Higher-order Laguerre-Gauss modes for future gravitational wave detectors

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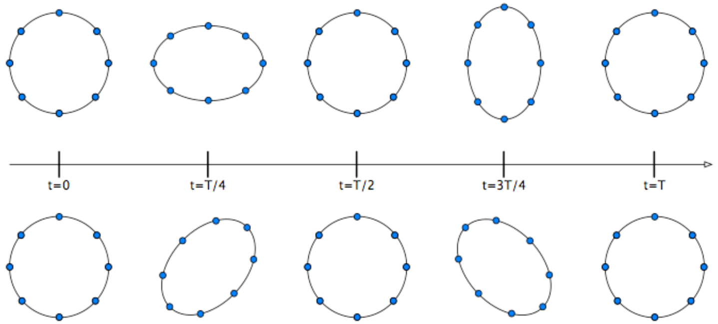
- Gravitational-wave detectors - introduction
- Mirror thermal noise in future gravitational wave detectors
- Noise reduction with Laguerre-Gauss modes
- Table top experiment: scope, layout, results
- Conclusions and next steps

The gravitational waves (GW)

- Perturbations of the space-time metrics



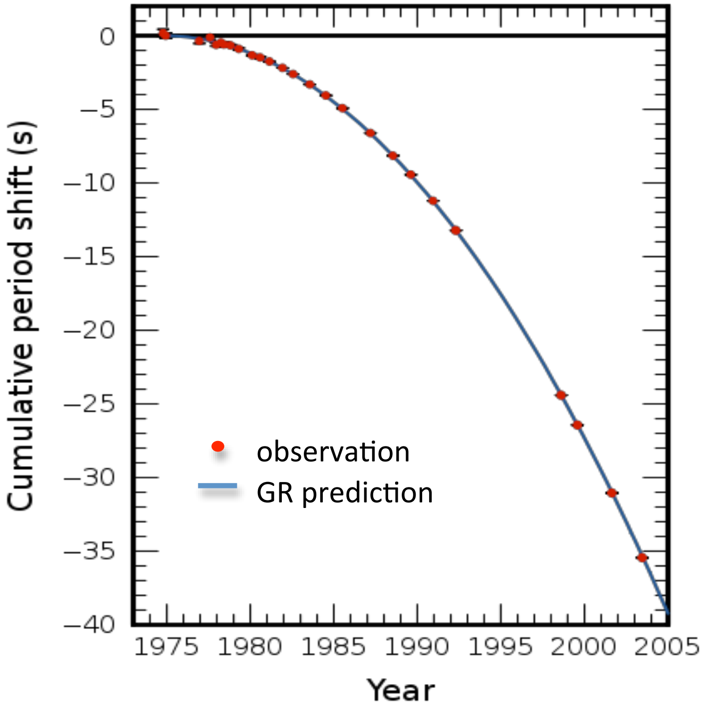
General Relativity

- Propagation at the speed of light
- Tranverses, 2 polarisations at 45 degrees
- Generated by mass quadrupole acceleration

- Order of magnitude: coalescence of neutron stars of 1.4 Msun at 15 Mpc

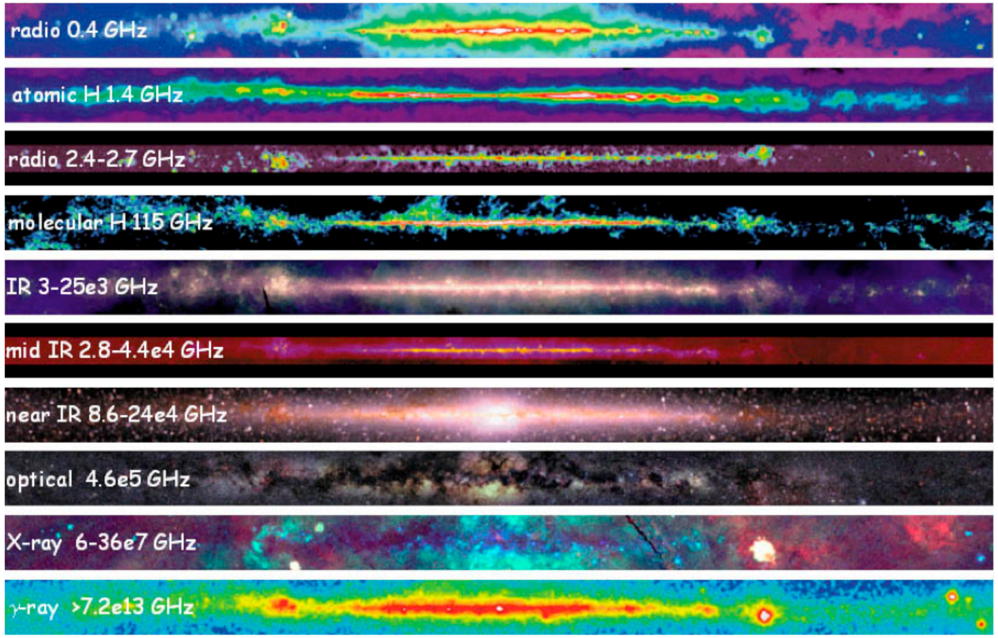
$$h \approx \delta L / L = 10^{-21}$$

- No direct detection
- Indirect detection: decrease of orbital period of PSR1913+16 (and other similar systems)



The possible Science with the gravitational waves

- Test of the General Relativity
- Understand Gamma ray bursts progenitor
- Information on the equation of state of neutron stars
- Study of supernovae Physics
- Cosmology: standard candles
- Search of a cosmological gravitational-wave background

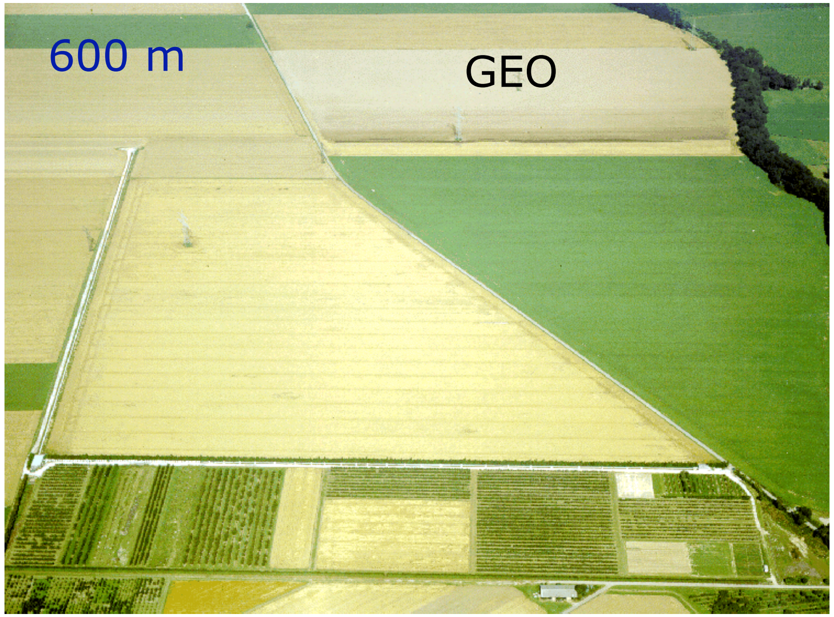


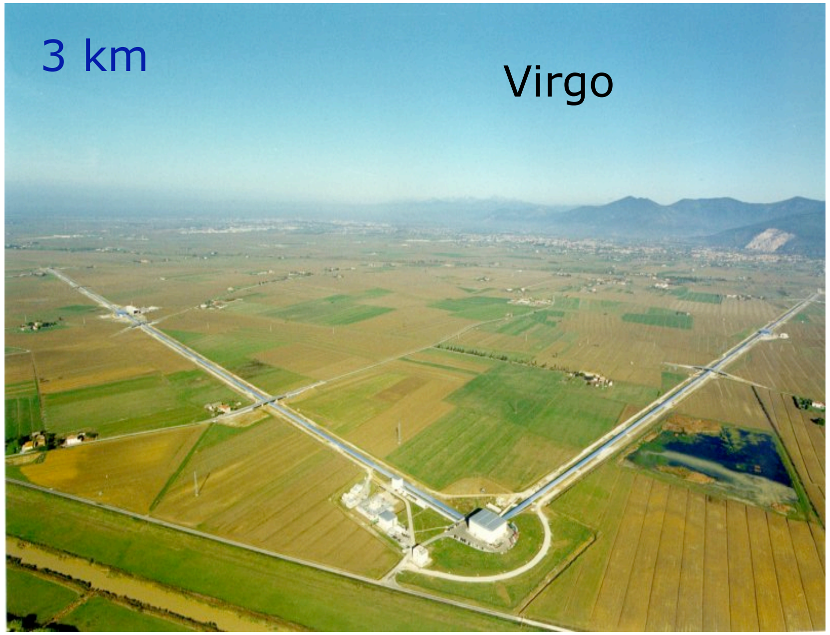
Gravitational-wave sky ?

...a new messenger

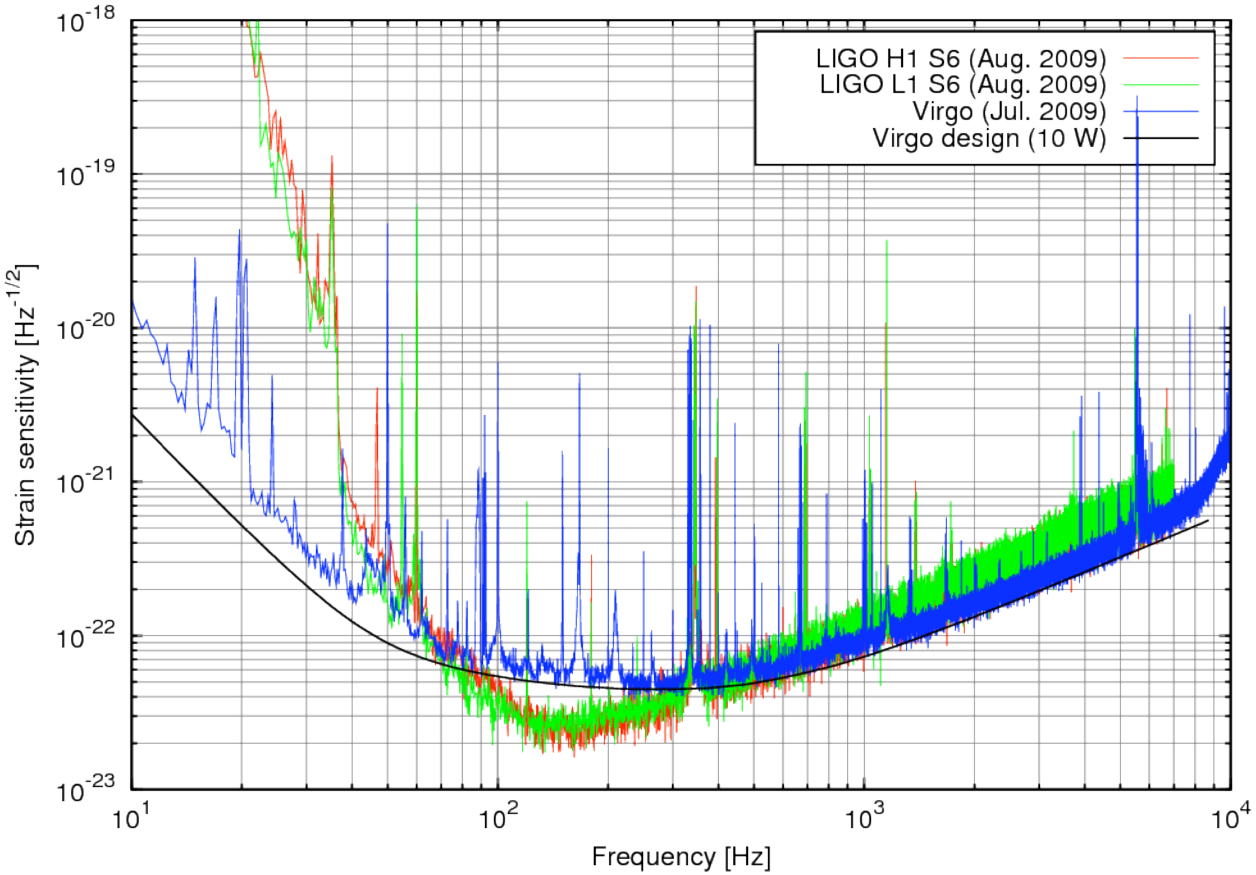
Physics, *Astrophysics and Cosmology*
With Gravitational Waves, Satyaprakash and Shultz
Living review in Relativity

First generation detectors





First generation detectors: sensitivities



Best NS-NS horizon

LIGO ~ 20 Mpc
Virgo ~ 10 Mpc

- ☐ Sensitivities at design level
- ☐ Excellent duty cycles (up to ~80%)
- ☐ km scale GW interferometer technology demonstrated
- ☐ ...but expected rates of events expected very low

Coalescing binaries: estimates for initial detectors and upper limits

Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors, Class. Quant. Grav. 27, 173001 (2010)

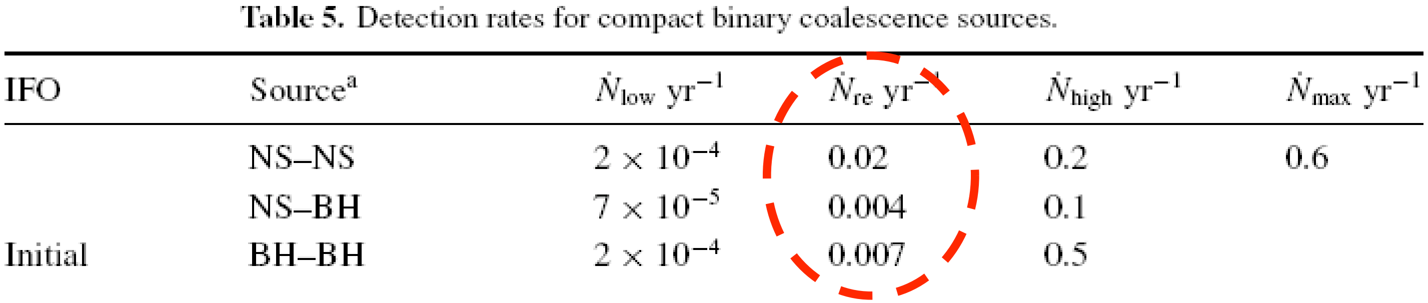
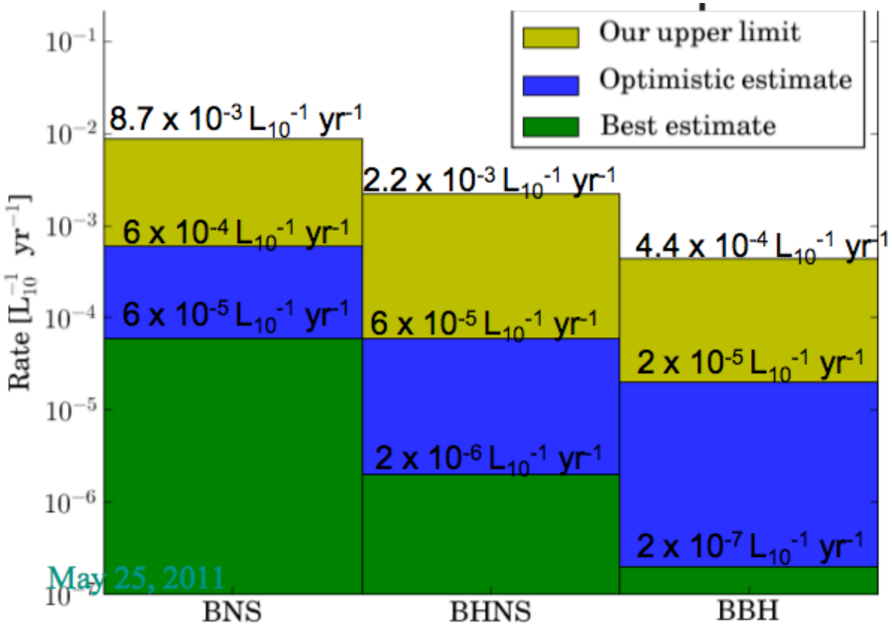


Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\text{low}}\ \text{yr}^{-1}$	$\dot{N}_{\text{re}}\ \text{yr}^{-1}$	$\dot{N}_{\text{high}}\ \text{yr}^{-1}$	$\dot{N}_{\text{max}}\ \text{yr}^{-1}$
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	

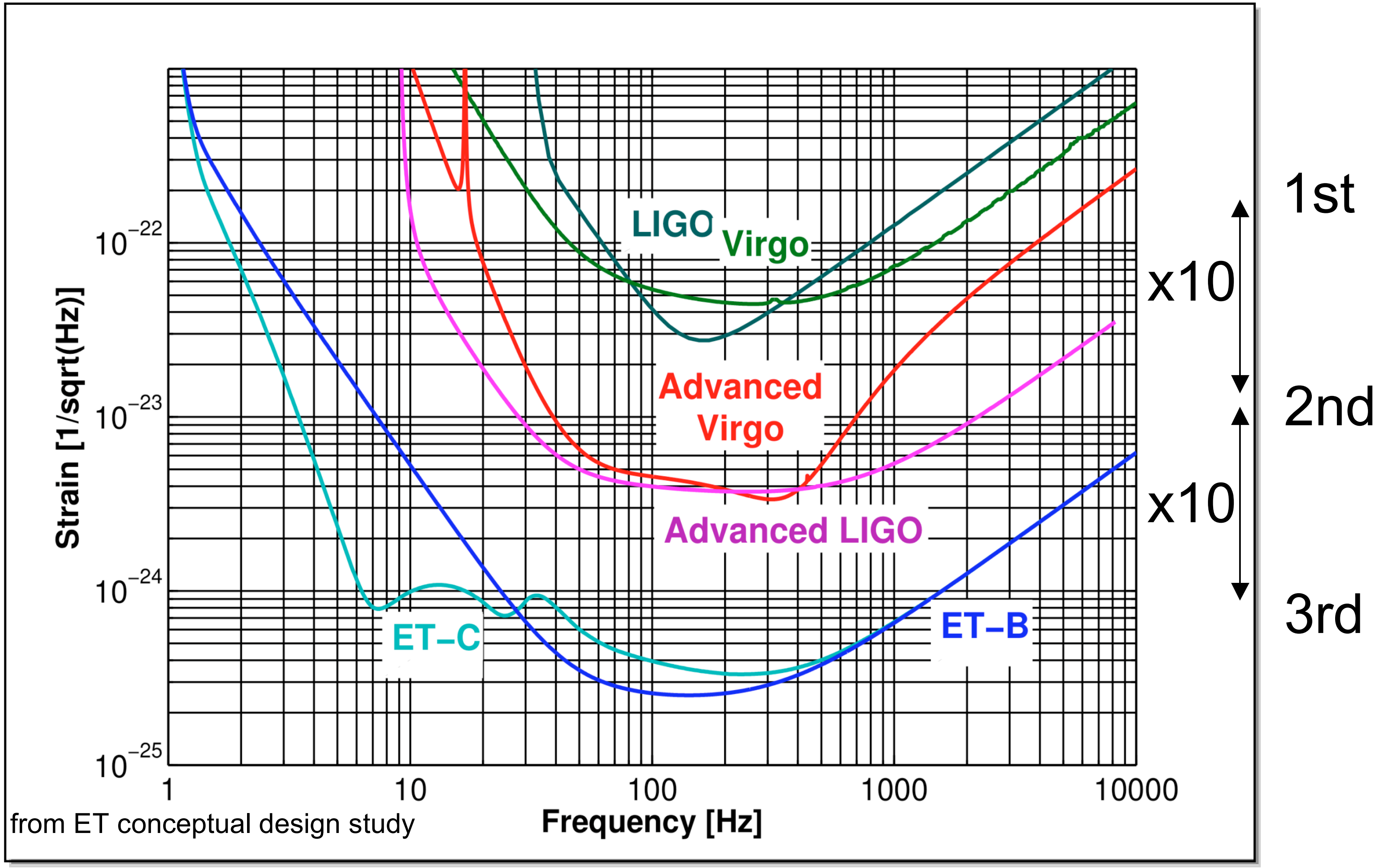


May 25, 2011

- Rate upper limits from LIGO-S5/Virgo-VSR1 data
- 1-2 orders of magnitude above optimistic estimates

Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1, PRD 82 (2010) 102001

Future ground-based GW detectors



from ET conceptual design study

rate increase ~ (sensitivity increase) ^{3}

Rate estimates for 2nd generation detectors

Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors, Class. Quant. Grav. 27, 173001 (2010)

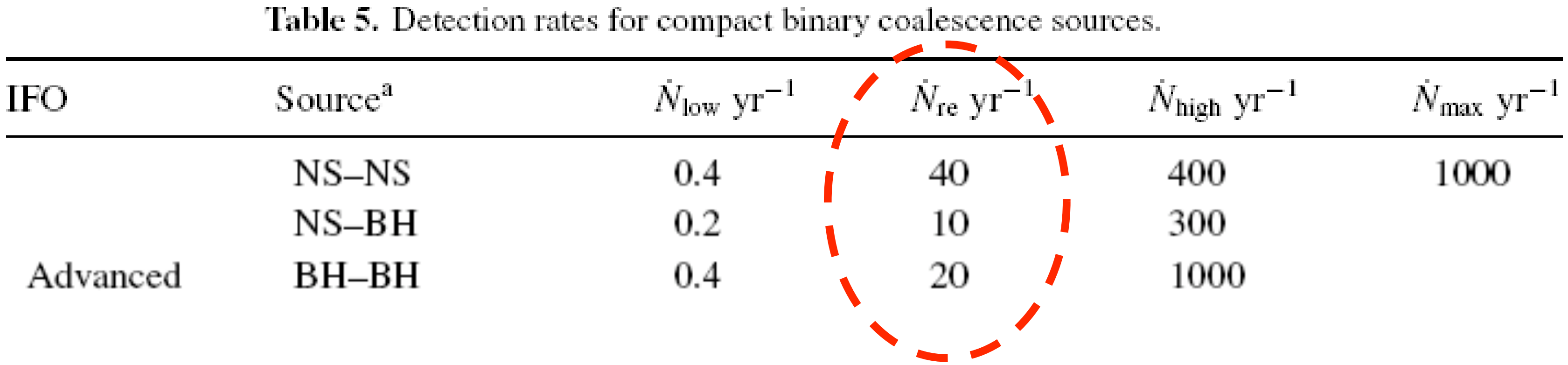


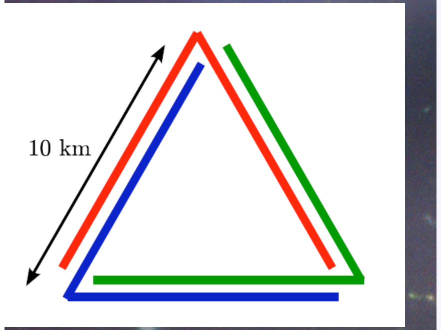
Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	

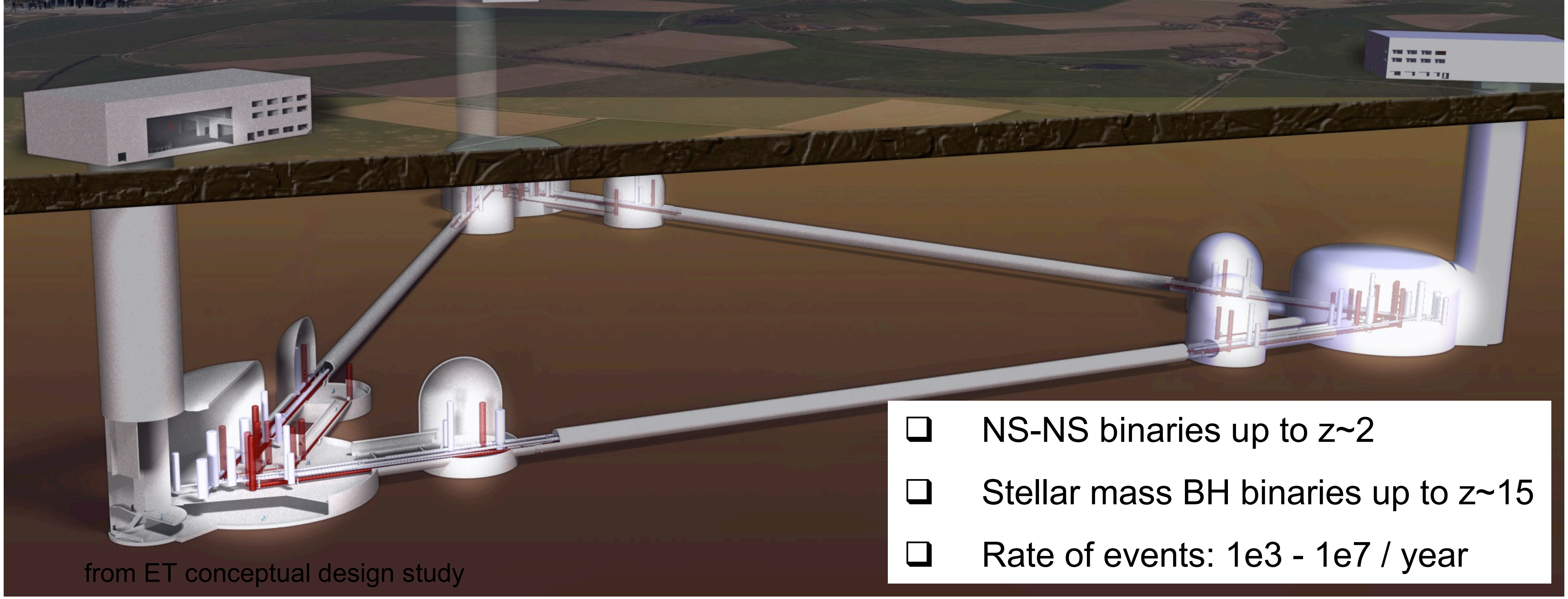
- NS-NS ~ 200 Mpc
- BH-BH ~ 1 Gpc

Likely detection by second generation interferometers

Einstein Telescope



- Design study of a 3rd generation European interferometer (under FP7)
  - Goal: increase the sensitivity by a factor 10 with respect to 2nd generation interferometers (Advanced Virgo and Advanced LIGO)
  - Extend the detection band down to 1 Hz
- Underground - triangle - 10 x 3 km of tubes
- design study document ready (pre-released)
- Next step - technical design
- Science data > 2025 (if funded)

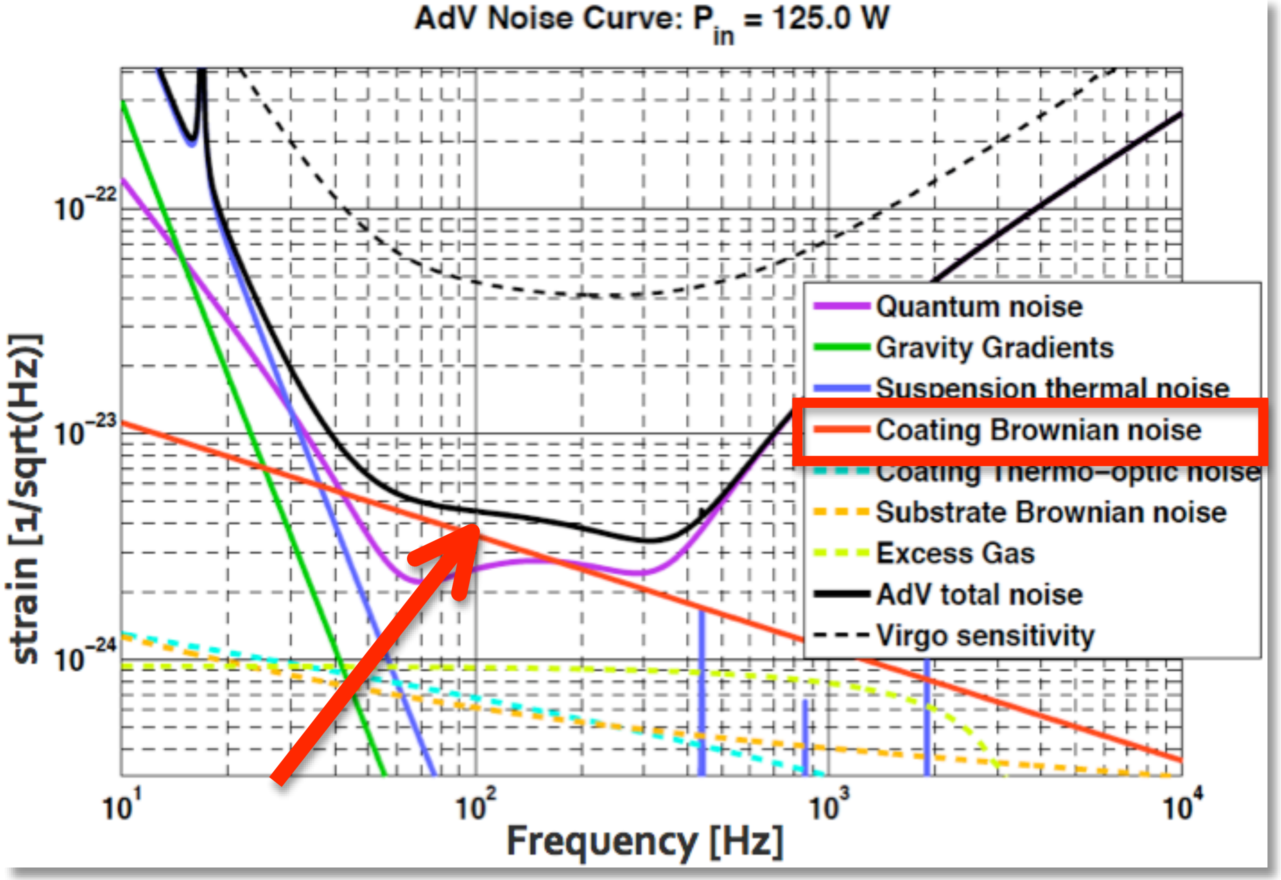


- NS-NS binaries up to z~2
- Stellar mass BH binaries up to z~15
- Rate of events: 1e3 - 1e7 / year

from ET conceptual design study

Mirror thermal noise in future detectors

- MTN is predicted to limit the sensitivity of advanced (aLIGO [1] and AdVirgo [2]) and third generation (Einstein Telescope [3]) detectors around 100 Hz



[1] aLIGO team, LIGO-M060056-v1 [2] Virgo coll., VIR-027A-09 [3] Punturo et al., Class. Quantum Grav. 27, 2010

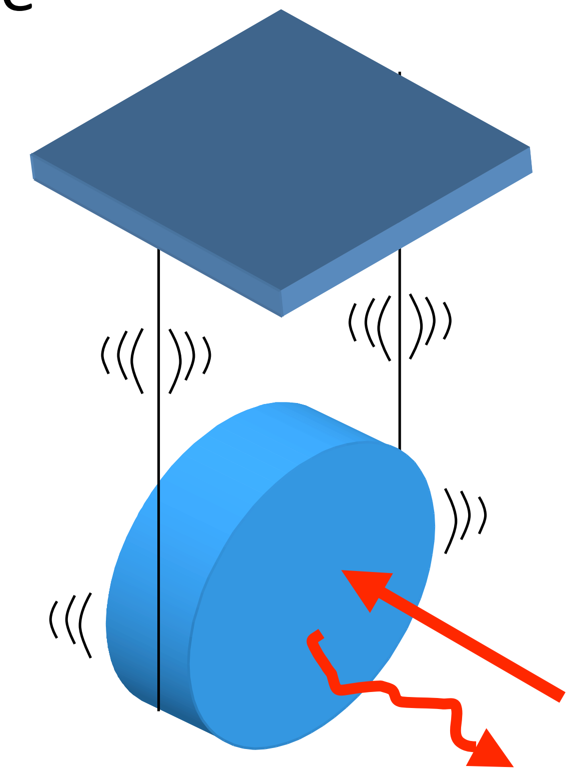
The thermal noise

- *fluctuation-dissipation theorem*

$$\boxed{F^2(f) = 4k_bT\,\mathrm{Re}(Y(f))}$$

  - Example: the Johnson-Nyquist noise

$$V^2(f) = 4k_bTR$$

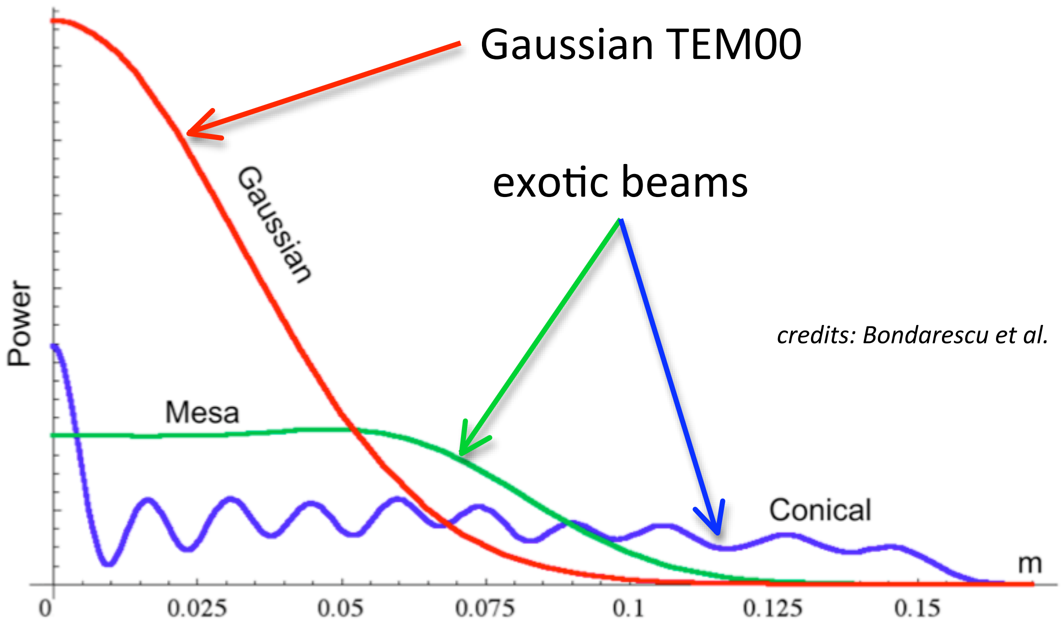


    - Reduction
      - Better materials
      - cryogenics
      - Increase the beam size
      - Non gaussian beams

$$x(f) = \alpha\sqrt{\frac{4k_bT\phi}{f}\frac{1}{w}}$$

New read-out beam geometries

MTN could be efficiently averaged out by using mesa [4, 6] or conical beams [5]



Gaussian TEM00

exotic beams

credits: Bondarescu et al.

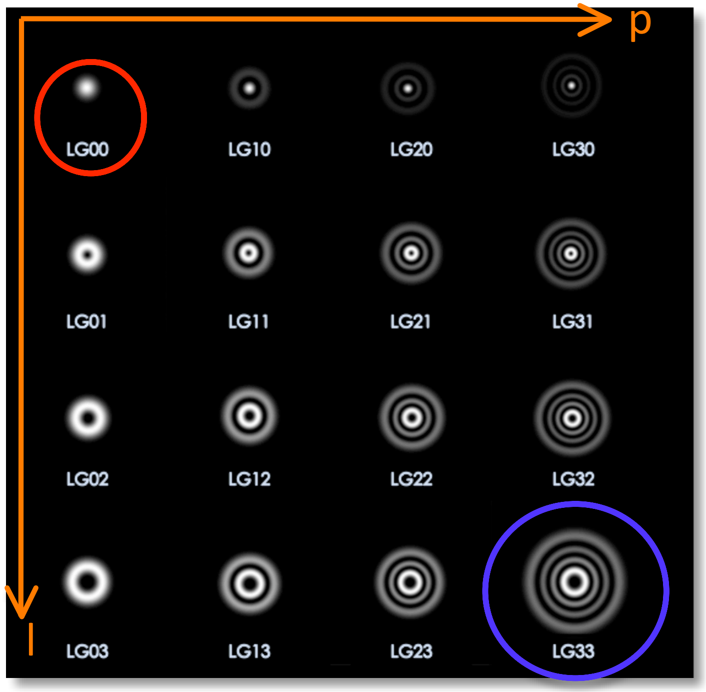
[4] E. D’Ambrosio, Phys. Rev. D 67, 2003

[5] M. Bondarescu et al., Phys. Rev. D 78, 2008

[6] M. G. Tarallo et al., Appl. Opt. 46, 2007

Problem: these beams resonate in cavities with non-spherical mirrors

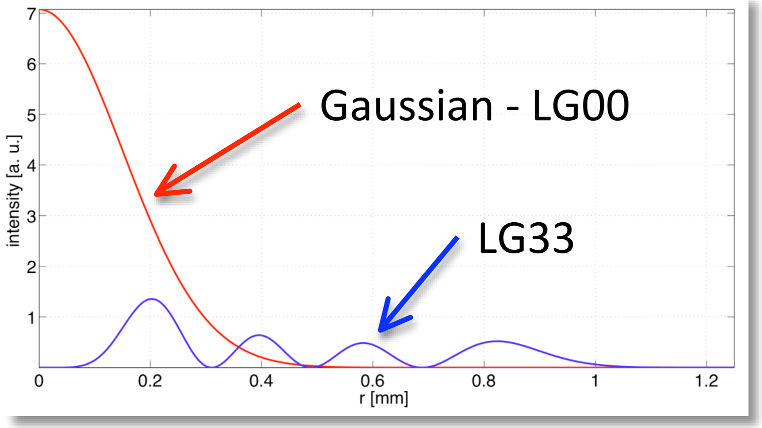
Laguerre-Gauss (LG) modes [7]



- ✓ eigenmodes of spherical-mirror resonators (like present arm cavities of Virgo and LIGO)
- ✓ laser beam power spread over a larger surface
- ✓ the higher the order N=2p+l ➔ the wider the beam shape ➔ the larger the expected noise reduction [7]
- ✓ predicted **noise reduction factors** [8]:

AdVirgo with LG33: **1.76**

Einstein Telescope [HF] with LG33: **1.83**



[7] B. Mours et al., Class. Quantum Grav. 23, 2006

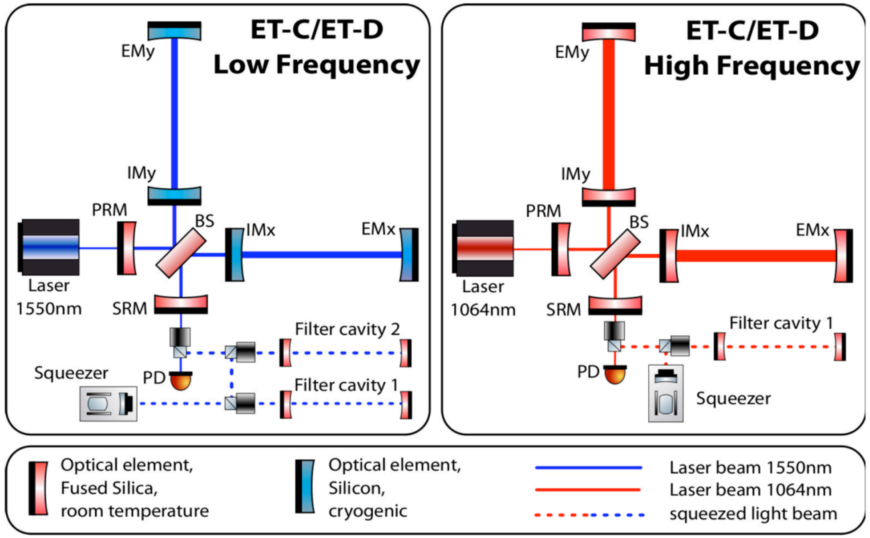
[8] J. Franc et al., ET-0002A-10

LG modes and Einstein Telescope

Cryogenic (10 K)

Low power input (3 W)

Silicon mirrors

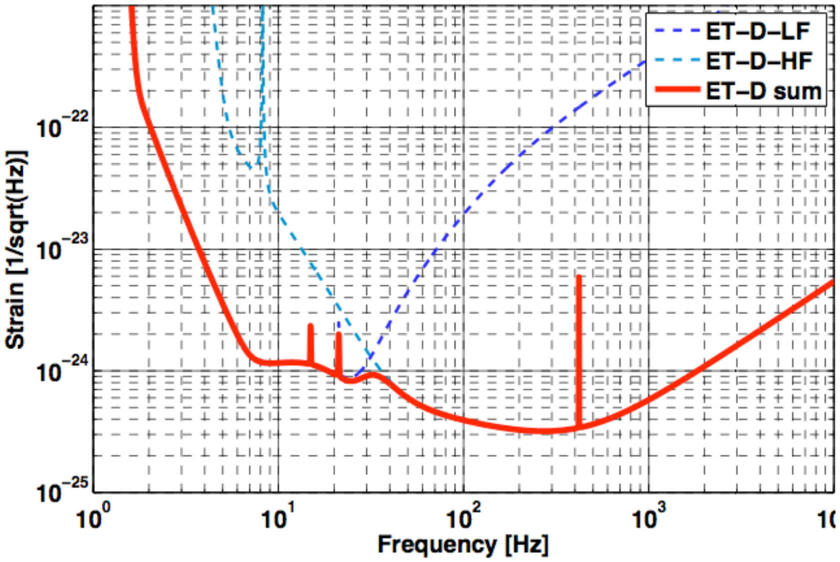


Room temperature

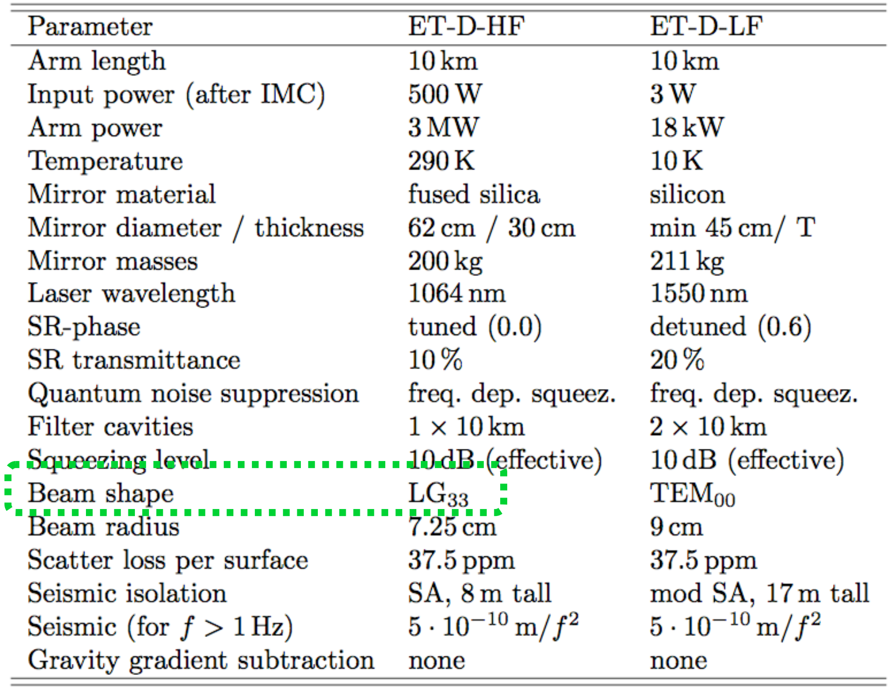
High power input (500 W)

3 MW in the arms

Fused silica mirrors



from ET conceptual design study



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)	$5 \cdot 10^{-10}$ m/f^2	$5 \cdot 10^{-10}$ m/f^2
Gravity gradient subtraction	none	none

Goal of the table-top experiment

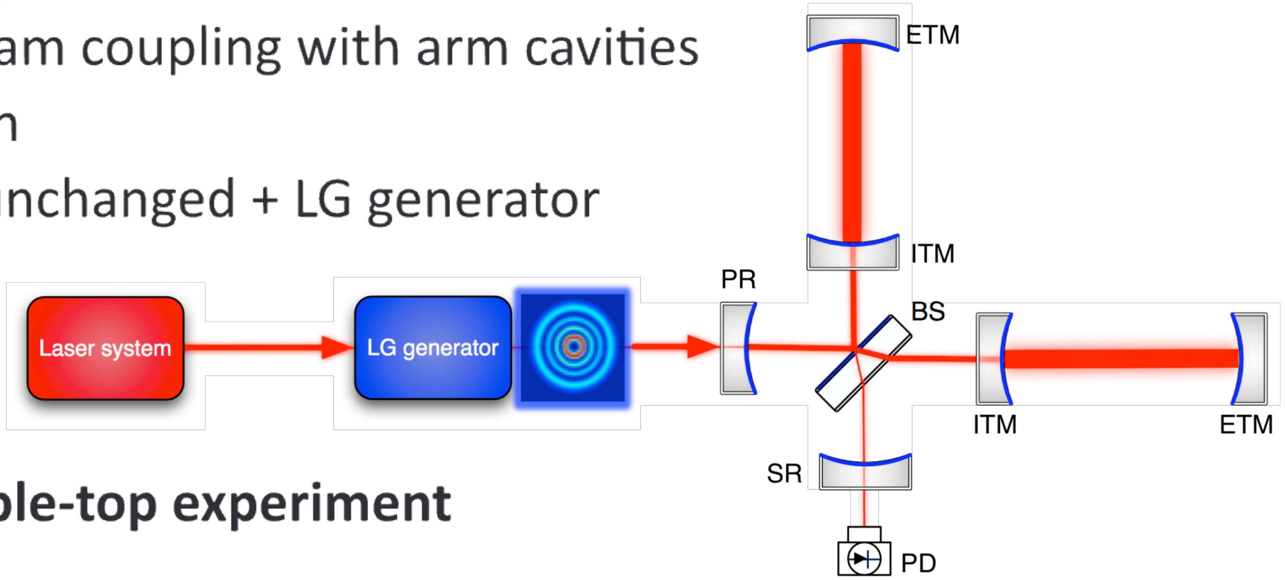
LG beams have never been used for GW detection. We need to study:

1. optimal technique for LG mode generation
2. optical performances and control requirements of LG beams

We aim to:

I. Develop **efficient and suitable** technique to generate **high-purity** LG modes :

- high efficiency ➔ low power loss
- high purity ➔ high beam coupling with arm cavities
- simple implementation
  ➔ laser system unchanged + LG generator



II. **test LG beams on a table-top experiment**

Generation technique

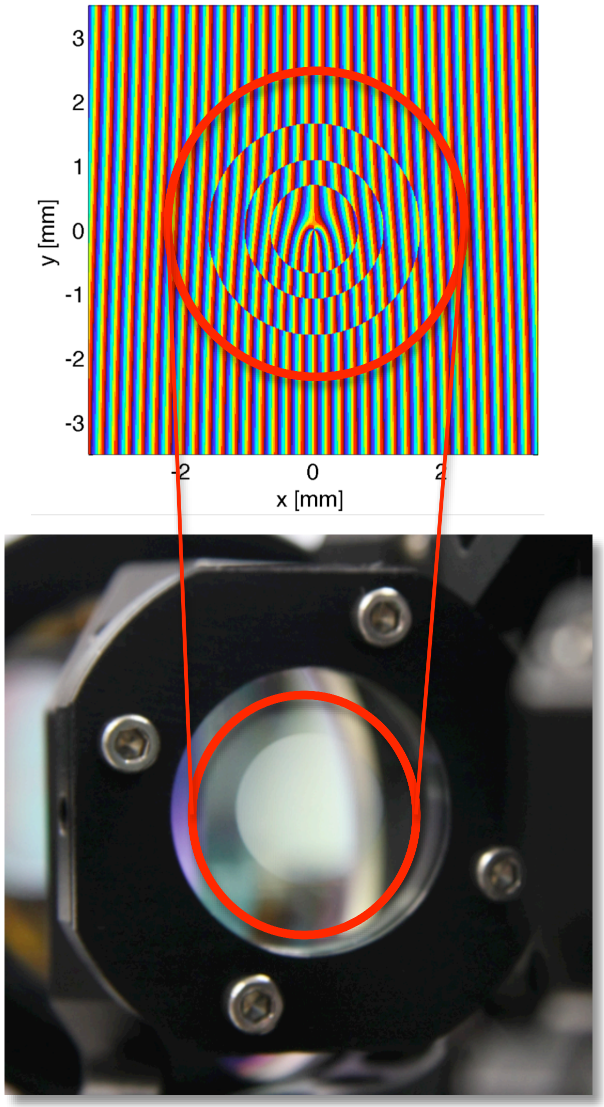
We selected an etched-glass diffractive plate (DP) to generate an LG33 mode:

- simple technique: the DP is a phase retarder
- stable passive optic
- can handle high power beams

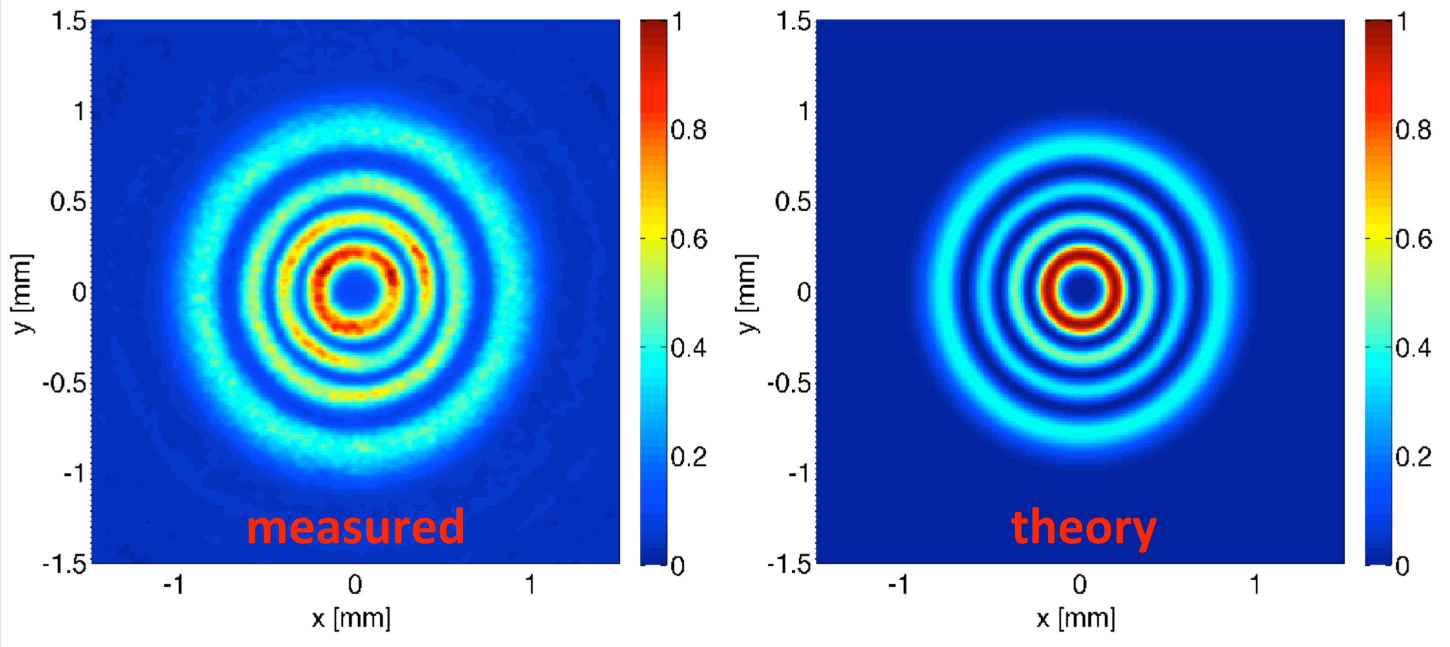
➔ scalable to future GW detectors ✓

Creation of Laguerre-Gaussian laser modes using diffractive optics, Kennedy et al., Phys Rev A, 2002

- DP realized by SILIOS Technologies
- Phase pattern: LG33 phase + blazed grating
- 2400x2400 pixels, 1 pixel = 5.9 µm
- 16 phase levels etched on the surface



Generated pseudo-LG33 mode



- mode purity ≡ 2D-amplitude overlap integral at a given point along propagation (upper limit, phase is neglected): $\gamma = \left\langle LG_{33theory} \middle| LG_{33measure} \right\rangle = 88\%$
- coupling losses: $L = 1 - \gamma^2 = 23\%$

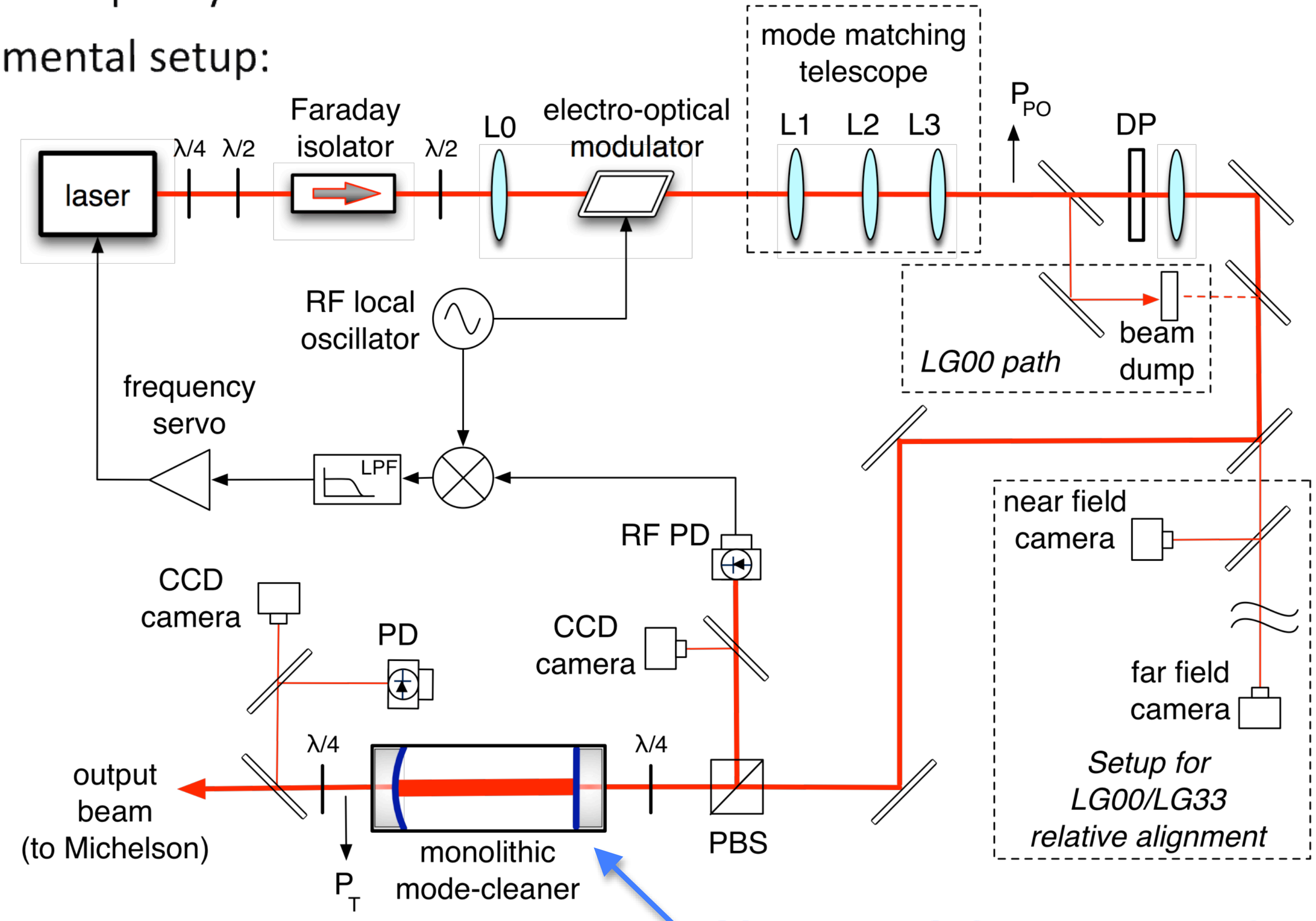
due to:

- design of the diffractive plate pattern

- astigmatic input LG00 beam

Spatial filtering for high-purity LG33 modes

- The generated pseudo-LG33 mode can be flitered in a mode-cleaner cavity to increase its purity
- Experimental setup:

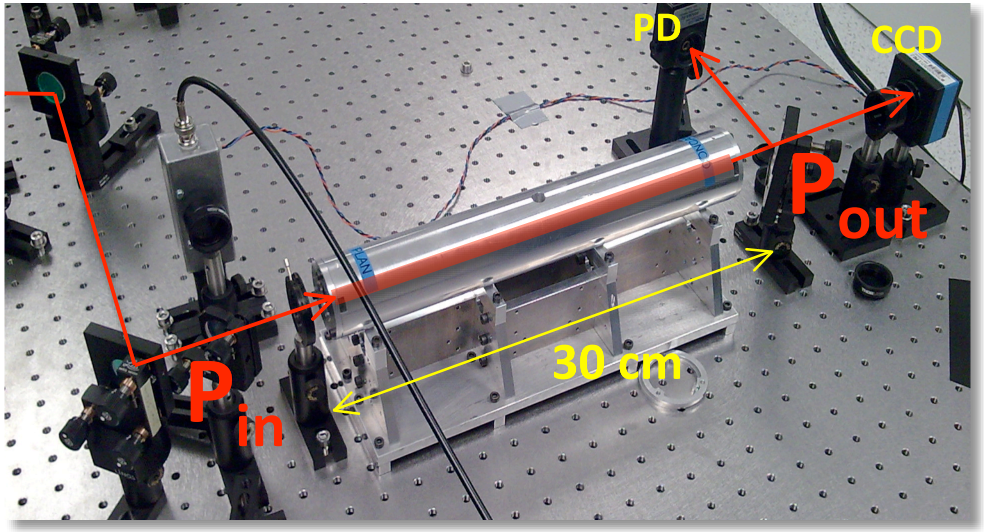


filtering of the generated LG33

LG33 mode filtering

mode-cleaner:

- plano/concave monolithic cavity
- Finesse = 103 , FSR = 500 MHz
- **stable locking (hours) on LG33 eigenmode resonance**



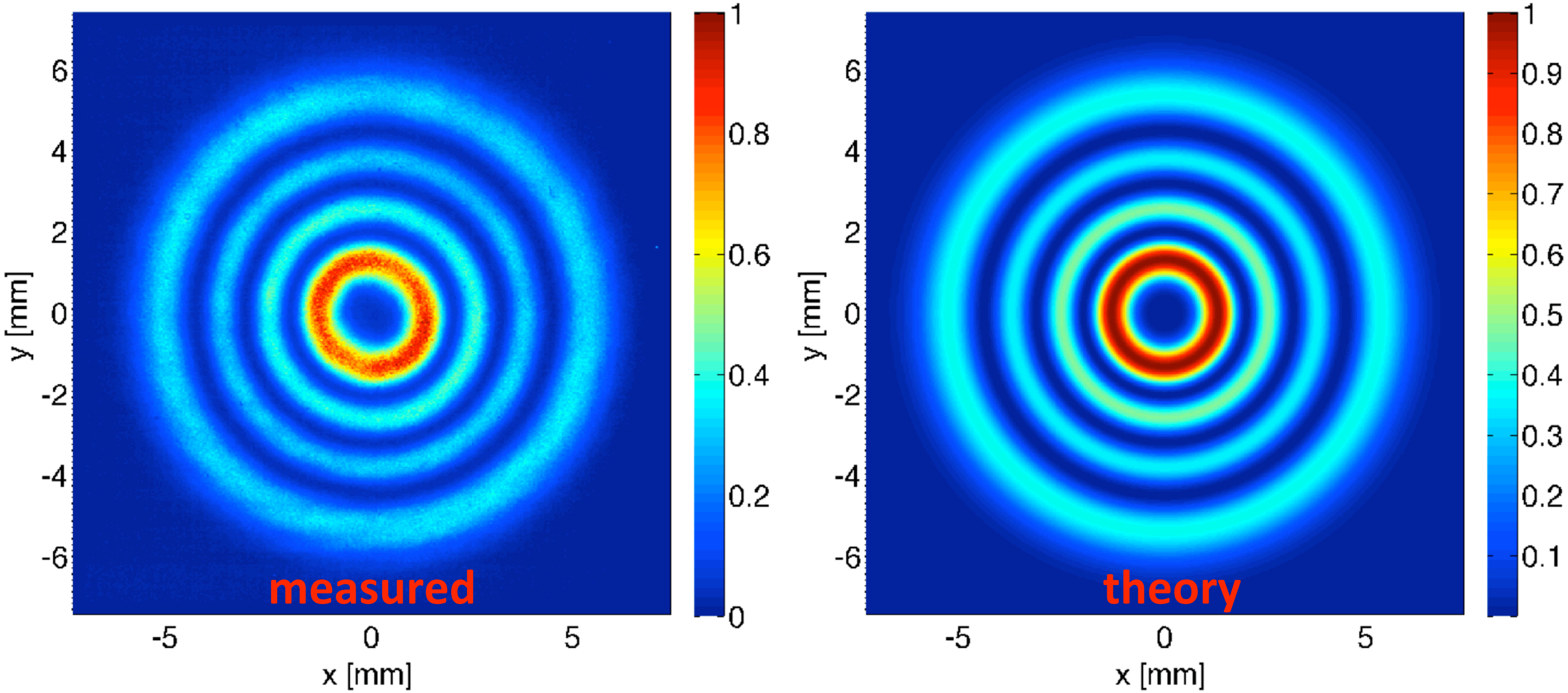
LG33 transmission: $P_{out} / P_{in} = 58\ \%$

throughput: $\tau = 90\ \%$ ➡ **P_{in} LG33 = 64 %**

power on other modes: $P_{other} / P_{total} = 19\ \%$

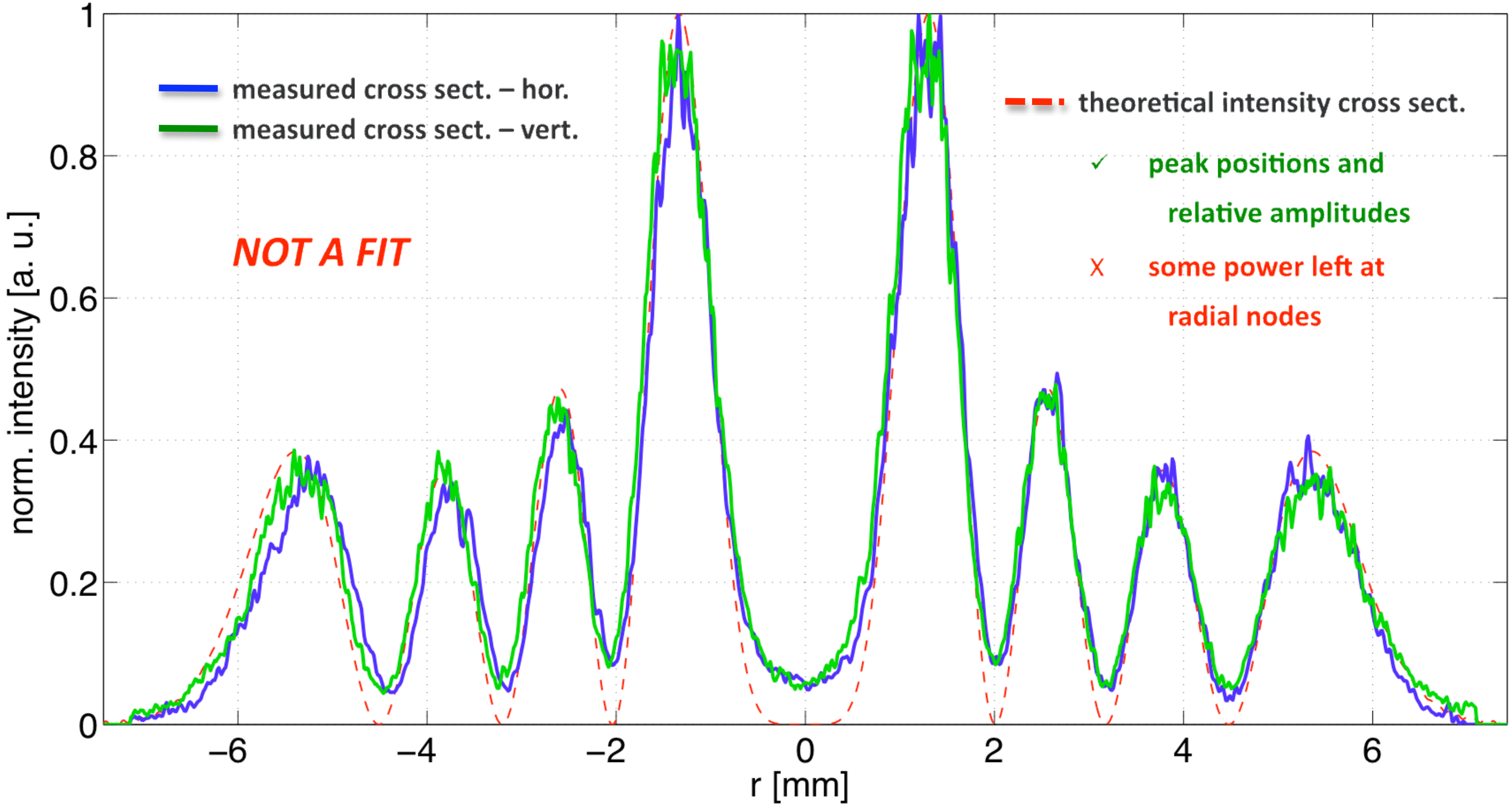
High-purity transmitted LG33 mode [1]

- Beam far-field images:



- Purity is higher: $\gamma = \left\langle LG_{33th} \middle| LG_{33meas} \right\rangle = 98\%$
- Coupling losses are 6 times smaller: $L = 1 - \gamma^2 = 4.0\%$

High-purity transmitted LG33 mode [2]

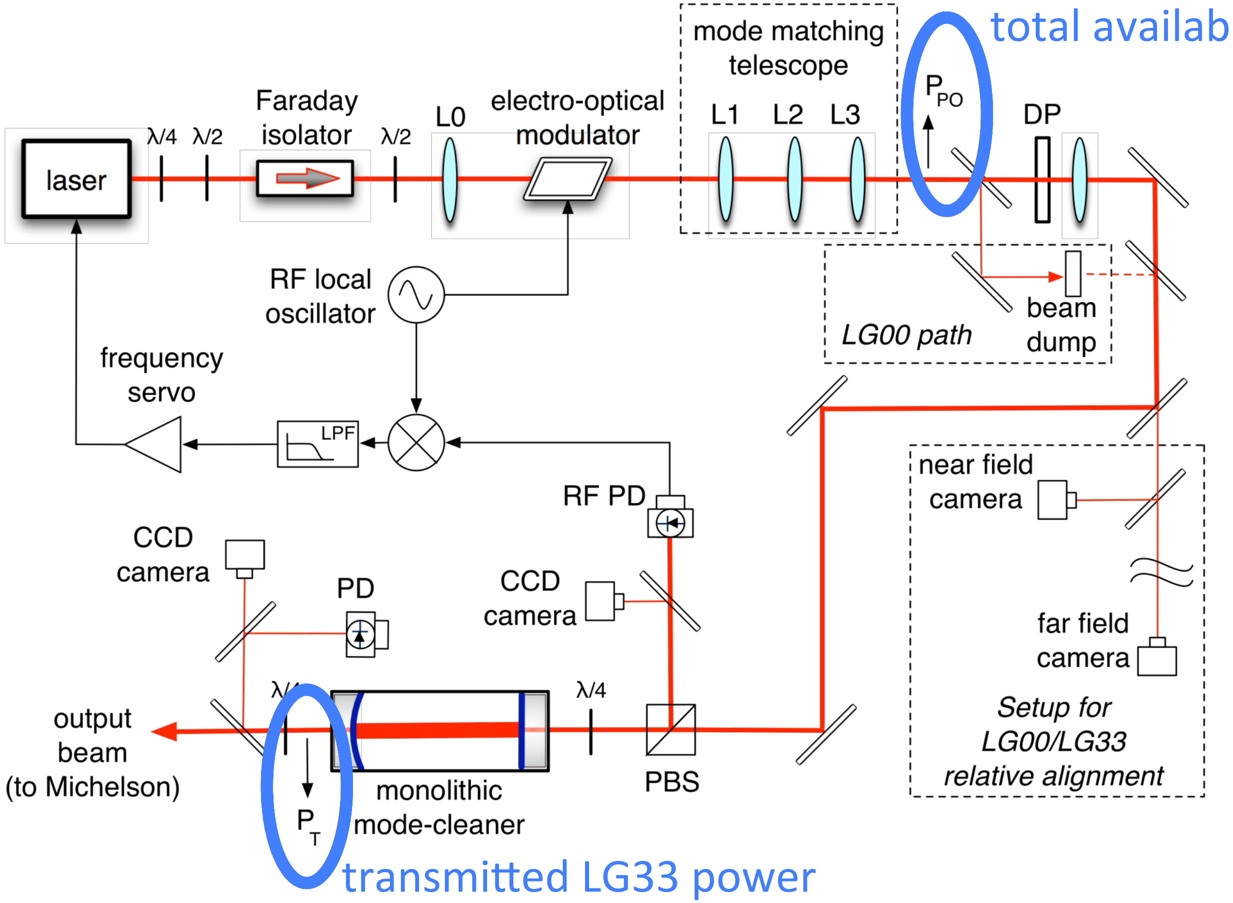


NOT A FIT

✓ peak positions and relative amplitudes

X some power left at radial nodes

Global conversion efficiency



total available power

transmitted LG33 power

$$(P_{33})_T / P_{PO} = 36\ \%$$

the transmission of the setup is measured with the Gaussian LG00 beam

LG33 conversion efficiency:

$$\boldsymbol{\varepsilon = \gamma^2 (P_{33})_T / (P_{00})_T = 49\ \%}$$

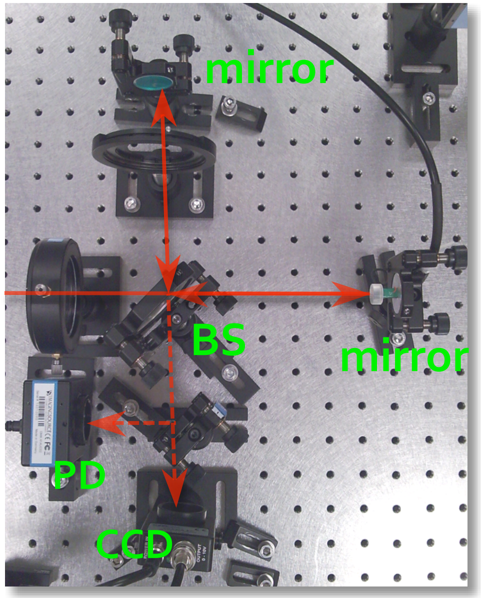
towards higher conversion efficiency: optimization of input LG00 beam shape
of DP phase pattern
of cavity mode-matching

A table-top interferometer with LG modes

Goal: test table-top LG33 power recycled Fabry-Perot Michelson

- test the optical performances
- validation of a sensing scheme for longitudinal & angular control
- measure the sensitivity of the LG33 beam to misalignments

1st step: operation of a simple Michelson



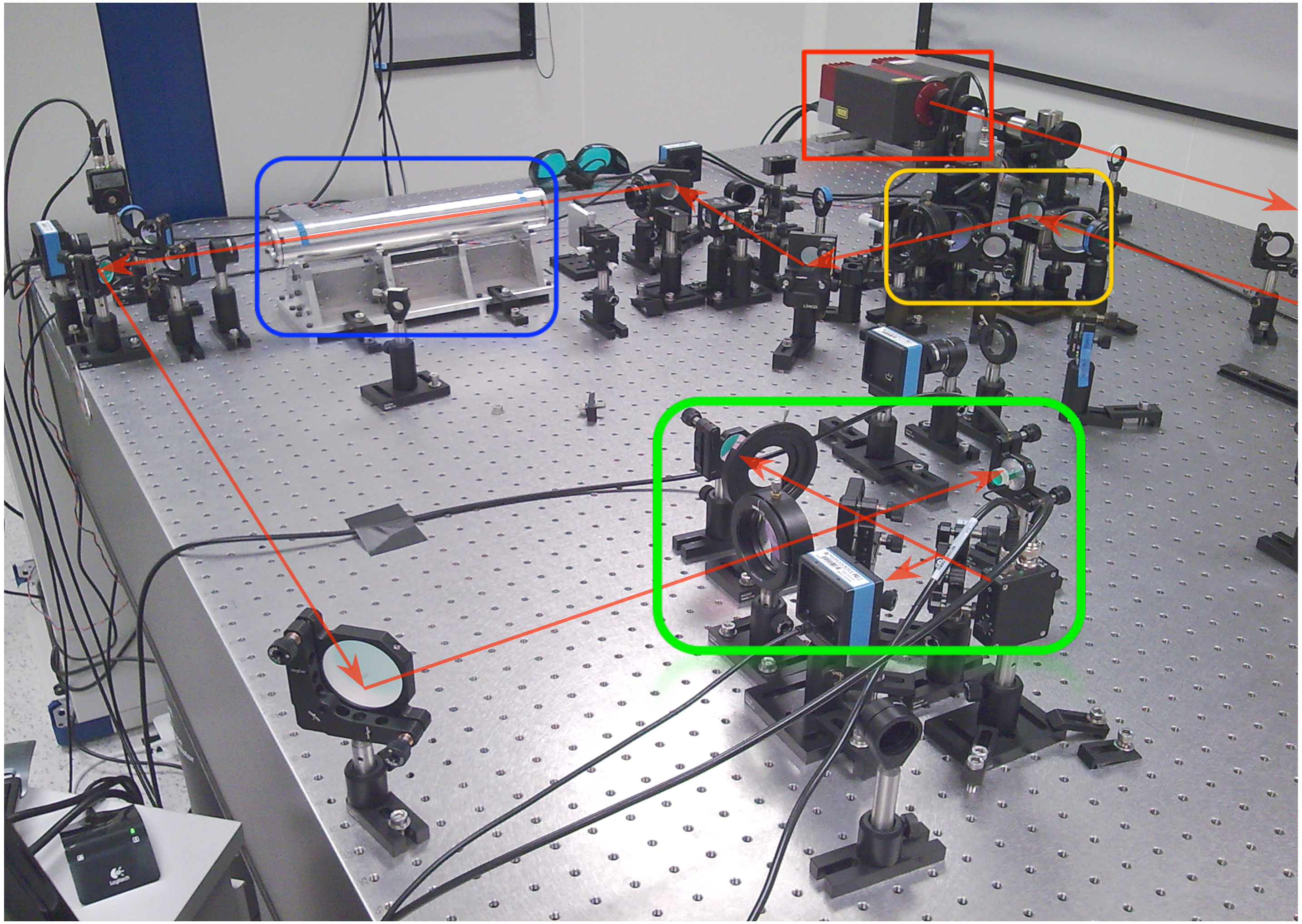
locked using the same digital control system of Virgo

preliminary fringe visibility:

$$V = (P_{max}-P_{min}) / (P_{max}+P_{min}) = 99\ \%$$

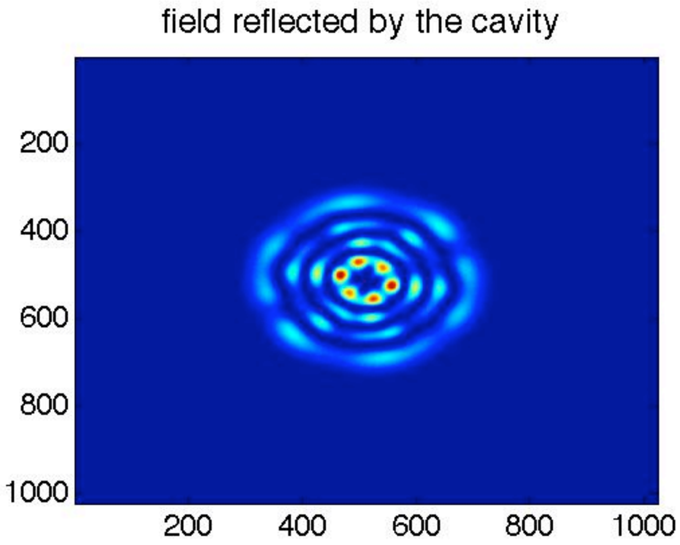
2nd step (yet to come): upgrade of the optical configuration

The experimental set-up



The degeneracy problem

- The critical point of this technique is the degeneracy of high-order LG modes (simulations by Adhikari et al., Caltech, Galimberti et al., LMA-Lyon)
- Mirror figure errors could excite degenerate modes of the same order of the LG33 (N=2P+l = 9), spoiling the contrast of the interferometer
- Mirror quality required is higher than what is available with present technology
- Efforts to understand/mitigate this problem on going



Conclusions

- A generator based on an etched fused silica plate and a mode-cleaner cavity is able to produce high-purity LG33 modes with good efficiency
- This technique can be extended to the high power required in future GW detectors and its efficiency can be further improved
- The alignment and the lock of the mode-cleaner and of the simple Michelson demonstrated the feasibility of higher-order LG mode basic interferometry

For more details:

M. Granata, C. Buy, R. Ward, M. Barsuglia, 'Higher-order Laguerre-Gauss mode generation and interferometry for gravitational wave detectors', Phys. Rev. Lett. 105 (2010) 231102

Next steps

- Try to solve/mitigate the degeneracy problem
- Test performances and control schemes of a table-top complex interferometer illuminated with an LG33 mode
- Improve the efficiency of the generator