Near-unstable cavities for future gravitational wave detectors

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A brief introduction of myself Haoyu Wang

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Zonghong Zhu

Motivation

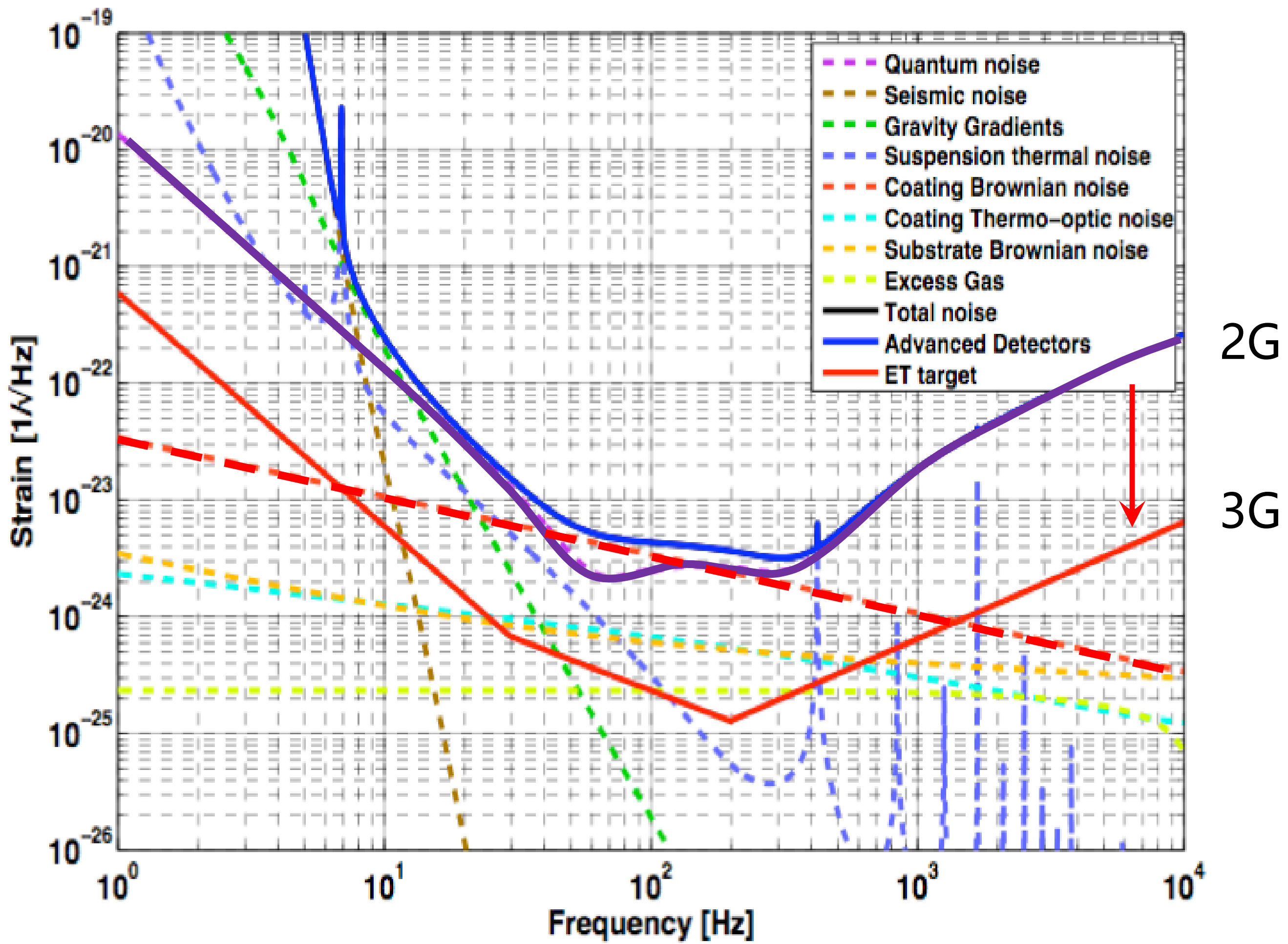
Coating thermal noise

Molecular Brownian motion

Thermally excited vibrational modes

Ways to reduce:

- Cryogenic techniques: reduce T
- Better coatings: lower losses
- Improve configuration: larger beam size



Near-unstable cavity (NUC)

- Stability criterion:

$$0 < g_1 g_2 < 1,$$

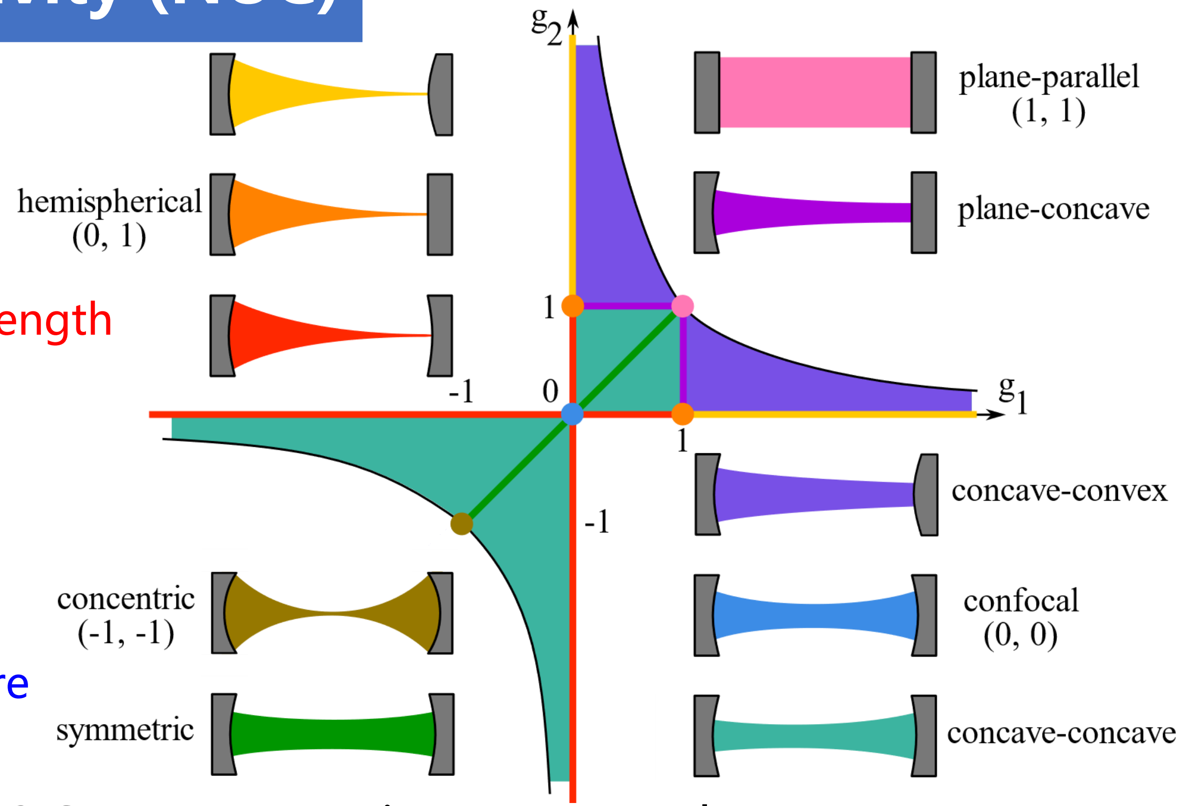
with

$$g_1 = 1 - \frac{L}{R_{c1}}$$

$$g_2 = 1 - \frac{L}{R_{c2}}$$

cavity length

radius of curvature



An old document: LIGO 3 Strawman Design, Team Red (LIGO DCC/public/T1200046)

Input mirror: 5.31cm -> 8.46cm (60%)
End mirror: 6.21cm -> 9.95cm (60%)

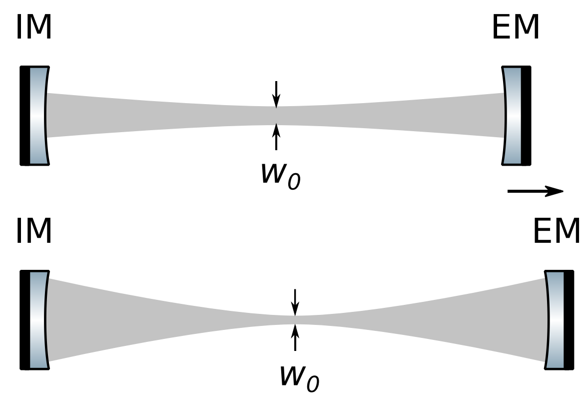
g-factor: 0.832 -> 0.974

Coating thermal noise expected to be reduced by a factor of 1.6 by using larger beam size on arm cavity mirrors

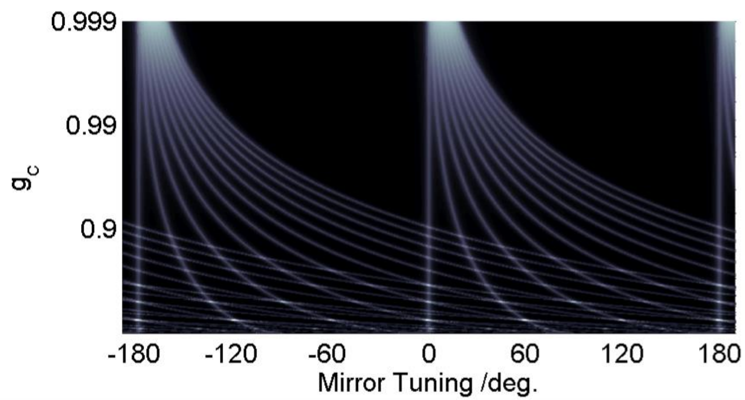
- Recycling cavities in Advanced Virgo currently are near-unstable

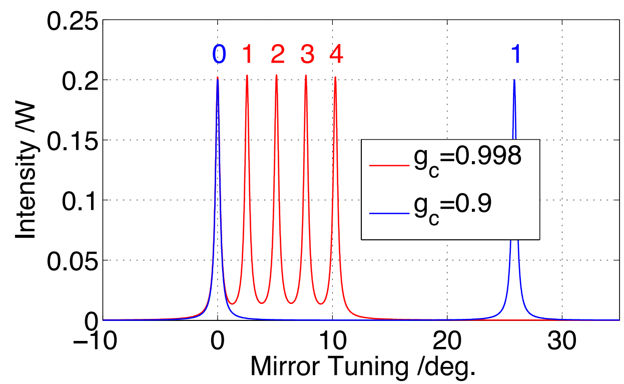
Problems of NUCs

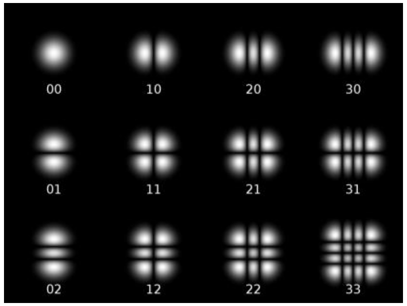
- Beam parameters change dramatically: easy to lose stability



- Mode bunching: lack of Gouy phase

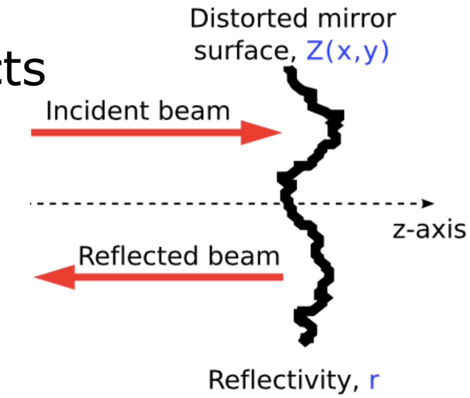


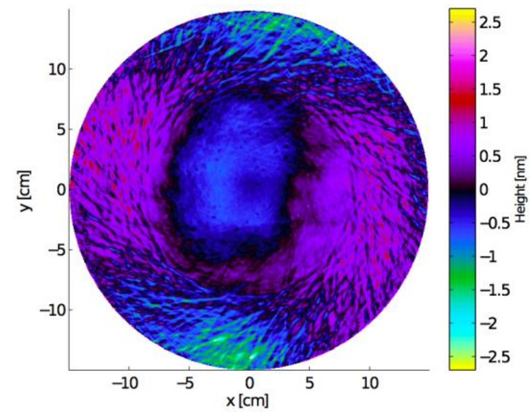




- Easily affected by mirror defects

TEM00 -> TEM01, TEM02, ...

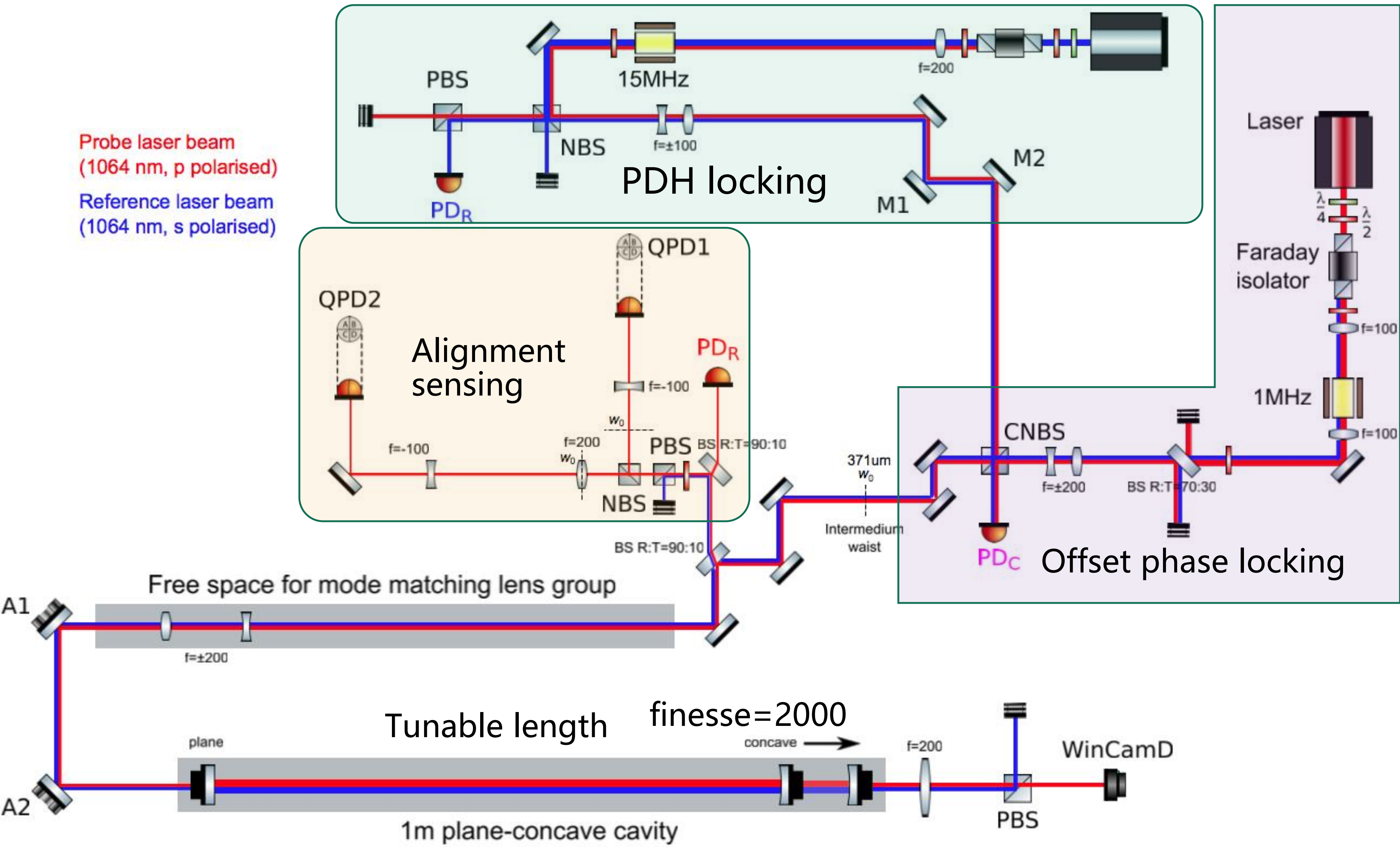




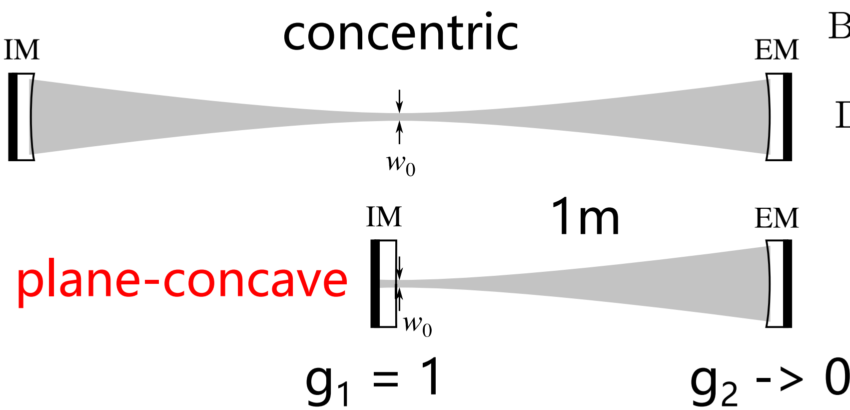
- Angular instability

Tabletop Experiment https://doi.org/10.1103/PhysRevD.97.022001

Goal: how far away can we go towards the stability edge without causing too much problems?

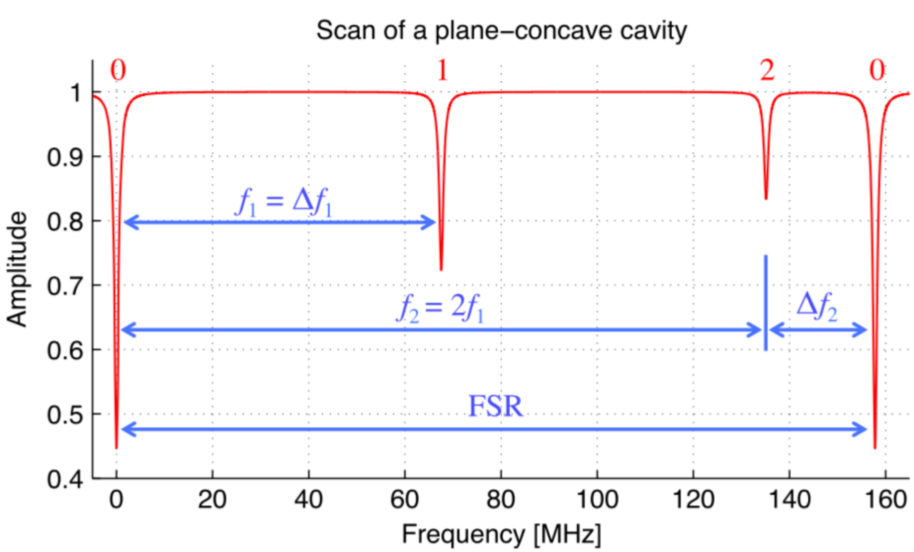


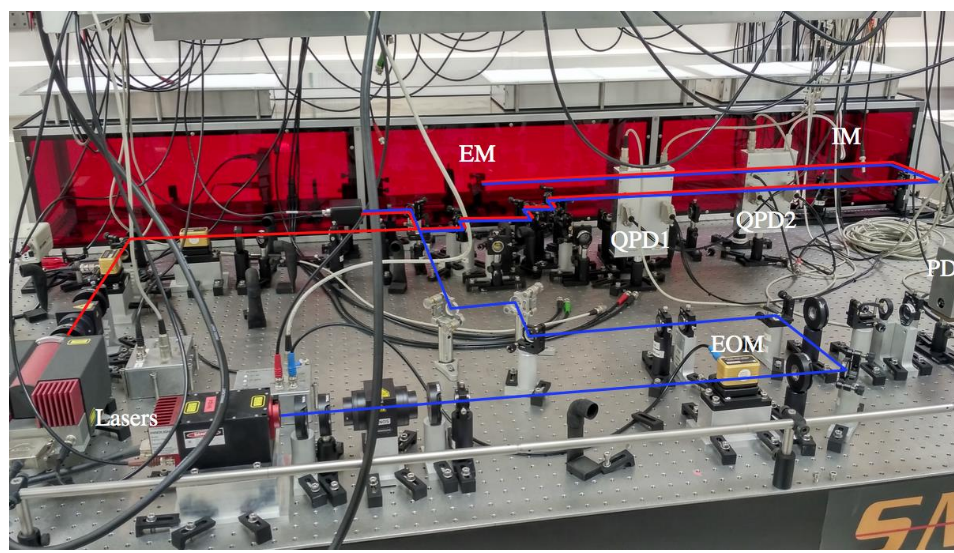
The plane-concave cavity



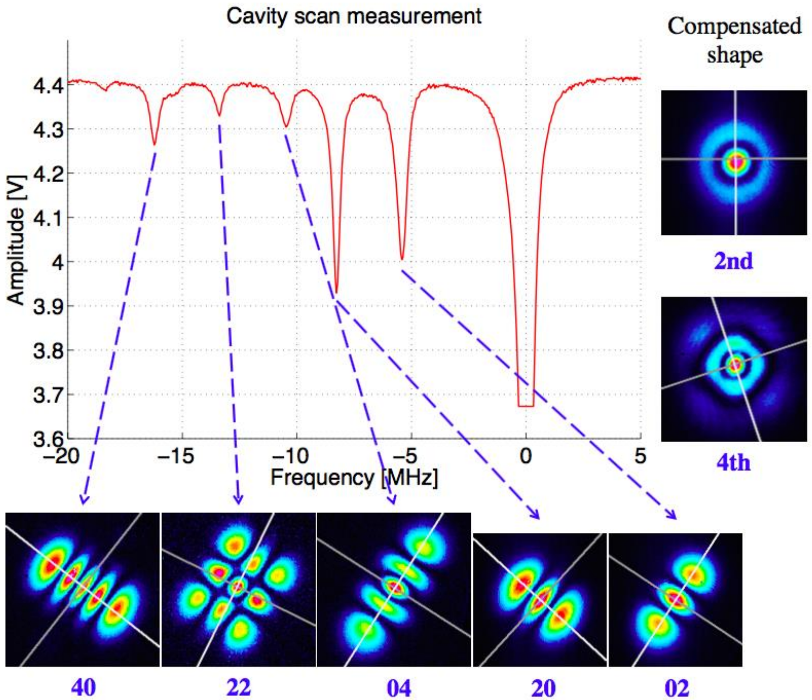
Parameters of our plane-concave cavity

Cavity length (m)	0.956	0.993	0.999	0.9999
Beam waist (μm)	263.56	168.04	103.46	58.19
Beam spot at EM (mm)	1.26	2.01	3.27	5.82
Rayleigh range (mm)	205.10	83.37	31.61	10.00
Divergent angle (mrad)	1.29	2.02	3.27	5.82
FSR (MHz)	156.80	150.95	150.05	149.91
f_1 ($\times$FSR)	0.433	0.474	0.490	0.497
f_2 ($\times$FSR)	0.865	0.947	0.980	0.994
δ_2	563.2	223.2	84.6	26.6
g_c	0.044	0.007	0.001	0.0001
g_c^*	0.832	0.972	0.996	0.9996

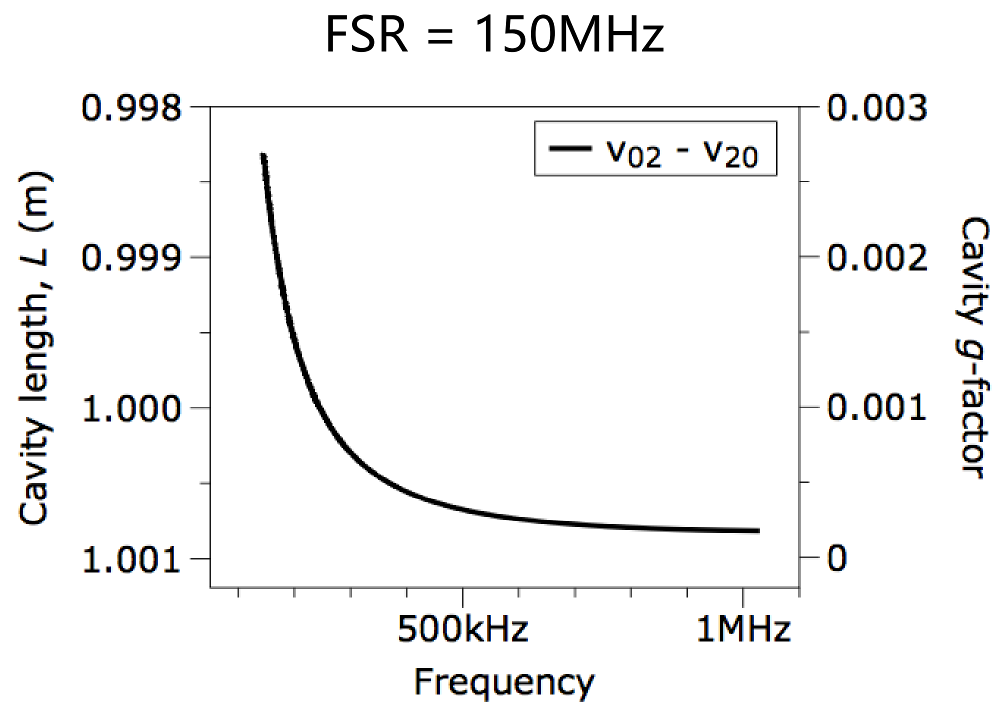




Mode splitting observed



Mode splitting observed
(measurement)



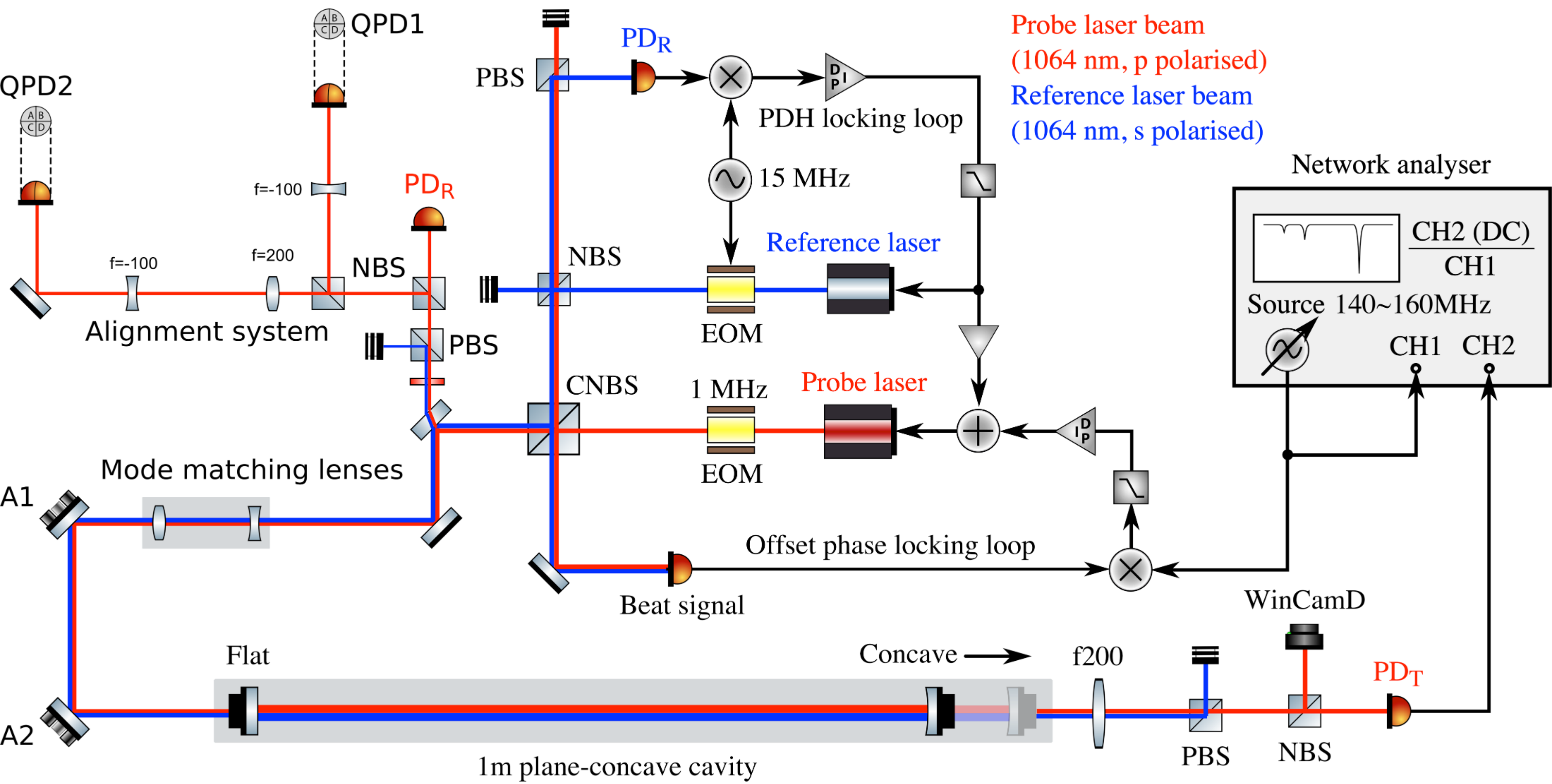
Mode splitting as a function of g-factor
(simulation)

The surface of the EM is ellipsoidal.

The separation can be reduced by increasing the stress of the screw holding the spherical mirror, thus compensating the surface deformation.

The measurement

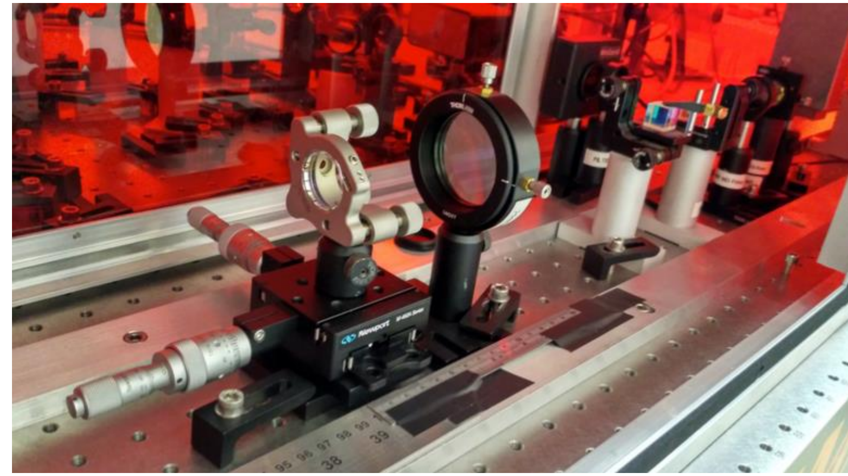
- We measure resonant frequencies of 2nd modes and the fundamental mode.

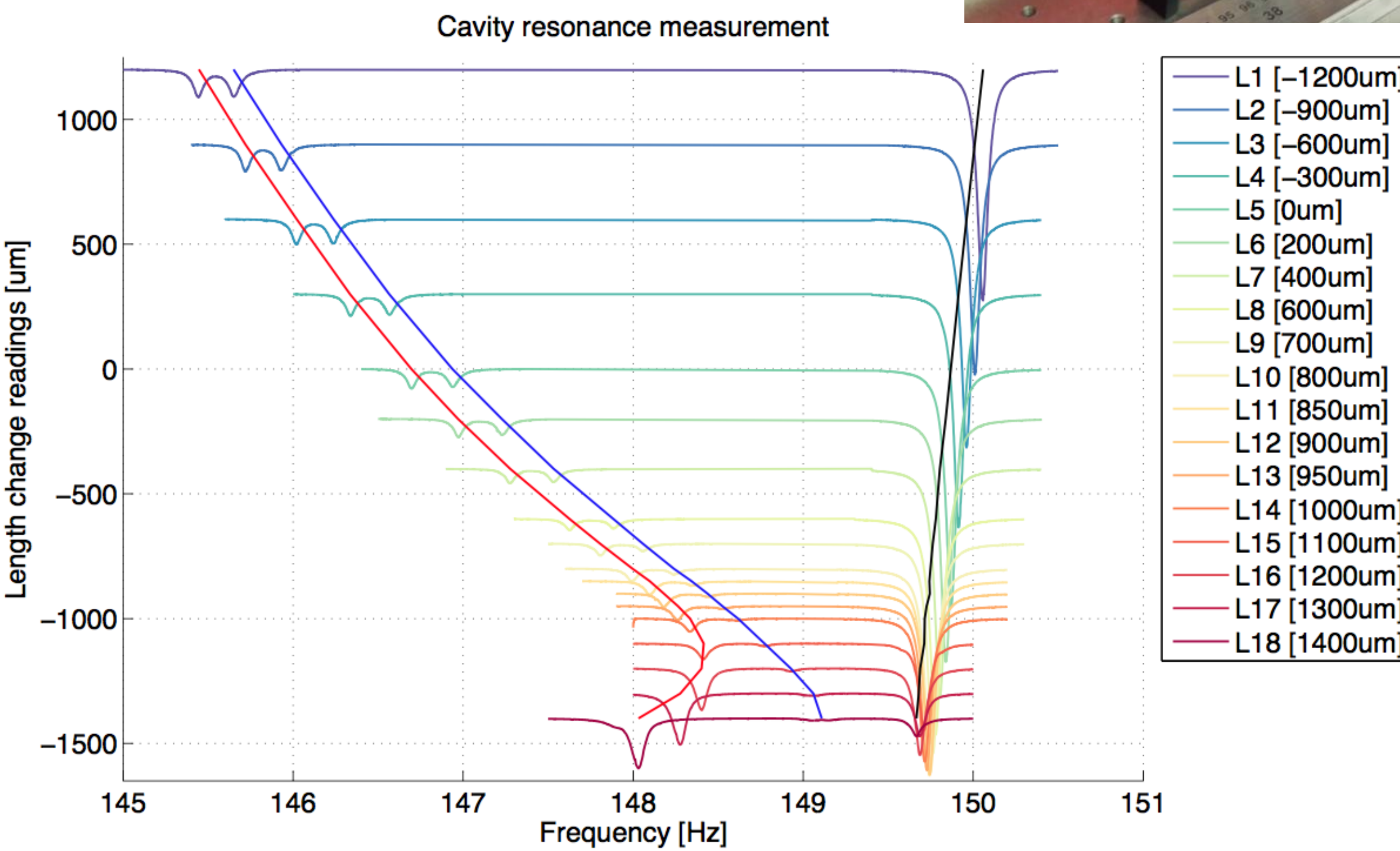


Measurement of resonances

Cavity length as a function of mode spacing frequency for the plane-concave cavity

$$L_0 + \Delta L = \frac{R_c}{2}\left[1 - \cos\left(\frac{\Delta f^{02}}{\mathrm{FSR}}\pi\right)\right]$$

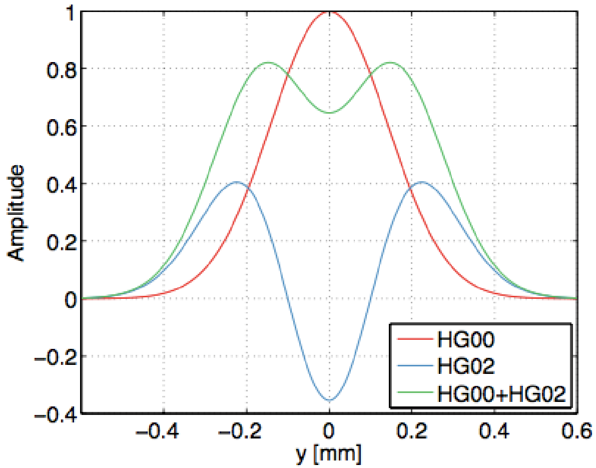




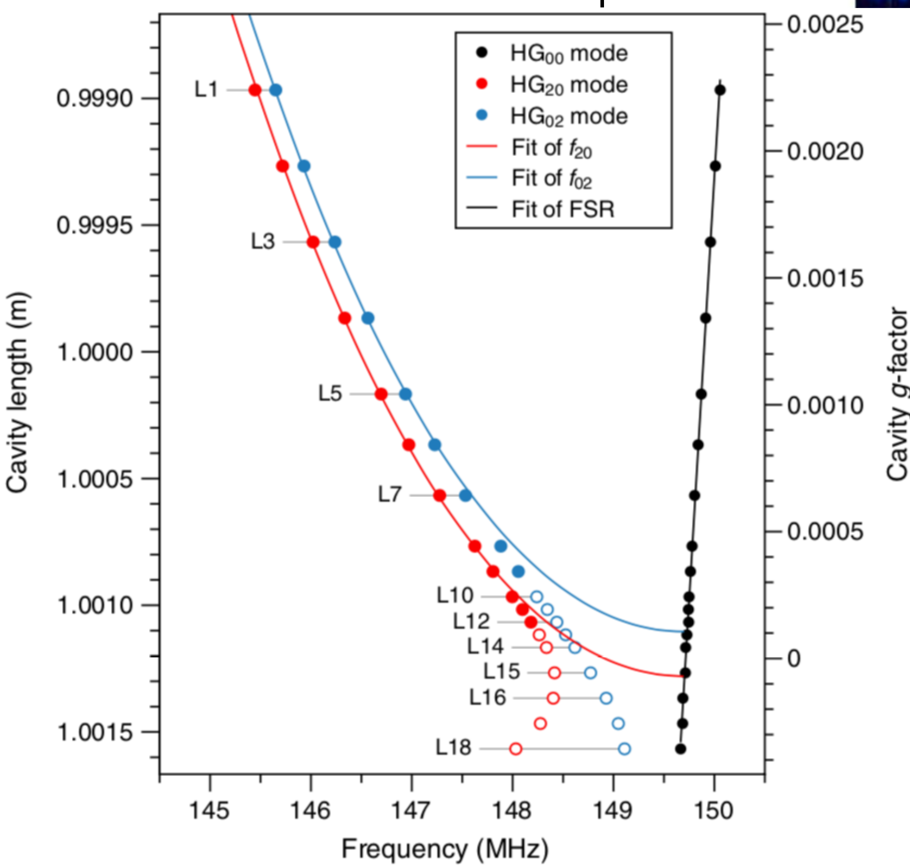
We change the position of the concave end mirror via a translation stage and take 18 measurements.

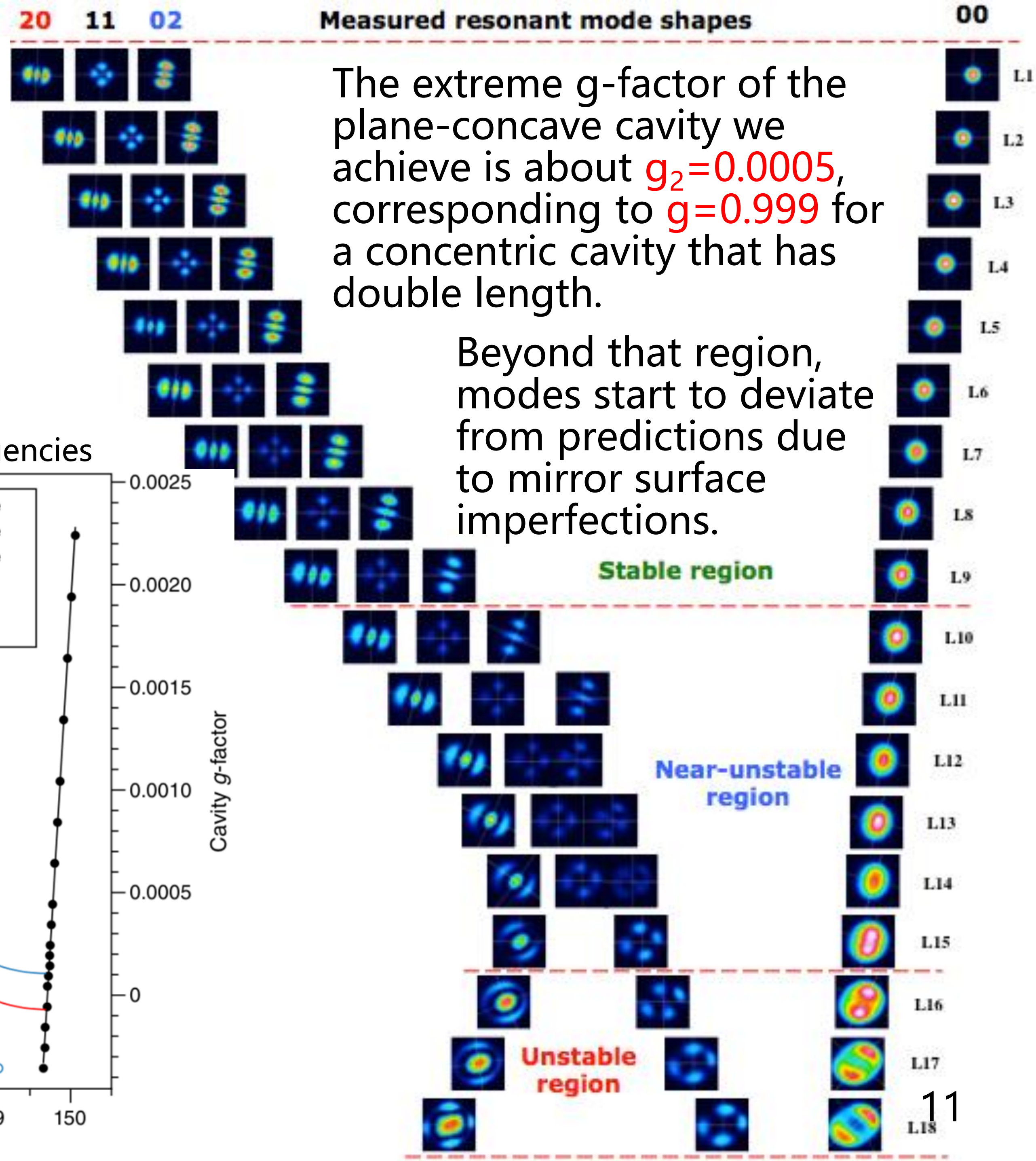
The mode matching is very difficult.

sum of HG00 and HG20 modes



Measured modes' frequencies

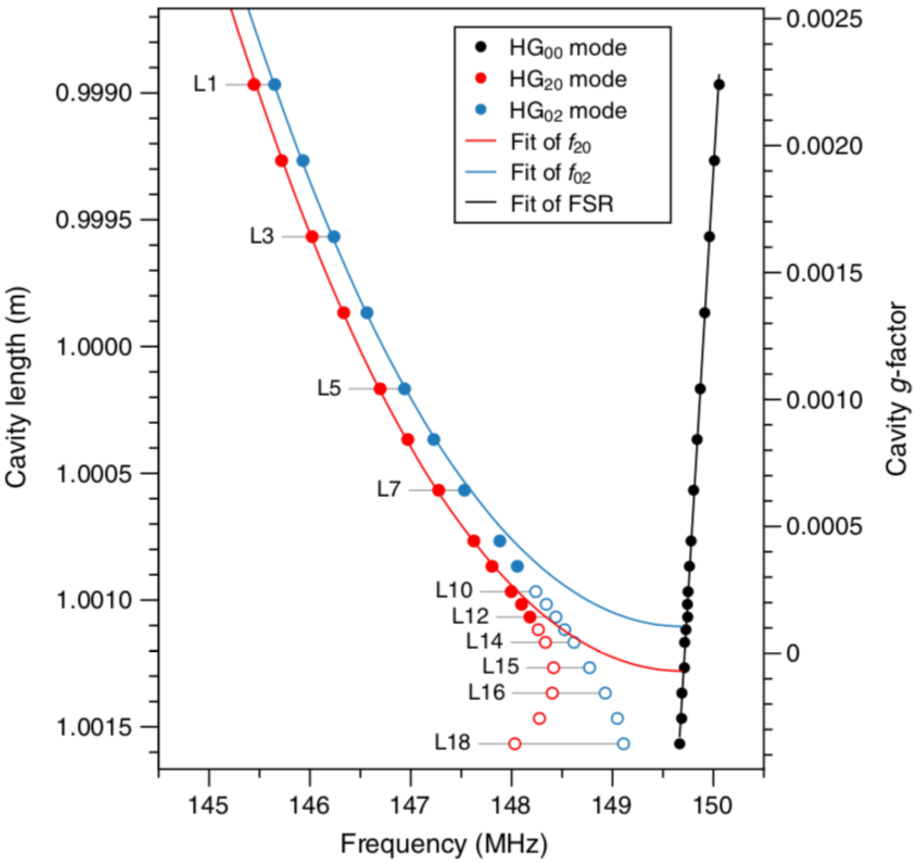




The extreme g-factor of the plane-concave cavity we achieve is about $g_2=0.0005$, corresponding to $g=0.999$ for a concentric cavity that has double length.

Beyond that region, modes start to deviate from predictions due to mirror surface imperfections.

Fitting the frequency change



$$L_0 + \Delta L = \frac{R_{2+}}{2}\left[1 - \cos\left(\frac{f_{20}}{\mathrm{FSR}}\pi\right)\right]$$

$$L_0 + \Delta L = \frac{R_{2-}}{2}\left[1 - \cos\left(\frac{f_{02}}{\mathrm{FSR}}\pi\right)\right]$$

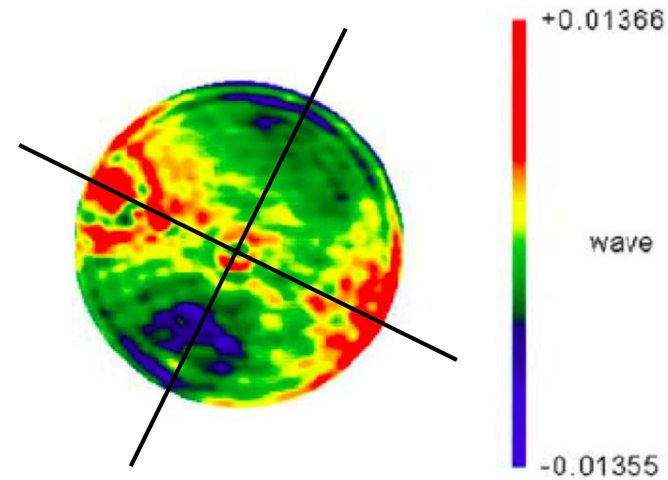
R_{2+} = 1,001,284.9 ± 4.6 μm

R_{2-}= 1,001,140.0 ± 15.7 μm

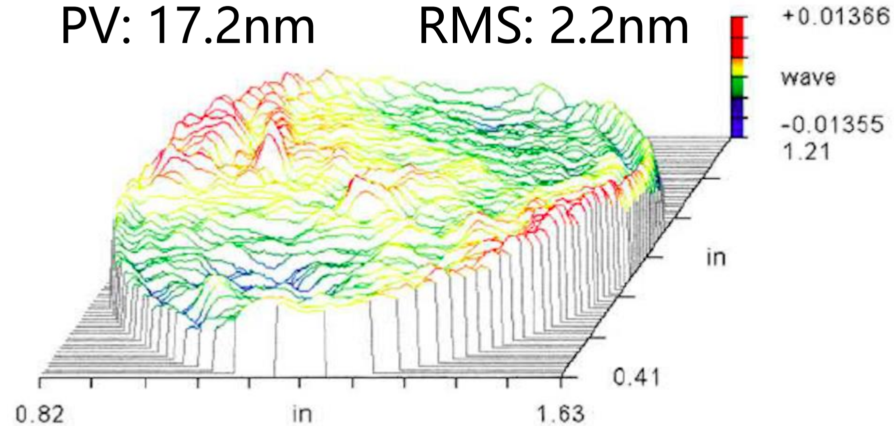
The difference is about 145 μm

ZYGO measurement

The mirror map: phase map



PV: 17.2nm RMS: 2.2nm

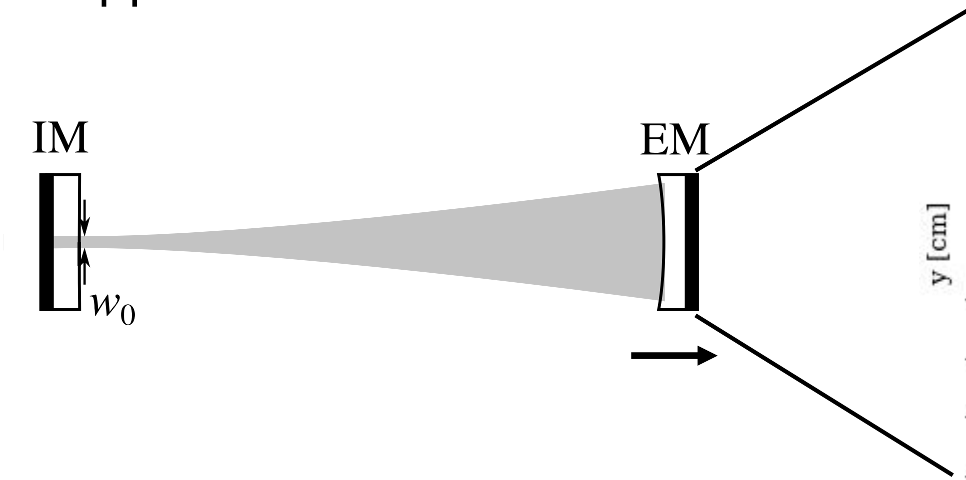


By fitting mode frequency changes,

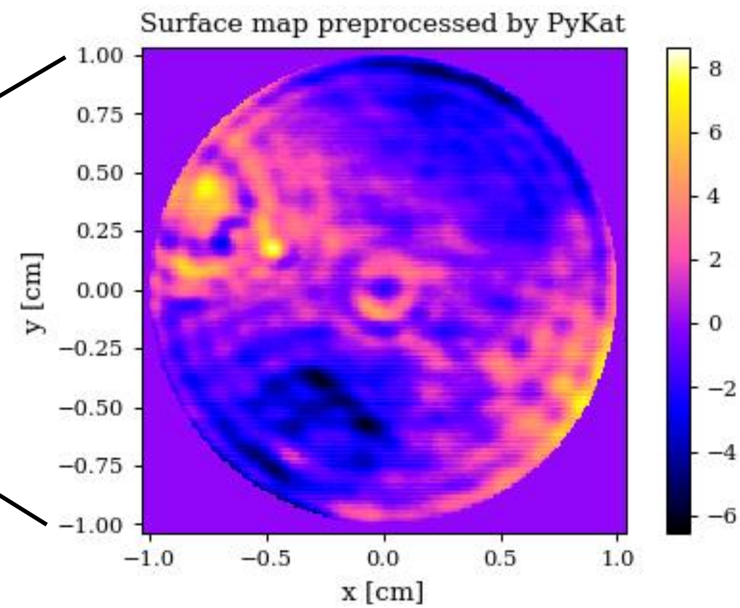
- we can quantify the stability
- study mode behaviors
- it is possible to infer the shape of the mirror surface

FINESSE simulation

The measured mirror map is applied the the EM in FINESSE.

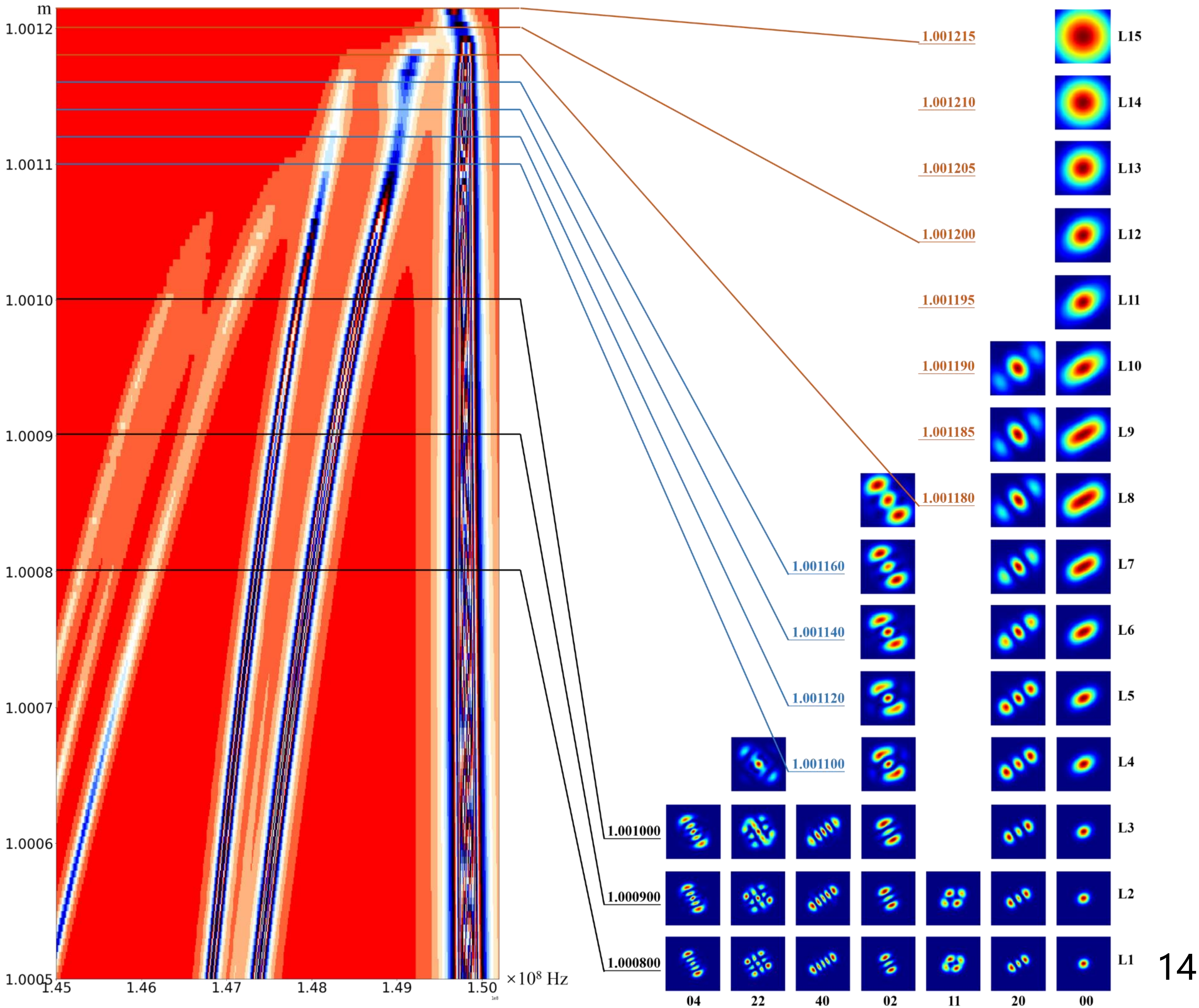


The phase map processed by FINESSE.



The goal of the simulation is trying to understand mode deviations.

We use FINESSE to derive resonances and shapes of the higher order modes and the 00 mode.


m
1.0012
1.0011
1.0010
1.0009
1.0008
1.0007
1.0006
1.0005
1.45
1.46
1.47
1.48
1.49
1.50
×10^8 Hz
1.001215
1.001210
1.001205
1.001200
1.001195
1.001190
1.001185
1.001180
1.001160
1.001140
1.001120
1.001100
1.001000
1.000900
1.000800
L15
L14
L13
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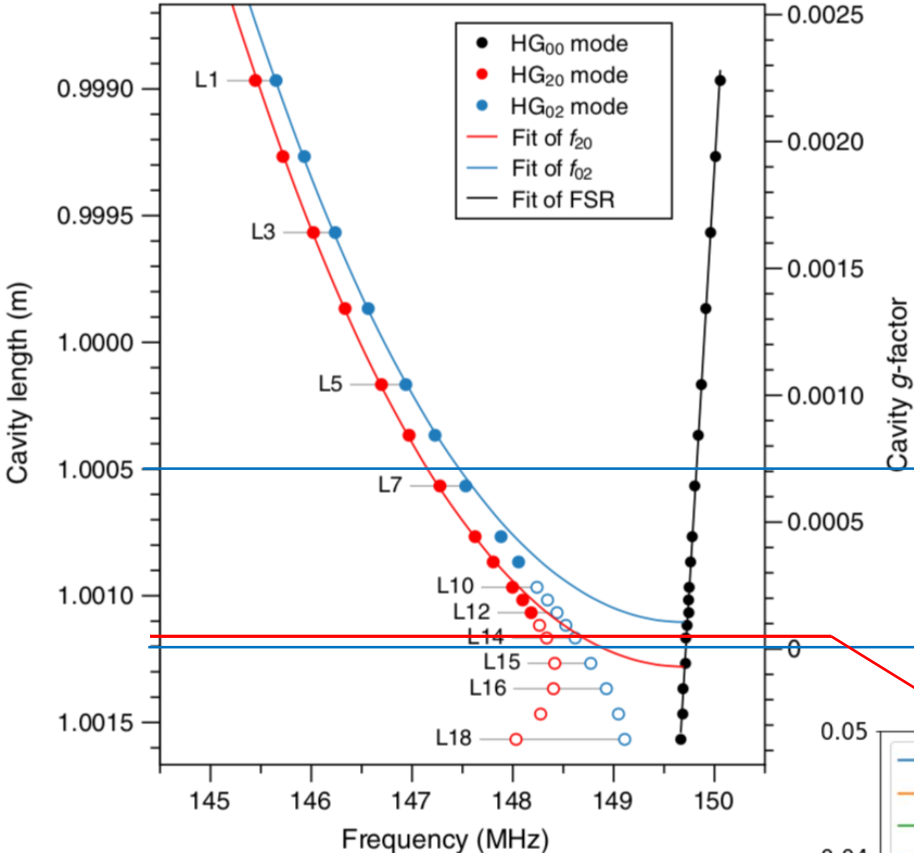
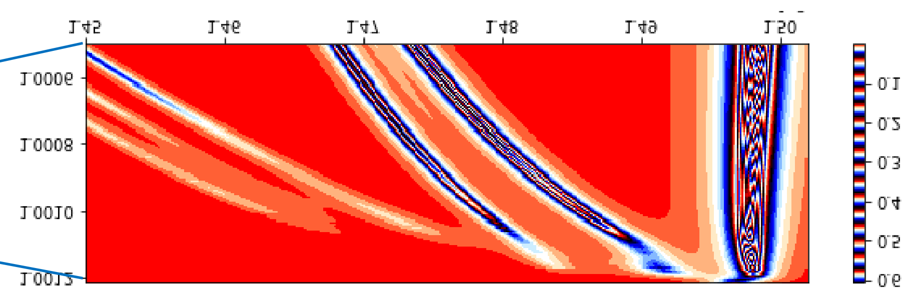
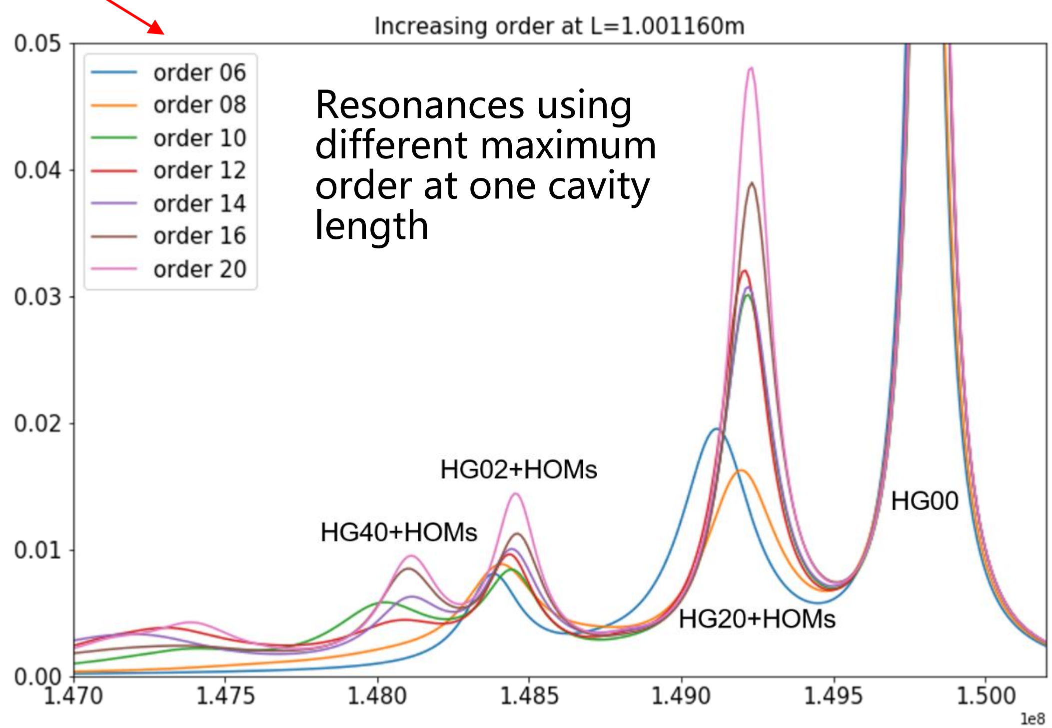


The maximum HOM order taken into account for calculation is 6.





However, the maximum order of HOMs for calculation does matter very much.

The higher the maximum order taken into account, the longer the calculation time.

Summary

- In order to use larger beam size on cavity mirrors to reduce coating thermal noise for 3rd generation GW detectors, we need to push the cavity to the edge of stability.
- A tabletop setup had been built to investigate the performance of NUCs and some preliminary results are achieved.
- The main factor that determines the mode behavior in this extreme near-unstable condition is instead thought to be mirror imperfections
- We are working hard on simulations trying to explain measured behaviors of HOMs.

Thank you！