Gravitational Waves Detection
And Fourier Methods

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Overview

1. Gravitational Waves in General Relativity
2. Astrophysical sources
3. Interferometric detection
4. Data Analysis methods
5. The LIGO-Virgo network
Part I

Gravitational waves in General Relativity
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 $h_x$:

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

Corresponding Graviton properties:

- Graviton has null mass
- Graviton has spin 2
THE GRAVITATIONAL WAVE SPECTRUM

Wave Period

10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}

AGE OF THE UNIVERSE

INFLATION PROBE (NASA)
polarization map of cosmic microwave background

precision timing of millisecond pulsars (1982 -)

LISA (ESA/NASA, 2010)
BIG BANG OBS (NASA)

laser tracking of drag-free proof mass in spacecraft orbiting the sun

GEO, LIGO, VIRGO, TAMA (2002 -)
laser interferometers on Earth (also bar detectors)

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
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:

$$h_{\mu\nu}^{TT}(\bar{x}, t) = \frac{2G}{R c^4} \dot{Q}_{\mu\nu}^{TT}(t - R/c)$$

Hence:

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

$$h_\times^{TT}(\bar{x}, t) = \frac{2G}{R c^4} \dddot{Q}_{12}^{TT} (t - R/c)$$

Where the **reduced quadrupole** moment:

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

Regular quadrupole (inertia) moment:

$$q_{\mu\nu} = \iiint d^3 x \rho \ x_\mu x_\nu$$

$$\rho \sim T_{00}/c^2 : \text{density of the source}$$
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:
\[ \begin{align*}
    x_1(t) &= \cos(\omega_0 t) \\
    y_1(t) &= \sin(\omega_0 t) \\
    x_2(t) &= -\cos(\omega_0 t) \\
    y_2(t) &= -\sin(\omega_0 t)
\end{align*} \]

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:
\[ \begin{align*}
    h_+ (t) &= -\frac{2G}{r} ma^2 \omega^2 \cos(\omega(t - r/c)) \\
    h_\times (t) &= -\frac{2G}{r} ma^2 \omega^2 \sin(\omega(t - r/c))
\end{align*} \]

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

Note that if we look on the x direction:
\[ \begin{align*}
    h_+ (t) &= -\frac{G}{r} ma^2 \omega^2 \cos(\omega(t - r/c)) \\
    h_\times (t) &= 0
\end{align*} \]

Face-on binary => **circular** polarization
Edge-on binary => **linear** polarization
**Gravitational Wave emission: Orders of magnitude**

Luminosity (Einstein quadrupole formula):

\[
P = \frac{G}{5c^5} \left\langle Q_{\mu\nu} Q^{\mu\nu} \right\rangle
\]

\[
G/5c^5 \approx 10^{-53} \text{ W}^{-1}
\]

Factor ridiculously « small » !

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance</th>
<th>( h )</th>
<th>( P ) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel bar, 500 T, ( \varnothing = 2 \text{ m} )</td>
<td>1 m</td>
<td>( 2 \times 10^{-34} )</td>
<td>( 10^{-29} )</td>
</tr>
<tr>
<td>L = 20 m, 5 cycles/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H bomb, 1 megatonne</td>
<td>10 km</td>
<td>( 2 \times 10^{-39} )</td>
<td>( 10^{-11} )</td>
</tr>
<tr>
<td>Asymmetry 10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supernova 10 M, asymmetry 3%</td>
<td>10 Mpc</td>
<td>( 10^{-21} )</td>
<td>( 10^{44} )</td>
</tr>
<tr>
<td>Coalescence 2 black holes 10 M</td>
<td>10 Mpc</td>
<td>( 10^{-20} )</td>
<td>( 10^{50} )</td>
</tr>
</tbody>
</table>

**Hertz experiment is impossible for GWs ...**
Gravitational Wave emission and compact stars

Pb : $G/c^5$ is very « small ». $c^5/G$ would be much better !!!

Source : mass $M$, size $R$, period $T$, asymmetry $a$ ⇒

$$\ddot{Q} \approx a \frac{M}{T^3}$$

Quadrupole formula becomes :

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

New parameters
- caracteristic speed $v$
- Schwarzchild Radius $R_s = 2GM/c^2$

Huge luminosity if
- $R \to R_s$
- $v \to c$
- $a \to 1$

compact stars
Part II

Astrophysical sources of Gravitational waves
Gravitational Wave sources

Compact stars

“High frequency” sources \( (f > 1 \, \text{Hz}) \)

- 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:

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

**Black hole formation:**

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

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

+ oscillations...
Gravitational Supernovae: GW amplitudes

Complex physics => numerical studies


Dimmelmeier et al., 2007.
Gravitational Supernovae: GW amplitudes

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

Main conclusions:
+ Waveforms not well predicted
+ weak amplitudes -> only Galactic Supernova detectable ?

Ott and Burrows, 2006.

Marek et al., 2008.
Gravitational Supernovae: How far can we “see”? 

Preliminary reach estimates

- Betelgeuse
- SN2008bk

- Initial LIGO (simulated)
- GEO-HF (simulated)
- Advanced LIGO (projected)
- ET (projected)

Estimates over the range of the model parameter space.
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)

\[
\begin{align*}
  h_+^{TT}(t) &= \frac{4(GM)^{5/3}}{Rc^4} \frac{1+\cos^2 i}{2} \left(\pi f(t)^2\right)^{2/3} \cos \varphi(t) \\
  h_\times^{TT}(t) &= \frac{4(GM)^{5/3}}{Rc^4} \cos i \left(\pi f(t)^2\right)^{2/3} \sin \varphi(t)
\end{align*}
\]

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

A "chirp"

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

\[t_c : \text{coalescence time}\]
Binary inspirals: the chirp signal

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

2 neutron stars @ 10Mpc

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

$f_{max}$ (last stable orbit) $\sim 1$ kHz
Binary inspirals: the merger signal

Baker et al. 2007

Simulation of 2 inspiraling Black holes

*Numerical “tour de force”*
Binary inspirals: rate of events  
(first generation detectors)

- **NS-NS**: \(1.4M_\odot + 1.4M_\odot\)  
  - 0.001 - 1 / yr \(\rightarrow\) 20 Mpc  
  (Kalogera et al astro-ph/0111452)

- **NS-BH**: \(1.4M_\odot + 10M_\odot\)  
  - 0.001 - 1 / yr \(\rightarrow\) 43 Mpc

- **BH-BH**: \(10M_\odot + 10M_\odot\)  
  - 0.001 - 1 / yr \(\rightarrow\) 100 Mpc

- **Gain Factor 10** on detector sensitivity

  Gain factor 1000 on the event rate
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>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$P$ (s)</td>
<td>27906.9807807(9)</td>
</tr>
<tr>
<td>$dP/dt$</td>
<td>-2.425(10)·10^{-12}</td>
</tr>
<tr>
<td>$d\omega/dt$ ($^o$/yr)</td>
<td>4.226628(18)</td>
</tr>
<tr>
<td>$M_p$</td>
<td>$1.442 \pm 0.003 \ M_\odot$</td>
</tr>
<tr>
<td>$M_c$</td>
<td>$1.386 \pm 0.003 \ M_\odot$</td>
</tr>
</tbody>
</table>

Gravitational Waves do exist!
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 ($h < 10^{-24}$)

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

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:

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

Theoretical predictions (cosmology):

\[ h_0^2 \Omega_{GW} < 10^{-6} \quad \text{rather} \quad \rightarrow 10^{-13} \]

LIGO/Virgo (1 yr integration time) sensitive to

\[ h_0^2 \Omega_{GW} \sim 10^{-7} \]
Which is the physical effect we can detect on Earth?
Detectable effect of GW

GW
⇒ perturbation of the metric
⇒ measurements of distances (*) are affected

A

GW

B

⇒ Variation of measured distance between A and B

Amplitude $h(t)$ ⇔ rate of deformation of space-time!

(*) modern measurement e.g. by time of flight of photons

Geodesic deviation equation (weak field):

$$\frac{d^2 x^\mu}{dt^2} = -\frac{1}{2} \frac{d^2 h_{\mu\nu}}{dt^2} x^\nu$$

$$\delta L \approx \frac{1}{2} hL$$
Effect of GW on a set of test masses

Effect of $h_+$

Effect of $h_x$

One cycle
Ideas for detecting a GW?

- GW modifies light travels
- Effect is differentiel
- Effect is tiny (needs sensitive measurement)

must be sensitive to $h \sim 10^{-21}$

$\Rightarrow$ Michelson interferometer!
Part III

Interferometric detection of Gravitational Waves
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; detector (Weber)</td>
</tr>
<tr>
<td>1963</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; idea interferometric detection (Gersenshtein&amp;Pustovoit, Weber)</td>
</tr>
<tr>
<td>1969</td>
<td>Wrong claim (Weber)</td>
</tr>
<tr>
<td>197X</td>
<td>Weber detectors all over the world</td>
</tr>
<tr>
<td>1972</td>
<td>Itf feasibility study (Weiss) and 1&lt;sup&gt;st&lt;/sup&gt; prototype (Forward)</td>
</tr>
<tr>
<td>1974</td>
<td>PSR1913+16 (Hulse&amp;Taylor)</td>
</tr>
<tr>
<td>1974</td>
<td>End 70s cryogenic bars, itf prototypes (Glasgow, Garching, Caltech)</td>
</tr>
<tr>
<td>1986</td>
<td>Birth of collaboration VIRGO (France+Italy, Nikhef joined in 2006)</td>
</tr>
<tr>
<td>1989</td>
<td>VIRGO proposal, LIGO proposal (USA)</td>
</tr>
<tr>
<td>1992</td>
<td>LIGO funded</td>
</tr>
<tr>
<td>1993</td>
<td>VIRGO funded</td>
</tr>
<tr>
<td>1996</td>
<td>Start construction VIRGO et LIGO</td>
</tr>
<tr>
<td>2005</td>
<td>LIGO in operation</td>
</tr>
<tr>
<td>2007</td>
<td>VIRGO in operation</td>
</tr>
<tr>
<td>2007-2011</td>
<td>LIGO-VIRGO joint data takings</td>
</tr>
<tr>
<td>2011-12</td>
<td>Start upgrades -&gt; Advanced LIGO and Advanced VIRGO</td>
</tr>
<tr>
<td>2015</td>
<td>First science runs for aLIGO and AdVIRgo...</td>
</tr>
</tbody>
</table>
Resonant detectors
(Weber’s bars)

From Weber (60’s) ...

... to Auriga (2000s)
Itf detection principle

GW $\rightarrow$ optical paths are modified $\rightarrow$ detected power is modified

$P_{\text{det}} = \frac{P_0}{2} [1 + C \cos(\Delta \phi)]$
The optical signal is proportional to $h(t)$!

$$P_{\text{det}} = \frac{P_0}{2} \left[ 1 + C \cos(\Delta \phi) \right]$$

$C \approx 1$

where

$$\Delta \phi = \Delta \phi_{\text{OP}} + \delta \phi_{\text{GW}} = \frac{4\pi \Delta L}{\lambda} + \frac{4\pi h L}{\lambda}$$

Static dephasing (itf tuning)

Effect of the GW

$$P_{\text{det}} \approx \frac{P_0}{2} \left[ 1 + \cos(\Delta \phi_{\text{OP}}) - \sin(\Delta \phi_{\text{OP}}) \times \delta \phi_{\text{GW}} \right]$$

The signal!

It remains to show that $\delta \phi_{\text{GW}}$ is prop. to $h$ ...
The optical phase is proportional to $h(t)$
(exercise)

Assume ift arms along $x$ and $y$ directions and GW with normal incidence and polarized along ift arms (only $h_+$)

Start from space-time interval $ds^2 = 0$ for photons

Integrate along the $x$ axis (back and forth) – assume long wavelength approximation

Derive the round trip travel time for photons in the $x$ arm

Do the same for the other arm

Deduce the round trip time difference between the two arms

Finally give the OPD or equivalently the dephasing due to GW:

$$\delta \phi_{GW} = \frac{4\pi h_+ L}{\lambda}$$

Phase shift is proportional to $h(t)$!
And if the GW has any incidence and any polarization?

(could be an exercise!)

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

in the wave frame

Euler angles \((\Theta, \Phi, \Psi)\)-> itf frame

(arms along \(x\) and \(y\) axis)

\(h_+(t)\) of previous page has to be replaced by:

\[ h(t) = F_+(\Theta, \Phi, \Psi)h_+(t) + F_x(\Theta, \Phi, \Psi)h_x(t) \]

where we define the “beam patterns” as

\[ F_+(\Theta, \Phi, \Psi) = \frac{1}{2}(1 + \cos^2 \Theta) \cos 2\Phi \cos 2\Psi - \cos \Theta \sin 2\Phi \sin 2\Psi \]

\[ F_x(\Theta, \Phi, \Psi) = \frac{1}{2}(1 + \cos^2 \Theta) \cos 2\Phi \sin 2\Psi + \cos \Theta \sin 2\Phi \cos 2\Psi \]
The interferometric detector is not directional

Response if not directional => impossible to reconstruct completely $h(t)$ with a single itf

but not uniform either => detector can be blind (null response along bisectors)

=> 2 (very good) reasons to operate more than one detector!
Noises in interferometric detectors

- optical readout noise (photon counting noise + radiation pressure noise)
- seismic noise (and filtering)
- thermal noise
- laser noises
- others

⇒ General design of itf detectors
Optical readout noise

2 aspects: photon counting noise (or shot noise) and radiation pressure noise

Counting statistics (Poisson):
- Let’s note $n = \text{rate of arrival on PD (Hz)}$
- Average number of photons incident on the PD during time $\tau$ is then $N = n\tau$
- Standard deviation $\sigma_N = \sqrt{N}$
- Detected power $P_{\text{det}} = \hbar \omega = N\hbar \omega / \tau$ in average
- Detected power fluctuation (RMS) $\delta P_{\text{det}} = \sqrt{N\hbar \omega / \tau}$
\[ P_{\text{det}} \approx \frac{P_0}{2} \left[ 1 + \cos(\Delta \phi_{\text{OP}}) - \sin(\Delta \phi_{\text{OP}}) \times \delta \phi_{\text{GW}} \right] \]

**Noise:**
\[ P_{\text{det}} = \frac{P_0}{2} \left[ 1 + \cos(\Delta \phi_{\text{OP}}) \right] = P_0 \cos^{2} \left( \frac{\Delta \phi_{\text{OP}}}{2} \right) \]
\[ \Delta P_{\text{det}} = \sqrt{N \hbar \omega / \tau} \]
\[ P_{\text{det}} = N \hbar \omega / \tau \]

**Signal:**
\[ P_s = P_0 \sin \left( \frac{\Delta \phi_{\text{OP}}}{2} \right) \cos \left( \frac{\Delta \phi_{\text{OP}}}{2} \right) \times \delta \phi_{\text{GW}} \]

**Signal to noise ratio:**
\[ \left( \frac{S}{N} \right) = \frac{P_s}{\Delta P_{\text{det}}} = \sqrt{\frac{P_0 \tau}{\hbar \omega}} \left| \sin \left( \frac{\Delta \phi_{\text{OP}}}{2} \right) \right| \times \delta \phi_{\text{GW}} \]

**Phase sensitivity:**
\[ \delta \phi \approx \frac{\hbar \omega}{P_0} \]

**Sensitivity:**
\[ \tilde{h}_{\text{shot}} \approx \frac{\lambda}{4\pi L} \sqrt{\frac{\hbar \omega}{P_0}} \]

\(~ 10^{-10} \text{ rad/Hz}^{1/2} \text{ for } P_0 = 20 \text{ W and } @ 1.06 \mu\text{m}~\)
Radiation pressure noise

Decreasing the shot noise => increasing the power!
Power fluctuations => radiation pressure (RP) force fluctuations => Mirror position fluctuations!

RP force on a mirror

\[ F_{\text{rp}} = \frac{P}{c} \]

where \( P \) is the incident power on a mirror (=\( P_0/2 \)).

The force fluctuation is then

\[ \sigma_F = \frac{\sigma_P}{c} \]

Where (as derived in previous slide)

\[ \sigma_P = \sqrt{N\hbar\omega/\tau} = \sqrt{\frac{P_0\hbar\omega}{2\tau}} \]

The RP force spectral density is then

\[ \tilde{F}_{\text{RP}}(f) = \frac{1}{c} \sqrt{\frac{P_0\hbar\omega}{2}} = \sqrt{\frac{2\pi\hbar P_0}{2\lambda c}} \]

(white).

The mirror response to this force is then:

\[ \tilde{x}(f) = \frac{1}{m(2\pi f)^2} \tilde{F}_{\text{RP}}(f) = \frac{1}{4mf^2} \sqrt{\frac{\hbar P_0}{\pi^3 \lambda c}} \]

In term of GW amplitude sensitivity:

\[ \tilde{h}_{\text{RP}}(f) = \frac{2}{L} \tilde{x}(f) = \frac{1}{2mLf^2} \sqrt{\frac{\hbar P_0}{\pi^3 \lambda c}} \]
Optical readout noise as quadratic sum of shot and RP noises

\[ \tilde{h}_{\text{readout}}(f) = \sqrt{\tilde{h}_{\text{shot}}(f)^2 + \tilde{h}_{\text{RP}}(f)^2} \]

L = 3000; % arm length (meters)
\( \lambda = 1.06 \times 10^{-6} \); % wavelength (meters)
P0 = 20; % laser power (Watts)
mass = 10; % mirror mass (kg)

RP noise only relevant at low frequencies
=> Non relevant for first generation itfs
Standard quantum limit

\[ \tilde{h}_{\text{readout}}(f) = \tilde{h}_{\text{shot}}(f)^2 + \tilde{h}_{\text{RP}}(f)^2 = AP_0 + \frac{B}{P_0} \]

is minimum for

\[ P_{0,\text{min}} = \frac{A}{B} = \pi M \lambda f^2 \]

To each frequency corresponds one optimum \( P_{0,\text{min}} \) and the envelope of all the optima for the readout noise defines the standard quantum limit:

\[ \tilde{h}_{\text{sql}}(f) = \frac{\hbar}{\sqrt{4\pi^2 mL^2 f^2}} \]

The SQL is a 1/f noise

The SQL depends only on the mirror masses (and arm length)

The SQL is not a real limit. It can be beat in some frequency band (other optical configurations, squeezed states of light ....)
How to improve the detection scheme?

Shot noise limited itf:
\[ \tilde{h}_{\text{shot}} = \frac{\lambda}{4\pi L} \sqrt{\frac{\hbar\omega}{P_0}} = \frac{1}{2L} \sqrt{\frac{\hbar\lambda c}{2\pi P_0}} \]

We can play only on the arm length \( L \) and the power \( P_0 \)

**Increase the (optical) length:**
- Kilometric arm length (not more than a few km: cost and ... Earth curvature !!!)
- Fold the light in the arms => Fabry-Perot (FP) cavities
- FP cavity of length 3 km and finesse 50 => optical length \( \sim 100 \) km

**Increase the circulating power:**
- Itf tuned at a dark fringe => all the light is reflected back to the laser.
  - The itf can be seen as a (almost) perfectly reflecting optical device.
  - The idea is to add an extra mirror between the laser and the beamsplitter ("recycling mirror")
  - New FP cavity with power gain if at resonance for the laser wavelength ("recycling cavity")
Optical design is completed

LASER power: $P_{in} = 20 \text{ W}$

sensitivity: $h \propto 1/\sqrt{P_{in}}$

Gain: $3000 \times 30 \times \sqrt{50} \approx 10^6$

sensitivity: $h \sim 3 \times 10^{-22} / \sqrt{\text{Hz}}$

(shot noise)

→ kilometric arm length: 1 m → 3 km

→ add Fabry-Perot cavities (Finesse = 50 ⇒ Gain ~ 30)

→ add « recycling » mirror ($P = 1 \text{ kW on the beamsplitter}$)
Virgo optical design

+ Clean the Gaussian mode of the laser beam
+ filter HF laser fluctuations

Laser Nd:YAG
P=20 W
1.06 µm (IR)

Input Mode Cleaner
Length = 144 m

Recycling
P=1kW

L=3km
Finesse=50

Output Mode Cleaner
Length = 4 cm

Filter spurious beams (increase the contrast)
Seismic noise

Measure on site:
\[ \tilde{x}(f) \approx 10^{-6} \frac{m}{\sqrt{Hz}} \]

\[ \Rightarrow \text{Must be attenuated} \]

Simple spring:
\[ m \frac{d^2 x}{dt^2} + k (x-x_s) = 0 \]

Transfer function:
\[ H(\omega) = \frac{\tilde{x}(\omega)}{\tilde{x}_s(\omega)} = \frac{\omega_s^2}{\omega_s^2 - \omega^2} \]

Above resonance:
\[ |H(\omega)| \approx \left( \frac{\omega_s}{\omega} \right)^2 \]

N dampers:
\[ |H(\omega)| \approx \left( \frac{\omega_s}{\omega} \right)^{2N} \]

5 dampers with fundamental freq. \( \sim 0.6 \text{ Hz} \):
\[ \tilde{n}_{sism} \approx 7 \times 10^{-22} / \sqrt{\text{Hz}} \text{ @ } 10\text{Hz} \]
Virgo « superattenuator »

- **L ~ 7 m; M ~ 1 ton**
- **inverted pendulum**

Seismic attenuation: \( \sim 10^{14} @ 10 \text{ Hz} \) (measured)

\[
f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} - g
\]

\[\Rightarrow f_{\text{res}} \sim 30 \text{ mHz}\]
Thermal noise

*Fluctuation dissipation theorem* (Callen et al., 1951 ...) ⇒ dissipation is source of noise in any mechanical system

Fluctuating force power spectral density

\[ \tilde{F}_{\text{therm}}(f) = 4k_B T \Re(Z(f)) \]
(\text{where} \; Z \text{ is the mechanical impedance})

Gives rise to fluctuating motion (position noise)

\[ \tilde{x}_{\text{therm}}(f) = \frac{k_B T}{\pi^2 f^2} \Re(Y(f)) \]
(\text{where} \; Y = 1/Z \text{ is the mechanical admittance})

**Exemple of gas-damped spring or pendulum**

From the equation of motion

\[ \ddot{x} + \frac{\omega_0}{Q} \dot{x} + \omega_0^2 x = F/m \]

show that the position (thermal) noise is

\[ \tilde{x}_{\text{therm}}(\omega) = \frac{4k_B T \omega_0}{mQ} \frac{1}{\left(\omega_0^2 - \omega^2\right)^2 + \omega_0^2 \omega^2 / Q^2} \]

Where \( \omega = 2\pi f \) is the angular frequency (more simple)
Thermal noise

Mirrors+suspensions: a lot of mechanical oscillators under vacuum

*Internal friction* is the relevant dissipation source.

Internal friction modeled by a generalization of Hooke’s Law:

\[ F_{\text{spring}} = -k(1 + i\phi(f))x \]

\[ \phi = \text{“loss angle”} \text{  (related to spring anelasticity)} \]

From the new equation of motion and assuming \( \phi = \text{cste} = 1/Q \), show that the thermal noise power spectrum in case of internal friction is

\[ \tilde{x}_{\text{therm}}^2(\omega) = \frac{4k_B T \omega_0}{mQ} \frac{\omega_0}{\omega} \frac{1}{\omega_0^2 - \omega^2 + \omega_0^4 / Q^2} \]

Note that both models (gas-damped and internal friction) give the same noise at resonance (\( \omega = \omega_0 \)) but differ considerably off resonance

- **LF:** gas-damp noise -> cst
  - internal noise -> cst/\( \omega^{1/2} \)

- **HF:** gas-damp noise -> cst/\( \omega^2 \)
  - internal noise -> cst/\( \omega^{5/2} \)
Thermal noise

- Internal friction: $1/f^{1/2}$
- Gas-damped spring: $1/f^{5/2}$
- Independent of frequency: $1/f^2$

- $Q=10^6$
- $f_0=1$ kHz
- $M=30$ kg
- $T=300$ K
Frequency fluctuations + length asymmetry ⇒ phase noise

\[
\delta \tilde{\phi} = \frac{2\pi dl}{c} \delta \tilde{\nu}
\]

If optical path difference \( d=0 \): no constraint
But asymmetry unavoidable: \( d = \Delta(FL) = L \Delta F + F \Delta L \)

Recall shot noise limited phase sensitivity:

\[
\delta \tilde{\phi} \approx \frac{2\pi \nu}{c} FL \tilde{h}
\]

So laser frequency noise induces new noise:

\[
\tilde{h}_{\text{no}} \approx \left( \frac{\Delta L + \Delta F}{L F} \right) \times \frac{\delta \tilde{\nu}}{\nu}
\]

- target sensitivity: \( \tilde{h} \approx 3 \times 10^{-23} / \sqrt{\text{Hz}} \)
- asymmetry \( \approx 10^{-3} \)
- freq. \( \nu \approx 2.8 \times 10^{14} \) Hz

⇒ spec. \( \delta \tilde{\nu} < 10^{-5} \text{ Hz}/\sqrt{\text{Hz}} \)

Active laser frequency stabilization + « mode-cleaner » cavity
(Fabry-Perot = low pass filter !)
LASER frequency stabilization

Laser servoed to reference cavity
Rigid cavity (ULE) => etalon

Under vacuum

Under the input bench
Ultra High Vacuum

**Residual gas index fluctuations** $\Rightarrow$ phase noise

$\Rightarrow$ Ultra high Vacuum is needed

**Requirement**: residual pressure $< 10^{-7}$ mbar

**Solution for Virgo:**
- Steel tubes $\varnothing \sim 1.2$ m, $e \sim 4$ mm.
- 200 modules ($15$ m long) in each arm.
- Bake out $400^\circ$C after production, $150^\circ$C ($H_2O$) on site.
- 10 pumping stations / arm.

Vacuum volume in VIRGO: $2\times3km\times1.2m \sim 7000 \text{ m}^3$
LIGO (itf center : beamsplitter and input FP mirrors)
Mirrors

- Spec: total losses < 2% (guarantee 1kW on beamsplitter):
  - « coating » absorption (< 1 ppm) and substrate absorption (<2 ppm/cm)
  - Diffusion losses < 5 ppm
  - Geometrical Aberrations (δz < λ/100)
  - Curvature asymmetry < 3%
  - Finesse asymmetry < few % (laser noises)

Solution: pure Silica mirrors (SiO₂) with special design from manufacturer

Virgo mirrors: Ø = 35 cm and width = 10 or 20 cm
Virgo beamsplitter installation
Residual mirror rugosity $\Rightarrow$ scattered light + seismic motion of tubes $\Rightarrow$ phase noise!

**Solution:**
- very good mirrors OK.
- Baffles (80 in each bras)
  - steel baffles in the tubes
  - black glass in towers (close to mirrors)
Sensitivity curve
(Virgo design example)
Interferometer control

Virgo control system
+ 4 “lengths” to control
+ Angular motion

6.26 MHz
8.35 MHz
Interferometer control

Coil + magnet
Virgo sensitivity evolution

Not an easy task to reach the design sensitivity!
Towards advanced detectors

Virgo site: Beginning of 2012
Advanced Virgo setup

Changes in optical configuration:

- Laser power increase
- Higher finesse cavities
- Signal recycling

Plus
- Improved thermal compensation
- Suspended external benches
- Diffused light mitigation
- Fused Silica suspension wires
- ...
Advanced Virgo sensitivity

Goal: gain of a factor 10 in sensitivity (events rate x 1000 !!!)

Signal recycling: sensitivity can be tunable
Part IV

GW Data Analysis
The problem

Search for a temporal signal $s(t)$ in a noise $n(t)$ with complex structure.

What is recorded is $h(t) = n(t) + s(t)$ ... so **how to extract $s(t)$?**

The noise is characterised by its **spectral density** (see next slide)

Well known problem of Signal Processing (radar, telecommunications ...)

Solution is easy if the signal is known *a priori* => matched filtering

Binary systems : chirp signal is approximately known - up to 3PN order, ie $(v/c)^6$
⇒ Matched filtering can be applied

Supernovae : signal is poorly known (not a robust prediction)
⇒ Other methods

Rotating neutron stars : (quasi) periodic signal
⇒ Fourier analysis (nothing but matched filtering for sinusoidal signals)

**Nota Bene: In practice the noise is not Gaussian and not stationary!**
Noise spectral density

Autocorrelation of process $x(t)$:

$$A_x(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} dt \, x(t)x(t+\tau)$$

**Power Spectral Density (PSD):** $S_x(f) = \text{Fourier Transform of } A_x(t)$

Dimension of $S_x(f) = \text{(dimension of } x)^2 / \text{frequency}$

**Amplitude Spectral Density:**

$$\tilde{x}(f) = \sqrt{S_x(f)}$$

In practice, we use the estimator:

$$S_x(f) = \lim_{T \to \infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} dt \, x(t)e^{-2\pi i ft} \right|^2$$

If $x(t)$ corresponds to a stochastic process (noise), its DSA gives the contribution of each frequency to the total noise

→ Link between PSD and RMS:

$$\sigma^2 = \int_0^\infty S_x(f) \, df$$
Matched filtering principle
(Wiener, 1949)

Usable if the signal is known *a priori* (and optimal if Gaussian noise)

**Principle:** correlate the data with a template (a copy of the expected signal)

Signal to noise ratio $\rho^2$:

$$\rho^2 = 4 \int_0^{+\infty} \frac{h(f) \times t(f)^*}{S_h(f)} df$$

$h$: detector output  \quad t: template

$S_h$: detector noise (one-sided) spectral density

Signal to noise ratio (squared) $\rho^2$ can be seen as a scalar product:

$$\rho^2 = <h|t>$$
Matched filtering principle

\[ \rho^2 = 4 \int_{-\infty}^{\infty} \frac{\tilde{h}(f) \times \tilde{t}(f)^*}{S_h(f)} \, df \]
Matched filtering: example

Signal and template: identical shapes
Template: \( w = 1 \text{ ms} \)
Signal: \( w = 1 \text{ ms} \)
Template: normalized \( \langle t | t \rangle = 1 \)
Signal: Intrinsic SNR = \( \langle h | h \rangle = 10 \)
Filter max output: \( \rho = \langle h | t \rangle = 7 \)

Signal and template: mismatched shapes
Template: \( w = 1 \text{ ms} \)
Signal: \( w = 5 \text{ ms} \)
Template: normalized \( \langle t | t \rangle = 1 \)
Signal: Intrinsic SNR = \( \langle h | h \rangle = 10 \)
Filter max output: \( \rho = \langle h | t \rangle = 7 \)
Matched filtering for binary inspirals

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

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

The phase \( \varphi(t) \) depends primarily on star masses

\[ \Rightarrow 2 \text{ unknown (intrinsic) parameters} \]

+ extrinsic parameters (angles) that play no role in the detection process apart a scaling of the amplitude.

Parameter space \((M1, M2)\) must be tiled with templates

General scheme:

- Define the ambiguity function:
  \[ \Gamma(\lambda, d\lambda) = \langle t(\lambda) | t(\lambda + d\lambda) \rangle \]

- And expand up to second order:
  \[ \Gamma(\lambda, d\lambda) \approx 1 - \frac{1}{2} g_{\mu\nu} d\lambda^\mu d\lambda^\nu \]

- Set a minimal match between nearby templates:
  \[ \Gamma(\lambda, d\lambda) \geq MM \]

- Criteria to locate templates
  \[ \frac{1}{2} g_{\mu\nu} d\lambda^\mu d\lambda^\nu \leq 1 - MM \]
Matched filtering for binary inspirals

2D parameter space $\Rightarrow$ condition

\[
\frac{1}{2} g_{\mu\nu} d\lambda^\mu d\lambda^\nu \leq 1 - \text{MM}
\]

defines ellipses in the plane!

Physical boundaries

$\tau_{1.5} (\text{sec.})$

$\tau_0 (\text{sec.})$

M1 and M2 = [1;30] $M_\odot$, MM=0.95, f=[40;2000]Hz
PN order =2, template number = 11369
Matched filtering for binary inspirals

**Current (theoretical) issues**

- Chirp phase known today up to 3 PN order (3.5 PN being computed)
- Spins correction (→ 4 intrinsic parameters)
- Template frequency cut-off, last stable orbit?

2PN proved to be robust for detection purposes but not for parameter estimation (extraction of masses)

**Current (technical) issues**

- Data to be processed with high number of templates
- Cluster of machines
- Memory access etc...

Worse with network analysis => hierarchical searches
The problem of burst data analysis

Supernova waveforms prediction

Not robust predictions => matched filtering can not be robust!

⇒ Robust detections methods needed (but necessarily suboptimal)

However matched filter can be used for catching some part of the signal

For example Gaussian peak templates can be used for detecting main peak appearing in some burst waveforms (of course part of the signal SNR is lost)

Some other burst signals are also well known, e.g. black hole oscillations <-> ringdown signals with 2 parameters (frequency and damping time) related to BH mass and angular momentum => matched filtering must be used. (but marginal signals in term of detectability)
Burst data analysis
Examples of suboptimal methods

Energy excess
In moving window

Signal in white noise

Moving average

Slope change detector

Offset detector

Combination of SF and OF
(quadratic filter)
Burst data analysis
Time-frequency methods

Wavelet methods

S-transform

\[ S(f, \tau) = \int_{-\infty}^{+\infty} h(t) e^{-\frac{(t-\tau)^2}{2}} e^{-2i\pi f t} dt \]

Q-pipeline

\[ X(f, \tau, Q) = \int_{-\infty}^{+\infty} h(t) w(t - \tau, f, Q) e^{-2i\pi f t} dt \]

Etc...

More versatile methods
Burst data analysis
Time-frequency methods

Whatever the details of the method: search some **excess power** in a time-frequency map.
The necessity of network analysis

Events are very rare

Output of one detector is mainly (non Gaussian) noise!

One single detector cannot reliably distinguish a real event from a fake one (unless you perfectly know your detector …)

Coincidences with other detector(s) may allow such a selection (or at least eliminate a number of candidates)

**Coincidences with other GW detectors**
At least 3 detectors needed to reconstruct the GW signal (GW timing => triangulation to determine the sky position box)

**Coincidences with other messengers**
GRBs (collapses or mergers)
Neutrinos (collapses)
...

The golden way to validate a first direct detection: detection by the GW network and prediction of the source direction and confirmation of a HE event by GRB satellites or ν detectors …
Network data analysis

Virgo
LIGO-Hanford
LIGO-Livingston

Light time of flight: HL \sim 10 \text{ msec.}, VL \sim 26 \text{ msec.} \text{ and } VH \sim 27 \text{ msec.}

Times delays set the Source Reconstruction Accuracy:

Minimal angular resolution \sim 1^\circ

(could be much worse)
Network data analysis
Source location reconstruction

2 itfs: source localized on a Great Circle of the celestial sphere
3 itfs: intersection of 2 Great Circles: 2 points
(true location + mirror image wrt plane of 3 itfs)
4 itfs: no degeneracy
Network data analysis
Coincident approach

Trigger lists in one day of simulated data.
Simulated burst events with varying $h$ from constant direction (Galactic center).

Coincidences efficiencies:

<table>
<thead>
<tr>
<th>Bursts</th>
<th>H</th>
<th>L</th>
<th>V</th>
<th>HLV</th>
<th>HL</th>
<th>HV</th>
<th>LV</th>
<th>HLV u HV u LV</th>
</tr>
</thead>
<tbody>
<tr>
<td>False alarm rate ($Hz$)</td>
<td>0.1</td>
<td>10^{-6}</td>
<td>10^{-6}</td>
<td>~ 3.10^{-6}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>63</td>
<td>60</td>
<td>55</td>
<td>19</td>
<td>41</td>
<td>22</td>
<td>22</td>
<td>60</td>
</tr>
</tbody>
</table>
Network data analysis
Coherent approach

Coincidences with 3 GW detectors: the easiest way to proceed.

Another way is to combine all 3 GW data streams into a single one
⇒ Coherent approach

Single data stream that keeps all the information (even the one which would be “under threshold” in a single detector)

But very heavy method (need to test every cell in the sky)
⇒ in practice coincidence method with coherent follow-up on candidates

Possibility to build “null streams”, i.e. data stream combinations that kill the GW event, to veto events of instrumental origine.
Real data analysis
Data Quality Studies

One single itf: non Gaussian and non stationary noise with many “glitches”
Many glitches look like GW events !

First step is to clean the data stream from identified artifacts or suspicious events.

Help of many probes (acoustic, seismic, magnetic ...) whose signals are recorded in auxiliary channels.

If an event in main (GW) channel is coincident with an event in some aux. channel : suspicious event which must be flagged !
Real data analysis
Data Quality Studies

Exemple of glitches in the Virgo main channel (and origines)

LIGO&Virgo coll., Class. Quantum Grav. 29 (2012) 155002
Hierarchical Data Quality Flags (typically 3 categories):

<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Prescription for analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT1</td>
<td>Flags obvious and severe malfunctions of the detector.</td>
<td>Science data are re-defined when removing CAT1 segments.</td>
</tr>
<tr>
<td>CAT2</td>
<td>Flags noisy periods where the coupling between the noise source and the DF is well-established.</td>
<td>Triggers can be automatically removed if flagged by a CAT2 veto. Good performance.</td>
</tr>
<tr>
<td>CAT3</td>
<td>Flags noisy periods where the coupling between the noise source and the DF is not well-established.</td>
<td>CAT3 flags should not be applied automatically. Triggers flagged by a CAT3 veto should be followed up carefully.</td>
</tr>
</tbody>
</table>
Real data analysis
Data Quality Studies

Effect of DQ flags on single itf triggers

Search for NS-NS binaries
Double coincident events
Full VSR2 period

LIGO&Virgo coll.,
Class. Quantum Grav. 29 (2012) 155002
Real data analysis
Background estimation and significance

Data Quality studies help to reduce the number of artefacts but are not sufficient to estimate the background of a search for a certain signal.

Lot of (high) SNR events remain: we don’t fully understand itf’s noise and we can’t predict the background distribution.

Hopefully we have a powerful method to estimate background in a coincidence experiment (e.g. GW events in 2 iffs).

By time-shifting 2 data streams we have a new coincidence experiment.
Real data analysis
Background estimation and significance

With many time shifts we obtain many coincident triggers and construct our analysis background.

Time shifts must be:
- larger than time delays between triggers
- larger than signal durations
- but not too large to avoid long period coherence (day-night...)

Finally, distribution of time shifts -> estimation of the analysis background.
Real data analysis
Sensitivity estimation

The sensitivity is estimated by injecting known signals in the data
Recovery (or not) of injected signals => **efficiency curves**

Detection efficiency Vs. signal strain for SineGaussian signals
(235Hz and 1304Hz central frequencies) with linear or elliptical polarisations.
Real data analysis
Tuning

Exemple of a toy analysis: looking for coincident events between 2 itfs

- **Blue**: background (time shifted events)
- **Pink**: injections
- **Green**: zero-lag events

Cuts on individual SNRs and on combined (SNR1*SNR2) in order to have a small remaining false alarm rate (e.g. 1 ev event every 10 yrs) and to keep a good sensitivity.

Once you are happy, you look finally at the true (“zero-lag”) coincidences.

**REAL BLIND ANALYSIS!**
Network data analysis
The use of other messengers

External triggers ease the search!
⇒ Have to look for events only in a **restricted time window**
around the event and for a **known location** in the sky.

Lot of studies for instance with
- **GRBs** (Swift, Fermi ...)
- **Soft Gamma Repeaters**
- **High Energy Neutrinos** (ICECUBE, Antares)
- **Low Energy Neutrinos** (SuperK)

⇒ Main outcome is upper-limit on possible GW emission

In general **GAIN of a FACTOR 2-3** wrt all sky blind analysis
(“see” ~ one order of magnitude further)
Network data analysis
The use of other messengers

**An exemple**

Coincidences with neutrinos in case of gravitational collapse

GW emission \( \sim \) coincident with the bounce

Neutrino flash delayed by \( \Delta t_{\text{vflash-GW}} \sim 3.5 +/- 0.5 \text{ ms} \)

+ delay due to propagation of massive neutrino:

\[
\Delta t_{\nu_e\text{-GW}} \approx 5.2 \text{ ms} \times \left( \frac{d}{10 \text{ kpc}} \right) \times \left( \frac{m_\nu c^2}{1 \text{ eV}} \right)^2 \times \left( \frac{10 \text{ MeV}}{E_\nu} \right)^2.
\]

\( \Rightarrow \) GW and neutrinos detected within 10ms (add safety factor and detector systematic errors)

- Neutrino detection can validate a GW flash detection in case of Galactic supernova
- Coincident detection can set constraint on neutrino masses
  Upper-limit \( m_\nu \leq 0.7 \text{ eV} \) (current detectors)
Network data analysis
The use of other messengers

Another exemple

GWs and GRBs

Short GRB <-> NS-NS coalescence
Long GRB <-> Gravitational collapse (hypernova)

Analysis window
~10 minutes
fits astrophys. scenario
The LIGO-Virgo network

(Today and tomorrow)
The GW detectors (near-future) world

- LIGO
- GEO600
- Virgo
- KAGRA
- LIGO-India
- AIGO ?
The worldwide collaboration

LIGO + LIGO Science Community (aggregate GEO600) and Virgo have joined their forces in 2007

- joint data takings
- full data sharing
- 4 joint search groups with co-chairs from each collaboration
  - bursts
  - compact binary coalescences
  - continuous waves (pulsars)
  - stochastic GWs
- Joint run and planning committee

Agreement renewed last year (2011) -> cover the Advanced detectors area (data taking to re-start end of 2014)

+ Ongoing discussions with Japan (KAGRA collaboration)
LIGO-Virgo joint data takings

Virgo duty cycle ~90%
The LIGO-Virgo network
Compared sensitivities

S6/VSR2, Preliminary
The LIGO-Virgo network
A selection of scientific results

Search for compact binary coalescences:
No detection (yet)
\(\rightarrow\) **upper limits** on event rates

![Graph showing rate estimates for BNS, NSBH, BBH](image)


The gap is less than 1 order of magnitude!
(important for advanced detectors)
The LIGO-Virgo network
A selection of scientific results

Search for bursts: upper limits on event rates Vs signal strength
(here generic SineGaussian signals)

Search sensitivity at these frequencies

Limit due to finite observation time

FIG. 5: Upper limits at 90% confidence on the rate of gravitational-wave bursts at Earth as a function of $h_{\text{rms}}$ signal amplitude for selected sine-Gaussian waveforms with $Q = 9$. The results include all the LIGO and LIGO–Virgo observations since November 2005.

The LIGO-Virgo network
A selection of scientific results

Short GRB detected in direction of M31

Search for binary coalescences in the GRB error box

No GW event found
-> GRB occurred in a further galaxy behind M31 (if it is a real GRB)

SGR scenario not excluded by GW Search.

The LIGO-Virgo network
A selection of scientific results

Search for continuous GWs (pulsars)
Spin-down limit for known pulsars (1 yr integration time)

Advanced-Virgo sensitivity
The LIGO-Virgo network
A selection of scientific results

Results for the Crab pulsar (30Hz):

\[ h_0 \sim 3.4 \times 10^{-25} \]
(4x below the spin-down limit)

Excluded by GW searches

Results for Vela (11Hz):

\[ h_0 \sim 2 \times 10^{-24} \]
(1.7x below the spin-down limit)


Excluded by e.m. observations
The LIGO-Virgo network
A selection of scientific results

Search for cosmological background(s)

The itf detectors are sensitive to amplitude $h(t)$ so increasing the sensitivity by a factor 2 increases the detection range also by 2 and the volume of observable universe by $2^3$!

- Advanced detectors (improvement of sensitivity by factor 10)
  $\Rightarrow$ Detection of binary inspirals guaranteed! \((\text{event rate} > 1/\text{yr})\)
The next decade

Advanced LIGO and Advanced VIRGO: first data in 2015?
+ LIGO India
+ KAGRA in Japan

+ LISA (now eLISA/NGO) Space mission (date ?)
KAGRA (prev. “LCGT”) itf in Japan
Located in the Kamioka site
Underground (less seismic noise)
Cryogenic (less thermal noise)
And after!!!
(The 3rd generation)

Cryogenic interferometric detectors

Underground detectors

All reflective optics
(gratings as beamsplitters etc ...)

Triangular detectors

Capacitive drivers for mirror control
Conclusions

A new experimental field!

(astro)physics is not yet there ... but be patient

Binary inspirals detection likely to be routine in the next decade

GW detectors matched for Galactic Supernovae (likely to be the case forever...)

GW astronomy soon full partner of multi-messenger HE astrophysics

Some science prospects:
- Tests of gravitation (GW celerity and polarization ...)
- First direct Black Hole observations
- Collapse dynamics
- Equation of state of compact stars
- Cosmology (compact binaries as standard candles)
- ...

New messenger ... new vision of the Universe?
Some references

http://www.ligo.caltech.edu/
http://wwwcascina.virgo.infn.it/
http://lisa.nasa.gov/
http://www.einsteinathome.org/  Help the GW community in pulsar detection!


Signal recycling configuration
(Advanced LIGO and Advanced Virgo)

Advantages:
• Beat the SQL in some band
• Can tailor the frequency response
Burst data analysis
How to compare methods

Many methods that can be compared in terms of

- efficiency
- time resolution
- frequency resolution if adapted to method

Universal method does not exist
⇒ Necessary to use different methods to be sure to cover the "parameter space"