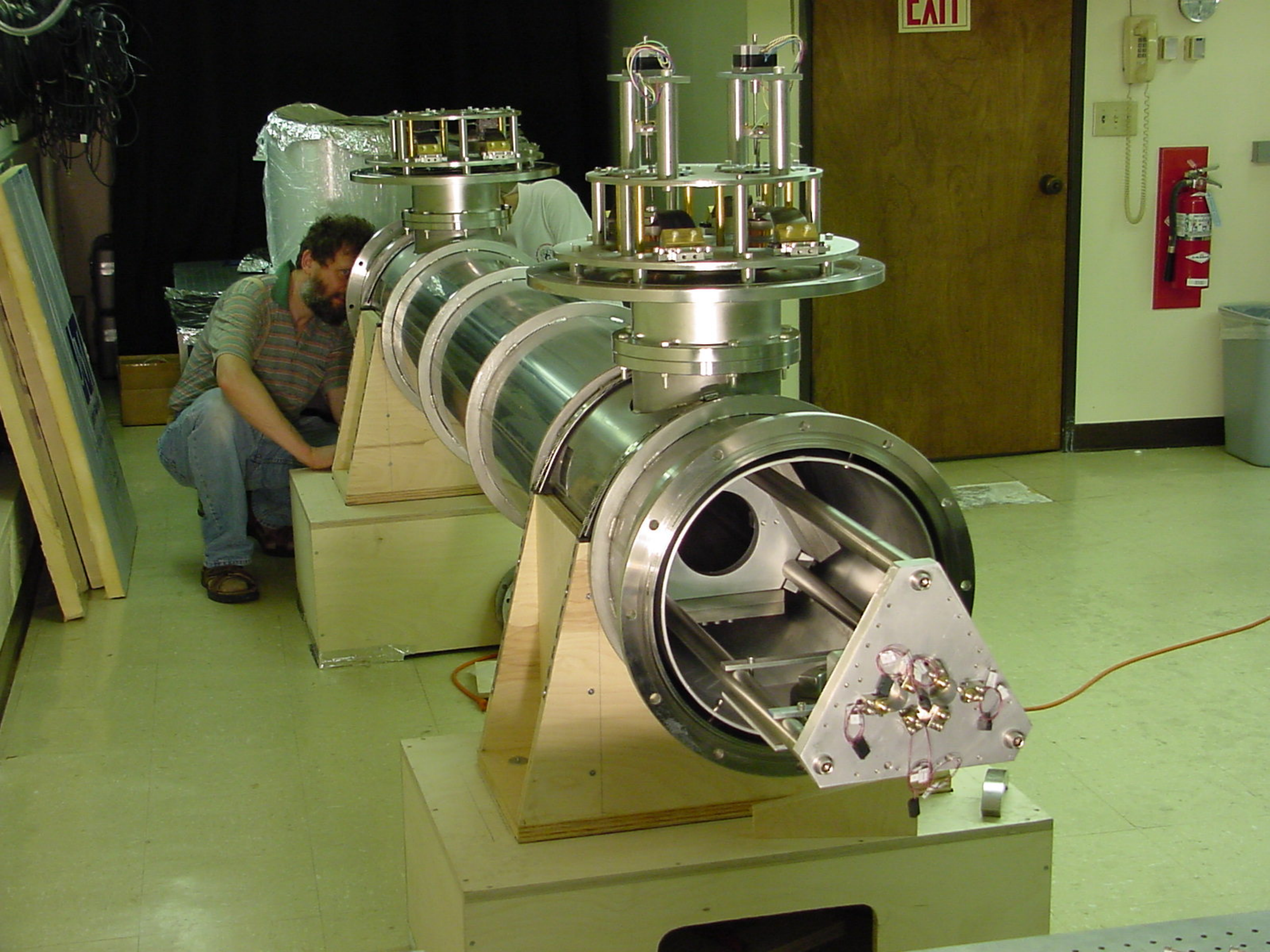

EXIT

LIGO

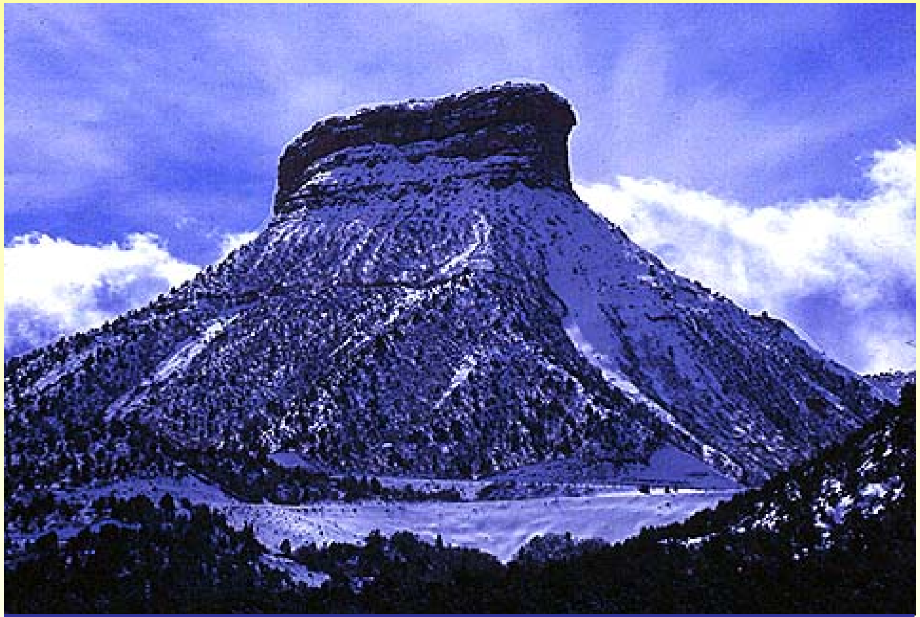
IGR

Mesa Beams

John Miller
University of Glasgow
Caltech, 7th August 2007

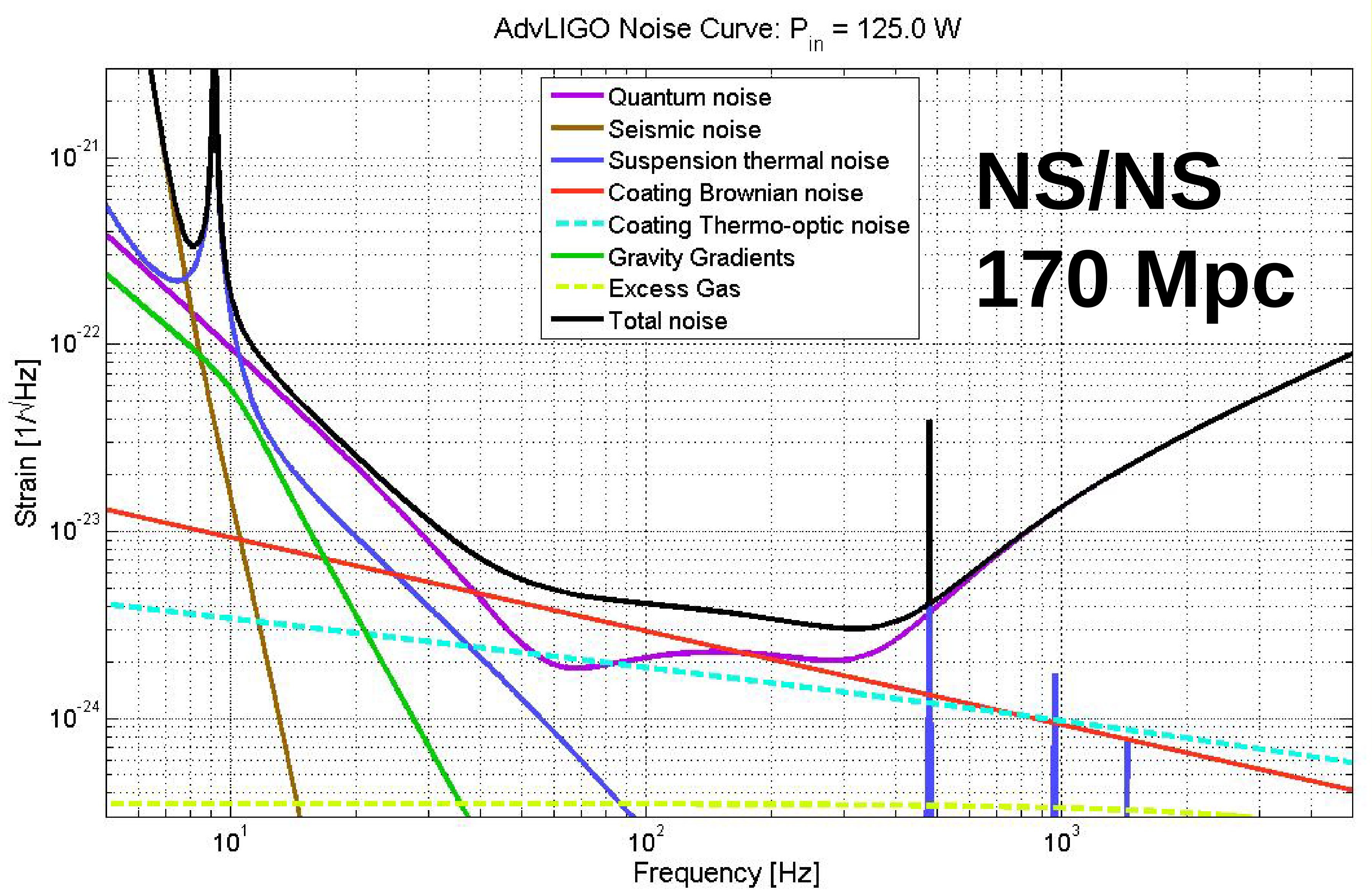
Preface

- Introduction
- Experiment
  - Past, present, future
  - locking
  - alignment
  - coupled cavities
- Theory
  - Thermal noise*
  - TCS
- Other beams
- Conclusions


A mesa. Look Out Point in Mesa Verde National Park, CO.

*preliminary results, remains to be checked

Noise



AdvLIGO Noise Curve: P_{in} = 125.0 W
Quantum noise
Seismic noise
Suspension thermal noise
Coating Brownian noise
Coating Thermo-optic noise
Gravity Gradients
Excess Gas
Total noise
NS/NS
170 Mpc
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{1}
10^{2}
10^{3}
Frequency [Hz]

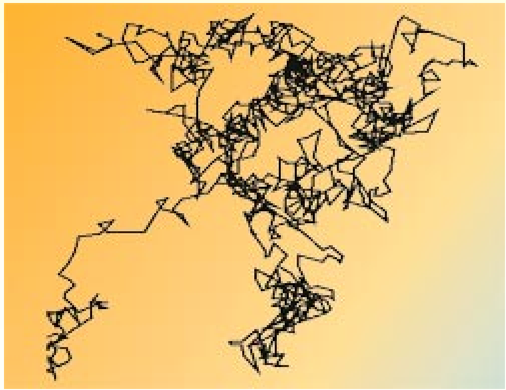
Thermal noise

- Brownian
  - internal friction
  - impurities, dislocation of atoms
- Thermoelastic
  - random heat flow in substrate and coating
  - non-null coefficient of thermal expansion
  - thermodynamic fluctuations result in displacements

$$\alpha \neq 0$$

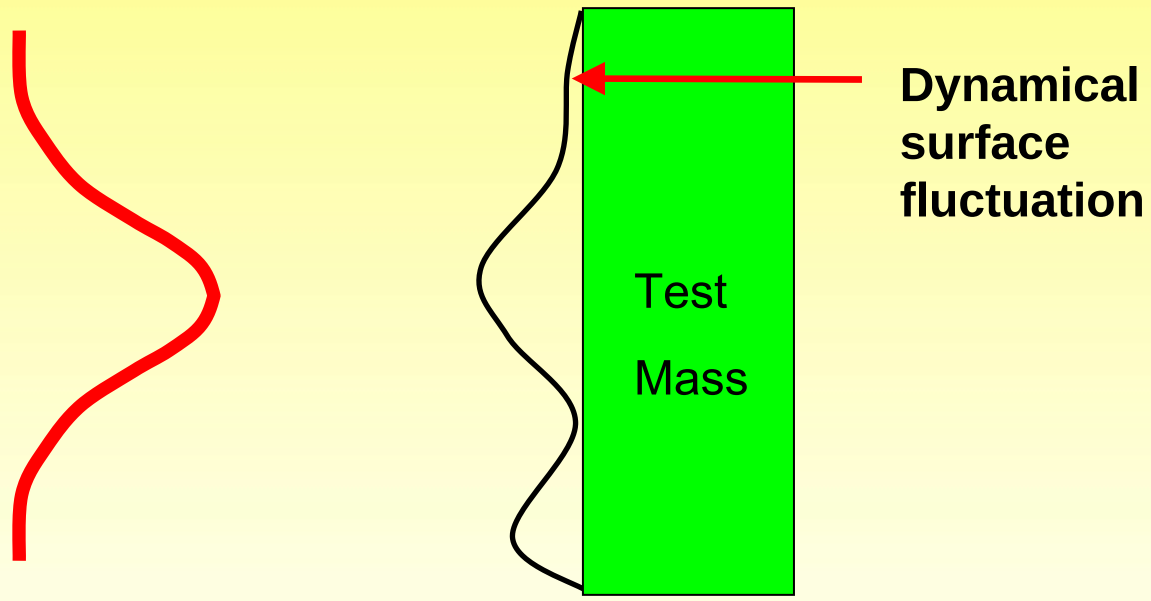
- Thermorefractive
  - refractive index changes with temperature

$$\beta = \frac{dn}{dT} \neq 0$$



Motivation

Sensitive to test mass position *as sensed by laser*

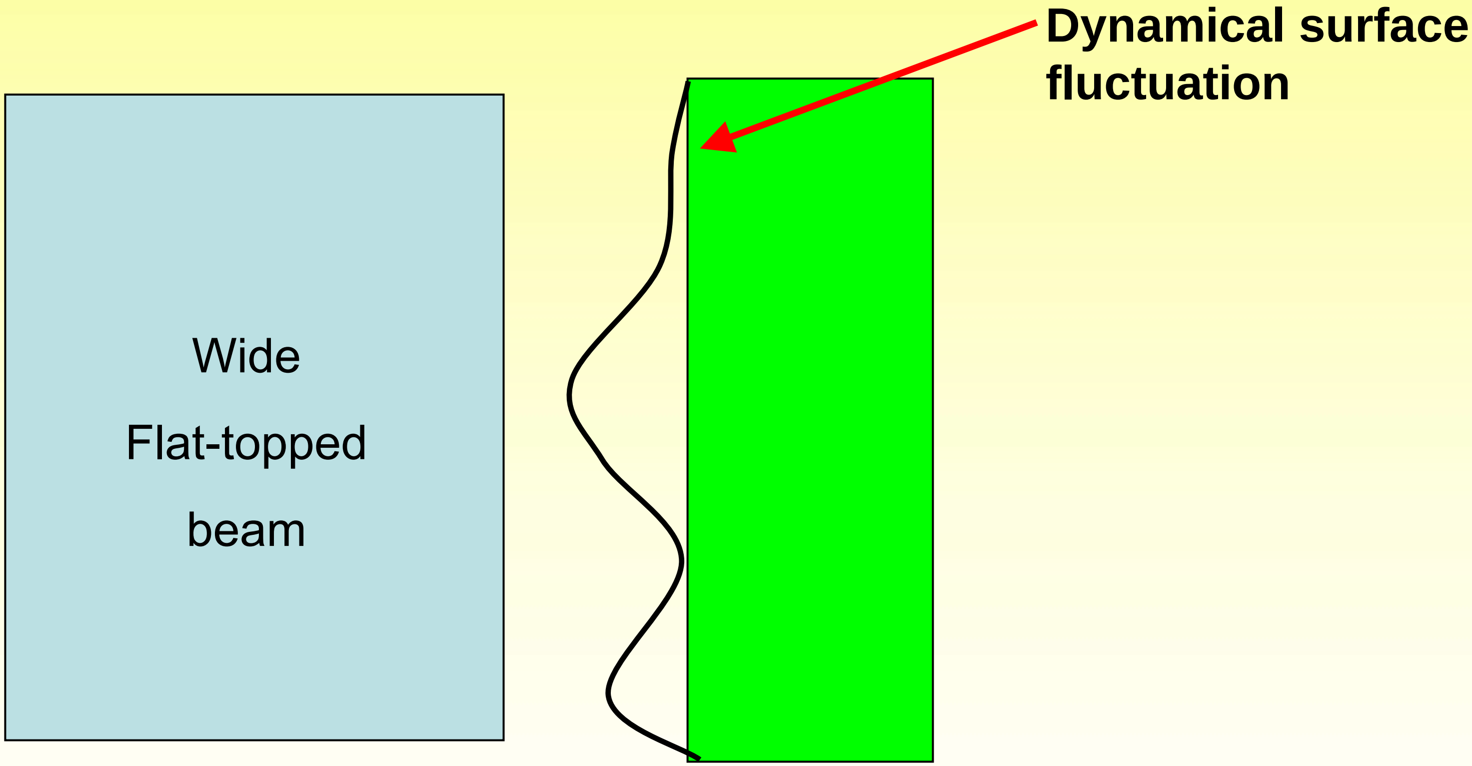


- Steep gradient provides a poor spatial avg.

- For Gaussian Beams (GB) bigger is better
  - diffraction loss

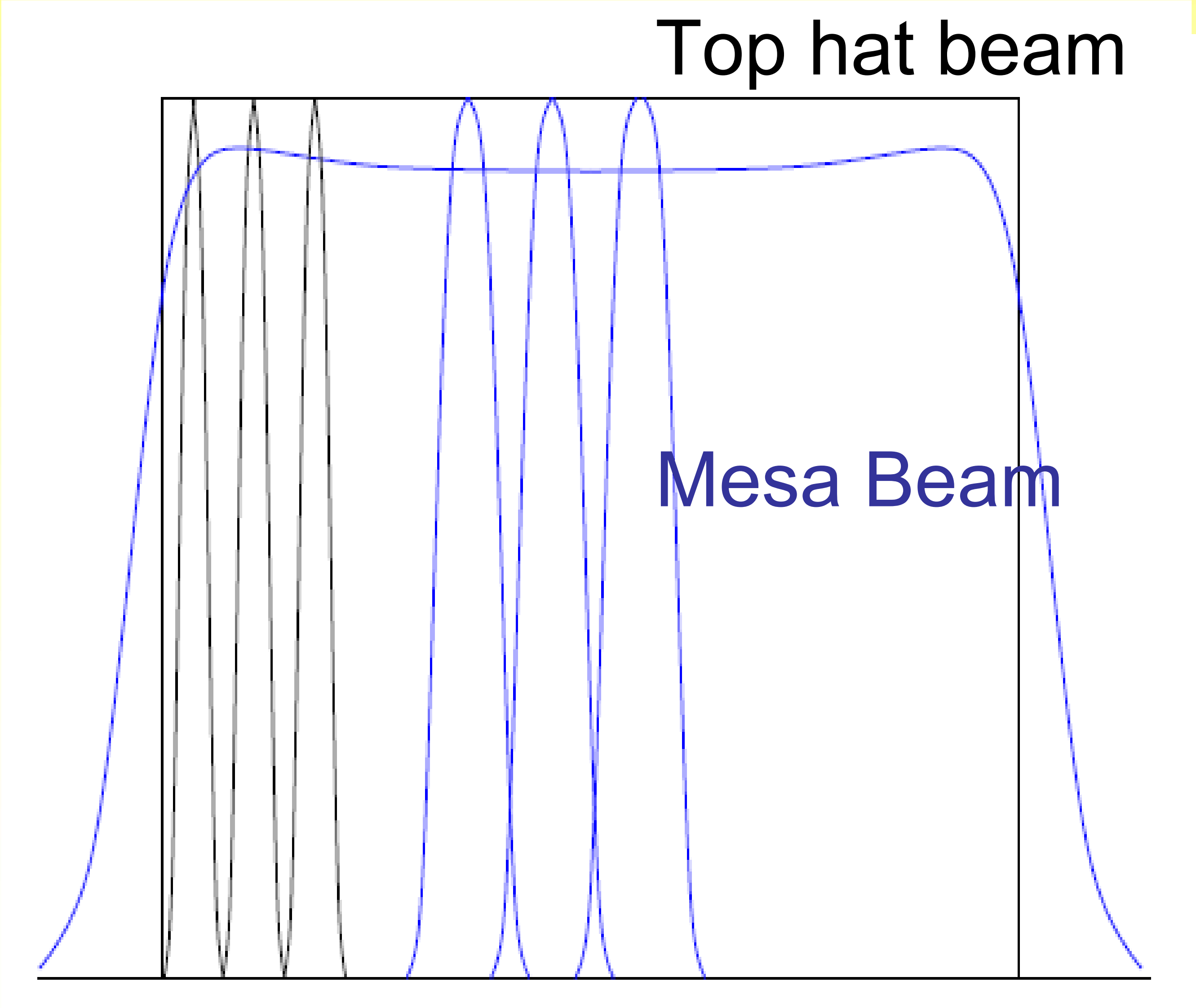
$S \sim 1 / w^n$

Ideal beam



- Not really a valid picture for finite masses

How to make a mesa beam (MB)



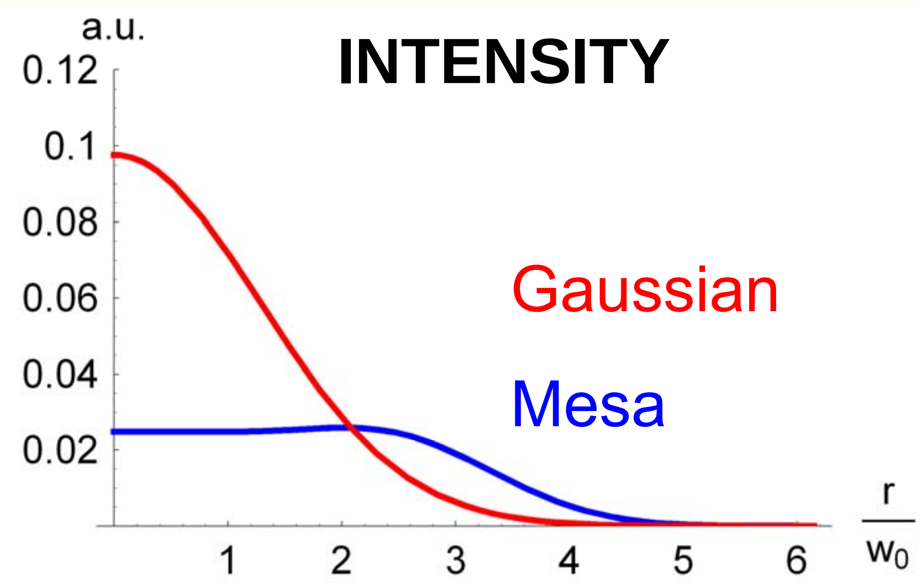
Mesa beam/MexHat Mirrors

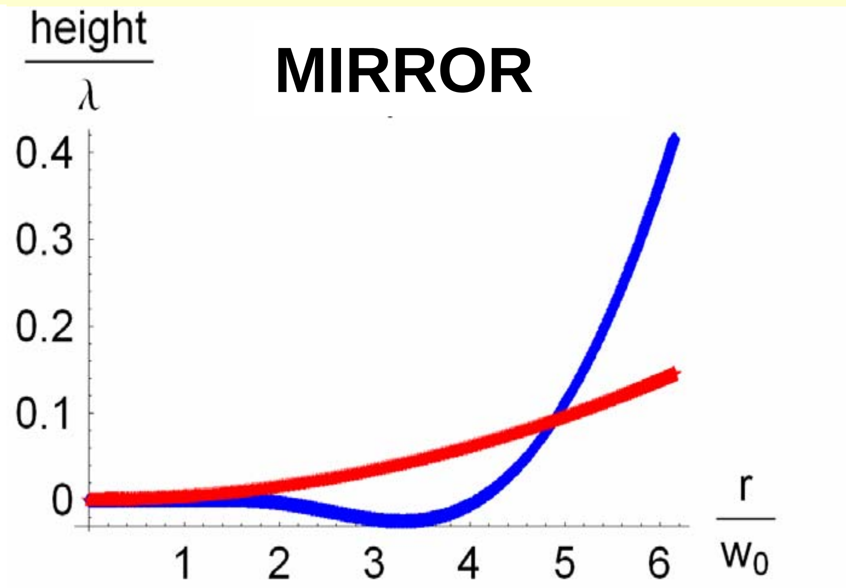
Mesa

Field at

Mirror

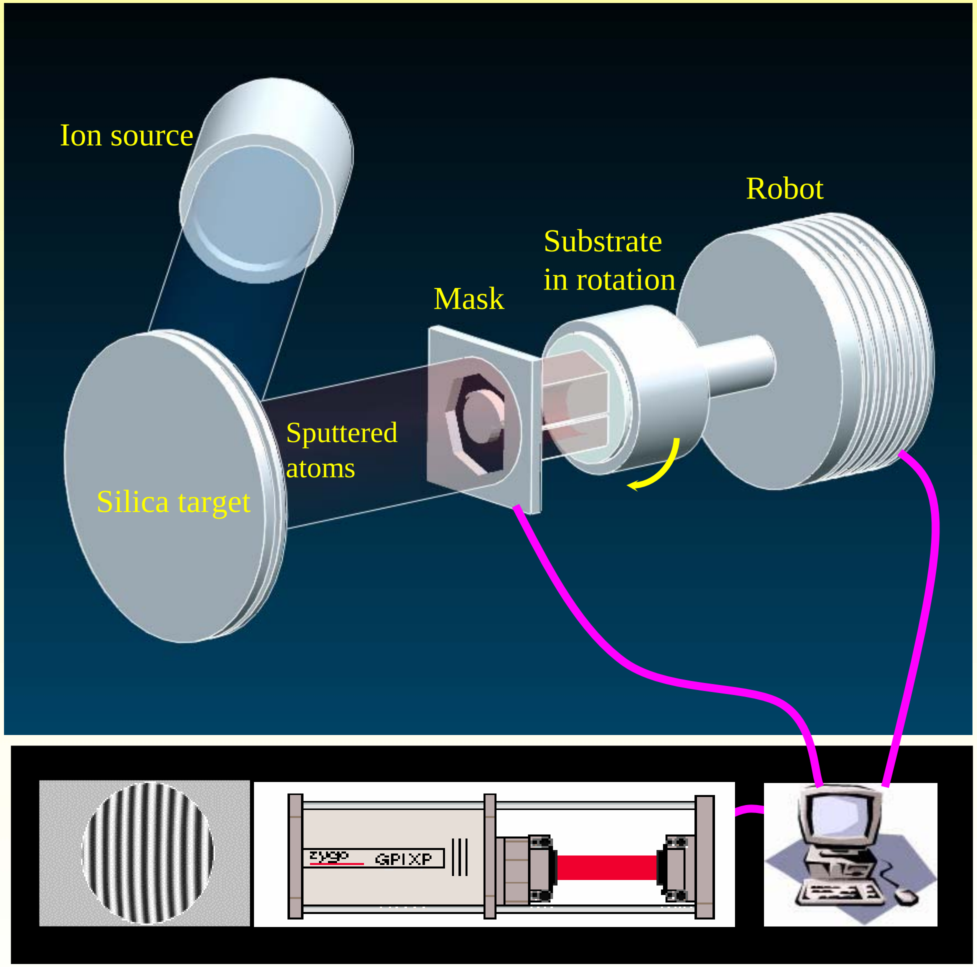
$$U \sim \int_{C_D} \exp\left[\frac{-[(x-x_0)^2+(y-y_0)^2][1+i]}{2w_0}\right] dx_0 dy_0$$

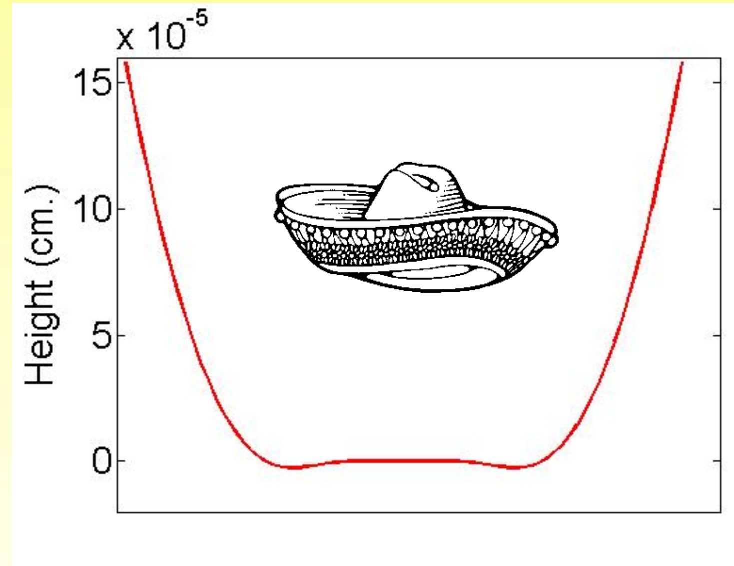




- Also Hyperboloidal, Bessel & Laguerre-Gauss beams amongst others

Mirror Construction

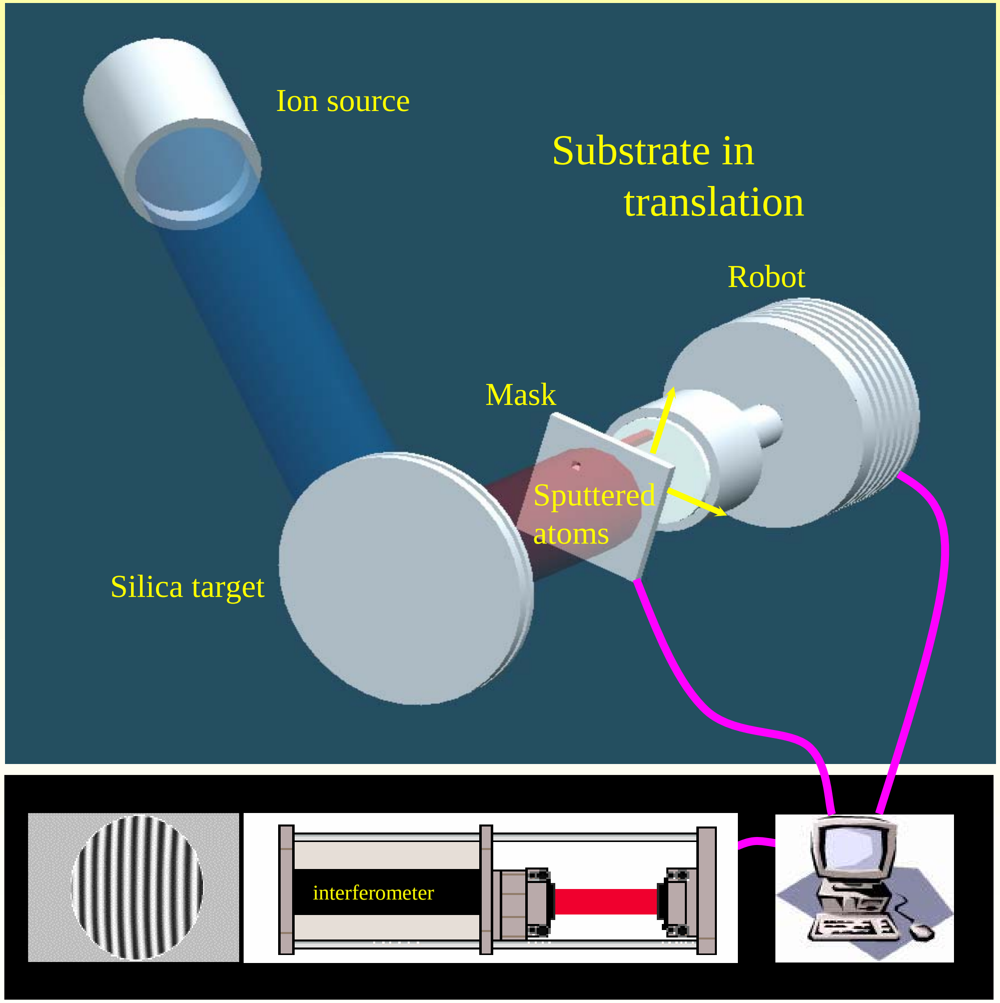




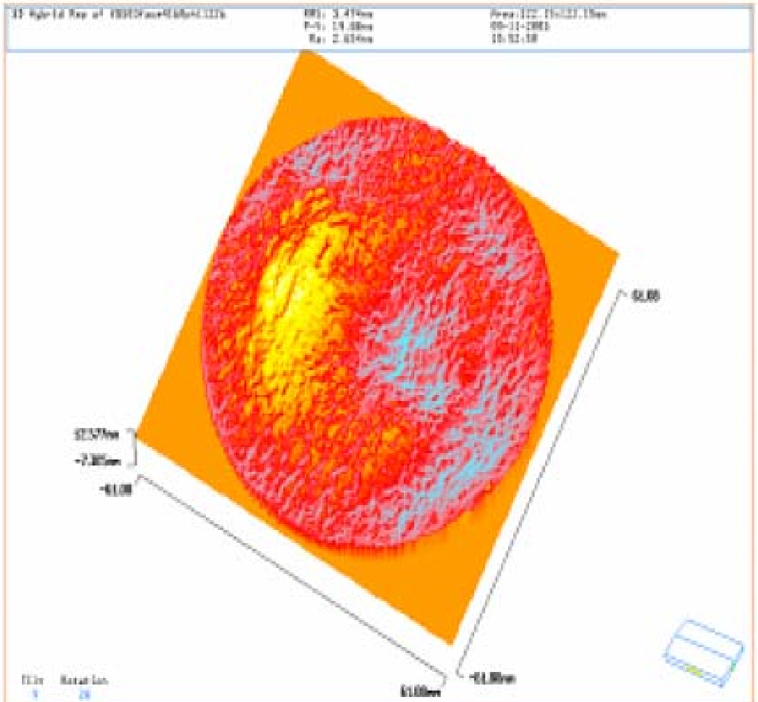
- Two step process
- Step 1
  - Rotation gives rough shape
- 500 nm/mm
  - remember this number for later

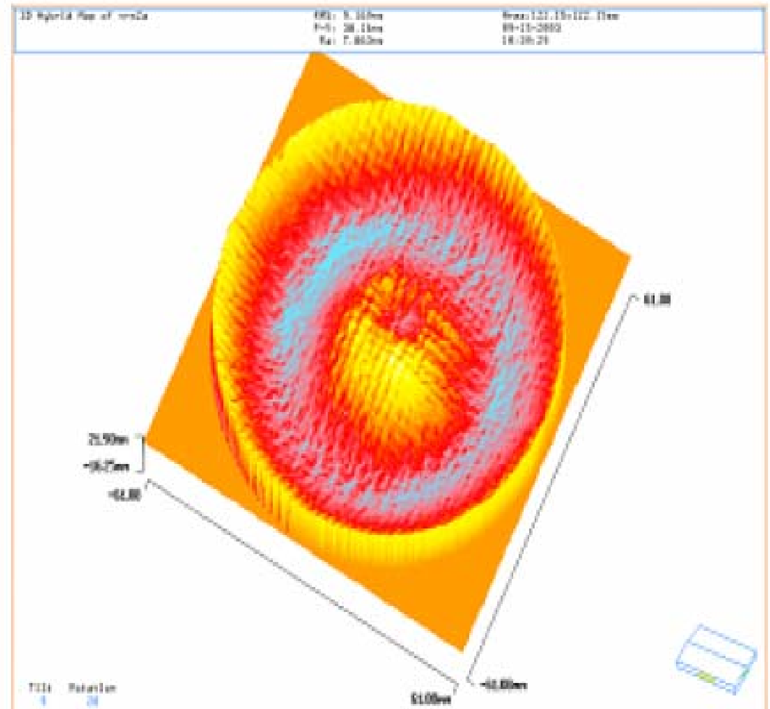
Mirror Construction

- Stage 2
- Atomic pencil
- LIGO sized optics are easy



MH Coating





- Before corrective coating
- After

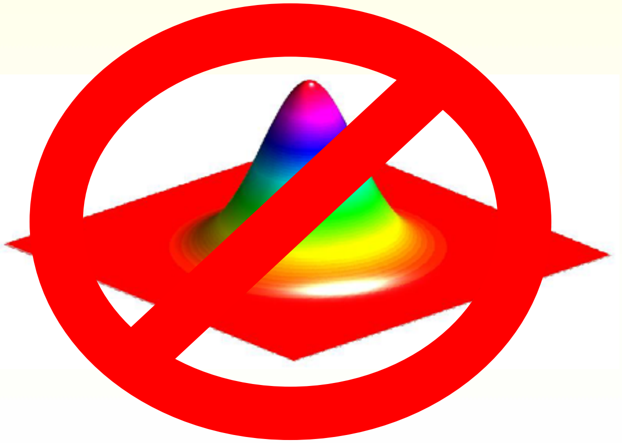
Thermal noise reduction

Noise Source	Fused Silica (34x20cm)
Coating Brownian	~1.9
Substrate Brownian	~1.6
Coating Thermoelastic	~1.9
Substrate Thermoelastic	~2.2

- Ratio of displacement noise Gaussian/Mesa in $mHz^{-1/2}$
- Single fused silica test mass
- Conclusion....noise down by x2

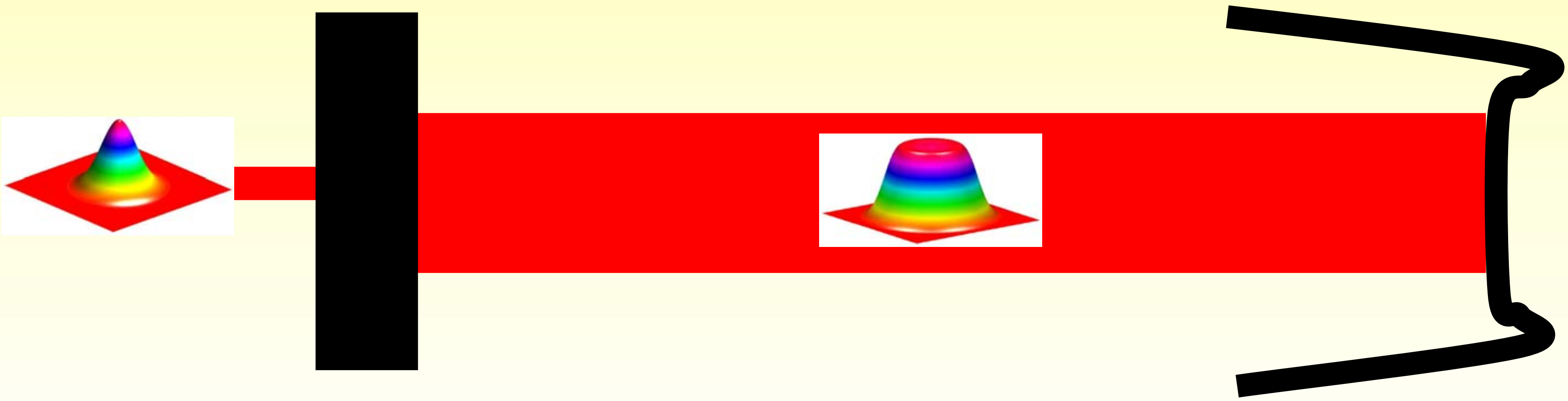
Idea

- Reduce the impact of mirror thermal noise in advanced detectors by reshaping the light beams and mirrors in the arm cavities



The experiment

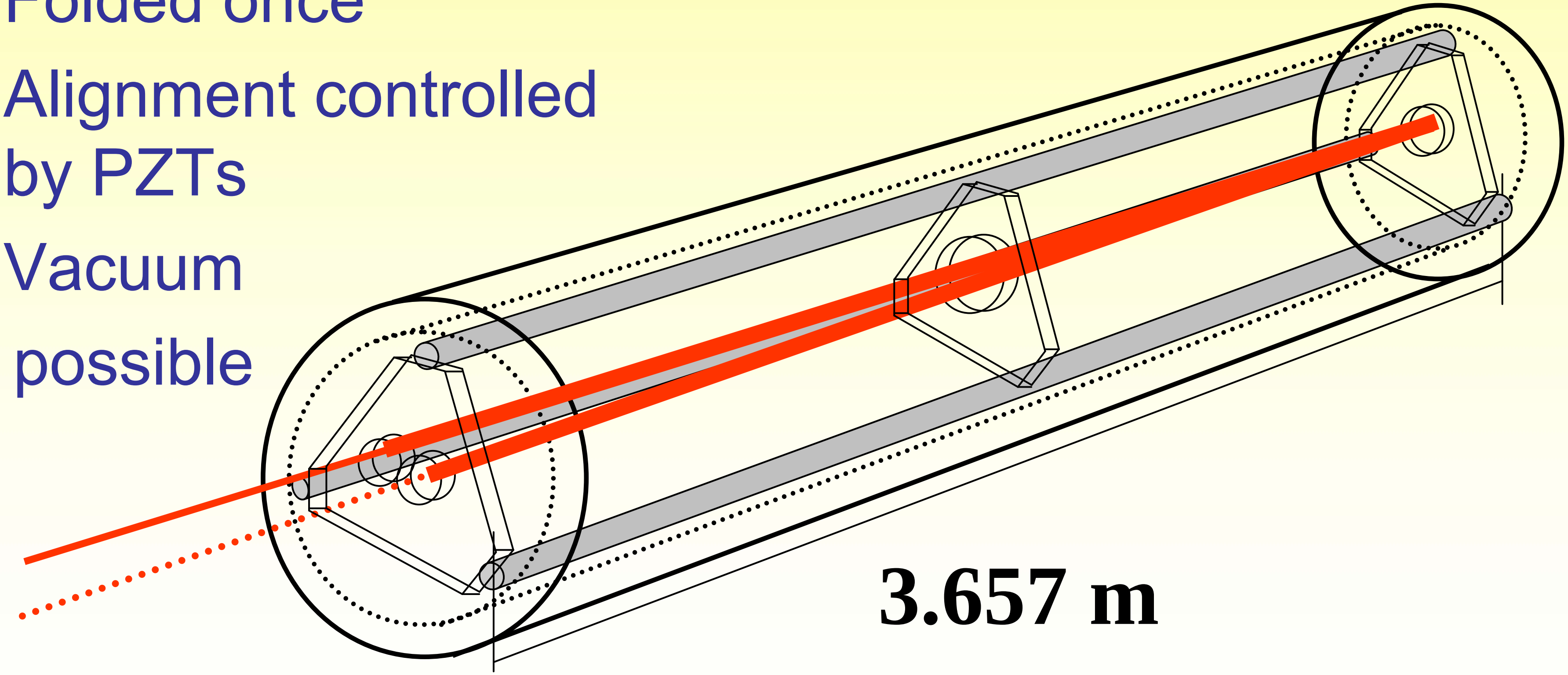
- Like an ‘arm’ cavity



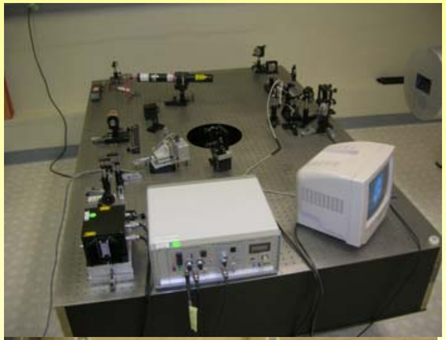
- Transforms GB to MB

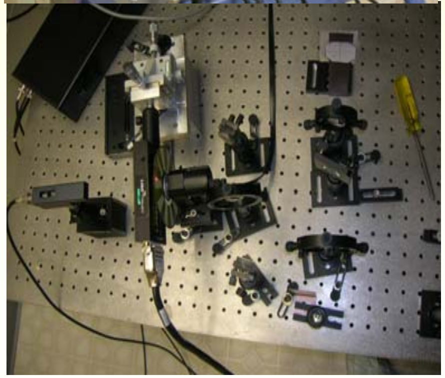
Our experiment

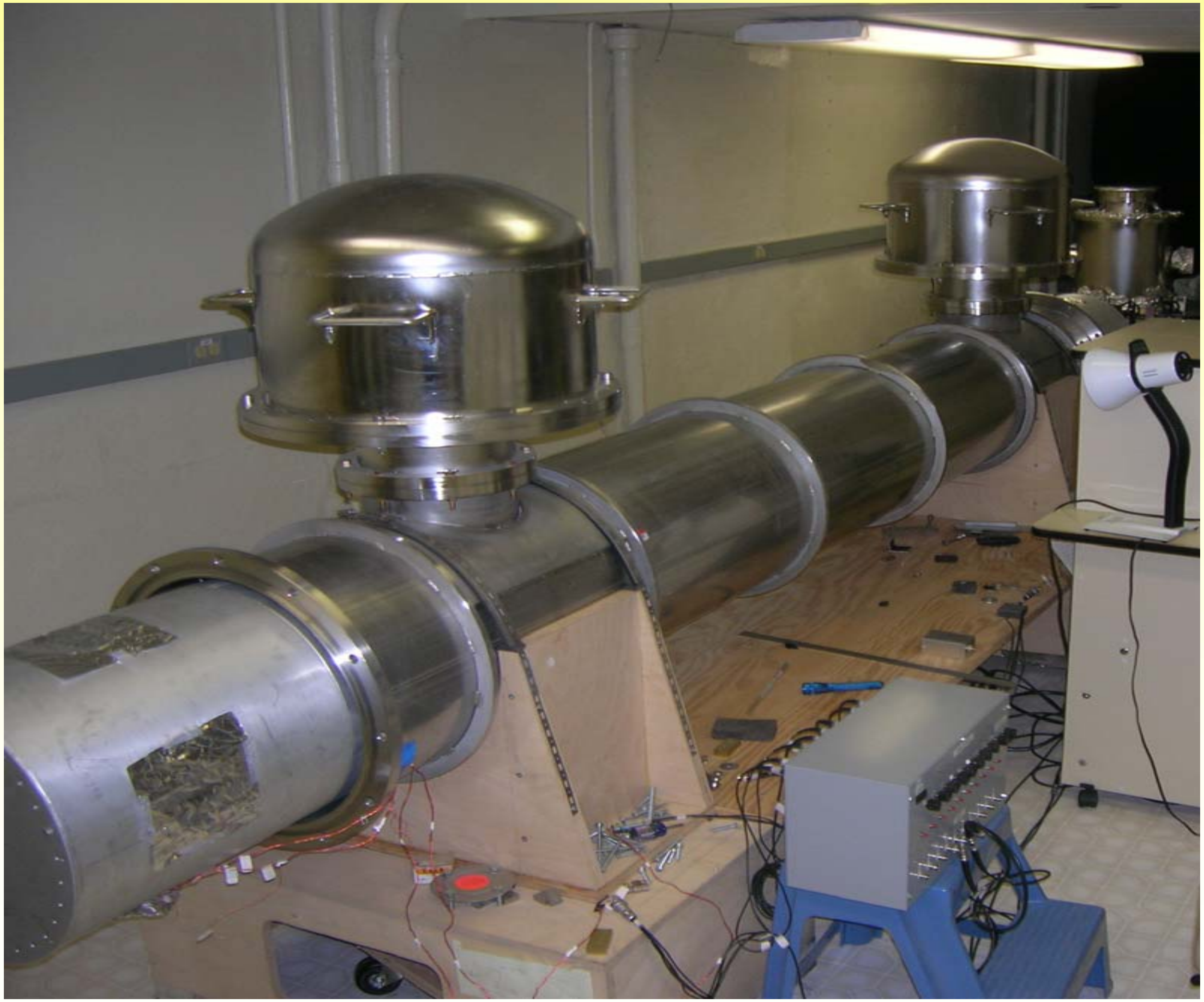
- Rigid, suspended, FP cavity
- Folded once
- Alignment controlled by PZTs
- Vacuum possible



Our experiment

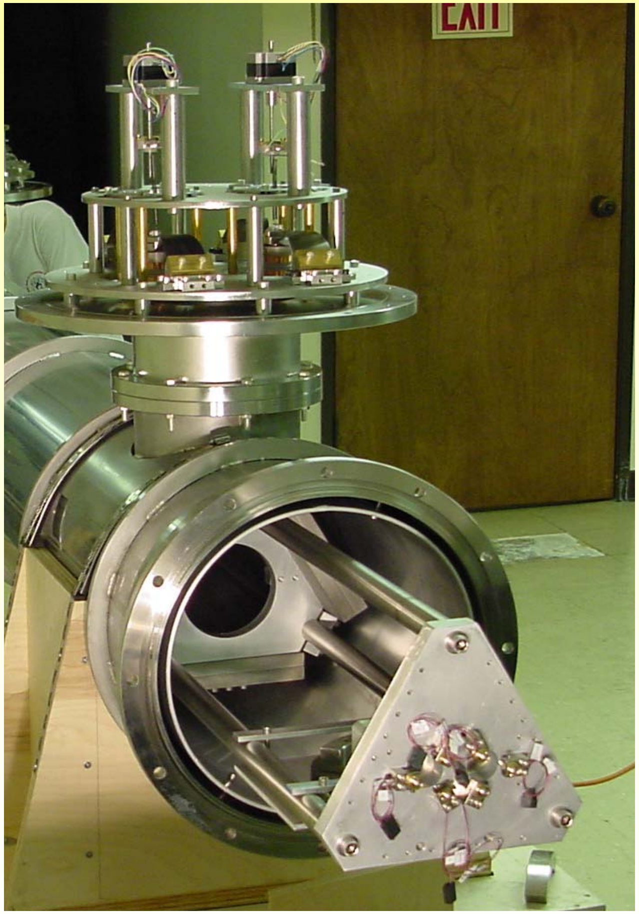




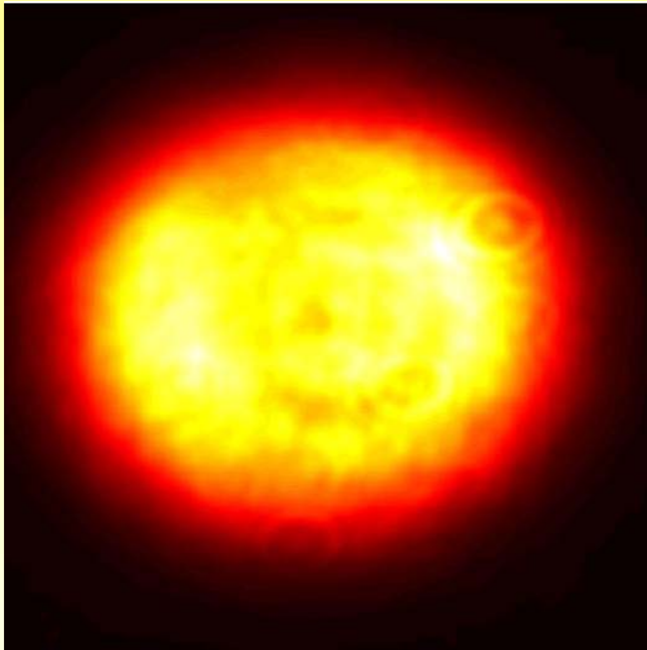


Goals

- Resonate mesa beam
- Obtain error signal – lock
- Measure tilt sensitivity
- Study alignment
- Coupled cavities

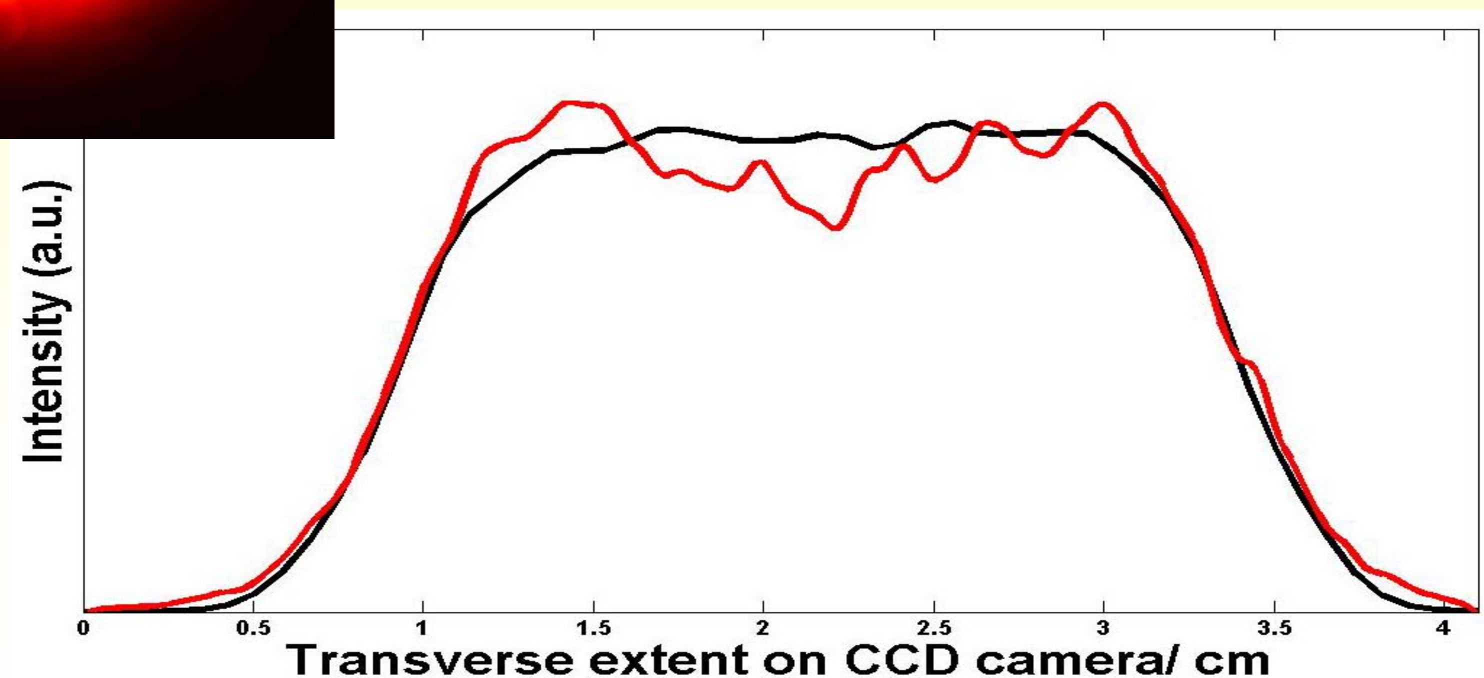


Fundamental

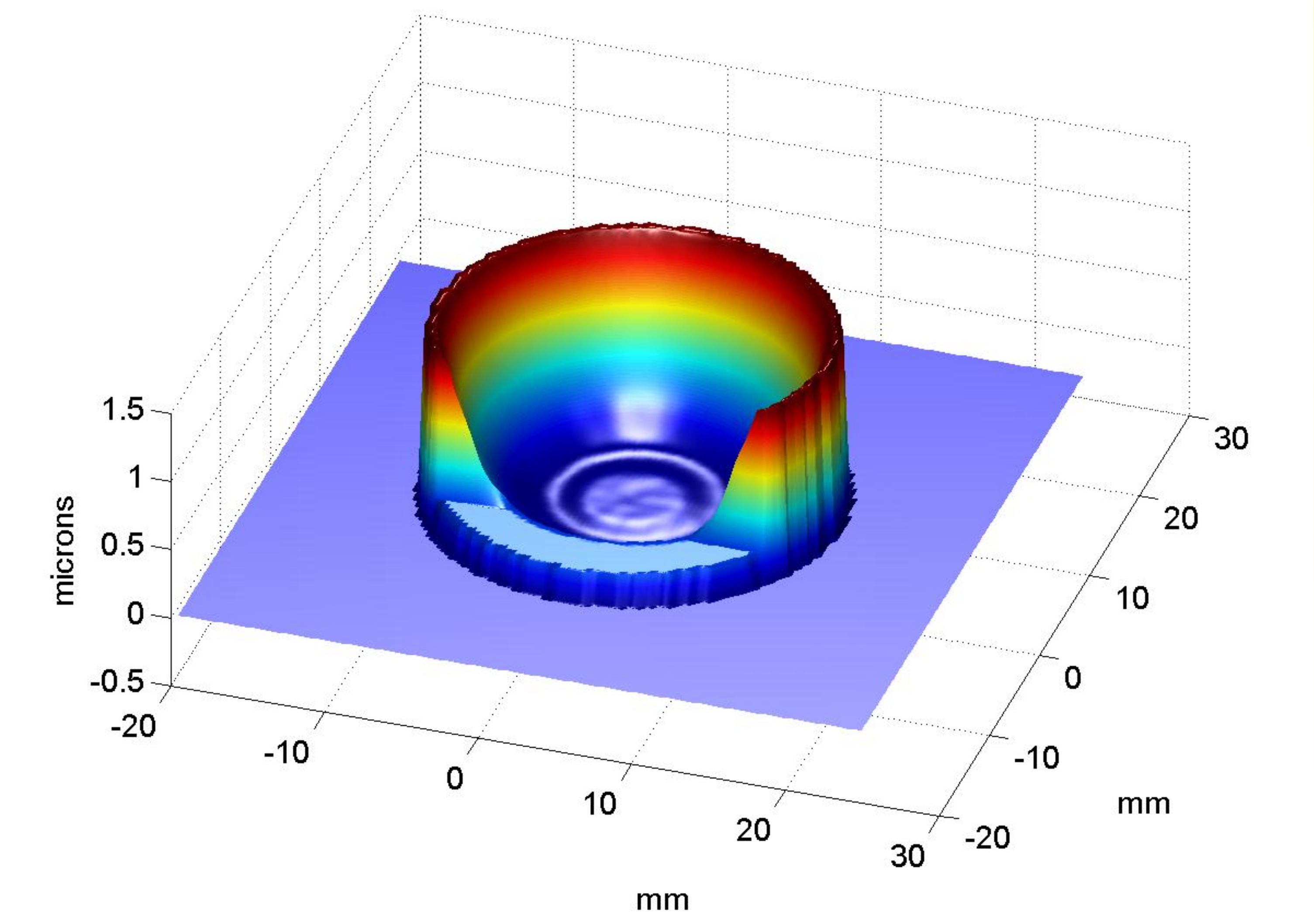


SIMULATION – idealised optics and alignment

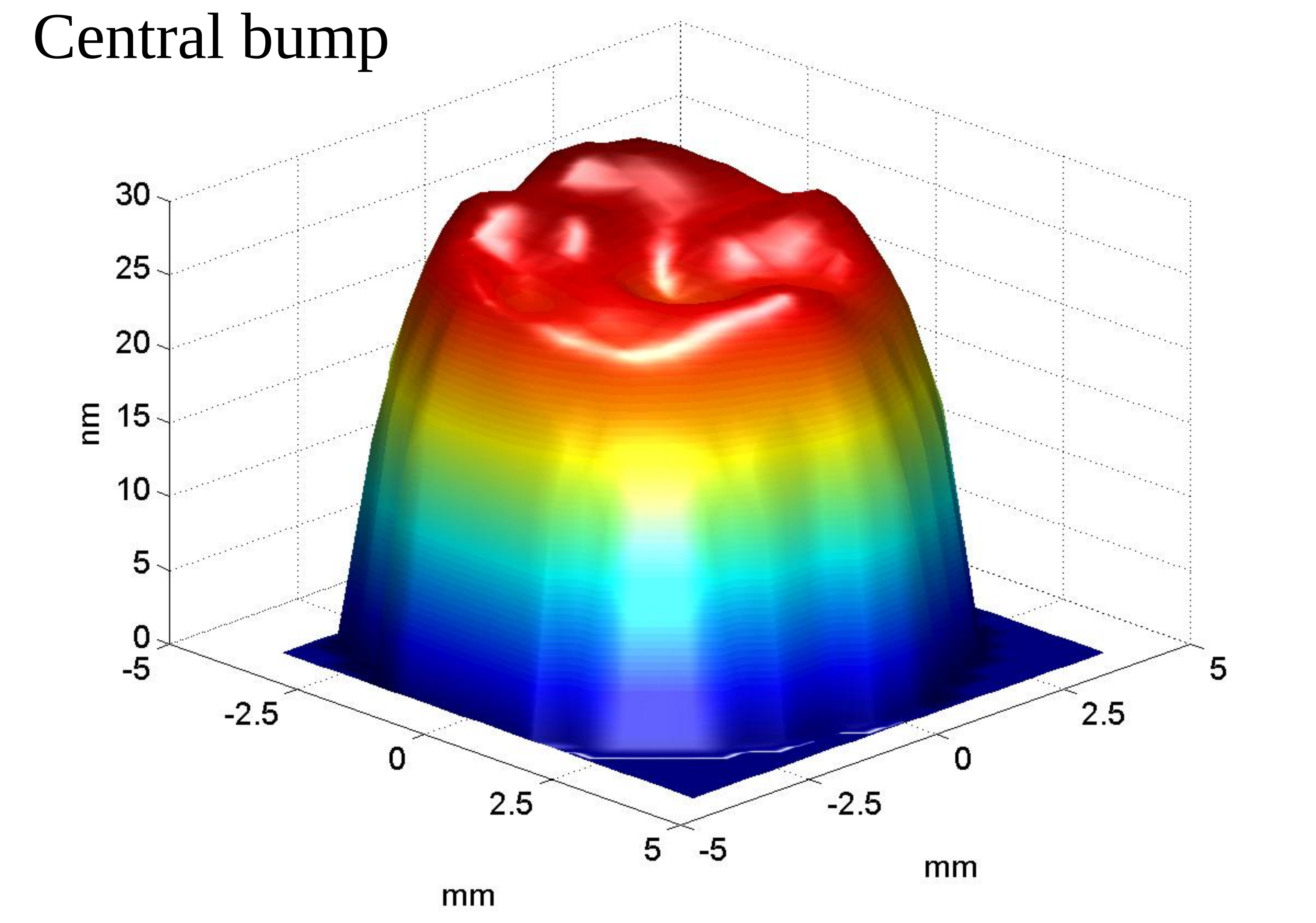
EXPERIMENTAL DATA



MH mirror map

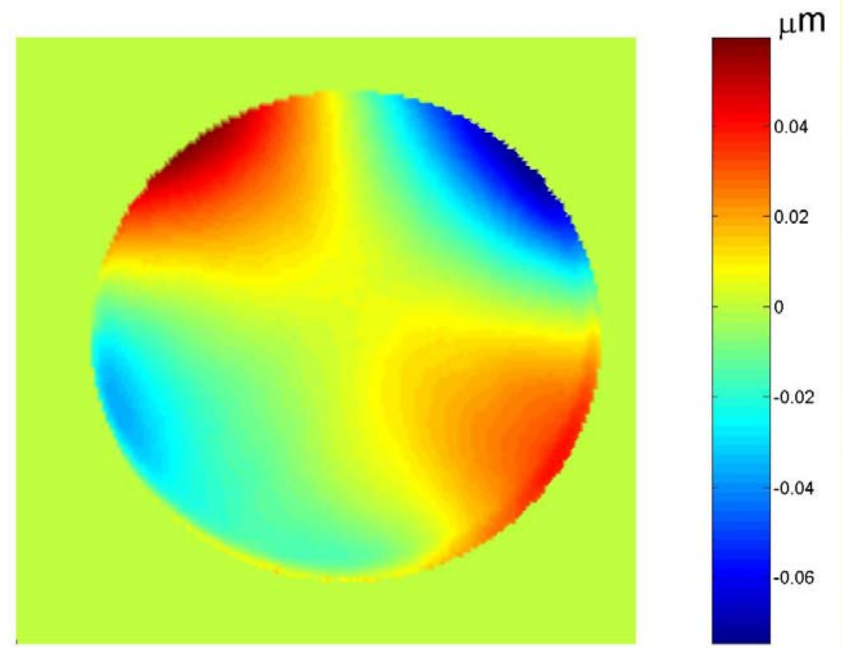


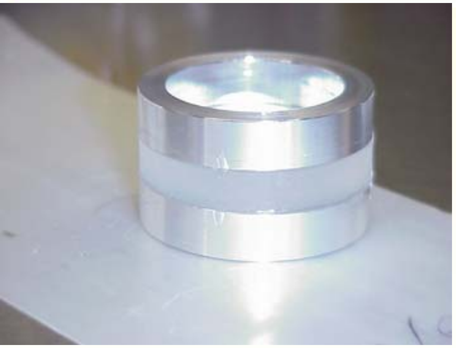
MH mirror map

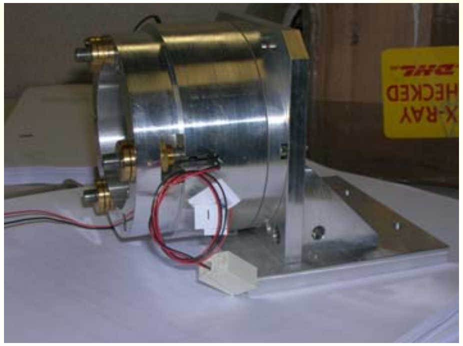


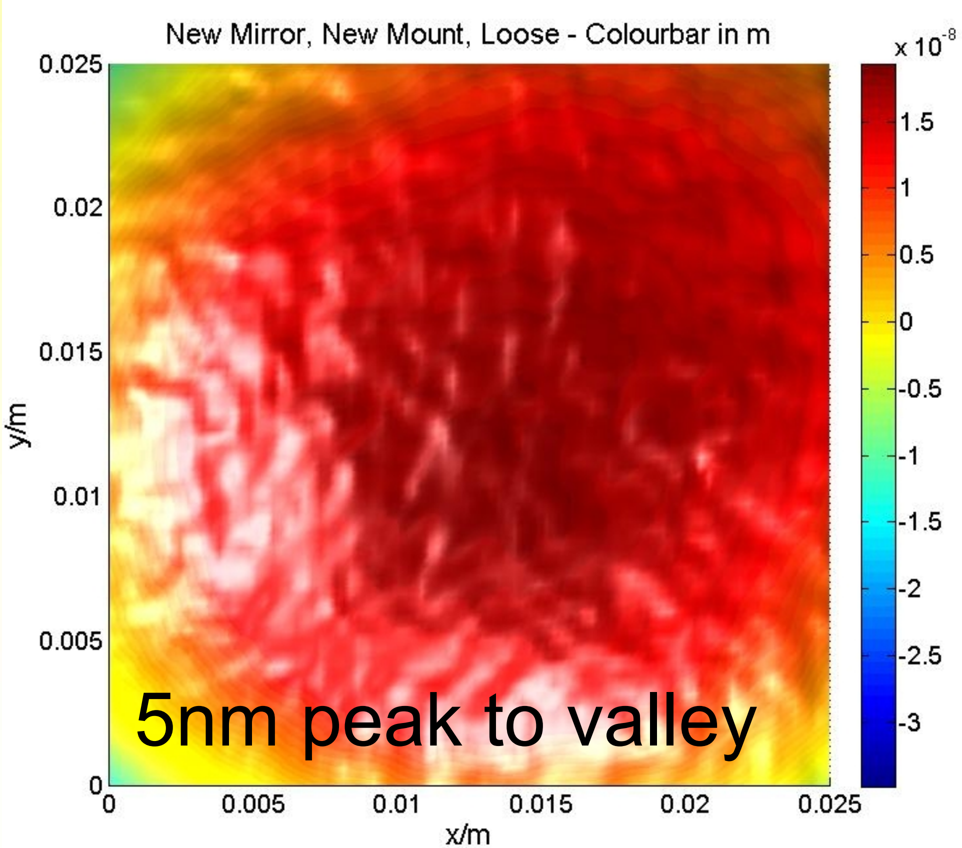
‘Flat’ mirror map

- Our cavity has two flat mirrors in addition to Mexican hat





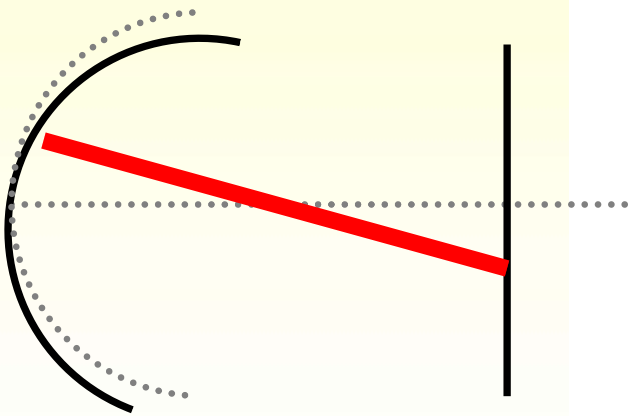


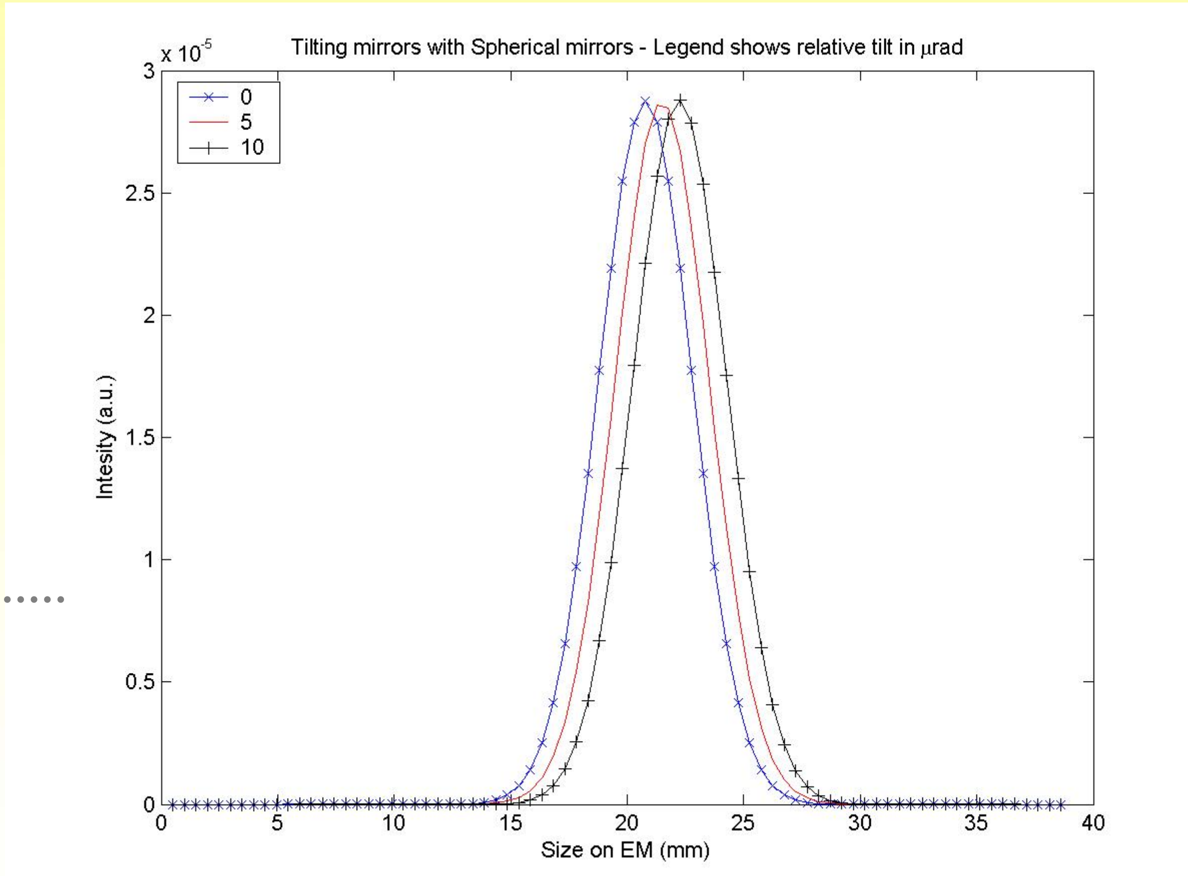


Thanks to GariLynn

Tilts of Spherical Mirrors

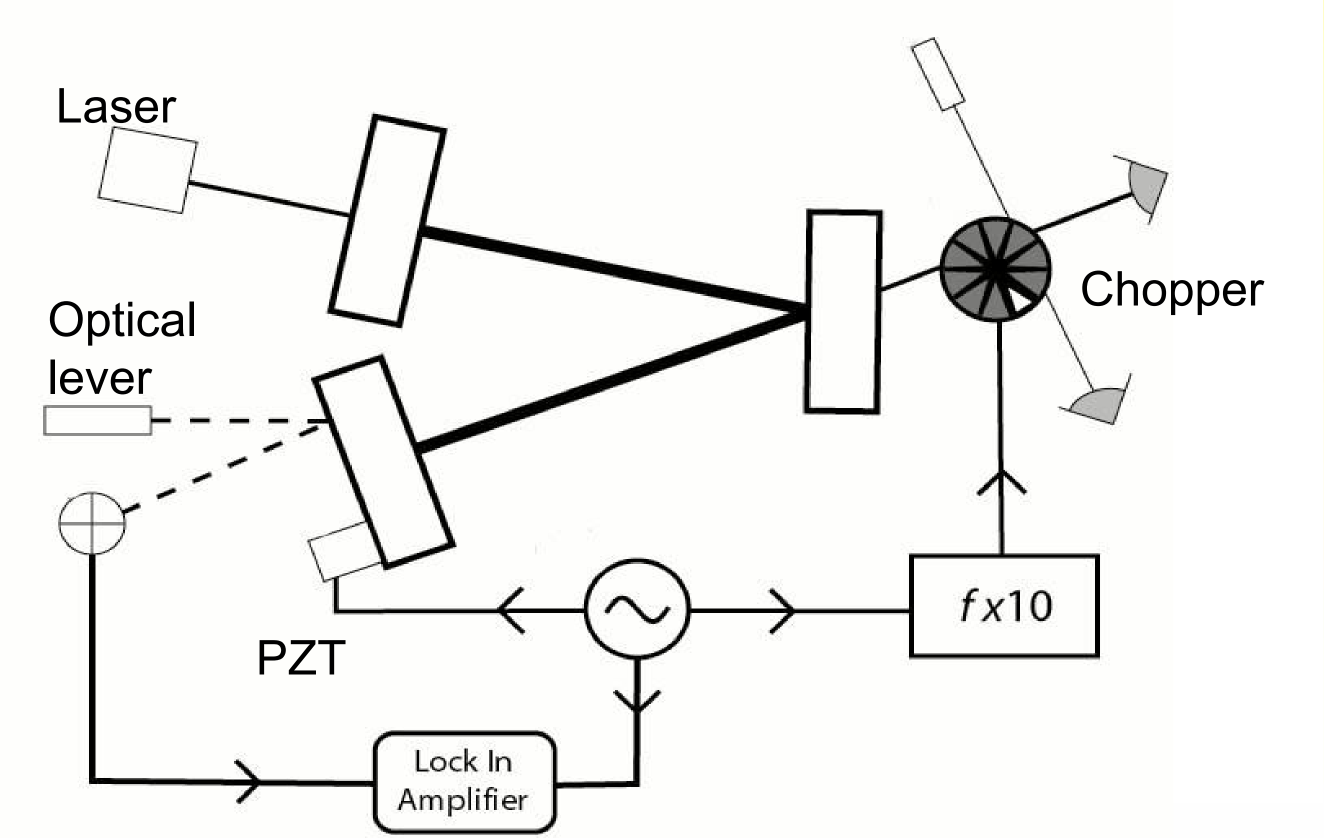
- Tilts of spherical mirrors translate optical axis

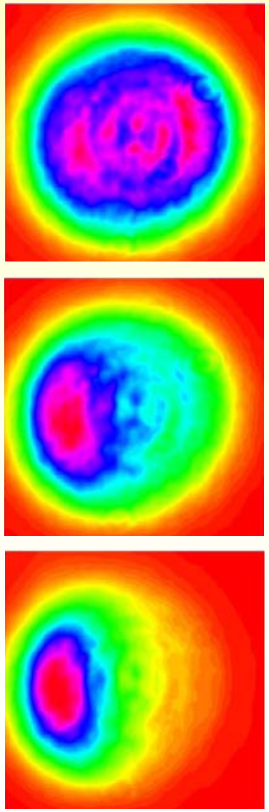




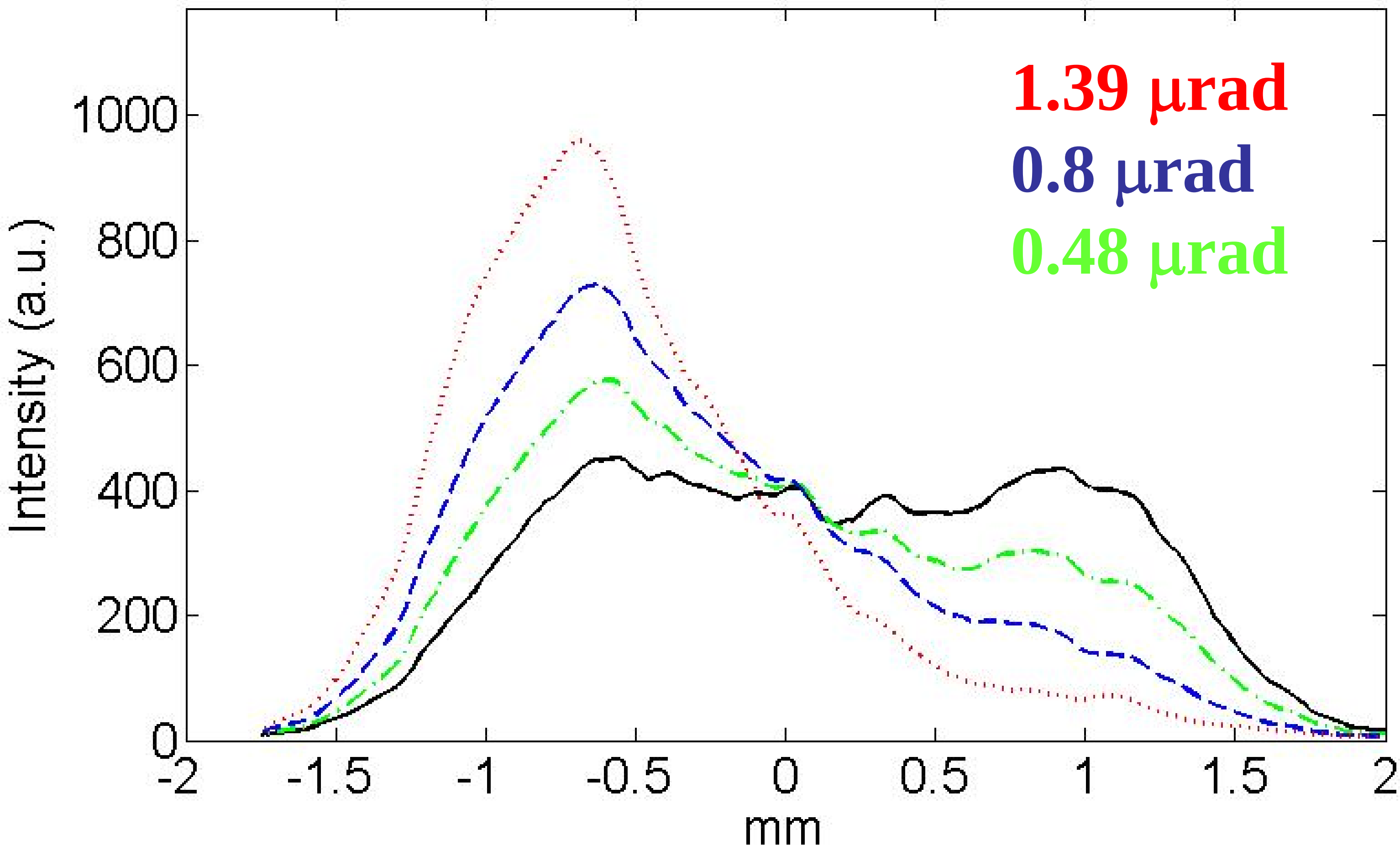
Tilt sensitivity

- Measure max tilt using lock in detection
- Use chopper and secondary laser to align and capture beam at correct tilt

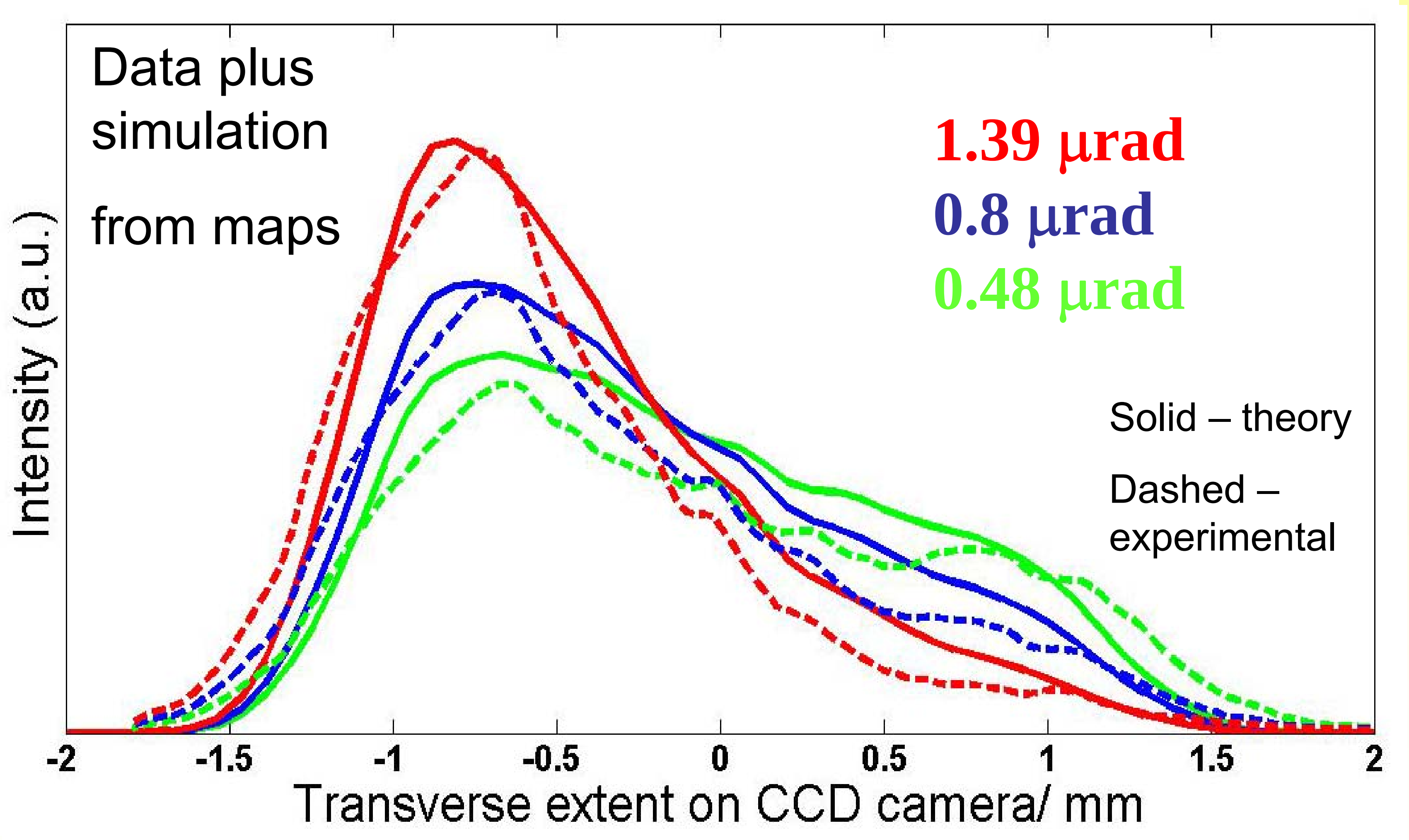




Tilt sensitivity - results

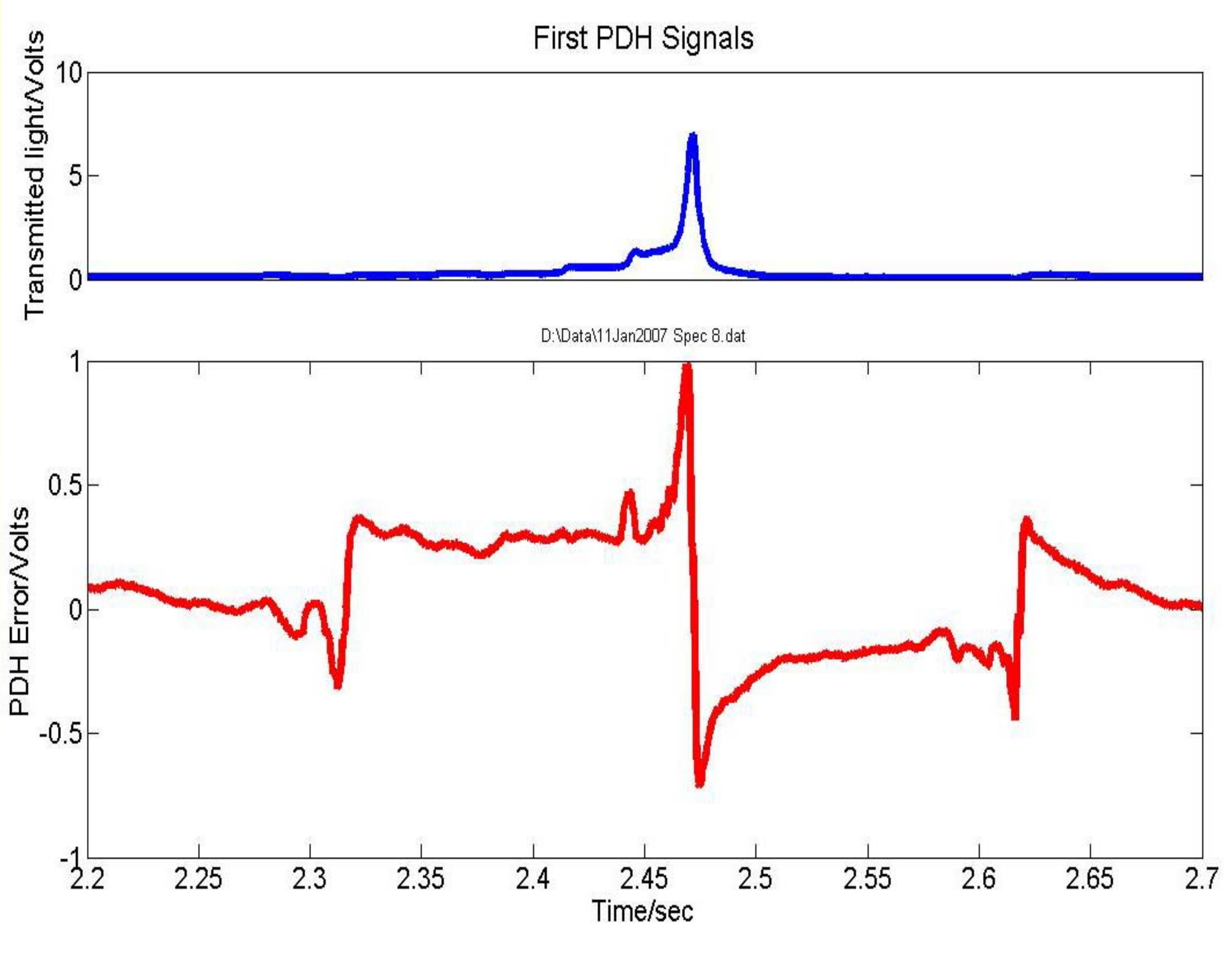


Tilt sensitivity - results



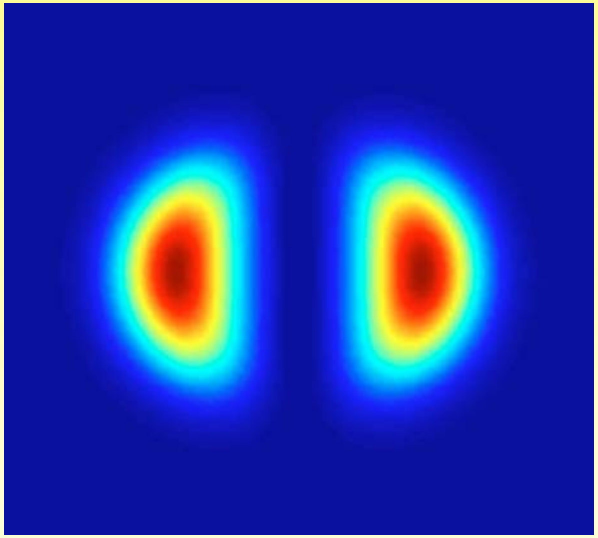
Locking and Alignment

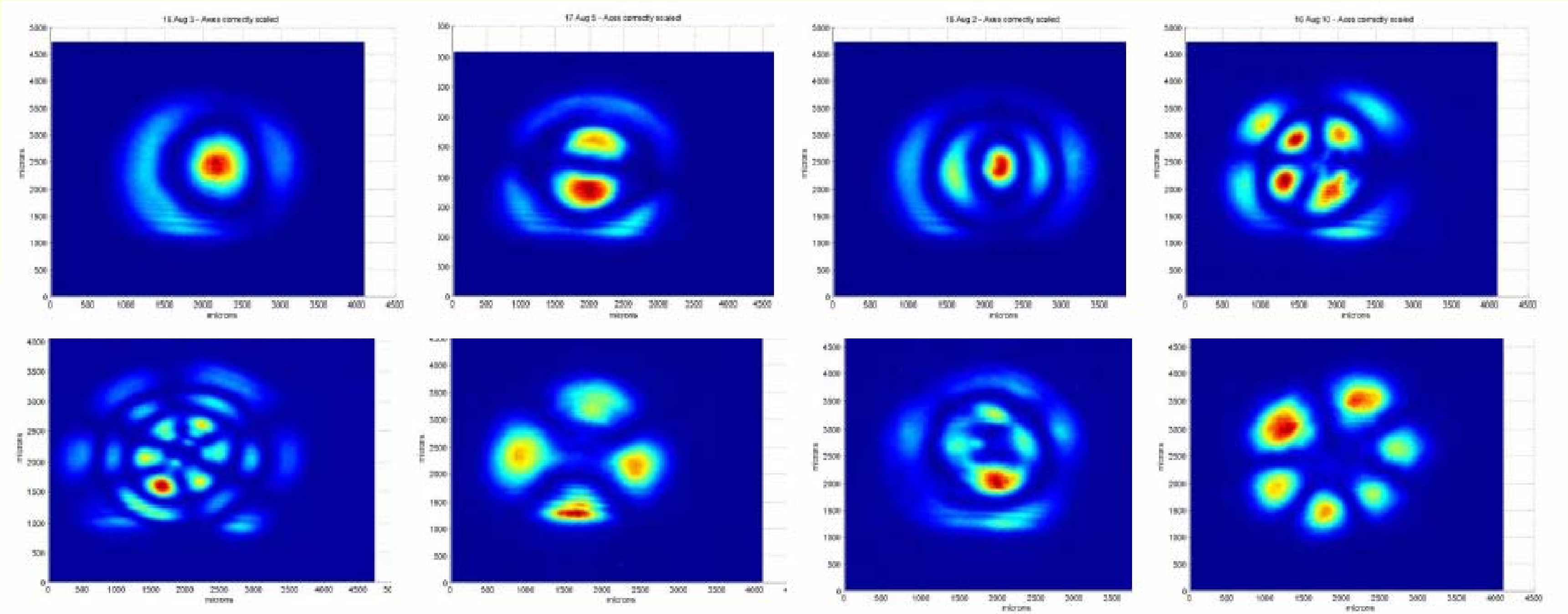
- Pound, Drever, Hall locking
  - done, not yet optimised
- Wavefront sensing
  - ready to go
  - what about higher order modes?



Higher order modes

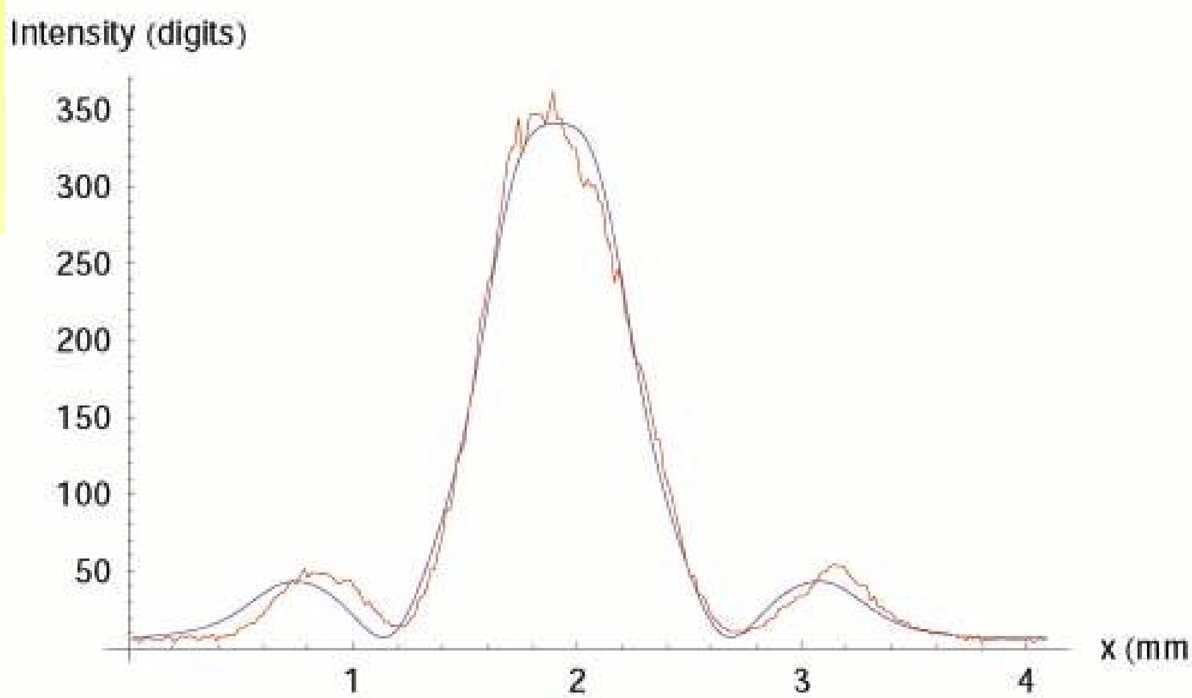
- Odd contribution upon mirror tilts is just like $HG_{01/10}$
- 'Hermite' and 'Laguerre' families as for GB



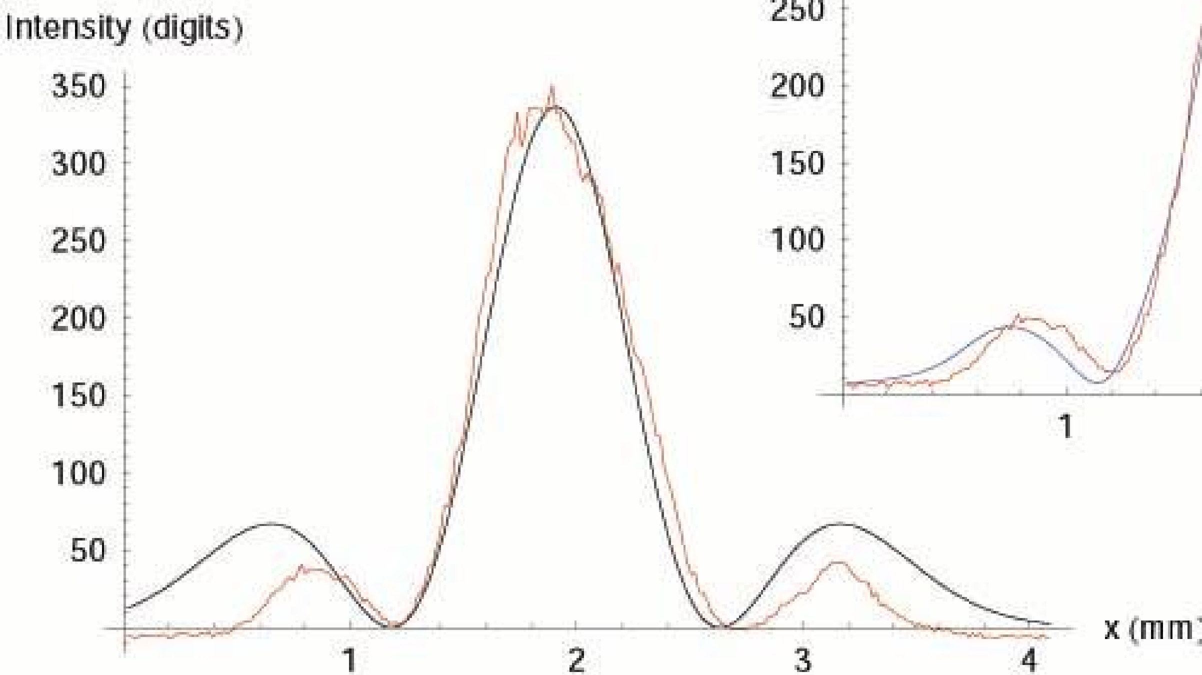


Gaussian?

- Modes resemble Hermite and Laguerre sets



- MH_{10} fit



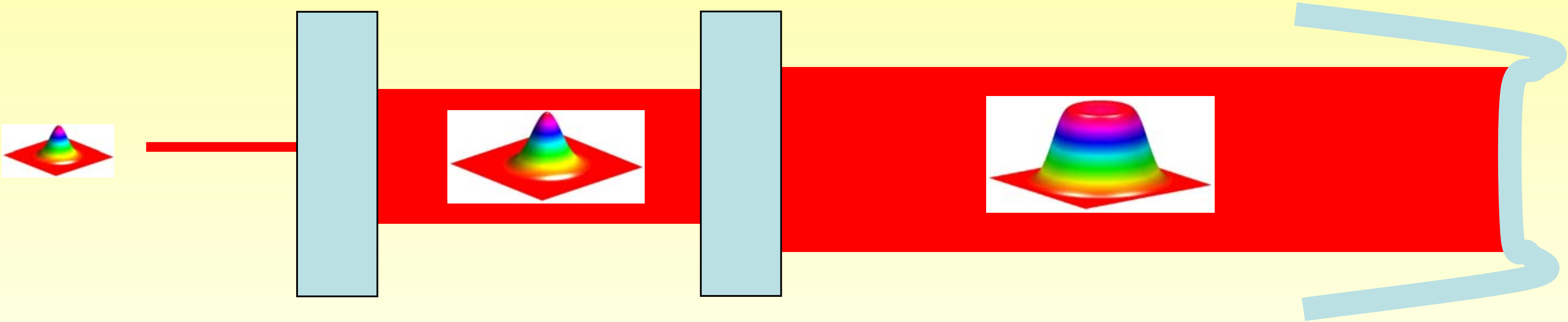
- LG_{10} fit

Experimental work

- Lab closed at present

Future work - coupled cavity

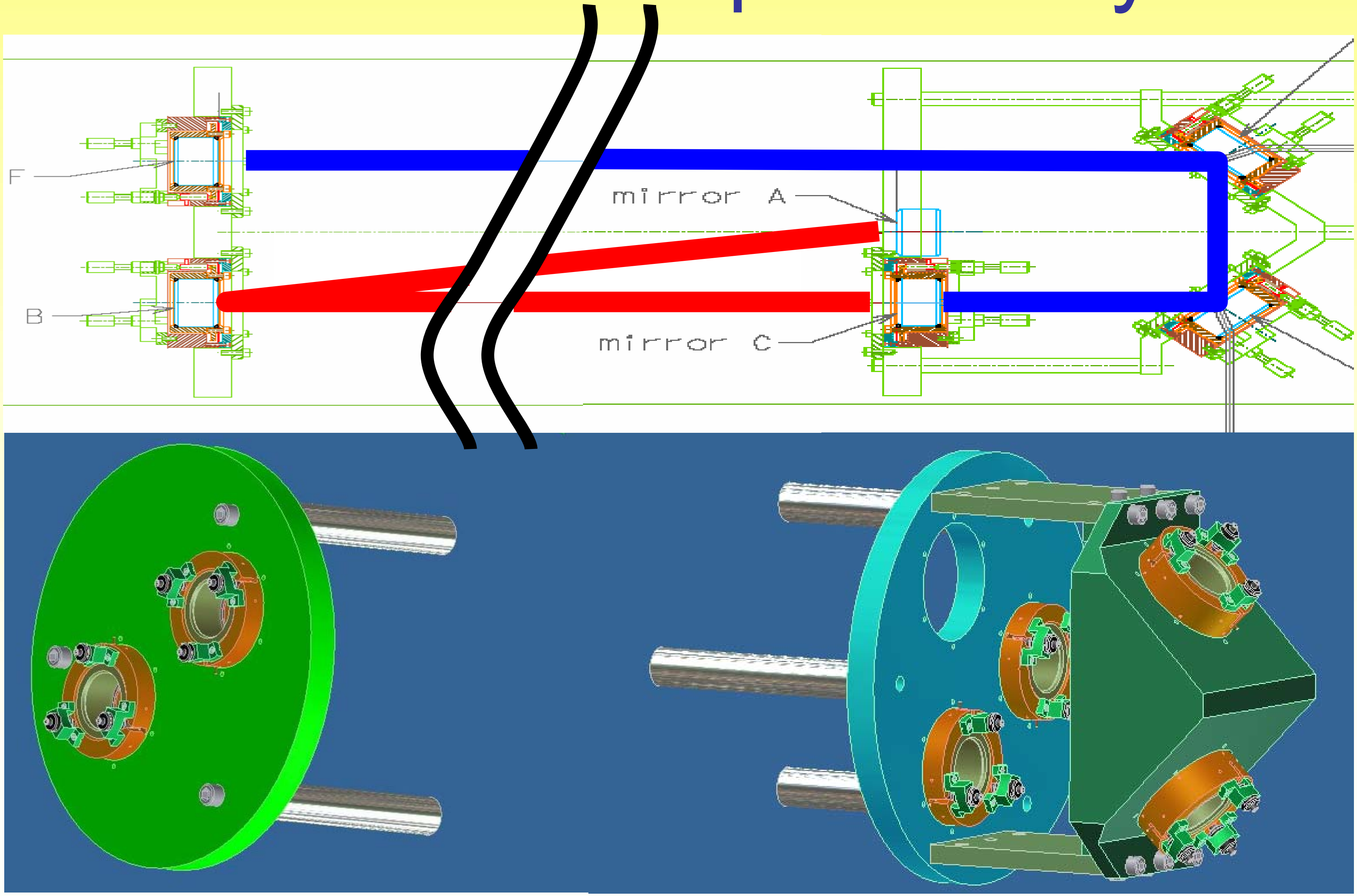
- 3-mirror coupled system



- mechanics
- simulation and design
- fields, coupling, alignment

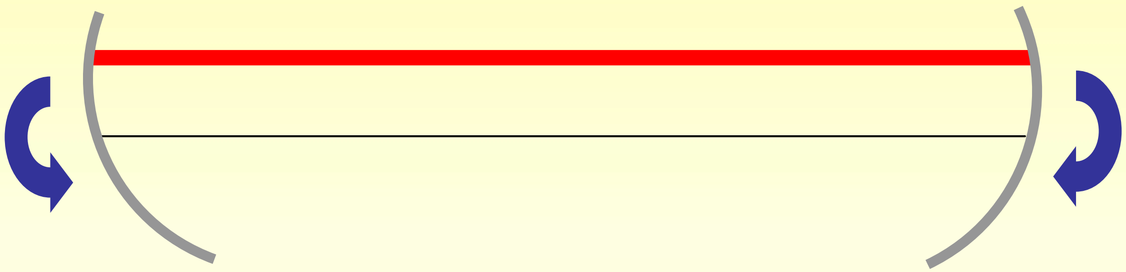
- locking
  - single side band
  - amplitude modulation
  - phase modulation
  - sub-carrier

'3-mirror' coupled cavity



Tilt Instability

- Serious tilt instability for nearly flat cavity (Sidles, Sigg)
  - Similar to Gaussian beam cavity

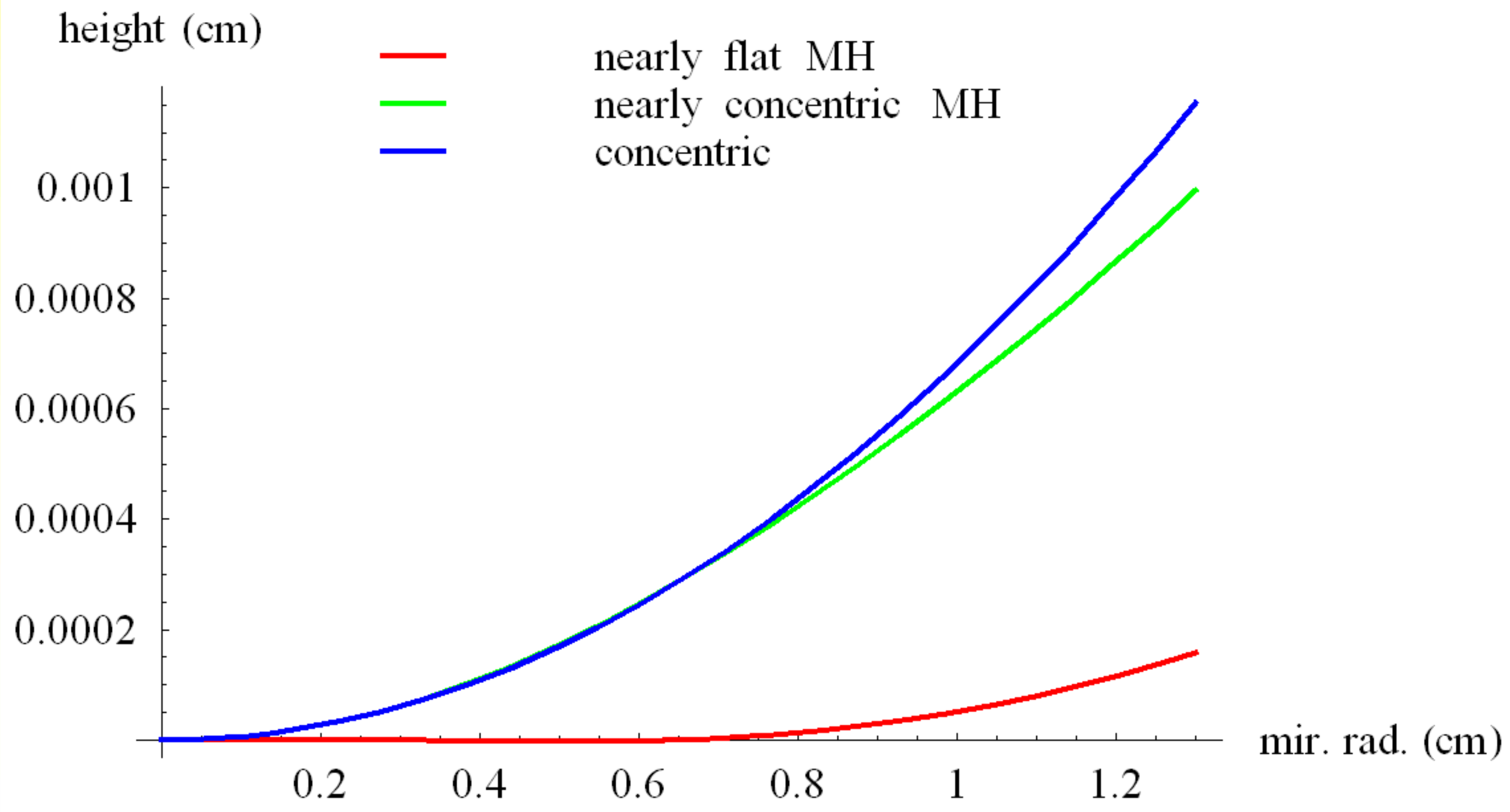


- Problem is mitigated by nearly concentric cavities
- Ratio of torques for concentric mesa (CM) and concentric Gaussian (CG) cavities

$$T_{CM} / T_{CG} = 0.91$$

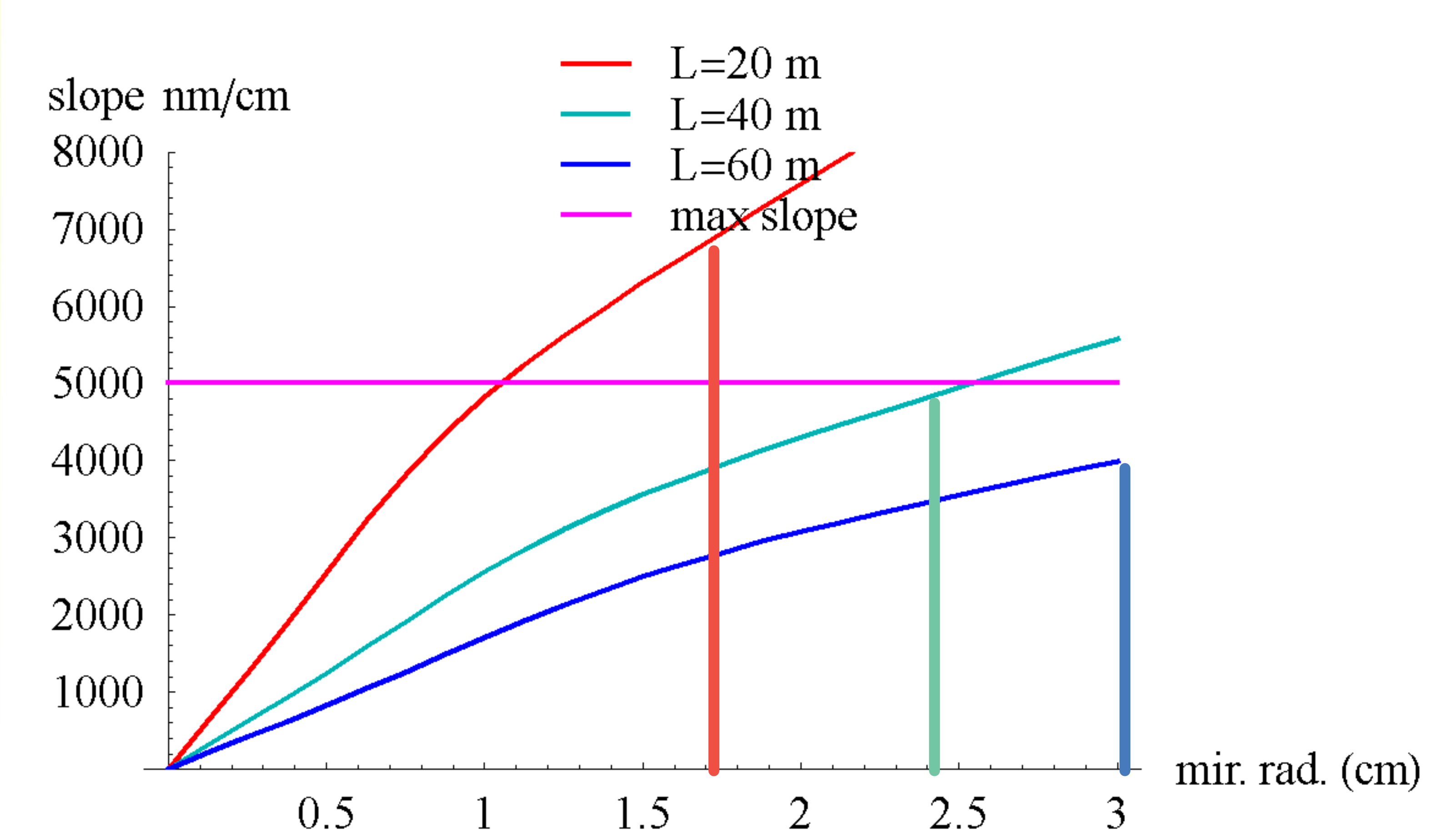
Concentric cavity

- Flat mirrors - Add MH profile to flat substrate
- Concentric mirrors - Subtract MH profile from spherical substrate (gr-qc/0409083)



Concentric cavities

- Mirror profile must not be as steep as the maximum resolvable slope

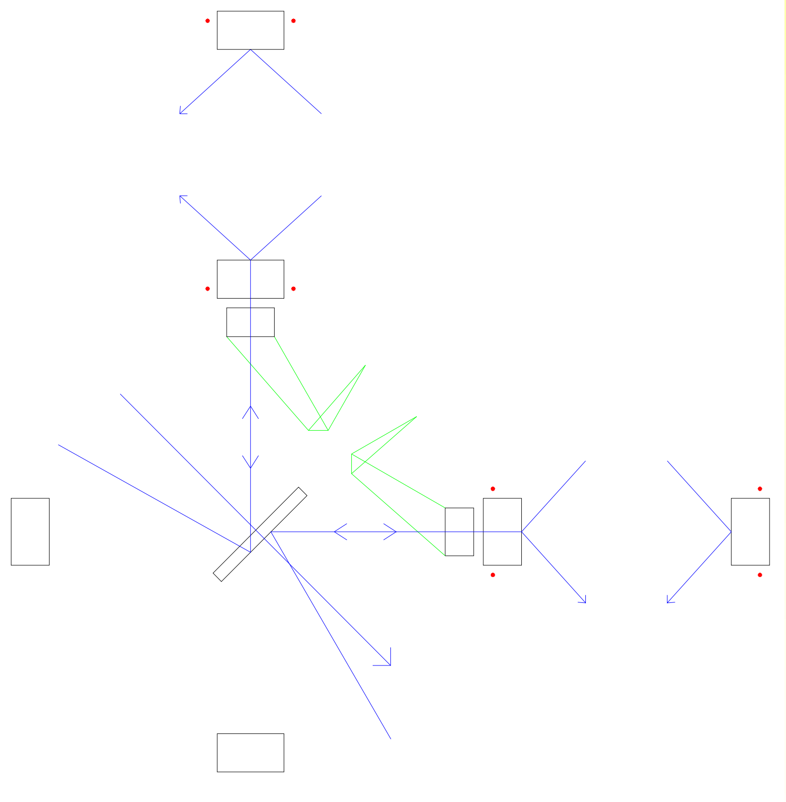


Possible developments

- Concentric MH cavity possible if ROC $\geq$ 40 m.
- Circa 150 m. for full test cavity
- Independently suspended/controlled optics
  - Experience of injection systems
  - Noise
  - ideal intermediate step before implementation in a full-scale IFO
- Test bed for all ‘exotic’ beams – see later

Thermal effects

- Study deformation of arm cavity mode with absorbed power
  - power limit for mesa beams?
- Thermal noise implications
- Thermal compensation system (TCS) thoughts
- Model
  - flat-flat, mesa, AdLIGO cavity
  - no substrate absorption.
    5x less power absorbed vs. coating
  - no lensing
  - input beam fixed
  - instant response
- Static FFT model and Mathematica

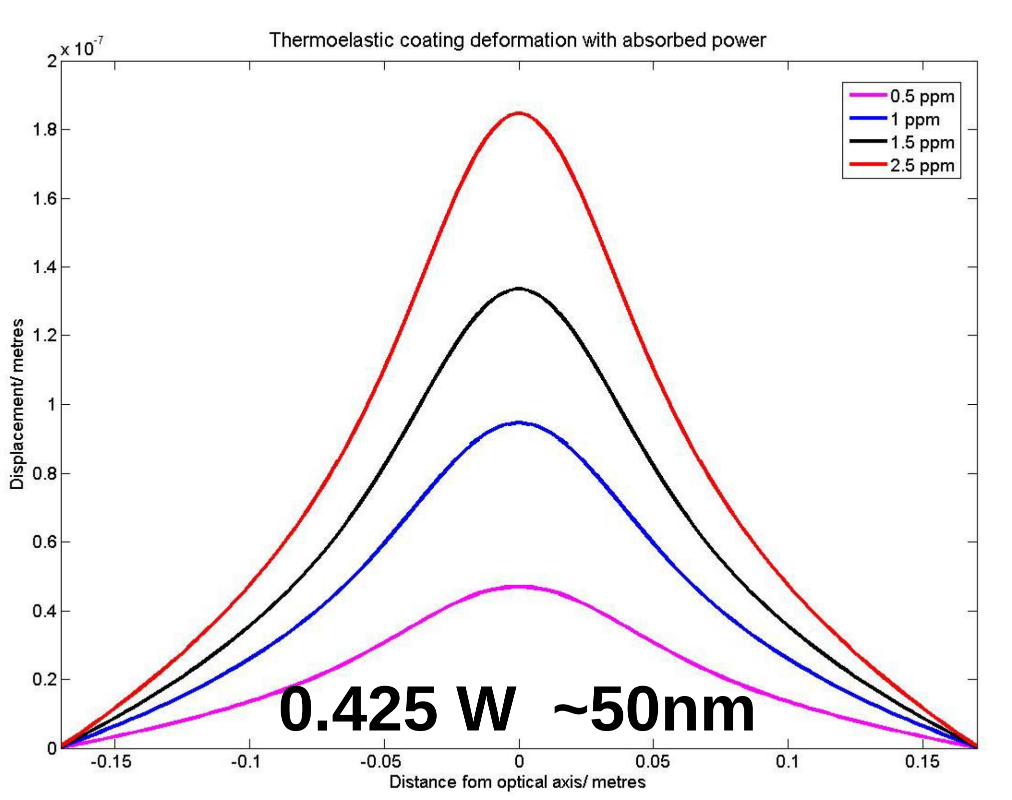


AdLIGO TCS

Thanks to Hiro

Heating - Gaussian

- For Gaussian beam - mirrors become less concave and spot size goes from 6 to ~5.4cm
- Total thermal noise increases by ~11%

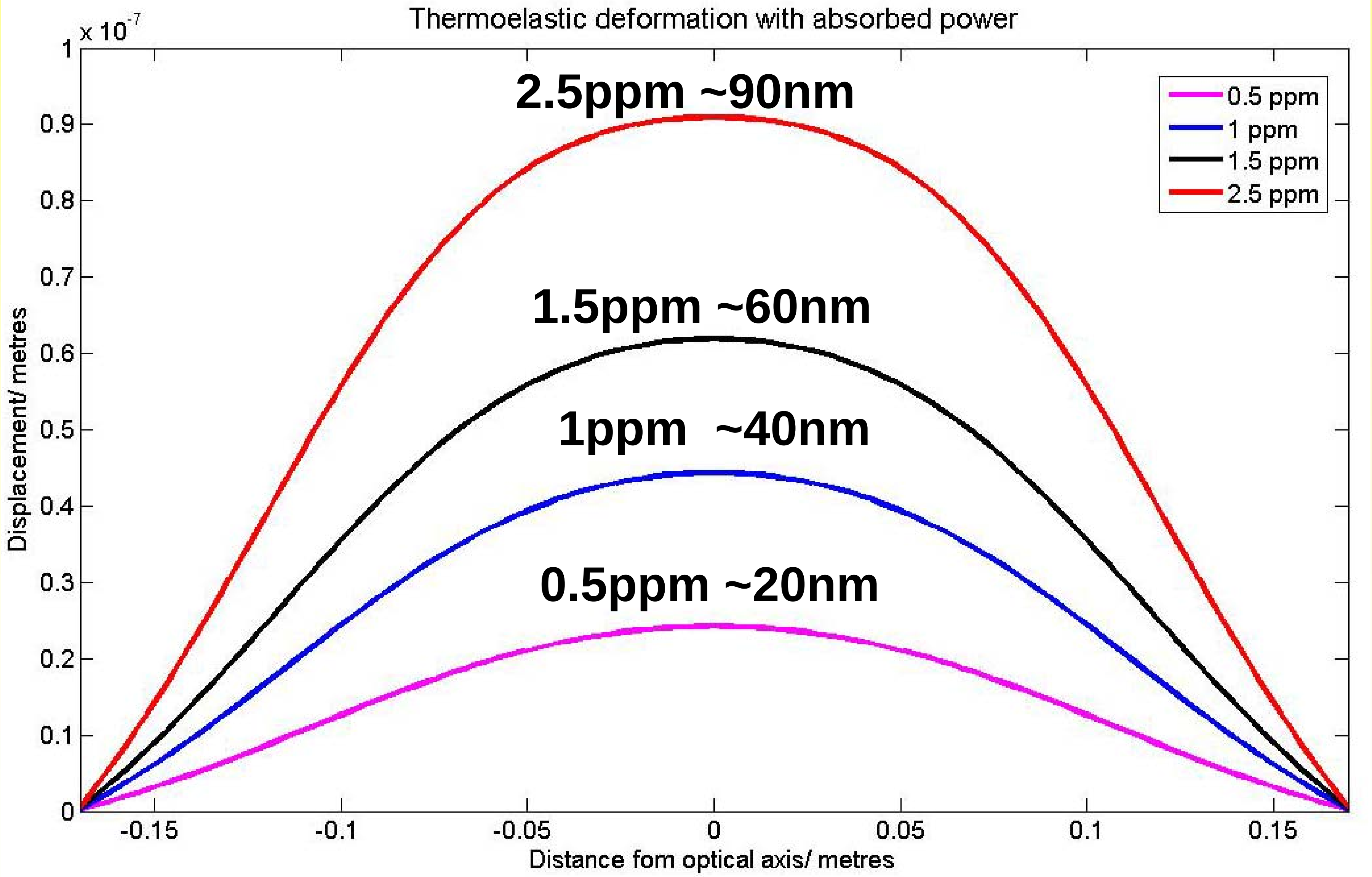


Thermoelastic deformation for AdvLIGO

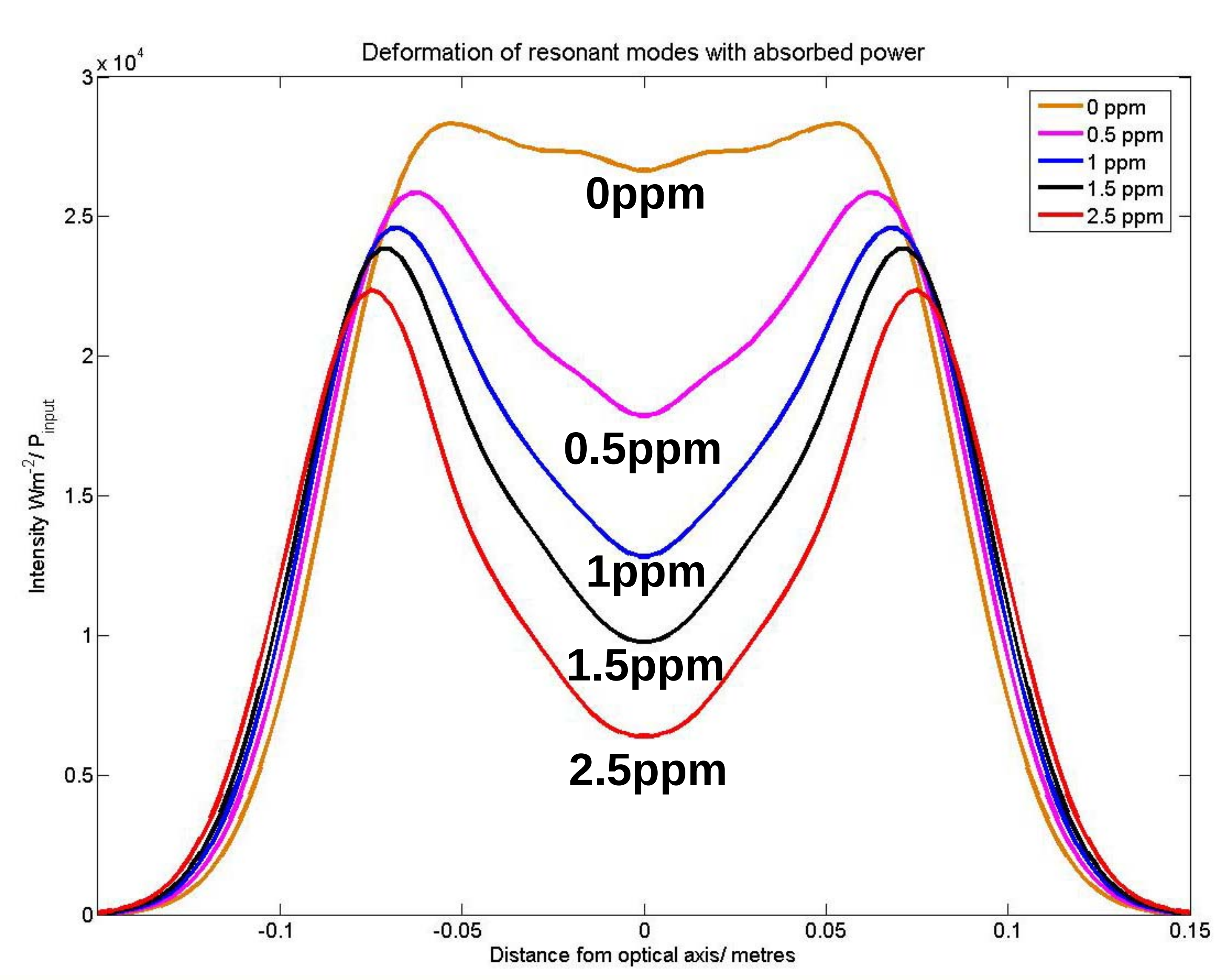
P_{circ} = 850kW,

Coating absorption=0.5ppm

Heating - Mesa



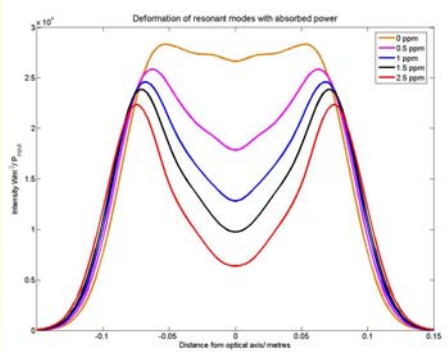
Heating - mesa



MH thermal noise

- Semi analytical model – numerical integrals

Cavity	Mesa				
Coating Absorption (ppm)	0	0.5	1	1.5	2.5
Substrate Brownian $\times 10^{21} \frac{\sqrt{HZ}}{m}$	2.09	1.97	1.90	1.84	1.77
Substrate TE $\times 10^{22} \frac{\sqrt{HZ}}{m}$	0.71	0.68	0.68	0.68	0.68
Coating Brownian $\times 10^{21} \frac{\sqrt{HZ}}{m}$	4.19	3.96	3.84	3.76	3.65
Coating TE $\times 10^{21} \frac{\sqrt{HZ}}{m}$	1.18	1.11	1.06	1.04	1.00
Equivalent Strain $\times 10^{24} \frac{\sqrt{HZ}}{m}$	2.41	2.28	2.21	2.16	2.09



- Noise goes **DOWN** with increased absorption!
- To be checked by FEM
- Results are surprising but similar has been seen before...

MH losses

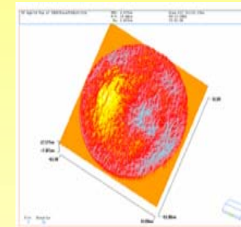
- Other things discovered during this study

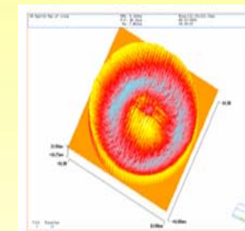
Cavity	Coating Absorption ppm	Cavity Gain	Diffraction Loss ppm	Mode Matching Loss ppm
Mesa	0	744	9.36	149.39
	0.5	719	19.72	220.33
	1	696	21.21	289.02
	1.5	679	12.77	352.08
	2.5	643	18.00	456.95

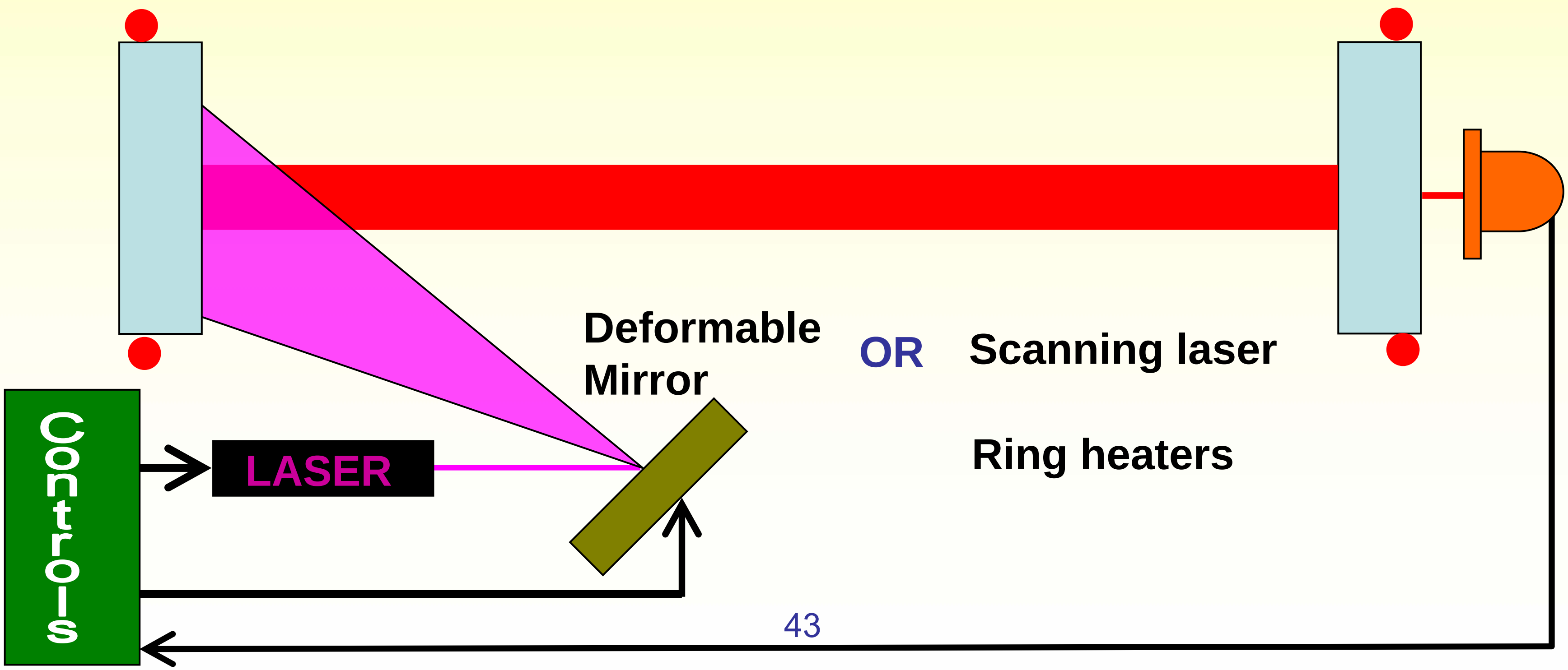
- Insertion (mode-matching) loss lower than expected
  - always good news
- Diffraction loss higher
  - wide parameter space for tuning

TCS Strategy

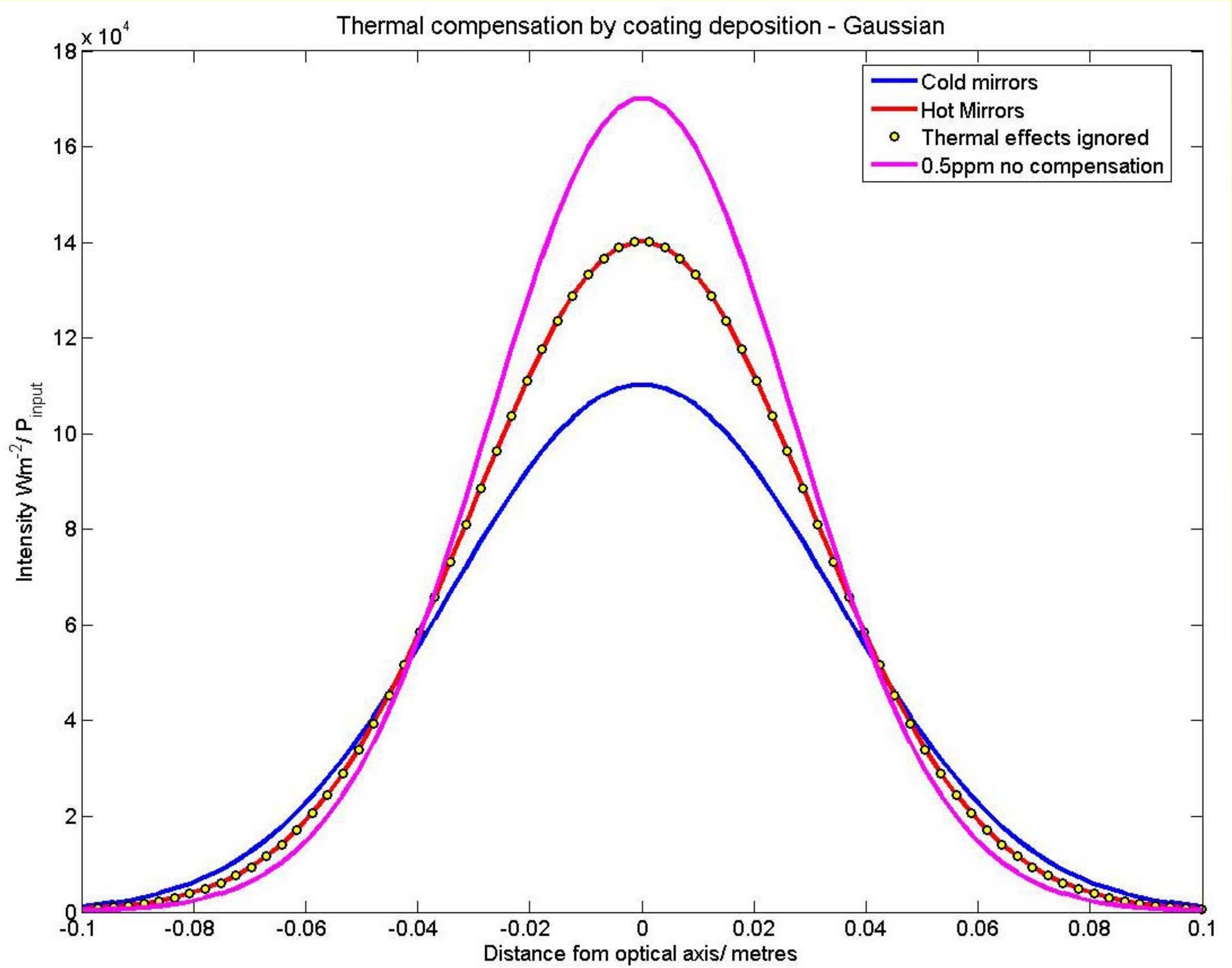
- Make ‘bad’ mirrors which achieve the correct figure at operating power
- Turned off for science mode – no noise injected
- Need to know optics very well – single point solution



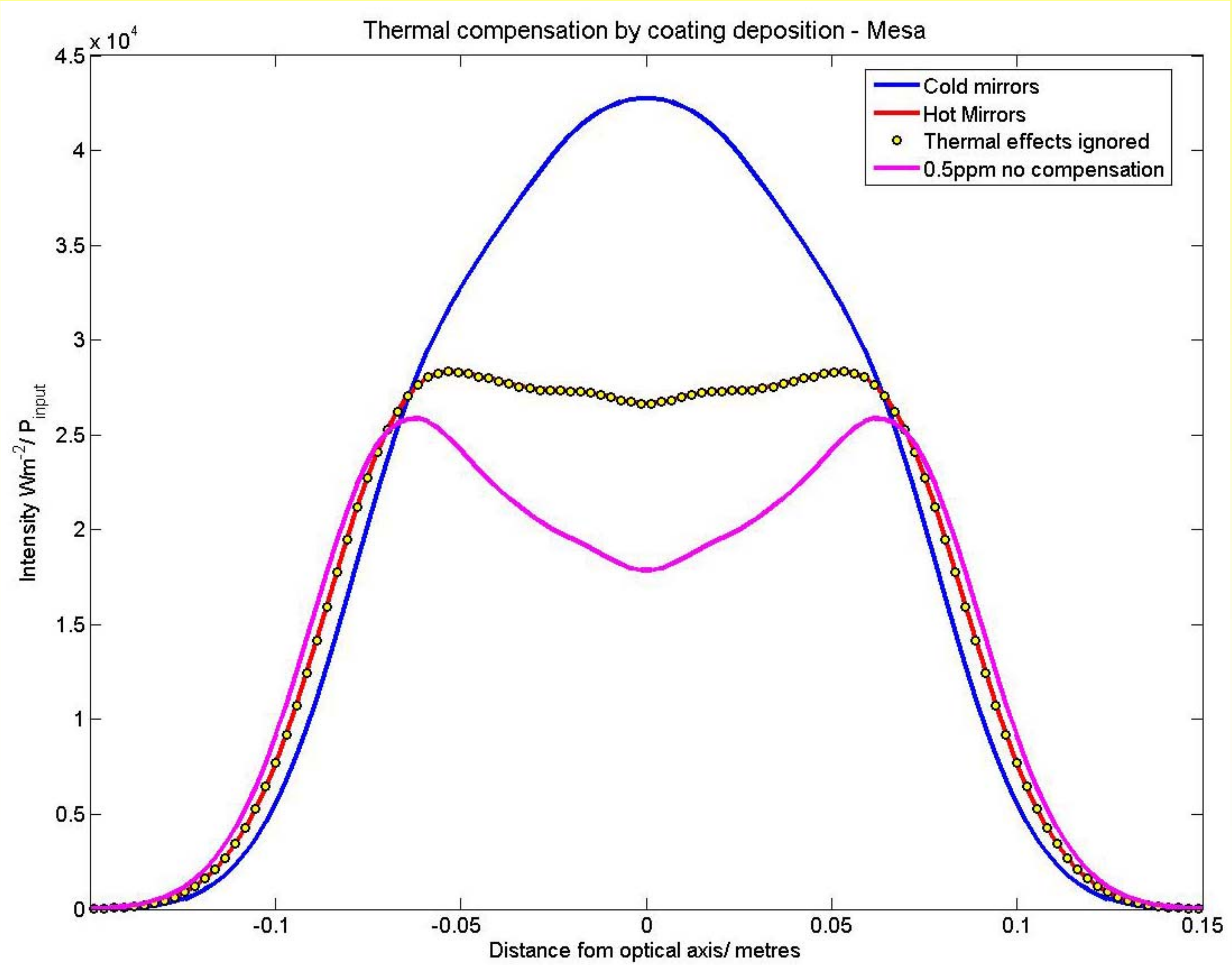




TCS Gaussian



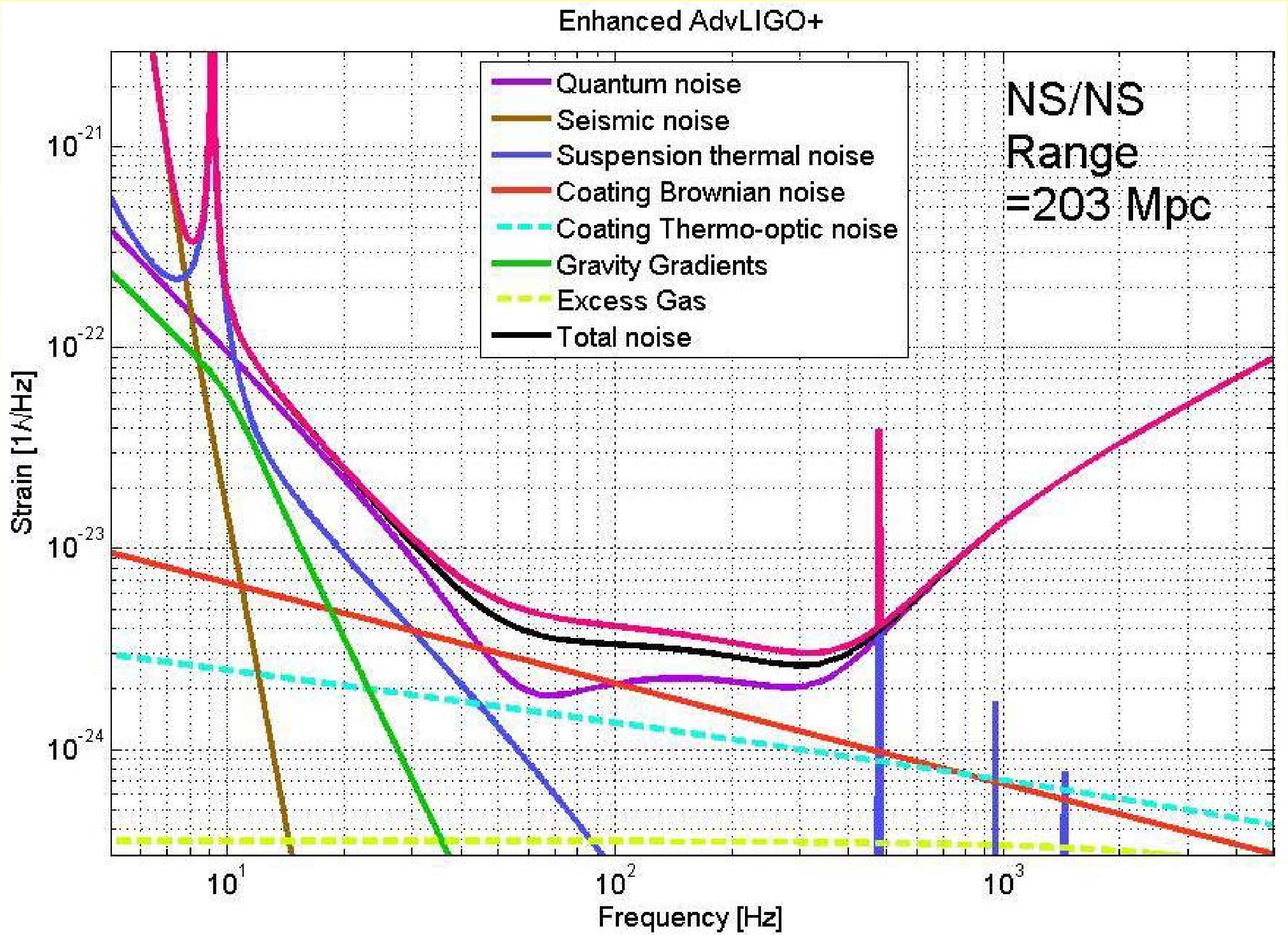
TCS Mesa



Thermal compensation by coating deposition - Mesa
x 10^4
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Intensity Wm^-2 / P_input
-0.1
-0.05
0
0.05
0.1
0.15
Distance fom optical axis/ metres
Cold mirrors
Hot Mirrors
Thermal effects ignored
0.5ppm no compensation

Enhanced AdvLIGO+ II

- Mesa beam arms - crude model

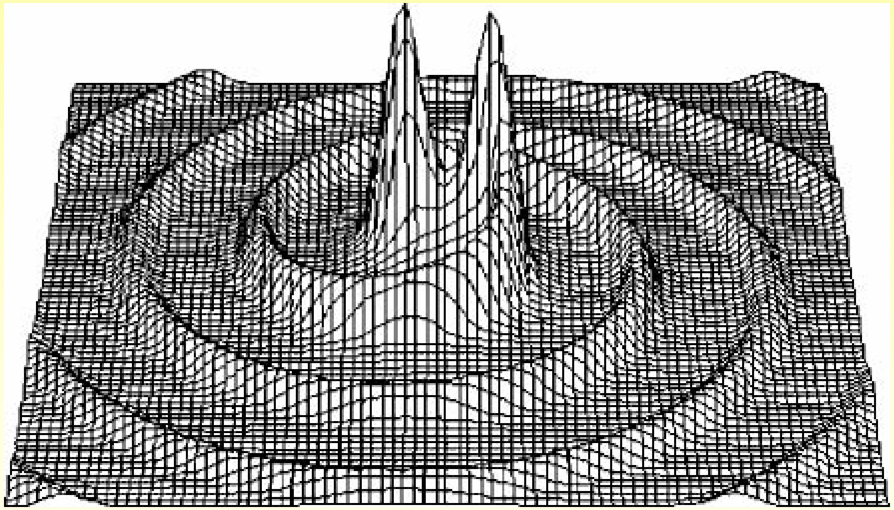


Gaussian in **magenta**

Mesa in **black**

Enhanced AdvLIGO+ II

- h noise down by x1.8 @100Hz
- NS/NS range
  - 170 → 205 Mpc
- BH/BH range
  - 990 → 1143 Mpc
- Stochastic Ω_{GW}
  - 2.34e-9 → 1.98e-9
- Event rate
  - Up by ~1.75



Here we ignore other possible developments

Materials, Coatings, Cryogenics

Squeezing, QND

etc

Pros

- Reduce impact of thermal noise
- Less susceptible to Sidles-Sigg instabilities
- Good coupling to Gaussian
- Increase range and detection rate

Cons

- Can’t do small mirrors (yet)
- 9.4cm waist GB in recycling cavity
- Slightly tighter tolerances
  - figure error x~2
  - tilt x~3

Other beams – LG_{55}

- LG beams
  - x2.5 better

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Class. Quantum Grav. 23 (2006) 5777–5784 doi:10.1088/0264-9381/23/20/001

Thermal noise reduction in interferometric gravitational wave antennas: using high order TEM modes

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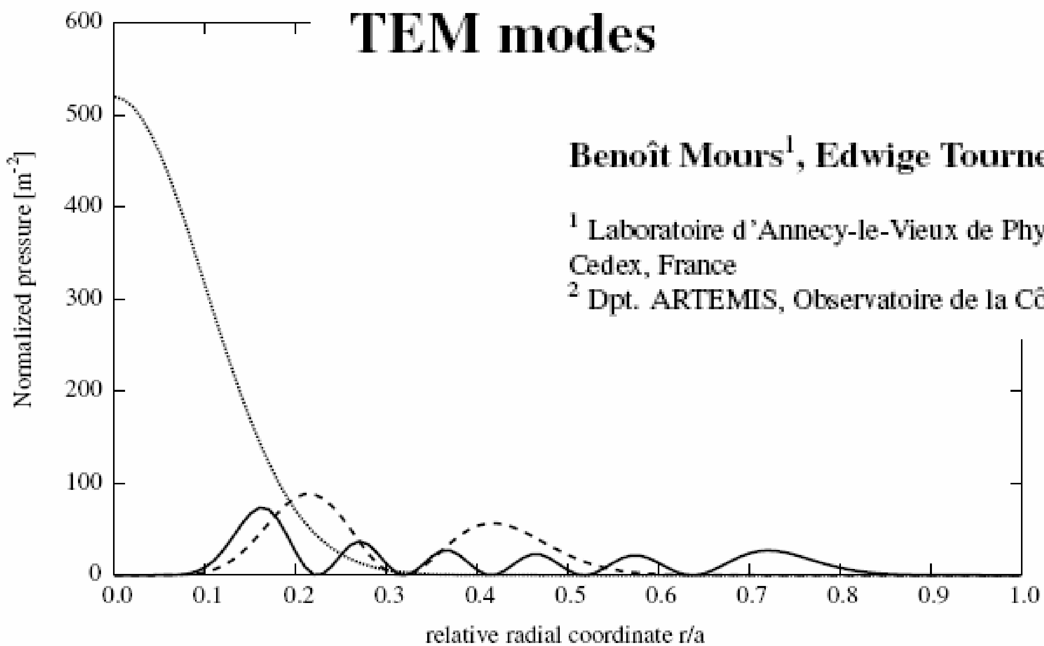

Figure 1. Pressure profiles of Laguerre–Gauss modes. $LG_{0,0}$: dotted line, $LG_{4,1}$: dashed line and $LG_{5,5}$: solid line.

- HG beams
  - formalism breaks down

Other beams - hyperboloidal

PHYSICAL REVIEW D **74,** 082003 (2006)

New family of light beams and mirror shapes for future LIGO interferometers

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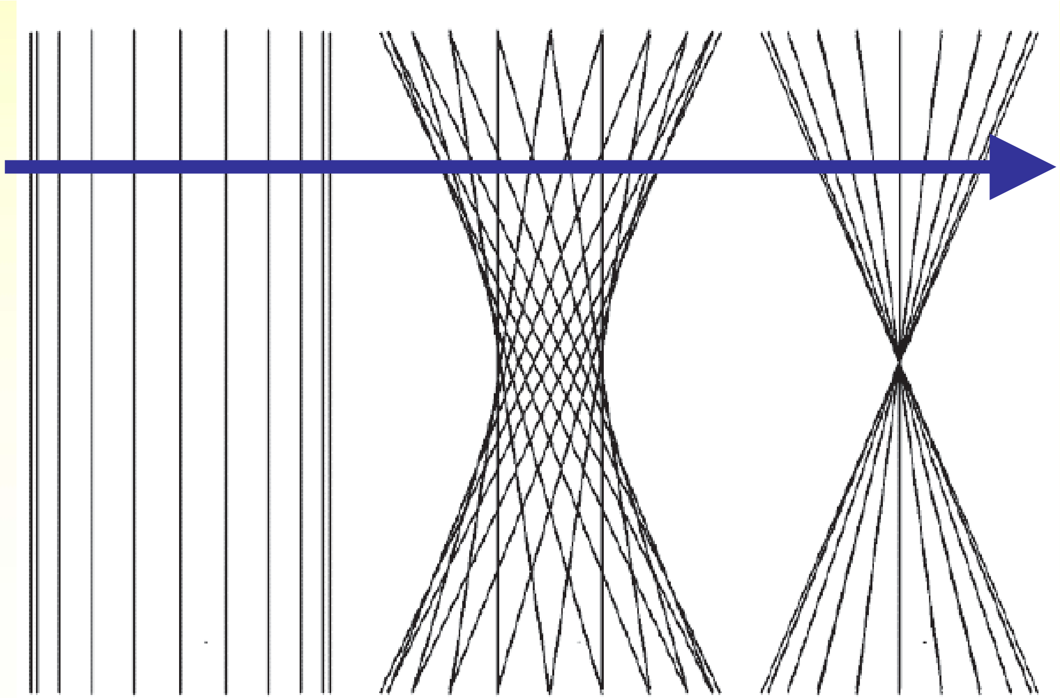
(Received 21 September 2004; revised manuscript received 16 August 2006; published 9 October 2006)

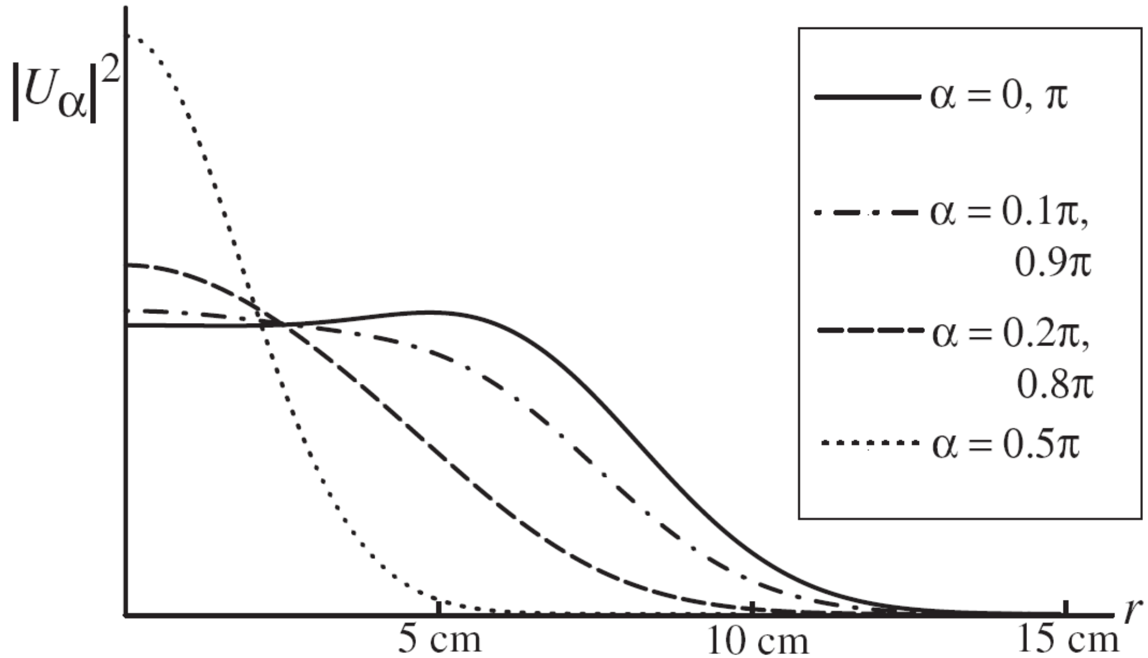
FLAT



CONCENTRIC

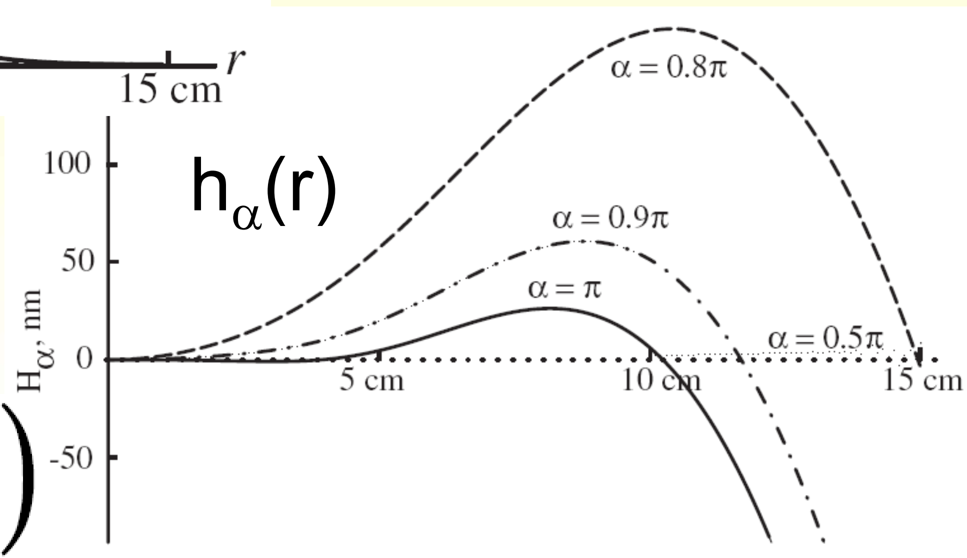
Other beams - hyperboloidal

Intensity



$$S_\alpha(r) \equiv \sqrt{l^2 - r^2\sin^2(\alpha/2)}$$

$$z = S_\alpha(r) - h_\alpha(r)$$

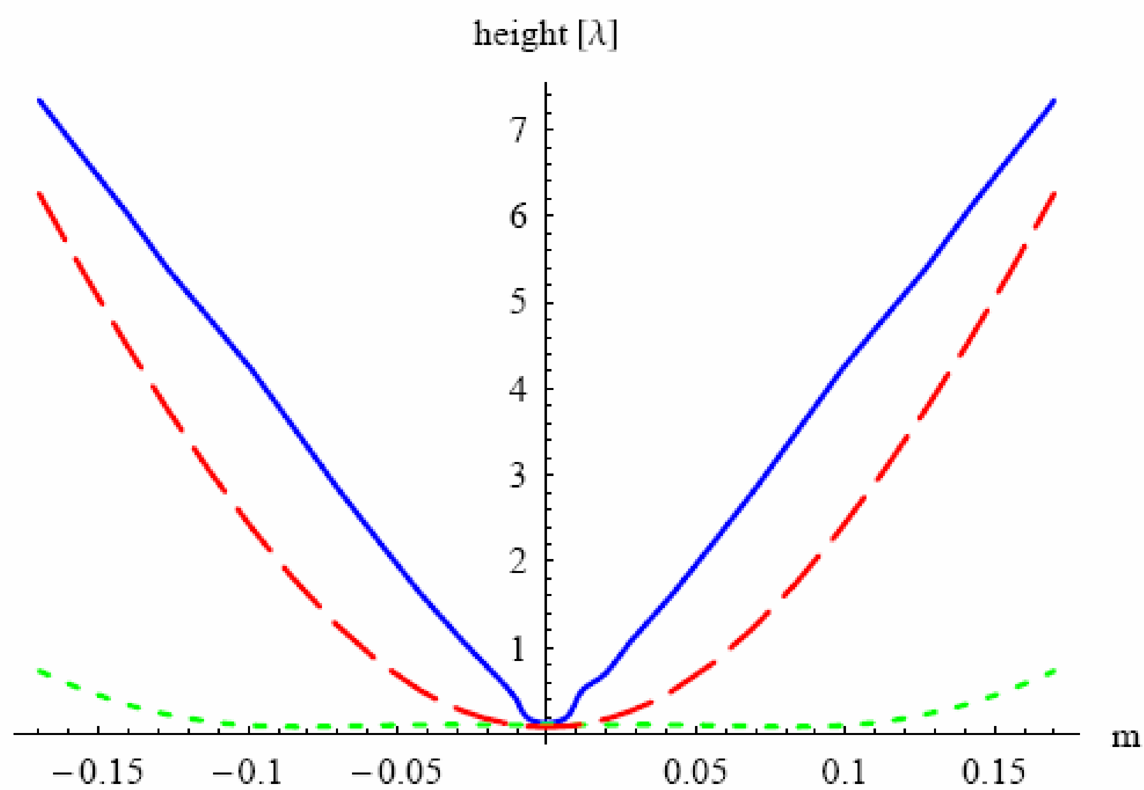


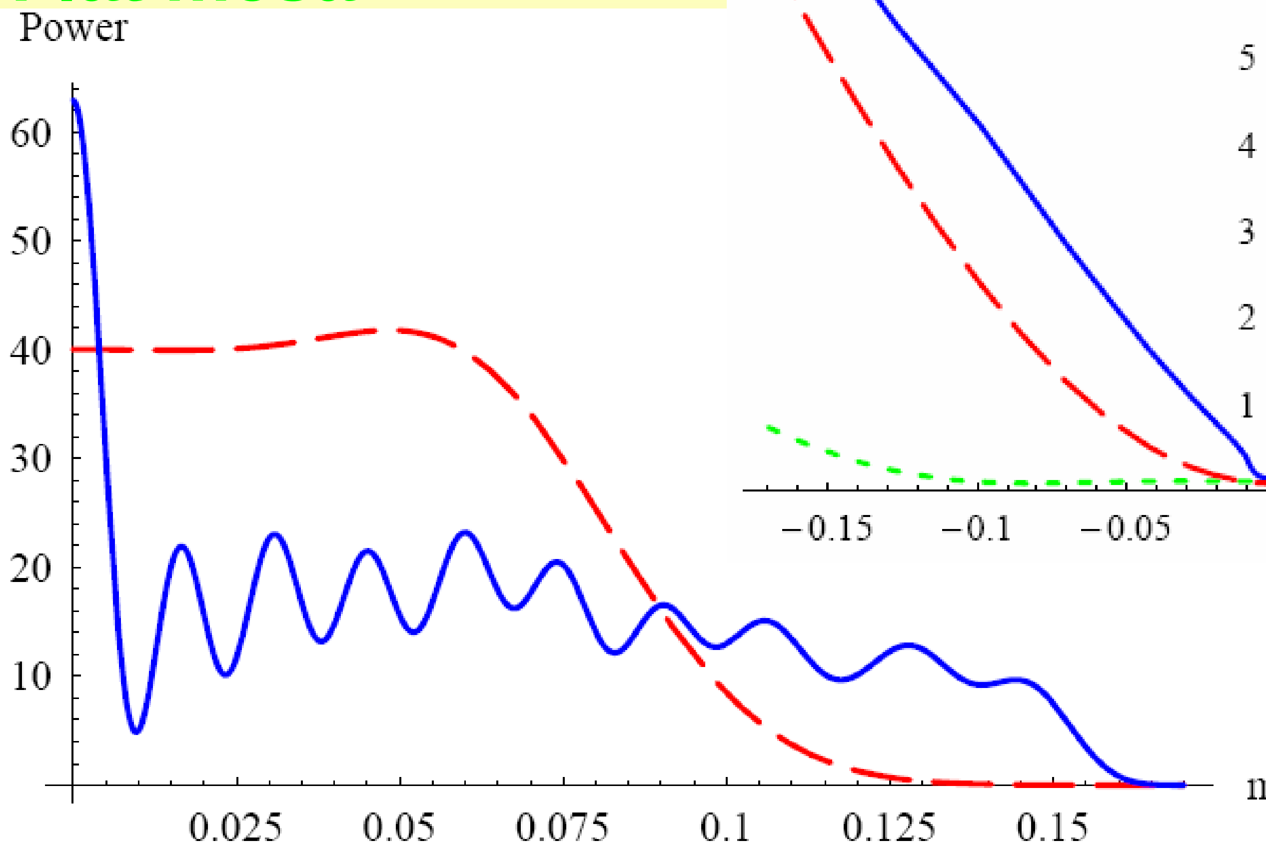
Other beams - Conical

Conical

Concentric mesa

Flat mesa





Noise	Brownian	Thermoelastic
Coating	2.339	2.339
Substrate	1.534	3.302

M. Bondarescu

Other beams – fully optimised

Perspectives on Beam-Shaping Optimization for Thermal-Noise Reduction in Advanced Gravitational-Wave Interferometric Detectors: Bounds, Profiles, and Critical Parameters

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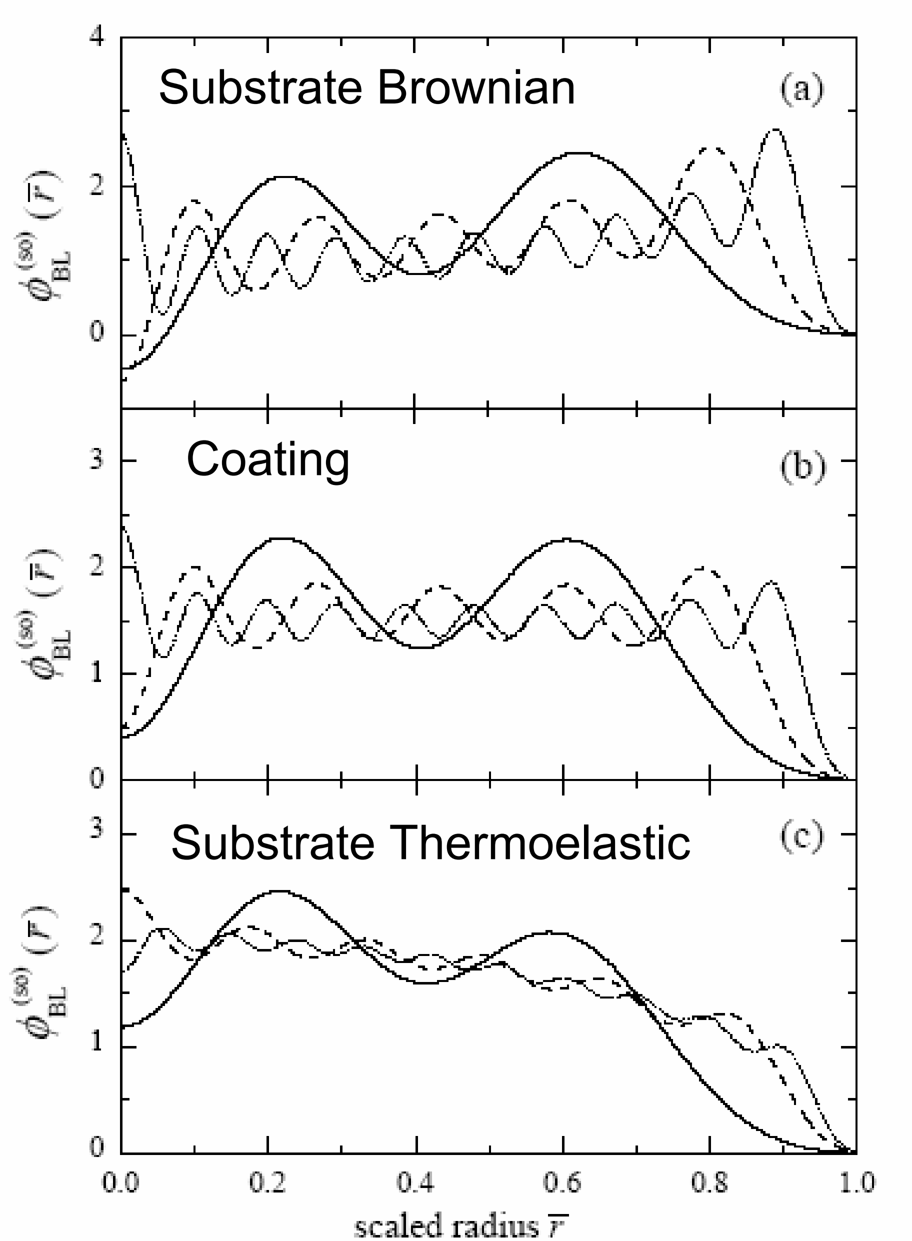
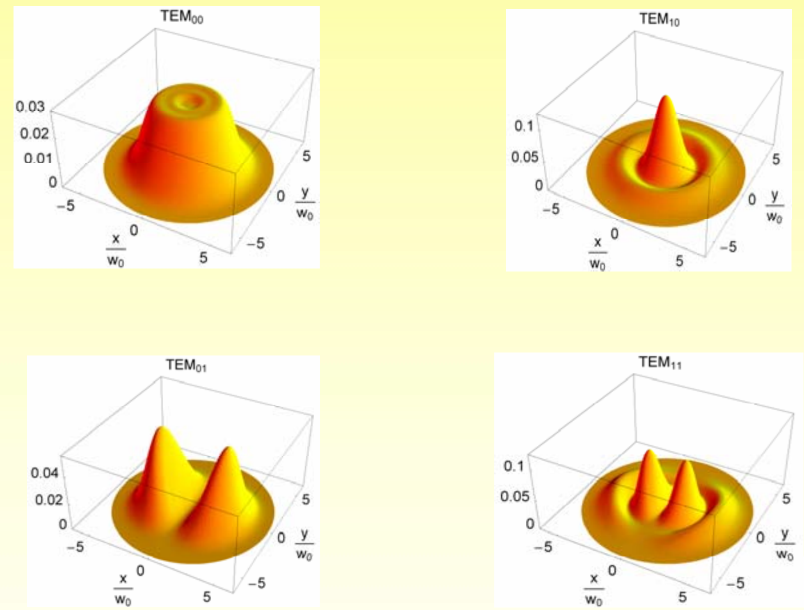
Other beams – fully optimised

- Optimisation is difficult – done for single noise sources
- Realistic constraints makes large difference
- MB non optimal up to x3 better achievable



Conclusions

- Mesa beams predicted reduce thermal noise
- Built experiment to study
  - Goals
    - resonate beam ✓
    - lock ✓
    - cf. theory ✓
    - alignment ?
    - coupled system ?
- Thermal noise characteristics interesting



- M. G. Tarallo, J. Miller et. al., “**Generation of a flat-top laser beam for gravitational-wave detectors by means of a non-spherical Fabry-Perot resonator”** . App. Opt., doc. ID 80265 (posted 13 July 2007, in press).
  - Vol 46, No. 26, 9/10/07

With lots of help from

- Rich Abbot
- Rana Adikhari
- Juri Agresti
- GariLynn Billingsley
- Livia Cerullo
- Erika D'Ambrosio
- Riccardo DeSalvo
- Eric Gustafson
- Norna Robertson
- Zeb Rocklin
- Sheila Rowan
- Mike Smith
- Ken Strain
- Marco Tarallo
- Phil Willems
- Hiro Yamamoto
- et al

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