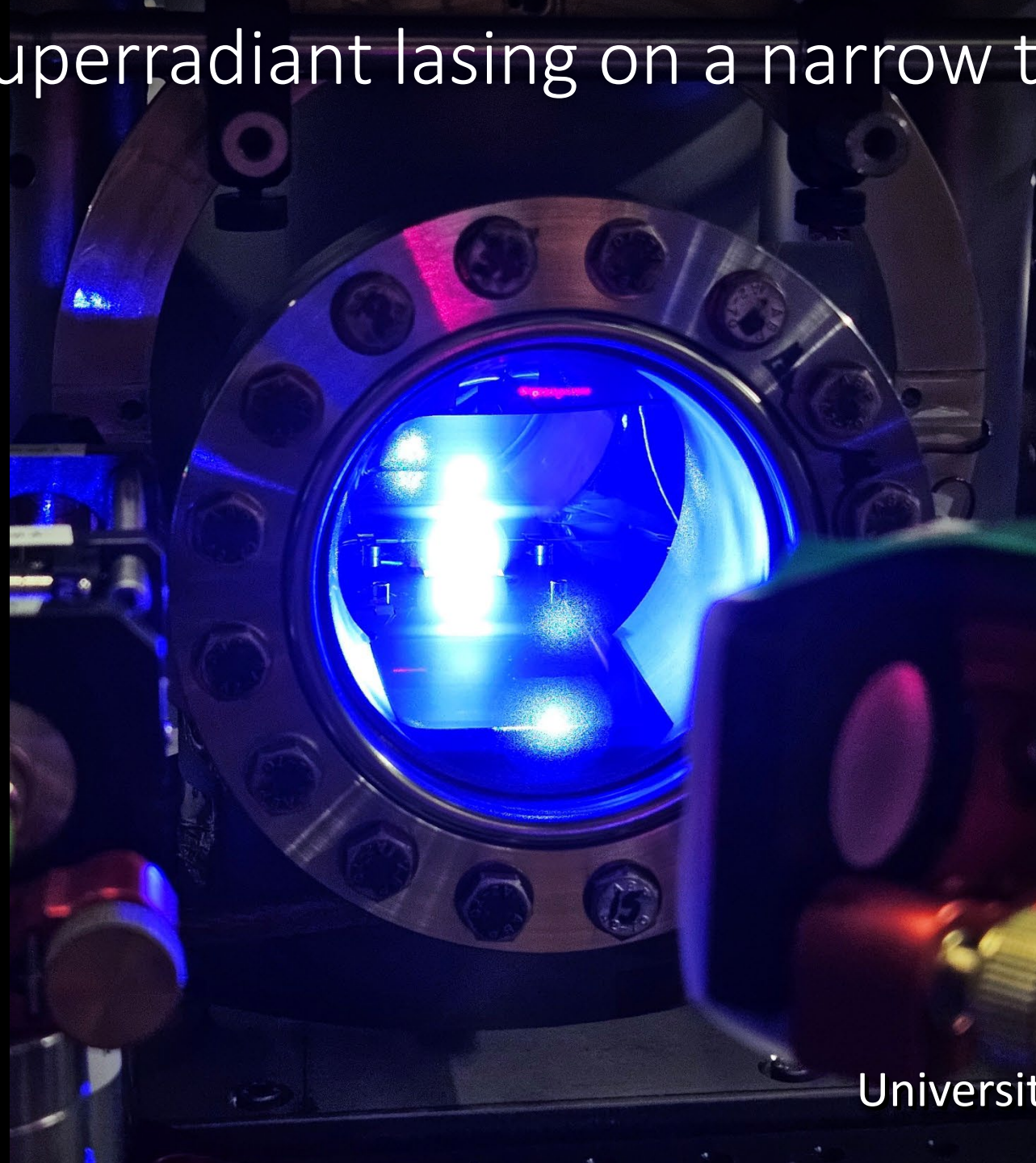


Continuous superradiant lasing on a narrow transition



Florian Schreck
University of Amsterdam

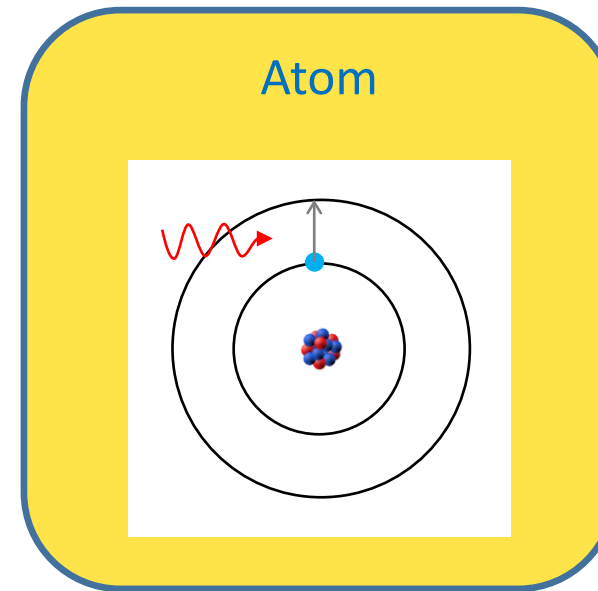
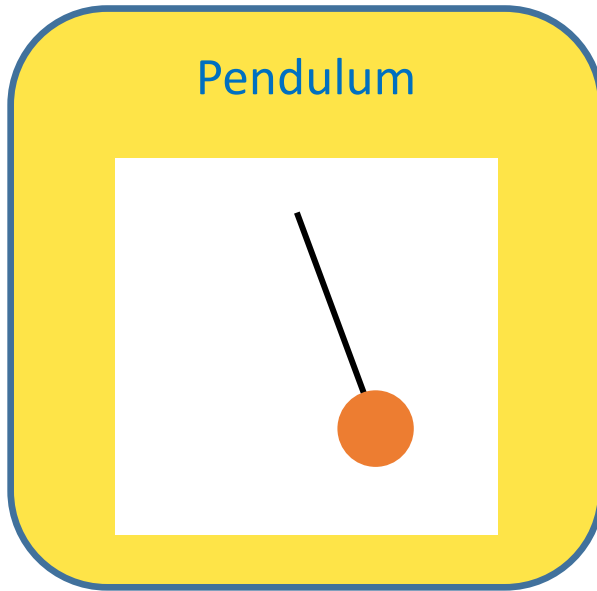








Classical vs. quantum sensors

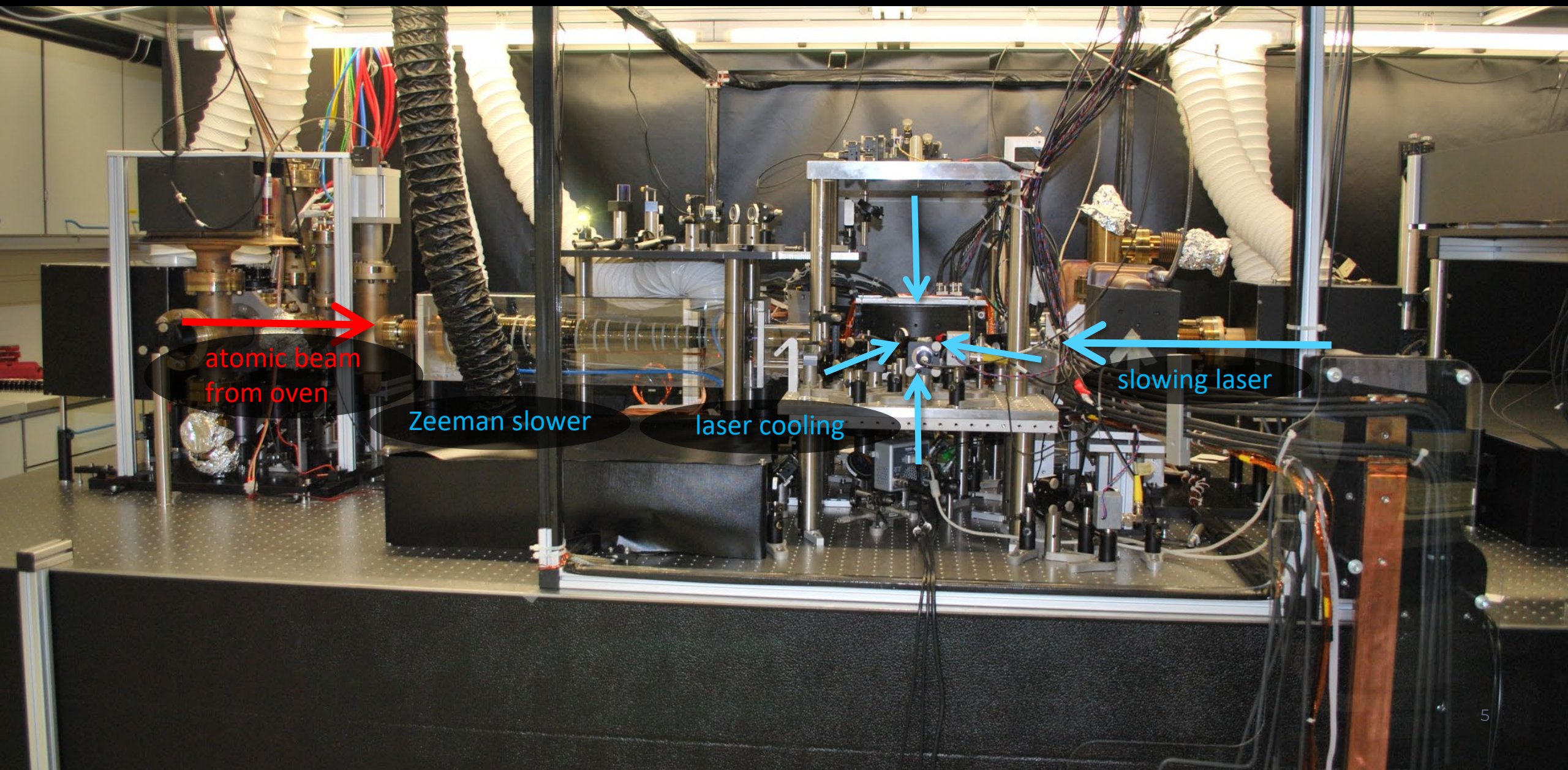


Highest accuracy

High transition frequency	→	optical transitions
Narrow transition	→	mHz linewidth
Large signal	→	use many atoms
Undisturbed by other atoms	→	use gas of atoms
No Doppler shift	→	cool atoms to standstill



Ultracold fridge



atomic beam
from oven

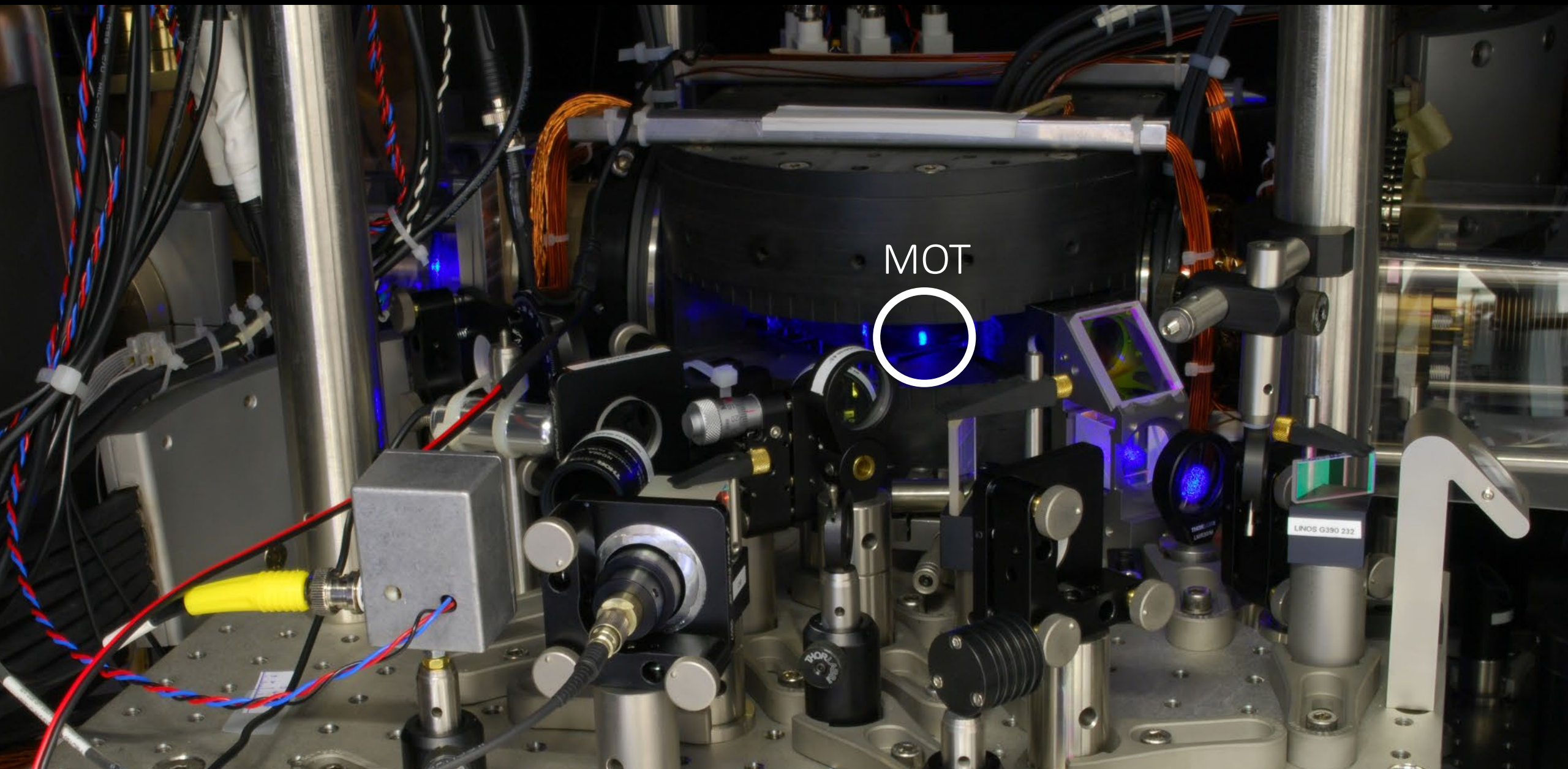
Zeeman slower

laser cooling

slowing laser

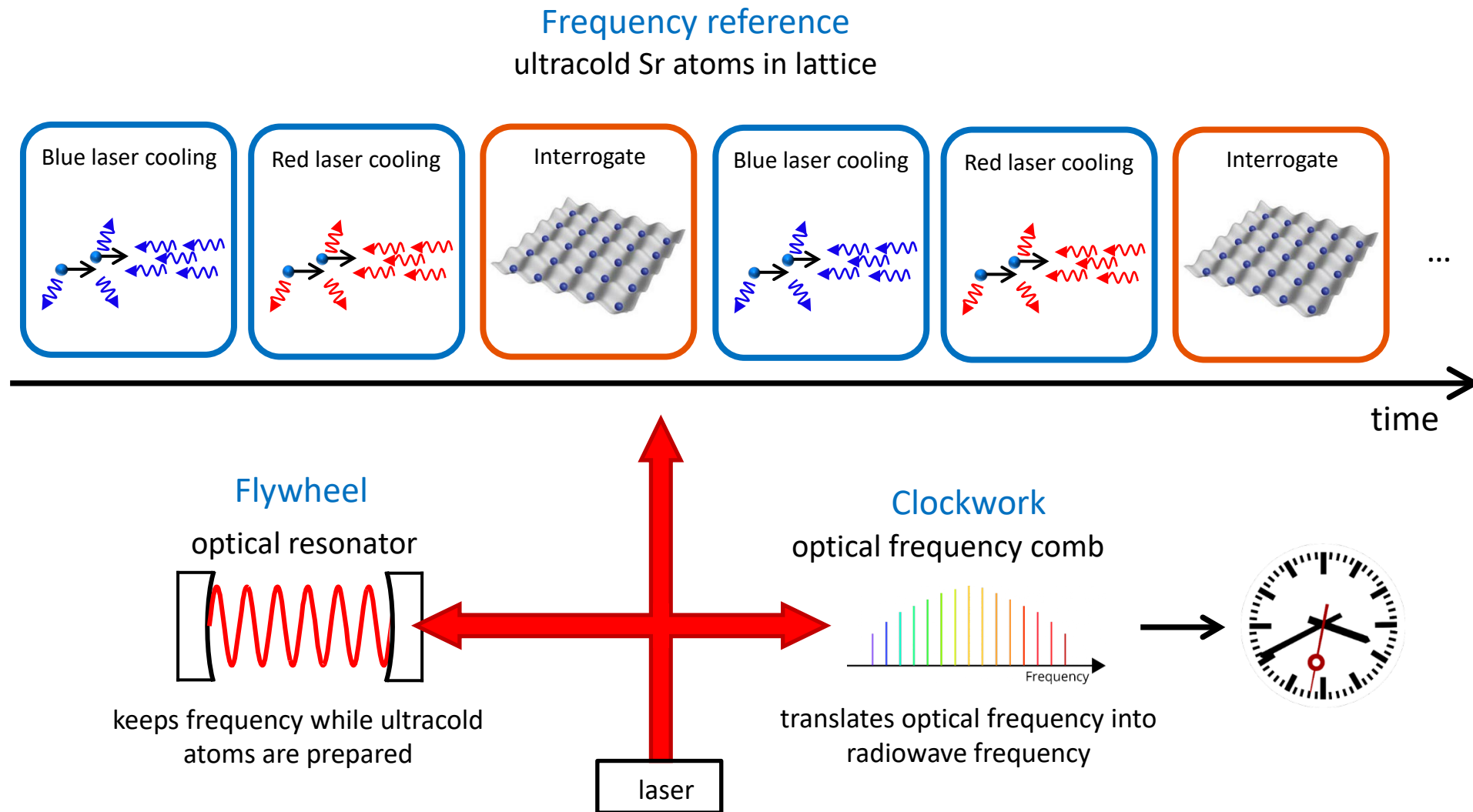


Magneto-optical trap of strontium





Clock operation scheme

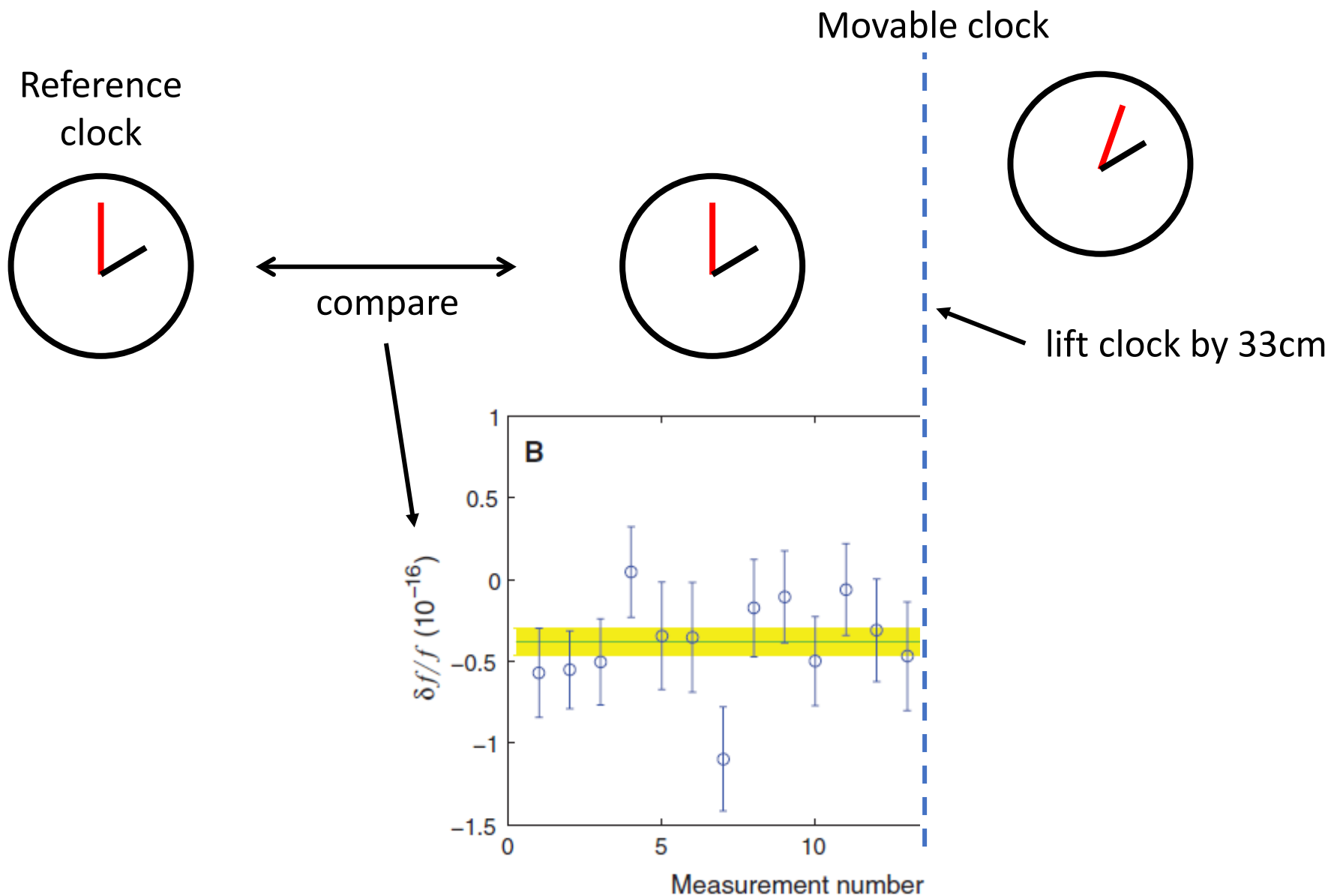




Interstellar



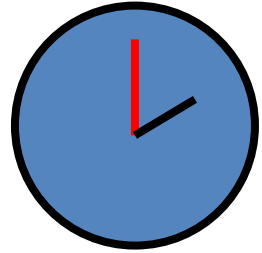
Time and gravity



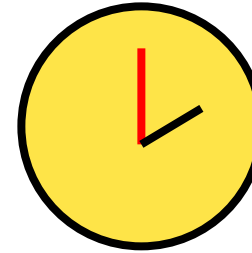


Are the „constants of Nature“ constant?

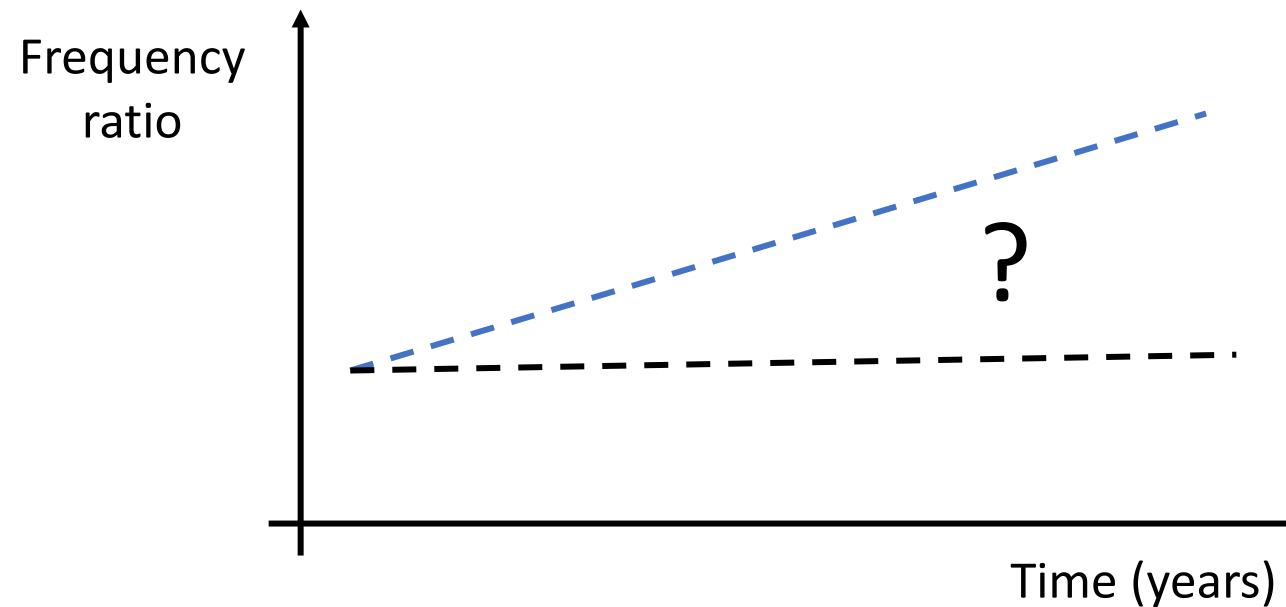
Clock
using Sr



Clock
using Yb



←→
compare

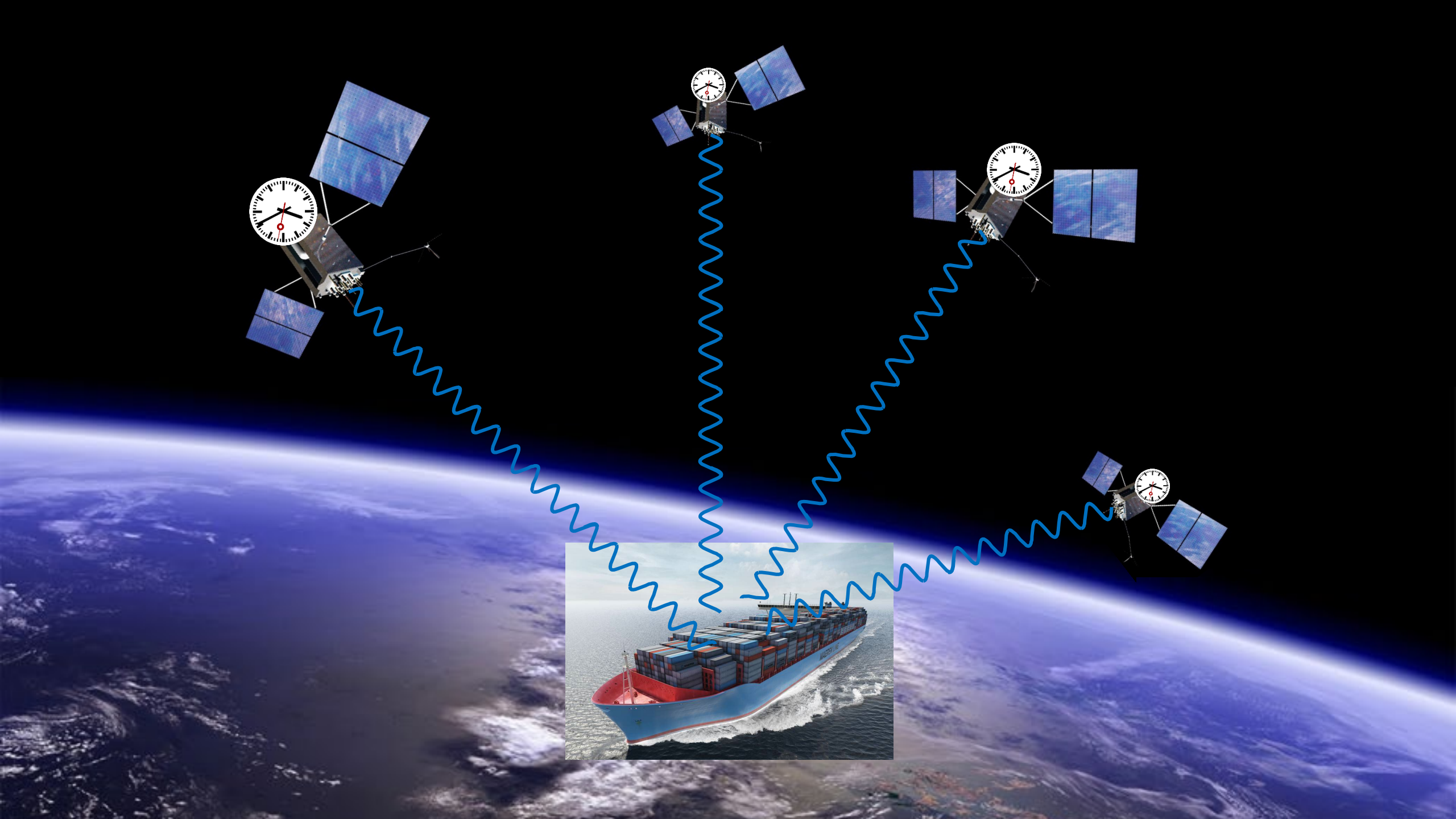


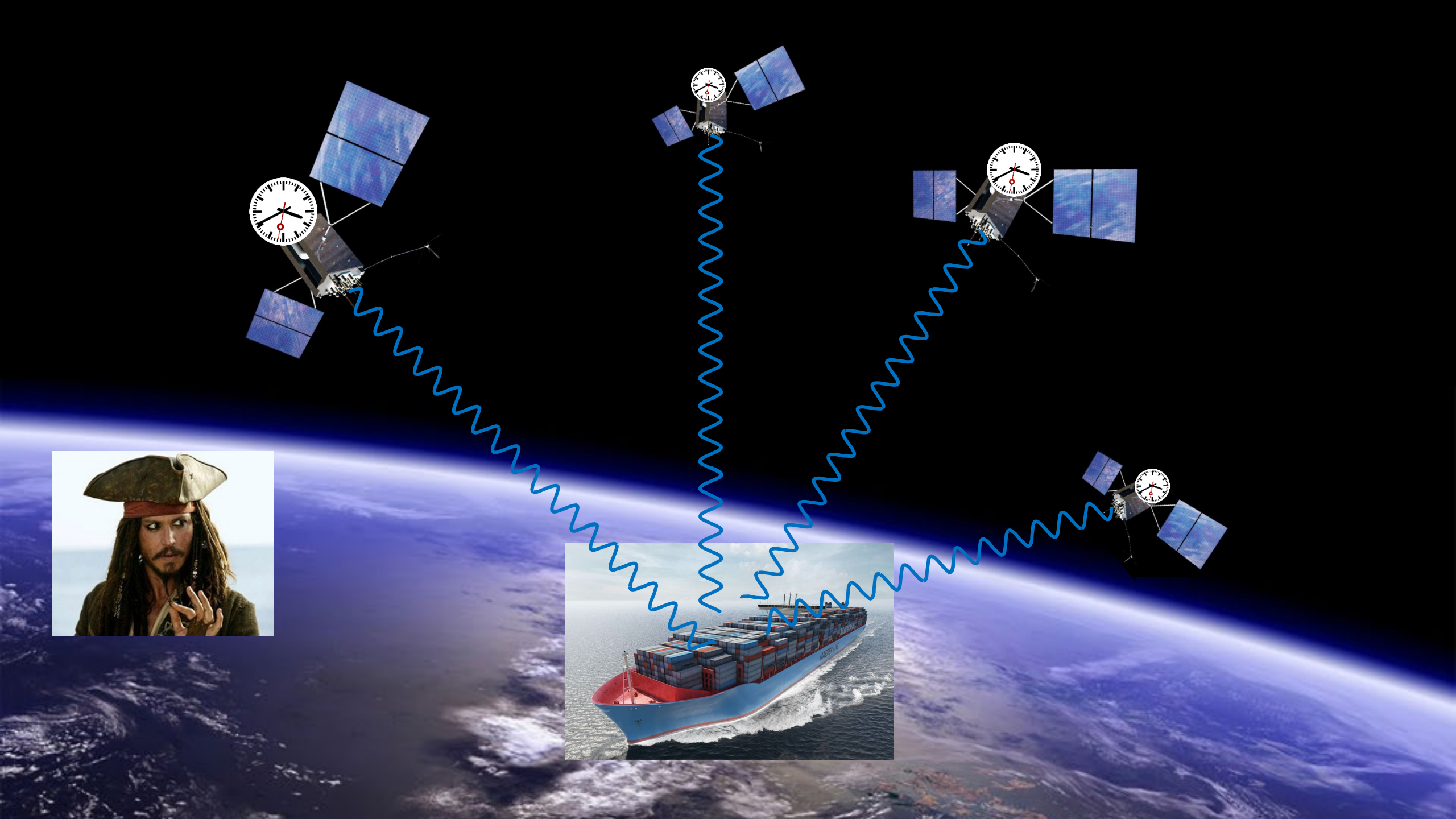
Infrasound gravitational wave detection

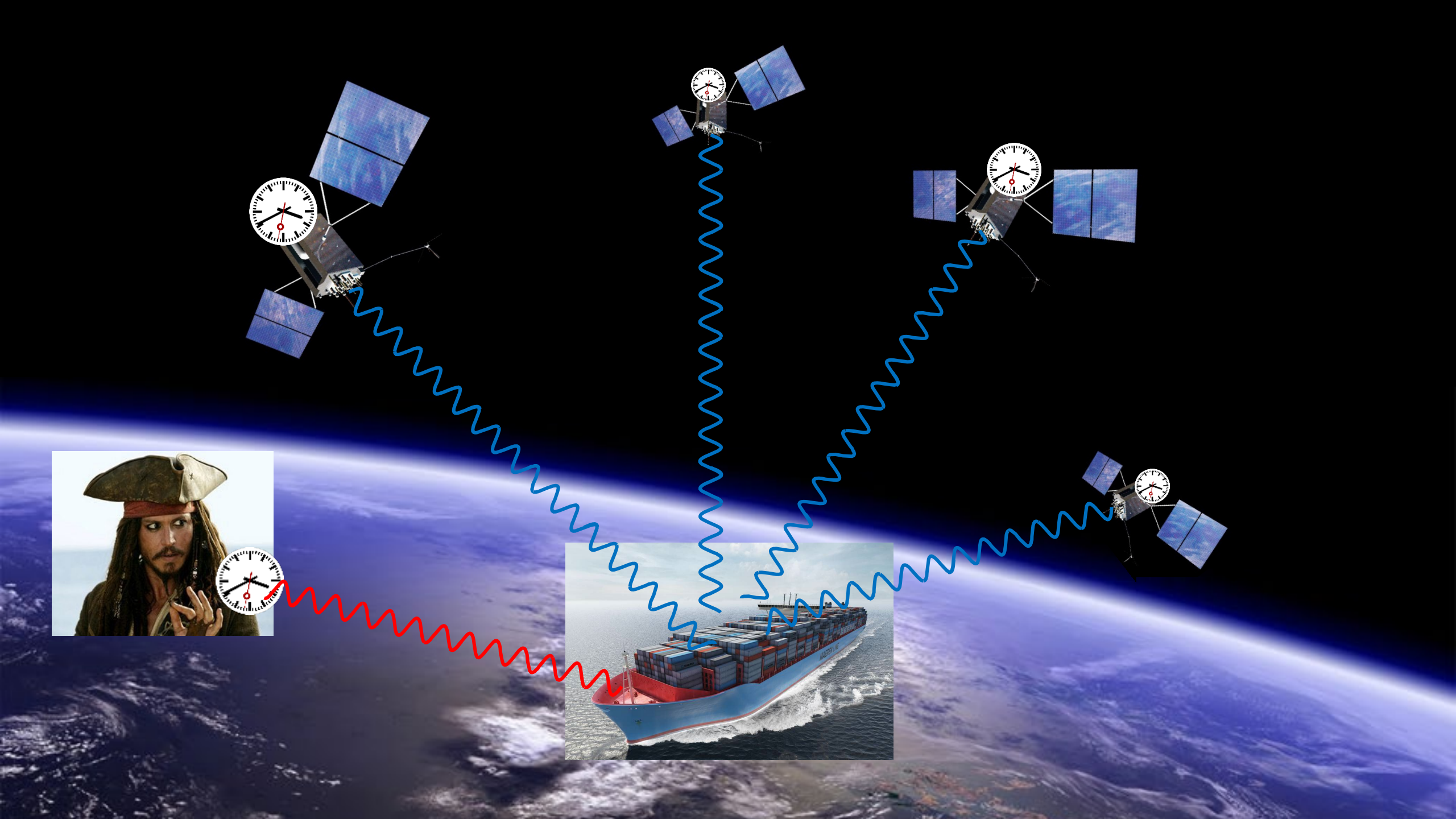
S. Kolkowitz et al., Phys. Rev. D 94, 124043 (2016)

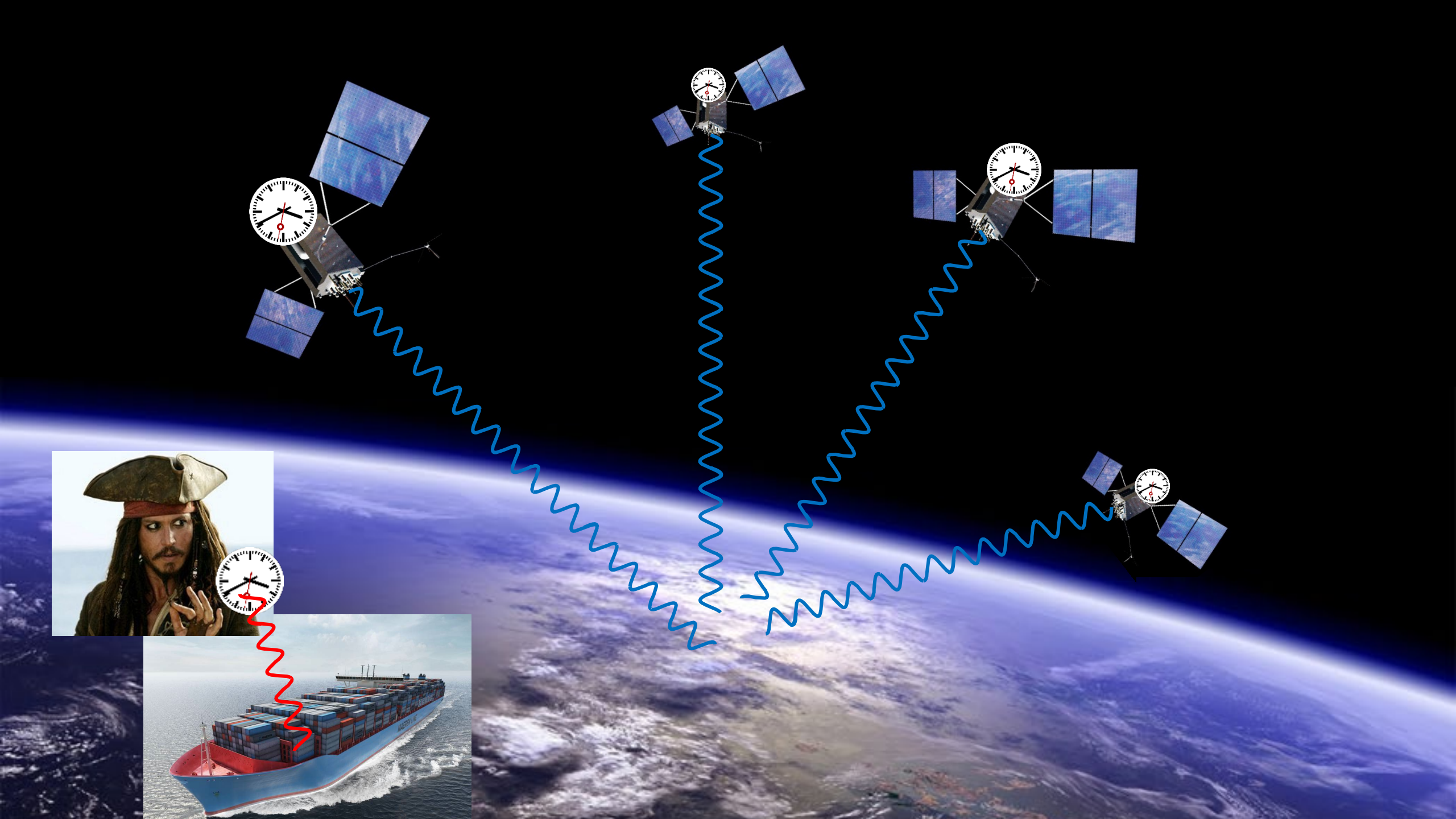
*Picture credits:
ESA, ARTEMIS*

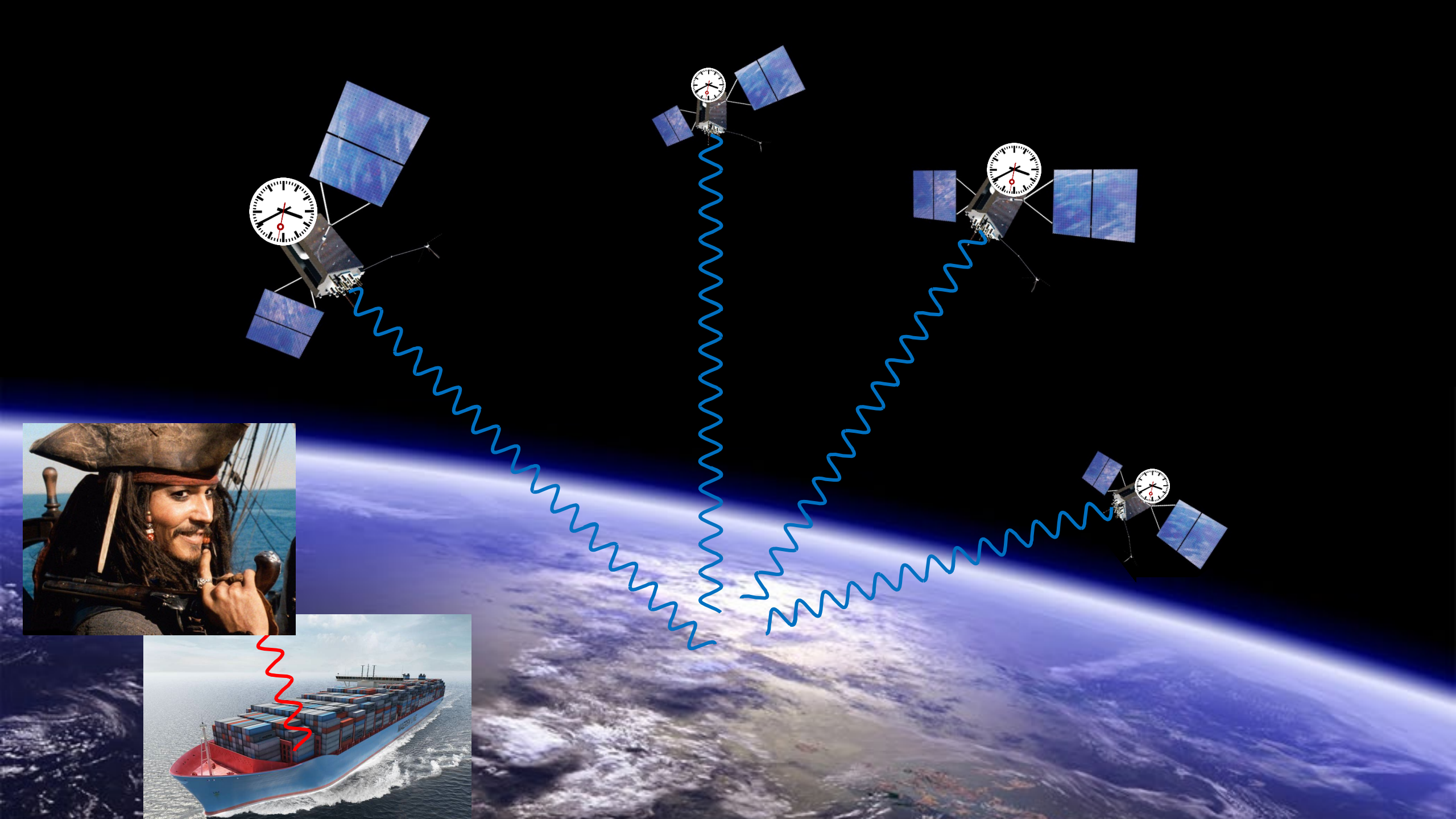


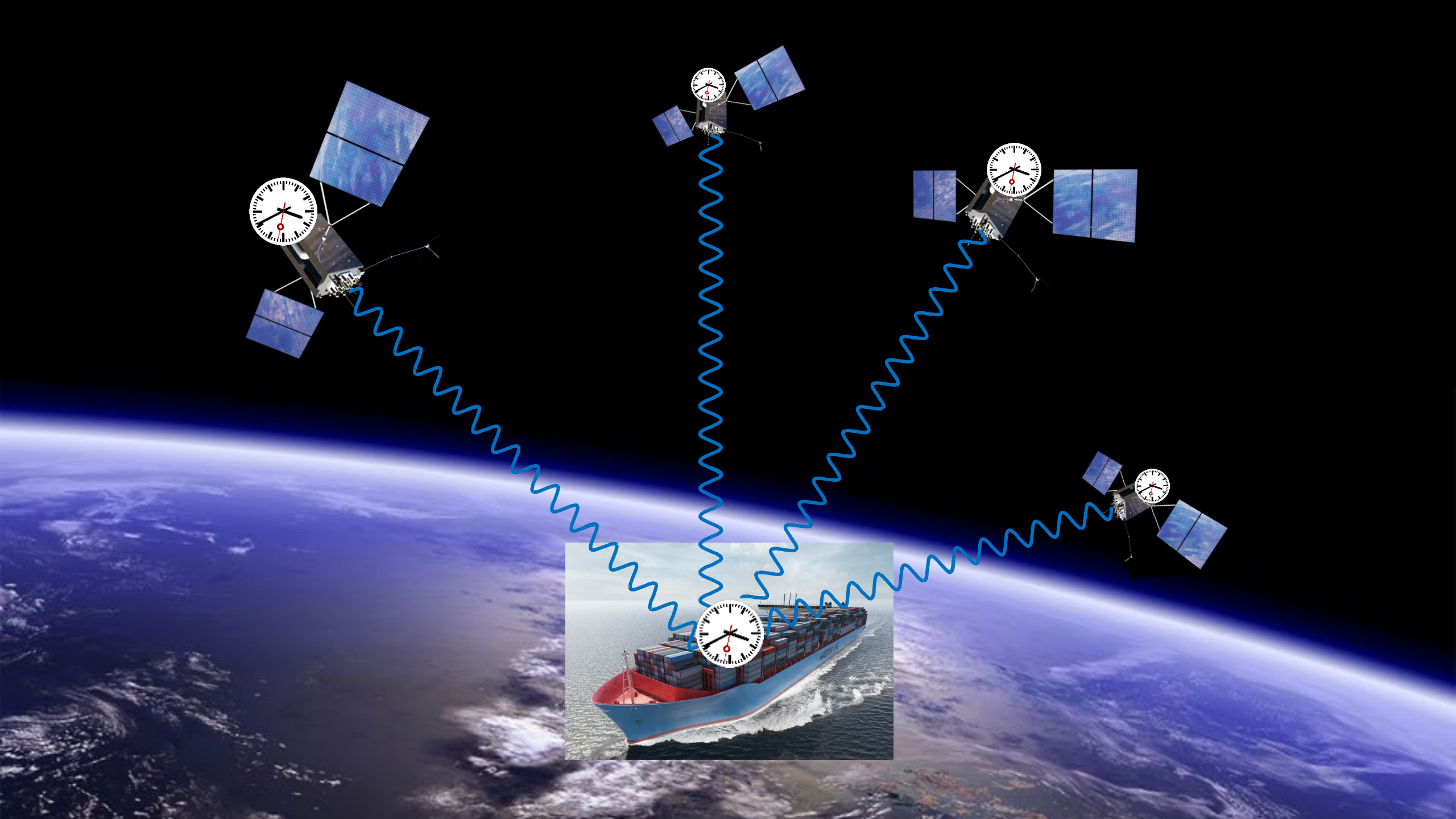


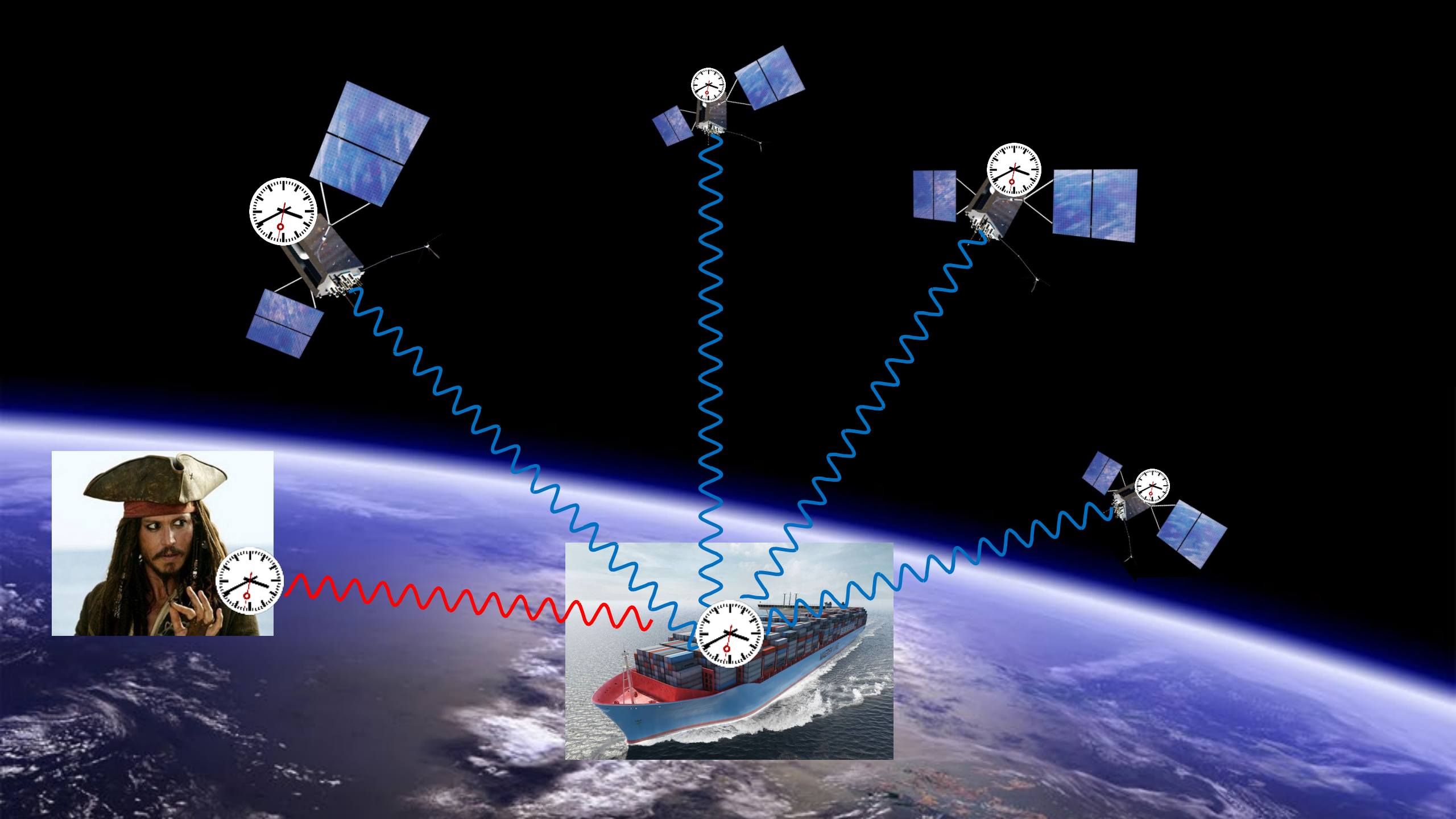


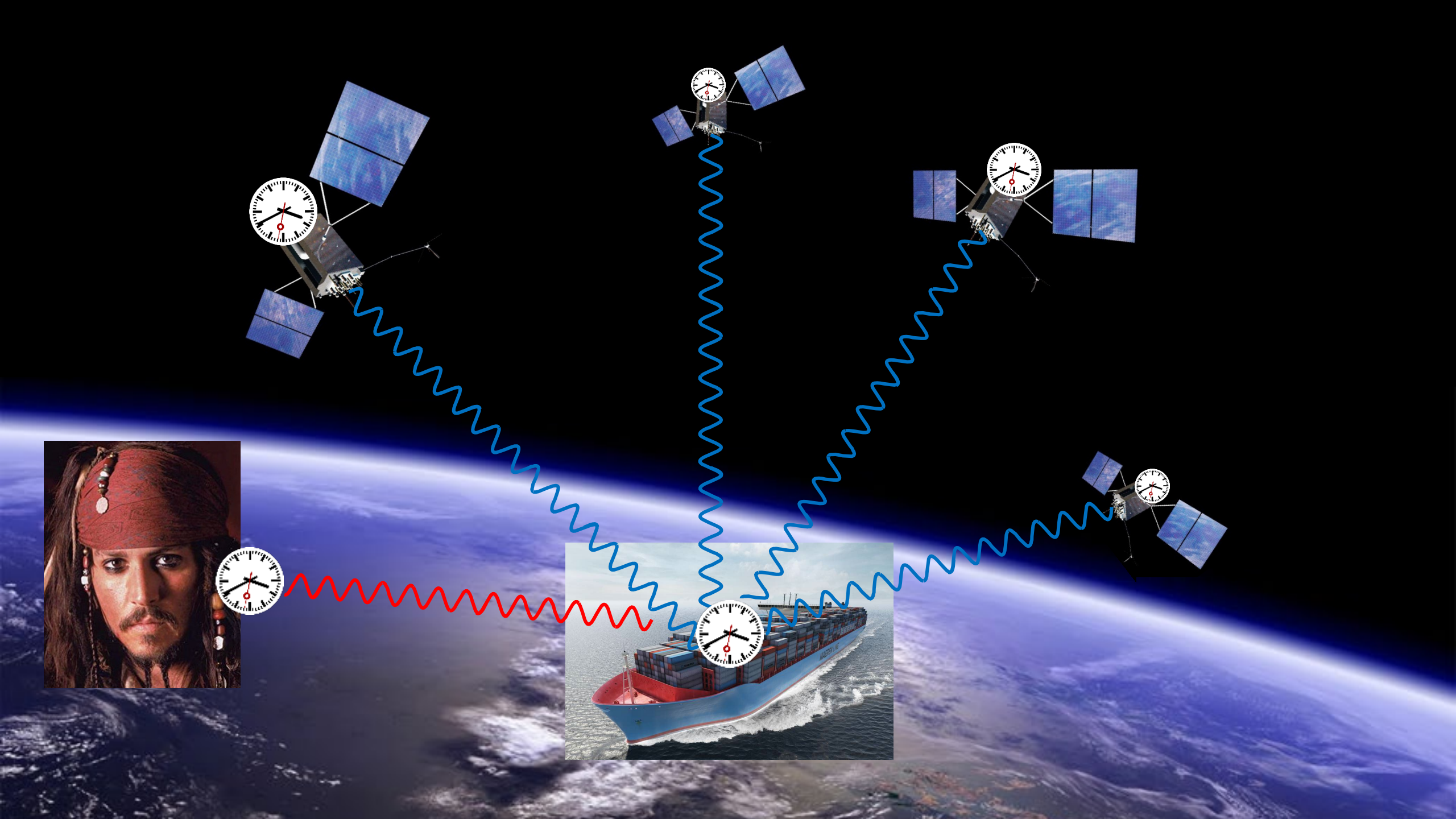


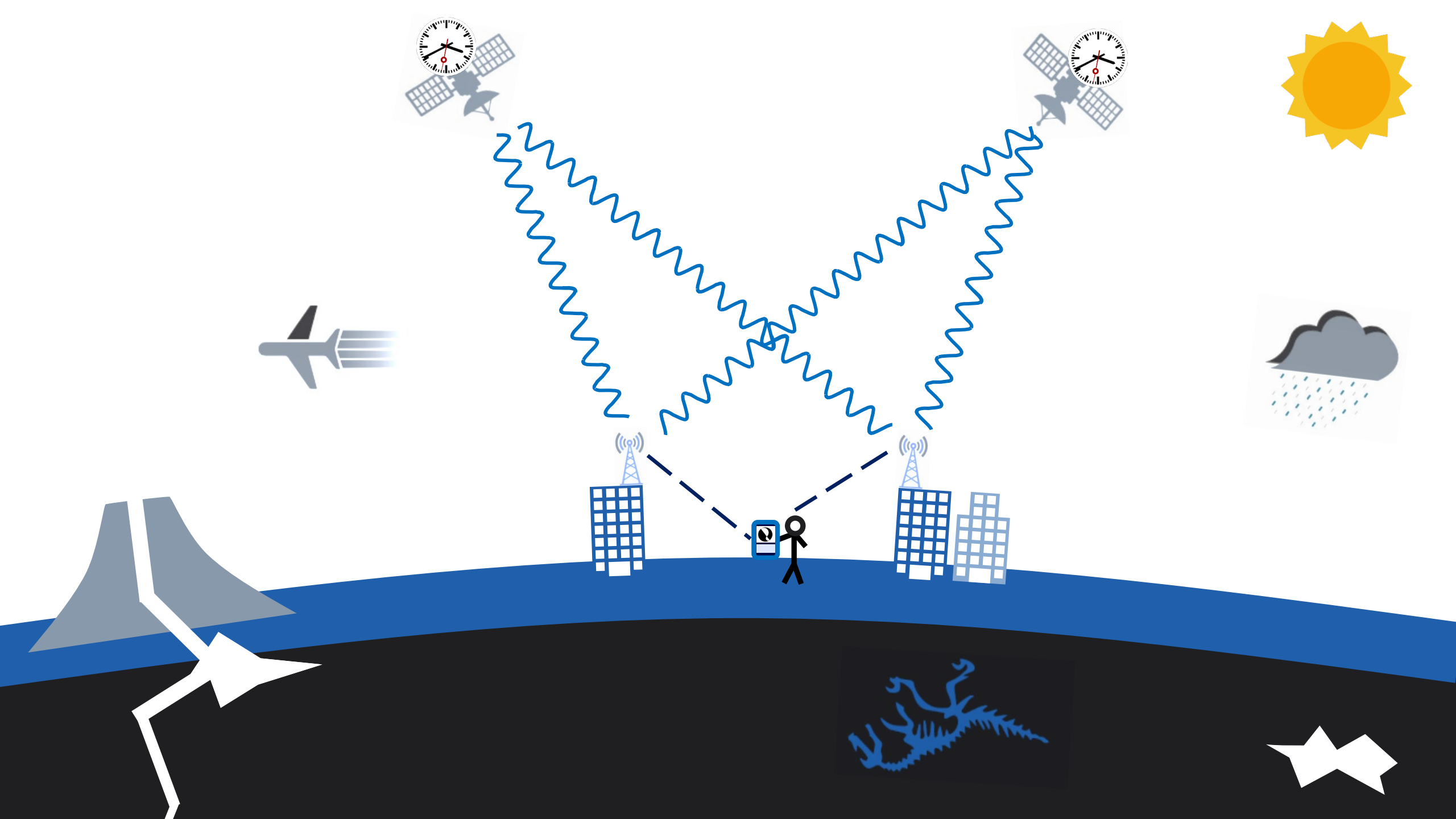


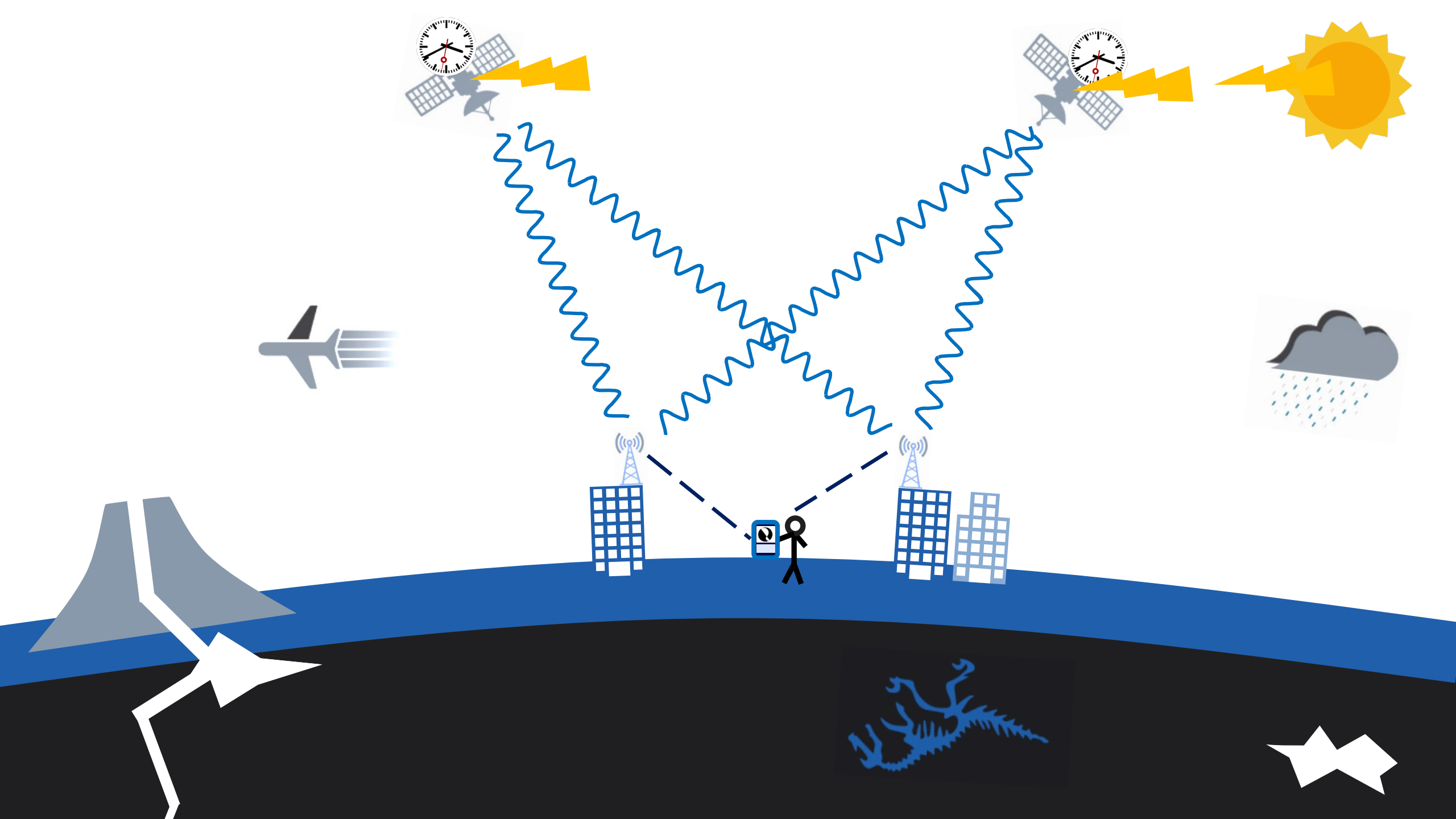


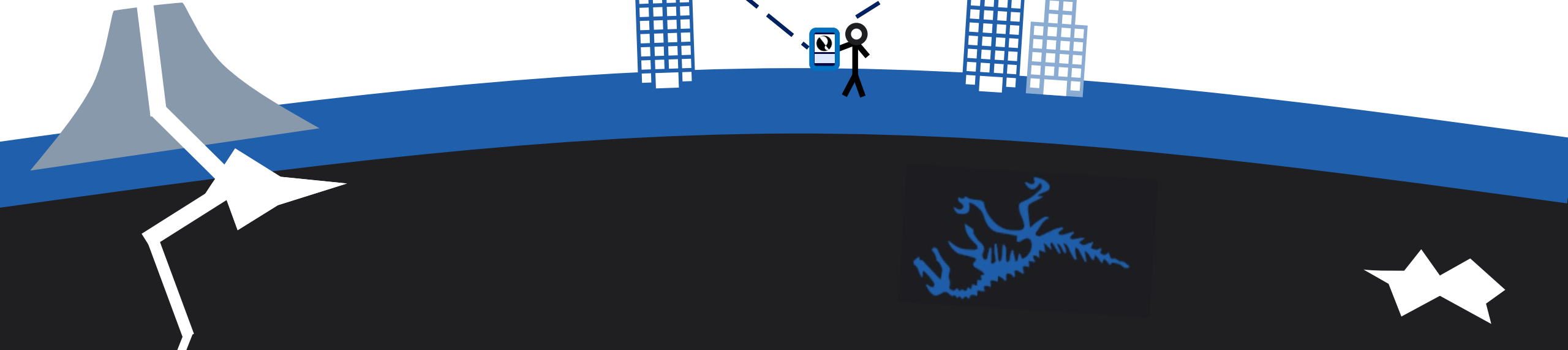
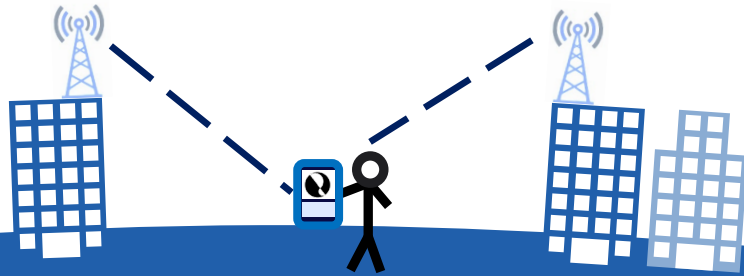
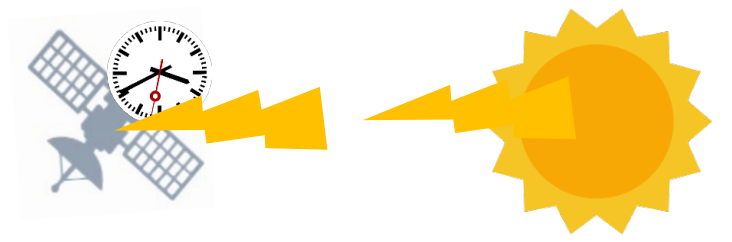
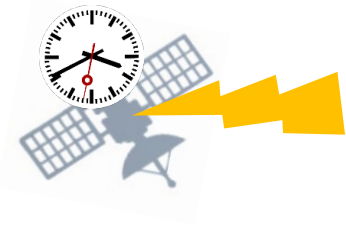


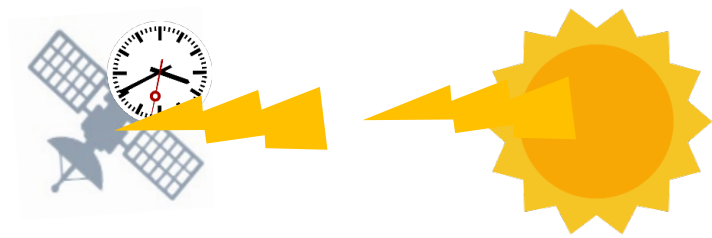
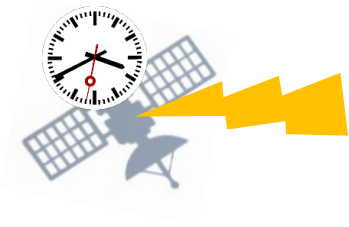


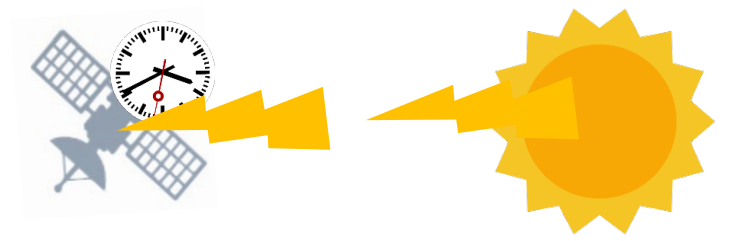
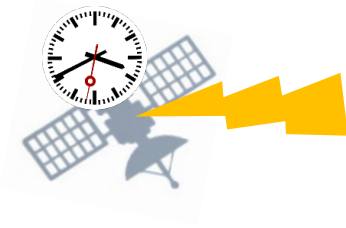


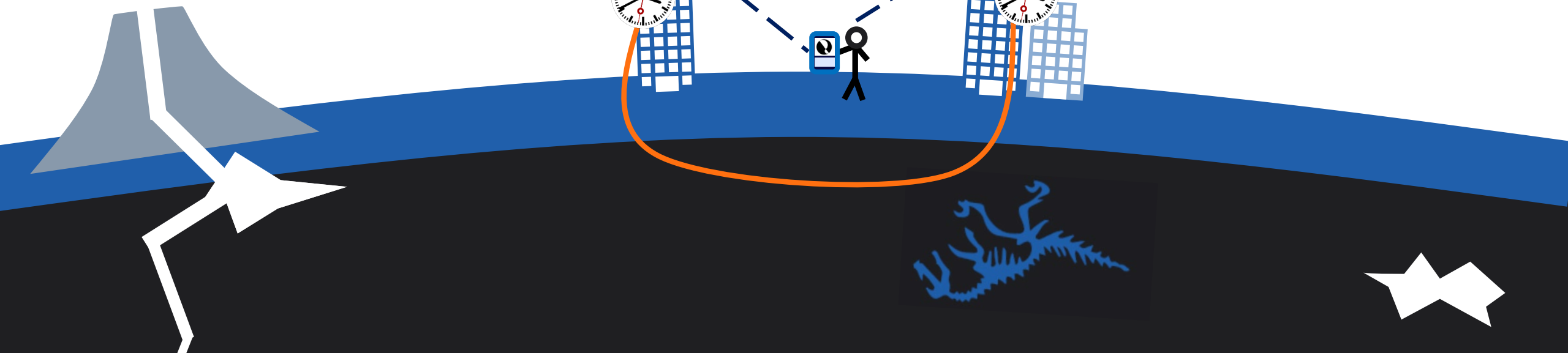
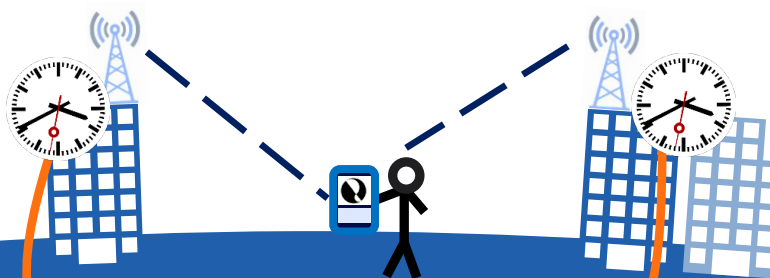


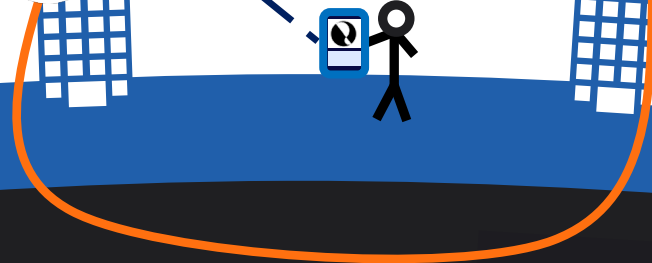
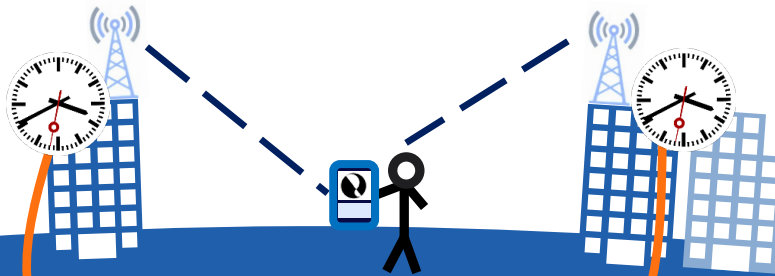
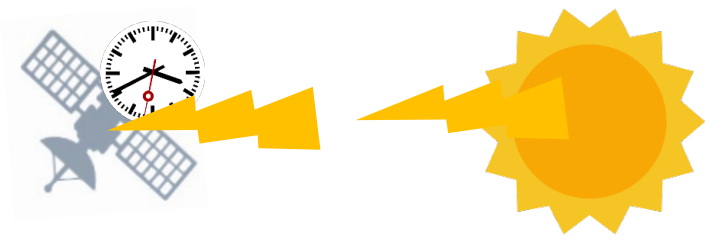
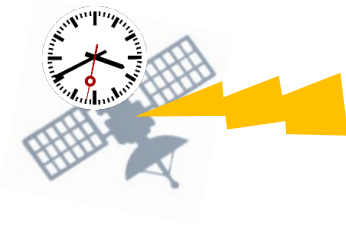




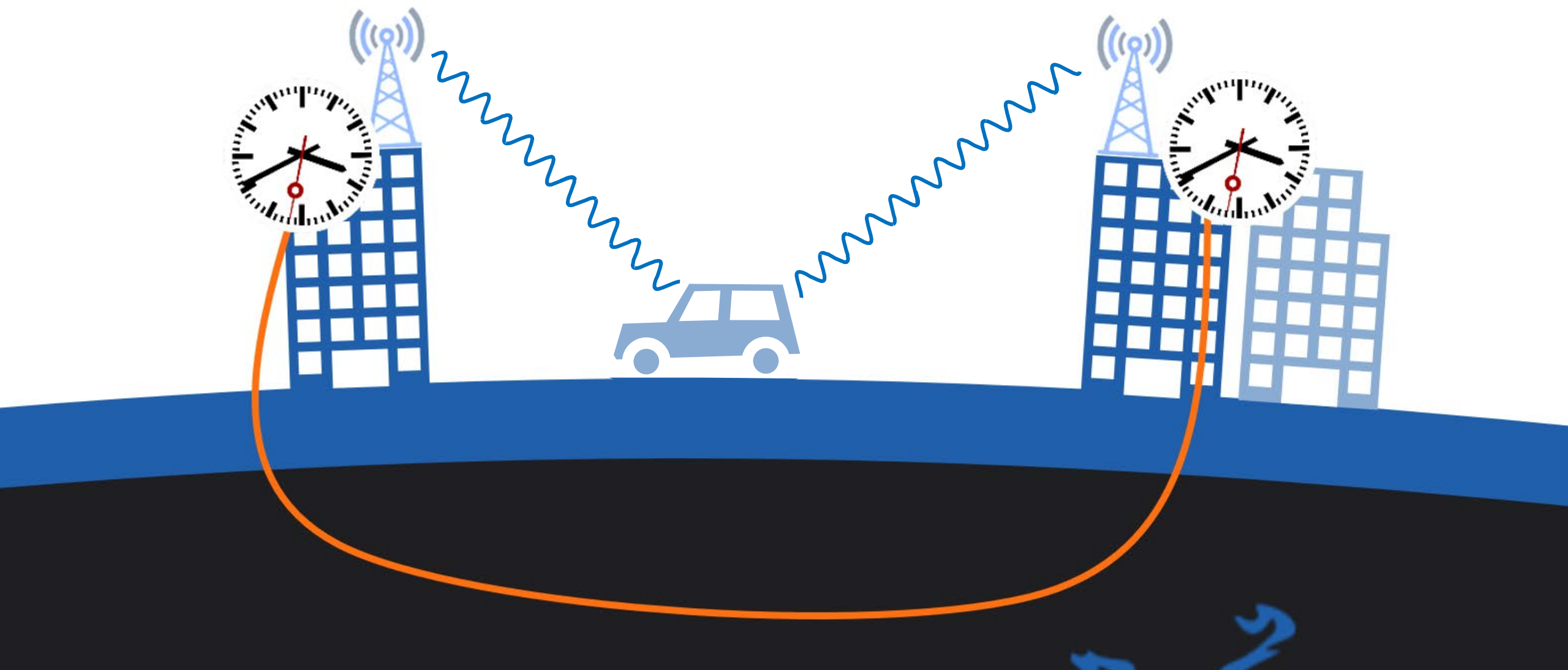






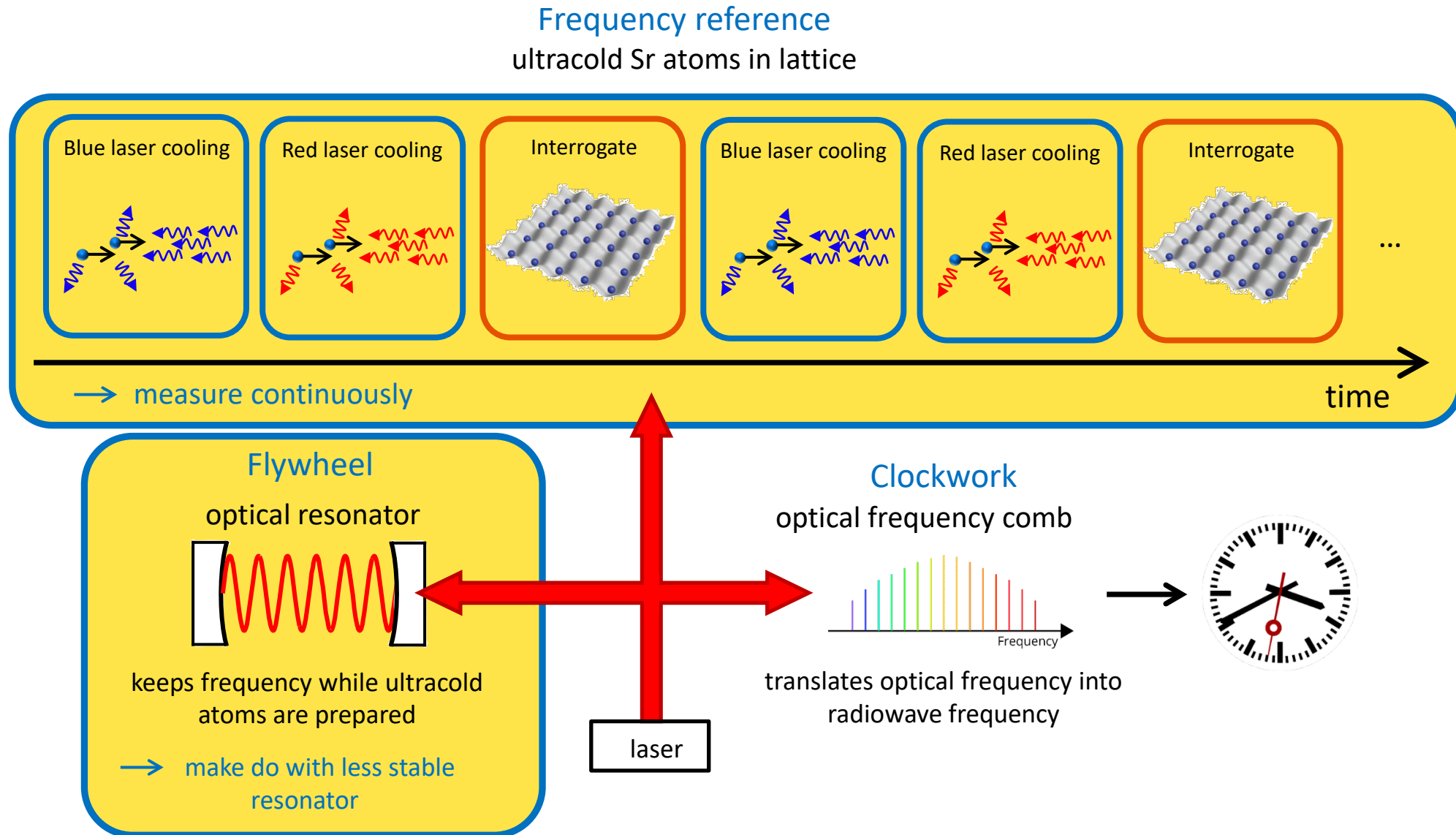








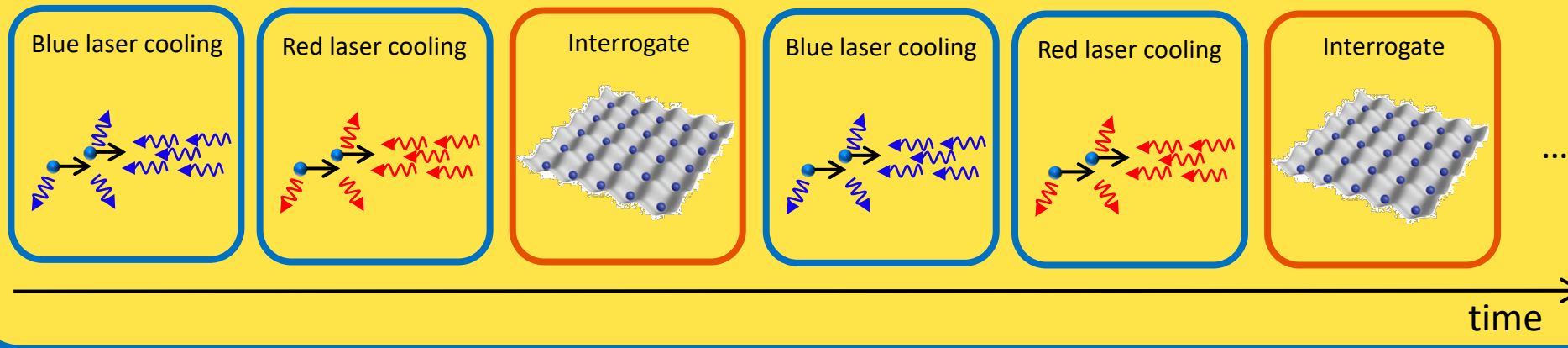
Improving clocks: from pulsed to continuous operation



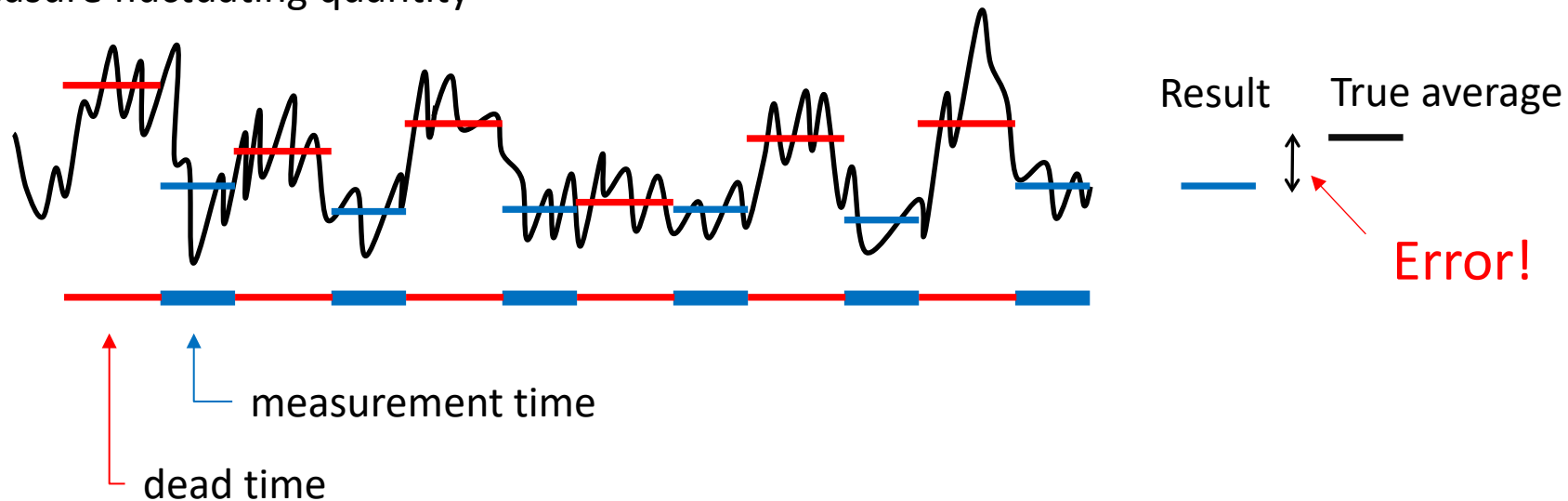


Challenge: measurement deadtime

Ultracold atoms only intermittently available



Measure fluctuating quantity



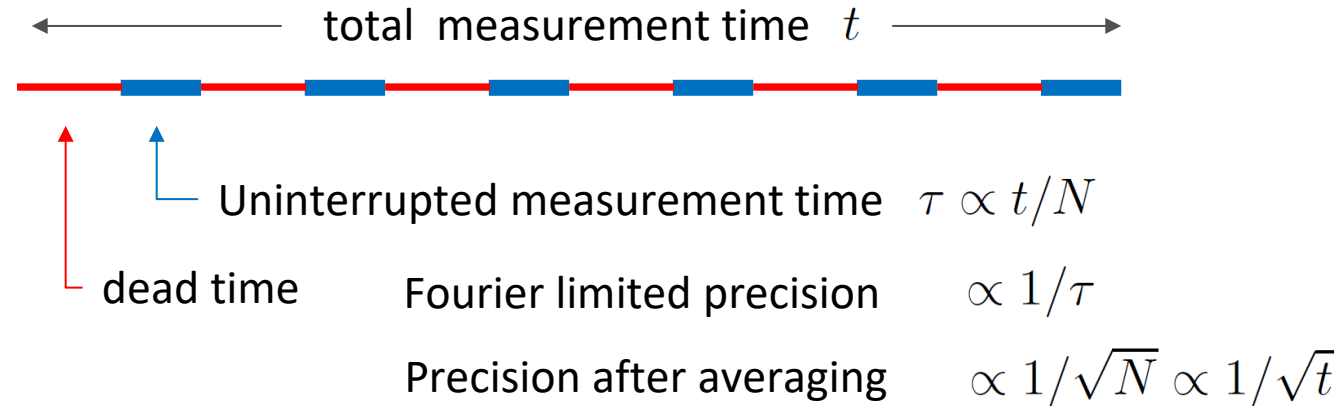
Solution for inertial sensors: combine classical high-bandwidth sensor with atomic high-accuracy sensor



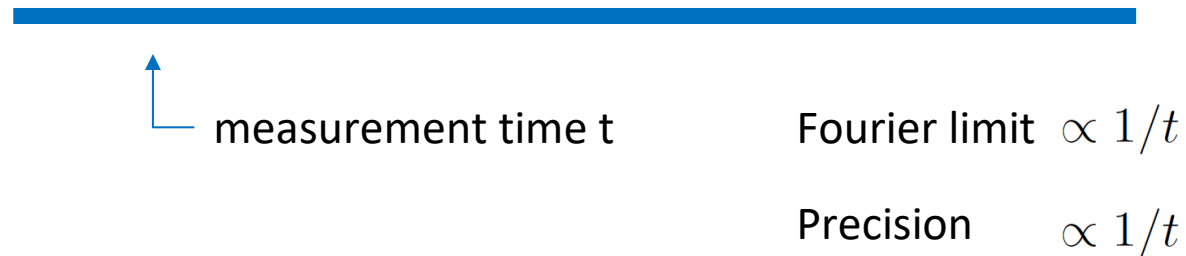
Challenge: measurement deadtime

Measurement precision over time

With dead time



Continuous measurement



→ Opportunity to reach 10^{-18} precision in 100 s instead of 10 000 s !

Need high signal-to-noise to work, i.e. high atom flux



Continuous ultracold atom optical clocks

More & more groups: Tokyo, Boulder, Copenhagen, Torun, Besancon, Paris, Bordeaux, London, Amsterdam,...

Zero-deadtime clock demonstrations: Ludlow group, Nature Photonics **11**, 48 (2017)
Yu-Ao Chen, Jian-Wei Pan group: arXiv:2509.15100

Continuous cavity spectroscopy proposal: JILA clock groups, PR A **92**, 053820 (2015).

Continuous Ramsey spectroscopy on ultracold atomic beam: Hidetoshi Katori, Appl. Phys. Express **14**, 072006 (2021).

Continuous superradiant clock proposals: Jingbiao Chen, arXiv:physics/0512096 (2005), Chinese Science Bulletin **54**, 348 (2009)
D. Meiser, J. Ye, D. R. Carlson, M. J. Holland, PRL **102**, 163601 (2009)

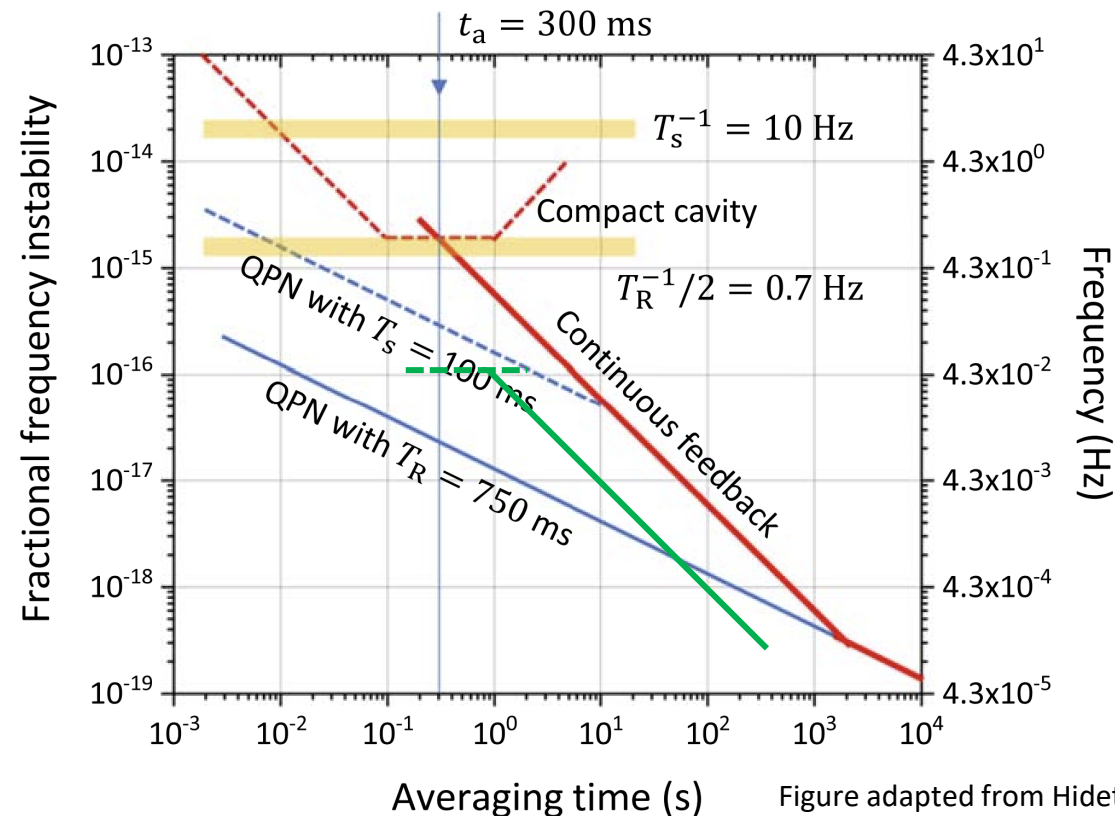


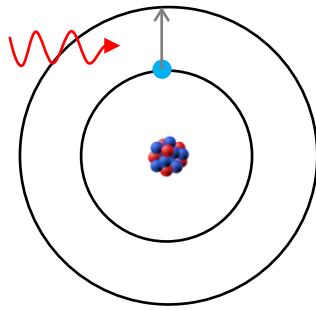
Figure adapted from Hidetoshi Katori, Appl. Phys. Express **14**, 072006 (2021).



Passive and active clocks

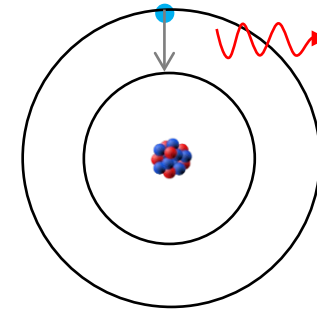
Passive clock

Light absorption
(spectroscopy)



Active clock

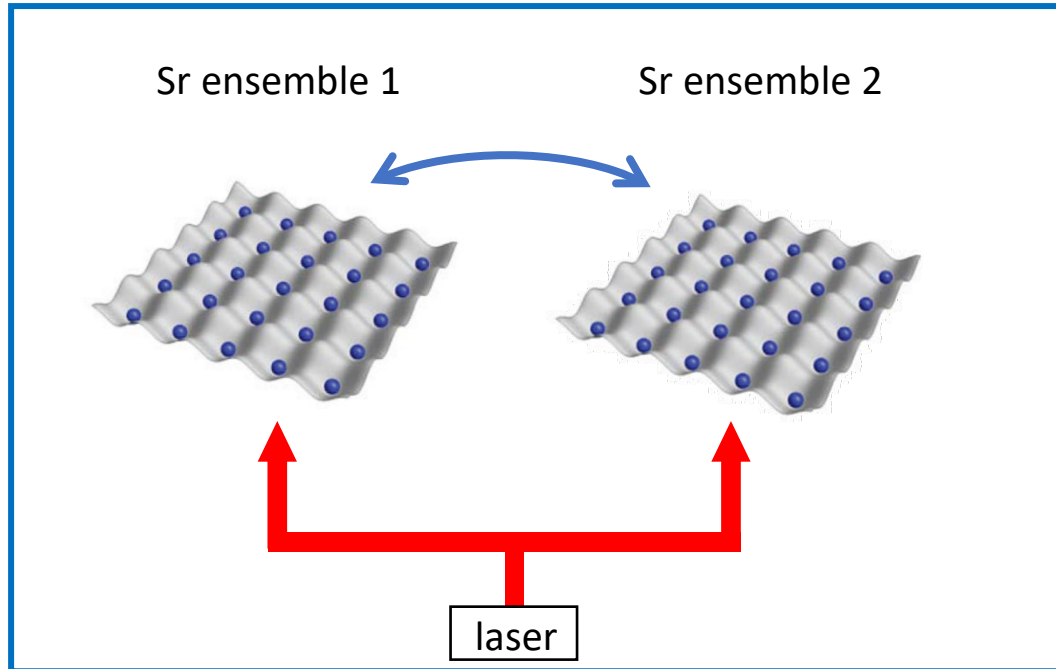
Light emission
(lasing)



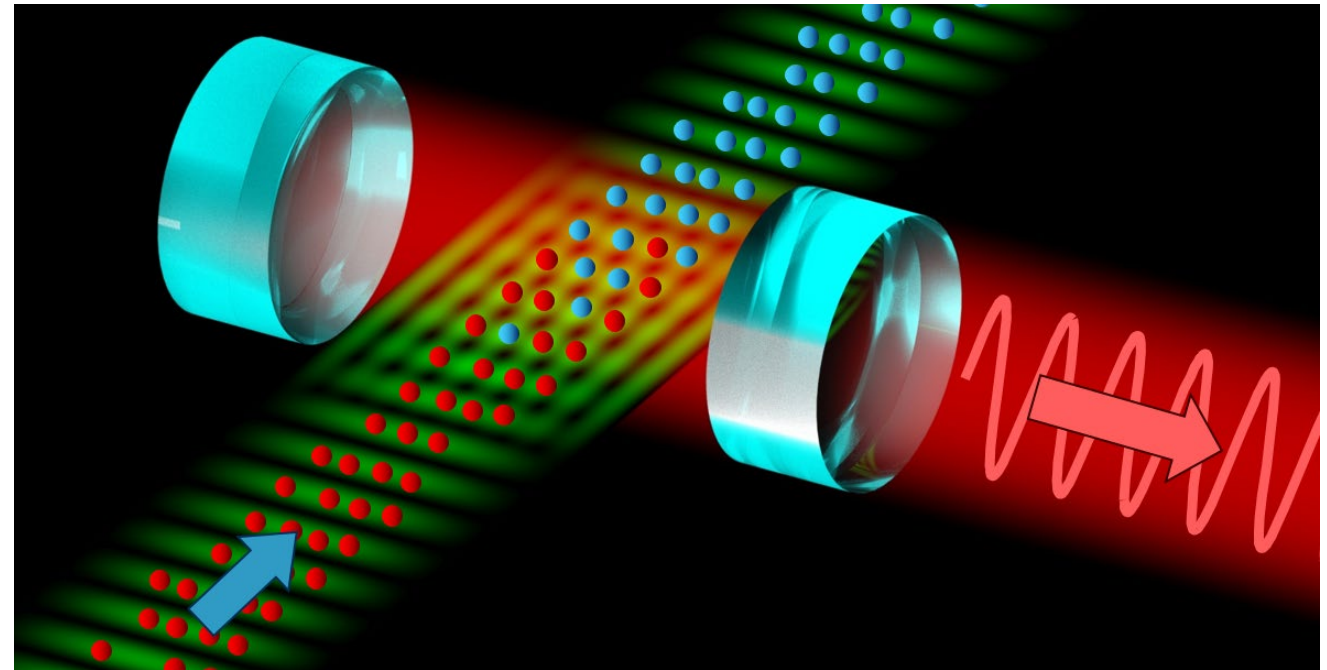


Continuous clock developments in our lab

Passive, zero-deadtime clock



Active, superradiant clock



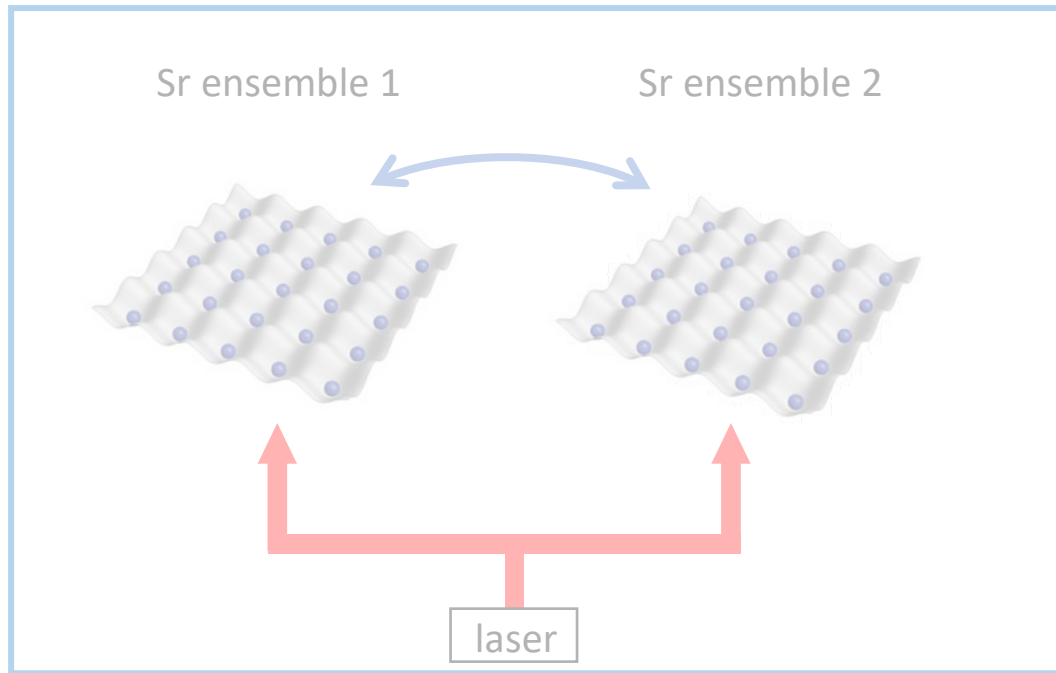
Continuous ultracold strontium beam in

Clock laser beam out

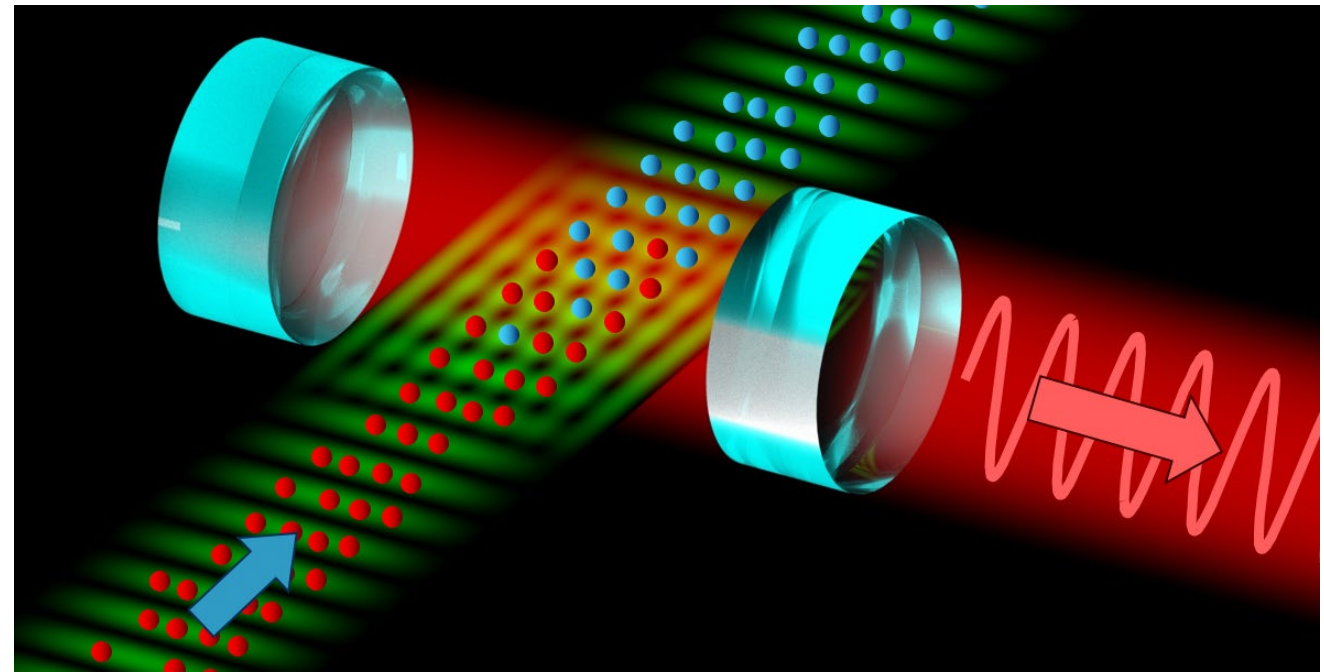


Continuous clock developments in our lab

Passive, zero-deadtime clock



Active, superradiant clock



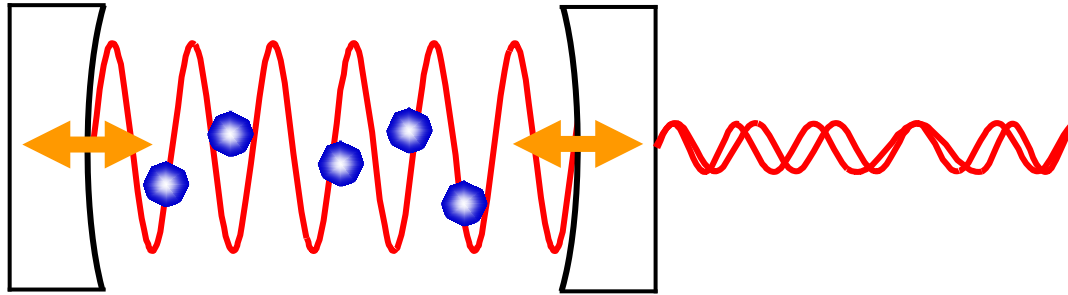
Continuous ultracold strontium beam in

Clock laser beam out



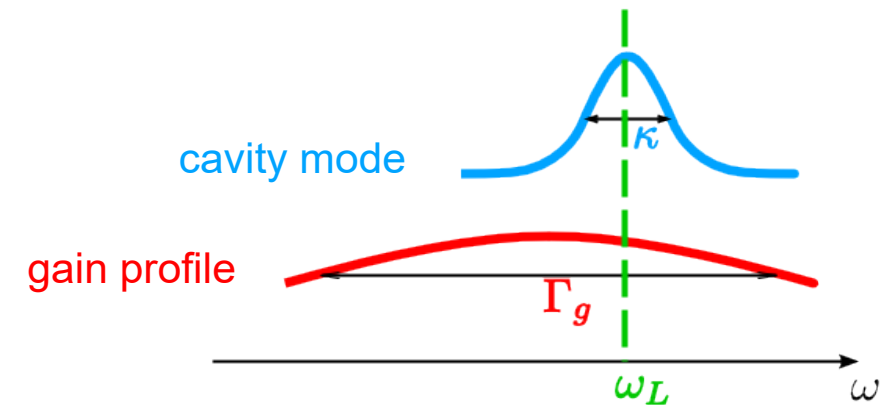
Comparison to standard laser

Standard laser: frequency stability from length of cavity

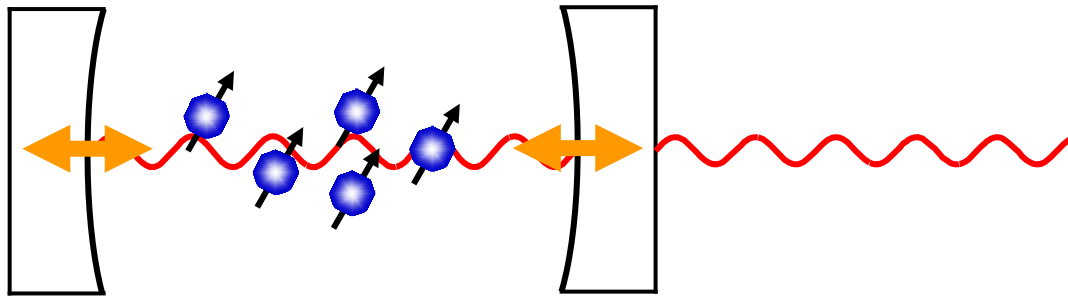


Good-cavity regime

$$\kappa \ll \Gamma_g$$

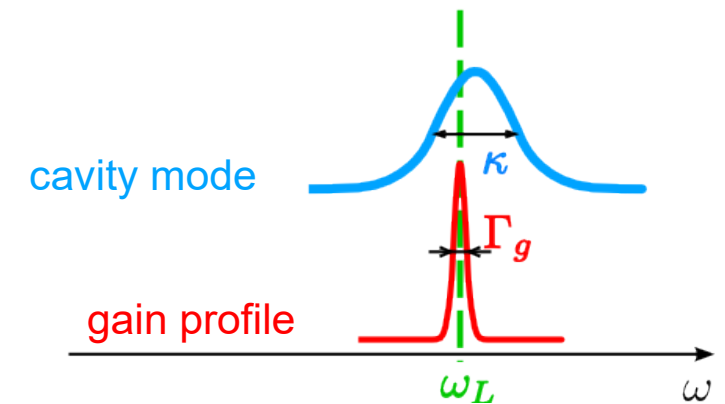


Superradiant clock laser: frequency stability from collective spin of atoms



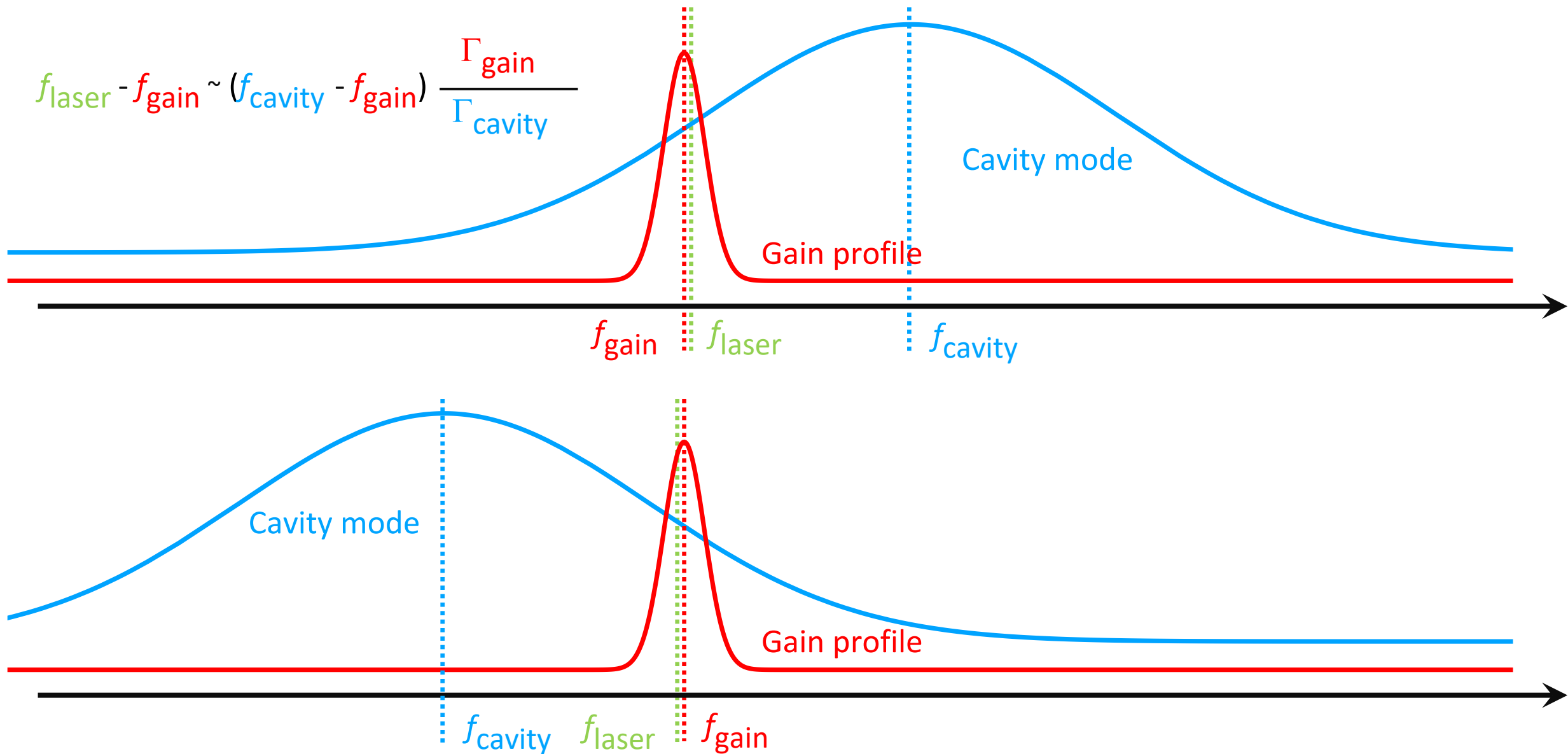
Bad-cavity regime

$$\kappa \gg \Gamma_g$$





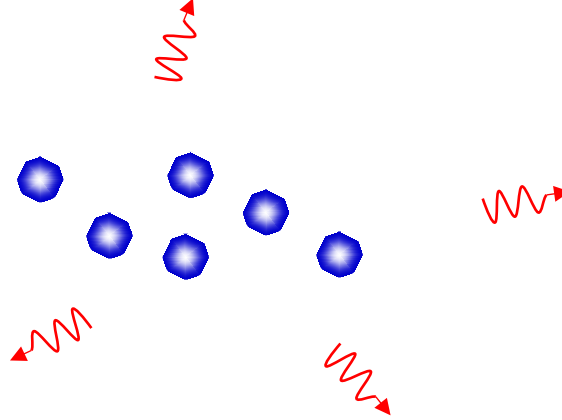
Cavity pulling





Superradiant optical clock

Goal: photons from mHz linewidth transition



Challenges:

- minutes of excited state lifetime
- emission into 4π

Solution: enhance emission into single mode by superradiance

Proposals:

Jingbiao Chen, arXiv:physics/0512096 (2005), Chinese Science Bulletin **54**, 348 (2009)

D. Meiser, J. Ye, D. R. Carlson, M. J. Holland, PRL **102**, 163601 (2009)

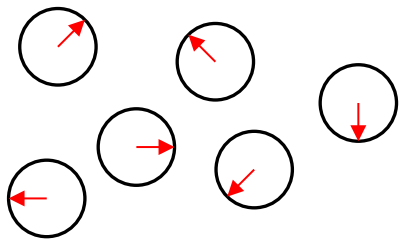
Pulsed demonstration:

M. A. Norcia, M. N. Winchester, J. R. K. Cline and J. K. Thompson, Science Advances, **2**, e1601231 (2016)

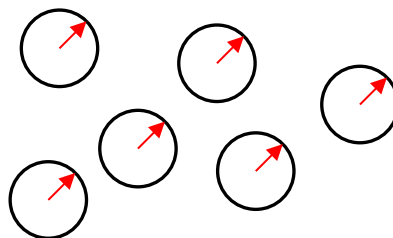


Phased array of N emitters

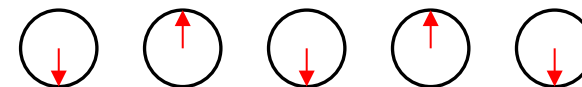
Closer spaced than wavelength
Random phase



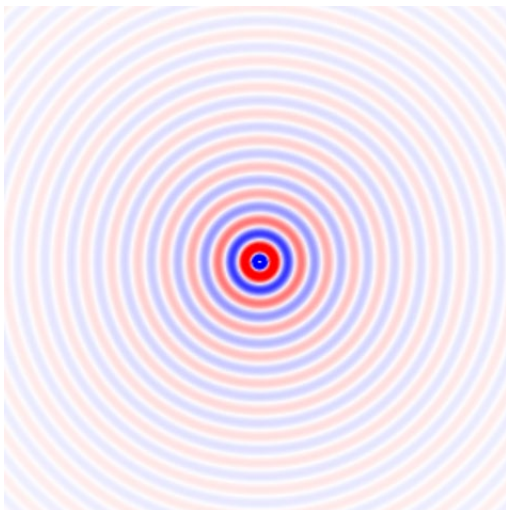
Closer spaced than wavelength
Same phase



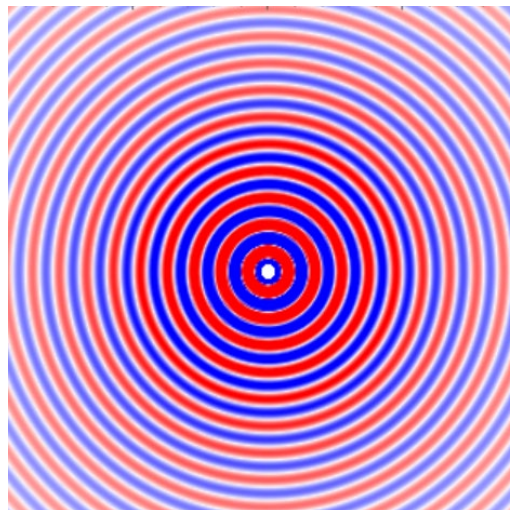
Spaced wavelength/2 along axis
Alternating phase



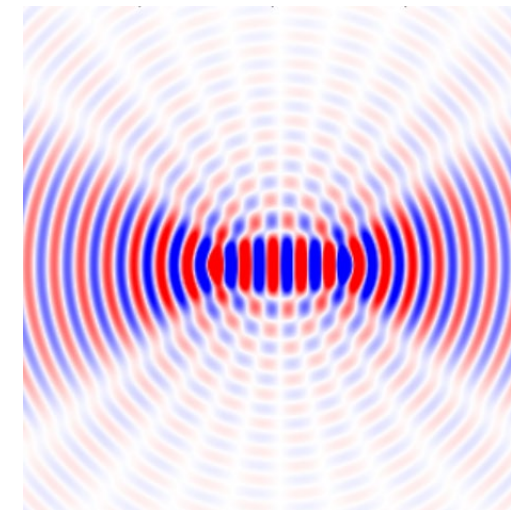
Electric field



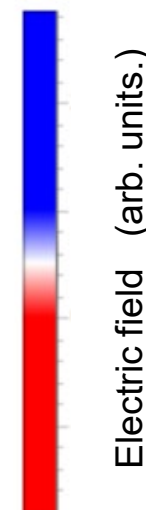
Random interference
E-field $\sim \text{Sqrt}(N)$
Power $\sim N$



Constructive interference
E-field $\sim N$
Power $\sim N^2$

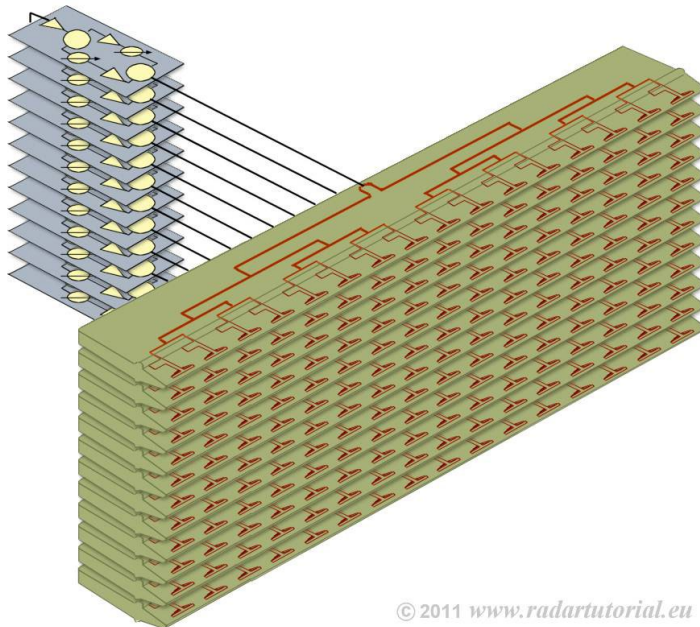
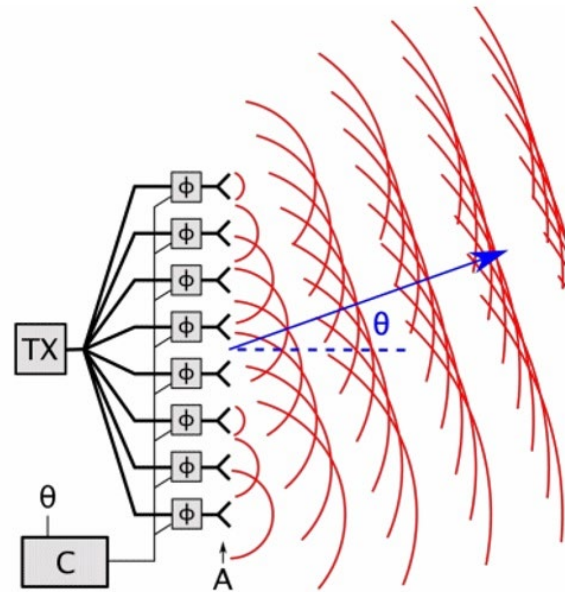


Constructive interference
along axis
Power along axis $\sim N^2$

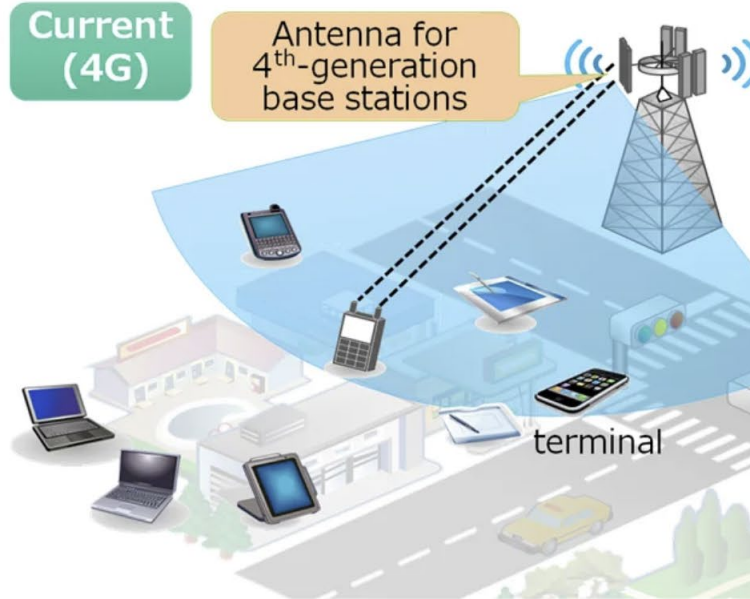




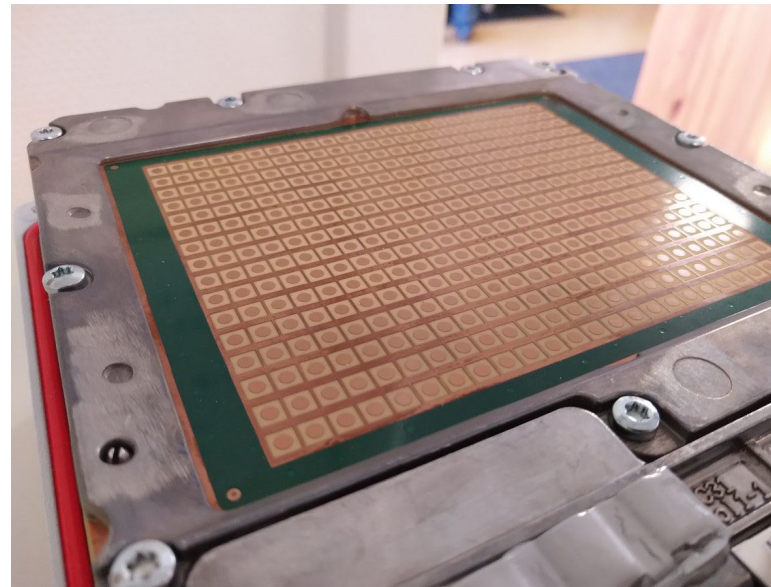
Phased-array antenna



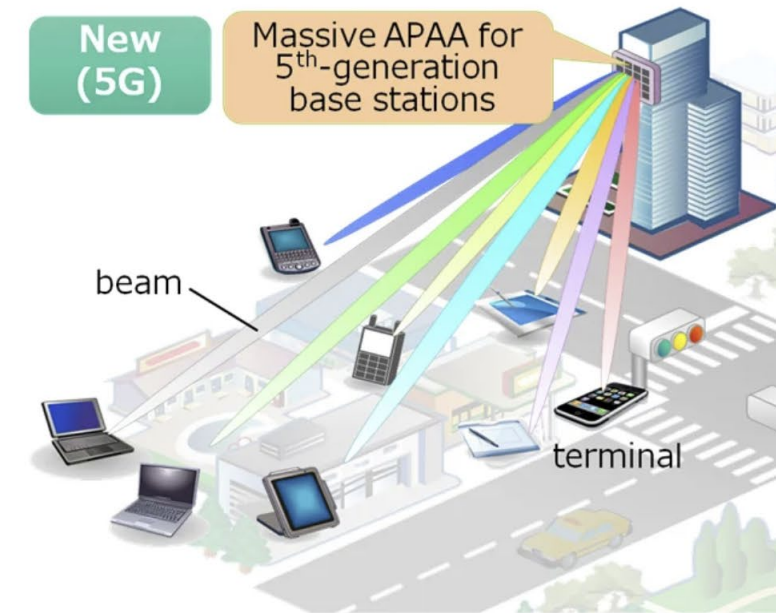
© 2011 www.radartutorial.eu



Ericsson 5G antenna



Mitsubishi 5G antenna



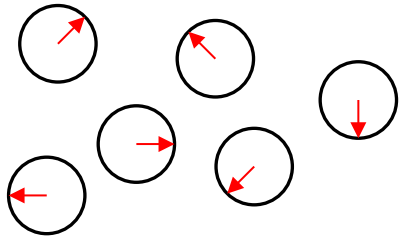
AST SpaceMobile BlueWalker 3 (BW3) LEO satellite



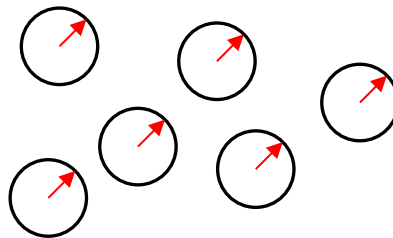


Phased array of N emitters

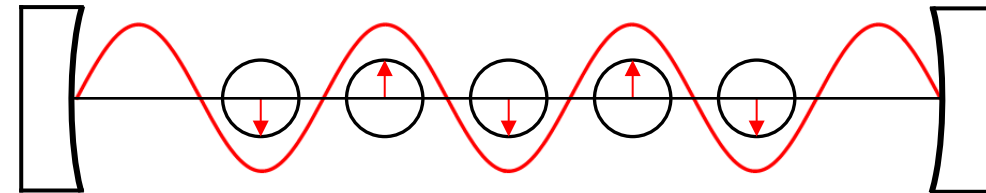
Closer spaced than wavelength
Random phase



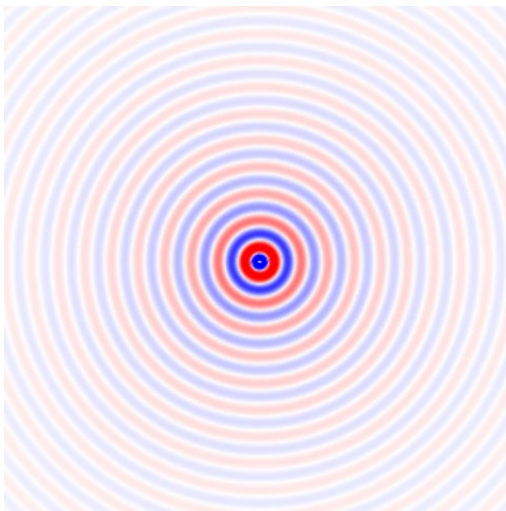
Closer spaced than wavelength
Same phase



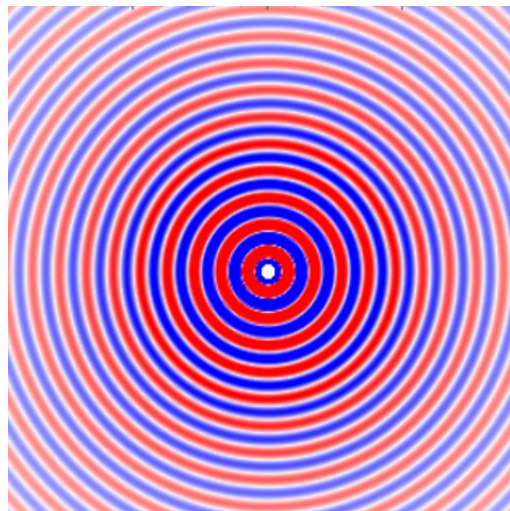
Spaced wavelength/2 along axis
Alternating phase



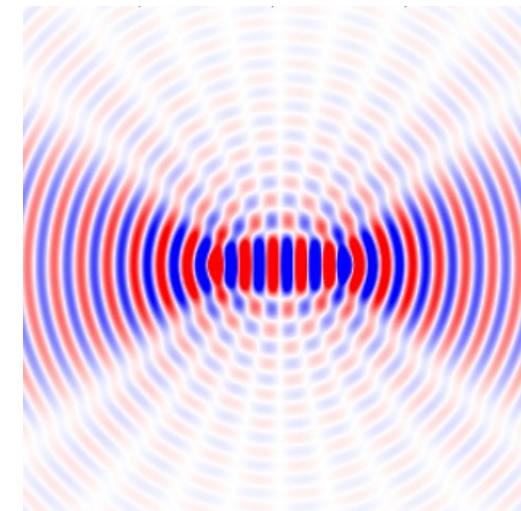
Electric field



Random interference
E-field $\sim \sqrt{N}$
Power $\sim N$



Constructive interference
E-field $\sim N$
Power $\sim N^2$

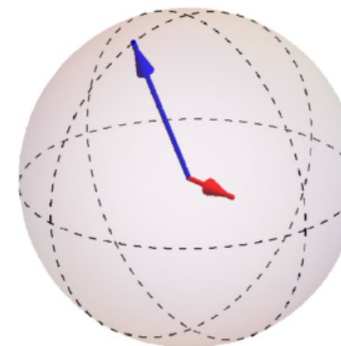
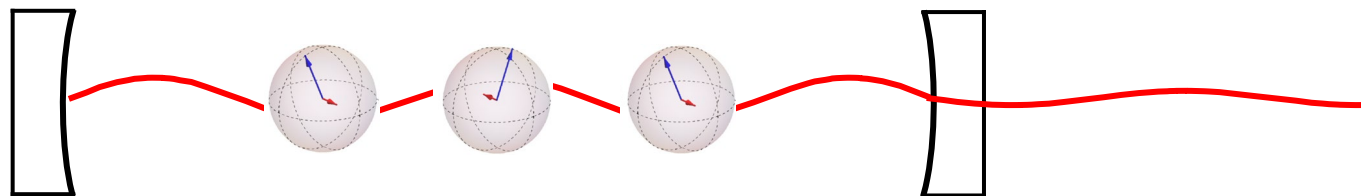


Constructive interference
along axis
Power along axis $\sim N^2$

Electric field (arb. units.)

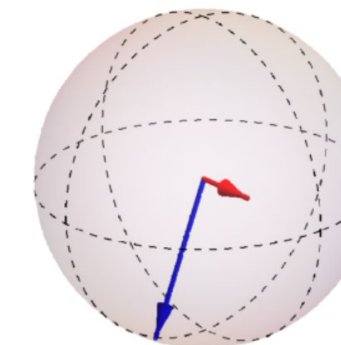
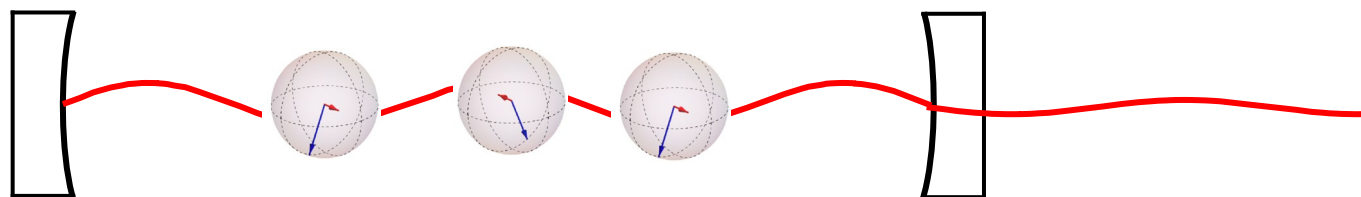
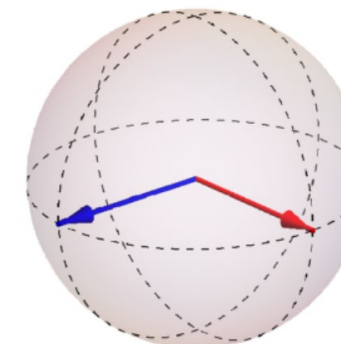
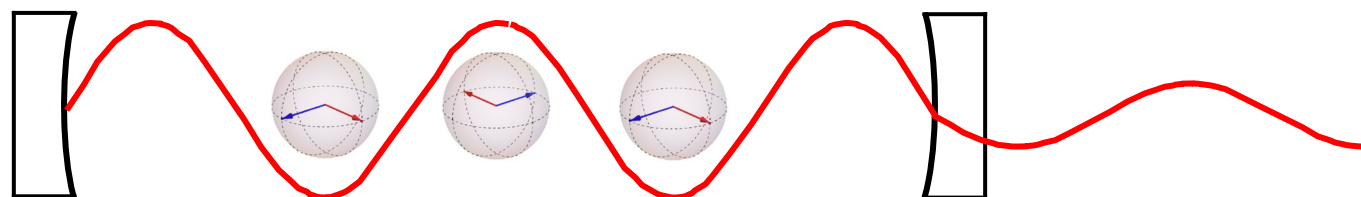


How is superradiance established?



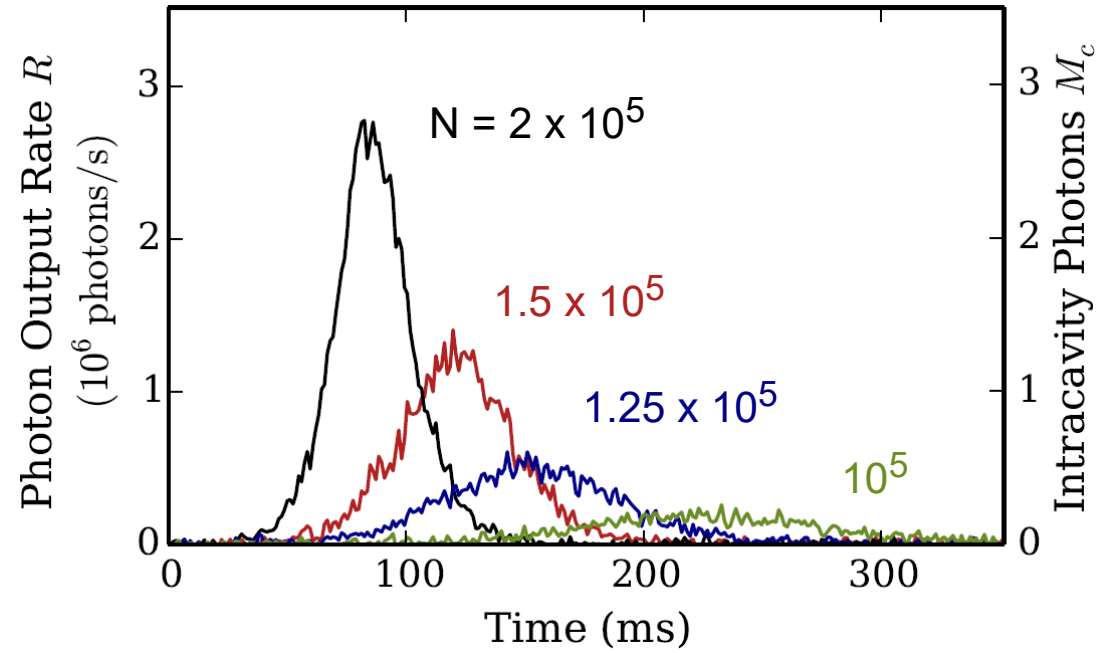
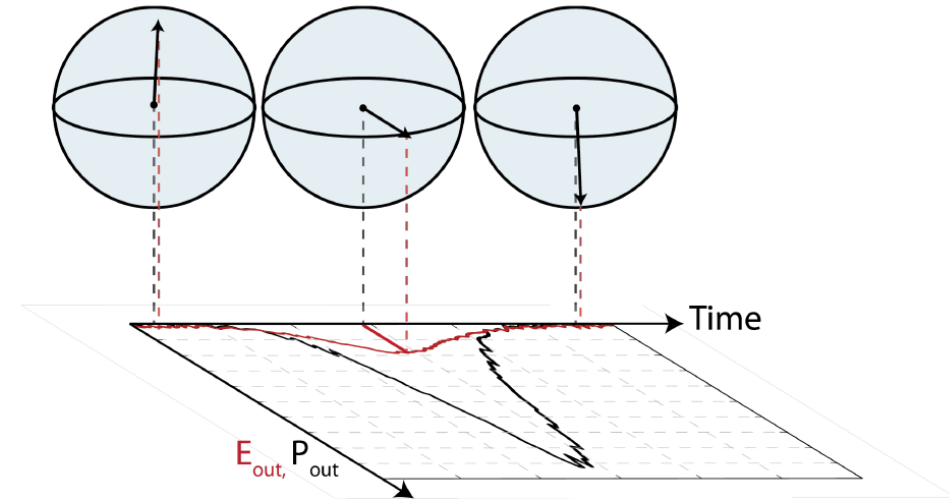
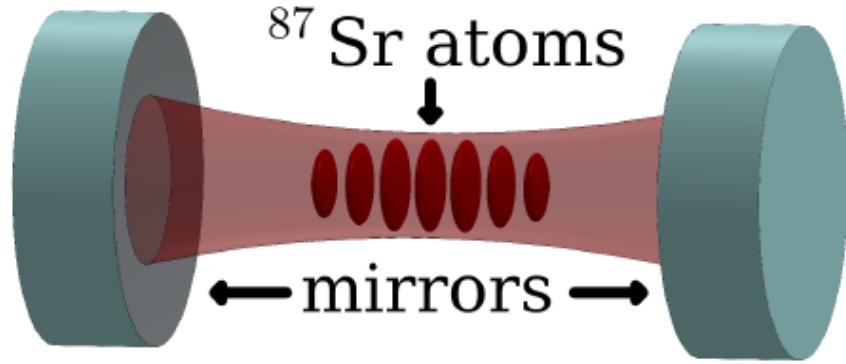
Bloch vector

E-field



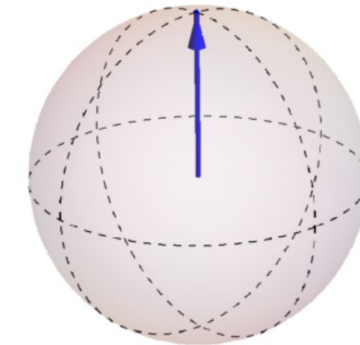
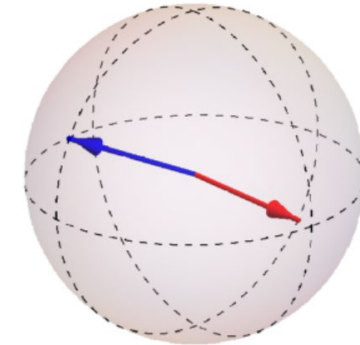
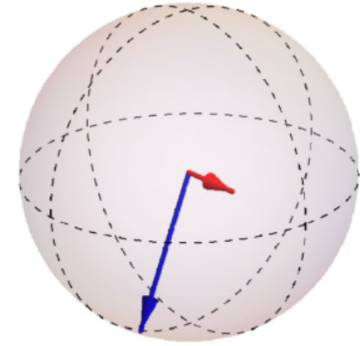
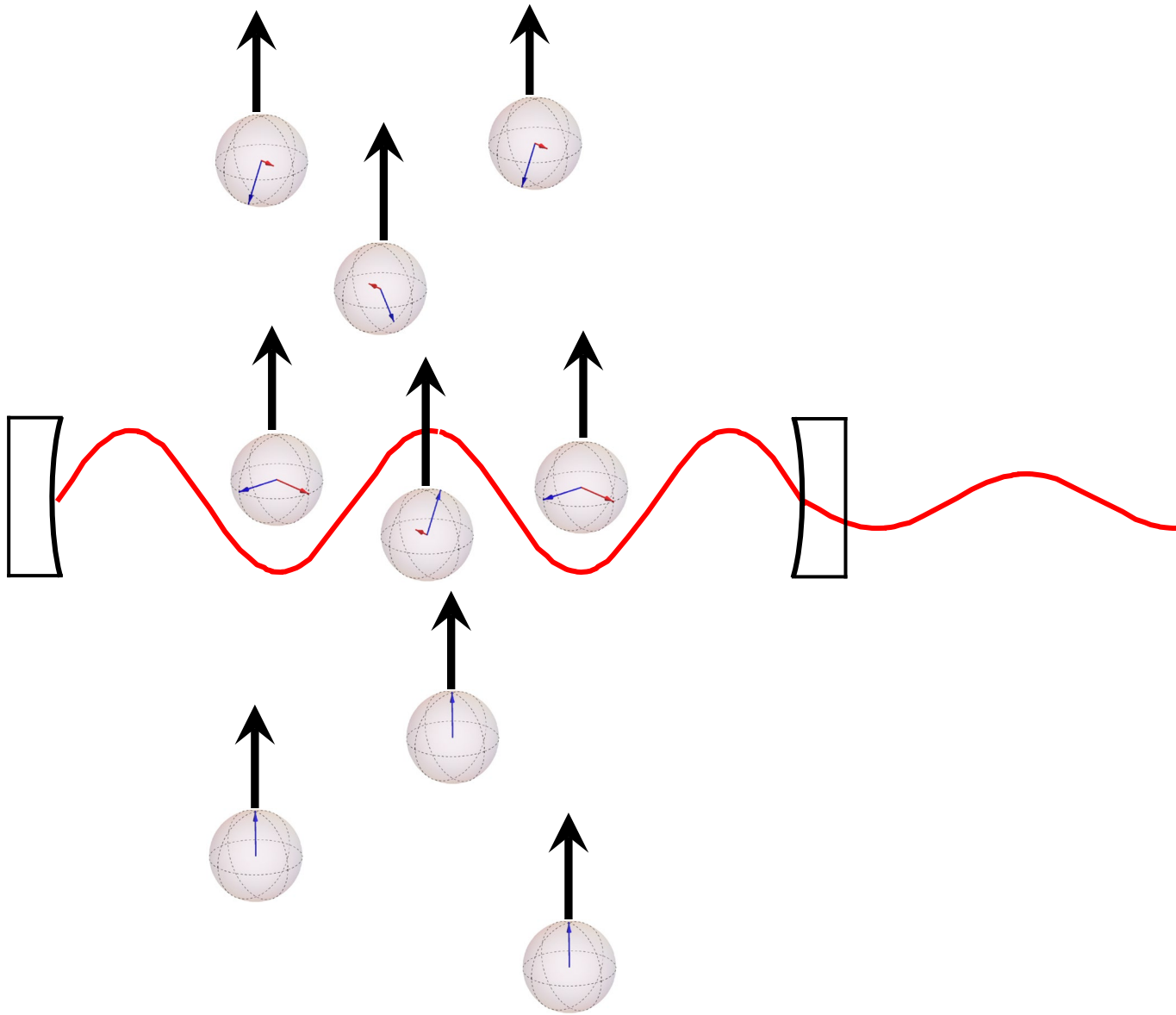
Pulsed superradiant clock laser

James Thompson group, JILA,
Science Advances, 2, e1601231 (2016)



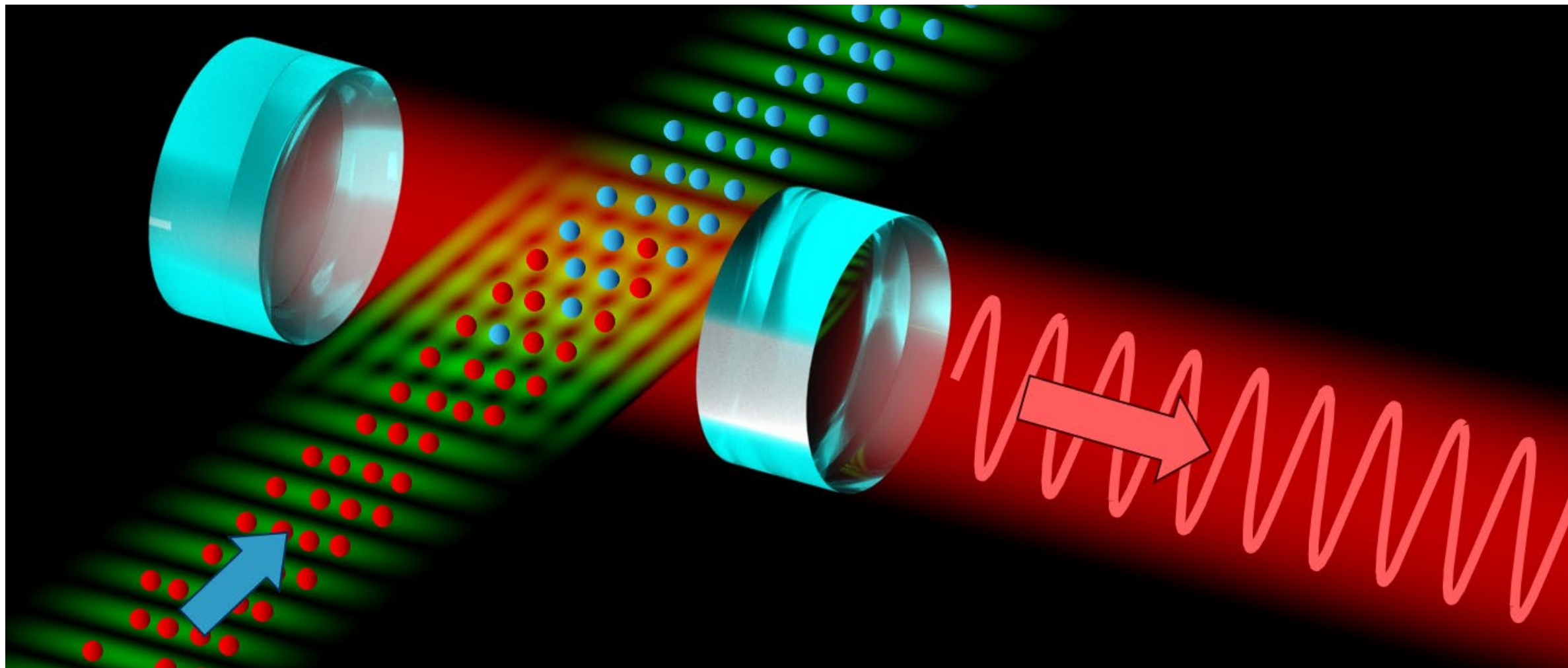


How can superradiance be maintained?





Continuous superradiant clock

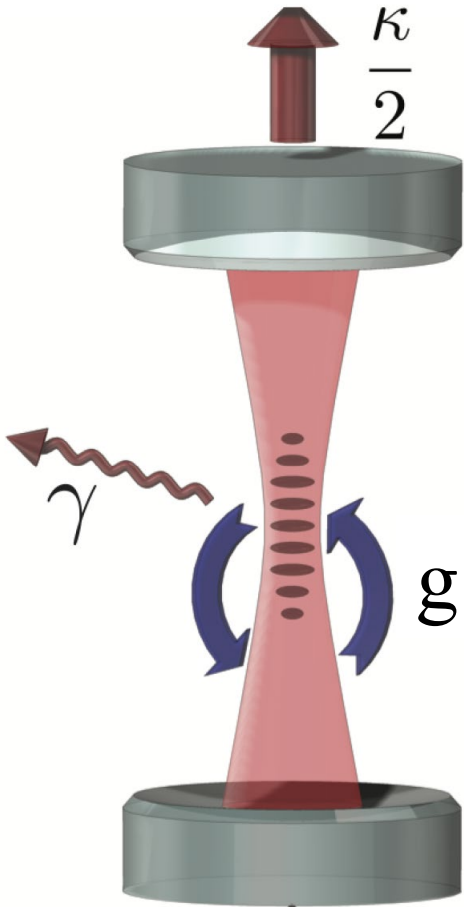


Continuous strontium beam in

Clock laser beam out



Theory



Jaynes-Cummings Hamiltonian: single atom coupled to cavity, no decay

$$\hat{H} = \hbar\omega_a \hat{\sigma}^+ \hat{\sigma}^- + \hbar\omega \hat{c}^\dagger \hat{c} + \hbar g (\hat{\sigma}^- \hat{c}^\dagger + \hat{\sigma}^+ \hat{c})$$

Here: atom and cavity decay, many atoms, atomic motion, quantum fluctuations

$$\frac{ds_j^x}{dt} = \frac{\Gamma_c}{2} \eta_j \left[\mathcal{J}^x s_j^z - \eta_j s_j^x (s_j^z + 1) \right] - \sqrt{\Gamma_c} \eta_j s_j^z \xi^p,$$

$$\frac{ds_j^y}{dt} = \frac{\Gamma_c}{2} \eta_j \left[\mathcal{J}^y s_j^z - \eta_j s_j^y (s_j^z + 1) \right] + \sqrt{\Gamma_c} \eta_j s_j^z \xi^q,$$

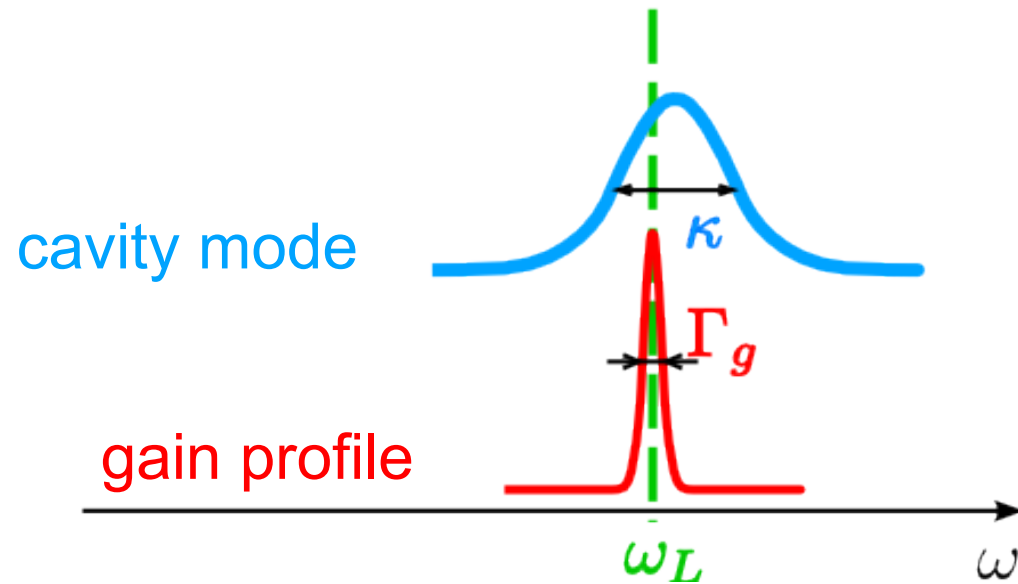
$$\begin{aligned} \frac{ds_j^z}{dt} = & -\frac{\Gamma_c}{2} \eta_j \left\{ \mathcal{J}^x s_j^x + \mathcal{J}^y s_j^y - \eta_j \left[(s_j^x)^2 + (s_j^y)^2 \right] \right\} \\ & - \Gamma_c \eta_j^2 (s_j^z + 1) + \sqrt{\Gamma_c} \eta_j (s_j^x \xi^p - s_j^y \xi^q). \end{aligned}$$

H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson, ***Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam***, PRL 125, 253602 (2020).



Conditions for continuous superradiant lasing

1) Bad-cavity regime $\kappa \gg \Gamma_g$



cavity linewidth
 $\gg$

gain linewidth

i.e.

Atomic linewidth

Doppler broadened linewidth

Transit time broadened linewidth

Inhomogeneously broadened linewidth

(B-field, dipole trap inhomogeneities)

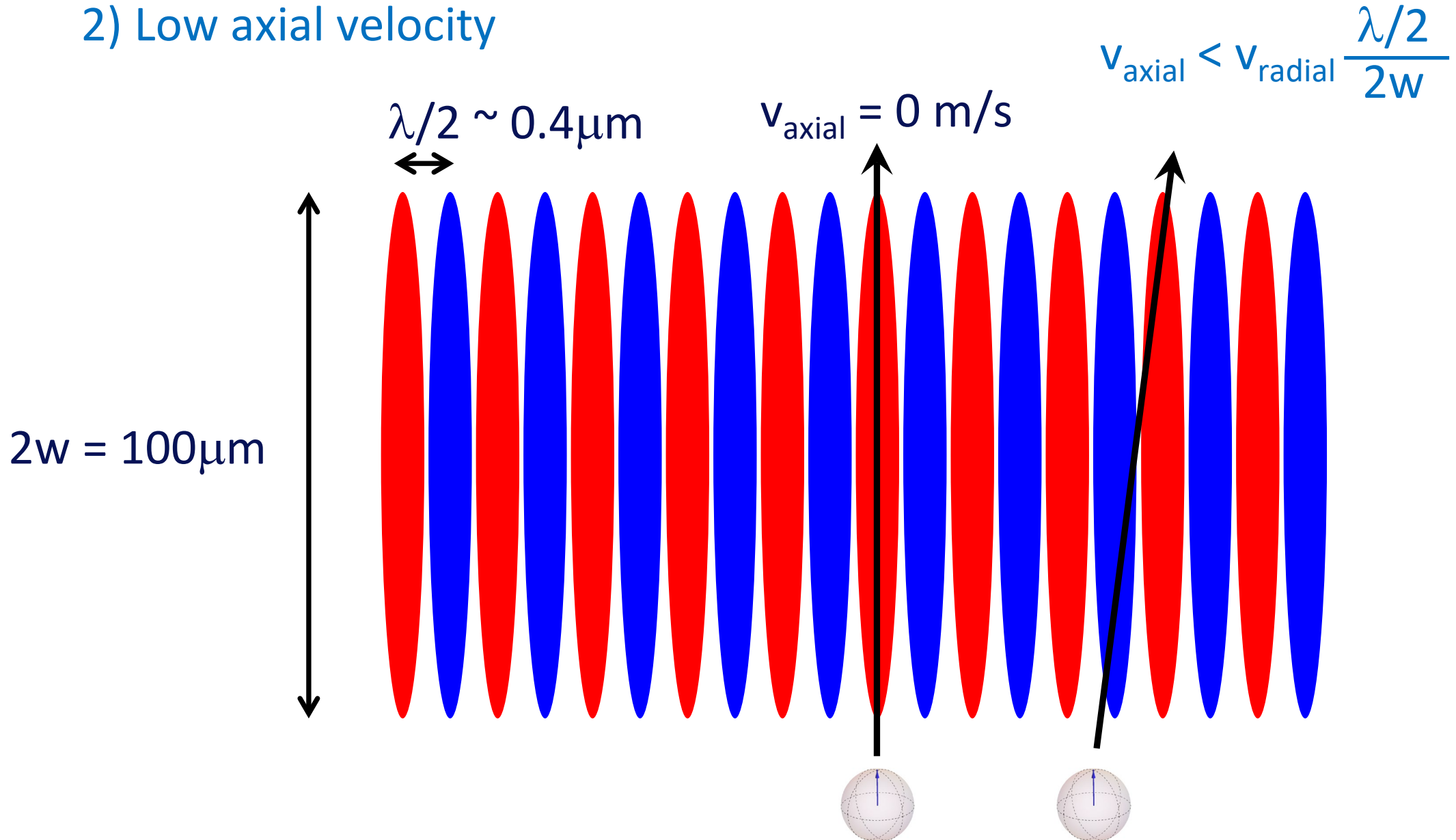
cavity linewidth $\gg$ collective coupling

$$\Gamma \gg \sqrt{N}g$$



Conditions for continuous superradiant lasing

2) Low axial velocity



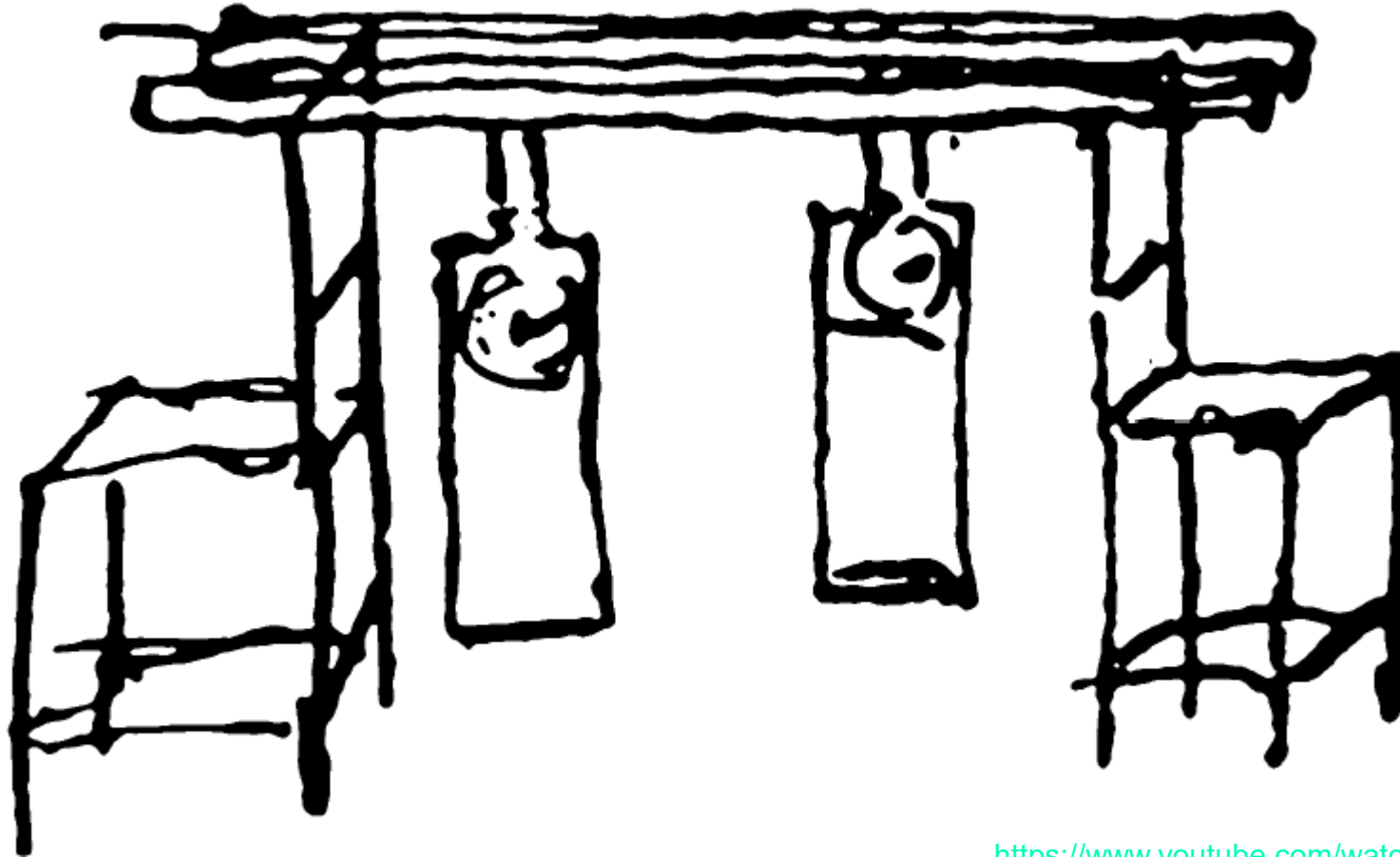


Conditions for continuous superradiance

3) Collective dipole sufficiently phase stable to synchronize new atoms

How do atoms synchronize?

Christiaan Huygens, ~1665: two pendulum clocks hanging from slightly movable bar do synchronize







Conditions for continuous superradiant lasing

3) Collective dipole sufficiently phase stable to synchronize new atoms

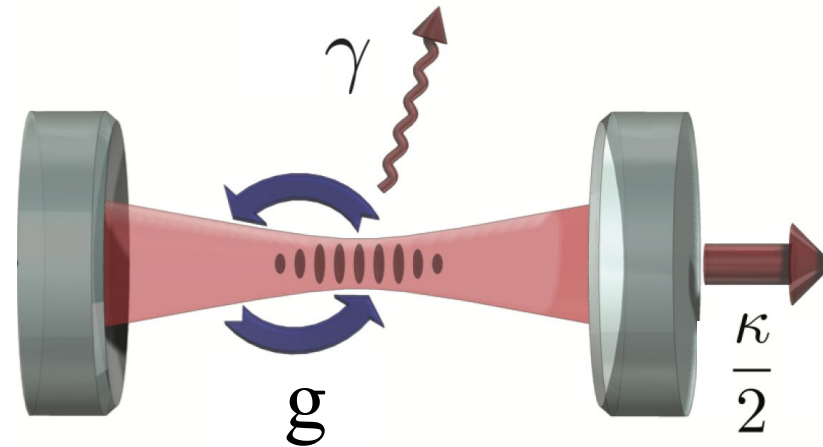
- enough atoms N in cavity
- long transit time τ to synchronize atoms

compared to coherence time scale of laser $\sim 1 / \Gamma_c$

$$N \tau > 8 / \Gamma_c$$

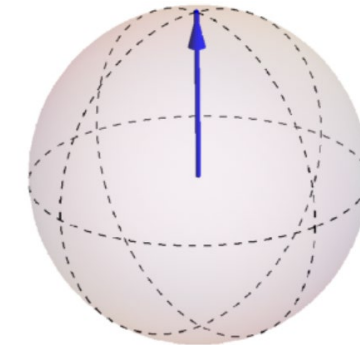
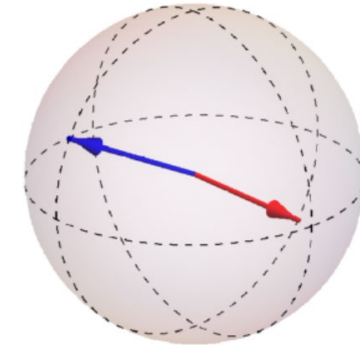
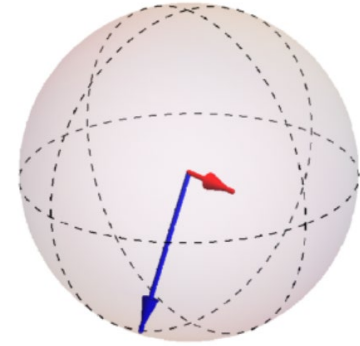
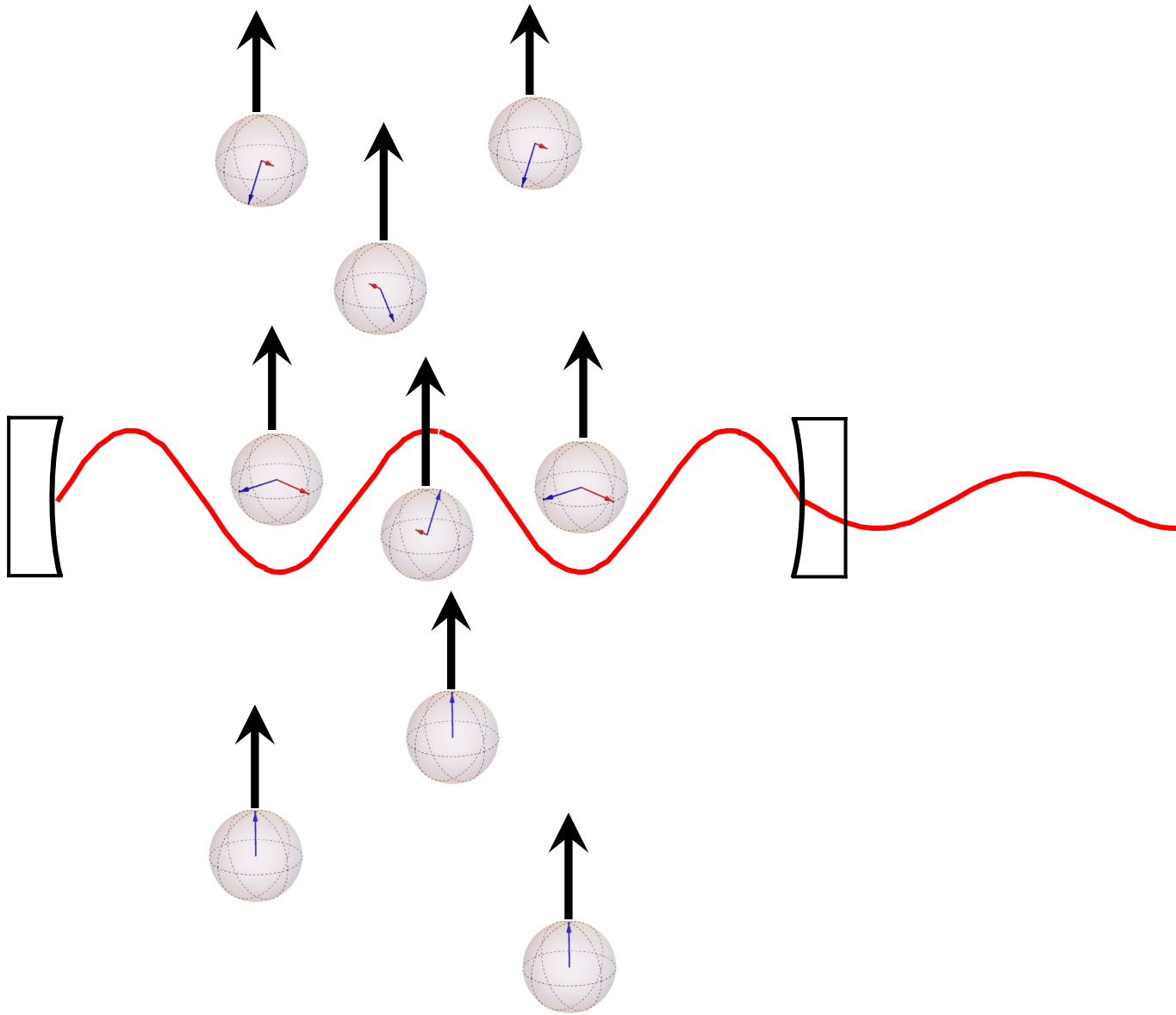
Scale of laser linewidth $\Gamma_c = \mathcal{C} \gamma$

Cooperativity $\mathcal{C} = g^2 / (\kappa \gamma)$



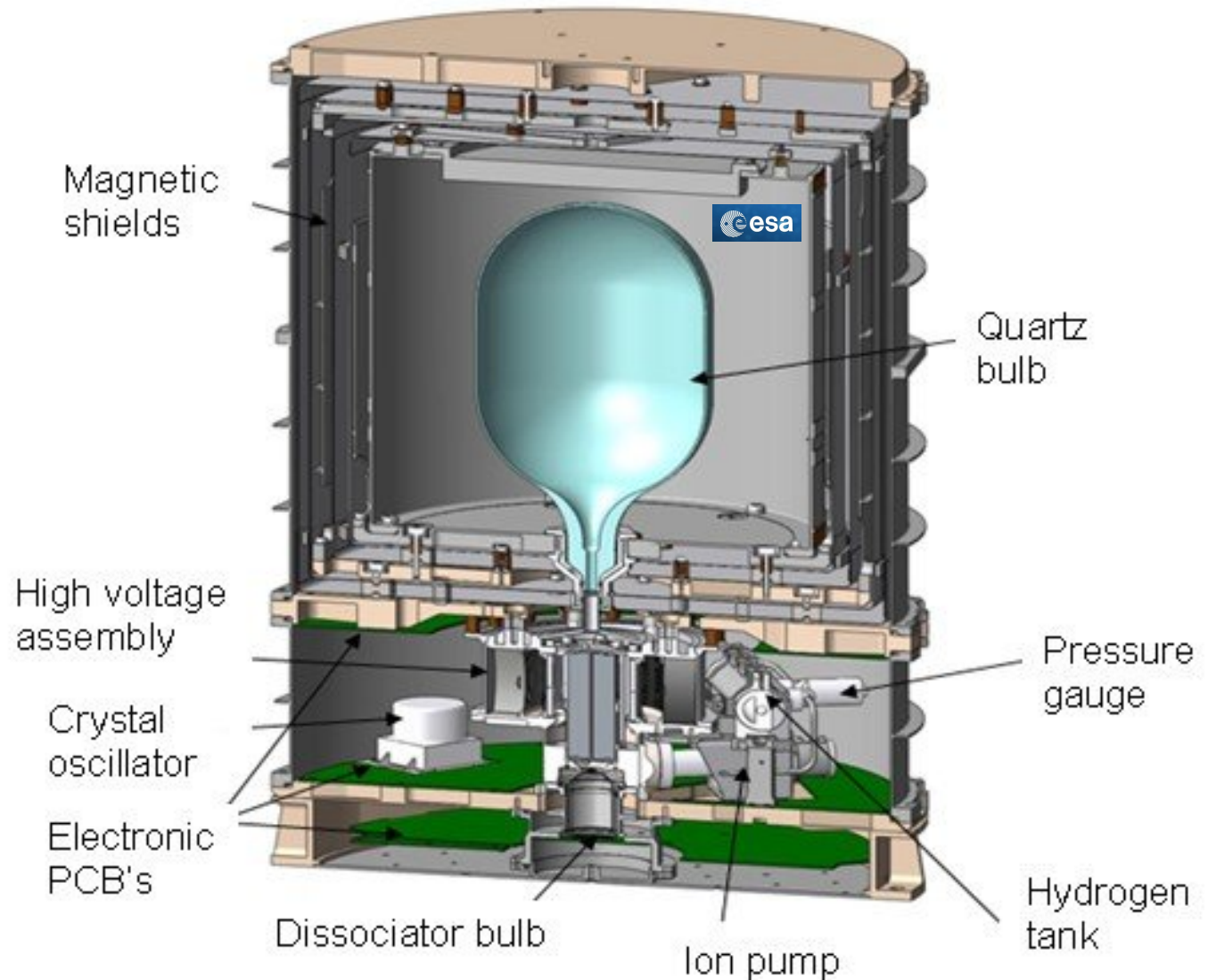
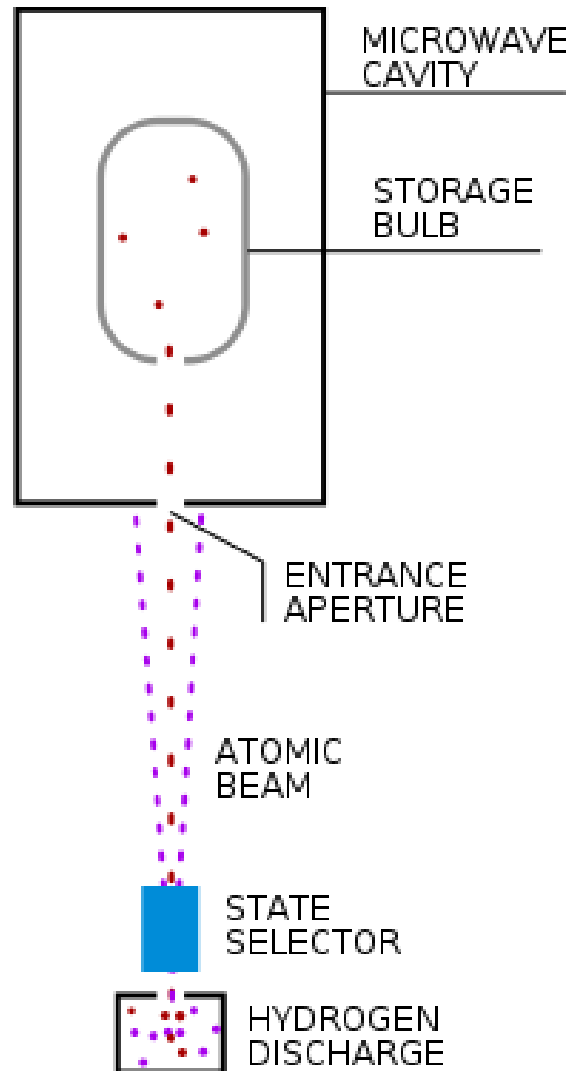


How can superradiance be maintained?



Maser

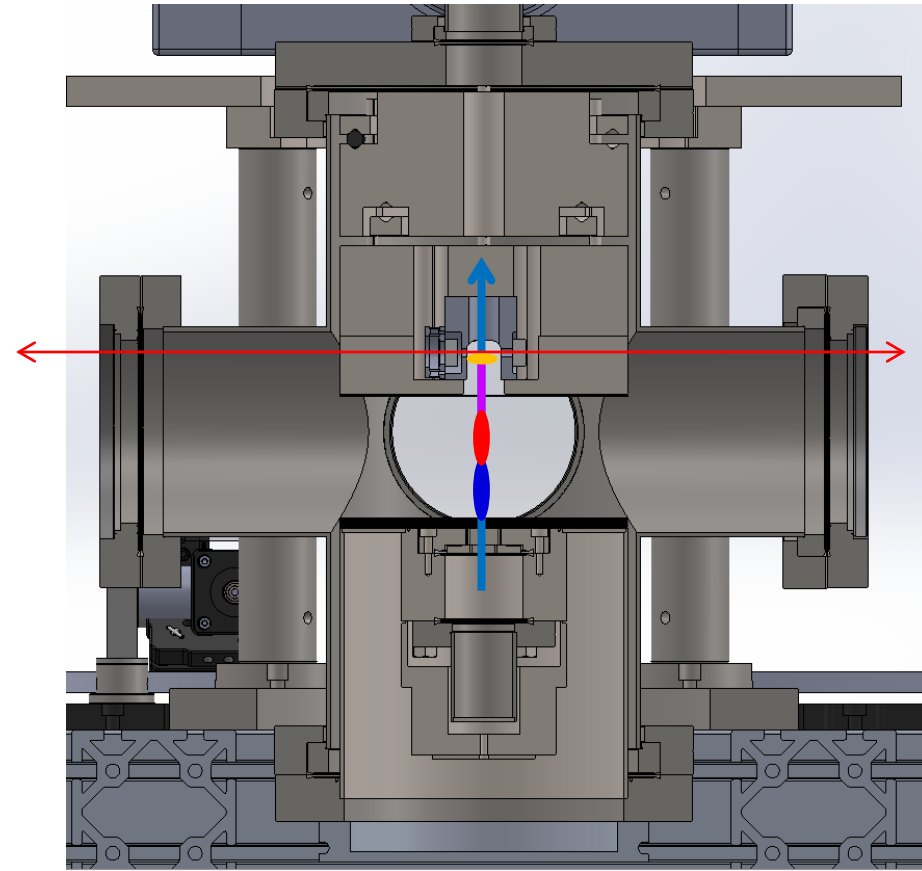
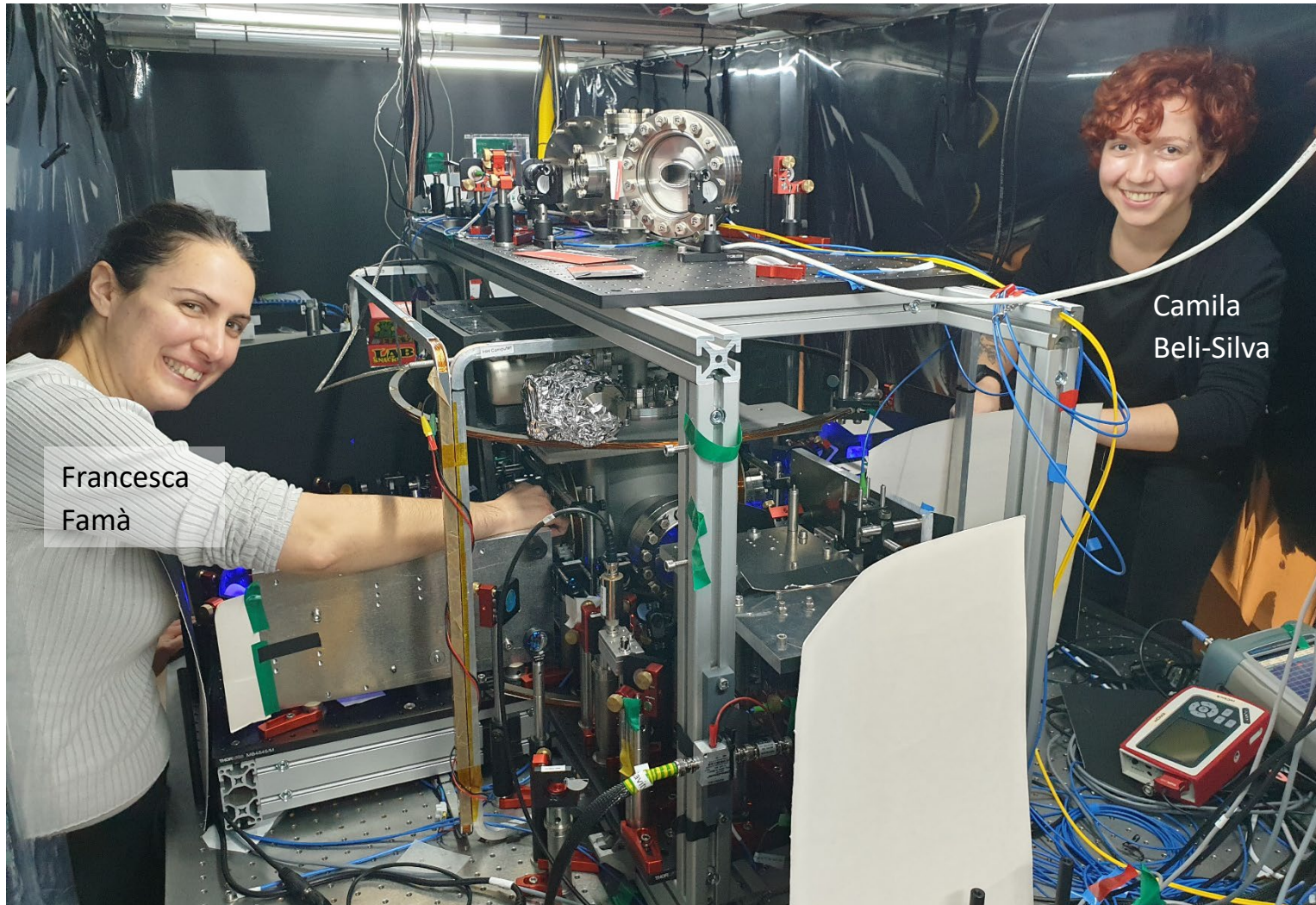
Continuous superradiant microwave emission, used as frequency standard





V1: kHz-transition superradiant Sr laser

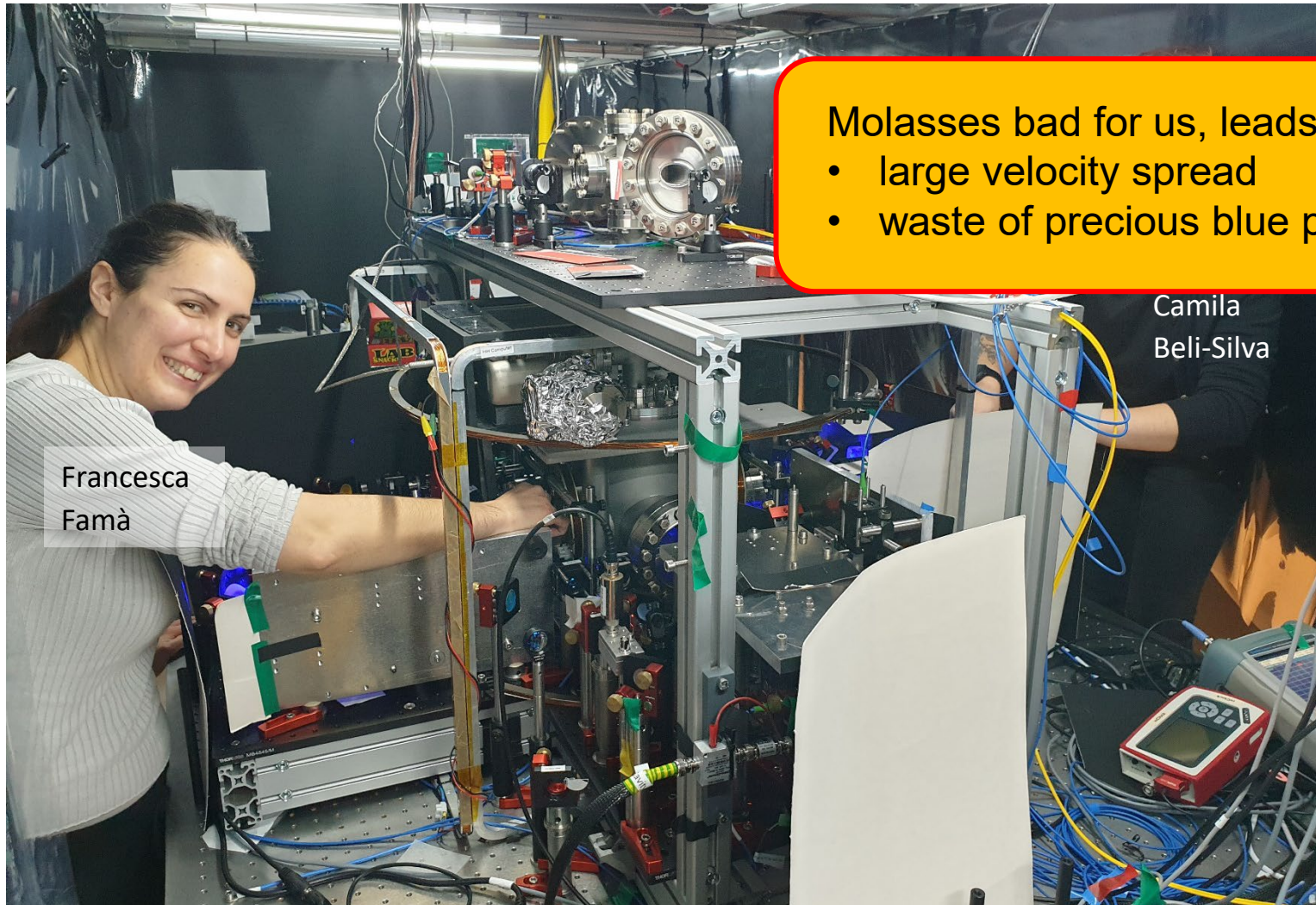
H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson,
Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam,
PRL 125, 253602 (2020).





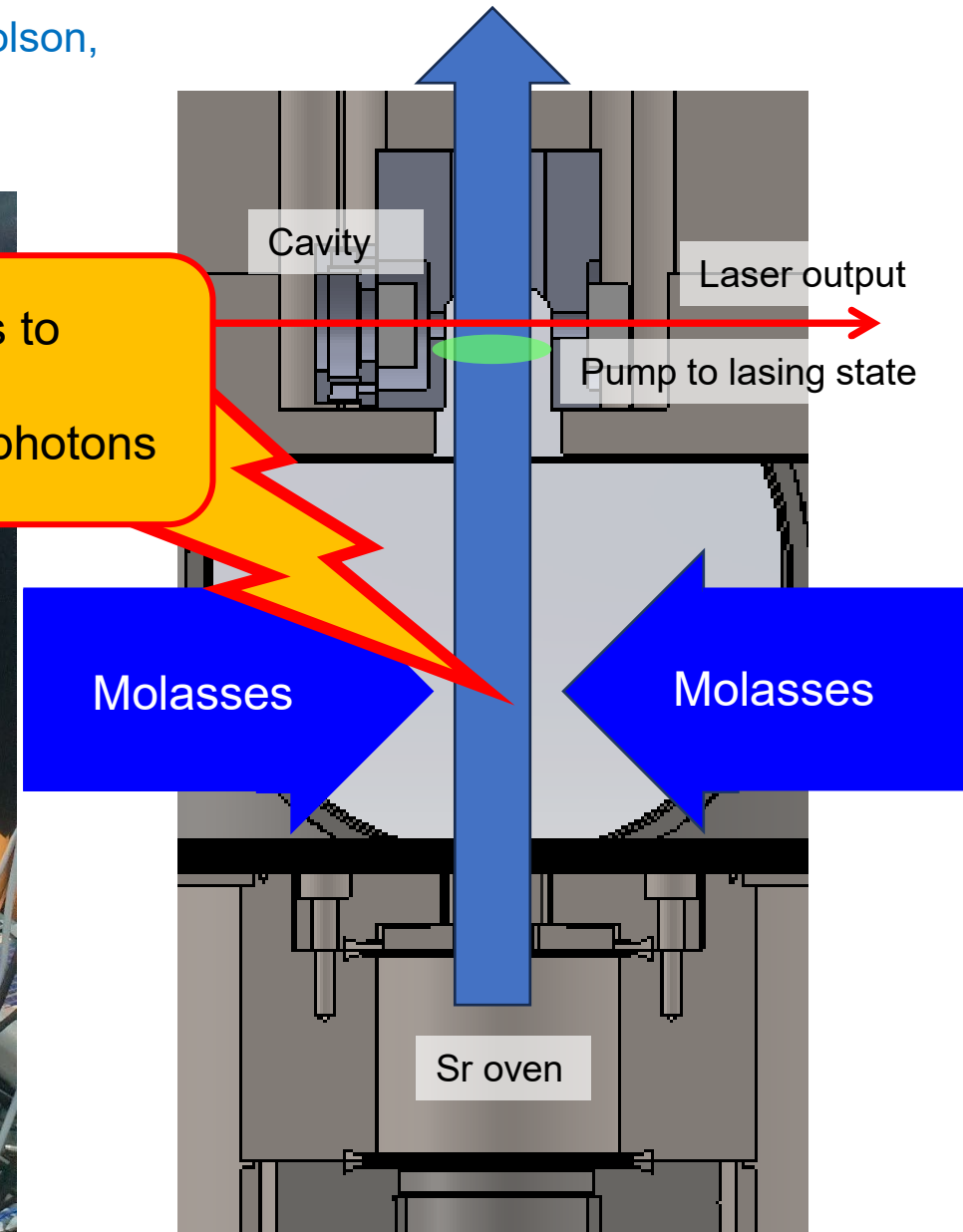
V1: kHz-transition superradiant Sr laser

H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson,
Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam,
PRL 125, 253602 (2020).



Molasses bad for us, leads to

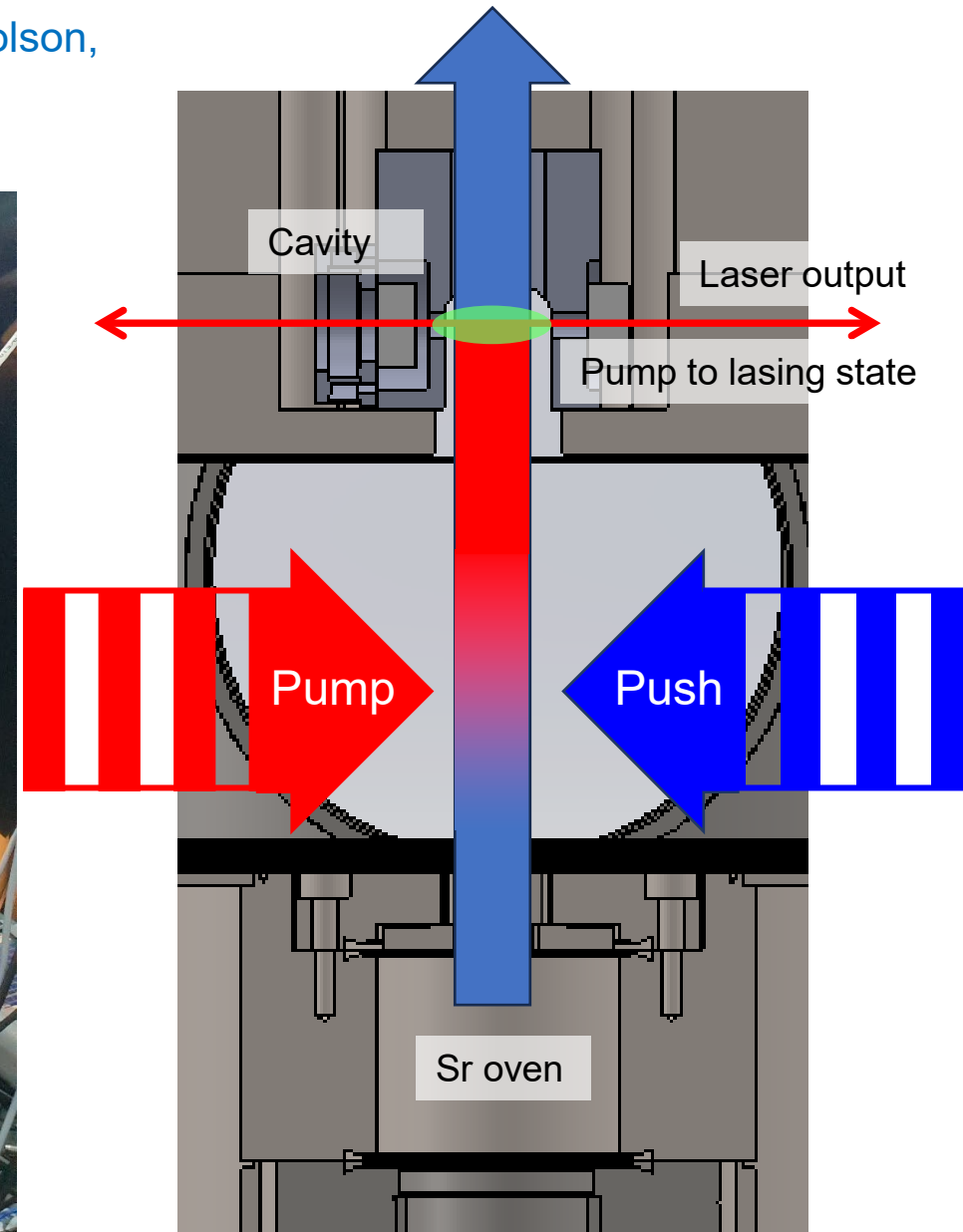
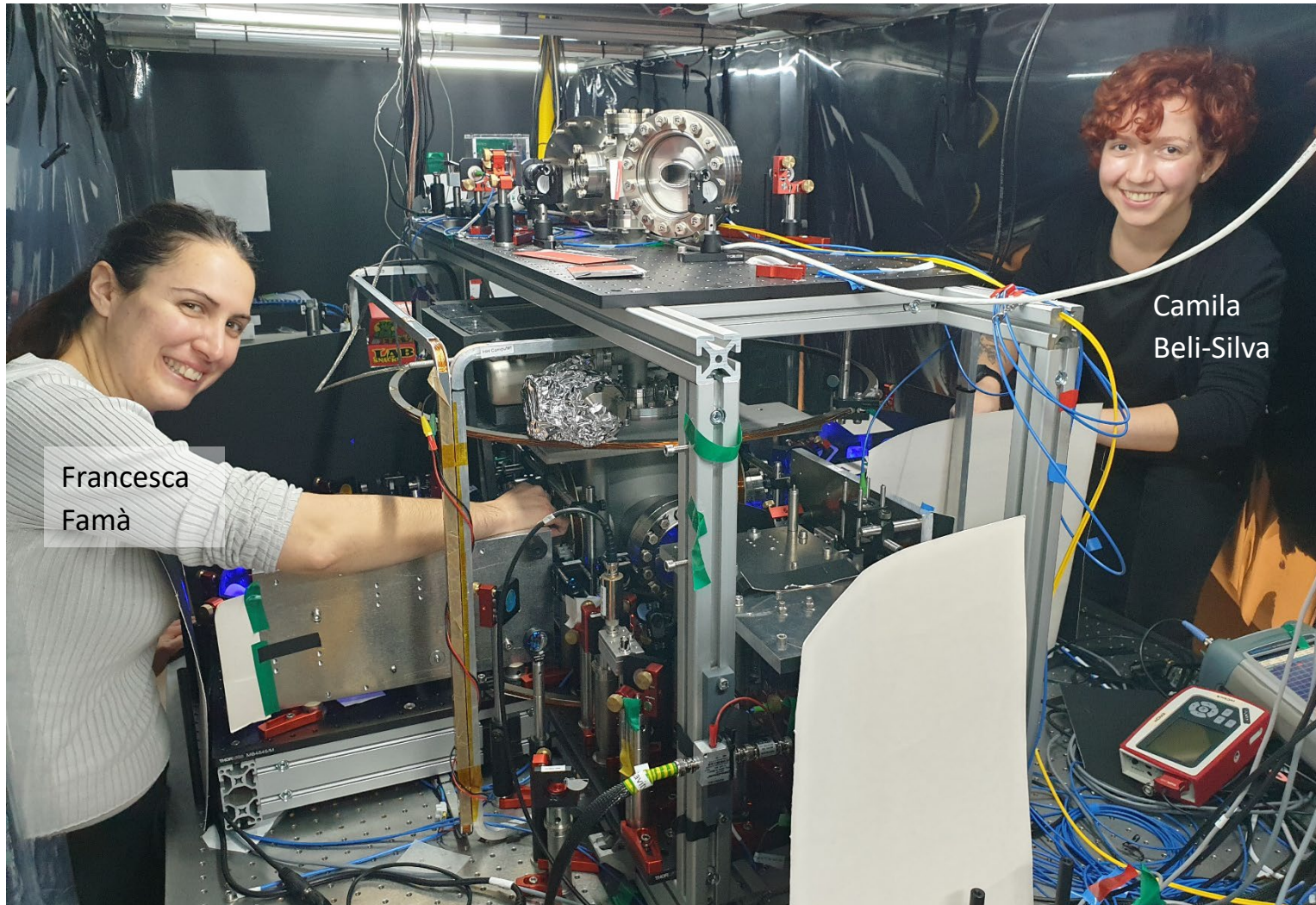
- large velocity spread
- waste of precious blue photons





V1: kHz-transition superradiant Sr laser

H. Liu, S. B. Jäger, X. Yu, S. Touzard, A. Shankar, M. J. Holland, and T. L. Nicholson,
Rugged mHz-Linewidth Superradiant Laser Driven by a Hot Atomic Beam,
PRL 125, 253602 (2020).

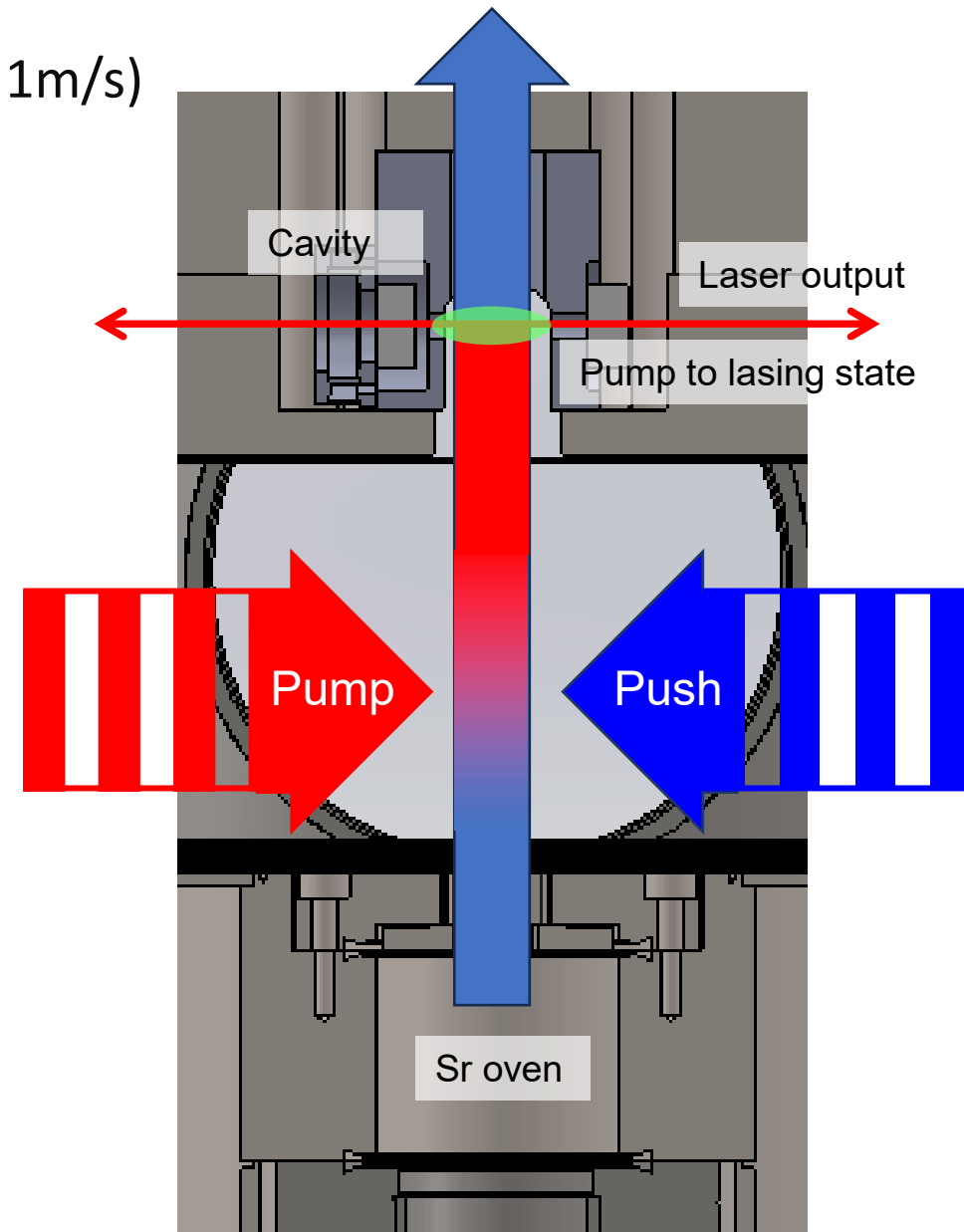
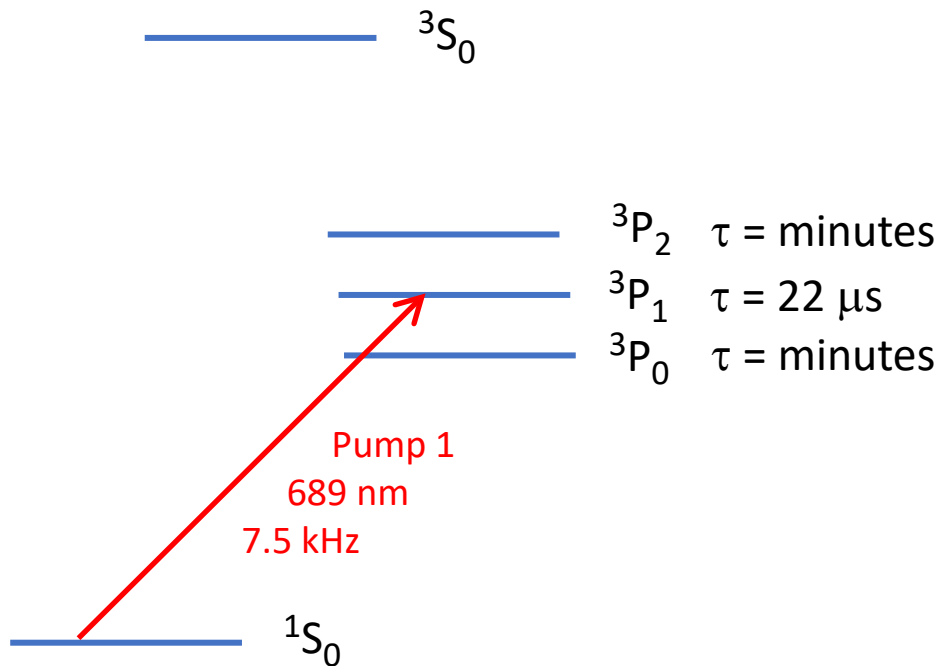




V1: kHz-transition superradiant Sr laser

Goal: atoms entering cavity in 3P_1 state and slow along cavity ($\pm 1\text{m/s}$)

Sr level scheme

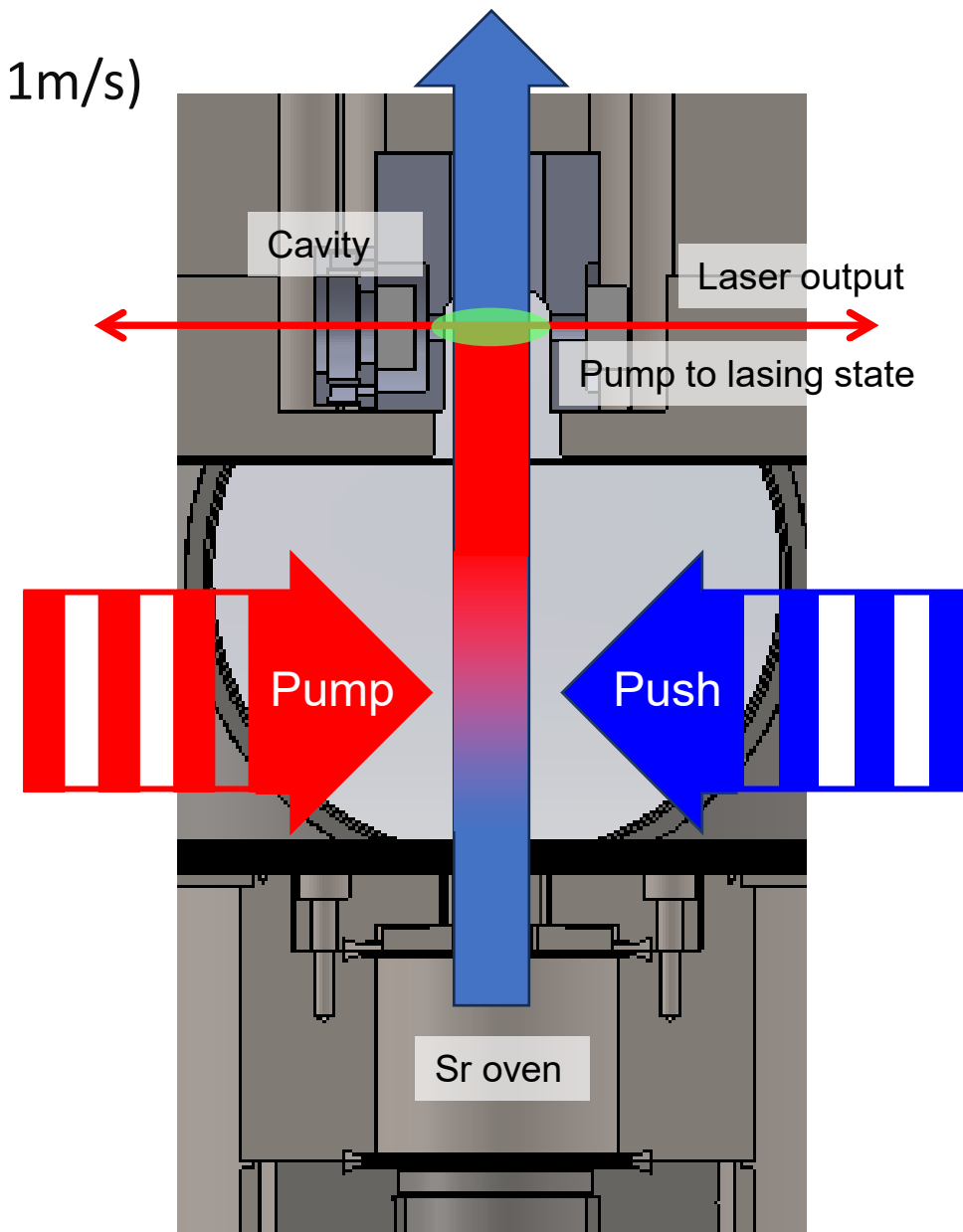
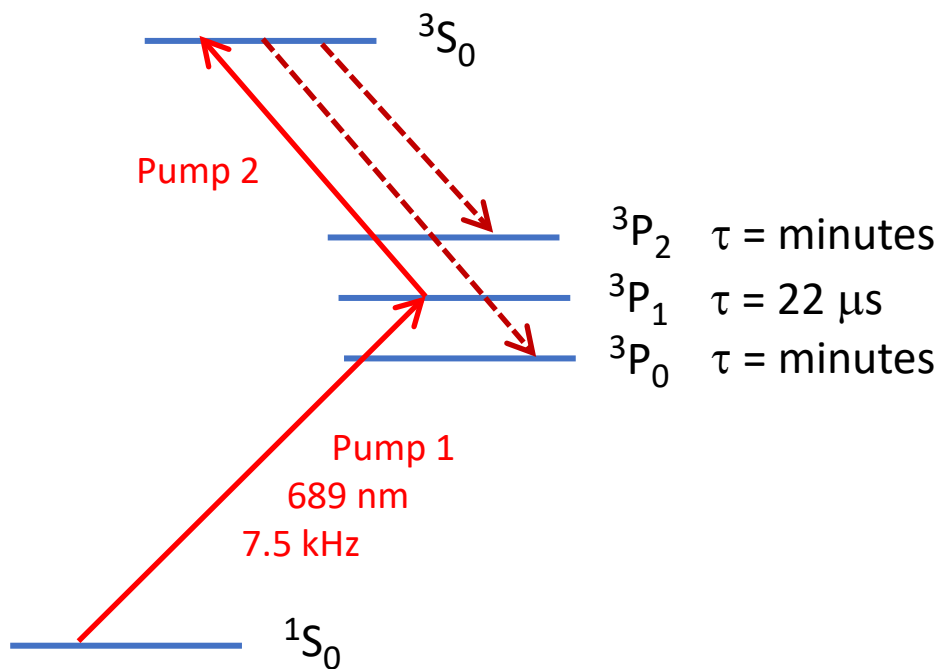




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Sr level scheme

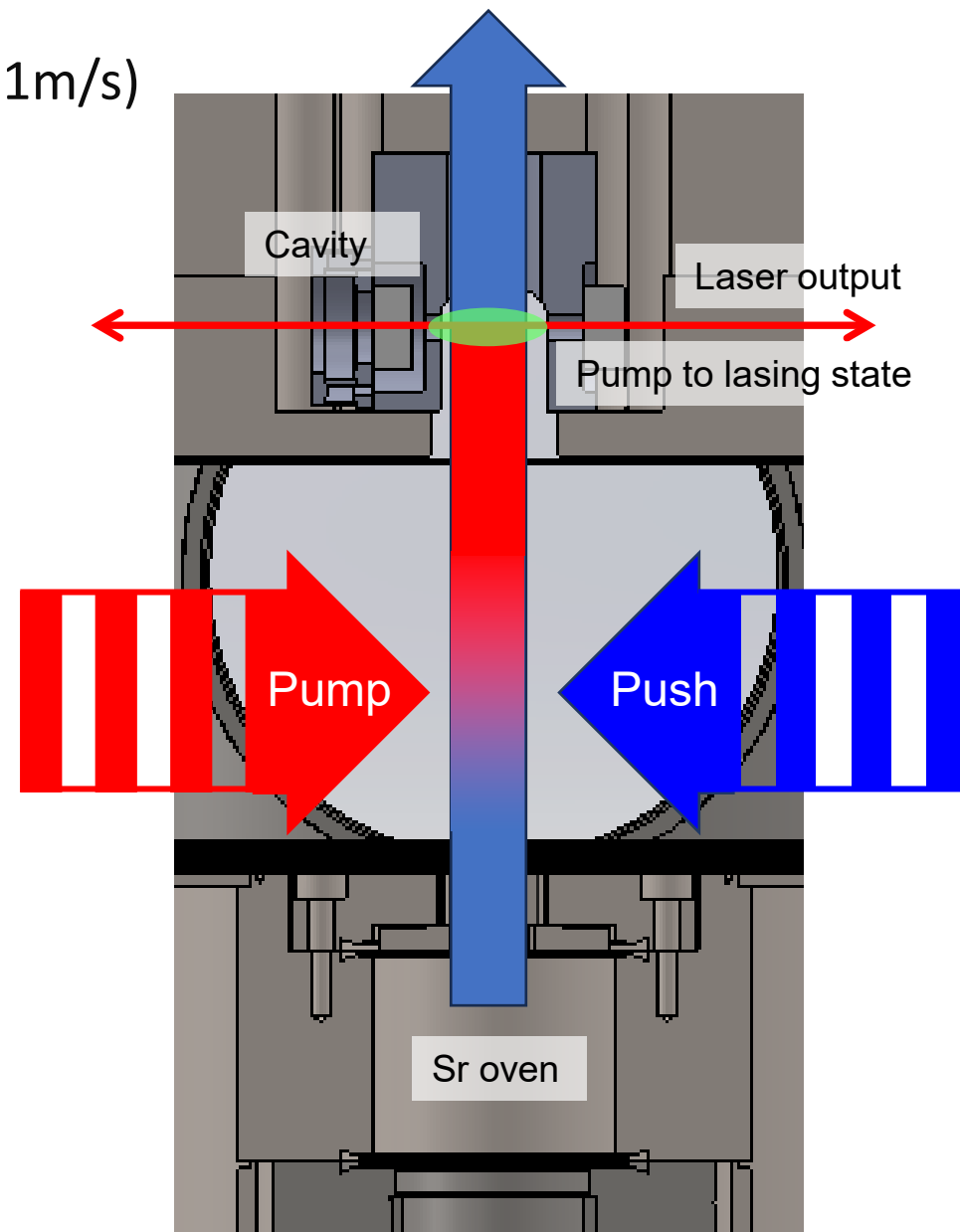
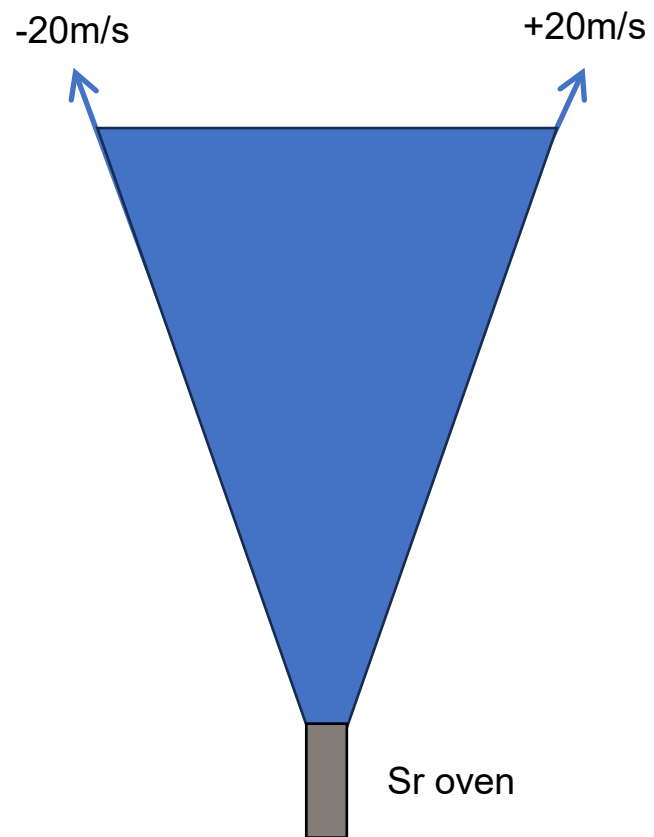
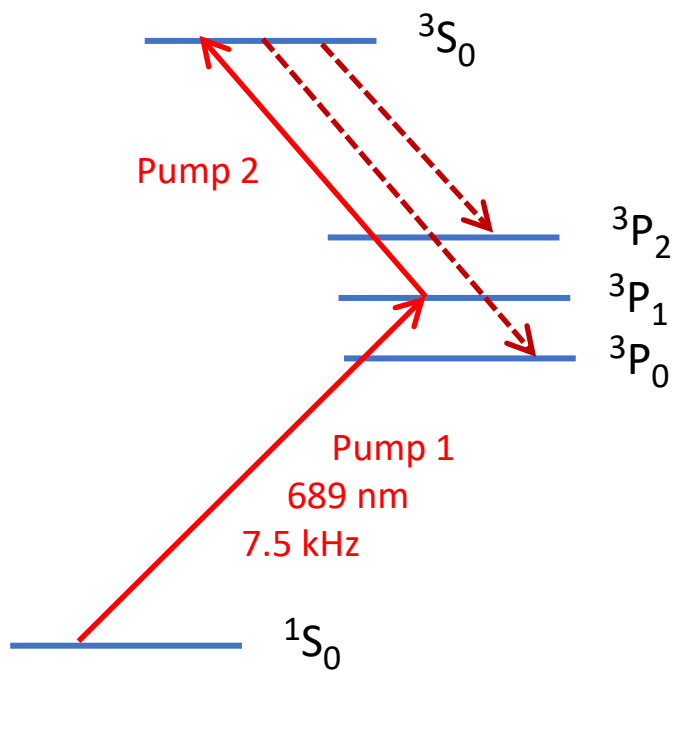




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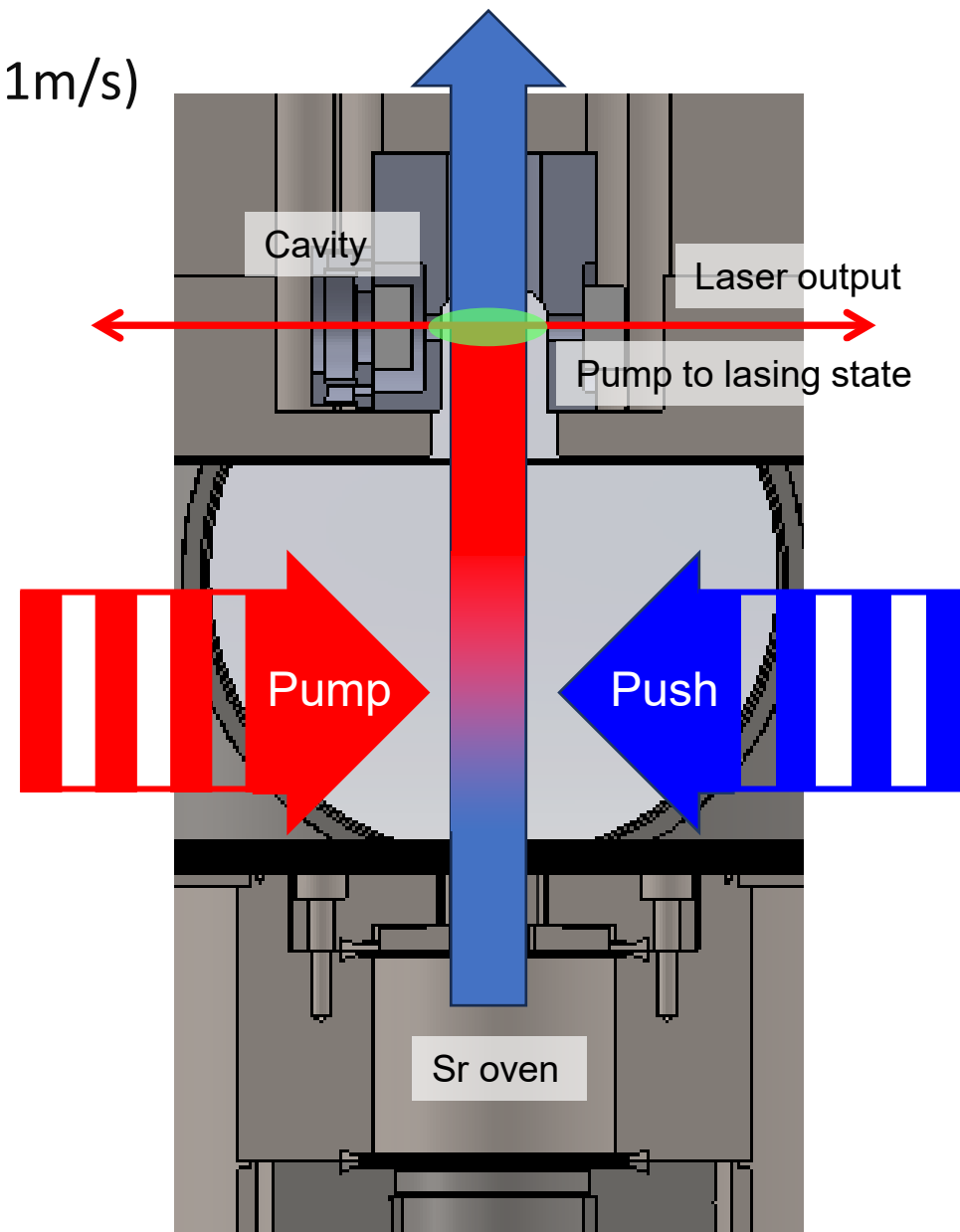
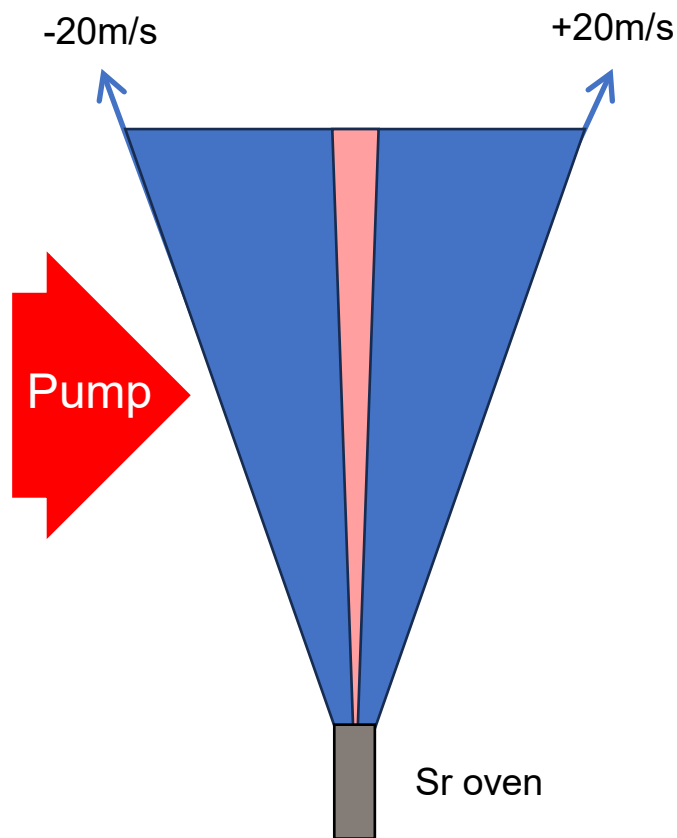
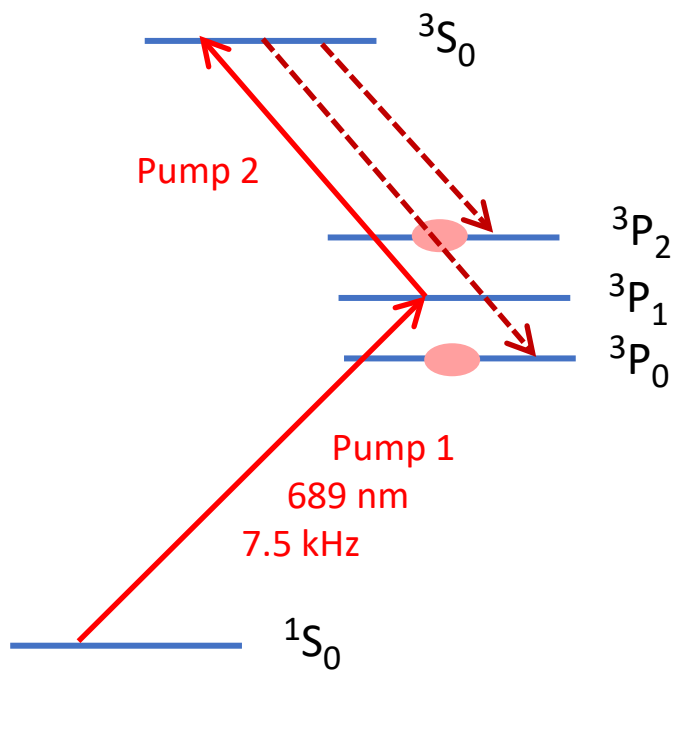




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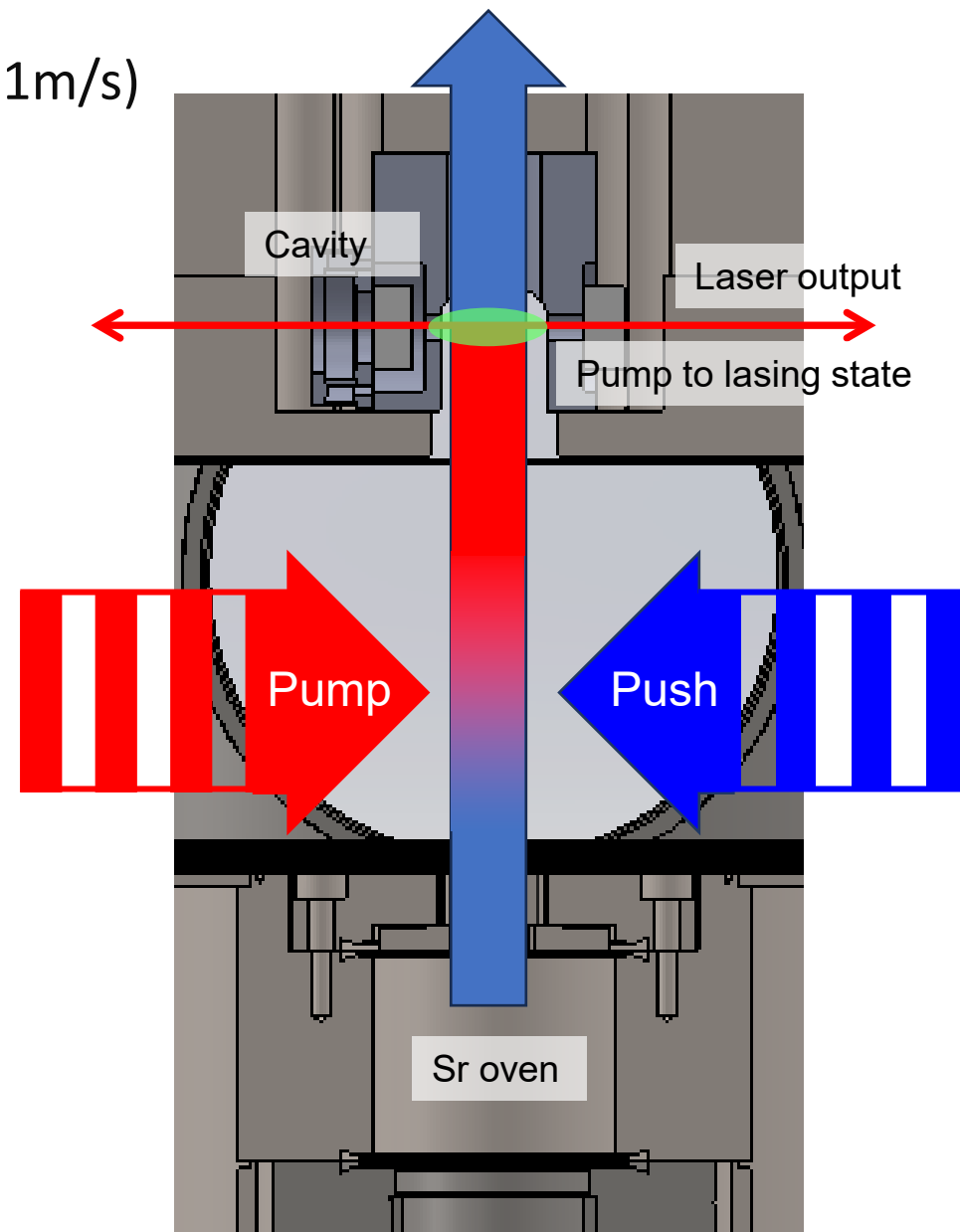
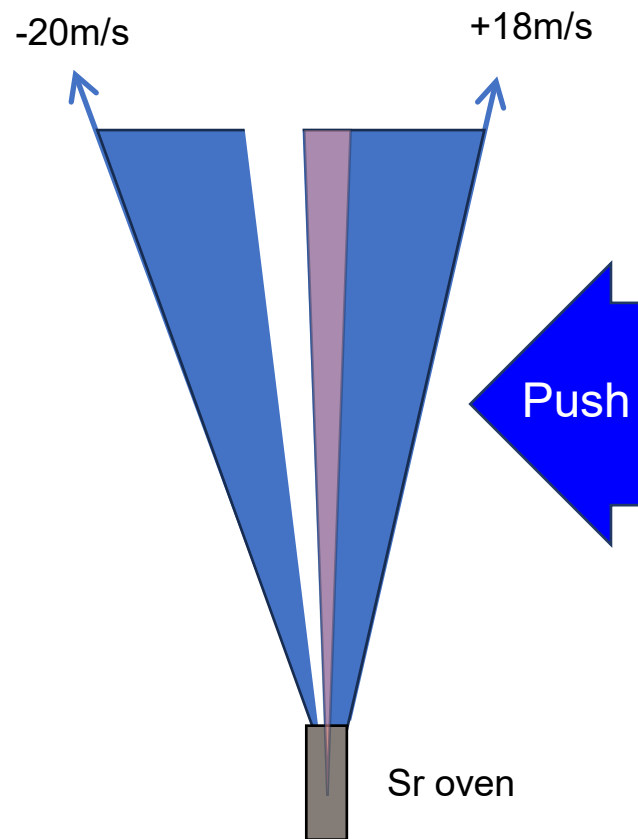
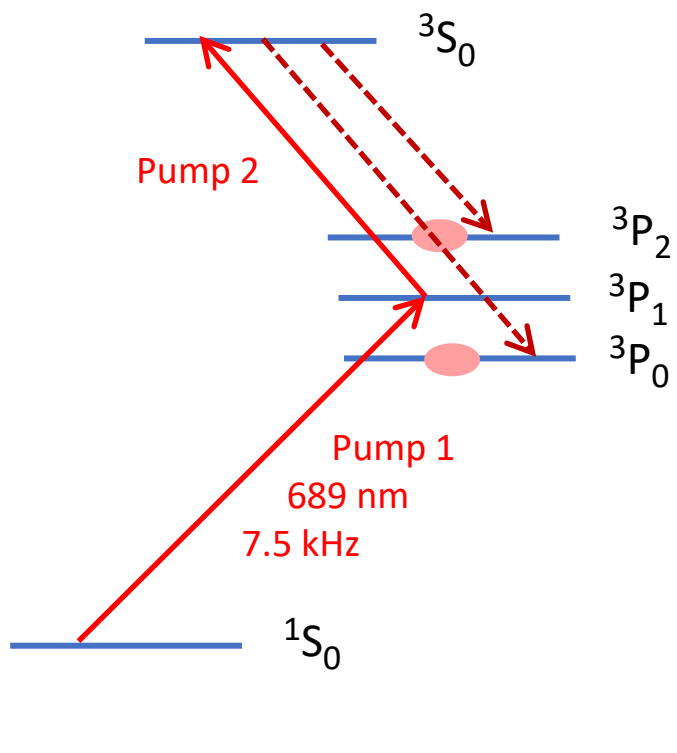




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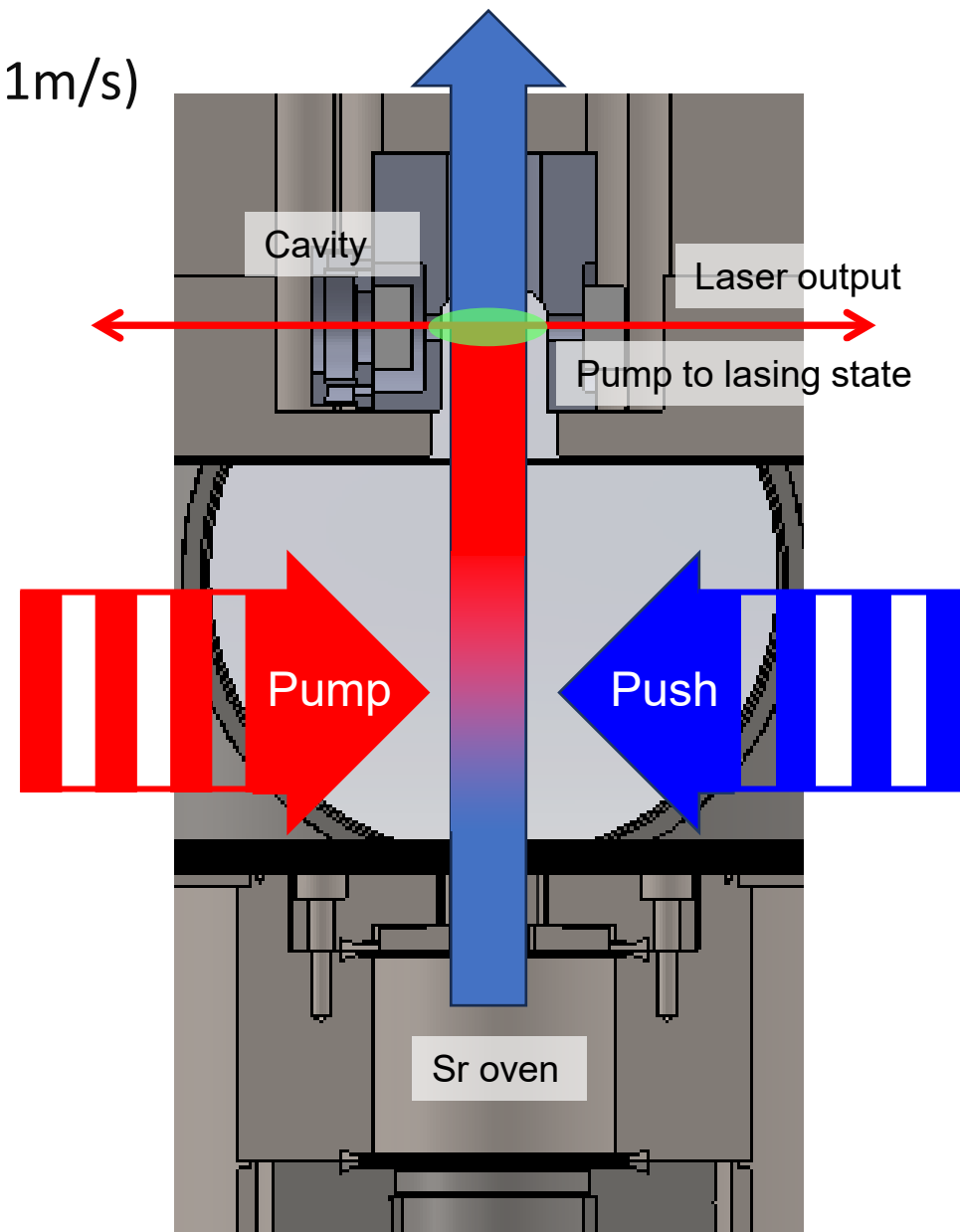
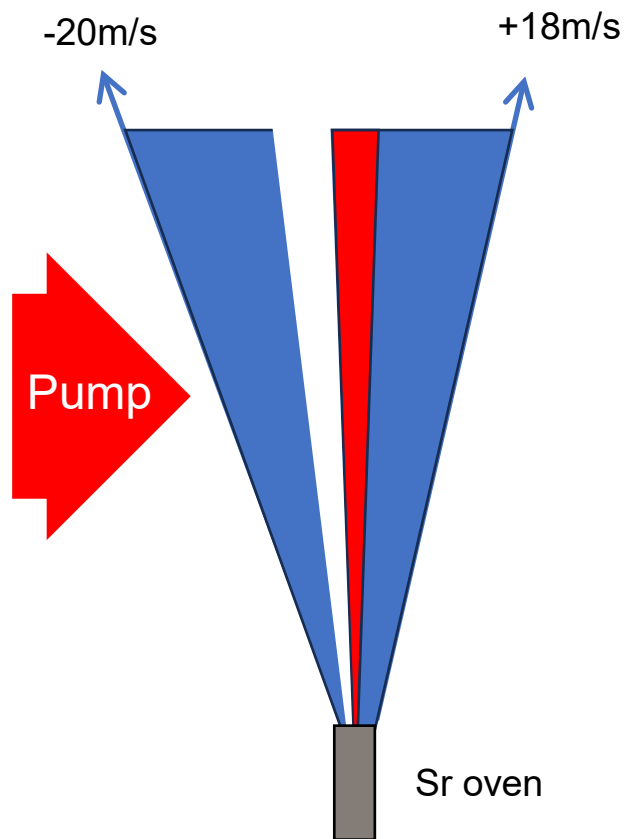
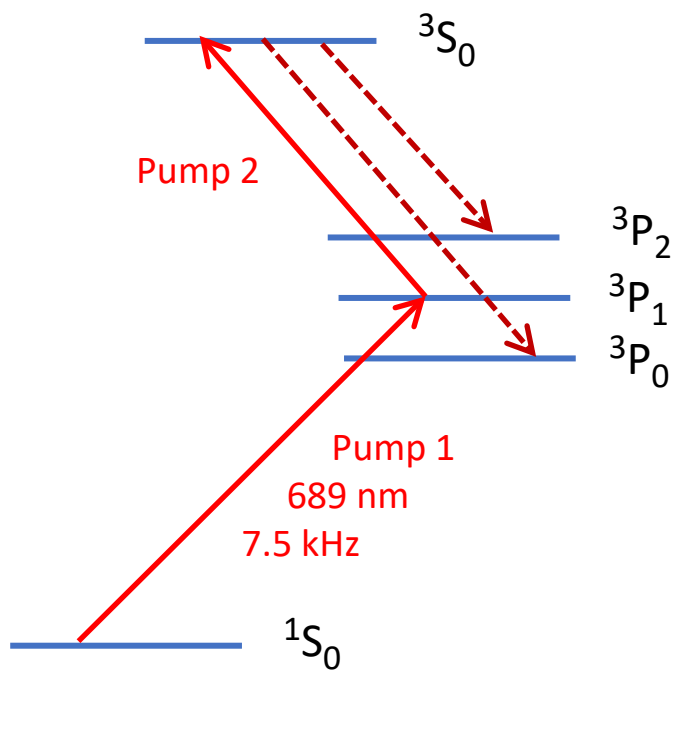




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Sr level scheme

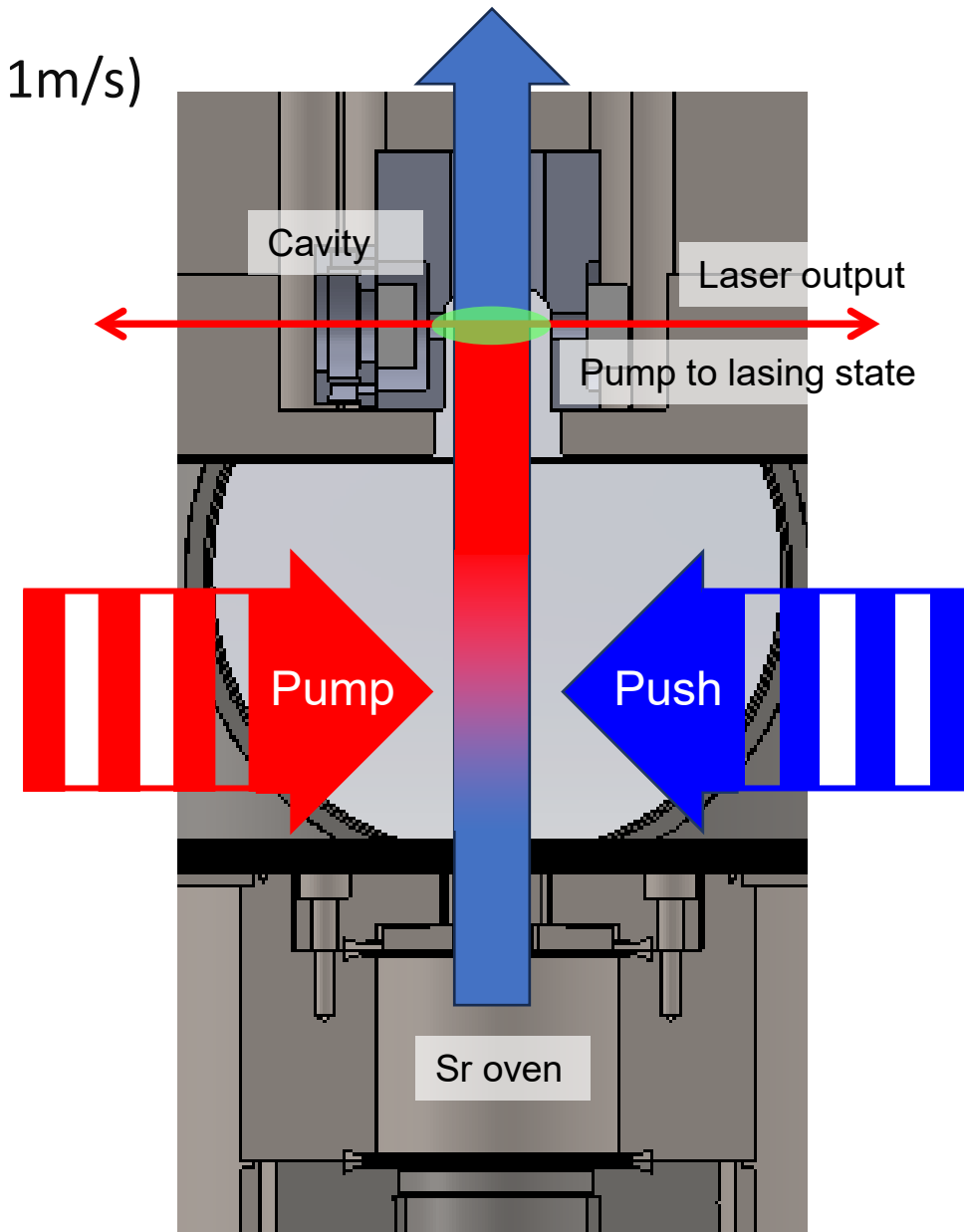
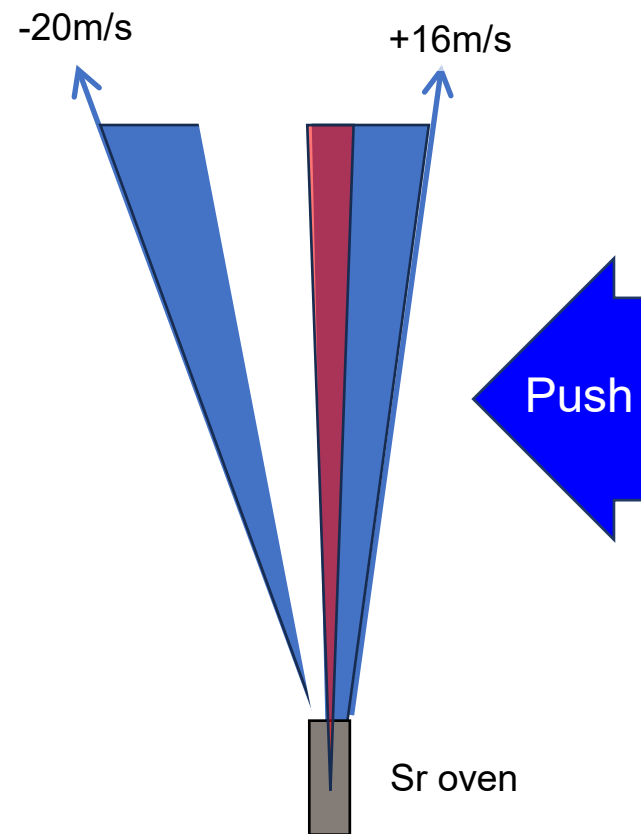
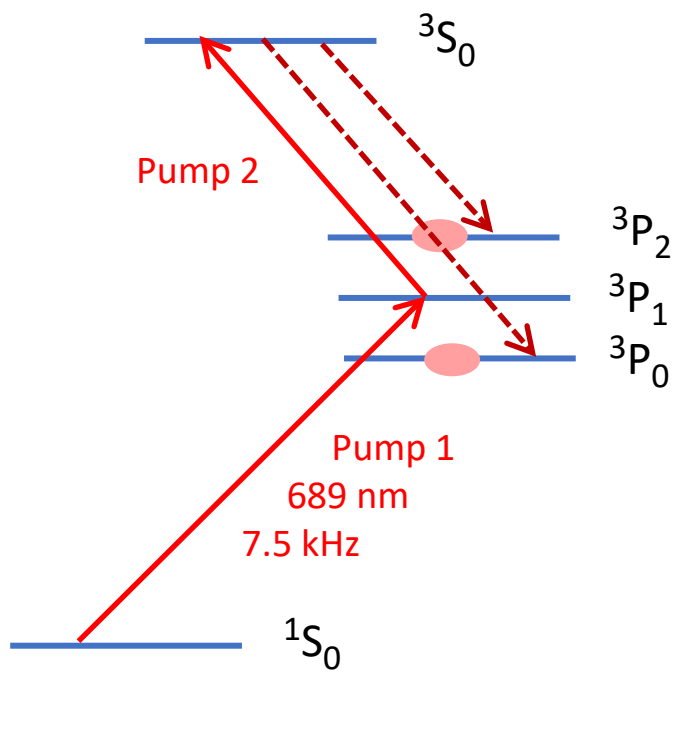




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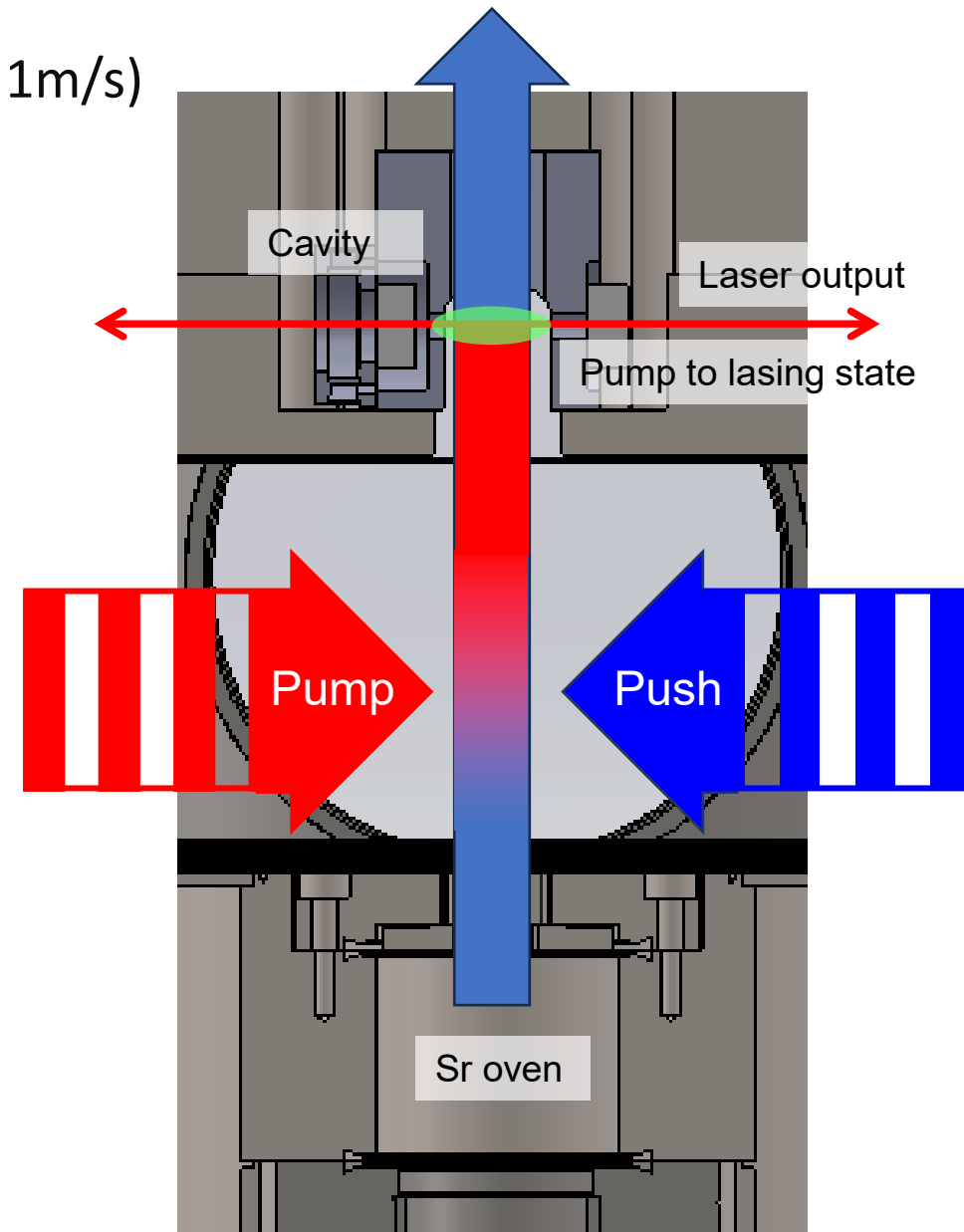
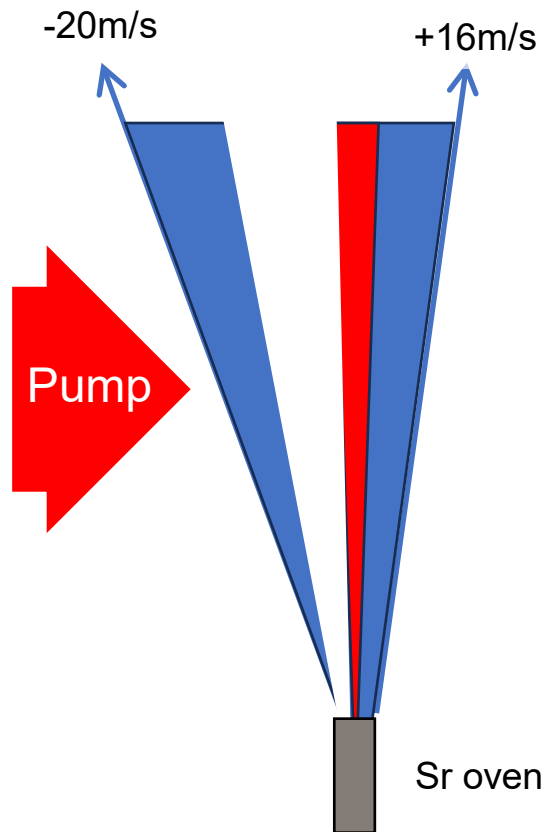
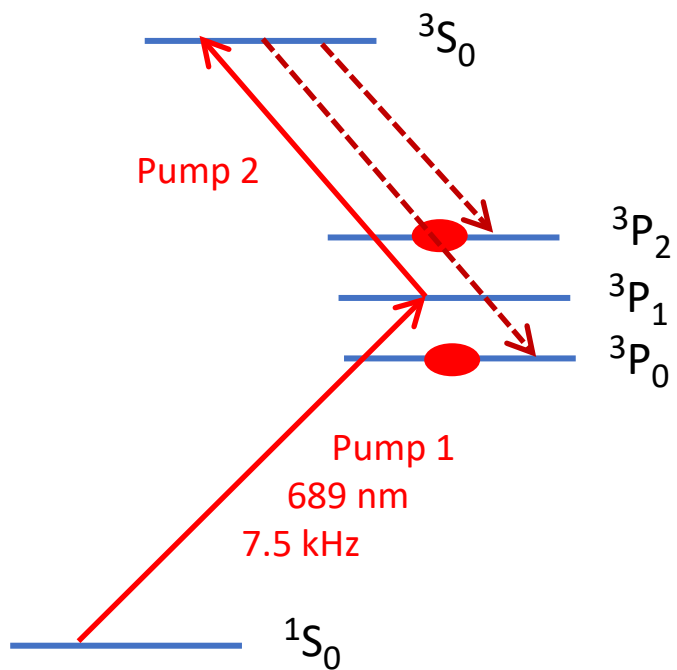




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Sr level scheme

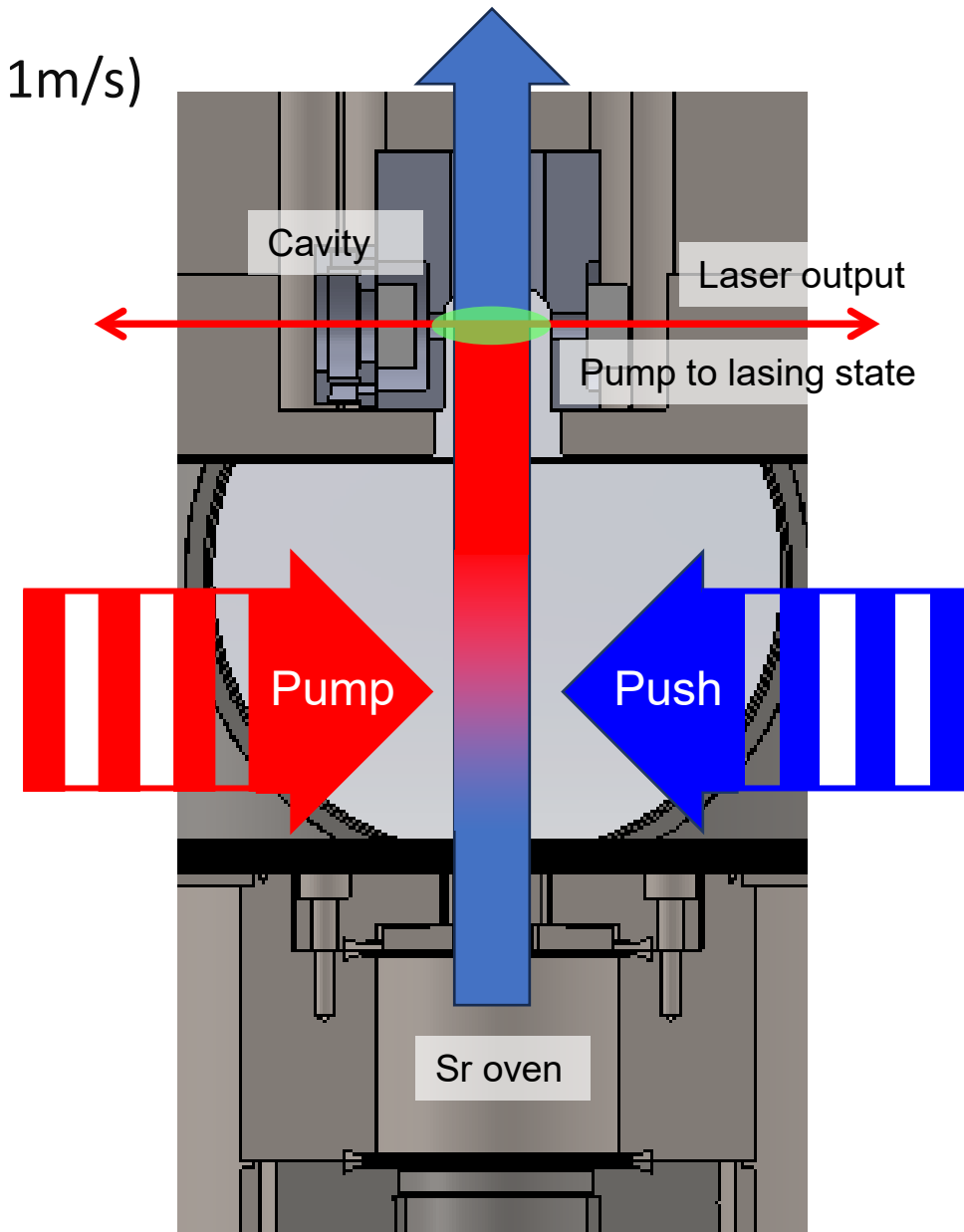
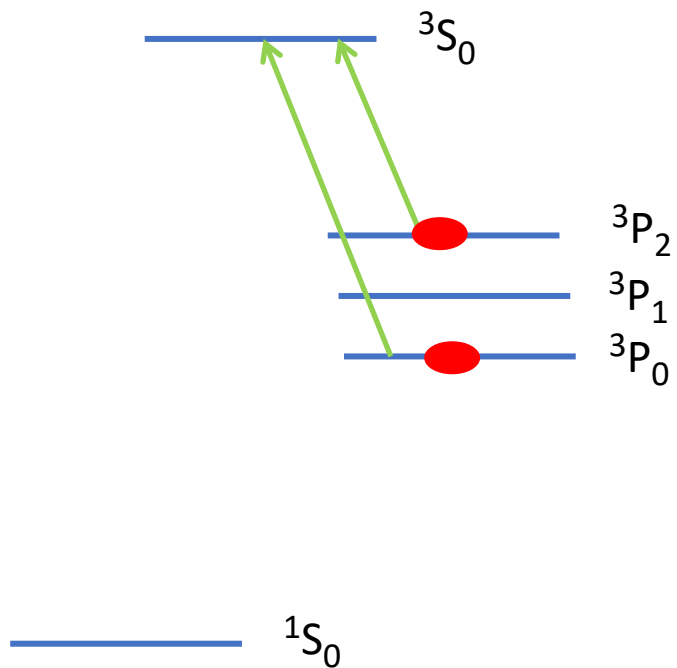




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Goal: atoms entering cavity in 3P_1 state and slow along cavity ($\pm 1\text{m/s}$)

Sr level scheme

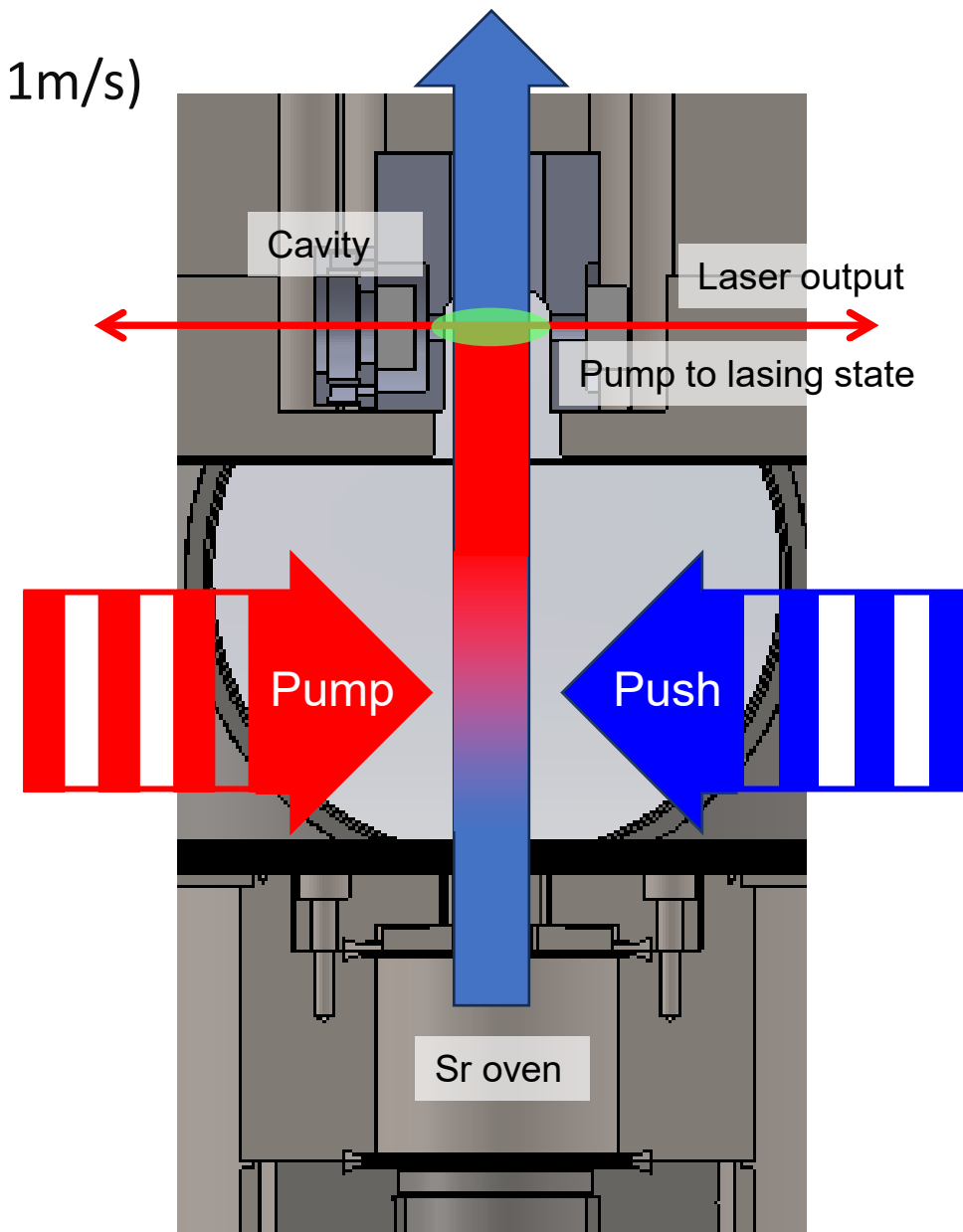
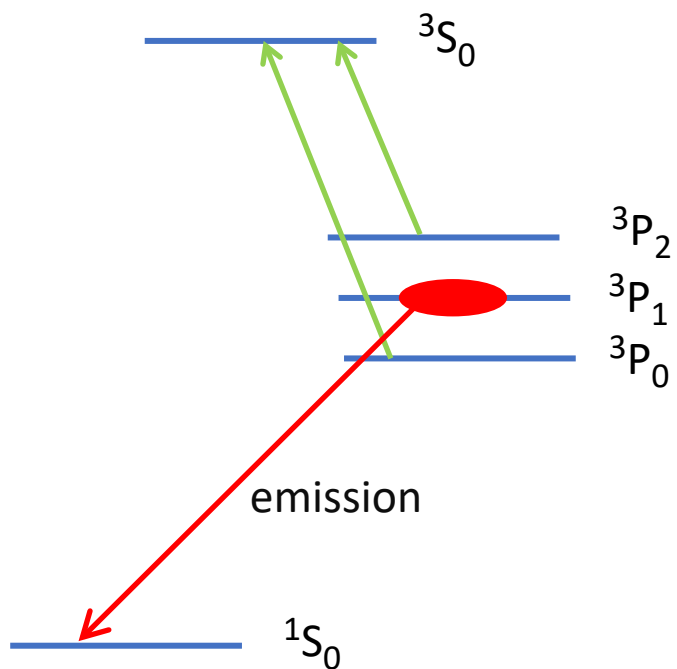




V1: kHz-transition superradiant Sr laser

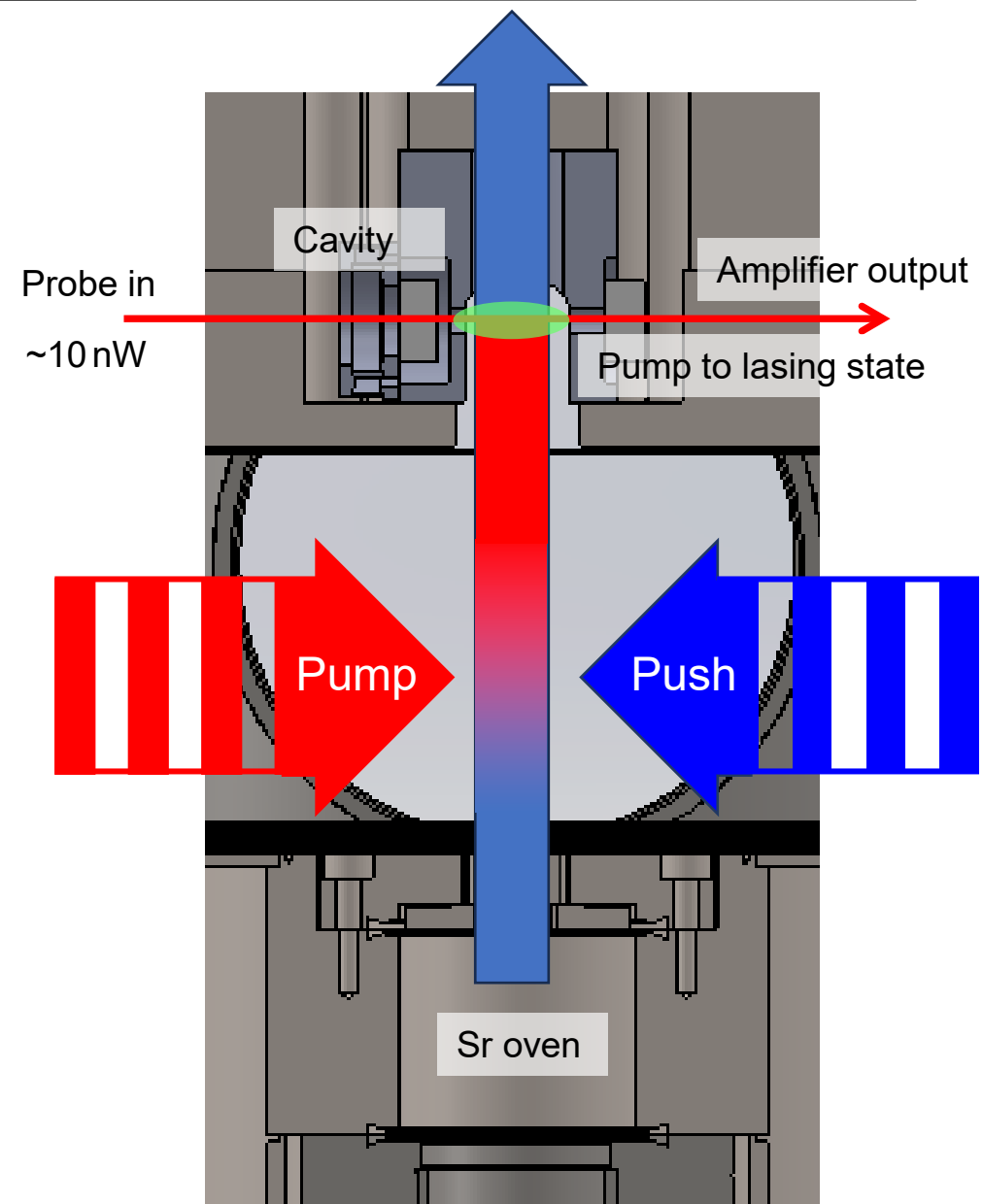
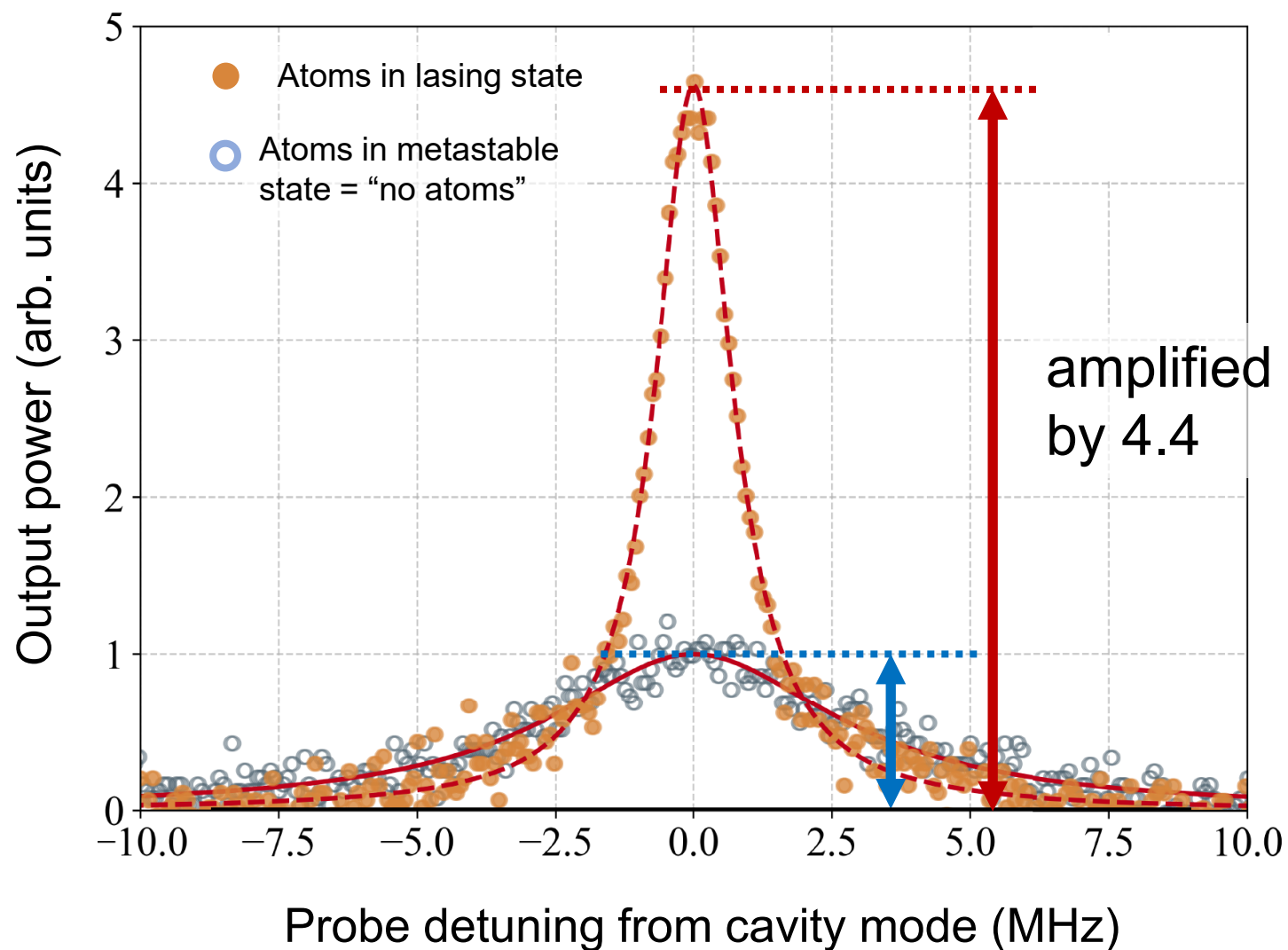
Goal: atoms entering cavity in 3P_1 state and slow along cavity ($\pm 1\text{m/s}$)

Sr level scheme



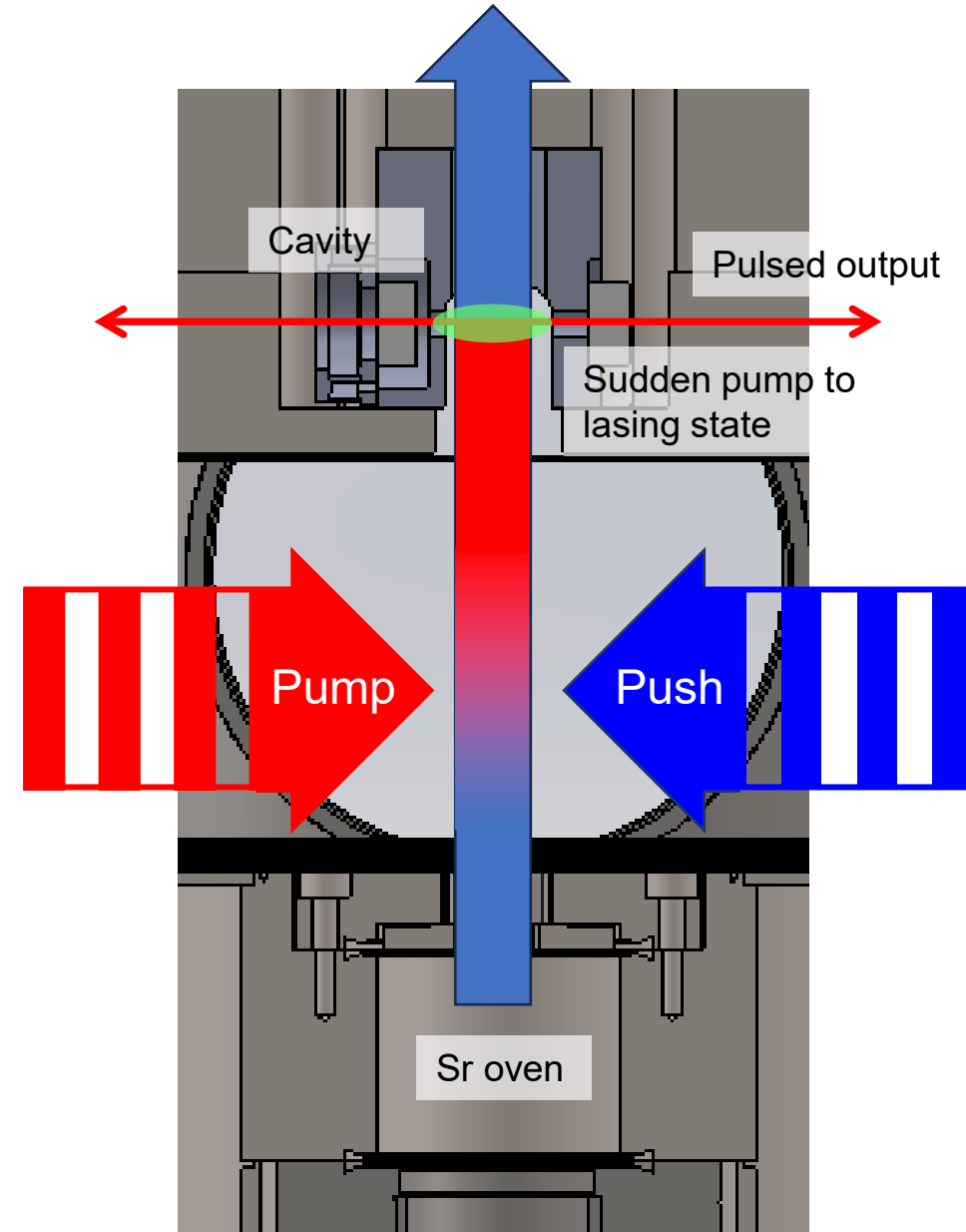


Gain





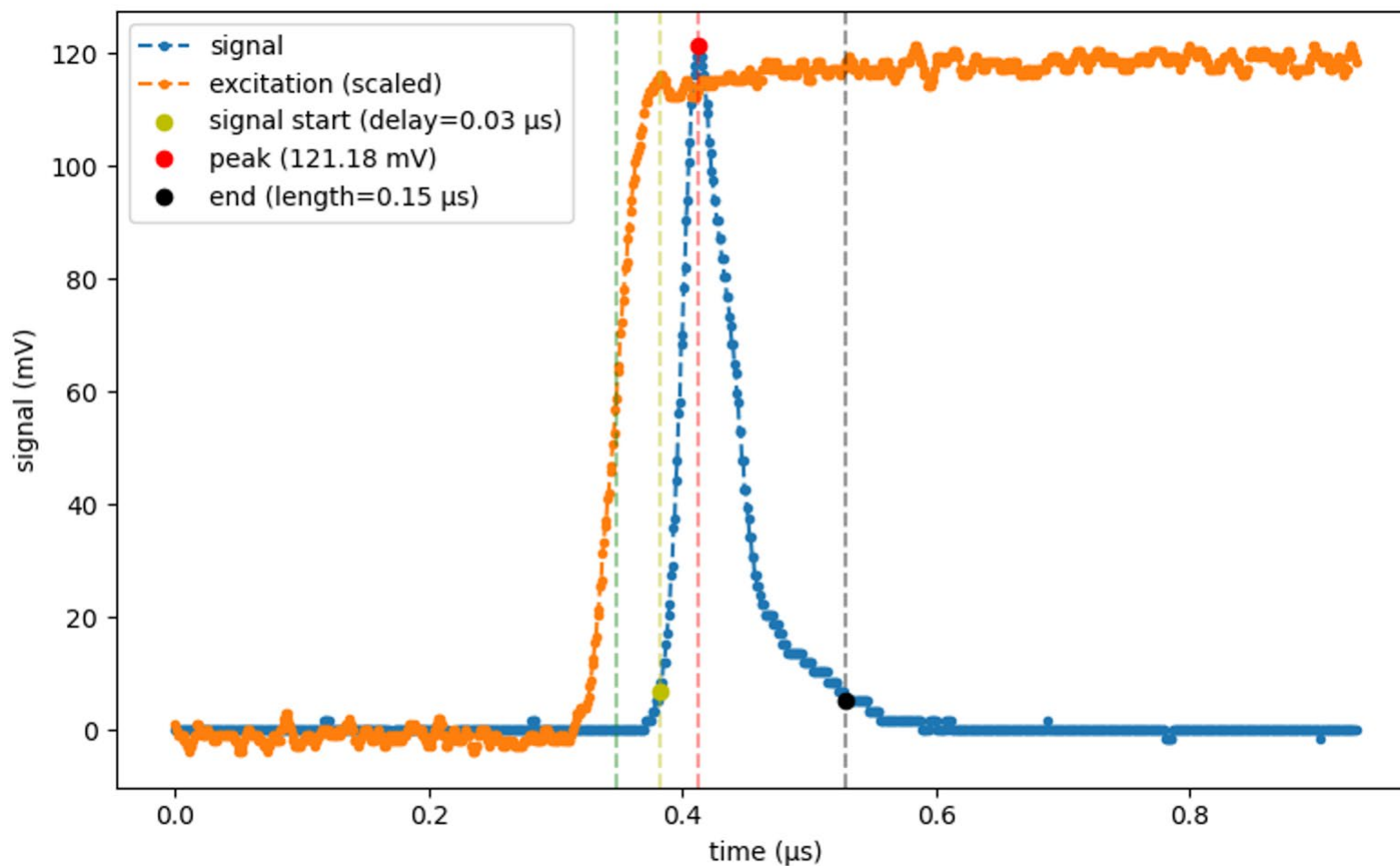
Emission pulse after sudden pump to lasing state





Another push

Labbook 19.3.2026



Ananya
Sitaram

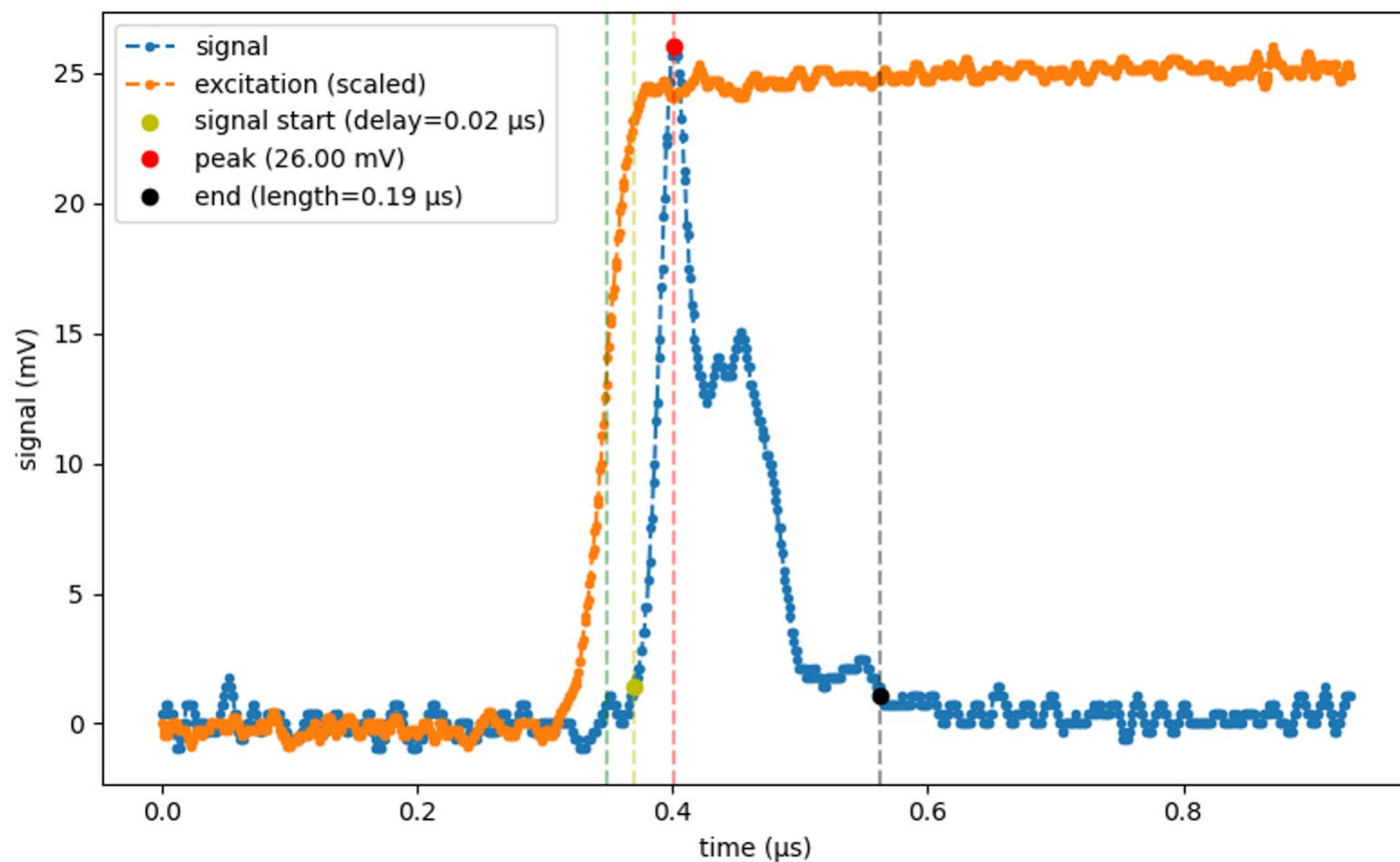


Benedikt
Heizenreder



Another push

Labbook 19.3.2026



Ananya
Sitaram

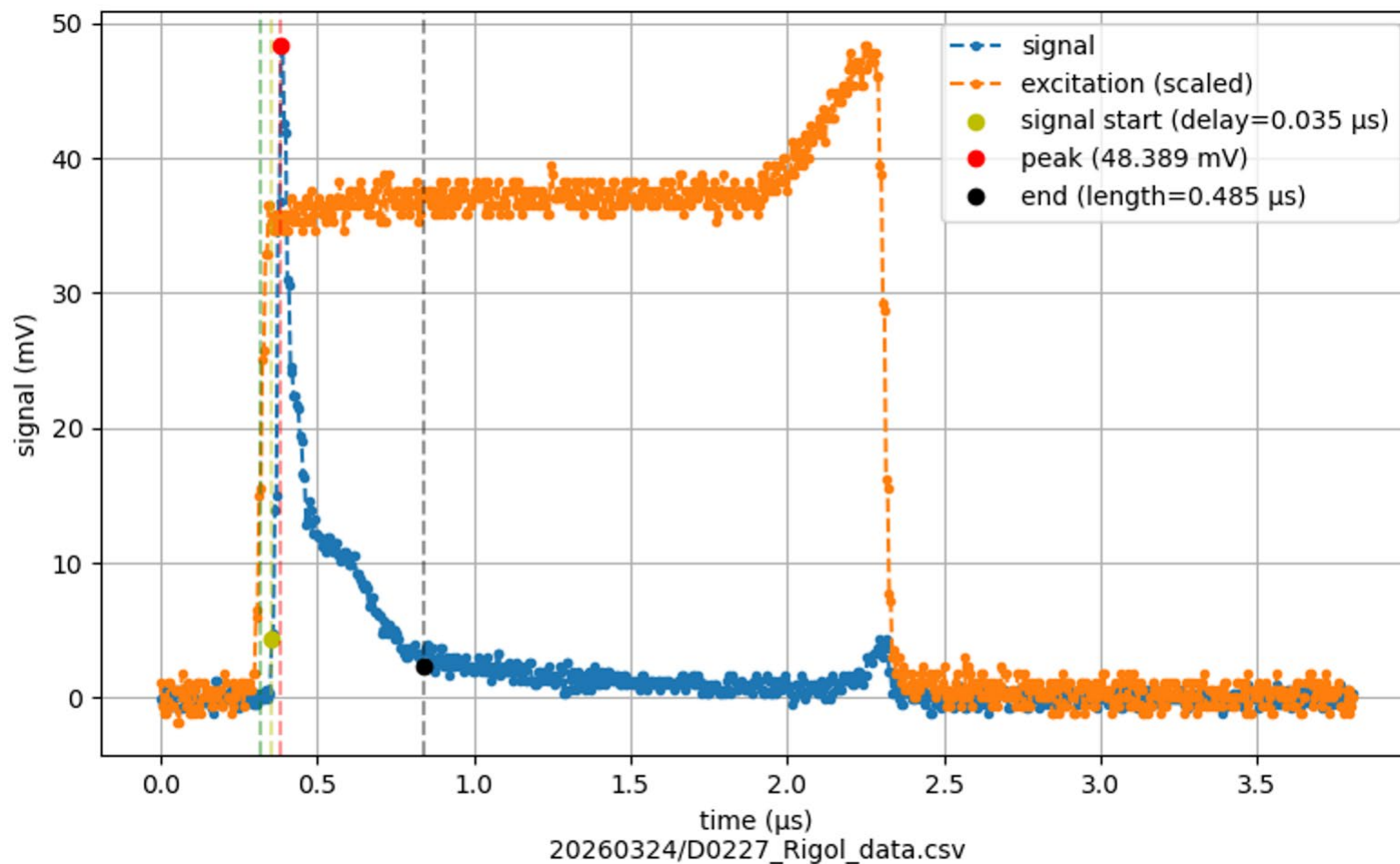


Benedikt
Heizenreder



Another push

Labbook 24.3.2026



Ananya
Sitaram

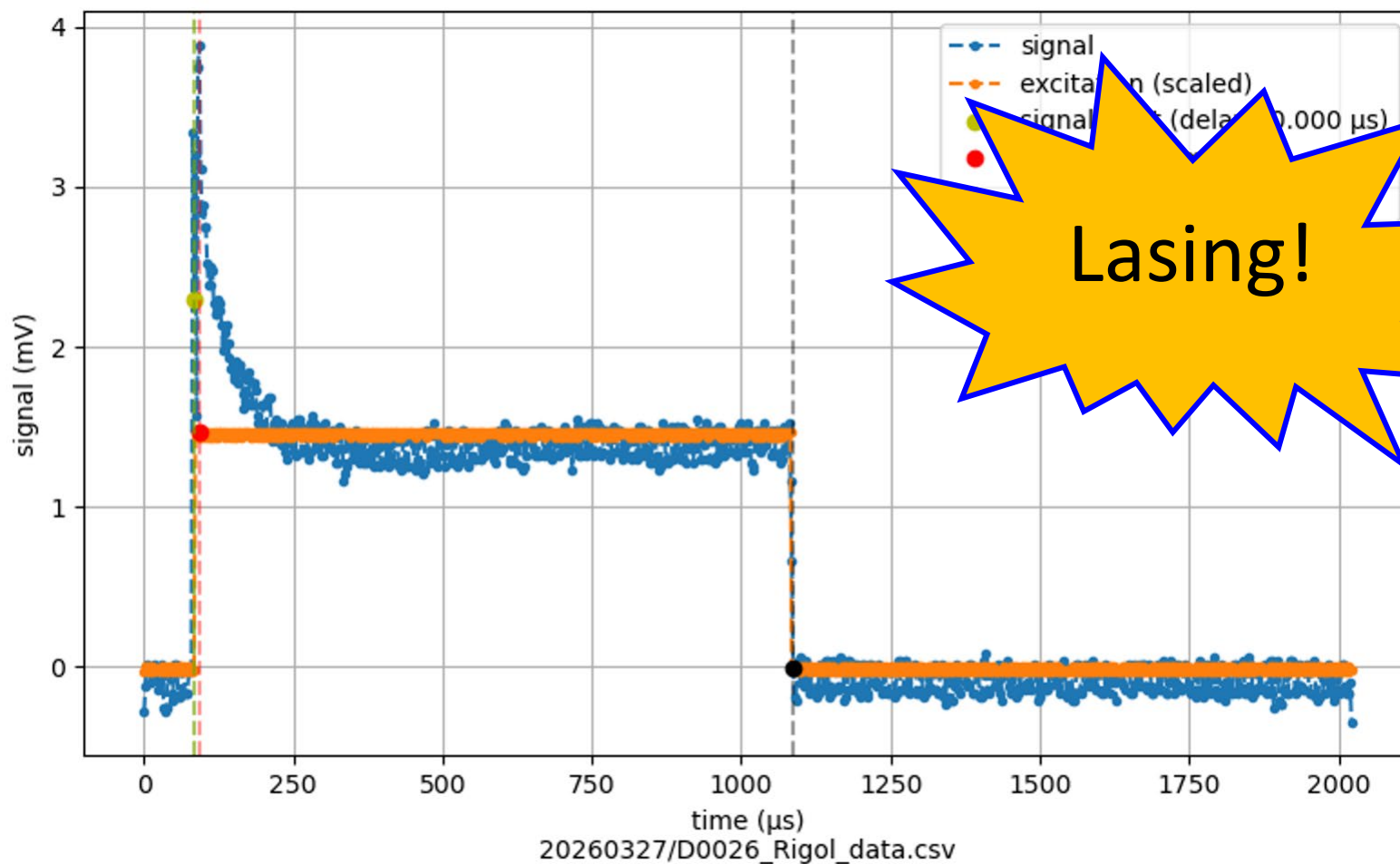


Benedikt
Heizenreder



Last step: homogeneous B-field

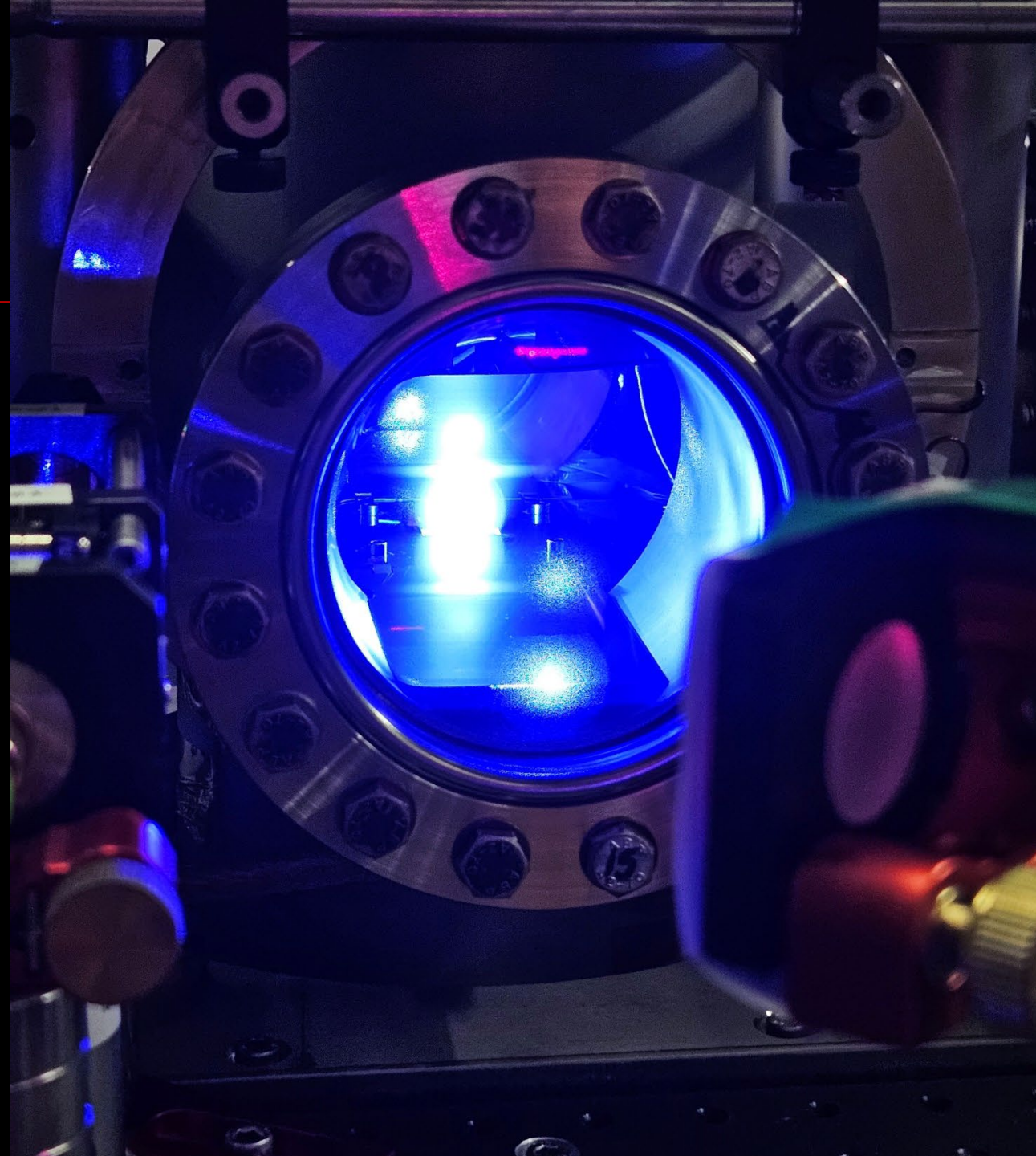
Labbook 27.3.2026



Ananya
Sitaram

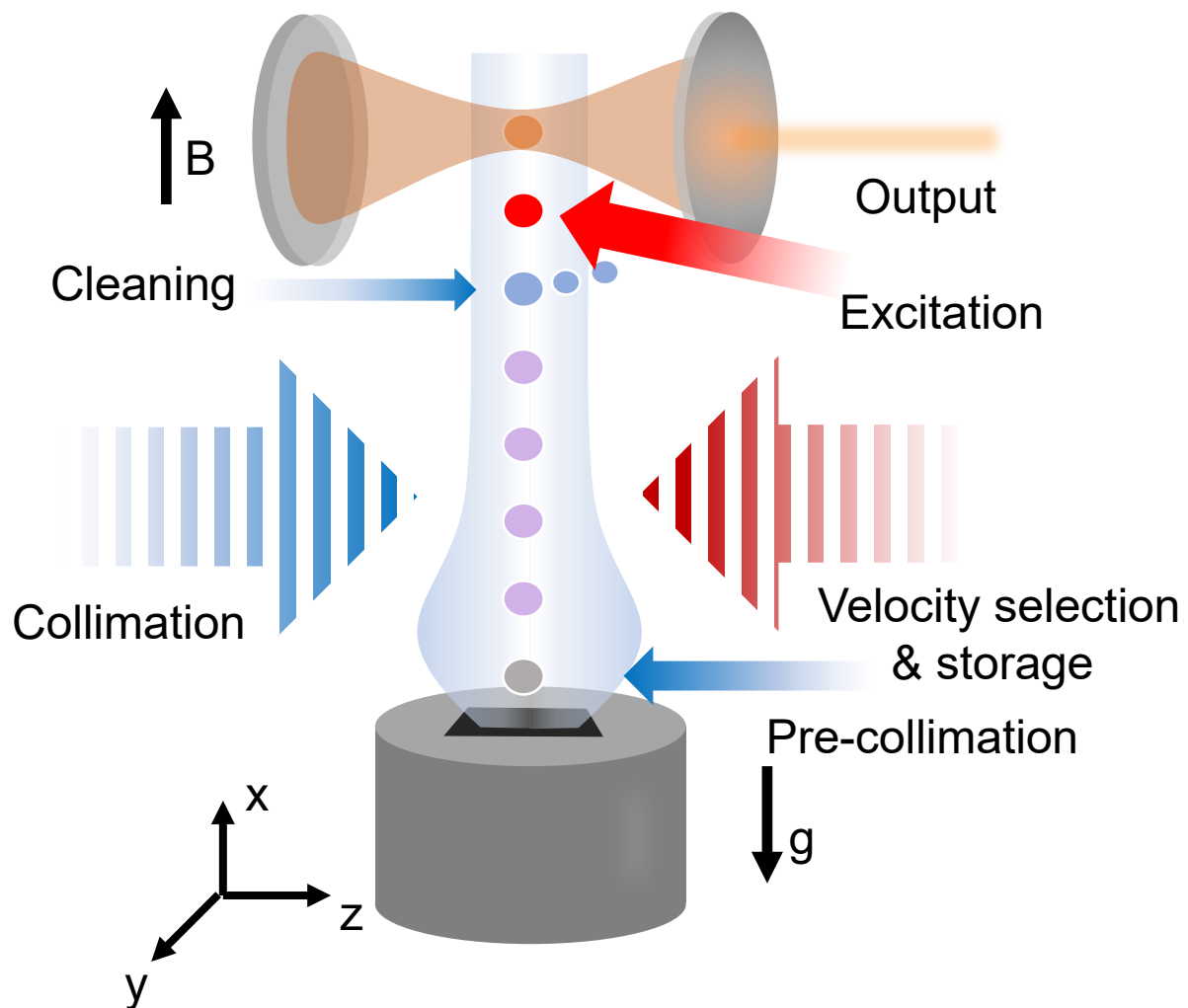


Benedikt
Heizenreder

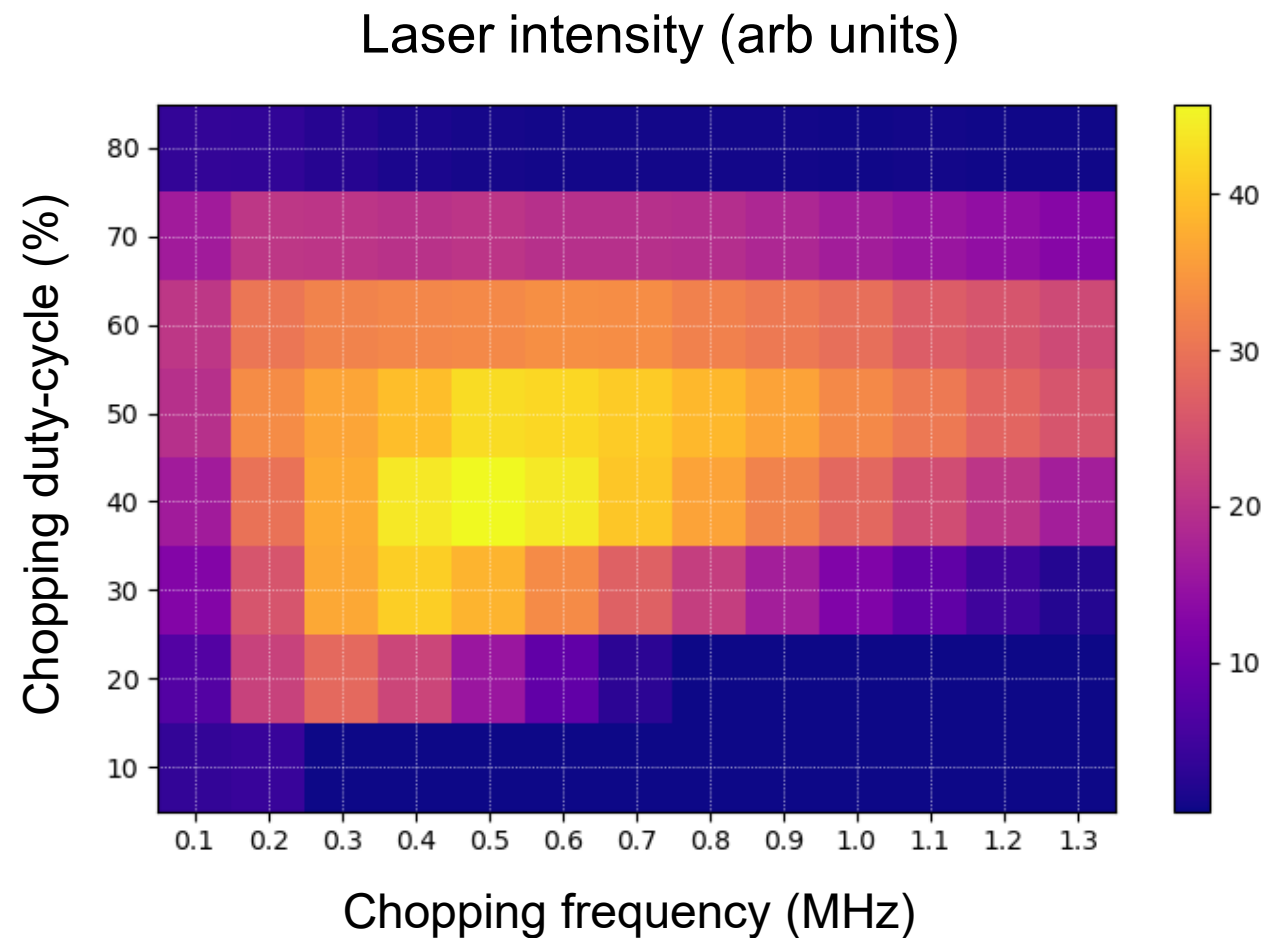




Optimizing everything

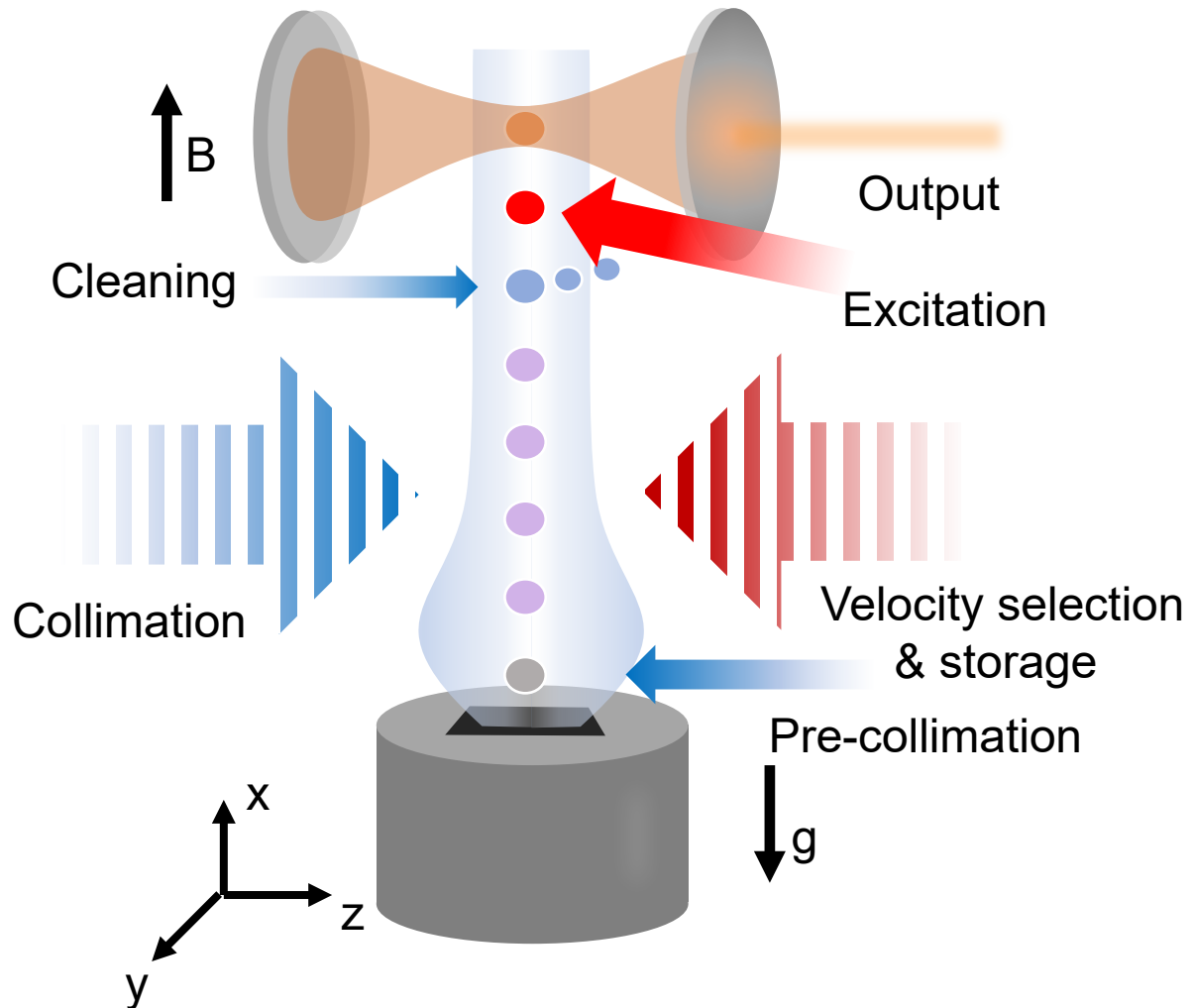


Maximum output power $\sim 50\text{nW}$





Key parameters



Cavity

Waist

$$\omega_0 = 87 \mu m$$

Finesse

$$F = 890$$

Cavity linewidth

$$\kappa = 2\pi \times 6.8 \text{ MHz}$$

Single-atom cooperativity

$$C = 0.01$$

Atomic beam

Flux into cavity mode

$$\sim 10^{11}/s$$

Vertical velocity

$$\sim 350 \text{ m/s}$$

Velocity in cavity direction

$$\sim 1 \dots \text{few m/s}$$

Timescales / Linewidths

Cavity linewidth

$$\kappa = 2\pi \times 6.8 \text{ MHz}$$

Atomic linewidth

$$\gamma = 2\pi \times 7.5 \text{ kHz}$$

Transit time

$$\tau \sim 0.5 \mu s$$

Transit time broadening

$$1/\tau \sim 2 \text{ MHz}$$

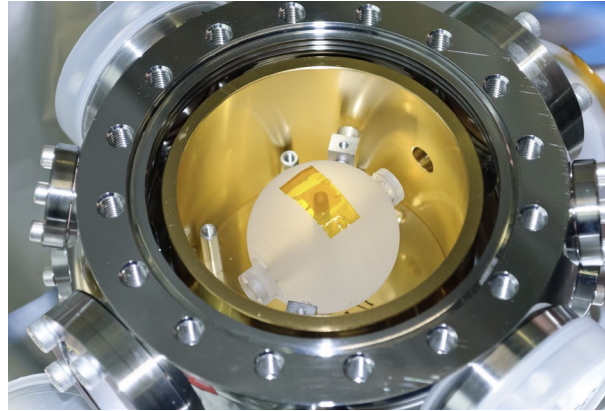
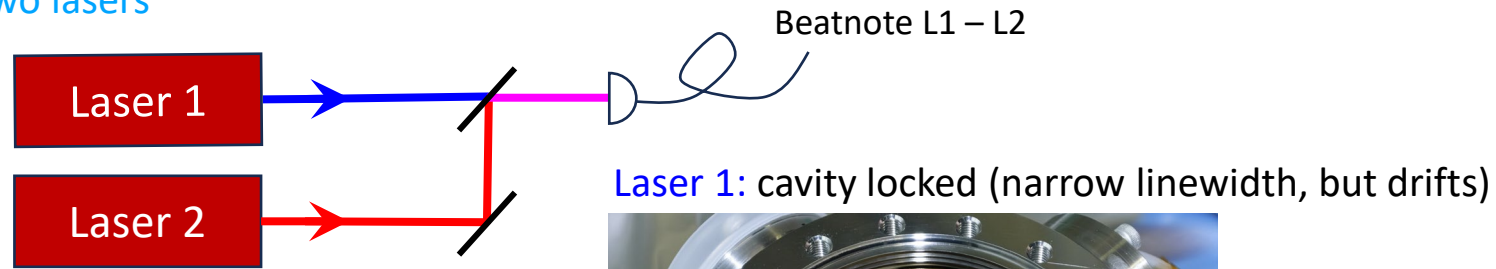
Doppler broadening

$$\Gamma_D \sim 1 \dots 10 \text{ MHz}$$

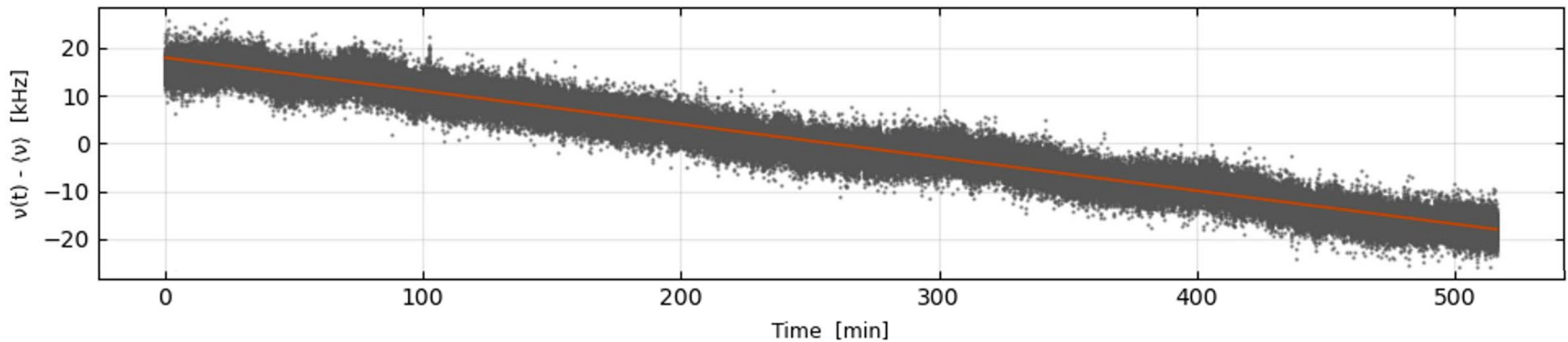
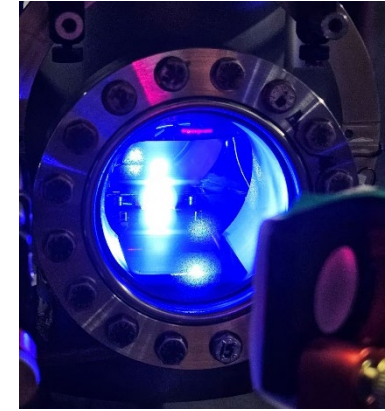


Linewidth

Beat between two lasers

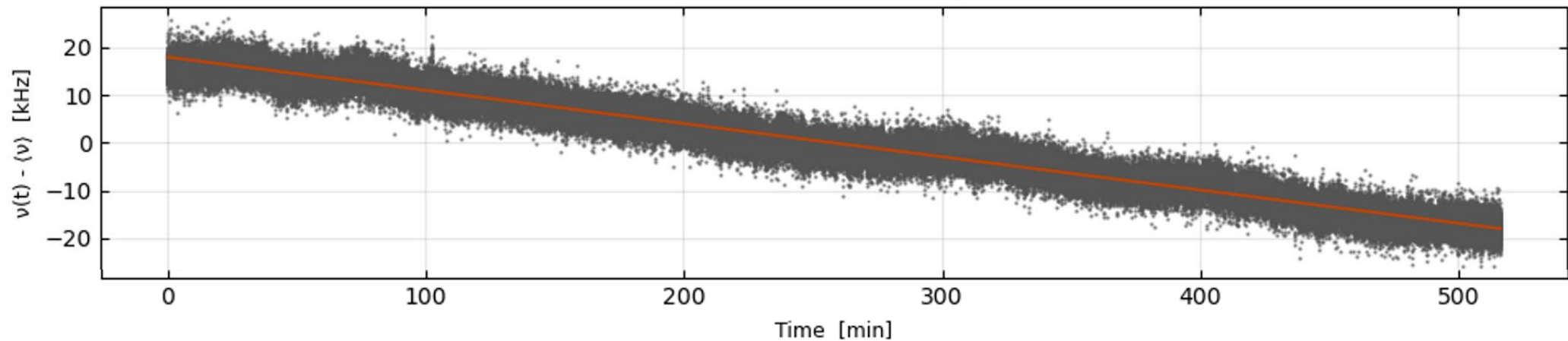


Laser 2: superradiant laser

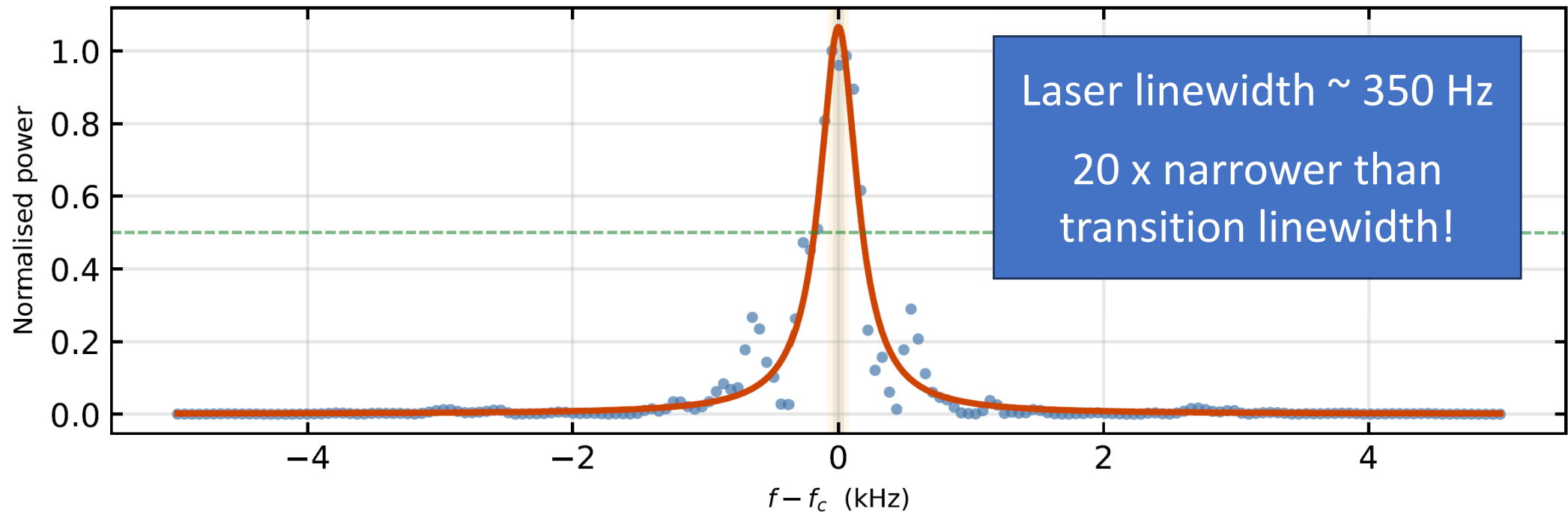




Linewidth



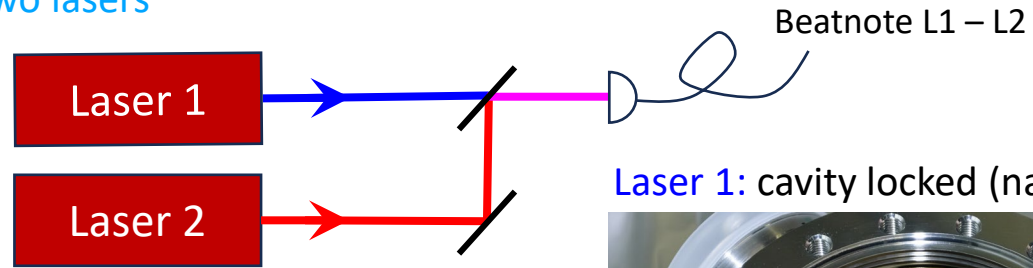
Fourier transform and Lorentzian fit:





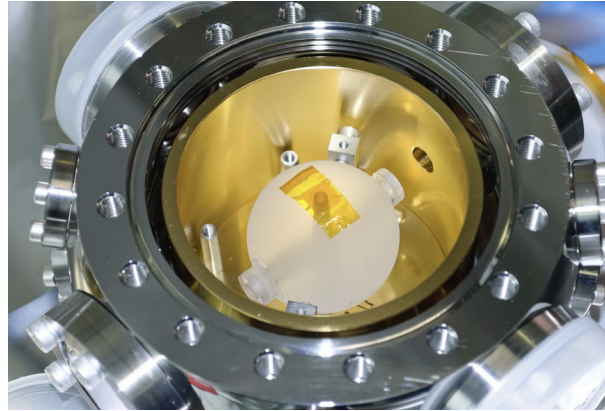
Linewidth

Beat between two lasers

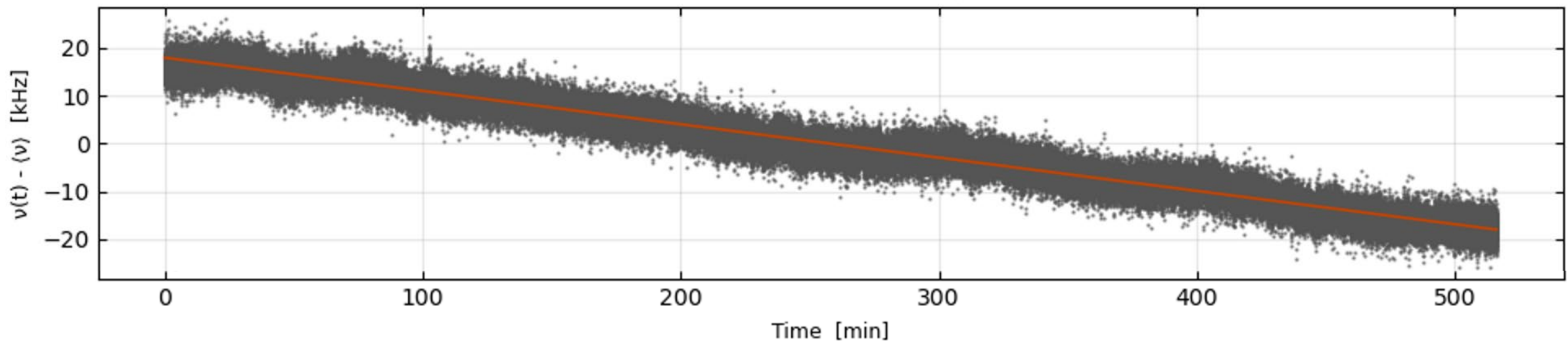
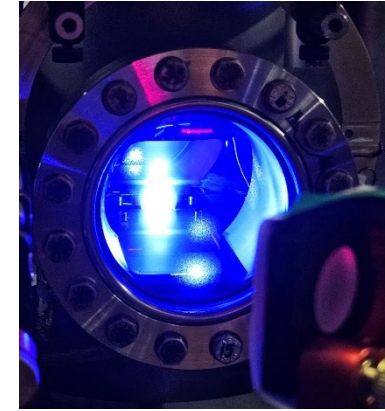


Which laser's frequency changed?

Laser 1: cavity locked (narrow linewidth, but drifts)



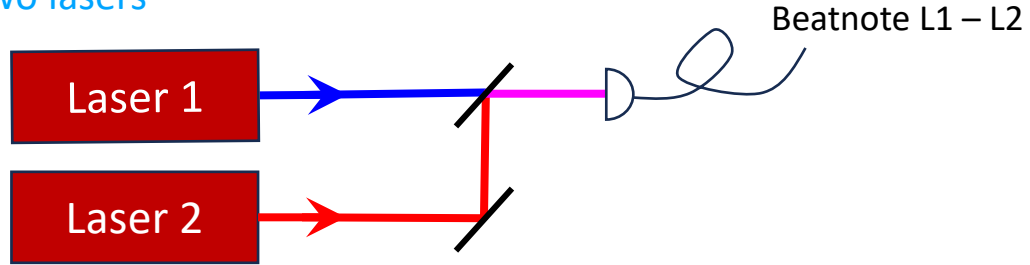
Laser 2: superradiant laser





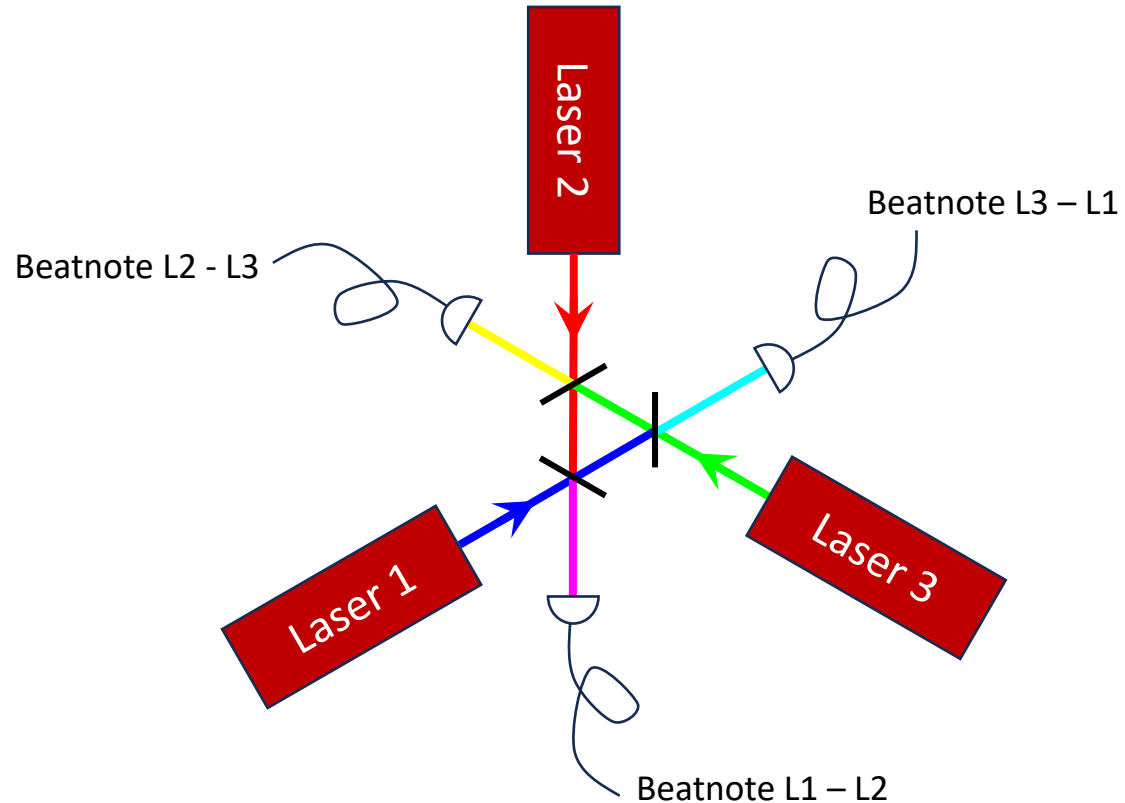
Laser frequency stability: 3-cornerd hat comparison

Beat between two lasers



Which laser's frequency changed?

Beat between three lasers

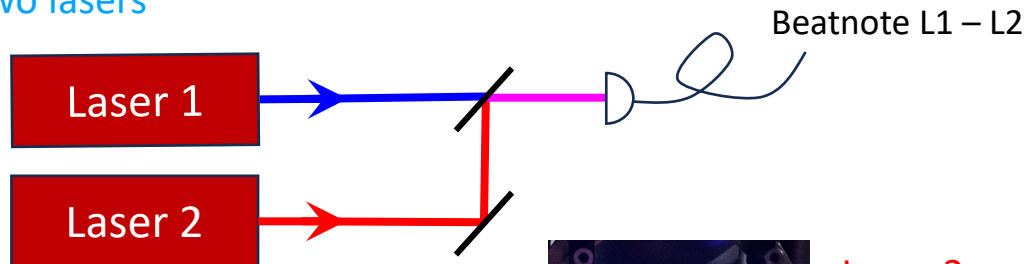


I know which laser's frequency changed!



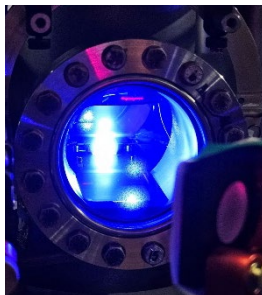
Laser frequency stability: 3-cornerd hat comparison

Beat between two lasers

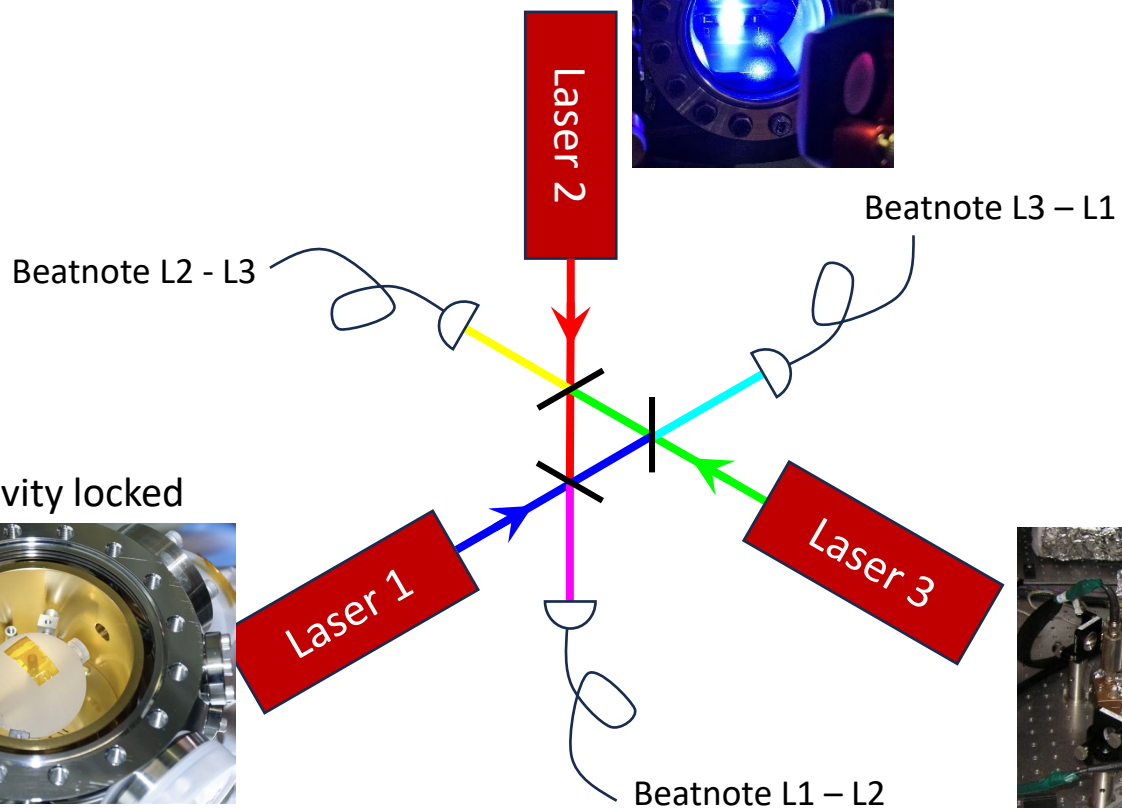


Which laser's frequency changed?

Laser 2: superradiant laser

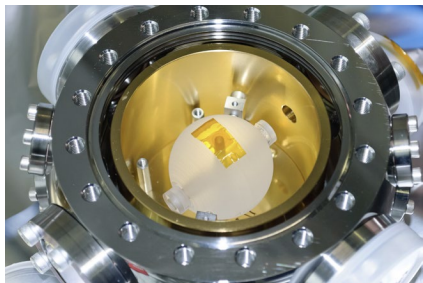


Beat between three lasers

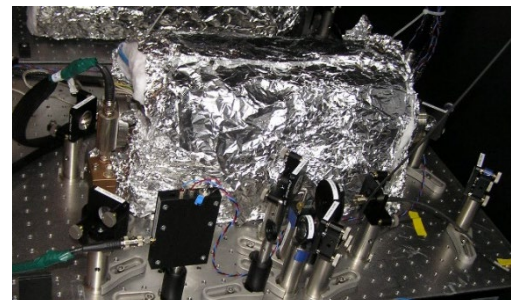


I know which laser's frequency changed!

Laser 1: cavity locked

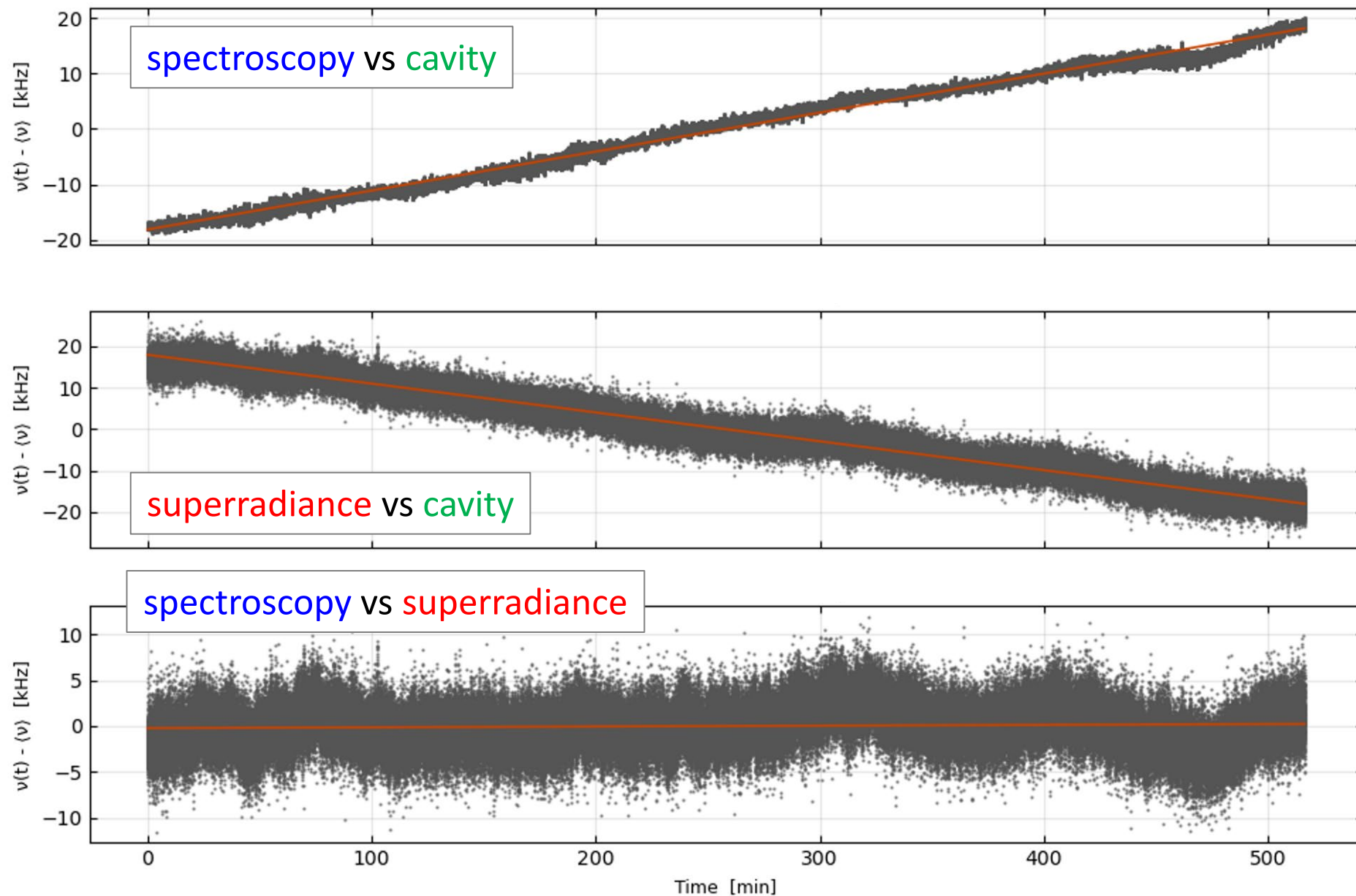


Laser 3: spectroscopy locked



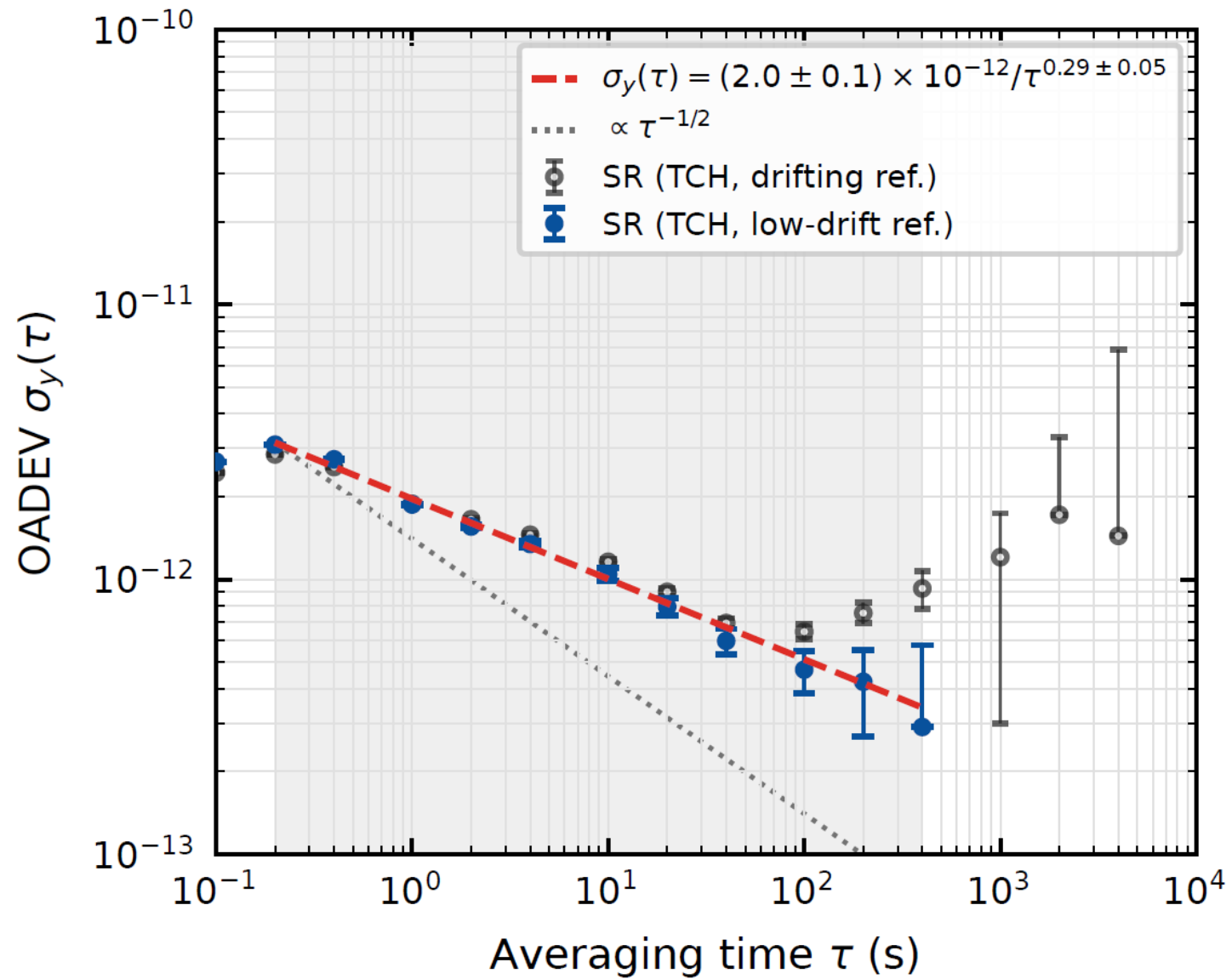


3-cornerd hat comparison: frequency drift over 500 minutes





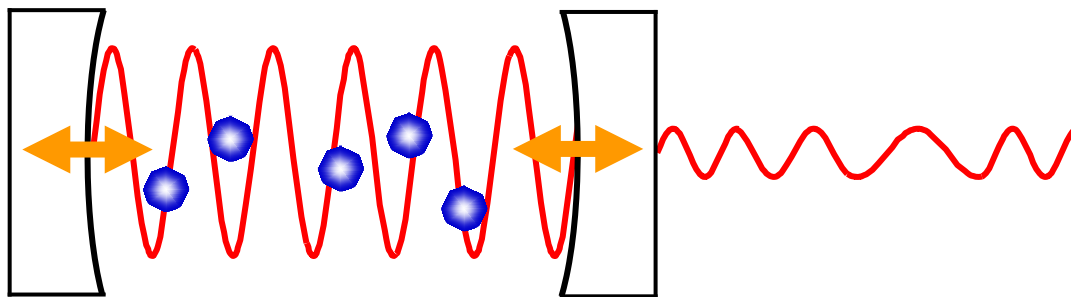
Allan deviations





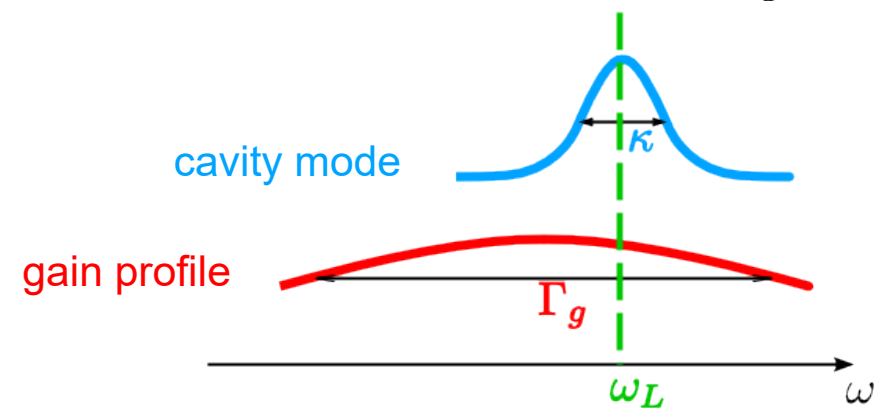
Cavity pulling

Standard laser: frequency stability from length of cavity

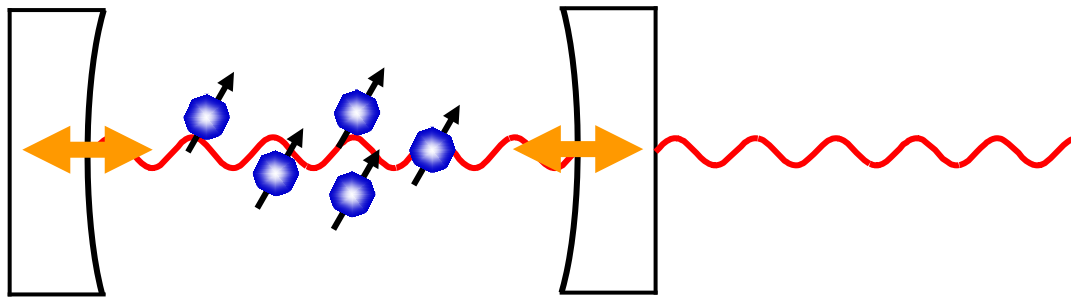


Good-cavity regime

$$\kappa \ll \Gamma_g$$

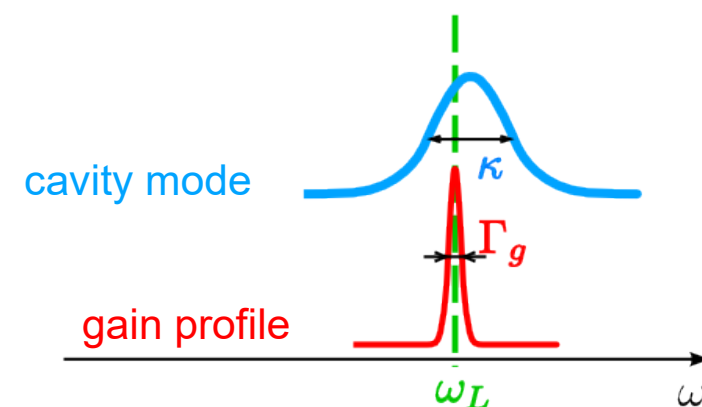


Superradiant clock laser: frequency stability from collective spin of atoms



Bad-cavity regime

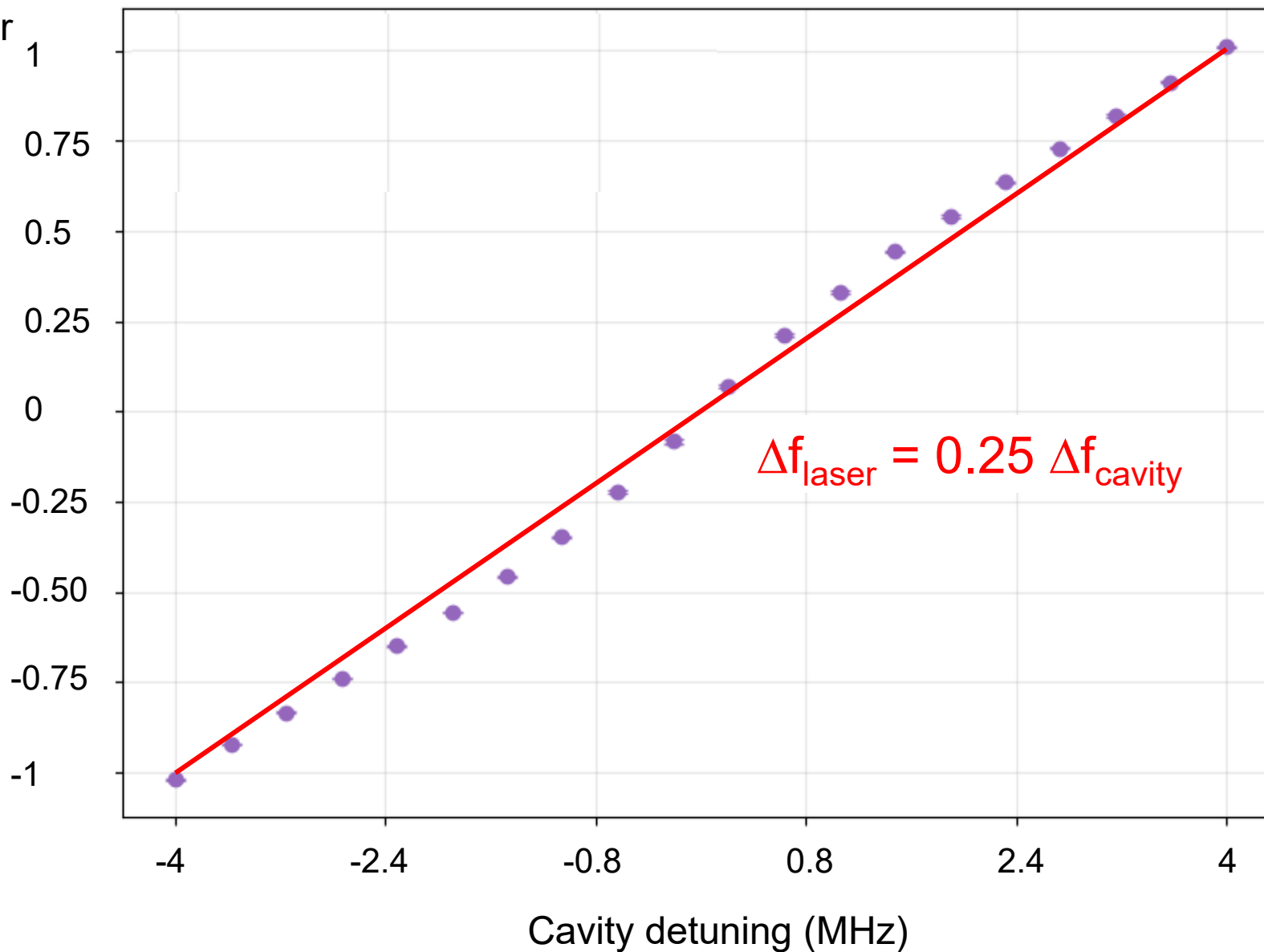
$$\kappa \gg \Gamma_g$$





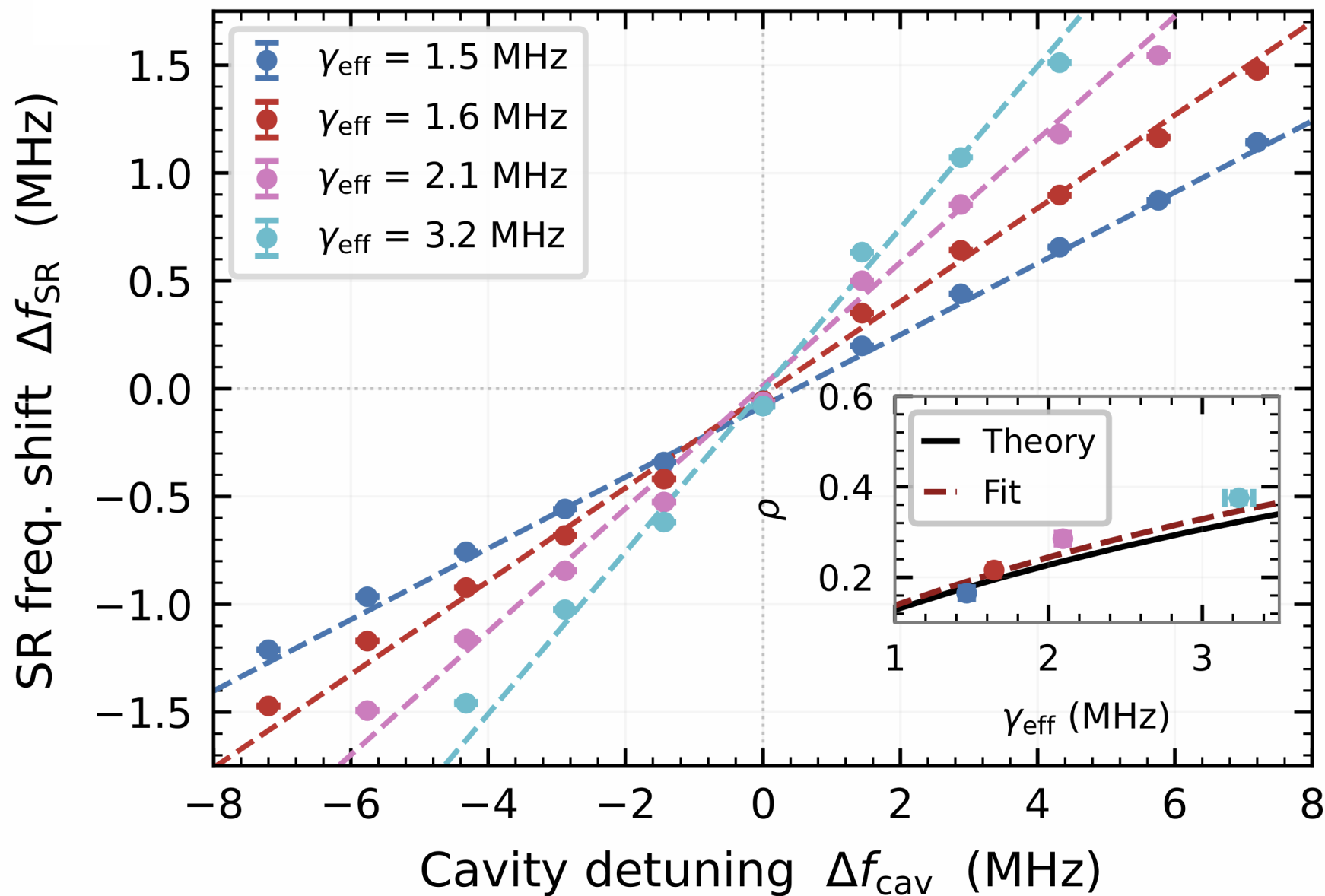
Cavity pulling suppressed by x4

Superradiant laser
detuning (MHz)





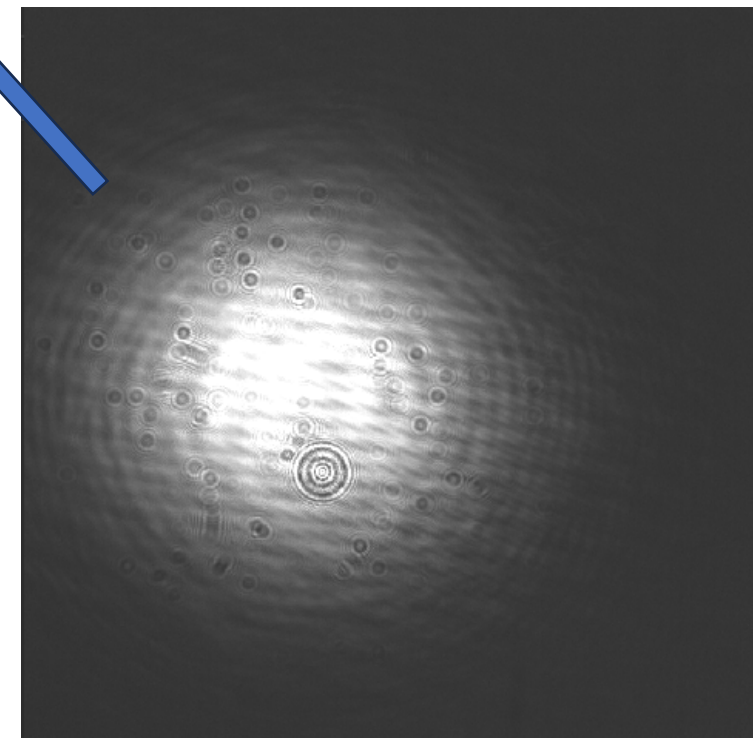
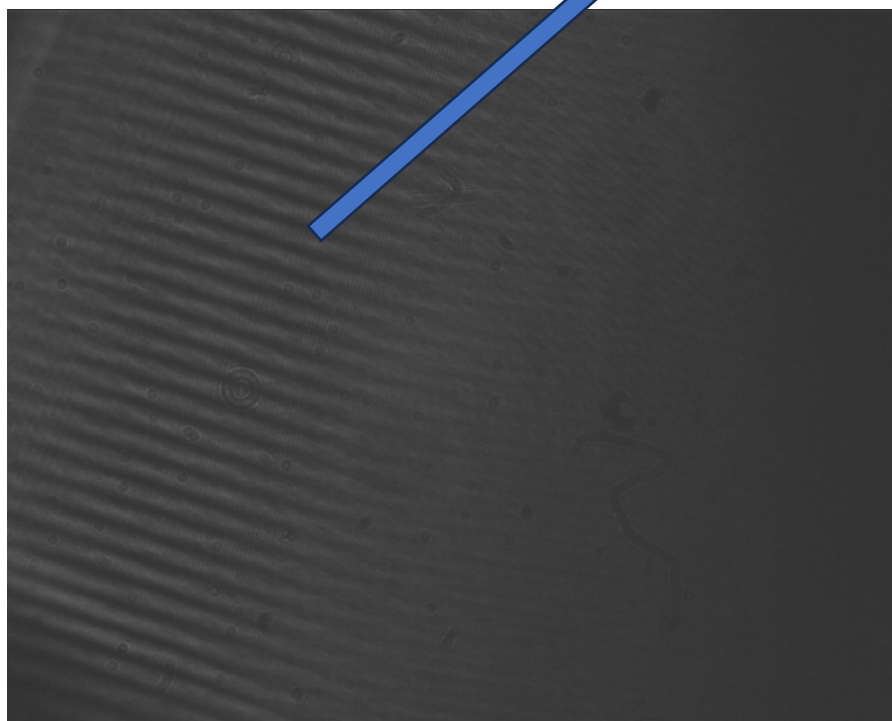
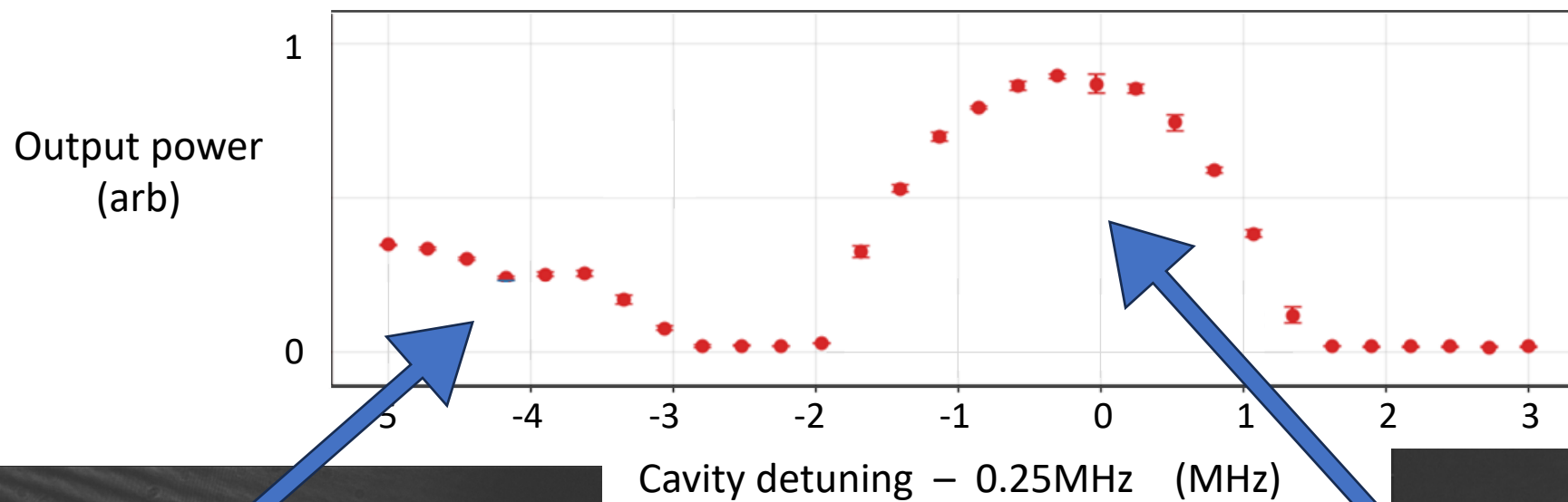
Cavity pulling for different gain medium linewidths





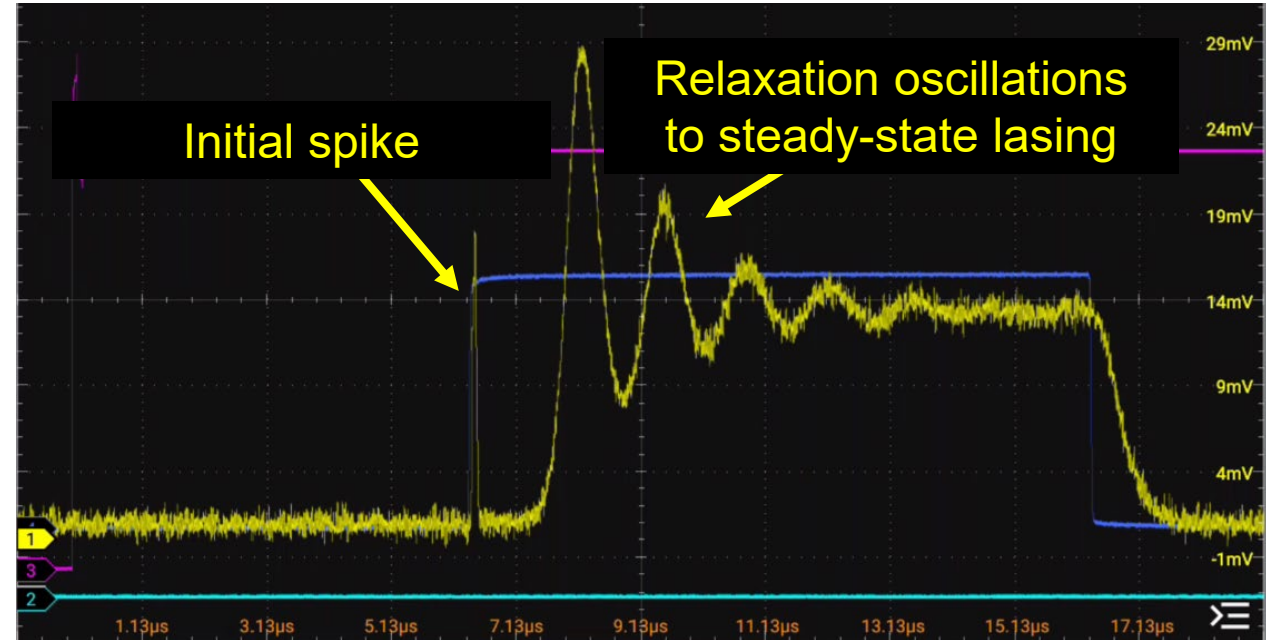
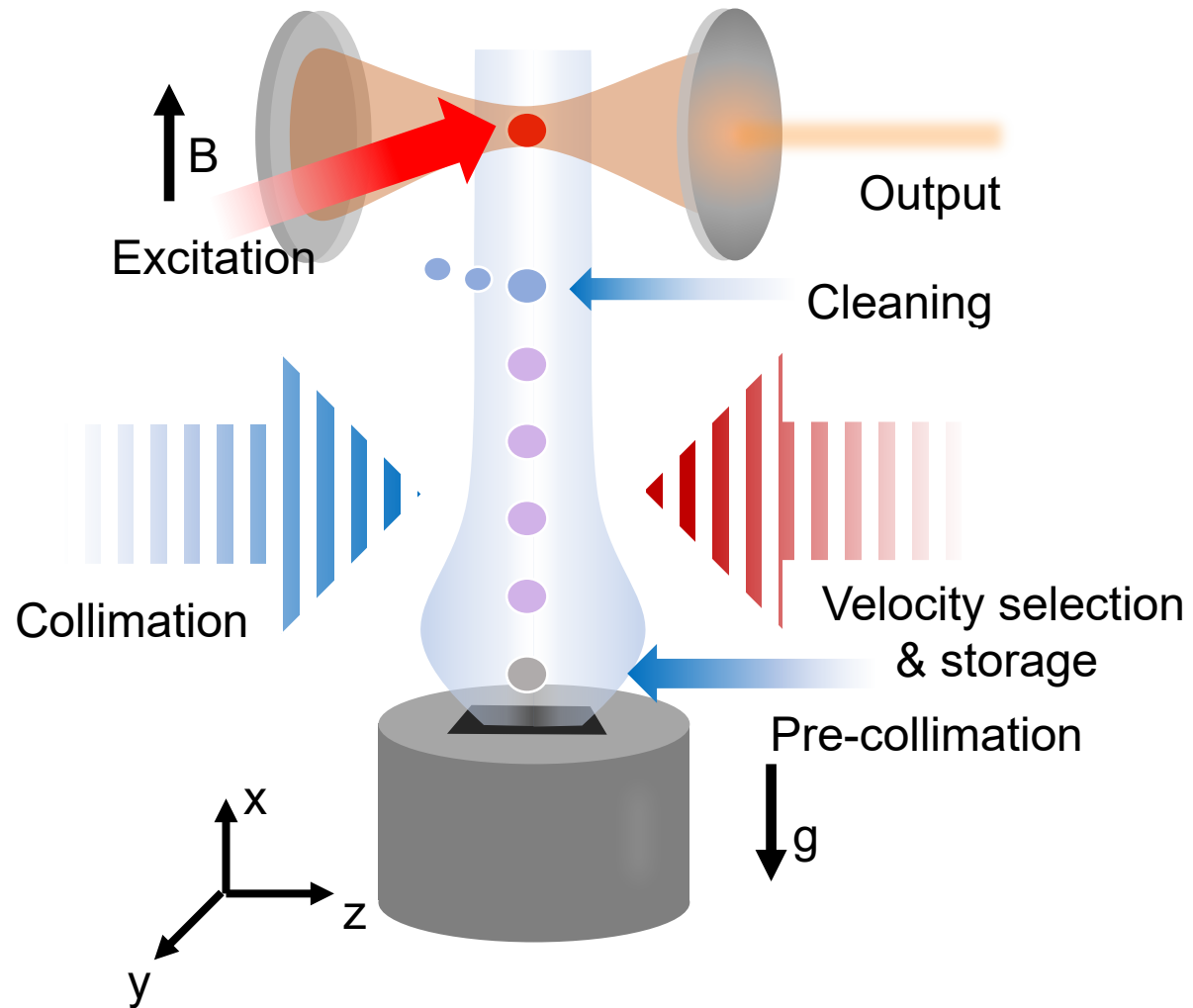
Lasing mode

5



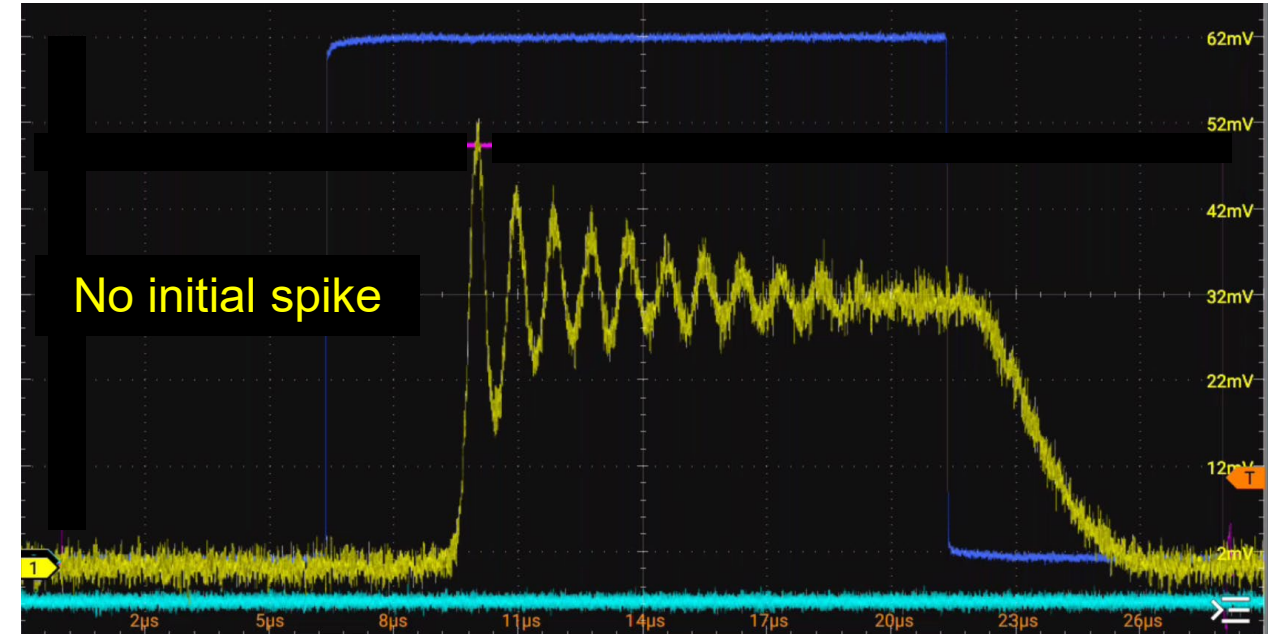
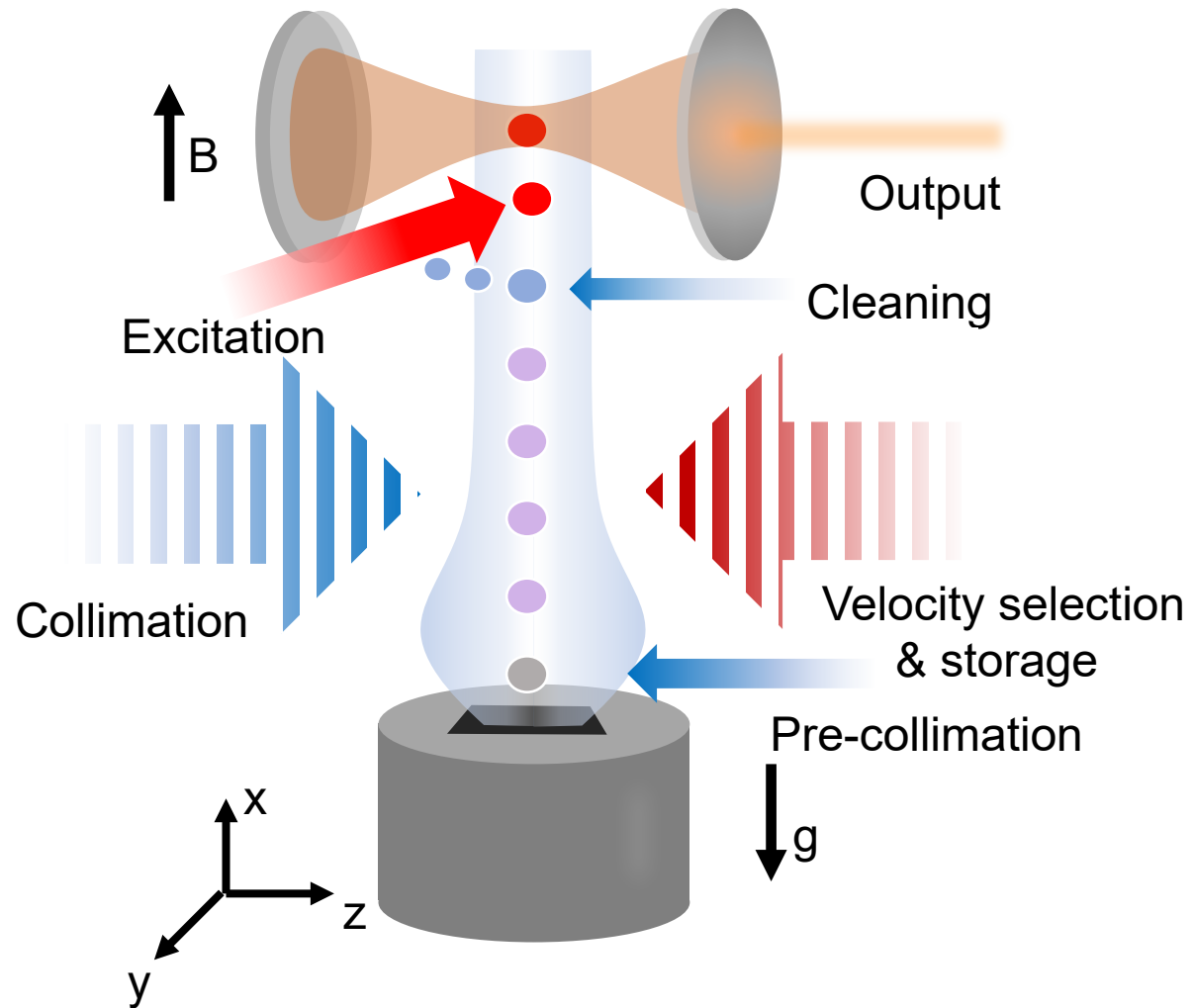


Early time dynamics: sudden inversion



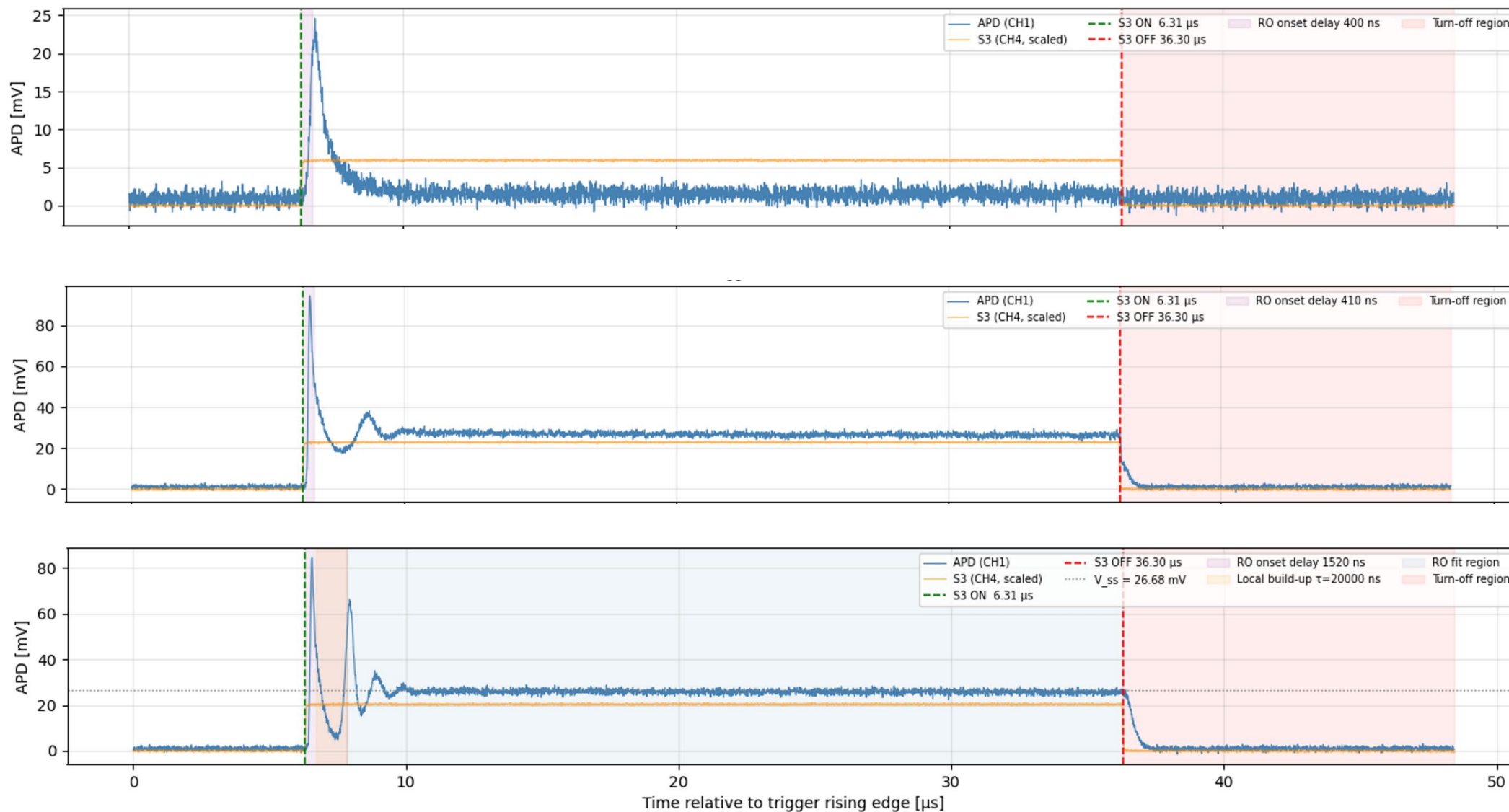


Early time dynamics: slow onset of inversion





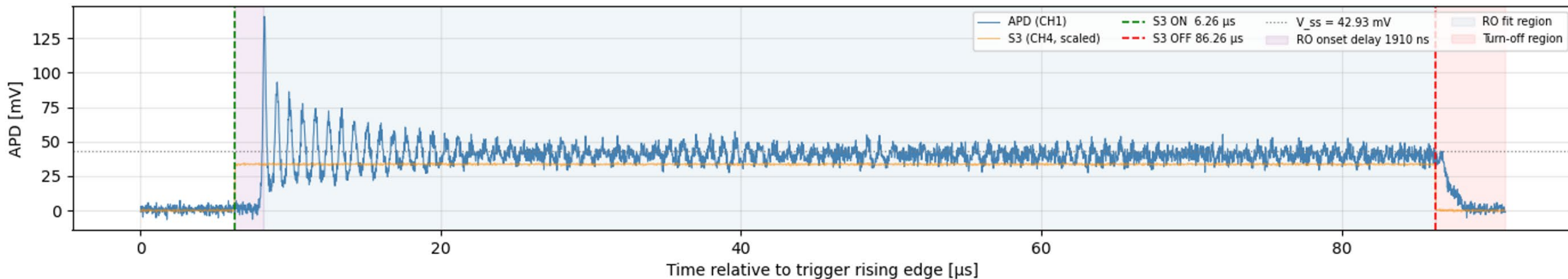
Pulses for increasing atom number



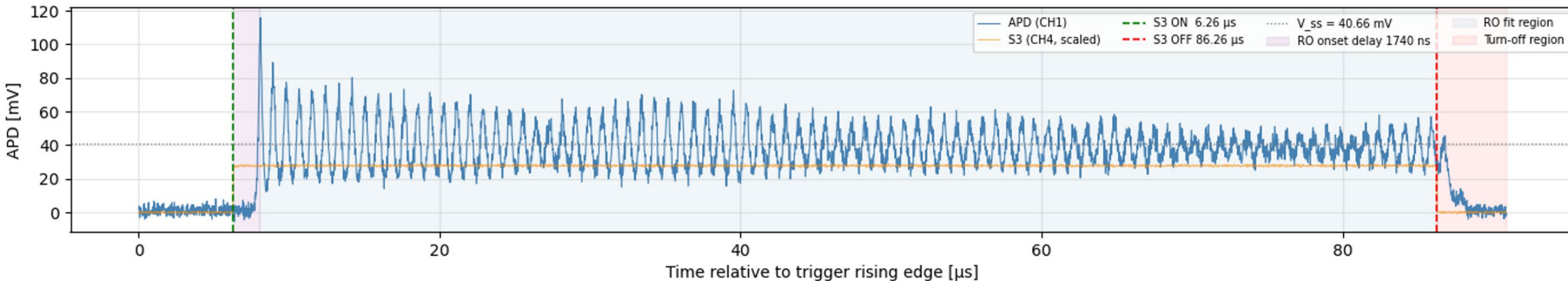


Multi frequency component superradiant lasing

Medium Doppler broadening of beam



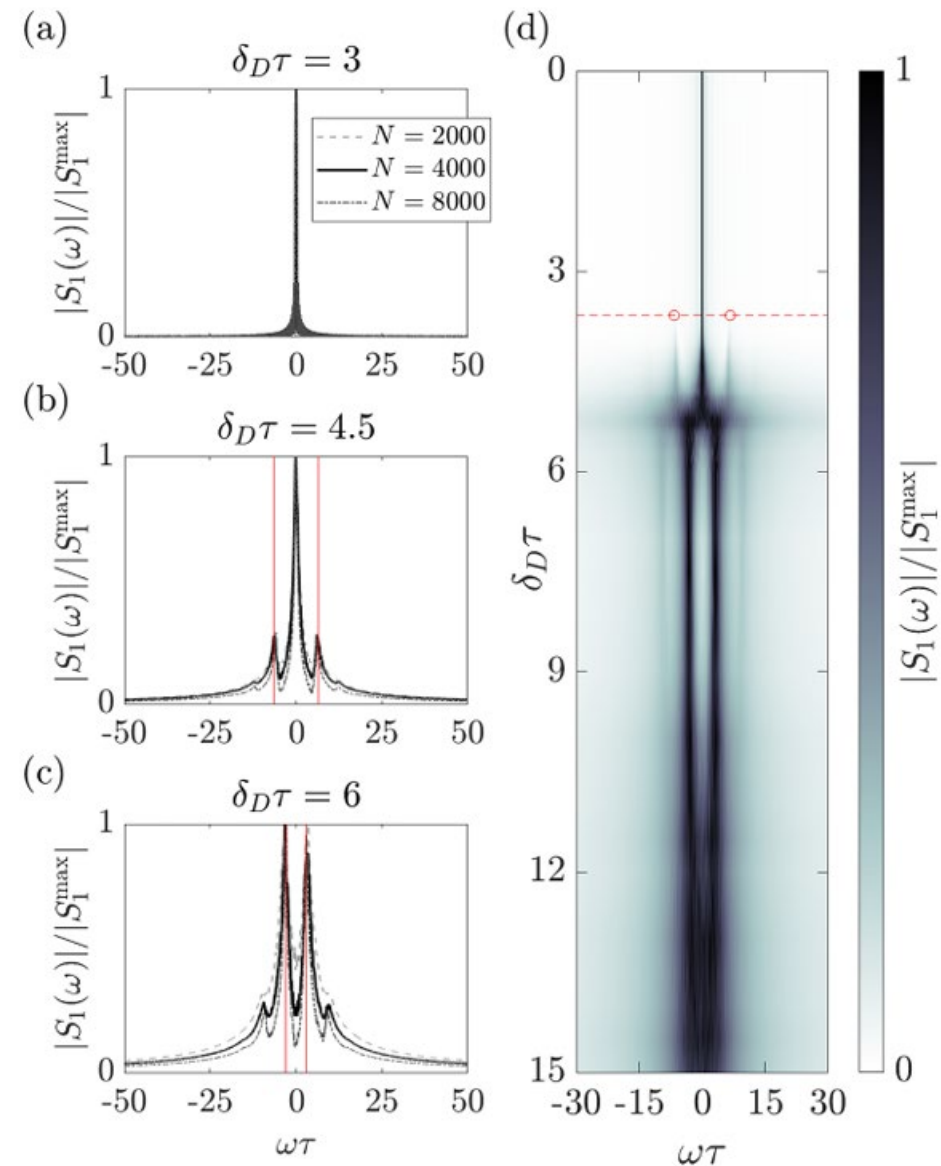
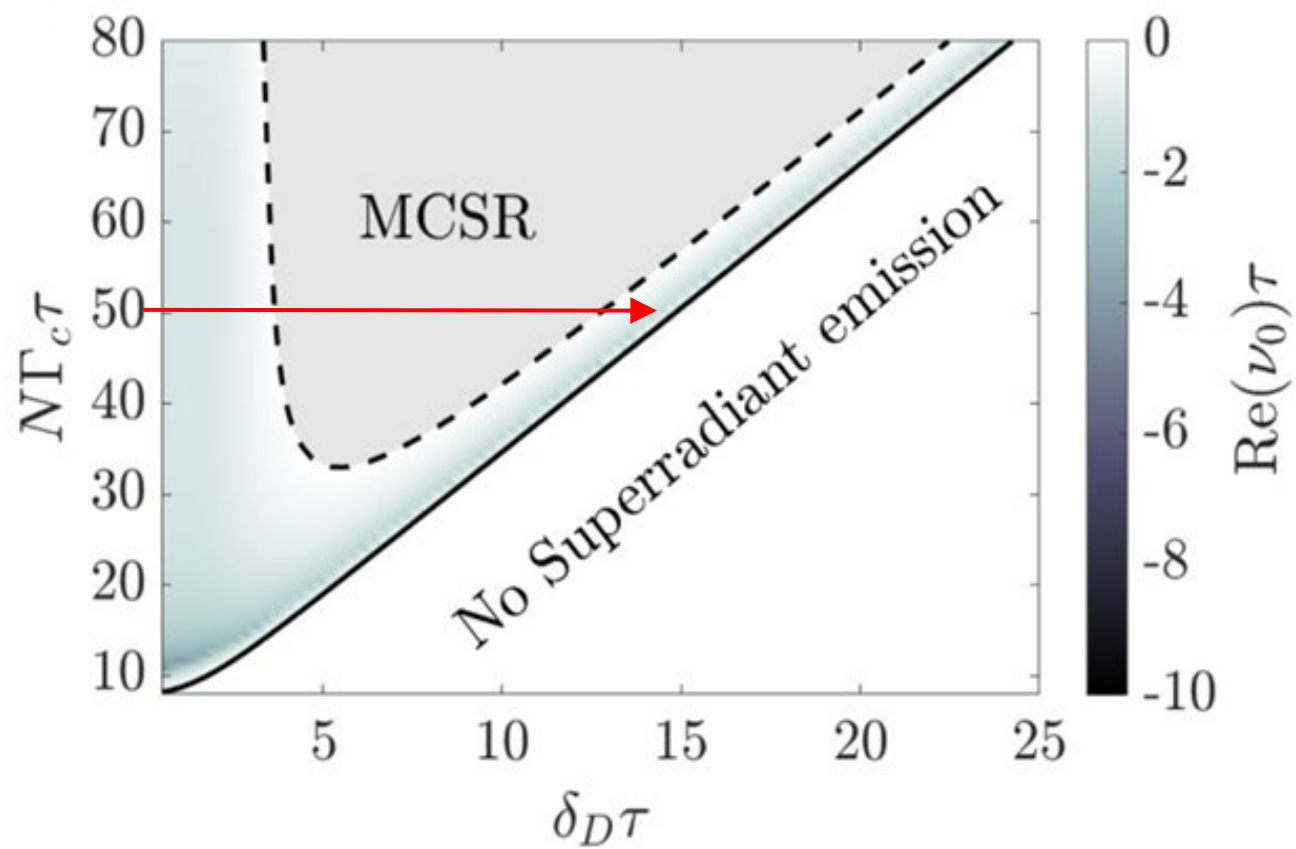
Large Doppler broadening of beam





Multi frequency component superradiant lasing

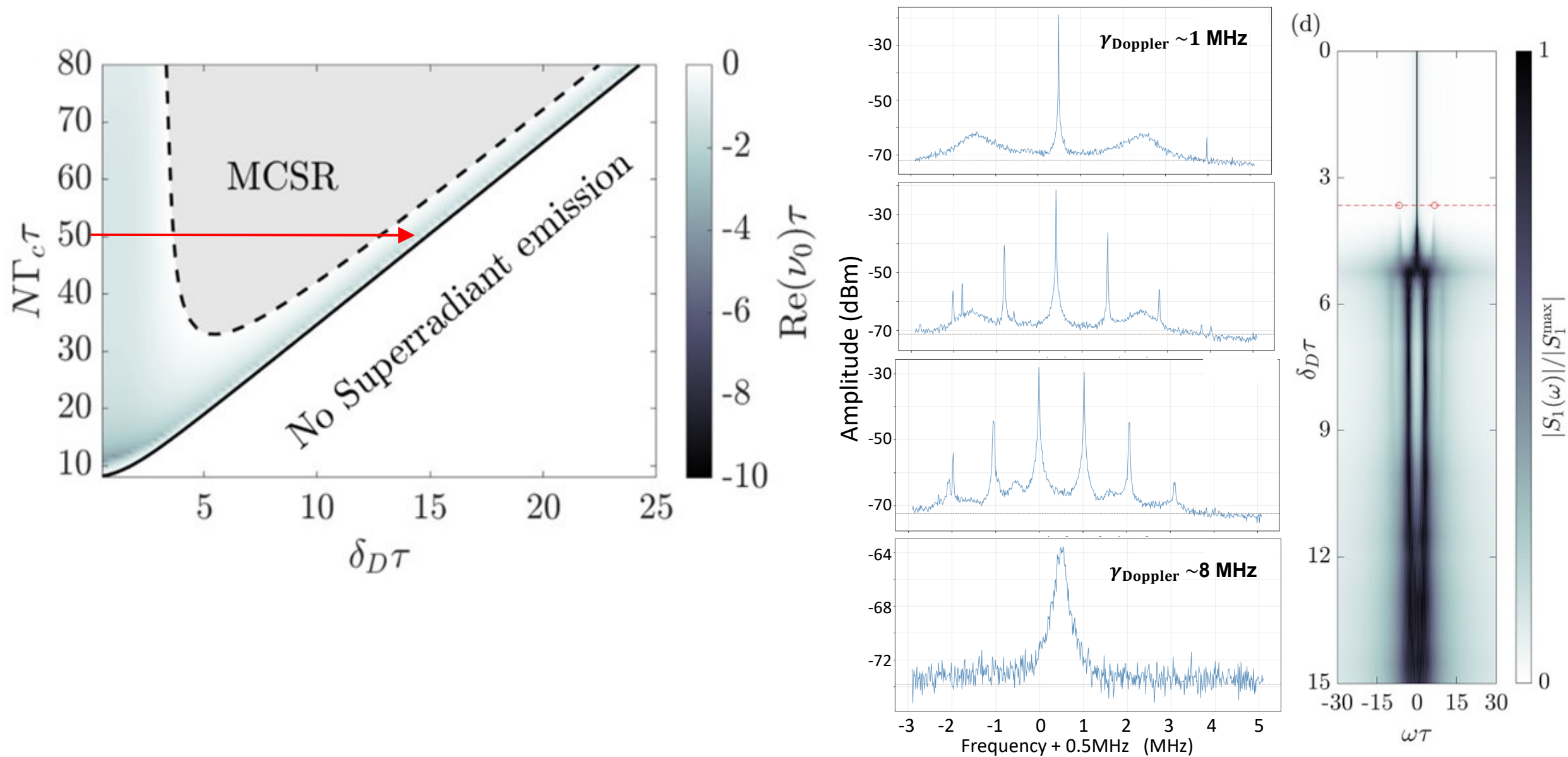
Simon B. Jäger et al., *Superradiant emission of a thermal atomic beam into an optical cavity*, PR A **104**, 033711 (2021)





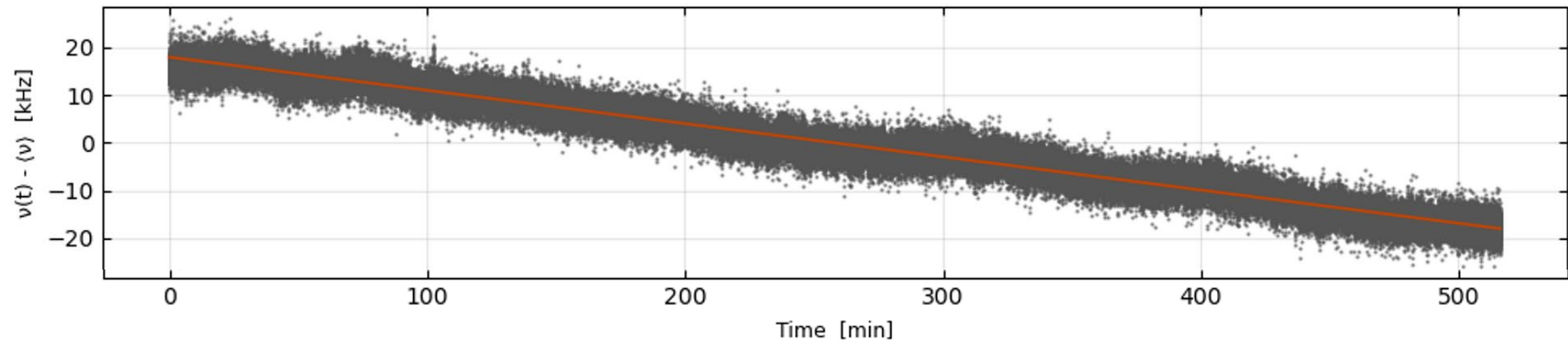
Multi frequency component superradiant lasing

Simon B. Jäger et al., *Superradiant emission of a thermal atomic beam into an optical cavity*, PR A **104**, 033711 (2021)

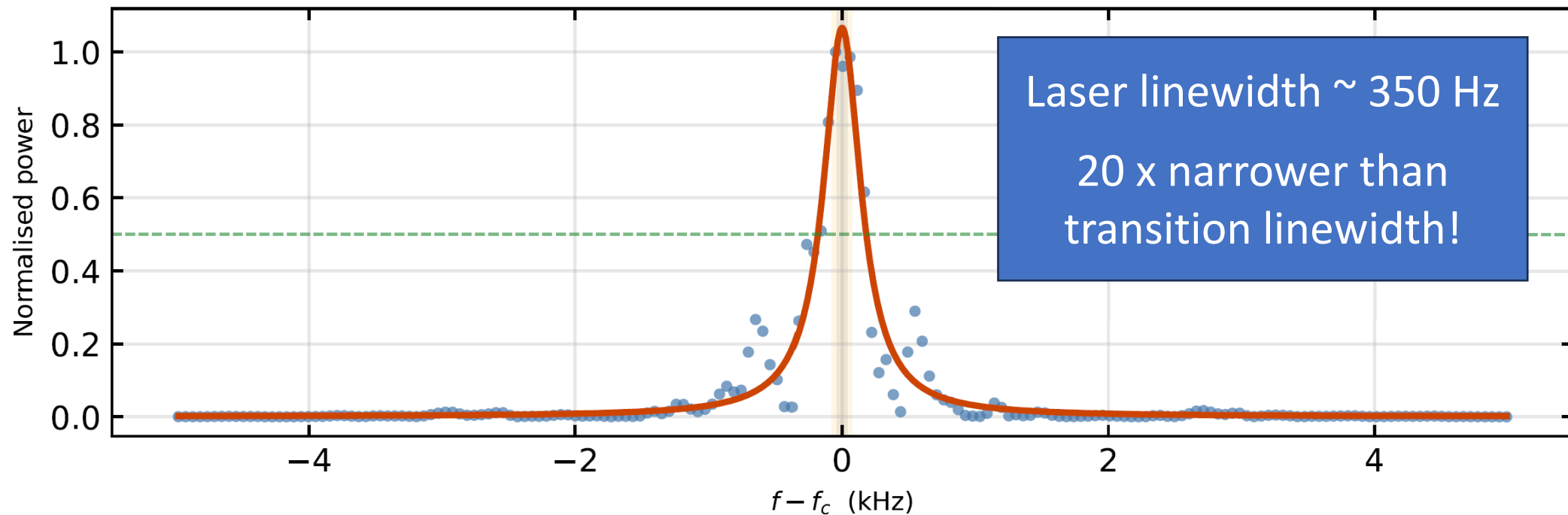




Linewidth



Fourier transform and Lorentzian fit:

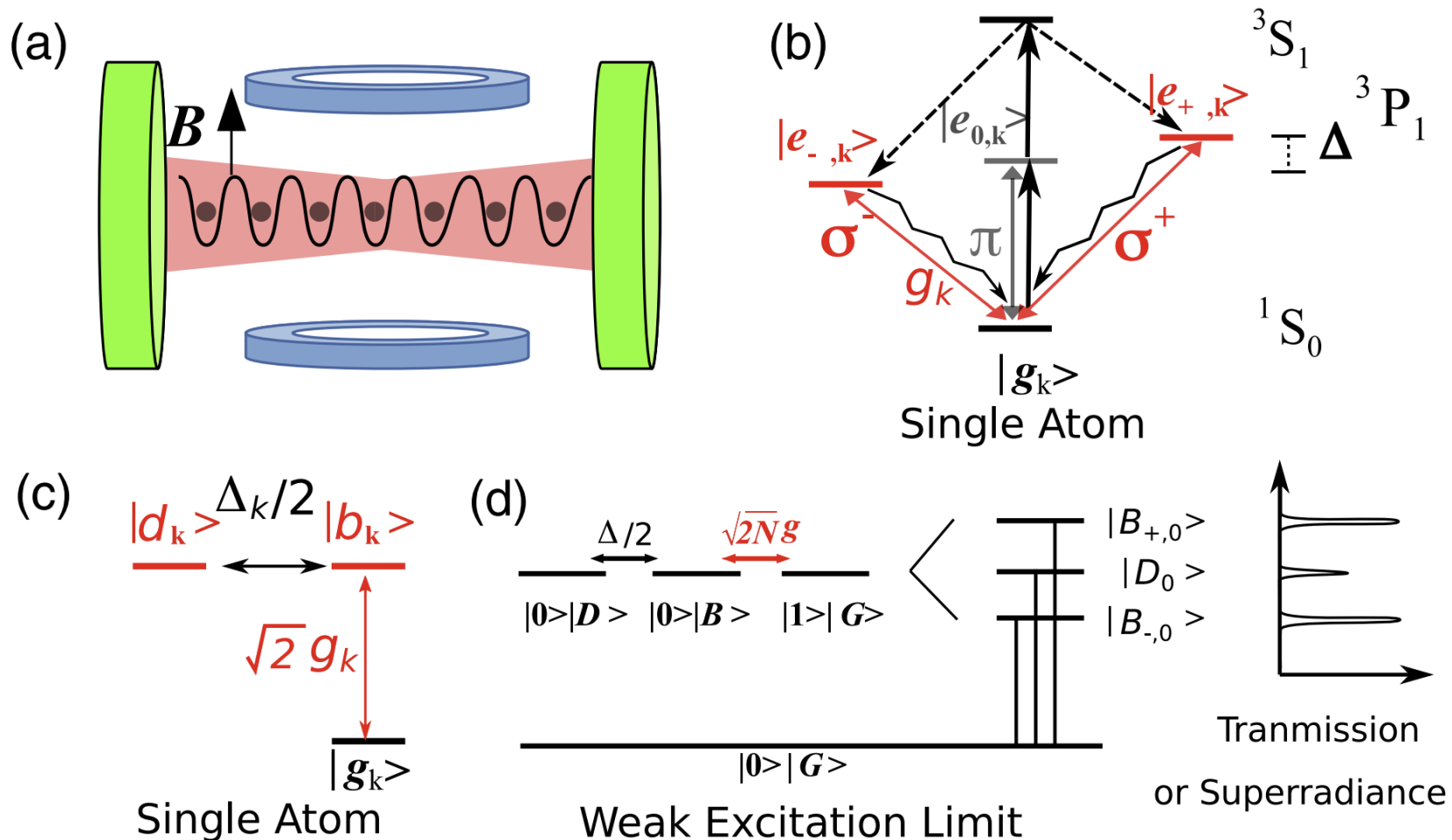




Linewidth: can we do better?

Yuan Zhang, Chongxin Shan, and Klaus Mølmer say “Yes!”

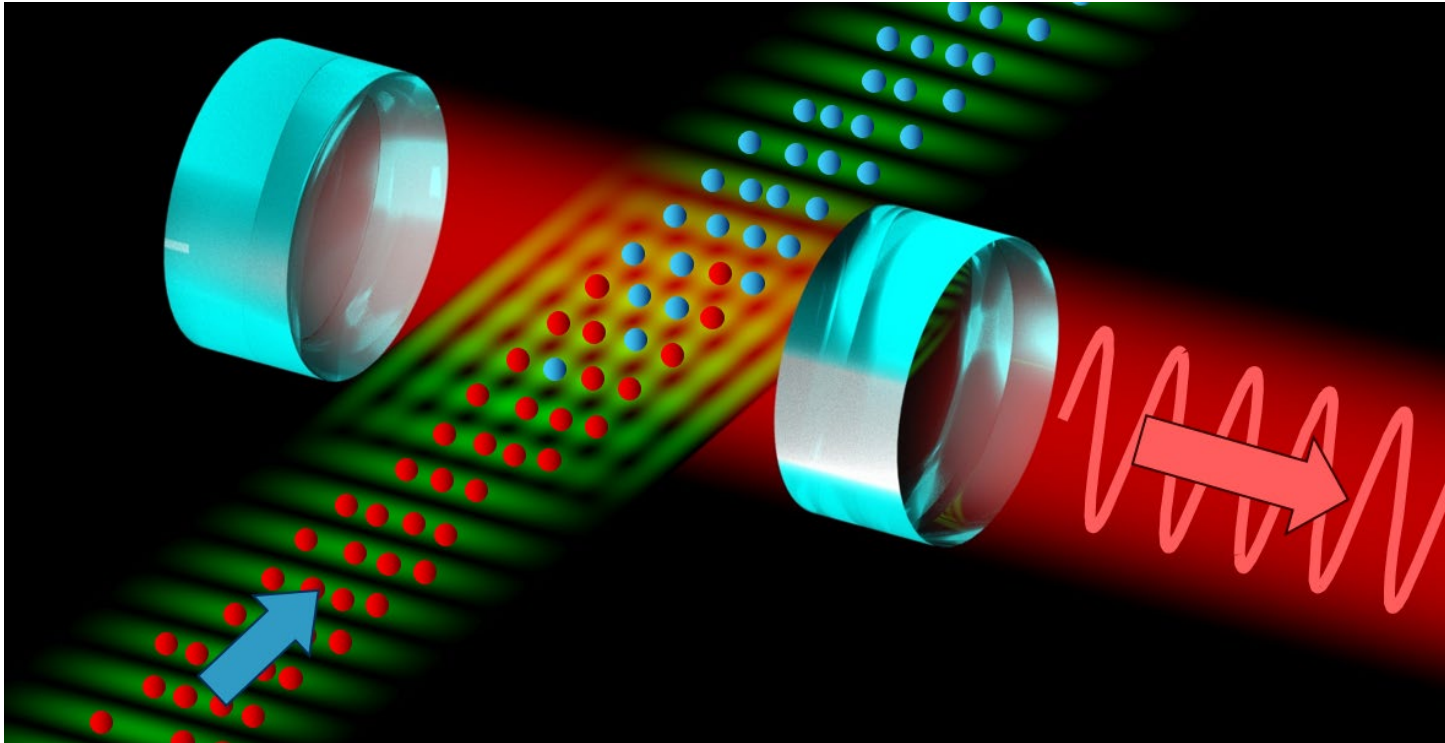
Ultranarrow Superradiant Lasing by Dark Atom-Photon Dressed States, PRL **126**, 123602 (2021).





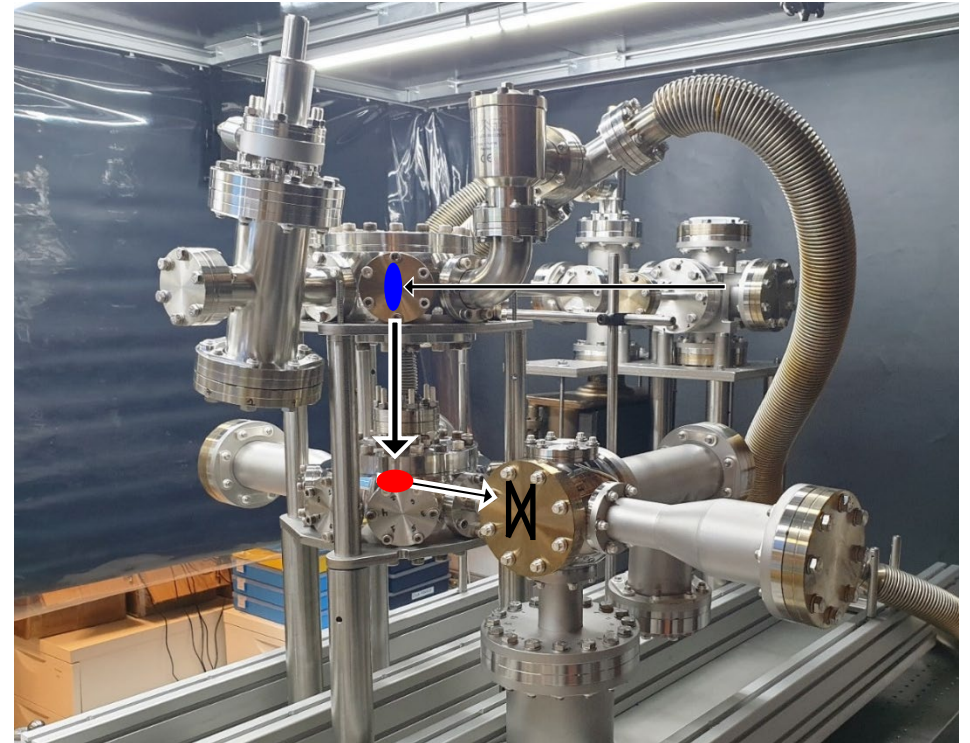
Linewidth: can we do even better?

V2: Continuous superradiant mHz clock



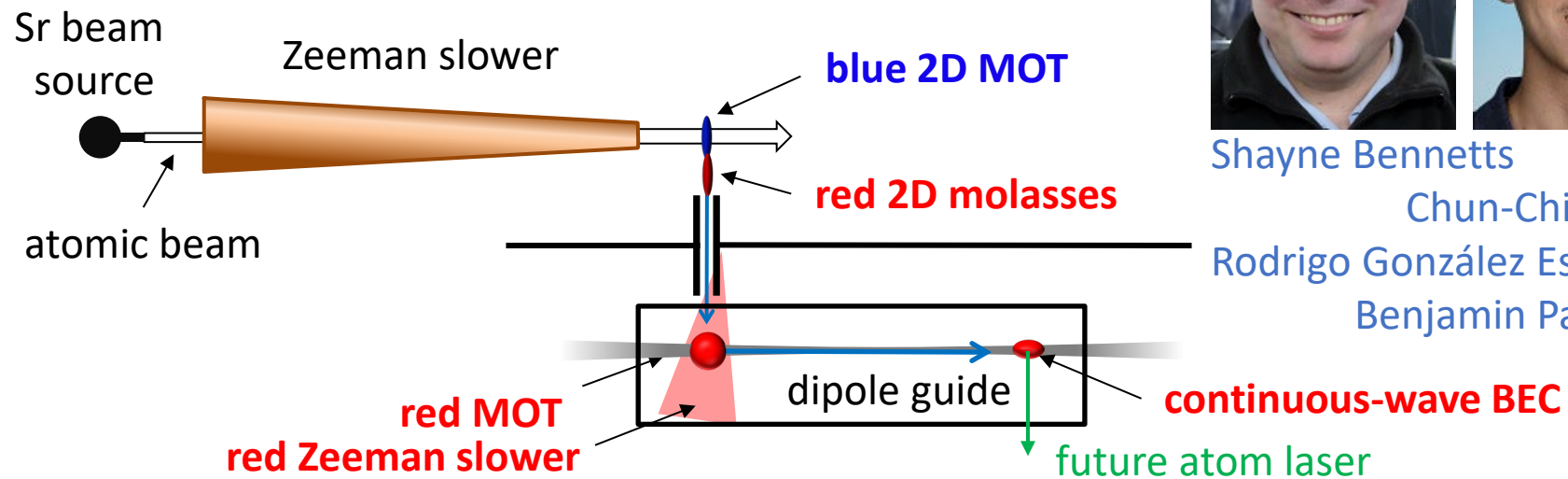
Continuous ultracold strontium beam in

Clock laser beam out





Continuous Bose-Einstein condensation



Shayne Bennetts

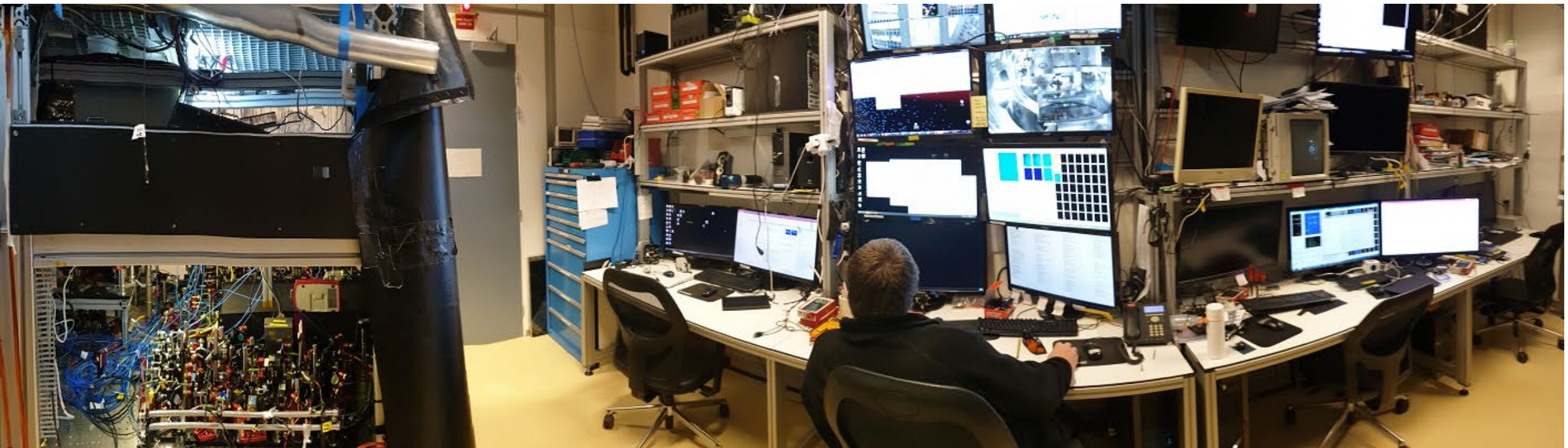


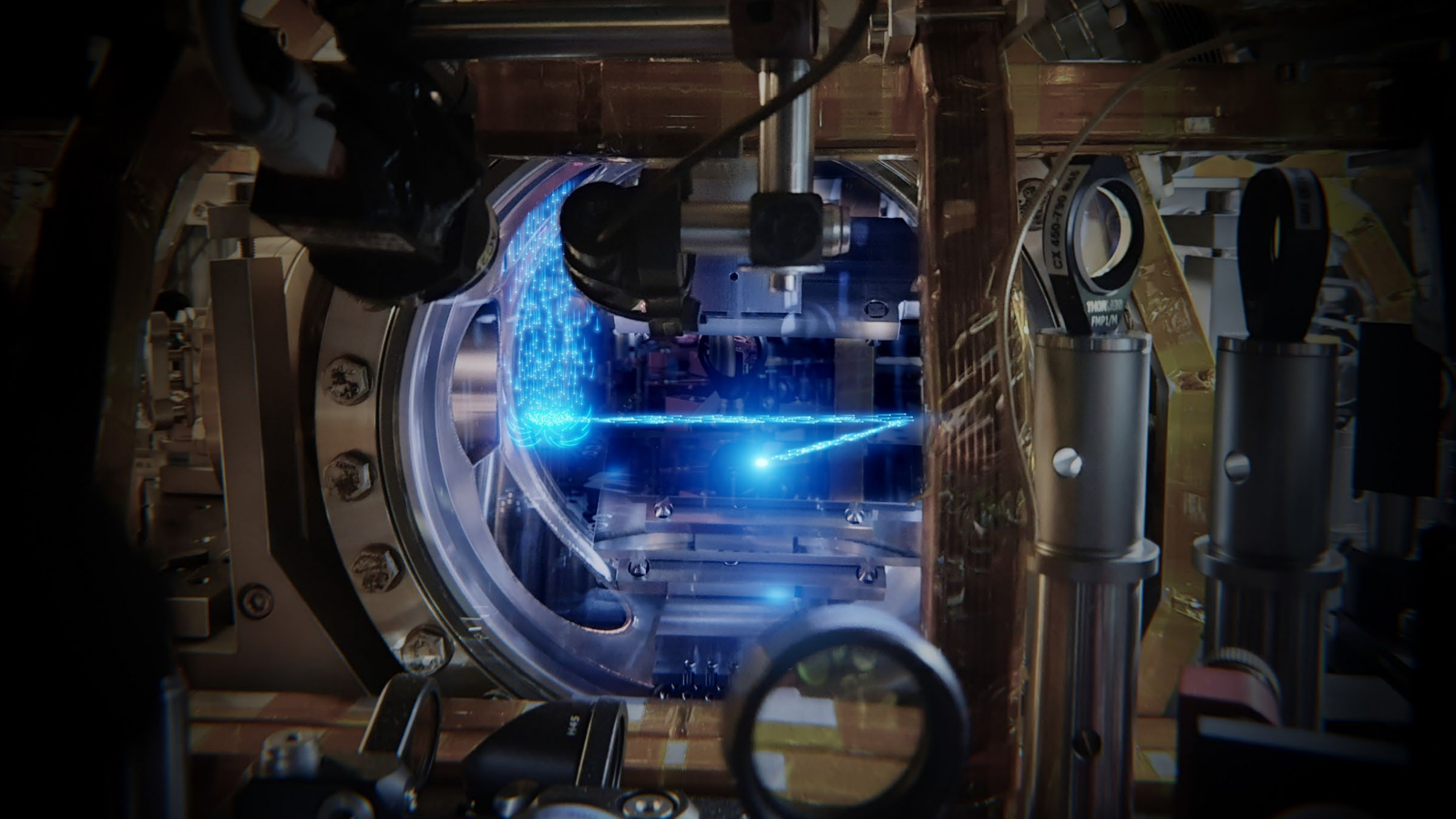
Chun-Chia Chen

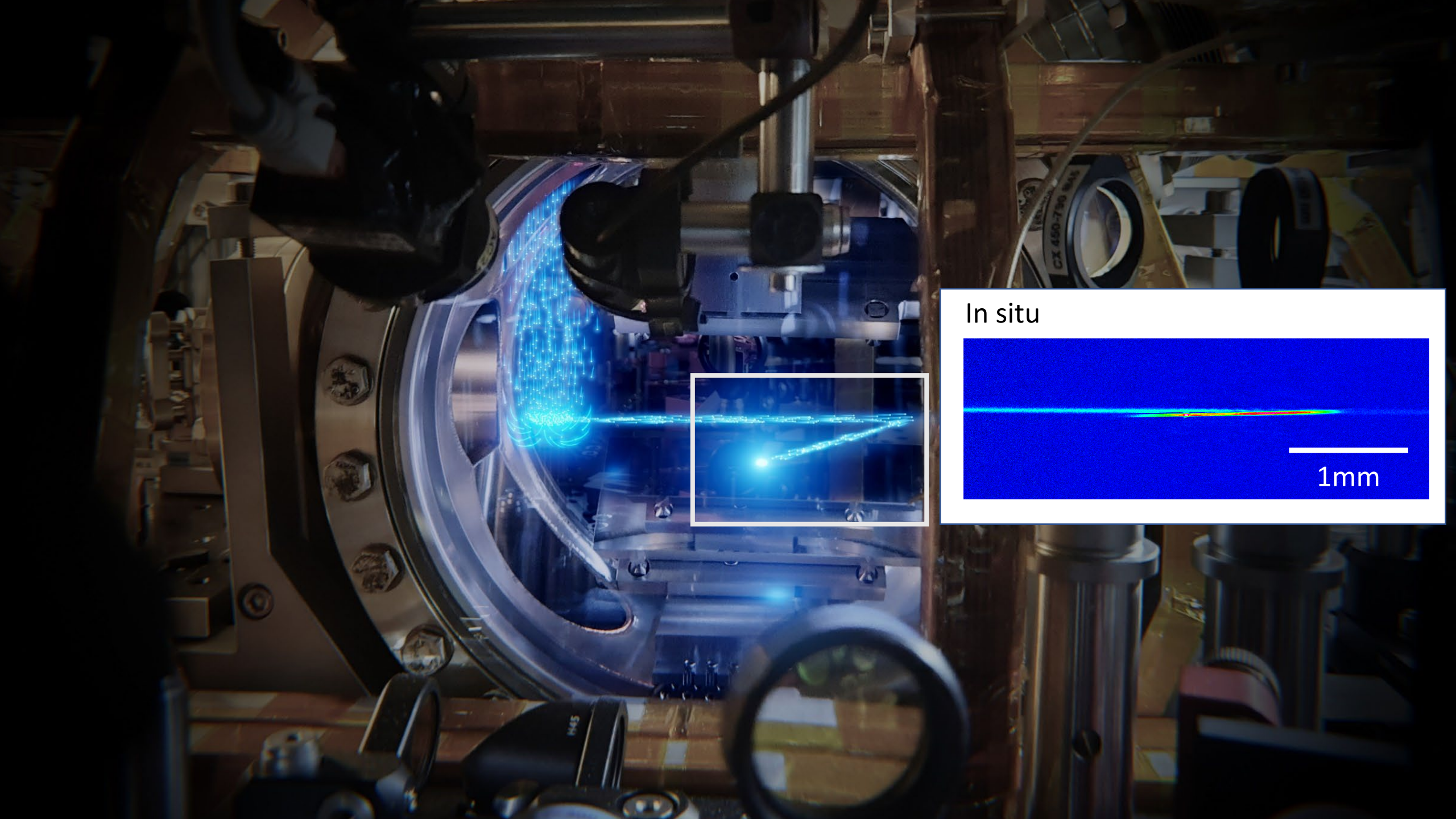


Rodrigo González Escudero

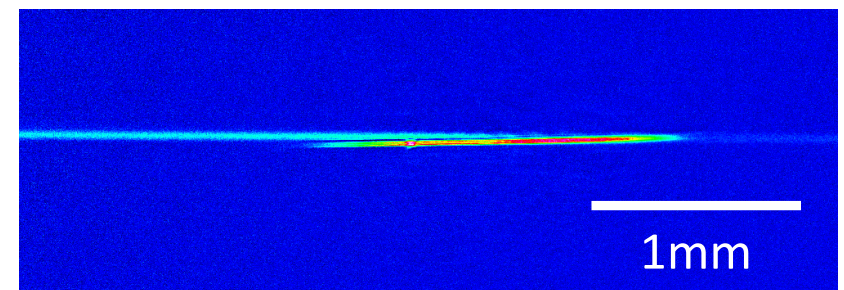
Benjamin Pasquiou

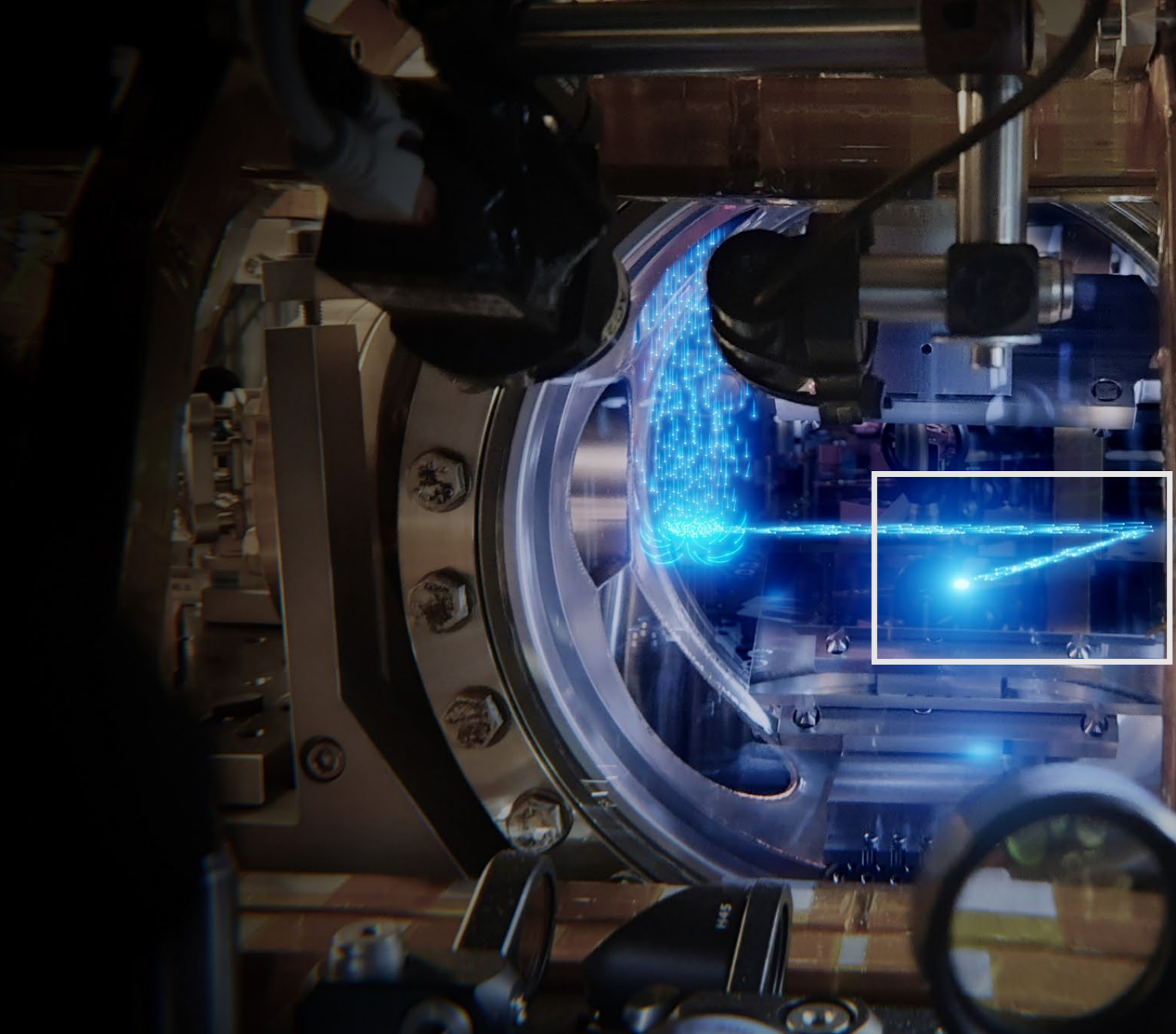




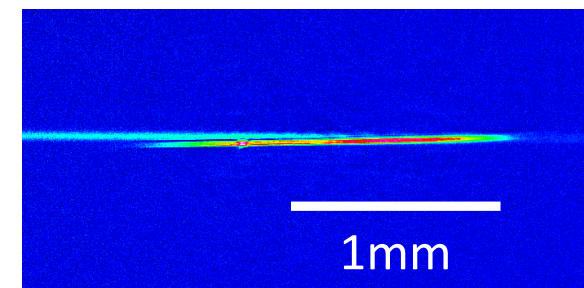


In situ

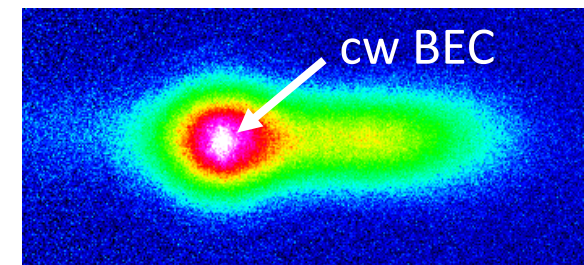




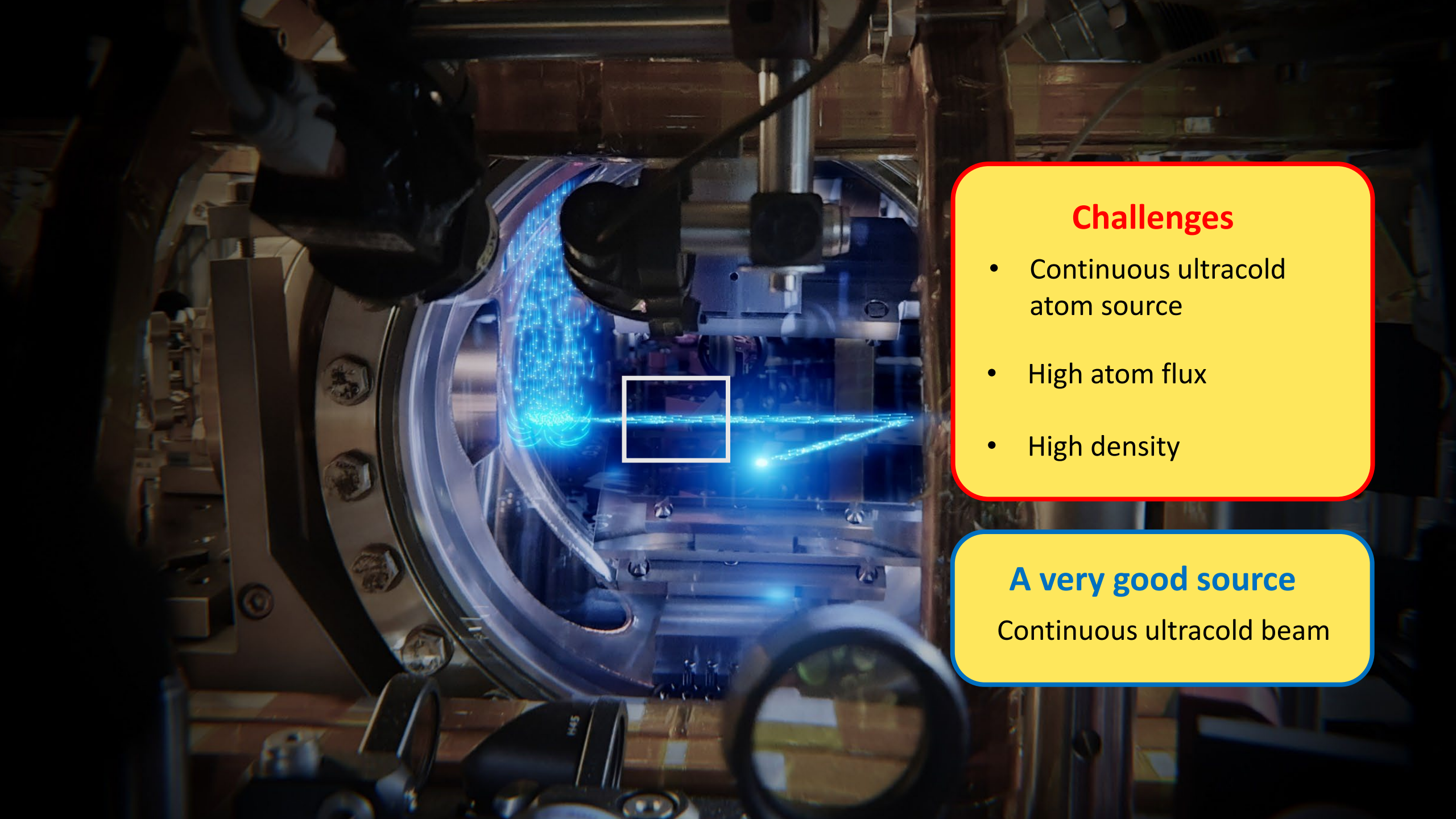
In situ



18 ms expansion



Nature **606**, 683 (2022)



Challenges

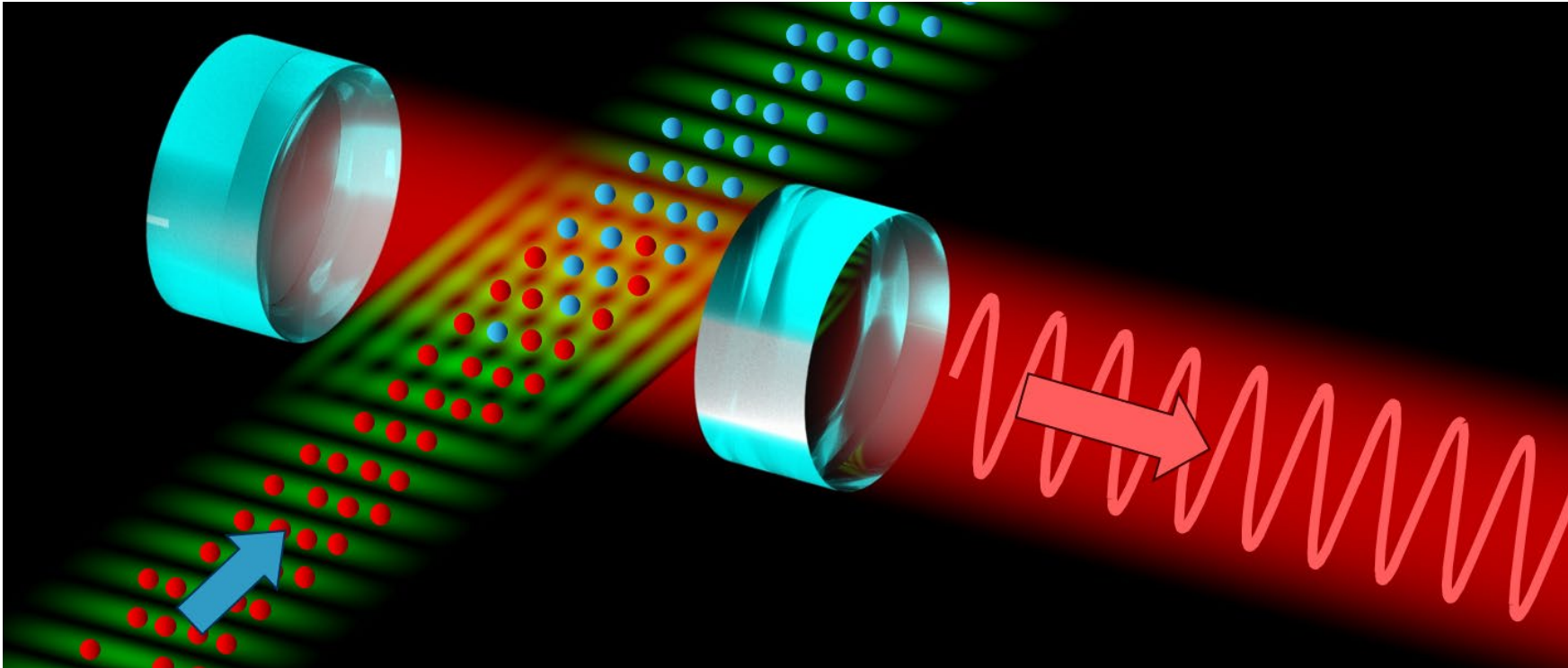
- Continuous ultracold atom source
- High atom flux
- High density

A very good source

Continuous ultracold beam

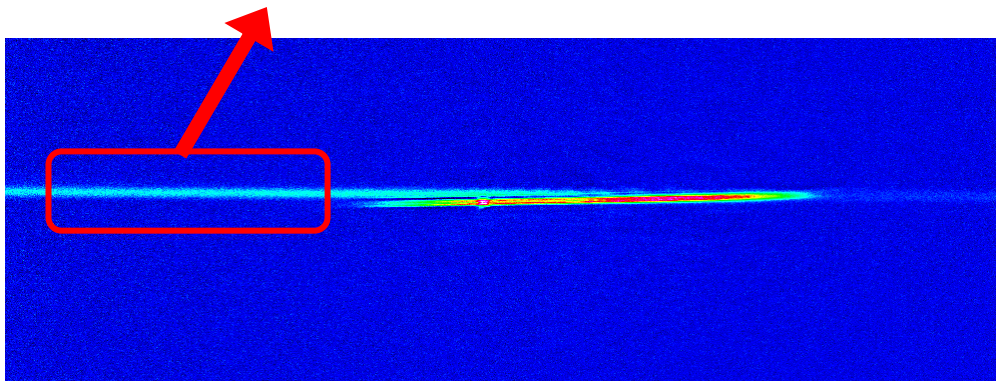


Continuous superradiant clock



Continuous ultracold strontium beam in

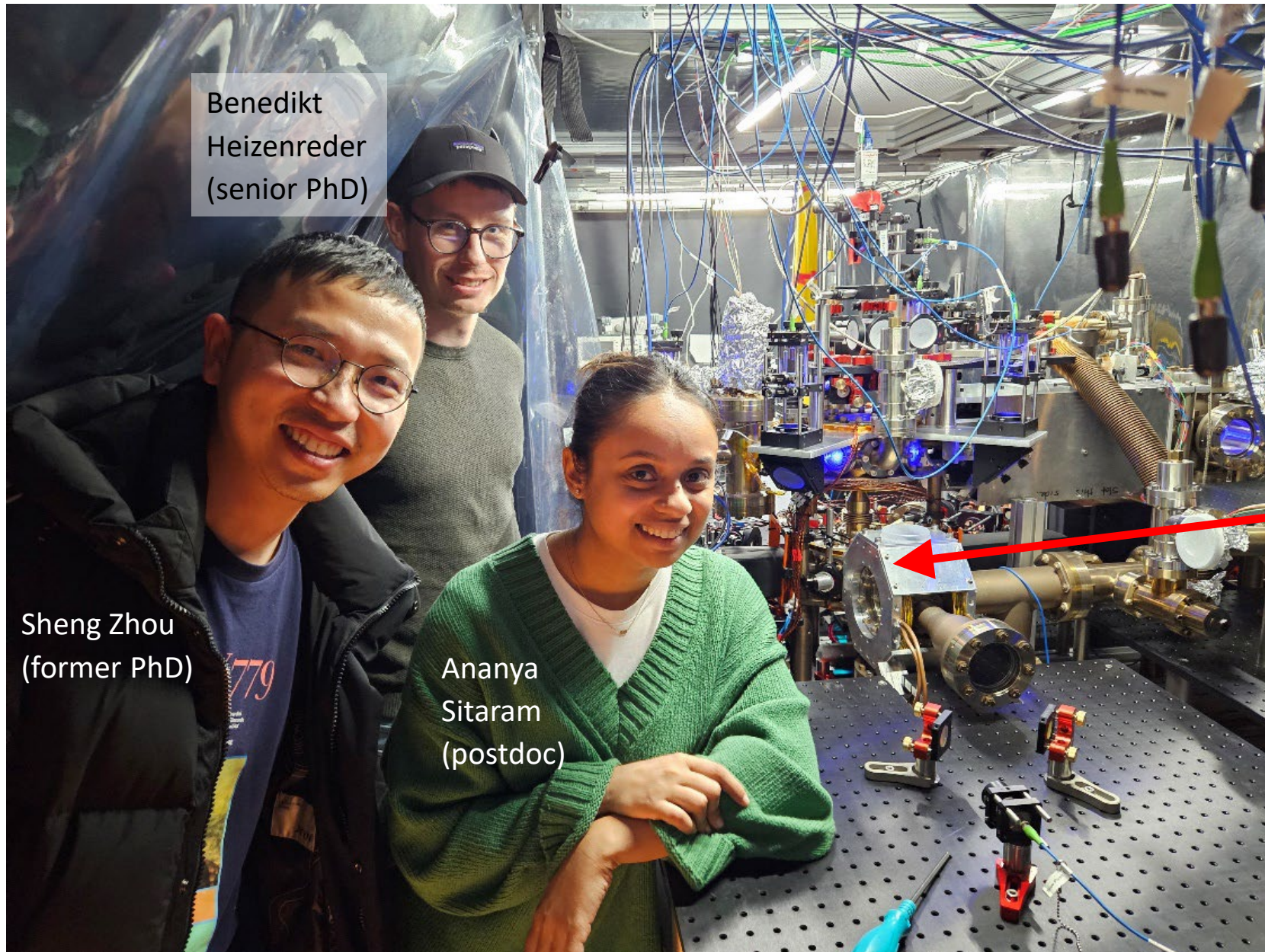
Clock laser beam out



See also James Thompson group, JILA
Pulsed superradiant emission on Sr clock line
Science Advances, **2**, e1601231 (2016)



Continuous superradiant mHz clock



Benedikt
Heizenreder
(senior PhD)

Sheng Zhou
(former PhD)

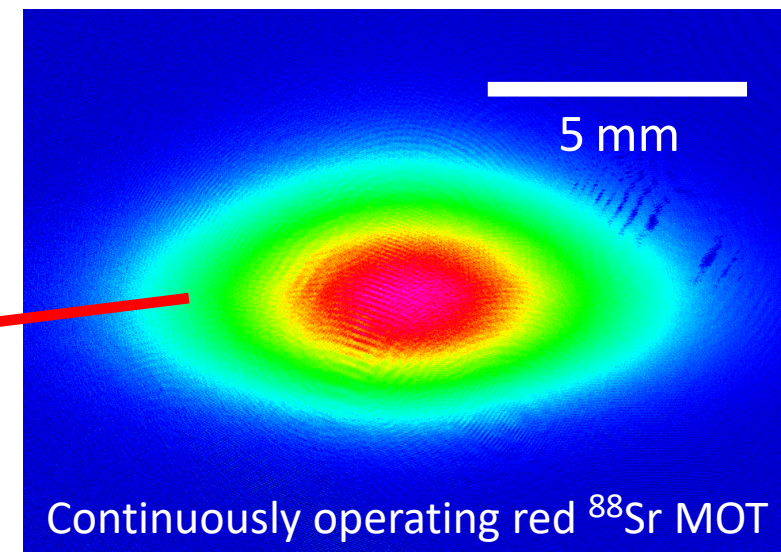
Ananya
Sitaram
(postdoc)



Luuk Michels
(master)



Elisa Wenzel
(master)



Continuously operating red ^{88}Sr MOT

$$\text{Flux} = 3 \times 10^8 \text{ atoms/s}$$

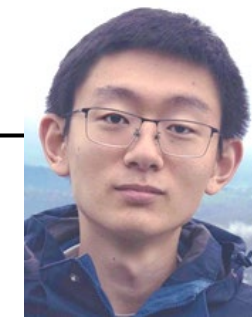
$$\text{Atom number} = 5.5 \times 10^8$$



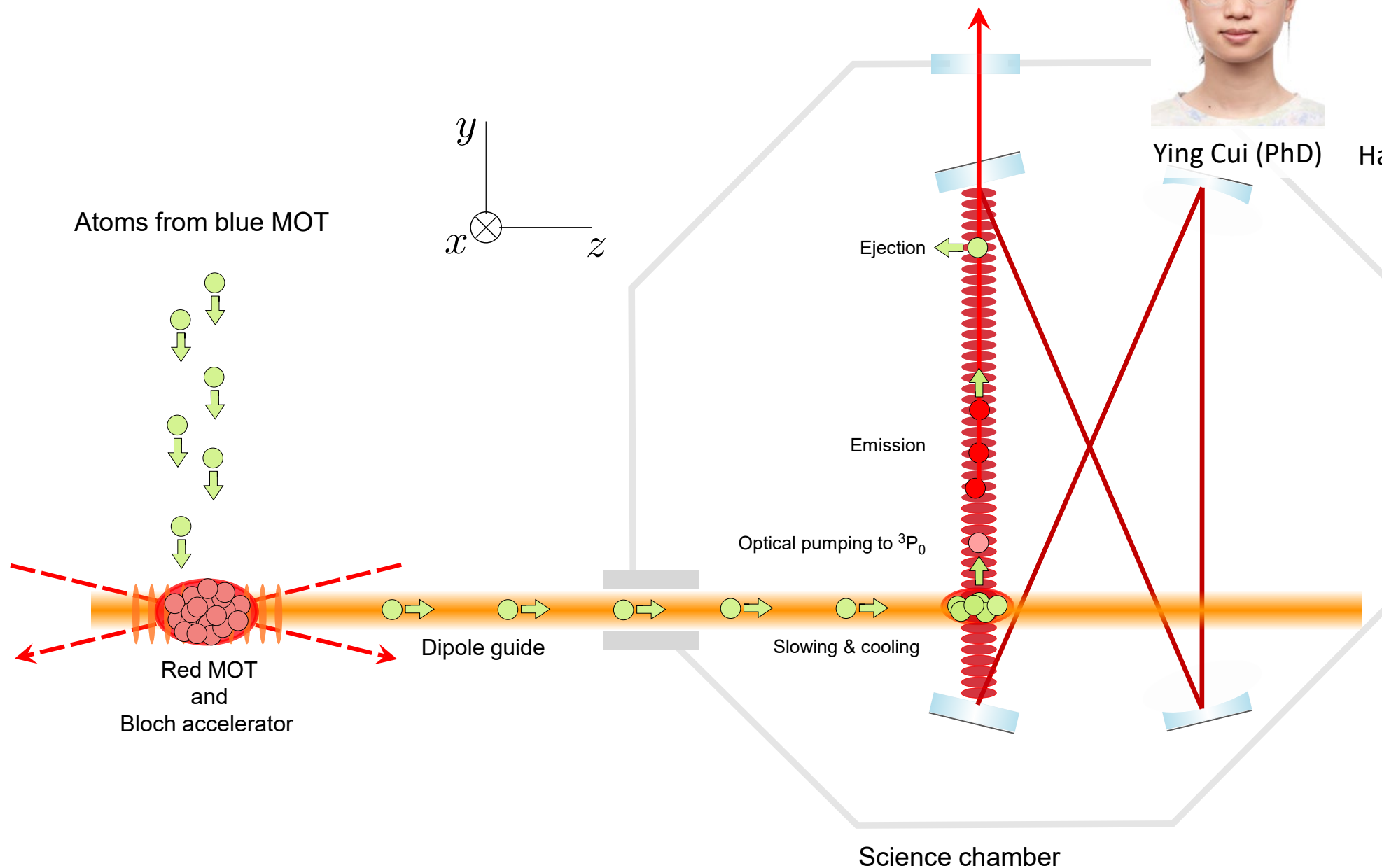
Continuous operation scheme



Ying Cui (PhD)

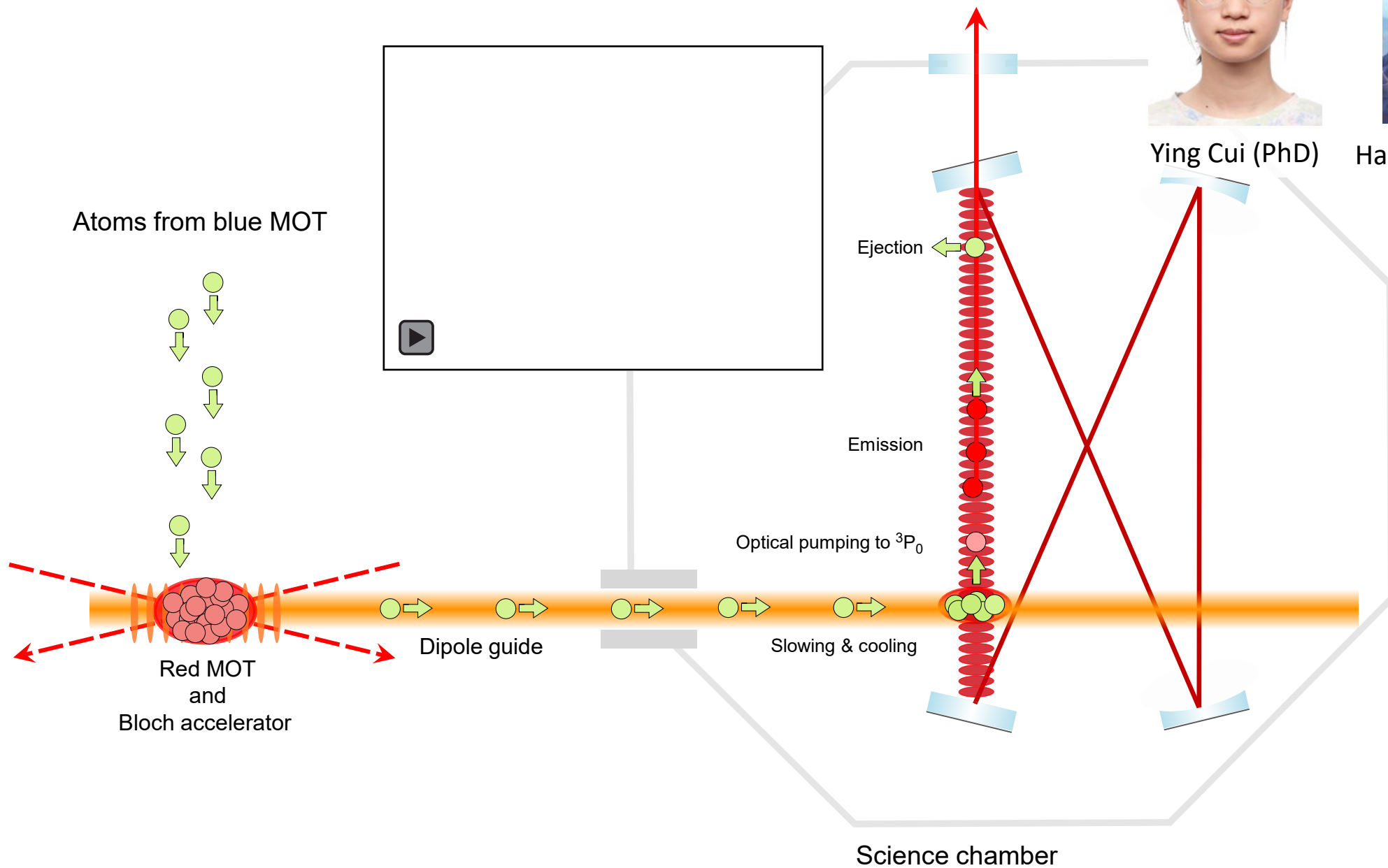


Haiwei Wang (PhD)

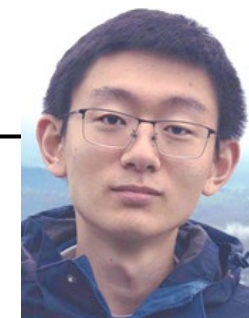




Continuous operation scheme



Ying Cui (PhD)

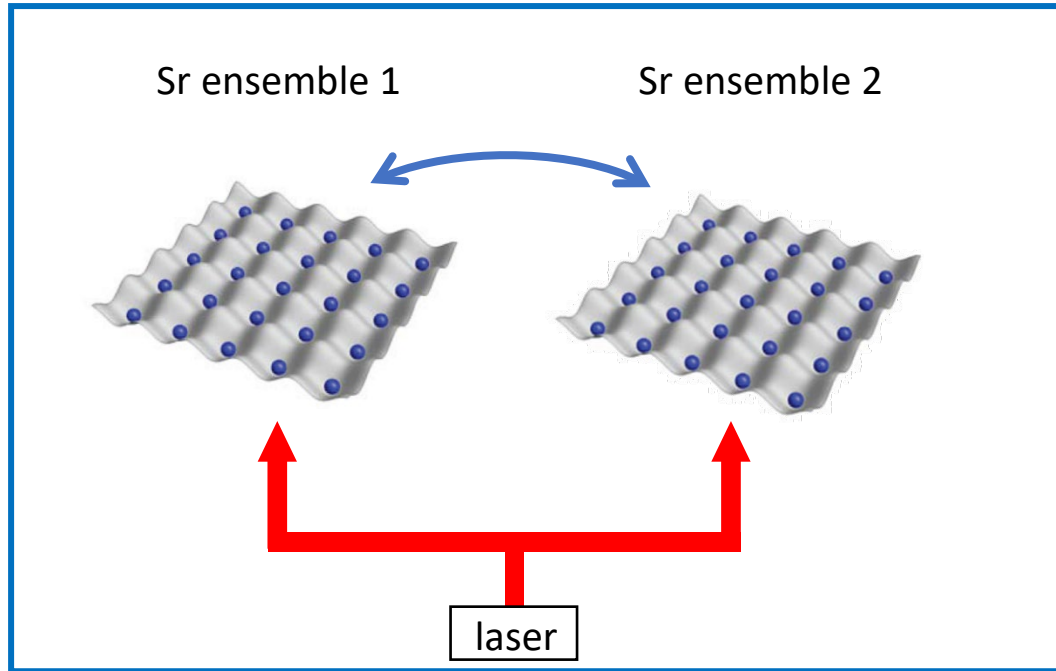


Haiwei Wang (PhD)

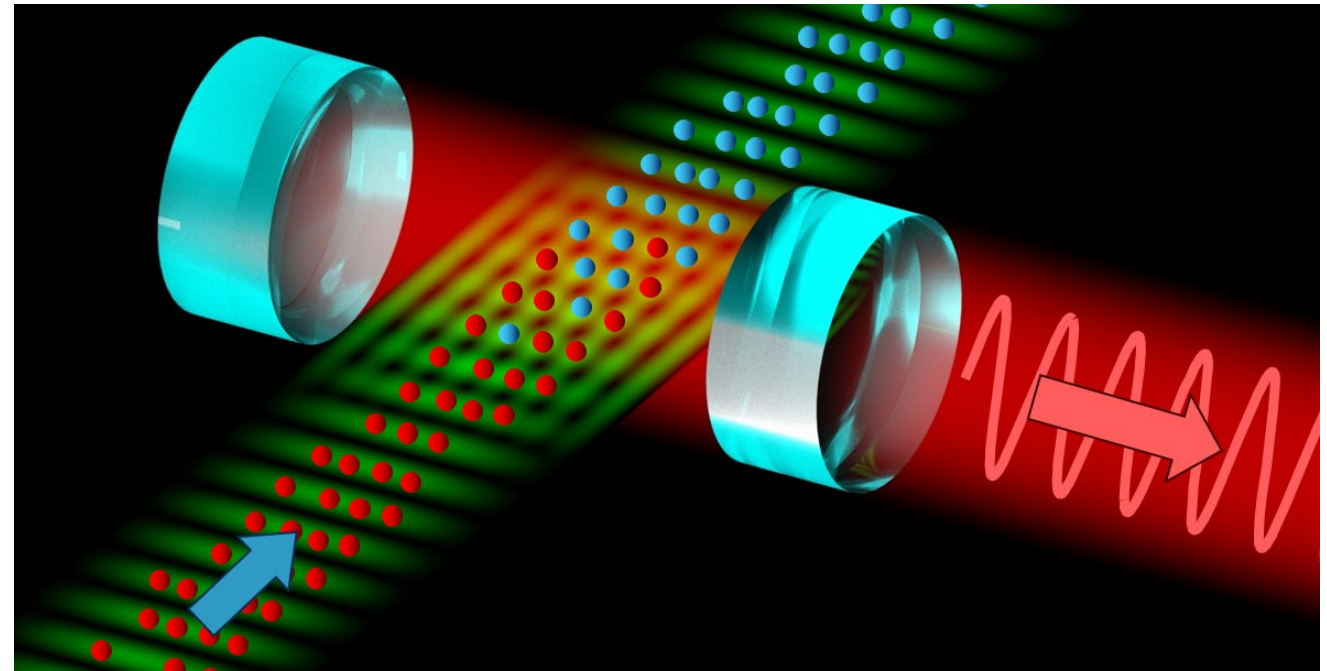


Continuous clock developments in our lab

Passive, zero-deadtime clock



Active, superradiant clock

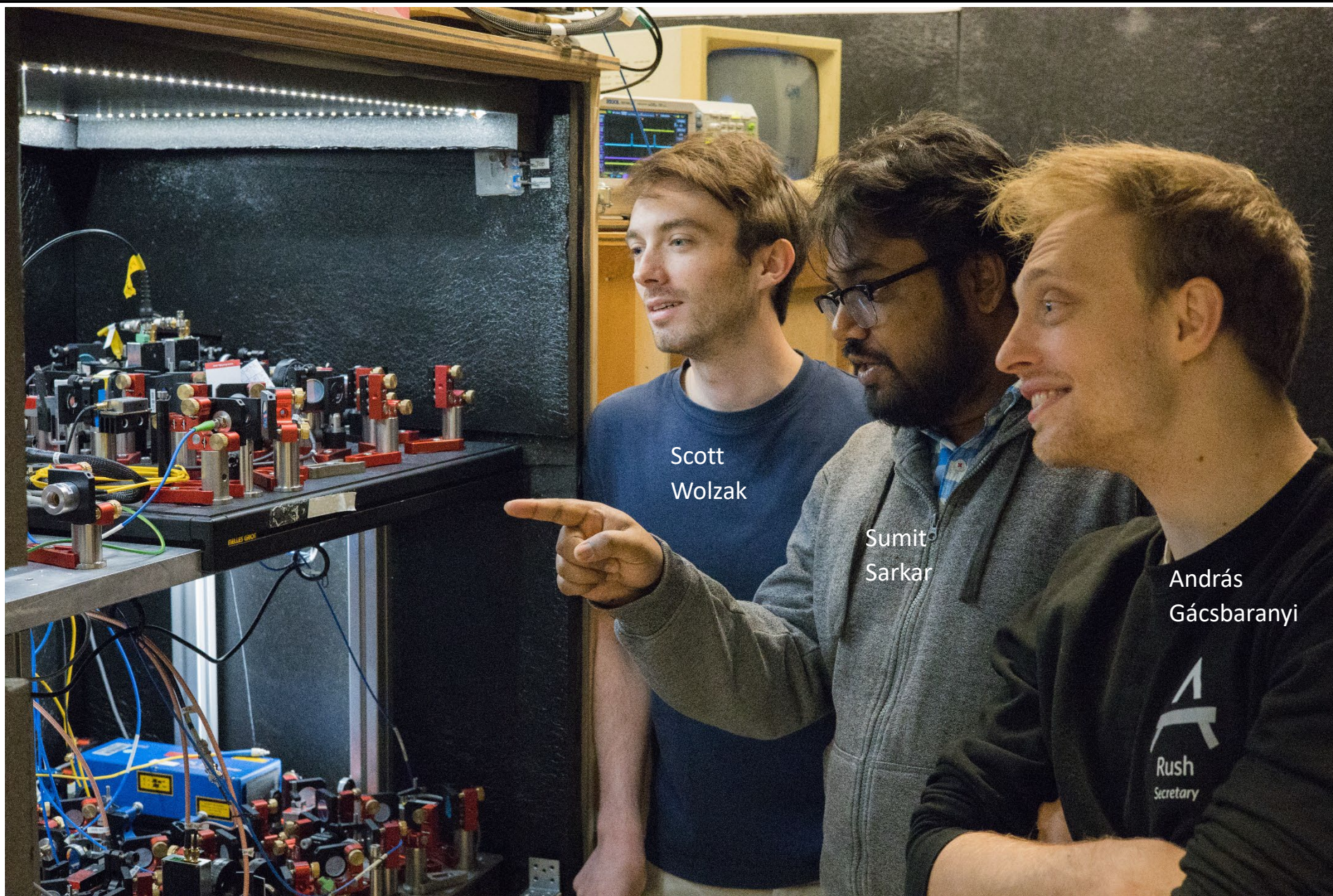


Continuous ultracold strontium beam in

Clock laser beam out



Zero-deadtime clock



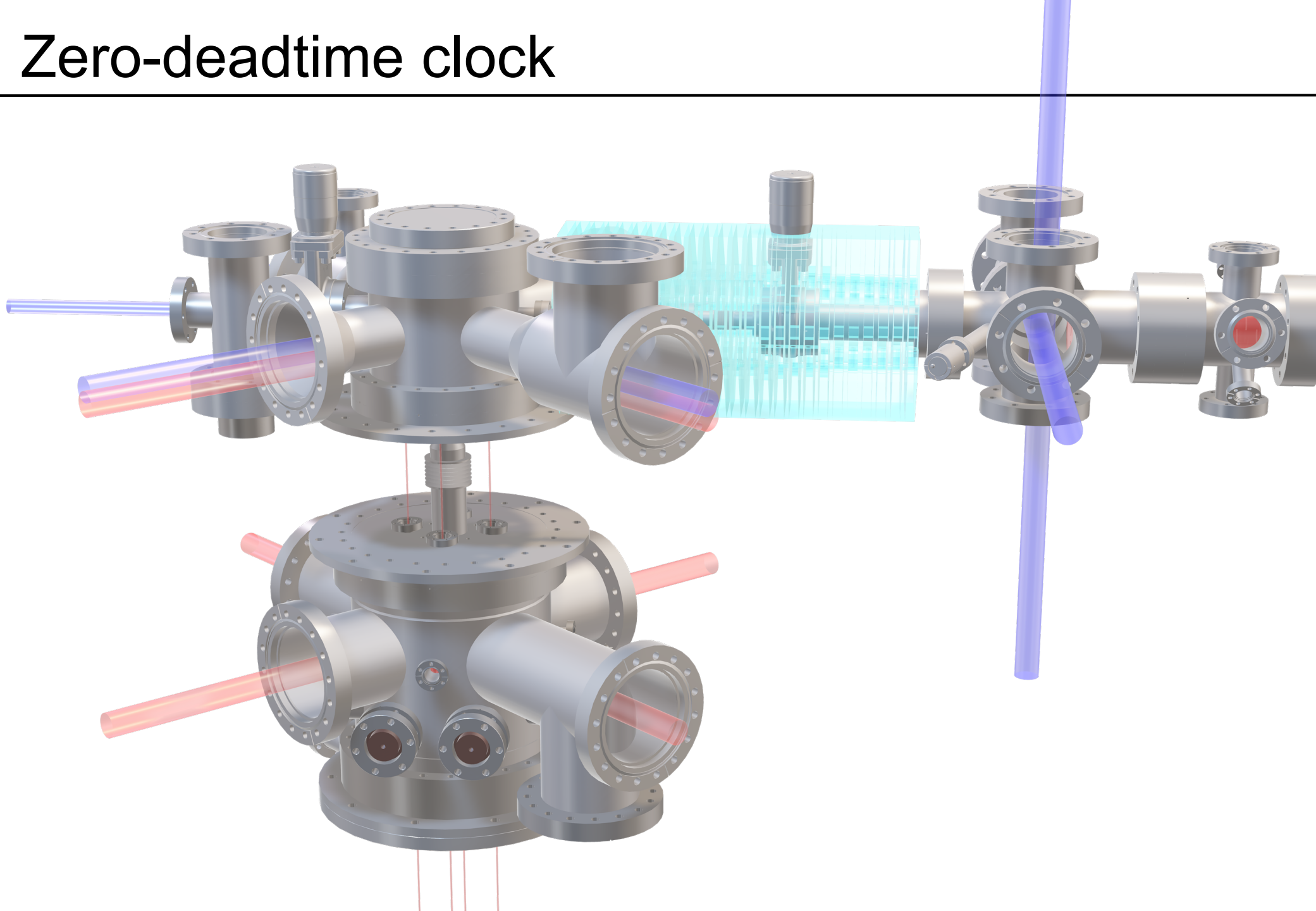
Scott
Wolzak

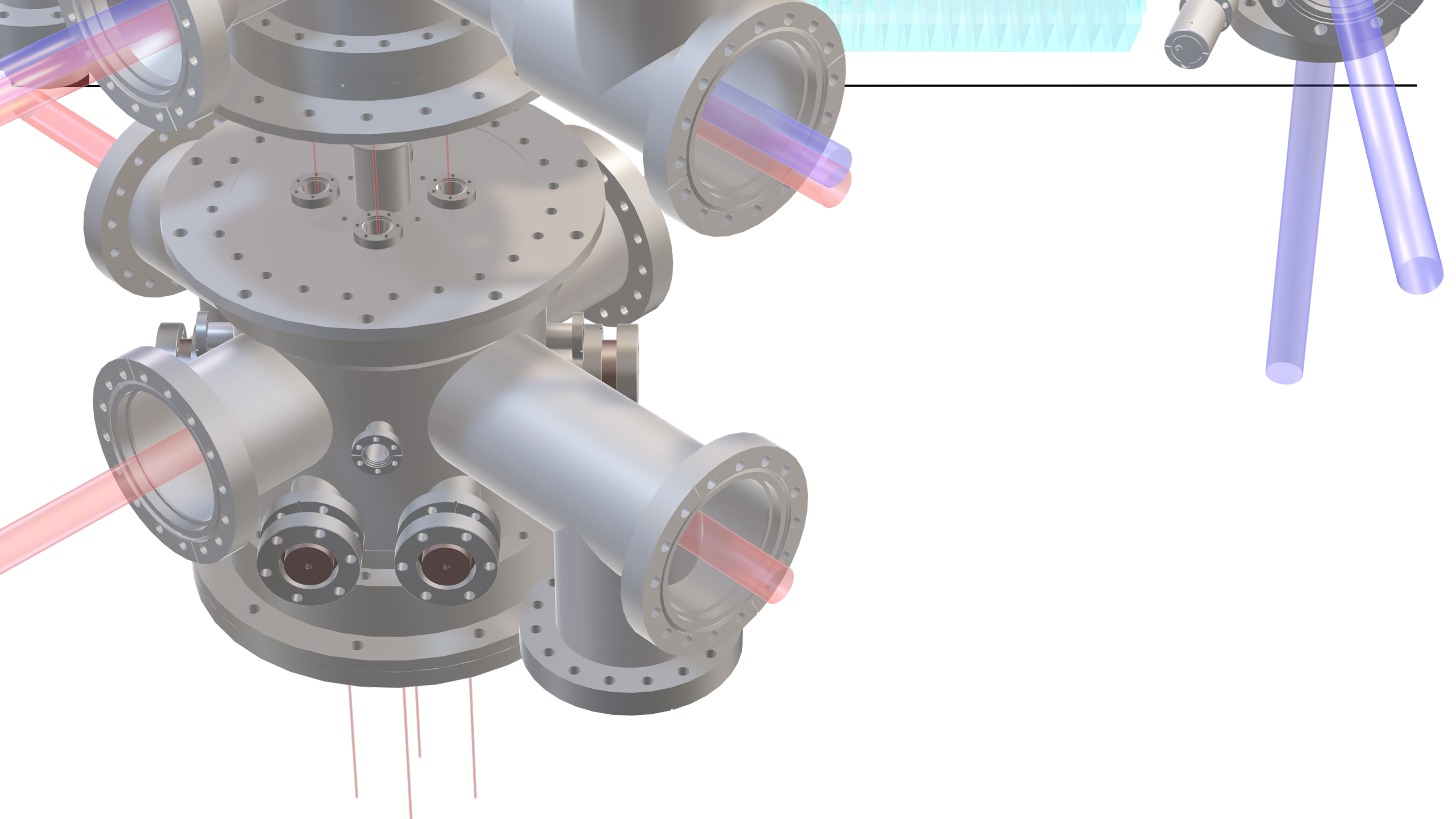
Sumit
Sarkar

András
Gácsbaranyi



Zero-deadtime clock



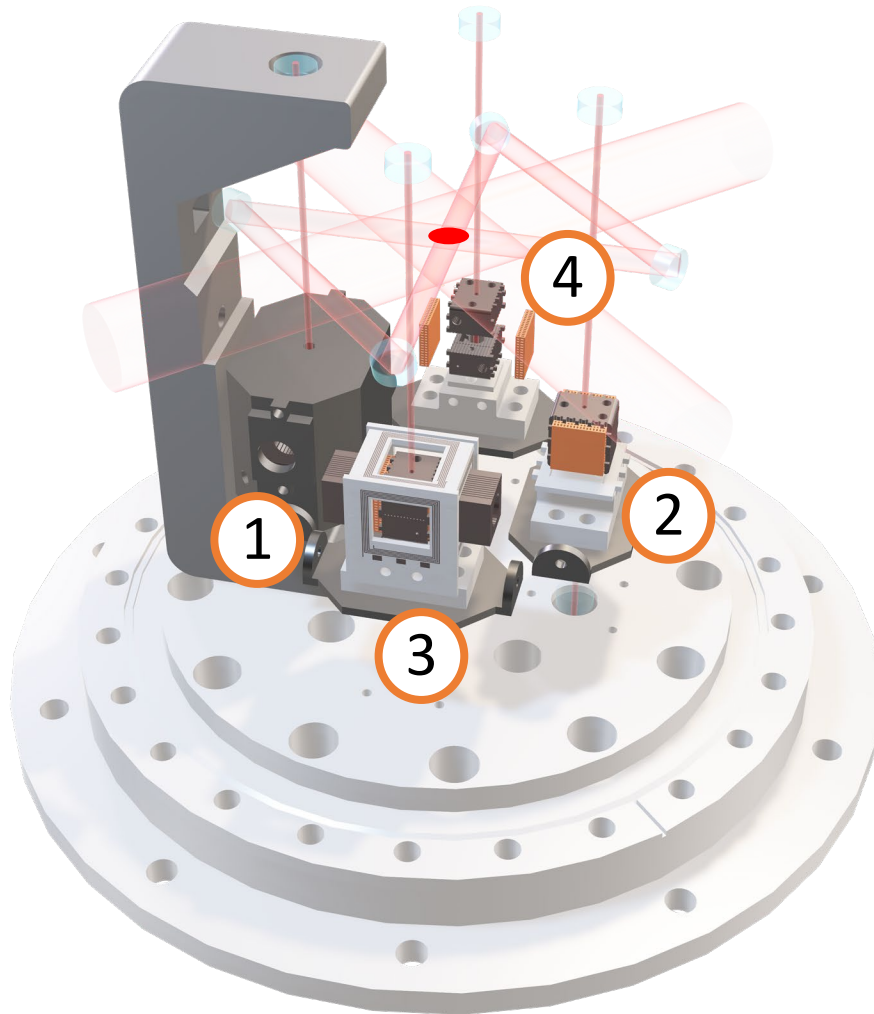




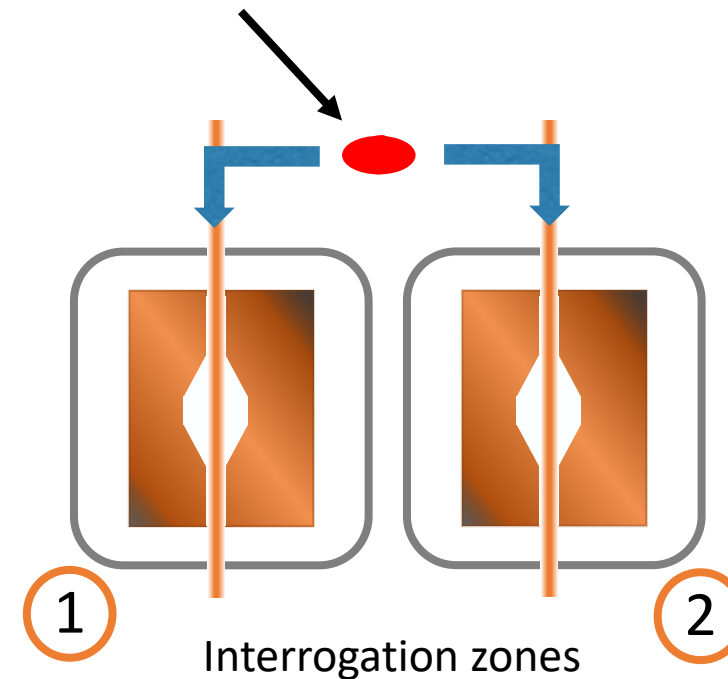
Zero-deadtime clock

Using independent clocks: Ludlow group, Nature Photonics 11, 48 (2017)

Yu-Ao Chen, Jian-Wei Pan group: arXiv:2509.15100



steady-state ultracold atom source



Alternative continuous clock schemes: continuous Ramsey spectroscopy, Hidetoshi Katori, Appl. Phys. Express **14**, 072006 (2021)
continuous cavity spectroscopy, JILA clock groups, PR A **92**, 053820 (2015)



Zero-deadtime clock

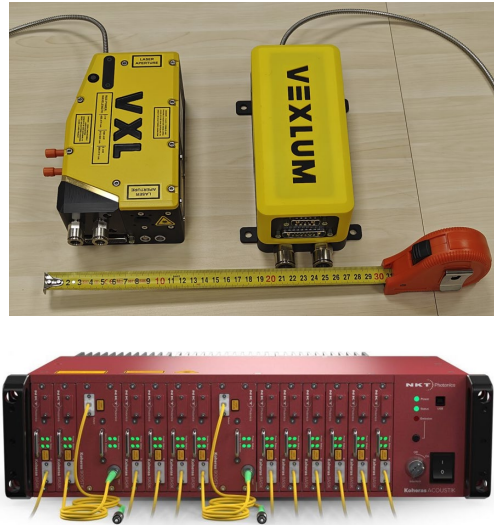




AQuRA: transportable Sr optical clock



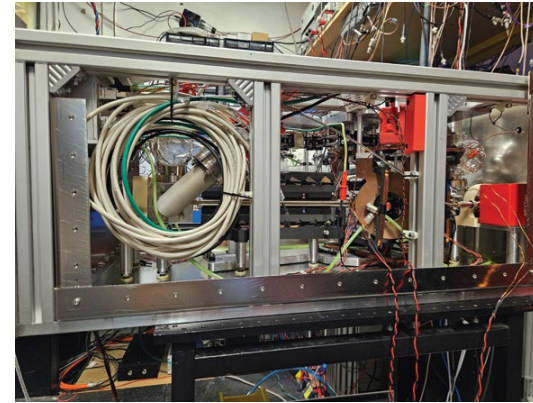
Laser sources



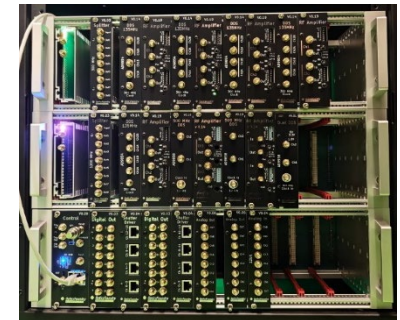
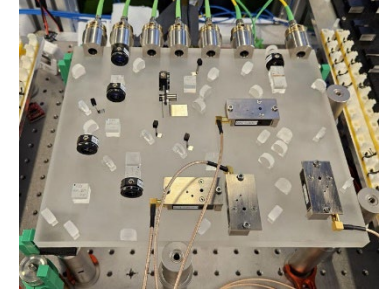
Optical frequency comb



Physics package



Optical circuits



Benchmarking



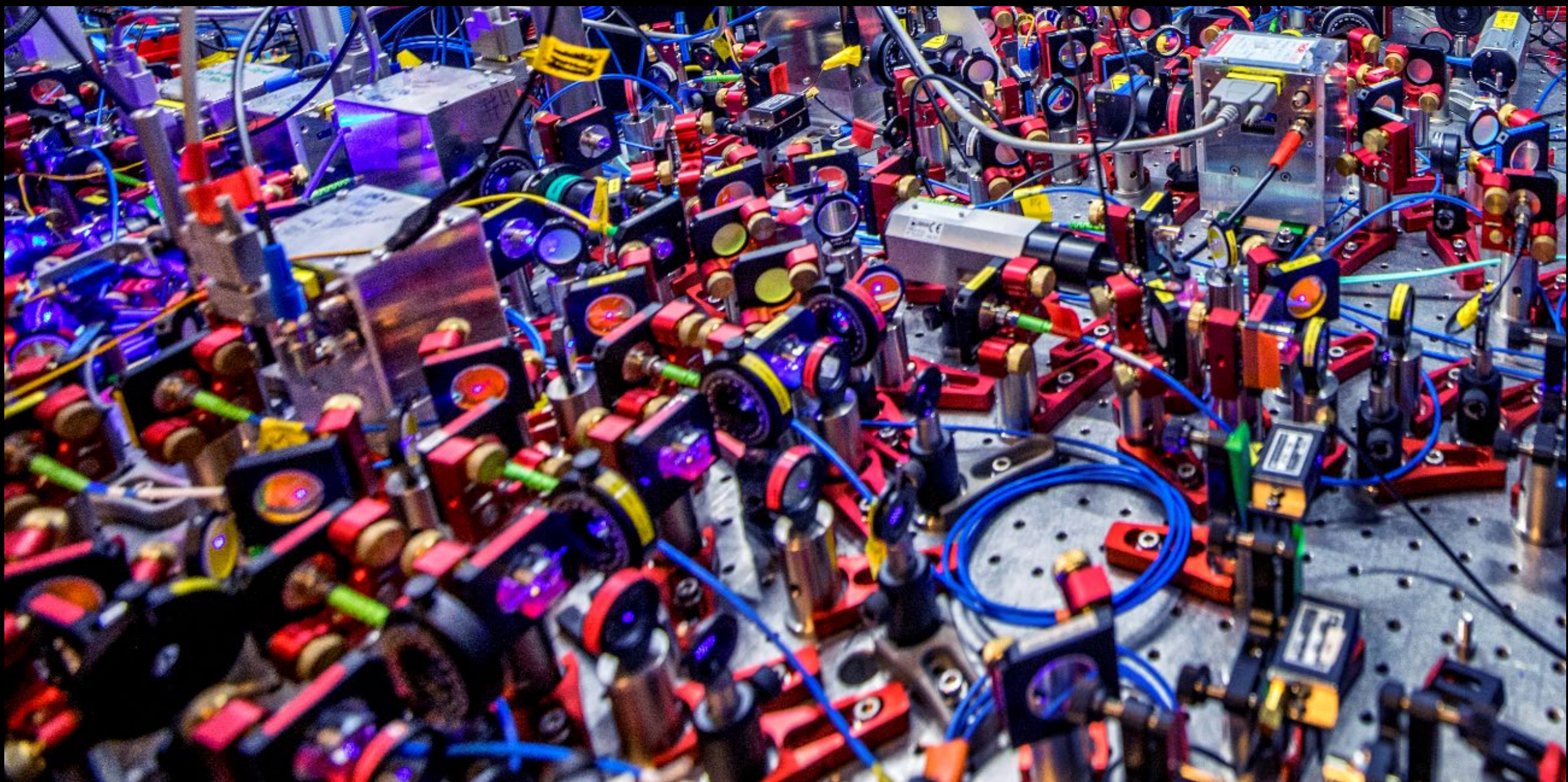
Network connection



Optics is complicated and fragile



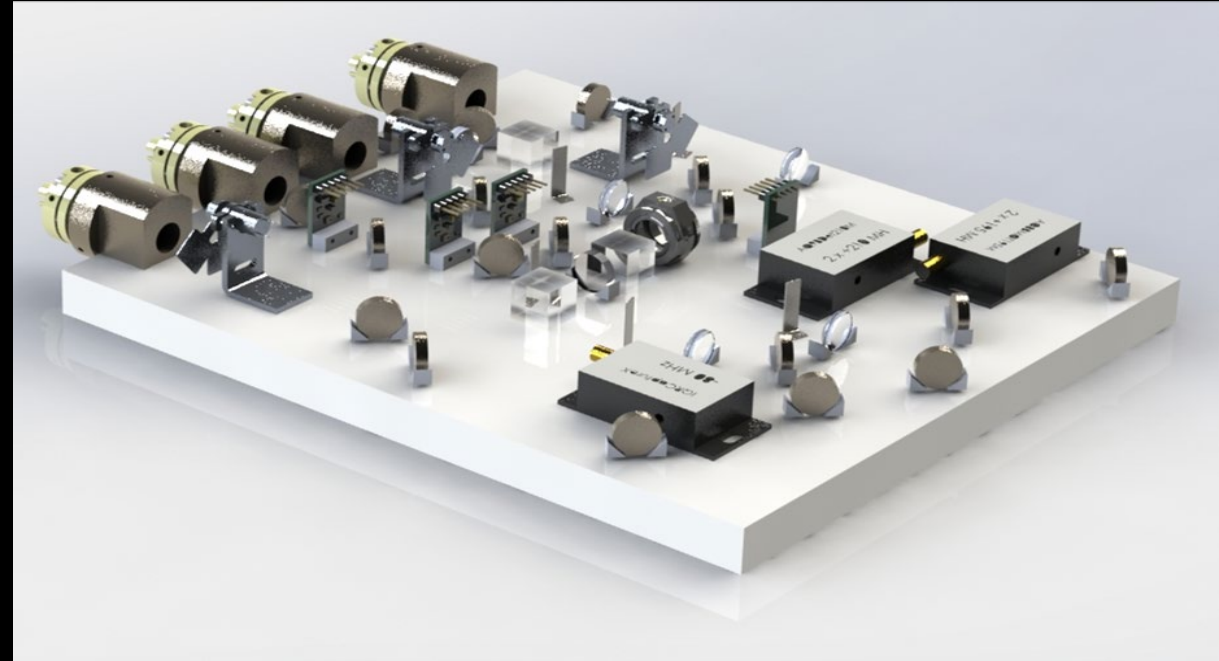
Optics is complicated and fragile



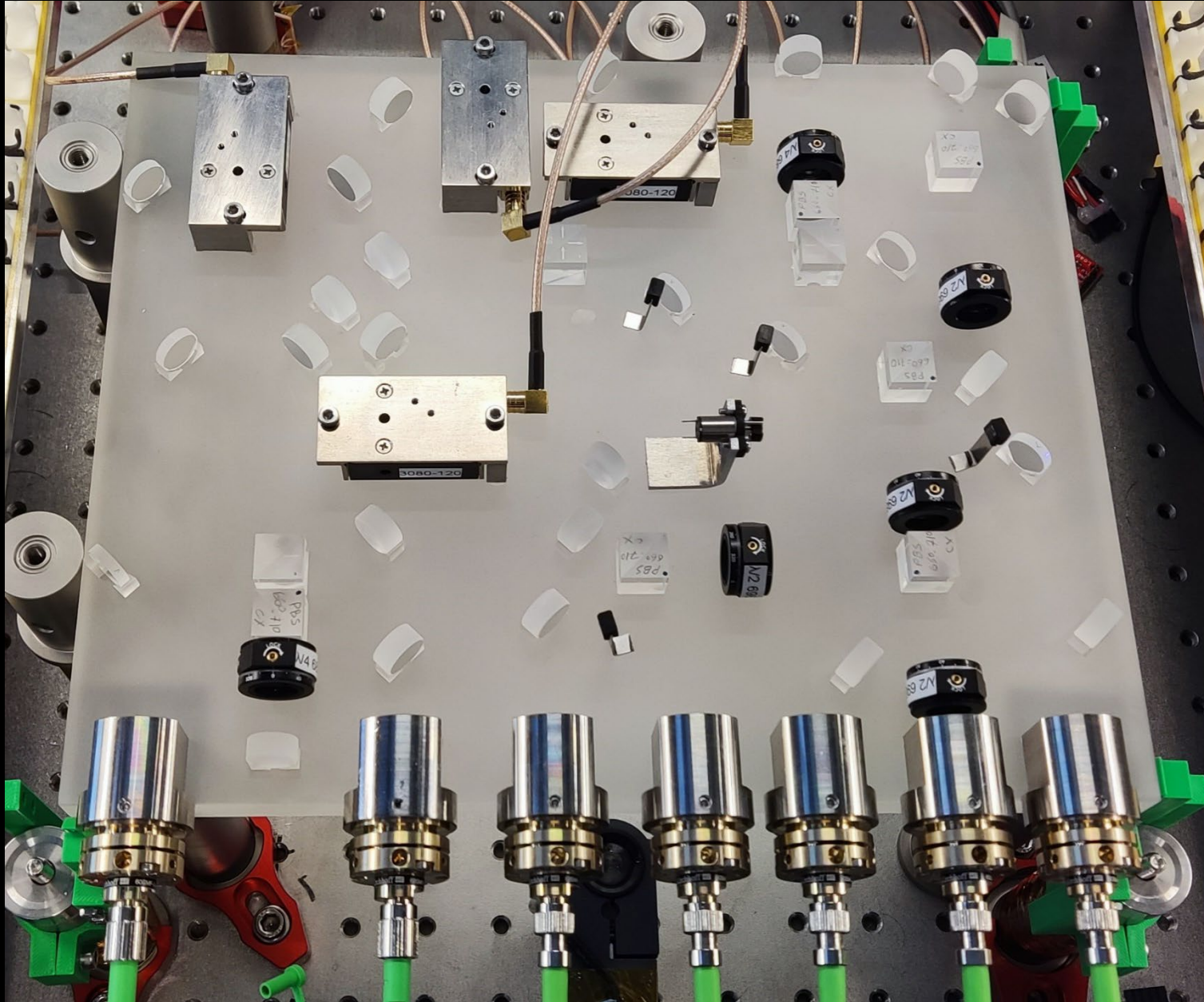
We need a better way to make optics:



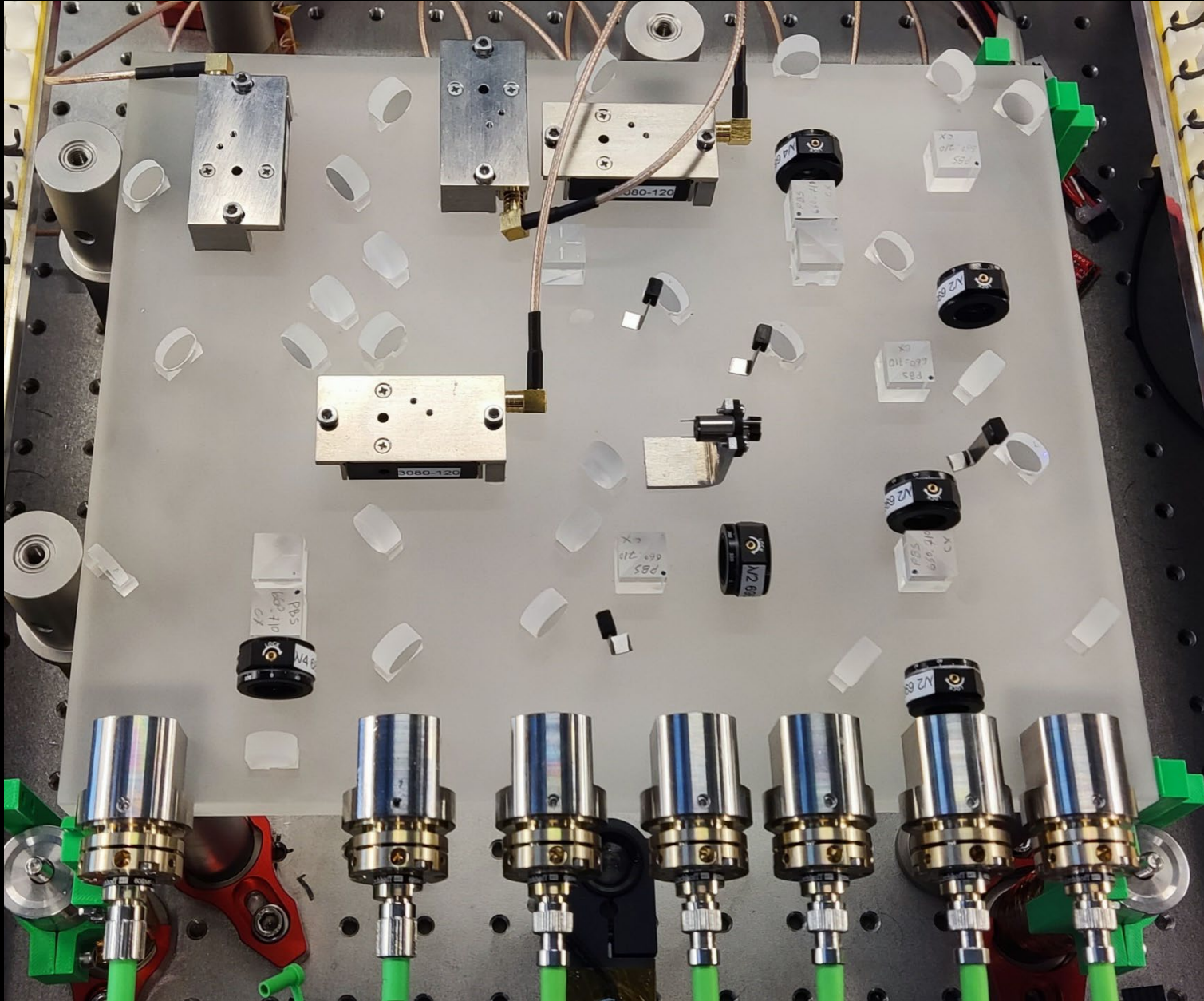
Integrated optical benches



Optics Foundry
Making optics easy

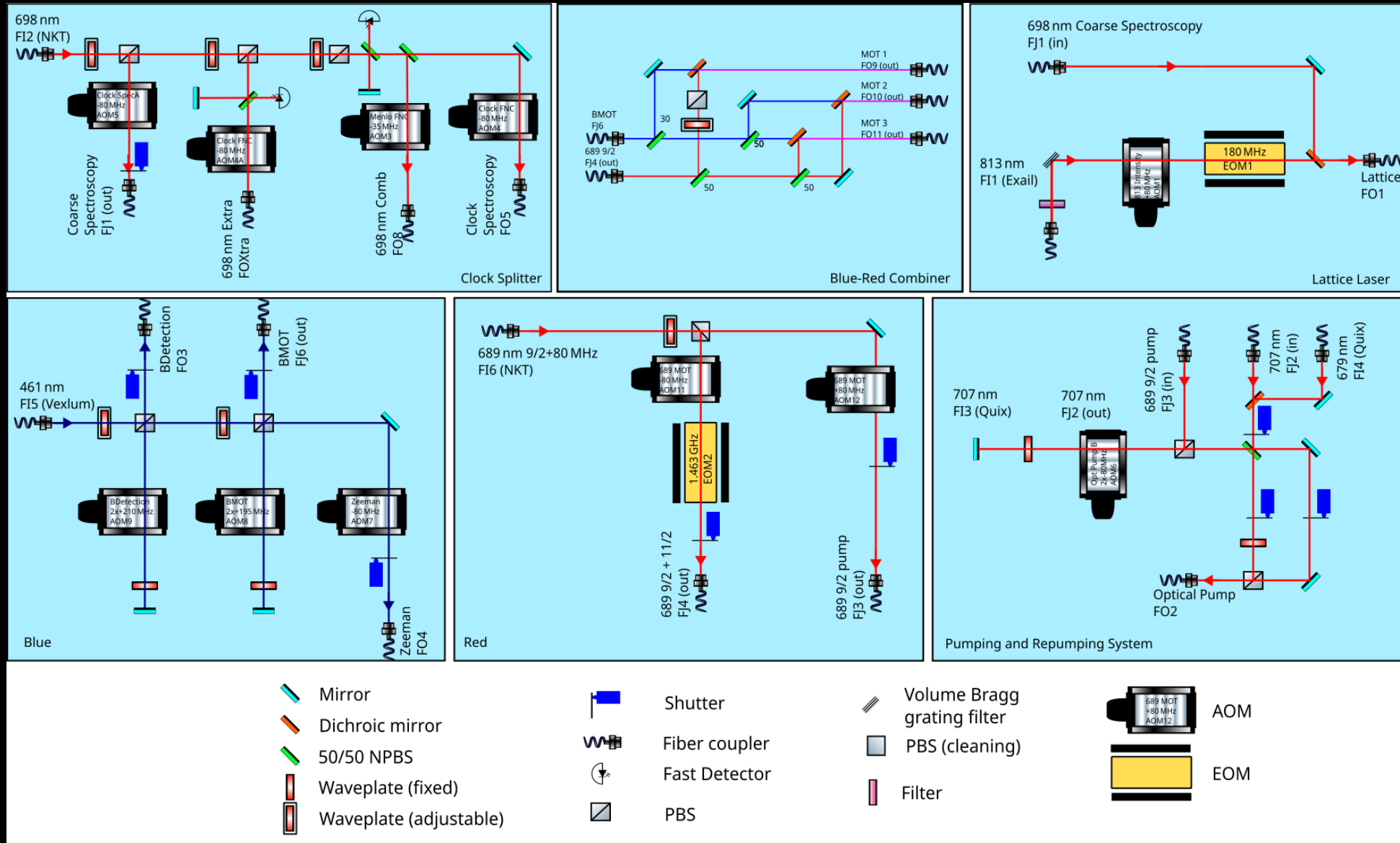


Integrated optical benches

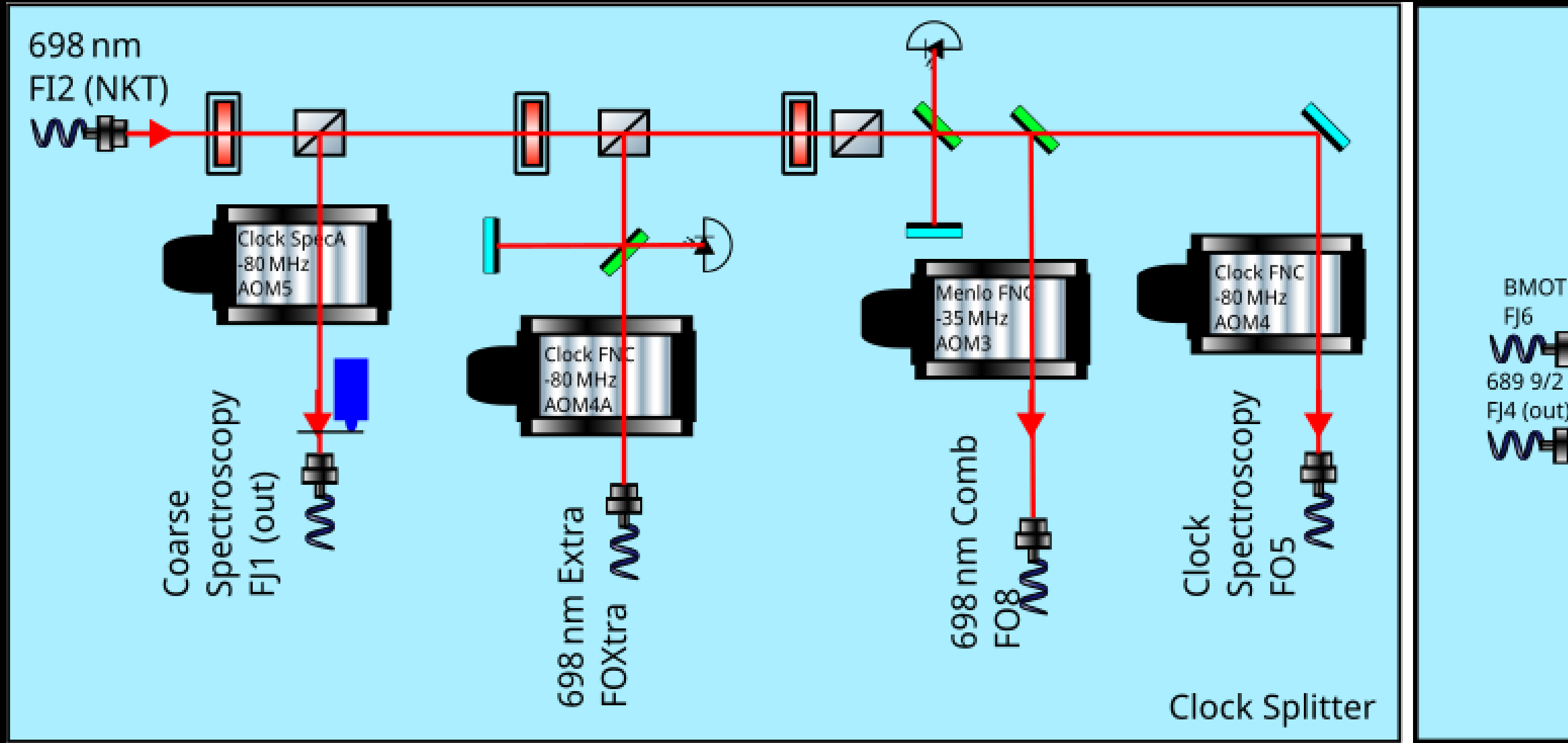


- Robustly glued
- Ultra-low thermal sensitivity
- Robotically manufactured
- Flexible design
- Fast delivery

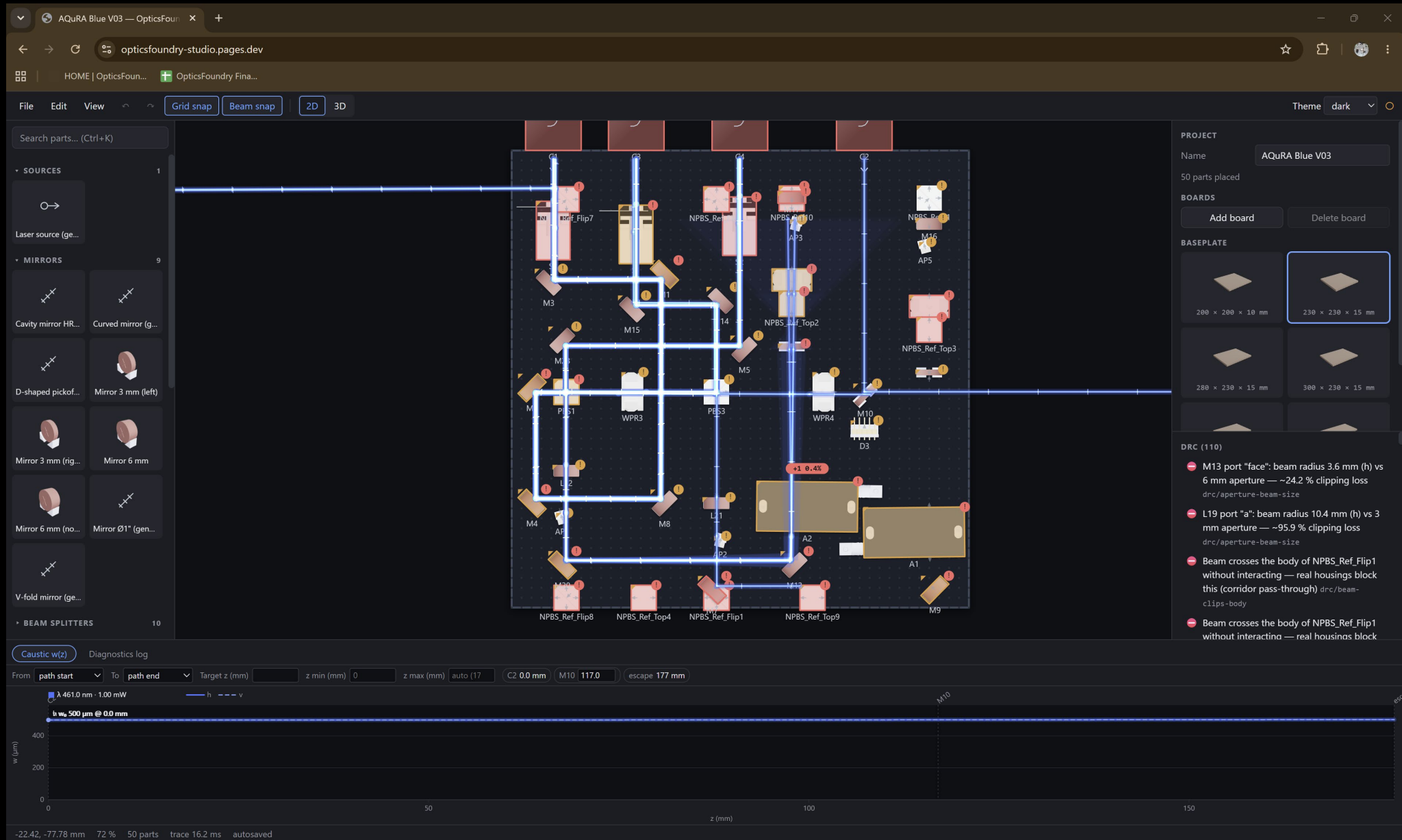
Production cycle: 1) circuit idea



Production cycle: 1) circuit idea



2) OpticsFoundry Design Studio



Search parts... (Ctrl+K)

SOURCES 1

Laser source (ge...

MIRRORS 9

Cavity mirror HR... Curved mirror (g...

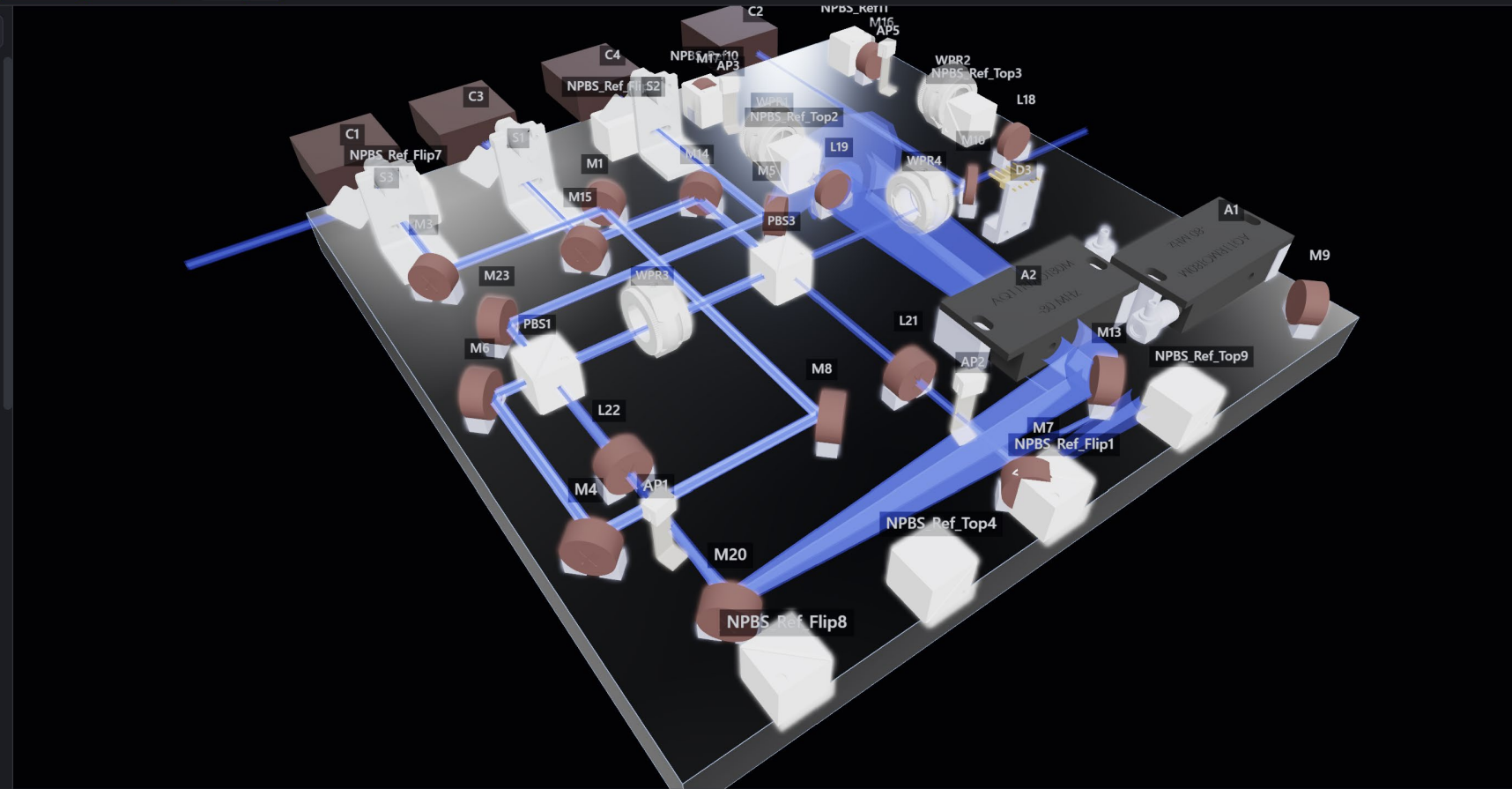
D-shaped pickof... Mirror 3 mm (left)

Mirror 3 mm (rig... Mirror 6 mm

Mirror 6 mm (no... Mirror Ø1" (gen...

V-fold mirror (ge...

BEAM SPLITTERS 10



PROJECT

Name AQuRA Blue V03

50 parts placed

BOARDS

Add board Delete board

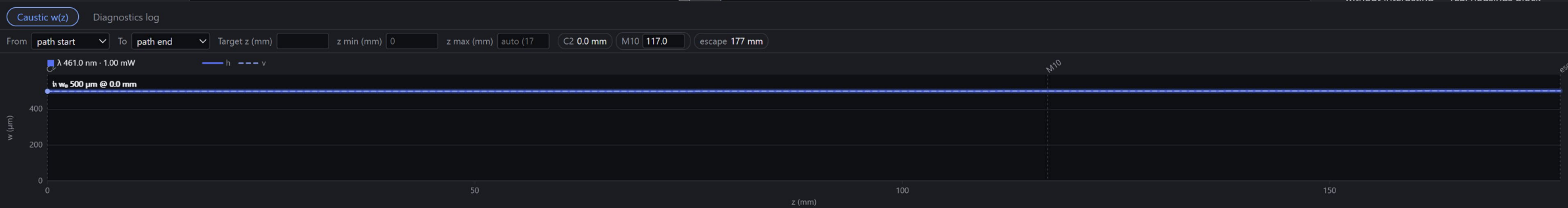
BASEPLATE

200 × 200 × 10 mm 230 × 230 × 15 mm

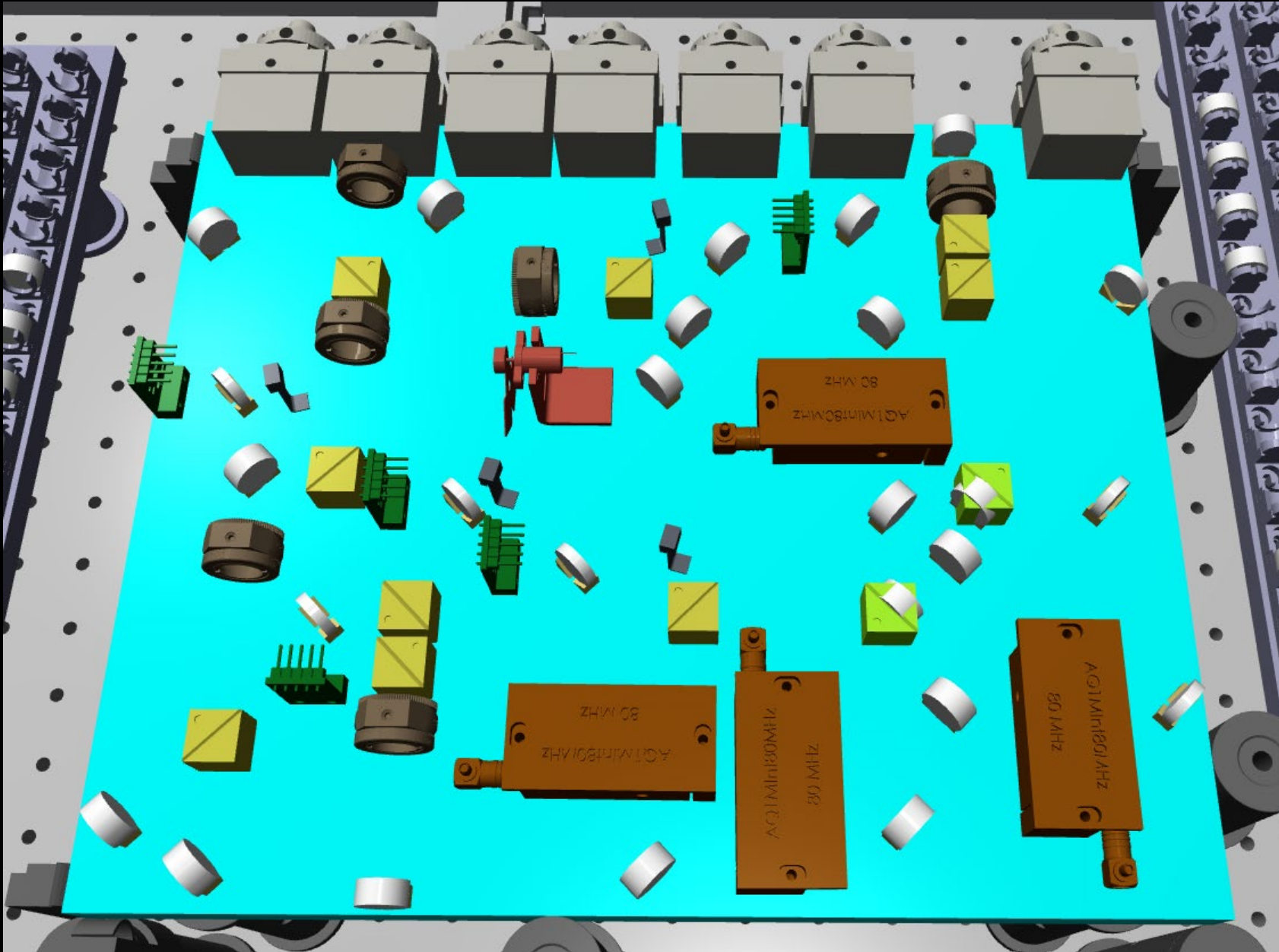
280 × 230 × 15 mm 300 × 230 × 15 mm

DRC (110)

- M13 port "face": beam radius 3.6 mm (h) vs 6 mm aperture — ~24.2 % clipping loss drc/aperture-beam-size
- L19 port "a": beam radius 10.4 mm (h) vs 3 mm aperture — ~95.9 % clipping loss drc/aperture-beam-size
- Beam crosses the body of NPBS_Ref_Flip1 without interacting — real housings block this (corridor pass-through) drc/beam-clips-body
- Beam crosses the body of NPBS_Ref_Flip1 without interacting — real housings block this (corridor pass-through) drc/beam-clips-body

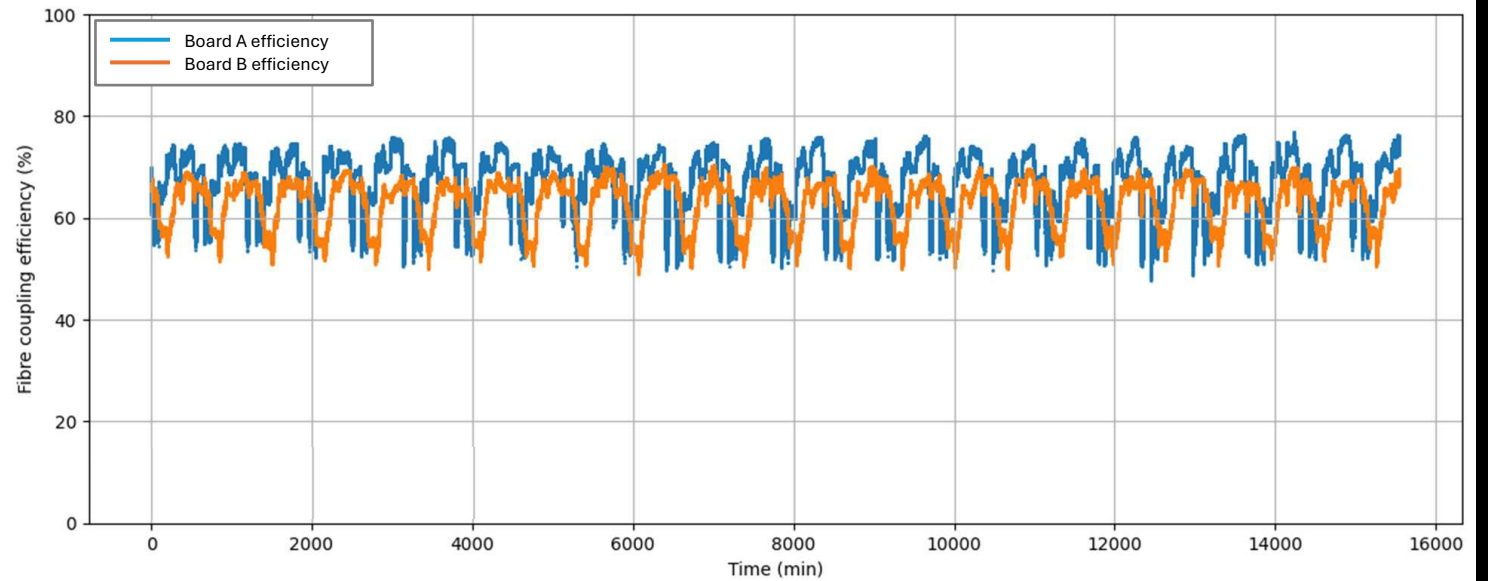
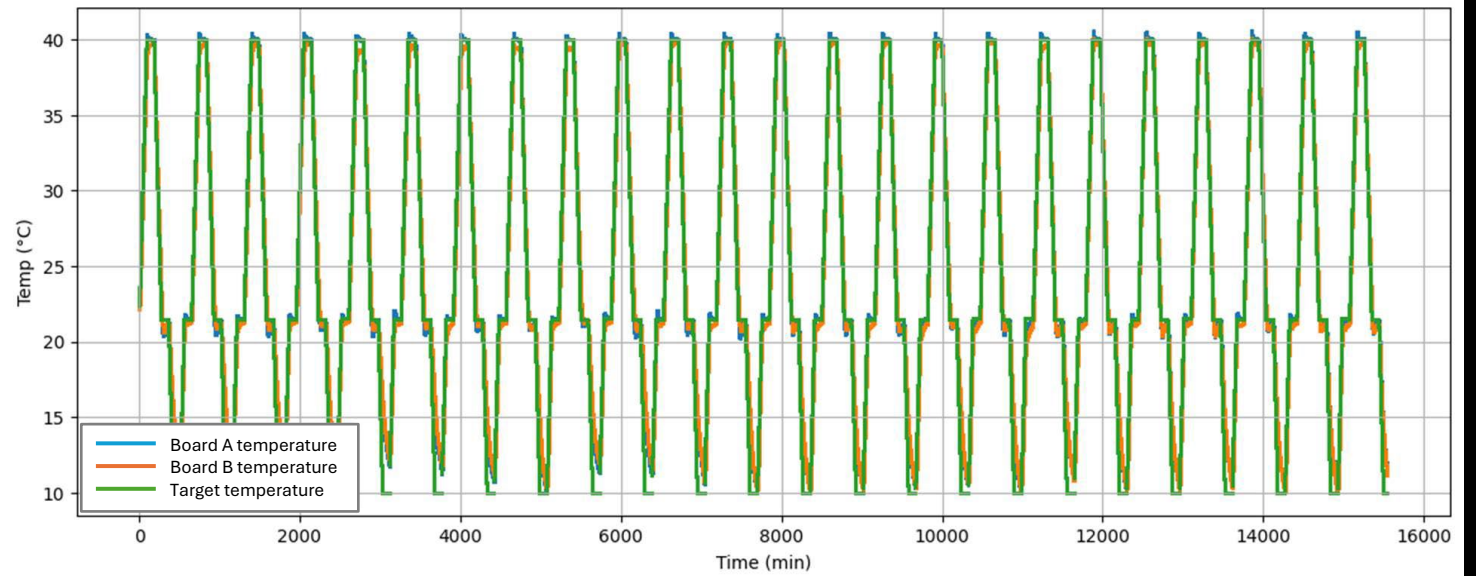
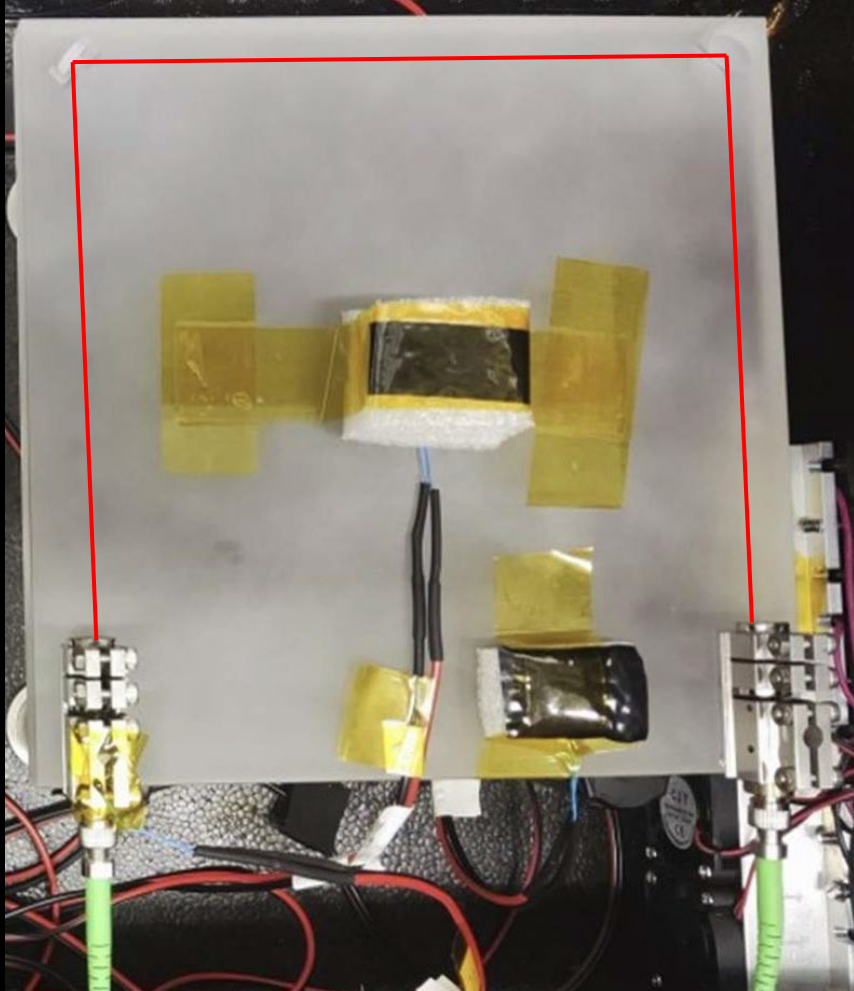


3) data transfer to robot





Temperature chamber tests





AQURA Sr optical clock circuit boards

OpticsFoundry

Making optics easy



Shayne Bennetts



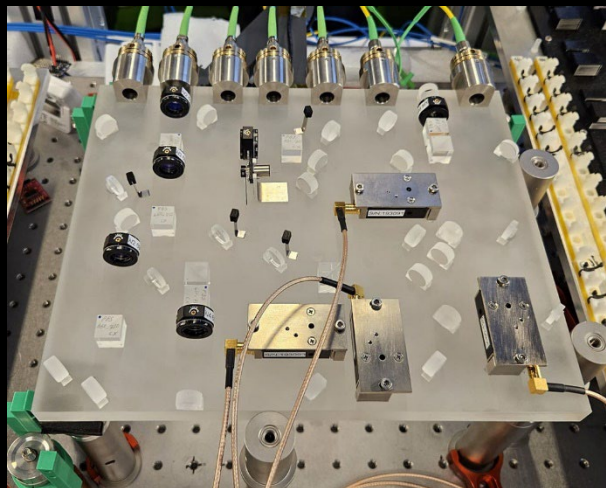
Mehrdad Zarei



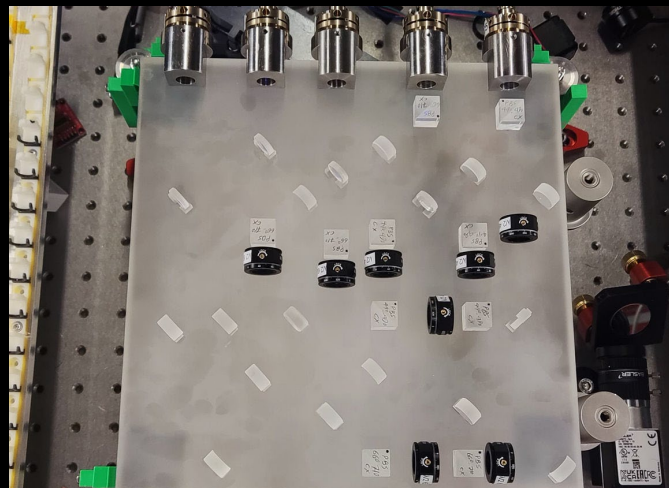
Sheng Zhou



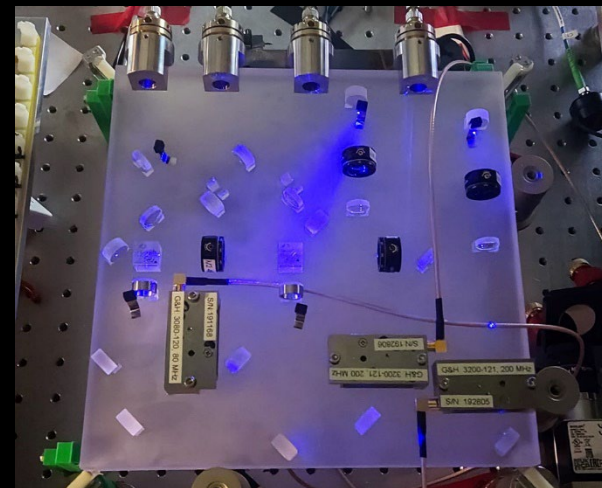
Gonçalo Nunes



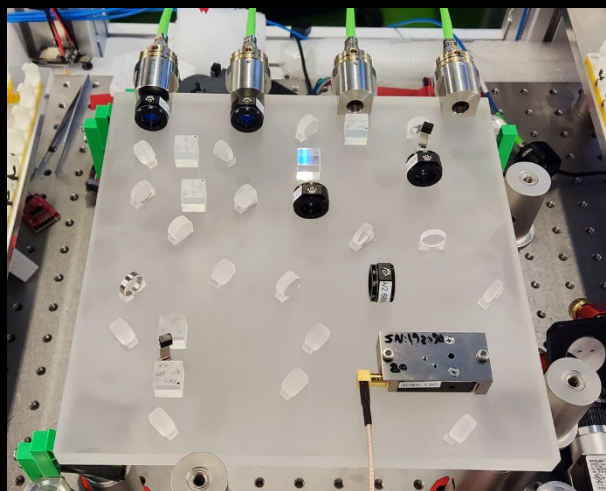
698 nm clock distribution



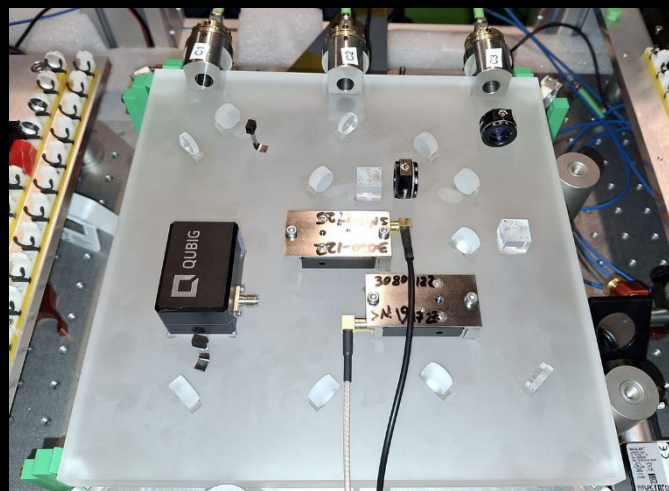
Red + blue MOT combiner



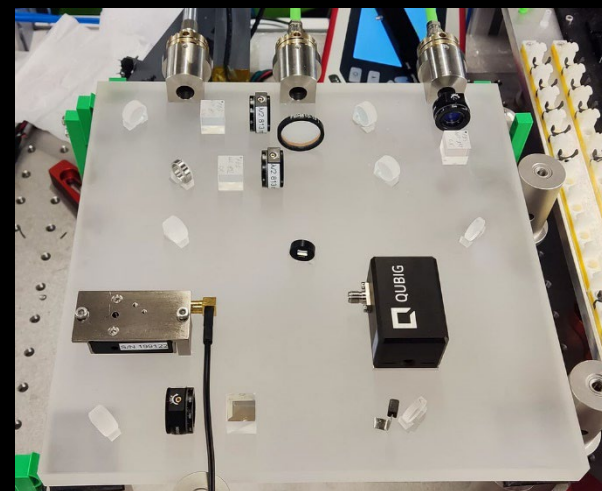
461 nm, blue MOT



Optical (re)pumping

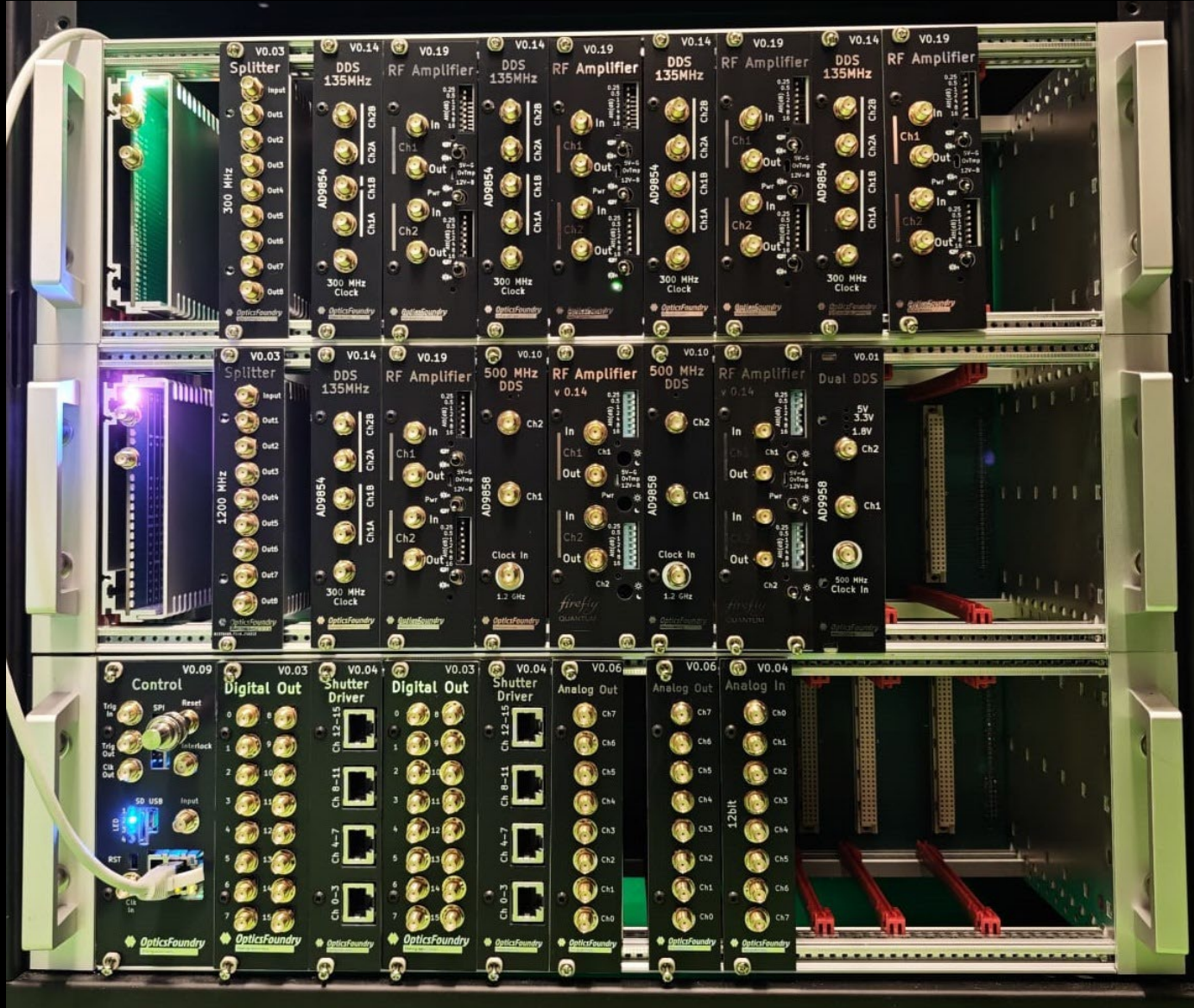


689 nm, red MOT



813 nm magic wavelength lattice

OpticsFoundry control electronics & software



- Ethernet connected FPGA sequencer
- DDS & radiofrequency amplifiers
- Digital & analog IO
- Open-source low-level Python, C, C++ API for Linux and Windows
- Open-source high-level GUI experiment control

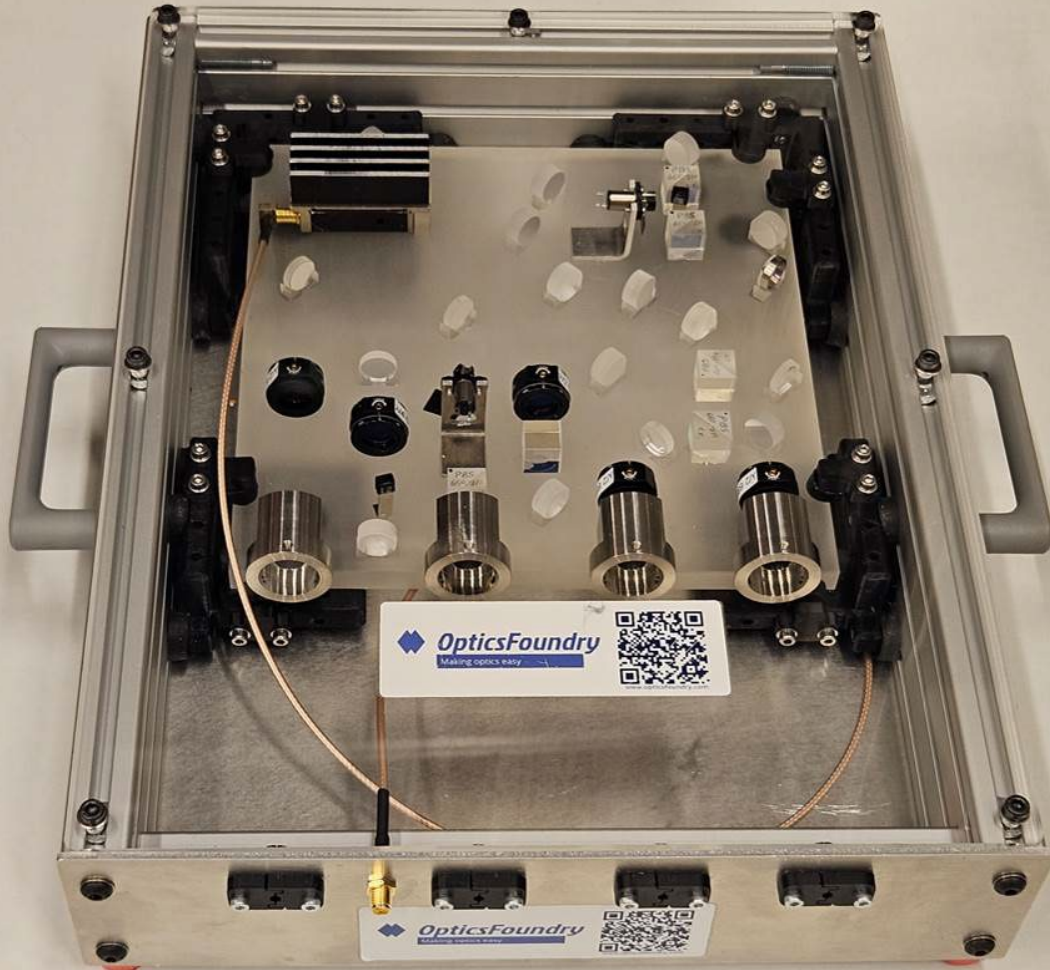
```
import control_light_api

cla = control_light_api.ControlLightAPI()

cla.initialize()
cla.switch_debug_mode(True, "DebugSequence")
start_time = 0
for i in range(10):
    cla.start_assembling_sequence()
    cla.sequencer_start_analog_in_acquisition(0, 0, 0, 0, 100, 0.1)
    for j in range(100):
        cla.set_voltage(0, 24, 10.0 * j / 100.0)
        cla.wait_ms(0.1)
        frequency = 1000.0 * j / 100.0
        cla.set_frequency(0, 232, frequency)
    cla.execute_sequence()
    input = cla.wait_till_end_of_sequence_then_get_input_data(timeout=
    print("Input data length:", input["length"], " duration:", input\
    start_time = input["end_time_of_cycle"]
```


Vibration & shock protected packaging

Transport box

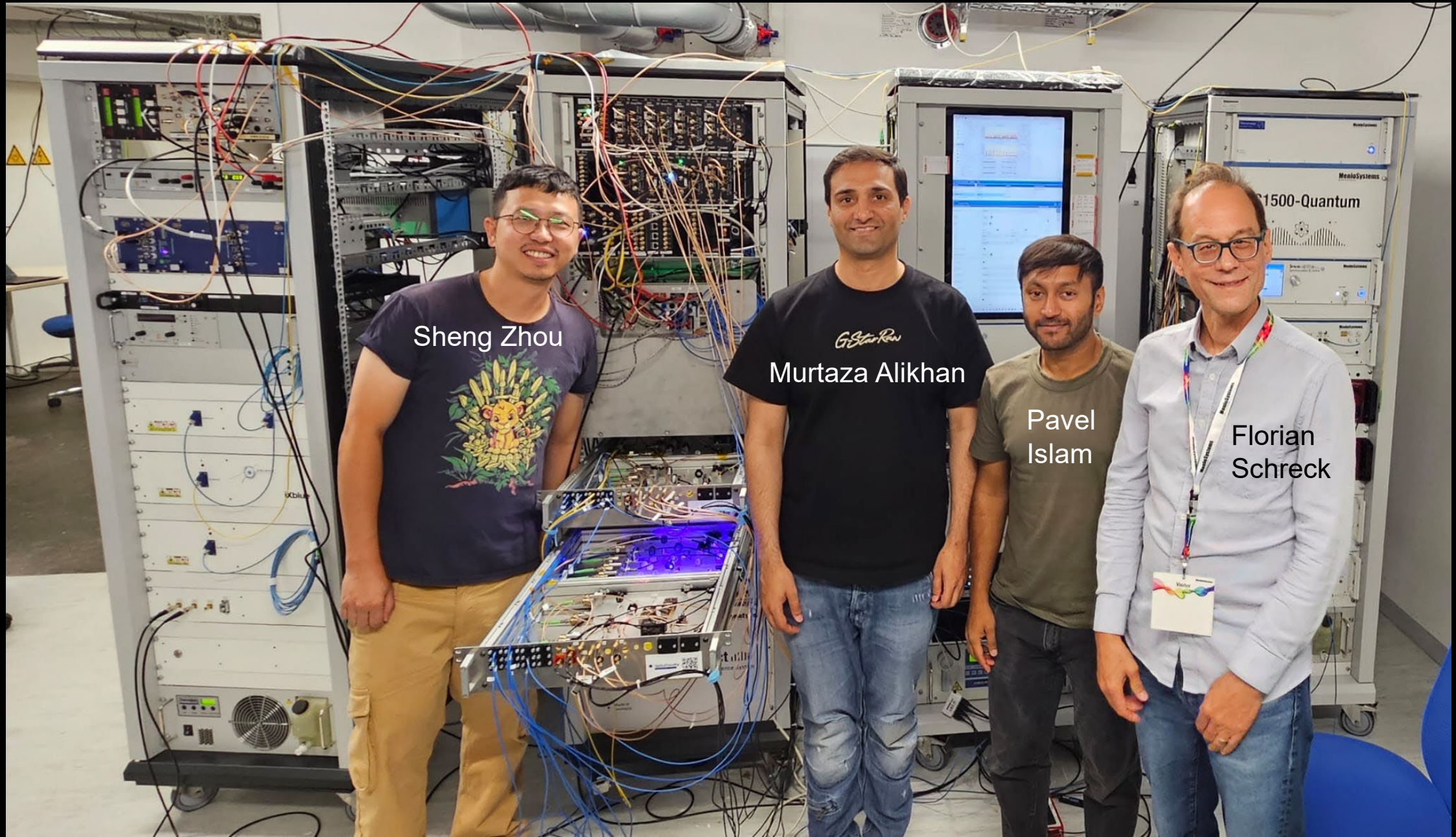


Rack mounting example



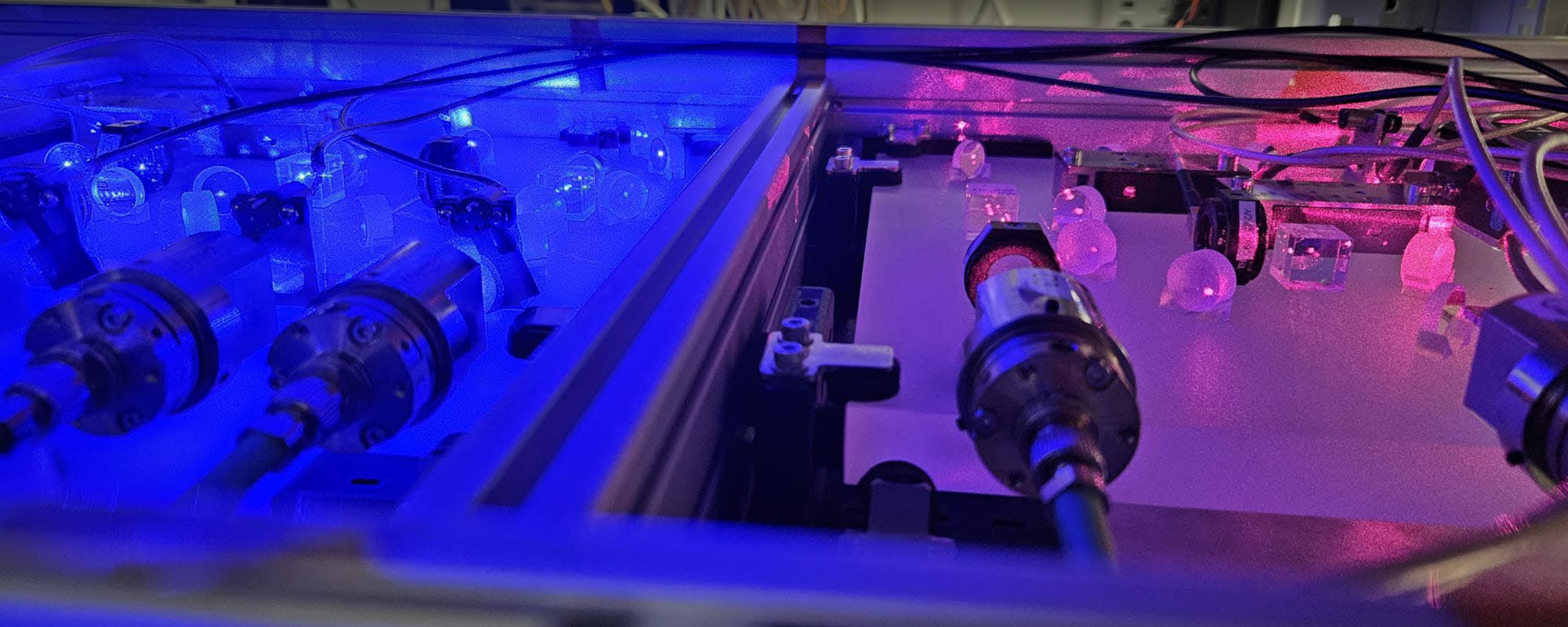


AQuRA Sr optical clock taking shape at Menlo Systems in Munich



OpticsFoundry

Making optics easy



Experiment

Theory



Sheng Zhou



Shayne Bennetts



Anna Bycheck



Simon Jäger



Francesca Famà



Camila Beli Silva



Stefan Alaric Schäffer



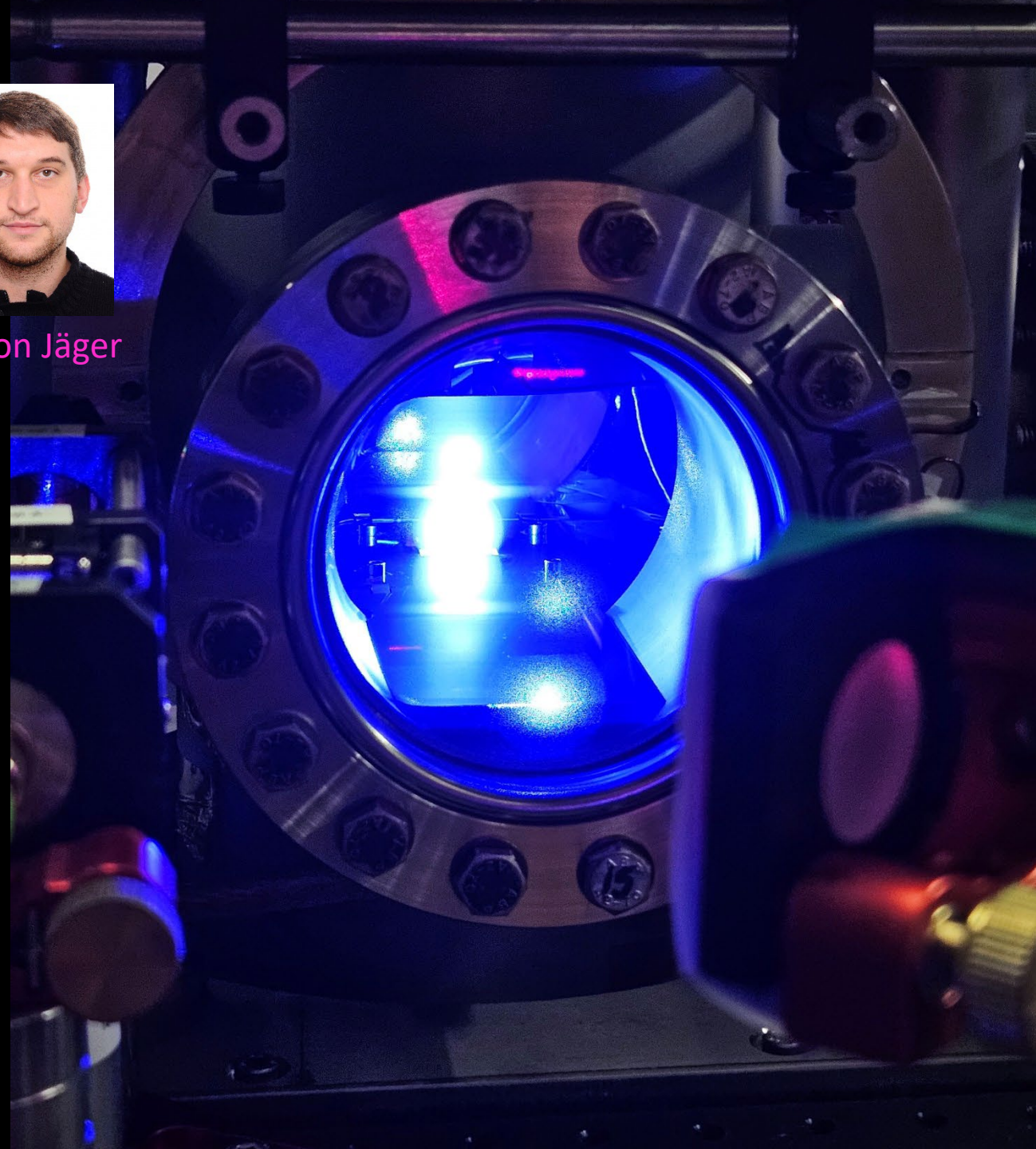
Benedikt
Heizenreder



Ananya
Sitaram



Ying Cui

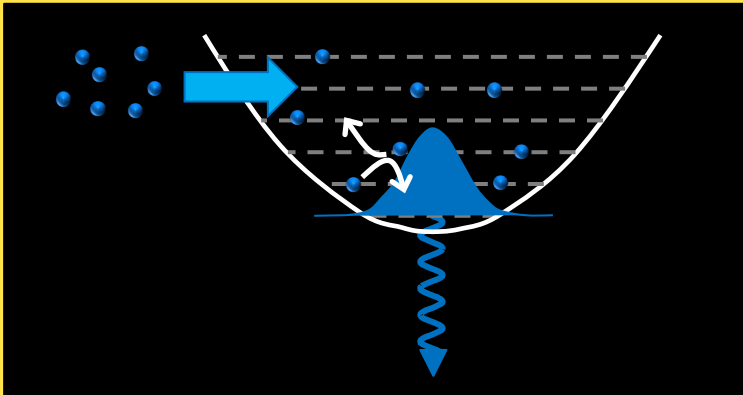




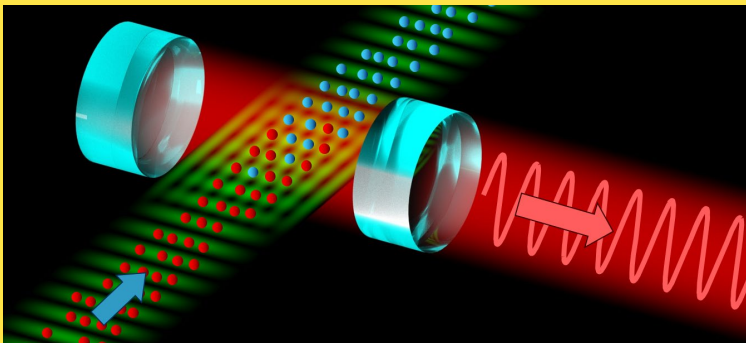
Our projects

Quantum sensing

Continuous atom laser

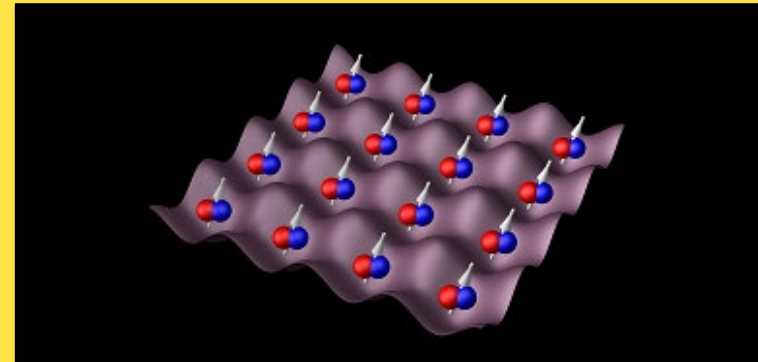


Continuous Clocks

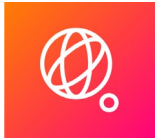
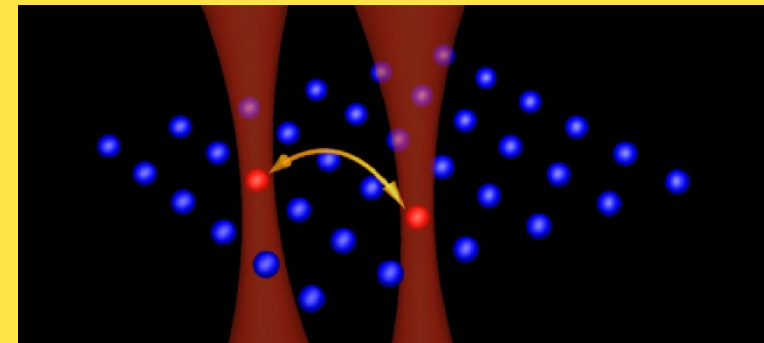


Quantum simulation

RbSr molecules



Rydberg coupled Sr atoms



Quantum Flagship

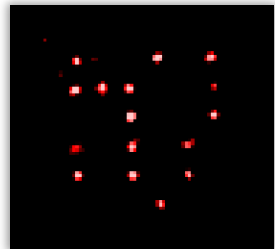


MoSaiQC | ITN
Modular Systems for advanced Integrated Quantum Clocks

M. J. Holland &
T. L. Nicholson
groups



EuRyQa





Mehrdad Zarei
(postdoc)



Sheng Zhou
(postdoc)



Philippe Bouyer
(PI)



Gentle Dash
(postdoc)

András Gácsbaranyi
(PhD)

Sumit Sarkar
(postdoc)

Robert Spreeuw
(PI)

Mateusz Borkowski
(former research assistant)

Ivo Krottnerus
(PhD)

Klaasjan van Druten
(PI)

Noah Wach
(former master)

Junyu He
(postdoc)

Digvijay
(PhD)

Davide Natale
(PhD)

Benedikt Heizenreder
(PhD)

Yu Chih Tseng
(PhD)

Ananya Sitaram
(postdoc)

Alex Urech
(postdoc)

Florian Schreck
(PI)

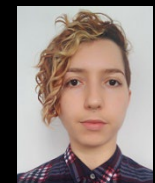
Atom interferometry
Clocks
RbSr
Sr tweezer



Premjith Thekkeppat
(former PhD)



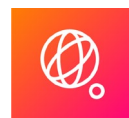
Francesca Famà
(former PhD)



Camila Beli Silva
(former PhD)



Shayne Bennetts
(former postdoc)



Veni & Vici
NWA Startimpuls II QuNav

Programme QuSim 2.0
Zwaartekracht QCS



Quantum
Delta NL



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