The gravitational wave detector VIRGO

for the VIRGO collaboration

Raffaele Flaminio

Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP)

IN2P3 - CNRS

Summary

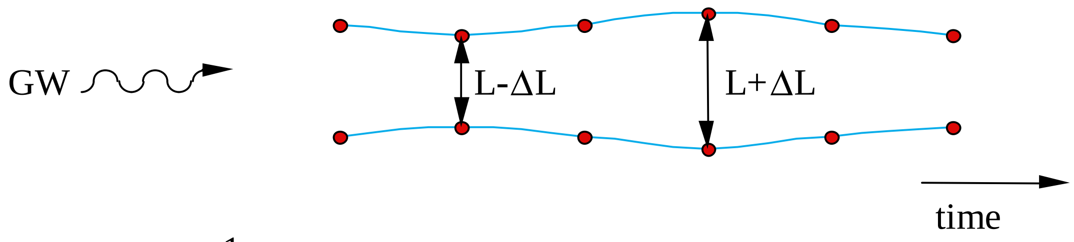
I. A bit of gravitational wave physics

Gravitational waves

• GW = space-time metric waves

⇓

distances variation



$\Delta L = \frac{1}{2} h\, L$ h = GW amplitude

• GW produced by masses acceleration

$$h \approx \frac{2G}{c^4} \frac{d^2 Q}{dt^2} \frac{1}{d}$$

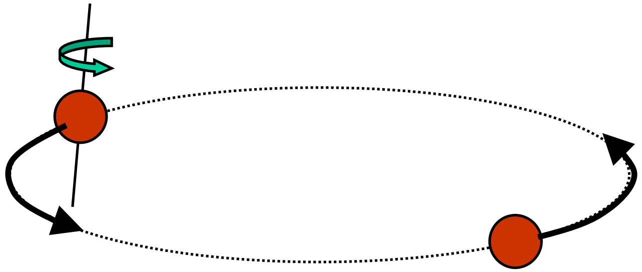
d = source distance
Q = quadripole moment

• Small coupling factor

⇒ GW generation on earth not possible

⇒ astrophysical sources

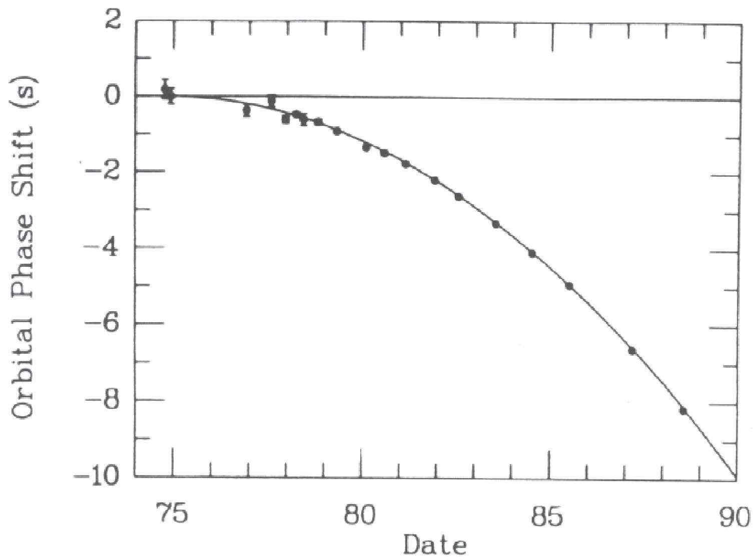
Gravitational waves exist



• PSR 1913+16 (Taylor et Hulse 1974)

binary system formed by two neutron stars (one pulsar)
period ~ 8 hours

• Energy loss due to gravitational wave emission (excellent agreement with GR theory)



$$\frac{\dot{P}_{obs}}{\dot{P}_{theorie}} = 1.0023 \pm 0.005$$

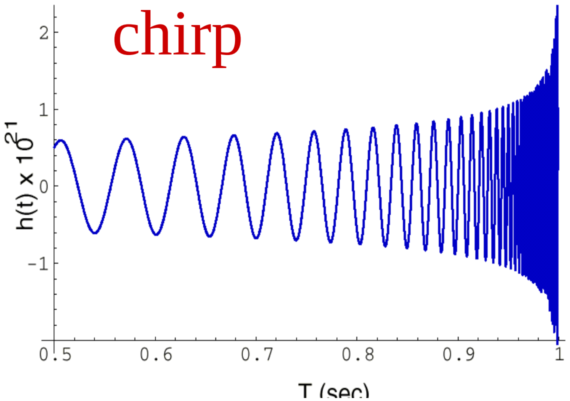
(Taylor et al. 1992)

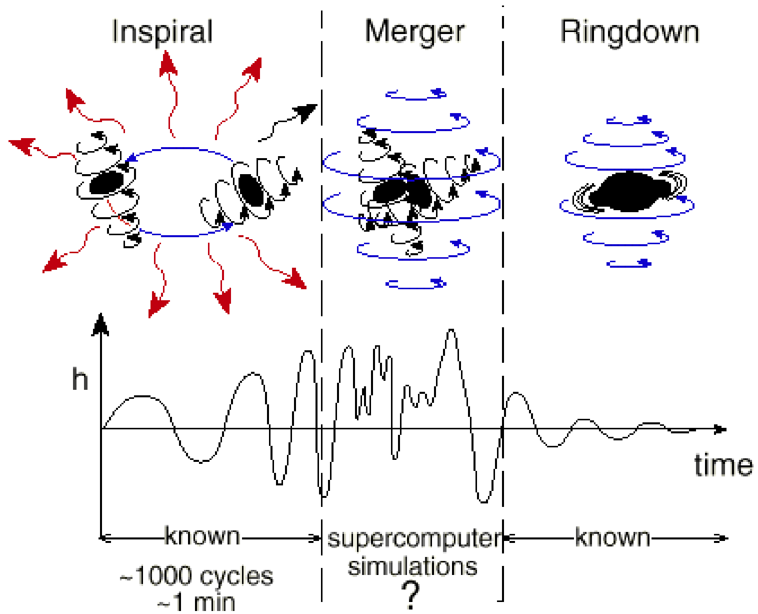
• stars will coalesce in 10^8 years

Coalescing binaries

• Binaries formed by compact stars (NS/NS, NS/BH, BH/BH)

• Inspiral signal accurately predictable
(more energy at low frequency)





• Event rate:

- statistical analysis ~ 1/10^5 yr in the Milky Way

~ 3 / yr inside a radius of 200 Mpc (Narayan et al. 1991, Phinney 1991)

- evolutionary model ~ 3 / yr inside a radius of 40 Mpc (Lipunov et al. 1994)

Coalescing binaries as physics lab

- *Standard candles:*
  distance of the source can be found out of the waveform of a NS/NS
  [Schutz, *Nature*, 1986]

- *Test for GR*:
  accurate measurements of inspiral waveform can test gravity in the strong field regime [Damour, Esposito-Farese, gr-qc/9803031]

- *Nuclear physics*:
  before coalescence waveform sensitive to the equation of state
  [Cutler *et al.*, *PRL*, **70**, 1993]

Other sources in the sky

- Supernovae
  - star core collapse (non-spherical collapse)
  - impulsive event
  - waveform and amplitude difficult to predict
  - rates: tens/year in the VIRGO cluster

- Rotating neutron stars
  - GW emitted if non perfectly spherical star
  - periodical signals, amplitudes unknown, upper limits from pulsars slow down
  - ~ 800 pulsars known today, ~10^9 neutron stars in the galaxy

- Relic stochastic background
  - imprinting of the early expansion of the universe
  - stochastic signals (two correlated detectors needed)
  - signal too weak if standard inflation, signals larger from some string models

- ???

The goals of VIRGO

- First direct detection of gravitational waves

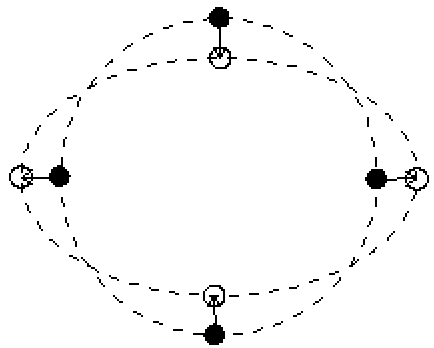
- Study of gravitational force
    - weak force not well known
    - small amount of data available in strong field conditions and on non-linear effects

- New window on the universe
    - signals emitted by coherent motion of large quantity of matter
    - very small absorption through matter

II. Gravitational wave detection

GW detection using interferometers

- Gravitational wave effect (spin 2 wave)

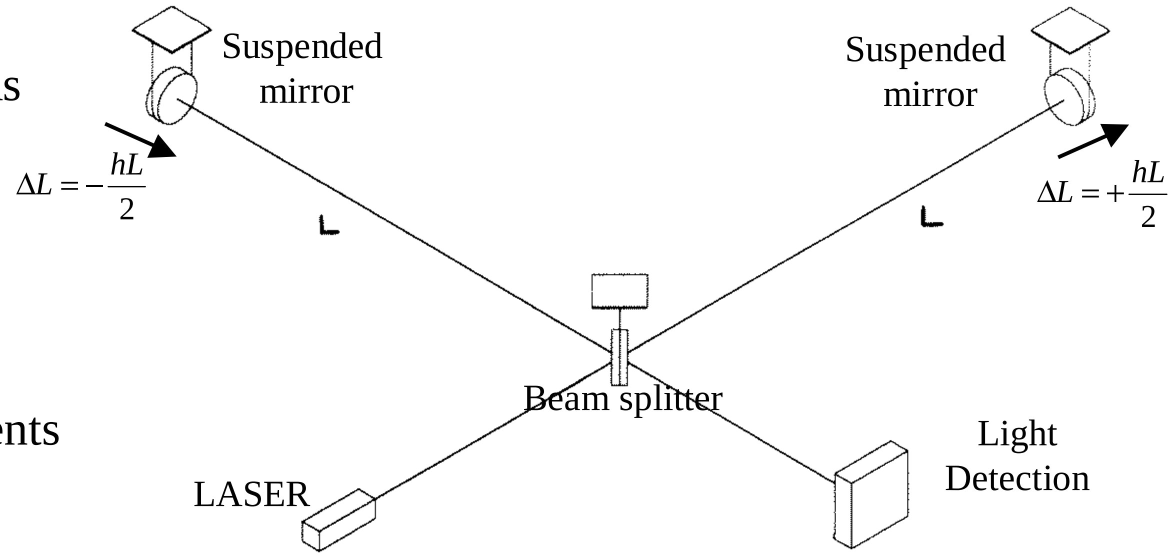


- Michelson interferometer

- All mirrors suspended through pendulums
  = 'free falling masses'

- h = 10^{-21} , L = 3 km $\Rightarrow \Delta L \approx 10^{-18}$ m

- GW detection = measure tiny displacements

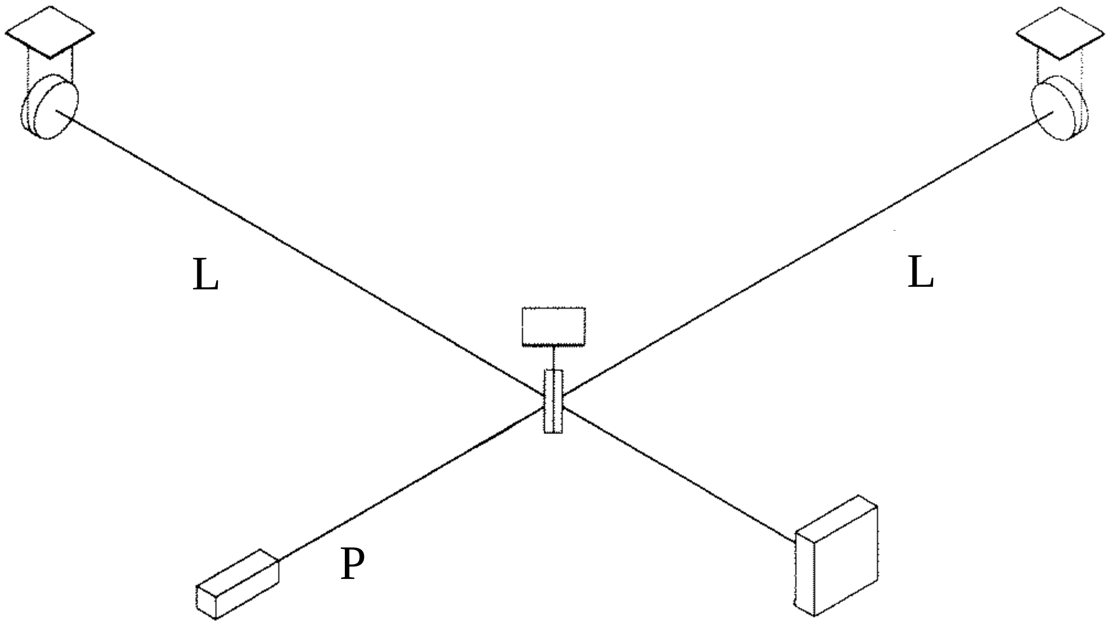


Photons shot noise

- GW $\Rightarrow$ phase shift $\Delta\Phi = \frac{4\pi}{\lambda} hL$
- Minimum measurable phase shift $\propto N_\gamma^{-\frac{1}{2}}$

$$\tilde{\phi} = \sqrt{\frac{2\hbar\omega}{P}}$$

$$\tilde{h} \geq \frac{\lambda}{4\pi}\frac{1}{L}\sqrt{\frac{2\hbar\omega}{P}}$$



- with L = 100 km and P = 1 kW

$h \sim 3 \cdot 10^{-23}$

Photons shot noise

$$\tilde{h} \geq \frac{\lambda}{4\pi} \frac{1}{L} \sqrt{\frac{2\hbar\omega}{P}}$$

- Effective length increased
  with Fabry-Perot

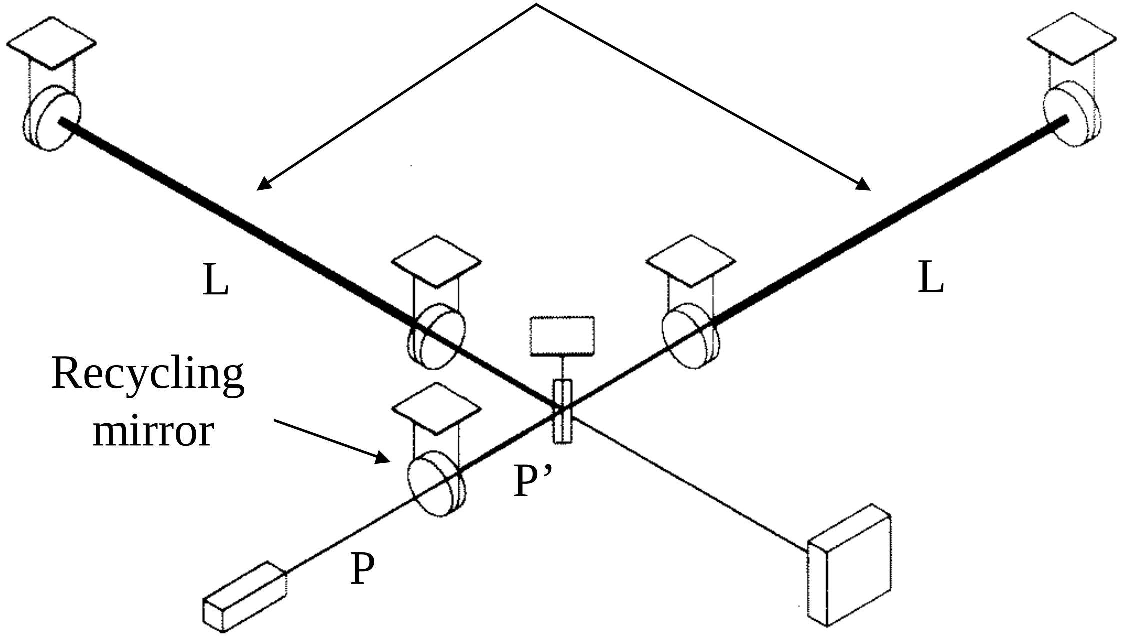
$L' = \frac{2}{\pi} \cdot F \cdot L$ (F = finesse FP)

L' = 100 km with L = 3 km

- Amount of photons increased
  using recycling mirror

$P' = R \cdot P$ (R = recycling factor)

P' = 1 kW avec P = 20W



Seismic noise

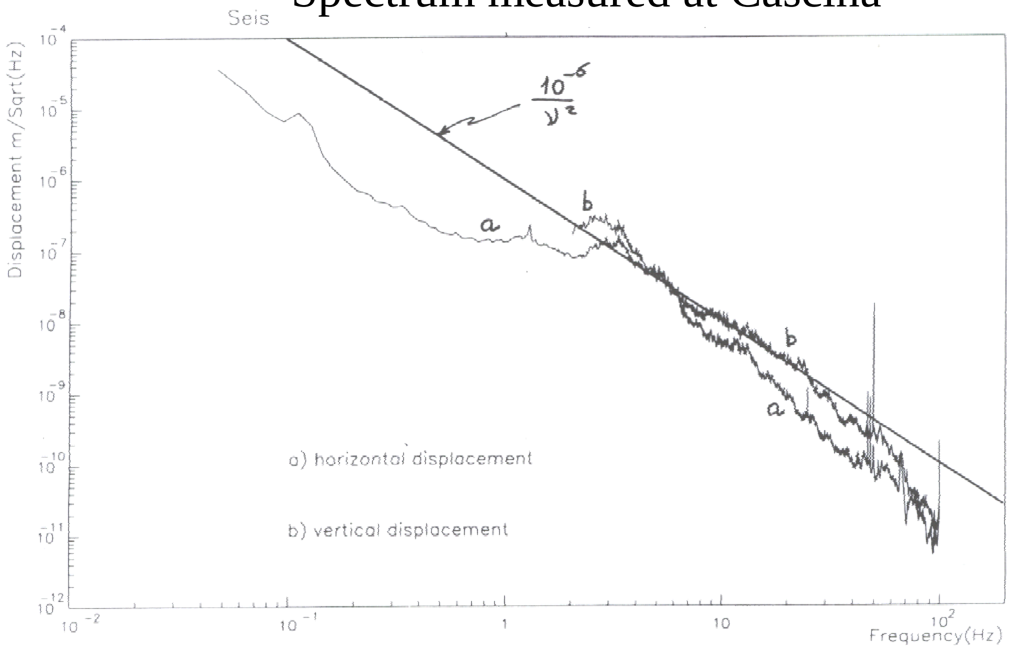
- Seismic noise spectrum

  for frequencies f ≥ few Hz $\tilde{x}_s = \frac{a}{f^2}\frac{m}{\sqrt{Hz}}$ (a ≈ 10 $^{-6}$ - 10 $^{-7}$)

  larger at low frequency

- Main limitation at low frequencies
- Very large attenuation required

Spectrum measured at Cascina

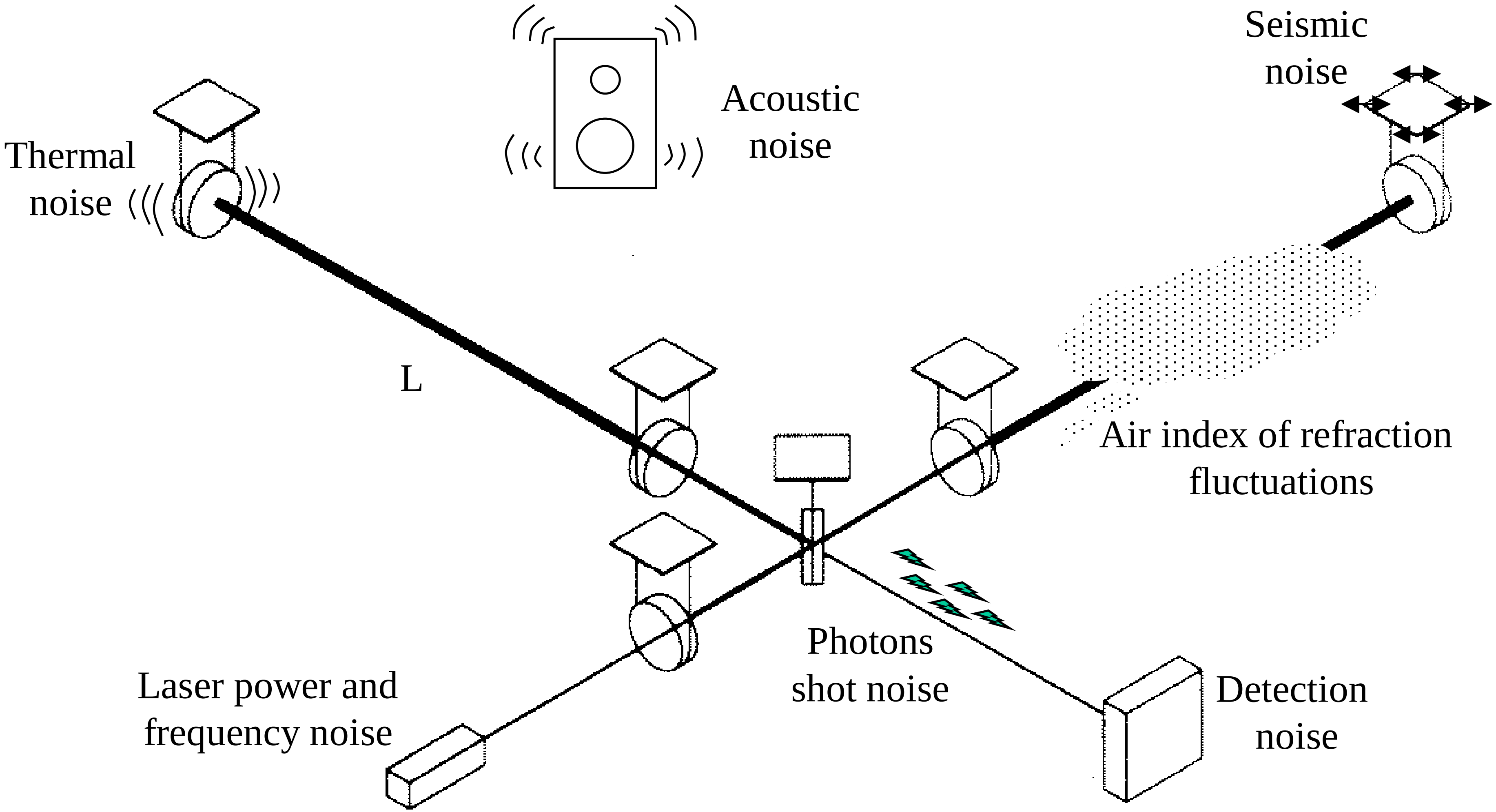


- Noise level sensitive to human activit

(agricultural activity in Cascina)

- Security distances
  - road > 500 m
  - agricultural activity > 100 m

Other noise sources



III. The VIRGO design

The VIRGO project

- French-Italian collaboration

- 11 laboratories:

LAPP Annecy, INFN Firenze, INFN Frascati, IPN Lyon,
INFN Napoli, Observatoire de Nice, LAL Orsay, ESPCI Paris,
INFN Perugia, INFN Pisa, INFN Roma

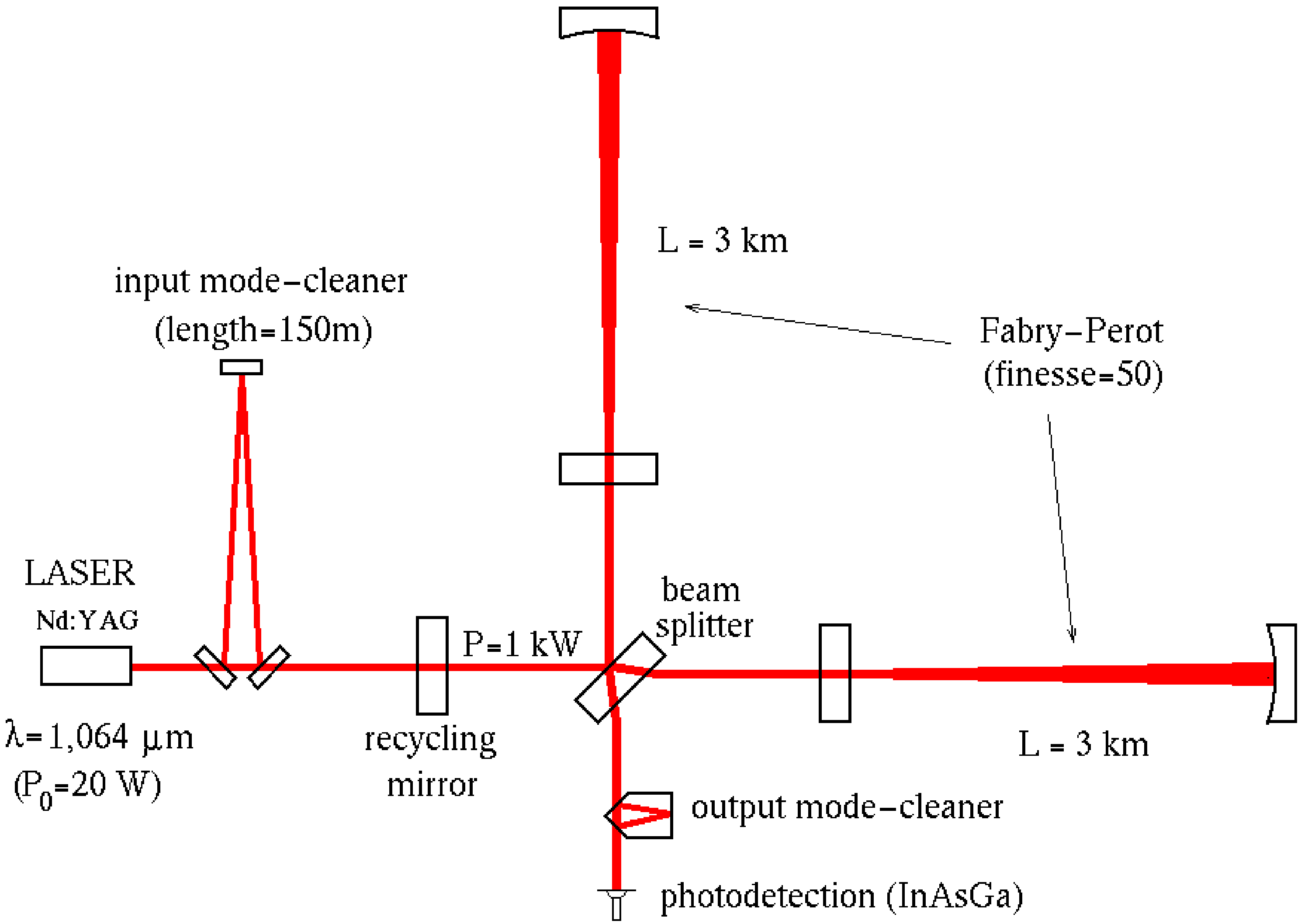
- About 150 persons involved (physicist + engineers + technicians)

- Funded by INFN in Italy and CNRS in France

- Set up a 3 km arm long interferometer near Pisa (Italy)

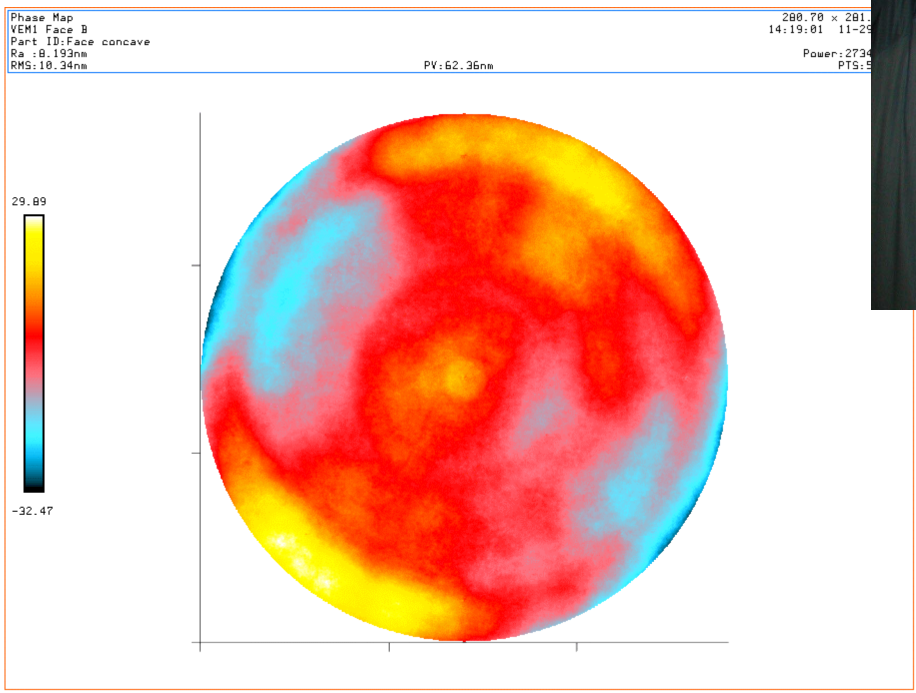
- Construction started in 1996

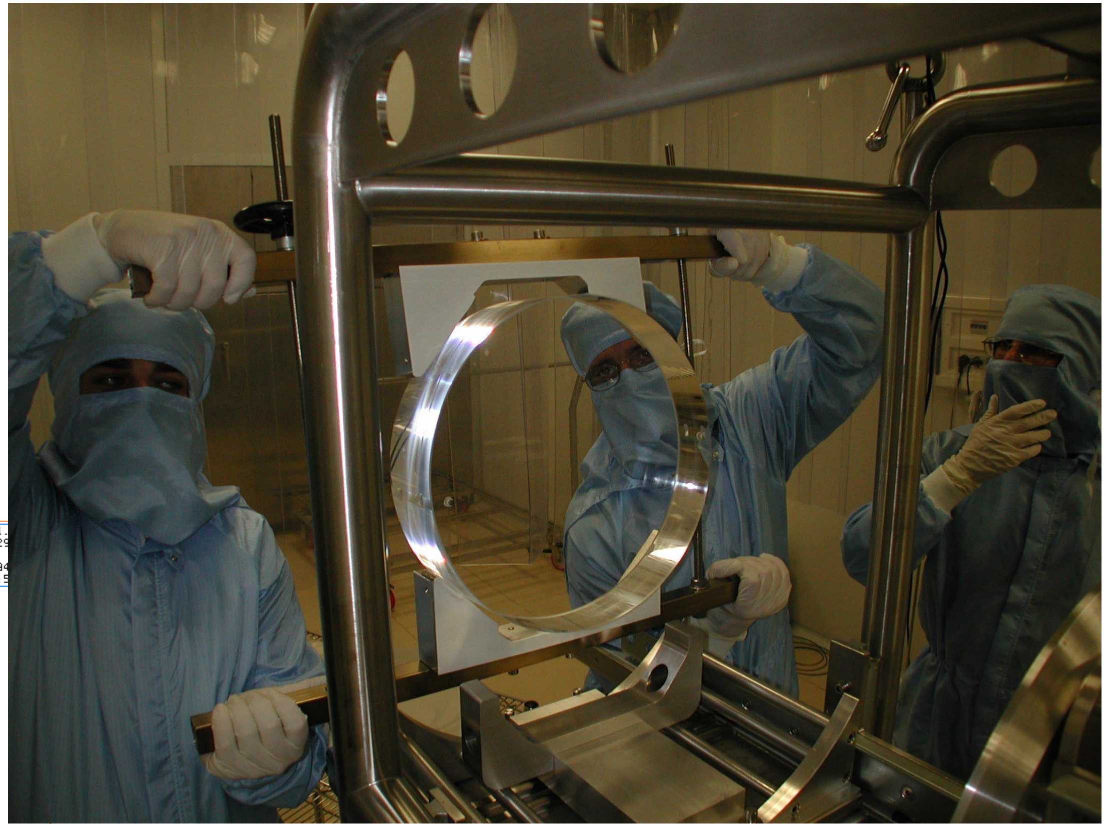
The VIRGO interferometer



The mirrors

- Dimensions: ∅ 35 cm, 10 cm thick
- Mass: 20 kg
- Suspended by 4 steel wires (∅ 200µm)
- Made of fused silica





- Coating made in VIRGO
- Metrology made in VIRGO
- Absorption and diffusion < few ppm
- Wave-front < λ/100

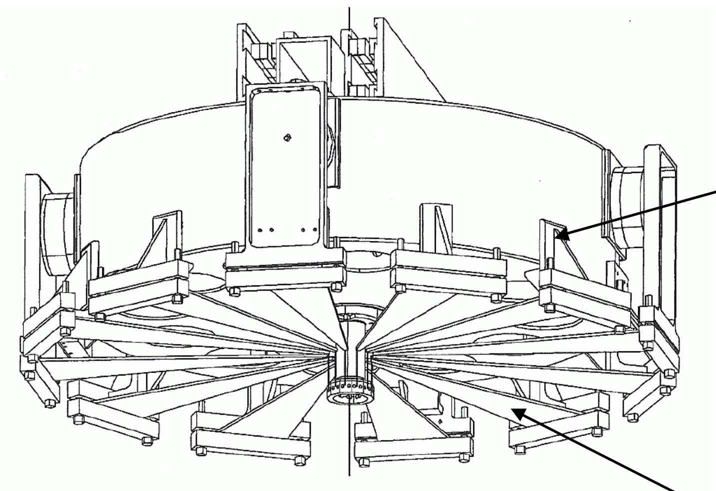
Seismic isolation

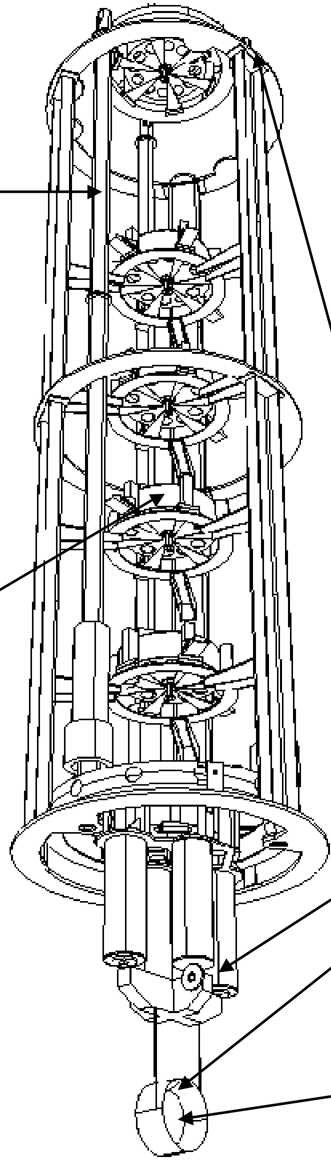
- Seismic isolator:

- cantilever springs for vertical isolation
- pendulums for horizontal isolation
- an inverted pendulum as pre-isolator

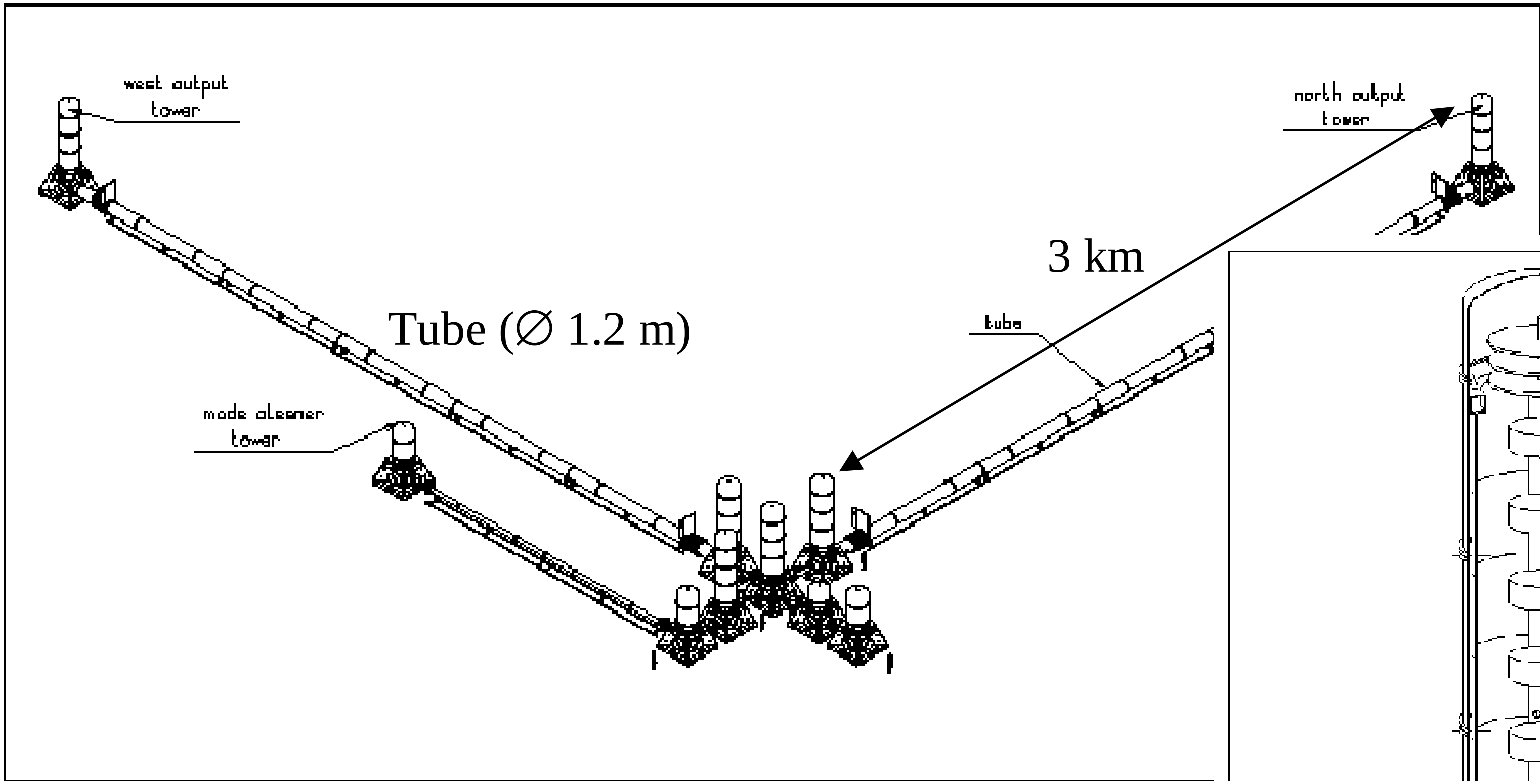
- Six stages in cascade

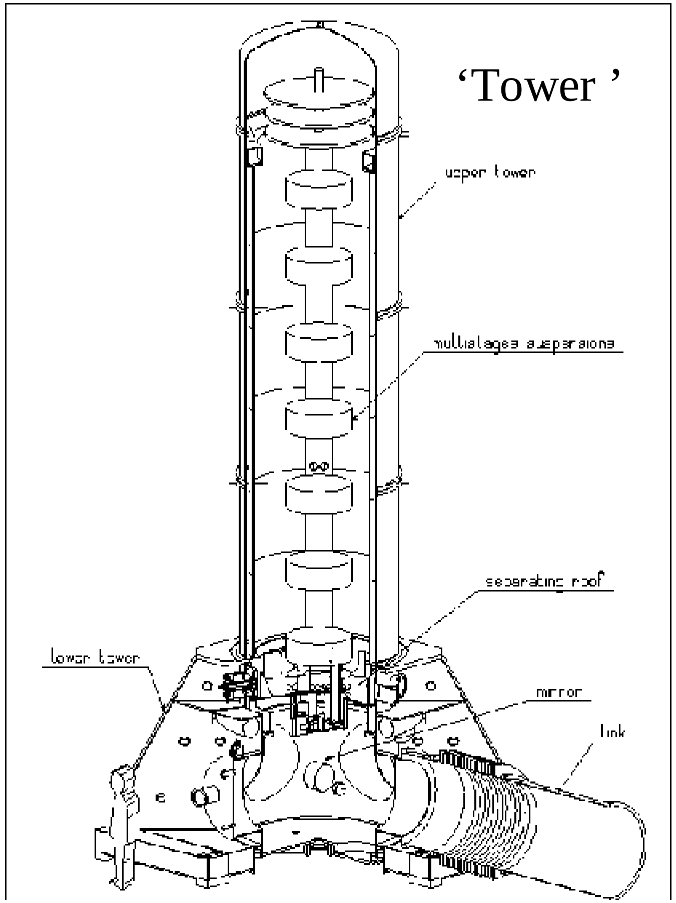
- Total attenuation ~ 10^{10} @ 10 Hz





Vacuum system

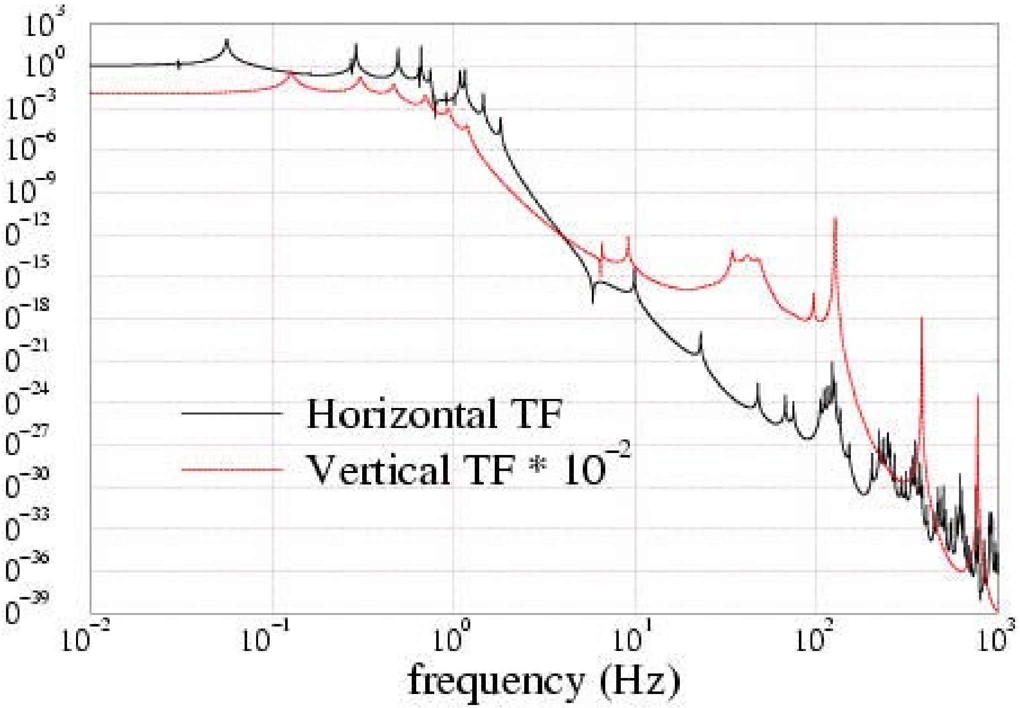




- Pressure ~ 10^{-9} mBar
- Very low hydro-carbon contamination

Interferometer control

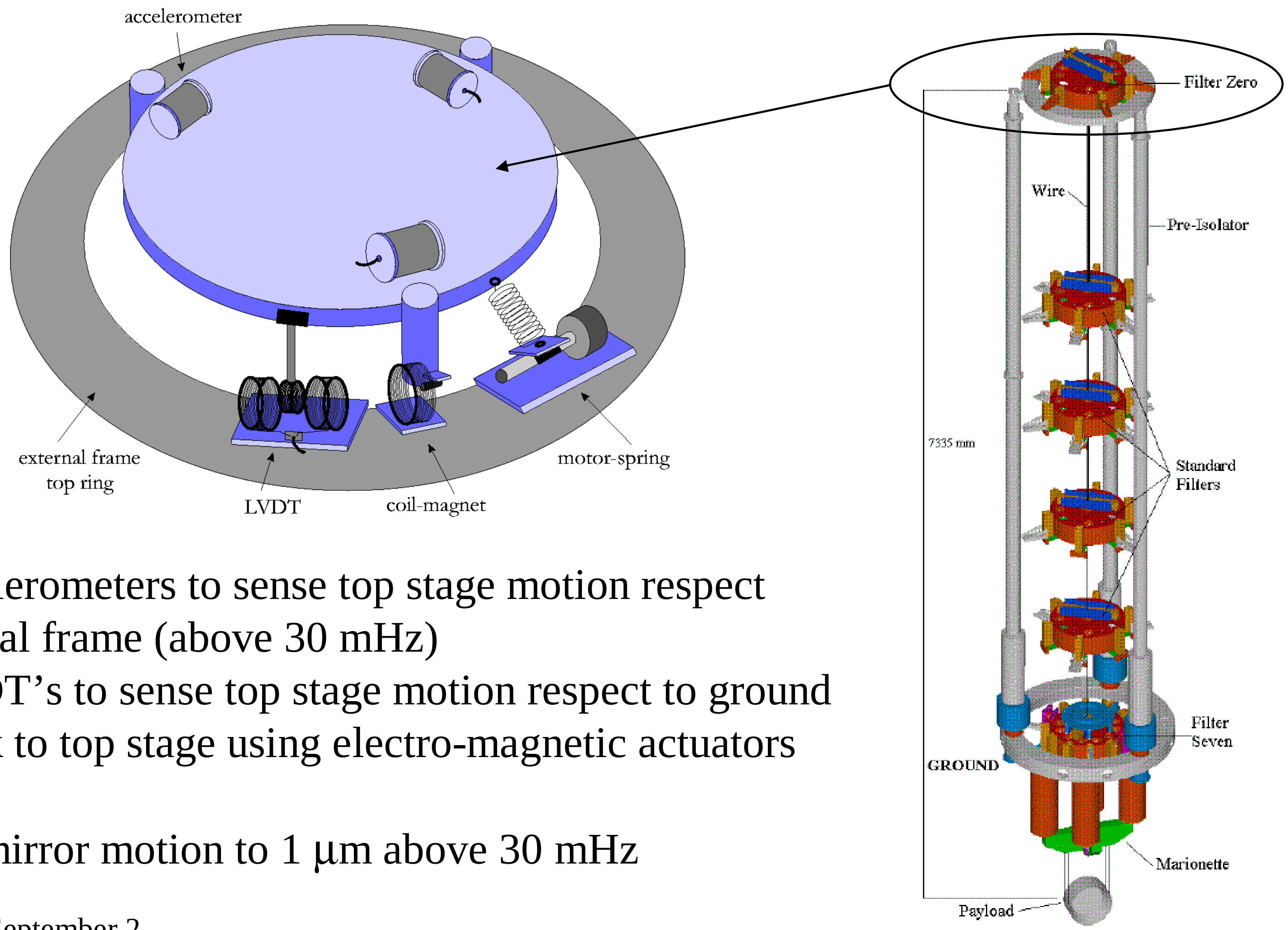
- Large seismic attenuation in the detection band (above few Hz)
- No attenuation or amplification (due to suspension internal resonance's) below few Hz
- Large mirrors motion/drifts at low frequency ~ 10^{-4}-10^{-3} m



- Active controls needed

1) to keep the interferometer aligned
2) to maintain the interferometer in required interference conditions

Inertial damping

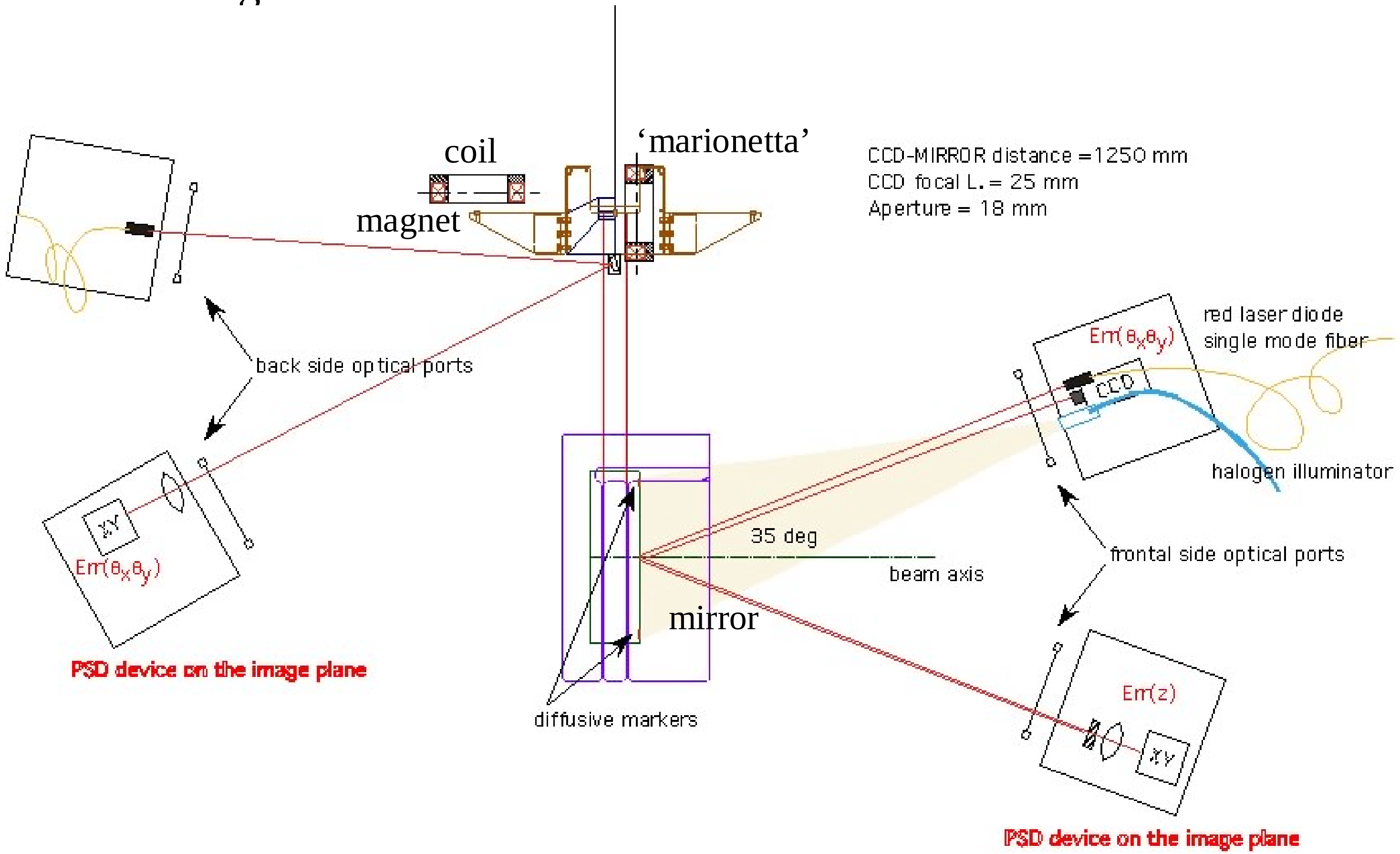


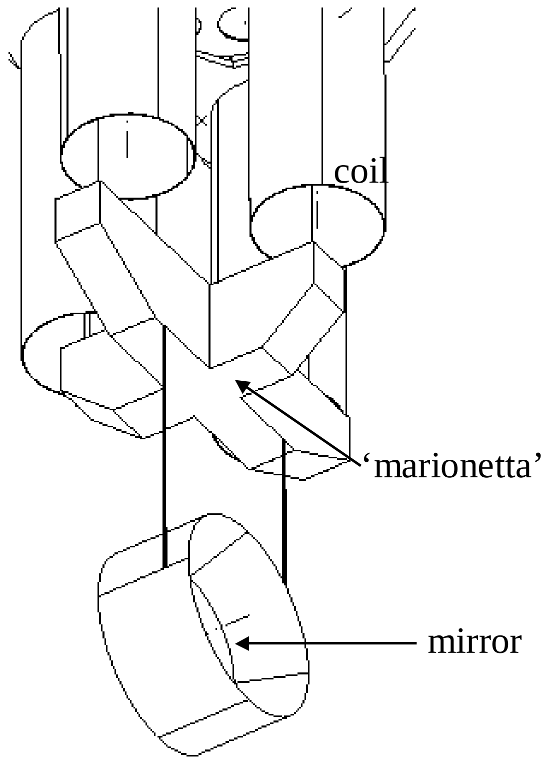
- Use accelerometers to sense top stage motion respect to an inertial frame (above 30 mHz)
- Use LVDT's to sense top stage motion respect to ground
- Feedback to top stage using electro-magnetic actuators

- Reduce mirror motion to 1 μm above 30 mHz

Interferometer alignment

- Coarse alignment: CCD camera looking at marks on mirror (10 μrad)
- Finer alignment: CCD camera and optical lever (1 μrad)
- Final alignment using interference signal (1 nrad)
- Actuation through coils acting on ‘marionetta’
- Digital control





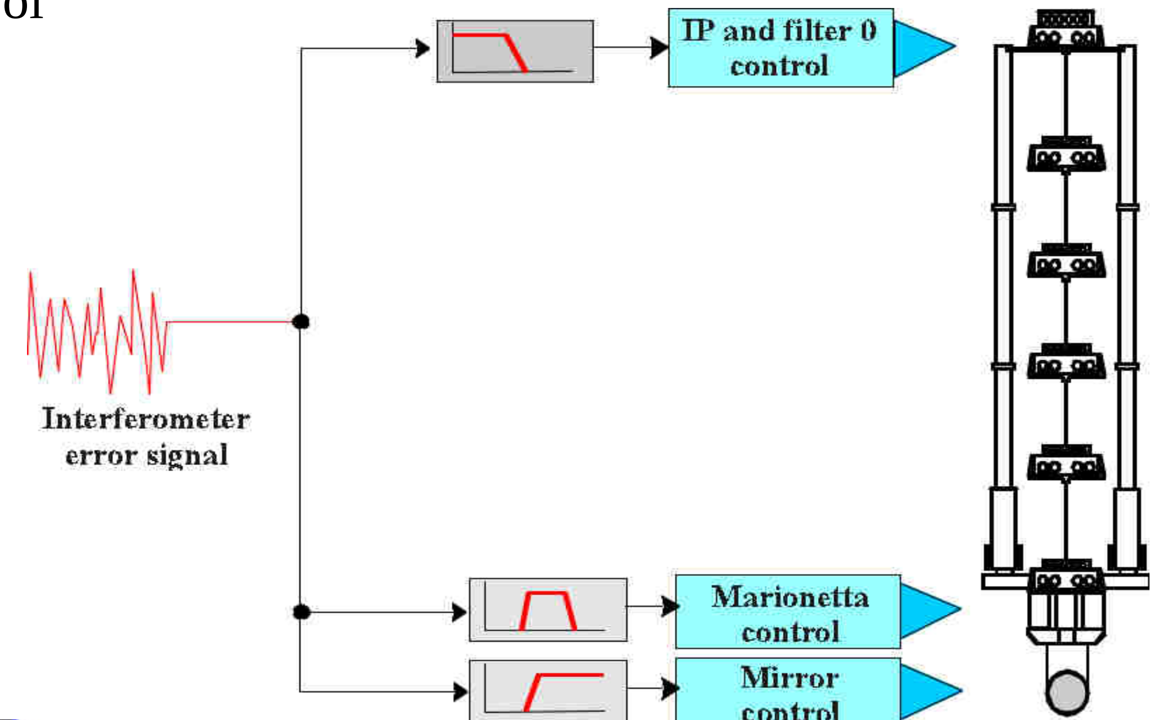
Interferometer length control

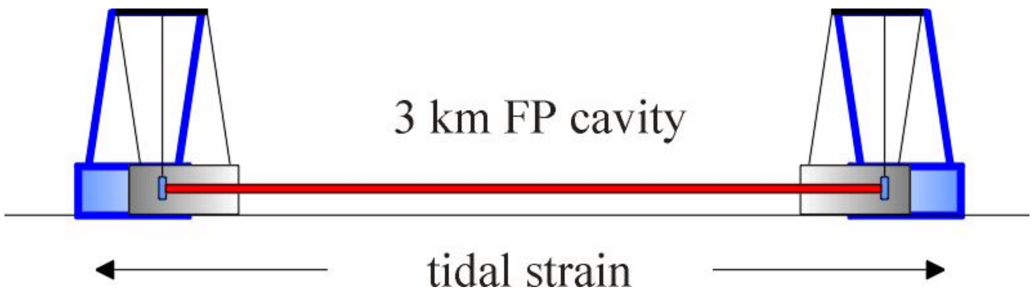
• Interferometer operation needs to control cavities length accurately ~ 10^{-12} m

• Residual motion above 30 mHz reduced to 1 µm using inertial damping

• Further reduction using interferometer signal

• Split signal in bands and use suspension actuators hierarchically



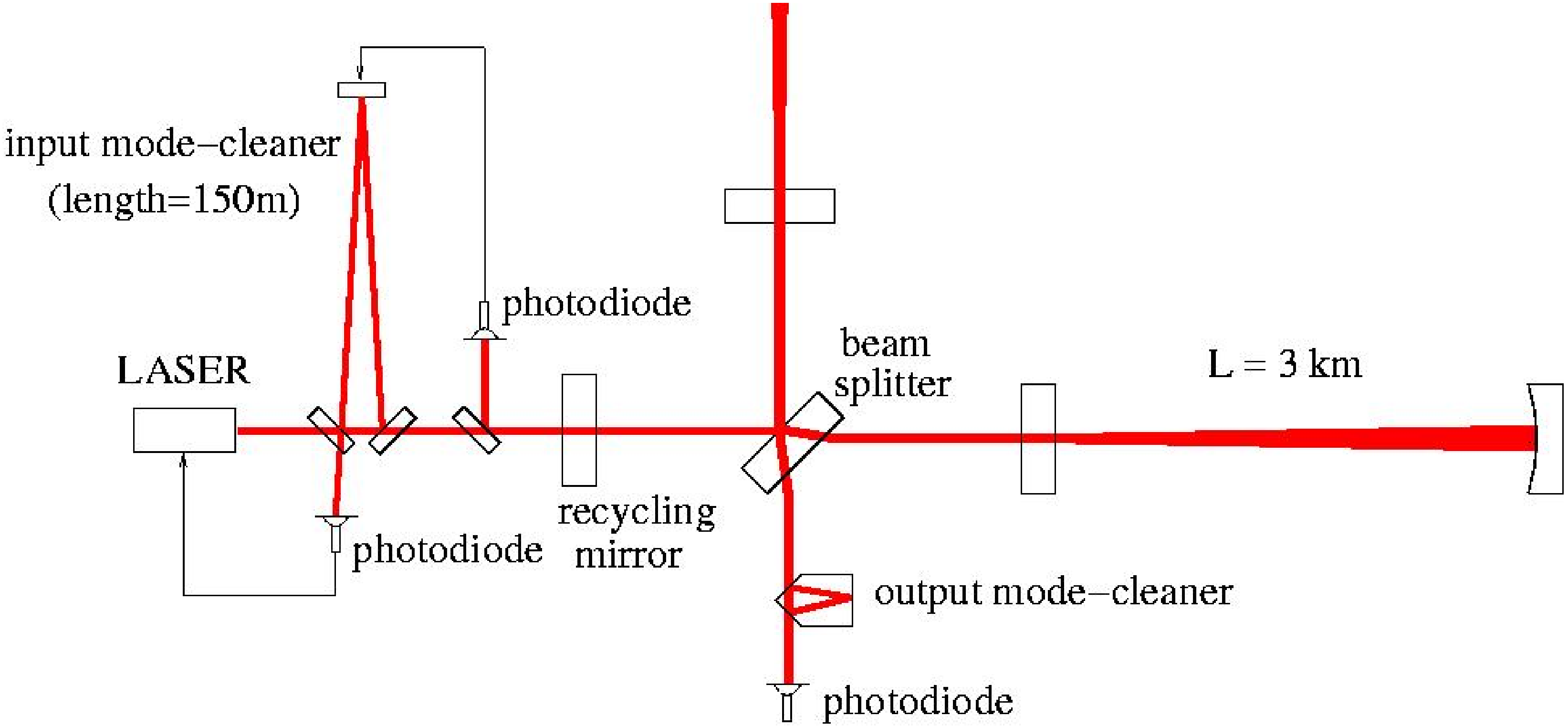


• Larger drift correction using inverted pendulum

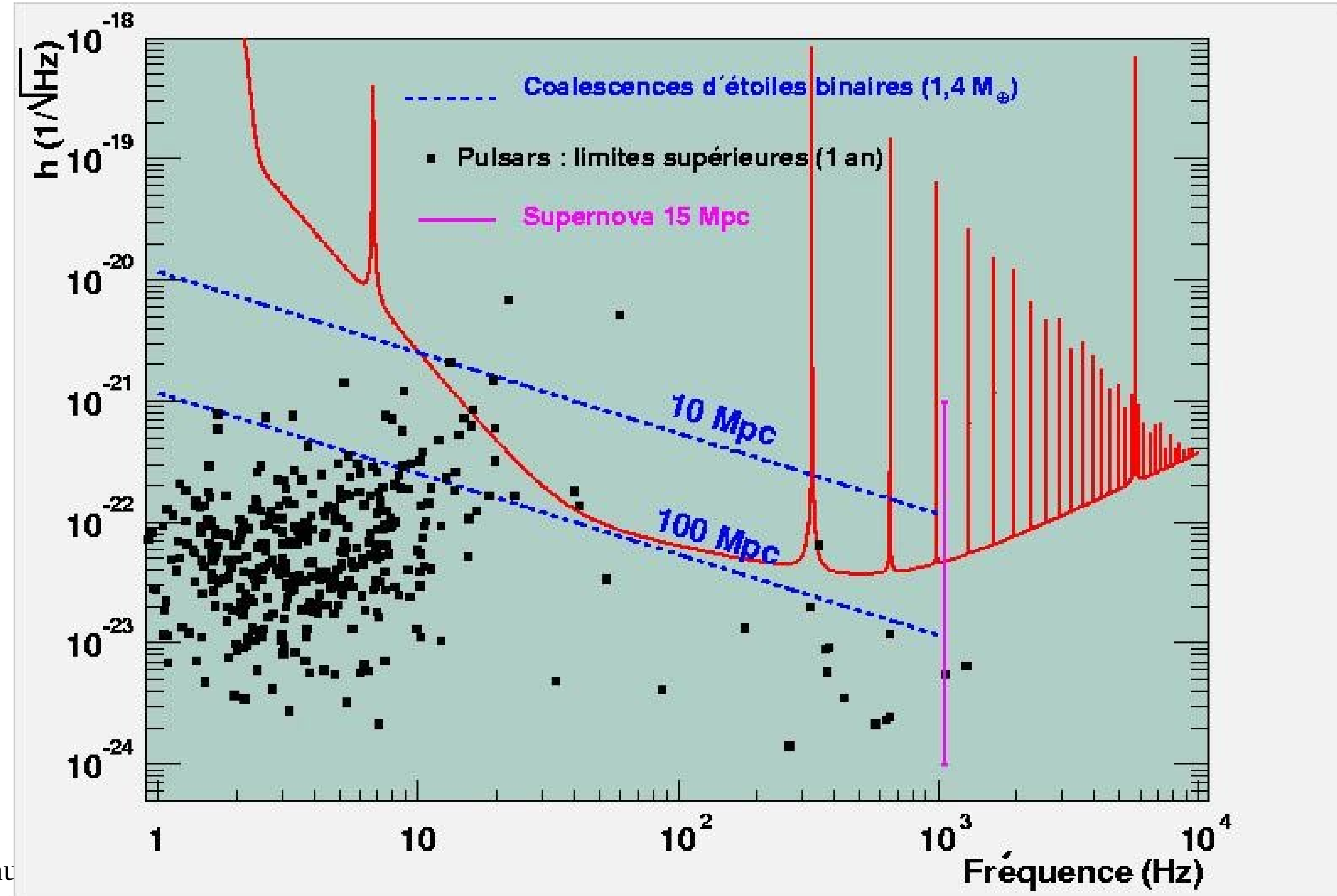
• Fine corrections applied directly to mirror

Laser frequency stabilization

- Free running laser: frequency stability ~ 1 kHz
- Pre-stabilization using input mode-cleaner as reference cavity ($\sim 10^{-2}$ Hz/√Hz)
- Final stabilization using interferometer as reference cavity ($\sim 10^{-6}$ Hz/√Hz)



VIRGO planned sensitivity

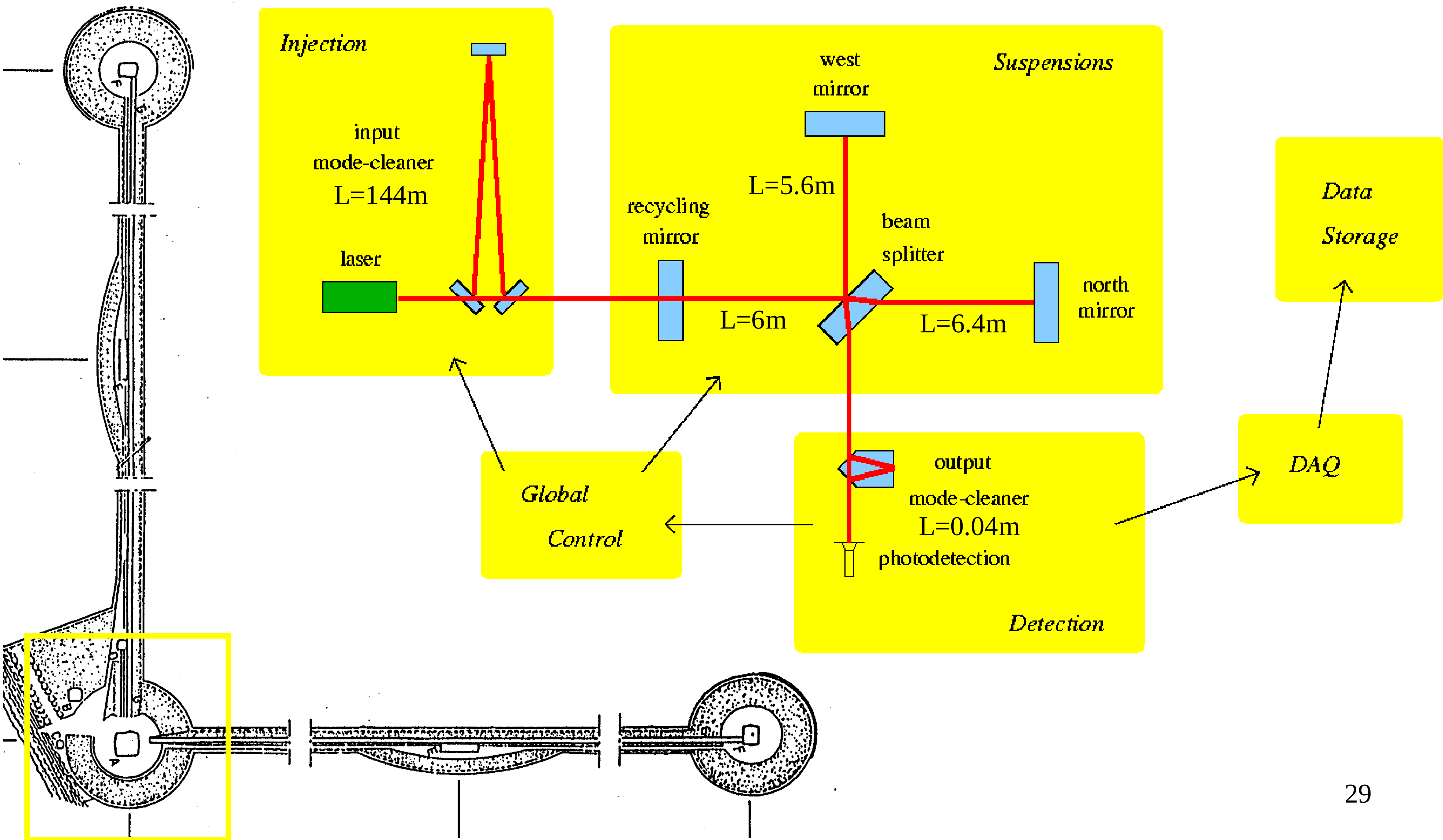


IV. Status of VIRGO

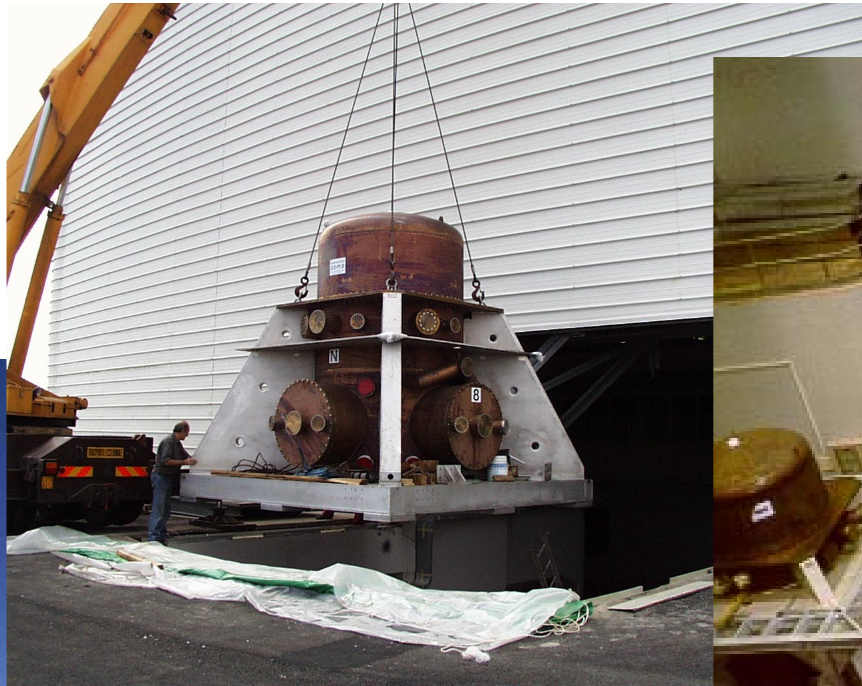
Civil engineering

- 3 km arms and all buildings completed last winter
- Central area available since 1998

The central interferometer (CITF)

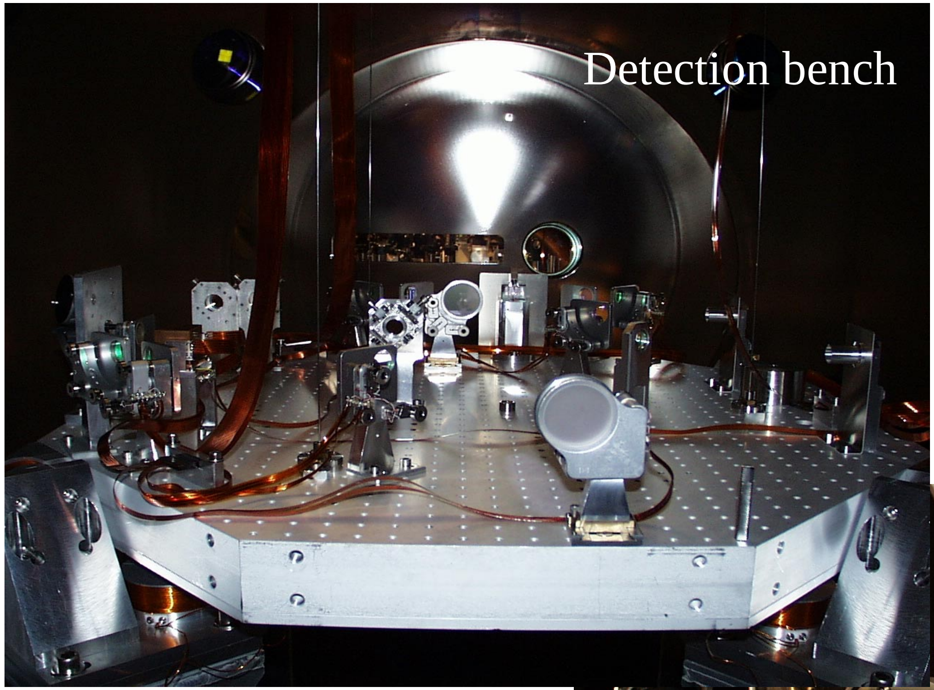


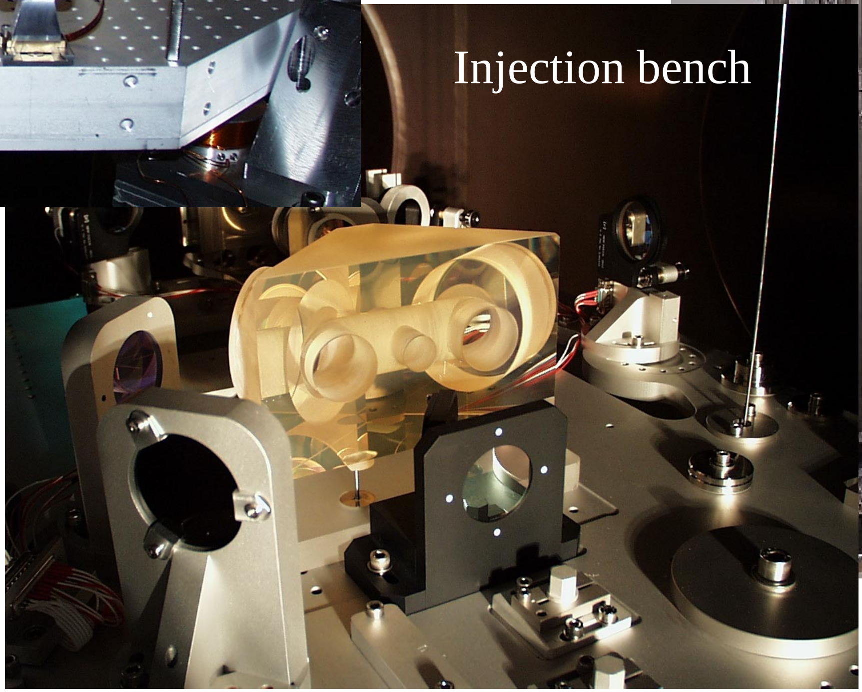
Vacuum chambers installation

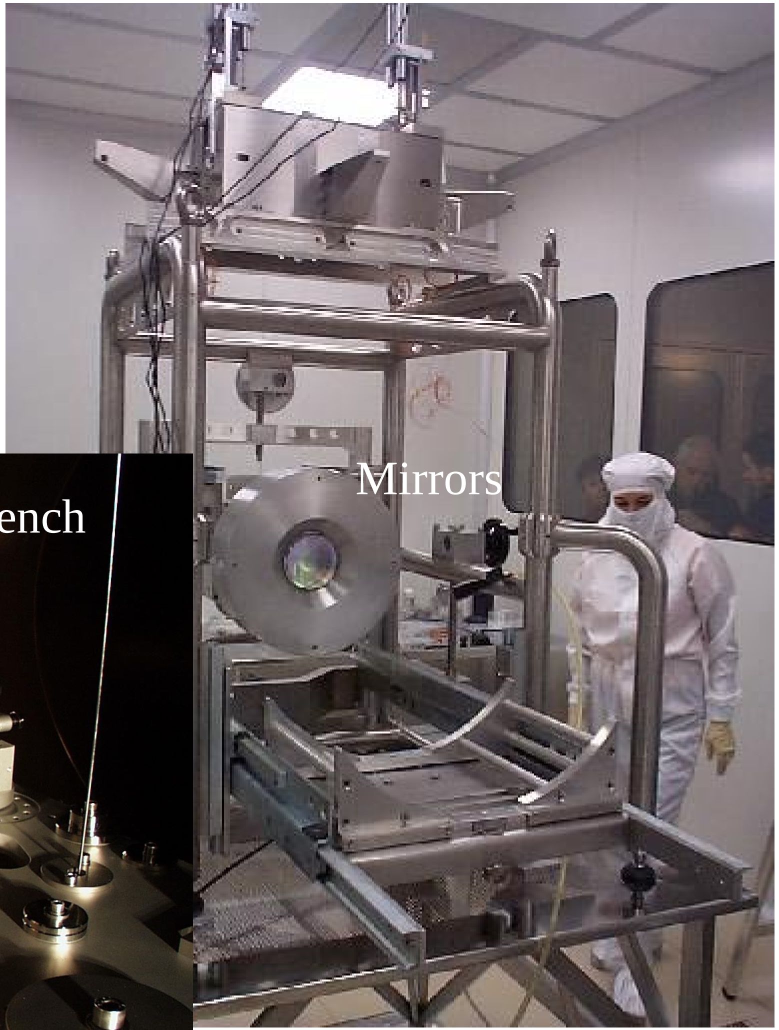


Suspensions installation

Optics installation





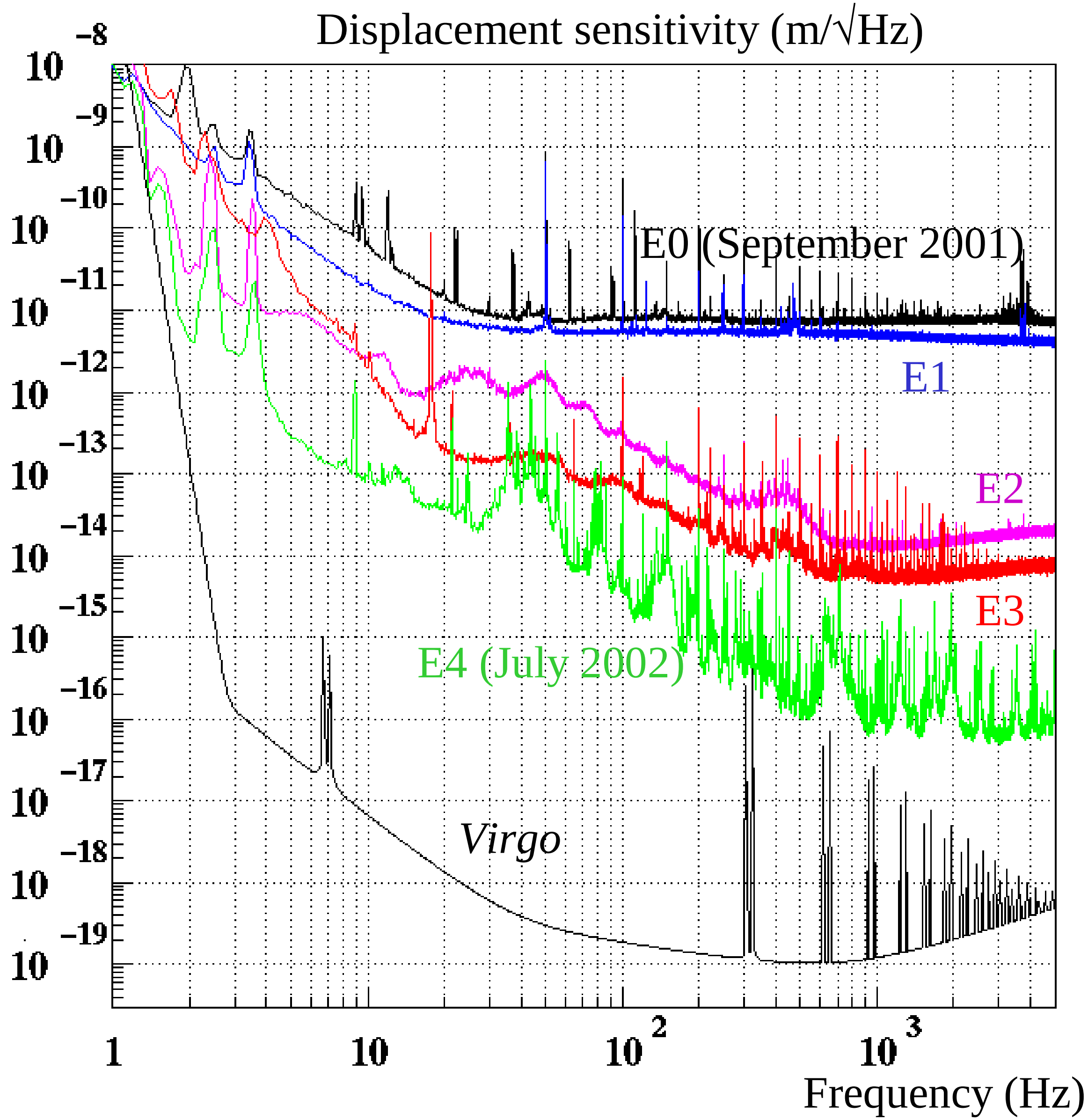


CITF commissioning

- Main purposes
- verify technical choices made for Virgo
- gain experience
- train people

- Achievements
- interferometer controlled
- performances and reliability understood
- 5 engineering runs performed (E0-E4)

- End of commissioning last July:
- few changes planned for Virgo



Tube installation

- 2 × 3 km → 400 modules (15 m)
- all modules installed
- few links to be installed
- vacuum achieved ~ 3 à 5 10^{-10} mbar

- Installation will be complete next October

Conclusion: next steps

- 2002 Upgrade CITF to Virgo

- Suspensions and mirrors installation in the end buildings
- Installation of final mirrors in the central area

- 2003 Virgo commissioning

- Set-up control systems
- First engineering runs

- 2004 First science run

VIRGO planned sensitivity