Requirements for ET arm cavity mirrors

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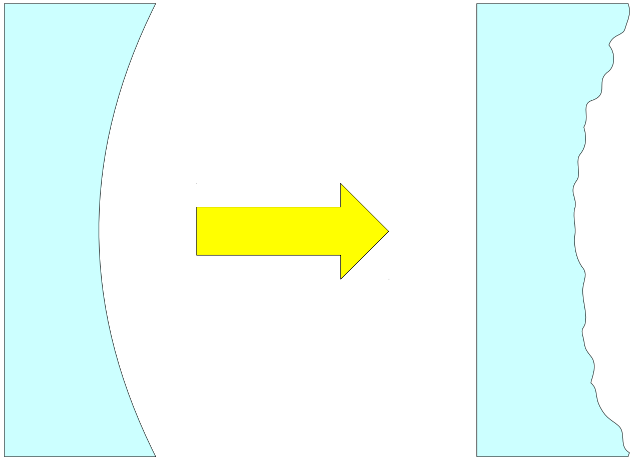
Outline

- Goals & motivations
- Simulation tool: SIESTA
- Mirror surface characterization & simulation
- ET arm cavity simulation

Goal

Mirror requirements: are they realistic?
Can we make them?



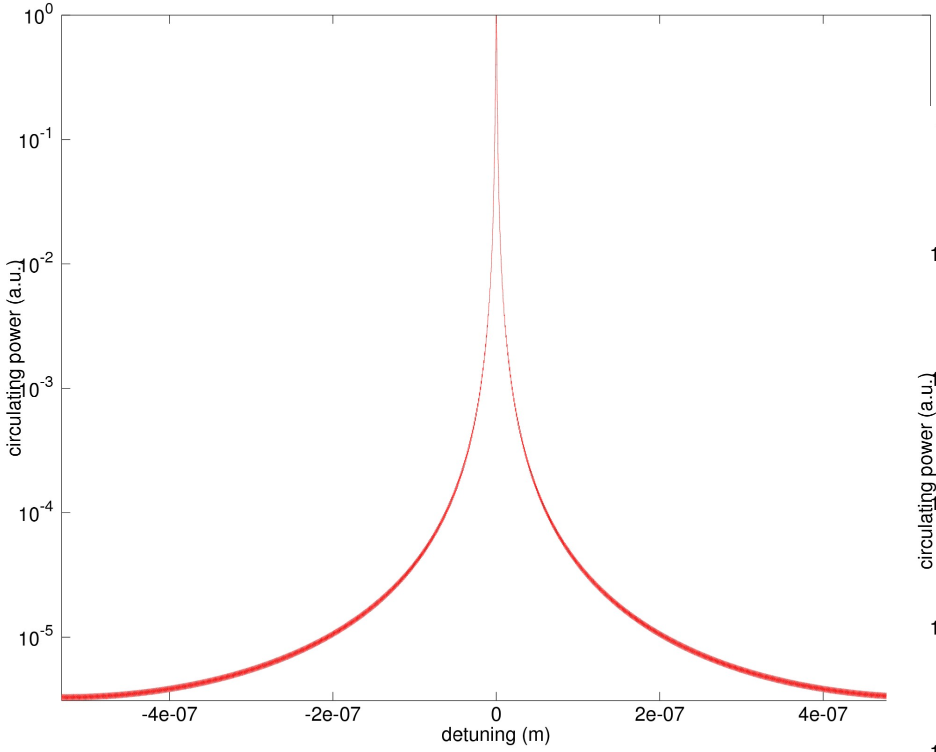
Real mirror defects:

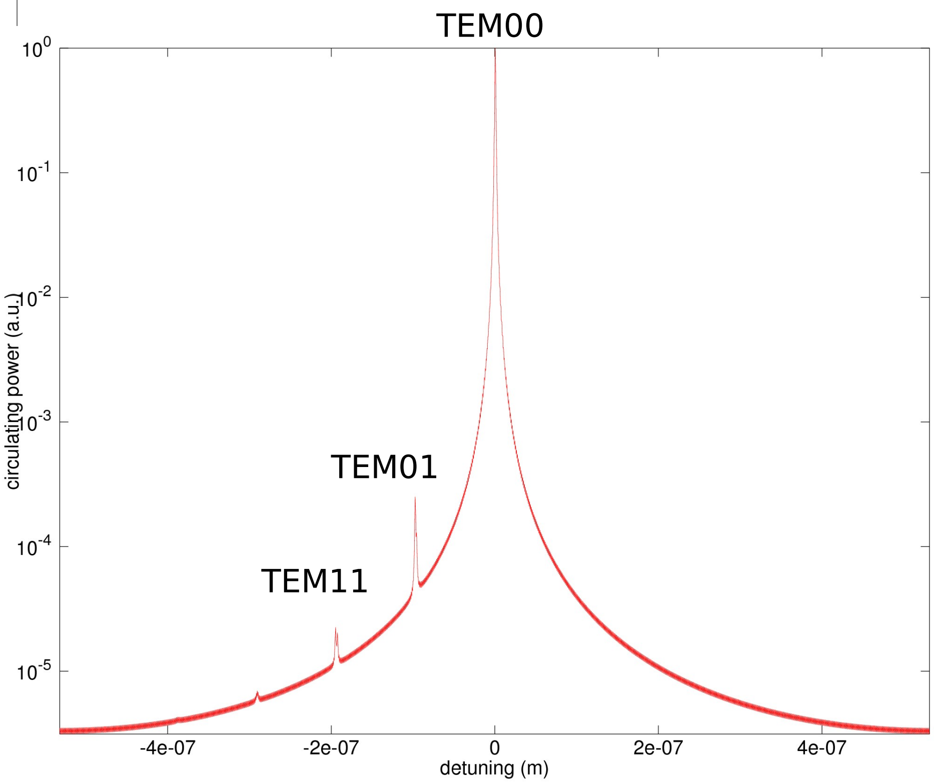
☹ aberrations (long-scale, low freq)
☹ flatness defects (short-scale, low to intermediate freq)
☹ roughness (microscopic scale, high freq)

Why should we care?

1) defects → losses

2) HOMs:





Outline

✔ Goals & motivations

- Simulation tool: SIESTA
  - what it is
  - why it has been chosen
  - what has been done

- Mirror surface characterization & simulation

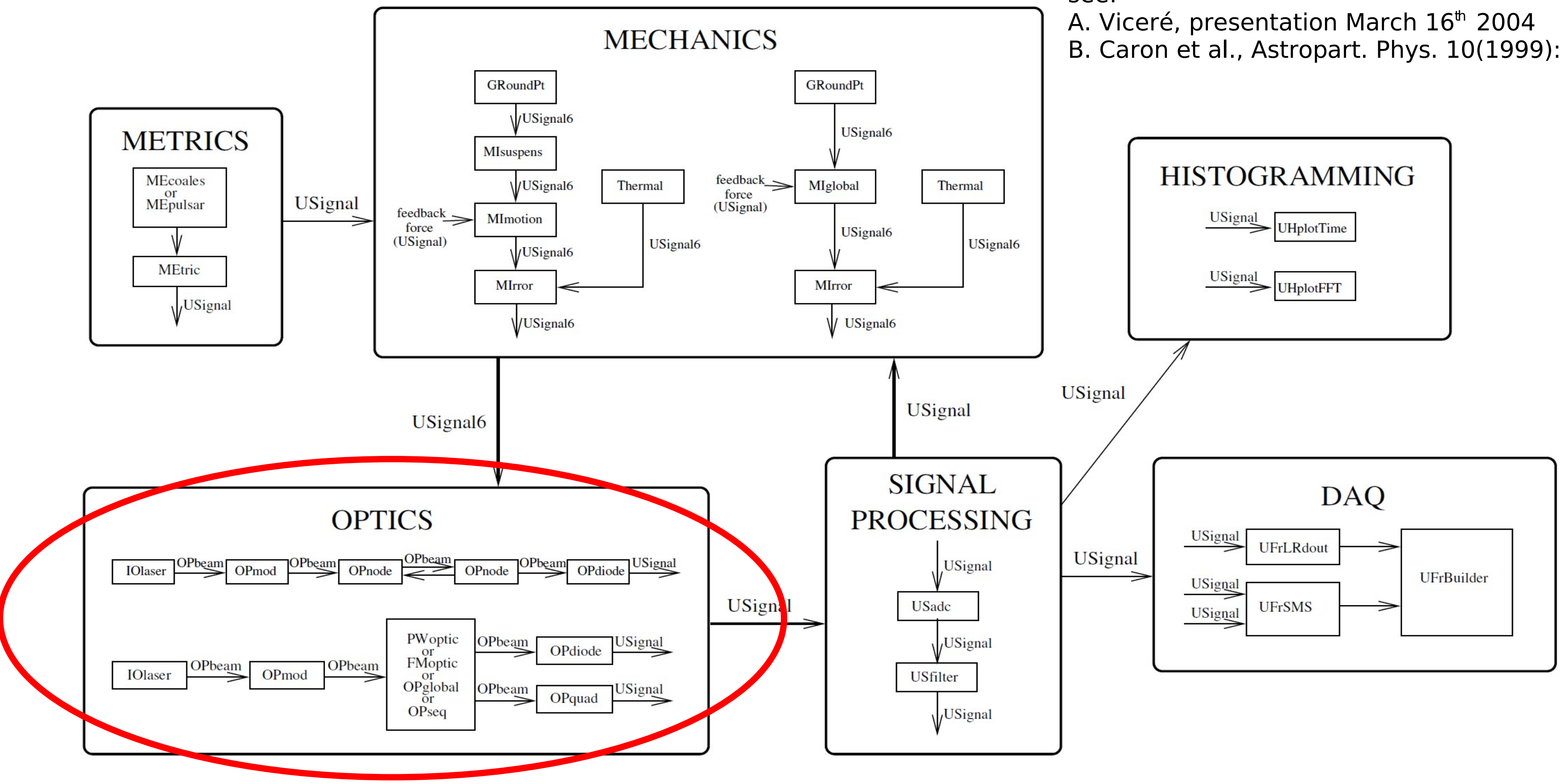
- ET arm cavity simulation

- What’s next

SIESTA

SIESTA is the simulation program for Virgo

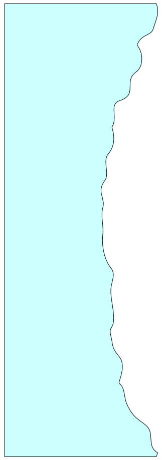
see:
A. Viceré, presentation March 16th 2004
B. Caron et al., Astropart. Phys. 10(1999):369



Features

- written in C
- modular architecture
- discrete time-based simulation, driven by one or more user-defined clocks
- reads data from a configuration file
- inputs/outputs data in the LIGO/Virgo format to perform analysis or mix real data and simulation (allows e.g. use of graphical tools)
- elementary programming structures (*if*, *for*) and arithmetics

Why SIESTA?



flatness defects → FFT-based simulations

- ready-to-use FFT engine
- easily expandable
- simulation of mirror surfaces
- cross-check with other programs: SIS (H. Yamamoto), DarkF (J.-Y. Vinet); OSCAR (J. Degaillaix) – stationary
- ITF dynamics
- in perspective, simulation of entire ITF + GW signals

What has been done

- FP cavity: scan for resonances
- FP cavity: lock and stationary solution
- generation of surface maps (more in following section)
- Laguerre-Gauss modes (HG modes already there)

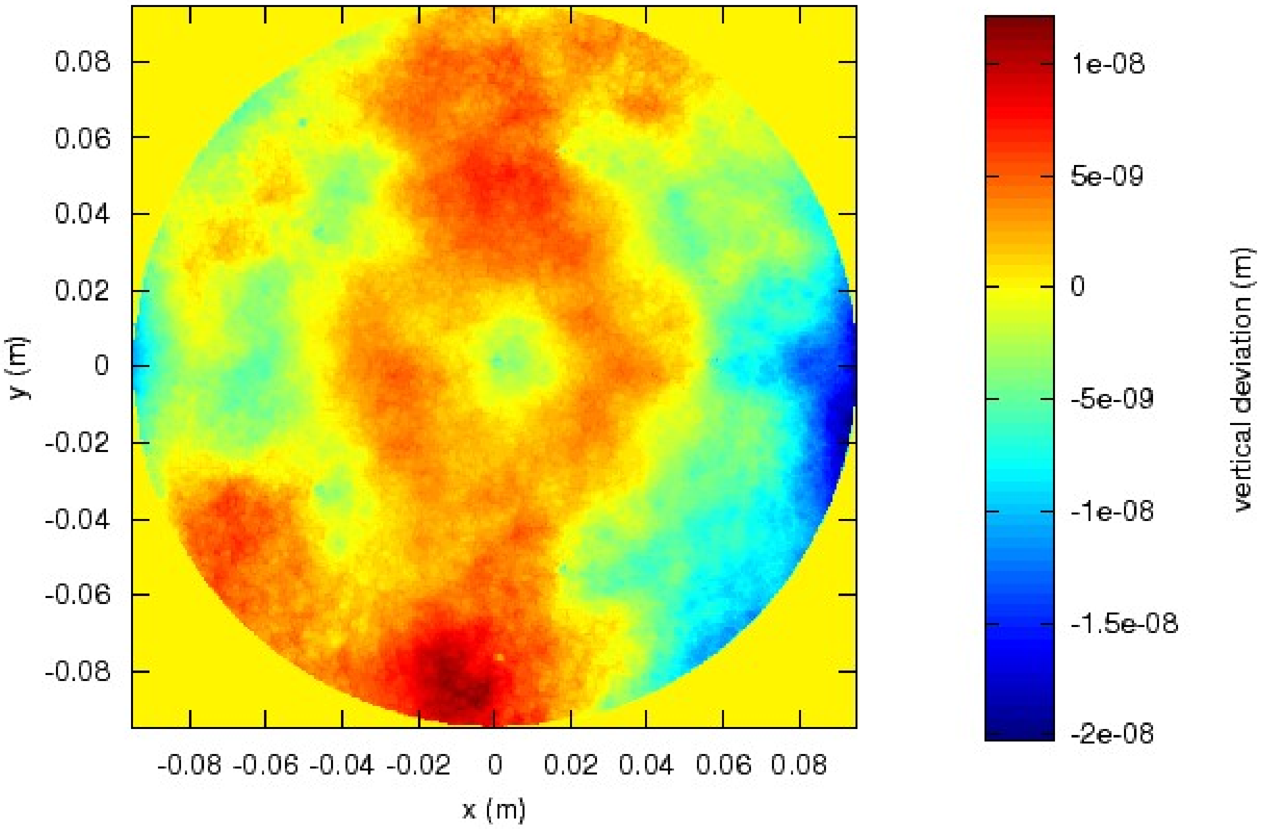
SIESTA FFT applied to FP cavity with the Virgo measured mirror maps:
results comparable to those obtained with SIS and OSCAR (see work by Q. Benoit, LMA)

Work in progress...

Outline

- ✔ Goals & motivations
- ✔ Simulation tool: SIESTA
- Mirror surface characterization & simulation
  - analysis of real surfaces
  - surface simulation
- ET arm cavity simulation

Real mirror surfaces



Surface (deviation from ideal shape) of Virgo NI mirror

rms flatness = 3.2 nm on Ø 150 mm

How to characterize it?

Power spectral density

E.L. Church, *Appl. Opt.* 27:1518 (1988)

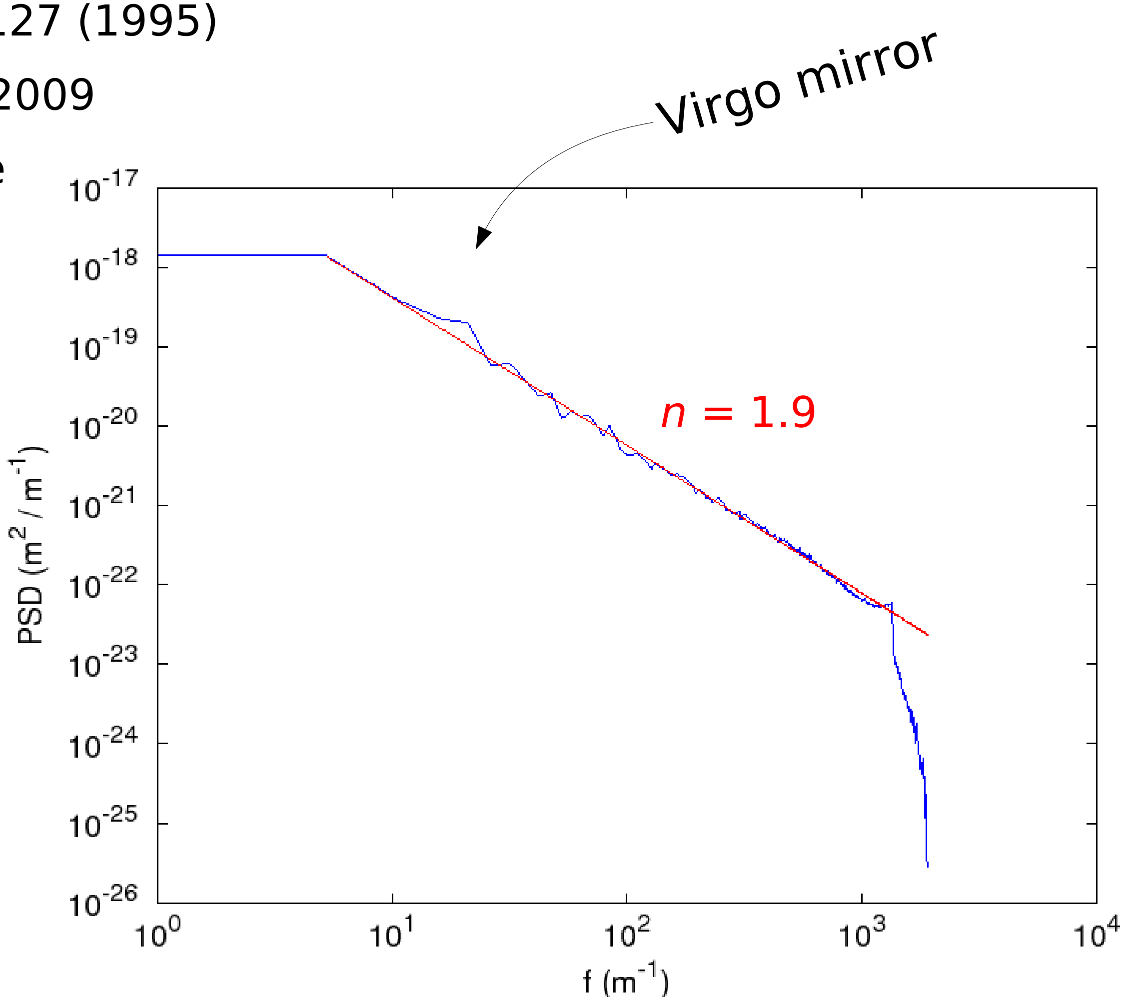
V. Loriette, VIR-NOT-PCI-1380-127 (1995)

F. Bondu, AdV meeting, 09/04/2009

F. Bondu, *MirrorShape* software

"Fractal polishing":

$$\mathrm{PSD}(f) \sim \frac{1}{f^n}$$



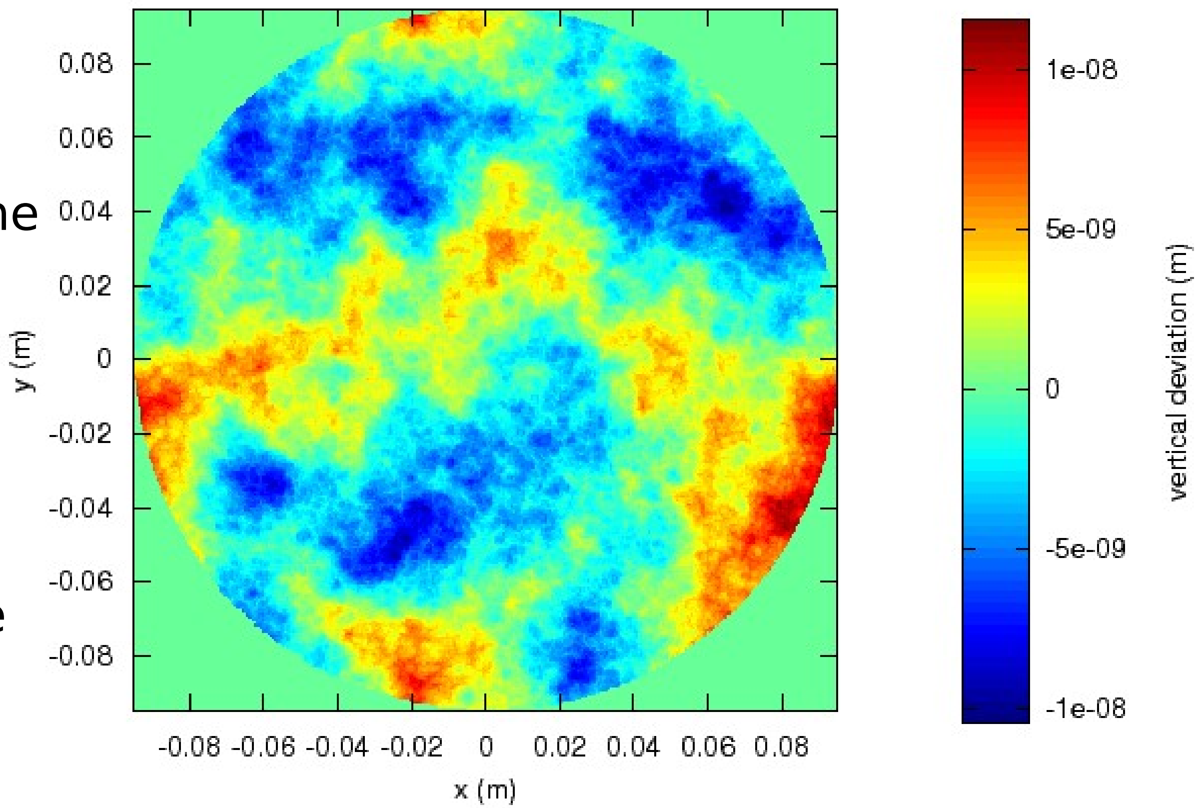
Simulation of mirror surfaces (1)

1) create a map in the frequency plane $\sim f^{-n}$ (where $f=\sqrt{f_x^2+f_y^2}$)
→ modulus of the FT of the surface

2) add a random phase

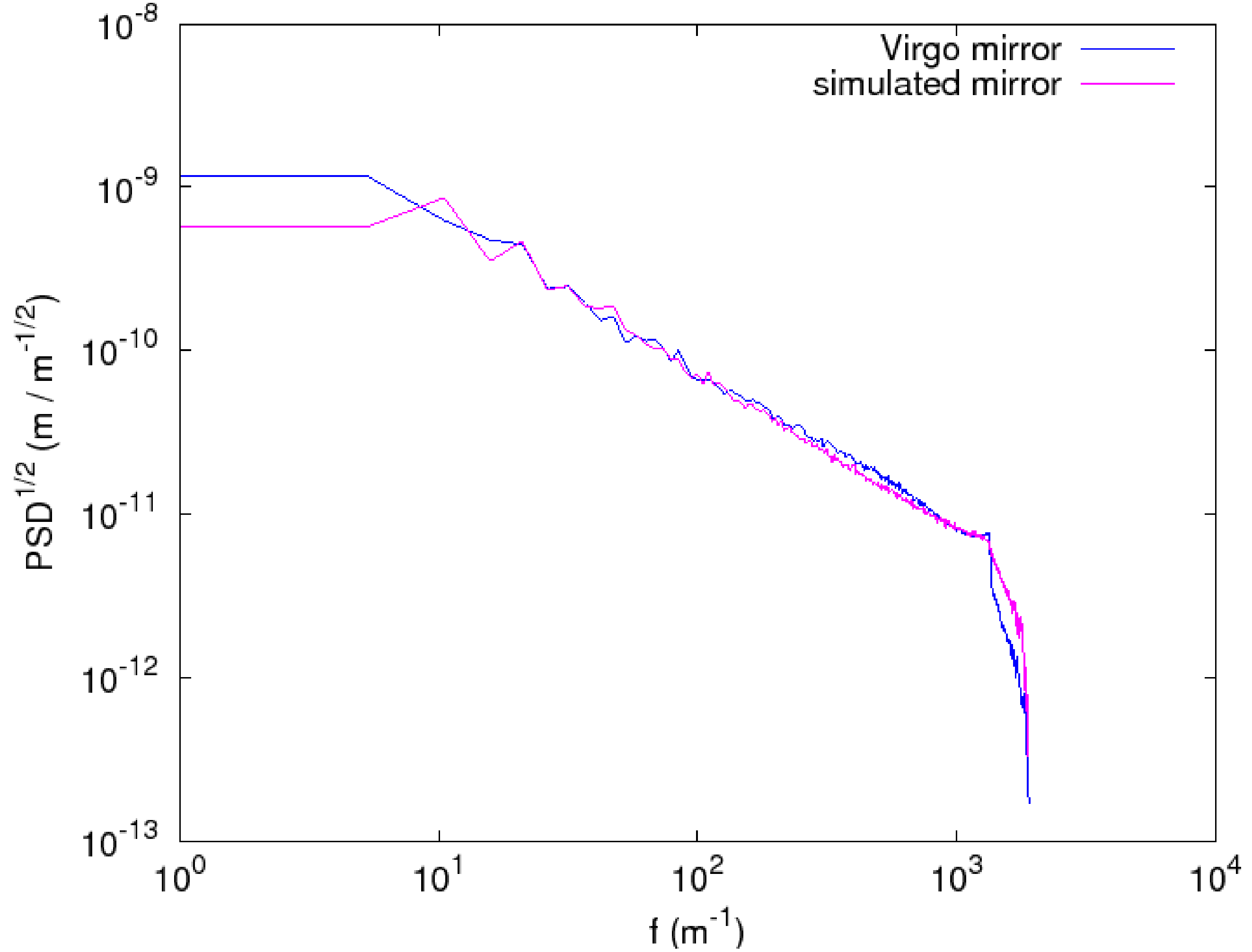
3) iFFT → random surface

4) scale surface to the required rms



rms flatness = 3.2 nm on Ø 150 mm
(as Virgo NI mirror)

Simulation of mirror surfaces (2)



A word of caution

This seems all right, but...

• simulations for ET are done with n = 1.9 as in Virgo:
we do not know what n will be for ET mirrors! (or even AdV or AdLIGO)

• we assumed surface defects to be homogeneous and isotropic,
which is likely to be wrong (how much?)

Outline

✔ Goals & motivations

✔ Simulation tool: SIESTA

✔ Mirror surface characterization & simulation

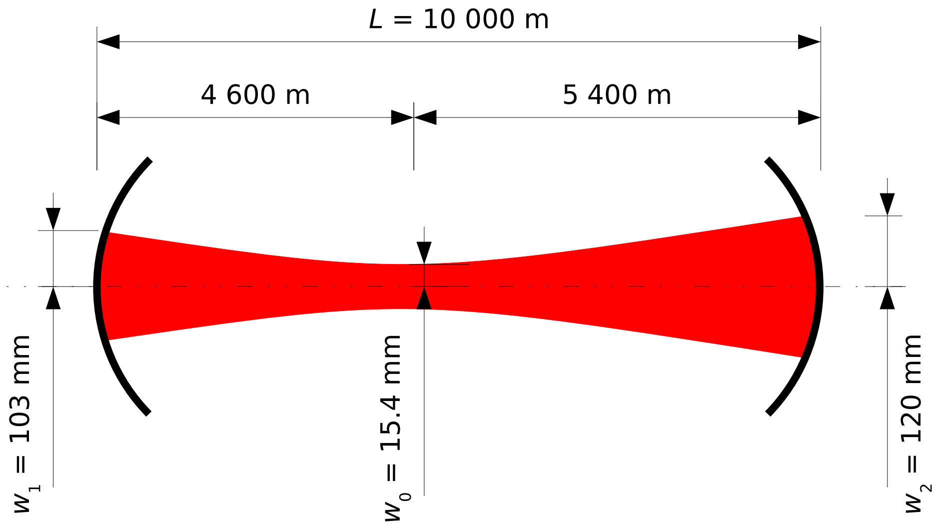
- ET arm cavity simulation
  - configurations & methods
  - results

Configurations (1)

see e.g Hild et al., “A Xylophone Configuration...”

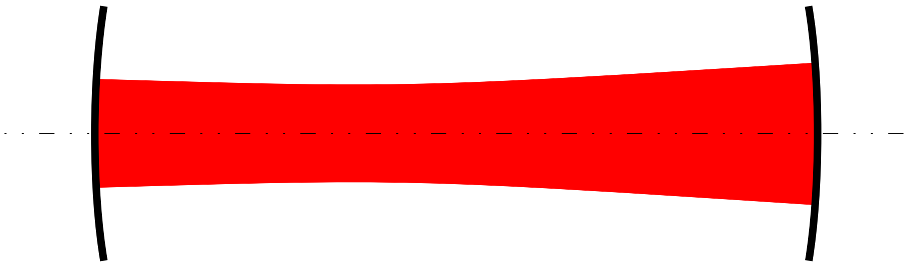
- Cavity length *L* = 10 km
- Test masses diameter: 620 mm
- Finesse = 893.8 (as AdV)
- Two wavelengths: 1064 and 1550 nm
- Two modes: TEM00 and LG33
- Spotsize on ETM: 120 mm TEM00, 72.5 mm LG33 } 1.6 ppm clipping losses
- Same ratios *L/R* as in AdV → same stability and degeneracy
- Four rms flatness: 0 nm (perfect mirrors)
  0.5 nm
  1.0 nm
  2.0 nm
  (defined on whole mirror surface)

Configurations (2)



TEM00
1064 nm
"curved" mirrors

*R*1 = 4706 m
*R*2 = 5490 m



twin configuration
same spot sizes
"flat" mirrors

*R*1 = 384760 m
*R*2 = 329270 m

What has been computed

For every configuration, with cavity locked at resonance

1) circulating power

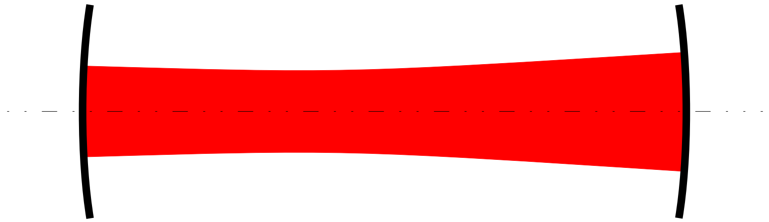
2) round-trip losses:

$$\text{r.t. losses} = \frac{P_{\text{inj}} - P_{\text{trans}} - P_{\text{refl}}}{P_{\text{circ}}}$$

For every rms flatness:

10 simulations (10 pairs of generated surfaces)

Results for “flat” mirrors



- Radii of curvature extremely large (~ 10^5 m)
  → difficult/impossible

- Results almost identical to equivalent configuration with “curved” mirrors → no influence of ROC on P_{circ} and r.-t. losses

- Put it aside

Results for “curved” mirrors

rms flatness	1064 nm				1550 nm	
	TEM00		LG33		TEM00	
	Pcirc (W/W)	*r.t. losses (ppm)*	*Pcirc (W/W)*	*r.t. losses (ppm)*	*Pcirc (W/W)*	*r.t. losses (ppm)*
0 nm	568	2	568	3	568	3
0.5 nm						
1.0 nm						
2.0 nm						

(from theory: P_{circ} = 568.2 W/W)

Results for “curved” mirrors

rms flatness	1064 nm					
	TEM00					
	Pcirc (W/W)	*r.t. losses (ppm)*				
0 nm	568	2				
0.5 nm	561 ± 2	45 ± 10				
1.0 nm	542 ± 6	171 ± 38				
2.0 nm	501 ± 28	426 ± 243				

1.0 nm rms over Ø 620 mm ≈ 0.5 nm rms over Ø 150 mm
(AdV and AdLigo specification)

Results for “curved” mirrors

rms flatness	1064 nm				1550 nm	
	TEM00				TEM00	
	Pcirc (W/W)	*r.t. losses (ppm)*			*Pcirc (W/W)*	*r.t. losses (ppm)*
0 nm	568	2			568	3
0.5 nm	561 ± 2	45 ± 10			565 ± 1	23 ± 4
1.0 nm	542 ± 6	171 ± 38			555 ± 3	83 ± 16
2.0 nm	501 ± 28	426 ± 243			523 ± 15	297 ± 100

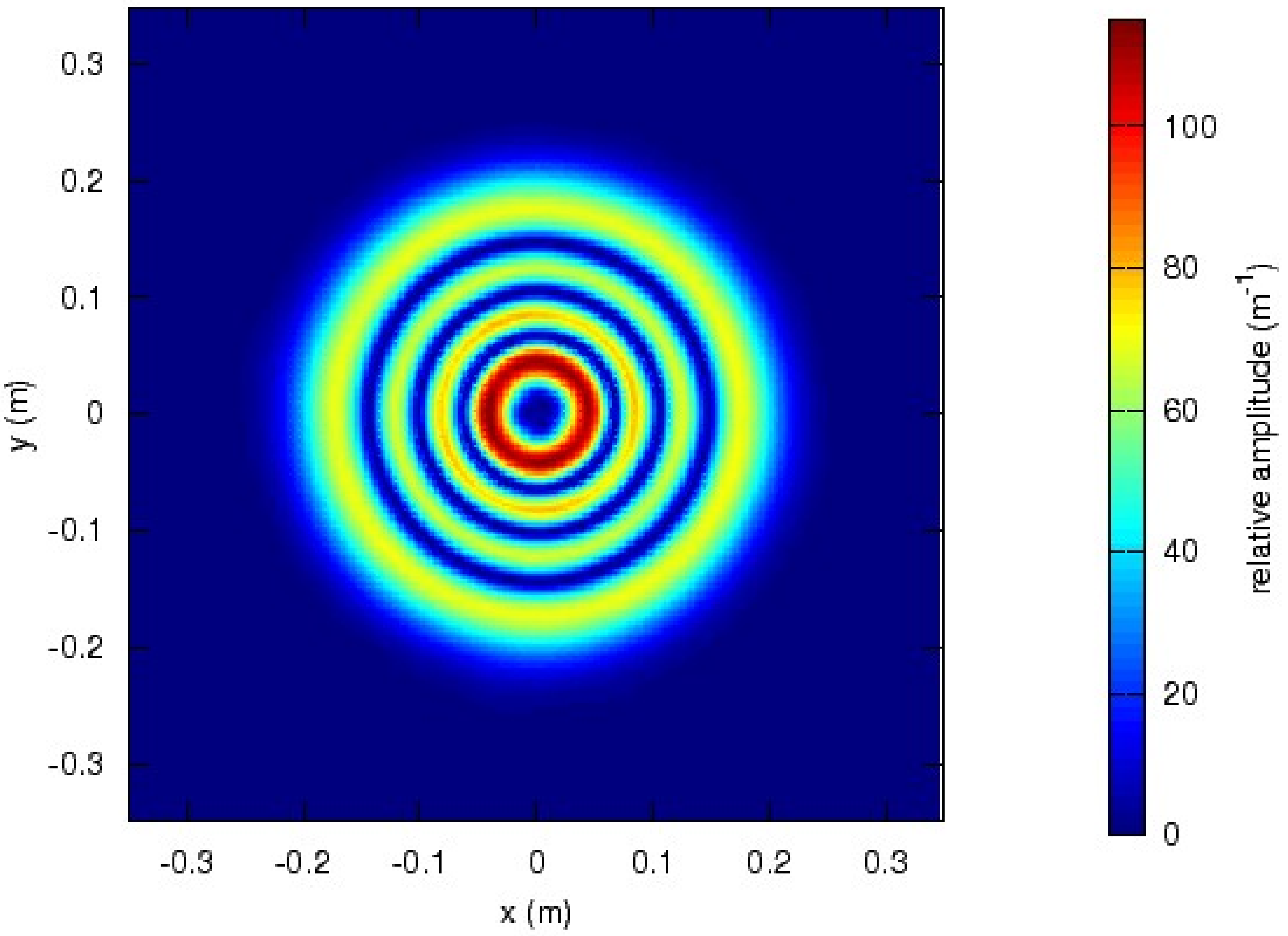
1.0 nm rms over Ø 620 mm ≈ 0.5 nm rms over Ø 150 mm
(AdV and AdLigo specification)

Results for "curved" mirrors

rms flatness	1064 nm				1550 nm	
	TEM00		LG33		TEM00	
	Pcirc (W/W)	*r.t. losses (ppm)*	*Pcirc (W/W)*	*r.t. losses (ppm)*	*Pcirc (W/W)*	*r.t. losses (ppm)*
0 nm	568	2	568	3	568	3
0.5 nm	561 ± 2	45 ± 10	558 ± 1	63 ± 9	565 ± 1	23 ± 4
1.0 nm	542 ± 6	171 ± 38	531 ± 5	244 ± 36	555 ± 3	83 ± 16
2.0 nm	501 ± 28	426 ± 243	441 ± 17 (*)	937 ± 161	523 ± 15	297 ± 100

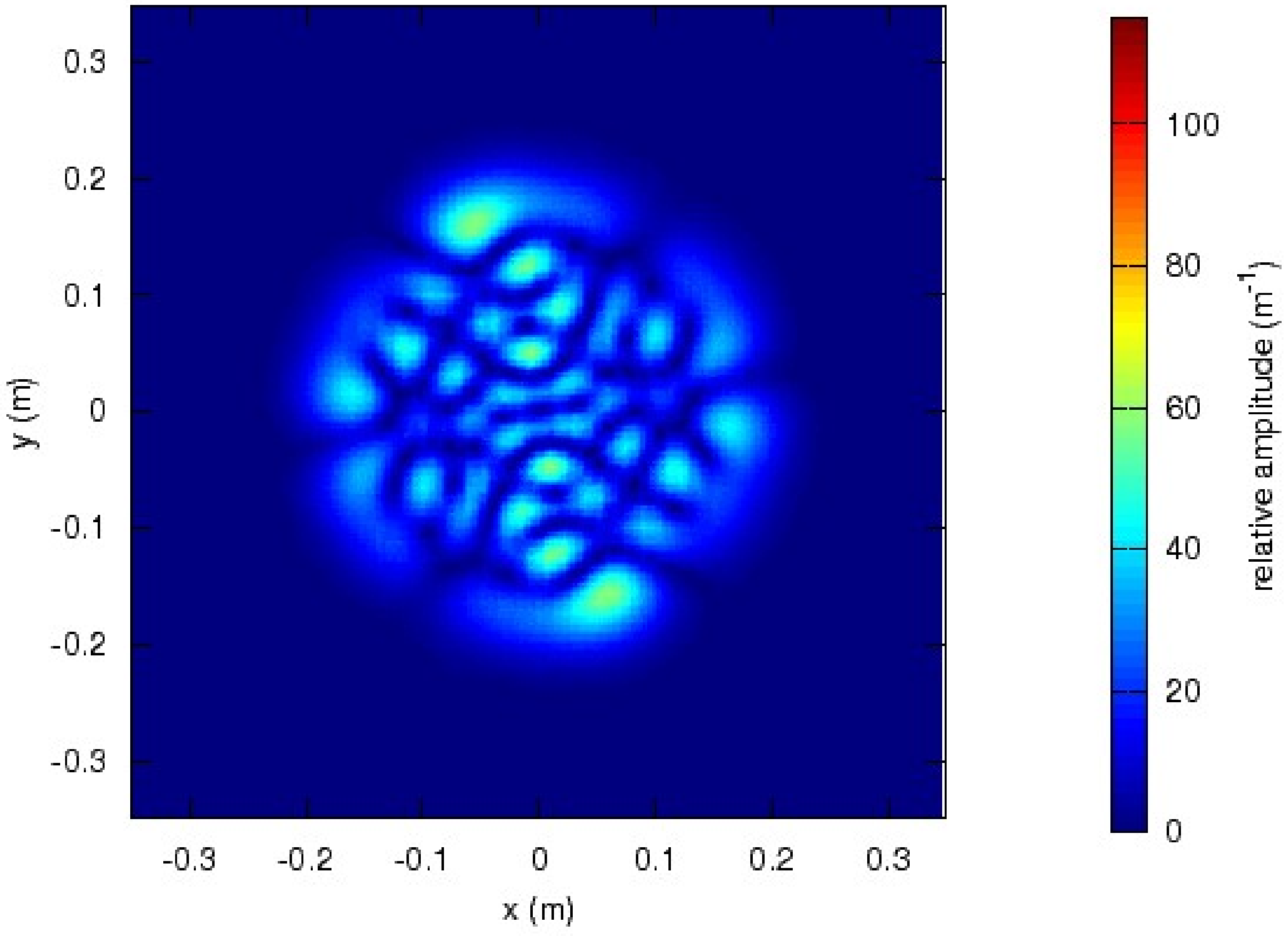
1.0 nm rms over Ø 620 mm ≈ 0.5 nm rms over Ø 150 mm
(AdV and AdLigo specification)

Be careful with LG33 (1)



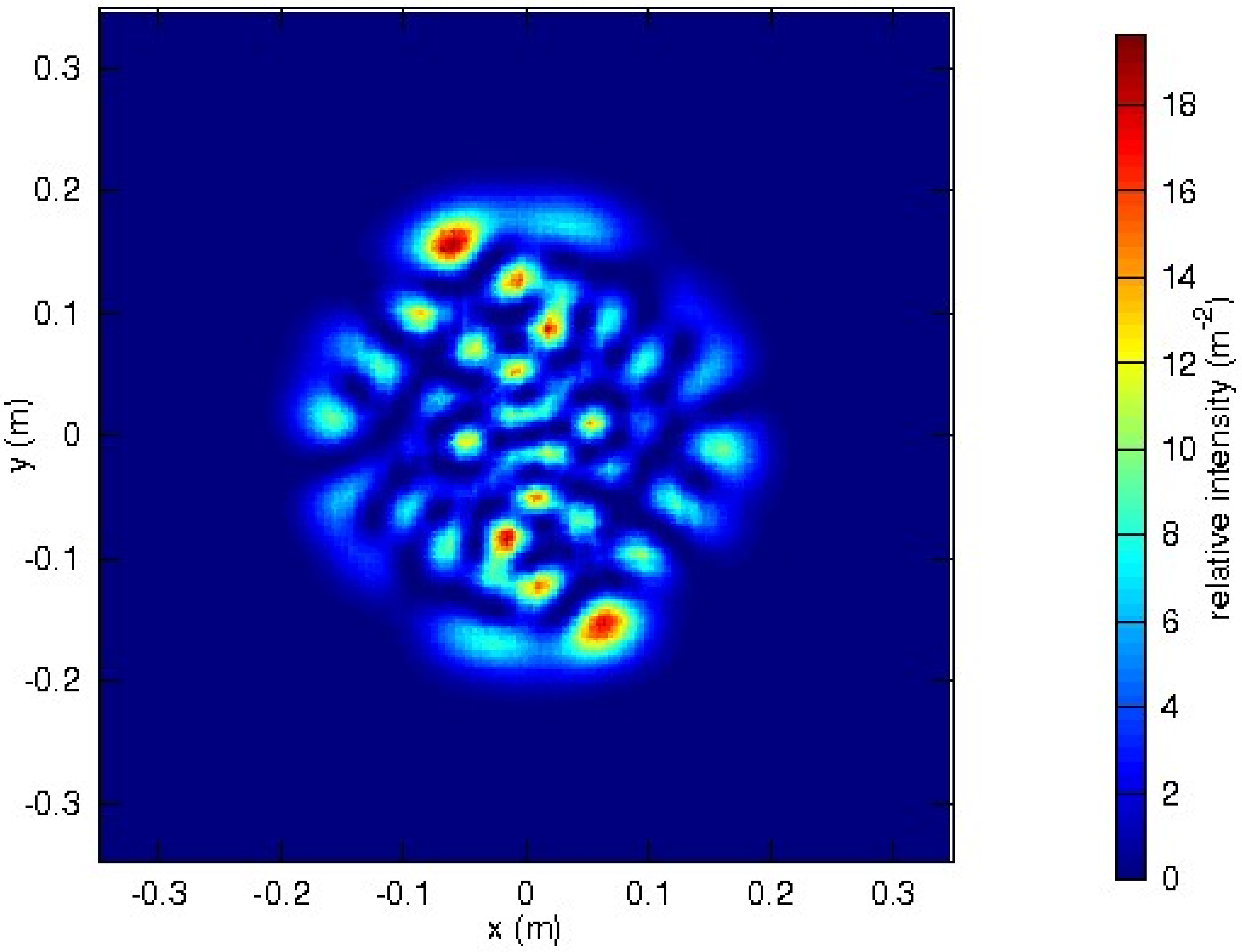
second worst simulation @ 2.0 nm rms

Be careful with LG33 (2)



... some problems

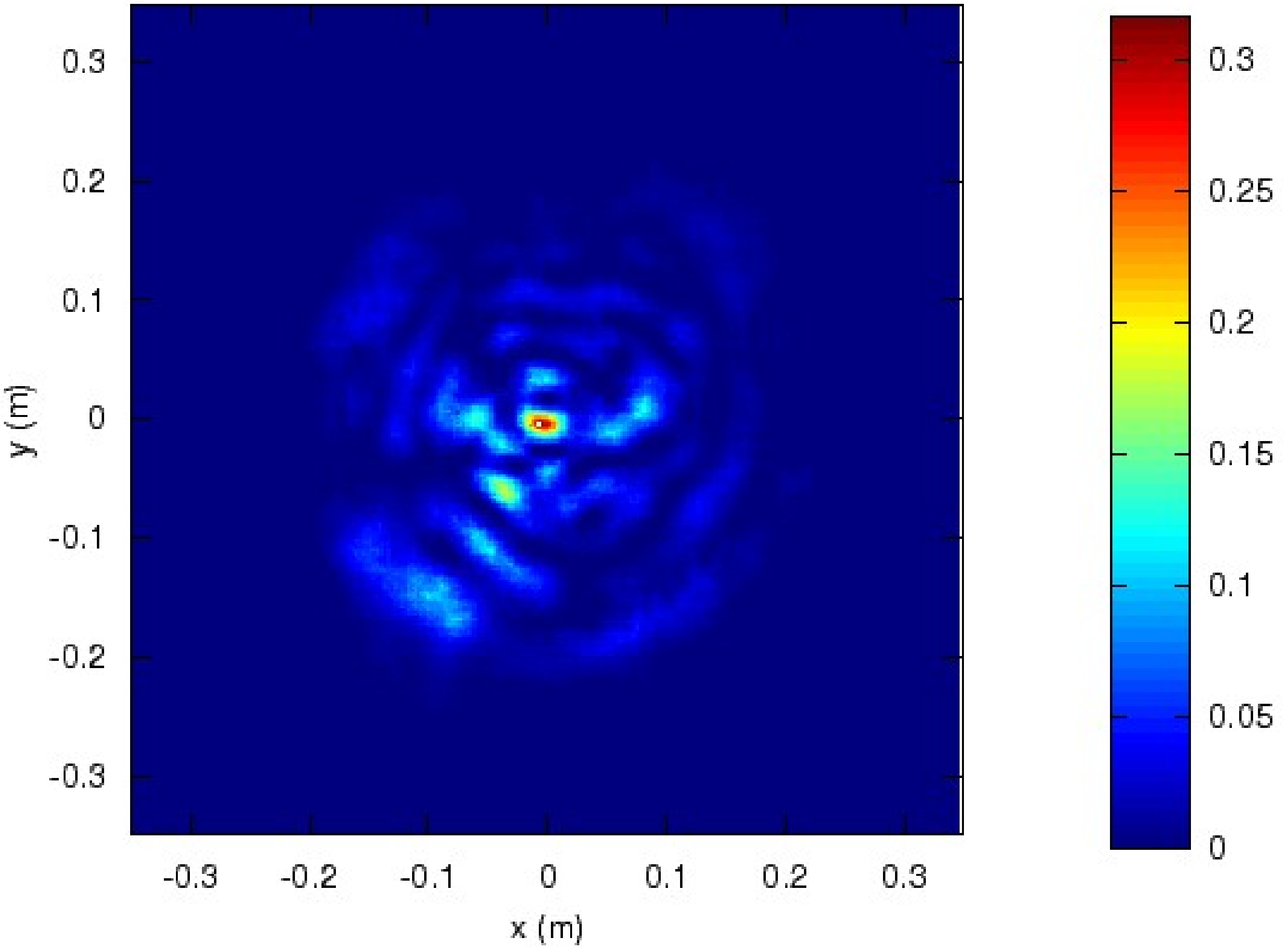
This one is to scare you



what would be seen on the dark fringe

(contrast = 0.689)

This one is to reassure you



dark fringe
two different cavities
with 1.0 nm rms
("Ad-detectors-like")

(contrast = 0.998)

Conclusions

☺ ROCs do not influence performances

☺ losses are reasonable for flatness up to 1 nm rms (approx. equivalent to requirements for AdV and AdLIGO)

☺ TEM00: λ = 1550 nm gives slightly better performances

😐 LG33: ok on average but more sensitive to defects

To do next

➔ take into account corrective coating (see F. Bondu's work)

➔ expand SIESTA FFT code to recycling cavities and entire ITF

That is all...

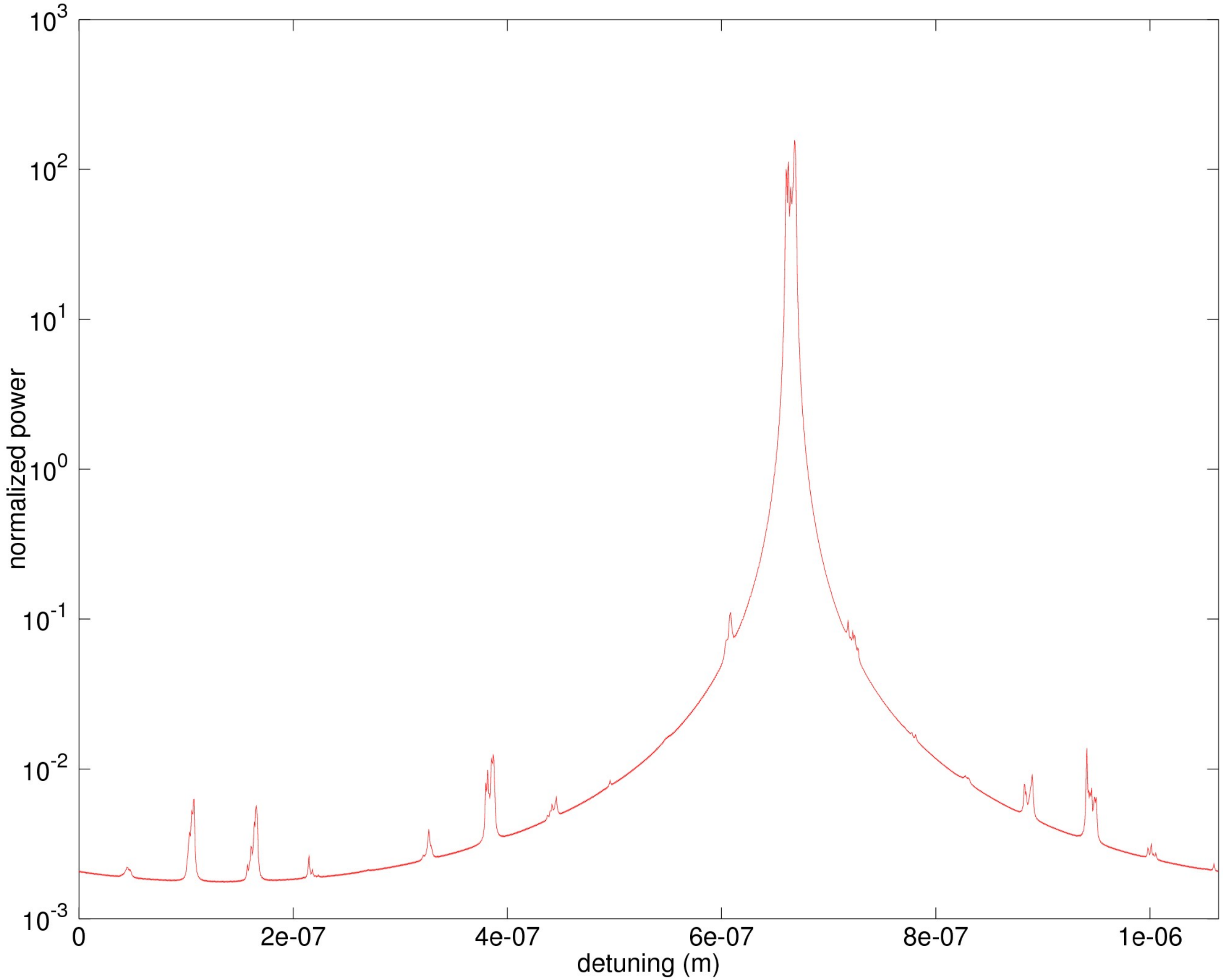
... thank you for your attention!

Spares

Simulation parameters

		curved mirrors			flat mirrors		
		1064 nm		1550 nm	1064 nm		1550 nm
		TEM00	LG33	TEM00	TEM00	LG33	TEM00
w0	(mm)	15.4	27.2	22.6	119	61.2	118
w1	(mm)	103	63.4	103	120	63.4	119
w2	(mm)	120	72.5	120	120	72.5	120
l1	(m)	4600	4600	4600	4600	2980	4600
l2	(m)	5400	5400	5400	5400	7020	5400
R1	(m)	4706	5640	4883	384760	440780	176870
R2	(m)	5490	6286	5599	329270	244660	152160
$g1 = 1 - L/R1$		-1.1251	-0.77308	-1.07	0.97401	0.77313	0.94346
$g2 = 1 - L/R2$		-0.82148	-0.59088	-0.786	0.96963	0.59127	0.93428
g1*g2		0.924	0.457	0.840	0.944	0.457	0.881

Fancy LG33



normalized power
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
2e-07
4e-07
6e-07
8e-07
1e-06
detuning (m)

How FFT works (1)

Propagation in Fourier space:

diffraction kernel $K(x,y) = \frac{1}{i\lambda z} \exp\left(ik \frac{x^2+y^2}{2z} \right)$

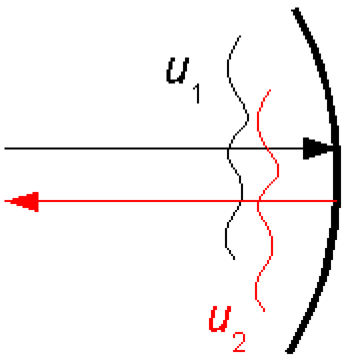
propagator $\hat{K}(f_x, f_y) = \exp\left(-i\pi\lambda z(f_x^2 + f_y^2)\right)$

Propagation equation:

$$\hat{U}_1(f_x, f_y) = \hat{K}(f_x, f_y) \cdot \hat{U}_0(f_x, f_y)$$

How FFT works (2)

Propagation in an optical system:



Mirror:

$$u_2(x,y) = \exp\left(ik\frac{x^2+y^2}{R_c}\right) \cdot u_1(x,y)$$

(in direct space!)

$$\Rightarrow \quad M(x,y) = \exp\left(ik\frac{x^2+y^2}{R_c}\right)$$

General scheme

$$u_0(x,y) \qquad\qquad u_1(x,y) \longrightarrow \times M(x,y) \longrightarrow u_2(x,y)$$

$$\downarrow \qquad\qquad \uparrow \qquad\qquad \downarrow$$

$$\hat{U}_0(f_x,f_y) \longrightarrow \times \hat{K}(f_x,f_y) \longrightarrow \hat{U}_1(f_x,f_y) \qquad\qquad \ldots$$