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Reducing thermal noise: The prospects of optimised beam shapes and higher-order Laguerre-Gauss modes

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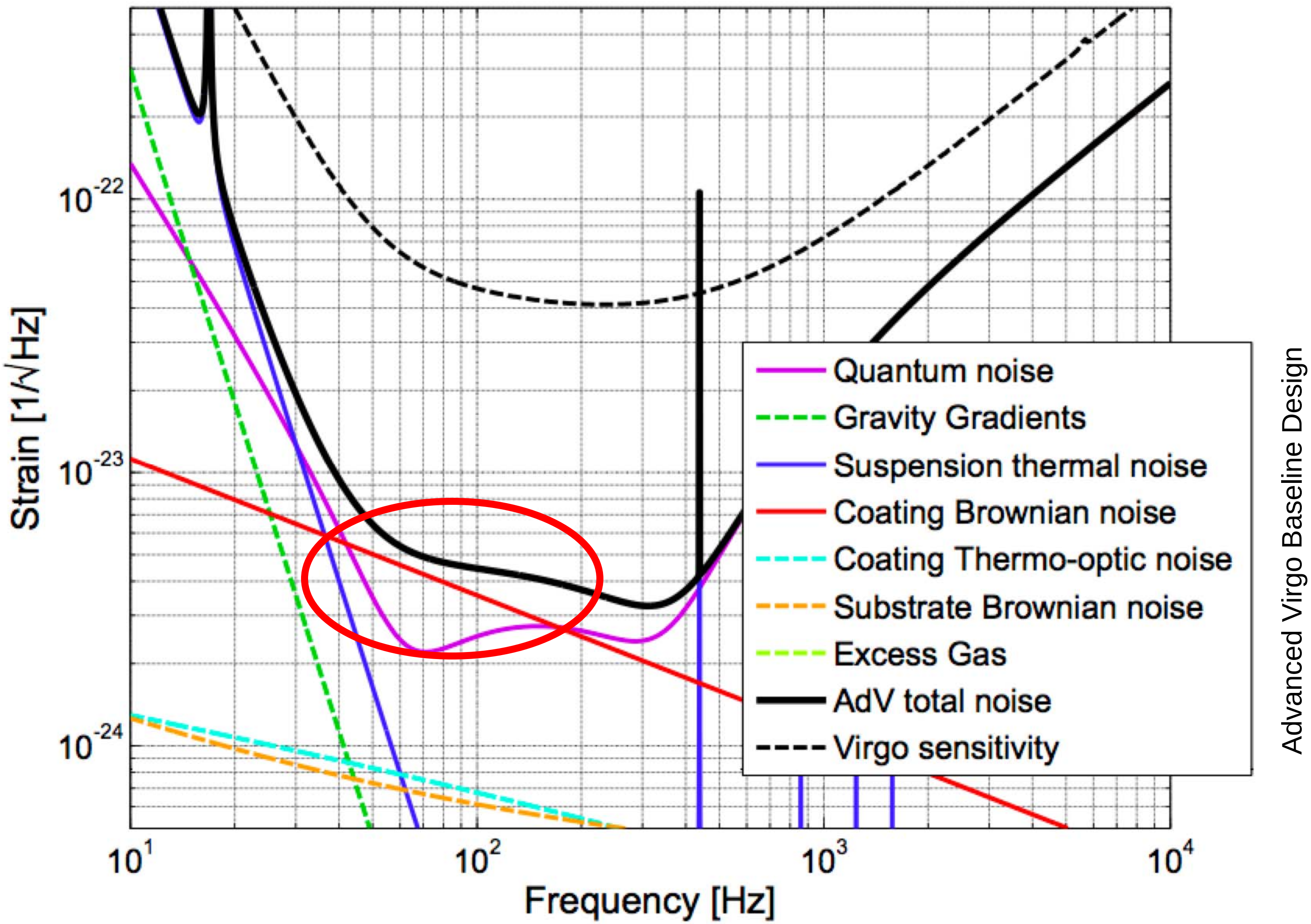
G0900650-v1

Overview

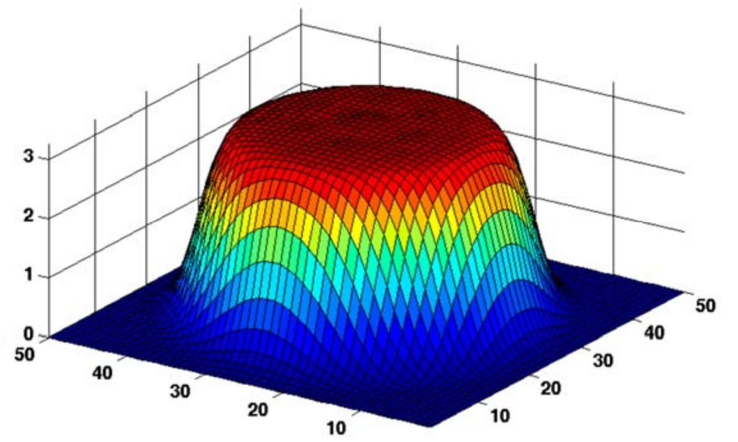
- Thermal noise reduction using alternative beam shapes
- A brief history of `flat' beams for GW detectors
    - Mesa beams
    - Optimised beam shapes
    - Higher order Laguerre Gauss modes
- Interferometry with LG beams
- Production of `flat' beams

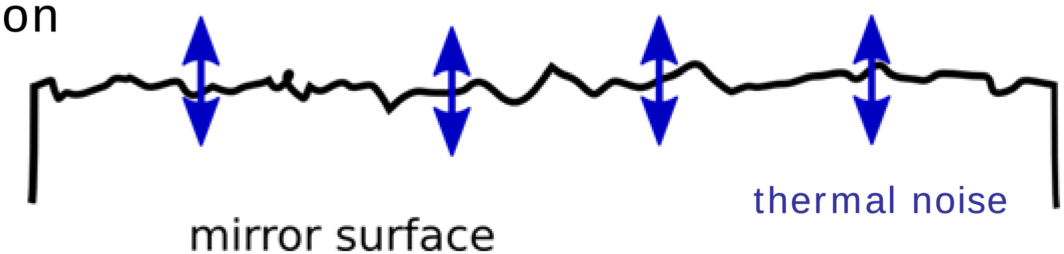
Thermal noise in future GW detectors



Possible Thermal Noise Reduction

- Coating Brownian thermal noise dynamically distorts the surface of the mirrors
- This results in noise in the dark fringe, proportional to the magnitude of the `average' phase change in the reflected wave fronts
- This `average' can be improved by widening and flattening the beam size on the mirror





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Thermal noise in mirrors

Loss angle

$$S_x(f) = \frac{4k_BT}{\pi f}\Phi U$$

Vinet CQG **22** (2005)

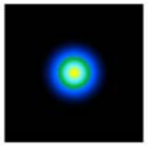
Levin Phys. Rev. D **57** 659 (1998)

the strain energy stored in the test mass by a pressure normalized to 1 N, and having the same distribution as the light intensity in the readout beam

For simplicity this and the following considers only Brownian substrate noise for substrates of infinite size. A lot of effort has gone into computing accurate numbers for the coating noises, thermo-optic noise, both infinite and finite size mirrors.
A good review of this topic will be published soon:

`On thermal issues in advanced Gravitational Wave Interferometric detectors'
J. Y. Vinet, *Living Reviews in Relativity*, to be published

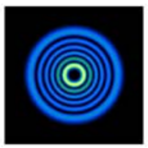
Thermal noise of Flat beams



LG00 mode:

Bondu et al. Physics Letters A **246** (1998) 227

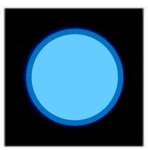
$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\,\sqrt{\pi}\,Y\,w}$$



LGnm modes:

Bondu et al. Physics Letters A 246 (1998) 227

$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\,\sqrt{\pi}\,Y\,w}\,\alpha_n^m$$



Flat beams:

J.-Y. Vinet CQG **22** (2005) 1395

$$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{8\,\left(1-\sigma^2\right)}{3\,\pi^2\,Y\,b}$$

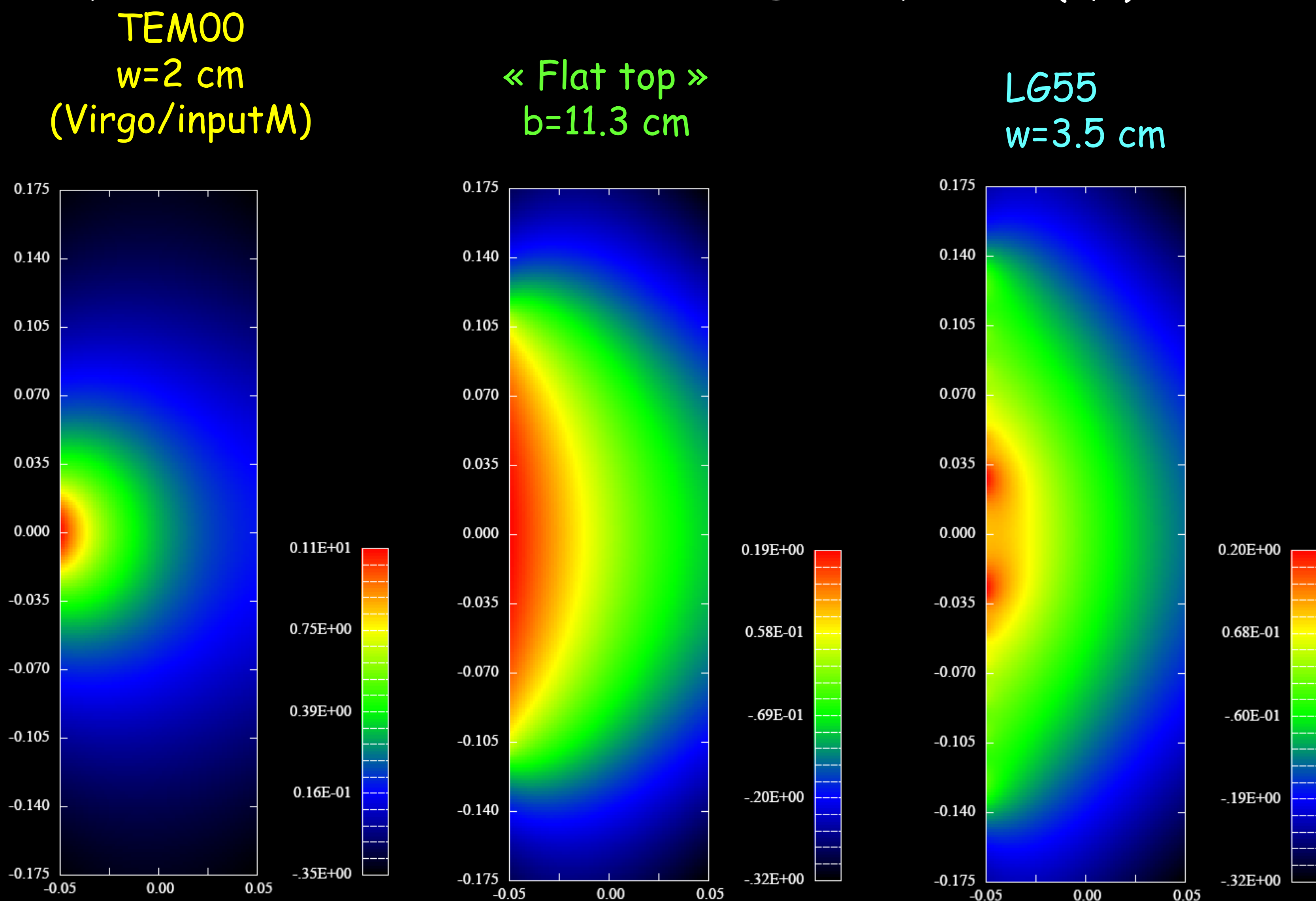
Reduction factors given in this talk are collected from various papers and refer to different examples (mirror size, clipping loss, coating parameters,…). Equations to re-compute these factors properly can be found in (again):

`On thermal issues in advanced Gravitational Wave Interferometric detectors'
J. Y. Vinet, *Living Reviews in Relativity*, to be published

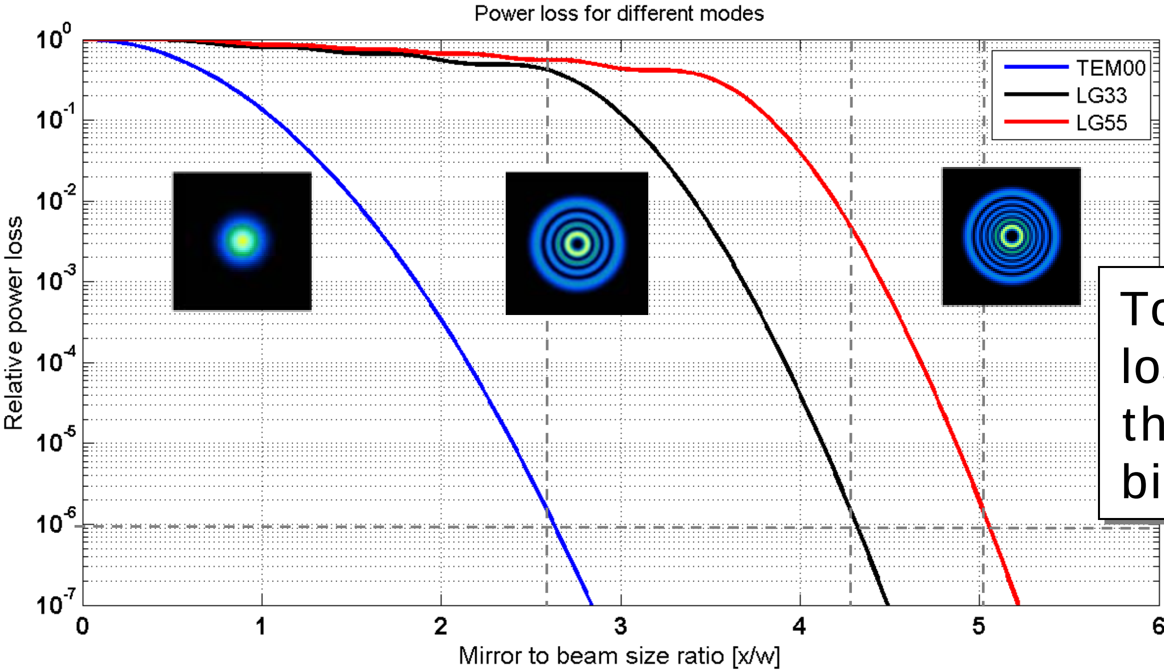
Slide by J. Y. Vinet

[Vinet CQG 24 (2007)]

Temperature field in the substrate (coating absorption) T(r,z)



Constraint: clipping loss



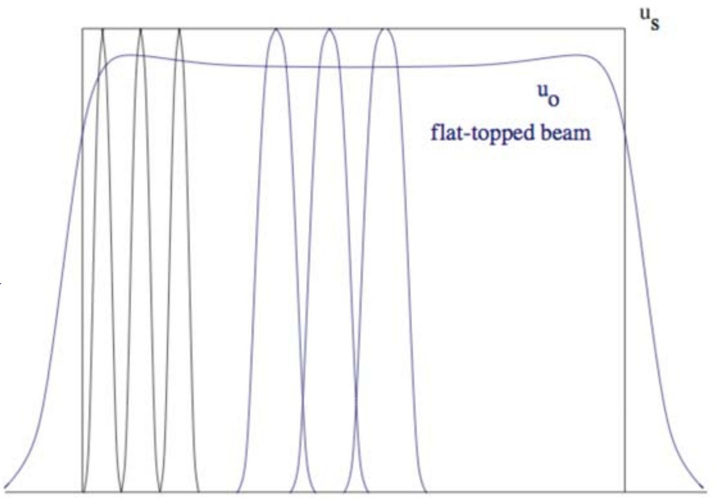
To get the same clipping loss we need to change the mirrors ROC (or use bigger mirrors).

Mode scaling factors	LG00	LG33	LG55
Mirror size	1	1.64	1.92
Beam size	1	0.61	0.52

Mesa Beams: Multiple Flat Top Gaussian Beam

A sum of many small Gauss Beam create a flat top beam with low diffraction

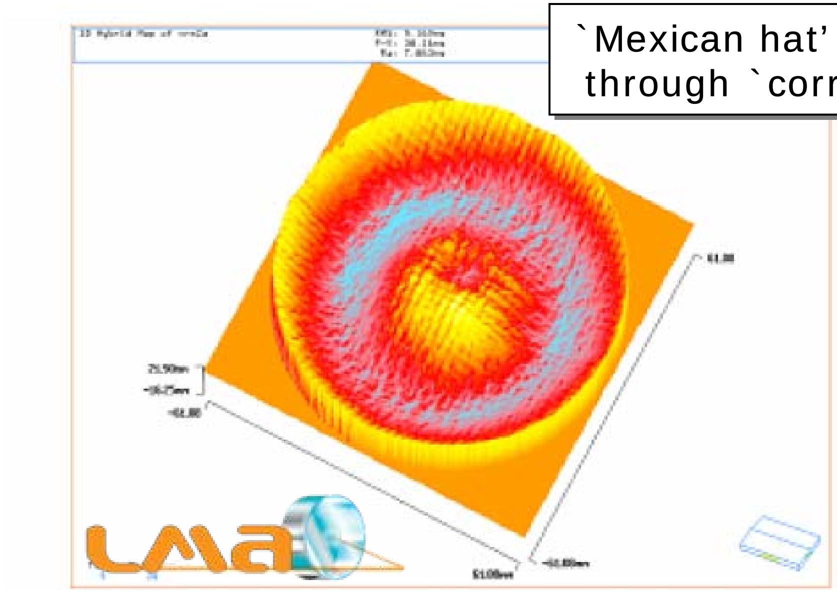
Goal: reduction of thermoelastic noise by a factor ~3 [D'Ambrosio PRD 67 (2003)]

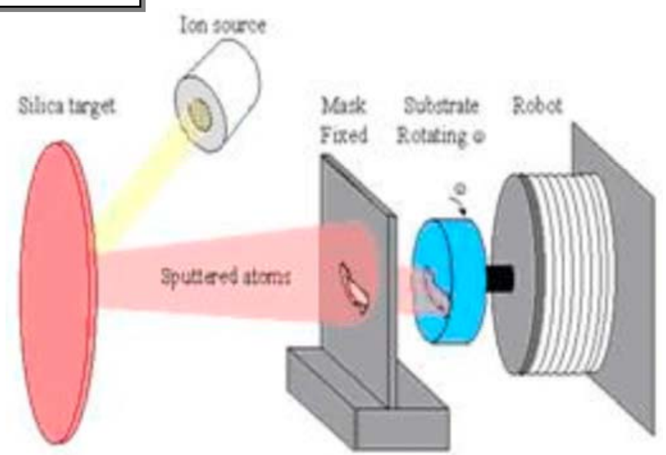


[D'Ambrosio et al 2004]

`Mexican hat' mirror profile through `corrective coating'

[Talk J. Miller 2008]





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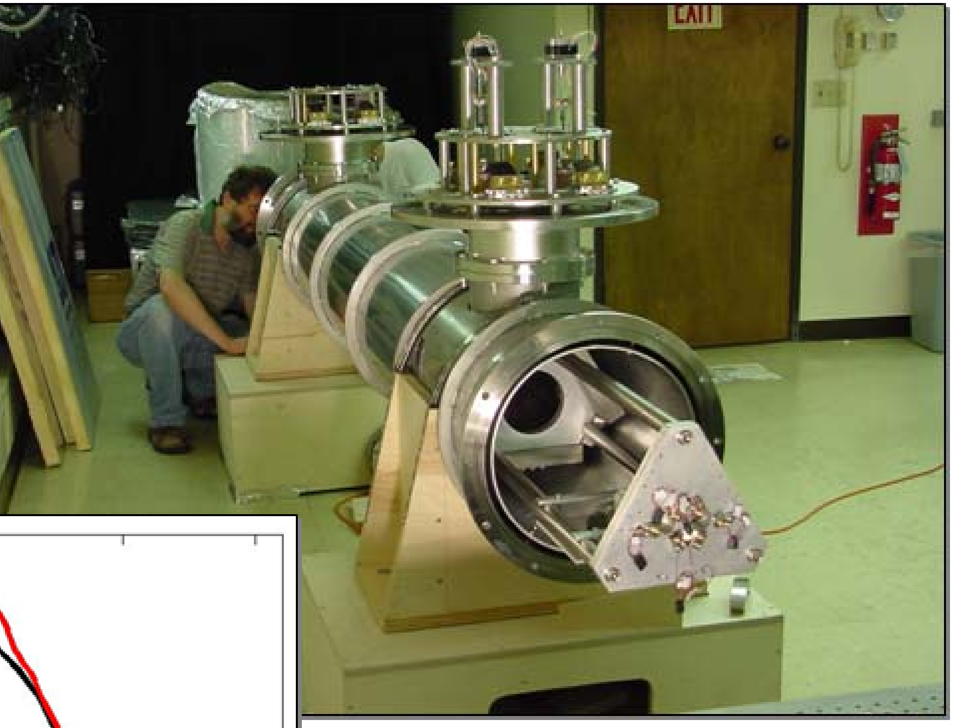
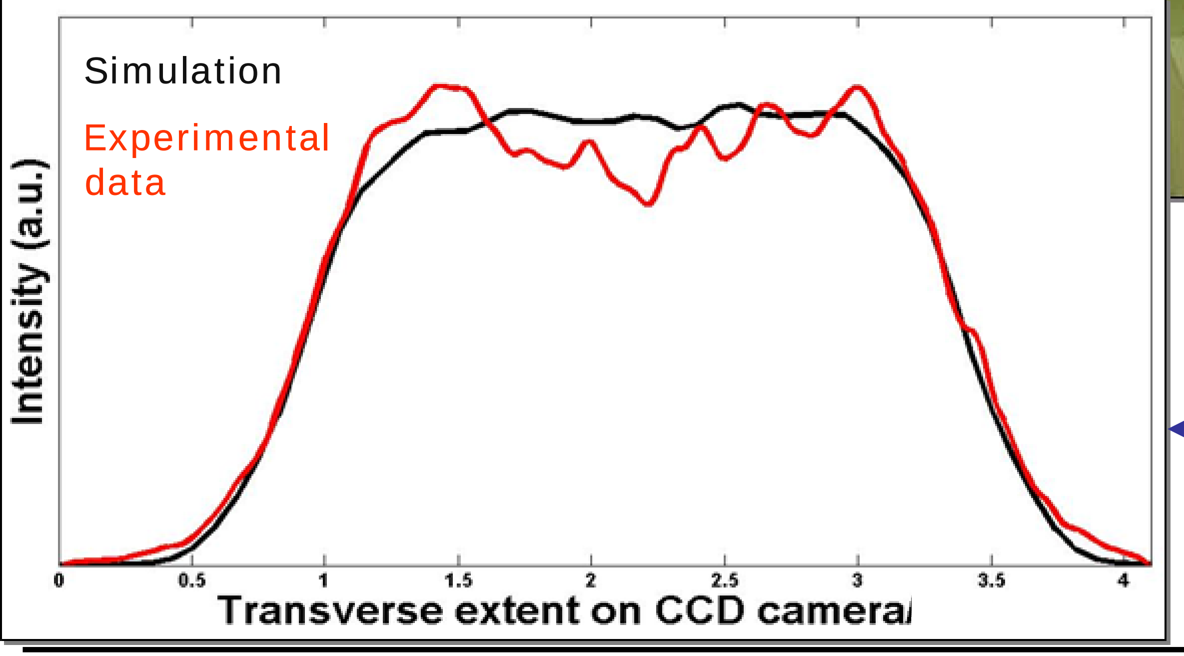
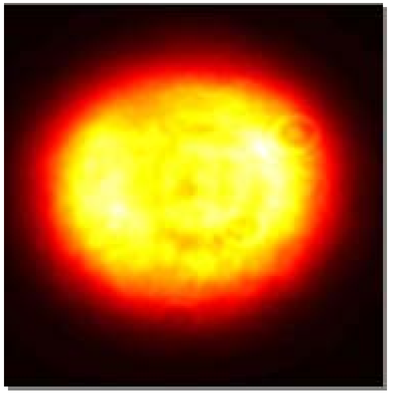
Mesa beam prototype experiment







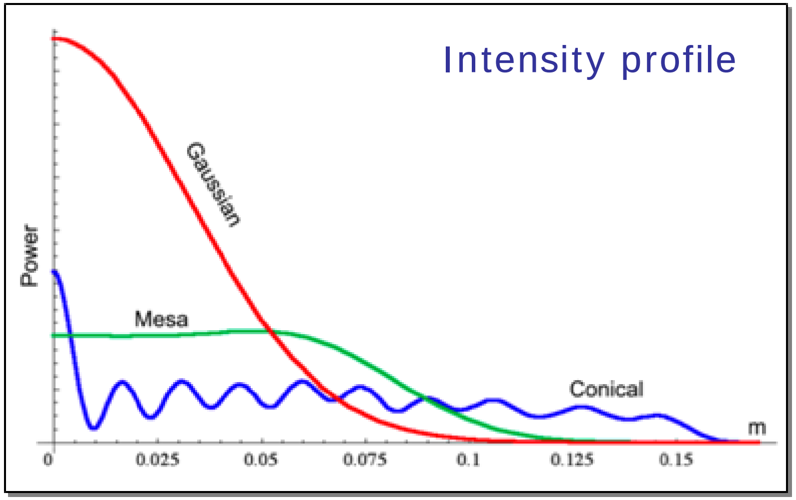
Optimised beams

Mesa beams where a simple approach to achieve a flat beam with low diffraction

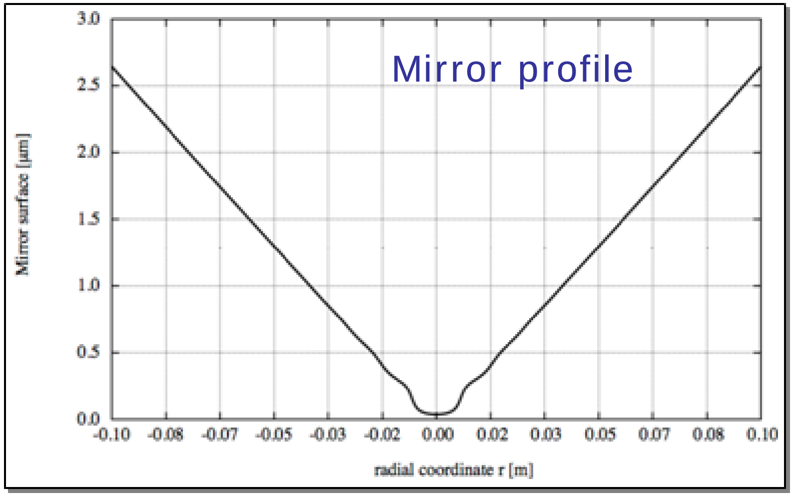
Bondarscu et al (and others) have extended this approach to optimise the beam shape for low thermal noise for a given clipping loss.

Expected thermal noise reduction: 2.3 (compared to 1.5 with Mesa beams) for the case of Advanced LIGO.

Challenges come from non-spherical mirror profile: e.g. need to control DC position to 4 um and/or 3nrad to keep losses below 10ppm.



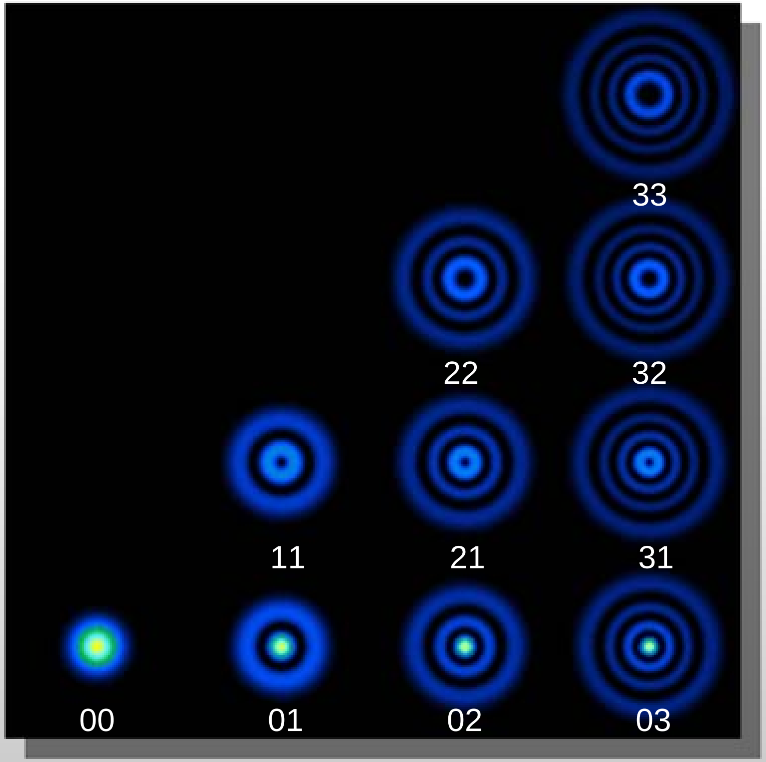
[Bondarescu et al PRD 2008]



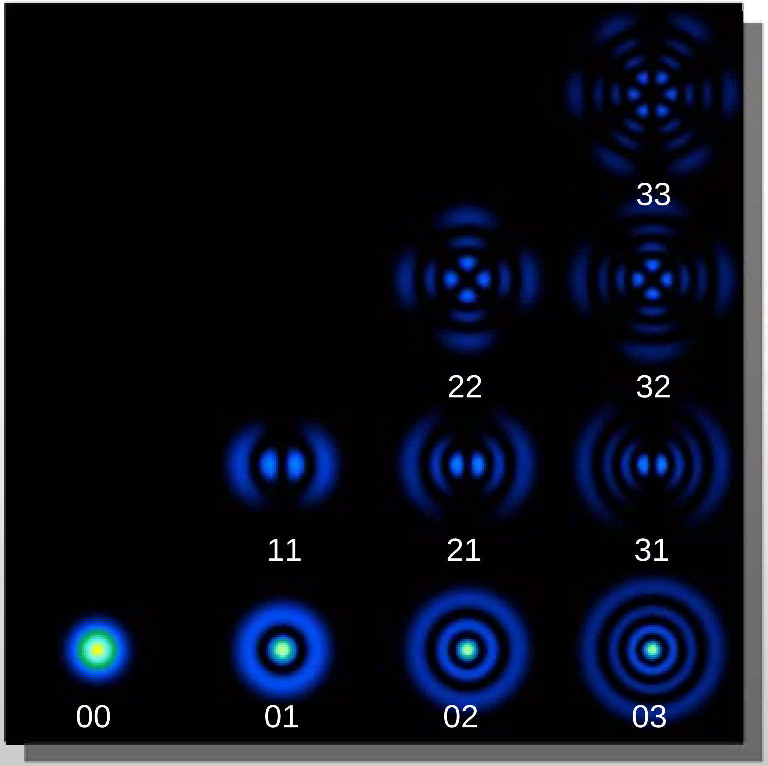
[Vinet 2009 (in. prep)]

Laguerre-Gauss modes

Helical Laguerre-Gauss modes



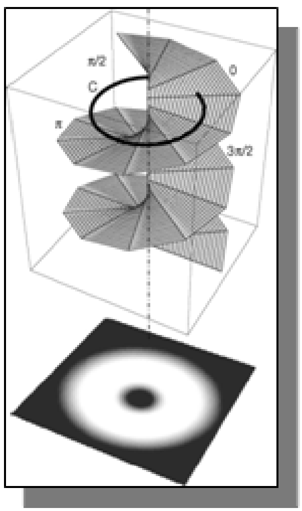
Sinusoidal Laguerre-Gauss modes

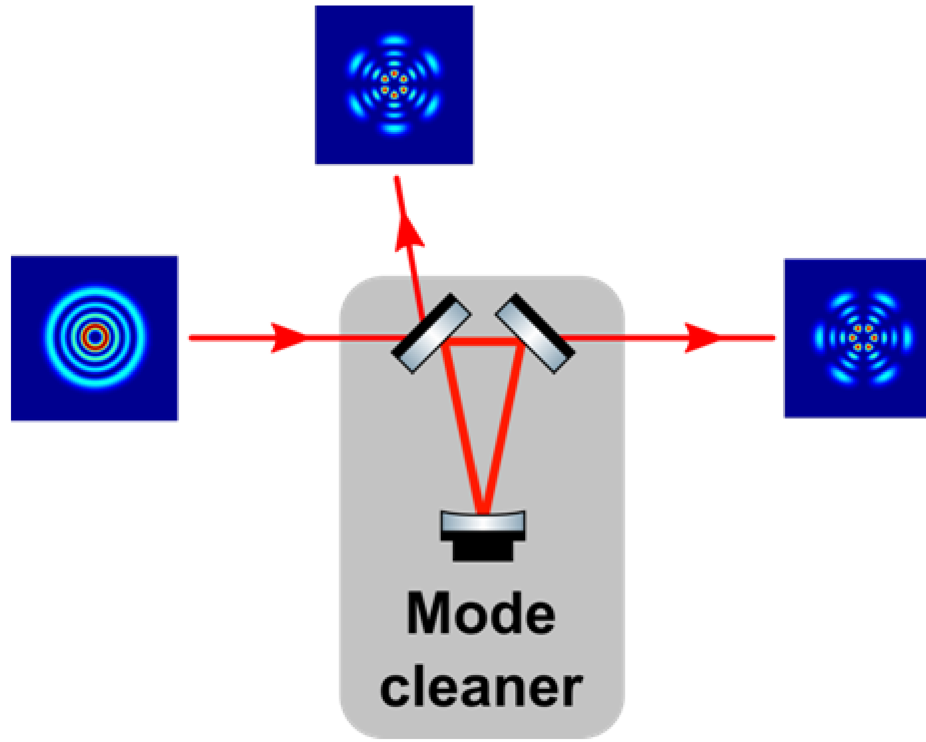


Helical LG modes versus triangular cavities

Helical LG modes

- Continuous ring structure
- Helical phase distribution





Two possible solutions for this problem:

a) Do not use triangular cavities (e.g. use bow-tie configurations)

b) Use sinusoidal LG modes (with slightly worse thermal noise reduction factors)

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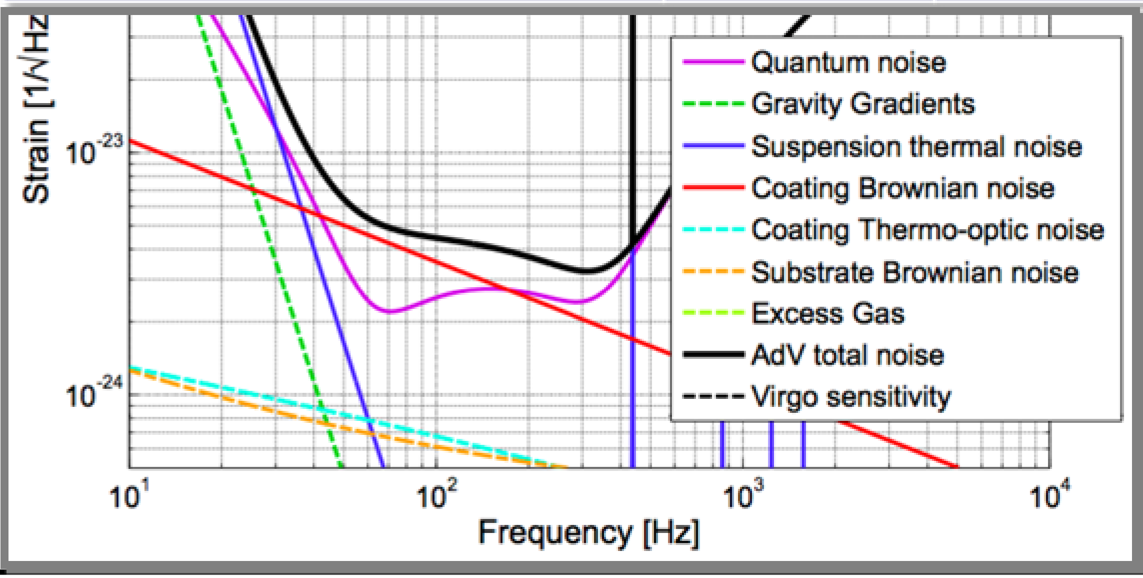
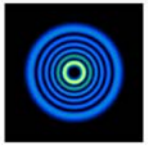
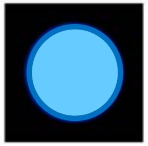
Expected thermal noise improvements

Reduction factor of thermal noise	LG00 / HG00	LG33	LG55	Mesa beam
Coating thermal noise	1	~2.2	~2.3	~1.5
Substrate thermal noise	1	~2.7	~2.7	~1.8
Thermo elastic noise	1	~0.6	~0.4	~1.8

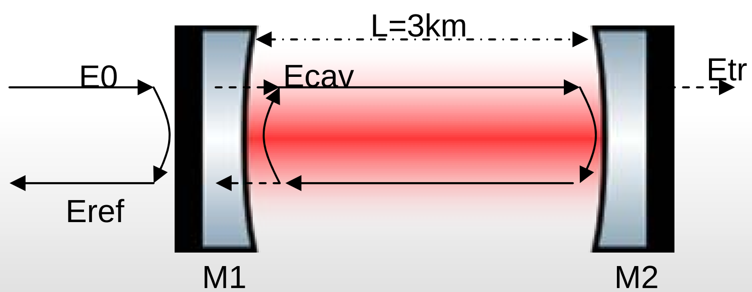




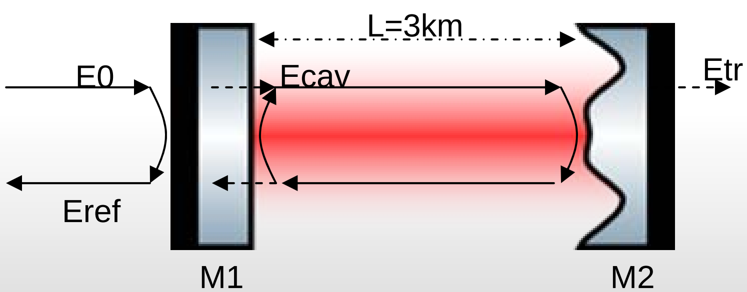


References:
C. TN: personal communication J.-Y. Vinet
S. TN: Mours *et al.* . CQG 23 (2006),5777
T. E. N: personal communication J.-Y. Vinet

Why LG modes rather than flat top beams?



HG & LG mode cavity design



Flat top beam cavity design

By M. Laval and J.-Y. Vinet

- Spherical phase fronts
- Compatible with current interferometers

- Beam shape and phase fronts change on propagation
- Mirror surfaces are more complex

Pro LG: LG modes are compatible with all current optics
Con LG?: cavities resonant to higher order modes are resonant for several modes (of the same order)

Upgrade Advanced Virgo (or other future detectors) to use an LG33 mode

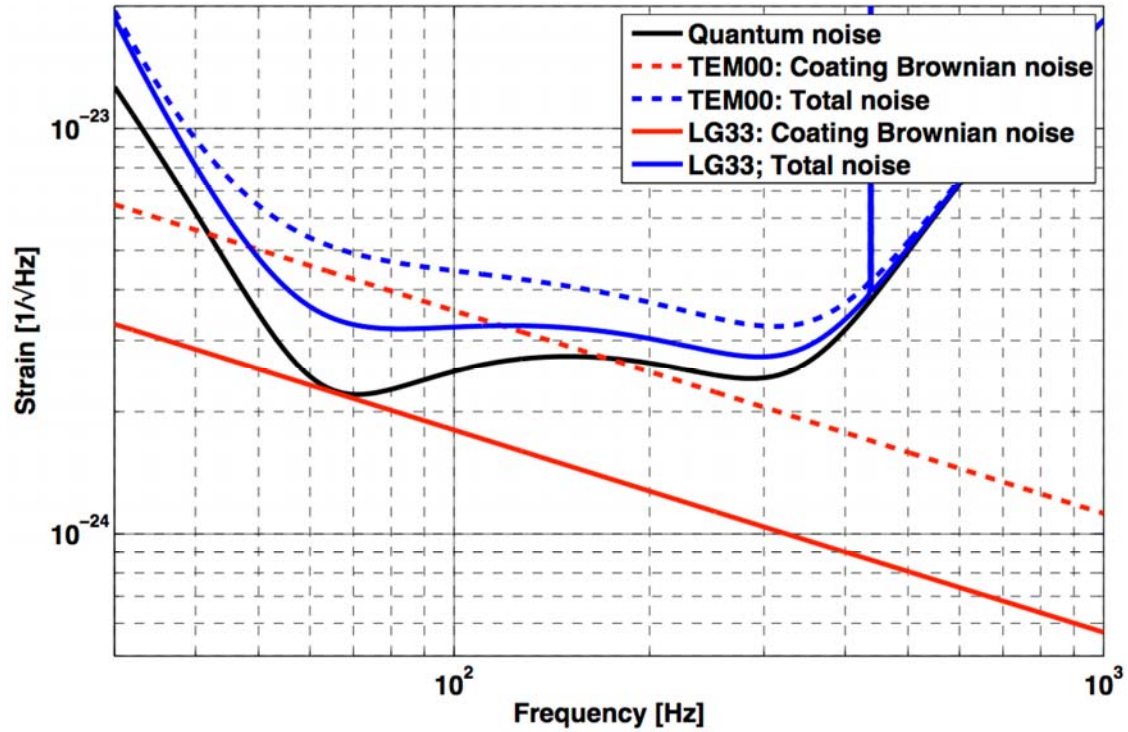
What we need to change:

- Add LG00 to LG33 converter on the laser table
- Change 3-mirror IMC to 4-mirror IMC
- Exchange core optics with mirrors of same size but different ROC
- Retune or replace mode matching optics

What we don’t need to change:

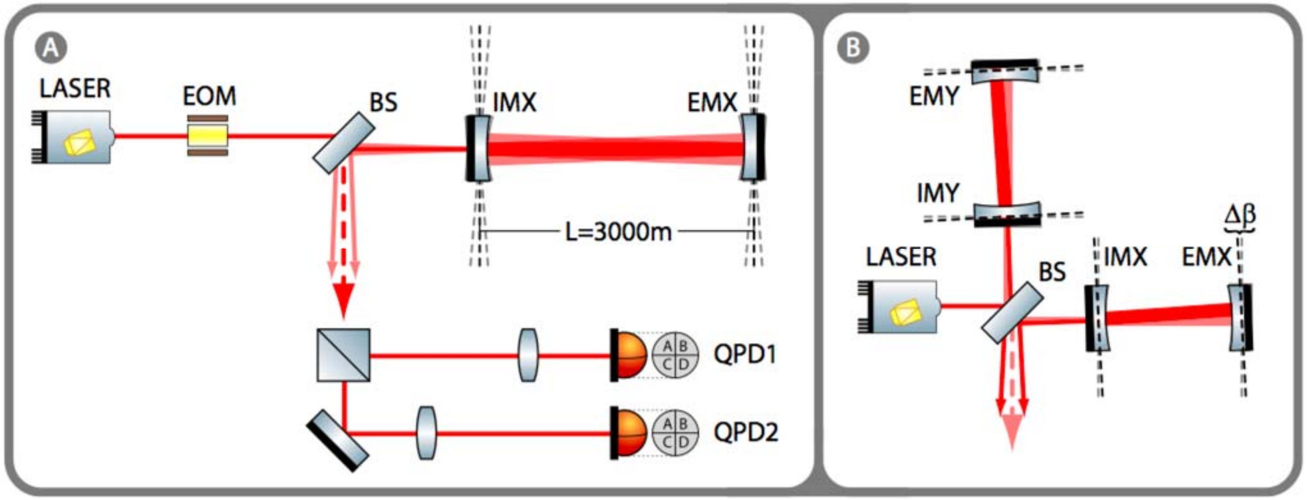
- Input/output optics (EOMs, isolators, …)
- Interferometer control systems (ISC/ASC)
- Vacuum system, suspension system, photodiodes, cameras, baffles, …

Advanced Virgo: inspiral range improvements



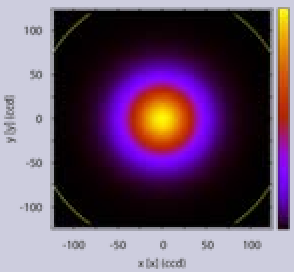
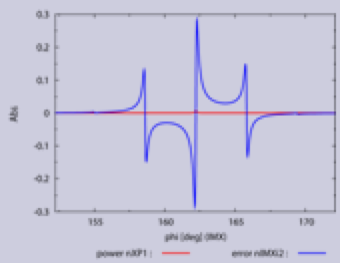
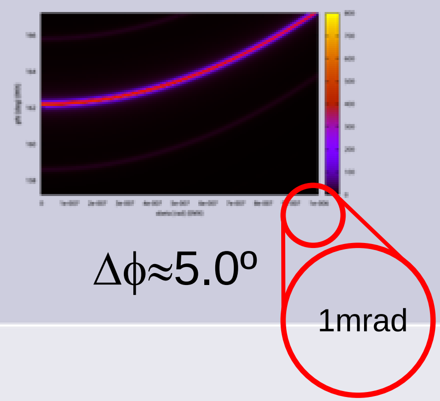
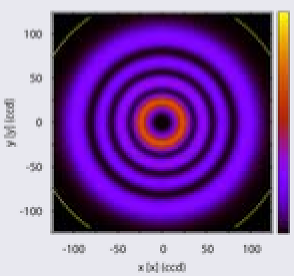
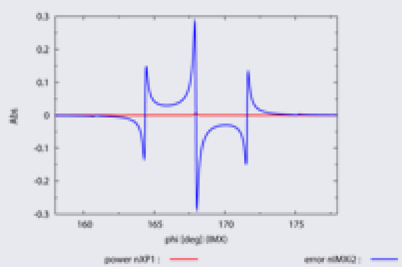
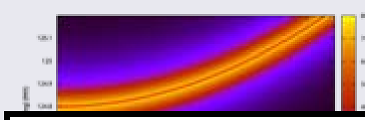
	LG00	LG33 (not optimised)
SR detuning [Hz]	300	300
Beam size [cm]	6	~ 4
NS/NS inspiral range [Mpc]	145	191

Comparison of length and alignment signals



Important to compute also the beam jitter noise or coupling of alignment fluctuation into phase noise. As a first step: a simple cavity, a simple Michelson to look for trouble.

Comparison of length and alignment signals

Transversal mode	Longitudinal error signal	Coupling tilt into longitudinal phase	Control Matrix for alignment signals
LG00 		 $\Delta\phi \approx 5.0^{o}$	$\begin{pmatrix} 1 & 0.862 \\ 0.645 & 0.153 \end{pmatrix}$ $\begin{pmatrix} \text{IMX to Qb} & \text{EMX to Qb} \\ \text{IMX to Qa} & \text{EMX to Qa} \end{pmatrix}$
LG33 			$\begin{pmatrix} 1 & 2.96e-3 \\ 0.368 & 0.641 \end{pmatrix}$

The performance regarding interferometric sensing and control of the LG33 mode is found to be similar, if not even better in all aspects of interest. Coupling of alignment into phase noise is comparable or better.

[Chelkowski et al (arxiv.org/abs/0901.4931)]

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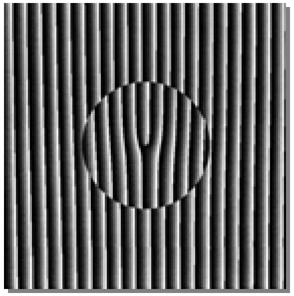
Generation of alternative beam shapes

TABLE I. Comparison of LG_p^ℓ beam characteristics using different construction methods.

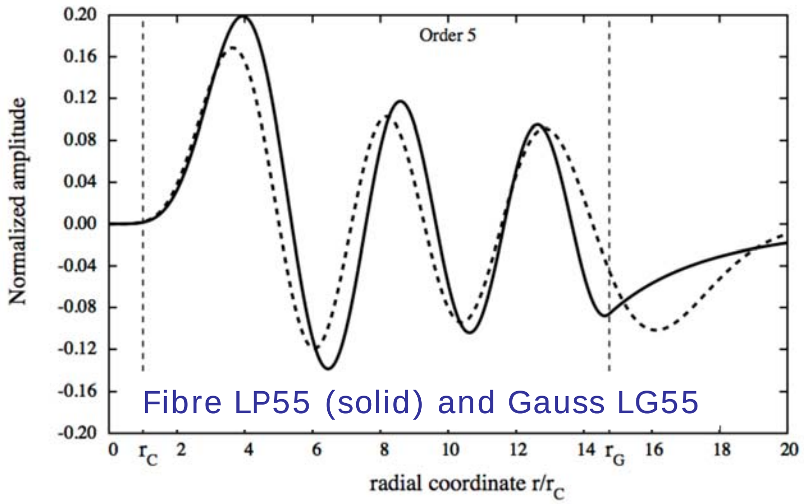
Creation method	ℓ mode	Mode purity $p=0$	Mode purity $p=1$	Conversion efficiency	Extinction ratio
Spiral phase plate	1	78.5% [14]			
	2	50% [14]			
Computer generated holograms	1	93% [17]	80% [16]	40%	
	3	77% [17]			
	6	62.8% [17]			
Diffractive optics (this work)	1	92.9%		40%	$(2.5\pm0.8)\times10^{-2}$
	2		99.3%	60%	$(3.3\pm0.8)\times10^{-2}$

[Kennedy et al, Phys. Rev. A 66 (2002)]



[Arlt et al (1998)]

Other methods exist, for example, modes in custom made fibres could be used to pump a mode cleaner cavity.



[Vinet (in preparation)]

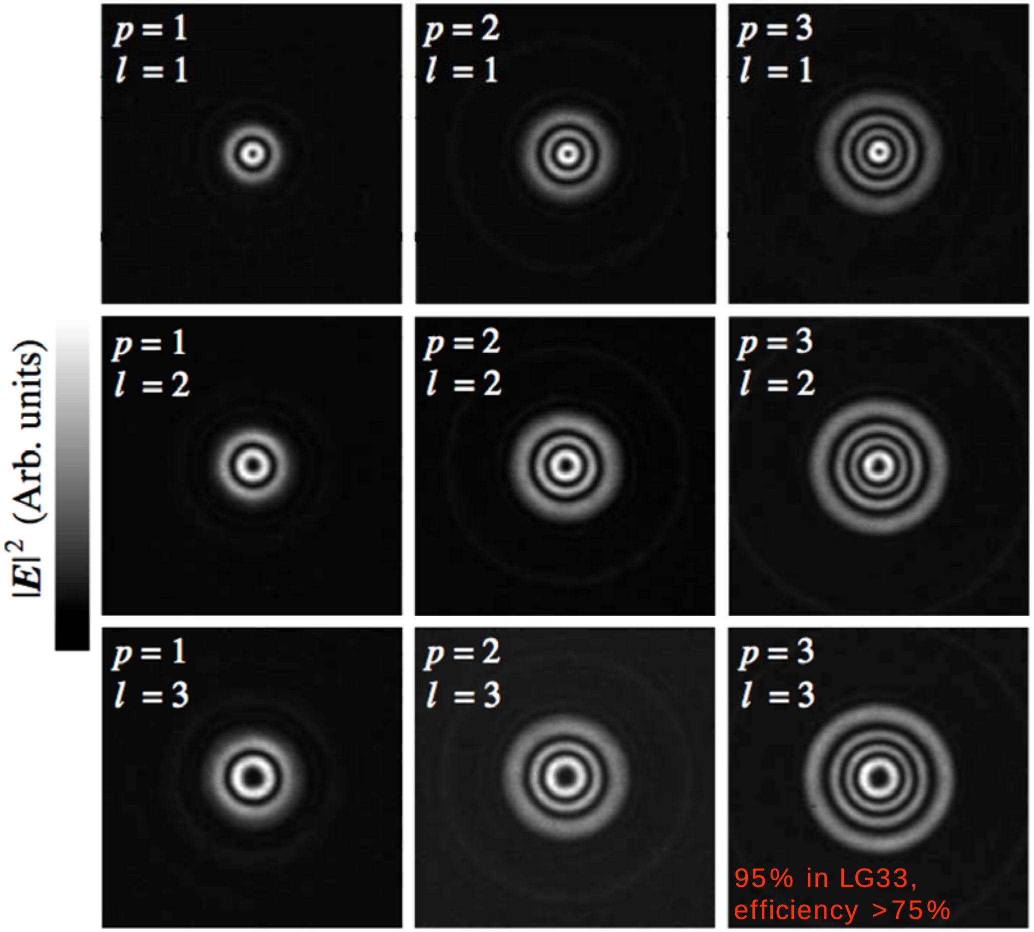
Generation of alternative beam shapes

Generation of alternative beam shapes is an active research topic (guides for atom traps, laser gain optimisation,…)

Example: LG modes created from a LG00 mode with a spatial light modulator →

To be done: test for noise!

- amplitude noise
- phase noise
- beam jitter



[Matsumo et al JOSA A 2008]

Readiness

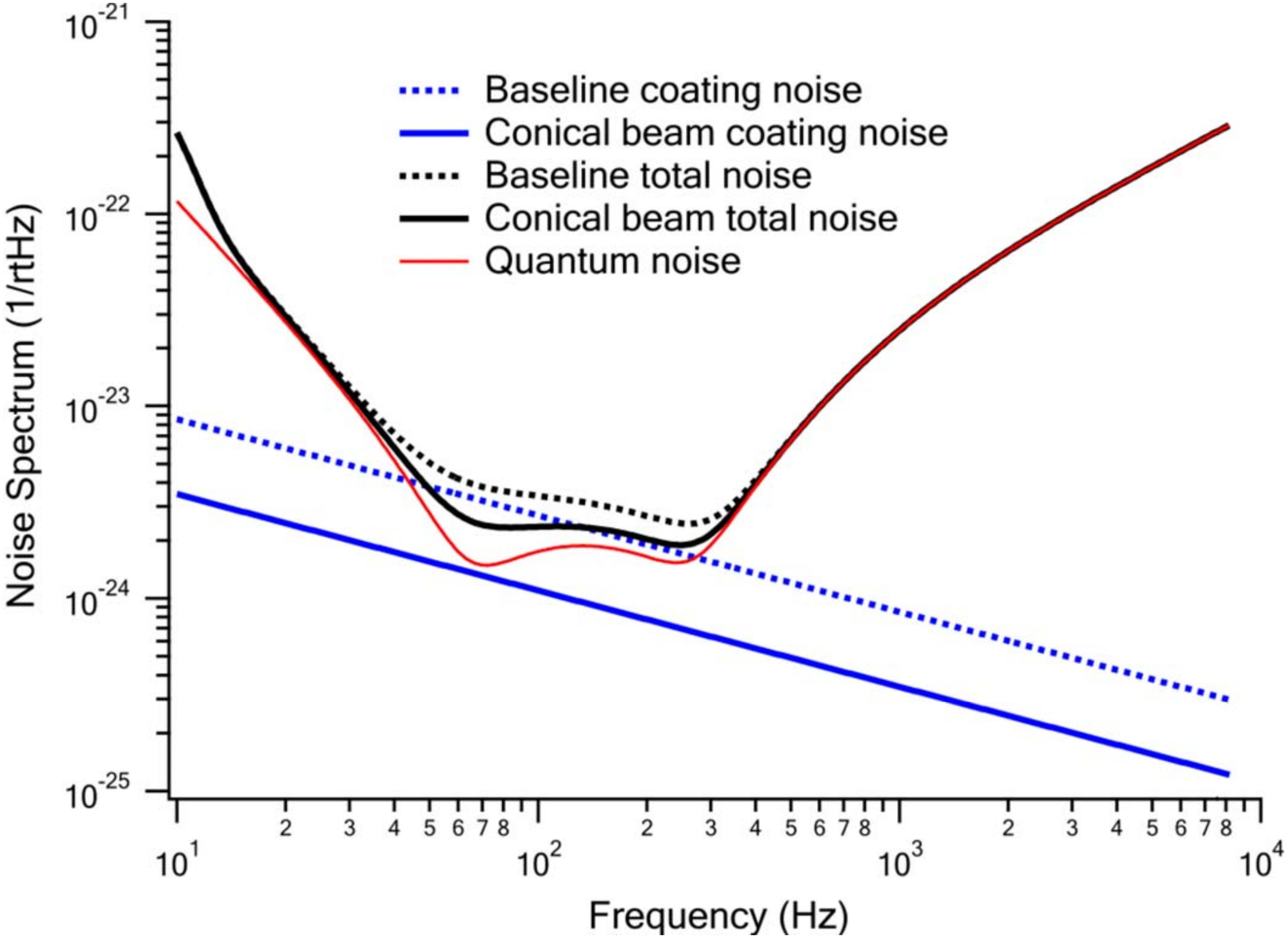
- Thermal effect
  - Thermal noise calculations — OK
  - Thermal lensing calculations — OK
- Generation of LG modes
  - Conversion methods — OK
  - Efficiency, mode purity — in progress
  - Noise performance of LG converter — to be done
- Interferometery with LG modes
  - Simulation of sensing and control — OK
  - Table-top, prototype verification — in progress
- Implementation into GW detectors
  - Core optics design — OK

Summary

- Alternative beam shapes are an interesting (and in comparison rather simple) method for reducing thermal effects (thermal noise, thermal lensing)
- Thermal noise can be reduced by factors >2 (linear spectral density)
- Generation of such beams seem to be feasible (information from other fields, to be verified)
- LG modes would be compatible with current optical designs, it is easy to make a design for upgrading advanced detectors

...end

Optimised beams in AdLigo



[Bondarescu et al PRD 2008]

Use thermal compensation system to the change RoC