Gravitational-Wave Interferometric Detectors

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Bologna, March 10th, 2016

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Present frame of GW detecors:

- LIGO: two 4km-arm interferometers, online after a 5-years long stop for upgrading to 2nd generation (http://www.ligo.org/)
- EGO-Virgo: one 3km-arm interferometer, stop operations in late 2011, planned to be back online during 2016 after upgrading to 2nd generation (http://public.virgo-gw.eu/language/en/)
- KAGRA: one 3km-arm interferometer, in construction (http://gwcenter.icrr.u-tokyo.ac.jp/en/)
- Indigo: one 4km-arm interferometer, approved, will use LIGO hardware (http://gw-indigo.org/tiki-index.php?page=LIGO-India)

Warning

- This will be a “Virgo-centric” talk, but only because Virgo is the machine I know better

- Virgo and LIGO technologies are very similar in principle, they only differ somewhat in implementations

- Virgo and LIGO collaborations share data and information since 2004

Outline

EGO - VIRGO

- 14 Sep 2015: a new Era in Astronomy!
- The challenge
- A century-old ruler: Michelson interferometer
- Meet the villain: Noise!
- [Spoiler] We did it!

New Era in Astronomy!

14 Sep 2015: First detection of Gravitational Waves!

229,000 paper downloads from APS in the first 24 hours, servers down!

PHYSICAL REVIEW LETTERS

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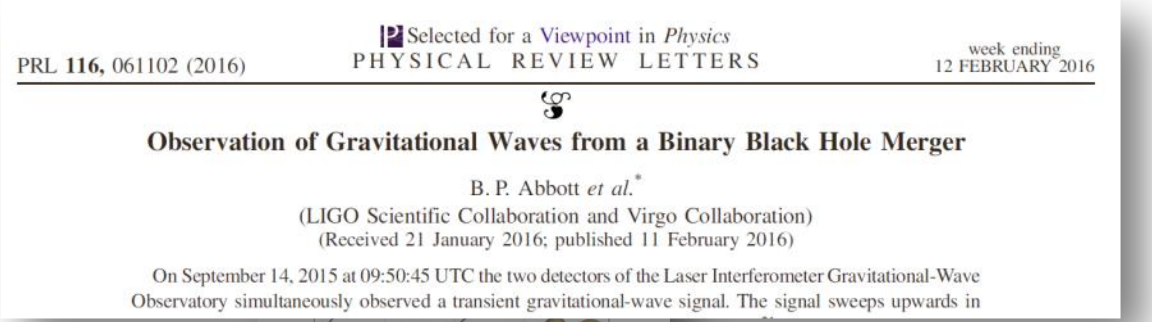


Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

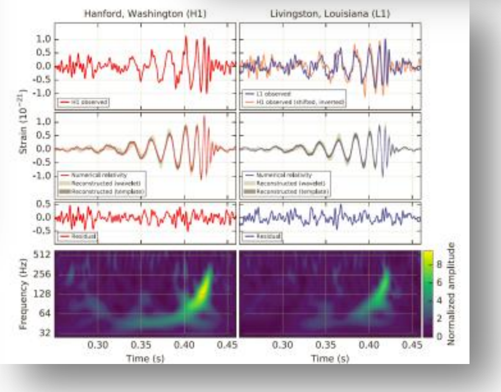
Observation of Gravitational Waves from a Binary Black Hole Merger

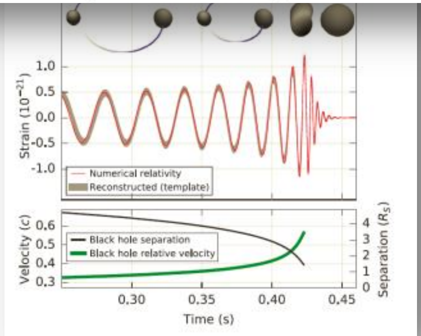
B. P. Abbott *et al.*[*]

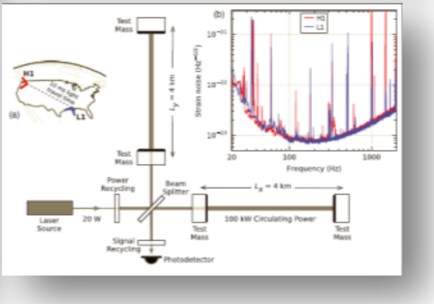
(LIGO Scientific Collaboration and Virgo Collaboration)

(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







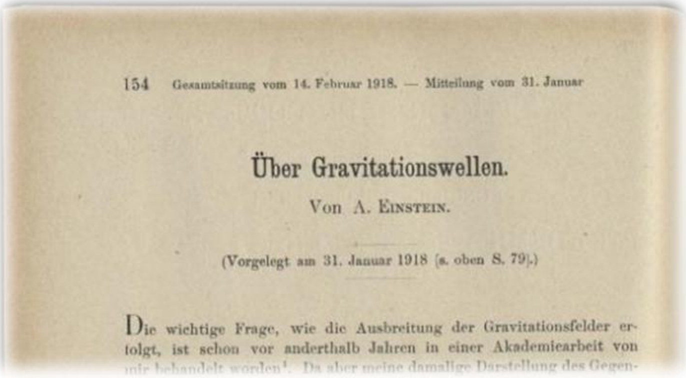
Signal detected by aLIGO interferometers

New Era in Astronomy!

Much ado, about what?

Let's go back in time 100 years ago…

Gravitational Waves



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

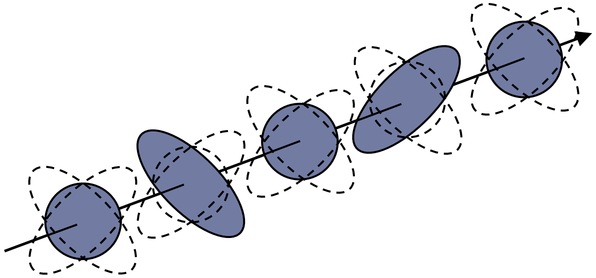
Über Gravitationswellen.

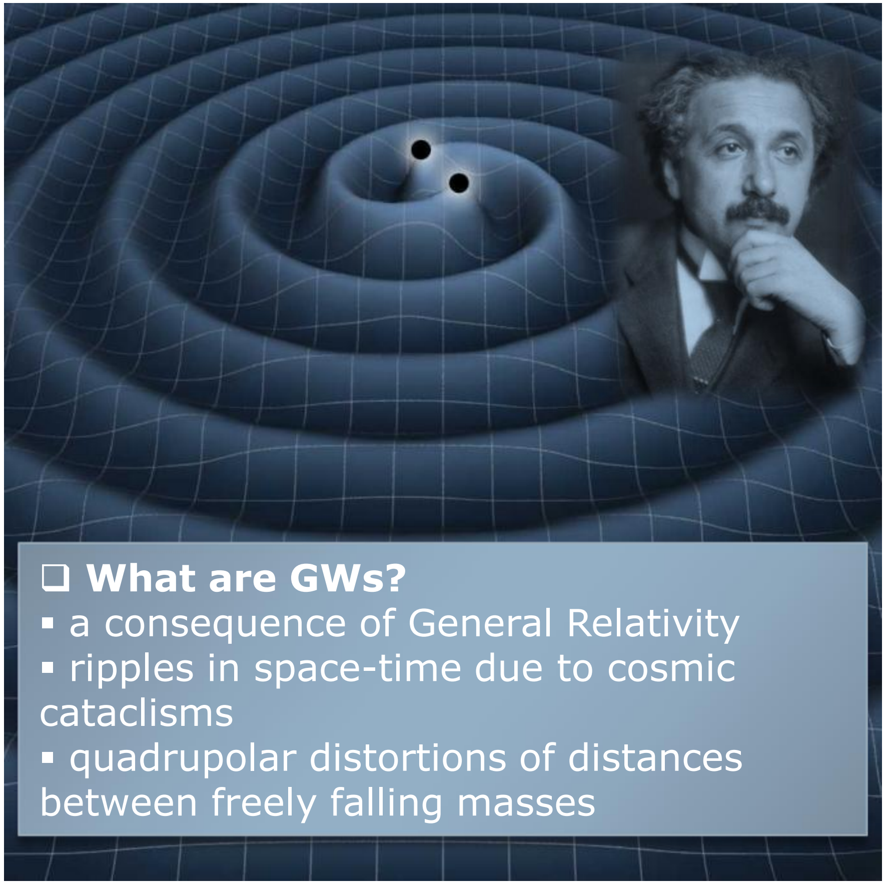
Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegen-

… when Einstein firstly predicted the gravitational waves

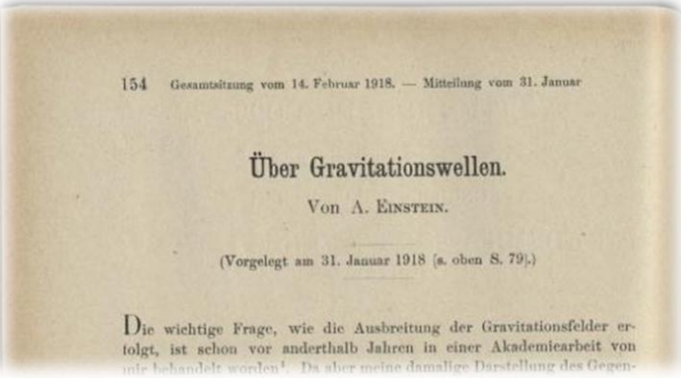




❑ **What are GWs?**
- a consequence of General Relativity
- ripples in space-time due to cosmic cataclisms
- quadrupolar distortions of distances between freely falling masses

Tiny interaction with matter:
- Extremely difficult to detect
- Ideal messengers from remote space-time regions
- *Can bring a whole new view of the Universe*

Gravitational Waves (digression)



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… when Einstein firstly predicted the gravitational waves

And then changed his mind
And then again…

1916 – First paper about GW (with mistake)
1918 – First paper about GW with quadrupole formula
1937a – Doubt about GW existence, fought with Physical Review
1937b - Eventually got convinced, exact solutions for GW

Bottom line: if it took 20 years for Einstein…

You are not the only one to get confused by GWs!

EGO - VIRGO

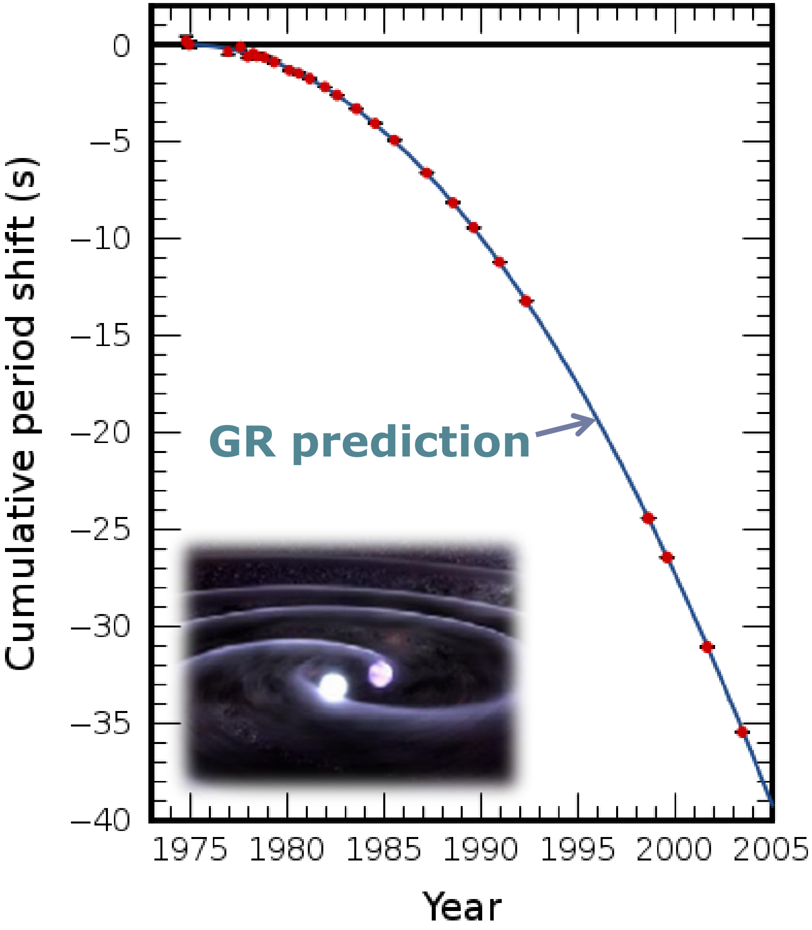
How did we know GWs exist?

Indeed…

The Nobel Prize in Physics 1993
Russell A. Hulse, Joseph H. Taylor Jr.

Ok, but how to *directly* detect it?

Binary Pulsar 1913+16



J. M. Weisberg, J. H. Taylor,
http://arxiv.org/abs/astro-ph/0407149

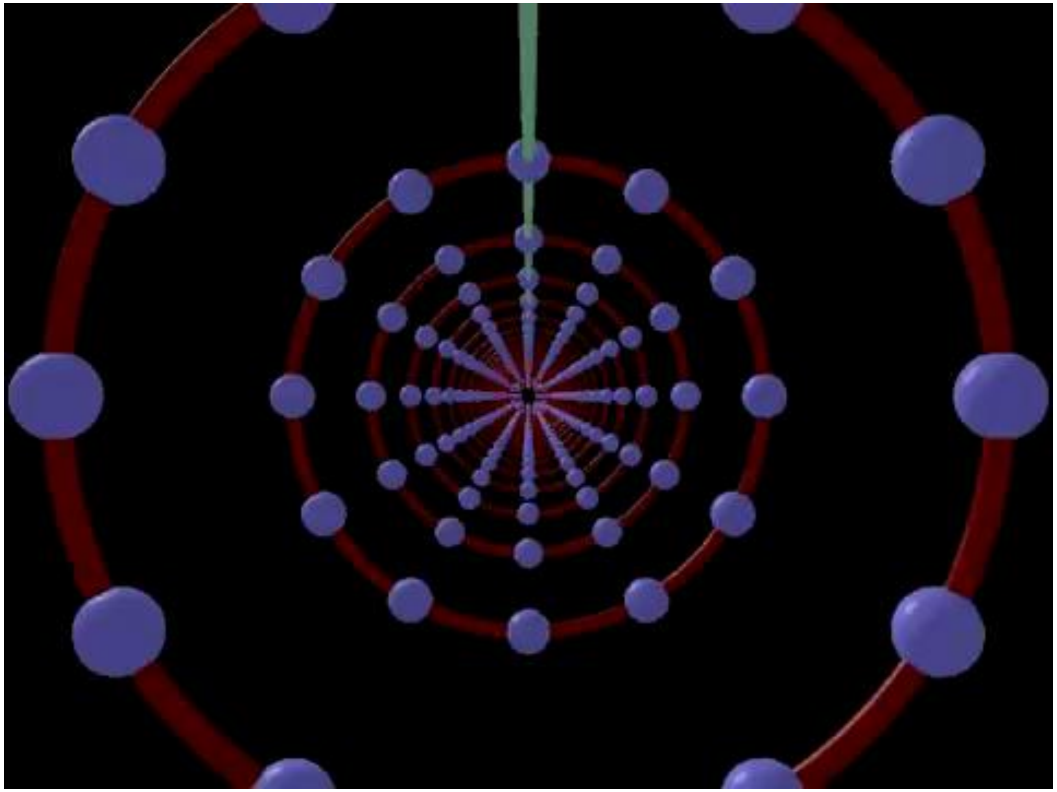
Gravitational Waves

☐ Effect of GWs:

Squeeze and stretch the space in perpendicular directions:
strain ***h*** **= ΔL/L**

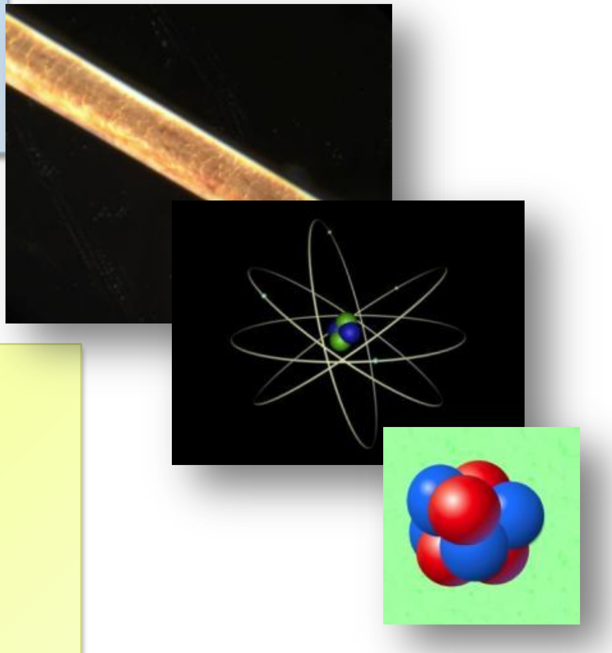
☐ What is the plausible "strain"?

Even for the most tremendous events in Universe, ***h~10^-21***



The challenge

With h = ΔL/L ~10^-21,
- even with test masses L~km far apart,
- displacement is ΔL~10^-18m



Reminder:
- Diameter of human hair: 10^-5 m
- Diameter of atom: 10^-10 m
- Diameter of atomic nucleus: 10^-14 m
- Diameter of proton: 10^-15 m

ΔL~10^-18m looks rather small

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 small is "small"?

Ocean surface:

70% x 4pi x R_earth^2 =
0.7 x 4 x 3.14 x (6.37e6 m)^2
~ 3.6e14m^2

Glass volume:

~ 0.25e-3 m^3

Ocean rise:

delta_h~ V_glass/Ocean surface
~ **1e-18m**

This is the kind of displacement we need to detect

We need a (good) ruler

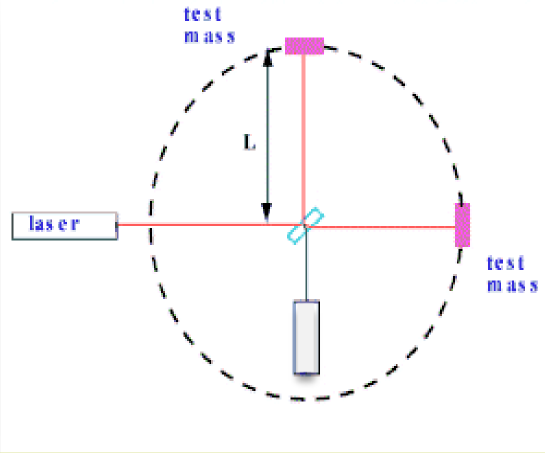
- ☐ How to detect strain?

Joseph Weber c. 1965

- measure oscillations in mechanical resonators

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

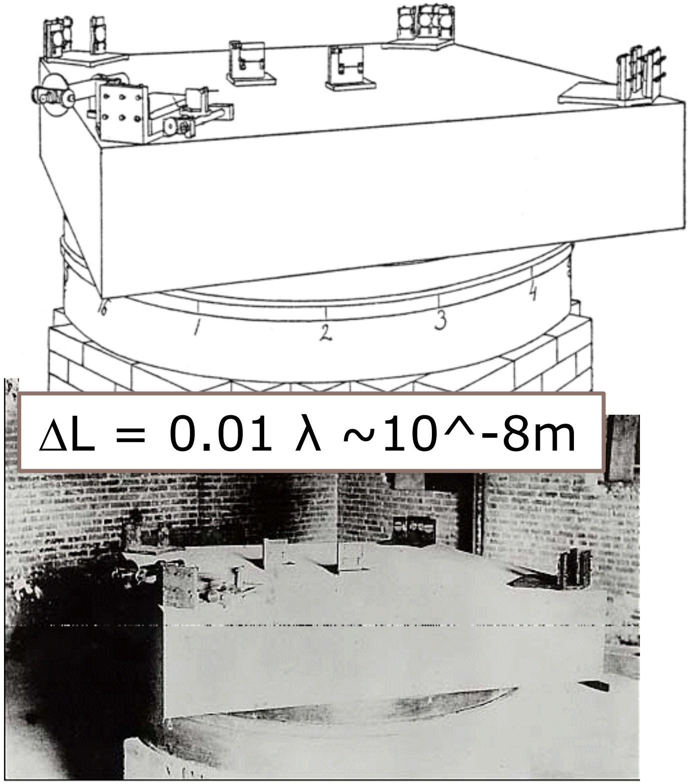
Michelson interferometer



- measure distances between free masses

A century-old ruler

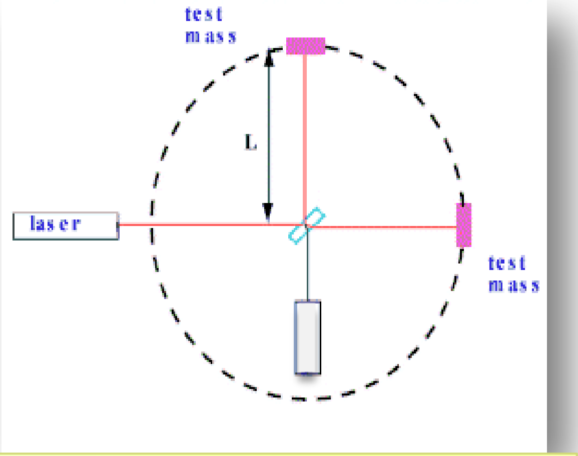
- How to detect strain?



ΔL = 0.01 λ ~10^-8m

Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive

Michelson interferometer



- measure distances between free masses

A century-old ruler

❑ How does it work?

-Michelson adjusted so that no light comes out from anti-symmetric port

- GW stretches and squeezes the two arms alternatively

- Wavefront takes longer to go back and forth in one of the arm than in the other

- Interference at anti-symmetric port is no longer completely distructive, and light reaches the photodetector: a signal!

A century-old ruler

- How does it work?

Credits: Marco Kraan - Nikhef

A century-old ruler, reloaded

How to improve sensitivity?

- Very long arms
To get a larger displacement

- Fabry-Perot cavity in each arm
To increase phase change

- Recycle injected power
To increase input power

- Recycle outgoing signal
To amplify the output

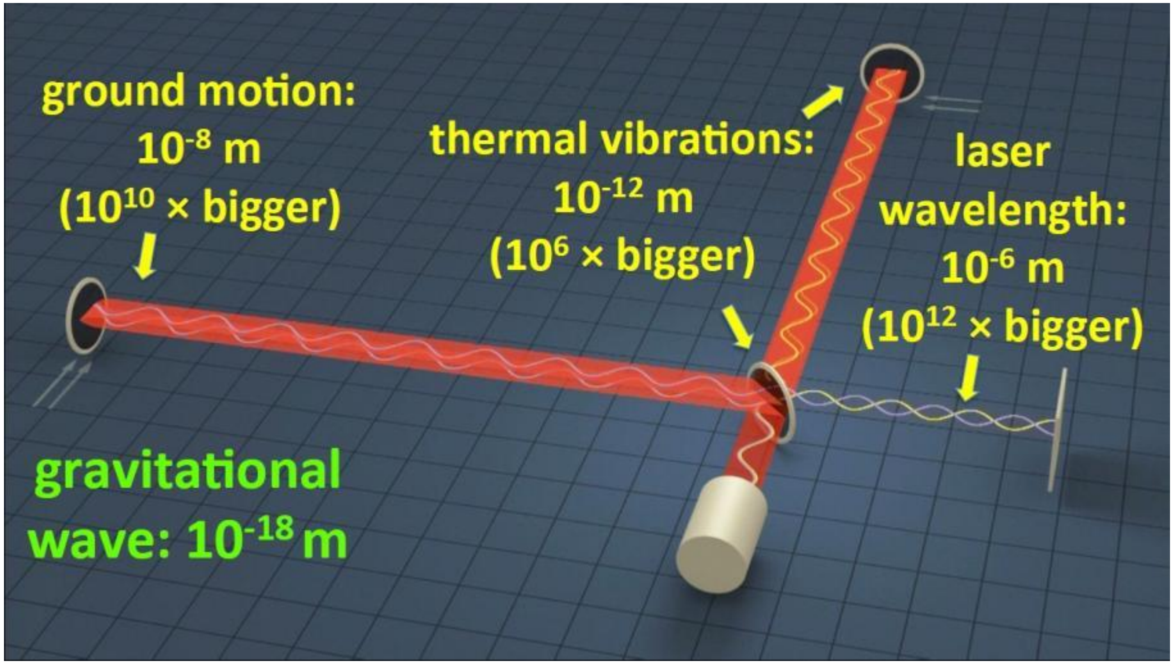
A century-old ruler, reloaded

How to improve sensitivity?

Credits: Marco Kraan - Nikhef

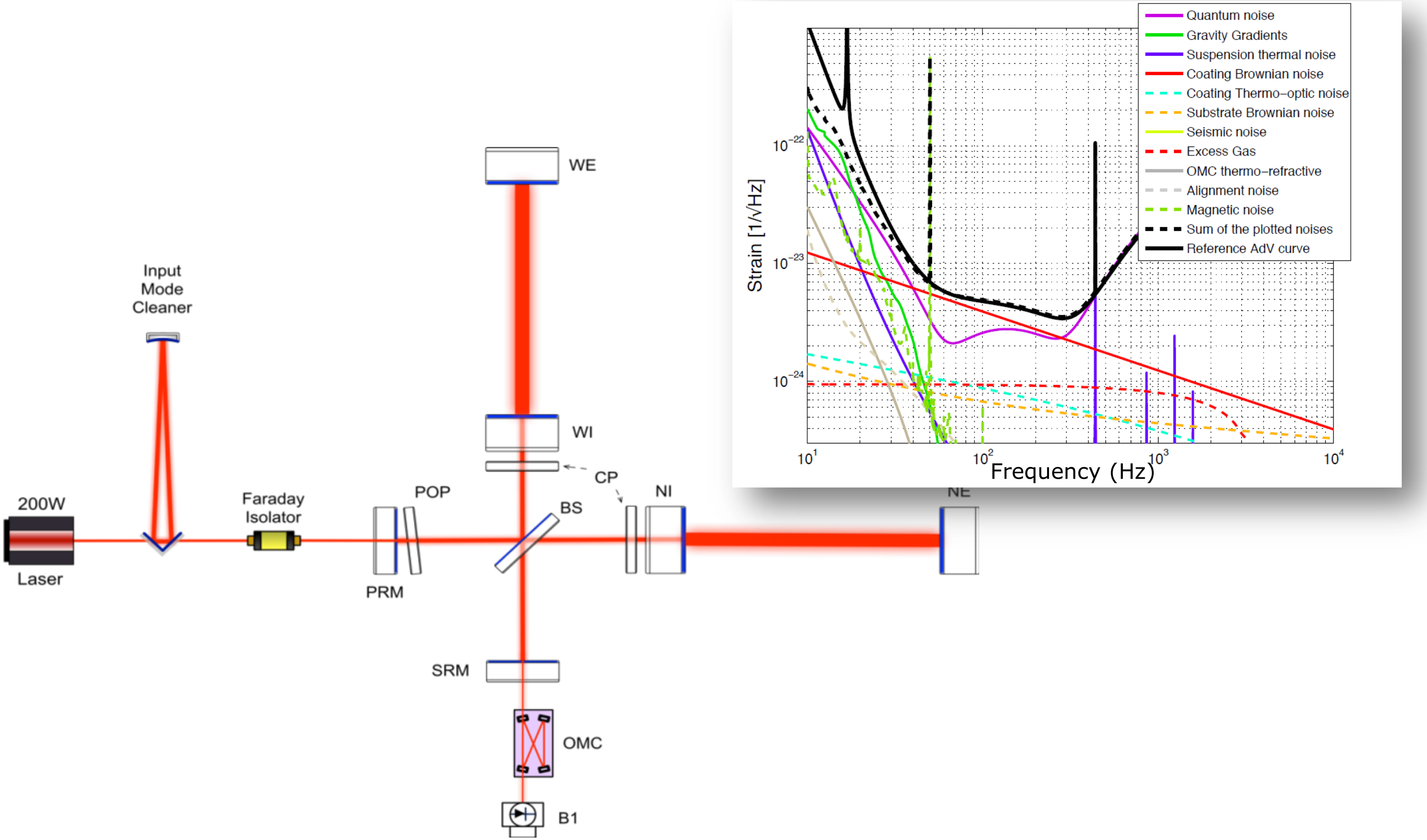
Meet the Villain: Noise!

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

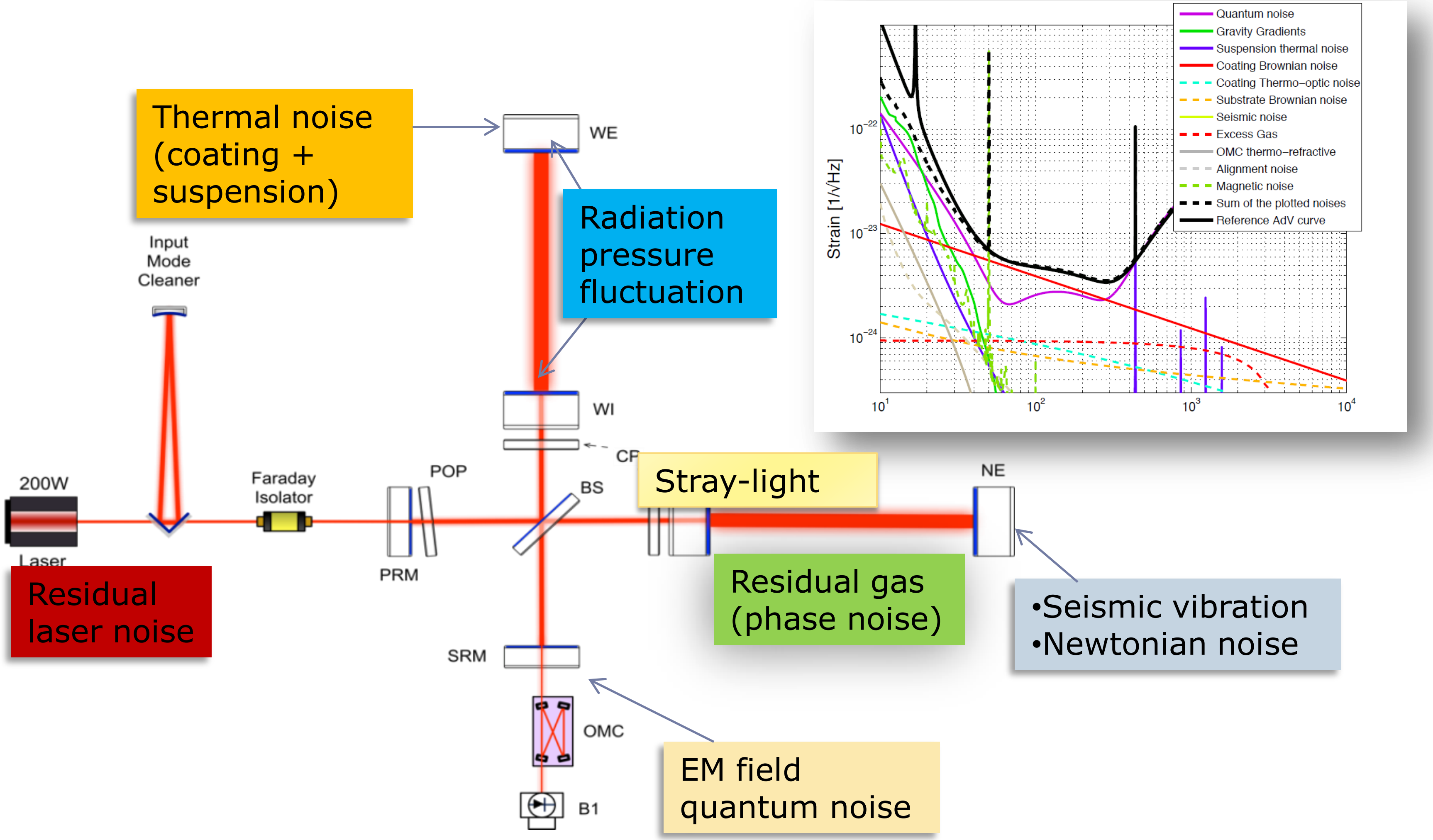


Credits: Stephen Fairhurst

Meet the Villain: Noise!



GW Detectors - Noise



Thermal noise (coating + suspension)

Radiation pressure fluctuation

Stray-light

Residual laser noise

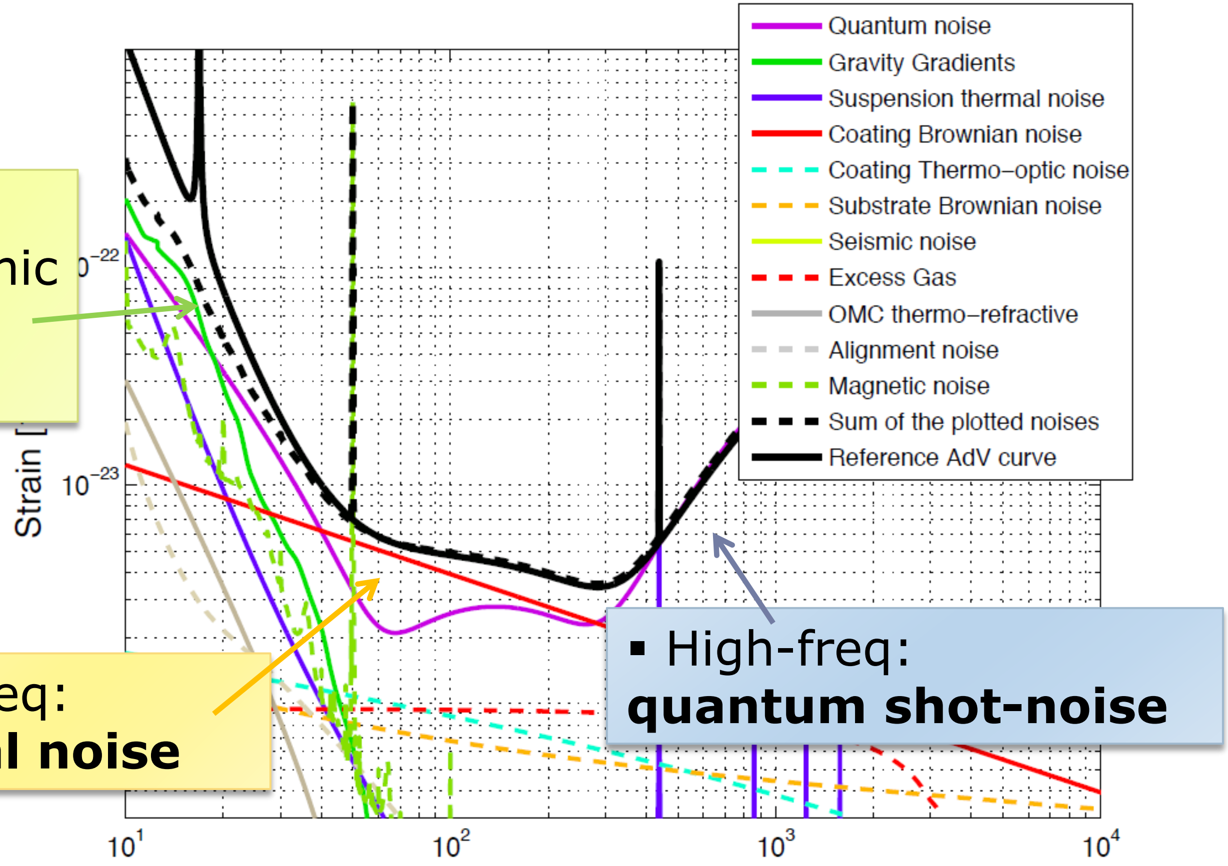
Residual gas (phase noise)

- Seismic vibration
- Newtonian noise

EM field quantum noise

GW Detectors - Noise

Limiting noises at different frequency ranges:



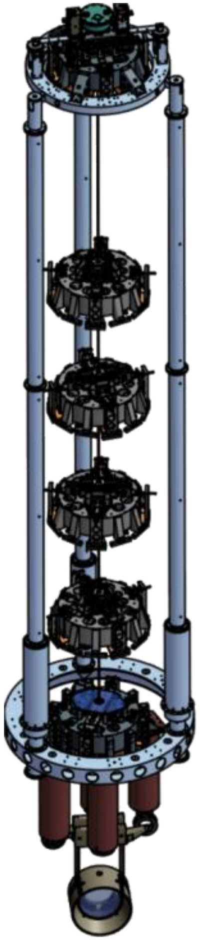
- Low-freq: **newtonian noise**, seismic noise, residual technical noises

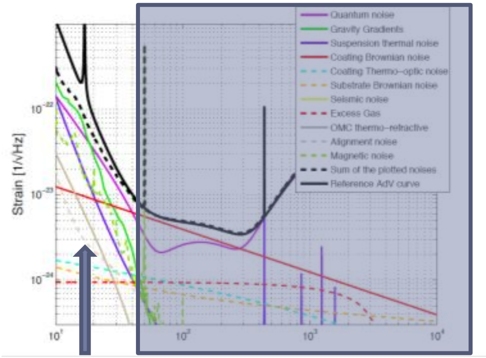
- Mid-freq: **thermal noise**

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

Coping with Noise

- Low frequency range:
  - Dominated by *seismic noise*
  - Managed by suspending the mirrors from extreme vibration isolators (attenuation > 10^12)
  - Technical noises of different nature are the real challenge in this range
  - Ultimate limit for ground-based detectors: *gravity gradient noise*





Coping with Noise

Seismic noise

Credits: Marco Kraan - Nikhef

Coping with Noise

Gas pressure noise: UHV environment with pressure ~10^-9mbar

Credits: Marco Kraan - Nikhef

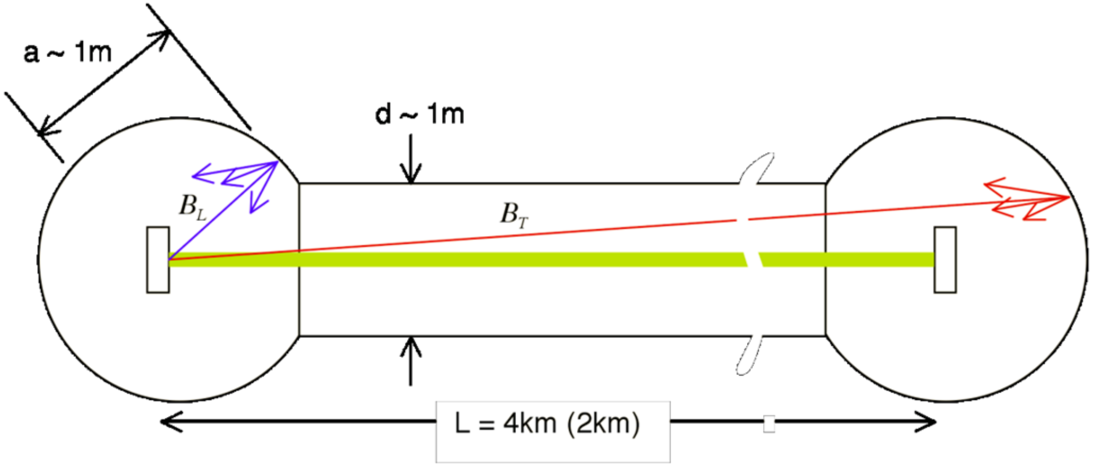
Coping with Noise

Gas pressure noise: UHV environment with pressure ~10^-9mbar

Coping with Noise

EGO - VIRGO

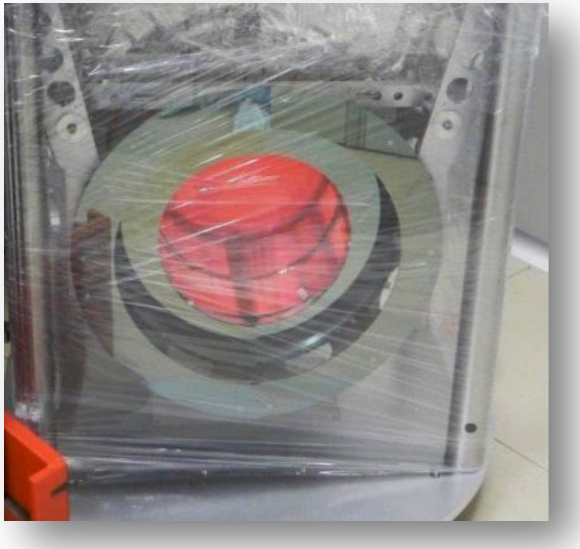
- Stray-light mitigation:
  - Learned form 1st generation: back-scattered light is one of the major risks towards the final sensitivity goal
  - Light scattered off suspended mirror can probe vibrations of ground-connected mechanical structures and then recombine with main beam: this would bury any GW signal!

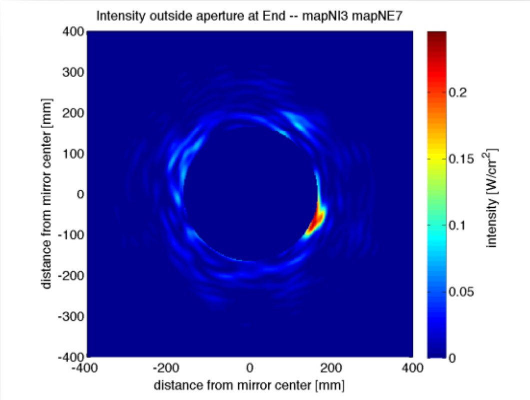


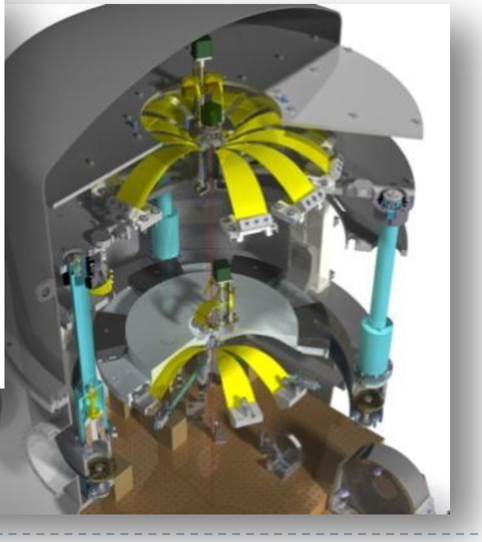
Less than 5 photons per second allowed to recombine after scattering

Coping with Noise

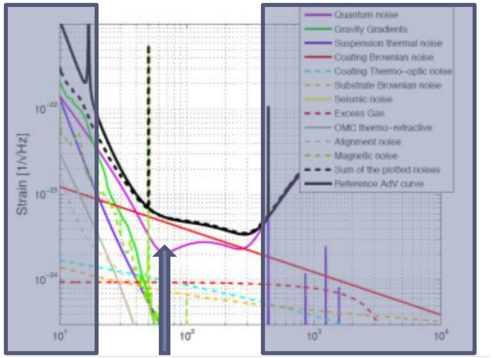
- Stray-light mitigation:
  - Learned form 1st generation: scattered light is one of the major risks towards the final sensitivity goal
  - Large investment to mitigate it:
    - Better optics quality
    - Baffles to shield mirrors, pipes, vacuum chambers exposed to scattered light
    - Photodiodes suspended in vacuum to isolate them from acoustic/seismic noise
    - If required, control the position of the benches wrt the interferometer
    - Significant simulation effort



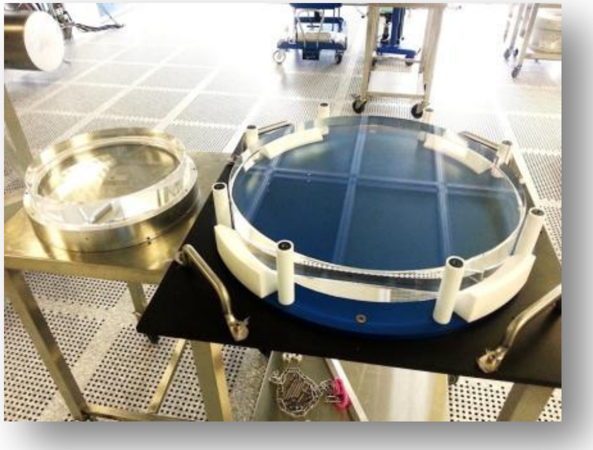


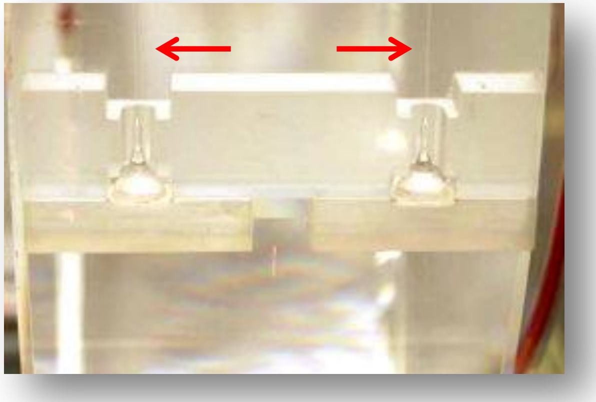


Coping with Noise

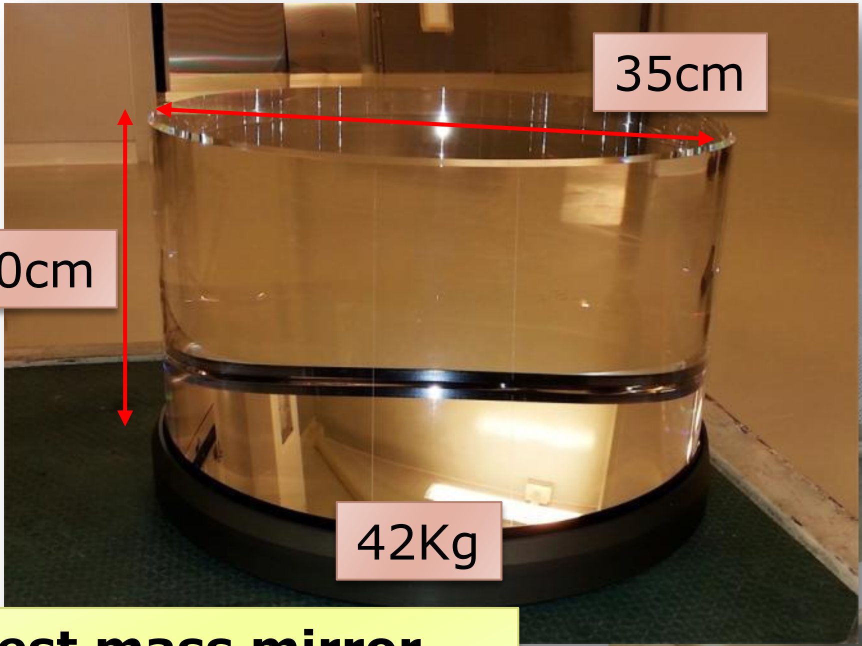


- Mid frequency range:
  - Dominated by thermal noise of mirror coatings and suspensions
- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses

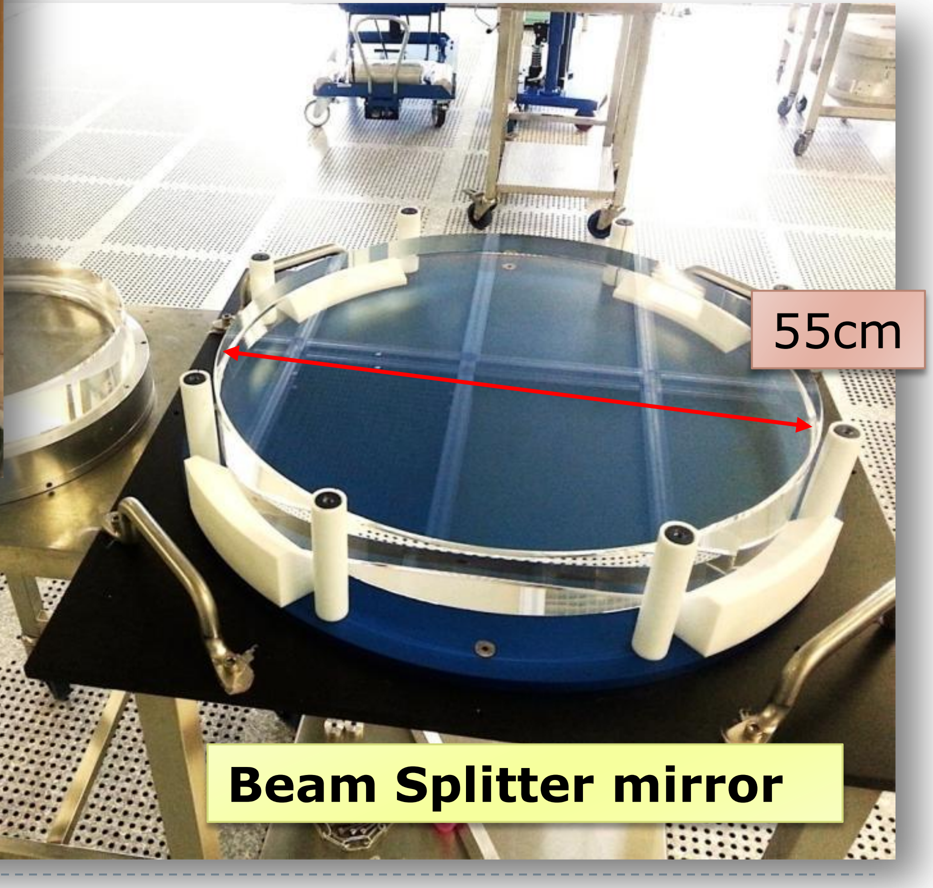




Mirrors

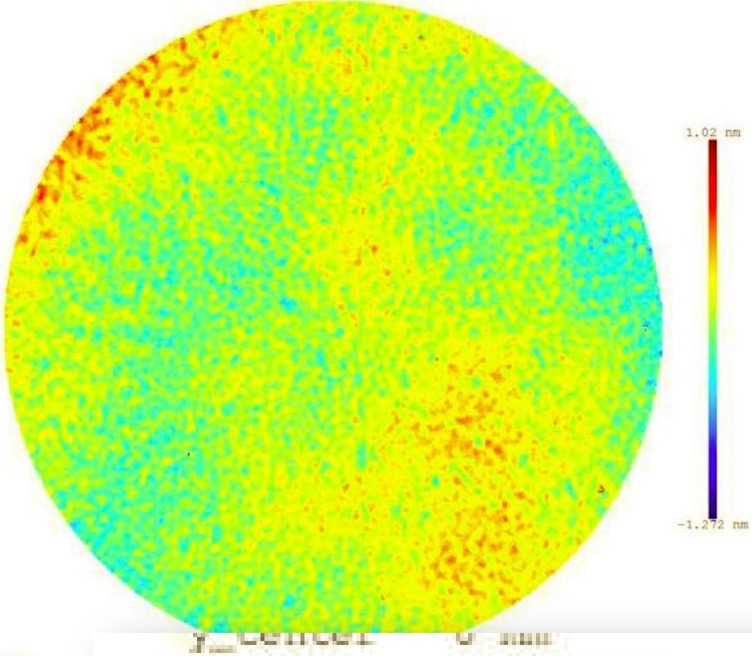


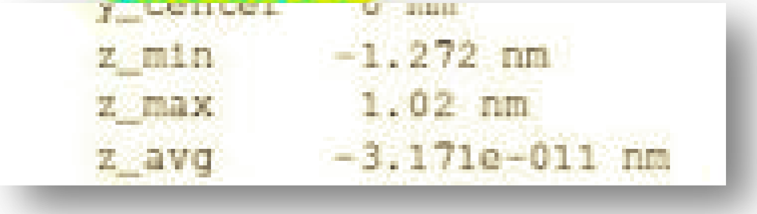
Test mass mirror



Beam Splitter mirror

Mirrors

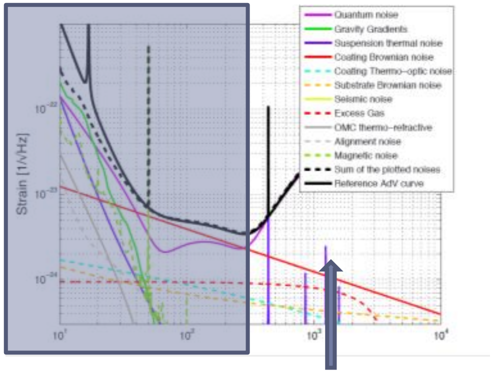




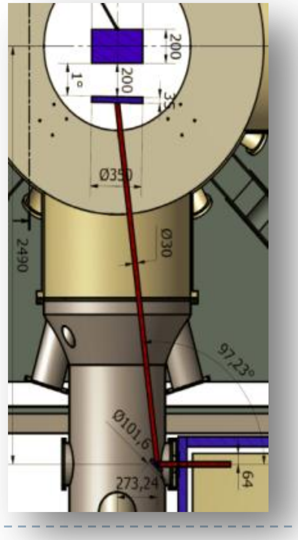
z_min	-1.272 nm
z_max	1.02 nm
z_avg	-3.171e-011 nm

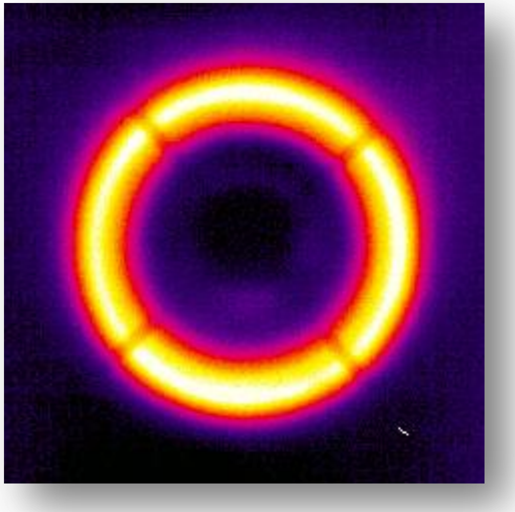
The surface figure of the polished test masses is such that with a mirror as large as Emilia-Romagna, ***highest mountains would be 1mm***

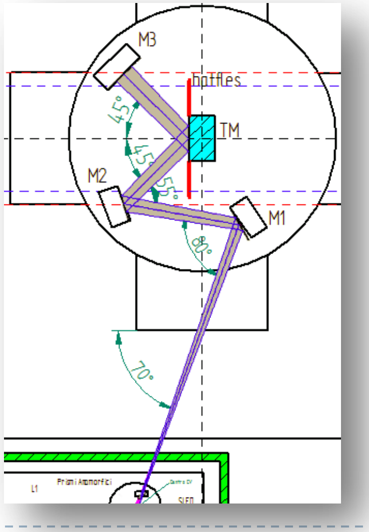
Coping with Noise

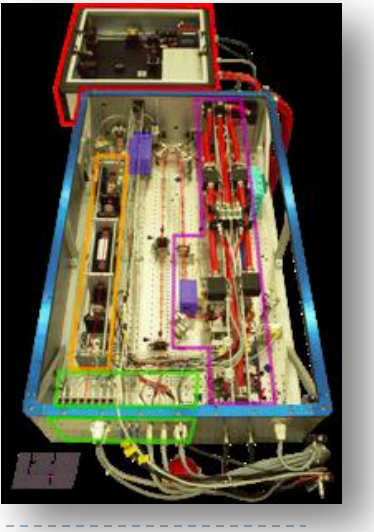


- High frequency range:
  - Dominated by laser shot noise. Improved by increasing the power: ***>100W input***, ~1 MW in the cavities
- Requires:
  - New laser amplifiers (solid state, fiber)
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations



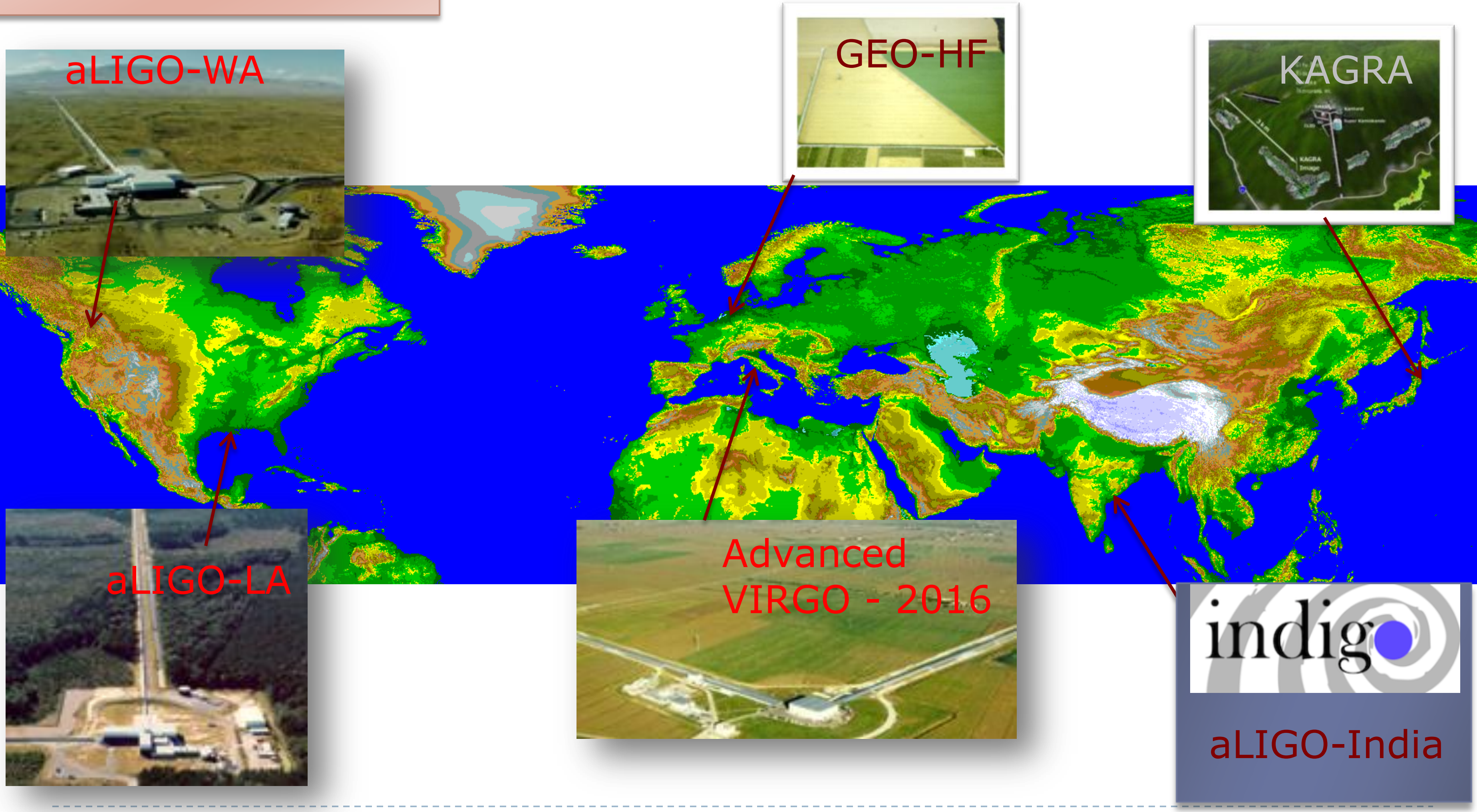






GW Detectors – The network

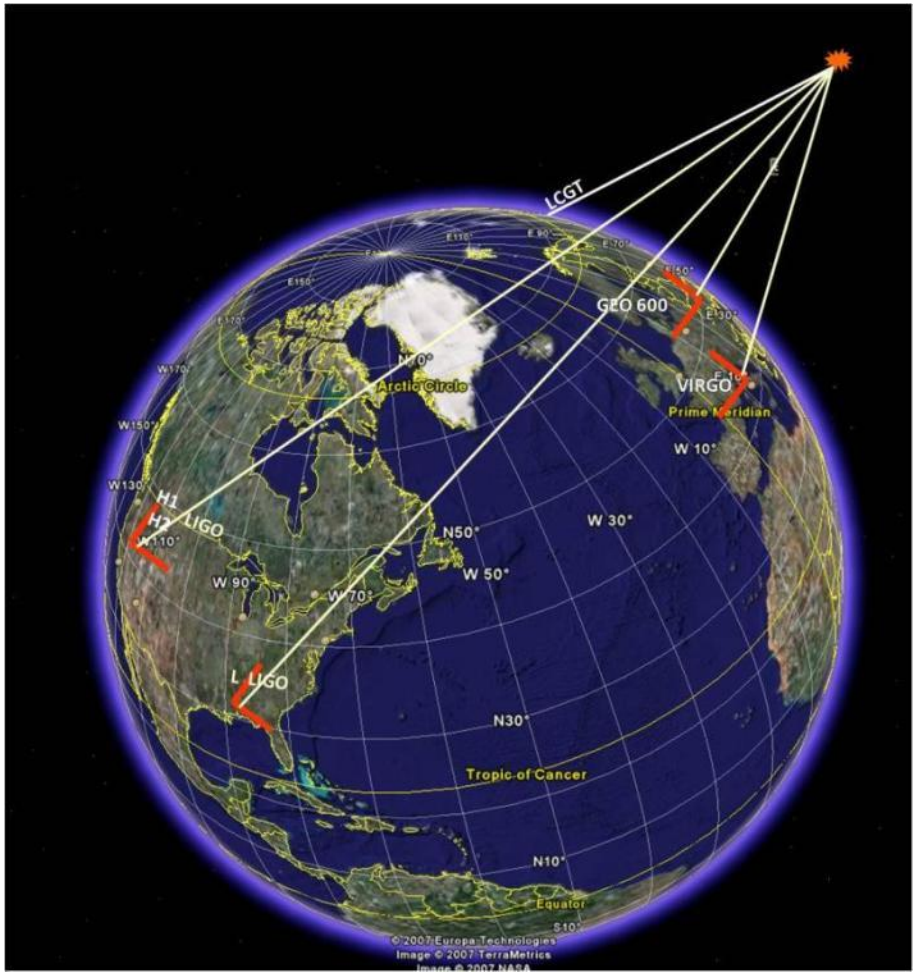
A world-wide effort...



GW Detectors – The network

A world-wide effort...

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

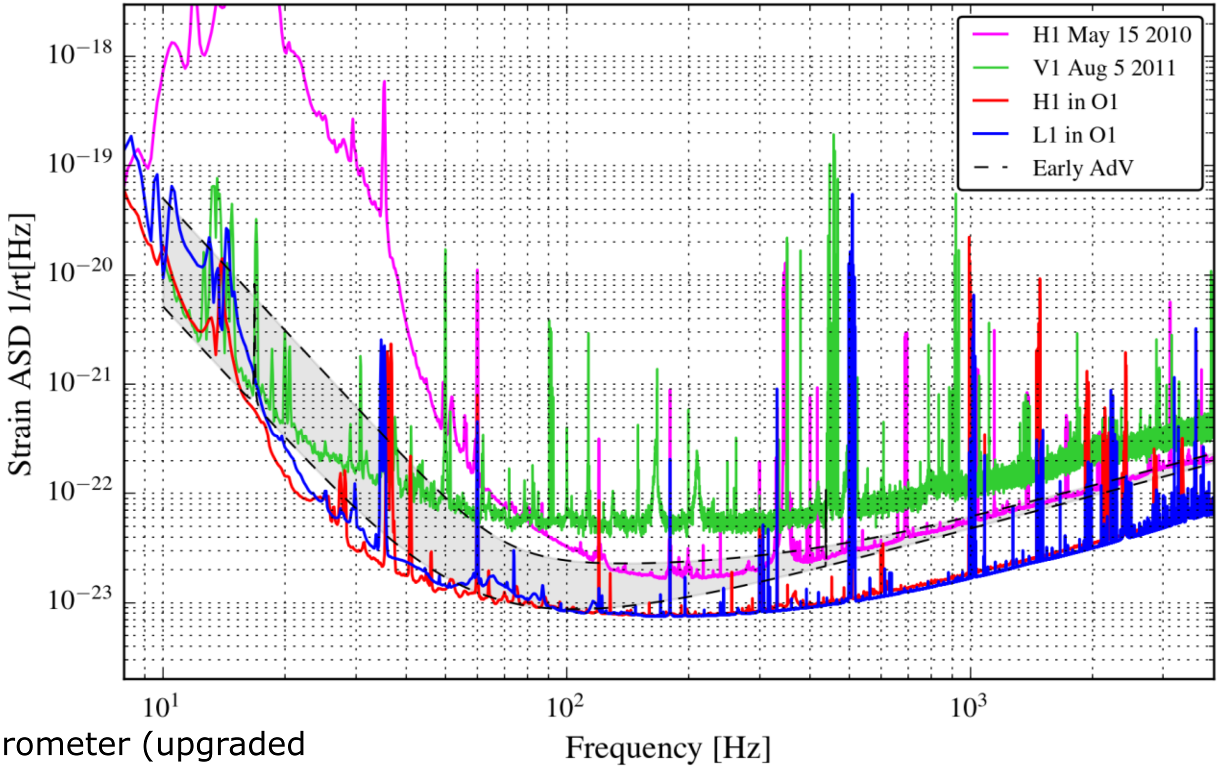


© 2007 Europa Technologies
Image © 2007 TerraMetrics
Image © 2007 NASA

GW Detectors - Strain

EGO - VIRGO

Comparison of actually measured residual strain noise



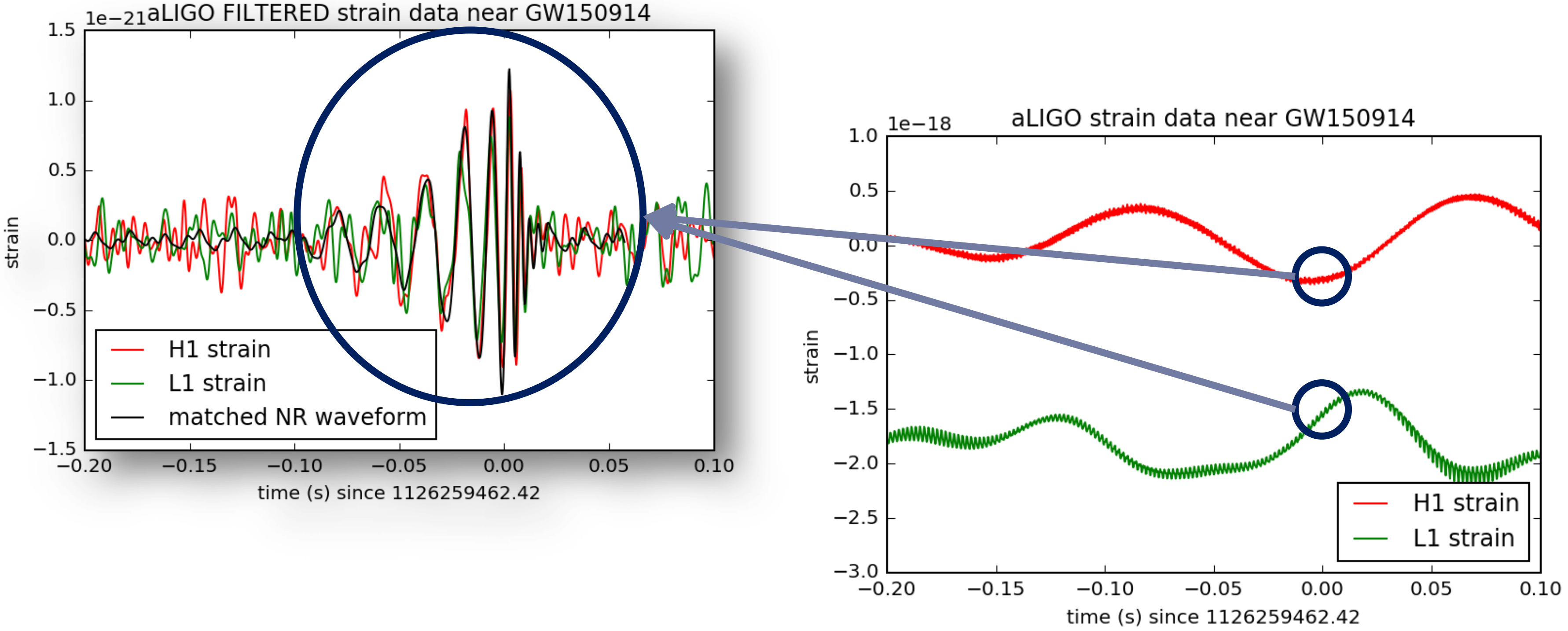
- H1, L1 are the two LIGO interferometer (upgraded to aLIGO)
- V1 is the Virgo interferometer before upgrading
- AdV: Advanced Virgo is the interferometer that will be online by the end of 2016

Credits: Daniel Hoak - aLIGO

Not the end of the story…

Despite all the efforts, signal still buried in noise.
How do you extract the signal from noise?

Elena Cuoco has got an answer for you...

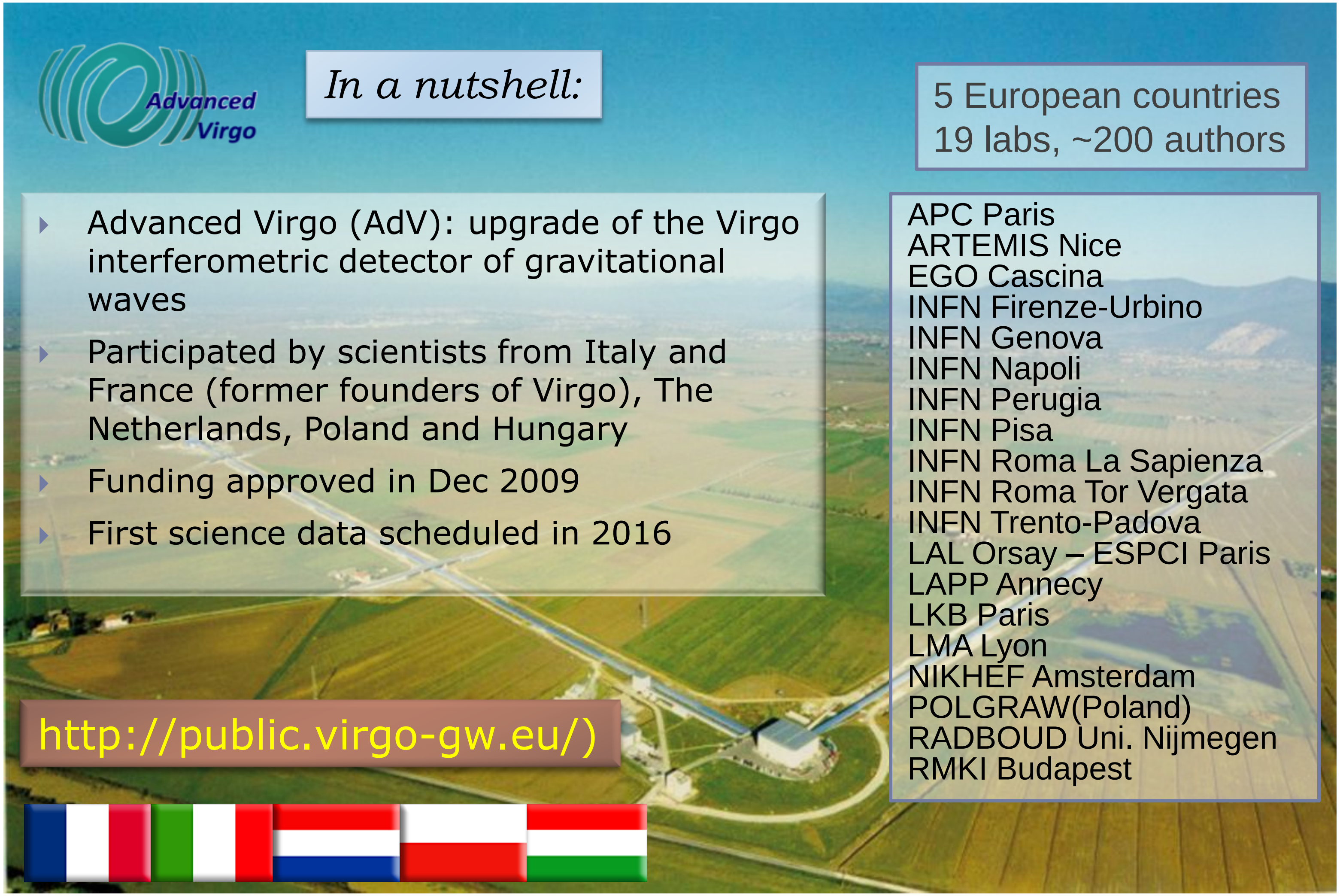


Advanced Virgo

EGO - VIRGO

http://public.virgo-gw.eu/language/en/

Advanced Virgo



In a nutshell:

- 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
- First science data scheduled in 2016

http://public.virgo-gw.eu/)

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

Thank you

The European Gravitational Observatory is a consortium of:

INFN
Istituto Nazionale di Fisica Nucleare

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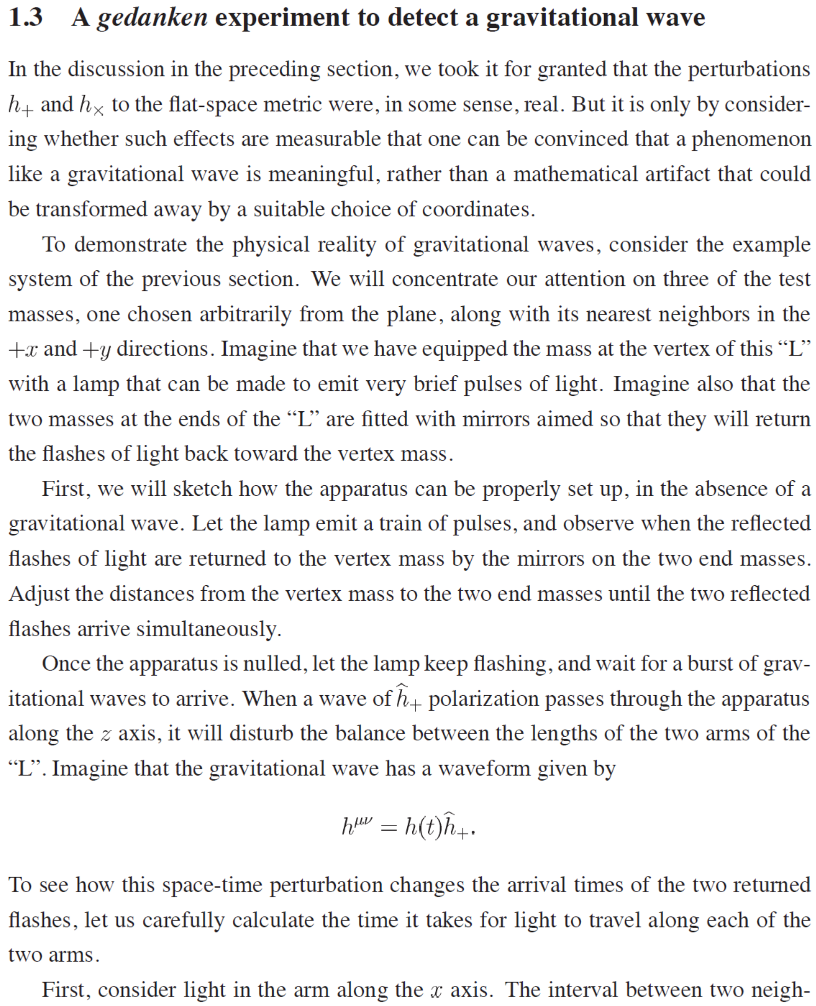
Extra-slides, effect of GW on interferometer

EGO - VIRGO



1.3 A *gedanken* experiment to detect a gravitational wave

In the discussion in the preceding section, we took it for granted that the perturbations h_+ and $h_\times$ to the flat-space metric were, in some sense, real. But it is only by considering whether such effects are measurable that one can be convinced that a phenomenon like a gravitational wave is meaningful, rather than a mathematical artifact that could be transformed away by a suitable choice of coordinates.

To demonstrate the physical reality of gravitational waves, consider the example system of the previous section. We will concentrate our attention on three of the test masses, one chosen arbitrarily from the plane, along with its nearest neighbors in the $+x$ and $+y$ directions. Imagine that we have equipped the mass at the vertex of this "L" with a lamp that can be made to emit very brief pulses of light. Imagine also that the two masses at the ends of the "L" are fitted with mirrors aimed so that they will return the flashes of light back toward the vertex mass.

First, we will sketch how the apparatus can be properly set up, in the absence of a gravitational wave. Let the lamp emit a train of pulses, and observe when the reflected flashes of light are returned to the vertex mass by the mirrors on the two end masses. Adjust the distances from the vertex mass to the two end masses until the two reflected flashes arrive simultaneously.

Once the apparatus is nulled, let the lamp keep flashing, and wait for a burst of gravitational waves to arrive. When a wave of $\hat{h}_+$ polarization passes through the apparatus along the z axis, it will disturb the balance between the lengths of the two arms of the "L". Imagine that the gravitational wave has a waveform given by

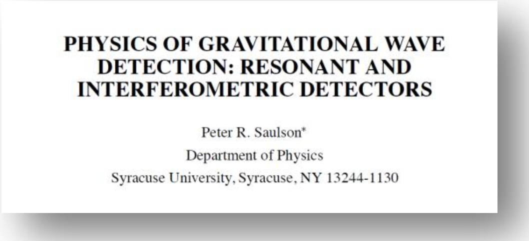
$$h^{\mu\nu} = h(t)\hat{h}_+.$$

To see how this space-time perturbation changes the arrival times of the two returned flashes, let us carefully calculate the time it takes for light to travel along each of the two arms.

First, consider light in the arm along the x axis. The interval between two neigh-

Taken from:

http://www.slac.stanford.edu/cgi-wrap/getdoc/ssi98-005.pdf



PHYSICS OF GRAVITATIONAL WAVE DETECTION: RESONANT AND INTERFEROMETRIC DETECTORS

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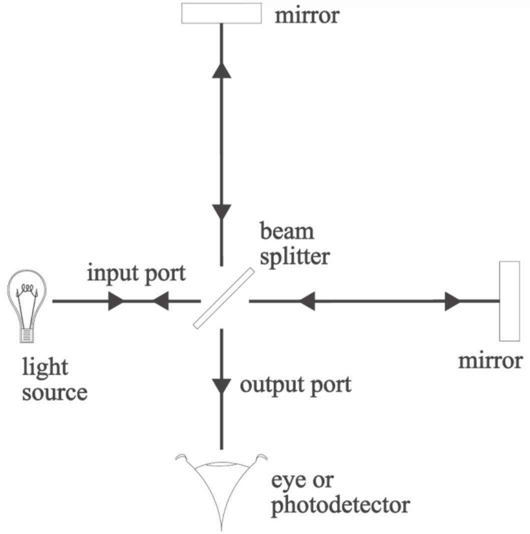
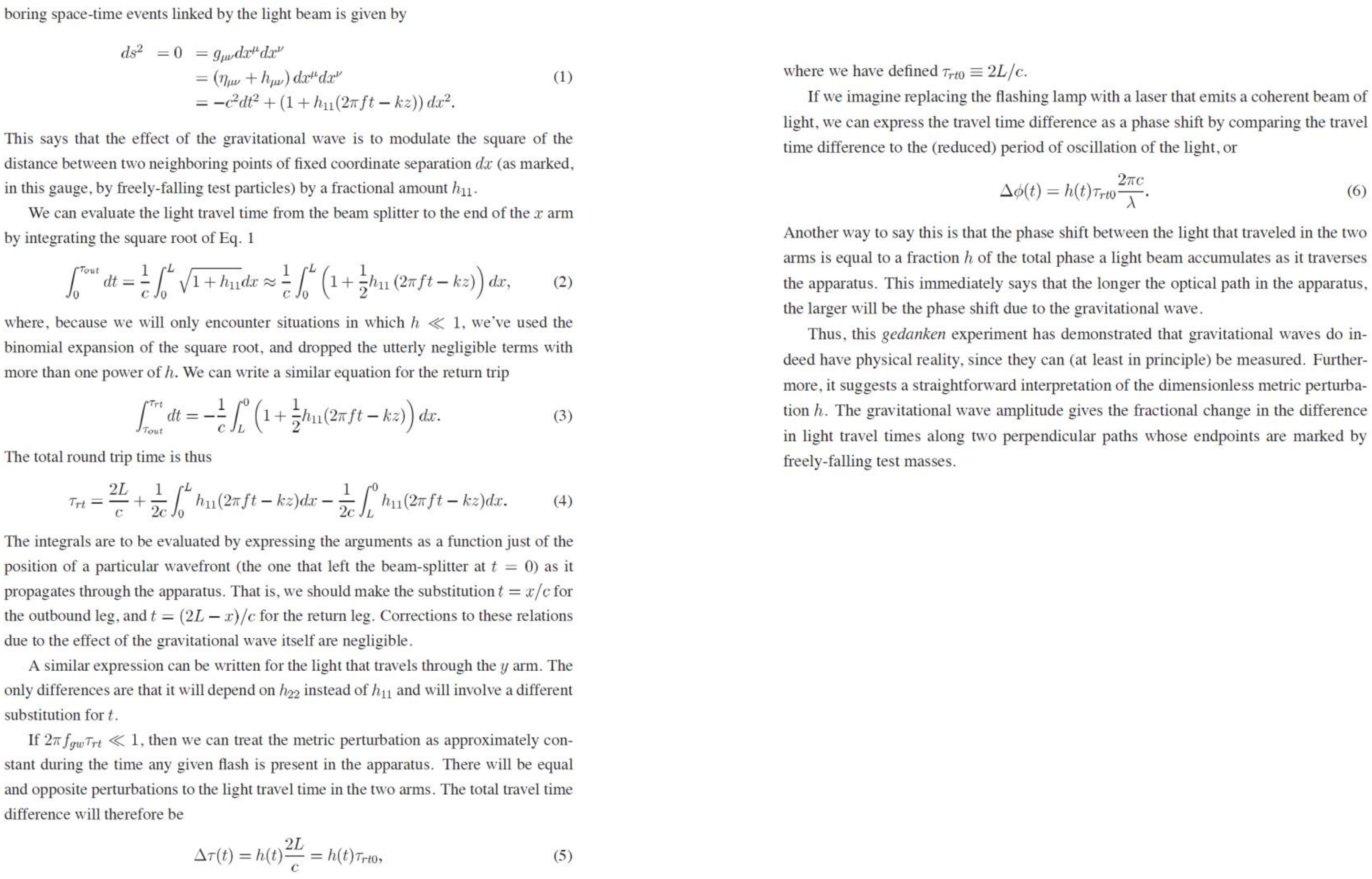


Fig. 2. A schematic diagram of an apparatus that can detect gravitational waves. It has the form of a Michelson interferometer.

Extra-slides, effect of GW on interferometer



boring space-time events linked by the light beam is given by

$$\begin{aligned} ds^2 &= 0 = g_{\mu\nu} dx^\mu dx^\nu \\ &= (\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu dx^\nu \\ &= -c^2 dt^2 + (1 + h_{11}(2\pi f t - kz))\, dx^2. \end{aligned} \quad (1)$$

This says that the effect of the gravitational wave is to modulate the square of the distance between two neighboring points of fixed coordinate separation dx (as marked, in this gauge, by freely-falling test particles) by a fractional amount h_{11}.

We can evaluate the light travel time from the beam splitter to the end of the x arm by integrating the square root of Eq. 1

$$\int_0^{\tau_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1 + h_{11}}\, dx \approx \frac{1}{c}\int_0^L \left(1 + \frac{1}{2} h_{11}\left(2\pi f t - kz\right)\right) dx, \quad (2)$$

where, because we will only encounter situations in which $h \ll 1$, we've used the binomial expansion of the square root, and dropped the utterly negligible terms with more than one power of h. We can write a similar equation for the return trip

$$\int_{\tau_{out}}^{\tau_{rt}} dt = -\frac{1}{c}\int_L^0 \left(1 + \frac{1}{2} h_{11}(2\pi f t - kz)\right) dx. \quad (3)$$

The total round trip time is thus

$$\tau_{rt} = \frac{2L}{c} + \frac{1}{2c}\int_0^L h_{11}(2\pi f t - kz) dx - \frac{1}{2c}\int_L^0 h_{11}(2\pi f t - kz) dx. \quad (4)$$

The integrals are to be evaluated by expressing the arguments as a function just of the position of a particular wavefront (the one that left the beam-splitter at $t = 0$) as it propagates through the apparatus. That is, we should make the substitution $t = x/c$ for the outbound leg, and $t = (2L - x)/c$ for the return leg. Corrections to these relations due to the effect of the gravitational wave itself are negligible.

A similar expression can be written for the light that travels through the y arm. The only differences are that it will depend on h_{22} instead of h_{11} and will involve a different substitution for t.

If $2\pi f_{gw}\tau_{rt} \ll 1$, then we can treat the metric perturbation as approximately constant during the time any given flash is present in the apparatus. There will be equal and opposite perturbations to the light travel time in the two arms. The total travel time difference will therefore be

$$\Delta\tau(t) = h(t)\frac{2L}{c} = h(t)\tau_{rt0}, \quad (5)$$

where we have defined $\tau_{rt0} \equiv 2L/c$.

If we imagine replacing the flashing lamp with a laser that emits a coherent beam of light, we can express the travel time difference as a phase shift by comparing the travel time difference to the (reduced) period of oscillation of the light, or

$$\Delta\phi(t) = h(t)\tau_{rt0}\frac{2\pi c}{\lambda}. \quad (6)$$

Another way to say this is that the phase shift between the light that traveled in the two arms is equal to a fraction h of the total phase a light beam accumulates as it traverses the apparatus. This immediately says that the longer the optical path in the apparatus, the larger will be the phase shift due to the gravitational wave.

Thus, this *gedanken* experiment has demonstrated that gravitational waves do indeed have physical reality, since they can (at least in principle) be measured. Furthermore, it suggests a straightforward interpretation of the dimensionless metric perturbation h. The gravitational wave amplitude gives the fractional change in the difference in light travel times along two perpendicular paths whose endpoints are marked by freely-falling test masses.

Extra-slide, 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/