LAGRANGIANS TO LASERS... (IISERP STUDENTS JOURNAL CLUB)

"SO WHAT?" TALK SERIES

WHAT IT TAKES TO BUILD AN ULTRA-STABLE LASER?

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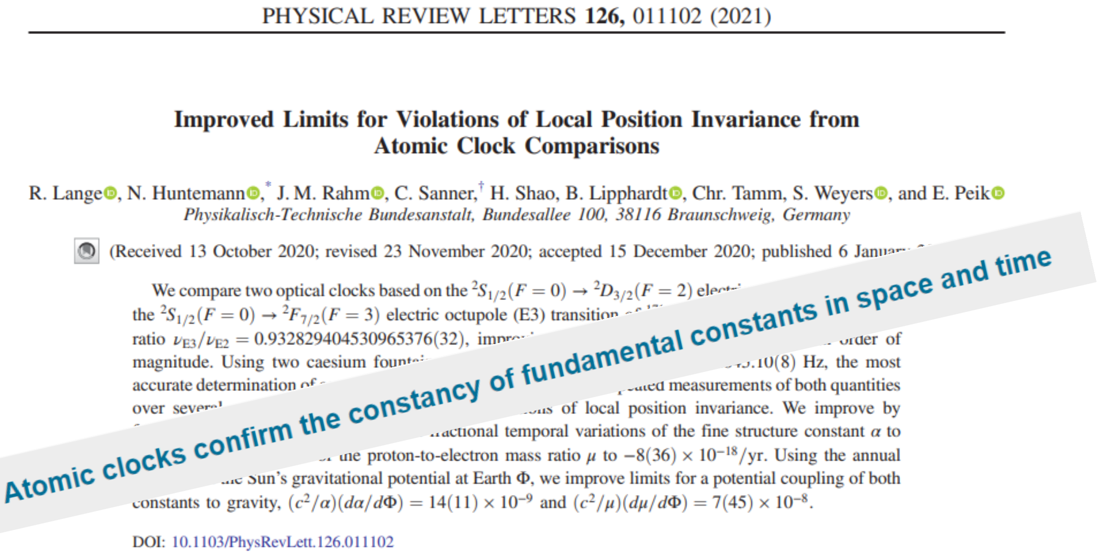
CAUTION: PHYSICS IN DANGER?

LIV – Lorentz Invariance Violation Tests



PHYSICAL REVIEW LETTERS **126,** 011102 (2021)

Improved Limits for Violations of Local Position Invariance from Atomic Clock Comparisons

R. Lange, N. Huntemann,* J. M. Rahm, C. Sanner,† H. Shao, B. Lipphardt, Chr. Tamm, S. Weyers, and E. Peik
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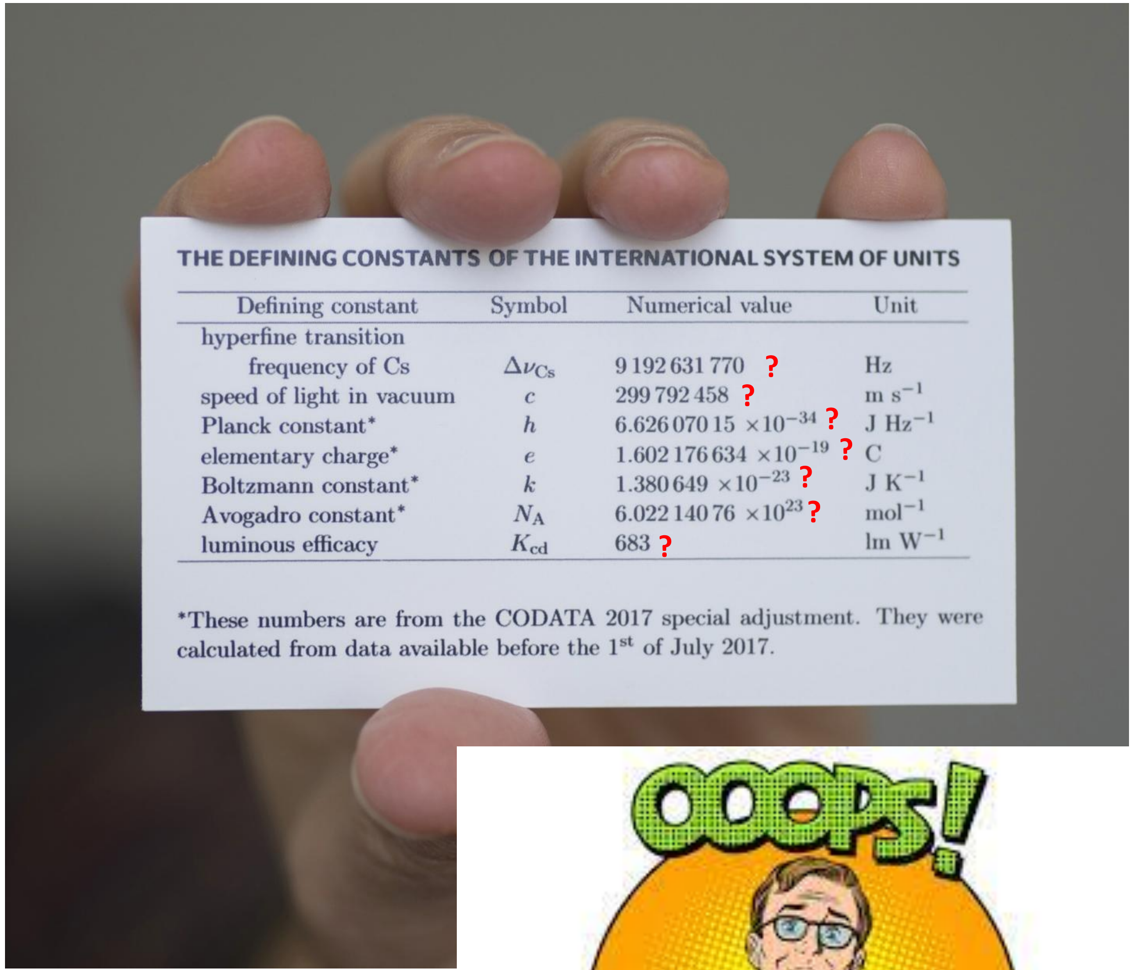
(Received 13 October 2020; revised 23 November 2020; accepted 15 December 2020; published 6 Janu...)

We compare two optical clocks based on the $^2S_{1/2}(F=0) \to {}^2D_{3/2}(F=2)$ elec... the $^2S_{1/2}(F=0) \to {}^2F_{7/2}(F=3)$ electric octupole (E3) transition ... ratio $\nu_{E3}/\nu_{E2} = 0.932829404530965376(32)$, impr... order of magnitude. Using two caesium foun... .10(8) Hz, the most accurate determination of ... measurements of both quantities over sever... of local position invariance. We improve by ... fractional temporal variations of the fine structure constant α to ... the proton-to-electron mass ratio μ to $-8(36) \times 10^{-18}$/yr. Using the annual ... Sun's gravitational potential at Earth Φ, we improve limits for a potential coupling of both constants to gravity, $(c^2/\alpha)(d\alpha/d\Phi) = 14(11) \times 10^{-9}$ and $(c^2/\mu)(d\mu/d\Phi) = 7(45) \times 10^{-8}$.

DOI: 10.1103/PhysRevLett.126.011102

Atomic clocks confirm the constancy of fundamental constants in space and time



$\Delta\nu \approx 0.01$ Hz

$\nu \approx 10^{14}$ Hz

$\Delta\nu/\nu = 10^{-16}$

ULTRA-STABLE LASER!

During the measurements, the frequency of one of the two ytterbium clocks was also determined with highest precision: The frequency, which is 642×10^{12} Hz, was determined with an accuracy of 0.08 Hz and represents the most accurate measurement of an optical frequency with caesium clocks to date.

CONTENT OF THE TALK…

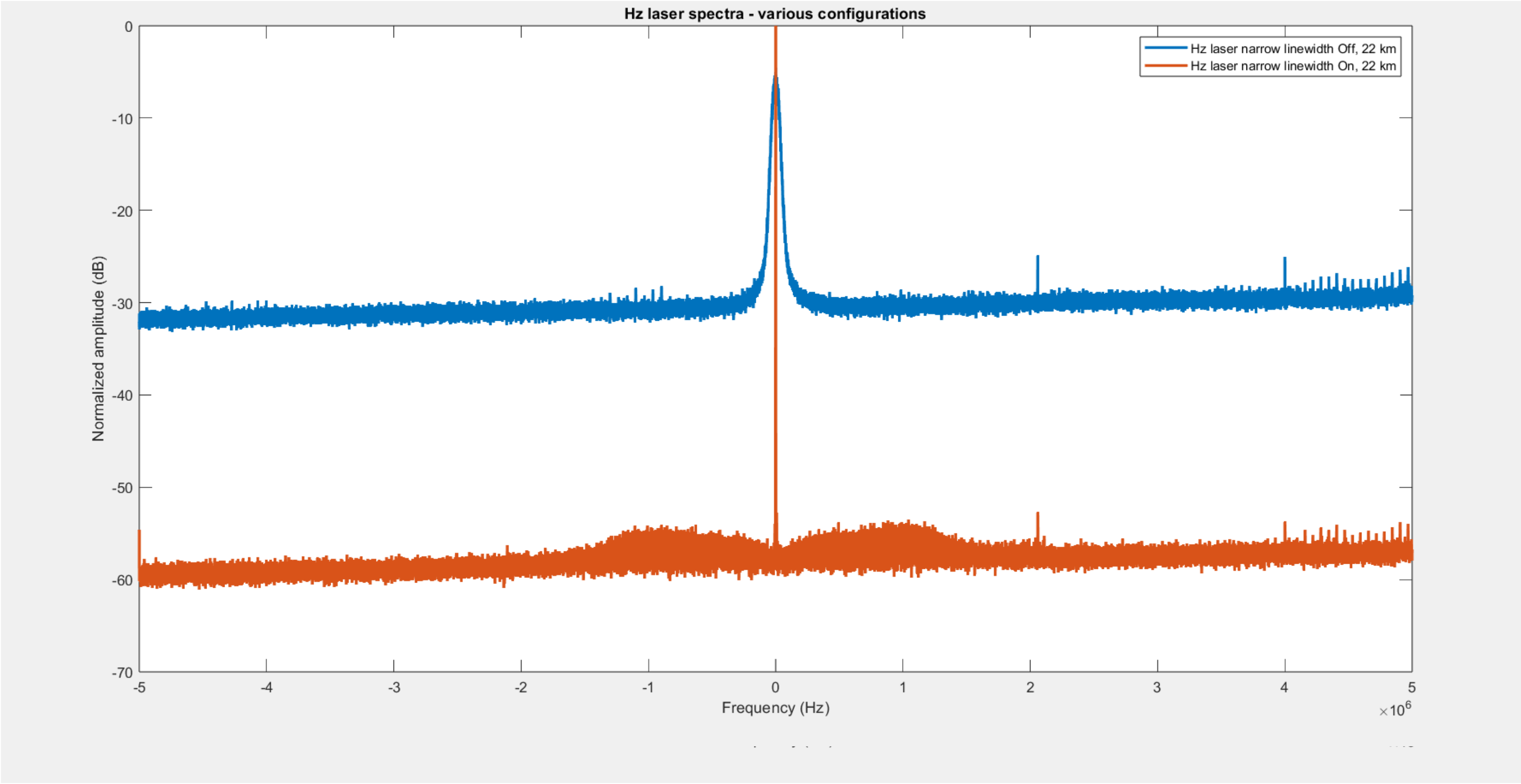
- *What (is an Ultra-stable Laser)?*
- *How (to build an Ultra-stable Laser)?*
- *Why (to build an Ultra-stable Laser)?*

ULTRA-STABLE LASER

- Laser with very low frequency noise.

- Commercial lasers Mode-locked/Feedback Ultra-stable lasers

Commercial lasers	Mode-locked/Feedback	Ultra-stable lasers	
MHz linewidth	kHz linewidth	**sub-Hz linewidth**	- Output freq. spectrum



ULTRA-STABLE LASER

- Frequency noise can arise from:

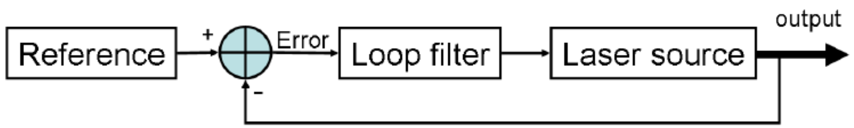
Temporal fluctuations of the optical pump power/current

Refractive index

Length changes due to temp. fluctuations

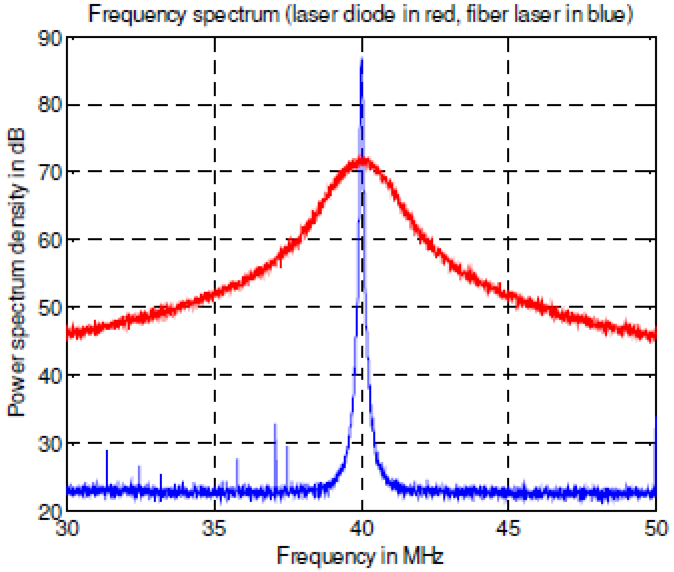
Mechanical vibrations

- General scheme of a frequency-stabilised laser:

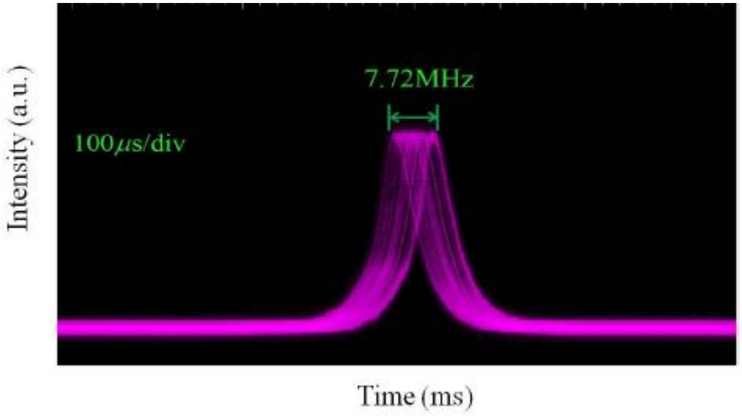


Fabry-Perot cavity!

Linewidth broadening

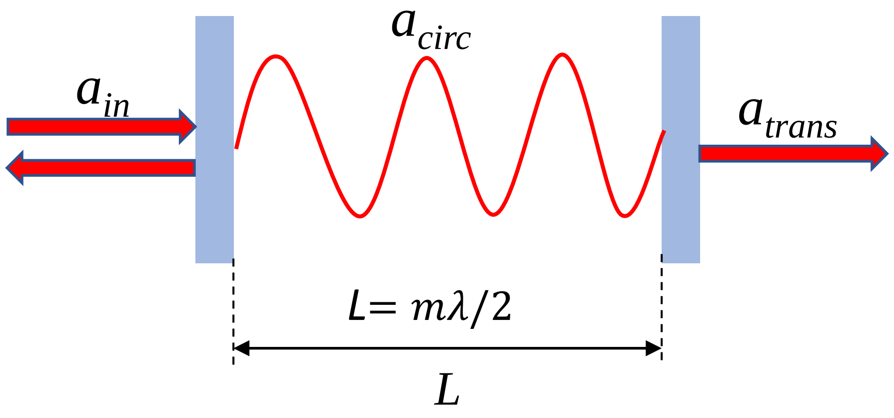


Inherent linewidth

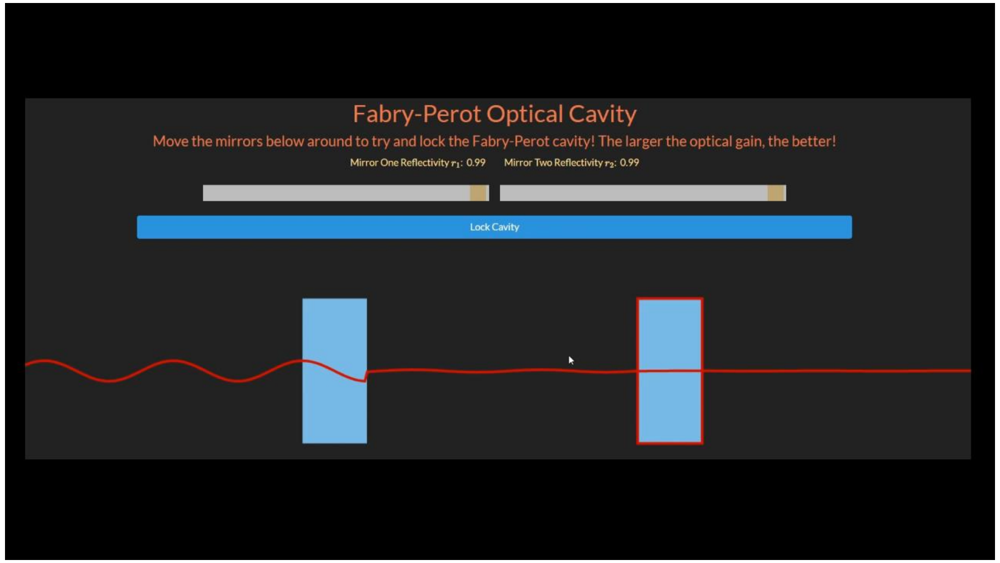


Frequency drift

Fabry-Perot Cavity



(Standing waves in a FP cavity)

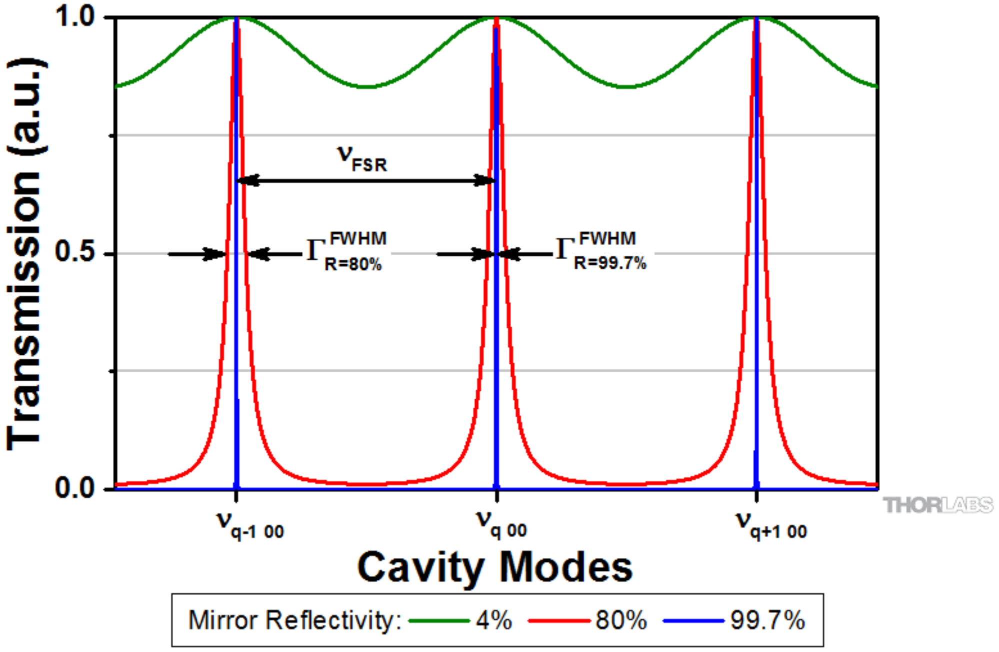


Resonance condition:

$$\nu = m \frac{c}{2nL}$$

$$\frac{\Delta L}{L} = \frac{-\Delta \nu}{\nu}$$

Frequency stability

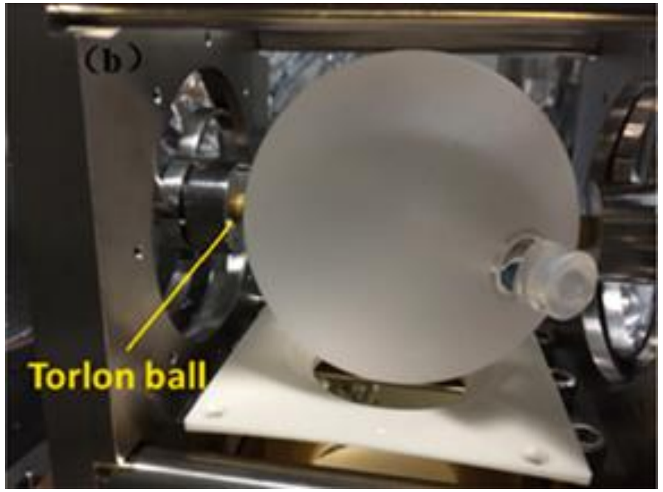


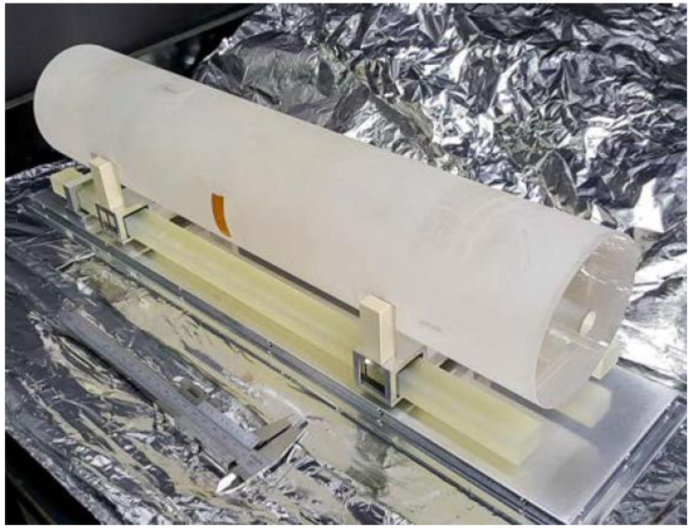
(Mode spectrum of FP cavity. Source: Thorlabs)

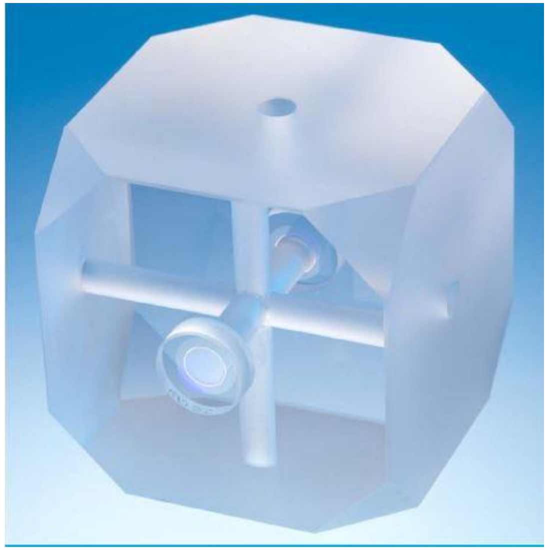
Key Parameters of FP cavity:

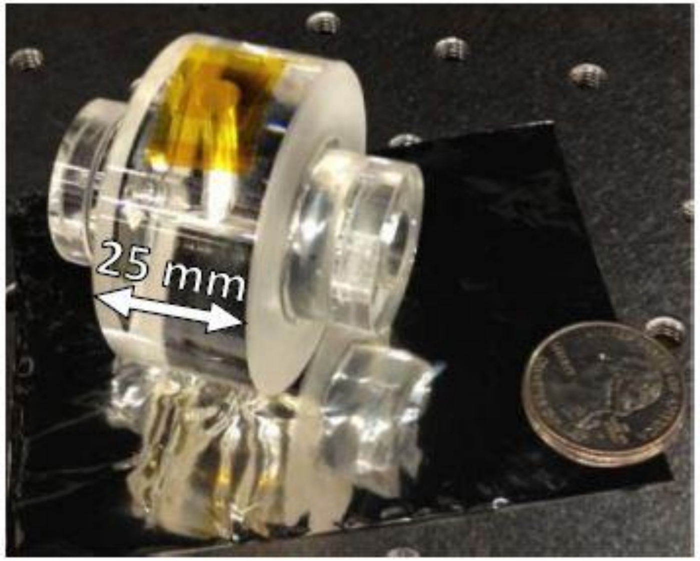
1. FSR = $\frac{c}{2nL}$
2. Finesse, $\mathscr{F} = \frac{\pi\sqrt{R}}{(1-R)}$
3. Linewidth = $\frac{FSR}{\mathscr{F}}$

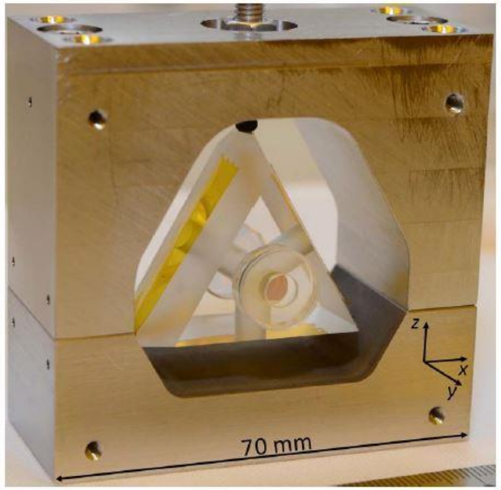
Fabry-Perot cavities….

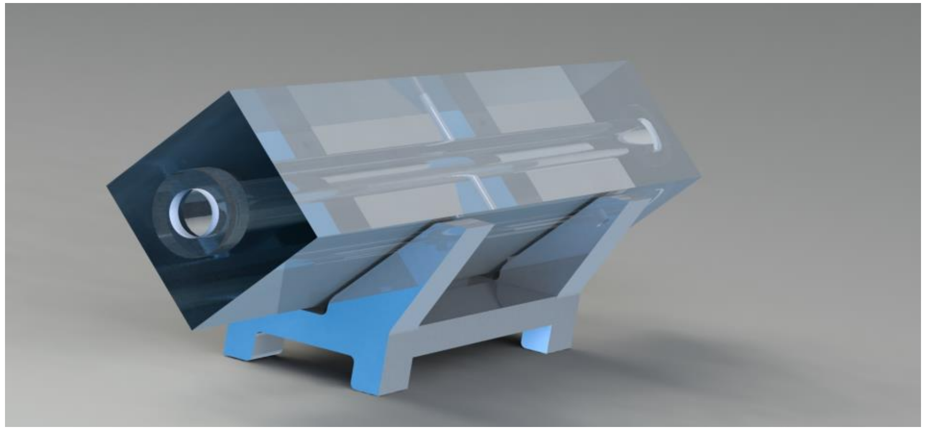












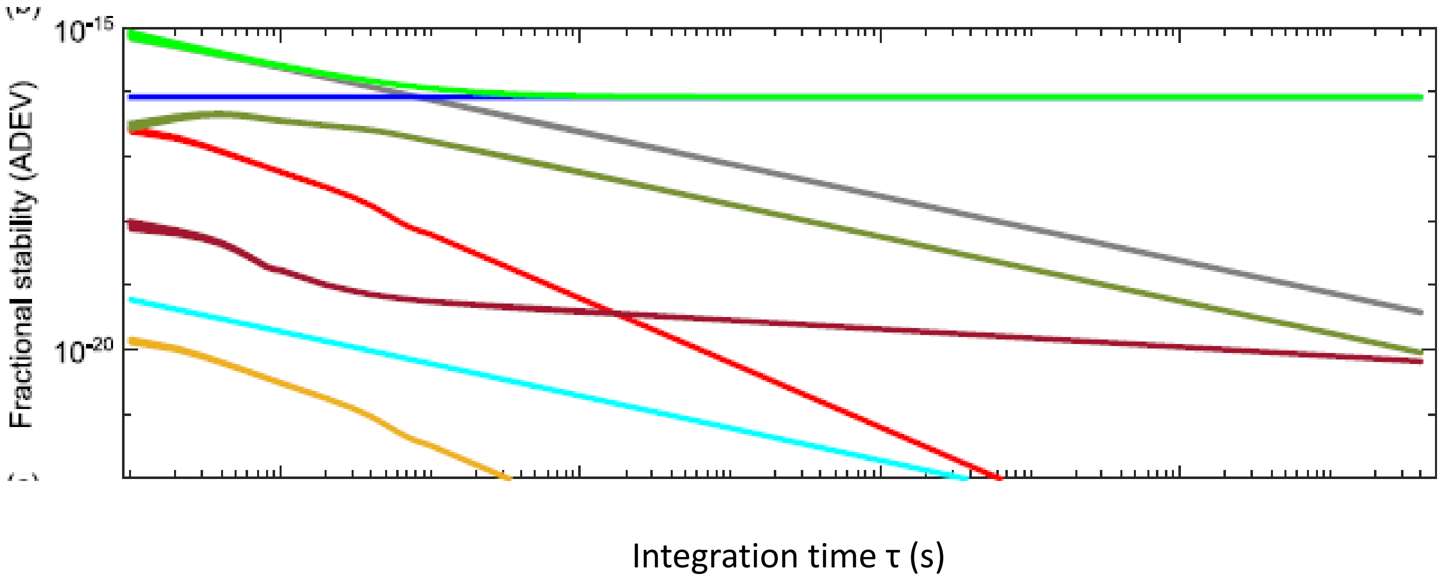
Cavities come in different shapes and sizes….

Instabilities in a laser locked to a cavity:

- Sources of noise:

Grey -	1. Thermal fluctuations	Cause fluctuations in cavity length
Red -	2. Mechanical vibrations	
	3. Pressure fluctuations	
Olive green -	4. Electronic hardware noise/PDH loop	
Cyan -	5. Radiation pressure	
Blue -	6. Brownian noise limit	

- LIMITATIONS!



Ref: Banerjee, S. et. al. (2023)

Thermal instability in a cavity

- Temperature fluctuations expand/contract materials → ΔL

- Selection of material with minimum thermal expansion coefficient

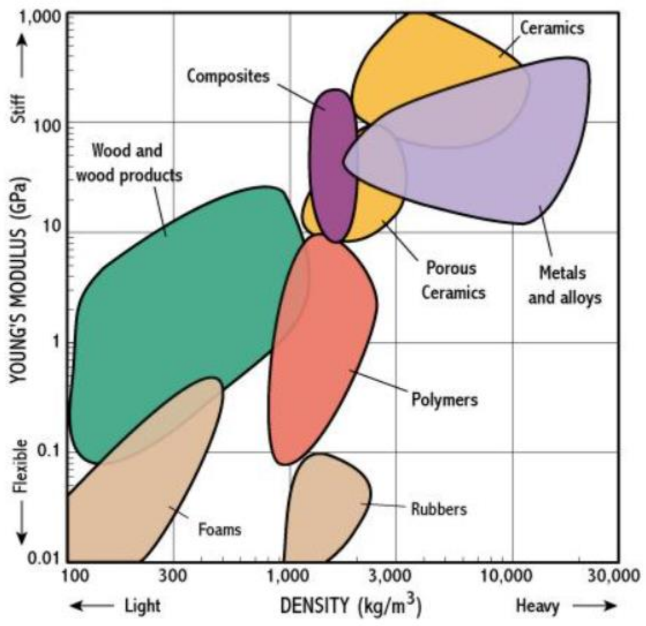
  (High mechanical stiffness, low creep/ageing)

  \- **CERAMICS!**

- Generally, longer cavities are better for thermal stabilization.

- **Brownian noise of materials & limit!**

  (Spacer, mirror substrate, mirror coatings)



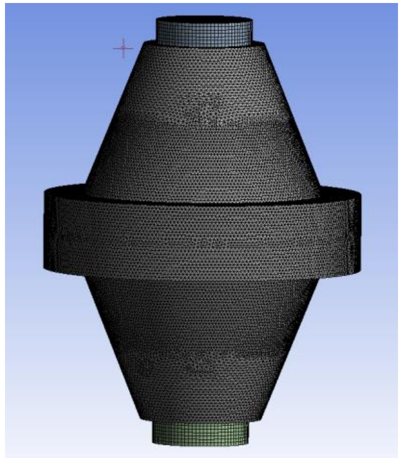
(Mech. Props in Physics & Design, Uni of Cambridge)

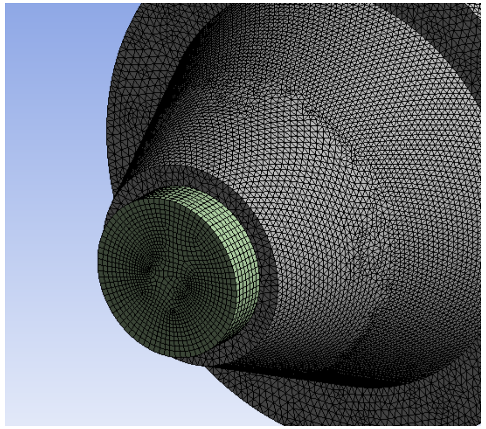
FINITE ELEMENT ANALYSIS (FEA)

- A computational method for approximate solutions
- Used for verifying designs, checking functionality, optimising components etc.

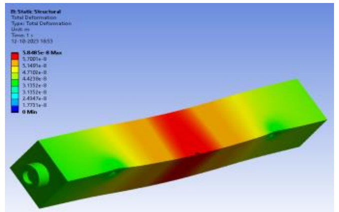
- 3 main types of analysis:

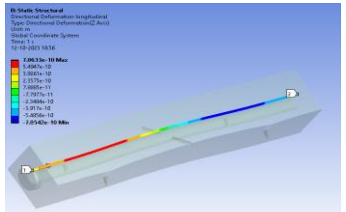
1. Static analysis **2. Dynamic analysis** **3. Modal analysis**

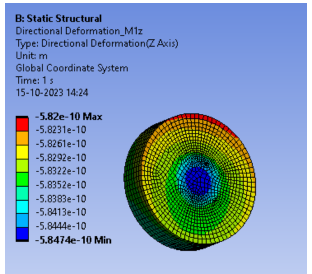


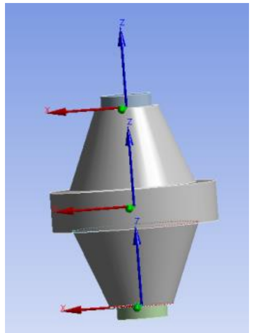


(Fig. Meshing on a conical cavity)









Define the problem
(eg. Finding stress/strain)

DISCRETIZATION/
Meshing

Define Element Stiffness Matrices

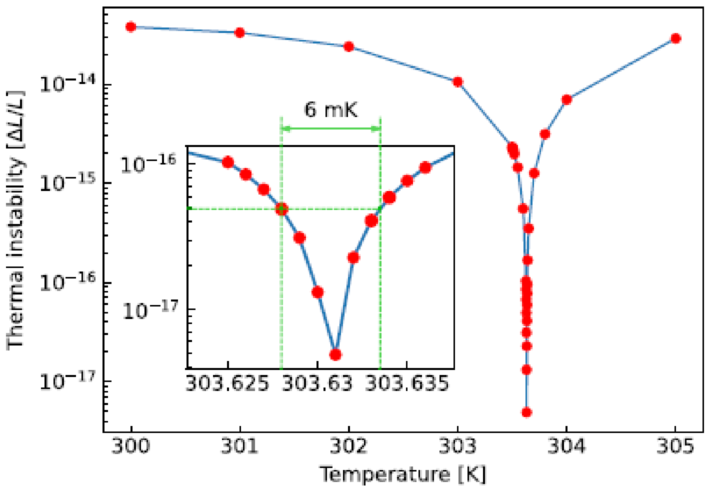
$$\{f\} = [k]\,\{u\}$$

Combining all element relations
=> Global Stiffness Matrix

SOLVE

Thermal instability in a cavity

- Room-temperature cavities: **Determine optimum temp for operation**



Effective coefficient of thermal expansion ×10⁻⁹/K, rate of change of cavity mode frequency with temperature ($\Delta\nu/\Delta T$) kHz/mK, and fractional frequency instability due to Brownian noise ×10⁻¹⁶ (at 1 Hz) for different combinations of spacer and mirror materials, respectively.

Mirror \ Spacer annuli	ULE	Fused Silica	Zerodur	Sapphire	Clearceram-Z
ULE	0.3 −0.06 0.94	487 −94.23 0.93	19.5 −3.77 1.1	5362 −1034.5 0.93	19.5 −3.77 1.1
Fused Silica	12.9 −2.49 0.45	500 −96.75 0.43	32.07 −6.2 0.73	5374 −1036.8 0.43	32.07 −6.21 0.74
Zerodur	0.8 −0.15 3.21	487.93 −94.41 3.21	20 −3.9 3.26	5362 −1034.5 3.21	20 −3.87 3.26
Sapphire	0.14 −26.7 0.21	625.69 −121.06 0.15	157.7 −30.52 0.61	5500 −1061 0.14	157.7 −30.52 0.62
Clearceram-Z	0.8 −0.15 3.2	487.93 −94.41 3.23	20 −3.9 3.29	5362 −1034.5 3.23	20 −3.9 3.29

Sitall [58] exhibits the same properties as Zerodur.

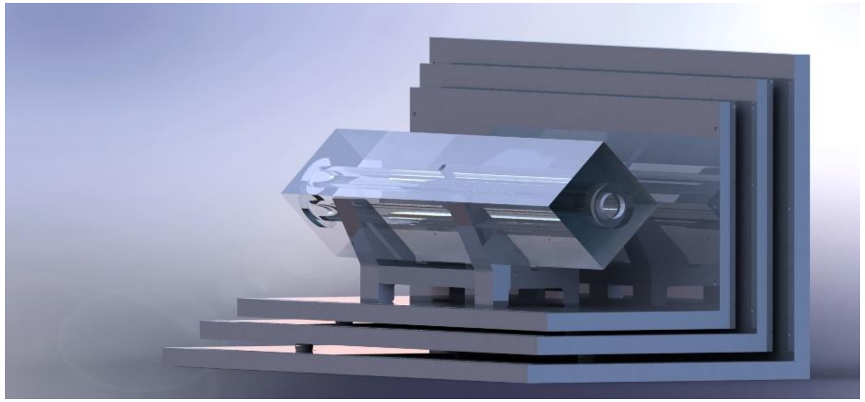
Thermal CTE minima

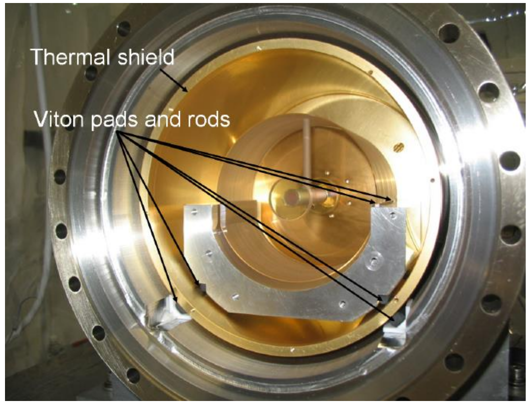
Ref: Banerjee, S. et. al. (2023)

- **Thermal shield design:**

  Low thermal conductivity

  Low emissivity





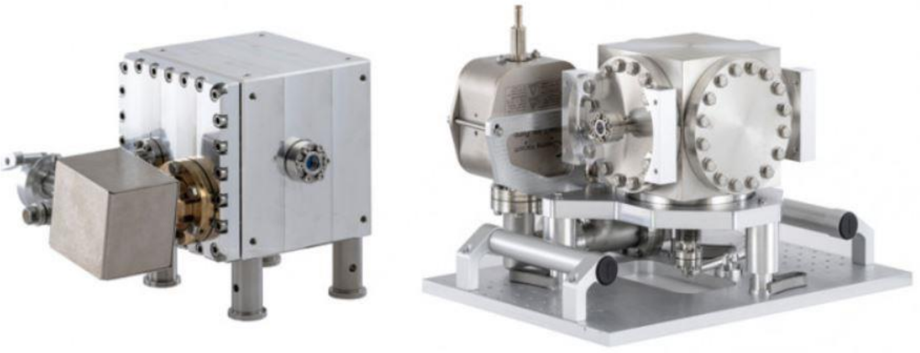
D. Alvarez et. Al (2018)

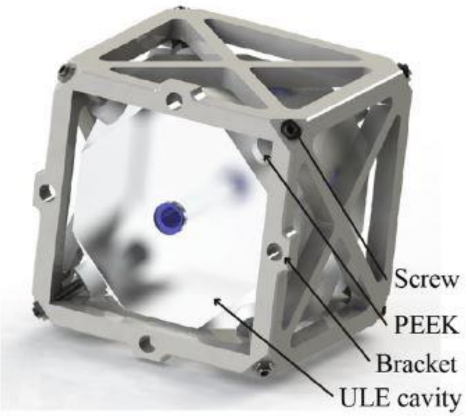
Transportable FP Cavity

A transportable cavity is characterised by its stable & robust mounting, which allows it to maintain its integrity during the course of transport, and achieve the same stability before and after transport.

Requirements (Qualitatively):

1. **The cavity needs to be compact, with robust mounting**
2. **Motion constrained in all directions (translational and rotational)**
3. **Sustain Acceleration & Vibrations during transport.**
4. **Minimum deformation due to support/compressive forces.**

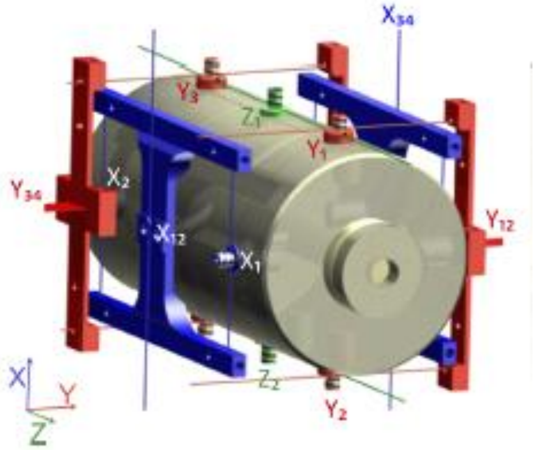




(a)

Cubical cavity (UCAS, China)

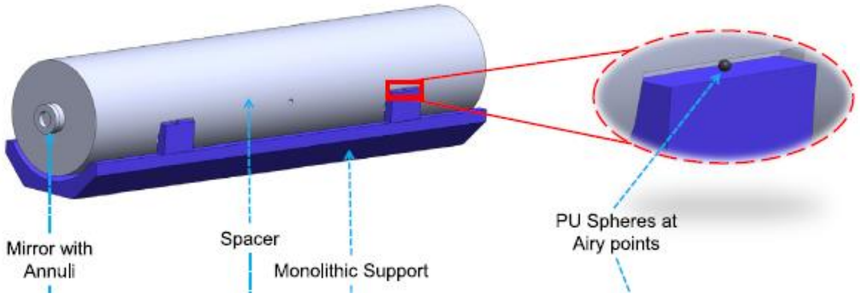
10^{-16}	10^{-14} - 10^{-15}	10^{-17} - 10^{-18}
• Ultra-stable lasers outside laboratory • Long term stability cavities for fundamental physics	• Space-based applications • GPS & Navigation	• Best Optical Clocks • Next gen GW detectors/DM Hunt

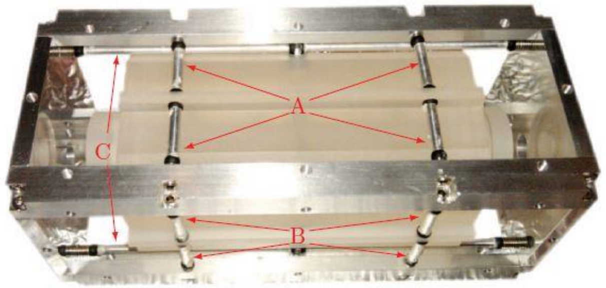


Cylindrical cavity with mounting (PTB, Germany)

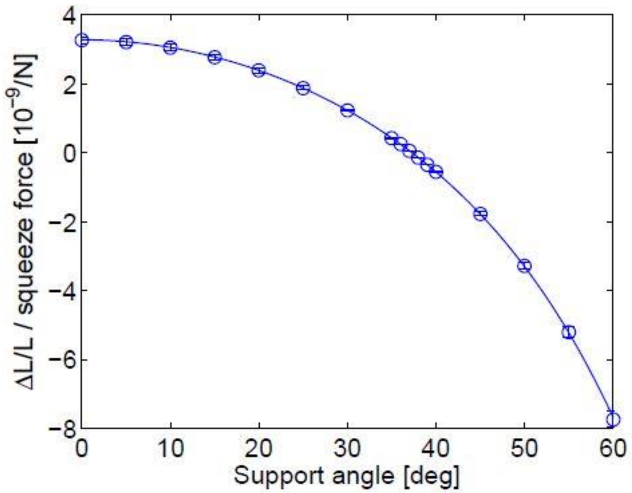
Vibrational stability:

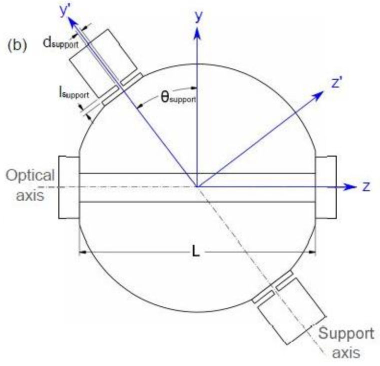
- Seismic vibrations from ground travel through components causing length fluctuations – dynamic change (Random vibrations)
- Soft mounting vs Rigid mounting

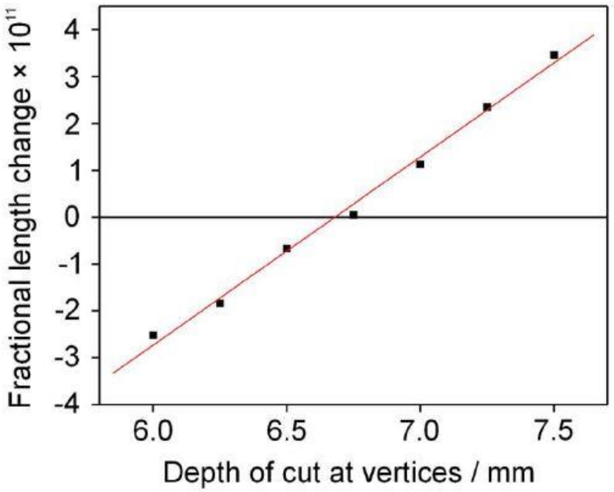


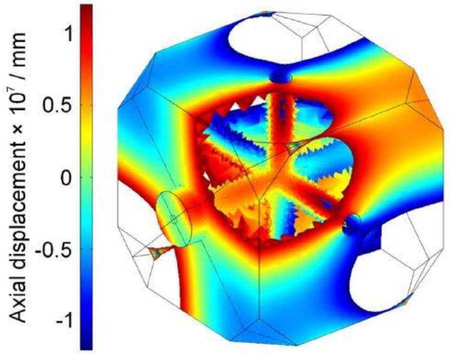


- Zero-crossing in deformation due to mounting forces:



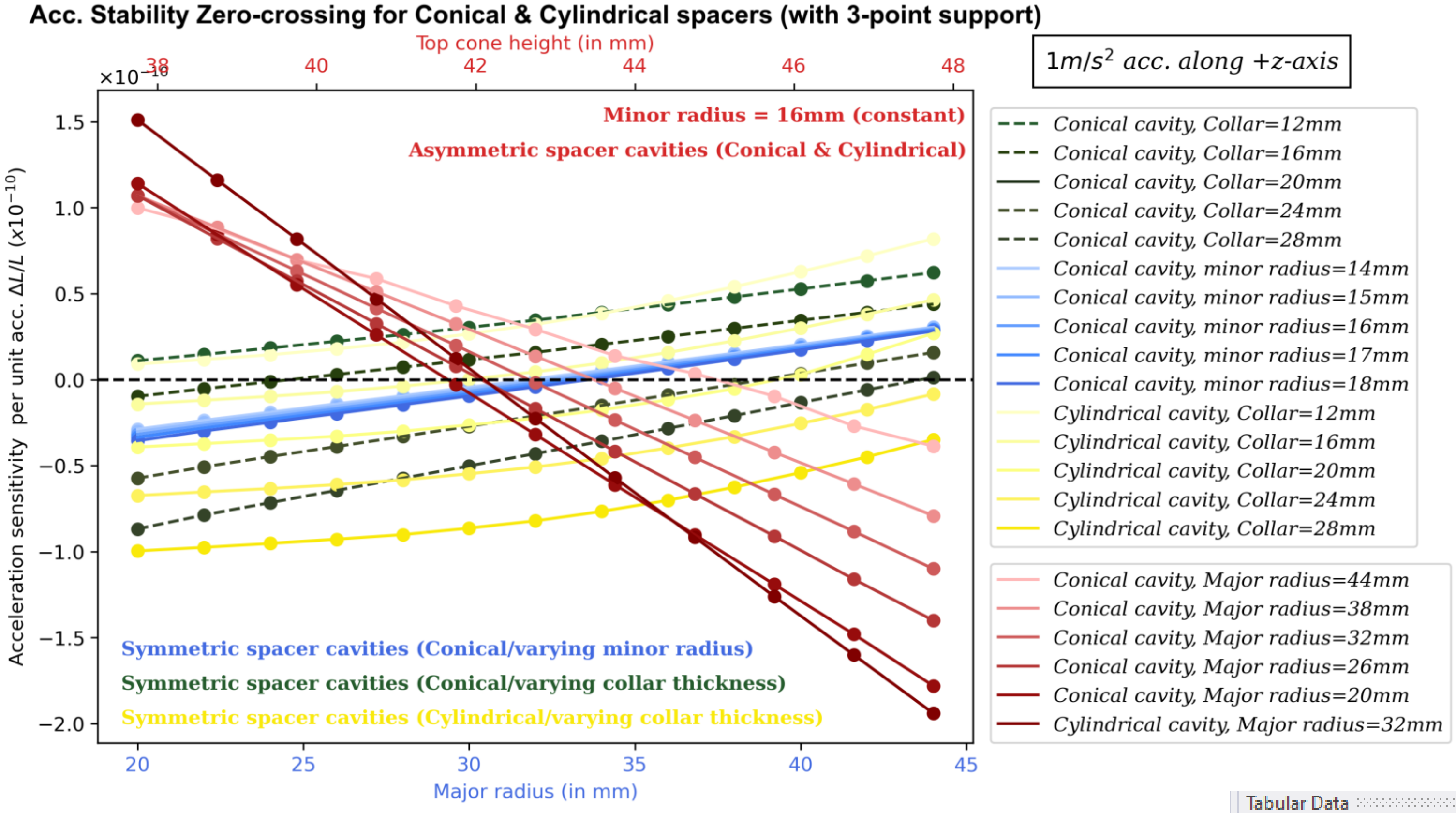




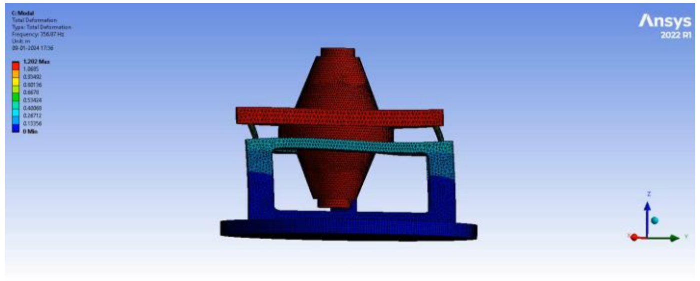


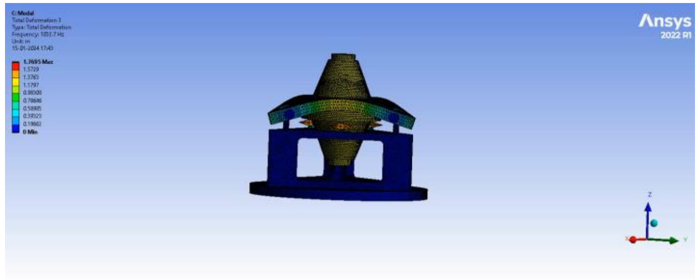
Vibrational stability:

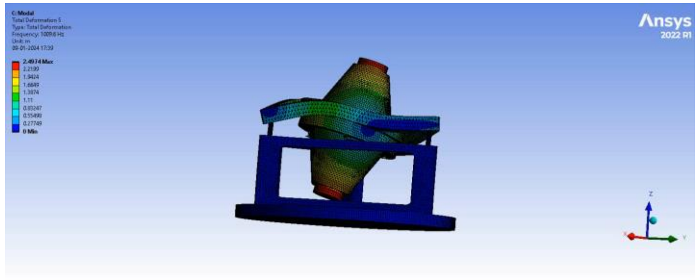
Dimension optimisation



Increasing natural resonance modes



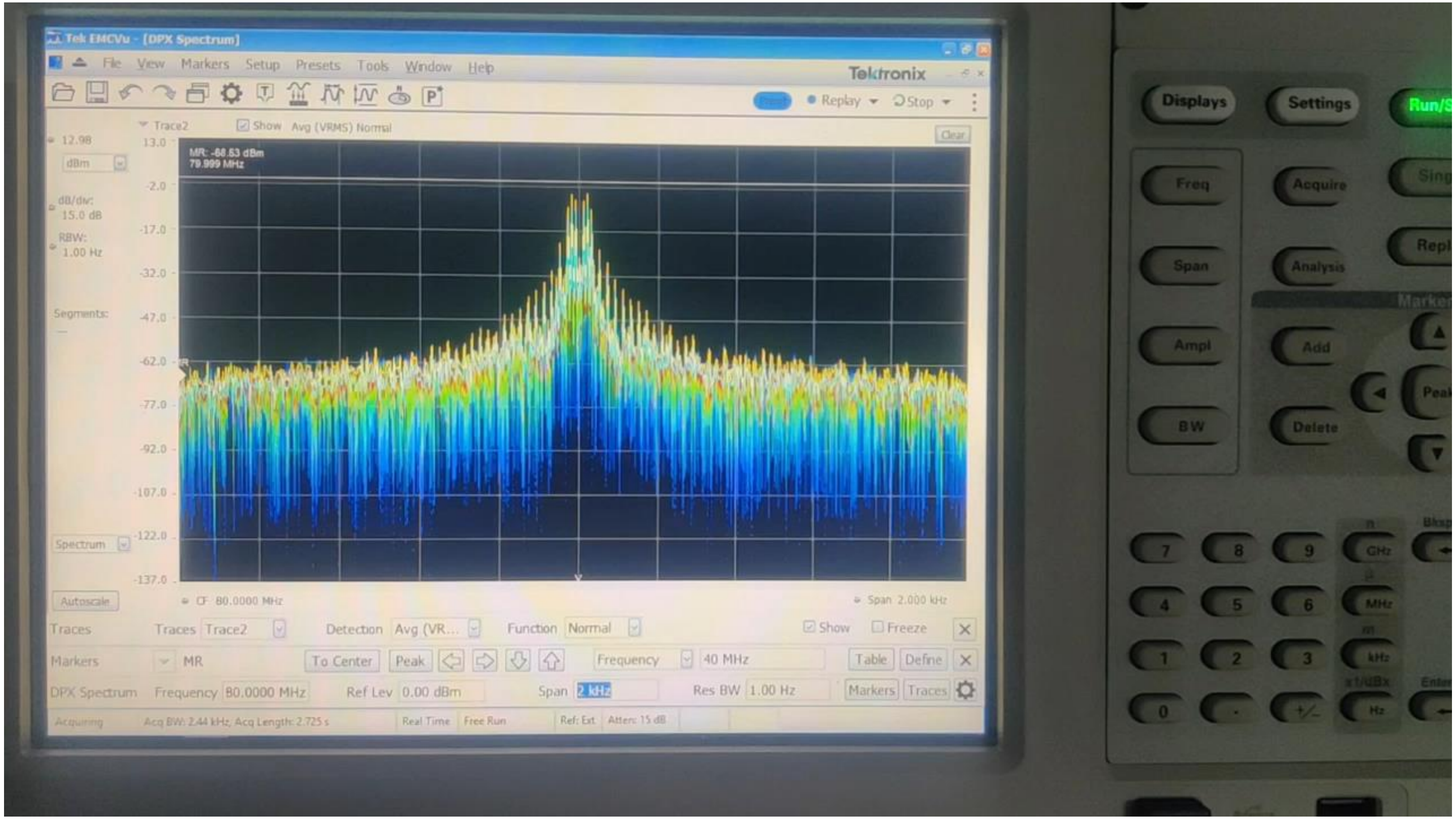




Tabular Data

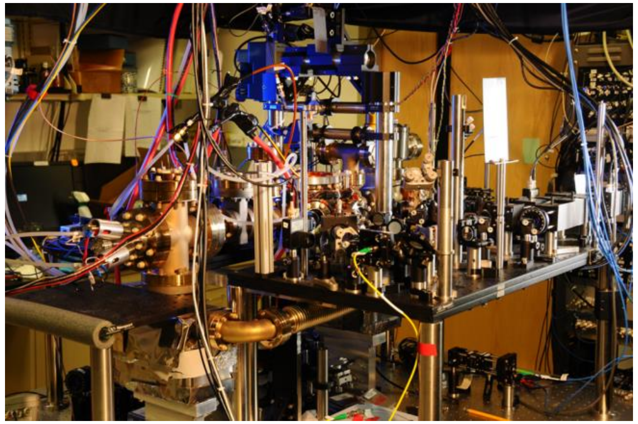
	Mode	Frequency [Hz]
1	1.	349.1
2	2.	349.35
3	3.	694.27
4	4.	777.28
5	5.	1204.5
6	6.	1204.6
7	7.	2021.2

Locking laser to cavity → Ultra-stable Laser!

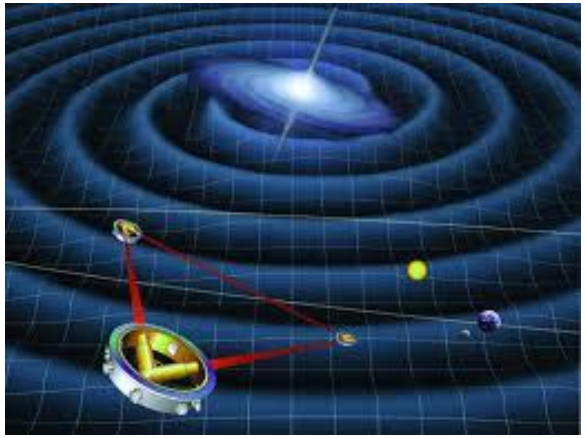


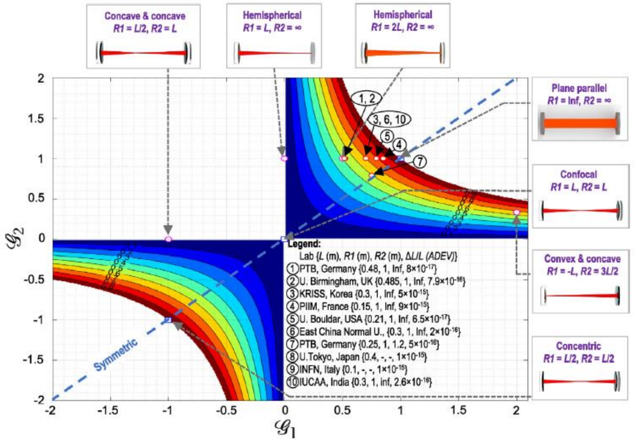
Credits:
Dr. Stanley Johnson
Post Doctoral Fellow
@ PQM Lab, IUCAA

"So what?"……
What can be achieved once you obtain an Ultra-stable Laser?



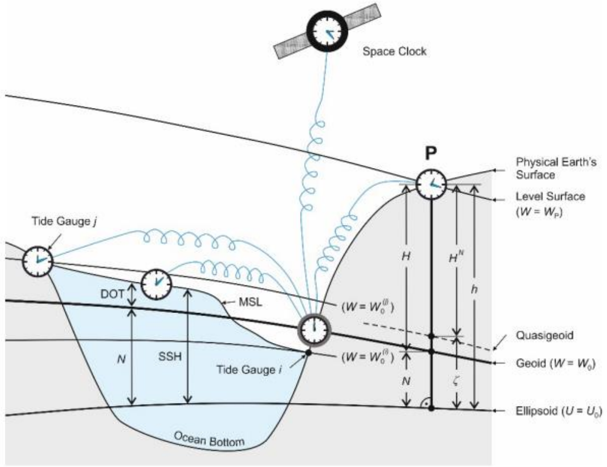
Optical clocks

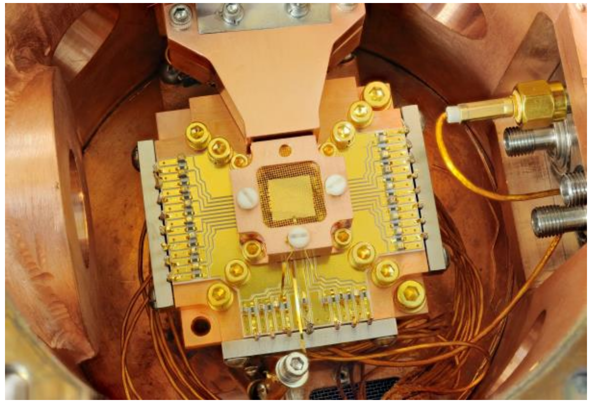




Next-gen GW Detectors – LISA & NUC based interferometers

Geodesic measurements





Trapped ion qubits

THANK YOU…..

Safe to say we have traversed from Lagrangians to LASERS!......