Reducing Thermoelastic Noise by Reshaping the Light Beams and Test Masses

Research by

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Talk by Kip S. Thorne

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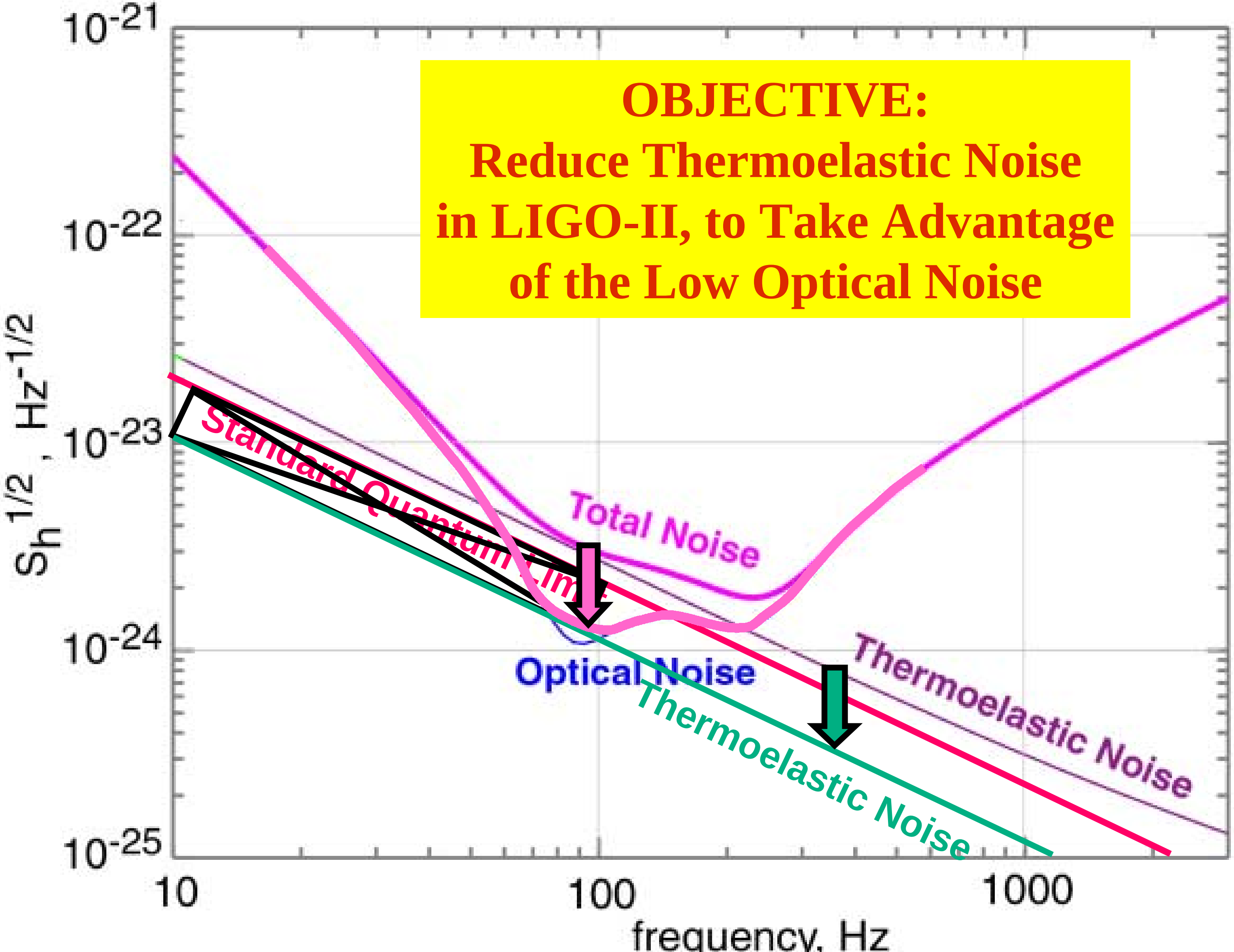
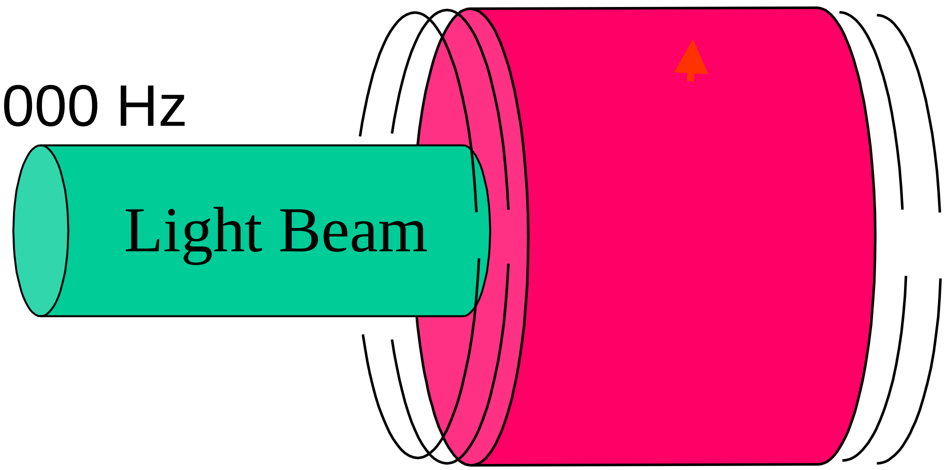
CONTEXT AND OVERVIEW

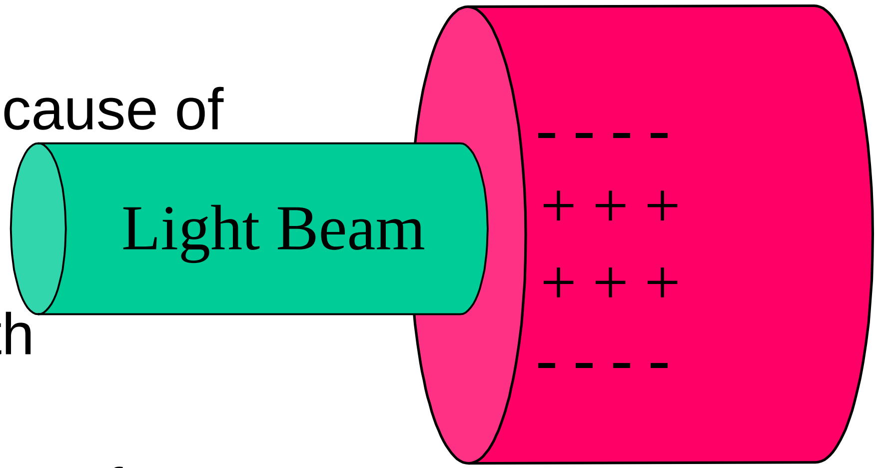


Thermoelastic Noise Contrasted with Conventional Thermal Noise

- **Conventional Thermal Noise [normal-mode random walk]**
  - mode frequencies: ~ 10,000 Hz
  - random walk of amplitude & phase -> noise in LIGO band, ~10 to 1000 Hz

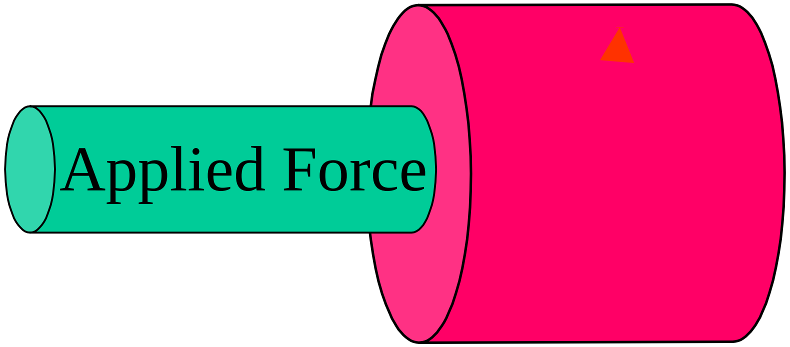


- **Thermoelastic Noise [random heat flow; thermal expansion]**
  - especially bad in sapphire because of high thermal conductivity
  - on timescales 0.01sec fluctating hot & cold spots with size ~ 0.5 mm
  - beam averages over them; imperfect average



Computation of All Forms of Thermal Noise [Levin's "Direct Method"]

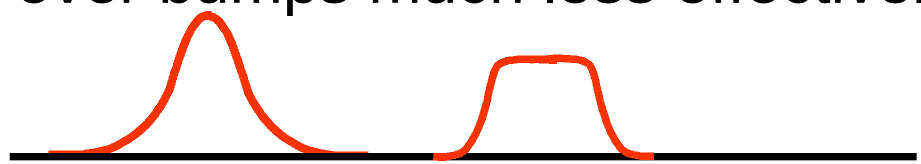
- To compute spectral density of noise at frequency f:
- Apply an oscillating force with frequency f and cross-sectional profile same as light beam
- Compute total rate of dissipation (rate of entropy increase, i.e. of thermal heating), W_{diss}
- Spectral density of thermal noise ~ W_{diss}



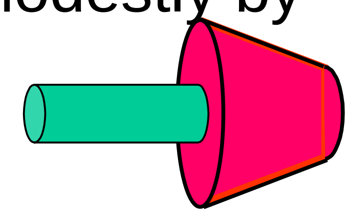
- Classify noise sources by dissipation mechanism
- **Conventional thermal noise:** dissipation mechanism unknown; ***predicted spectrum not reliable***
- **Thermoelastic noise:** dissipation due to heat flowing down Temperature gradiant; ***predicted spectrum reliable***

Strategy to Reduce Thermoelastic Noise

- The larger the laser spot on the test masses, the better the averaging over ~0.5mm fluctuating bumps:
  amplitude noise $\sim 1/r_o^{3/2}$
  - Step 1: keep Gaussian beam shape; enlarge beam radius r_o^3
- Gaussian beam averages over bumps much less effectively than a flat-topped beam.



  - Step 2: reshape the beam, making it as flat topped as is compatible with diffraction in LIGO's 4 km arms; Achieve this by (i) preparing light, before power recycling mirror, in new shape; (ii) reshaping arm-cavity mirrors so excited eigenmode has the flattened shape. Desired mirrors are dish shaped:
- Noise also depends on shape of test mass; gain modestly by
  - Step 3: reshape the test masses



The Quantitative Gains From Each Step

[Work in progress; numbers are tentative; modeling is far from complete]

- Present baseline design:
  - r_o = 6cm (1/e in amplitude; $1/e^2$ in power)
  - **h_{TE} = 1.45 h_{SQL}**
  - diffraction losses on each mirror:
    - **1ppm**
    - Total losses: 4 x 1ppm x 830kW = **3.3W** (vs. 125 W into IFO)
- Step 1: keep beam Gaussian; increase radius
  - r_o = 6.5 cm
  - diffraction losses on each mirror increased to **10ppm**
    - Total losses: 4 x 10ppm x 830kW = **33W** (about 25% of the 125 W into IFO)
  - h_{TE} reduced by **0.88** from baseline, to **1.30 h_{SQL}**
  - NS/NS observable distance increased from 300 to **320Mpc**
  - Inspiral event rate increased by factor **1.2**

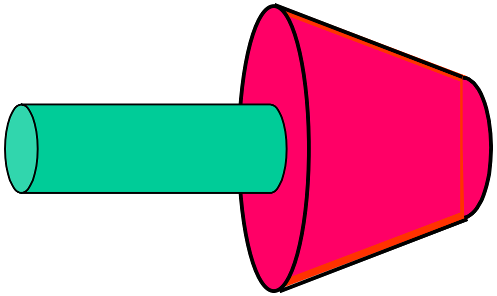
The Quantitative Gains [continued]

[Work in progress; numbers are tentative; modeling is far from complete]

- Step 2: flatten beam; dish shaped mirror surfaces
  - choose beam radius such that the diffraction losses are held fixed at 10ppm on each mirror
  - h_{TE} reduced by factor **0.56** - - net 0.88x0.56 from baseline, to **0.73 h_{SQL}**
  - NS/NS detectable distance increased from 300Mpc (baseline) to **425Mpc**
  - Inpiral rate increased by factor **2.9**

The Quantitative Gains [continued]

[Work in progress; numbers are tentative; modeling is far from complete]



- Step 3: Reshape test masses
  - e.g., keep thickness fixed (13cm); increase radii from 15.7cm to **17.2 cm & 14.4 cm** [input masses], **20cm & 13 cm** [end masses]
  - h_{TE} reduced by factor **0.8** - - net 0.88x0.56x0.8 from baseline, to **0.59 h_{SQL}**
  - NS/NS detectable distance increased from 300Mpc (baseline) to **450Mpc**
  - Inpiral rate increased by factor **3.5** over baseline

Parasitic Modes in Arm Cavities

- We see no sign of problematic parasitic modes
  - not in end to end model
  - not in mode computations

ESTIMATED EFFECTS OF MIRROR TILT

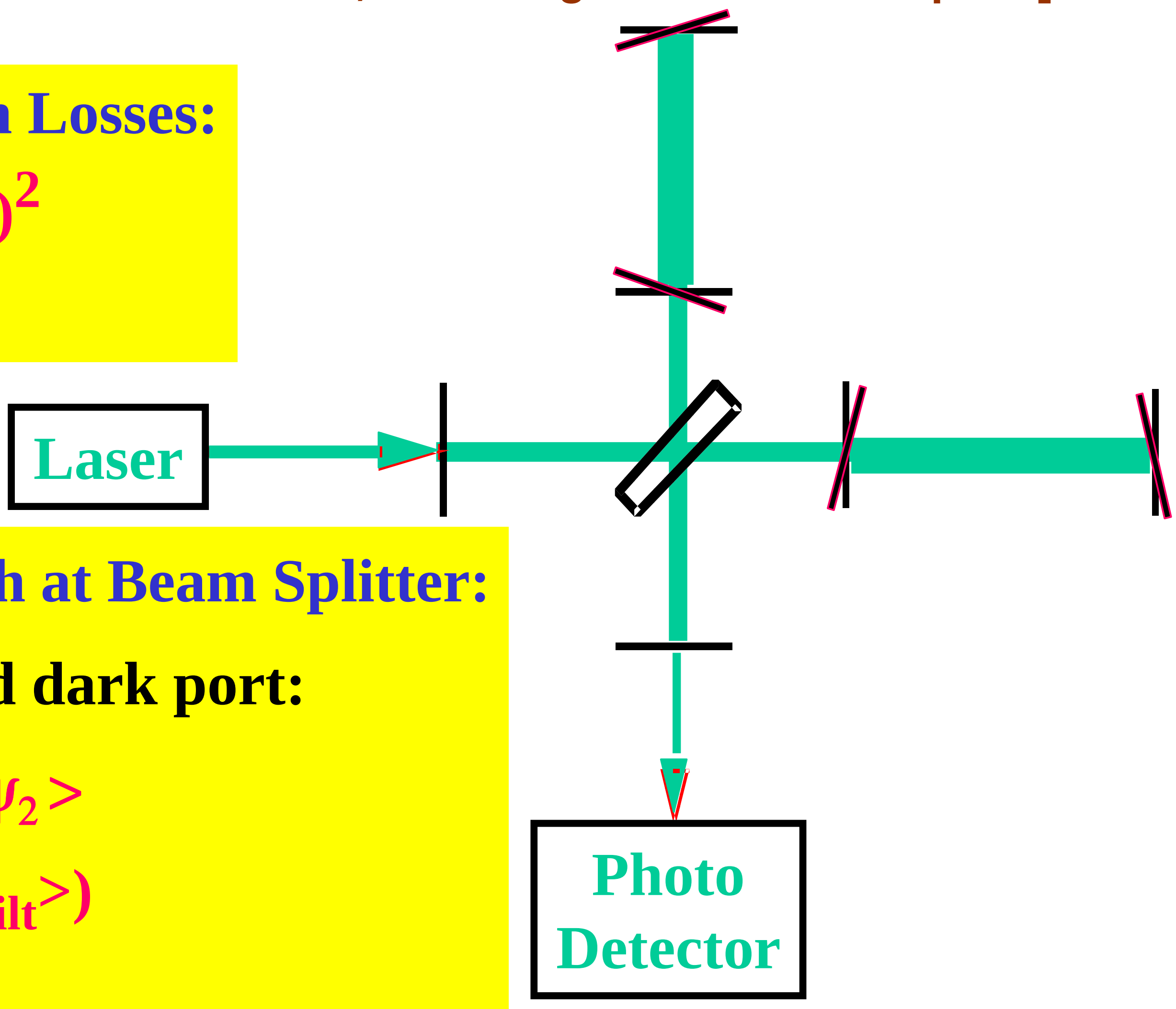
[from d'Ambrosio's adaptation of end-to-end model]

[Work in progress; numbers are tentative; modeling is far from complete]

Increased Diffraction Losses:

~10ppm $(\theta/10^{-8}\ \mathrm{rad})^2$

at each mirror



Wave-front Missmatch at Beam Splitter:

carrier power toward dark port:

$IDP/Io = 1\text{-}Re < \psi_1,\psi_2 >$

$\varphi\ 4(1\text{-}Re <\psi_{notilt},\psi_{tilt}>)$

$\varphi\ 10^{-4}\ (\theta/10^{-9}\ \mathrm{rad})^2$

Conclusion

- By:
  - increasing the beam size (to diffraction losses of 10ppm),
  - reshaping the beam (by changing mirror face from spherical to dish-shaped)
  - reshaping the test masses (from cylinders to truncated cones)
- We can gain about a factor 3.5 in inspiral event rate [increase NS/NS range from 300 Mpc to 450 Mpc]
- The biggest gain (by a substantial amount) comes from the beam reshaping
- The practical problems in this proposal might be manageable.