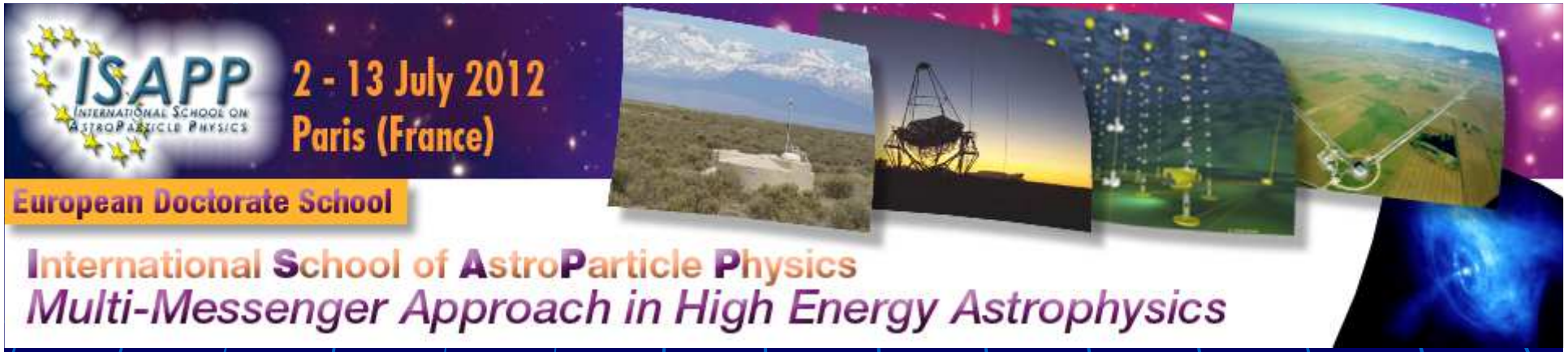

Gravitational Waves Detection And Fourier Methods

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VIRGO

LAL

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir®

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

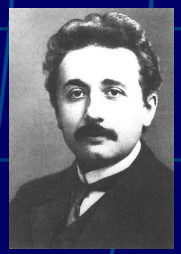
What are Gravitational Waves ?

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

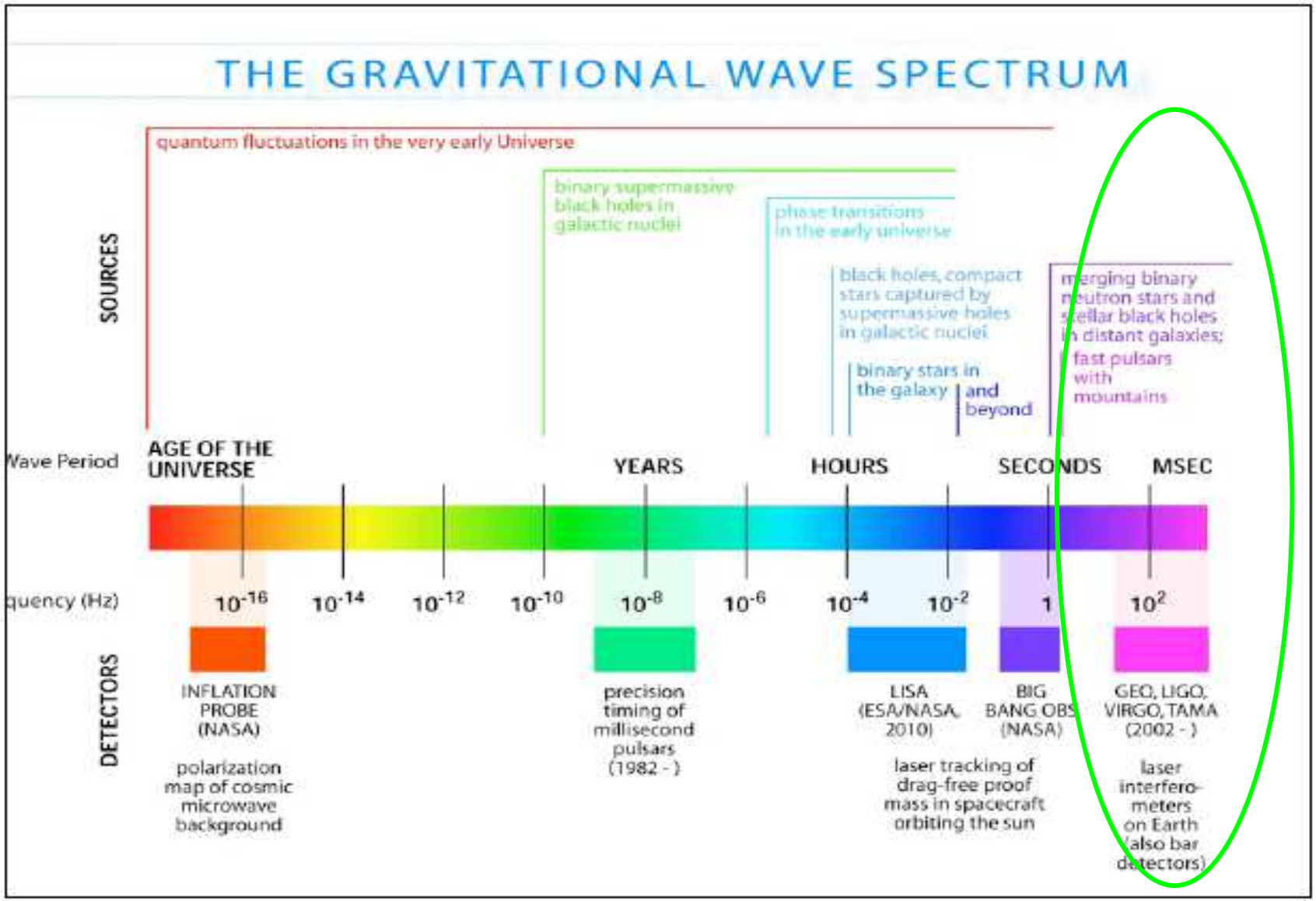
- GW propagate at speed of light
- GW have two polarizations "+" and "x"
- GW emission is quadrupolar at lowest order

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

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

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
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
binary stars in the galaxy
and beyond
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
quency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
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 interfero-meters on Earth (also bar detectors)

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

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

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

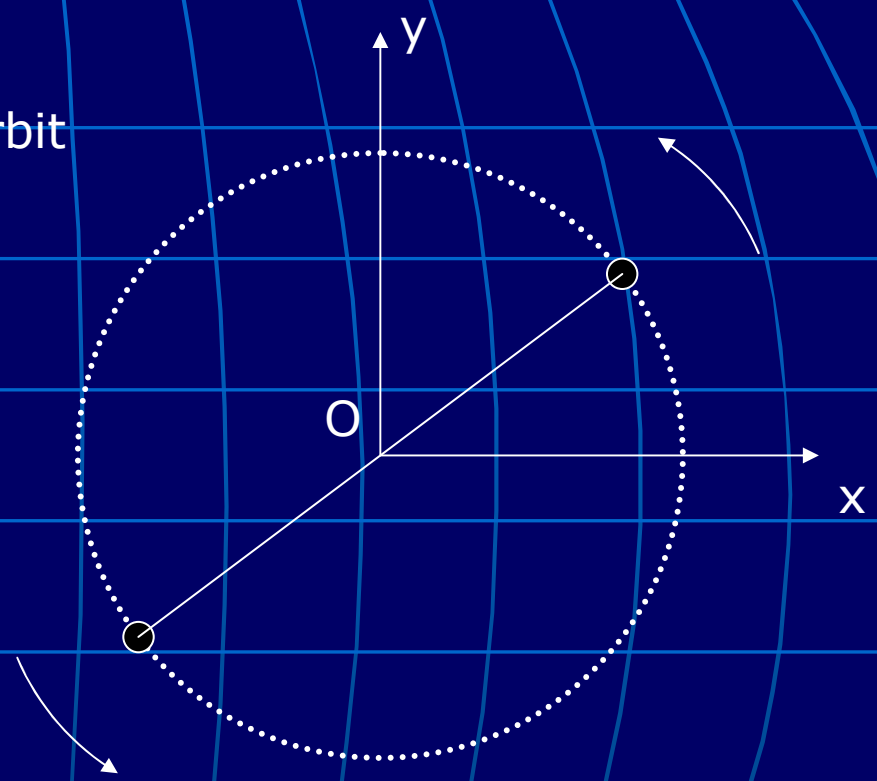
Regular quadrupole (inertia) moment: $q_{\mu\nu} = \iiint d^3x\, \rho\, x_\mu x_\nu$

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

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:

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

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

Note that if we look on the x direction:

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

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

Gravitational Wave emission:
Orders of magnitude

Luminosity (Einstein quadrupole formula):

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

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

Factor ridiculously « small » !

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

Hertz experiment is impossible for GWs ...

Gravitational Wave emission and compact stars

© J. Weber (1974)

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

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

Quadrupole formula becomes :

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

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

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

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

compact stars

Part II

Astrophysical sources of Gravitational waves

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

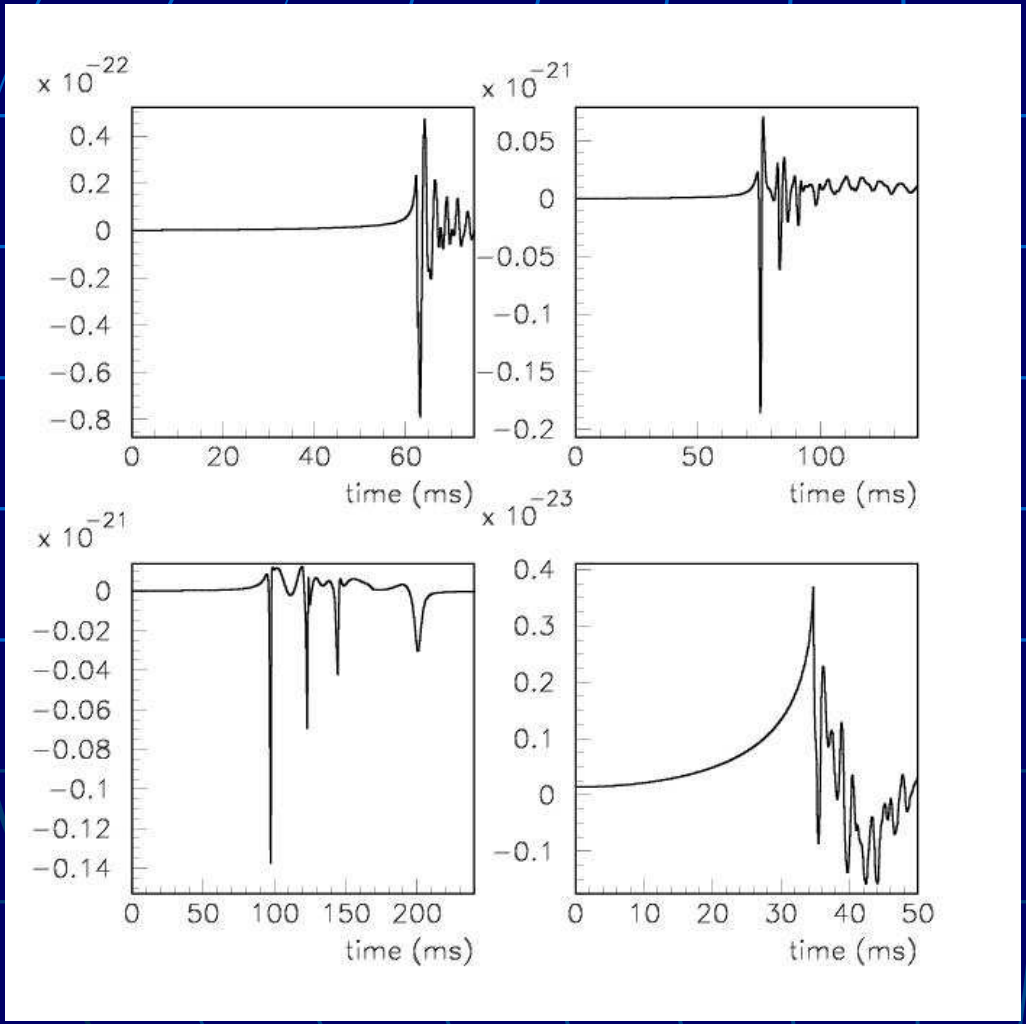
Black hole formation:
Progenitor too massive → collapse → black hole

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

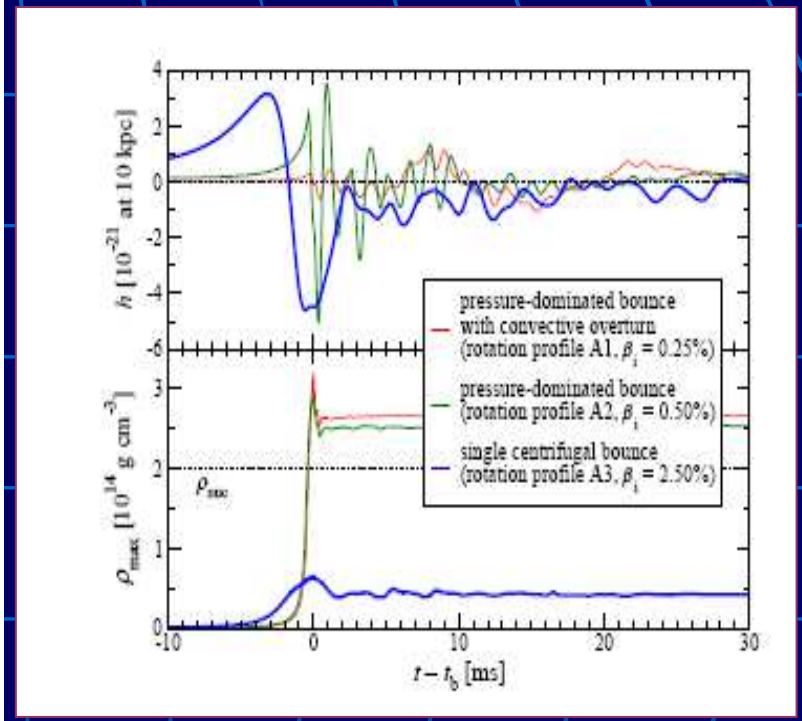
+ oscillations…

Gravitational Supernovae: GW amplitudes

Complex physics => numerical studies



Zwerger & Müller, 1997.

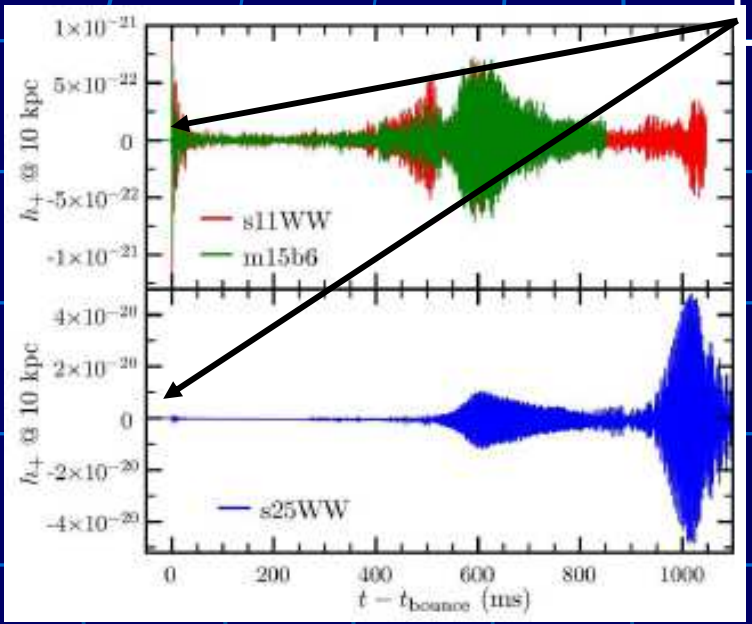


Dimmelmeier et al., 2007.

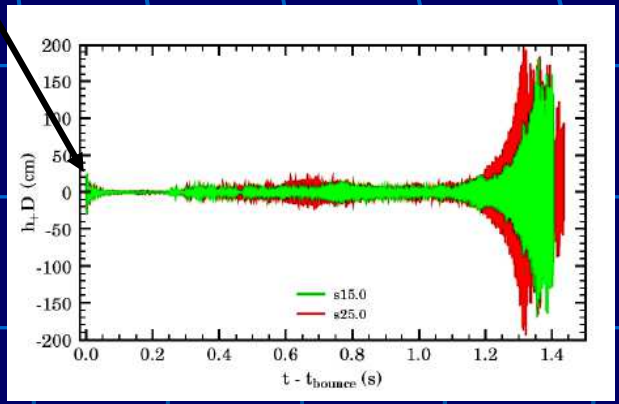
Gravitational Supernovae: GW amplitudes

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

collapse



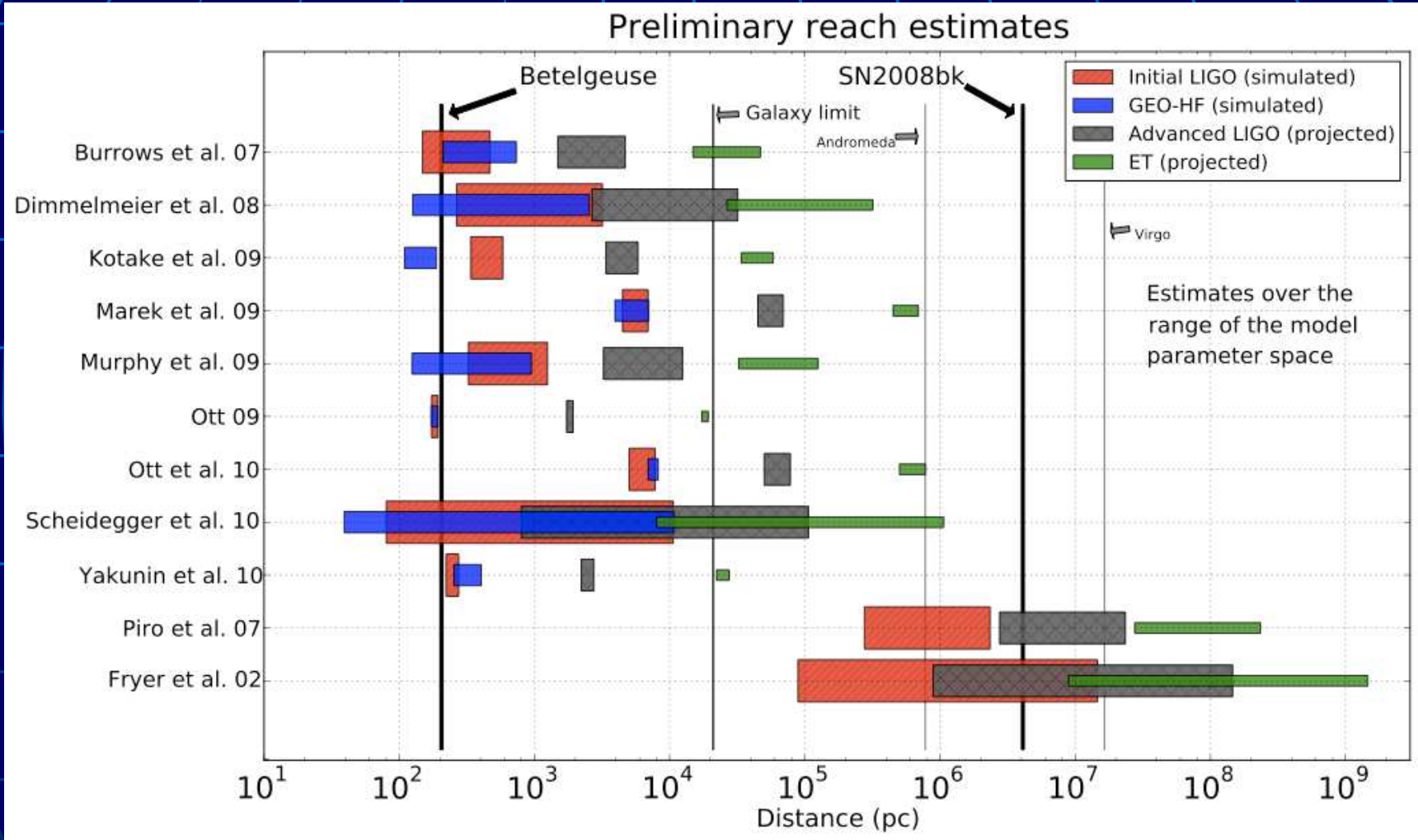
Ott and Burrows, 2006.



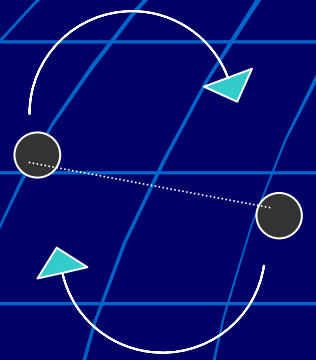
Marek et al., 2008.

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

Gravitational Supernovae: How far can we "see"?



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"

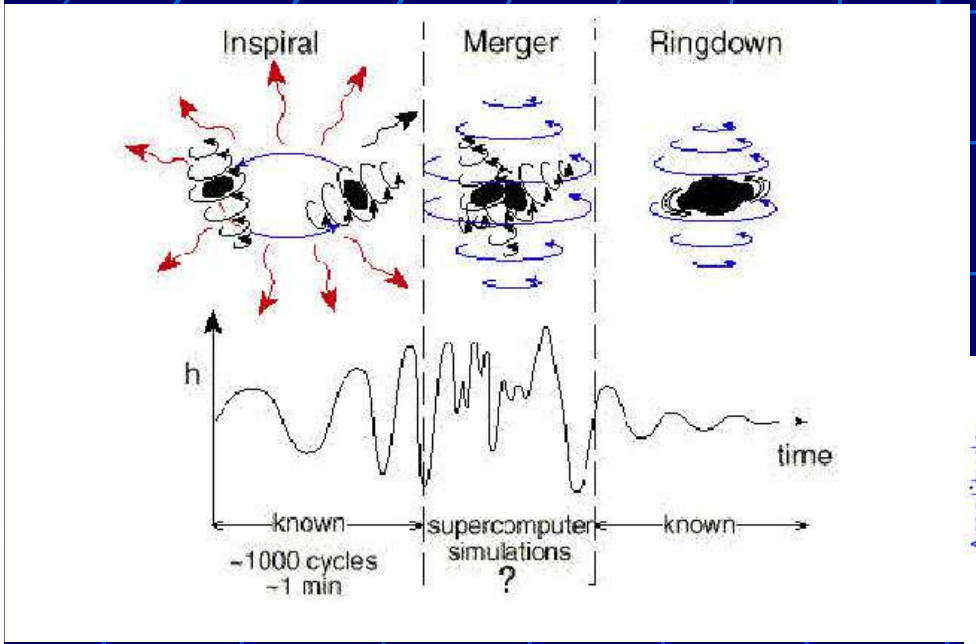
$$h(t) \propto \left(t_c - t\right)^{-1/4}$$

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

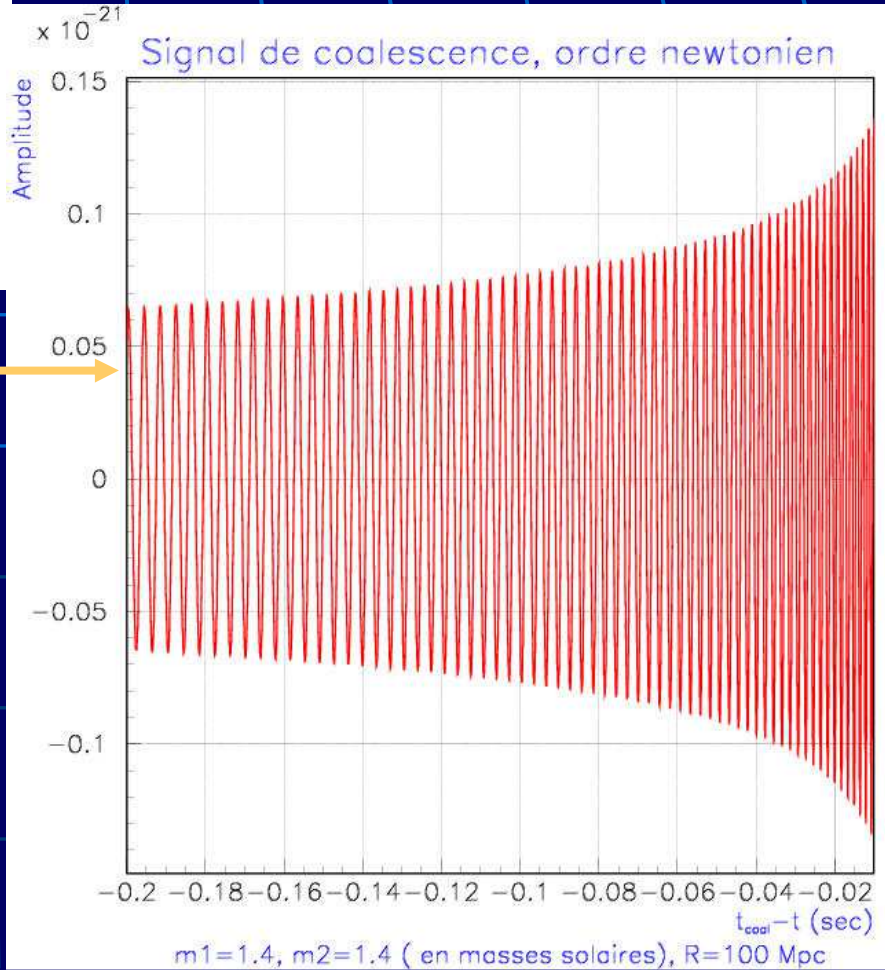


2 neutron stars @ 10Mpc

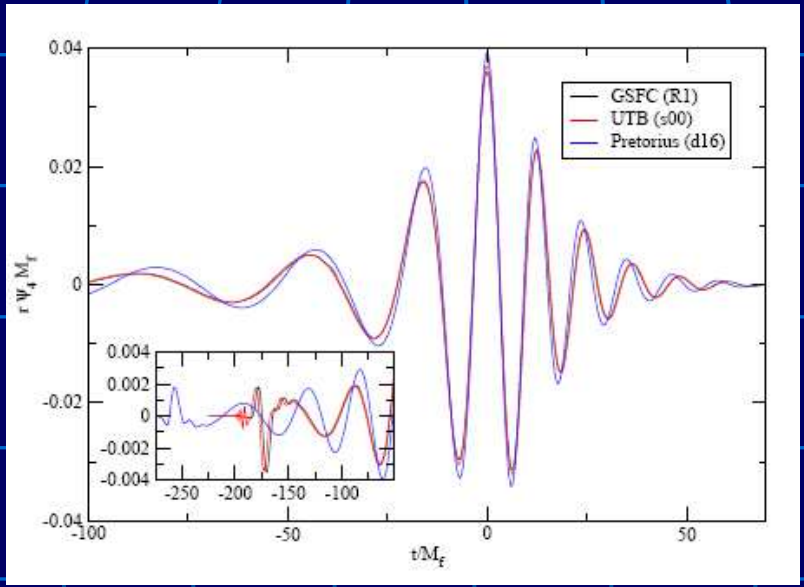
h_{max} ~10^{-21}

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: 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: $1.4M_\Theta + 1.4M_\Theta$ (Kalogera et al astro-ph/0111452)
  - 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

GW (indirect) discovery PSR 1913+16

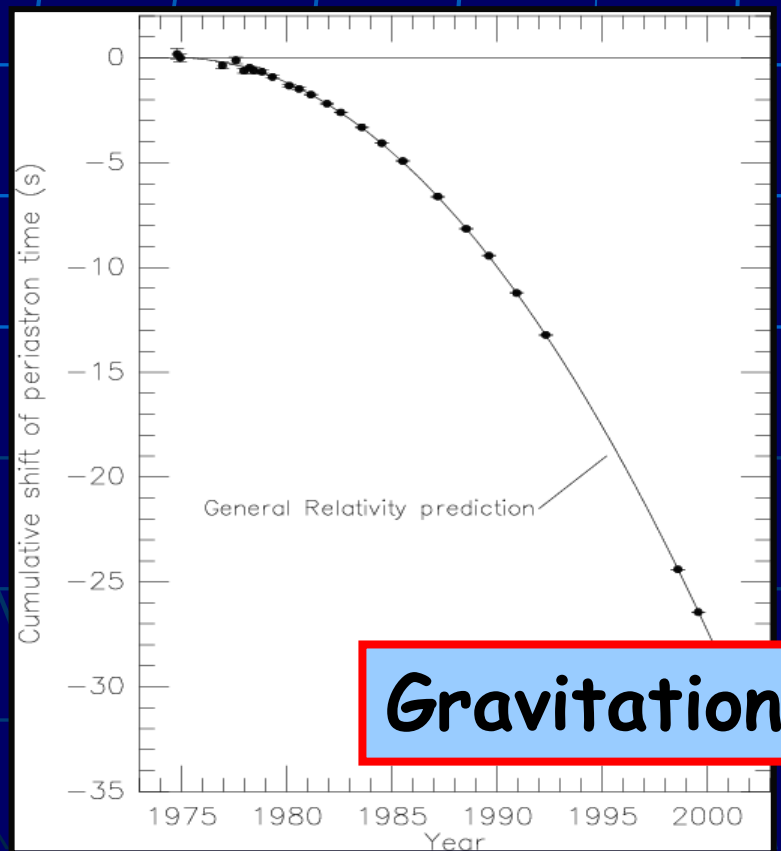
(Hulse & Taylor, Nobel'93)

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 !

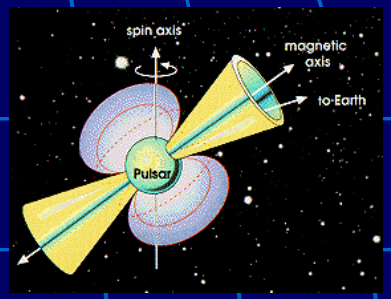
Other sources

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 …



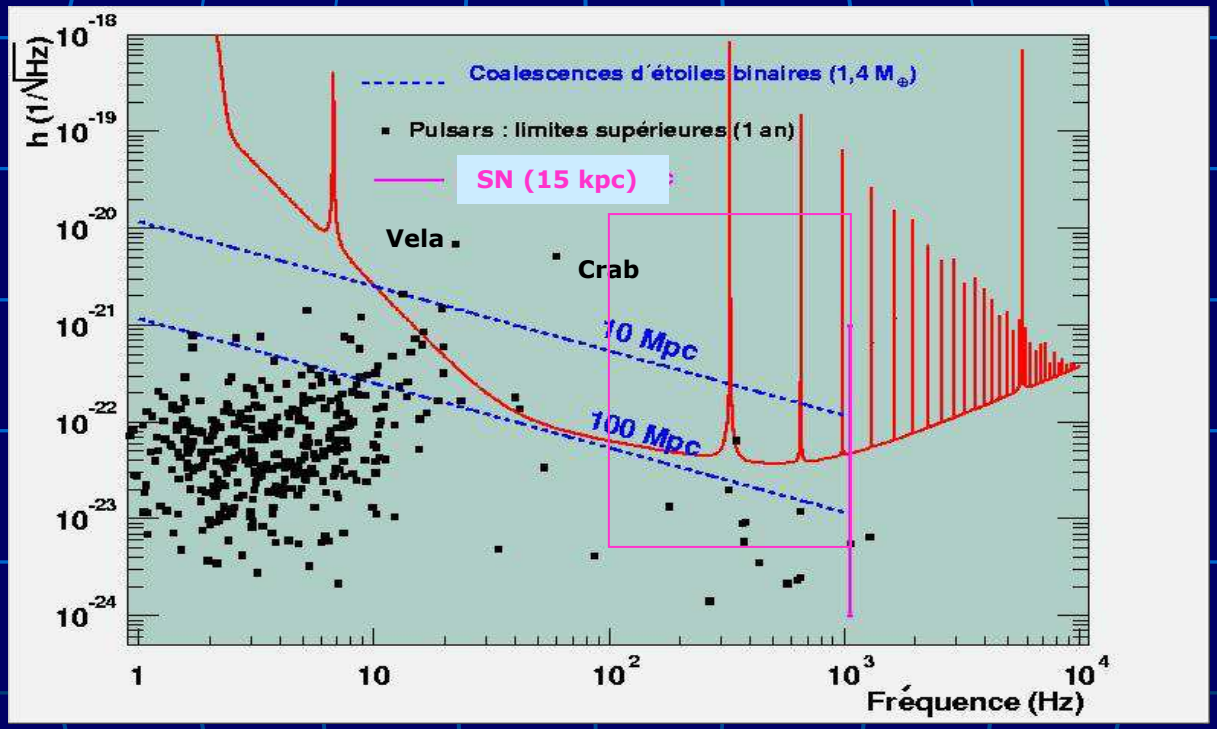
Radio-astronomy observation of pulsar slowdown sets upper limits on GW emission and neutron star asymmetry
(if rate of slowdown totally assigned to GW emission)

⇒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


Coalescences d'étoiles binaires (1,4 M⊕)
Pulsars : limites supérieures (1 an)
SN (15 kpc)
Vela
Crab
10 Mpc
100 Mpc
h (1/√Hz)
Fréquence (Hz)

Other sources

Stochastic background

A lot of possible ideas
- cosmological backgrounds, phase transitions
- cosmic string vibrations
- superposition of unresolved sources
- …

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

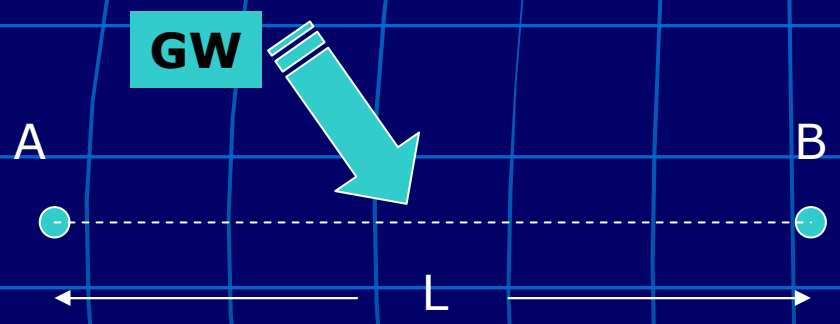
Theoretical predictions (cosmology): $h_0^2 \Omega_{\mathrm{GW}} < 10^{-6}$ rather $\rightarrow 10^{-13}$

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

Which is the physical effect we can detect on Earth ?

Detectable effect of GW

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



Geodesic deviation equation (weak field):

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

⇒ Variation of measured distance between A and B $\delta L \approx \frac{1}{2} hL$

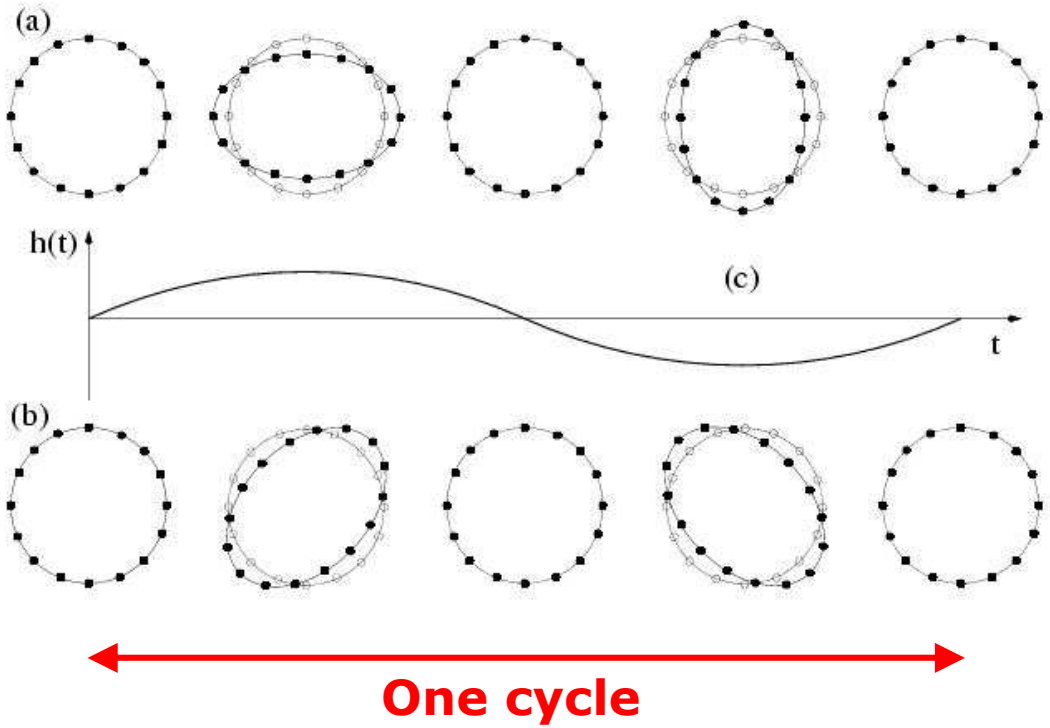
Amplitude h(t) ⇔ rate of deformation of space-time !

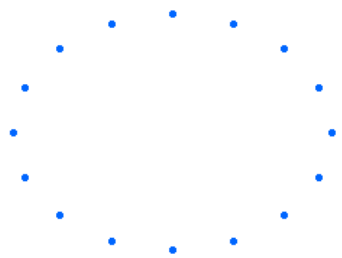
(*) modern measurement e.g. by time of flight of photons

Effect of GW on a set of test masses

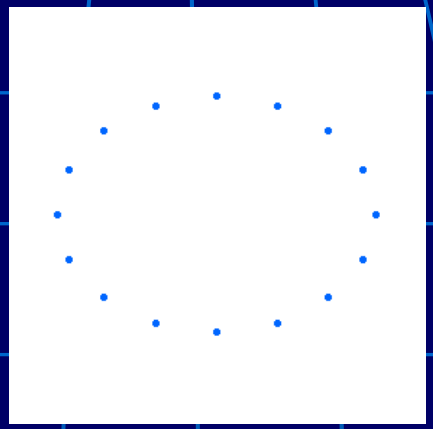
Effect of h_+

Effect of h_x





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

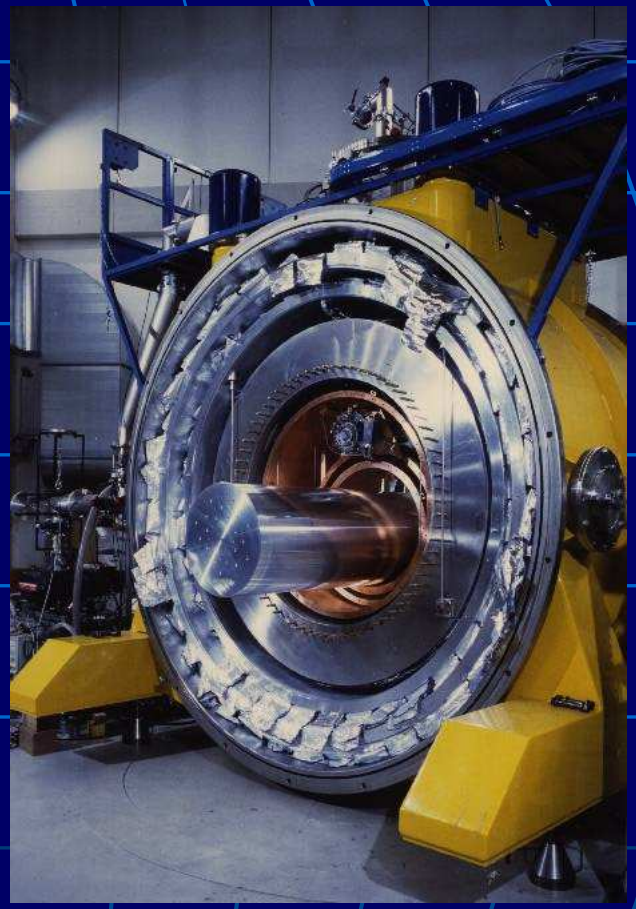
Interferometric detection of Gravitational Waves

History

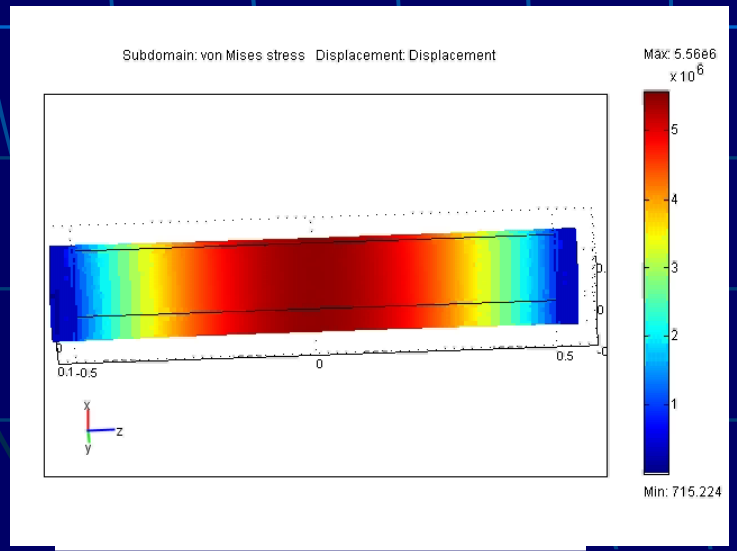
1960 1st detector (Weber)
1963 1st idea interferometric detection (Gersenshtein&Pustovoit, Weber)
1969 Wrong claim (Weber)
197X Weber detectors all over the world
1972 Itf feasibility study (Weiss) and 1st prototype (Forward)
1974 **PSR1913+16** (Hulse&Taylor)
End 70s cryogenic bars, itf prototypes (Glasgow, Garching, Caltech)
1986 birth of collaboration VIRGO (France+Italy, *Nikhef joined in 2006*)
1989 **VIRGO proposal**, **LIGO proposal** (USA)
1992 LIGO funded
1993 VIRGO funded
1996 start construction VIRGO et LIGO
2005 LIGO in operation
2007 VIRGO in operation
2007-2011 LIGO-VIRGO joint data takings
2011-12 Start upgrades -> Advanced LIGO and Advanced VIRGO
2015 First science runs for aLIGO and AdVIrgo…

Resonant detectors (Weber's bars)

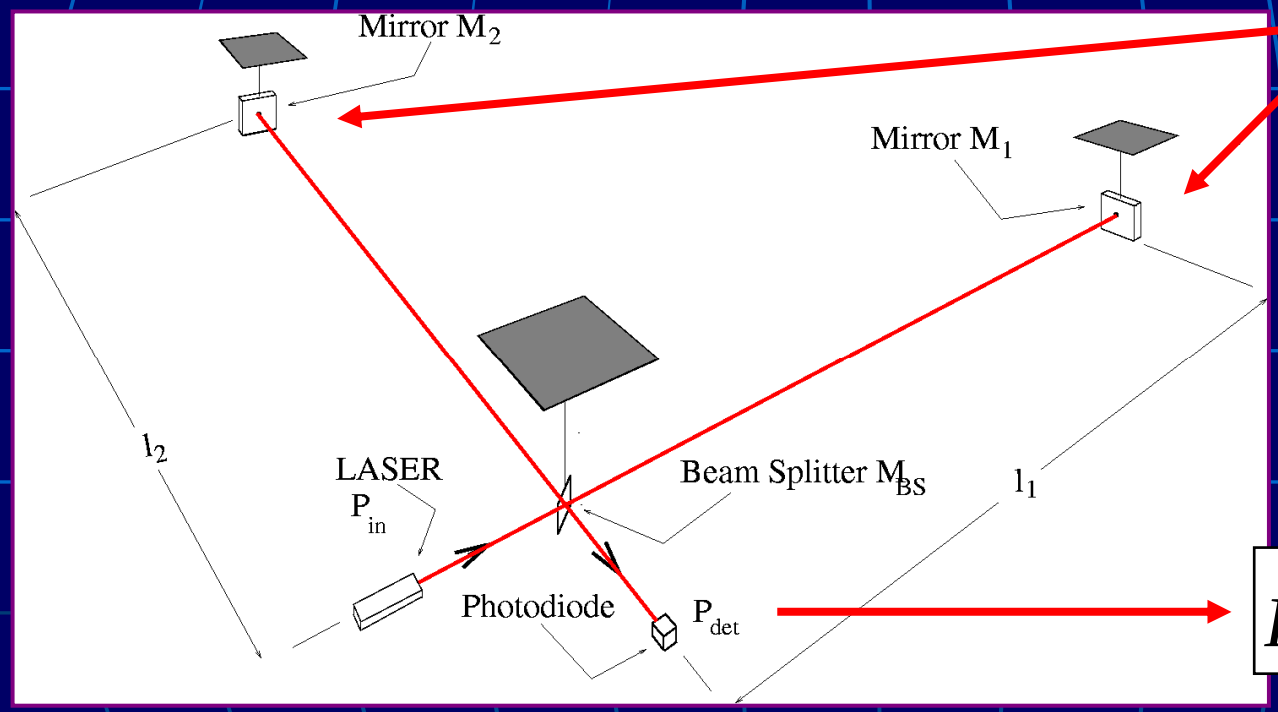
From Weber (60's) …



… to Auriga (2000s)



Itf detection principle



Suspended mirrors
⇔ Test masses

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

GW → optical paths are modified → detected power is modified

The optical signal is proportional to *h*(t) !

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

$C \approx 1$

where

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

Static dephasing (itf tuning)

Effect of the GW

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

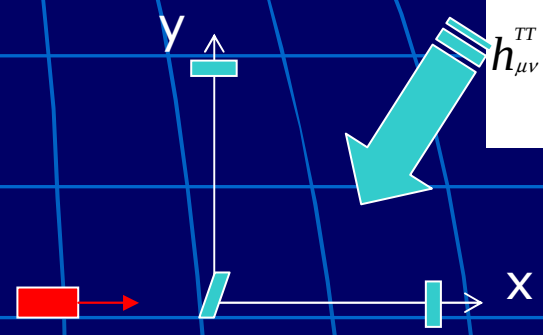
The signal !

It remains to show that $\delta\phi_{GW}$ is prop. to *h* …

The optical phase is proportional to *h*(t)

(exercise)

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



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

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

$$ds^2 = 0 = g_{\mu\nu} dx^\mu dx^\nu = \left(\eta_{\mu\nu} + h_{\mu\nu}\right) dx^\mu dx^\nu$$

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:

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

Phase shift is proportional to *h*(t) !

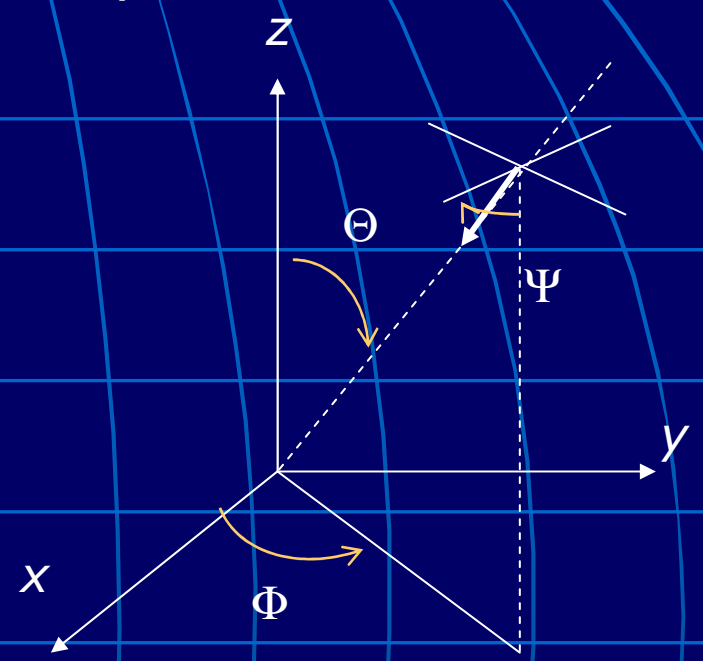
And if the GW has any incidence and any polarization ?

(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 (Θ, Φ, Ψ)-> itf frame
(arms along *x* and *y* axis)



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

$$h(\mathrm{t}) = F_+(\Theta,\Phi,\Psi)h_+(\mathrm{t}) + F_\times(\Theta,\Phi,\Psi)h_\times(\mathrm{t})$$

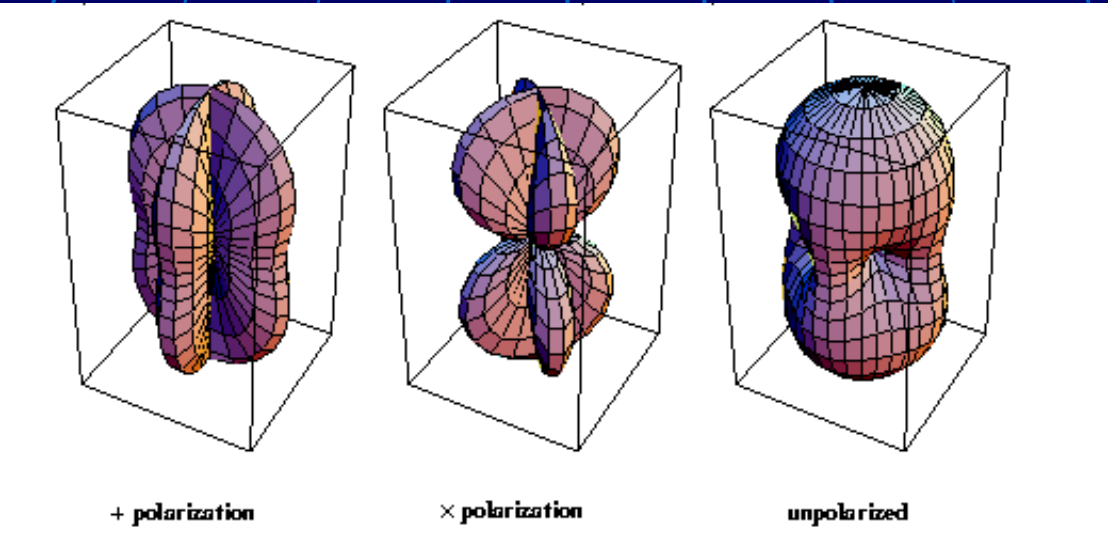
where we define the "beam patterns" as

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

$$F_\times(\Theta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\Theta)\cos 2\Phi\sin 2\Psi + \cos\Theta\sin 2\Phi\cos 2\Psi$$

The interferometric detector is not directional

Antenna patterns



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)

=> **<u>2 (very good) reasons to operate more than one detector !</u>**

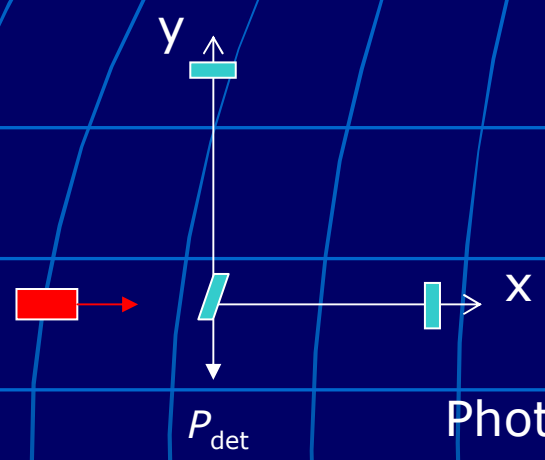
Noises in interferometric detectors

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

$\Rightarrow$ General design of itf detectors

Optical readout noise

<u>2 aspects:</u> photon counting noise (or shot noise) and radiation pressure noise



Photons detected by photodiode (PD) at the output

Counting statistics (Poisson):

- Let's note n = rate of arrival on PD (Hz)
- Average number of photons incident on the PD during time τ is then $N = n\tau$
- Standard deviation $\sigma_N = \sqrt{N}$
- Detected power $P_{\text{det}} = n\hbar\omega = N\hbar\omega/\tau$ in average
- Detected power fluctuation (RMS) : $\delta P_{\text{det}} = \sqrt{N}\hbar\omega/\tau$

Shot noise

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

NOISE SIGNAL

Noise:

$$P_{\det} = \frac{P_0}{2}\left[1+\cos(\Delta\phi_{OP})\right] = P_0\cos^2\left(\frac{\Delta\phi_{OP}}{2}\right)$$

$$\begin{cases}\delta P_{\det} = \sqrt{N}\hbar\omega/\tau \\ P_{\det} = N\hbar\omega/\tau\end{cases} \longrightarrow \delta P_{\det} = \sqrt{\frac{P_0\,\hbar\omega}{\tau}}\left|\cos\left(\frac{\Delta\phi_{OP}}{2}\right)\right|$$

Signal : $\longrightarrow$

$$P_S = P_0\sin\left(\frac{\Delta\phi_{OP}}{2}\right)\cos\left(\frac{\Delta\phi_{OP}}{2}\right)\times\delta\phi_{GW}$$

Signal to noise ratio : $\longrightarrow$

$$\left(\frac{S}{N}\right) = \frac{P_s}{\delta P_{\det}} = \sqrt{\frac{P_0\tau}{\hbar\omega}}\left|\sin\left(\frac{\Delta\phi_{OP}}{2}\right)\right|\times\delta\phi_{GW} \longrightarrow \Delta\phi_{OP} = \pi$$

Dark fringe

Phase sensitivity : $\delta\tilde{\phi} \approx \sqrt{\frac{\hbar\omega}{P_0}}$

sensitivity : $\tilde{h}_{shot} \approx \frac{\lambda}{4\pi L}\sqrt{\frac{\hbar\omega}{P_0}}$ White spectral density

$\sim 10^{-10}$ rad/Hz$^{1/2}$ for P_0 = 20 W and @ 1.06 μm

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 $F_{\mathrm{rp}} = \frac{P}{c}$ where P is the incident power on a mirror ($=P_0/2$)

The force fluctuation is then $\sigma_{\mathrm{F}} = \frac{\sigma_{\mathrm{P}}}{c}$

Where (as derived in previous slide) $\sigma_{\mathrm{P}} = \sqrt{N}\hbar\omega/\tau = \sqrt{\frac{P_0\hbar\omega}{2\tau}}$

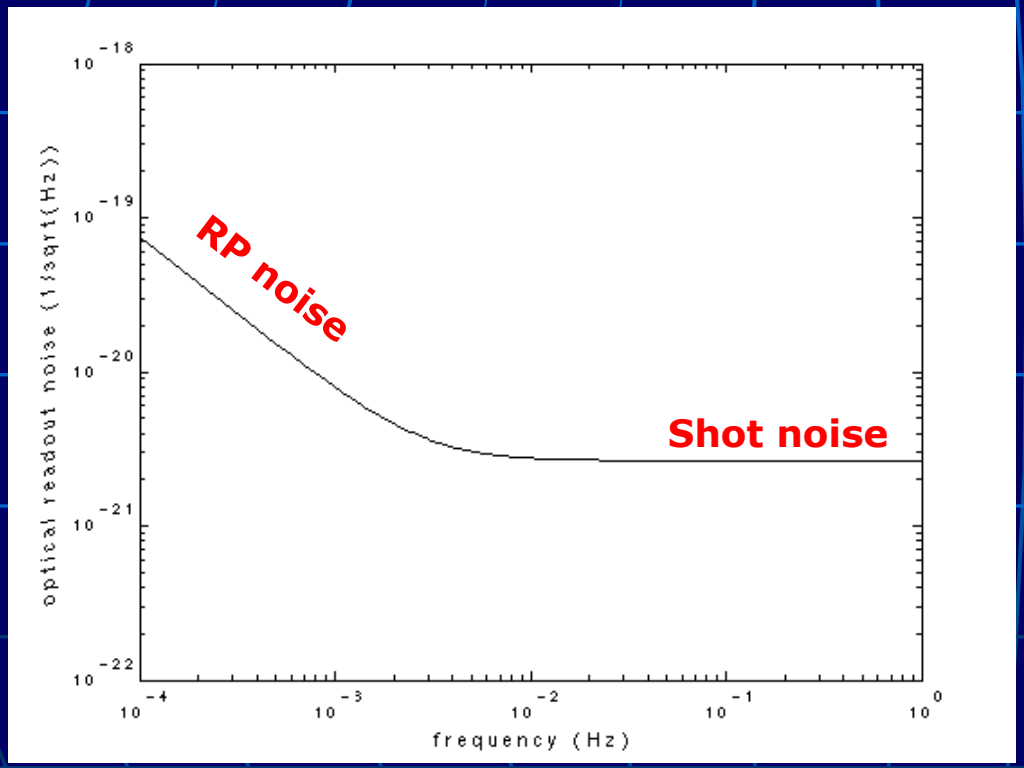
The RP force spectral density is then $\tilde{F}_{\mathrm{RP}}(f) = \frac{1}{c}\sqrt{\frac{P_0\hbar\omega}{2}} = \sqrt{\frac{2\pi\hbar P_0}{2\lambda c}}$ (white).

The mirror response to this force is then: $\tilde{x}(f) = \frac{1}{m(2\pi f)^2}\tilde{F}_{\mathrm{RP}}(f) = \frac{1}{4mf^2}\sqrt{\frac{\hbar P_0}{\pi^3\lambda c}}$

In term of GW amplitude sensitivity: $\tilde{h}_{\mathrm{RP}}(f) = \frac{2}{L}\tilde{x}(f) = \frac{1}{2mLf^2}\sqrt{\frac{\hbar P_0}{\pi^3\lambda c}}$

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=1.06e-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

$$\tilde{h}_{\text{readout}}{}^2(f) = \tilde{h}_{\text{shot}}(f)^2 + \tilde{h}_{\text{RP}}(f)^2 = AP_0 + \frac{B}{P_0}$$ is minimum for $$P_{0,\,\min} = \frac{A}{B} = \pi M \lambda c f^2$$

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

$$\tilde{h}_{\text{sql}}(f) = \sqrt{\frac{\hbar}{4\pi^2 m L^2 f^2}}$$

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 $\boldsymbol{P_0}$

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 ~ 100 km

Increase the circulating power:

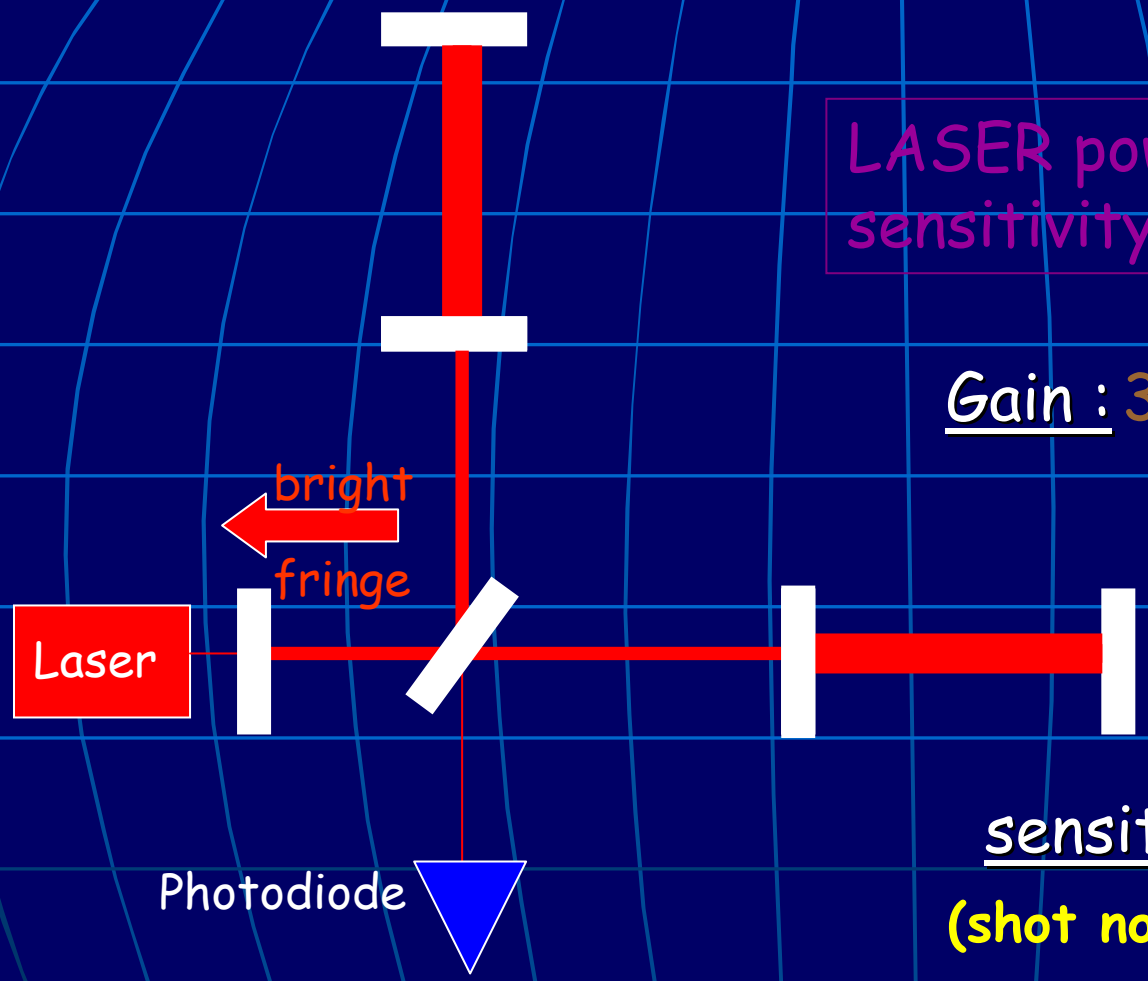
+ itf tuned at a dark fringe => all the light is reflected back to the laser.

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

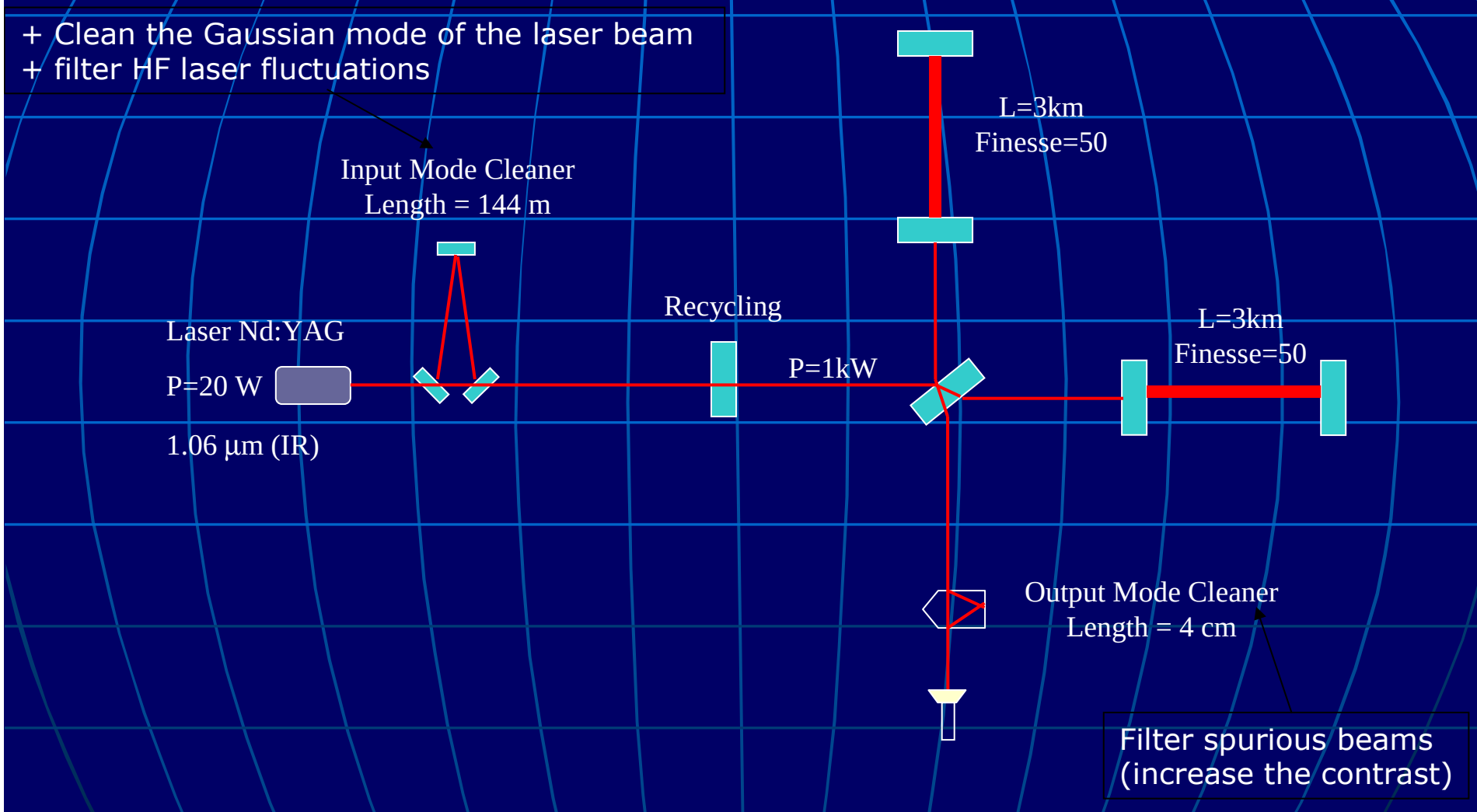
Gain : $3000 \times 30 \times \sqrt{50} \sim 10^6$

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

(shot noise)

→ kilometric arm length : 1 m → 3 km
→ add Fabry-Perot cavities (Finesse = 50 ⇒ Gain ~ 30)
→ add « recycling » mirror (P = 1 kW on the beamsplitter)

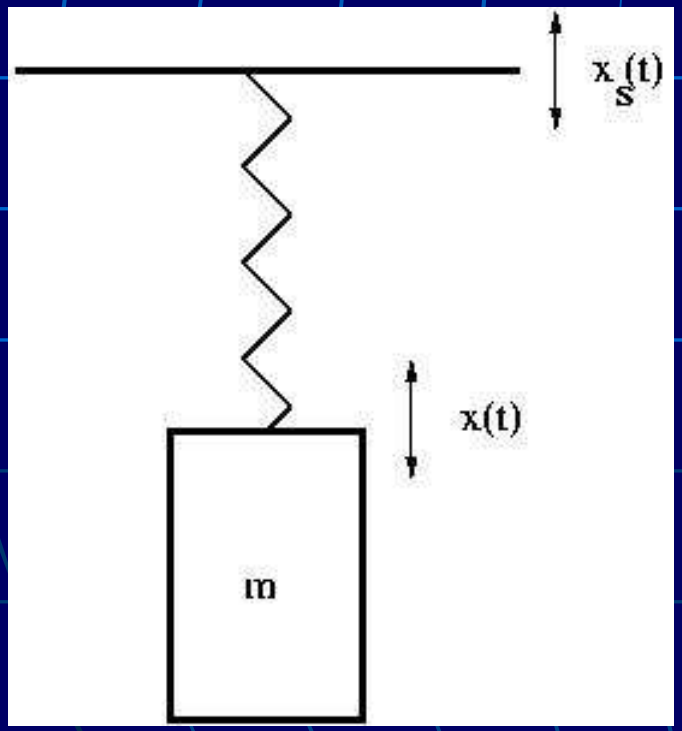
Virgo optical design



Seismic noise

Mesure on site : $\tilde{x}(f) \approx \frac{10^{-6}}{f^2}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ $\Rightarrow$ **Must be attenuated**

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



Transfer function : $\tilde{H}(\omega) = \frac{\tilde{x}(\omega)}{\tilde{x}_s(\omega)} = \frac{\omega_0^2}{\omega_0^2 - \omega^2}$

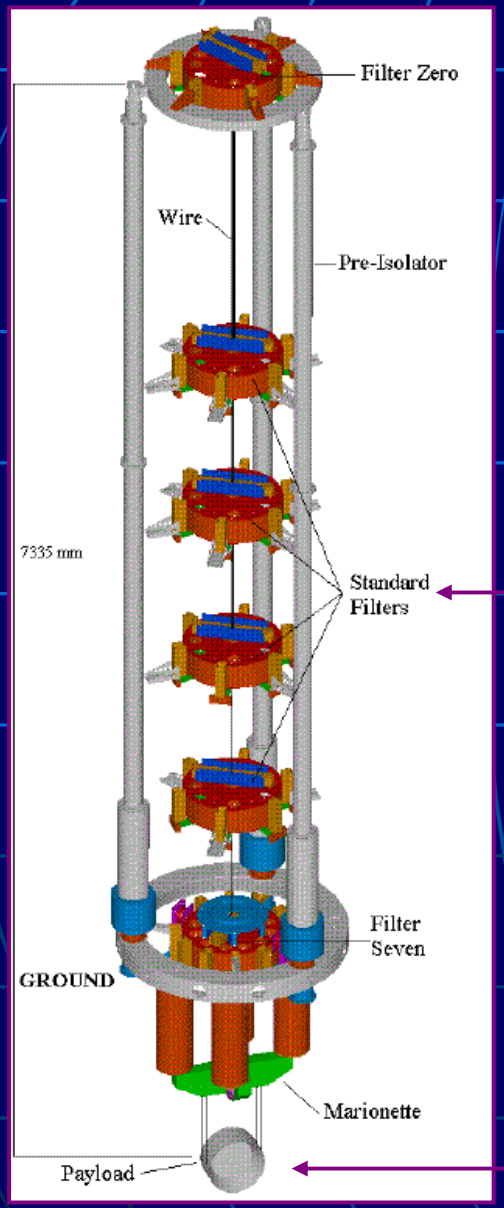
Above resonance : $|\tilde{H}(\omega)| \approx \left(\frac{\omega_0}{\omega}\right)^2$

N dampers : $|\tilde{H}(\omega)| \approx \left(\frac{\omega_0}{\omega}\right)^{2N}$

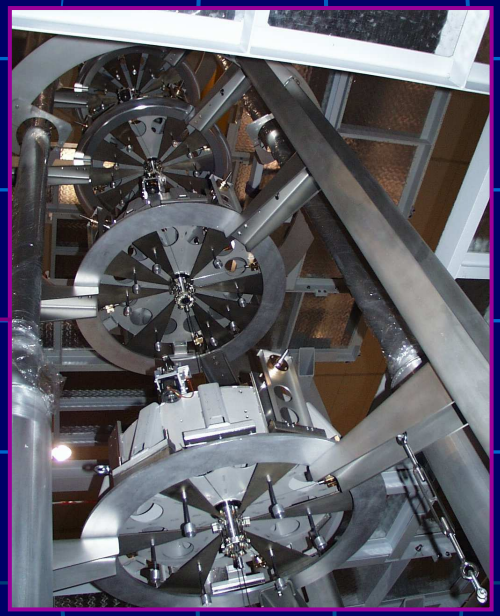
5 dampers with fundamental freq. ~ **0.6 Hz** :

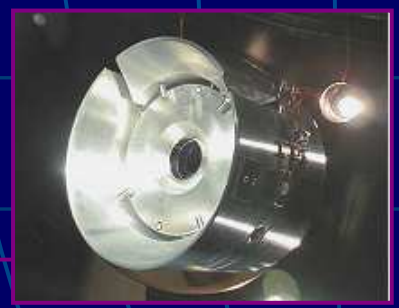
$\rightarrow$ $\tilde{h}_{sism} \approx 7\mathrm{x}10^{-22}/\sqrt{\mathrm{Hz}}$ @ 10Hz

Virgo « superattenuator »



L ~ 7 m; M ~ 1 ton
+ inverted pendulum





$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \frac{g}{l}}$$

$\Rightarrow f_{res} \sim 30$ mHz

Seismic attenuation:
~ 10^{14} @ 10 Hz
(measured)

Thermal noise

Fluctuation dissipation theorem (Callen et al., 1951 …)
$\Rightarrow$ dissipation is source of noise in any mechanical system

Fluctuating force power spectral density $\tilde{F}_{\text{therm}}{}^2(f) = 4k_{\text{B}}T\,\Re(Z(f))$

(where Z is the mechanical impedance)

Gives rise to fluctuating motion (position noise) $\tilde{x}_{\text{therm}}{}^2(f) = \dfrac{k_{\text{B}}T}{\pi^2 f^2}\Re(Y(f))$

(where $Y=1/Z$ is the mechanical admittance)

<u>Exemple of gas-damped spring or pendulum</u>

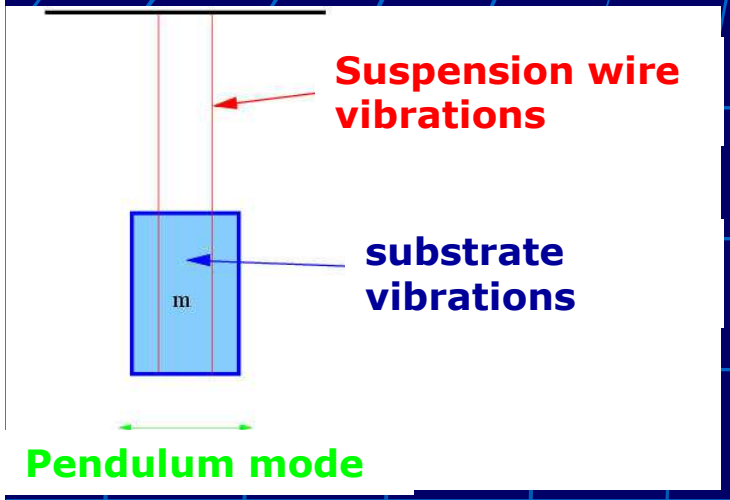
From the equation of motion $\ddot{x} + \dfrac{\omega_0}{Q}\dot{x} + \omega_0{}^2 x = F/m$ show that the position

(thermal) noise is

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

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:

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

ϕ = "loss angle" (related to spring anelasticity)

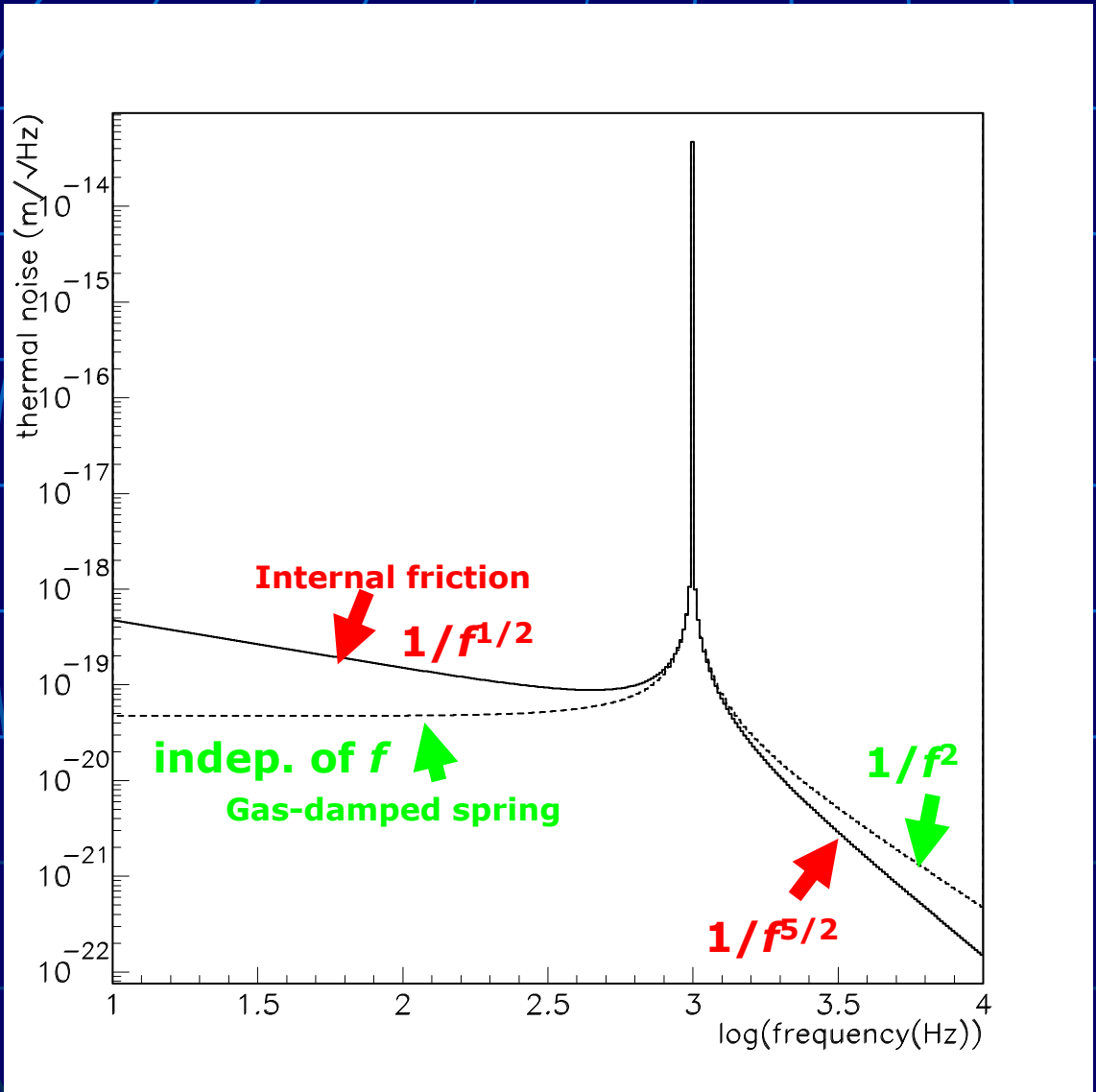
From the new equation of motion and assuming ϕ=cste =1/Q, show that the thermal noise power spectrum in case of internal friction is

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

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/ω^2
  internla noise -> cst/$\omega^{5/2}$

Thermal noise



$Q=10^6$
$f_0=1$ kHz
M=30 kg
T=300 K

LASER frequency noise

Frequency fluctuations + length asymmetry ⇒ phase noise

$$\delta\tilde{\phi} = \frac{2\pi d}{c}\,\delta\tilde{\nu}$$

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: $\tilde{h}_{OG} \approx \left(\frac{\Delta L}{L} + \frac{\Delta F}{F}\right) \times \frac{\delta\tilde{\nu}}{\nu}$

- target sensitivy : $\tilde{h} \approx 3\,\mathrm{x}10^{-23} / \sqrt{\mathrm{Hz}}$
- asymmetry ~10^{-3}
- freq. $\nu \approx 2.8 \times 10^{14}$ Hz

⇒ spec. $\delta\tilde{\nu} < 10^{-5}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$

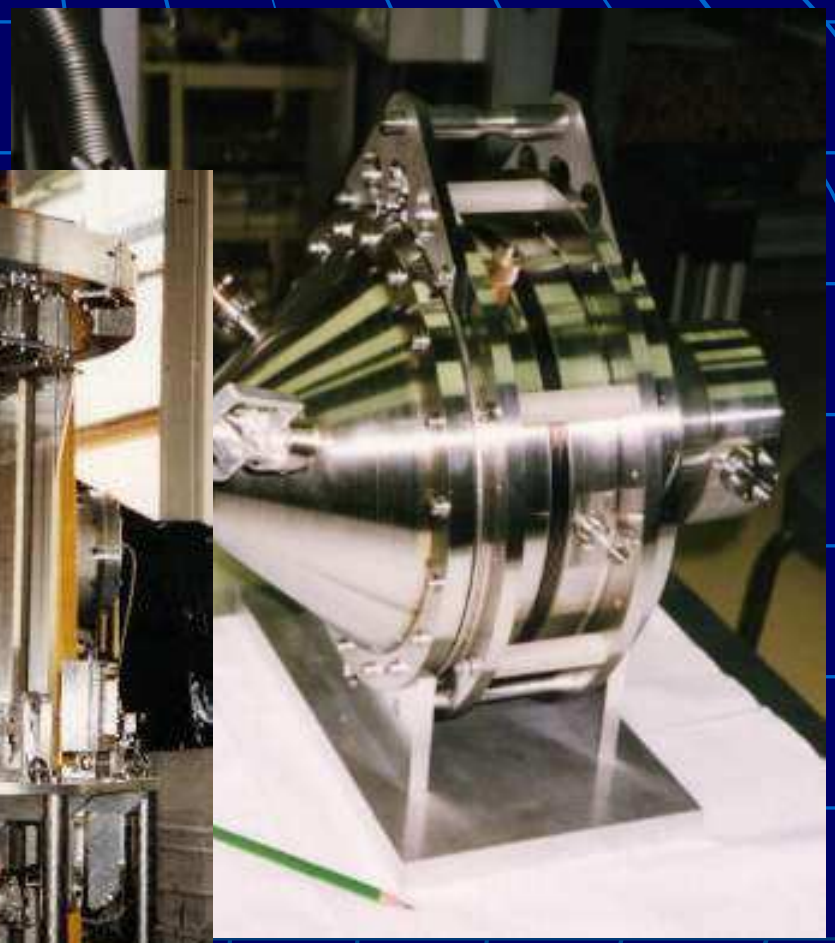
Active laser frequency stabilization + « mode-cleaner » cavity

(Fabry-Perot = low pass filter !)

LASER frequency stabilization

Laser servoed to
Rigid cavity (ULE

Under the input bench



Under vacuum

Ultra High Vacuum

Residual gas index fluctuations ⇒ phase noise

→ **Ultra high Vacuum is needed**

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

Solution for Virgo:

- Steel tubes Ø ~1.2 m, e ~ 4 mm.
- 200 modules (15 m long) in each arm
- bake out 400°C after production,
  150 °C (H_2O) on site
- 10 pumping stations / arm

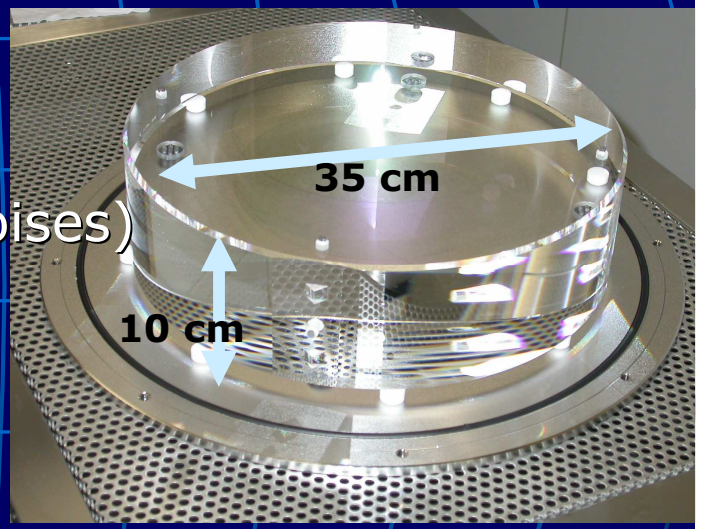
Vacuum volume in VIRGO : **2x3kmx1.2m ~ 7000 m^3** !

LIGO (itf center : beamsplitter and input FP mirrors)

Virgo (itf center)

Mirrors

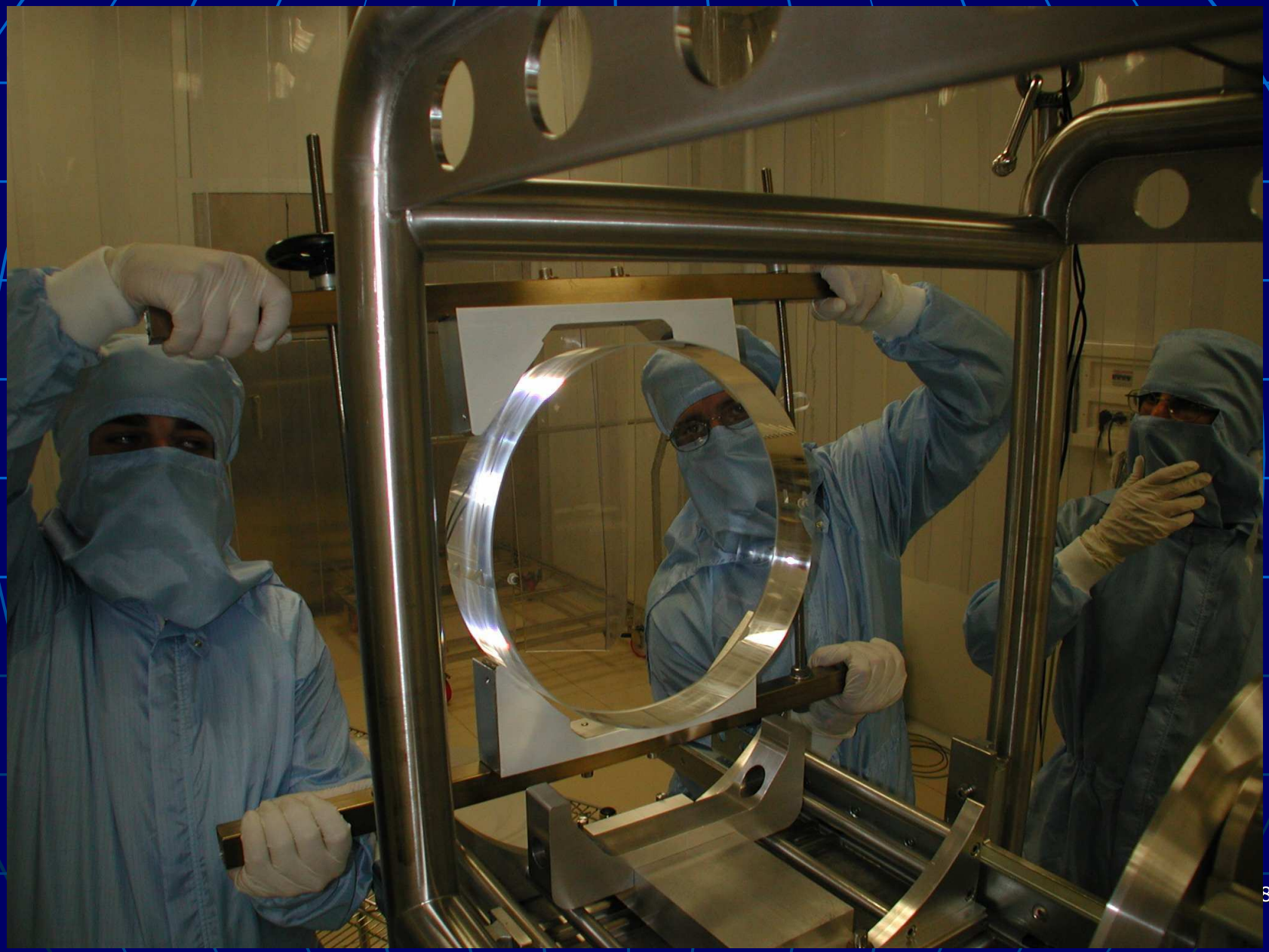
- Spec: total losses < 2% (guarantee 1kW on beamsplitter):
  - « coating » absorption (< 1 ppm) and substrate absorption (<2 ppm/cm)
  - Diffusion losses < 5 ppm
  - Geometrical Aberrations ($\delta z < \lambda/100$)
  - Curvature asymmetry < 3%
  - Finesse asymmetry < few % (laser noises)



Solution : pure Silica mirrors (SiO_2) with special design from manufacturer

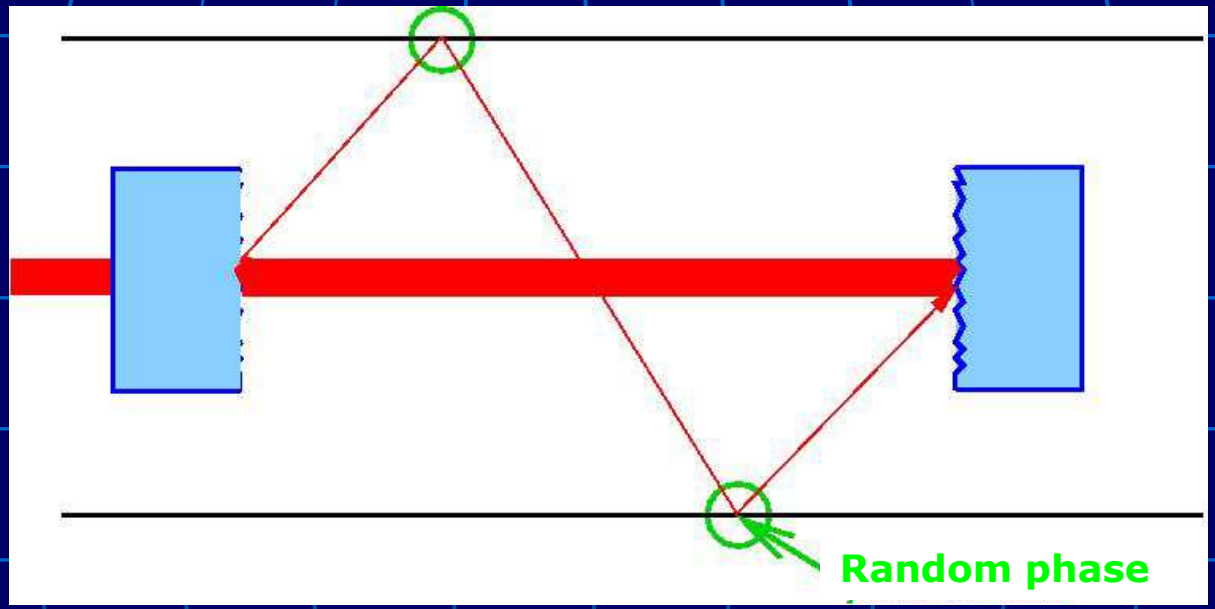
Virgo mirrors : Ø = 35 cm and width = 10 or 20 cm

Virgo beamsplitter installation



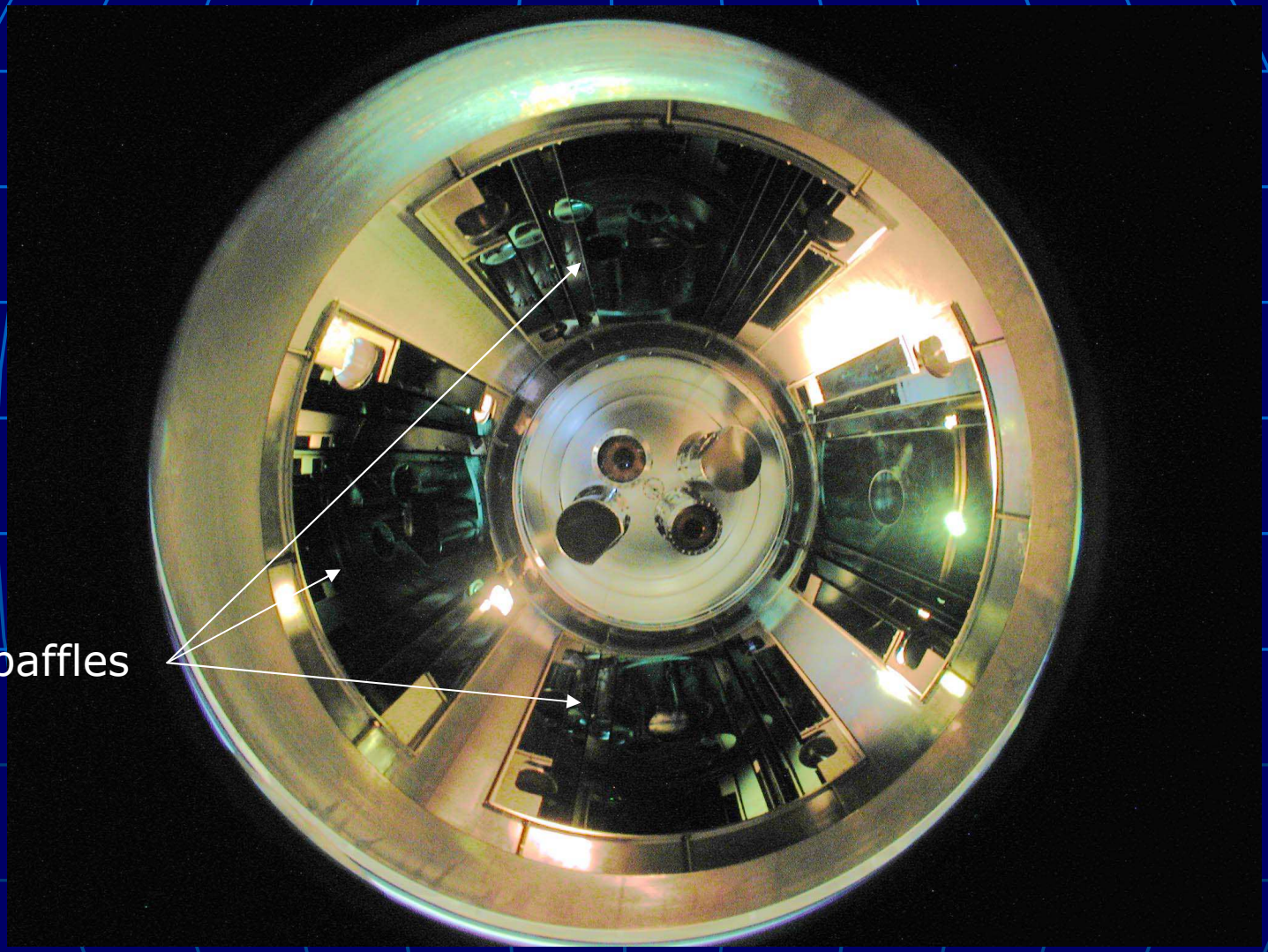
Scattered light

Residual mirror rugosity ⇒ scattered light + seismic motion of tubes
⇒ phase noise !

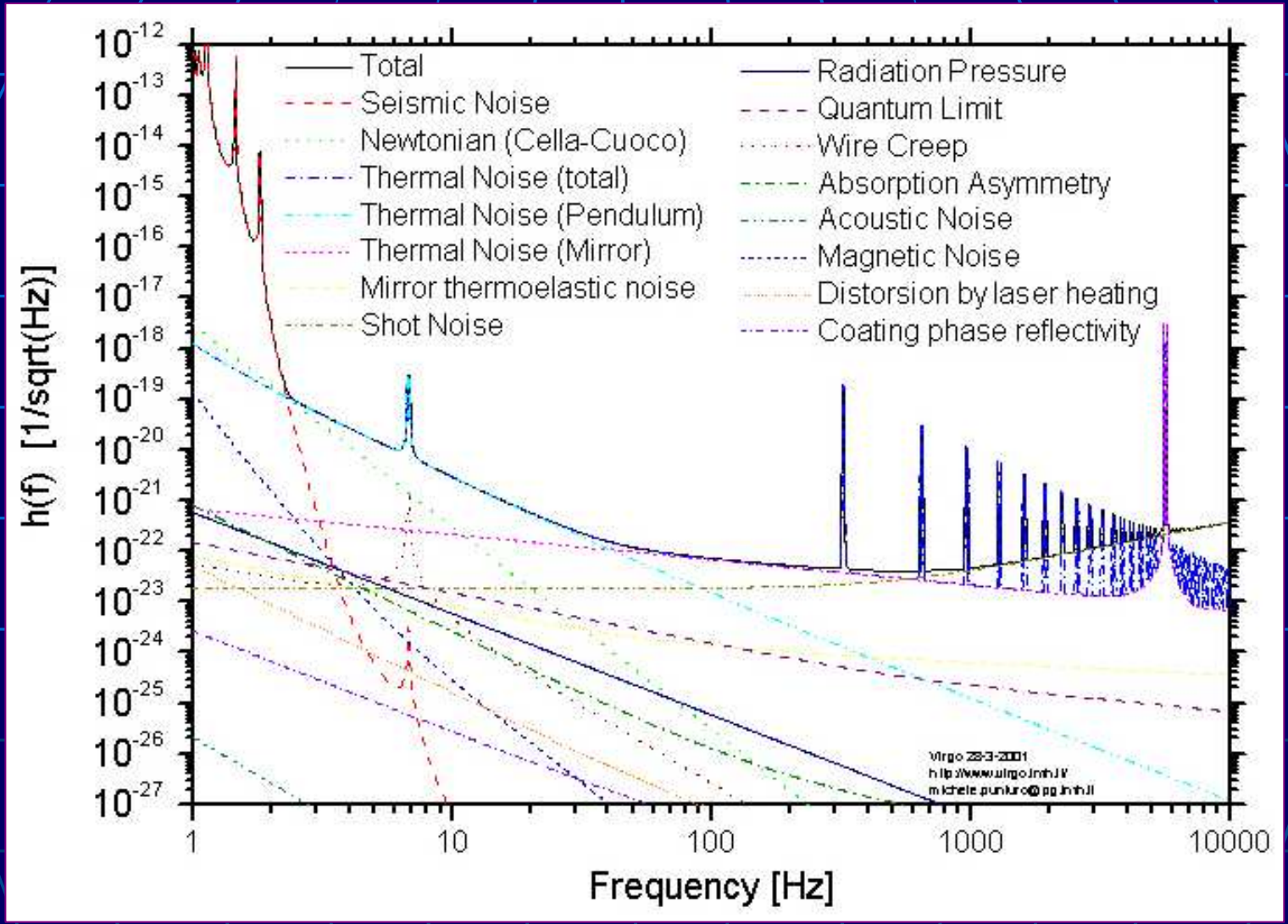


solution:

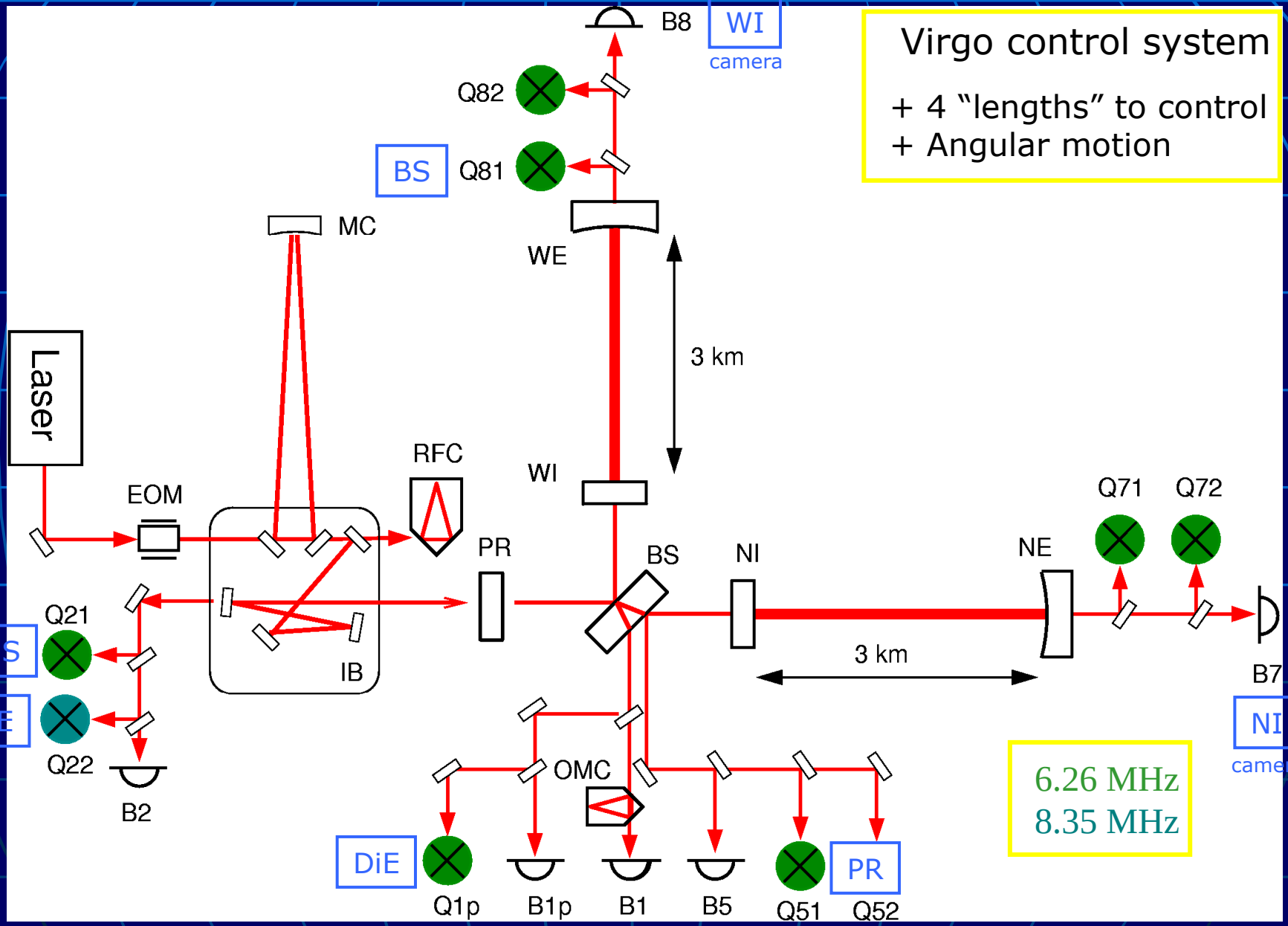
- very good mirrors OK.
- Baffles (80 in each bras)
  - steel baffles in the tubes
  - black glass in towers (close to mirrors)


Glass baffles

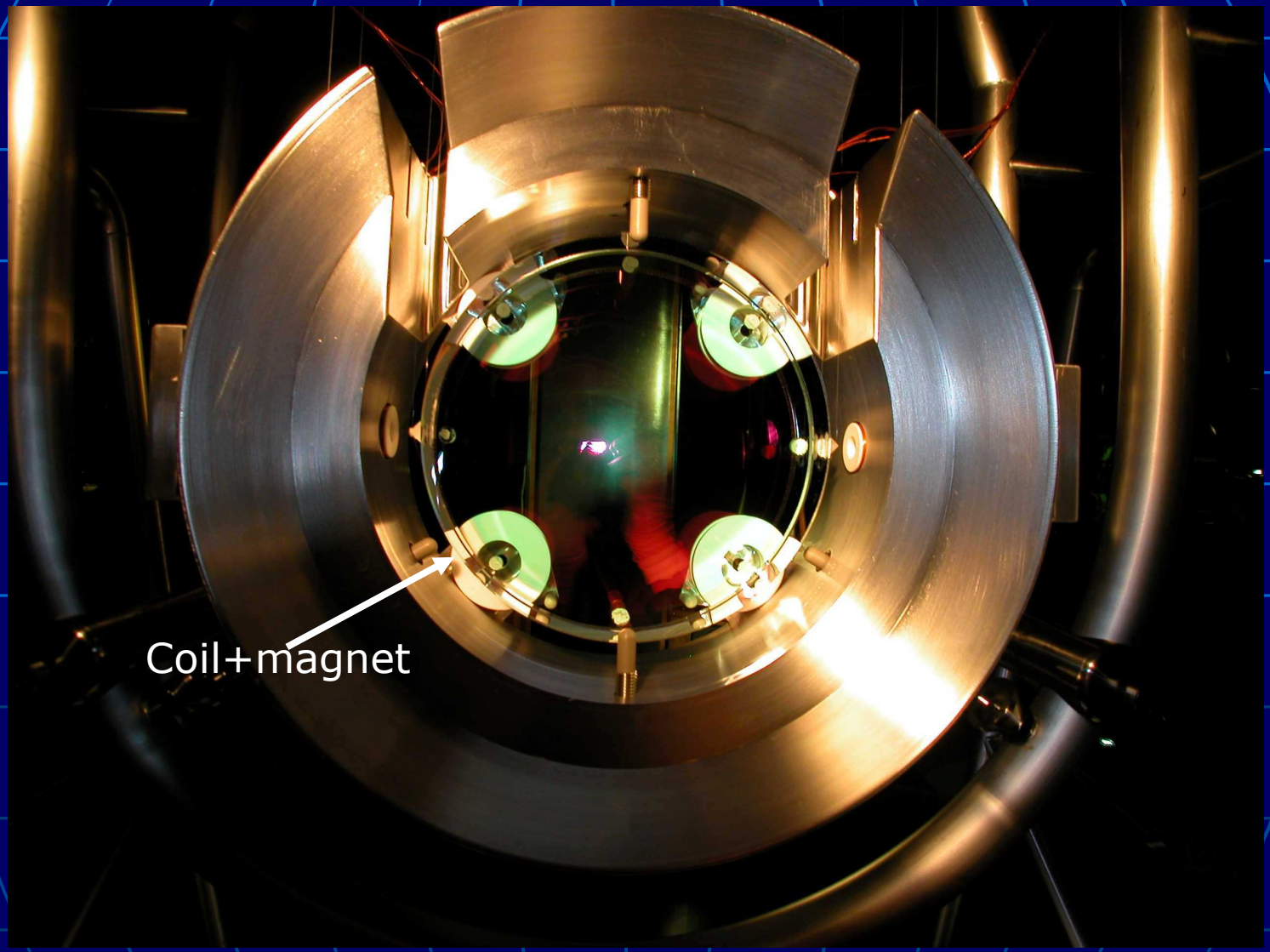
Sensitivity curve
(Virgo design example)



Interferometer control

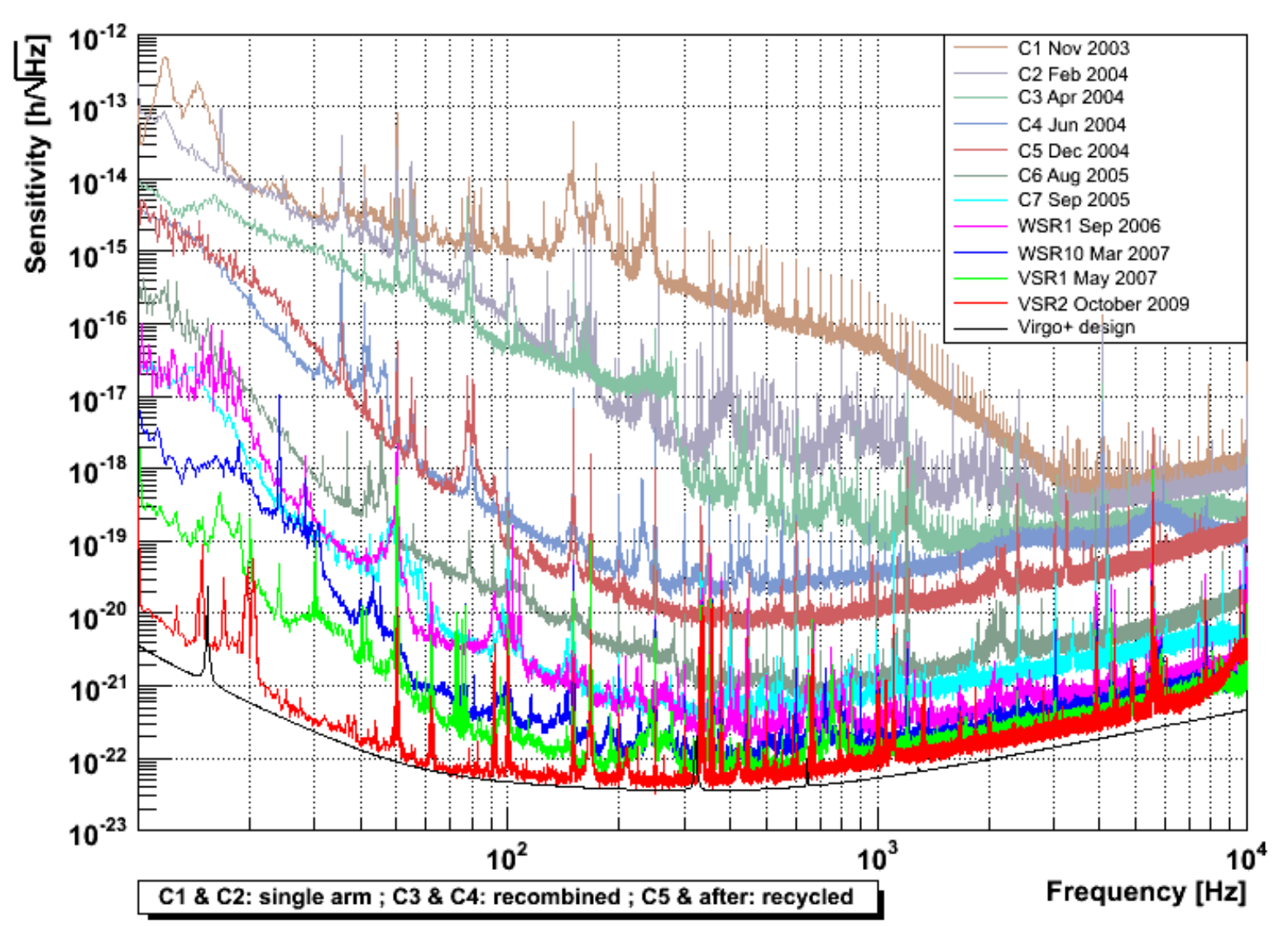


Interferometer control



Virgo sensitivity evolution

Not an easy task to reach the design sensitivity !



Towards advanced detectors

Virgo site:
Beginning of 2012

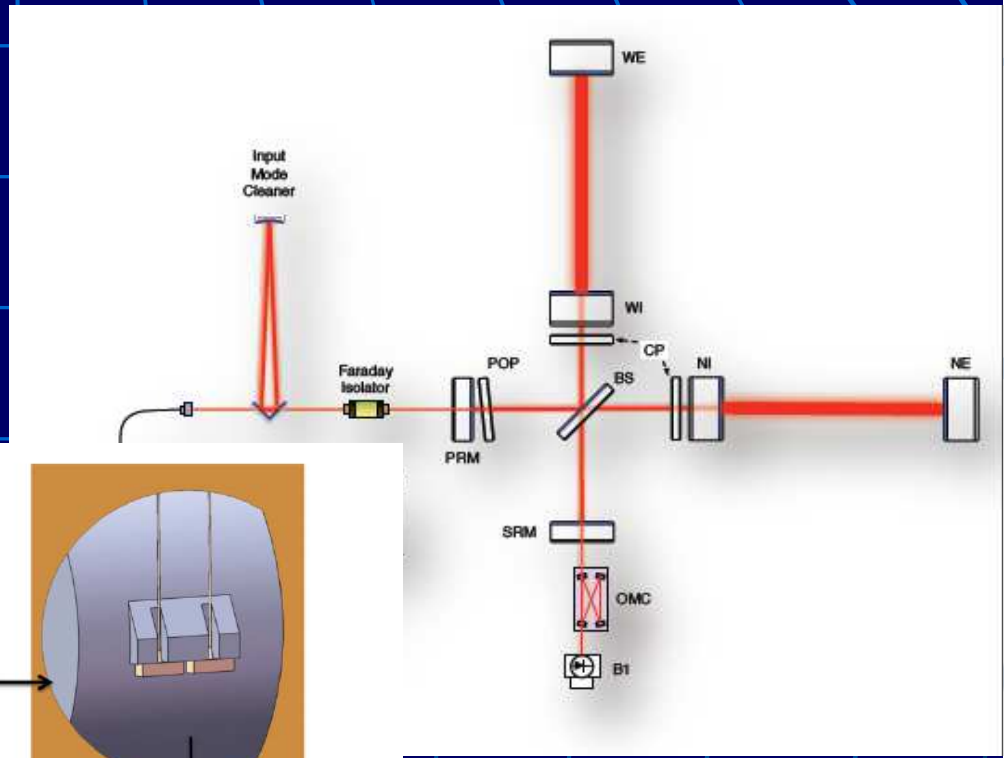
Advanced Virgo setup

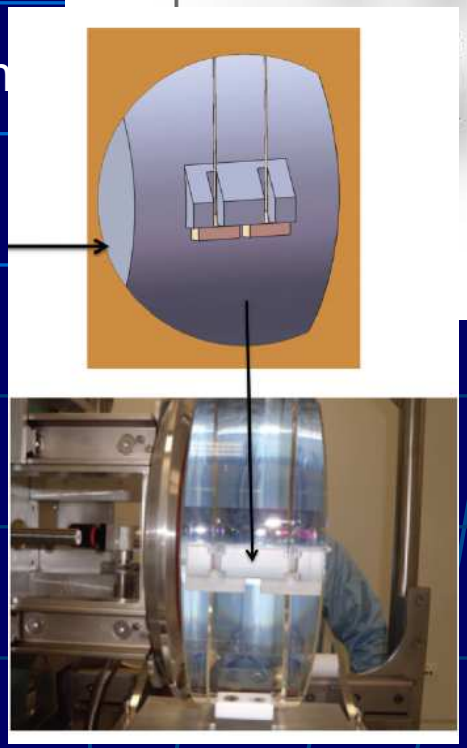
Changes in optical configuration:

- Laser power increase
- Higher finesse cavities
- Signal recycling

Plus

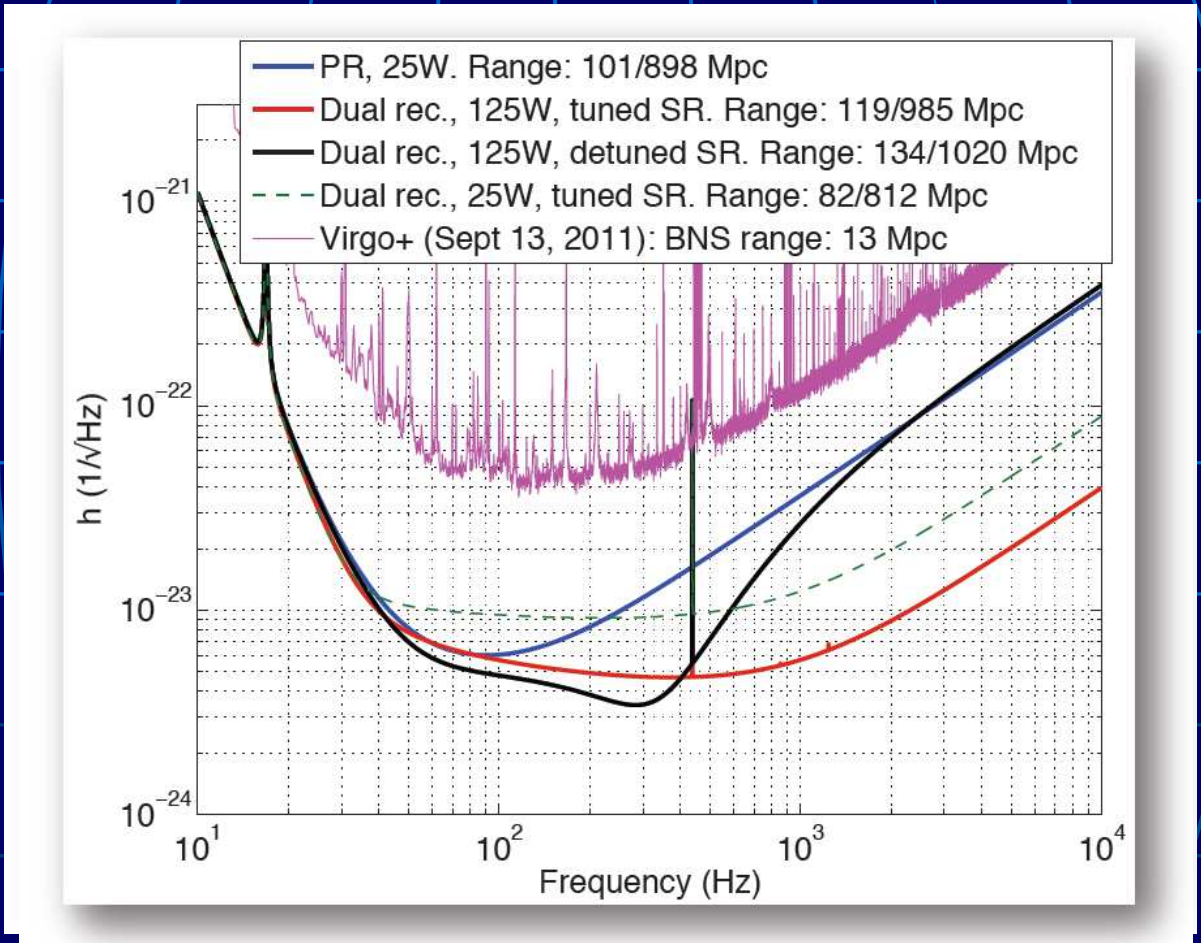
- Improved thermal compensation
- Suspended external benches
- Diffused light mitigation
- Fused Silica suspension wires
- …





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) : $S_x(f)$ = Fourier Transform of $A_x(t)$

Dimension of $S_x(f)$ = (dimension of x)^2 / frequency

Amplitude Spectral Density :

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

In practice, we use the estimator:

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

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)

<u>Principle:</u> correlate the data with a template (a copy of the expected signal)

Signal to noise ratio ρ :

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

$\boldsymbol{h}$: detector output $\boldsymbol{t}$: template

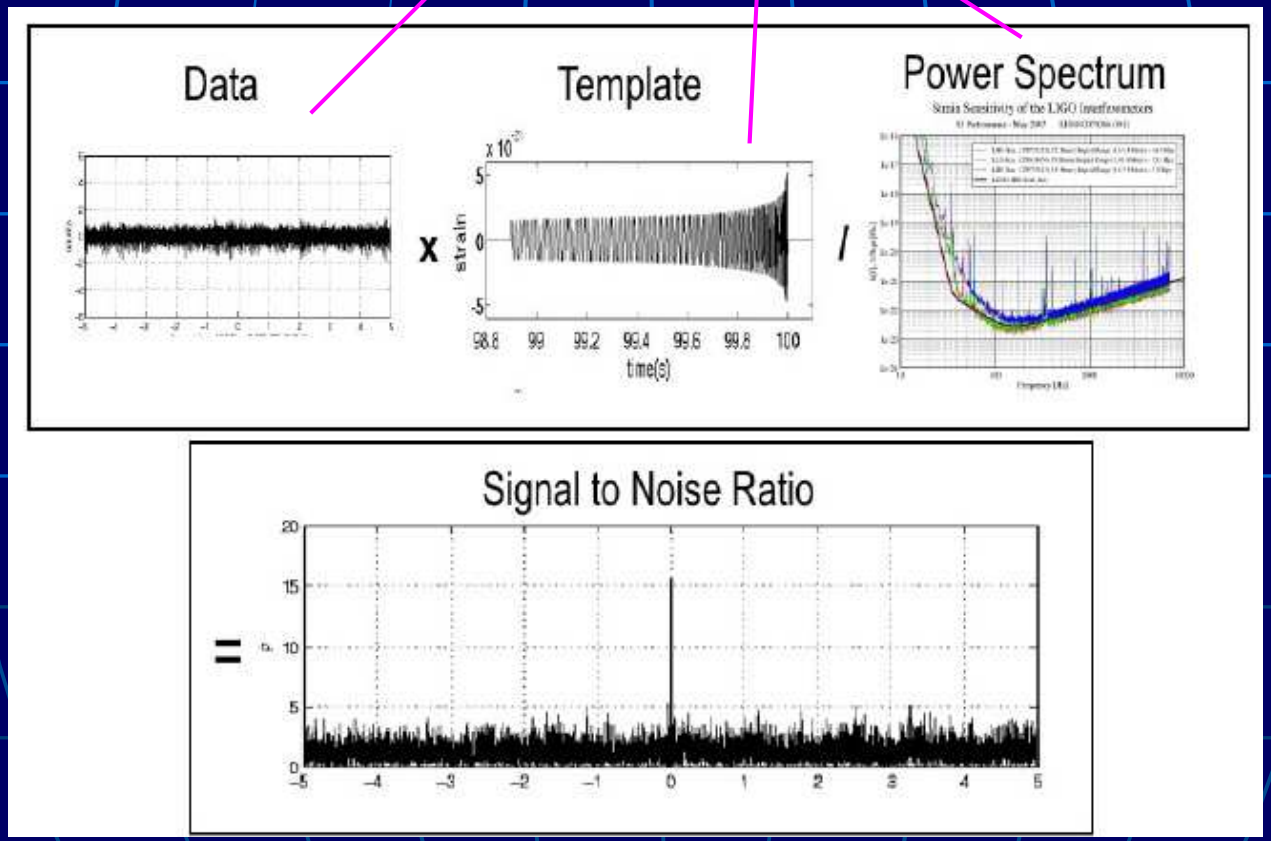
$\boldsymbol{S_h}$: detector noise (one-sided) spectral density

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

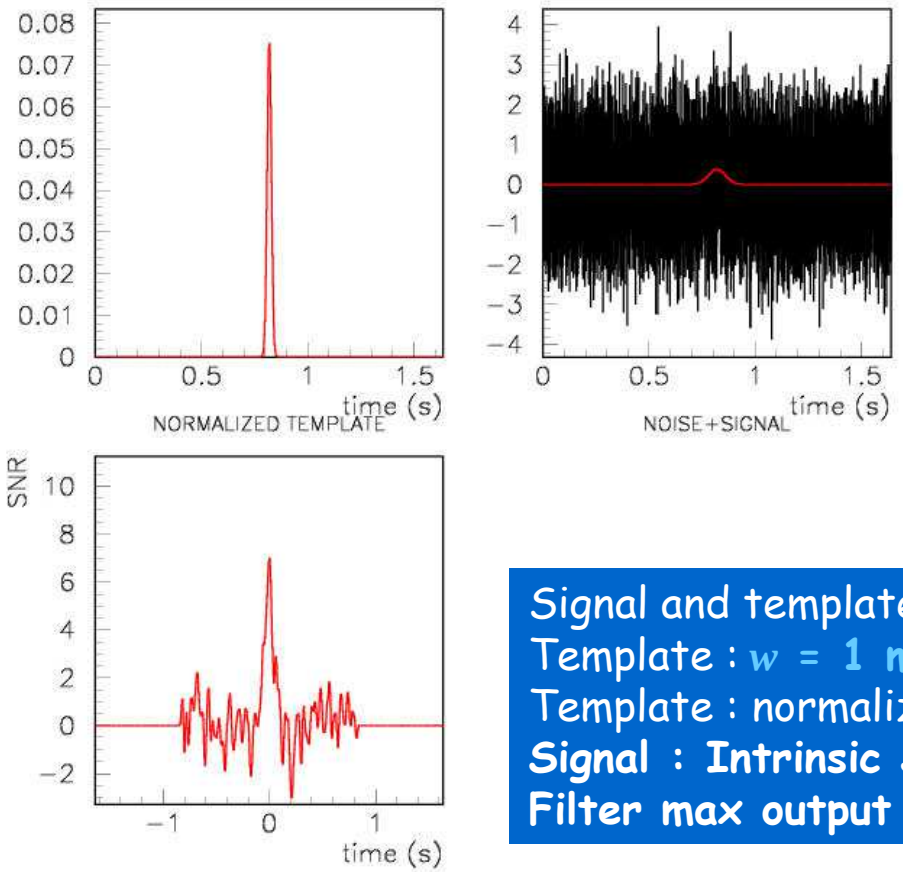
$$\rho^2 = \langle \boldsymbol{h} | \boldsymbol{t} \rangle$$

Matched filtering principle

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

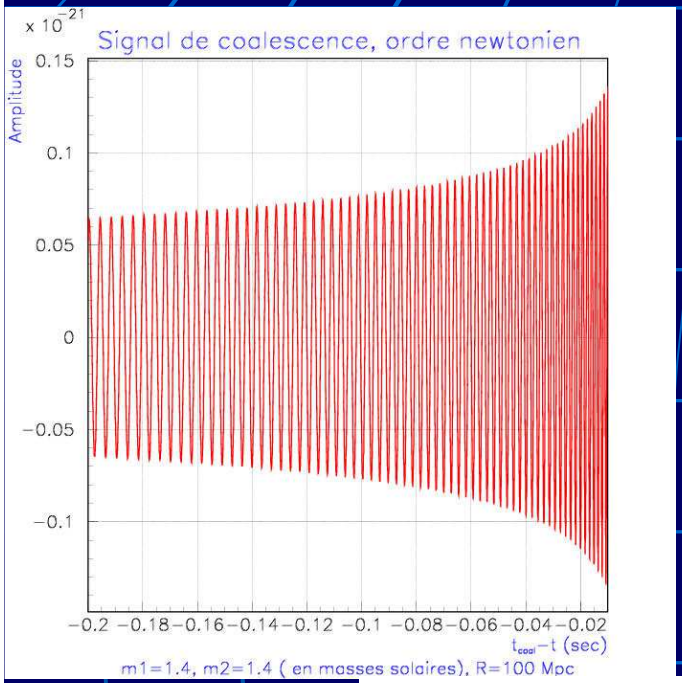


Matched filtering : example



Signal and template : mismatched shapes
Template : w = 1 ms. Signal : w = 5 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



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

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

The phase φ(t) depends primarily on star masses

$\Rightarrow$ 2 unknown (intrinsic) parameters
+ extrinsinc parameters (angles) that play no role in the detection process apart a scaling of the amplitude.

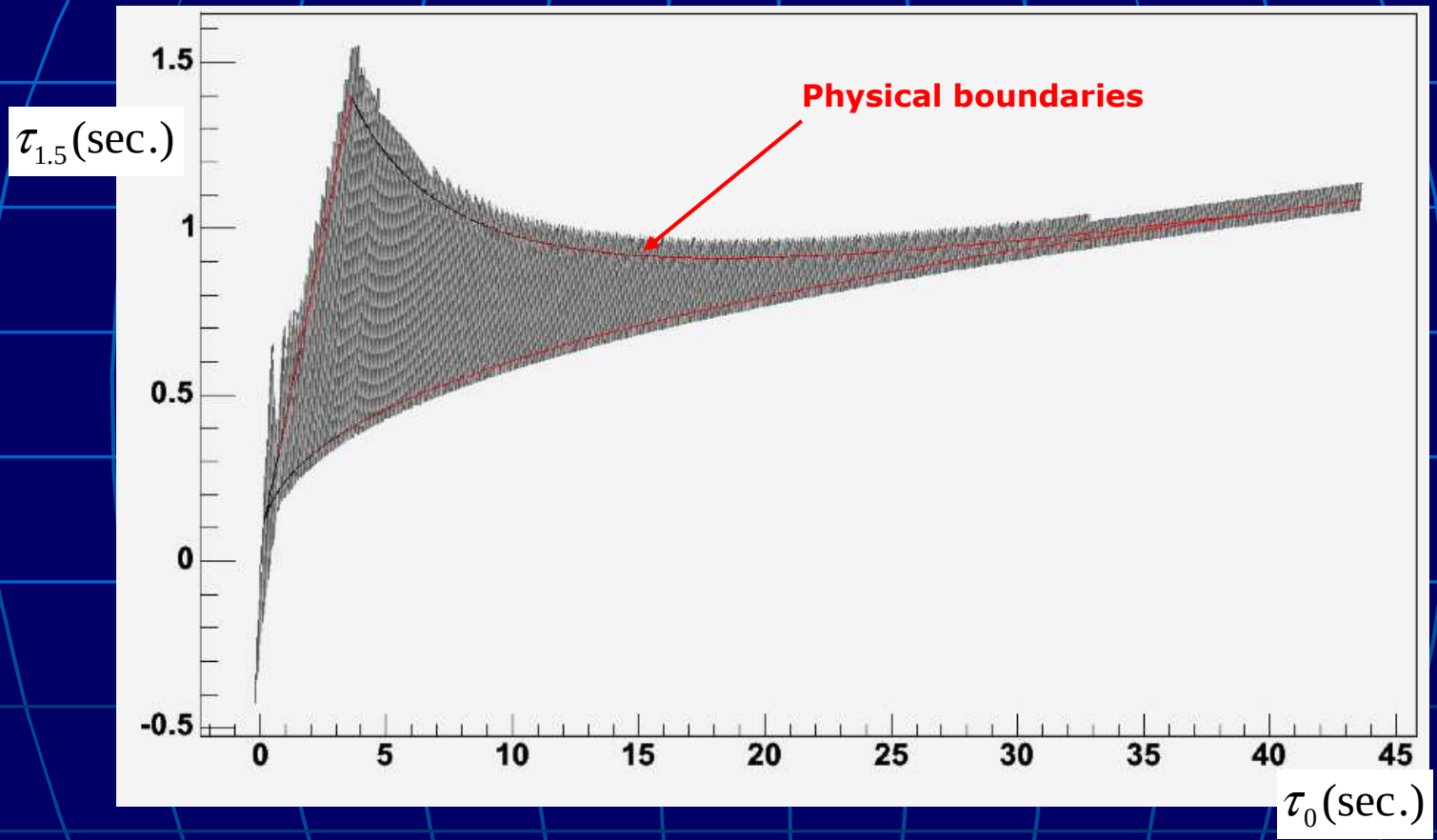
Parameter space (M1, M2) must be tiled with templates

General scheme:

- Define the ambiguity function: $\Gamma(\vec{\lambda}, d\vec{\lambda}) = \langle t(\vec{\lambda}) \,|\, t(\vec{\lambda} + d\vec{\lambda}) \rangle$
- And expand up to second order: $\Gamma(\vec{\lambda}, d\vec{\lambda}) \approx 1 - \frac{1}{2} g_{\mu\nu} d\lambda^\mu d\lambda^\nu$ → defines a metric in parameter space!!!
- Set a minimal match between nearby templates: $\Gamma(\vec{\lambda}, d\vec{\lambda}) \geq \mathrm{MM}$
- criteria to locate templates $\frac{1}{2} g_{\mu\nu} d\lambda^\mu d\lambda^\nu \leq 1 - \mathrm{MM}$

Matched filtering for binary inspirals

2D parameter space => condition $\frac{1}{2} g_{\mu\nu} d\lambda^{\mu} d\lambda^{\nu} \leq 1 - \mathrm{MM}$ defines **ellipses** in the plane !



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

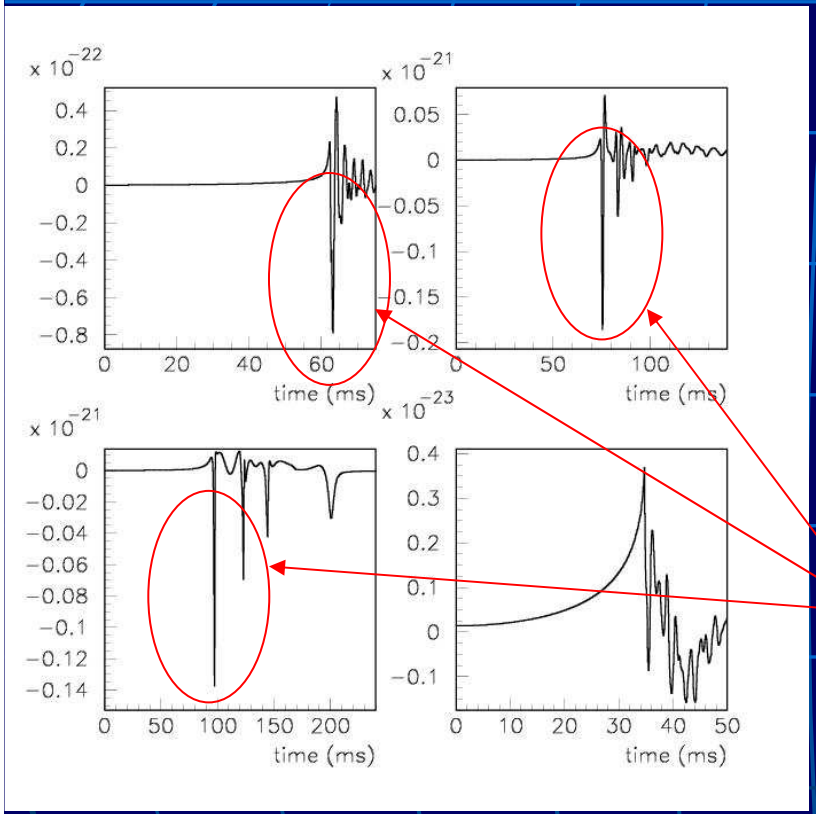
Data to be processed with high number of templates

- 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 !

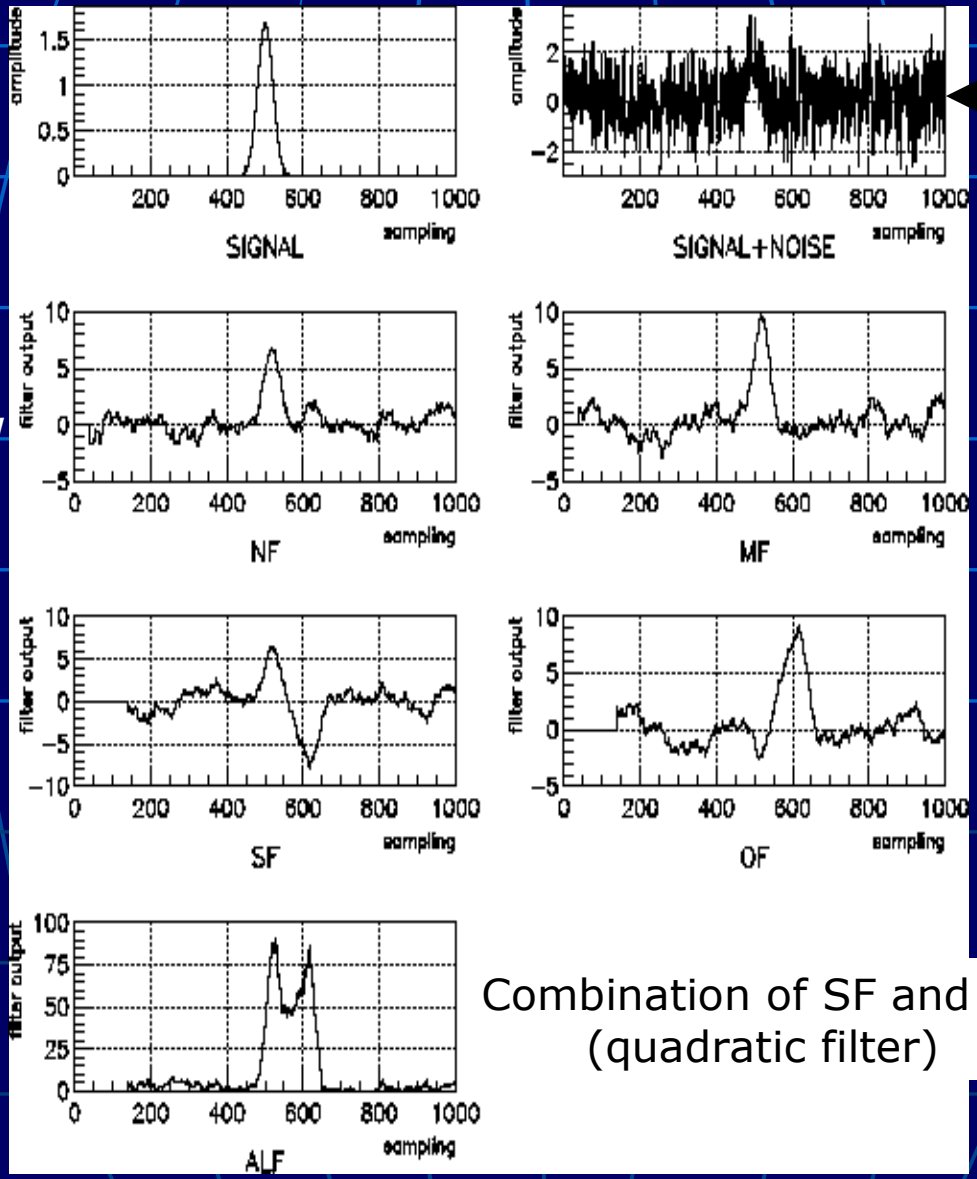
⇒<u>Robust detections methods needed</u>
(but necessarily suboptimal)

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



Signal in white noise

Energy excess
In moving window

Moving average

Slope change
detector

Offset detector

Combination of SF and OF
(quadratic filter)

Burst data analysis
Time-frequency methods

Wavelet methods

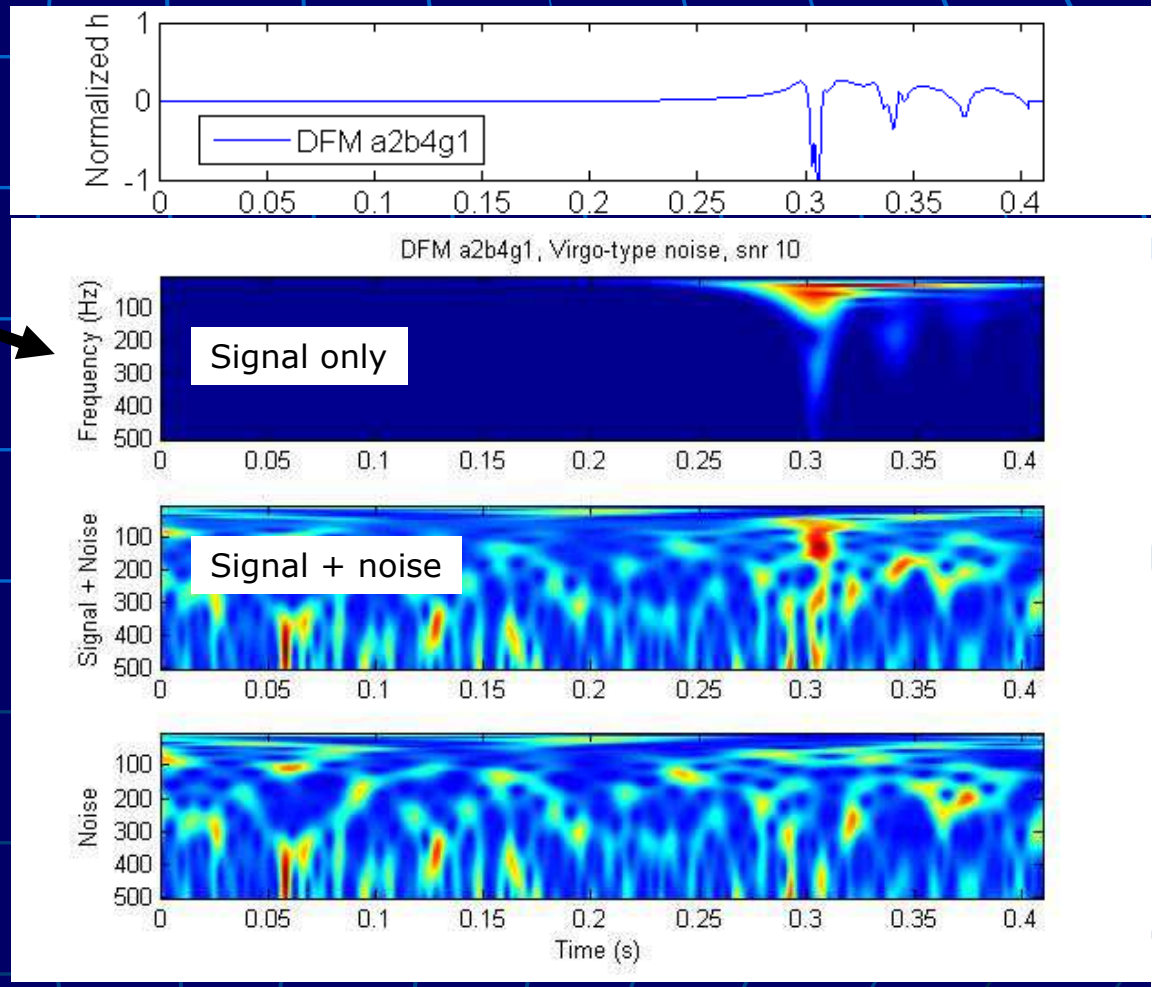
S-transform

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

Q- pipeline

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

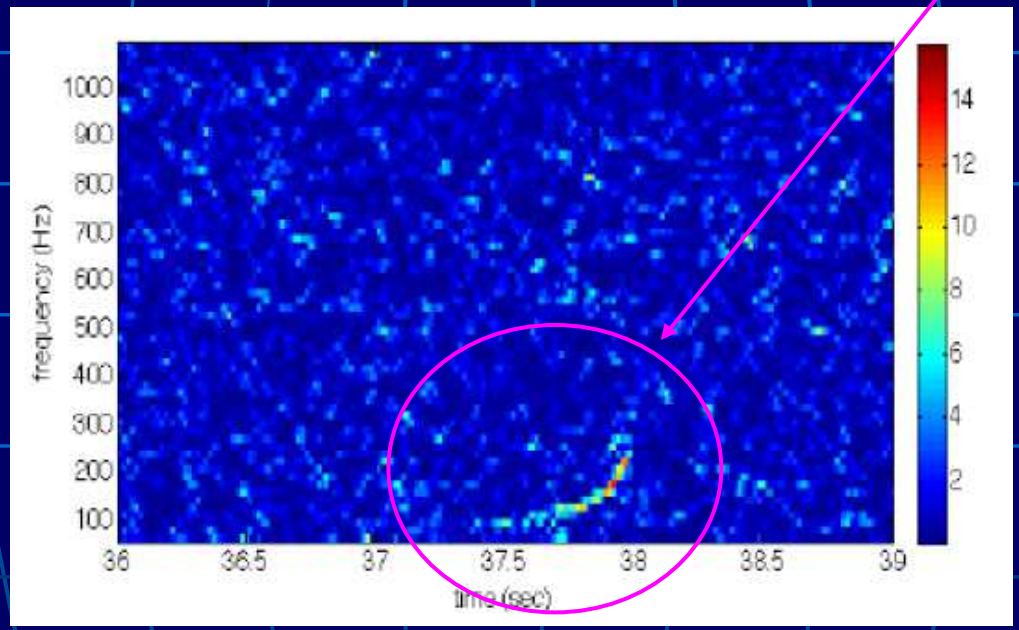
Etc…



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 can not 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

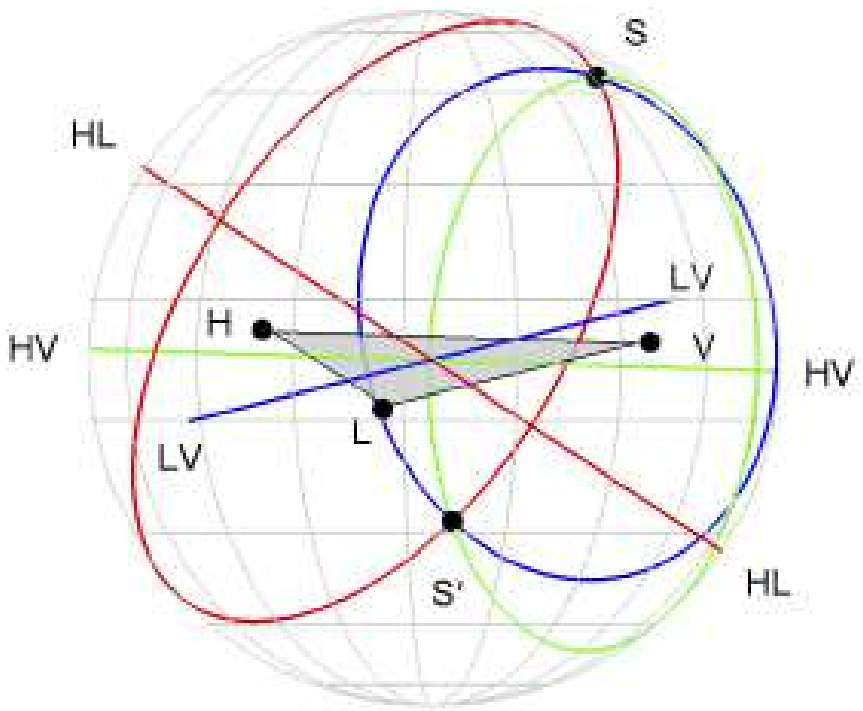
Light time of flight : HL ~ 10 msec., VL ~ 26 msec. and VH ~ 27 msec.

Times delays set the Source Reconstruction Accuracy:

Minimal angular resolution ~ 1°

(could be much worse)

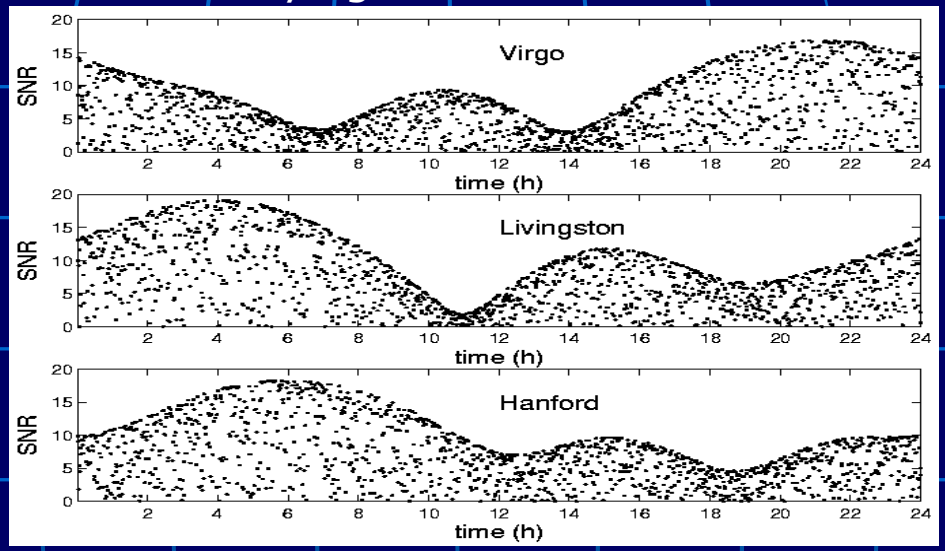
Network data analysis
Source location reconstruction



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 :

Bursts	H	L	V	HLV	HL	HV	LV	HL ∪ HV ∪ LV
False alarm rate (*Hz*)	0.1			10^{-6}	10^{-6}			$\sim 3.10^{-6}$
Efficiency (%)	63	60	55	19	**41**	22	22	**60**

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
$\Rightarrow$ 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)
$\Rightarrow$ 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 !

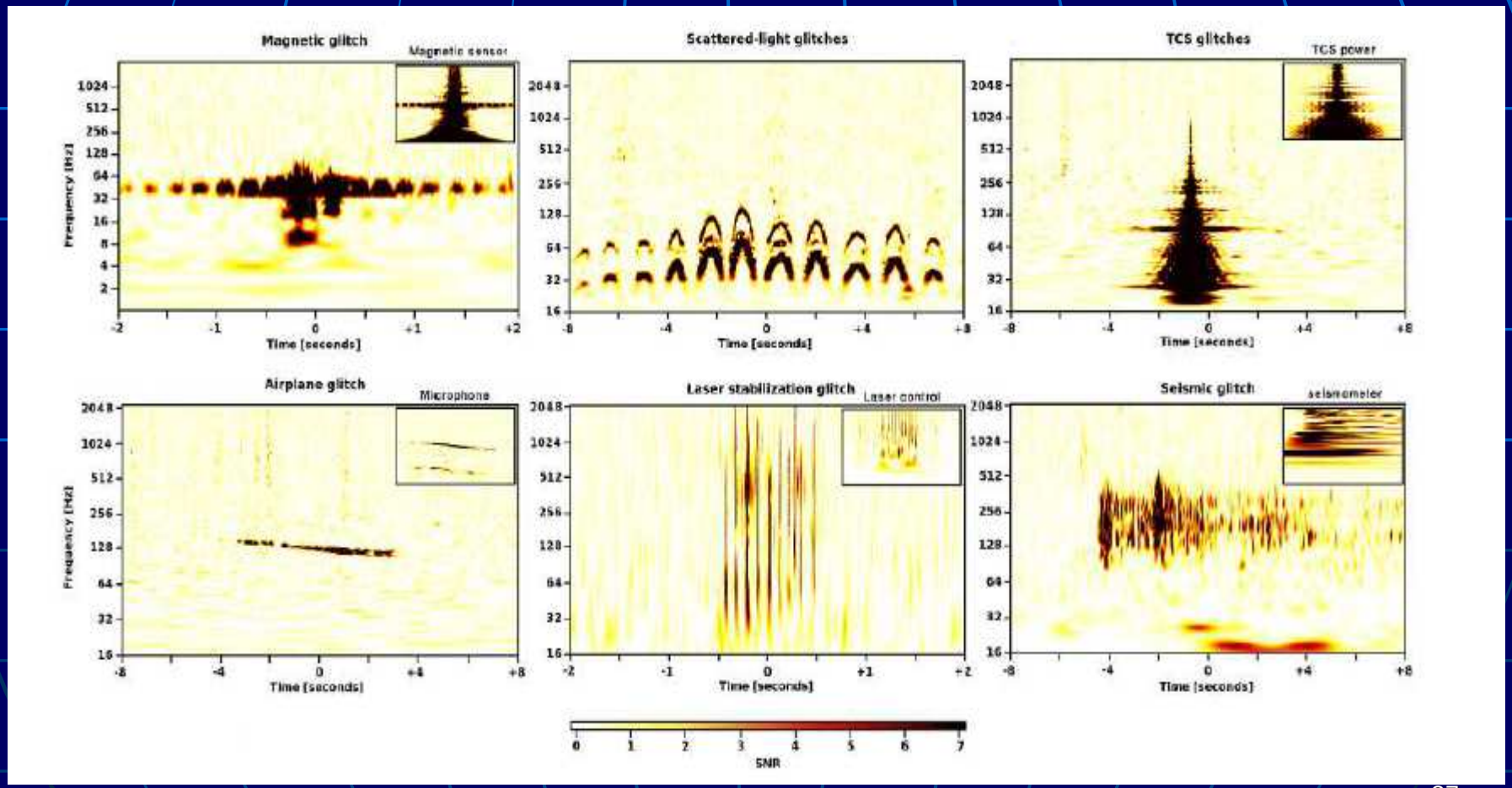
First step is to clean the data stream from identified artifacts or suspicious events.

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

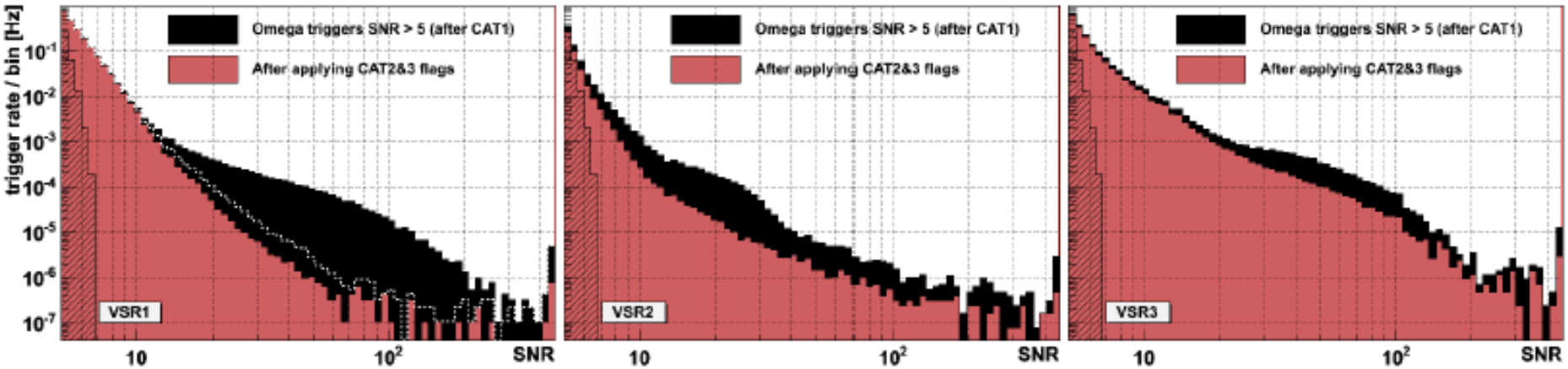
Real data analysis
Data Quality Studies

Hierarchy of Data Quality Flags (typically 3 categories):

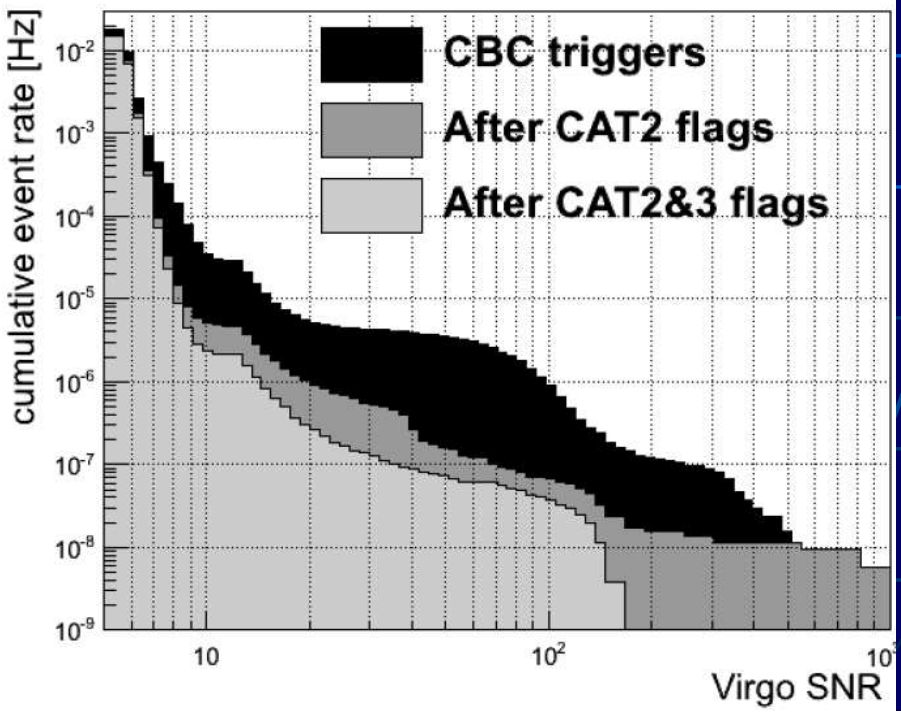
Category	Definition	Prescription for analyses
CAT1	Flags obvious and severe malfunctions of the detector.	Science data are re-defined when removing CAT1 segments.
CAT2	Flags noisy periods where the coupling between the noise source and the DF is well-established.	Triggers can be automatically removed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

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

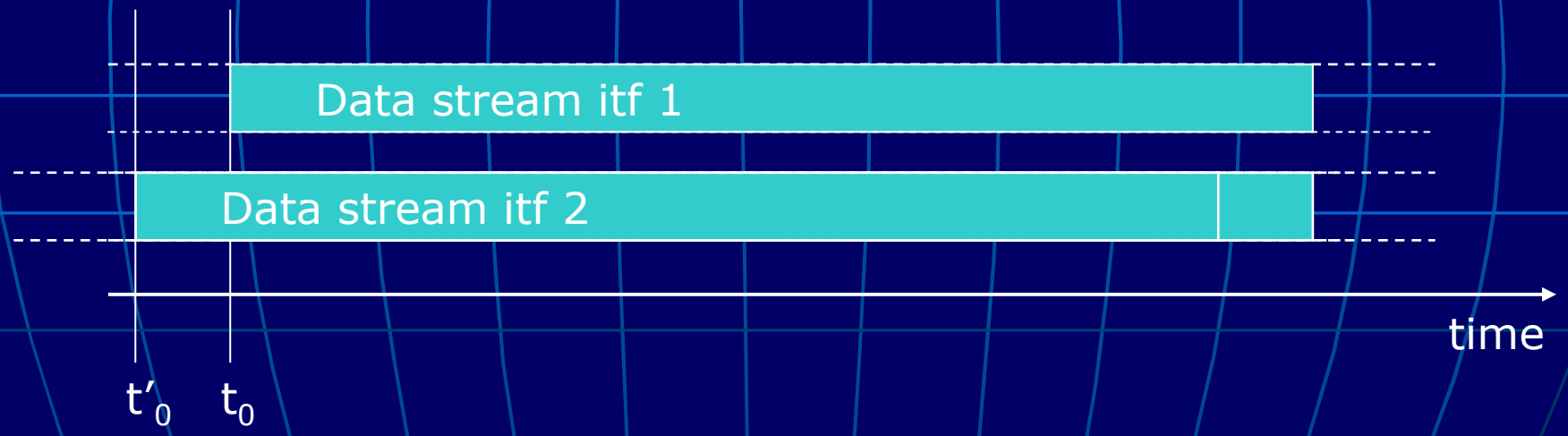
Real data analysis

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 powerfull method to estimate background in a coincidence experiment (e.g. GW events in 2 itfs)



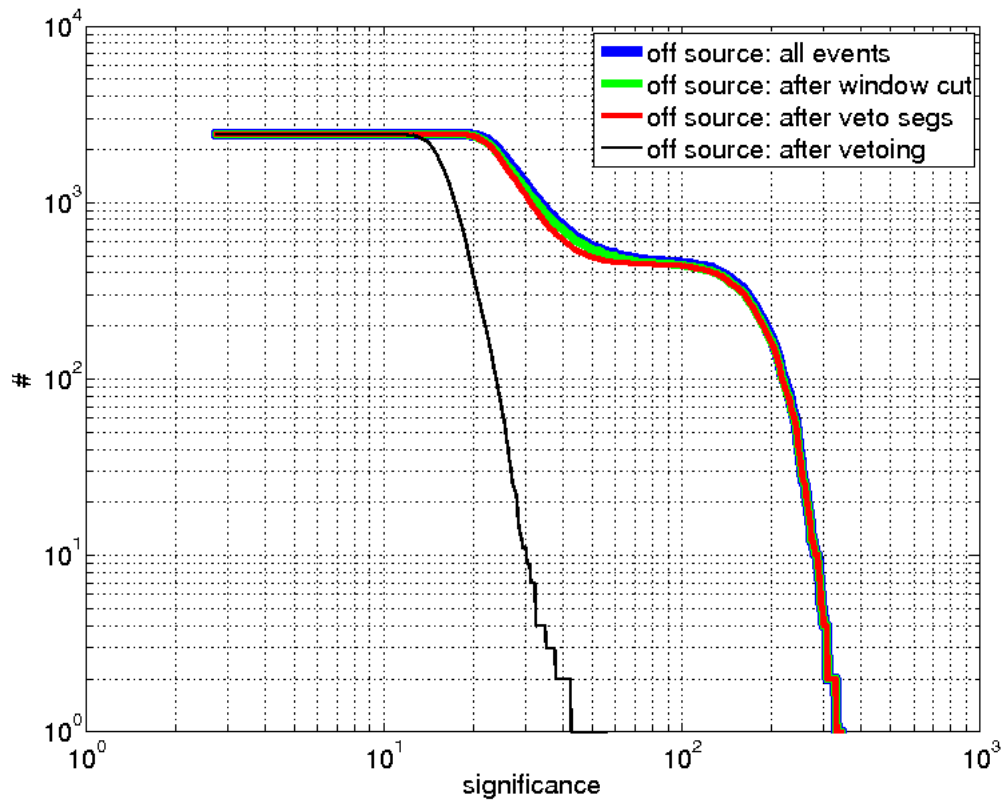
By time-shifting 2 data streams we have a new coincidence experiment

Real data analysis
Background estimation and significance

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

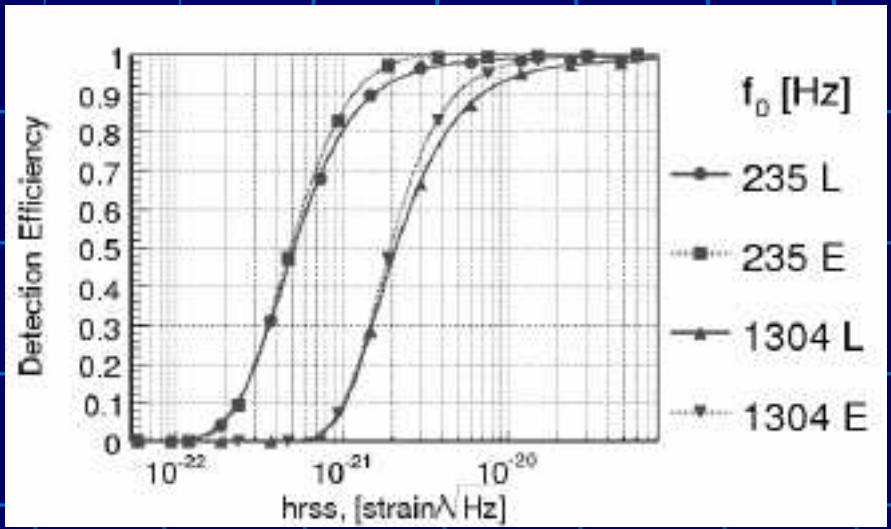
Time shifts must be
- larger than time delays between itfs
- larger then signal durations
- but not too large to avoid l

Finally distribution of time shi
-> estimation of the analysis



Real data analysis
Sensitivity estimation

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

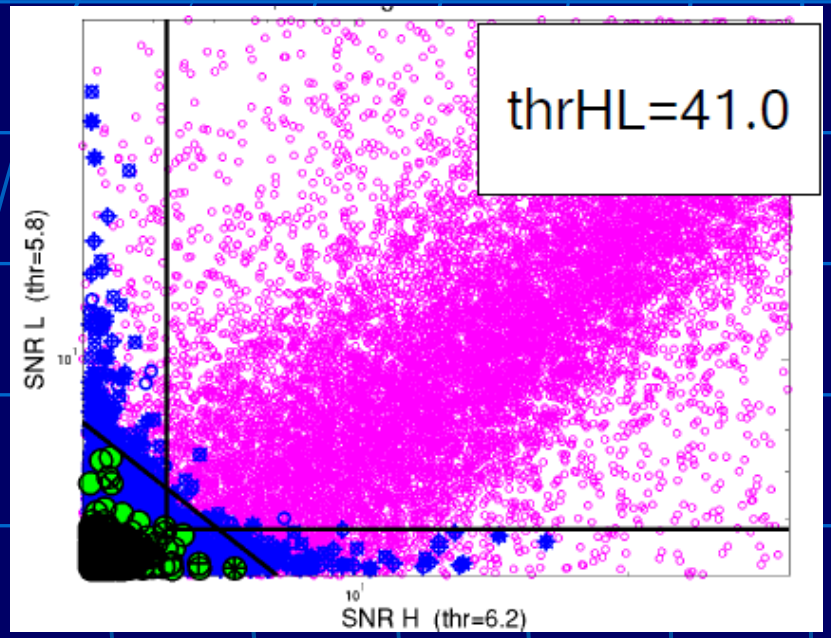


$$h_{rss} = \sqrt{\int_{-\infty}^{+\infty} h^2(t)dt}$$

Detection effiency 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 ~ coincident with the bounce

Neutrino flash delayed by $\Delta t_{\nu\text{flash-GW}}$ ~ 3.5 +/- 0.5 ms

+ delay due to propagation of massive neutrino:

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

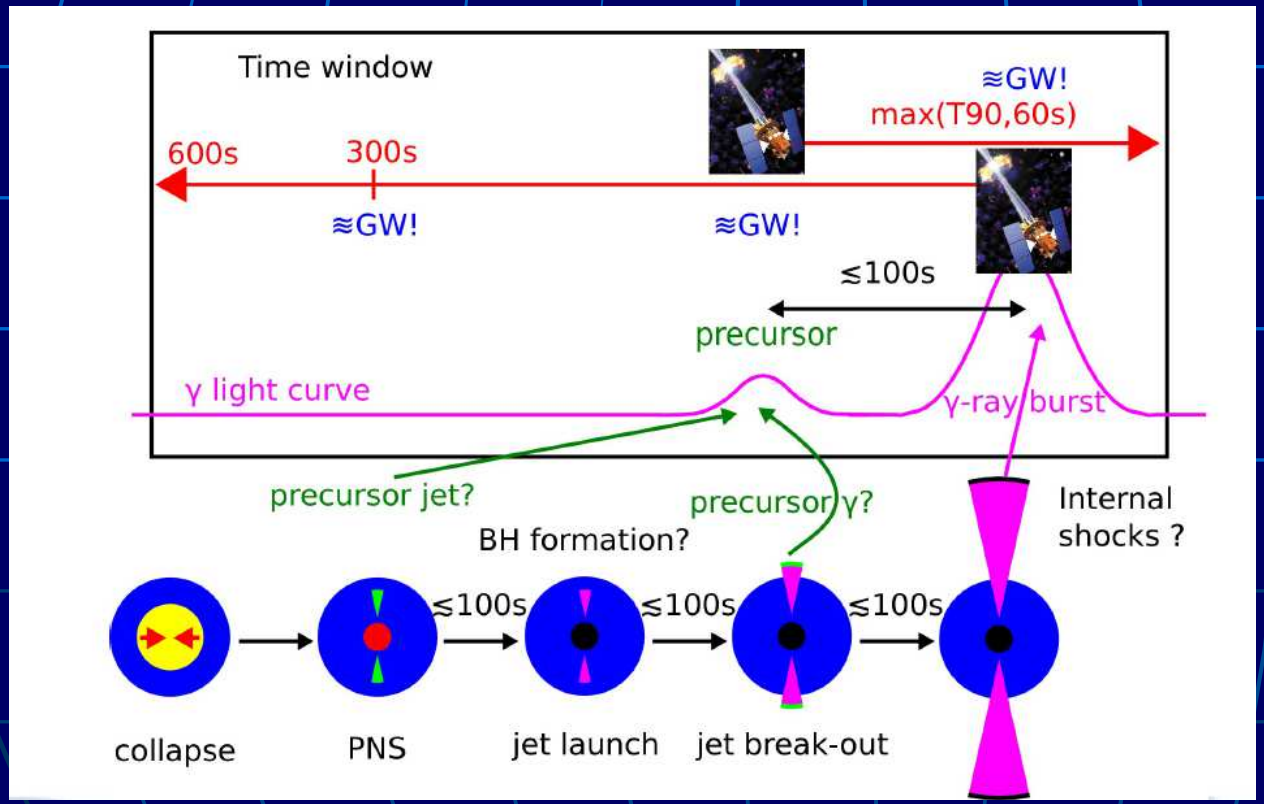
$\Rightarrow$ GW and neutrinos detected within 10ms (add safety factor and detector systematic errors)

- 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)

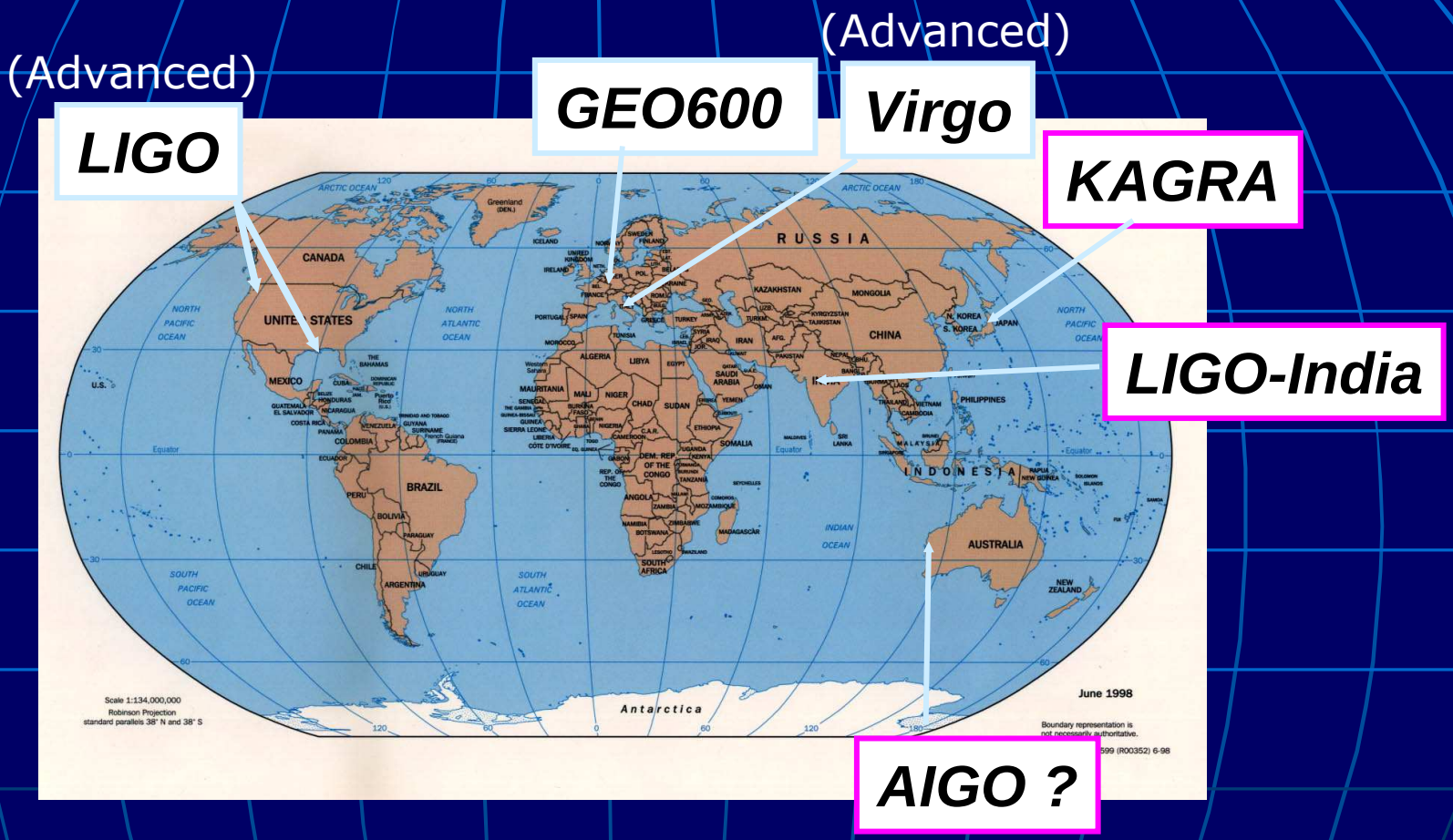


Analysis window
~10 minutes
fits astrophys. scenario

The LIGO-Virgo network

(Today and tomorrow)

The GW detectors (near-future) world



The worldwide collaboration

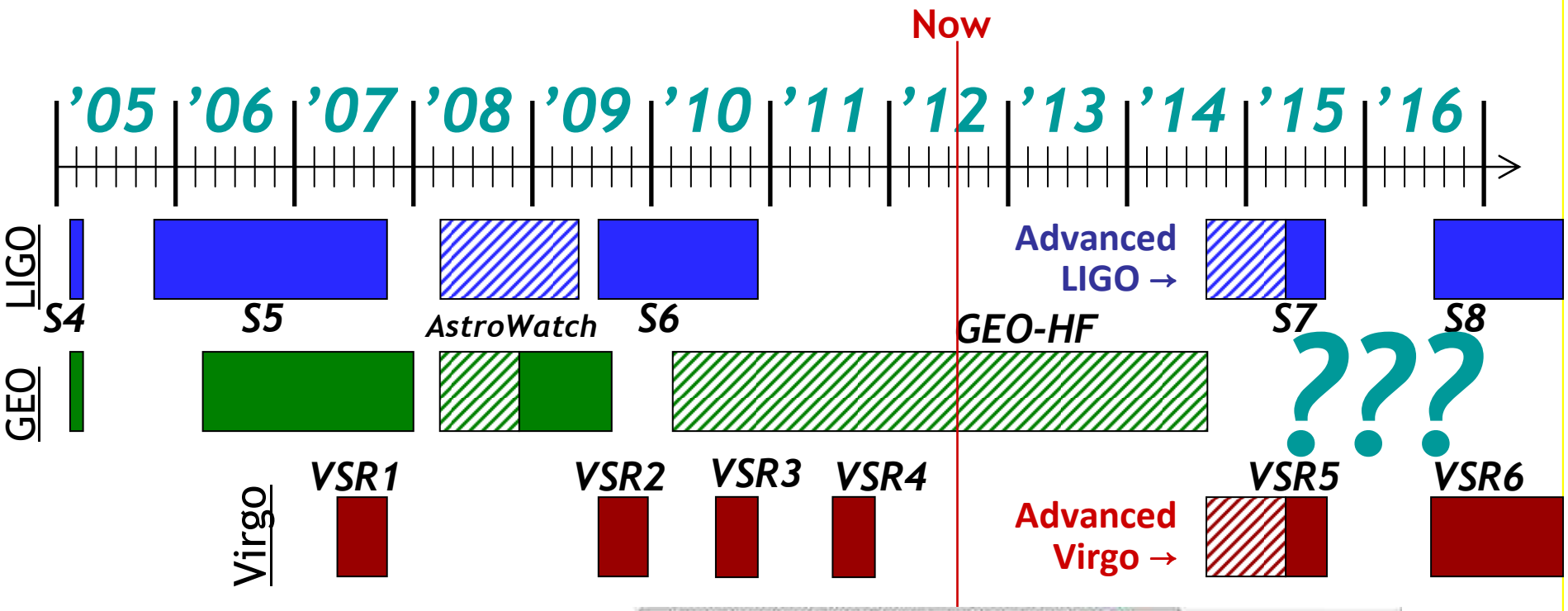
LIGO + LIGO Science Community (aggregate GEO600)
and Virgo
have joined their forces in 2007

- 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

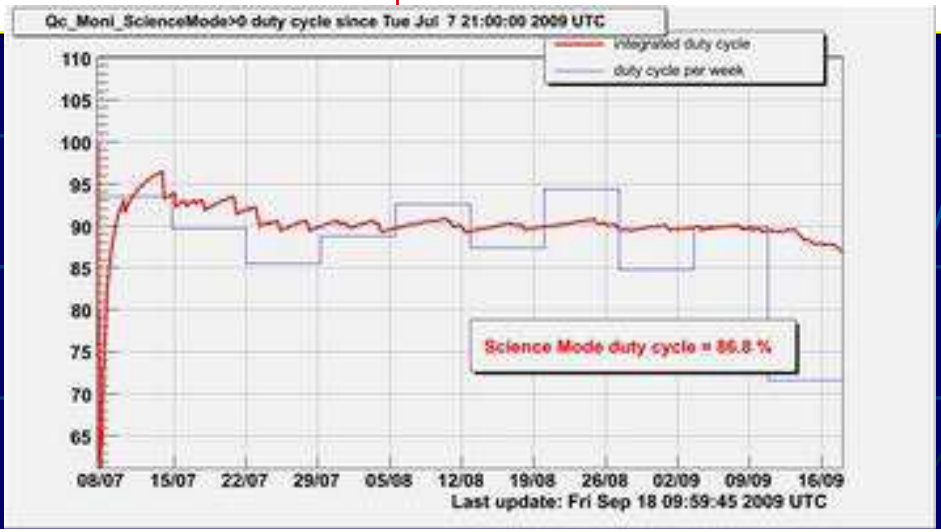
Agreement renewed last year (2011) -> cover the Advanced detectors area (data taking to re-start end of 2014)

+ Ongoing discussions with Japan (KAGRA collaboration)

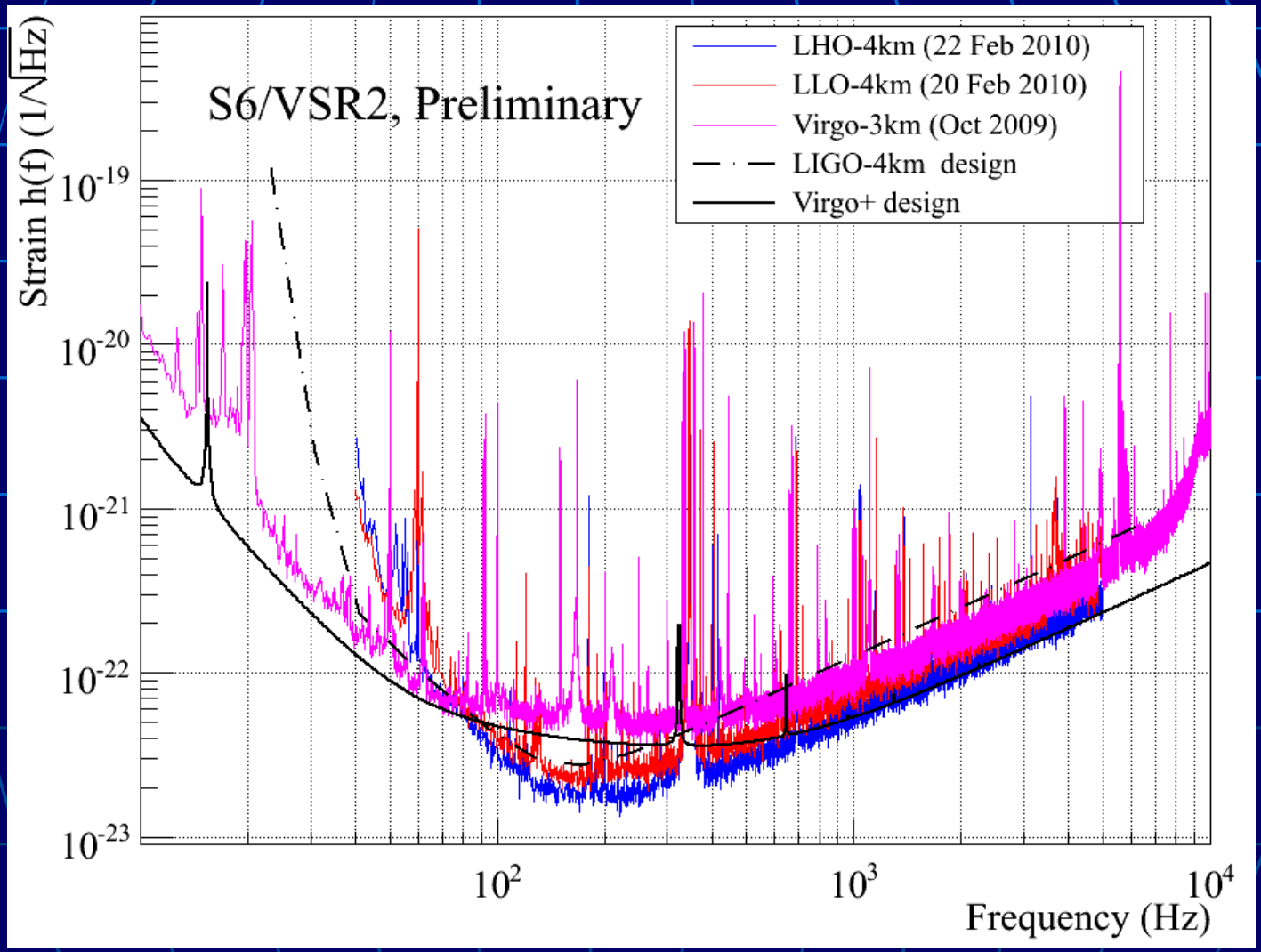
LIGO-Virgo joint data takings



Virgo duty cycle ~90%



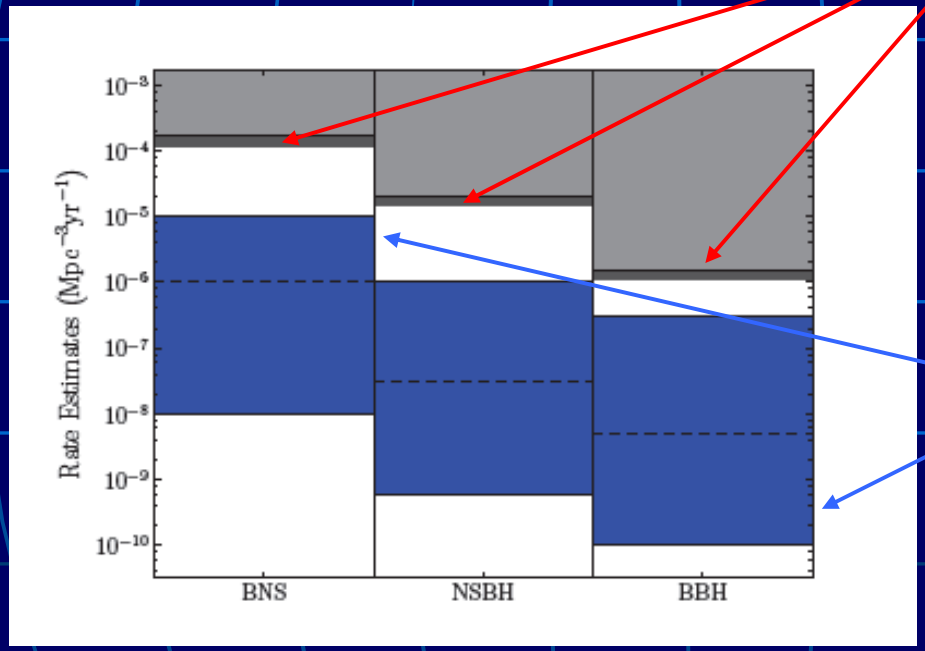
The LIGO-Virgo network
Compared sensitivities



The LIGO-Virgo network
A selection of scientific results

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

Best UL's



Range of astrophysical predictions

LIGO&Virgo coll., Phys.Rev.D **85**:082002 (2012)

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)

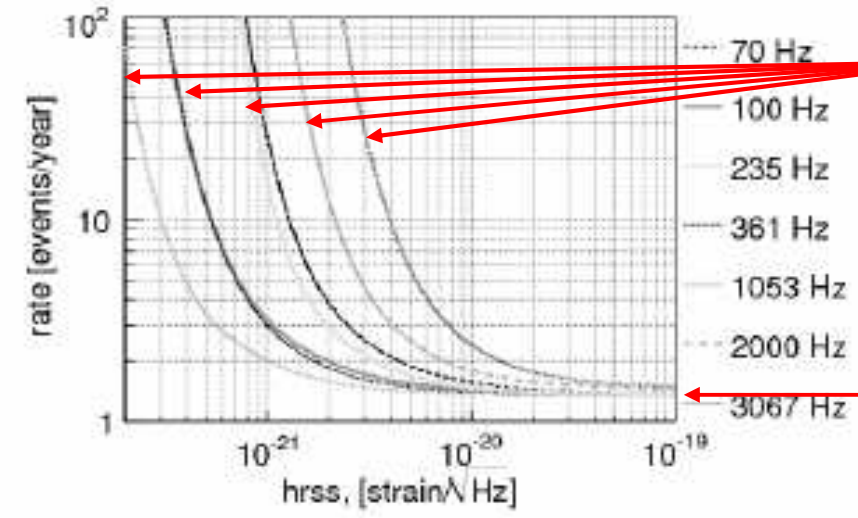


FIG. 5: Upper limits at 90% confidence on the rate of gravitational-wave bursts at Earth as a function of h_{rss} signal amplitude for selected sine-Gaussian waveforms with $Q = 9$. The results include all the LIGO and LIGO–Virgo observations since November 2005.

Search sensitivity at these frequencies

Limit due to finite observation time

LIGO&Virgo coll., arXiv1202.2788 [gr-qc] (2012)

The LIGO-Virgo network
A selection of scientific results

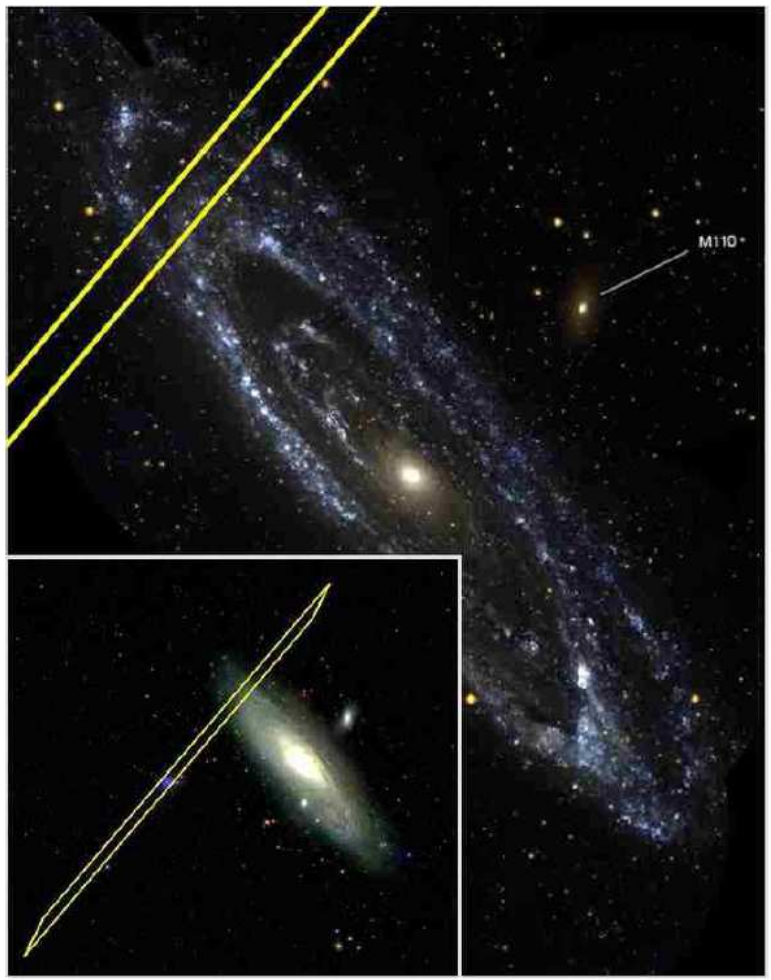


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

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)

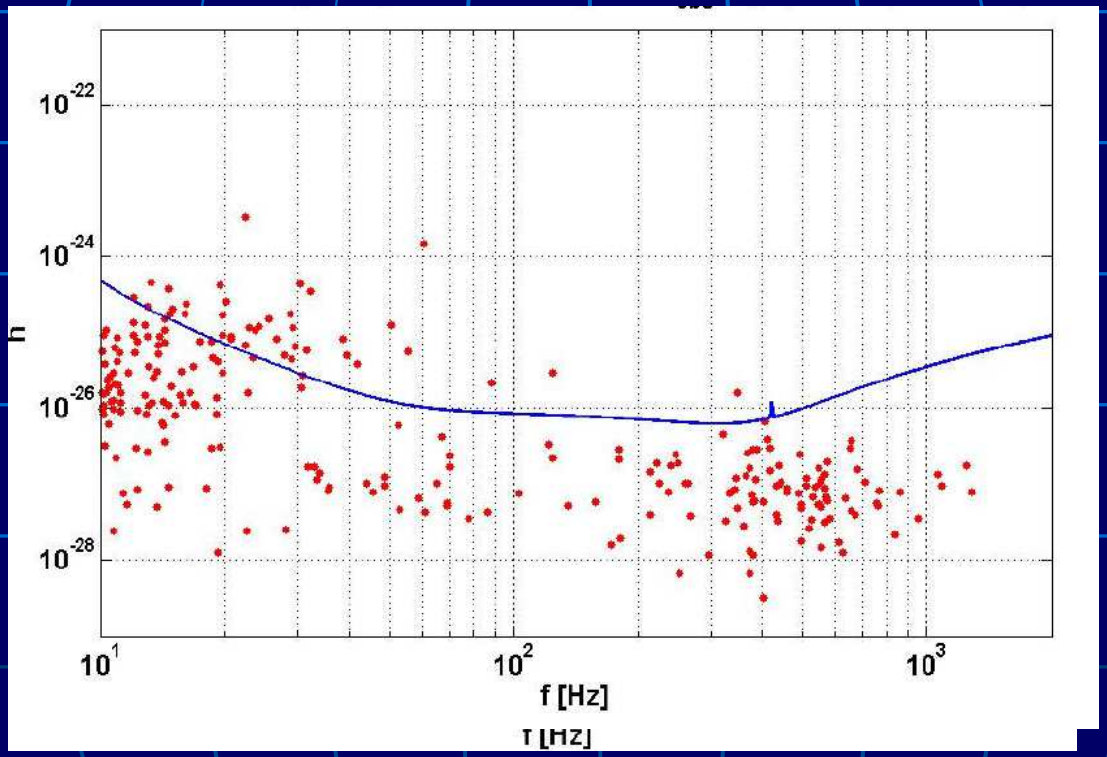
SGR scenario not excluded by GW Search.

Astrophys.J.**681**:1419-1428 (2008)

The LIGO-Virgo network
A selection of scientific results

Search for continuous GWs (pulsars)

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



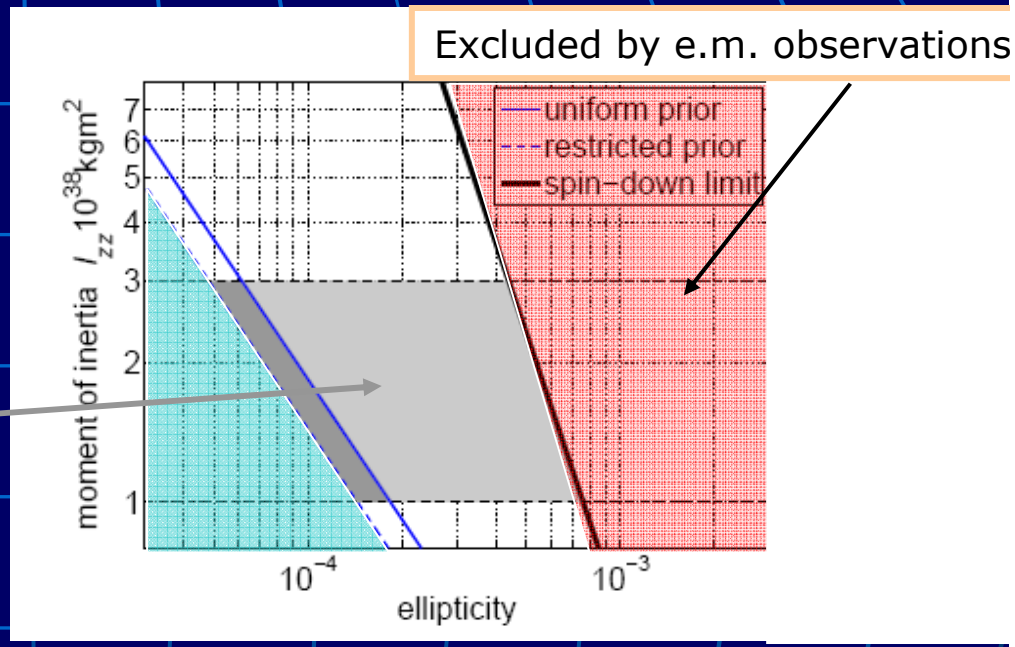
Advanced-

Virgo sensitivity

The LIGO-Virgo network
A selection of scientific results

Results for the Crab pulsar(30Hz):
h_0~3.4x10^{-25}
(4xbelow the spin-down limit)

Excluded by GW searches



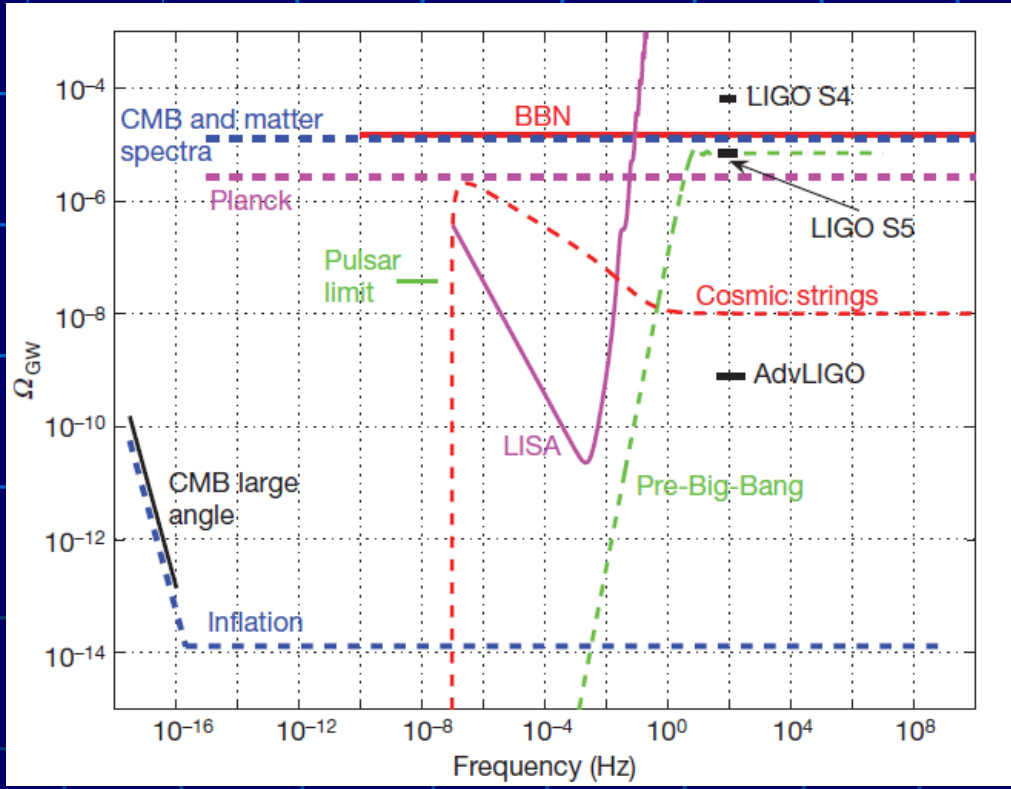
LIGO coll., Astrophys.J.**683**:L45-L50 (2011)

Results for Vela (11Hz): ***h_0~2x10^{-24}*** (1.7x below the spin-down limit)

(LIGO&Virgo coll., Astrophys.J.**737**:93 (2011))

The LIGO-Virgo network
A selection of scientific results

Search for cosmological background(s)



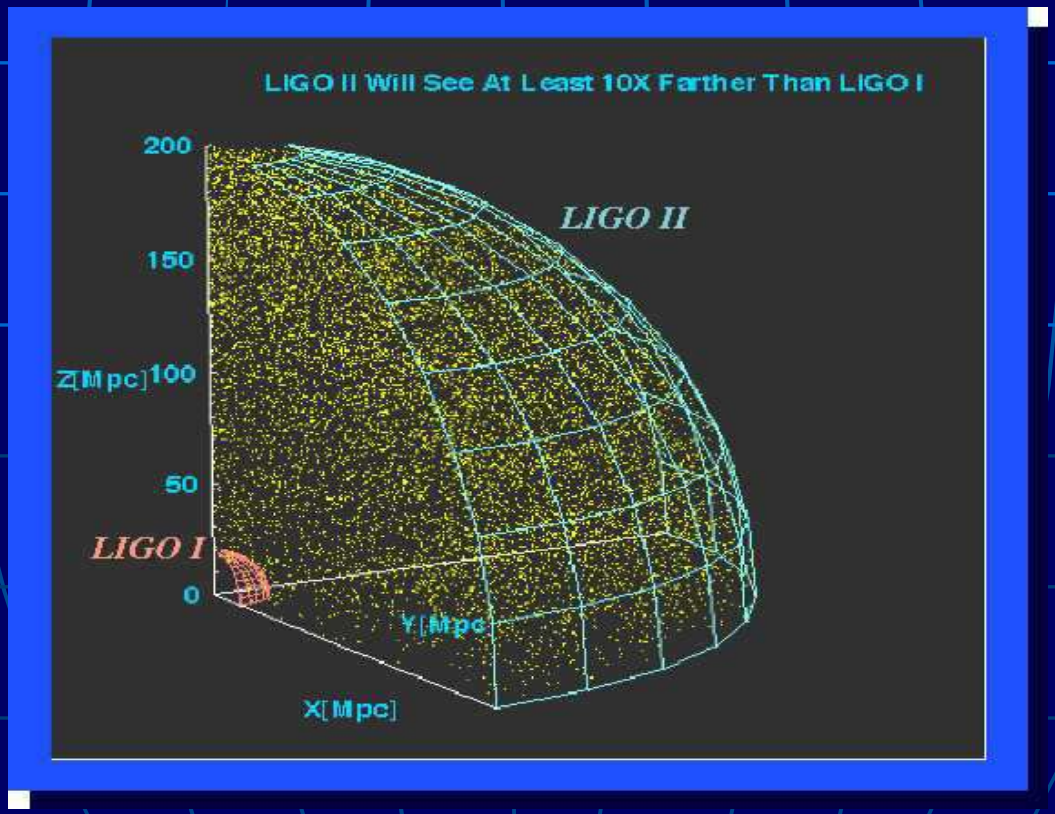
LIGO&Virgo coll., Nature **460**-994 (2009)

The LIGO-Virgo (and others) network
The Future

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

- Advanced detectors (improvement of sensitivity by factor 10)

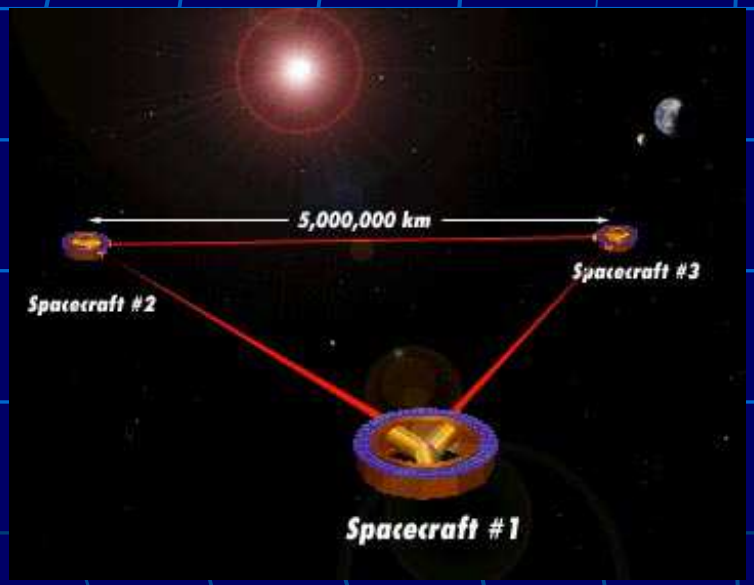
$\Rightarrow$ Detection of binary inspirals guaranteed ! **(event rate > 1/yr)**

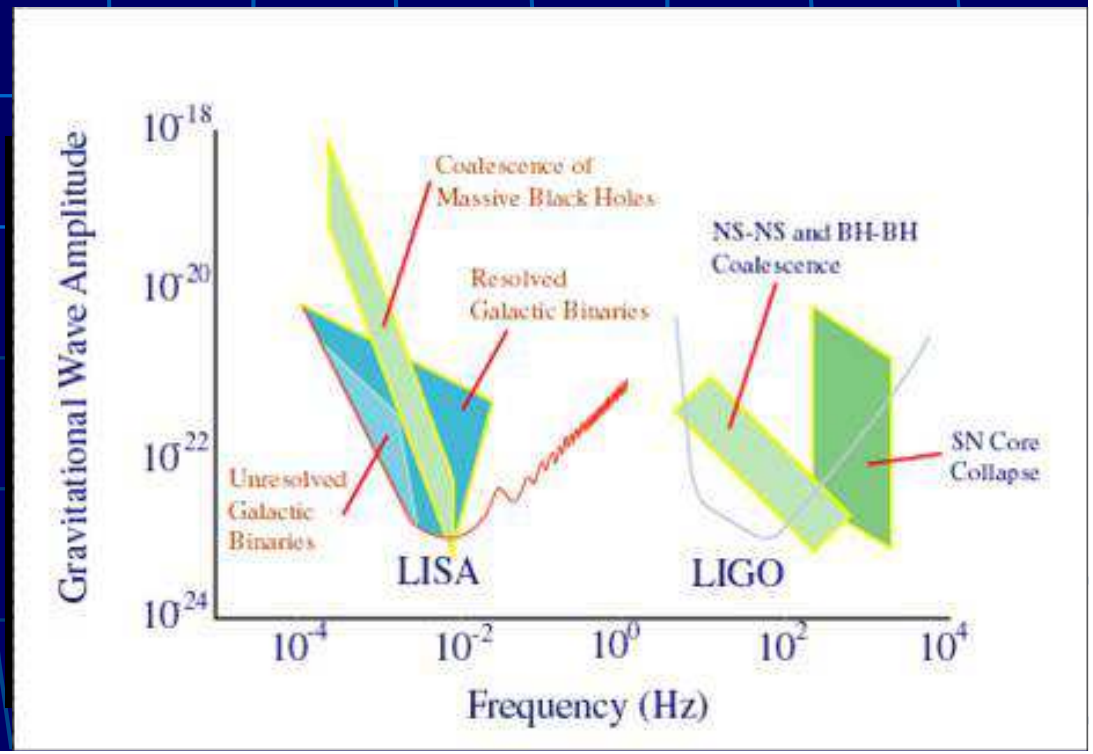


The next decade

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)

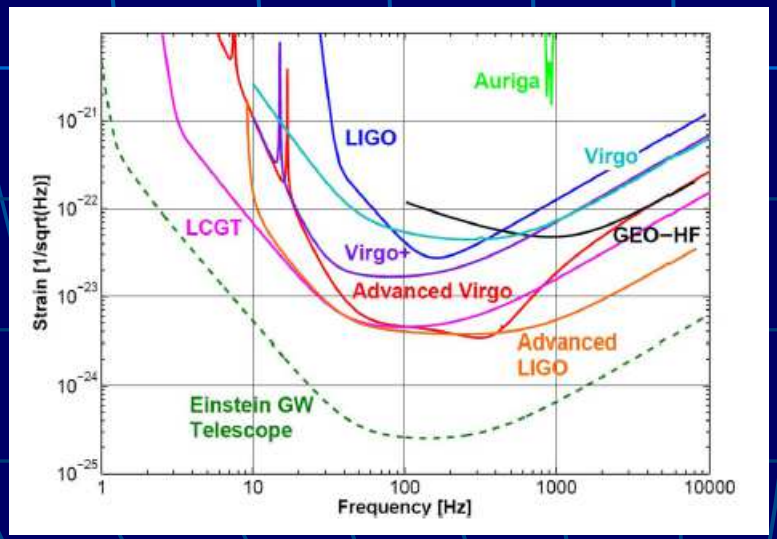
Cryogenic interferometric detectors

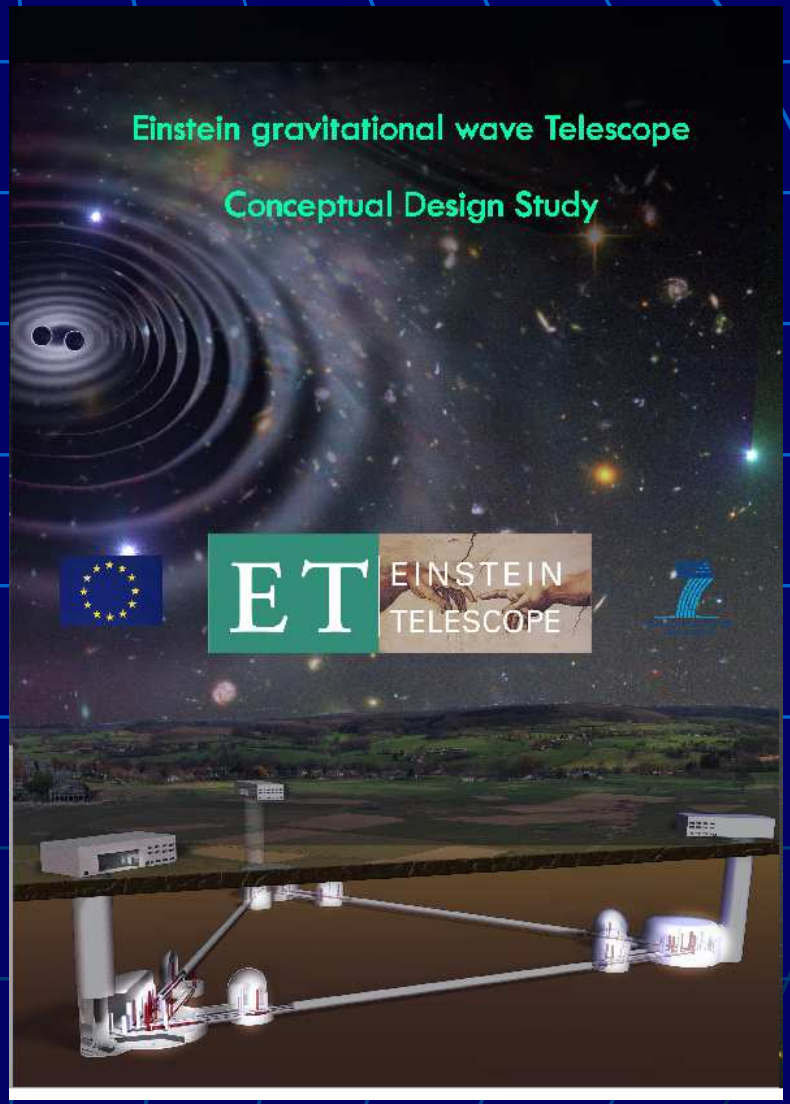
Underground detectors

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/

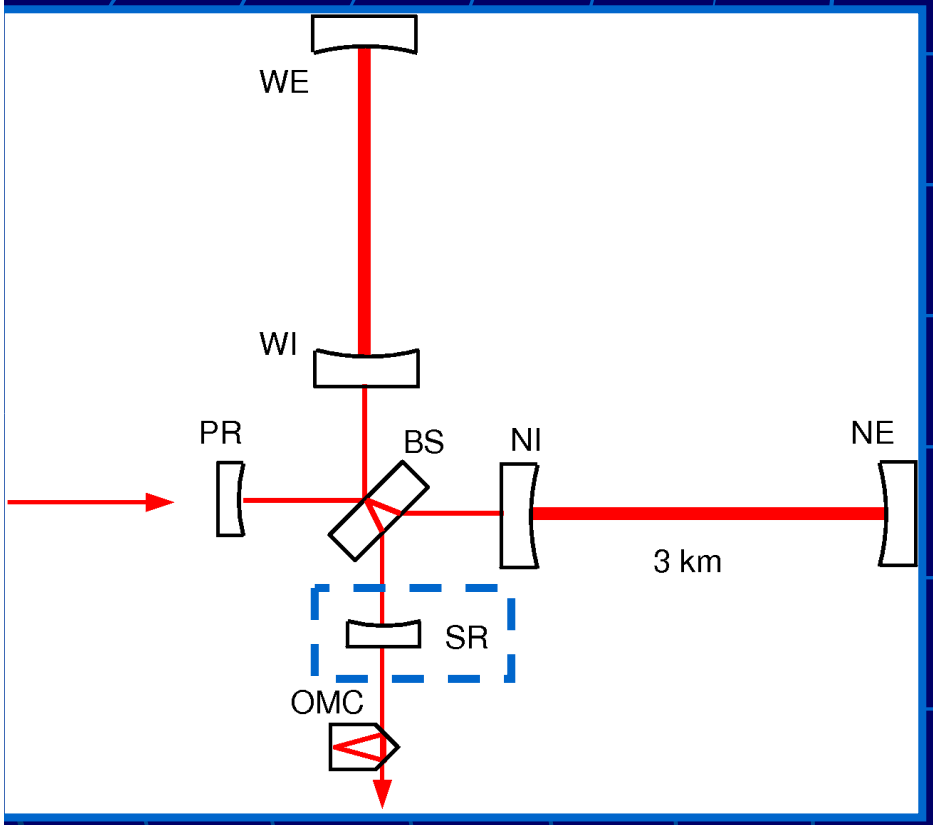
http://www.einsteinathome.org/ Help the GW community in pulsar detection !

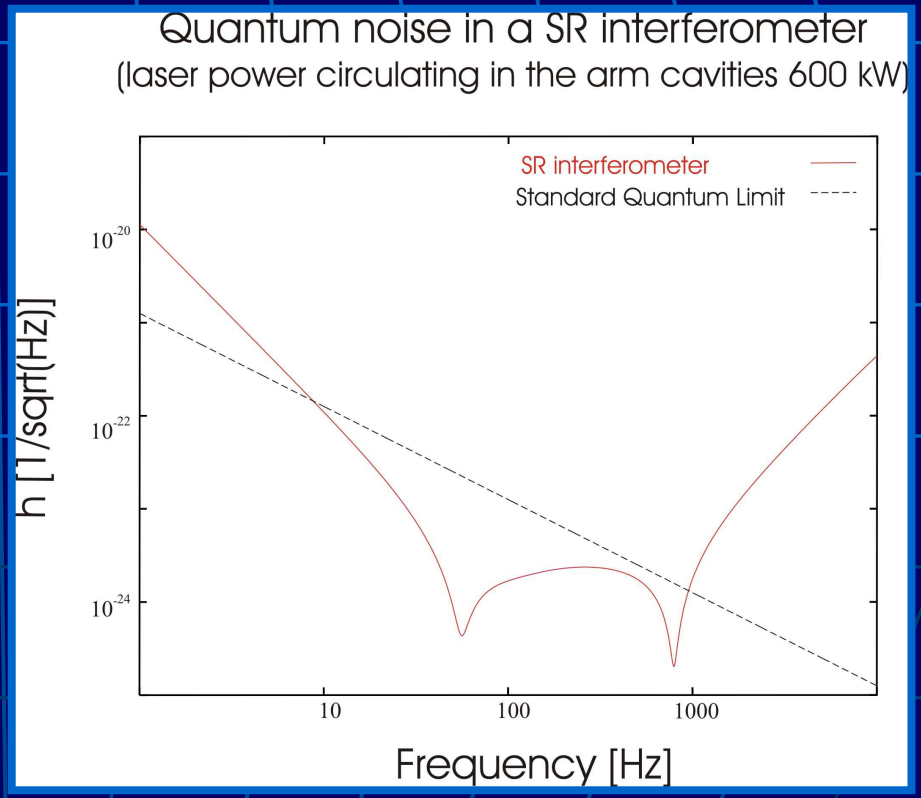
Peter Saulson,
"Fundamentals of interferometric gravitational wave detectors",
World Scientific, 1994.

J.D.E. Creighton, W.G. Anderson,
"Gravitational-Wave Physics and Astronomy",
Wiley series in Cosmology, 2011.

Signal recycling configuration

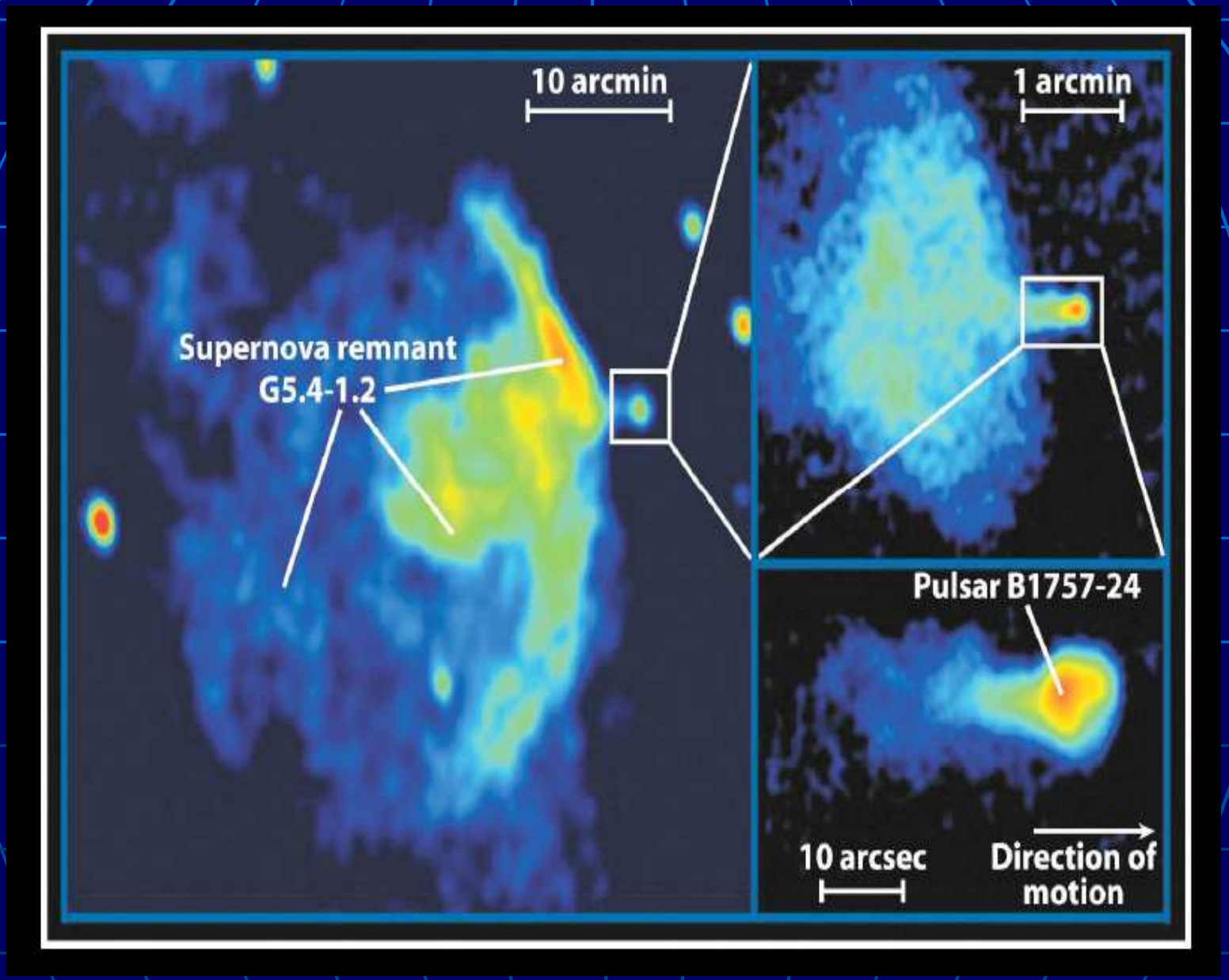
(Advanced LIGO and Advanced Virgo)





Advantages:

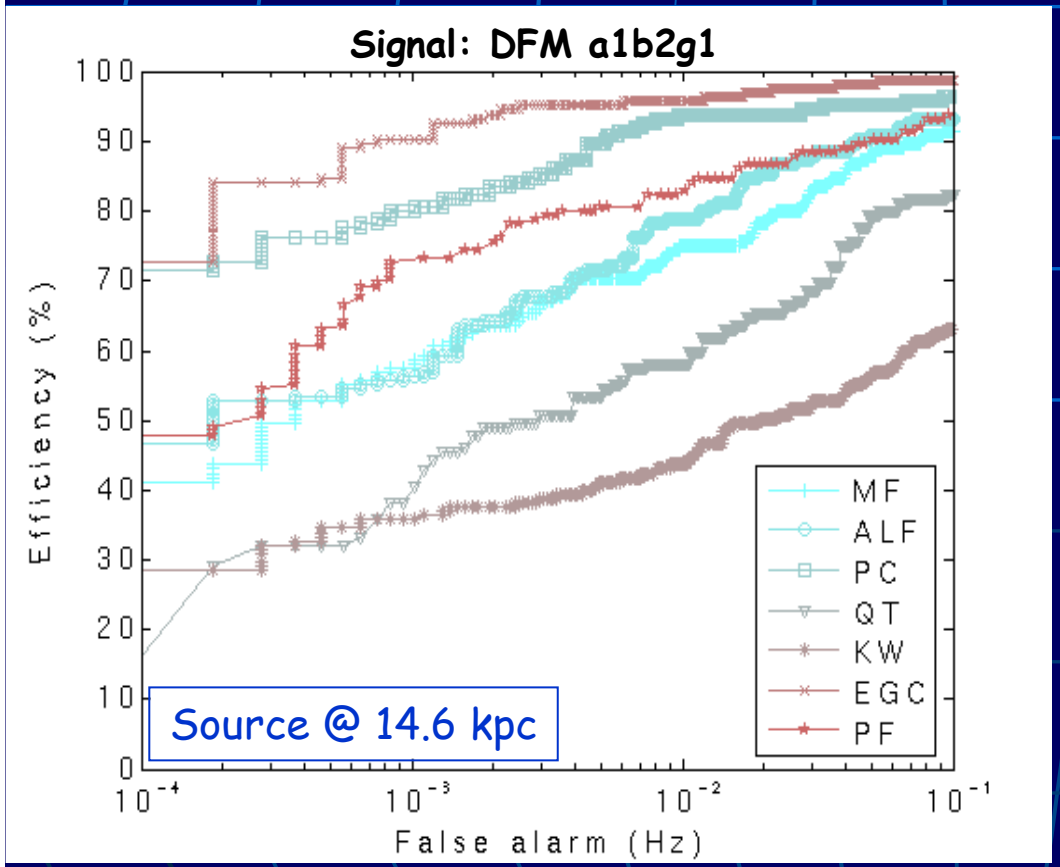
- **Beat the SQL in some band**
- **Can tailor the frequency response**


10 arcmin
1 arcmin
Supernova remnant
G5.4-1.2
Pulsar B1757-24
10 arcsec
Direction of
motion

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"