Optical Techniques for Gravitational-Wave Detection

M. Tacca

Nikhef - Amsterdam

Nikhef- 2017 July 14th

Introducing Myself

Born in Novara (Italy)

PostDoc Fellow @ Nikhef (since July 2017)

Laurea & PhD @ Politecnico di Milano (Italy)

Researcher @ APC - Paris (France)

PostDoc Fellow @ EGO - Virgo site (Italy)

Introducing Myself

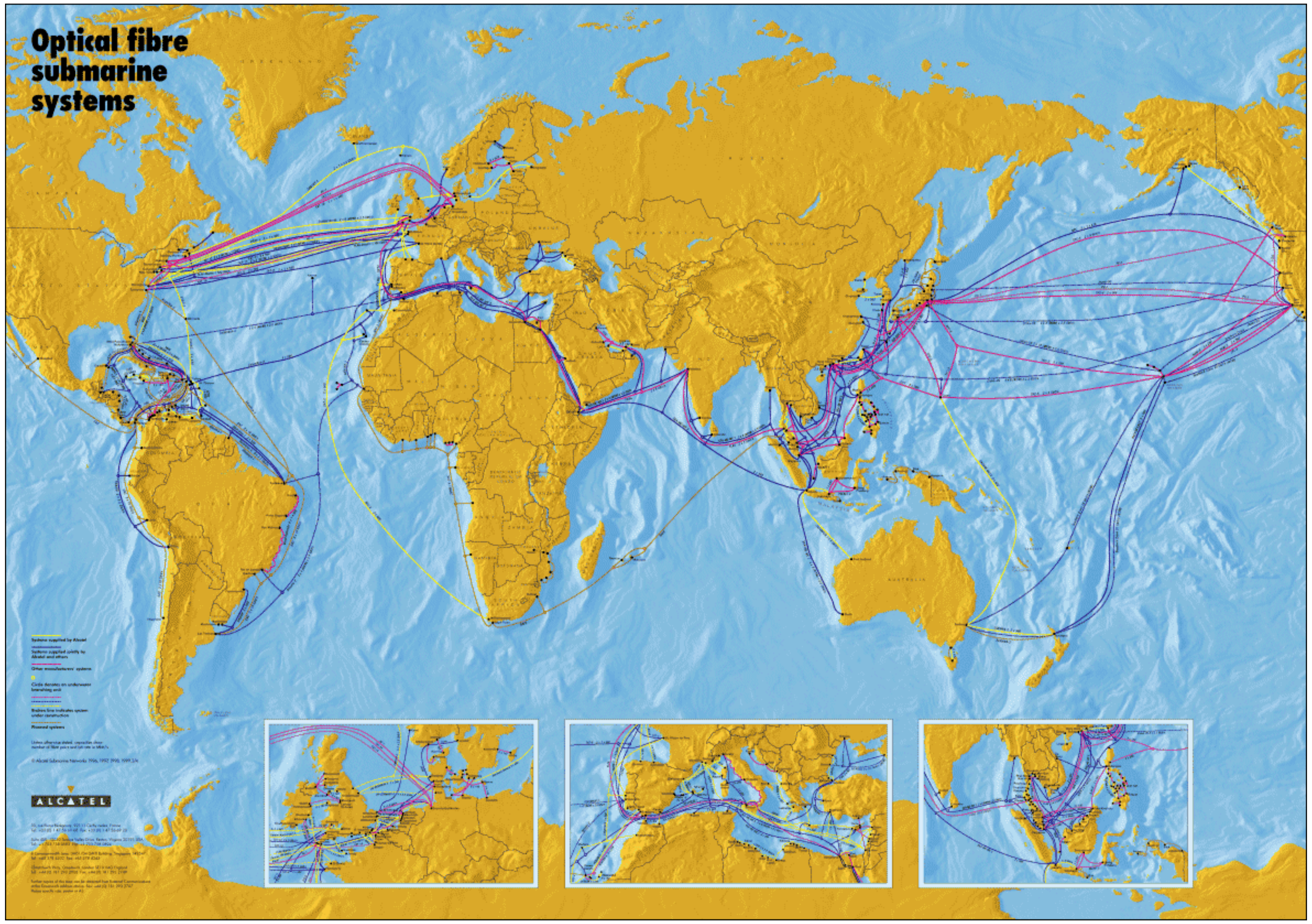
Telecommunications

- From 2003 to 2009: CoreCom/Policom laboratory @ Politecnico di Milano (Laurea and PhD):
  - Study of the opto-mechanical and propagation properties of the optical fibers.
  - Close collaboration with Prysmian, a world leader company of systems for energy and telecommunications.

Gravitational-Wave detection

- From 2009 to 2012: European Gravitational Observatory (EGO) -> Virgo site
  - Virgo+ commissioning.
  - Advanced Virgo design.
- From 2013 to June 2107: Laboratoire AstroParticule et Cosmologie
  - Advanced Virgo design, installation & commissioning.
  - R&D for the third generation of gravitational-wave detectors.

Telecommunications: Long Haul Network

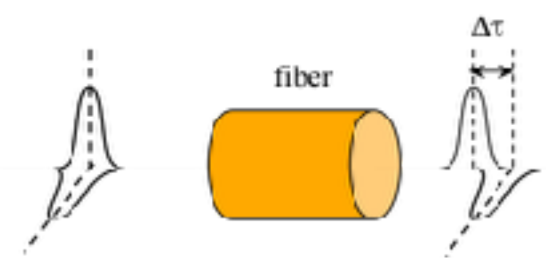


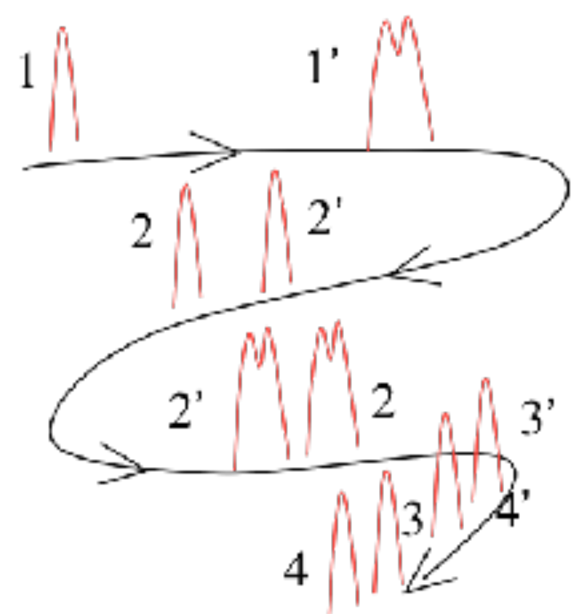
High Bit-Rate

- 10 Gb/s to 100 Gb/s
- WDM @ 1550 nm

Polarization Mode Dispersion (PMD)

- Real Standard Single Mode Optical Fibers are birefringent.
- *A* propagation delay is accumulated between the polarization modes.
- Pulses are broadened and split along the optical links.





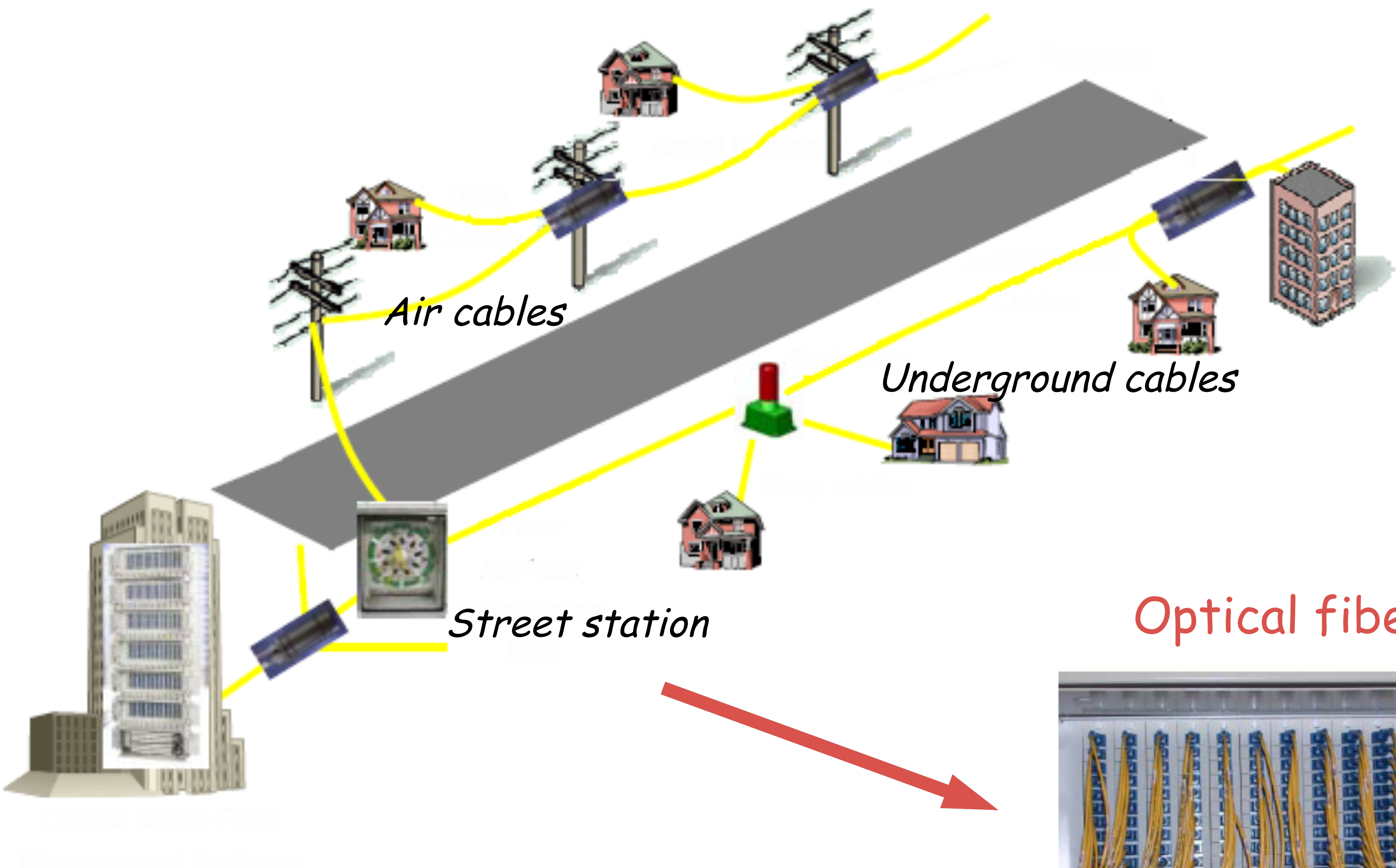
Telecommunications: Local Network

FTTH (Fiber To The Home)

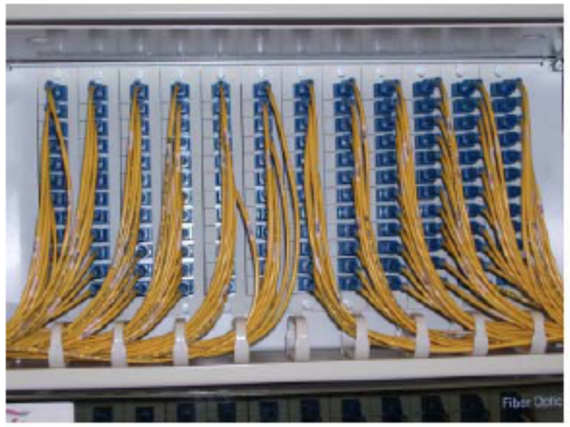
- Local/Corporate Network @ 810 nm
- Final user access @ 1310 nm and 1550 nm

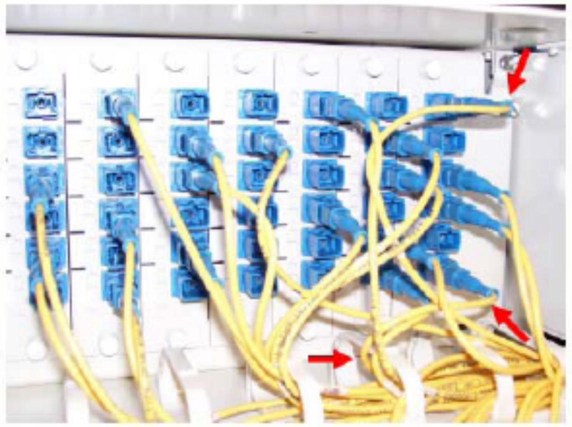
Problems

- Optical Fibers Bending Losses
- Higher-order Modes Propagation



Optical fibers in street stations

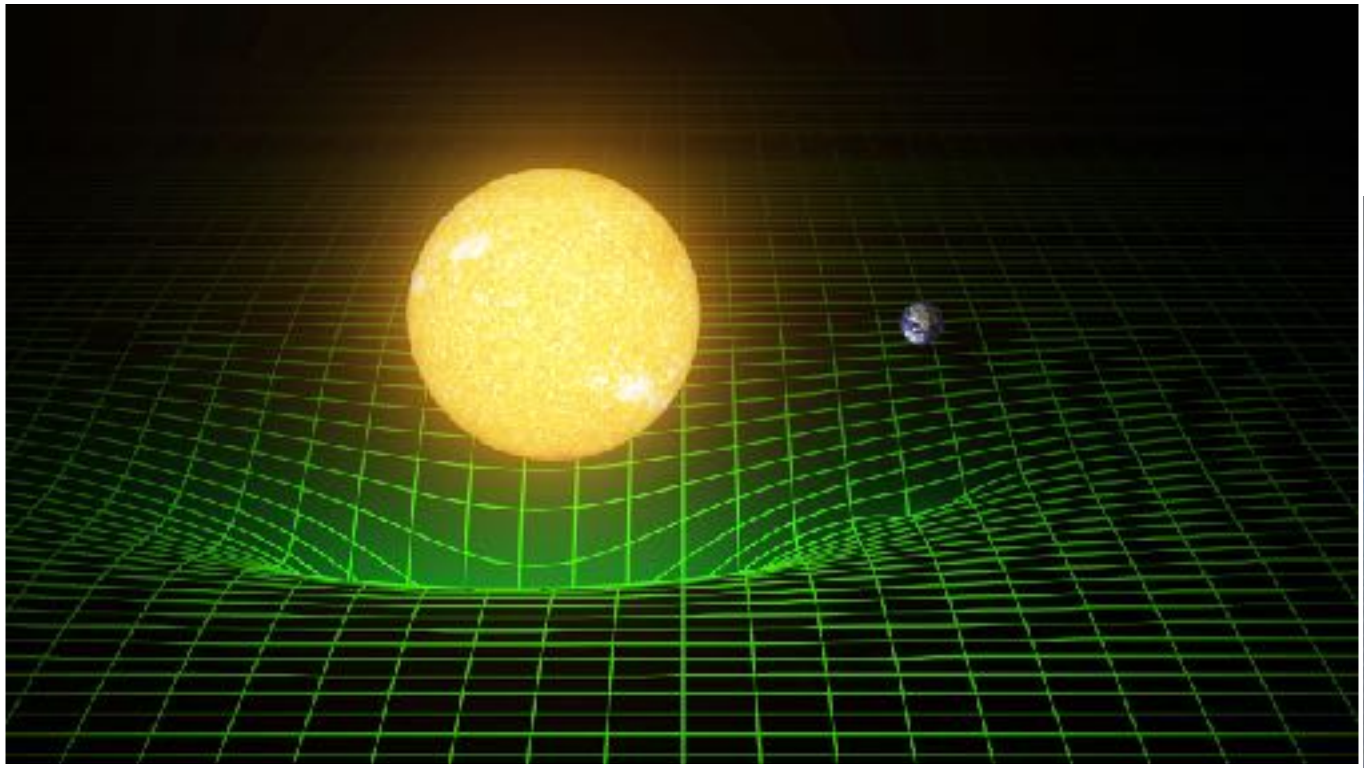


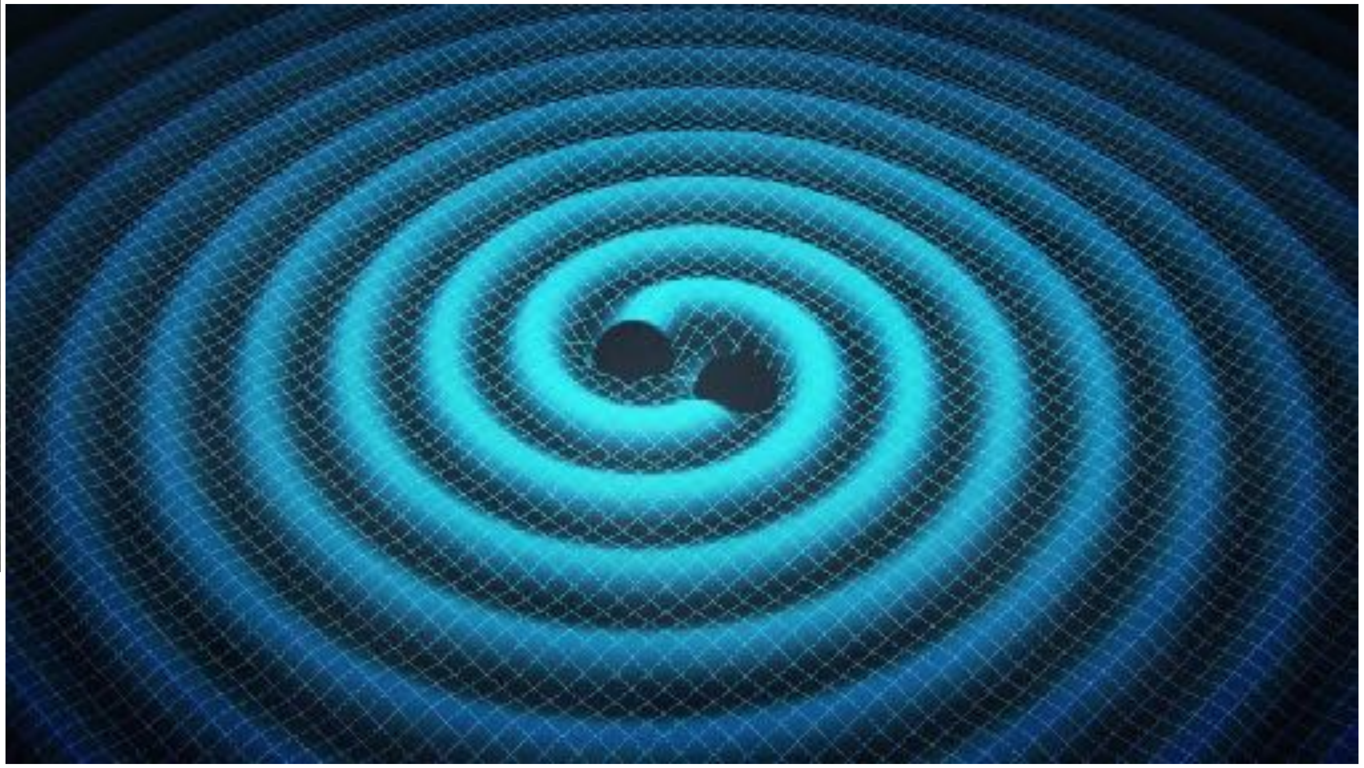


General Relativity & Gravitational Waves

- 1915: General Relativity -> dynamic space-time
  gravity = space-time curvature

- 1916: Gravitational Waves -> ripples in space-time propagating at the speed of light



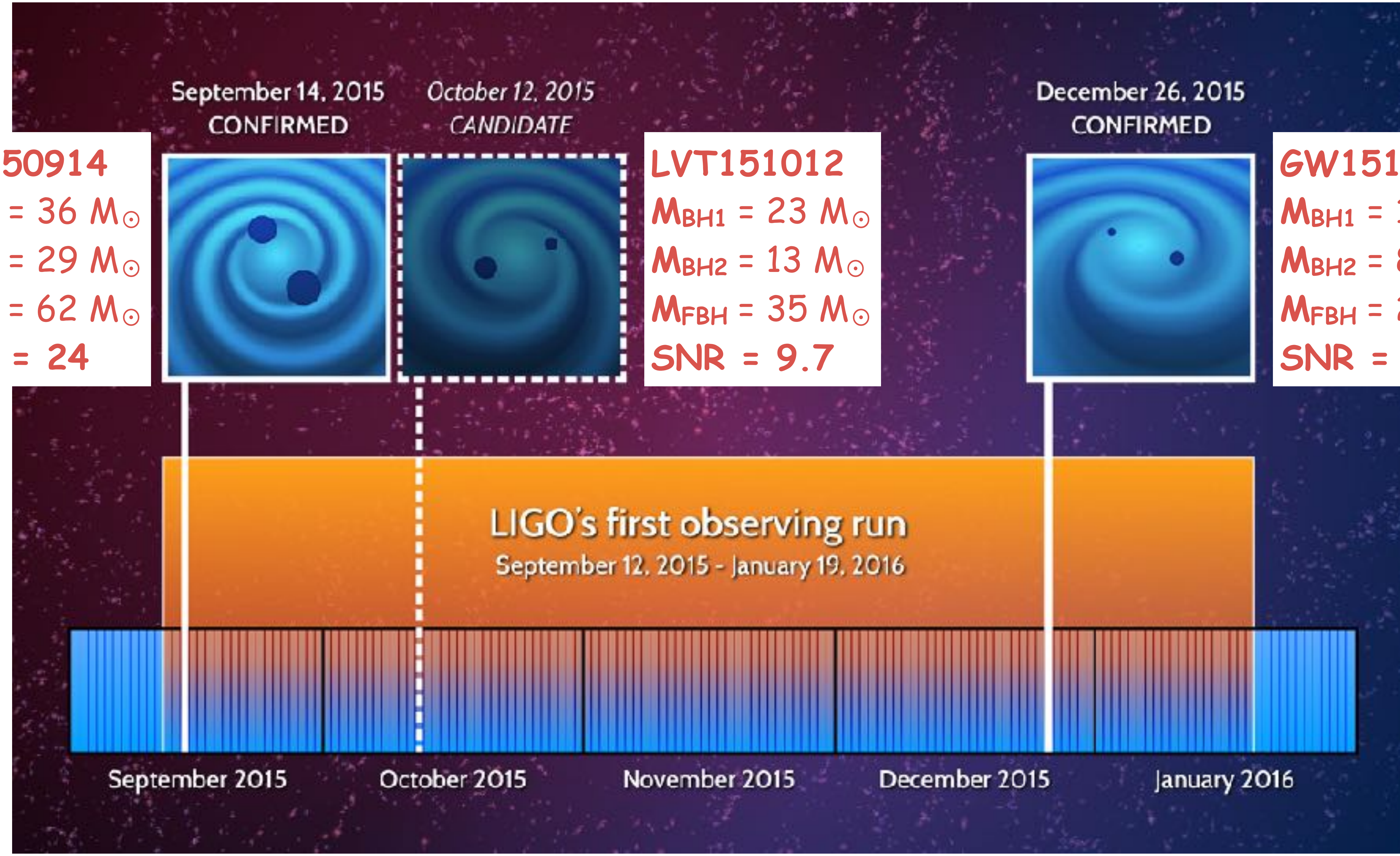


100 years later -> Gravitational Waves Observations

GW150914
$M_{BH1} = 36\ M_\odot$
$M_{BH2} = 29\ M_\odot$
$M_{FBH} = 62\ M_\odot$
SNR = 24

LVT151012
$M_{BH1} = 23\ M_\odot$
$M_{BH2} = 13\ M_\odot$
$M_{FBH} = 35\ M_\odot$
SNR = 9.7

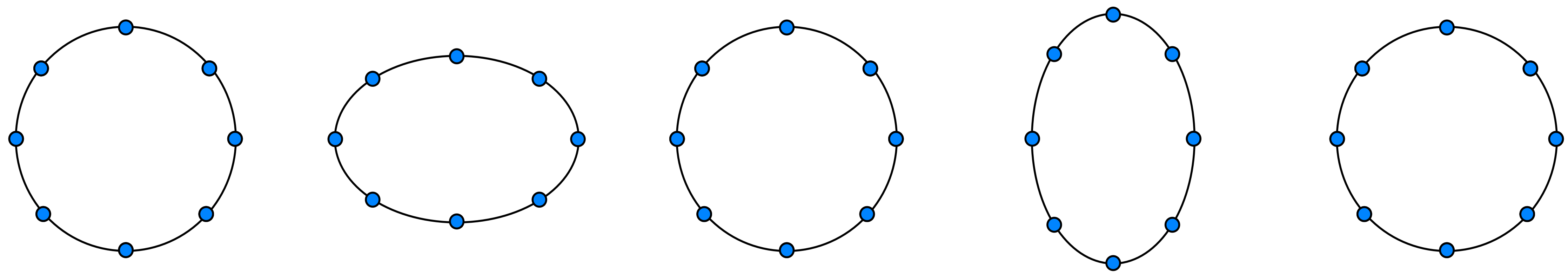
GW151226
$M_{BH1} = 14\ M_\odot$
$M_{BH2} = 8\ M_\odot$
$M_{FBH} = 21\ M_\odot$
SNR = 13



The events begin to reveal a population of stellar mass black hole mergers

How to measure Gravitational Waves?

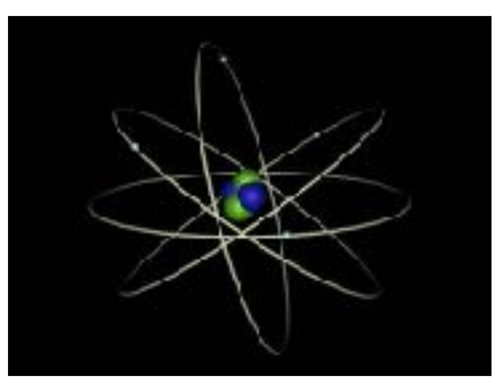
Gravitational Waves on Earth modify distances: stretch space in one direction and compress space in the other direction.



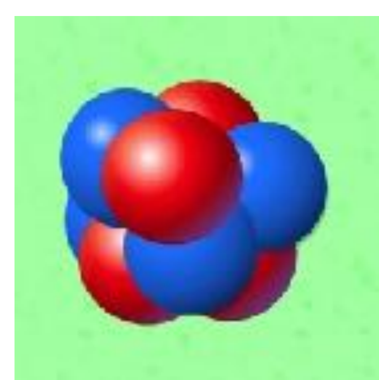
This deformation is TINY:

$d = 10^{-18}$ m = 0.000000000000000001 m

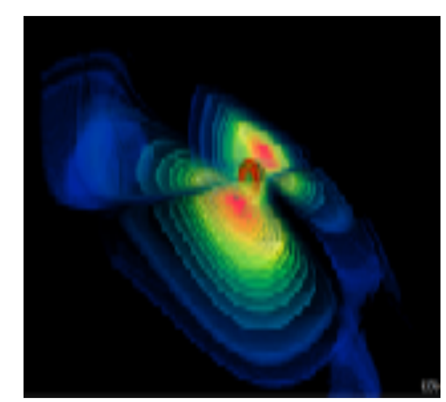
1 m



10^{-10} m



10^{-15} m

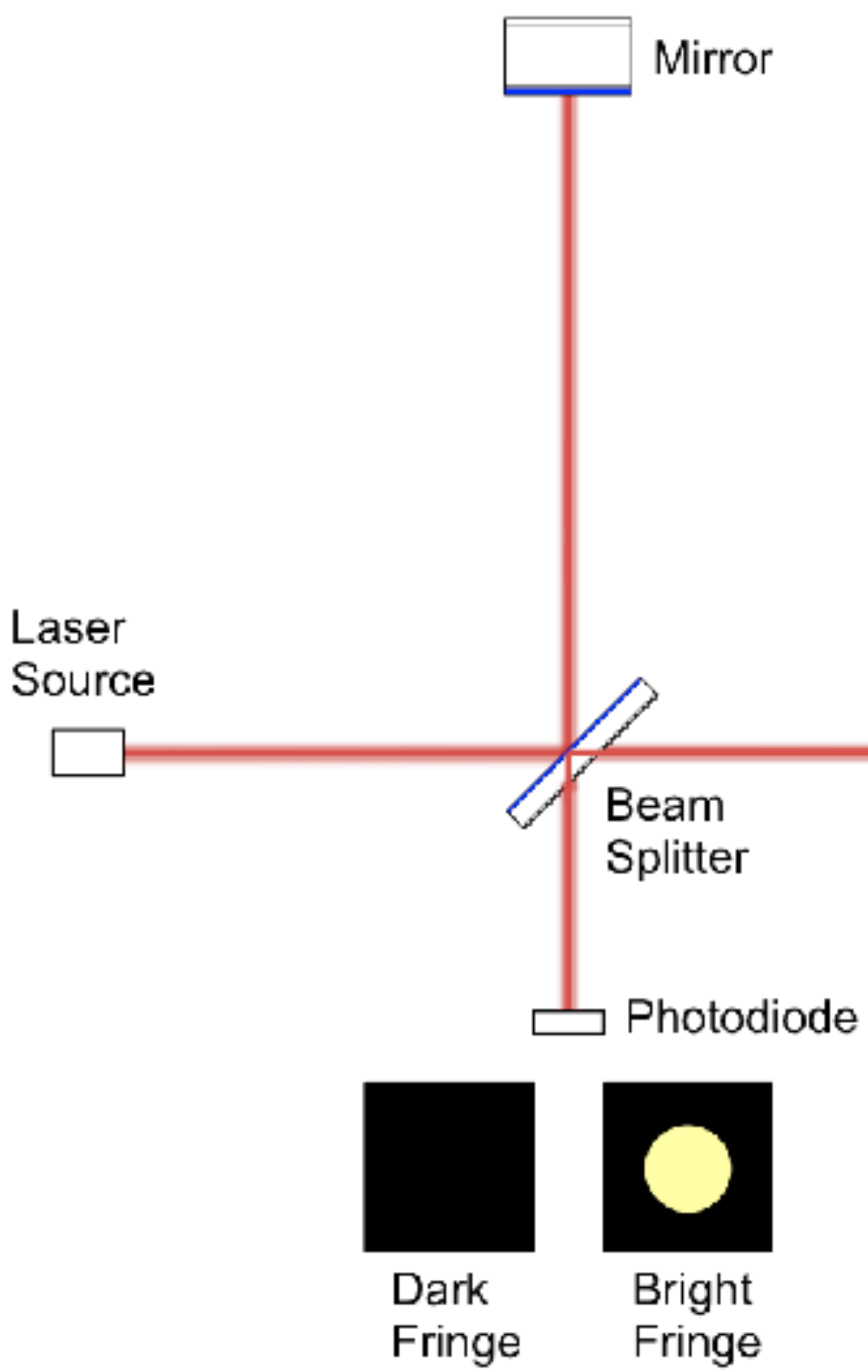


10^{-18} m

How to measure this tiny deformation?

How to measure Gravitational Waves?

The Michelson Interferometer detects differential effects in arms.

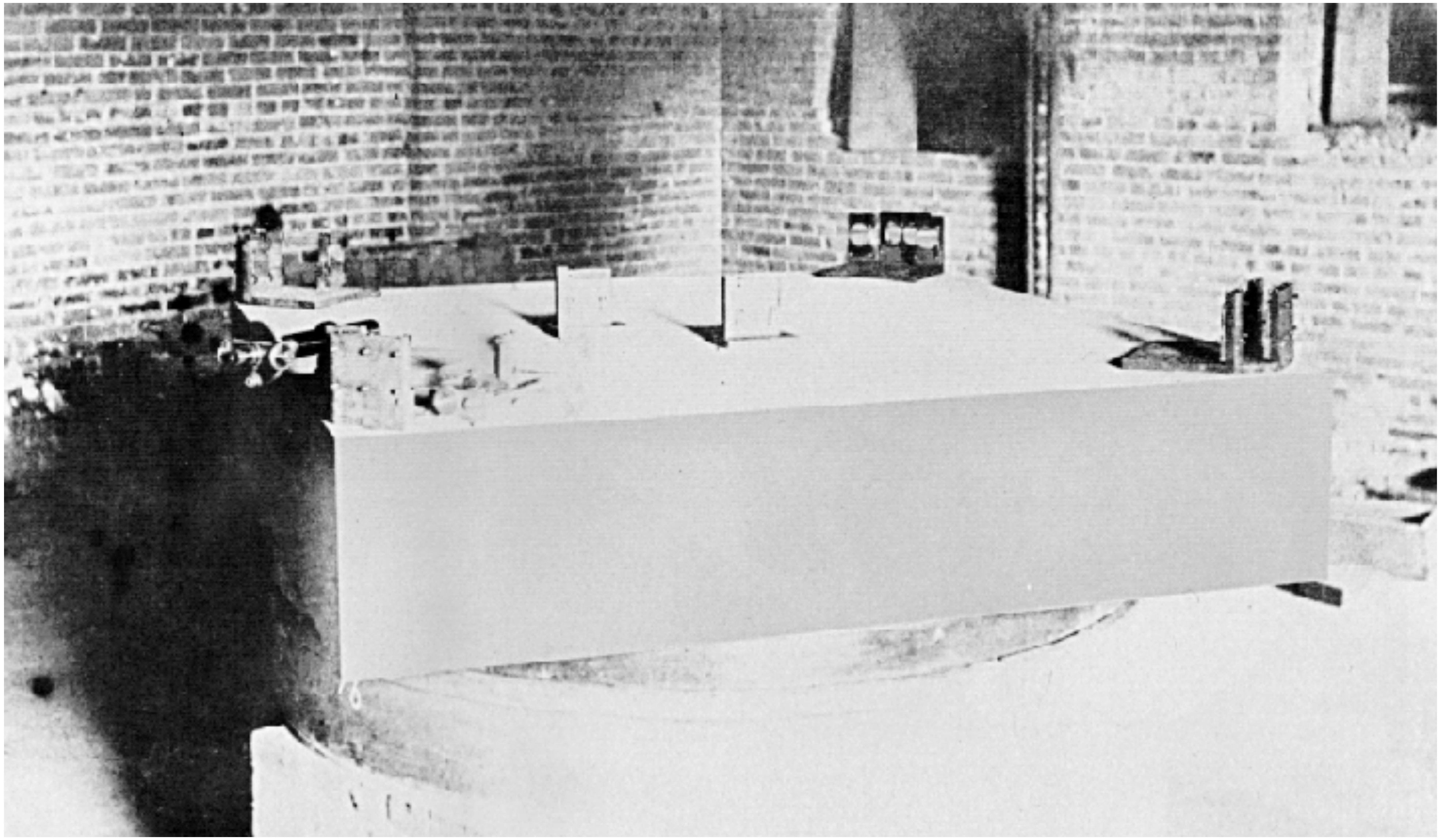


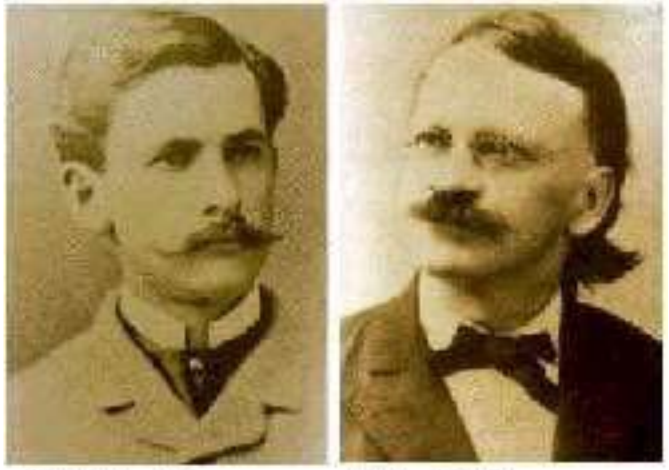
Dark Fringe: destructive field recombination.

Bright Fringe: constructive field recombination.

GW passage changes the working point.

Gravitational Waves & Michelson Interferometer





A.A. Michelson
1852 - 1931

E.W. Morley
1838 - 1923

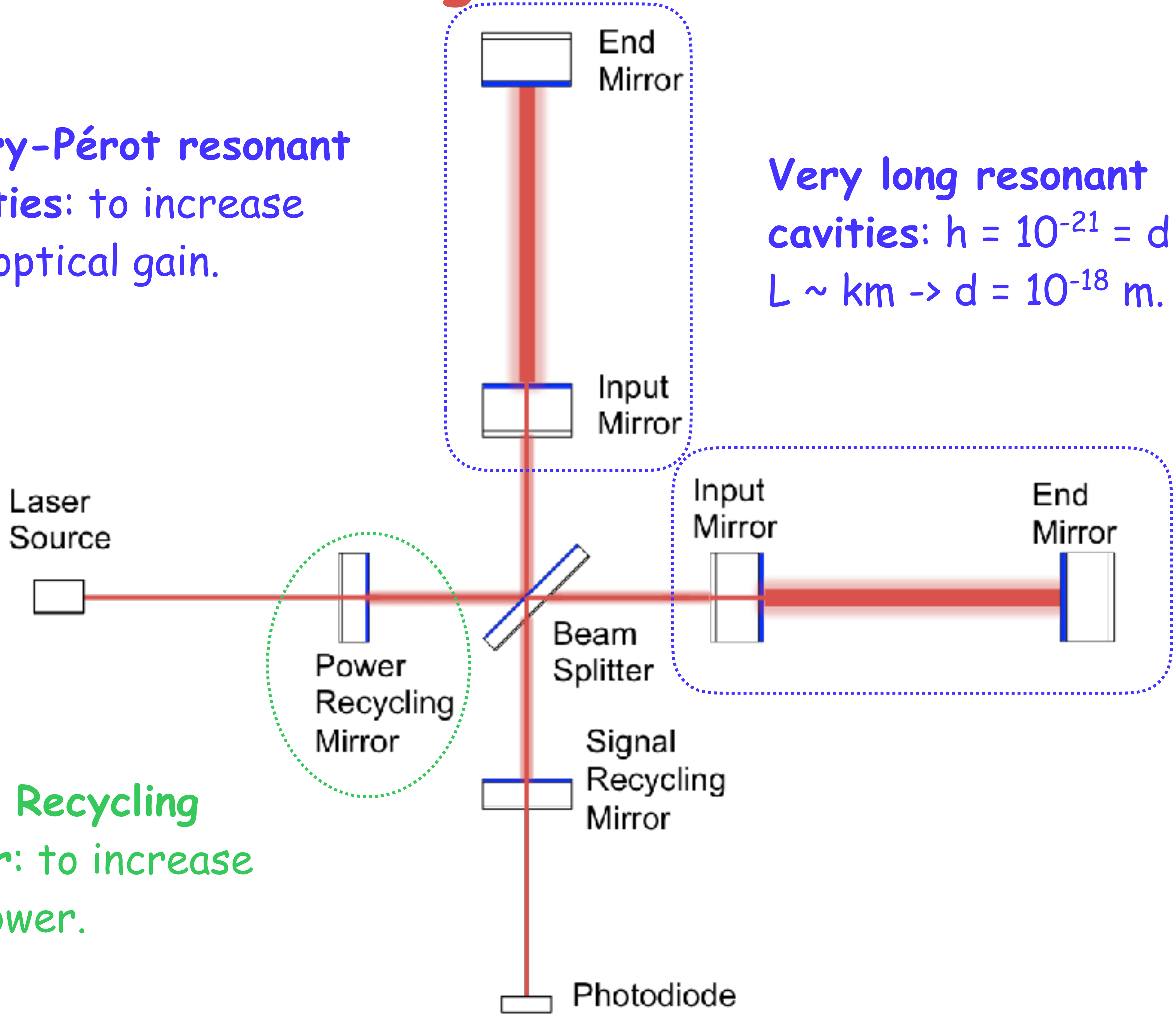
$d \sim \lambda / 50$

How to measure $d = 10^{-18}$ m $= \lambda / 10^{12}$?

LIGO & Virgo Interferometers

Fabry-Pérot resonant cavities: to increase the optical gain.

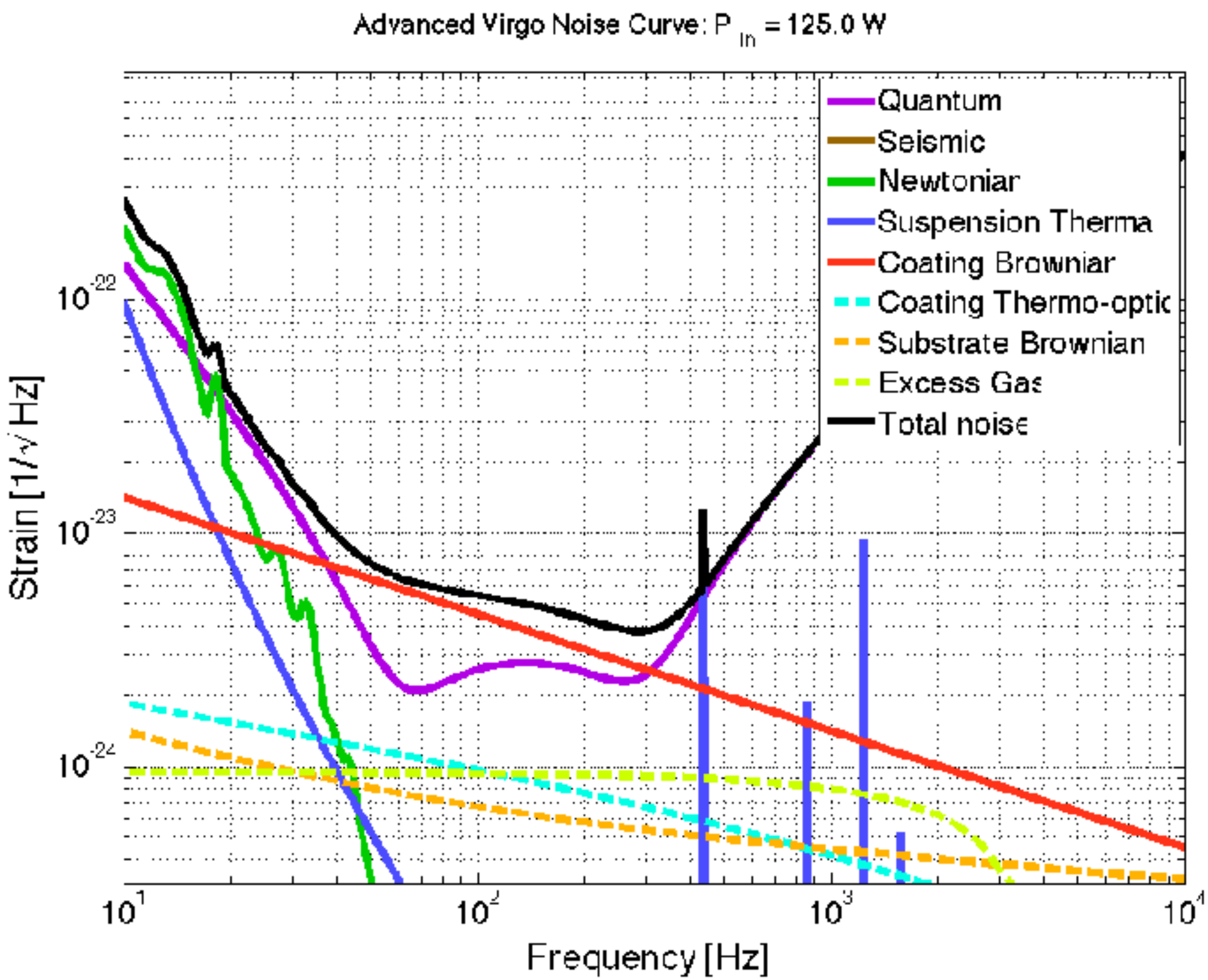
Very long resonant cavities: $h = 10^{-21} = d / L$; $L \sim km \rightarrow d = 10^{-18}$ m.



Power Recycling Mirror: to increase the power.

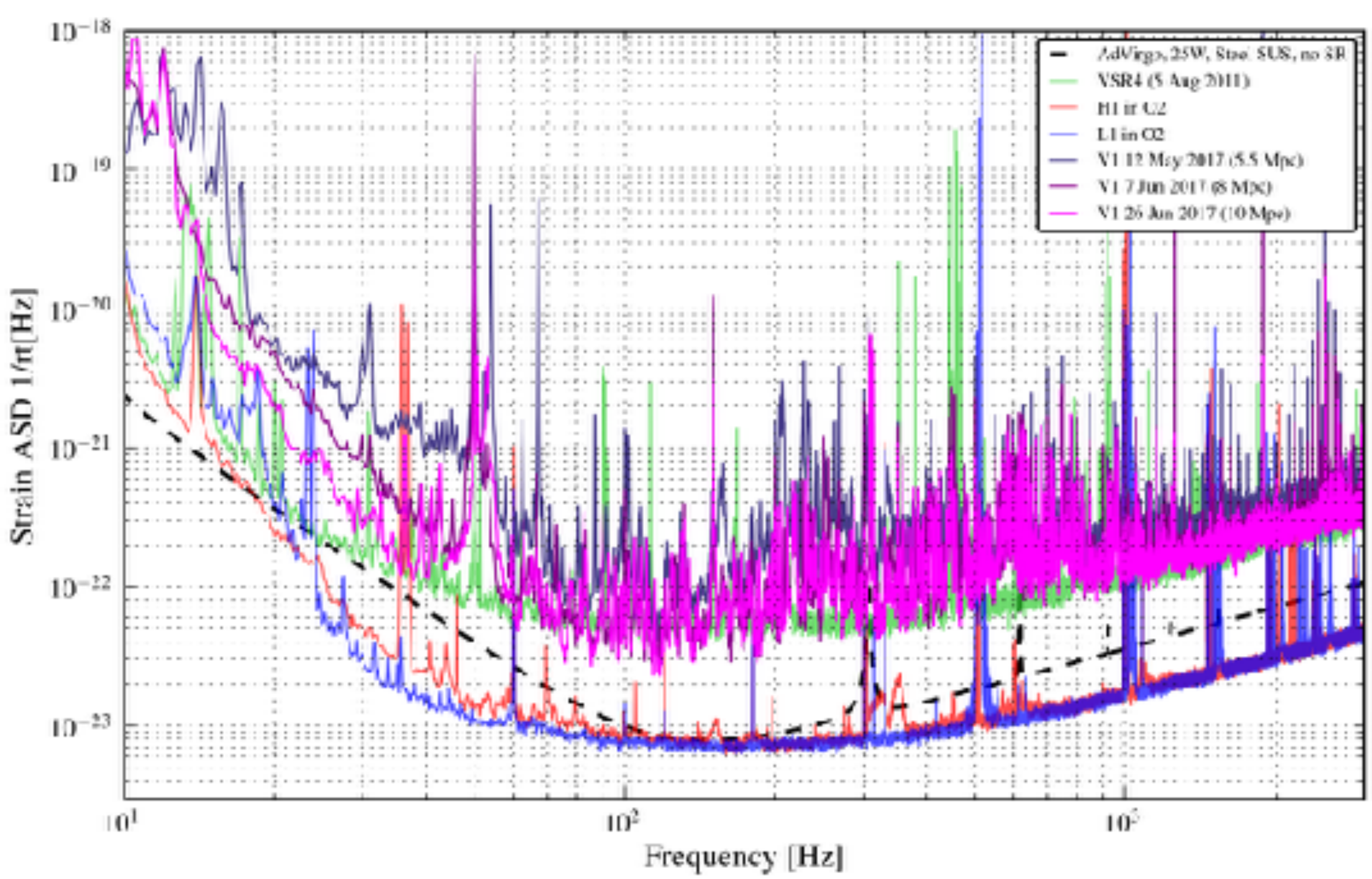
Advanced Virgo Sensitivity

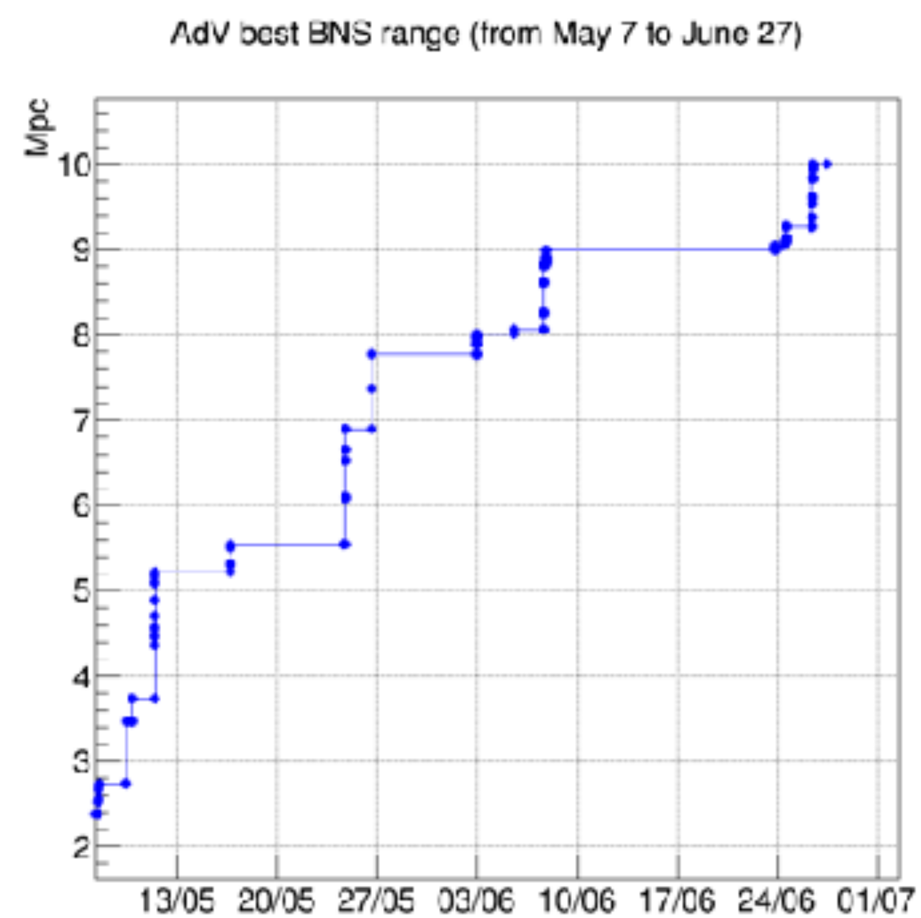
Definition of the science case and the needed sensitivity



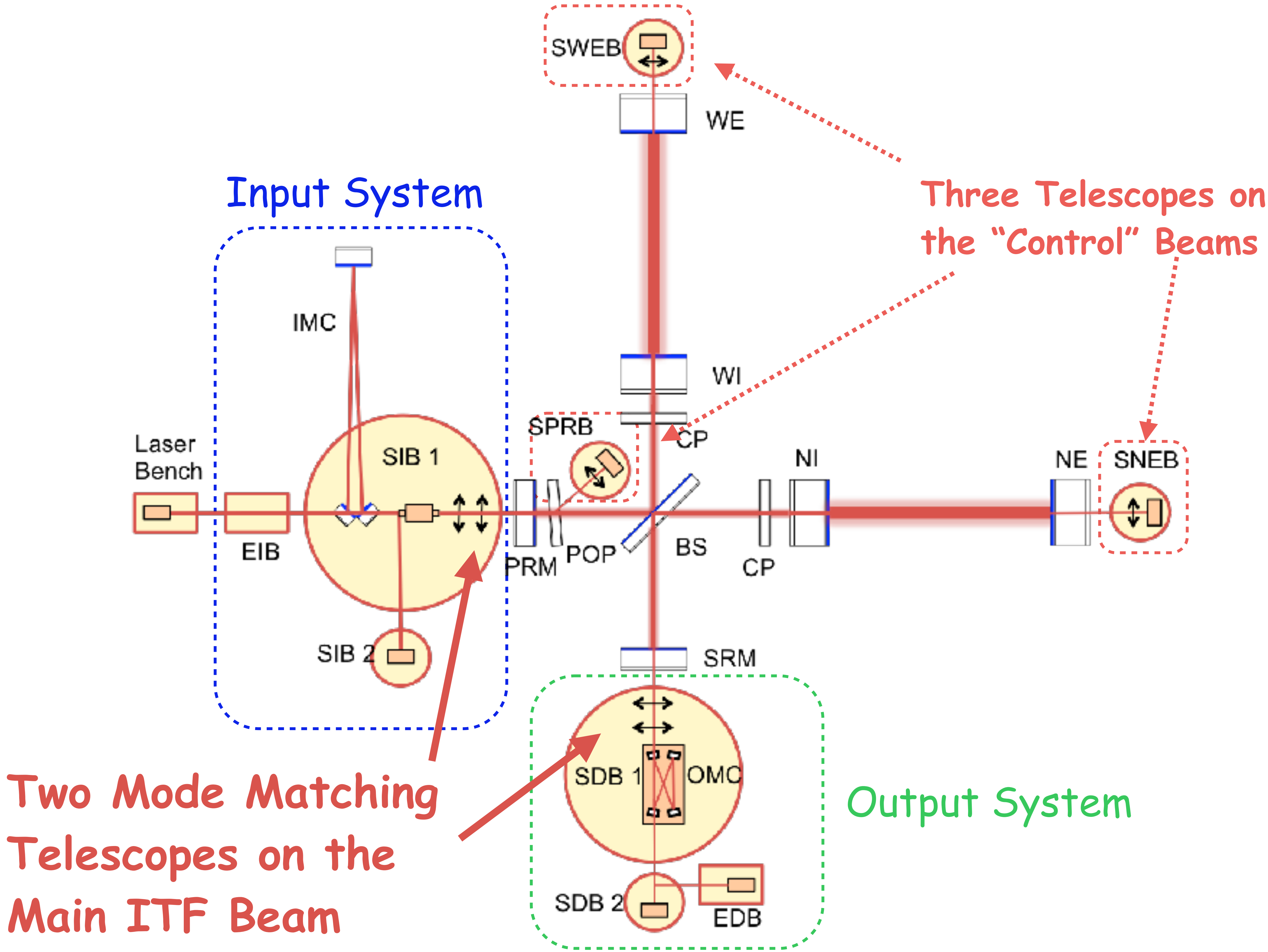
Detectors Commissioning

- Tuning of all the components to find the proper working point
- Implement all the control systems
- Noise hunting to identify and remove the technical and environmental noise sources
- Estimation of the fundamental noises level
- Improve the sensitivity





Advanced Virgo Telescopes



Advanced Virgo Mode Matching Telescopes

Design Constraints:

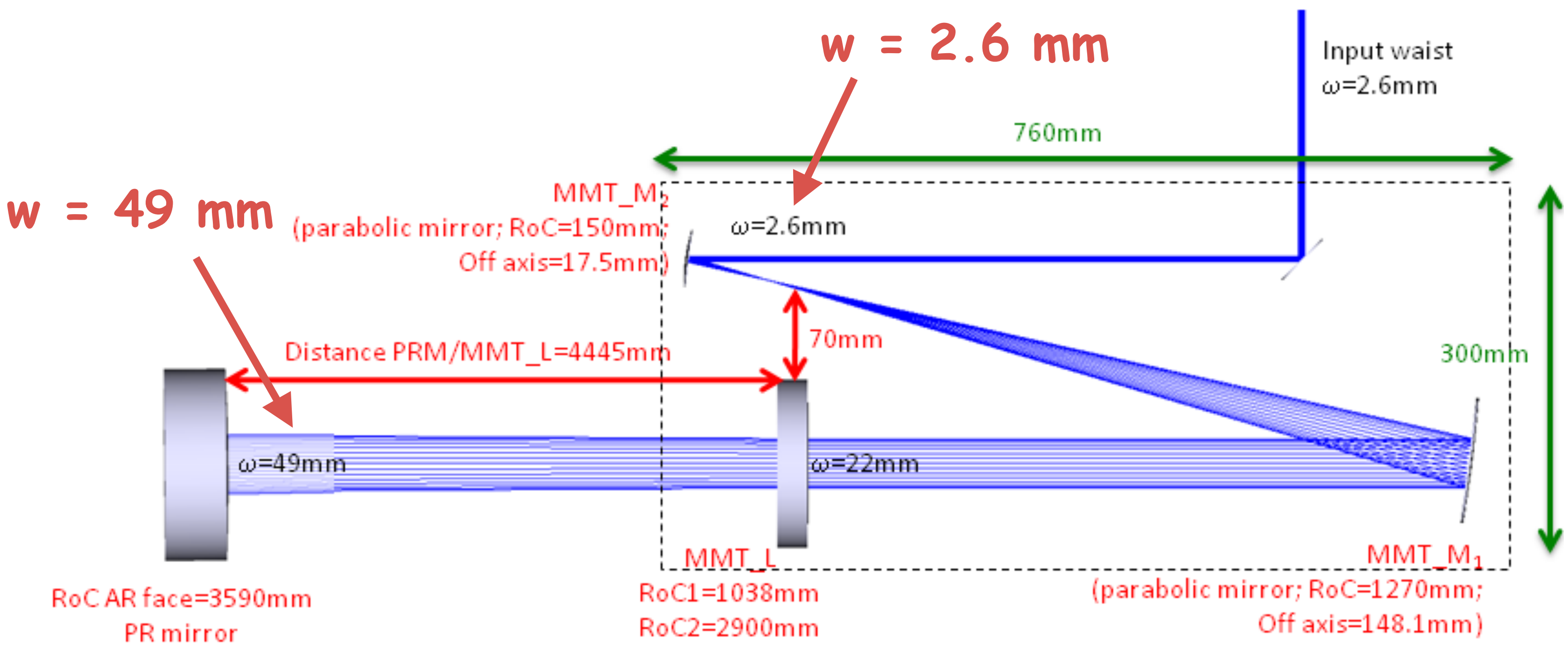
- Small beam at input/output, huge beam in the cavities: Large Magnification
- Negligible Aberrations
- Small Size: 80x30 cm
- Small Weight: < 15 kg
- High Rigidity
- Motorized Displacements: angular, transversal and longitudinal
- Displacement Range: given by optics tolerances

→

Catadioptric telescopes:

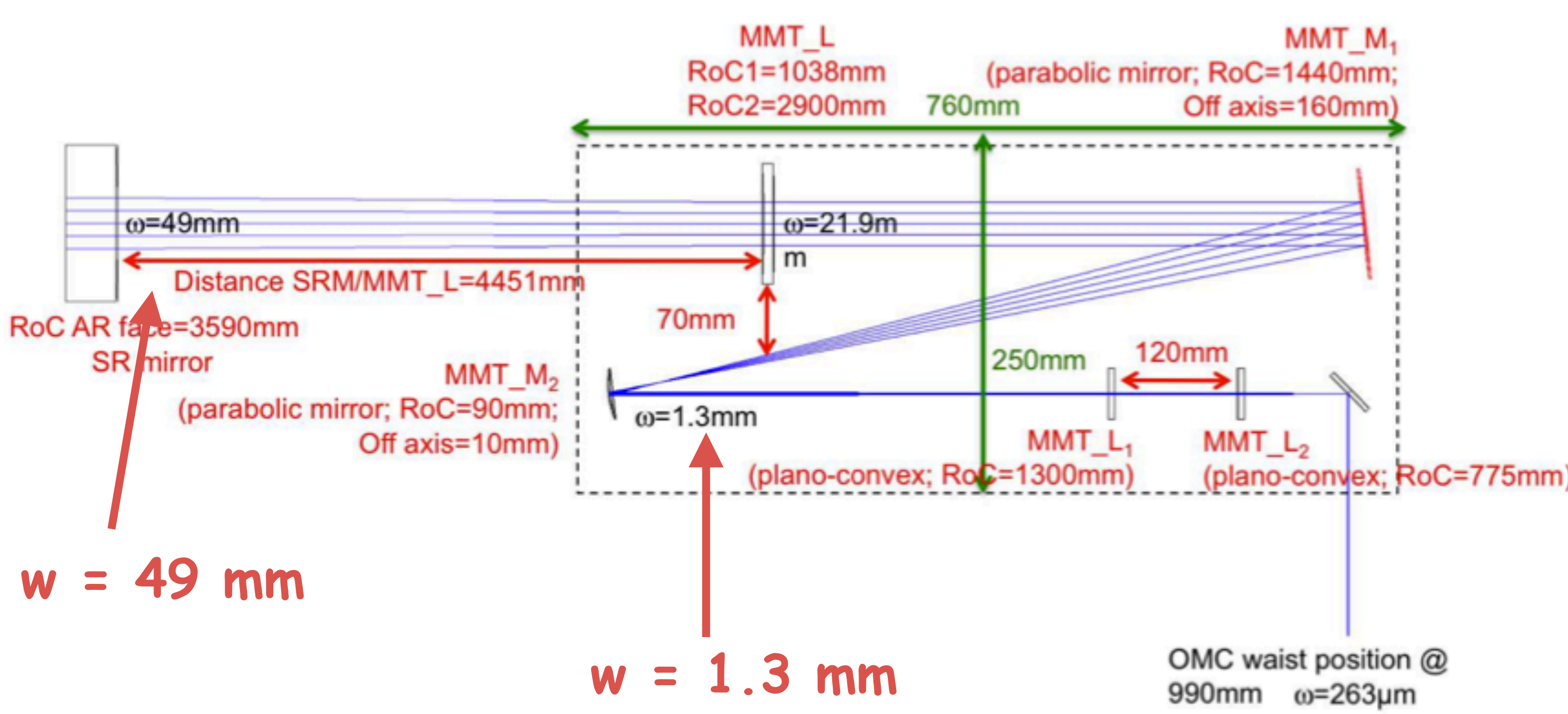
- **Two Parabolic Mirrors: off-axis afocal configuration**
- **One Meniscus Lens**
- **Lens on the AR face of the PR/SR mirror**

Advanced Virgo Mode Matching Telescopes



Input Telescope (match the laser beam to the ITF):

- global magnification = 18.9
- parabolic telescope magnification = **8.5**



Output Telescope (match the ITF beam to the Output Mode Cleaner - OMC):

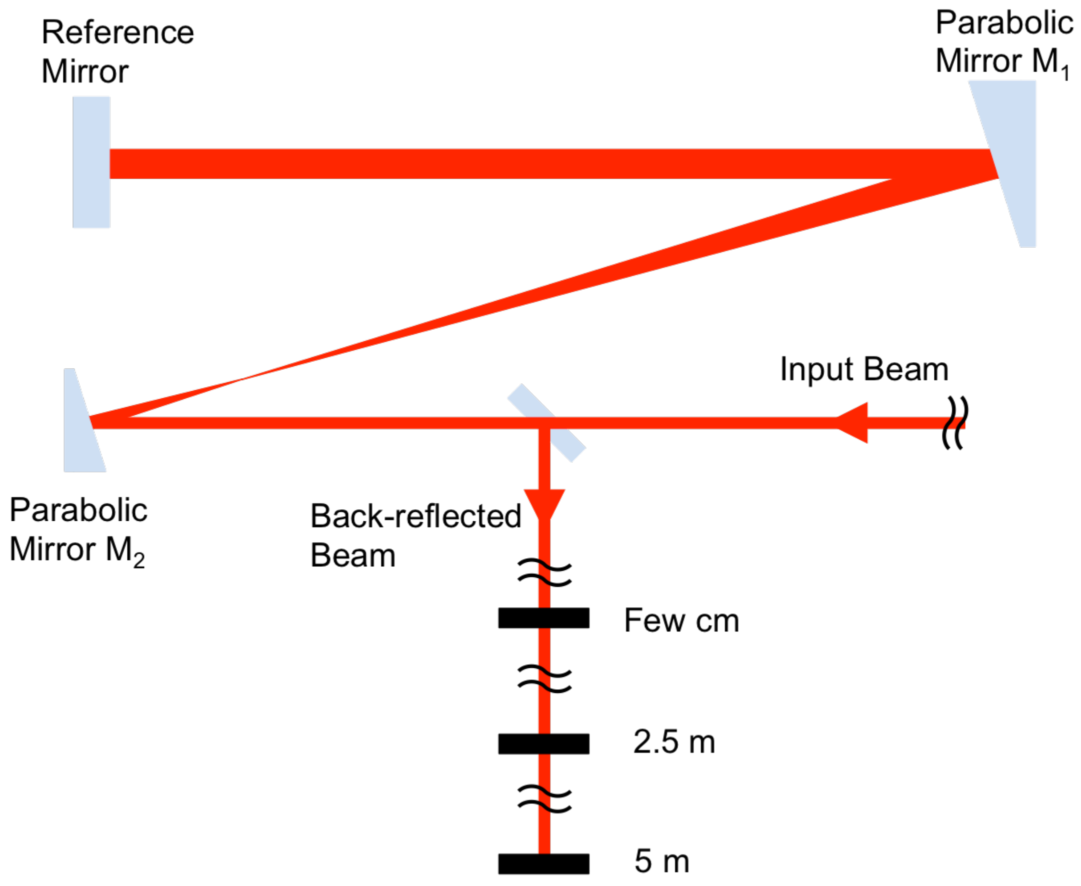
- global magnification = 37.7
- parabolic telescope magnification = **16.9**

Two more lenses to couple with the Output Mode Cleaner Cavity

Afocal Parabolic Telescope Pre-Alignment

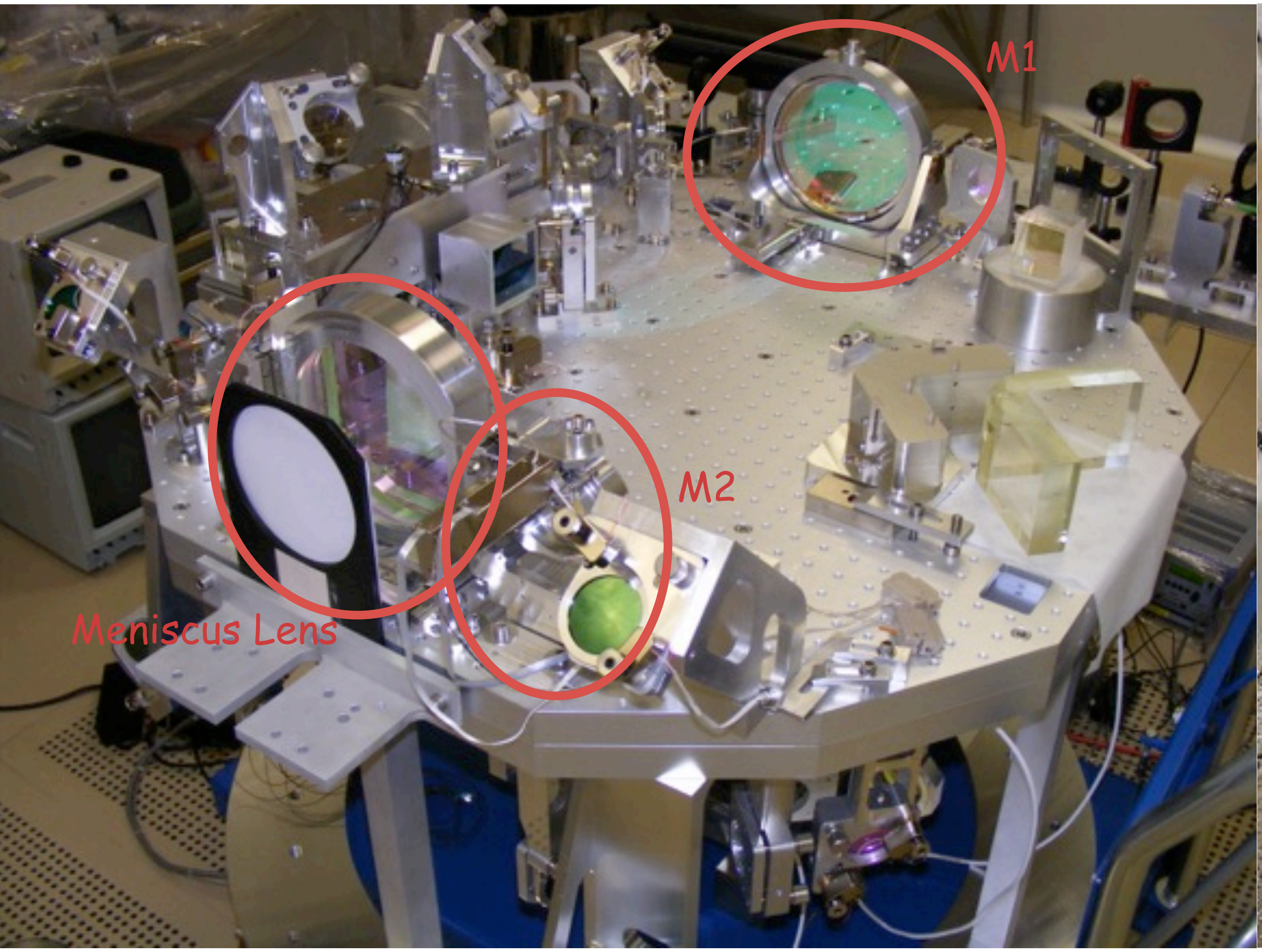
Parabolic mirrors in afocal configuration with large magnification:
- need a very precise relative alignment of transversal position, longitudinal position and angles.

Study of the quality of the beam after the propagation through the telescope:
- coupling of the output beam (single-pass in the telescope) with an ideal gaussian one.
- coupling of the back-reflected beam (double-pass in the telescope) with an ideal gaussian one (since the single-pass is not very sensitive to the telescope defects).

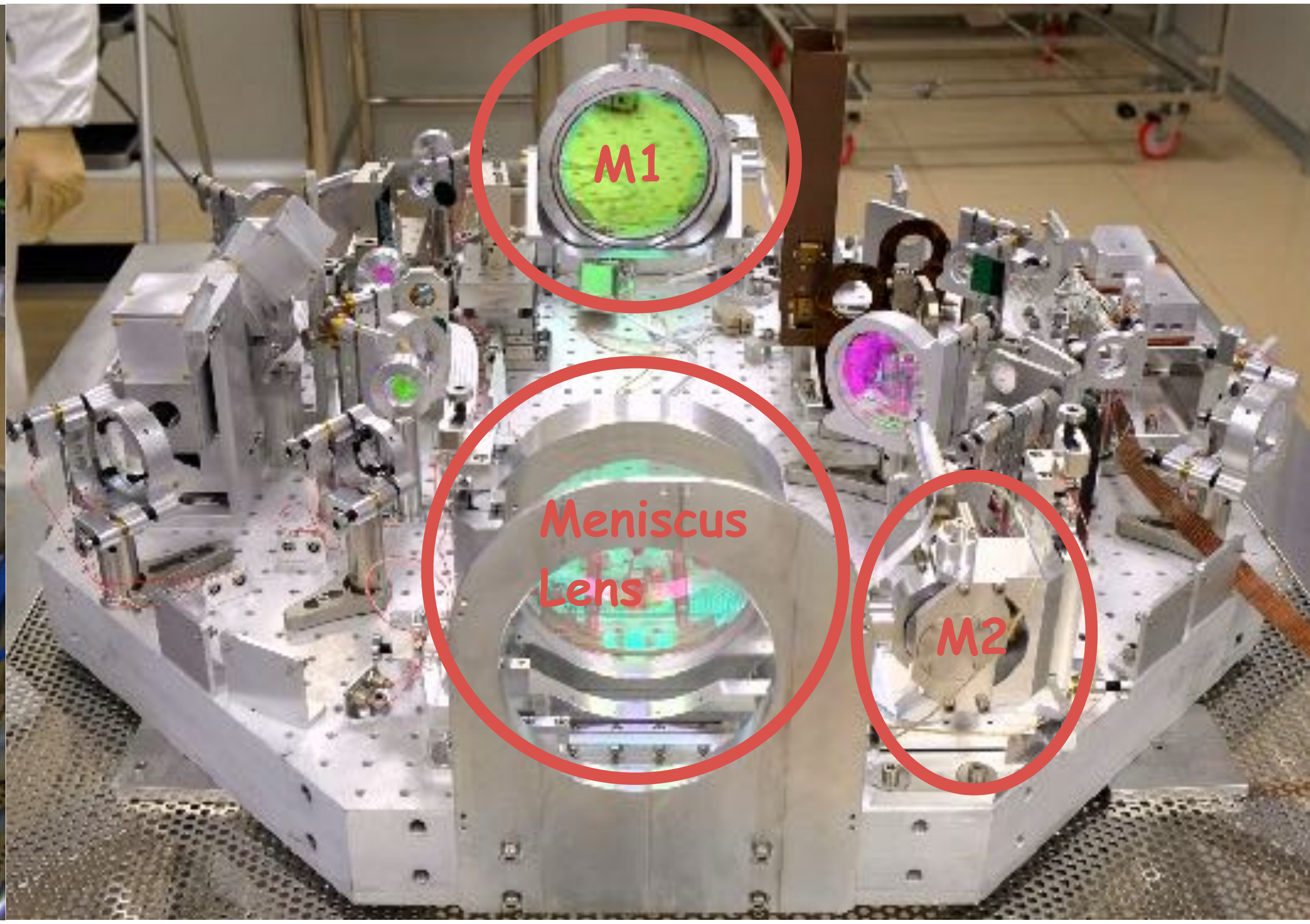


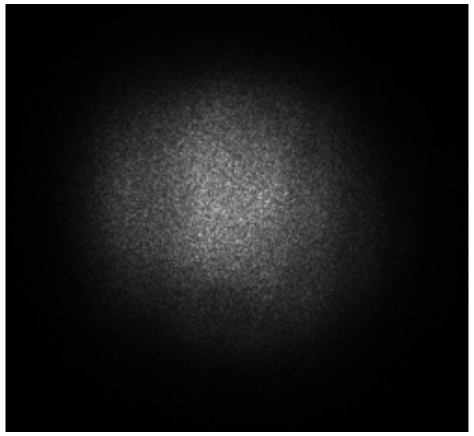
Advanced Virgo Telescopes

Input Telescope

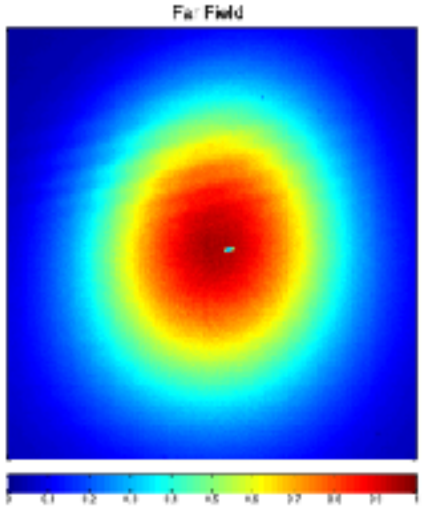


Output Telescope





Coupling with an ideal Gaussian beam > 99%
Coupling in Advanced Virgo cavities > 98%



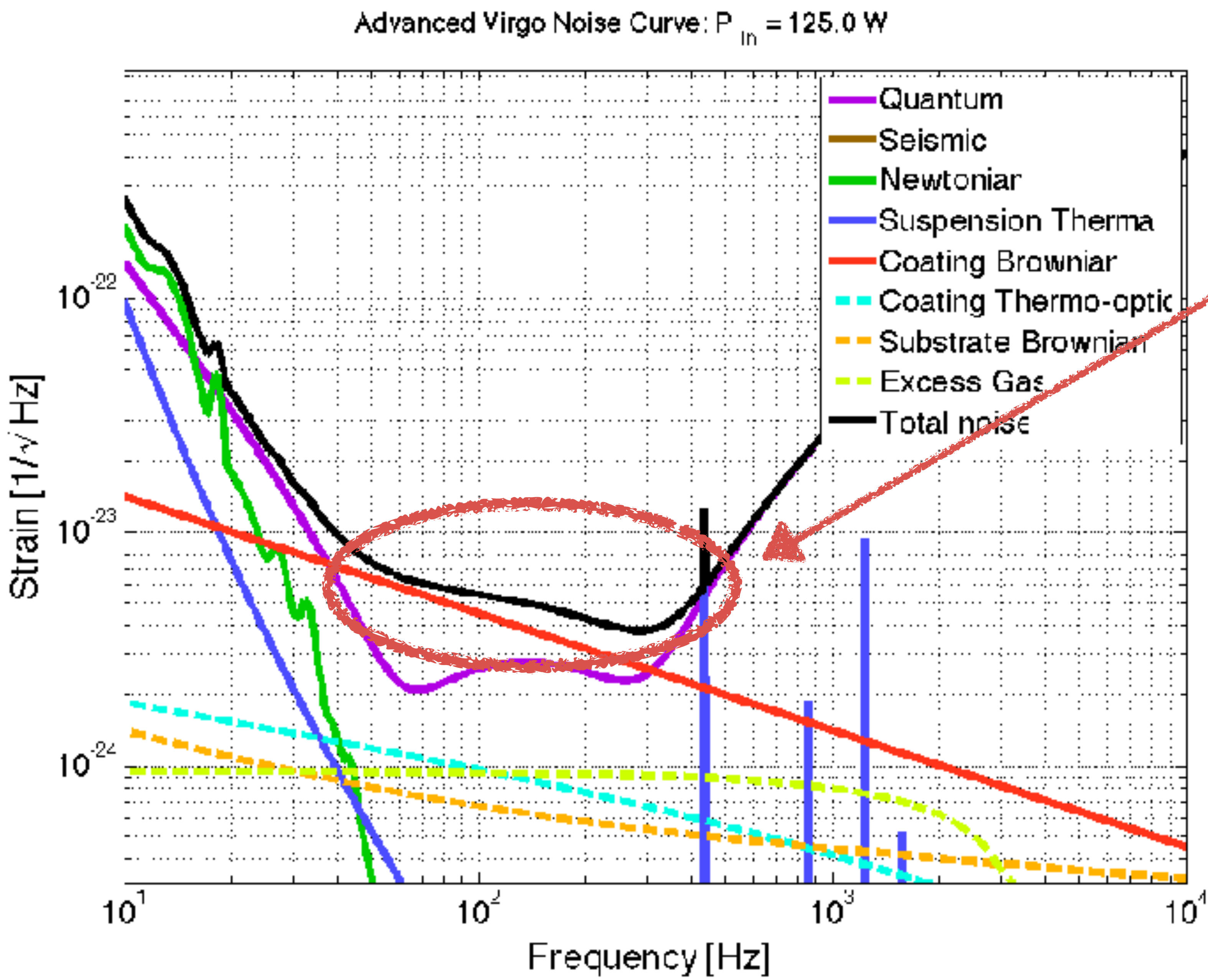
Coupling with an ideal Gaussian beam > 99%
Coupling in Advanced Virgo OMC > 95%

High coupling mandatory to reduce losses to apply techniques for future upgrades

R&D for Future Detectors

- Define the science case and the needed sensitivity
- Define the limitations of the sensitivity
- Define strategies/techniques to reduce the impact of the fundamental noises
- Implement table-top experiments and facilities to test the proposed techniques
- Make models and simulations to validate the experimental results and to deeply study the proposed techniques
- Submit global/common proposals (i.e. to the EU) to create a robust community to make an organized R&D
- Submit single proposal (i.e. to National Funding Agency) to make R&D on specific topics

Reduction of the Thermal Noise Impact



Mid-Range Frequency:
Sensitivity Limited by Mirrors Coating Thermal Noise

$$x_c^2(\omega) = \frac{4k_BT}{\omega}\frac{1-\sigma^2}{\sqrt{\pi}E_0 w}\phi_{eff,c}(\omega)$$

- directly proportional to material properties (σ, E_0, $\phi_{eff,c}$)
- inversely proportional to the beam spot size on the mirrors (w)

Virgo -> Advanced Virgo: increase the spot size on the mirrors but **not the only possible solution**

Laguerre-Gauss modes and GW detectors

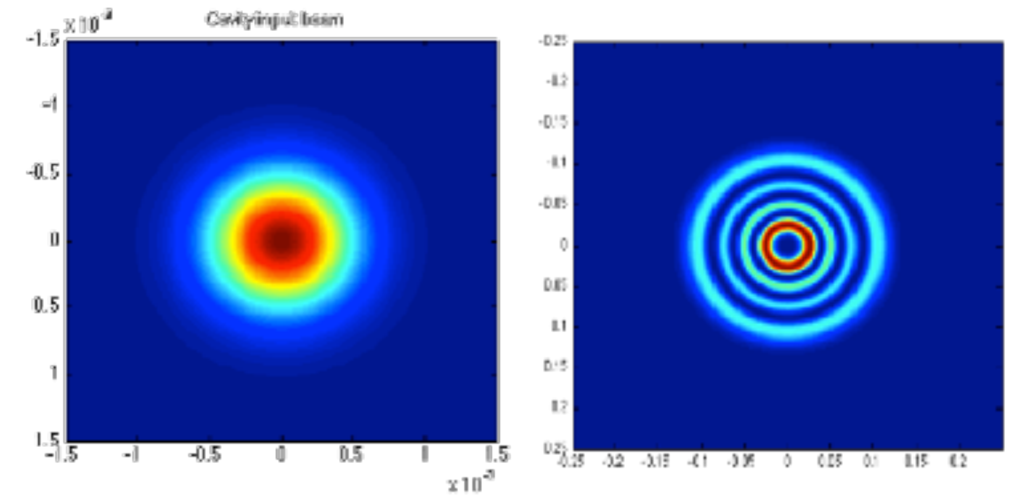
- Compared to the fundamental Gaussian mode, higher-order Laguerre-Gauss (LG_{lp}) modes reduce thermal noise thanks to their large coverage of the surface.

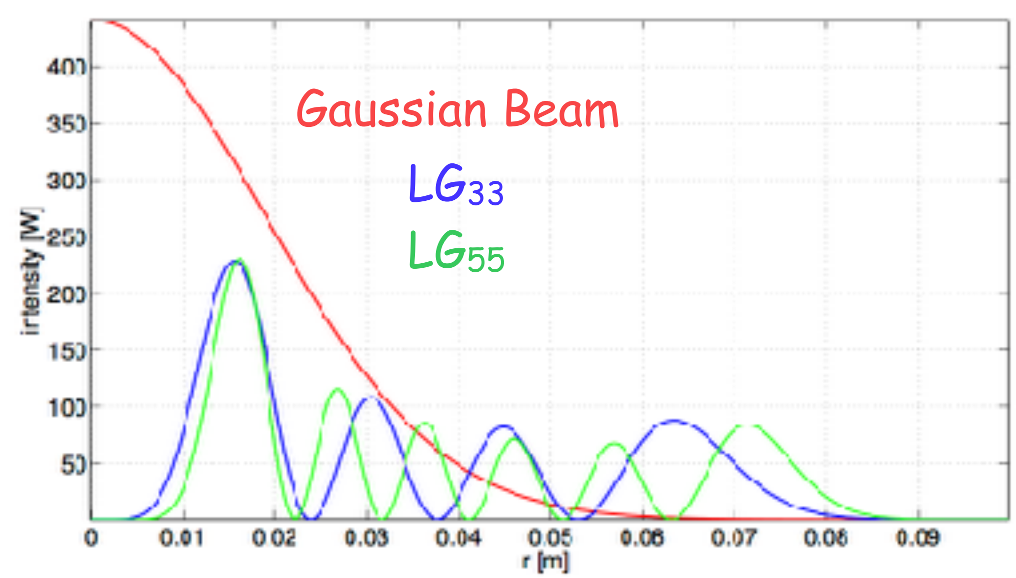
- Compatible with current spherical mirrors.

- Laguerre-Gauss modes resonate in spherical Fabry-Pérot cavities.

- LG_{33} mode is currently planned in the Einstein Telescope (ET-D-HF) design.

- Higher-order Laguerre-Gauss modes -> TN reduction factor (LG_{33}) ~ 1.7 for AdV -> events rate increased by a factor 5





LG Main Problem: Degeneracy

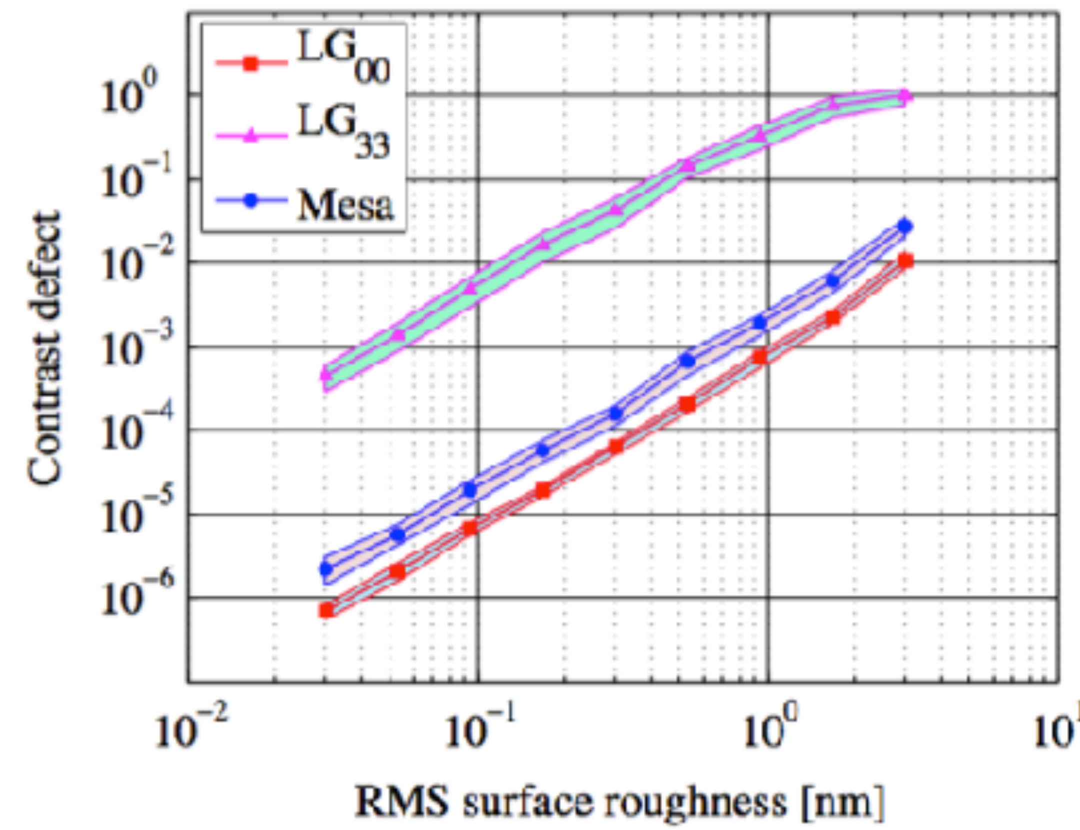
$$u_{LG_{lp}}(r,z) \propto u_{TEM_{00}}(r,z) L_p^{|l|}(r,z)$$
$$\times exp(i(2p+|l|+1)\psi(z))$$

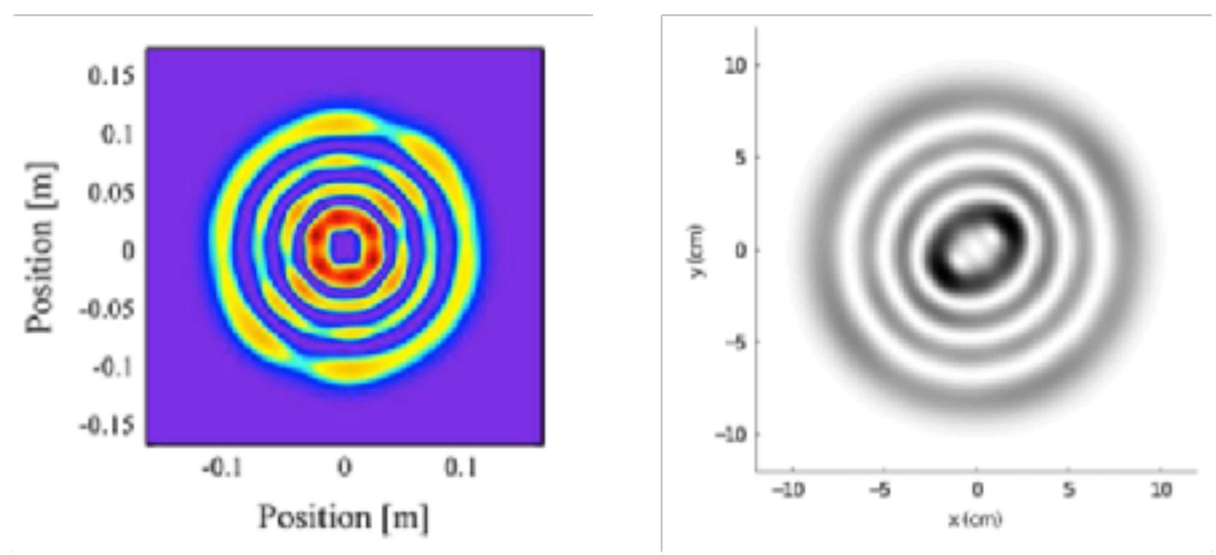
- n = 2p + l -> modes order

- Degeneracy of the modes of the same order: a n-order LG mode is n-time degenerated.

- Coupling among modes through lower order mirrors defects.

- Expected contrast defect 3 order of magnitude worse than Gaussian beam: target value (10^{-4}) reached for an impossible (today) quality of the mirrors -> RMS ~ 0.01 nm.





Realistic not-pure simulated LG_{33} beams

A Non-Gaussian Interferometer

A table-top interferometer using a Non-Gaussian mode (LG_{33}) has been realized to:

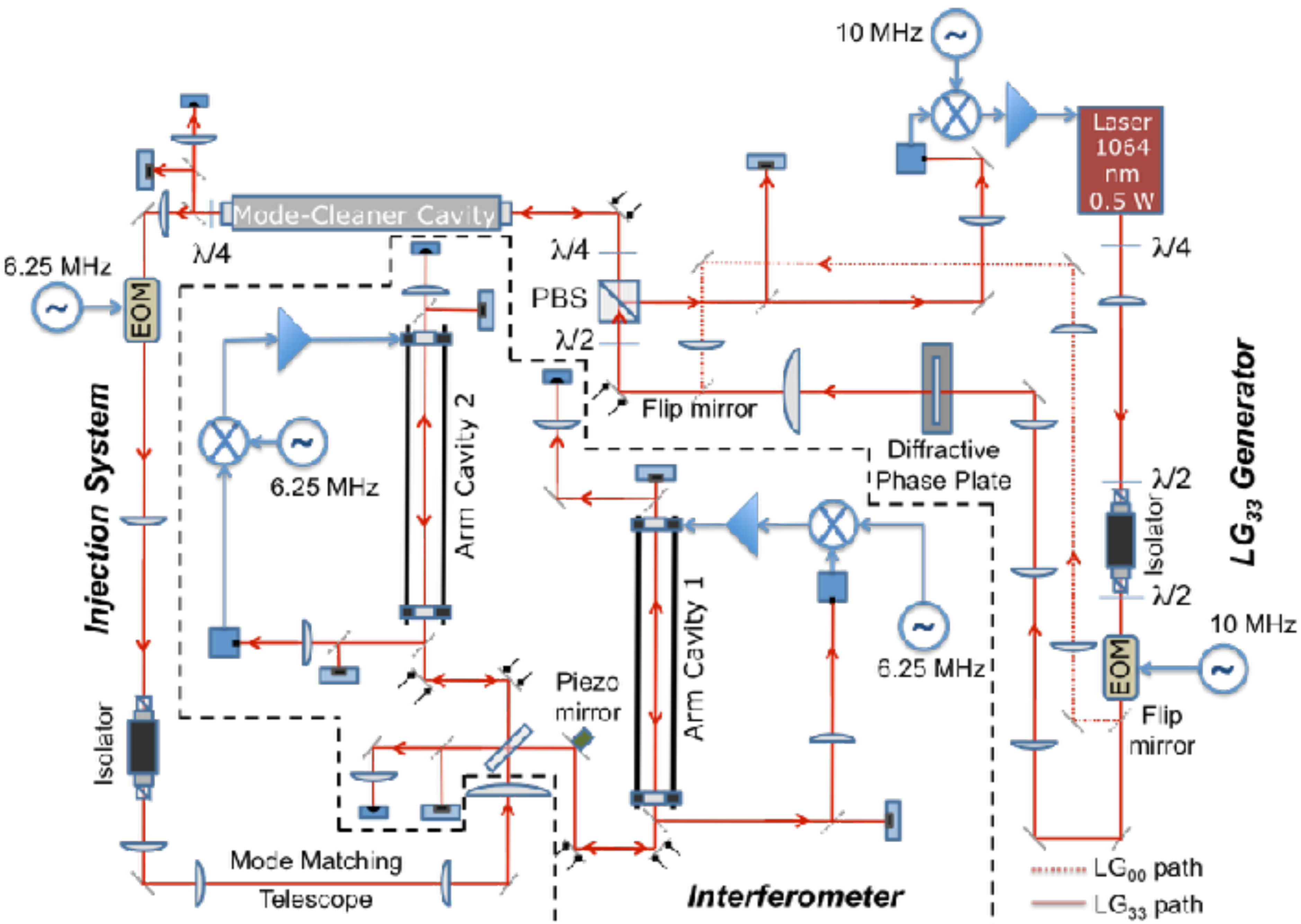
- Test Laguerre-Gauss system feasibility
    - Matching and pre-alignment procedures using a Gaussian beam
    - Control systems

- Identification of the main limits and constraints

- Comparison between measurements and simulations

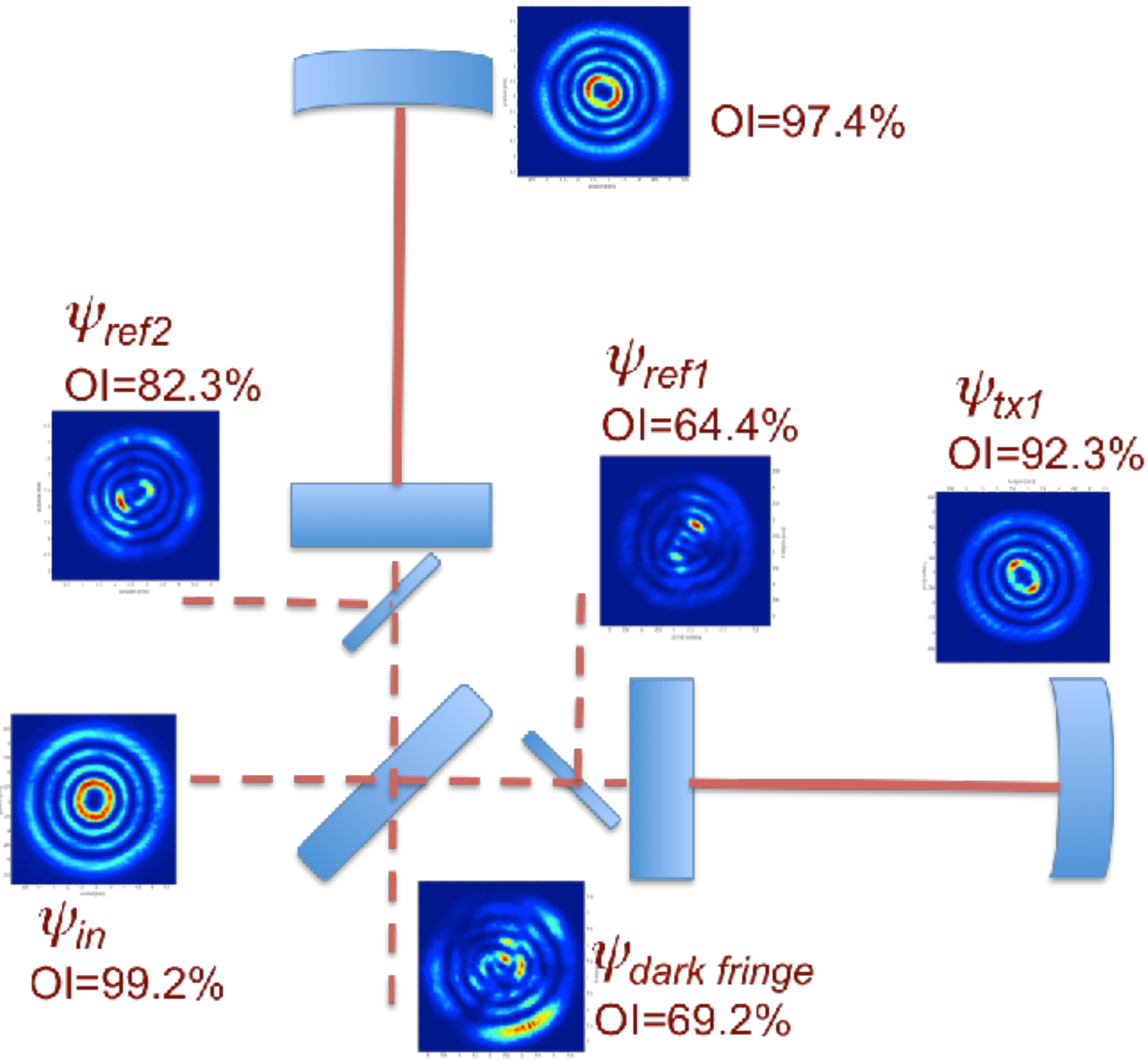
- Test possible technique to solve the degeneracy problem

Interferometer Optical Scheme



- **Generation**:
  - phase plate
  - linear mode cleaner cavity
- **Injection System**:
  - mode matching telescope
- **Interferometer**:
  - symmetric Michelson interferometer
  - 30-cm long plano-concave Fabry-Pérot arm cavities

Interferometer Images Analysis (i)



Interferometer performance estimated the fringe visibility:

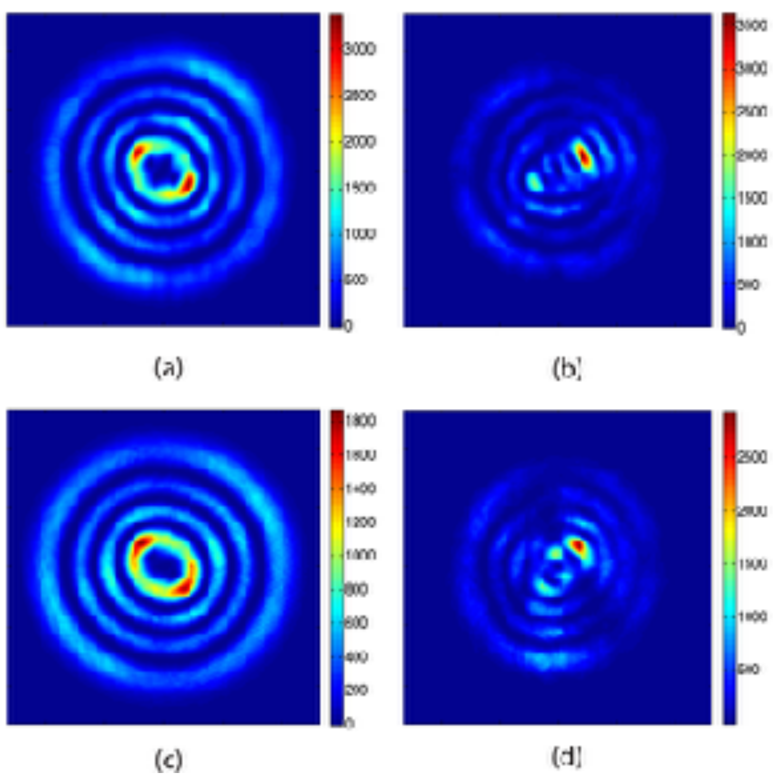
$$V = \frac{P_{max} - P_{min}}{P_{max} + P_{min}}$$

Best visibility ~ 84 %.

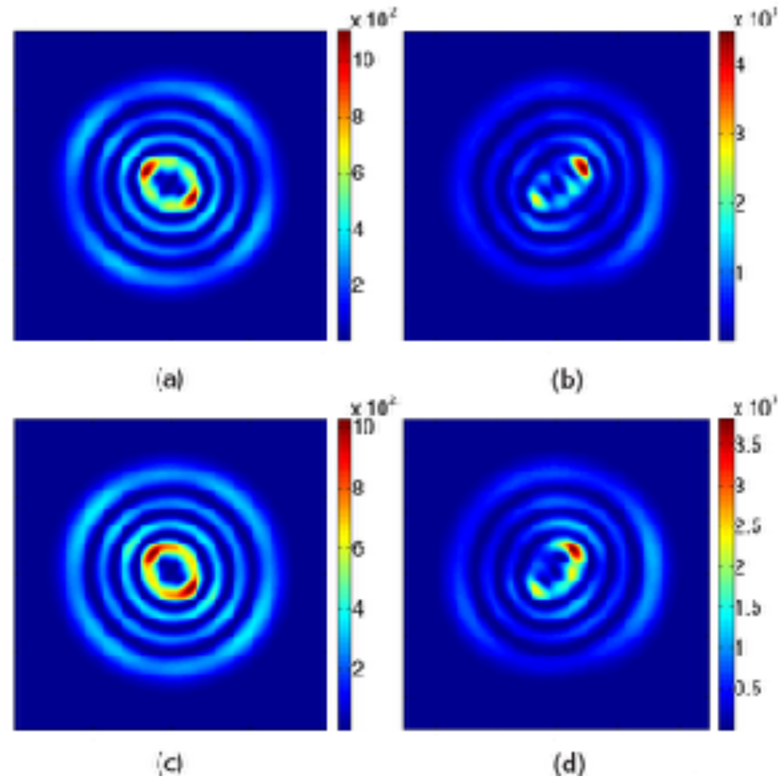
Simulations to explain obtained results:

- resonance scans: **mismatching**.
- transmitted beams: **astigmatism** estimation.
- reflected beams / resonance scans: **tilts** estimation.

Interferometer Images Analysis (ii)

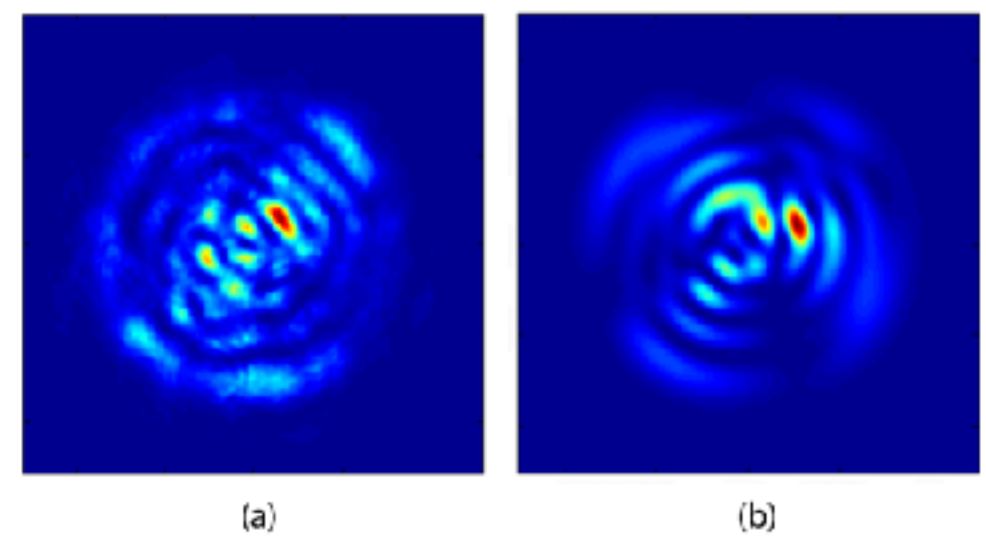


Cavities: measured



Cavities: simulated

Dark Fringe



Measured: Visibility ~ 84 %

Simulated: Visibility ~ 83 %

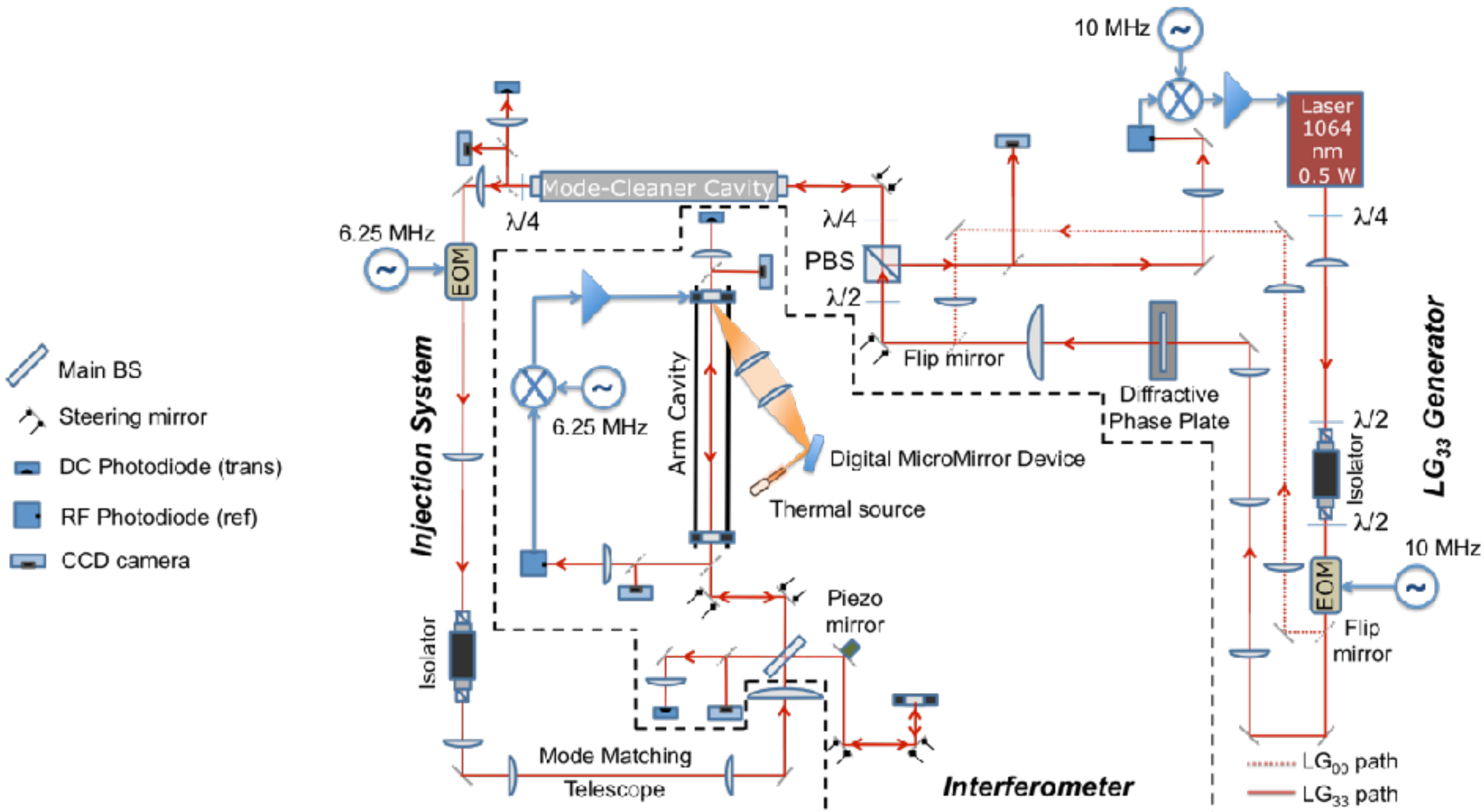
TABLE II. Model parameters.

	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)

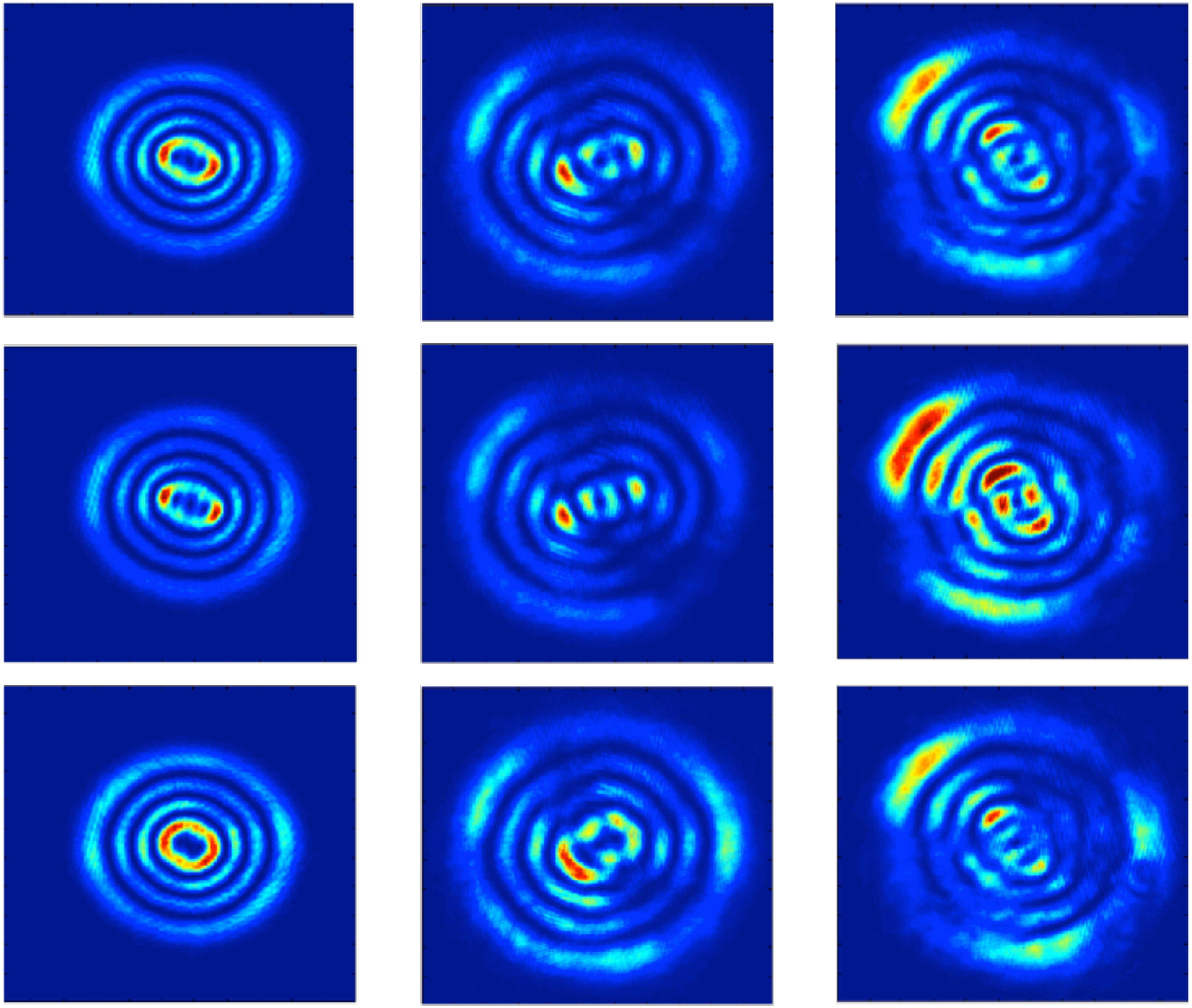
Connected to degeneracy

Interferometer & Thermal Compensation (i)

Table-top asymmetric interferometer (1 cavity and 1 mirror) using a non-Gaussian (LG_{33}) mode and a thermal compensation system: feasibility study of the correction of mirrors defects.



Interferometer & Thermal Compensation (ii)



No correction
Measured:
Visibility ~ 50 %

More astigmatism
Measured:
Visibility ~ 35 %

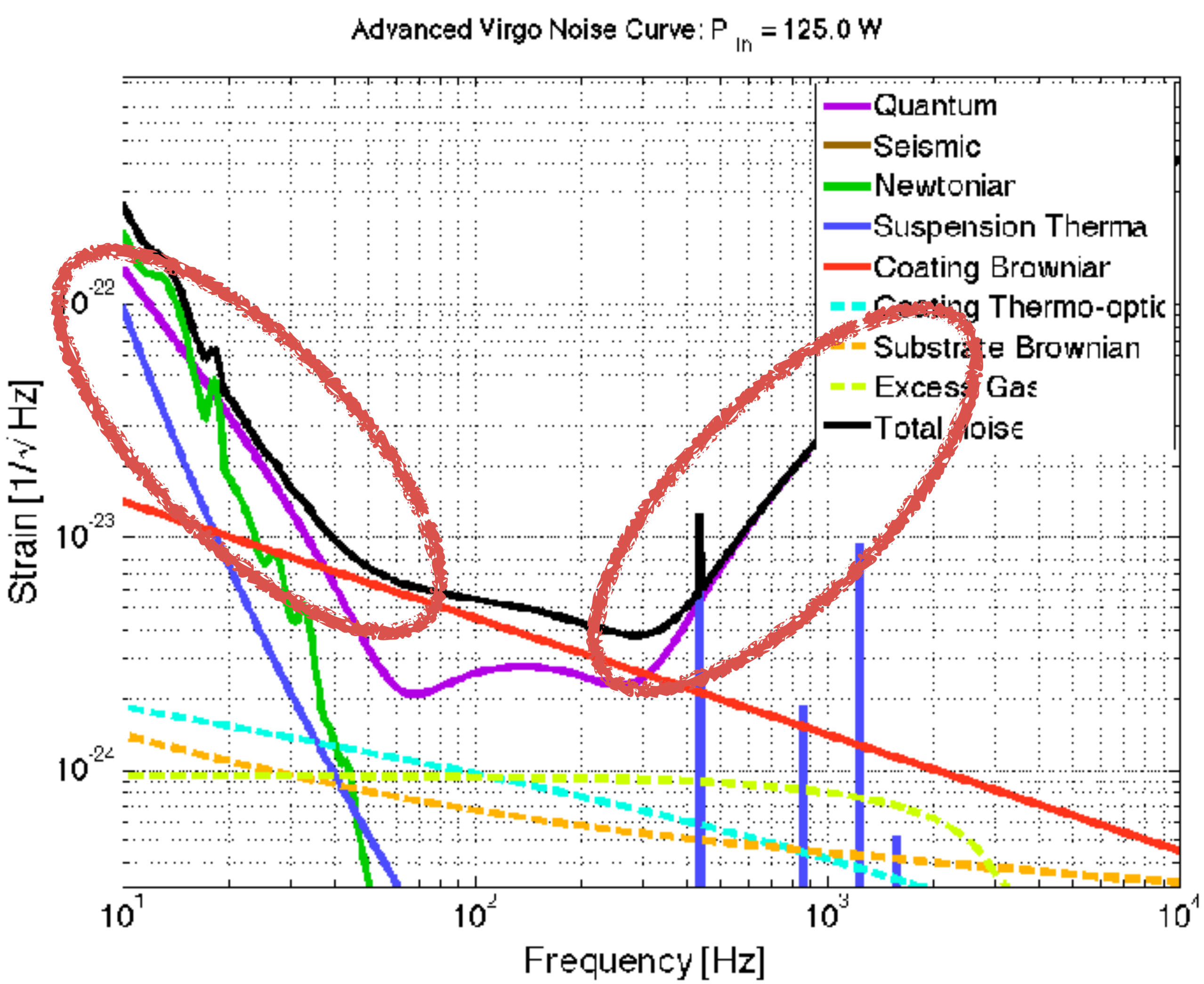
Less astigmatism
Measured:
Visibility ~ 62.5 %

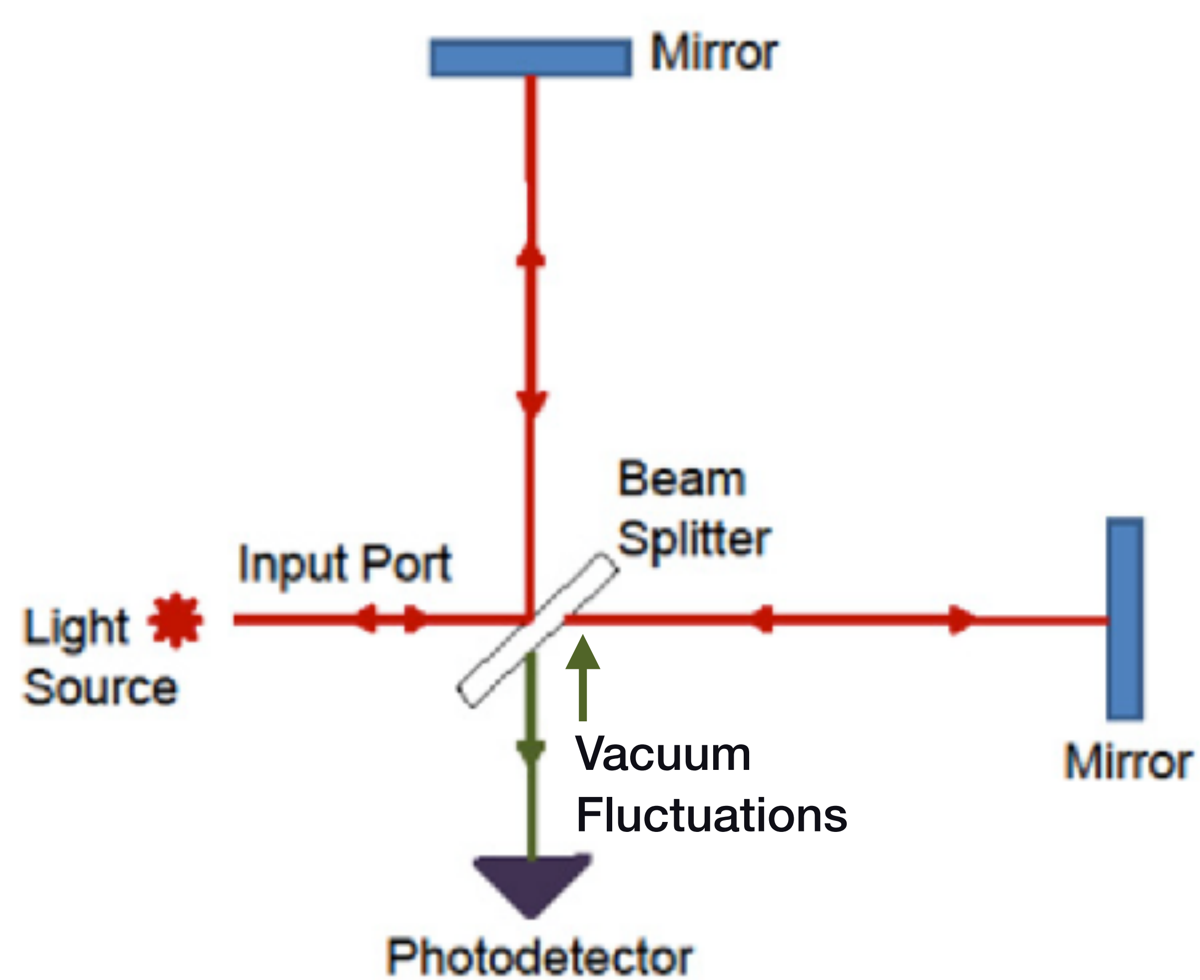
Transmitted Beam | Reflected Beam | Dark Fringe

Reduction of the Quantum Noise Impact

Quantum noise is produced by vacuum fluctuations entering the dark port.
Vacuum fluctuations have equal uncertainty in phase and amplitude:

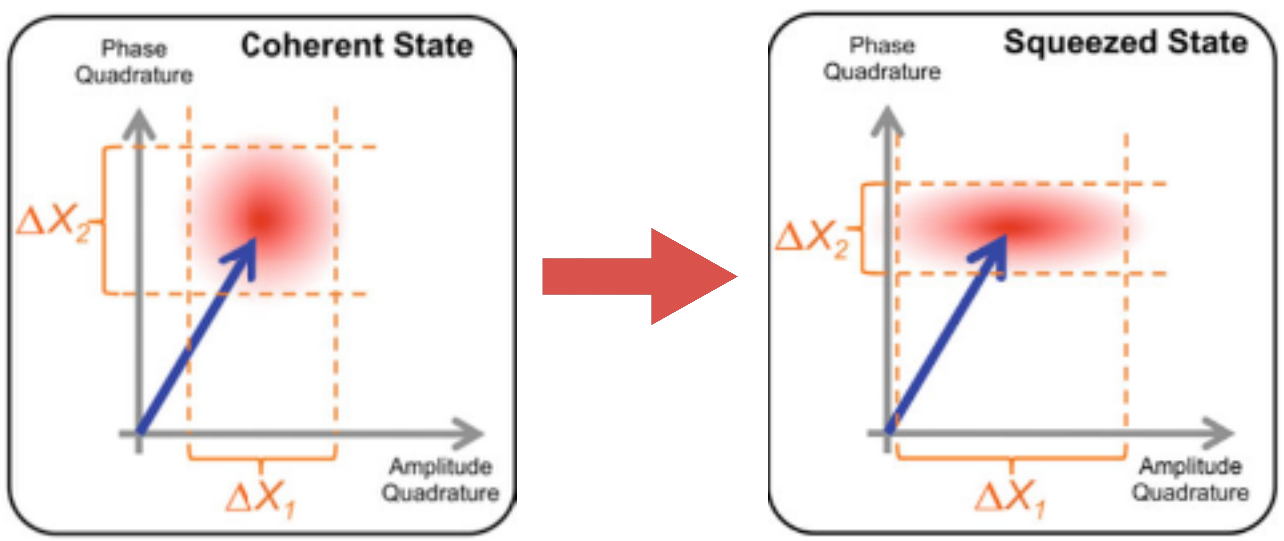
- Phase -> Shot Noise (High Frequency Range)
- Amplitude -> Radiation Pressure Noise (Low Frequency Range)

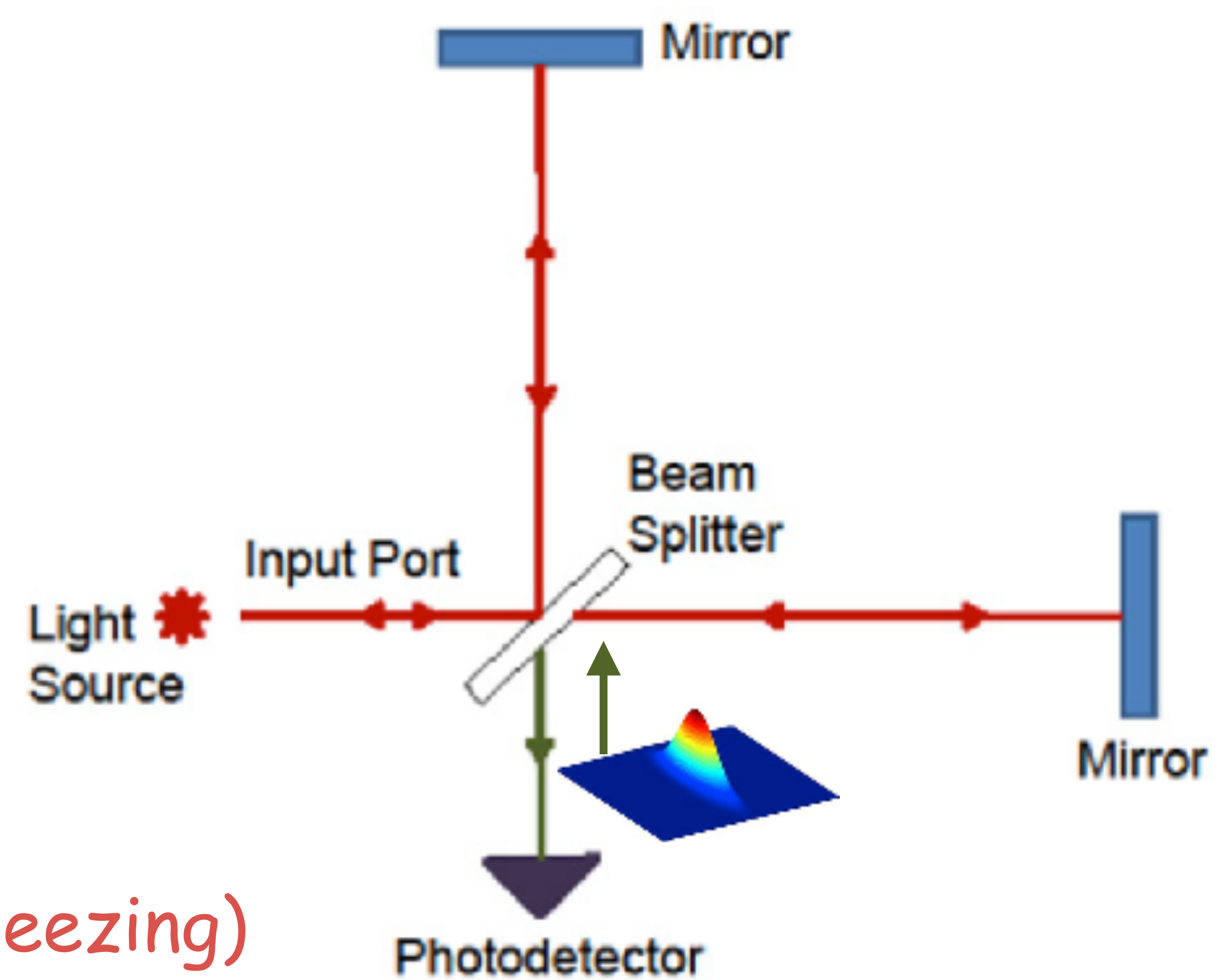




Reduction of the Quantum Noise Impact

Reduce quantum noise by injecting squeezed vacuum -> less uncertainty in one of the two quadratures.
Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one.



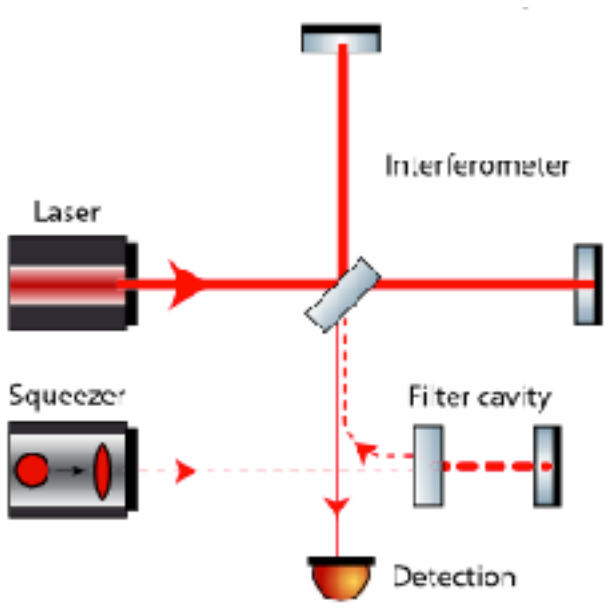


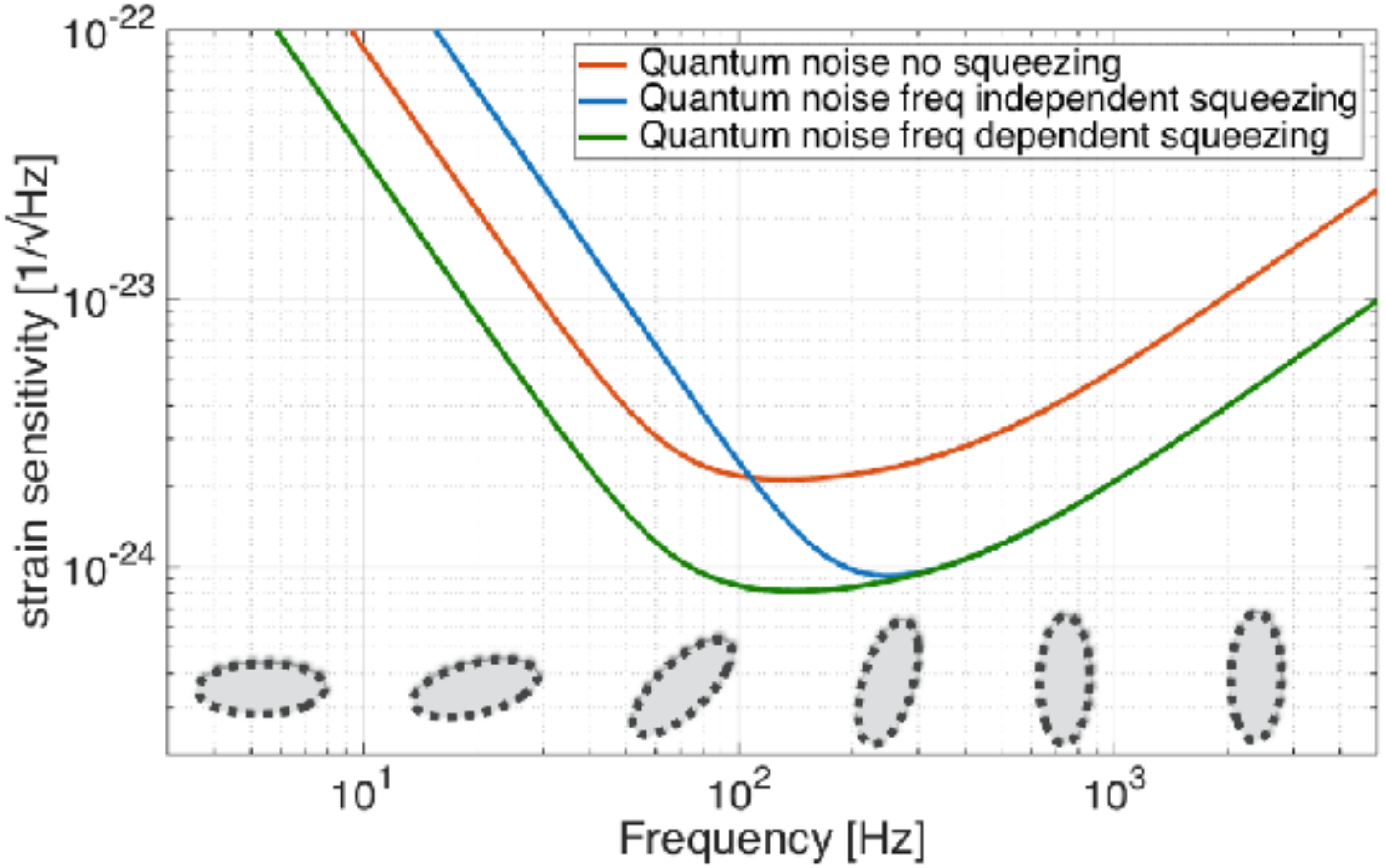
Each state is characterized by:
- squeezing factor (magnitude of the squeezing)
- squeezing angle (orientation of the ellipse)

The use of Filter Cavities

- Squeezing ellipse rotates inside the interferometer -> squeezing angle should change with the frequency for an optimal noise reduction.
- Filter cavities impress a frequency dependent rotation on the squeezing ellipse.
- Reduced noise quadrature always aligned with signal.

Reflect frequency dependent squeezing of a Fabry-Pérot cavity



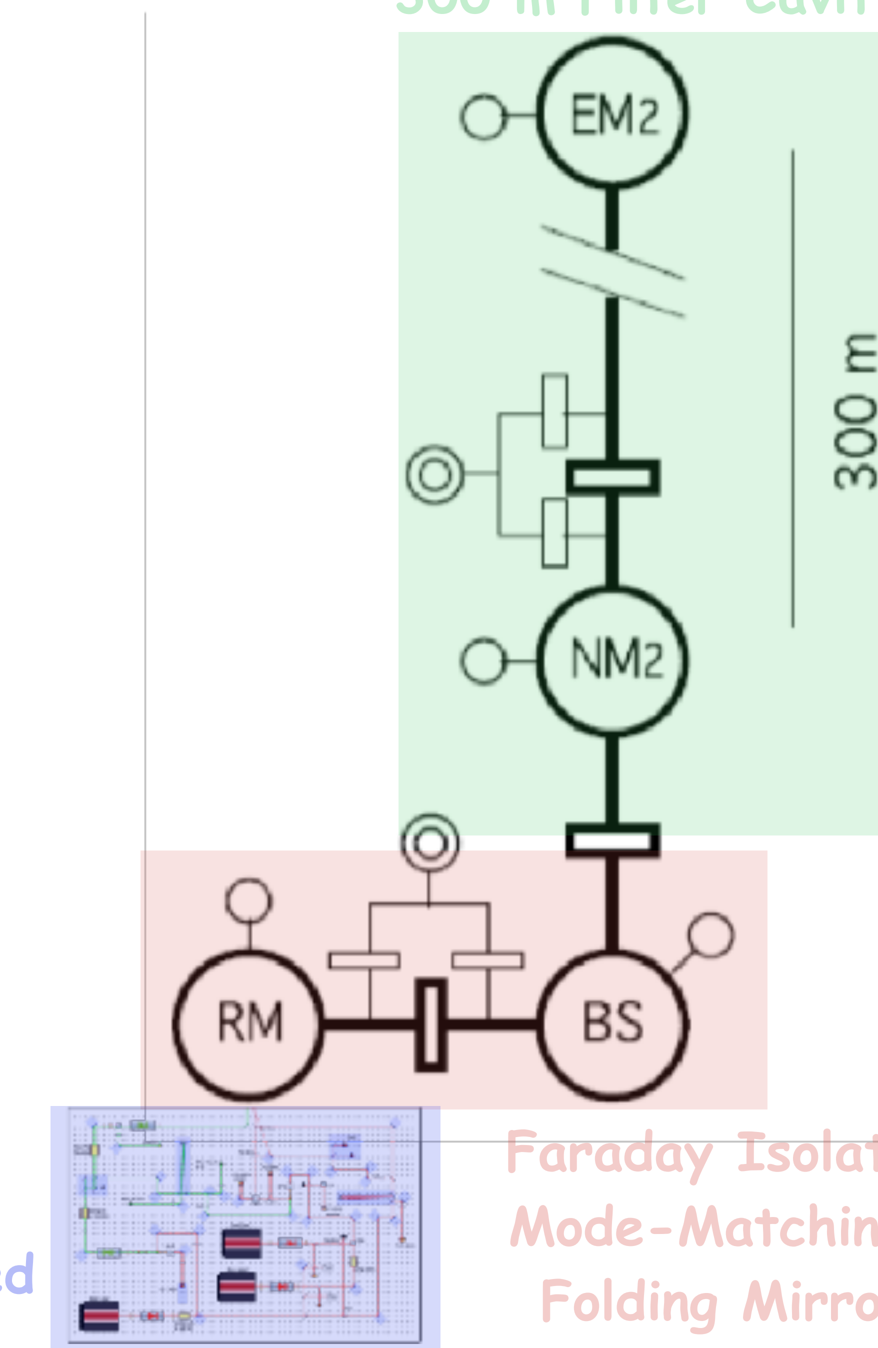


Included in the upgrade plans for advanced detectors and in the ET design

Filter Cavity Project @ NAOJ

The APC Virgo group is collaborating with a group at the National Astronomical Observatory of Japan (NAOJ) in the design and implementation of a long filter cavity for KAGRA detector.

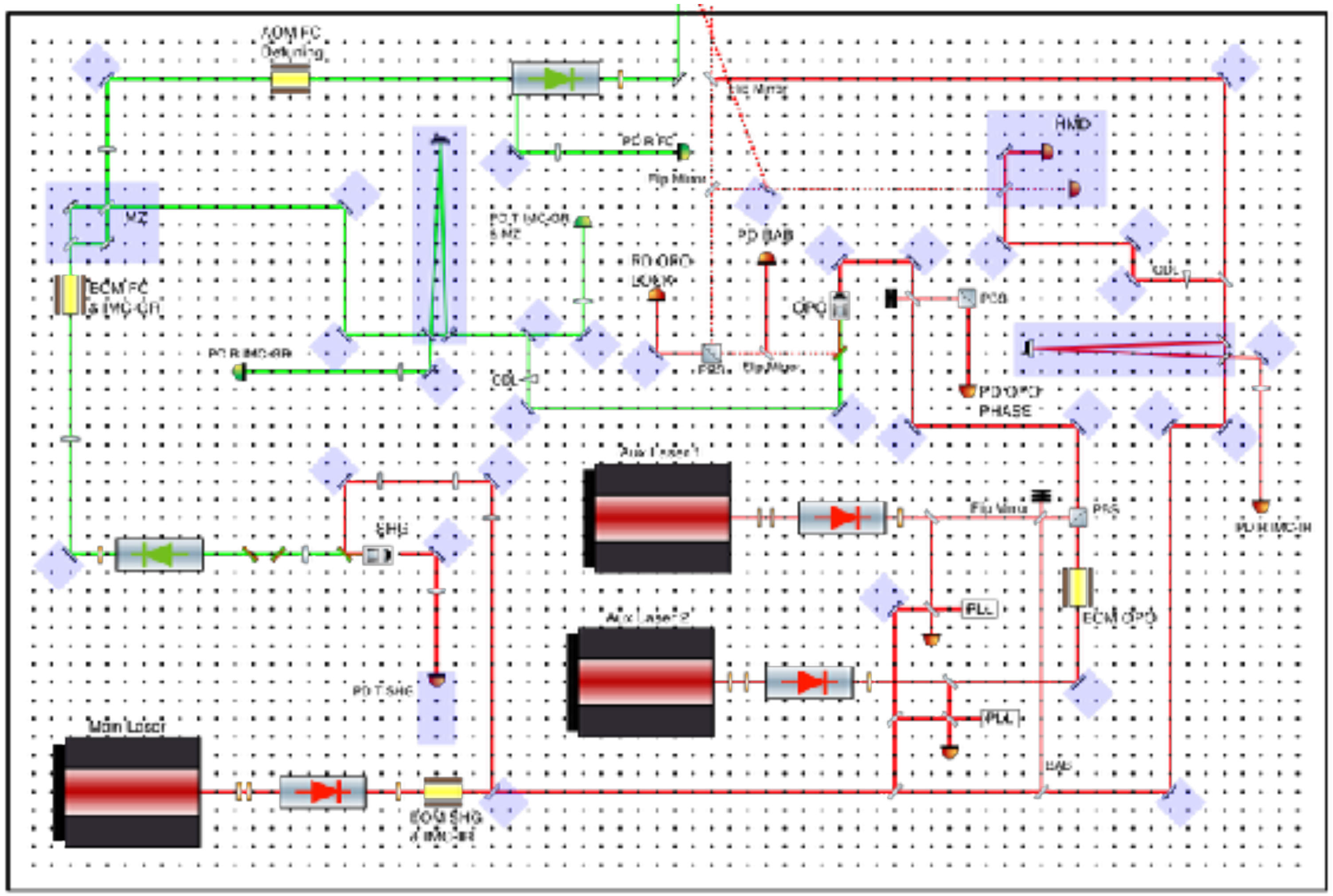
- The requirements for a 300-m filter cavity optical components have been defined to have the optimal frequency dependent squeezing.
- Optical scheme of the vacuum squeezed source bench has been designed.
- The injection system of the squeezed light has been designed.
- The filter cavity prototype is being installed at NAOJ.

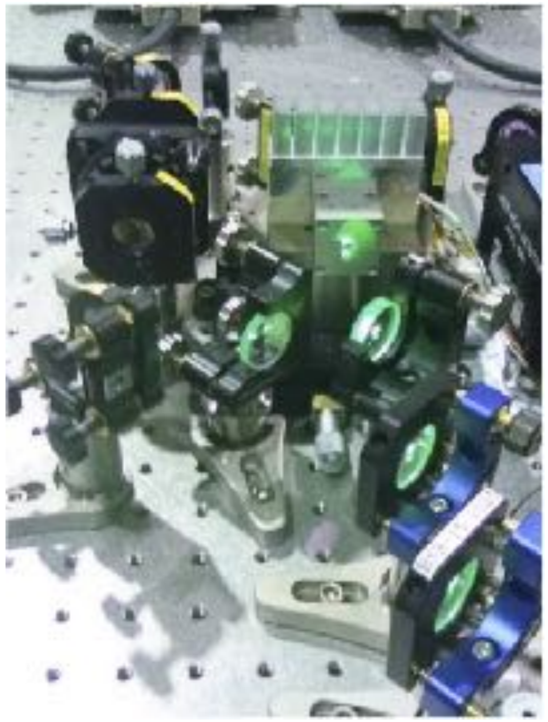


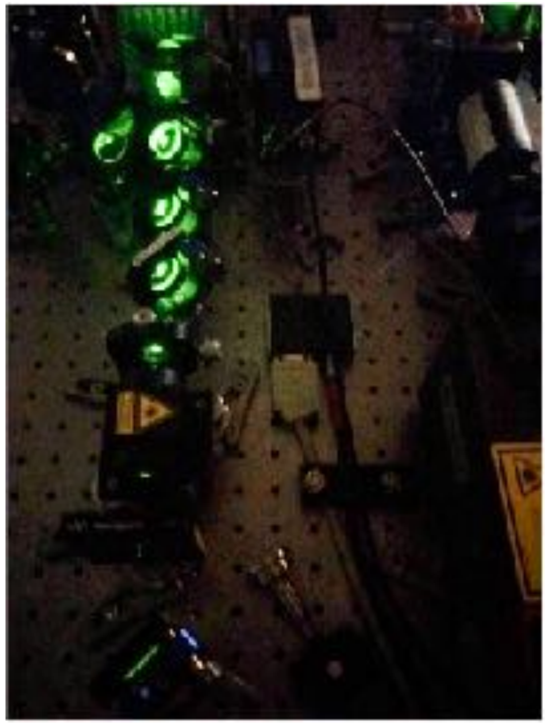
Filter Cavity Project @ NAOJ

Vacuum squeezed source:

- Second Harmonic Generator (SHG) installed
- Optical Parametric Oscillator (OPO) installation in progress
- Green beam from the SHG used to pump the OPO and to control the filter cavity



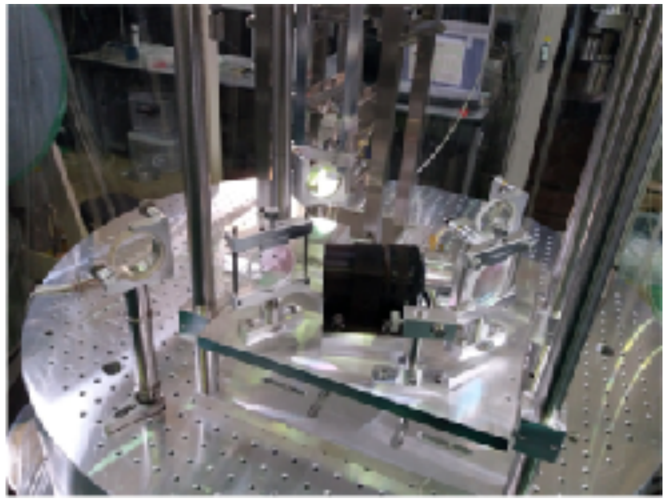




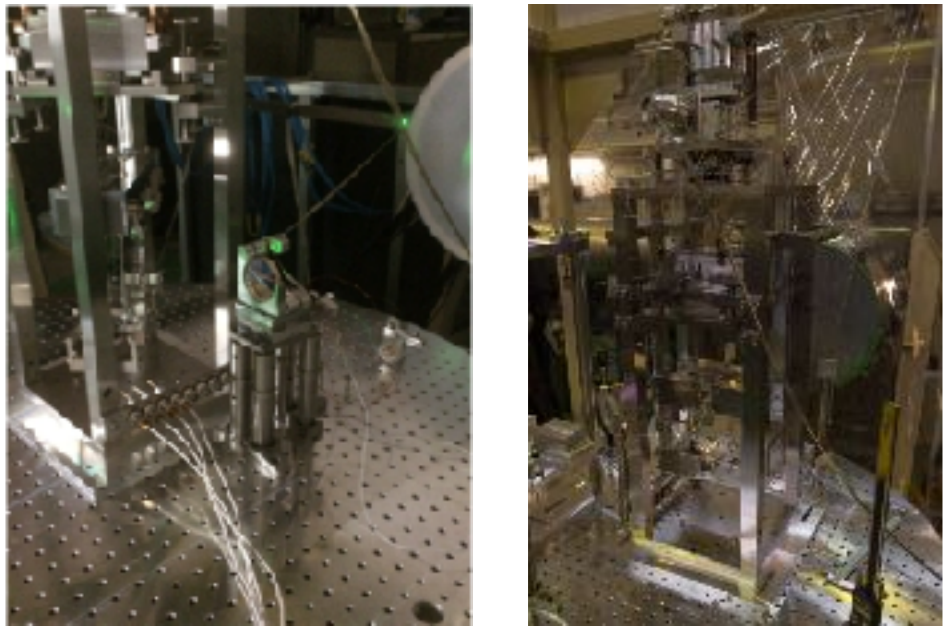
Filter Cavity Project @ NAOJ

Faraday Isolator, Mode-Matching and Folding Mirrors:

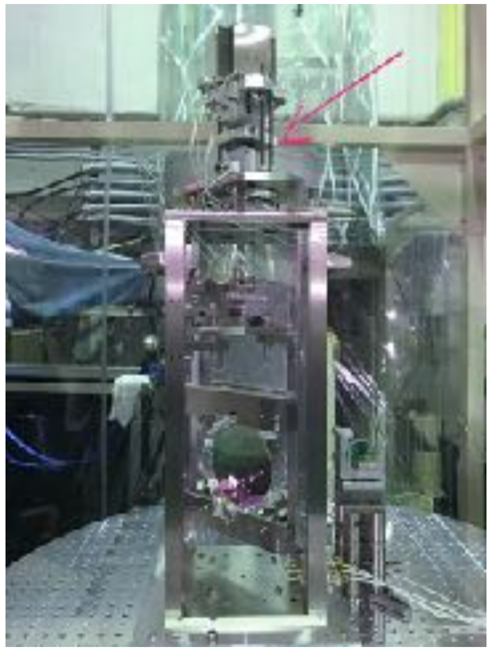
- all the components installed, aligned and in vacuum



Faraday Isolator



Mode-Matching Telescope



Folding Mirror

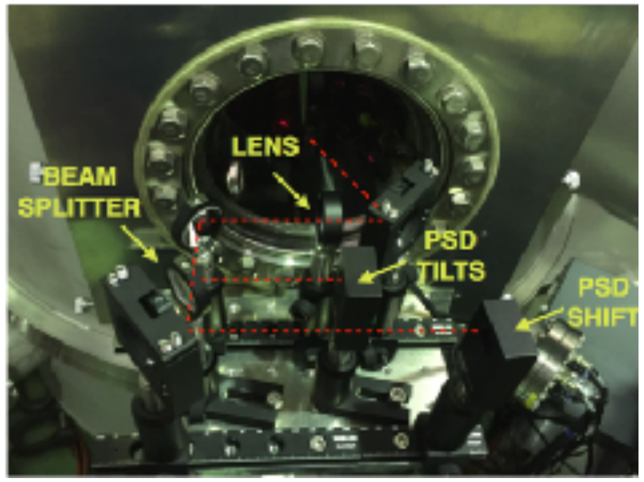
Light at 300 m

Filter Cavity Project @ NAOJ

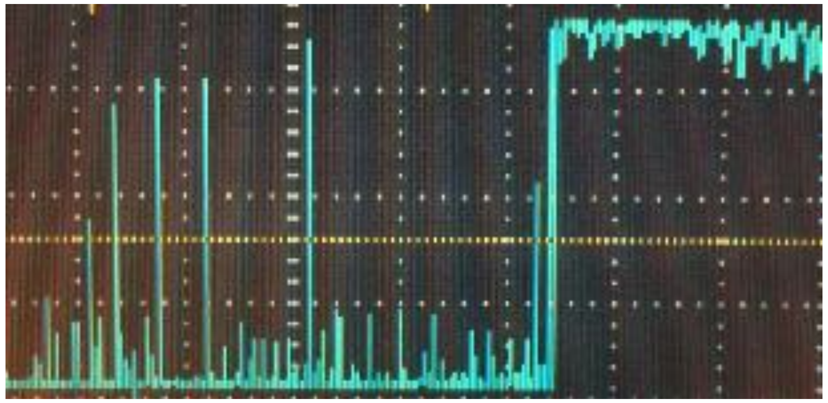
Filter Cavity:
- input and end mirrors suspended
- suspensions control system installed
- auxiliary optics installed
- vacuum in the cavity
- cavity controlled (aligned and locked)

Cavity Transmitted Beam

Cavity End Mirror



Suspension Control System



Cavity Transmitted Power

Future Research

- **Very Short Term** (few moths): Advanced Virgo commissioning to improve the sensitivity to detect gravitational waves: responsibility of the Phase Camera @ Nikhef.
- **Short-Mid Term** (1 years): carry on the design, the installation and the commissioning of the Filter Cavity @ NAOJ and contribute to the design of a Filter Cavity for Advanced Virgo (with other groups).
- **Short-Mid Term 1**(few years): increase my responsibilities in Advanced Virgo.
- **Short-Mid Term 2** (few years): create a working group to carry on the research on optical techniques to reduce the thermal noise impact for the future generation of detectors and the research to improve the squeezing of arbitrary spatial modes.
- **Mid-Long Term**: contribute to the design an the integration of the third generation of detectors (Einstein Telescope).
- **Mid-Long Term**: investigating contributions to spatial detectors.