Parametric Instabilities In Advanced Laser Interferometer Gravitational Wave Detectors

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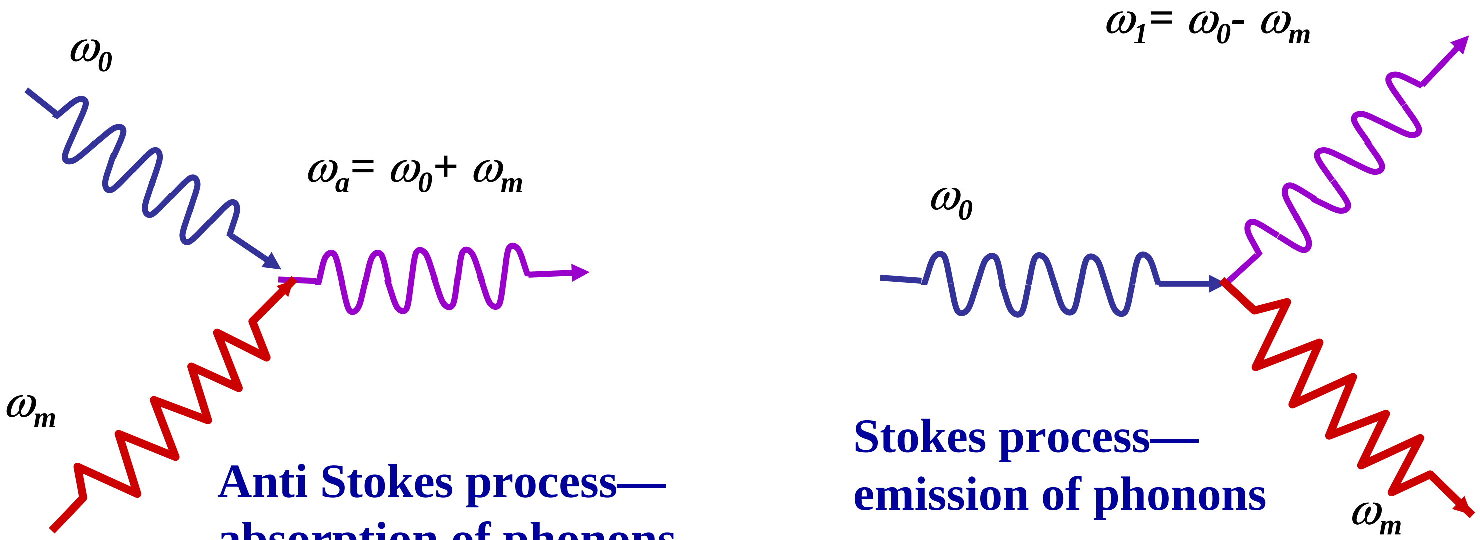
Content

- Parametric instabilities
- Analysis for Adv/LIGO
- Suppression of instabilities
  - Thermal tuning
  - Q reduction
  - Feedback control

When energy densities get high things go unstable…

- **Braginsky et al predicted parametric instabilities can happen in advanced detectors**
  - **resonant scattering of photons with test mass phonons**
  - **acoustic gain like a laser gain medium**

Photon-phonon scattering



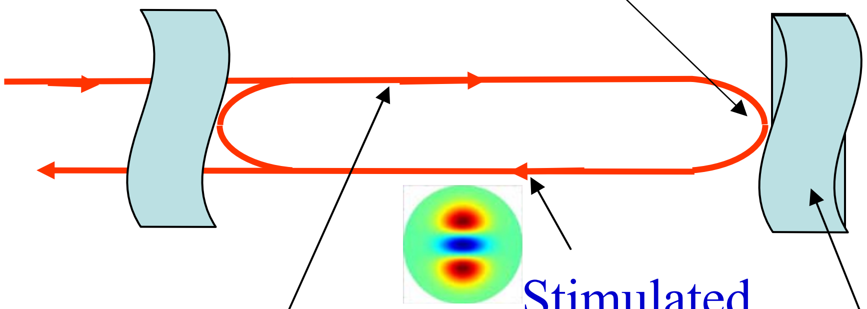
Anti Stokes process—absorption of phonons

Stokes process—emission of phonons

Instabilities from photon-phonon scattering

- A test mass phonon can be **absorbed** by the photon, increasing the photon energy (damping);
- The photon can **emit** the phonon, decreasing the photon energy (potential acoustic instability).

Schematic of Parametric Instability



Radiation pressure force

input frequency ω_o

$$\omega_0 - \omega_1 = \omega_m$$

Stimulated scattering into ω_1

Cavity Fundamental mode (Stored energy ω_o)

Acoustic mode ω_m

Instability conditions

- **High circulating power P**
- **High mechanical and optical mode Q**

+

- **Mode shapes overlap (High overlap factor Λ)**
- **Frequency coincidence—Δω small**

R>1,
Instability

Unstable conditions

Parametric gain[1]

Stokes mode contribution

Anti-Stokes mode contribution

Power

Mechanical Q

$$R \approx \frac{2PQ_m}{McL\omega_m^2}\left(\frac{Q_1\Lambda_1}{1+\Delta\omega_1^2/\delta_1^2} - \frac{Q_{1a}\Lambda_{1a}}{1+\Delta\omega_{1a}^2/\delta_{1a}^2}\right) > 1$$

$$\Delta\omega_{1(a)} = \left|\omega_0 - \omega_{(1(a)}\right| - \omega_m$$

Fundamental mode frequency

High order transverse mode frequency

Acoustic mode frequency

Λ—overlap factor

$$\delta_{1(a)} = \frac{\omega_{1(a)}}{2Q_{1(a)}}$$

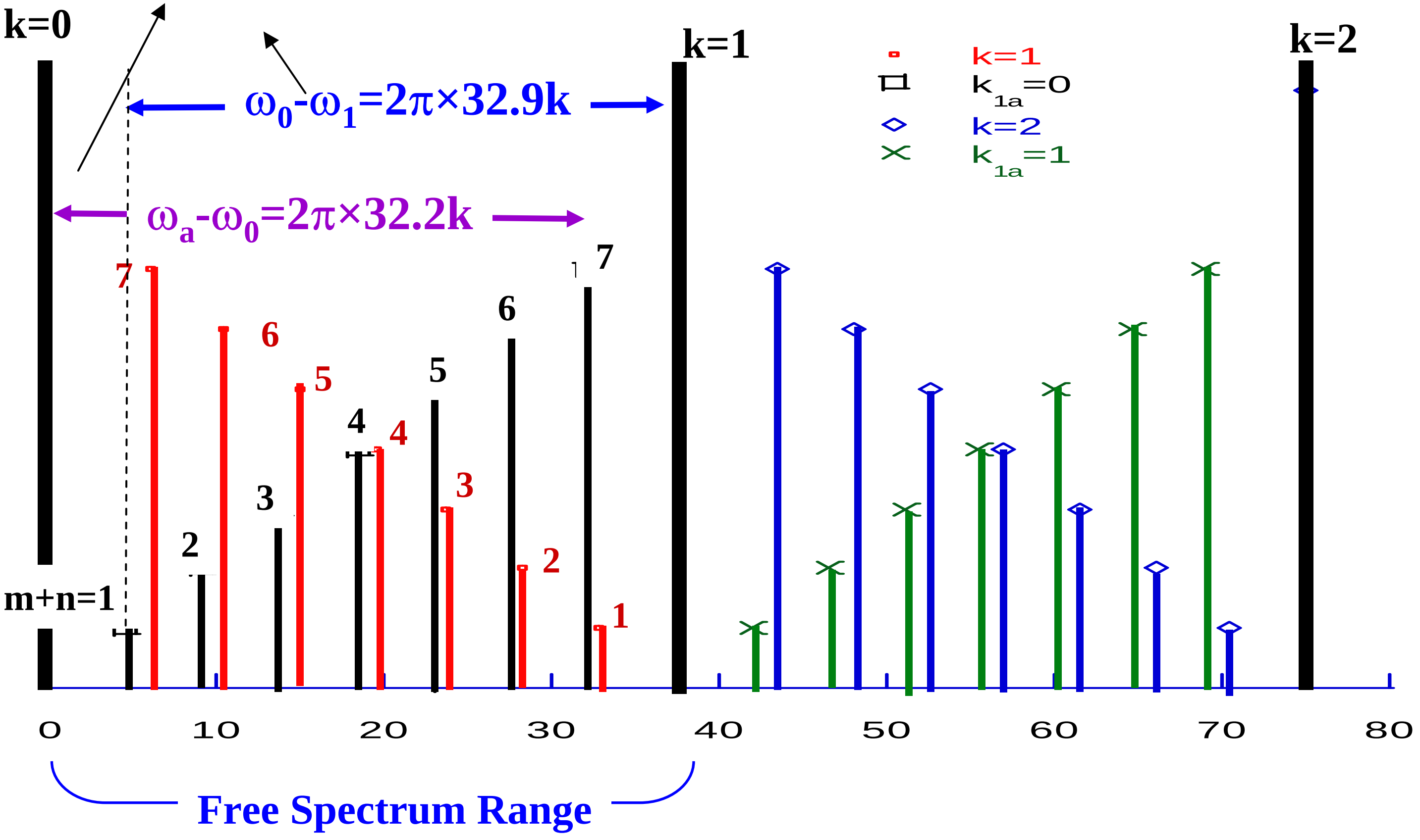
[1] V. B. Braginsky, S.E. Strigin, S.P. Vyatchanin, *Phys. Lett. A*, 305, 111, (2002)

Distribution of Stokes and anti-Stokes modes around carrier modes

$\Delta\omega_1 \sim \Delta\omega_\alpha$

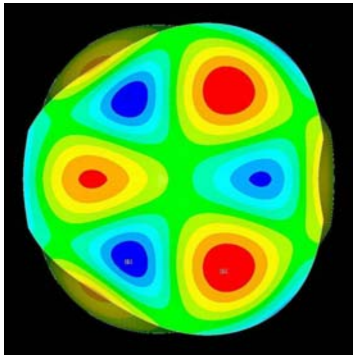
$\delta_1 << \delta_\alpha$

- **Stokes & anti-Stokes modes contributions are usually not compensated**

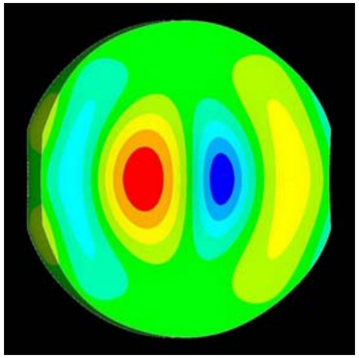


Example of acoustic and optical modes for Al2O3 AdvLIGO

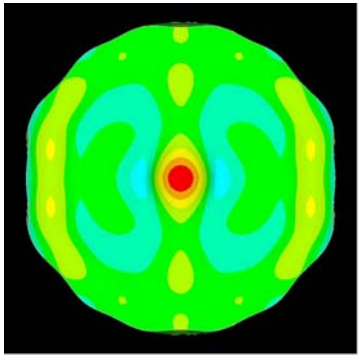
44.66 kHz



47.27 kHz

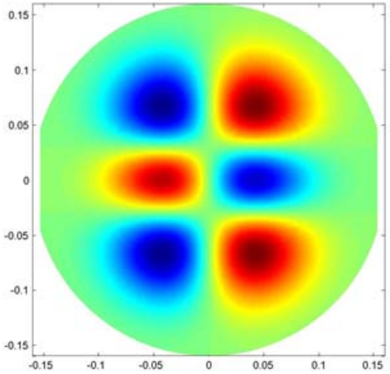


89.45kHz

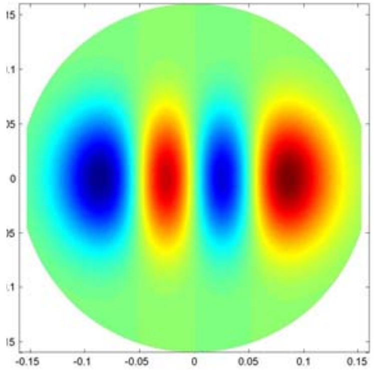


acoustic mode

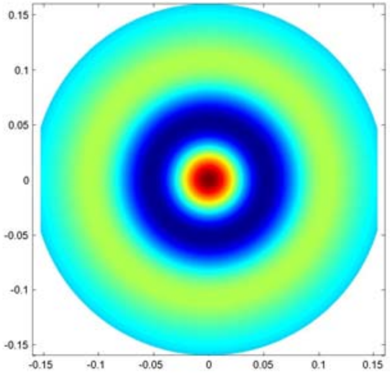
HGM12



HGM30



LGM20

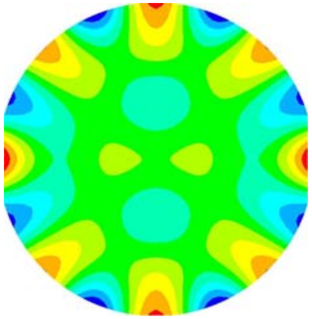


optical mode

Λ	**0.203**	**0.800**	**0.607**

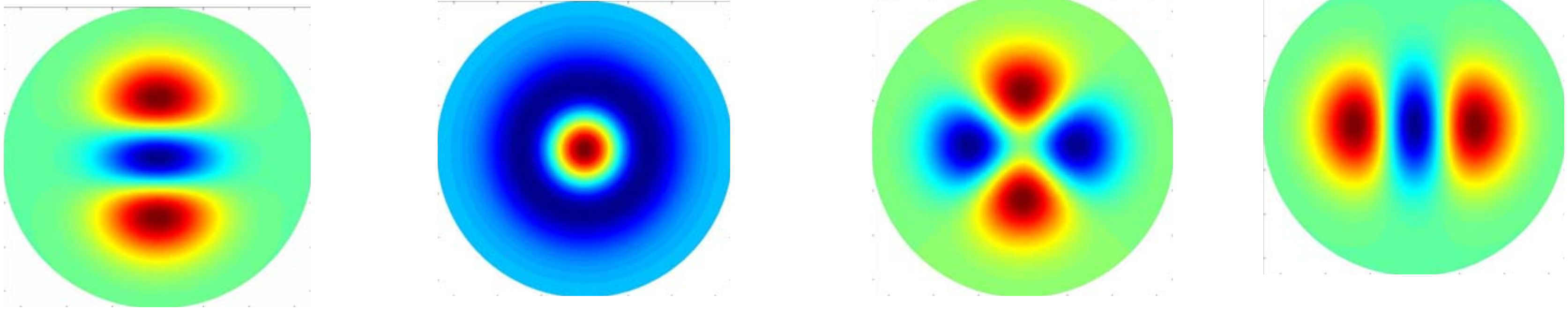
Λ overlapping parameter

Parametric gain—
multiple modes contribution (example)



Mechanical mode shape
(f_m=28.34kHz)

Optical modes



$\Lambda=0.007$
R=1.17

$\Lambda=0.019$
R=3.63

$\Lambda=0.064$
R=11.81

$\Lambda=0.076$
R=13.35

Parametric gain— multiple modes contribution

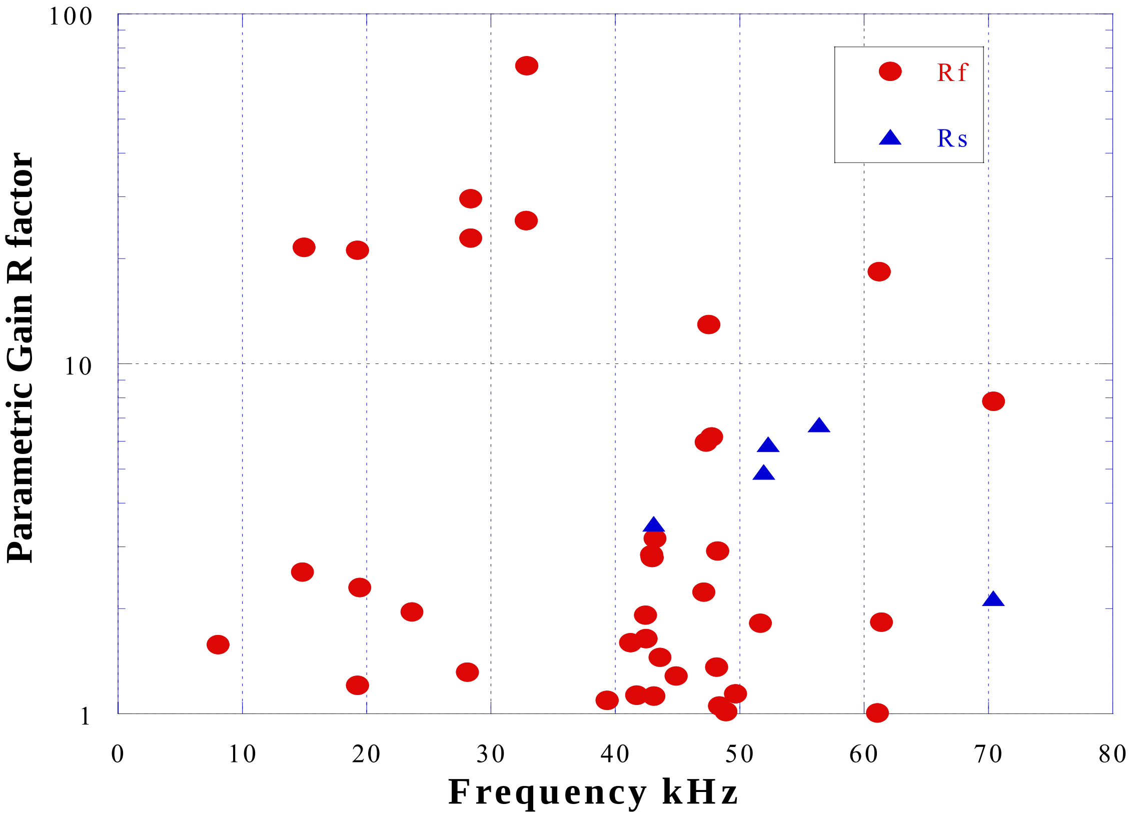
- Many Stokes/anti-Stokes modes can interact with single mechanical modes

- Parametric gain is the **sum** of all the possible processes

$$\boxed{R = \frac{2PQ_m}{McL\omega_m^2}\left(\sum_{i=1}^{\infty}\frac{Q_{1i}\Lambda_{1i}}{1+\Delta\omega_{1i}^2/\delta_{1i}^2} - \sum_{j=1}^{\infty}\frac{Q_{1aj}\Lambda_{1aj}}{1+\Delta\omega_{1aj}^2/\delta_{1aj}^2}\right) > 1}$$

Unstable modes for Adv/LIGO

Sapphire & Fused silica nominal parameters



Fused silica test mass has much higher mode density

- Sapphire—5 unstable modes (per test mass)
- Fused silica—31 unstable modes (per test mass) (6 times more unstable modes)

Instability Ring-Up Time

- For R > 1, ring-up time constant is ~ $\boldsymbol{\tau_m/(R-1)}$

Mechanical ring down time constant

Time to ring from thermal amplitude to cavity position bandwidth (10^{-14}m to 10^{-9} m) is

~ 100-1000 sec.

- To prevent breaking of interferometer lock, cavities must be controlled within ~100 s or less

Suppress parametric instabilities

- **Thermal tuning**
- **Mechanical Q-reduction**
- **Feedback control**

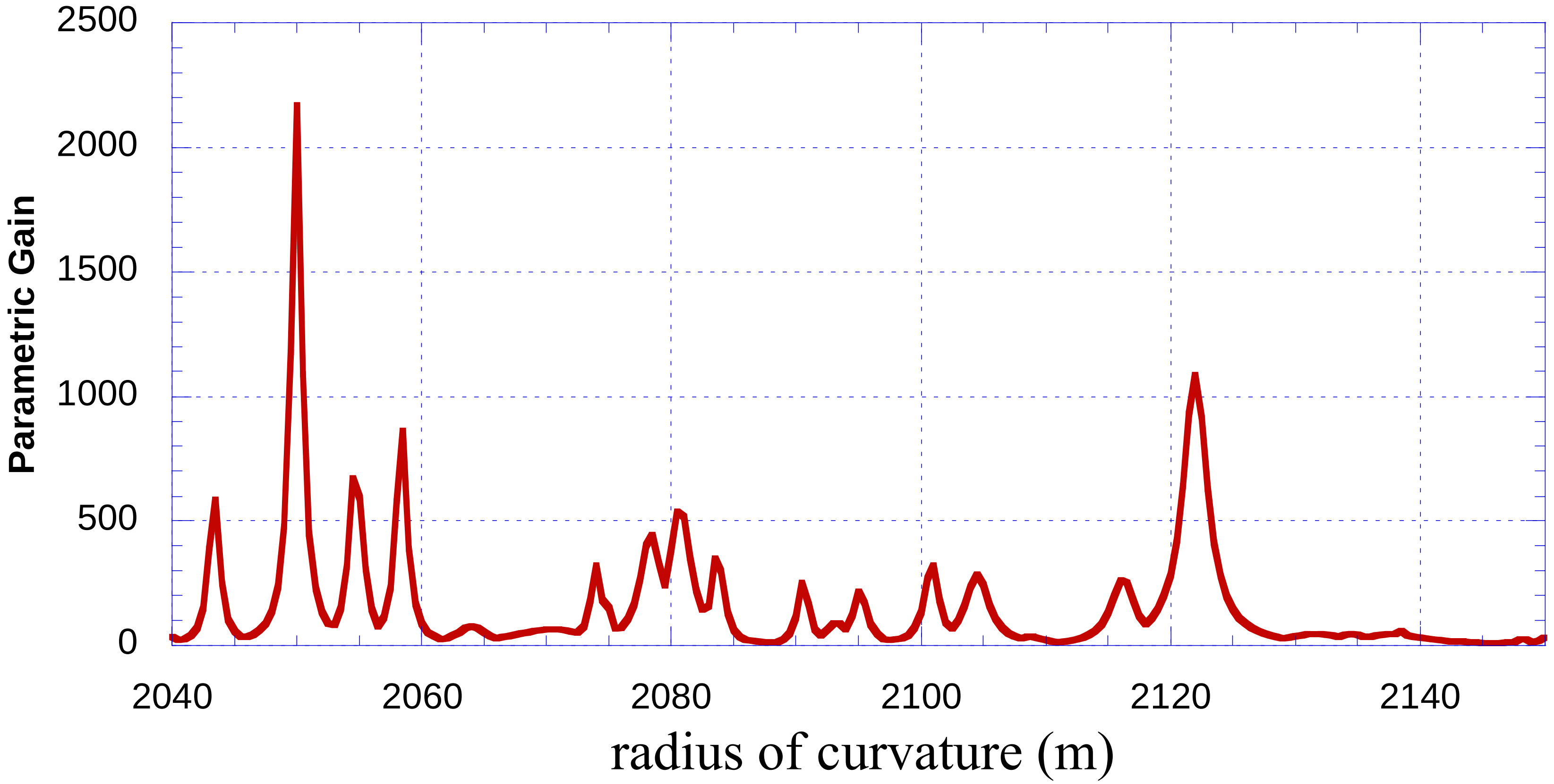
Thermal tuning

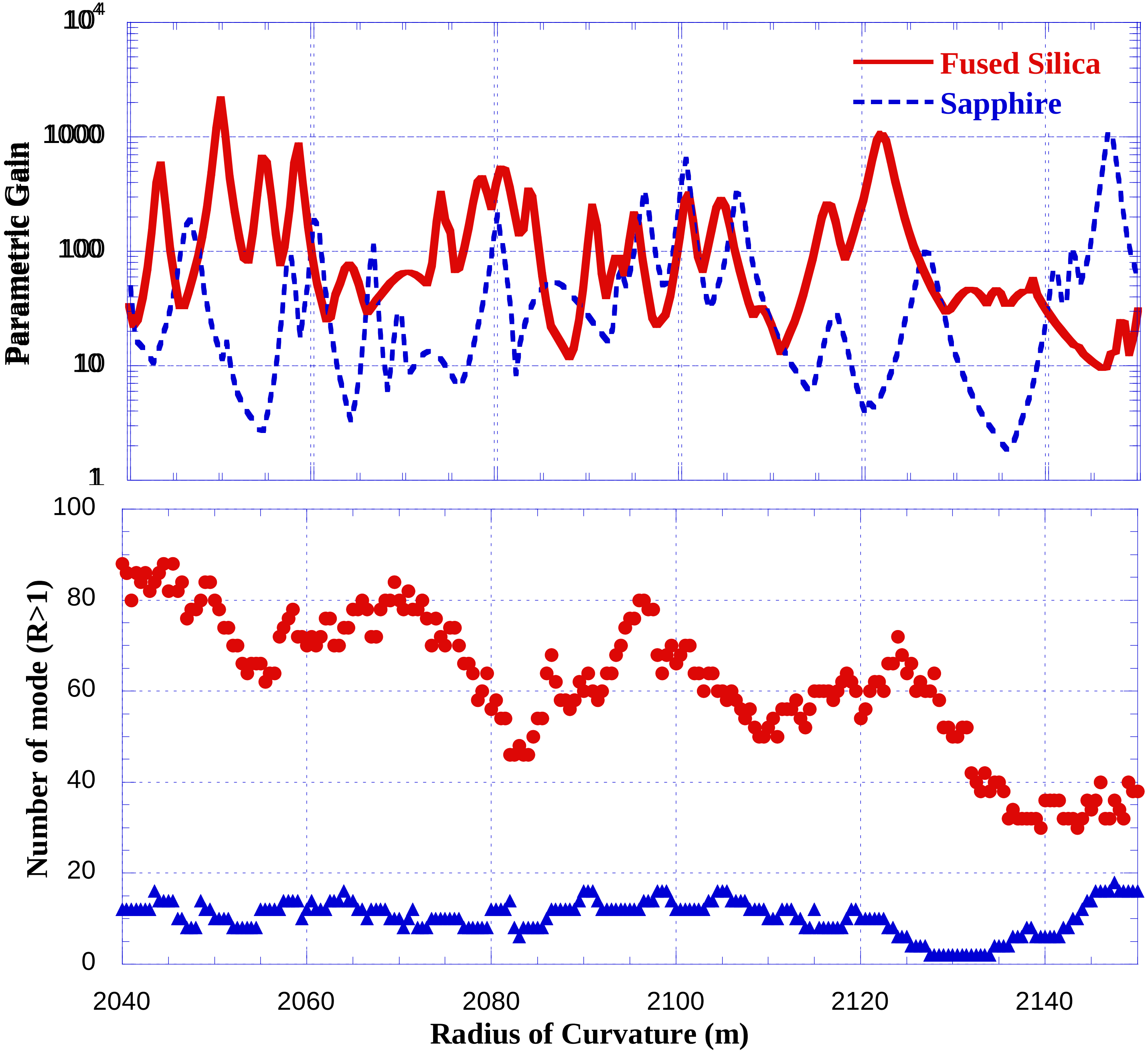
- **Optical high order mode offset (ω_0-ω_1) is a strong function of mirror radius of curvature**
- **Change the curvature of mirror by heating**
- **Detune the resonant coupling**

- **How fast?**
- **How much R reduction?**

Thermal tuning

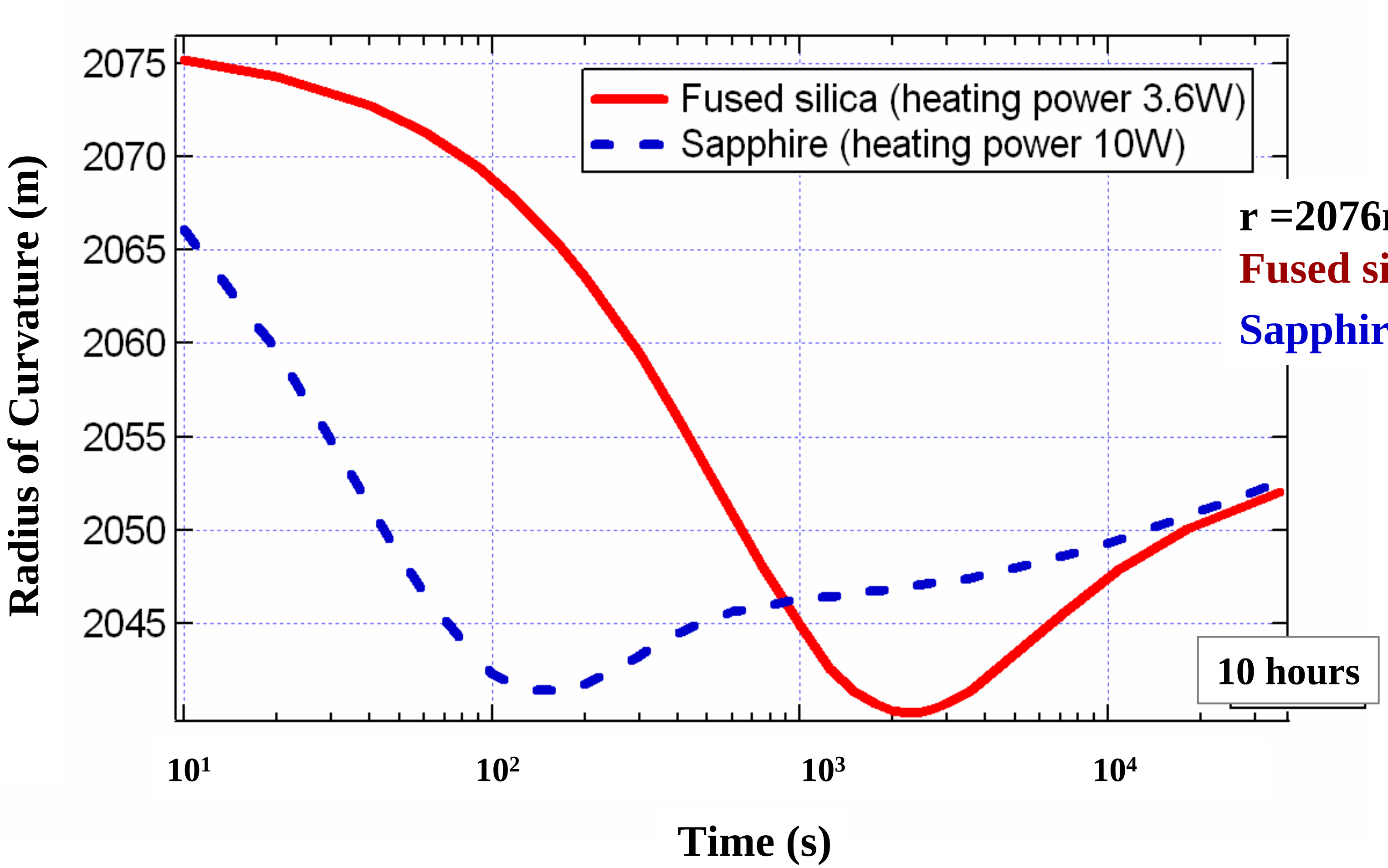
Fused silica





10^4
1000
100
10
1
Parametric Gain
Fused Silica
Sapphire
100
80
60
40
20
0
Number of mode (R>1)
2040
2060
2080
2100
2120
2140
Radius of Curvature (m)

Thermal tuning time—sapphire is faster



r =2076m ->2050m

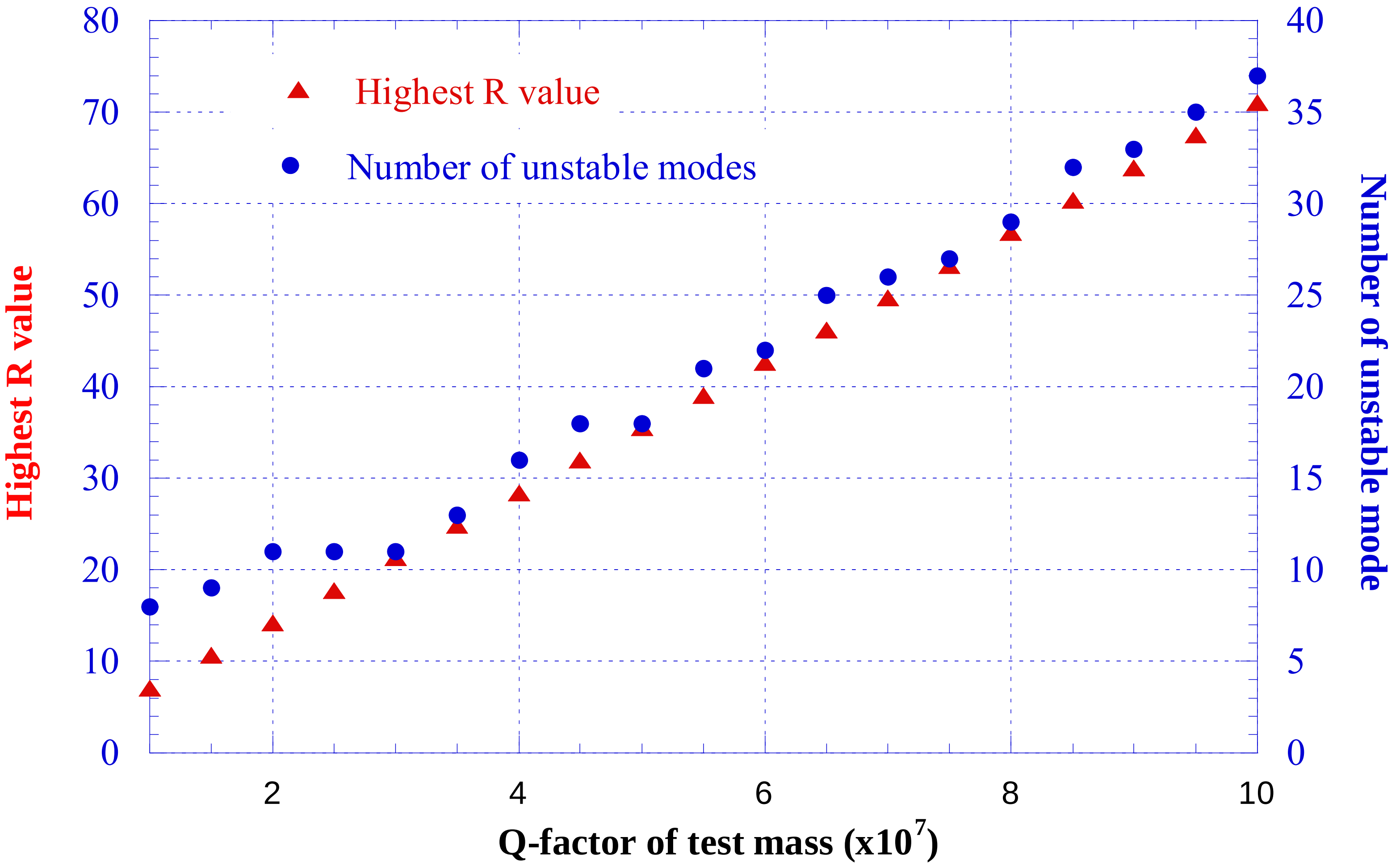
Fused silica: ~1000s

Sapphire: ~100s

Suppress parametric instabilities

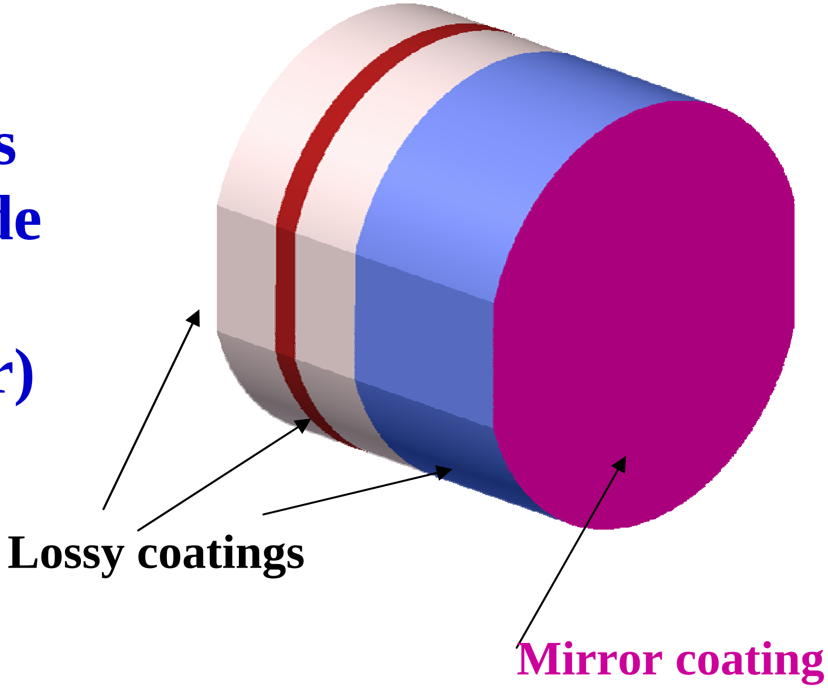
- Thermal tuning
- **Q-reduction** (Poster by S. Gras)
- Feedback control

Parametric instability and Q factor of test masses



Applying surface loss to reduce mode Q-factor

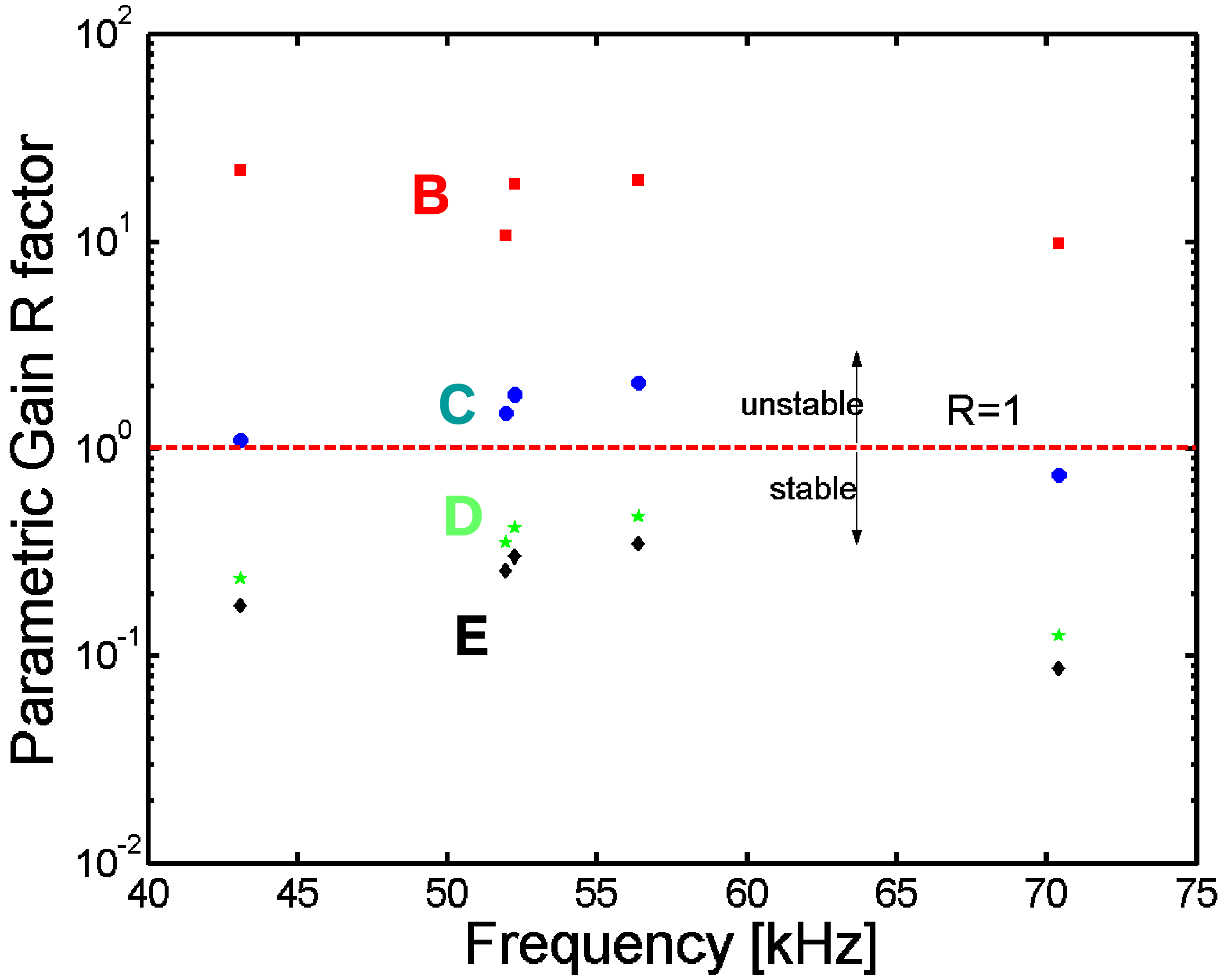
It is possible to apply lossy coatings ($\varphi \sim 10^{-4}$) on test mass to reduce the high order mode Q factors without degrading thermal noise (S. Gras poster)



- A: Loss strip and front face coating
- B: Front face coating only
- C: Back face coating and 50% cylinder wall coating, $\varphi_{\mathrm{back}} = 5\mathrm{x}10^{-4}$, $\varphi_{\mathrm{wall}} = 5\mathrm{x}10^{-4}$, d=20µm
- D: Back face coating and 100% cylinder wall coating, $\varphi_{\mathrm{back}} = 3\mathrm{x}10^{-3}$, $\varphi_{\mathrm{wall}} = 5\mathrm{x}10^{-4}$, d=20µm
- E: The same as D with high loss coatings,

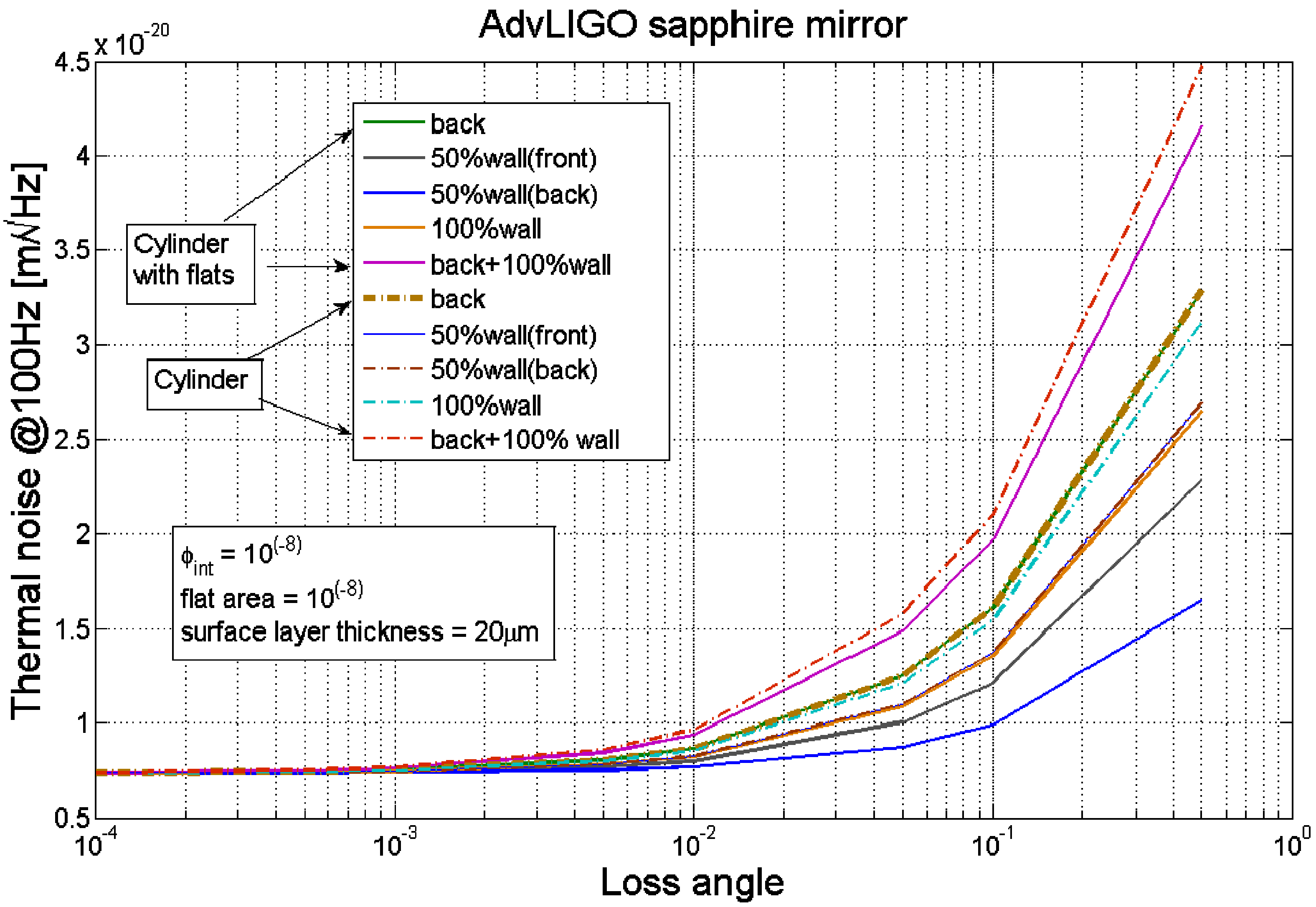
  $\varphi_{\mathrm{back}} = 3\mathrm{x}10^{-3}$, $\varphi_{\mathrm{wall}} = 5\mathrm{x}10^{-4}$, d=20µm

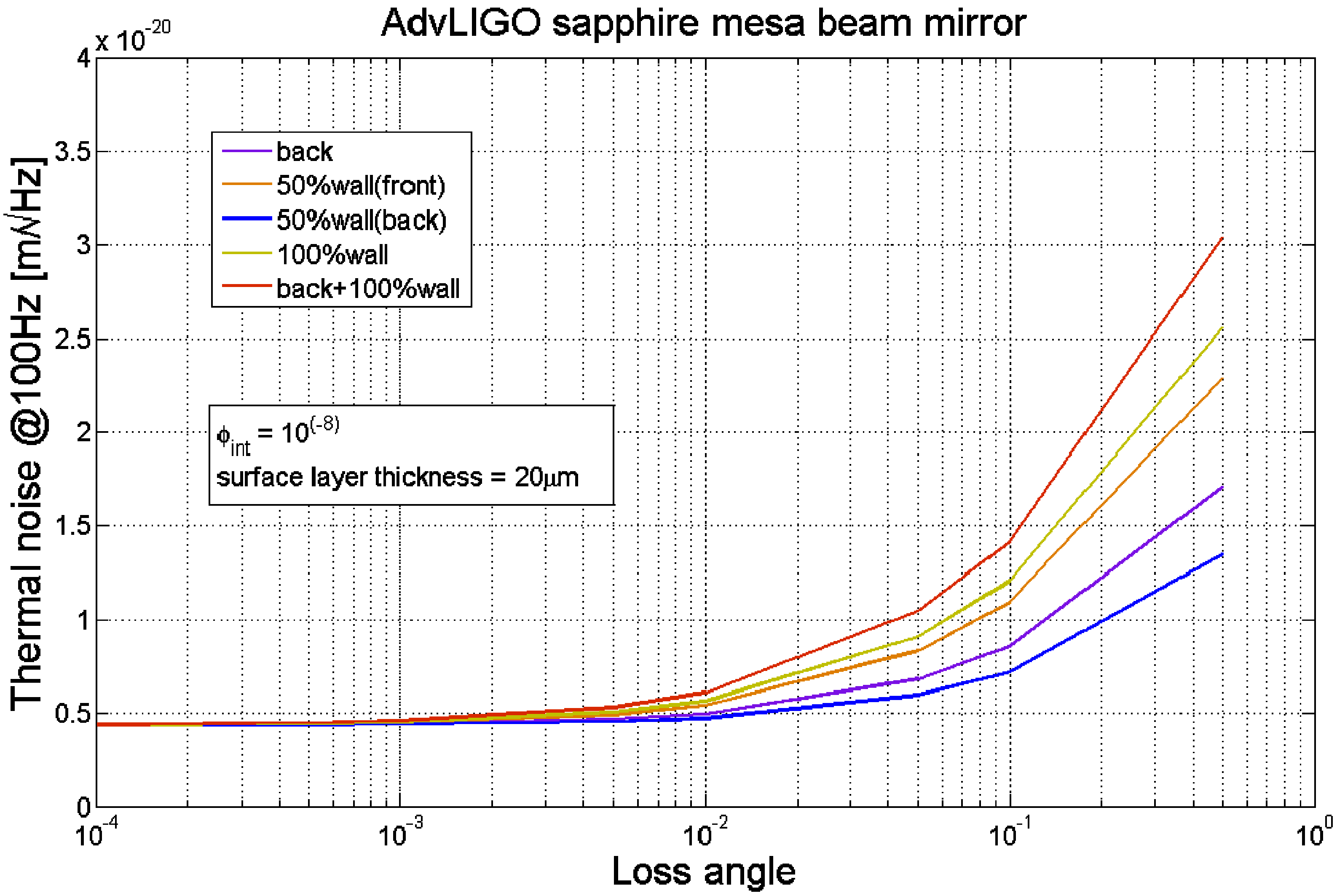
Parametric gain reduction

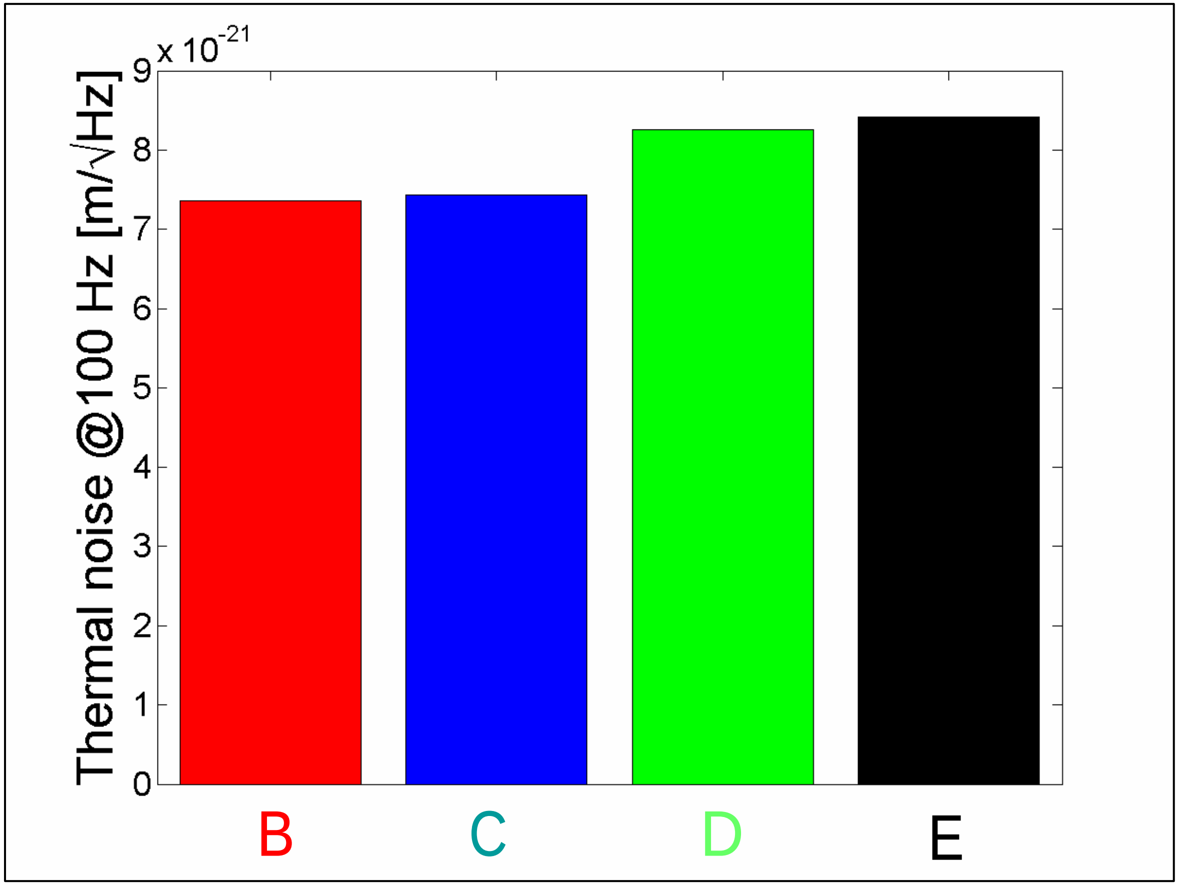


Effect of localised losses on thermal noise

Side and Back




AdvLIGO sapphire mesa beam mirror
x 10^-20
4
3.5
3
2.5
2
1.5
1
0.5
0
Thermal noise @100Hz [m/√Hz]
back
50%wall(front)
50%wall(back)
100%wall
back+100%wall
$\phi_{int} = 10^{(-8)}$
surface layer thickness = 20μm
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
Loss angle


x 10^{-21}
Thermal noise @100 Hz [m/√Hz]
0
1
2
3
4
5
6
7
8
9
B
C
D
E

Suppress parametric instabilities

- Thermal tuning
- Q-reduction
- **Feedback control**

- If Advance interferometer sapphire test masses are coated on the cylindrical wall and the back face with coatings comparable to typical optical coatings, the parametric gain can be reduced below unity for all previously unstable modes.

- Cost of 14% degradation of the noise performance.

- This method can reduce R by factor of order of 100, but for the worst case parametric gain can exceed $2\text{x}10^3$.

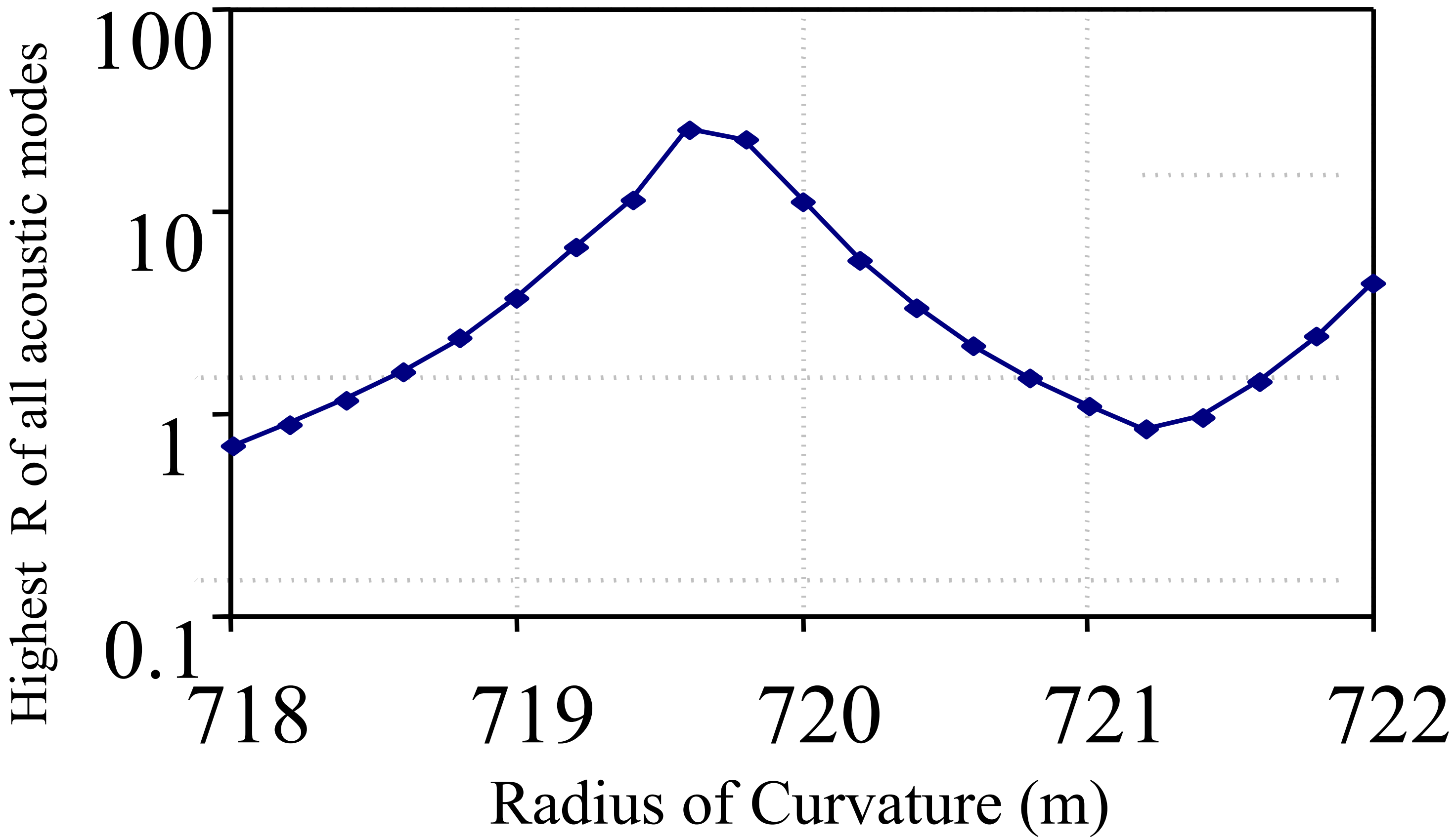
- Mesa beams are more sensitive to position to localised losses. Mode suppression will be more difficult because the system is less tolerant to additional losses.

Feedback control

- Tranquiliser cavity (short external cavity)
  - Complex
- Direct force feedback to test masses
  - Capacitive local control
  - Difficulties in distinguish doublets/quadruplets
- Re-injection of phase shifted HOM
  - Needs external optics only
  - Multiple modes

Gingin HOPF Prediction

- ACIGA Gingin high optical power facility 80m cavity will have chance to observe parametric instability (poster)
- Expect to start experiment this year



Conclusion

- Parametric instabilities are inevitable.
- FEM modeling accuracy/test masses uncertainties—precise prediction impossible
- Thermal tuning can minimise instabilities but can not completely eliminate instabilities.

  (Zhao, *et al*, PRL, **94**, 121102 (2005))
- Thermal tuning may be too slow in fused silica.
- Sapphire ETM gives fast thermal control and reduces total unstable modes (from ~64 to 43 (average))

  (3 papers submitted to LSC review)
- Instability may be actively controlled by various schemes
- Gingin HOPF is an ideal test bed for these schemes.
- Welcome any suggestions