Progettando ET: come si disegna un interferometro per onde gravitazionali

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Gravitational Waves

Perturbation of the space-time metrics

$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$

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

Flat metric

Small perturbation $h_{\mu\nu} \ll 1$

Effect on matter: ***tidal force*** on bodies it passes through

Gravitational Waves polarization

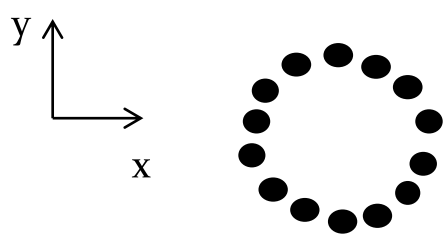
$$h_{\mu\nu} = \varepsilon_{\mu\nu} \exp[i(\omega_{GW} t - \mathbf{k} \cdot \mathbf{r})]$$

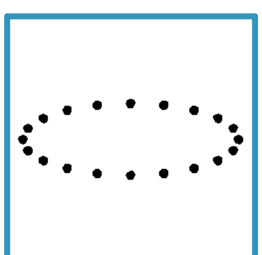
2 degrees of freedom

+ polarization

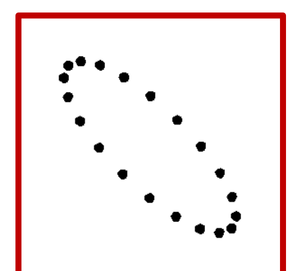
$$\varepsilon_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h^{+} & h^{\times} & 0 \\ 0 & h^{\times} & -h^{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

× polarization

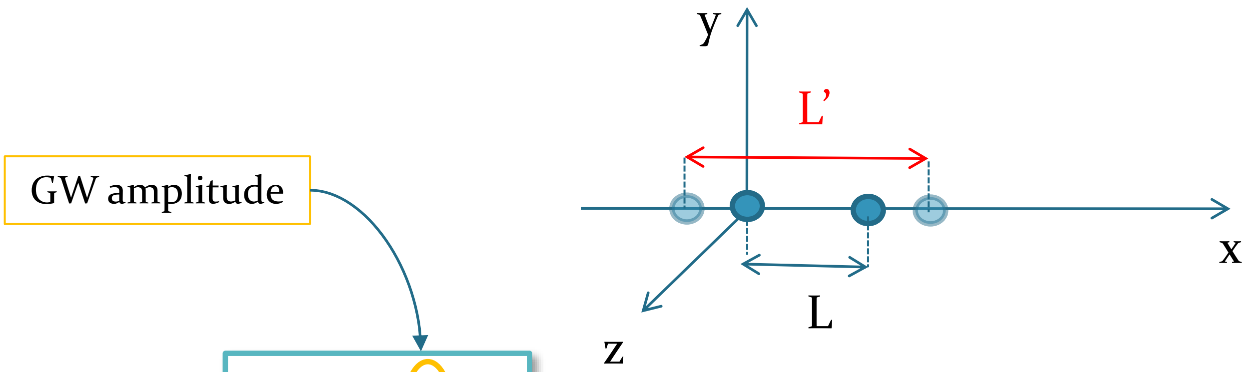




For a wave travelling in the z direction…



The effect of Gravitational Waves on free falling masses



$$\delta L \propto h\, L$$

Very weak amplitude: $h \approx 10^{-21}$ for GW produced by huge astrophysical sources

The distance between two free-falling masses separated by ~Km will change by
$\boldsymbol{\delta L \approx 10^{-18}}$**m**

"That is comparable to a hair's-width change in the distance from the Sun to Alpha Centauri, its nearest star".

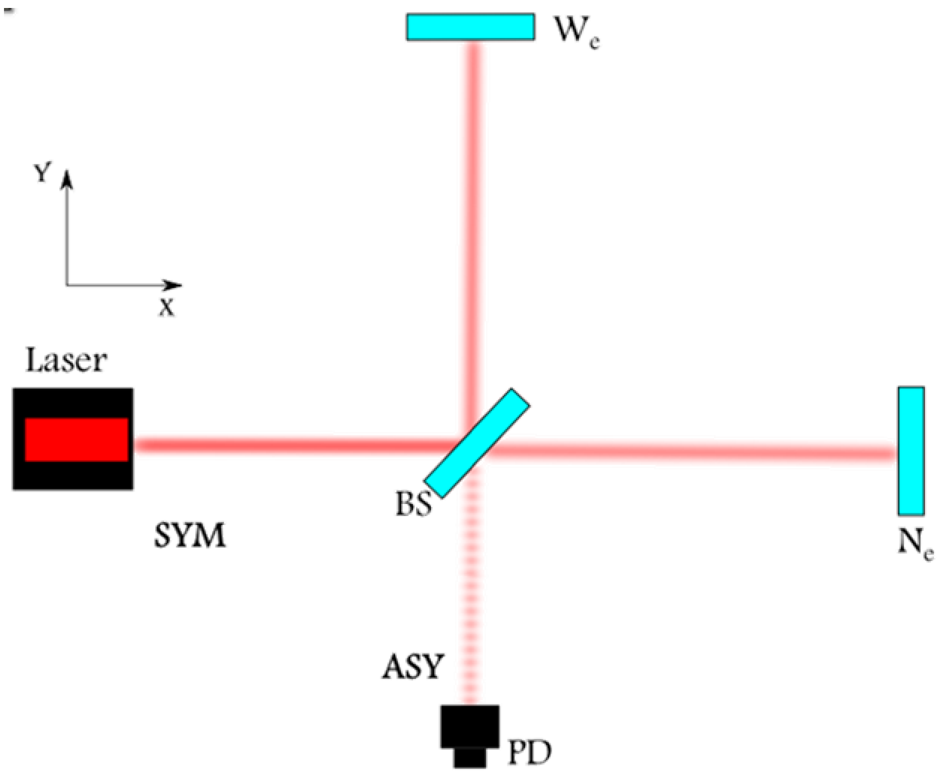
HOW DO WE MEASURE THE EFFECT OF GRAVITATIONAL WAVES?

Michelson Interferometry to detect GWs

$\delta L \propto h\, L$

Use an interferometer as a transducer: convert **displacements** into **optical signals**

$$\delta\phi = G\,\delta L$$



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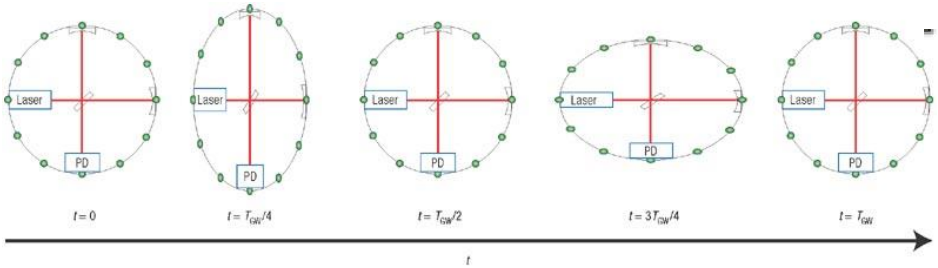
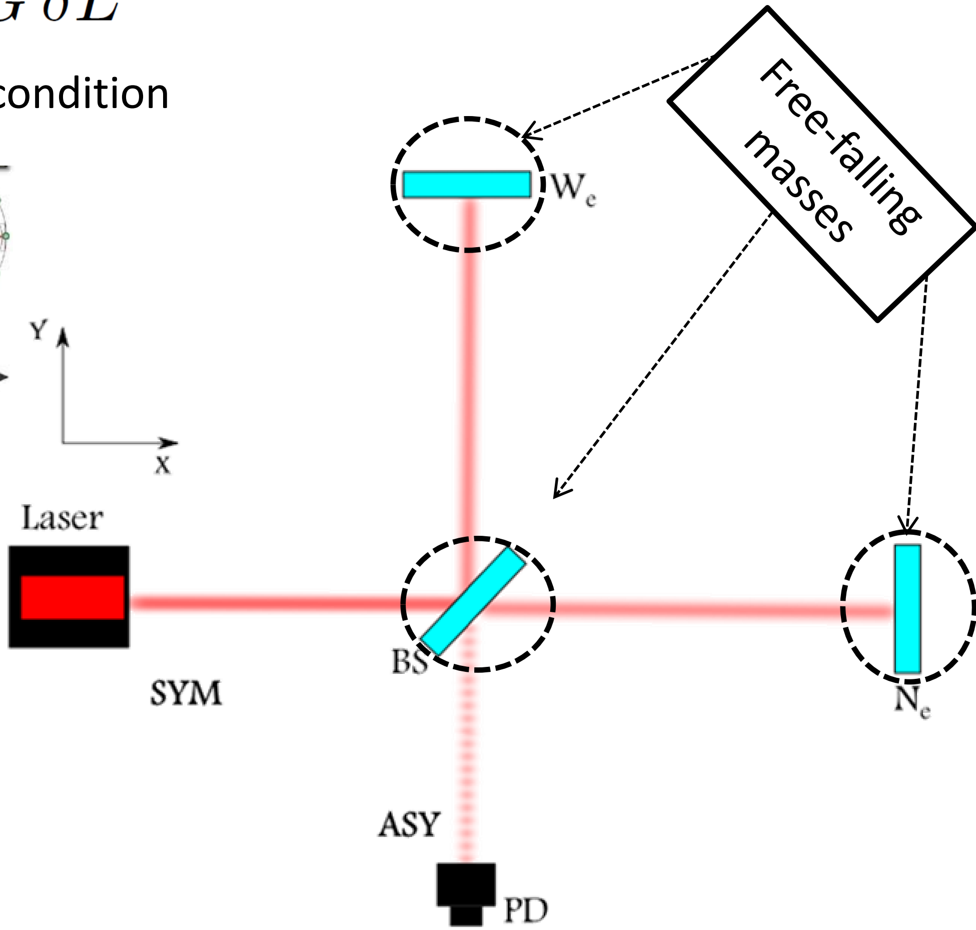
Suspended mirrors to reproduce the free-fall condition



GWs produce a differential variation of the arm lengths which is revealed at the ***antisymmetric port*** (ASY) of the interferometer



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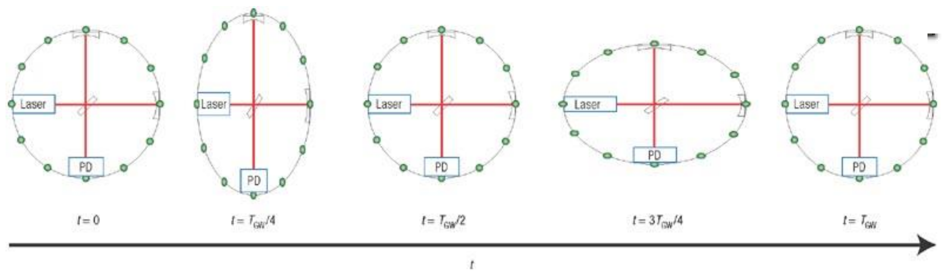
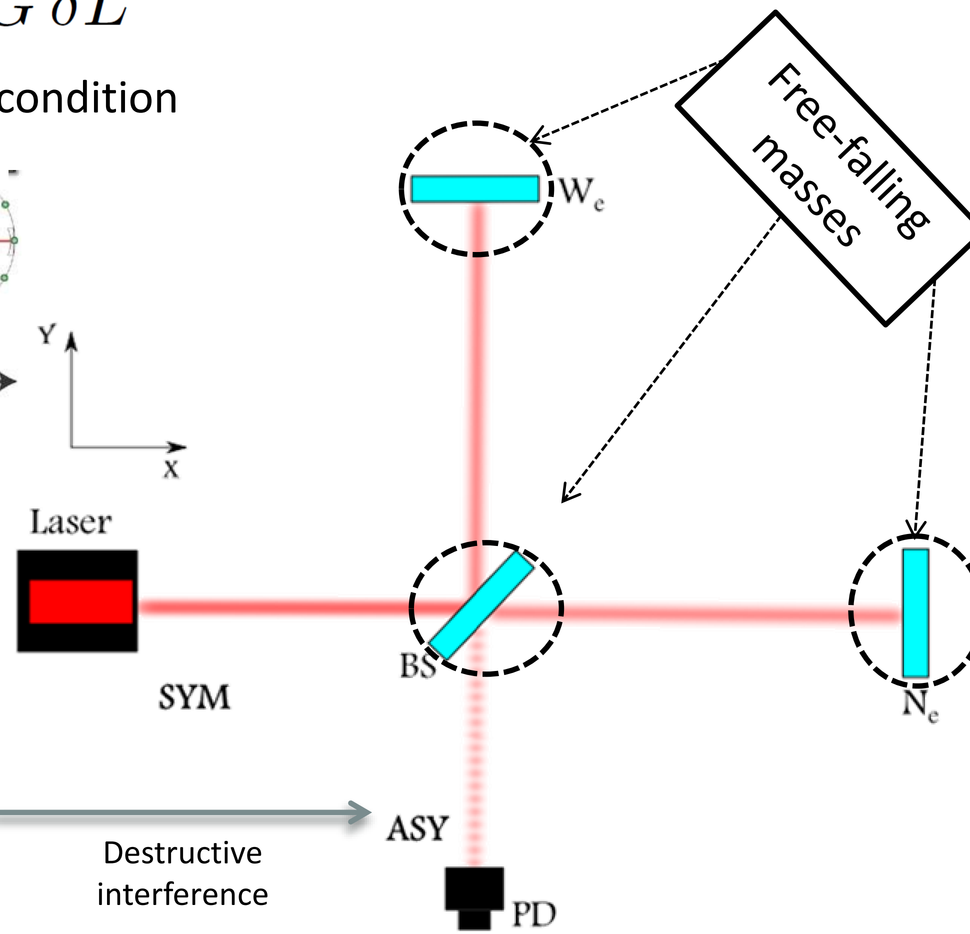
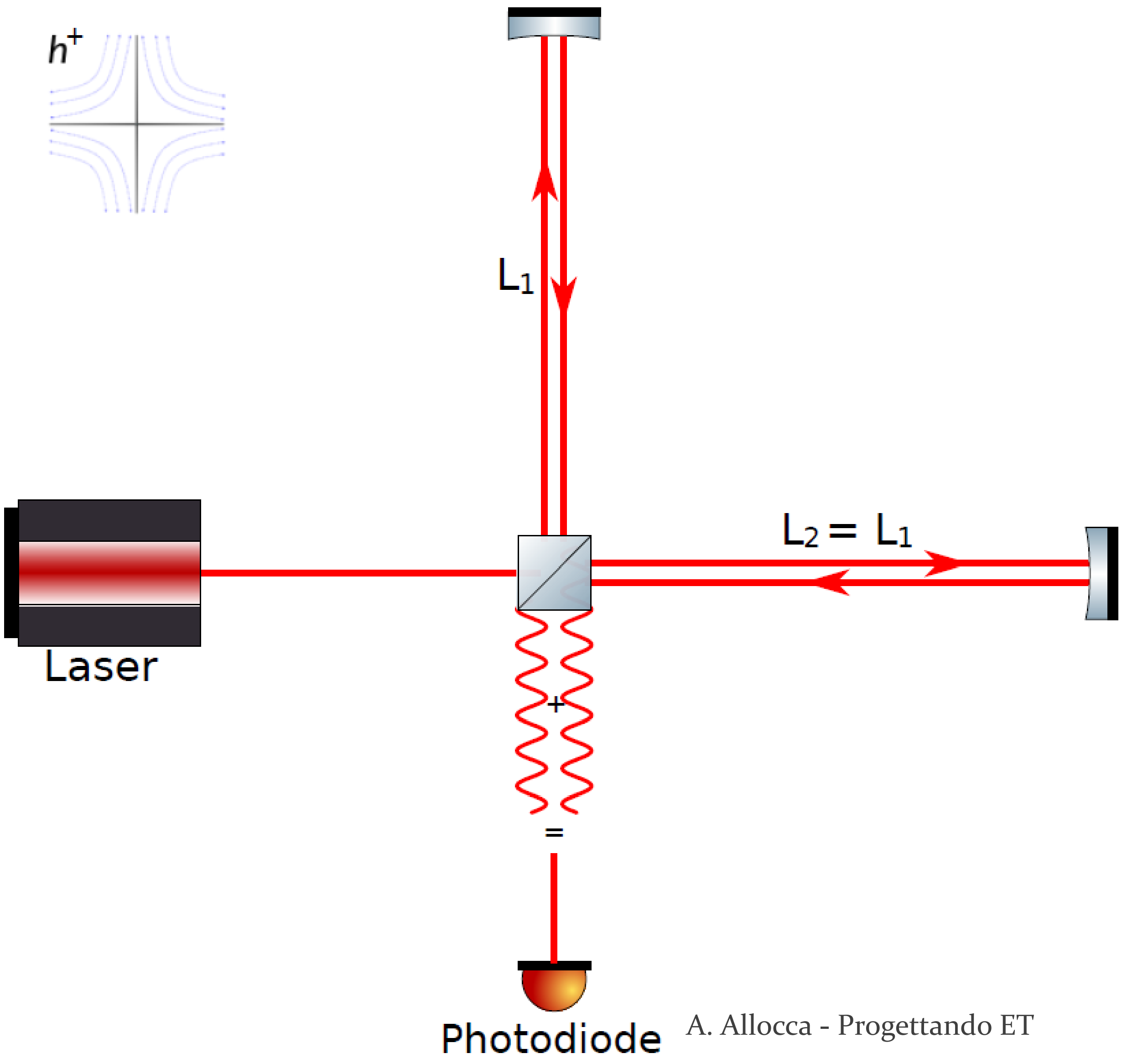


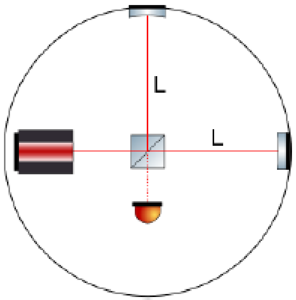
GWs produce a differential variation of the arm lengths which is revealed at the ***antisymmetric port*** (ASY) of the interferometer

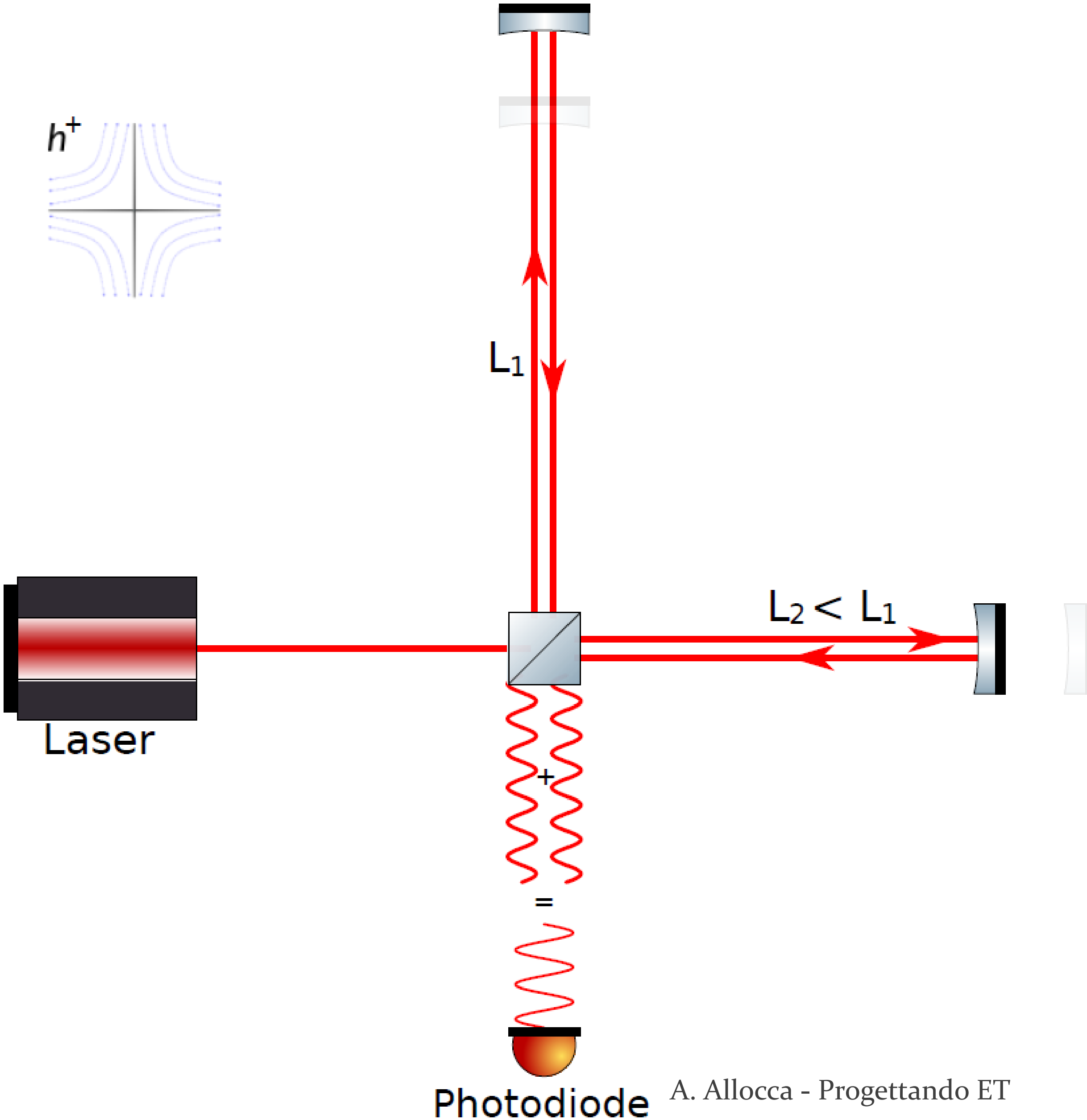
Interferometer working point: **dark fringe** condition (to be more sensitive to power variation due to a Gravitational Wave)

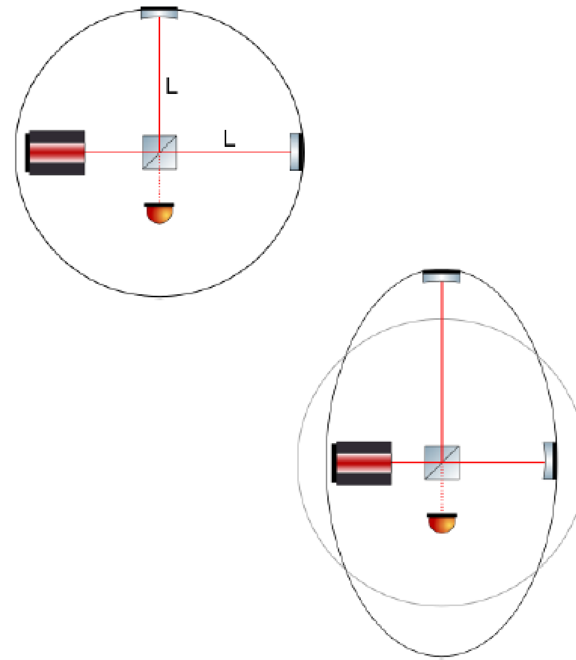


Interferometer response to h^+

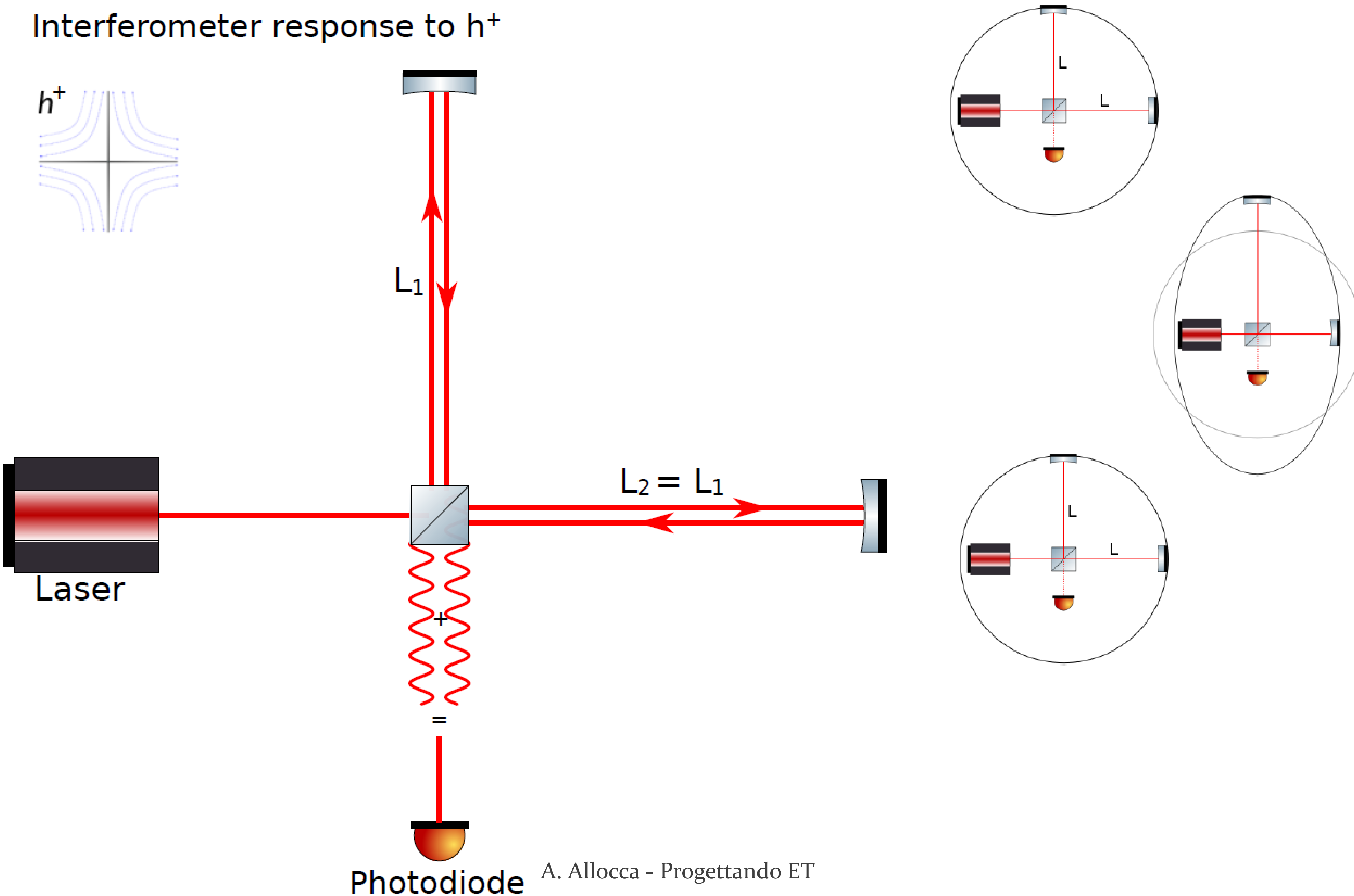




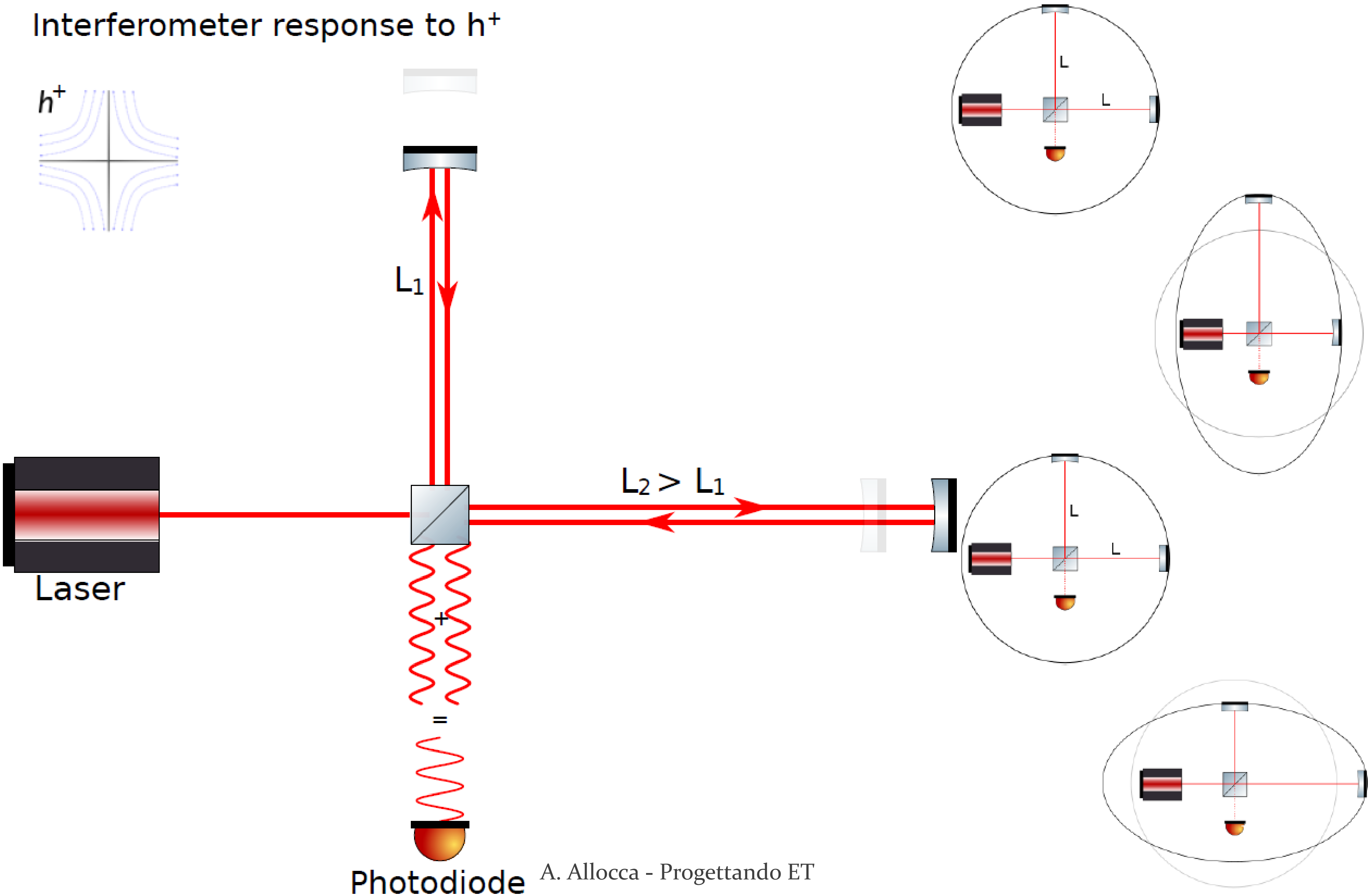

h+
L1
L2 < L1
Laser
+
=
Photodiode


L
L

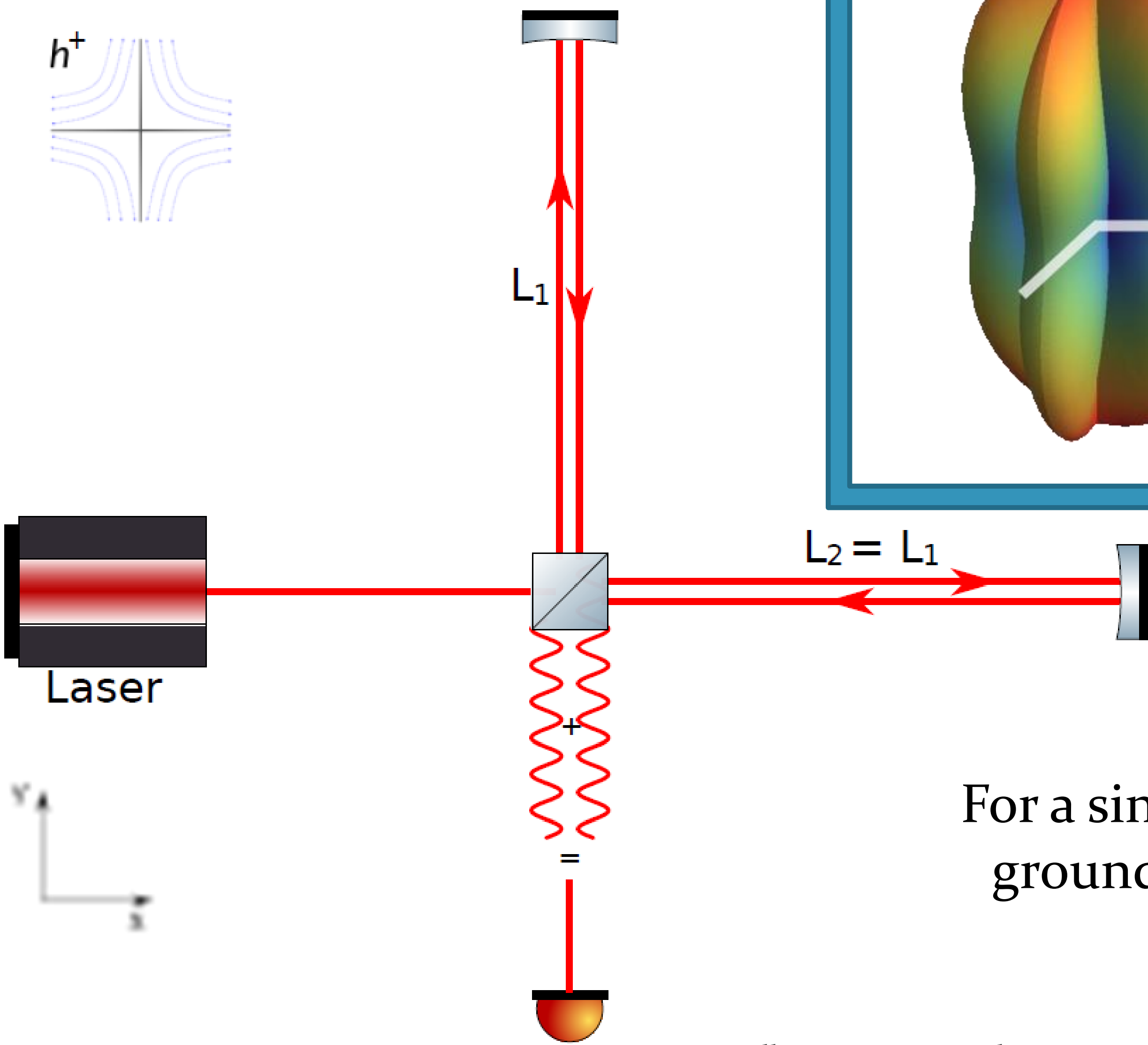
Interferometer response to h^+



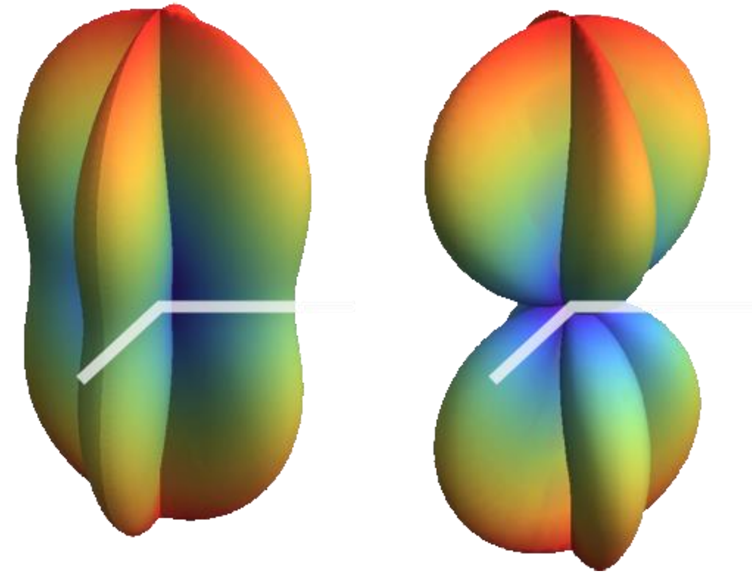
Interferometer response to h^+



Interferometer response to h^+



Interferometer response along the xy plan to a «+» polarized and «x» polarized GW



Antenna pattern

For a single, L-shaped, km-scale ground-based interferometer

A challenge against noise

Enhance the signal / **Reduce the noise**

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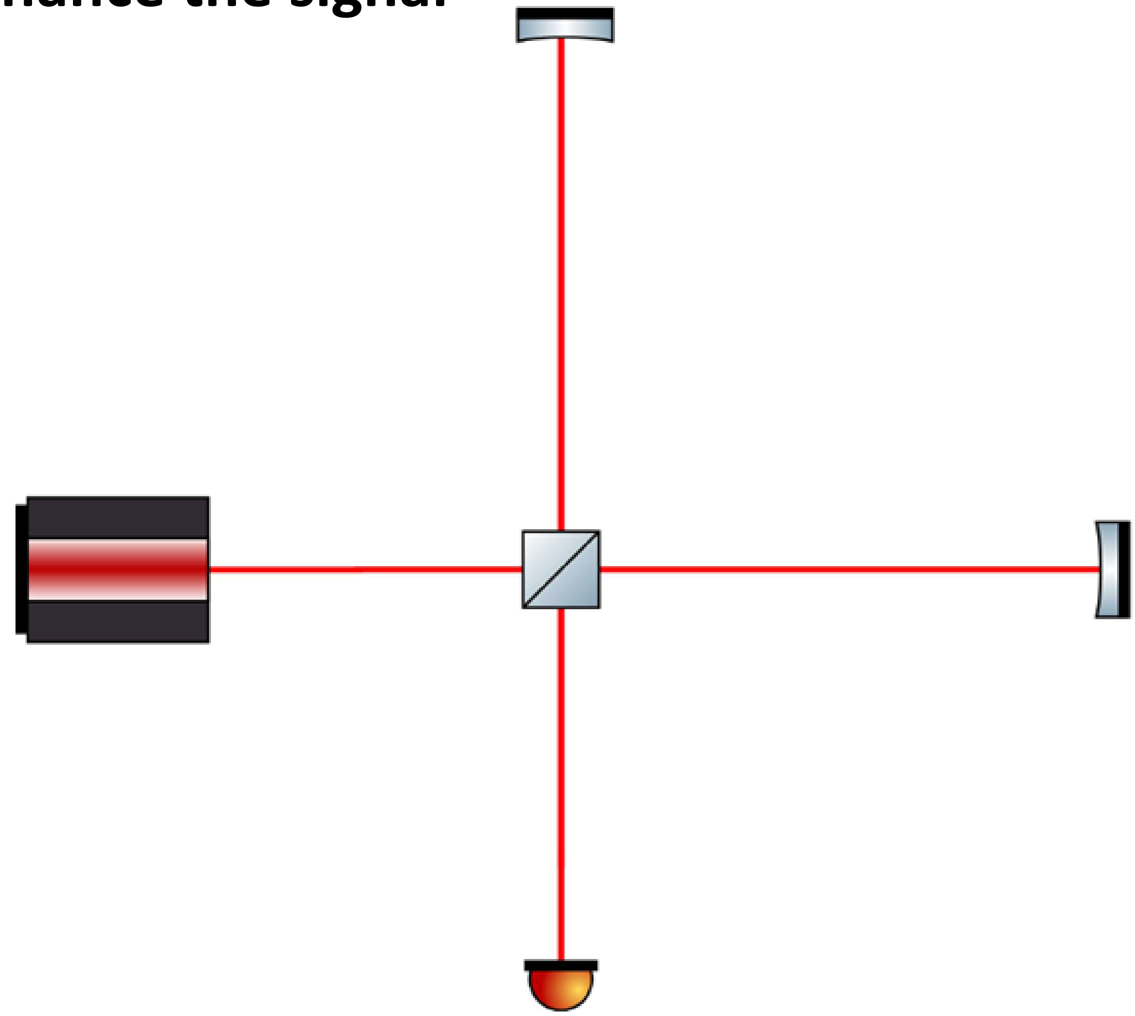
Enhance the signal / **Reduce the noise**

Michelson Interferometry to detect GWs

$\delta L \propto h\, L$

Enhance the signal



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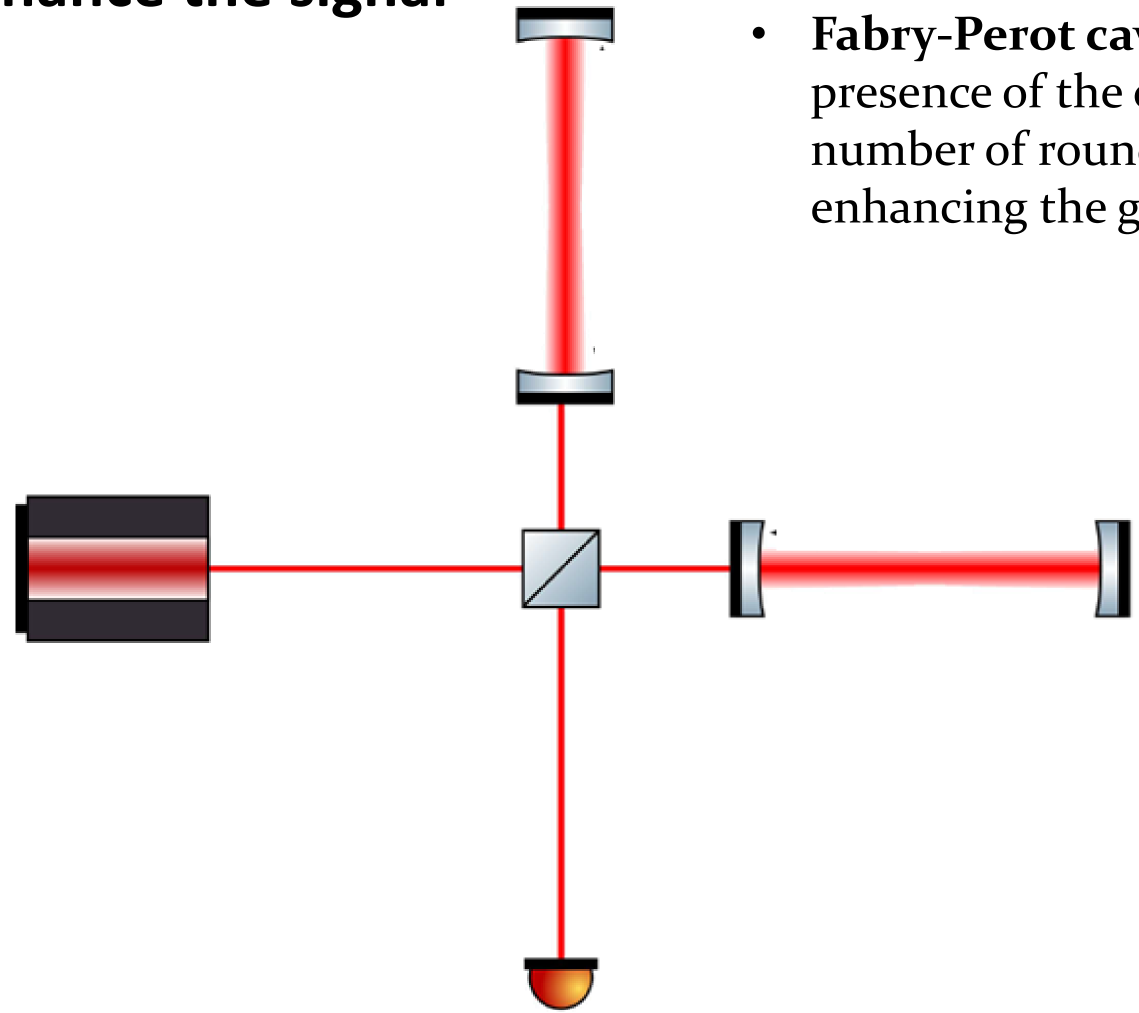

- **Fabry-Perot cavity for “longer arms”**: the presence of the optical cavities increases the number of round trip of the light, therefore enhancing the gain of the instrument

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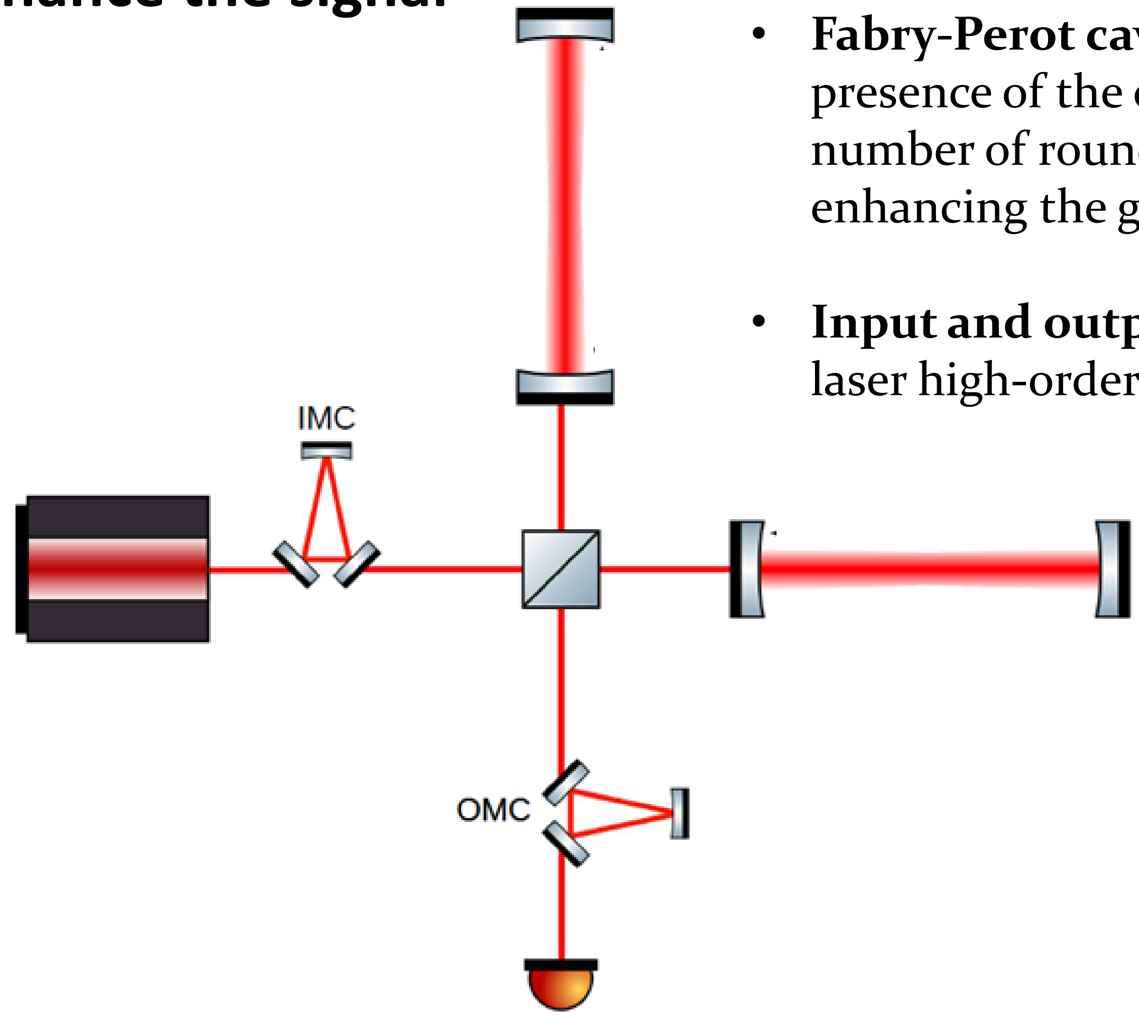
Enhance the signal



- **Fabry-Perot cavity for "longer arms"**: the presence of the optical cavities increases the number of round trip of the light, therefore enhancing the gain of the instrument
- **Input and output mode cleaner** to reject the laser high-order modes

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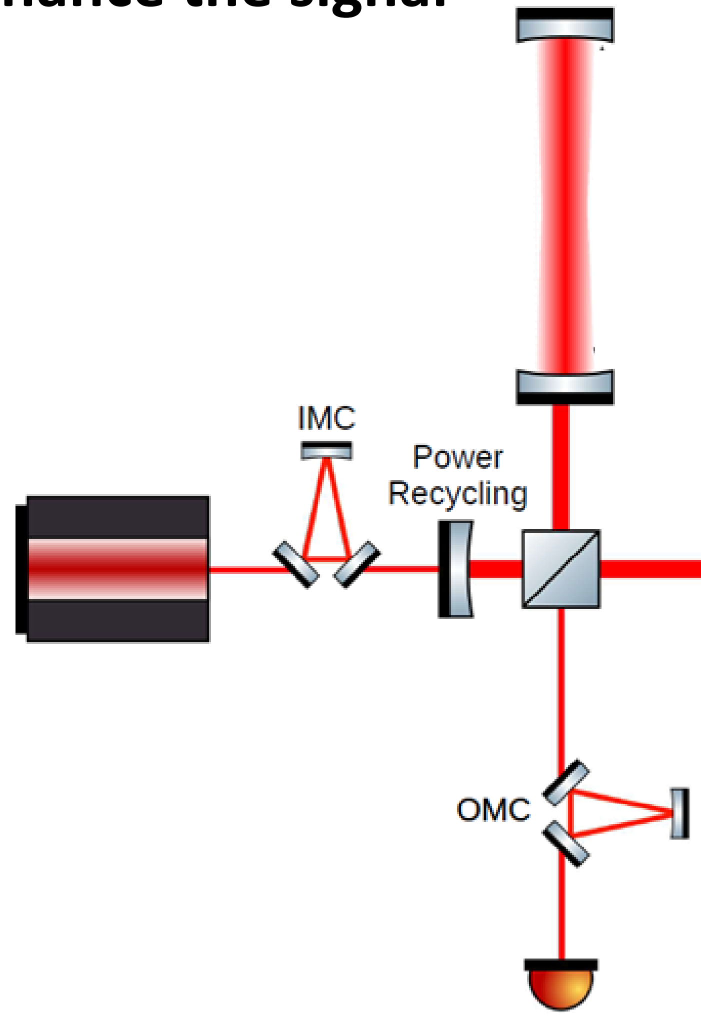
Enhance the signal



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- **Power Recycling mirror** to recover the power reflected from the arms and increase the optical power (***PR***)

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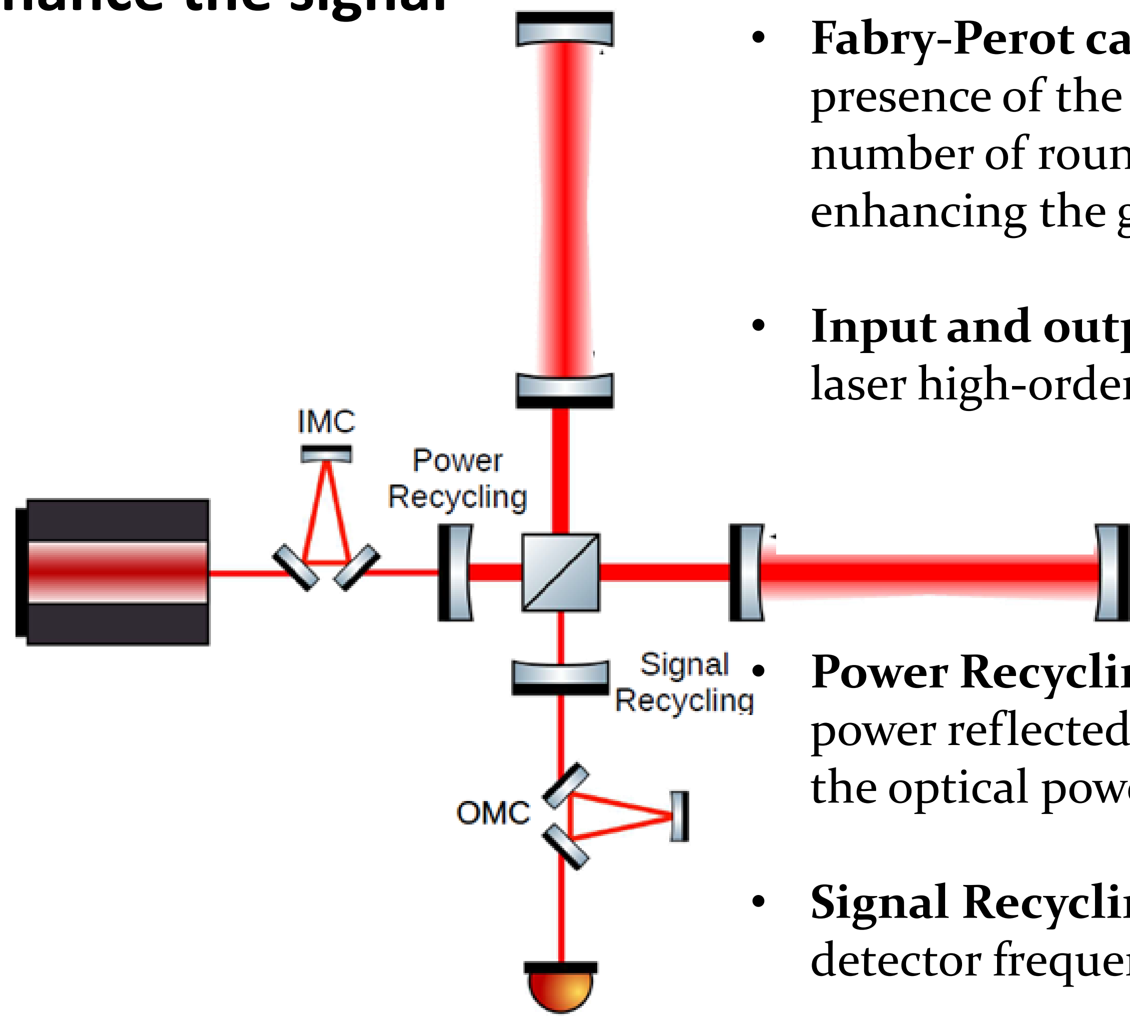

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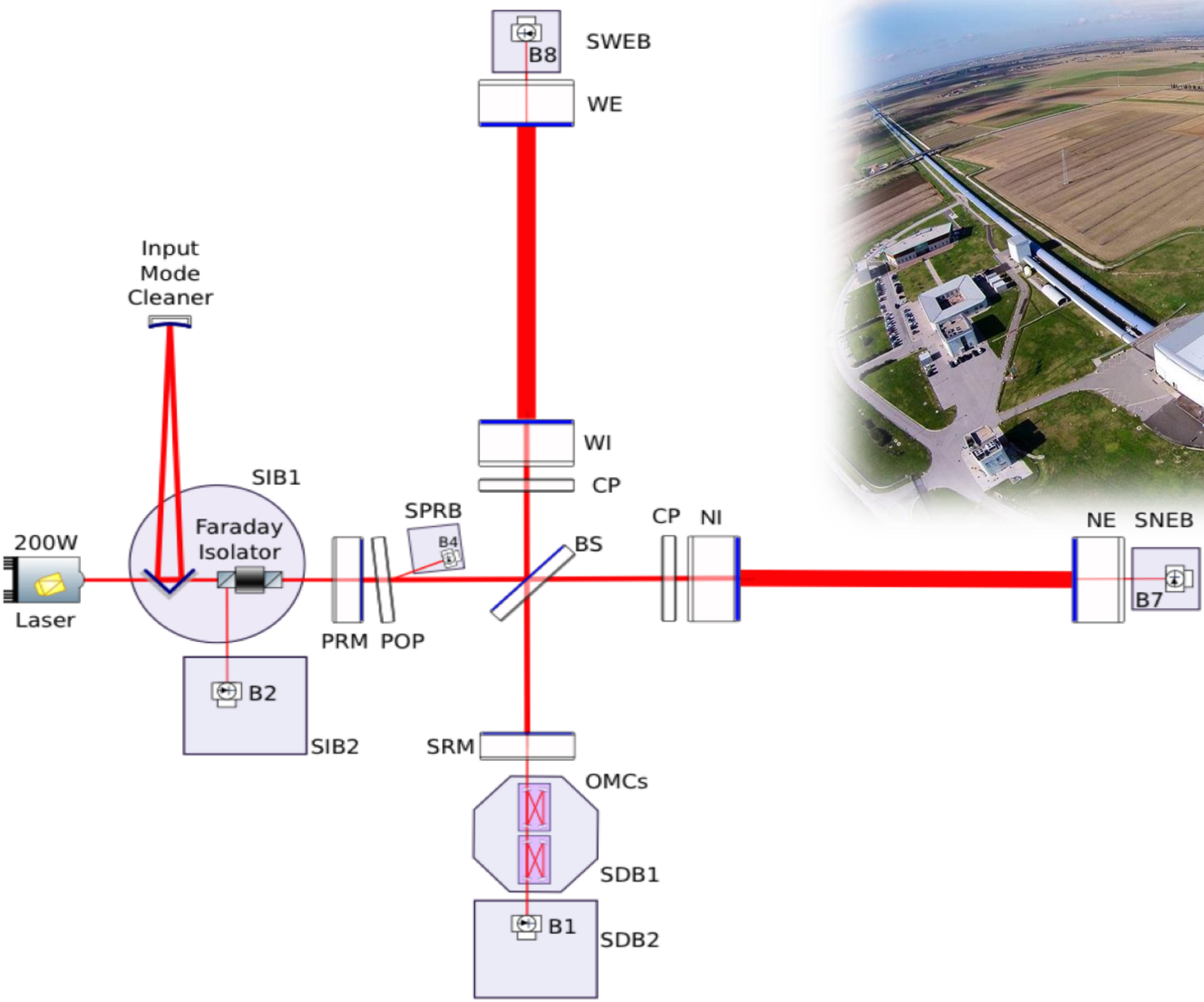
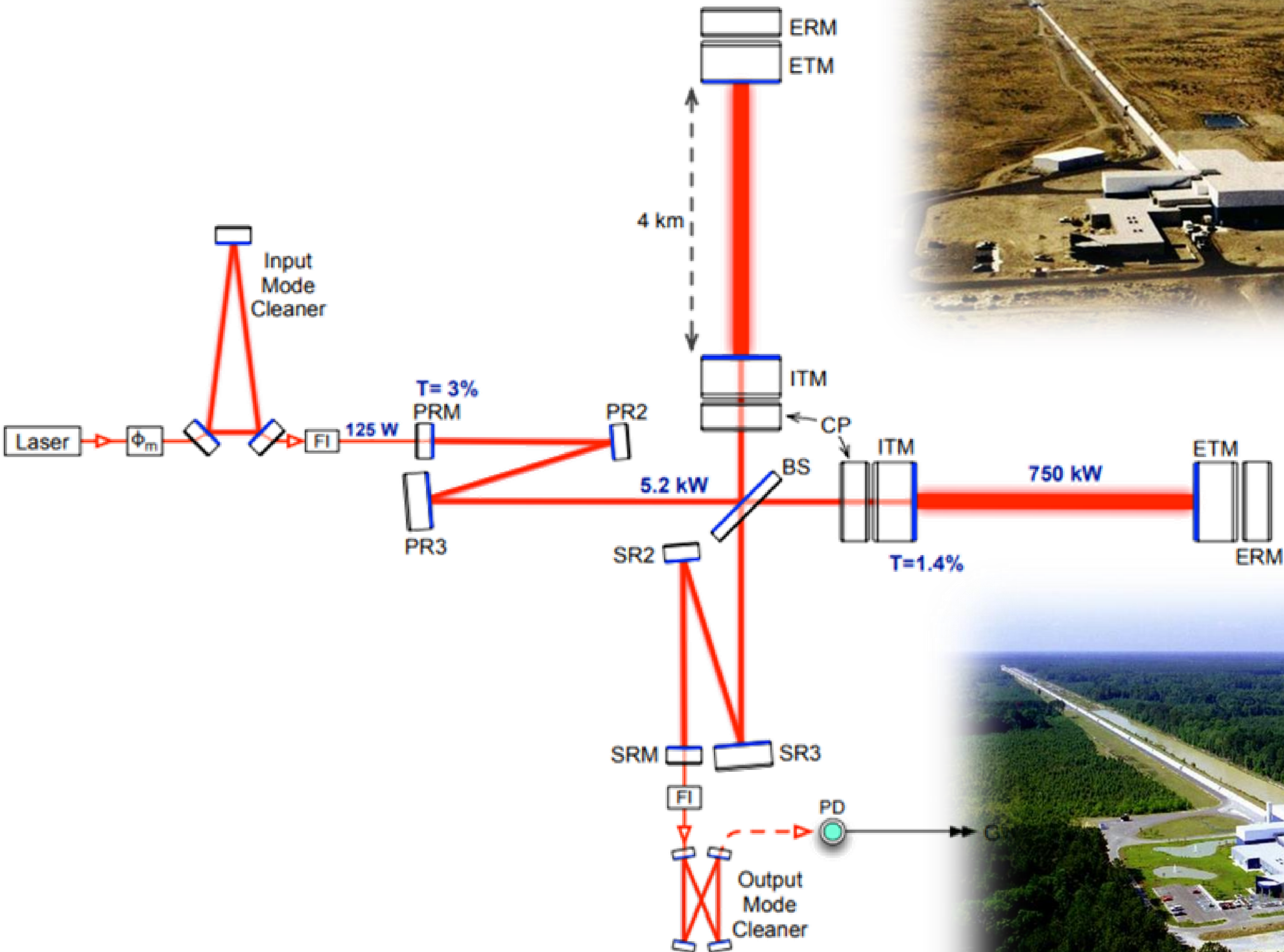
- **Input and output mode cleaner** to reject the laser high-order modes
- **Power Recycling mirror** to recover the power reflected from the arms and increase the optical power (***PR***)
- **Signal Recycling mirror** to reshape the detector frequency response

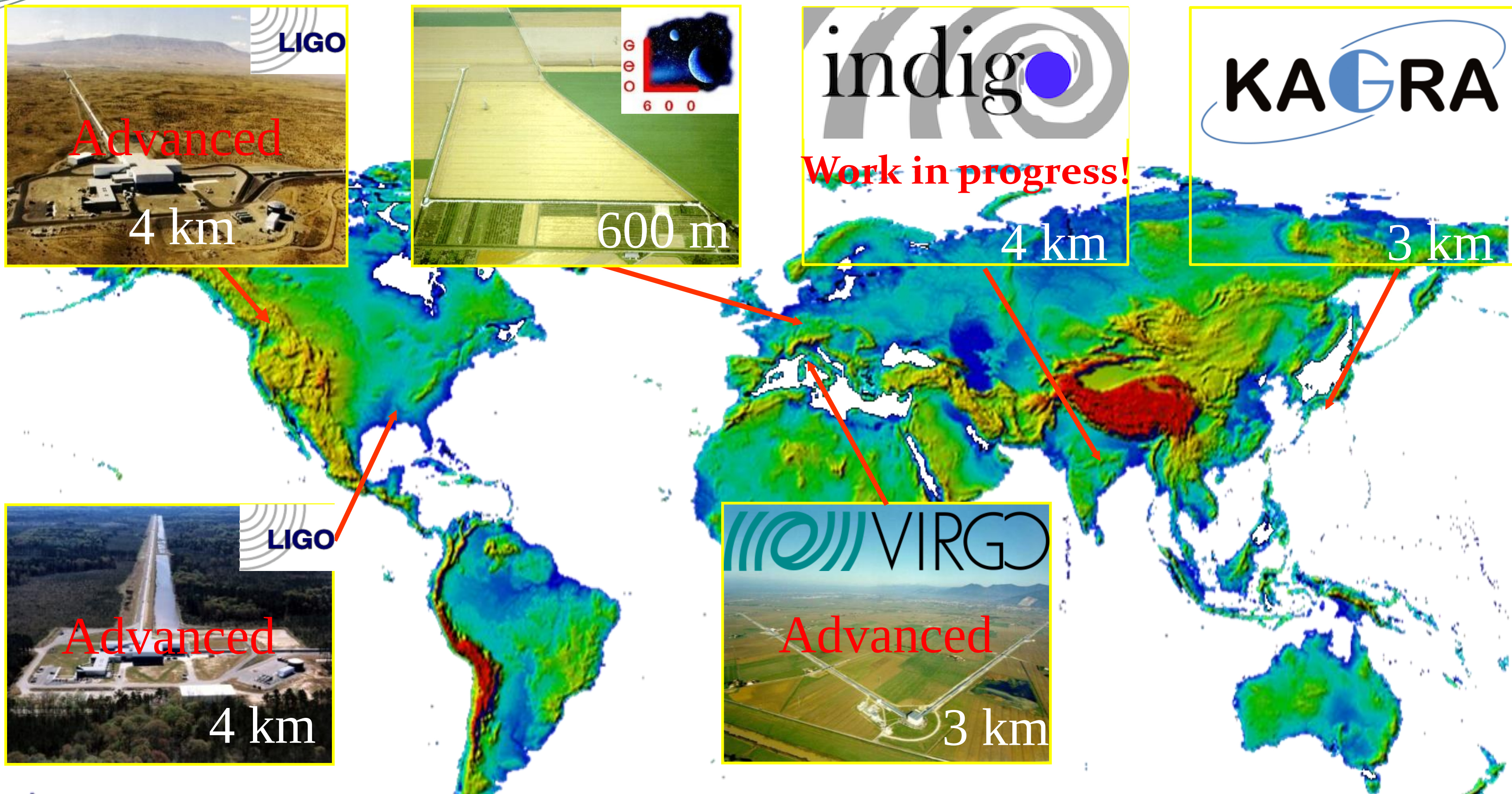
That's the scheme of Virgo



… and LIGO


ERM
ETM
4 km
Input
Mode
Cleaner
ITM
T= 3%
PRM
PR2
CP
Laser
Φ_m
FI
125 W
5.2 kW
BS
ITM
750 kW
ETM
PR3
SR2
T=1.4%
ERM
SRM
SR3
FI
PD
Output
Mode
Cleaner

The current detector network

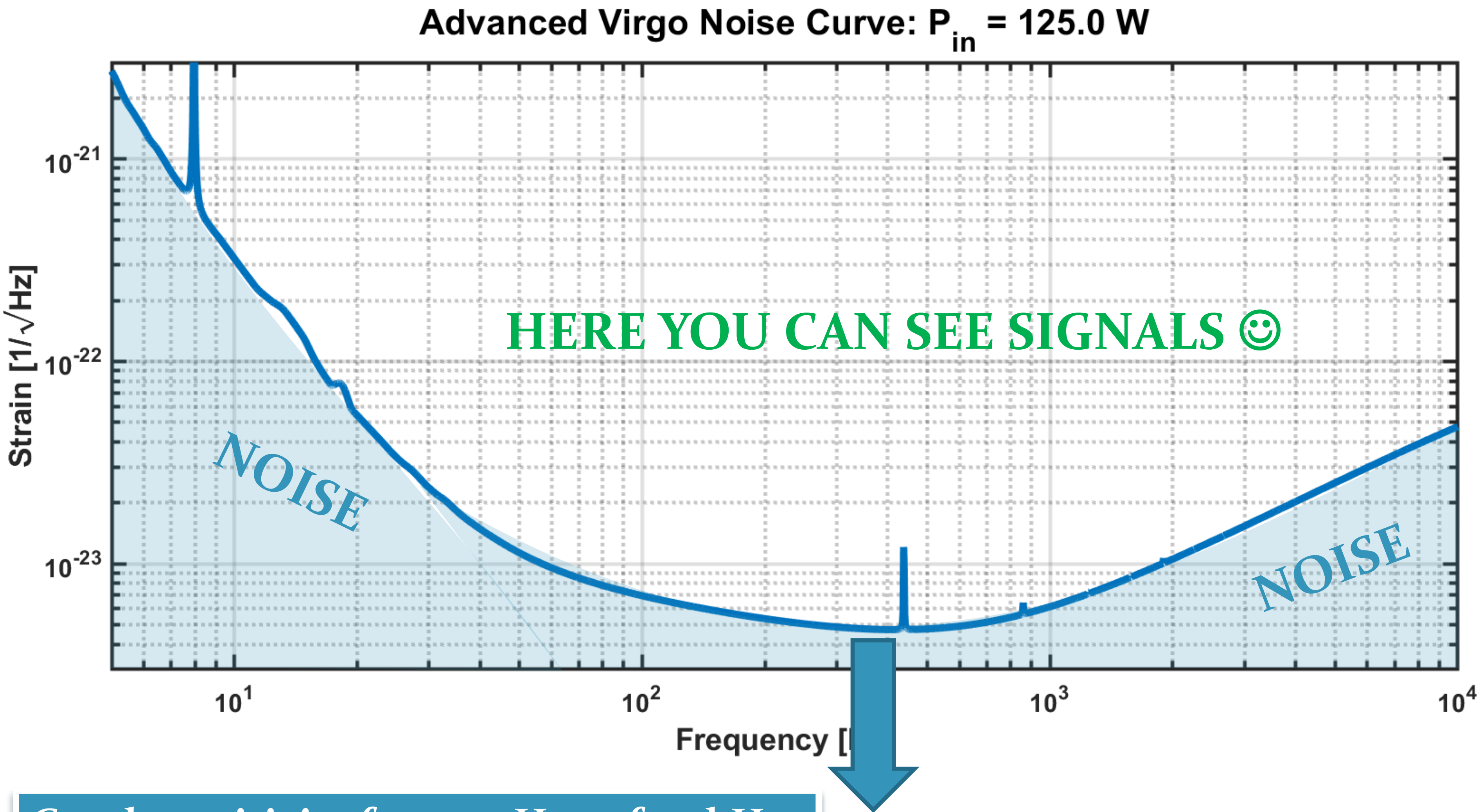


Having a network improves significantly the accuracy in the localization of the sources and allows to reject false signals exploiting coincidence

A challenge against noise

Enhance the signal / **Reduce the noise**

Advanced Virgo design sensitivity curve

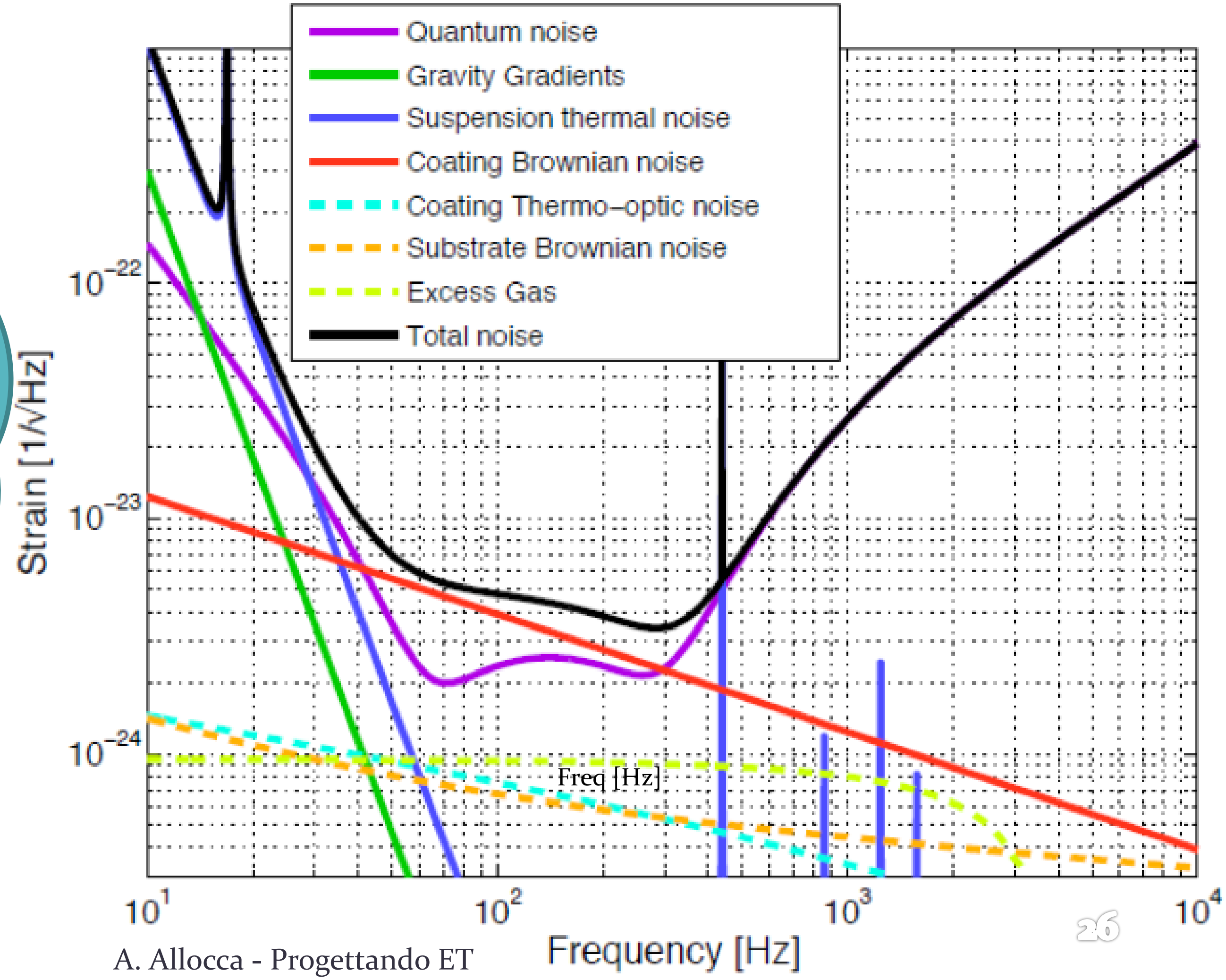


Good sensitivity from 10 Hz to few kHz

GW detector sensitivity curve

Sum of limiting noises at different frequency ranges:

Let's start from AdV sensitivity to analyze the limiting noise sources

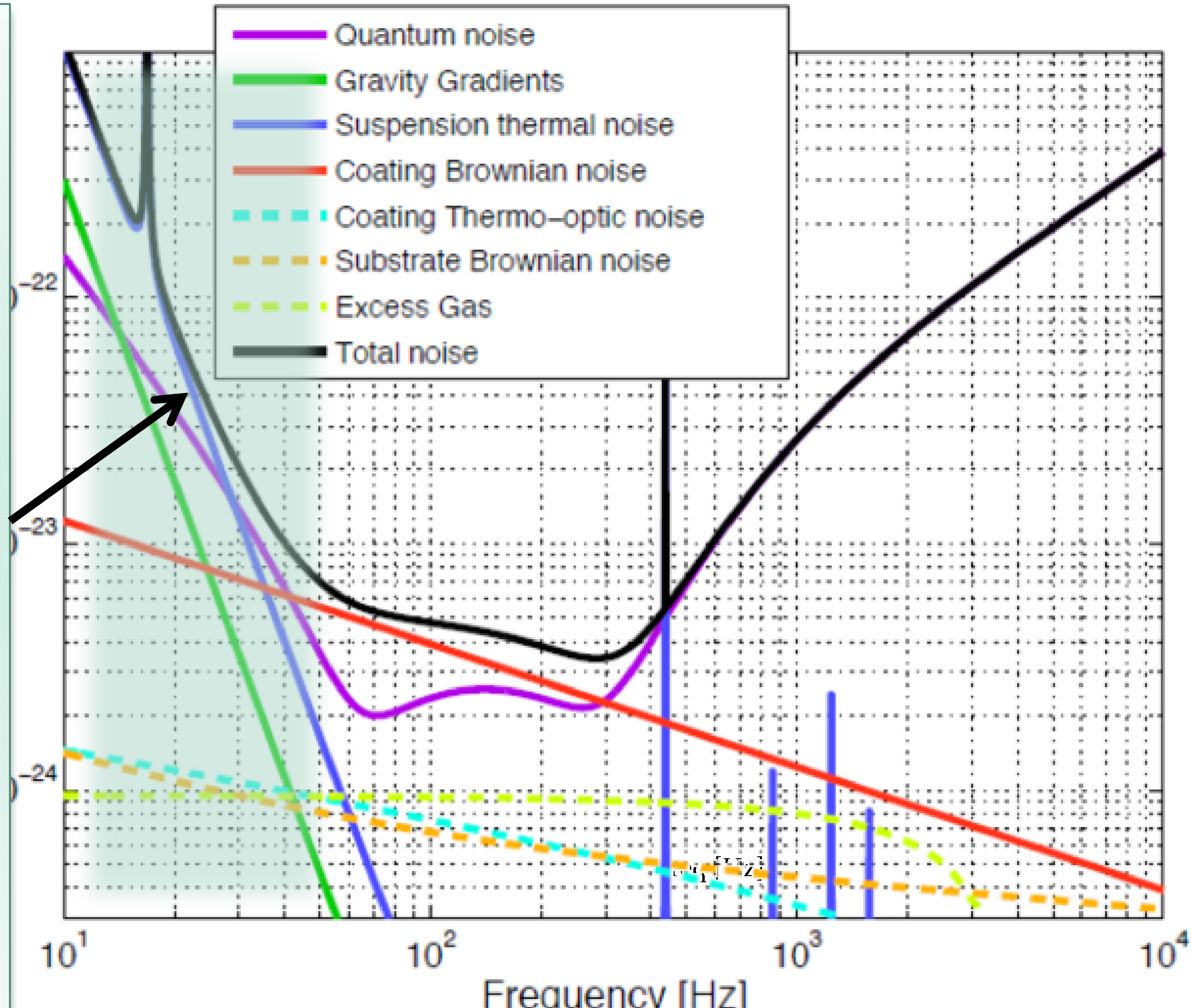


Advanced Virgo sensitivity curve

Limiting noises at different frequency ranges:

Low-freq:

- seismic noise – *not limiting for AdV* – (site location, isolation) and newtonian noise *not limiting for AdV* – (site location, subtraction schemes)
- suspension thermal (temp, material)
- radiation pressure (low power, large mass, squeezing)
- residual gas – *not limiting for AdV* – (UHV in arms and towers)

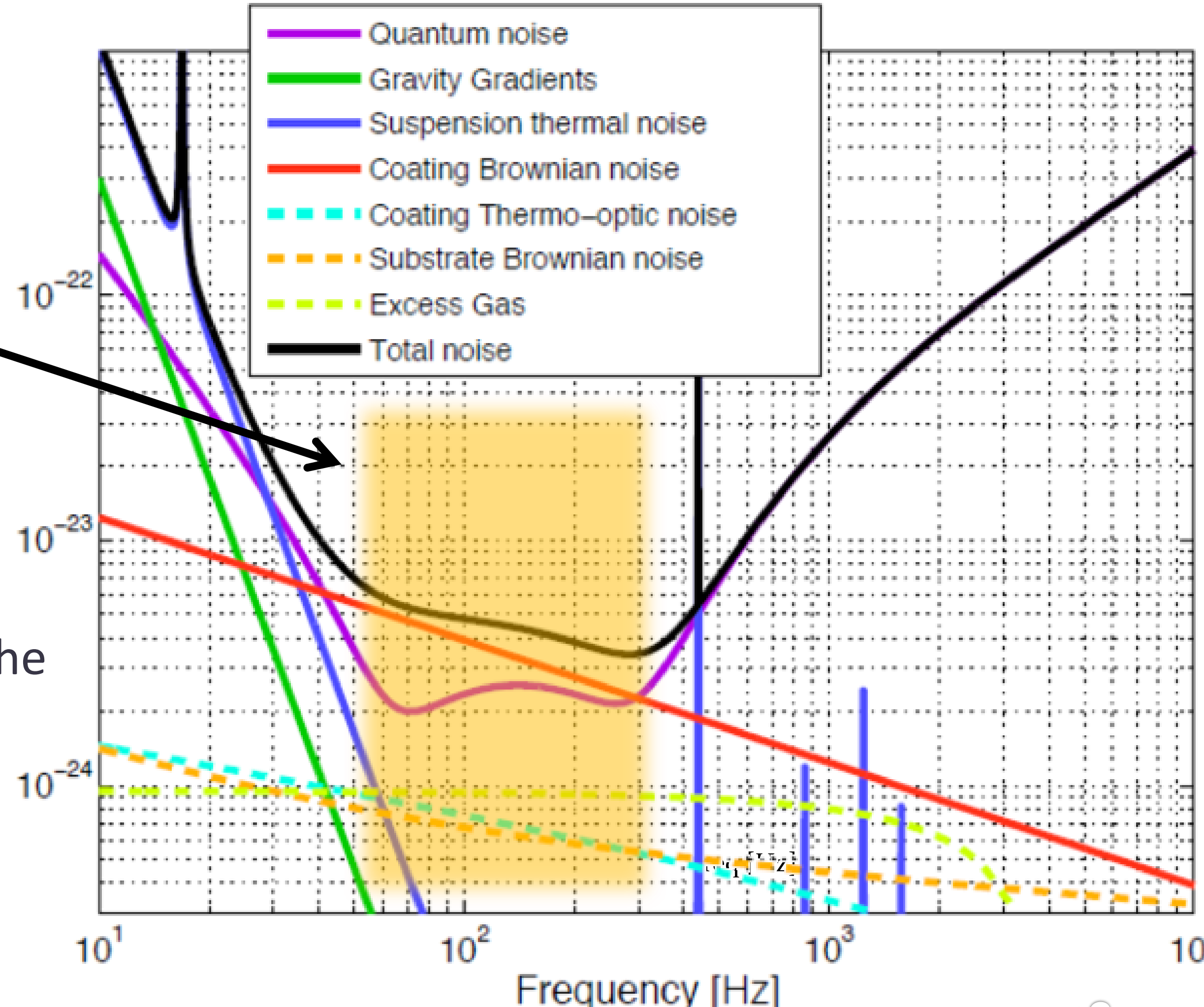


GW detector sensitivity curve

Limiting noises at different frequency ranges:

- **Mid-freq**: thermal noise

- Reducing thermal noise:
  - beam size as large as possible
  - State-of-art coating techniques to reduce the losses
  - SiO_2 Monolithic suspensions

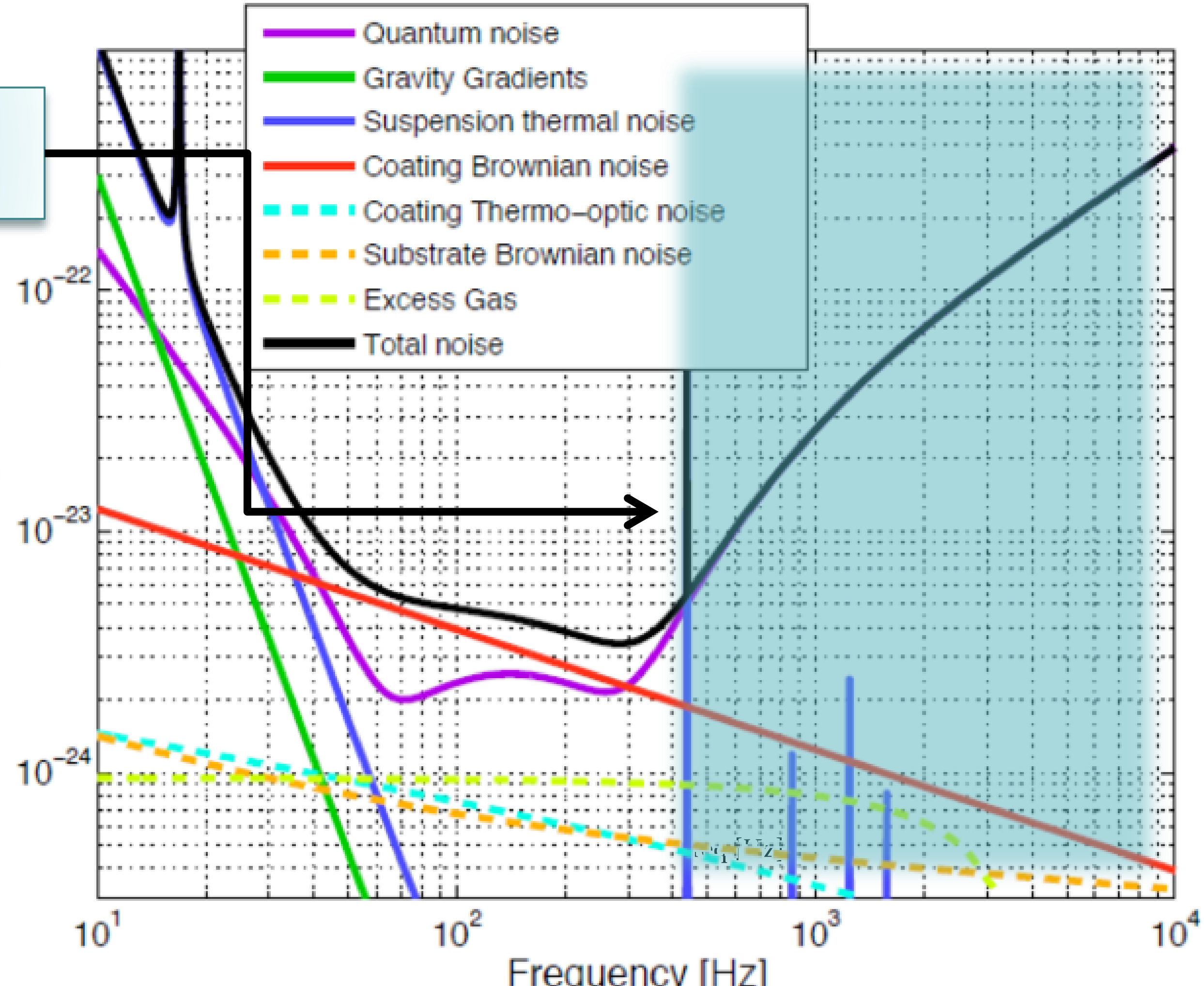


GW detector sensitivity curve

Limiting noises at different frequency ranges:

- High-freq:
quantum shot-noise

- Reducing quantum noise:
  - Increased finesse of arm cavities (9x larger than iVirgo, 3x larger than Virgo+)
  - High power laser
  - Squeezing technique

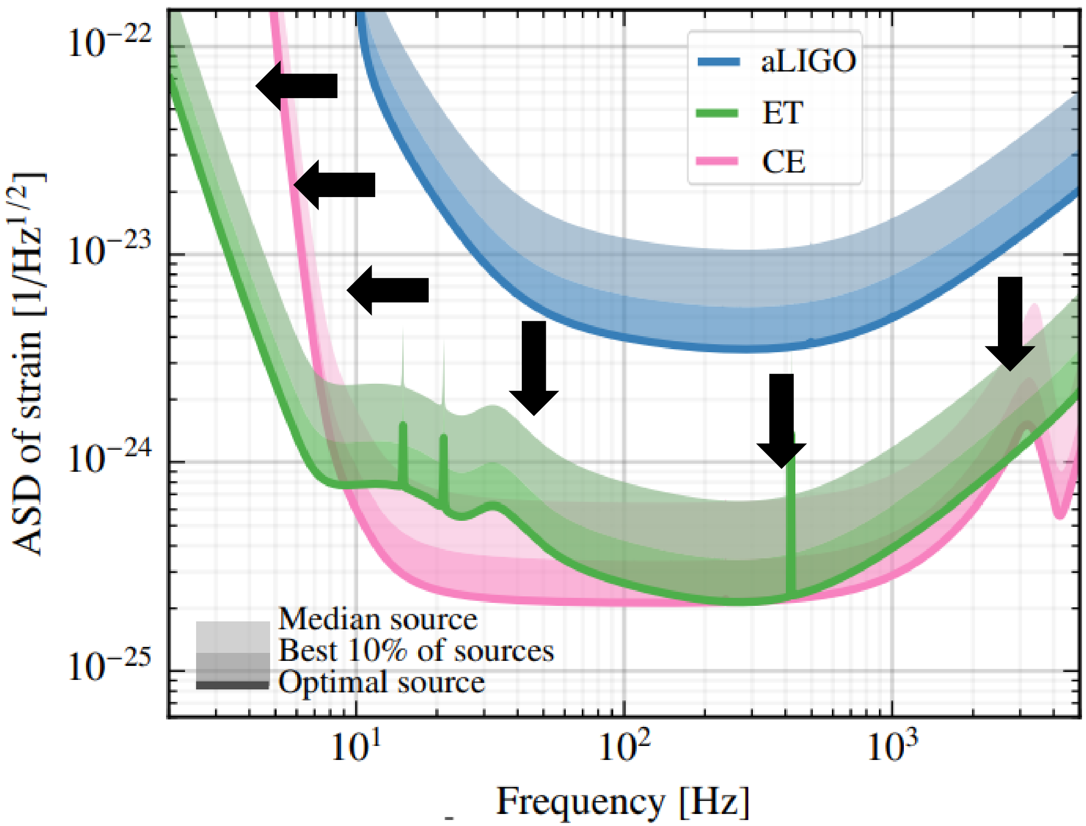


Detection distance of GW Detectors

Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

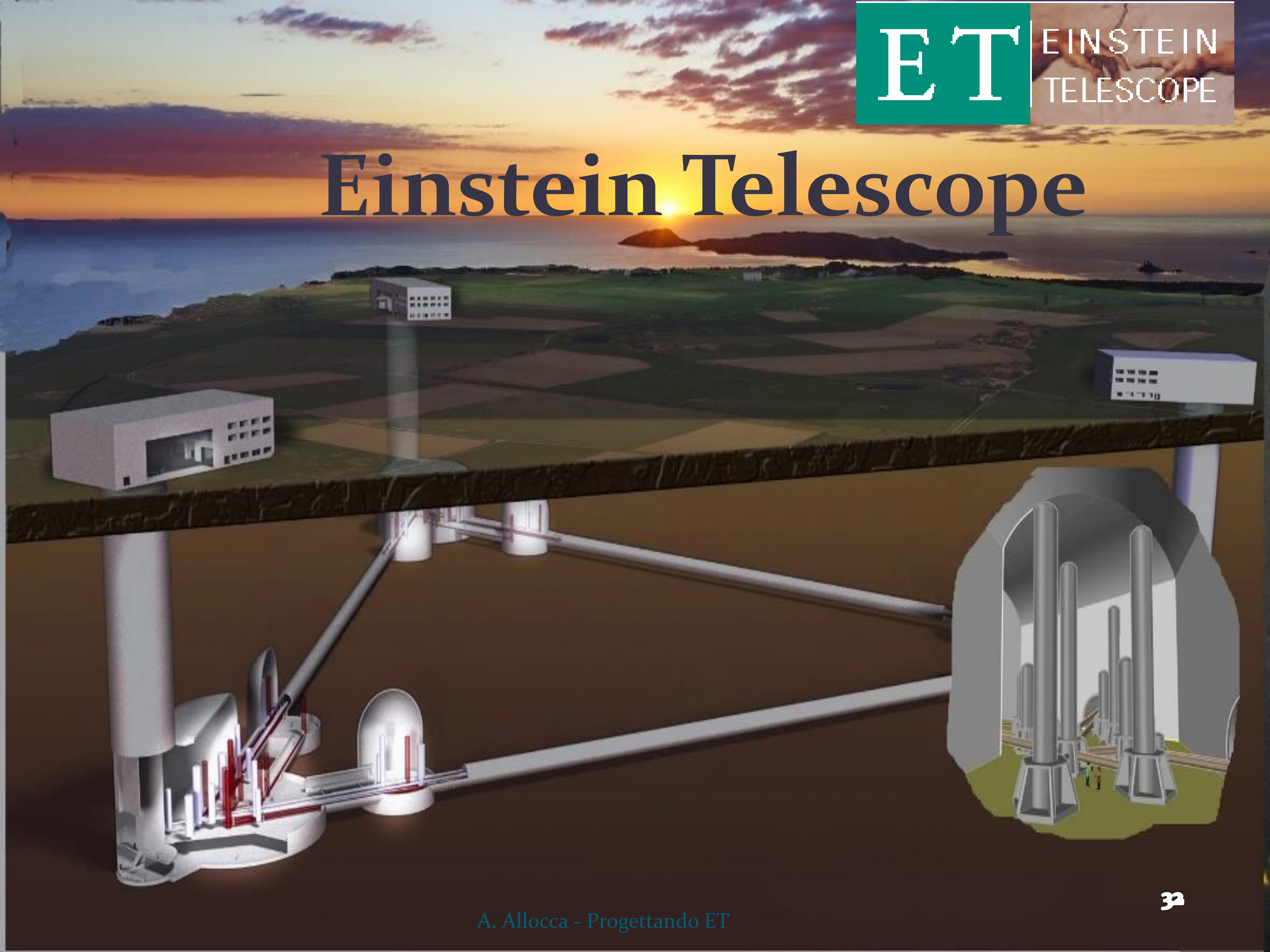
3° generation detector sensitivity

- Detector **10X more sensitive** than the current instruments <u>over the entire detection frequency band</u> accessible to ground-based detectors, and
- Bandwidth extended **below 10 Hz**
- Third-generation facilities **lifetimes of the order of 50 years** in order to house detectors with far more sensitivity than the initially proposed designs



From ET design report update 2020
https://apps.et-gw.eu/tds/?content=3&r=17245

Einstein Telescope

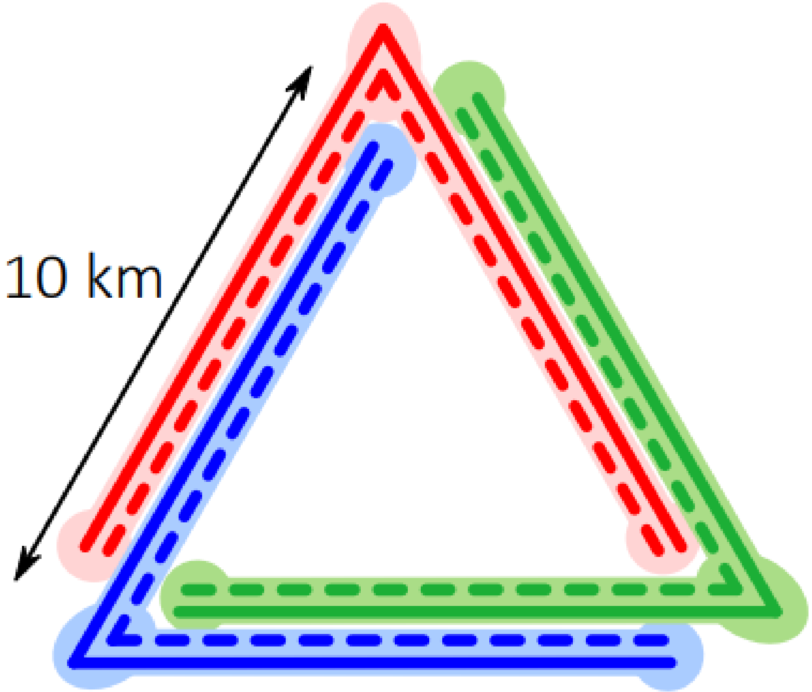


Einstein Telescope

- **Underground**, to reduce the seismic noise contribution
- **Cryogenic**, to reduce the effect of the thermal noise
- **10 Km arm long, 3 (double)interferometers in one,** XYLOFONE (separately optimize low and high frequency sensitivities)
- **Governance Mondiale together with Cosmic Explorer (USA)**

3° generation detectors: Einstein Telescope

The sensitivity goal can only be reached by significantly increasing the size of the detector beyond the size of currently available instruments (10 km)

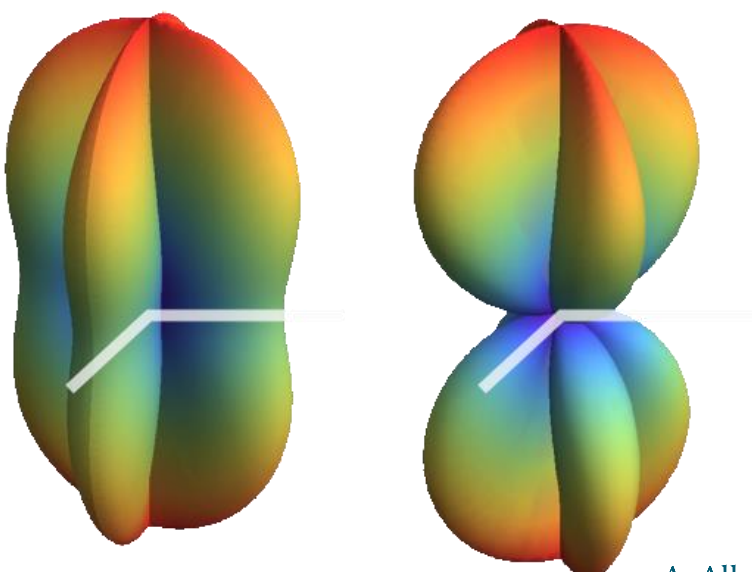


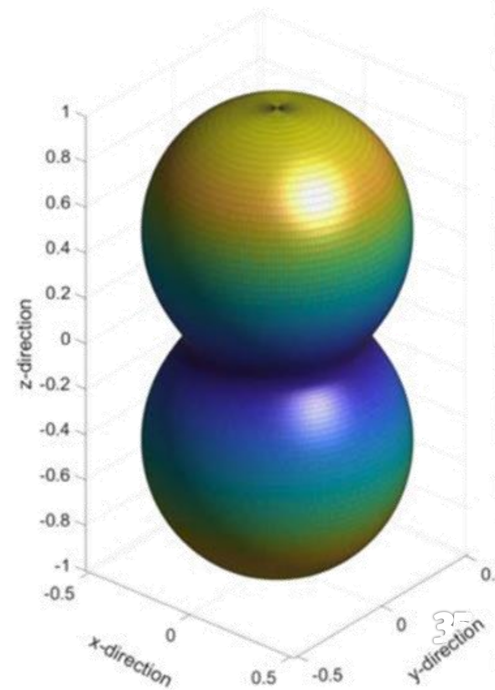
Einstein Telescope will consist of **three nested detectors**, arranged in a triangular pattern

3° generation detectors: Einstein Telescope

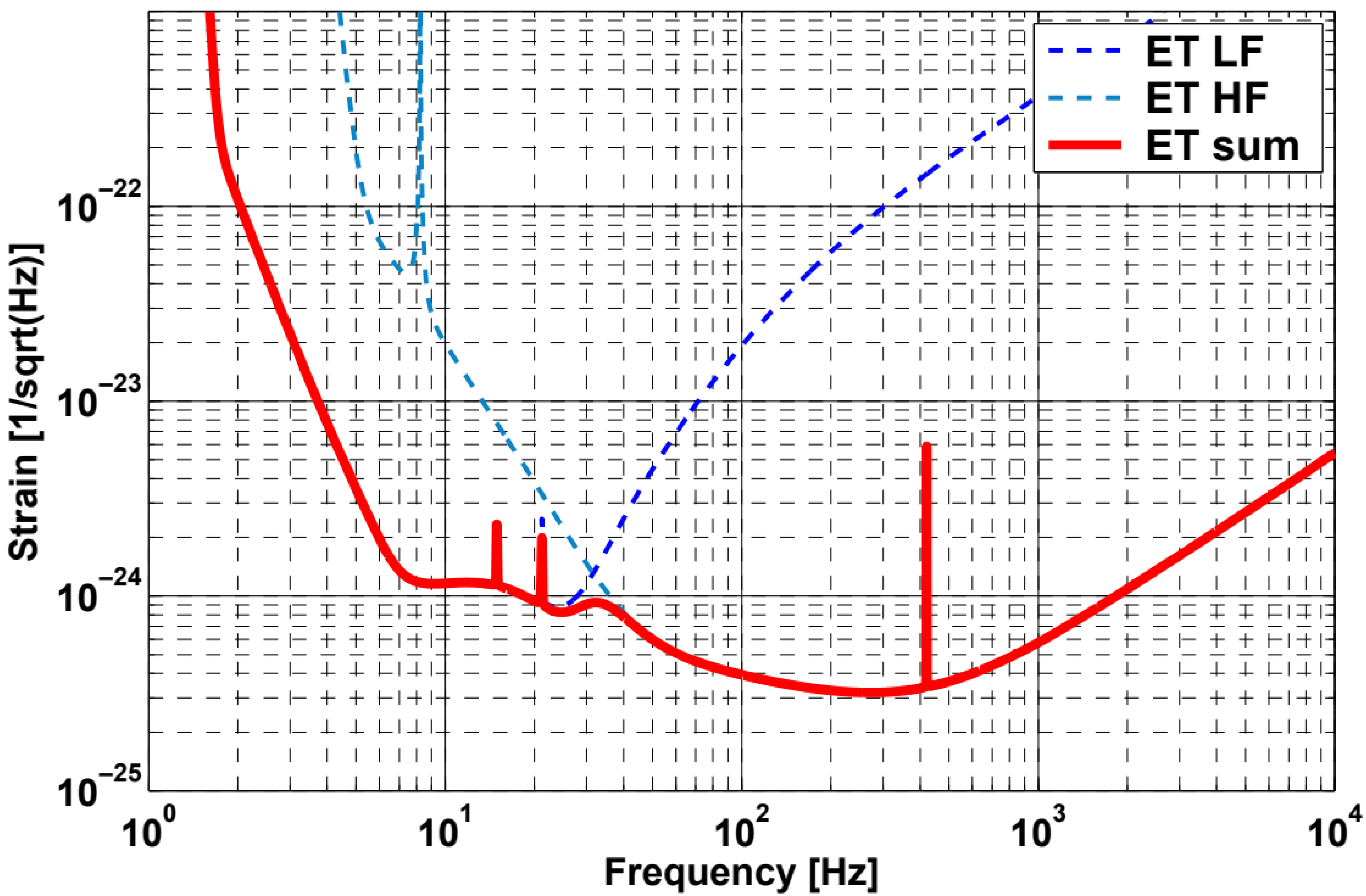
Advantages with respect to the single 10km L-shape detector:

- equally sensitive to both GW polarizations
- more isotropic antenna pattern compared to the L-shaped detectors, overall frequency range from 2 Hz to few tens of kHz
- Good background rejection through null-stream, good localization accuracy



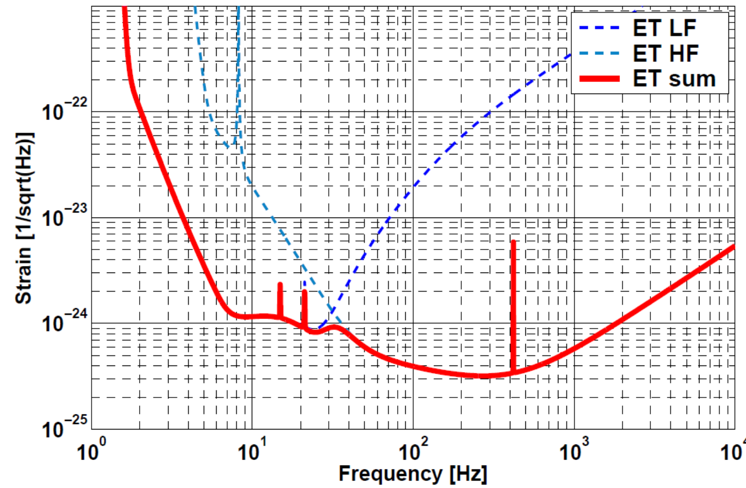


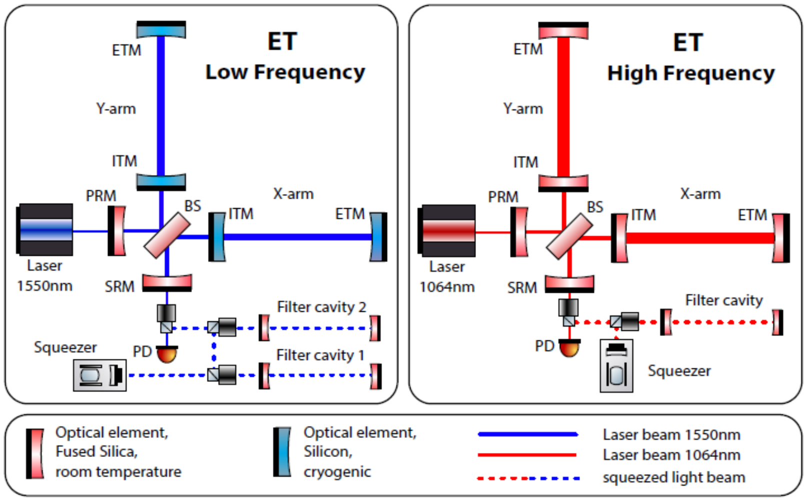
3° generation detector: Einstein Telescope



The Xylophone

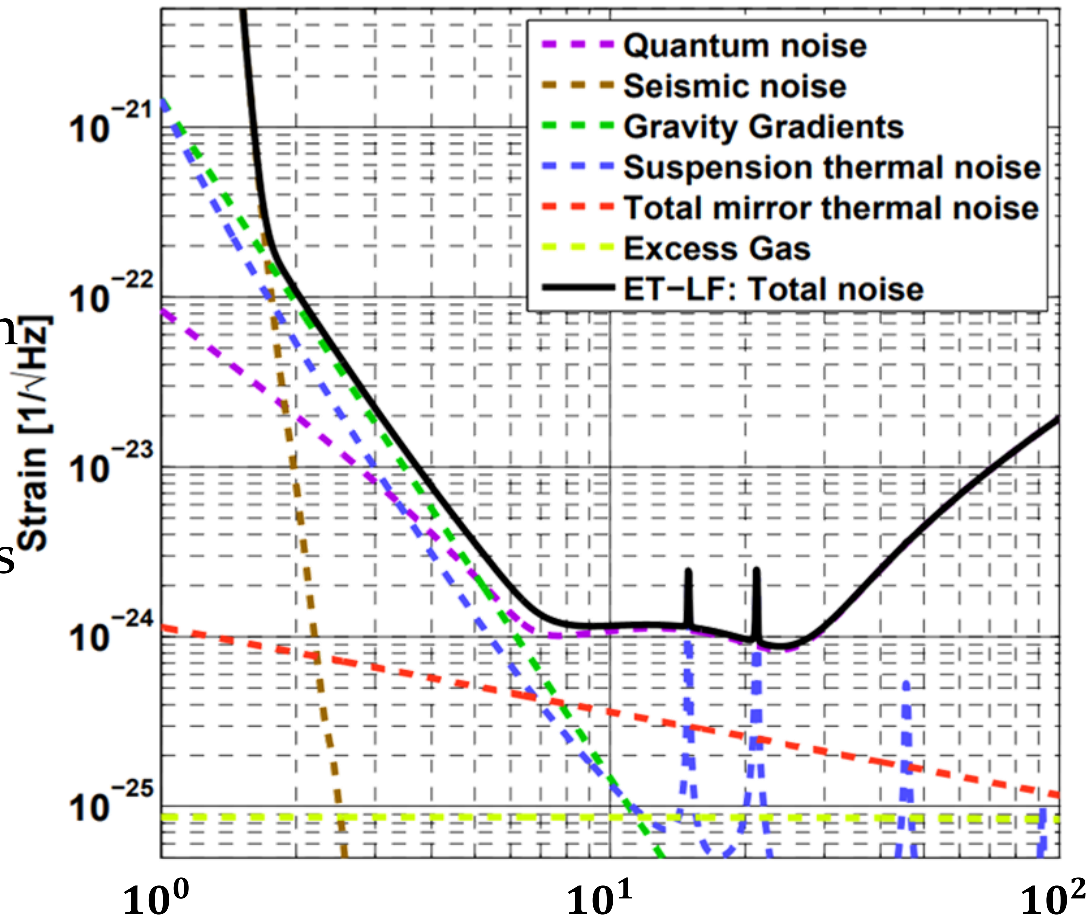
Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM$_{00}$	TEM$_{00}$
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\, \mathrm{m}/f^2$	$5 \cdot 10^{-10}\, \mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few





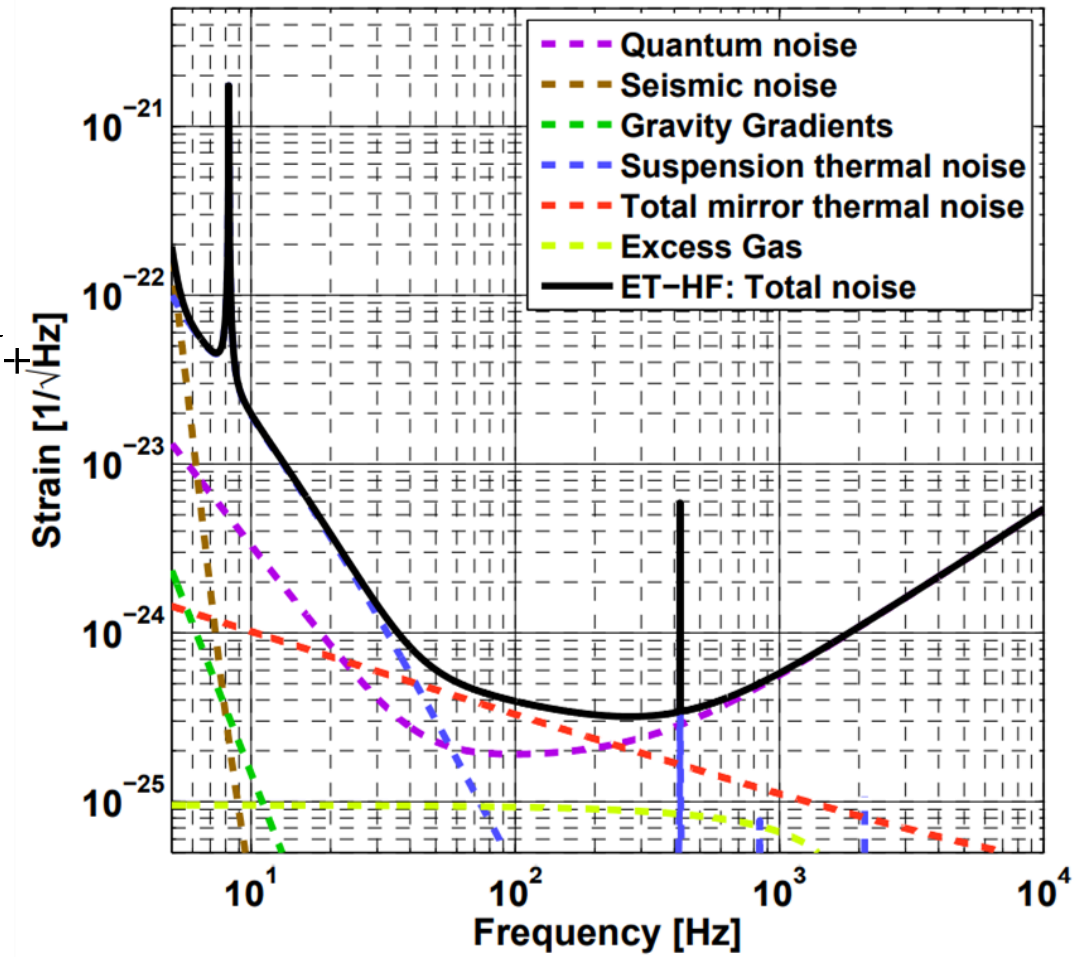
The LF detector

- Cryogenic (10-20 K) to reduce suspension and mirror thermal noise
- Seismic isolation and low noise site
- Newtonian noise cancellation
- Laser wavelength 1550-2000 nm
- Silicon (sapphire) test masses
- Large test masses
- New coatings
- Frequency dependent squeezing, filter cavities



The HF detector

- Room temperature
- Laser wavelength 1064 nm
- High-power
  - Input power: 500 w (AdV+ 40-80W)
  - Arm power: 3 MW (Adv+ 120-400 kW)
- Large test masses 200 kg (AdV+ 100 kg)
- Improved coatings (loss reduced by a factor of ~7 – optical absorption <1ppm)
- Frequency dependent squeezing: 10dB (AdV+ 3-6dB)



Most of these technological challenges will be addressed as part of the Virgo post-O5 development

From AdV to ET

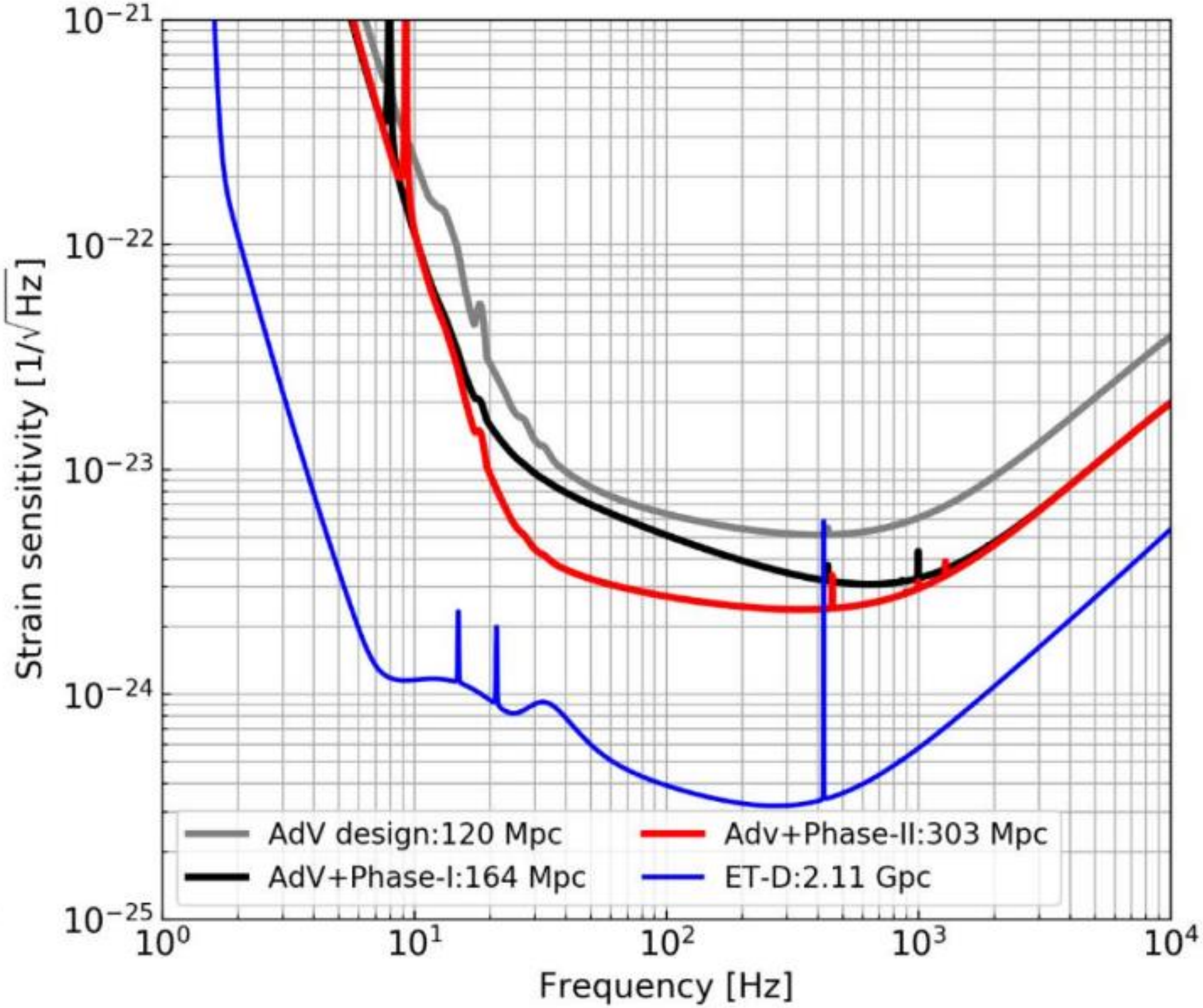


Figure 3.1: *Expected evolution of the Virgo sensitivity, and BNS range, after the completion of the two proposed upgrade phases. The design sensitivities of AdV and Einstein Telescope are also shown for reference.*

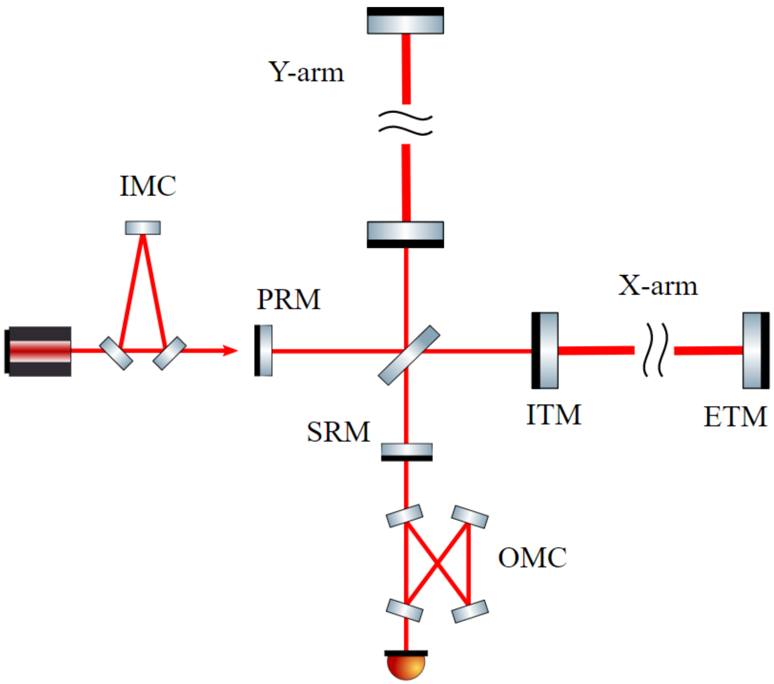
What can I do?

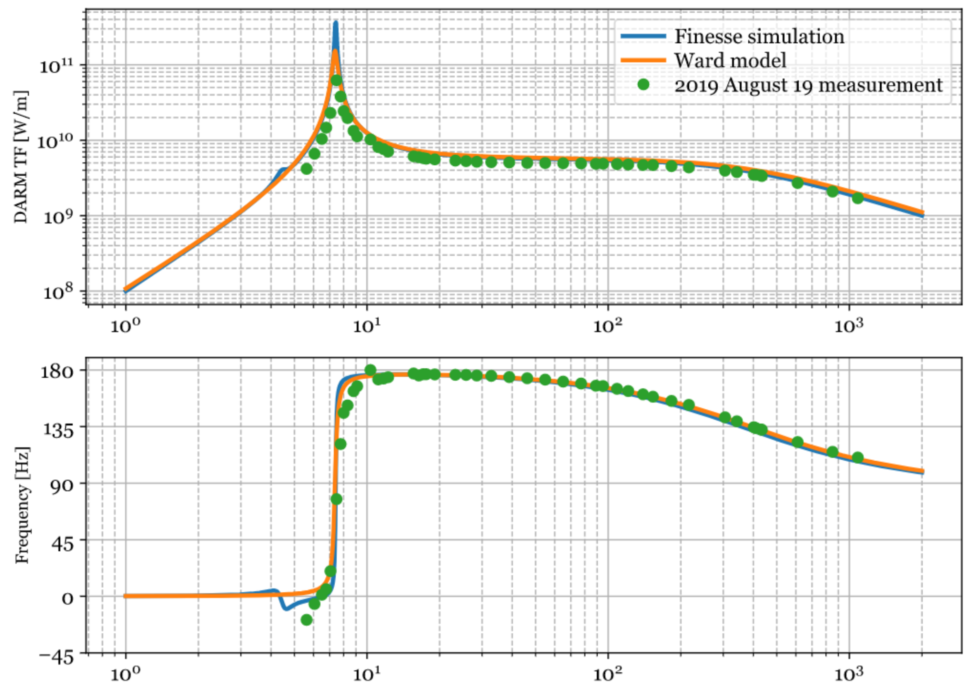
Still a lot to do! – Modelling

- Optical cavities design still to define (circulating beam size, telescopes magnification, shape and position, …)

(Frequency domain INterfErometer Simulation SoftwarE)

http://www.gwoptics.org/finesse/





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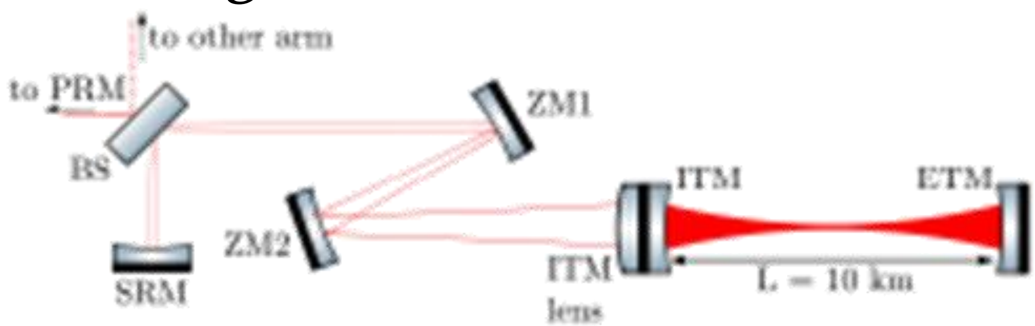
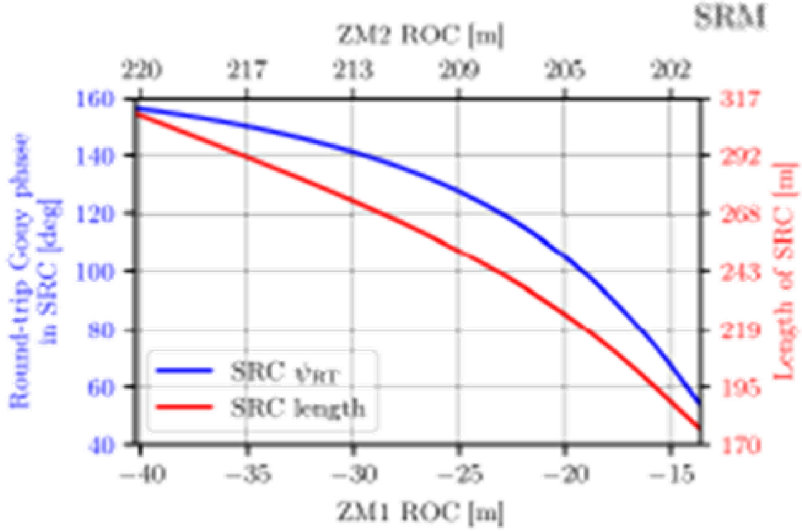
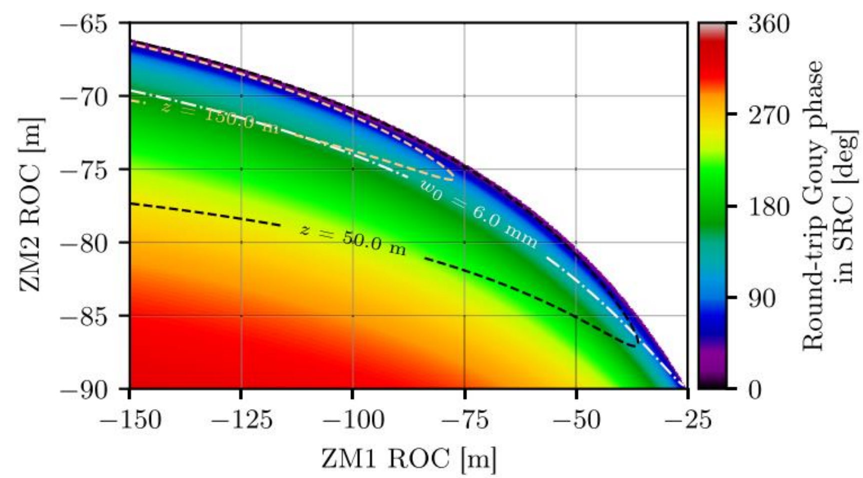
- Optical cavities design still to define (circulating beam size, telescopes magnification, shape and position, …)

  Example: telescopes optical configuration

Define telescope parameters as a function of the recycling cavities stability







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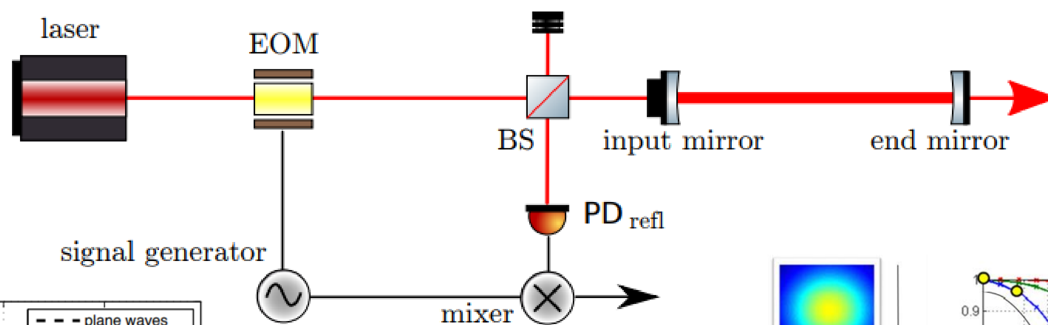
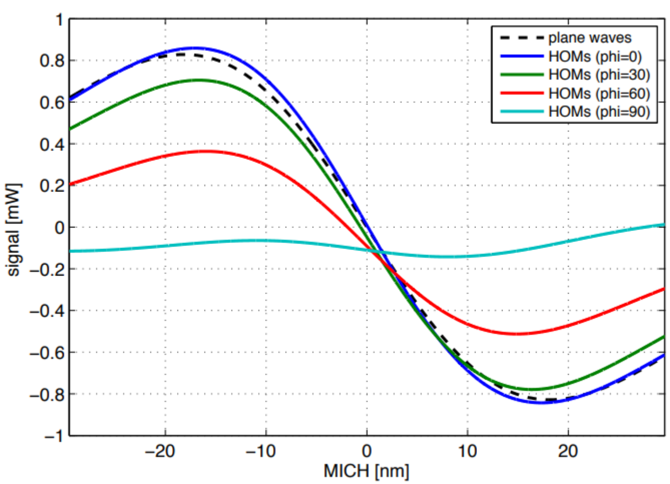
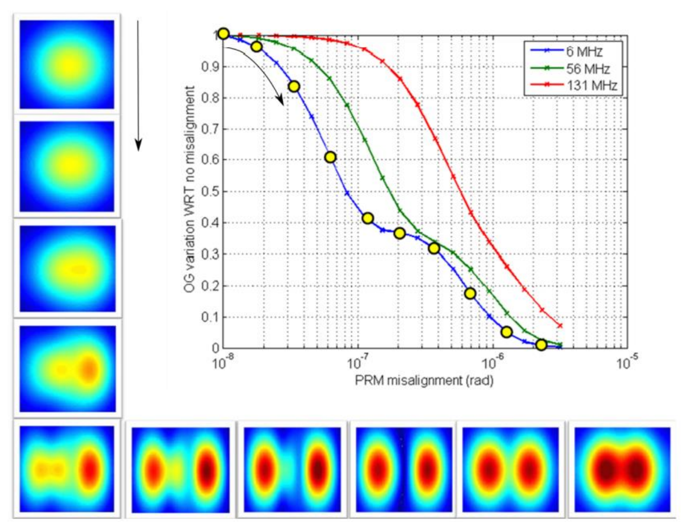
Still a lot to do! – Modelling

Finesse
(Frequency domain INterfErometer Simulation SoftwarE)

- Control systems to be developed, to have:
  - Good control of the mirrors
  - Control noise as low as possible (not to re-inject noise in the interferometer sensitivity)







Still a lot to do! – Modelling

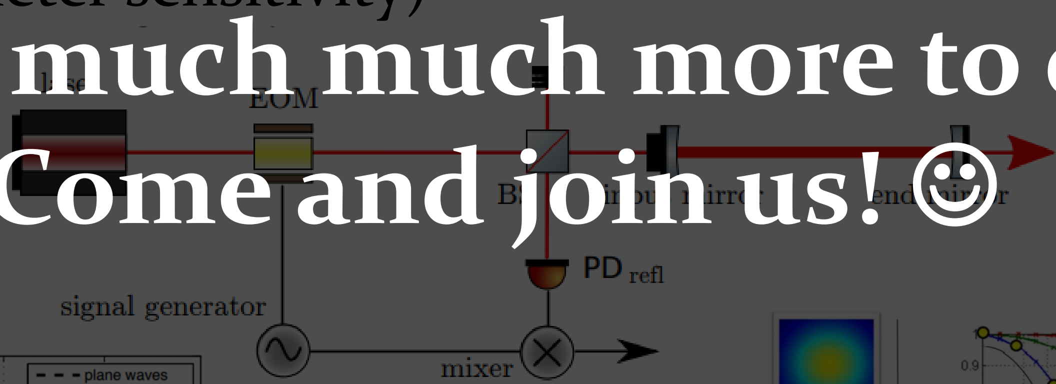
Finesse

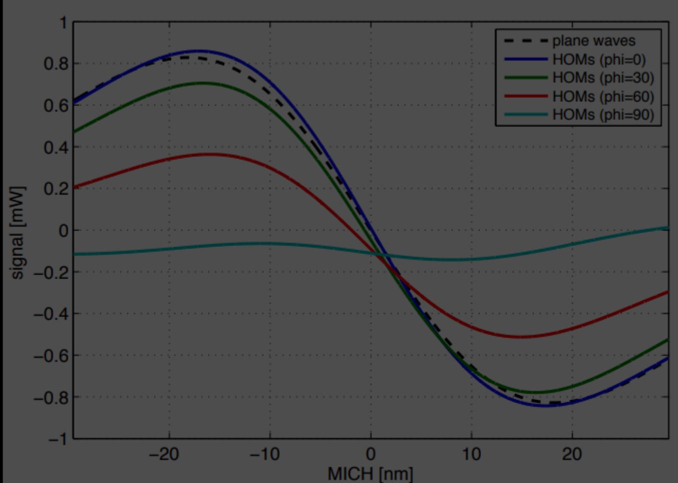
(Frequency domain INterfErometer Simulation SoftwarE)

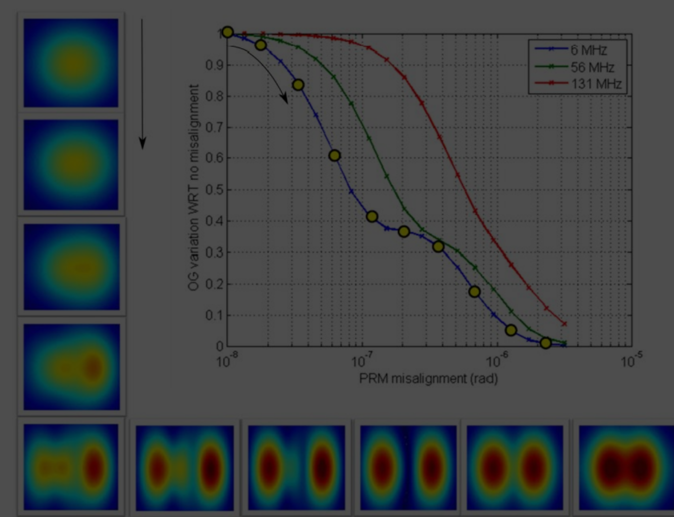
- Control systems to be developed, to have:
  - Good control of the mirrors
  - Control noise as low as possible (not to re-inject noise in the interferometer sensitivity)

And much much more to do!

Come and join us! ☺








Thank you for your attention