Gravitational waves

Theory, detection principles and VIRGO

Damir Buskulic, LAPP/Université de Savoie
School of theoretical physics, July 2013

Context

- Linearized gravity
- Gravitational waves
- Generation of gravitational waves
- Scientific goals

The full calculations can be found, for example, in :

"General Relativity", R.M. Wald, The University of Chicago Press
"General Relativity", M.P. Hobson, G. Efstathiou and N. Lasenby Cambridge University Press

Linearized gravity

- General Relativity (Einstein, 1916)
- Minkowski flat space-time with a small perturbation of the metric

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

- where (Minkowski flat space-time metric) :

$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- and $h_{\mu\nu} \ll 1$ is a perturbation of this metric
- then...

Linearized gravity

- start from the Einstein equations

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

- After
  - linearization of the connexions
    - replace $g_{\mu\nu}$ by $\eta_{\mu\nu} + h_{\mu\nu}$
    - remove the higher order terms in $h_{\mu\nu}$
  - linearization of the Riemann tensor
- One obtains the equivalent equation :

$$\Box \bar{h}_{\mu\nu} + \eta_{\mu\nu} \partial_\rho \partial_\sigma \bar{h}^{\rho\sigma} - \partial_\nu \partial_\rho \bar{h}^\rho_\mu - \partial_\mu \partial_\rho \bar{h}^\rho_\nu = -2 \frac{8\pi G}{c^4} T_{\mu\nu}$$

where the trace reverse is defined as : $\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} h$

Linearized gravity

- Further simplification in the harmonic gauge (or Lorentz gauge)
- For an infinitesimal coordinate transformation :

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

$h_{\mu\nu}$ transforms like : $h'_{\mu\nu} = h_{\mu\nu} - \partial_\mu \xi_\nu - \partial_\nu \xi_\mu$

- Choose the functions $\xi^{\mu}(x)$ such that (gauge conditions)

$$\partial_\mu \bar{h}^{\mu\nu} = 0$$

- The field equations may be written as :

$$\Box \bar{h}^{\mu\nu} = -2 \frac{8\pi G}{c^4} T^{\mu\nu}$$

Gravitational waves

- In vacuum ($T_{\mu\nu} = 0$), the Einstein field equations are equivalent to a wave equation :

$$\Box\, \bar{h}_{\mu\nu} = 0 \quad \Leftrightarrow \quad \{\frac{\partial^2}{\partial t^2} - \nabla^2\}\bar{h}_{\mu\nu} = 0$$

with a gauge condition : $\partial_\mu \bar{h}^{\mu\nu} = 0$

- where c = 1 and a harmonic gauge choice

- in the following, consider solutions

$$\bar{h}_{\mu\nu} = Re\,\{A_{\mu\nu} \exp\left(-ik_\rho x^\rho\right)\}$$

Gravitational waves

- Constraints
  - Satisfying the wave equation $\Box\, \bar{h}_{\mu\nu} = 0$:

$$k_\rho k^\rho = 0$$

$$\Rightarrow \quad \omega^2 = c^2 |\vec{k}|^2 \quad \Longrightarrow$$ the wave propagates at the speed of light c

  - Use the gauge conditions $\partial_\mu \bar{h}^{\mu\nu} = 0$:

$$k_\rho A^{\rho\sigma} = 0$$

$\Longrightarrow$ 6 remaining independent elements in the amplitude tensor

Gravitational waves

- Can still simplify the expression of the amplitude
- Choice of a particular harmonic gauge s.t.

$$A_{0\sigma} = 0 \qquad \Rightarrow \text{ number of independent elements further reduced to 2}$$

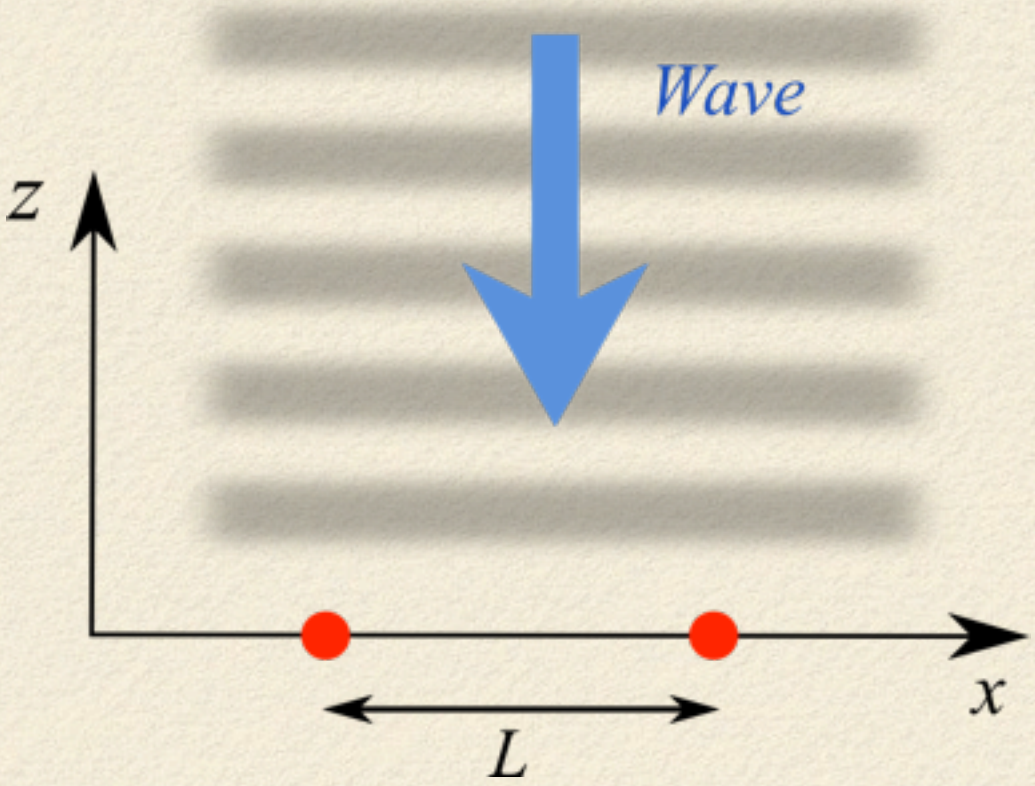
- for a wave traveling along the z axis, the amplitude is then :

$$A_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & A_{11} & A_{12} & 0 \\ 0 & A_{12} & -A_{11} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- choice $A_{11} = 1, \; A_{12} = 0$, polarization called "+"
- choice $A_{11} = 0, \; A_{12} = 1$, polarization called "x"
- This particular gauge is called Transverse Traceless (TT)

Gravitational waves

- Proper length between two test masses in free fall



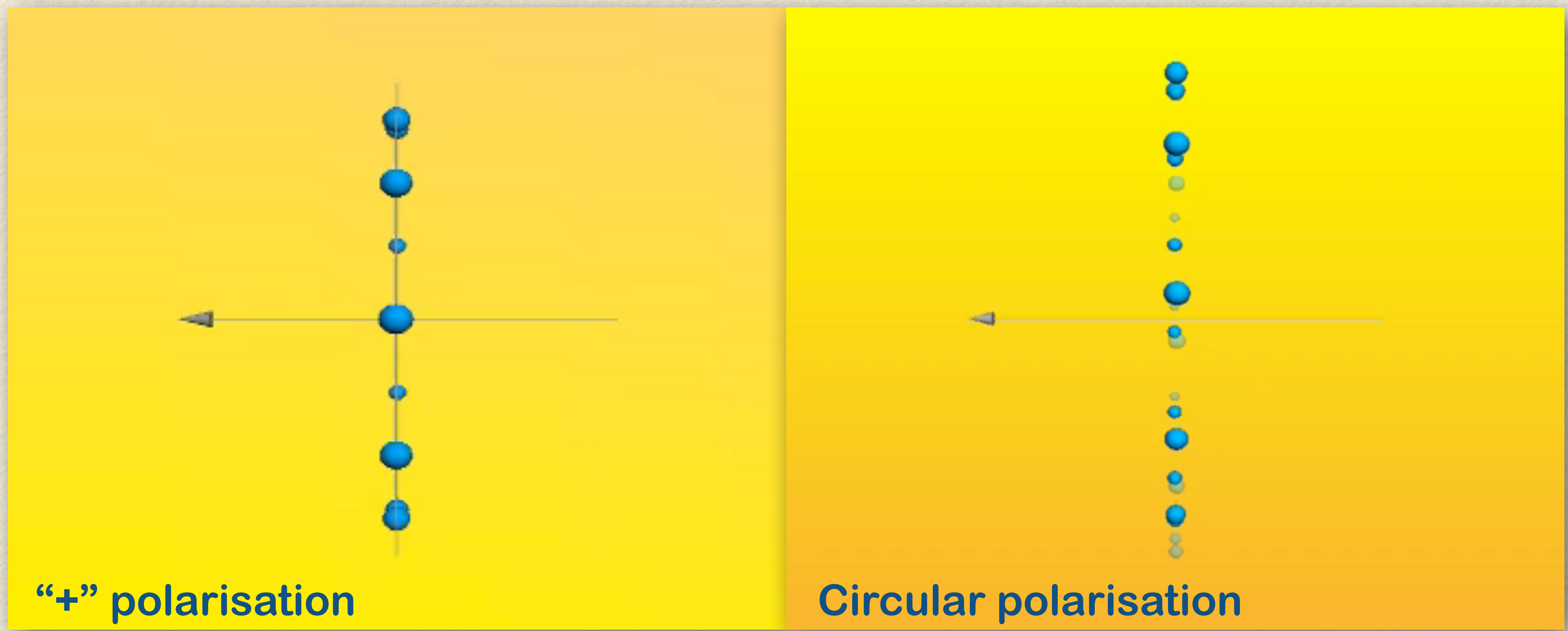
$$L = \int_0^{\Delta x} dx \sqrt{-g_{xx}} = \int_0^{\Delta x} dx \sqrt{1 - h_{xx}^{TT}(t, z=0)}$$

$$\approx \int_0^{\Delta x} dx \left[1 - \frac{1}{2} h_{xx}^{TT}(t, z=0)\right] = \Delta x \left[1 - \frac{1}{2} h_{xx}^{TT}(t, z=0)\right]$$

- h is the relative variation in proper length between the two test masses

Effect of the gravitational waves

- Effect of GW on matter
- Set of free test particles distributed on a circle
  illustration of the metric variation



Generation of GW

- Emission of the gravitational waves
  - Linearized Einstein equations with a stress-energy tensor

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

  - Use Green functions
    - Solutions of the wave equation in the presence of a point source
  - Retarded potential

$$\bar{h}_{\mu\nu}(t, \vec{x}) = -\frac{4G}{c^4} \int_{source} \frac{T_{\mu\nu}(t - \frac{|\vec{x} - \vec{x}'|}{c}, \vec{x}')}{|\vec{x} - \vec{x}'|} d^3x'$$

Generation of GW

- Approximations :
  - isolated source
  - compact source
  - observer far from the source (R >> typical size of the source)
- Amplitude of the wave written as a function of I_{ij}

$$\bar{h}_{ij}(t) = \frac{2G}{Rc^4}\frac{d^2 I_{ij}}{d\,t^2}\left(t - \frac{R}{c}\right)$$

I_{ij} = reduced quadrupolar moment of the source

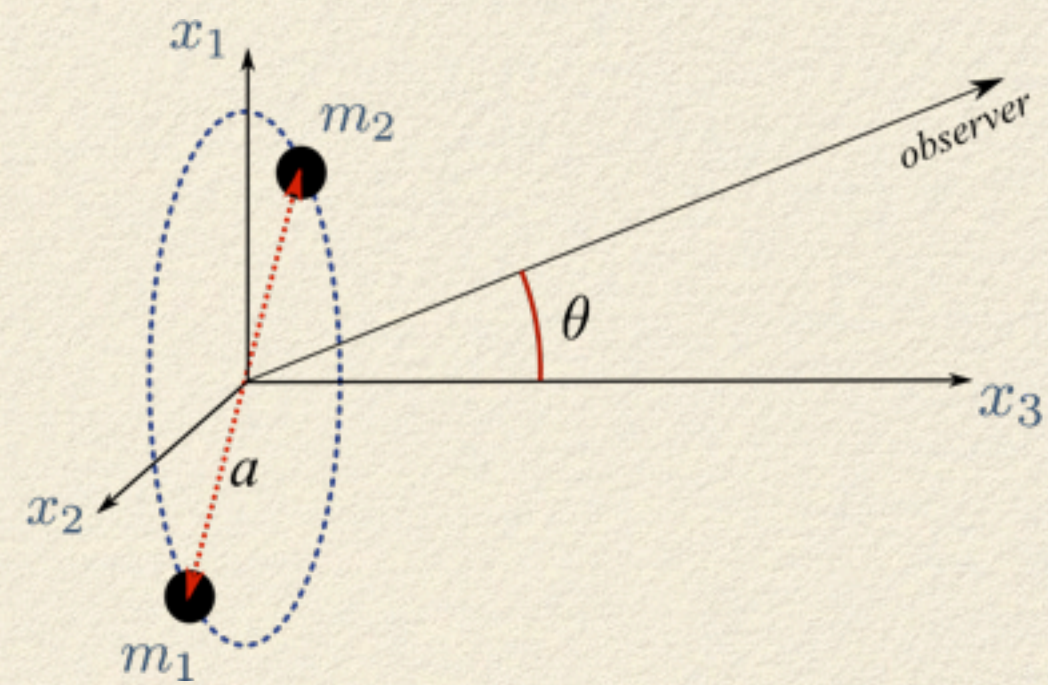
$$= \int_{source} d\vec{x}\; x_i x_j\; T_{00}(t, \vec{x})$$

- Remark :

  Need a quadrupolar moment to generate a GW, the dipolar case is impossible (because of momentum conservation).

Generation : binary system

- Example : binary system of two compact objects
  - Masses m_1 and m_2
  - Distance between the objects : a
  - Total mass : $M = m_1 + m_2$
  - Reduced mass : $\mu = \dfrac{m_1 m_2}{M}$
- Newtonian approximation
  - 3[d] Kepler law : $\omega = \sqrt{\dfrac{GM}{a^3}}$



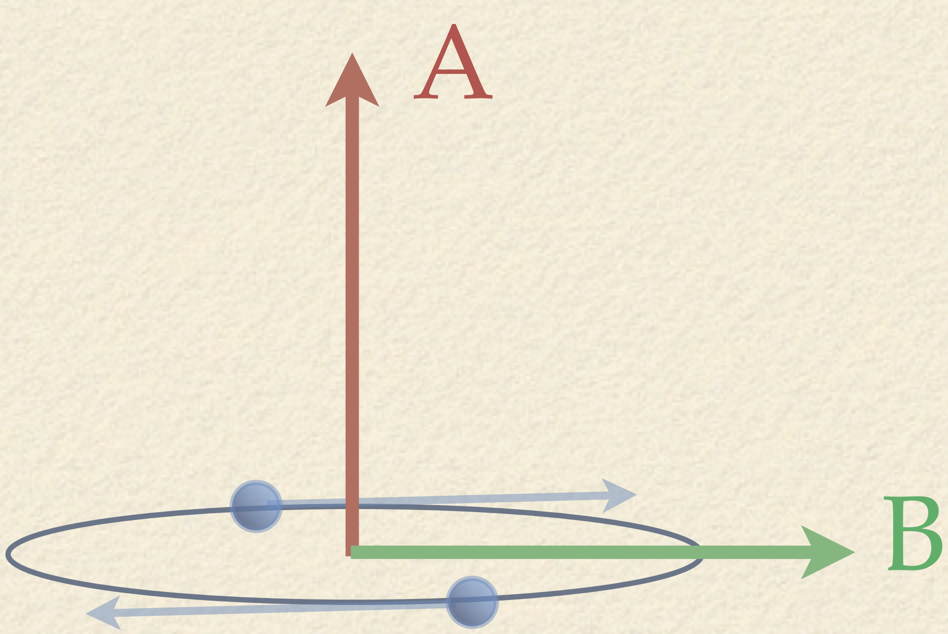
- Take circular orbits
- Compute h_+ and $h_\times$, the amplitude of the two modes of the emitted wave seen by an observer situated at a distance $R \gg a$
- Relative coordinates : $x_1(t) = a\cos\omega t,\;\; x_2(t) = a\sin\omega t\,,\;\; x_3(t) = 0$

Generation : binary system

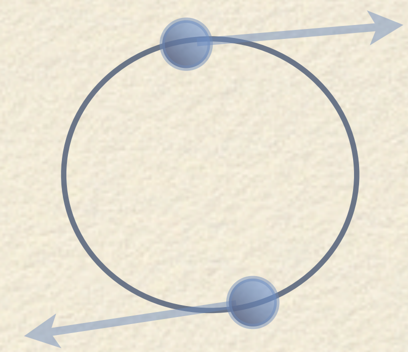
- One obtains

$$h_+(t) = \frac{4G\mu a^2\omega^2}{Rc^4}\frac{1+\cos^2\theta}{2}\cos 2\omega t$$

$$h_\times(t) = \frac{4G\mu a^2\omega^2}{Rc^4}\cos\theta\sin 2\omega t$$



Observer A : $\cos\theta = 1$
sees the two polarizations



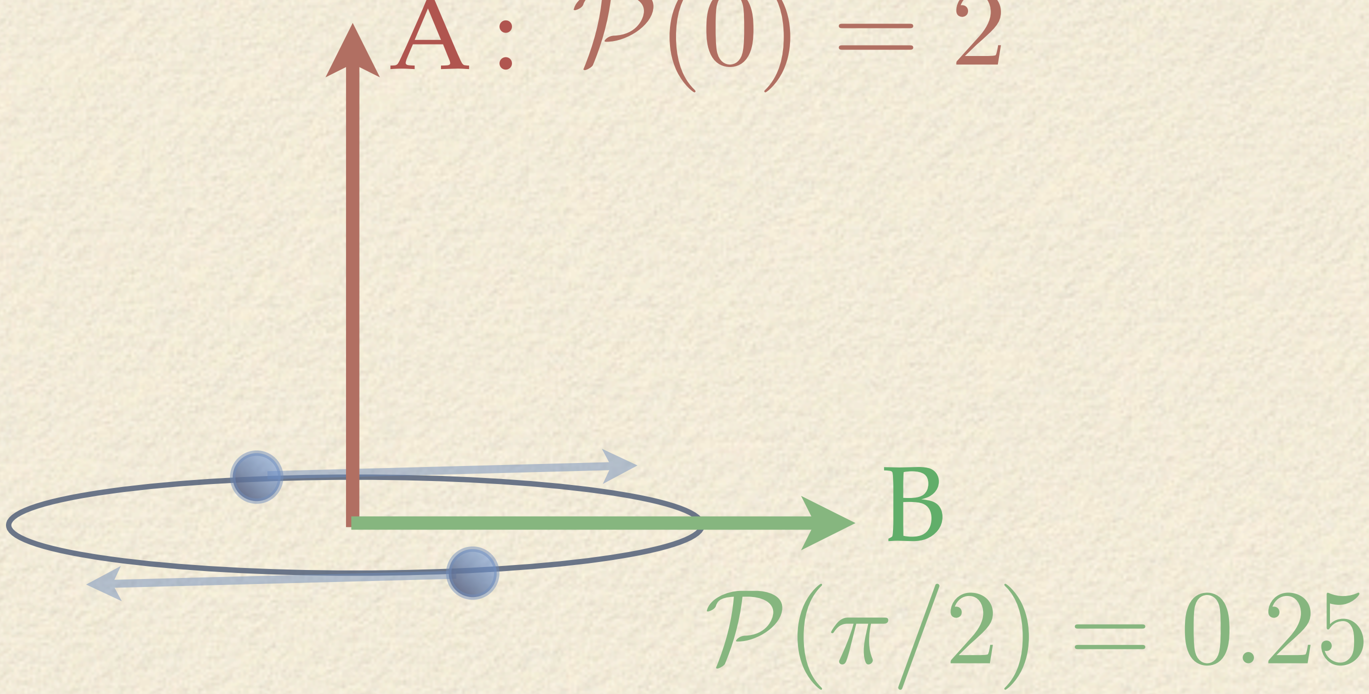
Observer B : $\cos\theta = 0$
sees a linear polarization

Generation : binary system

- Radiated power per unit solid angle $$\frac{dP}{d\Omega} = \frac{2G\mu^2 a^4 \omega^6}{\pi c^5}\mathcal{P}(\theta)$$

$$\mathcal{P}(\theta) = \frac{1}{4}(1 + 6\cos^2\theta + \cos^4\theta)$$

- Radiated power non zero whatever the direction of emission



- Total radiated power

$$P = \frac{32G\mu^2 a^4 \omega^6}{5c^5}$$

Generation : binary system

- Some examples
- Sun-Jupiter system

$$m_J = 1.9 \times 10^{27}\text{kg}, \quad a = 7.8 \times 10^{11}\text{m}, \quad \omega = 1.68 \times 10^{-7}\text{s}^{-1}$$
$$\Rightarrow \quad P = 5 \times 10^3 \quad \text{J/s}$$

  - Very small, compared to the light power emitted by the sun :

$$L_\odot \approx 3.8 \times 10^{26}\,\text{J/s}$$

- Binary pulsar PSR1913+16 (Hulse and Taylor) : $P = 7.35 \times 10^{24}\ \text{J/s}$

Generation : binary system

- Radiated energy taken to the gravitational energy of the system
  - Grav. energy of the system decreases, radius of the orbits decreases
  - Frequency of the GW increases
  - Conservation of energy : $\frac{dE}{dt} = -P$ (E total energy of the system)
- Newtonian $E = -G\frac{m_1 m_2}{2a}, \quad \omega^2 = \frac{GM}{a^3}$
- Hence

$$\dot{a} = -\frac{2}{3}(a\omega)\left(\frac{\dot{\omega}}{\omega^2}\right)$$

radial speed

tangential speed

adiabatic factor

Generation : binary system

- Goal : calculate the evolution of the frequency of the wave
- Calculation of the adiabatic factor

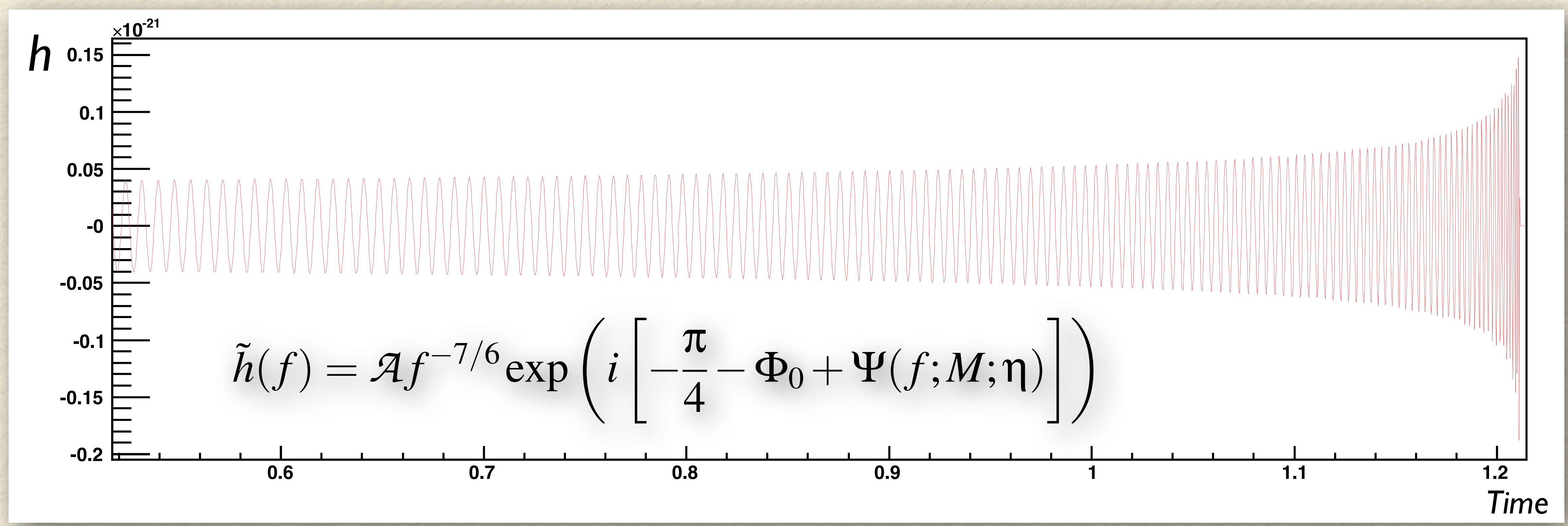
$$E = -G\frac{m_1 m_2}{2a}, \quad \omega^2 = \frac{GM}{a^3} \quad \Rightarrow \quad \dot{E} = -G^{2/3}\frac{m_1 m_2}{2M^{1/3}}\frac{2}{3}\,\dot{\omega}\,\omega^{-1/3}$$

$$\dot{E} = -P \quad \Rightarrow \quad G^{2/3}\frac{m_1 m_2}{2M^{1/3}}\frac{2}{3}\,\dot{\omega}\,\omega^{-1/3} = \frac{32 G \mu^2 a^4 \omega^6}{5c^5}$$

- Replace *a* by its expression as a function of ω : $\frac{\dot{\omega}}{\omega^2} = \frac{96}{5}\frac{G^{5/3}}{c^5}\frac{\mu}{M}(M\omega)^{5/3}$
- Frequency : $\dot{f}_{OG} = \frac{96}{5}\frac{G^{5/3}}{c^5}\pi^{8/3}\mathcal{M}^{5/3} f_{OG}^{11/3}$ (since $2\pi f_{OG} = 2\omega$)
  - where we define the "chirp mass" : $\mathcal{M} = \mu^{3/5} M^{2/5}$

Generation : binary system

- Calculated waveform before the "plunge" :



Generation : binary system

- Post-newtonian corrections
- Development around the newtonian limit in $\epsilon = \left(\frac{v}{c}\right)^2$
  - v = relative speed of the two stars (dimensionless) $\quad v = (M\omega)^{1/3}$
- For example, development of the orbital phase

$$\phi(t) = \phi_{ref} + \phi_N \sum_{k=0}^{n} \phi_{\frac{k}{2}PN} v^k$$

- The successive terms become more and more complex
  - higher order effect, spin-spin interaction, spin-orbit, radiation.

k	N	2	3	4	5
$\mathcal{F}_k$	$\frac{32\eta^2 v^{10}}{5}$	$-\frac{1247}{336} - \frac{35\eta}{12}$	4π	$-\frac{44711}{9072} + \frac{9271\eta}{504} + \frac{65\eta^2}{18}$	$-\left(\frac{8191}{672} + \frac{535\eta}{24}\right)\pi$
t_k^v	$-\frac{5m}{256\eta v^8}$	$\frac{743}{252} + \frac{11\eta}{3}$	$-\frac{32\pi}{5}$	$\frac{3058673}{508032} + \frac{5429\eta}{504} + \frac{617\eta^2}{72}$	$-\left(\frac{7729}{252} + \eta\right)\pi$
ϕ_k^v	$-\frac{1}{16\eta v^5}$	$\frac{3715}{1008} + \frac{55\eta}{12}$	-10π	$\frac{15293365}{1016064} + \frac{27145\eta}{1008} + \frac{3085\eta^2}{144}$	$\left(\frac{38645}{672} + \frac{15\eta}{8}\right)\pi \ln\left(\frac{v}{v_{\rm lso}}\right)$
ϕ_k^t	$-\frac{2}{\eta\theta^5}$	$\frac{3715}{8064} + \frac{55\eta}{96}$	$-\frac{3\pi}{4}$	$\frac{9275495}{14450688} + \frac{284875\eta}{258048} + \frac{1855\eta^2}{2048}$	$\left(\frac{38645}{21504} + \frac{15\eta}{256}\right)\pi \ln\left(\frac{\theta}{\theta_{\rm lso}}\right)$
F_k^t	$\frac{\theta^3}{8\pi m}$	$\frac{743}{2688} + \frac{11\eta}{32}$	$-\frac{3\pi}{10}$	$\frac{1855099}{14450688} + \frac{56975\eta}{258048} + \frac{371\eta^2}{2048}$	$-\left(\frac{7729}{21504} + \frac{3}{256}\eta\right)\pi$
τ_k	$\frac{3}{128\eta}$	$\frac{5}{9}\left(\frac{743}{84} + 11\eta\right)$	-16π	$2\phi_4^v$	$\frac{1}{3}\left(8\phi_5^v - 5t_5^v\right)$

Generation : binary system

- PSR 1913+16 (Hulse et Taylor)
- points = observations, line = GR prediction

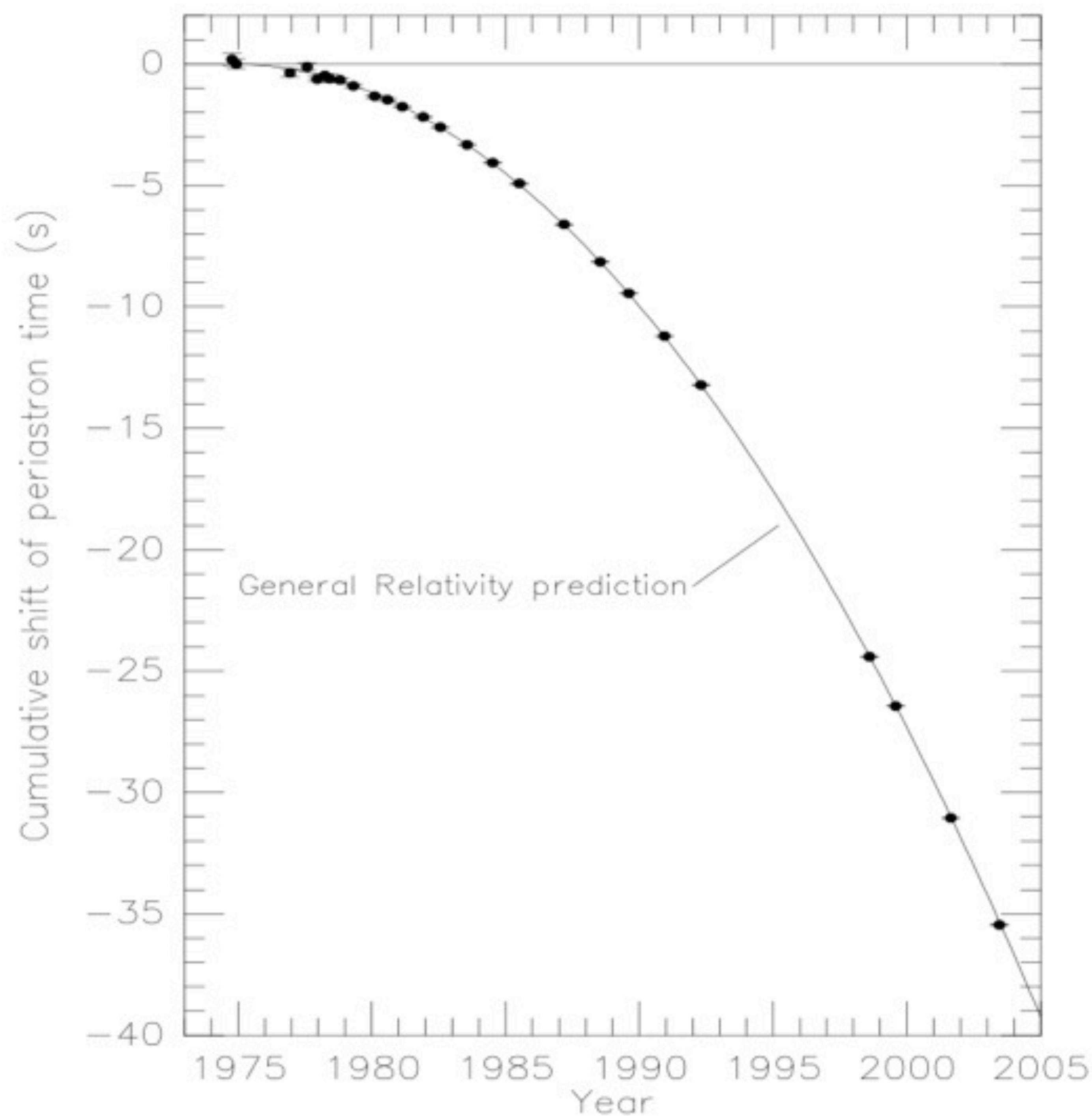


Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

Scientific goals

- Confirmation of GW — Detectors on earth, in space
- Study properties, test GR — Detectors on earth, in space
  - Speed = c ? Really quadrupolar ?
- Measure the Hubble constant
  - Coalescing binaries should be standard candles if the redshift and distance are known — Detectors on earth, in space

Impossible with only one detector for most of the sources → Build a worldwide obervatory of gravitational waves

Scientific goals

- Study characteristics
  - of neutron stars
  - of solar mass black holes (BH)
    - Ellipticity, vibration modes, higher order moments
- Study supermassive black holes
  - cartography of space-time around a supermassive BH (Kerr).
  - study of their distribution, galactic evolution
- Stochastic background of GW :
  - first moments of the universe ?
- ...

Detectors on earth

Detectors in space

Detectors on earth ?

Detectors in space ?

Detection of gravitational waves by optical interferometry

- Historical introduction
- Principle of the interferometric detectors
- The noise makes the detector
- From Virgo to Advanced Virgo (AdV)
- A world wide detector network

A rather complete and very pedagogical introduction :
"Fundamentals of Interferometric Gravitational Wave Detectors", P.R. Saulson, World Scientific, 1994

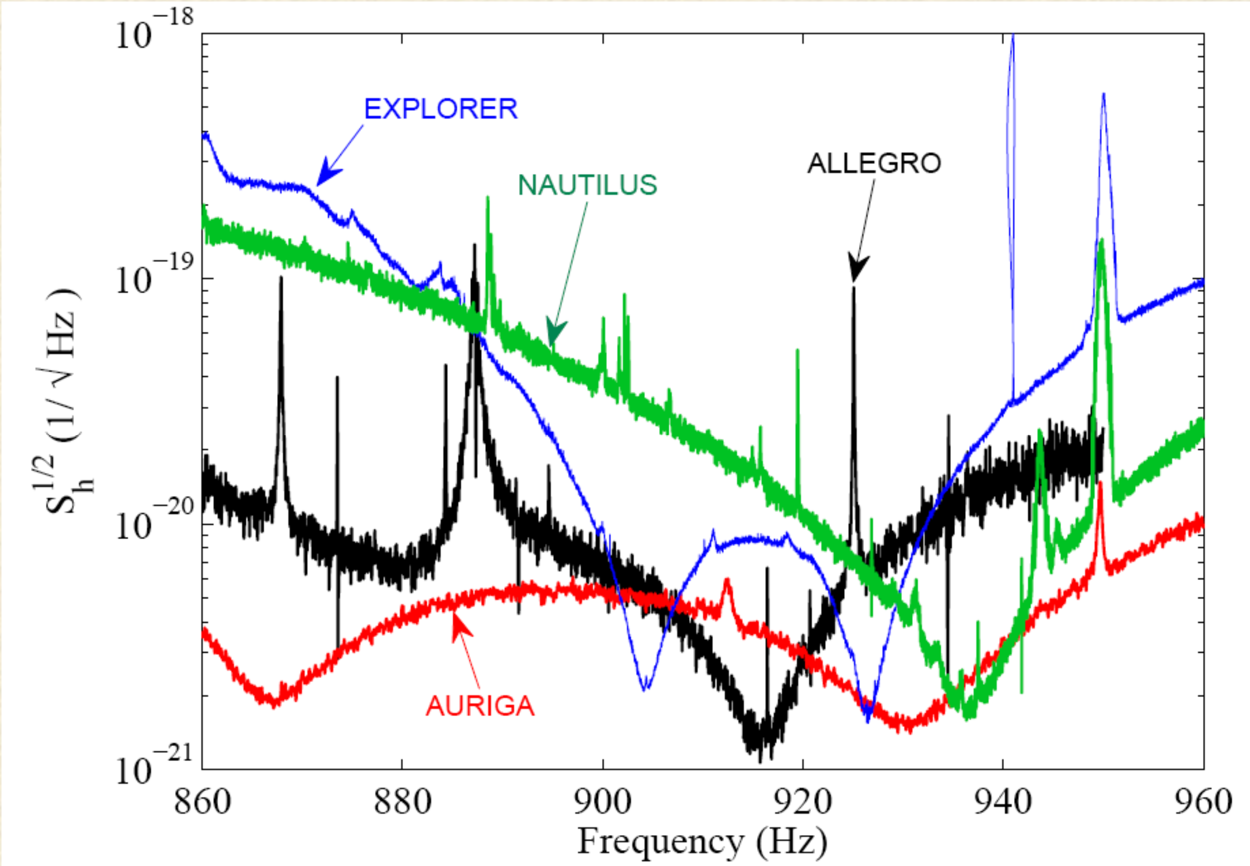
History

- First idea : resonant bars or spheres
  - J. Weber 1966 : the GW changes the resonance condition of a resonant bar of a few tons
  - Claims the detection of GW (1968-1969)
    - Various problems, other experiments have not confirmed the discovery
- Other idea : measure the time of flight of photons between two test masses, Michelson interferometer
  - Gertsenshtein & Pustovoit (1962)
  - First interferometer for GW :

    R. L. Forward & al (1971)
  - Foundations for the modern interferometers :
    Rainer Weiss (1972)

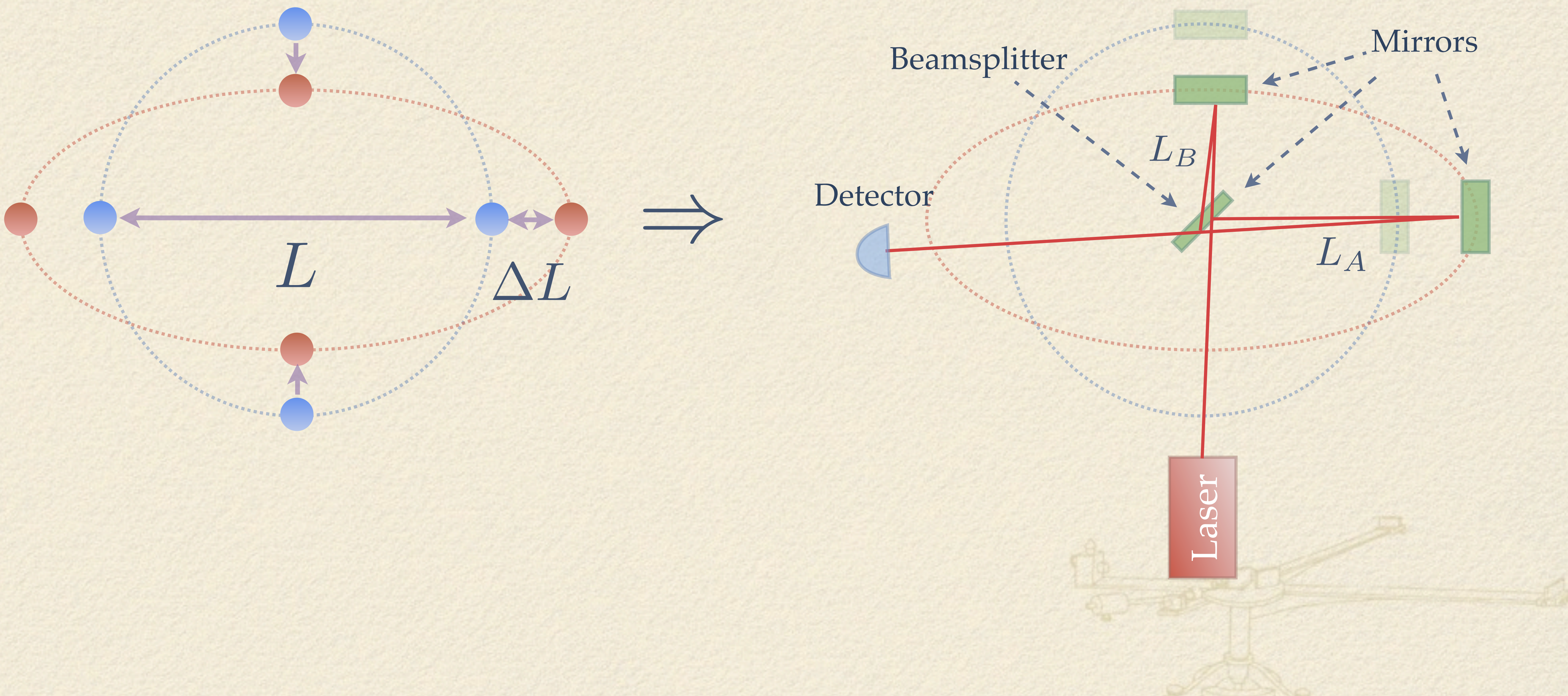
Resonant detectors

- J. Weber 1966 : the GW changes the resonance condition of a resonant bar of a few tons
- Two experiments (Auriga and Nautilus) run in «astrowatch» mode
- $f_s = 700 - 1000 \text{ Hz}, \Delta f = 50 - 200 \text{ Hz}$
- sensitivity : $h \approx 10^{-19}$ à 10^{-21}



Interferometric detectors : Principle of detection

Detection principle

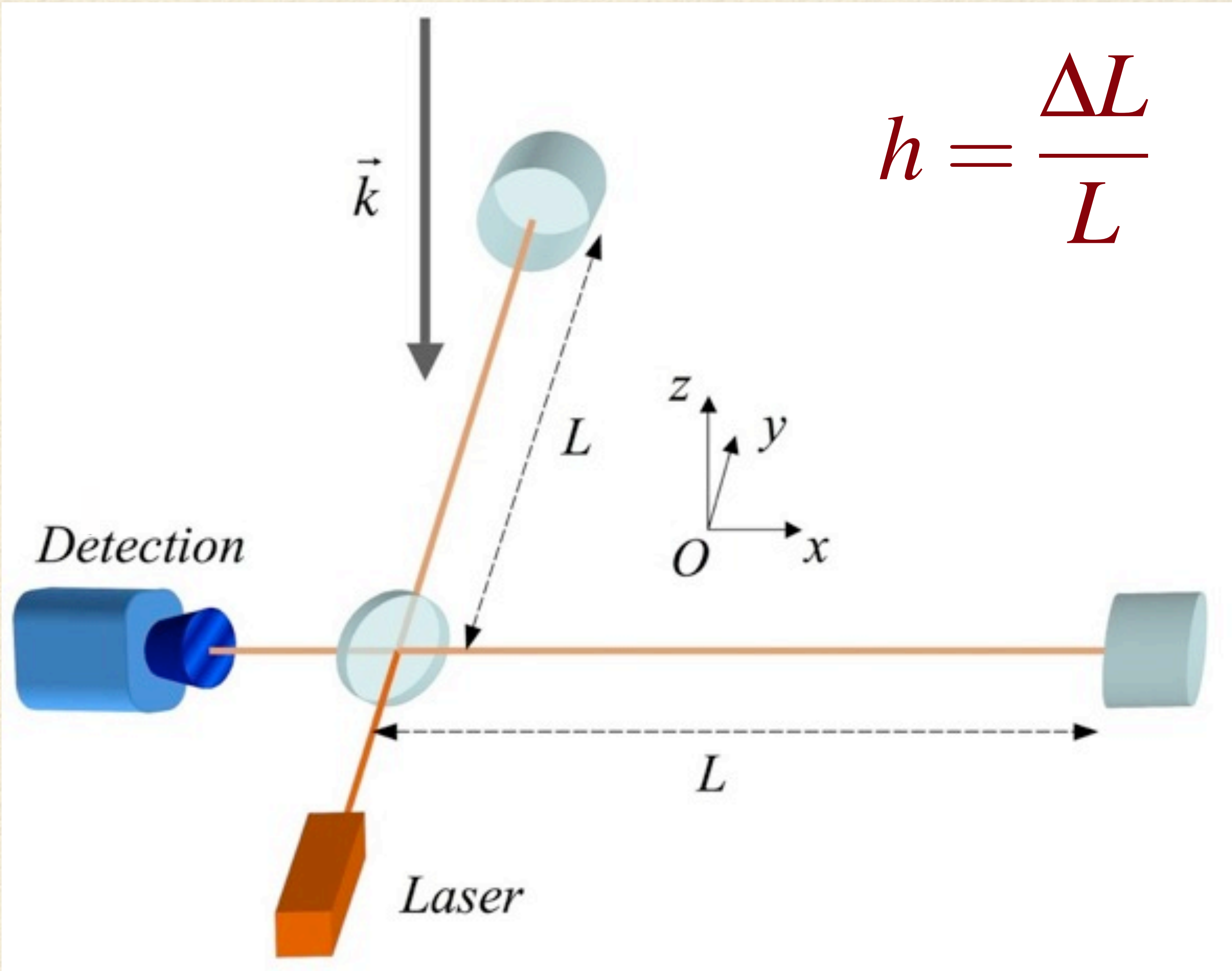


Detection principle

- Michelson interferometer

The detector measures the optical path length difference between the two arms

most of the elements (mirrors, injection and detection systems) are suspended and behave like free falling masses in the interferometer plane (for $f \gg f_{pend}$)



Detection principle

- Photon in a field , general case

$$ds^2 = 0 = g_{\alpha\beta}dx^\alpha dx^\beta = \eta_{\alpha\beta}dx^\alpha dx^\beta + h_{\alpha\beta}dx^\alpha dx^\beta$$

- Particular case : wave along z, polarization "+" along one of the arms

$$ds^2 = 0 = -c^2dt^2 + (1 + h_+(t))dx^2 + (1 - h_+(t))dy^2 + dz^2$$

- Round trip time of the photons,
  integration on the path, for example for the arm along *x*

$$\frac{1}{c}\int_0^L dx = \int_0^{\tau_{aller}} \frac{1}{\sqrt{1 + h_+(t)}}\, dt \approx \int_0^{\tau_{aller}} \left(1 - \frac{1}{2}h_+(t)\right) dt$$

- Consider
  - round trip in one arm
  - wavelength of the GW >> length of one arm
    $\lambda_{OG} \gg L \quad \Rightarrow \quad h_+(t)$ independent of the position along the arm
  - period of the GW << round trip time of the light in one arm
    $\Rightarrow \quad h_+(t) = cte = h_+$

Detection principle

- For the arm along the "*x*" direction

$$\int_0^{\tau_{arx}} \left(1 - \frac{1}{2}h_+(t)\right)\, dt \approx \frac{1}{c}\left(\int_0^L dx - \int_L^0 dx\right) = \frac{2L_x}{c}$$

$$= \tau_{arx} - \frac{1}{2}\int_0^{\tau_{arx}} h_+(t)dt = \tau_{arx} - \frac{1}{2}\int_0^{\frac{2L_x}{c}} h_+(t)dt$$

$$\Rightarrow \quad \tau_{arx} = \frac{2L_x}{c} + \frac{1}{2}\int_0^{\frac{2L_x}{c}} h_+(t)dt$$

- arm along "*y*" : $\Rightarrow \quad \tau_{ary} = \frac{2L_y}{c} - \frac{1}{2}\int_0^{\frac{2L_y}{c}} h_+(t)dt$
- time difference (suppose *h* constant) if : $L_x = L_y = L$

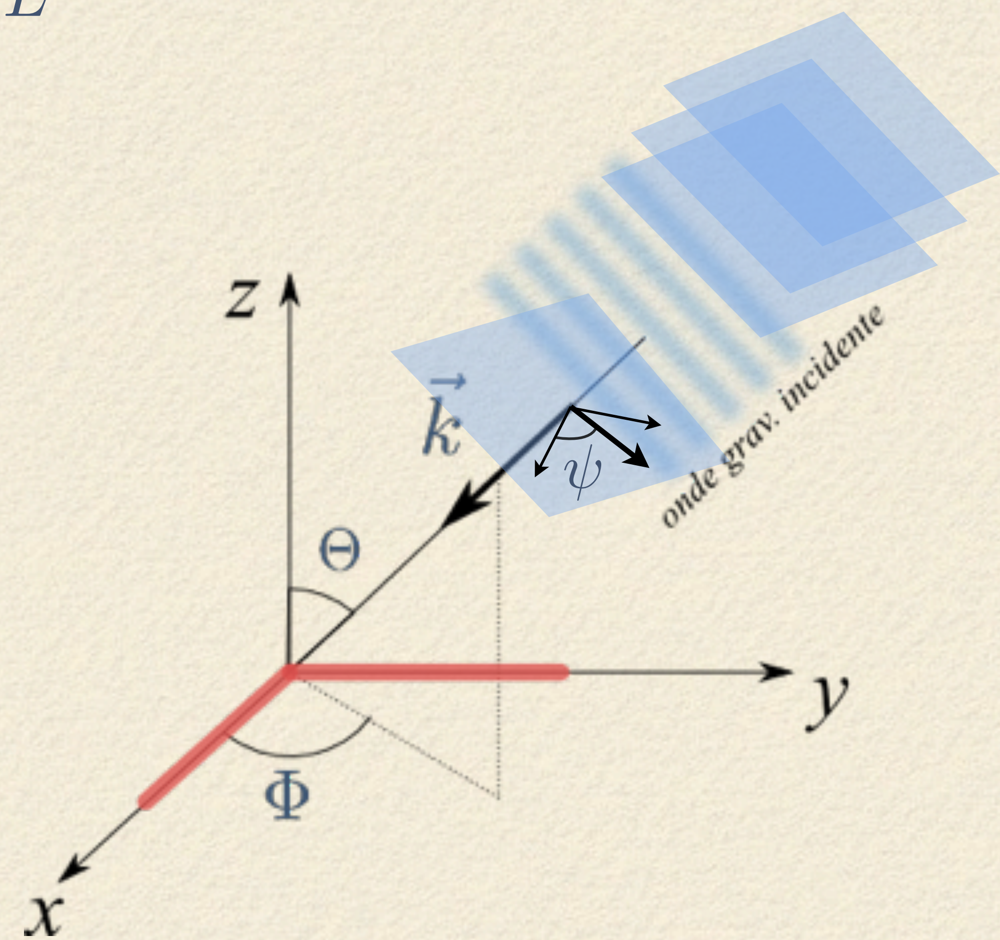
$$\delta\tau_{ar} = \frac{1}{2}h_+\left(\frac{2L_x}{c} + \frac{2L_y}{c}\right) = h_+\frac{2L}{c}$$

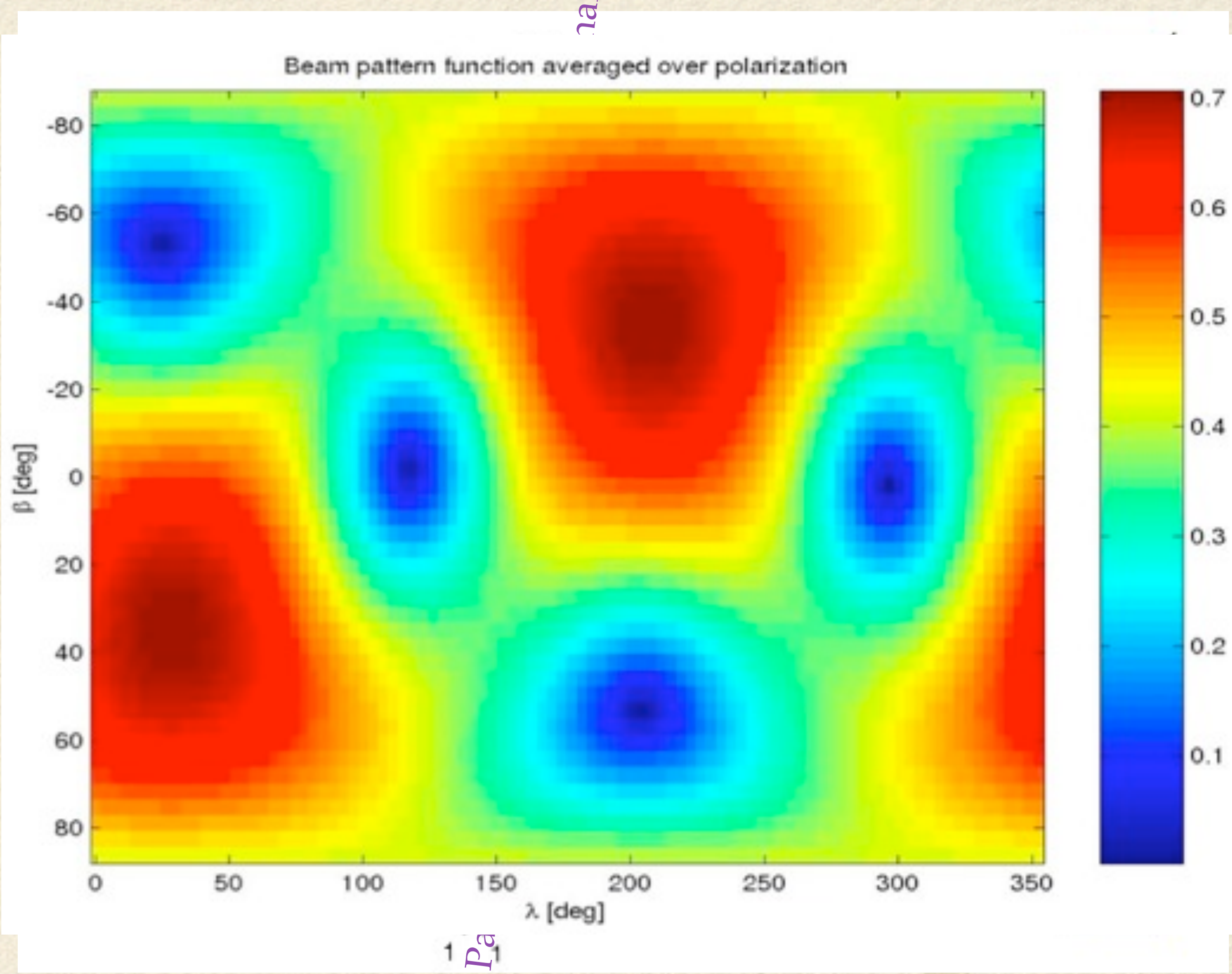
- accumulated phase difference : $\delta\phi = \omega_{\text{laser}}\ \delta\tau_{ar} = \frac{4\pi}{\lambda_{\text{laser}}}Lh_+$
- proportional to *h* and *L*

Angular response

- Interferometer angular response
  - Average on the polarization of the incident wave

$$\frac{\Delta L}{L} = F_+(\Theta,\Phi,\psi)\;h_+ + F_\times(\Theta,\Phi,\psi)\;h_\times$$





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

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

"quasi" omni-directional detector

Interferometric detectors : the noise makes the detector

Limitations of interferometry

- Phase difference measurement $\delta\phi$
  - What is the best configuration/tuning of a Michelson ?
- Limits of the apparatus ?
  - Shot noise is the “ultimate” noise
  - Light power on the photodiodes

$$\Longrightarrow \text{ photon counting statistic}$$

$$N \text{ photons during time } T \Longrightarrow \text{ variance } \sqrt{N} \text{ if } N \text{ large}$$

- Interferometer limitations
  - Limited laser power
  - Not perfect contrast (< 1)
  - Noise(s) of the laser (power noise...)

- Only the beginning of the problems...

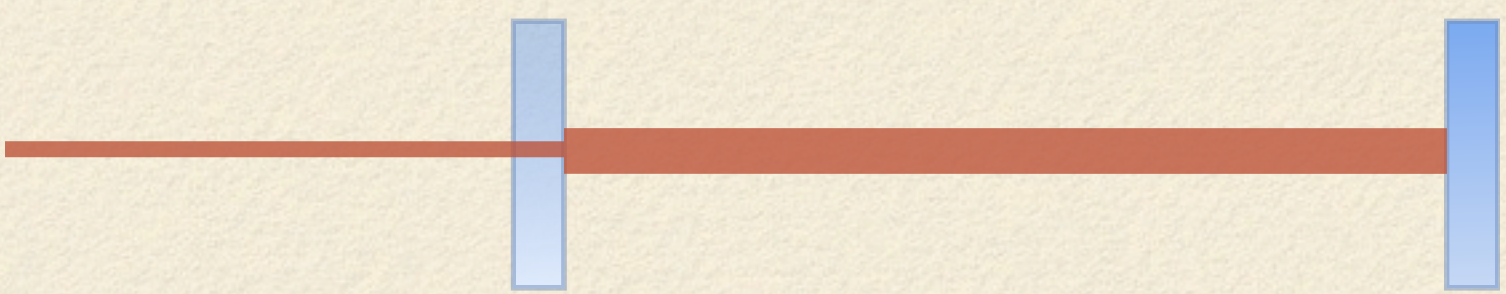
Overcoming some limitations

- Sensitivity
  - Noise power spectral density $S_b = \sqrt{2h\nu P_{DC}} \quad \mathrm{W}/\sqrt{\mathrm{Hz}}$
  - sensitivity : ratio of the shot noise (in $W/\sqrt{\mathrm{Hz}}$) to the response of the interferometer (in W/m) normalized to the length L :

$$\sigma_h = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{4\pi P_{max}}} \quad 1/\sqrt{\mathrm{Hz}}$$

- Fold the arms : Fabry-Perot

reflectivity : r_i $\qquad r_e = 1$

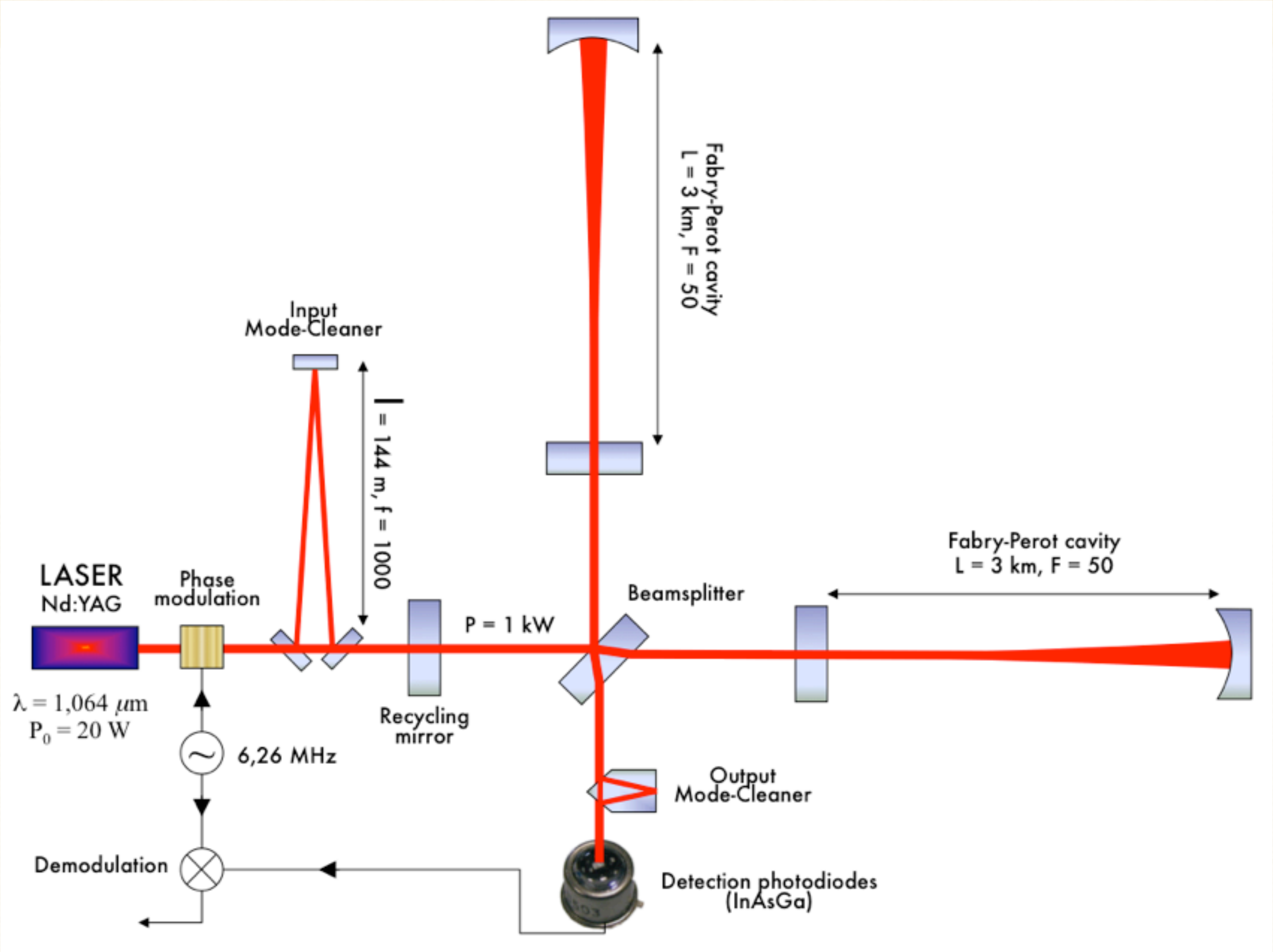


- Average number of round trips of photons in the arm :

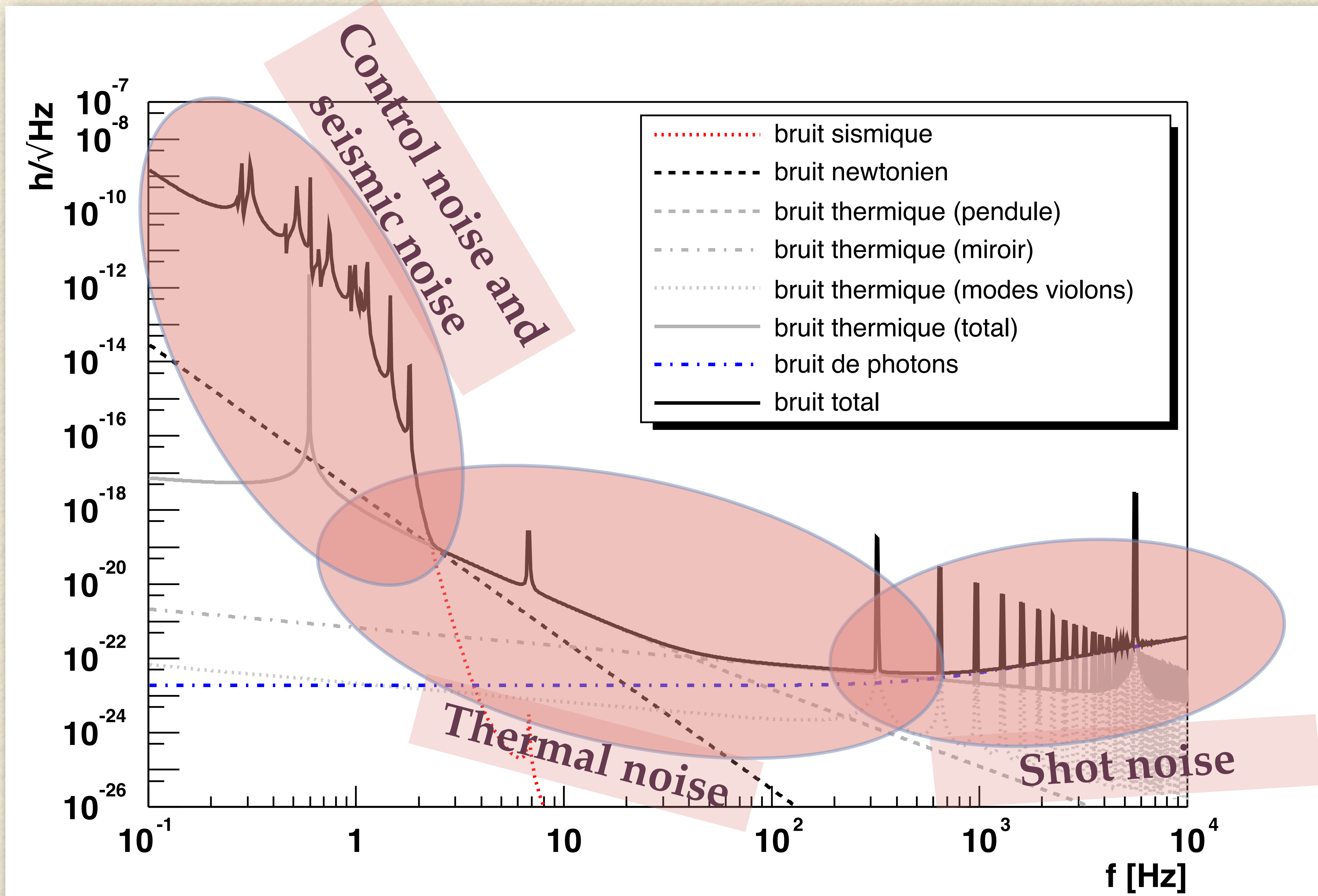
$$\overline{N} = \frac{2\mathcal{F}}{\pi}$$

$$\sigma_h = \frac{\pi}{2\mathcal{F}L}\sqrt{\frac{\hbar c \lambda}{4\pi P_{max}}} \quad 1/\sqrt{\mathrm{Hz}}$$

Optical configuration of VIRGO



Nominal sensitivity

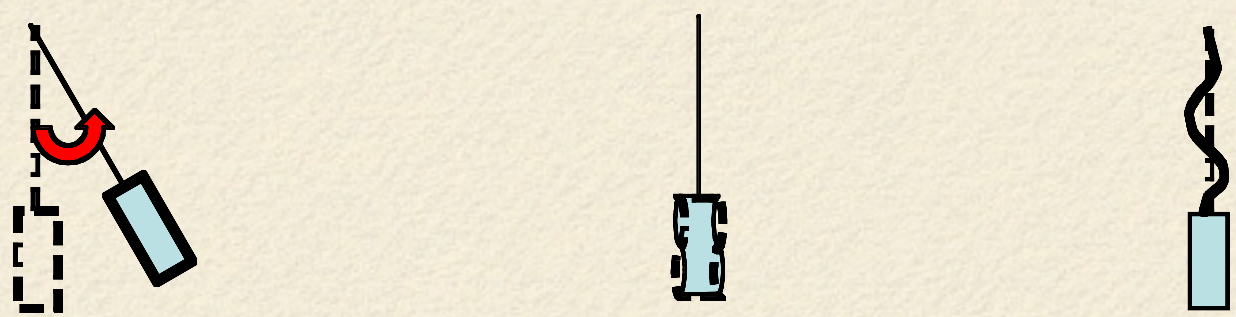


Fighting noises

- **Acoustic vibrations + refraction index fluctuations** in the tube
  ➥ laser beam and mirrors under vacuum (10^{-8} mbar)

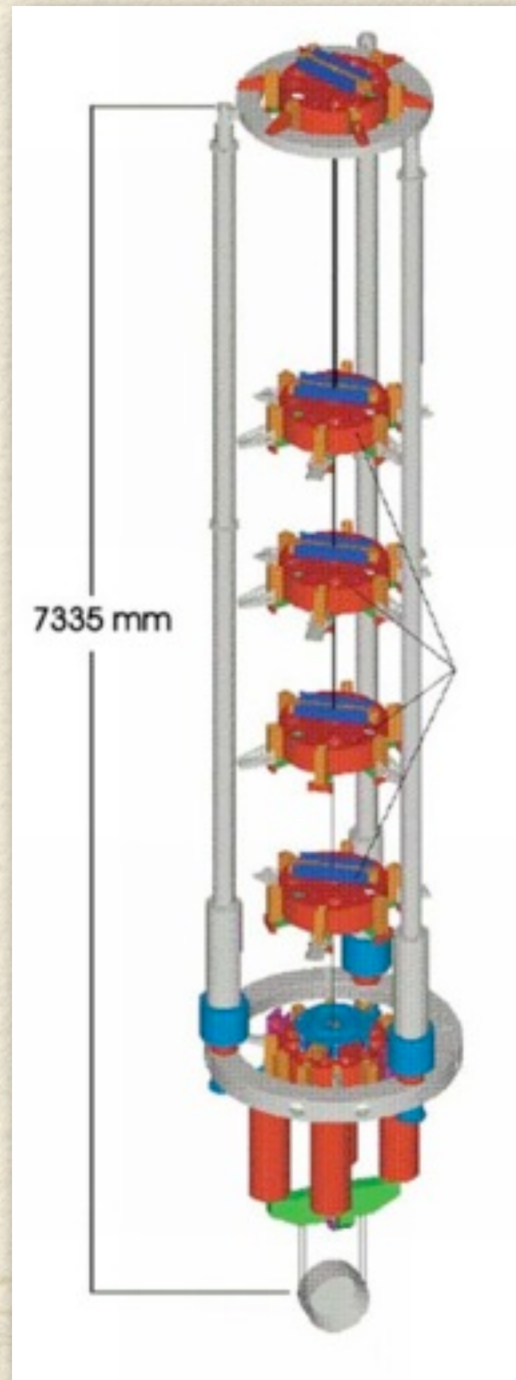
- **Sismic noise** (*dominant* : < 3 Hz)
  ➥ Super-attenuators (set of mechanical filters)

- **Thermal noise** (*dominant* : 3-500 Hz) : random movement of the mirrors due to thermal energy dissipation



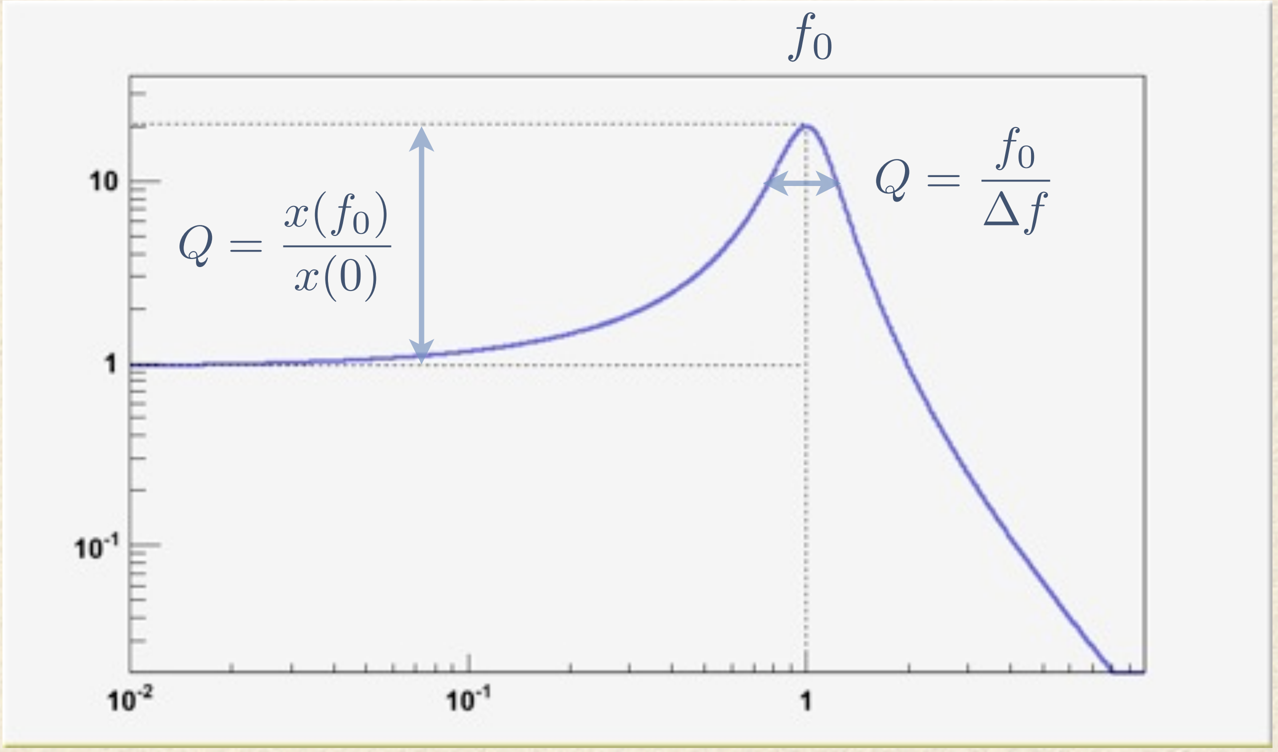
Pendulum mode (dominant : 3-40 Hz) — *"Mirror" mode (dominant : 40-200 Hz)* — *"Violin" mode (dominant : 200-500 Hz)*

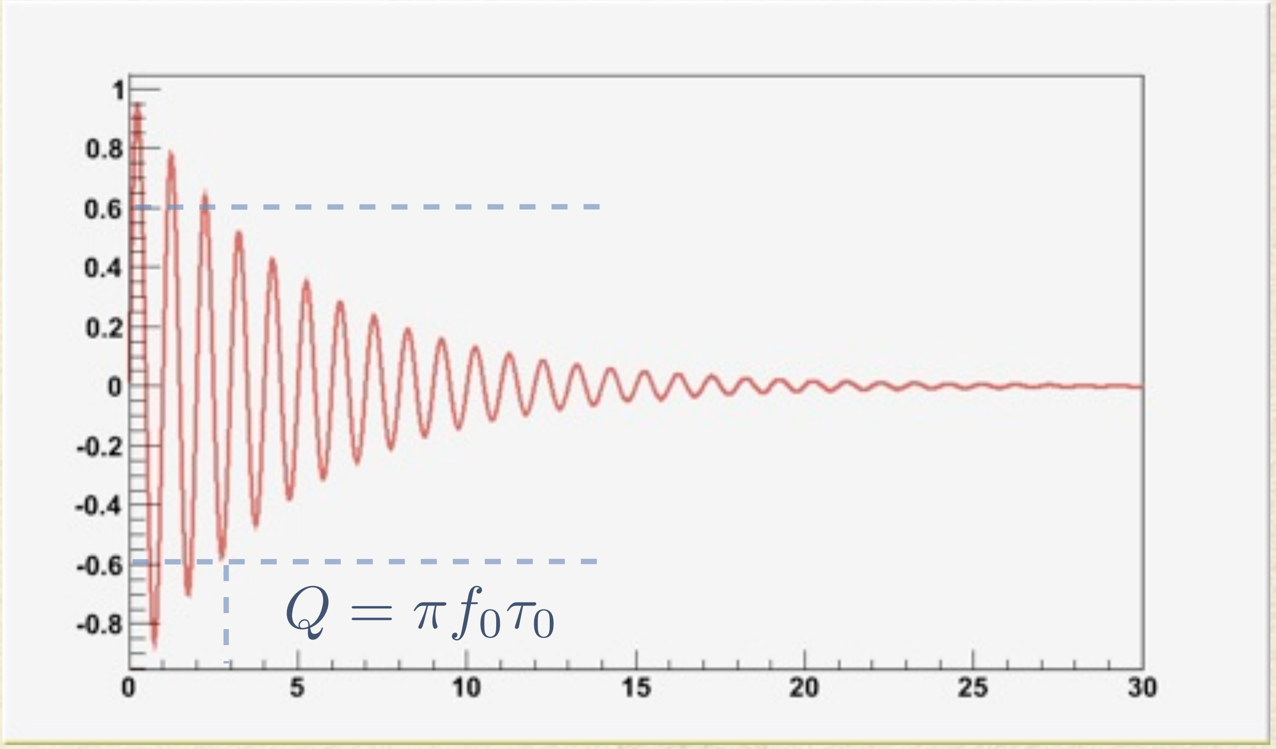
- **Shot noise** (*dominant* : >500 Hz) : statistical uncertainty on the number of photons hitting the photodiode



Element example : Suspensions

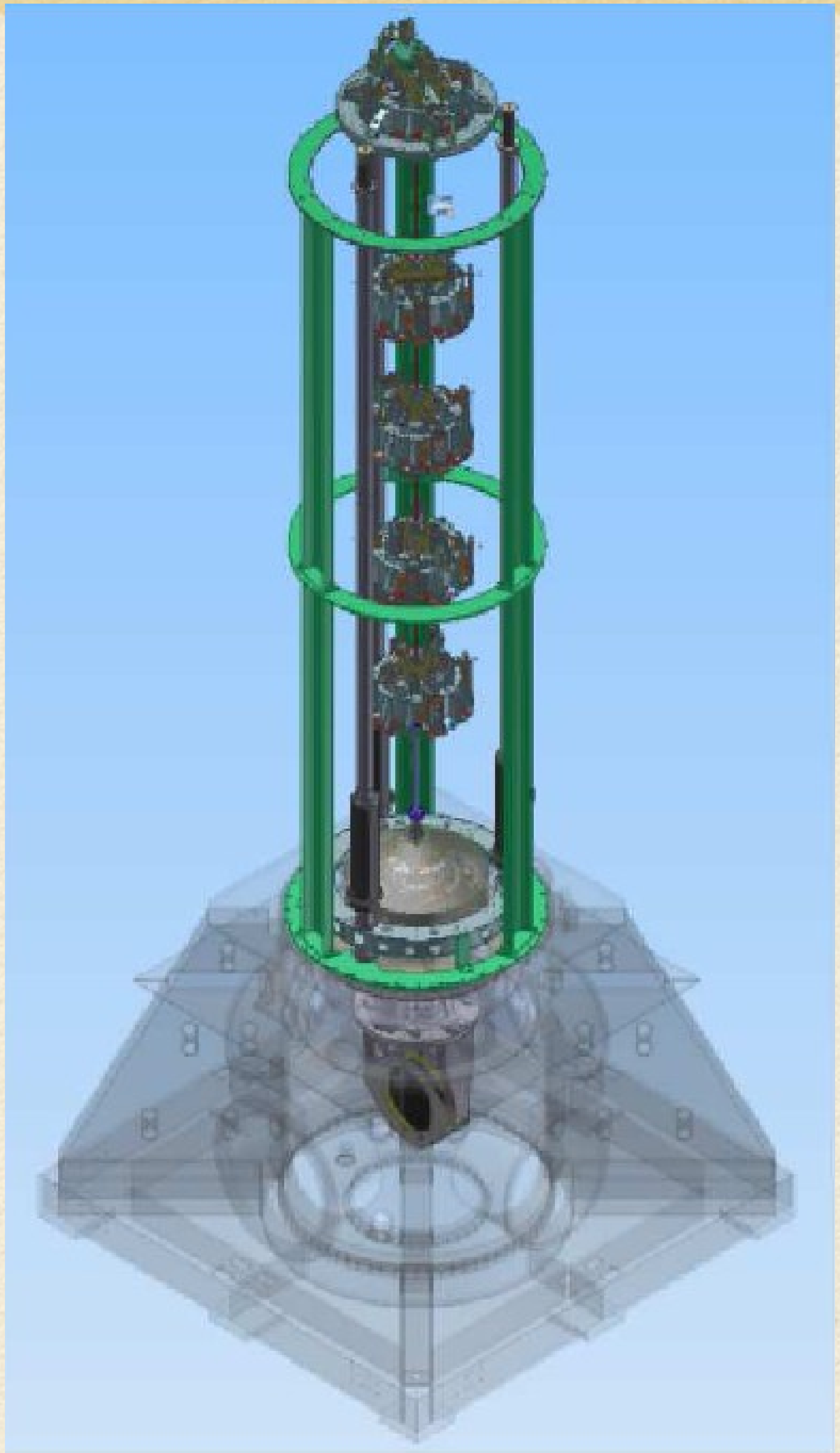
- Principle :
  - damping of a vibration by a pendulum (more generally a damped oscillating system)
  - fluctuation-dissipation theorem links the spectrum of the position fluctuations of a system to it's dissipation properties.
    - we want a very low dissipation system
- Alternate form of the principle
  - all mechanical elements should have a high quality factor
  - the energy concentrates in the peak (small frequency band)





Element example : Suspensions

- Isolates optics from the ground motion
- 7 stages of attenuation
- Mirrors are suspended with silica fibers : «monolithic suspensions»
  - Higher Q, improve thermal noise

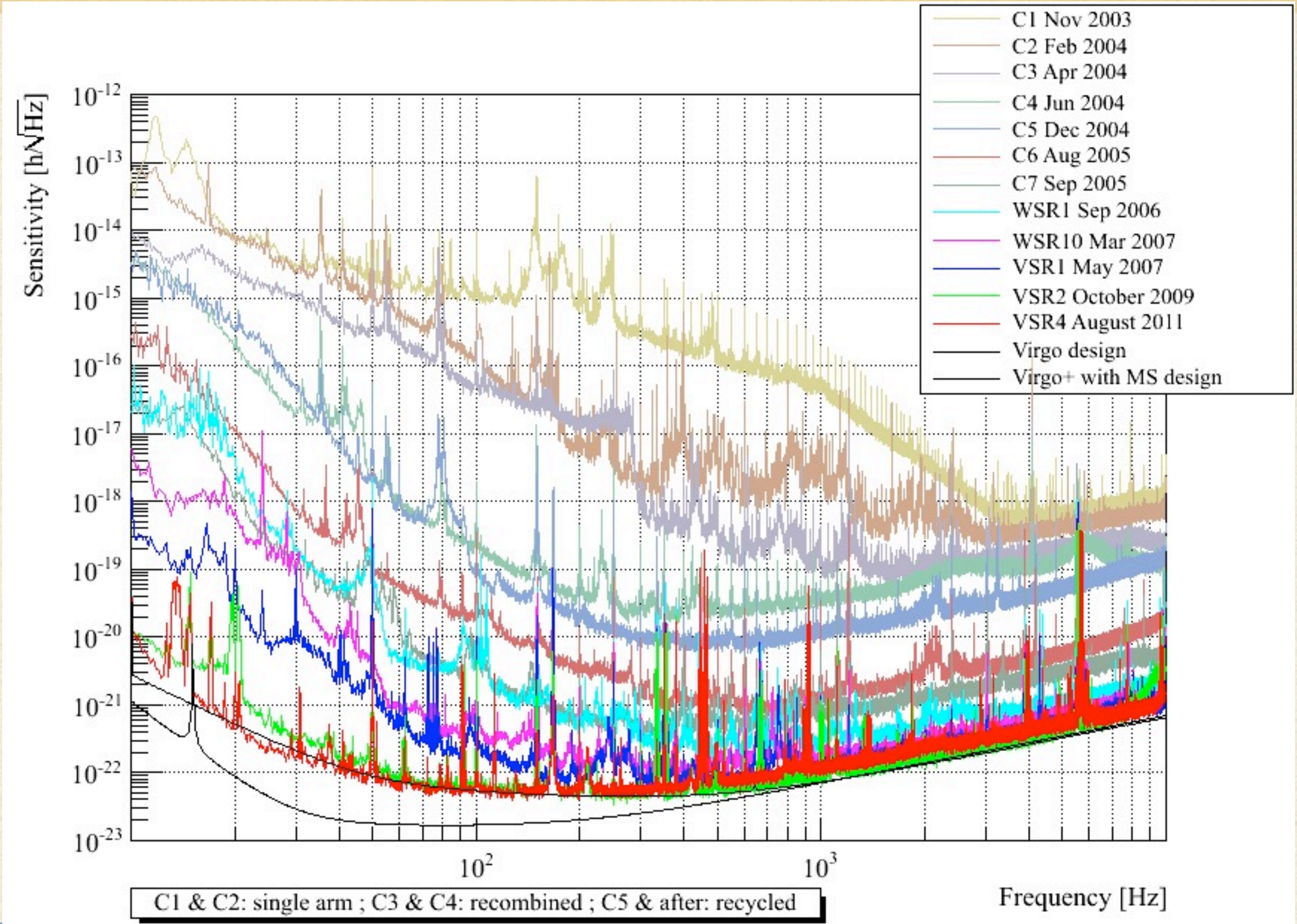


Other elements

- Injection system : modulate, stabilize and shape the beam
  - 50W laser
  - Input mode cleaner
- Detection system : read the optical signal, give signals to the control system
  - Output mode cleaner
  - Set of photodiodes + Electronics (amplifiers + Analog-Digital Converters)
- Data acquisition system
  - Preprocessing (filtering...)
  - Collection of data (photodiodes + environmental) ~ 20-40 Mb/s
  - Real-time processing
  - Control of the active elements (suspensions, mirror positions,...)




Evolution of the sensitivity



Past and future from Virgo to Advanced Virgo

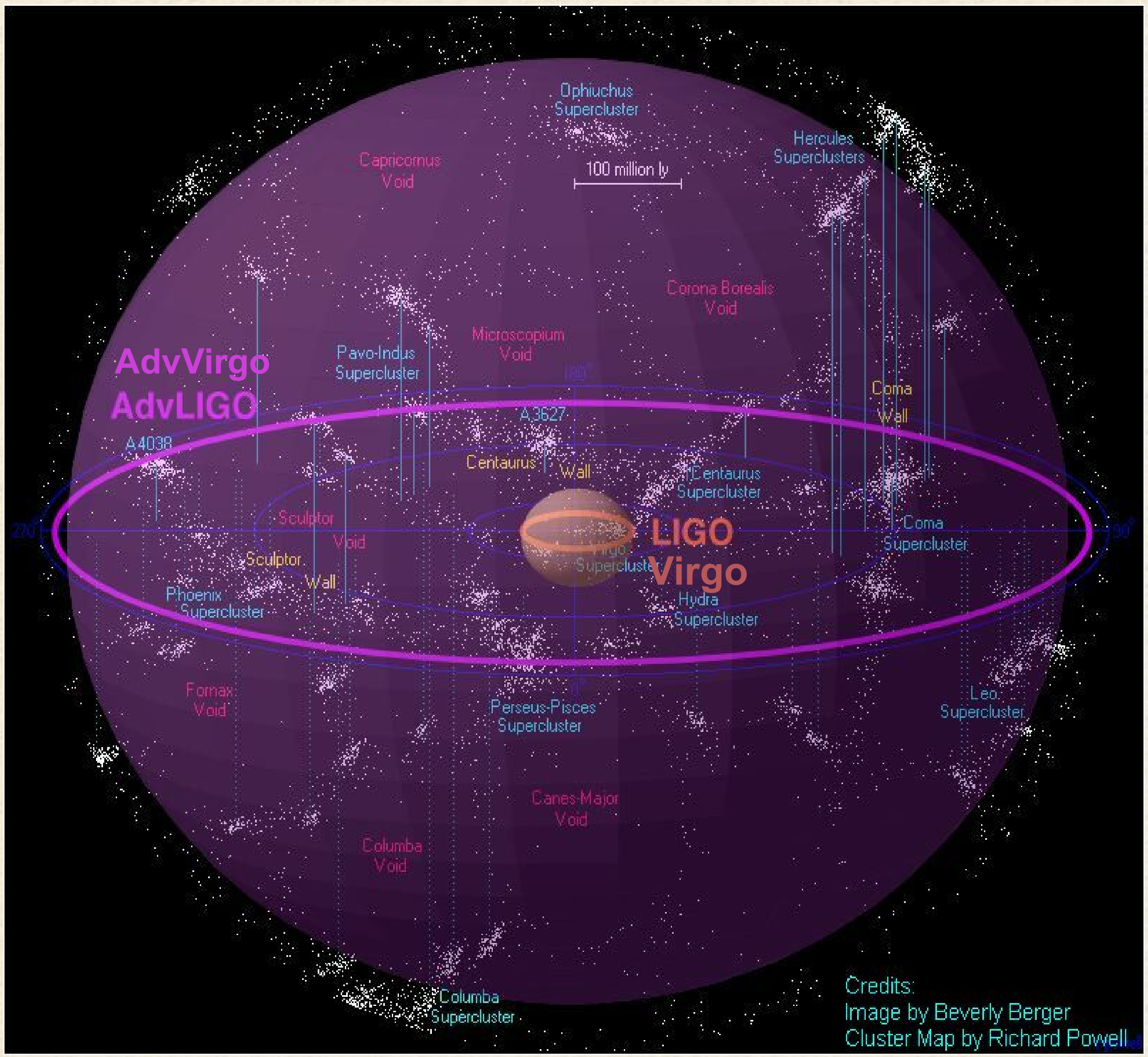
Past Virgo runs

- 4 scientific runs with varying sensitivity
- VSR1 : may-sept 2007
- VSR2 : jul-dec 2009
- VSR3 : aug-oct 2010
- VSR4 : june-sept 2011

- No detection !

Advanced detectors

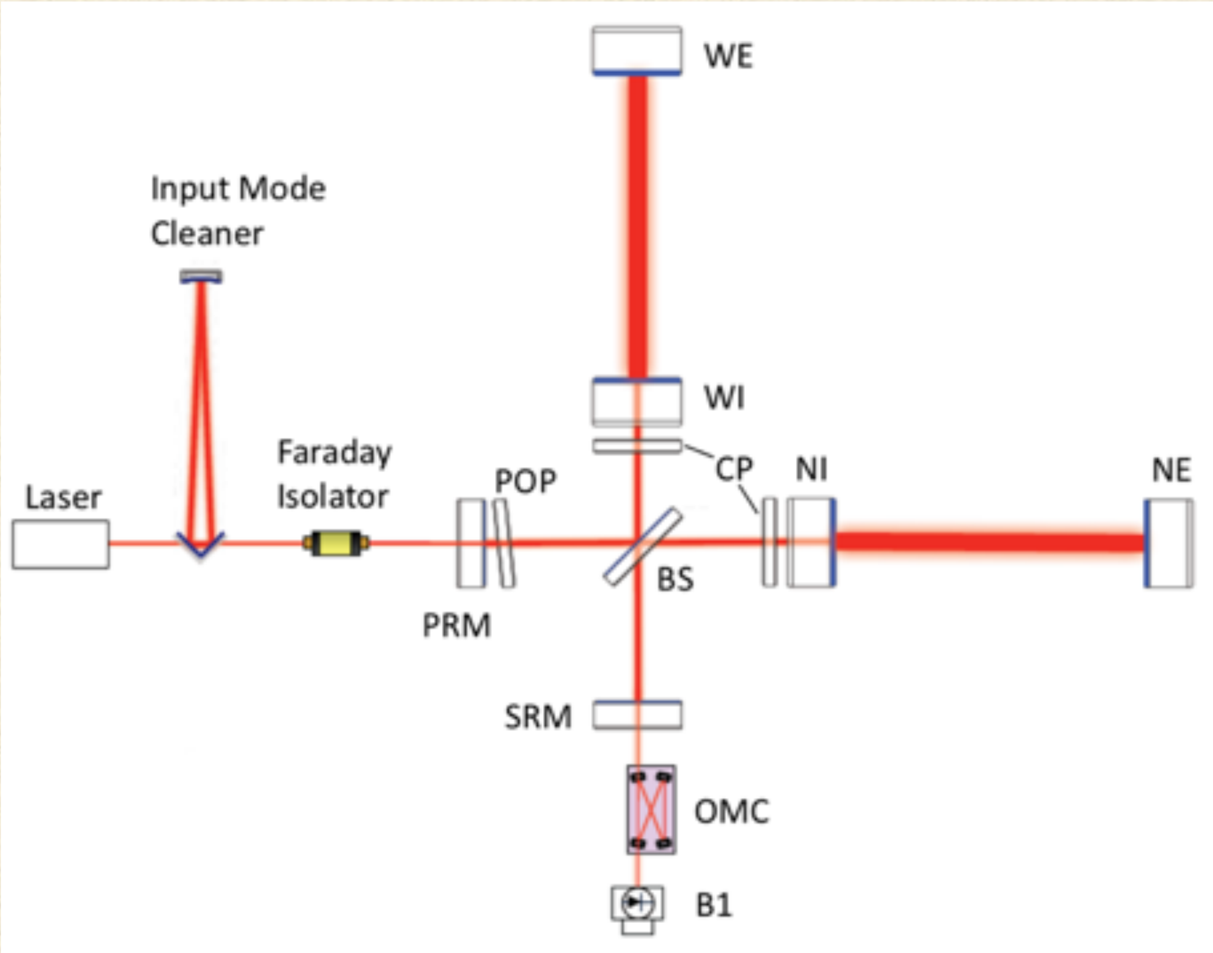
- Advanced LIGO / Advanced Virgo



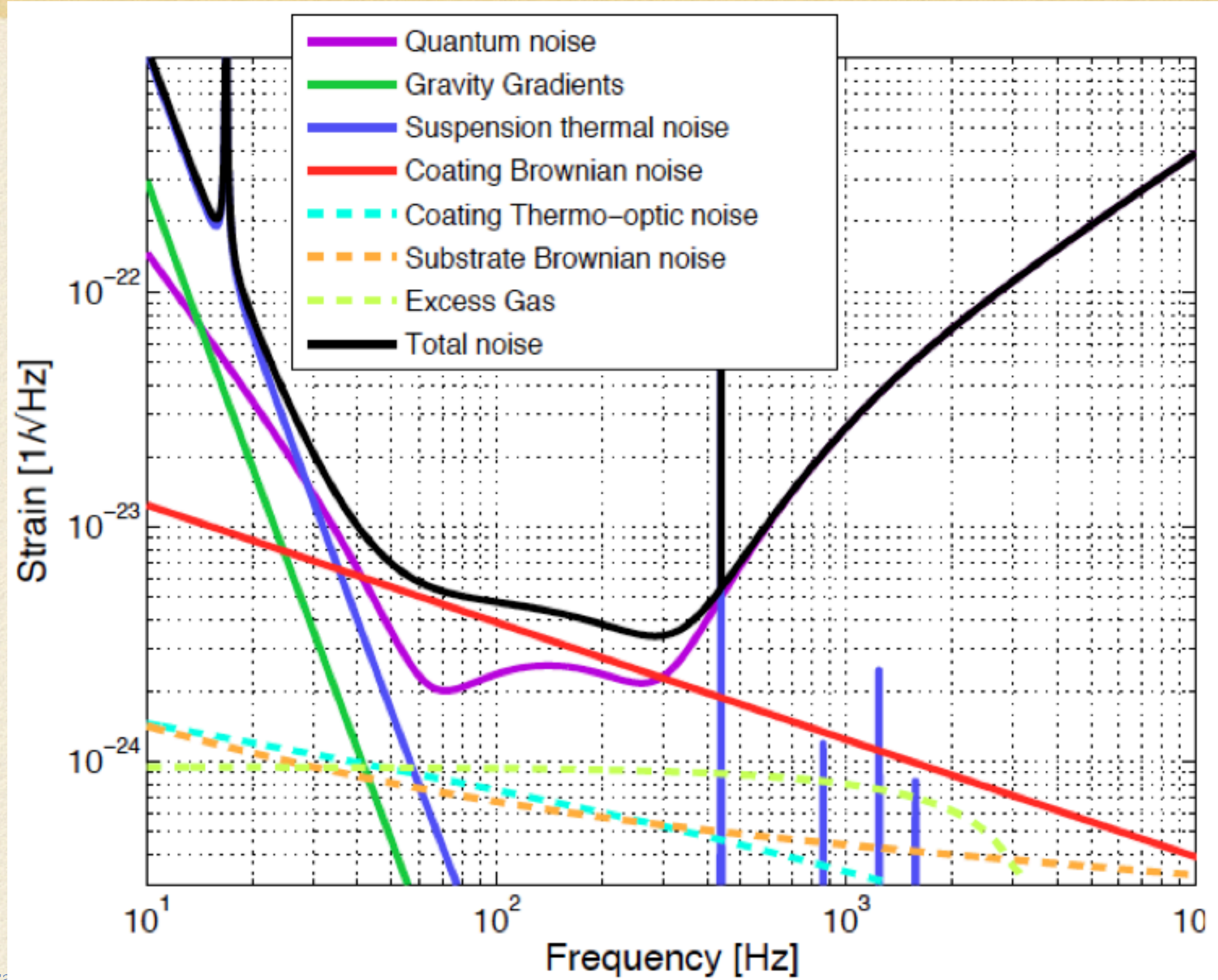
- Goal : improve the sensitivity by a factor 10 (w.r.t. Virgo/LIGO I)
- accessible volume $\propto$ (horizon)^3 $\propto$ (1/sensitivity)^3
- improve the rates by a factor 1000

In preparation : Advanced Virgo

- Updated optical configuration
- Laser 200 W, gaussian beam, waist in the middle of the Fabry-Perot cavities
- Thermal compensation
    - mirrors are deformed by the deposition of heat when the beam traverses them
- DC detection
- Heavier mirrors, better surface quality (flatness 0.5 nm RMS)



In preparation : Advanced Virgo



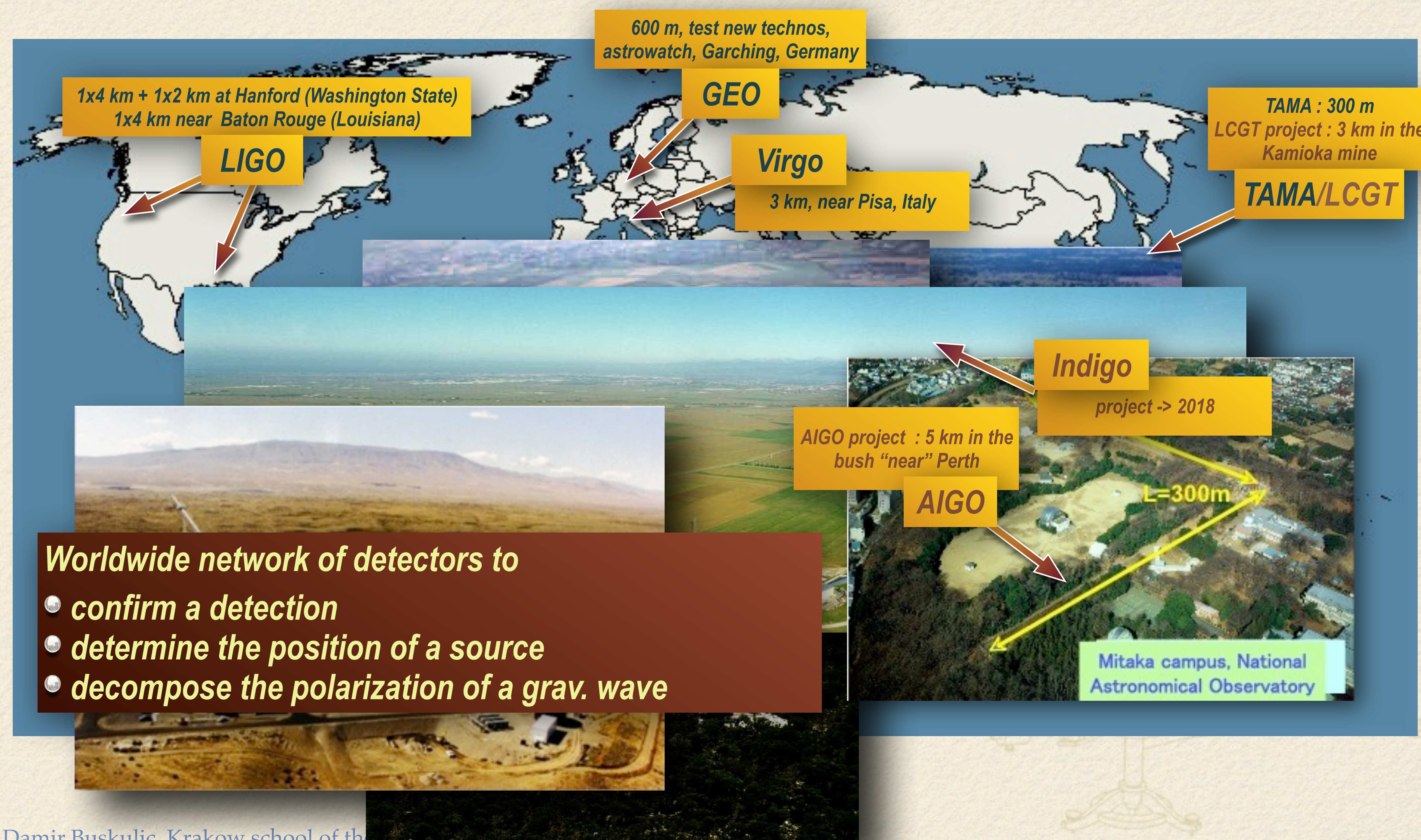
Goals and likely results

- Detection likely
  - NS coalescences : ~ 40 / yr
  - BH coalescences : ~ 20 / yr,

    up to z ~ 0.1
    - ... cosmology !?
  - Pulsars : ellipticity down to $\varepsilon \sim 10^{-8}$
  - More on that in Ilya's presentation
- but only if we work together with LIGO !
- Plan :
  - Horizon = distance at which a NS binary coalescence (1.4+1.4 $M_{\odot}$, averaged orientation) can be seen with a Signal over Noise Ratio (SNR) of 8 by the detectors.
  - Several runs from 2015 to 2022, with varying reach of 40 Mpc to 200 Mpc (aLIGO) and 20 Mpc to 130 Mpc (AdVirgo)

Worldwide network of detectors
Status end perspectives

Worldwide network of detectors



Worldwide network of detectors to

- confirm a detection
- determine the position of a source
- decompose the polarization of a grav. wave

Multi-messenger astronomy

- Coincident analysis of signals GW - Electromagnetic or GW - Neutrino
- Driven by EM :
  - Search for GRB (short and long)
  - Coherent unmodeled burst search in window [-600; 60] s around GRB
  - Coherent matched filtering search in window [-5;1] s around time of short GRB
  - During 2009-2010 science run, search for 154 GRB, of which 26 were short
    - J. Abadie et al. Search for gravitational waves associated with gamma-ray bursts during LIGO science run 6 and Virgo science run 2 and 3. Astrophys. J., 760:12, 2012.
- Driven by GW :
  - Low latency pipelines
  - GW detectors send «alert» within a few minutes (< 20 min) to observatories
  - Search for an radio/optical/gamma counterpart
  - During S6/VSR3, sent to a dozen of partners
    - J. Abadie et al. , A&A., 539, 2012.

Ze End

of ze first part

(as we say in french)