

# Astrofisica Nucleare e Subnucleare

## Gravitational Waves

# Exercise #3

- Find recent information on the status of LIGO, Virgo and other GW interferometers
- Find the status of (e)LISA GW observatory
- Find the status of PTA GW methods



# Introduzione



## Gravitational wave astronomy

past, present and future

**Eugenio Cocchia**

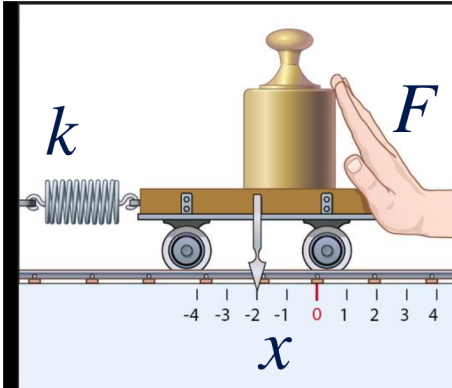
*Gran Sasso Science Institute and INFN*

SciNeGHE 2016

High-energy gamma-ray experiments at the dawn of gravitational wave astronomy

Pisa, 18 October 2016

# Introduzione



$$F = -kx$$

$$F \Leftrightarrow T_{\mu\nu}$$

$$x \Leftrightarrow G_{\mu\nu}$$

$$k \Leftrightarrow \frac{c^4}{8\pi G}$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$c = 299\,792\,458 \text{ m/s} = 3 \times 10^8 \text{ m/s}$$

$$G = 0,000\,000\,000\,066\,7 \frac{\text{m}^3}{\text{kg s}^2} = 6,67 \times 10^{-11} \frac{\text{m}^3}{\text{kg s}^2}$$

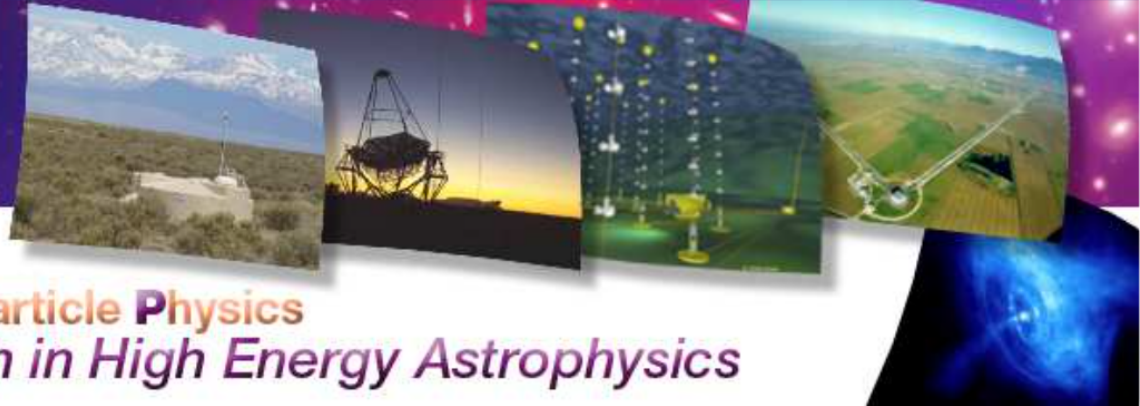
$$k \approx 10^{45} \frac{\text{kg}}{\text{s}^2} \quad \text{STIFF!}$$



2 - 13 July 2012  
Paris (France)

European Doctorate School

International School of AstroParticle Physics  
*Multi-Messenger Approach in High Energy Astrophysics*



# Gravitational Waves Detection And Fourier Methods

ISAPP2012  
Paris, France, July 2012

Patrice Hello

Laboratoire de l'Accélérateur Linéaire  
Orsay-France



Comprendre le monde,  
construire l'avenir®

# What are Gravitational Waves ?

Gravitational Waves (GW) are ripples of space-time

## Theory of GW :

1. Einstein equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

2. Far from sources:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$

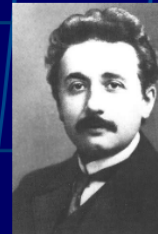
3. Linearization:

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

4. Gauge TT:

$$\nabla^2 h_{\mu\nu}^{TT} = 0$$

Propagation of some tensor field –  $h$  - on flat space-time



**Prediction  
in 1916 !**

# Gravitational Wave general properties

- GW propagate at speed of light
- GW have two polarizations “+” and “x”
- GW emission is quadrupolar at lowest order

Example: plane wave propagating along z axis with 2 polarization amplitudes  $h_+$  and  $h_x$ :

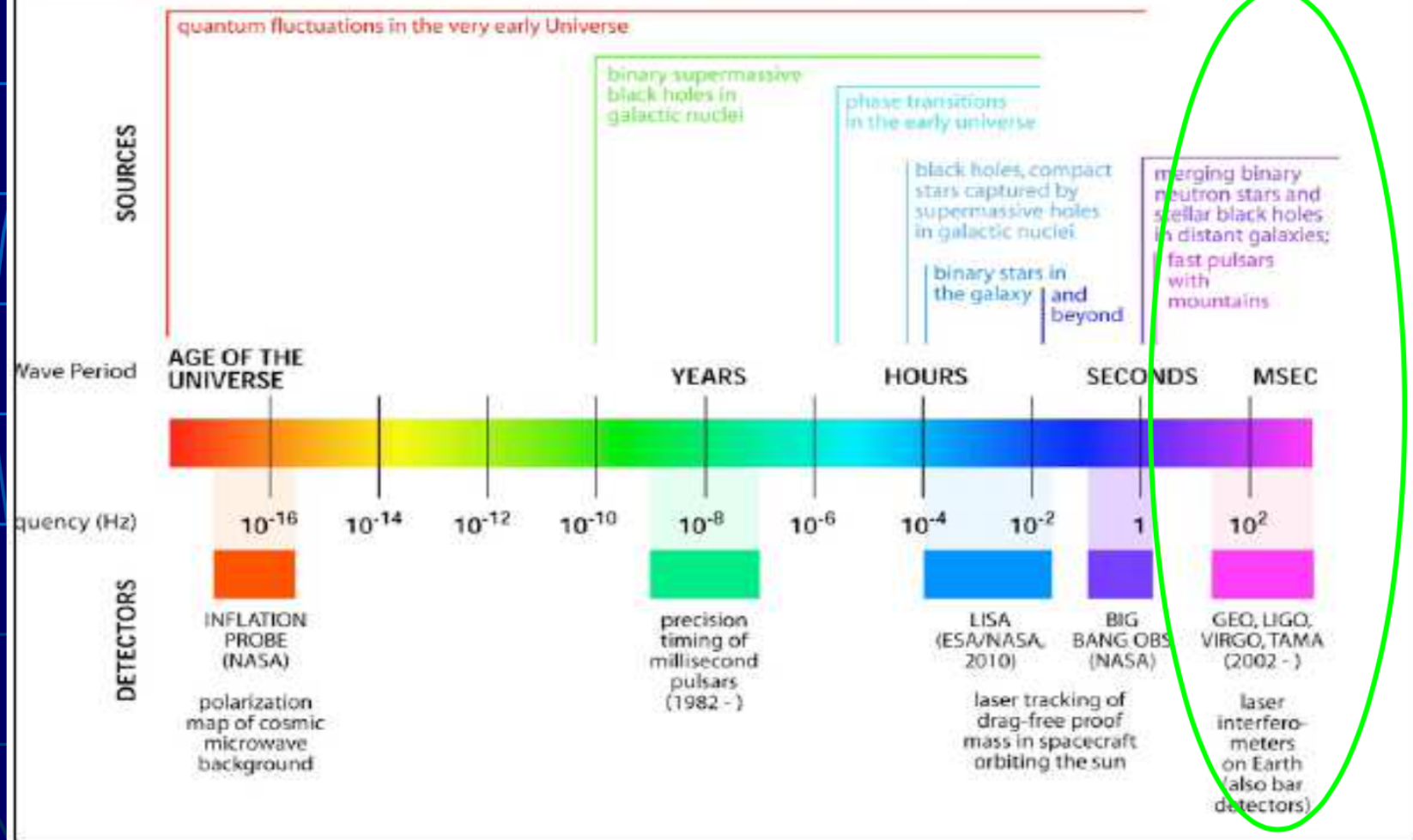
$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_x & 0 \\ 0 & h_x & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Corresponding *Graviton* properties:

- Graviton has null mass
- Graviton has spin 2



# THE GRAVITATIONAL WAVE SPECTRUM





# GW (indirect) discovery PSR 1913+16



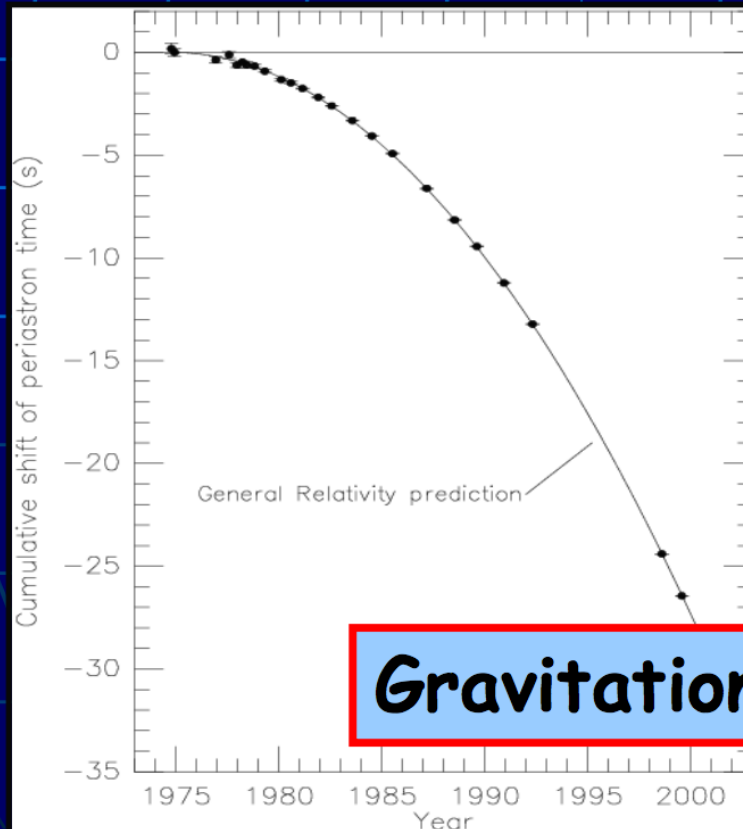
(Hulse & Taylor, Nobel'93)

PSR 1913+16 : binary pulsar (system of 2 neutron stars, one being a radio pulsar seen by radiotelescopes) at ~ 7 kpc from Earth.

⇒ tests of Gravitation theory in strong field and dynamical regime

Loss of energy by GW emission : orbital period decreases

(merge in 300 billions years)



$P$ (s)	<b>27906.9807807(9)</b>
$dP/dt$	<b><math>-2.425(10) \cdot 10^{-12}</math></b>
$d\omega/dt$ ( $^{\circ}/yr$ )	<b>4.226628(18)</b>
$M_p$	<b><math>1.442 \pm 0.003 M_{\odot}</math></b>
$M_c$	<b><math>1.386 \pm 0.003 M_{\odot}</math></b>

**Gravitational Waves do exist !**

SUPAGWD

**An Introduction to  
General Relativity,  
Gravitational Waves  
and  
Detection Principles**

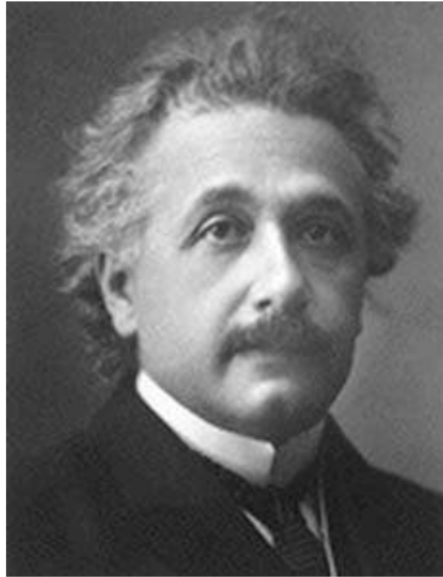
Prof Martin Hendry  
University of Glasgow  
Dept of Physics and Astronomy

October 2012

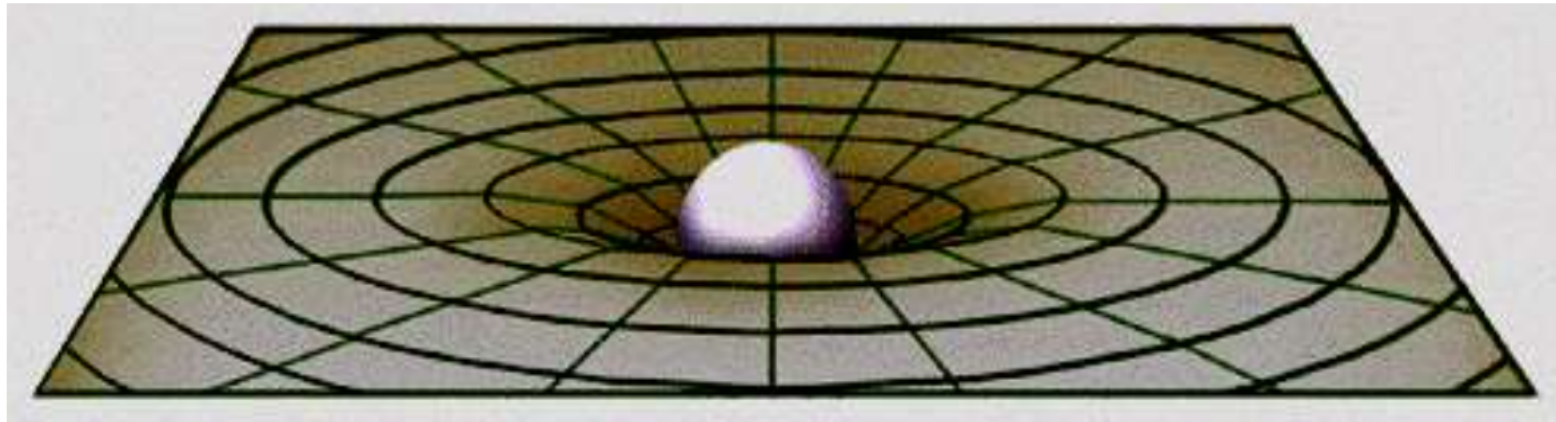




# Gravity in Einstein's Universe



Spacetime tells matter  
how to move, and  
matter tells spacetime  
how to curve





*“...joy and amazement at the beauty and grandeur of this world of which man can just form a faint notion.”*

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Spacetime  
curvature

Matter  
(and energy)

## 6. Wave Equation for Gravitational Radiation (pgs.46 - 57)

### Weak gravitational fields

In the absence of a gravitational field, spacetime is flat. We define a weak gravitational field as one in which spacetime is 'nearly flat'

i.e. we can find a coord system such that

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$$

where  $\eta_{\alpha\beta} = \text{diag}(-1, 1, 1, 1)$   
 $|h_{\alpha\beta}| \ll 1$  for all  $\alpha$  and  $\beta$

This is known as a Nearly Lorentz coordinate system.

If we find a coordinate system in which spacetime looks nearly flat, we can carry out certain coordinate transformations after which spacetime will *still* look nearly flat:

### 1) Background Lorentz transformations

Hence, our original nearly Lorentz coordinate system remains nearly Lorentz in the new coordinate system. In other words, a spacetime which looks nearly flat to one observer still looks nearly flat to any other observer in uniform relative motion with respect to the first observer.

If we find a coordinate system in which spacetime looks nearly flat, we can carry out certain coordinate transformations after which spacetime will *still* look nearly flat:

1) Background Lorentz transformations

*Under this transformation*

$$g'_{\alpha\beta} = \eta'_{\alpha\beta} + \frac{\partial x^\mu}{\partial x'^\alpha} \frac{\partial x^\nu}{\partial x'^\beta} h_{\mu\nu} = \eta_{\alpha\beta} + h'_{\alpha\beta}$$

provided  $v \ll 1$ , then if  $|h_{\alpha\beta}| \ll 1$

for all  $\alpha$  and  $\beta$ , then  $|h'_{\alpha\beta}| \ll 1$  also.



If we find a coordinate system in which spacetime looks nearly flat, we can carry out certain coordinate transformations after which spacetime will *still* look nearly flat:

## 2) Gauge transformations

Suppose now we make a very small change in our coordinate system by applying a coordinate transformation of the form

$$x'^{\alpha} = x^{\alpha} + \xi^{\alpha}(x^{\beta})$$

we now demand that the  $\xi^{\alpha}$  are small, in the sense that

$$|\xi^{\alpha}_{,\beta}| \ll 1 \quad \text{for all } \alpha, \beta$$

If we find a coordinate system in which spacetime looks nearly flat, we can carry out certain coordinate transformations after which spacetime will *still* look nearly flat:

## 2) Gauge transformations

Suppose now that the unprimed coordinate system is nearly Lorentz

*Then* 
$$g'_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} - \xi_{\alpha,\beta} - \xi_{\beta,\alpha}$$

*and we can write* 
$$h'_{\alpha\beta} = h_{\alpha\beta} - \xi_{\alpha,\beta} - \xi_{\beta,\alpha}$$

If we find a coordinate system in which spacetime looks nearly flat, we can carry out certain coordinate transformations after which spacetime will *still* look nearly flat:

## 2) Gauge transformations

The above results tell us that – once we have identified a coordinate system which is nearly Lorentz – we can add an arbitrary small vector  $\xi^\alpha$  to the coordinates  $x^\alpha$  without altering the validity of our assumption that spacetime is nearly flat. We can, therefore, choose the components  $\xi^\alpha$  to make Einstein's equations as simple as possible. We call this step choosing a **gauge** for the problem – a name which has resonance with a similar procedure in electromagnetism – and coordinate transformations of this type given by equation are known as **gauge transformation**. We will consider below specific choices of gauge which are particularly useful.



## Einstein's equations for a weak gravitational field

The Einstein tensor is the (rather messy) expression

$$G_{\mu\nu} = \frac{1}{2} \left[ h_{\mu\alpha,\nu}{}^{,\alpha} + h_{\nu\alpha,\mu}{}^{,\alpha} - h_{\mu\nu,\alpha}{}^{,\alpha} - h_{,\mu\nu} - \eta_{\mu\nu} (h_{\alpha\beta}{}^{,\alpha\beta} - h_{,\beta}{}^{,\beta}) \right]$$

but we can simplify this by introducing  $\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h$

So that

$$G_{\mu\nu} = -\frac{1}{2} \left[ \bar{h}_{\mu\nu,\alpha}{}^{,\alpha} + \eta_{\mu\nu}\bar{h}_{\alpha\beta}{}^{,\alpha\beta} - \bar{h}_{\mu\alpha,\nu}{}^{,\alpha} - \bar{h}_{\nu\alpha,\mu}{}^{,\alpha} \right]$$

And we can choose the **Lorentz gauge** to eliminate the last 3 terms

## Einstein's equations for a weak gravitational field

To first order, the R-C tensor for a weak field reduces to

$$R_{\alpha\beta\gamma\delta} = \frac{1}{2} (h_{\alpha\delta,\beta\gamma} + h_{\beta\gamma,\alpha\delta} - h_{\alpha\gamma,\beta\delta} - h_{\beta\delta,\alpha\gamma})$$

and is invariant under gauge transformations.

Similarly, the Ricci tensor is

$$R_{\mu\nu} = \frac{1}{2} (h_{\mu,\nu\alpha}^{\alpha} + h_{\nu,\mu\alpha}^{\alpha} - h_{\mu\nu,\alpha}^{\alpha} - h_{,\mu\nu})$$

where

$$h \equiv h_{\alpha}^{\alpha} = \eta^{\alpha\beta} h_{\alpha\beta}$$

$$h_{\mu\nu,\alpha}^{\alpha} = \eta^{\alpha\sigma} (h_{\mu\nu,\alpha})_{,\sigma} = \eta^{\alpha\sigma} h_{\mu\nu,\alpha\sigma}$$

In the Lorentz gauge, then Einstein's equations are simply

$$-\bar{h}_{\mu\nu,\alpha}{}^{,\alpha} = 16\pi T_{\mu\nu}$$

And in free space this gives

$$\bar{h}_{\mu\nu,\alpha}{}^{,\alpha} = 0$$

Writing  $\bar{h}_{\mu\nu,\alpha}{}^{,\alpha} \equiv \eta^{\alpha\alpha}\bar{h}_{\mu\nu,\alpha\alpha}$

or

$$\left( -\frac{\partial^2}{\partial t^2} + \nabla^2 \right) \bar{h}_{\mu\nu} = 0$$

Remembering that we are taking  $c = 1$ , if instead we write

$$\eta^{00} = -\frac{1}{c^2}$$

then

$$\left( -\frac{\partial^2}{\partial t^2} + c^2 \nabla^2 \right) \bar{h}_{\mu\nu} = 0$$

This is a key result. It has the mathematical form of a wave equation, propagating with speed  $c$ .

We have shown that the metric perturbations – the ‘ripples’ in spacetime produced by disturbing the metric – propagate at the speed of light as waves in free space.

## 7. The Transverse Traceless Gauge (pgs.57 - 62)

Simplest solutions of our wave equation are **plane waves**

$$\bar{h}_{\mu\nu} = \text{Re} [A_{\mu\nu} \exp (ik_{\alpha}x^{\alpha})]$$

Wave amplitude

Wave vector

Note the wave amplitude is symmetric  $\rightarrow$  10 independent components.

Also, easy to show that

$$k_{\alpha} k^{\alpha} = 0$$

i.e. the wave vector is a **null** vector

Thus

$$\omega = k^t = (k_x^2 + k_y^2 + k_z^2)^{1/2}$$

Also, from the Lorentz gauge condition

$$\bar{h}^{\mu\alpha}_{,\alpha} = 0$$

which implies that

$$A_{\mu\alpha} k^\alpha = 0$$

i.e. the wave amplitude components must be orthogonal to the wave vector  $\mathbf{k}$ .

But this is 4 equations, one for each value of the index  $\mu$ .

Hence, we can eliminate 4 more of the wave amplitude components,

Can we do better? **Yes**

Our choice of Lorentz gauge, chosen to simplify Einstein's equations, was not unique. We can make small adjustments to our original Lorentz gauge transformation and still satisfy the Lorentz condition.

We can choose adjustments that will make our wave amplitude components even simpler – we call this choice the **Transverse Traceless** gauge:

$$A_{\mu}^{\mu} = \eta^{\mu\nu} A_{\mu\nu} = 0 \quad (\text{traceless})$$

$$A_{\alpha t} = 0 \quad \text{for all } \alpha$$

Suppose we orient our coordinate axes so that the plane wave is travelling in the positive  $z$  direction. Then

$$k^t = \omega, \quad k^x = k^y = 0, \quad k^z = \omega$$

and

$$A_{\alpha z} = 0 \quad \text{for all } \alpha$$

i.e. there is no component of the metric perturbation in the direction of propagation of the wave. This explains the origin of the 'Transverse' part



So in the transverse traceless gauge,

$$\bar{h}_{\mu\nu}^{(\text{TT})} = A_{\mu\nu}^{(\text{TT})} \cos[\omega(t - z)]$$

where

$$A_{\mu\nu}^{(\text{TT})} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A_{xx}^{(\text{TT})} & A_{xy}^{(\text{TT})} & 0 \\ 0 & A_{xy}^{(\text{TT})} & -A_{xx}^{(\text{TT})} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Also, since the perturbation is traceless

$$\bar{h}_{\alpha\beta}^{(\text{TT})} = h_{\alpha\beta}^{(\text{TT})}$$

## 8. Effect of Gravitational Waves on Free Particles (pgs.63 - 75)

Choose Background Lorentz frame in which test particle initially at rest. Set up coordinate system according to the TT gauge.

Initial acceleration satisfies  $\left(\frac{dU^\beta}{d\tau}\right)_0 = 0$

i.e. coordinates do not change, but adjust themselves as wave passes so that particles remain 'attached' to initial positions.

Coordinates are frame-dependent labels.

What about **proper distance** between neighbouring particles?

Consider two test particles, both initially at rest, one at origin and the other at  $x = \epsilon, y = z = 0$

$$\Delta l = \int |g_{\alpha\beta} dx^\alpha dx^\beta|^{1/2}$$

i.e. 
$$\Delta l = \int_0^\epsilon |g_{xx}|^{1/2} \simeq \sqrt{g_{xx}(x=0)} \epsilon$$

Now 
$$g_{xx}(x=0) = \eta_{xx} + h_{xx}^{(\text{TT})}(x=0)$$

so

$$\Delta l \simeq \left[ 1 + \frac{1}{2} h_{xx}^{(\text{TT})}(x=0) \right] \epsilon$$

In general, this is time-varying

More formally, consider geodesic deviation  $\xi^\alpha$  between two particles, initially at rest

i.e. initially with  $U^\mu = (1, 0, 0, 0)^T$   $\xi^\beta = (0, \epsilon, 0, 0)^T$

Then 
$$\frac{\partial^2 \xi^\alpha}{\partial t^2} = \epsilon R_{ttx}^\alpha = -\epsilon R_{txt}^\alpha$$

and 
$$R_{txt}^x = \eta^{xx} R_{xtxt} = -\frac{1}{2} h_{xx,tt}^{(TT)}$$

$$R_{txt}^y = \eta^{yy} R_{ytxt} = -\frac{1}{2} h_{xy,tt}^{(TT)}$$

Hence

$$\frac{\partial^2}{\partial t^2} \xi^x = \frac{1}{2} \epsilon \frac{\partial^2}{\partial t^2} h_{xx}^{(TT)} \quad \frac{\partial^2}{\partial t^2} \xi^y = \frac{1}{2} \epsilon \frac{\partial^2}{\partial t^2} h_{xy}^{(TT)}$$

Similarly, two test particles initially separated by  $\epsilon$  in the  $y$ -direction satisfy

$$\frac{\partial^2}{\partial t^2} \xi^x = \frac{1}{2} \epsilon \frac{\partial^2}{\partial t^2} h_{xy}^{(\text{TT})} \quad \frac{\partial^2}{\partial t^2} \xi^y = -\frac{1}{2} \epsilon \frac{\partial^2}{\partial t^2} h_{xx}^{(\text{TT})}$$

We can further generalise to a ring of test particles: one at origin, the other initially a

$$x = \epsilon \cos \theta \quad y = \epsilon \sin \theta \quad z = 0$$

$$\frac{\partial^2}{\partial t^2} \xi^x = \frac{1}{2} \epsilon \cos \theta \frac{\partial^2}{\partial t^2} h_{xx}^{(\text{TT})} + \frac{1}{2} \epsilon \sin \theta \frac{\partial^2}{\partial t^2} h_{xy}^{(\text{TT})}$$

$$\frac{\partial^2}{\partial t^2} \xi^y = \frac{1}{2} \epsilon \cos \theta \frac{\partial^2}{\partial t^2} h_{xy}^{(\text{TT})} - \frac{1}{2} \epsilon \sin \theta \frac{\partial^2}{\partial t^2} h_{xx}^{(\text{TT})}$$

So in the transverse traceless gauge,

$$\bar{h}_{\mu\nu}^{(\text{TT})} = A_{\mu\nu}^{(\text{TT})} \cos[\omega(t - z)]$$

where

$$A_{\mu\nu}^{(\text{TT})} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A_{xx}^{(\text{TT})} & A_{xy}^{(\text{TT})} & 0 \\ 0 & A_{xy}^{(\text{TT})} & -A_{xx}^{(\text{TT})} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Also, since the perturbation is traceless

$$\bar{h}_{\alpha\beta}^{(\text{TT})} = h_{\alpha\beta}^{(\text{TT})}$$

Solutions are:

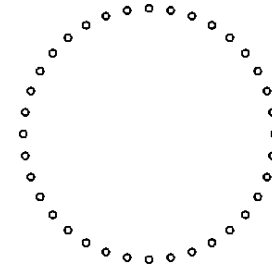
$$\xi^x = \epsilon \cos \theta + \frac{1}{2} \epsilon \cos \theta A_{xx}^{(\text{TT})} \cos \omega t + \frac{1}{2} \epsilon \sin \theta A_{xy}^{(\text{TT})} \cos \omega t$$

$$\xi^y = \epsilon \sin \theta + \frac{1}{2} \epsilon \cos \theta A_{xy}^{(\text{TT})} \cos \omega t - \frac{1}{2} \epsilon \sin \theta A_{xx}^{(\text{TT})} \cos \omega t$$

Suppose we now vary  $\theta$  between 0 and  $2\pi$ , so that we are considering an initially circular ring of test particles in the  $x$ - $y$  plane, initially equidistant from the origin.

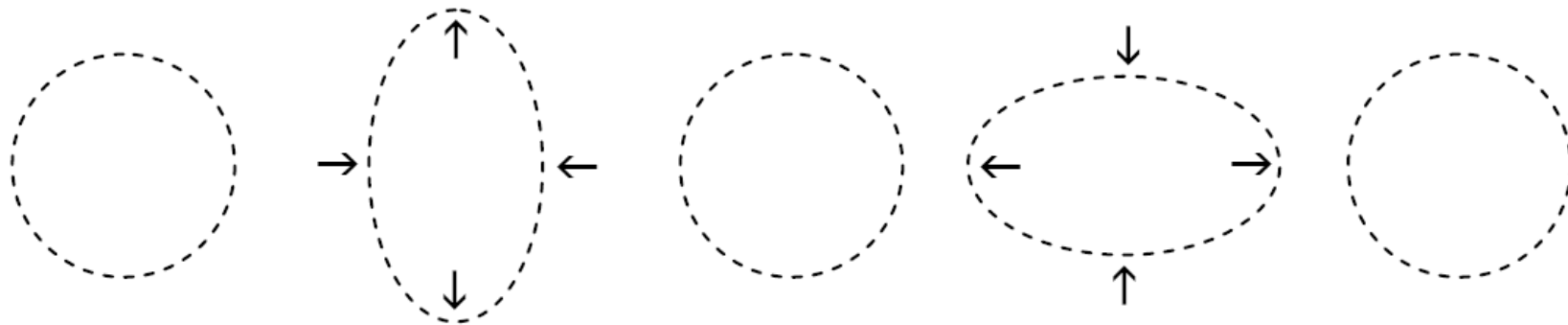
$$A_{xx}^{(TT)} \neq 0 \quad A_{xy}^{(TT)} = 0$$

$$\xi^x = \epsilon \cos \theta \left( 1 + \frac{1}{2} A_{xx}^{(TT)} \cos \omega t \right)$$



$$\xi^y = \epsilon \sin \theta \left( 1 - \frac{1}{2} A_{xx}^{(TT)} \cos \omega t \right)$$

$A_{xx}^{(TT)} \neq 0$     **+ Polarisation**

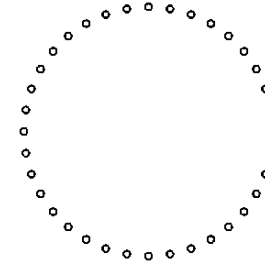




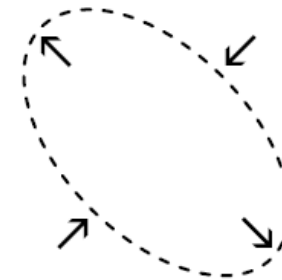
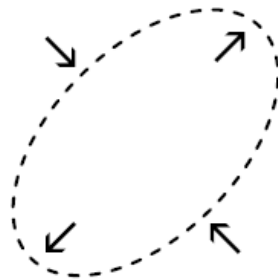
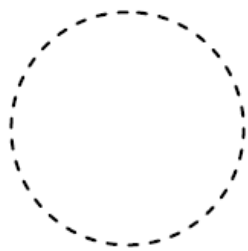
$$A_{xy}^{(TT)} \neq 0 \quad A_{xx}^{(TT)} = 0$$

$$\xi^x = \epsilon \cos \theta + \frac{1}{2} \epsilon \sin \theta A_{xy}^{(TT)} \cos \omega t$$

$$\xi^y = \epsilon \sin \theta + \frac{1}{2} \epsilon \cos \theta A_{xy}^{(TT)} \cos \omega t$$



$A_{xy}^{(TT)} \neq 0$     **× Polarisation**



Rotating axes through an angle of  $-\pi/4$  to define

$$x' = \frac{1}{\sqrt{2}} (x - y)$$

We find that

$$\xi'^x = \epsilon \cos\left(\theta + \frac{\pi}{4}\right) + \frac{1}{2}\epsilon \sin\left(\theta + \frac{\pi}{4}\right) A_{xy}^{(\text{TT})} \cos \omega t$$

$$y' = \frac{1}{\sqrt{2}} (x + y)$$

$$\xi'^y = \epsilon \sin\left(\theta + \frac{\pi}{4}\right) + \frac{1}{2}\epsilon \cos\left(\theta + \frac{\pi}{4}\right) A_{xy}^{(\text{TT})} \cos \omega t$$

These are identical to earlier solution, apart from rotation.

- The two solutions, for  $A_{xx}^{(\text{TT})} \neq 0$  and  $A_{xy}^{(\text{TT})} \neq 0$  represent two independent gravitational wave **polarisation states**, and these states are usually denoted by ‘+’ and ‘×’ respectively. In general any gravitational wave propagating along the  $z$ -axis can be expressed as a linear combination of the ‘+’ and ‘×’ polarisations, i.e. we can write the wave as

$$\mathbf{h} = a \mathbf{e}_+ + b \mathbf{e}_\times$$

where  $a$  and  $b$  are scalar constants and the *polarisation tensors*  $\mathbf{e}_+$  and  $\mathbf{e}_\times$  are

$$\mathbf{e}_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad \mathbf{e}_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- Distortions are **quadrupolar** - consequence of fact that acceleration of geodesic deviation non-zero only for tidal gravitational field.
- At any instant, a gravitational wave is invariant under a rotation of 180 degrees about its direction of propagation.  
(c.f. spin states of gauge bosons; graviton must be  $S=2$ , tensor field)

# Metodi di rivelazione

## Chapter 14

### Measurement of Classical Gravitation Fields

*Felix Pirani*

Because of the principle of equivalence, one cannot ascribe a direct physical interpretation to the gravitational field insofar as it is characterized by Christoffel symbols  $\Gamma_{\nu\rho}^{\mu}$ . One can, however, give an invariant interpretation to the variations of the gravitational field. These variations are described by the Riemann tensor; therefore, measurements of the relative acceleration of neighboring free particles, which yield information about the variation of the field, will also yield information about the Riemann tensor.

Now the relative motion of free particles is given by the equation of geodesic deviation

$$\frac{\partial^2 \eta^\mu}{\partial \tau^2} + R_{\nu\rho\sigma}^{\mu} \eta^\nu v^\rho v^\sigma = 0 \quad (\mu, \nu, \rho, \sigma = 1, 2, 3, 4) \quad (14.1)$$

Here  $\eta^\mu$  is the infinitesimal orthogonal displacement from the (geodesic) worldline  $\zeta$  of a free particle to that of a neighboring similar particle.  $v^\nu$  is the 4-velocity of the first particle, and  $\tau$  the proper time along  $\zeta$ . If now one introduces an orthonormal frame on  $\zeta$ ,  $v^\mu$  being the timelike vector of the frame, and assumes that the frame is parallelly propagated along  $\zeta$  (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (14.1) becomes

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + R_{0b0}^a \eta^b = 0 \quad (a, b = 1, 2, 3,) \quad (14.2)$$

Here  $\eta^a$  are the physical components of the infinitesimal displacement and  $R_{0b0}^a$  some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One

can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

Now the Newtonian equation corresponding to (14.2) is

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + \frac{\partial^2 v}{\partial x^a \partial x^b} \eta^b = 0 \quad (14.3)$$

It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence  $R_{0b0}^a \sim \frac{\partial^2 v}{\partial x^a \partial x^b}$  between equations (14.2) and (14.3), for the respective empty-space equations may be written  $R_{0a0}^a = 0$  and  $\frac{\partial^2 v}{\partial x^a \partial x^b} = 0$ . (Details of this work are in the course of publication in *Acta Physica Polonica*.)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a  $\frac{d\eta}{d\tau}$  term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

LICHNEROWICZ: Is it possible to study stability problems for  $\eta$ ?

PIRANI: It is the same as the stability problem in classical mechanics, but I haven't tried to see for which kind of Riemann tensor it would blow up.

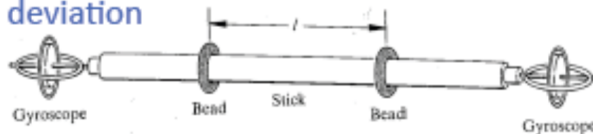
# Metodi di rivelazione



F.A.E. Pirani,  
GW geodesic  
deviation



H. Bondi : beads on  
rod, energy in GW



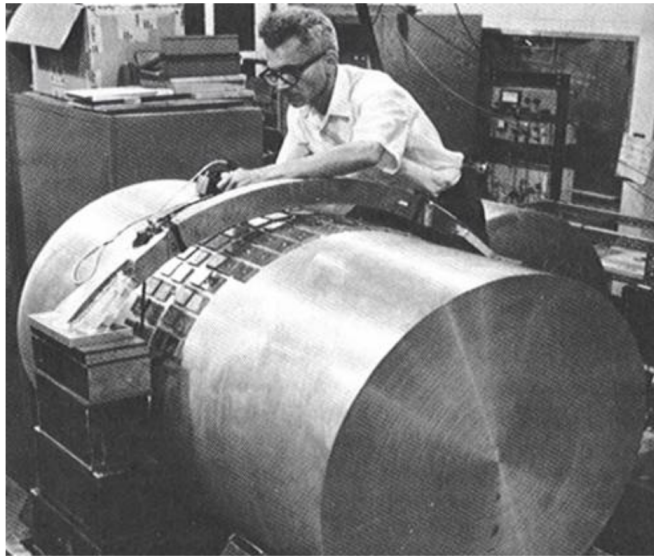
The main point of this presentation was that it is relative accelerations of neighboring free particles that are the physically meaningful (i.e., measurable) ways to observe gravitational effects. Pirani points out the transparent connection between the equation of geodesic deviation and Newton's Second Law, as long as one identifies  $R_{a0b0}$  with the second derivative of the Newtonian potential (i.e., as the tidal field.)

To make sure everyone sees how important and simple this is, he remarks, “By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor”.

from: P. Saulson, *Gen Relativ Gravit* (2011) 43:3289–3299

# Metodi di rivelazione

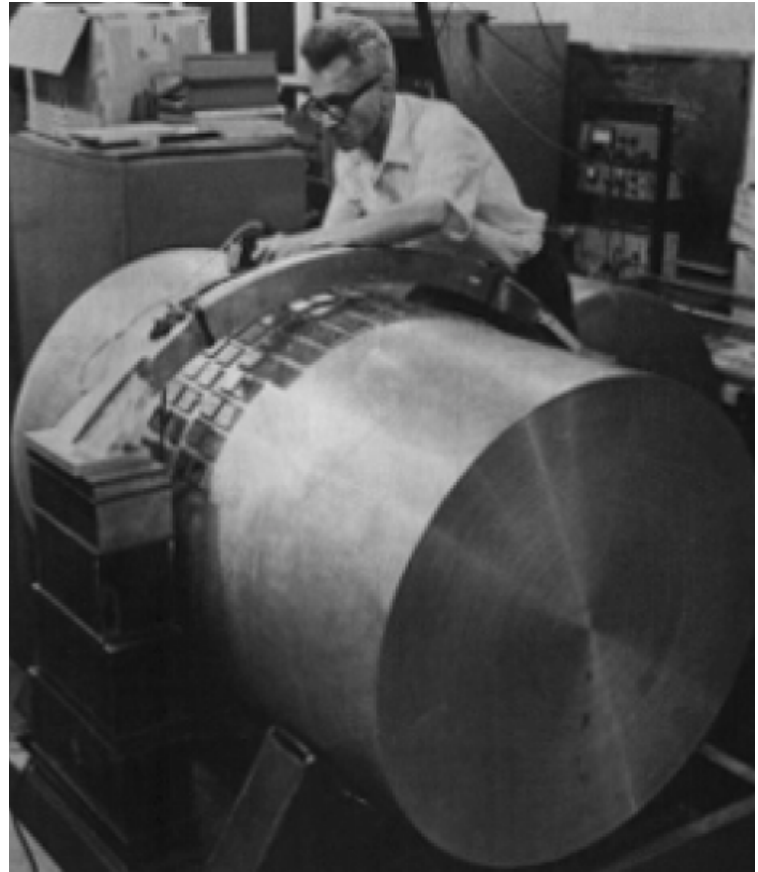
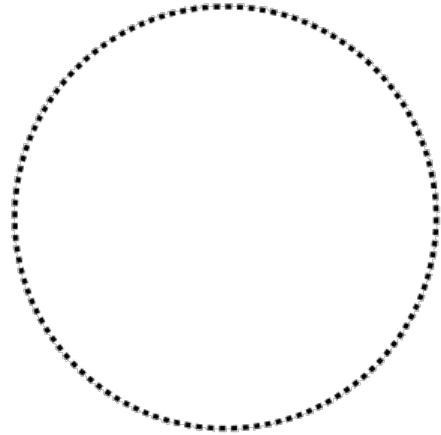
## Weber's bar



Weber's detector embodied Pirani's *gedankenexperiment*.

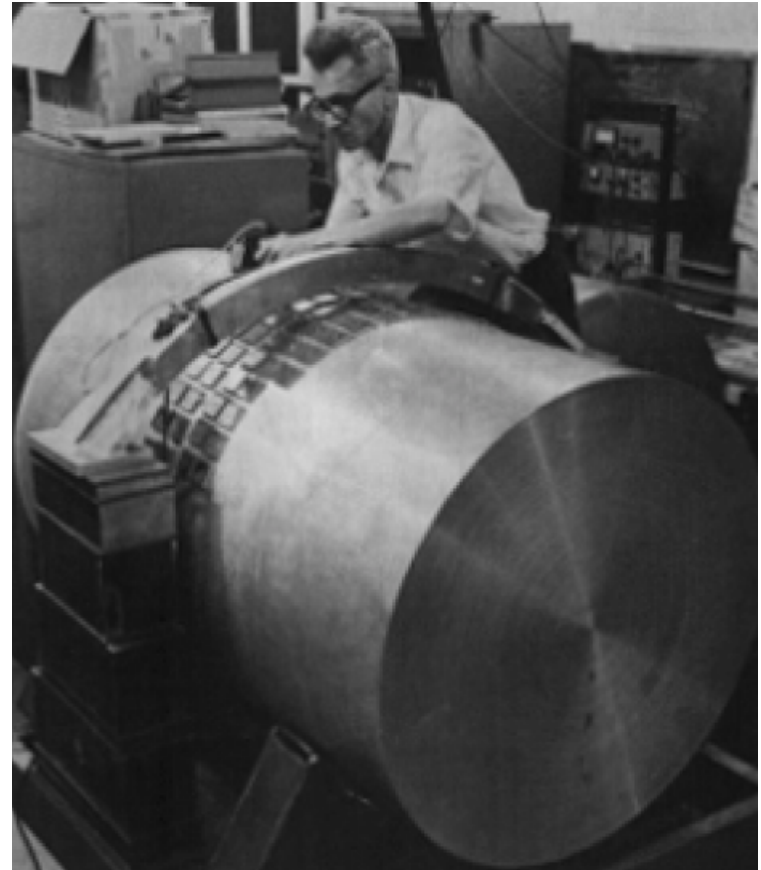
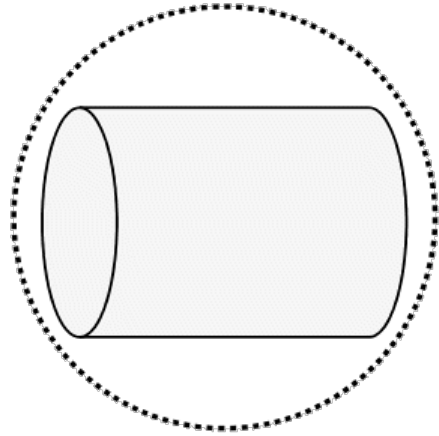
It was a cylinder of aluminum, each end of which is like a test mass, while the center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

## Design of gravitational wave detectors





## Design of gravitational wave detectors



# Metodi di rivelazione

## Weber started seeing things

In 1969, Weber made his first of many announcements that he was seeing coincident excitations of two detectors.

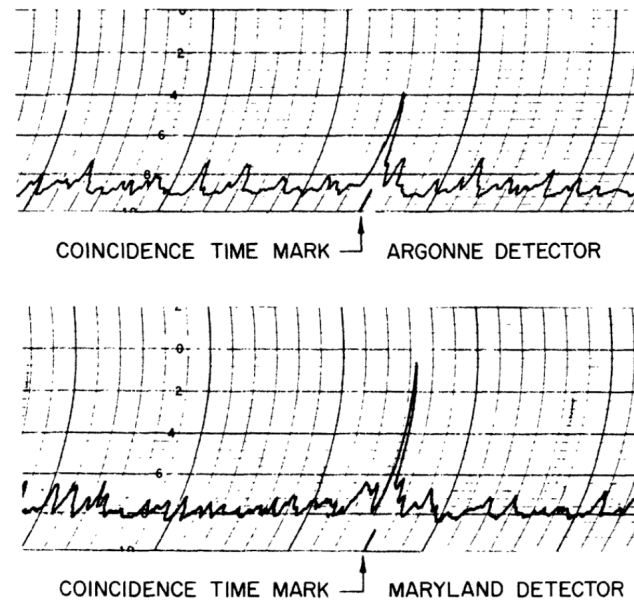
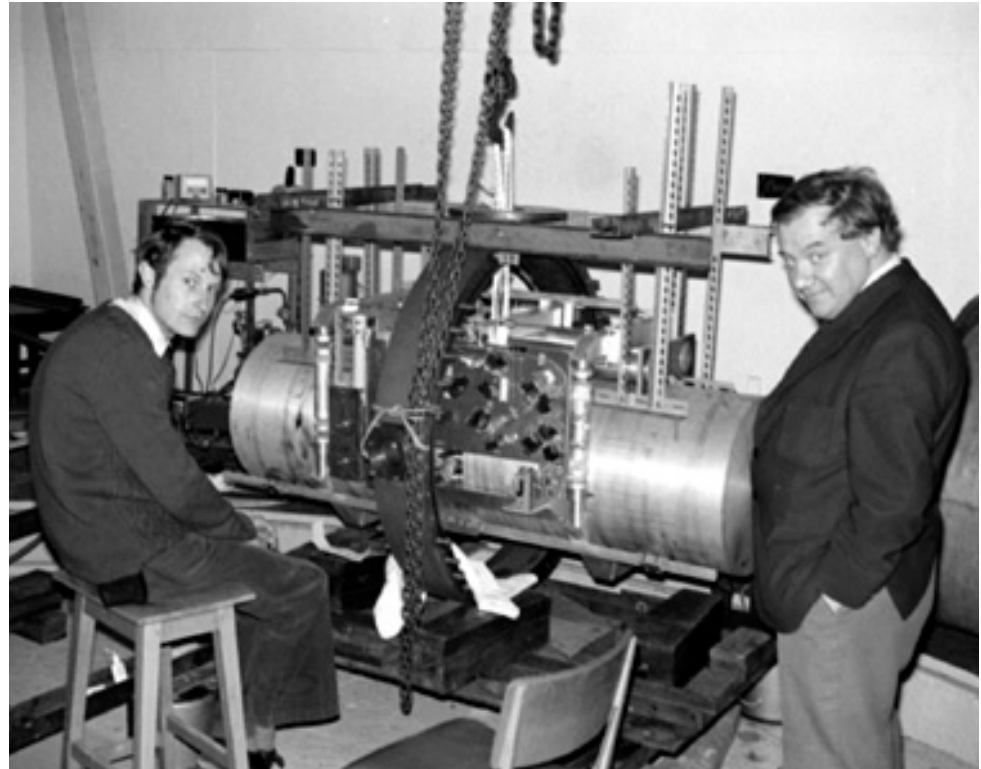
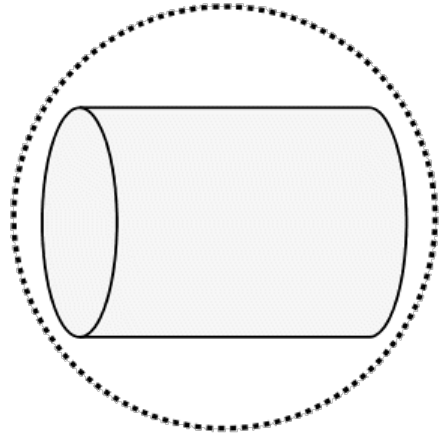
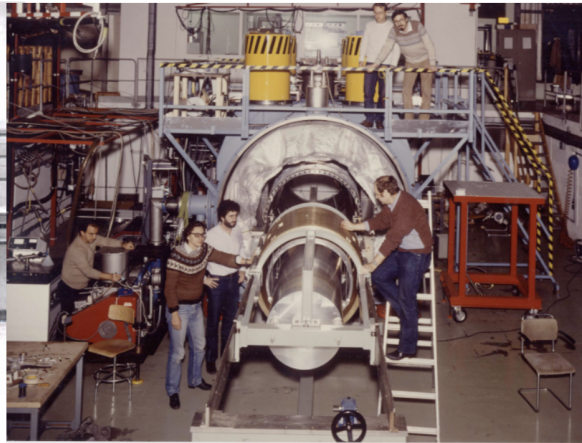


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

## Design of gravitational wave detectors



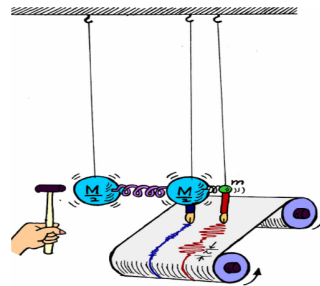
# Metodi di rivelazione



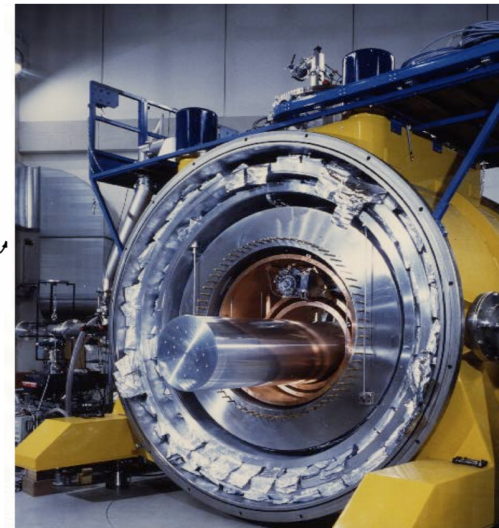
Explorer, CERN



Nautilus, LNF

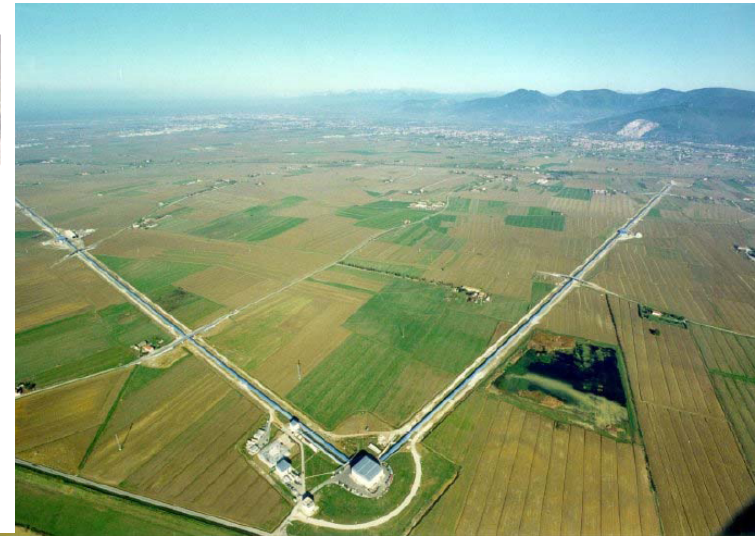
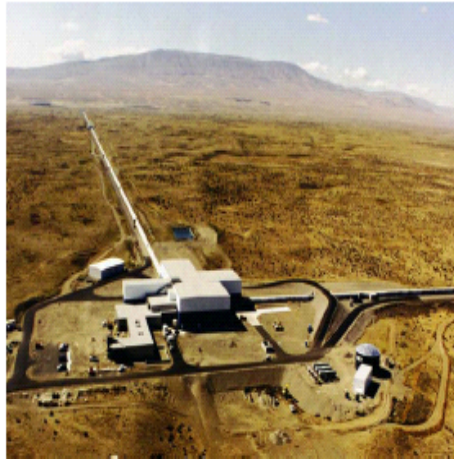
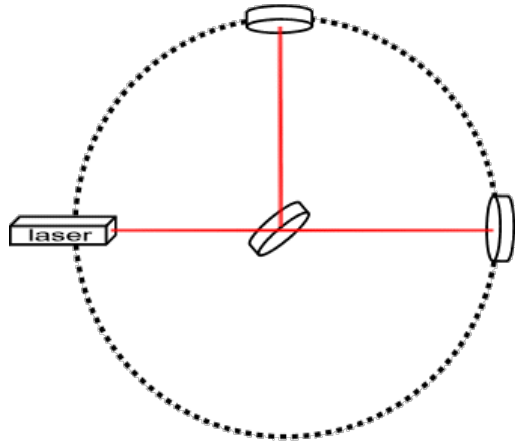


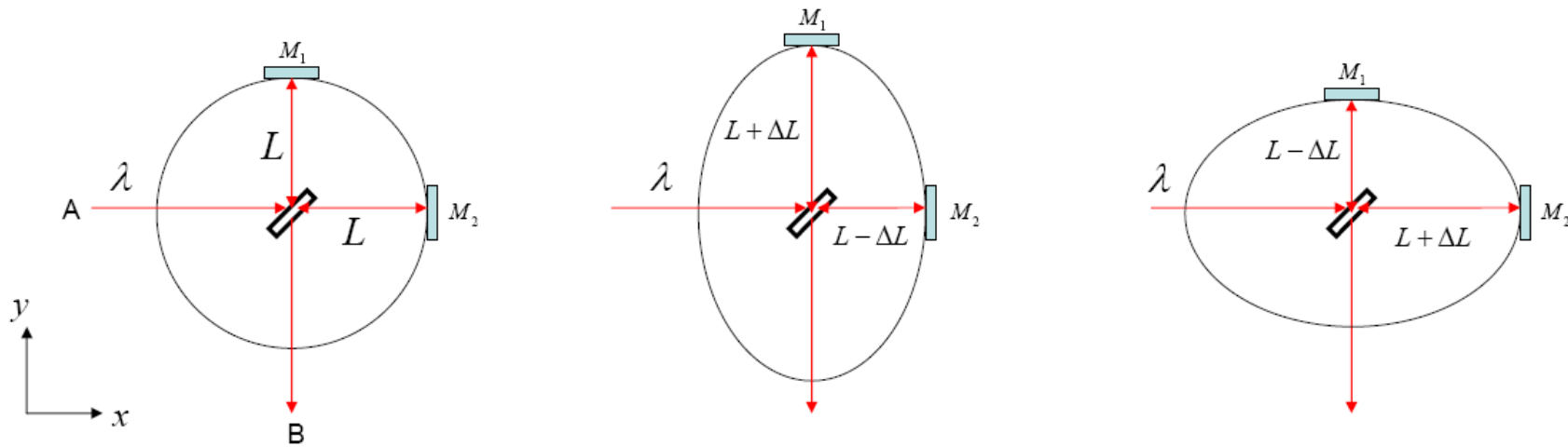
Auriga, LNL





# 34 yrs on - Interferometric ground-based detectors





Gravitational wave  $\mathbf{h} = h\mathbf{e}_+$  propagating along  $z$  axis.

Fractional change in proper separation

$$\frac{\Delta L}{L} = \frac{h}{2}$$

More generally, for  $\mathbf{h} = h \mathbf{e}_+$

Detector 'sees'

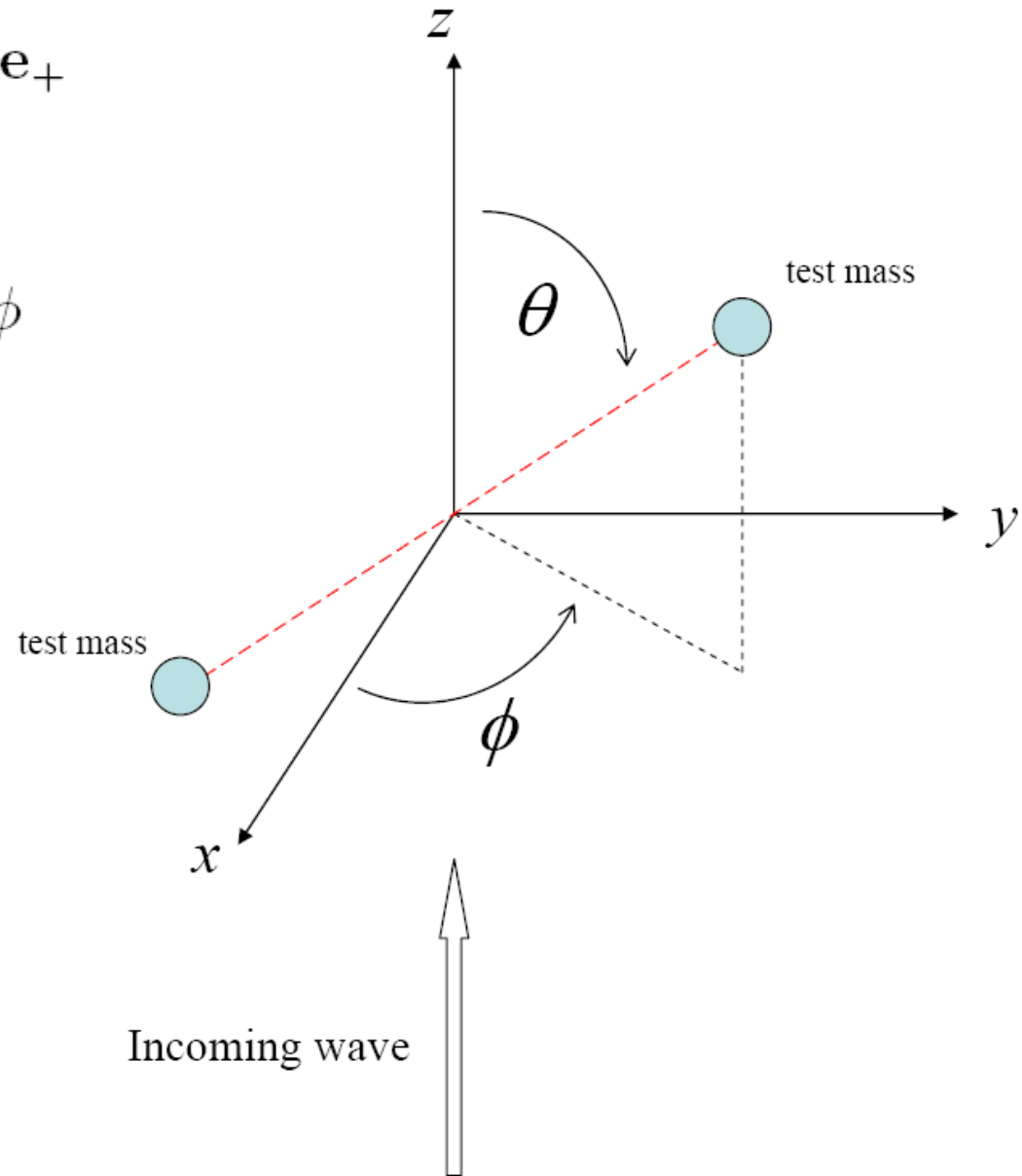
$$h_+ = h \sin^2 \theta \cos 2\phi$$

Maximum response for

$$\theta = \pi/2 \quad \phi = 0$$

Null response for

$$\theta = 0 \quad \phi = \pi/4$$



More generally, for  $\mathbf{h} = h \mathbf{e}_x$

Detector 'sees'

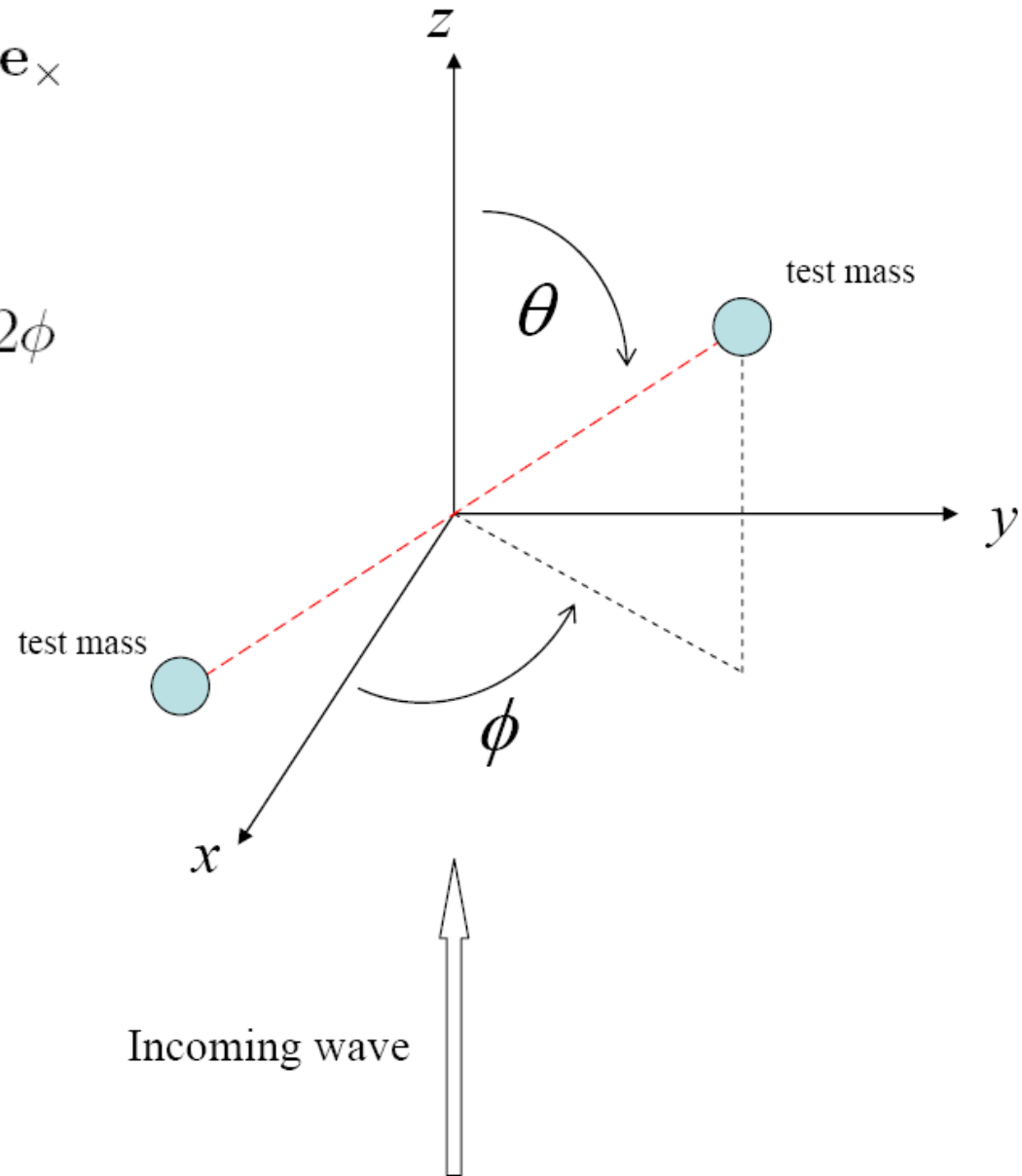
$$h_x = h \sin^2 \theta \sin 2\phi$$

Maximum response for

$$\theta = \pi/2 \quad \phi = \pi/4$$

Null response for

$$\theta = 0 \quad \phi = 0$$





# Astrofisica Nucleare e Subnucleare

## Sources of GW

# Gravitational Wave emission (quadrupole formalism)

Emission equation in the TT Gauge:  $\nabla^2 h_{\mu\nu}^{TT} = -\frac{16\pi G}{c^4} T_{\mu\nu}$

Retarded solution:  $h_{\mu\nu}^{TT}(\vec{x}, t) = \frac{2G}{Rc^4} \ddot{Q}_{\mu\nu}^{TT}(t - R/c)$

Hence:  $h_+^{TT}(\vec{x}, t) = \frac{G}{Rc^4} [\ddot{Q}_{11}^{TT} - \ddot{Q}_{22}^{TT}](t - R/c)$        $h_{\times}^{TT}(\vec{x}, t) = \frac{2G}{Rc^4} [\ddot{Q}_{12}^{TT}](t - R/c)$

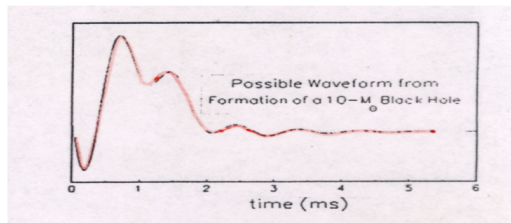
Where the **reduced quadrupole** moment:

$$Q_{\mu\nu}^{TT} = \iiint d^3x \rho (x_{\mu} x_{\nu} - \frac{1}{3} \delta_{\mu\nu} r^2)$$

Regular quadrupole (inertia) moment:  $q_{\mu\nu} = \iiint d^3x \rho x_{\mu} x_{\nu}$

$\rho \sim T_{00}/c^2$  : density of the source

# Tipi di segnale

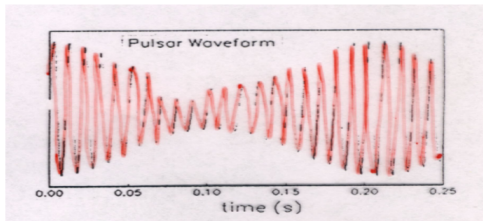


## SUPERNOVAE.

If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

## Information

Inner detailed dynamics of supernova  
See NS and BH being formed  
Nuclear physics at high density

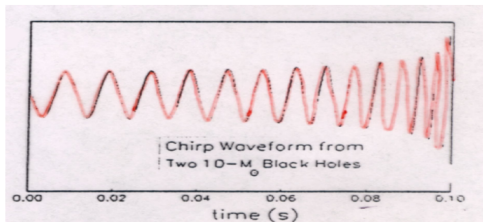


## SPINNING NEUTRON STARS.

Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

## Information

Neutron star locations near the Earth  
Neutron star Physics  
Pulsar evolution

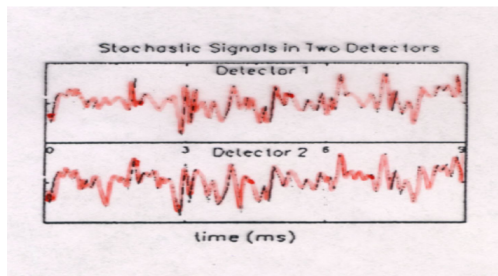


## COALESCING BINARIES.

Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

## Information

Masses of the objects  
BH identification  
Distance to the system  
Hubble constant  
Test of strong-field general relativity



## STOCHASTIC BACKGROUND.

Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

## Information

Confirmation of Big Bang, and inflation  
Unique probe to the Planck epoch  
Existence of cosmic strings

## 9. The Production of Gravitational Waves (pgs 76 - 80)

We can understand something important about the nature of gravitational radiation by drawing analogies with the formulae that describe electromagnetic radiation. This approach is crude at best since the electromagnetic field is a vector field while the gravitational field is a tensor field, but it is good enough for our present purposes. Essentially, we will take familiar electromagnetic radiation formulae and simply replace the terms which involve the Coulomb force by their gravitational analogues from Newtonian theory.

$$L_{\text{electric dipole}} \propto e^2 \ddot{\mathbf{d}}^2$$

Net electric  
dipole moment

$$L_{\text{magnetic dipole}} \propto \ddot{\mu}$$

$$\mu = \sum_{q_i} (\text{position of } q_i) \times (\text{current due to } q_i)$$

Gravitational analogues?...

Mass dipole moment:

$$\mathbf{d} = \sum_{A_i} m_i \mathbf{x}_i$$

But  $\dot{\mathbf{d}} = \sum_{A_i} m_i \dot{\mathbf{x}}_i \equiv \mathbf{p}$

Conservation of **linear momentum** implies no mass dipole radiation

$$L_{\text{magnetic dipole}} \propto \ddot{\mu}$$

$$\mu = \sum_{q_i} (\text{position of } q_i) \times (\text{current due to } q_i)$$

Gravitational analogues?...

$$\mu = \sum_{A_i} (\mathbf{x}_i) \times (m_i \mathbf{v}_i) \equiv \mathbf{J}$$

Conservation of **angular momentum** implies no mass dipole radiation

Also, the quadrupole of a **spherically symmetric mass distribution** is zero.

Metric perturbations which are spherically symmetric don't produce gravitational radiation.

Example: binary neutron star system.

$$h_{\mu\nu} = \frac{2G}{c^4 r} \ddot{I}_{\mu\nu}$$

where  $I_{\mu\nu}$  is the **reduced quadrupole moment** defined as

$$I_{\mu\nu} = \int \rho(\vec{r}) \left( x_\mu x_\nu - \frac{1}{3} \delta_{\mu\nu} r^2 \right) dV$$

Consider a binary neutron star system consisting of two stars both of Schwarzschild mass  $M$ , in a circular orbit of coordinate radius  $R$  and orbital frequency  $f$ .

$$I_{xx} = 2MR^2 \left[ \cos^2(2\pi ft) - \frac{1}{3} \right]$$

$$I_{yy} = 2MR^2 \left[ \sin^2(2\pi ft) - \frac{1}{3} \right]$$

$$I_{xy} = I_{yx} = 2MR^2 [\cos(2\pi ft) \sin(2\pi ft)]$$



Thus

$$h_{xx} = -h_{yy} = h \cos(4\pi ft)$$

$$h_{xy} = h_{yx} = -h \sin(4\pi ft)$$

where

$$h = \frac{32\pi^2 G M R^2 f^2}{c^4 r}$$

So the binary system emits gravitational waves at **twice** the orbital frequency of the neutron stars.

Also 
$$h = 2.3 \times 10^{-28} \frac{R^2 [\text{km}] f^2 [\text{Hz}]}{r [\text{Mpc}]}$$

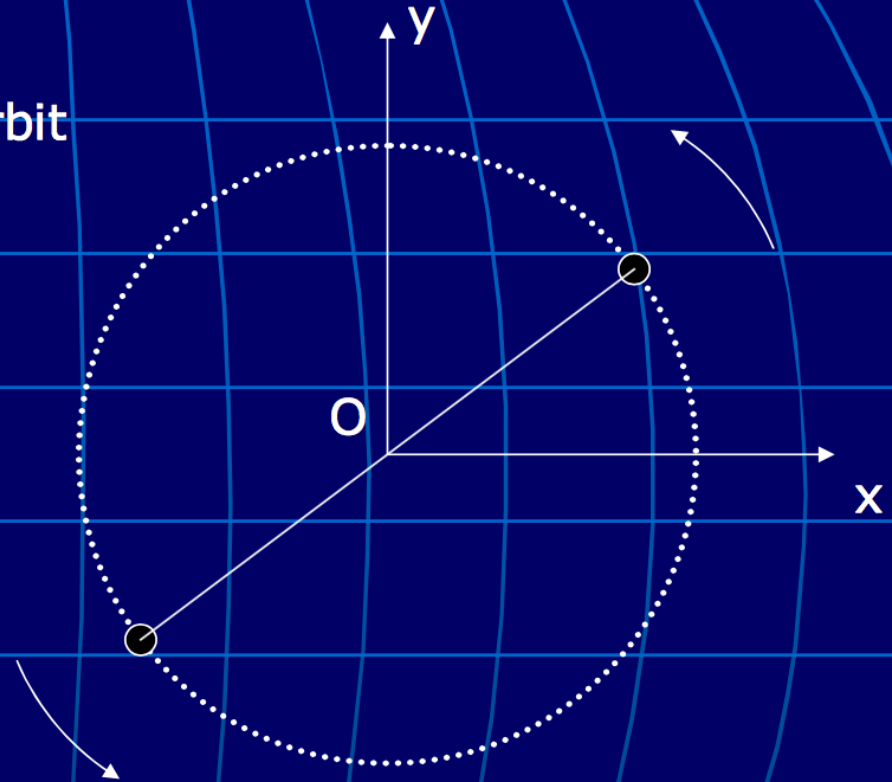


**Huge  
Challenge!**

# Gravitational Wave emission: an example

2 identical point masses in circular orbit  
around their center of mass

- Orbital plane :  $xOy$
- Mass :  $M$
- Orbit radius :  $a$
- Orbital frequency :  $f_0 = 2\pi\omega_0$



Q: Compute the 2 amplitudes  $h_+(t)$  and  $h_x(t)$  at a distance  $r$  on the  $z$  axis  
(without taking into account the radiation reaction !)

# Gravitational Wave emission: an example

Positions of the two masses:

$$x_1(t) = a \cos(\omega_0 t)$$

$$x_2(t) = -a \cos(\omega_0 t)$$

$$y_1(t) = a \sin(\omega_0 t)$$

$$y_2(t) = -a \sin(\omega_0 t)$$

So compute the reduced inertia tensor:

$$Q = \begin{pmatrix} ma^2 \left( \frac{1}{3} + \cos(2\omega_0 t) \right) & ma^2 \sin(2\omega_0 t) & 0 \\ ma^2 \sin(2\omega_0 t) & ma^2 \left( \frac{1}{3} - \cos(2\omega_0 t) \right) & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

After projection on the z direction:

$$h_+(t) = -\frac{2G}{rc} ma^2 \omega^2 \cos(\omega(t - r/c))$$

$$h_x(t) = -\frac{2G}{rc} ma^2 \omega^2 \sin(\omega(t - r/c))$$

Where  $\omega = 2\omega_0$  is **TWICE** the orbital angular frequency

Note that if we look on the x direction:

$$h_+(t) = -\frac{G}{rc} ma^2 \omega^2 \cos(\omega(t - r/c))$$

$$h_x(t) = 0$$

Face-on binary => **circular** polarization

Edge-on binary => **linear** polarization

# Gravitational Wave emission: Orders of magnitude

Luminosity (Einstein quadrupole formula):

$$P = \frac{G}{5c^5} \left\langle \ddot{Q}_{\mu\nu} \ddot{Q}^{\mu\nu} \right\rangle$$

$G/5c^5 \sim 10^{-53} \text{ W}^{-1}$

Factor ridiculously « small » !

source	distance	$h$	$P$ (W)
Steel bar, 500 T, $\varnothing = 2$ m L = 20 m, 5 cycles/s	1 m	$2 \times 10^{-34}$	$10^{-29}$
H bomb, 1 megatonne Asymmetry 10%	10 km	$2 \times 10^{-39}$	$10^{-11}$
Supernova $10 M_{\odot}$ asymmetry 3%	10 Mpc	$10^{-21}$	$10^{44}$
Coalescence 2 black holes $10 M_{\odot}$	10 Mpc	$10^{-20}$	$10^{50}$

**Hertz experiment is impossible for GWs ...**

# Gravitational Wave emission and compact stars

© J. Weber (1974)

Pb :  $G/c^5$  is very « small ».

$c^5/G$  would be much better !!!

Source : mass  $M$ , size  $R$ , period  $T$ , asymmetry  $a \Rightarrow \ddot{Q} \approx a M R^2 / T^3$

Quadrupole formula becomes :

$$P \approx \frac{G}{c^5} a^2 \frac{M^2 R^4}{T^6}$$

New parameters

- characteristic speed  $v$
- Schwarzschild Radius  $R_s = 2GM/c^2$

$$P \approx \frac{c^5}{G} a^2 \left( \frac{R_s}{R} \right)^2 \left( \frac{v}{c} \right)^6$$

Huge luminosity if

- $R \rightarrow R_s$
- $v \rightarrow c$
- $a \rightarrow 1$

**compact stars**

# Gravitational Wave sources

## Compact stars

“High frequency” sources ( $f > 1$  Hz)

- supernovae (bursts)
- binary inspirals (chirps)
- black holes ringdowns (damped sine)
- isolated neutron stars, pulsars (periodic sources)
- stochastic background (stochastic)
- ...

Amplitudes  $h(t)$  on Earth ?  
Rate of events ?

# Gravitational Supernovae

**type II SN** = gravitational collapse of the core (Fe) of a massive star ( $> 10 M_{\odot}$ ) after having burned all the H fuel  $\rightarrow$  neutron star formation

GW Emission ? Depends on asymmetry (**poorly known**)

Sources of asymmetry

- fast rotation (instabilities)
- companion star

Modern models :

$h \sim 10^{-23}$  @ 10 Mpc  
 $f$  peaks between 0.3 and 1 kHz  
1 SN/ 40 yrs / galaxy

**Black hole formation:**

Progenitor too massive  $\rightarrow$  collapse  $\rightarrow$  black hole

$h \sim 10^{-22}$  @ 10 Mpc  
 $f > 1$  kHz

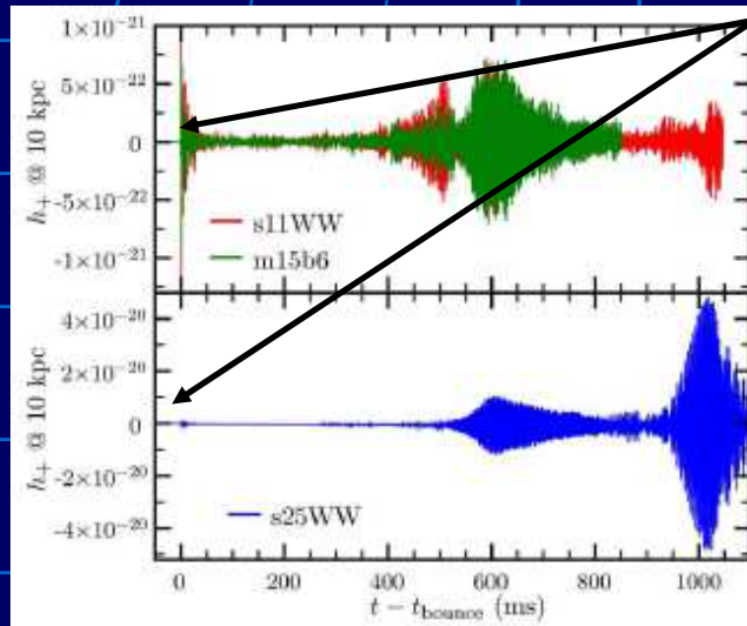
**+ oscillations...**



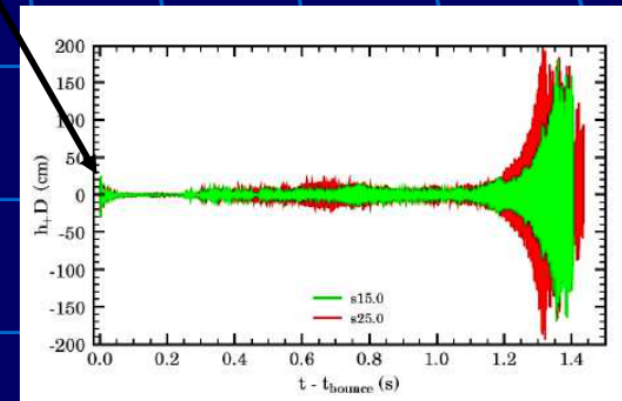
# Gravitational Supernovae: GW amplitudes

+ coupling between the proto-neutron star and the envelope  
(rotation instabilities induced by turbulence and accretion)

**collapse**



**Ott and Burrows, 2006.**



**Marek et al., 2008.**

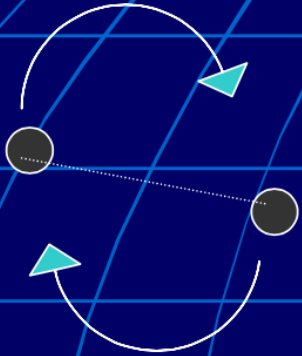
**Main conclusions:**

+ Waveforms not well predicted

+ weak amplitudes -> only Galactic Supernova detectable ?



# Binary inspirals: GW amplitudes



System of 2 close compact stars

- Varying quadrupole -> GW emission
- GW emission -> loss of energy and angular momentum
- Loss of (gravitational) energy -> stars become closer
- Finally 2 stars merge (or disrupt)

Spiraling phase  
(lowest order)

$$h_+^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4} \frac{1 + \cos^2 i}{2} (\pi f(t))^{2/3} \cos \varphi(t)$$

$$h_x^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4} \cos i (\pi f(t))^{2/3} \sin \varphi(t)$$

A "chirp"

$$h(t) \propto (t_c - t)^{-1/4}$$

where

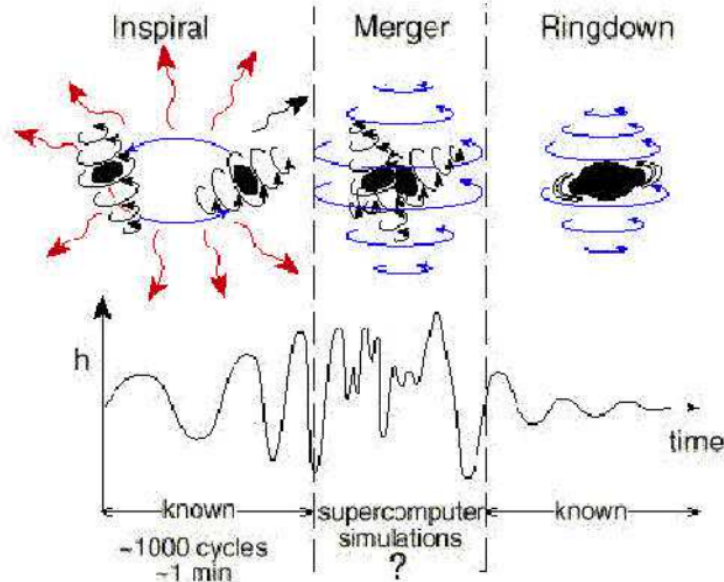
- Chirp mass:  $M = \mu^{3/5} M_{tot}^{2/5}$

- frequency:  $f(t) = \frac{1}{\pi} \left( \frac{256 (GM)^{5/3}}{5 c^5} (t_c - t) \right)^{-3/8}$

$t_c$  : coalescence time

- Phase:  $\varphi(t) = -2 \left( \frac{G^{5/3}}{c^5} \right)^{-3/8} \left( \frac{t_c - t}{5M} \right)^{5/8} + cste$

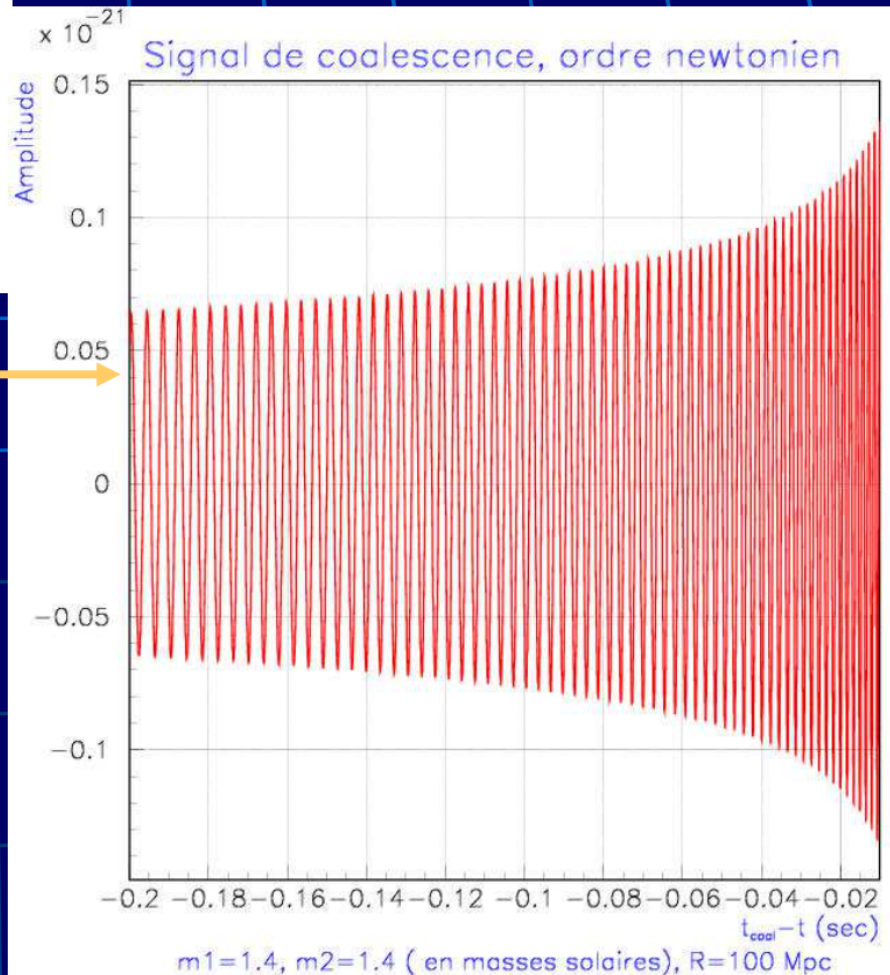
# Binary inspirals: the chirp signal



2 neutron stars @ 10Mpc

$$h_{max} \sim 10^{-21}$$

$f_{max}$  (last stable orbit) ~ 1 kHz



- « inspiral » :  $h(t)$  is a chirp
- « merger » : recent numerical progress
- « ringdown » : black hole quasi normal modes

# Binary inspirals: rate of events (first generation detectors)

- **NS-NS:**  $1.4M_{\odot} + 1.4M_{\odot}$  (Kalogera et al astro-ph/0111452)
    - 0.001 – 1 / yr → 20 Mpc
  - **NS-BH:**  $1.4M_{\odot} + 10M_{\odot}$ 
    - 0.001 – 1 / yr → 43 Mpc
  - **BH-BH:**  $10M_{\odot} + 10M_{\odot}$ 
    - 0.001– 1 / yr → 100 Mpc
- **Gain Factor 10** on detector sensitivity  
→ gain **factor 1000** on the event rate

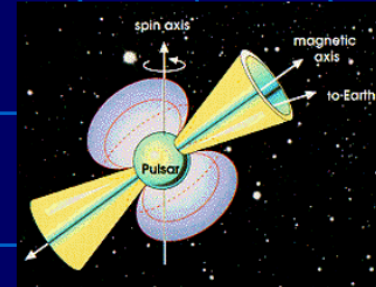
# Other sources

## Pulsars and rotating Neutron Stars

$10^5$  pulsars in the Galaxy, several thousands rapidly rotating.

Source of asymmetry ?

- rotation instabilities
- magnetic stress
- "mountains" on the solid crust ...



Radio-astronomy observation of pulsar slowdown sets upper limits on GW emission and neutron star asymmetry (if rate of slowdown totally assigned to GW emission)

⇒ Expected amplitudes are weak ( $h < 10^{-24}$ )

$$h \sim 10^{-26} \left( \frac{10 \text{ kpc}}{\text{distance}} \right) \left( \frac{f}{100 \text{ Hz}} \right)^2 \left( \frac{\epsilon}{10^{-6}} \right)$$

But the signal is periodic ! ("simple" Fourier analysis)

Signal to noise ratio  $S/N \propto \sqrt{T}$  where  $T$  is the observation time

# Other sources

## Stochastic background

A lot of possible ideas

- cosmological backgrounds, phase transitions
- cosmic string vibrations
- superposition of unresolved sources
- ...

GW density:

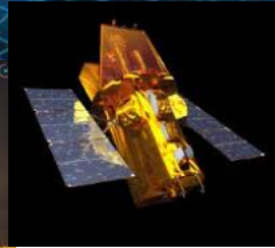
$$\Omega_{\text{GW}}(f) = \frac{1}{\rho_{\text{crit}}} \frac{d\rho_{\text{GW}}}{d \ln f}$$

Theoretical predictions (cosmology):  $h_0^2 \Omega_{\text{GW}} < 10^{-6}$  rather  $\rightarrow 10^{-13}$

LIGO/Virgo (1 yr integration time) sensitive to  $h_0^2 \Omega_{\text{GW}} \sim 10^{-7}$

Astrofisica Nucleare e Subnucleare  
Ground Detectors for GW





# Gravitational waves – Experiments and sources I PART



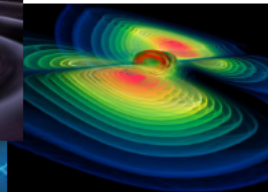
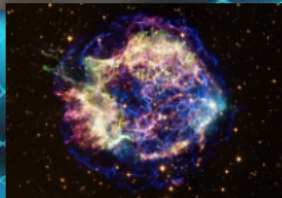
**M. Branchesi**



**(Università di Urbino/INFN Sezione di Firenze)**

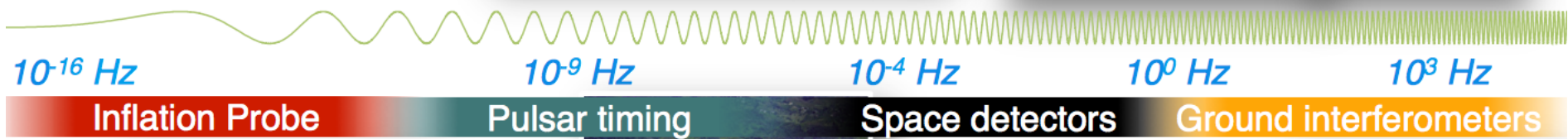
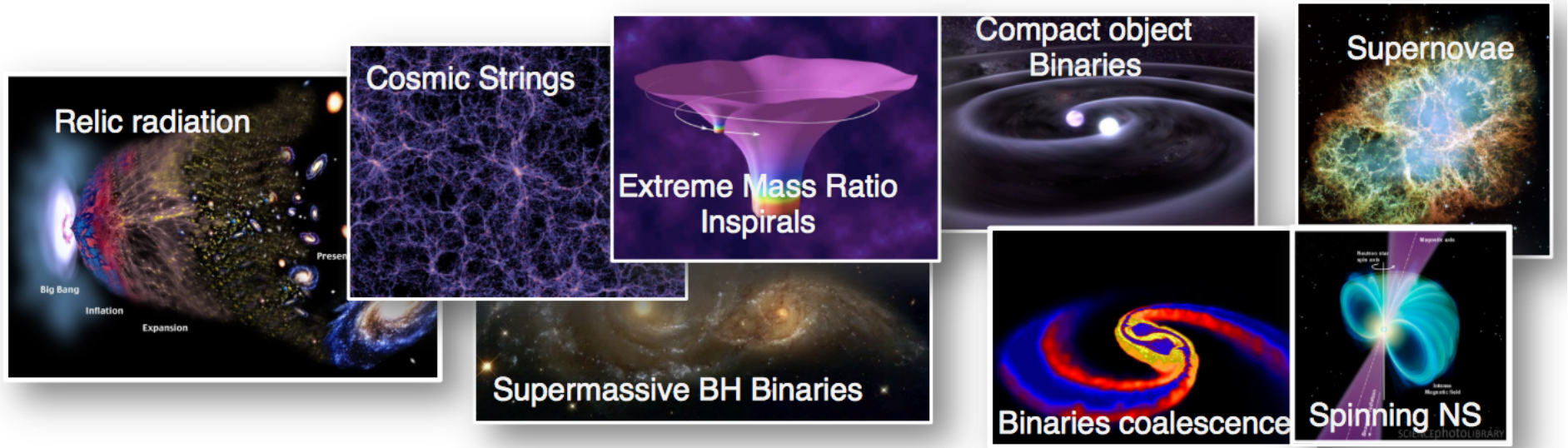


FIRST ICTP  
**ADVANCED SCHOOL ON  
 COSMOLOGY**  
 18-29 MAY 2015  
 Trieste, Italy



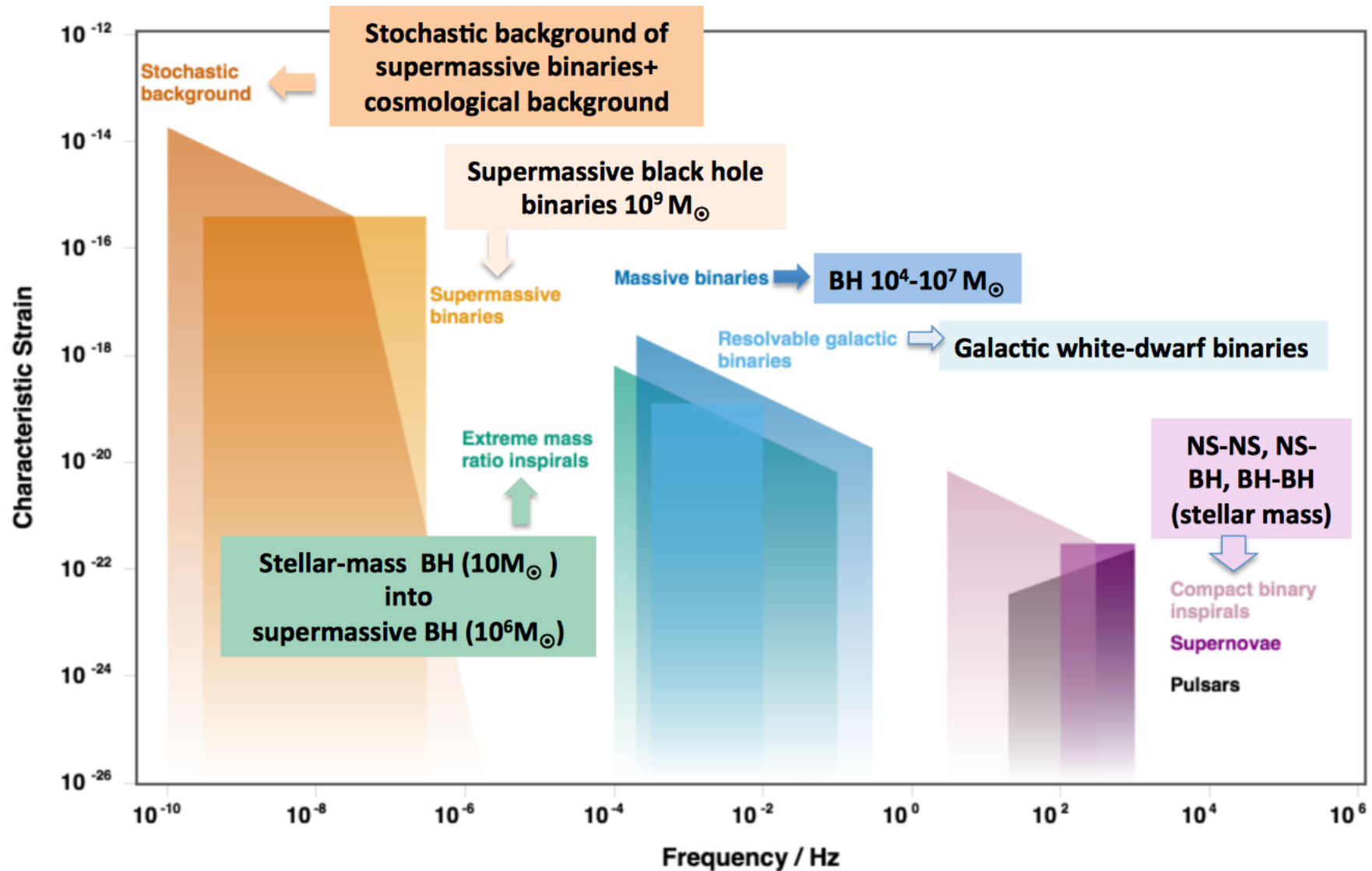


# The GW Spectrum



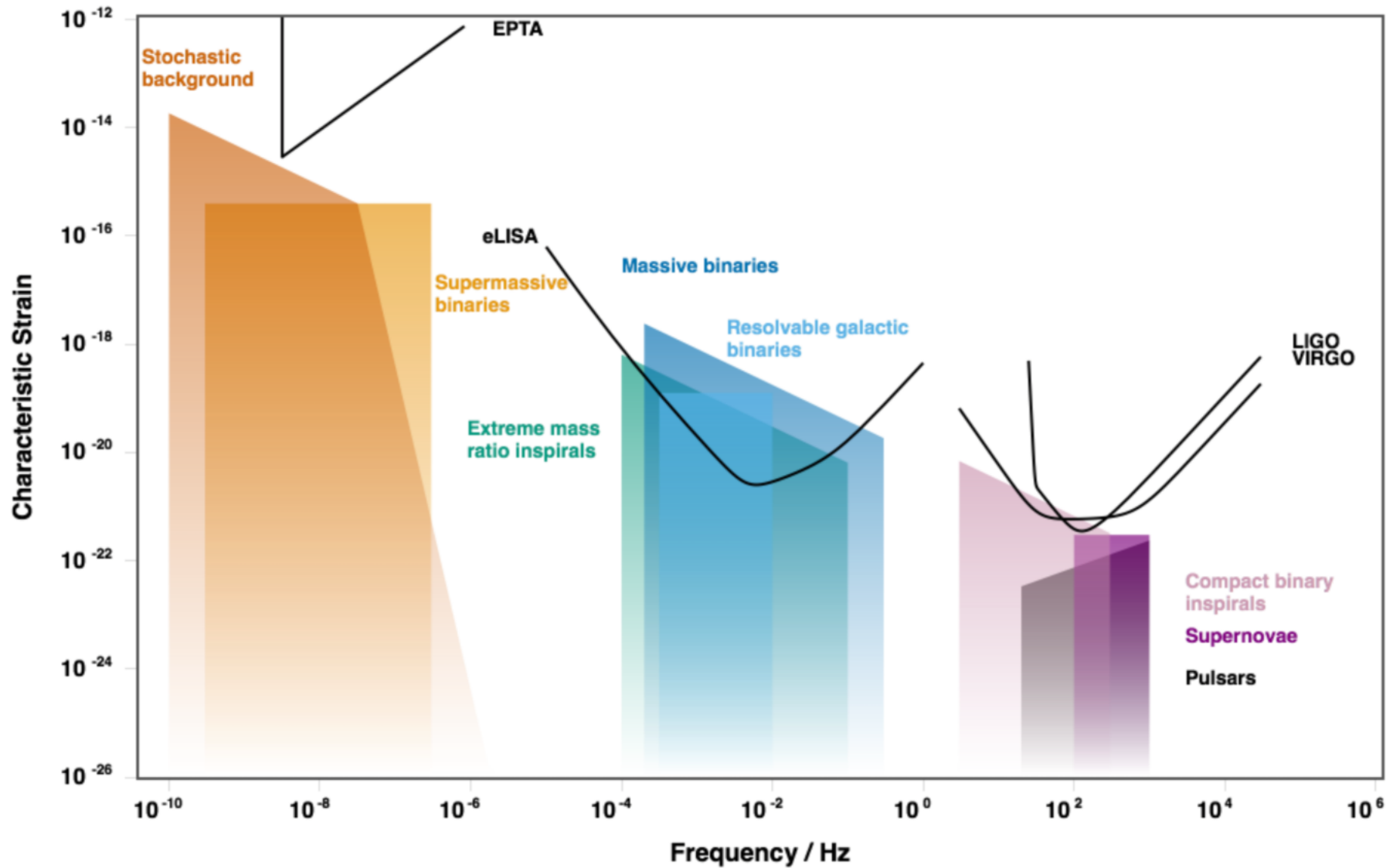


# Astrophysical Sources



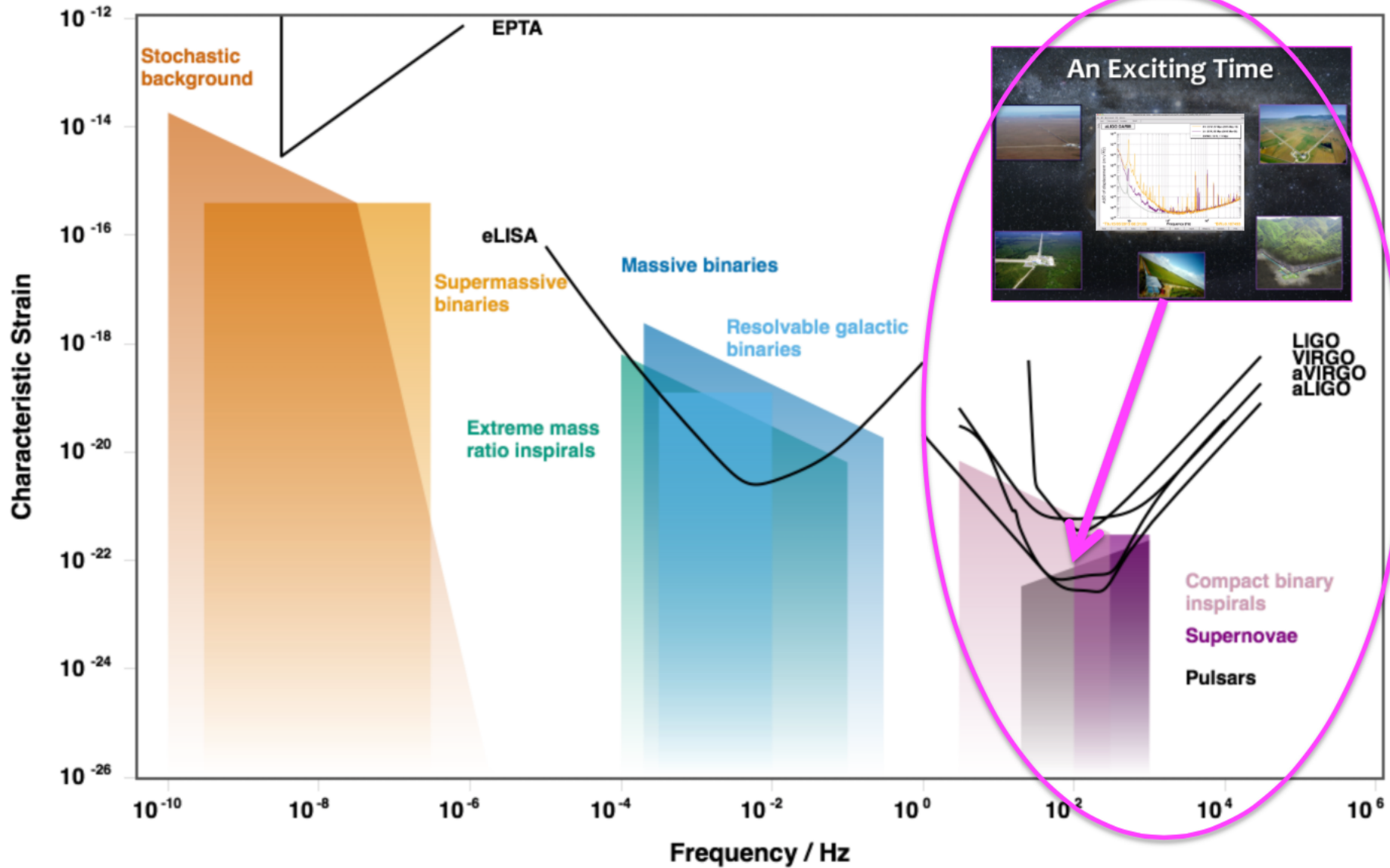
<http://rhcole.com/apps/GWplotter/>

# Astrophysical Sources

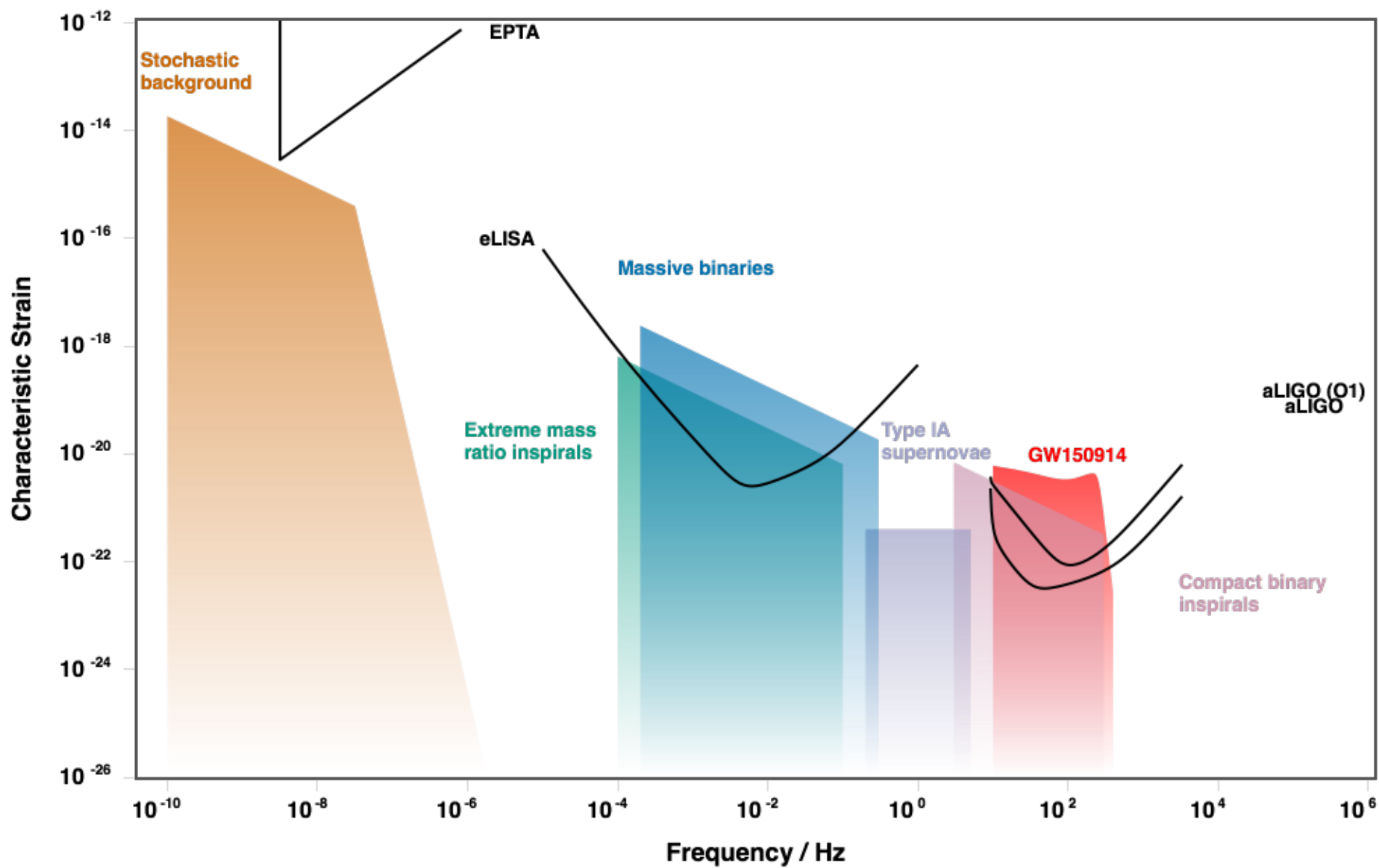


<http://rhcole.com/apps/GWplotter/>

# Astrophysical Sources



<http://rhcole.com/apps/GWplotter/>



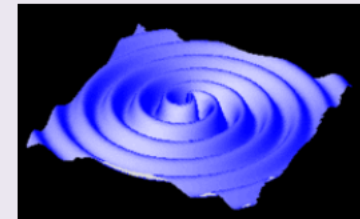
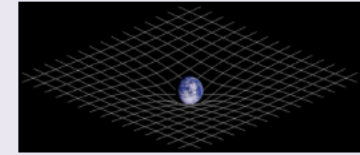
# To reiterate:



**1916 → Einstein's theory of relativity predicts the existence of a new type of wave: the gravitational waves**

**GWs are perturbations of the space-time metric:**

- Generated by mass distributions with time-varying quadrupole moments
- Propagating at the speed of light
- Change in the distance between stationary (inertial) masses



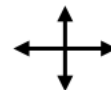
**According to GR, GWs have two independent polarization states**

Each GW signal can be described as a linear combination of them:

$$h = A_+ h_+(t) + A_x h_x(t)$$



Polarization "Plus"  $h_+$



"Cross"  $h_x$



# How can GWs be detected?

*A GW deforms space*

$$\Delta L = \frac{1}{2} L h(t)$$

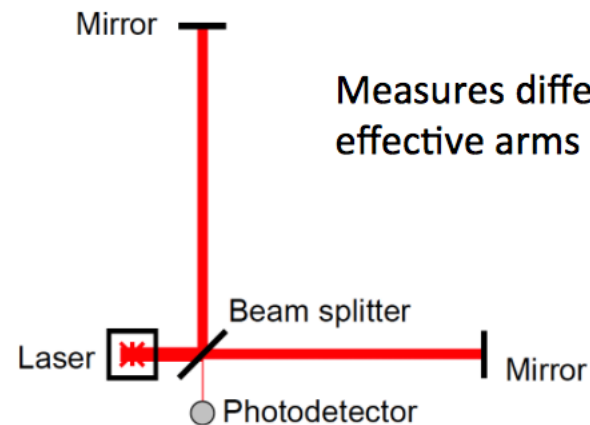
*The displacement is proportional to length:  
it is a **strain!***

Do we know how to detect displacement?

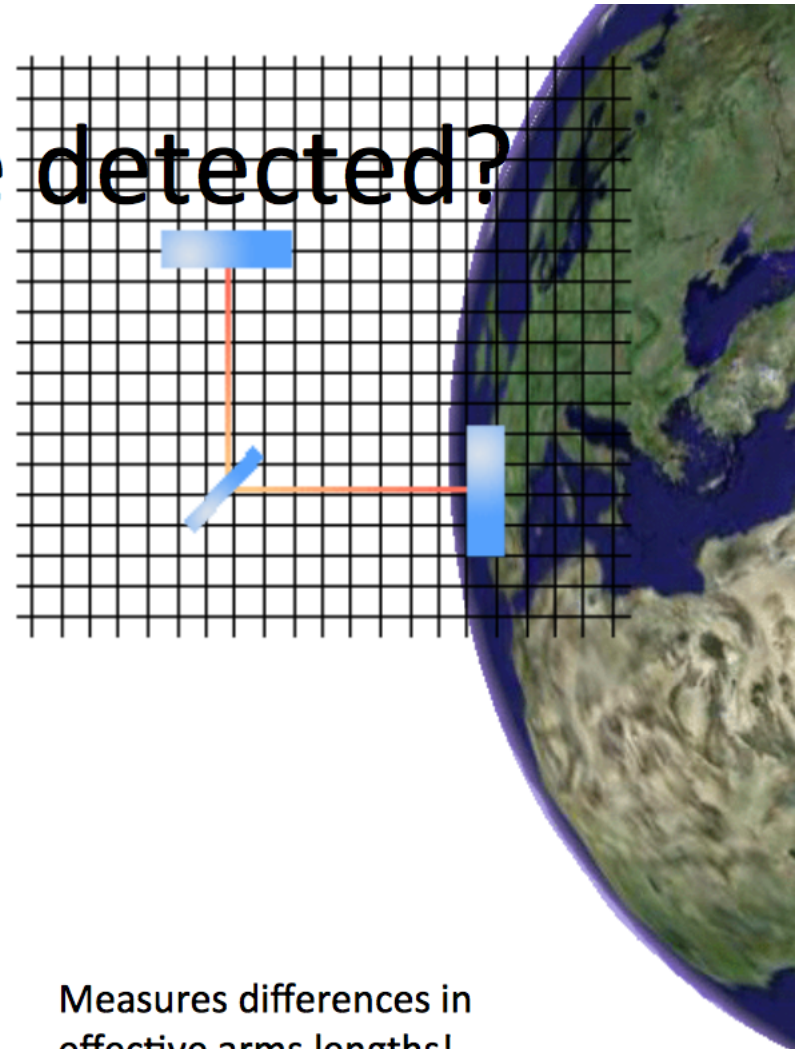
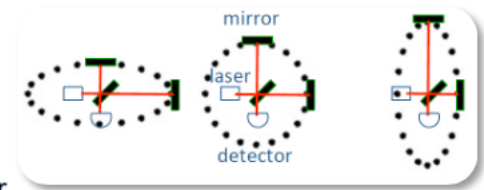


Michelson

*The length change is measured **interferometrically** by using a **laser light beam***

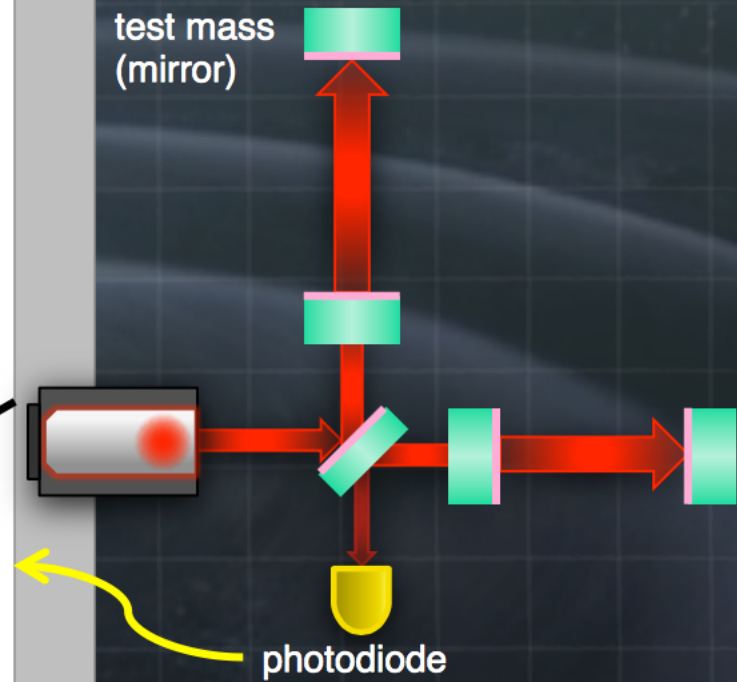
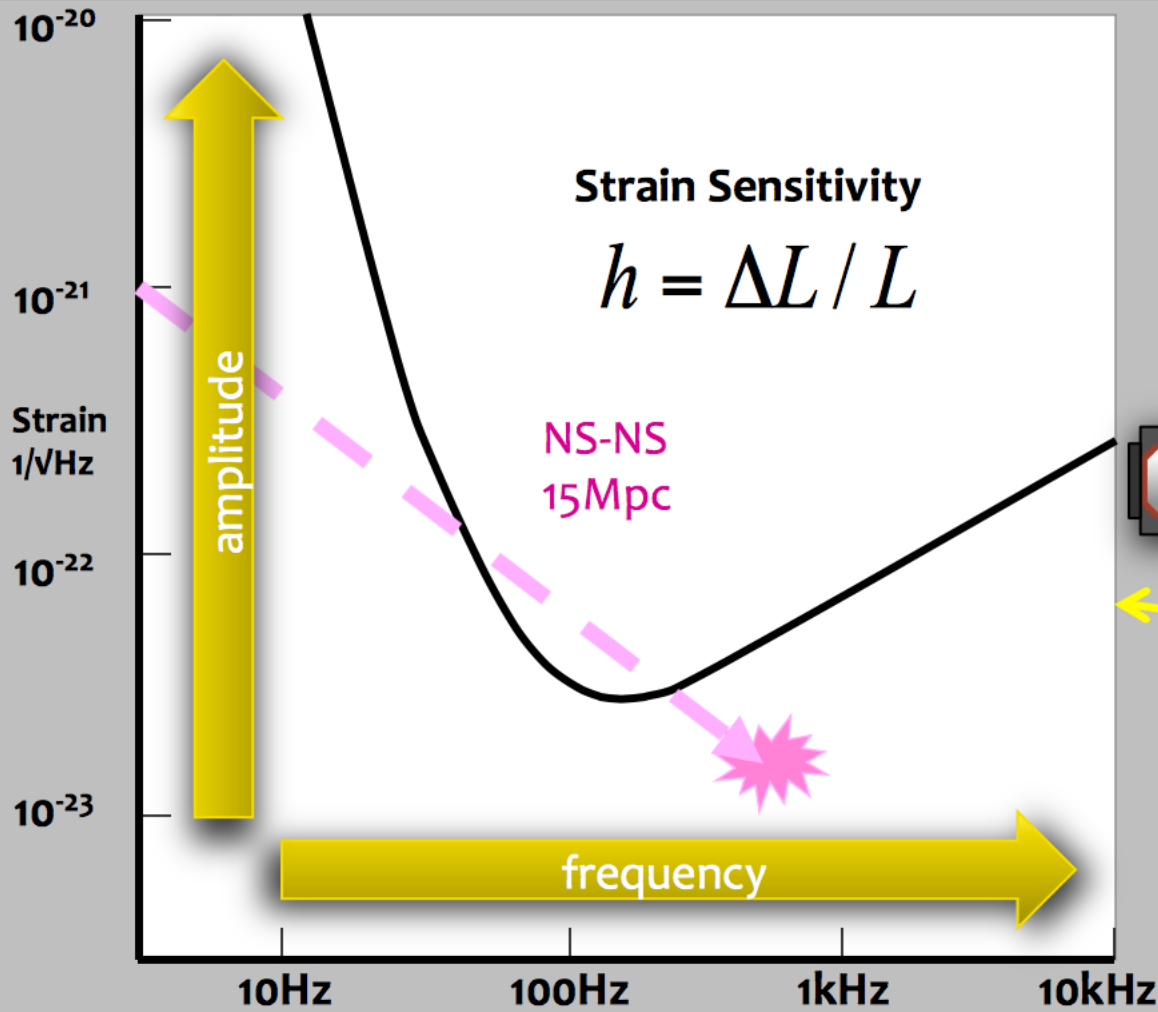


Measures differences in effective arms lengths!



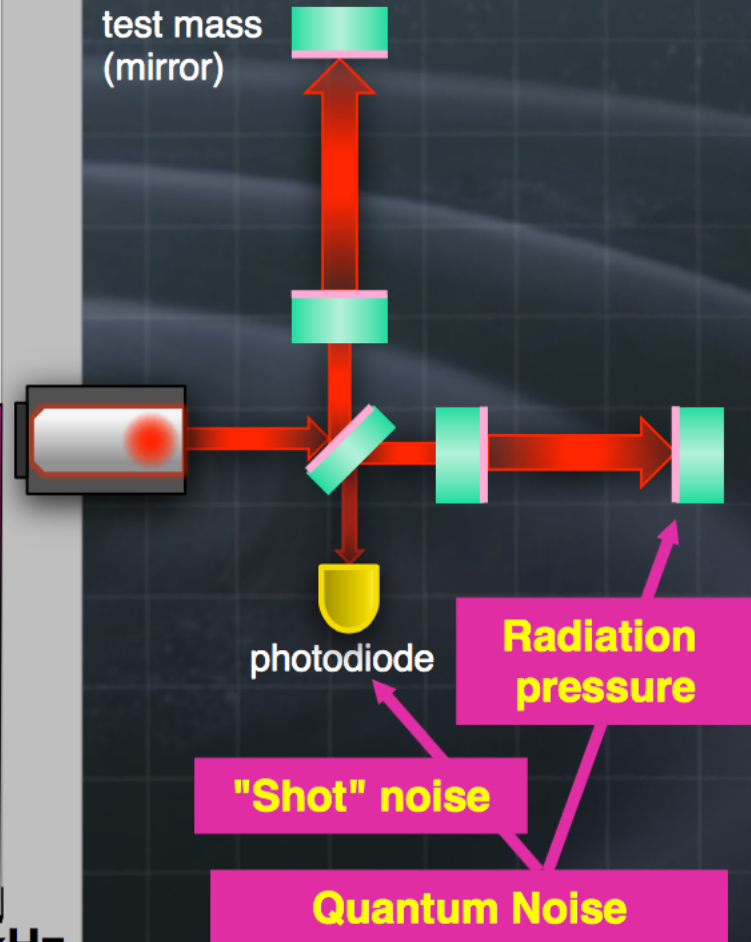
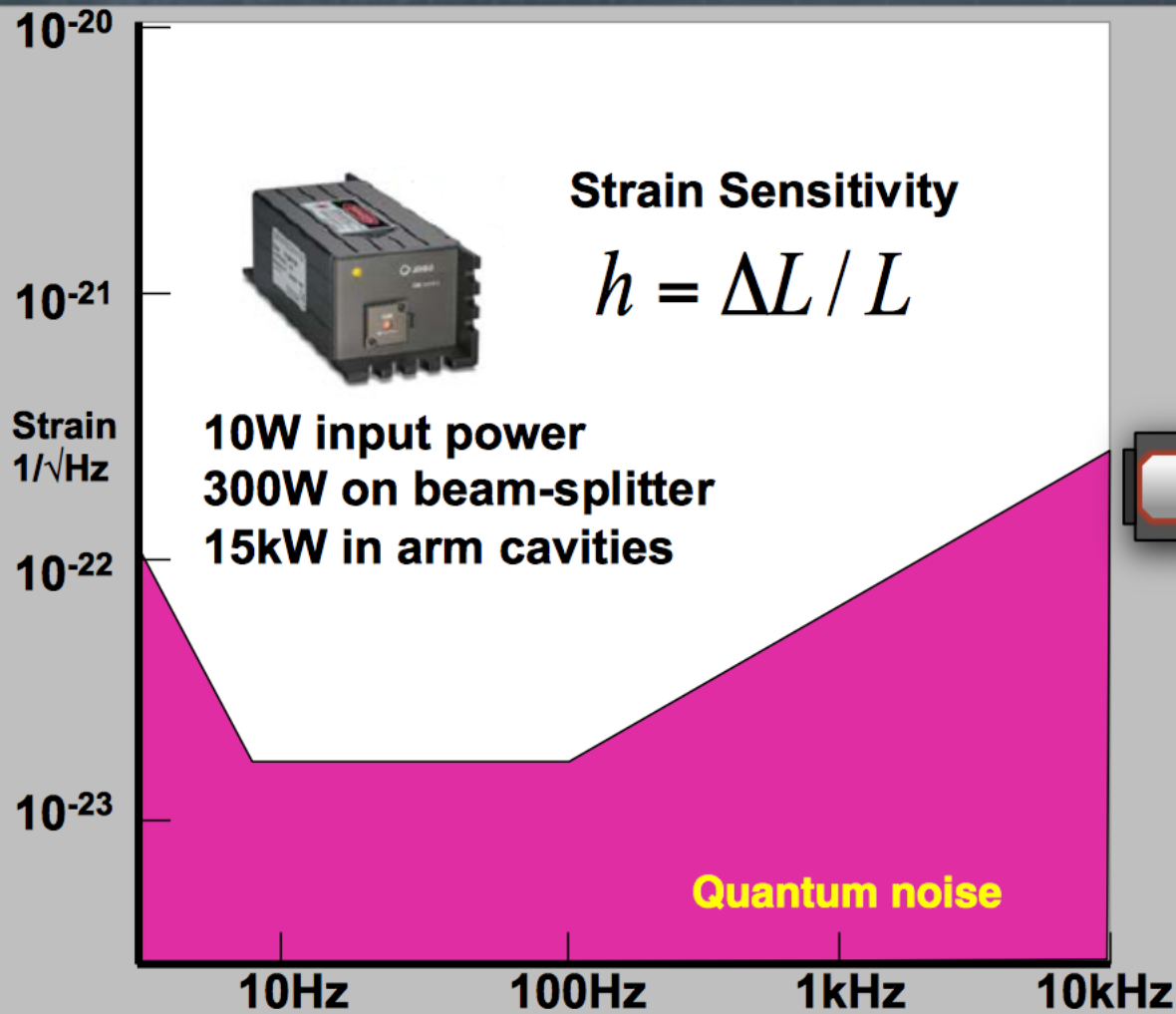


# First Generation Sensitivity



Slide Credit M. Evans,  
Amaldi 10

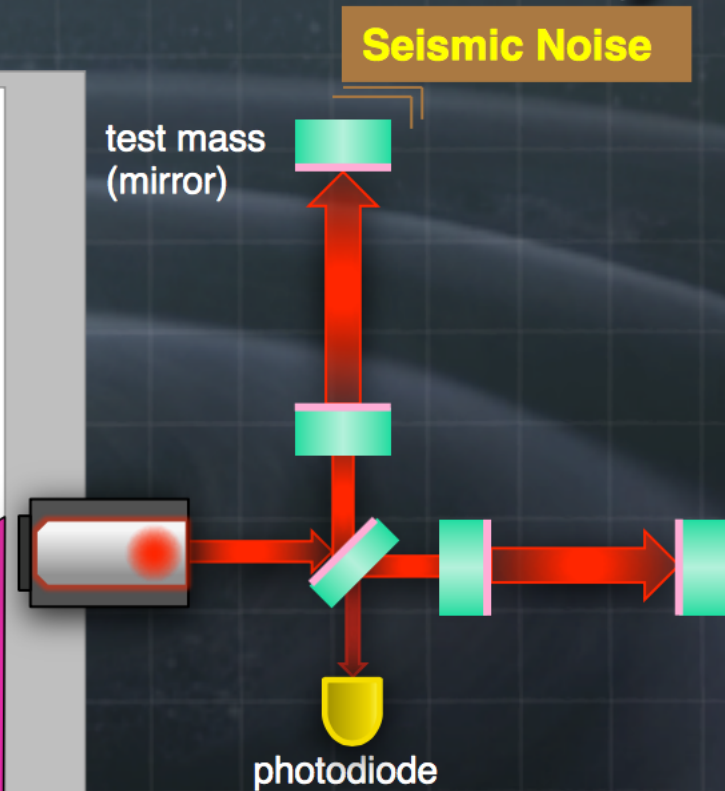
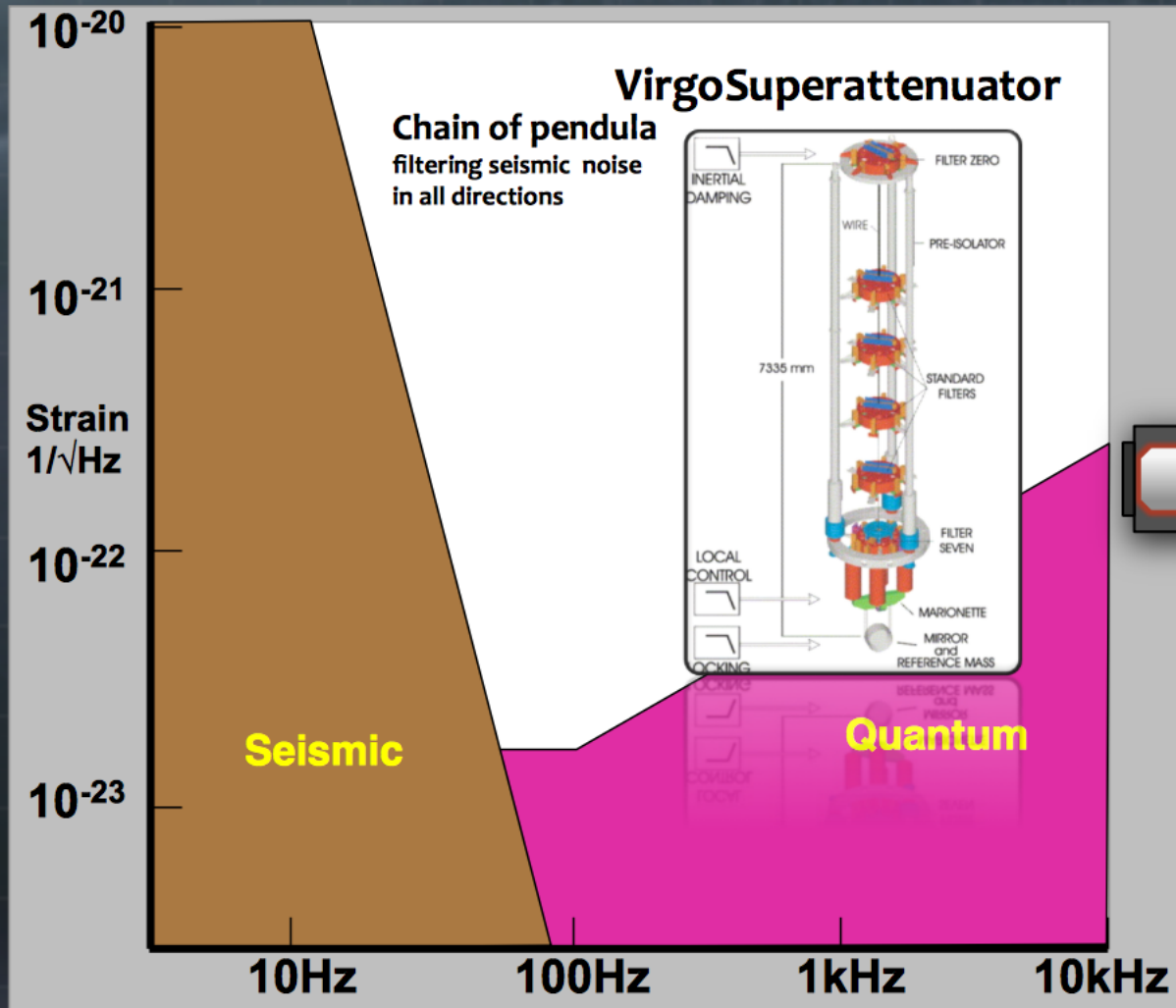
# First Generation Sensitivity



Slide Credit M. Evans,  
Amaldi 10



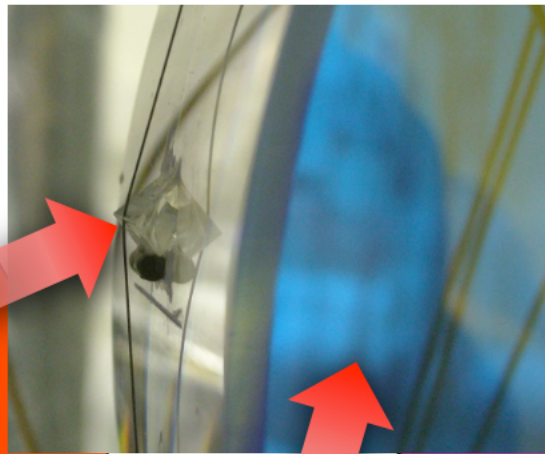
# First Generation Sensitivity



Slide Credit M. Evans,  
Amaldi 10

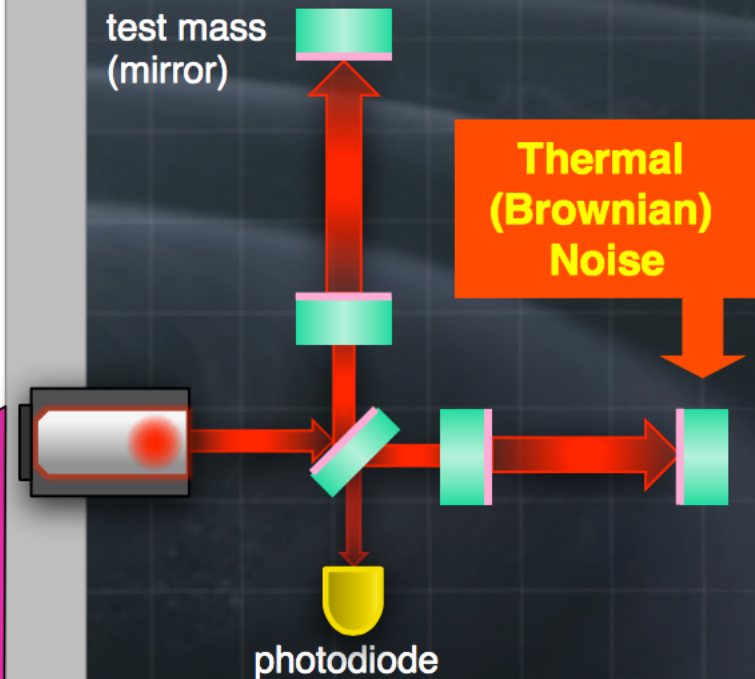
# First Generation Sensitivity

Wire Suspensions,  $Q \sim 100k$   
Fused Silica Test-Mass, 10kg



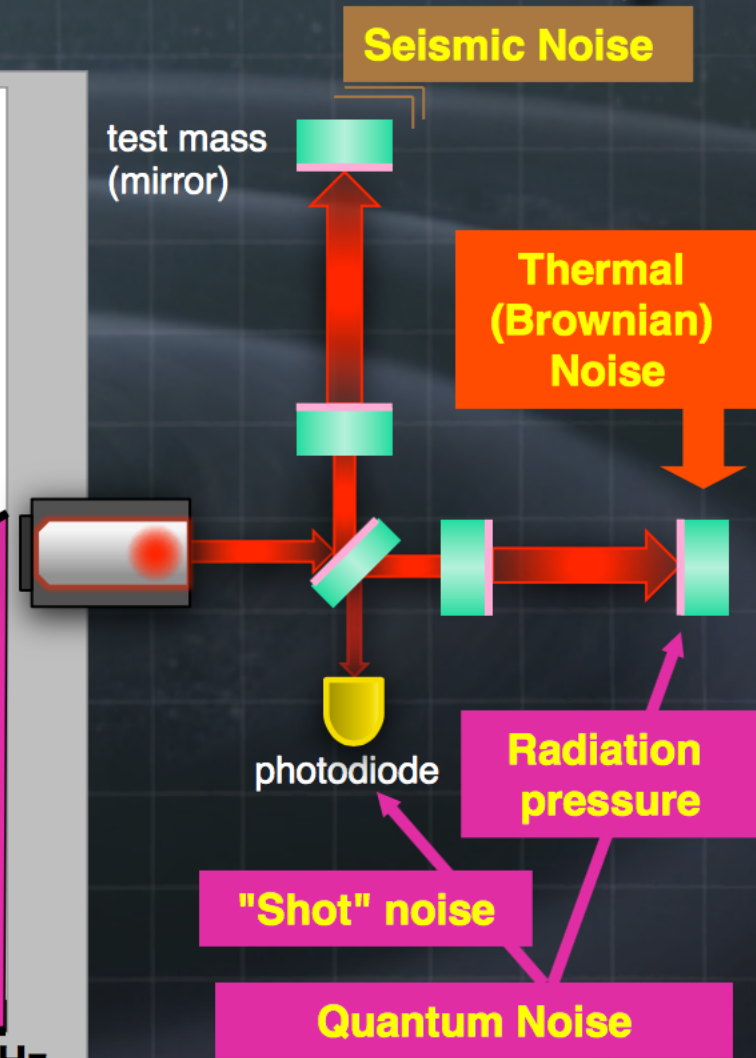
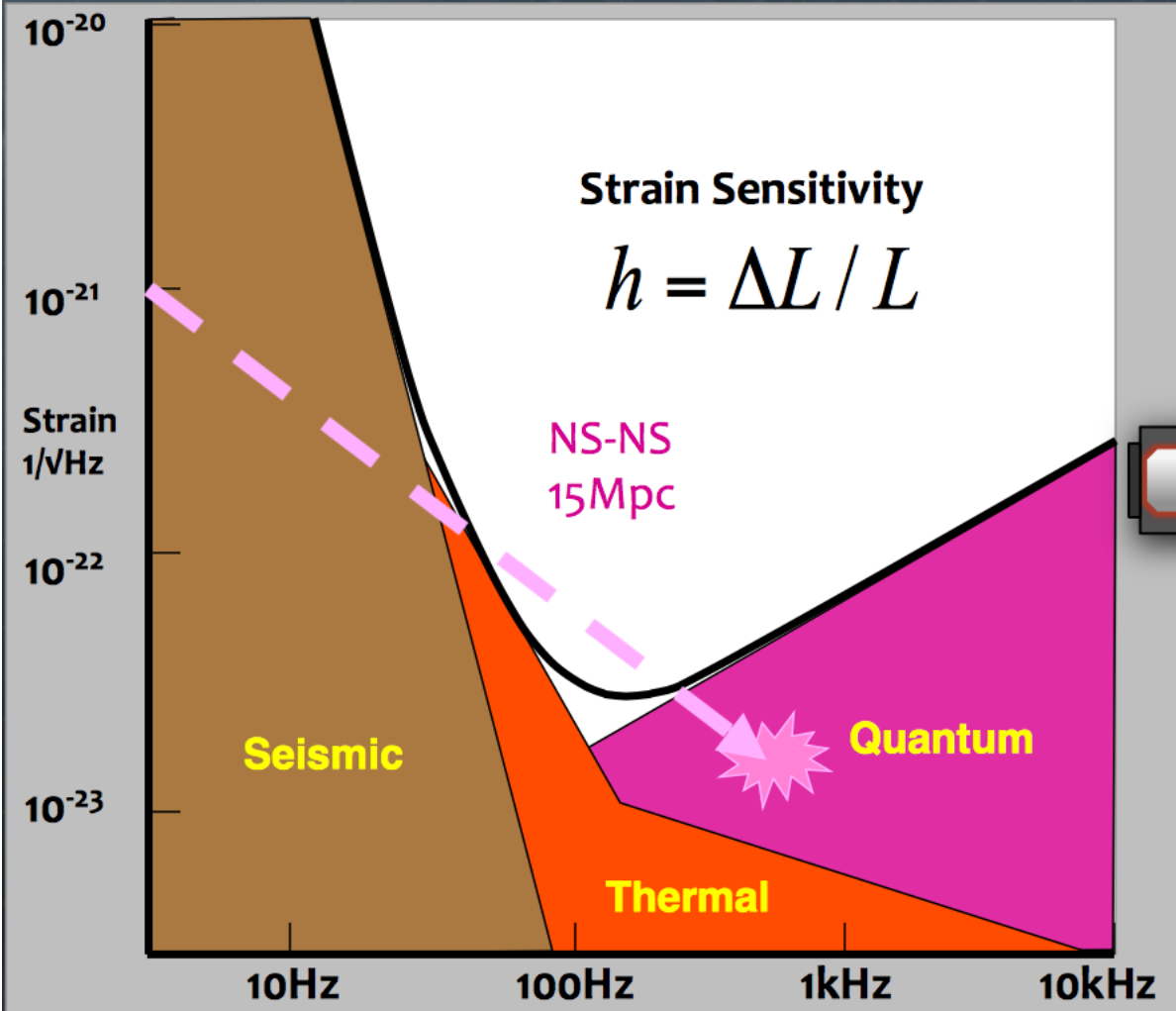
Thermal

Quantum



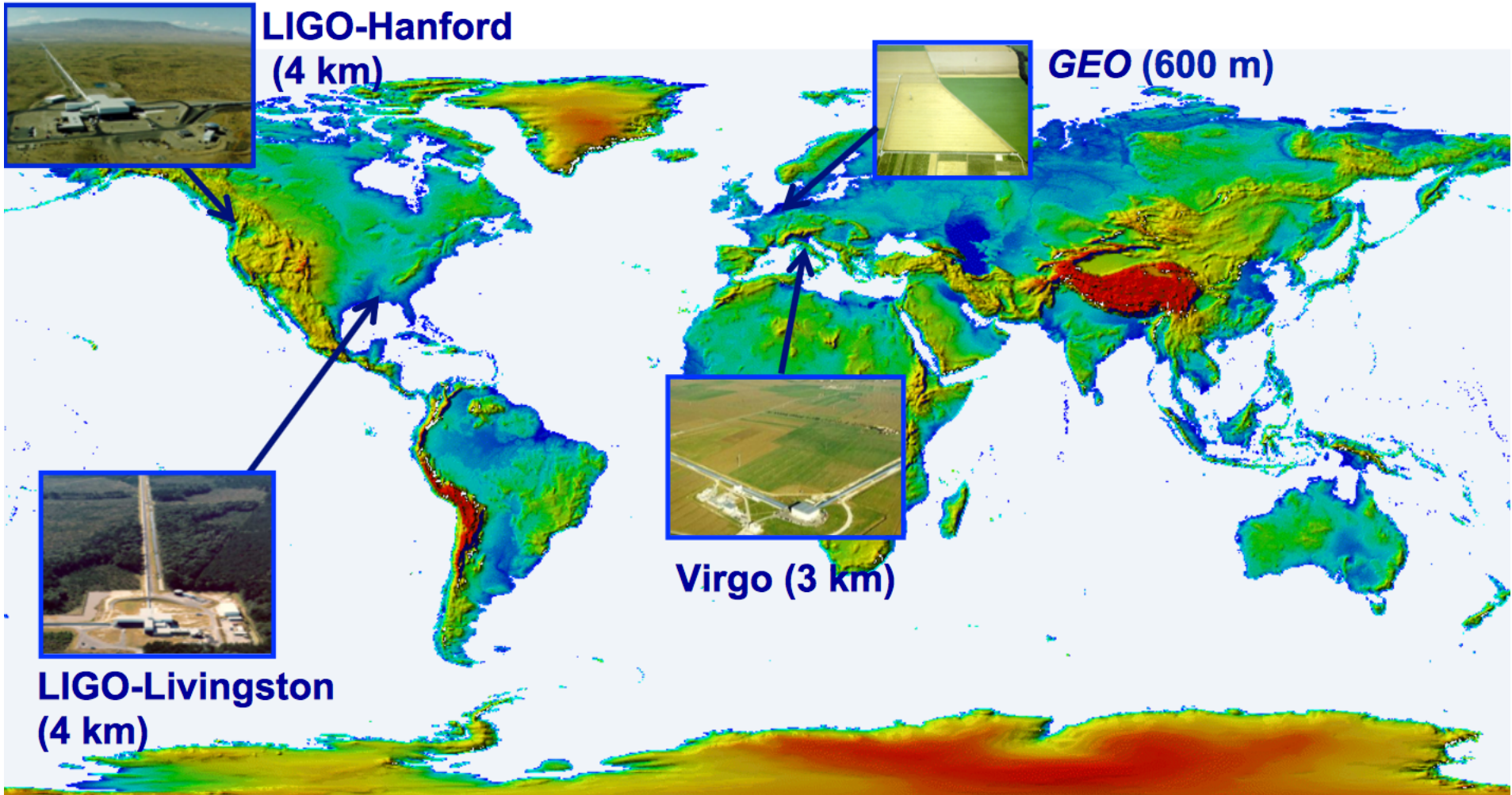
Slide Credit M. Evans,  
Amaldi 10

# First Generation Sensitivity



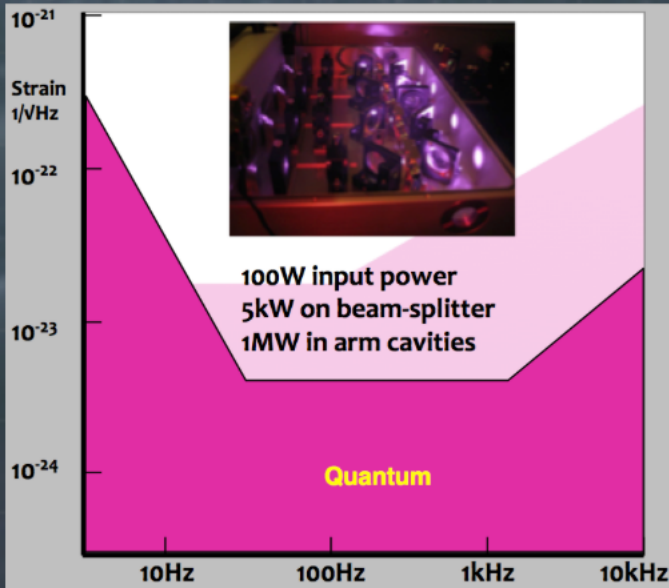


# Ground-based Gravitational Wave Detectors

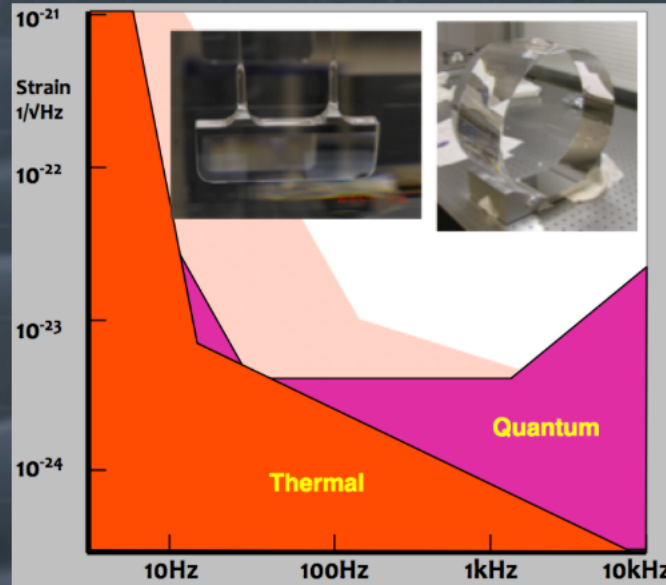


# Advanced GW detectors

More Laser Power...

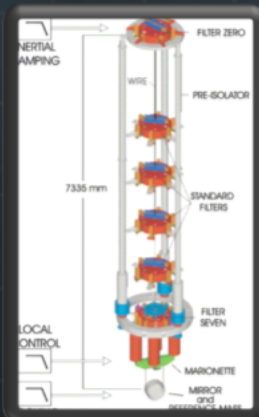


Better mechanical quality...

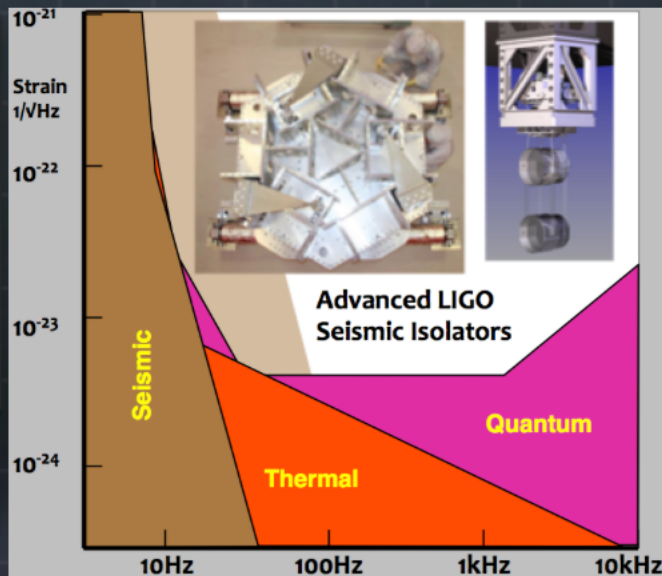


Test mass of 40kg  
suspended by 400  
micron glass  
fibers...

...and better isolation



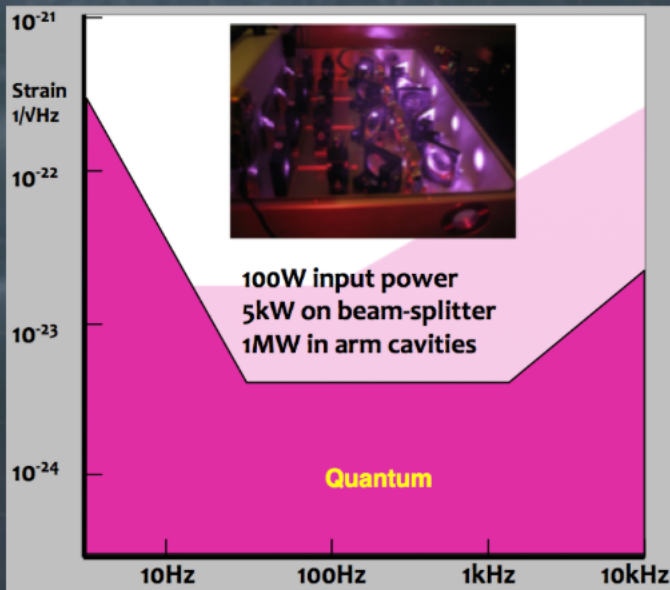
Virgo Super  
Attenuator



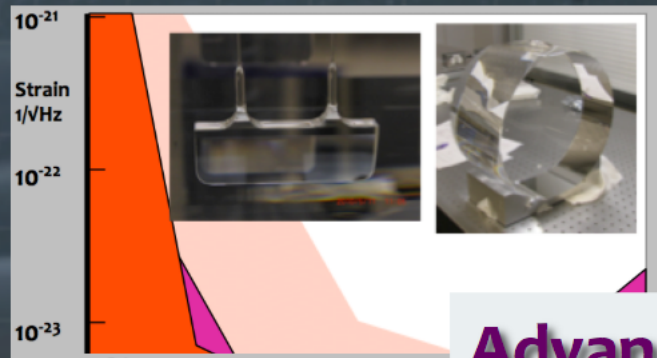


# Advanced GW detectors

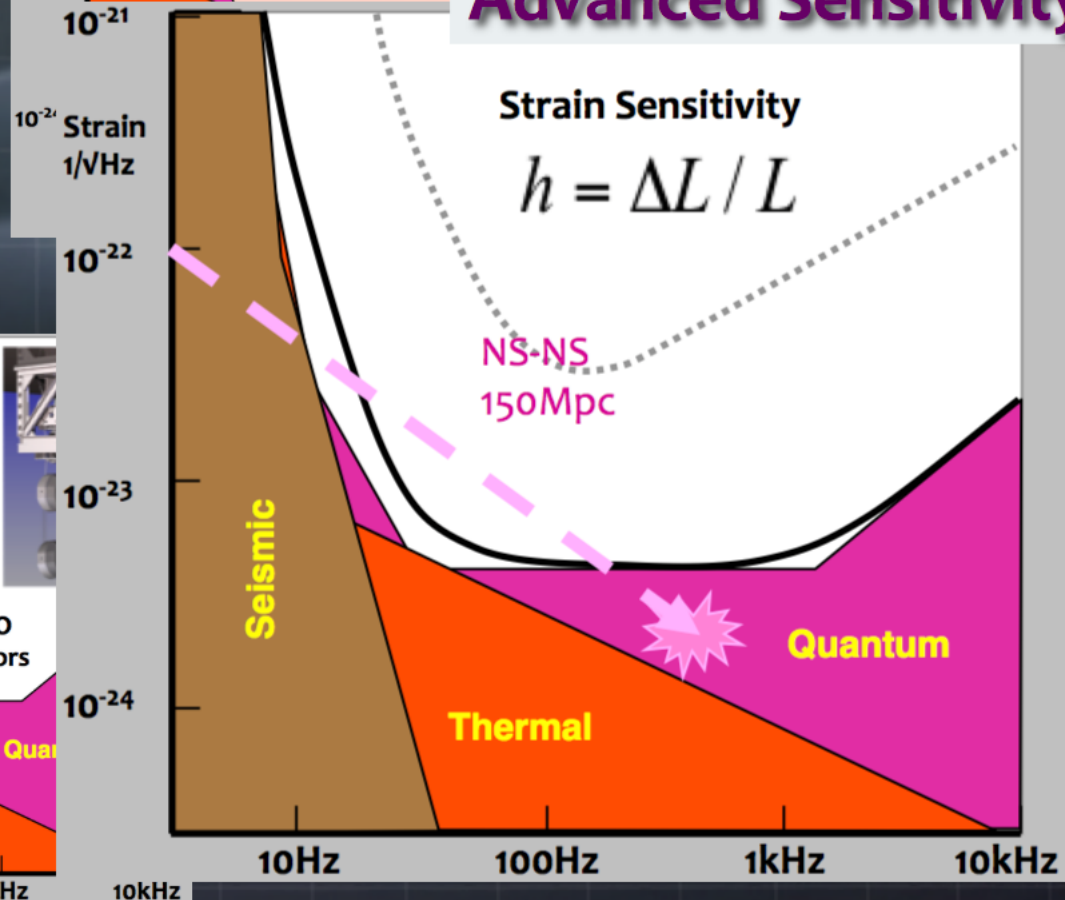
More Laser Power...



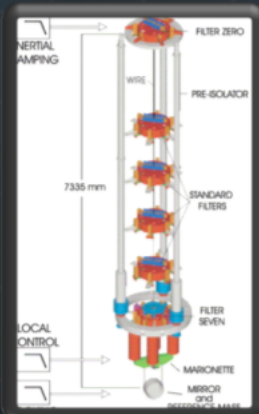
Better mechanical quality...



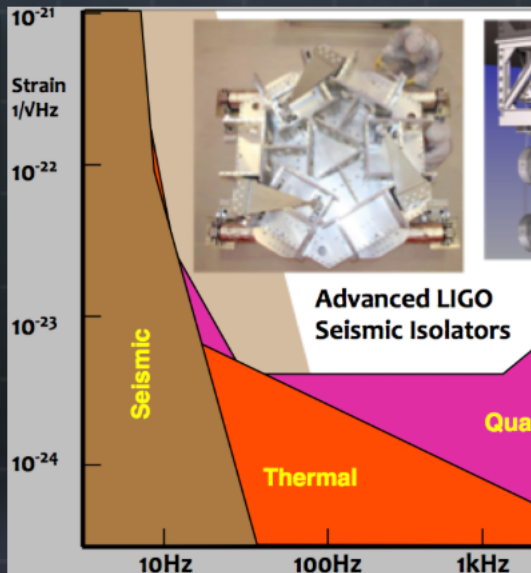
Advanced Sensitivity



...and better isolation



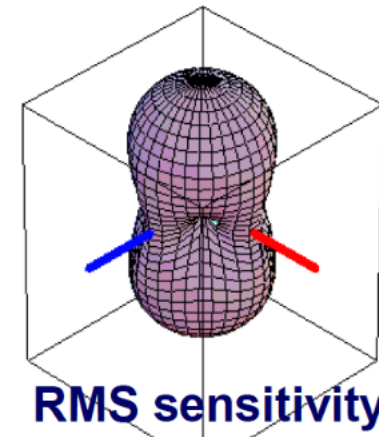
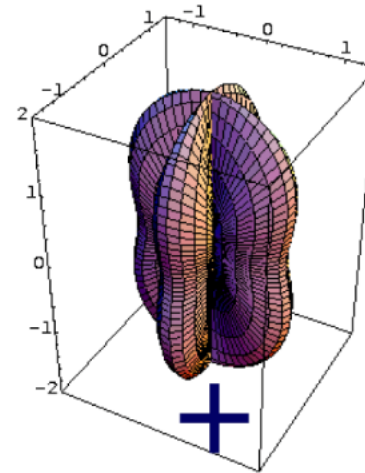
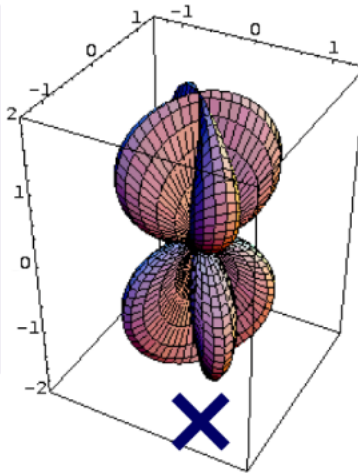
Virgo Super Attenuator



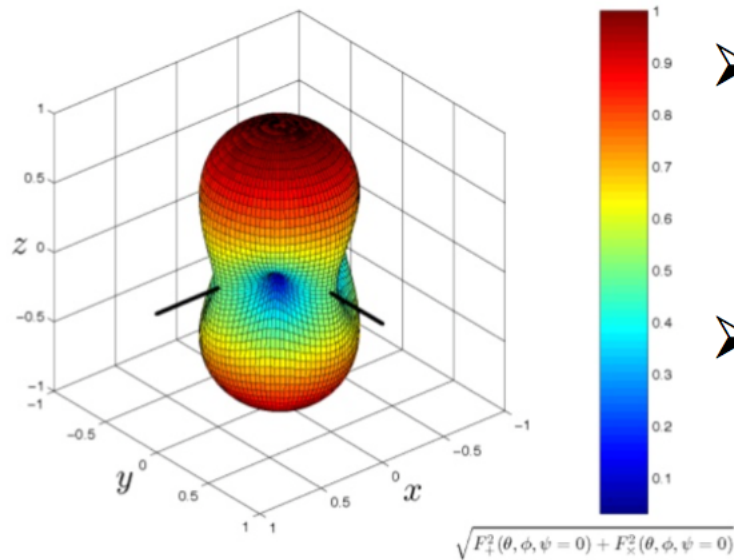
# Single GW detector directional sensitivity

$$\frac{\Delta L}{L} = h_{\text{det}}(t) = F_+ h_+(t) + F_x h_x(t)$$

The **antenna pattern** depends on the polarization in a certain (x,+) basis.



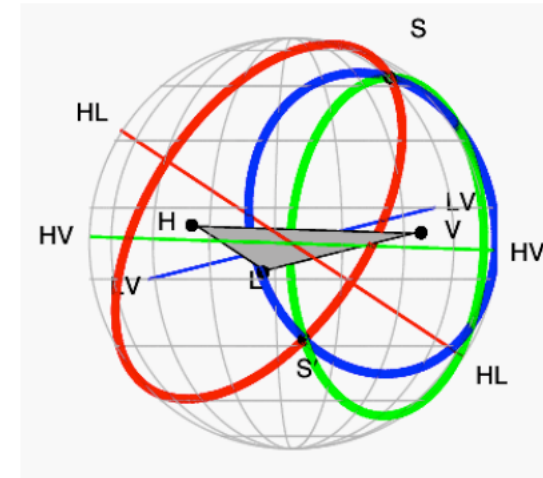
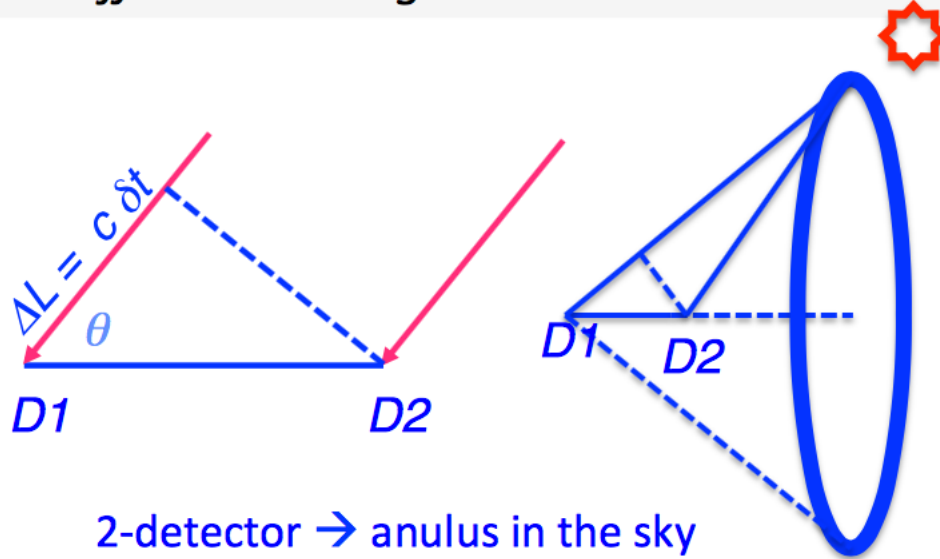
$$\sqrt{F_+(\theta, \phi)^2 + F_x(\theta, \phi)^2}$$



- Single GW detector is a **good all-sky monitor**, nearly omni-directional (the transparency of Earth to GWs)
- But does not have good directional sensitivity, **not a pointing instrument!** It has a very poor angular resolution (about 100 degrees)

## The source localization requires a network of GW detectors

The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites



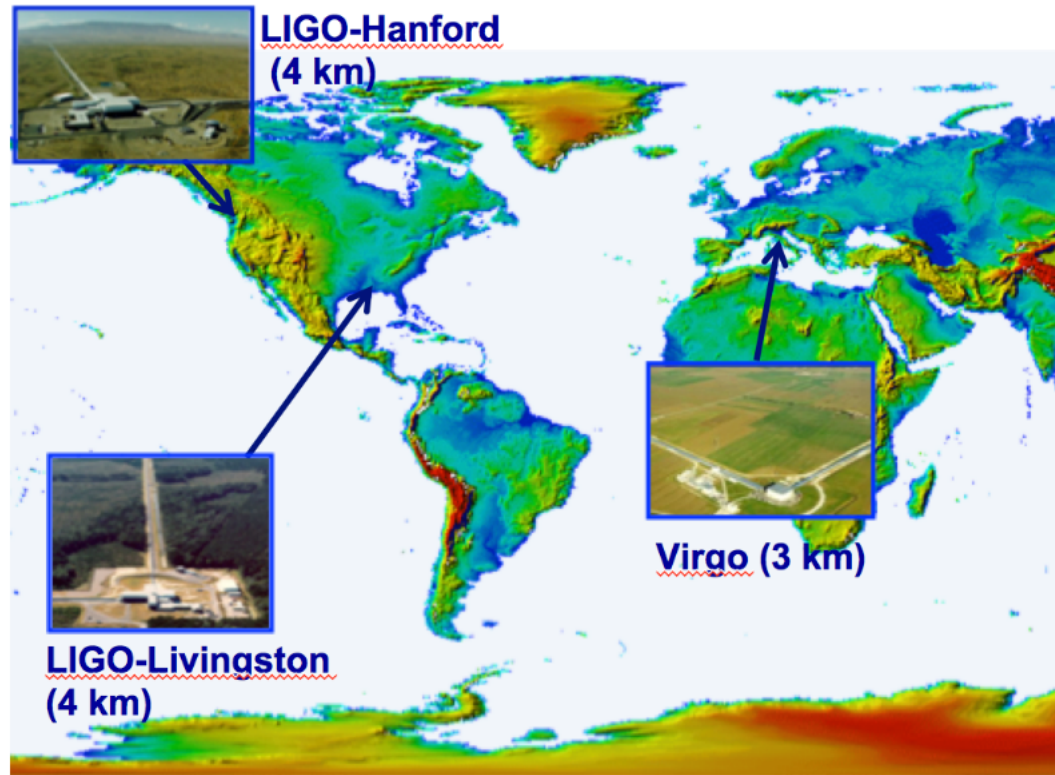
Detector baseline  $D = 3 \cdot 10^3 \text{ km}$   
 Wavelength  $\lambda \sim 3 \cdot 10^2 \text{ km}$   
 Angular resolution  $\frac{\lambda}{D} \sim 60^\circ$

The GW lengths are comparable to Earth diameter

→ longer baseline and greater number of the sites distributed worldwide significantly improve the sky-localization capabilities!



## Other benefits of a network of GW detectors



### Improvements:

- ❖ Sensitivity
- ❖ Observation time, and sky coverage
- ❖ In determining the polarization
- ❖ Ability to reconstruct the GW source parameters
- ❖ False alarm rejection thanks to coincidence

Virgo and the LIGO Scientific Collaborations have signed a MoA for full data exchange and joint data analysis and publication policy

**Advanced LIGOs and Virgo** will observe the sky (10-1000 Hz) as a **single network** aiming at the **first direct detection of GWs**

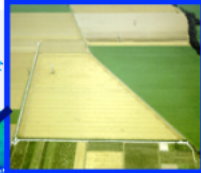
### Example of sky-localization capabilities

- NS-NS with SNR=7 in each of the LIGOs and Virgo:
- best case localization of **20 deg<sup>2</sup>**  
(signal is directly over the plane of network)
  - median of **40 deg<sup>2</sup>** (Fairhurst 2009)

# Near Future Gravitational Wave Detectors



LIGO-Hanford  
(4 km)



GEO (600 m)



Virgo (3 km)



KAGRA



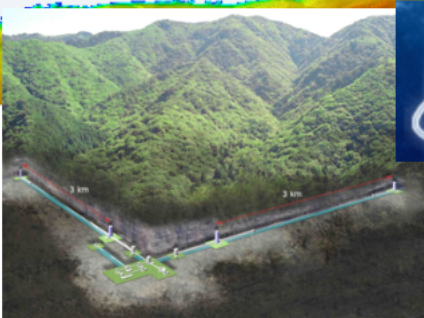
LIGO-India  
(2022+)



LIGO-Livingston  
(4 km)



Move one of the two LIGO detectors in Hanford to India

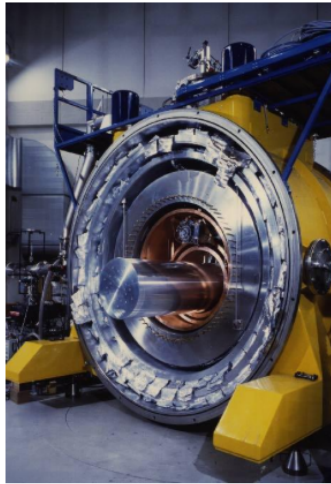


Underground detector in the Kamioka mine: 3km length, – Cryogenic mirrors (2nd phase)

Astrofisica Nucleare e Subnucleare  
Other Detectors for GW



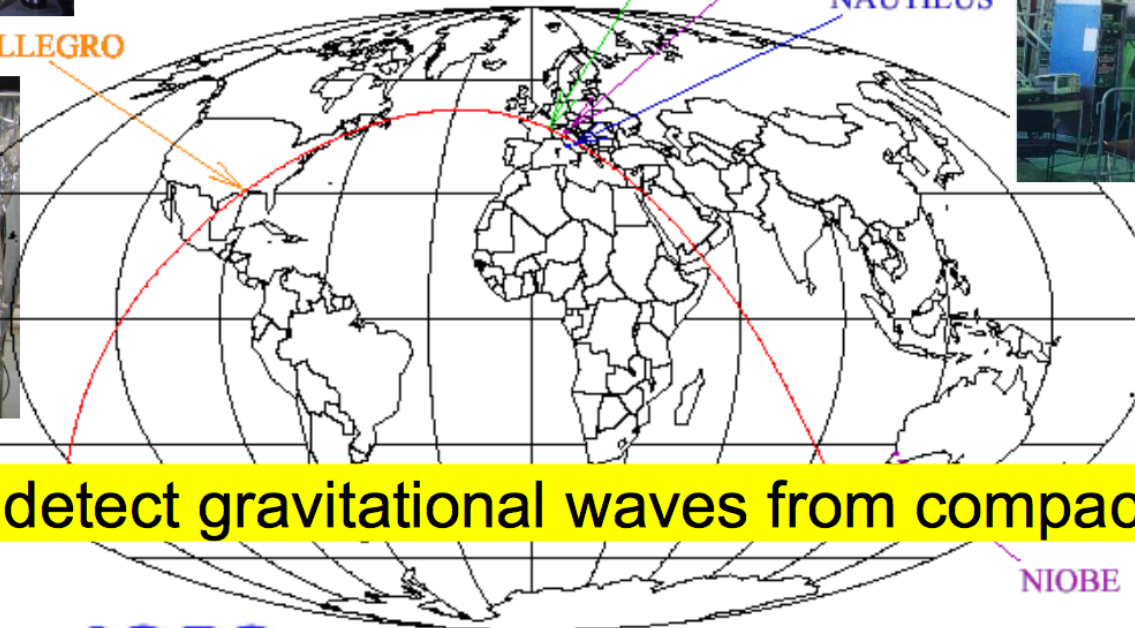
# Bar detectors: IGEC collaboration



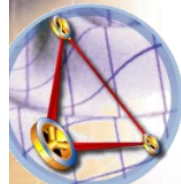
ALLEGRO

AURIGA

NAUTILUS



Built to detect gravitational waves from compact objects



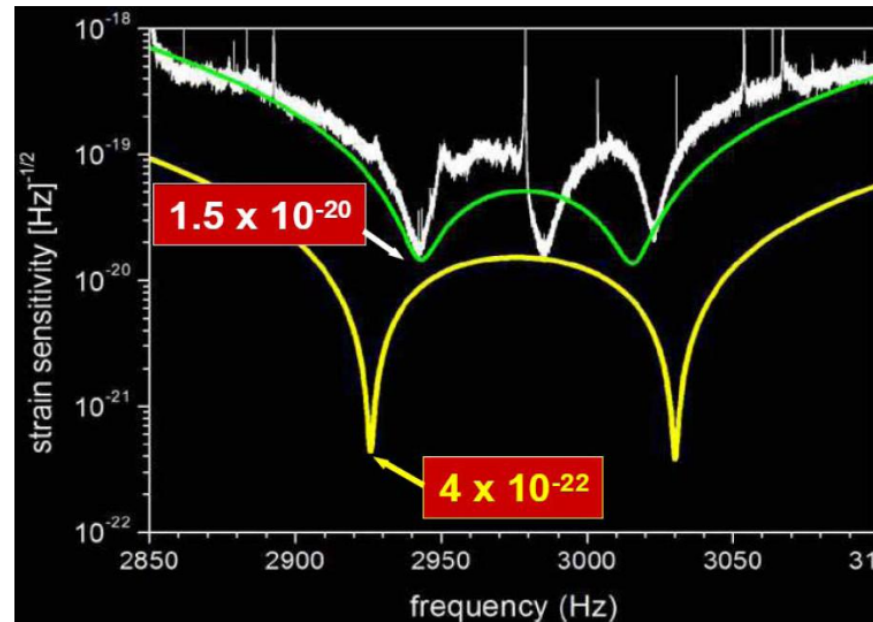
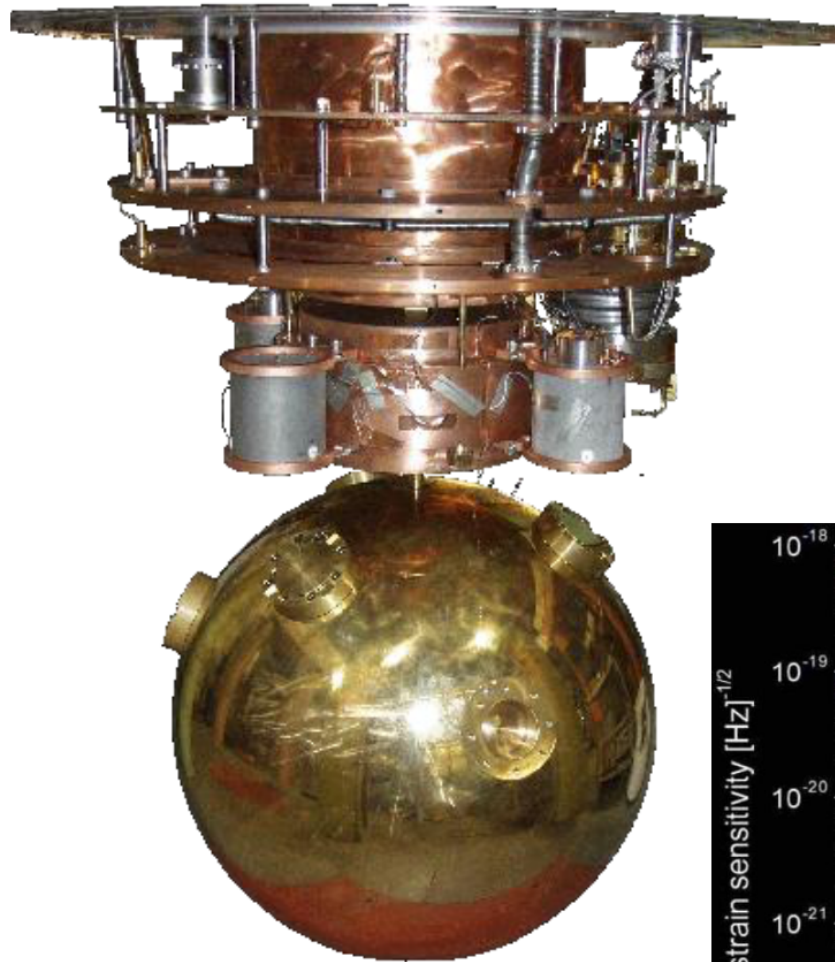
IGEC

Ladbrokes.com



NIOBE

# Mini-GRAIL: a spherical 'bar' in Leiden





# EINSTEIN TELESCOPE

gravitational wave observatory

CENTRAL FACILITY

COMPUTING CENTRE

DETECTOR STATION

*Creation of Adam - Michelangelo*

**Design Study Proposal approved by EU within FP7**  
**Large part of the European GW community involved**  
EGO, INFN, MPI, CNRS, NIKHEF, Univ. Birmingham, Cardiff, Glasgow

**Recommended in Aspera / Appec roadmap**

END STATION

TUNNEL  $\varnothing$  ~5 m

length ~10 km



Astrofisica Nucleare e Subnucleare  
Space Detectors for GW



eLISA: THE MISSION

LISA PATHFINDER

NEW ASTRONOMY

CONTEXT 2028

eLISA COMMUNITY



A New Astronomy

## Gravitational waves directly observed for first time

The first gravitational wave signal was observed from the highly relativistic merger of two massive black holes. GW150914 is the beginning of a new era of astronomy.

Login

Register

Username:

Password:

Login

If you forgot your password you can request a new one [here](#).

Register above to receive the eLISA newsletter.

LISA Pathfinder on Twitter

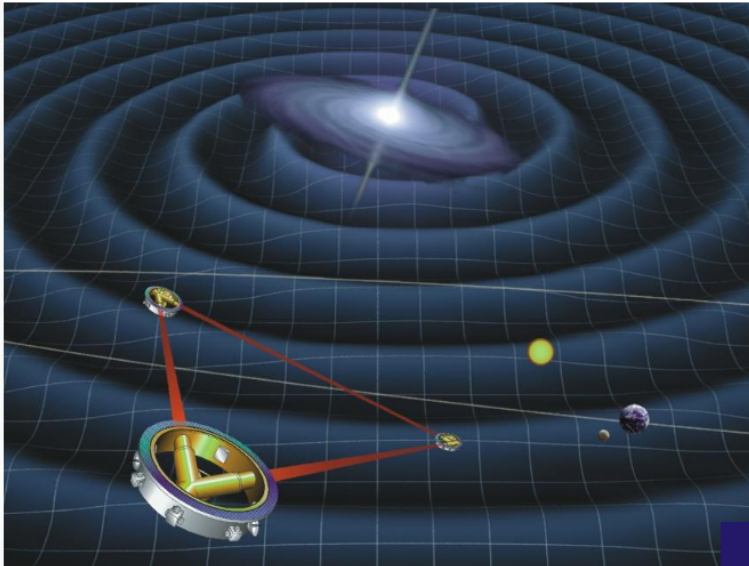
@ESA\_LPF: Follow LPF and get the latest news, information and developments from the groundbreaking mission!

1 2 3 4 5 6 7 8 9 10

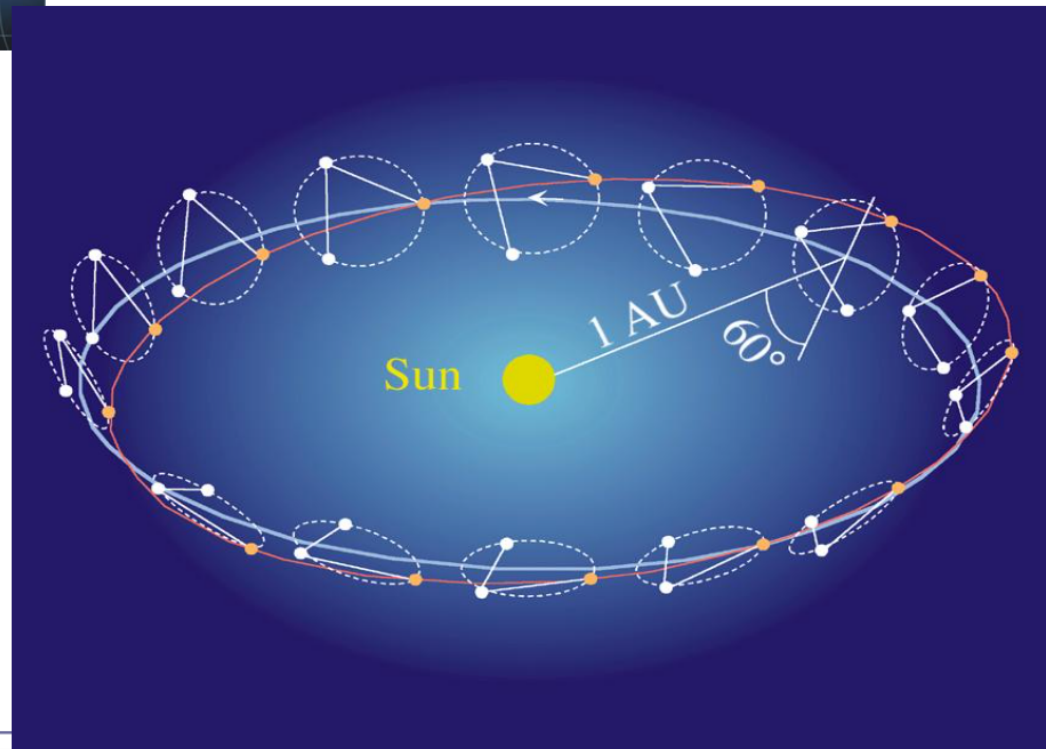
First detection also proves existence of BH binaries. Numerical simulation of GW150914 by SXS

»» News Overview: Latest news and consortium activities, conferences, publications, positions.

# Gravitational wave antenna in space - LISA

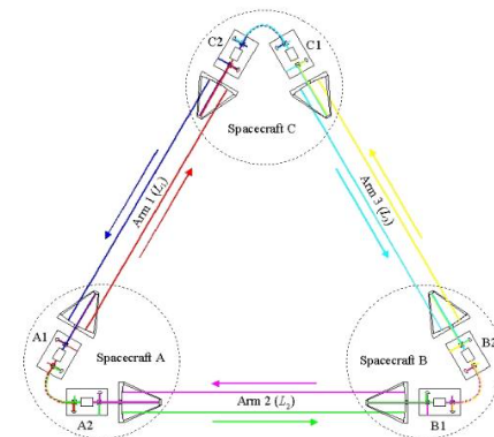
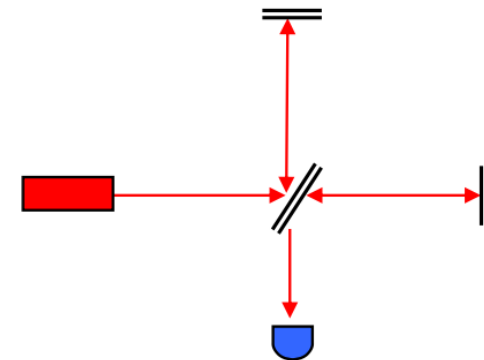
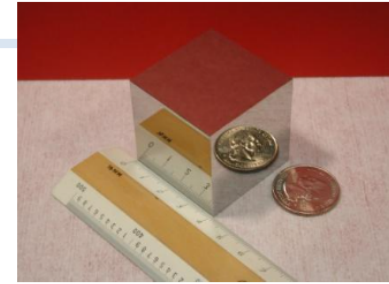


- *3 spacecraft in Earth-trailing solar orbit separated by  $5 \times 10^6$  km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between NASA and ESA*



# LISA interferometry

- “LISA is essentially a Michelson Interferometer in Space”
- However
  - No beam splitter
  - No end mirrors
  - Arm lengths are not equal
  - Arm lengths change continuously
  - Light travel time  $\sim 17$  seconds
  - Constellation is rotating and translating in space



# Astrofisica Nucleare e Subnucleare

## PTA Detector for GW



# What is a PTA?

PTA = Pulsar Timing Array

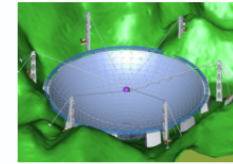
Term first described by Romani (1989) and Foster & Backer (1990)

First major realisation of a PTA was the Parkes Pulsar Timing Array project started by R. Manchester

Main goals: 1) **detect gravitational waves**, 2) search for irregularities in terrestrial time standards and 3) improve the Solar System planetary ephemeris

Numerous secondary goals ...

# PTAs in 2015



CPTA



ASKAP



Meerkat

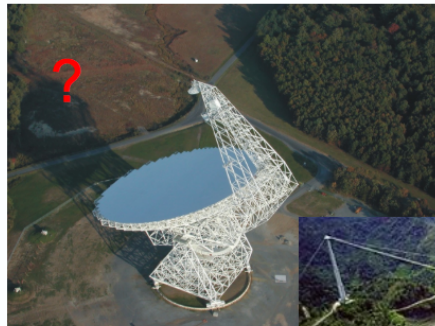


SKA

# IPTA

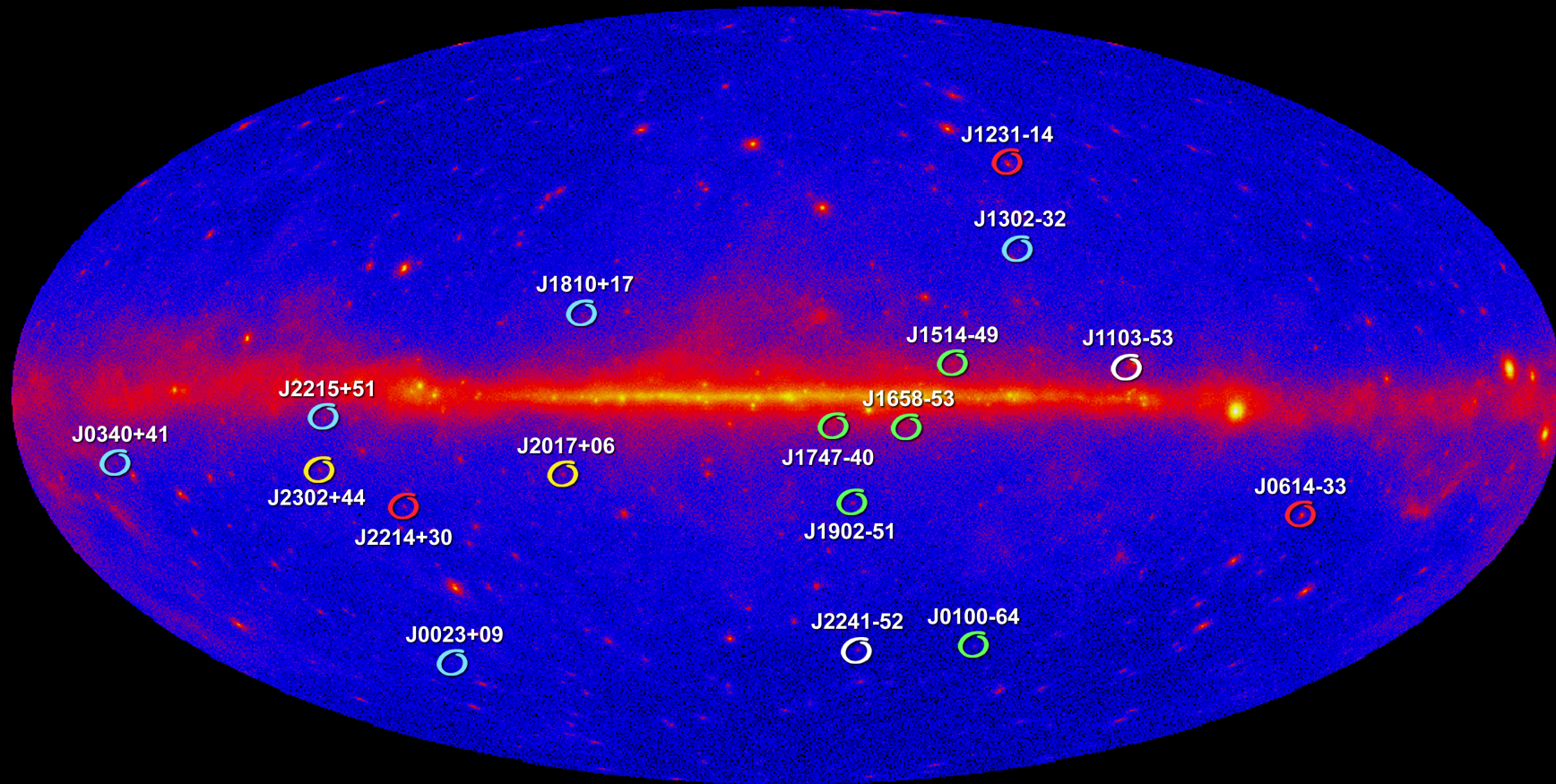
Interest in pulsar community






Interest in gravitational wave community





# New Millisecond Radio Pulsars Found in Fermi LAT Unidentified Sources



-  Led by Fernando Camilo (Columbia Univ.) using Australia's CSIRO Parkes Observatory
-  Led by Mallory Roberts (Eureka Scientific/GMU/NRL) using the NRAO's Green Bank Telescope
-  Led by Scott Ransom (NRAO) using the Green Bank Telescope
-  Led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope
-  Led by Mike Keith (ATNF) using Parkes Observatory



*Fermi Large Area Telescope first year map of the gamma-ray sky at energies above 100 MeV with the locations of the new millisecond pulsars shown. The symbols are color coded according to the discovery team: red led by Scott Ransom (NRAO) using NRAO's Green Bank Telescope (GBT), cyan led by Mallory Roberts (Eureka Scientific/GMU/NRL) also using the GBT, green led by Fernando Camilo (Columbia University) using Australia's CSIRO Parkes Observatory, white led by Mike Keith (ATNF) also using Parkes, and yellow led by Ismael Cognard (CNRS) using France's Nançay Radio Telescope. (Credit: NASA/DOE/Fermi LAT Collaboration)*