L’Interferometro Virgo

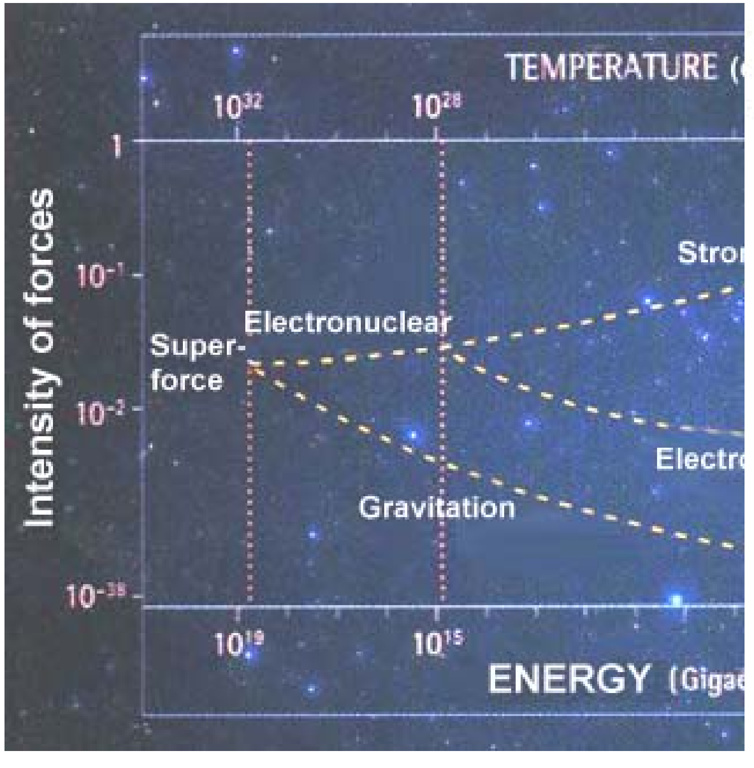
Michele Punturo

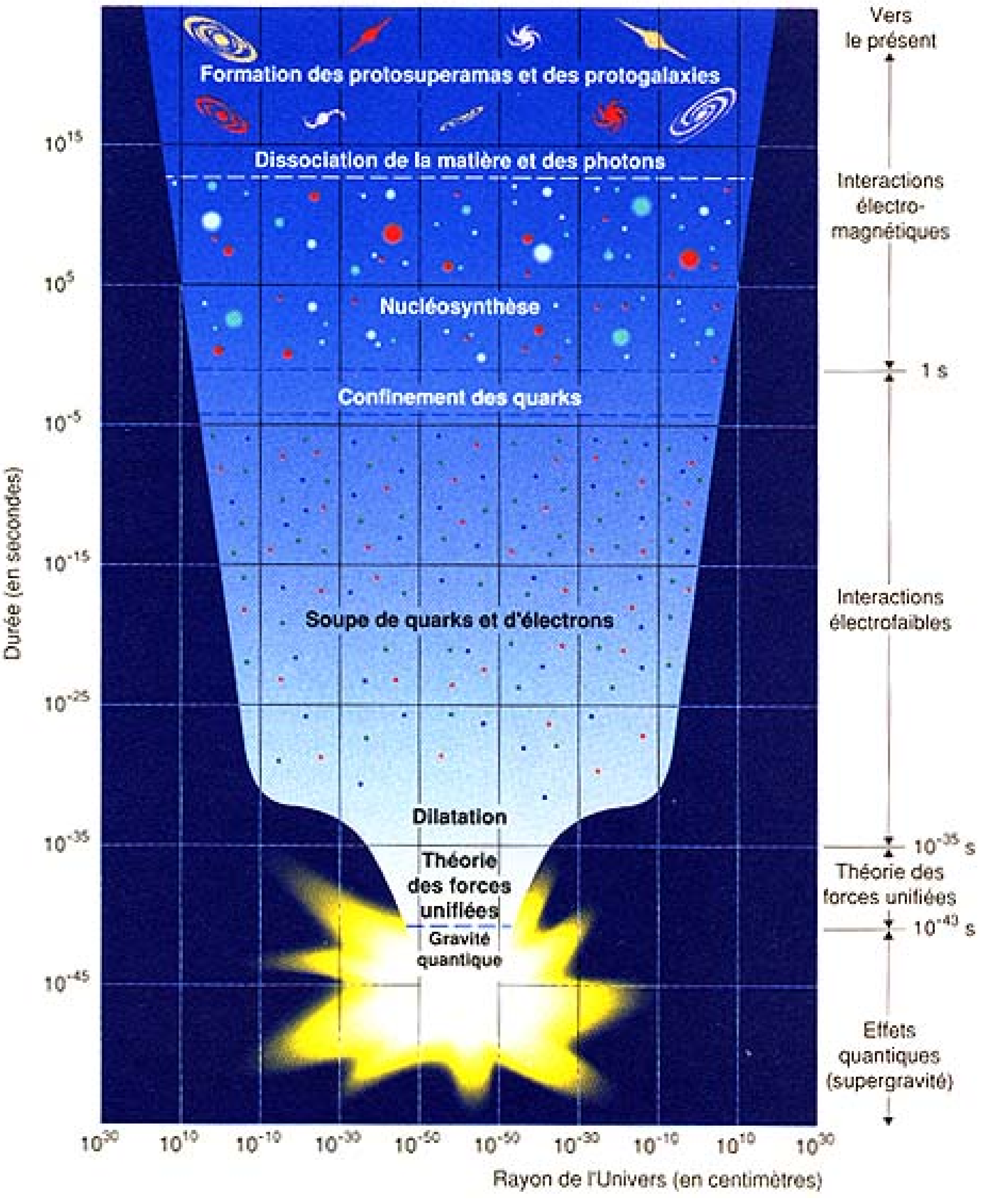
INFN Perugia

a nome della Collaborazione Virgo

Le onde gravitazionali all'IFAE?

- Cosa c'è di più di "Alta Energia" della gravitazione?





La collaborazione Virgo

•L’esperimento Virgo è realizzato da una collaborazione italo-francese

- Firenze/Urbino
- Frascati (LNF)
- Napoli
- Pisa
- Perugia
- Roma (Roma1)

- Annecy (LAPP)
- Lyon (IPNL)
- Orsay (LAL)
- Nice (ILGA/OCA)
- Paris (ESPCI)

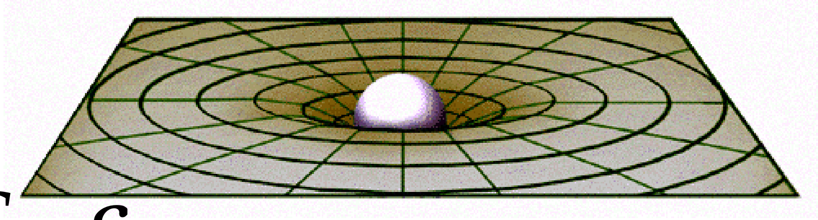
Gravitation in the General Relativity

- General Relativity field equation

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

Energy-Momentum tensor ($T_{\mu\nu}$)

Space-time deformation tensor ($G_{\mu\nu}$)



- Naïf interpretation of this equation:
  - Generalized Hooke equation:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl}$$

Stress tensor (σ_{ij})

Strain tensor (ε_{kl})

Elasticity coefficients tensor (C_{ijkl})

$E_{steel} \approx 2 \cdot 10^{11} \, Pa$

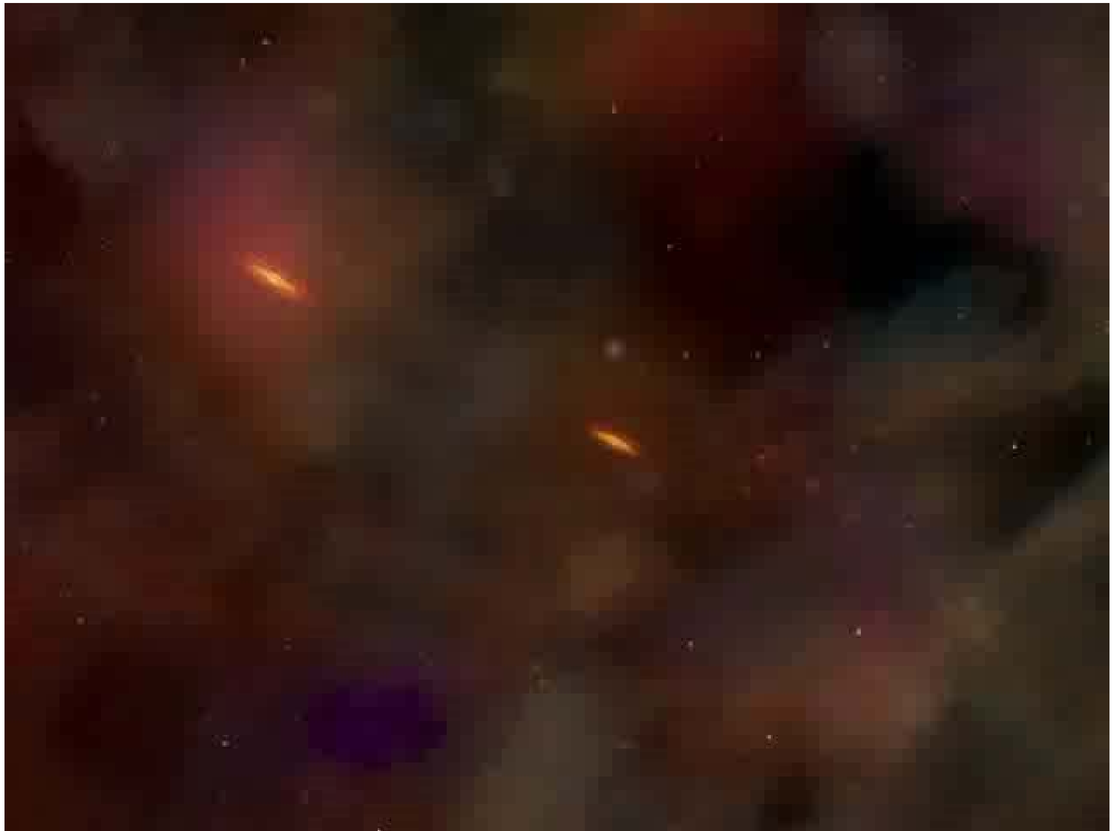
$\frac{c^4}{8\pi G} \approx 4.8 \cdot 10^{42} \, N$

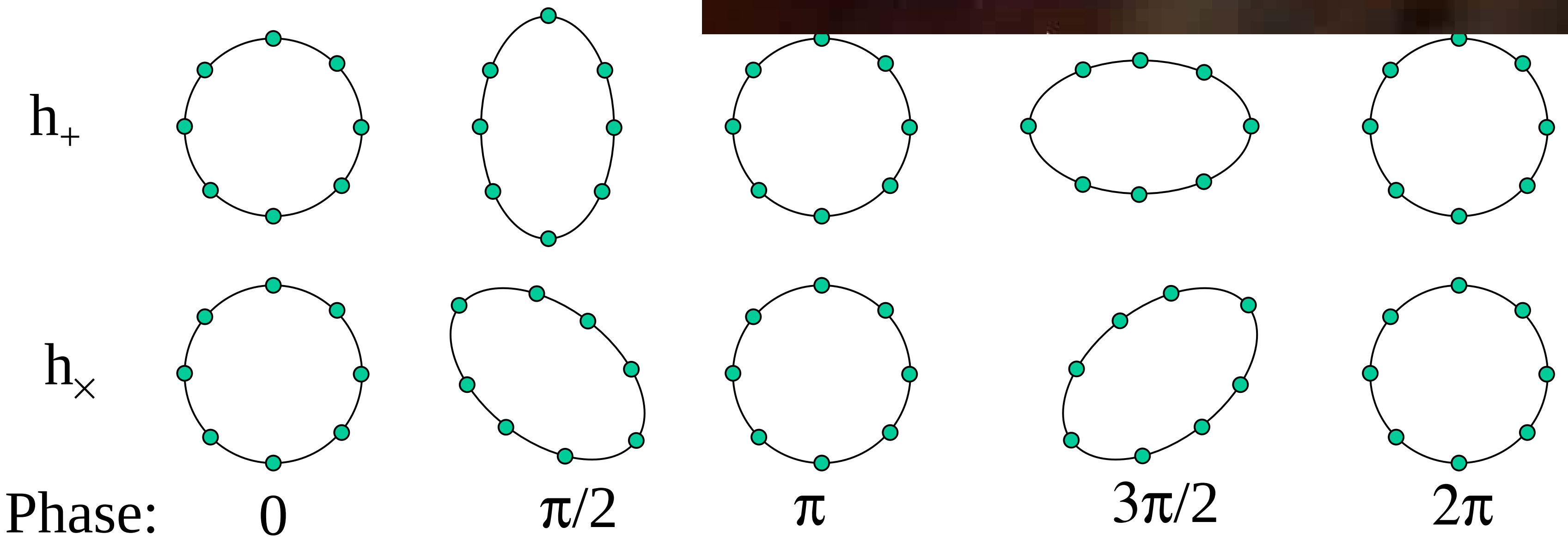
⇒ Space-time is a very rigid medium:
Linear approximation of the field equation is allowed

•A.Einstein proposed the linearized solution of the field equation in 1916 (wave propagating at speed c and with two polarizations):

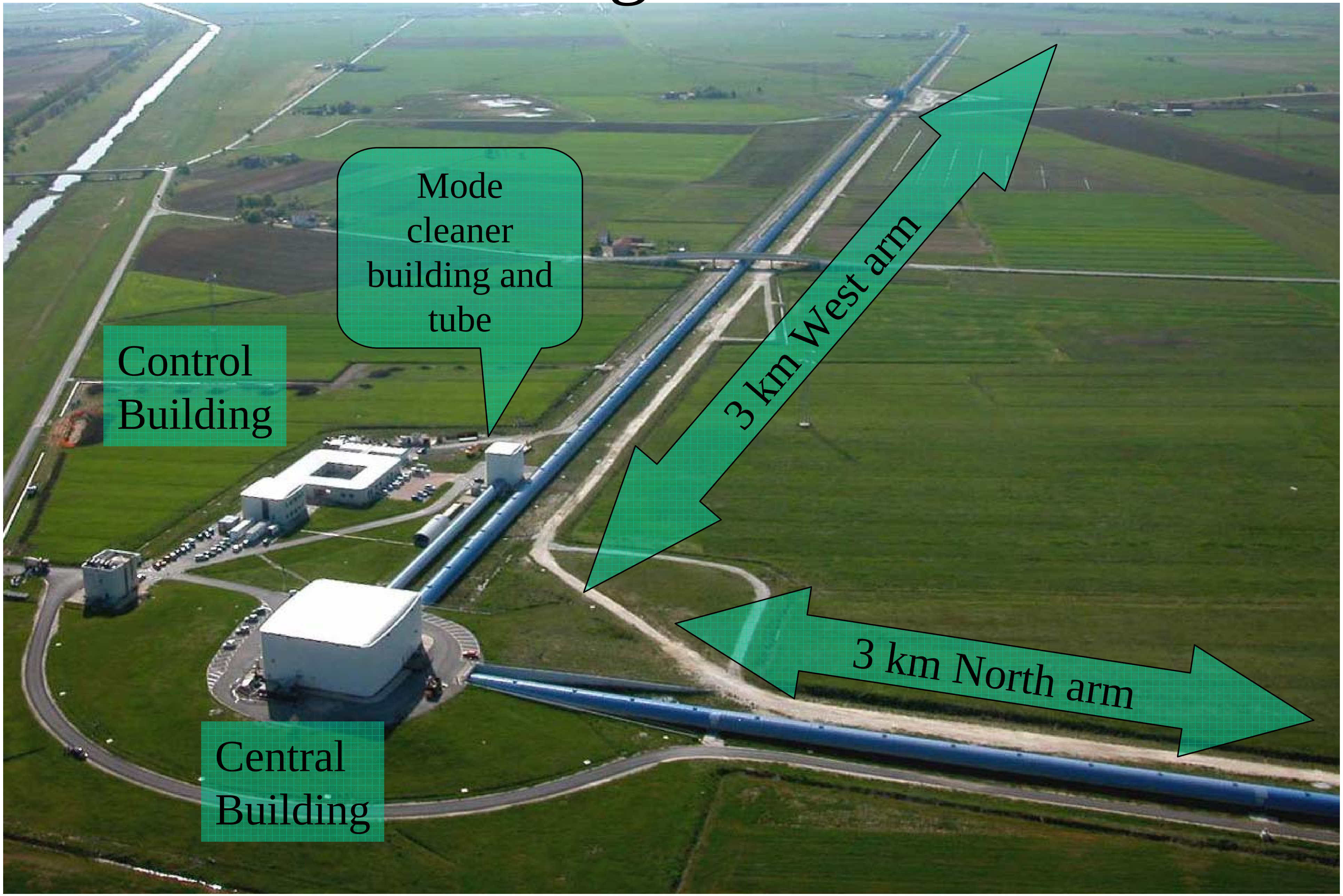
Gravitational Waves

$$\frac{\Delta l}{l} \approx \frac{h(t)}{2}$$





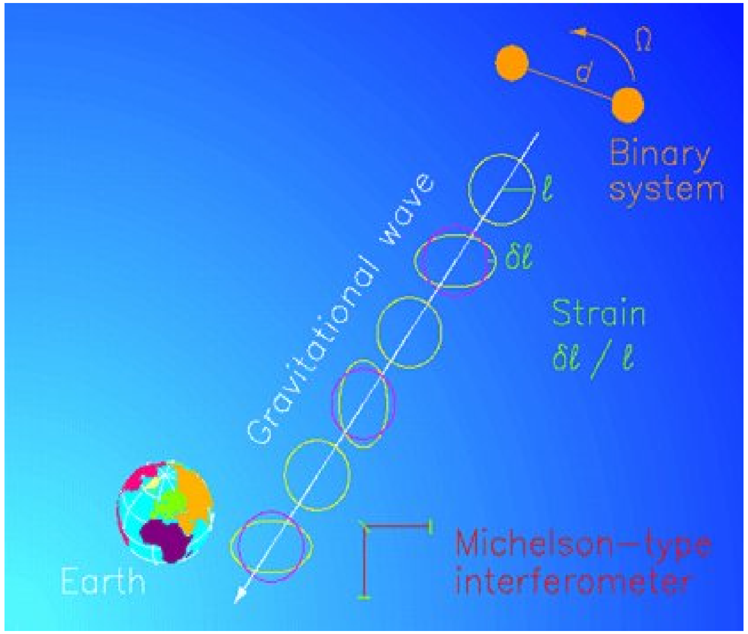
The Virgo Detector



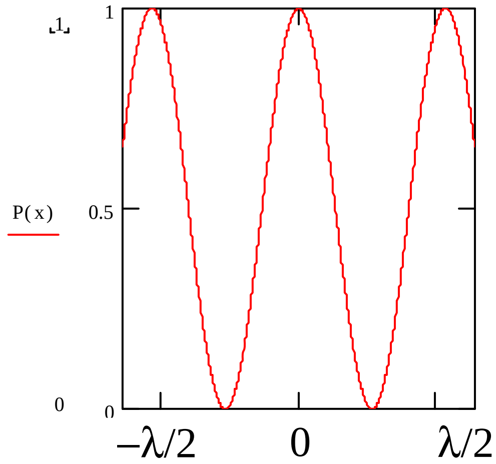
Working principle

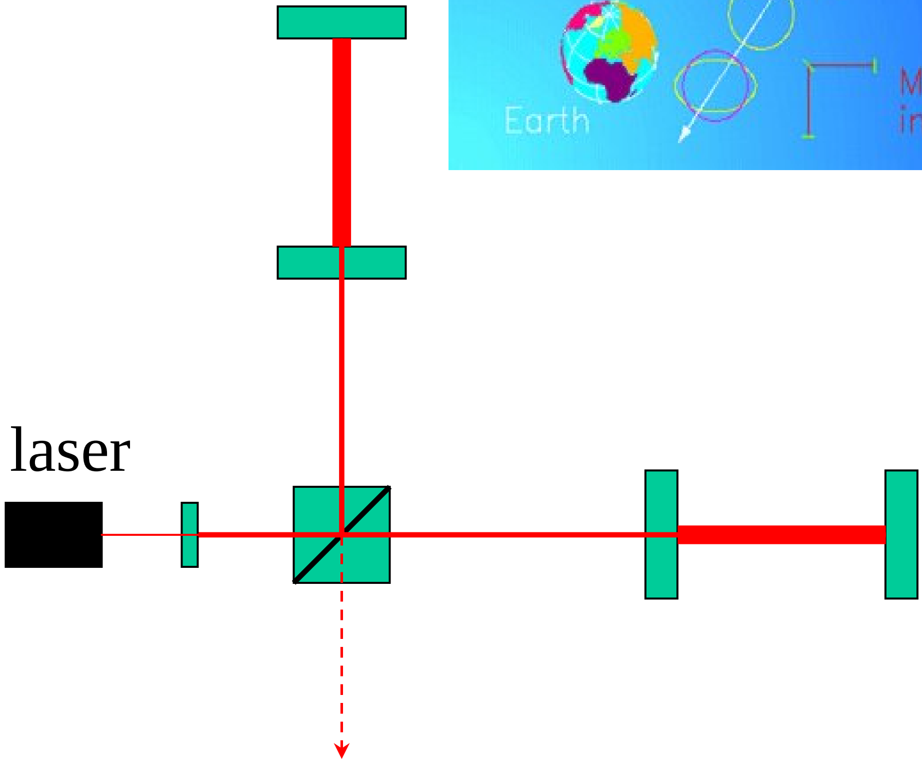
$$h \approx 10^{-23} \div 10^{-21}$$

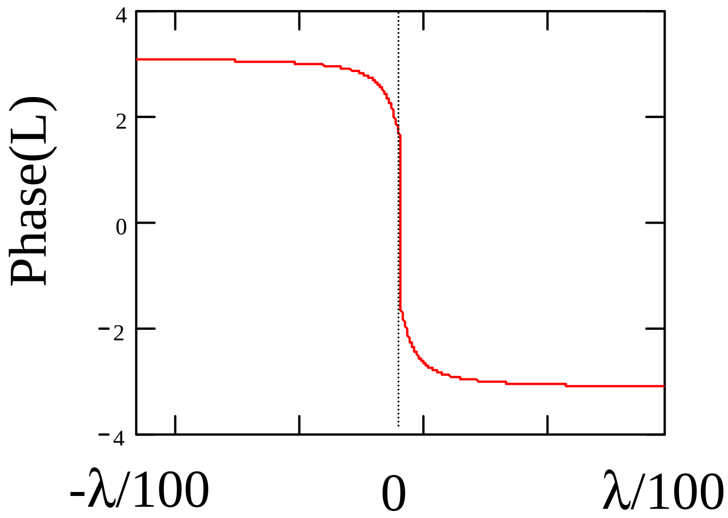
$$\Delta L \approx 10^{-20} \div 10^{-18}\, m$$



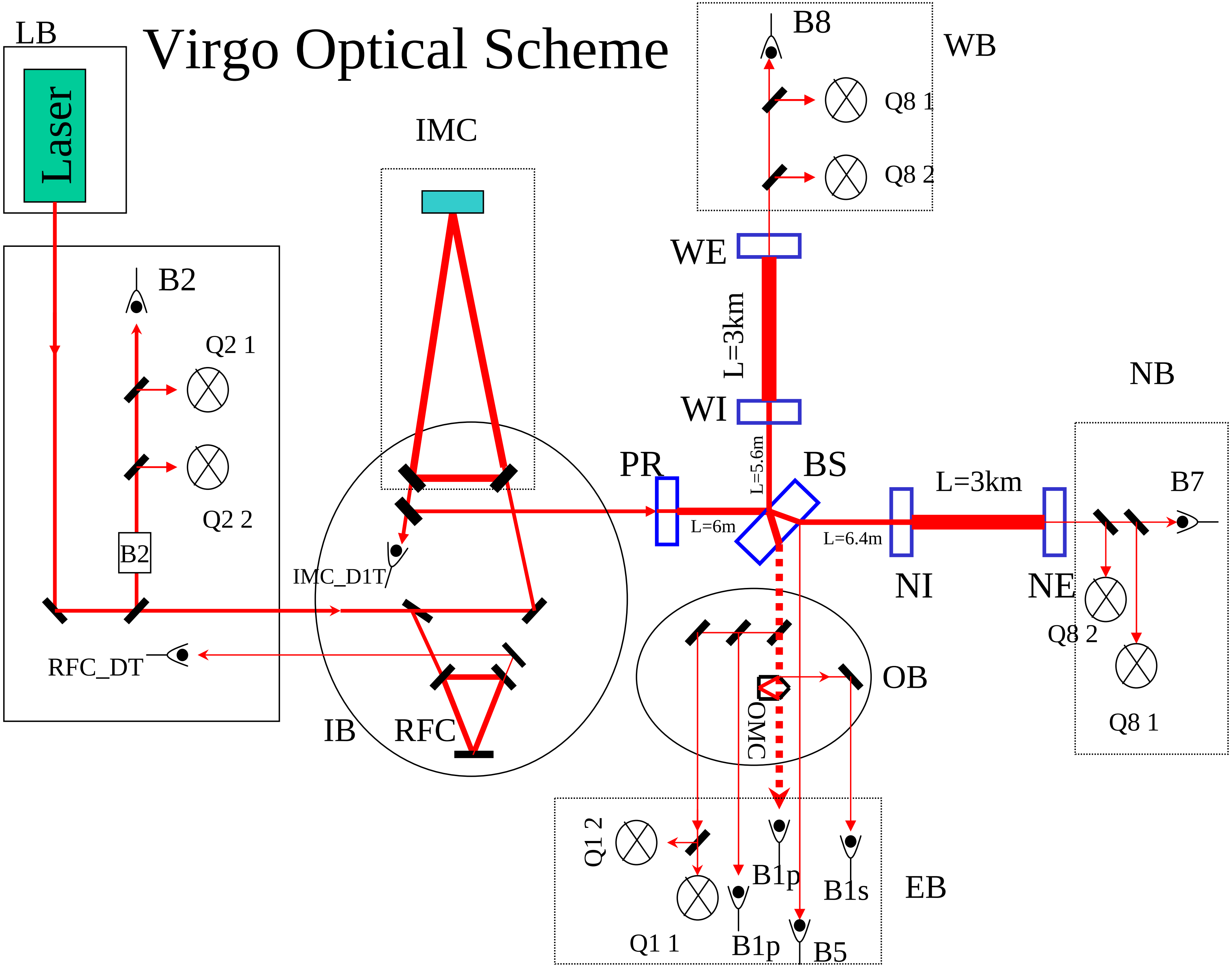
$$P_{out} = P_{in} \cdot \cos^2\left[\frac{2\pi}{\lambda_{laser}} \cdot L \cdot h\right]$$



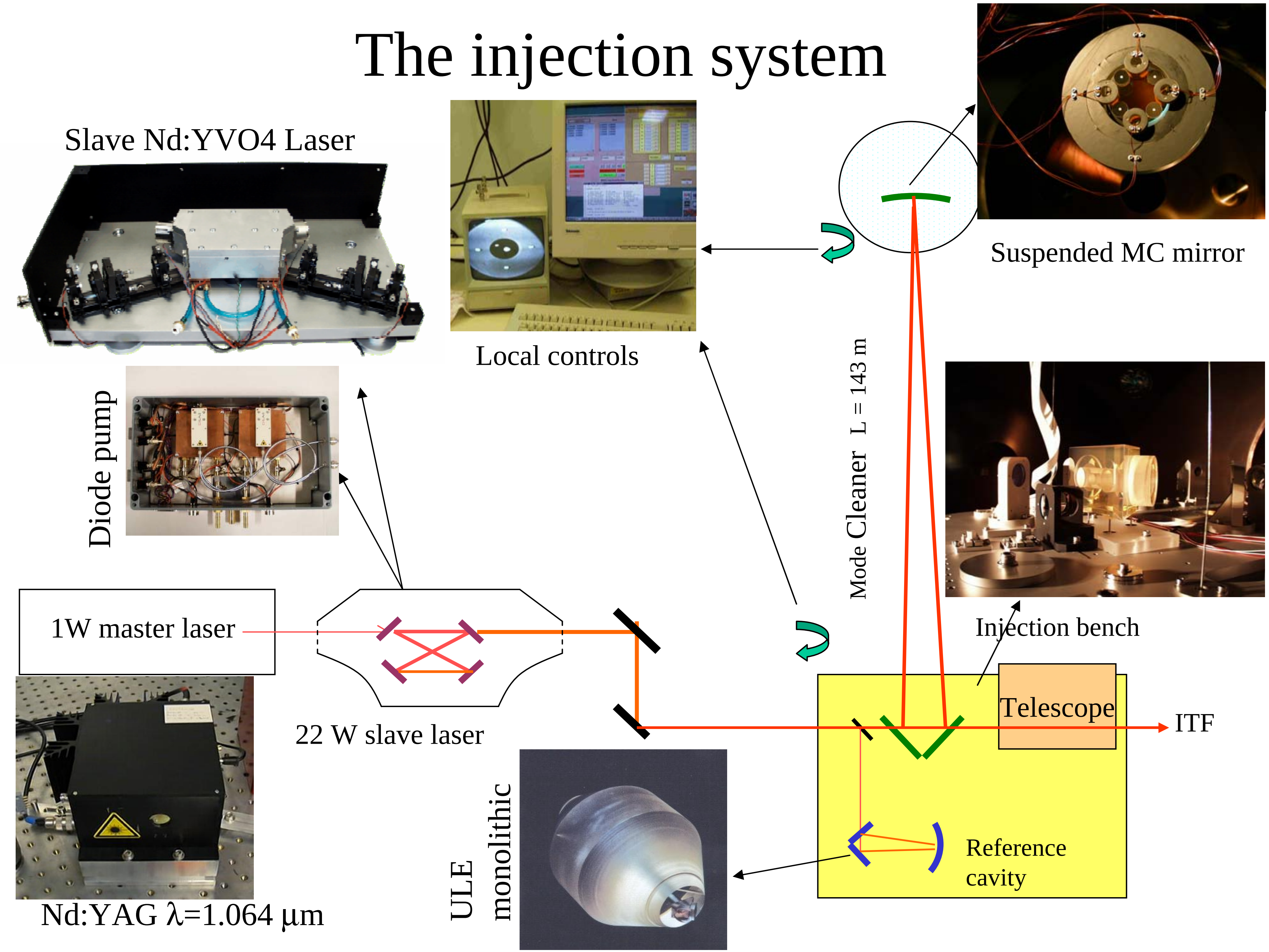




Virgo Optical Scheme



The injection system



The Vacuum System

- The largest high vacuum system in Europe:
  - About 7000 m^3
  - 1.2 m diameter pipe @ 10^{-7}mbar (H_2 partial pressure) (~6km long)
    - Reduction of light fluctuation given by air flux
  - 7 long towers (9m long) with differential vacuum:
    - Usual 10^{-7} mbar vacuum in the upper part
    - 10^{-9} mbar in the lower part, where mirrors are located
      - Thermal noise reduction
      - Mirror contamination control
  - Short towers @ 10^{-7}mbar

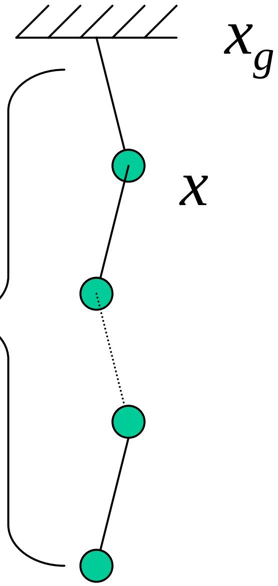
The seismic isolation

- What distinguishes Virgo from the competitors is the high sensitivity at low frequency
- In a GW detector, the low frequency range is dominated by seismic noise
- The typical spectral amplitude of the seismic ground vibration is

$$x_g(f) \approx \frac{10^{-7}}{f^2}$$

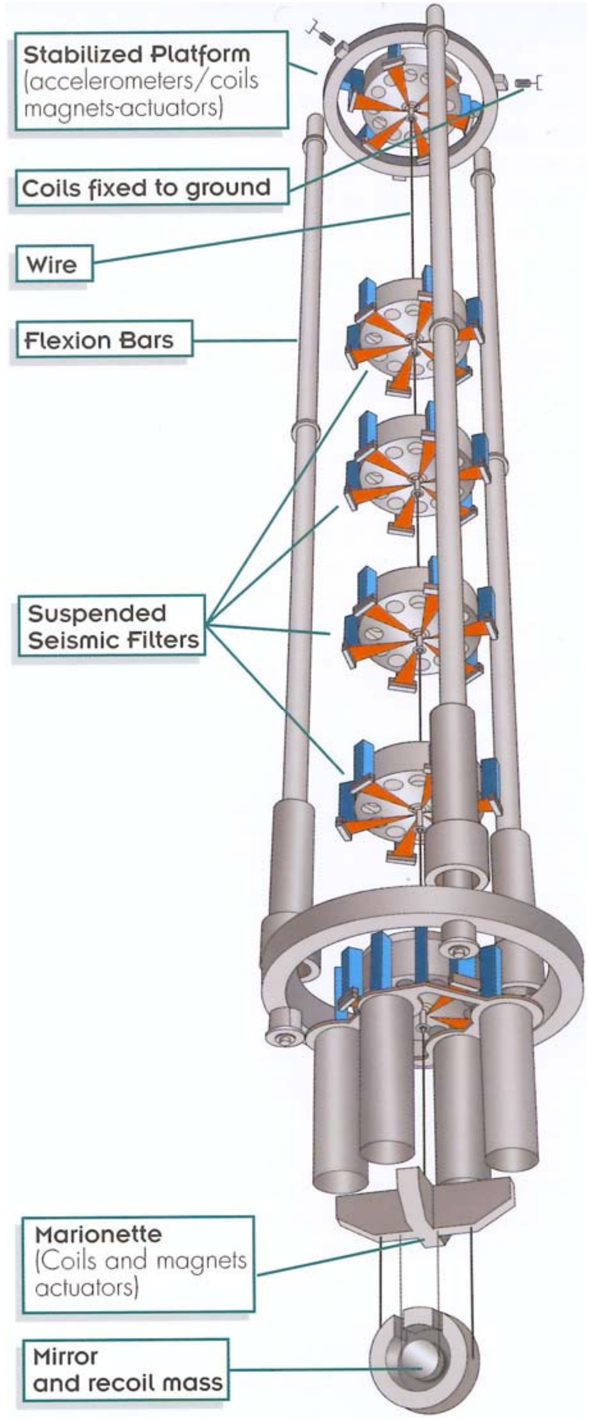
$$\frac{x(\omega)}{x_g(\omega)} = \frac{\omega_0^2}{\omega_0^2 - \omega^2} \xrightarrow{\omega >> \omega_0} \left|\frac{x(\omega)}{x_g(\omega)}\right| \approx \frac{\omega_0^2}{\omega^2}$$

N stages



$$\left|\frac{x(\omega)}{x_g(\omega)}\right|_{\omega >> \omega_0} \approx \left(\frac{\omega_0}{\omega}\right)^{2N}$$

The Super-Attenuator



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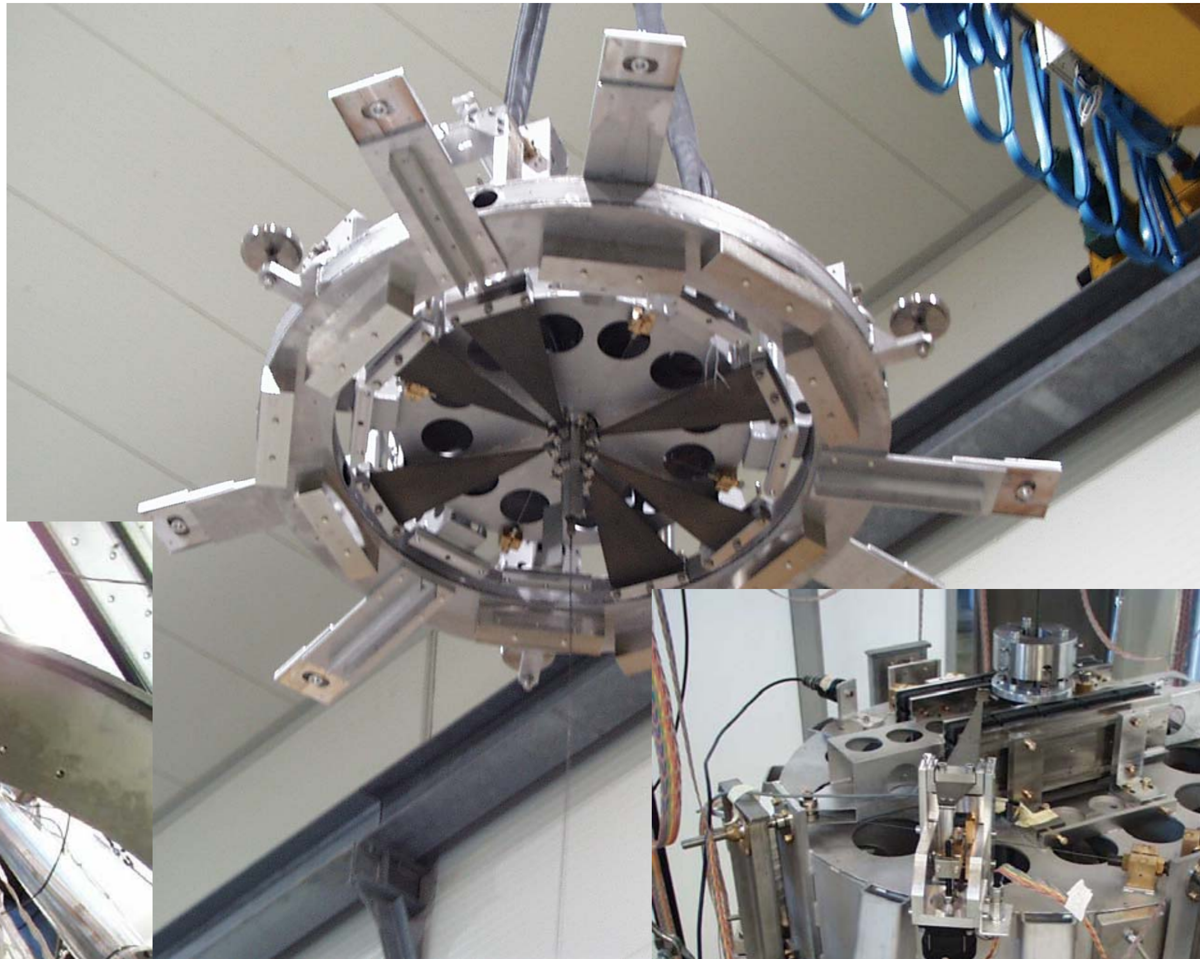
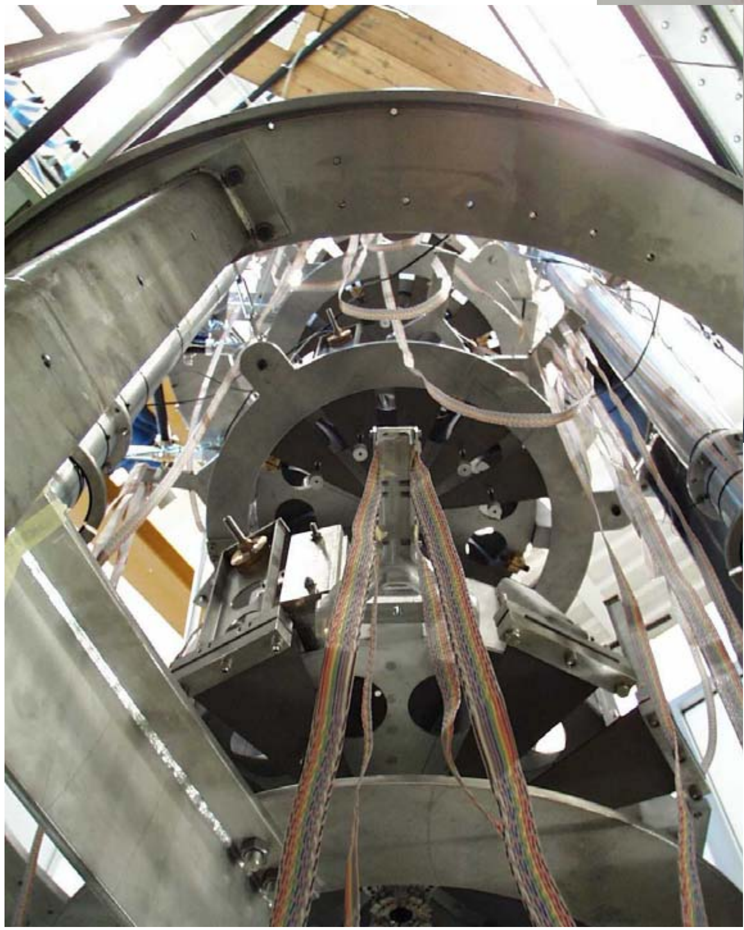
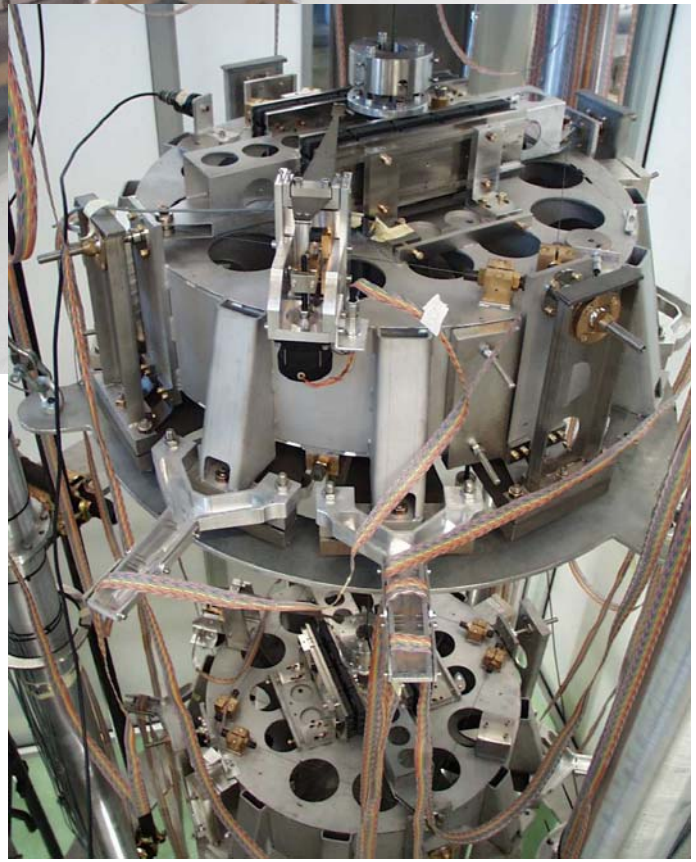
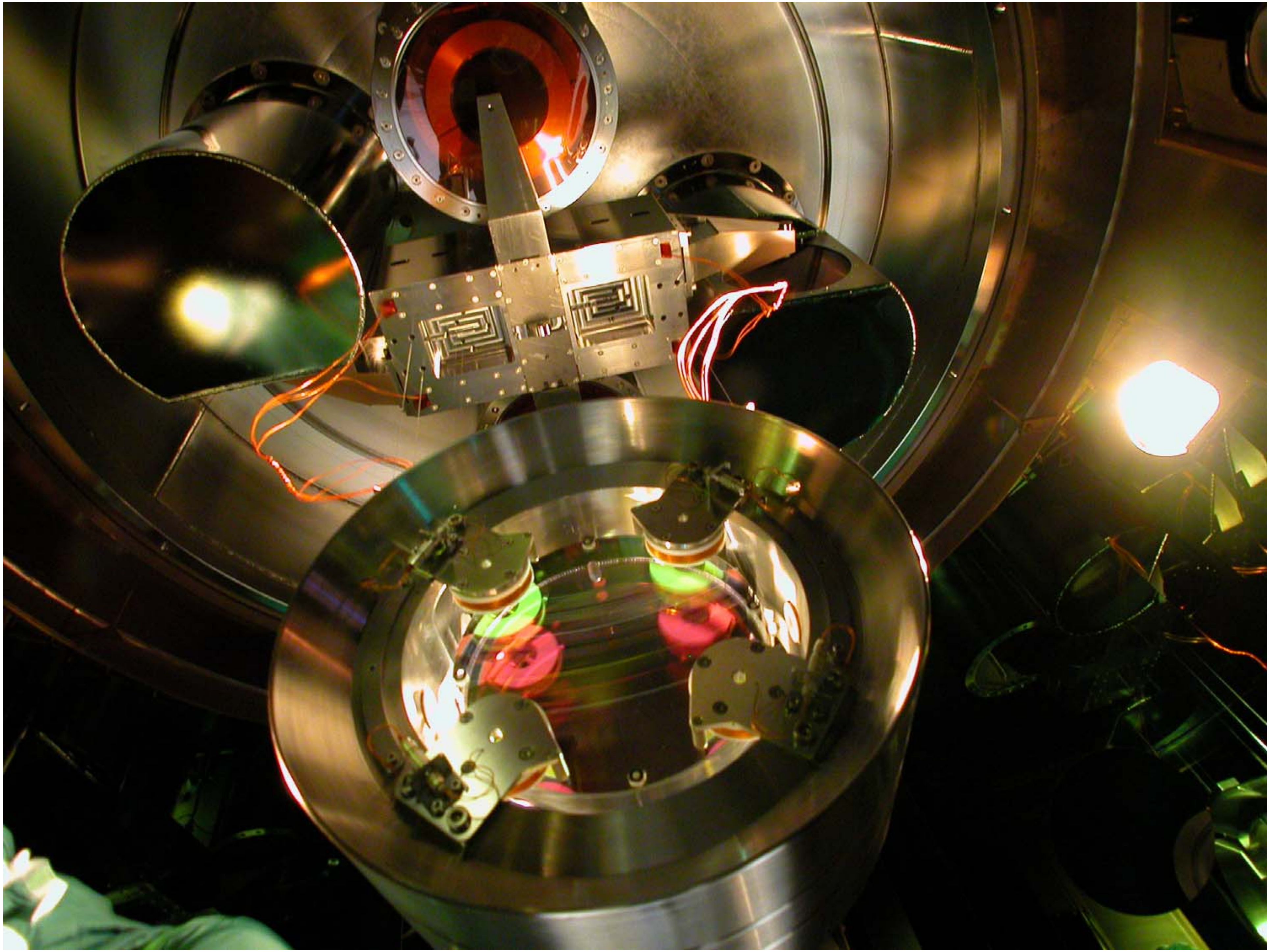






Last stage design

- The last stage has been designed to minimize the thermal fluctuation of the mirror
- The thermal noise is one of the fundamental limits to the Virgo sensitivity in the 5-500Hz frequency range

- Equi-partition theorem

$$\frac{1}{2} k_{pend} \left\langle x^2 \right\rangle_{rms} = \frac{1}{2} k_B T$$

$$\Downarrow$$

$$\left\langle x^2 \right\rangle_{rms} = \frac{k_B T}{m \omega_0^2} \Rightarrow \left\langle x \right\rangle_{rms} \approx 10^{-12} m$$

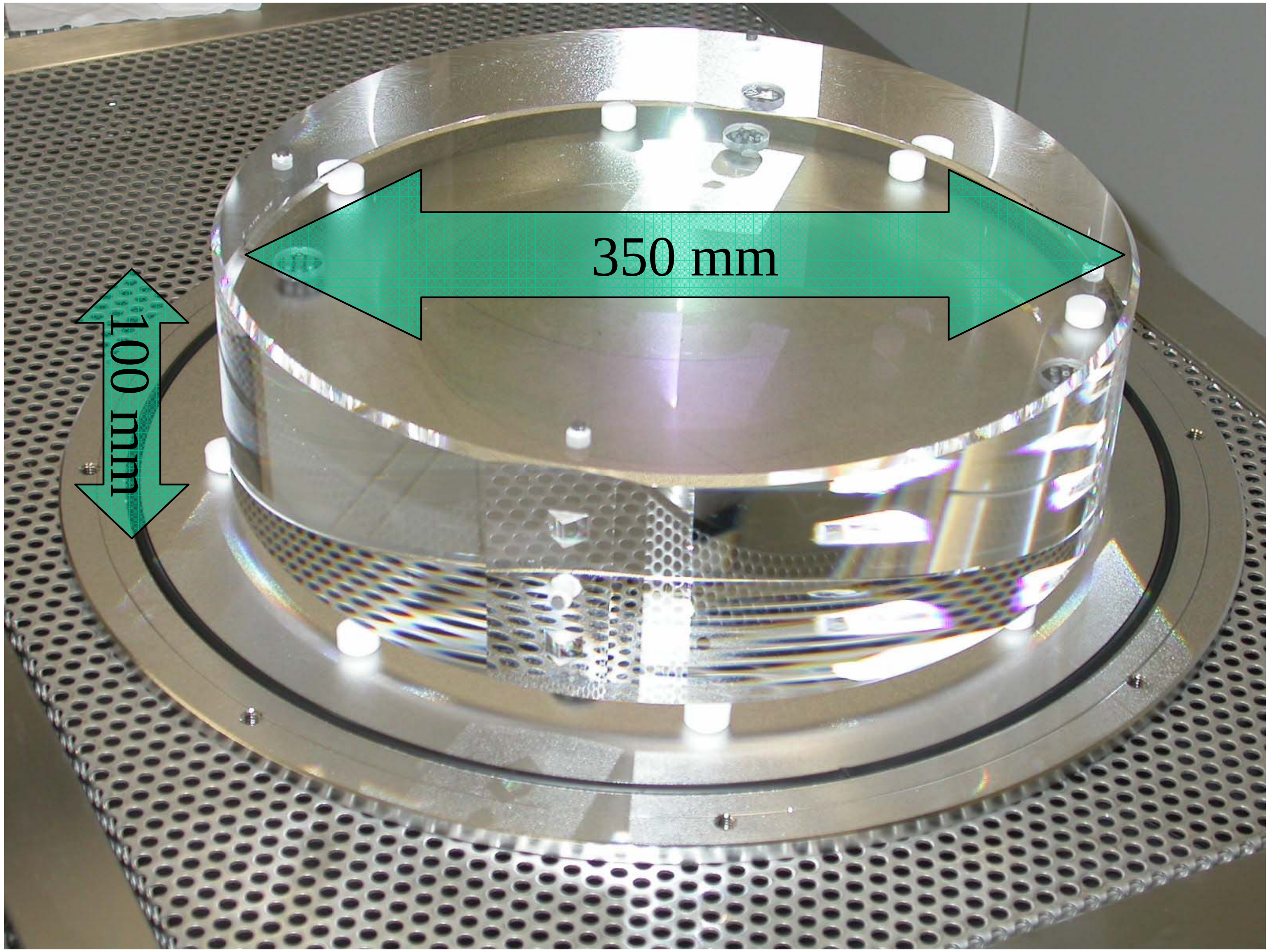
- Fluctuation-Dissipation theorem

$$x_{therm}^2(\omega) = \frac{4 k_B T}{\omega^2} \Re\left\{ \frac{1}{Z(\omega)} \right\}$$

$$x_{therm}^2(\omega) = \frac{4 k_b T}{m} \frac{\omega_0^2}{\omega} \frac{\phi(\omega)}{(\omega_0^2 - \omega^2)^2 + (\phi(\omega)\omega_0^2)^2}$$

Mirrors

- The Virgo mirrors are the largest (and more expensive) mirrors in the current GW detectors
- Very demanding requirements in term of absorption, birifrangence of the substrate and the coatings



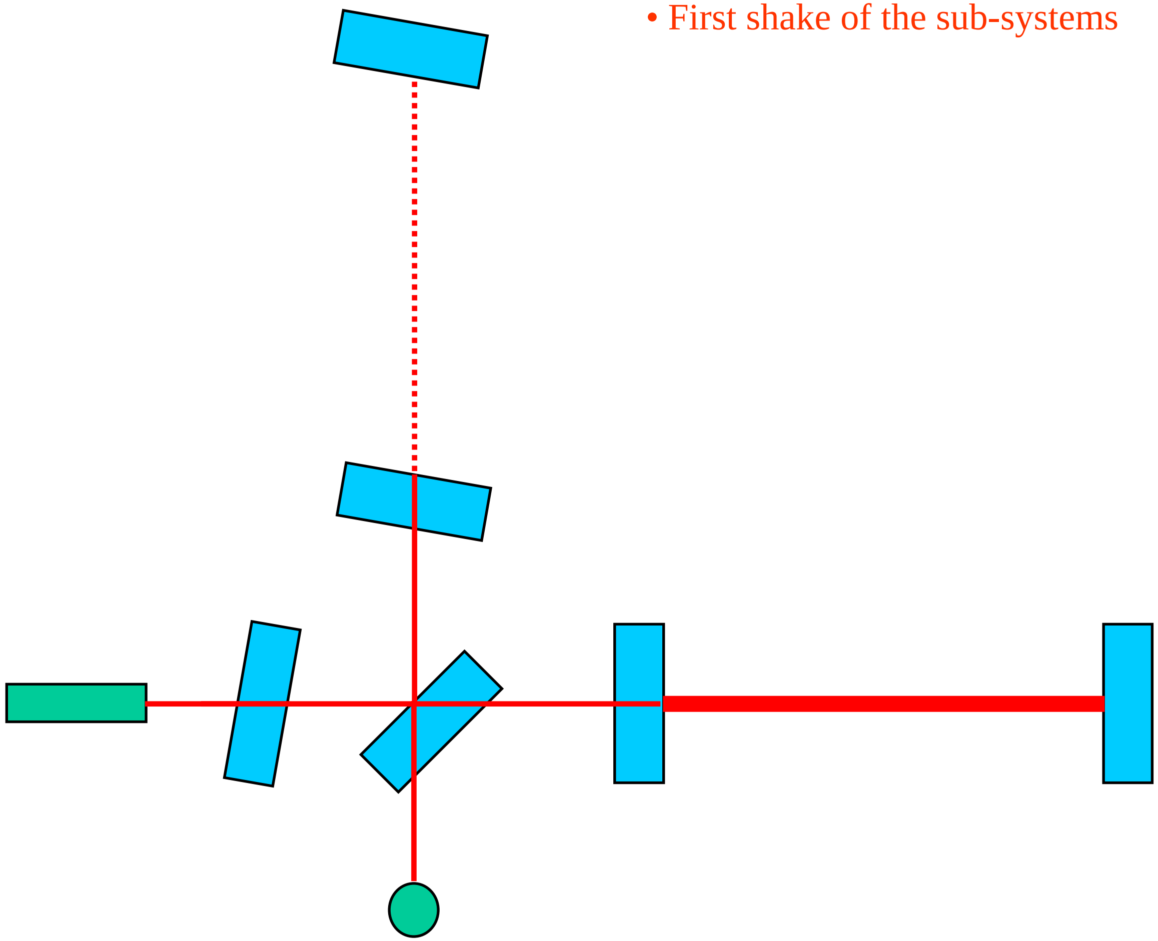
The Virgo Commissioning

- The last large mirror have been mounted in July 2003
- Virgo is a complex machine that needs a deep tuning of many parameters
  - Methods and technologies to do that are completely new
  - Progresses in the commissioning of the machine are demonstrated by the improvement of the duty cycle and by the enhancement of the sensitivity

Commissioning plan

Phase A: Commissioning of interferometer arms

- Test all aspects of control systems with a simple optical configuration
  - locking, automatic alignment, second stage of frequency stabilization and
    suspension hierarchical control (tidal and marionette)
- First shake of the sub-systems



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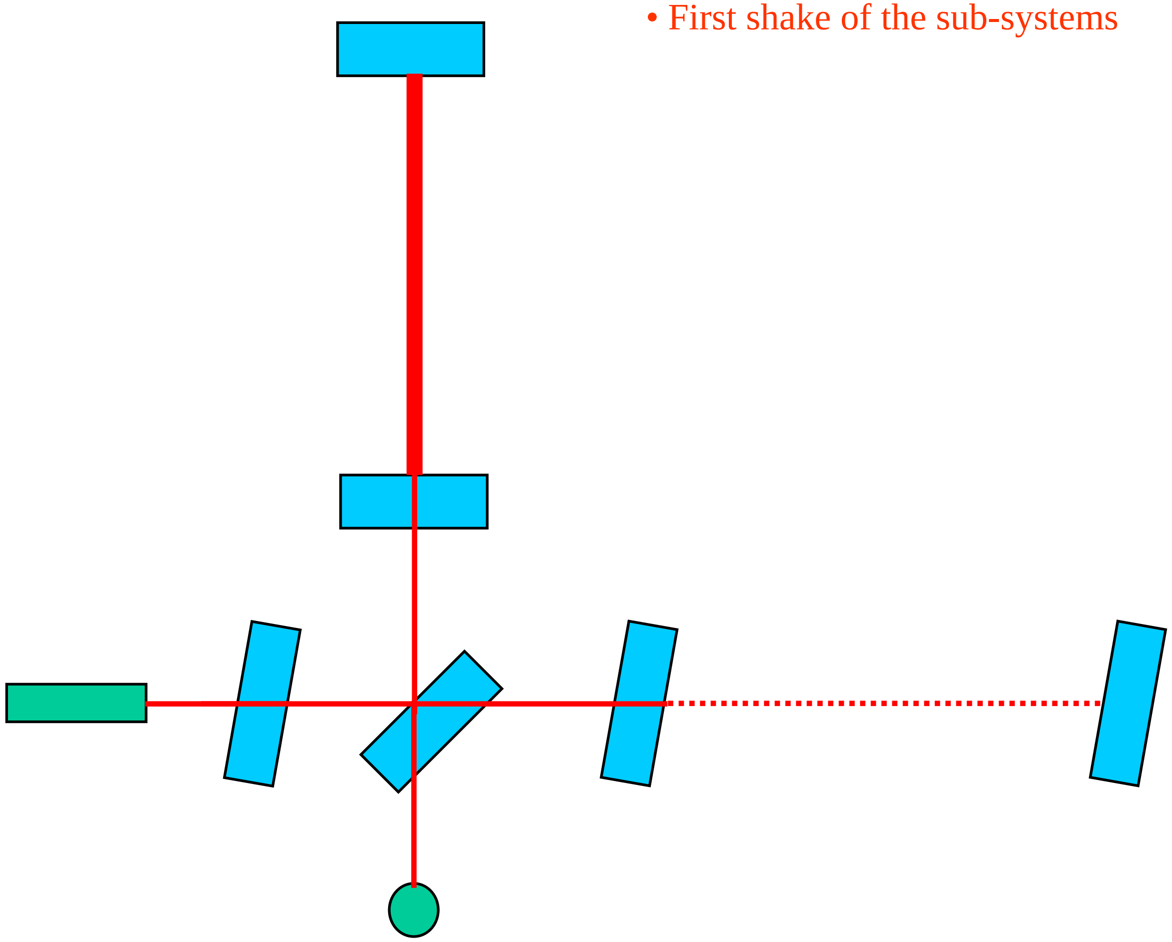

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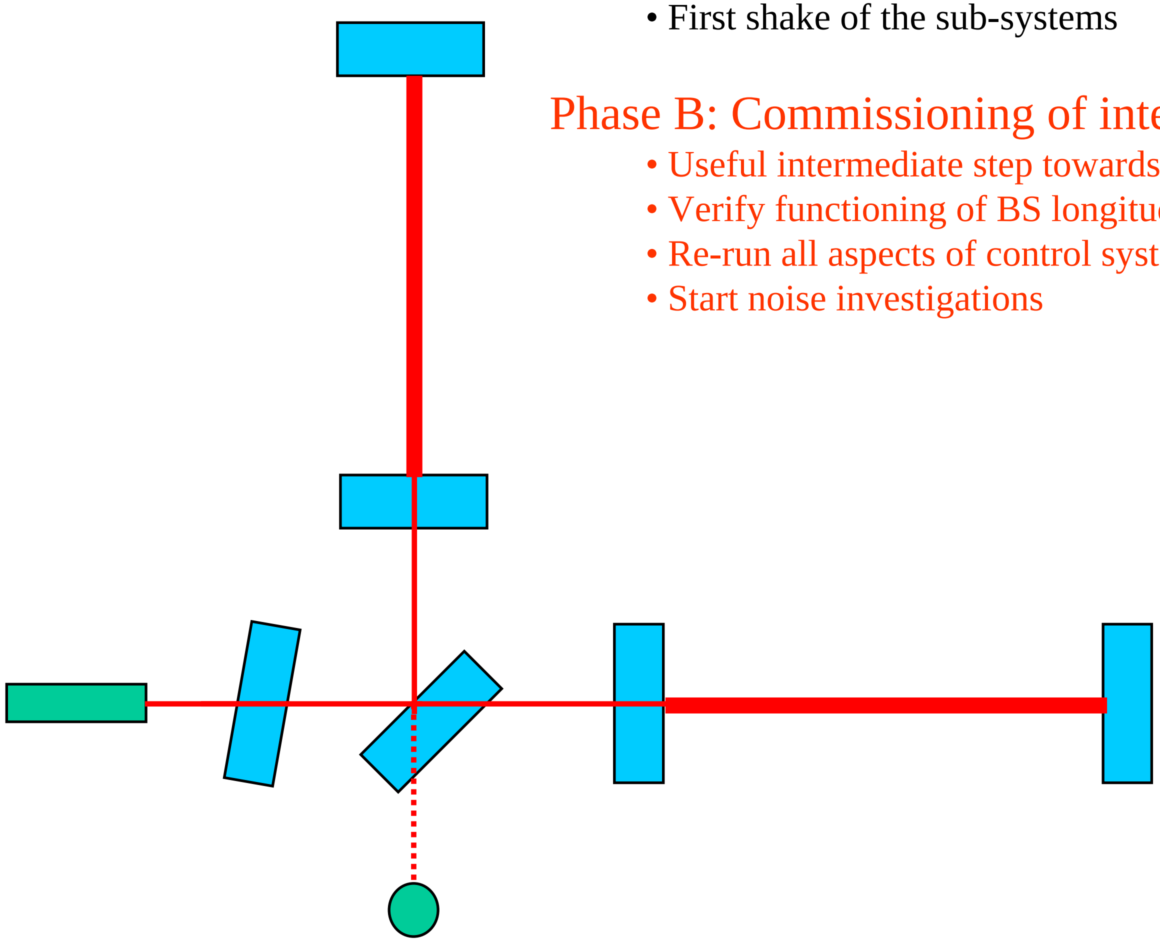
Phase B: Commissioning of interferometer in 'recombined mode'

- Useful intermediate step towards full interferometer lock
- Verify functioning of BS longitudinal control
- Re-run all aspects of control system in a more complex configuration
- Start noise investigations



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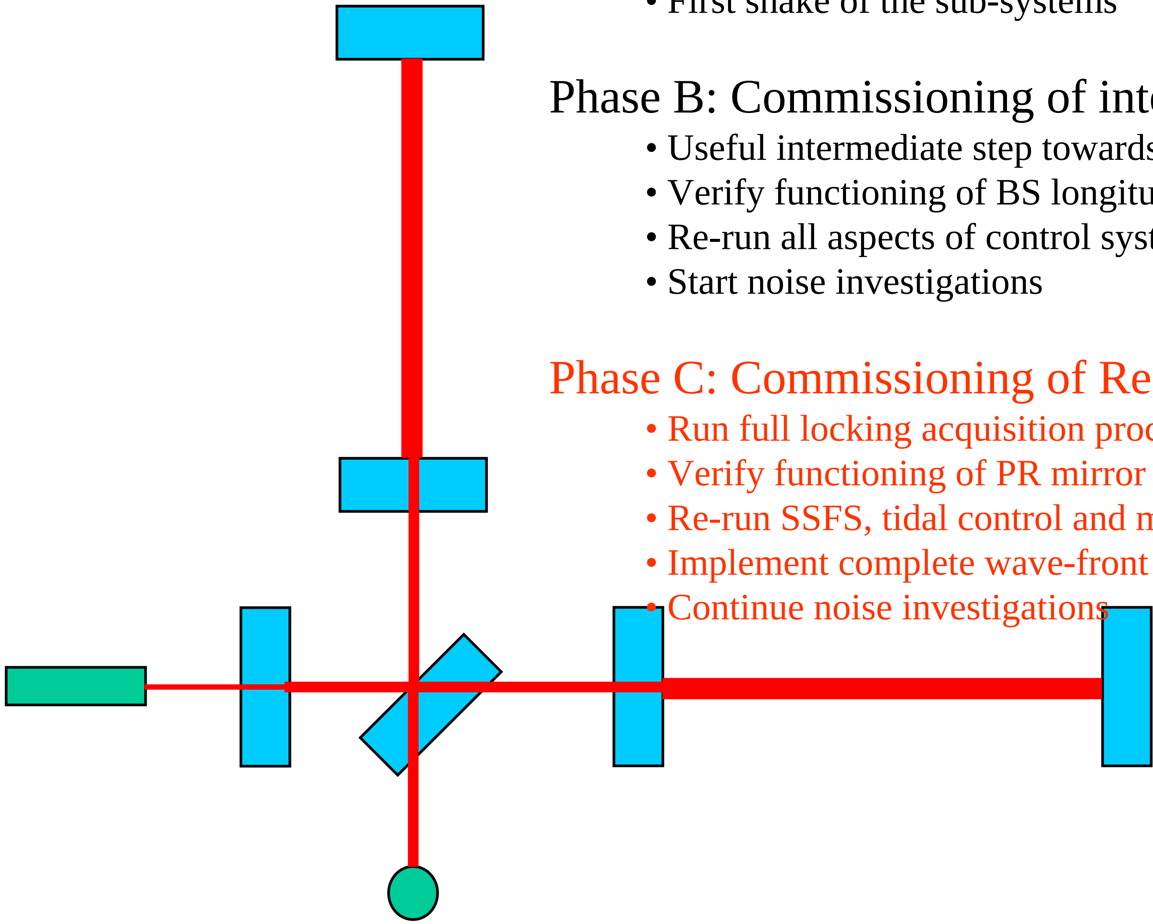
Phase C: Commissioning of Recycled Fabry-Perot interferometer

- Run full locking acquisition process
- Verify functioning of PR mirror longitudinal control
- Re-run SSFS, tidal control and marionette control
- Implement complete wave-front sensing control
- Continue noise investigations



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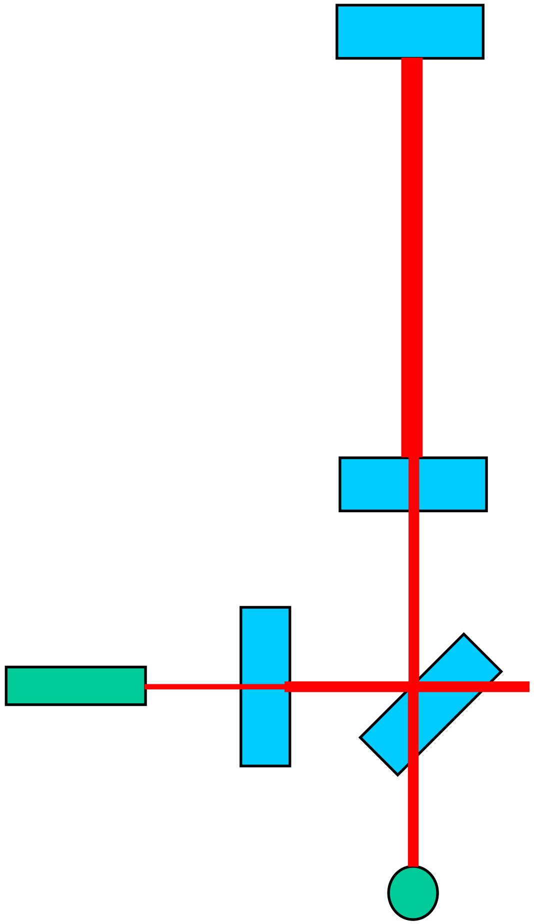

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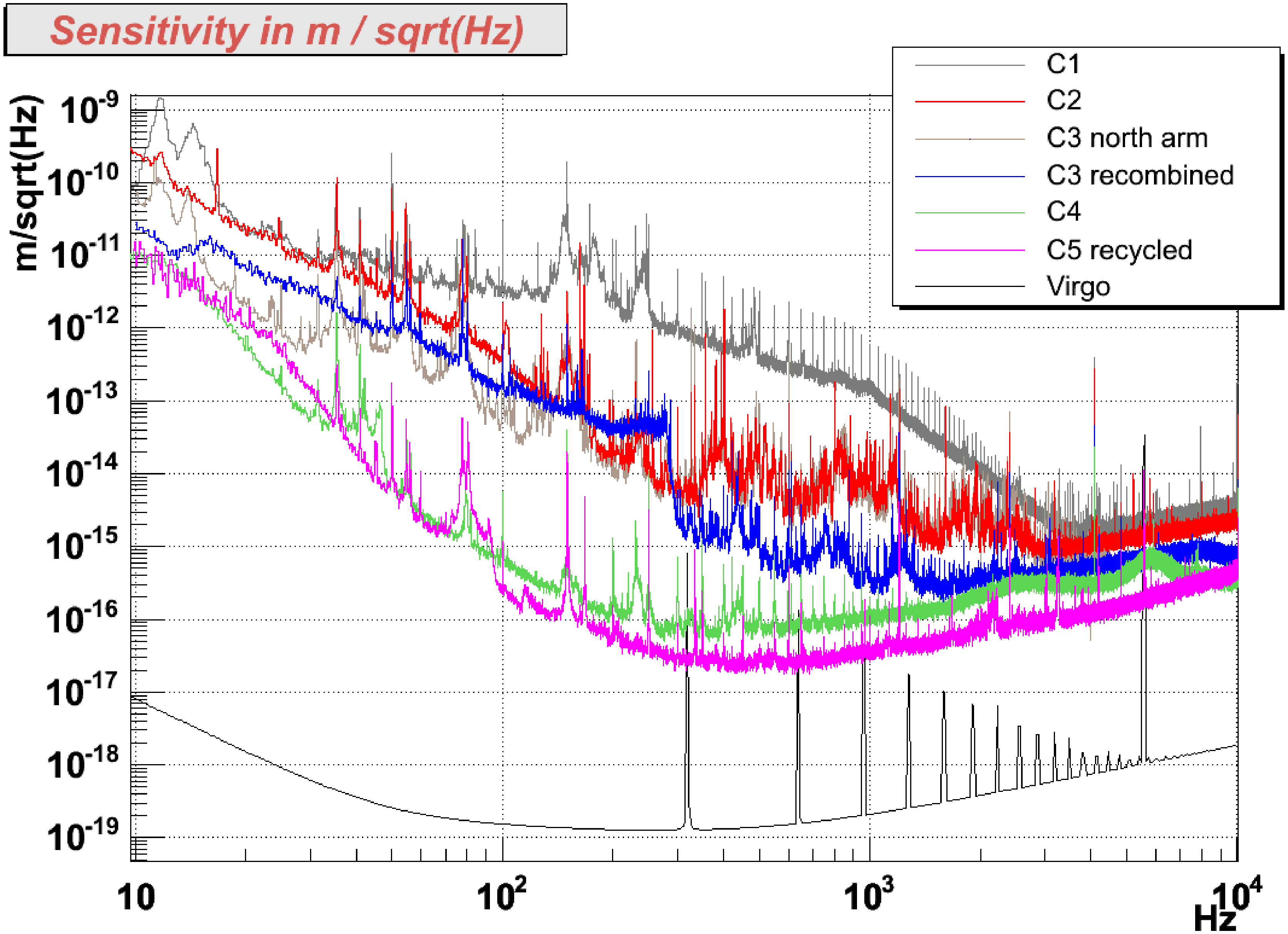
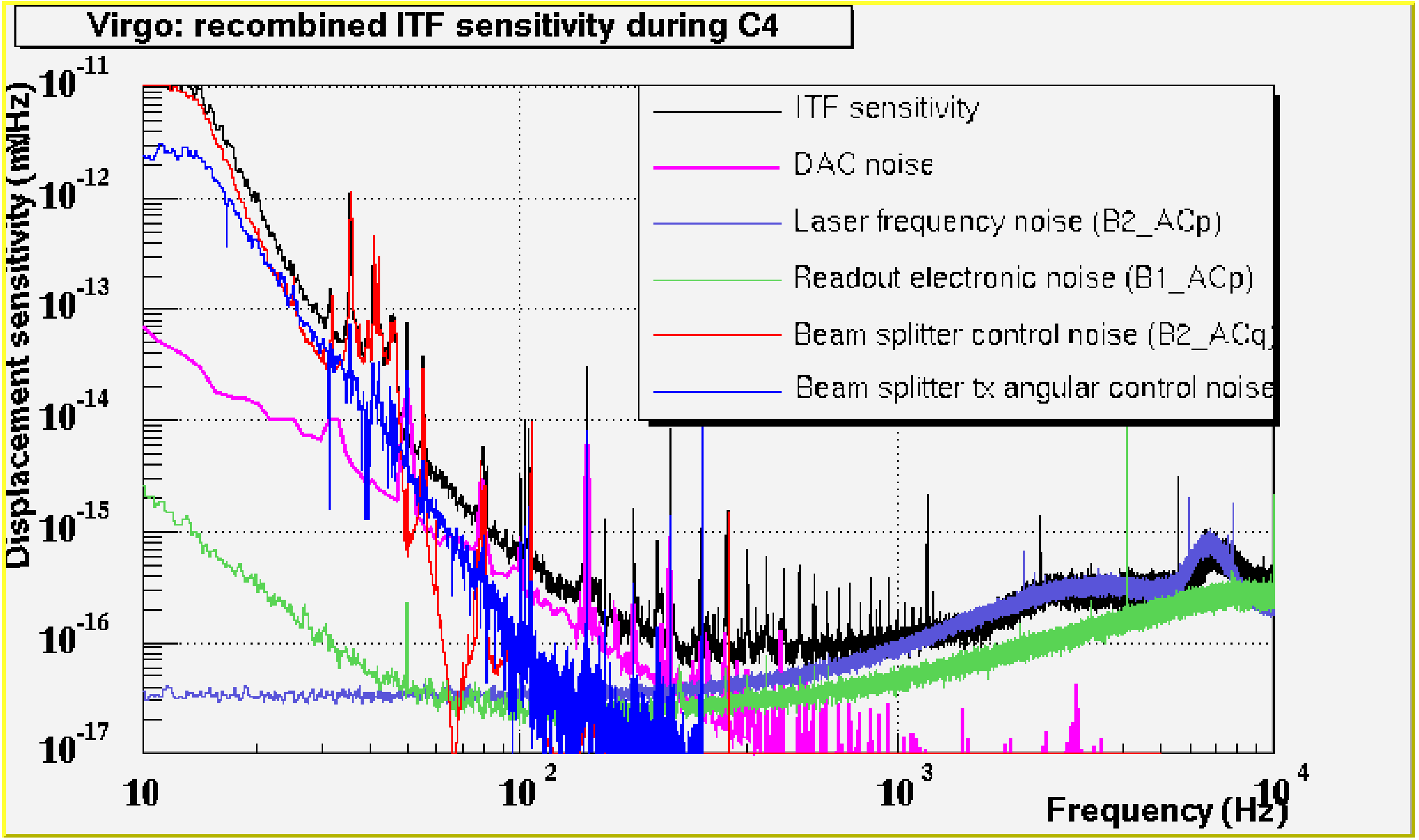
Phase D: Noise hunting

Sensitivity Improvement



Noise Budget

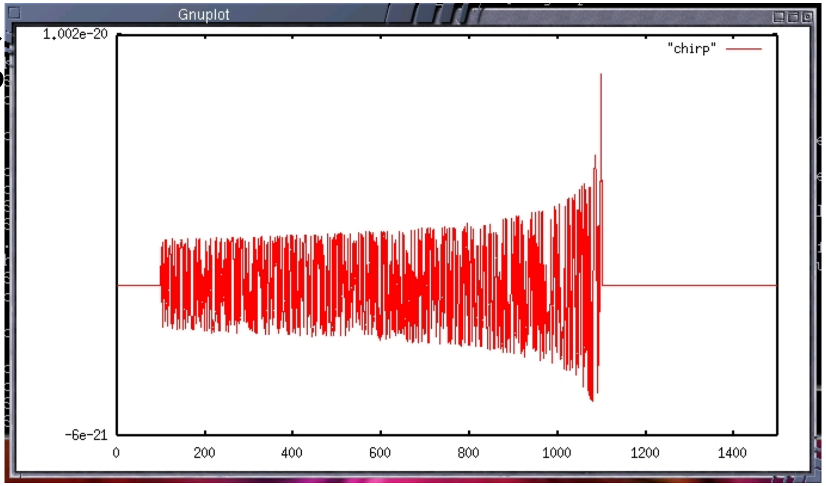


Data Analysis

- Three kinds of GW sources are expected:
  - Periodic sources:
    - Pulsars with quadrupolar moment
  - Burst:
    - Non-axisymmetric Supernova explosions
  - Coalescing binaries
    - Pair of stars (Neutron stars or Black Holes) rapidly rotating around the center of mass

CB detection

- Coalescing binaries detection needs the development of a new analysis strategy
- Hypothesis:
  - The signal shape is well known
    - The post-Newtonian approximation of the signal
  - The noise of the ITF is (almost) stationary and gaussian
- Optimal filtering method:
  - Wiener (or matched) filtering
    - Correlator in time space
    - “product” in frequency



Detection Strategy

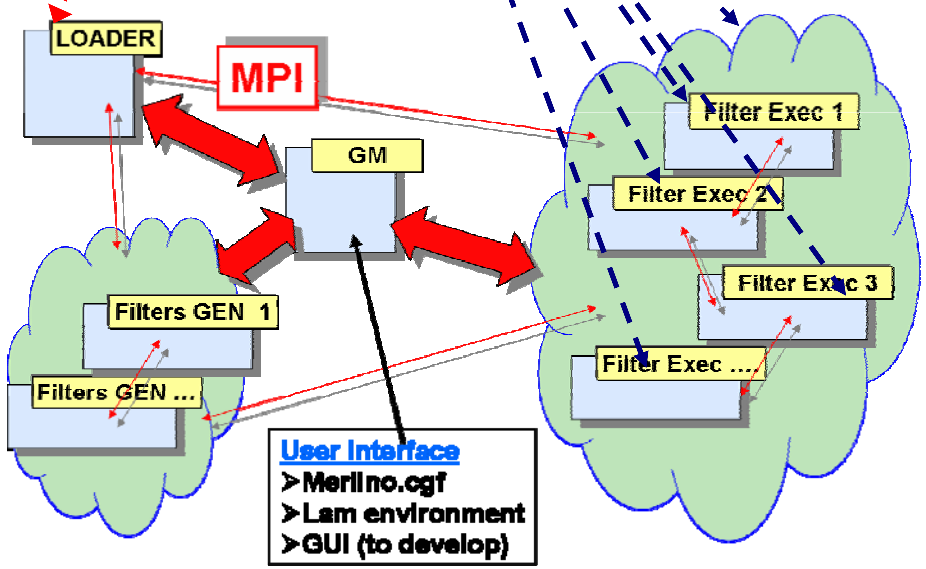
- The star masses are unknown parameters
  - we don’t know the optimal filter, but we can parametrize it
- Detection Strategy:
  - we define a priori the signal-to-noise that we can accept to loose respect to the optimal one (ambiguity function):
  - we select a frequency range, imposed by the apparatus sensitivity, where to detect the CB signal (25-1000 Hz)
  - We build-up a “templates” grid (about 45000 templates); the grid step is selected in such a way the SNR lost is below the defined threshold
  - We perform the matching (correlators) between the ITF output and all the templates
  - All the matching above threshold, are cross-checked with a sort of χ^2 test

Matched Filter implementation

$$c(t) = \int \frac{\tilde{X}(\omega)\,\tilde{h}^*(\omega)}{S_n(\omega)} e^{i\omega t} d\omega$$

x(t)→X(w)
Double Whitening

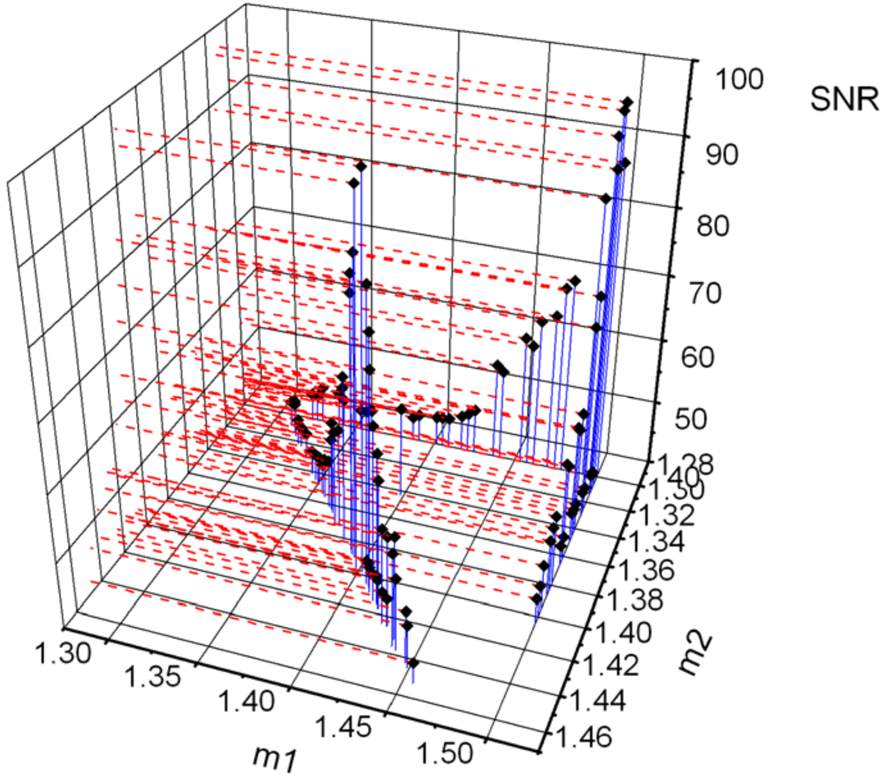
Template bank is generated $h_i(t) \rightarrow H_i(\omega)$
→ distributed on all the processes memory

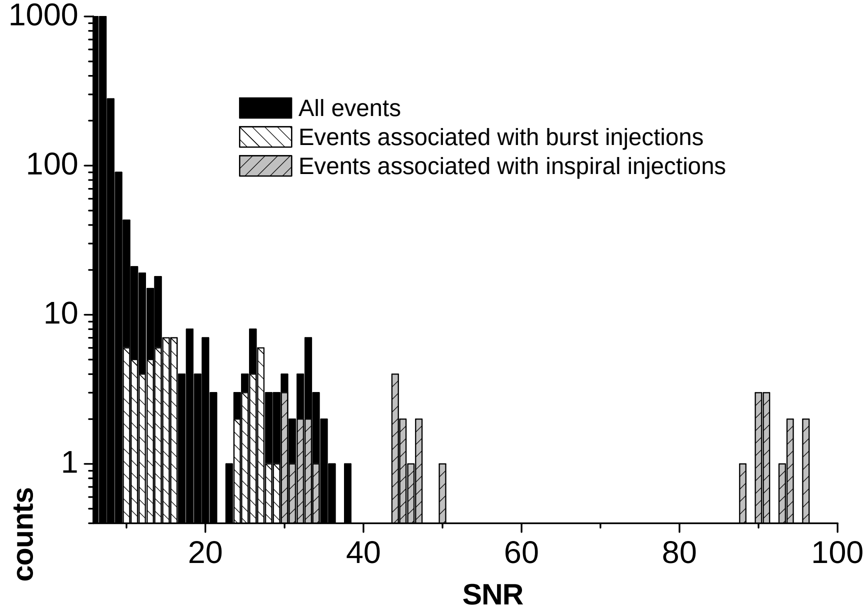


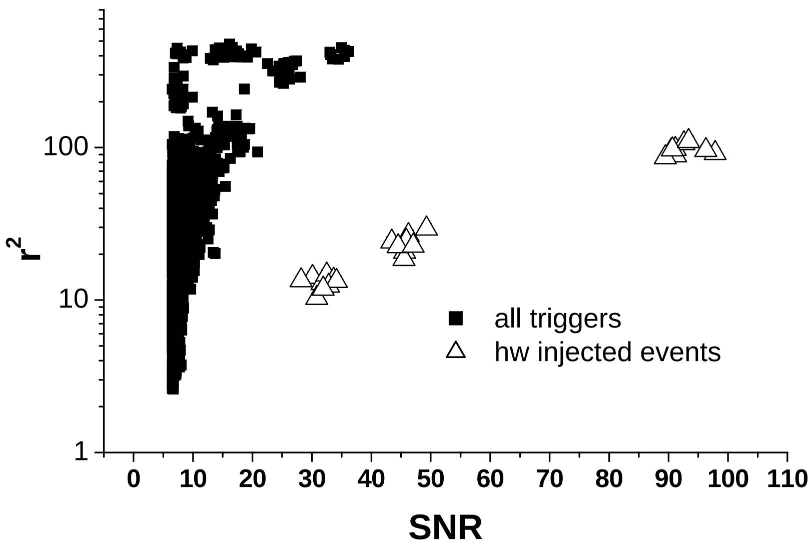
The integral is evaluated
→in each process
→for each template $h_i(t)$

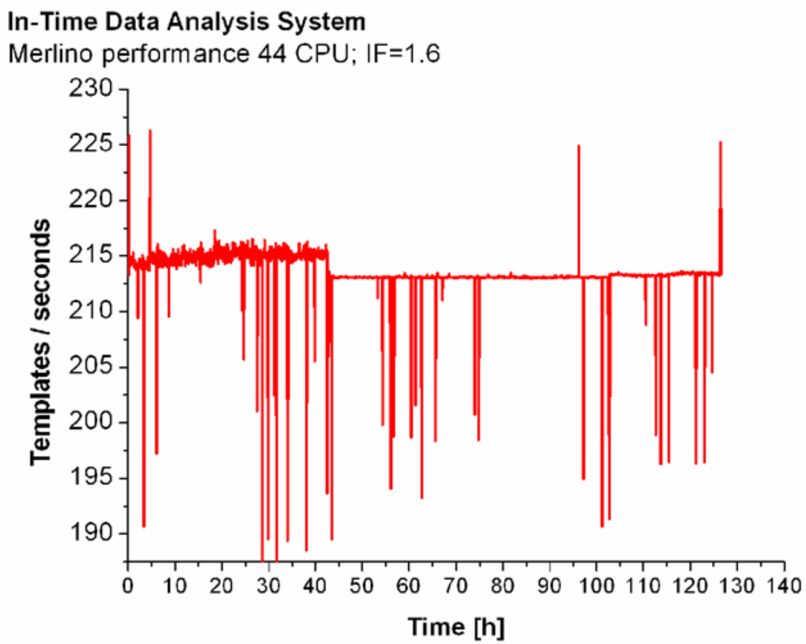
- Cluster BeoWulf of 23 Opteron 2GHz bi-processor

Hardware Injections









Conclusions

- The Virgo detector commissioning is under way
- Firs science run is expected for the end of 2005 – beginning of 2006
- The Data Analysis procedures are under development and testing