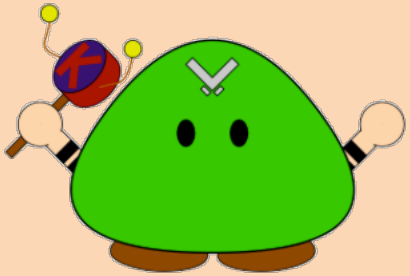
Thermal noise reduction with higher-order Laguerre-Gauss modes

A. Gatto, M. Tacca, C. Buy, F. Kéfélian and M. Barsuglia



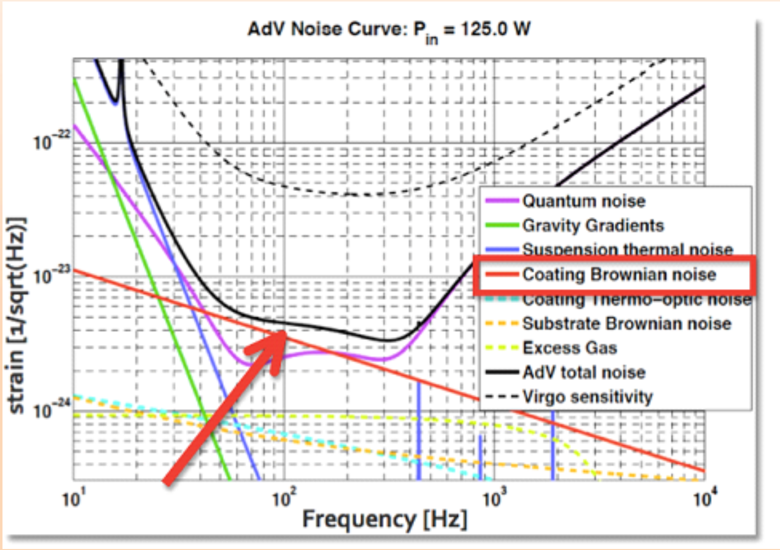
Laboratoire AstroParticule et Cosmologie - Paris

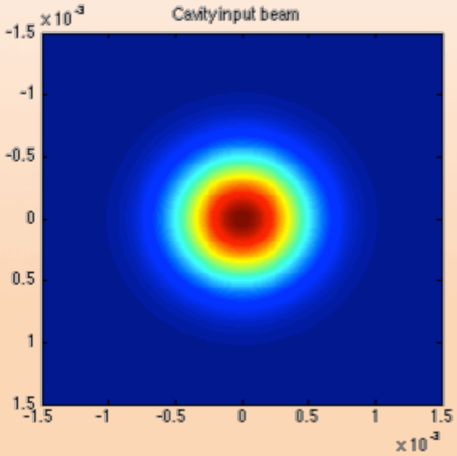
GWADW 2014

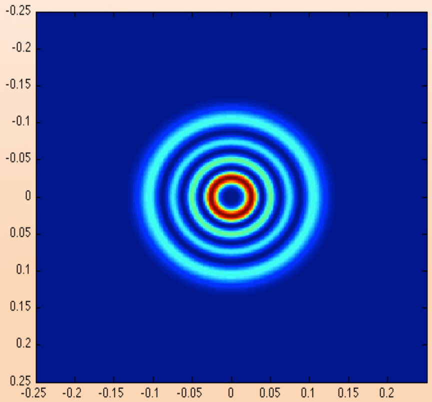
Outline

- ✧ Introduction
- ✧ State of the art
- ✧ Non-Gaussian interferometer at the APC
- ✧ Reduction of the degeneracy
- ✧ Conclusions

Introduction







- Sensitivity of 2nd generation gravitational wave detectors will be limited by coating thermal noise around 100 Hz
- For same diffraction losses, Laguerre-Gauss (LG_{pl}) modes reduce thermal noise thanks to their larger coverage of the surface
- LG modes resonate in spherical Fabry-Perot cavities
- **LG_{33} mode reduces thermal noise by ≈1.8 in AdVirgo geometry**

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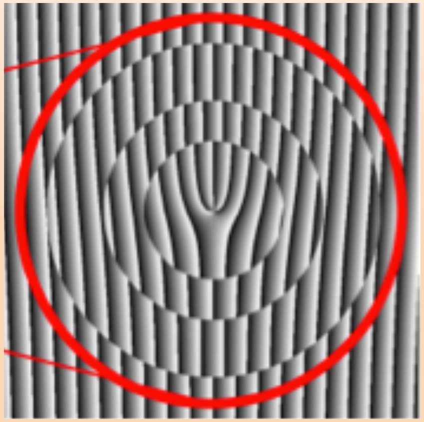
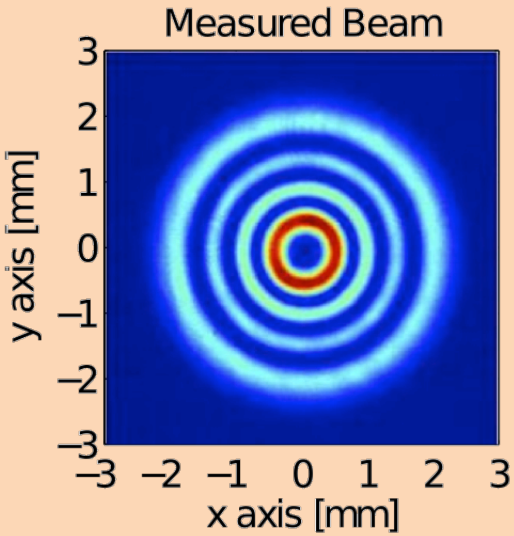
- Non-Gaussian interferometer at the APC
- Reduction of the degeneracy
- Conclusions

Beginning: LG generation

- A generic LG beam can be generated by spatial light modulators or diffractive phase plate and a mode cleaner cavity
- High modal purity achieved (~99%) [1,2]
- High power generation has been obtained using a phase plate [3]
  - 83 W on LG_{33} mode
  - Conversion efficiency 59%
  - Modal purity > 97% also at high power



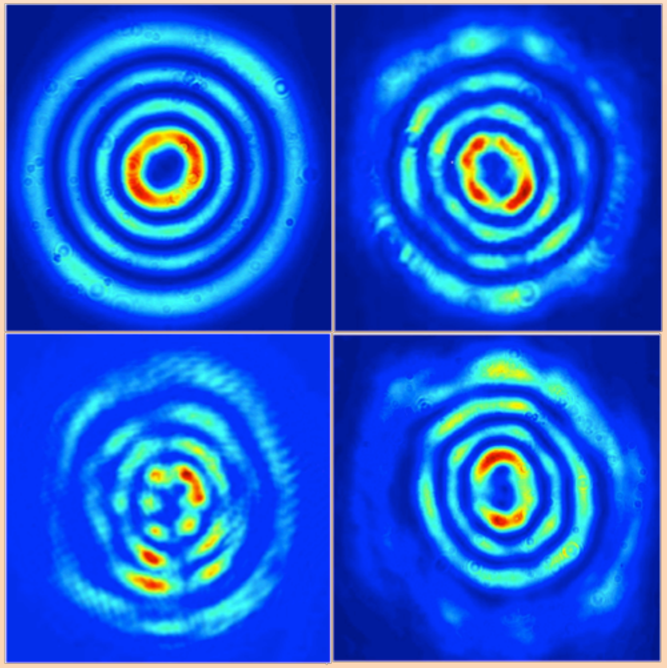


[1] M. Granata et al., PRL 105, 231102 (2010)
[2] P. Fulda et al., Physical Review D 82, 012002 (2010)
[3] L. Carbone et al., PRL 110, 251101 (2013)

Glasgow 10-m cavity

- ✧ First attempt to realize a suspended cavity resonating on LG_{33} mode
- ✧ Locking on the LG_{33} mode not achieved
- ✧ Complexity of the LG system
  - ➢ Clipping
  - ➢ Mode matching
  - ➢ Resonance splitting due to astigmatism

MC EOM

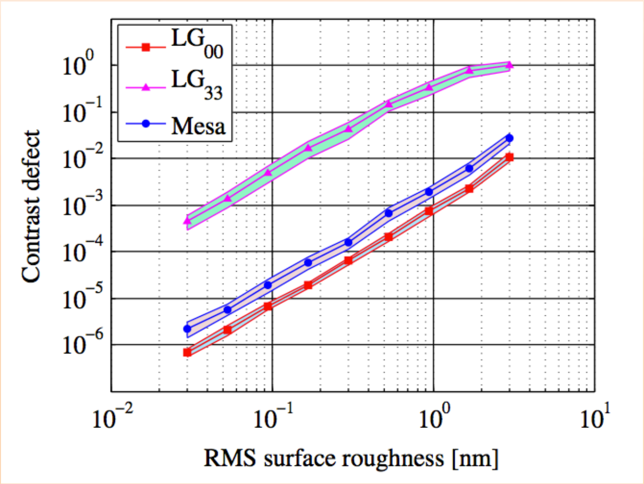


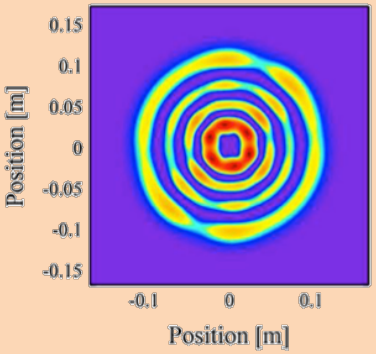
ETM (misaligned ITM) ITM

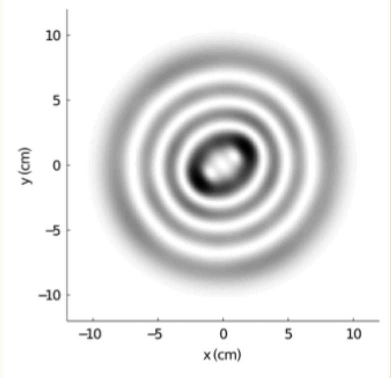
[4] B. Sorazu et al., Class. Quantum Grav. 30 (2013) 035004

Main problem: LG degeneracy

- A n-order LG mode is n-times degenerated
- Expected contrast defect 3 order of magnitude worse than Gaussian beam: target value (10^{-4}) reached for RMS < 0.01 nm [5]
- Greater coupling on other n-order modes due to lower order defects [6-7]

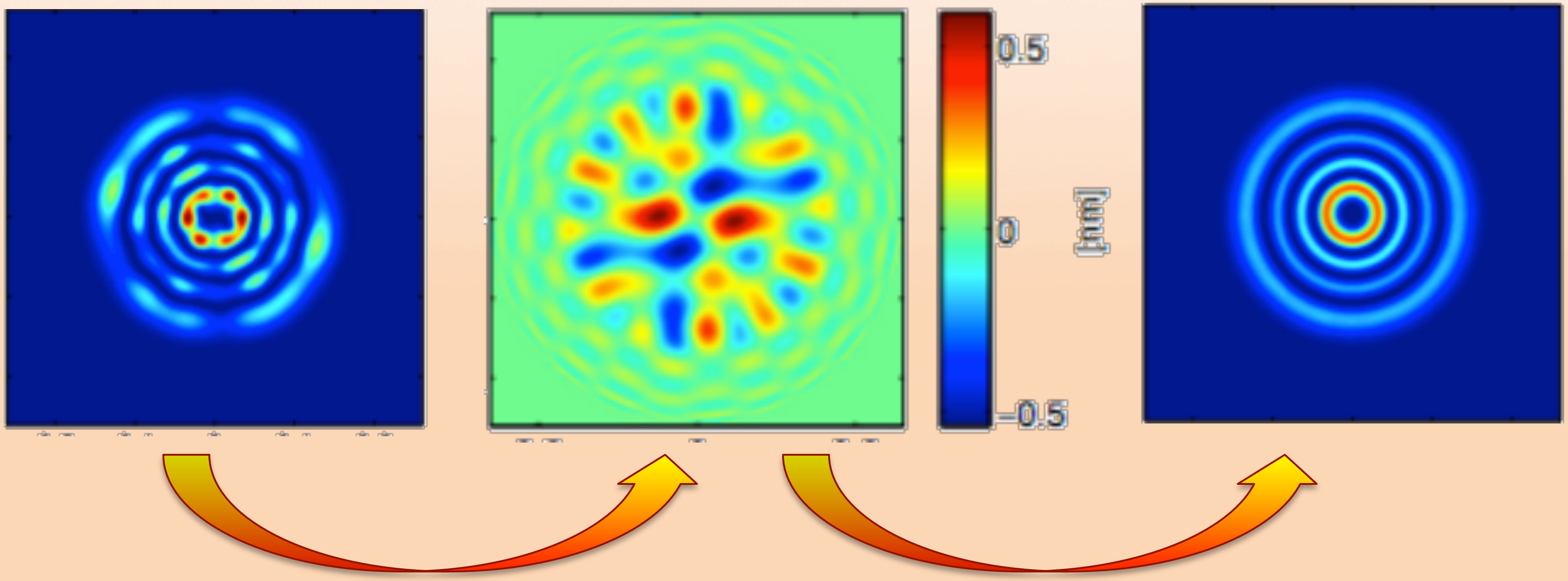






[5] T. Hong et al., Physical Review D 84, 102001 (2011)
[6] M. Galimberti et al, GWADW 2010
[7] C. Bond et al., Physical Review D 84, 102002 (2011)

Thermal compensation



- ✧ CHRAC: possible in-situ thermal correction of mirror defects to recover a high beam quality (> 99.9%) [8]
- ✧ Adaptive algorithm for estimating the map directly from the reflected intensity pattern [9]

[8] R. A. Day et al., Physical Review D 87, 082003 (2013)
[9] G. Vajente, R. A. Day, Physical Review D 87, 122005 (2013)

Questions

- ✧ Is a LG fabry-Perot Michelson interferometer feasible?
- ✧ Is the degeneracy an unsolvable problem?

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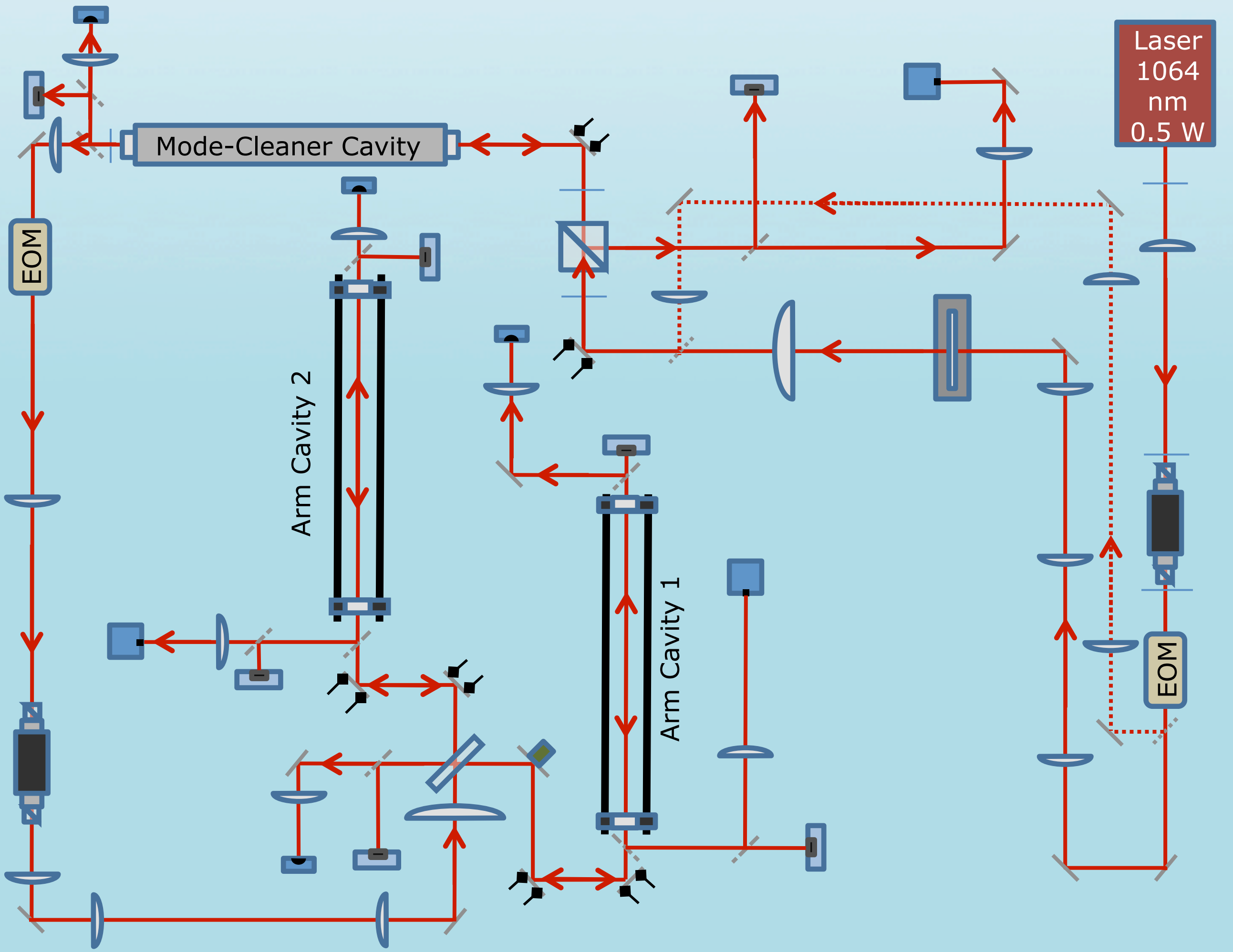
Aim of *Non-Gaussian ITF*

Realize a table-top interferometer using a non-Gaussian (LG_{33}) mode

- ✧ LG system feasibility
  - Matching and pre-alignment procedures using Gaussian beam
  - Control systems (longitudinal and angular)
- ✧ Identification of the main limits and constraints
- ✧ Comparison between measures and simulations

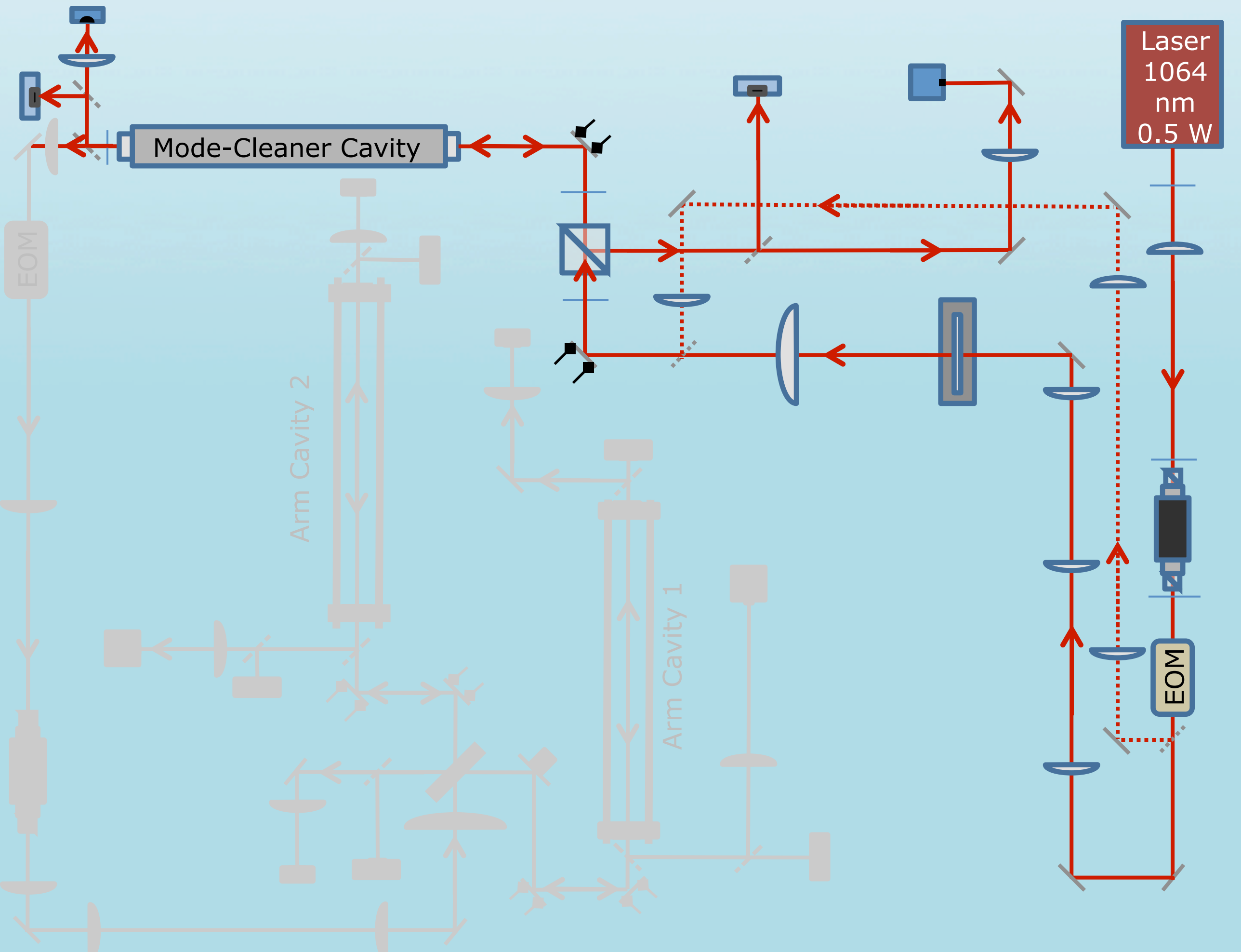
- ✧ Test other modes (LG and non-LG)
- ✧ Mirror thermal compensation

Optical scheme



- Generation:
  - Phase plate
  - Linear mode cleaner
- Mode matching telescope
- Fabry-Perot arm cavities (F=200)
- 30-cm long plano-concave cavities
- Gaussian beam used for alignment and matching

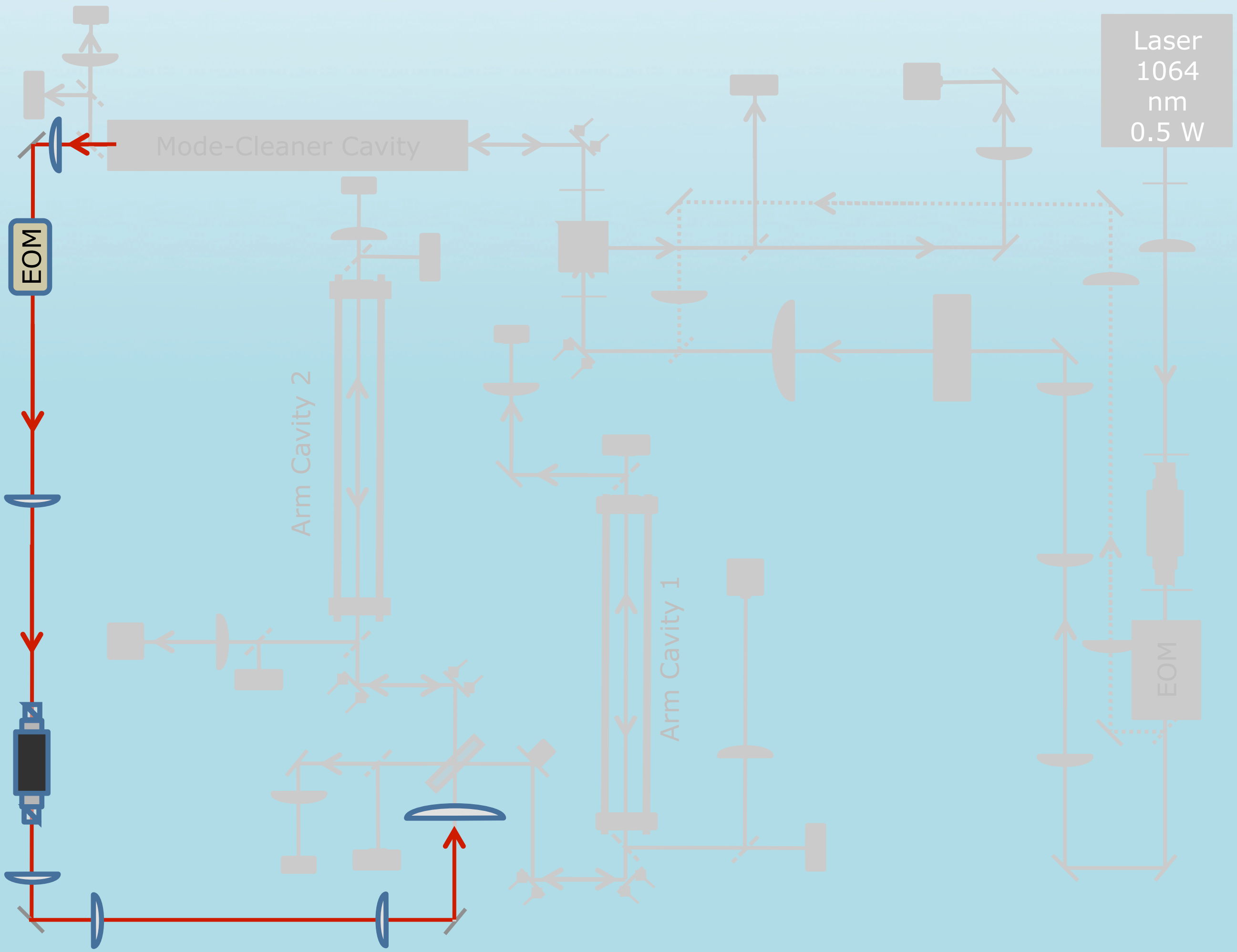
Optical scheme



- ✧ **Generation [1]:**
  - ➢ **Phase plate**
  - ➢ **Linear mode cleaner**
- ✧ Mode matching telescope
- ✧ Fabry-Perot arm cavities (F=200)
- ✧ 30-cm long plano-concave cavities
- ✧ Gaussian beam used for alignment and matching

[1] M. Granata et al., PRL 105, 231102 (2010)

Optical scheme



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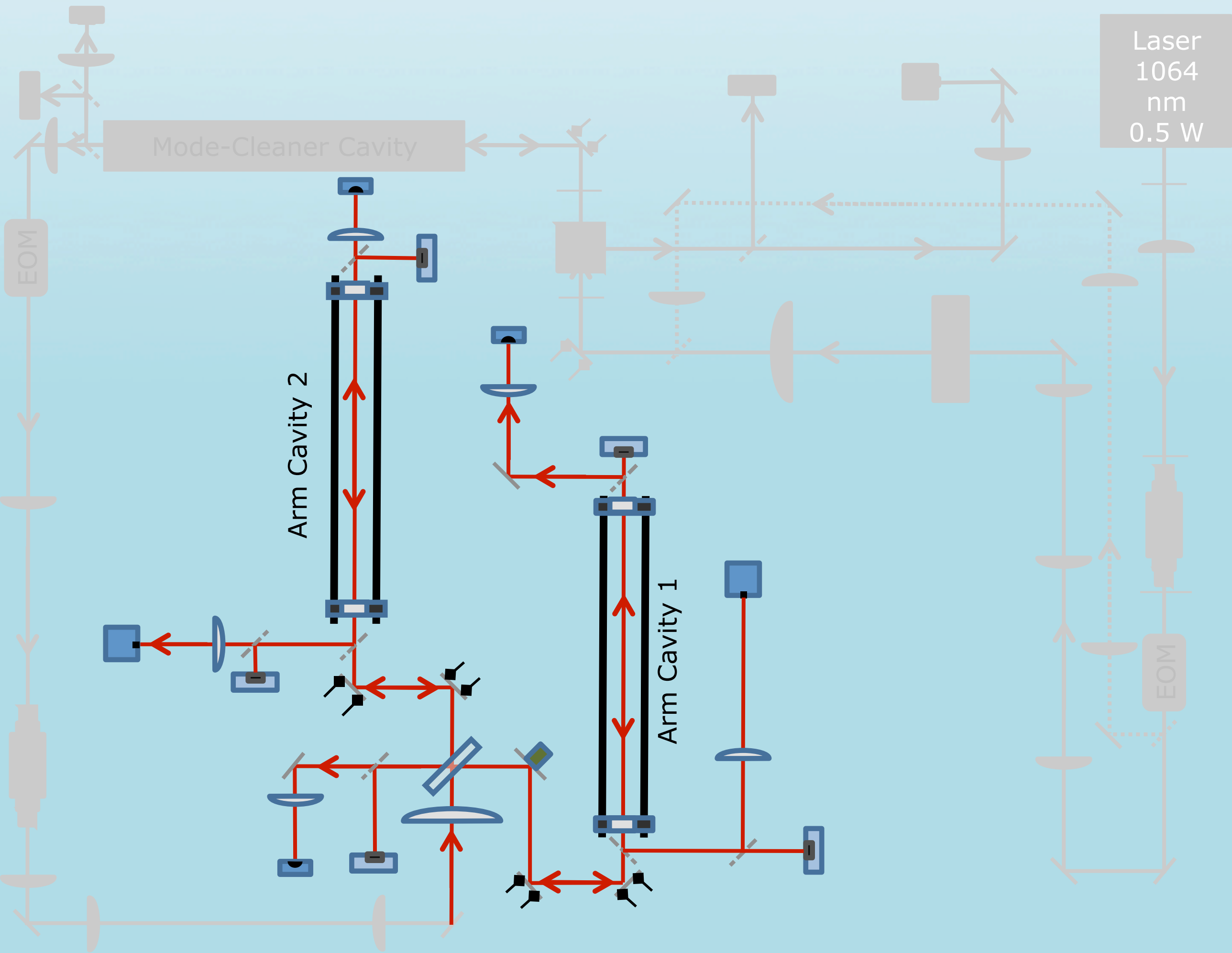
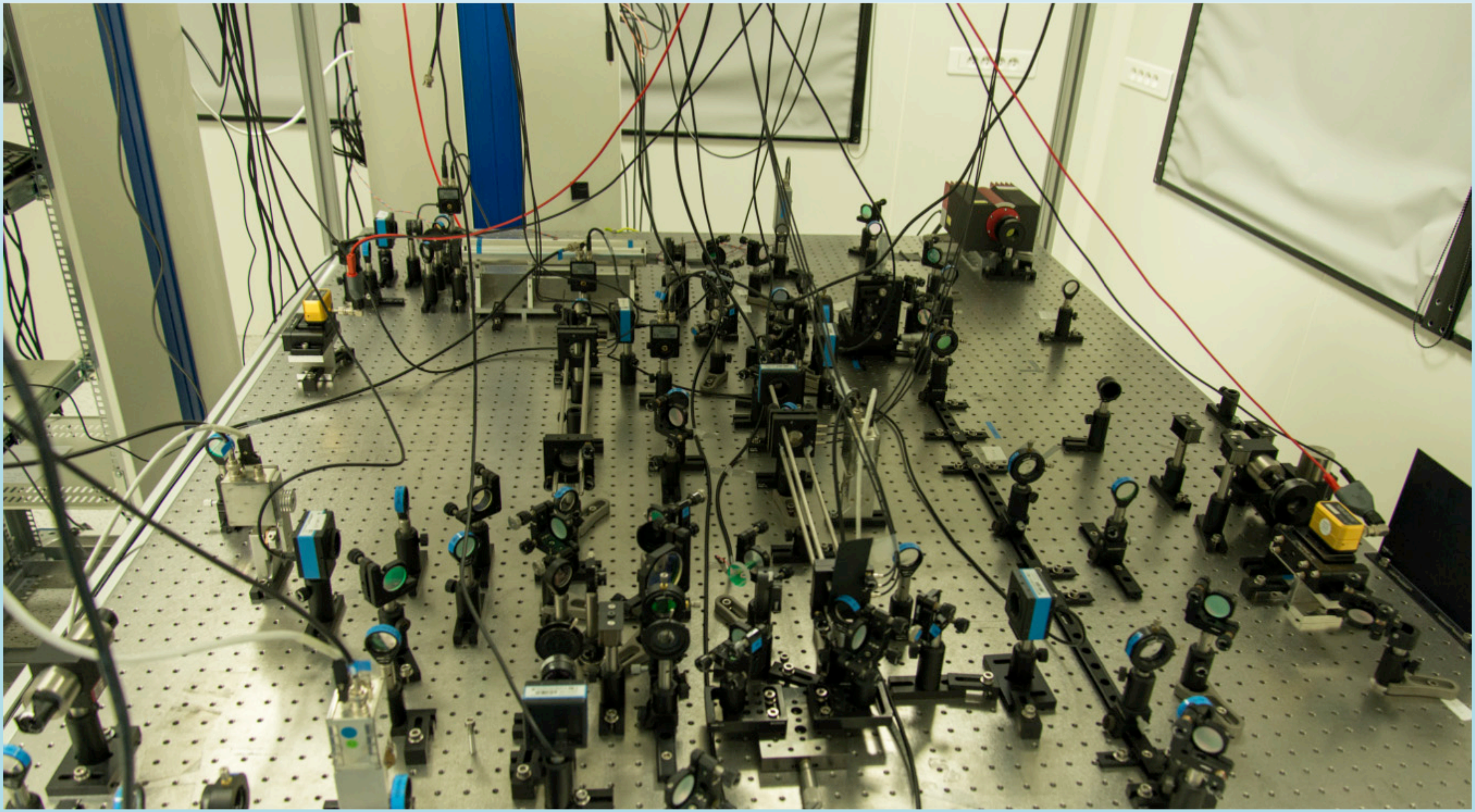
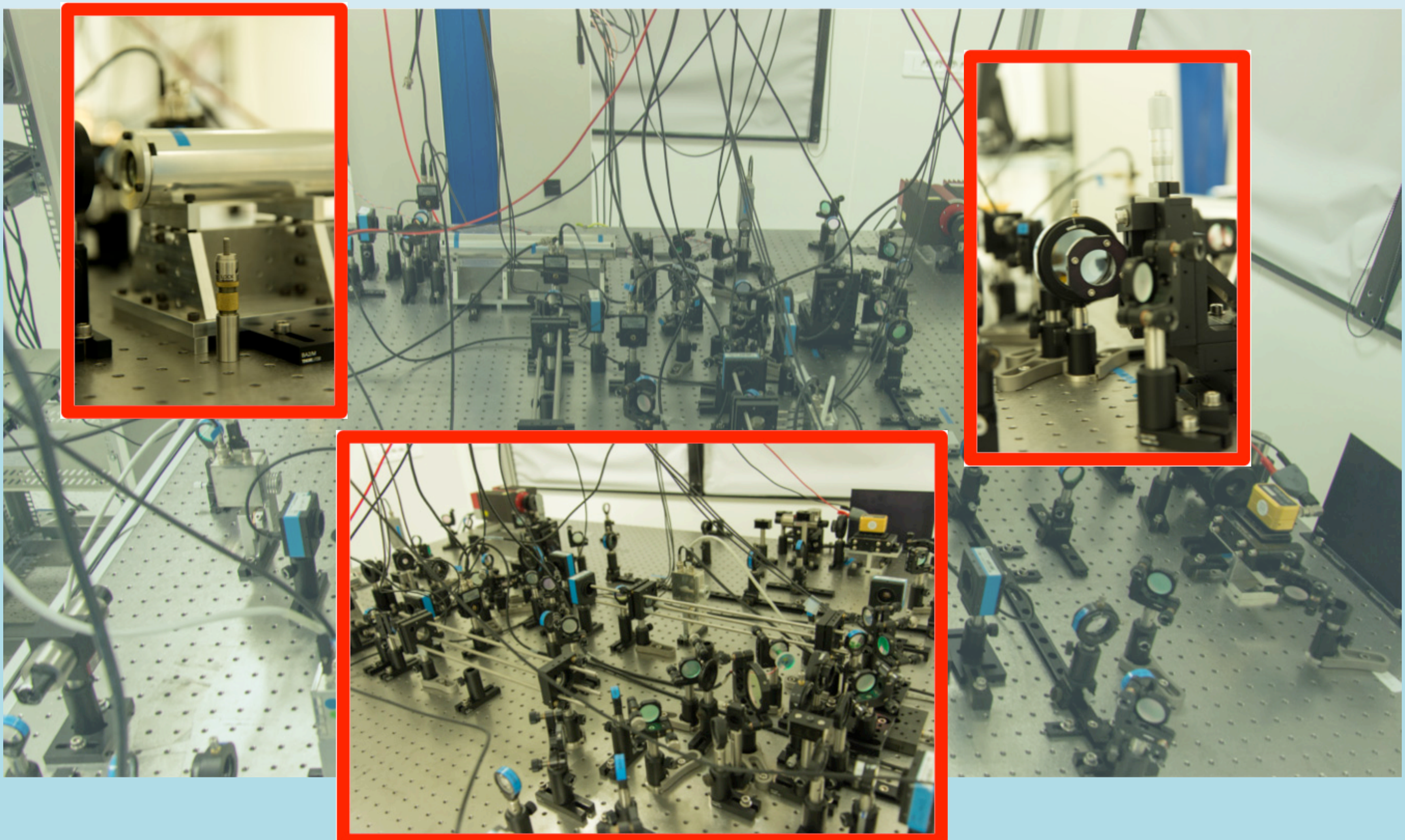


- Generation:
  - Phase plate
  - Linear mode cleaner
- Mode matching telescope
- **Fabry-Perot arm cavities (F=200)**
- 30-cm long plano-concave cavities
- Gaussian beam used for alignment and matching

Experimental setup

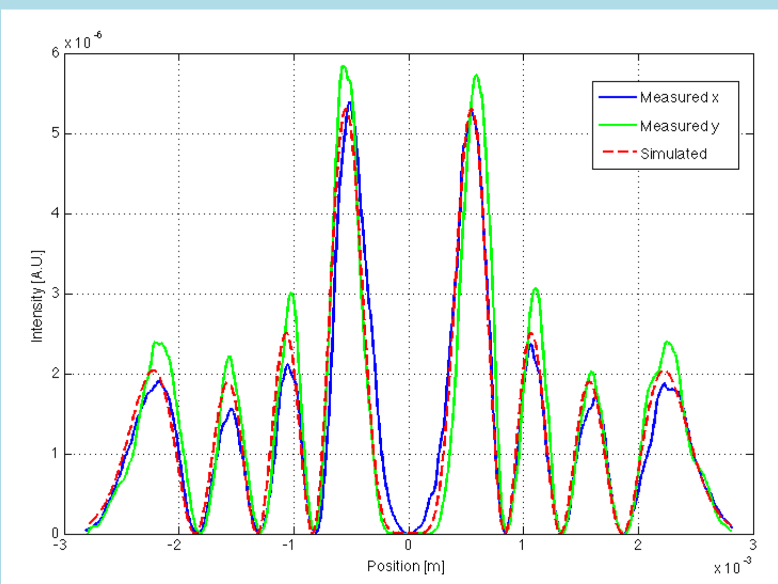


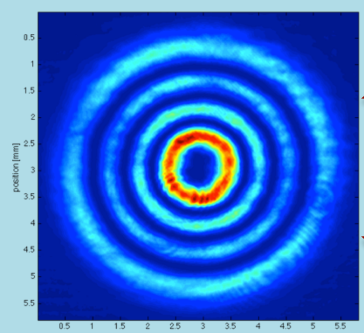
Experimental setup



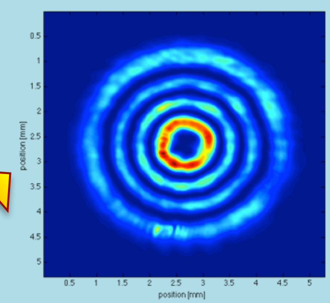
Input beam

- ✧ Gaussian and LG_{33} beams superposed before the mode cleaner input mirror
  - ➢ Alignment of the Gaussian beam in the MC cavity
  - ➢ Switching on the LG_{33} beam (only optimization required)
- ✧ LG_{33} purity (evaluated in terms od overlap integrals O.I.) maintained from mode cleaner to arm cavities input

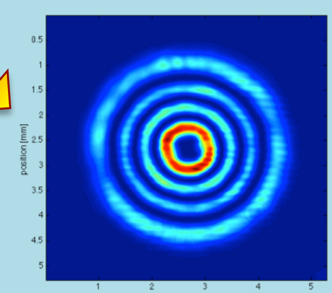




Mode cleaner output
O.I. 99.2%

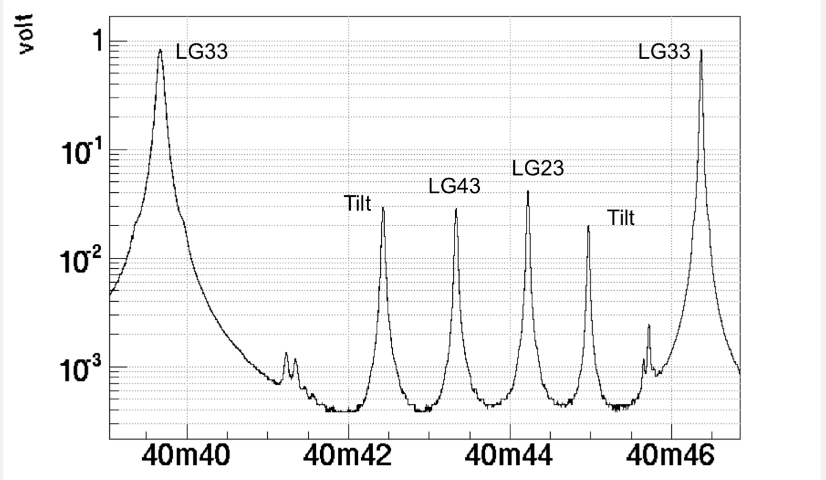


Cavity 1 input
O.I. 98.5%



Cavity 2 input
O.I. 98.9%

Cavities characterization

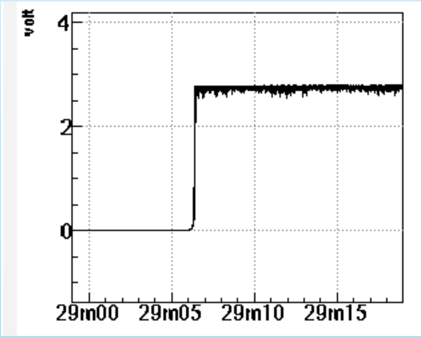


Gaussian	Tilt	Mismatching	
	0.8% - 3%	0.2%	
LG_{33}	Tilt	LG_{43}	LG_{23}
Cavity 1	3.6% - 2.4%	3.1%	5%
Cavity 2	5.5% - 4.3%	2.4%	4.2%

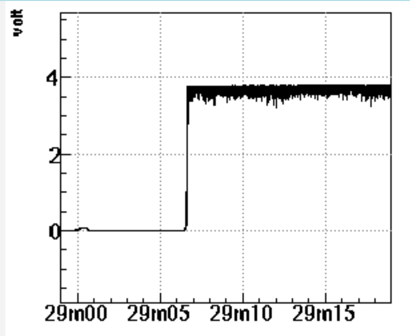
- ✧ Cavity characterization
  - ➢ Mismatching greater by a factor ~**40** (confirmed by theory and simulations)
  - ➢ Tilts recovered by a fine tuning of the cavity mirrors (possible only by piezo actuators)
- ✧ Mismatching analytical estimation
  - ➢ 4.5% waist size error (only waist size error)
  - ➢ 2.2 cm waist position error (only position error)

Interferometer control system

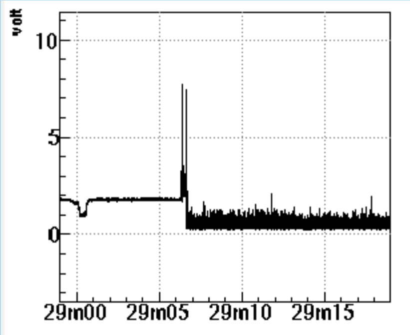
- Digital control system (AdVirgo-like)
- Arm cavities: standard control system (PDH)
- ITF: Schnupp asymmetry between arms not possible (huge impact on matching), Michelson error signal extracted through dithering
- Very fast lock and relock thanks to an automated system (software script)
- Stable locking of both arm cavities and Interferometer
- Power fluctuation given by acoustic noise (acoustic insulation received and installed in the next weeks)



Cavity 1



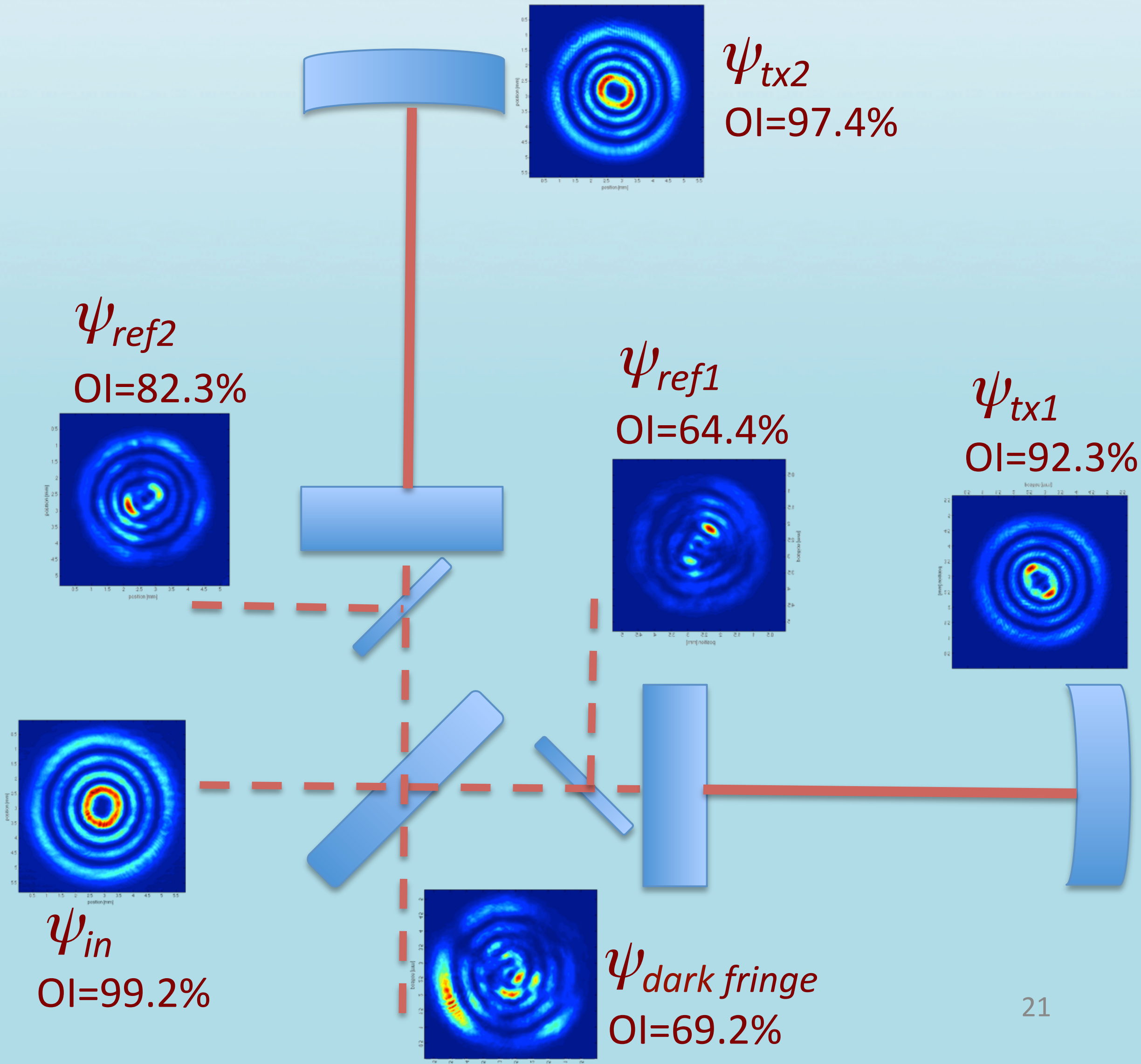
Cavity 2



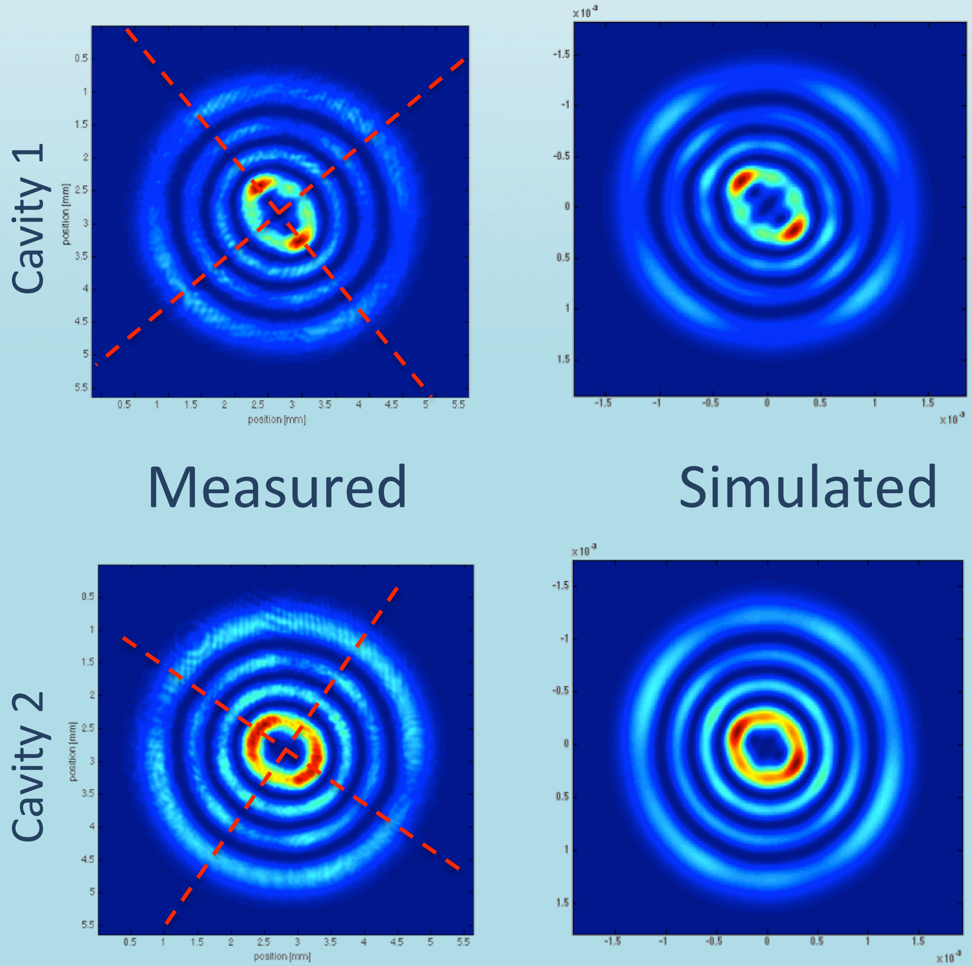
ITF

Image analysis

- ✧ Best visibility 74%
- ✧ Simulations carried out for explaining the obtained results



Transmitted beams

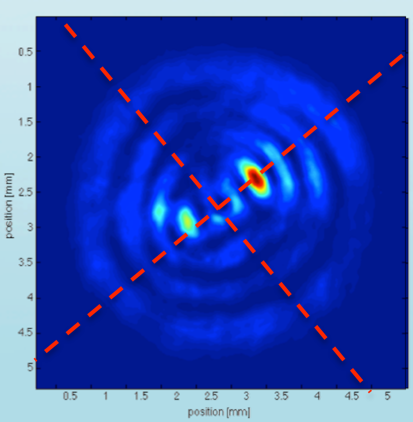


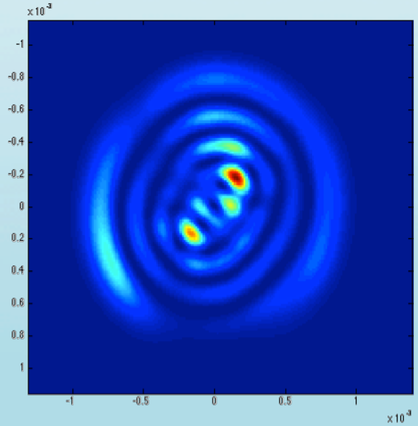
✧ Estimation starting from shapes and the relative overlap integrals

	Astigmatism
Cavity 1	0.27%
Cavity 2	0.16%

Reflected beams

Cavity 1

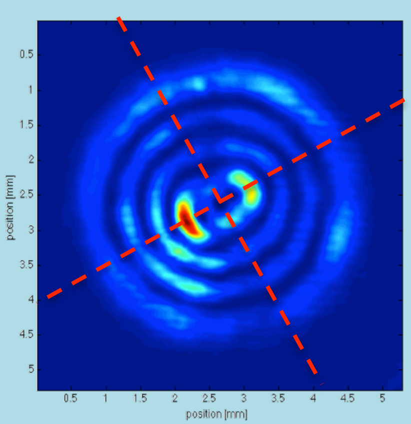


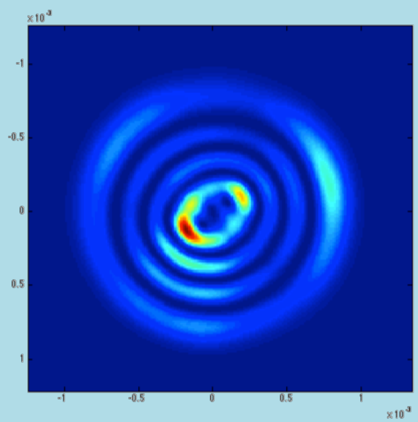


Measured

Simulated

Cavity 2





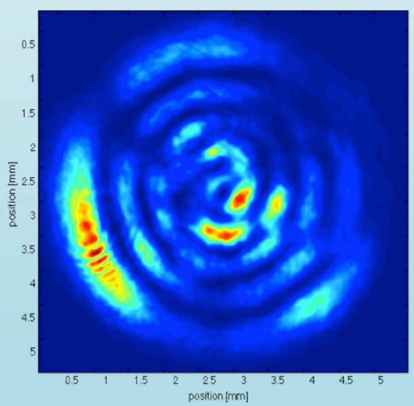
- Same astigmatism obtained in the previous slide
- Tilt estimation made from overlap integrals and resonance scans (amplitude of tilts modes)

	Tilt ITM	Tilt ETM
Cavity 1	-5 μrad (x) -50 μrad (y)	4 μrad (x) 5 μrad (y)
Cavity 2	8 μrad (x) 65 μrad (y)	-2 μrad (x) -12 μrad (y)

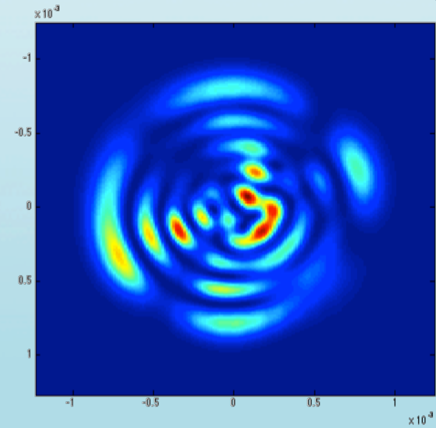
Dark fringe

Measured

Simulated

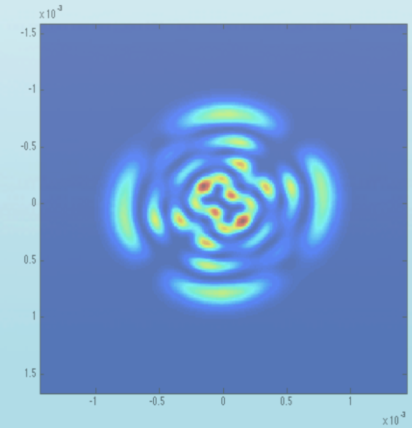


Visibility 74%



Visibility 72%

(astigmatism+mismatch +tilts)



Visibility 92%

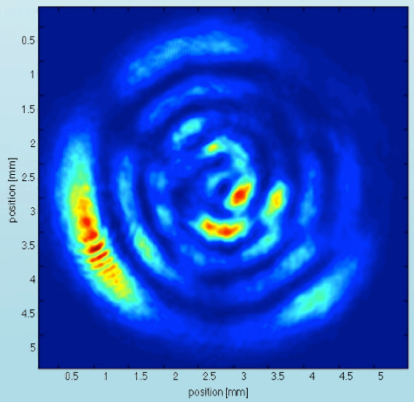
(astigmatism only)

✧ General agreement between the measured and simulated images

	Tilt ITM	Tilt ETM	Astigmatism
Cavity 1	-5 μrad (x) -50 μrad (y)	4 μrad (x) 5 μrad (y)	0.27%
Cavity 2	8 μrad (x) 65 μrad (y)	-2 μrad (x) -12 μrad (y)	0.16%

Dark fringe

Measured



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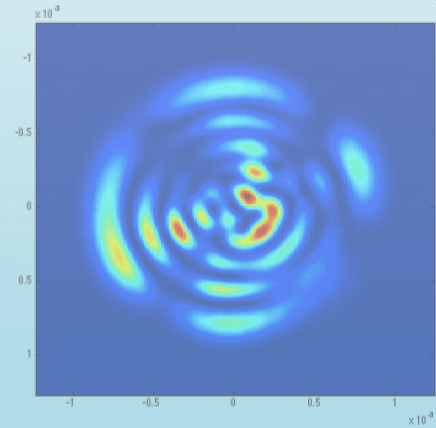

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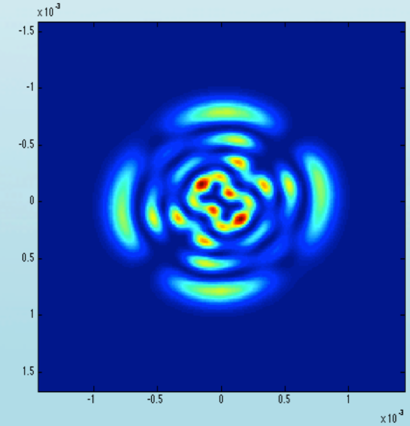

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	Tilt ITM	Tilt ETM	Astigmatism
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Cavity 2	8 μrad (x) 65 μrad (y)	-2 μrad (x) -12 μrad (y)	0.16%

Near-future steps

- Improve the quality of the dark fringe
  - Fine tuning of both input and end cavity mirrors by piezo actuators (planned in the next week)
  - Automatic alignment procedure using a quadrant photodiode at the dark fringe port (planned in the next week, Virgo quadrant)
- Measure of cavity mirrors maps
- Installation of acoustic insulation for acoustic noise reduction

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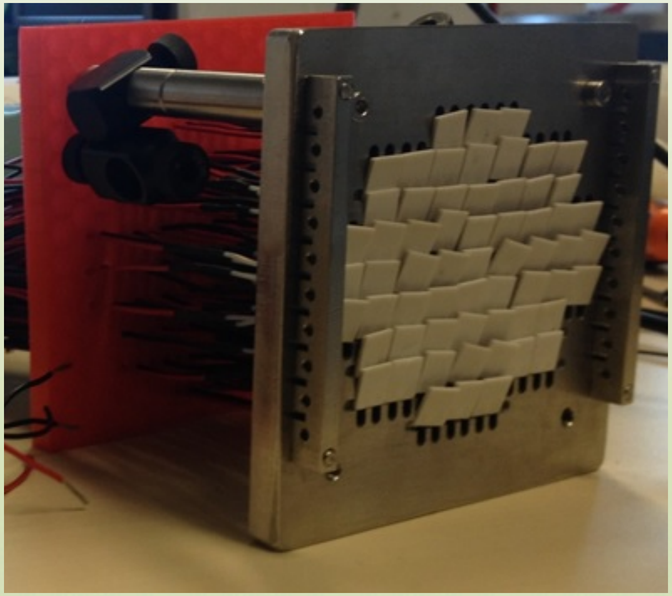
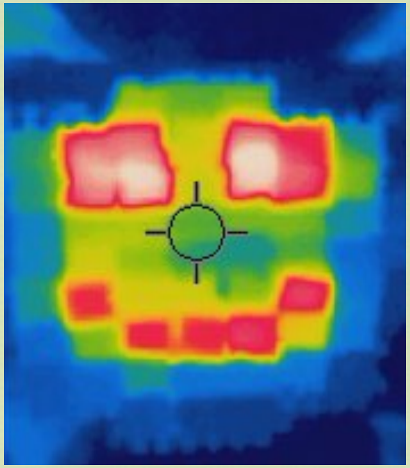
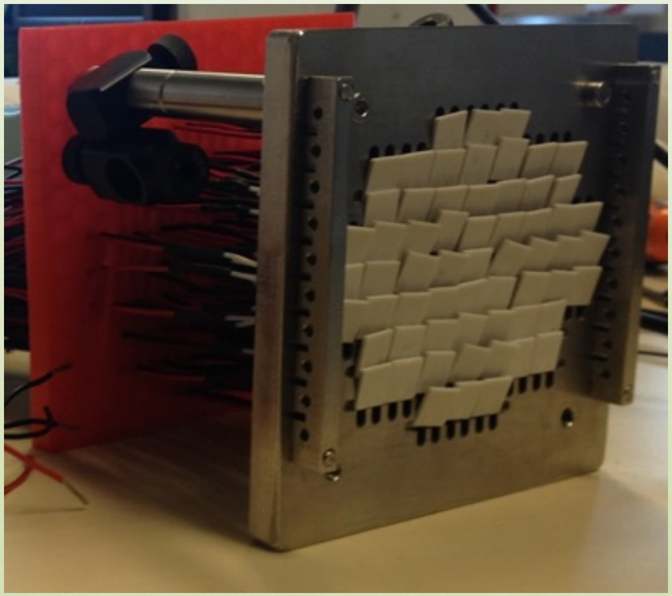
Thermal compensation & LG_{33}

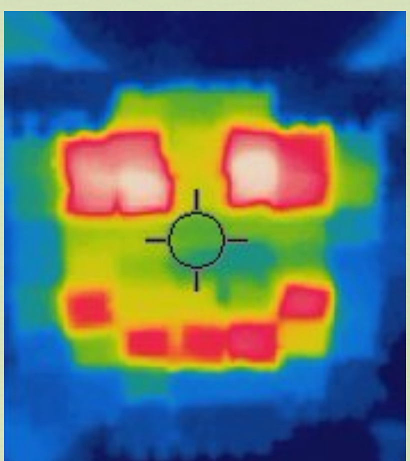




- ✧ Installation of the CHRAC-like thermal compensation system
  - ➢ Setup modified to accomodate the CHRAC
  - ➢ BK7 cavity mirrors (higher thermal coefficient)
- ✧ Correction of only one cavity
  - ✧ Simple cavity (transmitted and reflected beams)
  - ✧ Asymmetric ITF (1 FP cavity and 1 simple mirror)

Thermal compensation & LG_{33}





- Installation of the CHRAC-like thermal compensation system
  - Setup modified to accomodate the CHRAC
  - BK7 cavity mirrors (hig… thermal c…
  - …nd
  - Asymmetric ITF (1 FP cavity and 1 simple mirror)

See Annalisa Allocca Friday morning

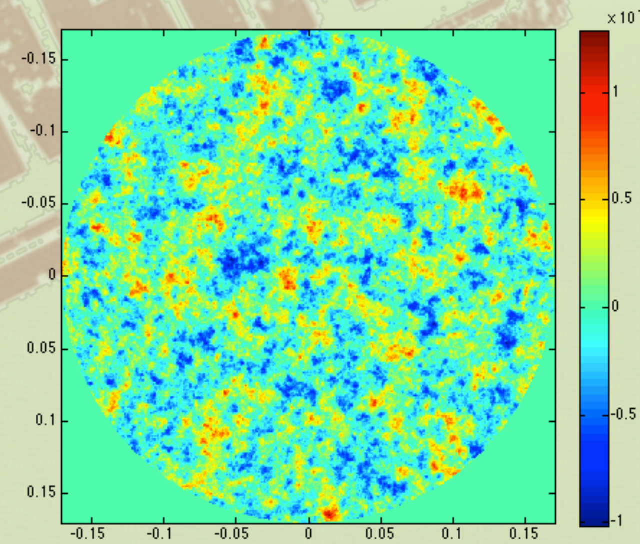
Other paths to reduce the degeneracy

AIM

Improving the contrast defect maintaining the same thermal noise reduction of LG_{33}

- ✧ 10 OSCAR simulations
- ✧ Advanced Virgo configuration
- ✧ Realistic mirror maps (generated by ITM04 PSD [5,10])

RMS roughness = 0.3

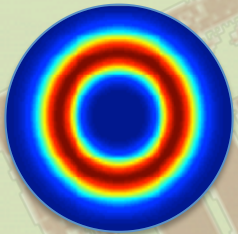


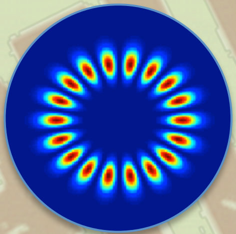
[5] T. Hong et al., Physical Review D 84, 102001 (2011)
[10] H. Yamamoto, LIGO-T1100353-v1 (2011)

LG_{09} + corrective coating

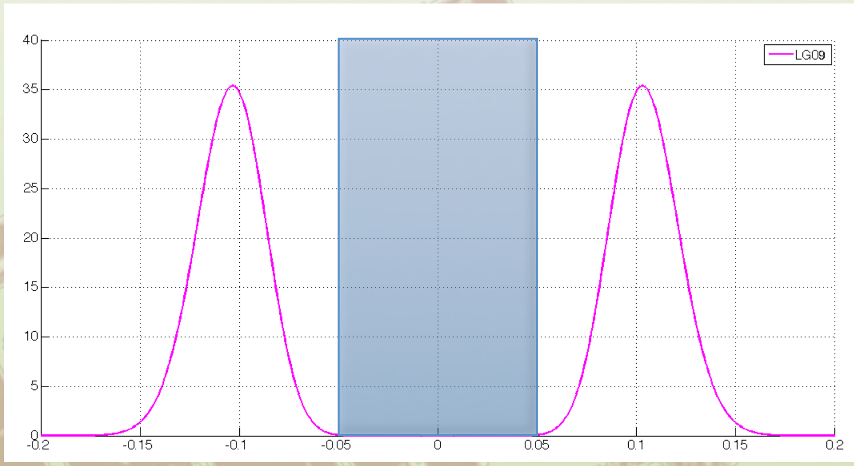
- Same order of LG_{33} mode
- Antireflective coating (as in [5] for reducing the insurgence of other modes

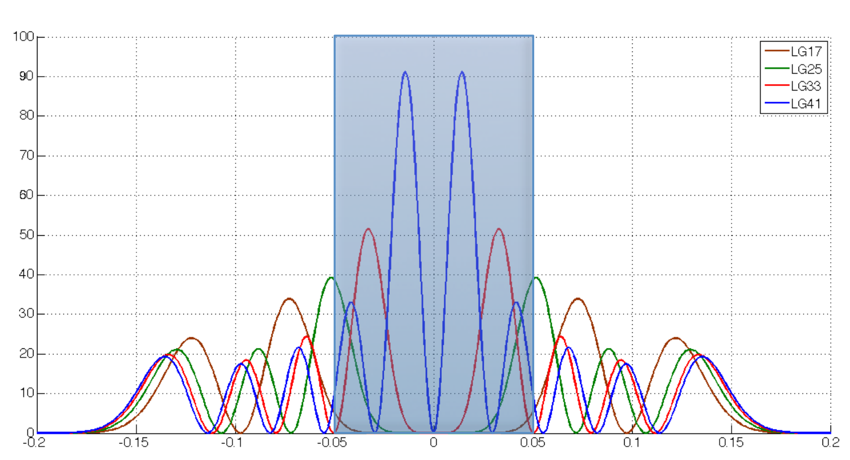
Helical or sinusoidal LG_{09} beam





	LG_{09}	Sin LG_{09}	LG_{09} hole	Sin LG_{09} hole
mean	1.6	1.7	4	**7.8**
std	0.5	0.8	2	6.4

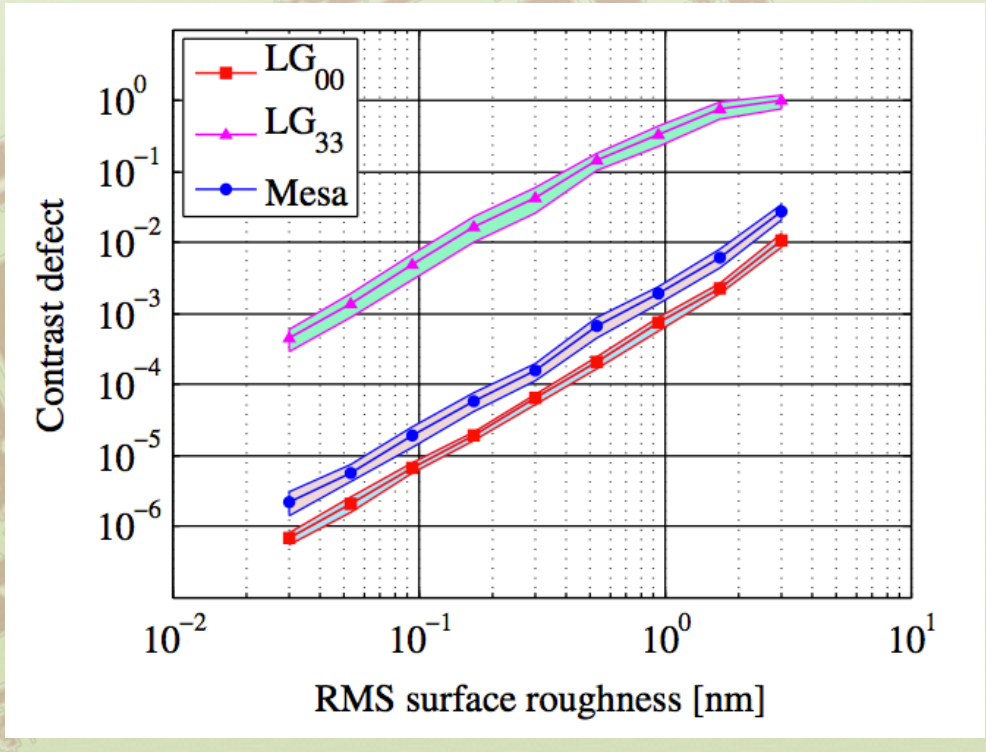




[5] T. Hong et al., Physical Review D 84, 102001 (2011)

But…

- In order to recover a feasible contrast defect a total gain of at least 2 order of magnitude is needed



Other solutions

✧ For obtaining an additional reduction other possible solutions have been considered

Configuration	Contrast defect
LG_{33}, F=450	**$5.8*10^{-2}$**
Sin LG_{09}, F=450	$3.4*10^{-2}$
Sin LG_{09}, hole, F=450	$7.7*10^{-3}$
Sin LG_{09}, hole, F=225	$1.9*10^{-3}$
Sin LG_{09}, hole, F=225, RMS=0.1 nm	**$3*10^{-4}$**

Change of modal shape

Corrective coating

Finesse reduction

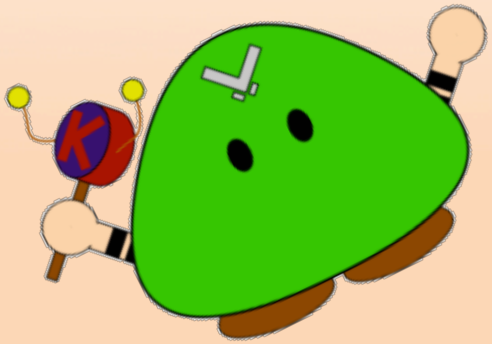
RMS reduction

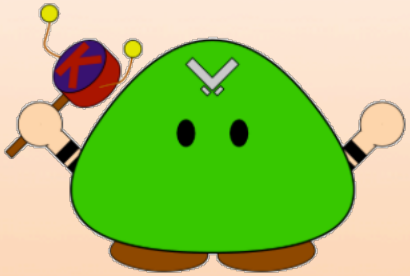
Conclusions

- State of the art
- LG_{33} Table-top experiment at the APC
  - Careful beam reduction to avoid clipping
  - LG_{33} modal purity ~99% at the input of both cavities
  - Good matching of both arm cavities (mismatching ~8%)
  - Stable locking of arm cavities and ITF with standard PDH error signals and dithering
  - Best visibility 74%, limited by astigmatism and residual tilts
  - General agreement between measures and simulations
- Reduction of the degeneracy
  - CHRAC-like thermal compensation system installation in LG_{33} experiment at APC
  - Other paths for Advanced Virgo configuration under exploration

Next steps

- Setup improvements:
  - Automatic alignment
  - Acoustic noise reduction
- Experimental application of the thermal compensation technique on LG_{33} table-top experiment at APC
- Under consideration
  - Study (by simulation and experiments) of other modes
  - Power recycling





Thank you!