Gravitational waves: listening to the whispers of the Universe

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14/09/2015: first observation of Gravitational Waves!!

First evidence of black holes

229.000 downloads in the first 24 hours!!

Outline

- The origin of Gravitational Waves and their effect on the matter
- Gravitational Waves detection
- The Virgo detector
- The detector network

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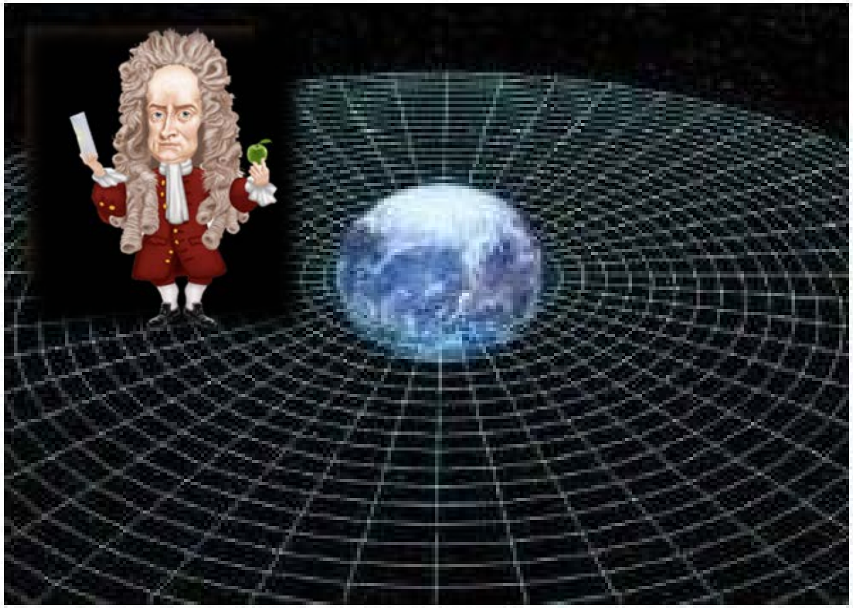
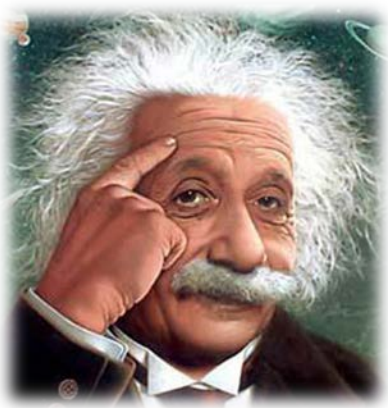
2015: 100 years of General Relativity



- The space is *flat* and the time is *absolute*
- Gravity is the *force* acting between two masses
- Gravitational attraction is an *instantaneous* force

- Space and time are connected
- Gravity is the effect of the spacetime curvature
- Gravitational field propagates at the speed of light

Einstein's Field Equations



$$\boxed{G_{\mu\nu}(g)} = 8\pi \boxed{T_{\mu\nu}}$$

GEOMETRY

MASS-ENERGY DISTRIBUTION

Matter tells the spacetime how to curve, and curved space tells to matter how to move (J. Wheeler)

Non-linear equation, solvable only in case of particular symmetry

The origin of Gravitational Waves

In the *weak field regime* we can linearize:

$$G_{\mu\nu}(\boxed{g}) = 8\pi T_{\mu\nu}$$

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Flat metric

Small perturbation $h_{\mu\nu} \ll 1$

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$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Flat metric

Small perturbation $h_{\mu\nu} \ll 1$

$$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x_i^2}\right) h_{\mu\nu} = 0$$

$$h_{\mu\nu} = \varepsilon_{\mu\nu}\exp[i(\omega_{GW} t - \mathbf{k}\cdot\mathbf{r})]$$

Gravitational Waves polarization

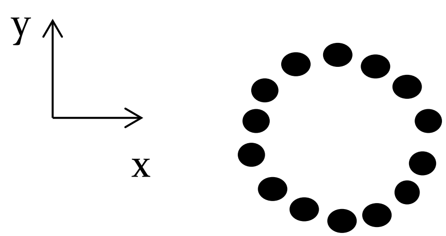
$$h_{\mu\nu} = \varepsilon_{\mu\nu} \exp[i(\omega_{GW} t - \mathbf{k} \cdot \mathbf{r})]$$

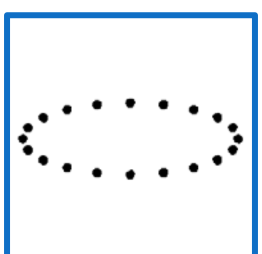
2 degrees of freedom

+ polarization

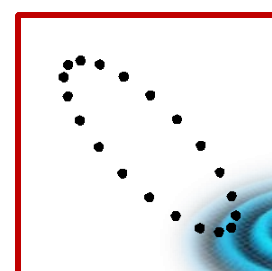
$$\varepsilon_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h^{+} & h^{\times} & 0 \\ 0 & h^{\times} & -h^{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

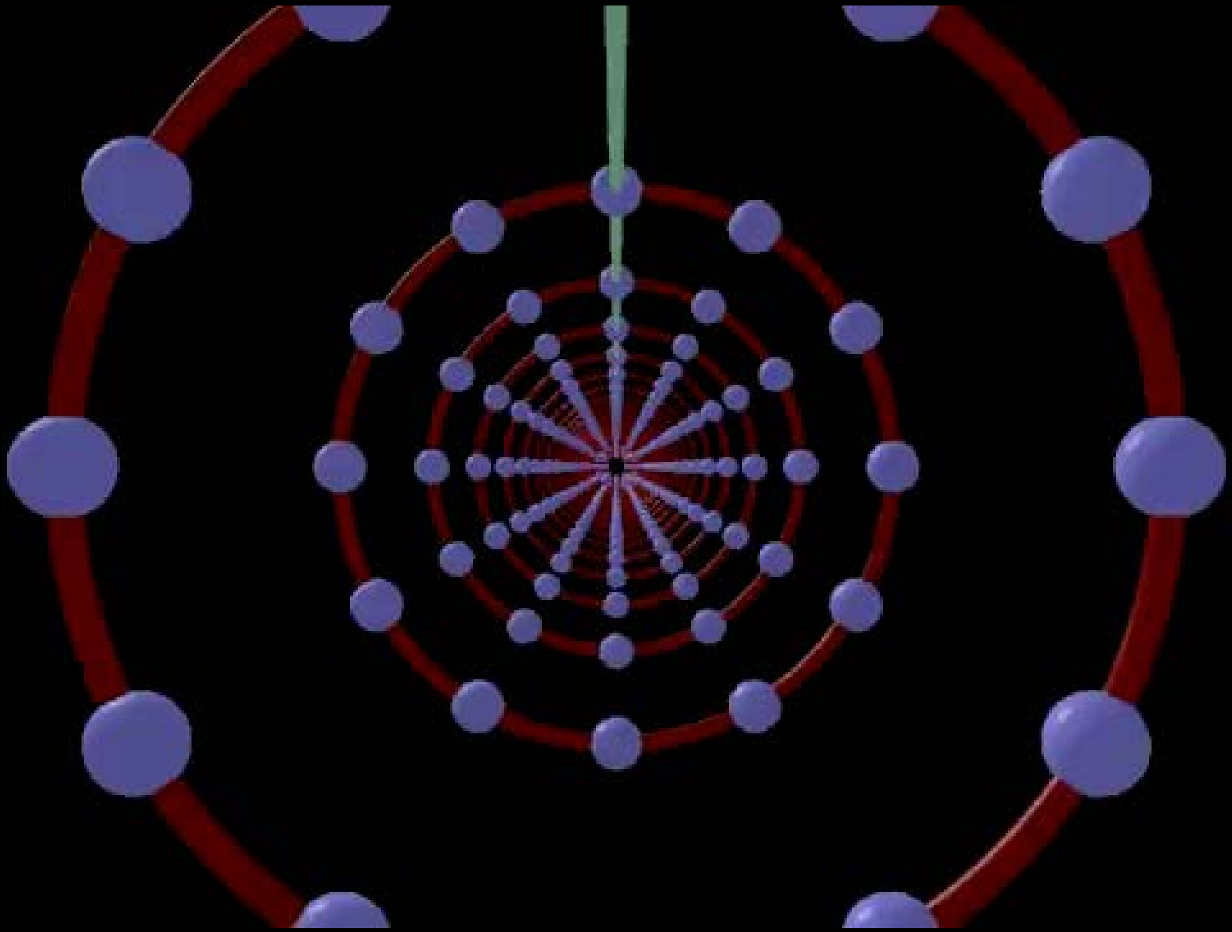
× polarization





For a wave travelling in the z direction…





Gravitational Waves sources

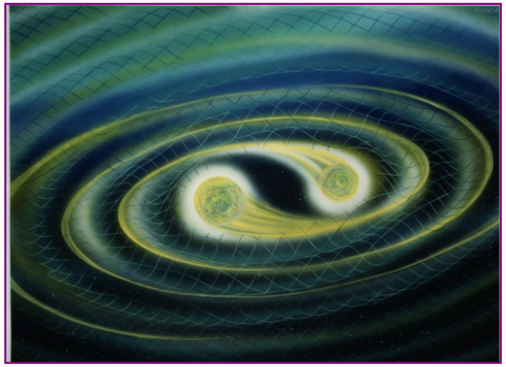
Any acceleration that is not spherically or cylindrically symmetric will produce a gravitational wave.

The amplitude of gravitational waves is proportional to the quadrupole moment of the masses which produce them through the constant **$G/c^4 \approx 10^{-45}\ N^{-1}$**

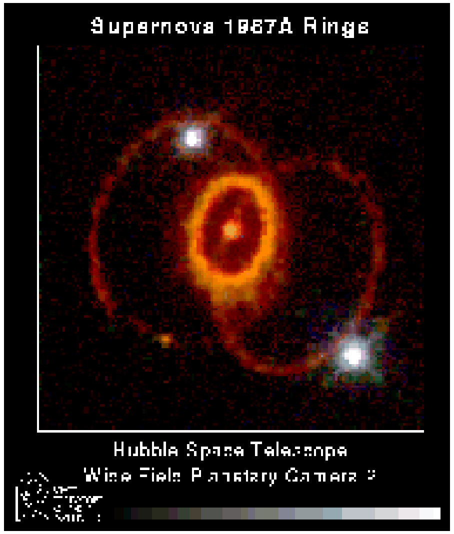
$$h_{jk}^{TT} = \frac{2G}{rc^4}\left(\frac{d^2 I_{jk}^{TT}}{dt^2}\right)_{t-r/c}$$

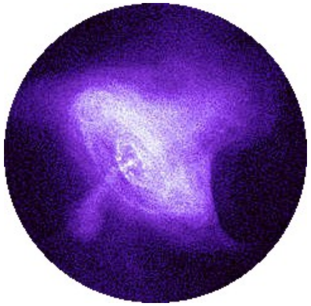
$$I_{jk} = \int d^3\overrightarrow{x}\,\rho\left(x_j x_k - \frac{1}{3}|\overrightarrow{x}|^2\right)$$

Gravitational Waves sources

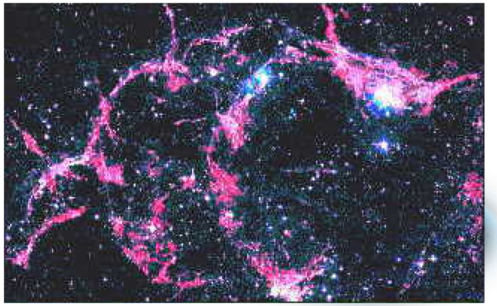


- Coalescence of binaries
  - NS-NS
  - NS-BH
  - BH-BH

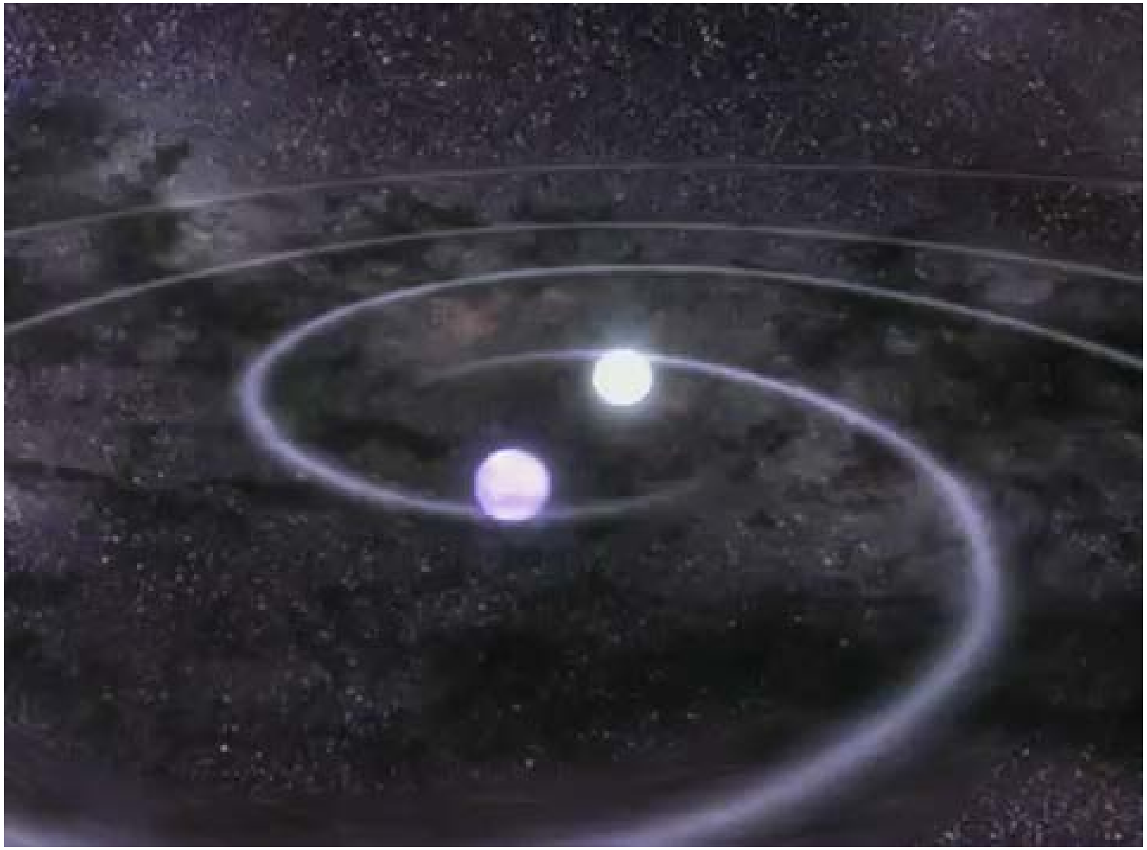


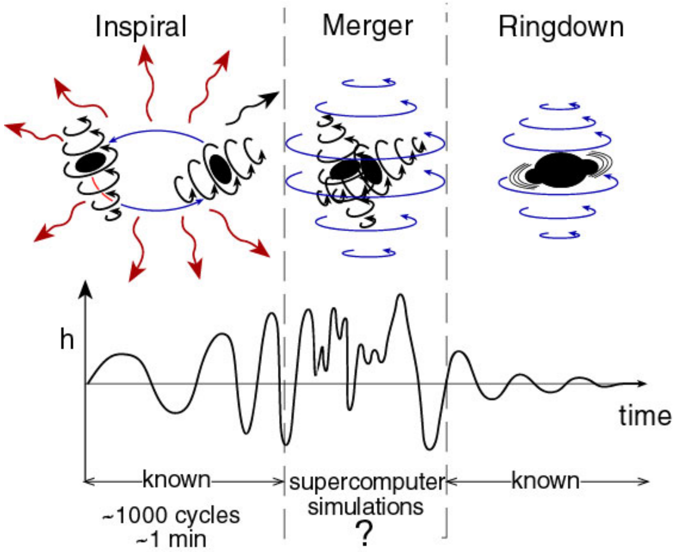


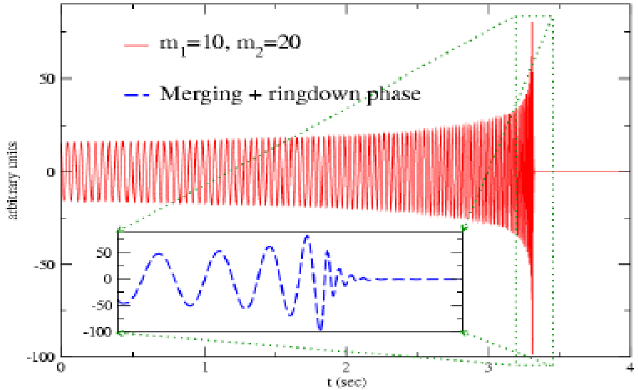
- Periodic sources
  - Pulsar
- Supernovae explosions
- Echoes from the Big Bang (*stochastic background*)



An example of a Waveform

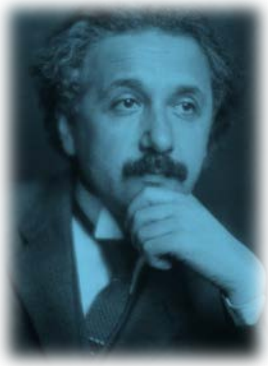






Einstein and gravitational waves: also the genius has doubts…

- 1915: published the theory of GR
- 1916: first paper about GW, but there's a mistake!
- 1918: Computes for the first time the effect of GW
- 1936: Published with Rosen the paper: "*Do Gravitational Waves Exist?*"
- 1937: Finally gets convinced about GW existence



They exist!

No, they cannot exist!

http://www.hs.uni-hamburg.de/DE/GNT/events/pdf/steinicke05.pdf

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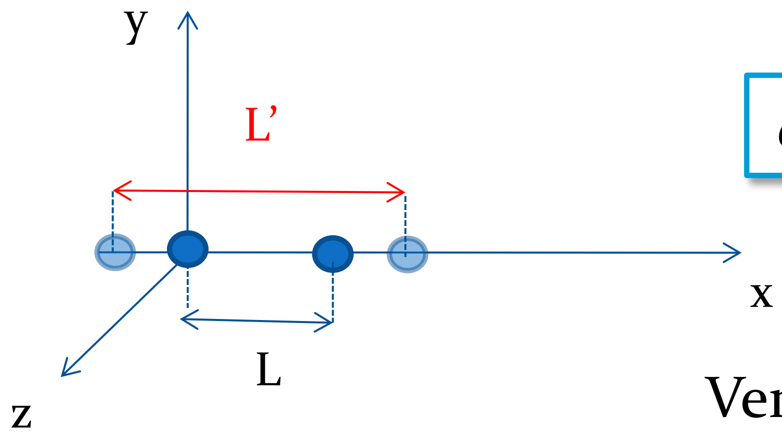
Gravitational Waves and their detection

Effect of a GW on free-falling masses



$$\boxed{\delta L \propto h\, L}$$

Very weak amplitude:
$\boldsymbol{h \approx 10^{-21}}$ for a GW produced by
two coalescing BH, each of 30 solar masses

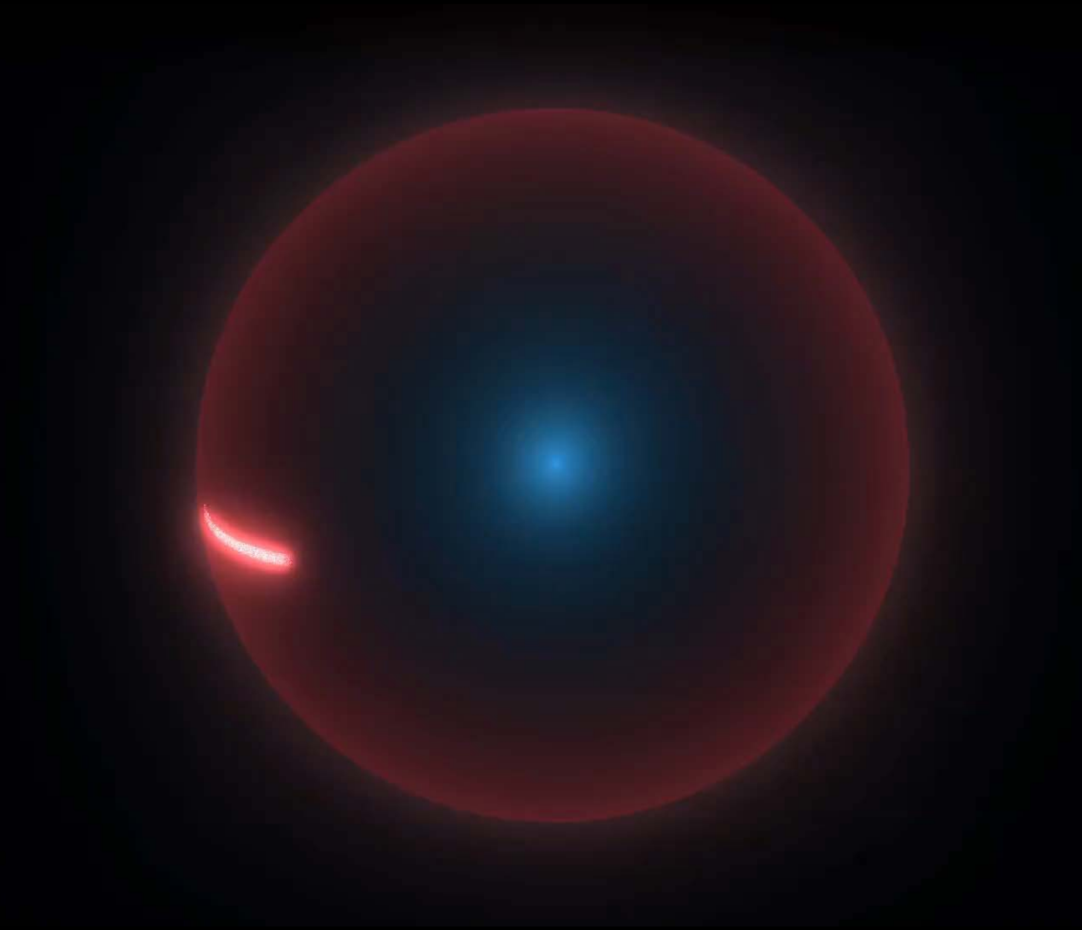
The distance between two masses separated by ~Km will
change by $\boldsymbol{\delta L \approx 10^{-18}}$**m**

How small is “small”?

Let’s suppose you pour a glass of wine into the ocean.

- *What is the rise of sea-level you get?*

How big is the effect of a gravitational wave compared to the atomic size?



We need a (good) ruler

Joseph Weber c. 1965

measure oscillations in mechanical resonators

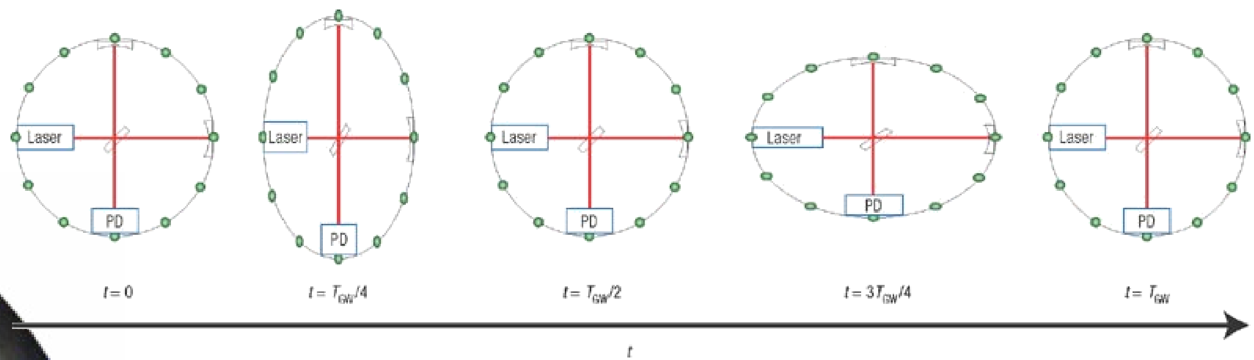
Monitored the amplitude of oscillation of the **fundamental mode of the bar**.
A gravitational wave signal of suitable strength would be *expected to change the amplitude or phase of the oscillations in the bar*

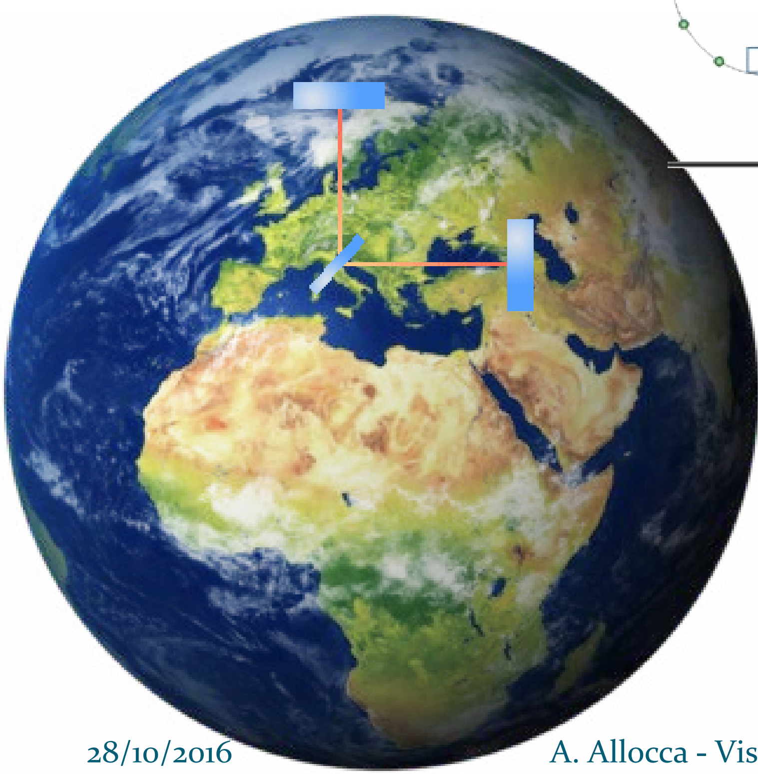
J. Weber Phys. Rev. Lett. 18, 498

Interferometer

Use an interferometer as a transducer: convert displacements into optical signals

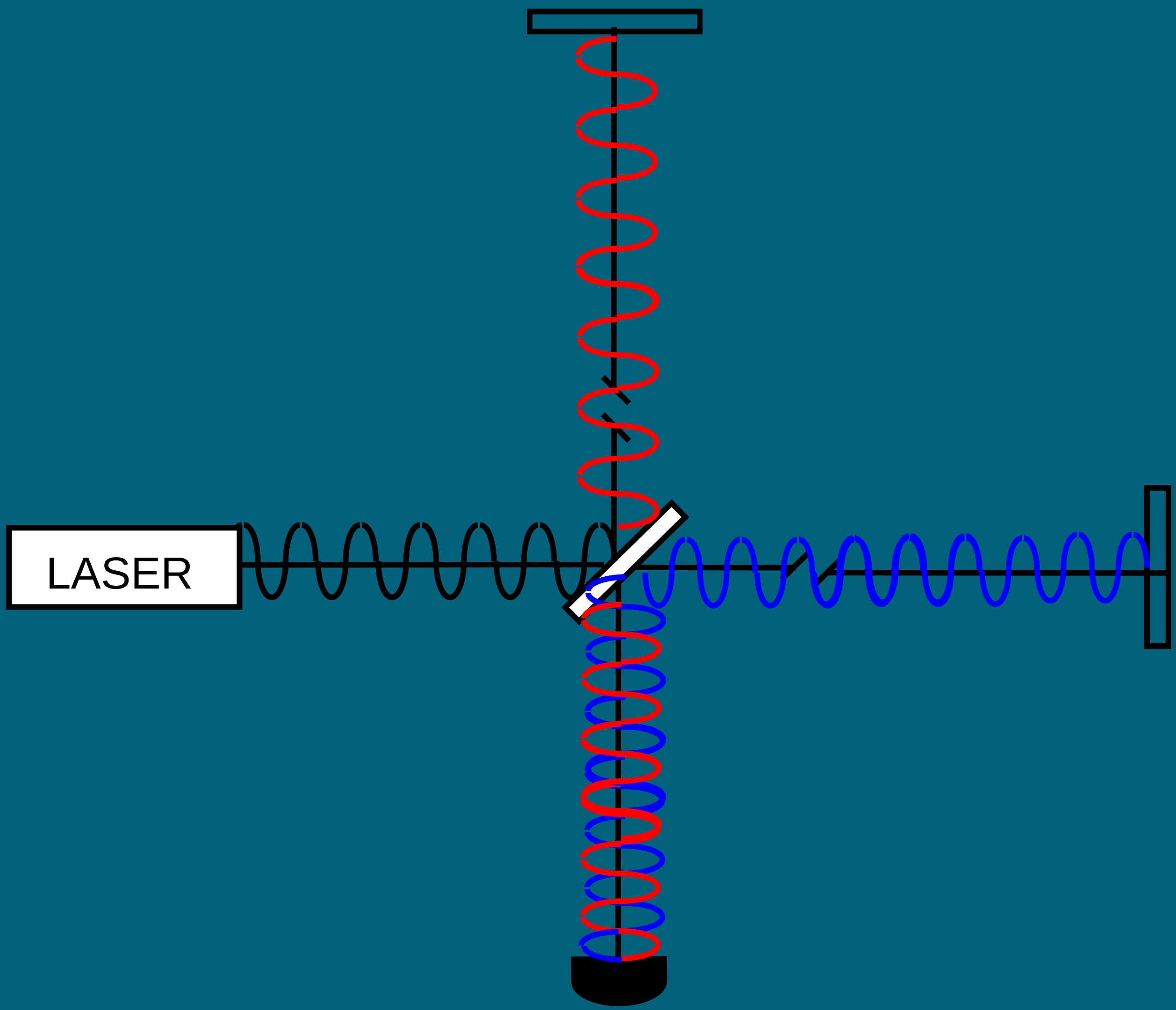
$$\delta\phi = G\,\delta L$$

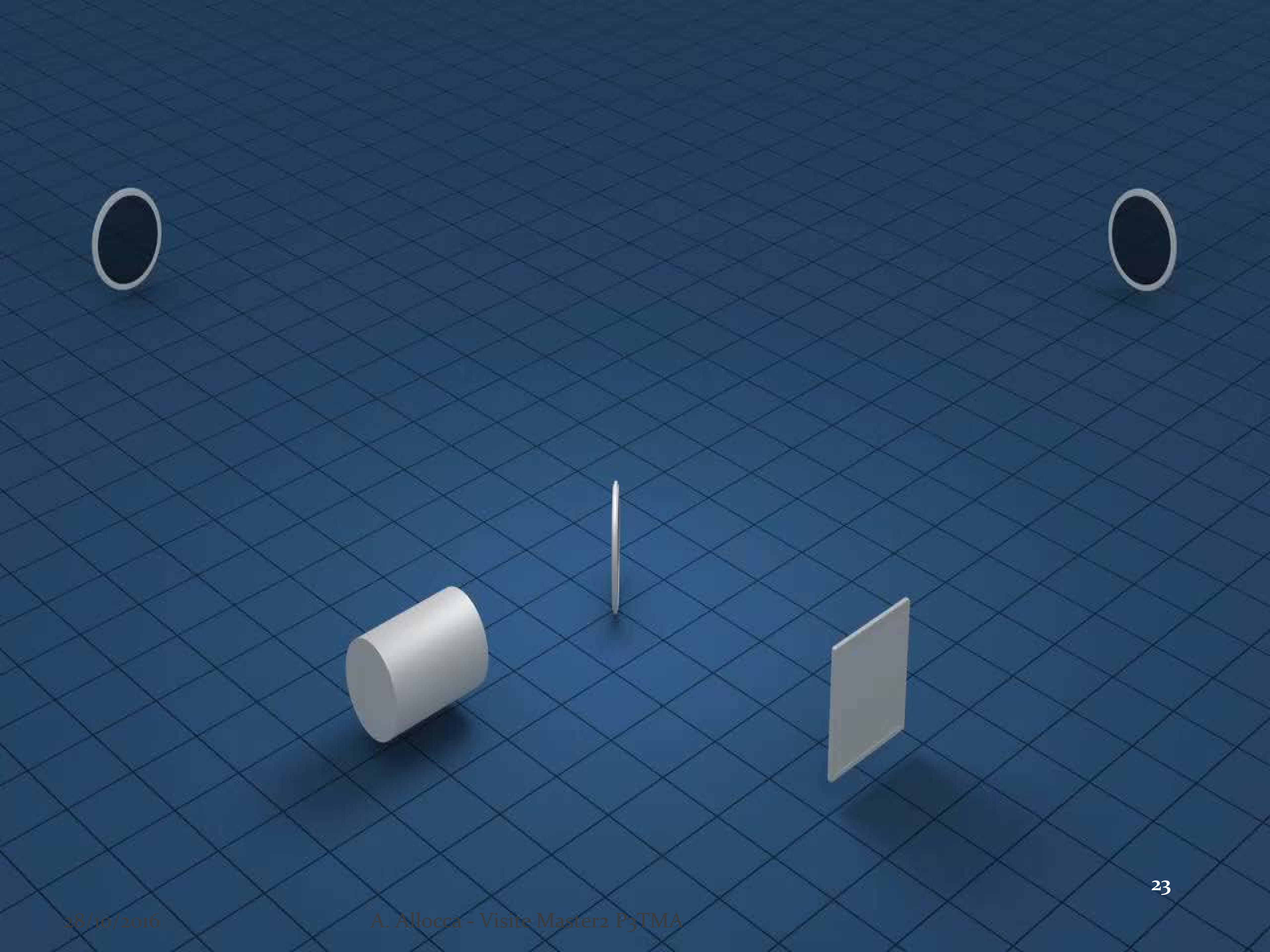




measure distances between free-falling masses

Basics of interferometry





A challenge against noise

Increase the sensitivity

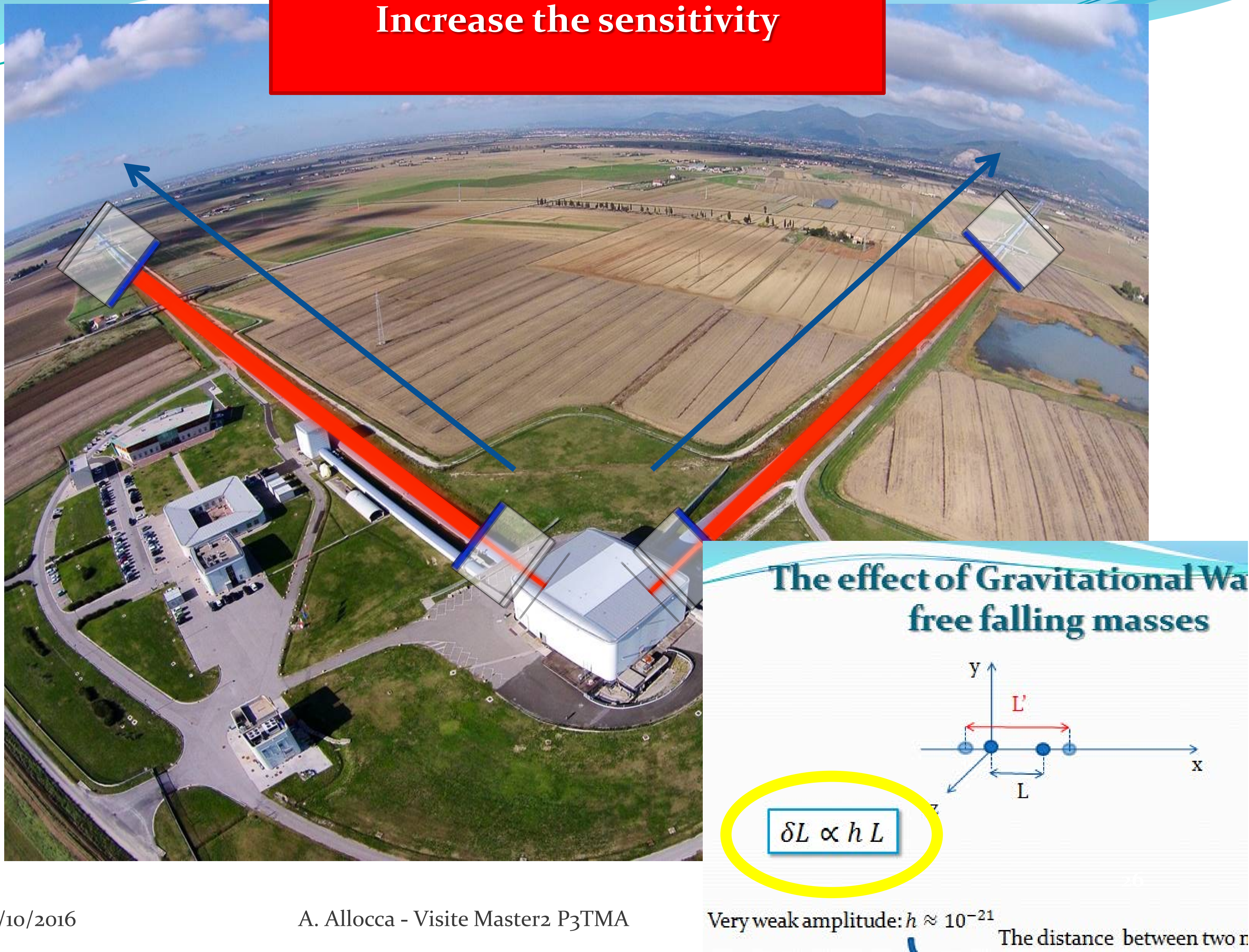
Reduce the noise

A challenge against noise

Increase the sensitivity

Reduce the noise

Increase the sensitivity



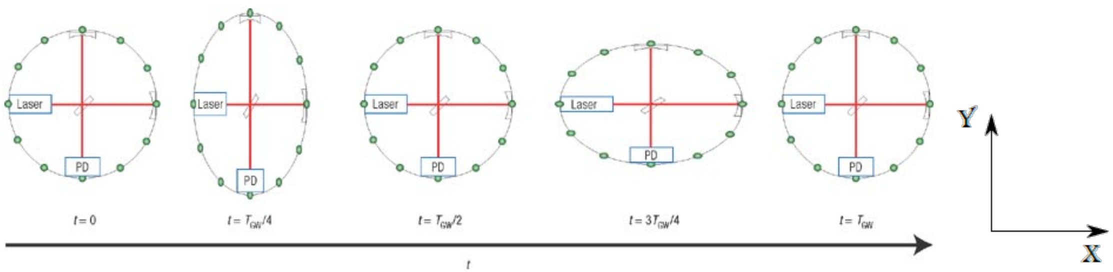
Michelson Interferometry to detect GWs

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

Use an interferometer as a transducer: convert displacements into optical signals

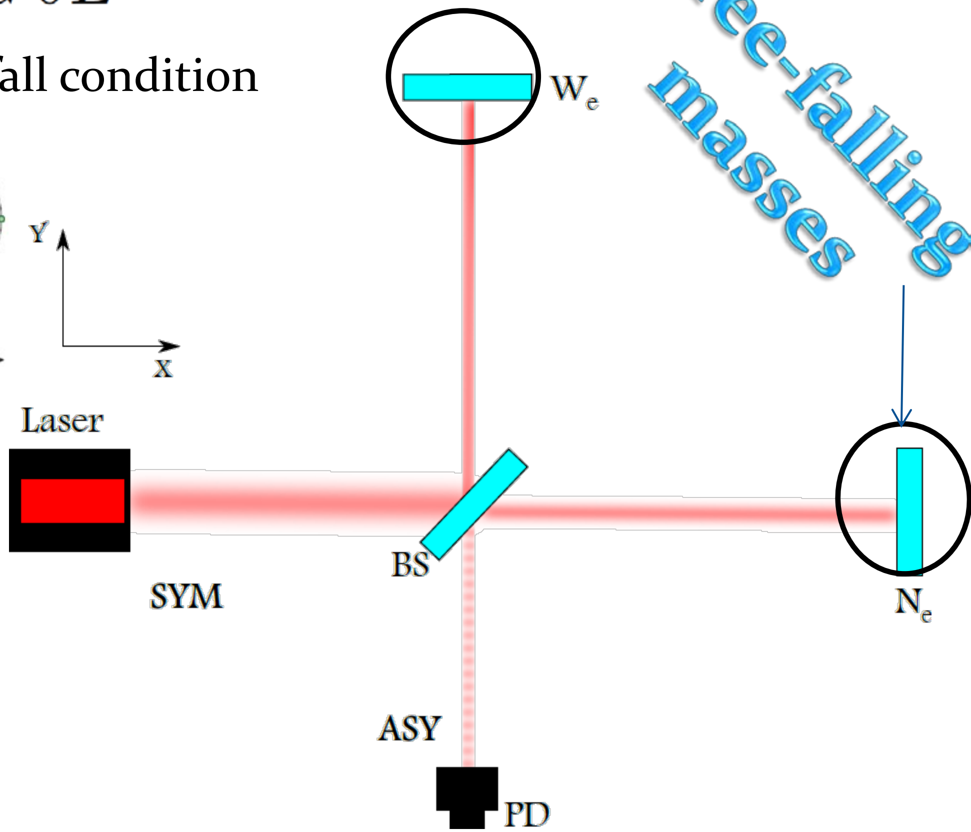
$$\delta\phi = G\,\delta L$$

Suspended mirrors to reproduce the free-fall condition



Enhance the signal

Free-falling masses



$$P_{ASY} \propto P_0 (2\, k\, \delta L)^2$$

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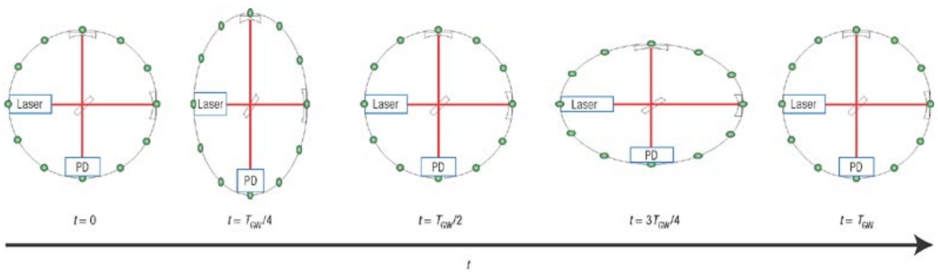
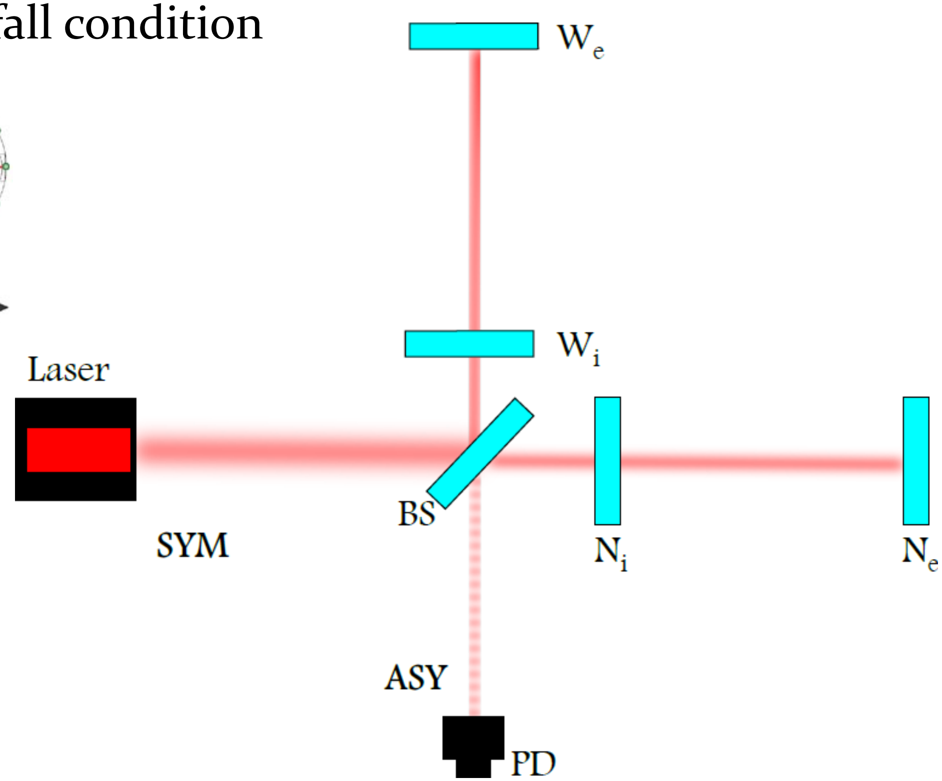


Enhance the signal

- Fabry-Perot cavity for “longer arms”



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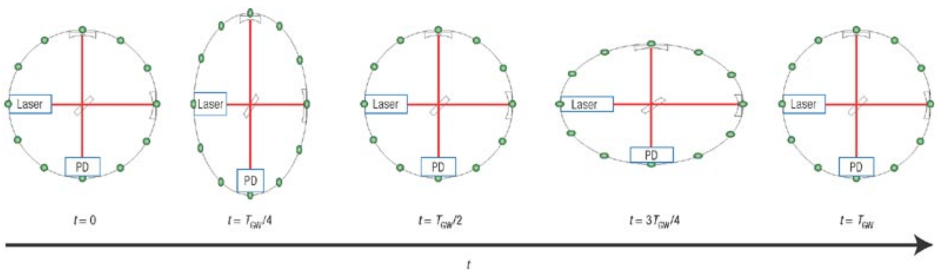
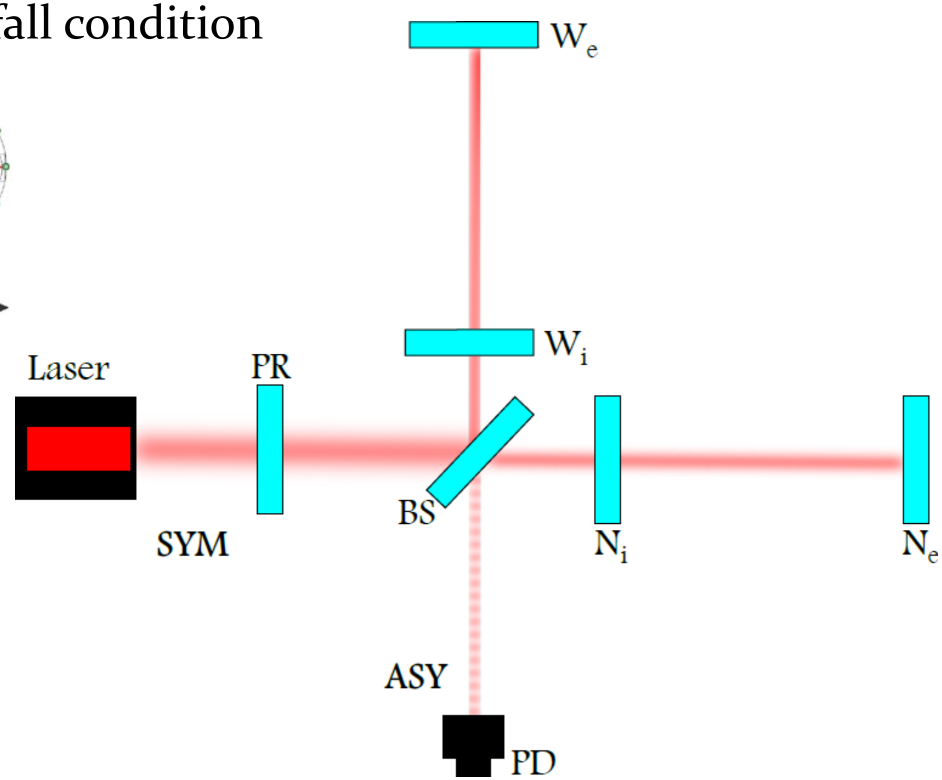


Enhance the signal

- Fabry-Perot cavity for “longer arms”
- Recycling mirror to recover the power reflected from the arms



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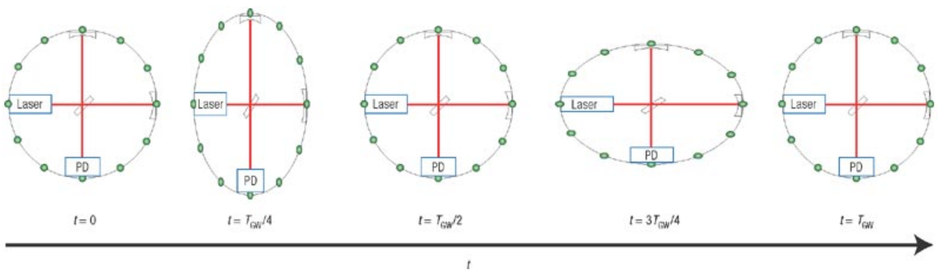
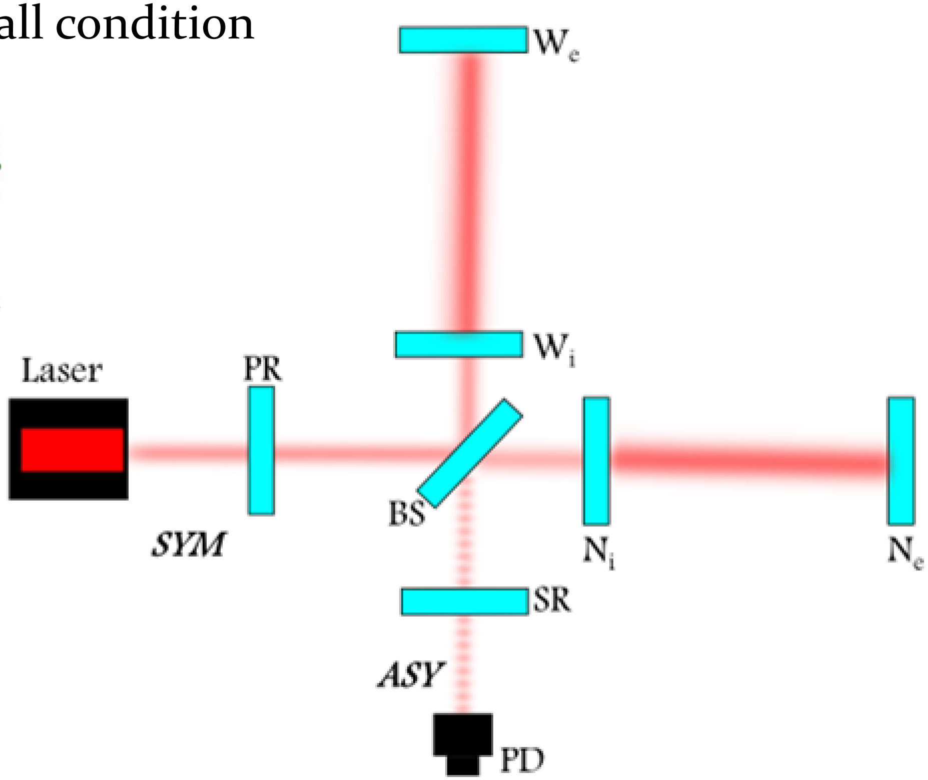


Enhance the signal

- Fabry-Perot cavity for “longer arms”
- Recycling mirror to recover the power reflected from the arms
- Recycling mirror to enhance GW audio sidebands



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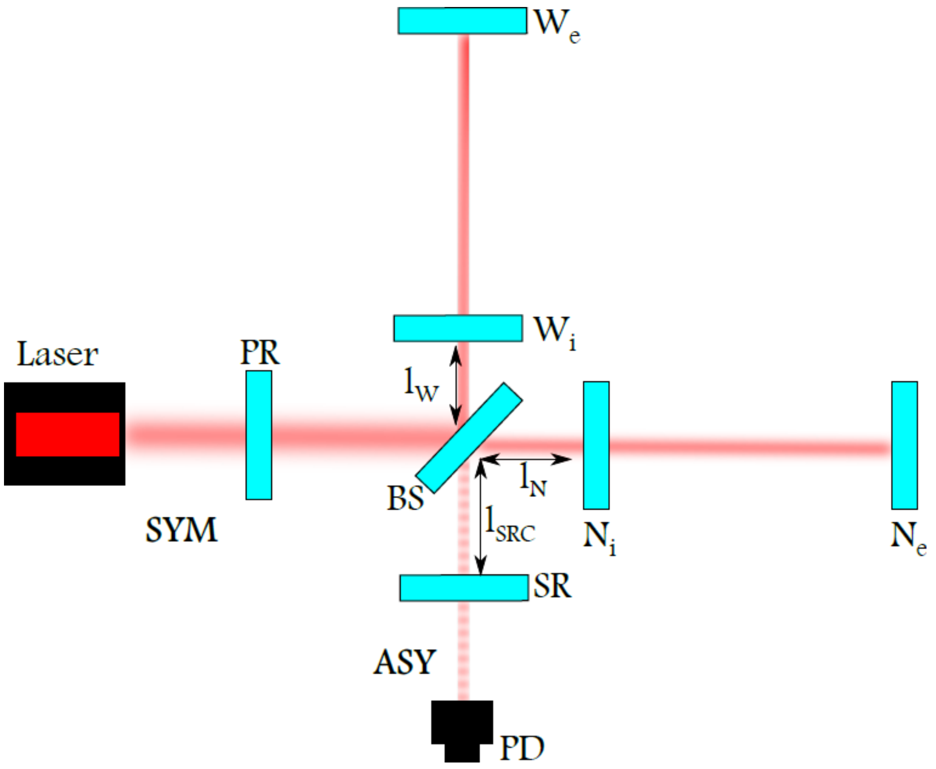
Michelson Interferometry to detect GWs



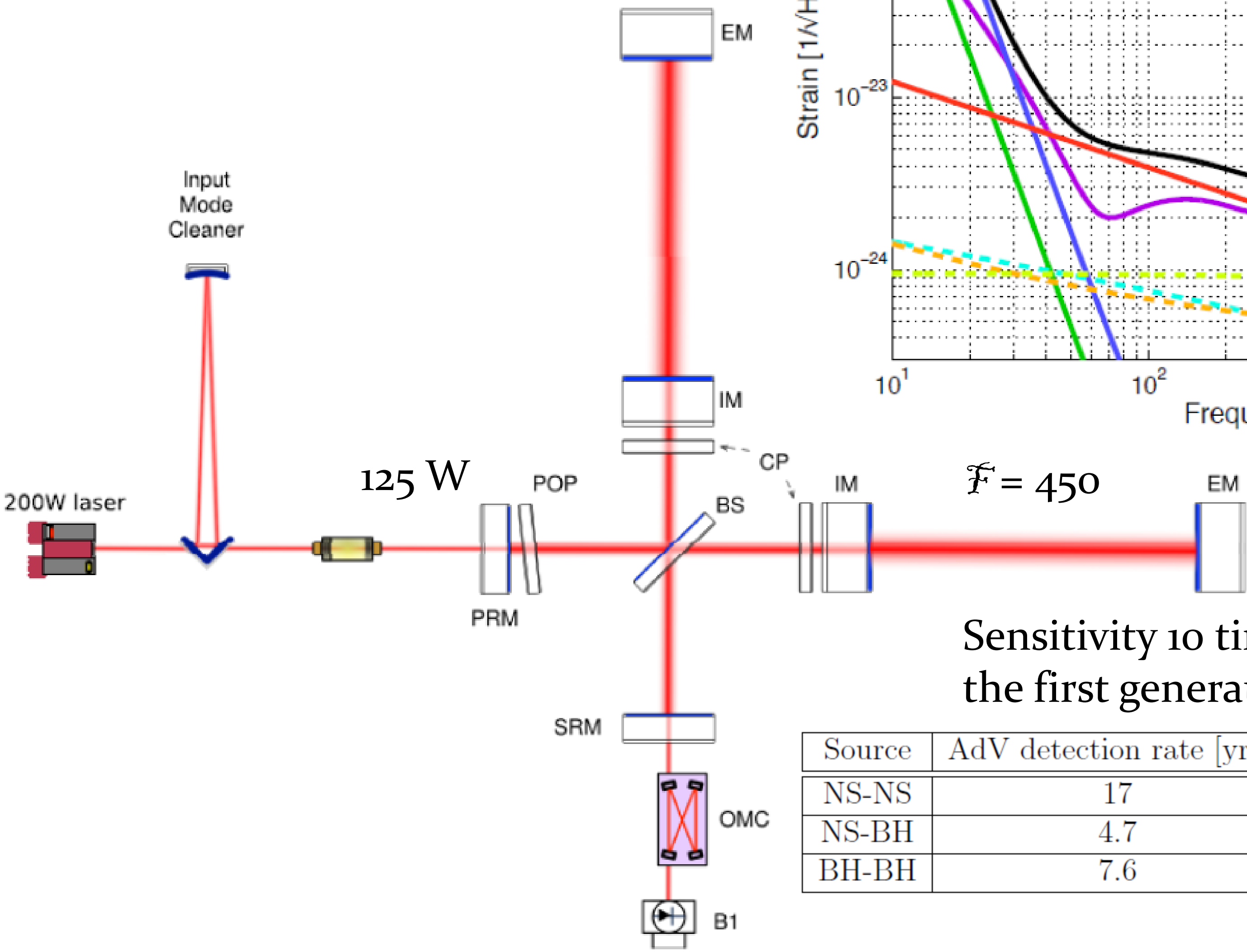
Crucial: high **contrast defect**

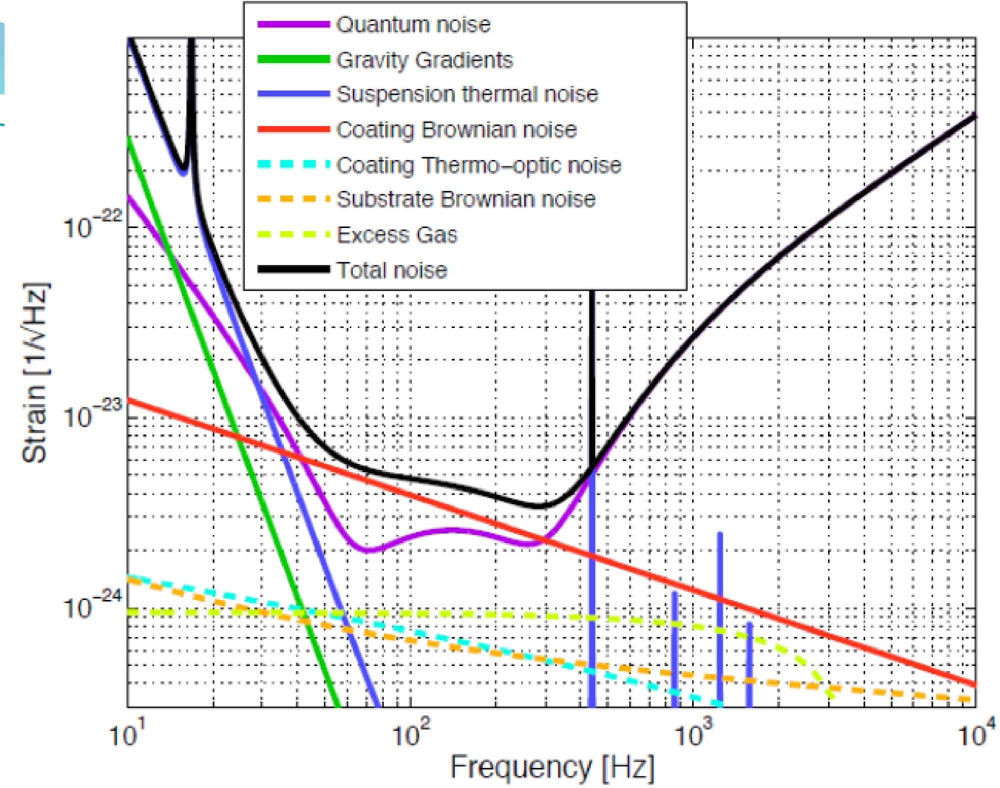
$$C = \frac{P_{BF} - P_{DF}}{P_{BF} + P_{DF}}$$

Limit effects preventing the perfect destructive interference between recombining beams

Interferometer working point: **dark fringe** condition (to be more sensitive to power variation due to a Gravitational Wave)

Advanced Virgo





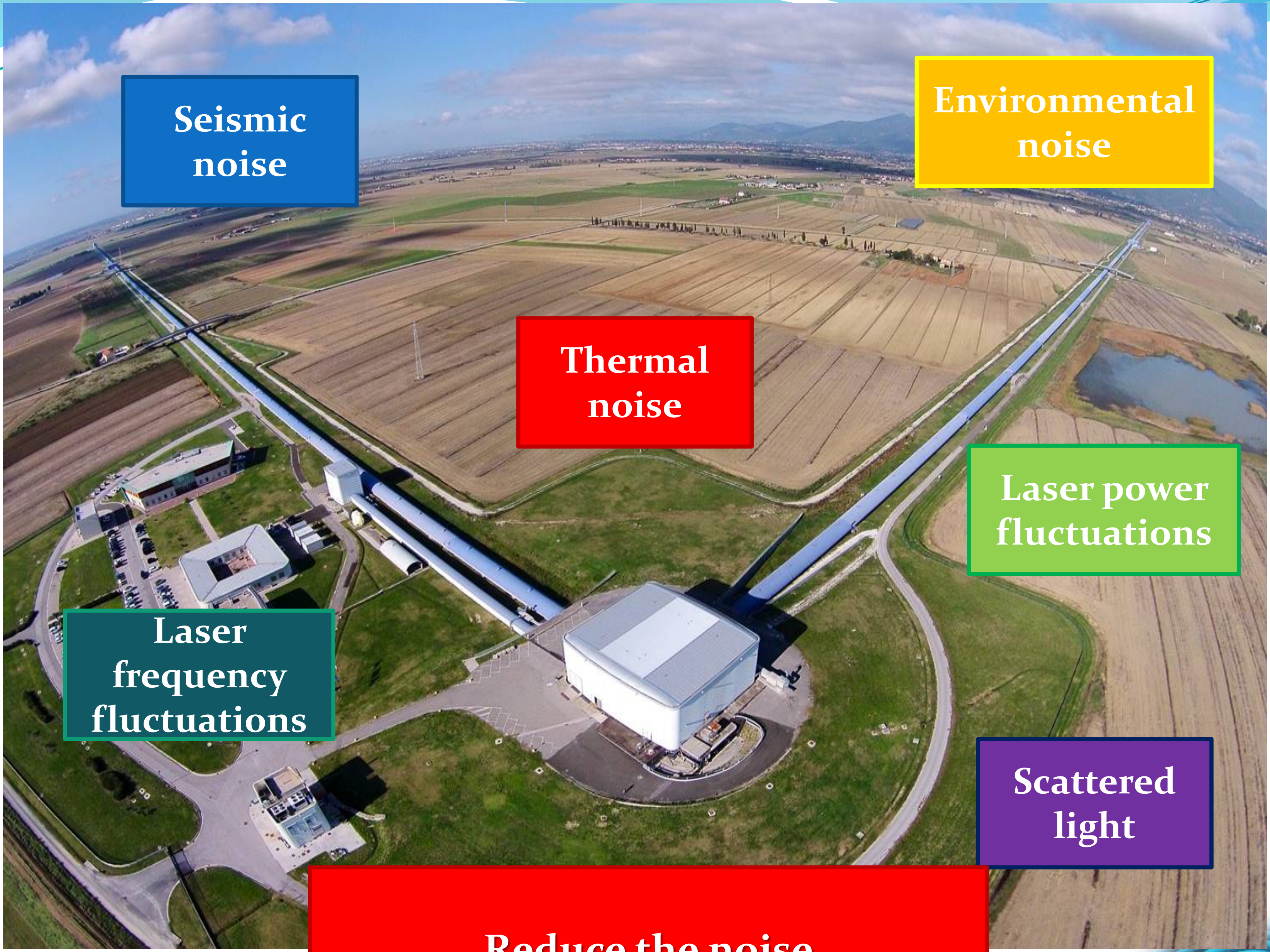
Sensitivity 10 times bigger than the first generation detectors

Source	AdV detection rate [yr^{-1}]	Virgo detection rate [yr^{-1}]
NS-NS	17	$4.5{\cdot}10^{-3}$
NS-BH	4.7	$1.2{\cdot}10^{-3}$
BH-BH	7.6	$1.9{\cdot}10^{-3}$

A challenge against noise

Increase the sensitivity

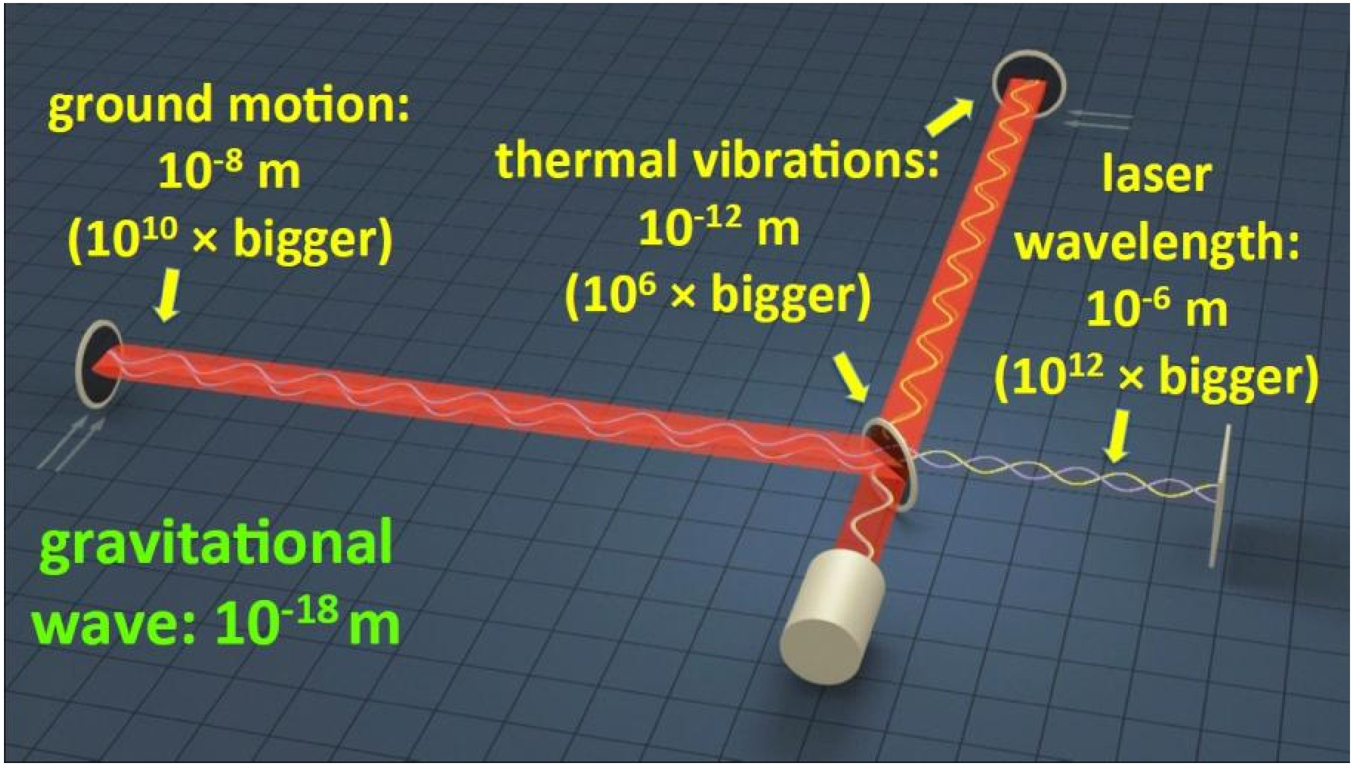
Reduce the noise



Reduce the noise

Meet the Villain: Noise!

Doesn't matter how sensitive you are,
if your noise is billions of times your signal



Credits: Stephen Fairhurst

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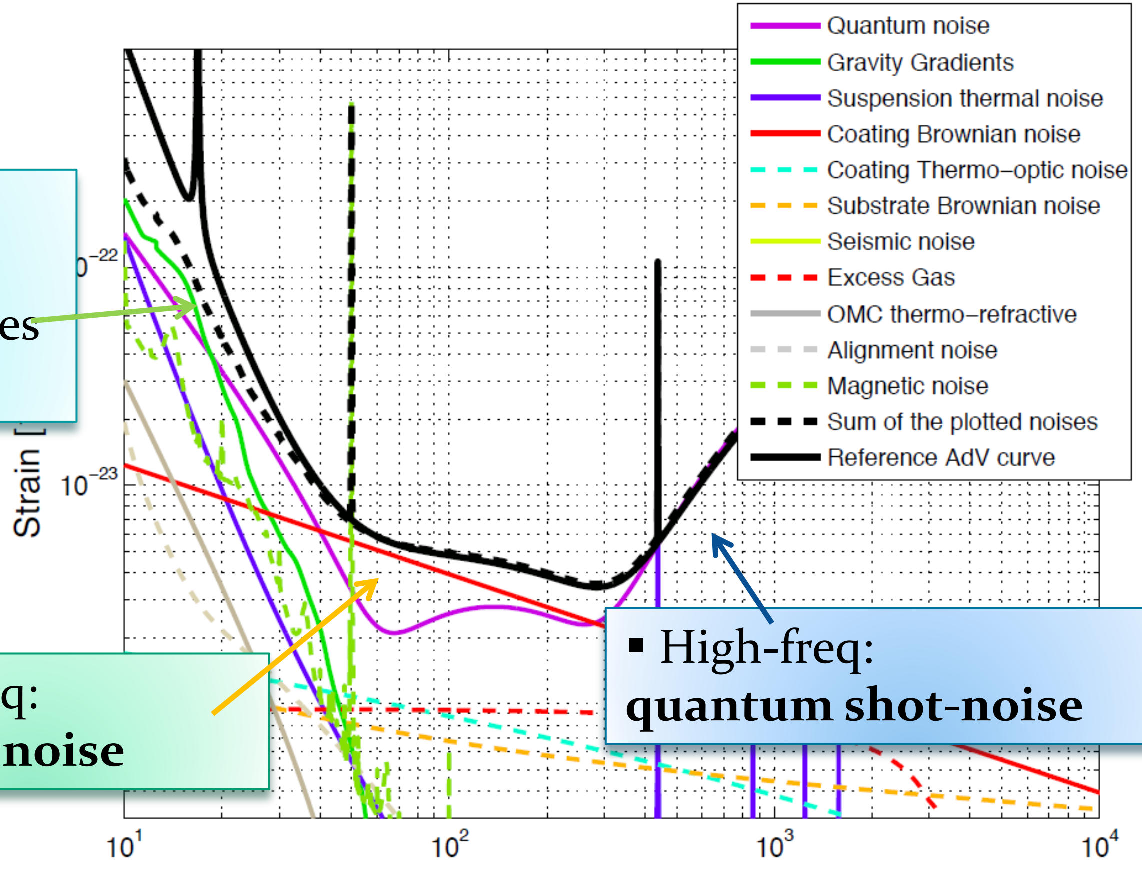
GW Detectors - Noise

Limiting noises at different frequency ranges:



- Low-freq: **newtonian noise**, seismic noise, residual technical noises

- Mid-freq: **thermal noise**

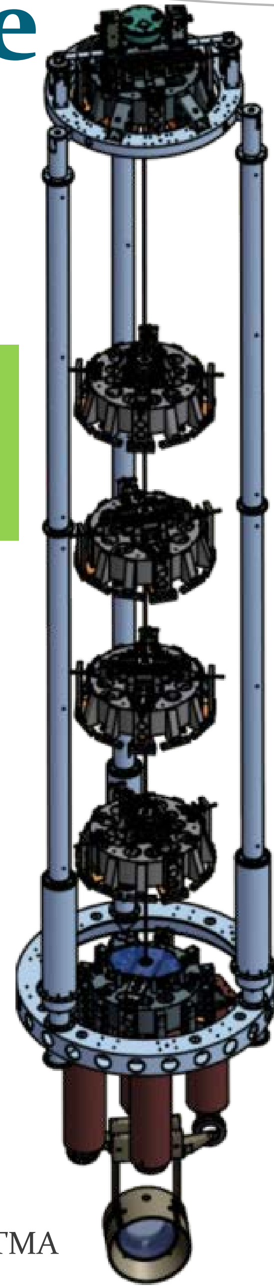
- High-freq: **quantum shot-noise**

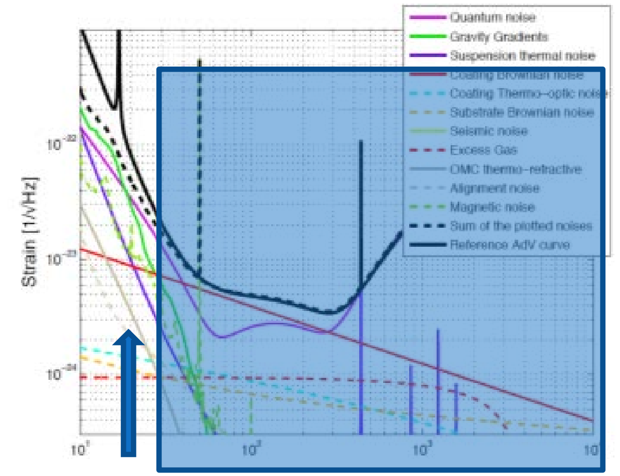
Coping with Noise

- Low frequency range:
  - ➢ dominated by *seismic noise*

The Superattenuator

Reduces mirrors seismic vibrations by a factor 10^{12}

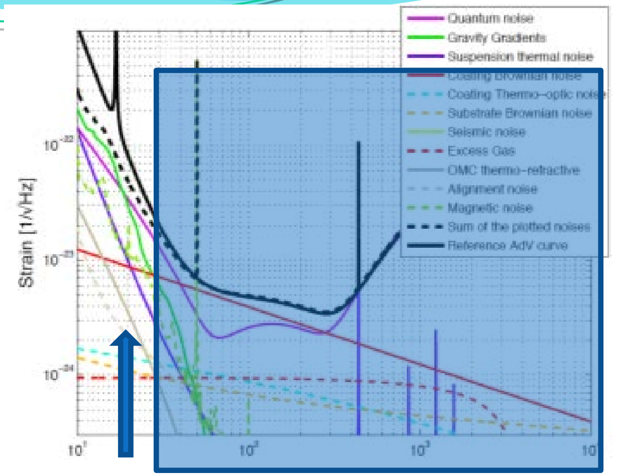




Coping with Noise

- Low frequency range:
  - gas pressure noise

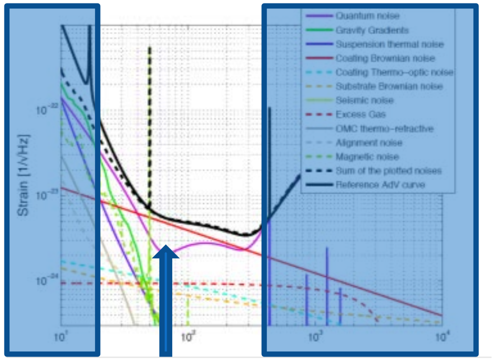
Ultra High Vacuum



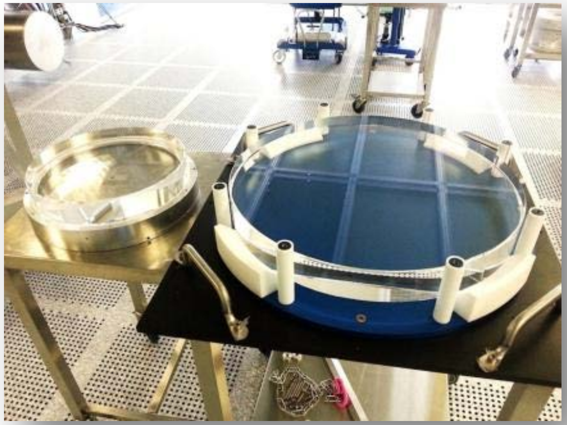
It has a total volume of 7000 m³ and is kept at a pressure of 10^{-7} mbar : the biggest *ultra-high-vacuum* system in Europe!

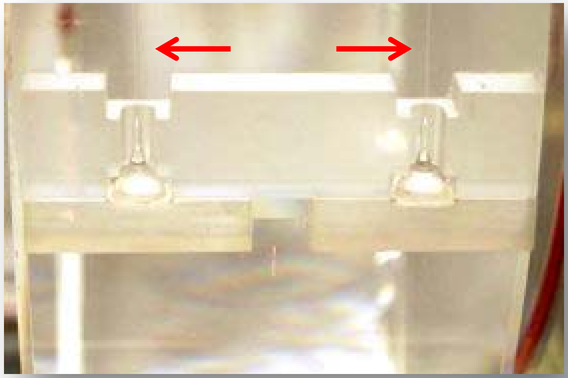
Coping with Noise

- Mid frequency range:
  - Dominated by thermal noise of mirror coatings and suspensions

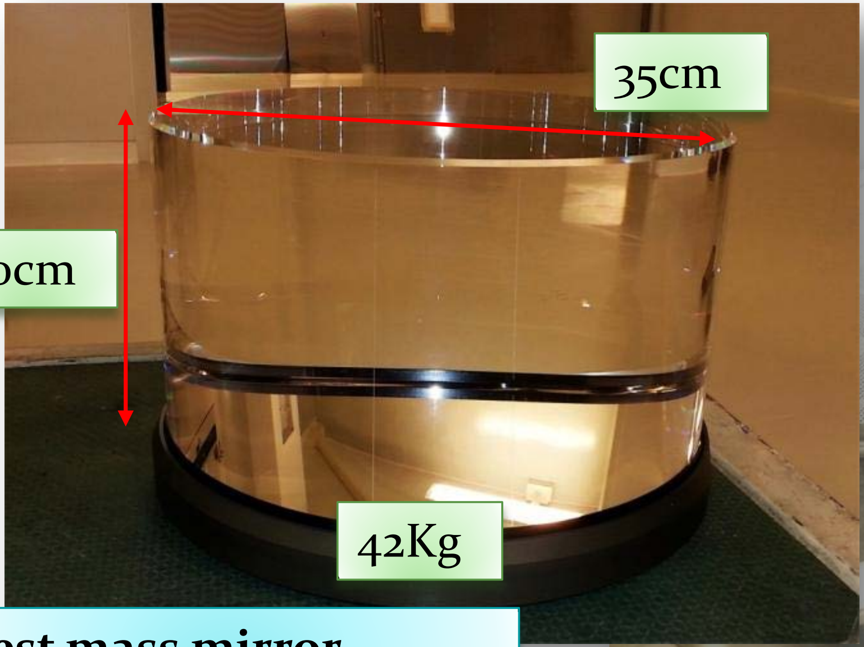


- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Mirror coatings engineered for low losses

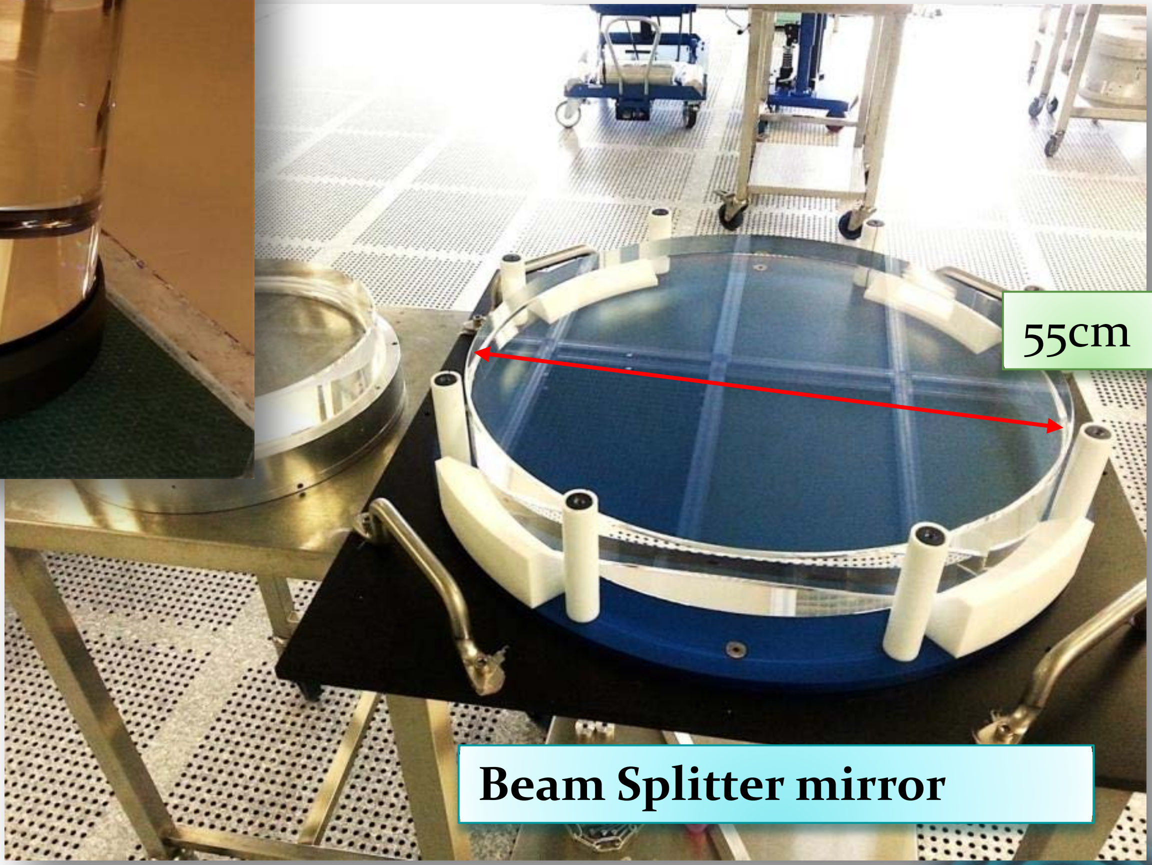




Mirrors

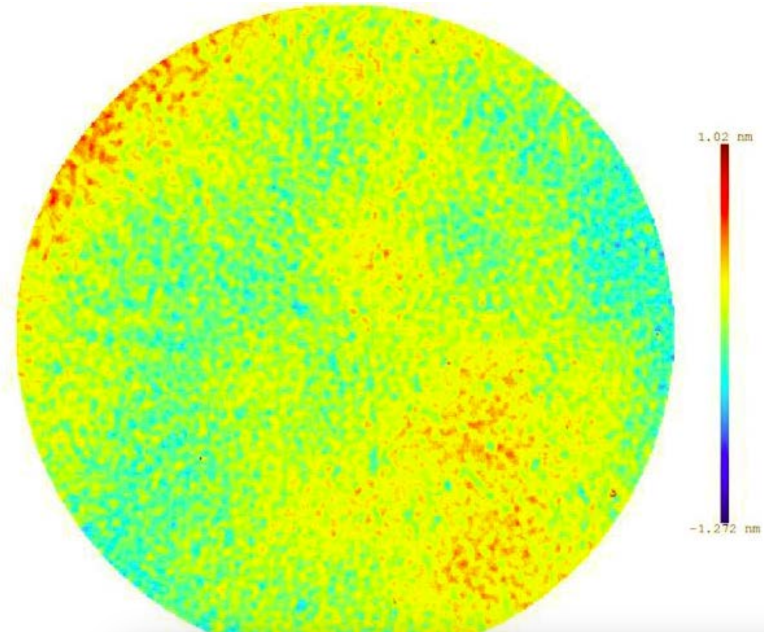


Test mass mirror



Beam Splitter mirror

Mirrors

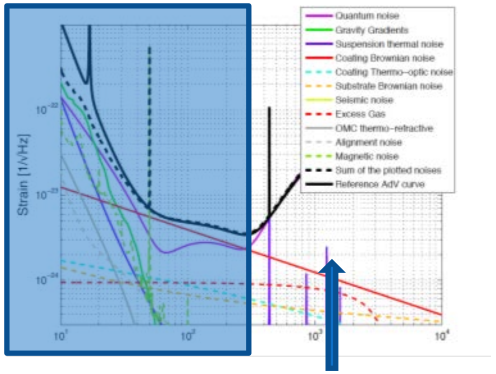


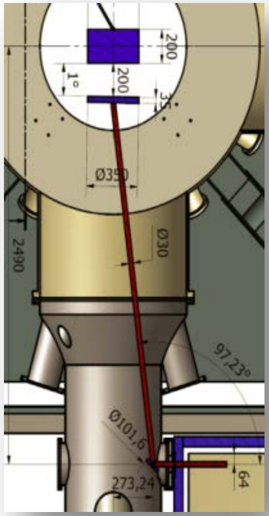
z_min	-1.272 nm
z_max	1.02 nm
z_avg	-3.171e-011 nm

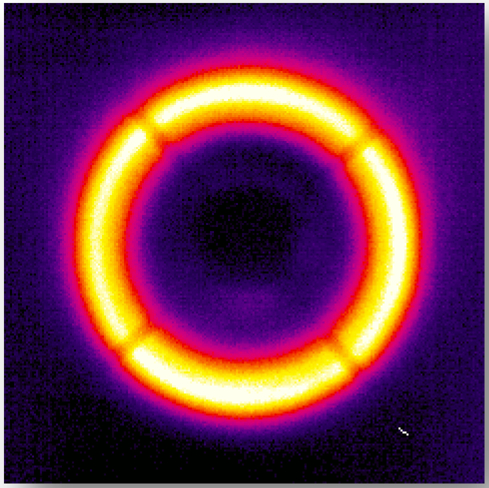
The surface figure of the polished test masses is such that with a mirror as large as Tuscany, ***highest mountains would be 1mm***

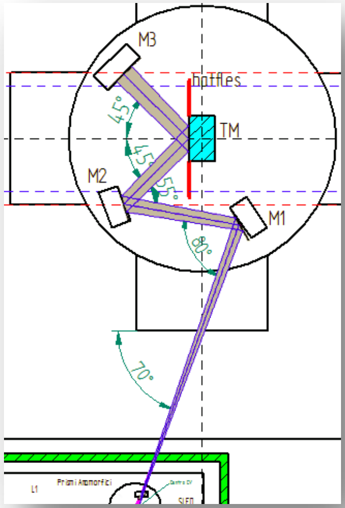
Coping with Noise

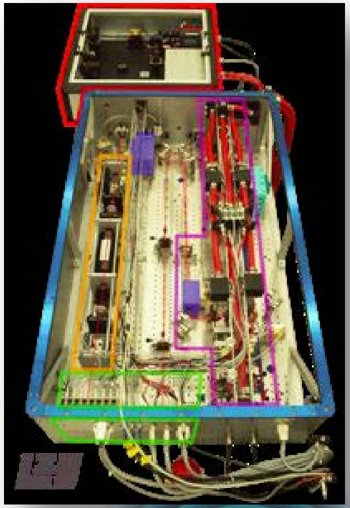
- High frequency range:
  - Dominated by laser shot noise. Improved by increasing the power: ***>100W input***, ~1 MW in the cavities
- Requires:
  - New laser amplifiers (solid state, fiber)
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations







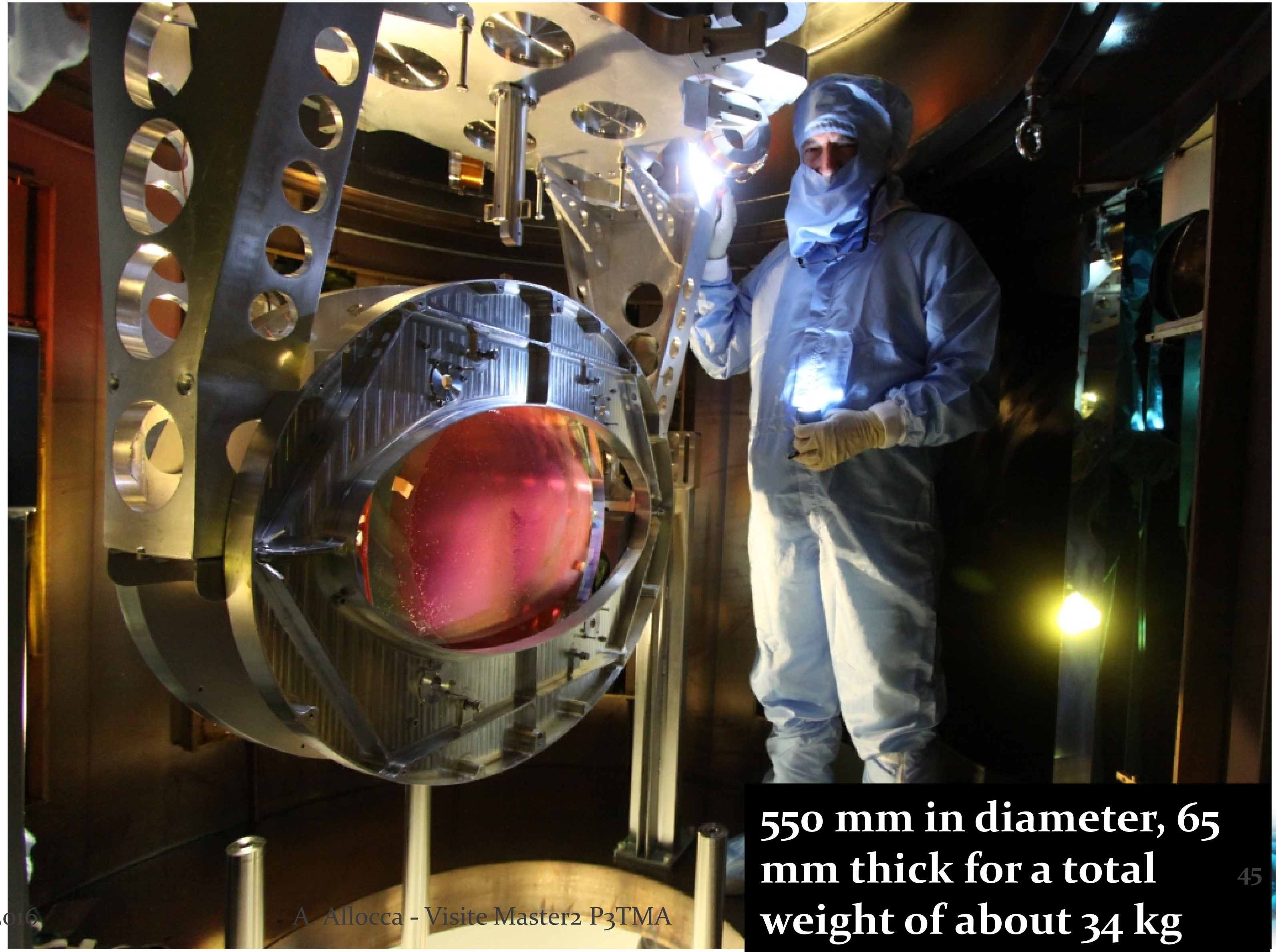




Advanced Virgo detector

Credits: Marco Kraan - Nikhef

The first "Advanced mirror": the Beam Splitter



550 mm in diameter, 65 mm thick for a total weight of about 34 kg

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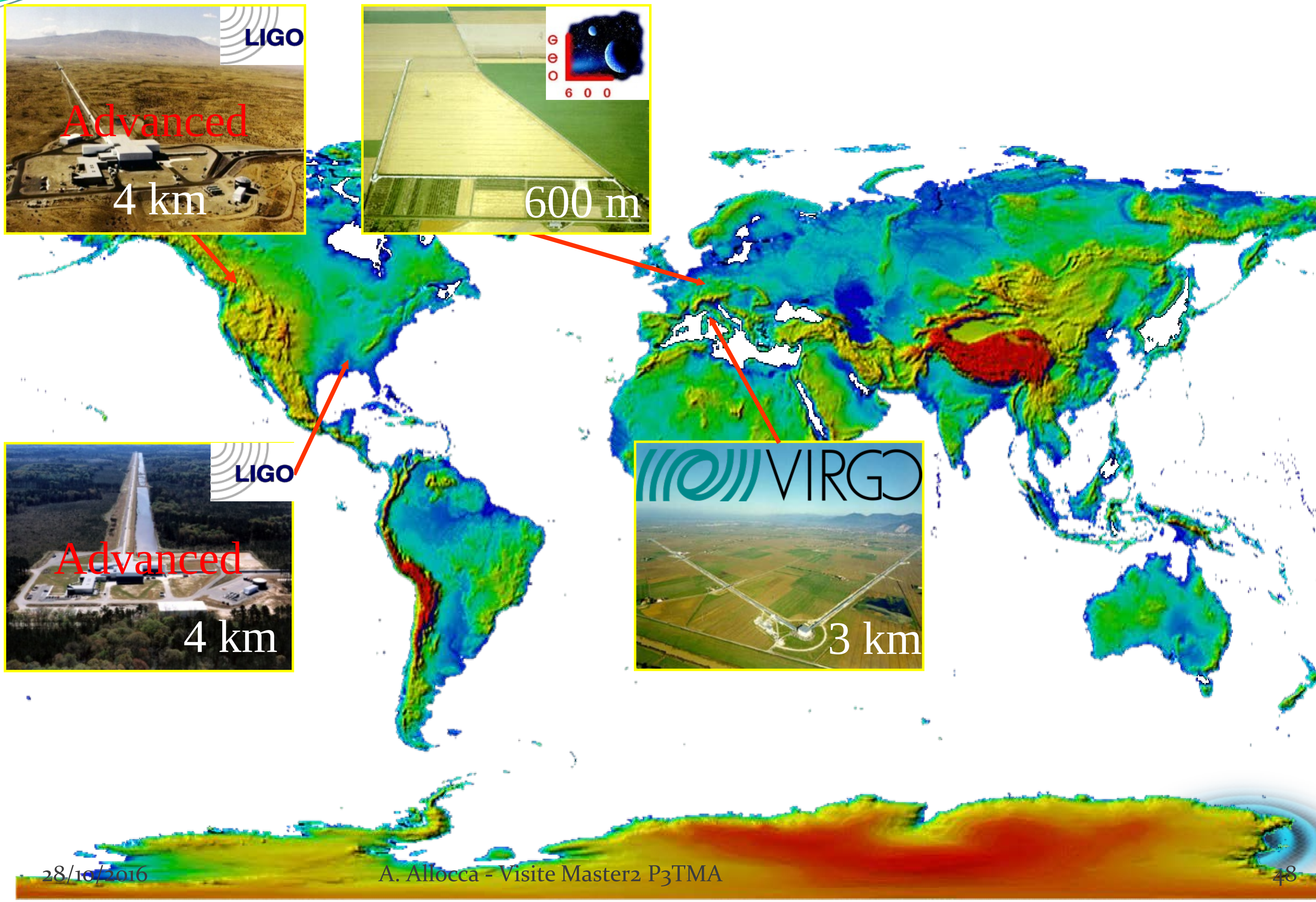
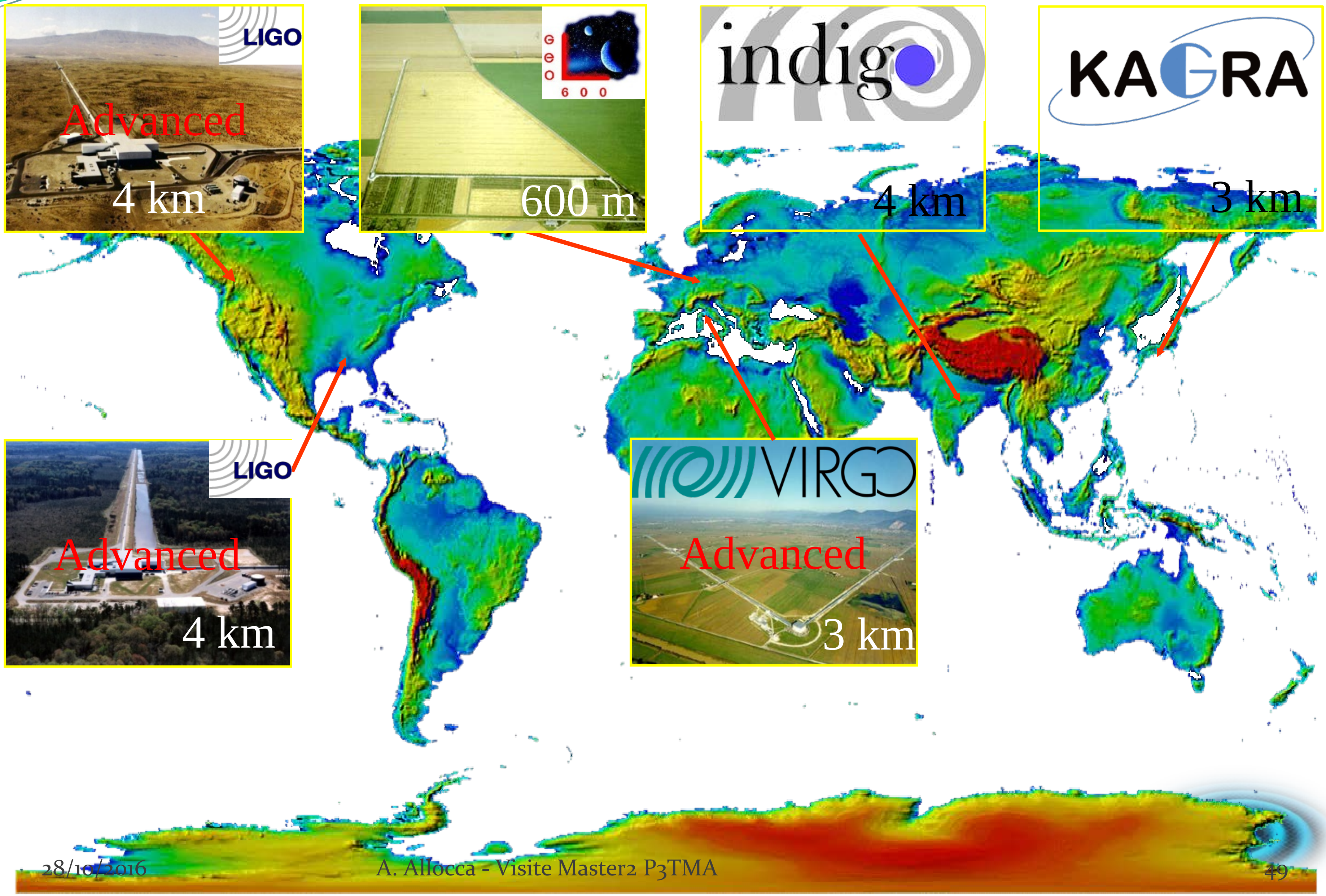
Competition & Collaboration (2015)



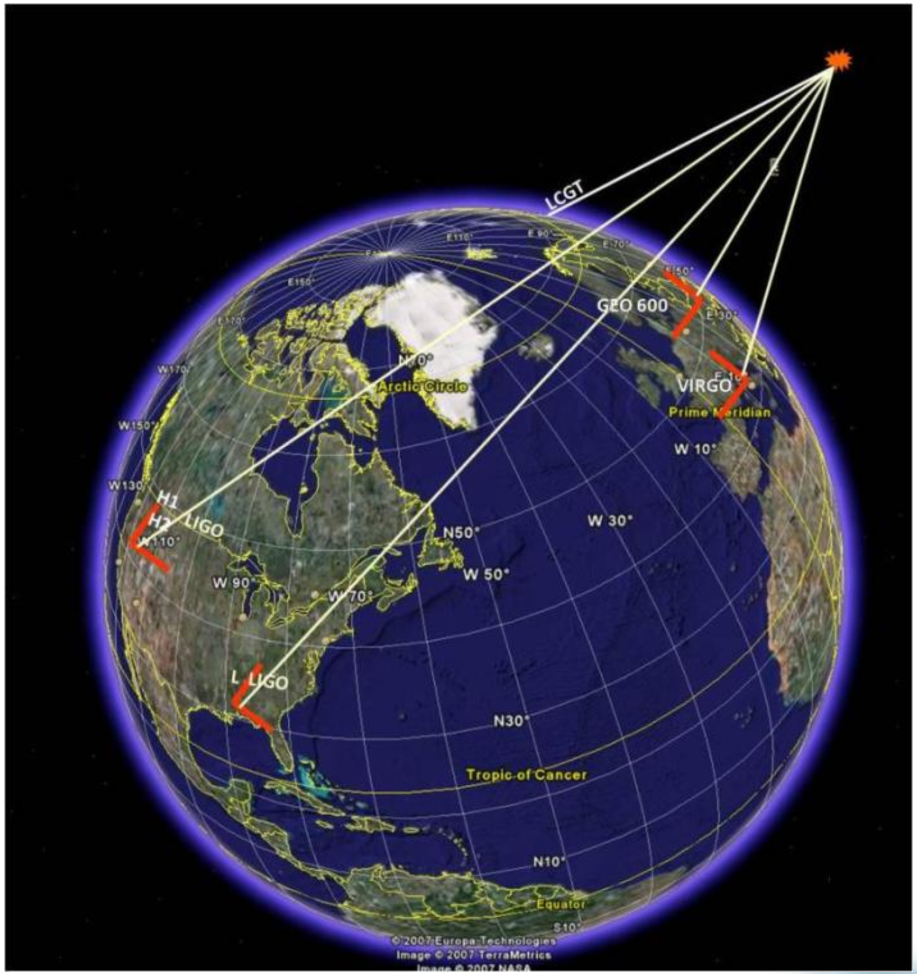
Competition & Collaboration (2015)



GW Detectors – The network

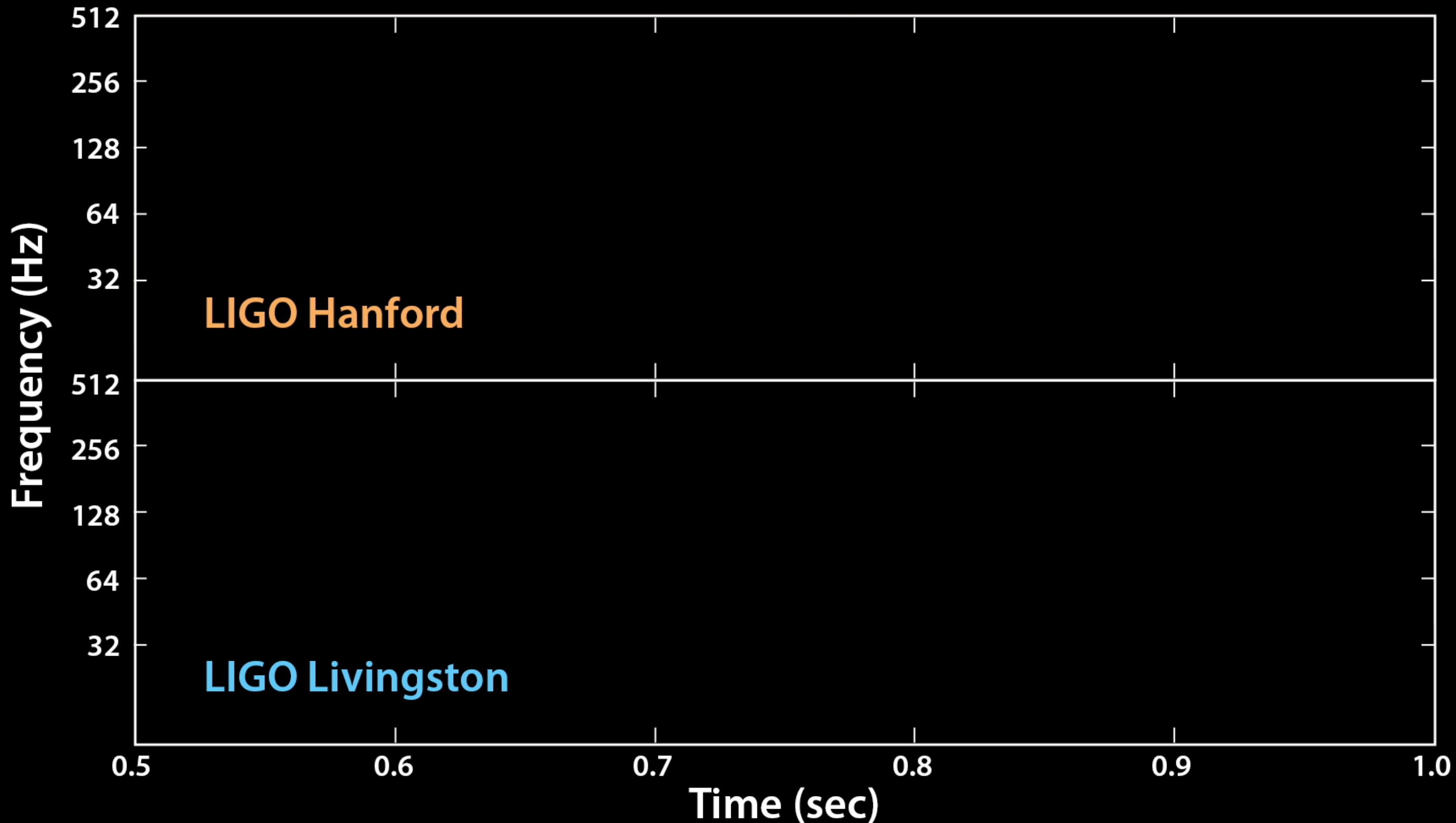
A world-wide effort…

- Identify GW source direction
- Increase statistic reliability by coincident detection



GW: a new era for astronomy

The whisper of the Universe



Thanks for your attention

Further reading

- Paper on the detection: LSC and VIRGO -Observation of Gravitational Waves from a Binary Black Hole Merger Phys. Rev. Lett. 116, 061102 (2016) - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102
- Companion papers: https://www.ligo.caltech.edu/page/detection-companion-papers
- Open data: https://losc.ligo.org/events/GW150914/
- On GW detection with interferometer:P. Saulson http://www.slac.stanford.edu/cgi-wrap/getdoc/ssi98-005.pdf
- On Advanced Virgo detector: The VIRGO collaboration - Advanced Virgo: a second-generation interferometric gravitational wave detector http://arxiv.org/pdf/1408.3978.pdf
- On aLIGO detectors: LSC – Advanced LIGO http://iopscience.iop.org/article/10.1088/0264-9381/32/7/074001/meta
- On close-future evolution of GW detectors:VIRGO, LSC - Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo http://relativity.livingreviews.org/Articles/lrr-2016-1/