THE UNIVERSITY OF WESTERN AUSTRALIA

Opto-mechanical interactions in advanced gravitational wave detectors

Li Ju

University of Western Australia

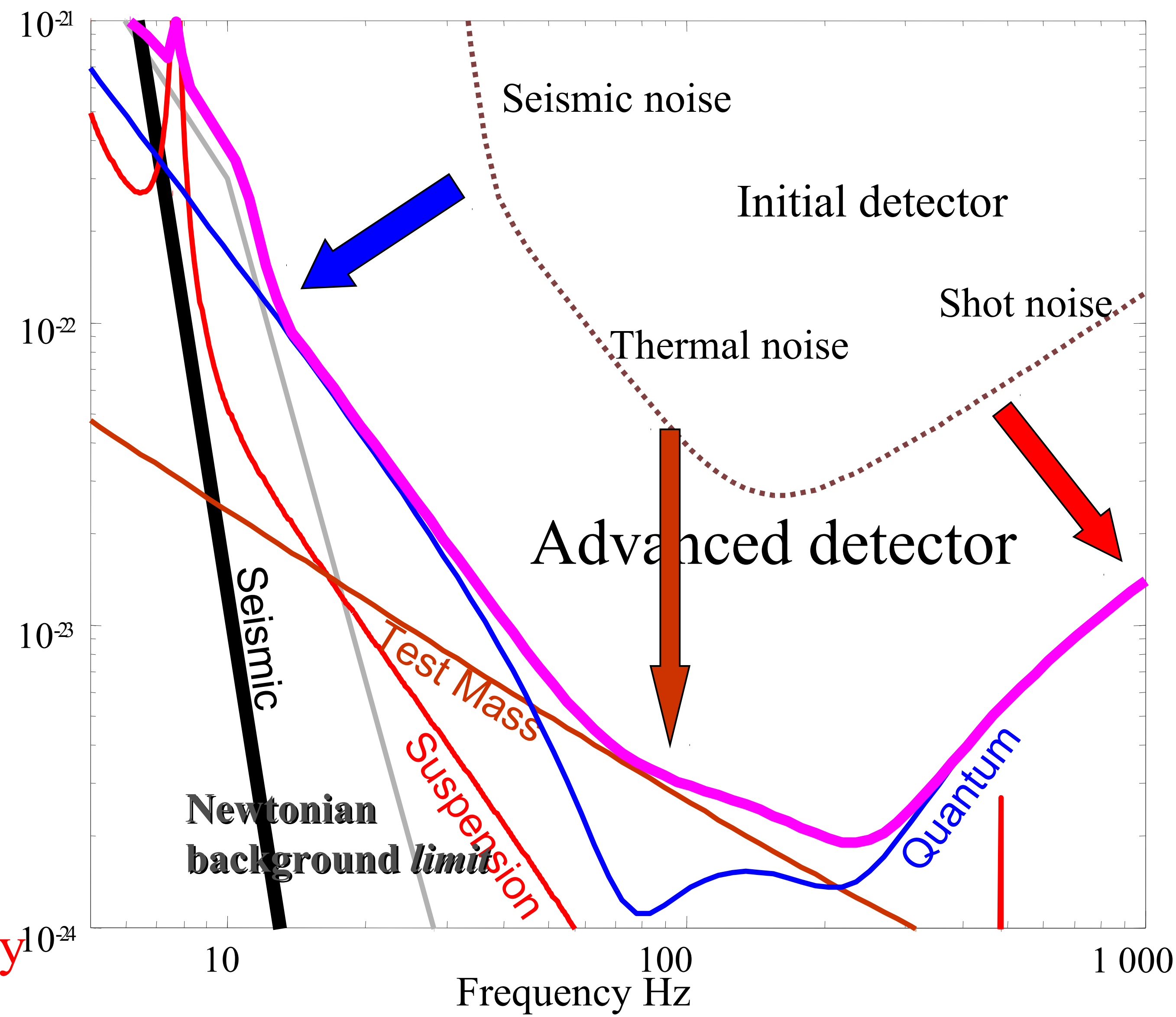
Outline

- Introduction
- Opto-acoustic Interactions
- Parametric Instability
- Observation of Parametric Interactions
- Schemes for Parametric Instability Control

Introduction

- International collaboration on investigating parametric instability in advanced detectors with Gingin facility
  - Testing the theory
  - Designing suppression schemes
  - Testing suppression techniques
- Collaboration Partners
  - Jesper Munch (U. Adelaide)
  - Gregg Harry (MIT)
  - Stan Whitcomb, Yanbei Chen (Caltech)
  - Stefan Gossler (AEI)
  - Antoine Heidman (ENS)

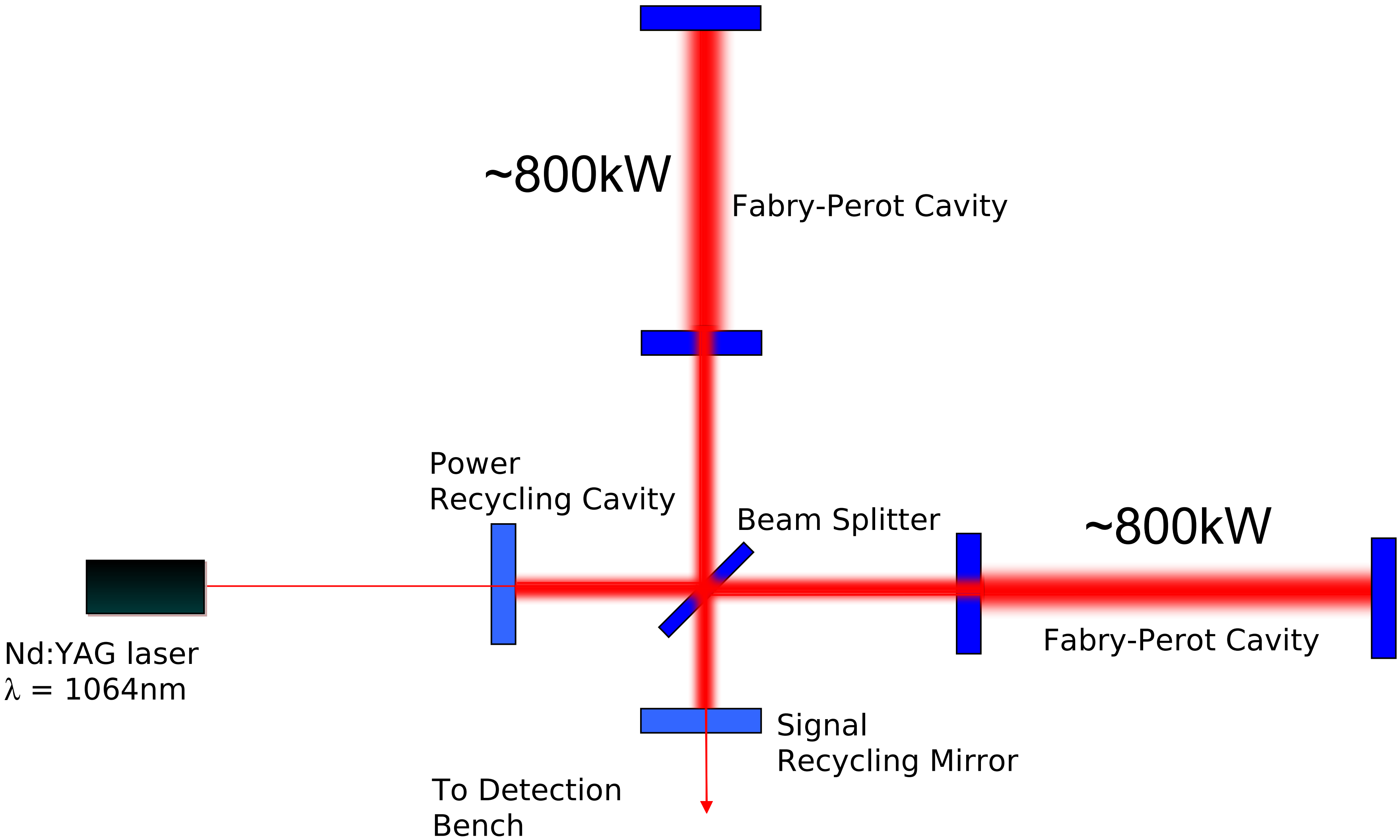
Seismic isolation: pre-isolation stage + isolation chain



Very high quality suspension and test masses

High laser intensity

Very high power inside cavities



High optical power effects

- **Thermal lensing**

  The optical power absorbed by test masses induces thermal expansion + thermal optical coefficient change

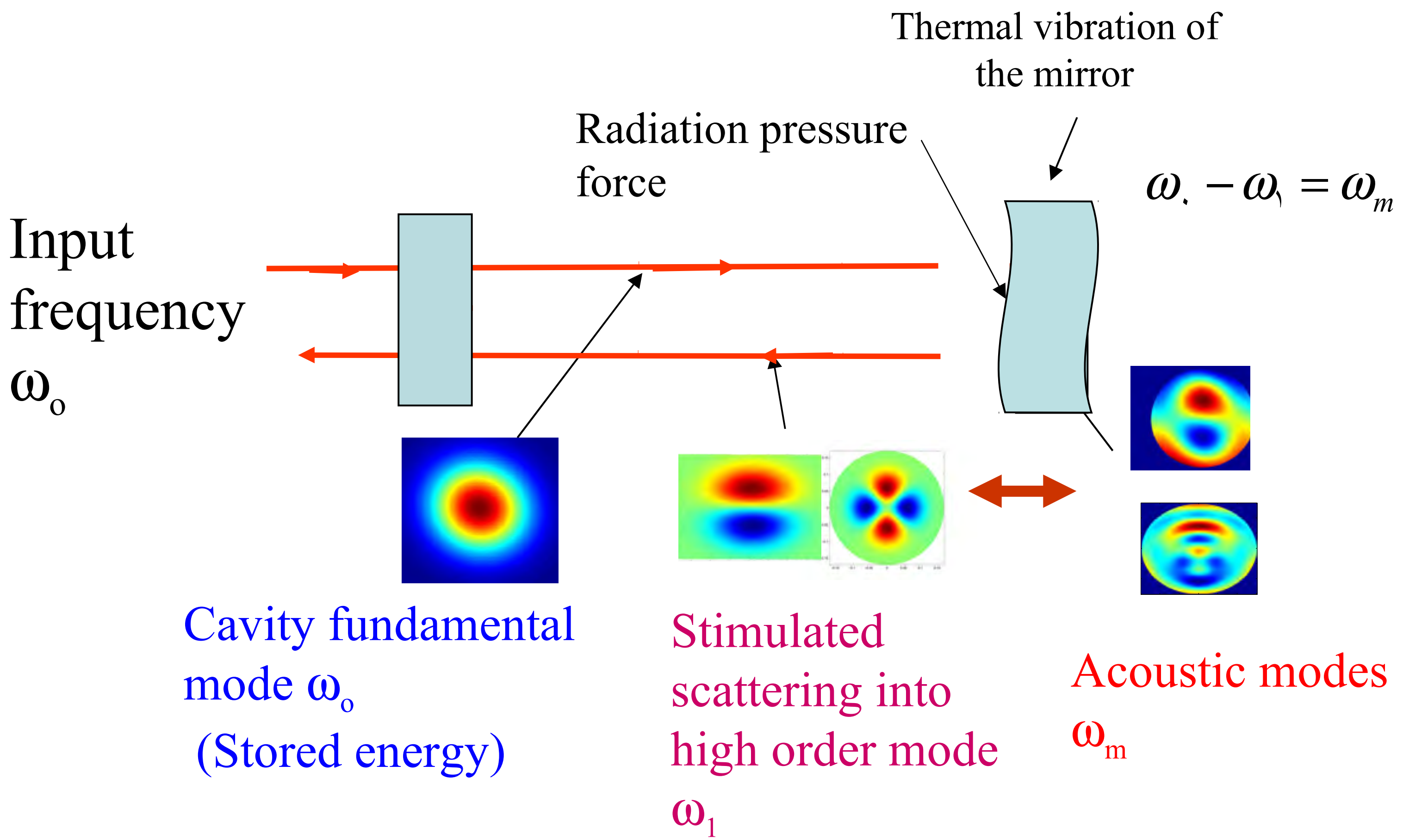
  → lensing effect.

- **Parametric instability**

  Opto-acoustic interactions between test mass acoustic modes and arm cavity optical modes could lead to excitation of test mass acoustic mode

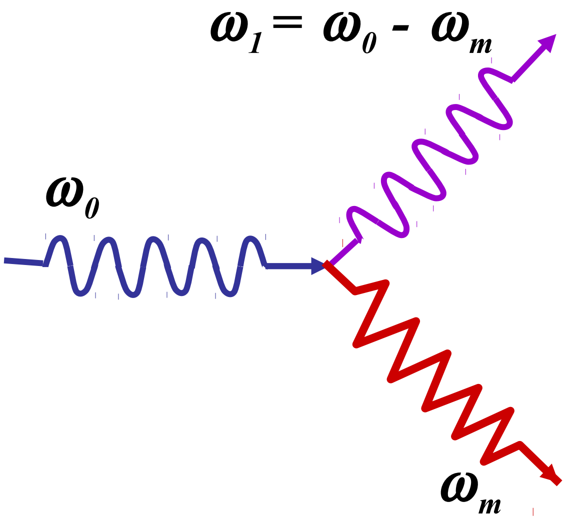
  →instabilities

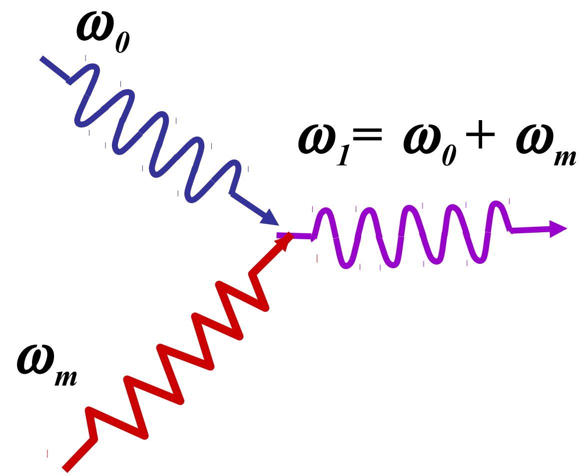
Parametric interaction in an optical cavity



3-mode interaction requires **frequency matching** and **spatial overlap** of acoustic and optical modes

Three Mode Parametric Interactions





Stokes process:
A photon of frequency ω_0 is scattered into a lower frequency photon ω_1, and emit a phonon of frequency ω_m
→ Parametric instability

Anti-Stokes process:
The scattering crates a higher frequency photon ω_1, absorption the phonon ω_m
→Cooling of the acoustic mode

Parametric Gain R

$R \propto Q_0 Q_1 Q_m$

- input power P_{in}
- main cavity Q_0
- high order mode Q_1
- Acoustic mode Q_m
- Spatial overlap B
- Frequency condition $\Delta\omega$

$$R = \pm \frac{8 P_{in} Q_0 Q_1 Q_m}{L^2 \omega_0 \omega_m} \frac{\gamma B}{1 + (\Delta\omega / \delta_1)^2}$$

R>1 → instability
R<0 → damping

Parametric Instability in Advanced Detectors

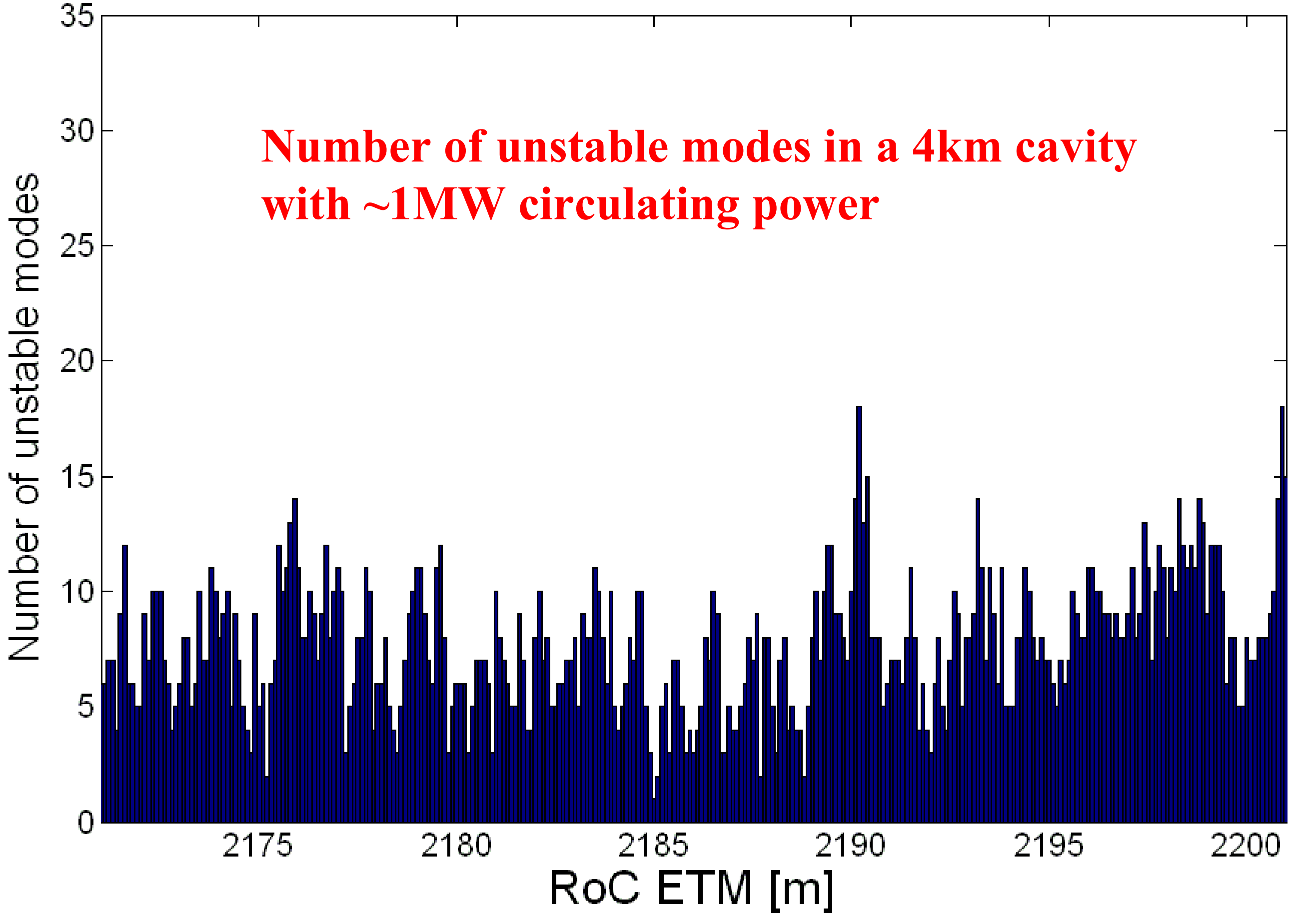
- Braginsky predicted that advanced detector would have parametric instability problem

Braginsky, et. al. *Phys. Lett. A*, **287**, 331-338 (2001)

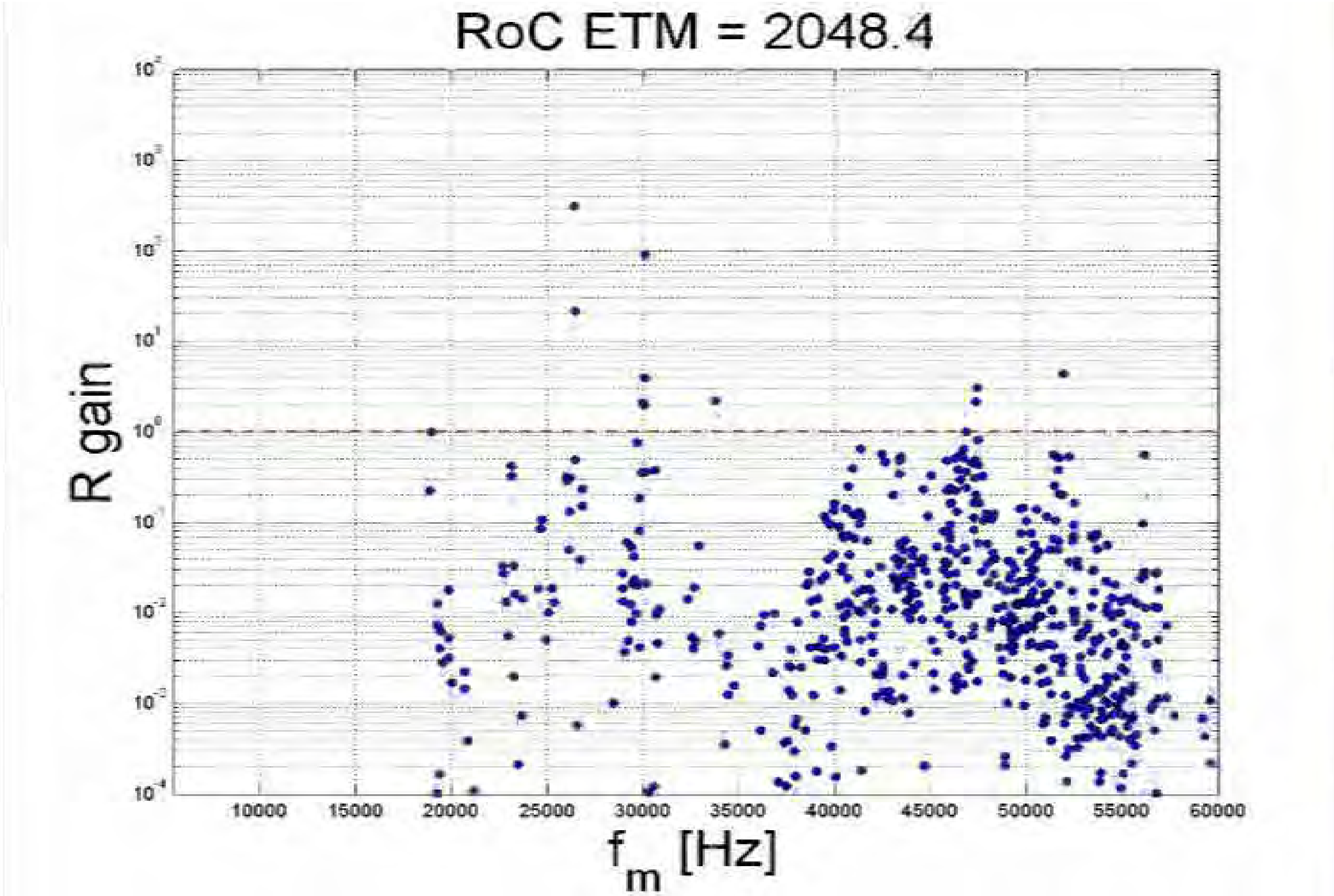
- UWA group did detailed modelling
  - There would be many unstable modes
  - R is sensitive to the Radius of Curvature (RoC) of the test masses in the cavity
  - The ring up time constant $1/\tau \sim R\omega_m/Q_m$

Zhao, *et al, Phys. Rev. Lett.* **94**, 121102 (2005)
Ju, *et al,Phys. Lett. A*, **354**, *360-365* (2006),
Gras, et al, *Class. Quantum. Grav.,* **26** 015002 (2010)
Ju, *et al, Phys. Lett. A*, **355**, 419-426 (2006)

Modeling of Parametric Instability in High power Cavities



Radius of Curvature of the end mirrors of the cavity



RoC ETM = 2048.4
R gain
10000
15000
20000
25000
30000
35000
40000
45000
50000
55000
60000
f_m [Hz]

Ring Up Time

Example

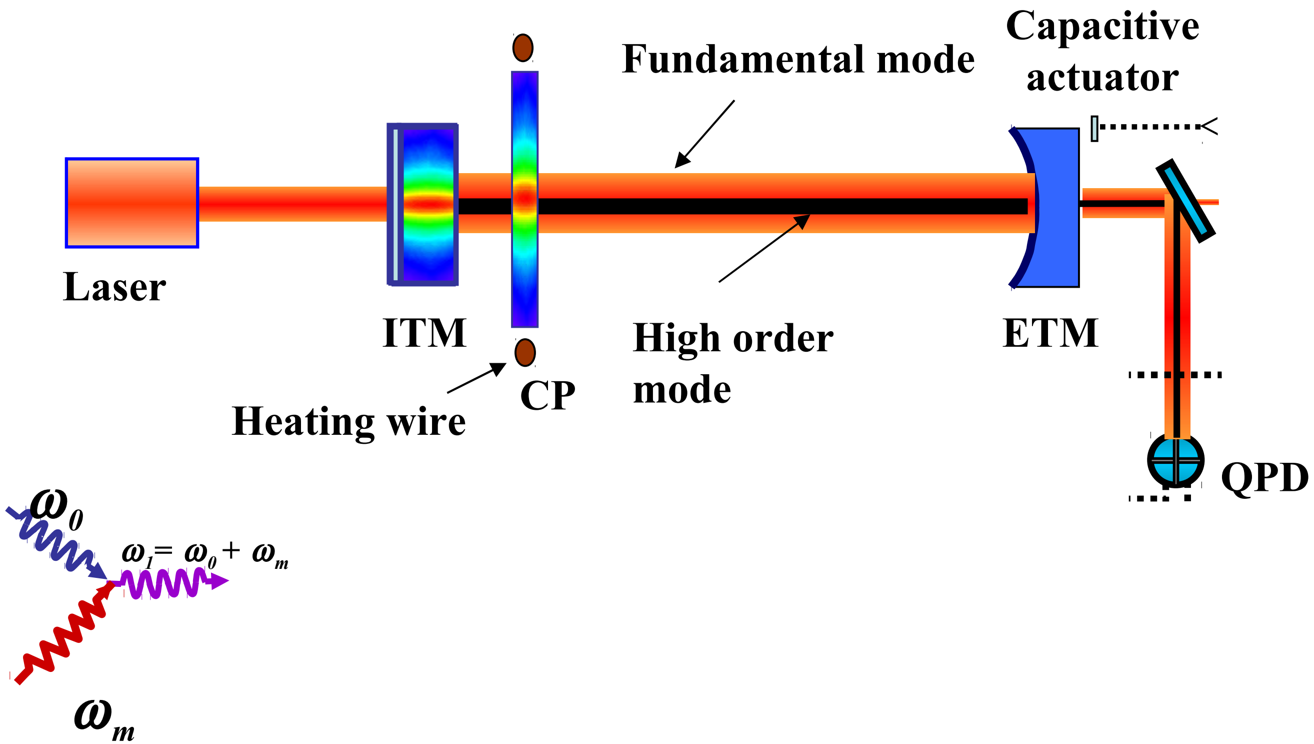
- Fused silica
  - $Q_m \sim 10^7$
- $f_m \sim 30$kHz
- R~10

$x = x_0 e^{t/\tau}, \;\; \tau \sim Q_m/\omega_m(R-1)$

from $x \sim 10^{-14}$ m (thermal peak)
to $x \sim 10^{-9}$ m (lose lock)

t ~10s!

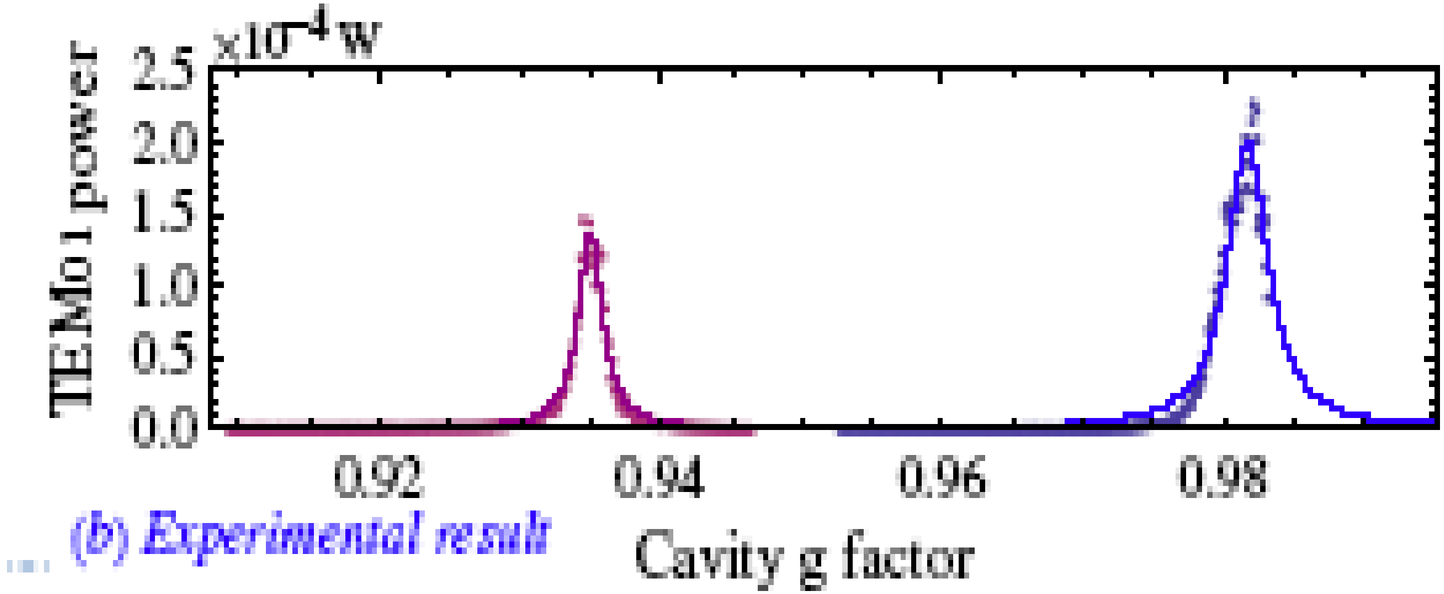
Experimental observation of parametric interaction



- Excite acoustic mode electrostatically
- Thermally tuning the cavity mode gap $(\omega_0 - \omega_1)$ using a Compensation Plate
- Observe the high order (TEM01) power change with $(\omega_0 - \omega_1)$.

Observation of 3-mode Parametric Interactions

Zhao , et al Phys. Rev. A, 78 023807 (2008)



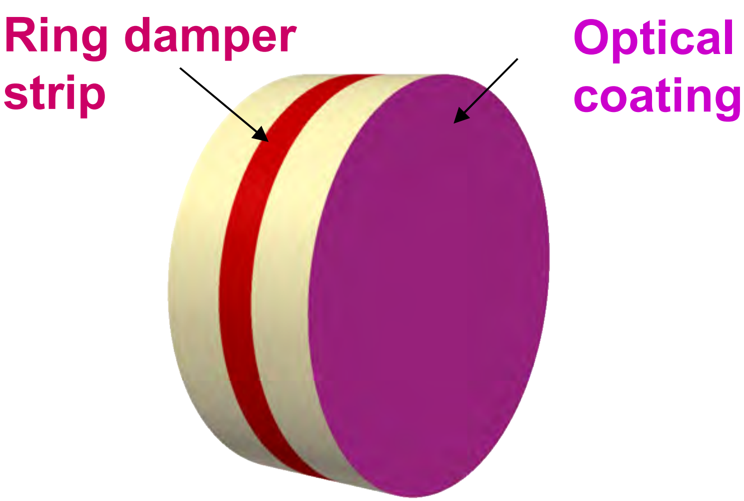
•Witnessed two high order transverse modes corresponding to two different mechanical modes of the mirror parametric gain ~ 0.01

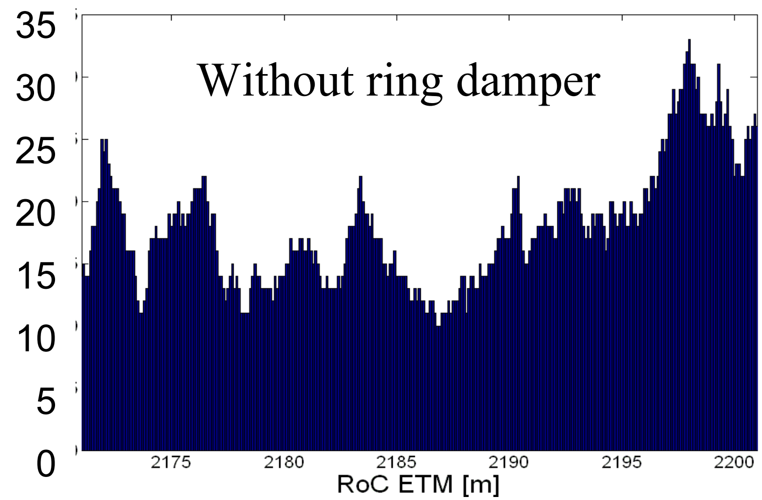
Control Strategies

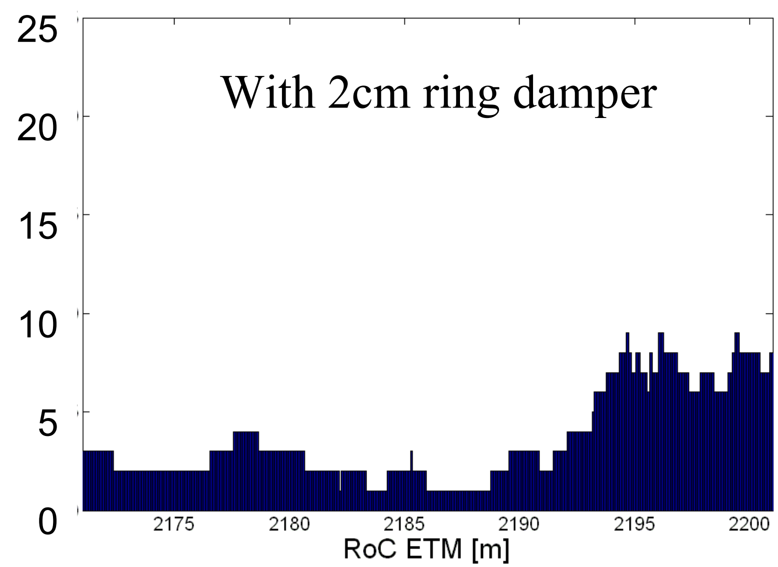
- Reduce acoustic Q of test masses
  - Ring damper
  - Acoustic mode damper
  - Electrostatic feedback
- Change $\Delta\omega$ (RoC tuning)
- Optical feedback control

Ring dampers

- Ring dampers
  - Eliminate most of the unstable modes
  - Have small thermal noise penalties

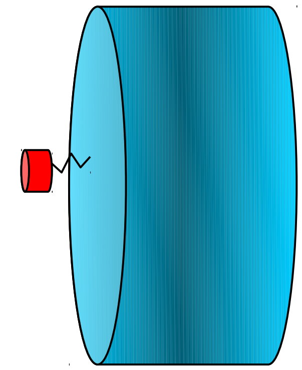






S. Gras, et al *Phys. Lett. A*, **372**,1348 (2008)

Acoustic Mode Dampers

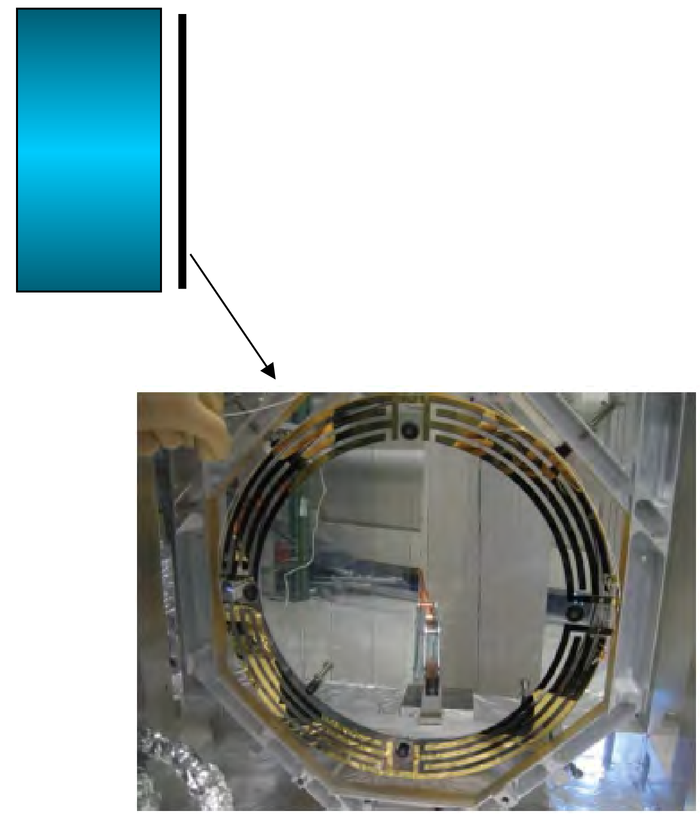


- Damper to absorb the energy of the “dangerous” test mass modes (broadband)
- MIT investigation
  - tested PZT damper Q
  - S. Gras (UWA graduate) modelling
- Effective damping of the Q of many modes but thermal noise exceed Advanced LIGO noise budget
- Needs more careful investigation of damper attachment

S. Gras, et al, LIGO document LIGO-G1001023-v1

Electrostatic damper

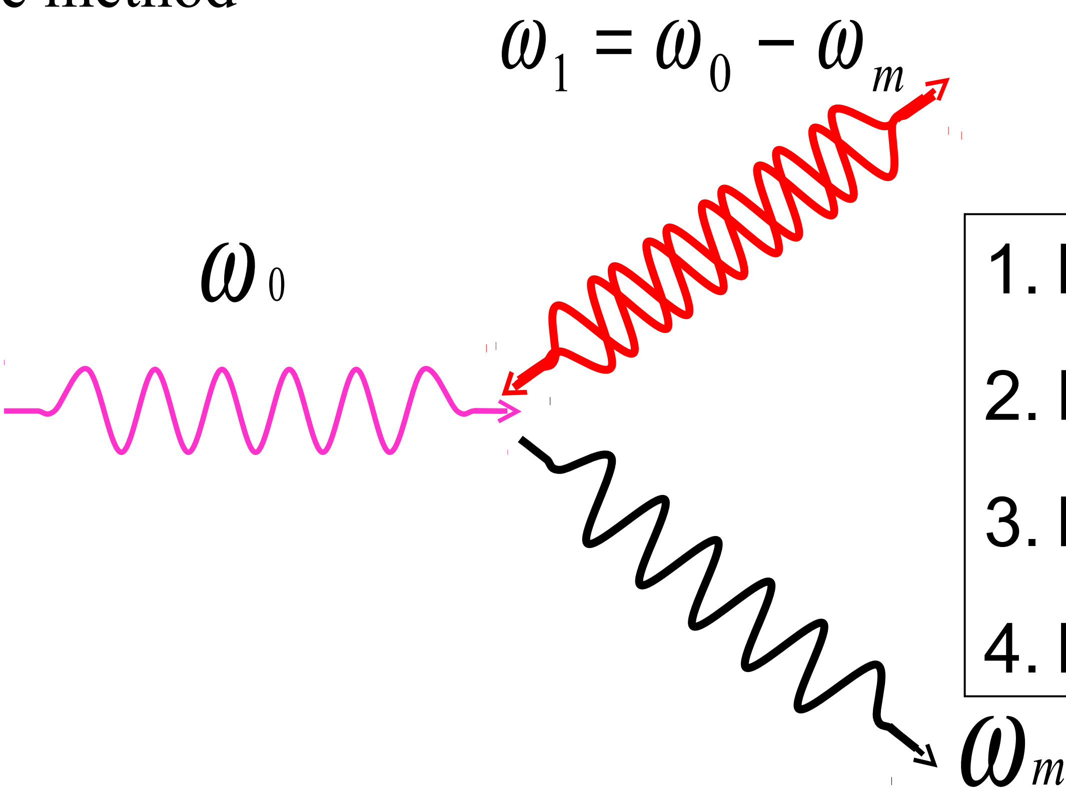
- Advanced LIGO electrostatic actuator could be used to damp the Q of the acoustic modes
- no issue of thermal noise degrading
- Difficulties
  - For multiple mechanical modes excitation, each mode needs a control loop
  - Identify the mechanical modes

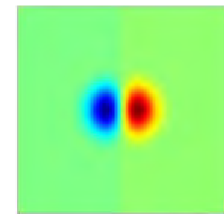


J. Miller, et al, *Phys. Lett. A*, **375**, 788-794 (2011)

Optical feedback control

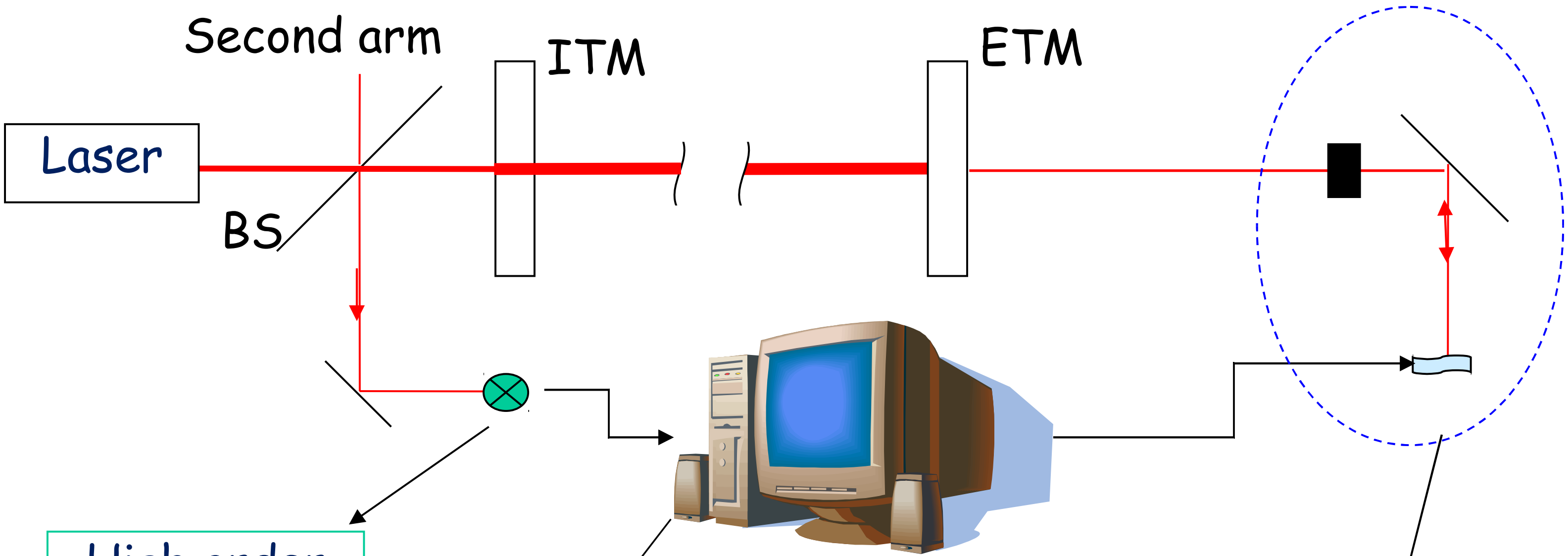
- Active method





1. Mode shape
2. Frequency
3. Phase
4. Power

Proposed ETM injection schematic



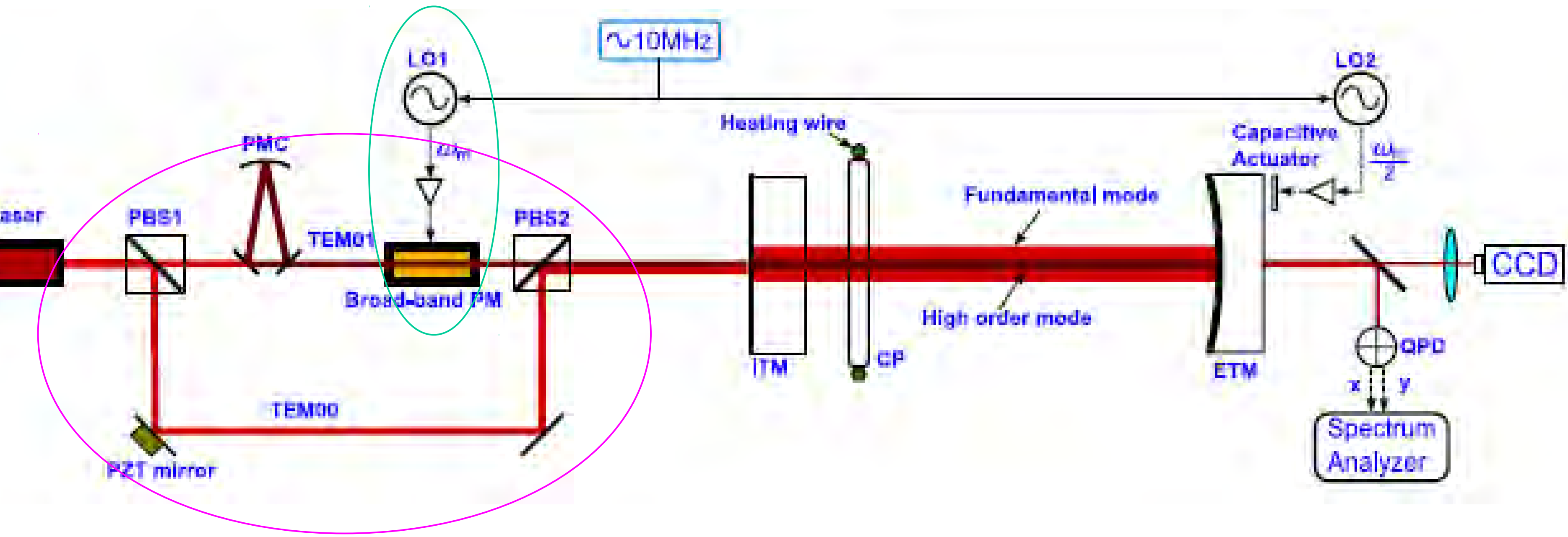
High order mode sensing with multi-segment PD

Mode decomposition & identification

- ETM "wasted" transmission to be re-injected into the cavity
- Deformable mirror generates suitable high order mode patterns
- AOM create right frequency shift

Proof of Principle Experiment

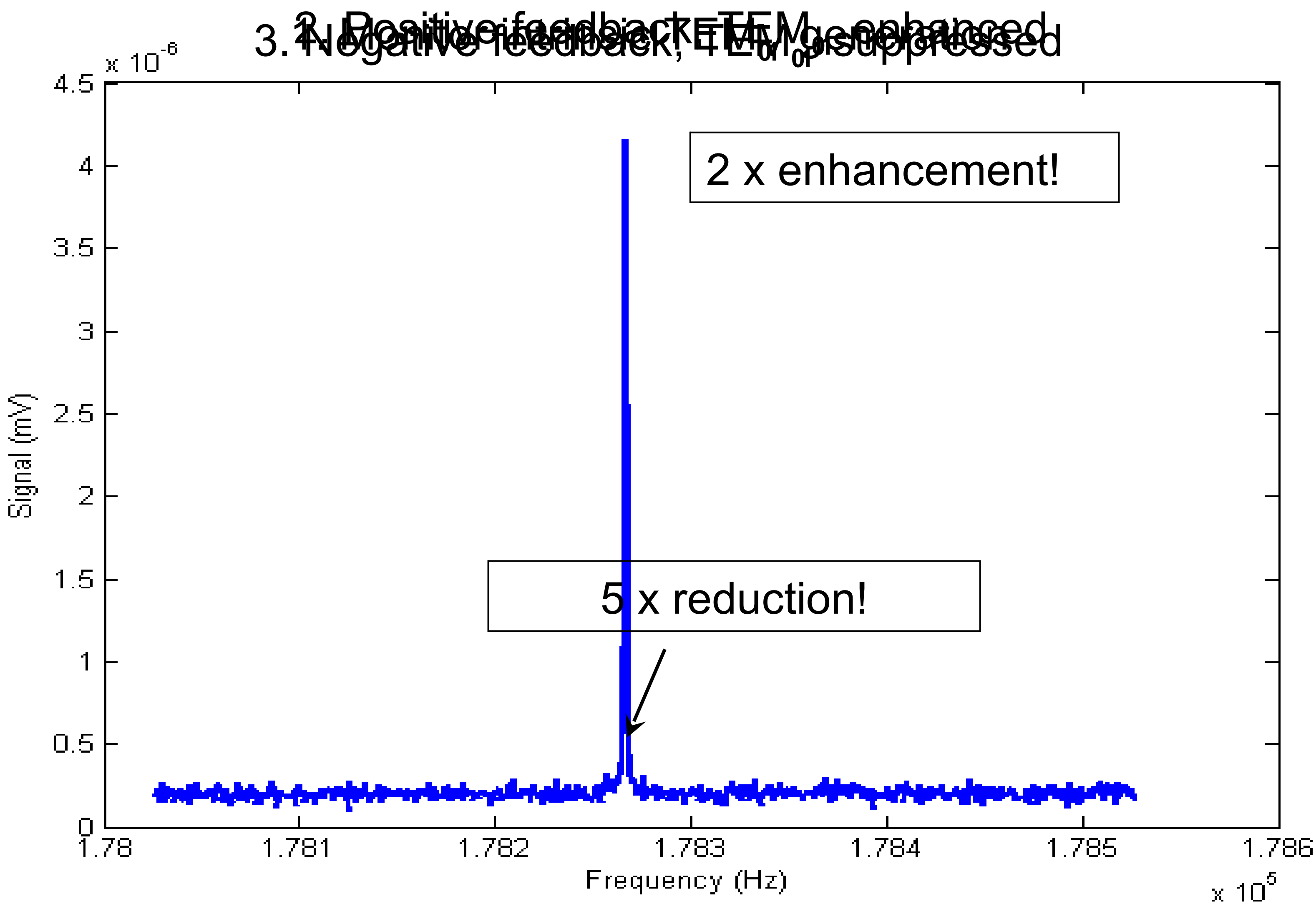
f, A modulation



2 optical modes injection

Fan, et. al, *Class. Quantum. Grav.*, **27** 084028 (2010)

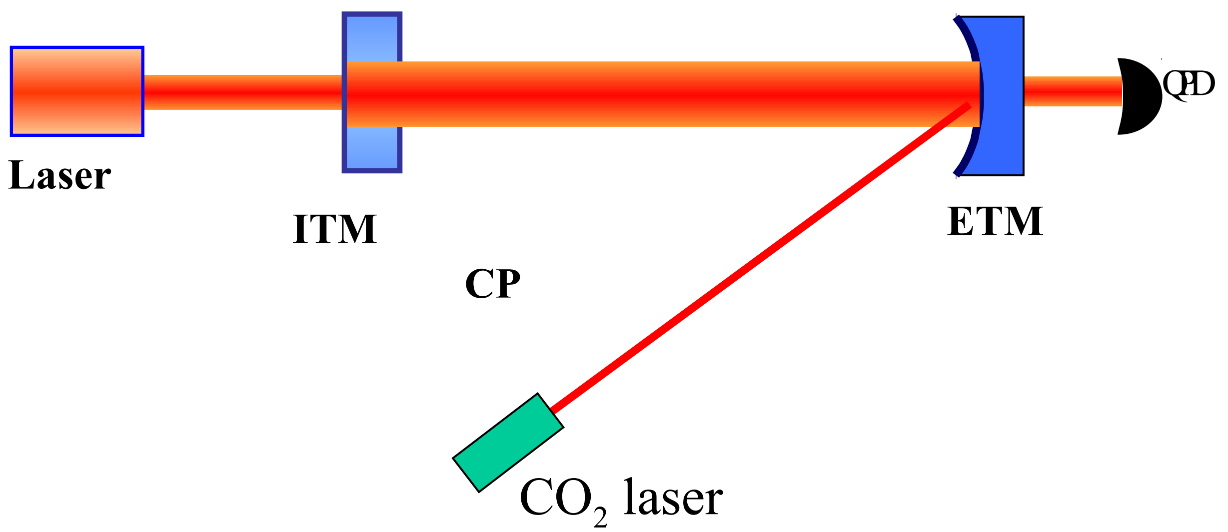
Demonstration of optical feedback control principle



3 mode interactions applications

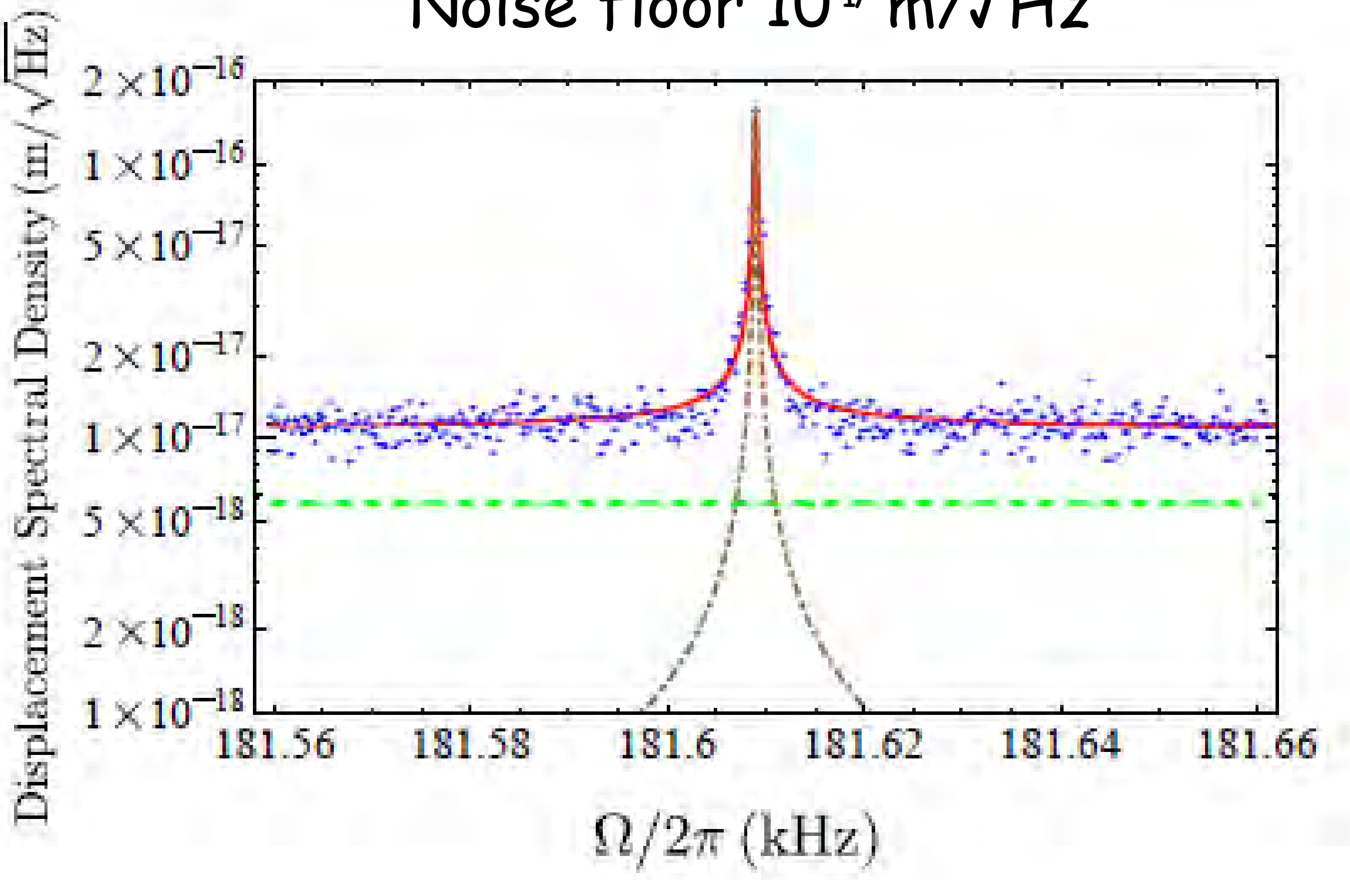
- High sensitive transducer for test mass acoustic modes
- Very strong coupling due to gain~$Q_0 Q_1 Q_m$
- Laser noise immunity
- 3 mode transducer is equivalent to a signal recycling interferometer

Opto-Acoustic Transducer



180kHz Acoustic mode thermal Peak

Noise floor 10^{-17} m/√Hz



*with unstabilised laser

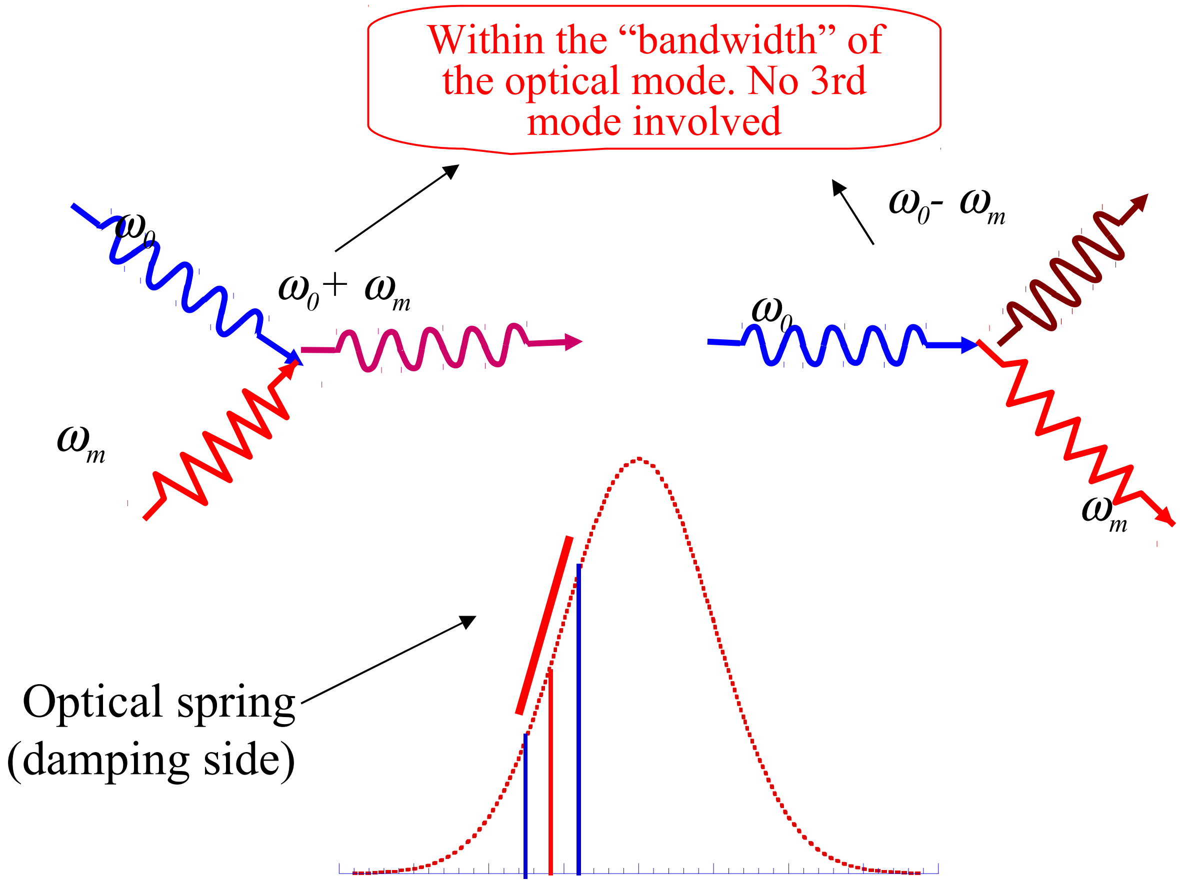
Other applications of 3 mode interaction

- Miniature opto-acoustic parametric amplifier for micro-mechanic quantum experiments

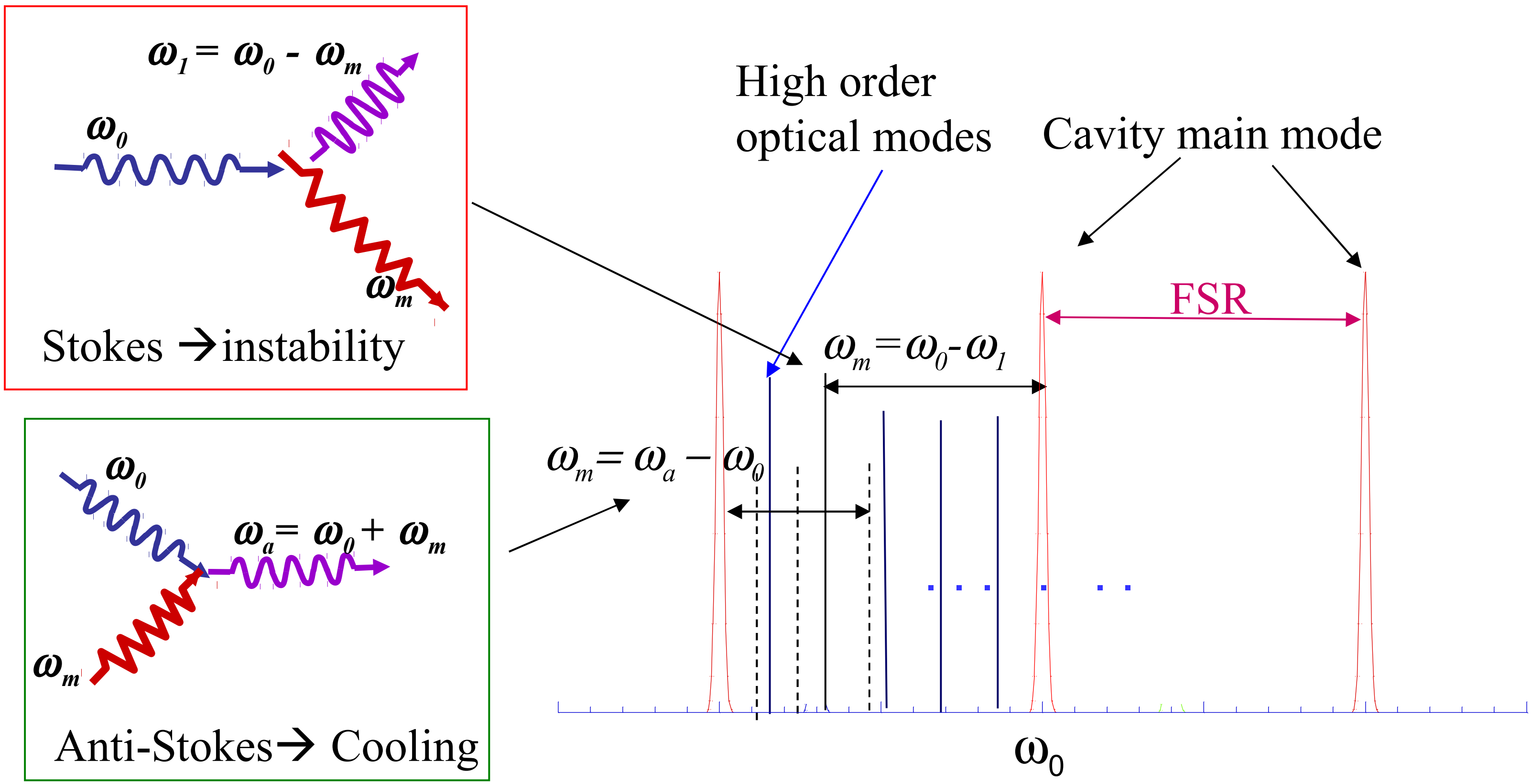
Conclusions

- Parametric Instability is a threat to Advanced detector
- More research is needed to develop effective control method without degrading detector performance
- Gingin facility will continue to investigate PI and PI control

2 modes interaction (optical spring)



Frequency condition for 3 mode parametric interactions



- 2 optical modes & 1 mechanical mode
  - Frequency conditions easily met in long cavities