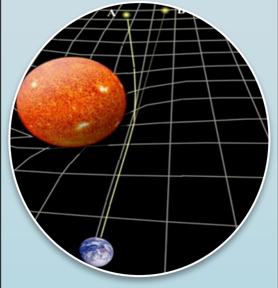
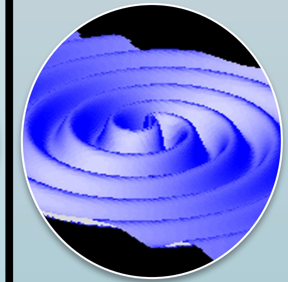
Virgo detector

Andre Contu
Domenico D'Urso
Davide Rozza
University of Cagliari, Sassari & INFN

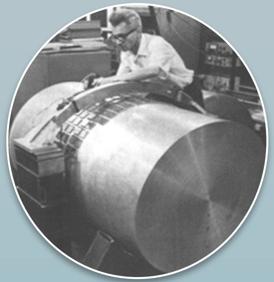
GW: a long history…



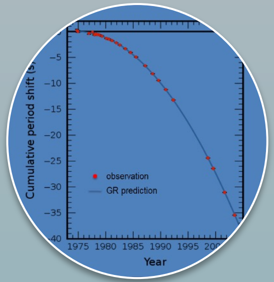
1915
- General Relativity



1916
- Gravitational Waves



1966
- Weber and Resonant Bars

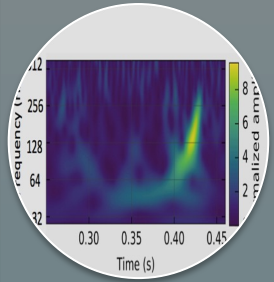


1974
- Hulse-Taylor:Observing the pulsar binary PSR B1913+16

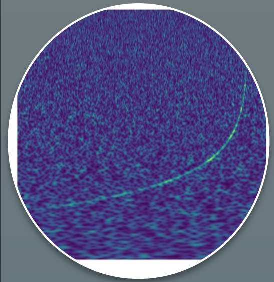
1980-1990
- Cryogenic Resonant Bars

1993
- The approval of Virgo Experiment

1999+
- Data taking from LIGO and Virgo

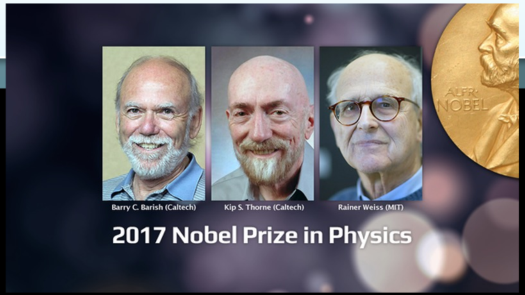


2015
- GW BHBH detection



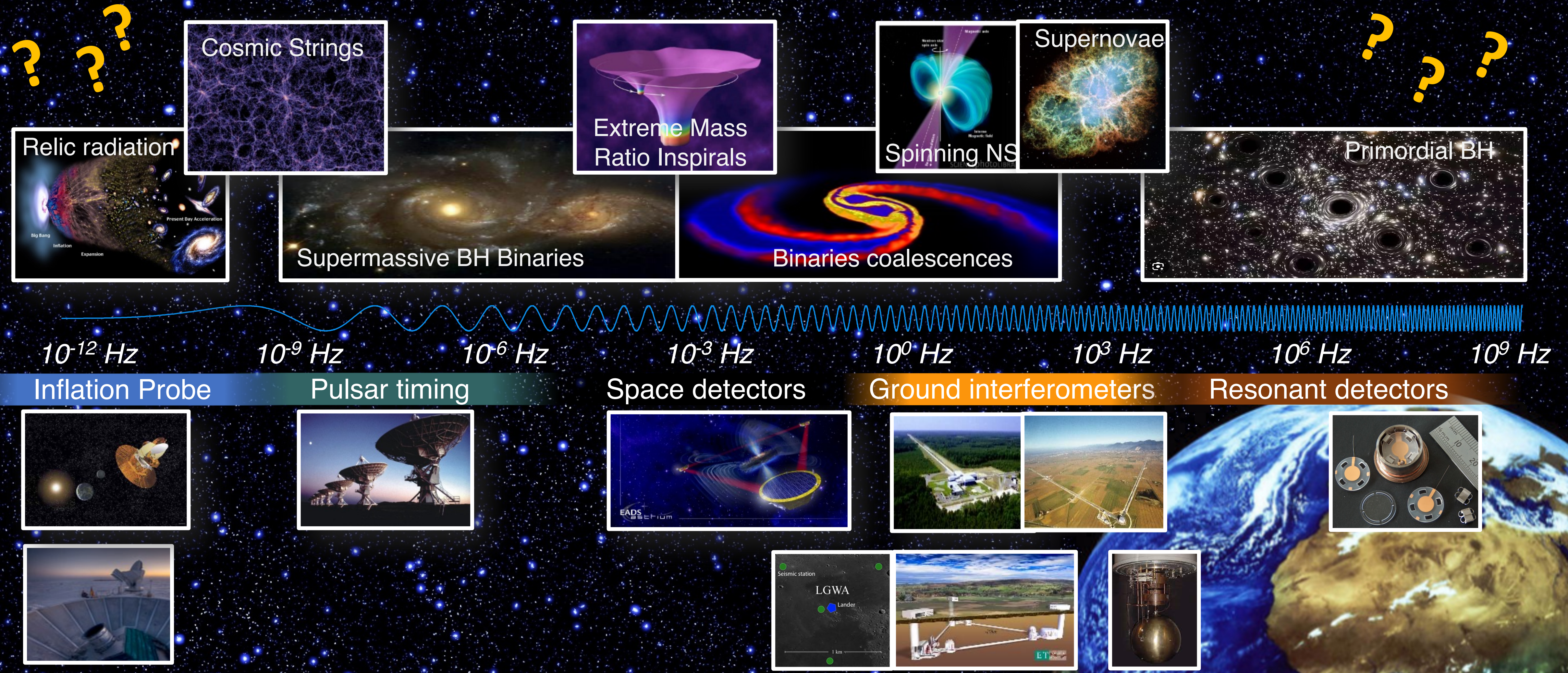
2017
- BNS detection: Multi-messenger Astronomy

~100 years



Credits to E. Cuoco et al.

GW spectrum



GW detectors

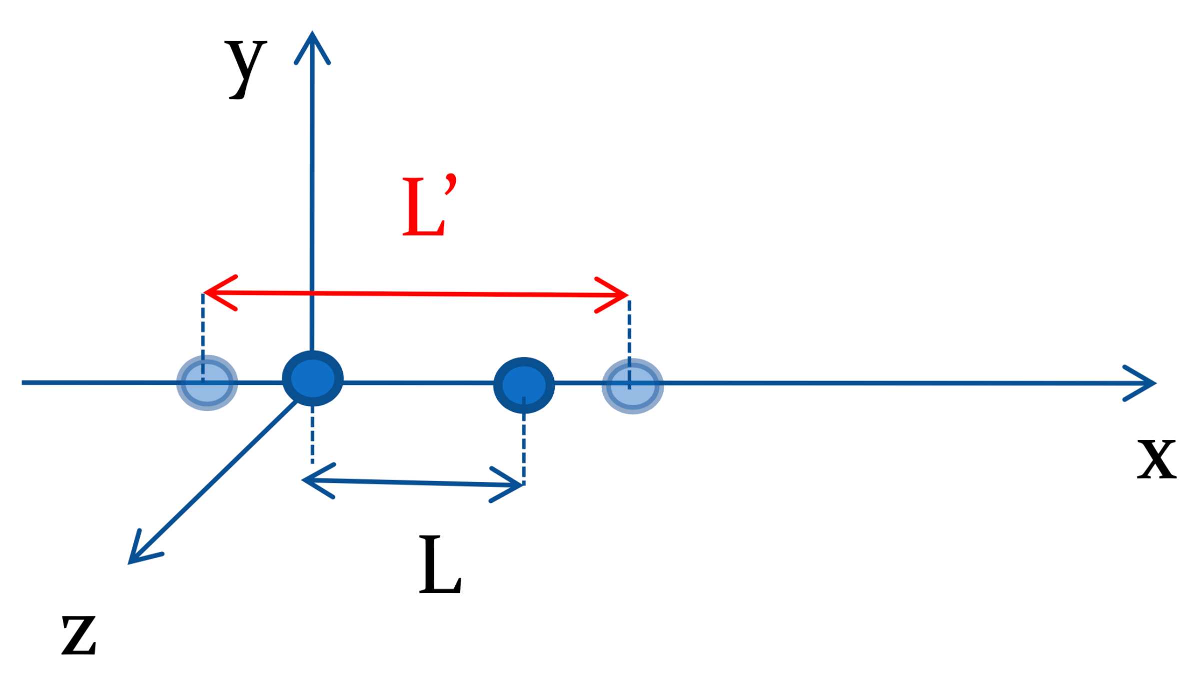
The effect of GW on free-falling masses

$\delta L \propto h \cdot L$

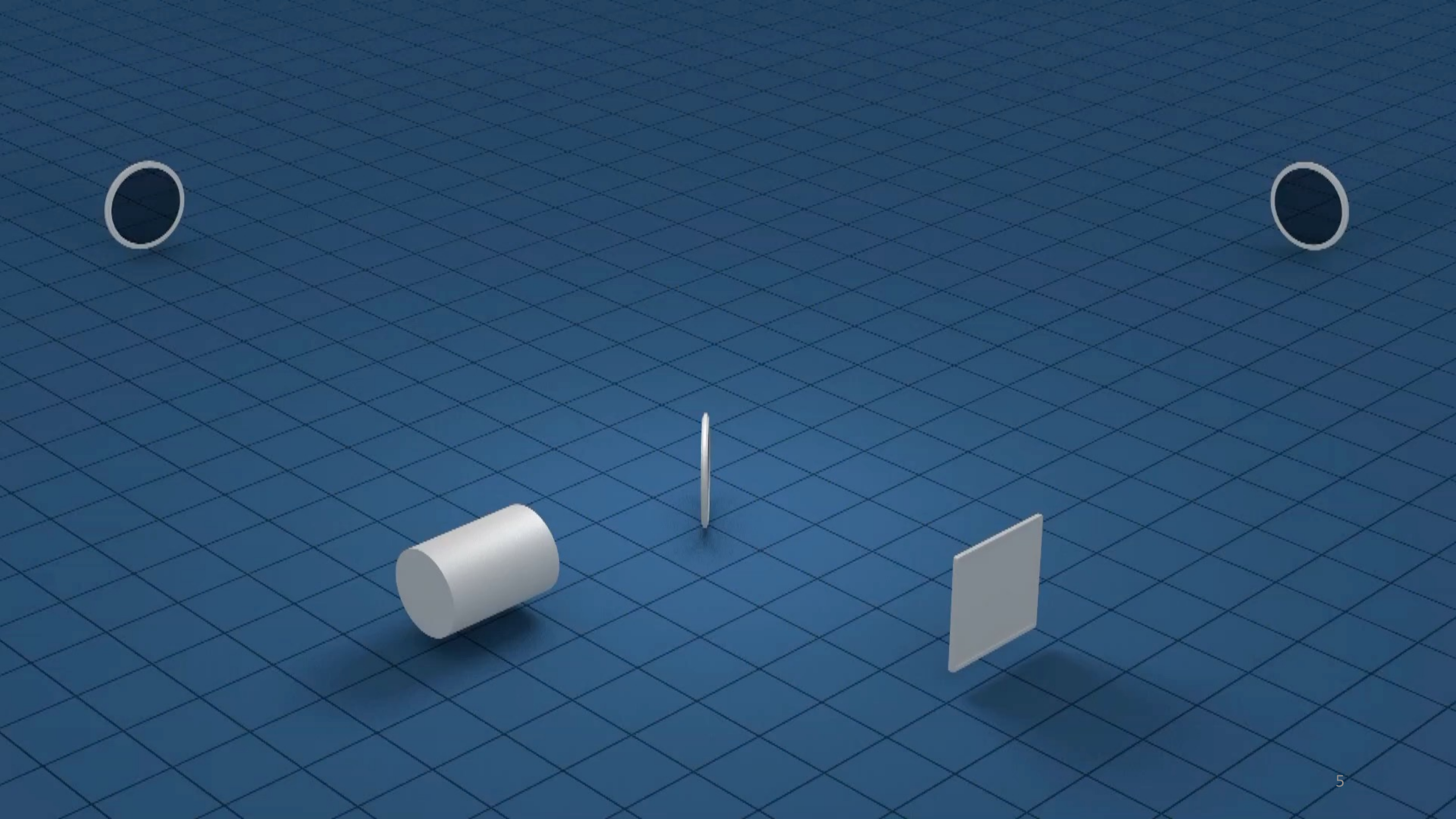
↓

GW amplitude

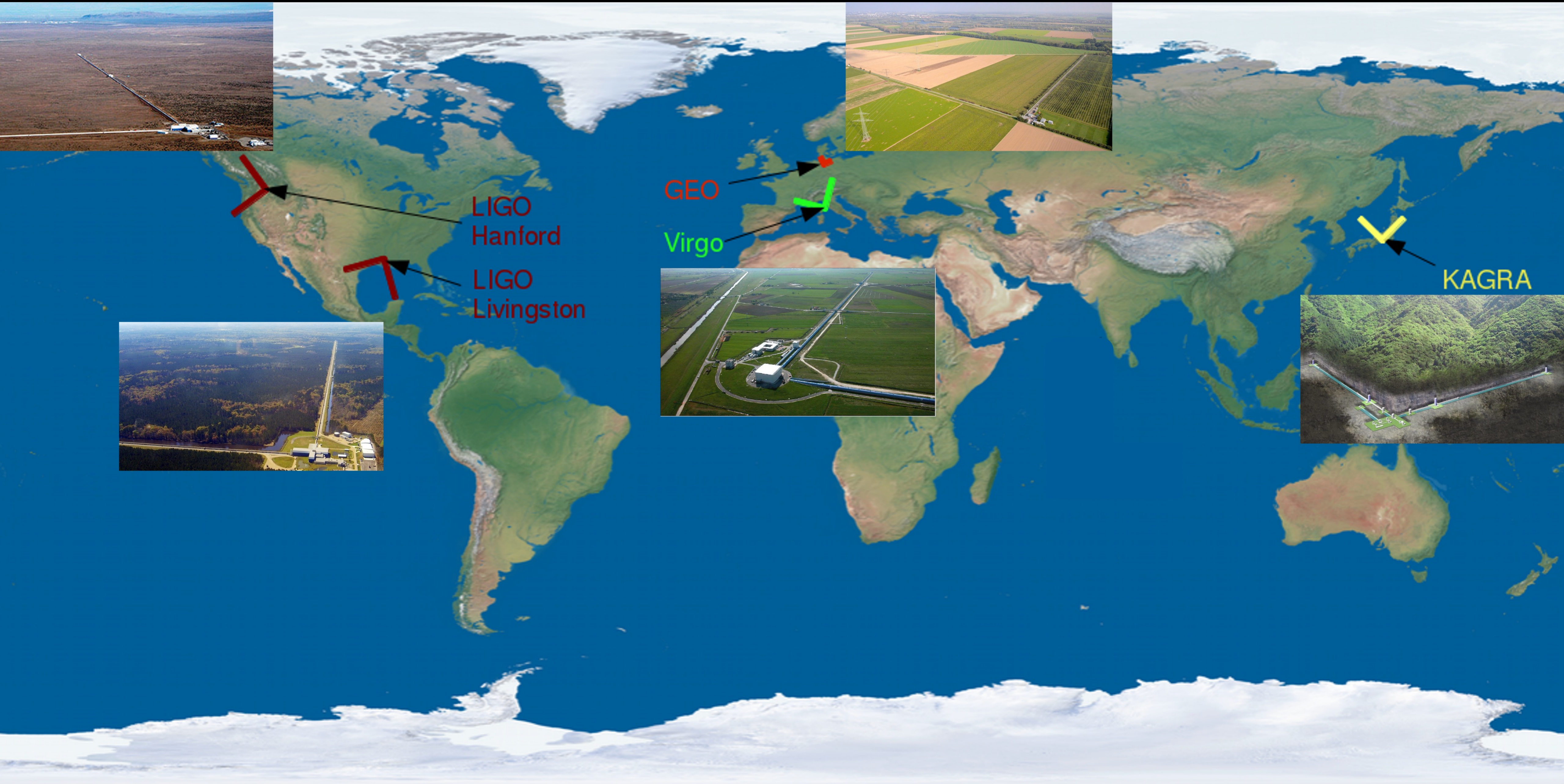
$h \approx 10^{-21}$



The distance between two free-falling masses separated by a km will change by $\delta L \approx 10^{-18}\ m$

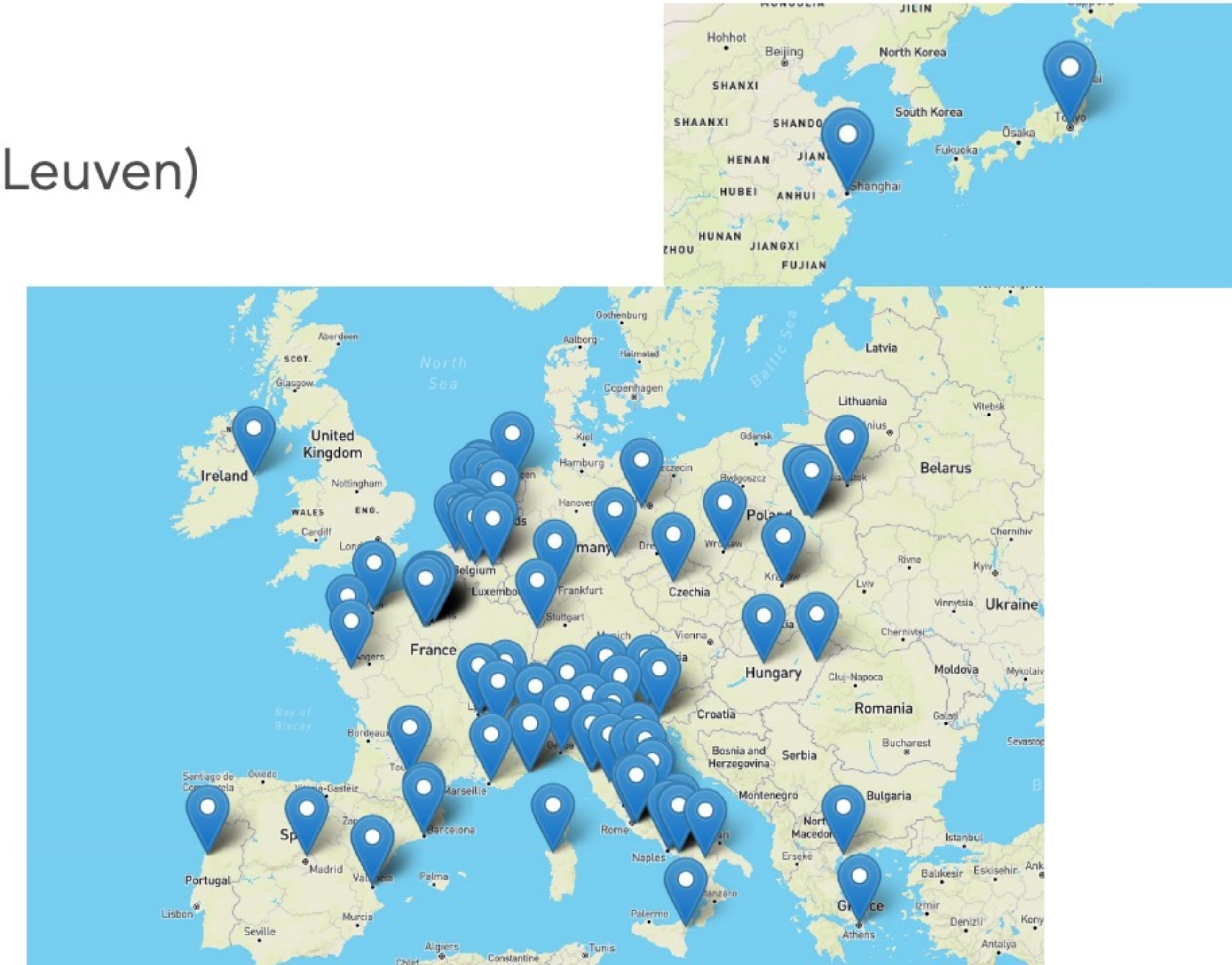


Gravitational wave interferometers



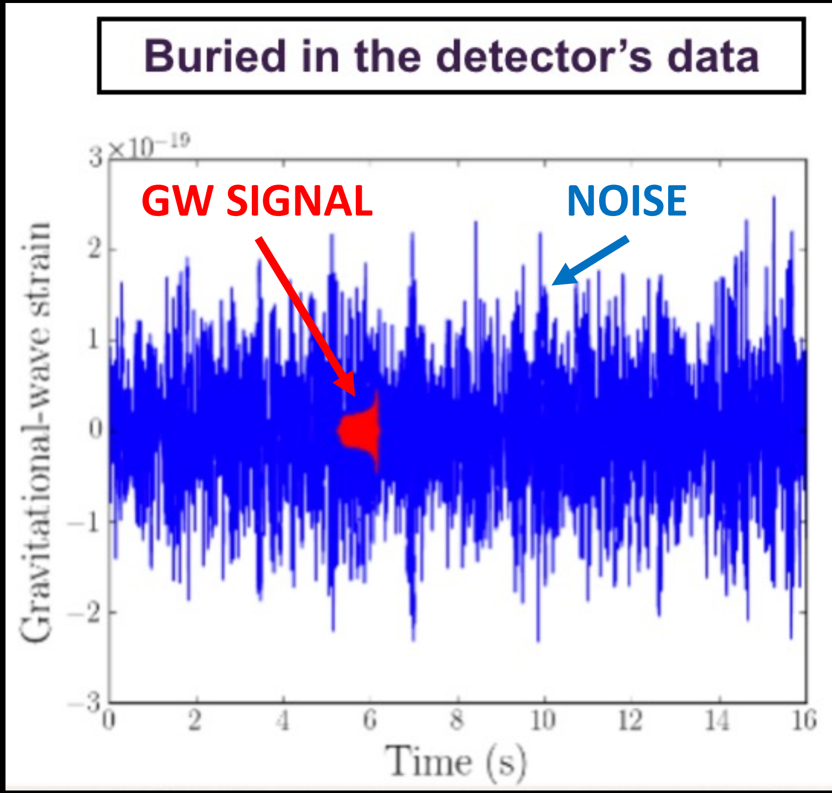
Virgo Collaboration

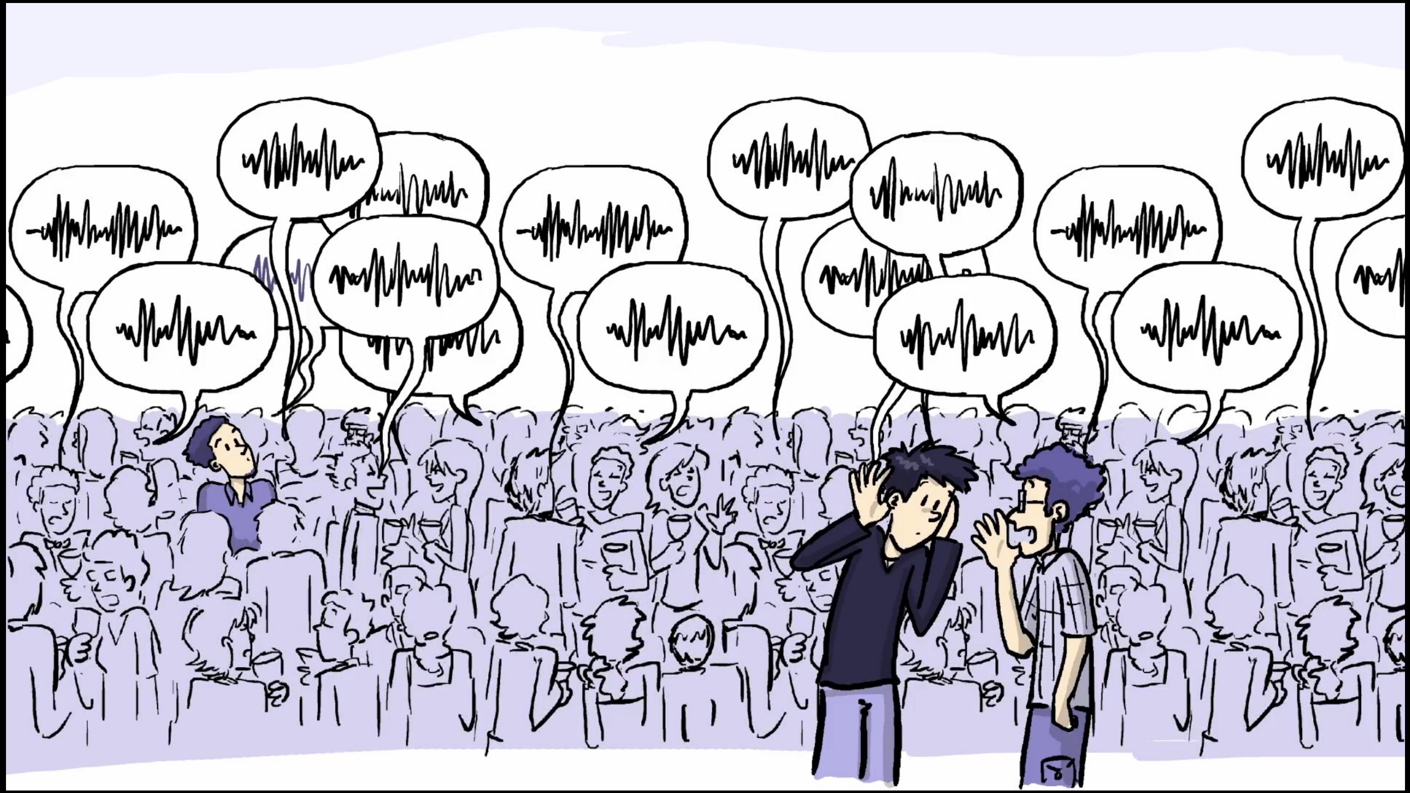
- ~770 members, ~450 authors, 131 institutions from 15 countries
- 34 Groups:
  - 32 full members
  - 2 in the first year (L2I Toulouse, KU Leuven)
- 9 countries represented in the VSC



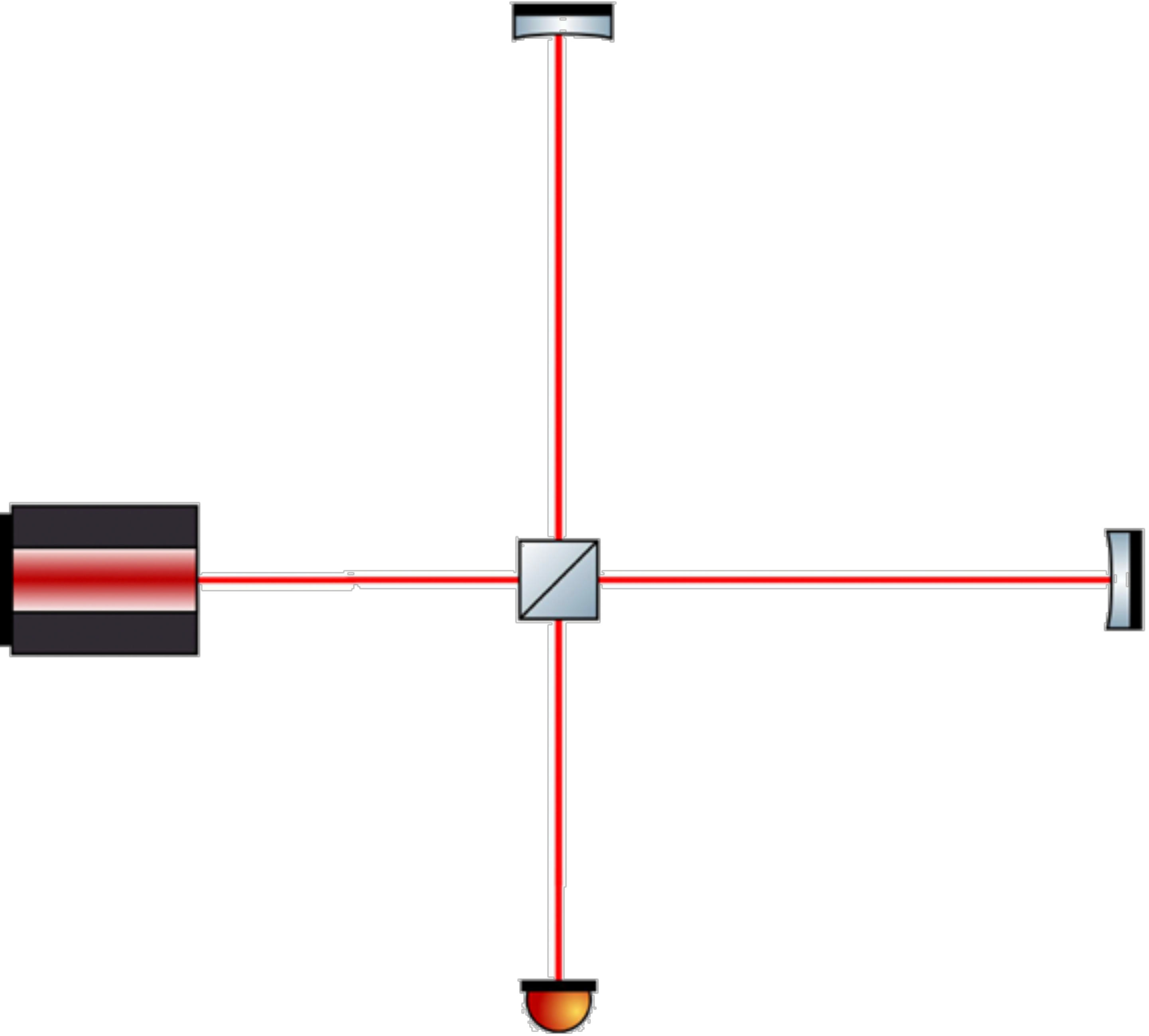
Credits to D. D'Urso et al.

GW DATA ANALYSIS

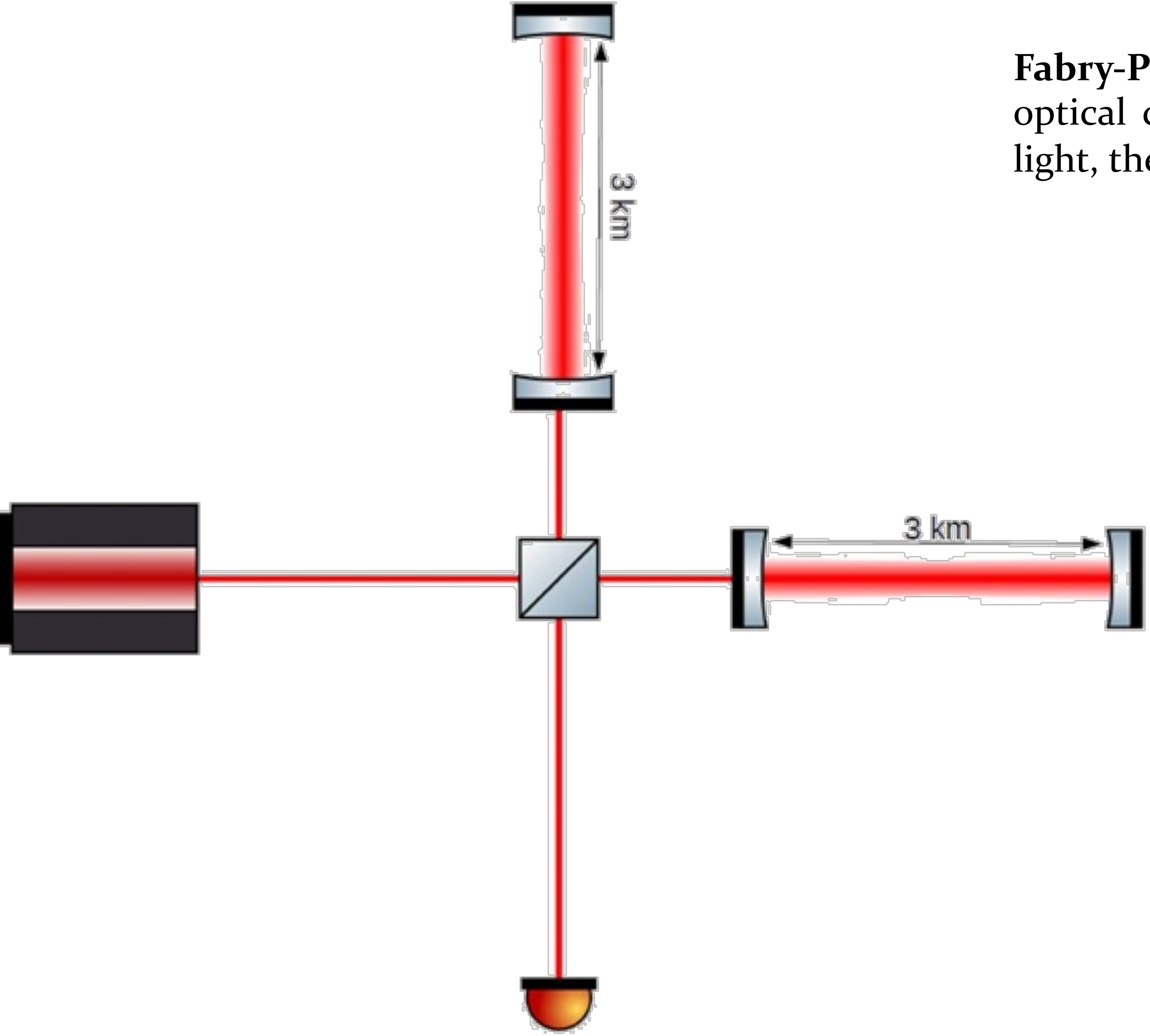




We need to enhance the signal and reduce the noise

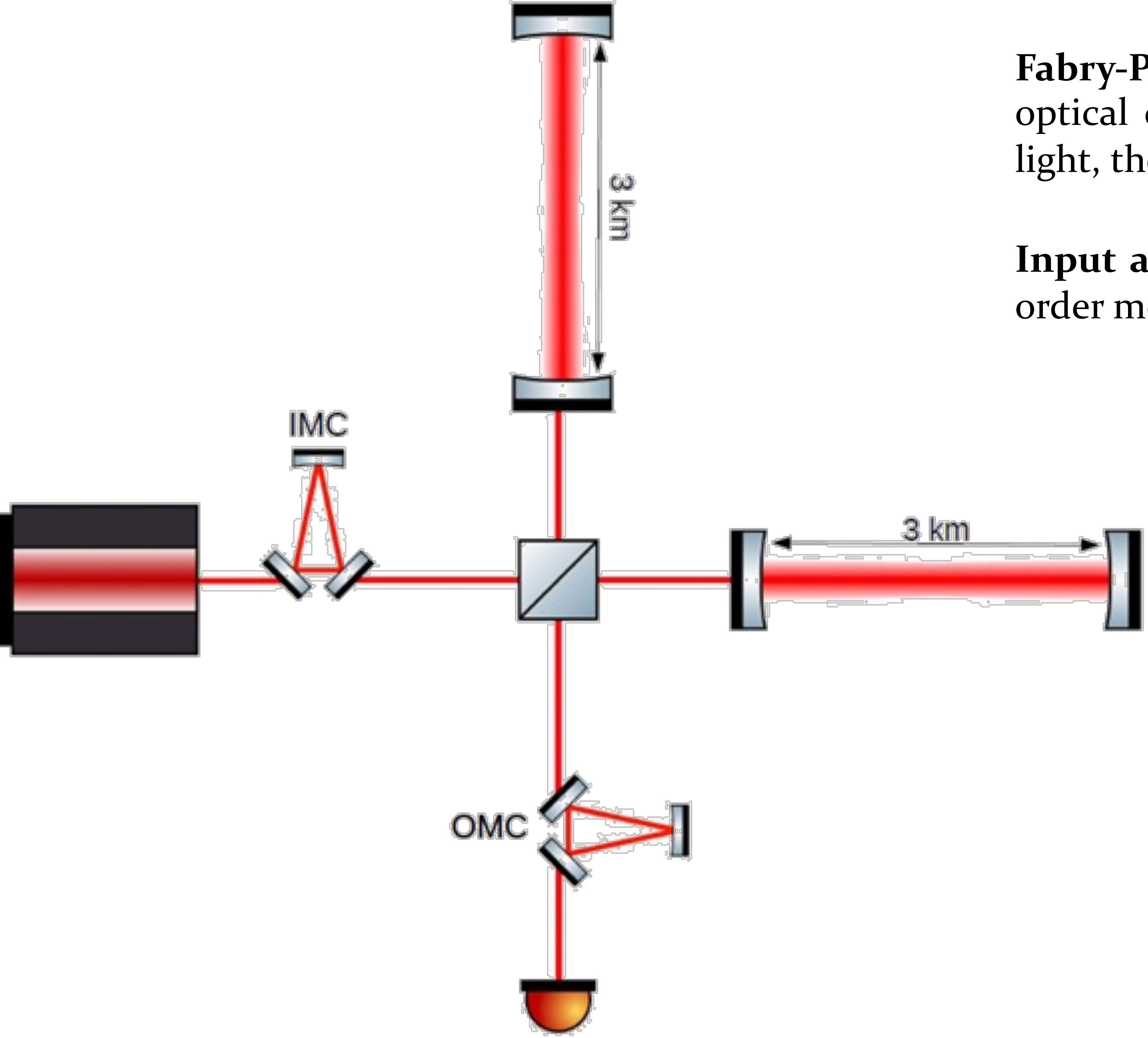


Enhance the signal



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

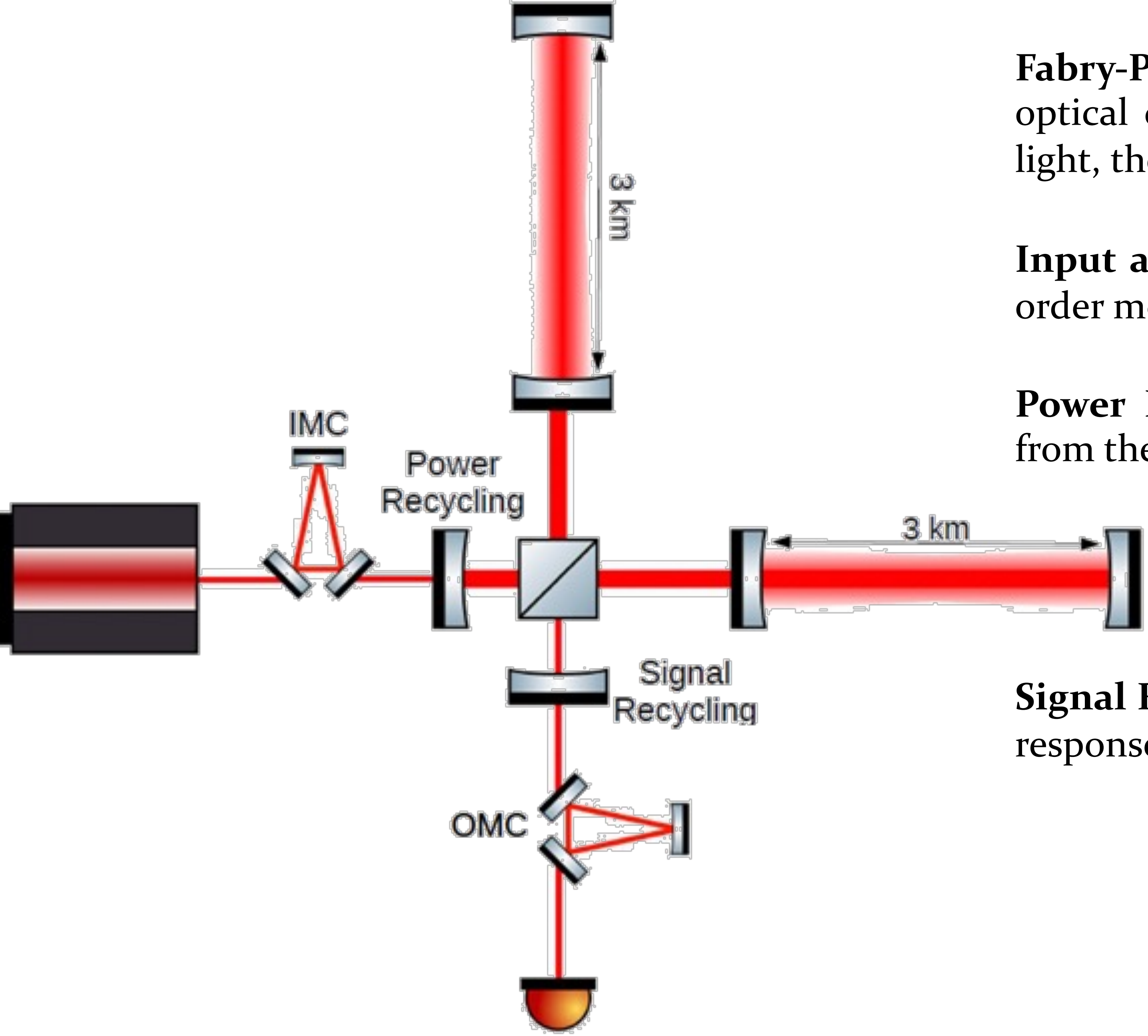
Enhance the signal



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

Enhance the signal



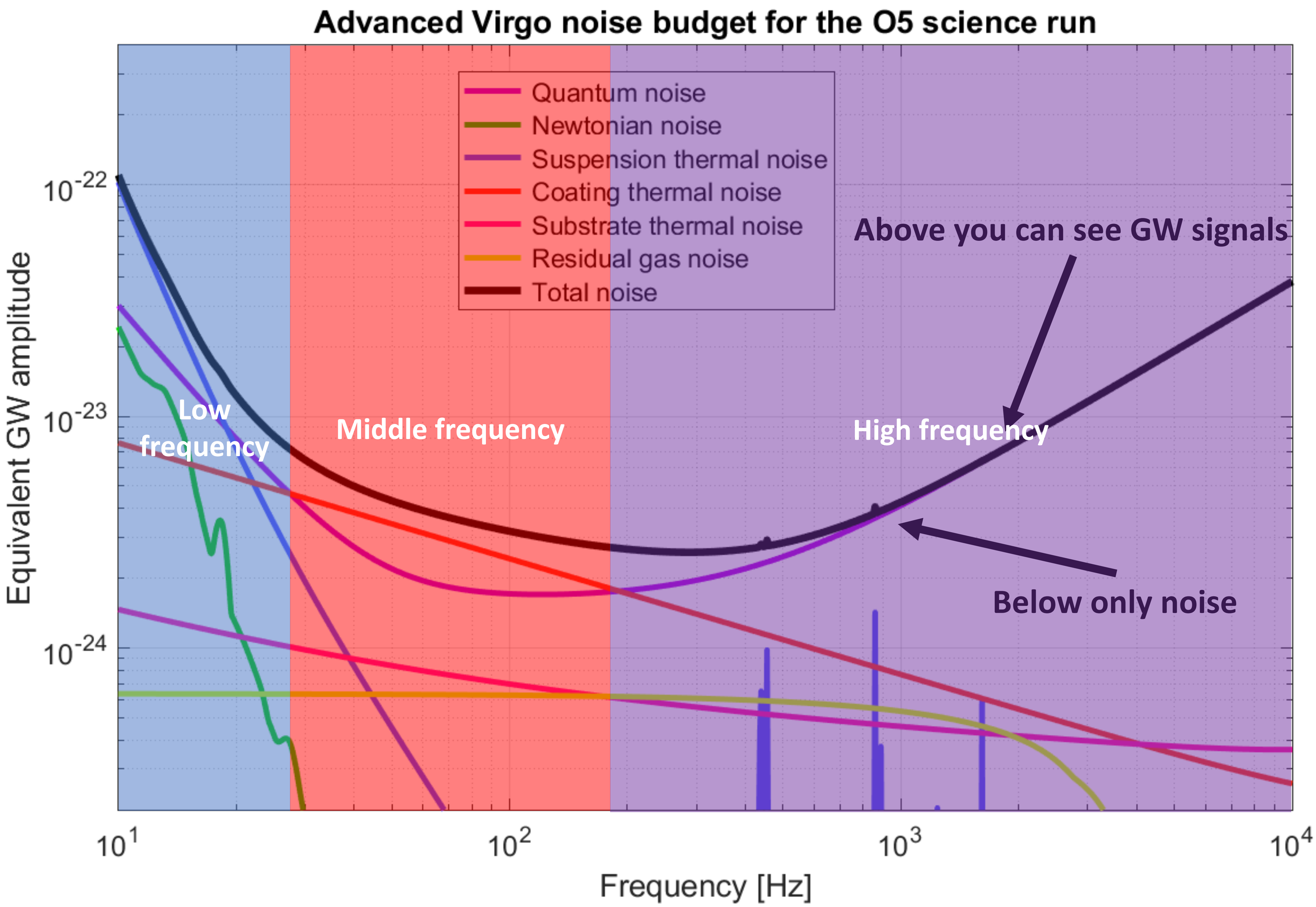
Fabry-Perot cavity for “longer arms”: the presence of the optical cavities increases the number of round trip of the light, therefore enhancing the gain of the instrument

Input and output mode cleaner to reject the laser high-order modes

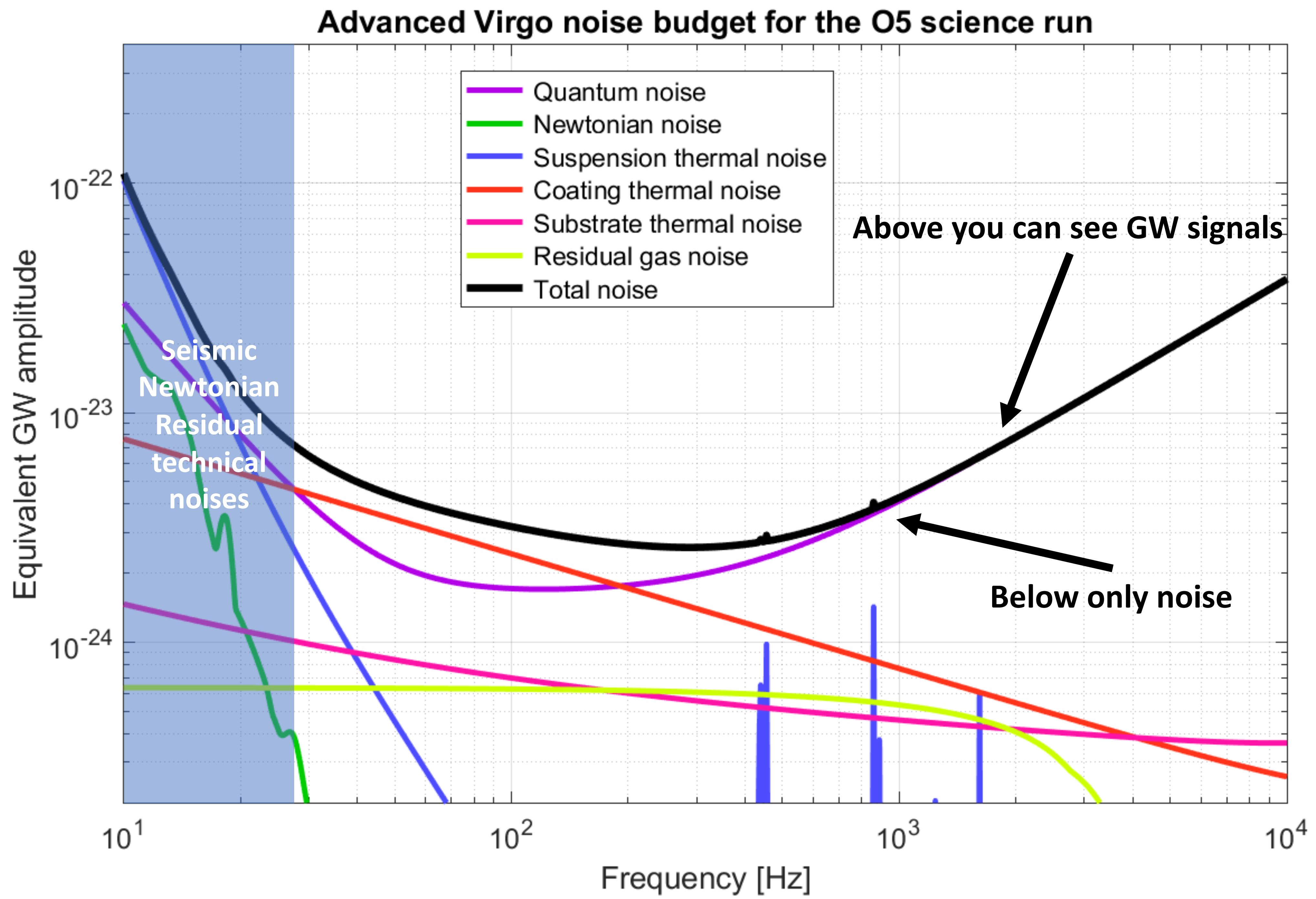
Power Recycling mirror to recover the power reflected from the arms and increase the optical power (***PR***)

Signal Recycling mirror to reshape the detector frequency response

Enhance the signal

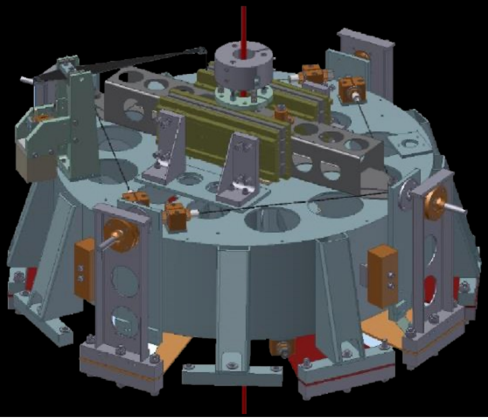


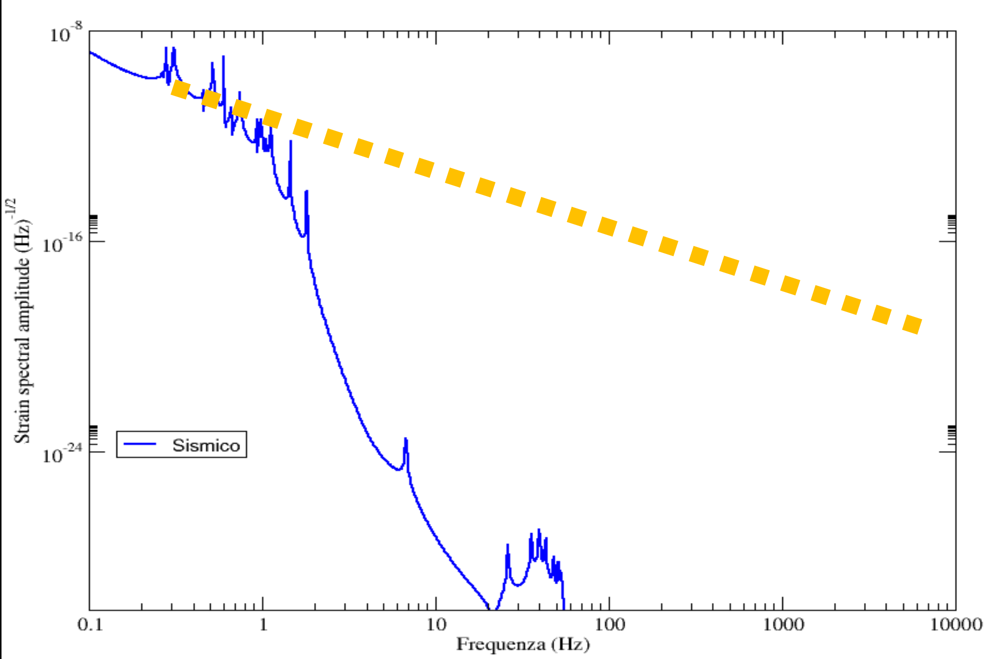
Advanced Virgo noise budget for the O5 science run
Quantum noise
Newtonian noise
Suspension thermal noise
Coating thermal noise
Substrate thermal noise
Residual gas noise
Total noise
Above you can see GW signals
Below only noise
Low frequency
Middle frequency
High frequency
Equivalent GW amplitude
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}

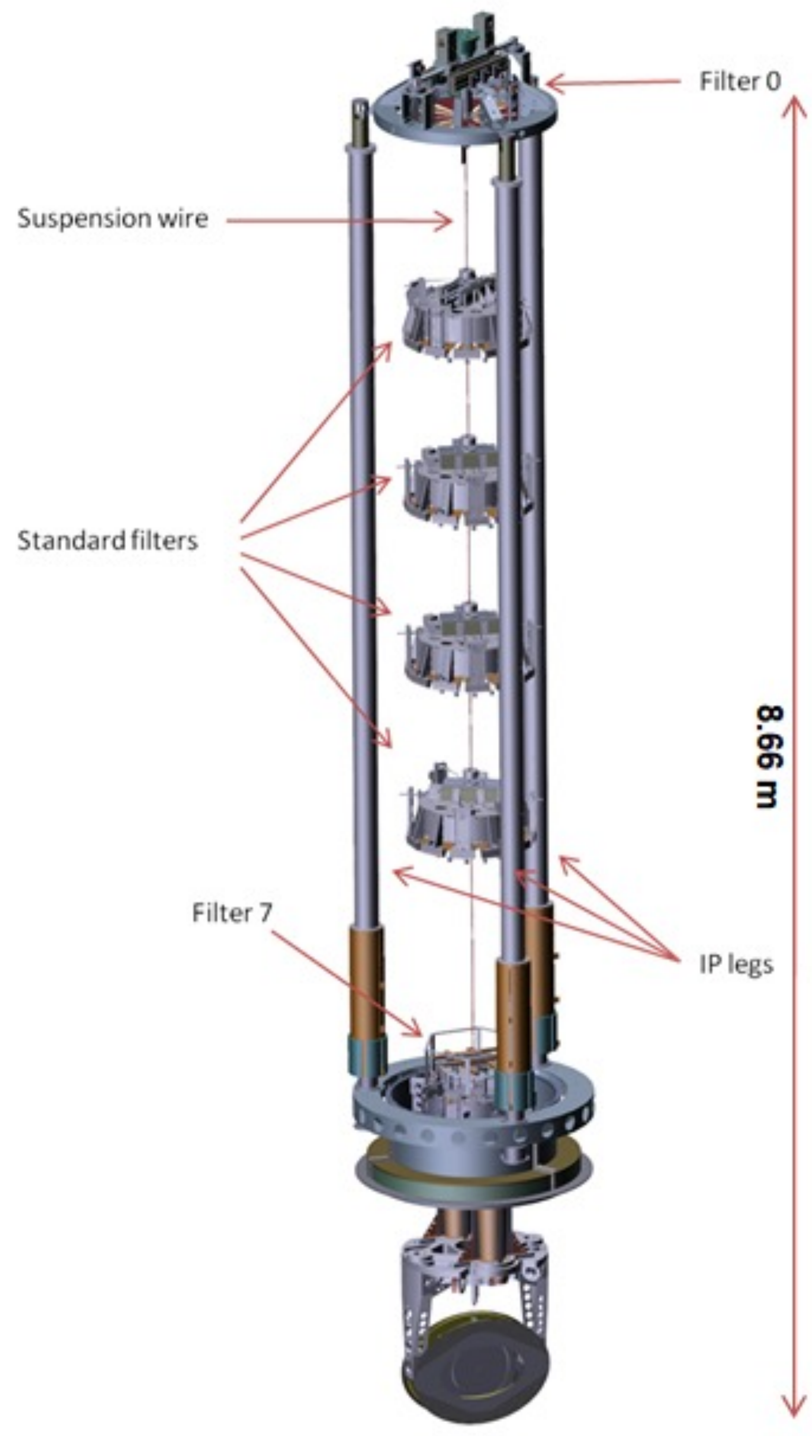

Advanced Virgo noise budget for the O5 science run
Quantum noise
Newtonian noise
Suspension thermal noise
Coating thermal noise
Substrate thermal noise
Residual gas noise
Total noise
Above you can see GW signals
Below only noise
Seismic
Newtonian
Residual
technical
noises
Equivalent GW amplitude
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}

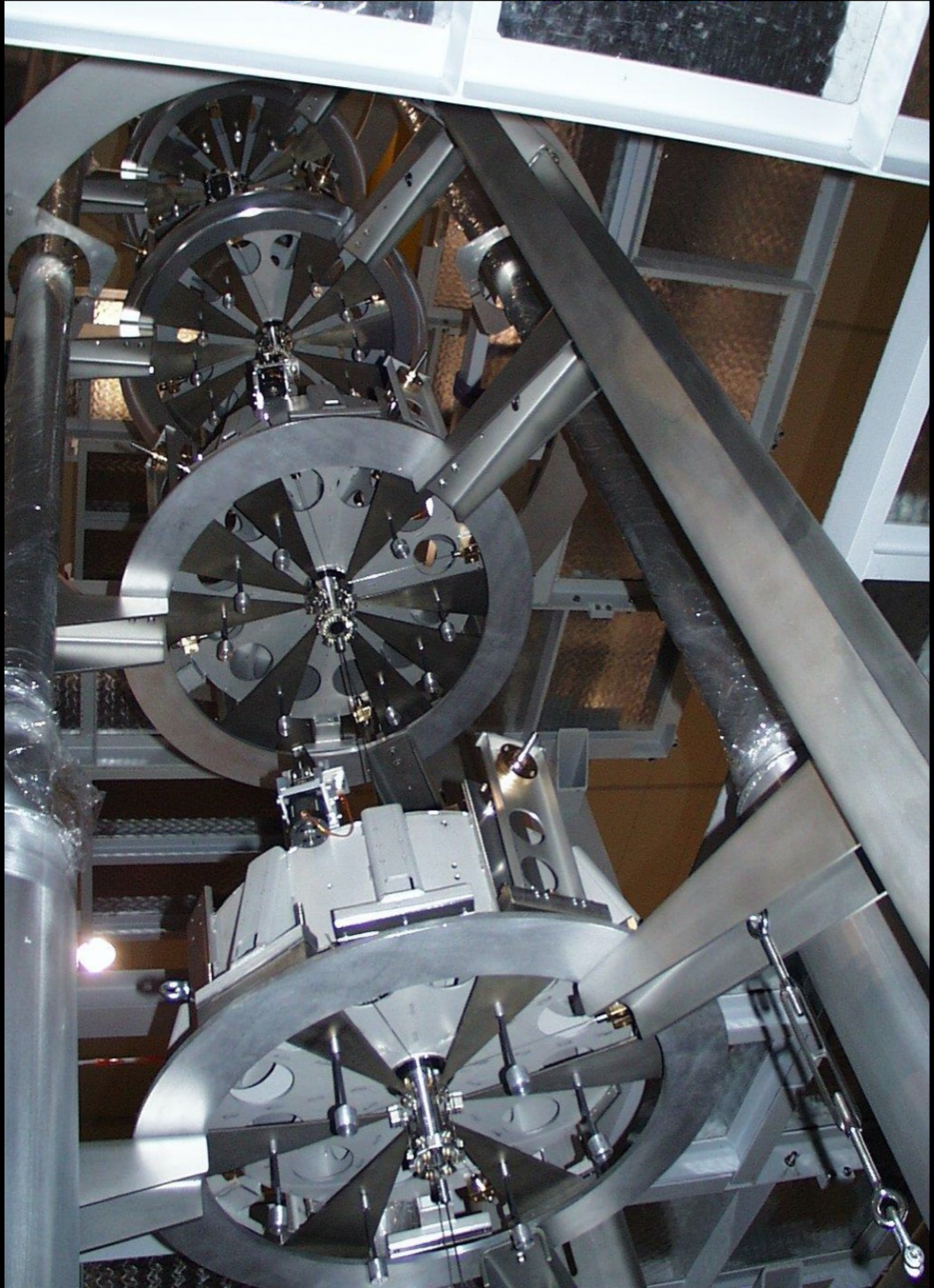
Reducing seismic noise:

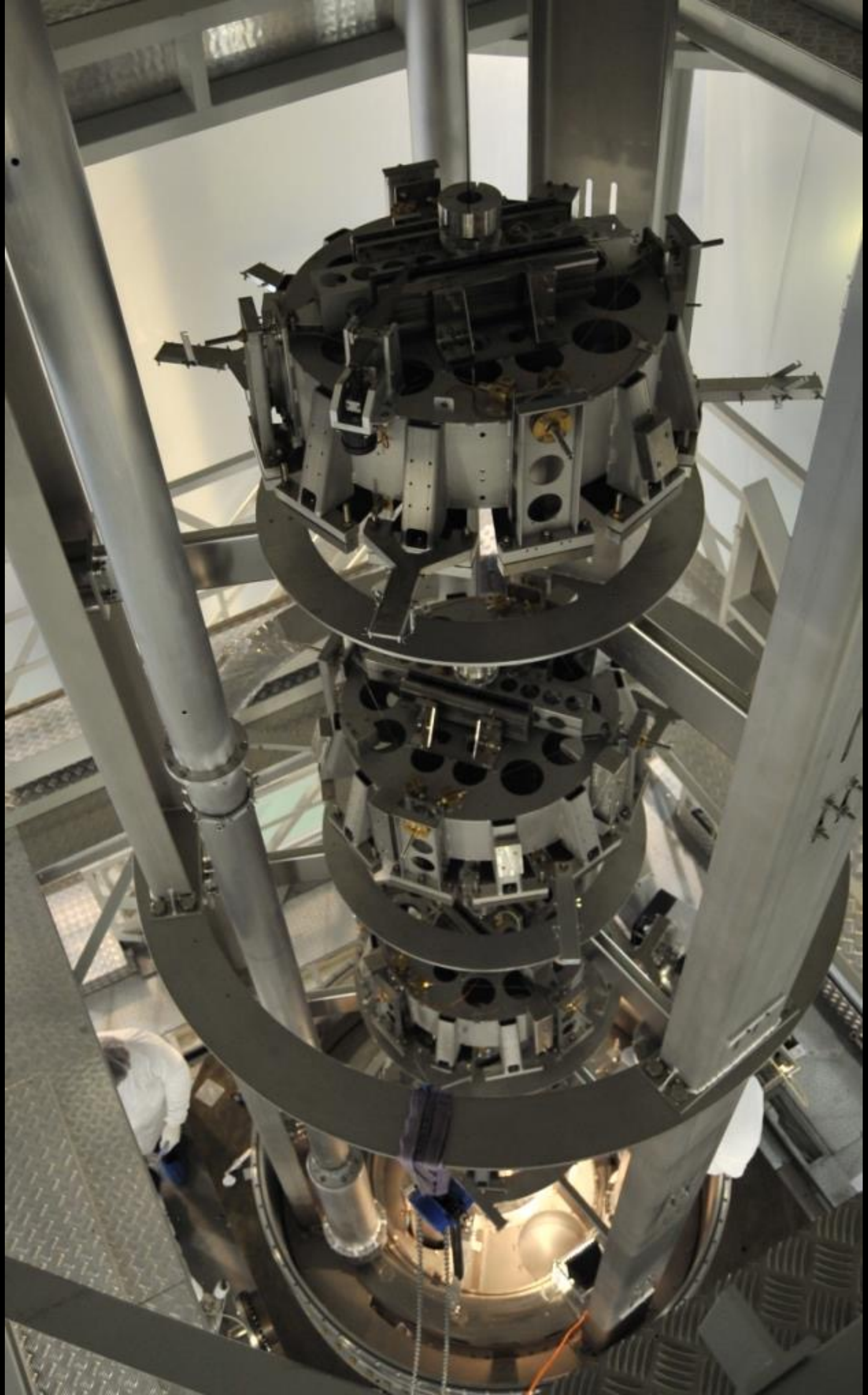
- **Choose a good location**
- **Superattenuator to reduce seismic vibration: reduces mirrors seismic vibration by a factor 10^{12}**







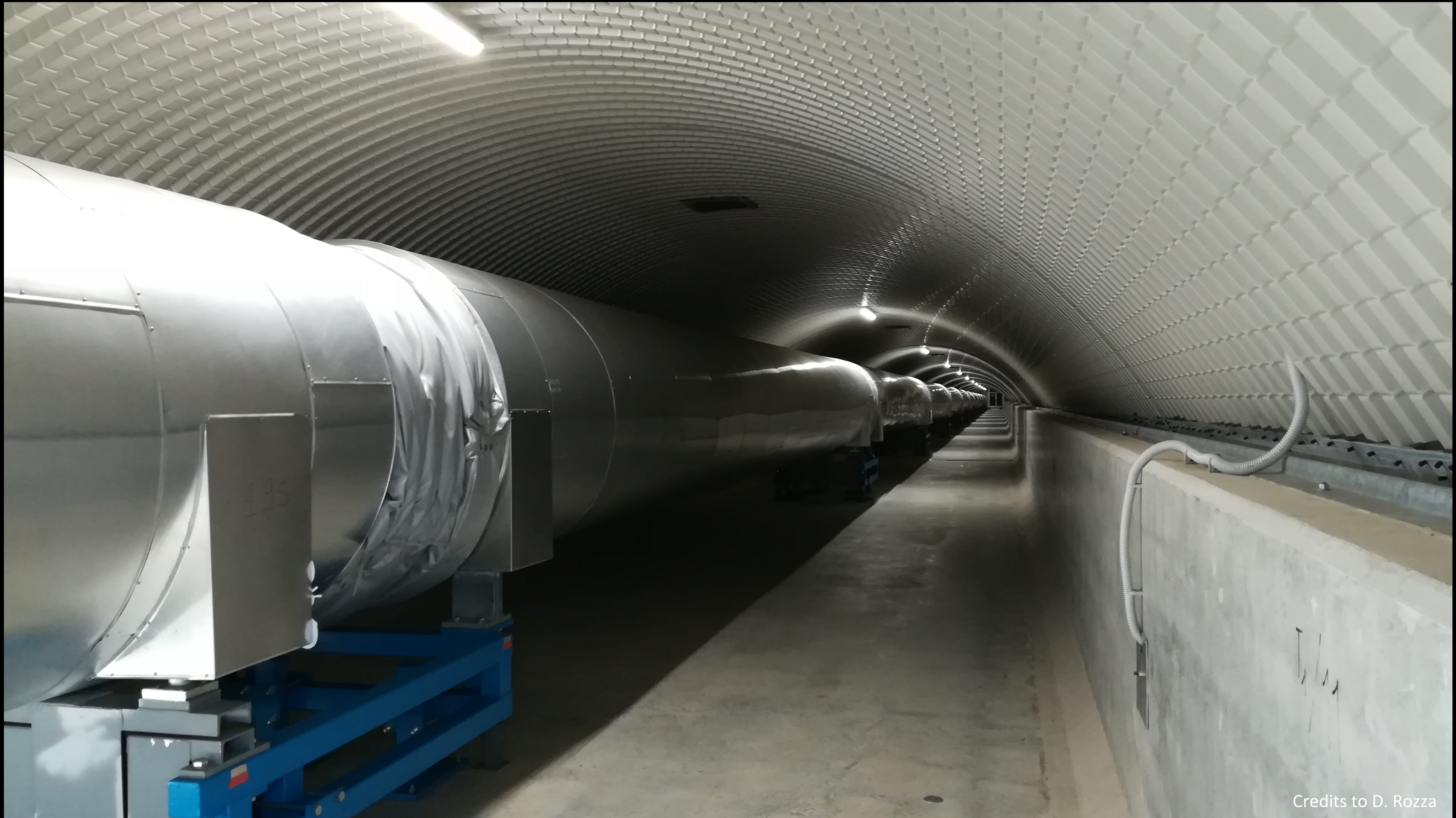




Credits to D. Rozza

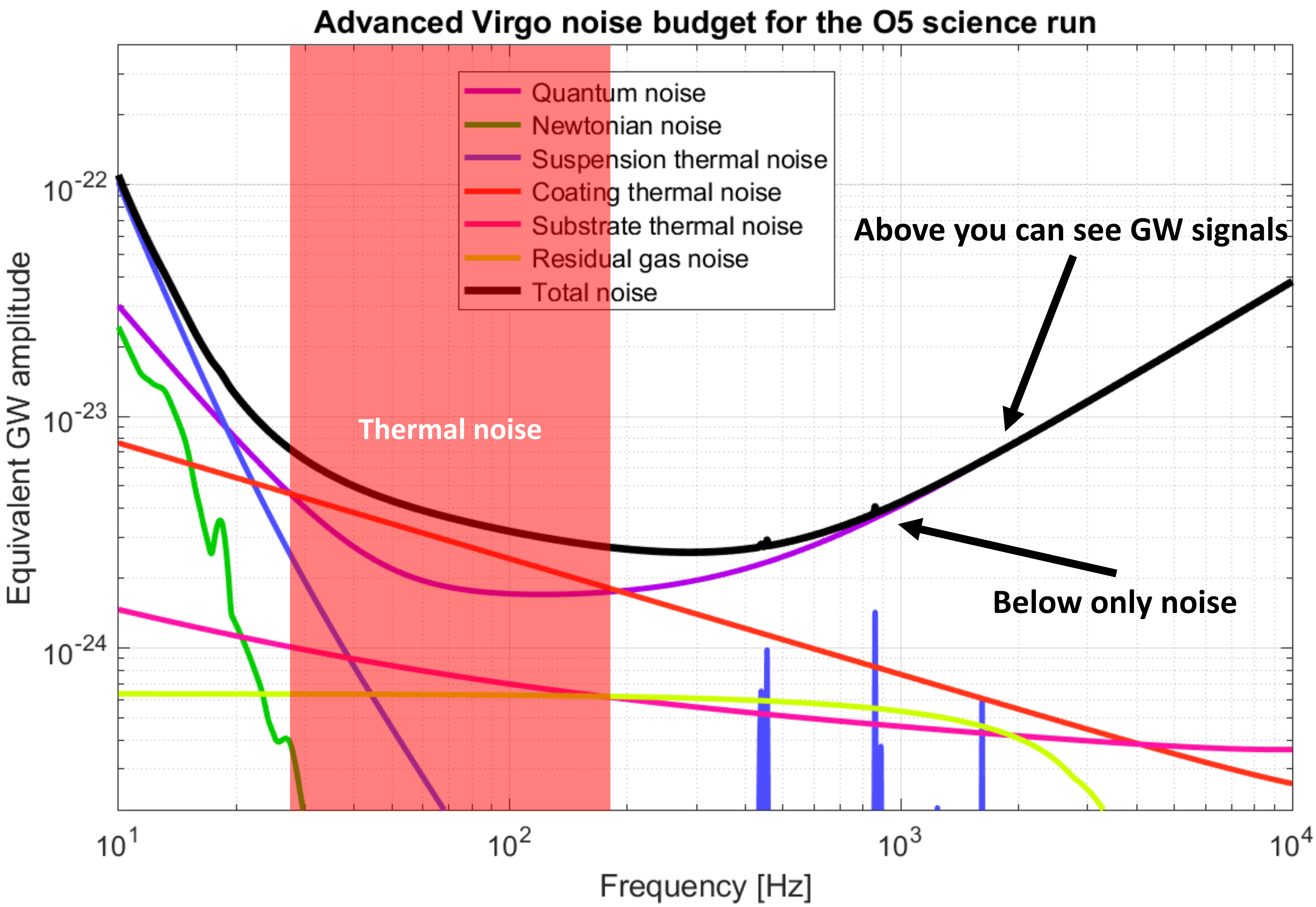
Reducing seismic noise:

- **Ultra high vacuum:**
  7000 m^3 @ pressure of 10^{-9} mbar
  The biggest ultra-high-vacuum system in Europe



Credits to D. Rozza

Credits to D. Rozza

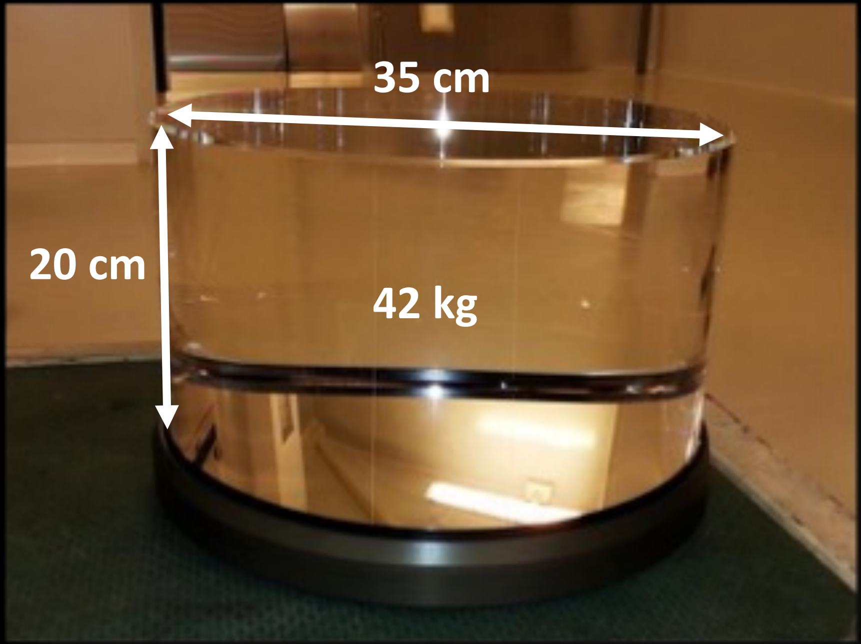


Advanced Virgo noise budget for the O5 science run
Quantum noise
Newtonian noise
Suspension thermal noise
Coating thermal noise
Substrate thermal noise
Residual gas noise
Total noise
Thermal noise
Above you can see GW signals
Below only noise
Equivalent GW amplitude
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

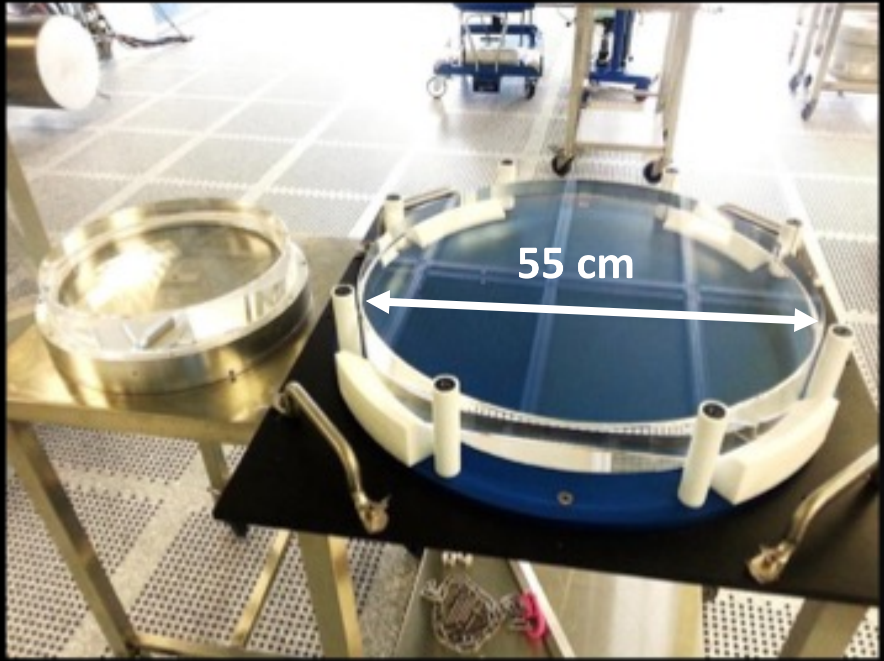
Reducing thermal noise:

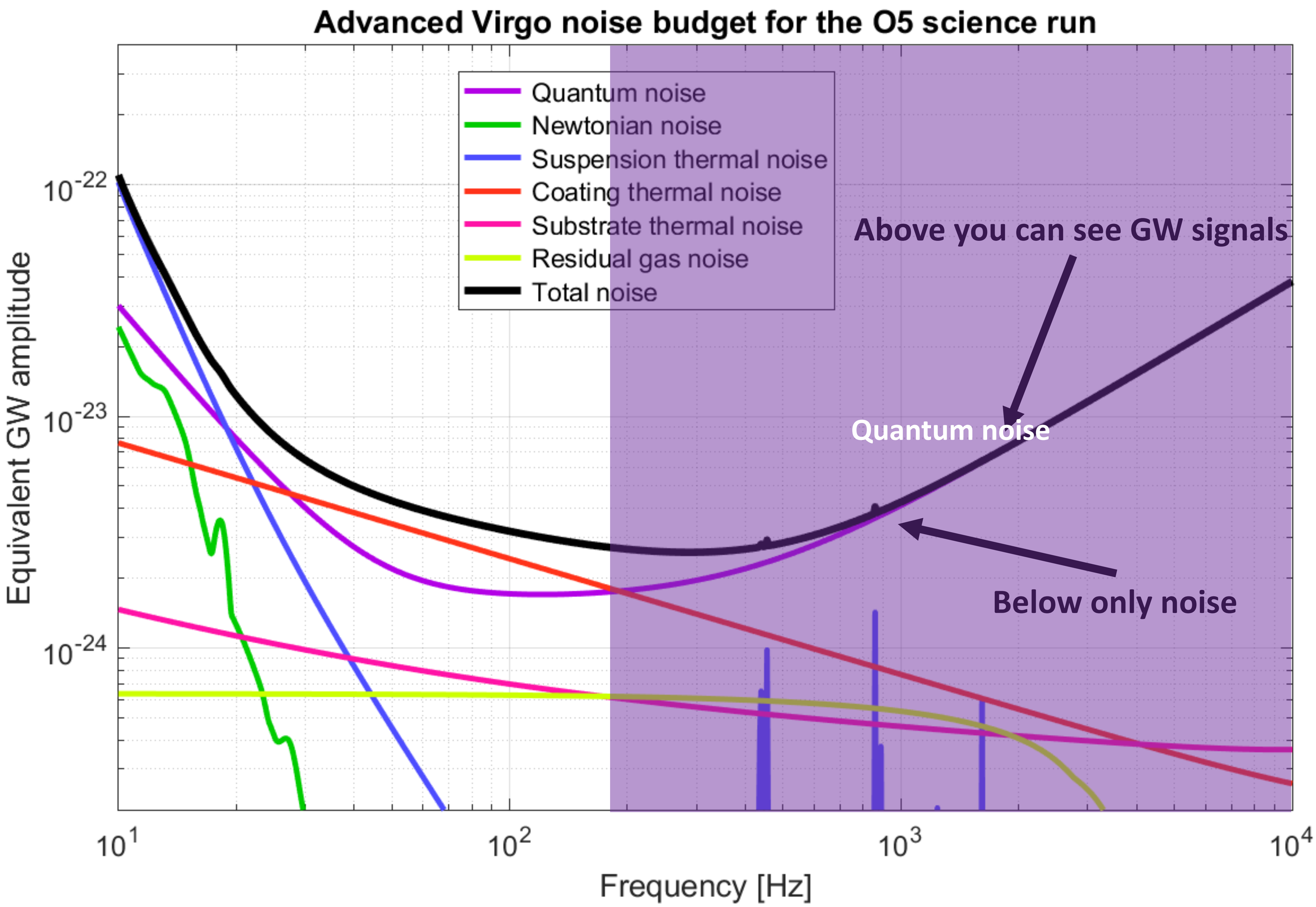
- Beam size as large as possible
- Coating techniques to reduce the losses
- SiO_2 monolithic suspensions 400 μm
- Mirrors of 42 kg in weight to reduce the effect of the radiation pressure
- SiO_2 mirrors with a residual roughness < 0.5 nm

Test mass mirrors



Beam splitter mirror



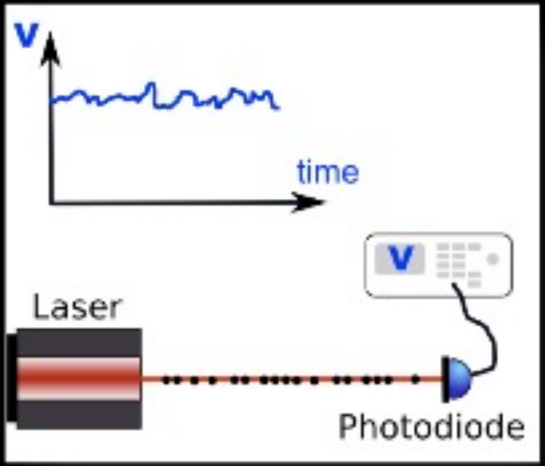


Advanced Virgo noise budget for the O5 science run
Quantum noise
Newtonian noise
Suspension thermal noise
Coating thermal noise
Substrate thermal noise
Residual gas noise
Total noise
Above you can see GW signals
Quantum noise
Below only noise
Equivalent GW amplitude
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
10^{4}

Reducing quantum noise:

- **Increased finesse of arm cavity**
- **High power laser**
- **Squeezing technique**

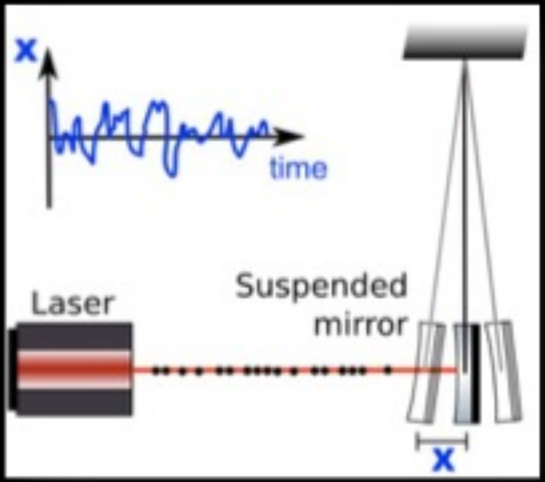
Shot noise: photon counting noise



$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}}$$

P = Power

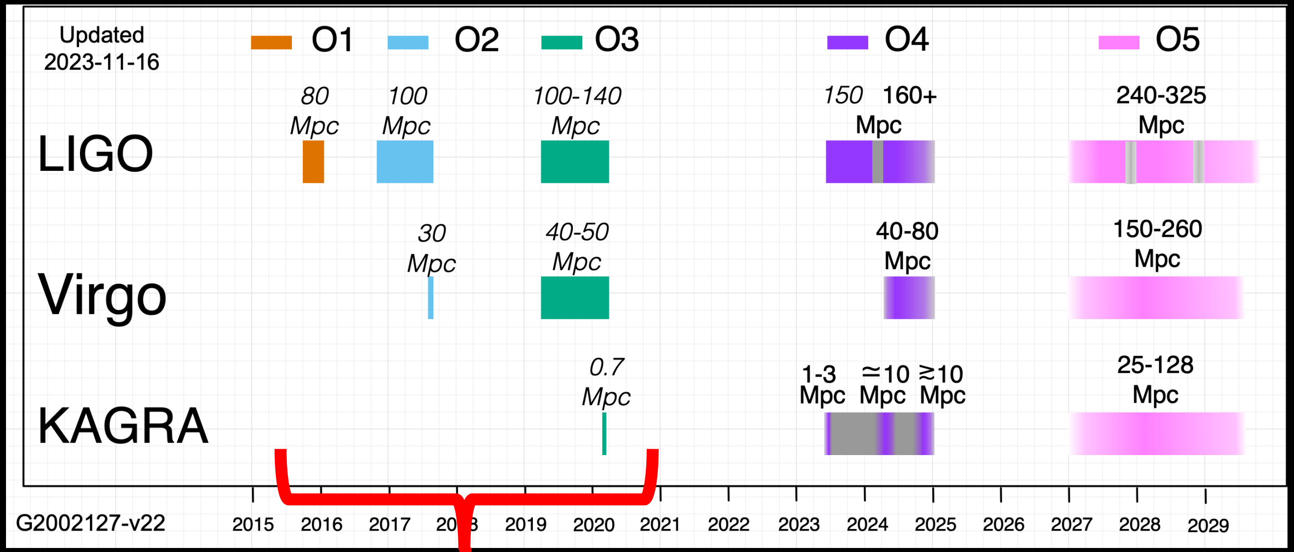
Radiation pressure noise: Photons fluctuations translate in radiation pressure fluctuations, giving rise to random motion of the mirrors



$$h_{rad} \propto \frac{1}{f^2 L}\frac{\sqrt{P}}{m}$$

Credits to D. Rozza

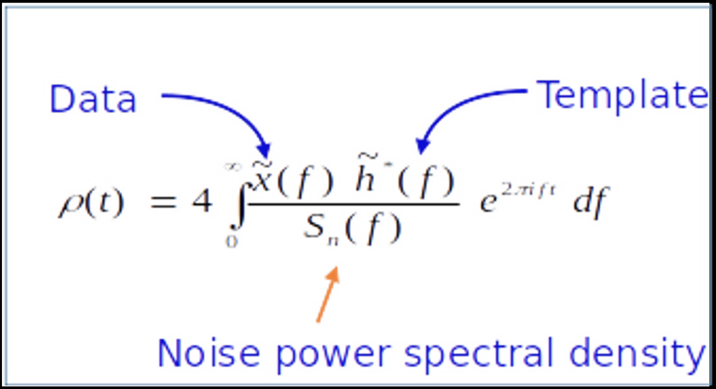
Gravitational wave events



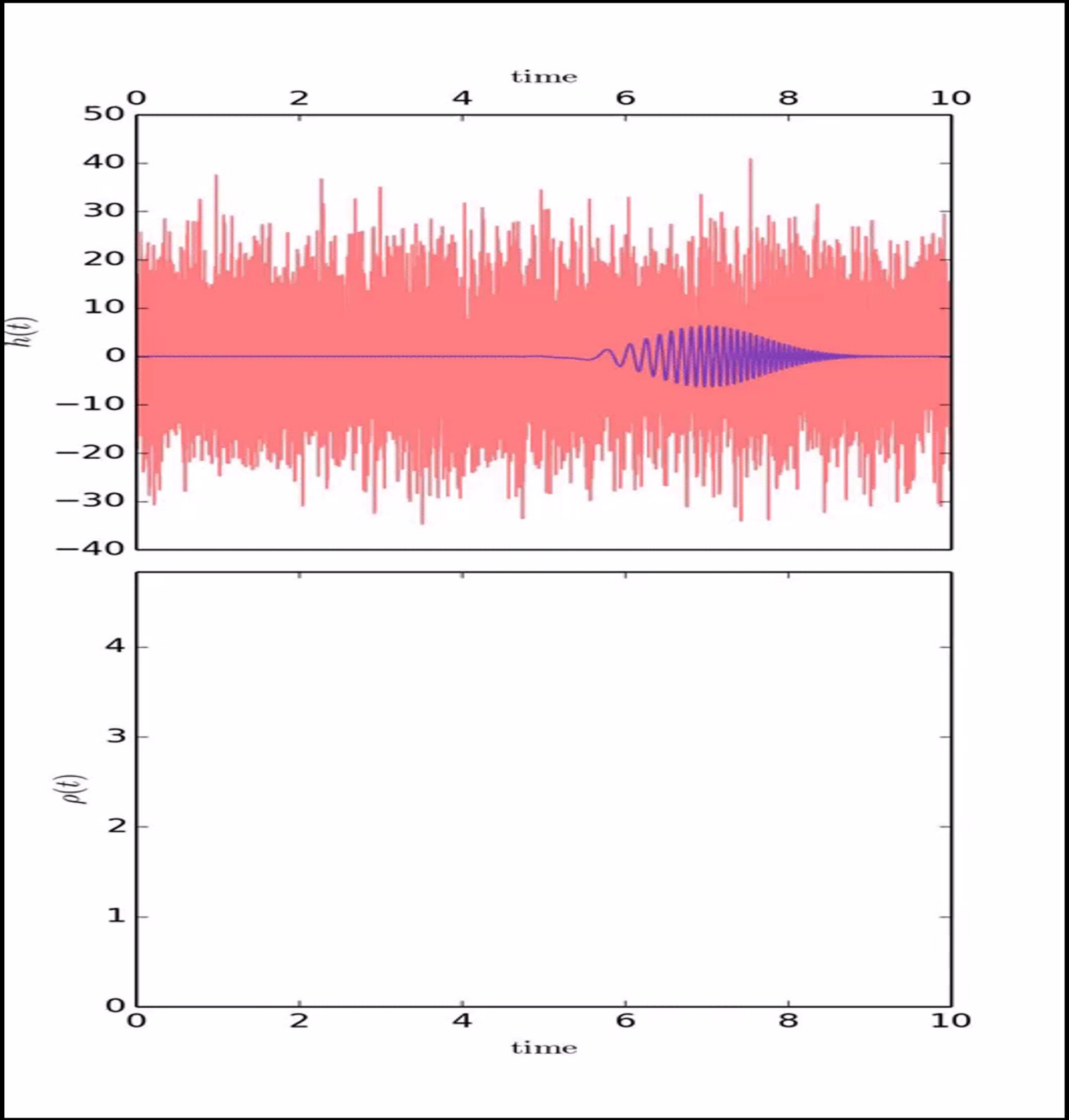
- Advanced LIGO and Advanced Virgo have completed the third observing run and are being upgraded toward LIGO A+ and AdV+ operations (O4: 2023-2024 – O5: 2026-2028)
- Further upgrades are being planned for post-O5

How we detect transient signals: modelled search

Matched-filter

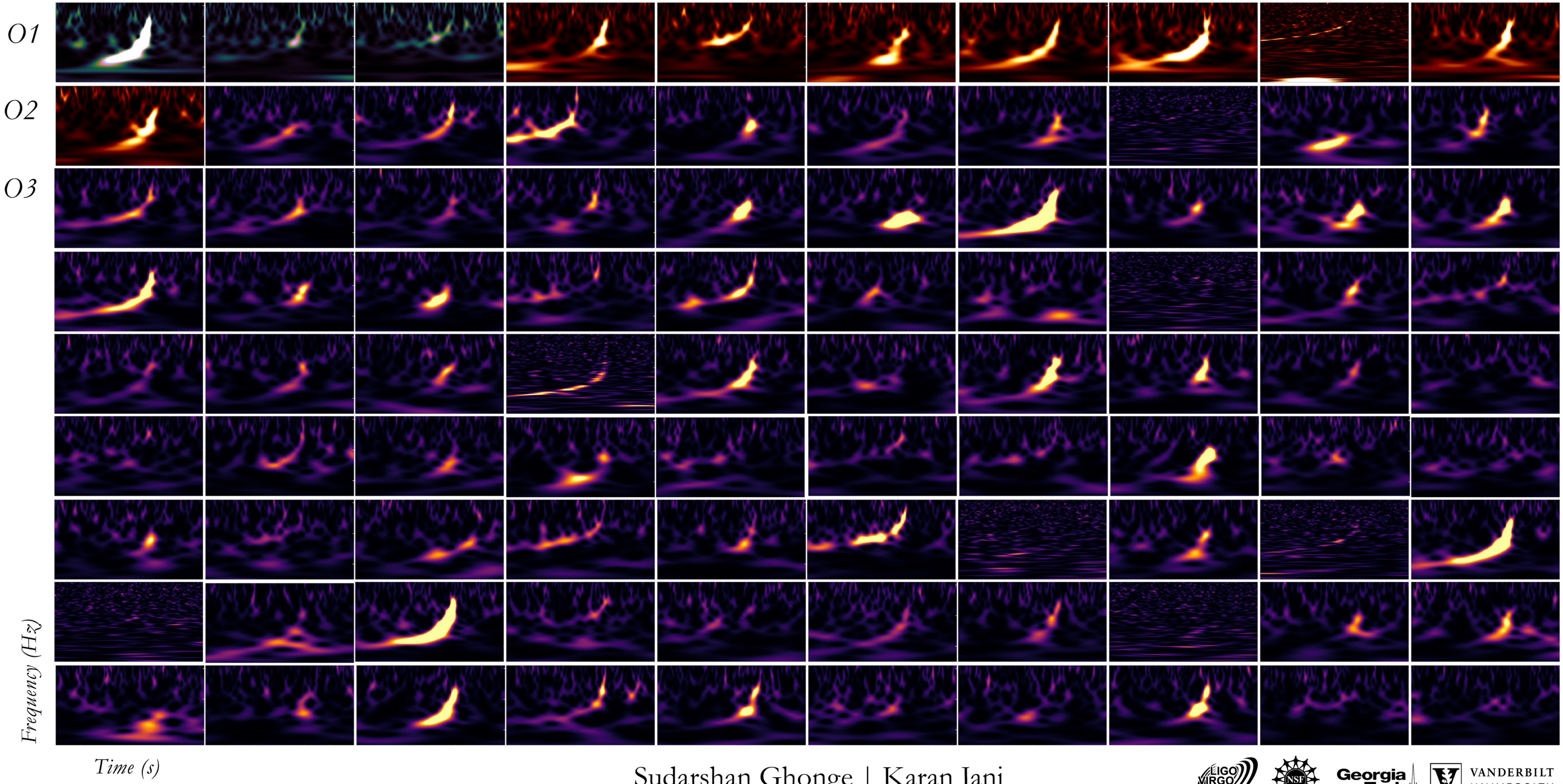


Credits to E. Cuoco et al.



Gravitational-Wave Transient Catalog

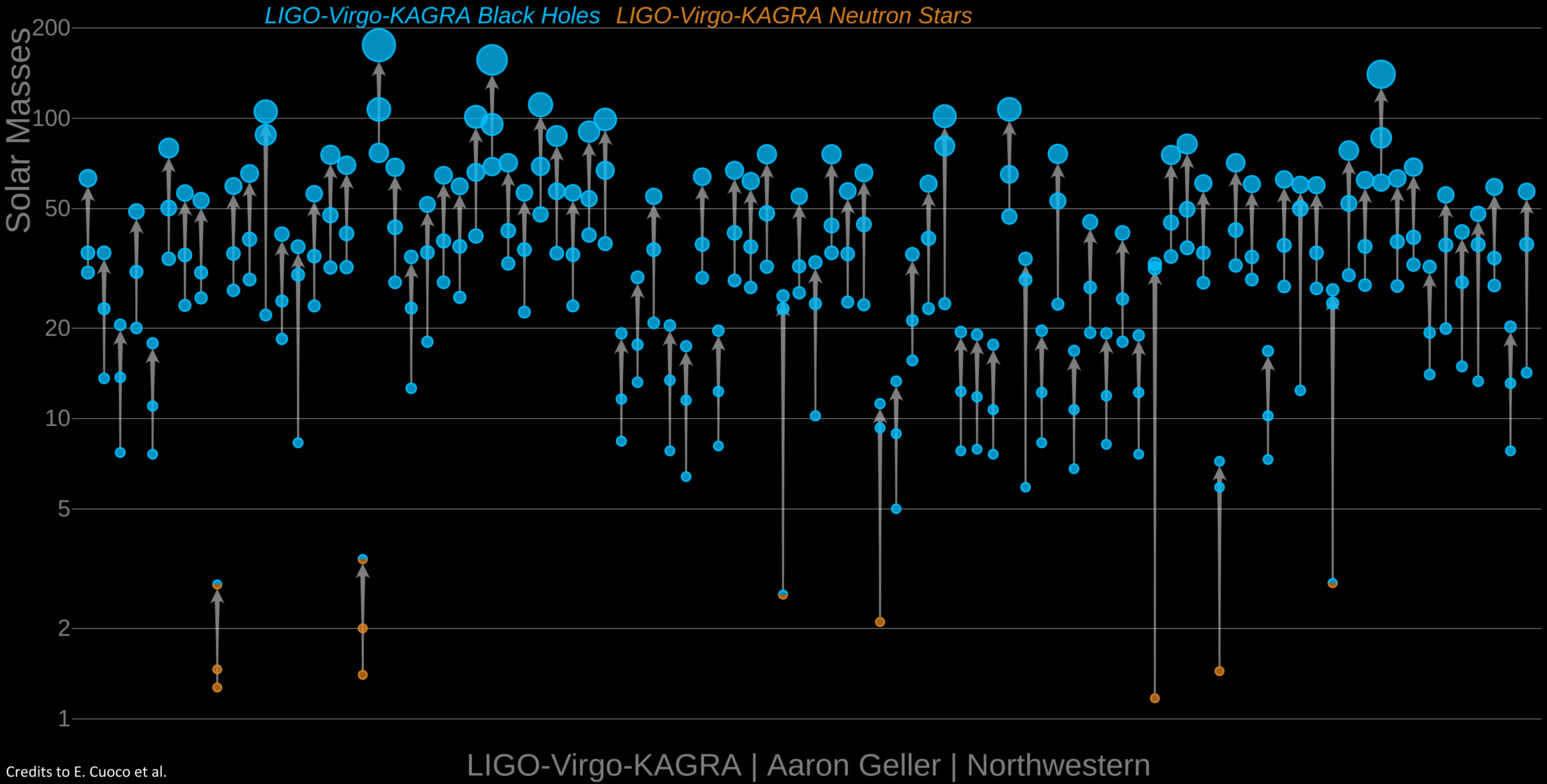
Detections from 2015-2020 of compact binaries with black holes & neutron stars



Sudarshan Ghonge | Karan Jani

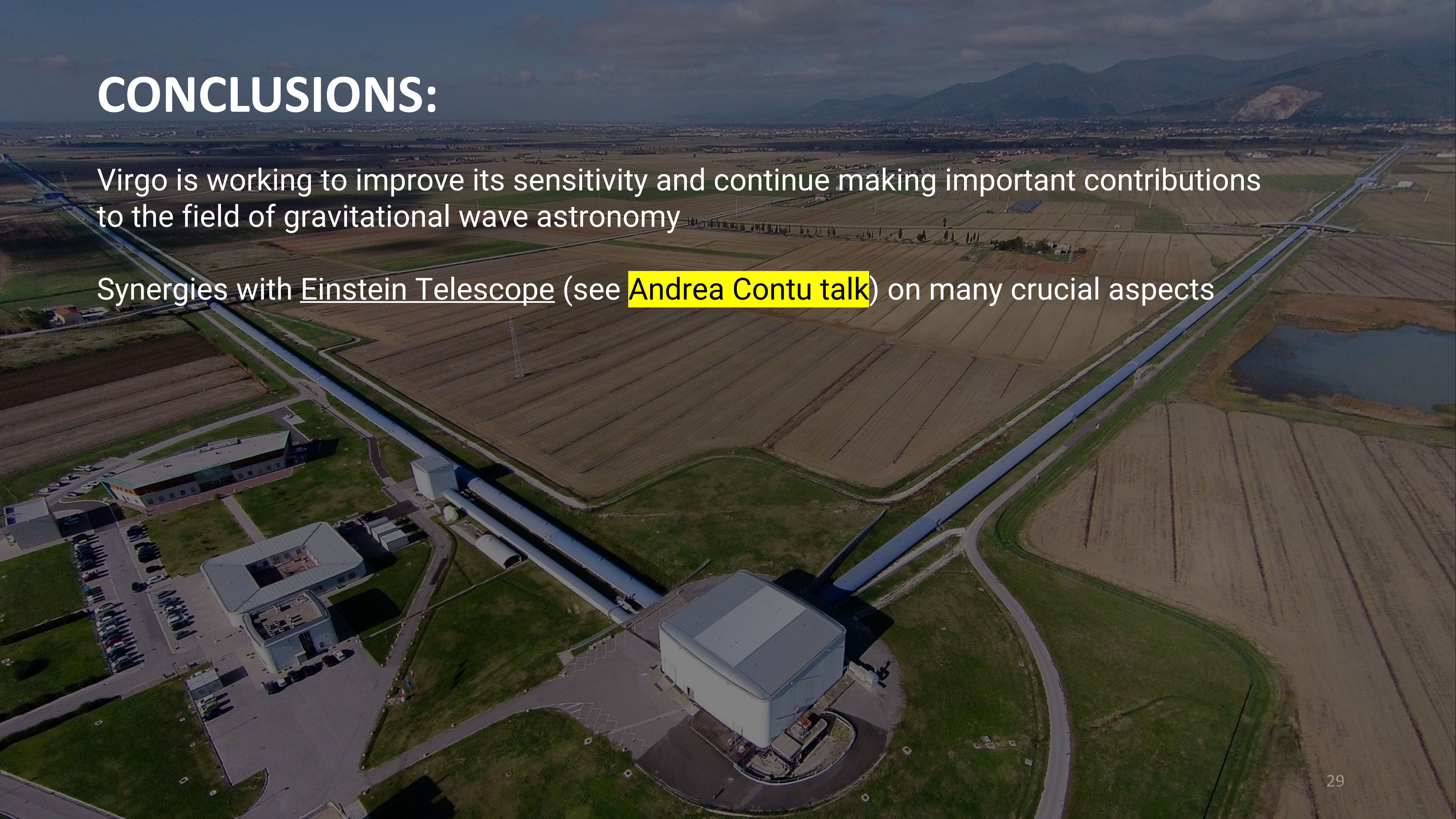
LIGO VIRGO KAGRA | NSF | Georgia Tech | VANDERBILT UNIVERSITY®

Masses in the Stellar Graveyard



Credits to E. Cuoco et al.

CONCLUSIONS:



Virgo is working to improve its sensitivity and continue making important contributions to the field of gravitational wave astronomy

Synergies with Einstein Telescope (see Andrea Contu talk) on many crucial aspects