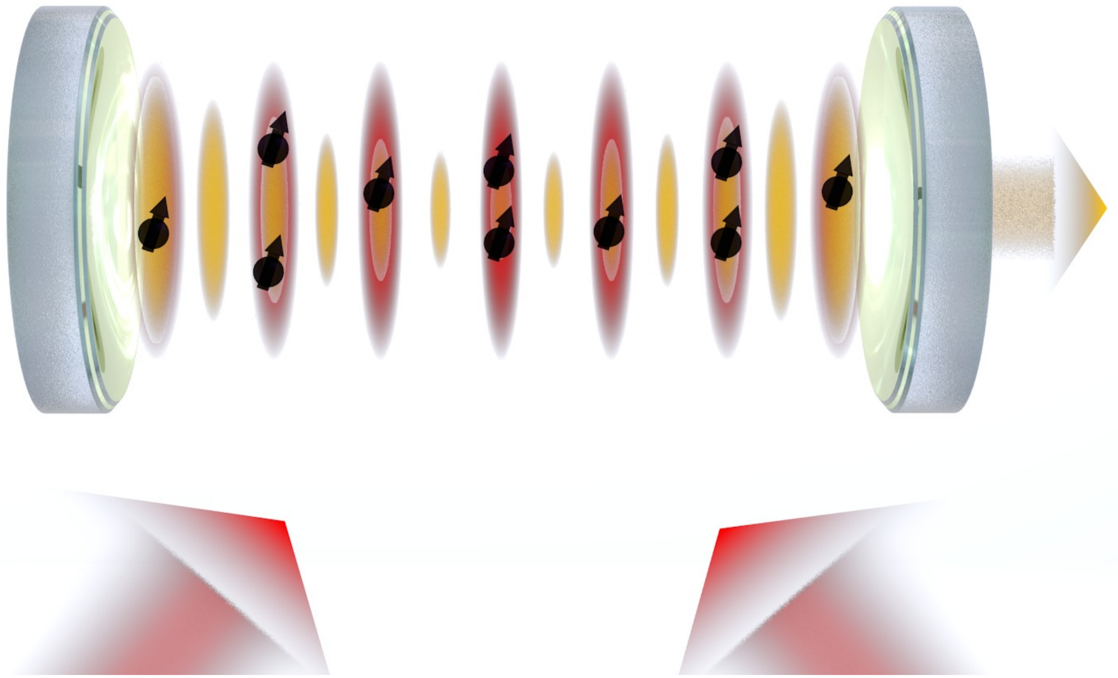
SURECO :

SUPERRADIANCE EN REGIME CONTINU

Marion Delehaye
Martin Robert de Saint Vincent



Bruno Bellomo
Martina Matusko (2020 - 2024)
Martin Hauden (2021 - 2024)
Jana El Badawi (2022 - 2025)
Francisco Sebastian Ponciano-Ojeda (2021 – 2024)
Joshua Ruelle (2024 - 2027)

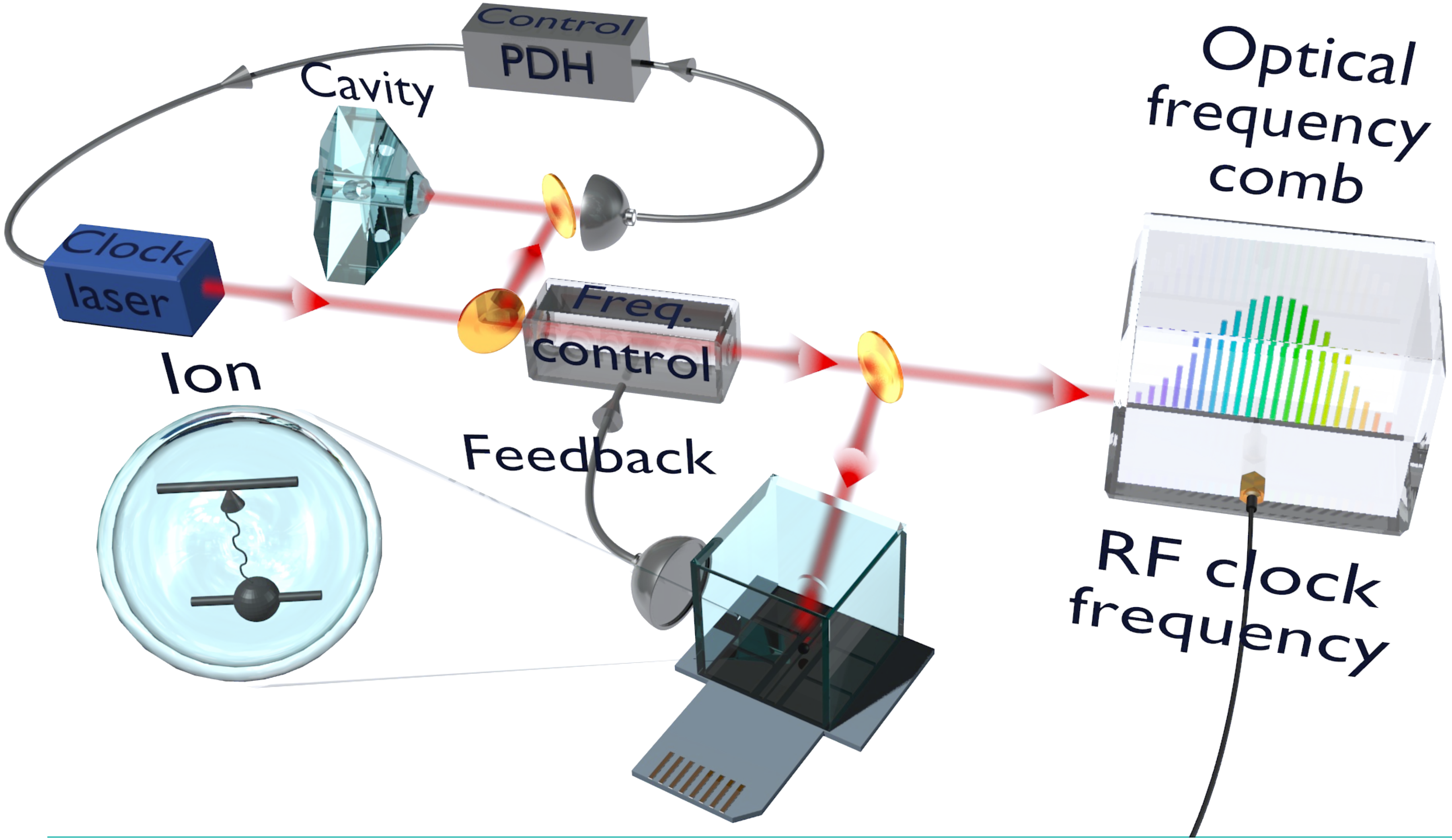
Bruno Laburthe-Tolra
Benjamin Pasquiou
Gregoire Coget (2021)
Ziyad Amodjee (2022)
Yannis Pargoire (2024 - 2027)

Oscillator IMP
cnrs
FIRST TF
anr
EIPHI-BFC GRADUATE SCHOOL CROSS DISCIPLINARY SCIENCE AND TECHNOLOGY

CONTENTS

,

Passive optical clocks



Accuracy ~ 10^{-18}
Stability ~ 10^{-16} @ 1s

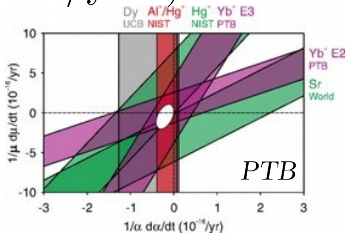
Bloom et al, Nature 506, 71 (2014)

,

Need of better frequency references

- sensitive to potential variations of fundamental constants ($\lesssim 10^{-16}$/year)

  Huntemann et al, PRL 113, 210802 (2014)



- sensitive to heights → relativistic geodesy

  Lisdat et al, Nat. Comm 7, 12443 (2016)

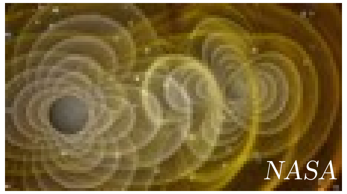
gravitational redshift : 10^{-16}/m ⇒ 10^{-18} : measurement of the geoid within a cm

→ monitor geophysical/plate subduction processes

Bondarescu et al, Geophys. J. Int. 202, 1770 (2015)
Tanaka&Katori, J. Geod. 95, 93 (2021)

- probably sensitive to dark matter ($\sim 10^{-19}$)

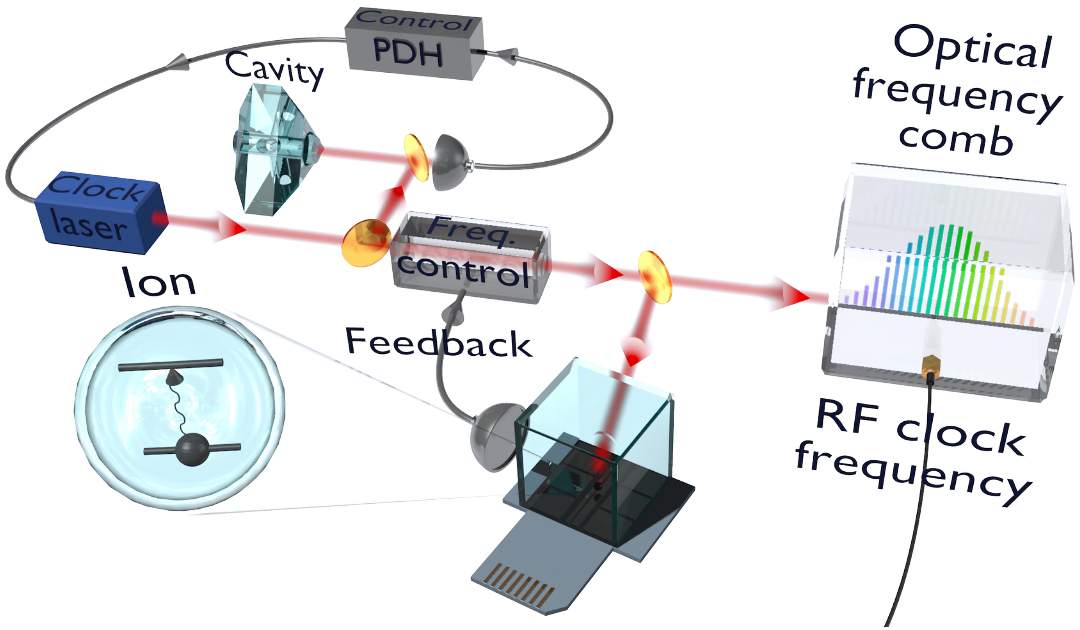
  Derevianko, J. Phys.: Conf. Ser. 723, 012043



- (soon) sensitive to gravitationnal waves ($\sim 10^{-20}\ \tau^{-1/2}$), on a different bandwidth than current detectors

  Kolkowitz et al, PRD 94, 124043 (2016)

Passive optical clocks: limitations



Quantum Projection Noise (QPN)

$$\sigma_{\mathrm{QPN}}(\tau) = \frac{0.264}{\nu_c T_p}\sqrt{\frac{T_c}{N\tau}}$$

(Rabi interrogation)

$\sigma_{\mathrm{QPN}} \sim 10^{-17}\,\tau^{-1/2}$ $(N \sim 5000)$

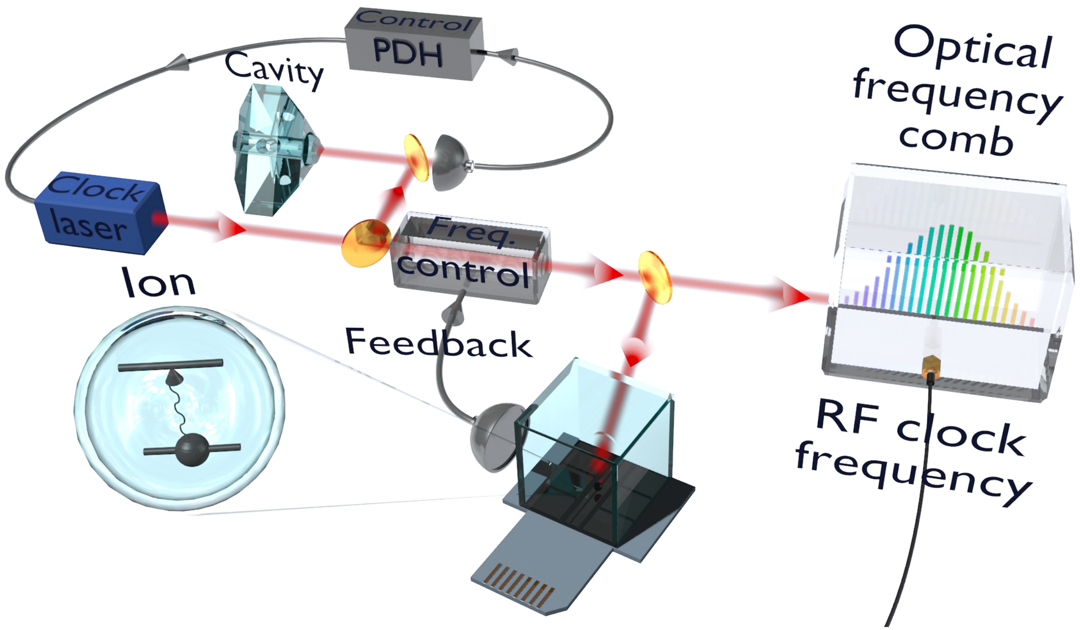
Mitigation possible by *squeezing*

Accuracy ~ 10^{-18}

Stability ~ 10^{-16} @ 1s

Bloom et al, Nature 506, 71 (2014)

Passive optical clocks: limitations



Accuracy $<10^{-18}$
Stability $\sim 10^{-16}$ @ 1s

Bloom et al, Nature 506, 71 (2014)

Quantum Projection Noise (QPN)

$$\sigma_{\rm QPN}(\tau) = \frac{0.264}{\nu_c T_p}\sqrt{\frac{T_c}{N\tau}}$$

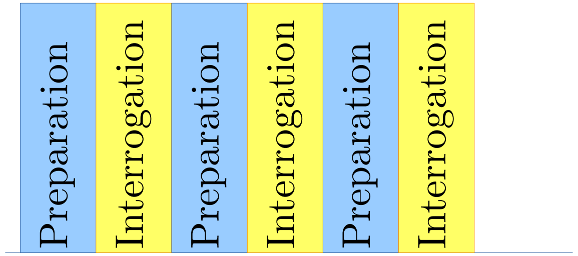
(Rabi interrogation)

$\sigma_{\rm QPN} \sim 10^{-17}\ \tau^{-1/2}$ (N ~ 5000)

Mitigation possible by *squeezing/QND*

Dick effect

Santarelli et al, IEEE Tr 45, 887 (1998)


Preparation Interrogation Preparation Interrogation Preparation Interrogation

$$\sigma^2_{\rm Dick}(\tau) = \frac{1}{\tau}\sum_{n=1}^{\infty}\left|\frac{G(n/T_c)}{G(0)}\right|^2 S_y(n/T_c)$$

$\sigma_{\rm Dick} \sim 10^{-16}\ \tau^{-1/2}$ (typ.)

Zero dead-time measurements

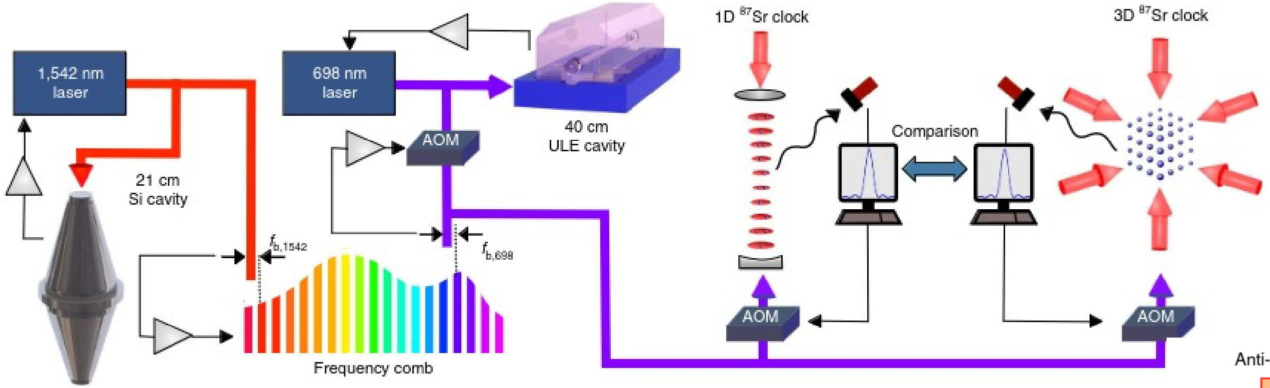
NIST (2019):

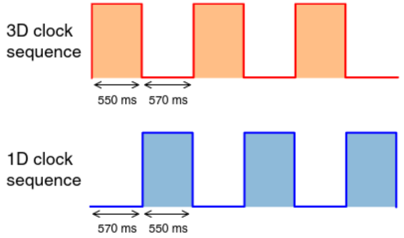

nature photonics

ARTICLES

https://doi.org/10.1038/s41566-019-0493-4

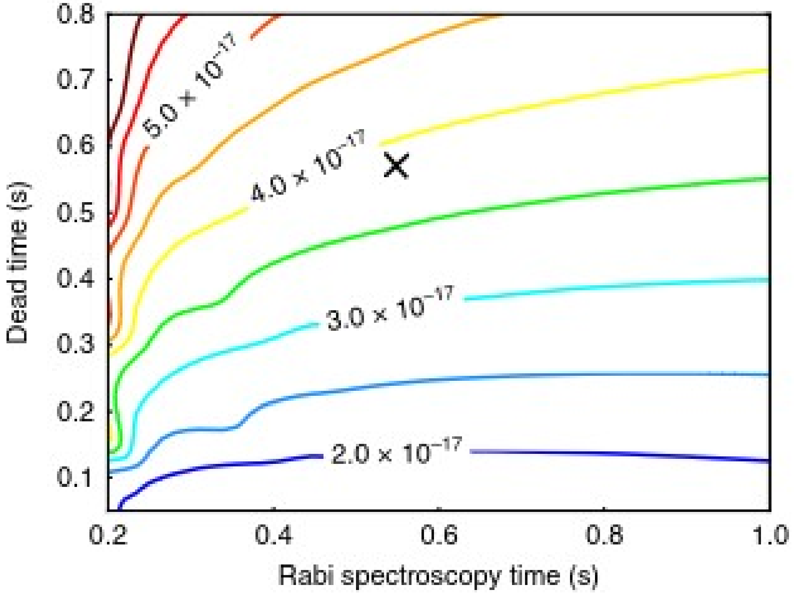
Demonstration of 4.8×10^{-17} stability at 1 s for two independent optical clocks





Oelker et al, Nat. Phot. 13, 714 (2019)

For a cavity with $\sigma_y = 6{,}5\times10^{-17}$



How to build better local oscillators ?


NIST

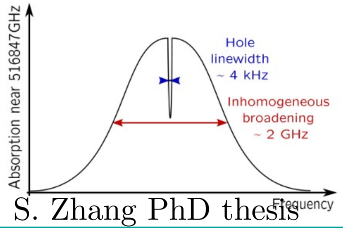
Now limited by thermal Brownian noise:
→ increase length → L = 48 cm
$\sigma_y \geq 8 \times 10^{-17}$ (Häfner et al, Optica 40, 2112 (2015))

$S_x(f) = S_x^{spacer}(f) + 2\ S_x^{substrate}(f) + 2\ S_x^{coat}(f) \quad \propto T$,
dominated by $S_x^{coat}(f)$ for silicon spacer
→ use crystalline coatings (Cole et al, Nat. Phot. 7, 644 (2013))
$S_x^{coat}(f) \rightarrow S_x^{coat}(f)\ /10$

→ reduce T → put cavities in cryostats
(4 K, 16-18 K, 124 K reported, prospects for 100 mK)
$\sigma_y \geq 3{,}5 \times 10^{-17}$ (21 cm, 124 K, crystalline coatings)

But: - no 50 cm long cavity in a cryostat...
- cryostat = hardly compatible with (future) tran

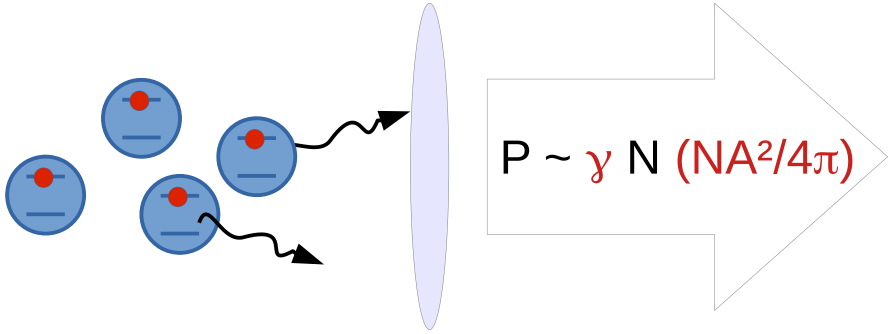
Spectral Hole Burning = promising, but still a cryostat



S. Zhang PhD thesis

Replacing the clock laser by a fluorescing source

Collect fluorescence of “static” atoms on a narrow line



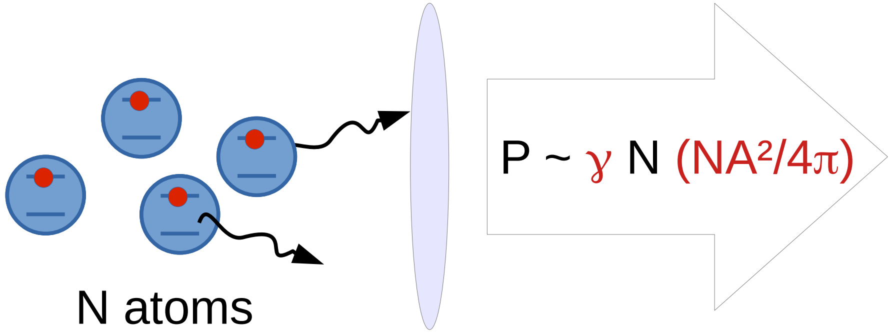
$P \sim \gamma N (NA^2/4\pi)$

light **continuously** self-referenced
to a narrow atomic transition

Collecting a useful amount of light ?

Replacing the clock laser by a fluorescing source

Collect fluorescence of “static” atoms on a narrow line

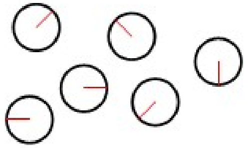


$P \sim \gamma N (NA^2/4\pi)$

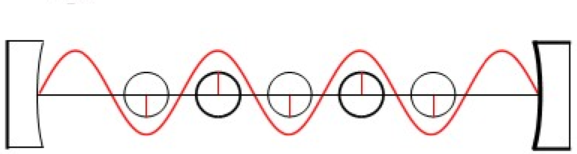
light **continuously** self-referenced
to a narrow atomic transition

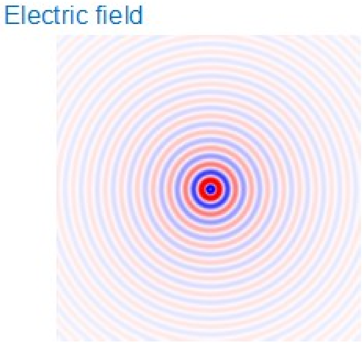
Collecting a useful amount of light ?

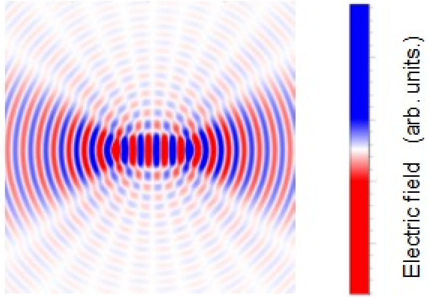
Emitting dipoles with random phases



Synchronized phases
along a well defined optical mode







<u>Superradiance</u> : a regime where the dipoles self-synchronize

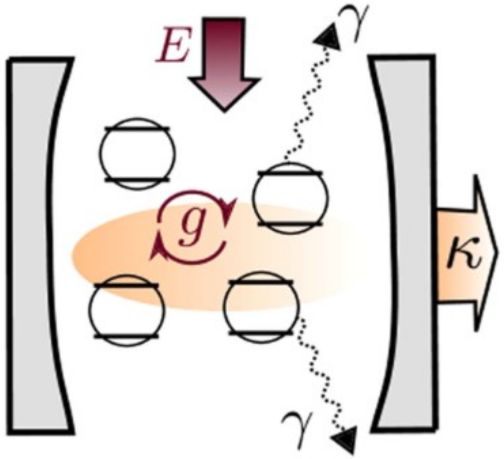
The cavity plays a lesser role than
in standard lasers
(mostly: defines the mode)

Random interference
Power ~ N

Constructive interference ($P \sim N^2$)
into a **directional** mode

The superradiant laser

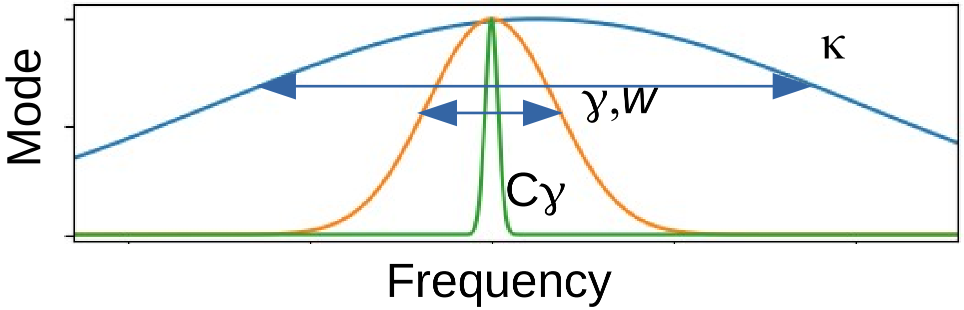
Mode defined by an
optical cavity



κ: optical mode lifetime
γ : atom linewidth
g : atom-photon coupling

Bad cavity limit:
κ >> γ and the various broadening mechanisms *w* :

→ radiation frequency robust to cavity length fluctuations



Cavity pulling resilience ~ w / κ

Weak coupling regime : $g^2/\kappa < \gamma$

(Cooperativity $C = g^2/\kappa\gamma < 1$)

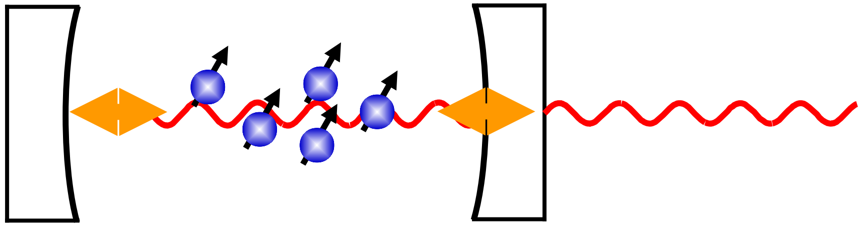
→ $g^2/\kappa = C\gamma$ = spontaneous emission rate *to the mode*
(Purcell rate)
~ linewidth of the superradiant laser

Reaching the superradiant regime

Quick photon leakage (κ > √N g)
the electric field E follows the total atomic dipole D $E(t) \sim D(t)$

→ One excited atom (dipole <d> = 0) is driven by H = - d.E towards the collective dipole D of the other atoms
→ will then emit in phase with the others

For N g²/κ >> γ, w ,
(NC > 1),
a macroscopic atomic dipole
becomes stationary



Much less photons than atoms in the cavity

Coherence in the collective atomic dipole

Linewidth can be down to the Purcell rate $\frac{4g^2}{\kappa} \ll \kappa / N_{photons}$

Foundational proposals:
Meiser, Holland, PRL 102, 163601 (2009): *Prospects for a Millihertz-Linewidth Laser*
JB Chen 2009, Chinese Science Bulletin 54, 348 (2009) : *Active optical clock*

LETTER

A steady-state superradiant laser with less than one intracavity photon

Justin G. Bohnet[1], Zilong Chen[1], Joshua M. Weiner[1], Dominic Meiser[1]†, Murray J. Holland[1] & James K. Thompson[1]

PHYSICAL REVIEW LETTERS

Subnatural Linewidth Superradiant Lasing with Cold ^{88}Sr Atoms

Sofus Laguna Kristensen, Eliot Bohr, Julian Robinson-Tait, Tanya Zelevinsky, Jan W. Thomsen, and Jörg Helge Müller

Phys. Rev. Lett. **130**, 223402 – Published 31 May 2023

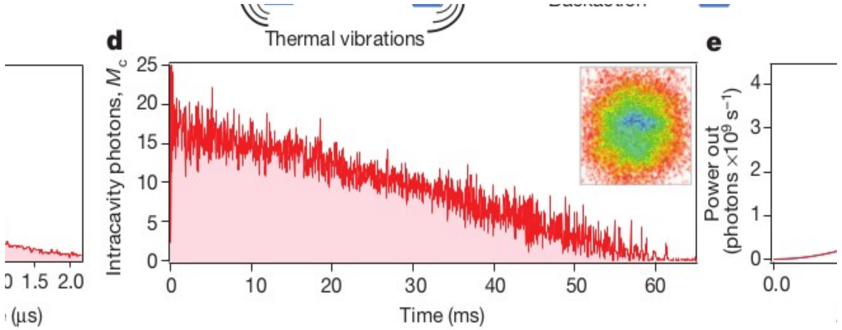
PHYSICAL REVIEW X

Frequency Measurements of Superradiance from the Strontium Clock Transition

Matthew A. Norcia, Julia R. K. Cline, Juan A. Muniz, John M. Robinson, Ross B. Hutson, Akihisa Goban, G. Edward Marti, Jun Ye, and James K. Thompson

Phys. Rev. X **8**, 021036 – Published 9 May 2018

But : always a finite-duration pulse



Other achievements e.g. in the Tomsen, Hemmerich, and Schreck groups

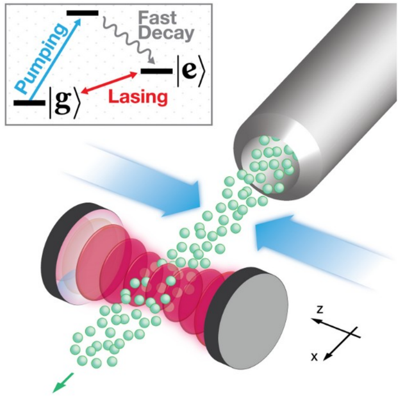
Current challenge: true continuous operation

Quasi-steady state: can be achieved by repumping (JILA) or by seeding atoms from a metastable state (Copenhagen)

BUT: finite lifetime of the atoms

→ how to bring in new atoms?

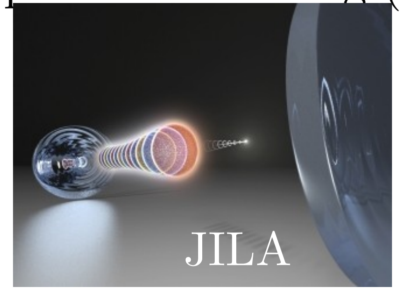
(Thermal) Beam operation



Chen, Chin. Sci. Bull. 54, 348 (2009)
Liu et al., PRL 125, 253602 (2020)

$$N_{\mathrm{th}} = 2/(C\,\gamma\,T_2)$$

Reloading of (cold) atoms
- ring cavity system (JILA)
- cold atomic beam (Amsterdam?)
- refill from MOT (Hamburg)
- sequential reloading (FEMTO-ST)



Current challenge: true continuous operation

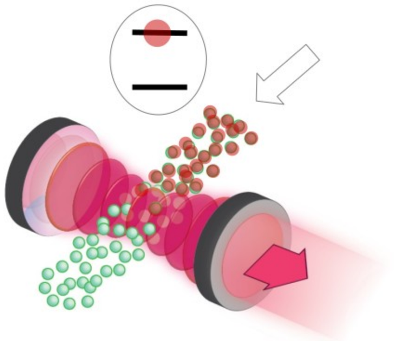
Quasi-steady state: can be achieved by repumping (JILA) or by seeding atoms from a metastable state (Copenhagen)

BUT: finite lifetime of the atoms

→ how to bring in new atoms?

(Thermal) Beam operation

Reloading of (cold) atoms

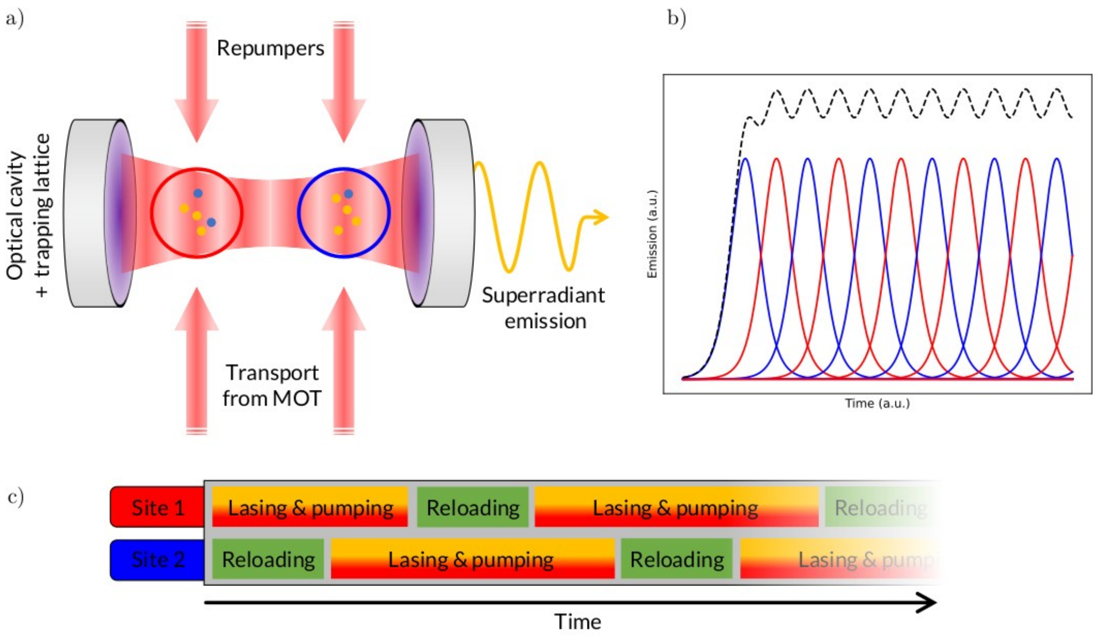


Insertion rate: Γ

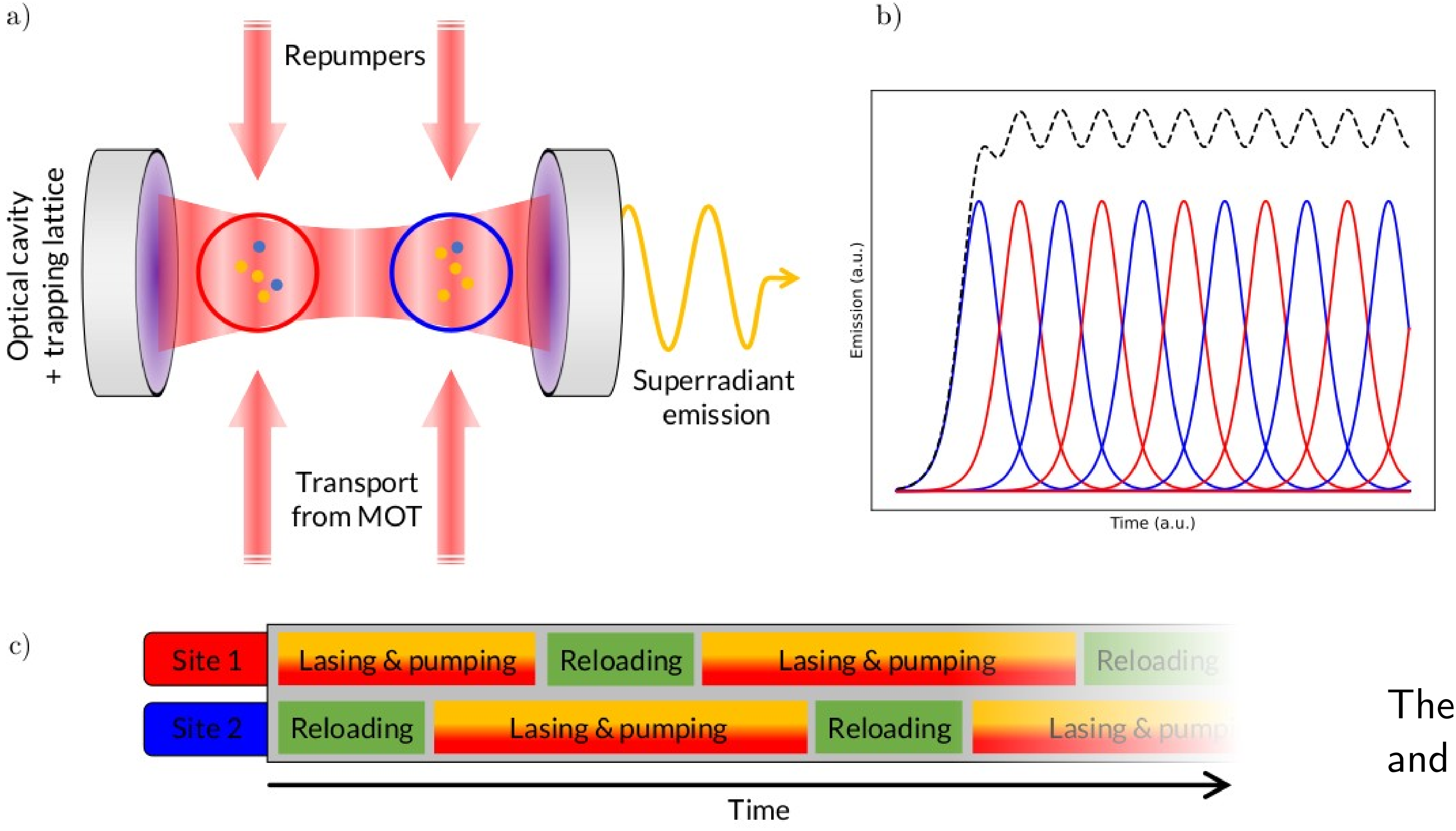
Transit rate: $\Gamma_R = \Gamma/N$

LPL

FEMTO-ST



FEMTO-ST Apparatus: cold ytterbium atoms with repumping and sequential reloading



Theory by Jana El Badawi and Bruno Bellomo

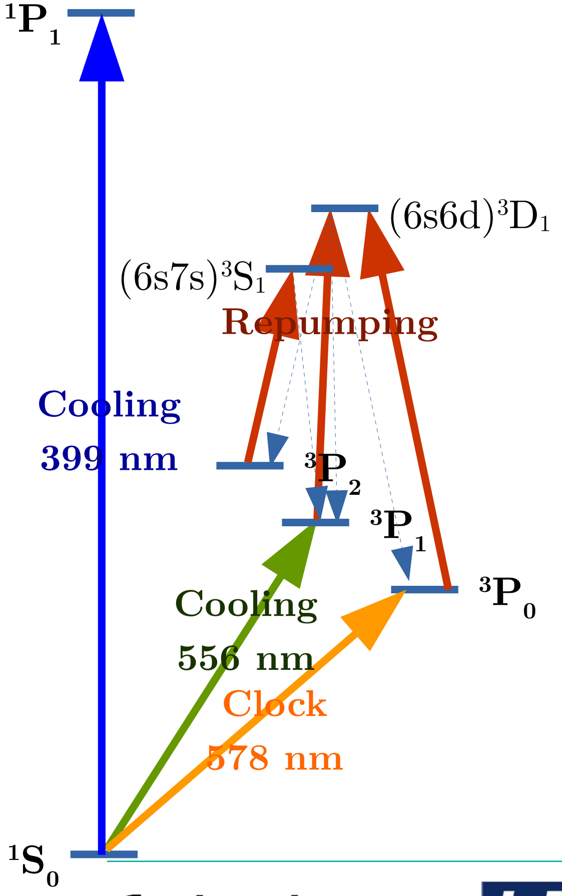
FEMTO-ST apparatus

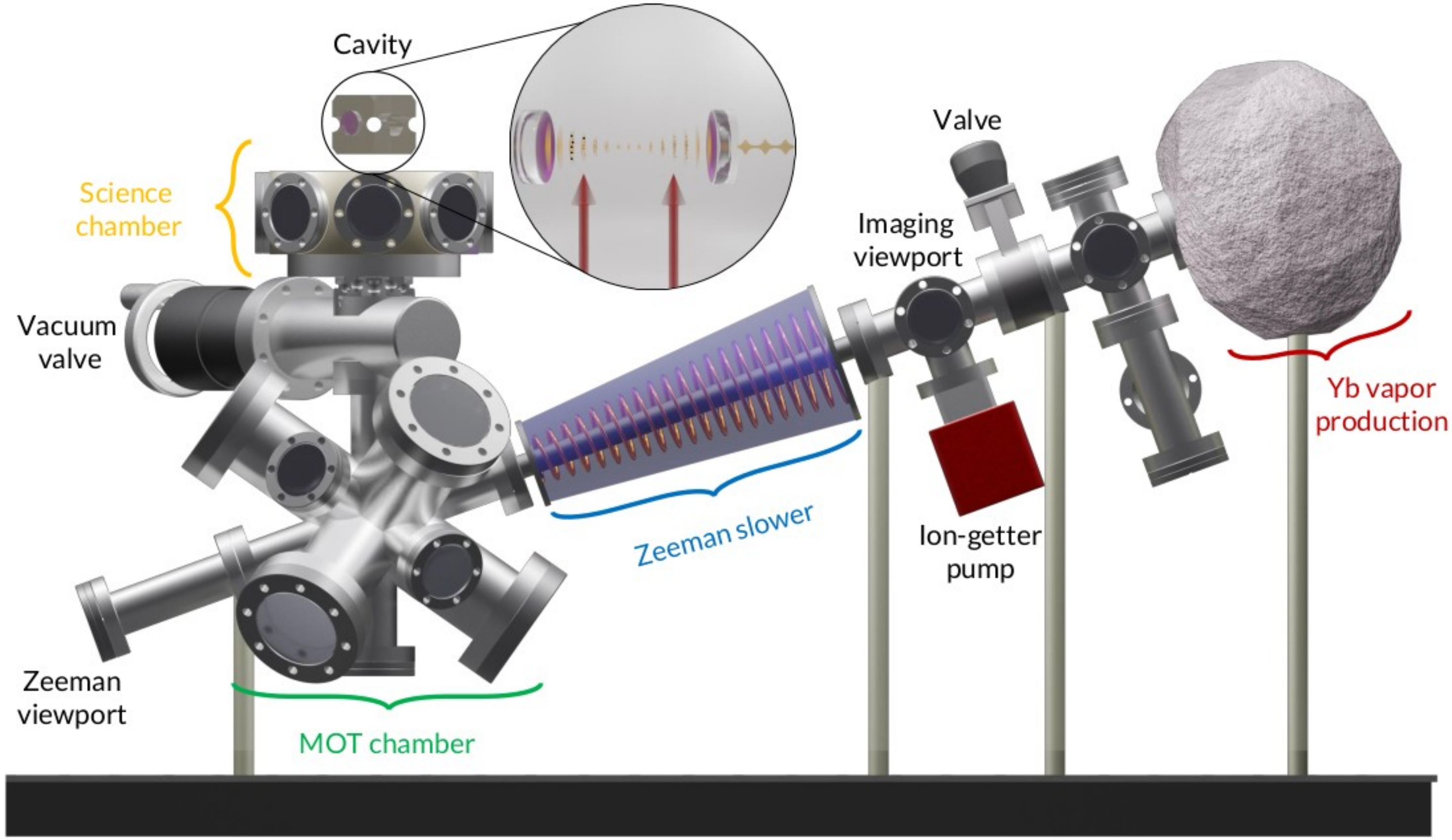
$$N_{\text{th}} = 2/(C\,\gamma\,T_2)$$

^{171}Yb: 7 mHz wide $^1S_0 \rightarrow {}^3P_0$ transition: threshold atom number 7× smaller than ^{87}Sr

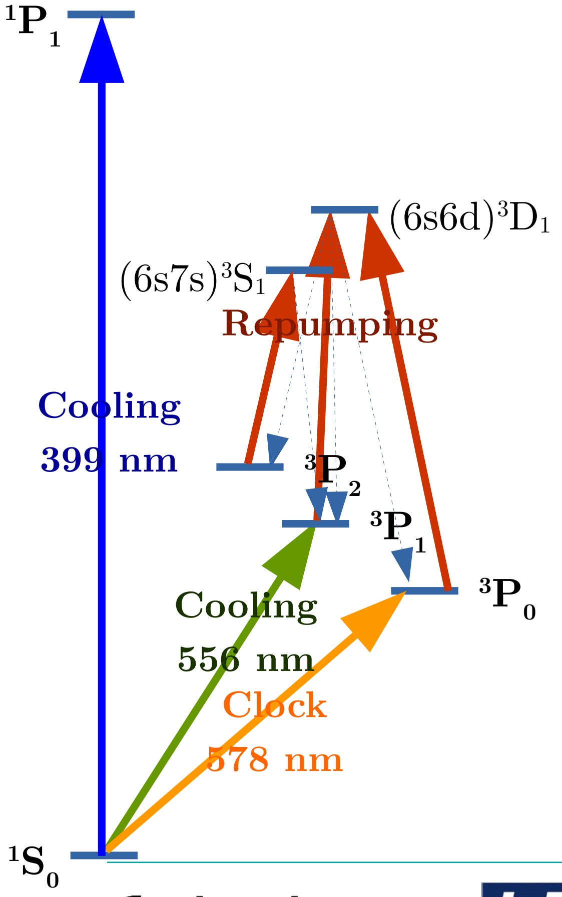
^{171}Yb : I = 1/2 : reduced scattering when repumping wrt ^{87}Sr

But no straightforward reservoir in $^3P_2$ (antitrapped by magic lattice)

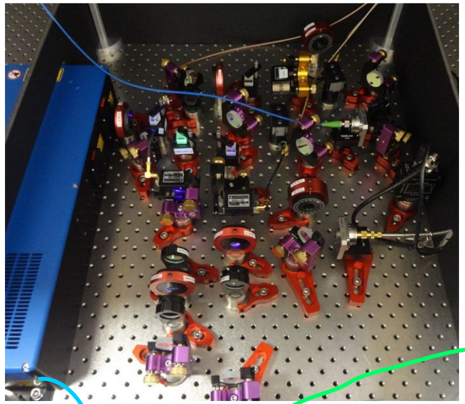


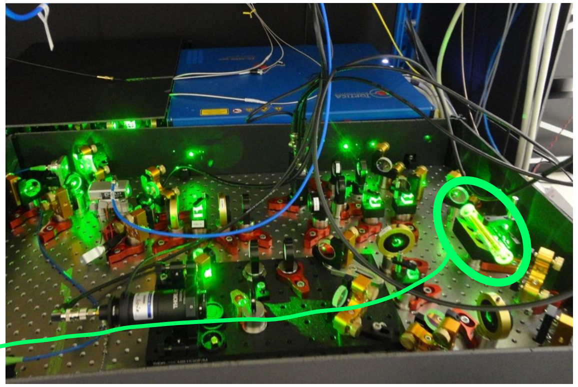


FEMTO-ST apparatus

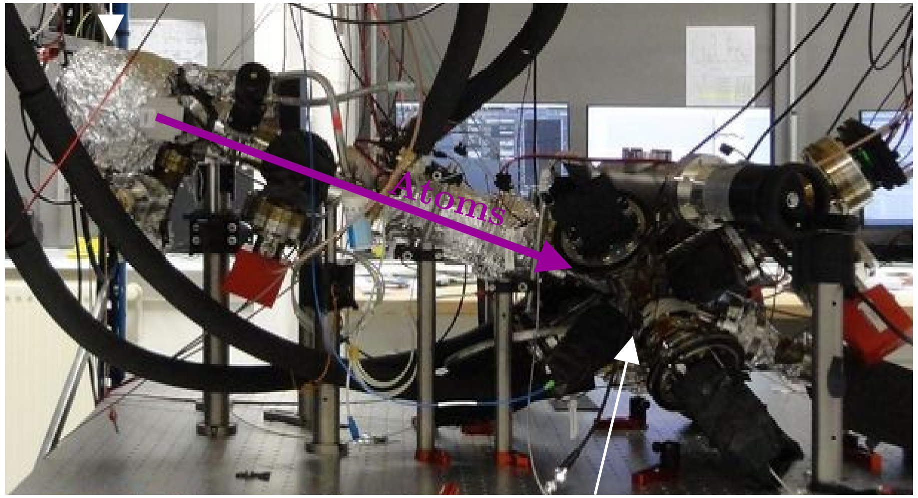


ATOMS

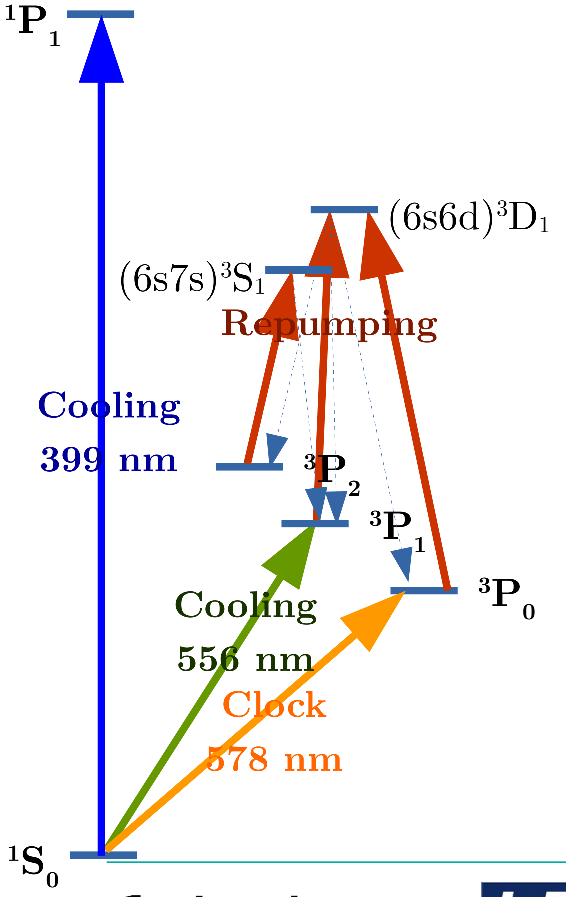


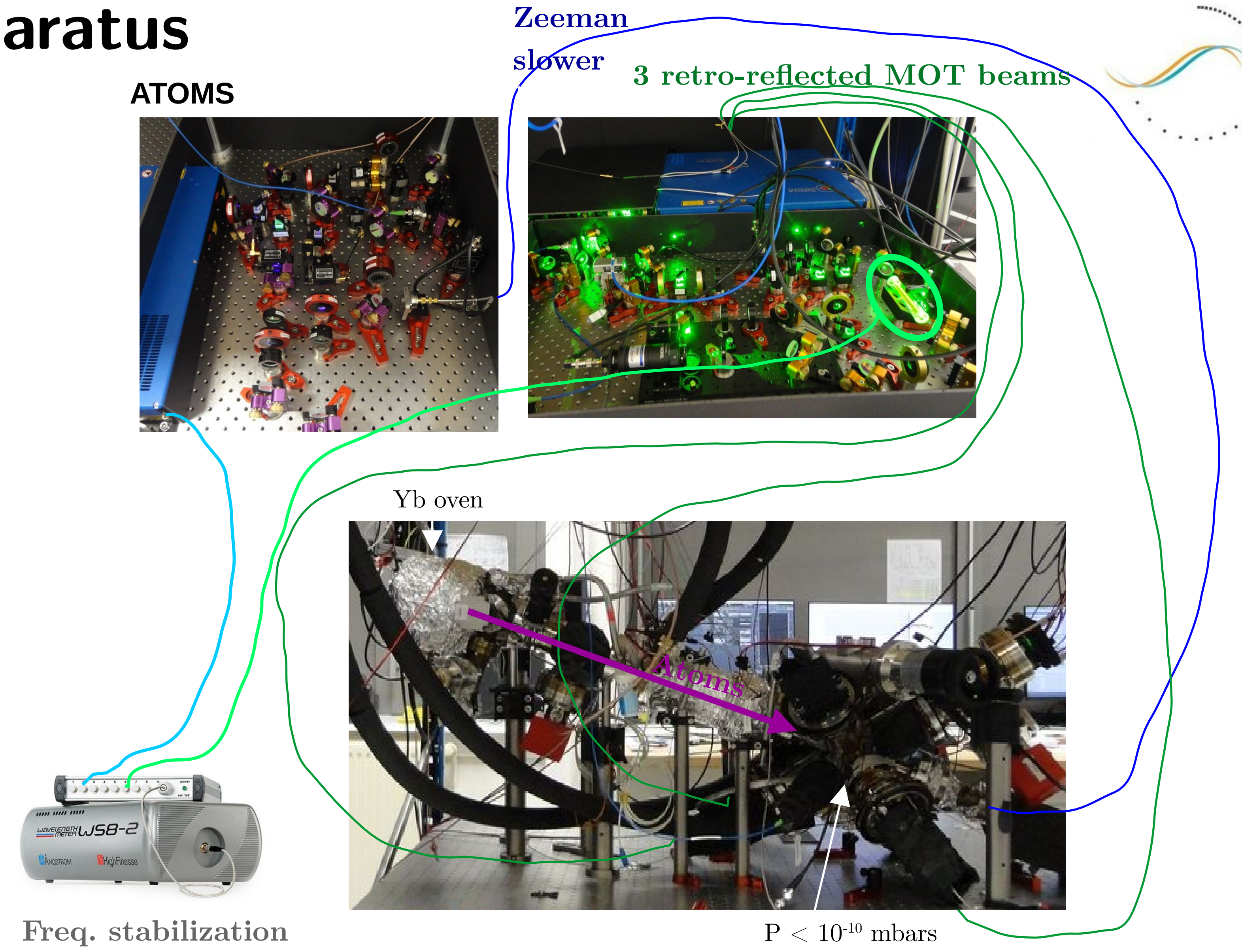


Freq. stabilization

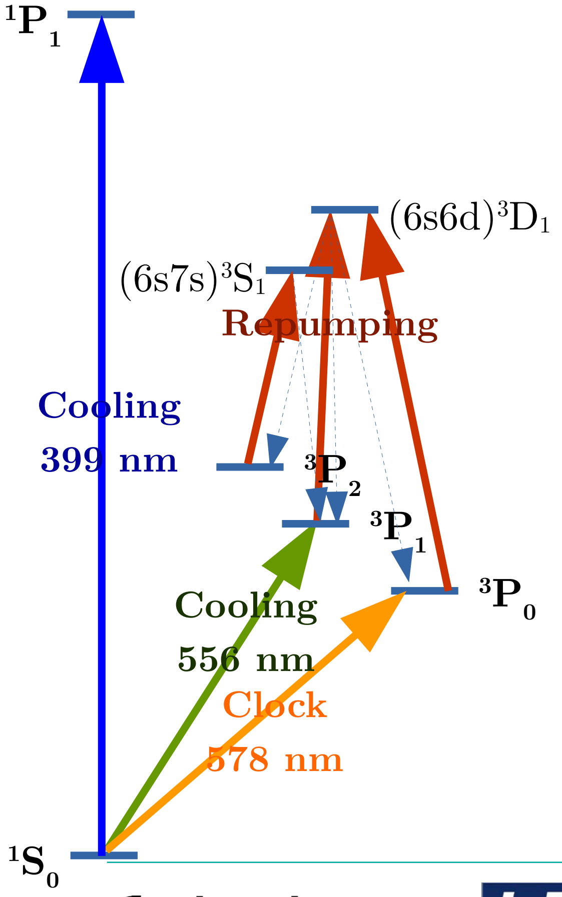


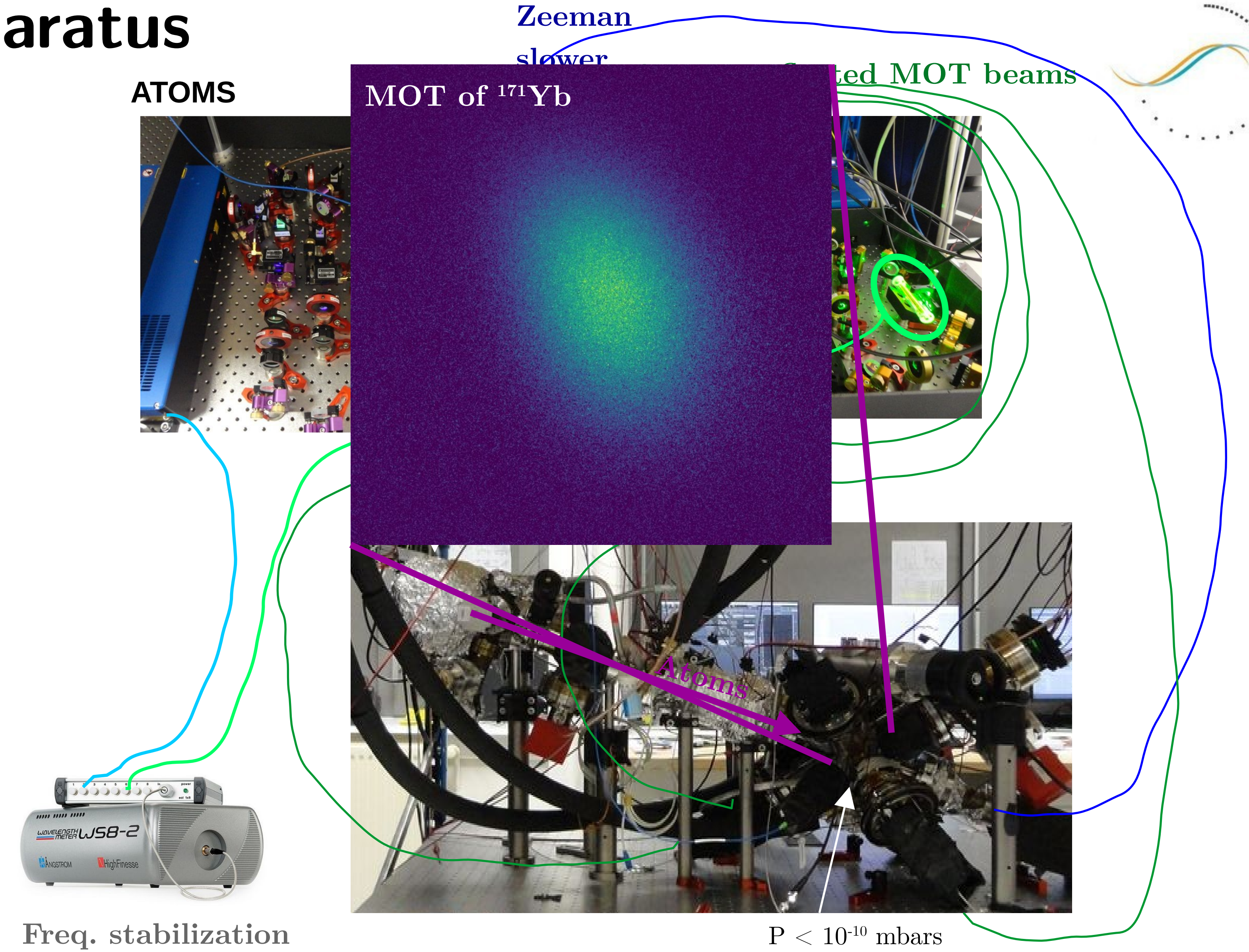
FEMTO-ST apparatus



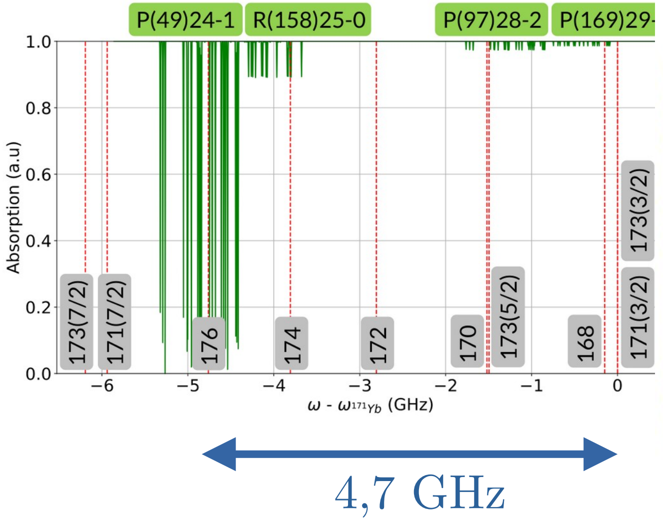


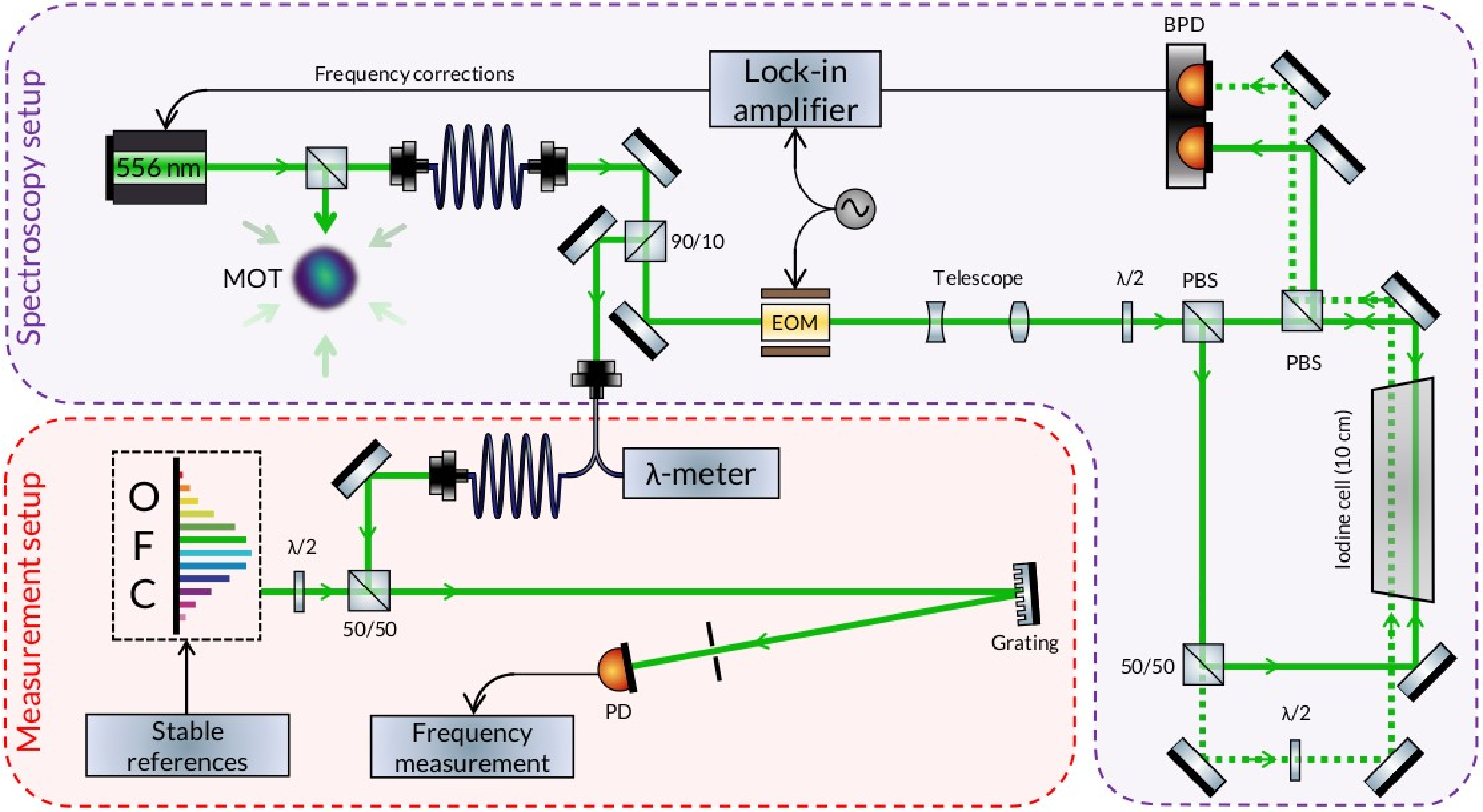
FEMTO-ST apparatus



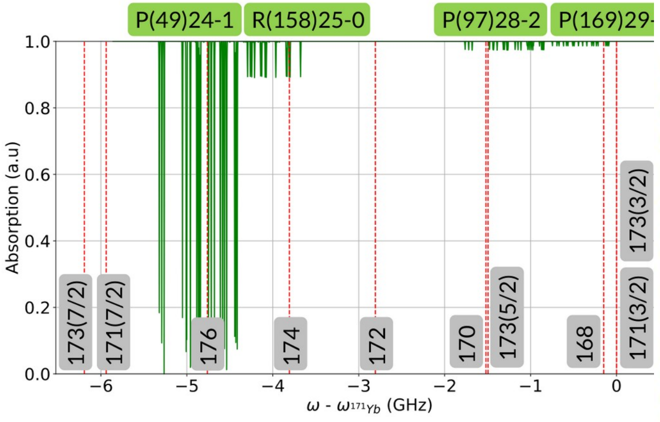


Iodine measurements

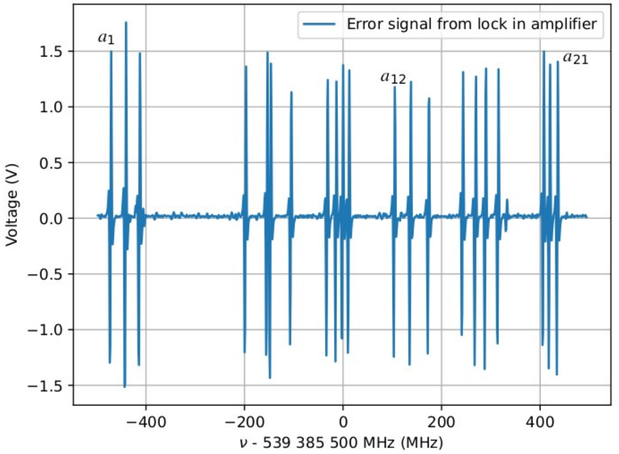


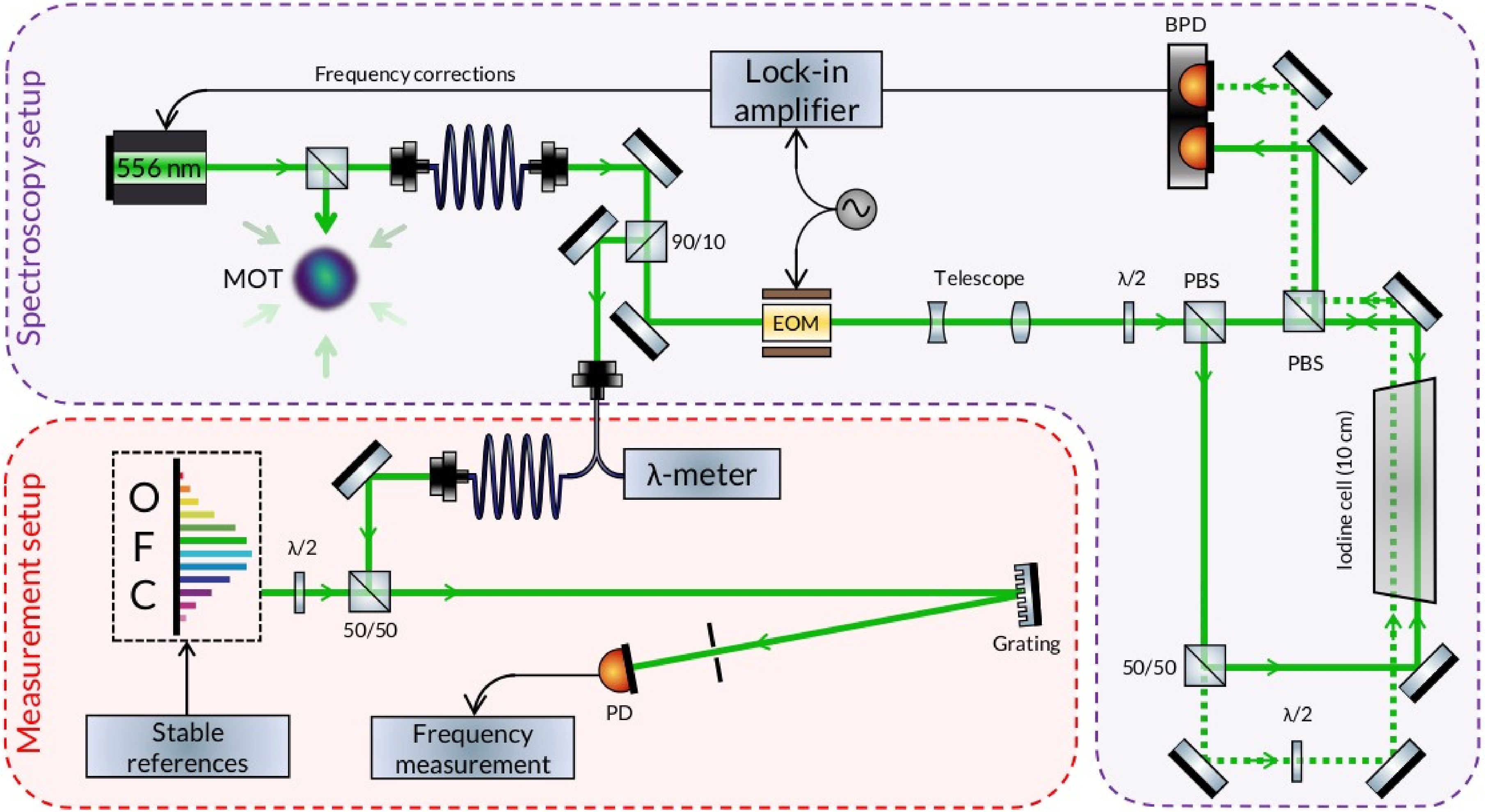


Iodine measurements

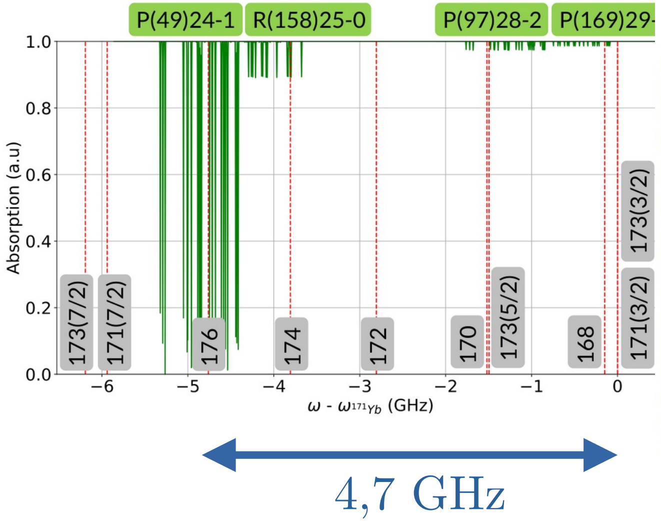


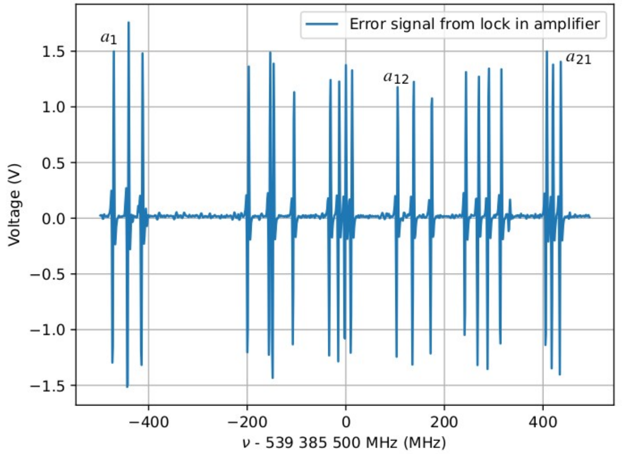
4,7 GHz

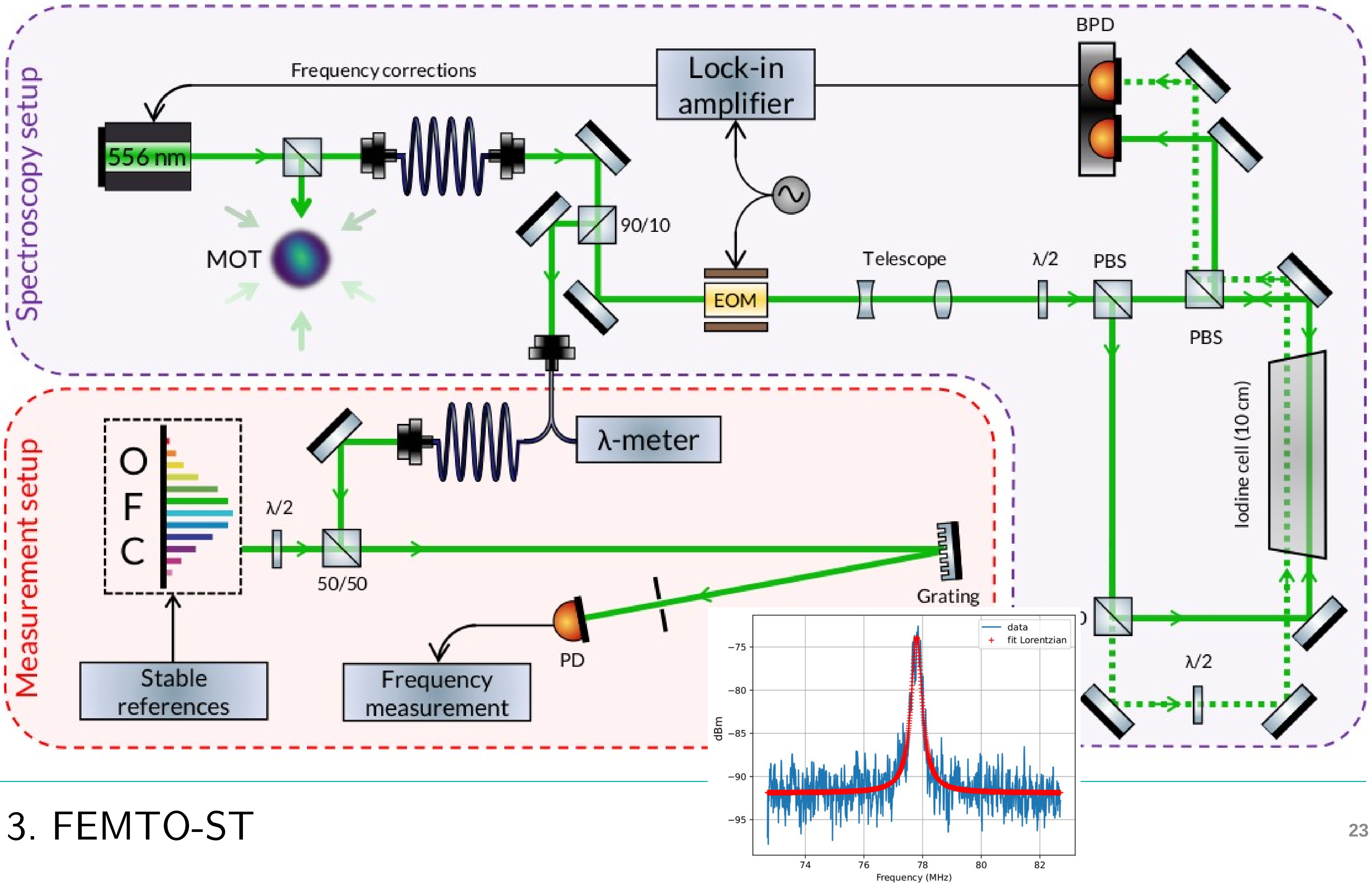




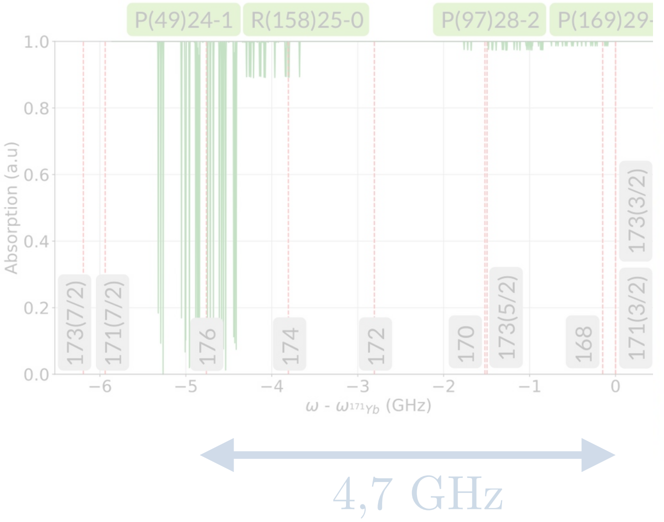
Iodine measurements

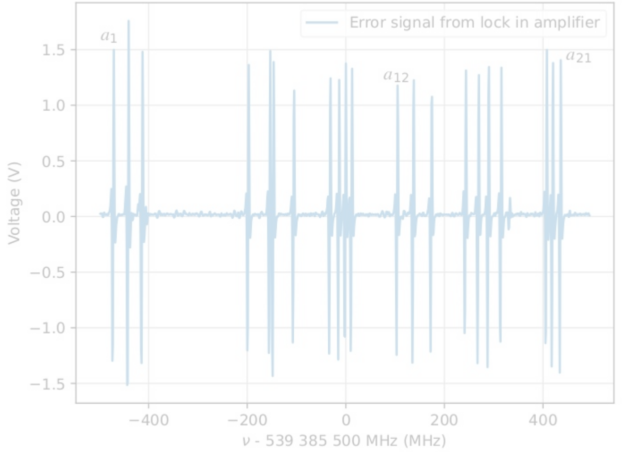


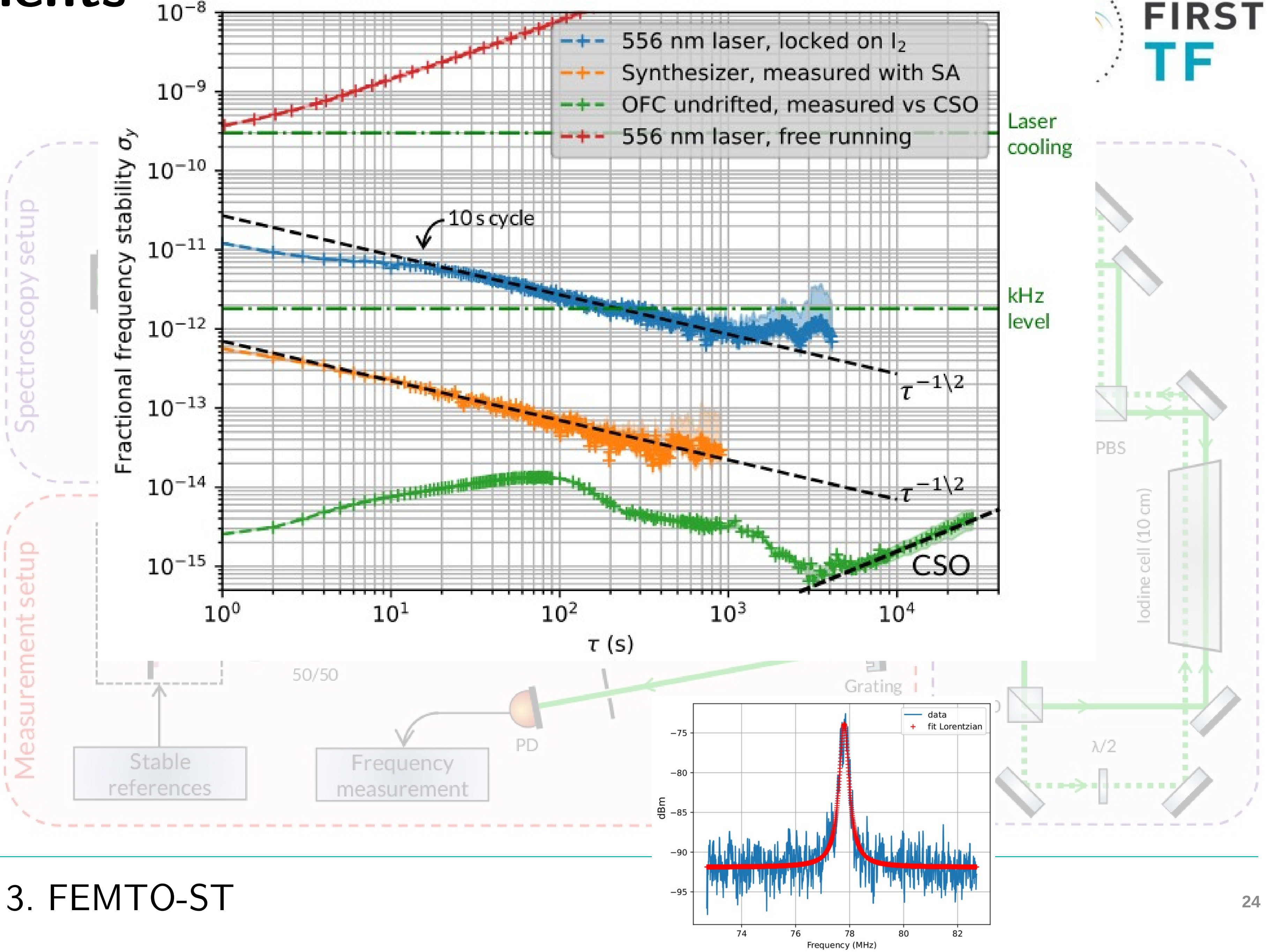




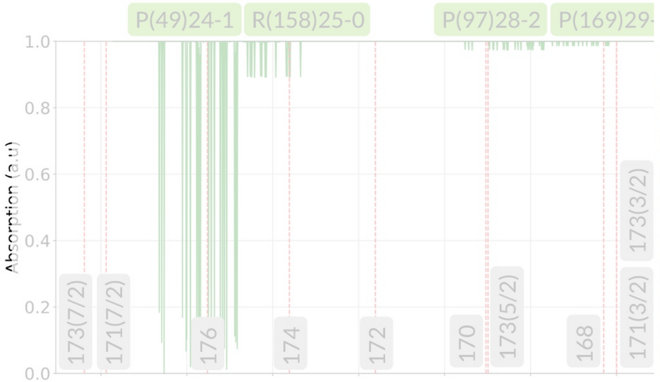
Iodine measurements

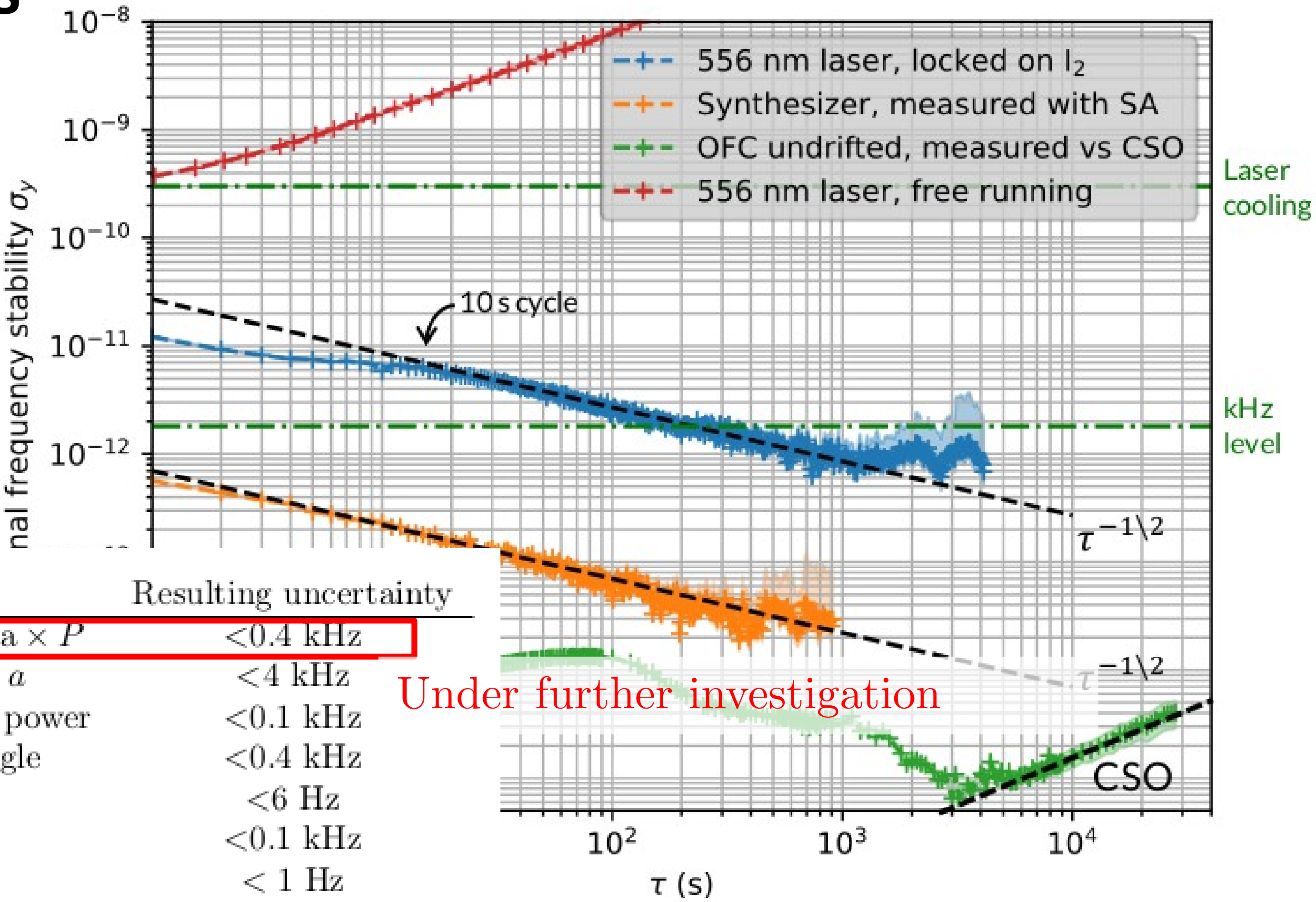






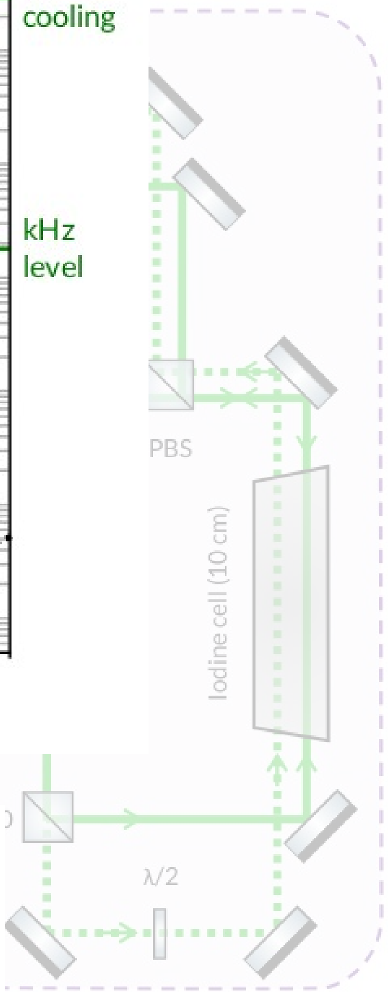
Iodine measurements

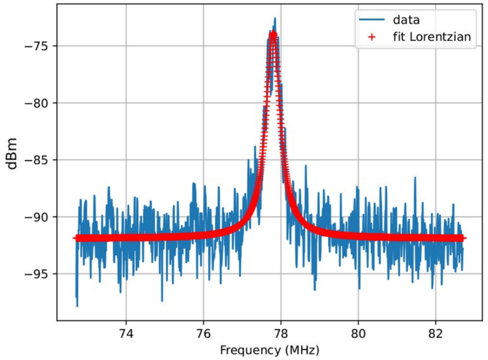




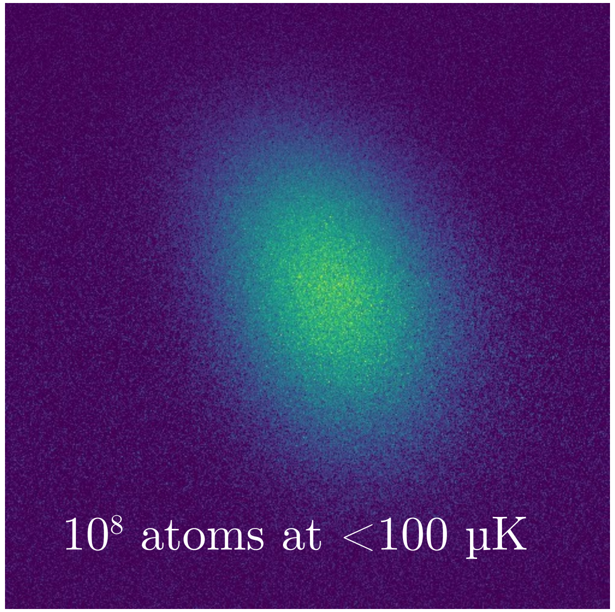
Effect	Shift	Resulting uncertainty
Pressure shift	(-7.15 ± 0.02) kHz/Pa × P	<0.4 kHz
Asymmetry shift	(-224 ± 5) kHz × a	<4 kHz
Residual light shift	(-141 ± 7) Hz/mW × power	<0.1 kHz
Alignment shift	(6 ± 4) kHz/° × angle	<0.4 kHz
HM shift	610 Hz	<6 Hz
Magnetic shift	100 Hz	<0.1 kHz
Gravitational shift	15 Hz	< 1 Hz
EOM	−4.6715 GHz	
Cell impurity		<5 kHz
Statistical		<1.3 kHz
Total		< 6.6 kHz

Under further investigation

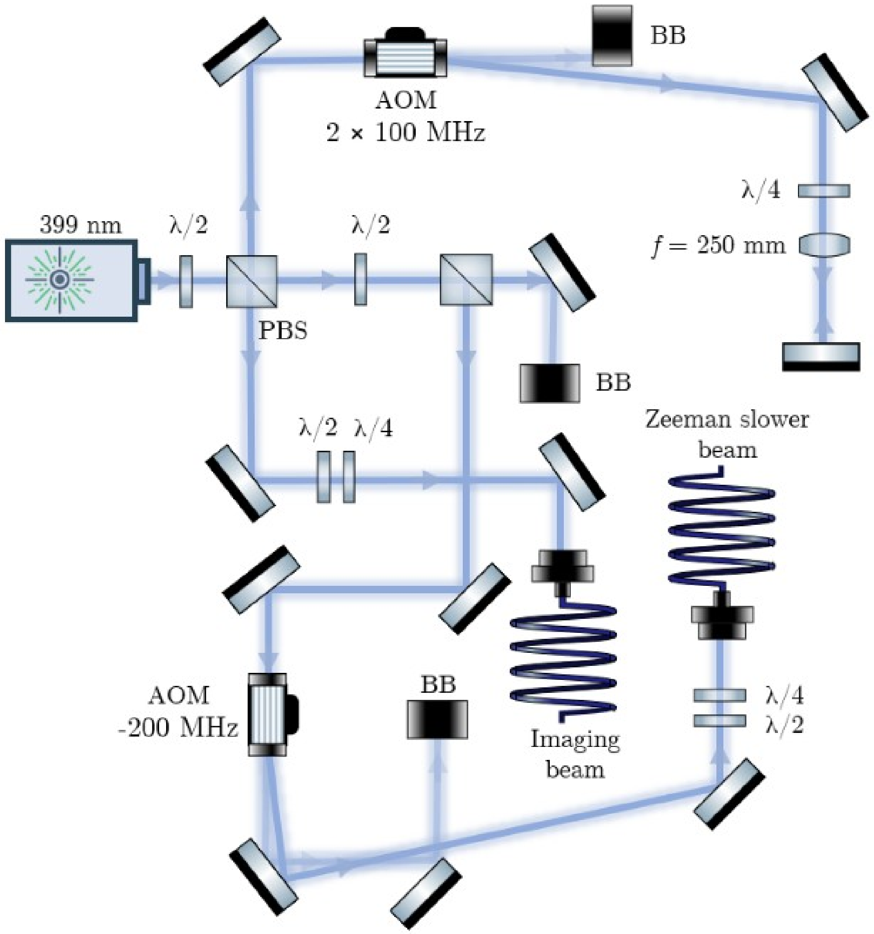




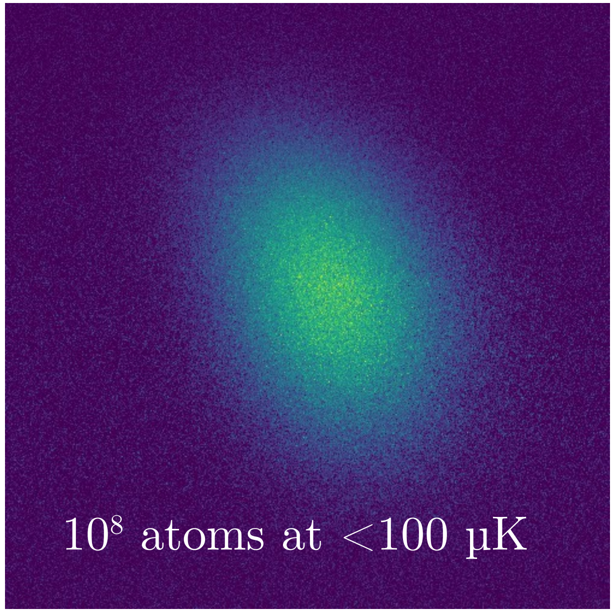
Ytterbium ensemble


10^8 atoms at <100 μK

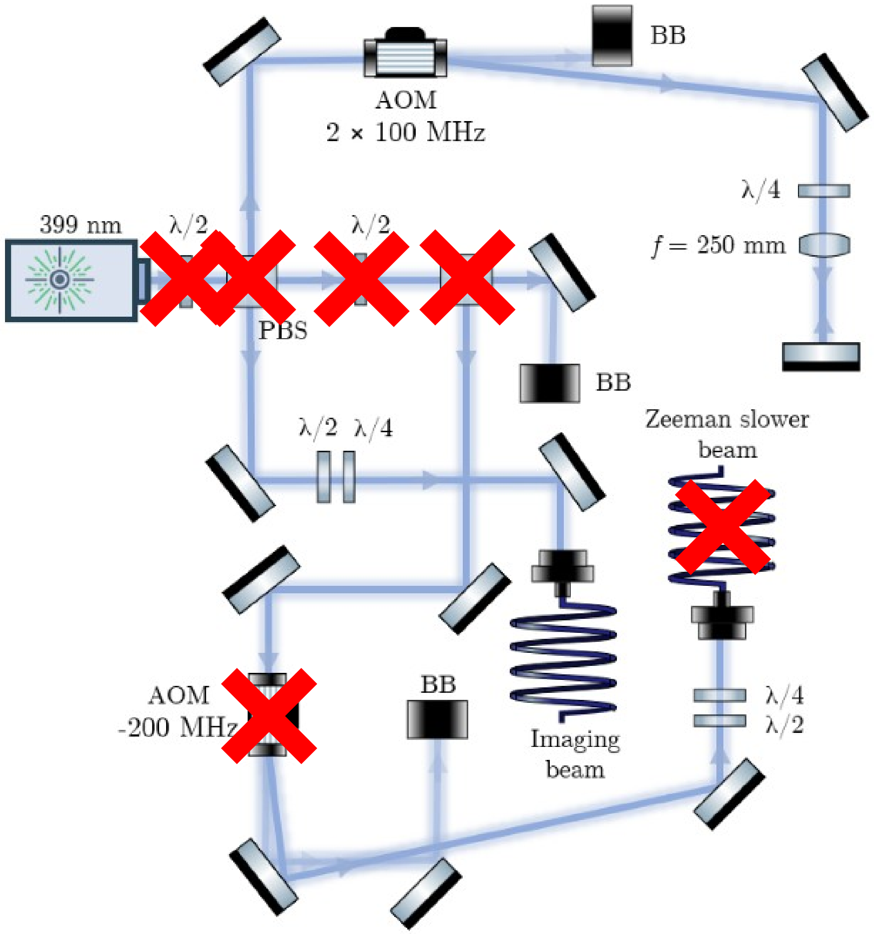
but ...



Ytterbium ensemble

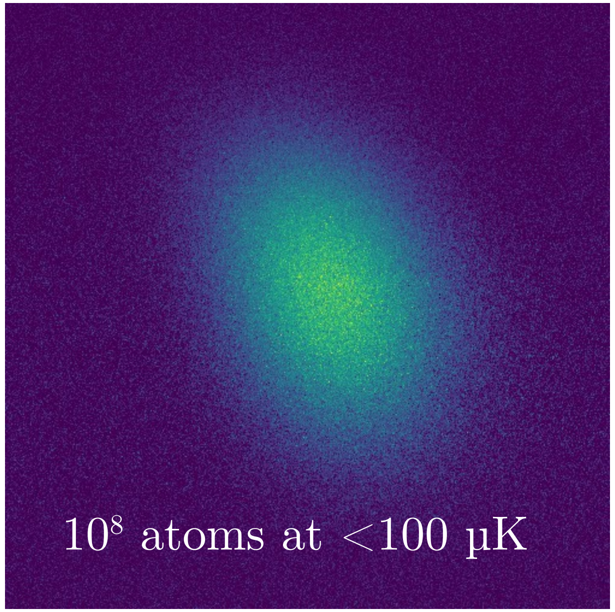


but ...

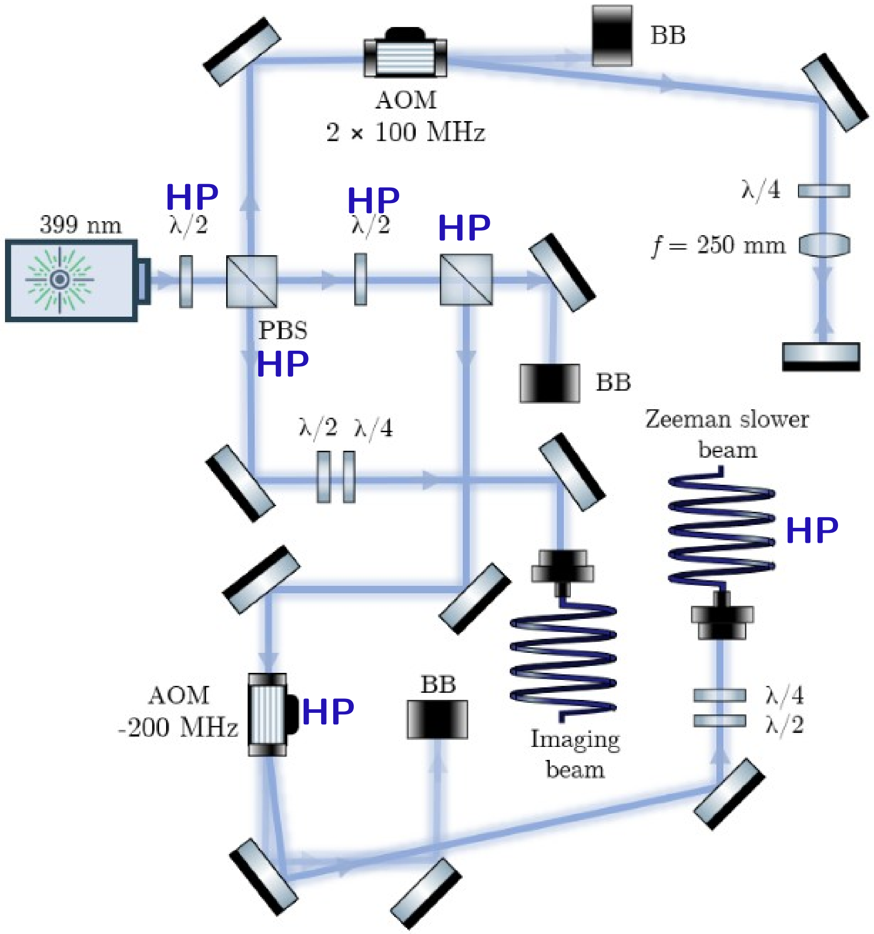


and then (Zeeman viewport) ...

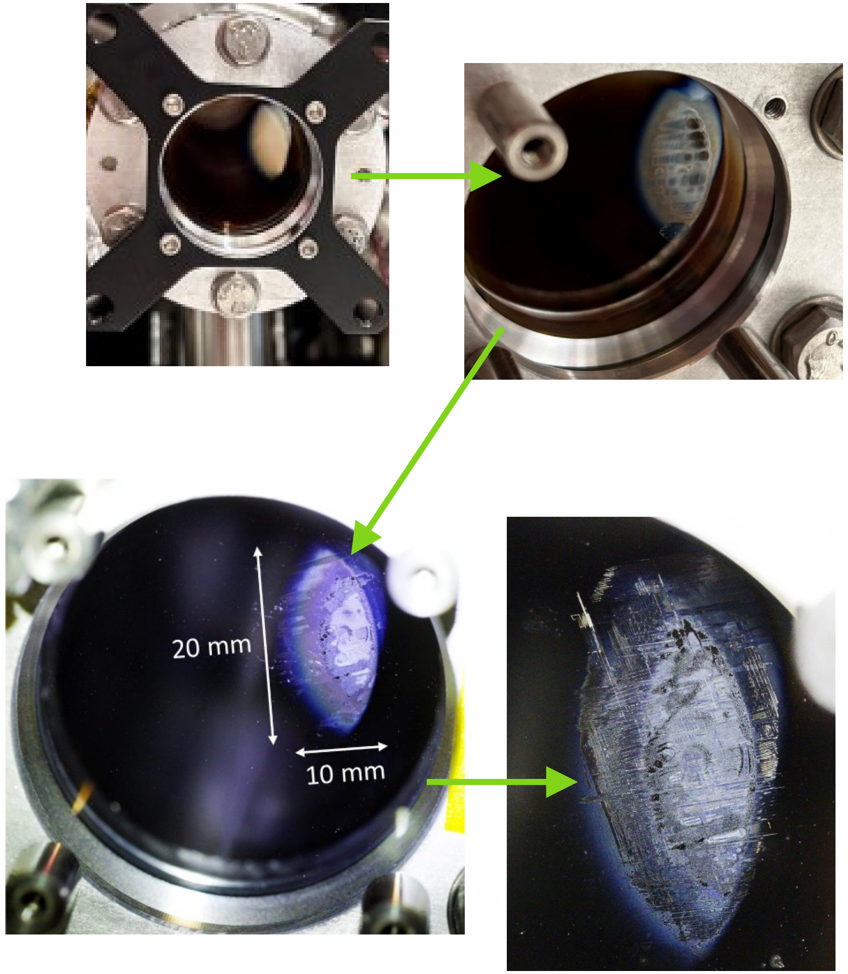
Ytterbium ensemble


10^8 atoms at <100 µK

but ...

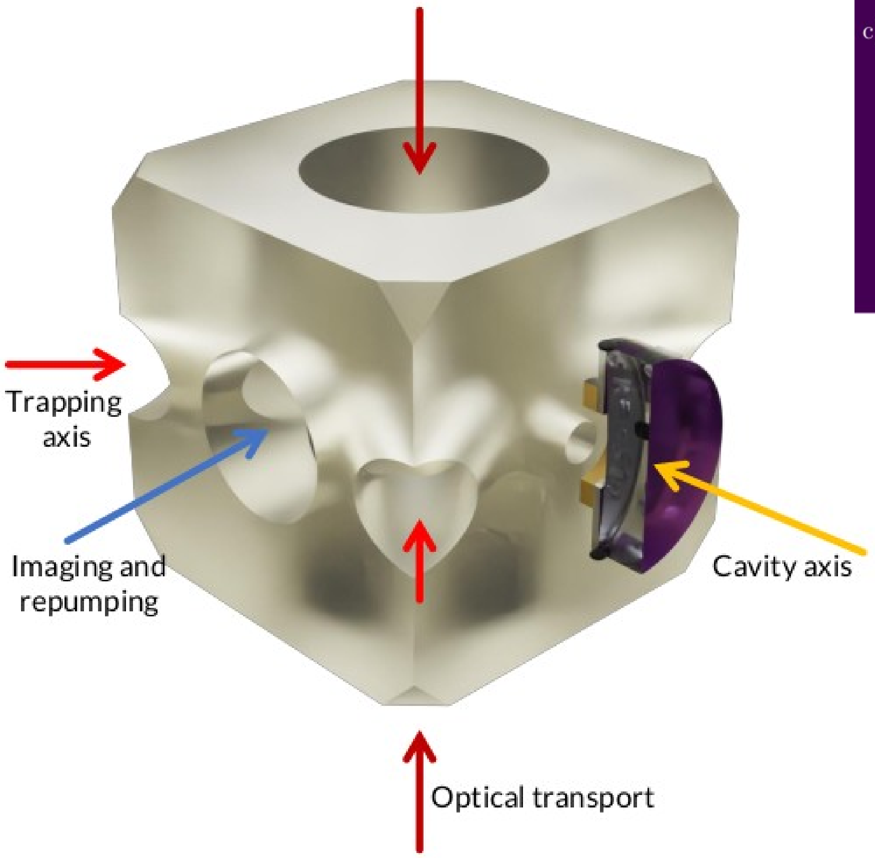


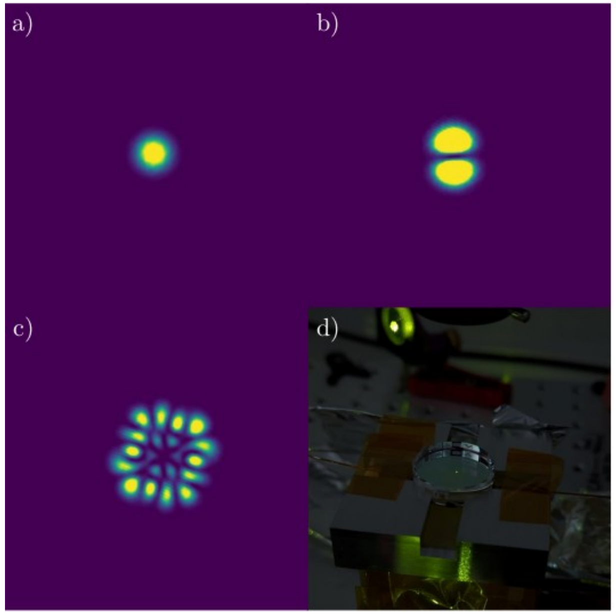
and then (Zeeman viewport) ...

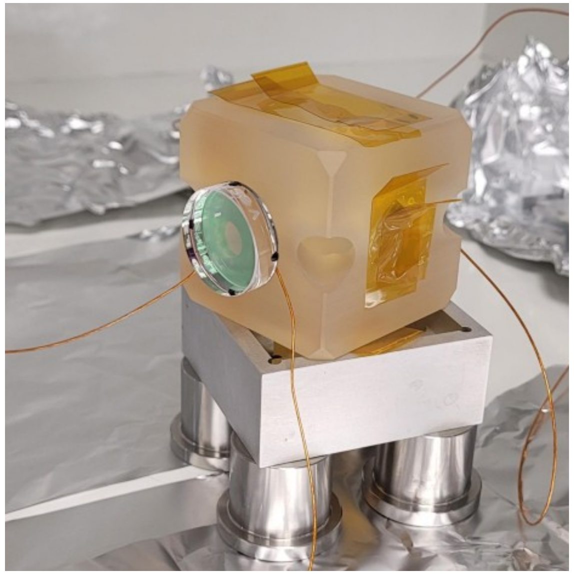


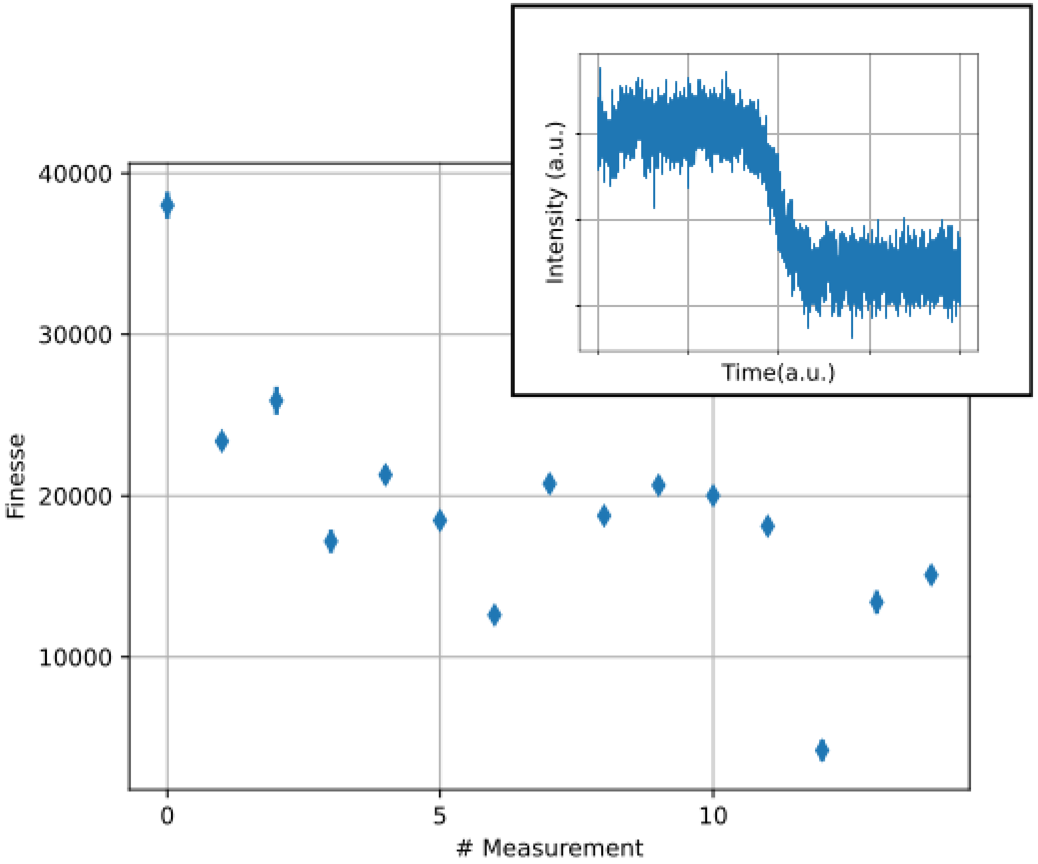
Work in progress

Cavity assembly

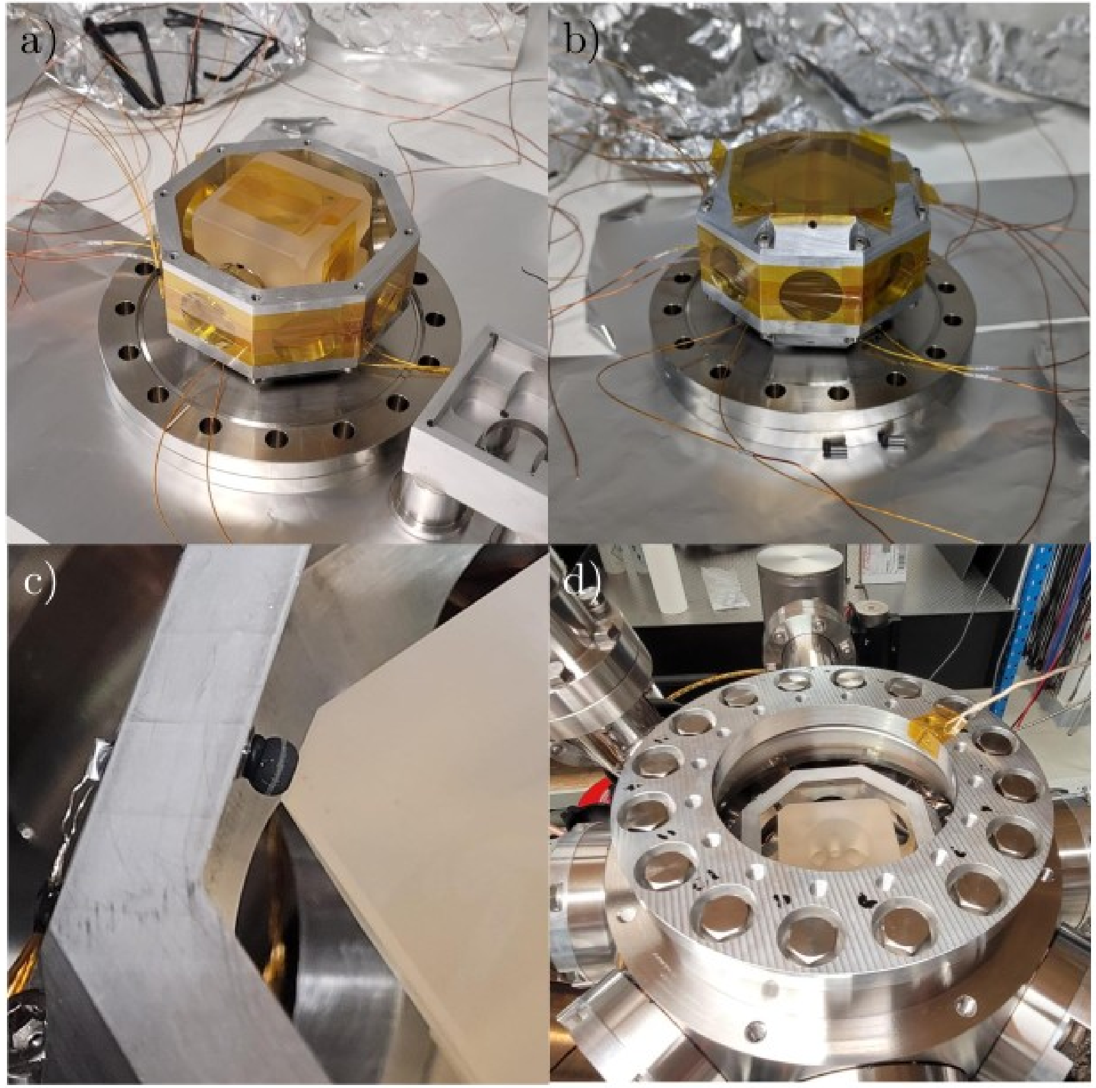


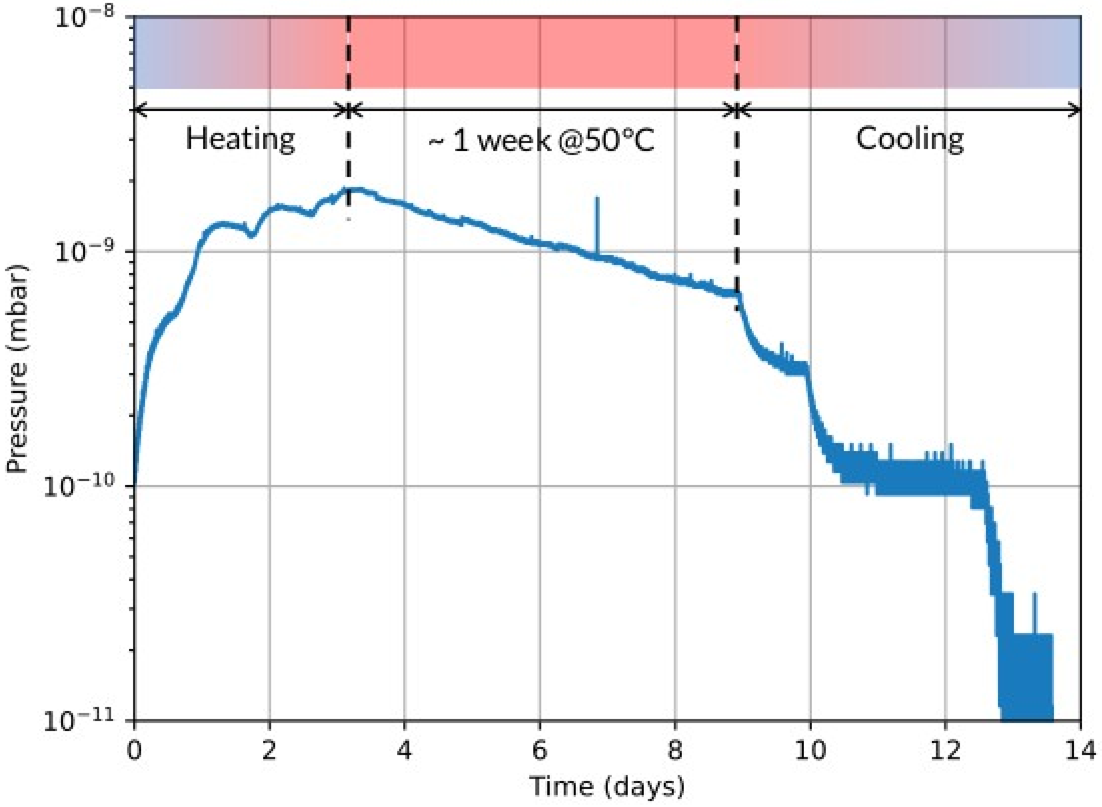




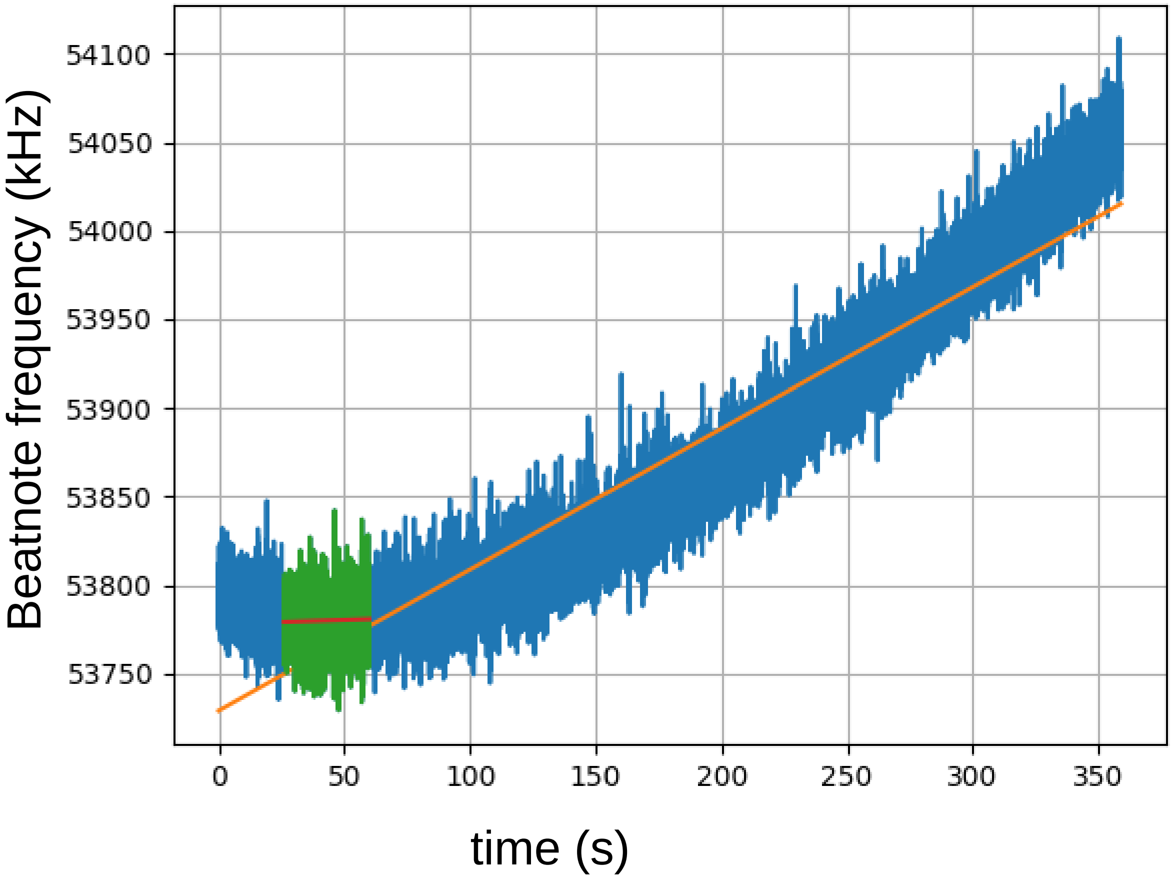


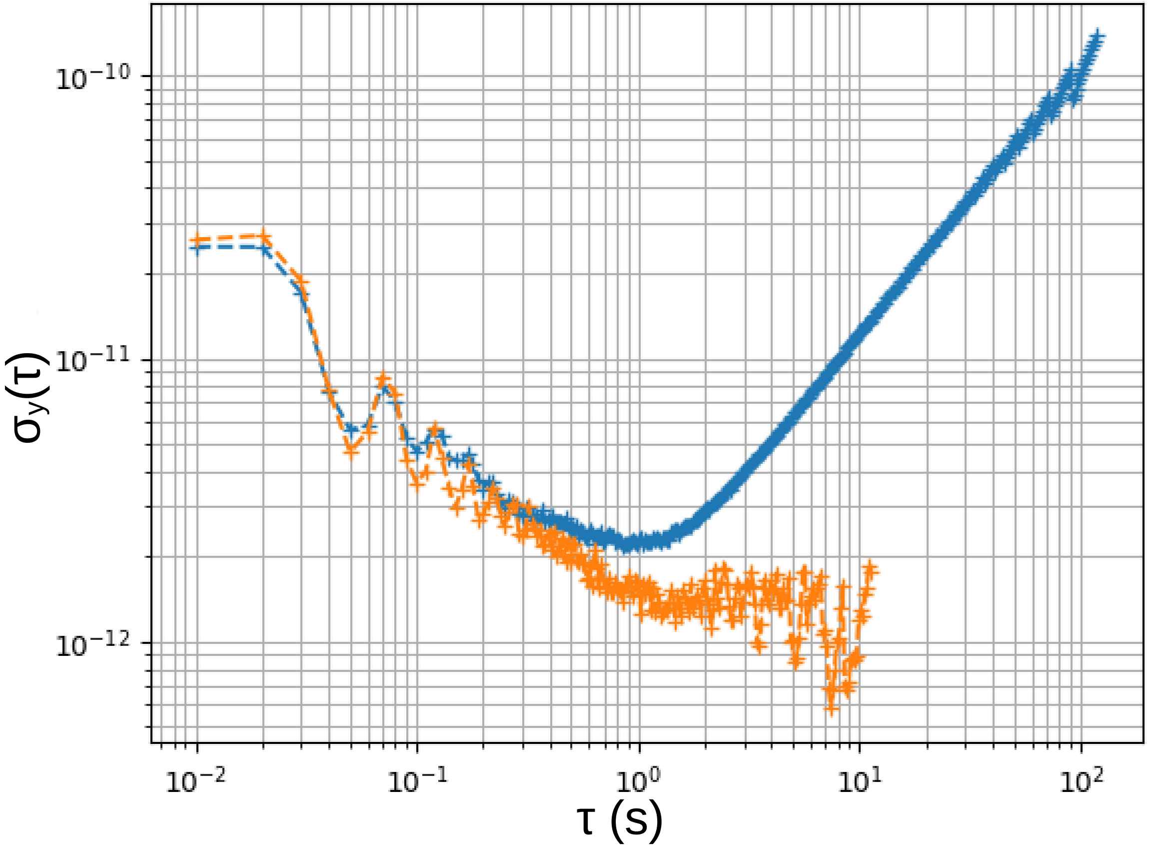
Cavity in vacuum





Cavity characterization – short term



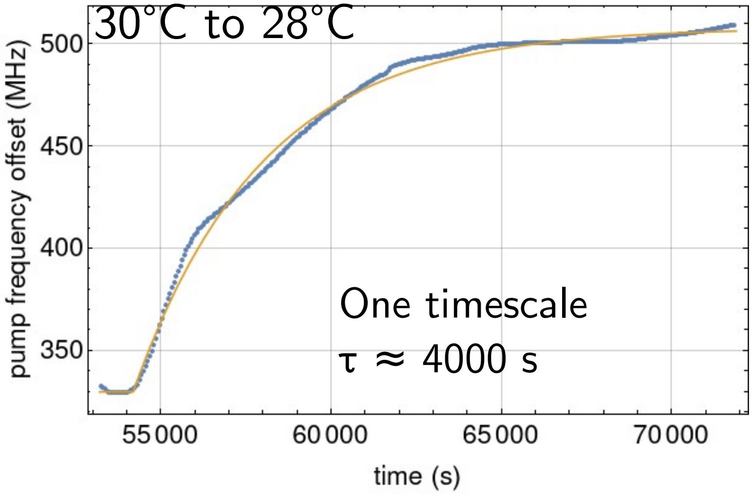


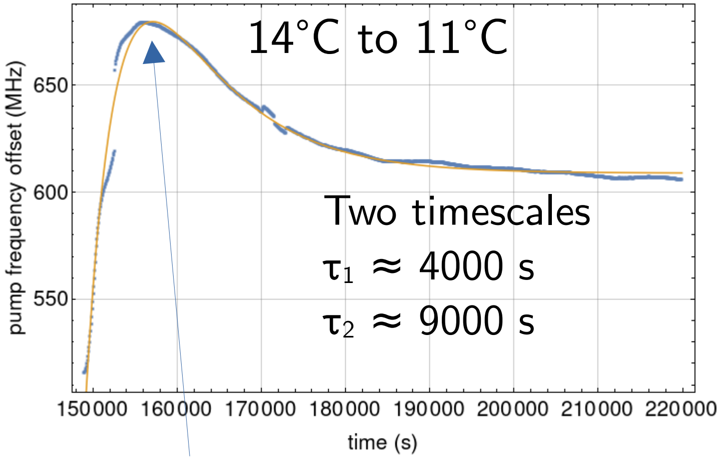
$\sigma_y(\tau) = 2 \times 10^{-12}$ at 1 s

Work in progress: improve PDH laser lock on the cavity – limited by drifts after 1s

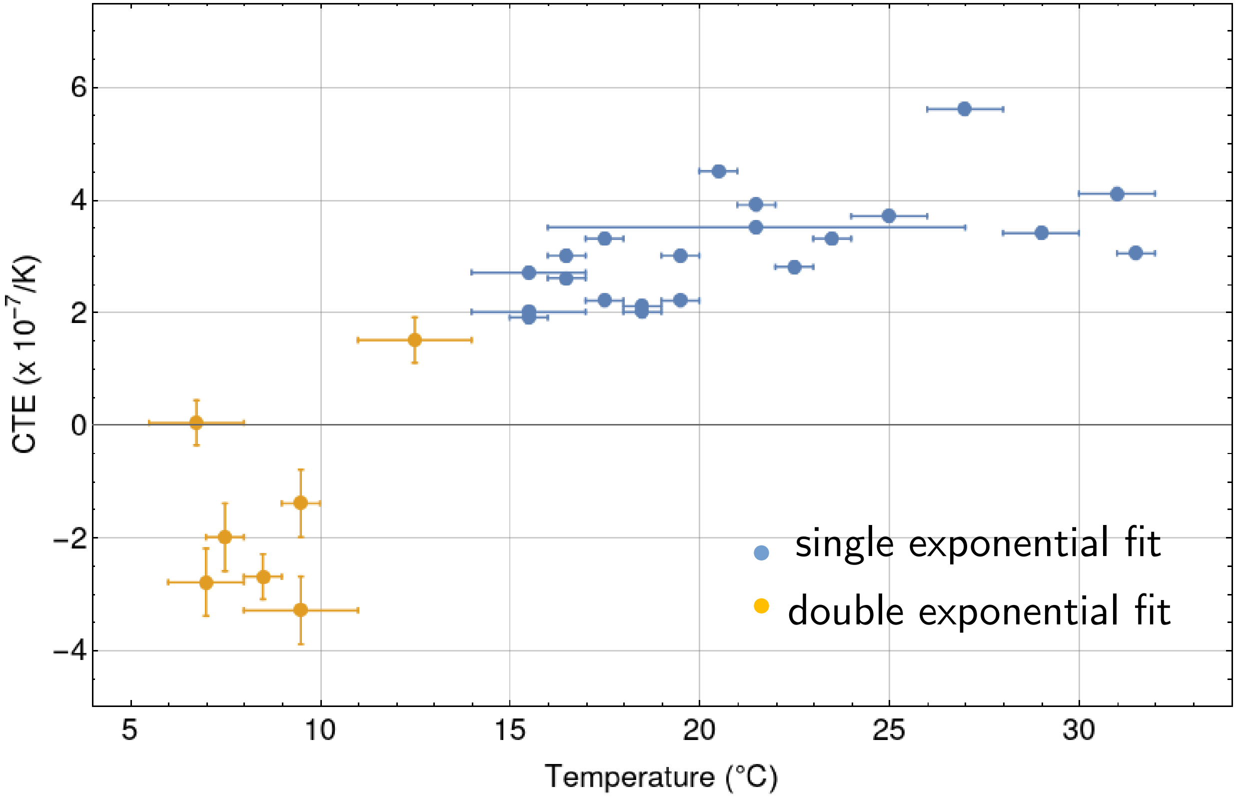
Cavity characterization – long term

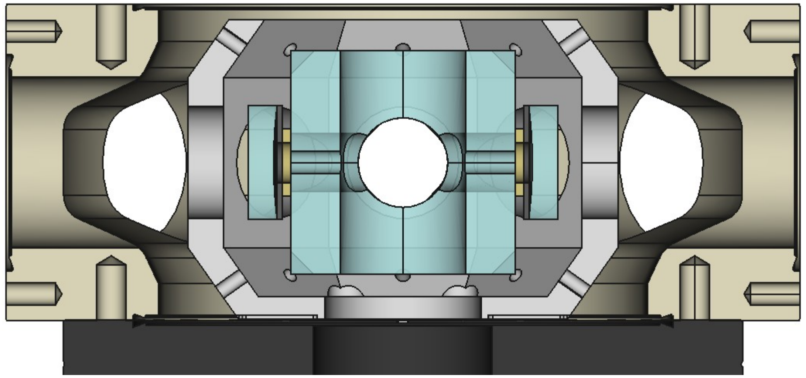
Thermal expansion coefficient





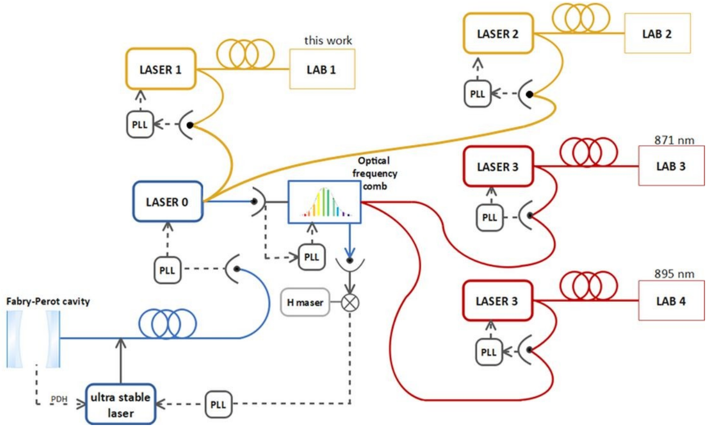
Possible crossing of inversion temperature https://doi.org/10.1364/OE.436112



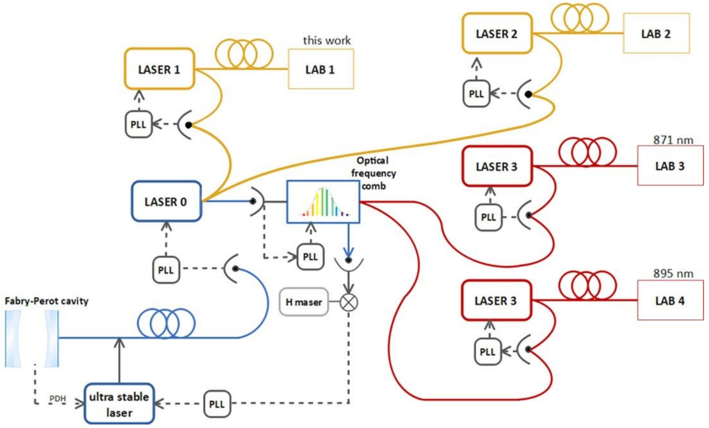


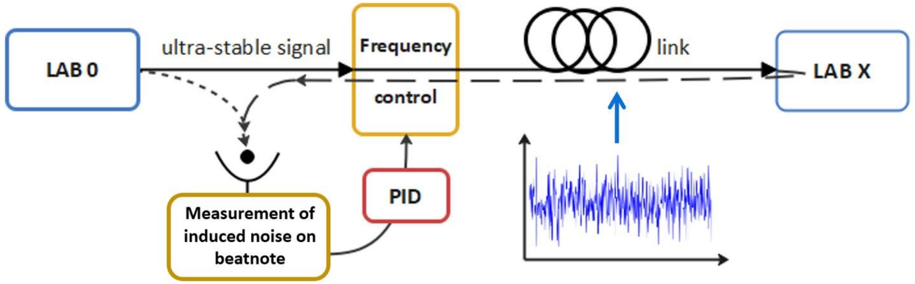
3. FEMTO-ST

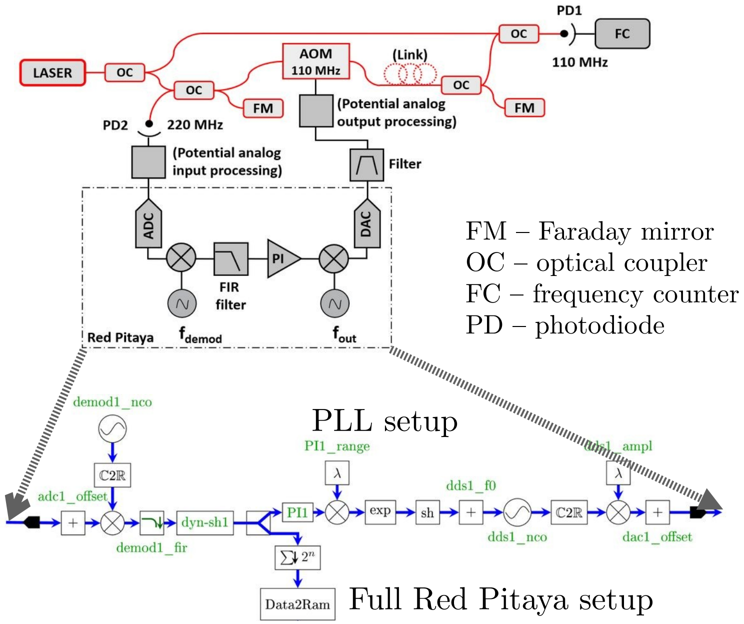
Optical fiber links



Optical fiber links



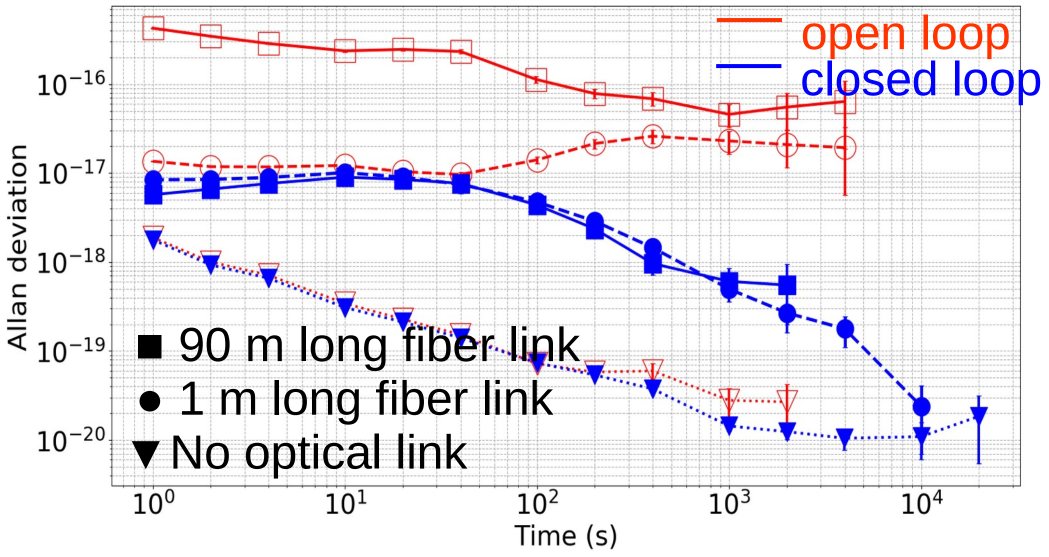




FM – Faraday mirror
OC – optical coupler
FC – frequency counter
PD – photodiode

PLL setup

Full Red Pitaya setup



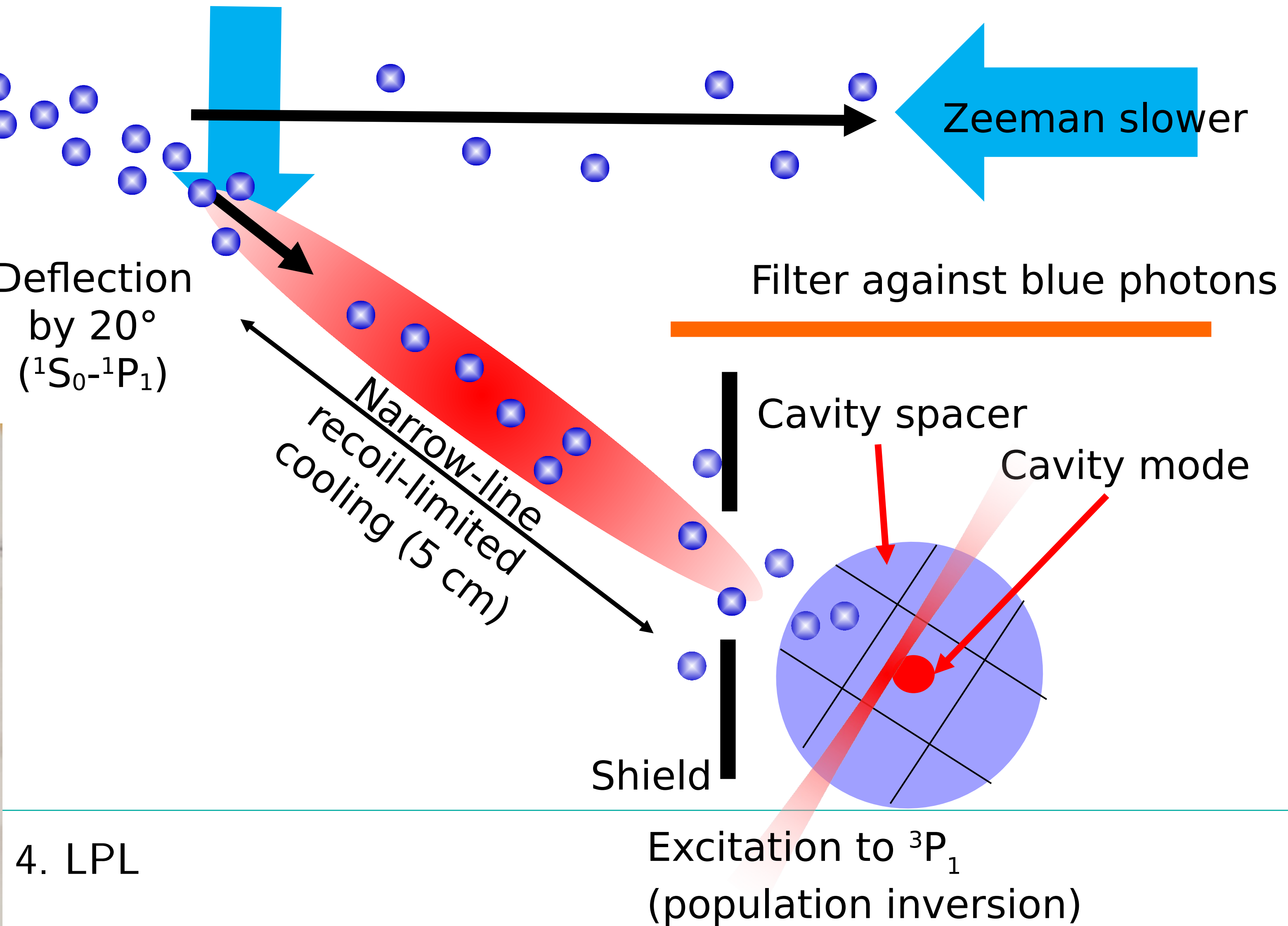
→ *OK for optical clock comparison at the 10^{-18} level*

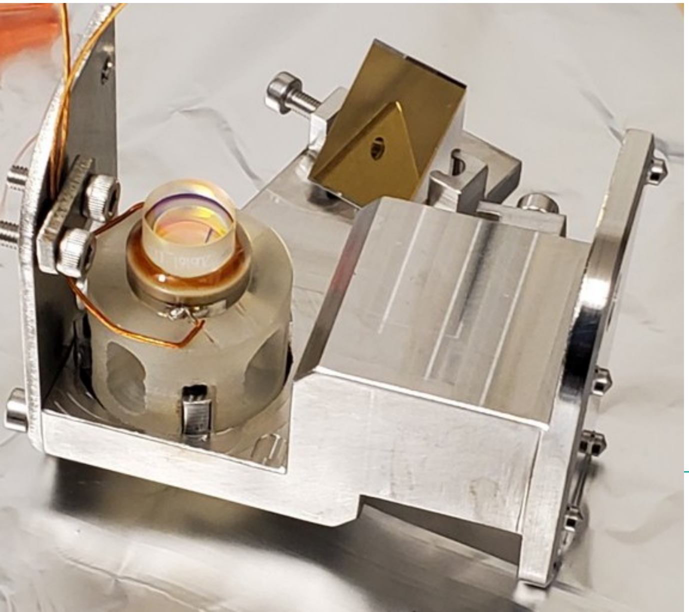
M.Matusko *et all*, Rev. Sci. Instrum. 94, 034716 (2023)

More at Jacques Millo's talk during REFIMEVE AG

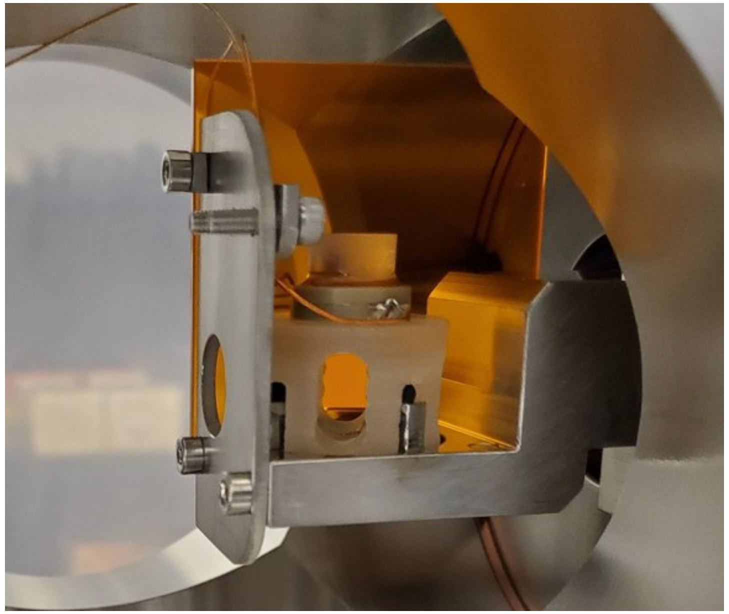
The LPL atomic-beam architecture

Strontium 88 superradiant laser on the 7 kHz wide intercombination line $^1S_0 \rightarrow {}^3P_1$





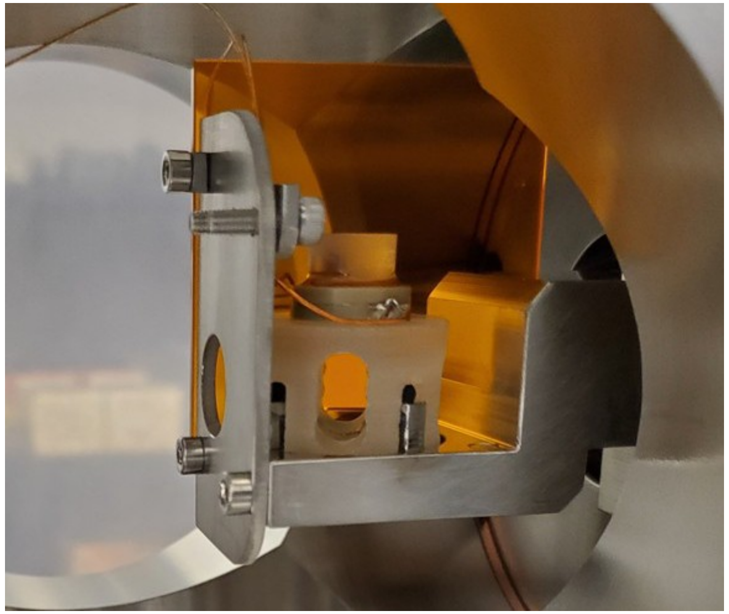
The LPL atomic-beam architecture



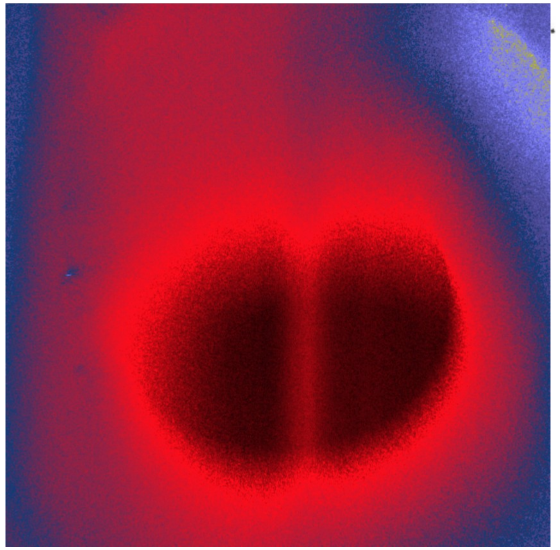
Finesse measured in vacuum : 9000 (over ISL 6.6 GHz)
Mirror losses 0.028% reduce outcoupling by a factor ~ 10

Mode waist : 68 µm
$g/2\pi$ = 20 kHz (rms)
$\gamma/2\pi$ = 7 kHz
$\kappa/2\pi$ = 630 kHz
C = 0.1 (spatial mean)

The LPL atomic-beam architecture



Atomic beam decelerated and deflected by a moving optical molasses to the cavity



Fluorescence (on broad line) of ~ 1000 atoms in the cavity mode, seen from the side

Finesse measured in vacuum : 9000 (over ISL 6.6 GHz)
Mirror losses 0.028% reduce outcoupling by a factor ~ 10

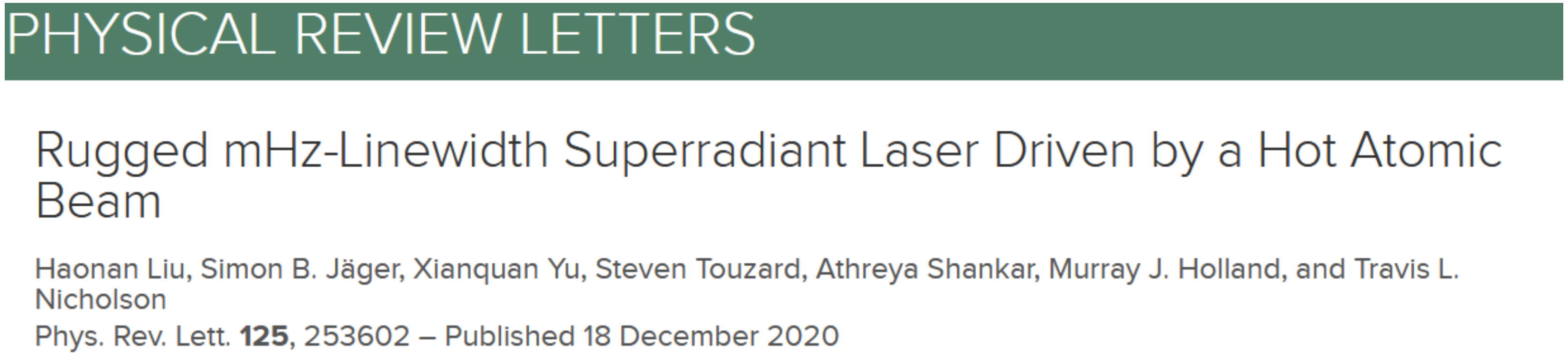
Mode waist : 68 µm
$g/2\pi$ = 20 kHz (rms)
$\gamma/2\pi$ = 7 kHz
$\kappa/2\pi$ = 630 kHz
C = 0.1 (spatial mean)

Tunable transit time broadening (40-200 kHz)
through atomic beam axial velocity : 20 – 100 m/s
Tunable Doppler shift distribution (down to 100 kHz)
through atomic beam transverse velocity spread
(operation starting now)

LPL design choices : κ

Our experiment is designed around “high” cooperativity to reach threshold at low atomic flux :
Oven temperature 440 °C → $N \sim 10^3$ → power ~ 50 pW
Although $\gamma/2\pi \sim 7$ kHz, each atom emits at rate ~ 100 kHz, and the linewidth is 700 Hz

For metrological application, reduce C (increase κ) and use high atomic flux
- → linewidth reduced g^2/κ
- → Cavity pulling resilience $\sim 1/\kappa\tau$



PHYSICAL REVIEW LETTERS

Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam

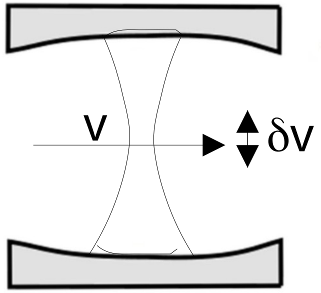
Haonan Liu, Simon B. Jäger, Xianquan Yu, Steven Touzard, Athreya Shankar, Murray J. Holland, and Travis L. Nicholson

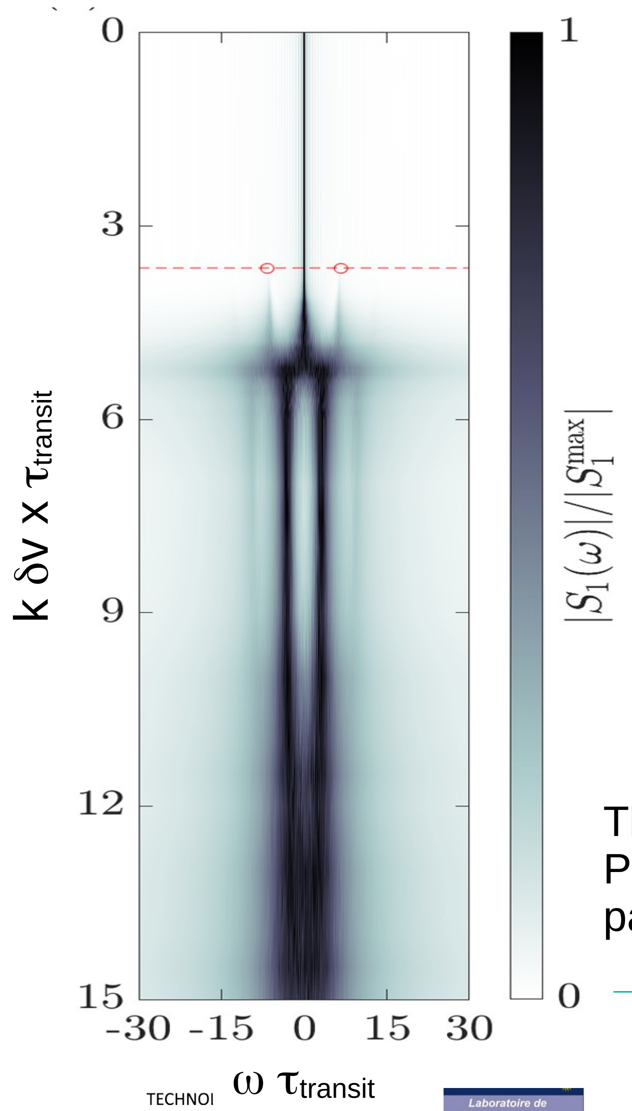
Phys. Rev. Lett. **125**, 253602 – Published 18 December 2020

$C = 2\ 10^{-5} \rightarrow \delta\omega = 0.2$ Hz
Cavity pulling rejection 0.004
Power 2 µW
(for 650°C oven …)

LPL design choices : mode waist

Tunable transit time and Doppler shift distribution



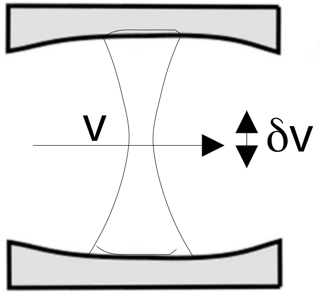


For Doppler spread k δv = 200 kHz,
with 2 10^9 atoms /s through mode,

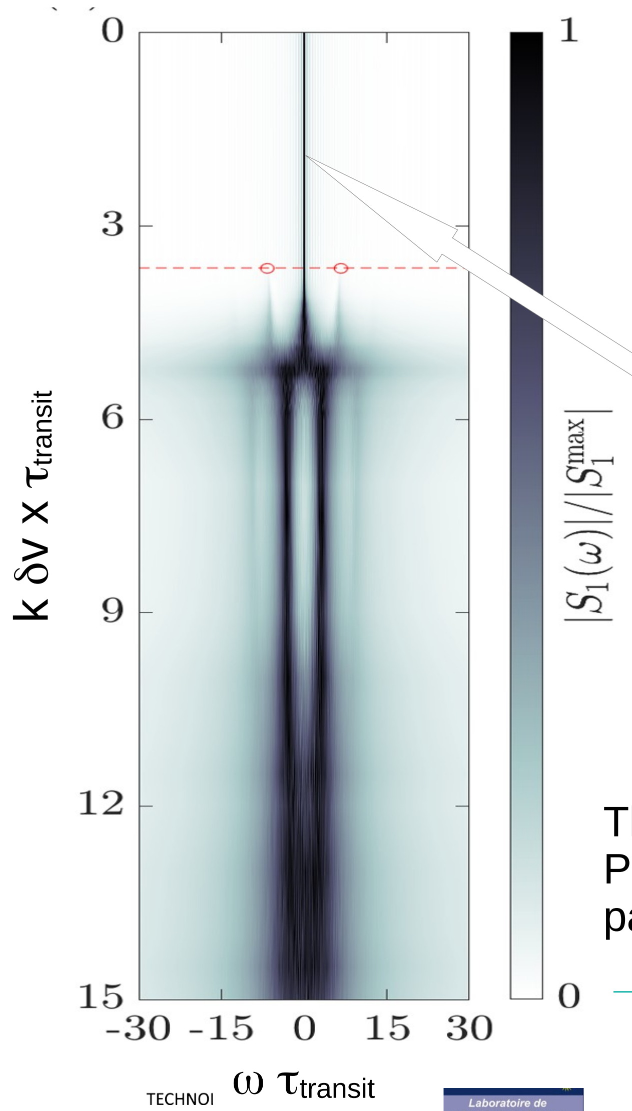
our experiment at beam velocity 50 m/s

Theory by S. Jäger et al,
Phys. Rev. A, vol. 104,
page 033711, 2021

LPL design choices : mode waist



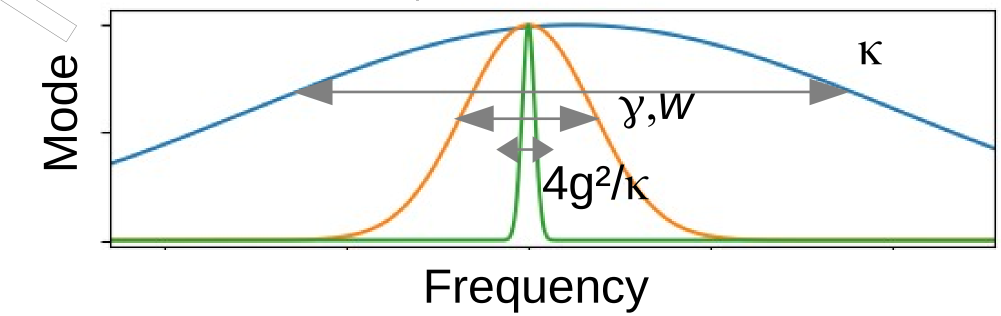
Tunable transit time and Doppler shift distribution



For Doppler spread $k\,\delta v = 200$ kHz,
with $2\ 10^9$ atoms /s through mode,

our experiment at beam velocity 50 m/s

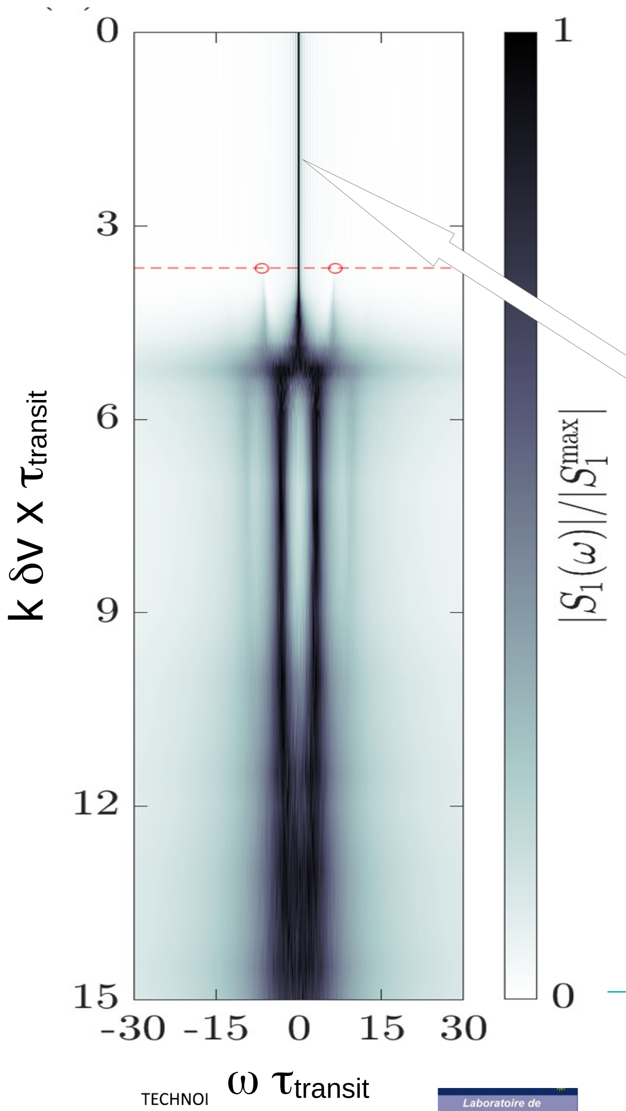
Monomode, sub-natural-linewidth



For us, κ ~ 630 kHz,
w ~ 100 kHz,
γ = 7 kHz
4g²/κ ~700 Hz

Theory by S. Jäger et al,
Phys. Rev. A, vol. 104,
page 033711, 2021

The LPL atomic-beam architecture : design choices



Theoretical literature of the atomic-beam SR laser based on Monte Carlo approaches

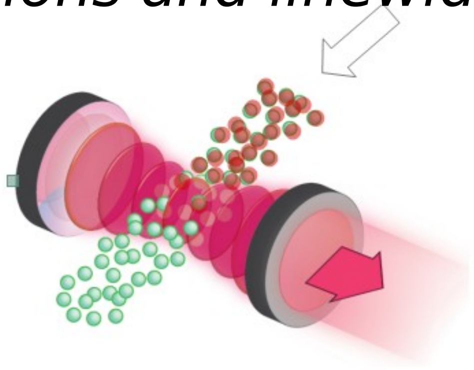
Our contribution :

- a **stand-alone** theoretical paper (from basics)
- **analytical expression** for threshold, power, atom-atom and atom-field correlations
- a picture to explain the **linewidth < γ**

Restriction : no Doppler shift, resonant cavity

→ Laburthe-Tolra et al, Scipost Physics Core 6, 015 (2023) *Correlations and linewidth of the atomic beam superradiant laser*

Laburthe-Tolra et al, Scipost Physics Core 6, 015 (2023)
Correlations and linewidth of the atomic beam superradiant laser



We derive the equations of evolution for:

- Intra-cavity atom population inversion (sz)
- Intra-cavity atom dipole quadrature (sx,sy or s+, s-)
- Intra-cavity field (b, b+)

Infinite set of coupled equations
(cumulant expansion)

cf Debnath, Zhang and Molmer, PRA 2018

$$\frac{d\left\langle s_j^-\right\rangle}{dt} = 2ig\left\langle s_j^z b\right\rangle - \frac{\Gamma}{N}\left\langle s_j^-\right\rangle - \frac{\gamma}{2}\left\langle s_j^-\right\rangle$$

$$\frac{d\left\langle s_1^z b\right\rangle}{dt} = \quad \ldots$$

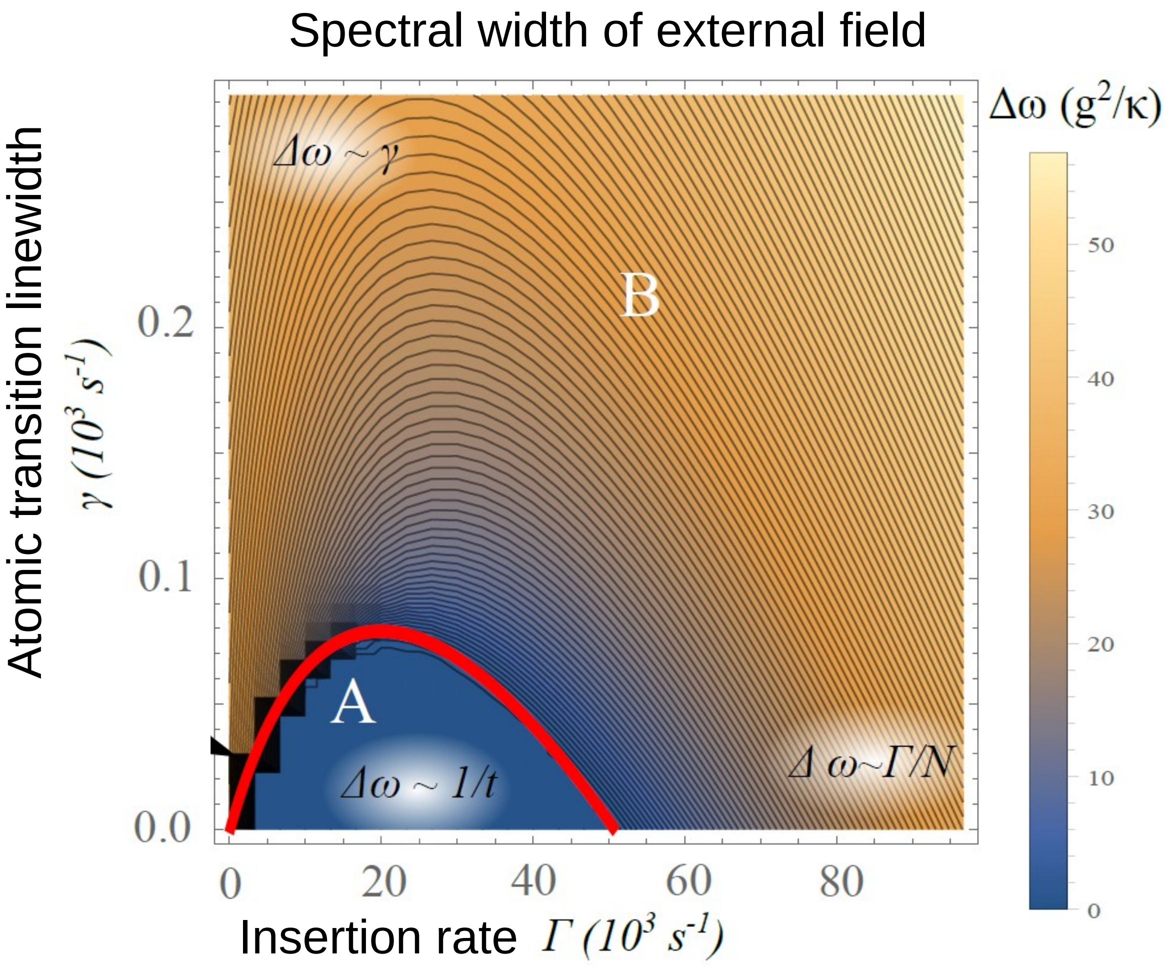
Choose approximation degree

Mean-field : <AB> = <A> <B>

To second order : <ABC> = <AB> <C> + <BC> <A> + <CA> <B> - 2 <A><B> <C>

Within mean field approximation (<A.B> =<A><B>) : understand the threshold

Plot at N constant



Γ: insertion rate:

$\Gamma_R = \Gamma/N$: transit rate (Refreshing rate)

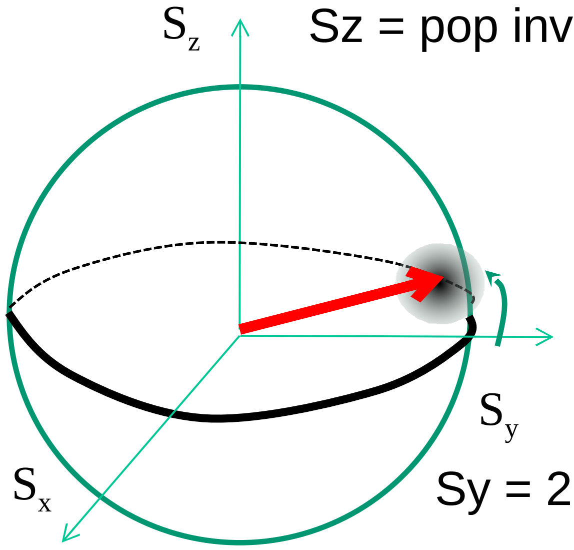
Red line : **analytical** requirement for steady-state macroscopic dipole

implies

$$\begin{cases} \Gamma_R > \gamma \\ N\dfrac{g^2}{\kappa} = N C \gamma > \dfrac{\Gamma_R}{2} \end{cases}$$

At second order in cumulants (<A.B.C> ~ <A.B><C> + <A><B.C> + ...): understand the coherence

Reminder : the electric field follows the collective atomic dipole



Sz = pop inversion

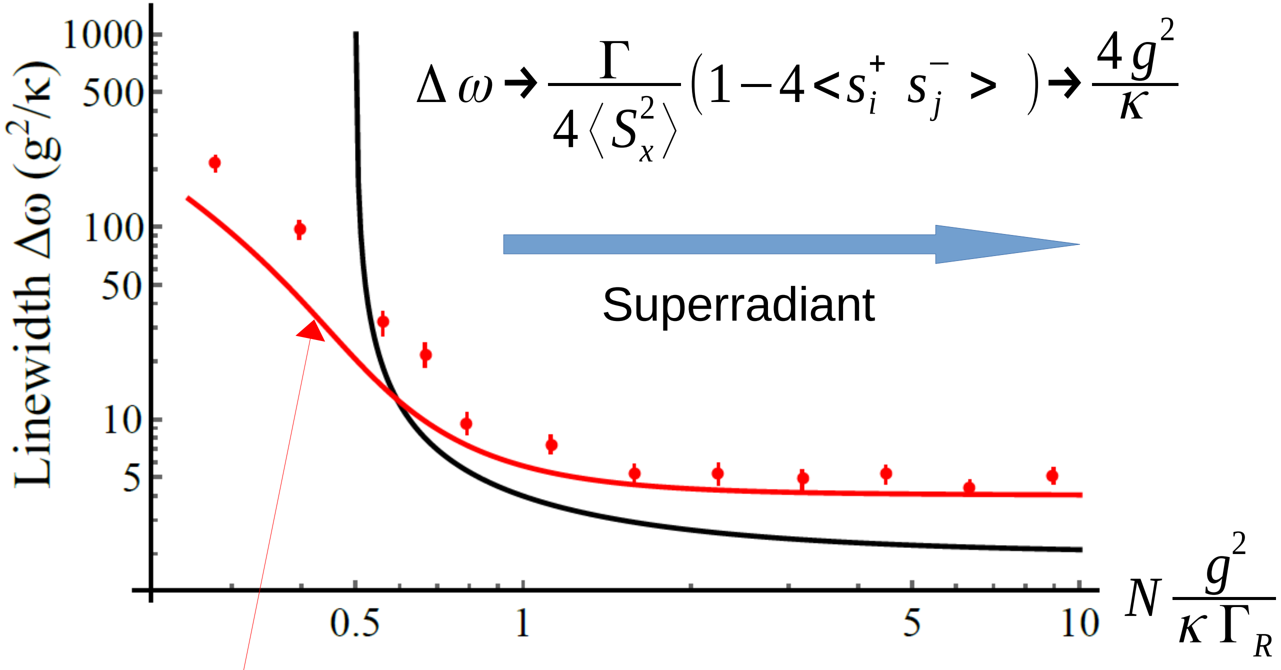
Sy = 2nd dipole quadrature

Sx = 1st dipole quadrature

Collective dipole phase diffusion:

$$\langle S_x(t+dt)S_x(t)\rangle = \langle S_x^2\rangle \exp\left(-\frac{dt}{\tau_c}\right)$$

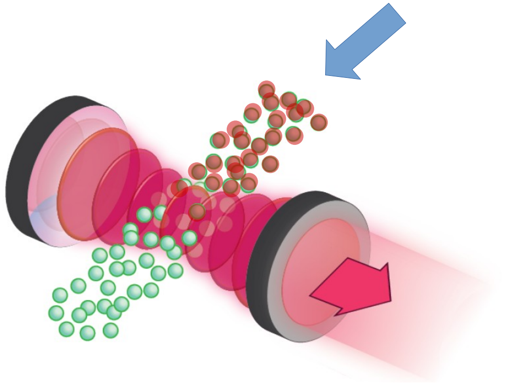
$$\boxed{\frac{1}{\tau_c} = \Delta\omega}$$

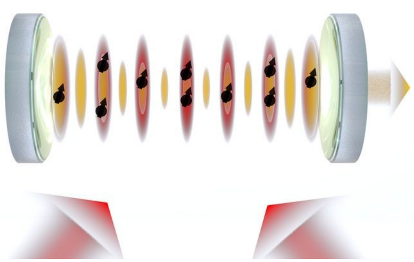


$$\Delta\omega \rightarrow \frac{\Gamma}{4\langle S_x^2\rangle}\left(1-4<s_i^+ s_j^- >\right) \rightarrow \frac{4g^2}{\kappa}$$

2nd order cumulant method, steady-state solution

Developing the two architectures





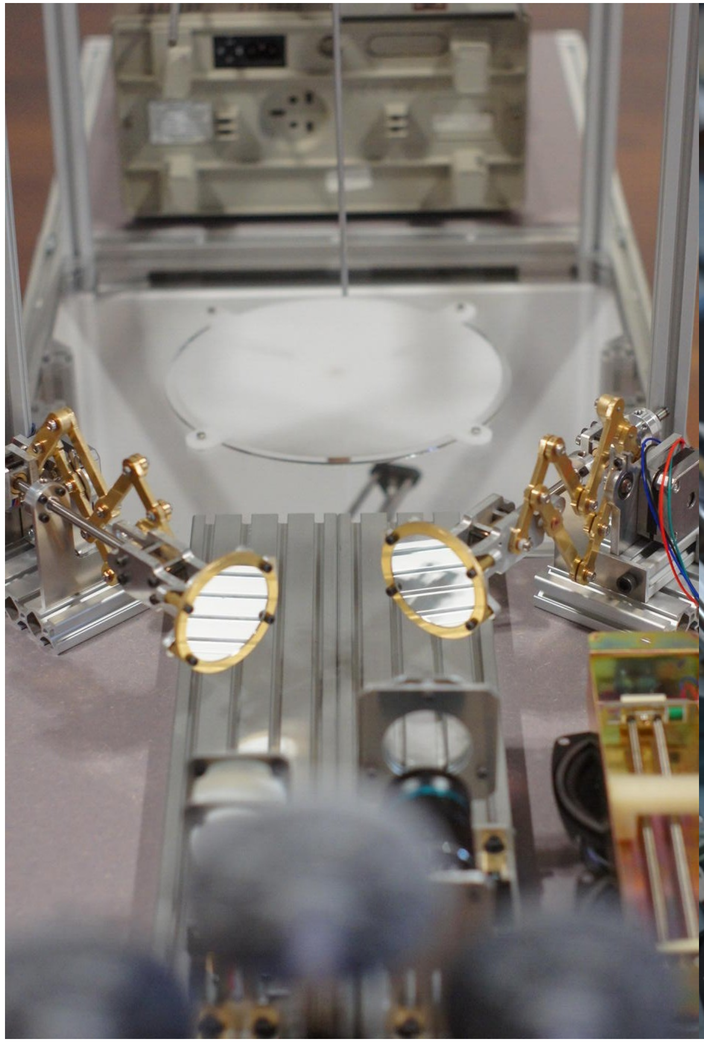
Complexity	Rather low	Rather high (trapping, cooling, conveyor belt, repumping lasers ...)
Optical transitions	The threshold requirement $NC\gamma > 1/t\_transit$ **$> k\,\delta v$** requires more atoms than NC > 1 → **require “broad” line** **γ ~ optical recoil energy optimal**	Motion essentially frozen Main condition remains NC > 1 → **Clock-line compatible**
Shifts	No first order transverse Doppler shift ***if cavity symmetric*** Second order Doppler shift at 20 m/s : - 1 Hz	Requires “magic” trapping wavelength Many laser fields (repumping, cav lock) Complex vacuum system (black body)
Role	Optical-domain flywheel	From optical-domain flywheel to “competitor” to lattice clocks? → **investigations required on systematic effects**

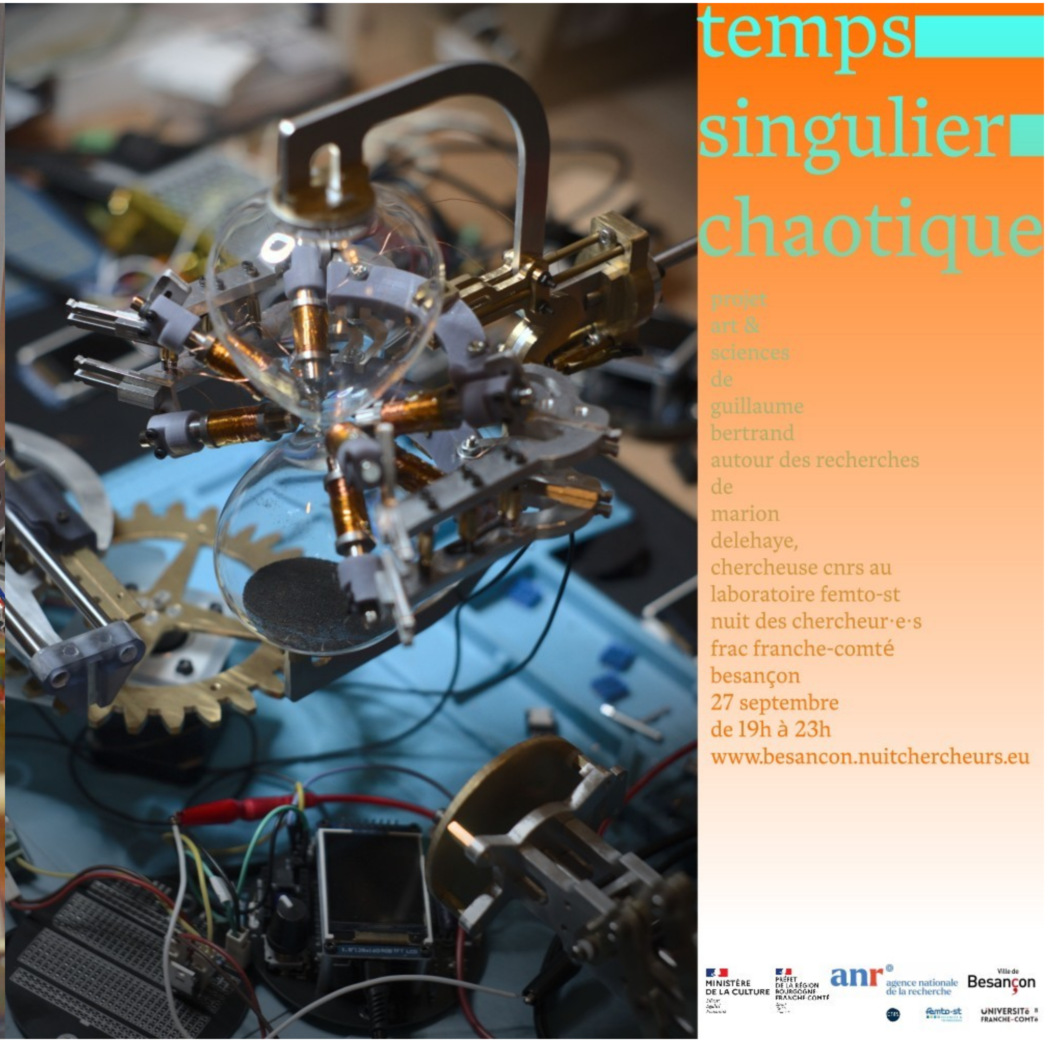
European Springboard

QURIOUS proposal (ITN)

- 🟥 Superradiant laser (exp.)
- 🟧 Superradiant laser (th.)
- 🟪 QND, squeezing
- 🟦 Industrial partner
- 🟨 Other academic partner

Arts&Science project: « Temps Singulier Chaotique »





temps
singulier
chaotique

projet
art &
sciences
de
guillaume
bertrand
autour des recherches
de
marion
delehaye,
chercheuse cnrs au
laboratoire femto-st
nuit des chercheur·e·s
frac franche-comté
besançon
27 septembre
de 19h à 23h
www.besancon.nuitchercheurs.eu

Funded by ANR CONSULA project