Astrofisica Nucleare e Subnucleare

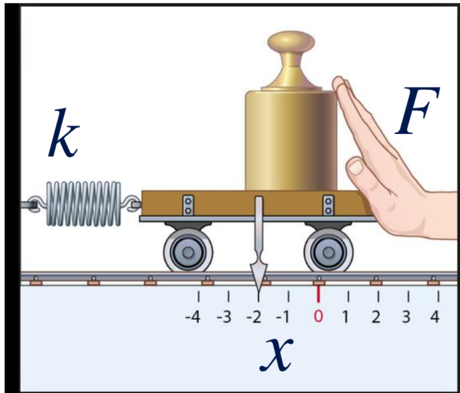
Gravitational Waves

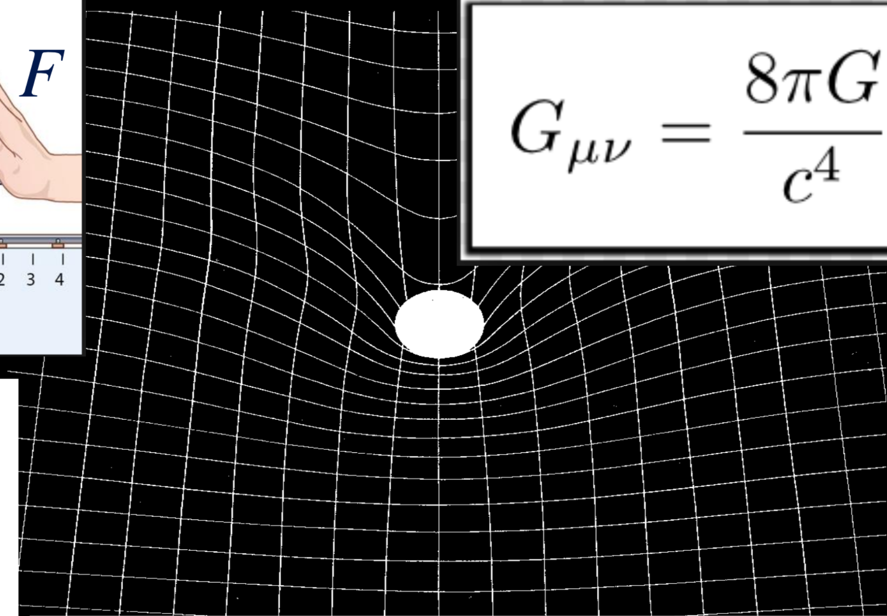
Exercise on GW

- Find recent information on the status of LIGO, Virgo, KAGRA
- Find the status of the LISA GW observatory
- Find the status of PTA GW methods

Introduzione

Introduzione





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

$$F = -kx$$

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

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

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

$$c = 299\ 792\ 458\ \ m/s = 3 \times 10^8\ \ m/s$$

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

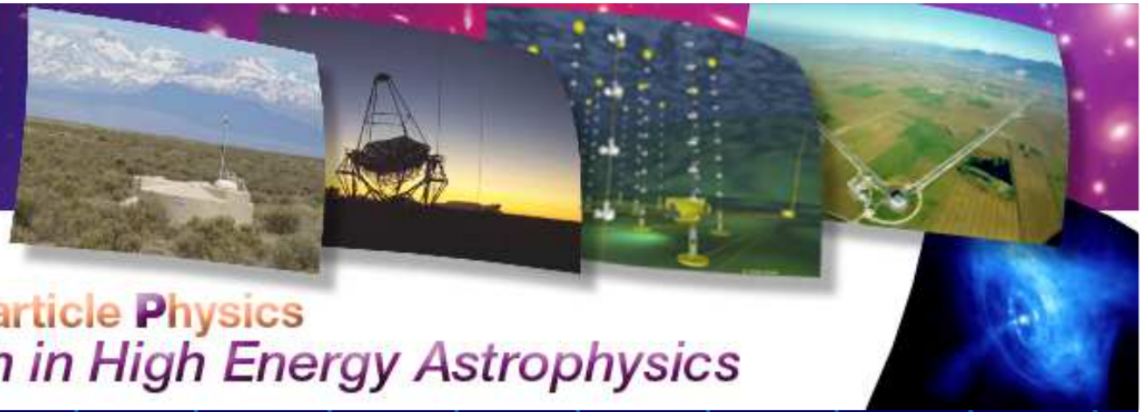
$$k \approx 10^{45}\ \frac{kg}{s^2} \qquad STIFF!$$

ISAPP International School on AstroParticle Physics

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

VIRGO

Université Paris Sud
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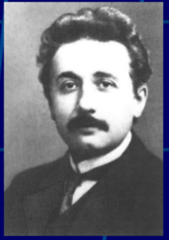
What are Gravitational Waves ?

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: $$\nabla^2 h^{TT}_{\mu\nu} = 0$$

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



Prediction in 1916 !

Gravitational Wave general properties

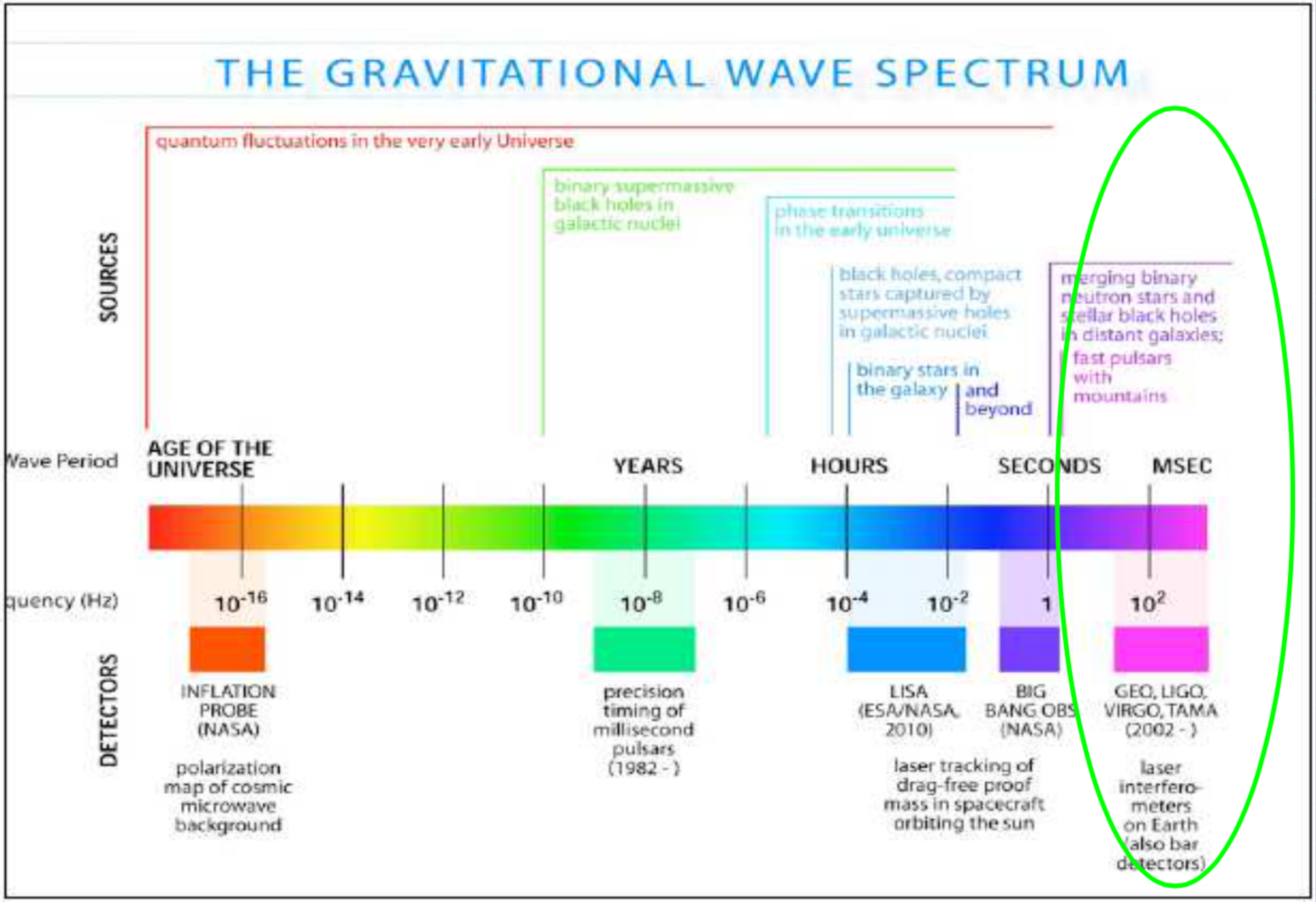
- GW propagate at speed of light
- GW have two polarizations "+" and "x"
- GW emission is quadrupolar at lowest order

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

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

Corresponding *Graviton* properties:

- Graviton has null mass
- Graviton has spin 2



THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
BIG BANG OBS (NASA)
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interferometers on Earth (also bar detectors)

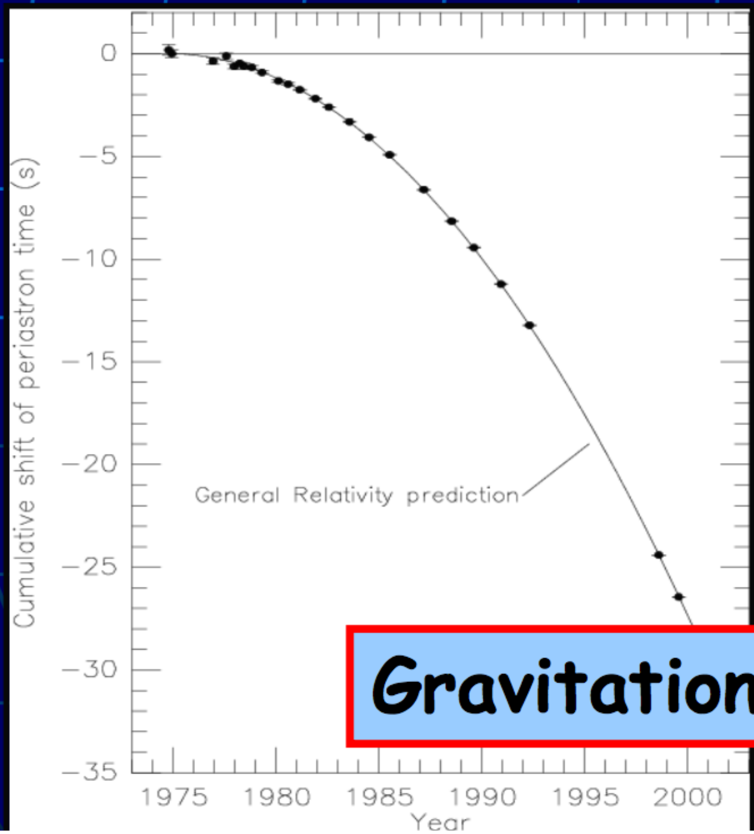
GW (indirect) discovery PSR 1913+16

(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)	**27906.9807807(9)**
dP/dt	**-2.425(10)·10^{-12}**
dω/dt (°/yr)	**4.226628(18)**
M_p	**1.442 ± 0.003 $M_\odot$**
M_c	**1.386 ± 0.003 $M_\odot$**

Gravitational Waves do exist !

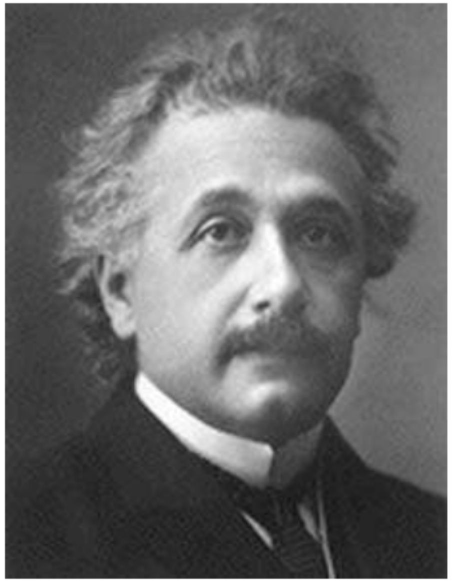
SUPAGWD

An Introduction to General Relativity, Gravitational Waves and Detection Principles

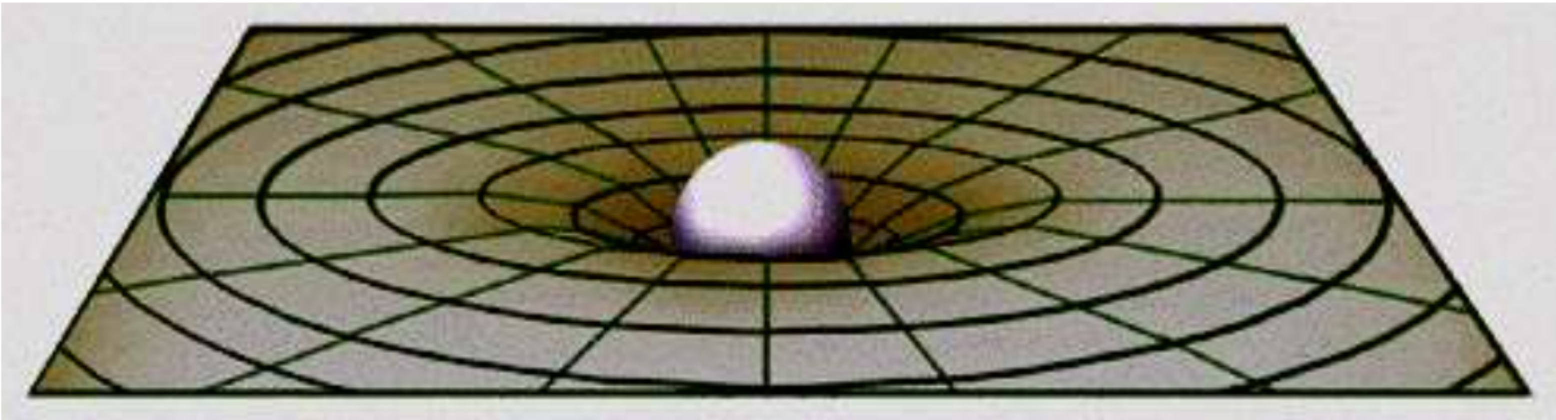
Prof Martin Hendry
University of Glasgow
Dept of Physics and Astronomy

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)

University of Glasgow

IGR SUPA

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 is 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

$$\eta_{\alpha\beta} = \text{diag}\ (-1, 1, 1, 1)$$

$$|h_{\alpha\beta}| << 1 \ \text{ for all } \ \alpha \ \text{ and } \ \beta$$

This is known as a Nearly Lorentz coordinate system.

Einstein's equations for a weak gravitational field

The Einstein tensor is the (rather messy) expression

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

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

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

and is invariant under gauge transformations.

Similarly, the Ricci tensor is

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

where

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

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

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**

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

Wave amplitude ($A_{\mu\nu}$)

Wave vector (k_α)

Note the wave amplitude is symmetric → 10 independent components.

Thus

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

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 μ.

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:

$$A^{\mu}_{\mu} = \eta^{\mu\nu} A_{\mu\nu} = 0 \qquad \text{(traceless)}$$

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

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

In the transverse traceless gauge,

$$\overline{h}^{(\mathrm{TT})}_{\mu\nu} = A^{(\mathrm{TT})}_{\mu\nu} \cos\left[\omega(t-z)\right]$$

where

$$A^{(\mathrm{TT})}_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A^{(\mathrm{TT})}_{xx} & A^{(\mathrm{TT})}_{xy} & 0 \\ 0 & A^{(\mathrm{TT})}_{xy} & -A^{(\mathrm{TT})}_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Also, since the perturbation is traceless $\overline{h}^{(\mathrm{TT})}_{\alpha\beta} = h^{(\mathrm{TT})}_{\alpha\beta}$

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 $x = \epsilon\,,\ y = z = 0$

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

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

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

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

In general, this is time-varying

More formally, consider geodesic deviation ξ^{α} between two particles, initially at rest

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

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

and
$$R^{x}_{txt} = \eta^{xx} R_{xtxt} = -\frac{1}{2} h^{(\mathrm{TT})}_{xx,tt}$$
$$R^{y}_{txt} = \eta^{yy} R_{ytxt} = -\frac{1}{2} h^{(\mathrm{TT})}_{xy,tt}$$

Hence
$$\frac{\partial^2}{\partial t^2}\xi^{x} = \frac{1}{2}\epsilon\frac{\partial^2}{\partial t^2} h^{(\mathrm{TT})}_{xx} \qquad \frac{\partial^2}{\partial t^2}\xi^{y} = \frac{1}{2}\epsilon\frac{\partial^2}{\partial t^2} h^{(\mathrm{TT})}_{xy}$$

Similarly, two test particles initially separated by ϵ in the y- direction satisfy

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

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

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

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

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

Solutions are:

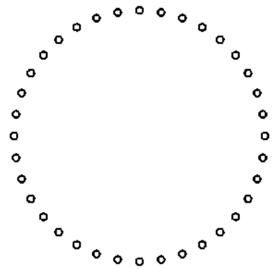
$$\xi^x = \epsilon\cos\theta + \frac{1}{2}\epsilon\cos\theta\, A_{xx}^{(\mathrm{TT})}\cos\omega t + \frac{1}{2}\epsilon\sin\theta\, A_{xy}^{(\mathrm{TT})}\cos\omega t$$

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

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

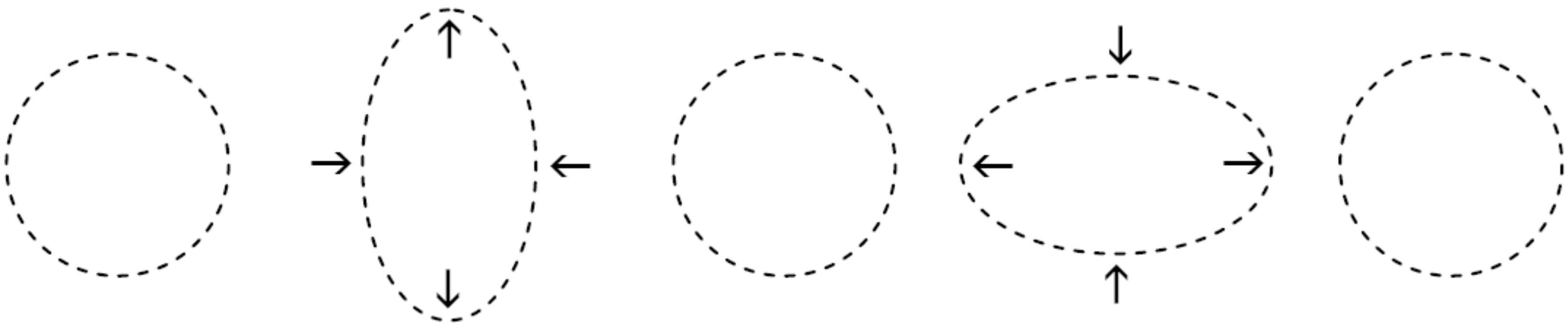
$$A_{xx}^{(\mathrm{TT})} \neq 0 \qquad A_{xy}^{(\mathrm{TT})} = 0$$

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



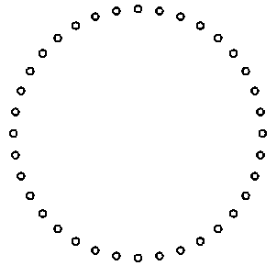
$$\xi^y = \epsilon \sin\theta \left(1 - \frac{1}{2} A_{xx}^{(\mathrm{TT})} \cos\omega t \right)$$

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



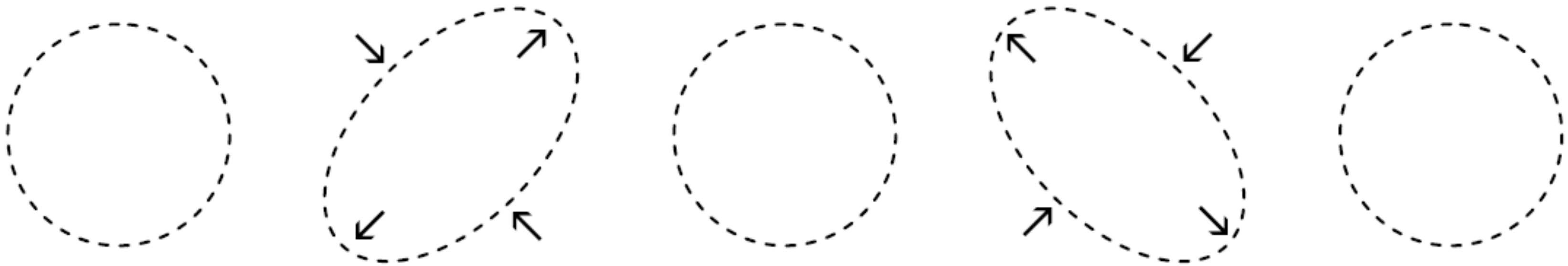
$$A^{(\mathrm{TT})}_{xy} \neq 0 \qquad A^{(\mathrm{TT})}_{xx} = 0$$

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



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

$A^{(\mathrm{TT})}_{xy} \neq 0$ ✕ **Polarisation**



- The two solutions, for $A_{xx}^{(\mathrm{TT})} \neq 0$ and $A_{xy}^{(\mathrm{TT})} \neq 0$ 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

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

- Distortions are **quadrupolar** - consequence of fact that acceleration of geodesic deviation non-zero only for tidal gravitational field.

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.

Net electric dipole moment

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

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

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

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?...

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

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

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

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 $\Gamma^{\mu}_{\nu\rho}$. 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

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

Here η^μ is the infinitesimal orthogonal displacement from the (geodesic) worldline ζ of a free particle to that of a neighboring similar particle. v^ν is the 4-velocity of the first particle, and τ the proper time along ζ. If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (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

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

Here η^a are the physical components of the infinitesimal displacement and R^a_{0b0} 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

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

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 $R^a_{0b0} \sim \frac{\partial^2 v}{\partial x^a \partial x^b}$ between equations (14.2) and (14.3), for the respective empty-space equations may be written $R^a_{0a0} = 0$ 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.

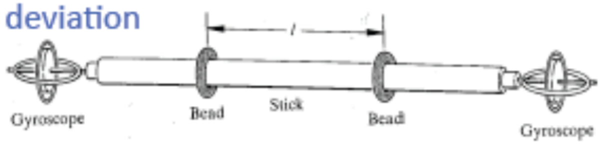
LICHNEROWICZ: Is it possible to study stability problems for η?

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



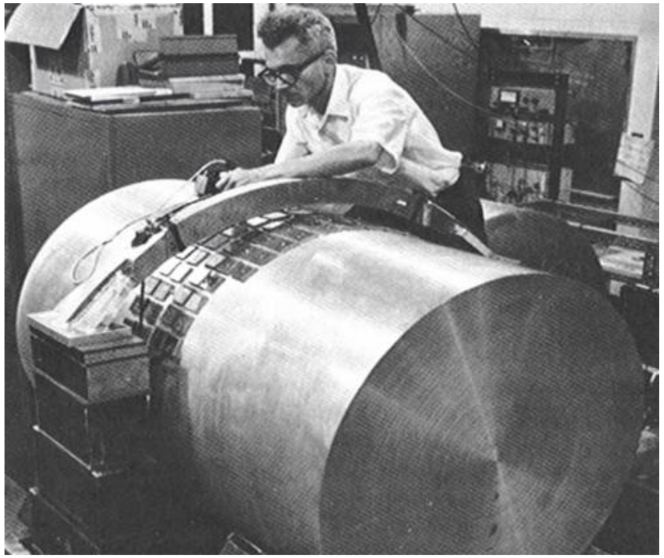
The main point of this presentation was that it is relative accelerations of neighboring free particles that are the physically meaningful (i.e.,measurable) ways to observe gravitational effects. Pirani points out the transparent connection between the equation of geodesic deviation and Newton's Second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

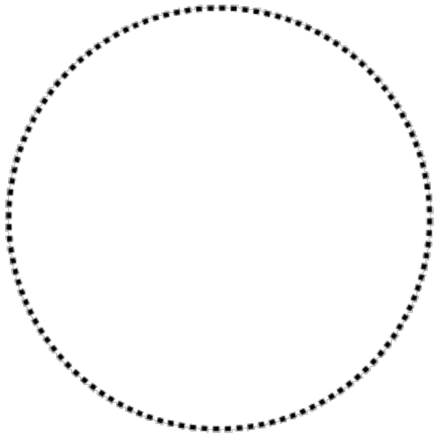
Weber's bar

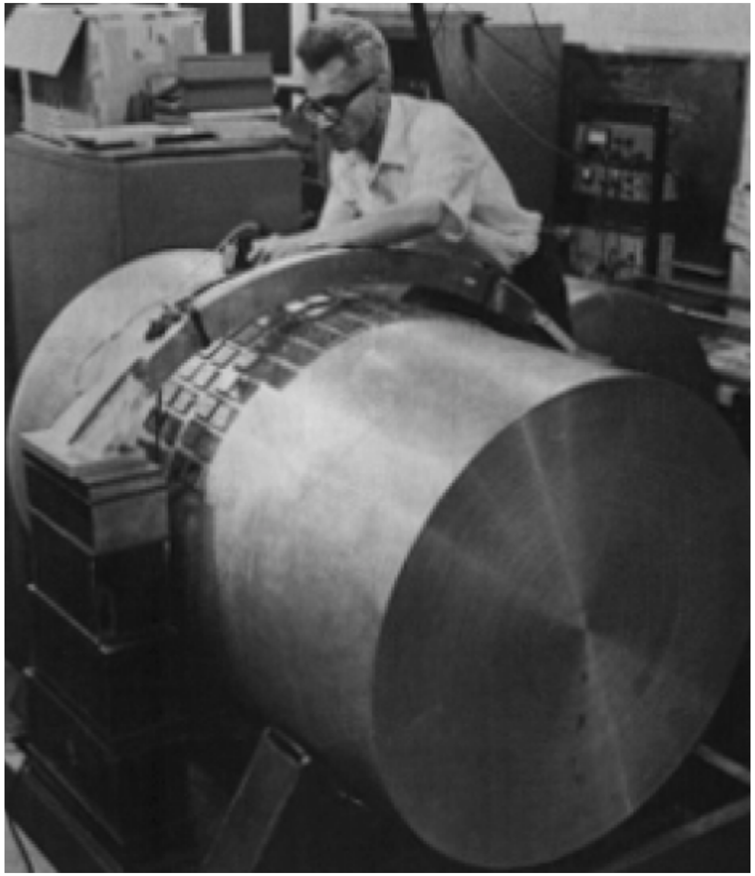


Weber's detector embodied Pirani's *gedankenexperiment.*

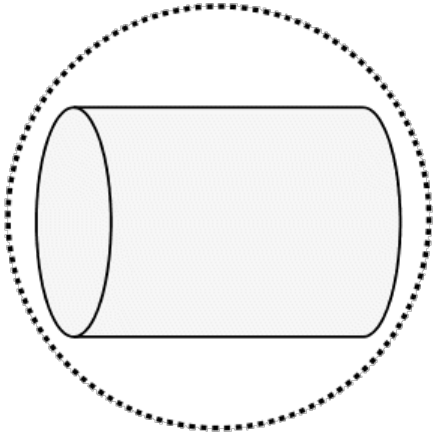
It was a cylinder of aluminum, each end of which is like a test mass, while the center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

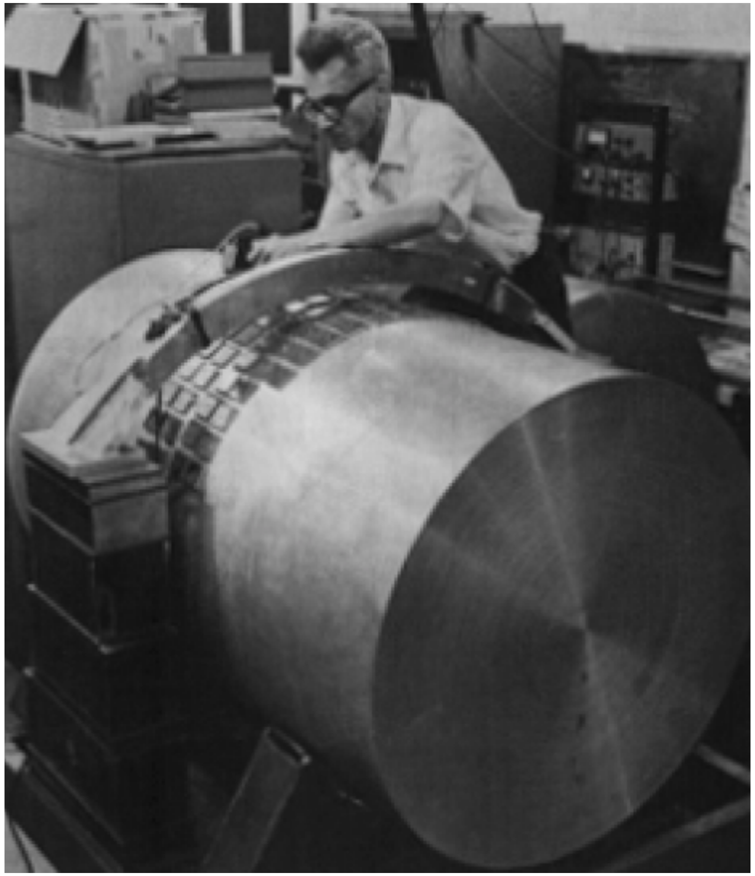
Design of gravitational wave detectors





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.

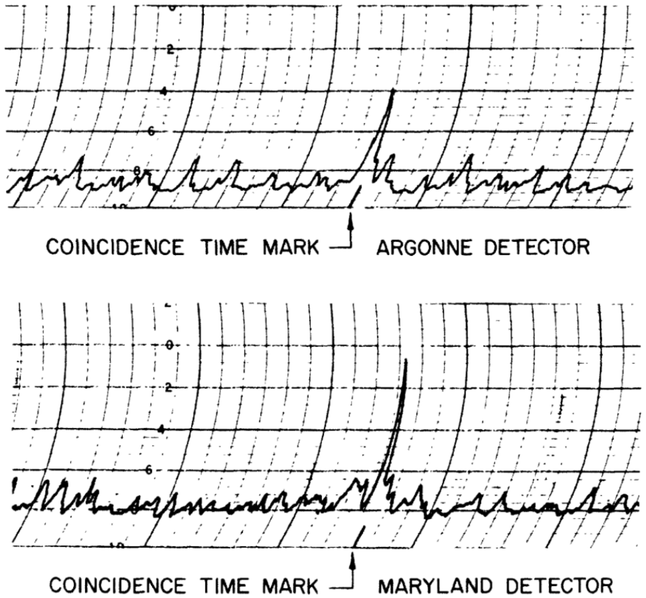
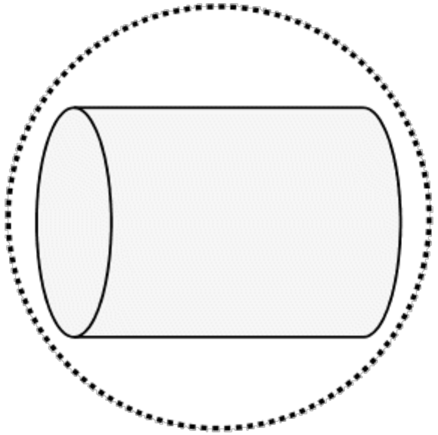
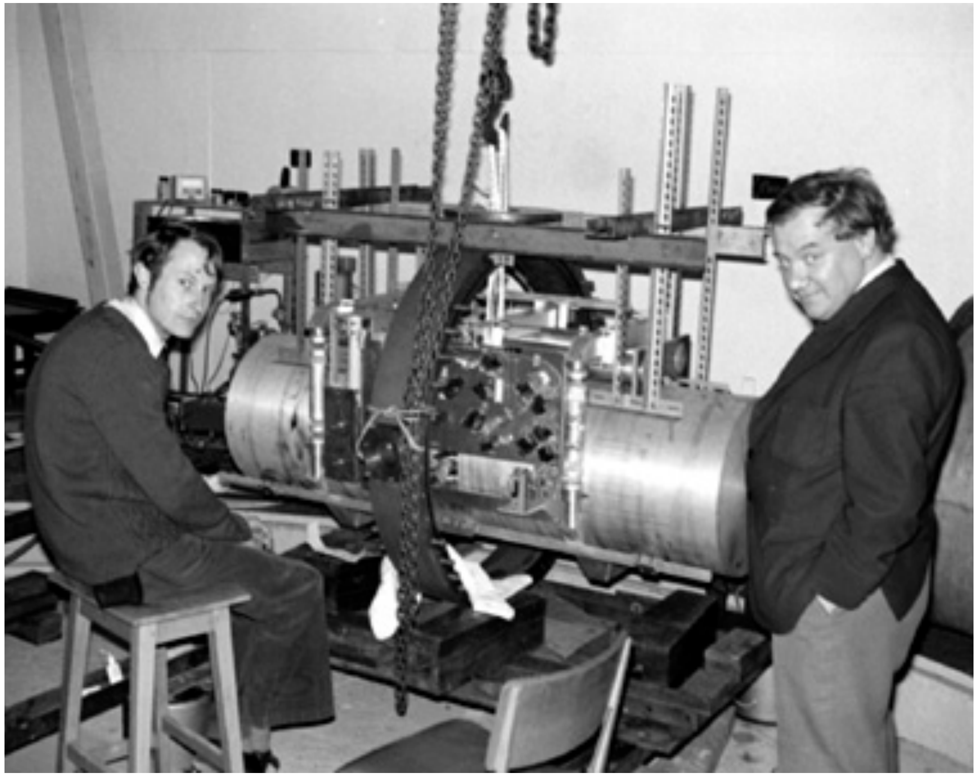


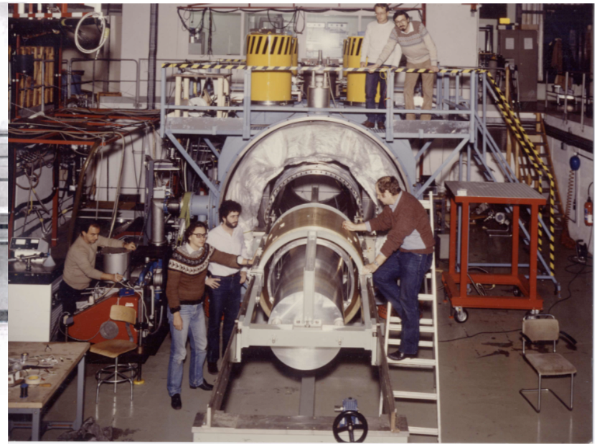
FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

Design of gravitational wave detectors



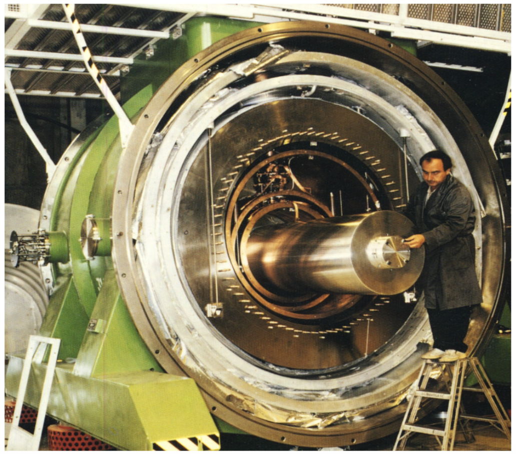


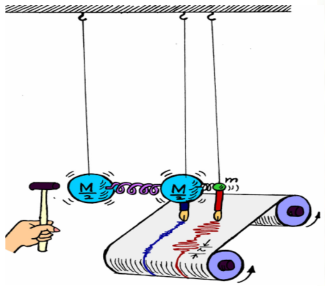
Metodi di rivelazione



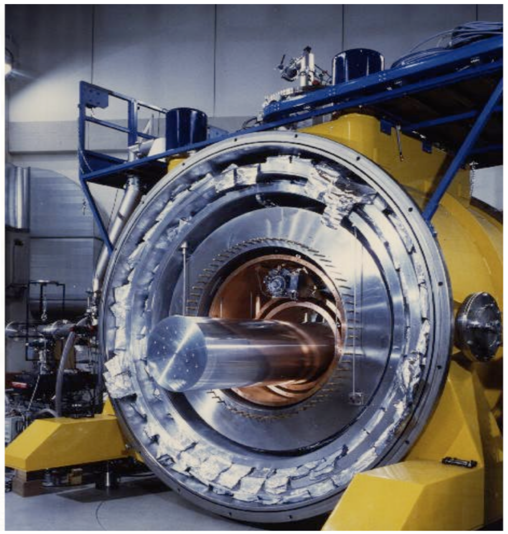
Explorer, CERN

Nautilus, LNF

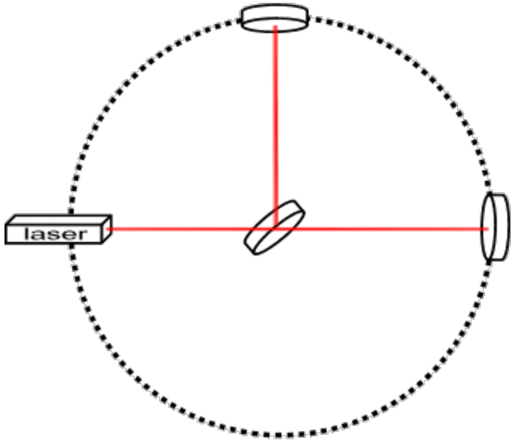


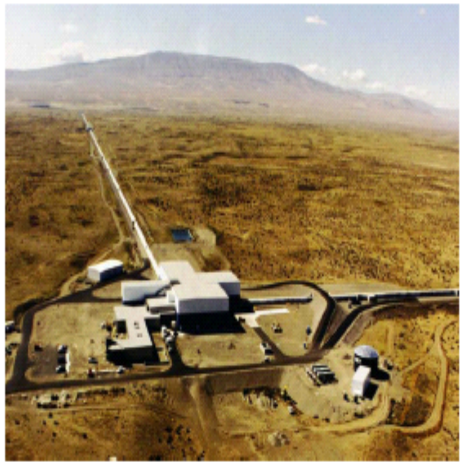


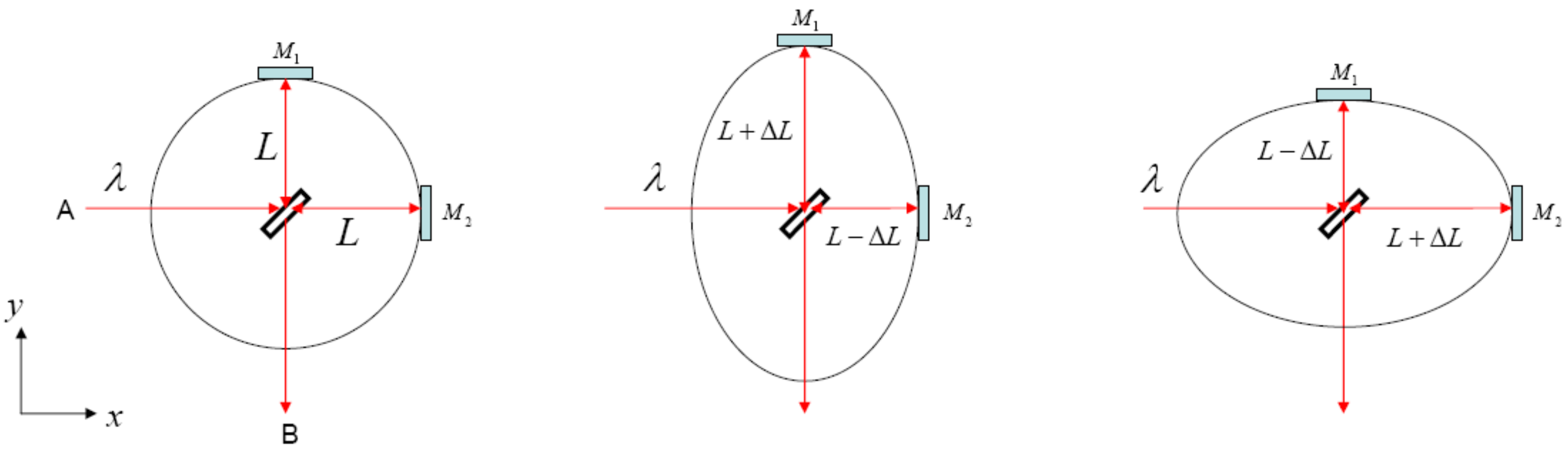
Auriga, LNL



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'

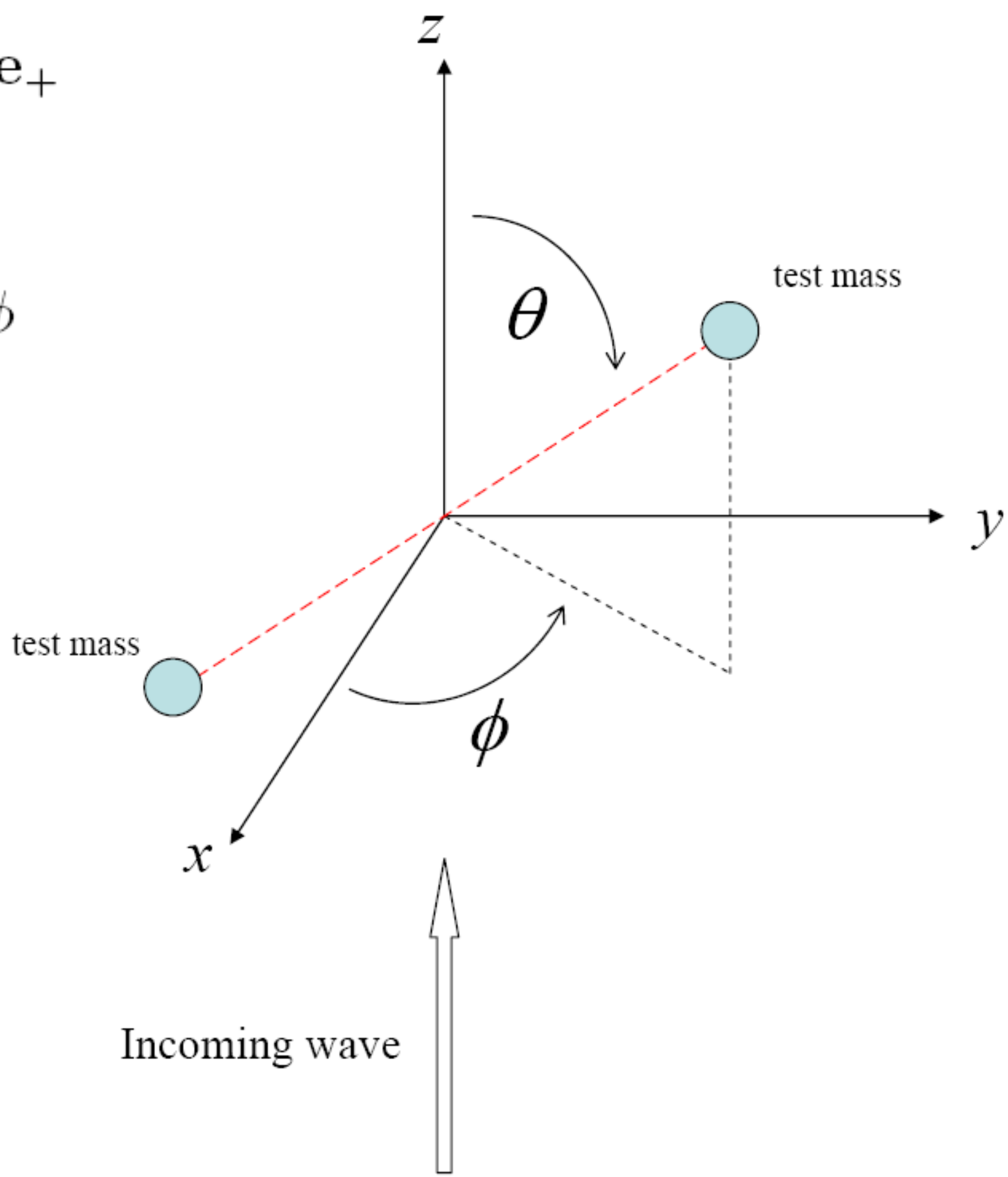
$$h_+ = h \sin^2\theta \cos 2\phi$$

Maximum response for

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

Null response for

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



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

Detector 'sees'

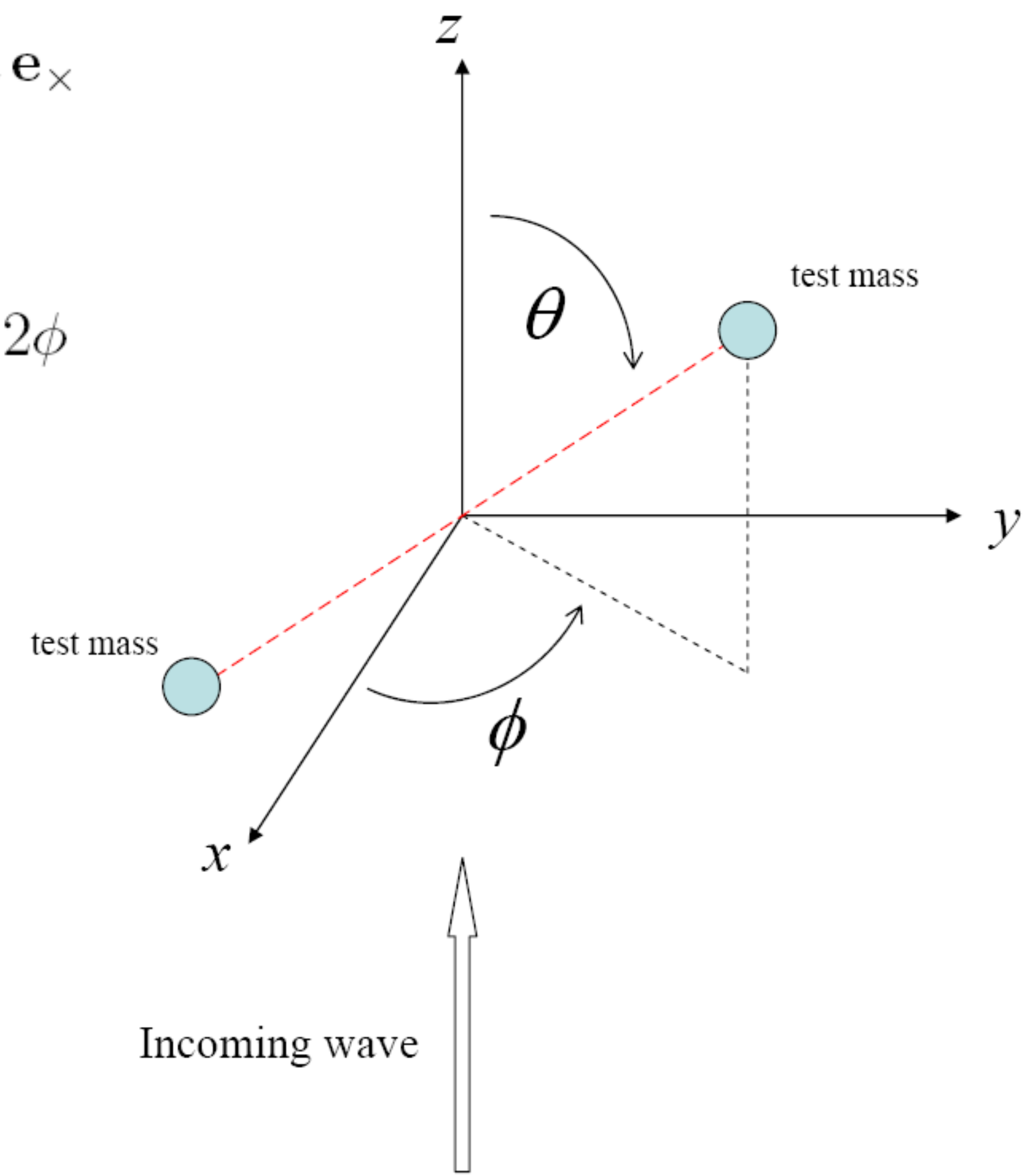
$$h_{\times} = h \sin^2\theta \sin 2\phi$$

Maximum response for

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

Null response for

$$\theta = 0 \qquad \phi = 0$$



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

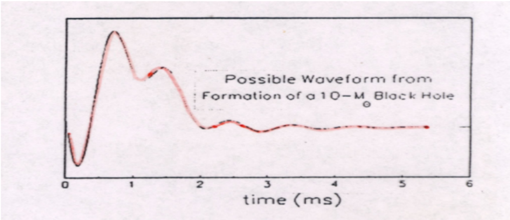
Where the ***reduced quadrupole*** moment:

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

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

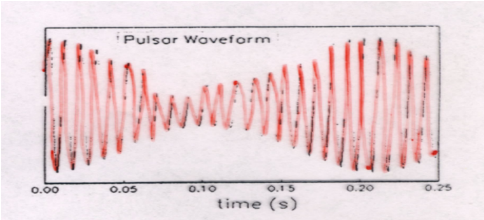
$\rho \sim T_{00}/c^2$: density of the source

Tipi di segnale



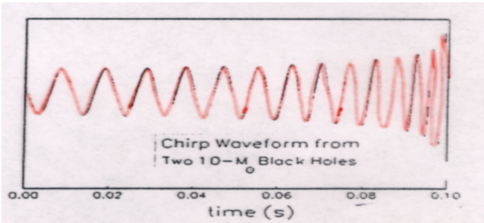
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

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



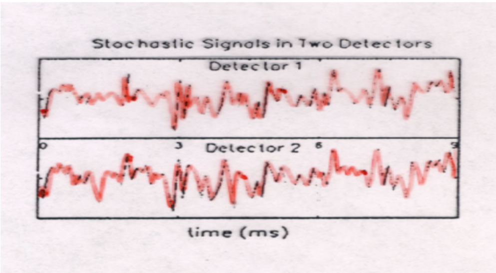
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

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



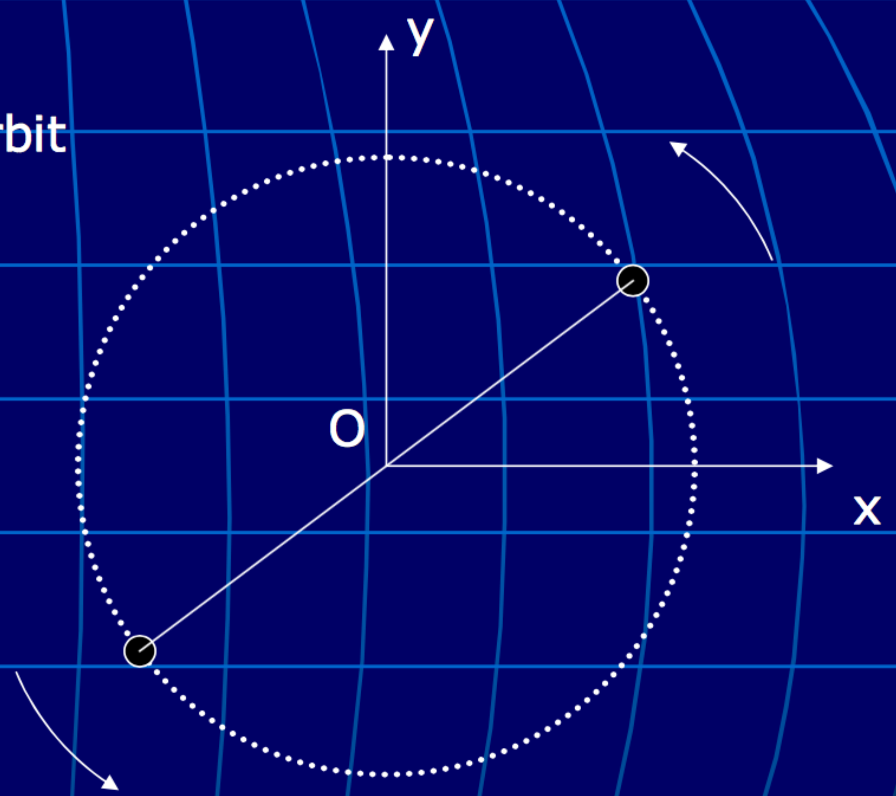
STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

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

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:

$$x_1(t) = a\cos(\omega_0 t) \qquad x_2(t) = -a\cos(\omega_0 t)$$
$$y_1(t) = a\sin(\omega_0 t) \qquad y_2(t) = -a\sin(\omega_0 t)$$

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:

$$h_+(t) = -\frac{2G}{rc^4} ma^2\omega^2 \cos\left(\omega(t - r/c)\right)$$
$$h_\times(t) = -\frac{2G}{rc^4} ma^2\omega^2 \sin\left(\omega(t - r/c)\right)$$

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

Note that if we look on the x direction:

$$h_+(t) = -\frac{G}{rc^4} ma^2\omega^2 \cos\left(\omega(t - r/c)\right)$$
$$h_\times(t) = 0$$

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

Gravitational Wave emission:
Orders of magnitude

source	distance	h
Steel bar, 500 T, Ø = 2 m L = 20 m, 5 cycles/s	1 m	2×10^{-34}
H bomb, 1 megatonne Asymmetry 10%	10 km	2×10^{-39}
Supernova 10 $M_\odot$ asymmetry 3%	10 Mpc	10^{-21}
Coalescence 2 black holes 10 $M_\odot$	10 Mpc	10^{-20}

Hertz experiment is impossible for GWs ...

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 → 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 → collapse → black hole

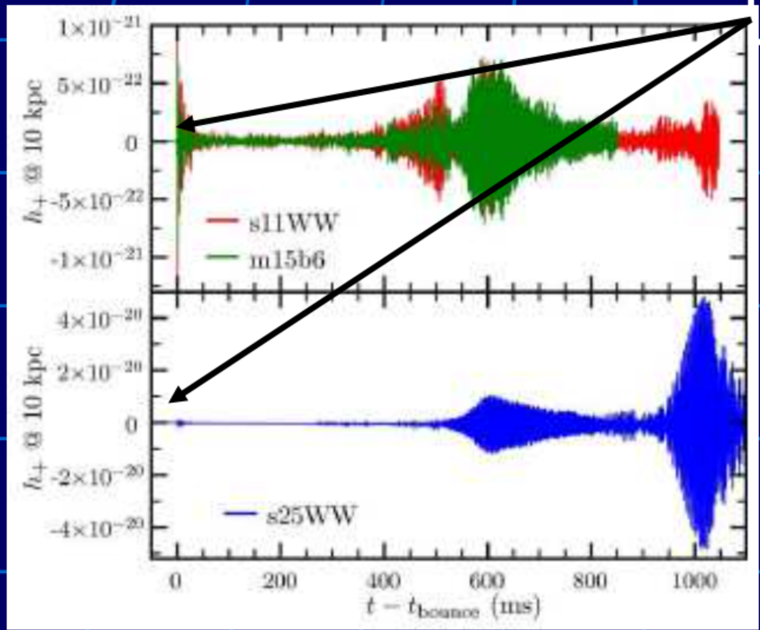
$h \sim 10^{-22}$ @ 10 Mpc
$f > 1$ kHz

+ oscillations...

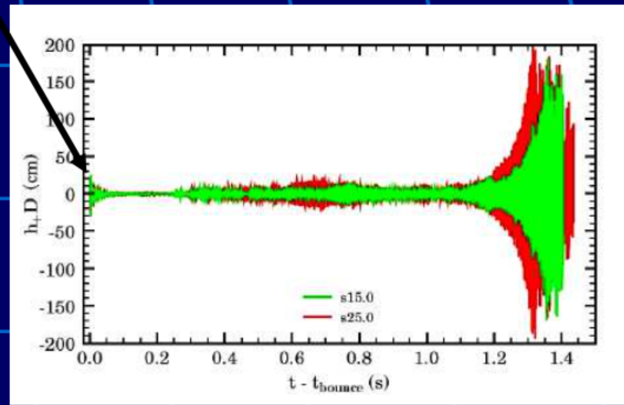
Gravitational Supernovae: GW amplitudes

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

collapse



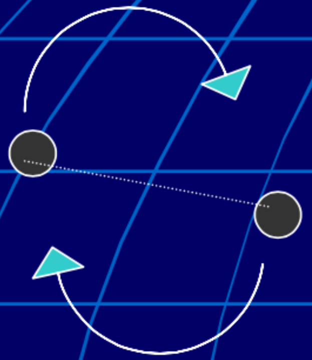
Ott and Burrows, 2006.



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)

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

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

A "chirp"

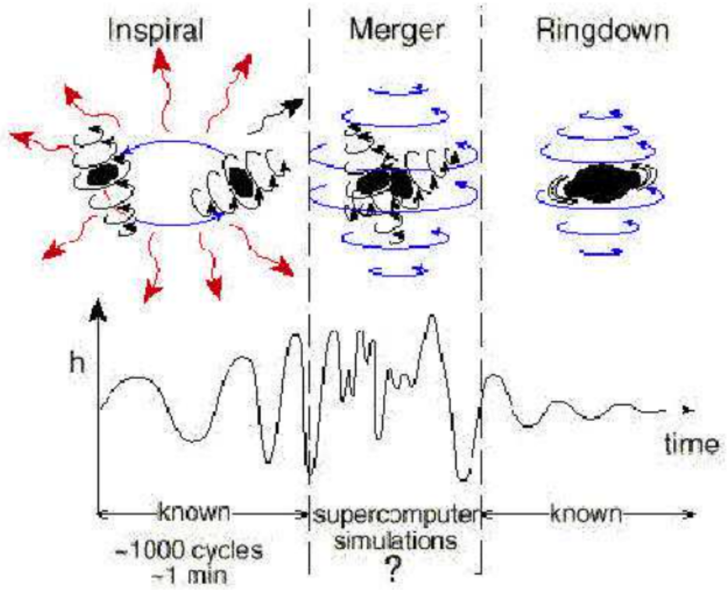
$$h(t) \propto (t_c - t)^{-1/4}$$

where

- Chirp mass: $M = \mu^{3/5} M_{tot}^{2/5}$
- frequency: $f(t) = \frac{1}{\pi}\left(\frac{256}{5}\frac{(GM)^{5/3}}{c^5}(t_c - t)\right)^{-3/8}$
- Phase: $\varphi(t) = -2\left(\frac{G^{5/3}}{c^5}\right)^{-3/8}\left(\frac{t_c - t}{5M}\right)^{5/8} + cste$

t_c : coalescence time

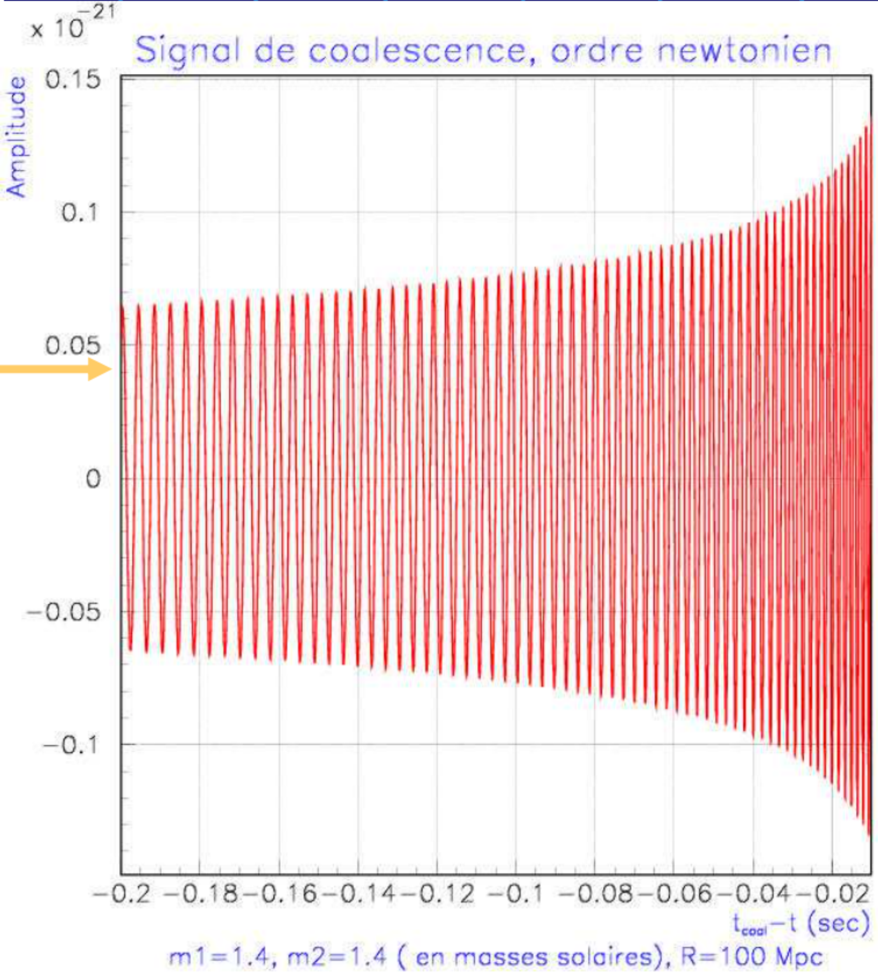
Binary inspirals: the chirp signal



2 neutron stars @ 10Mpc

h_{max} ~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)

(Kalogera et al astro-ph/0111452)

- NS-NS: $1.4M_\Theta + 1.4M_\Theta$
  - 0.001 – 1 / yr -> 20 Mpc
- NS-BH: $1.4M_\Theta + 10M_\Theta$
  - 0.001 – 1 / yr -> 43 Mpc
- BH-BH: $10M_\Theta + 10M_\Theta$
  - 0.001- 1 / yr -> 100 Mpc

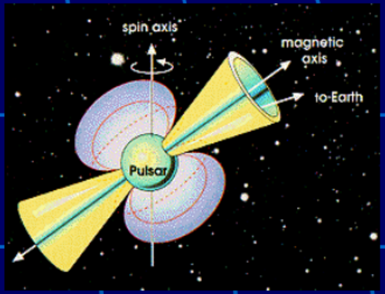
- **Gain Factor 10** on detector sensitivity

  ➡ 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 (**$h<10^{-24}$**)

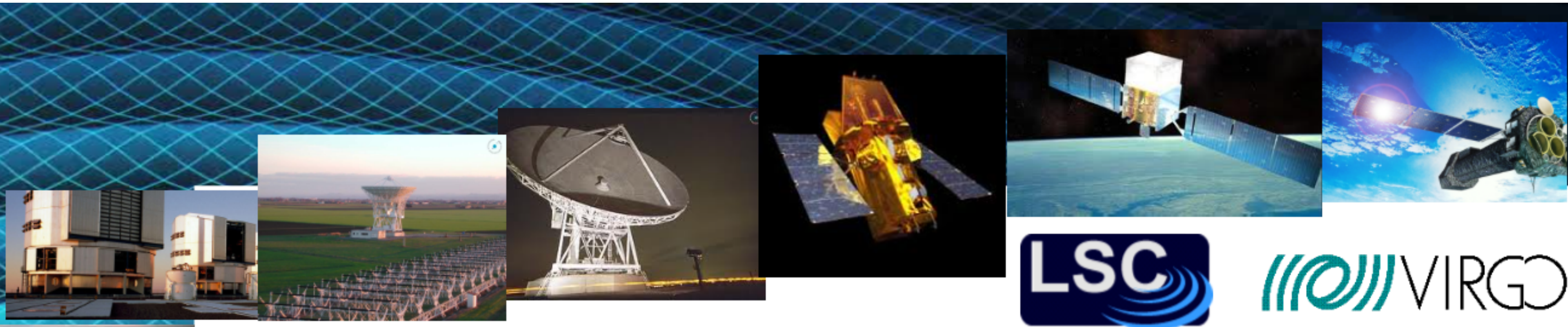
$$h \sim 10^{-26} \left(\frac{10\,\mathrm{kpc}}{\mathrm{distance}}\right)\left(\frac{f}{100\mathrm{Hz}}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

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

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

Astrofisica Nucleare e Subnucleare

Ground Detectors for GW



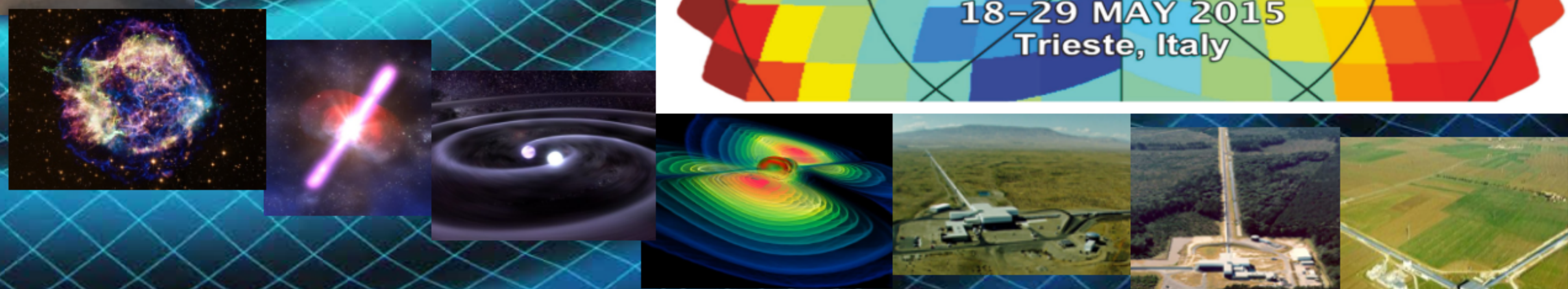
Gravitational waves – Experiments and sources

I PART

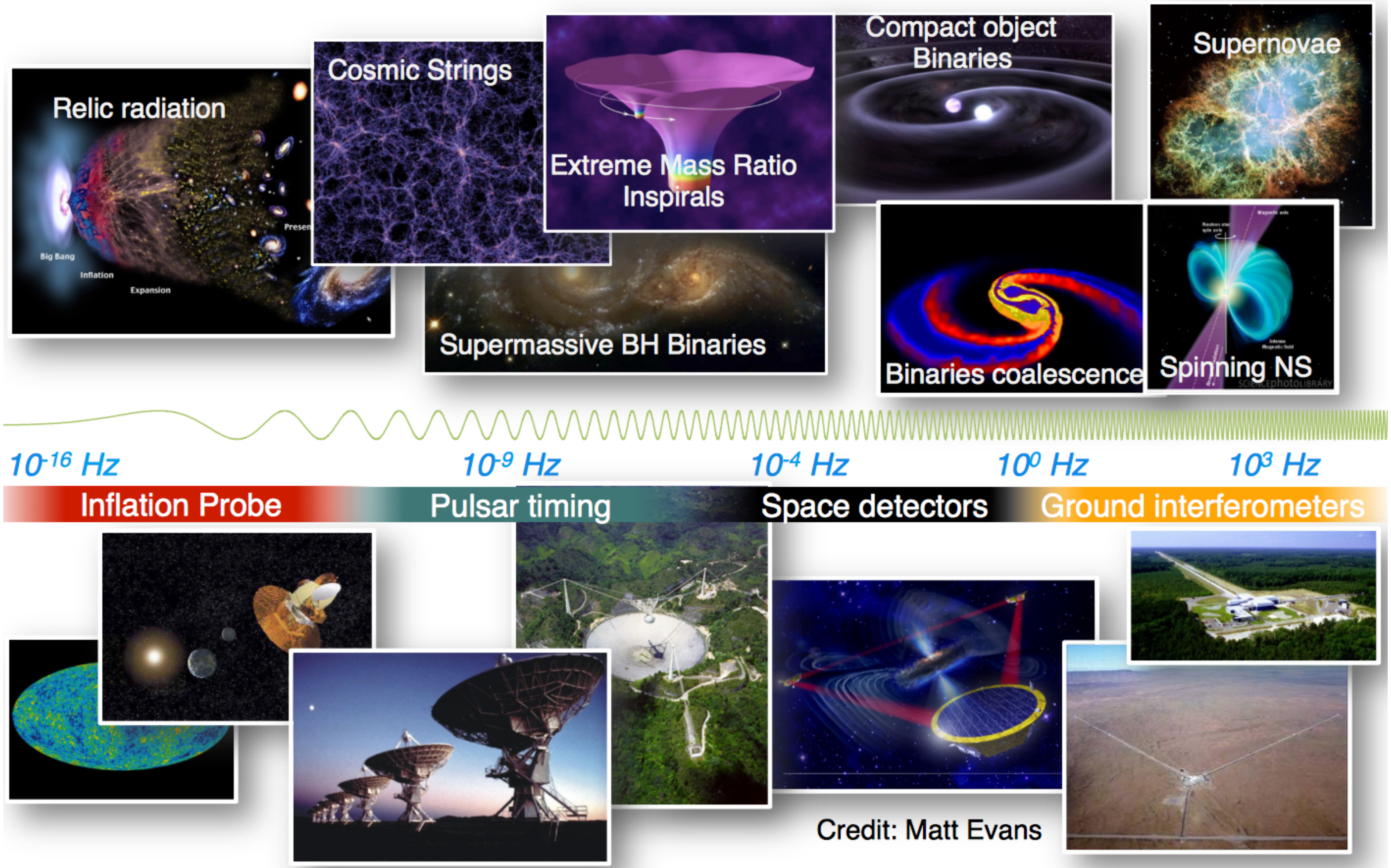
M.Branchesi

(Università di Urbino/INFN Sezione di Firenze)

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



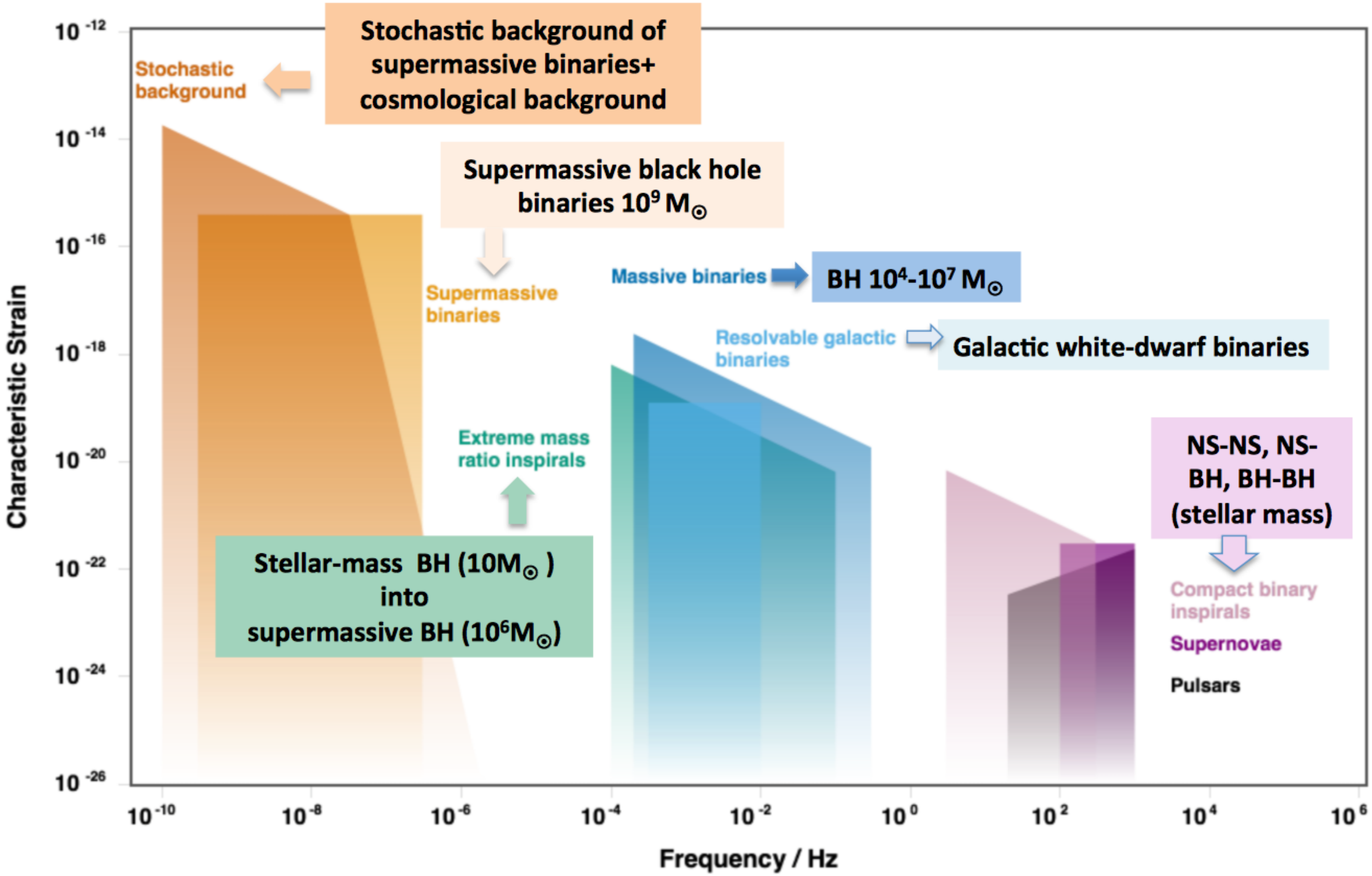
The GW Spectrum



Credit: Matt Evans

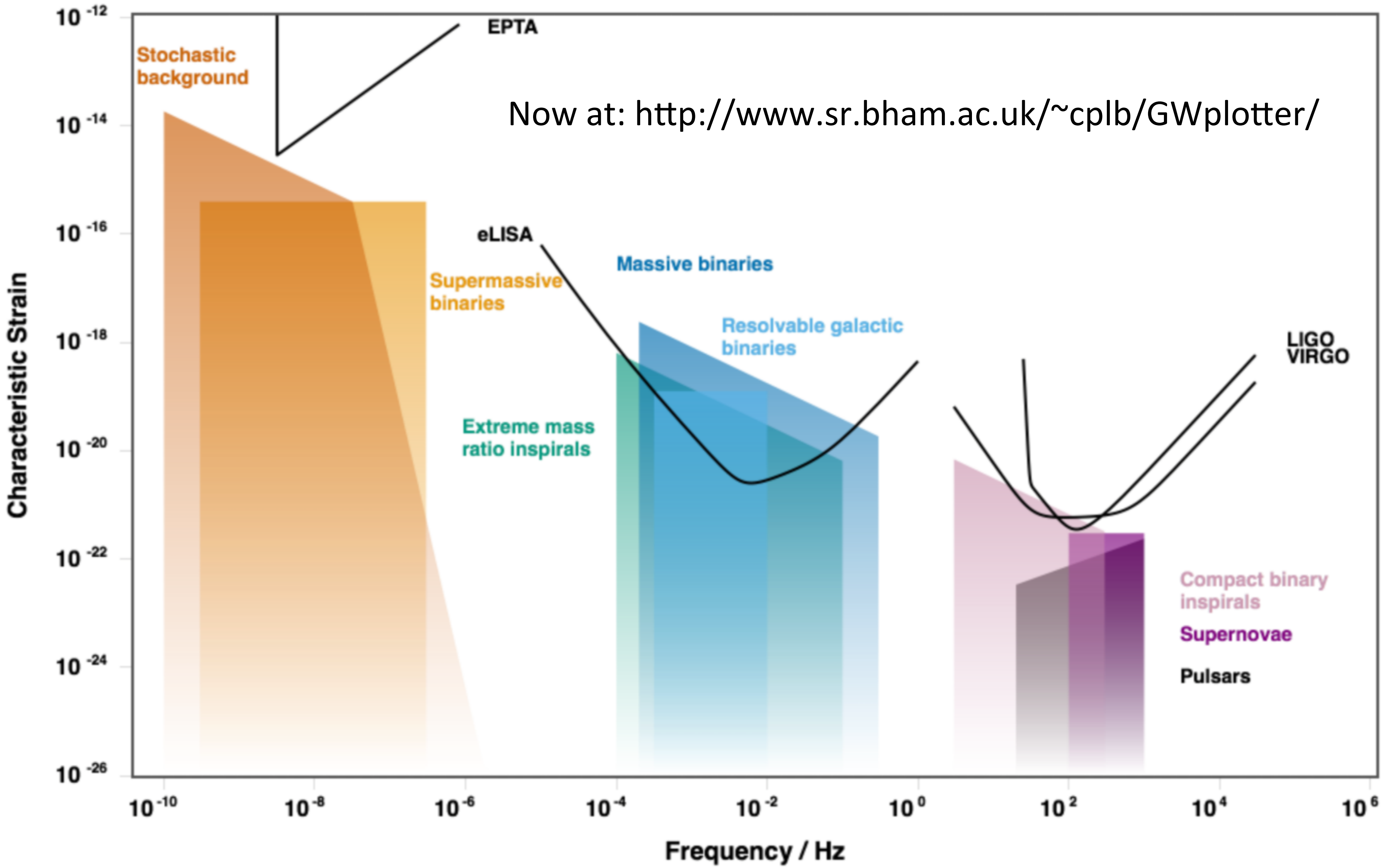
Astrophysical Sources

Now at: http://www.sr.bham.ac.uk/~cplb/GWplotter/



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

Astrophysical Sources



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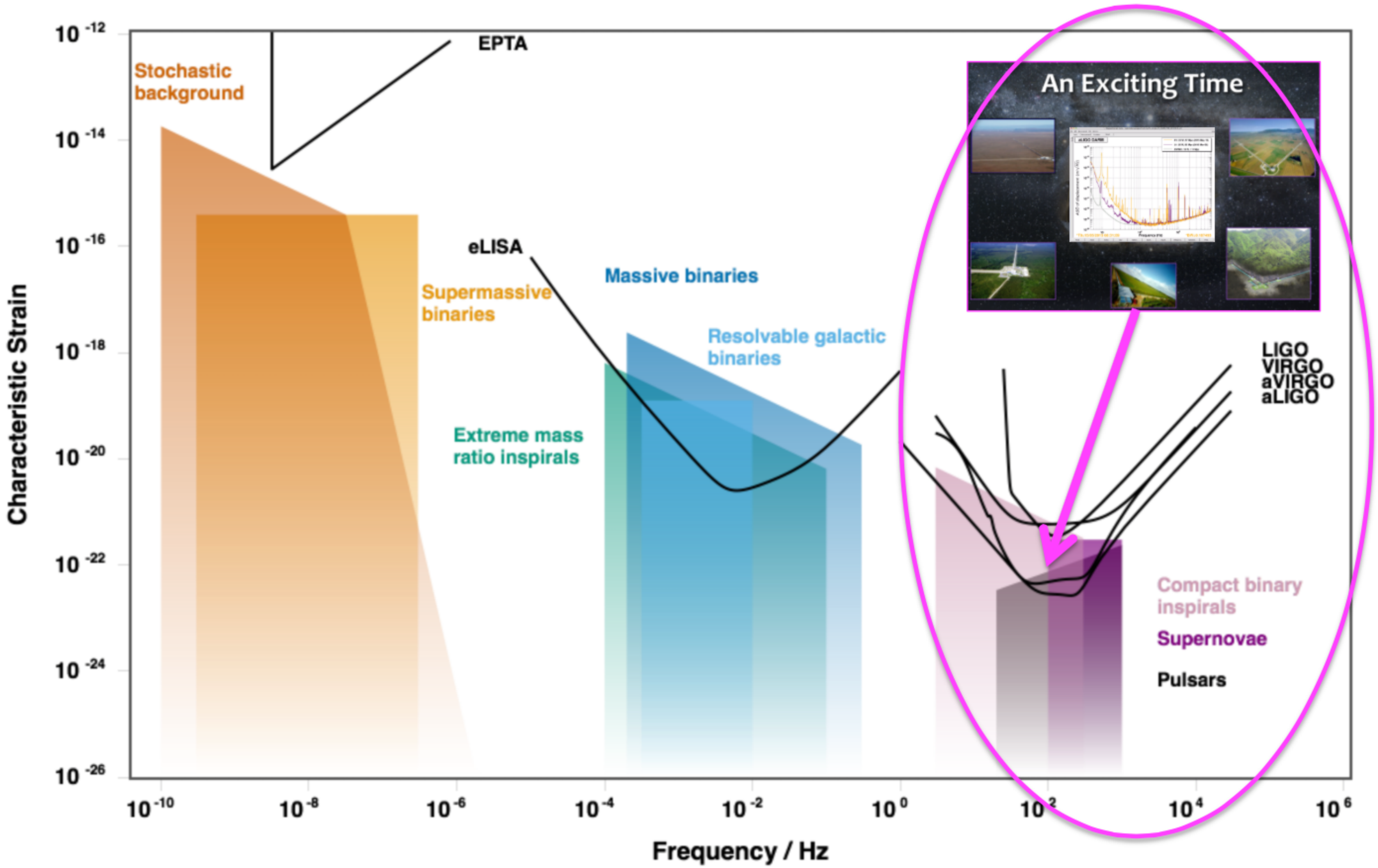

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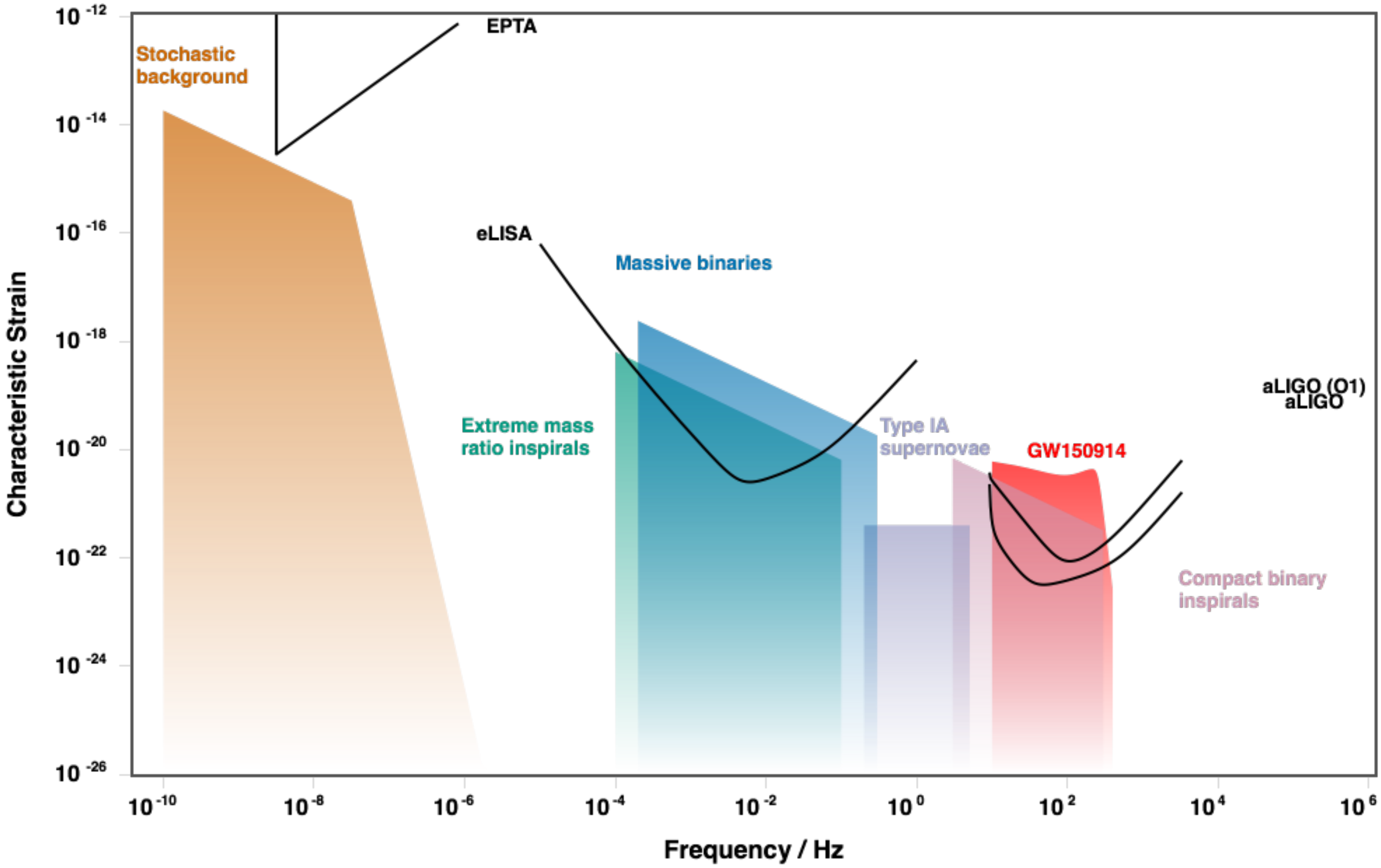
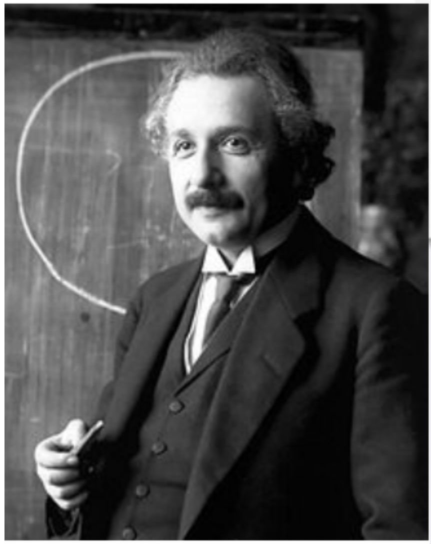
Now at: http://www.sr.bham.ac.uk/~cplb/GWplotter/



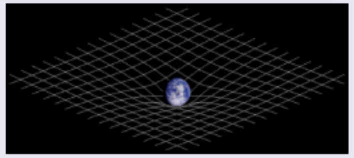
Now at: http://www.sr.bham.ac.uk/~cplb/GWplotter/

To reiterate:

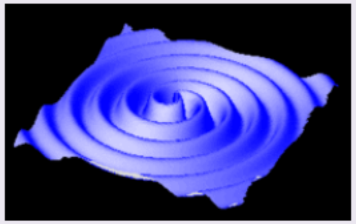


1916 → Einstein's theory of relativity predicts the existence of a new type of wave: the gravitational waves

GWs are perturbations of the space-time metric:



- Generated by mass distributions with time-varying quadrupole moments
- Propagating at the speed of light



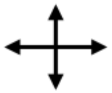
- Change in the distance between stationary (inertial) masses

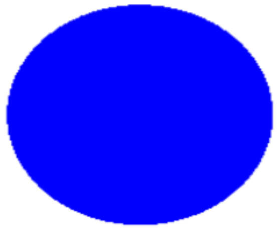
According to GR, GWs have two independent polarization states

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

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

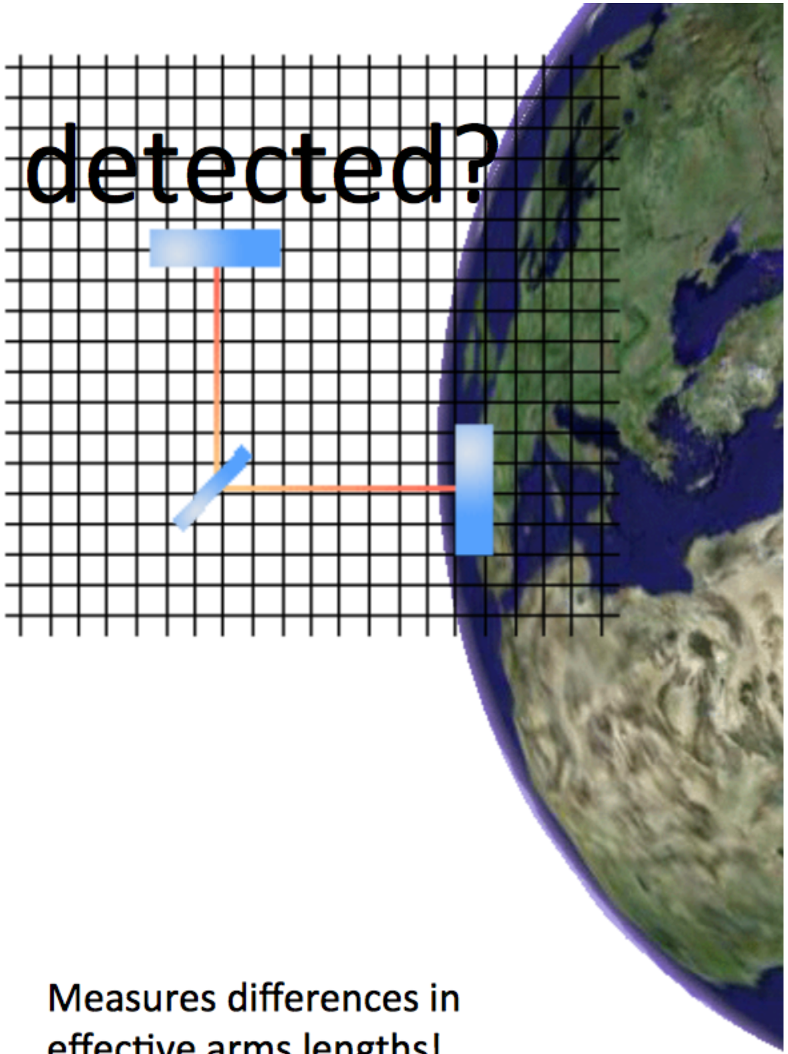
Polarization “Plus” h_+





“Cross” h_x

How can GWs be detected?



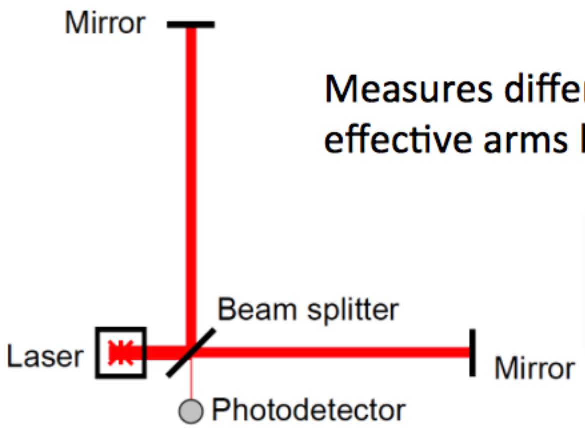
A GW deforms space

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

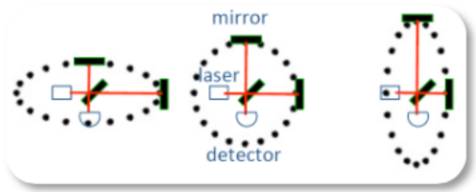
*The displacement is proportional to length: it is a **strain**!*

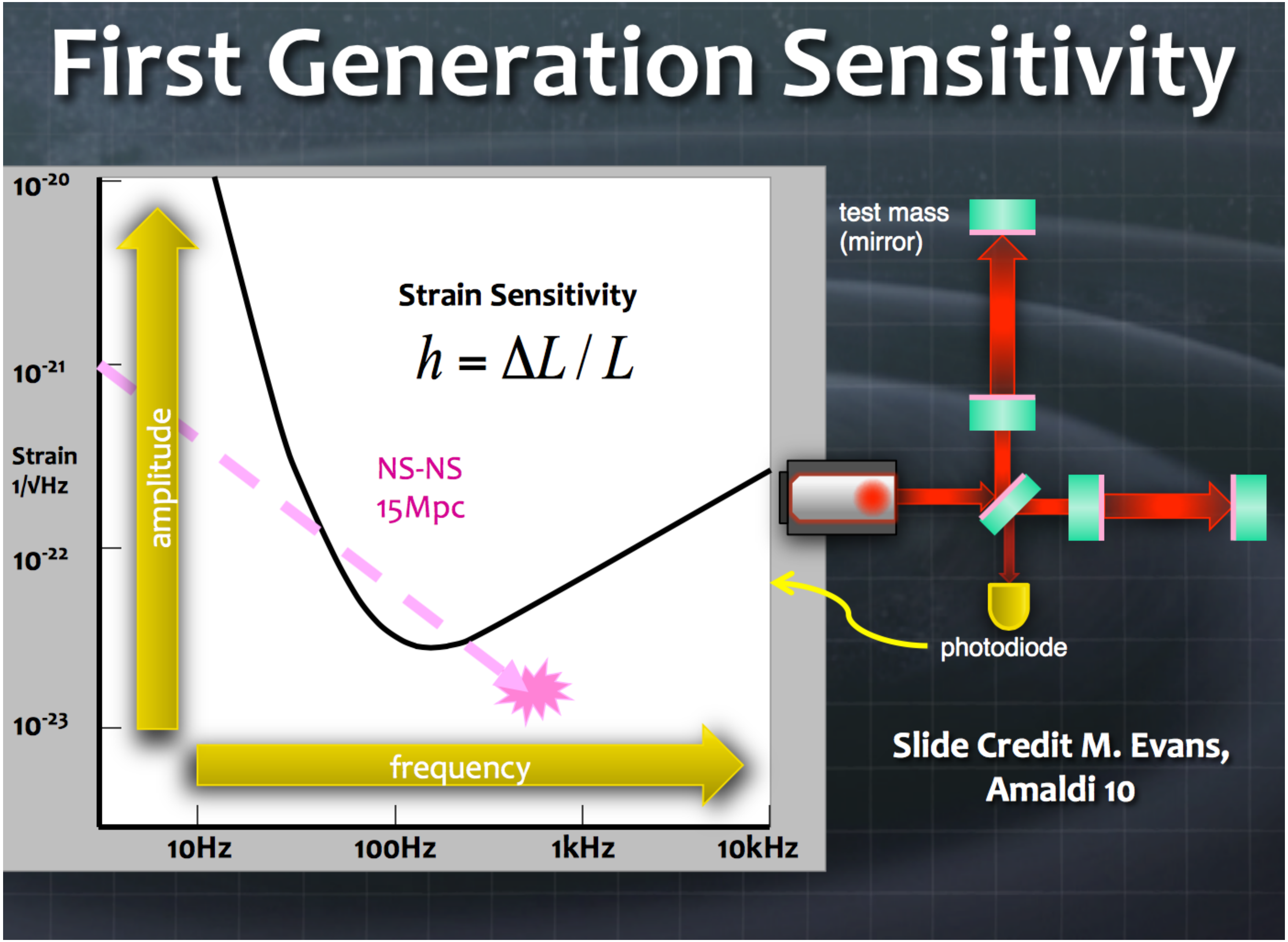
Do we know how to detect displacement?

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

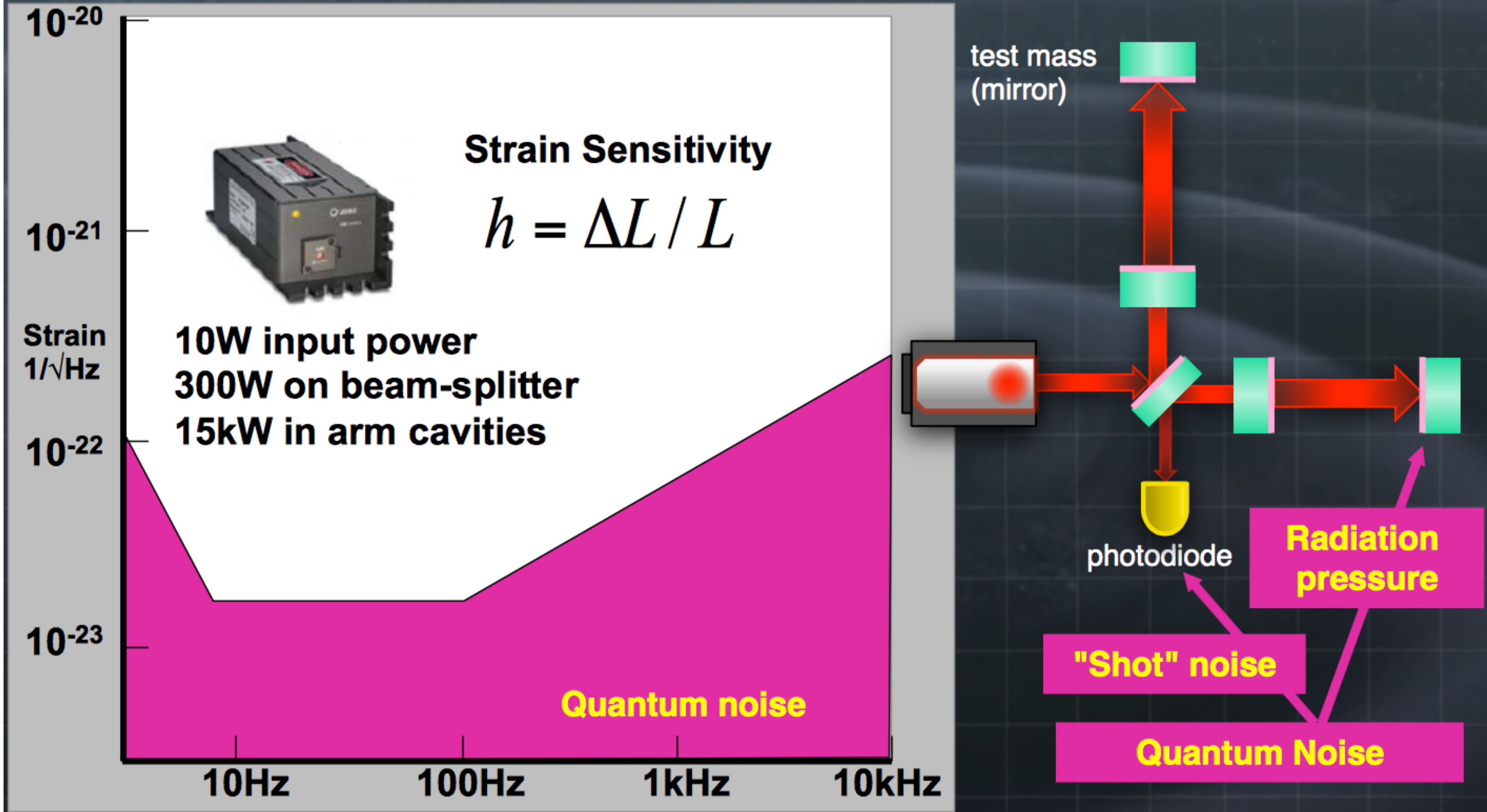


Measures differences in effective arms lengths!



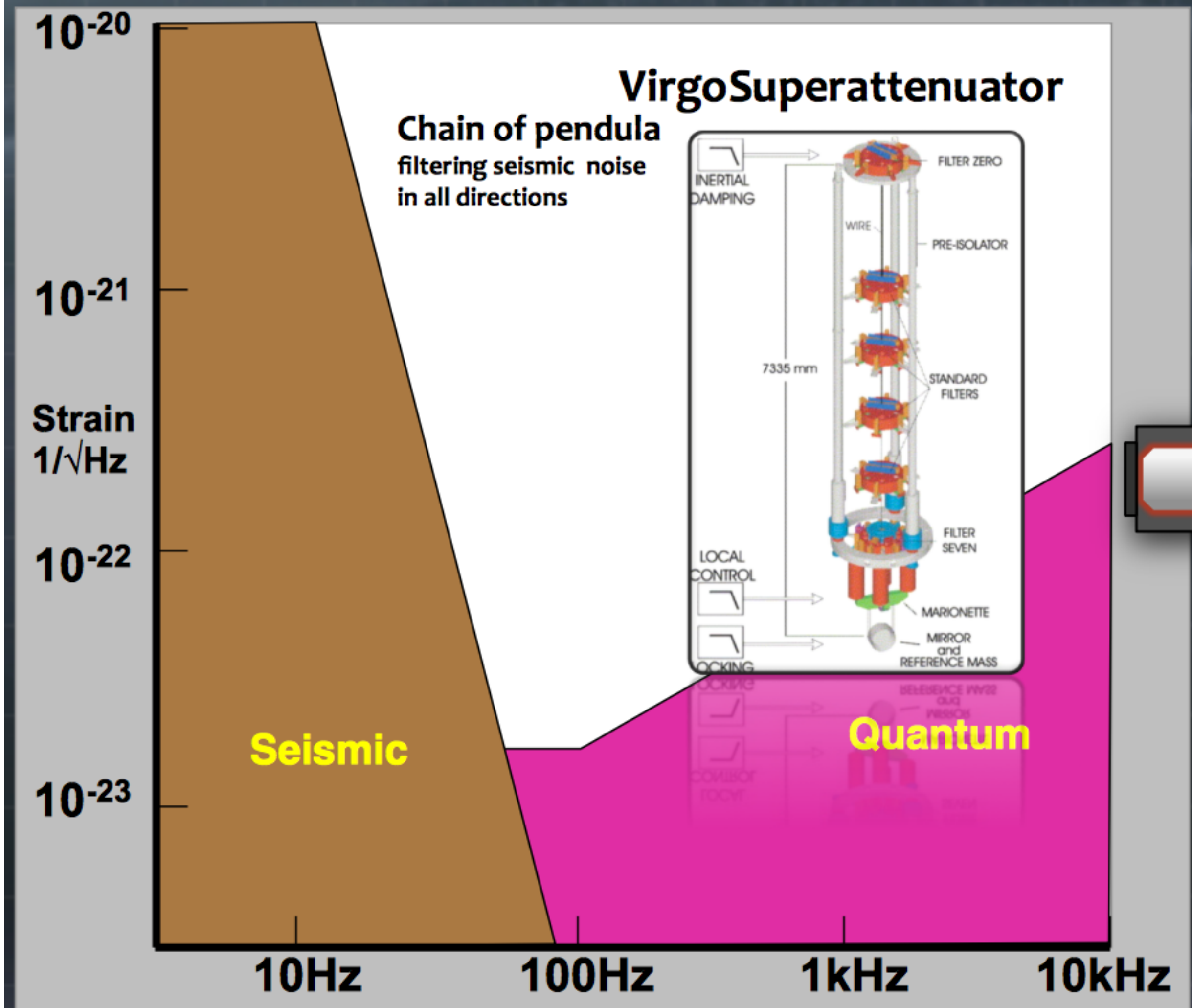

First Generation Sensitivity
10^-20
10^-21
Strain
1/√Hz
10^-22
10^-23
amplitude
Strain Sensitivity
$h = \Delta L / L$
NS-NS
15Mpc
frequency
10Hz
100Hz
1kHz
10kHz
test mass
(mirror)
photodiode
Slide Credit M. Evans,
Amaldi 10

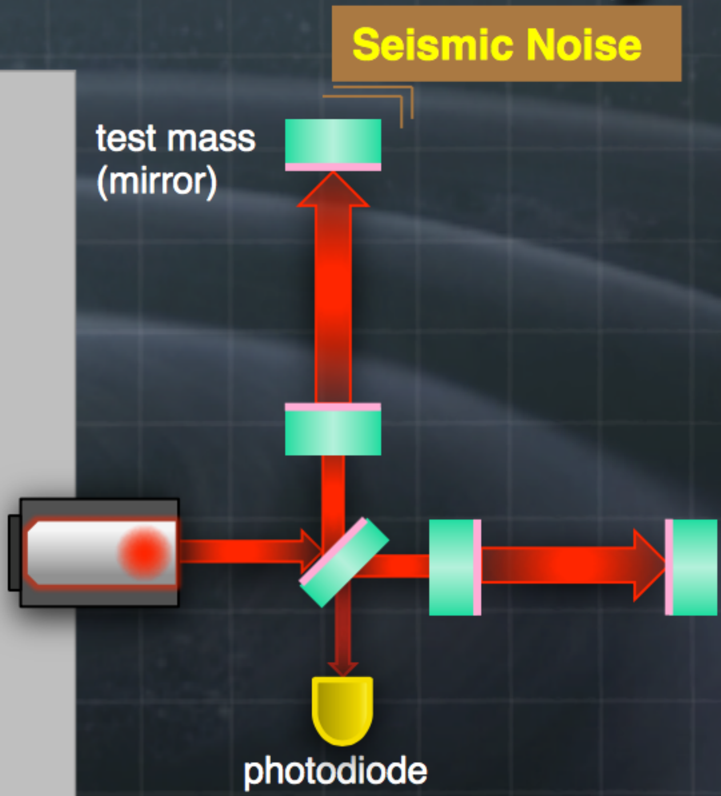
First Generation Sensitivity



Slide Credit M. Evans, Amaldi 10

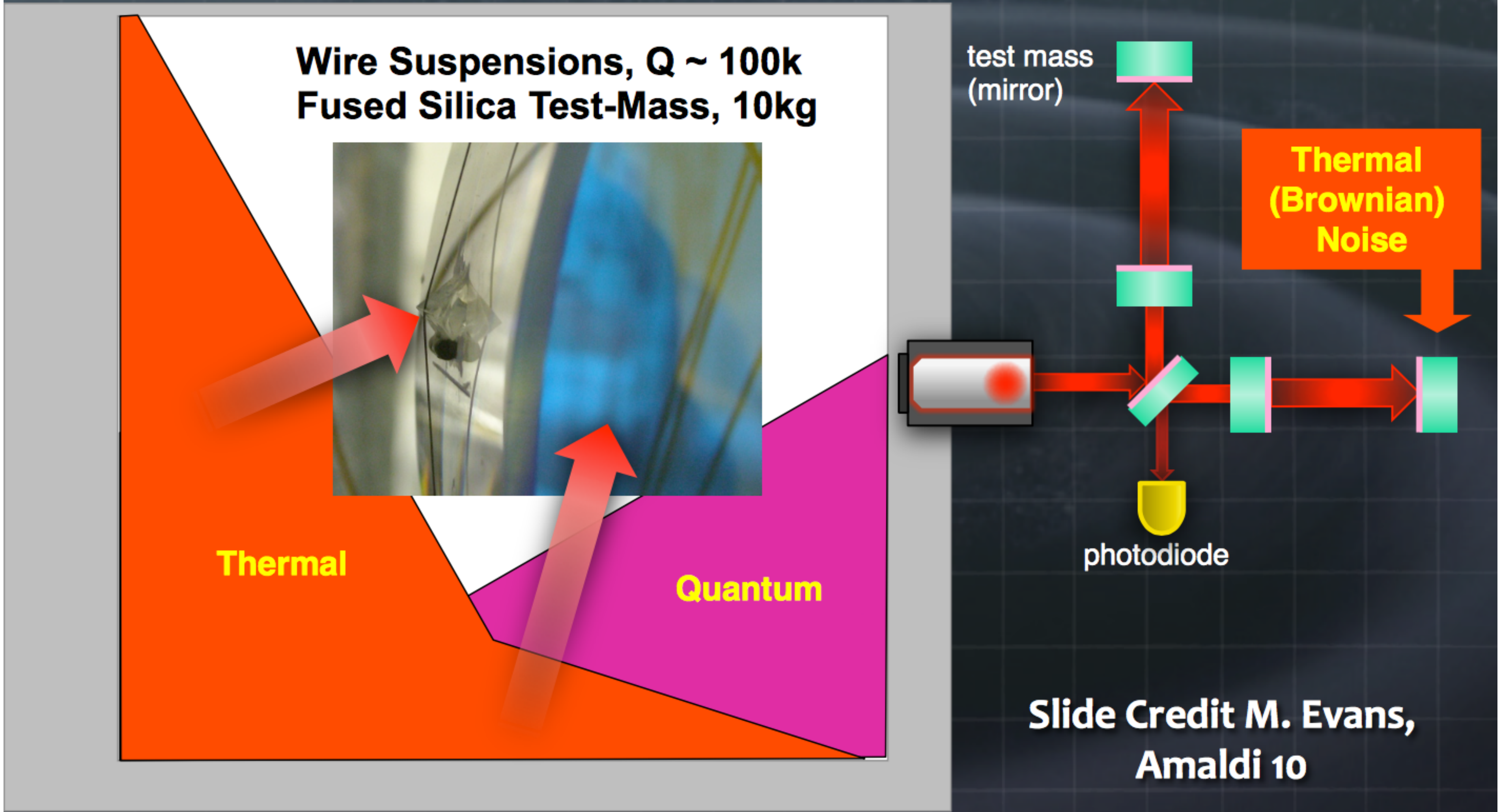
First Generation Sensitivity





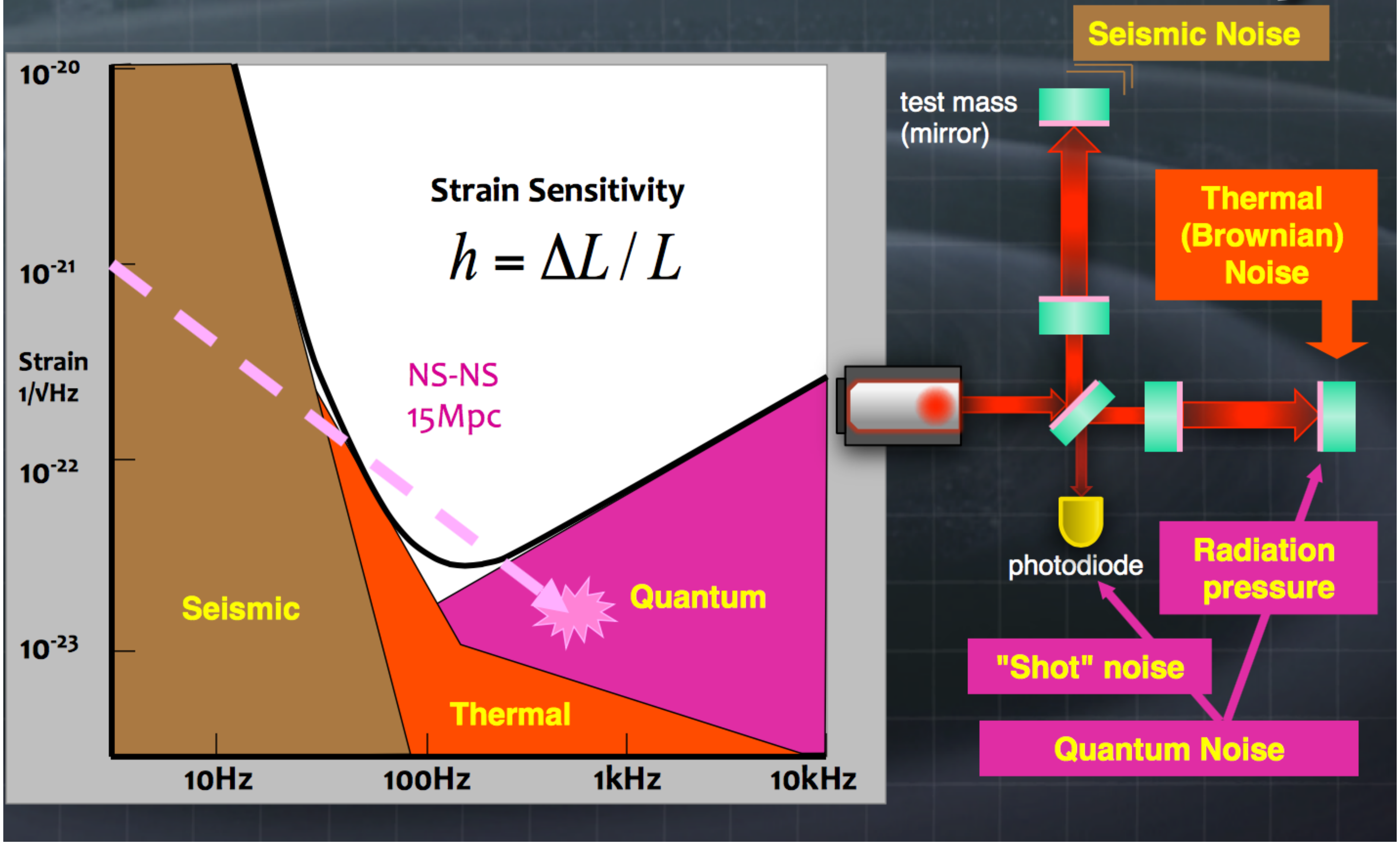
Slide Credit M. Evans,
Amaldi 10

First Generation Sensitivity

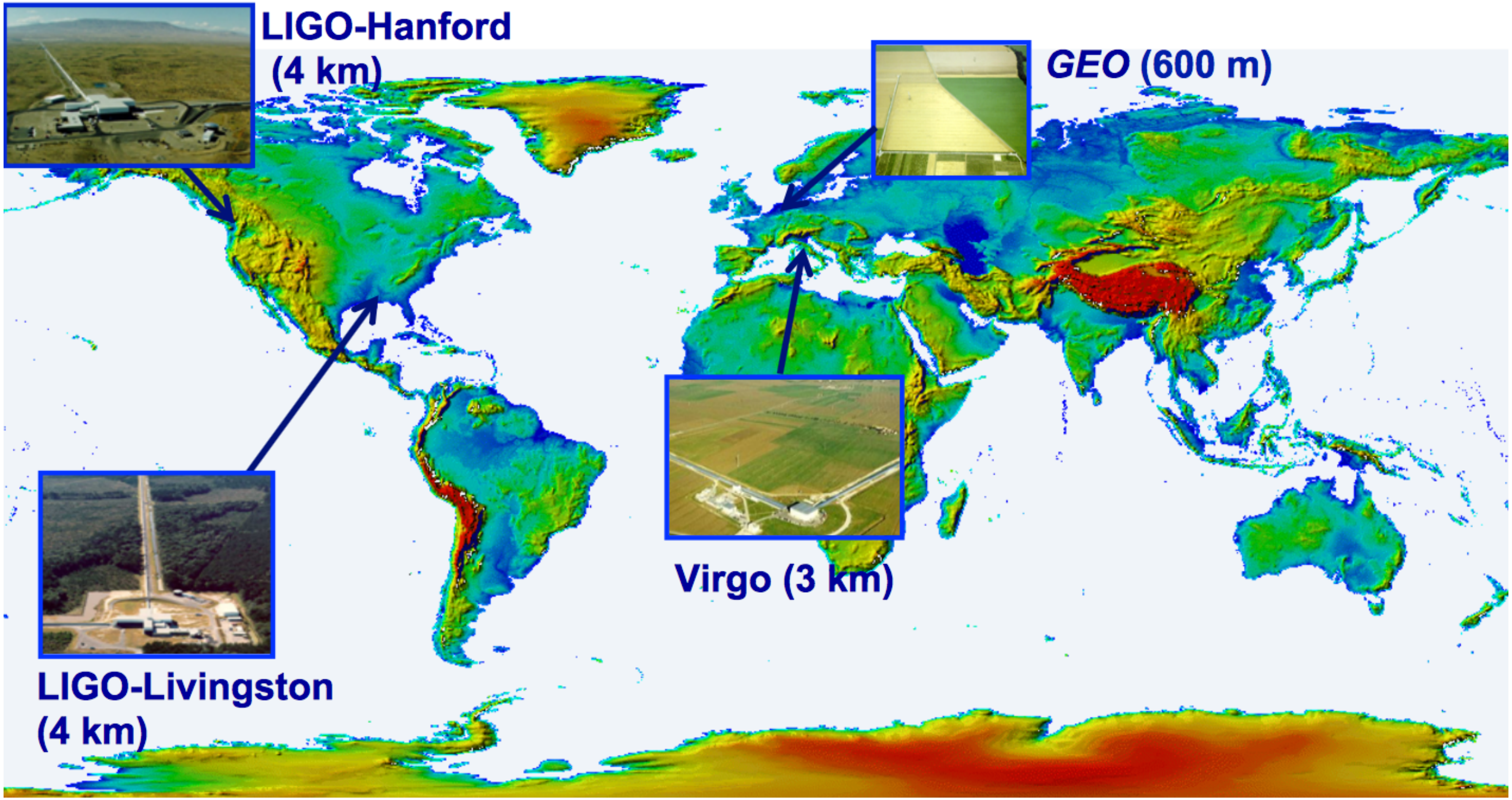


Slide Credit M. Evans, Amaldi 10

First Generation Sensitivity

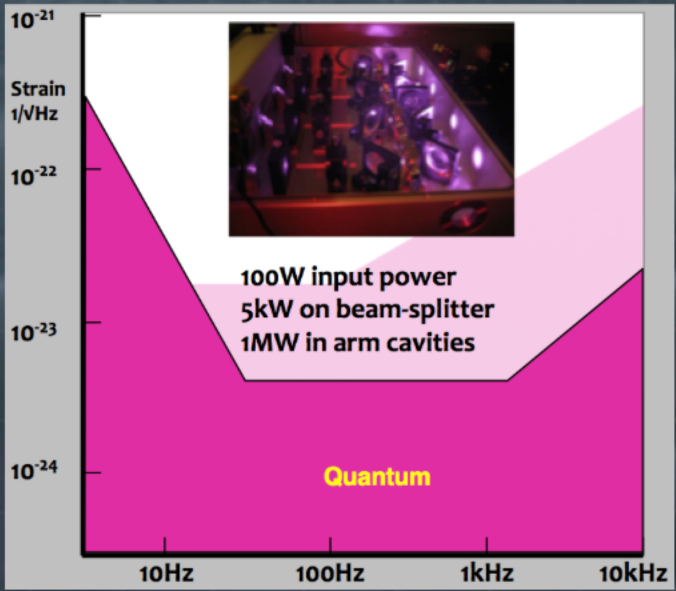


Ground-based Gravitational Wave Detectors

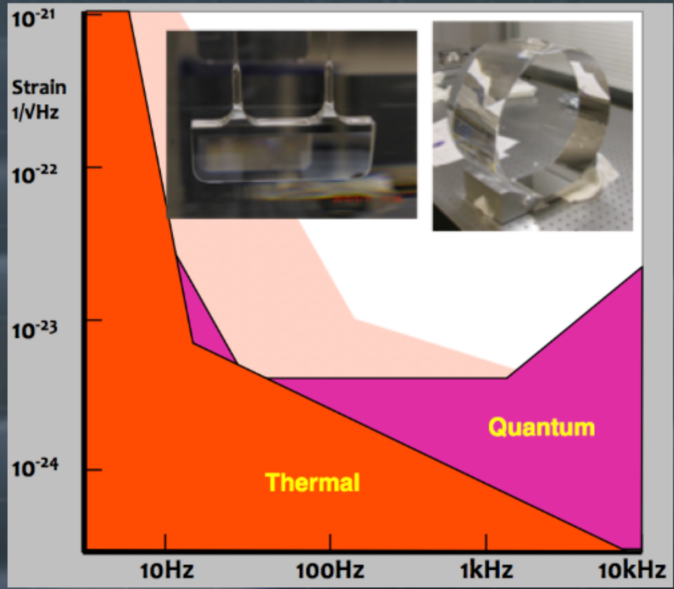


Advanced GW detectors

More Laser Power…

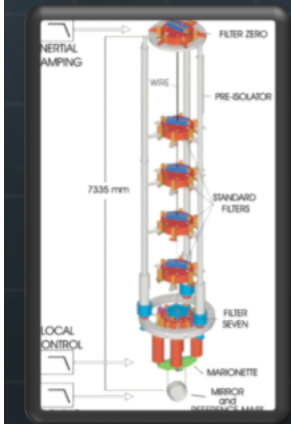


Better mechanical quality…

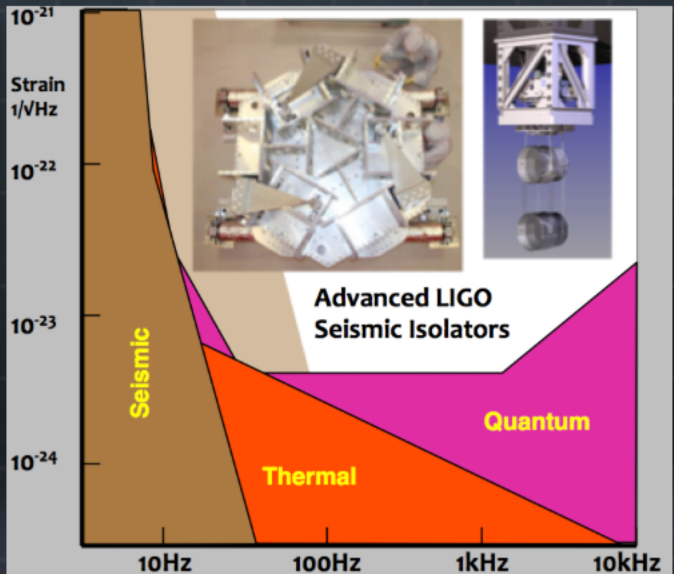


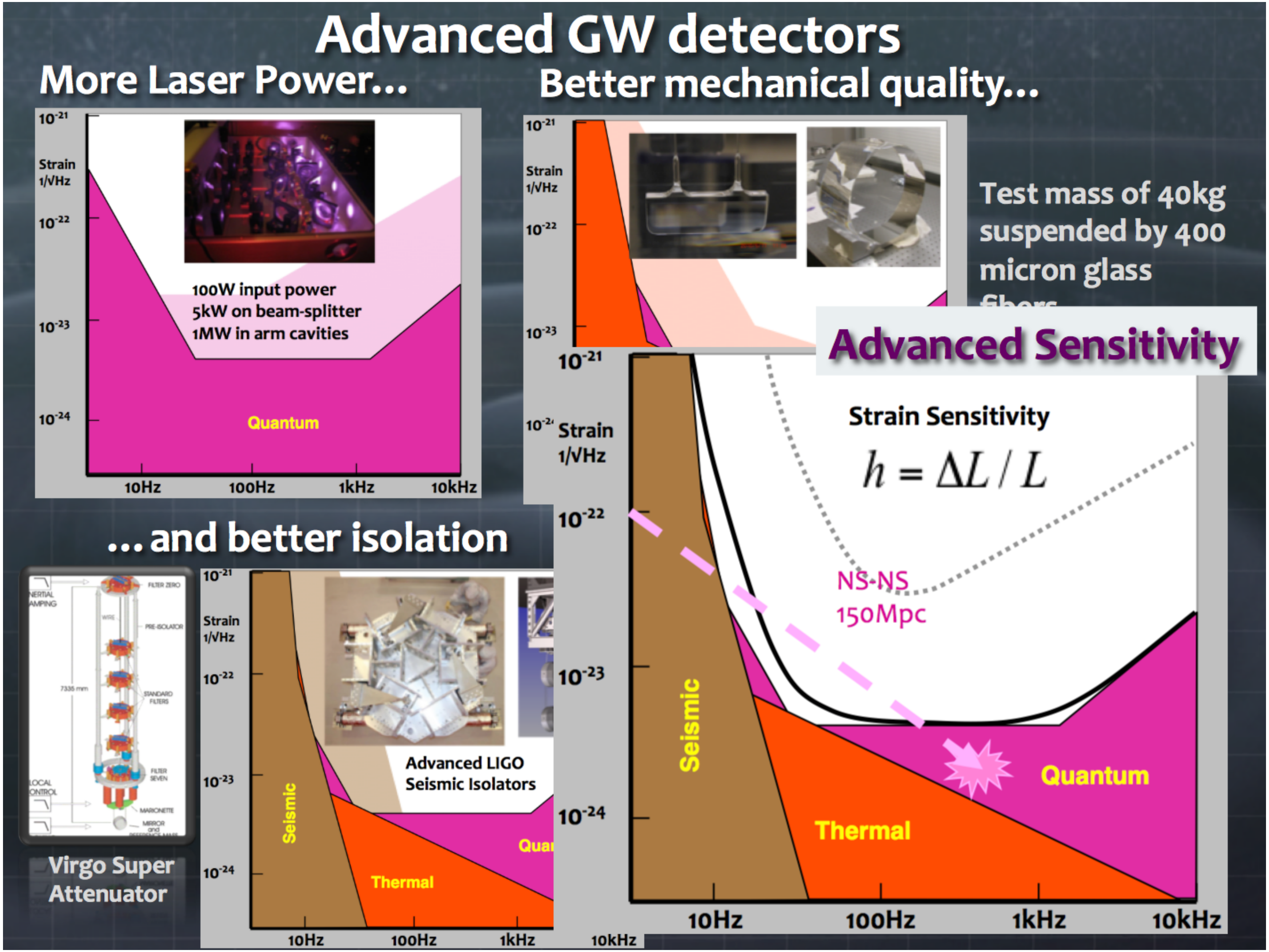
Test mass of 40kg suspended by 400 micron glass fibers…

… and better isolation



Virgo Super Attenuator



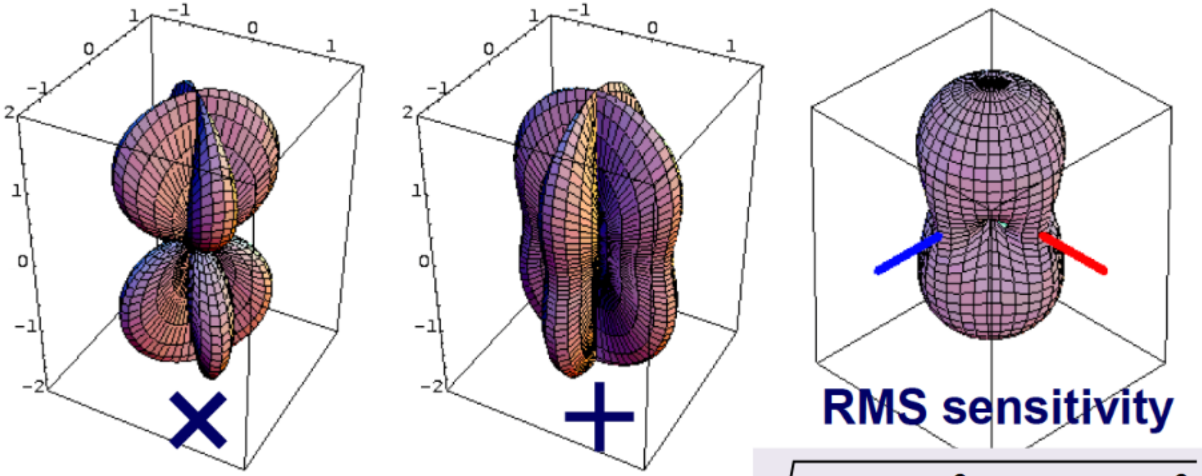


Advanced GW detectors
More Laser Power…
Better mechanical quality…
Test mass of 40kg suspended by 400 micron glass fibers
100W input power
5kW on beam-splitter
1MW in arm cavities
Quantum
Strain 1/√Hz
10Hz 100Hz 1kHz 10kHz
… and better isolation
Virgo Super Attenuator
Advanced LIGO Seismic Isolators
Seismic
Thermal
Advanced Sensitivity
Strain Sensitivity
$h = \Delta L / L$
NS-NS 150Mpc

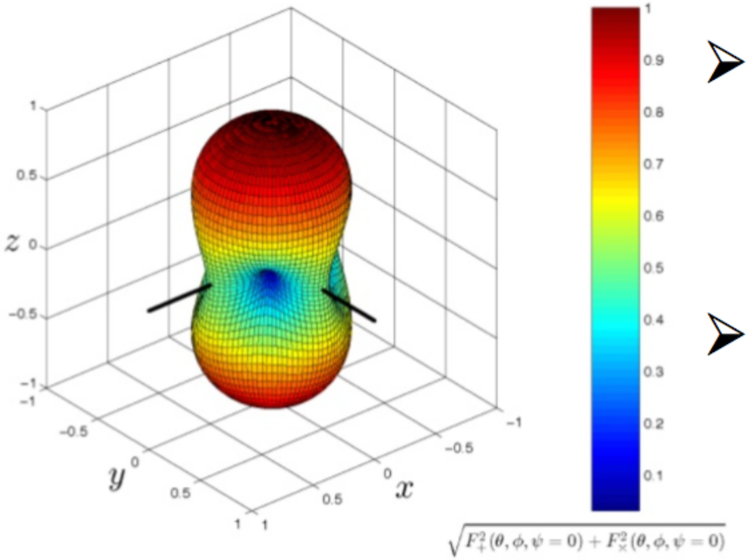
Single GW detector directional sensitivity

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

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



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

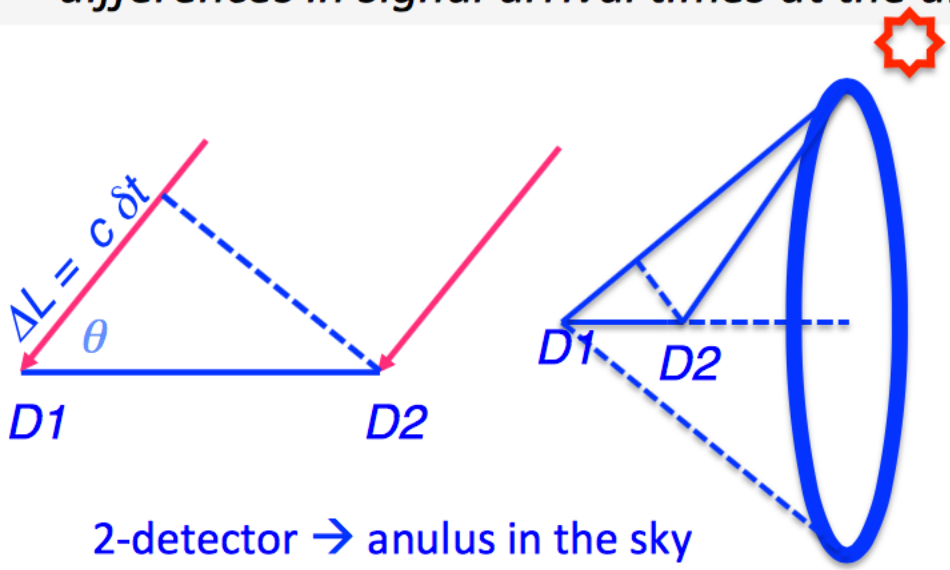


- Single GW detector is a **good all-sky monitor**, nearly omni-directional
  (the transparency of Earth to GWs)

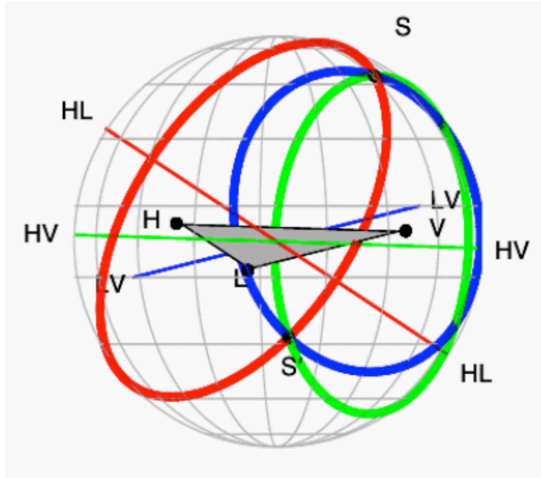
- But does not have good directional sensitivity, **not a pointing instrument!**
  It has a very poor angular resolution (about 100 degrees)

The source localization requires a network of GW detectors

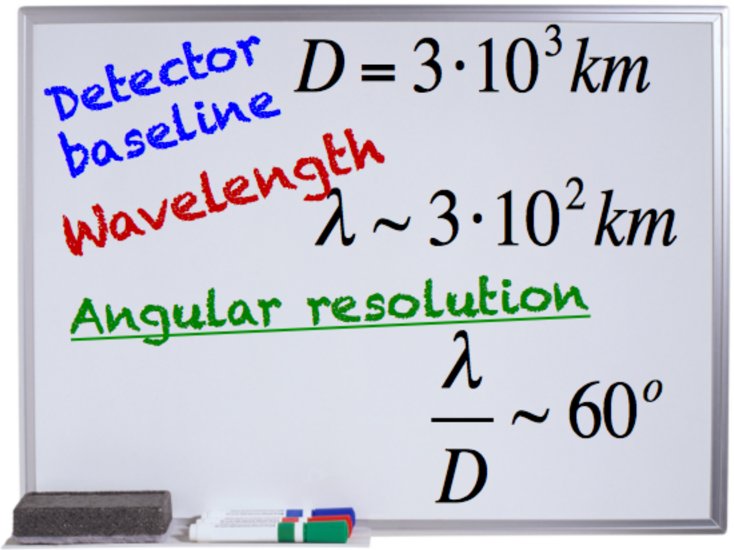
*The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different network detector sites*



2-detector → anulus in the sky



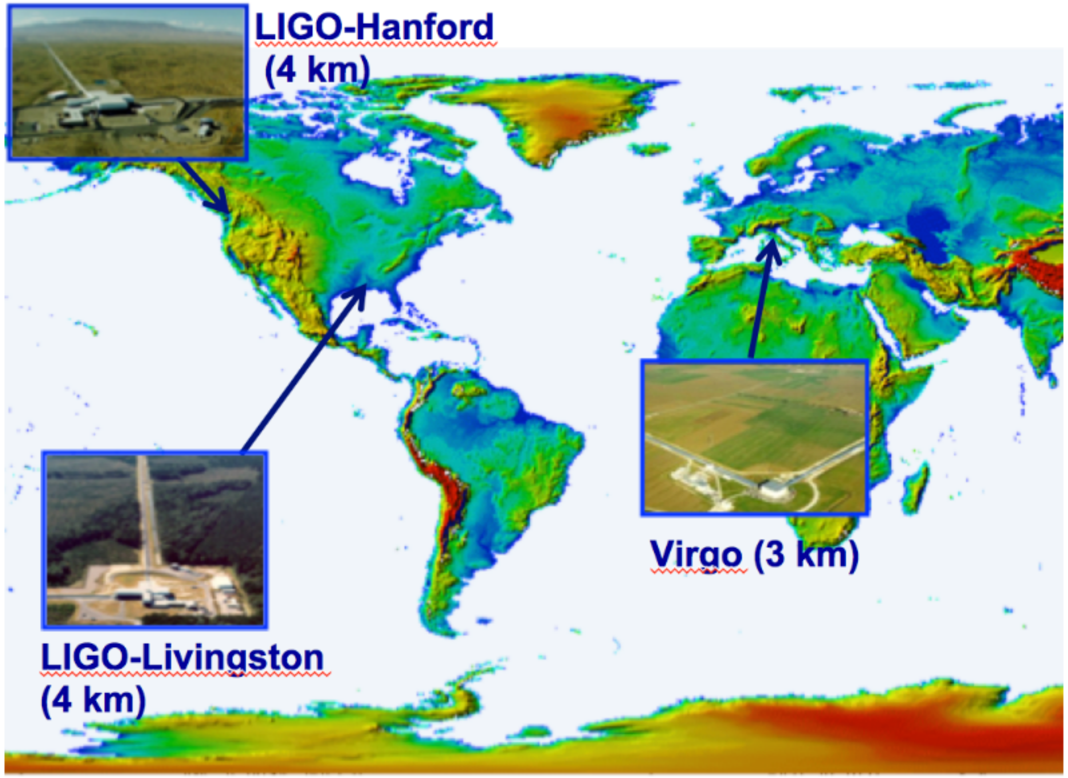
3-detectors → localize



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

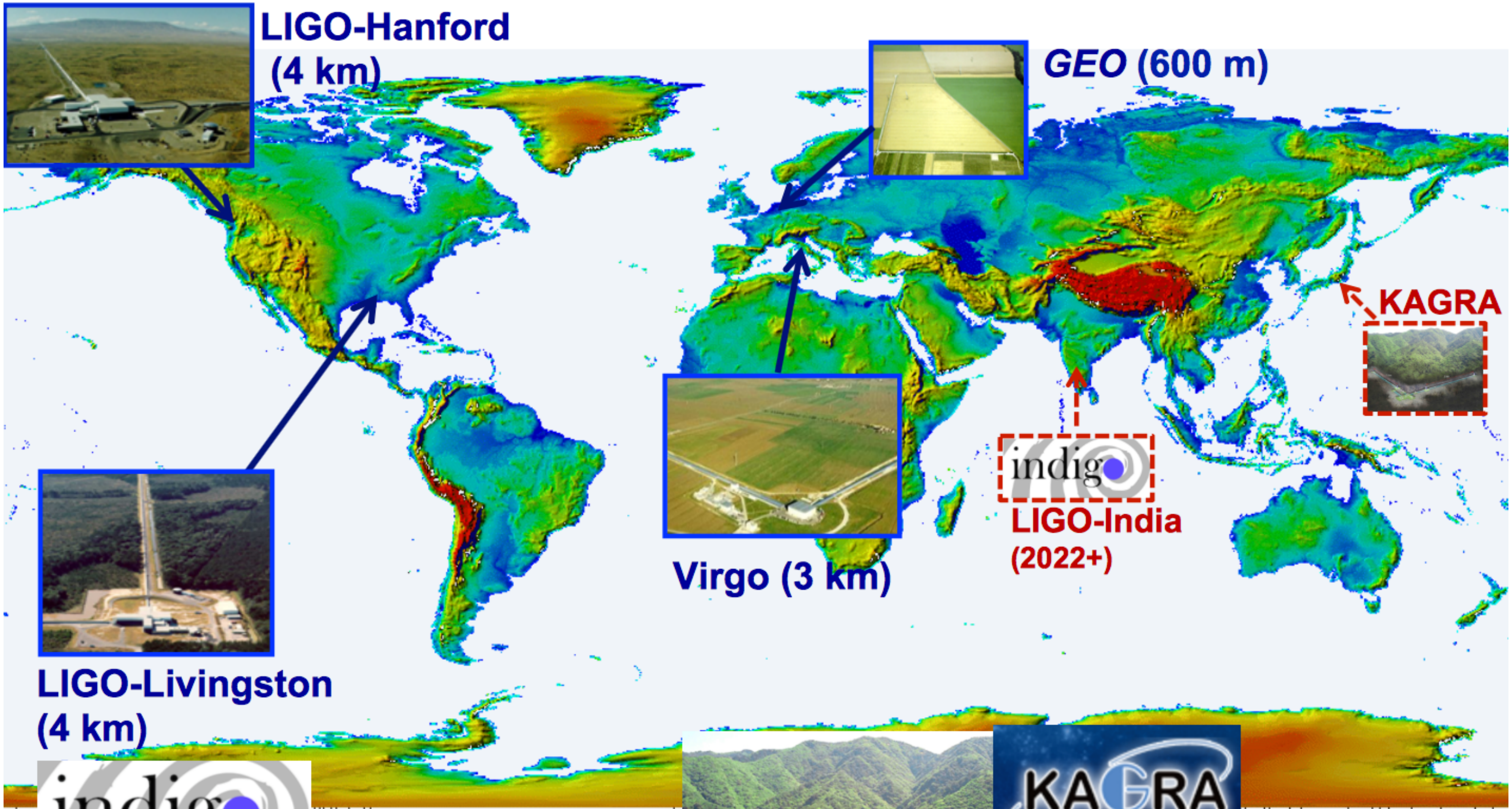
Advanced LIGOs and **Virgo** will observe the sky (10-1000 Hz) as a **single network** aiming at the **first direct detection of GWs**

Example of sky-localization capabilties

NS-NS with SNR=7 in each of the LIGOs and Virgo:

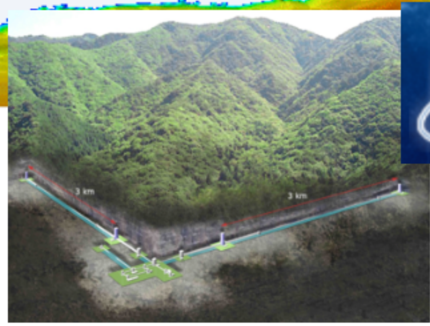
- best case localization of **20 deg^2** (signal is directly over the plane of network)
- median of **40 deg^2** **(Fairhurst 2009)**

Near Future Gravitational Wave Detectors



indigo

Move one of the two LIGO detectors in Hanford to India



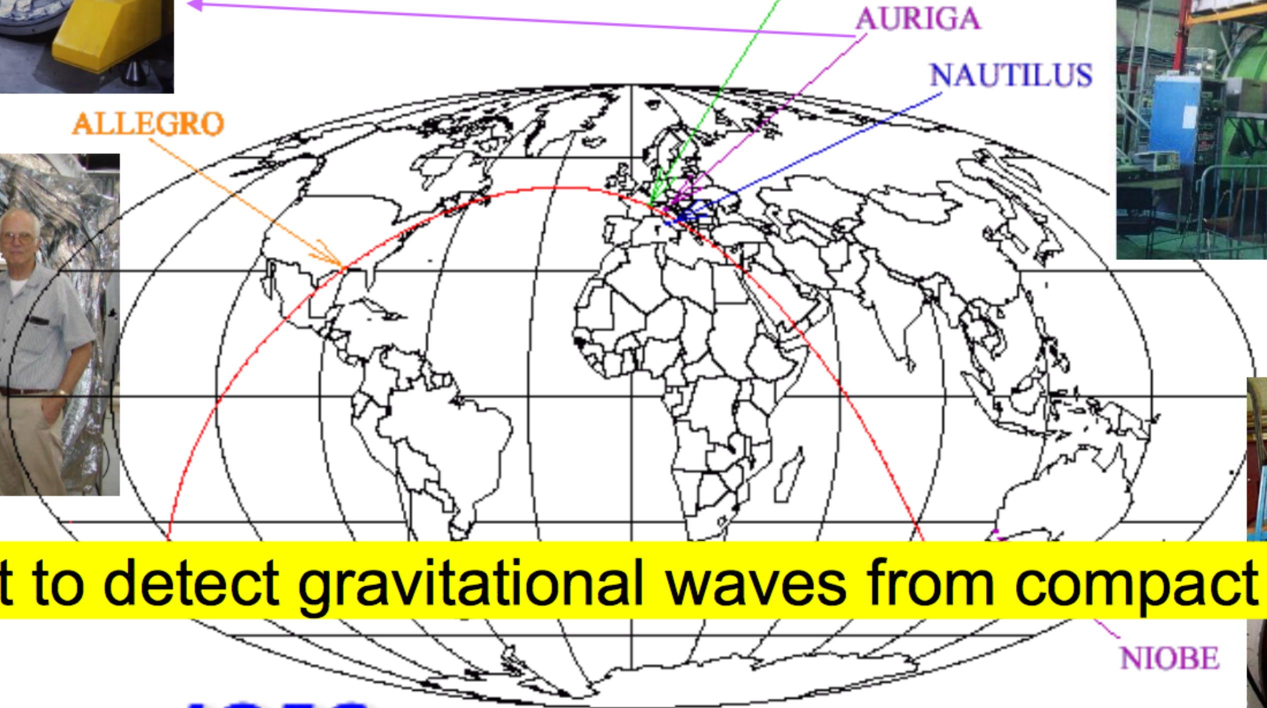
KAGRA

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

Astrofisica Nucleare e Subnucleare

Other Detectors for GW

Bar detectors: IGEC collaboration

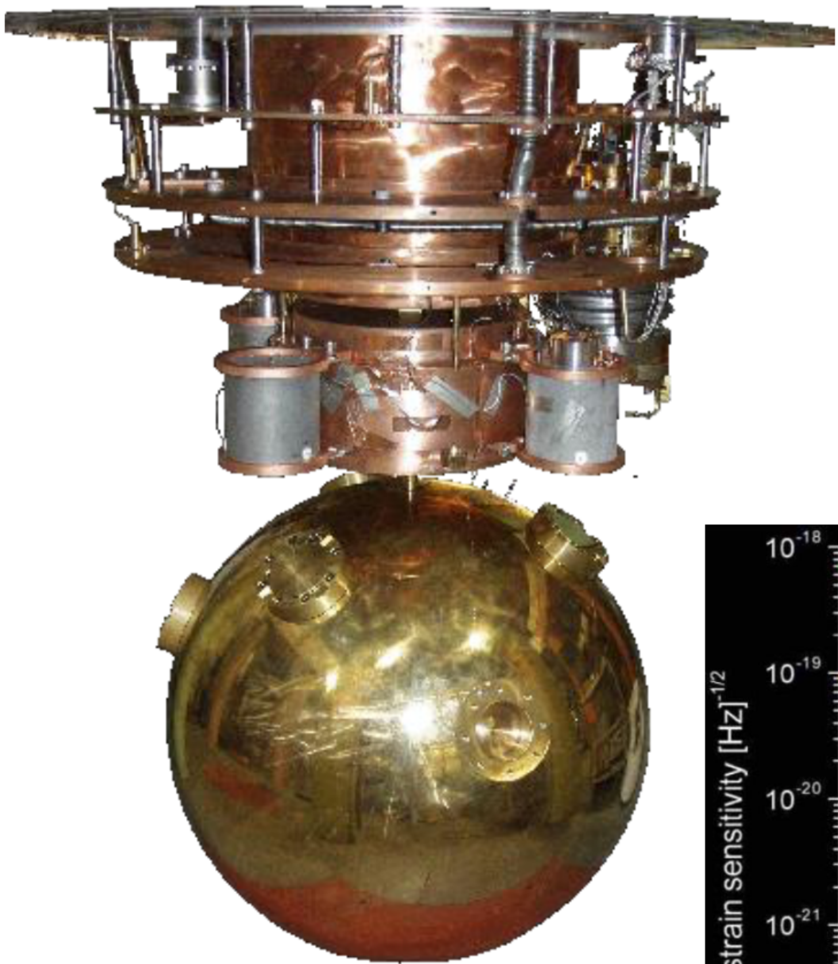


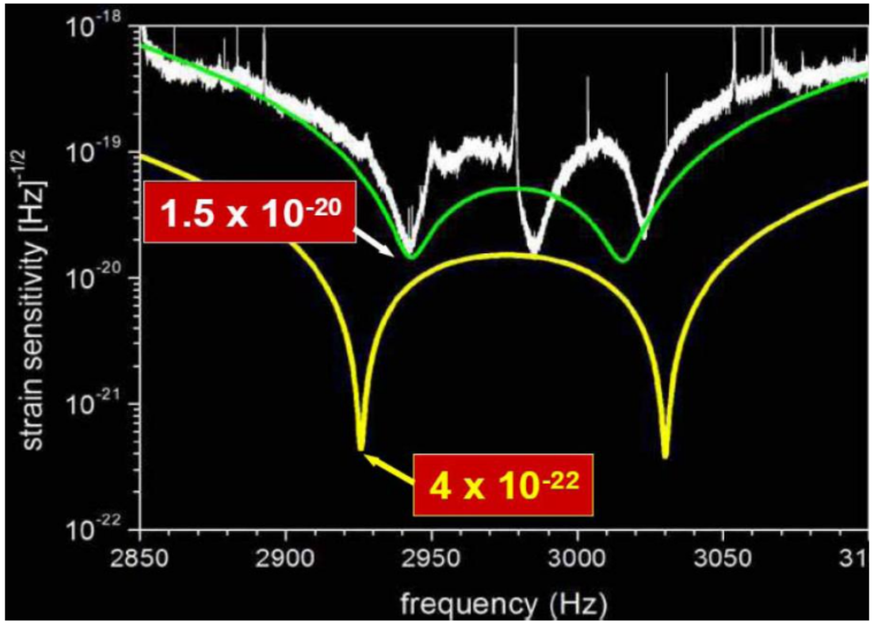
Built to detect gravitational waves from compact objects

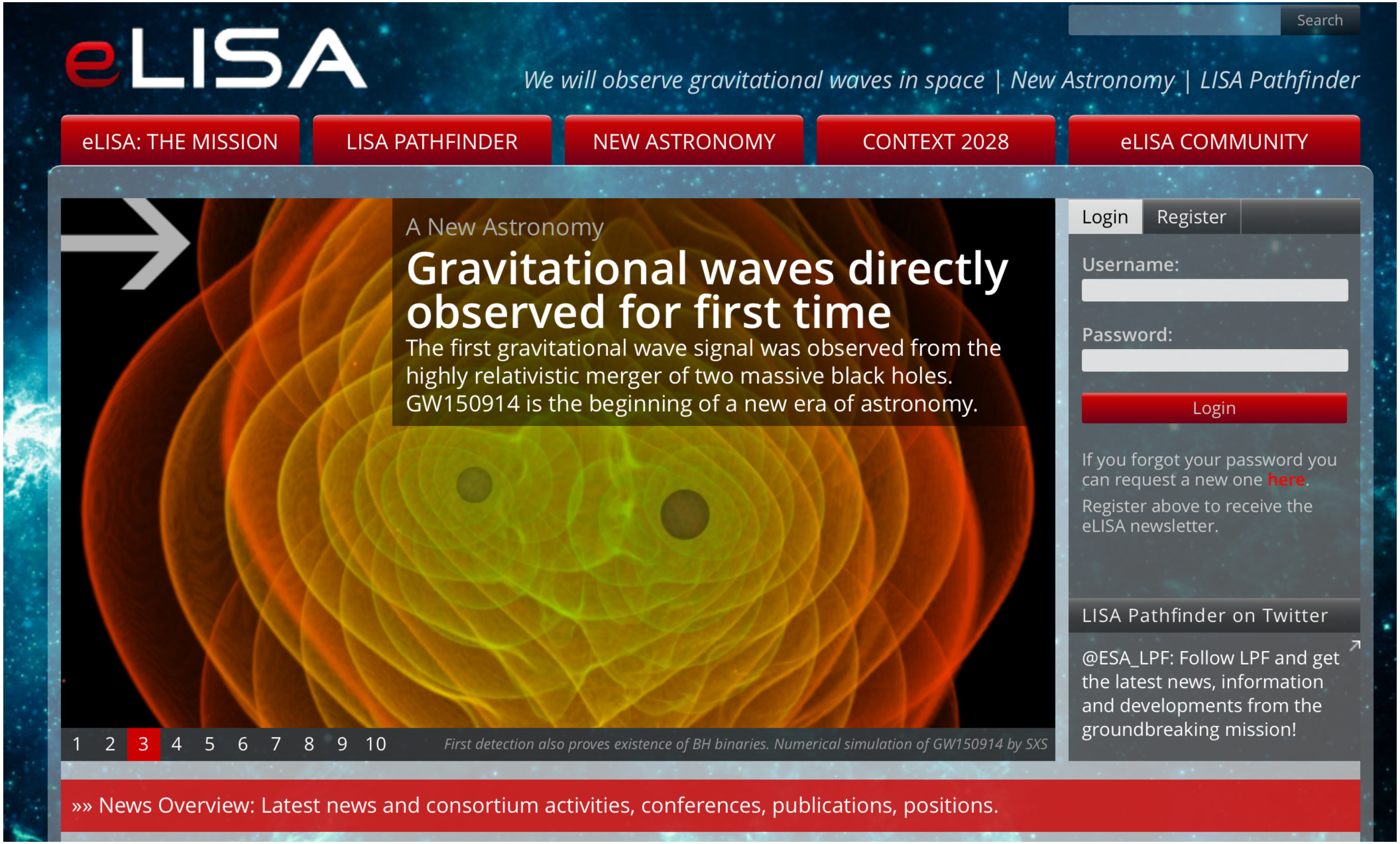
IGEC

Ladbrokes.com

Mini-GRAIL: a spherical `bar' in Leiden



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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.
1 2 3 4 5 6 7 8 9 10
First detection also proves existence of BH binaries. Numerical simulation of GW150914 by SXS
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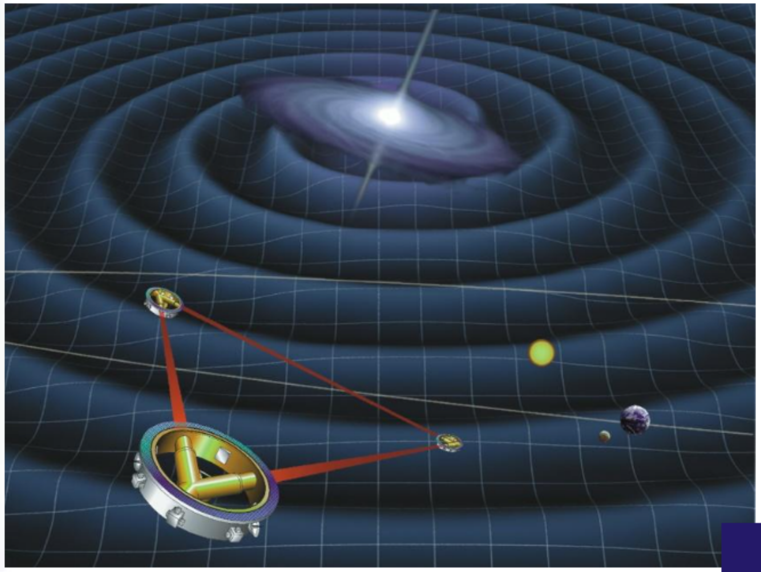
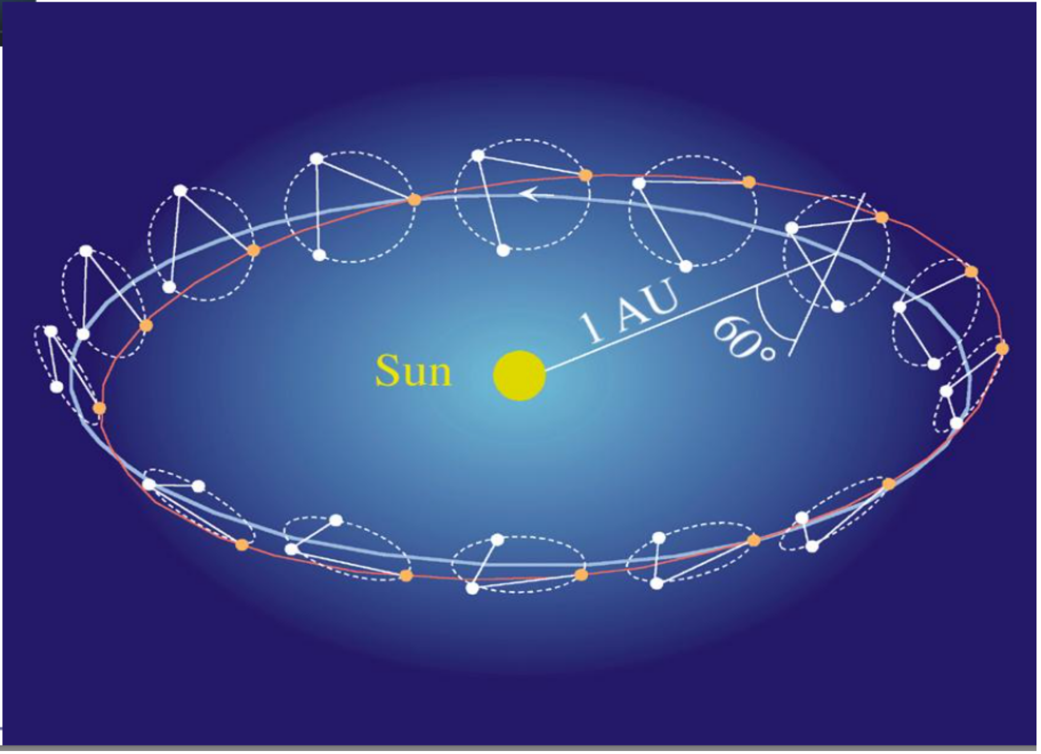
»» News Overview: Latest news and consortium activities, conferences, publications, positions.

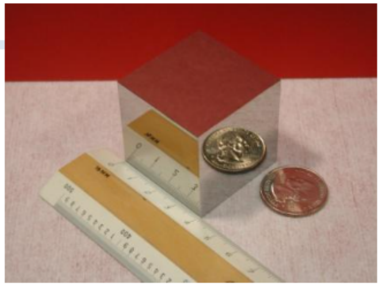
Gravitational wave antenna in space - LISA



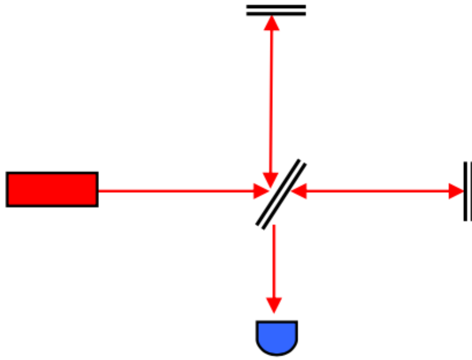
- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between NASA and ESA*

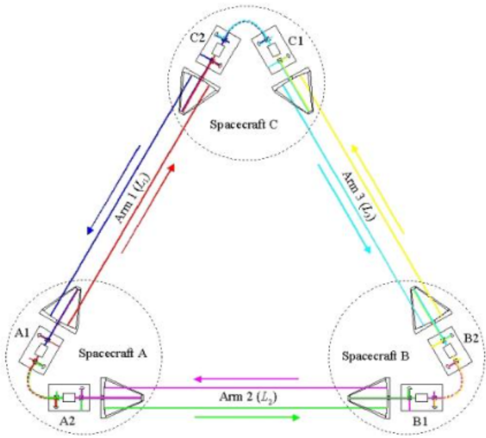


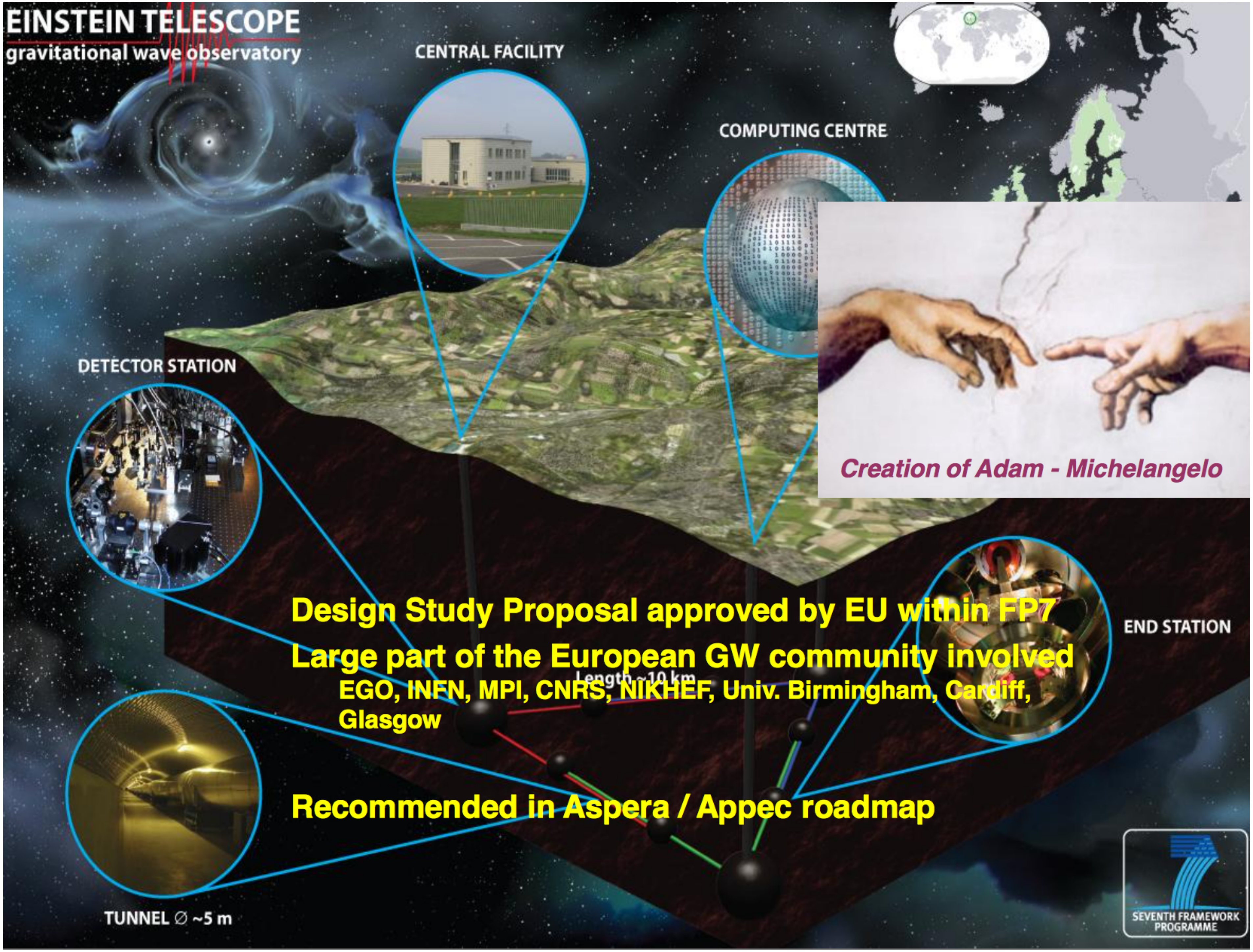
LISA interferometry



- "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 ~17 seconds
  - Constellation is rotating and translating in space







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

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)

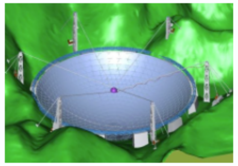
First major realisation of a PTA was the Parkes Pulsar Timing Array project started by R. Manchester

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

EPTA



CPTA

ASKAP

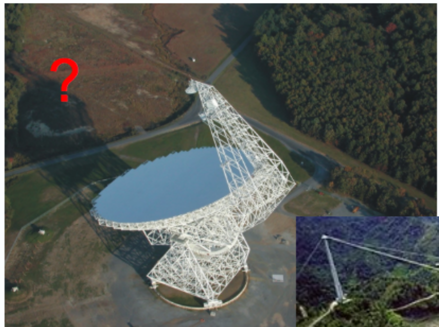
Meerkat

SKA

IPTA

Interest in pulsar community

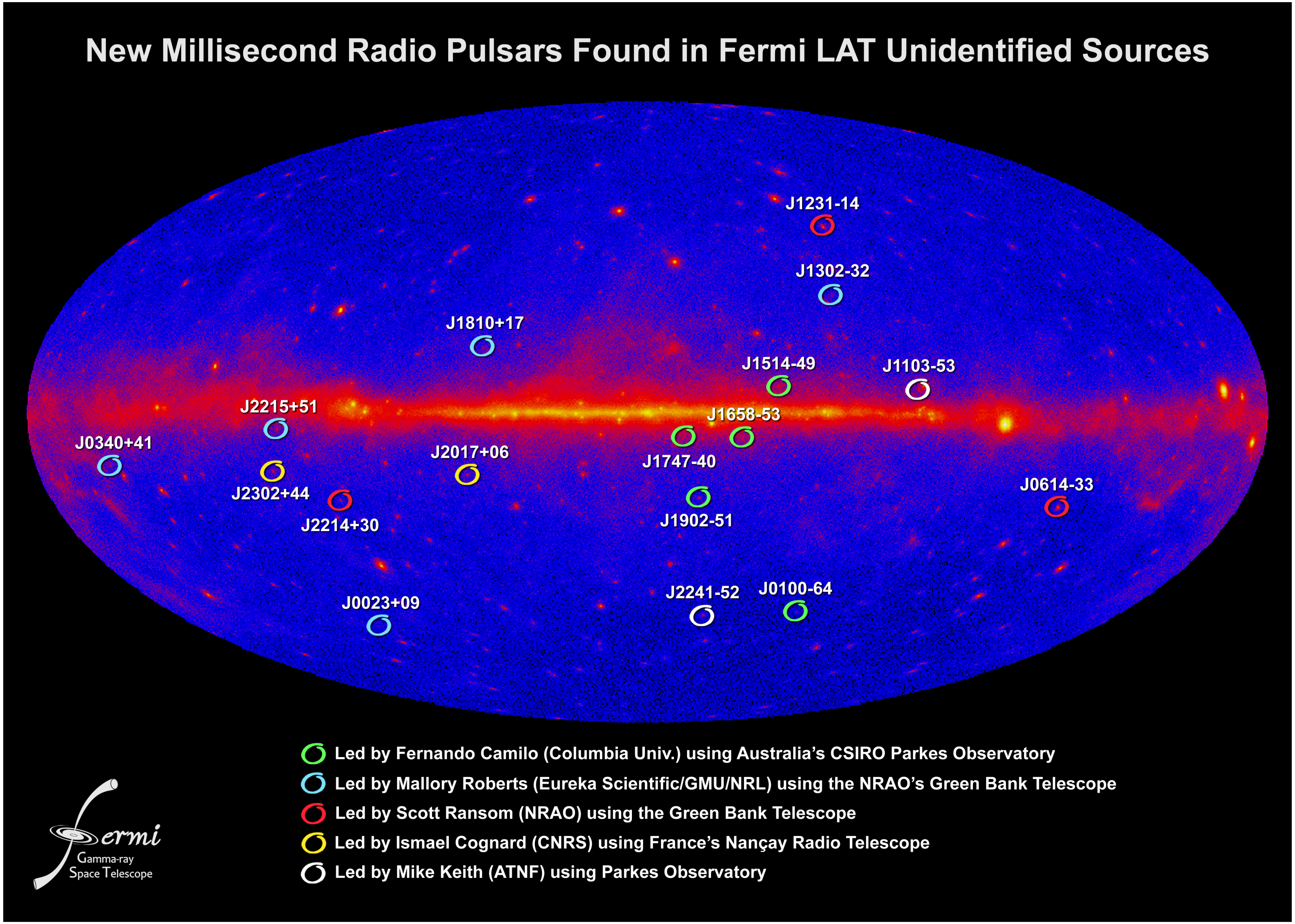
Interest in gravitational wave community



NANOGrav

PPTA

CSIRO



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)

Astrofisica Nucleare e Subnucleare

GRB and GW

Advanced Era GW-detectors (ADE)

LIGO-H

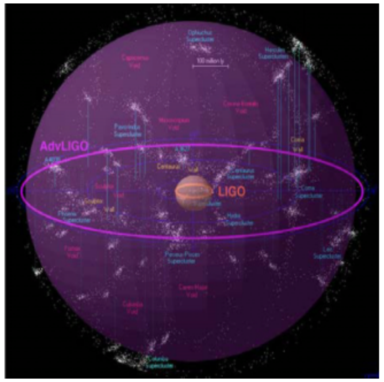
LIGO-L

Virgo

LIGO and **Virgo** detectors
are currently being **upgraded**

⬇

boost of sensitivity
by a factor of ten
(of 10^3 in number of detectable sources)



Advanced era
Detection rates of compact binary coalescences

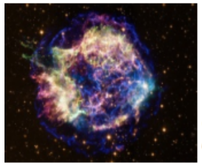
	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

(Abadie et al. 2010, CQG 27)

Mass: NS = 1.4 Mo
BH = 10 Mo

Advanced era
Sky location and orientation averaged range

197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH



Core-Collapse Supernovae

2-4 yr^{-1} EM-observed within **20 Mpc**

Rate of GW-detectable events unknown

GW-signal detectable **< Milky Way** (Ott et al. 2012, Phy.R.D.)
few Mpc (Fryer et al. 2002, ApJ, 565)

Optimistic models **10 - 100 Mpc** (Piro & Pfahl 2007)
(Fryer & New 2011)

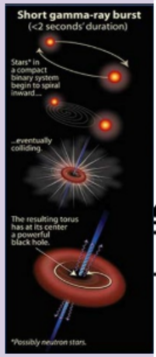
Electromagnetic emission

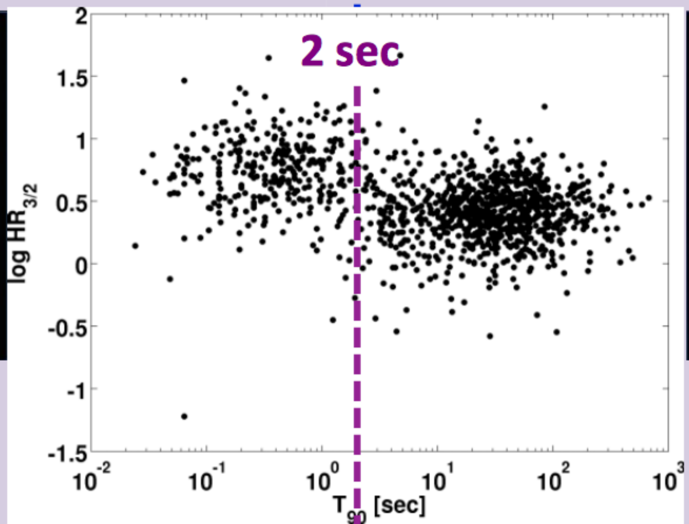
Merger of NS-NS / NS-BH

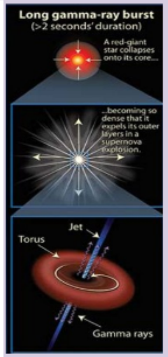
Core collapse of massive star

Gamma-Ray Burst

Short Hard GRB







Long Soft GRB

Kilonovae

(Optical/IR, radio remnant)

Supernovae

Type II, Ib/c

Short GRBs: how many on-axis/off-axis

Observed on-axis SHORT GRBs

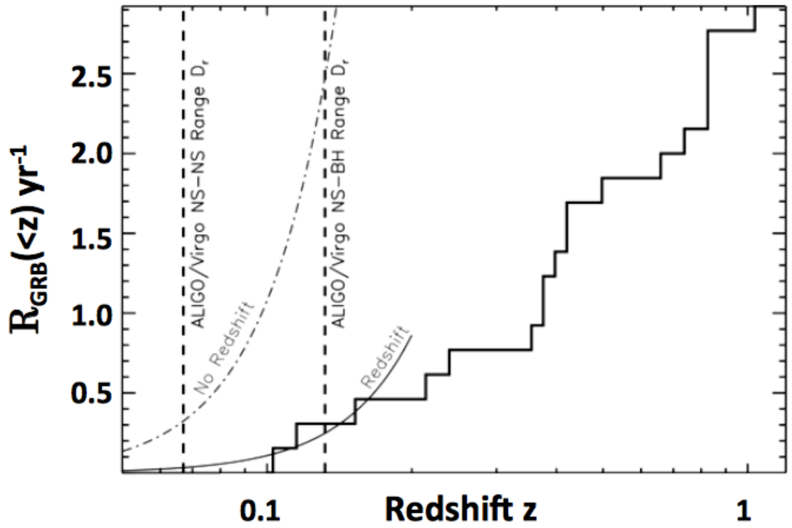
So far **~100** of which **~20** at known distance

<z>=0.5 = 3 Gpc

zmin = 0.12 = 560 Mpc

Energy = 10^{48-52} erg

GW/on-axis short GRB detection rate



All-sky gamma-ray monitor

→ **0.3 short GRBs per year** (NS-NS range)

→**3 short GRBs per year** (NS-BH range)

Metzger & Berger 2012, ApJ 746

*The **number of off-axis wrt on-axis** short GRB depend on the **beaming angle** that is very poorly constrained: **only two measures** → 7 and 14 degree*

Advanced LIGO and Virgo NS-NS detection rate based on short GRB observations

Assuming that the progenitor of all the short GRBs observed are NS-NS merger:

Short GRB observations → NS-NS merger rate

$$R_{NS\text{-}NS} = R_{GRB} / (1 - \cos(\theta))$$

$R_{NS\text{-}NS}$

8 -1100 $Gpc^{-3} yr^{-1}$ (Coward et al. 2012)

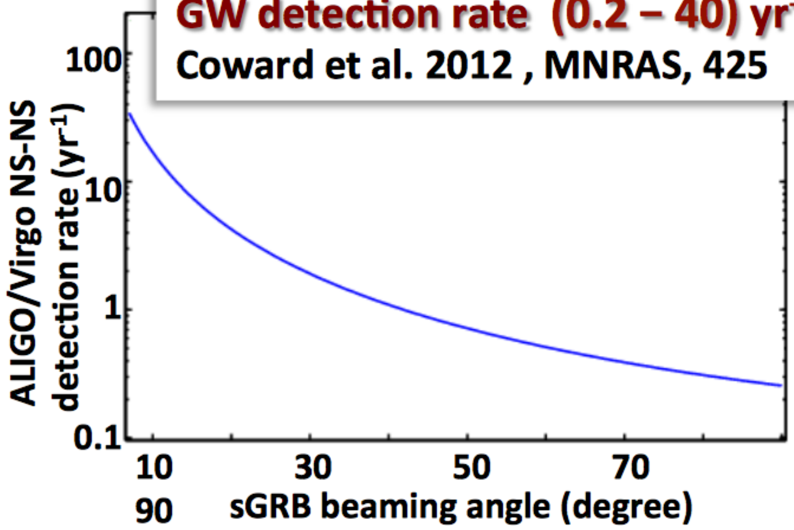
92–1154 $Gpc^{-3} yr^{-1}$ (Siellez et al. 2013)

Theoretical prediction

10-10000 $Gpc^{-3} yr^{-1}$ (Abadie et al. 2010)

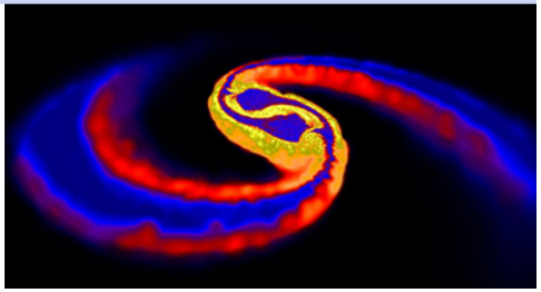
GW detection rate (0.2 – 40) yr^{-1}

Coward et al. 2012 , MNRAS, 425

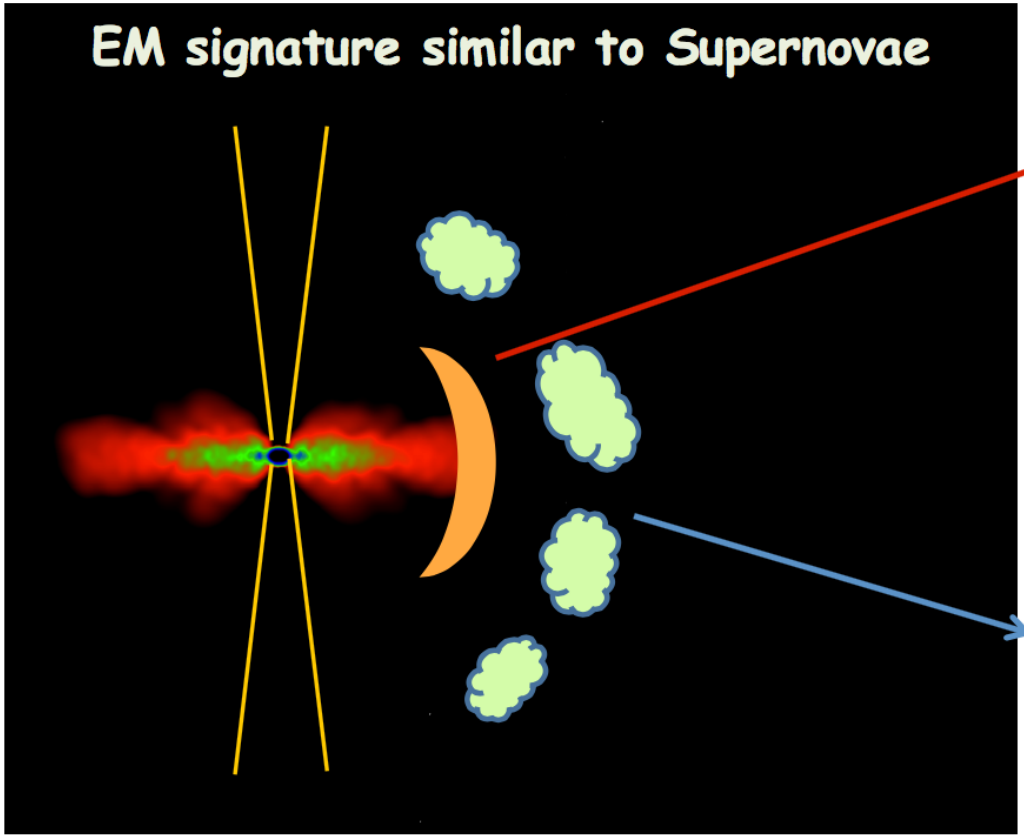


Kilonovae

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected** during **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.2 c)**



(Piran et al. 2013, MNRAS, 430; Rosswog et al. 2013 , MNRAS, 430)



Macronova – Kilonova

short lived IR-UV signal (days) powered by the radioactive decay of heavy elements synthesized in the ejected outflow

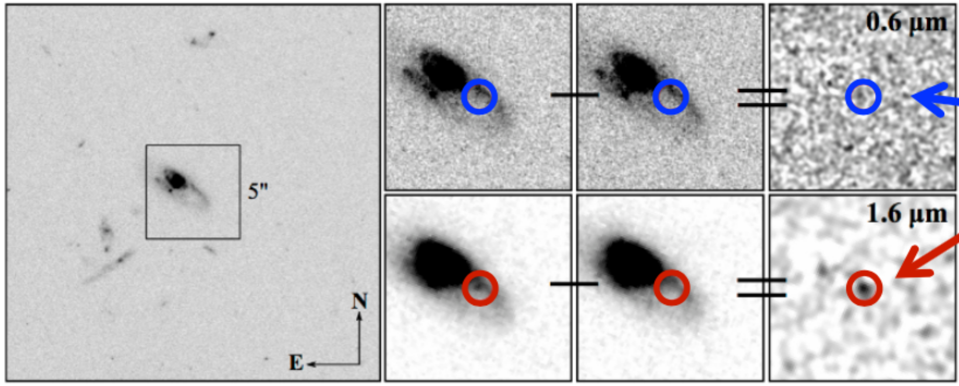
Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507 Metzger et al. 2010, MNRAS, 406; Piran et al. 2013, MNRAS, 430

RADIO REMNANT

long lasting radio signals (years) produced by interaction of ejected sub-relativistic outflow with surrounding matter **Piran et al. 2013, MNRAS, 430**

Possible HST kilonova detection for short GRB 130603B after 9.4 days

Tanvir et al. 2013, Nature ,500



Afterglow and host galaxy z=0.356

HST two epochs (9d, 30d) observations

F606W/optical

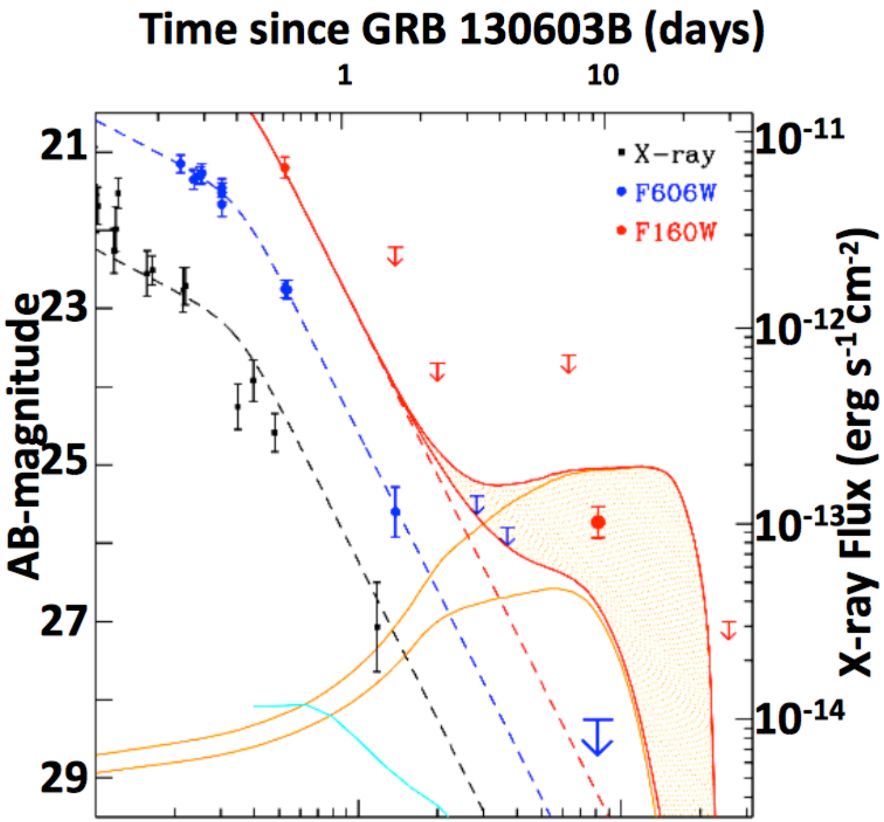
NIR/F160W

Orange curves → kilonova NIR model

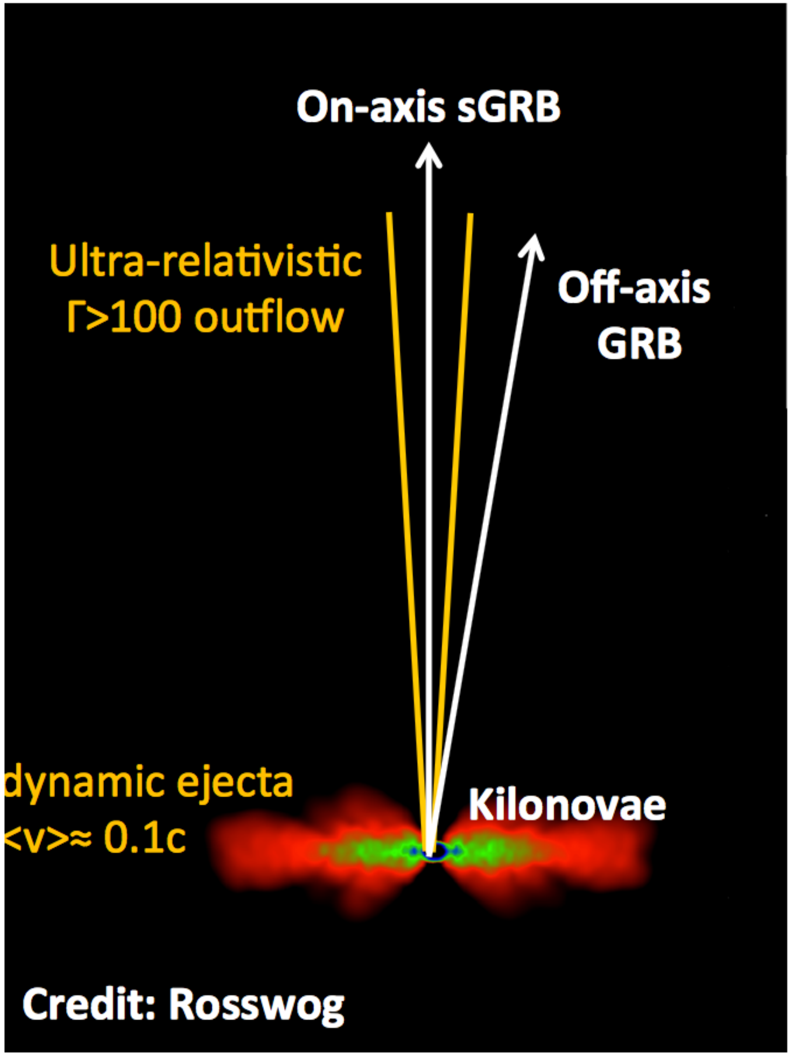
ejected masses of 10^{-2} Mo and 10^{-1}Mo

Solid red curves → afterglow +kilonova

Cyan curve → kilonova optical model



EM signals from NS-NS/NS-BH merger and massive star core-collapse



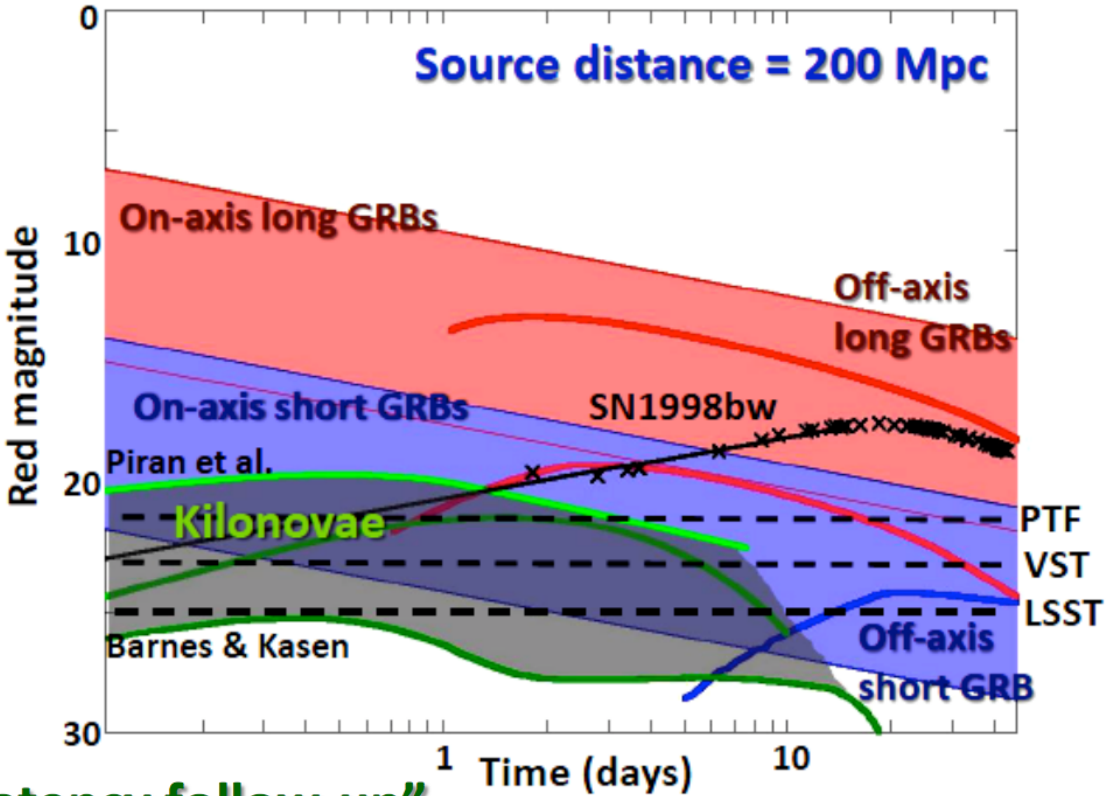
❖ **Prompt ϒ-ray emission (beamed):**

GRB → GW search **"GRB Triggered analysis"**

❖ **GRB afterglow emission, kilonovae:**

GW trigger → EM search

"Low-latency EM follow-up"

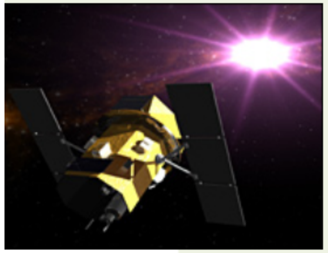


❖ **Radio:**

GW trigger → radio search **"High-latency follow-up"**

Blind radio search → GW search **"Triggered off-line analysis"**

GRB prompt emission → TRIGGERED GW SEARCH

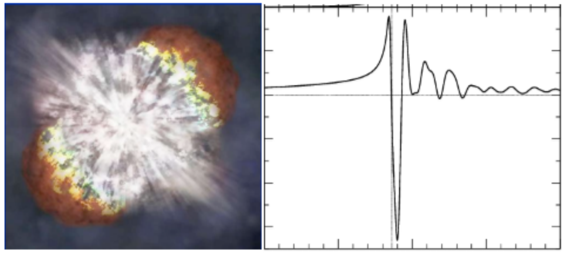


Known **GRB event time** and **sky position:**

→ **reduction in search parameter space**

→ **gain in search sensitivity**

GW transient searches

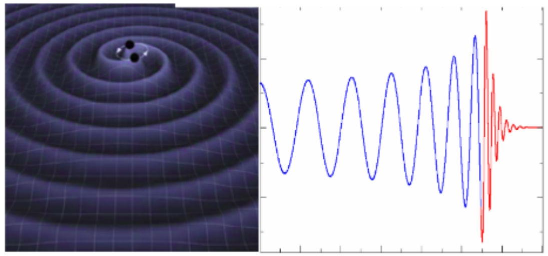


Unmodeled GW burst

(< 1 sec duration)

Arbitrary waveform

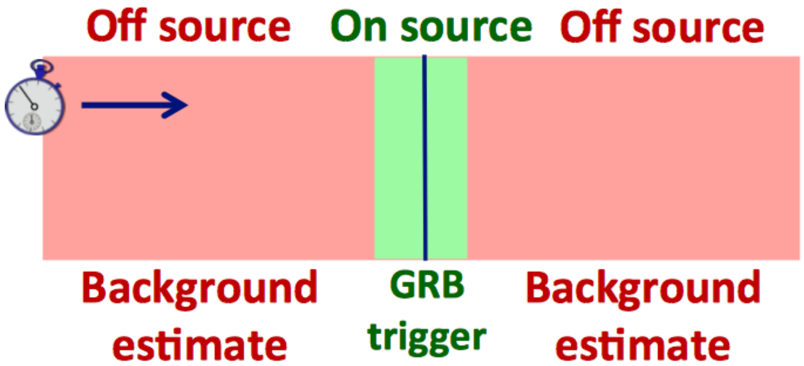
→ **Excess power**



Compact Binary Coalescence

Known waveform

→ **Matched filter**



Analyzed 154 GRBs detected by gamma-ray satellites during **2009-2010**
while 2 or 3 LIGO/Virgo detectors were taken good data
No evidence for gravitational-wave counterparts **Abadie et al. 2012, ApJ, 760**

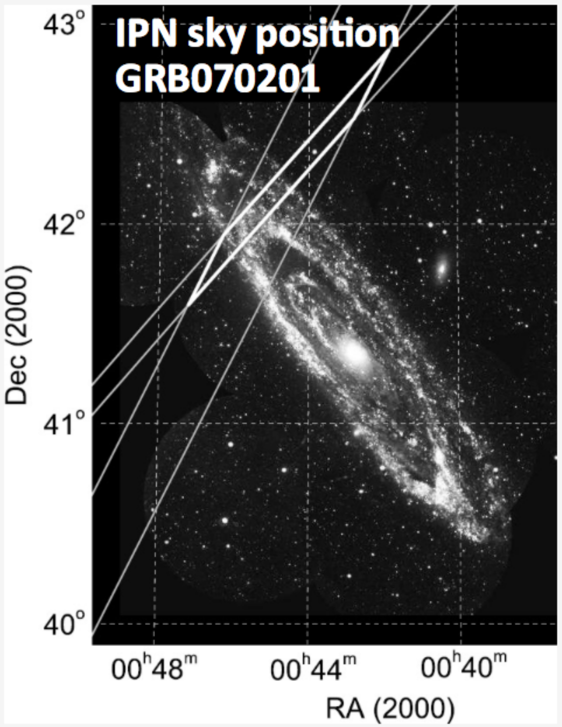
Astrophysical non-detection results for single events

Short GRB070201 / GRB051103

➢ gamma-ray emission:

→GRB070201 sky position overlaps with M31 (Andromeda, **770 kpc**)

→ GRB051103 sky position overlaps with M81 (**3.6 Mpc**)



➢ Non detection of GWs from binary coalescence

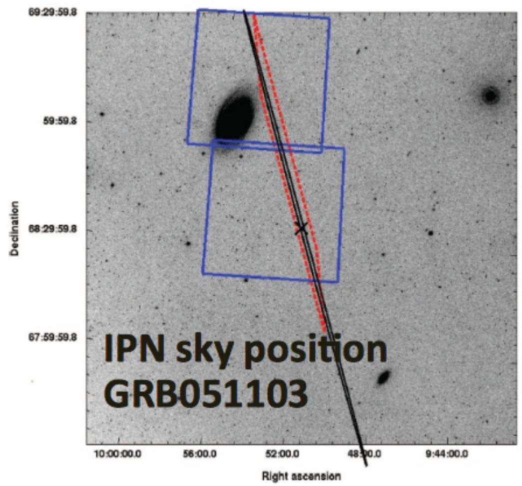
→ compact binary progenitor in M31excluded at 99% c.l.

→ comapct binary progenitor in M81excluded at 98% c.l.

➢ Non detection of GW burst sets limits on emitted energy compatible with:

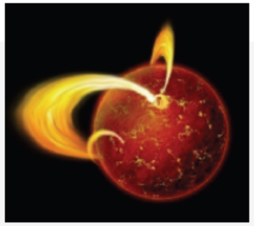
→ **soft gamma-ray repeater giant flare**

→ **coalescence in galaxy more distant than M31/M81**



Abbott et al 2008, ApJ, 681; Abadie et al. 2012, ApJ, 755

Other EM Triggered GW Searches



Soft Gamma Ray Repeaters & Anomalous X-ray Pulsars

- Magnetars which emit **hard X-ray/gamma repetitive 0.1 sec flares** (10^{42} erg/s) & **giant flares** (10^{47} erg/s)
- Maximum **energy available for GWs:**

→ Crust-cracking **10^{-7} - 10^{-4} $M_{\odot}c^2$**

→ Magnetic rearrangement **10^{-9}-10^{-6} $M_{\odot}c^2$**

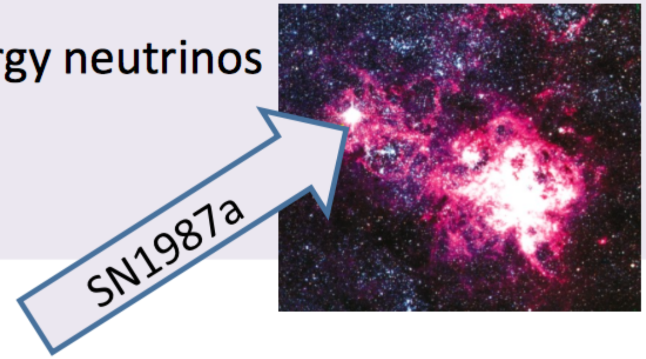
Abbott et al. 2008, PRL, 21110

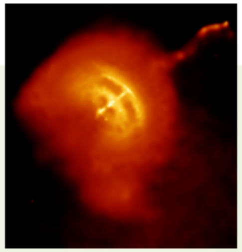
Abbott et al. 2009, ApJ, 701

Abadie et al. 2011, ApJ, 734

Core-Collapse Supernovae

- Energy in GW **10^{-8} - 10^{-4} $M_{\odot}c^2$**
- 2-4 yr^{-1} EM-observed within 20 Mpc
- Challenges in EM: **nightly/weekly optical/X-ray survey** of nearby galaxies
- Low-energy neutrinos





Pulsar glitches:

sudden increase in the NS rotational phase, frequency or frequency derivatives observable in **radio and gamma-ray pulsars**

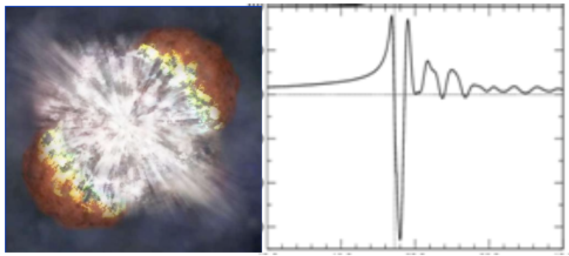
Expected energy in GW: **10^{-16} - 10^{-12} $M_{\odot}c^2$**

Abadie et al.2011PhRvD,83

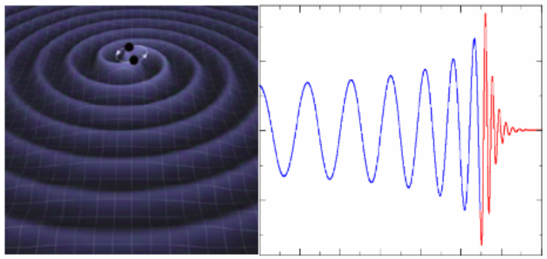
2009-2010 first Electromagnetic follow-up of candidate GW events

Low-latency GW data analysis pipelines

GW transient searches



Unmodeled GW burst
(< 1 sec duration)
Arbitrary waveform
→ Excess power



Compact Binary Coalescence
Known waveform
→ Matched filter

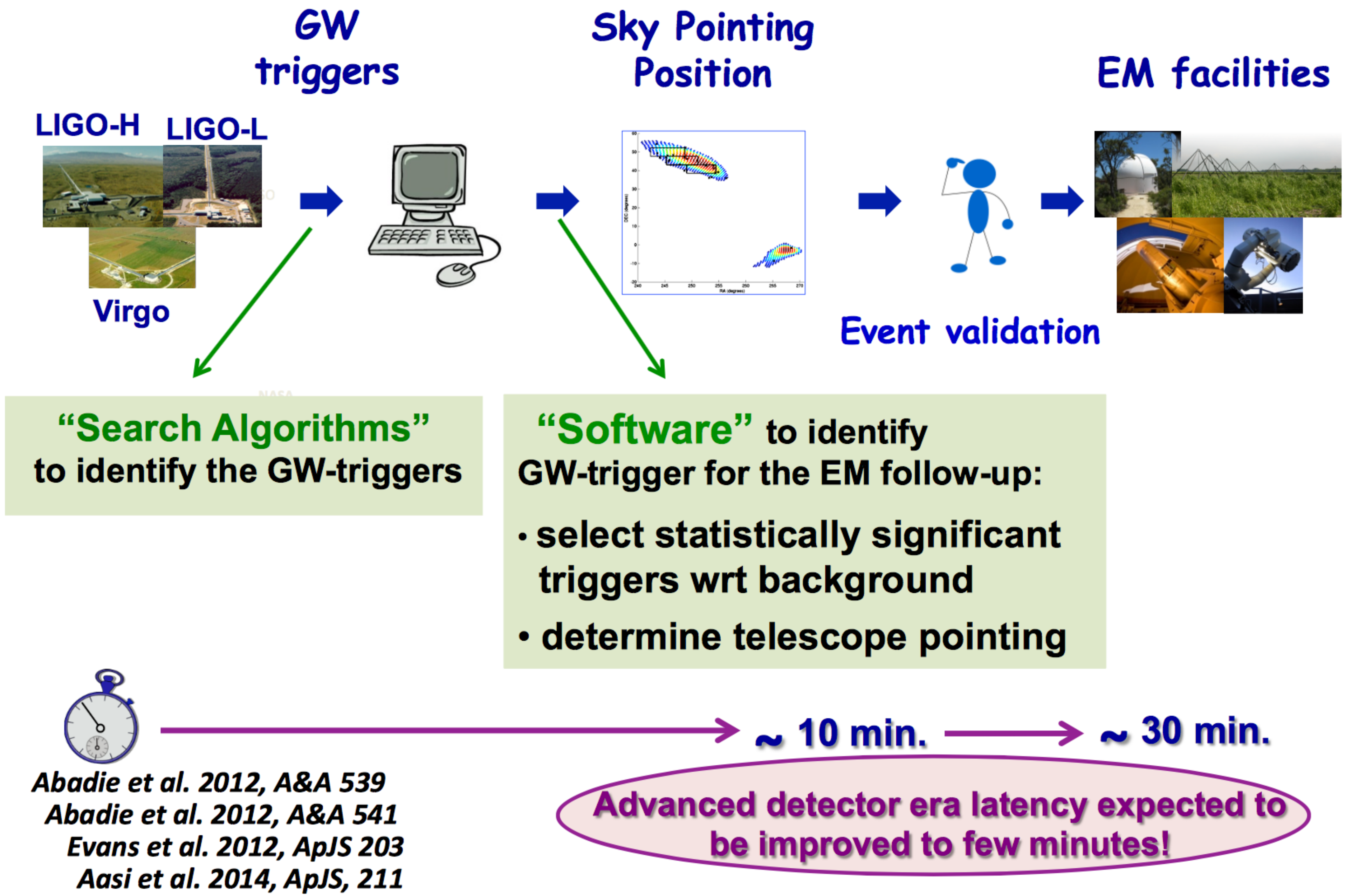
enabled us to:

1) identify GW candidates in "real time"

2) obtain prompt EM observations

Abadie et al. 2012, A&A 539

Abadie et al. 2012, A&A 541

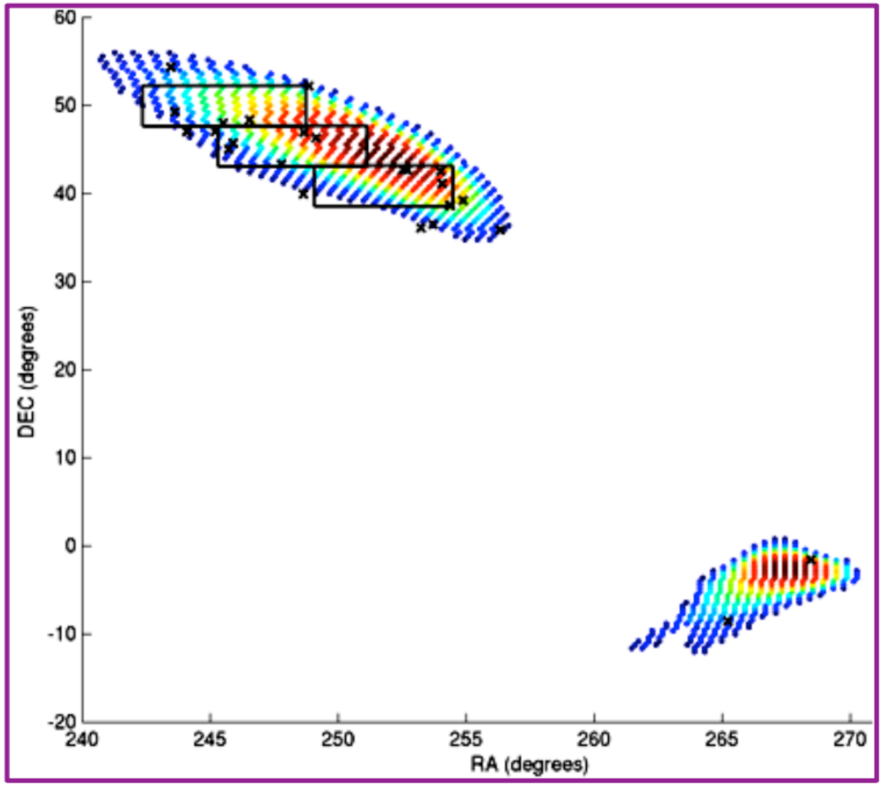

GW
triggers
Sky Pointing
Position
EM facilities
LIGO-H
LIGO-L
Virgo
Event validation
"Search Algorithms"
to identify the GW-triggers
"Software" to identify
GW-trigger for the EM follow-up:
• select statistically significant
triggers wrt background
• determine telescope pointing
~ 10 min.
~ 30 min.
Advanced detector era latency expected to
be improved to few minutes!
Abadie et al. 2012, A&A 539
Abadie et al. 2012, A&A 541
Evans et al. 2012, ApJS 203
Aasi et al. 2014, ApJS, 211

Additional priors to improve the localization accuracy and increase the chance to observe the EM counterpart

To determine each telescope pointing position:

The probability skymap of each GW trigger was 'weighted'

→ taking into account **luminosity** and **distance of galaxies within the LIGO/Virgo horizon** for binary containing a NS 50 Mpc

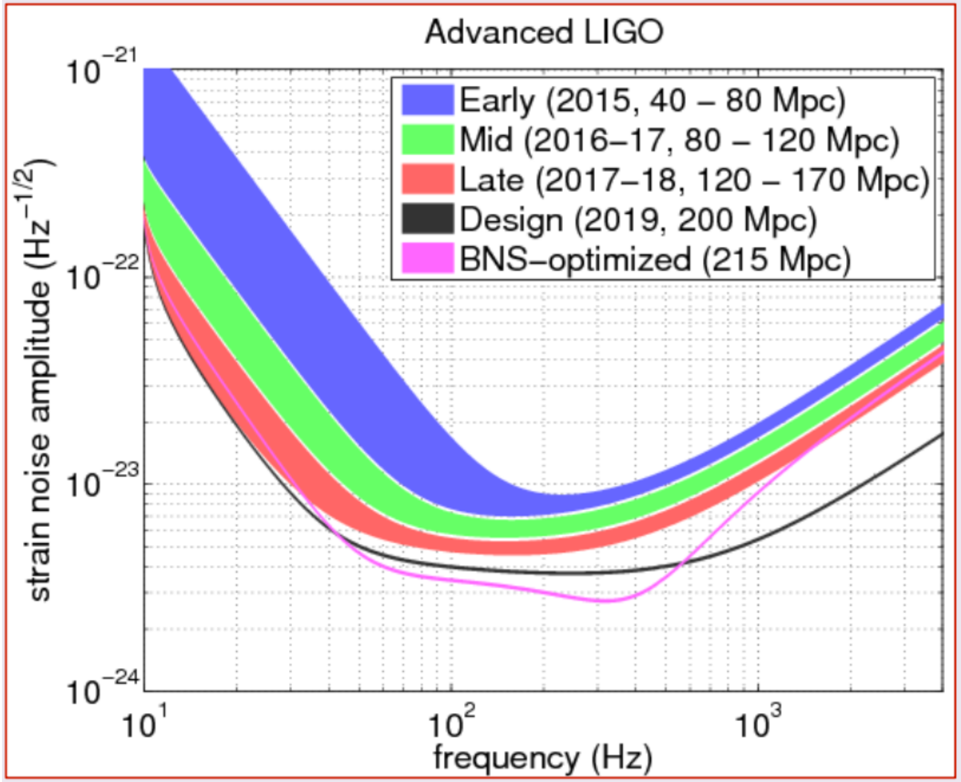


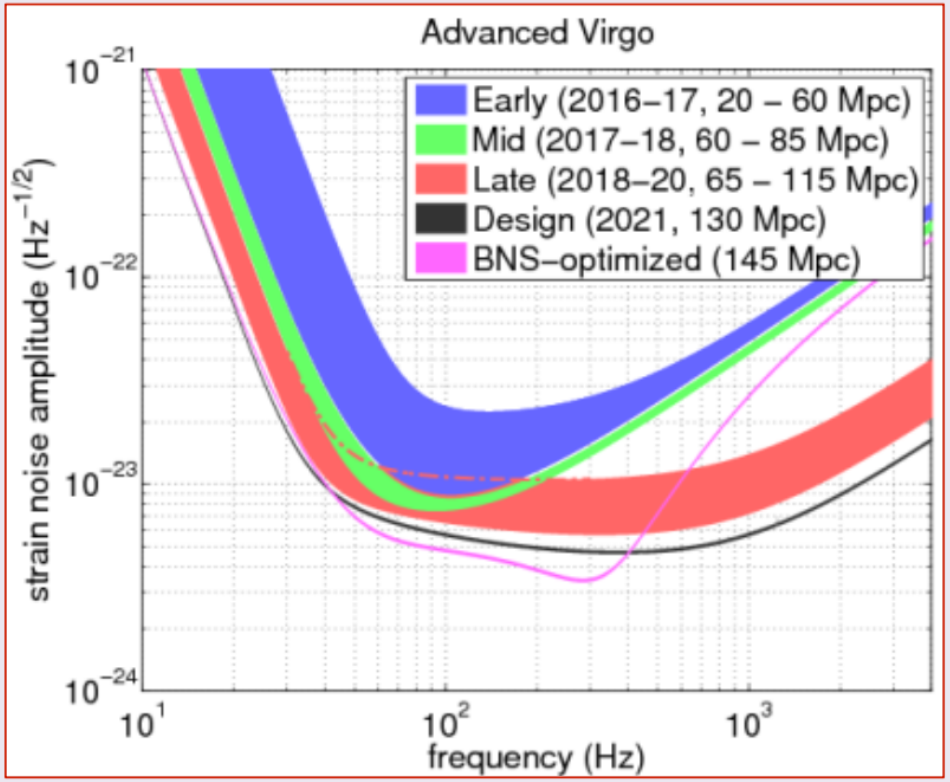
Galaxy targeting strategy

Advanced Detector Era Observing Scenario

LSC & Virgo Collaborations, arXiv:1304.0670

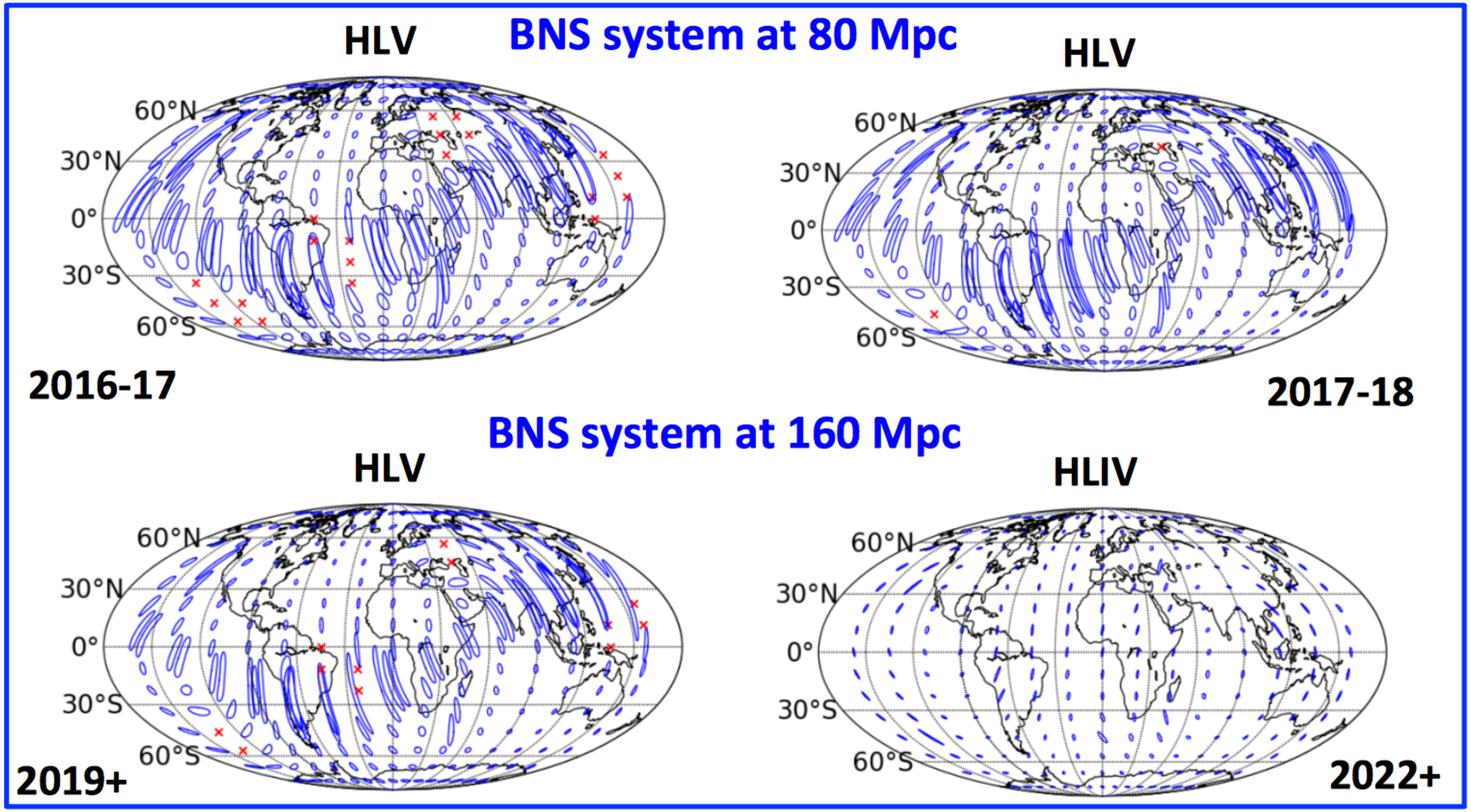
Progression of sensitivity and range for Binary Neutron Stars





Larger GW-detectable Universe

Sky Localization of Gravitational-Wave Transients



Position uncertainties with areas of **tens to hundreds of sq. degrees**

⬭ → **90% confidence localization areas**

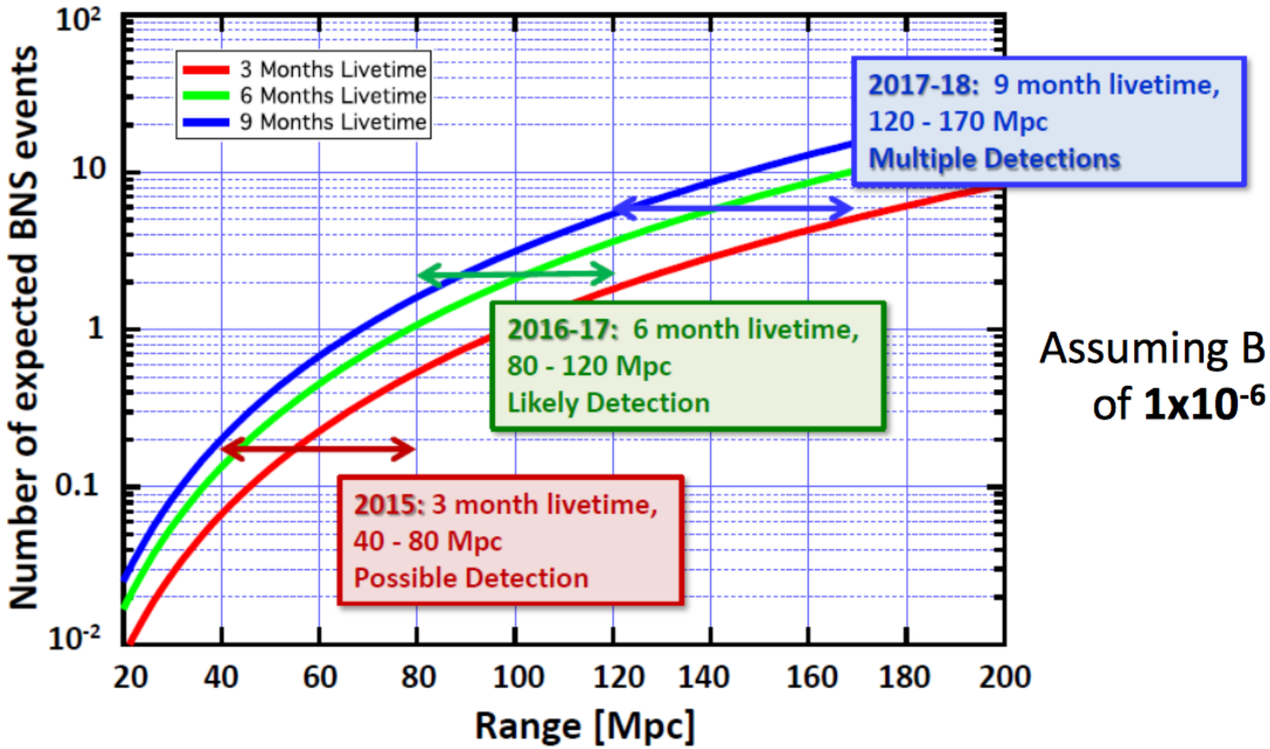
X → **signal not confidently detected**

Summary of plausible observing scenario

LSC & Virgo collaboration
arXiv:1304.0670

aLIGO/Virgo Range	Rate	Localization

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48



Assuming BNS merger rate of **1x10^{-6}** Mpc^{-3} year^{-1}