Present Status of Gravitational Wave Detection and Future Programs

Adalberto Giazotto

INFN-Pisa and

European Gravitational Observatory
The Indirect Evidences of GW Existence

1974: First Discovery
Taylor and Hulse

Coalescing Neutron Star System PSR 1913+16

Nobel Prize 1993

Orbital period decreasing changes periaster passage time in total agreement with GR

Now there are about 6 similar systems, and the “double pulsar” PSR J0737-3039 is already overtaking 1913 in precision. All agree with GR
The GW Amplitude in TT system
For a GW propagating along $X_3$ we obtain the amplitude:

$$h_{TT}^{\mu
u} = h_{TT}^{11} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} + h_{TT}^{12} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = h^+ e^+_{ik} + h^x e^x_{ik}$$

The polarizations $e^+_{ik}$ and $e^x_{ik}$ are exchanged with a $\pi/4$ rotation around $x_3$ axis i.e. GW are spin 2 massless fields.

In the limit of weak gravity, GW amplitude is proportional to the second time derivative of the source mass quadrupole moment:

$$h_{\alpha\beta} = -\frac{2G}{c^4 R_0} \left( \frac{\partial^2}{\partial t^2} \int \rho (x_\alpha x_\beta)^{TT} dV \right)_{t - R_0 / c}$$

- **Large Asymmetry**
  - "Large h"
  - ![Large h Diagram](image)
- **Small Asymmetry**
  - "Small h"
  - ![Small h Diagram](image)
- **Axy-symmetry**
  - "h=0"
  - ![Axy-symmetry Diagram](image)
1) Coalescing Binary Systems: NS and Black Holes

- Rate $\approx 0.01$ per year in a 100 Mly sphere.

2) Supernovae Explosions

- Explosions Rate:
  - Virgo Cluster ($h \approx 10^{-23}$) $\approx 30$ per year
  - Milky Way ($h \approx 10^{-20}$) $1/30$ years

3) Periodic Sources:

- For rotating Neutron Stars $h$ very "Small" $h < 10^{-25}$.
  - Very long integration time (1 year) increases S/N.

4) Big-Bang Cosmological BKG (CB):

- Since $\alpha_{\text{GRAV}} = 10^{-39}$ Big-Bang matter is mainly transparent to GW. In the Virgo bandwidth we may observe GW emitted after $10^{-24}$s from time zero.
F.A.E. Pirani in 1956 first proposed to measure Riemann Tensor by measuring relative acceleration of two freely falling masses. If A and B are freely falling particles, their separation $\xi^\alpha = (x_A - x_B)^\alpha$ satisfies the Geodesic Deviation equation:

$$\frac{D^2 \xi^\alpha}{dt^2} \Rightarrow \frac{1}{2} \ddot{h}_{\alpha\beta} \xi^\beta$$

The receiver is a device measuring space-time curvature i.e. the relative acceleration of two freely falling masses or, equivalently, their relative displacement.
Gravitational Waves create tidal forces on the masses

**Force increase with L until L < λ**

\[ F_\beta = -\frac{1}{2} M L_\alpha \frac{d^2}{dt^2} h_\beta \]

\[ \Delta L \sim h < 10^{-22} \]

**Effect of 2 Polarizations**

- \( h_+ \)
- \( h_\times \)
In 1959 Joseph Weber was the first to build a GW detector working on the principles of Geodesic Deviation Equation.

Figure courtesy of Massimo Cerdonio
Cryogenic Bar Detectors

*International Gravitational Event Collaboration*

Cryogenic Bar Detectors network founded in 1997
Cryogenic Bar Detectors Sensitivity & Stability

NAUTILUS (INFN LNF)

EXPLORER (INFN CERN)

IGEC-1 (1997-2000)

ALLEGRO (LSU)

IGEC-2 (2005--)

AURIGA (INFN LNL)
Bar Detectors situation at present

NIOBE (Perth) stopped operation and did not join IGEC-2
ALLEGRO (LSU) stopped operation in 2007

In 2006 INFN stopped R&D on Spherical Detectors and left running Auriga, Nautilus and Explorer on an annual evaluation.

Spherical Detectors in commissioning phase are Minigrail in Leyden Univ. (Nd) and Mario Schenberg in S. Paulo Univ. (Br)
INTERFEROMETRIC DETECTORS

Large L → High sensitivity
Very Large Bandwidth 10-10000 Hz

Displacement sensitivity can reach $\sim 10^{-19}-10^{-20}$ m, then, for measuring $\Delta L/L \sim 10^{-22}$, $L_A$ and $L_B$ should be km long.
Optical Noises cannot be overcome in standard ITF but can with QND techniques. Radiation Pressure Fluctuations contribution to phase shift can be completely cancelled.

Thermal Noise, the more subtle, can perhaps be overcome by bringing Mirror temperature close to 4 K°
Two Very Important Quantum Noises:
Shot noise and Radiation pressure Fluctuations

1) Shot Noise:
Uncertainty Prin. $\Delta \varphi \Delta N \geq 1$.
The phase of a coherent light beam fluctuates as:
$$\varphi \geq \frac{1}{\sqrt{N}} = \sqrt{\frac{h \nu}{W t}}$$

2) Radiation Pressure Noise
The photon number fluctuations create a fluctuating momentum on the mirrors of the FP cavities:
$$\delta \tilde{P} \approx F \frac{h \nu}{c} \sqrt{W} = \frac{F}{c} \sqrt{h \nu W}$$

The measurability cond. for Shot noise and Radiation Pressure noise is:
$$\tilde{h}^2 > \left( \frac{2}{LM\Omega^2 c} \right)^2 h \nu W F^2 + \frac{\lambda^2}{16\pi^2} \frac{h \nu}{W F^2} \frac{1 + \left( \frac{\Omega FL}{c} \right)^2}{L^2}$$
How to cancel Radiation Pressure Fluctuations for beating SQL

E.M. Field Vacuum Fluctuations
C. Caves-1963

\[
\begin{pmatrix}
a_0 \\ a_{\pi/2}
\end{pmatrix}
\]

- Intensity Fluct
- Phase Fluct.

Symmetrical ITF

Squeezing Factor

\[
K = \frac{32\omega_0 WF^2}{Mc^2\Omega^2}
\]

Rad. Press. Fluct.

Coherent State

\[
\begin{pmatrix}
a_{\pi/2} \\ a_0
\end{pmatrix}
\]

Laser

\[
\begin{pmatrix}
a_0 \\ a_{\pi/2}
\end{pmatrix}
\]

Detuned Cavity

\[
\begin{pmatrix}
1/K & -1 \\
1 & 1/K
\end{pmatrix}
\]

No Rad. Press. Fluct. anymore

\[
\begin{pmatrix}
a_0 \\ a_{\pi/2} + \Gamma hL - Ka_0
\end{pmatrix}
\]

\[
\frac{a_0}{K} - a_{\pi/2} - \Gamma hL + Ka_0
\]

\[
\frac{a_{\pi/2} + \Gamma hL}{K}
\]

\[
\frac{a_{\pi/2} - a_{\pi/2} - \Gamma hL + Ka_0}{K}
\]

Phase Noise

\[
\theta
\]

\[
\begin{pmatrix}
a_{\pi/2} \\ a_0
\end{pmatrix}
\]

Radiation Pressure Noise

\[
\cong K
\]

\[
\cong \frac{1}{K}
\]

Radiation Pressure Noise

\[
\cong K
\]
Signal Recycling may produce rotations in the ΔN-Δφ (a_0 a_{π/2}) space

**Power Recycling**

Laser W, \( \omega_0 \)

\[ \begin{pmatrix} h_0 \\ h_{π/2} \end{pmatrix}, \begin{pmatrix} a_0 \\ a_{π/2} \end{pmatrix} \]

**Signal Recycling**

\[ \begin{pmatrix} a_0 \\ a_{π/2} \end{pmatrix}, \begin{pmatrix} \beta_0 \\ \beta_{π/2} \end{pmatrix} \]

By Detuning D_3

Varying D_3 at each frequency for best S/N

SQL

R=0.9
R=0.99
R=0.999

No Recycling
Squeezed Vacuum Injection and the Photodiode Problem: Quantum Fluctuations Amplification

\[ \begin{align*}
&\left( a_\pi/2 \right)
\end{align*} \]

\[ \begin{align*}
&\left( a_\pi/2 \right)
\end{align*} \]

\[ \begin{align*}
&\left( a_\pi/2 \right)
\end{align*} \]

Laser

Detuned Cavity

Phase Fluct. Amplif.

Efficiency 1-\( \varepsilon \)

\[ Q = \sqrt{\varepsilon} \left( \frac{\eta_0}{\eta_{\pi/2}} \right) + \sqrt{1-\varepsilon} \left( \frac{Y_0}{Y_{\pi/2}} \right) \]

\[ T = \sqrt{\varepsilon} \]

\[ R = \sqrt{1-\varepsilon} \]

\[ \Gamma h L \geq \sqrt{\frac{1}{K^2} + \varepsilon \frac{K^2}{Z^2 (1-\varepsilon)}} \]

\[ \varepsilon = 410^{-2} \]

\[ \bar{K} \leq \frac{Z}{K} \sqrt{\frac{(1-\varepsilon)}{\varepsilon}} \approx 5 \frac{Z}{K} \]
Virgo Diagram

Ref. Cav. | Common mode
0-2Hz | 2-10000Hz
$\Delta \nu = 10^{-4} \text{Hz}^{1/2}$ | $\Delta \nu = 10^{-6} \text{Hz}^{1/2}$

Angular Alignment Matrix

F=30
GW Detectors have a very appealing Antenna pattern

Radiotelescope Antenna Pattern

Sources are localized
“Geometrically“

Interferometric GW Detector Antenna Pattern
ALL sky seen at once.

Less than 1" of arc
Global network of Detectors

Coherent Analysis: why?
- Sensitivity increase
- Source direction determination from time of flight differences
- Polarizations measurement
- Test of GW Theory and GW Physical properties

Astrophysical targets
- Far Universe expansion rate Measurement
- GW energy density in the Universe
- Knowledge of Universe at times close to Planck’s time
In 1999, TAMA is the first large ITF to start observations, in 2001 attained the world best sensitivity and made continuous observation more than 1000 hr with the highest sensitivity. Joint observations with LIGO/GEO during DT7-DT9

Best sensitivity: $h = 1.710^{-21} \sqrt{\text{Hz}} @ 1 \text{KHz}$

Recycling gain of 4.5
GEO 600 m - Hannover

GEO 600 is a Signal Recycling Interferometer

Power Recycling 1%
Signal Recycling 1%

Strain [1/μs(kHz)]

Typical Sensitivity: Science Runs

S1 Aug 26 '02
S3 Nov 2 '02
S2 Dec 31 '03
S4 Feb 22 '04
S5 N&W Mar 23 '06
S5 Jun 3 '06

ΔS/Δρ [1/μs(kHz)]

Freq. [Hz]
3 km-Cascina

France (CNRS) 50%
Italy (INFN) 50%
Virgo Sensitivity, Duty Cycle and Stability
First 5 weeks (started 18/5/2007) of Coincidence with LIGO/GEO

Progress of Virgo Sensitivity

- Virgo Design
- C1 (Nov. 2003)
- C2 (Feb. 2004)
- C3 (Apr. 2004)
- C4 (Jun. 2004)
- C5 (Dec. 2004)
- C6 (Aug. 2005)
- C7 (Sep. 2005)
- WSR1 (Sep. 2006)
- WSR9 (Feb. 2007)
- VSR1 (Sep. 2007)
- Last (Apr. 2008)
LIGO (Caltech/MIT)

One Vacuum Tube with
2 ITF: 4 km and 2 km
Hanford- Wash. State

4 km Arms
Livingstone-Louisiana

Strain Sensitivity for the LIGO Hanford 4km Interferometer

1999 2000 2001 2002 2003 2004 2005 2006

First Science Data

S1  S2  S3  S4  S5

Stop Oct. 2007
GW DETECTORS SENSITIVITY

Strain sensitivity [Hz^{-1/2}]

Frequency [Hz]

LIGO LHO 4km S5
LIGO LLO 4km S5
LIGO LHO 2km S5
GEO S5
Virgo (Apr. 2008)
Virgo Design

AURIGA,
NAUTILUS,
EXPLORER

TAMA 300
GEO600
LIGO
Virgo
Some comments on Virgo low frequency performances

SUPERATTENUATORS

Isolate mirrors and optical benches from Seismic noise ($10^{12}$ larger than signal @ 10 Hz)

6 SA for mirror suspension
3 SA for optical benches
Inertial Damping

Inverted Pendulum

\( \nu_{RES} = 40 \text{ mHz} \)

Mechanical Filters

\(~10\text{ m}\)

Marionet

Mirror

SA Transf. Function

Direct Transfer Function

Stage by Stage Transfer Function

6 \times 10^{-21}

4Hz

h(\sqrt{1/Hz})

- Seismic noise (Theory)
- Seismic noise (Measure)
- Thermal Noise
- Quantum Limit
- Shot Noise
- Newtonian
Superattenuator: Marionetta- Reference Mass - Mirror

Coils

marionetta

Mirror

Reference Mass
GW DETECTION STATUS

IGEC: Network of Bar Detectors Started in 1997 (Auriga, Explorer, Nautilus, Allegro) for impulsive GW detection. No evidence of a significant GW signal

LIGO-GEO600: GW from Pulsar (28 known) - $\varepsilon < 10^{-5} - 10^{-6}$ (no mountains > 10 cm) - $h$ upper limits: $2.10^{-24}@200Hz$, $5.10^{-24}@400Hz$, $10^{-23}@1KHz$ No evidence of a significant GW signal

LIGO, GEO600, TAMA: Up. lim.: Coalescing NS-NS $<1$ event/(gal.year) $2 < M_0 < 6$ Coalescing BH-BH $<1$ event/(gal.year) $10 < M_0 < 80$ No evidence of a significant GW signal

LIGO: Stockastic BKG

Virgo, LIGO, GEO 600: May 18th-Oct. 2007 started common data taking and coherent analysis; main target impulsive events. Analysis running
## The Future

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**Virgo+**

1) Cure low freq. Noise  
2) Fused silica suspens  
3) Increase arm finesse  
4) Higher power laser

**Enhanced Ligo**

1) DC readout  
2) Higher laser power  
3) Output modecleaner  
4) A factor of 2 improv. in sensitivity (8 in event rate)

(Data taking starts 2014)

---

**Advanced Virgo**

1) Larger mirror  
2) Improved coatings  
3) Higher laser power  
4) DC readout  
R&D underway  
Design decisions late 2008

(Data taking starts 2014)

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**Advanced Ligo**

1) Active anti-seismic system operating to down to 10 Hz  
2) Lower thermal noise suspensions and optics  
3) Higher laser power  
4) More sensitive and more flexible optical configuration
<table>
<thead>
<tr>
<th>Parameter</th>
<th>LIGO</th>
<th>Advanced LIGO</th>
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<tbody>
<tr>
<td>Input Laser Power</td>
<td>10 W</td>
<td>180 W</td>
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<tr>
<td>Mirror Mass</td>
<td>10 kg</td>
<td>40 kg</td>
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<td>Interferometer Topology</td>
<td>Power-recycled</td>
<td>Dual-recycled</td>
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<td>Fabry-Perot arm cavity</td>
<td>Fabry-Perot arm cavity Michelson</td>
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<td>GW Readout Method</td>
<td>RF heterodyne</td>
<td>DC homodyne</td>
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<tr>
<td>Optimal Strain Sensitivity</td>
<td>$3 \times 10^{-23}$/ rHz</td>
<td>Tunable, better than $5 \times 10^{-24}$/ rHz</td>
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<td>Seismic Isolation</td>
<td>$f_{low} \sim 50$ Hz</td>
<td>$f_{low} \sim 10$ Hz</td>
</tr>
<tr>
<td>Mirror Suspensions</td>
<td>Single Pendulum</td>
<td>Quadruple pendulum</td>
</tr>
</tbody>
</table>
The graph illustrates the frequency response of various noise sources, including quantum noise, gravity gradients, suspension thermal noise, coating Brownian noise, coating thermo-optic noise, substrate Brownian noise, and total noise. The graph shows the strain [1/\sqrt{Hz}] as a function of frequency [Hz], highlighting the impact of thermal noise and coatings.

Coatings pervasive Thermal Noise

Coatings pervasive
Sensitivity x10, Sky Vol. x1000
Two Projects very important for the future

**LCGT: A 3 km CRYOGENIC Interf. in Japan**

- Mirrors Cooled at 20 K
- Radiation outer shield
- Heat links start from this stage to inner radiation shield
- SAS: 3 stage anti-vibration system with inverted pendulum
- SPI auxiliary mir.
- Sapphire fiber suspending main mirror
- Main mirror
- Heat links start from this stage to inner radiation shield

**AIGO- A 5 km Interf. In Australia**

- Cost: US$ 135M
- Mirrors
- Cooled at 20 K
- Radiation outer shield
- Heat links start from this stage to inner radiation shield
- SAS: 3 stage anti-vibration system with inverted pendulum
- SPI auxiliary mir.
- Sapphire fiber suspending main mirror
- Main mirror
- Heat links start from this stage to inner radiation shield

**LCGT noise budget**

- Noise level [1/Hz^2]
- Frequency [Hz]
- LCGT noise budget:
  - Shot noise
  - Radiative noise
  - Radiation pressure
  - Suspensoid noise thermal
  - Mirror thermal
  - TAMA noise level

**With AIGO**

**Without AIGO**
LISA

- Launch >2018
- Mission duration up to 10 yrs.
- LISA Pathfinder technology demonstrator (ESA: 2011)

Courtesy B. Shutz
• Laser beams reflected off free-flying test masses
• Diffraction widens the laser beam to many kilometers
  - 0.7 W sent, 70 pW received
• Michelson with 3rd arm, Sagnac
• Can distinguish both polarizations of a GW
• Orbital motion provides direction information
Cluster of 3 LISA spacecraft
LISA Pathfinder

1) Qualification of every piece is done.
2) Flight model will be ready in 1 year.
3) Satellite ready.
4) Launch 2010-2011.
Einstein Telescope Baseline Concept

• Underground location
  – Reduce seismic noise
  – Reduce gravity gradient noise
  – Low frequency suspensions $f > 1 \text{ Hz}$

• Cryogenic & Squeezed

• Beam tube length 10+10 km

• Possibly different geometry
Einstein Telescope Configuration

1) ET will be the only surviving project. Virgo and LIGO will not have enough sensitivity for making a Network with ET

2) ET should be formed by at least 4 interferometers, well spaced in such a way to accurately measure source angle from time of flight differences. A wise decision could be in the same spirit as ESO whose telescopes are not in Europe. ET network should have at least one detector in southern hemisphere for better solving the “Inverse Problem”.
ET Sensitivity

Harald Lück
for the European Gravitational-Wave Community
Some exercise: Use of Superattenuators for ET

1) Inverted Pend. 40 mHz
2) 50 m tall mechanical filter chain

By assuming a seismic noise underground $10^{-8}m/\sqrt{Hz}$ @1Hz, from the TF optimized at 2Hz we obtain $h(2Hz)=10^{-25}/\sqrt{Hz}<<10^{-22}/\sqrt{Hz}$
ET Prototyping

It is likely that the majority of ET noises cannot be model, due to the extreme sensitivity needed:

a) Diffused light cannot be model
b) e.m. fields cannot be model
c) Ground Loops cannot be model

Etc........

To my opinion Interested nations should make a pool for building a full scale prototype.
Some Final Considerations

• Bar detectors have grown up, by means of a fantastic technological effort, to enormous and unexpected sensitivity and operation stability. Their operation was so good as to create the first GW network.

• The big steps forward in the last decade has been in the Interferometers technology. They reached design sensitivity almost to 10 Hz and stability is so good (unexpectedly) that we have created an efficient network. Virgo, now, is opening the very low frequency region and Advanced LIGO and Virgo will further reduce noise in this troublesome frequency region.

• Class Einstein, after what we have learned by the big machines, seems feasible with a very high probability of success. 1 Day of data of ET is equivalent to $10^6$ days of data taking with Virgo or LIGO. This seems to be the right way to go for starting GW astronomy.
Modern Interferometers with QND Signal Readout

Uncertainty Principle: \( \Delta \phi \Delta N \approx 1 \)

We only measure \( \phi \), the only one containing the signal, hence we can ignore \( \Delta N \).

In a Fix Mirror ITF, Rad. Press. Fluct. can’t move mirrors.

In a suspended Mirror ITF, Rad. Press. Fluct. move randomly mirrors, hence Phase noise is increased.

A Detuned Cavity can rotate in the \( \Delta \phi, \Delta N \) plane. Phase noise \( \Delta \phi \) has been decreased at expenses of \( \Delta N \).

\[
K = \frac{32\omega_0 WF^2}{Mc^2\Omega^2}
\]
Modern Interferometers with QND Signal Readout

\[ K = \frac{32\omega_0 WF^2}{Mc^2\Omega^2} \]

\[ K \approx \frac{1}{K} \]

\[ \Delta N \approx K \]

\[ \Delta \Phi \approx \frac{1}{K} \]

\[ \Phi \]

\[ \Delta \phi \]

\[ \text{Phase Fluct.} \]

\[ \text{Rad. Press. Fluct.} \]

\[ \text{Radiation Pressure Noise} \]

\[ \text{Signal} \]

\[ \text{Phase Noise} \]

\[ a_0 \left\{ a_{\pi/2} + \Gamma h L - K a_0 \right\} \]

\[ K = \frac{3\omega_0 WF^2}{Mc^2\Omega^2} \]
How to go below the SQL: Modern Interferometers with QND Signal Readout

In interferometric detectors, GW produce sidebands at frequency $\omega_0 \pm \Omega$ and emission of two correlated photons of frequency $\omega_0 \pm \Omega$:

$$e^{i\omega_0 t} e^{i\omega t} (t - \frac{\varepsilon}{c} \cos \Omega t) \approx e^{i\omega_0 t} - \frac{\varepsilon}{c} e^{i(\omega_0 + \Omega) t} \frac{1}{2} + e^{i(\omega_0 - \Omega) t}$$

The Total e.m. Field

$$a_0 (\Omega) = \frac{a_+ + a_-}{\sqrt{2}}$$
$$a_{\pi/2} (\Omega) = \frac{a_+ - a_-}{i \sqrt{2}}$$

$$E_{\text{Total}} = C \left[ (\alpha_0 + a_0 (t)) \cos \omega_0 t + (\alpha_{\pi/2} + a_{\pi/2} (t)) \sin \omega_0 t \right]$$

Classical Field

Carrier

Quantum Field

Quadratures

$$\alpha_0$$

$$\alpha_{\pi/2}$$

Intensity Fluct.

Phase Fluct.
If we find a way to rotate quadratures by an angle \( \theta = \arctan K \) we can get rid of Radiation Pressure Fluctuations in the phase shift channel.
\[
\frac{4\pi hL}{\lambda} \geq \sqrt{\frac{K+1}{K}}
\]

Detuned Cavity

\[
\left(\begin{array}{c}
\frac{1}{k}
\frac{-1}{k} \\
\frac{1}{k}
\frac{1}{k}
\end{array}\right) \left(\begin{array}{c}
a_0 \\
a_{\pi/2} + \Gamma hL - Ka_0
\end{array}\right) = \left(\begin{array}{c}
a_0 \\
a_{\pi/2} + \Gamma hL
\end{array}\right)
\]

\[
Y_0
\frac{Y_{\pi/2}}{\gamma}
\] = \[
\frac{a_0}{K - a_{\pi/2} - \Gamma hL + Ka_0}
\frac{a_{\pi/2} + \Gamma hL}{K}
\]

\[
Q = \sqrt{\epsilon} \left(\begin{array}{c}
\eta_0 \\
\eta_{\pi/2}
\end{array}\right) + \sqrt{1-\epsilon} \left(\begin{array}{c}
Y_0 \\
Y_{\pi/2}
\end{array}\right)
\]

Photodiode Efficency 1-\(\epsilon\)

\[
\Gamma hL \geq \sqrt{1 + K^2 \frac{\epsilon}{1-\epsilon}}
\]

\[
\epsilon = 410^{-2}
\]

\[
K \leq \sqrt{\frac{1-\epsilon}{\epsilon}} \approx 5
\]
\[ Q = \sqrt{\varepsilon} \left( \begin{array}{c} Y_0 \\ Y_{\pi/2} \end{array} \right) + \sqrt{1-\varepsilon} \left( \begin{array}{c} Y_0 \\ Y_{\pi/2} \end{array} \right) \]

\[ T = \sqrt{\varepsilon} \]

\[ R = \sqrt{1-\varepsilon} \]

\[ \Gamma h L \geq \sqrt{1 + K^2 \varepsilon} \]

\[ \varepsilon = 410^{-2} \]

\[ K \leq \frac{1-\varepsilon}{\varepsilon} \approx 5 \]
Inertial Damping

Inverted Pendulum $\nu_{RES} = 40 \text{ mHz}$

Mechanical Filters

Marionet

Mirror

SA Transf. Function

Direct Transfer Function

Stage by Stage Transfer Function

$6 \times 10^{-21}$
Some comments on Virgo low frequency performances

SUPERATTENUATORS

Isolate mirrors and optical benches from Seismic noise \((10^{12} \text{ larger than signal @ 10 Hz})\)

6 SA for mirror suspension
3 SA for optical benches
SUPERATTENUATORS: Isolate mirrors and optical benches from Seismic noise ($10^{12}$ larger than signal @ 10 Hz)

- Inertial Damping
- Inverted Pendulum
  - $\nu_{\text{RES}} = 40 \text{ mHz}$
- Mechanical Filters
- Marionet
- Mirror

SA Transf. Function

- Direct Transfer Function
- Stage by Stage Transfer Function