The Threat of Parametric Instabilities in Advanced Laser Interferometer Gravitational Wave Detectors

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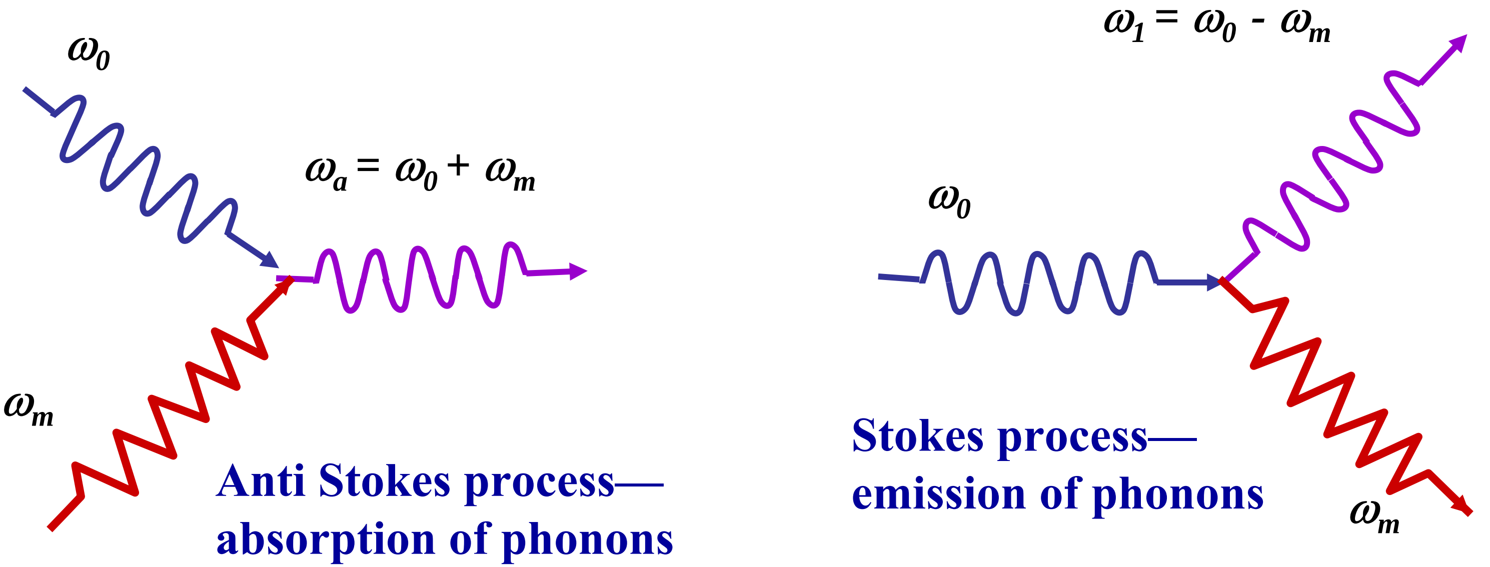
- **Parametric instabilities**
- **Minefield for Advanced Detectors**
- **Suppression of instabilities**
  - **Thermal tuning**
  - **Q reduction**
  - **Feedback control**
- **Future work**

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**

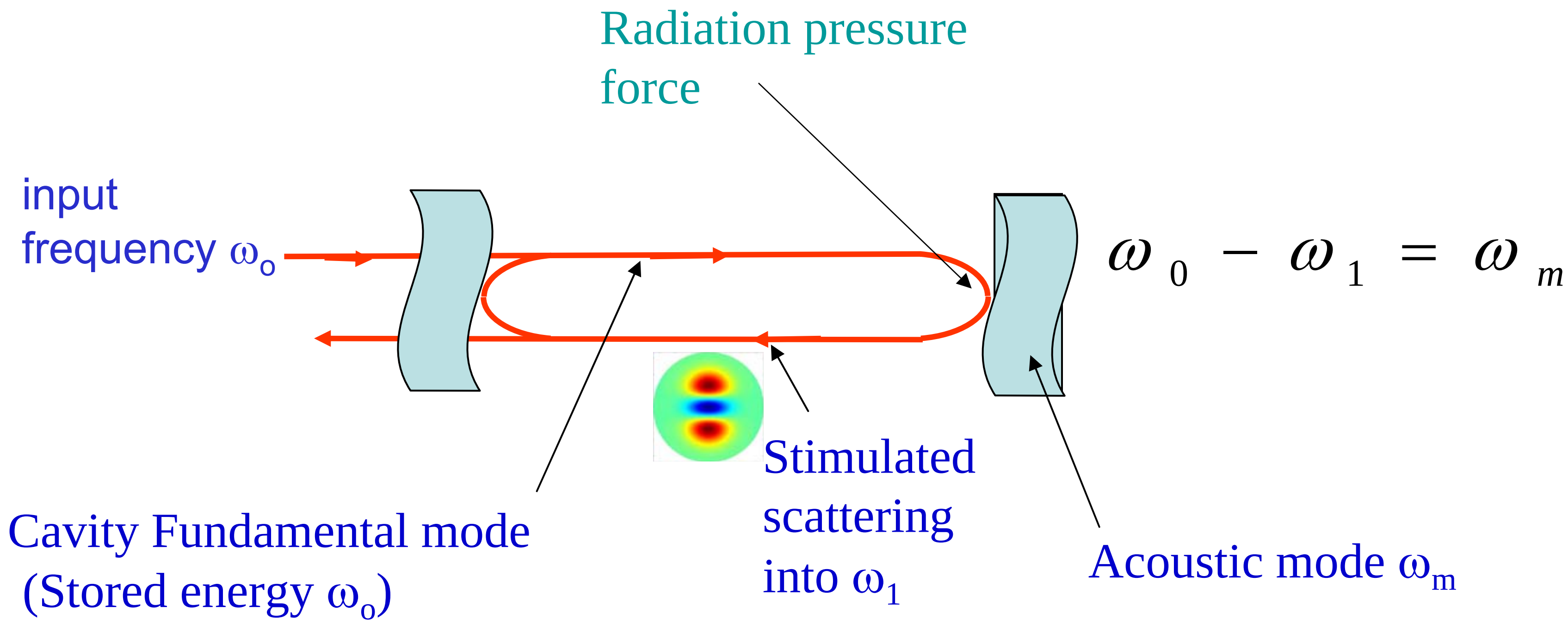
Photon-phonon scattering



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



Instability Condition

Parametric gain[1]

Stokes mode contribution

Anti-Stokes mode contribution

Cavity Power

Mechanical Q

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

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

Λ—overlap factor

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

Fundamental mode frequency

High order transverse mode frequency

Acoustic mode frequency

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

Instability conditions

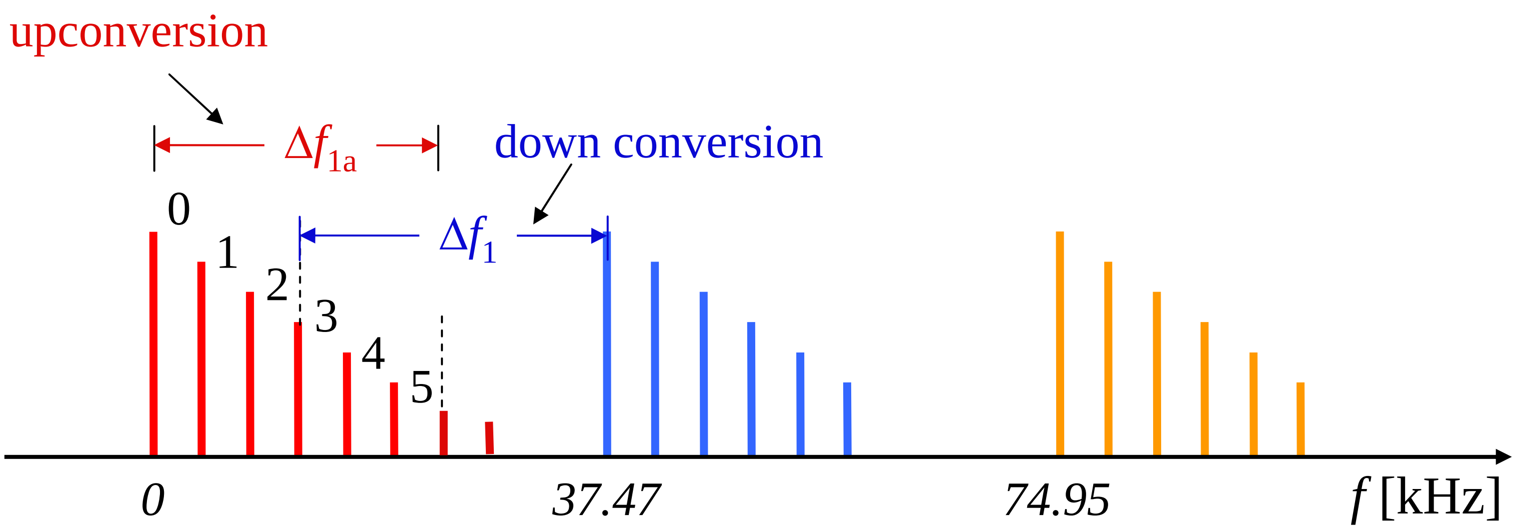
- **High circulating power P**
- **High mechanical**
- **High optical mode Q**

+

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

R>1,
Instability

Mode Structure



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

$\Lambda_1 \neq \Lambda_{1a}$

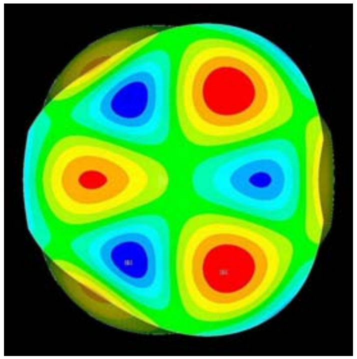
$\delta_1 \neq \delta_{1a}$

- **Stokes & anti-Stokes modes contributions do not usually compensate**

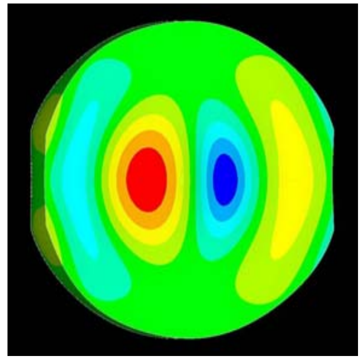
Example of acoustic and optical modes for Al2O3 AdvLIGO

acoustic mode

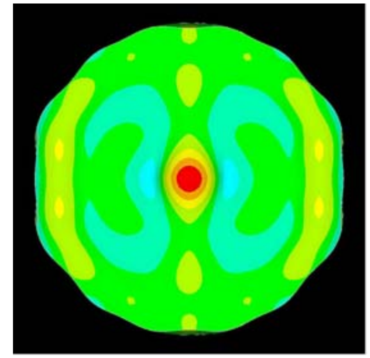
44.66 kHz



47.27 kHz

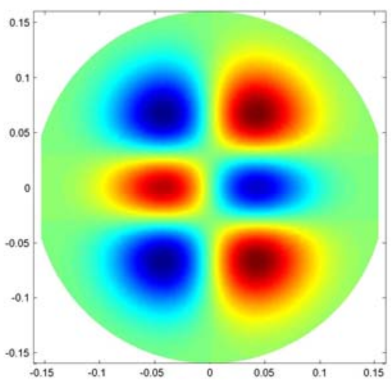


89.45kHz

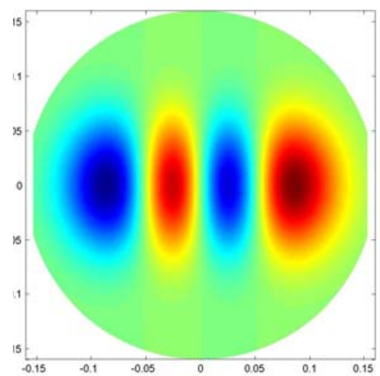


optical mode

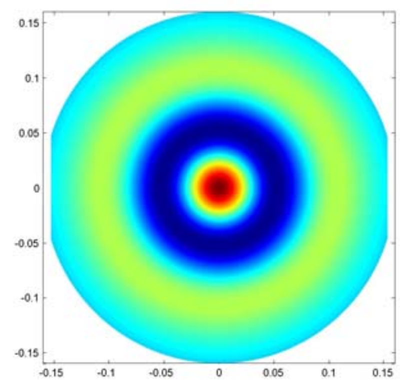
HGM12



HGM30



LGM20

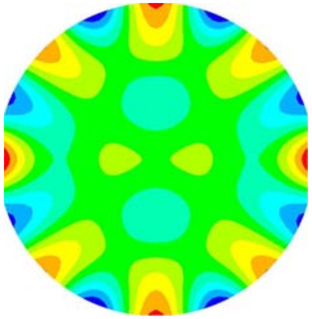


Λ	**0.203**	**0.800**	**0.607**

Λ overlapping parameter

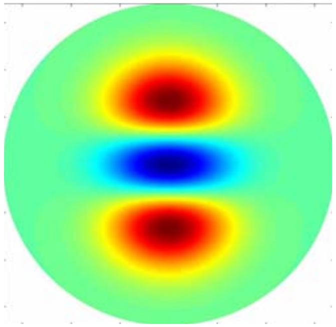
Summing over diagrams: multiple Stokes modes can drive a single acoustic mode.

Example

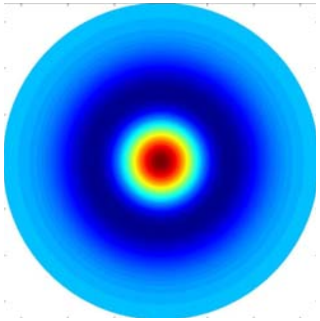


Mechanical mode shape (f_m=28.34kHz)

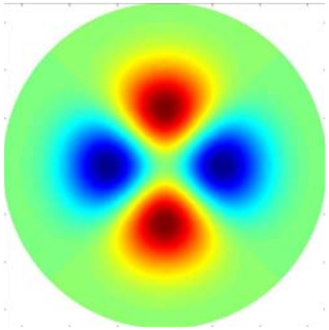
Optical modes



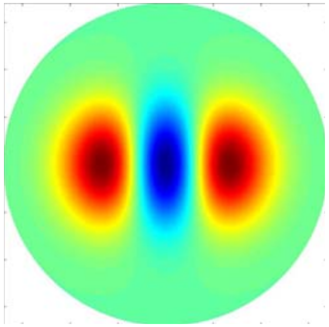
Λ=0.007
R=1.17



Λ=0.019
R=3.63



Λ=0.064
R=11.81



Λ=0.076
R=13.35

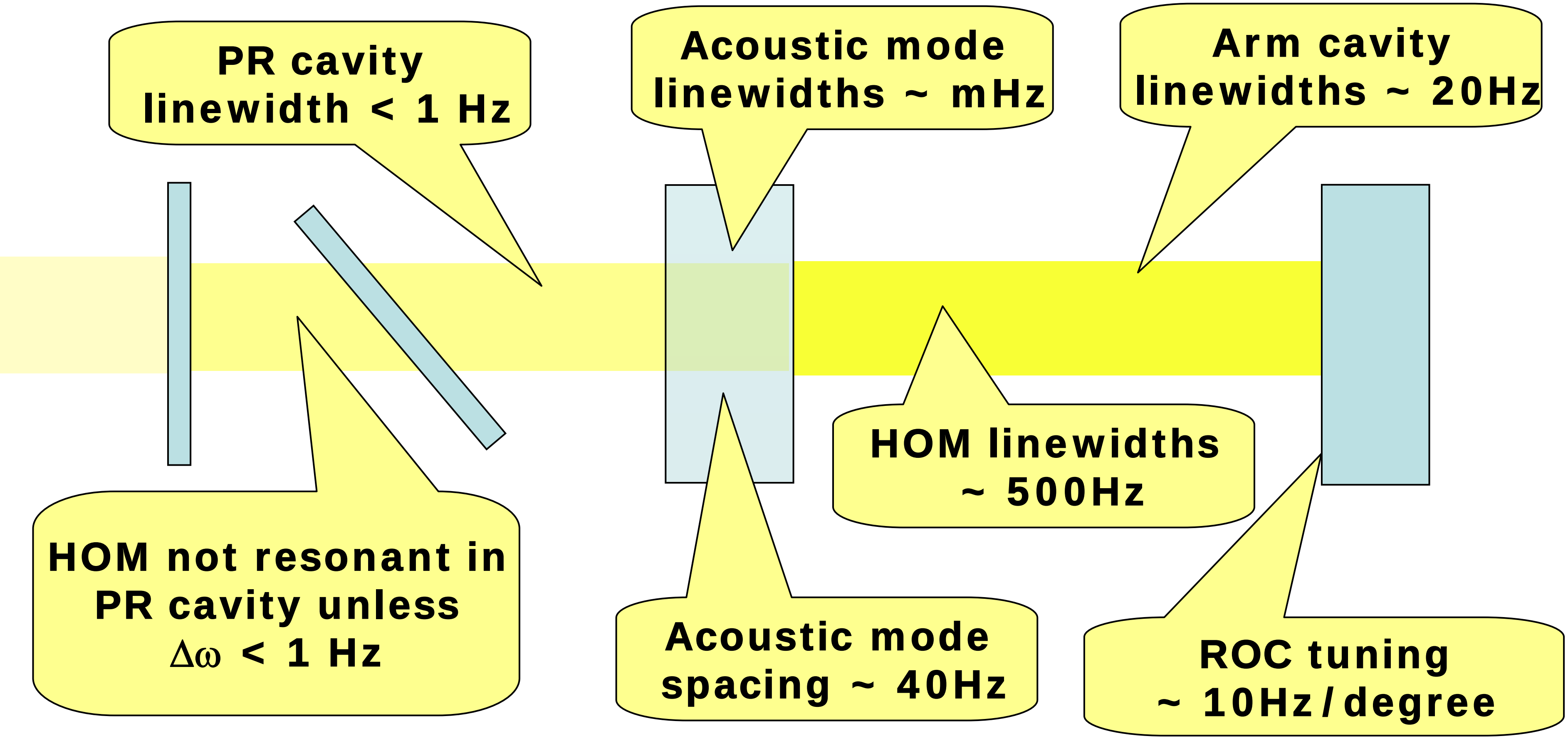
Parametric gain—multiple modes contribution

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

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

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

Influence of PR Cavity

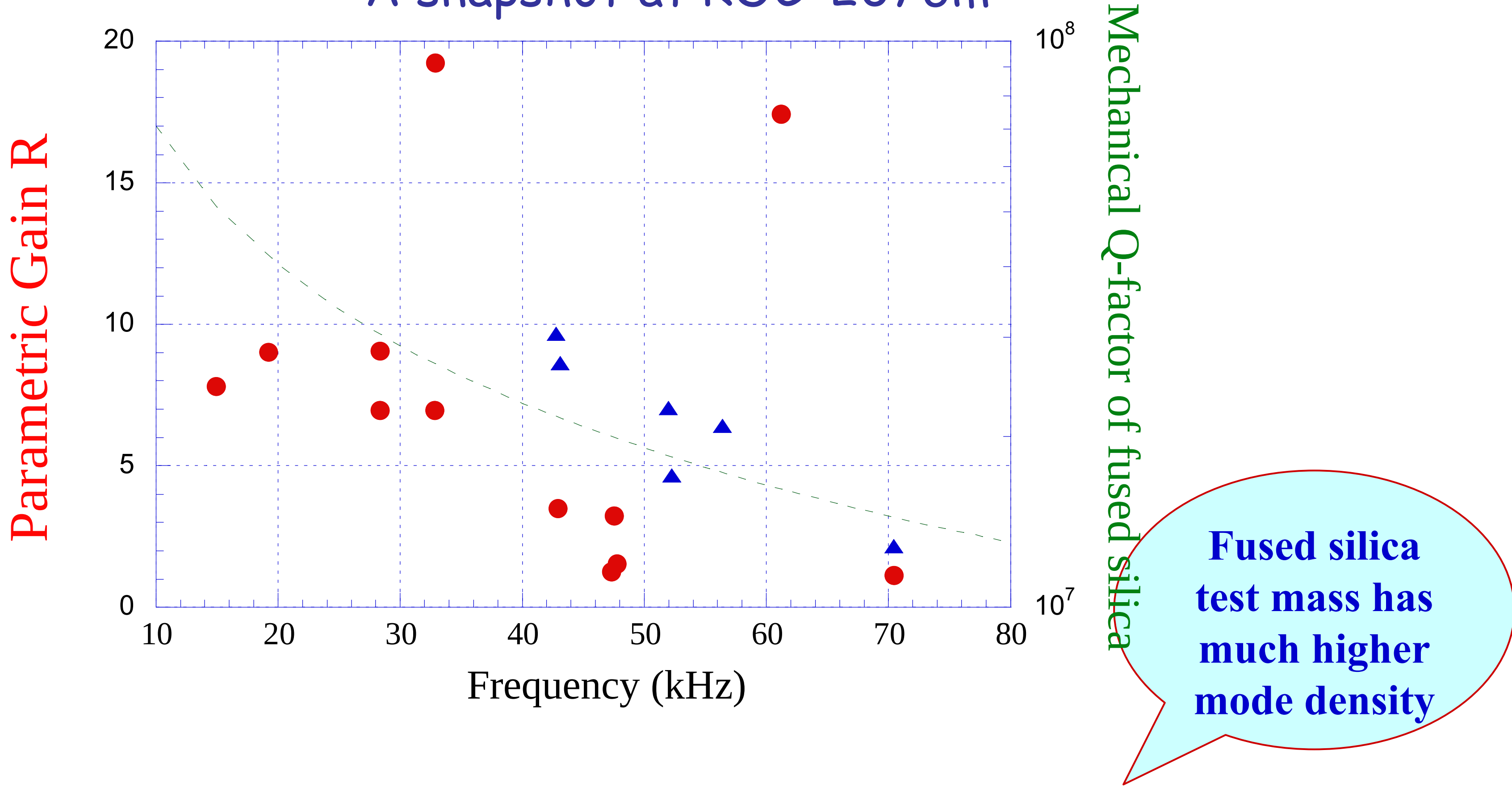


For $\Delta\omega >> 1$Hz no recycling of HOM.

We calculate linewidths of HOMs from transmission +overlap loss of ideal modeshapes.

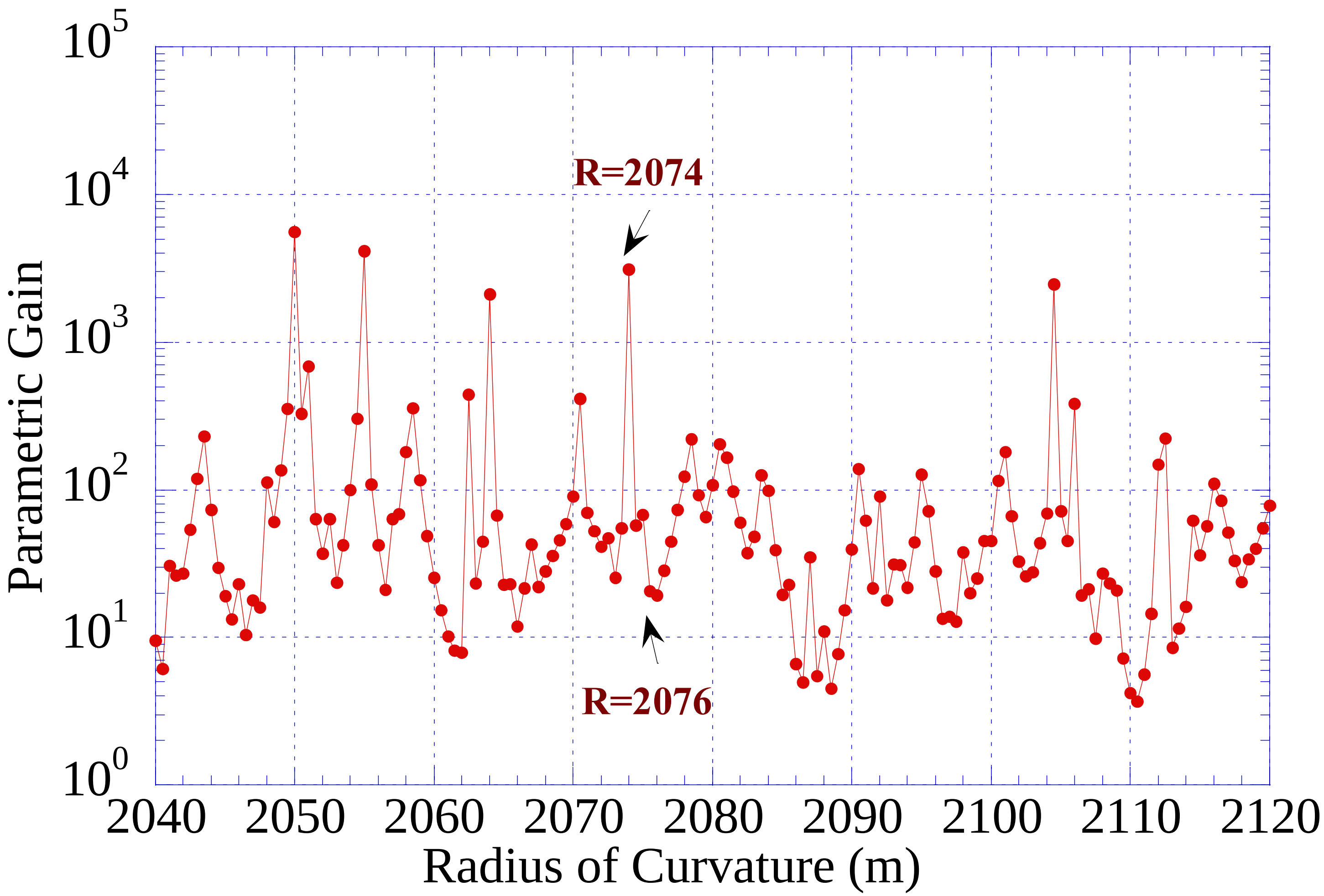
Unstable modes for Adv/LIGO

Sapphire & Fused silica nominal parameters
--A snapshot at ROC=2076m



- Sapphire — Q_m=10^8, 5 unstable modes (per test mass)
- Fused silica — $Q_m(f)$, 12 unstable modes (per test mass)

Landmines! There is one at 2074!



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Suppression of Parametric Instabilities

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

Tuning Coefficients

HOM Frequency Depends on ROC

For 2km ROC, typical ROC tuning dR/dT ~ 1m/K for FS, 10m/K for sapphire

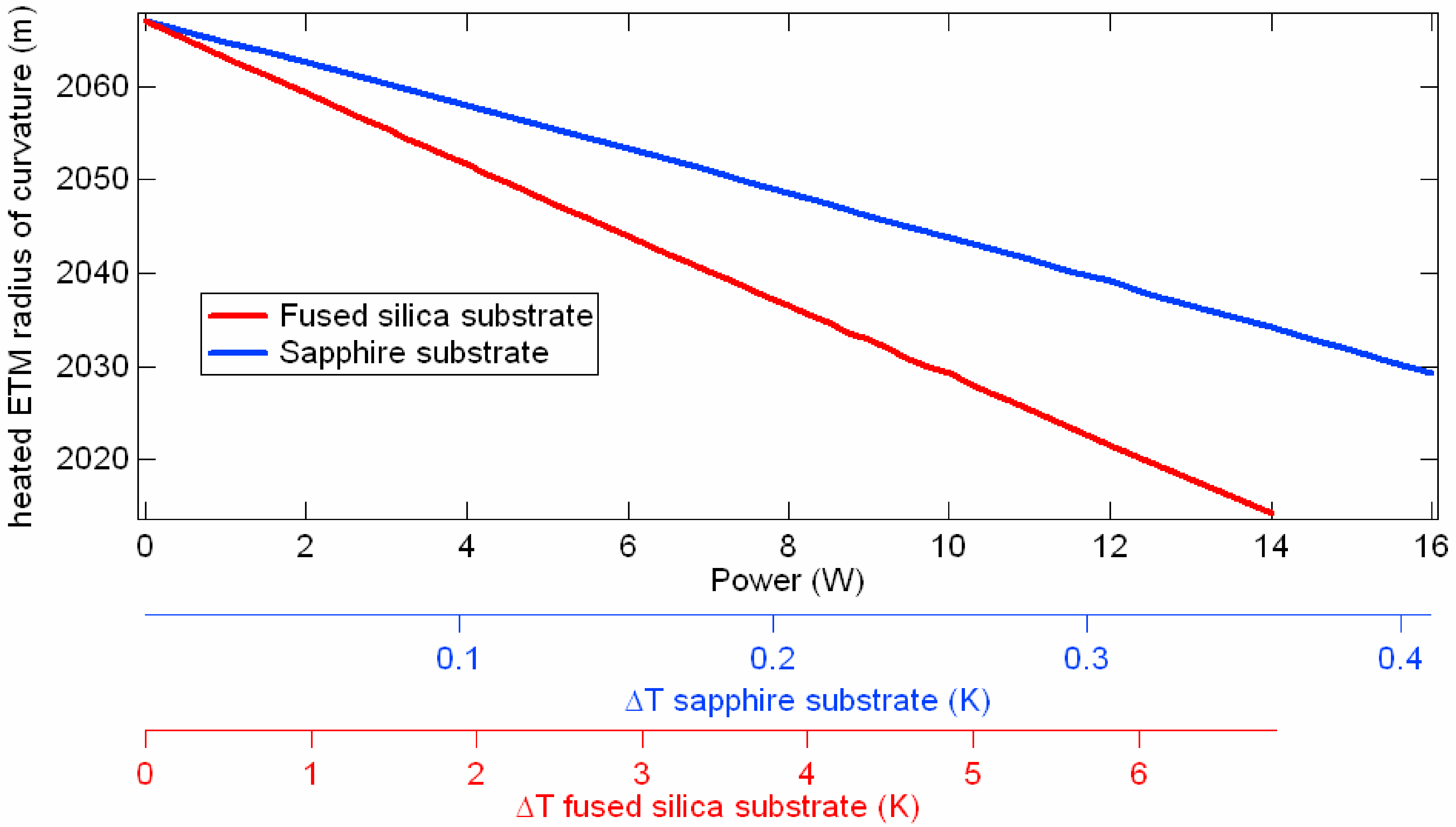
HOM frequency changes: df/dR ~ 10 Hz / m

Acoustic mode spacing: ~ 40Hz in fused silica

ROC uncertainty ~ 10m (?)

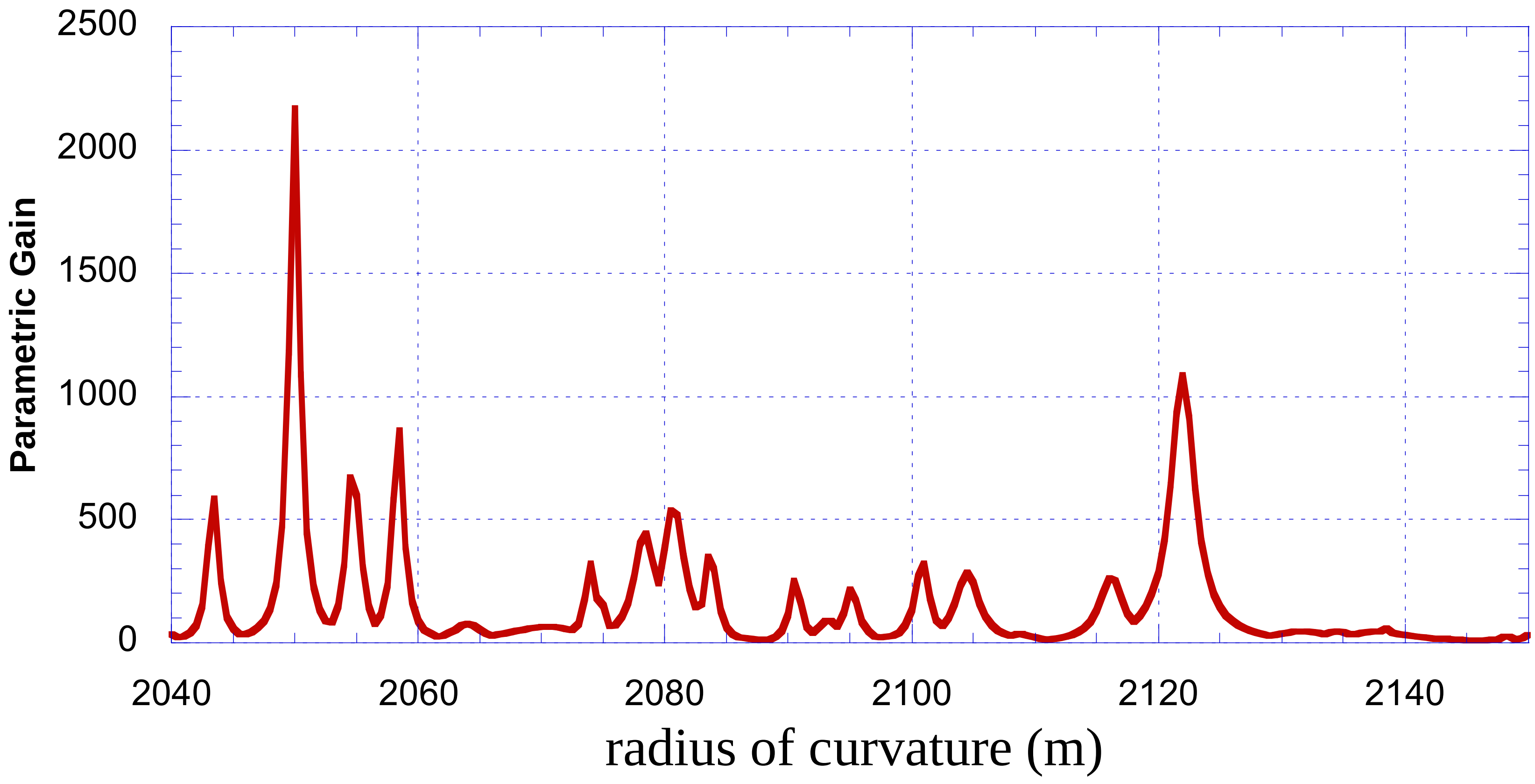
- **Change the curvature of mirror by heating**
- **Detune the resonant coupling**
- **How fast?**
- **How much R reduction?**

ETM radius of curvature vs heating

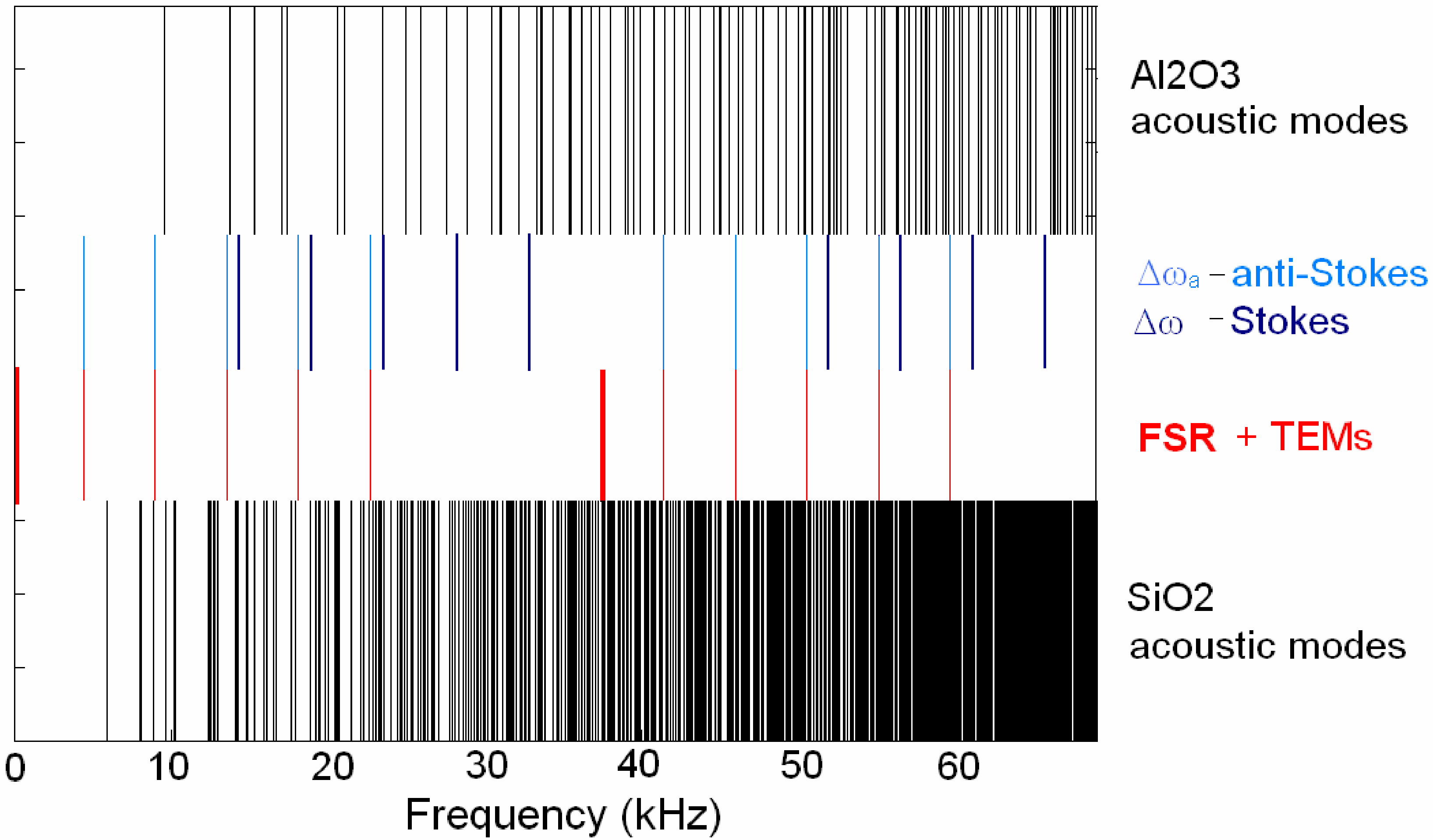


Thermal tuning without PR Cavity

Fused silica



Mode Structure for Advanced LIGO



If $\Delta\omega$-ω_m< optical linewidth resonance condition may be obtained
$\Delta\omega$ = (n*FSR –TEM_{mn}) - frequency difference between the main and Stokes/anti-Stokes modes
ω_m -acoustic mode frequency, δ - relaxation rate of TEM

Instability Ring-Up Time

Mechanical ring down time constant

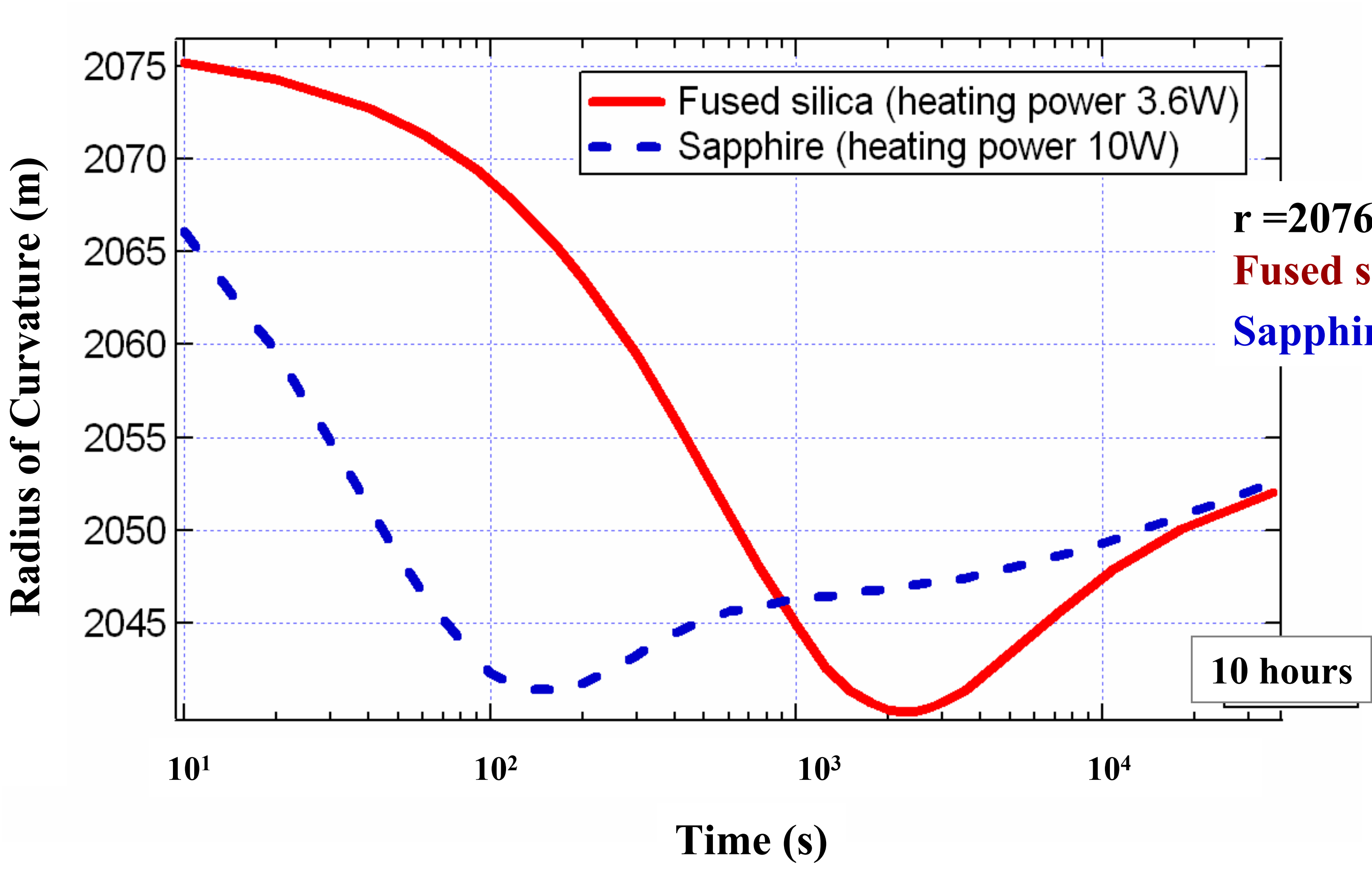
•For R > 1, ring-up time constant is ~ $\boldsymbol{\tau_m/(R-1)}$

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

Thermal tuning time—sapphire is faster



r =2076m ->2050m

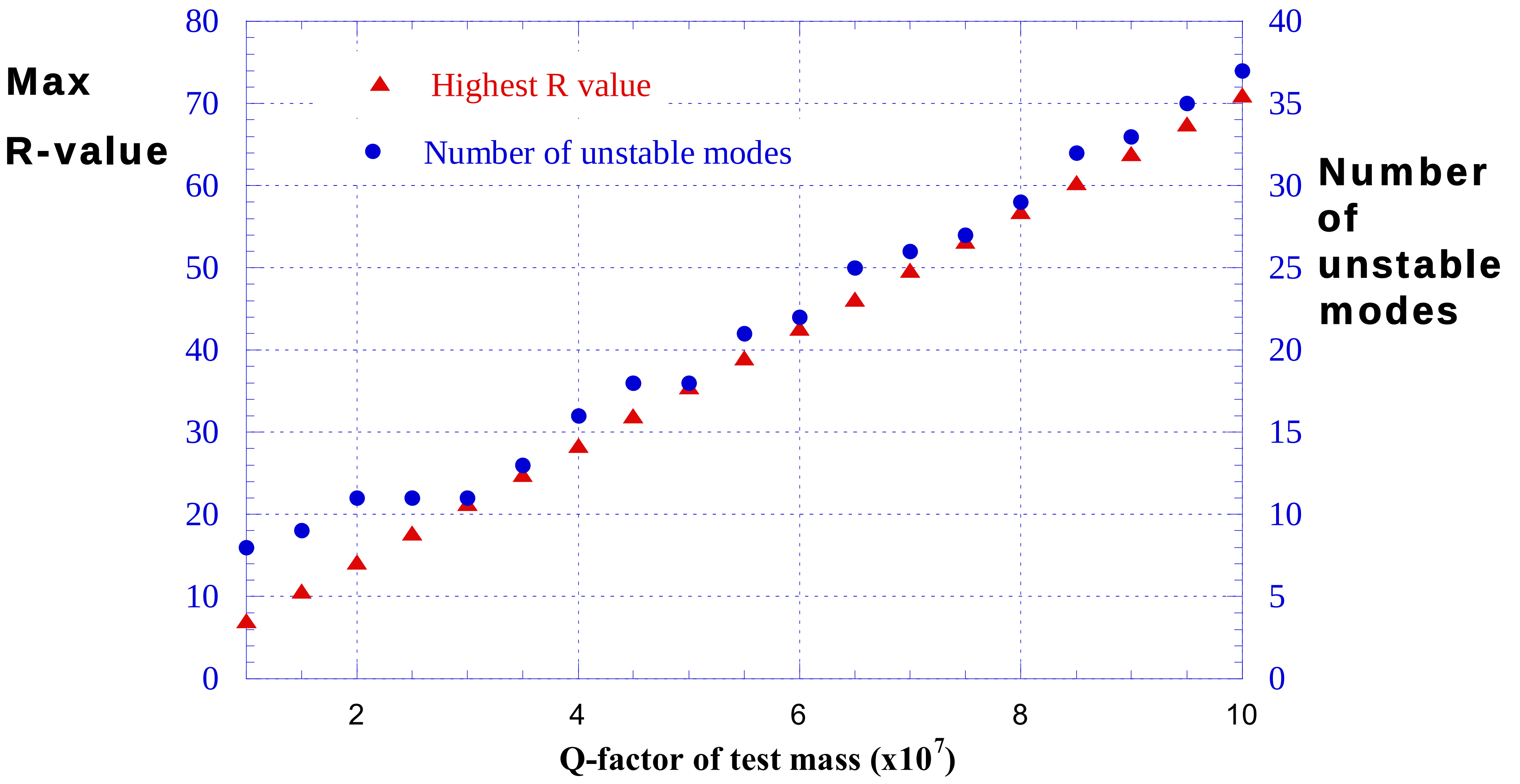
Fused silica: ~1000s

Sapphire: ~100s

Suppress parametric instabilities

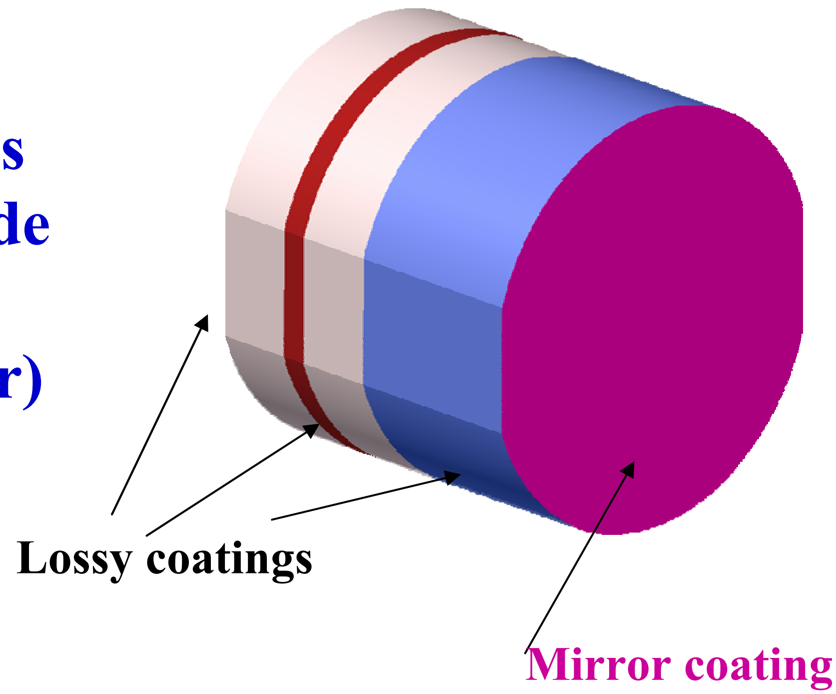
- Thermal tuning
- **Q-reduction**
- Feedback control

Parametric instability and Q factor of test masses

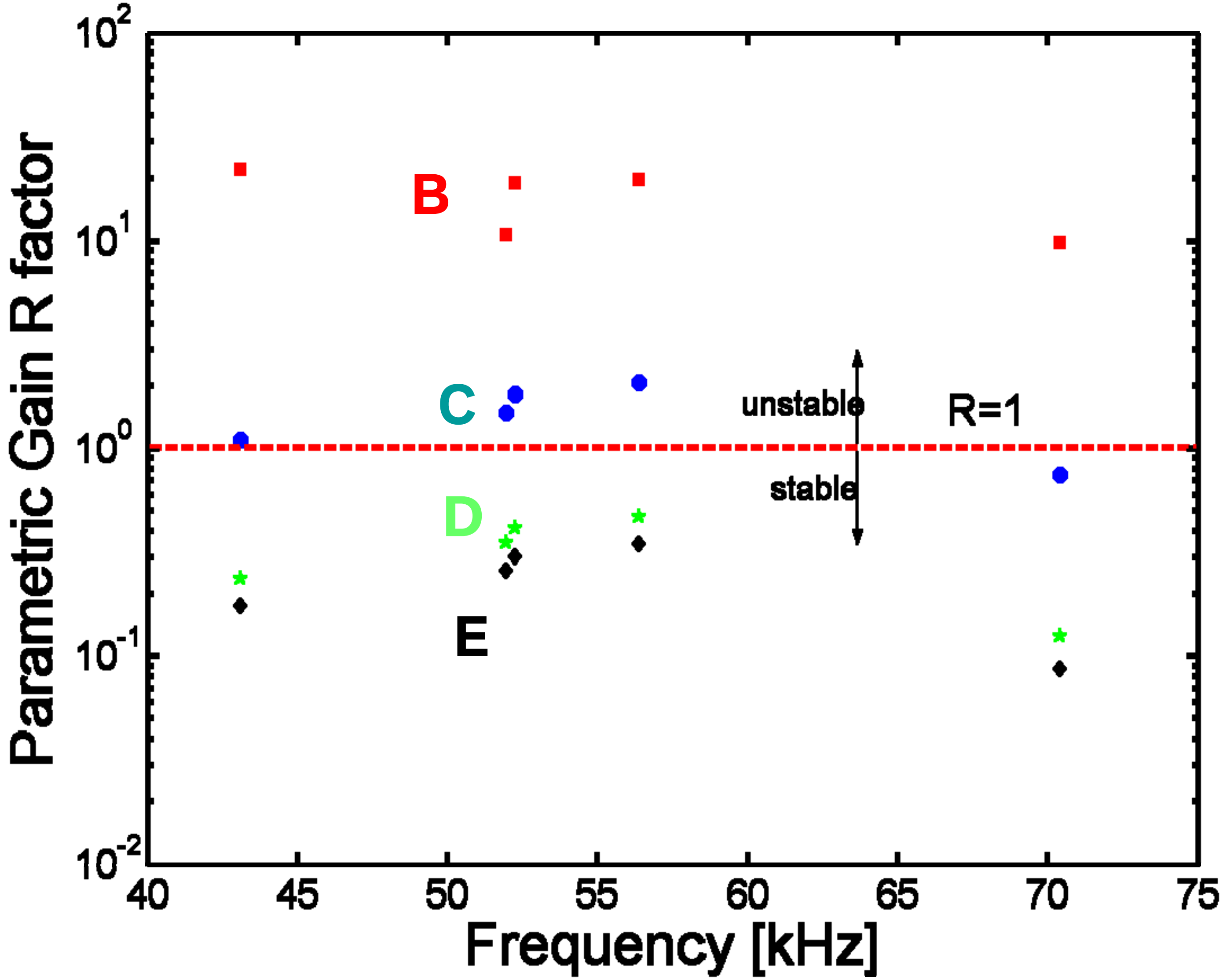


Applying surface loss to reduce mode Q-factor

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)



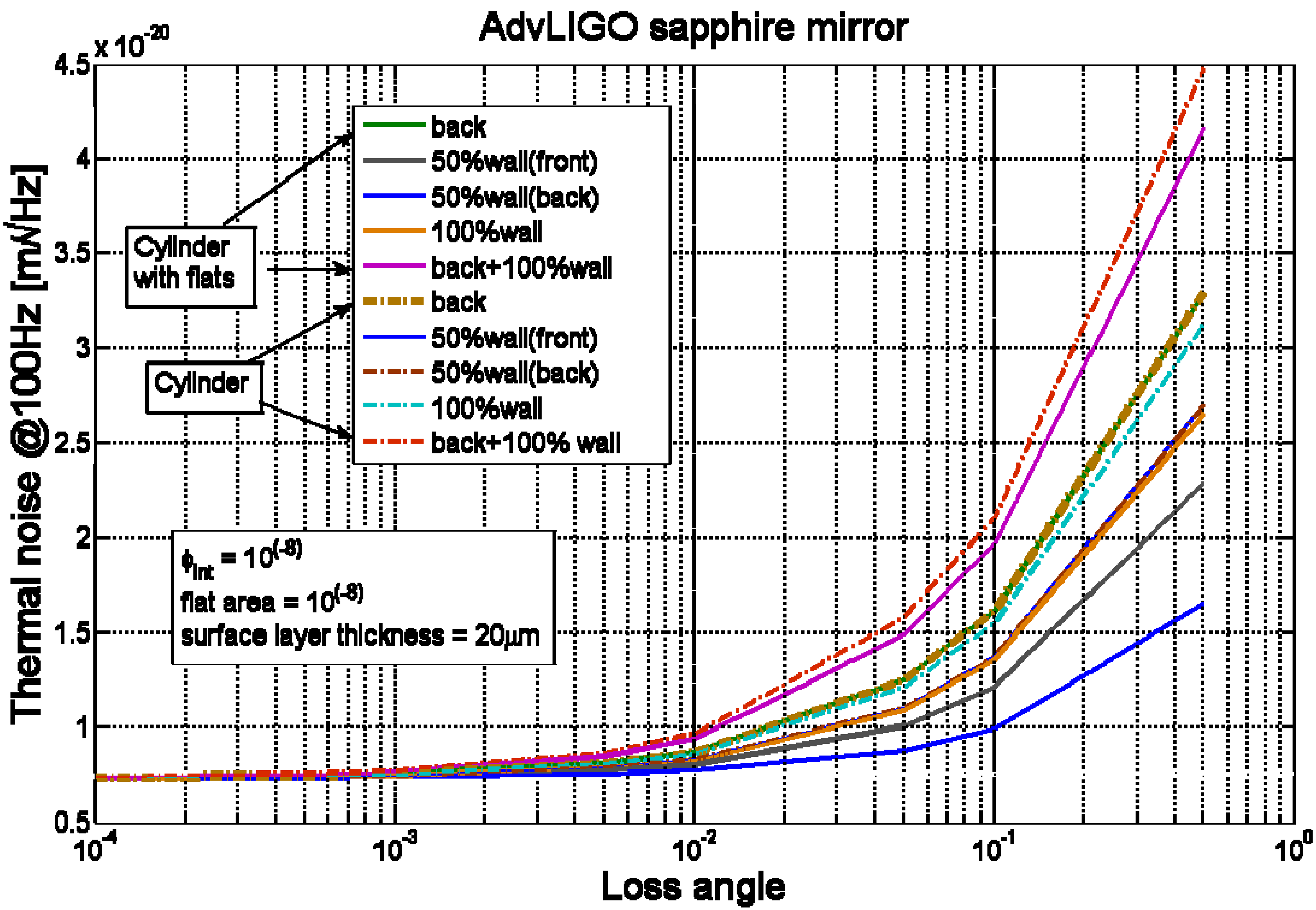
Parametric gain reduction



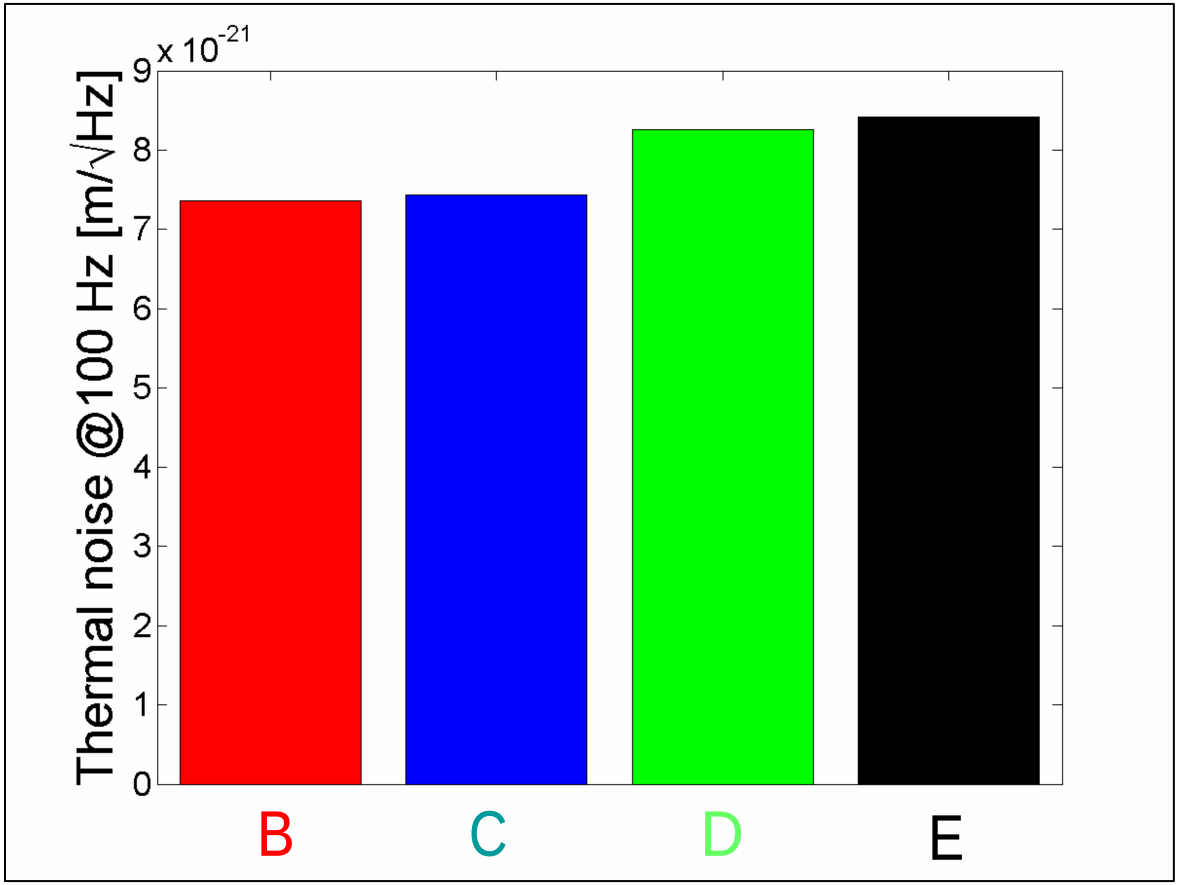
Unilateral stability for *nominal* AdvLIGO parameters

Effect of localised losses on thermal noise

Side and Back



Noise increase 14% to achieve stability



Suppress parametric instabilities

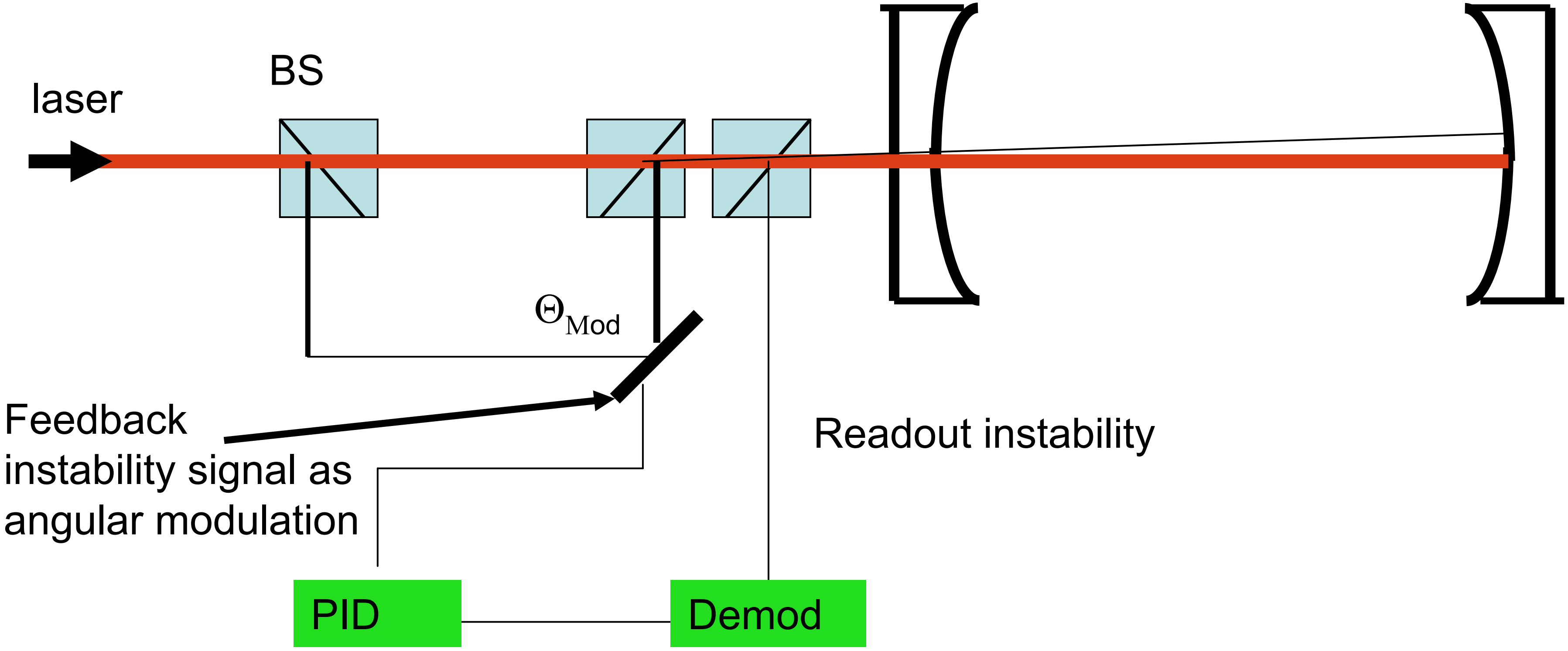
- Thermal tuning
- Q-reduction
- **Feedback control**
  - **Problem: if test masses are similar but not identical instabilities will appear as quadruplets and individual test mass will not be identified unless well mode mapped before installation**

Feedback control

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

Direct Cold Damping by Feedback of HOM Signal

•HOM signal can by definition transmit in arm cavity



Gingin HOPF Prediction

- ACIGA Gingin high optical power facility 80m cavity should observe parametric instability effect with 10W power
- Expect to start experiment this year (Zhao’s talk)

Conclusions

- 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.