Detection of Gravitational Waves with laser interferometers: focus on Virgo Laser and optics

Winter College on Optics, Trieste, February 24th, 2016

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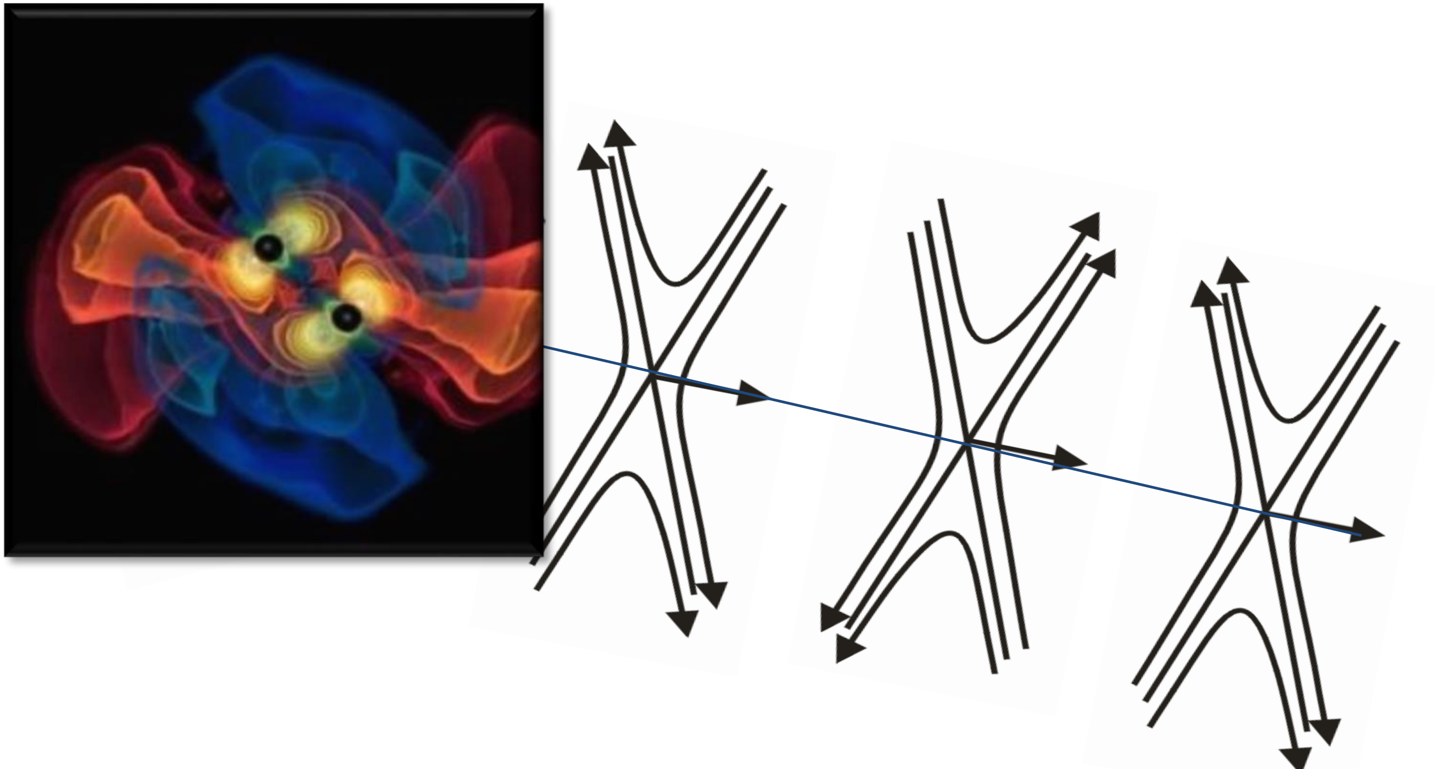
on behalf of the LIGO Scientific and VIRGO collaborations

Outline

- GW detection/GW150914
- A Laser interferometer to detect Gravitational waves
- Advanced Virgo/Ligo: Laser and optics

Introduction to Gravitational Waves



Gravitational waves are propagating dynamic fluctuations in the curvature of space-time ('ripples' in space-time)

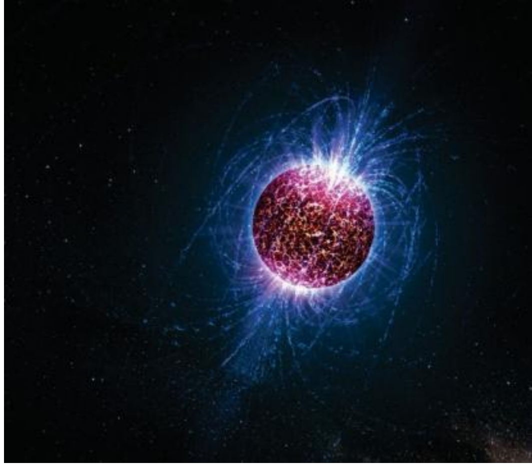
- Predicted by Einstein 100 years ago; confirmation by Hulse/Taylor/Weisberg

Emitted from accelerating mass distributions

- Sourced by the time-dependence of the quadrupole mass moment
- Practically, need massive objects at speeds approaching the speed of light

GWs carry *direct* information about the relativistic motion of bulk matter

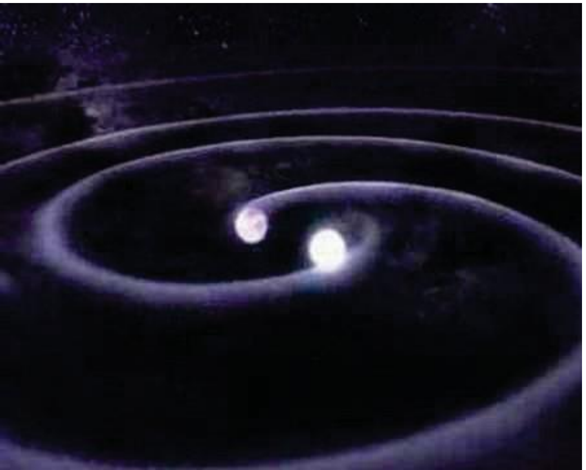
Supernovae



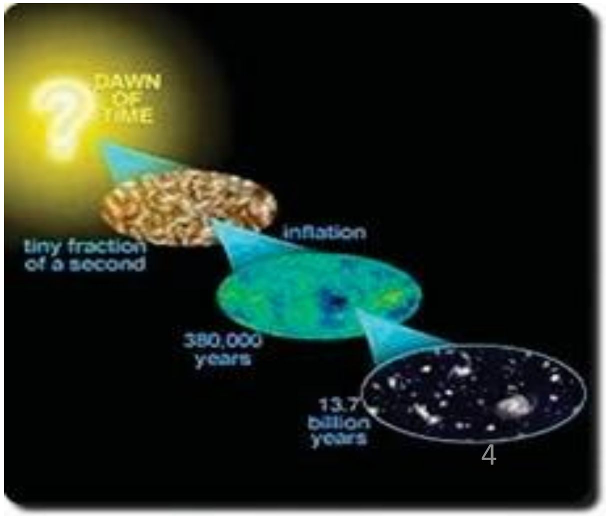
Rotating neutron stars

Hunting the GW signals

Coalescent Binary Sytem



GW stochastic background



The first event

- ***On September 14, 2015 at 09:50:45 UTC*** *the LIGO Hanford, WA, and Livingston, LA, observatories detected a coincident signal.*
- The event was flagged as GW150914
- Exhaustive investigations of instrumental and environmental disturbances were performed, giving ***no evidence*** that GW150914 is an instrumental artifact

→ Opens new perspectives, a new way to look at the Universe.

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

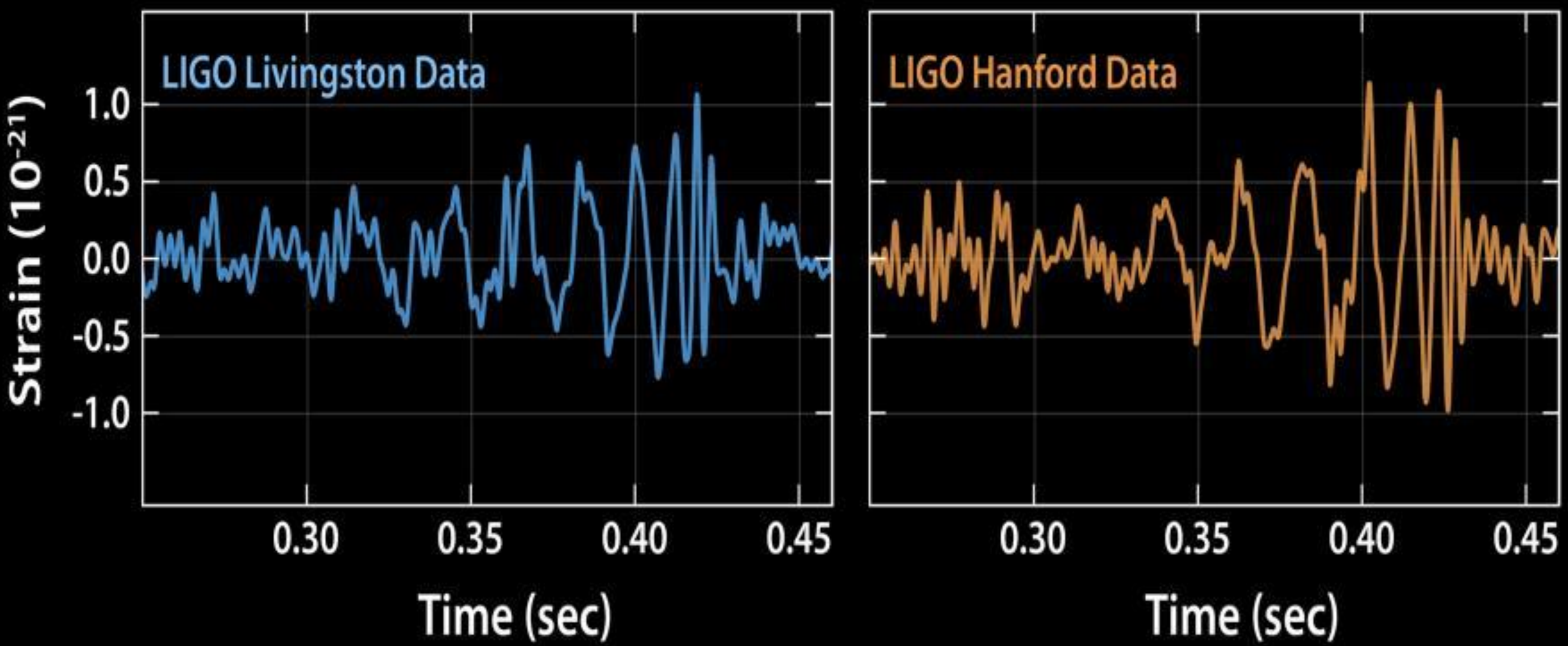
Observation of Gravitational Waves from a Binary Black Hole Merger

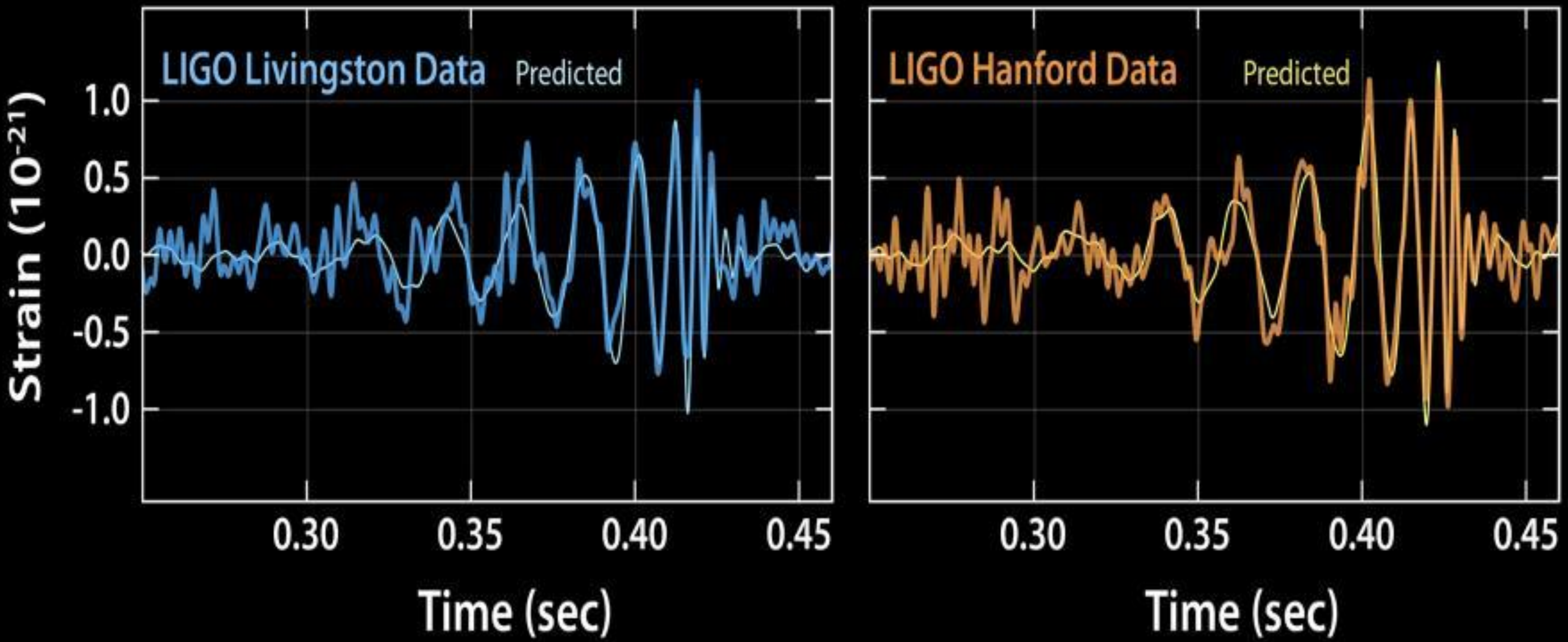
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

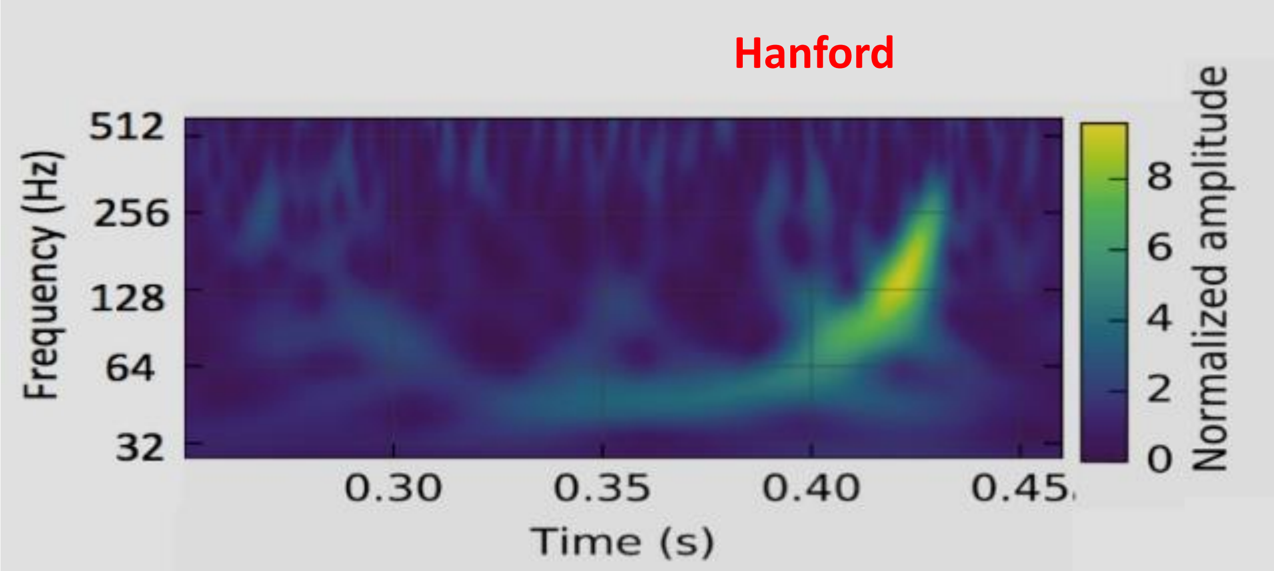
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

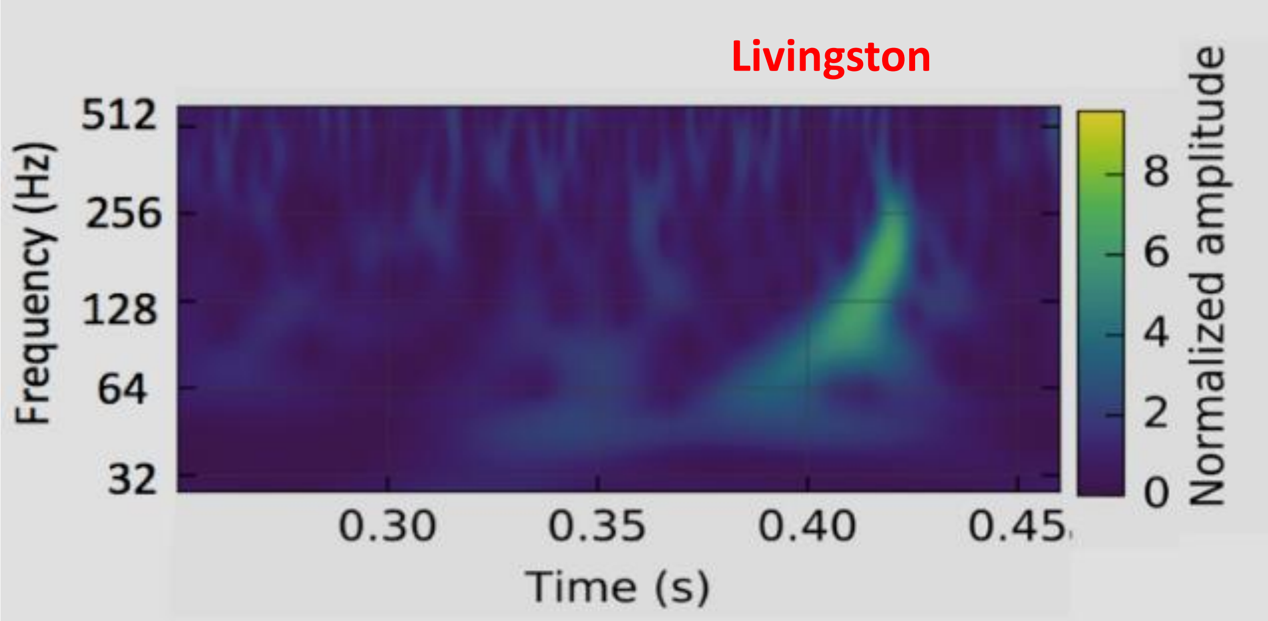
DOI: 10.1103/PhysRevLett.116.061102

http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.116.061102


LIGO Livingston Data
LIGO Hanford Data
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)


Hanford
512
256
128
64
32
Frequency (Hz)
0.30
0.35
0.40
0.45
Time (s)
8
6
4
2
0
Normalized amplitude


Livingston
512
256
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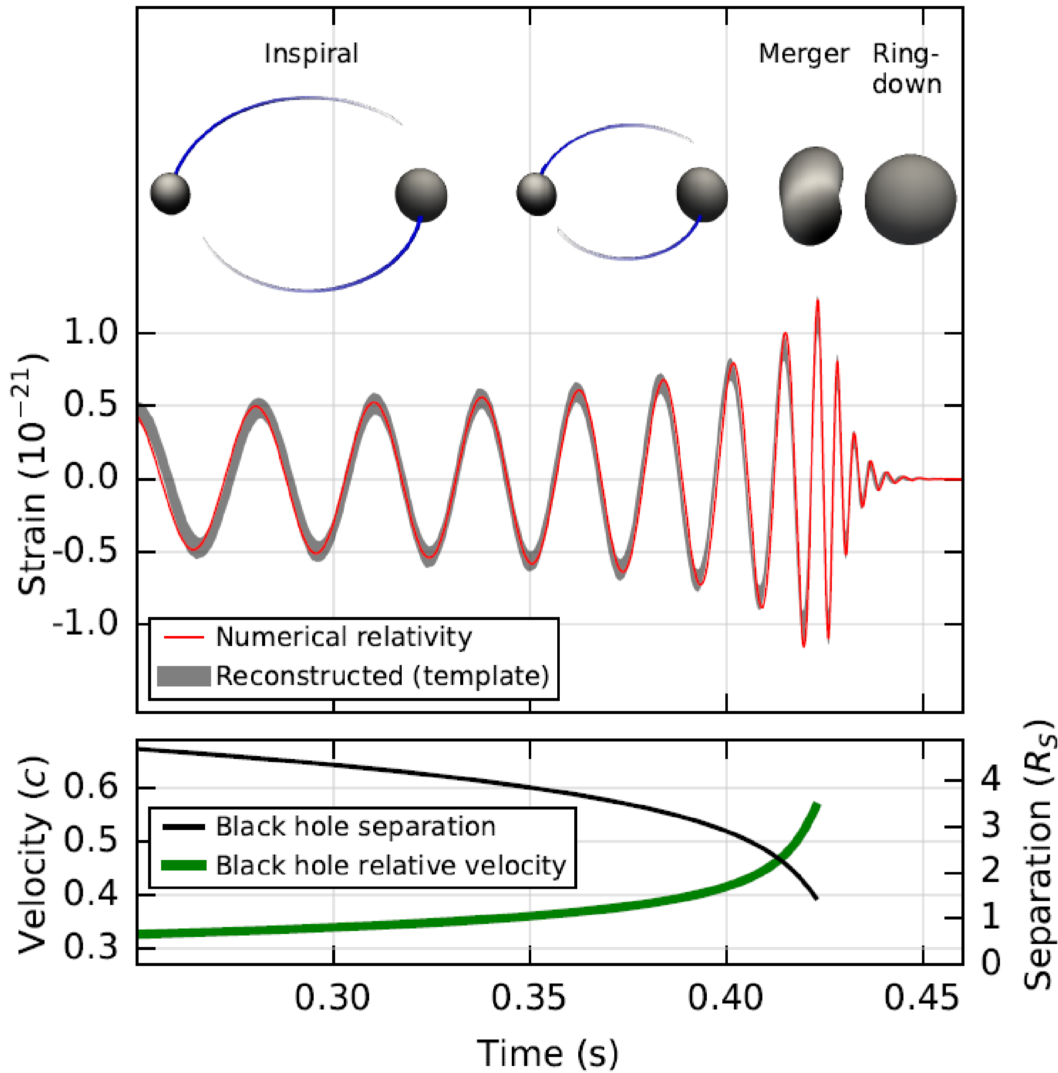
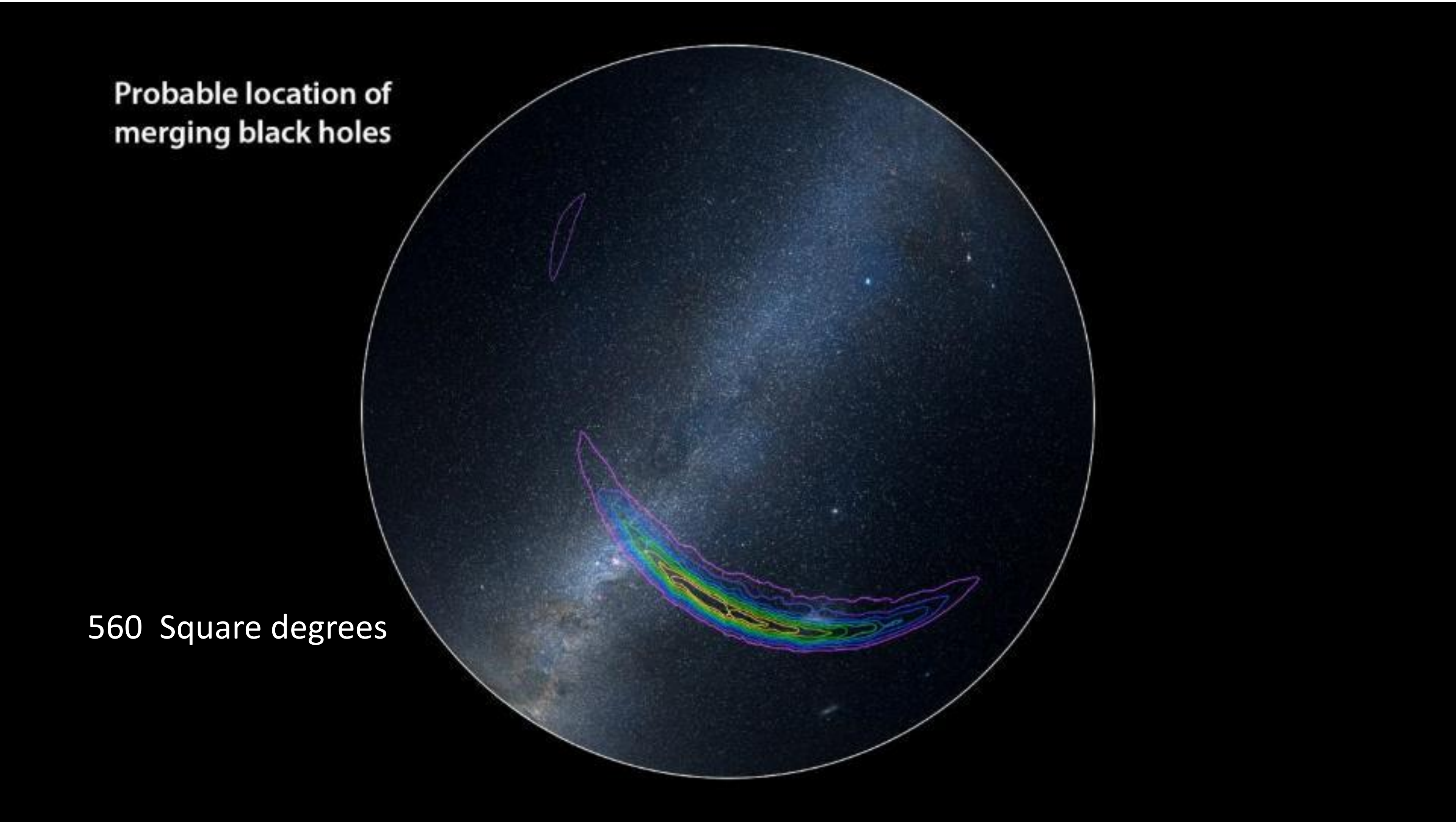
64
32
Frequency (Hz)
0.30
0.35
0.40
0.45
Time (s)
8
6
4
2
0
Normalized amplitude

Estimated GW Strain Amplitude for GW150914

Full bandwidth waveforms without filtering. Numerical relativity models of black hole horizons during coalescence

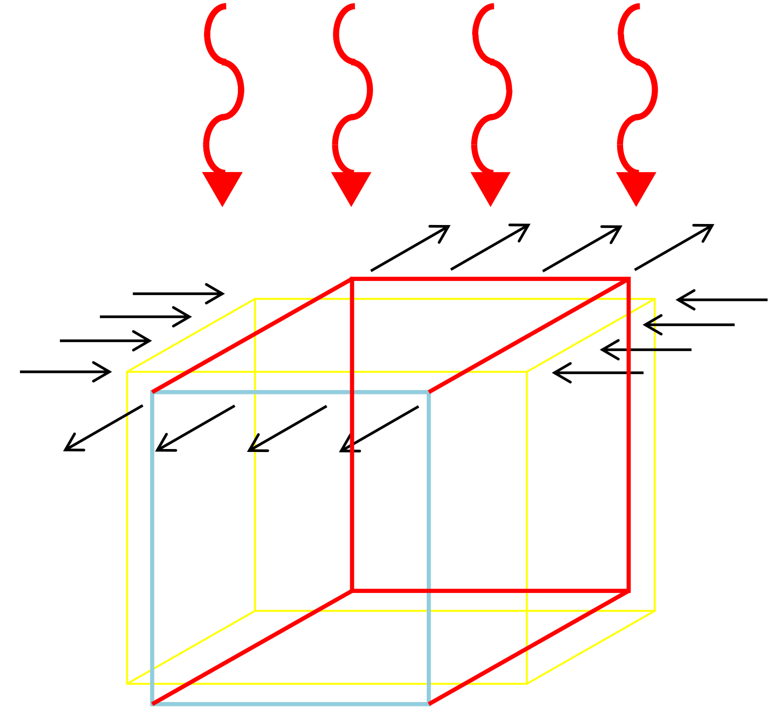
Effective black hole separation in units of Schwarzschild radius (R_s=2GM/c^2); and effective relative velocities given by post-Newtonian parameter v/c = $(GMpf/c^3)^{1/3}$




Probable location of
merging black holes
560 Square degrees

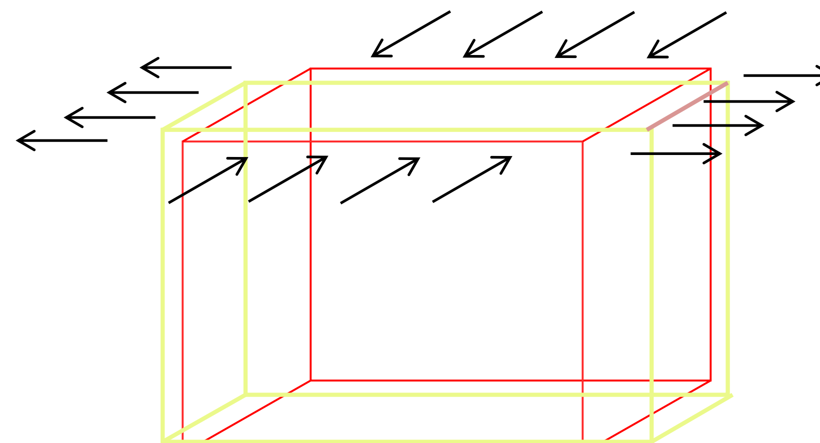
A Laser interferometer to detect GW

The physical Effect



GW squeeze and stretch the space in perpendicular directions

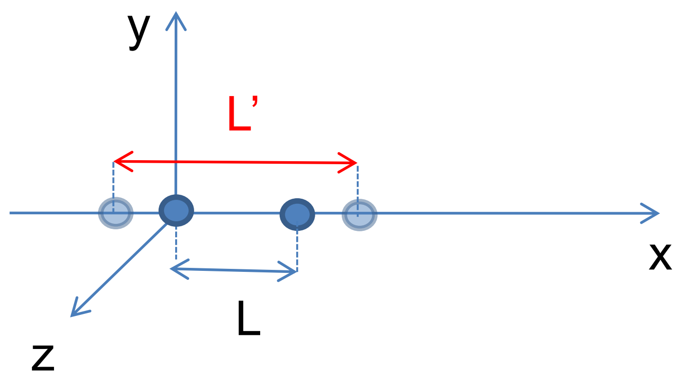
→ Deformation of elastic bodies
→ Displacement of free masses



To detect GW:

❑ monitor distances between free masses

The effect of Gravitational Waves on free falling masses



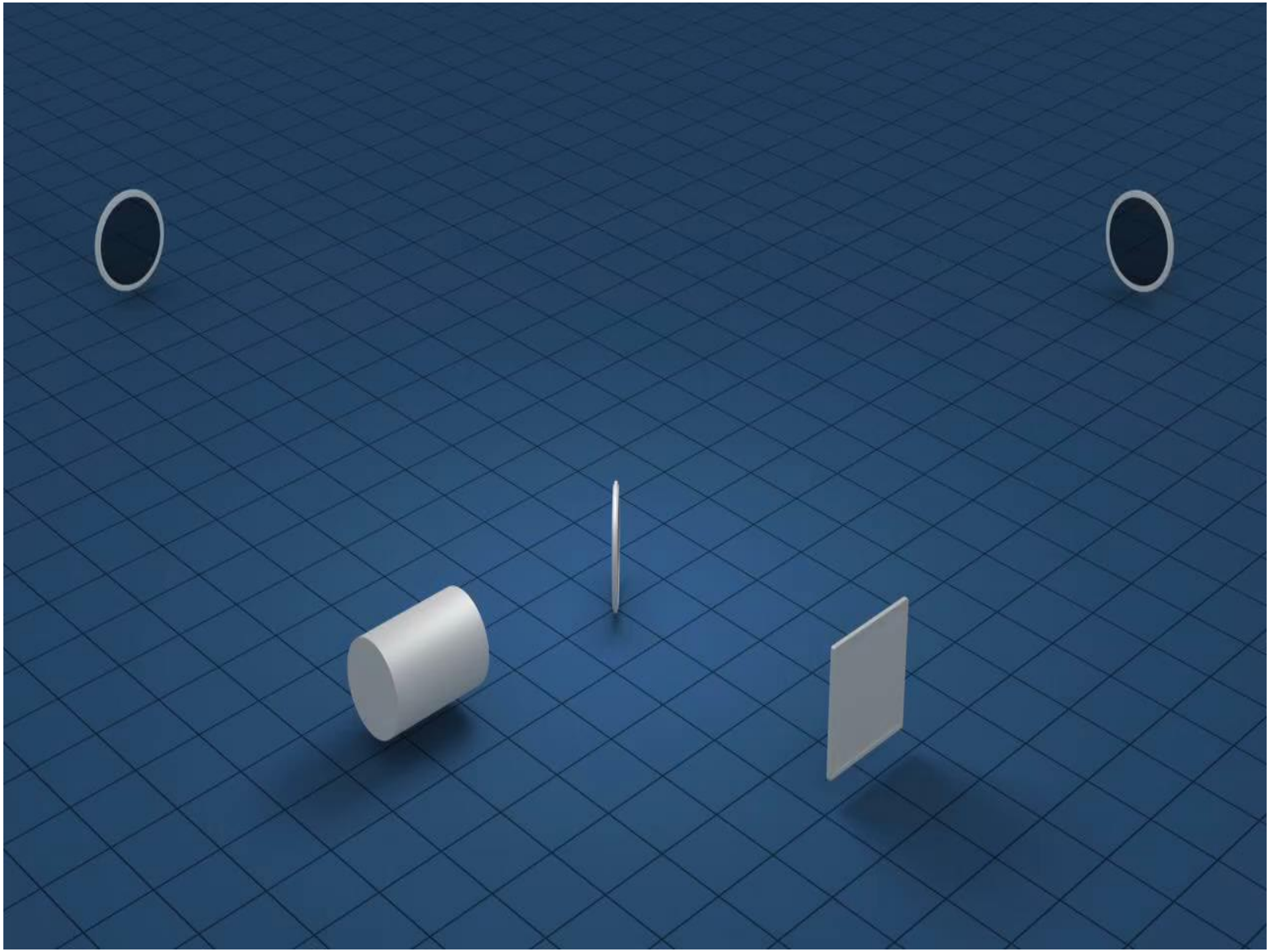
$$\delta L \propto h\,L$$

Very weak amplitude: $h \approx 10^{-21}$

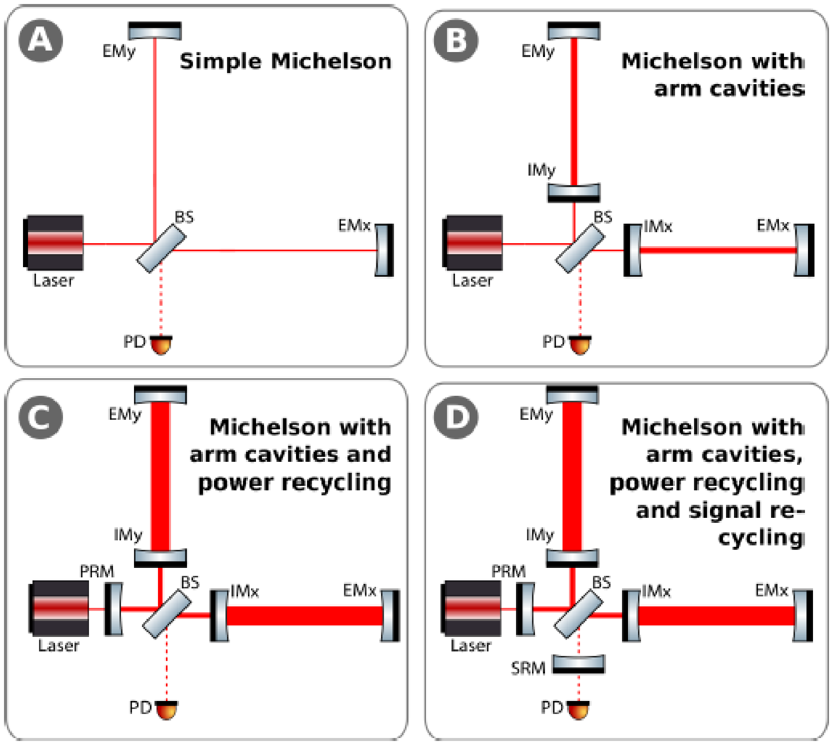
The distance between two masses separated by ~Km will change by $\boldsymbol{\delta L \approx 10^{-18}\mathrm{m}}$

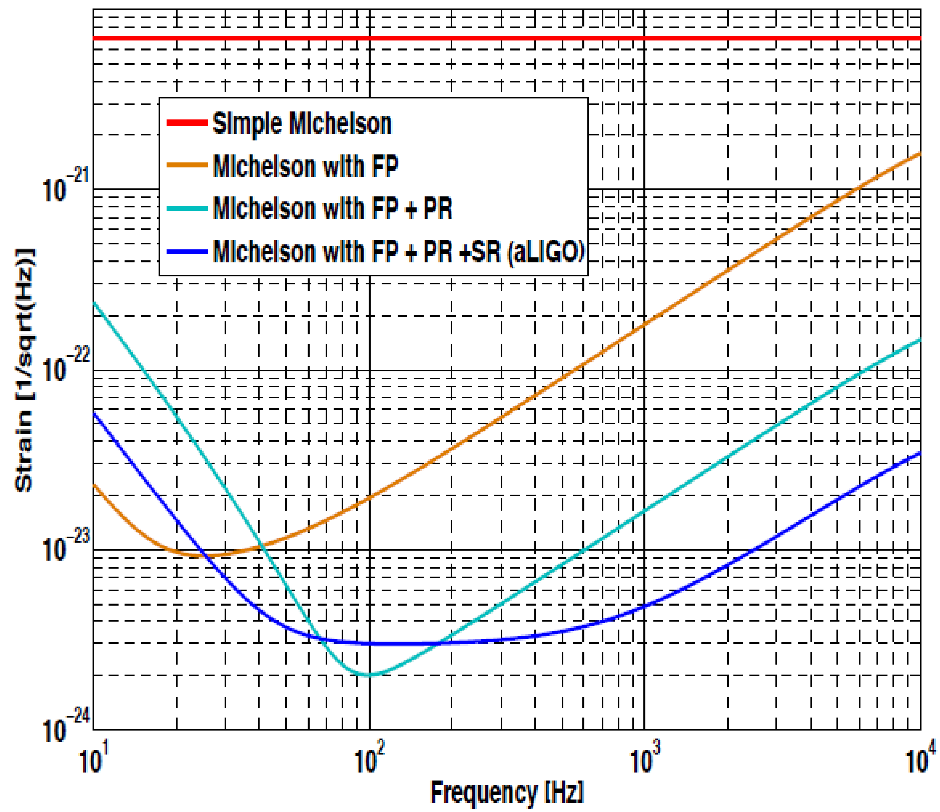
"That is comparable to a hair's-width change in the distance from the Sun to Alpha Centauri, its nearest star".

The solution: use a Michelson Interferometer



How to improve the Michelson interferometer sensitivity





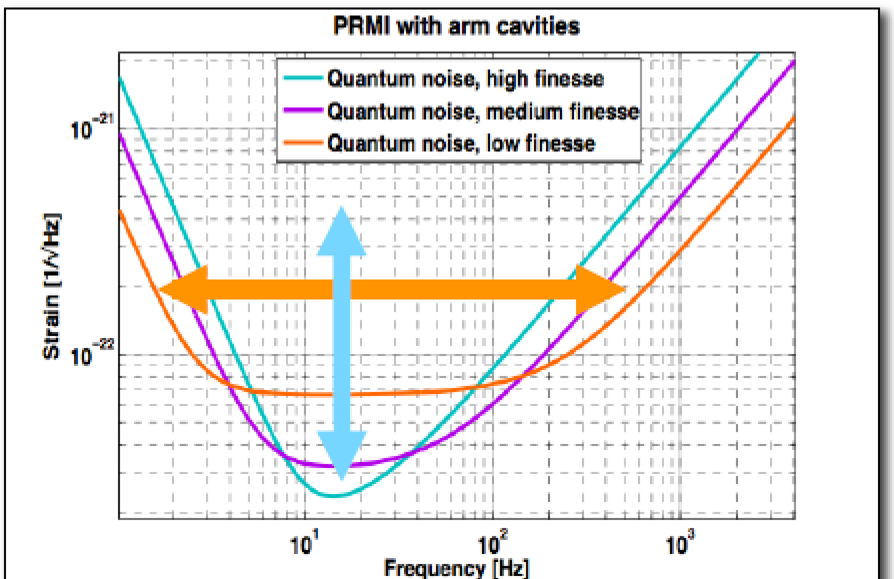
Credits: Stefan Hild (University of Glasgow)

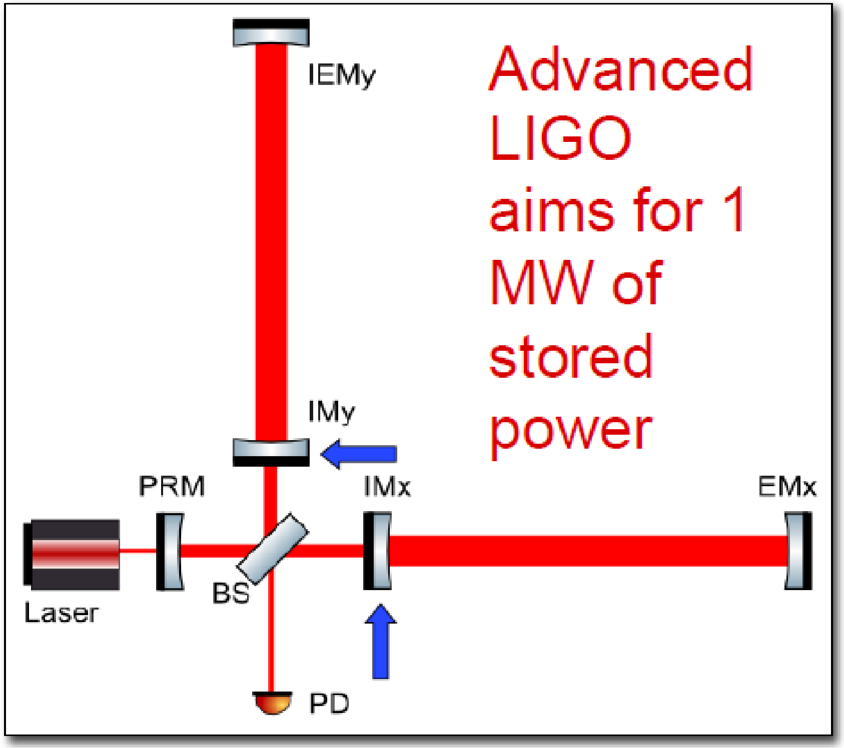
NB: Considered km long arms.

Arm cavity property

Increasing the storage time in the arms by using arm cavities.

Finesse of the arm cavities determines bandwidth of GW detector.

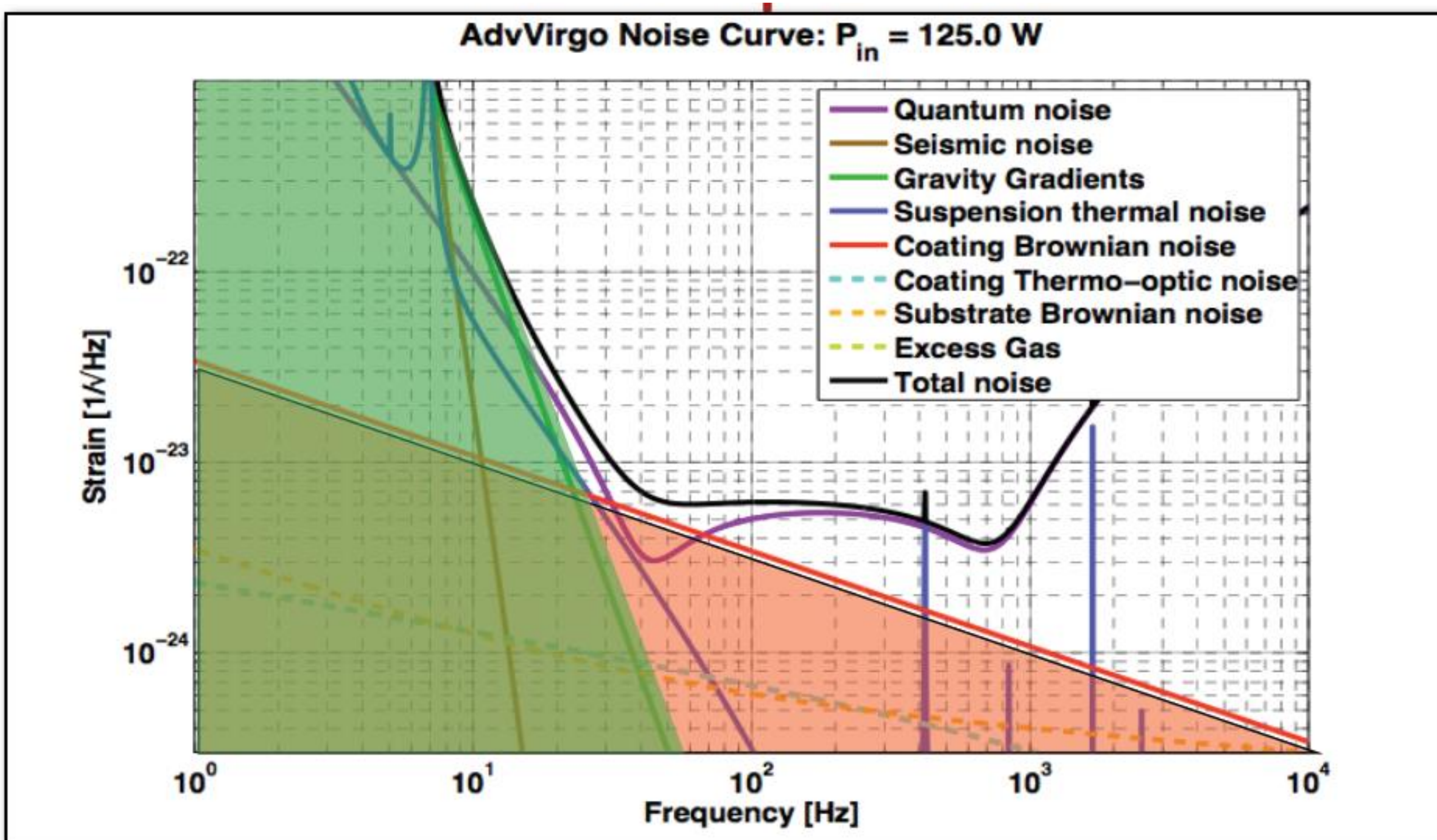




NB: Considered km long arms.

Credits: Stefan Hild (University of Glasgow)

Typical sensitivity curve for Advanced Virgo



Credits: Stefan Hild (University of Glasgow)

Mostly limited by quantum noise over the whole bandwidth.
But also by gravity gradient noise at low frequency
and coating thermal noise in mid frequency range

Location in the sky

- GW laser interferometers are not pointing telescopes,

- Sky location can be reconstructed through the time of arrival of GW radiation at the different detector sites, as well as the relative amplitude and phase of the GWs in different detectors.

→ It is mandatory to have a network of interferometer to better localize the source in the sky

The 2007 GW network

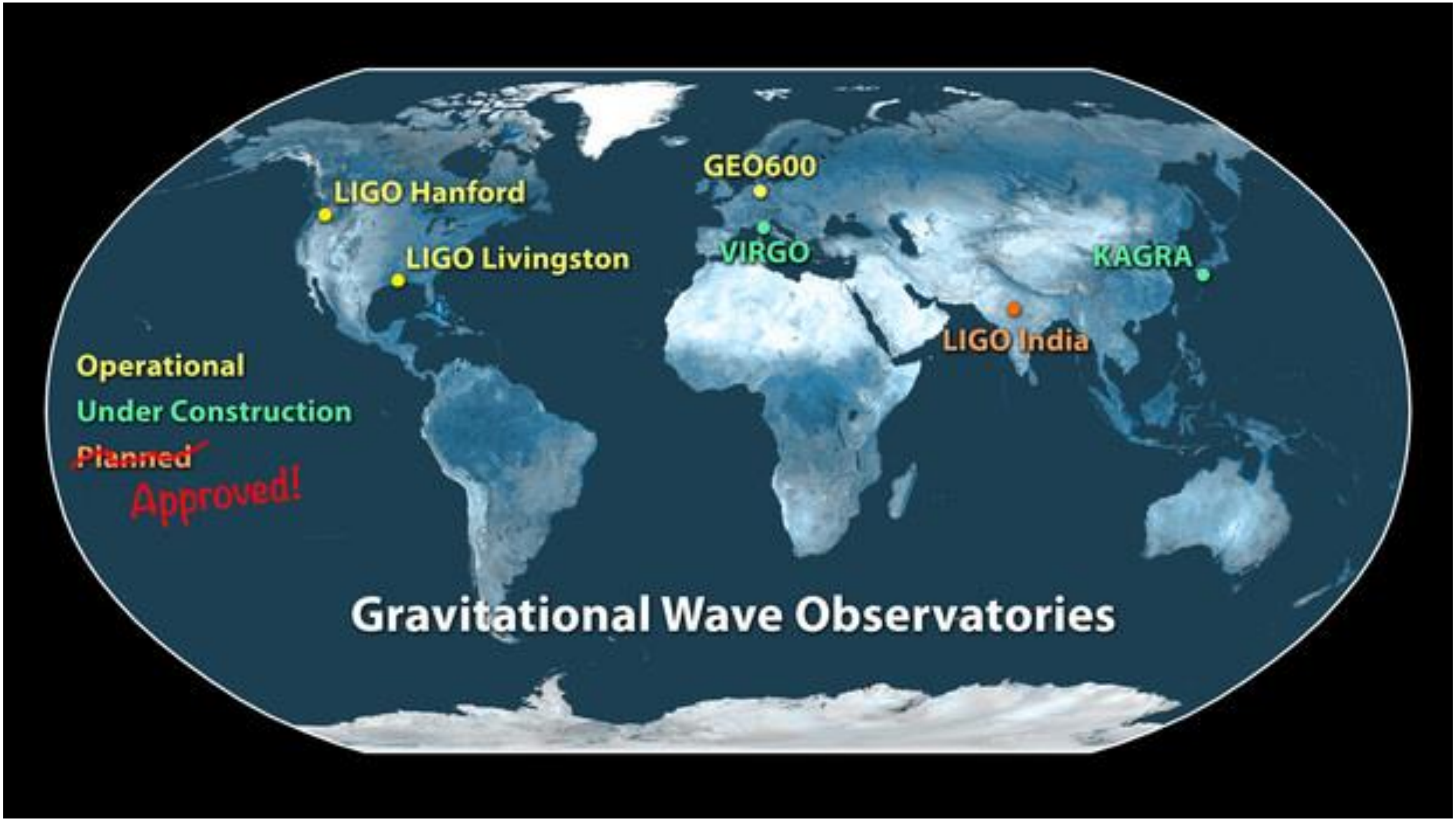
H1- Hanford – Washington state

Virgo – Cascina (Pisa) – EGO site

GEO600 – Hannover - Germany

L1- Livingston – Louisiana state

Expected network in coming years



H1- Hanford – Washington state

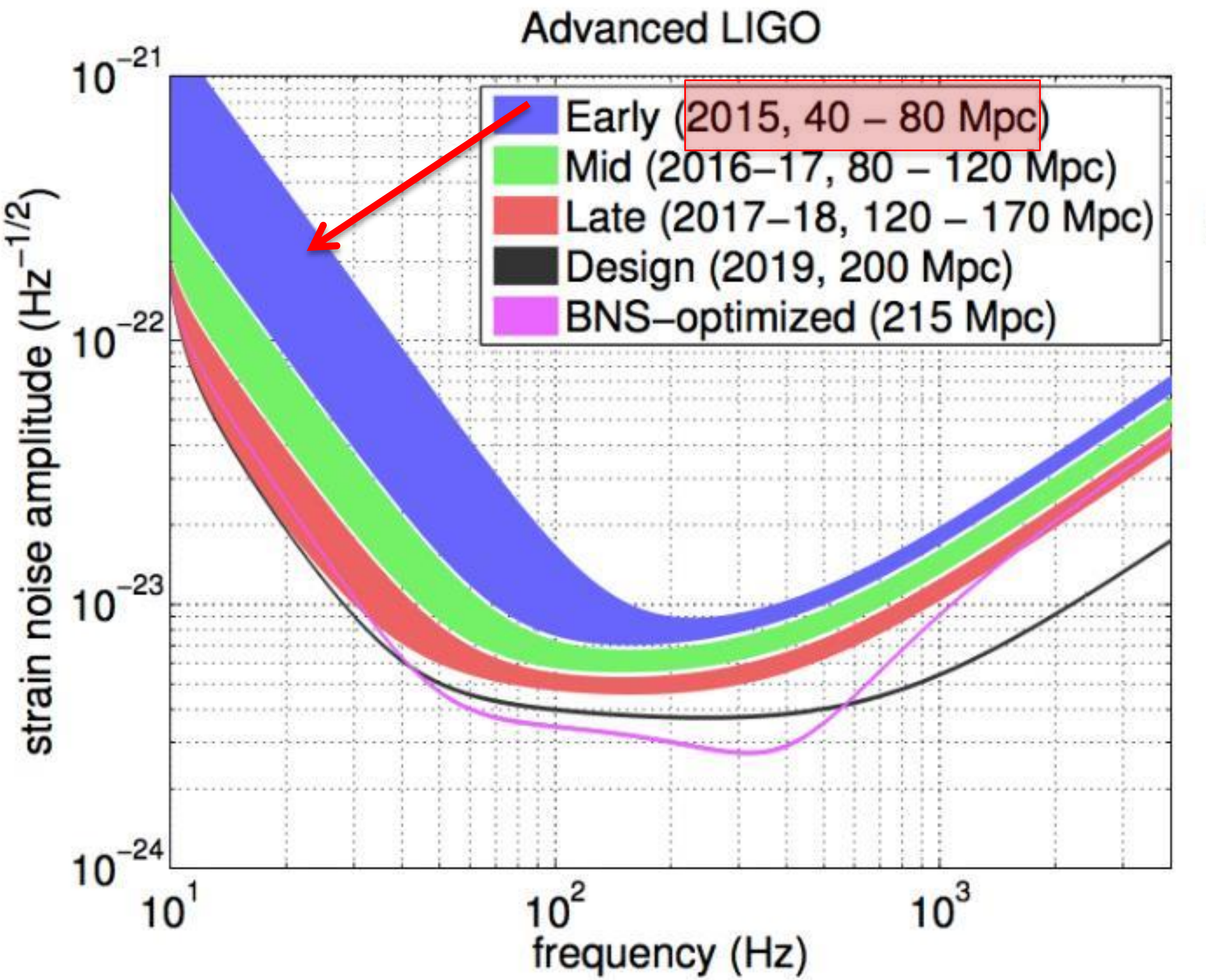
LIGO upgrade concluded

First data taking period from September 2015 to January 2016

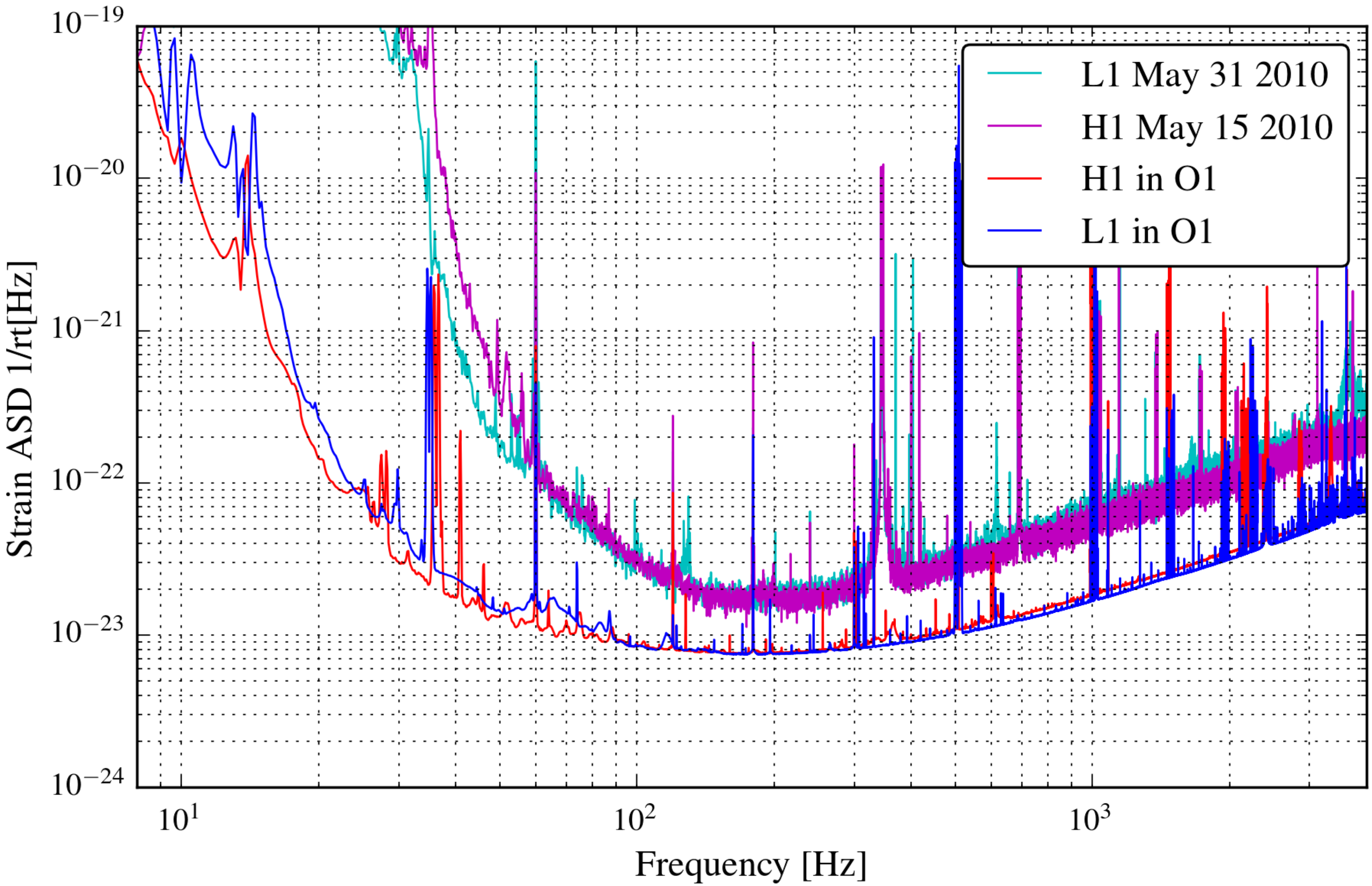
VIRGO will end the upgrade in 2016

L1- Livingston – Louisiana state

First sensitivity target achieved already !



From LIGO to aLIGO: Sensitivity improvements



What is ADVANCED VIRGO?

- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves
- Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary
- Funding approved in Dec. 2009
- Construction in progress. End of installation: Spring 2016
- First science data in 2016

5 European countries
19 labs, ~200 authors

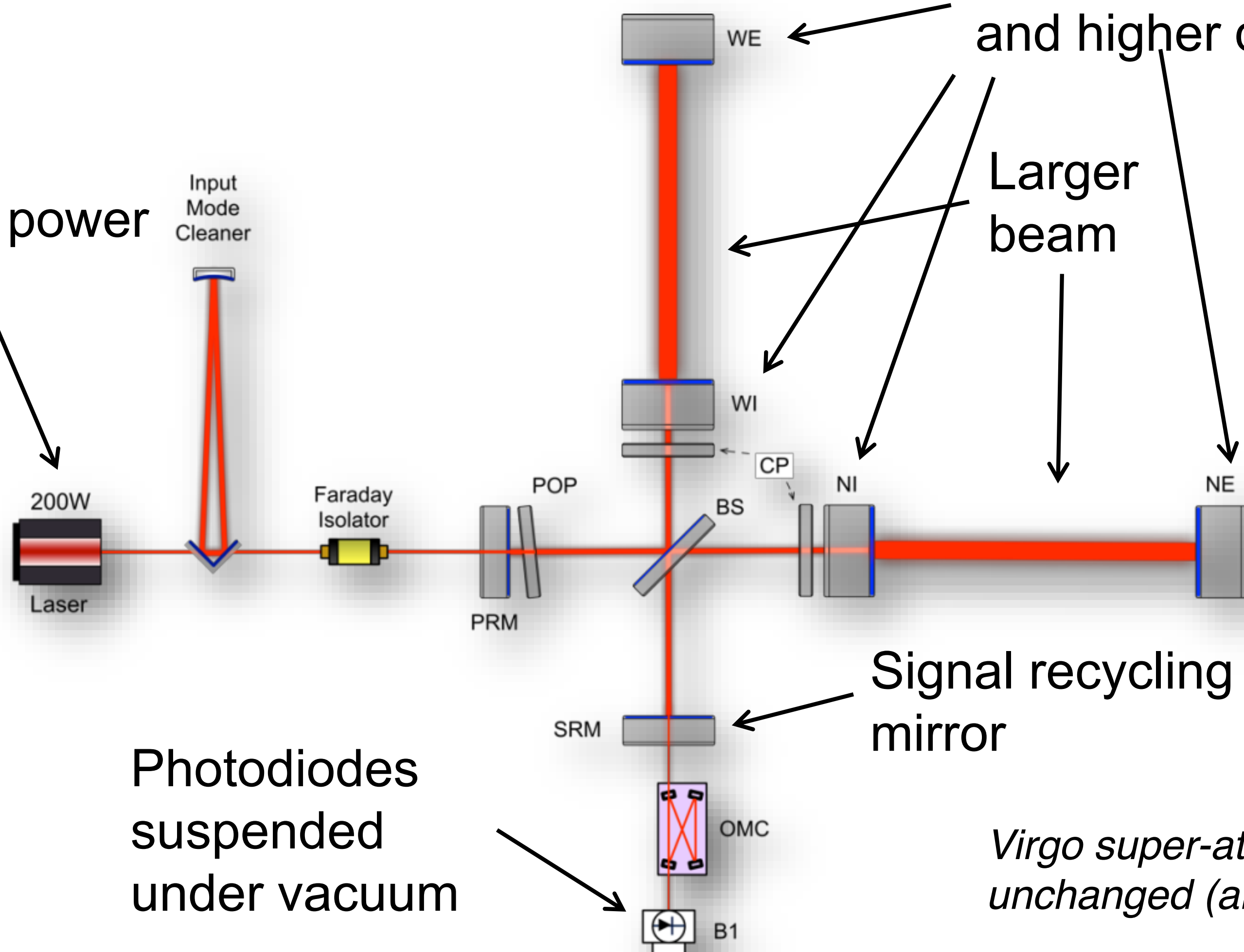
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

Detector design:
Main changes respect to 1st generation

Heavier mirrors (40 kg) and higher quality optics

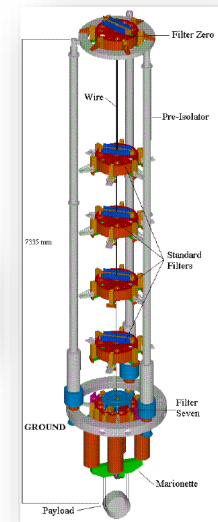
Larger beam

Higher power laser



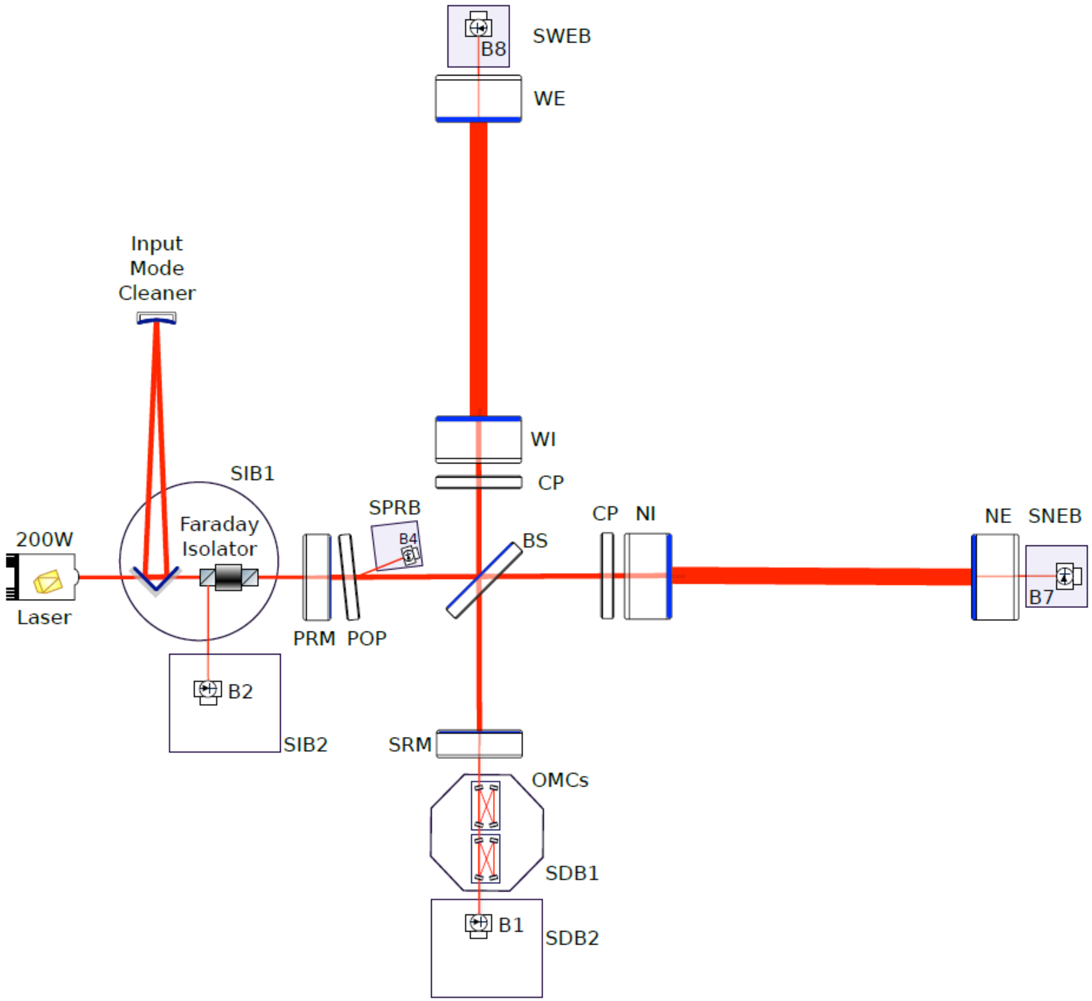
Signal recycling mirror

Photodiodes suspended under vacuum



Virgo super-attenuator kept unchanged (already compliant)

Virgo Overview



Advanced Virgo project baseline design

AdV Overview, Part I		
Subsystem and Parameters	**AdV design (TDR)**	**Initial Virgo**
Sensitivity		
Binary Neutron Star Inspiral Range	134 Mpc	12 Mpc
Anticipated Max Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\text{Hz}}$	$4 \cdot 10^{-23}/\sqrt{\text{Hz}}$
Instrument Topology		
Interferometer	Michelson	Michelson
Power Enhancement	Arm cavities and Power Recycling	Arm cavities and Power Recycling
Signal Enhancement	Signal Recycling	n.a.
Laser and Optical Powers		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	>175 TEM_{00} W	20 W
Optical Power at Interferometer Input	125 W	8 W
Optical Power at Test Masses	650 kW	6 kW
Optical Power on Beam Splitter	4.9 kW	0.3 kW
Test Masses		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	35 cm
Main Test Mass Weight	42 kg	21 kg
Beam Splitter Diameter	55 cm	23 cm
Test Mass Surfaces and Coatings		
Coating Material	Ti doped Ta_2O_5	Ta_2O_5
Roughness*	< 0.1 nm	< 0.05 nm
Flatness	0.5 nm RMS	< 8 nm RMS
Losses per Surface	37.5 ppm	250 ppm (measured)
Test Mass RoC	Input Mirror: 1420 m End Mirror: 1683 m	Input Mirror: flat End Mirror: 3600 m
Beam Radius at Input Mirror	48.7 mm	21 mm
Beam Radius at End Mirror	58 mm	52.5 mm
Finesse	443	50
Thermal Compensation		
Thermal Actuators	CO_2 Lasers and Ring Heater	CO_2 Lasers
Actuation points	Compensation plates and directly on mirrors	Directly on mirrors
Sensors	Hartmann sensors and phase cameras	n.a.

AdV figures vs Virgo
(Extract of AdV technical design report)

NB: 3km arm cavities linewidth=100Hz

The laser system

- The scope is to deliver a stable laser beam @ 1064 nm with the requested power, frequency stability and with small power fluctuations. So that the interferometer sensitivity can be achieved.
- We are relying on continuous technologic developments which allow us to start with a 20 W injection locked laser. This laser system has been further improved to deliver 50 Watts.
- A new more powerful (able to deliver 200 W CW at 1064 nm) is being developed: based on optical fiber laser technology.
  → Challenging but seems to be able deliver the required power with the requested stability.

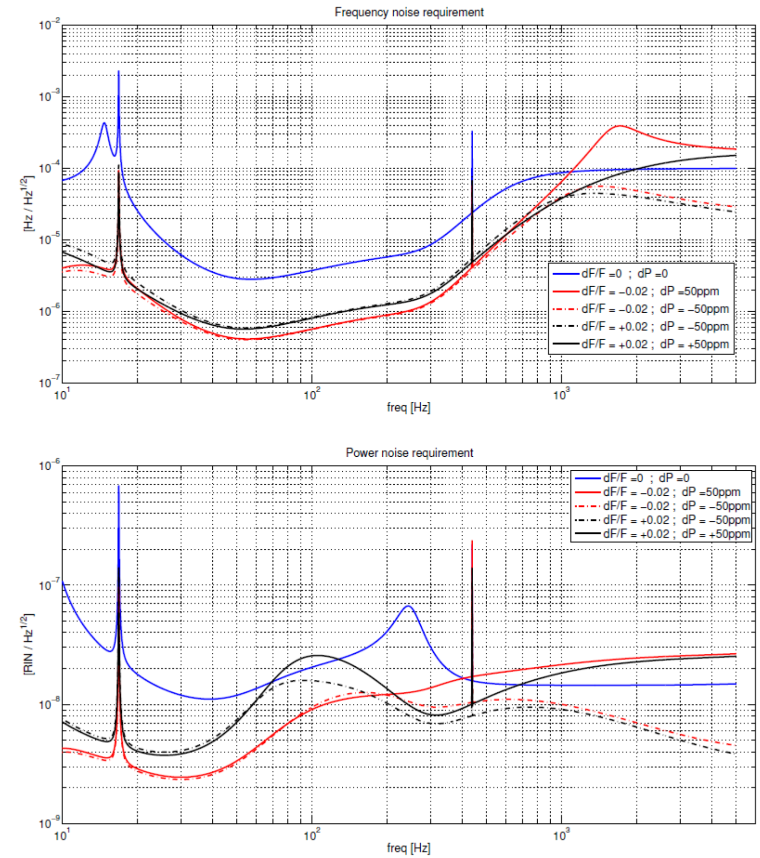


Figure 8.7: Dual recycled full power configuration, frequency and power noise requirements with a safety factor of ten used to draw the requirements from nominal sensitivity. Different values of finesse and loss asymmetries are used. Top: laser frequency noise at interferometer input. Bottom: laser intensity noise at the interferometer input. Blue curve: no defects. Red curves: dF/F = -2%; black curves: dF/F = +2%. Solid curves: dP = +50 ppm, dashed curves: dP = -50 ppm.

Requirements in term of frequency and power noise
Over the whole detector bandwidth

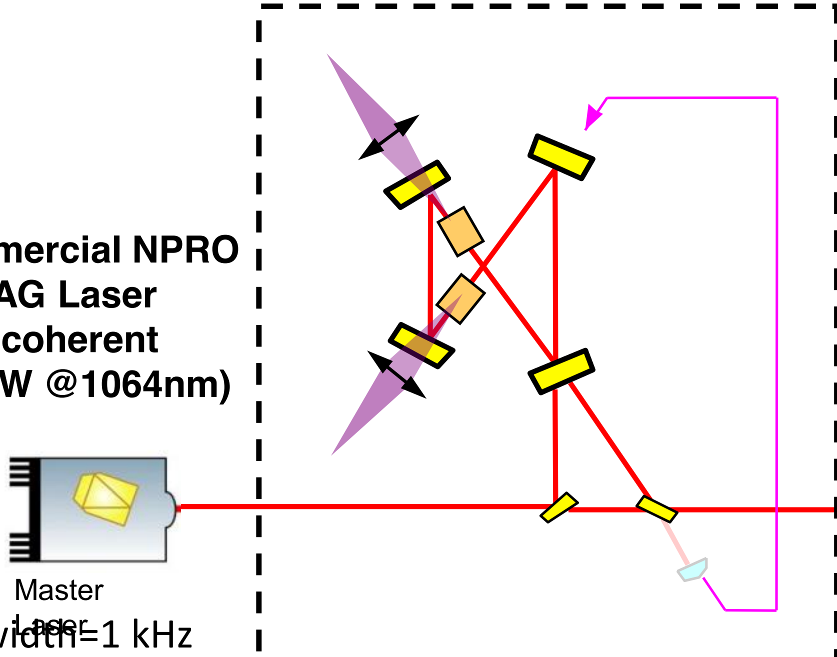
Laser frequency stability required for arm cavity locking: 1 Hz rms over 1 s.

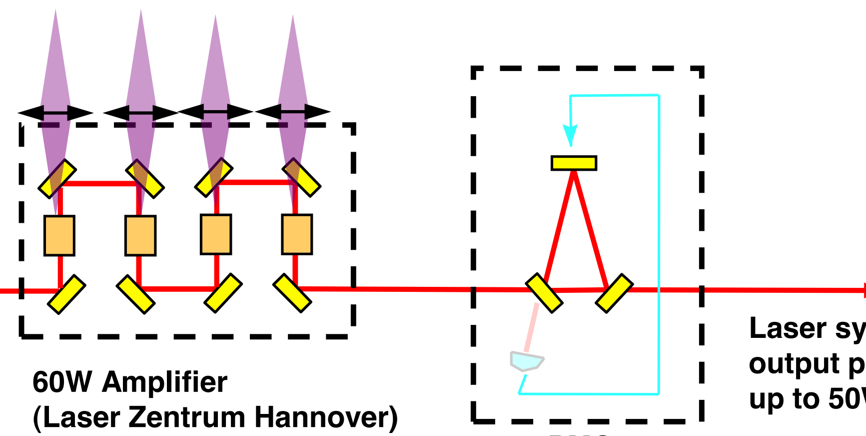
The Virgo/AdV (first phase) laser system

Four-stage end-pumped Nd:YVO4 60W amplifier

20 W Nd:YVO4 slave laser (Laser Zentrum Hannover) ***(injection-locked)***

Commercial NPRO Nd:YAG Laser from coherent (P=1 W @1064nm)





Laser system output power: up to 50W

Linewidth=1 kHz

Free running noise = $10^4/f$ Hz/sqrt(Hz)

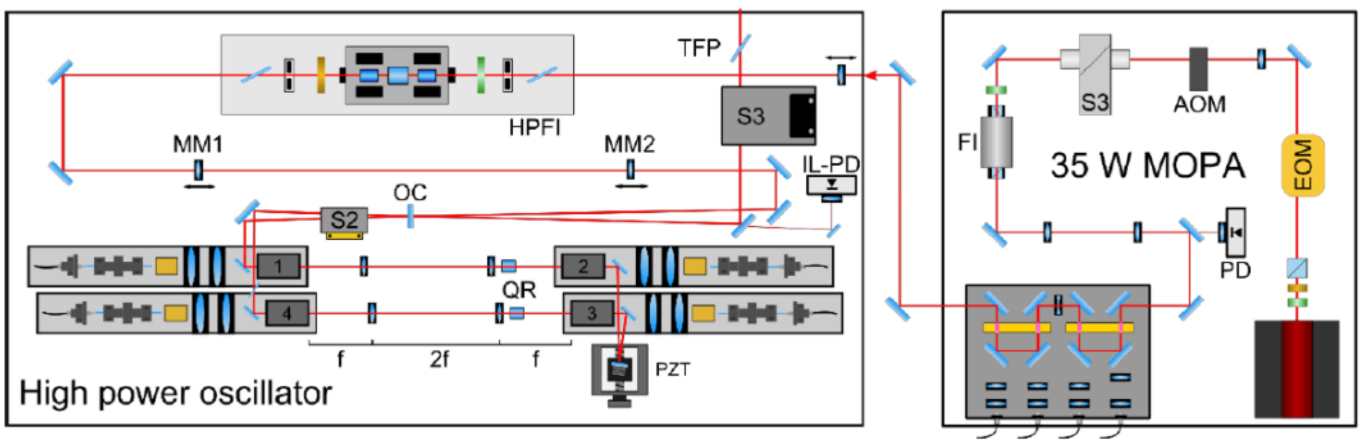
Nd-YvO4 crystal

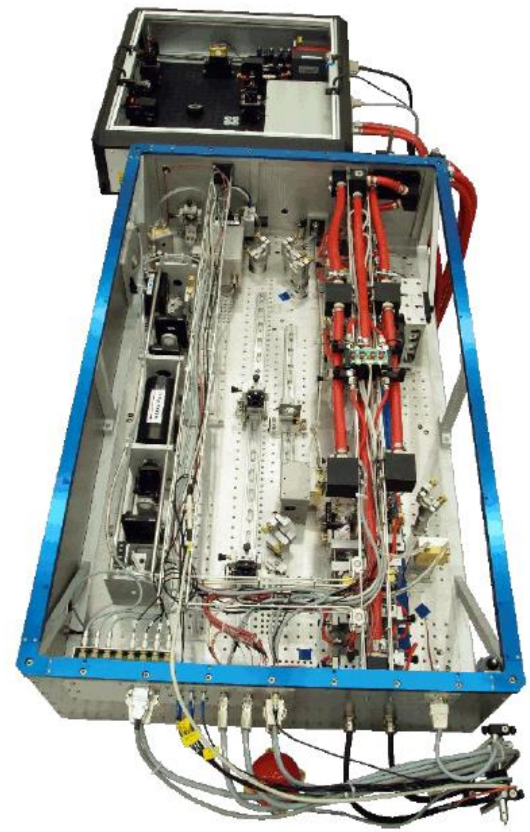
Crystal pumping module

The Pre Mode Cleaner is a triangular 13 cm long FP cavity (finesse=500), devoted to filter out the amplitude fluctuations of the laser (to be shot noise limited at the modulation frequency)

The aLigo laser system

200 W Nd:YVO4 slave laser
(Laser Zentrum Hannover)
(injection-locked)





Credits: O. Puncken (LZH)

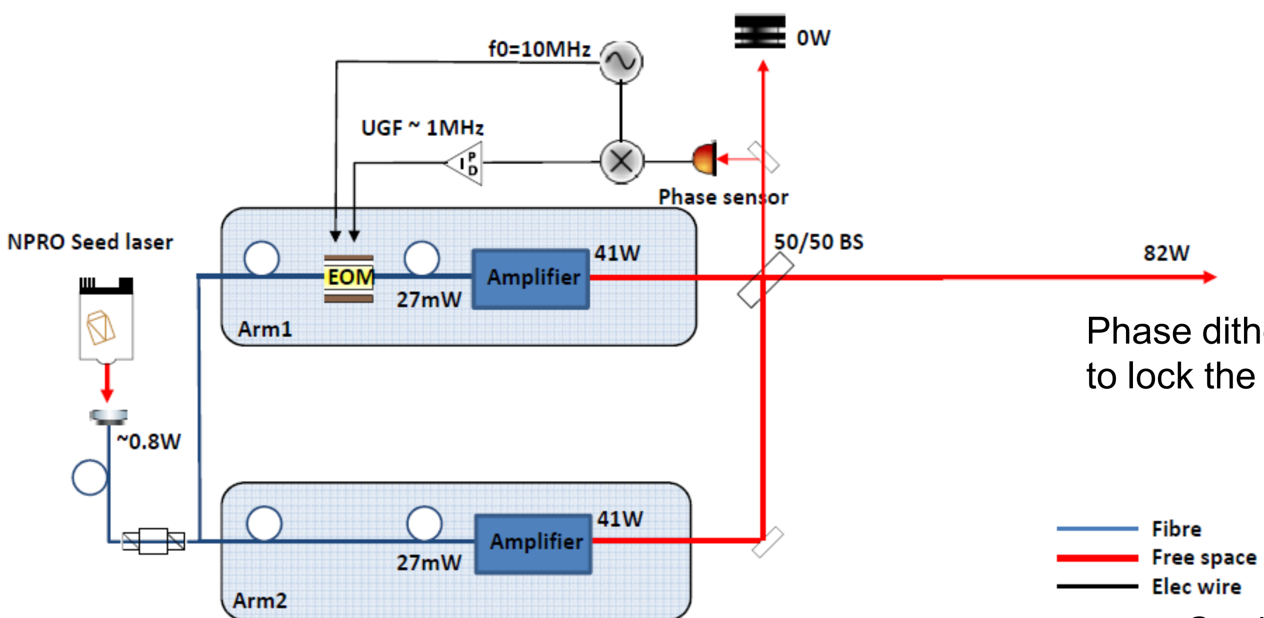
Laser Amplifier
(Laser Zentrum Hannover)

Commercial NPRO
Nd:YAG Laser
from coherent
(P=2 W @1064nm)
Linewidth=1 kHz
Free running noise = $10^4/f$ Hz/sqrt(Hz)

Development of a new laser source for Virgo

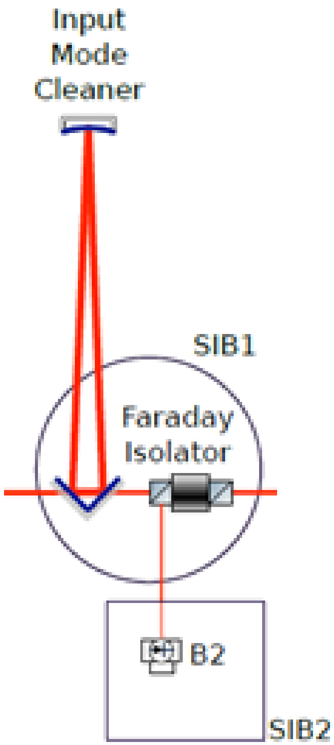
- This laser using fiber amplifiers is currently being developed at Observatoire de la Cote d'Azur (Nice, France).
- Based on commercial 50 W fiber amplifier module produced by ALS (Bordeaux, France).Other applications: Yb-doped crystal and glass lasers pumping, Parallel pumping : Er fiber and amplifiers, Atoms traping and laser cooling, Non-linear frequency generation in the visible

- Principle: sum coherently several laser amplifier modules up to get the required laser output power (200 W).



Phase dithering locking scheme is used to lock the Mach-Zehnder interferometer

Credits: F. Cleva (OCA)



The Injection system (INJ) of AdV takes care of the optics downstream of the high power laser, and of the interface of these optics with the laser and the Interferometer.

Main components:

- Electro optic modulation system: Phase modulation of the laser beam to control the optical cavities and the interferometer.
- Input Mode Cleaner cavity: passively filter out amplitude, frequency and beam jitter noise
- Faraday isolator: isolates the Laser from the back-reflected light of the interferometer.
- Mode matching optics: Adjust the beam dimension to properly match it on the interferometer to reduce as much as possible the light lost from the Laser bench to the ITF
- Reference cavity: Laser frequency pre-stabilization and in data-taking mode low frequency reference in frequency.

Parameter	Requirement
Transmission to the ITF	$> 70\%\ TEM_{00}$
Non-TEM_{00} power	$< 5\%$
Intensity noise	$2 \times 10^{-9}/\sqrt{(Hz)}$ at 10 Hz
Beam Jitter	$< 10^{-10}$ rad$/\sqrt{(Hz)}$ (f >10 Hz)
Frequency noise (for lock acquisition)	<1 Hz r.m.s

Requirements from the Technical report

Electro optic modulator

- ❑ Function: Phase modulate the laser beam at RF modulation frequencies needed for the control of the interferometer. We use the heterodyne detection technique which is commonly used to detect and analyze signals (radars, astronomy, telecommunications).
- ❑ Requirements:
  - ❑ Withstand 200W CW laser power @1064nm.
  - ❑ Limited thermal lensing effect.
  - ❑ Maximum modulation depth = 0.2 rad.
  - ❑ Provide 5 RF modulation frequencies (6.27, 8.36, 22. 304, 56.43, 131.67 MHz).
  - ❑ Low Residual Amplitude modulation (RAM) noise.

Applications:
- Optical cavities locking (heterodyne detection)
- Frequency- modulation spectroscopy (low RAM required)
- Telecommunications?

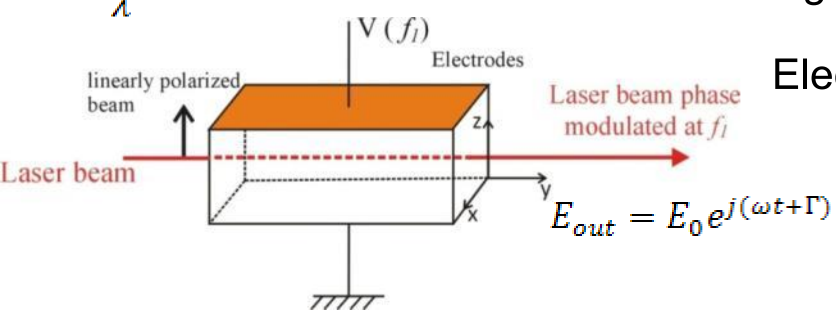
- ❑ Principle:

Phase shift induced by the electric field

$$\Gamma = \frac{2\pi}{\lambda} n_z L = \frac{2\pi}{\lambda} L(n_e - 0.5 n_e^3 r_{33} E_z) \qquad E_z = V/d$$

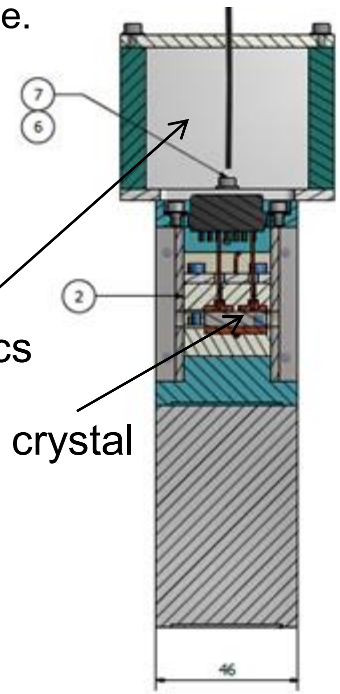
Modulation depth

$$\mathrm{m} = \frac{\pi}{\lambda} L(n_e^3 r_{33}) V_z / \mathrm{d}$$

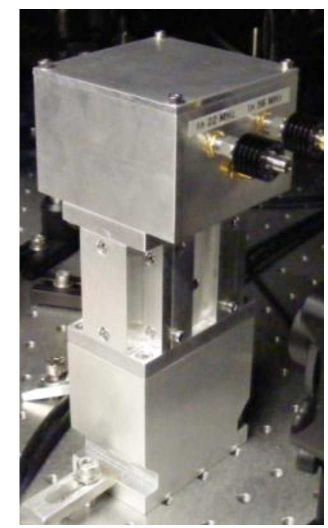


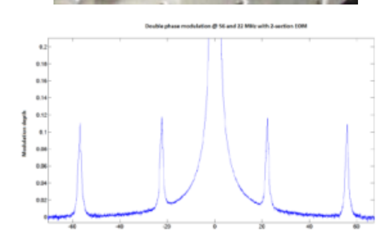
$$E_{out} = E_0 e^{j(\omega t + \Gamma)}$$

Electro optic material chosen: Rubidium Titanyle Phosphate – RbTiOPO4



2-frequencies EOM





E. Genin

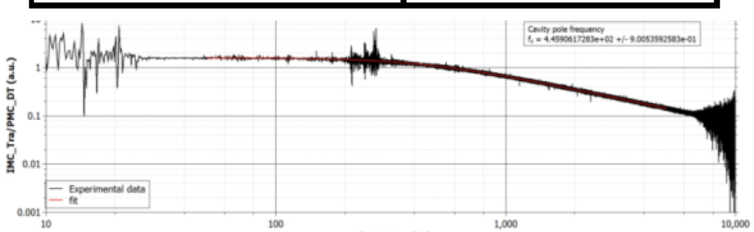
Input Mode Cleaner cavity

- Function: Beam spatial filtering, filter out beam jitter (1/*F*), to be used in Laser frequency stabilization loop, filter out frequency and power noise above its pole
- Main characteristics:
  - 144 m long suspended triangular resonant cavity (FSR=1.045 MHz)
  - *F* = 1000

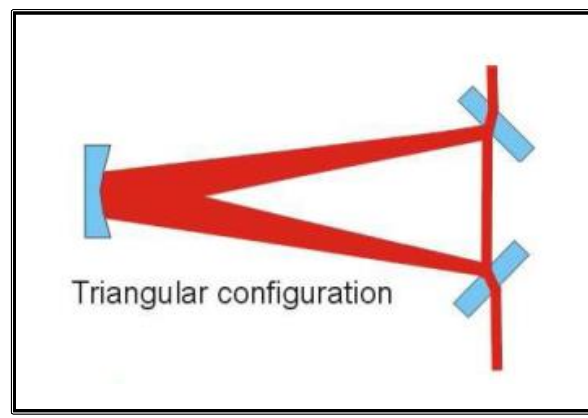
→ Cut-off frequency (cavity pole)≈ 500 Hz.

Applications:
- Laser Frequency stabilization
- Laser beam cleaning (M^2 close to 1)

Parameter	Measured value
FSR	1045137 Hz +/- 0.5 Hz
IMC Length	143.4225 m
Pole	520Hz +/- 2 Hz
Finesse	1005 +/- 4
Round-Trip losses	222 ppm+/-24 ppm
IMC cavity throughput	92.9 % +/- 0.5%
Transmission (mirror #1)	T1=3015 +/-15 ppm
Transmission (mirror #2)	T2=3015 +/-15 ppm
Absorption flat mirrors	<1ppm / mirror
Absorption End mirror	3ppm

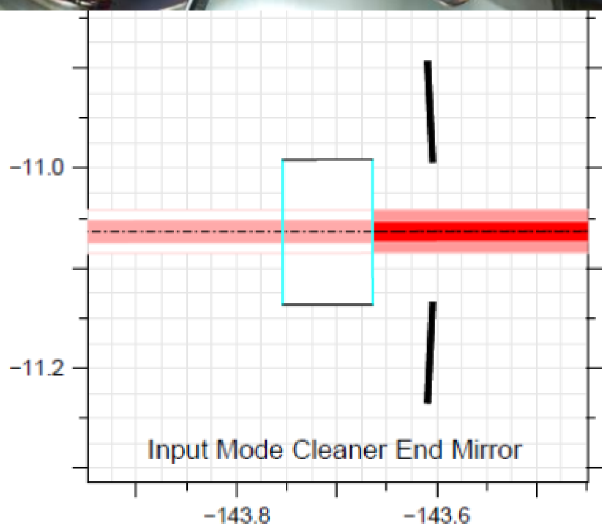


Example of IMC cavity pole measurement (injecting power noise before the cavity)

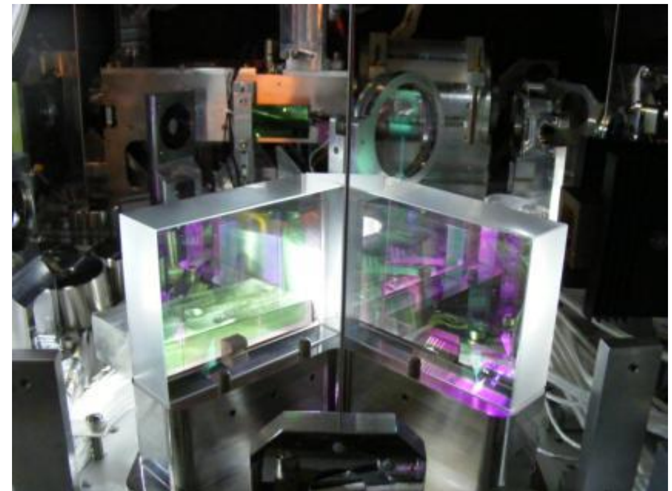


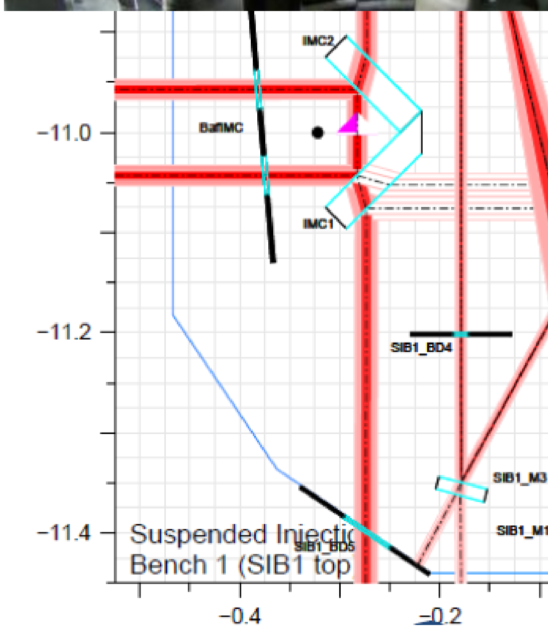
Input Mode Cleaner cavity: A few pictures

MC end mirror in MC tower



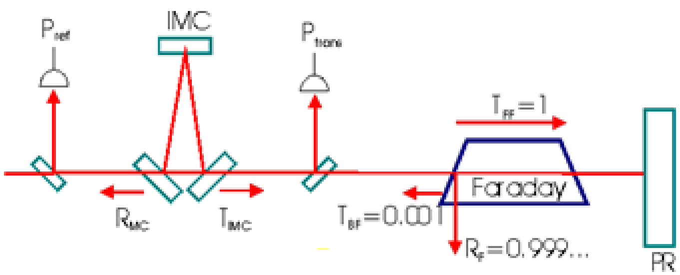
IMC dihedron (input and output flat mirrors optically contacted) on SIB1

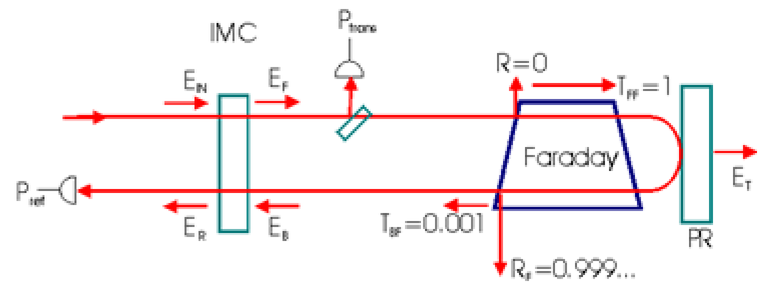




Faraday isolator

- Function:
  - avoid to create a spurious cavity Input Mode Cleaner/ Interferometer.
    Due to the fact that IMC cavity is long (144m), we have a small angle of incidence on 1 mirror of the cavity and the back-scattered light from this optics can easily be recoupled in the IMC cavity





  - have an easy way to get the interferometer reflection (to be used for the interferometer control).
  - avoid to re-inject light in the laser system and damage it.

In order to reduce these effects, we have to install a Faraday isolator between the IMC and the interferometer.

- Due to the high power of the laser inside the Faraday isolator which is installed under vacuum, we have to cope with several spurious effects:

  - Thermal lensing inside the magneto optic crystal [1]

$$f = \frac{\pi \kappa w^2}{L \alpha P (\mathrm{d}n/\mathrm{d}T)},$$

Material absorption

Laser power

  - Verdet constant change with temperature [2]

$$\frac{d\theta}{dT} = \frac{dV}{dT} nLB = \frac{dV}{dT}\frac{\theta}{V}$$

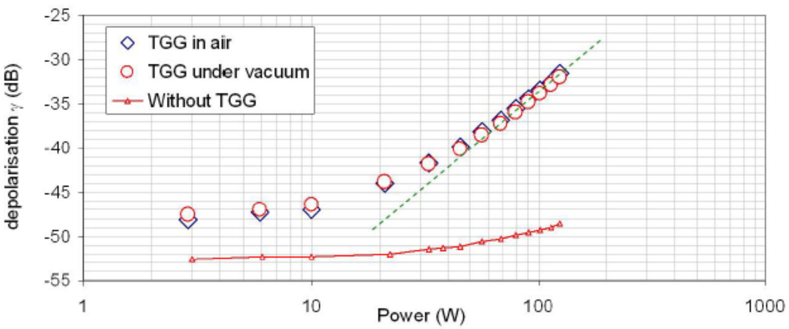
Mean rotation angle

Verdet constant

  - Thermally induced depolarization [3]

    Birefringence induced by laser beam heating

Thermal depolarization of a TGG crystal placed in air/under vacuum



Reference:

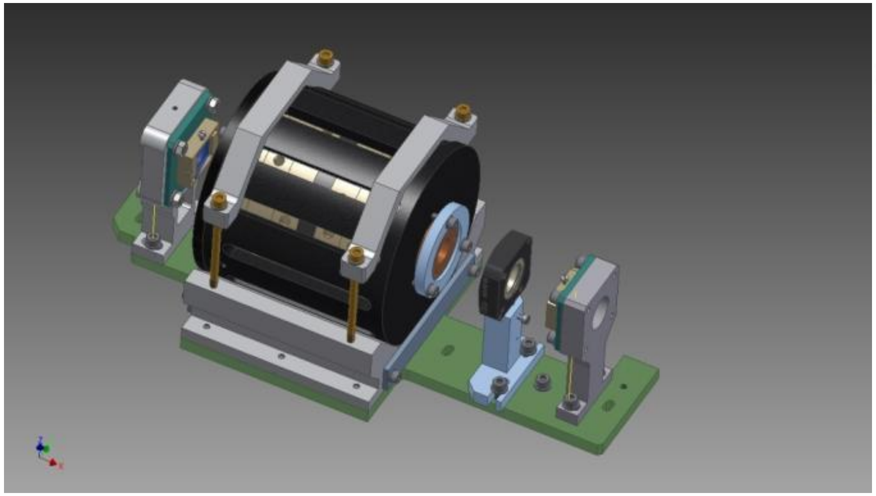
[1] The Virgo Collaboration, "In-vacuum optical isolation changes by heating in a Faraday isolator," Appl. Opt. **47**, 5853-5861 (2008)

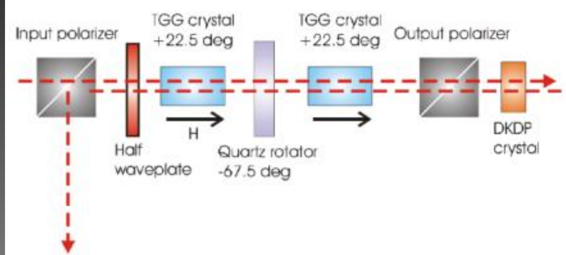
[2] The Virgo Collaboration , "In-vacuum Faraday isolation remote tuning," Appl. Opt. **49**, 4780-4790 (2010)

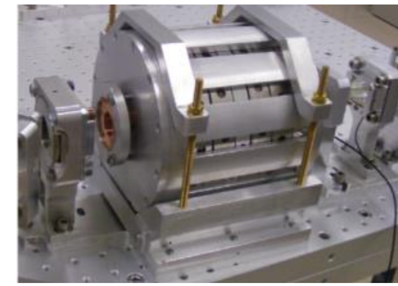
[3] Mosca, S. and Canuel, B. and Karimi, E. and Piccirillo, B. and Marrucci, L. and De Rosa, R. and Genin, E. and Milano, L. and Santamato, E., Photon self-induced spin-to-orbital conversion in a terbium-gallium-garnet crystal at high laser power, Phys. Rev. A, vol. 82, issue 4 (2010).

Faraday isolator

- A vacuum compatible Faraday isolator has been developed in collaboration with the Institute of Applied Physics and the University of Florida (LIGO group)

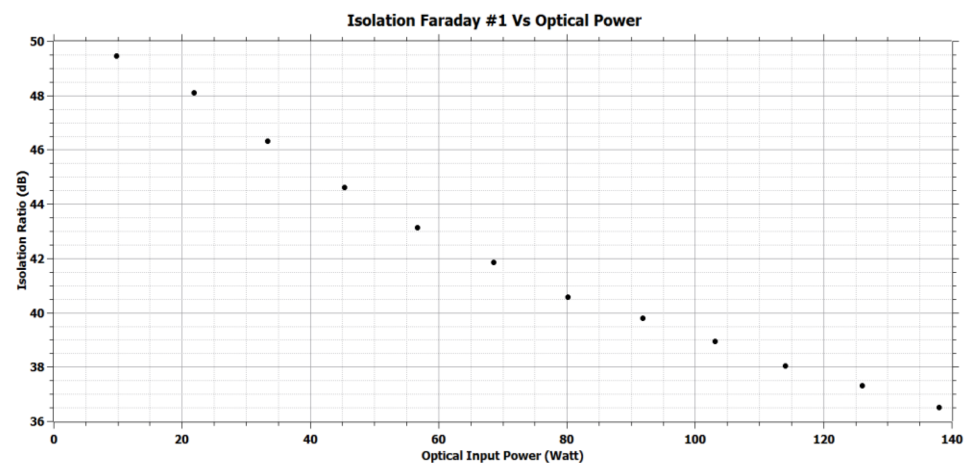






Parameter	Requirement
Isolation(low to 150 W)	$\geq$ 40 dB
Total throughput	$\geq$ 95%
Residual thermal lens	$>$ 100 m or $<$0.01 diopters at 150 W
Clear aperture	$\geq$ 20 mm
Vacuum compatibility	$< 10^{-6}$ mBar

UHV Faraday isolator requirements

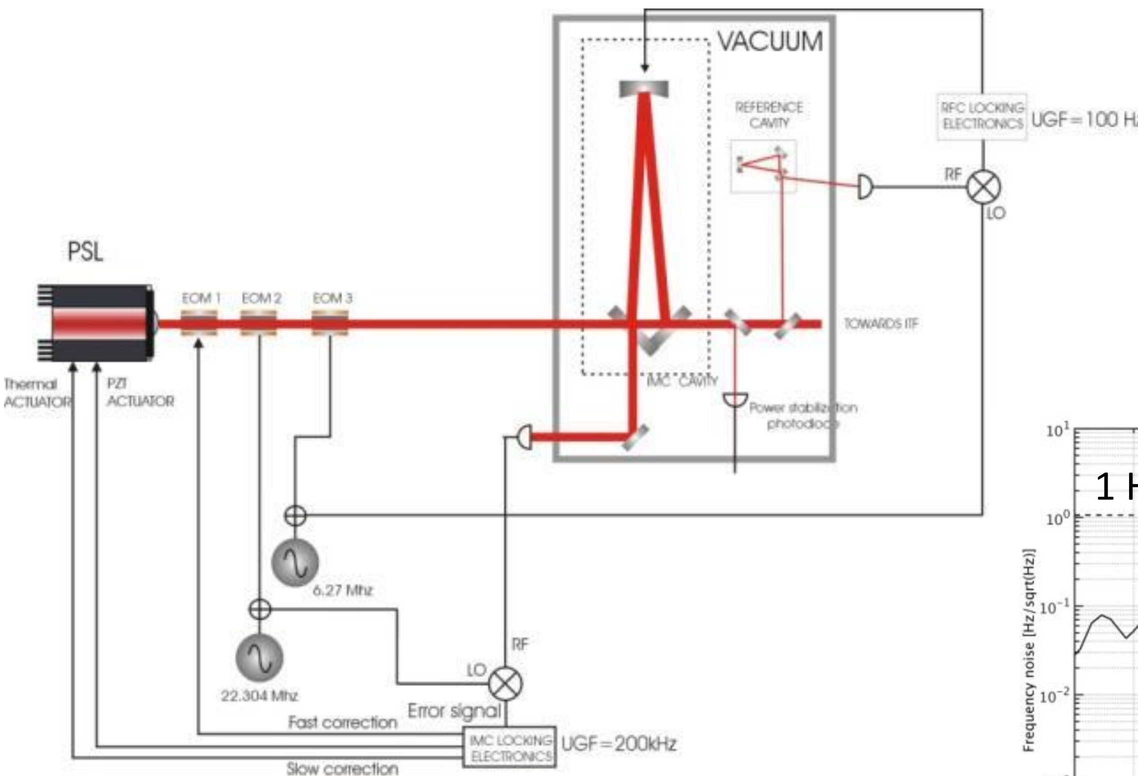


Isolation ratio vs laser input power

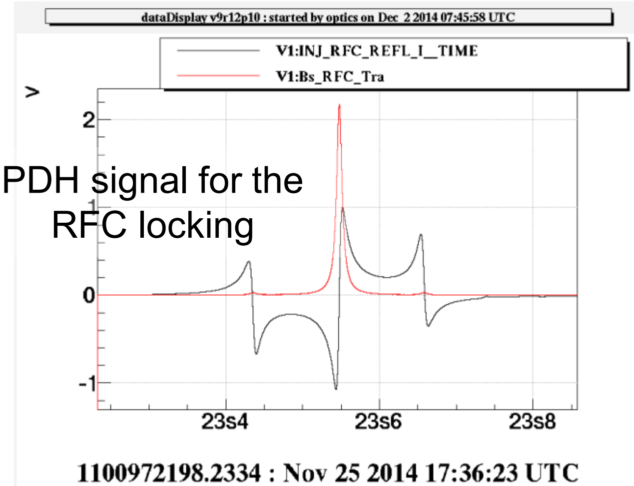
Reference:

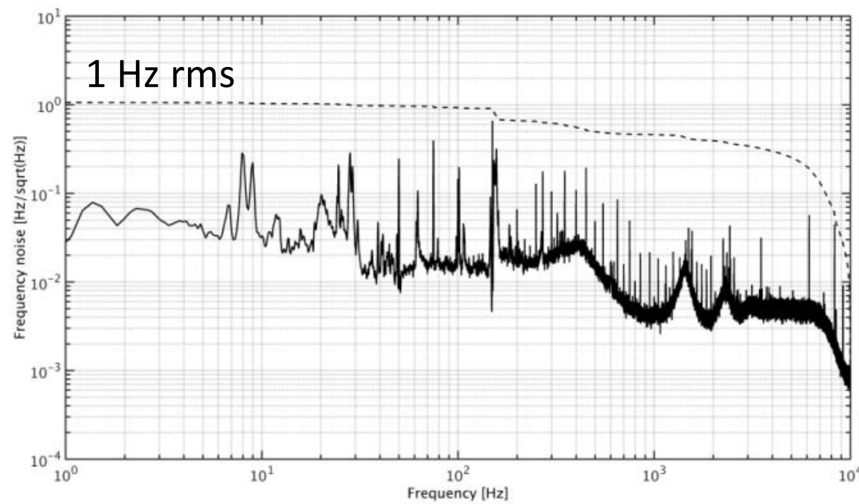
[1] O. Palashov, D. Zheleznov, A. Voitovich, V. Zelenogorsky, E. Kamenetsky, E. Khazanov, R. Martin, K. Dooley, L. Williams, A. Lucianetti, V. Quetschke, G. Mueller, D. Reitze, D. Tanner, E. Genin, B. Canuel, and J. Marque, High-vacuum compatible high-power Faraday isolators for gravitational-wave interferometers, JOSA B, Vol. 29, Issue 7, pp. 1784-1792 (2012).

- In order to lock, the 3km long arm cavities, we have to pre-stabilize the laser frequency. In this loop the IMC cavity and a reference cavity (made of ULE) are used to achieve the required 1 Hz rms.



Laser frequency pre-stabilization scheme



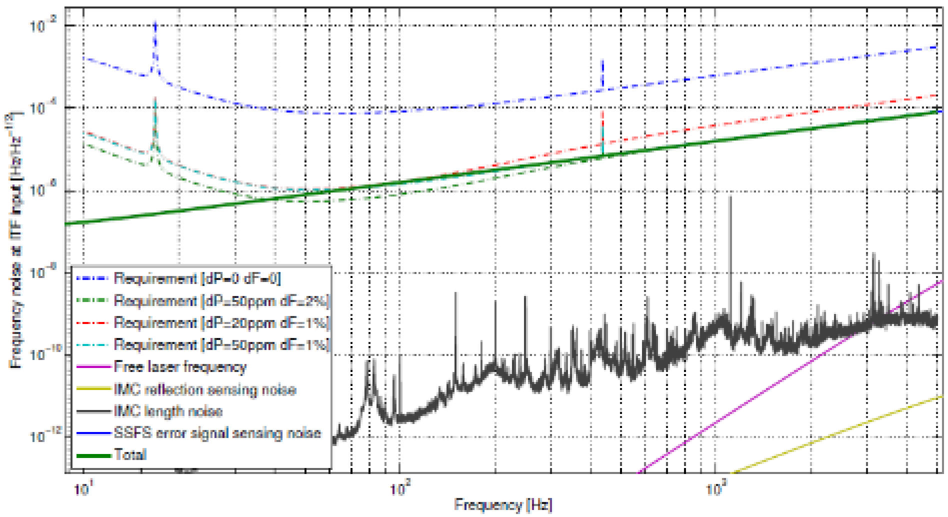


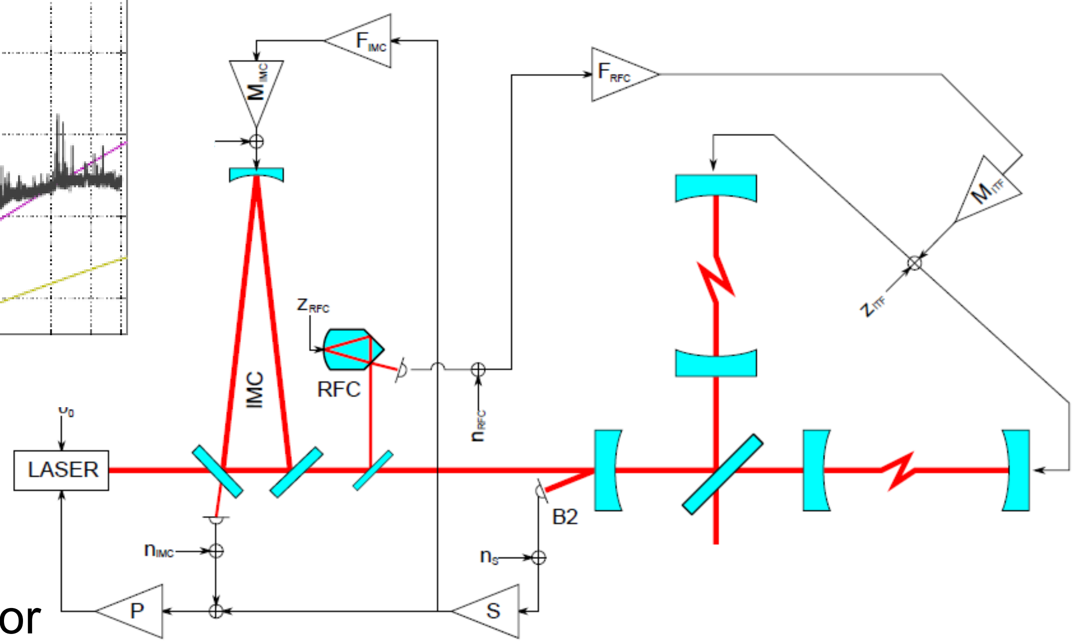
Residual frequency noise for the Pre-stabilized laser

Laser frequency second stage of frequency stabilization

- To achieve the sensitivity required, we should get a relative stability of the laser frequency better δν/ν than 10^{-21} (the long term drift of the frequency is not that important for us). (ν=300 THz)

IMC: Input Mode Cleaner
RFC: Reference cavity
B2 beam: interferometer reflection



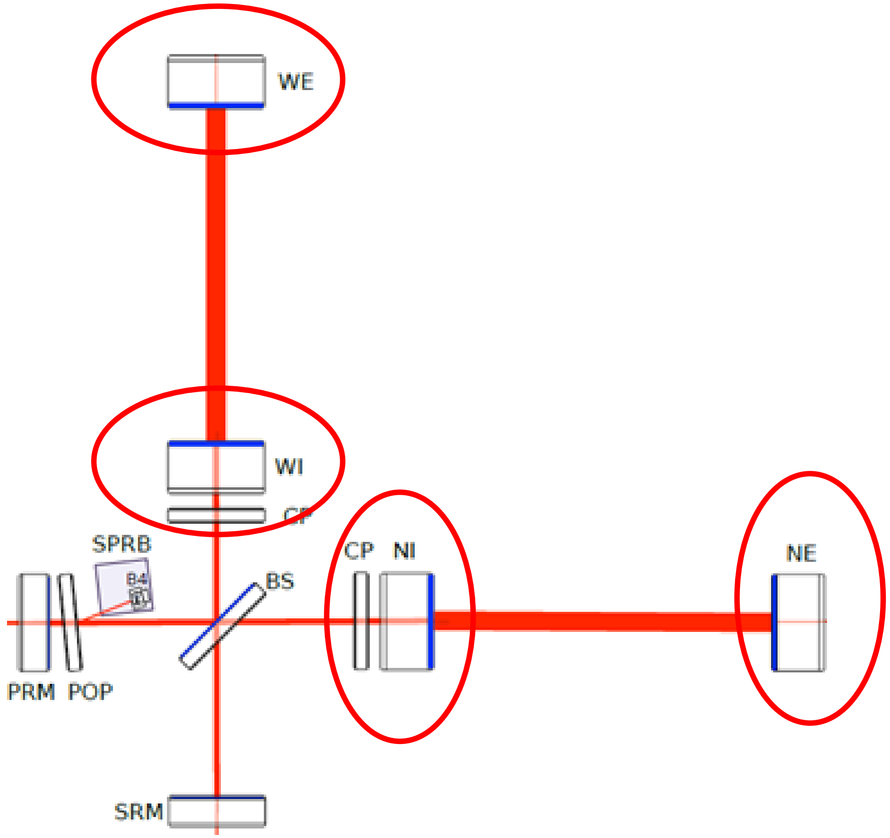


Laser frequency stabilization scheme

→ another error signal is extracted from the interferometer itself.
We use the arm cavity as a reference for this second stage of frequency stabilization.

Reference:
The Virgo collaboration, Laser with an in-loop relative frequency stability of 10^{-21} on a 100-ms time scale, PHYSICAL REVIEW A 79, 053824 , 2008.

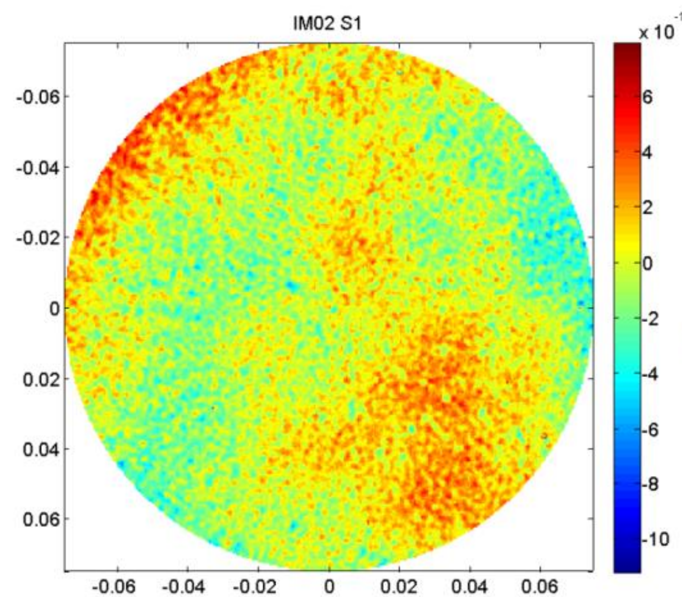
- Arm cavities optics are the most critical and demanding in term of roughness, and surface figures in general.



The Interferometer optics

- All the main optics of the interferometer has been realized under the supervision of Laboratoire des Matériaux avancés (Lyon, France).
- A suitable material (Suprasil 3002) has been selected as substrate: low-absorption of NIR light (0.3ppm/cm), good uniformity ($Dn<5.10^{-7}$). Heraeus (EU) produced all the substrates.
- The polishing has been carried out by ZYGO company (US)

Example of a 3 km arm cavity input mirror (350 mm in diameter, 200 mm thick)

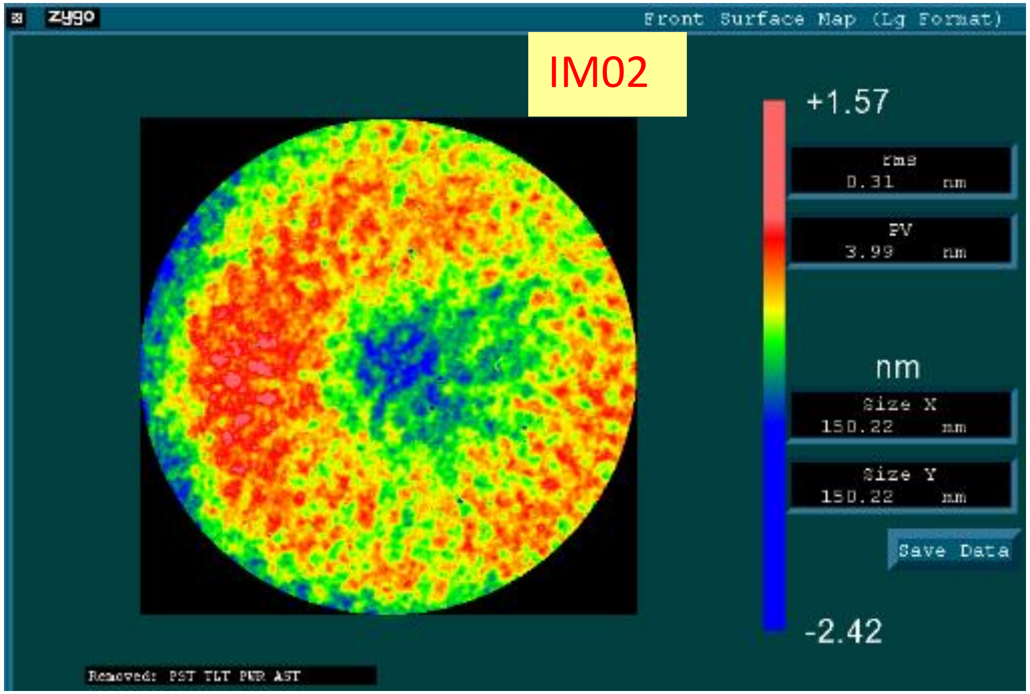


Input mirror surface map

IM surface 1
0.17 nm RMS
on Ø 150 mm
(spec. <0.5 nm RMS)

Credits: L. Pinard (LMA)

- The coatings have been realized by Laboratoire des Matériaux avancés.



Example of Input mirror surface map after coating (Credits: L. Pinard (LMA)).

- Good wavefront (**0.31 nm RMS on Ø150 mm**)
- Very good AR coating : **32 ppm and 56 ppm** of reflectivity
- Low absorption (**0.2 ppm**) and scattering (**3 ppm**)

Dielectric coatings:
They consist of thin (typically sub-micron) layers of transparent dielectric materials, which are deposited on a substrate.
Their function is to modify the reflective properties of the surface by exploiting the interference of reflections from multiple optical interfaces. They can be used to get whatever reflectivity at whatever wavelength.

- LMA is able to achieve the best coatings in the world for laser interferometry.

→ LMA has coated Advanced Virgo and Advanced Ligo mirrors.

Mirror aberrations

- Mirror aberrations (cold and thermal defects) can spoil the sensitivity of the interferometer
- **Mechanisms worsening the sensitivity**
  - **Mode mismatch** – beam intensity profile and phase don't match that of the resonator
  - **Scattering** – the cavity beam is scattered off by the surface roughness.
  - **Frequency splitting** – modes of the same order see a different overall radius of curvature, and their resonance frequencies result to be different.
- **Principle of thermal correction**
  - Use an auxiliary heat source to induce controlled thermal effects in the optics and therefore correct the beam phase aberrations

$$OPL = S_0 + n\Delta d + d\Delta n_T + d\Delta n_E$$

Thermoelastic deformation $\Delta d \propto \alpha \Delta T$

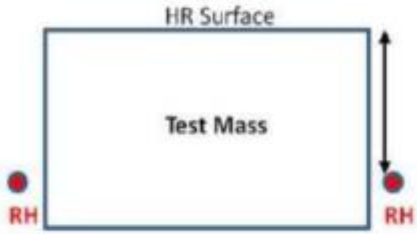
Thermorefractive effect $\Delta n_T = \frac{dn}{dT}\Delta T$

Elastooptic effect $\Delta n_E \approx -\alpha(1+\nu)n\Delta T$

Credits: A. Allocca (INFN)

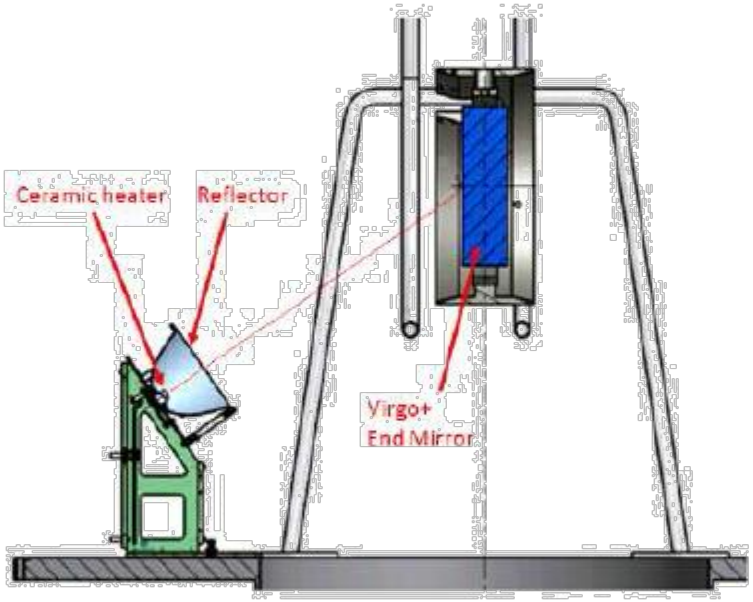
Thermal compensation devices

- Correct the radius of curvature with Ring Heater…



Heating Ring surrounding the mirror induces a change of the RoC

- …or with CHRoCC

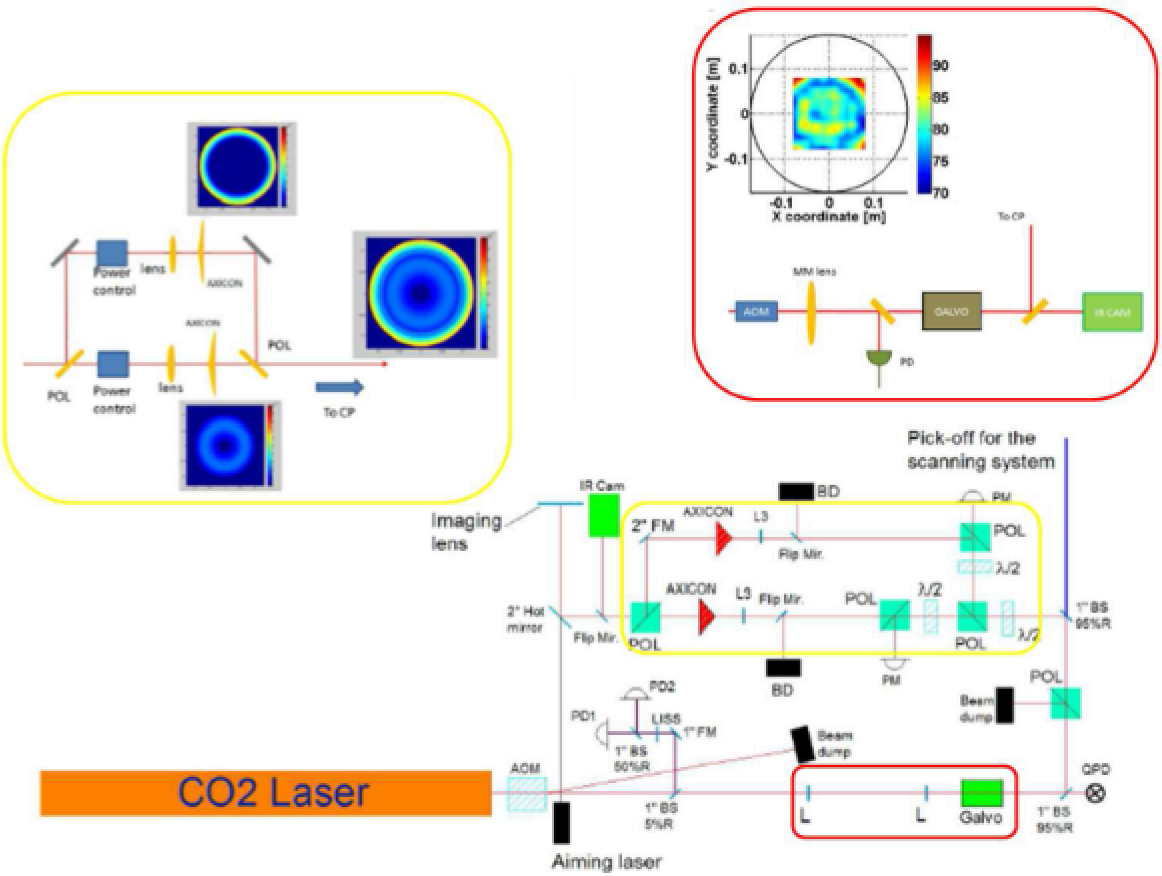


Heat projection on the mirror rear face to induce a change of the RoC

- Correct high spatial frequency defects with CO2 laser…

Scanning system for non-symmetrical defects

Double axicon for symmetrical aberrations



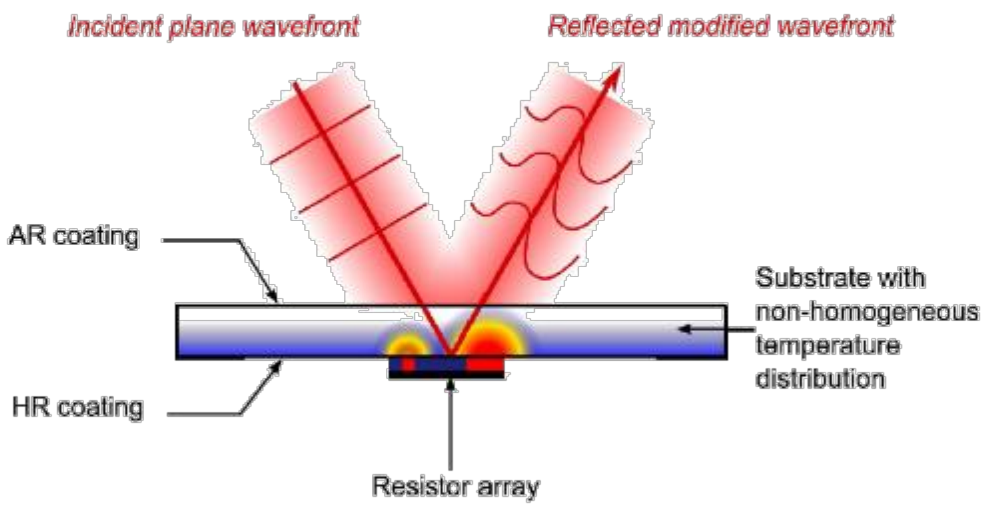
E. Genin

Thermal compensation devices

- Reduce mode mismatch: thermally deformable mirrors

Array of resistors attached to the rear surface of the mirror inducing a change of temperature inside the substrate

Change of the substrate refractive index → Change of the beam OPL



[1] B. Canuel, R. Day, E. Genin, P. La Penna and J. Marque, "Wavefront aberration compensation with thermally deformable mirror", Class. Quantum Grav. 29, 085012 (2012)
[2] M. Kasprzack, B. Canuel, F. Cavalier, R. Day, E. Genin, et al.. Performance of a thermally deformable mirror for correction of low-order aberrations in laser beams. Applied Optics, OSA, 2013, 52, pp.2909-2916.

Credits: A. Allocca (INFN)

Useful links to optical simulations used for the design of GW detectors

- Modal codes:
  - FINESSE (Frequency domain INterferomEter Simulation SoftwarE), Developped at GEO600 by Andreas Freise. http://www.gwoptics.org/finesse/.
  - MIST, developped at Virgo/Ligo by Gabriele Vajente https://sourceforge.net/projects/optics-mist/files/

- FFT-based codes:
  - SIS (with FOG inside), developped at Ligo/Virgo by Hiro Yamamoto and Richard day
  - OSCAR, developped at GEO by Jerome Degallaix http://www.mathworks.com/matlabcentral/fileexchange/20607-oscar

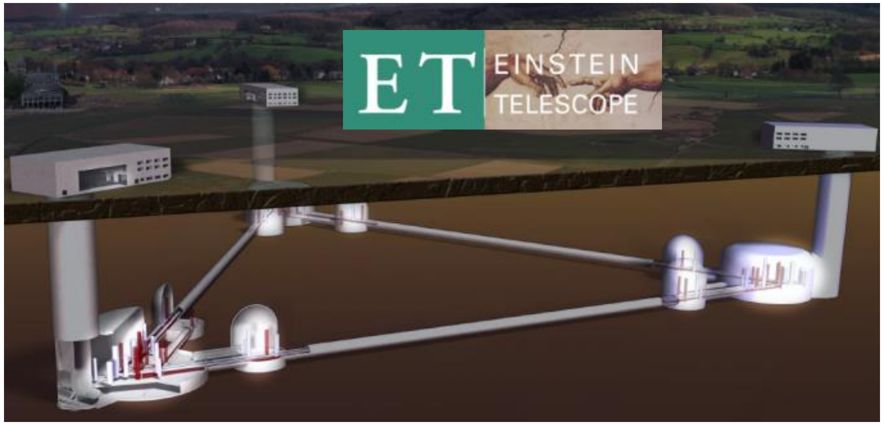
→ Those simulation tools are useful for the design of optical cavities and inteferometers.

Conclusion and next steps

- ❑ Advanced Virgo optics have been produced and are being installed.
- ❑ The laser and the input optics systems have been installed and are working since more than 1.5 year.

→ For the moment, almost all are workforce is working on a unique goal have the current interferometer operational and able to detect GW.

- ❑ Perspectives: Develop new components for future GW detectors (Einstein telescope for example http://www.et-gw.eu/) or US Lungo (40 km-long arms)
  - ❑ Components optimized for other wavelength: 1.55 um or 2 um
  - ❑ Improvement the coating uniformity/ reflectivity
  - ❑ Test new materials such as silicon at cryogenic temperature



Visit Virgo website
https://www.virgo-gw.eu/scientists.html

Extra slides

A bit of history

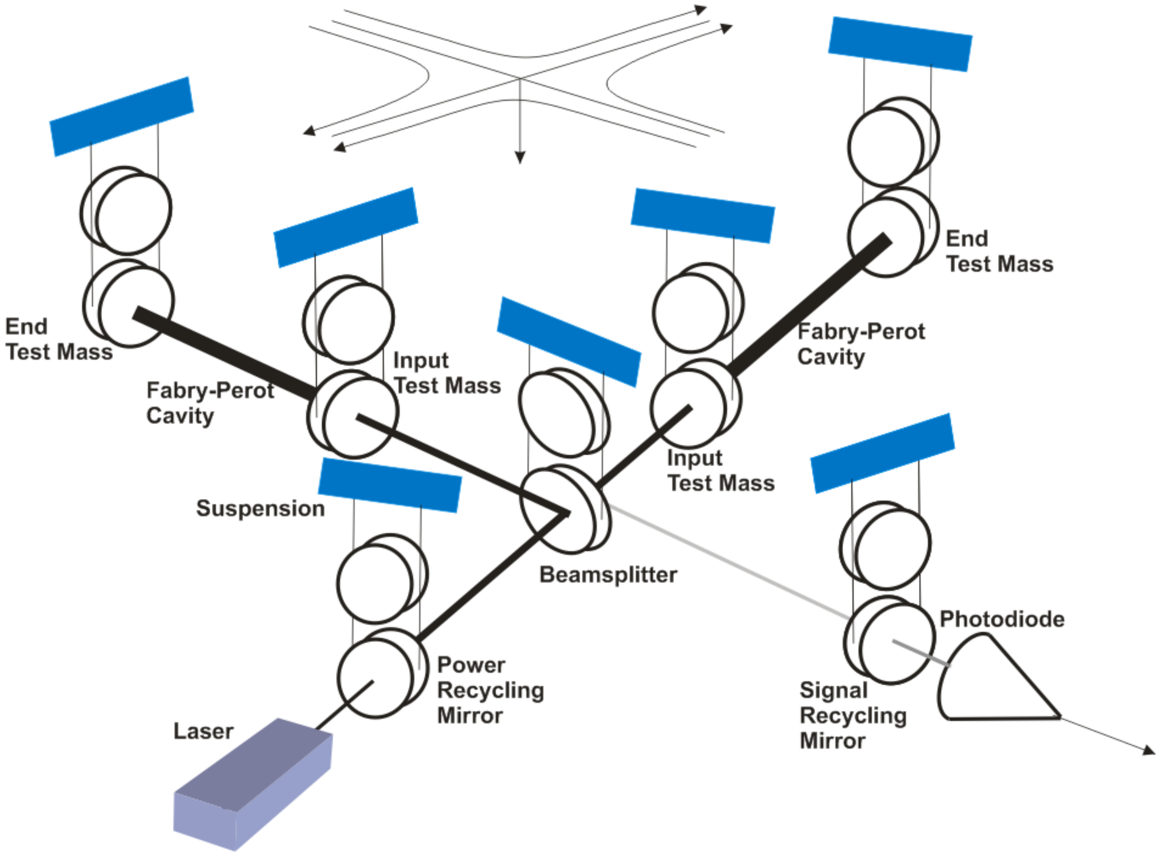
- *The **LIGO** project was approved in **1992** and inaugurated in **1999**. Built at a cost of almost $3x10^8$ $, LIGO was the largest single enterprise ever undertaken by the foundation. It started the operation in 2002.*

- **VIRGO** was formally proposed in 1989 and approved in 1993. The construction was divided in two step: it started in 1996 and then completed in 2003. The first science run is date 2007. The total investment done by CNRS and INFN was almost 8×10^7 $.

- ***GEO600** was proposed in 1994. Since September 1995 this British-German GW detector was under construction. The first science run was performed in 2002. In 2013 Squeezing light was used over one complete year!*

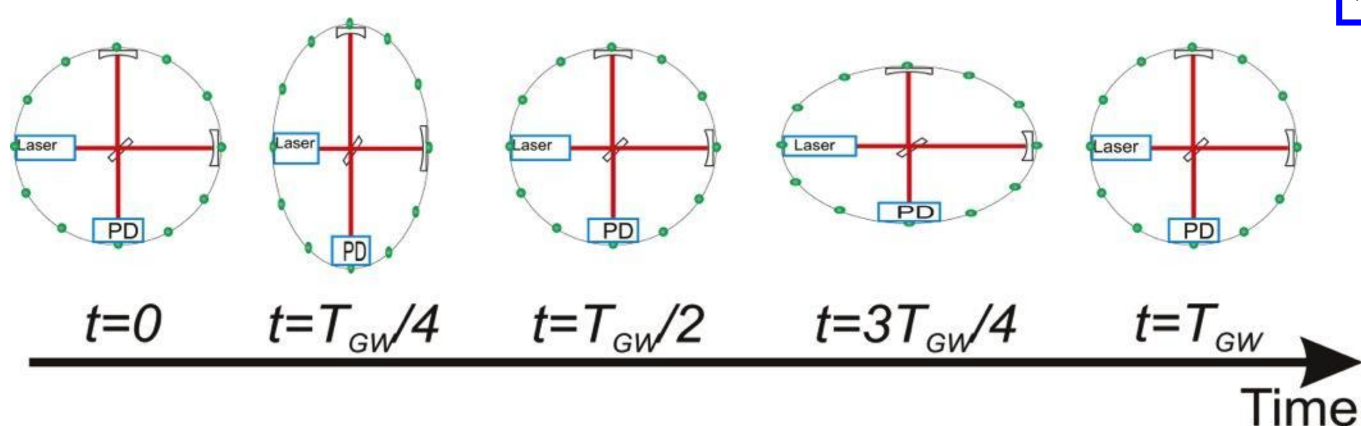
- First attempt to exchange data and mix the data analysis groups started in 2004. The formal **MoU of data sharing and common analysis** among **GEO-LIGO-VIRGO** was signed in **2007**.

Special features to improve the sensitivity

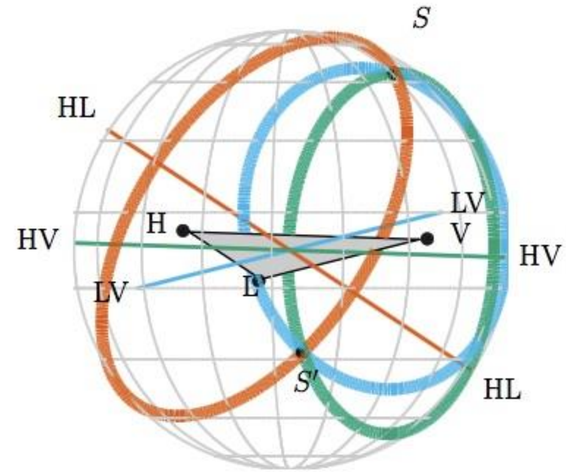


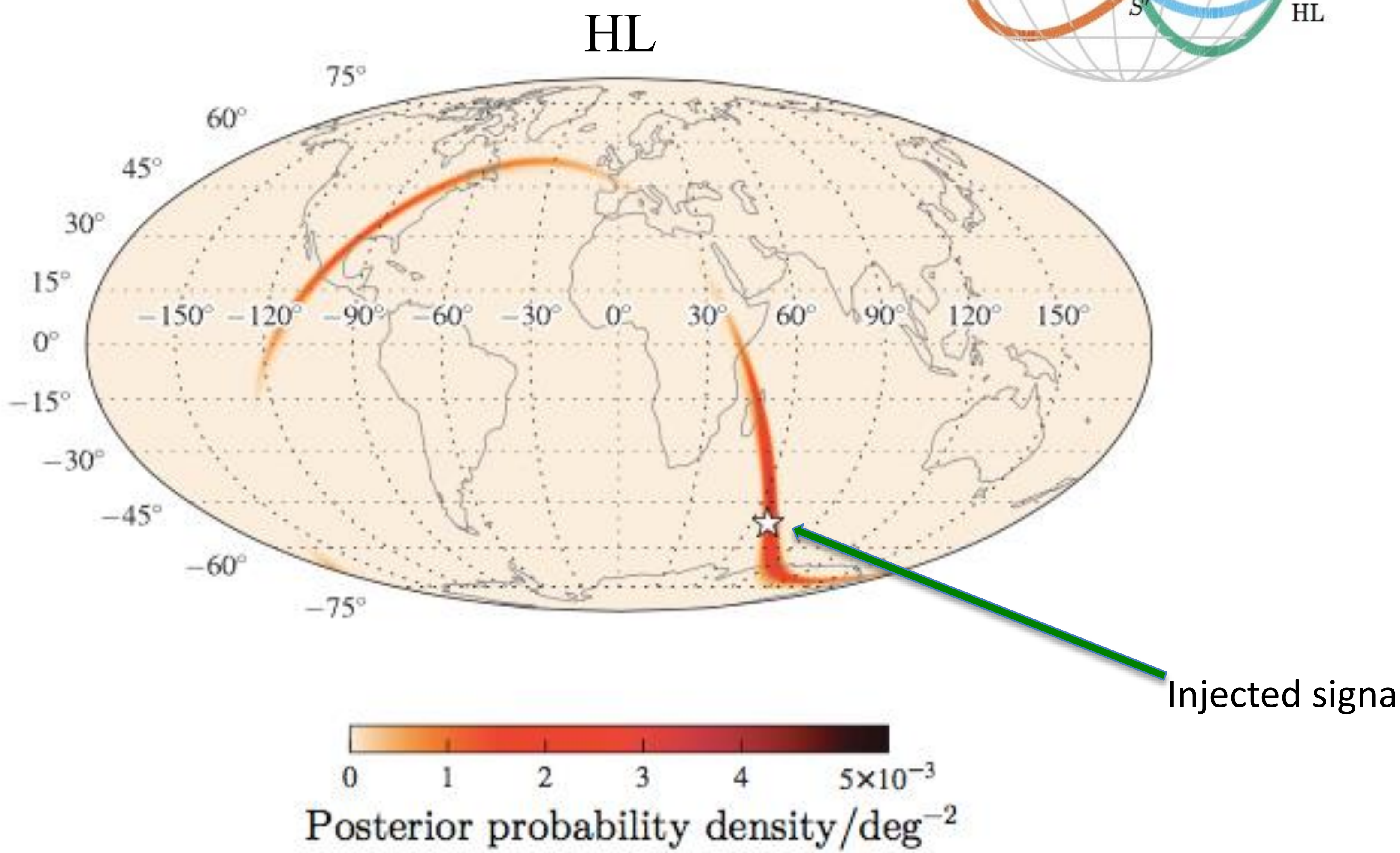
$$h = \frac{\Delta L}{L} \sim 10^{-21}$$

$$i_{pd}(t) = \frac{\Delta L}{L}(t)$$

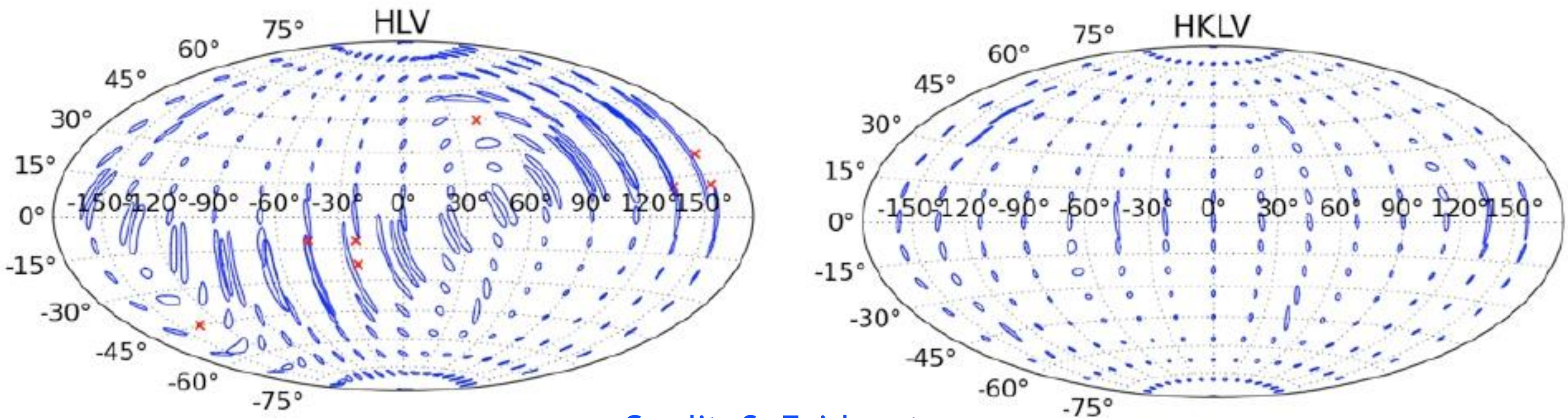


Transient Source Localization: 2 detectors

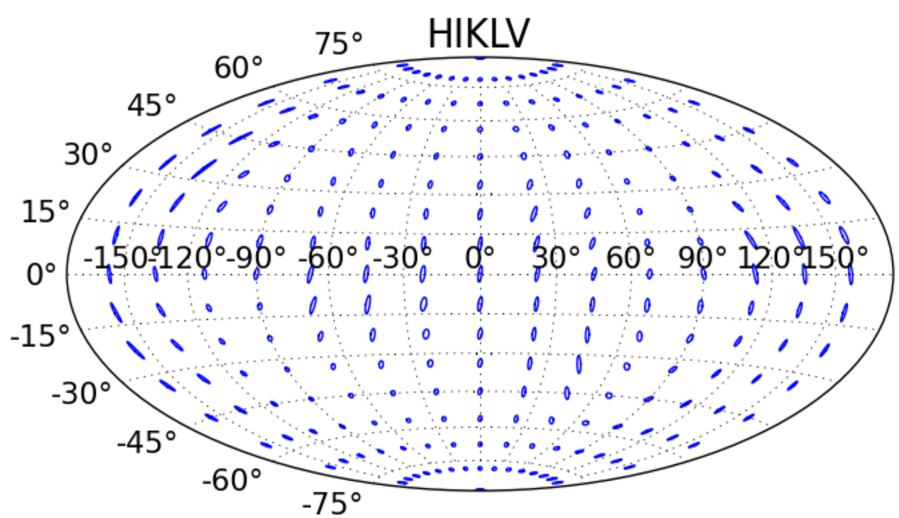




Transient Source Localization: 3 , 4 , 5 detectors

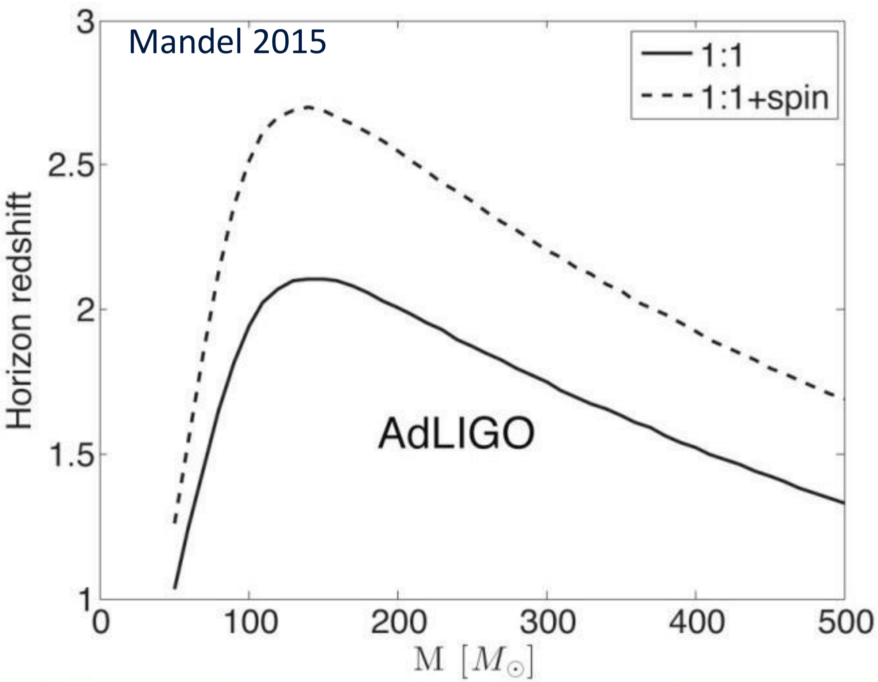


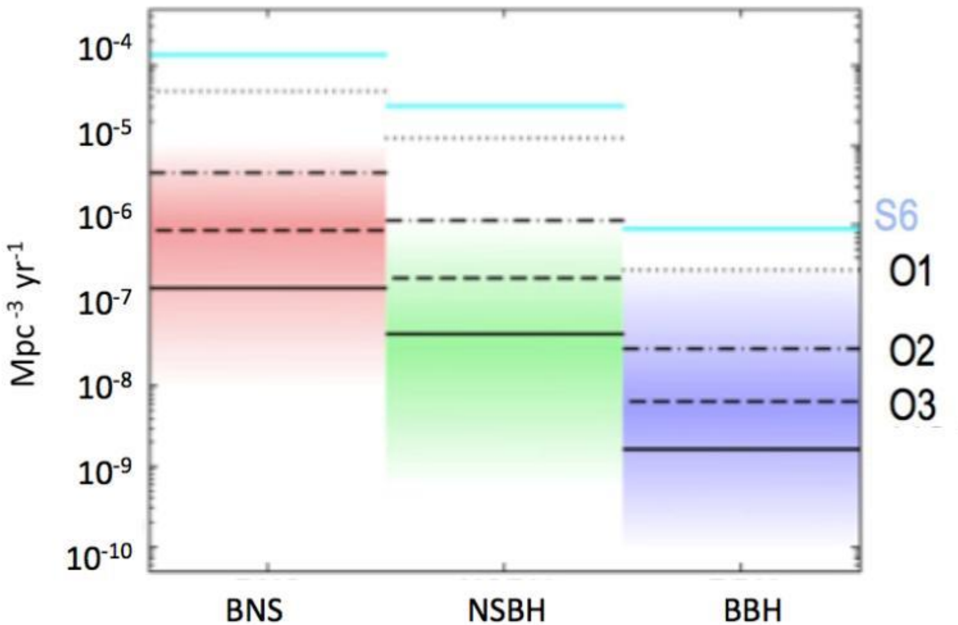
Credit: S. Fairhurst



Compact Coalescing Binaries

Detection perspectives with advanced detectors   Phys. Rev D85 (2012) 082002



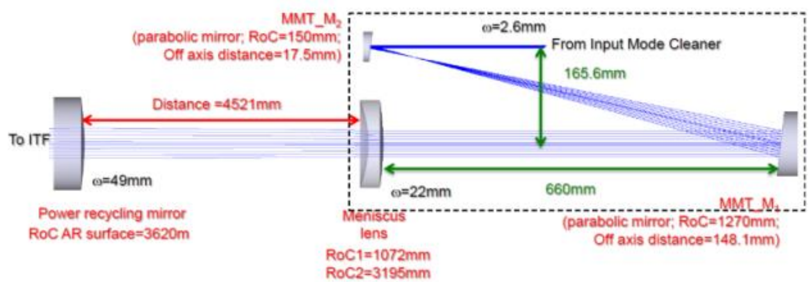


Epoch		2015	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	–	20–60	60–85	65–130	130
BNS detections		0.0004–3	0.006–20	0.04–100	0.2–200	0.4–400

Probe beyond local universe
100 M$_\odot$ + 100 M$_\odot$ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

Optical design activities: High magnification beam expander/reducer

- Due to the large laser beam and the limited space available, we had to design an original and compact design for the launching telescope for Advanced Virgo. This is a catadioptric system.



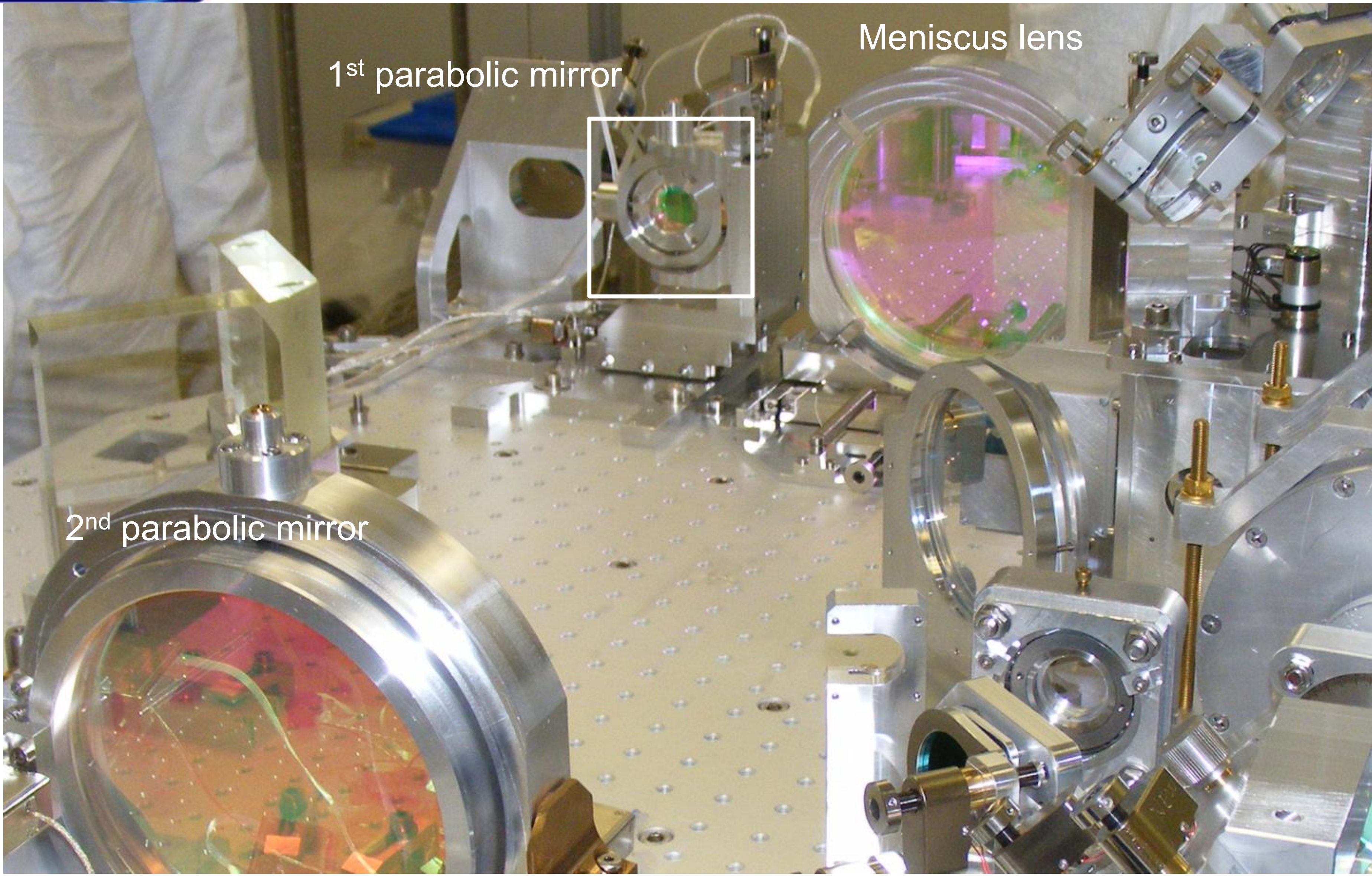
Applications:
- Astronomy (Laser guide stars)
- Whatever experiment which need a high magnification compact laser beam expander

→ This design has been chosen by the AdV Project for the interferometer input and output telescopes.

- Optimization has been made keeping in mind the compactness and the lowest possible aberrations (in particular spherical aberrations compensation was required as well as low astigmatism).
- A complete tolerancing study has been carried out to define the requirements on the mechanics and on the optics and to determine to actuators needed to adjust its alignment while under vacuum.
- Scattered light has been studied to determine the requirements on optics surface errors and on baffling.

Ref.: B. Canuel, E. Genin, G. Vajente, J. Marque, Displacement noise from back scattering and specular reflection of input and output optics in advanced GW detectors, Optics Express, Vol. 21, Issue 9, pp. 10546-10562 (2013).

AdV launching telescope

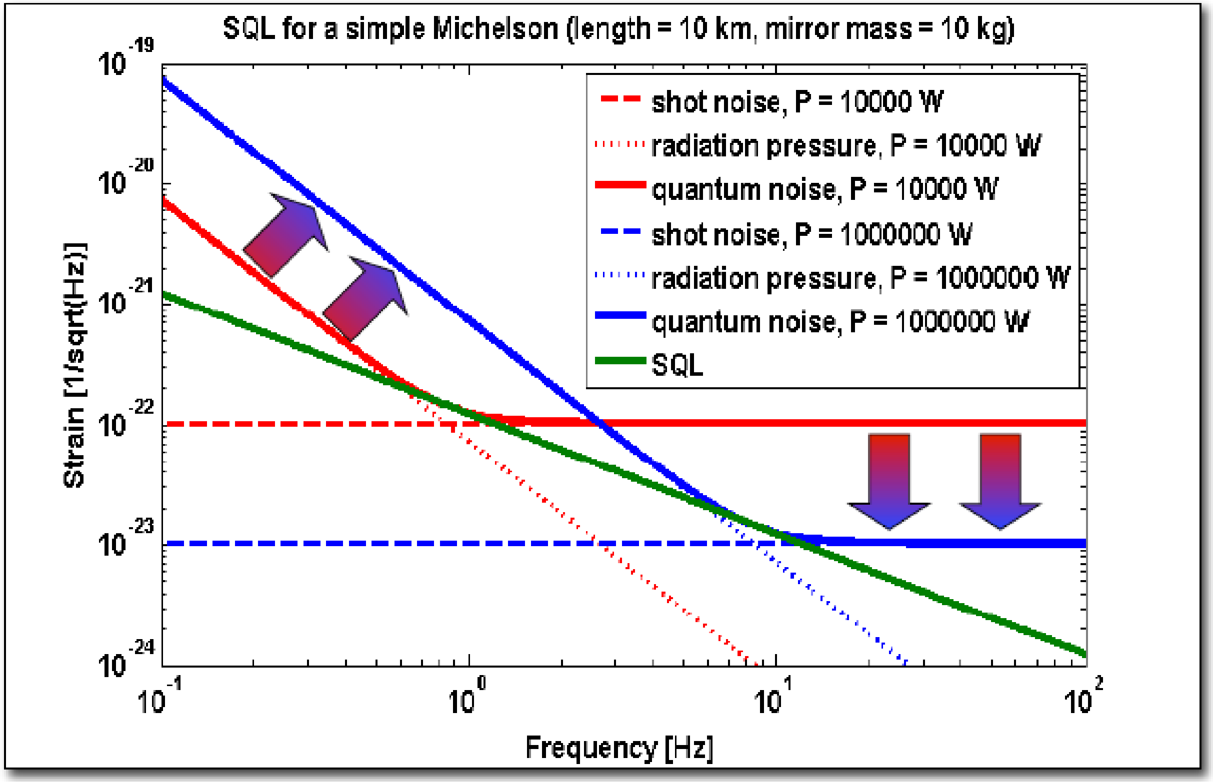


While shot noise contribution decreases with optical power, radiation pressure level increases:

$$h_{sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

wavelength, optical power, Arm length, Mirror mass

$$h_{rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$



The SQL is the minimal sum of shot noise and radiation pressure noise.

Using a classical quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)