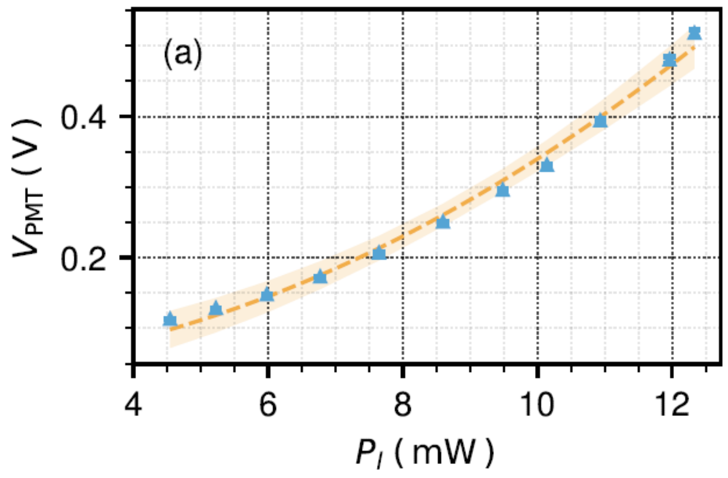


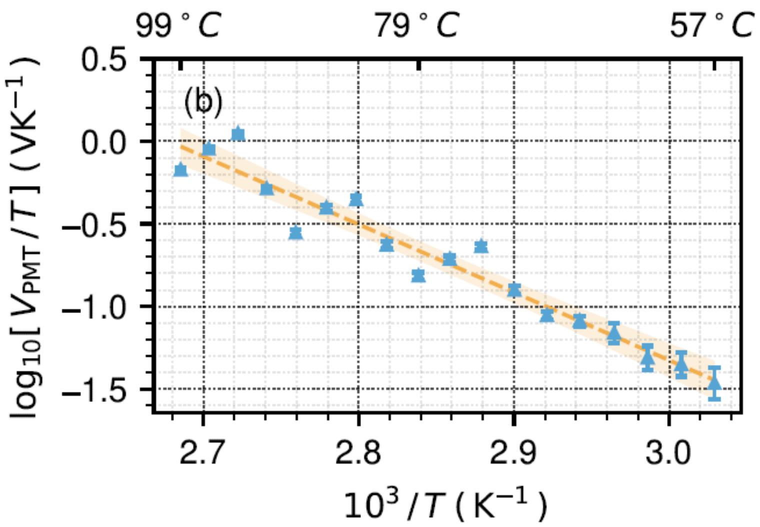
Lorentzian width (MEMS cell) ~ 900 kHz

Collisional broadening due to contaminants

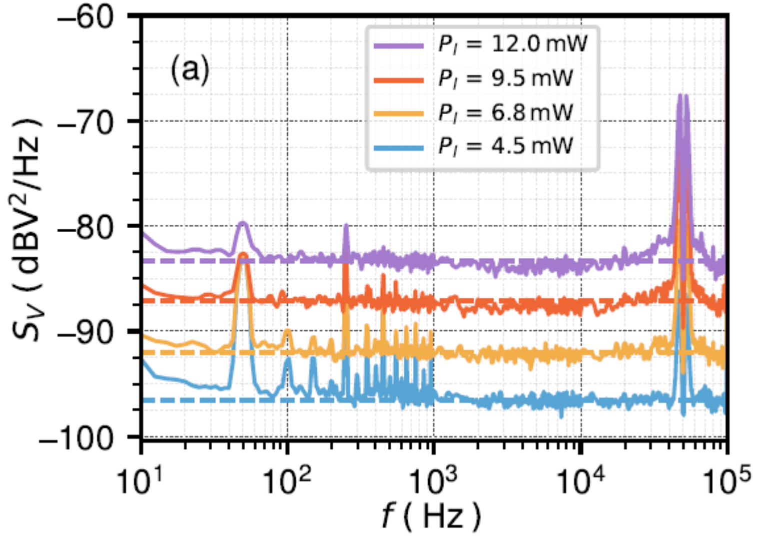
Spectroscopy and noise

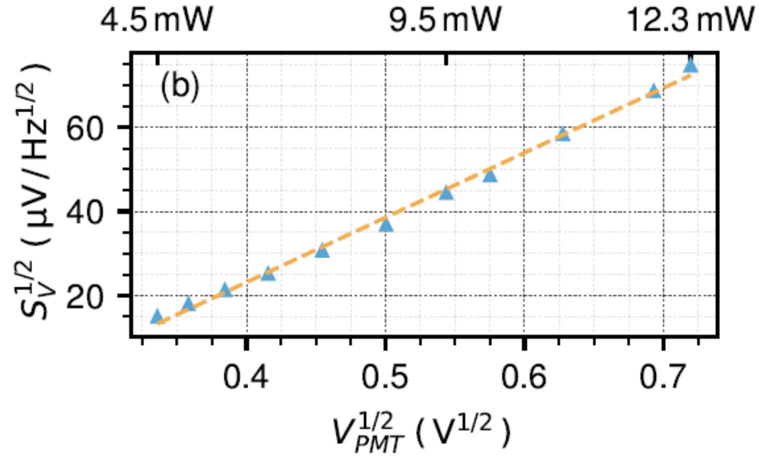
Signal





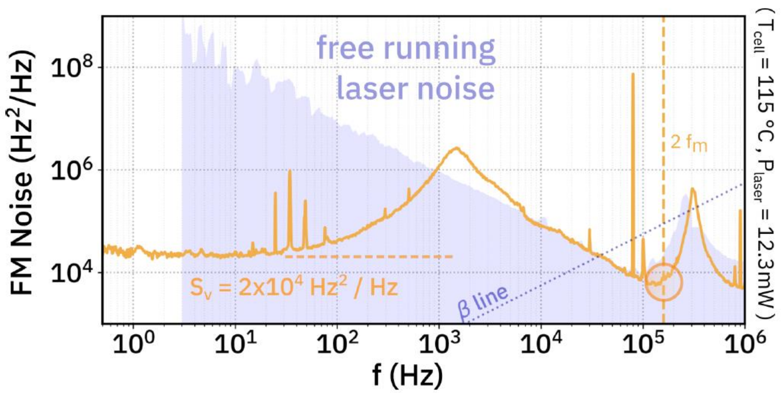
Noise





Limited by photon shot noise

Laser FM noise



Intermodulation limitation

$$\boxed{\sigma_y(\tau) \simeq \frac{1}{2}\sqrt{\frac{S_\nu(2f_m)}{\nu_0^2}}\frac{1}{\sqrt{\tau}}}$$

S_v = 6000 Hz^2/Hz @ 160 kHz

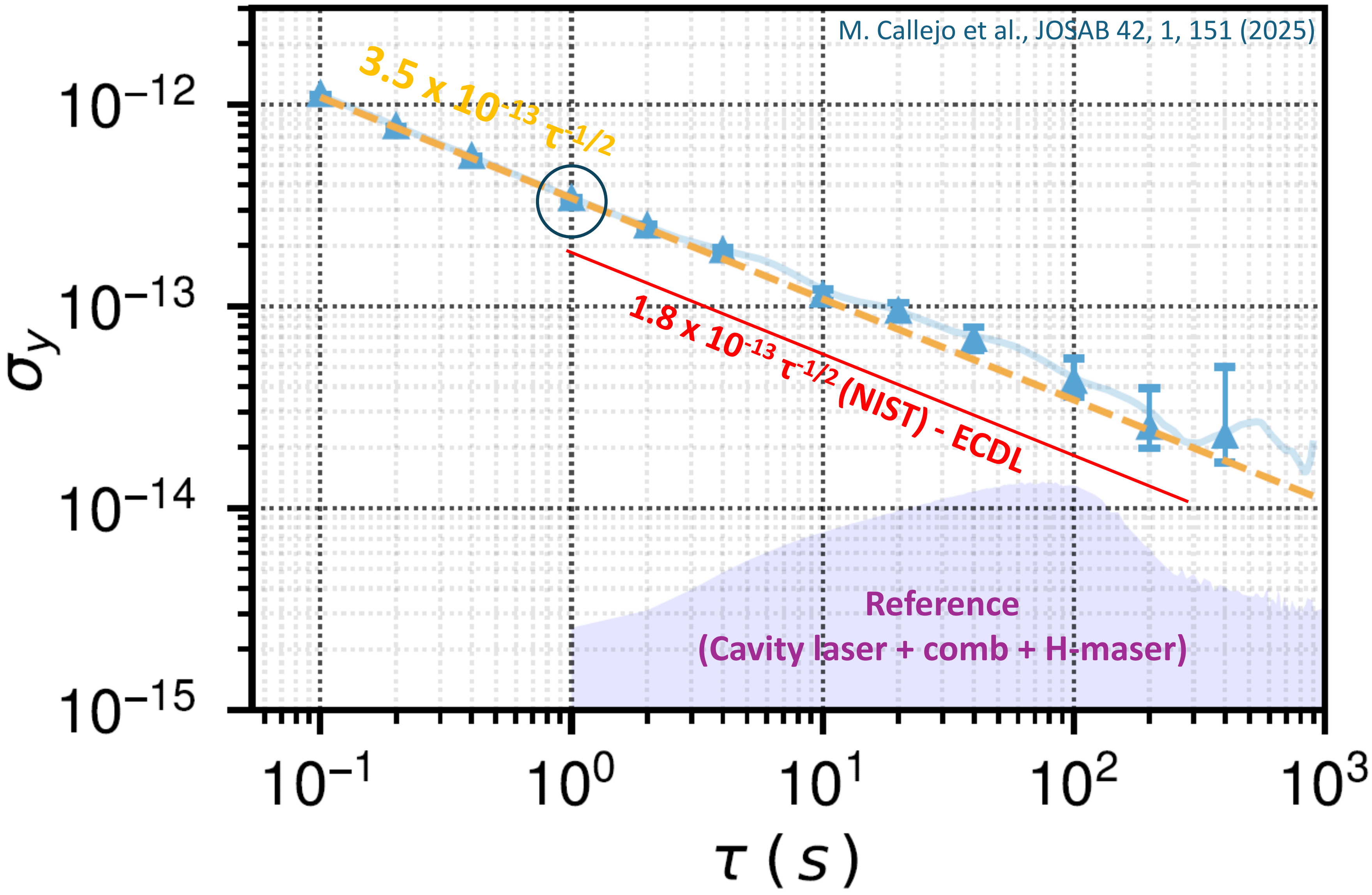
$\boxed{\sigma_{inter}\,(1s) = 1 \times 10^{-13}}$

Stability at 1 s (prediction)

S_v = 2x10^4 Hz^2/Hz @ 1 Hz

$\boxed{\sigma_y\,(1s) = 3.5 \times 10^{-13}}$

Short-term stability



Short-term limits

1/Photon shot noise

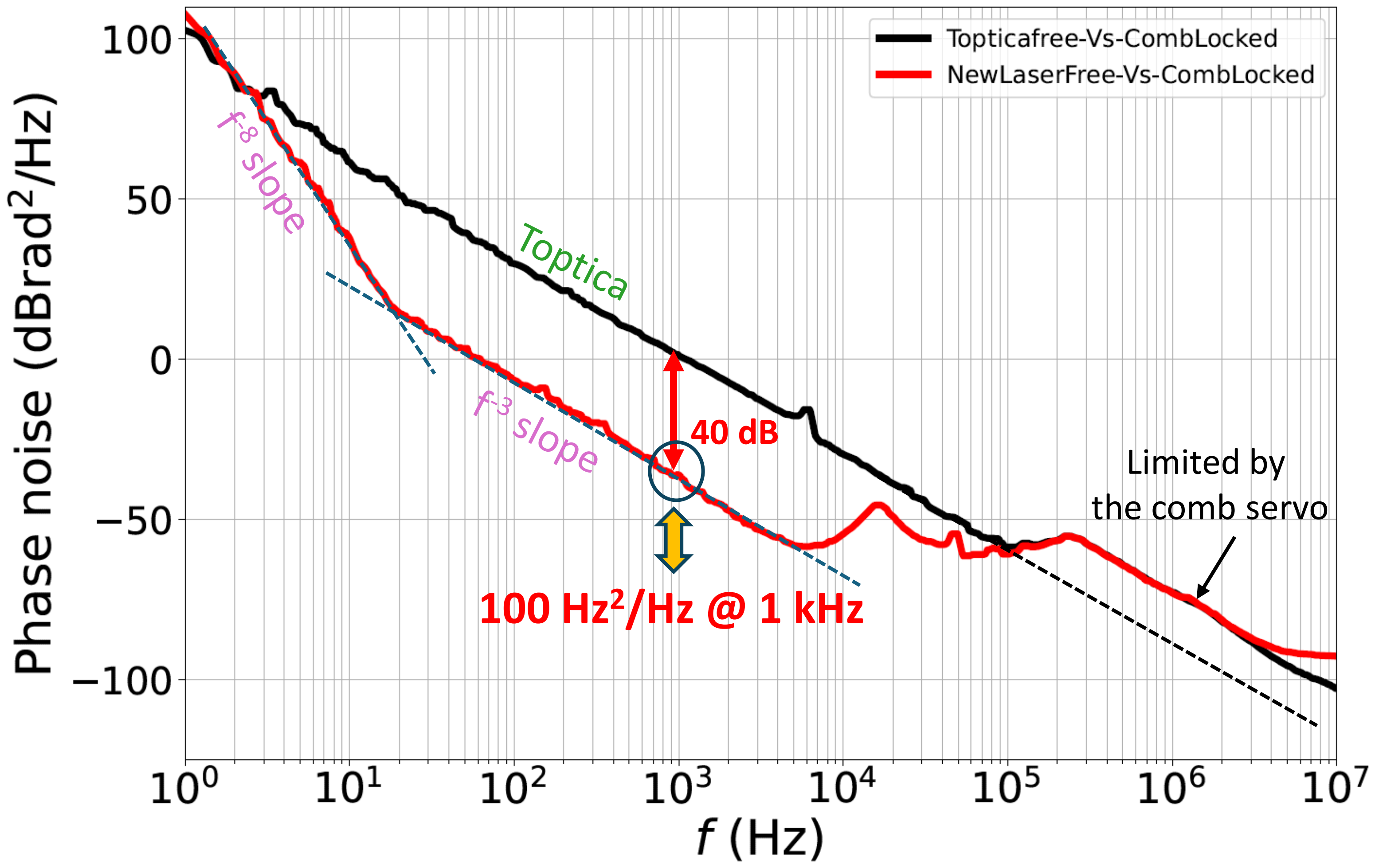
Design of a new cell architecture & physics package for enhanced atom number and photon collection

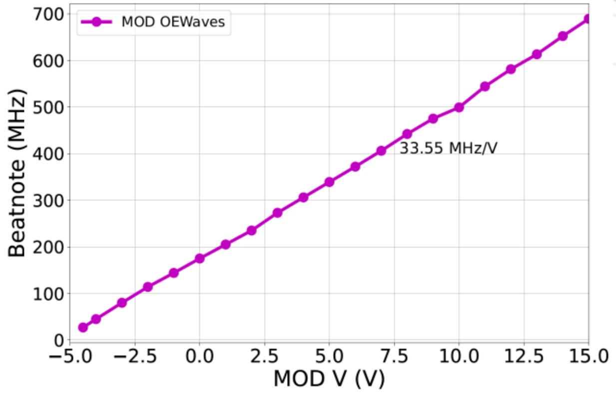
2/Laser FM noise (intermodulation)

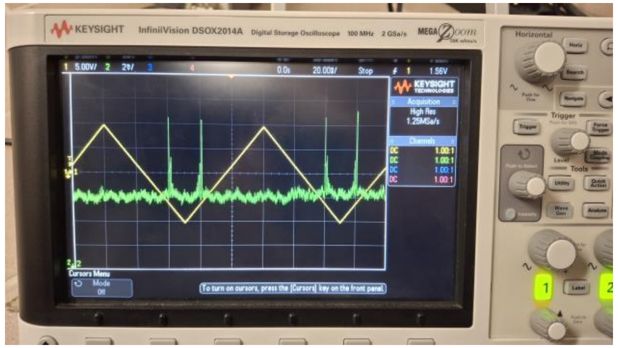
New laser with lower FM noise

A new 778 nm laser

Laser stabilized onto a WGM micro-optical resonator with integrated output optical amplifier







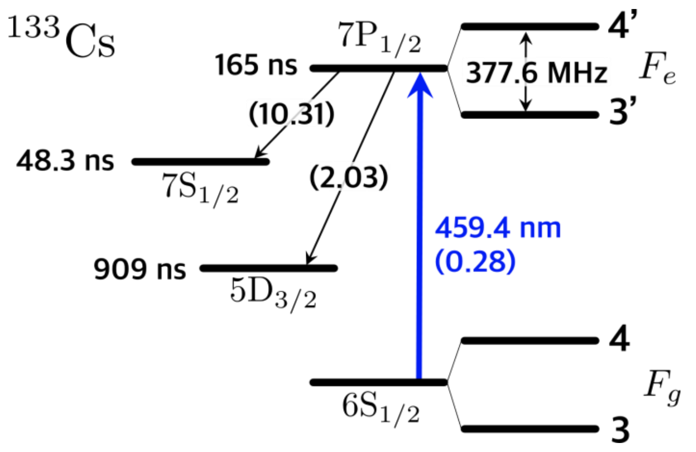
Rb lines detected
OK for tunability

Contribution of the intermodulation effect refuced by 2 orders of magnitude

Cs atom $6S_{1/2} \rightarrow 7P_{1/2}$ transition at 459 nm

Most results to date focus on near-IR transitions
(Rb: 780–778 nm, Cs: 852–895 nm)

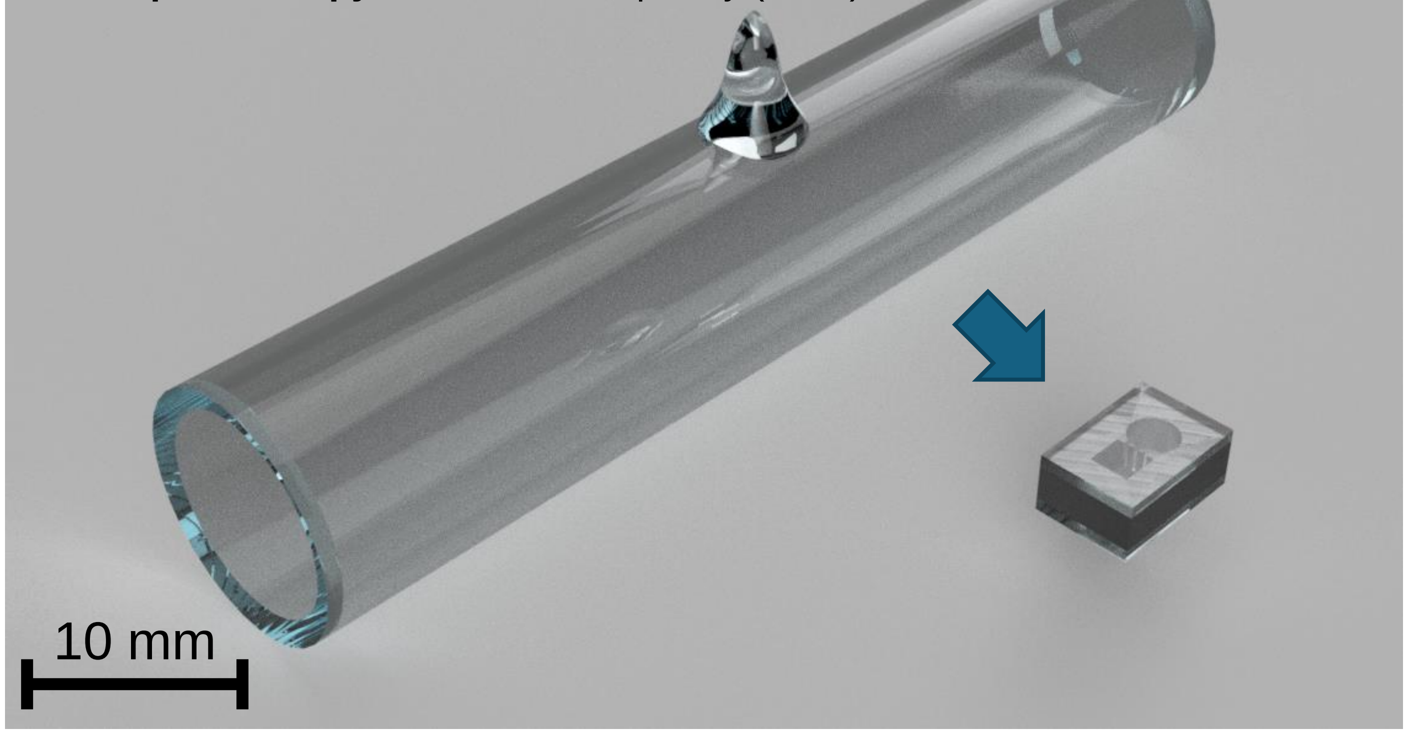
What about probing a **blue** transition?



Twice higher optical frequency (ν_0)
Narrow natural linewidth ($\Delta\nu$) ~ 1 MHz
Progress of near-UV/blue lasers/optics (S/N)

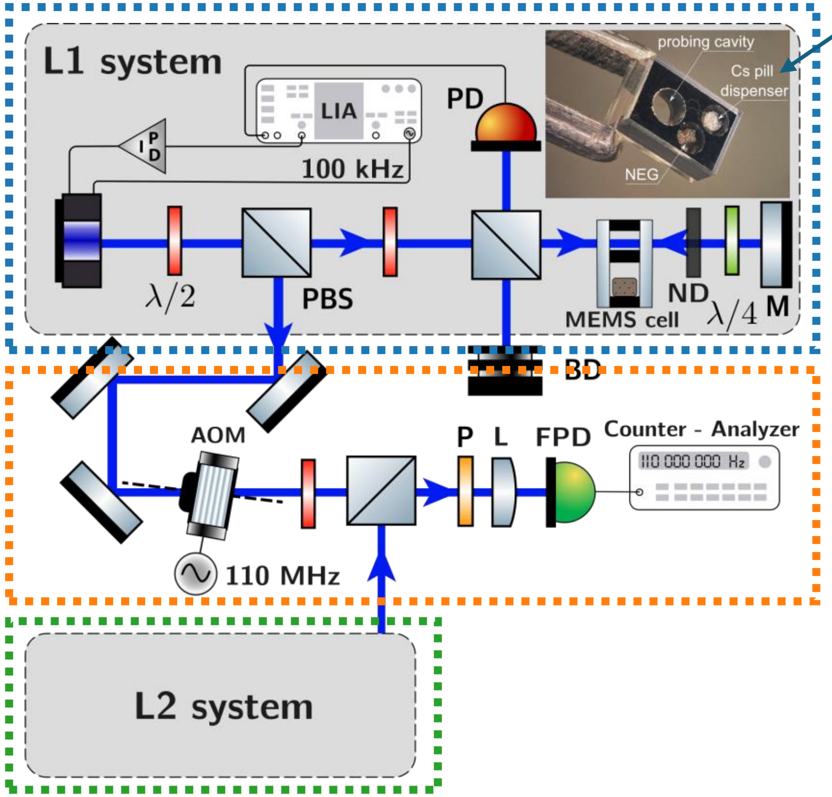
LEILA project
See also blue lasers from FOTON !!

J. Miao *et al.*, Phys. Rev. Appl. **18**, 024034 (2022)
$\sigma_y(1s) = 2.1 \times 10^{-13}$
MTS Spectroscopy: Additional complexity (EOM)

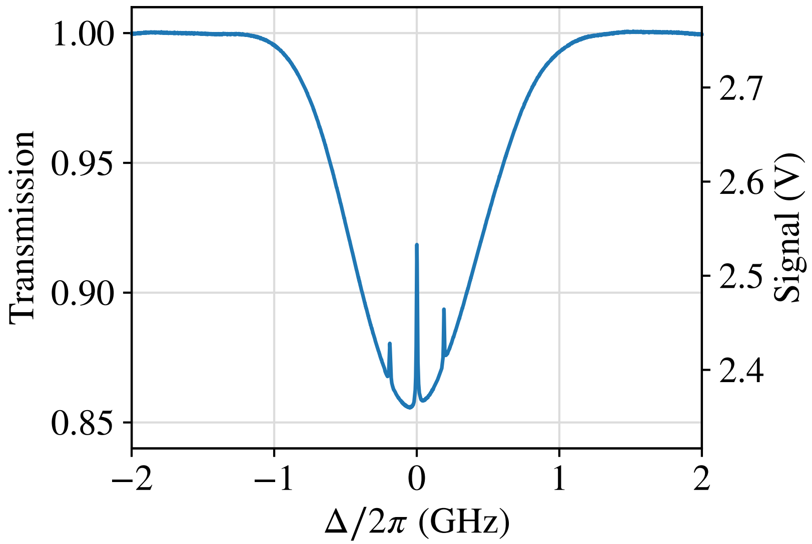


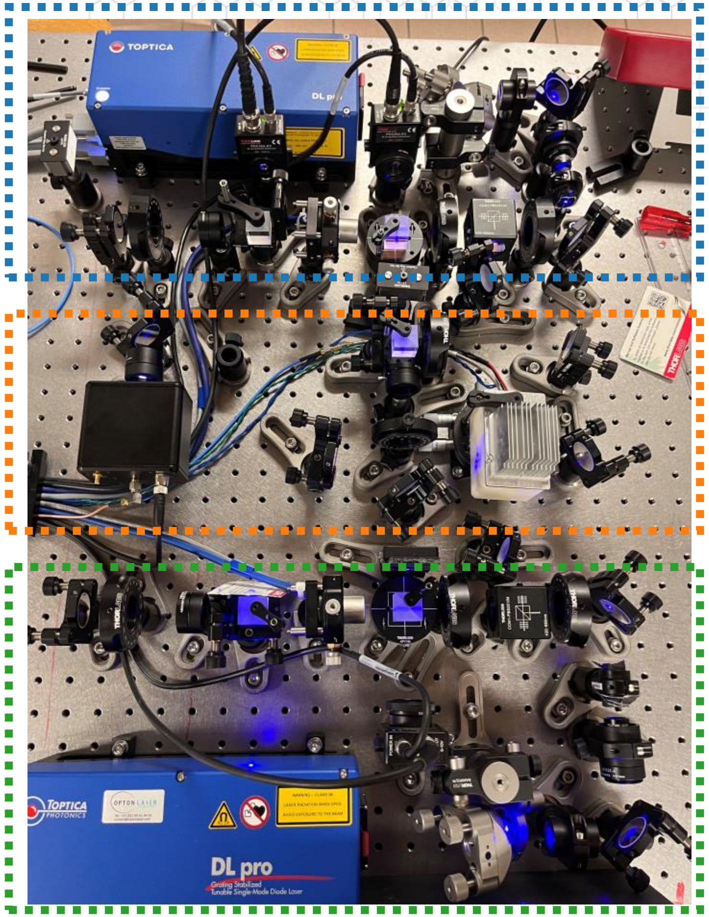
Exploring the Cs atom 459 nm transition in a MEMS cell in a simple SAS scheme

2025 First short-term stability tests



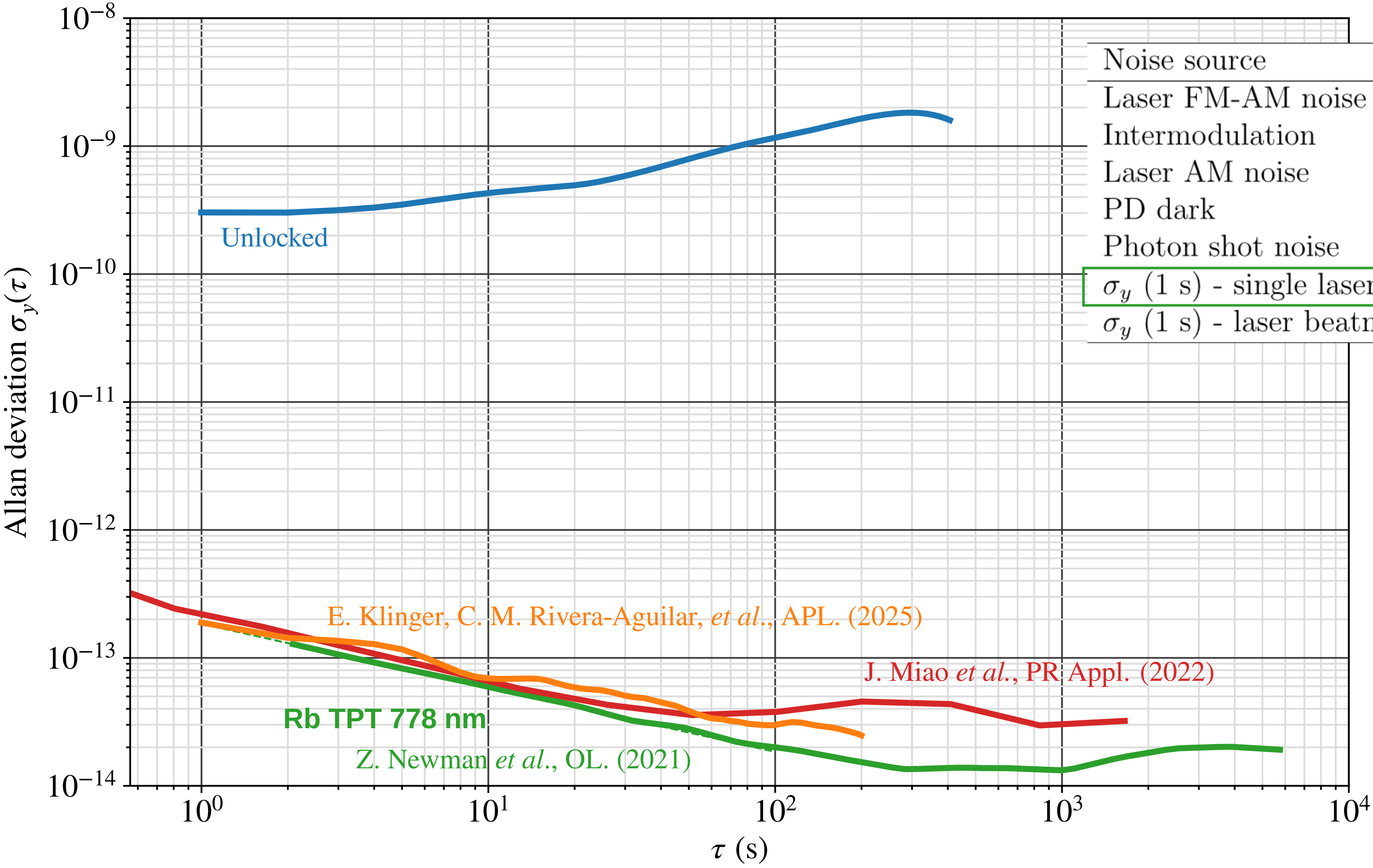
Cell with embedded NEG





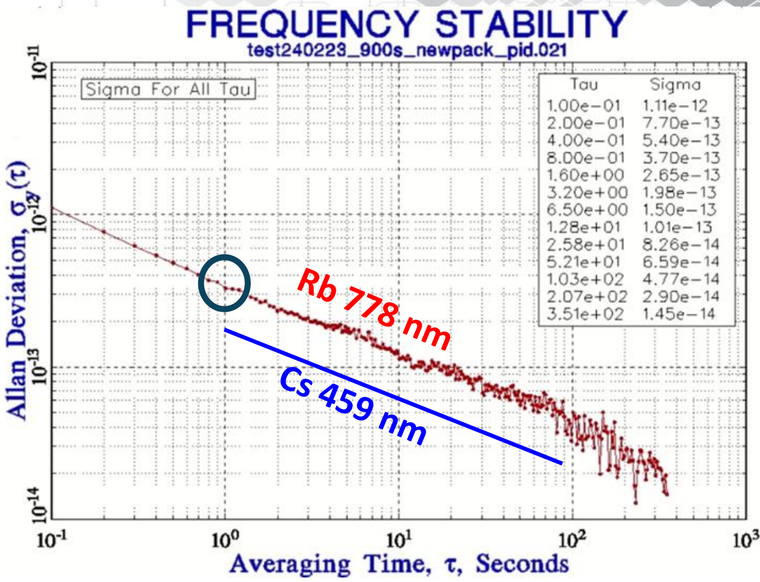
Simple SAS scheme with retroreflected beam configuration (no power stabilization, no EOM, no MTS)
Beat-note between two quasi-identical laser systems
New MEMS cell with improved atmosphere: NEG + ASG windows

Stability Results



Noise source	σ (1 s)
Laser FM-AM noise	1.2×10^{-13}
Intermodulation	7.8×10^{-14}
Laser AM noise	$< 3.8 \times 10^{-14}$
PD dark	3.8×10^{-14}
Photon shot noise	8.3×10^{-15}
σ_y (1 s) - single laser	1.6×10^{-13}
σ_y (1 s) - laser beatnote	2.3×10^{-13}

Conclusions and perspectives



Conclusions

- **Microcell-stabilized lasers** in **Cs/Rb vapor** with **stability** in the **low 10^{-13} range at 1 s**.
- Short-term stability limited by **laser FM noise** and/or **photon shot noise**
- Evacuated Cs and Rb microfabricated **cells** with **improved purity** (NEGs)
- Cell temperature operation > 120°C (for >2 years without visible degradation)

⇨ **A large margin of progress remains.**

Perspectives

- **New cell geometries** for enhanced signal, collection efficiency and purity.
- Use **low FM noise** and **integrated chip-lasers** for **low SWaP devices**
- **Improved physics packages** for better thermal/magnetic/mechanical stability.
- **Light-shift mitigation** strategies
- Frequency shifts + **Long-term stability** tests