Advanced Virgo detector

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Gravitational **W**aves (GW)

➔ Predicted by Einstein in 1916 → *consequence of General Relativity*

WHAT ARE GWs?

- *Perturbations of the metric* (geometry of space-time)
- *Caused by an acceleration of masses*
- Propagate at the *speed of light.*

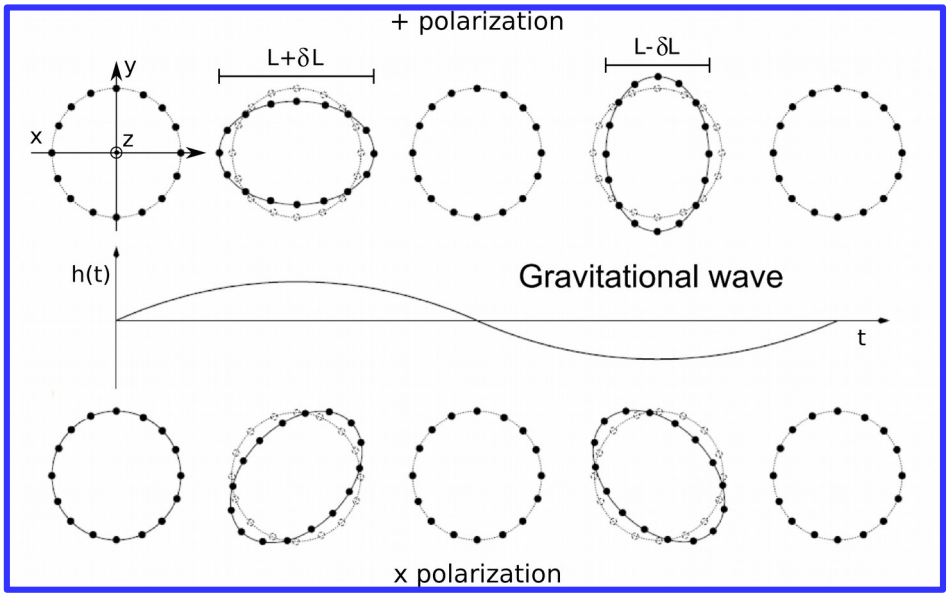
➔ **Effect** of the passage of a GW → *change on the distance between free masses*

Mass that senses only the gravitational force

$$\delta L / L \sim h$$

GW amplitude

➔ **Differential effect:**



GW detection principle

- Differential effect → **Michelson interferometer**
- Free test masses → **Suspended mirrors**

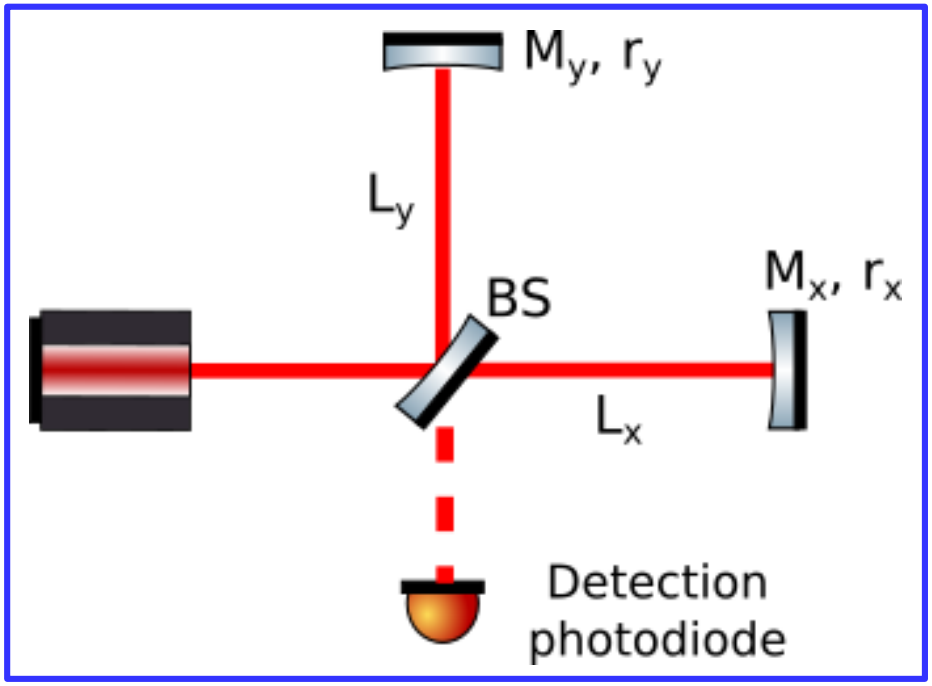
Interference depends on the phase difference between the Michelson arms → *sensitive to length difference*

$$\delta\phi = \frac{2\pi}{\lambda}\delta L$$

Change on the detected power

δP_{det}

Michelson interferometer



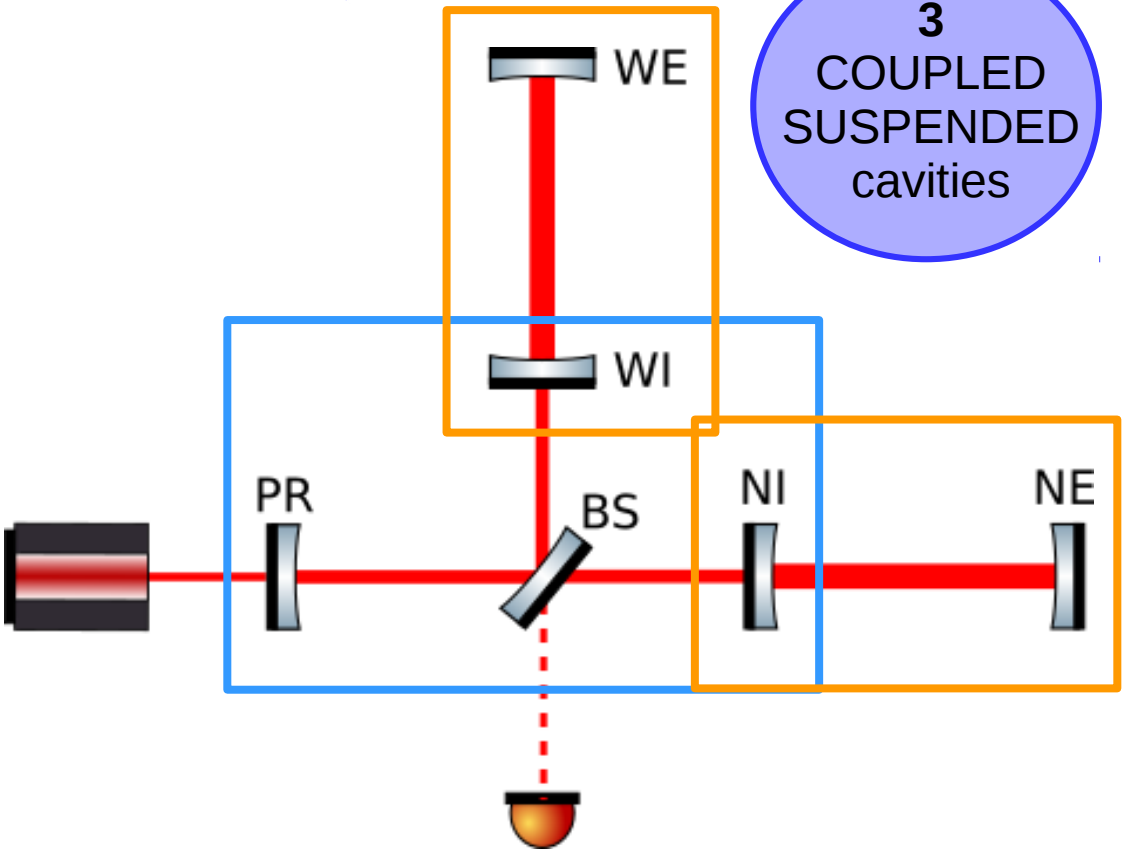
Which is the optimal working point?

- **Target:** reach the **maximal sensitivity** → *maximize the SNR* at the detection photodiode

GW detector working point

Sensitivity is limited by the ***shot noise***

Working point: Michelson in ***Dark Fringe***



3 COUPLED SUSPENDED cavities

Table top Michelson
not enough sensitivity
$h \sim 10^{-17}$

$$h_{shot} \propto 1 / (L \cdot \sqrt{P})$$

IMPROVEMENTS:

1) Fabry-Perot cavities in the arms (3 km) → increase the optical path

2) Power Recycling cavity → increase the circulating power

Fabry-Perot cavity

- Optical resonator: allows light to circulate in a closed path.
- **Resonance:** maximum power resonating inside the cavity

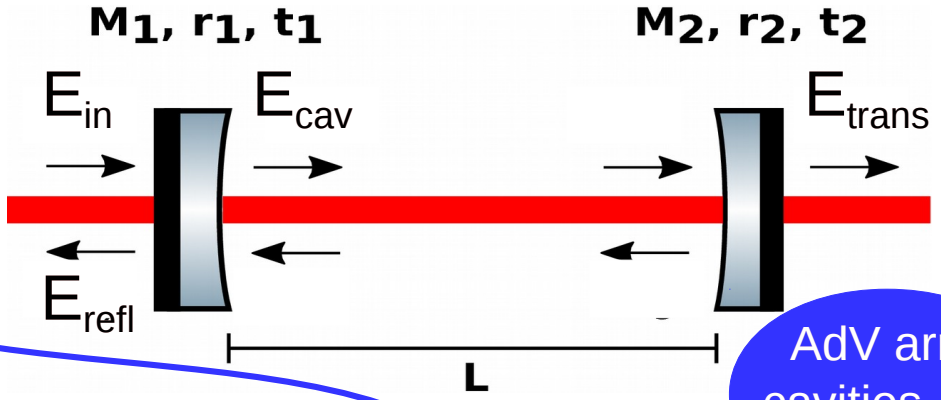
$$\delta\Phi \propto (\nu \cdot \mathbf{\delta L} + L \cdot \mathbf{\delta\nu})$$

- **Finesse:** it quantifies the quality factor of the cavity

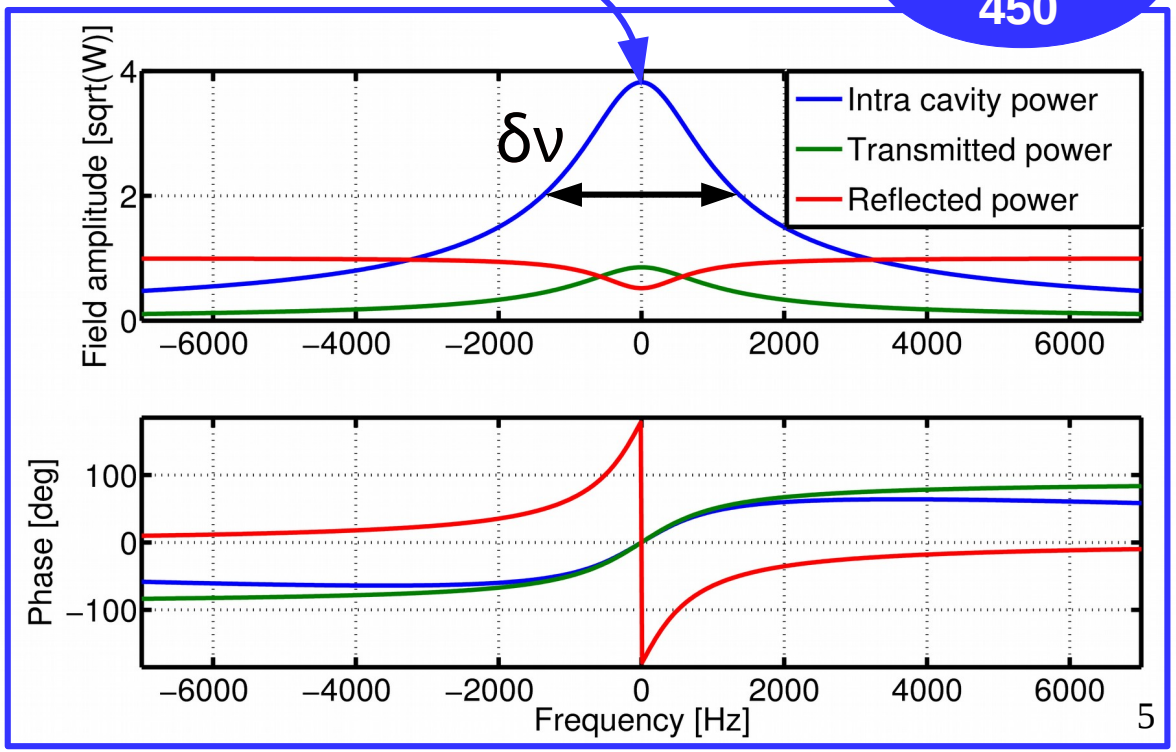
$$P_{cav} / P_{in} \approx 2 \cdot \mathcal{F} / \pi$$

- **Linewidth:** FWHM of the resonance in Hz

$$\mathbf{\delta\nu} = c / (\mathcal{F} \cdot 2 \cdot L)$$



AdV arm cavities $\mathcal{F}$ = **450**



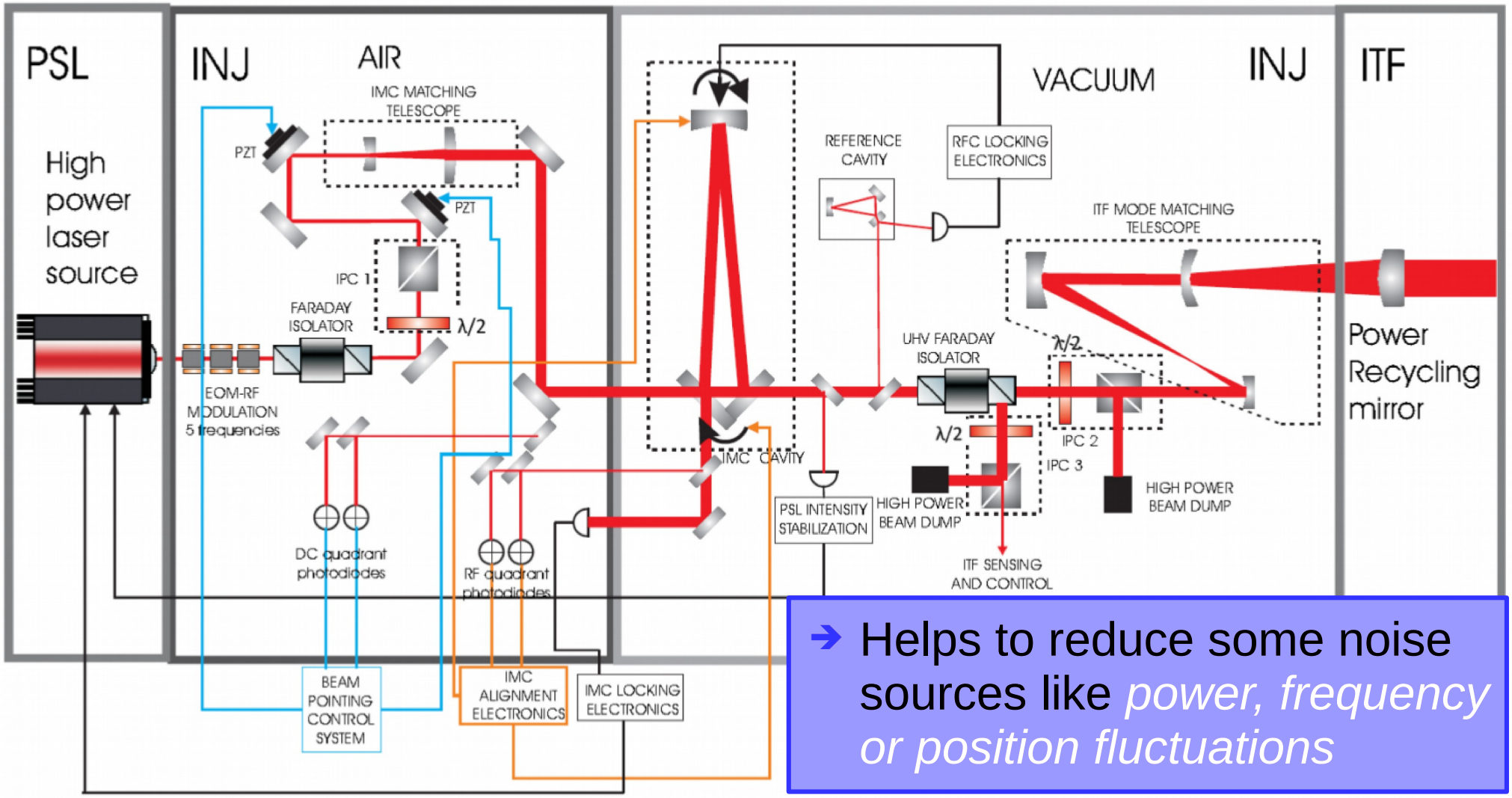
Limiting noises

- We want to measure a length difference of the order of 10^{-18} m → Noise becomes a limiting factor
- For Virgo we have developed extreme techniques to reduce the different noise sources

  - **Seismic noise:** mirrors are suspended by a "superattenuator" → 10^{12} of attenuation above 10 Hz
  - **Pressure fluctuations:** ultra-high vaccuum → P = 10^{-12} mbar
  - **Laser:** extremely stable in frequency ($\nu = 10^{15}$, $\delta\nu = 10^{-6}$ Hz) and very "clean" (high content of TEM00)
  - **Mirrors:** low roughness → 10^{-10} m RMS

Injection system

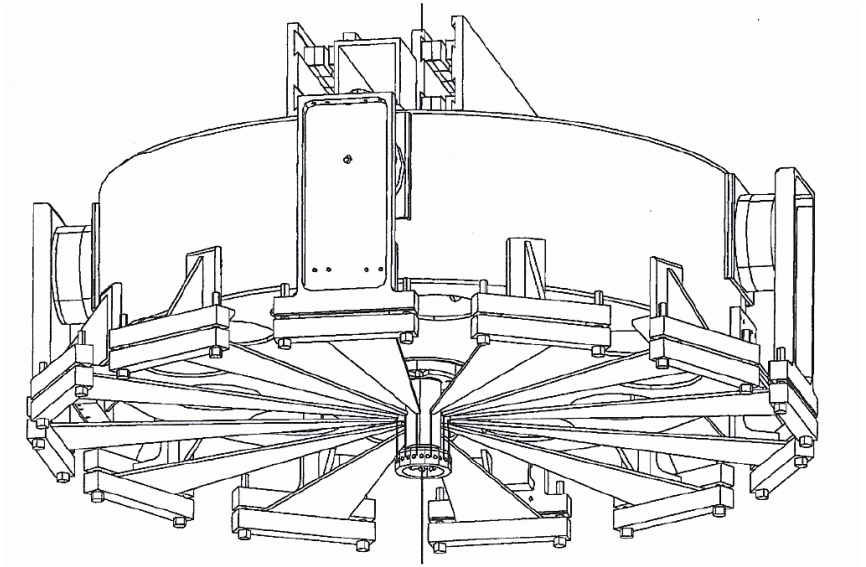
- Laser source 1064nm (Nd:YAG), continuous emission
- Complex system to *match the size, position and power* to the ITF

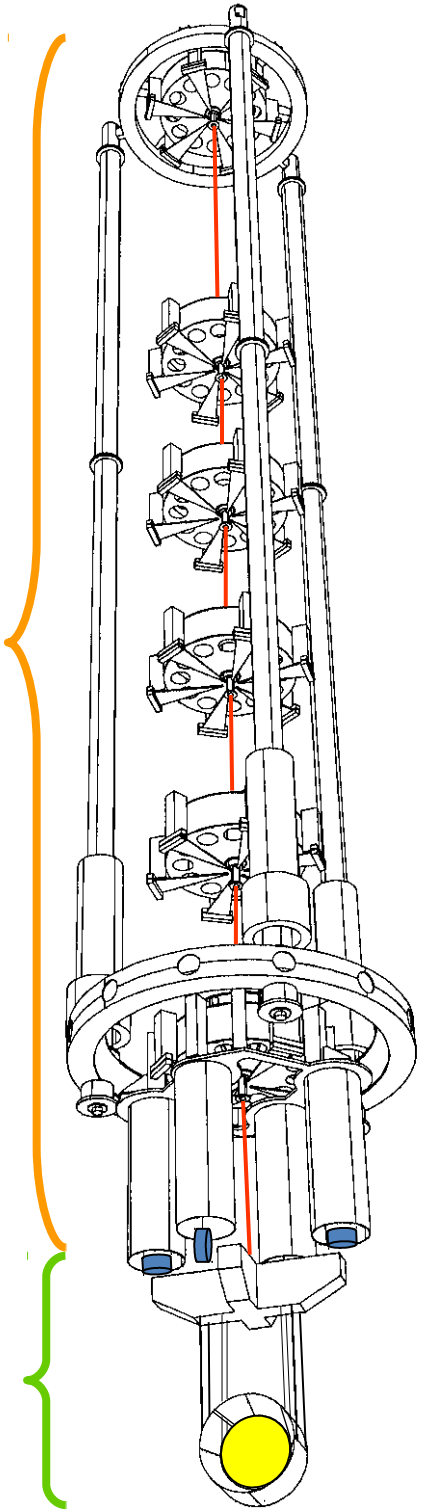


- Helps to reduce some noise sources like *power, frequency or position fluctuations*

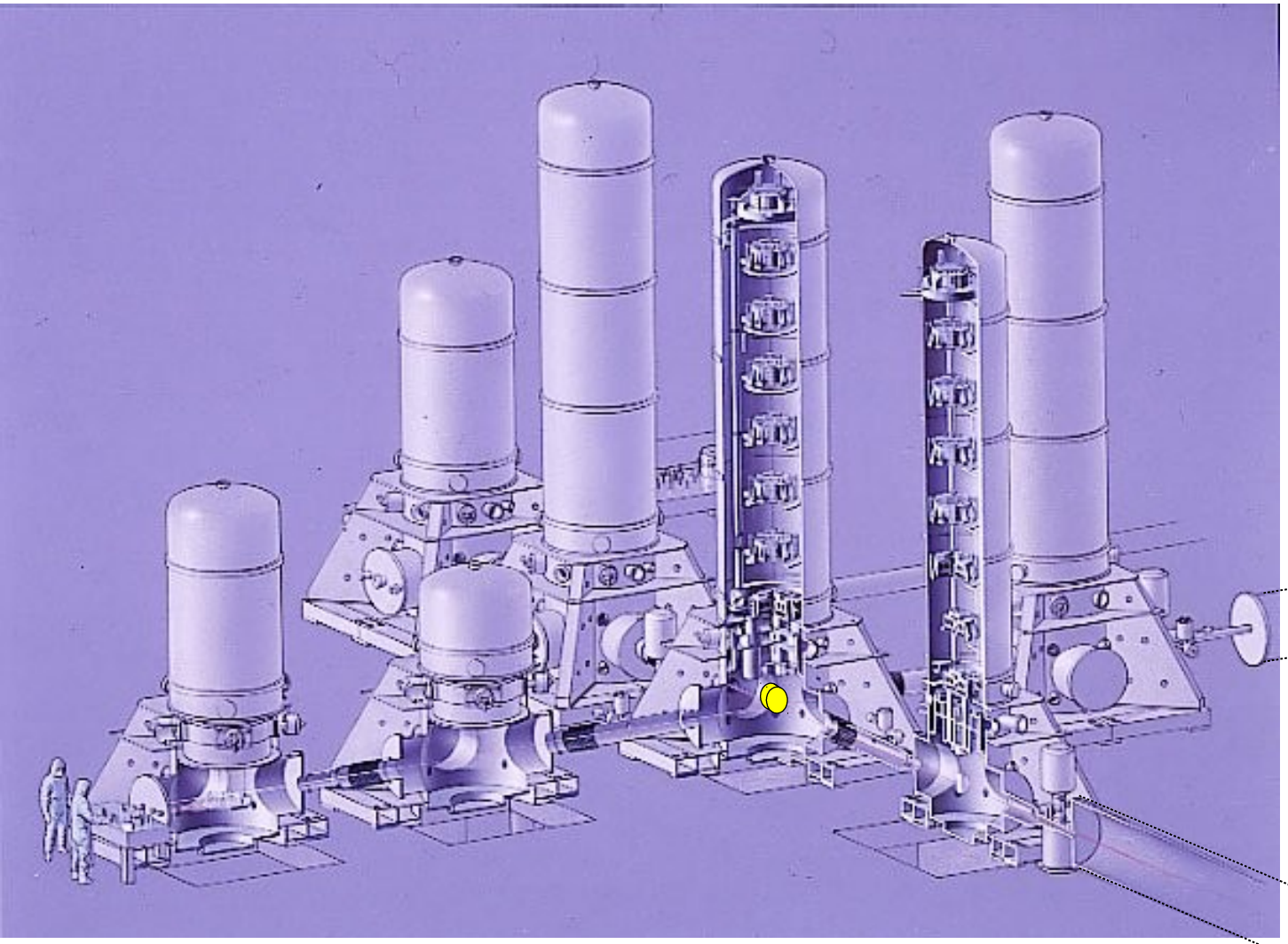
Superattenuators

- They are ~9m high
- **Top part:** Six mechanical filters + inverted pendulum
  - Total attenuation factor is the multiplication of each individual one $(f/f_0)^2$
- **Bottom part:** Marionetta + Mirror
  - They are controlled using Electromagnetic force (pairs coil-magnet)





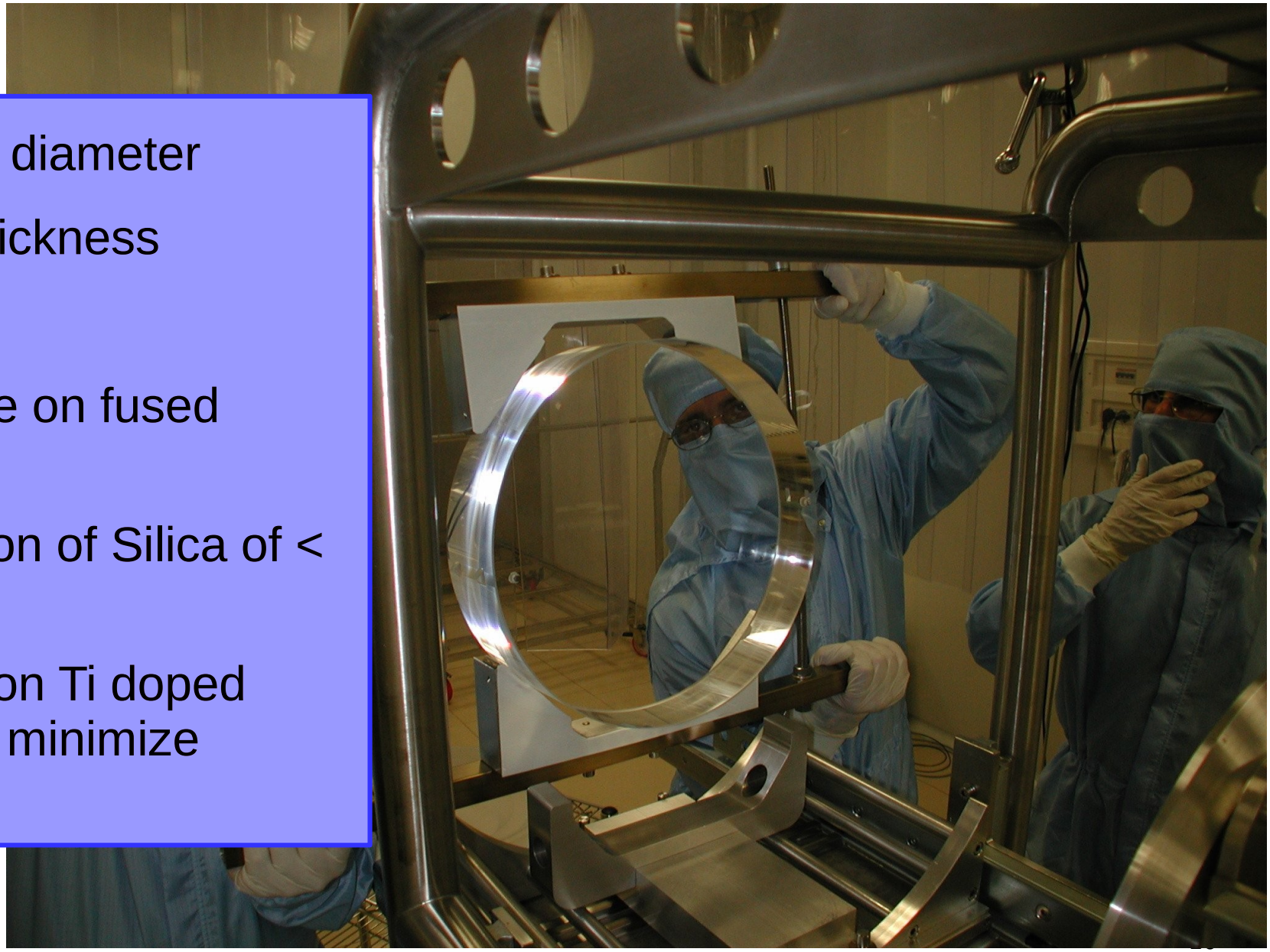
Vacuum system



- There are 7000m³ of vacuum → Biggest system of ultra-vacuum of Europe

Mirrors

- 35 cm of diameter
- 20 cm thickness
- 42 kg
- Substrate on fused Silica
- Absorption of Silica of < 1ppm
- Coating on Ti doped Ta_2O_5 → minimize losses

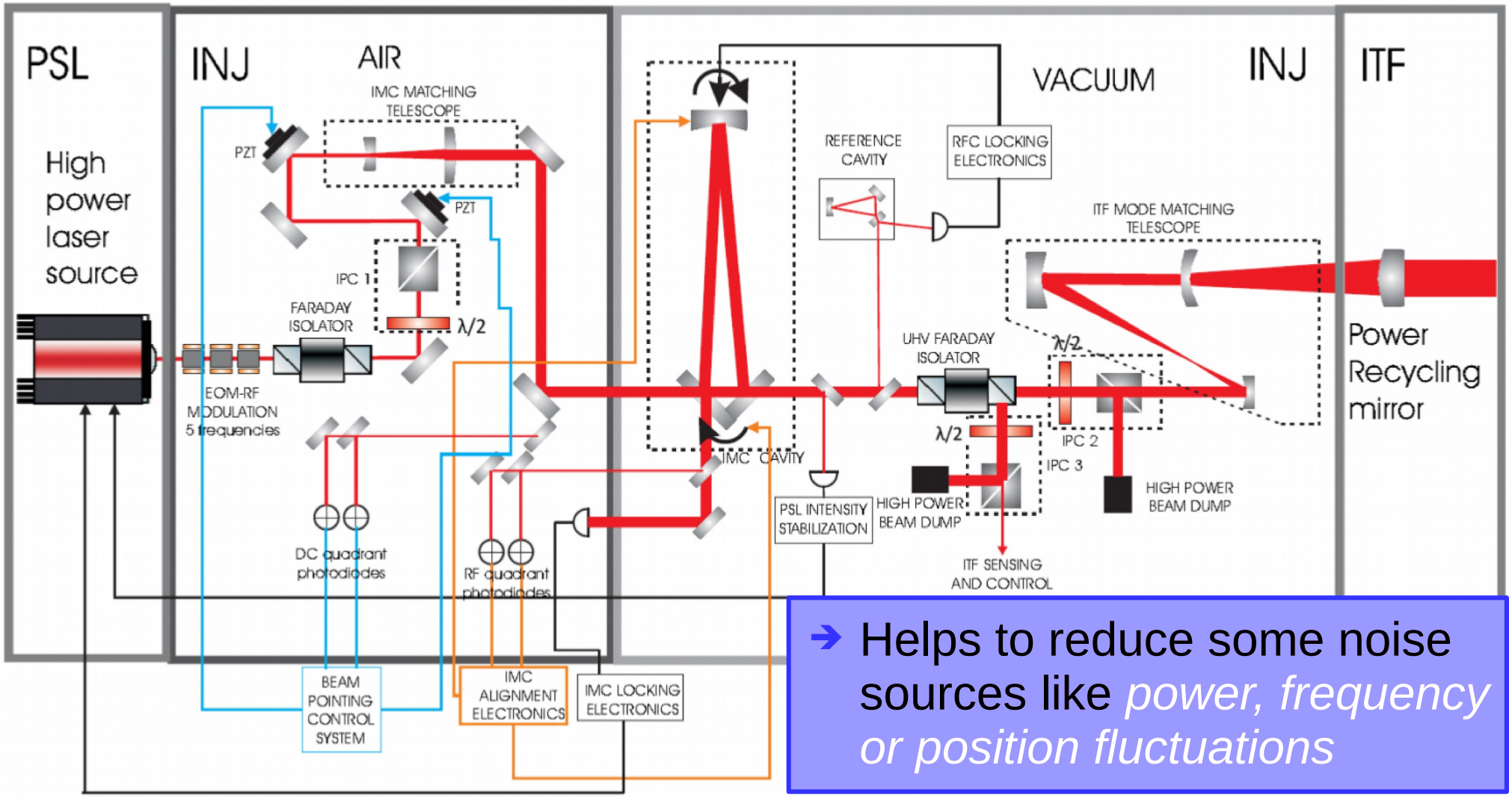


Monolithic fibers

- The fibers used to suspend the mirrors are made also in Silica
- Their diameter is 400 μm!

Injection system

- Laser source 1064nm (Nd:YAG), continuous emission
- Complex system to *match the size, position and power* to the ITF



- Helps to reduce some noise sources like *power, frequency or position fluctuations*

Residual mirror movement

TARGET:

Bring the interferometer to its working point:
Dark Fringe + Cavities on resonance

PROBLEM:

- Residual seismic noise (*~1μm rms, ~1μm/s*) moves the mirrors both angularly and longitudinally → working point of each DOF is crossed in a random way
- **Active control** is necessary to keep the ITF at its working point
  - *4 longitudinal* DOFs (lengths) + *frequency stabilization* (laser)
  - *16 angular DOFs* (Cavities, PR, BS and Input beam)

Longitudinal DOFs

Working point of maximum sensitivity:

- **Arm cavities** and **PRC** → *Resonance*
- **Michelson** → *Dark Fringe*

Longitudinal Degrees Of Freedom

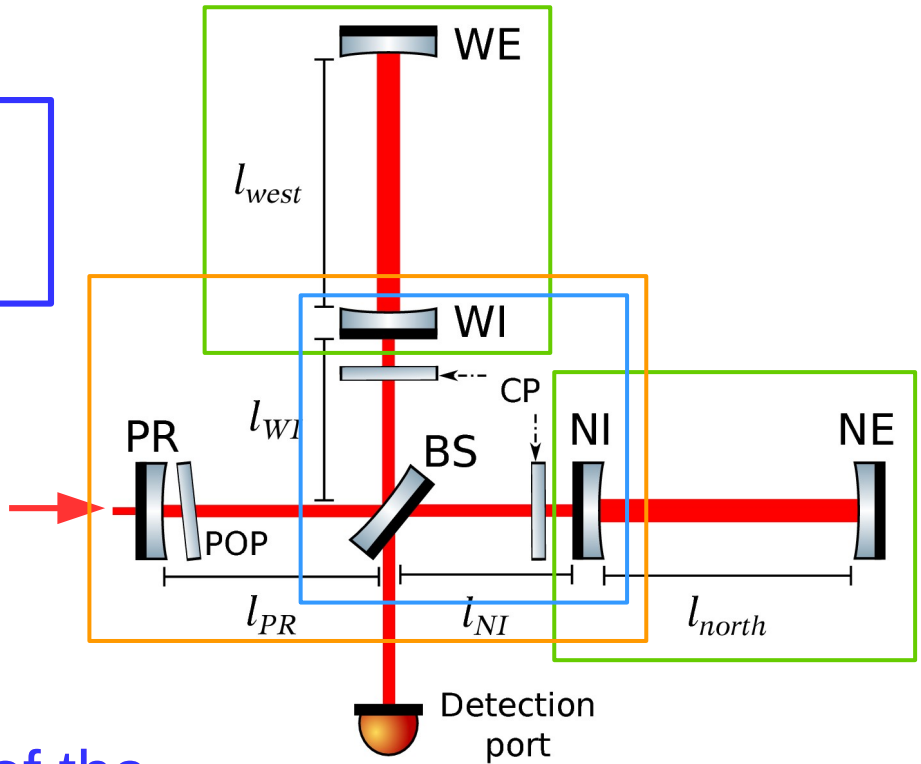
$$CARM = \frac{l_{north} + l_{west}}{2}$$

$$DARM = \frac{l_{north} - l_{west}}{2}$$

$$MICH = l_{NI} - l_{WI}$$

$$PRCL = l_{PR} + \frac{l_{NI} + l_{WI}}{2}$$

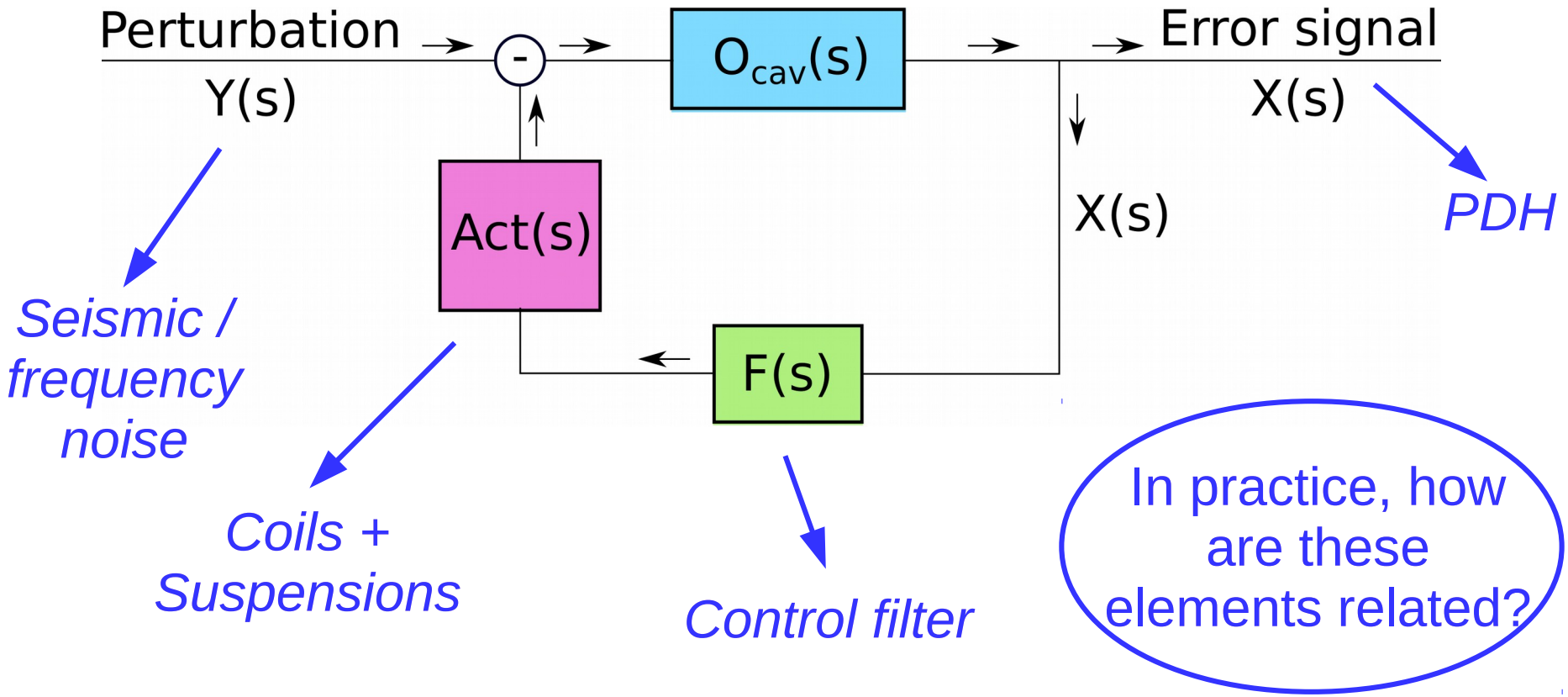
Estimation of the required control



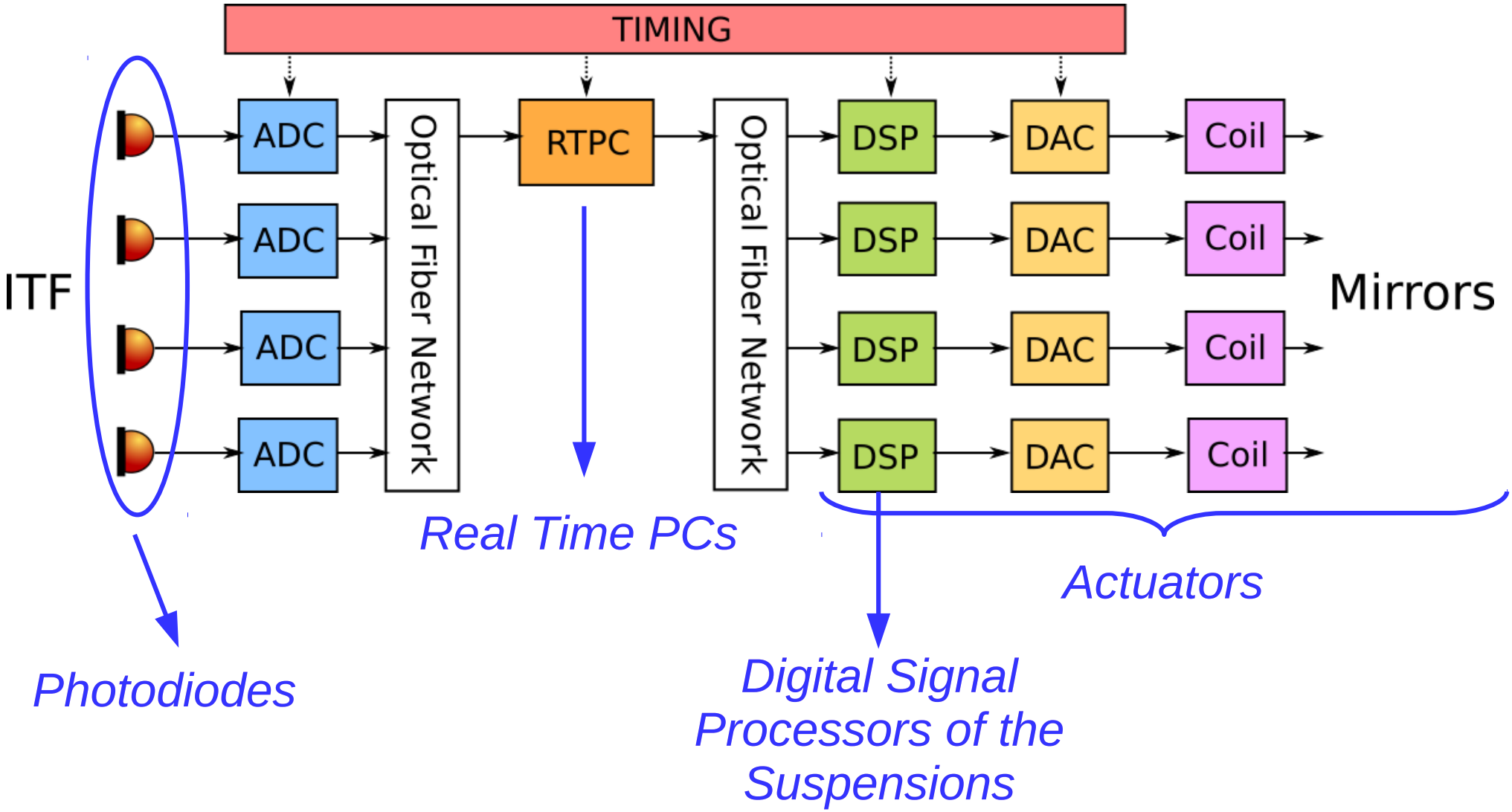
- CARM ~ 4·10^{-14} m
- DARM ~ 6·10^{-12} m
- MICH ~ 2·10^{-9} m
- PRCL ~ 7·10^{-11} m

Active control: feedback loop

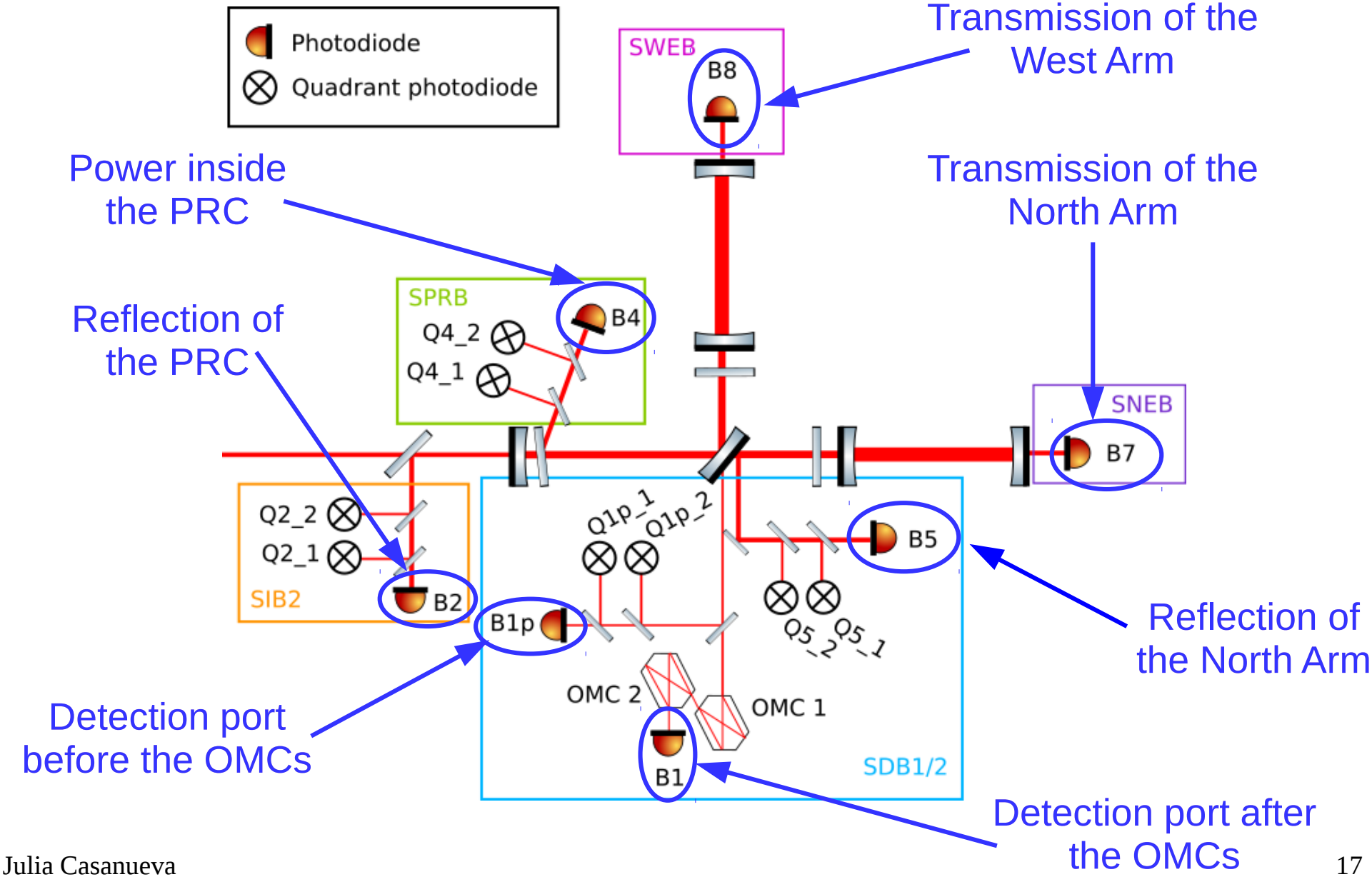
Control loops are composed of: **Plant** → Error signal → **Control Filter** → **Actuator** → **Plant**



Data Acquisition system



Detection layout



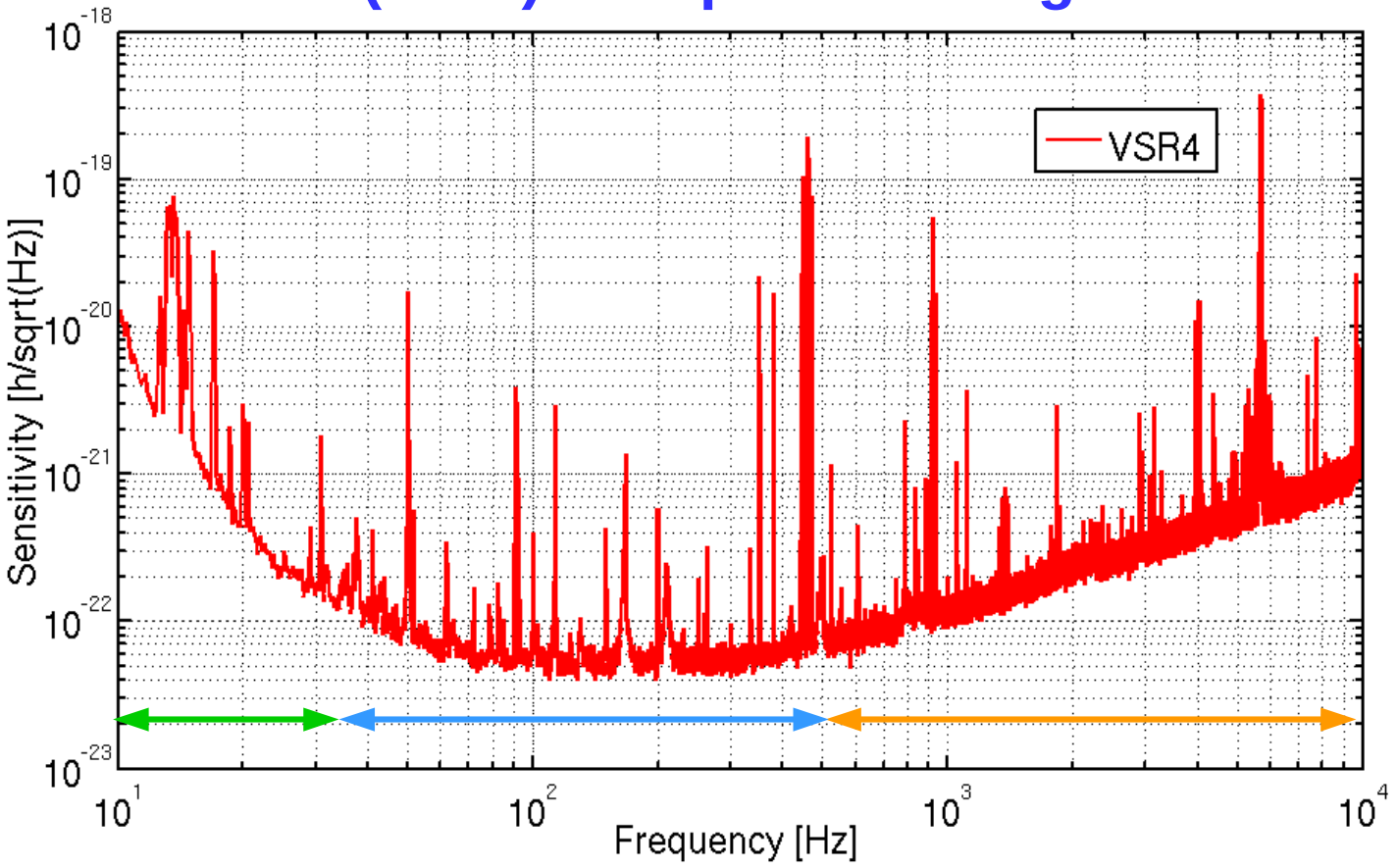
1st generation of GW detectors

- 1st generation served as a *proof of the working principle*
  - No detection was made → 2nd generation improve sensitivity by a factor 10!

Best *Initial Virgo* sensitivity (2011) 12 Mpc BNS range

Thermal noise limited (coating)

Thermal noise limited (suspensions)



Shot noise limited

Advanced Virgo upgrades

⇩ Reduce thermal noise:

- Increase the *mirror masses*
- *Geometry of the arm cavities* changed → waist in the middle to *increase beam size on the mirrors*

⇩ Reduce shot noise:

- *Increase finesse* of the arm cavities ~ 450 (factor 3 wrt *Initial Virgo*)

$h_{therm} \propto 1 / (m \cdot w)$

⇩ Reduce diffused light

- Detection benches *suspended* and in *vacuum*
- New system of *baffles* in strategic places to *absorb diffused light*

Advanced Virgo sensitivity

- Advanced Virgo joined the Avanced LIGO interferometers on the O2 data taking the 1st of August with *~80 % of duty cycle* and ~*26 Mpc of BNS range*