Reducing Thermoelastic Noise by Reshaping the Light Beams and Test Masses

Research by

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Talk by Thorne, O'Shaughnessy, d'Ambrosio

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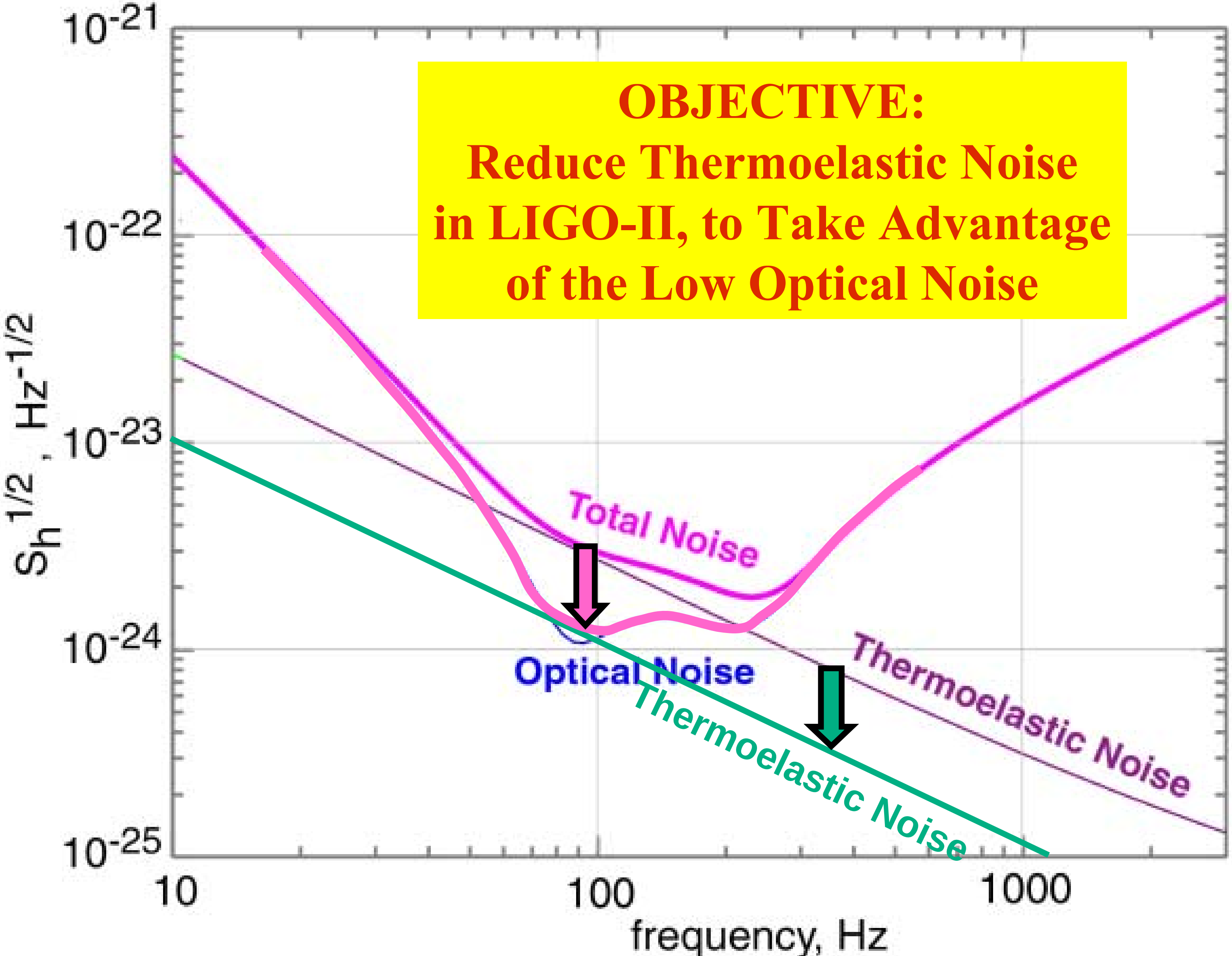
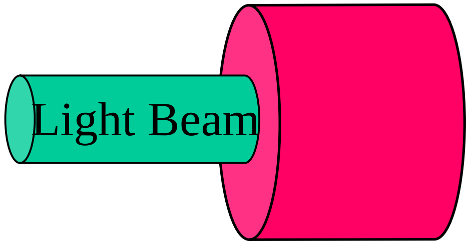
CONTEXT AND OVERVIEW
Sapphire Mirrors



KEY POINTS ABOUT THERMOELASTIC NOISE

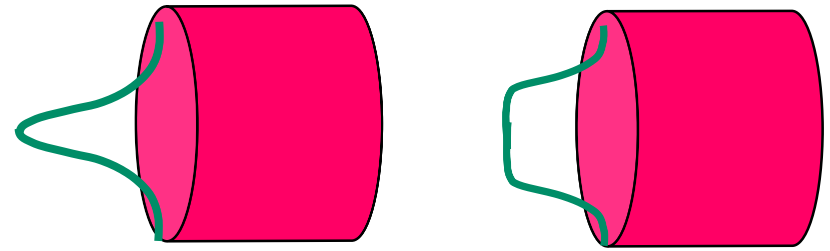
- **Physical Nature**
  - On timescale ~0.01 secs, random heat flow => hot and cold bumps of size ~0.5 mm
  - Hot bumps expand; cold contract
  - Light averages over bumps
  - Imperfect averaging => ***Thermoelastic noise***



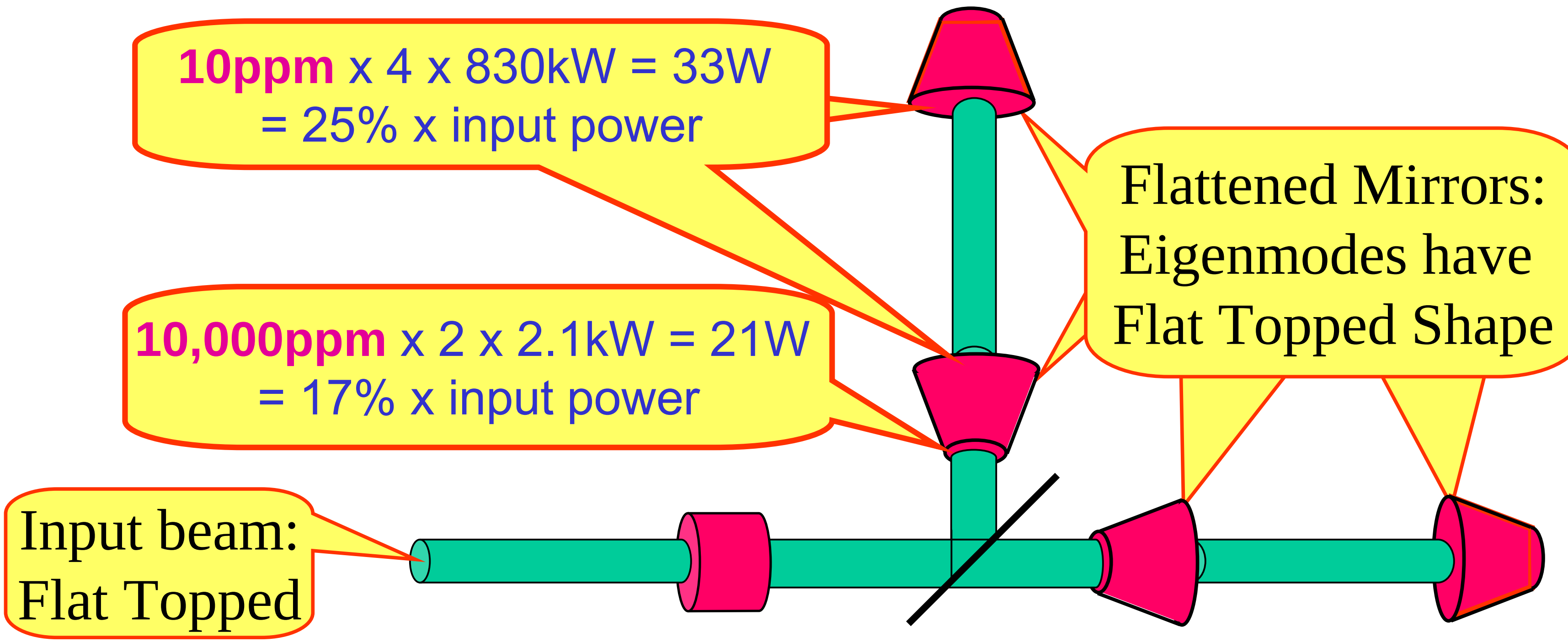
- **Computed via fluctuation-dissipation theorem**
  - Dissipation mechanism: heat flow down a temperature gradient => Computation highly reliable (by contrast with conventional thermal noise!)
  - This reliability gives us confidence in our proposal for reducing thermoelastic noise

Strategies to Reduce Thermoelastic Noise

- Gaussian beam averages over bumps much less effectively than a flat-topped beam.

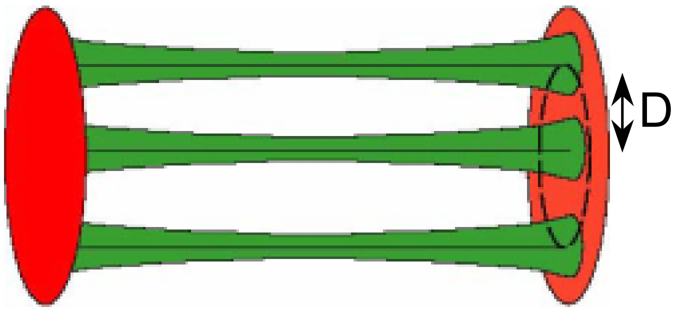


- The larger the beam, the better the averaging.
  - Size constrained by diffraction losses

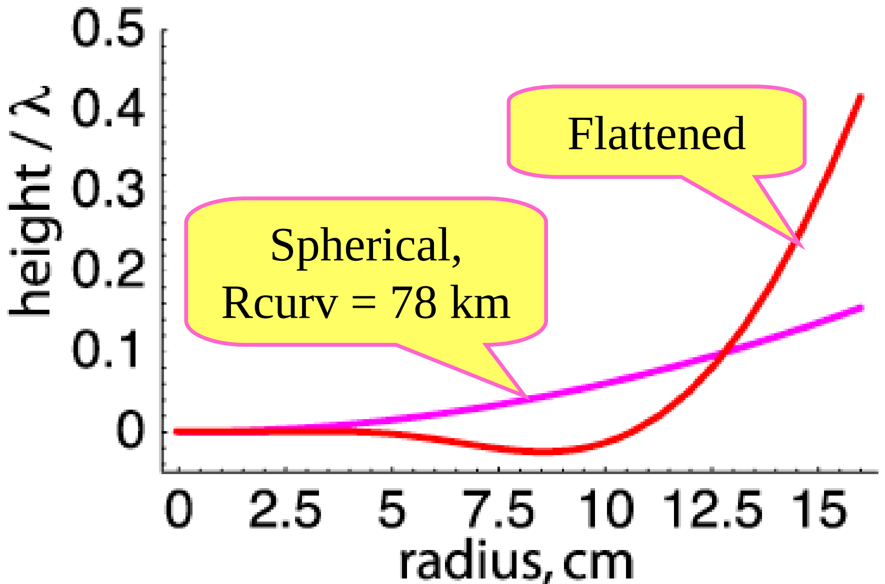


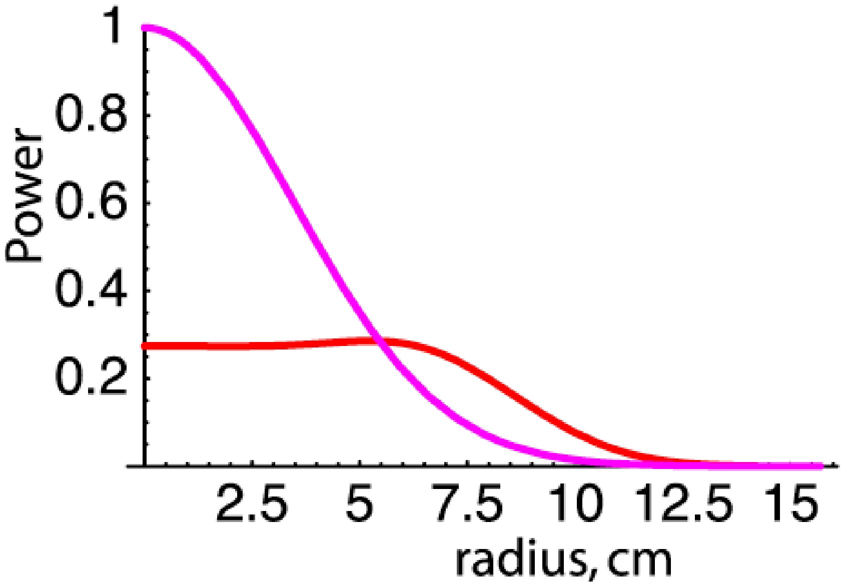
OUR FLATTENED MIRRORS & BEAMS

- **Compute desired beam shape:**
  – Superposition of minimal-spreading Gaussians -- axes uniformly distributed inside a circle of radius D
  – Choose D so diffraction losses are 10 ppm



- **Compute shape of mirror to match phase fronts**





PREVIEW OF OUR CONCLUSIONS

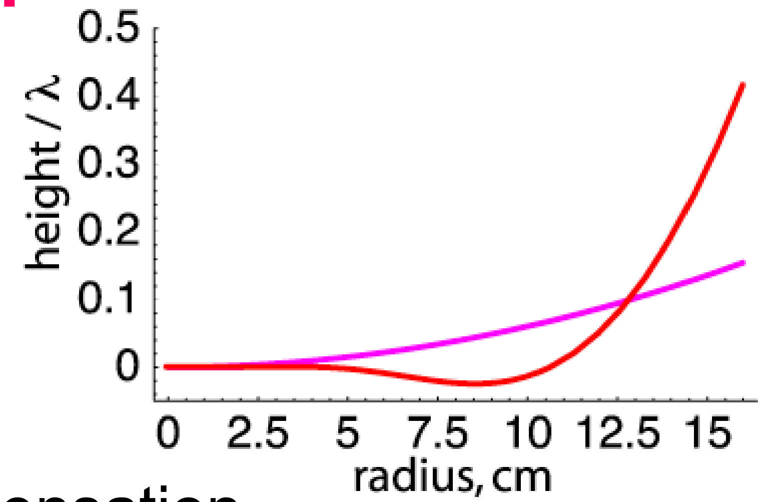
[same as in March!]

[details to be described by O'Shaugnessy & d'Ambrosio]

- **O'Shaugnessy:** By using these flattened mirrors and modes, thermoelastic noise can be reduced from that of the present LIGO-II baseline design by
  - $\sqrt{S_h} / \sqrt{S_{hBL}}$ = **0.42**;
    - NS/NS range increased from ***300 Mpc*** to ***455 Mpc***]
  - There appears to be ***little danger of exciting parasitic modes***
- **d'Ambrosio:**
  - FFT simulations, & perturbation theory analysis => ***it is sufficient to control mirror tilts to 0.01 microradians***
    - Negligible increase of diffraction losses
    - Power out dark port (for 125 W input & ignore losses):
      - before mode cleaner: 60 mW (tilt angle / 0.01 μrad)^2
      - After mode cleaner: 3 mW (tilt angle / 0.01 μrad)^4

ISSUES THAT NEED STUDY

- **Theoretical Modeling issues:**
  - **Tolerances on mirror shapes**
    - Absolute tolerances
    - Tolerances in relative differences between mirrors
    - Thermal lensing and its compensation
  - **Possible dynamical instabilities**
    - e.g., rocking motion due to positive rigidity combined with time delay in response
- **Laboratory prototyping**



Computing noise: Fluctuation dissipation theorem

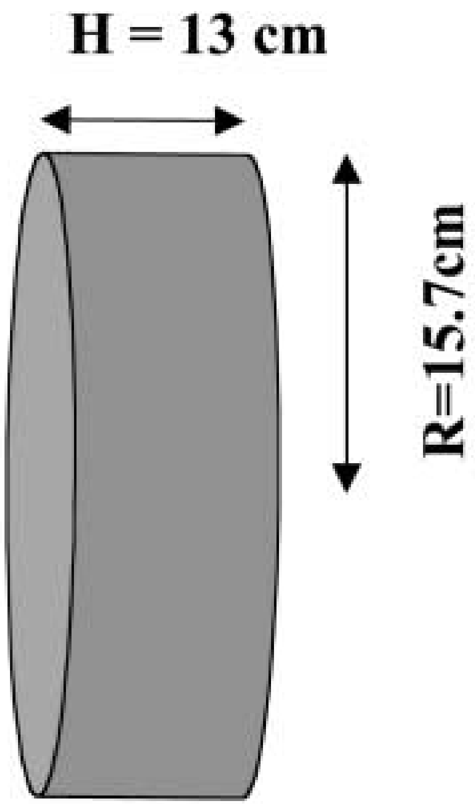
- **Thought experiment:**
  ***Static* pressure on mirror face**
  Shape is beam intensity profile, normalization F_o
  $\Rightarrow$

$$S_h = 4\left(\frac{k_b T \alpha E}{(1-2\nu) C_V \rho}\right)^2 \frac{1}{\omega^2} I \qquad I = \frac{1}{F_o^{\;2}} \int d^3 r \left|\nabla \theta\right|^2$$

- ***I* contains information about beam, mirror shape and size**
- **Find *I* via standard elasticity code (finite-element)**

Results: Cylindrical, LIGO-II Mirror

Sapphire Mirror: R=15.7 cm, H=13 cm,



Baseline design:

Gaussian beam,

2 ppm diffraction losses

↔ curvature R_c=54 km

Get $I=I_o$

→ $D_{NS\text{-}NS}$=300Mpc

Flattened Mirrors:

Flat-topped beam, 10 ppm losses, cylindrical mirrors

$$\sqrt{I/I_o} = \sqrt{S_h^{TE}/S_{h,o}^{TE}} = 0.54$$

→ $D_{NS\text{-}NS}$ = 410 Mpc , rate up x2.6

Results: Conical mirrors

Flat-topped beam

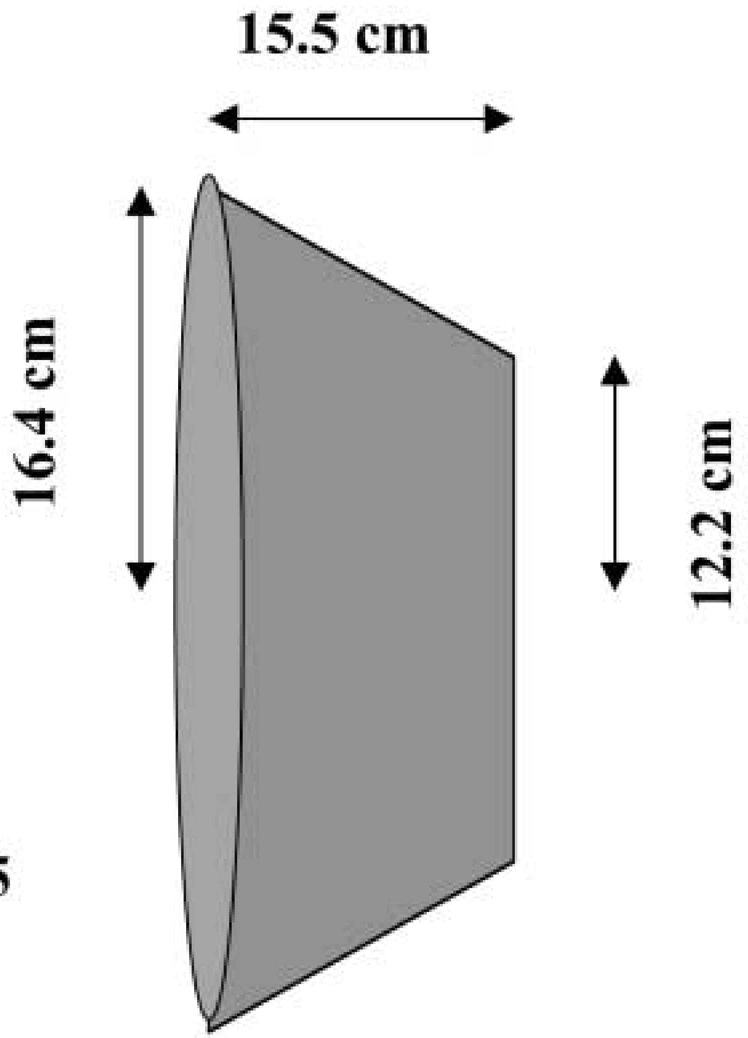
10ppm diffraction losses on inside

1% diffraction losses on outside

$$\sqrt{I / I_o} = \sqrt{S_h^{TE} / S_{h,o}^{TE}} = 0.42$$

→ **$D_{NS\text{-}NS}$ = 455 Mpc, rate up x3.5**

∞ **Asymmetric "conical" mirrors**
- **Use different-shape mirrors at each end**
- **Can be slightly more effective (x0.9)**



Nearly flat → problems?

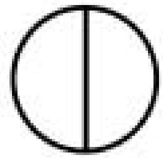
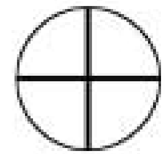
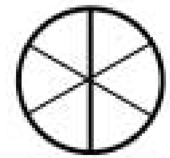
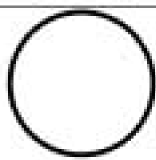
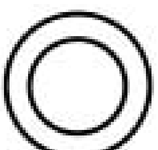
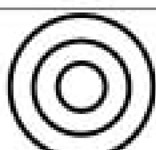
Degeneracy?

Flat spherical mirrors have close frequency seperation. Do ours?

$$\Delta\omega = \omega - \omega_{o,o}$$

Azimuthal Nodes

Radial Nodes

$\dfrac{\Delta\omega}{\pi c / L}$				
	0	**0.0404**	**0.1068**	**0.1943**
	**0.1614**	**0.2816**	**0.4077**	**-0.4581**
	**0.4303**	**-0.4140**	**-0.2570 (X)**	**-0.0812 (X)**
	**-0.2330 (X)**	**-0.0488 (X)**	**0.1406 (X)**	**(X)**

X → indicates diffraction losses per bounce > 1%