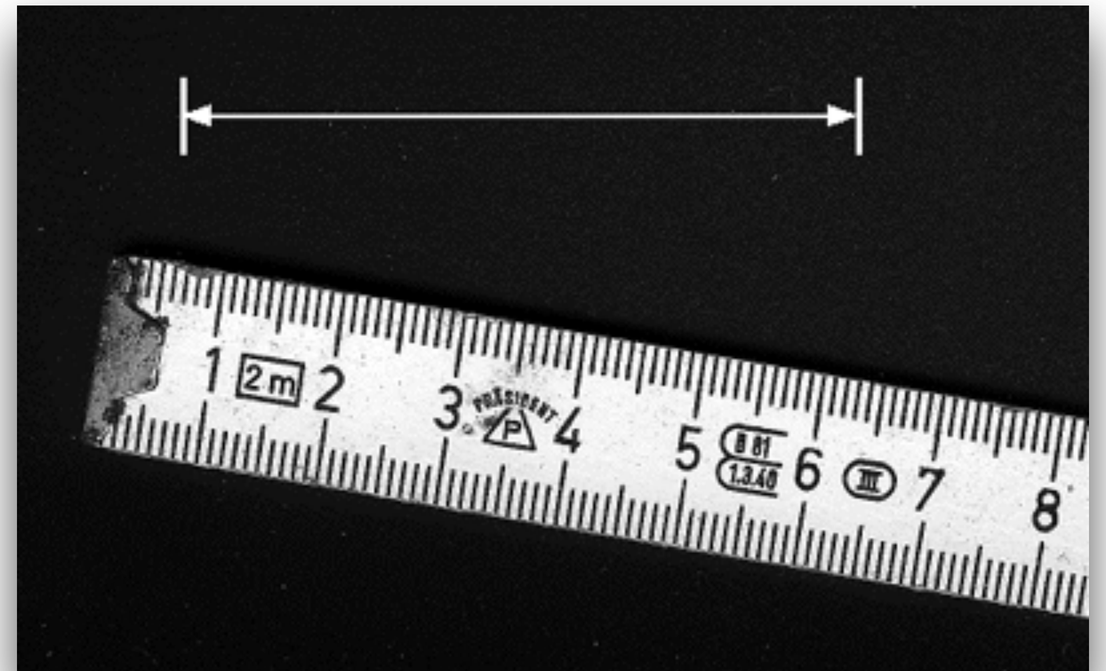
Ring Lasers for Geodesy and Seismology

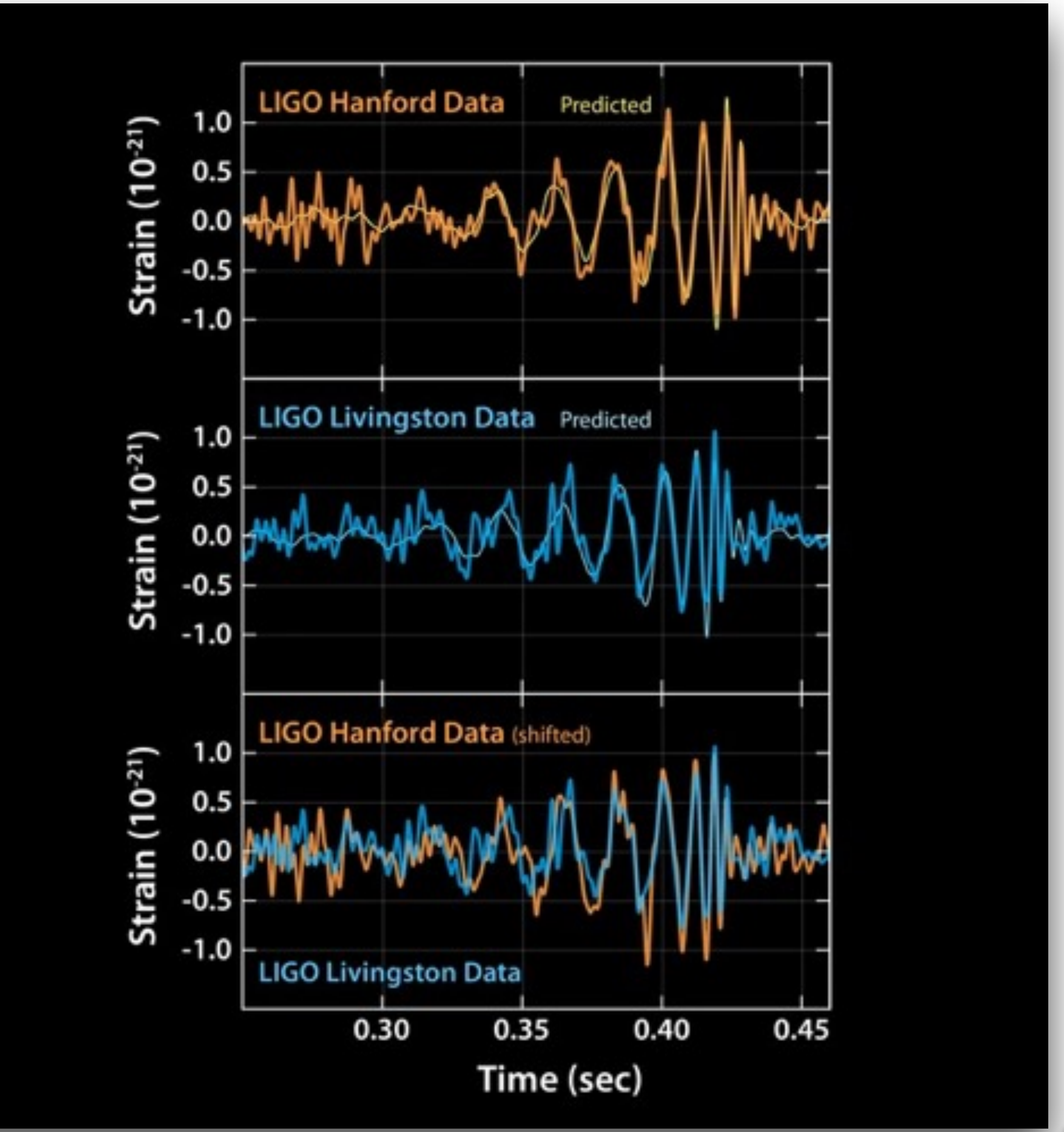
U. Schreiber, A. Gebauer, J.P. Wells, R. Hurst, H. Igel, J. Wassermann...

In geodesy we are very good at measuring distances

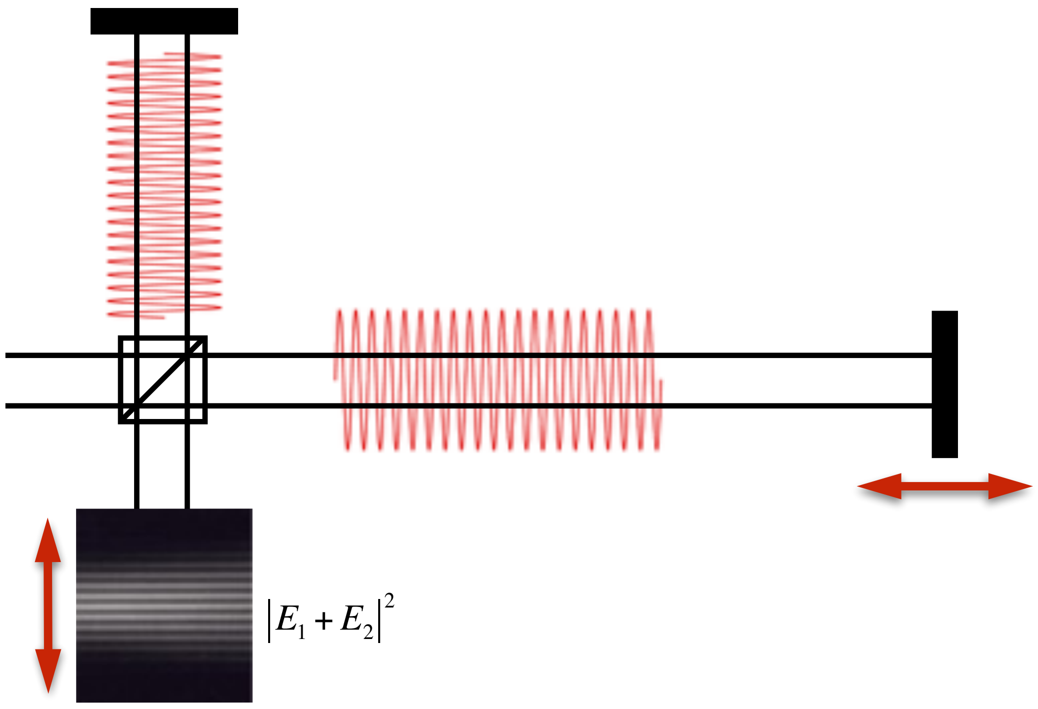


SLR

even from ground to space



https://www.ligo.caltech.edu/image/ligo20160211a

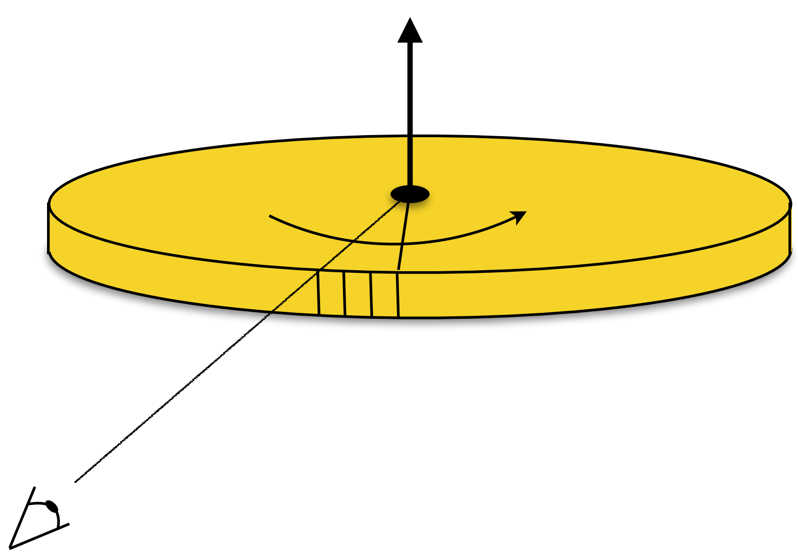


Interferometry with Light provides outstanding sensor resolution for the measurement of displacement…

…the latest example is the phenomenal achievement of detecting gravitational waves at strains of 10^{-21}.

How about applying the same concept for the measurement of rotation?

Rotation Sensing is much more difficult



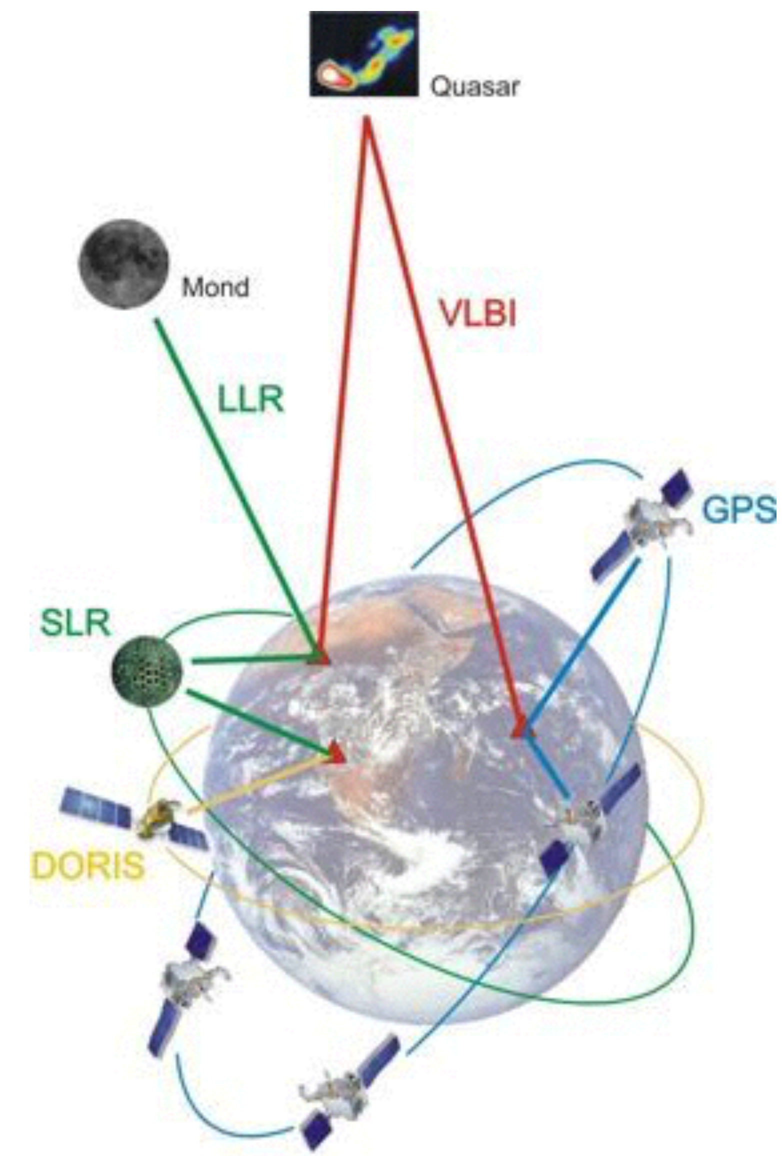
We sit on a rotating globe and don't really notice it...
... unless we are mapping star positions

Space Geodesy has a great interest in (Earth) rotation

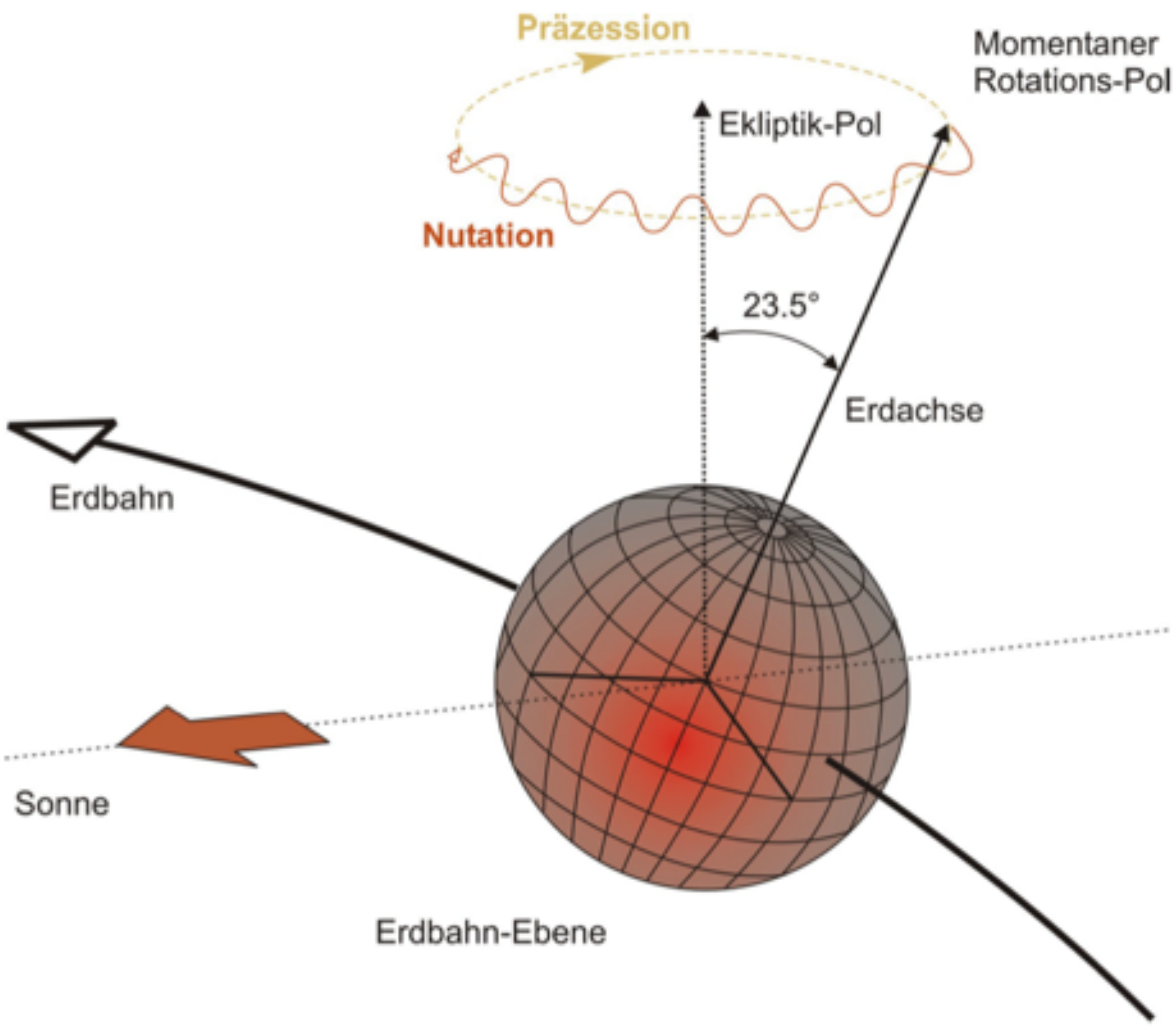
Navigation (GNSS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) have one thing in common:

The measurement objects are defined in a celestial frame of reference, while the sensors are located on the Earth.

In order to relate any two points on the Earth with an accuracy of less than 1 cm in position, 9 orders of magnitude in sensor resolution are required.



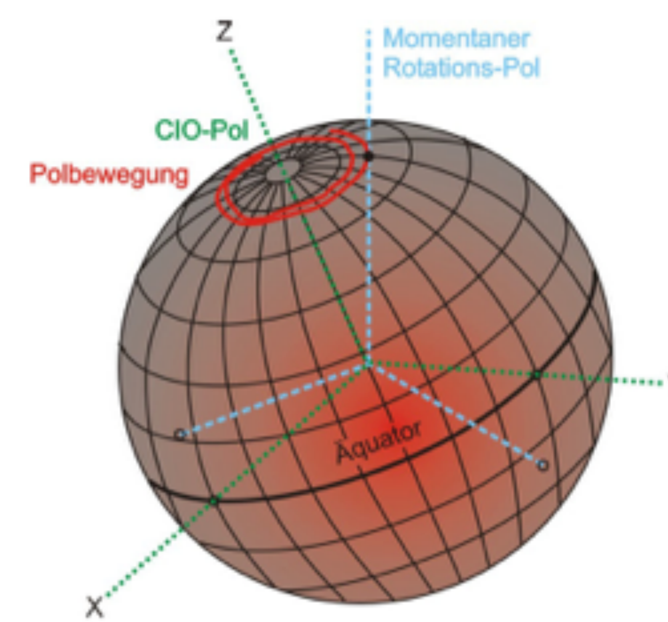
Earth rotation is the link between reference frames



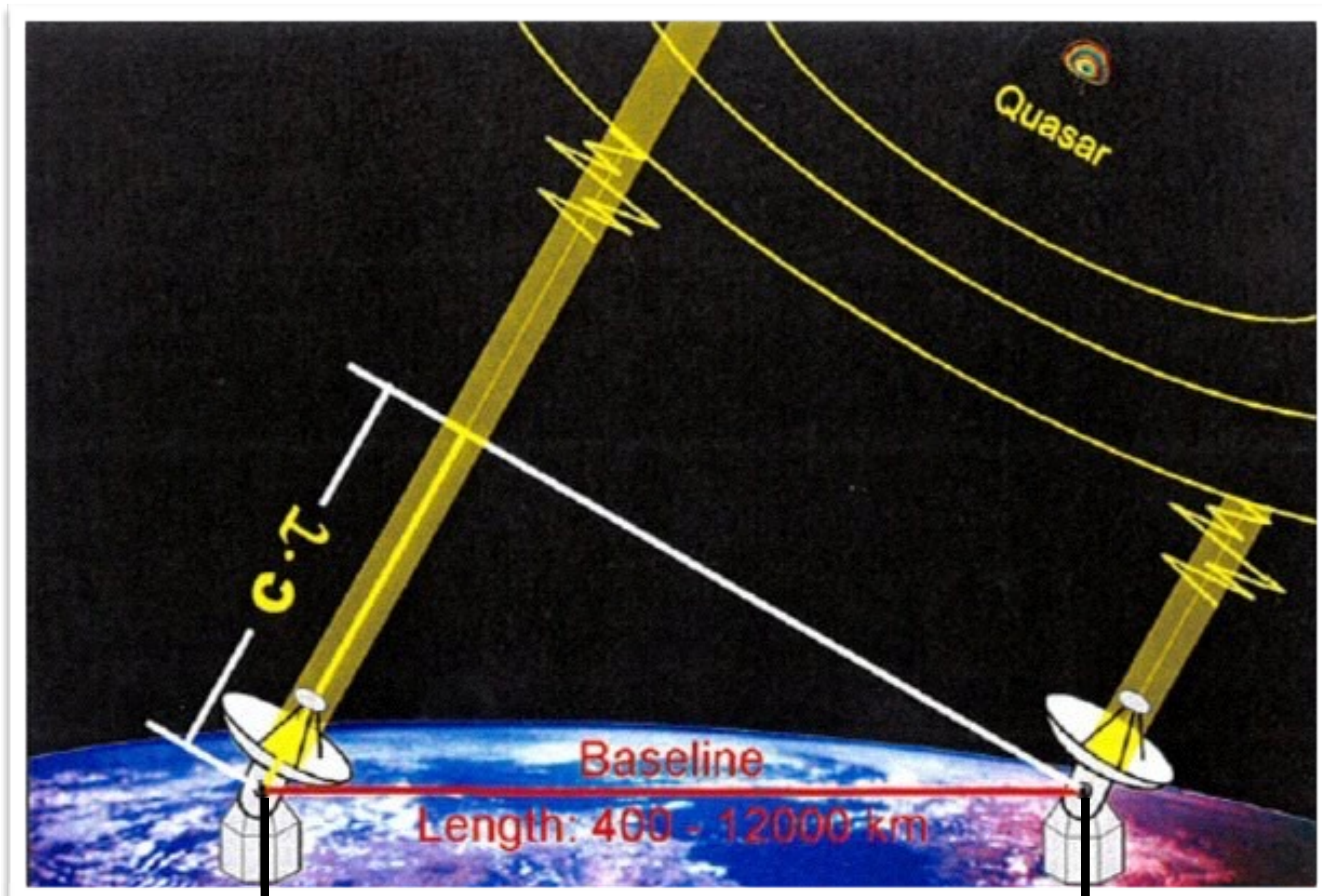
a) the rotation rate of the Earth is not constant. Deceleration by dissipation and variation by momentum exchange. Free oscillations excited by ocean, atmosphere

b) gravitational attraction of sun and moon on a near spherical object give rise to precession and nutation

c) mass redistribution on Earth and the fact that the figure axis and the axis of inertia are not coinciding, give rise to polar motion



Very Long Baseline Interferometry



http://www.mpifr-bonn.mpg.de/technologie/vlbi

LO — DAQ

DAQ — LO

Correlator

LoD:
≈ 100 μs

Orientation:
10 - 100 μas

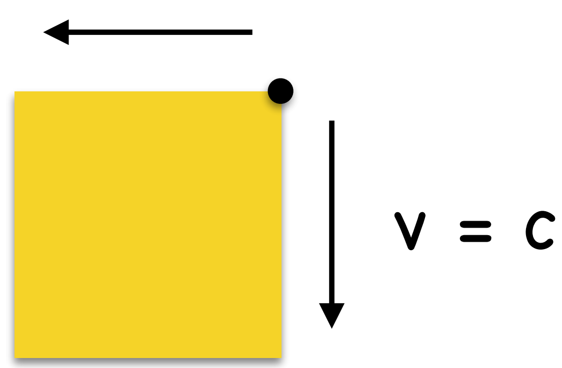
Practical ways for highly sensitive Earth Rotation

- Star observations provide access to Earth rotation...
- Without external reference we could use a Foucault Pendulum or exploit the Coriolis Force...
- Drawbacks: (By far) not enough resolution
- VLBI has the necessary stability and resolution, but is based on a rather involved process (not continuous)
- Wouldn't it be nice to compact rotation sensing into a small simple instrument - making use of the power of optical interferometry?

Consider a geometrically rigid Contour

Photons: no mass, constant velocity, open to interferometry

no rotation



path length is equal
velocity is finite and equal

both signals come back to
their origin at same time

Consider a geometrically rigid Contour

Photons: no mass, constant velocity, open to interferometry

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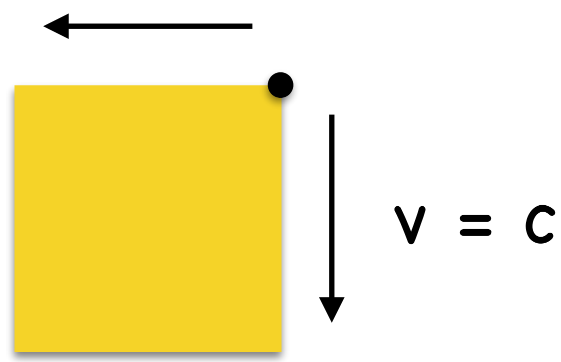
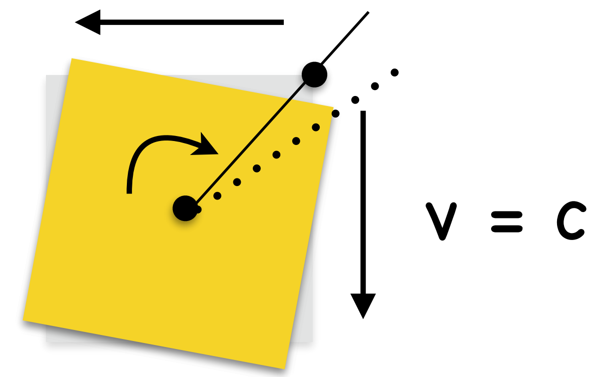


rotation

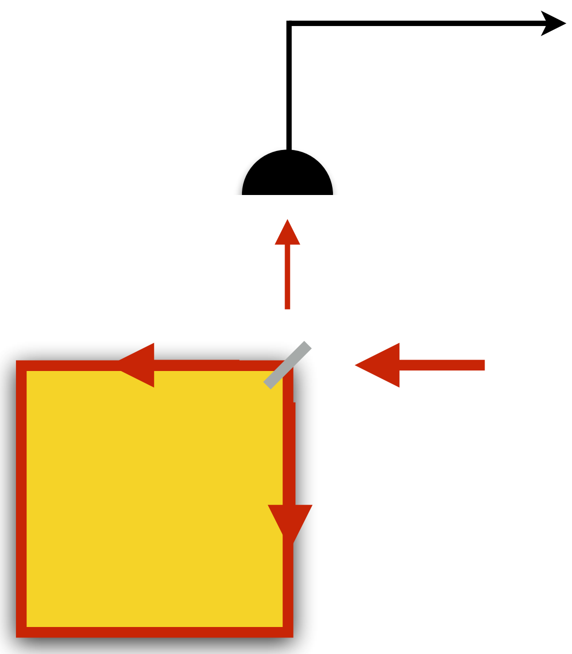


path length is equal
velocity is finite and equal

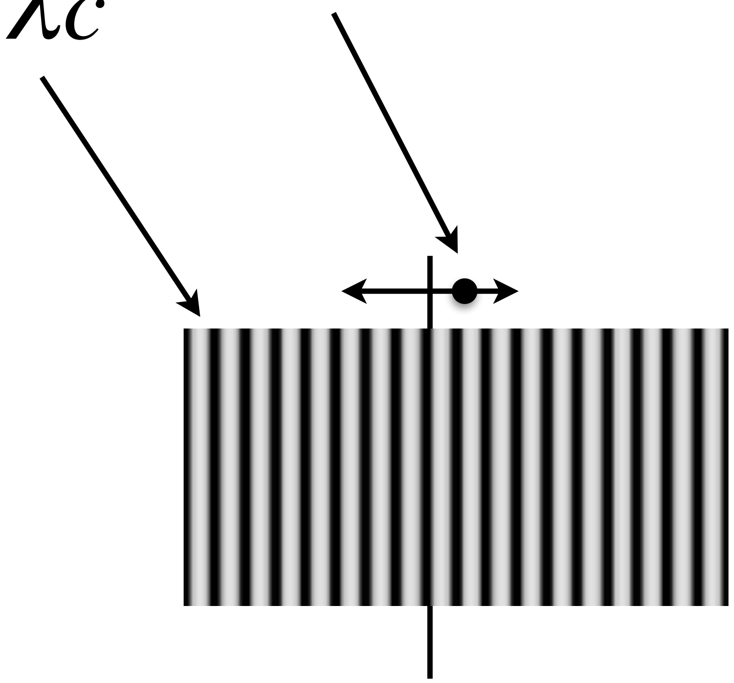
both signals come back to
their origin at same time

co-rotating path length is longer
anti-rotating path length is shorter
velocity is finite and equal

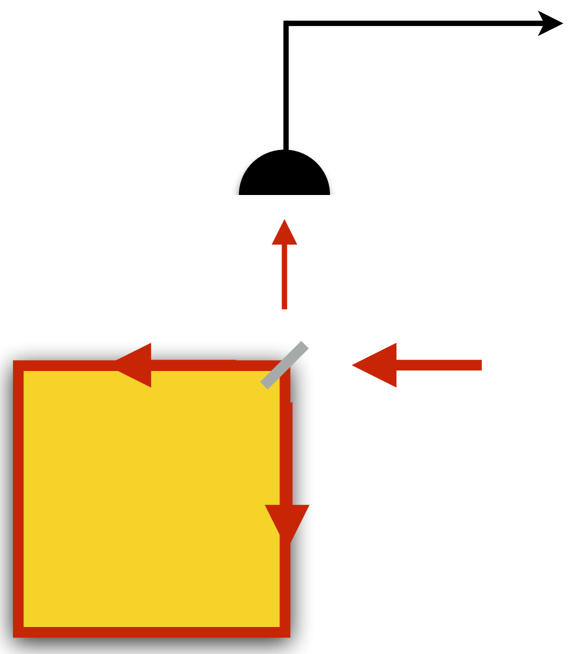
a phase difference is the result,
the phase angle is proportional to
the rate of rotation



$$\delta\phi = \frac{8\pi A}{\lambda c}\,\boldsymbol{n}\cdot\boldsymbol{\omega}$$

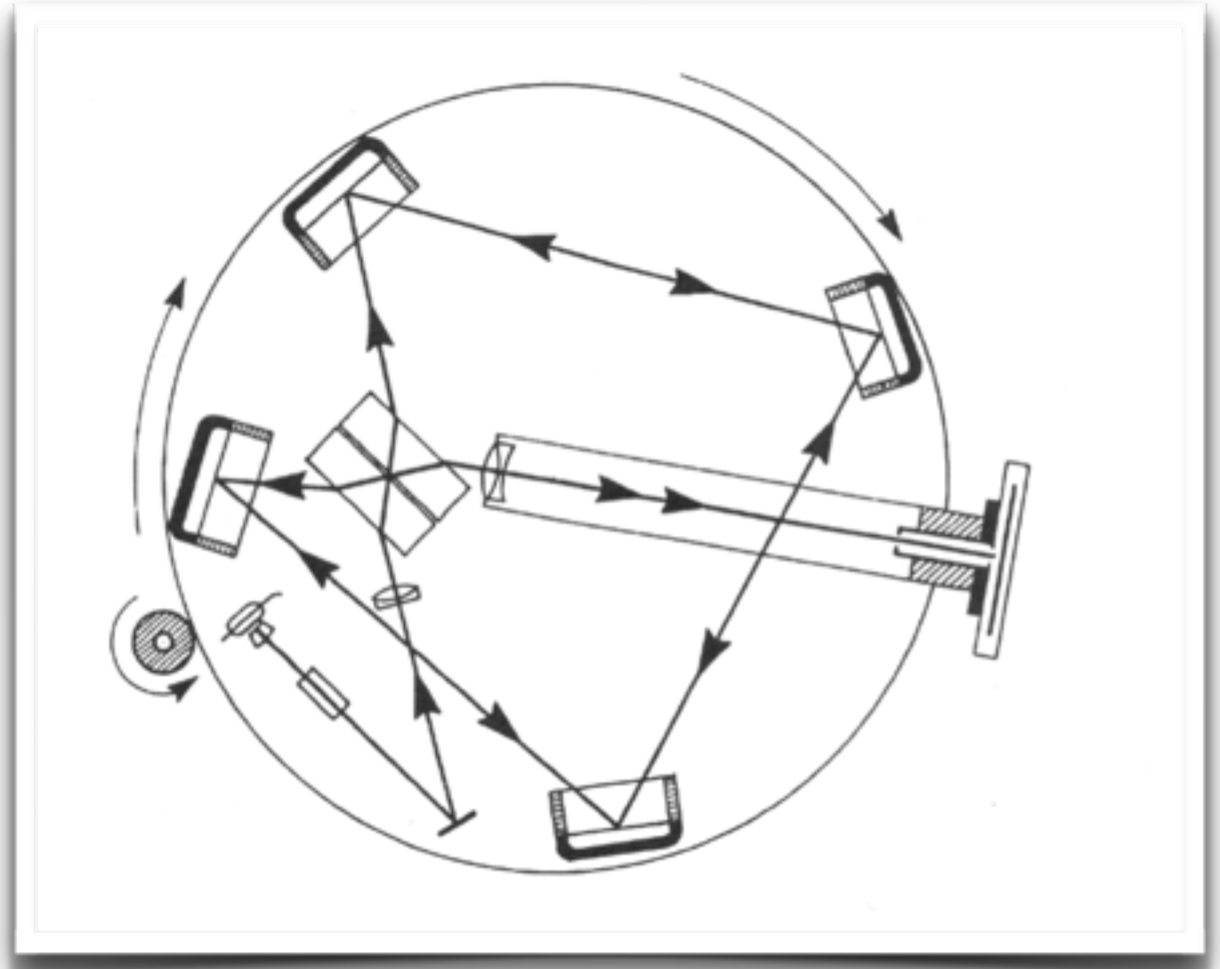


- Light from an external source is the probe: ⟶ we exploit c = const
- There are no moving parts involved
- The device is entirely insensitive to translations
- However, it is difficult to obtain high sensitivity from a small device



$$\delta\phi = \frac{8\pi A}{\lambda c}\boldsymbol{n}\cdot\boldsymbol{\omega}$$

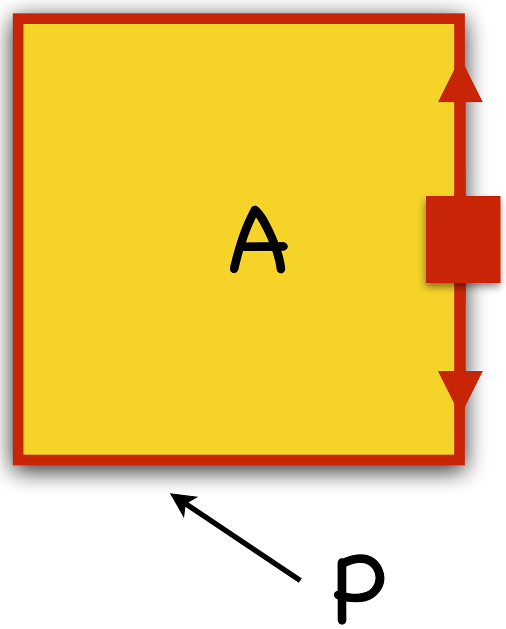
For 2 rev./s and A = 0.086 m^2 this turns out to be 0.07±0.01 fringes



Georges Sagnac was the first in 1913 to correctly combine theory with experiment.

We also acknowledge the experimental skill to build a sufficiently stable apparatus.

With the advent of the laser (1962) a massive boost of sensitivity became available



Instead of one turn around the contour, use many

Instead of an external light source make it a laser

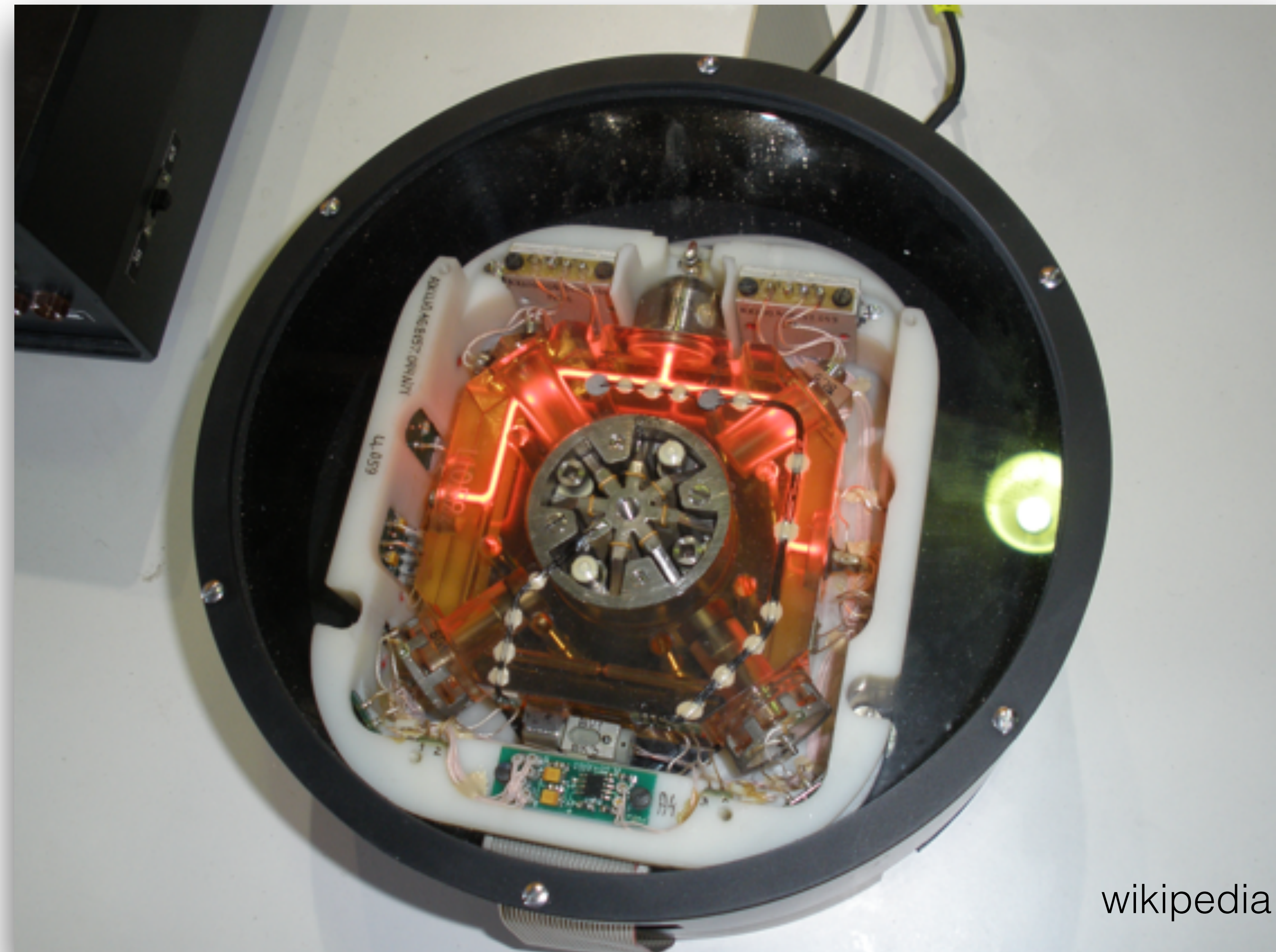
Condition for coherent amplification: $P = n\lambda$

This converts the measurement to change from phase to frequency

$$\delta f = \frac{4A}{\lambda P} \vec{n} \cdot \vec{\Omega}$$

... demonstrated by Macek and Davies, 1963

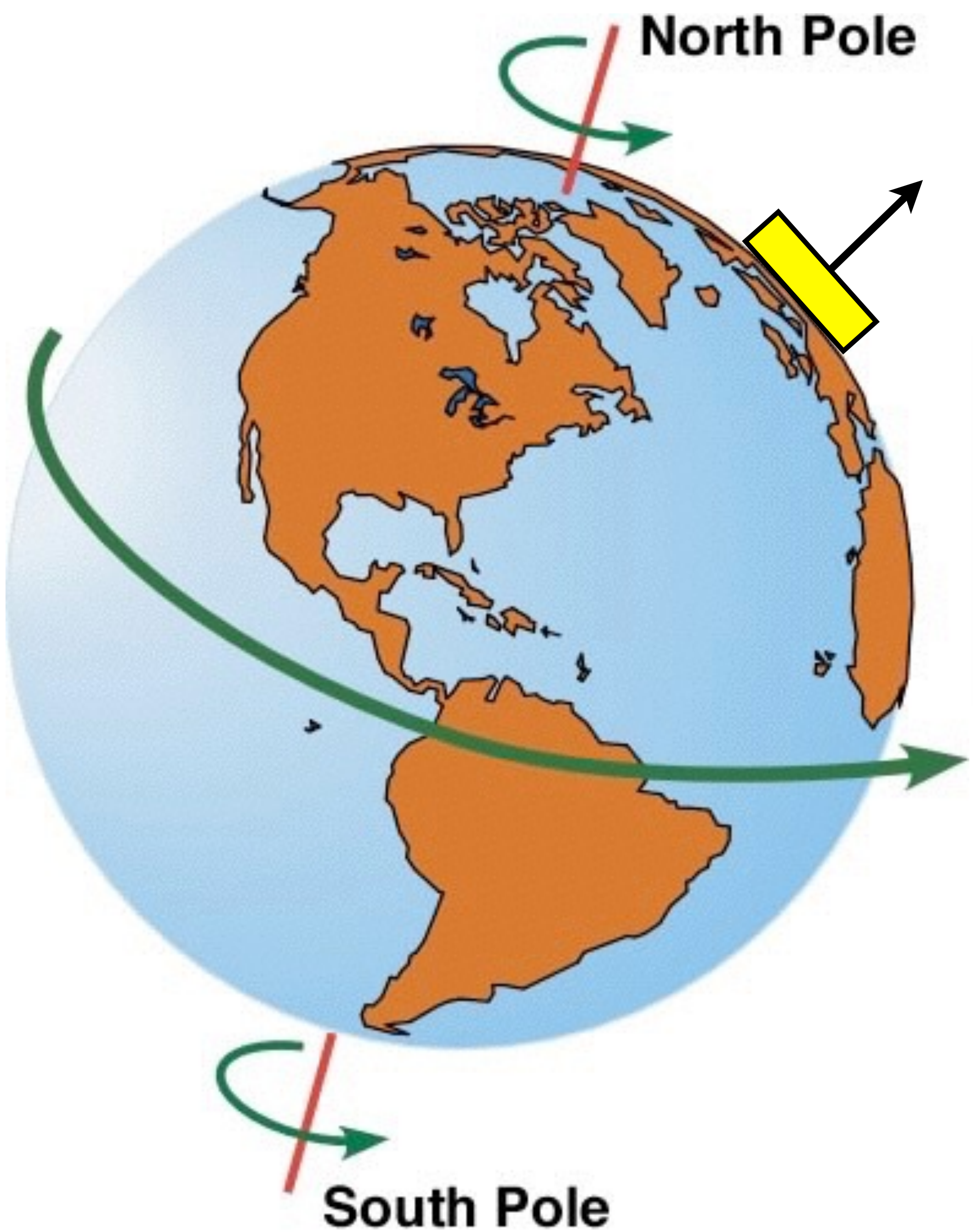
Technical Realization: The aircraft Gyro



$P \approx 40$ cm
$A \approx 0.01$ m^2

Stability ≈ 0.01 °/h - so what would we require in geodesy?

Requirements for Applications in Geodesy and Geophysics



Δ SKF $\leq 10^{-10}$

$\Delta \theta \leq 1$ n-rad

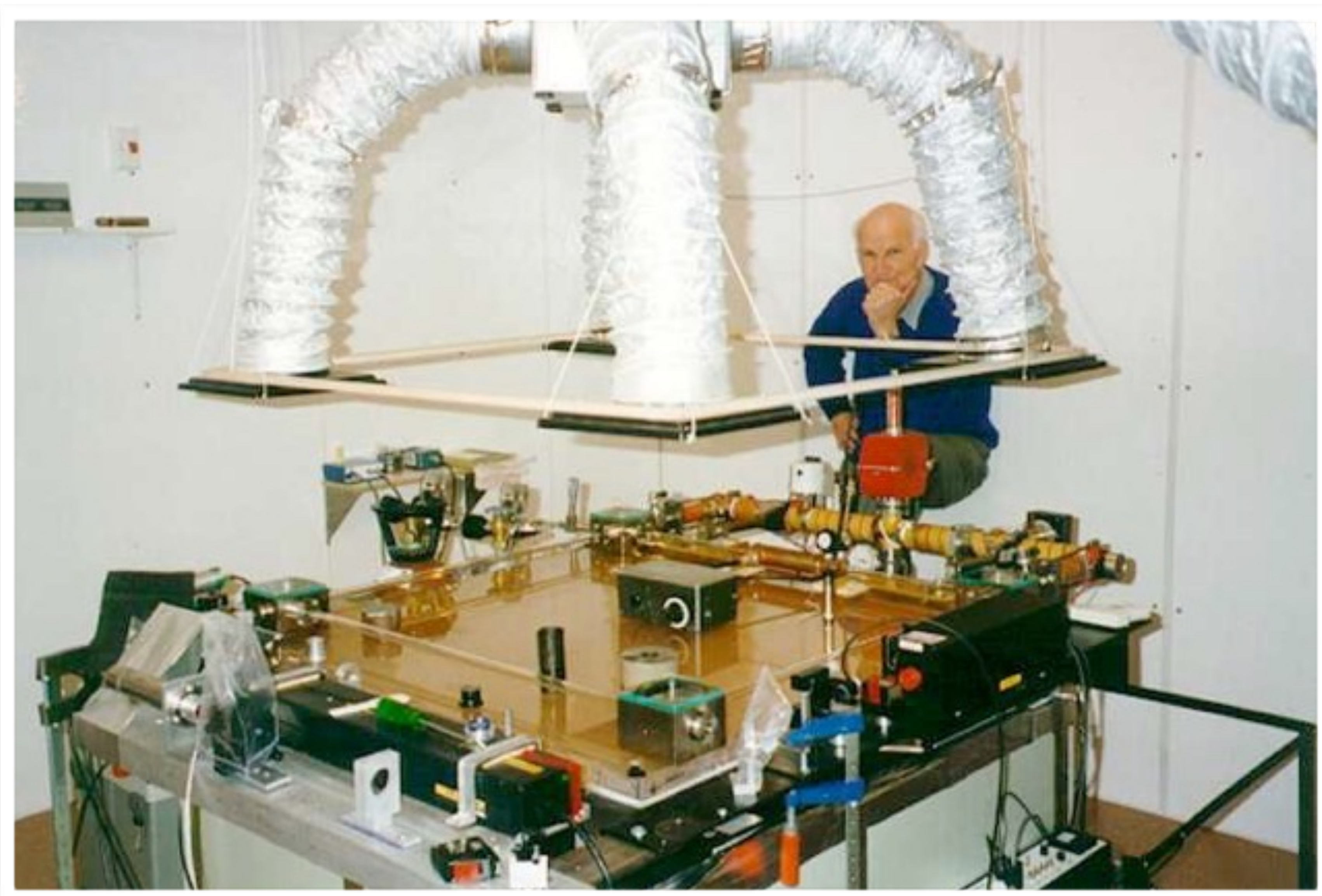
$$\delta f = \frac{4A}{\lambda P} \vec{n} \cdot \vec{\Omega} + f_{nr}$$

$10^{-9}\Omega_E \approx 0.07$ prad/s

$\Delta f_{nr} < 0.3$ μHz

www.uni-muenster.de/imperia/md/content/physik_ap/nlol/physika1213/

History of Large RLG



Canterbury Ring

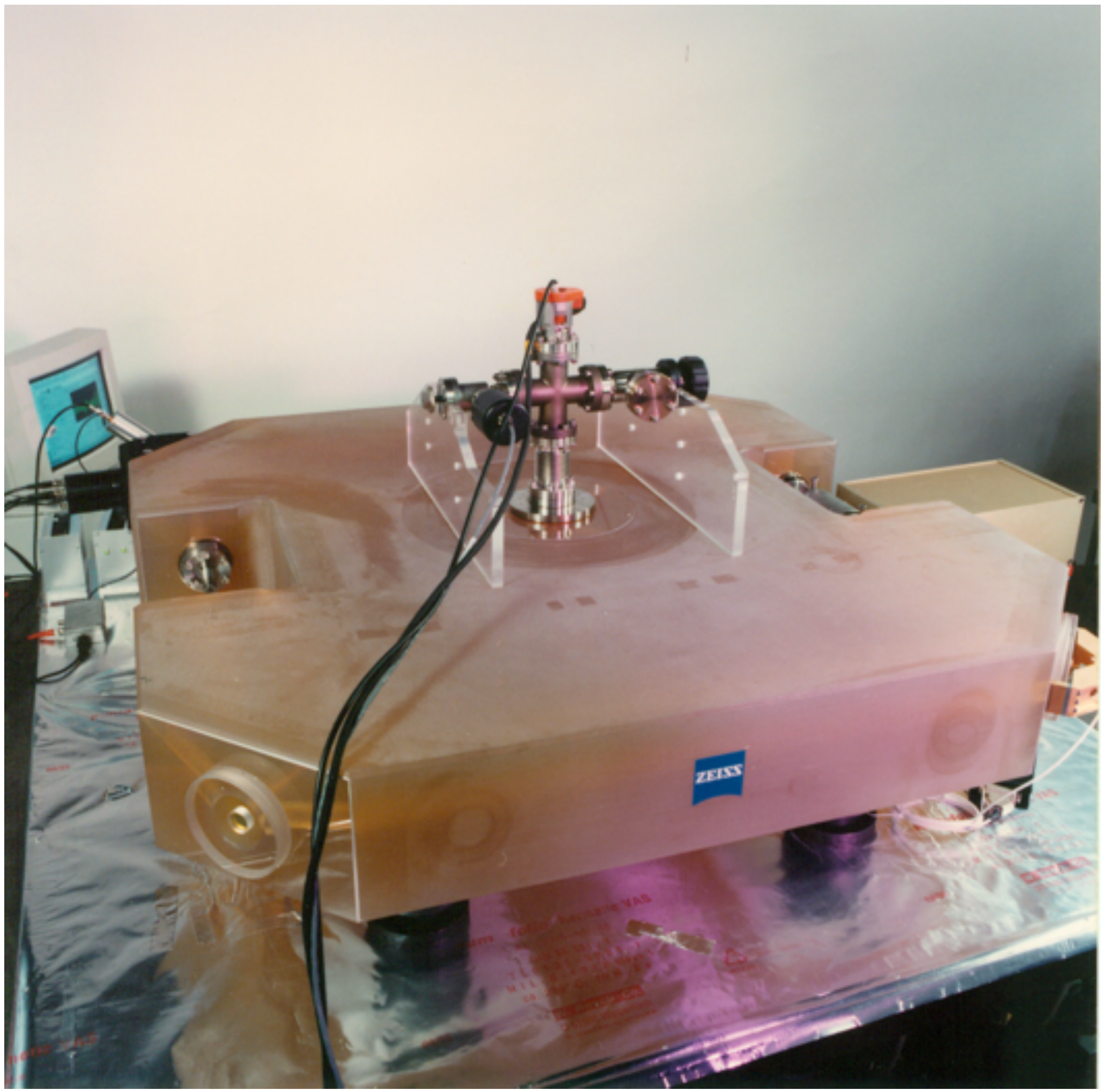
(1986 - 1998)

$\Omega_E \pm 5\%$

$A \approx 0.85\ m^2$
$\Delta f \approx 72\ Hz$

→ Large Ring Lasers are viable!

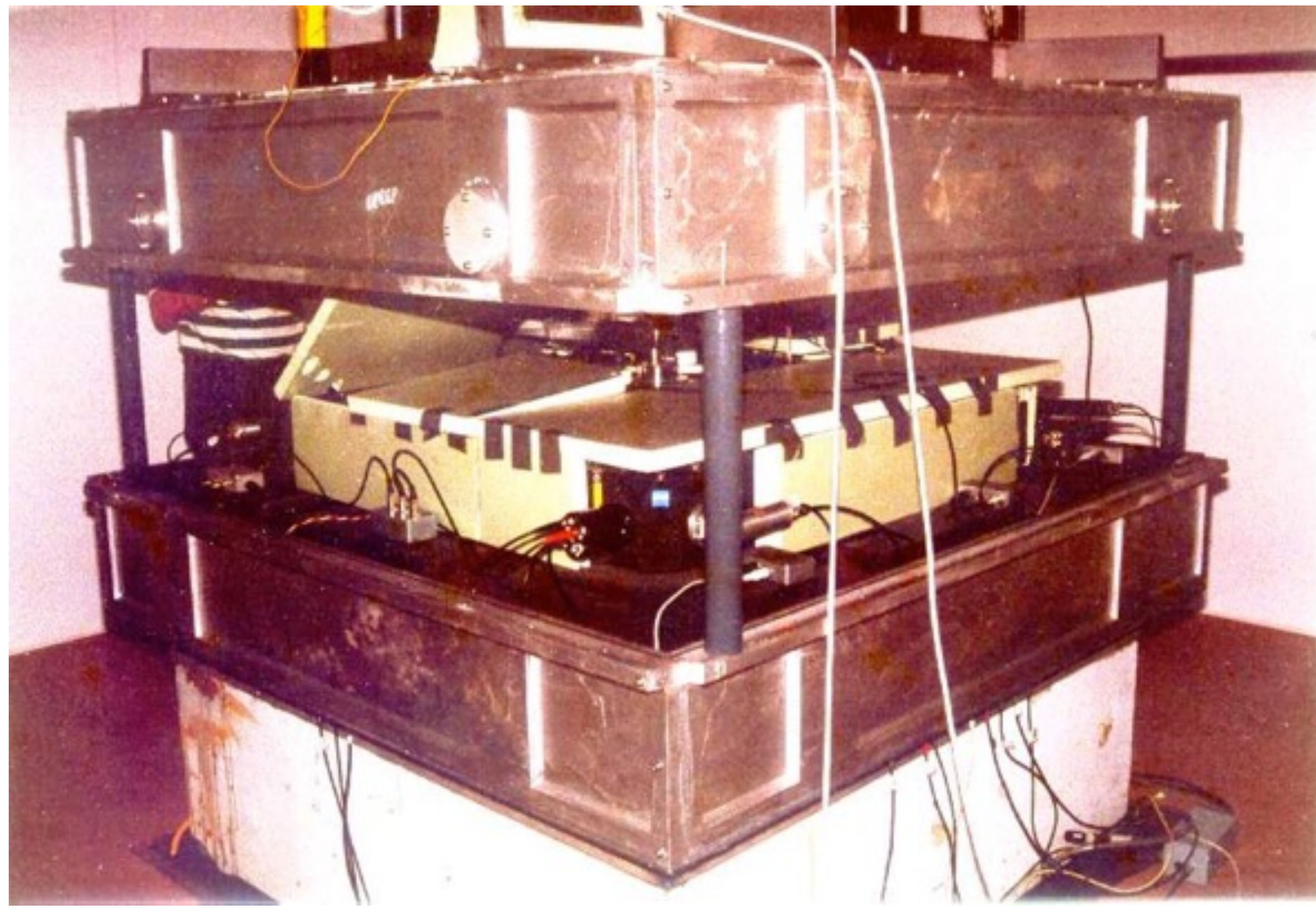
Canterbury Ring II (C-II)



- C-II (1997 - 2004)
- Perimeter 4 m
- Area 1 m^2
- Laser beam in neutral plane of a Zerodur body
- RF excitation
- $\Delta f \approx 79.4$ Hz

C-II in "Cashmere Cavern" (Port Hills, Christchurch)

under Pressure Tank: Oct. 2003



Installation: Jan. 1997

$\Omega_E \pm 0.001\%$

The 'G' - Ring is currently our best performing geodetic gyro

Since 2001 -

Perimeter: 16 m

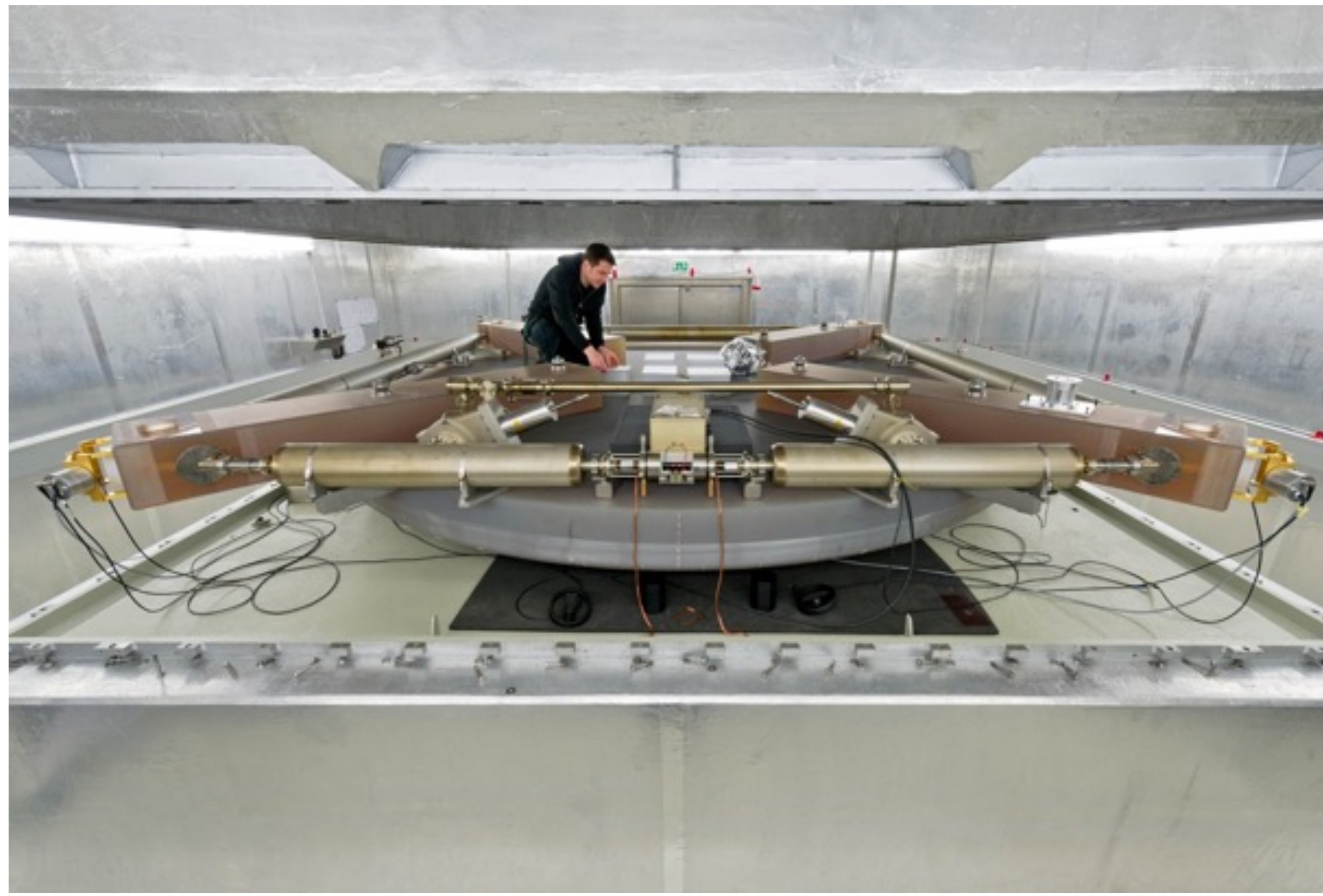
Area: 16 m^2

FSR 18.75 MHz

$\Delta\nu_L \approx 274\ \mu Hz$

5 ppm loss / mirror

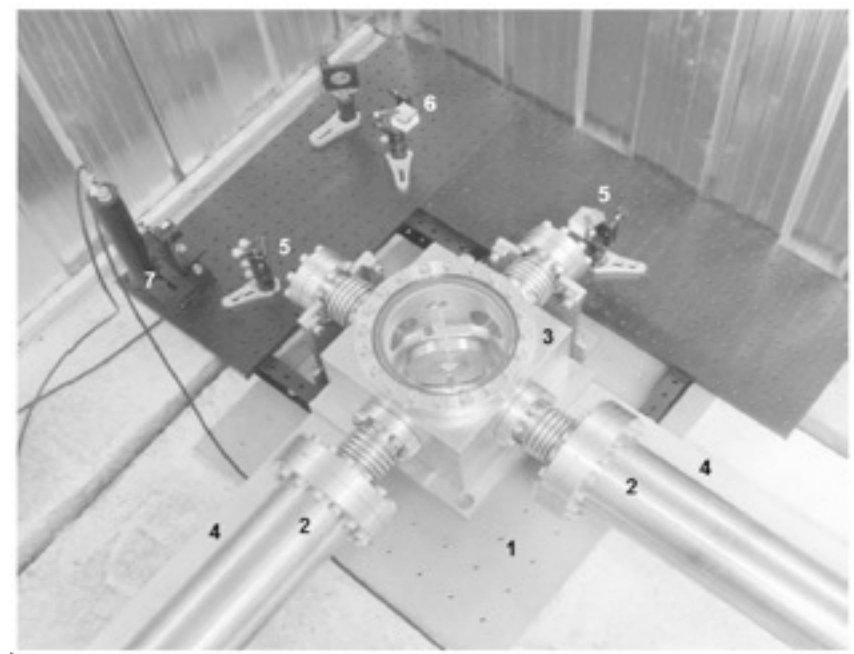
$Q = \omega\tau \approx 5x10^{12}$



10 mB gas pressure operated near laser threshold
Mode selection by gain starvation (self-locking)

$$\Omega_E \pm 5 \cdot 10^{-9}$$

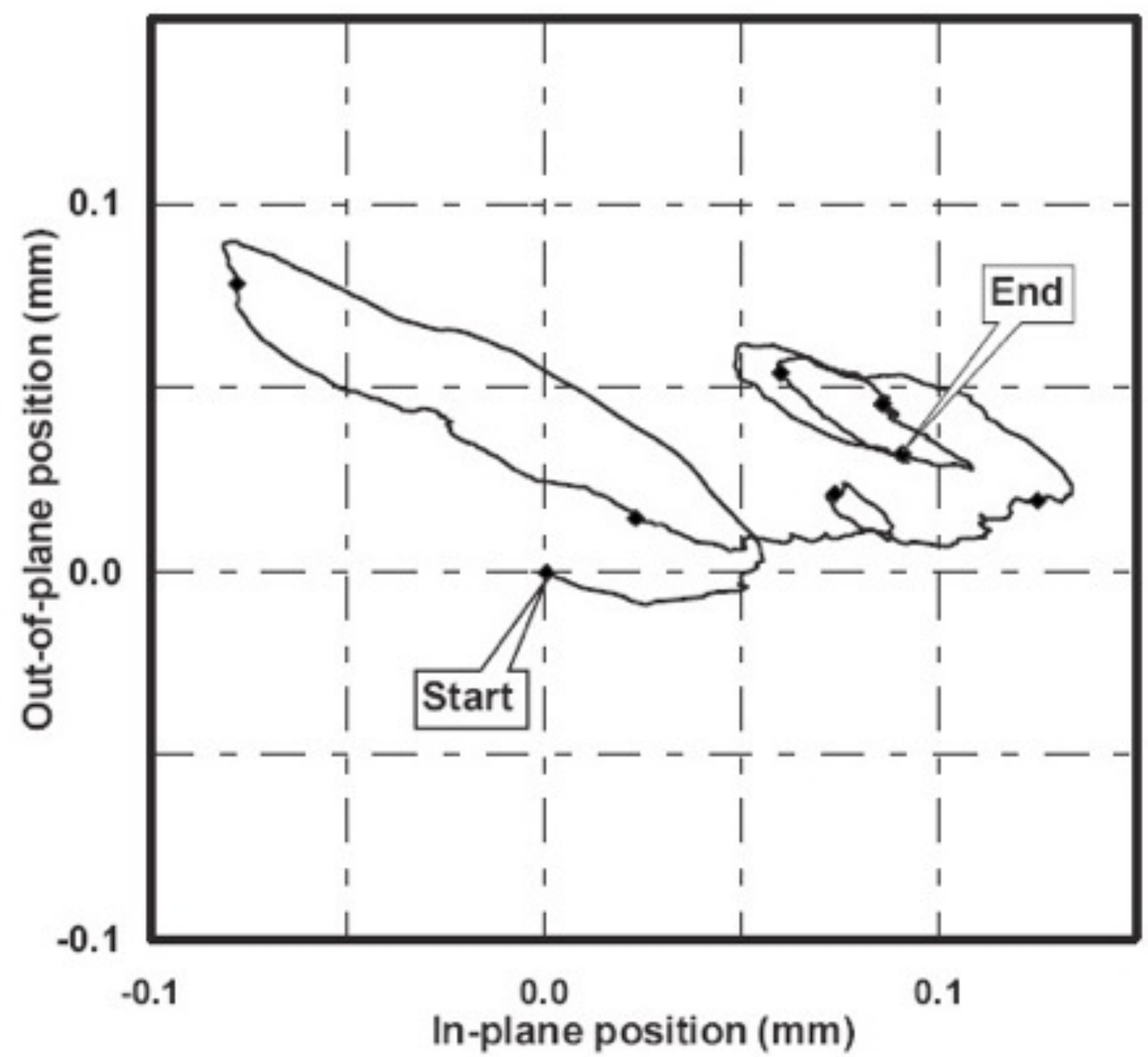
Heterolithic Concept: UG-2 RLG with 834 m^2 of Area

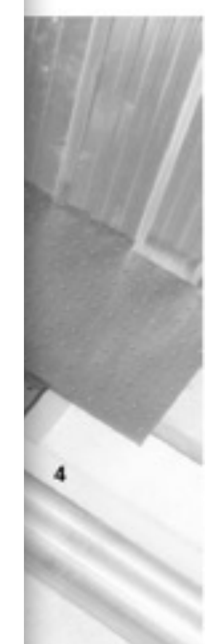


UG-2 built in 2003 with dimensions: 39.7 m x 21 m
Stainless steel rectangular structure mechanically unstable

Heterolithic Concept: UG-2 RLG with 834 m^2 of Area

Laser Beam Wander





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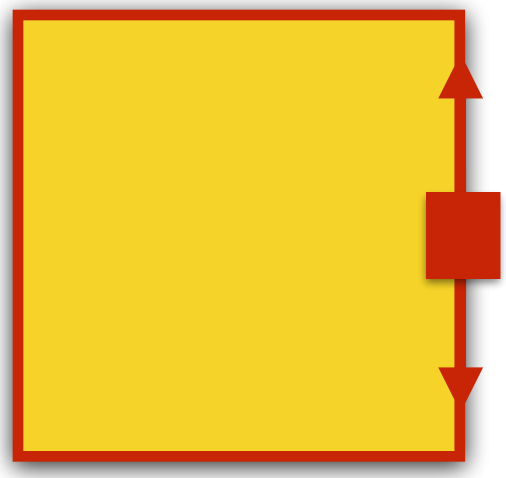
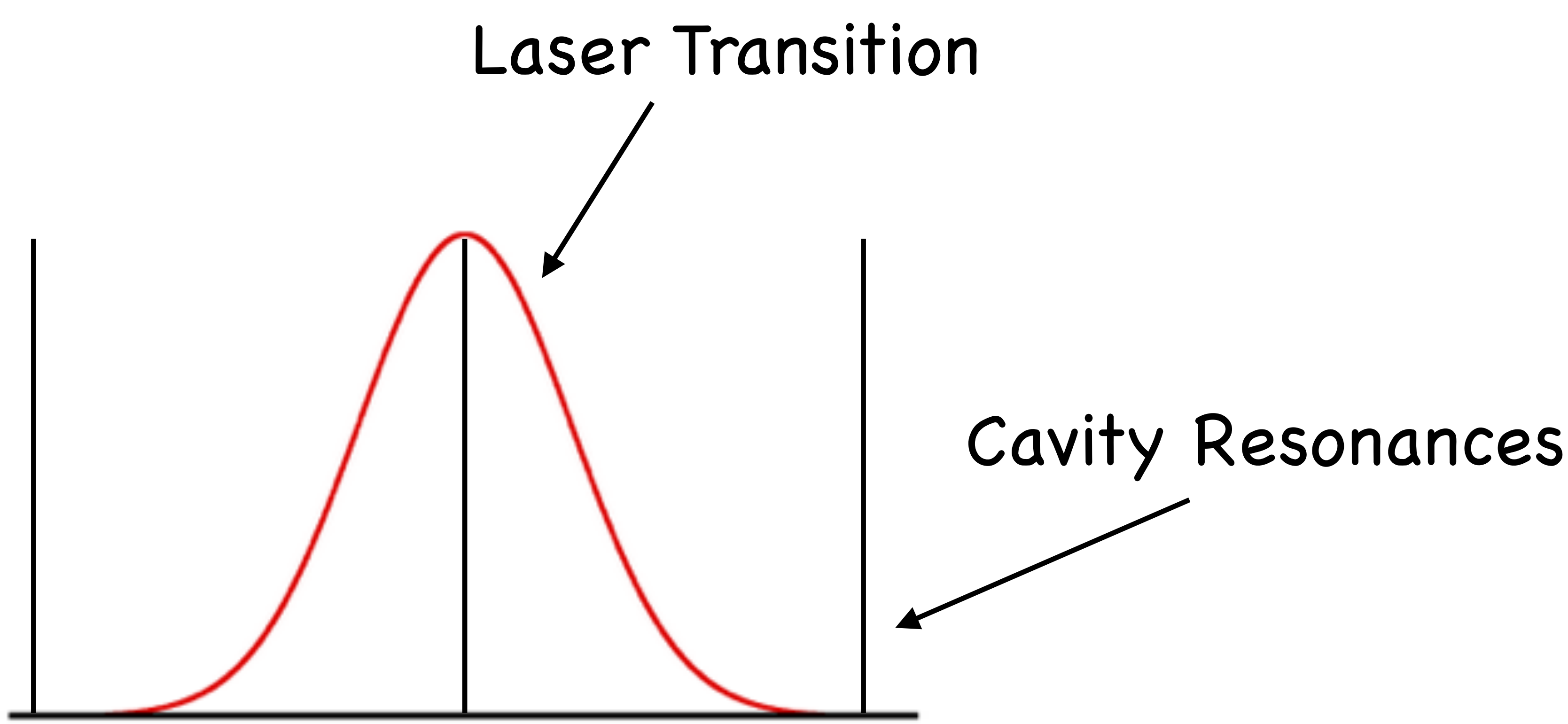
What is essential about Ring Lasers?



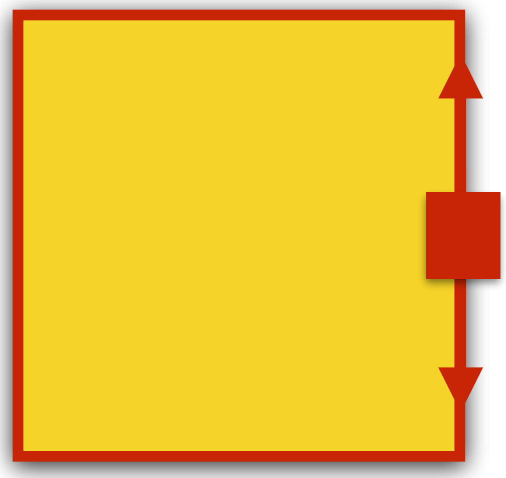
We want a clean Interferogram:

Task: Operate the system on one longitudinal laser mode per sense of propagation



aircraft gyro

What is essential about Ring Lasers?



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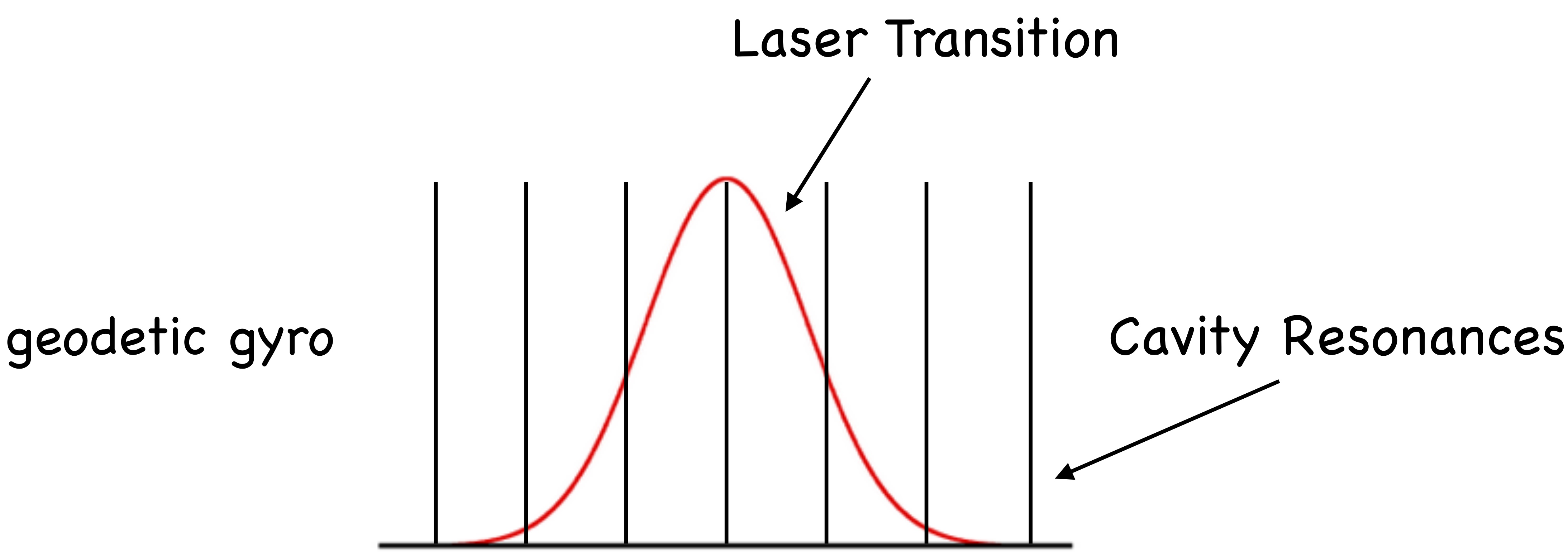

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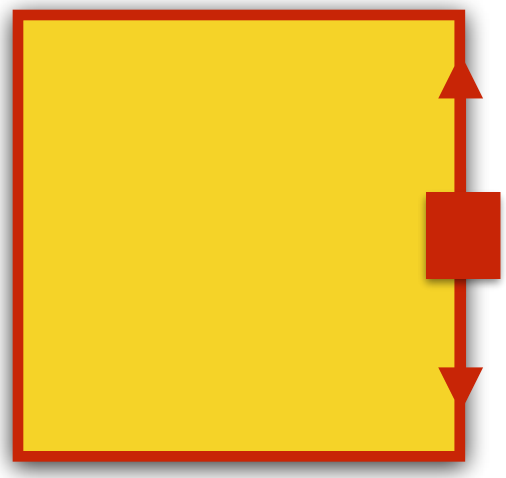

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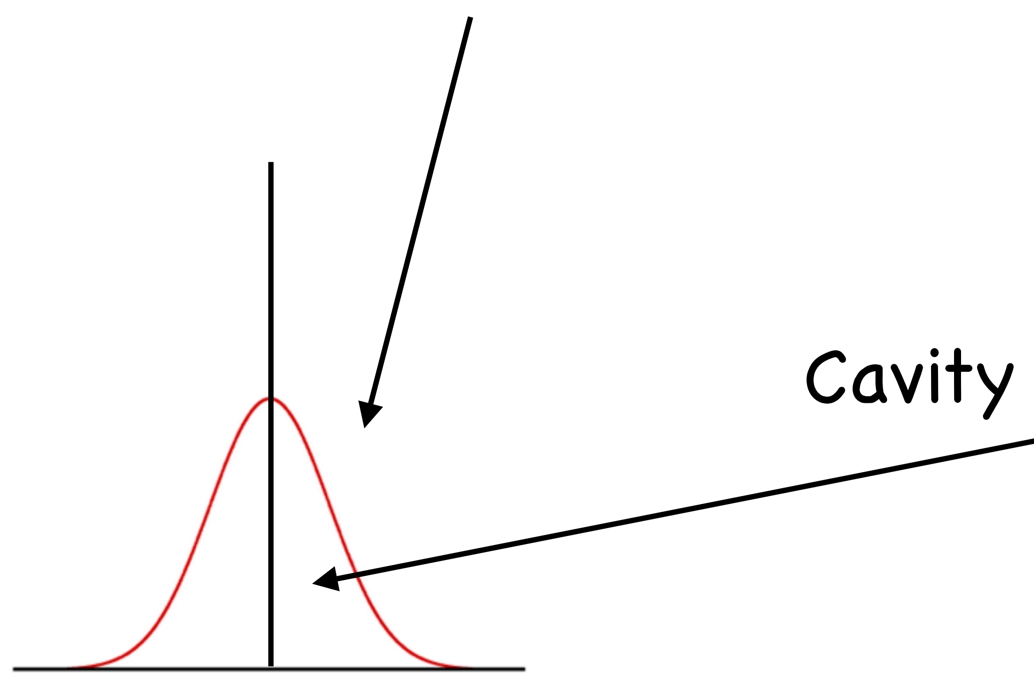
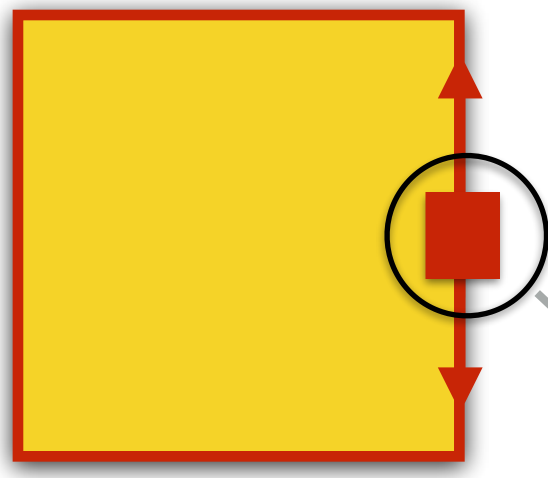
Task: Operate the system on one longitudinal laser mode per sense of propagation

geodetic gyro



Gain Starvation

What is essential about Ring Lasers?

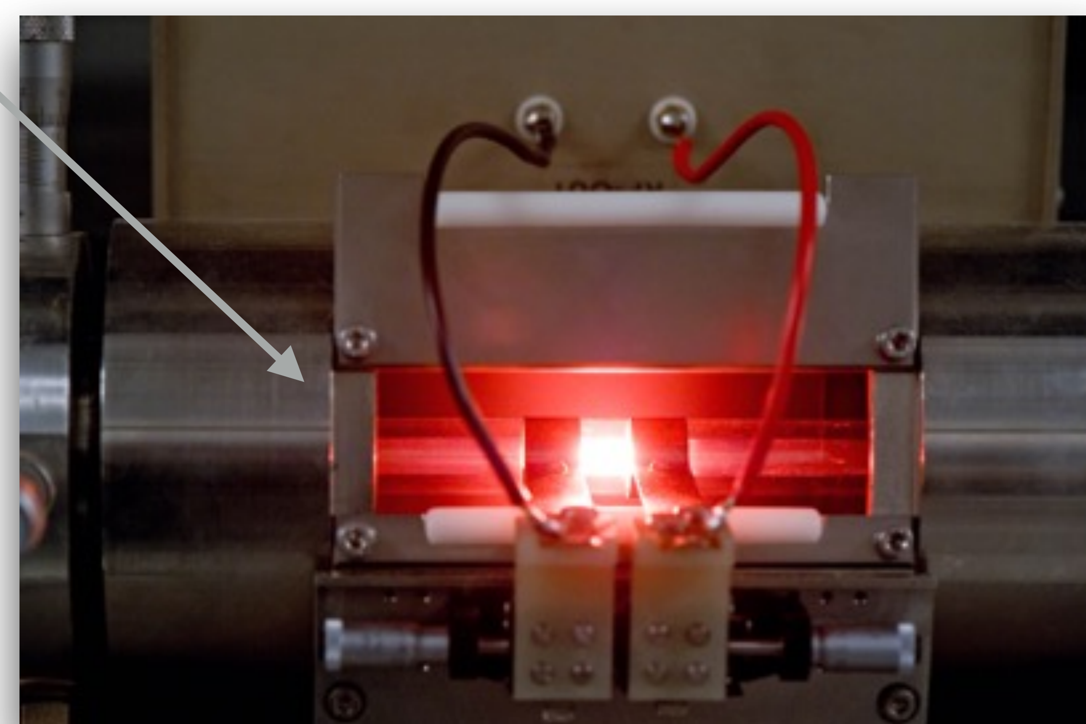


We want ultimate symmetry and low loss:

Keep the cavity as much reciprocal as possible

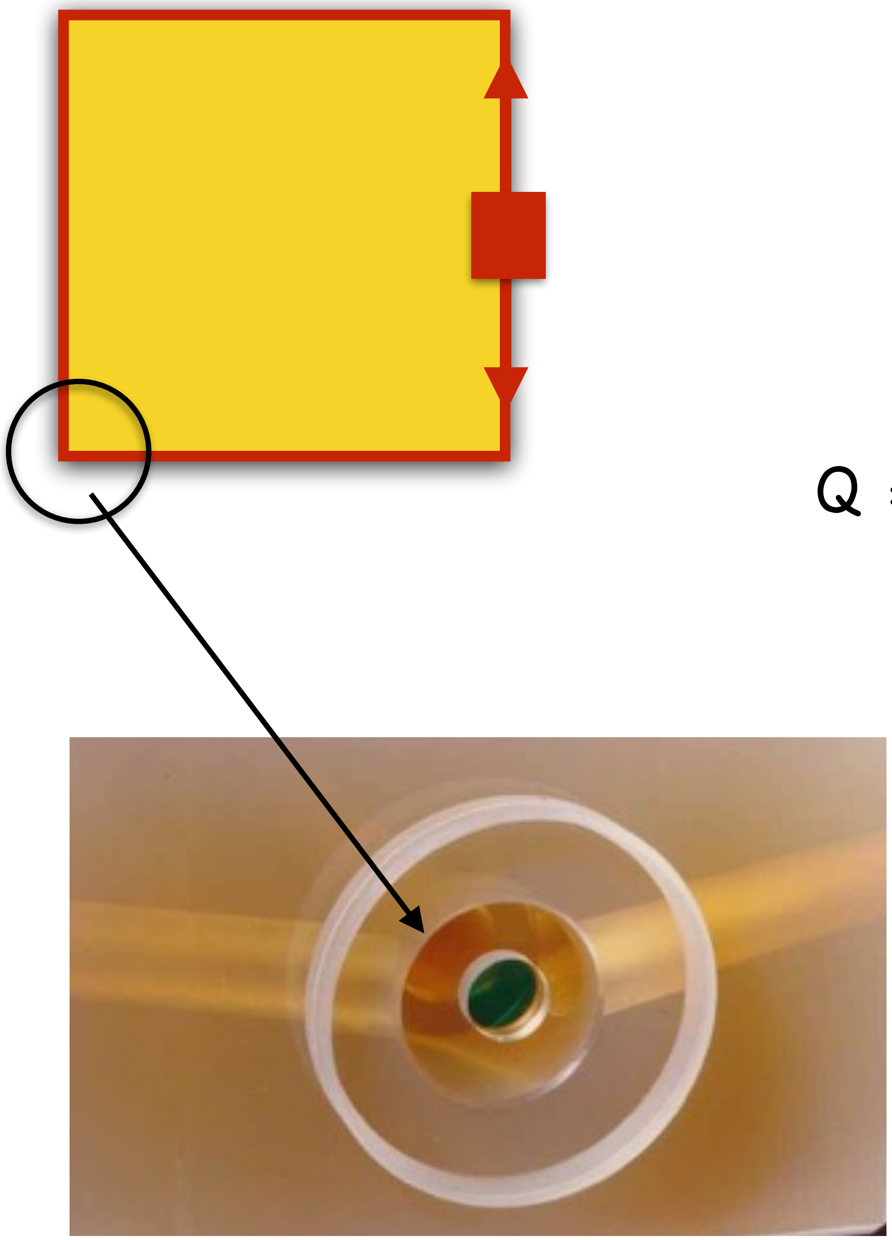
RF excitation to avoid gas flow

active gain medium takes optical linewidth from 10th of Hz to sub- mHz



2 cm length of plasma is evidence of low loss

What is essential about Ring Lasers?

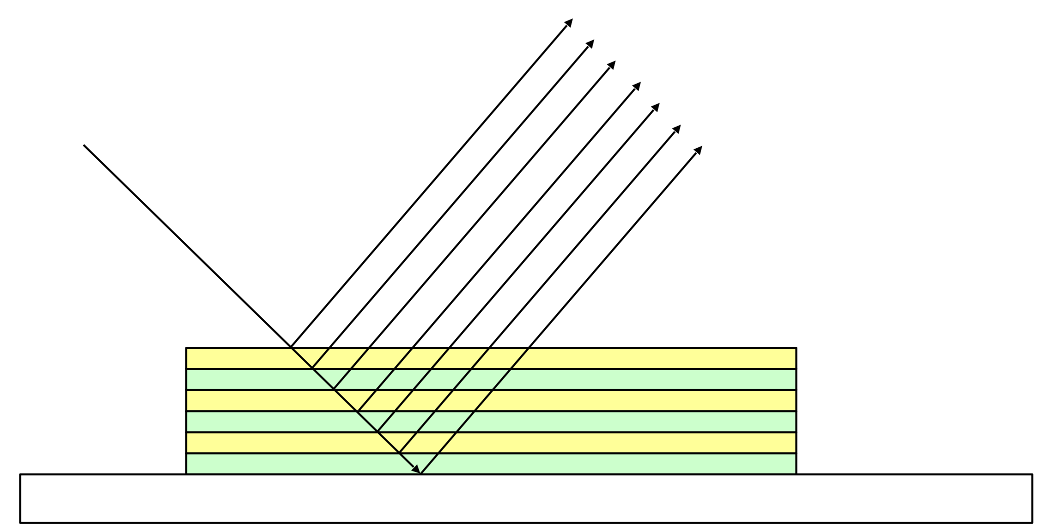


We want a sharp Interferogram:

Reduce all the losses to the bare minimum -> make the Q factor high

$Q = \omega\tau \approx 5\times10^{12}$

$\Delta\nu_L \approx 274\ \mu Hz$

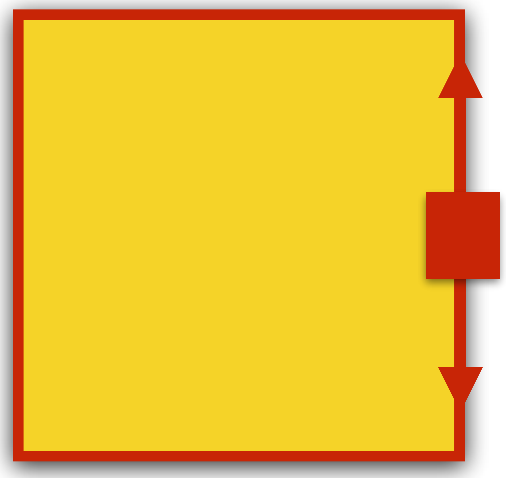


high: Ta_2O_5

low: SiO_2

What is essential about Ring Lasers?

f ≈ 474 THz



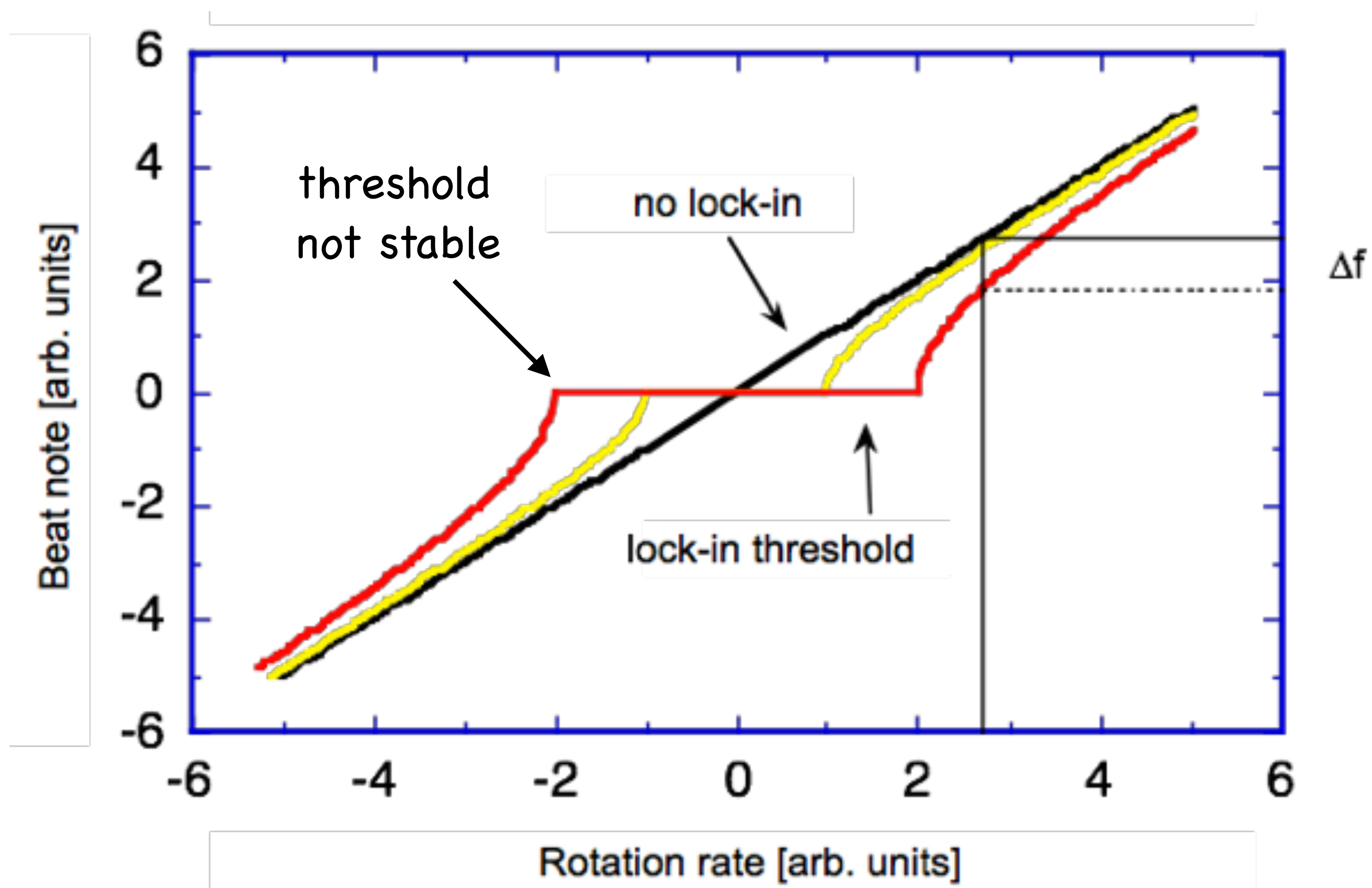
100 Hz ≤ f_{sag} ≤ 1.5 kHz

$$\Delta f = Skf\sqrt{\Omega^2 - \Omega_L^2}$$

$$\Omega_L = \frac{c\lambda^2\sqrt{R}}{32\pi A d}$$

We want the correct value:

Avoid coupling between the two counter-traveling laser modes at all cost



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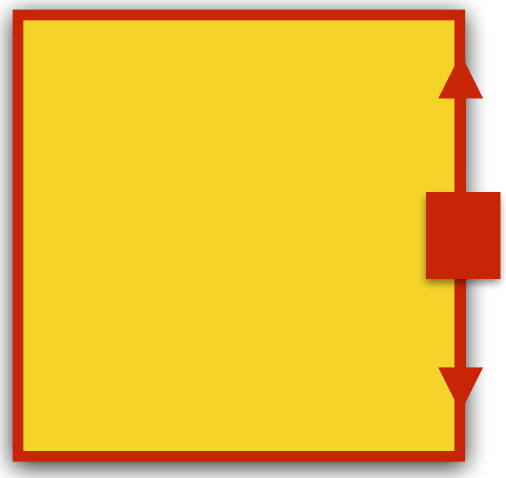


We measure the backscatter coupling:

$$\Delta f_S \approx \tfrac{1}{2} f_S \; m_1 m_2 \cos \varphi$$

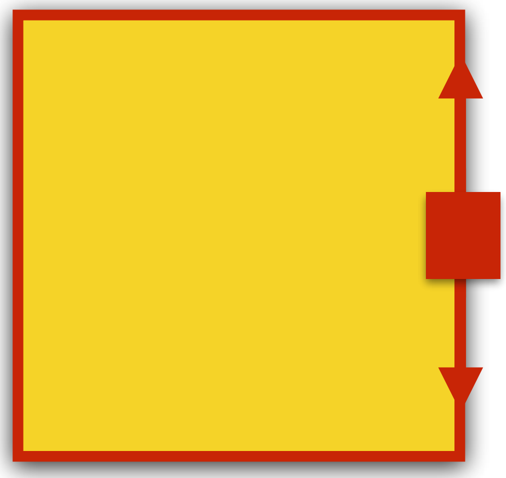
where m_1 and m_2 are the fractional beam modulations, and φ is the phase angle between them.

For given mirror quality, m_1 and m_2 scale approximately as $L^{-2.5}$ for cavity of linear size L.

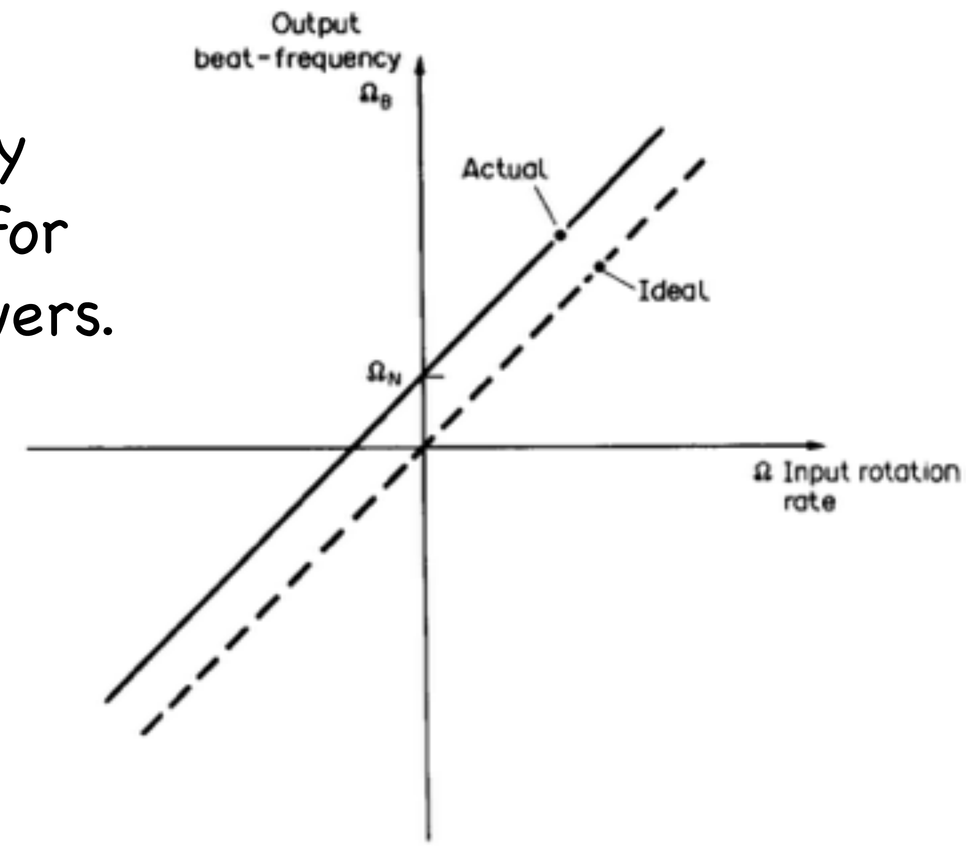
$\Delta f_S \,/\, f_S$ scales approximately as L^{-5} !!!

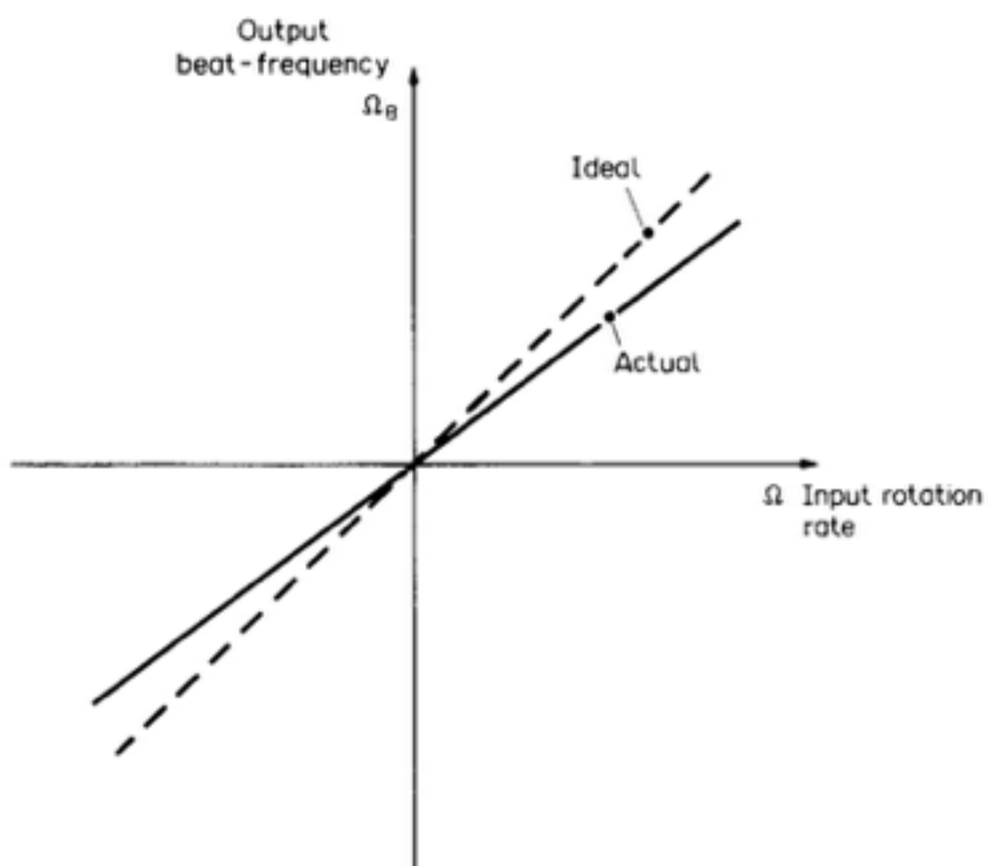
It is extremely important to maximize the size of the laser however this will cause mechanical stability to reduce.

What is essential about Ring Lasers?



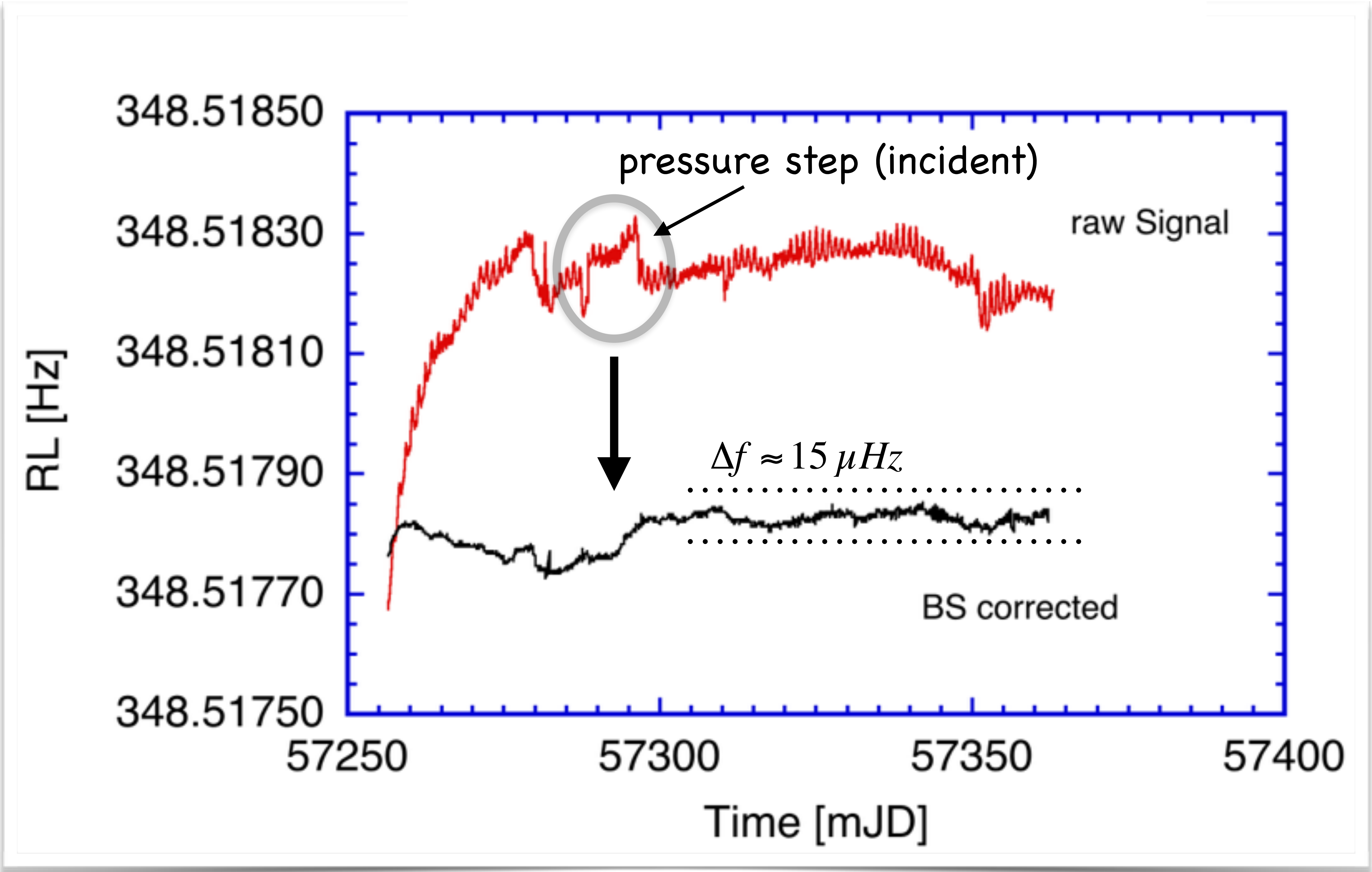
null shift error: This is a very common complication, caused for example by unequal beam powers.



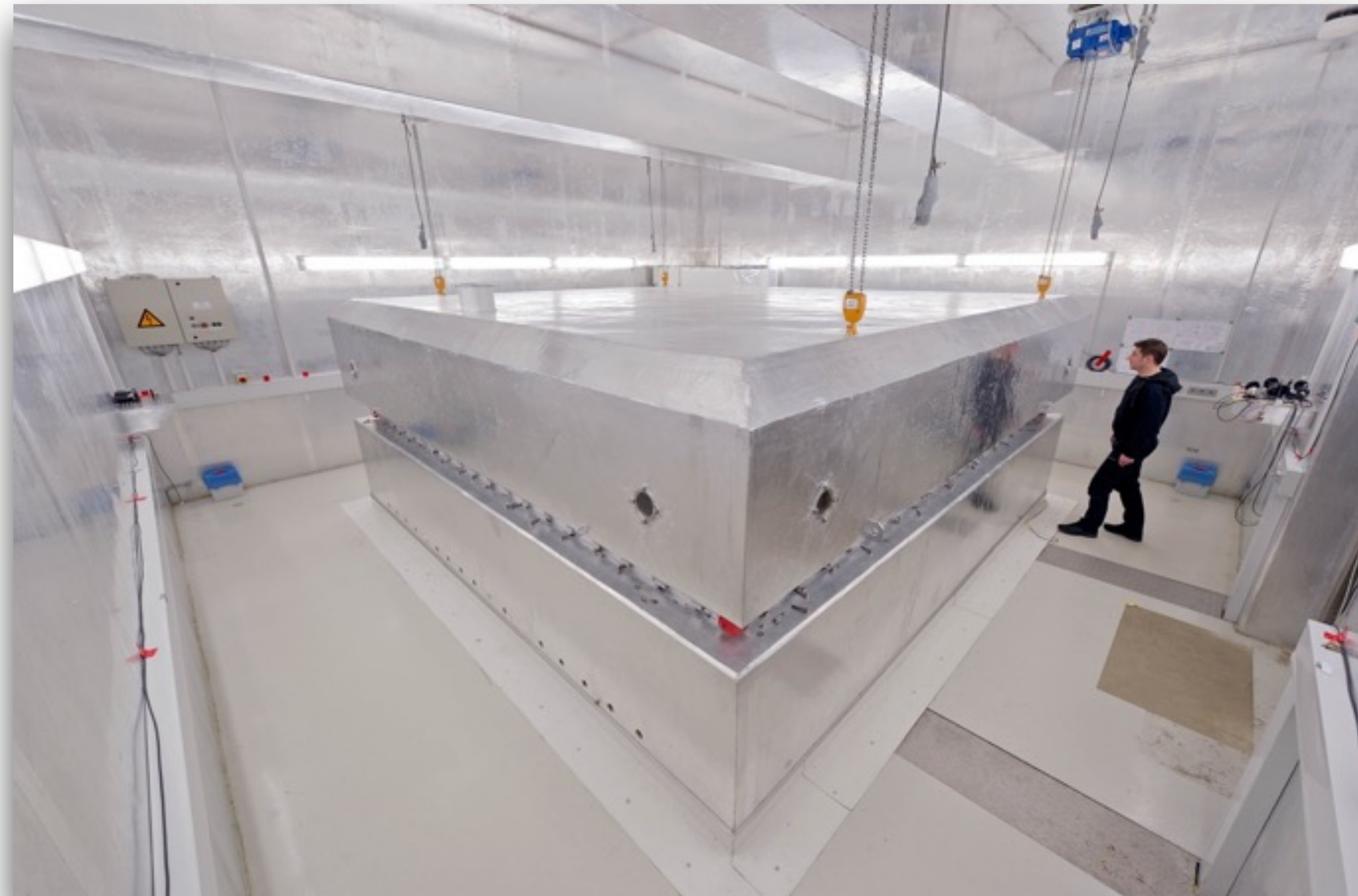


scale factor error: This can be a real hassle caused by misalignment or orientation issues and can easily be changing in time

Throwing it all together eventually gets us further

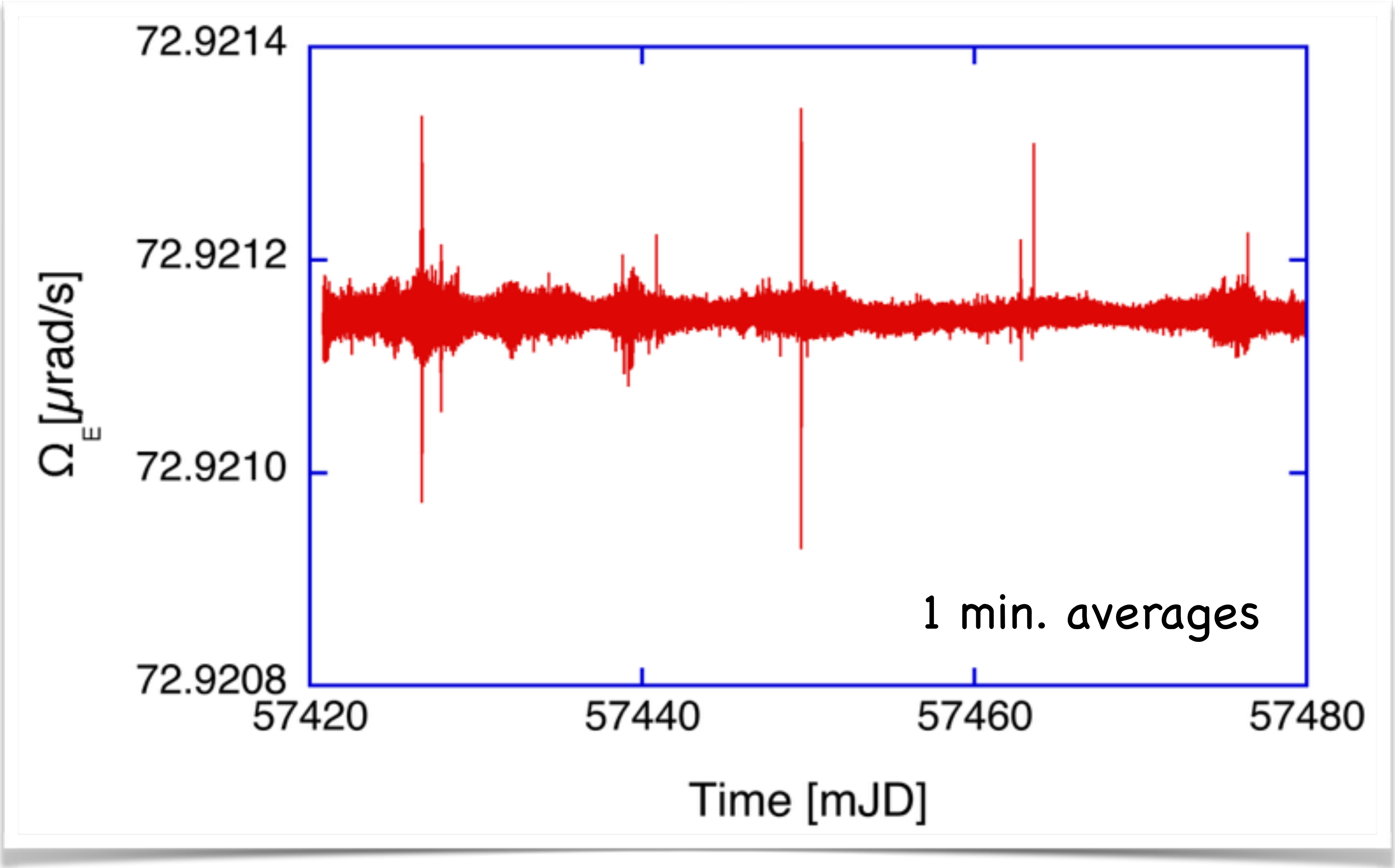


Operations need to be stabilized by controlling the perimeter via a pressure stab. vessel

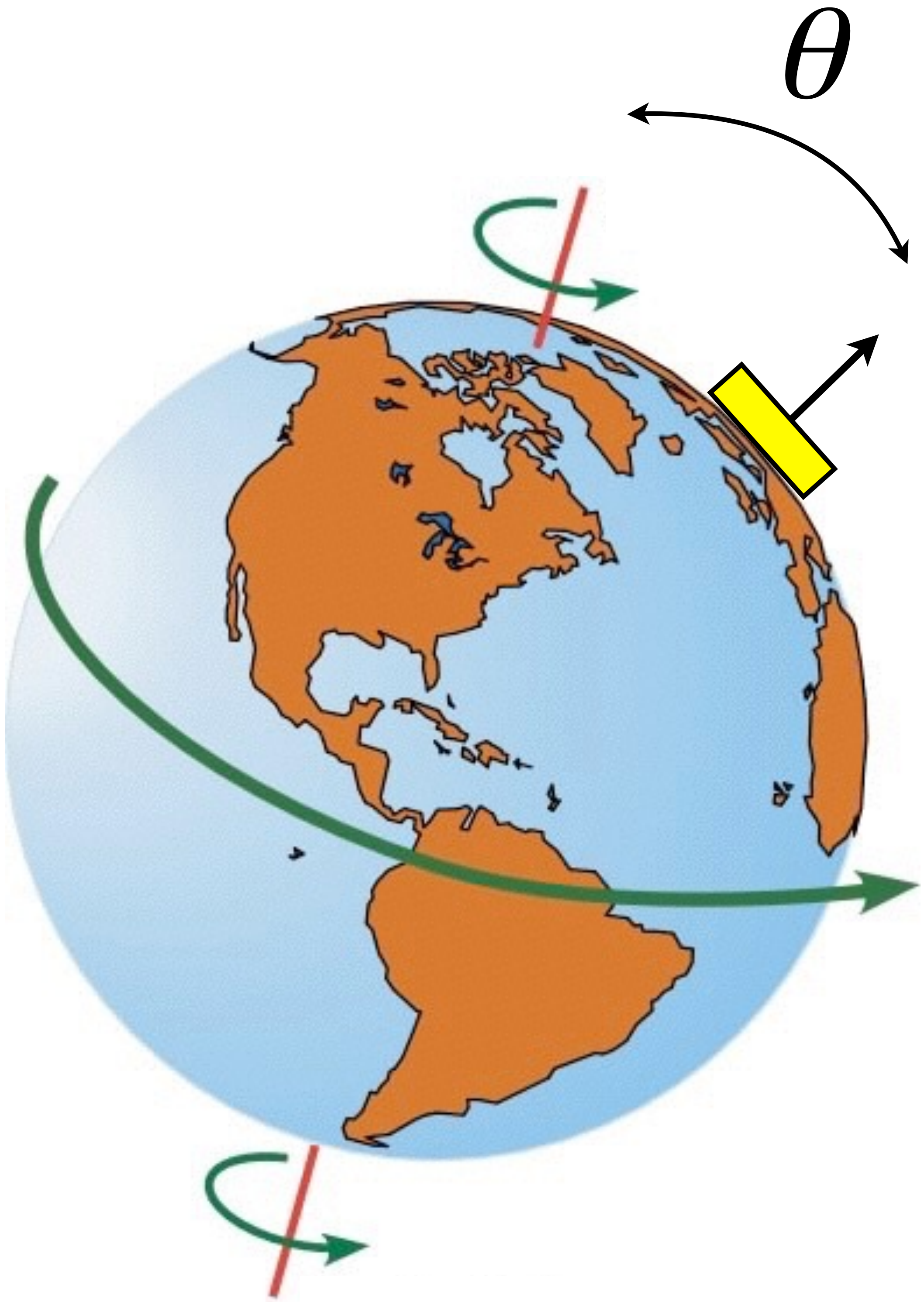


... now that we understand the interferometer, what do we get from it?

Observation of the instantaneous rotation rate of the Earth

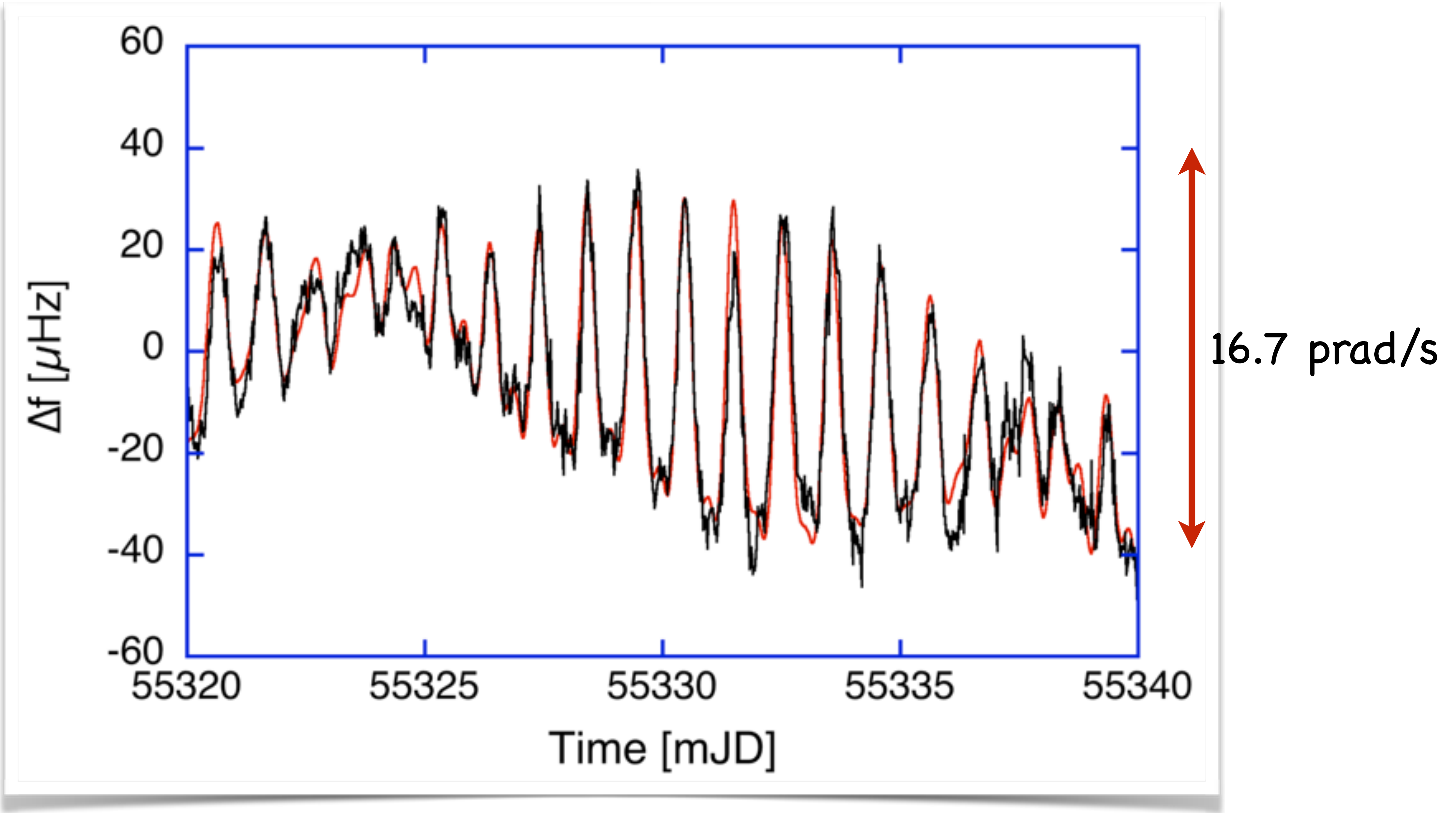


$\Delta f = 348.517$ Hz

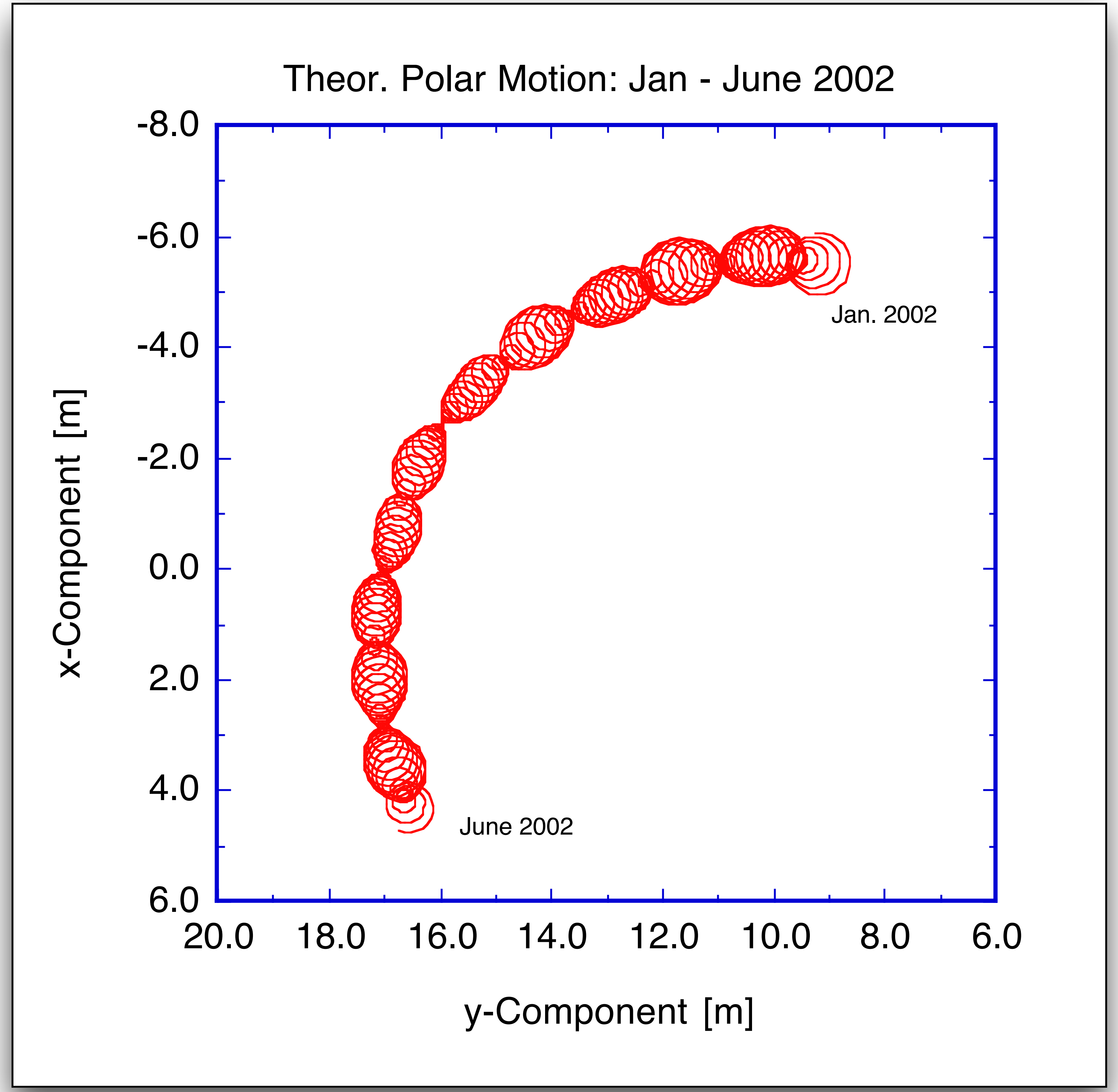


A single axis gyro only “sees” the projection of the rotation axis onto the gyro normal vector

Comparison of G tied to the Earth crust against the (known) geophysical signals due to orientation variation

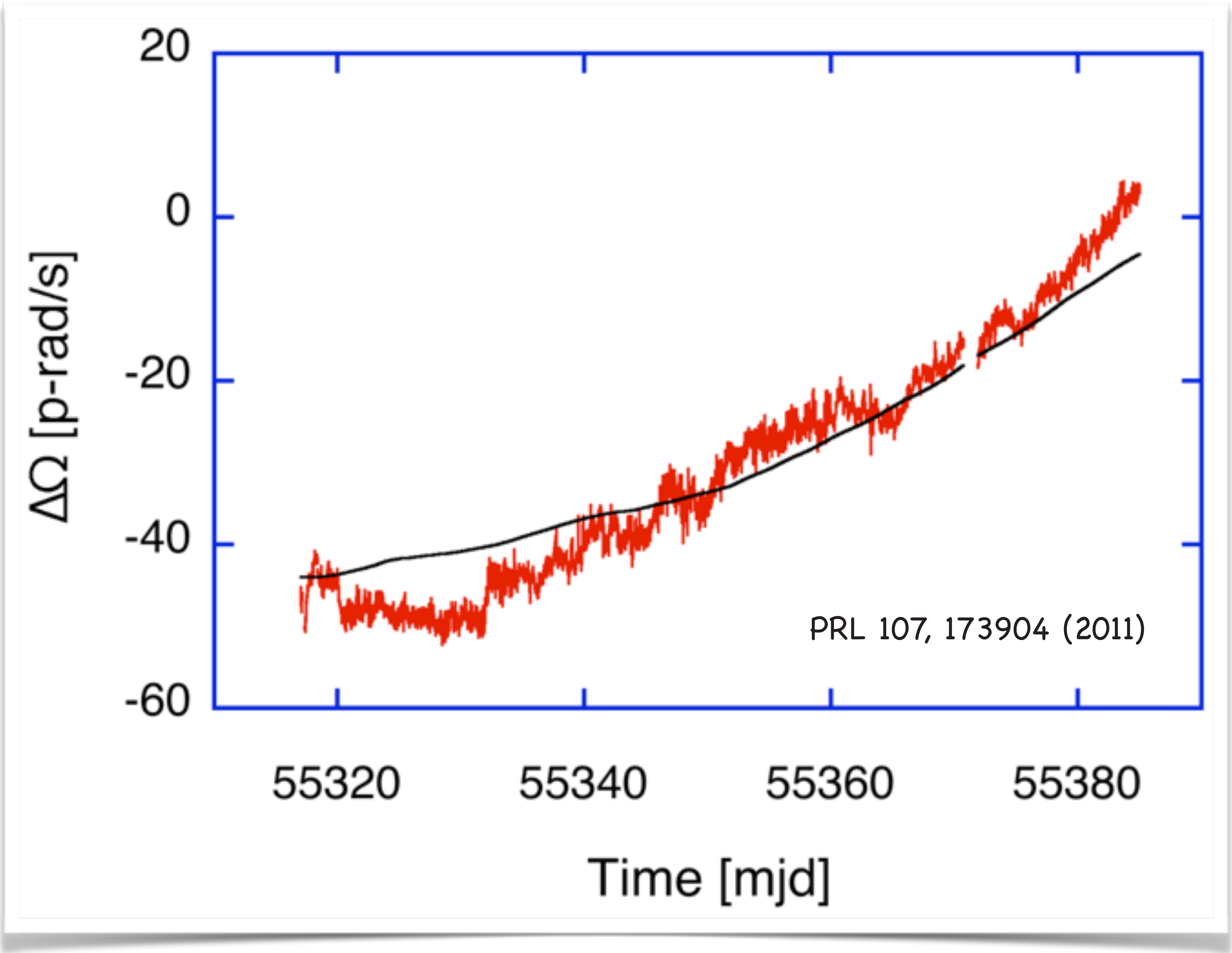


Earth rotation causes a beat note of 348.517 Hz. Tilt induced geophysical signals show signatures in the range of ±50 μHz

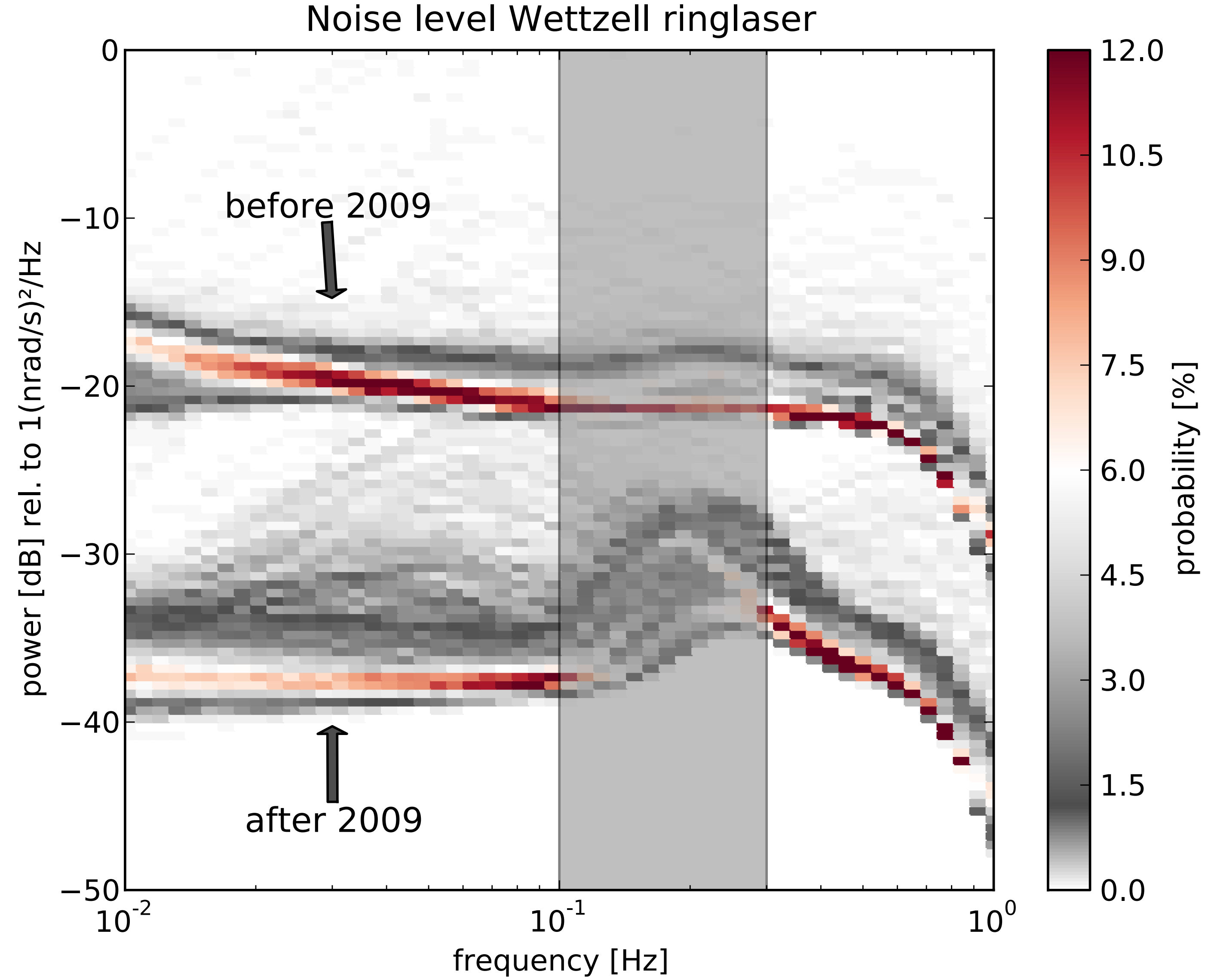

Theor. Polar Motion: Jan - June 2002
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
x-Component [m]
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
y-Component [m]
Jan. 2002
June 2002

Comparison to VLBI measurements

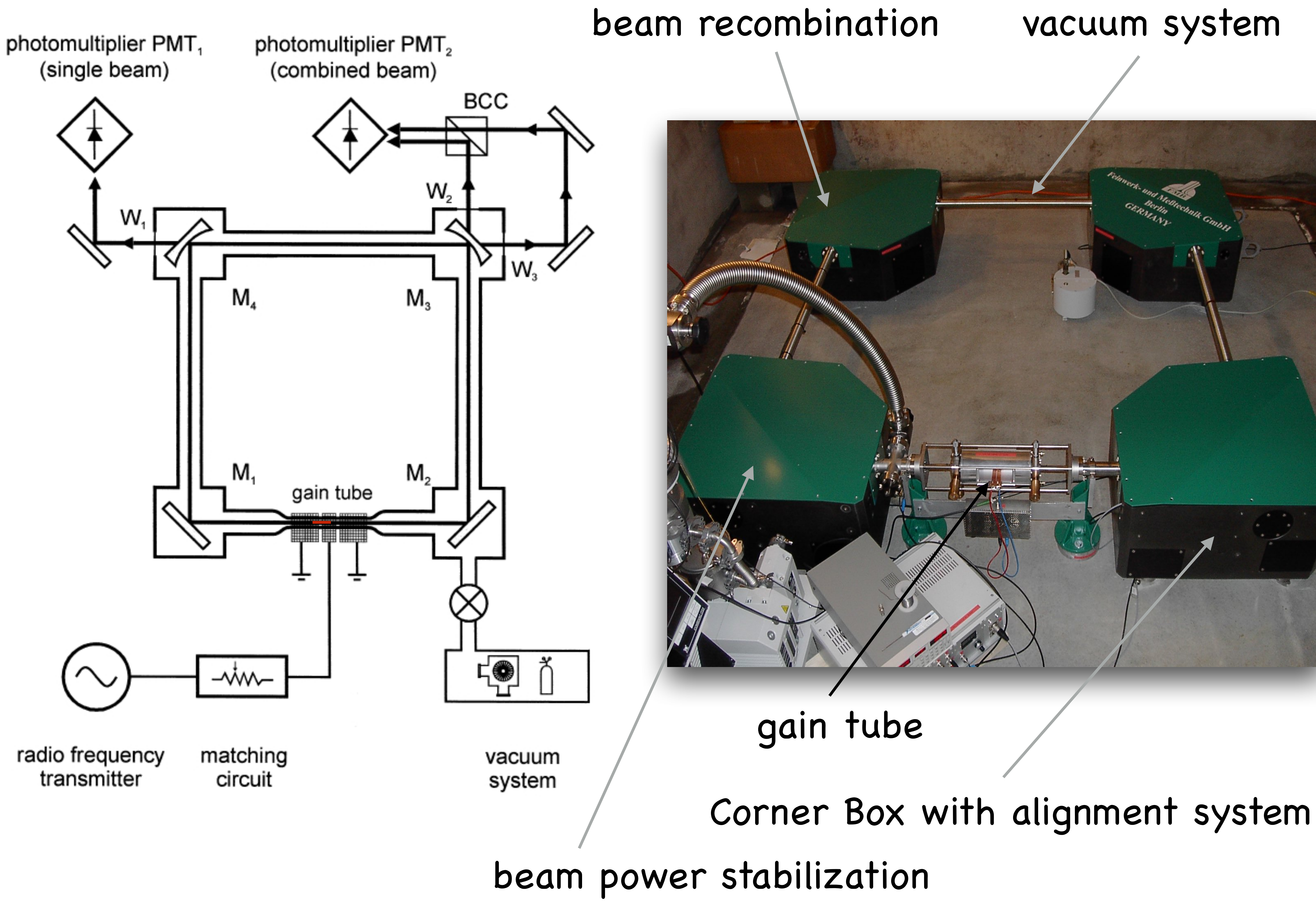
f ≈ 26 nHz



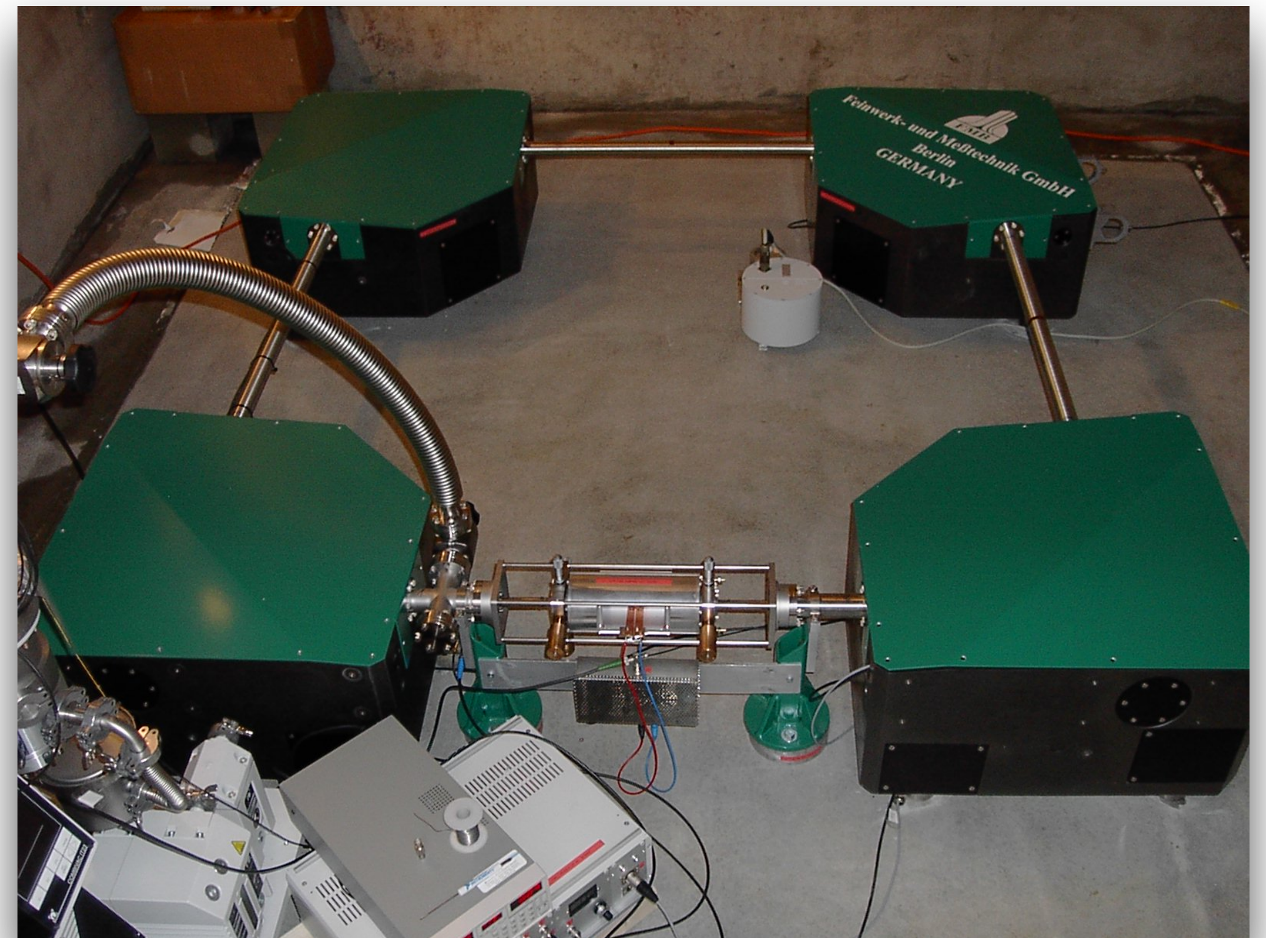
1 single axis gyro compared to the VLBI network



The role of the mirror coatings: Lower scatter due to better polish or higher mechanical Q of substrate?

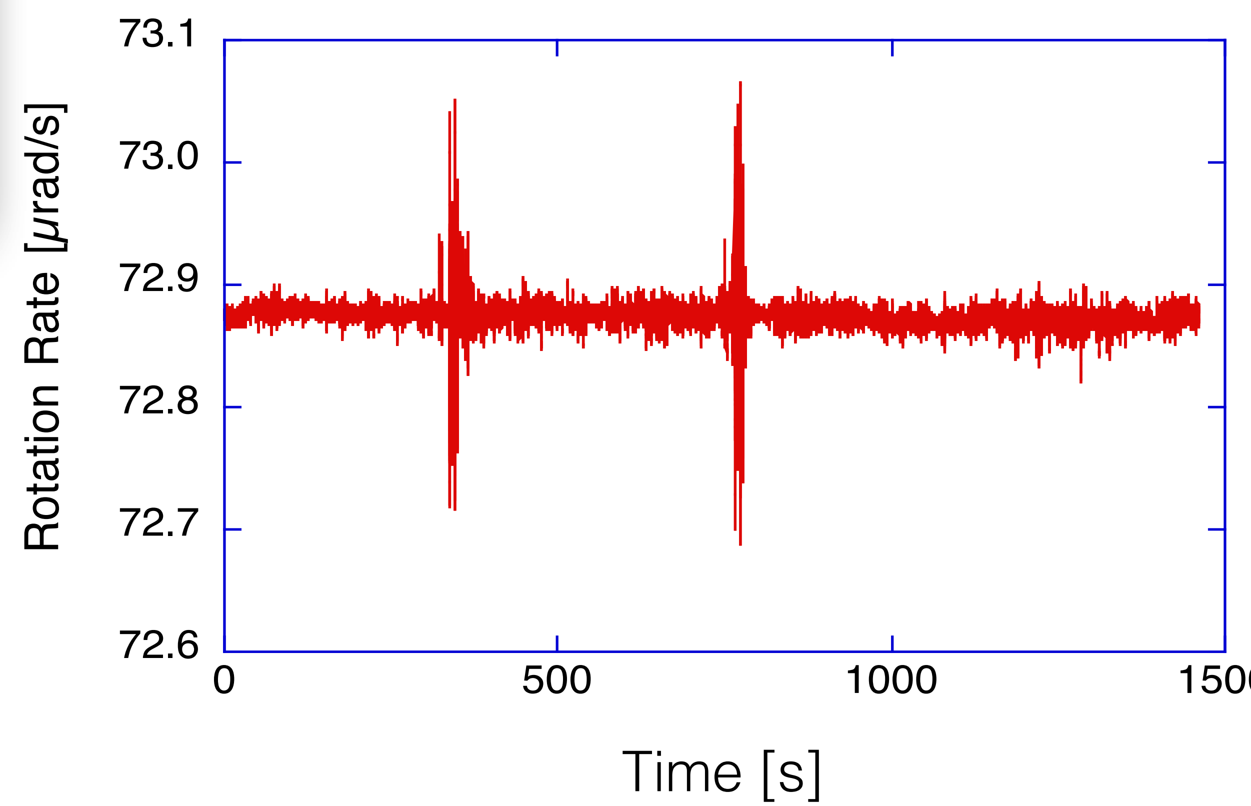

photomultiplier PMT_1
(single beam)
photomultiplier PMT_2
(combined beam)
BCC
W_1
W_2
W_3
M_4
M_3
M_1
M_2
gain tube
radio frequency transmitter
matching circuit
vacuum system
beam recombination
vacuum system
gain tube
Corner Box with alignment system
beam power stabilization

Installation of the GEOsensor in Pinon Flat



PFO Jan. 2005

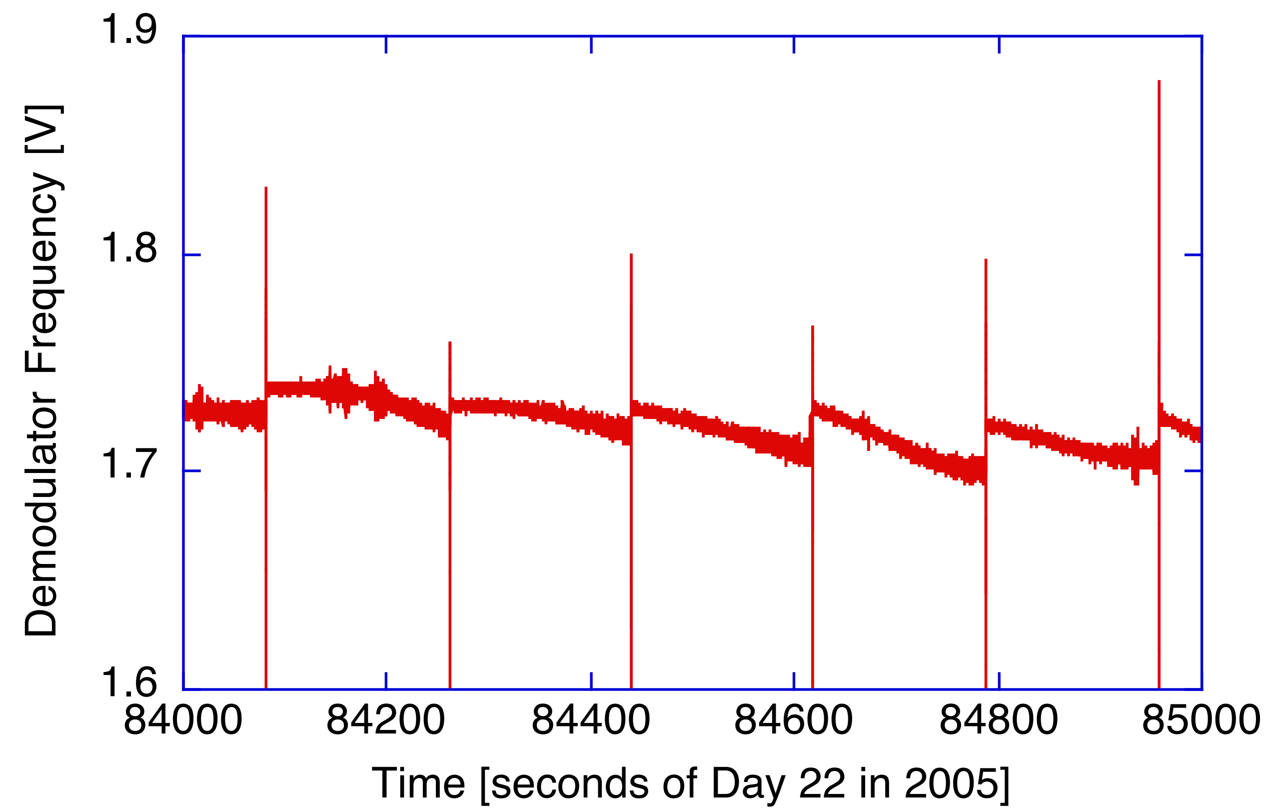
- A 3 x 3 m concrete slab 30 cm thick is the base
- Stainless steel tubes form the gyro
- Not so stable, but cheaper

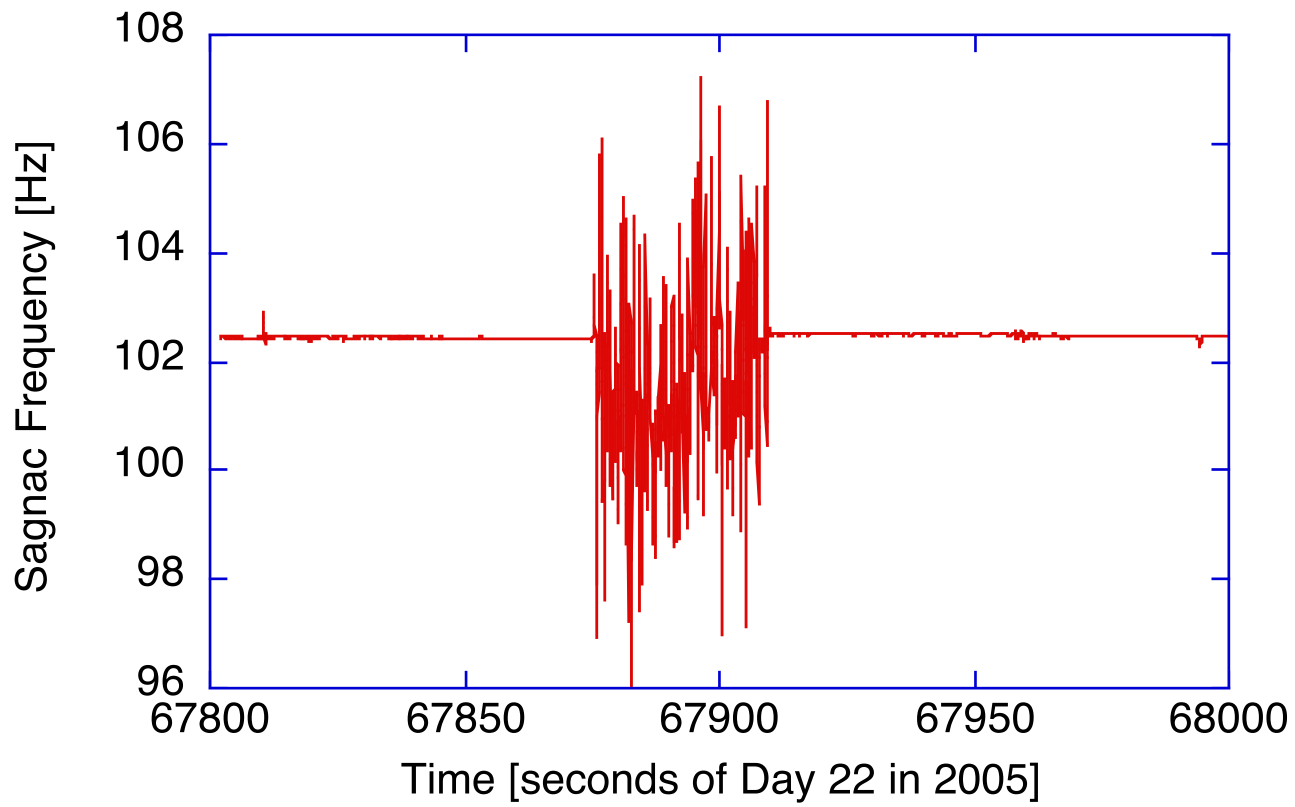


Thermal expansion of concrete and steel match

GEOsensor

mode changes because of temperature drift





Split-mode operation

What improvements would we like to see?

Geodesy

Sensitivity should improve by 1 order of magnitude

3D structure and networks

absolute orientation (new territory)

Seismology

Primary microseismics (Earth hum)

higher sensitivity for observatory type instrumentation (eigenmodes…)

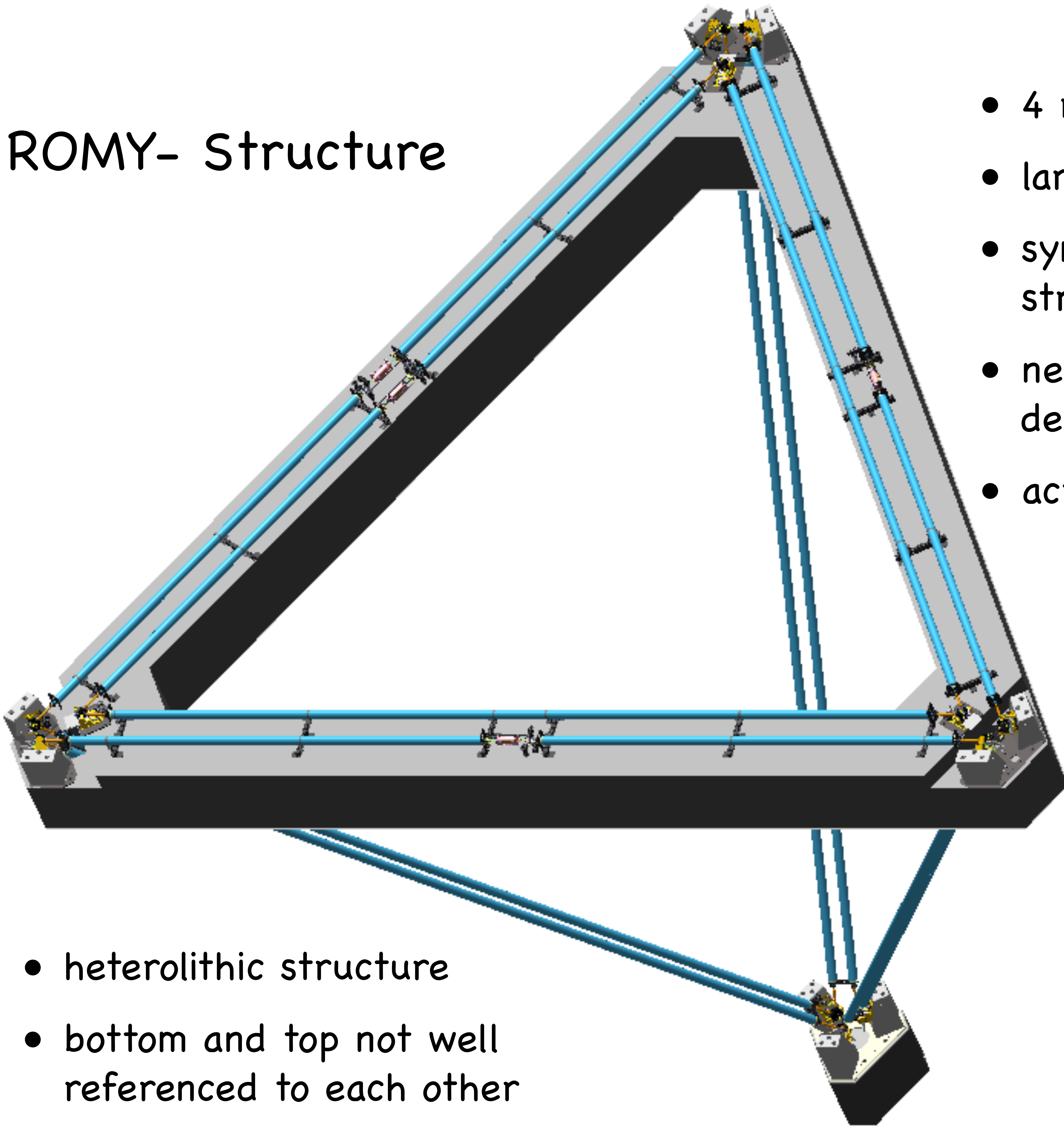
portable sensors at reasonable weight and power consumption

Fundamental physics

Sensitivity should improve by 1 order of magnitude or more

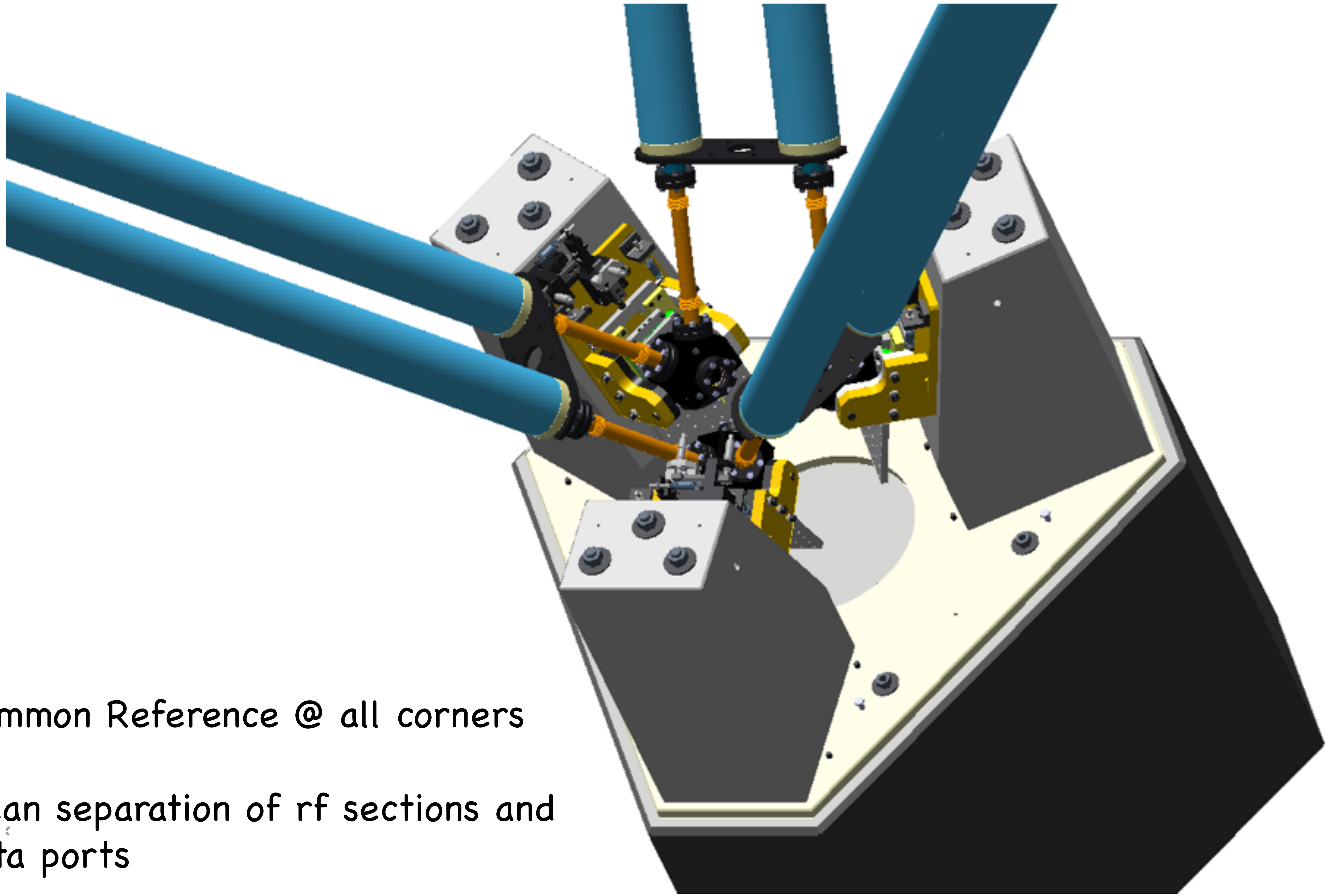
absolute scale factor and absolute orientation … and stability

ROMY- Structure

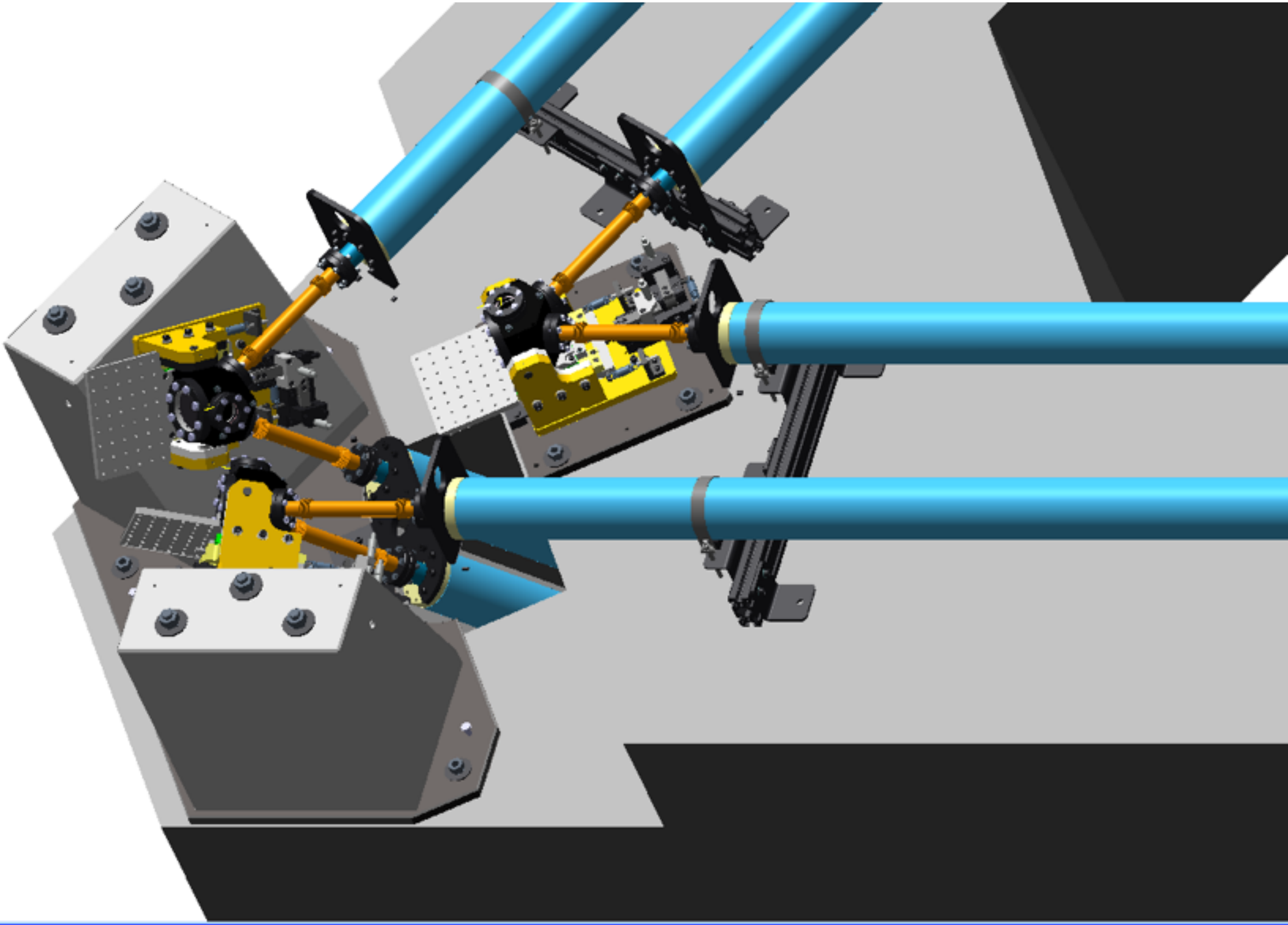


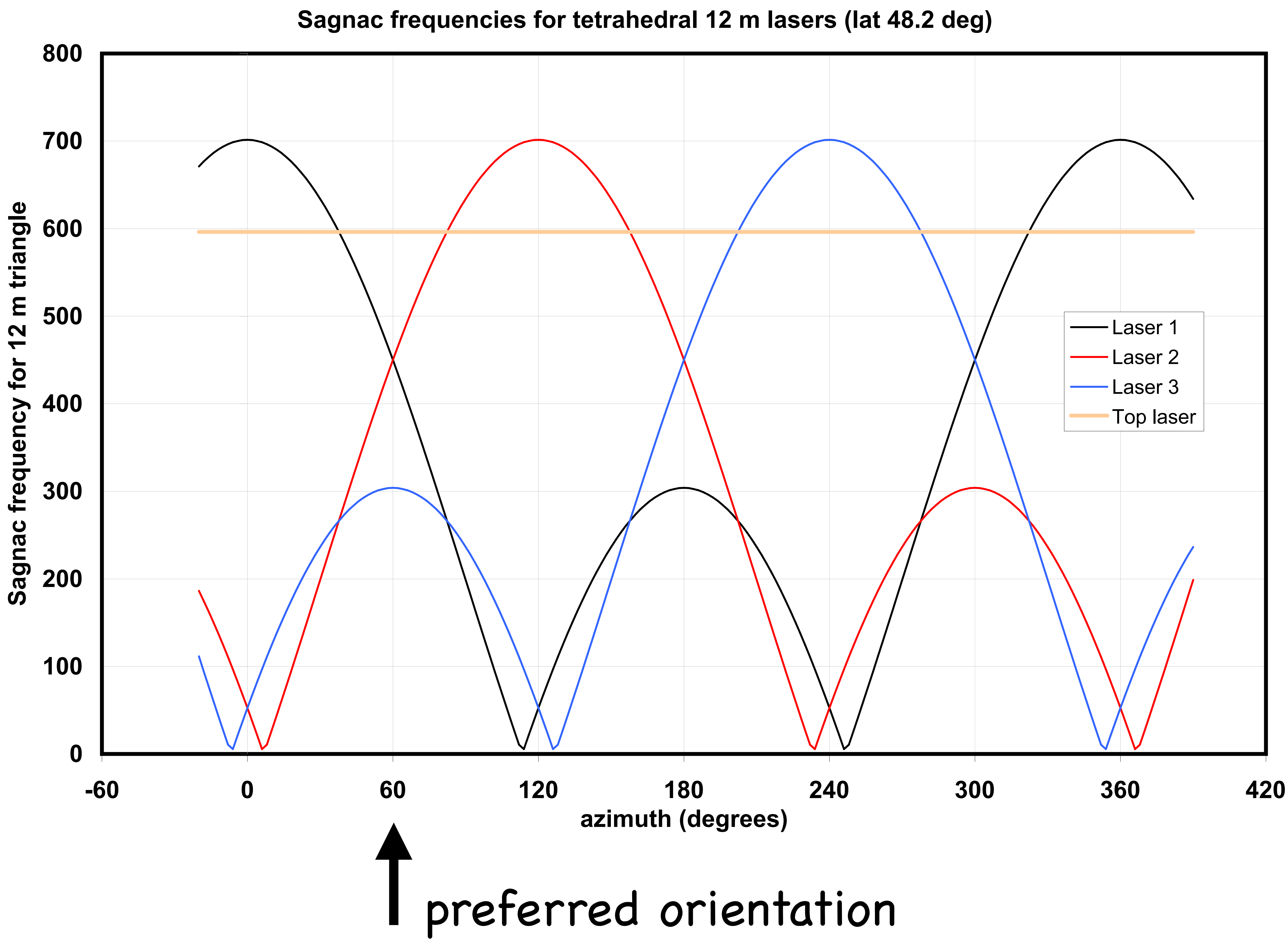
- 4 rings (redundancy)
- larger scale factor (x2)
- symmetric triangular structure
- new generation of mirror design
- active control option

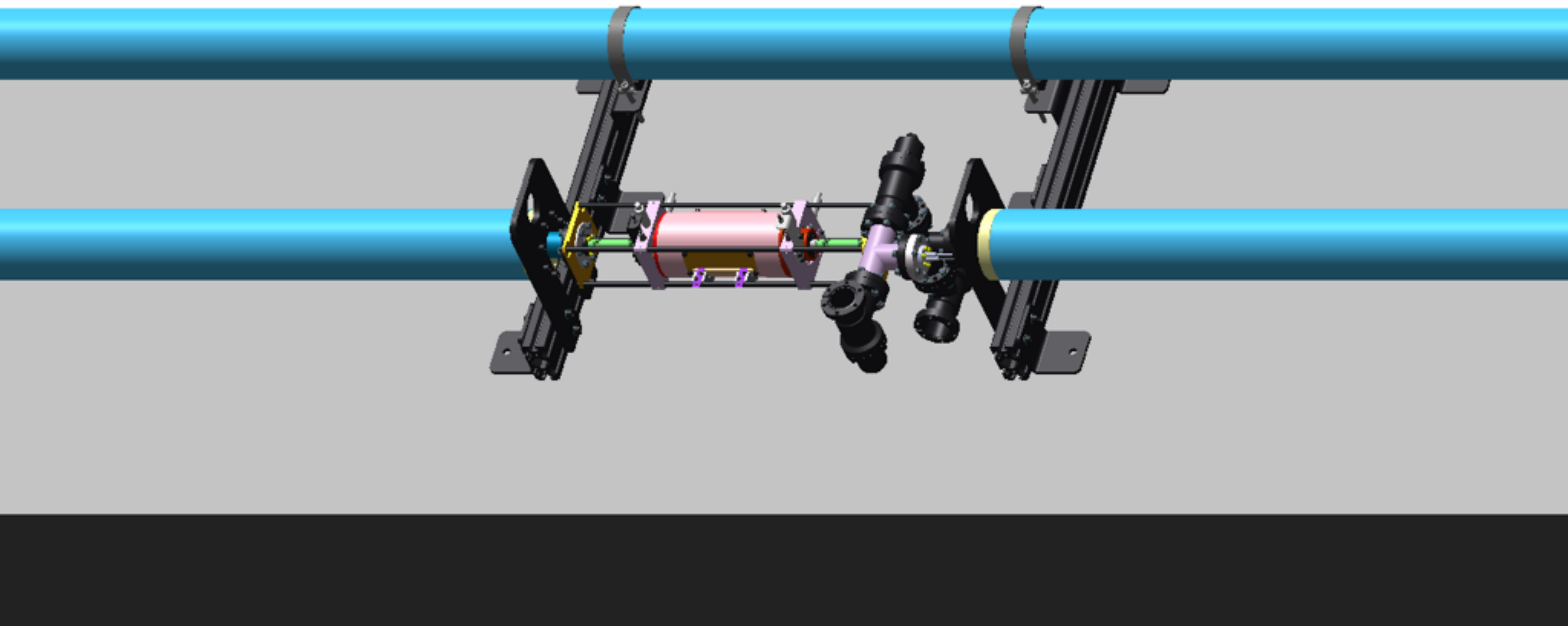
- heterolithic structure
- bottom and top not well referenced to each other



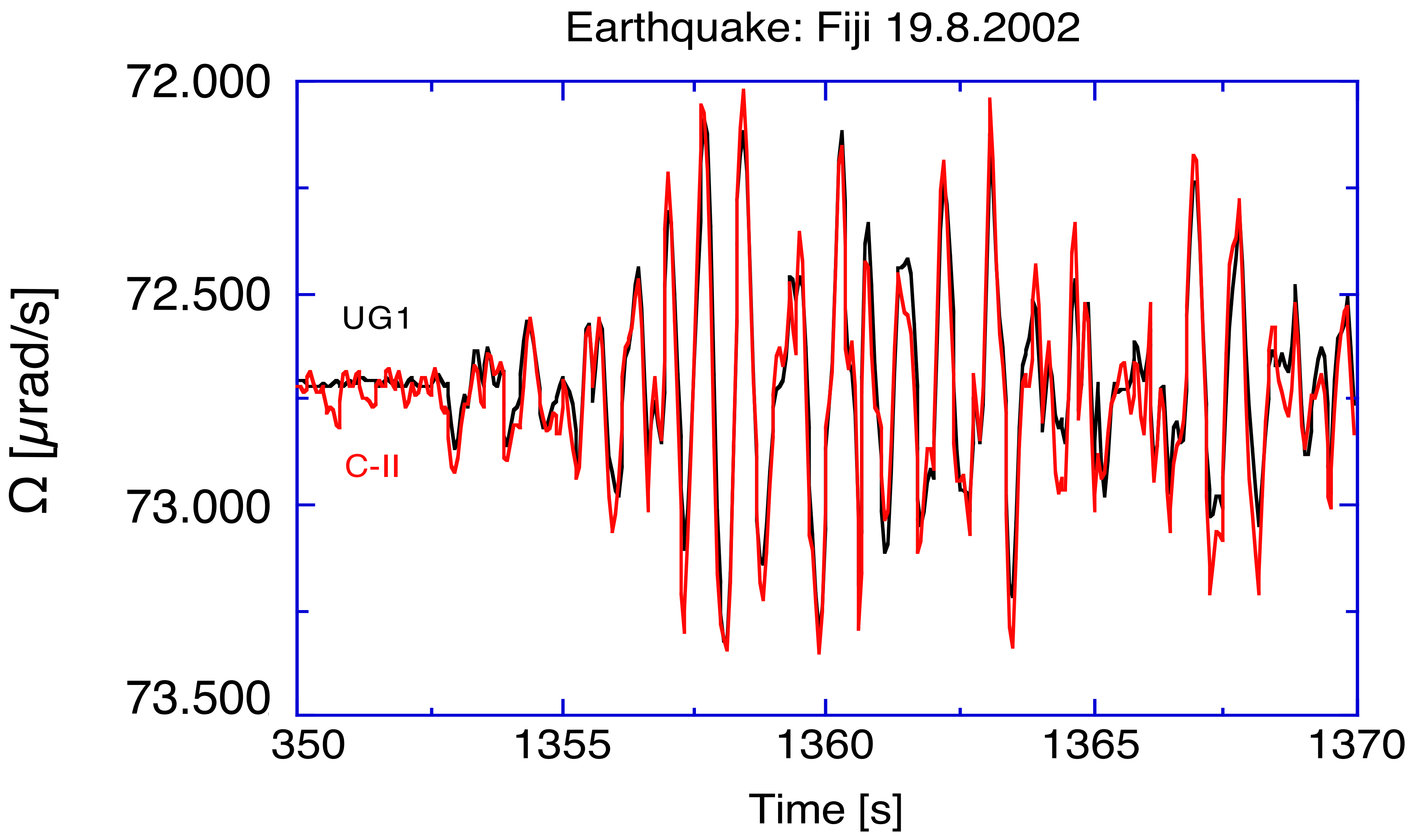
- Common Reference @ all corners
- clean separation of rf sections and data ports



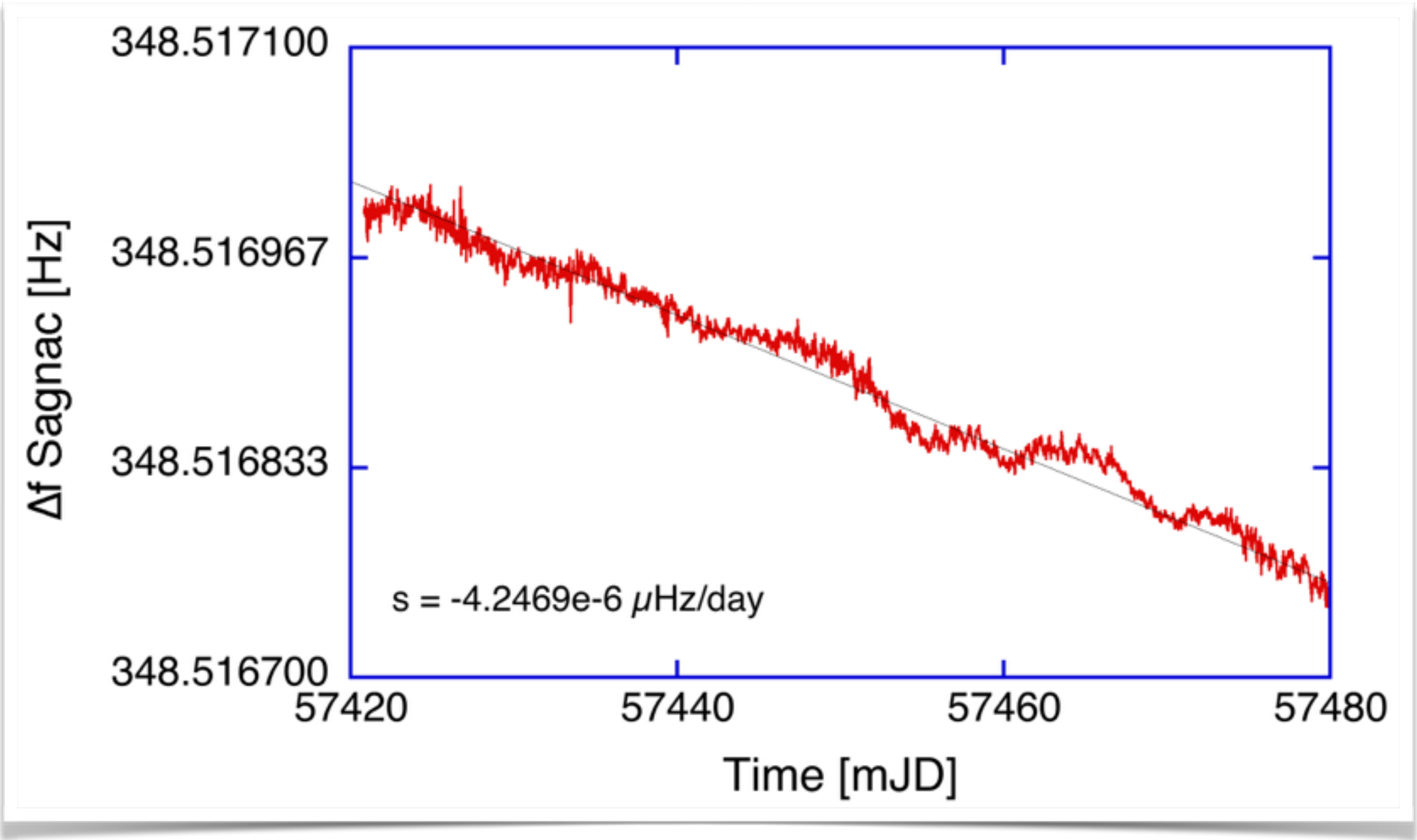

Sagnac frequencies for tetrahedral 12 m lasers (lat 48.2 deg)
Sagnac frequency for 12 m triangle
800
700
600
500
400
300
200
100
0
-60
0
60
120
180
240
300
360
420
azimuth (degrees)
Laser 1
Laser 2
Laser 3
Top laser
preferred orientation



Ring laser have a very large dynamic range and a transfer function of unity (no mechanical components)

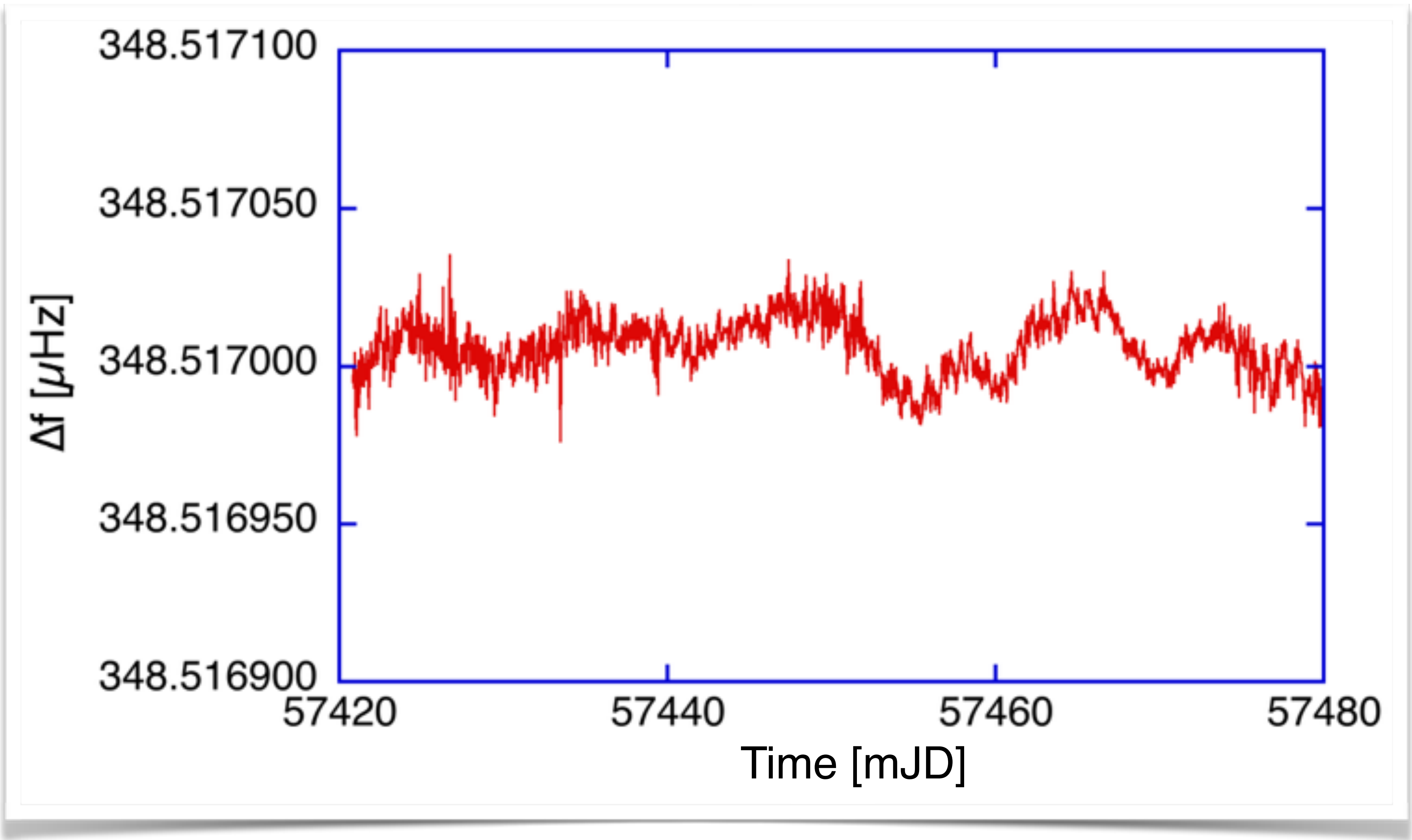


Where are we right now (2016) ?

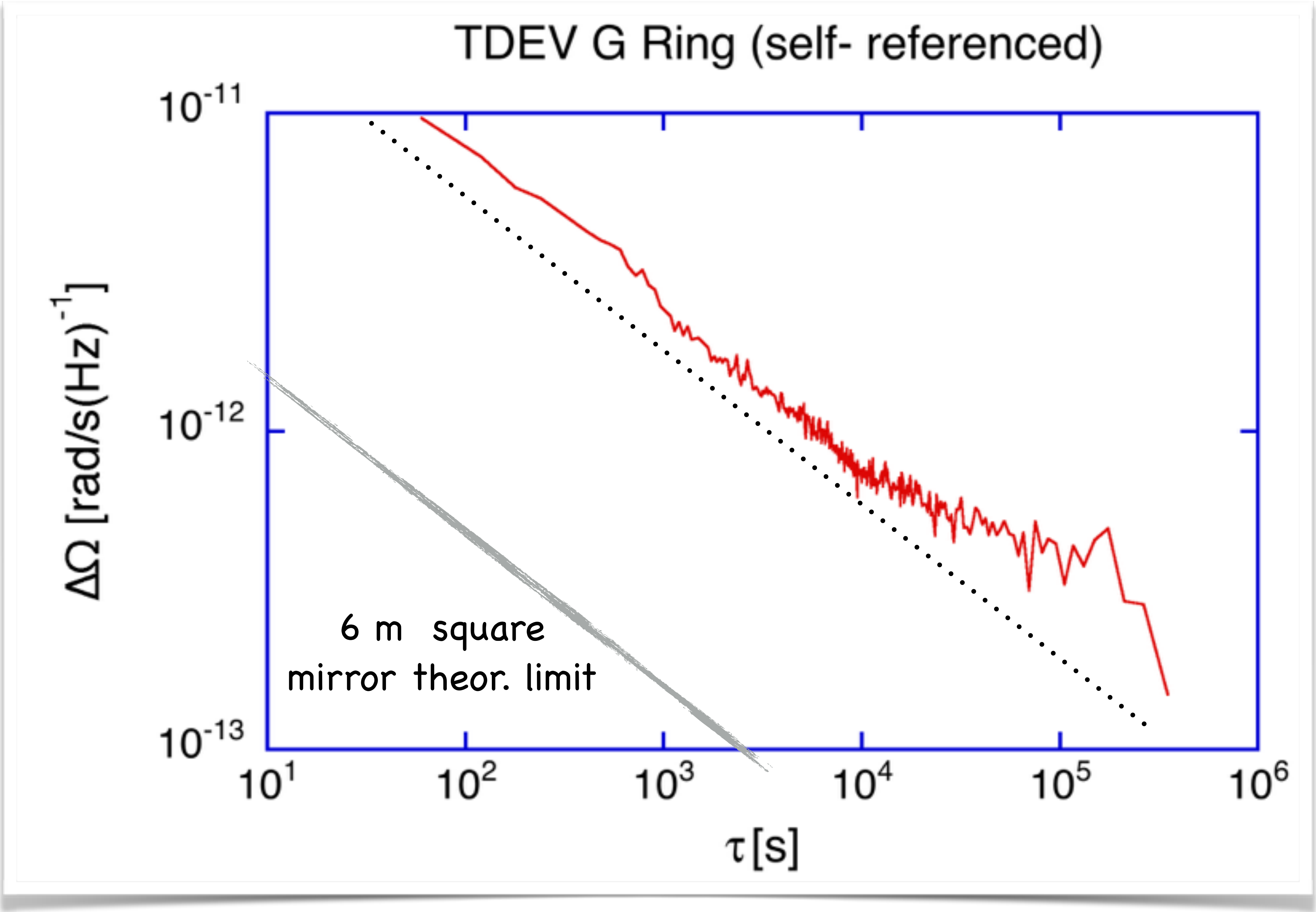


We accumulate a drift - maybe the limitation of the backscatter correction

Where are we right now (2016) ?



We accumulate a drift - maybe the (current) limitation of the backscatter correction or beam power stabilization



TDEV G Ring (self- referenced)
10-11
10-12
10-13
ΔΩ [rad/s(Hz)-1]
6 m square
mirror theor. limit
10^1
10^2
10^3
10^4
10^5
10^6
τ [s]