Thermal noise reduction with higher-order Laguerre-Gauss modes

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ET symposium, Lyon

Outline

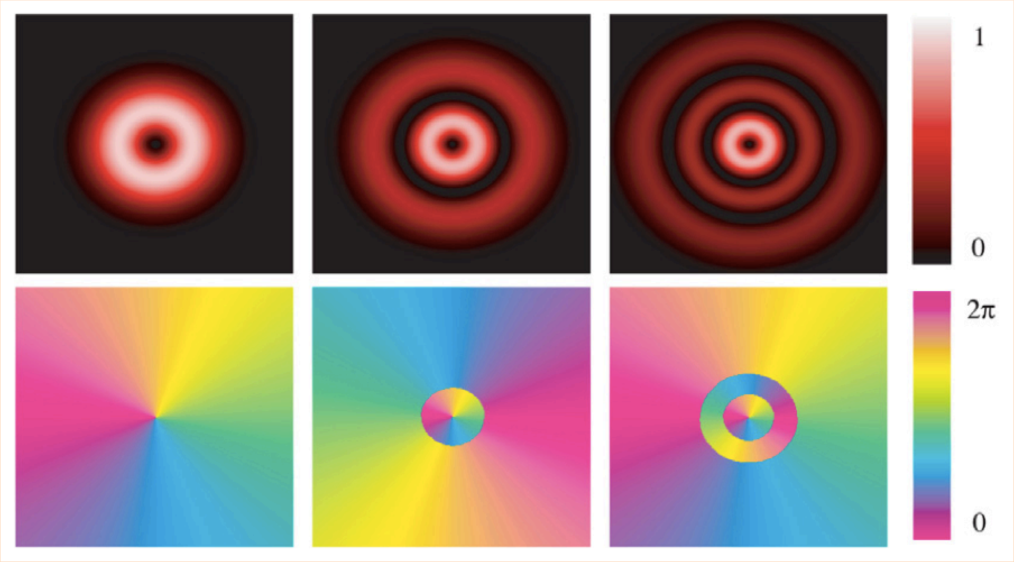
✧ Introduction/State of the art

✧ *Non-Gaussian* interferometer at the APC

✧ Reduction of the degeneracy

✧ Conclusions

Part 1:
Introduction and state of the art



Yao, A.M., and Padgett, M.J. *Orbital angular momentum: origins, behavior and applications*. Advances in Optics and Photonics, 2012

THE ASTROPHYSICAL JOURNAL, 597:1266–1270, 2003 November 10

PHOTON ORBITAL ANGULAR MOMENTUM IN ASTROPHYSICS

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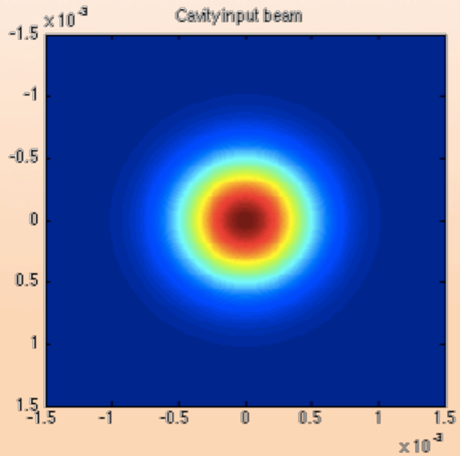
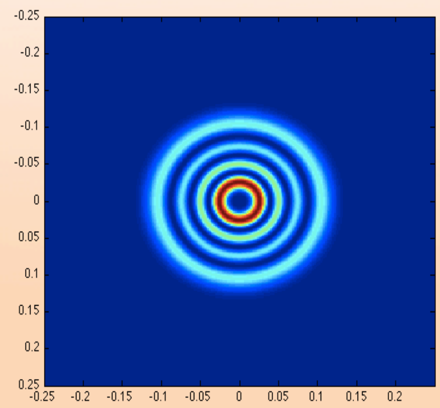
ABSTRACT

Astronomical observations of the *orbital angular momentum of photons*, a property of electromagnetic radiation that has come to the fore in recent years, have apparently never been attempted. Here I show how measurements of this property of photons have a number of astrophysical applications.

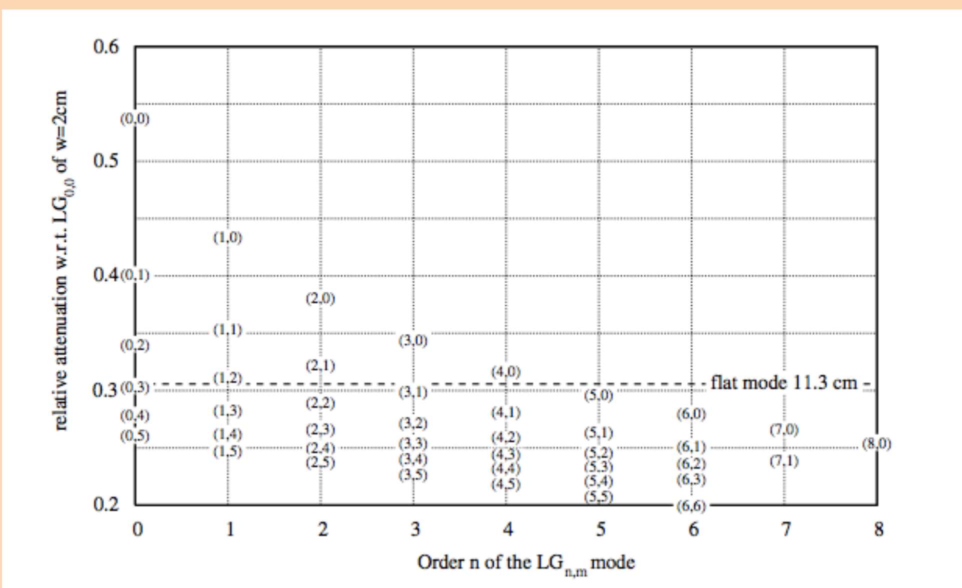
Subject headings: black hole physics — cosmic microwave background — extraterrestrial intelligence — instrumentation: miscellaneous — ISM: general — masers

Laguerre-Gauss modes for GW detectors





LG modes proposed in2006 in order to reduce thermal noise [1]



[1] B.Mours et al., CQG 2006
[2] Vinet, CQG 2007
[3] Vinet, LLR 2009
[4] Chelkowsky et al., PRD 2009

Laguerre-Gauss modes and ET

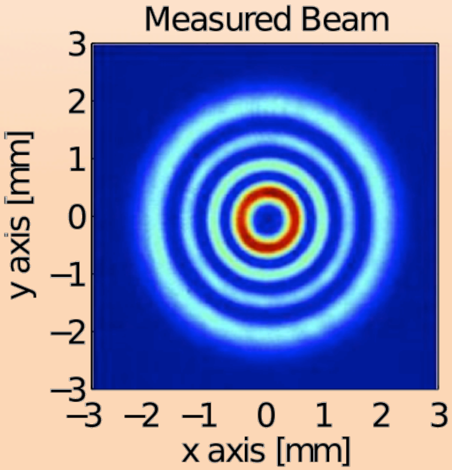
Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

Th noise reduction = 1.83

J. Franc et al., ET note, 2010

High purity LG_{33} generation

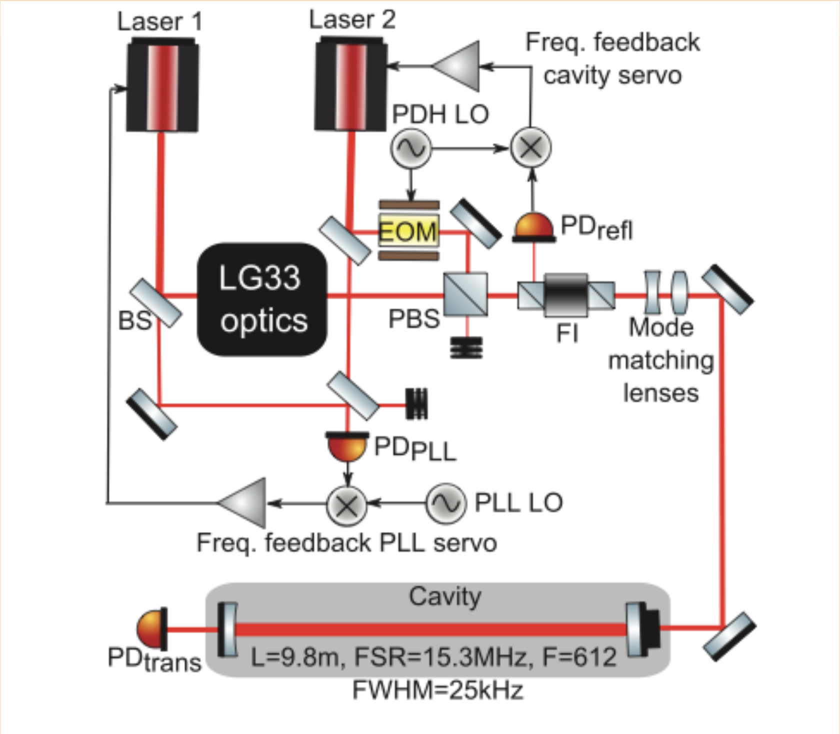
- High purity LG_{33} beam generated by spatial light modulators or diffractive phase plate and a mode cleaner cavity [1,2]
- High power generation has been obtained using a phase plate [3]
  - 83 W on LG_{33} mode, 59 % conversion efficiency

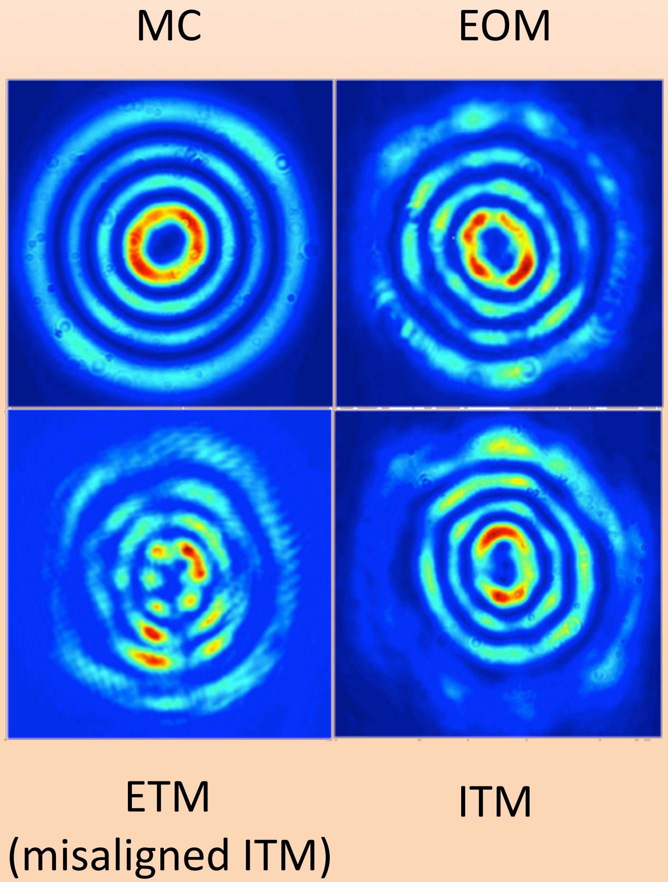


[1] M. Granata et al., PRL 105, 231102 (2010)
[2] P. Fulda et al., Physical Review D 82, 012002 (2010)
[3] L. Carbone et al., PRL 110, 251101 (2013)

Mid-scale experiment : Glasgow 10-m suspended cavity

- First attempt to realize a suspended cavity resonating on LG_{33} mode [1]

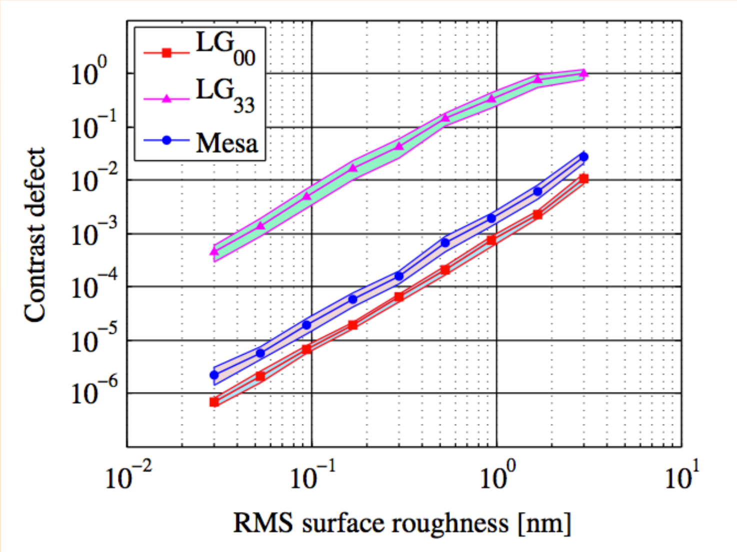


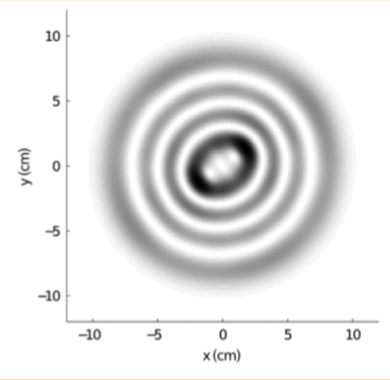


[1] B. Sorazu et al., Class. Quantum Grav. 30 (2013) 035004

Simulations: LG degeneracy

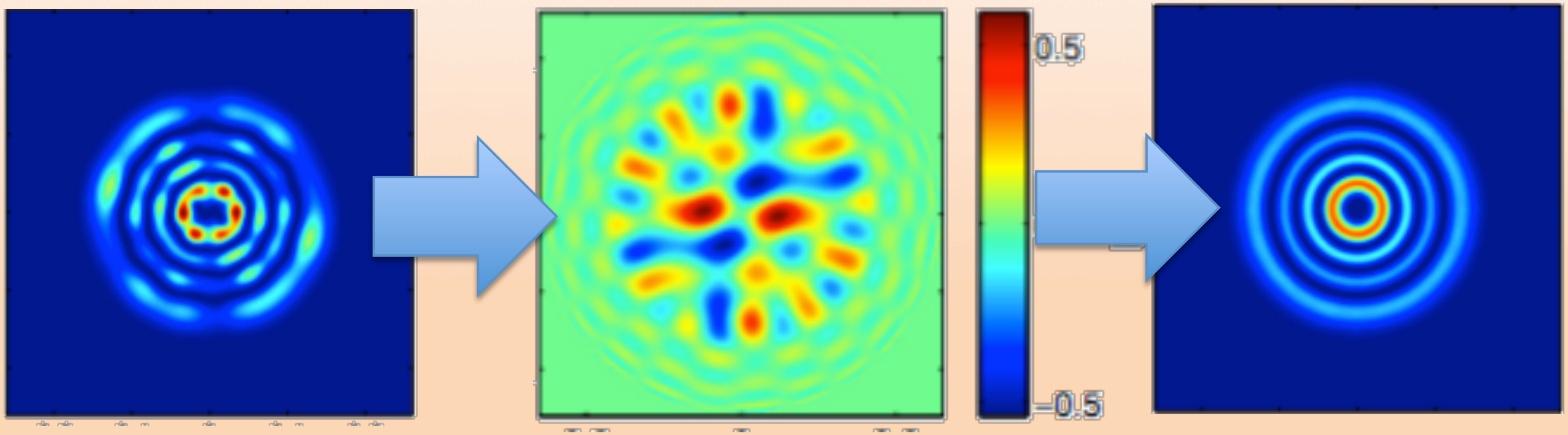
- ✧ Degeneracy of modes of the same order → coupling between modes through mirrors defects [1,2,3]
- ✧ Expected contrast defect ~ 10^3 worse than Gaussian beam: target value (~ 10^{-4}) reached for RMS ~ 0.01 nm [2]
- ✧ Selection rules / role of low spatial frequency mirror defects [3]





[1] M.Galimberti, presentation at the ET Workshop (Budapest, 2010).
[2] T. Hong et al., Physical Review D 84, 102001 (2011)
[3] C. Bond et al., Physical Review D 84, 102002 (2011)

Simulation about in-situ Thermal compensation



- Simulation of in-situ thermal correction of mirror defects to recover a high beam quality (> 99.9%) [1]
- Adaptive algorithm for estimating the map directly from the reflected intensity pattern [2]

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

Part 2:

Non-gaussian interferometer at APC

Generation
~ 30 cm
prototypes
Low power

Higher power

Longer /suspended
prototypes

More complex optical scheme

Fabry-Perot Michelson
interferometer (or more complex)

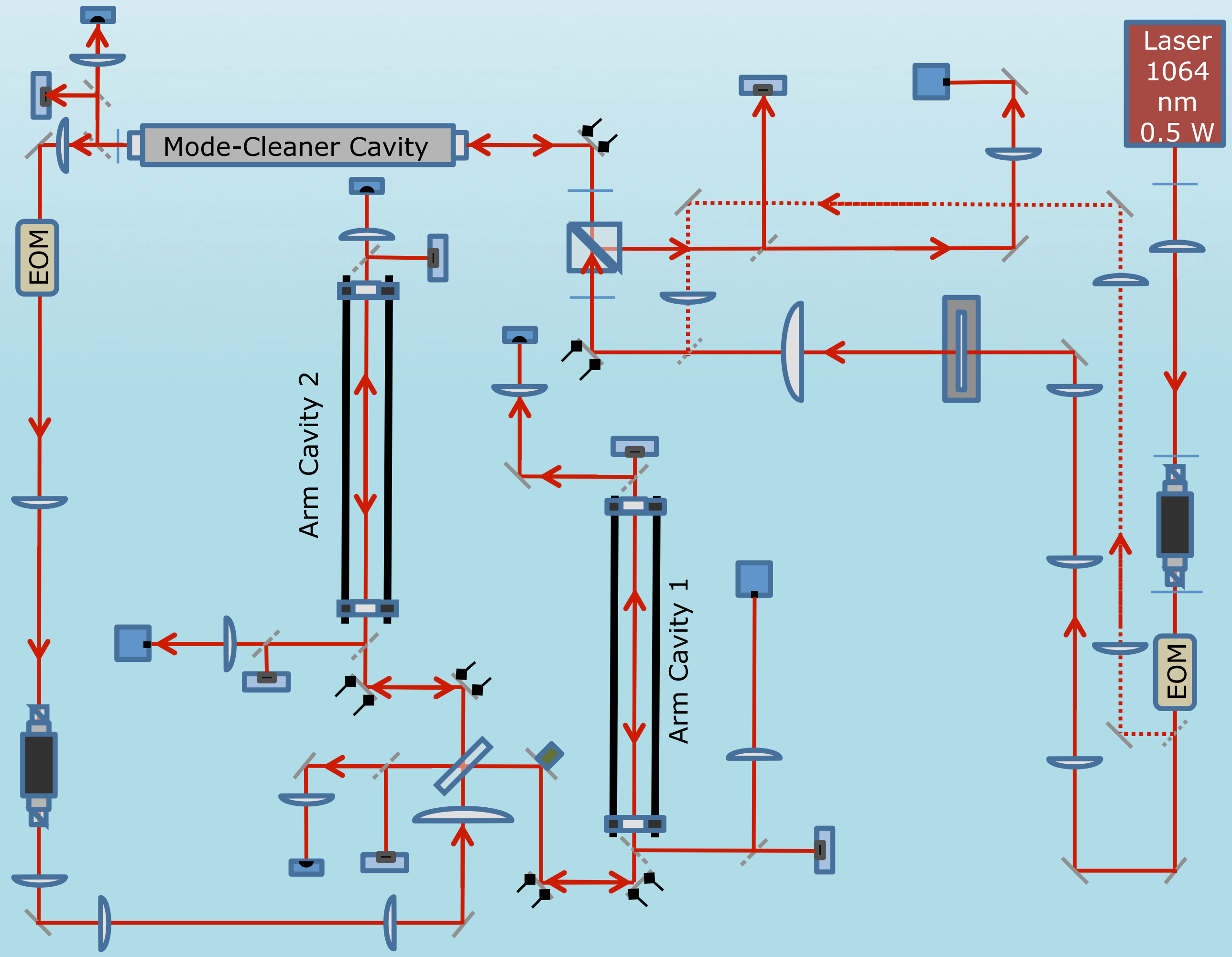
Non-Gaussian ITF at APC

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

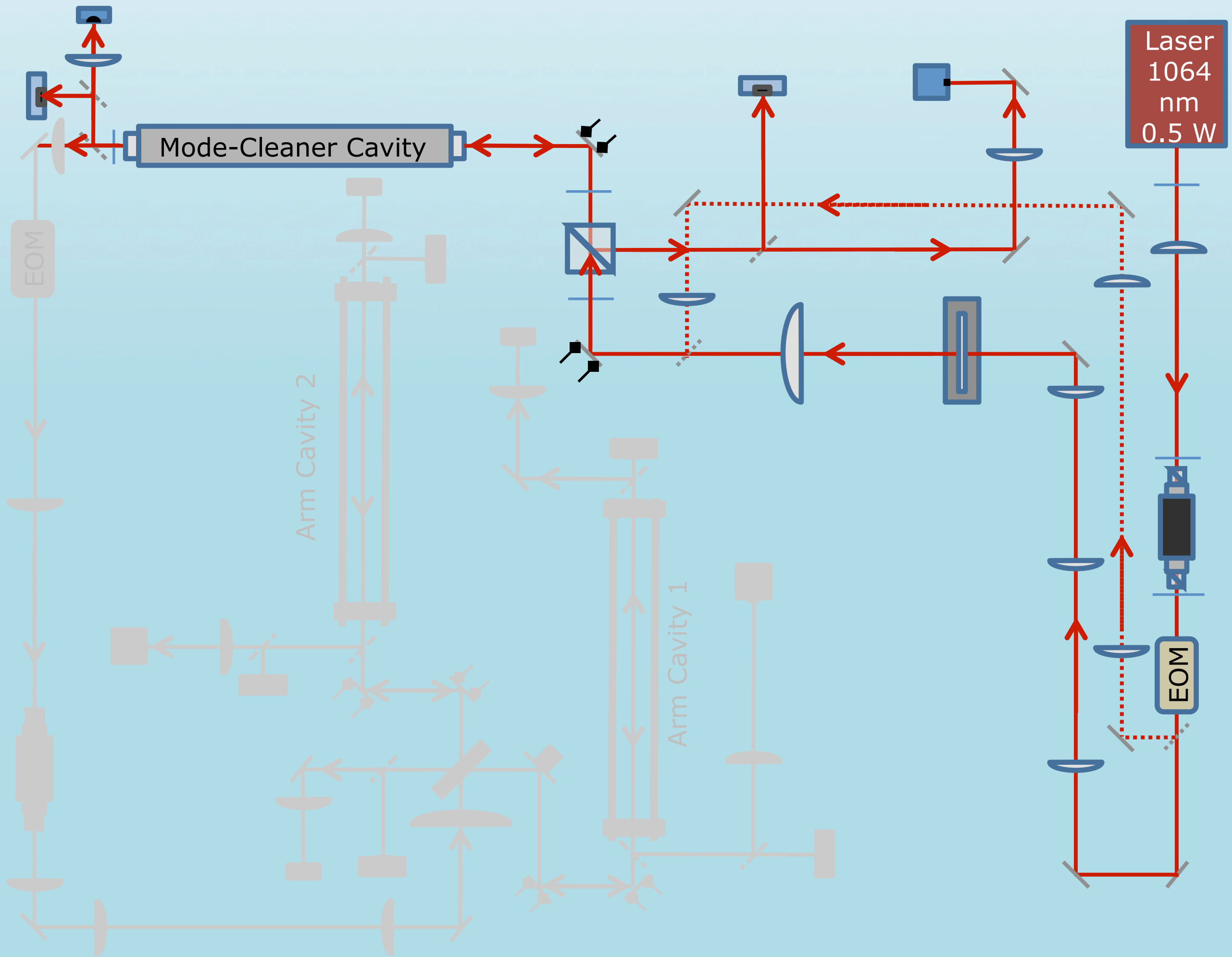
- ✧ Identification of possible experimental obstacles
- ✧ Study of the degeneracy
- ✧ Comparison between measures and simulations
- ✧ Study of the degeneracy reduction:
  - ✧ Mirror thermal compensation
  - ✧ Other modes?

A.Gatto, M.Tacca, F.Kéfélian, C.Buy and M.Barsuglia
A Fabry-Perot Michelson interferometer using higher-order Laguerre-Gauss modes
Accepted for publication in PRD

Optical scheme

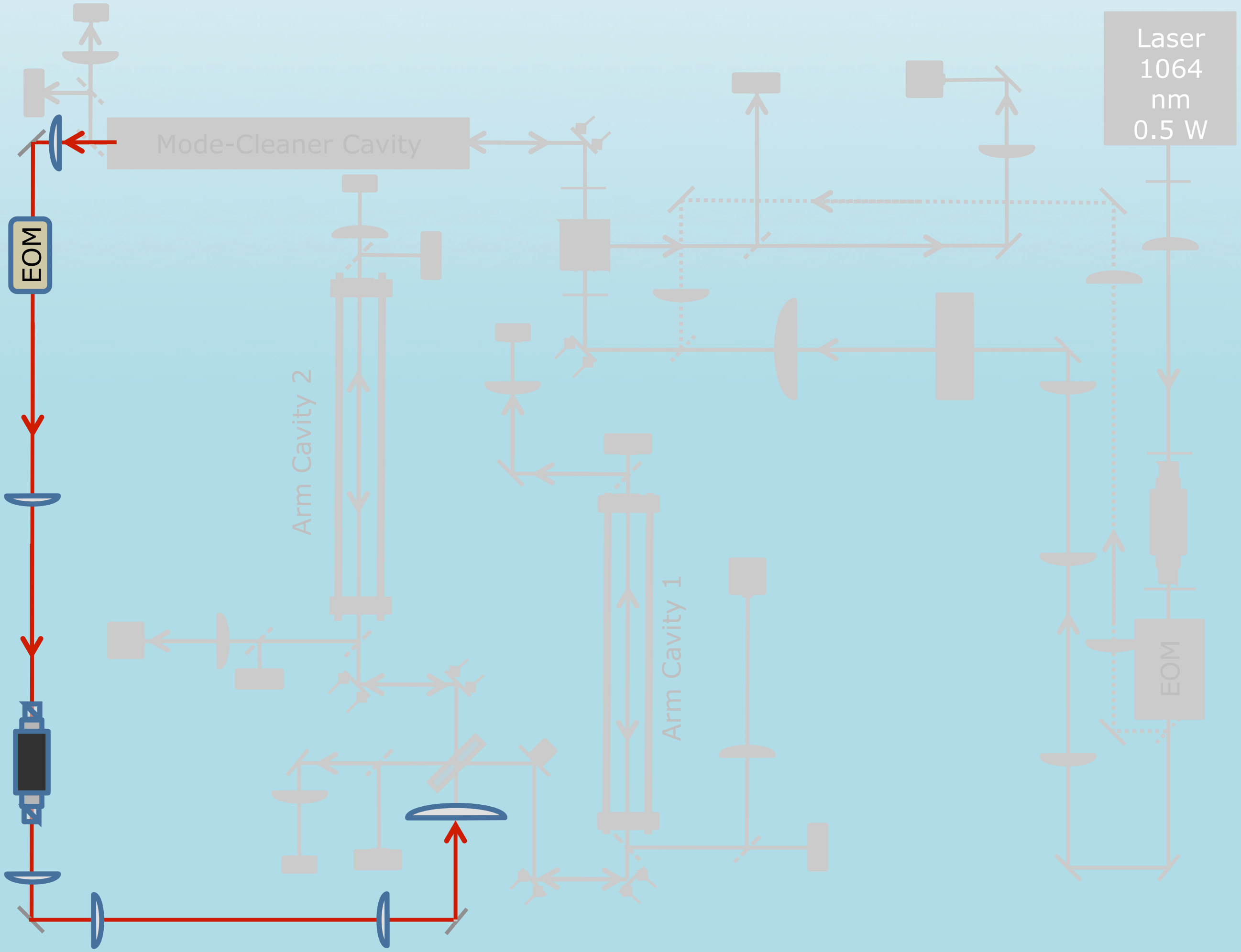


Optical scheme

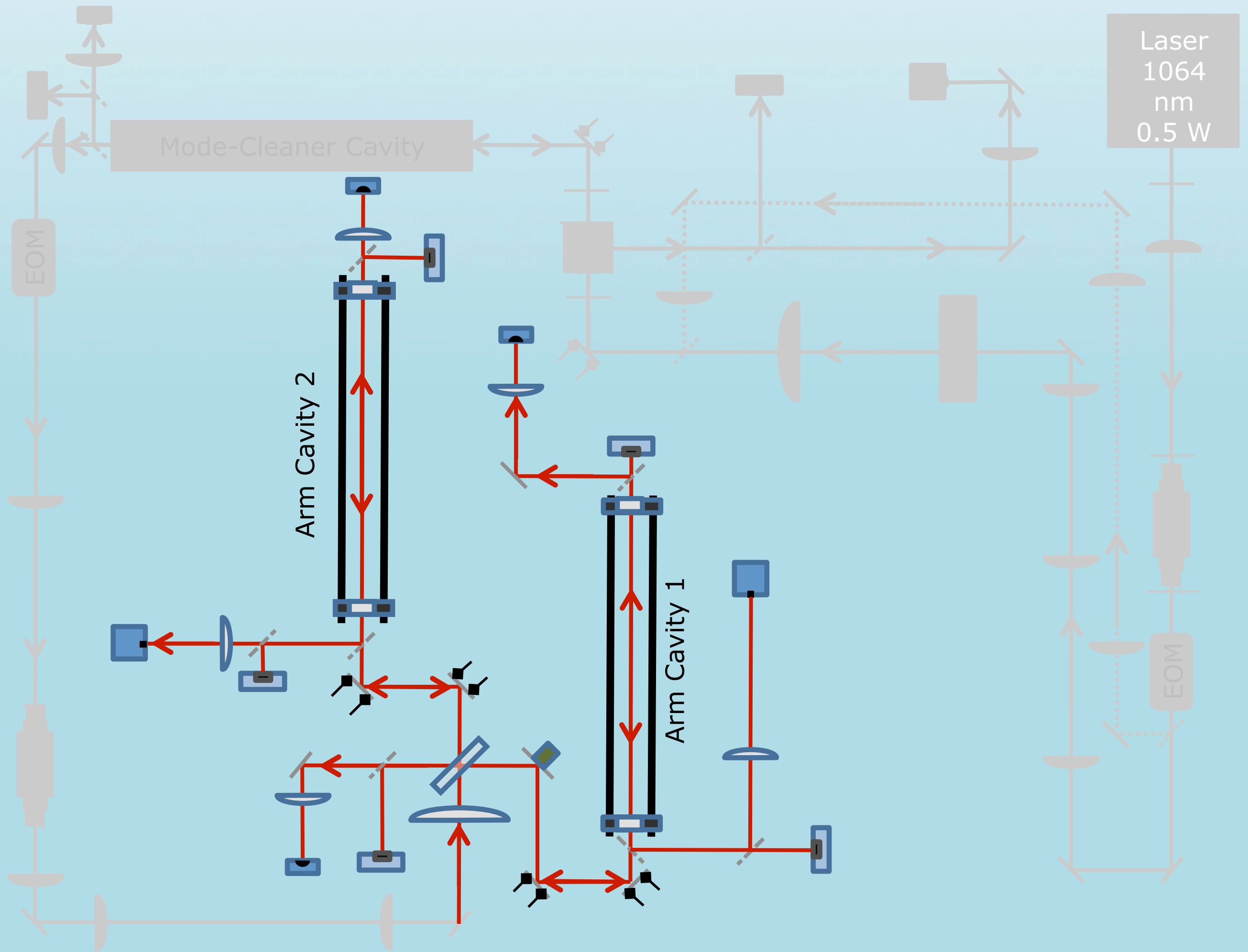


M. Granata et al., PRL 105, 231102 (2010)

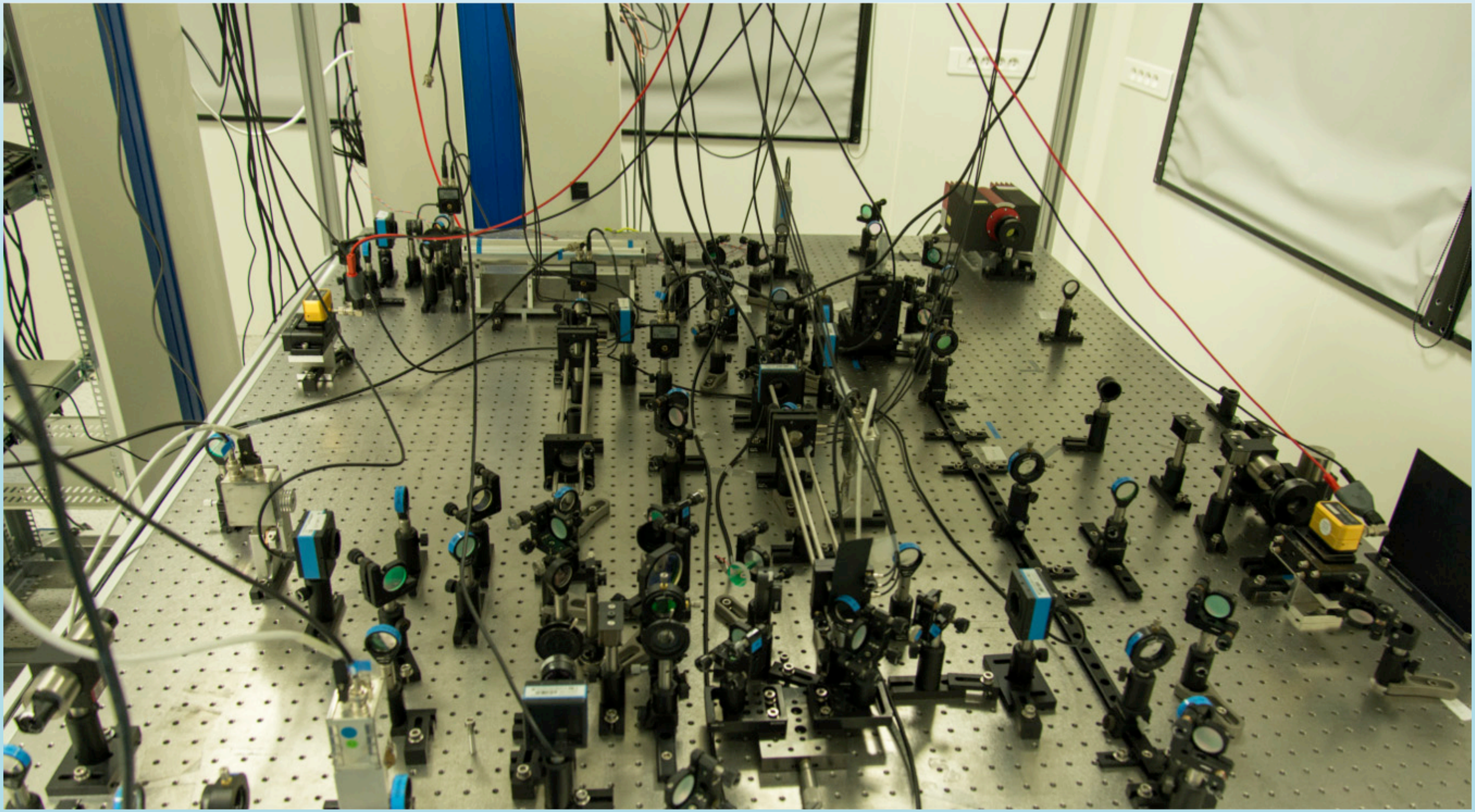
Optical scheme



Optical scheme



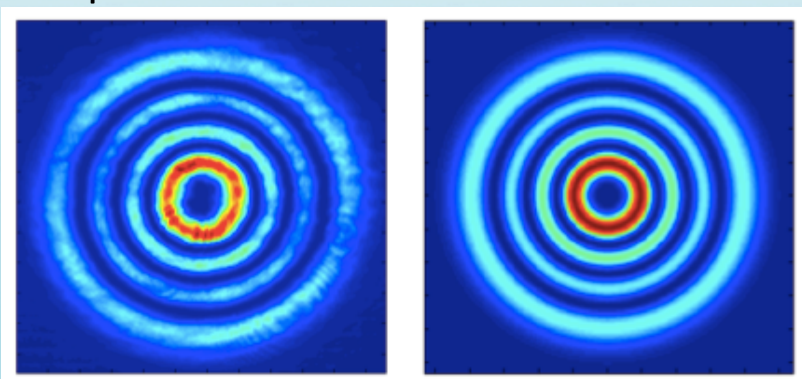
Experimental setup



Results:1: Input beam

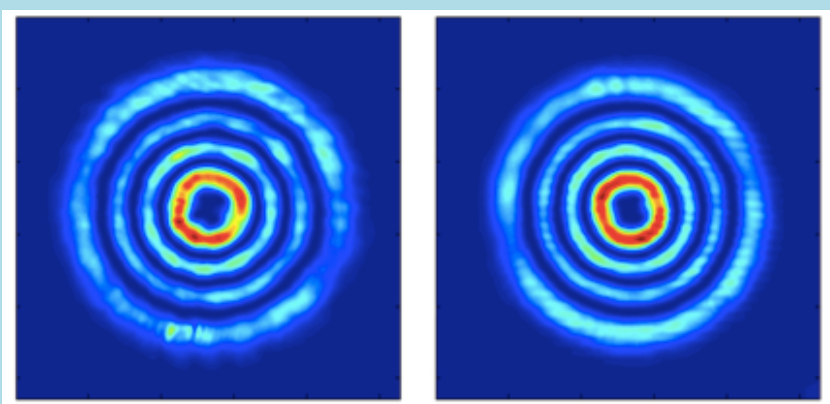
Mode-cleaner output

Theory



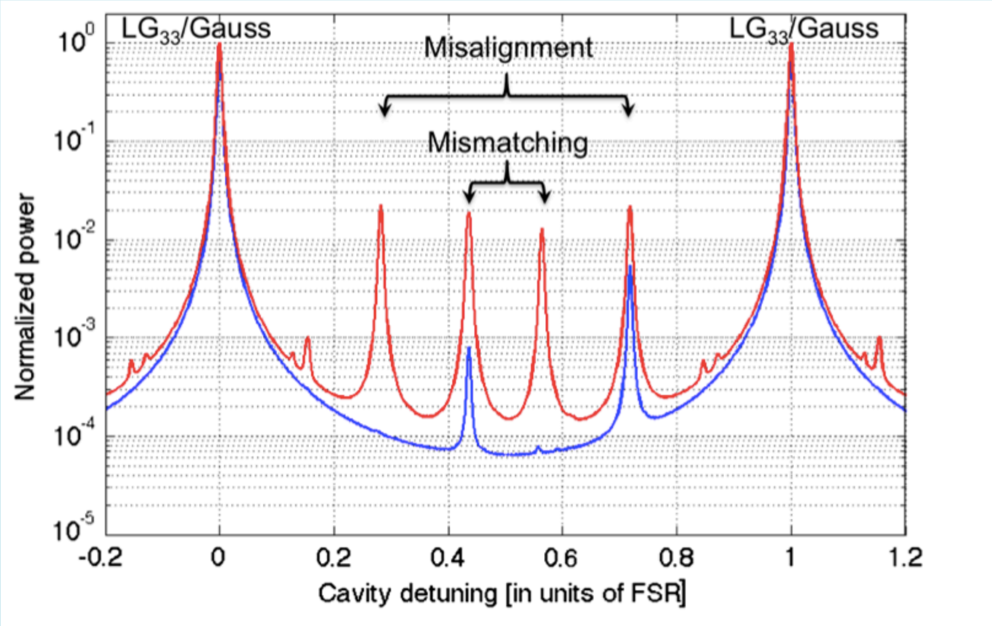
$$\gamma = \frac{\iint I_{\mathrm{meas}} \times I_{\mathrm{theory}} dS}{\sqrt{\iint I_{\mathrm{meas}}^2 dS} \times \sqrt{\iint I_{\mathrm{theory}}^2 dS}}$$

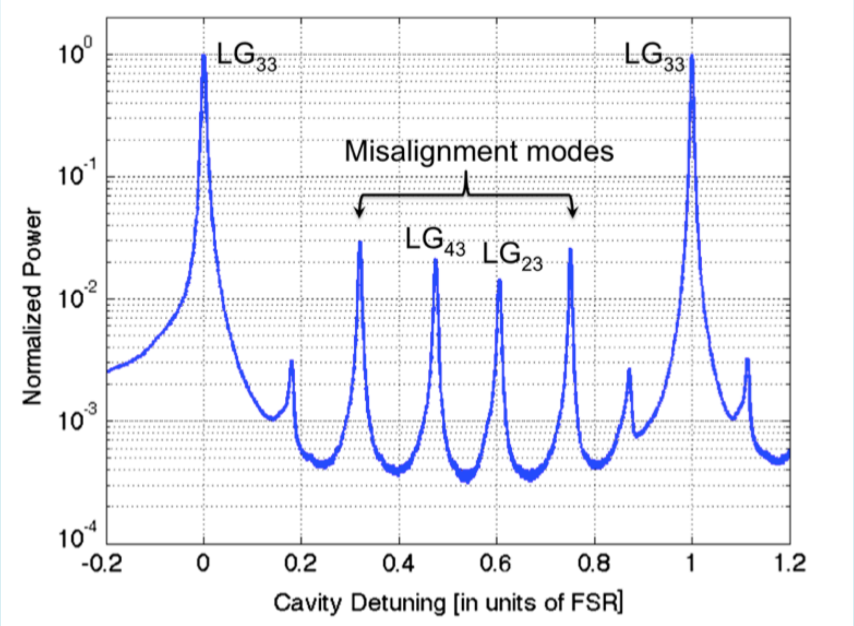
Cavity inputs



$\gamma \sim 99$ %

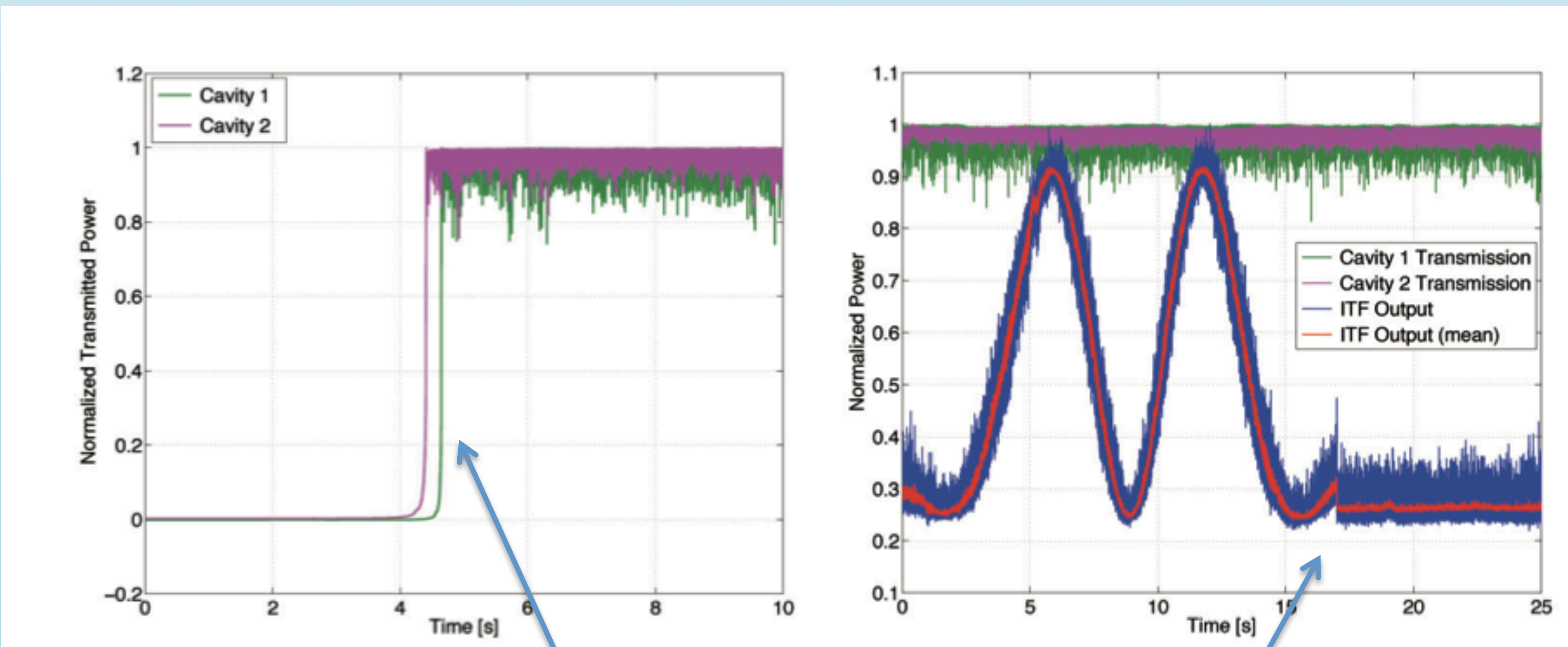
Results/2: itf alignment/matching





Gaussian	Misalignments	Mismatching
Cavity 1	0.8 %	0.0875 %
Cavity 2	1.6 %	0.075 %
LG_{33}	**Misalignments**	**Mismatching**
Cavity 1	6 %	3.5 %
Cavity 2	12 %	4 %

Results/3: Interferometer control

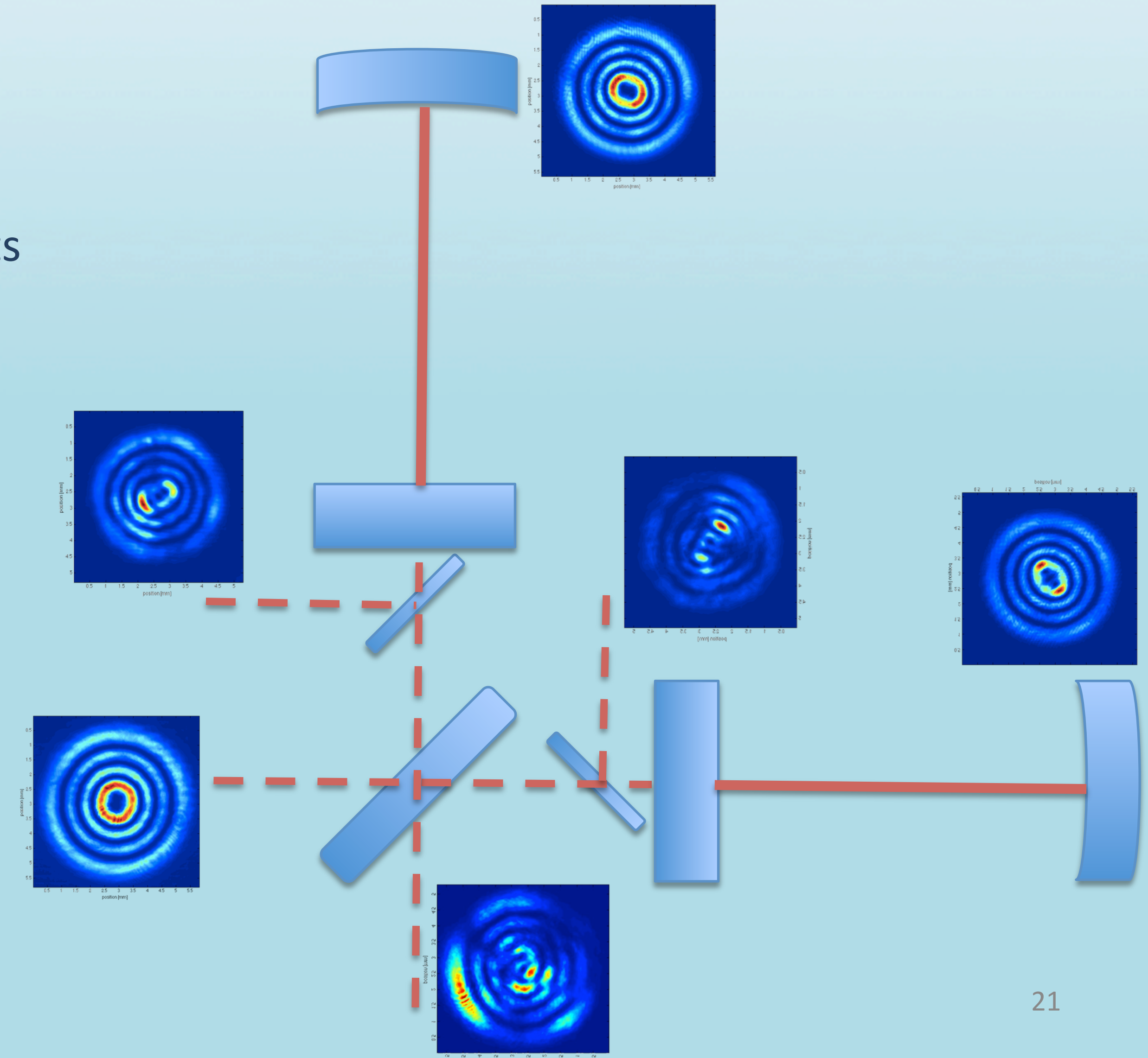


Cavities locked

Michelson locked

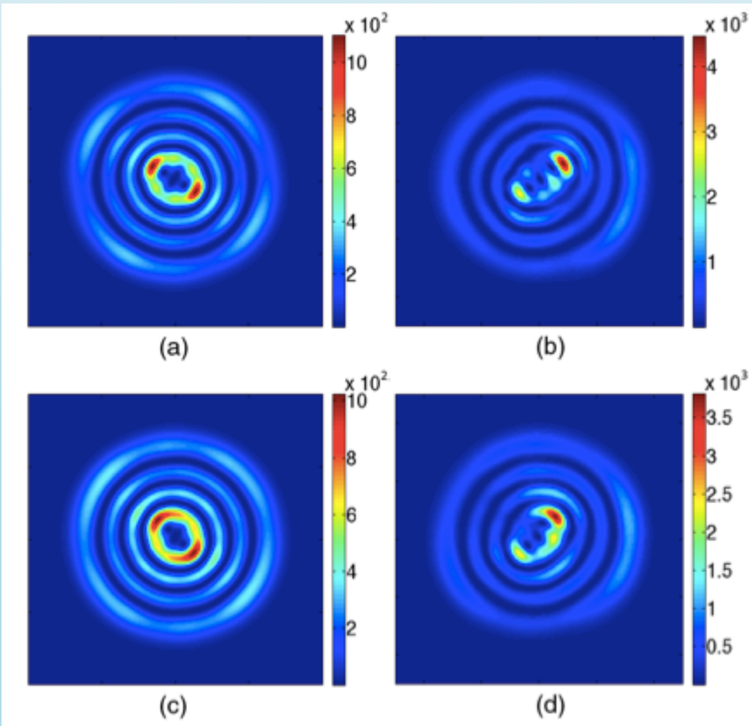
Results/4: beams analysis

- OSCAR Simulations compared with the results



Results/5: cavity beams

Simulated



Measured

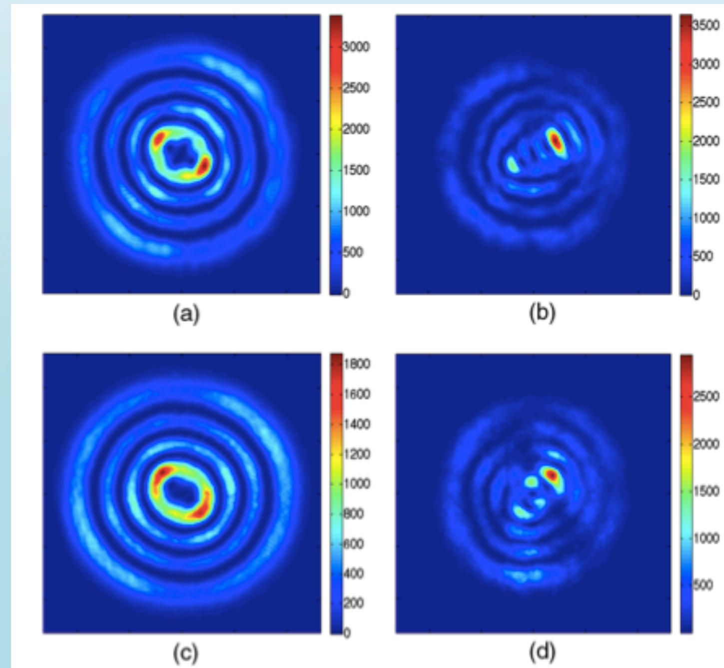
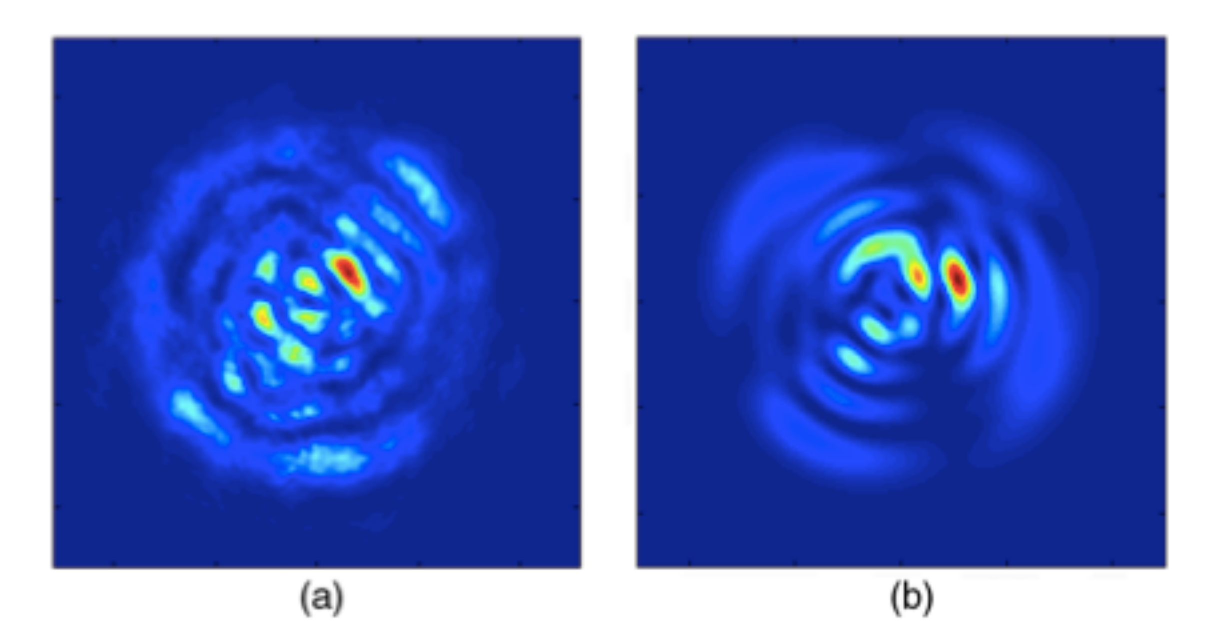


TABLE II. Model parameters.

	Astigmatism		Misalignments	
	Value	Orientation	ITM	ETM
Cavity 1	0.15%	11.65°	7 μrad (x) −35 μrad (y)	−15 μrad (x) −25 μrad (y)
Cavity 2	0.11%	0.4°	9 μrad (x) −38 μrad (y)	25 μrad (x) −39 μrad (y)

Results/6:Dark fringe

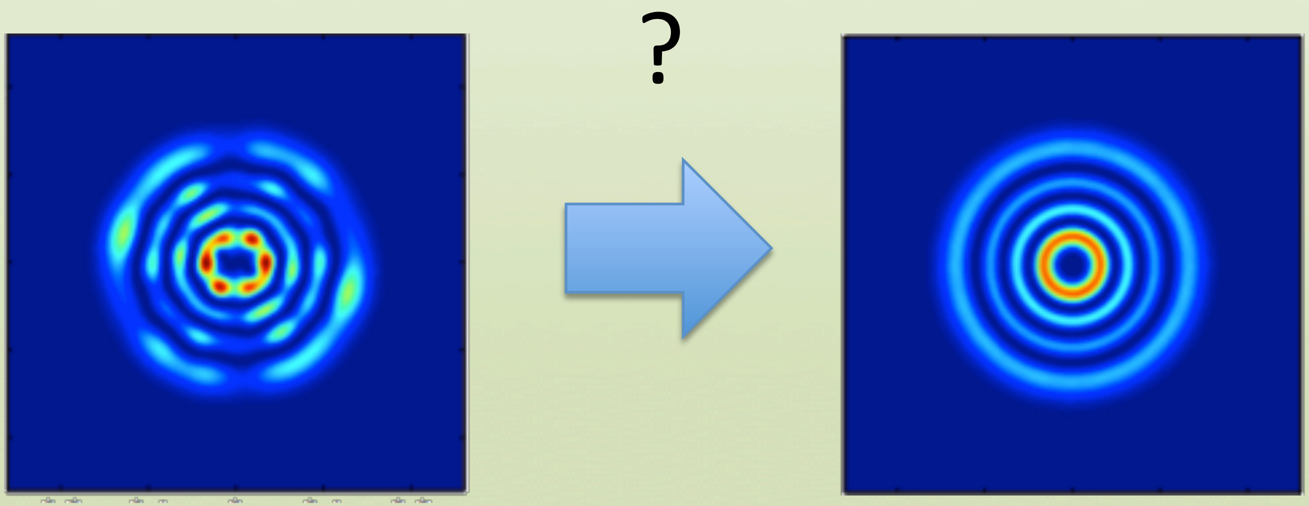
Measured | Simulated



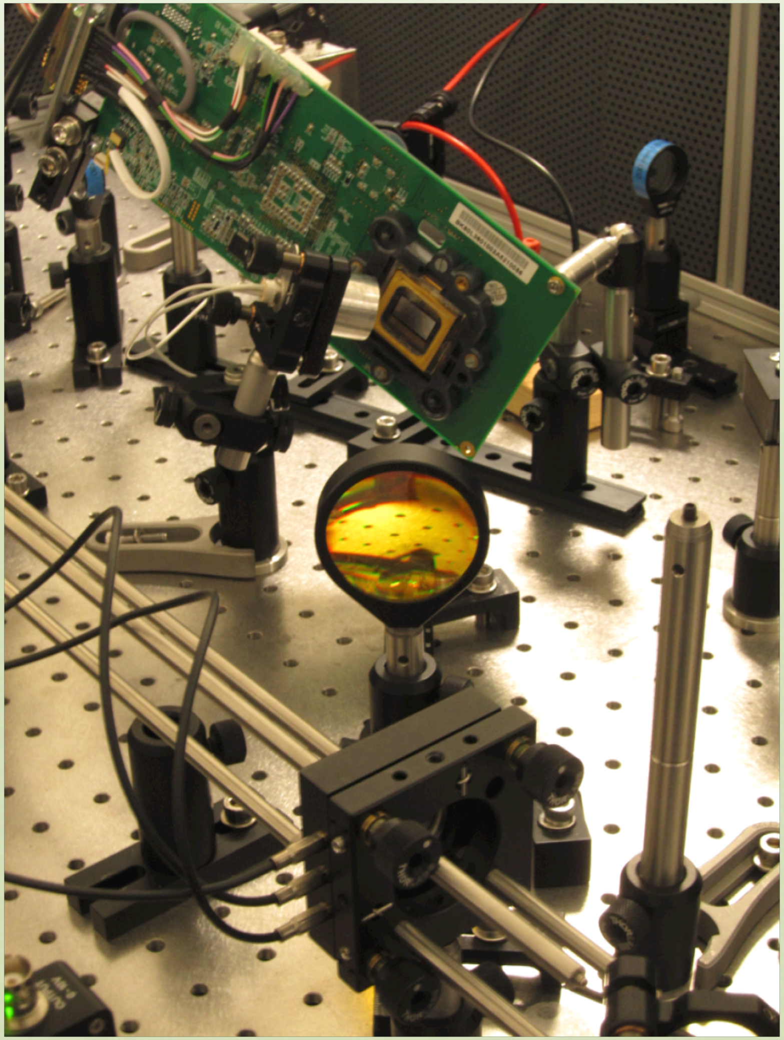
Visibility 84% | Visibility 83%

LG00 Visibility 96% (simulated 98%)

Part 3:
Reduction of the degeneracy



In-situ thermal correction



- ✧ Simple cavity
- ✧ Asymmetric ITF (1 FP cavity and 1 simple mirror)

A.Allocca, INFN Pisa (PhD thesis)

R.Day, EGO

G.Vajente, Caltech

+ APC team (A.Gatto, M.Tacca, C. Buy, M. Barsuglia)

Other paths to reduce degeneracy ?

Configuration	Contrast defect
LG_{33}, F=450 RMS=0.3	**6e-2**
Sin LG_{09}, F=450	3e-2
Sin LG_{09}, hole, F=450	8e-3
Sin LG_{09}, hole, F=225	2e-3
Sin LG_{09}, hole, F=225, RMS=0.1 nm	**3e-4**

Change of modal shape

Corrective coating

Finesse reduction

RMS reduction

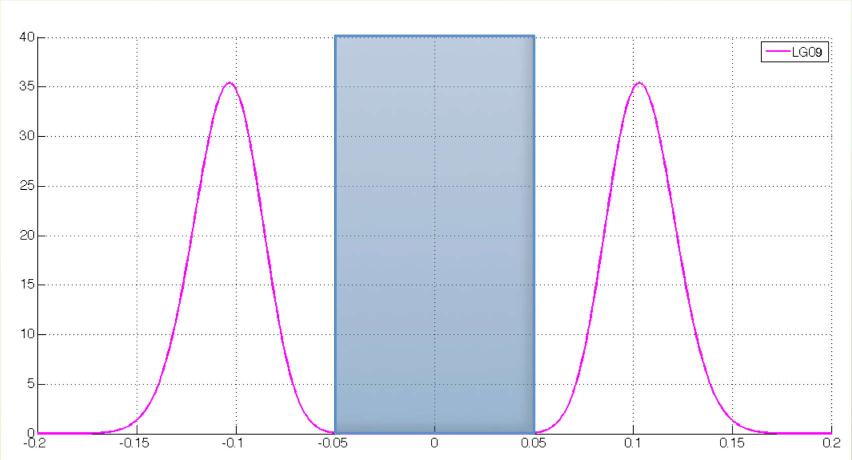
A.Gatto, M.Tacca, C.Buy and M.Barsuglia

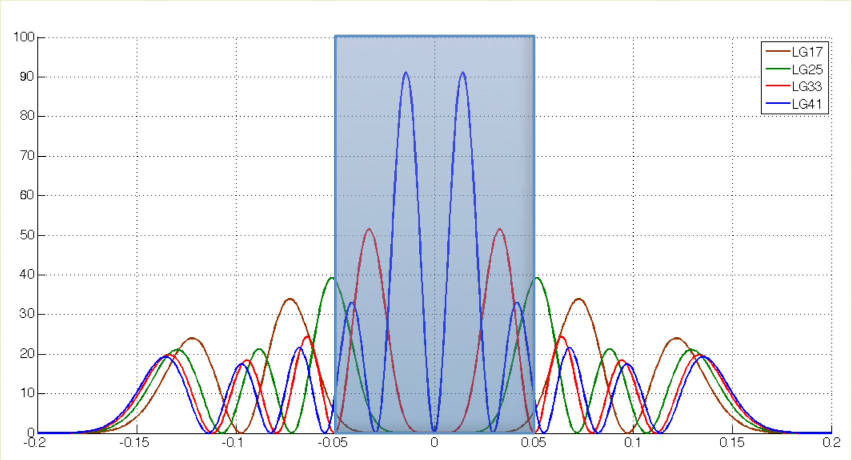
Paths to reduce the beam quality degradation in gravitational-wave interferometers illuminated with higher-order Laguerre-Gauss beams

Paper in preparation

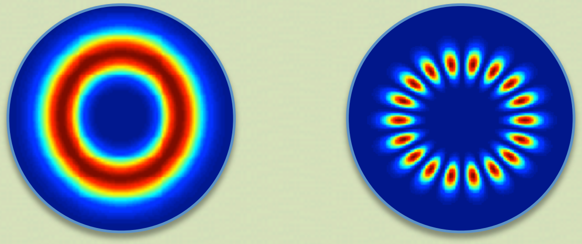
LG_{09} + corrective coating

- ✧ Same order of LG_{33} mode
- ✧ Antireflective coating (as proposed in [1] for LG_{33}) to reduce the resonance of other modes





Helical or sinusoidal LG_{09} beam



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

Summary

- State of the art (2006-2014)

- FP Michelson table-top experiment at the APC
  - LG_{33} modal purity ~99% at the input of both cavities
  - Good matching of both arm cavities (mismatching ~4%)
  - Stable locking of arm cavities and ITF with standard PDH error signals and dithering
  - Best visibility 84%, limited by degeneracy (astigmatism) and residual tilts
    - Visibility with Gaussian mode 96%
  - General agreement between measures and simulations

- Reduction of the degeneracy
  - In-situ thermal correction tested at APC
  - Some other paths under exploration

Open questions/next steps

- Main problem: degeneracy
  - Need ~ 1 order of magnitude reduction in mirror defect

    → not for short term upgrades

- No other *fundamental* obstacles so far

- Is it possible to combine in-situ correction with better mirrors?
  - Progress in mirror polishing/coating in the next ~ 10 years?
    - Discussion started
  - In-situ correction in the next ~ 10 years? Experimental program?
    - Use experience of Advanced detectors
    - Prototypes?
  - Simulation program about other paths (i.e. other modes)?

- Progress in other techniques to reduce thermal noise